galpy Documentation

Release v1.1

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May 09, 2022

Contents

galpy is a Python 2 and 3 package for galactic dynamics. It supports orbit integration in a variety of potentials, evaluating and sampling various distribution functions, and the calculation of action-angle coordinates for all static potentials.

CHAPTER 1

Quick-start guide

1.1 Installation

galpy can be installed using pip as:

```
> pip install galpy
```

or to upgrade without upgrading the dependencies:

```
> pip install -U --no-deps galpy
```

Some advanced features require the GNU Scientific Library (GSL; see below). If you want to use these, install the GSL first (or install it later and re-install using the upgrade command above).

The latest updates in galpy can be installed using:

```
> pip install -U --no-deps git+git://github.com/jobovy/galpy.git#egg=galpy
```

or:

```
> pip install -U --no-deps --install-option="--prefix=~/local" git+git://github.com/
↪jobovy/galpy.git#egg=galpy
```

for a local installation. The latest updates can also be installed from the source code downloaded from github using the standard python `setup.py` installation:

```
> python setup.py install
```

or:

```
> python setup.py install --prefix=~/local
```

for a local installation. A basic installation works with just the numpy/scipy/matplotlib stack. Some basic tests can be performed by executing:

```
> nosetests -v -w nose/
```

1.1.1 Advanced installation

Certain advanced features require the GNU Scientific Library (GSL), with action calculations requiring version 1.14 or higher. On a Mac you can make sure that the correct architecture is installed using Homebrew as:

```
> brew install gsl --universal
```

You should be able to check your version using:

```
> gsl-config --version
```

Other advanced features, including calculating the normalization of certain distribution functions using Gauss-Legendre integration require numpy version 1.7.0 or higher.

galpy uses OpenMP to parallelize various of the computations done in C. galpy can be installed without OpenMP by specifying the option `--no-openmp` when running the `python setup.py` commands above or when using pip as follows:

```
> pip install -U --no-deps --install-option="--no-openmp" git+git://github.com/jobovy/
↪galpy.git#egg=galpy
```

or:

```
> pip install -U --no-deps --install-option="--prefix=~/local" --install-option="--no-
↪openmp" git+git://github.com/jobovy/galpy.git#egg=galpy
```

for a local installation. This can be especially useful if one is using the `clang` compiler, which is the new default on macs with OS X (>= 10.8), but does not support OpenMP. This leads to errors in the installation of galpy such as:

```
ld: library not found for -lgomp

clang: error: linker command failed with exit code 1 (use -v to see invocation)
```

If you get these errors, you can use the commands given above to install without OpenMP, or specify to use `gcc` by specifying the `CC` and `LDSHARED` environment variables to use `gcc`.

1.2 Introduction

The most basic features of galpy are its ability to display rotation curves and perform orbit integration for arbitrary combinations of potentials. This section introduce the most basic features of `galpy.potential` and `galpy.orbit`.

1.2.1 Rotation curves

The following code example shows how to initialize a Miyamoto-Nagai disk potential and plot its rotation curve

```
>>> from galpy.potential import MiyamotoNagaiPotential
>>> mp= MiyamotoNagaiPotential(a=0.5,b=0.0375,normalize=1.)
>>> mp.plotRotcurve(Rrange=[0.01,10.],grid=1001)
```

The `normalize=1.` option normalizes the potential such that the radial force is a fraction `normalize=1.` of the radial force necessary to make the circular velocity 1 at R=1.

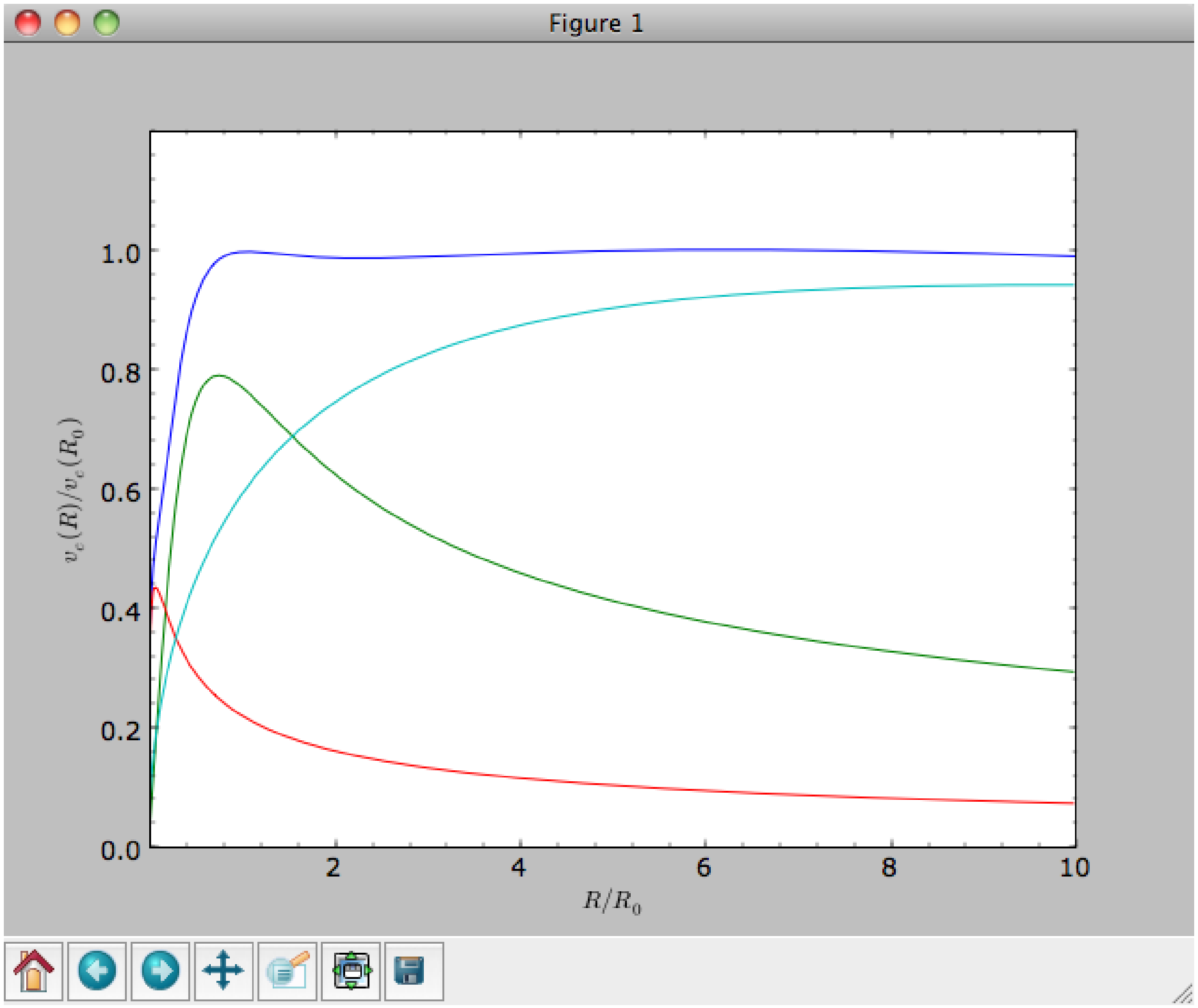
Similarly we can initialize other potentials and plot the combined rotation curve

```
>>> from galpy.potential import NFWPotential, HernquistPotential
>>> mp= MiyamotoNagaiPotential(a=0.5,b=0.0375,normalize=.6)
>>> np= NFWPotential(a=4.5,normalize=.35)
>>> hp= HernquistPotential(a=0.6/8,normalize=0.05)
>>> from galpy.potential import plotRotcurve
>>> plotRotcurve([hp,mp,np],Rrange=[0.01,10.],grid=1001,yrange=[0.,1.2])
```

Note that the `normalize` values add up to 1. such that the circular velocity will be 1 at R=1. The resulting rotation curve is approximately flat. To show the rotation curves of the three components do

```
>>> mp.plotRotcurve(Rrange=[0.01,10.],grid=1001,overplot=True)
>>> hp.plotRotcurve(Rrange=[0.01,10.],grid=1001,overplot=True)
>>> np.plotRotcurve(Rrange=[0.01,10.],grid=1001,overplot=True)
```

You'll see the following



As a shortcut the `[hp,mp,np]` Milky-Way-like potential is defined as

```
>>> from galpy.potential import MWPotential
```

This is *not* the recommended Milky-Way-like potential in `galpy`. The (currently) recommended Milky-Way-like potential is `MWPotential2014`:

```
>>> from galpy.potential import MWPotential2014
```

`MWPotential2014` has a more realistic bulge model and is actually fit to various dynamical constraints on the Milky Way (see *here* and the `galpy` paper).

1.2.2 Units in galpy

Above we normalized the potentials such that they give a circular velocity of 1 at R=1. These are the standard galpy units (sometimes referred to as *natural units* in the documentation). galpy will work most robustly when using these natural units. When using galpy to model a real galaxy with, say, a circular velocity of 220 km/s at R=8 kpc, all of the velocities should be scaled as v= V/[220 km/s] and all of the positions should be scaled as x = X/[8 kpc] when using galpy's natural units.

For convenience, a utility module `bovy_conversion` is included in galpy that helps in converting between physical units and natural units for various quantities. For example, in natural units the orbital time of a circular orbit at R=1 is 2π; in physical units this corresponds to

```
>>> from galpy.util import bovy_conversion
>>> print 2.*numpy.pi*bovy_conversion.time_in_Gyr(220.,8.)
0.223405444283
```

or about 223 Myr. We can also express forces in various physical units. For example, for the Milky-Way-like potential defined in galpy, we have that the vertical force at 1.1 kpc is

```
>>> from galpy.potential import MWPotential2014, evaluatezforces
>>> -evaluatezforces(1.,1.1/8.,MWPotential2014)*bovy_conversion.force_in_pcMyr2(220.,
↪8.)
2.0259181908629933
```

which we can also express as an equivalent surface-density by dividing by $2\pi G$

```
>>> -evaluatezforces(1.,1.1/8.,MWPotential2014)*bovy_conversion.force_in_
↪2piGmsolpc2(220.,8.)
71.658016957792356
```

Because the vertical force at the solar circle in the Milky Way at 1.1 kpc above the plane is approximately $70\,(2\pi G\,M_\odot\,\mathrm{pc}^{-2})$ (e.g., 2013arXiv1309.0809B), this shows that our Milky-Way-like potential has a realistic disk (at least in this respect).

`bovy_conversion` further has functions to convert densities, masses, surface densities, and frequencies to physical units (actions are considered to be too obvious to be included); see *here* for a full list. As a final example, the local dark matter density in the Milky-Way-like potential is given by

```
>>> MWPotential2014[2].dens(1.,0.)*bovy_conversion.dens_in_msolpc3(220.,8.)
0.0075419566970079373
```

or

```
>>> MWPotential2014[2].dens(1.,0.)*bovy_conversion.dens_in_gevcc(220.,8.)
0.28643101789044584
```

or about $0.0075\,M_\odot\,\mathrm{pc}^{-3} \approx 0.3\,\mathrm{GeV\,cm}^{-3}$, in line with current measurements (e.g., 2012ApJ...756...89B).

When `galpy` Orbits are initialized using a distance scale `ro=` and a velocity scale `vo=` output quantities returned and plotted in physical coordinates. Specifically, positions are are returned in units of kpc, velocities in km/s, energies and the Jacobi integral in (km/s)^2, the angular momentum o.L() and actions in km/s kpc, frequencies in 1/Gyr, and times and periods in Gyr.

1.2.3 Orbit integration

We can also integrate orbits in all galpy potentials. Going back to a simple Miyamoto-Nagai potential, we initialize an orbit as follows

```
>>> from galpy.orbit import Orbit
>>> mp= MiyamotoNagaiPotential(a=0.5,b=0.0375,amp=1.,normalize=1.)
>>> o= Orbit(vxvv=[1.,0.1,1.1,0.,0.1])
```

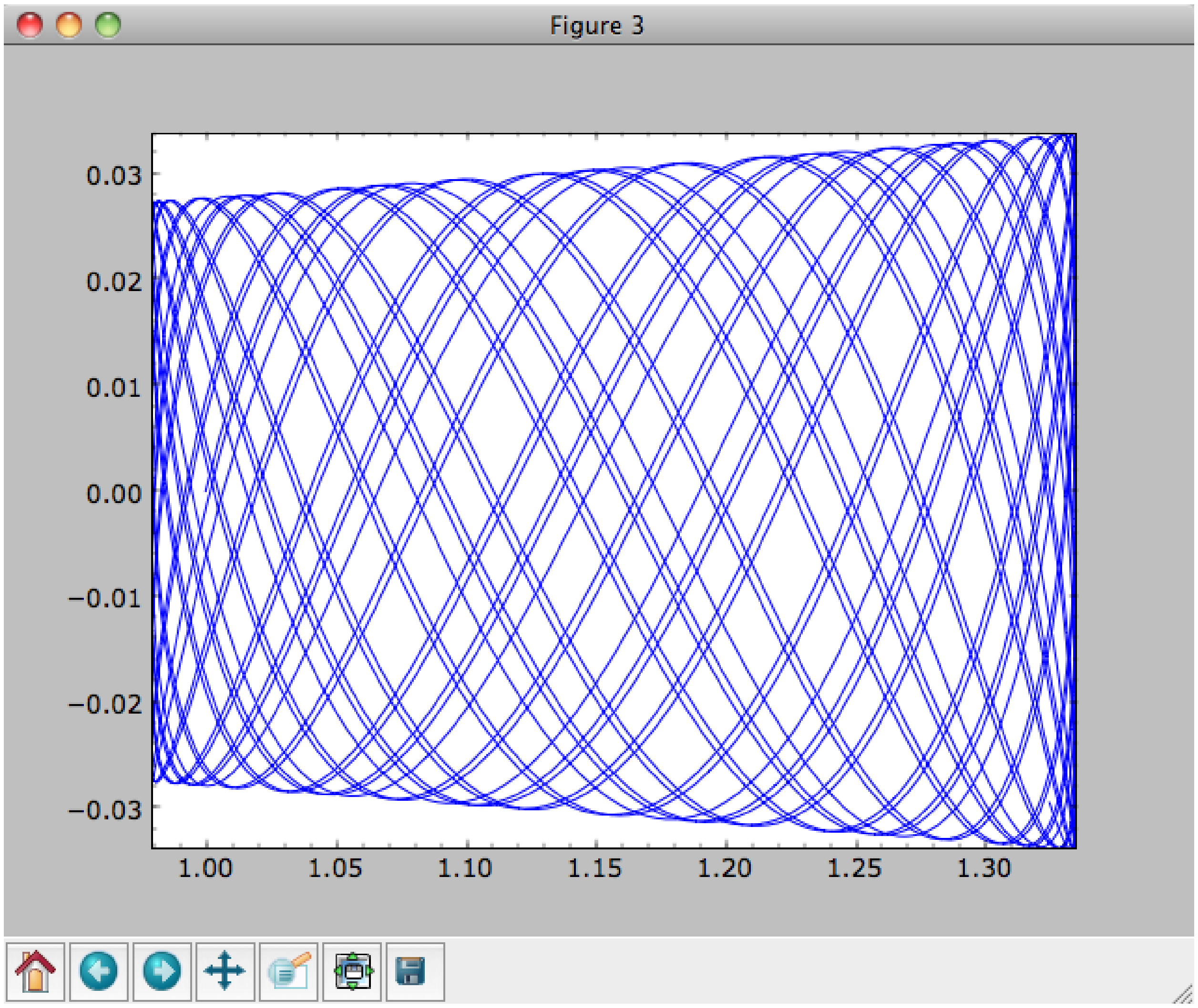
Since we gave `Orbit()` a five-dimensional initial condition `[R,vR,vT,z,vz]`, we assume we are dealing with a three-dimensional axisymmetric potential in which we do not wish to track the azimuth. We then integrate the orbit for a set of times `ts`

```
>>> import numpy
>>> ts= numpy.linspace(0,100,10000)
>>> o.integrate(ts,mp,nethod='odeint')
```

Now we plot the resulting orbit as

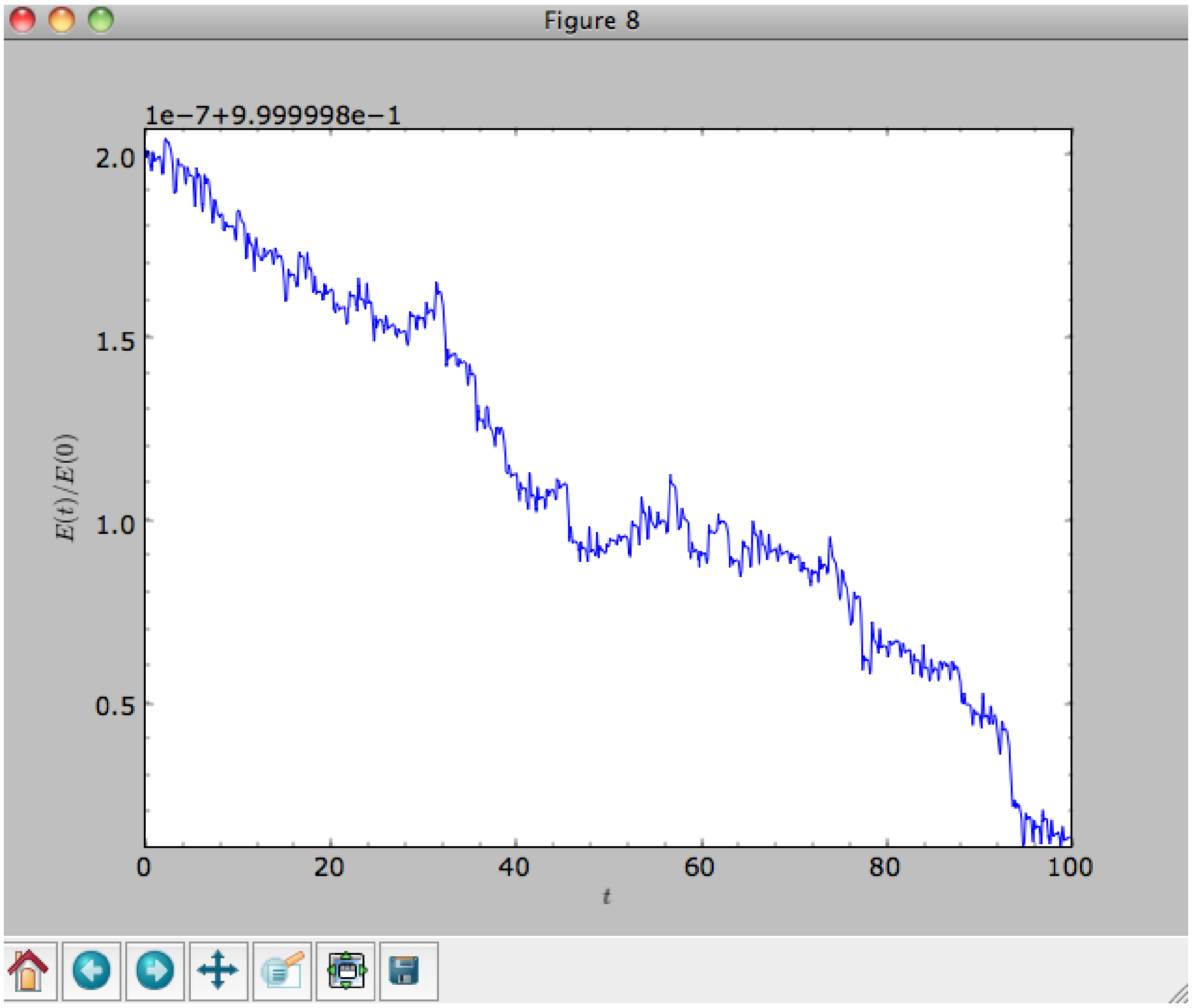
```
>>> o.plot()
```

Which gives



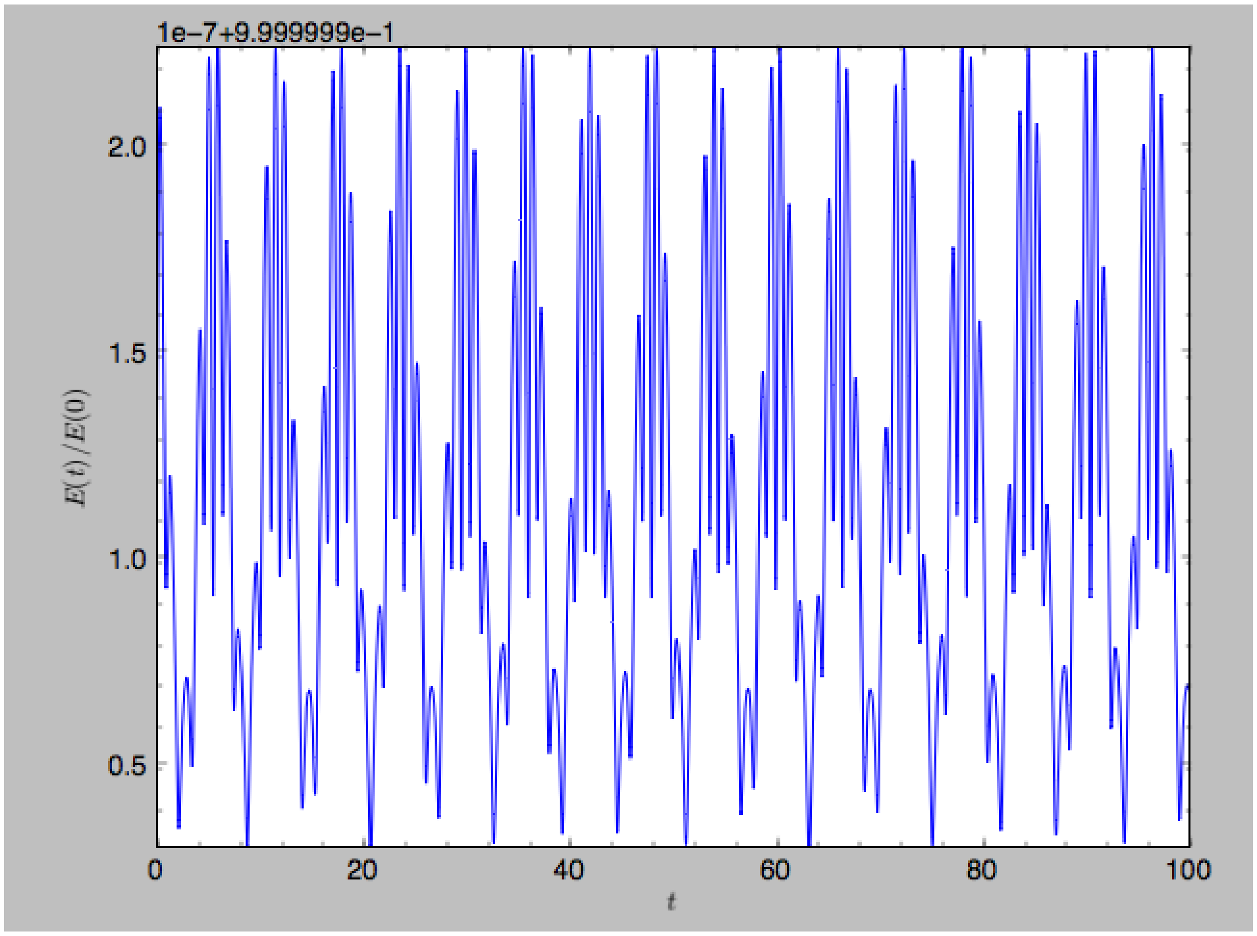
The integrator used is not symplectic, so the energy error grows with time, but is small nonetheless

```
>>> o.plotE(normed=True)
```



When we use a symplectic leapfrog integrator, we see that the energy error remains constant

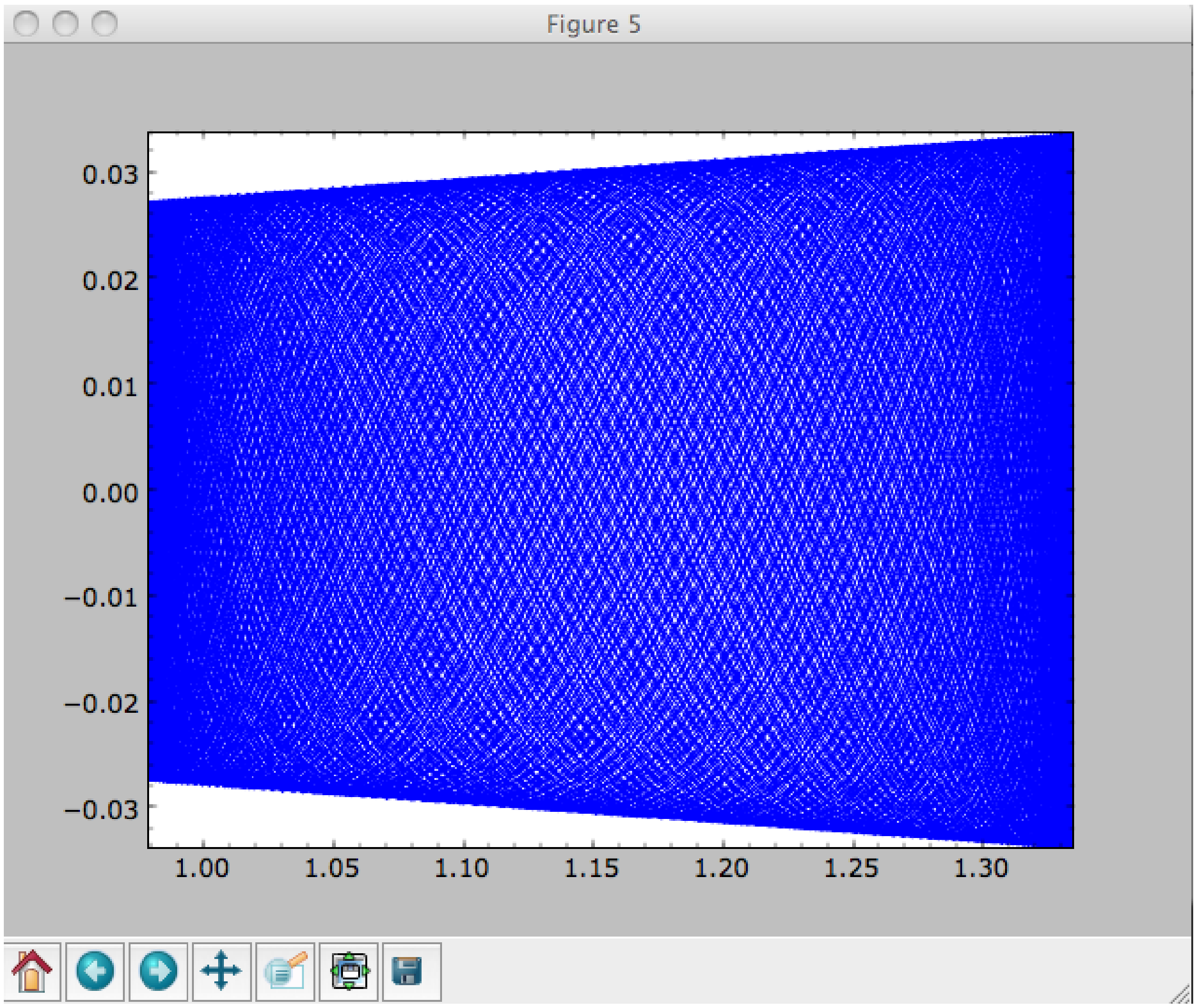
```
>>> o.integrate(ts,mp,method='leapfrog')
>>> o.plotE(xlabel=r'$t$',ylabel=r'$E(t)/E(0)$')
```



Because stars have typically only orbited the center of their galaxy tens of times, using symplectic integrators is mostly unnecessary (compared to planetary systems which orbits millions or billions of times). galpy contains fast integrators written in C, which can be accessed through the `method=` keyword (e.g., `integrate(..., method='dopr54_c')` is a fast high-order Dormand-Prince method).

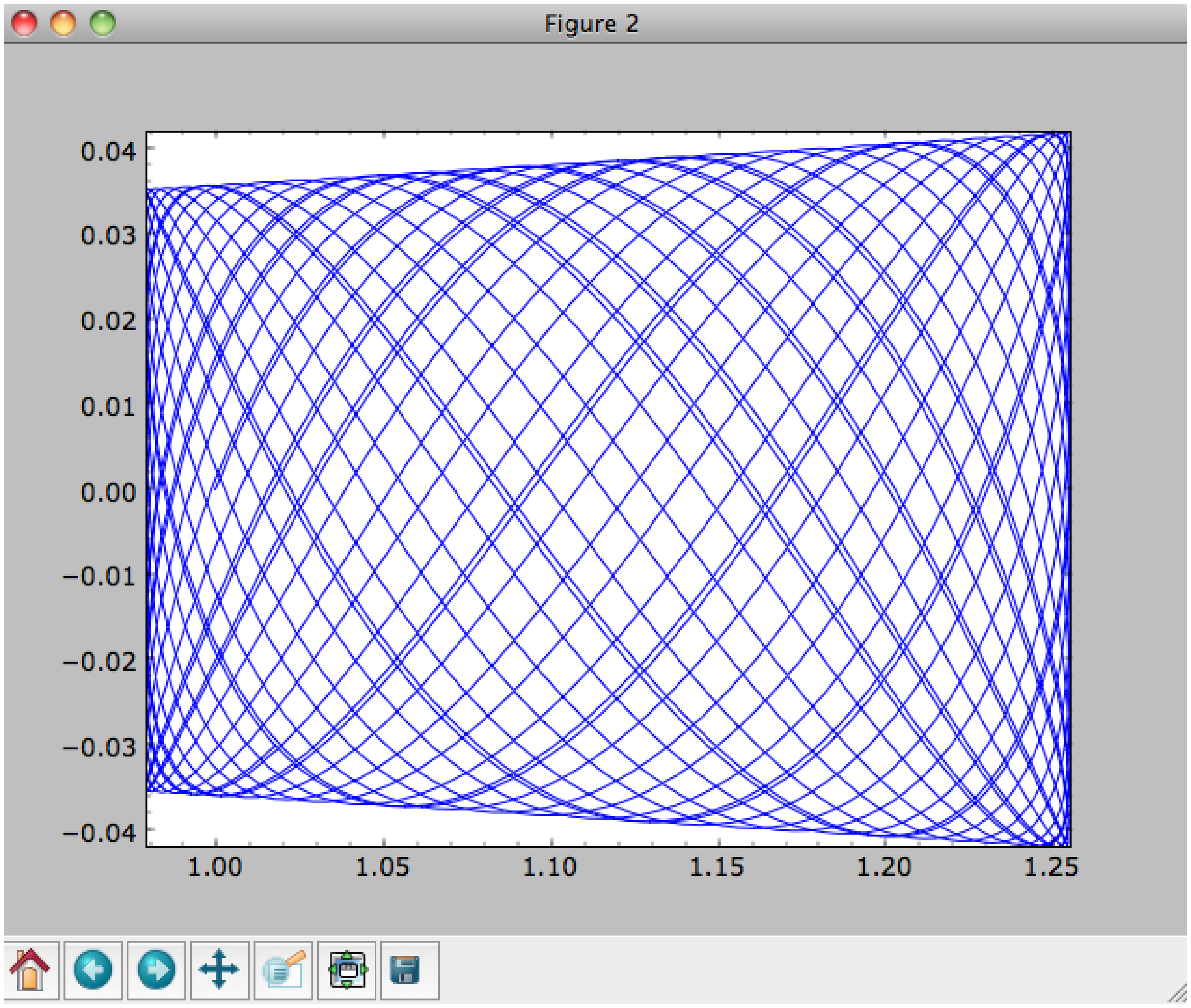
When we integrate for much longer we see how the orbit fills up a torus (this could take a minute)

```
>>> ts= numpy.linspace(0,1000,10000)
>>> o.integrate(ts,mp,method='odeint')
>>> o.plot()
```



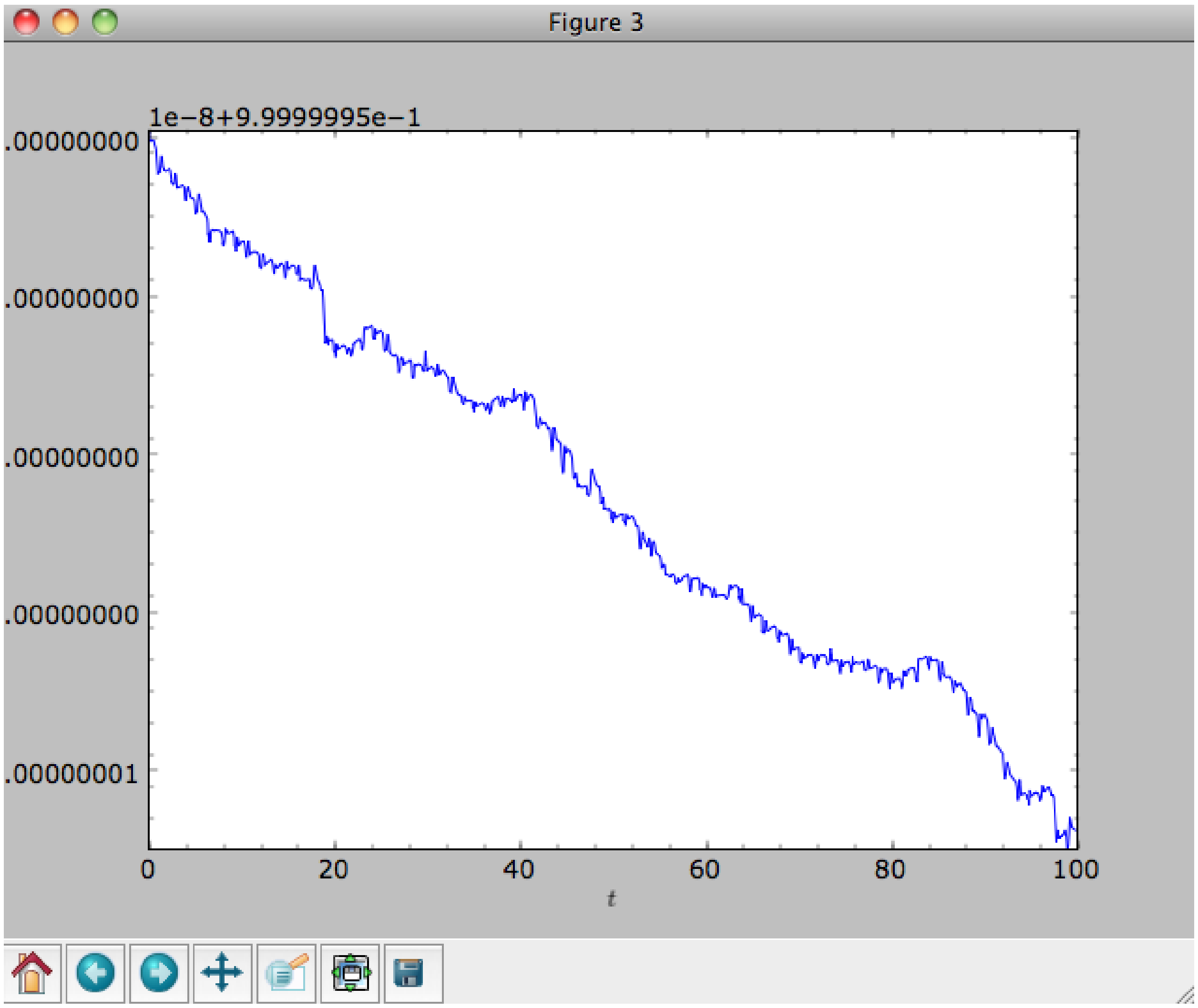
As before, we can also integrate orbits in combinations of potentials. Assuming `mp`, `np`, and `hp` were defined as above, we can

```
>>> ts= numpy.linspace(0,100,10000)
>>> o.integrate(ts,[mp,hp,np])
>>> o.plot()
```



Energy is again approximately conserved

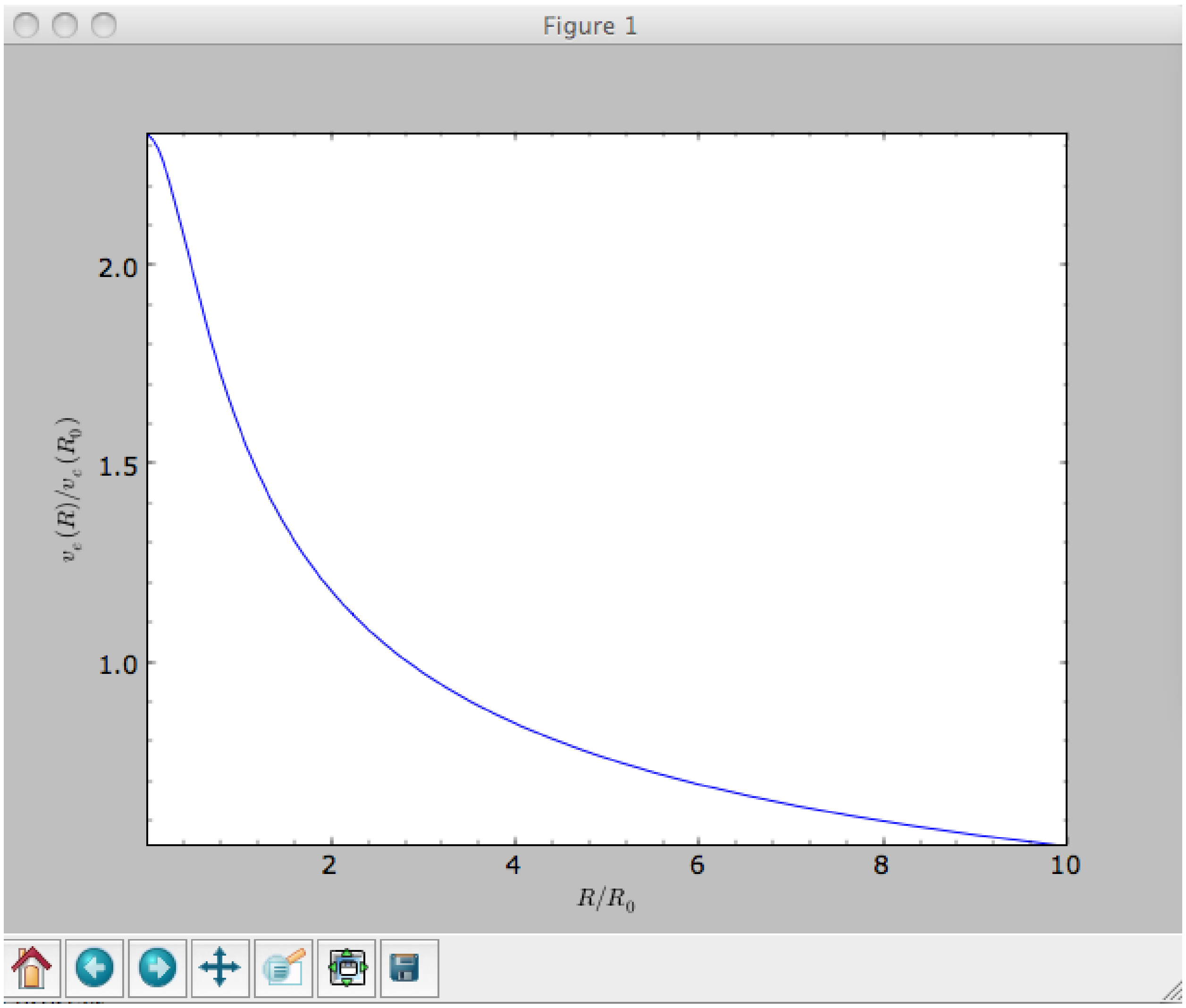
```
>>> o.plotE(xlabel=r'$t$',ylabel=r'$E(t)/E(0)$')
```



1.2.4 Escape velocity curves

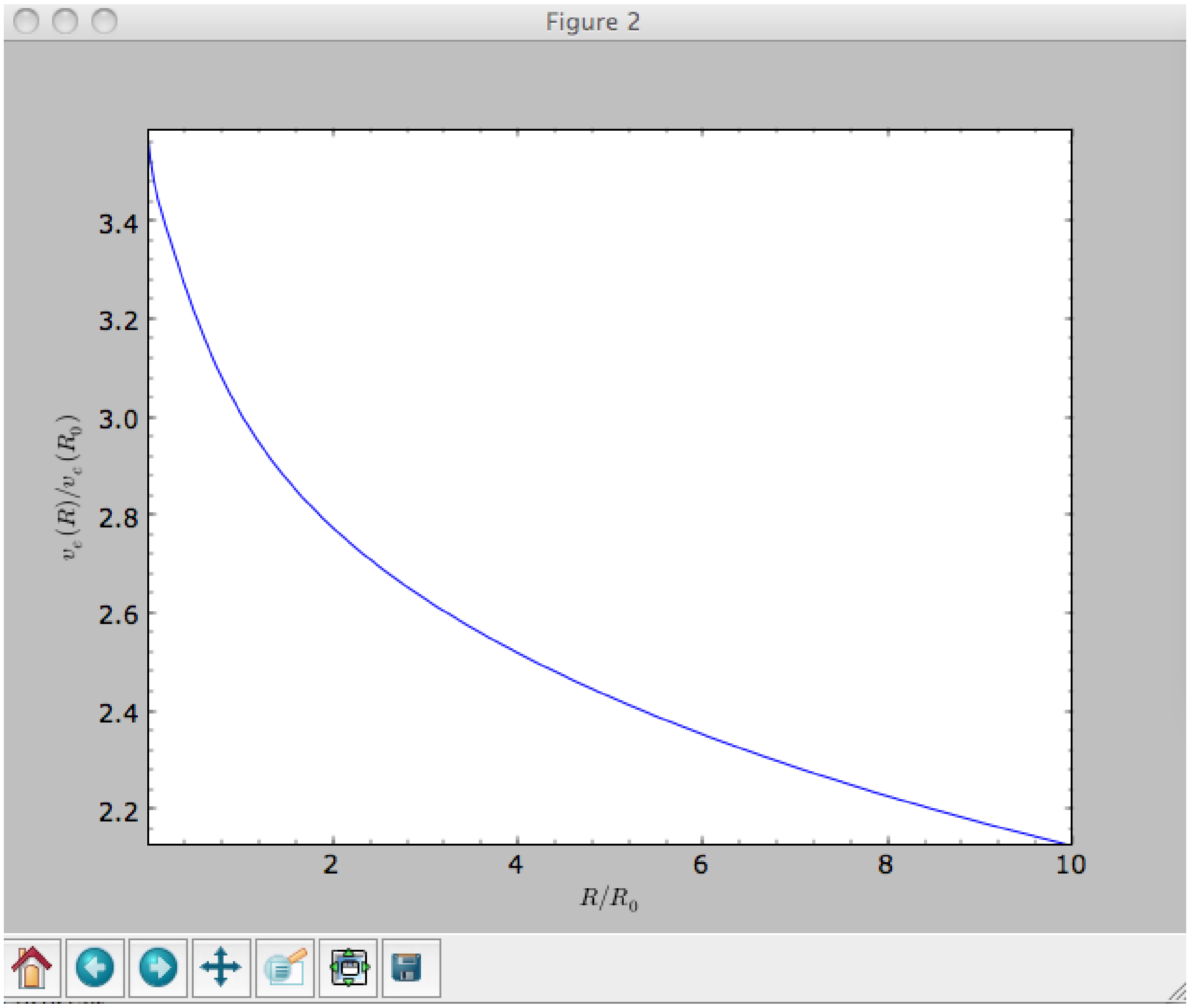
Just like we can plot the rotation curve for a potential or a combination of potentials, we can plot the escape velocity curve. For example, the escape velocity curve for the Miyamoto-Nagai disk defined above

```
>>> mp.plotEscapecurve(Rrange=[0.01,10.],grid=1001)
```



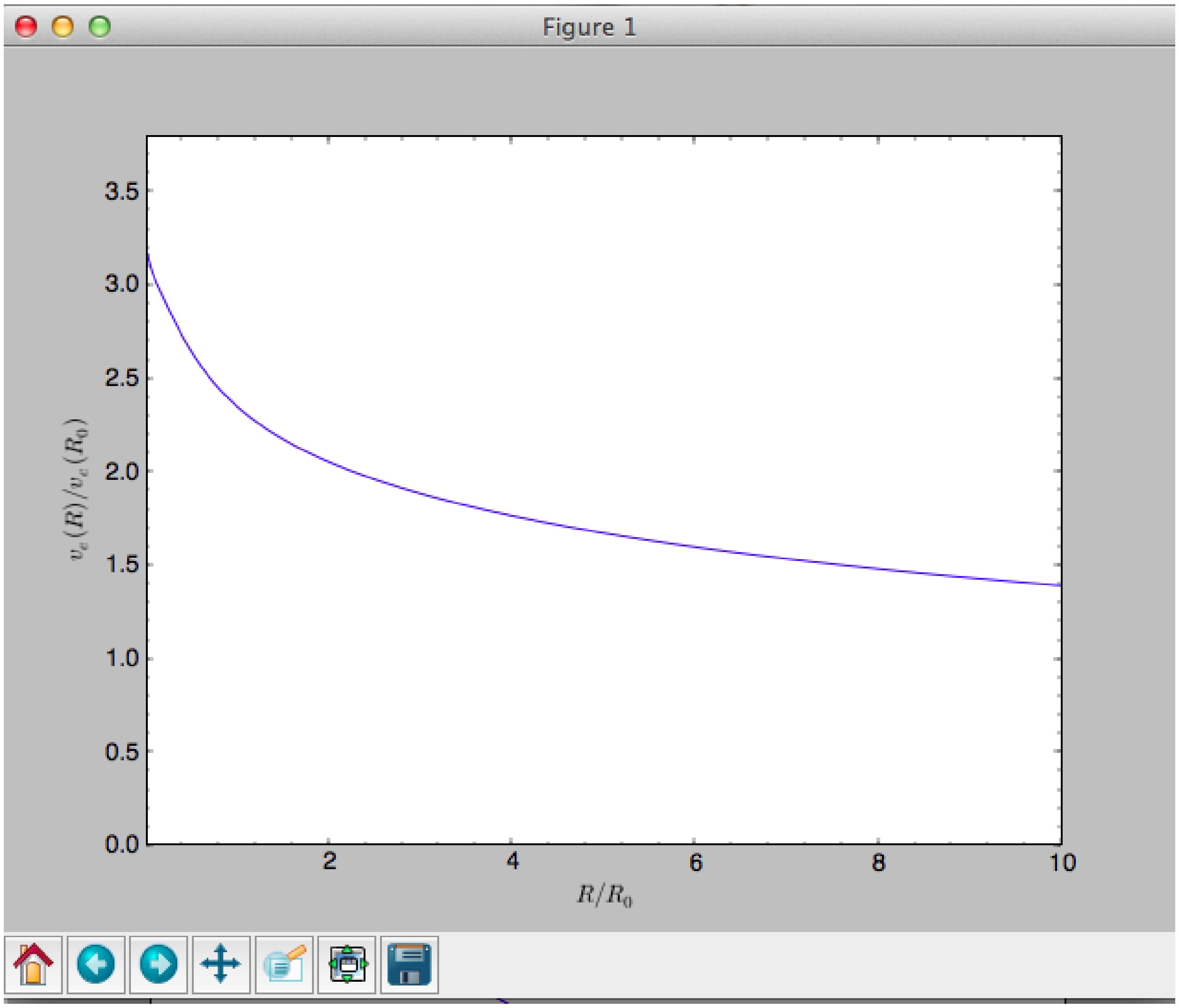
or of the combination of potentials defined above

```
>>> from galpy.potential import plotEscapecurve
>>> plotEscapecurve([mp,hp,np],Rrange=[0.01,10.],grid=1001)
```



For the Milky-Way-like potential `MWPotential2014`, the escape-velocity curve is

```
>>> plotEscapecurve(MWPotential2014,Rrange=[0.01,10.],grid=1001)
```



At the solar radius, the escape velocity is

```
>>> from galpy.potential import vesc
>>> vesc(MWPotential2014,1.)
2.3316389848832784
```

Or, for a local circular velocity of 220 km/s

```
>>> vesc(MWPotential2014,1.)*220.
512.96057667432126
```

similar to direct measurements of this (e.g., 2007MNRAS.379..755S and 2014A%26A…562A..91P).

1.3 Potentials in galpy

galpy contains a large variety of potentials in `galpy.potential` that can be used for orbit integration, the calculation of action-angle coordinates, as part of steady-state distribution functions, and to study the properties of gravitational potentials. This section introduces some of these features.

1.3.1 Potentials and forces

Various 3D and 2D potentials are contained in galpy, list in the *API page*. Another way to list the latest overview of potentials included with galpy is to run

```
>>> import galpy.potential
>>> print [p for p in dir(galpy.potential) if 'Potential' in p]
['CosmphiDiskPotential',
 'DehnenBarPotential',
 'DoubleExponentialDiskPotential',
 'EllipticalDiskPotential',
 'FlattenedPowerPotential',
 'HernquistPotential',
....]
```

(list cut here for brevity). Section *Rotation curves* explains how to initialize potentials and how to display the rotation curve of single Potential instances or of combinations of such instances. Similarly, we can evaluate a Potential instance

```
>>> from galpy.potential import MiyamotoNagaiPotential
>>> mp= MiyamotoNagaiPotential(a=0.5,b=0.0375,normalize=1.)
>>> mp(1.,0.)
-1.2889062500000001
```

Most member functions of Potential instances have corresponding functions in the galpy.potential module that allow them to be evaluated for lists of multiple Potential instances. `galpy.potential.MWPotential2014` is such a list of three Potential instances

```
>>> from galpy.potential import MWPotential2014
>>> print MWPotential2014
[<galpy.potential_src.PowerSphericalPotentialwCutoff.PowerSphericalPotentialwCutoff␣
↪instance at 0x1089b23b0>, <galpy.potential_src.MiyamotoNagaiPotential.
↪MiyamotoNagaiPotential instance at 0x1089b2320>, <galpy.potential_src.
↪TwoPowerSphericalPotential.NFWPotential instance at 0x1089b2248>]
```

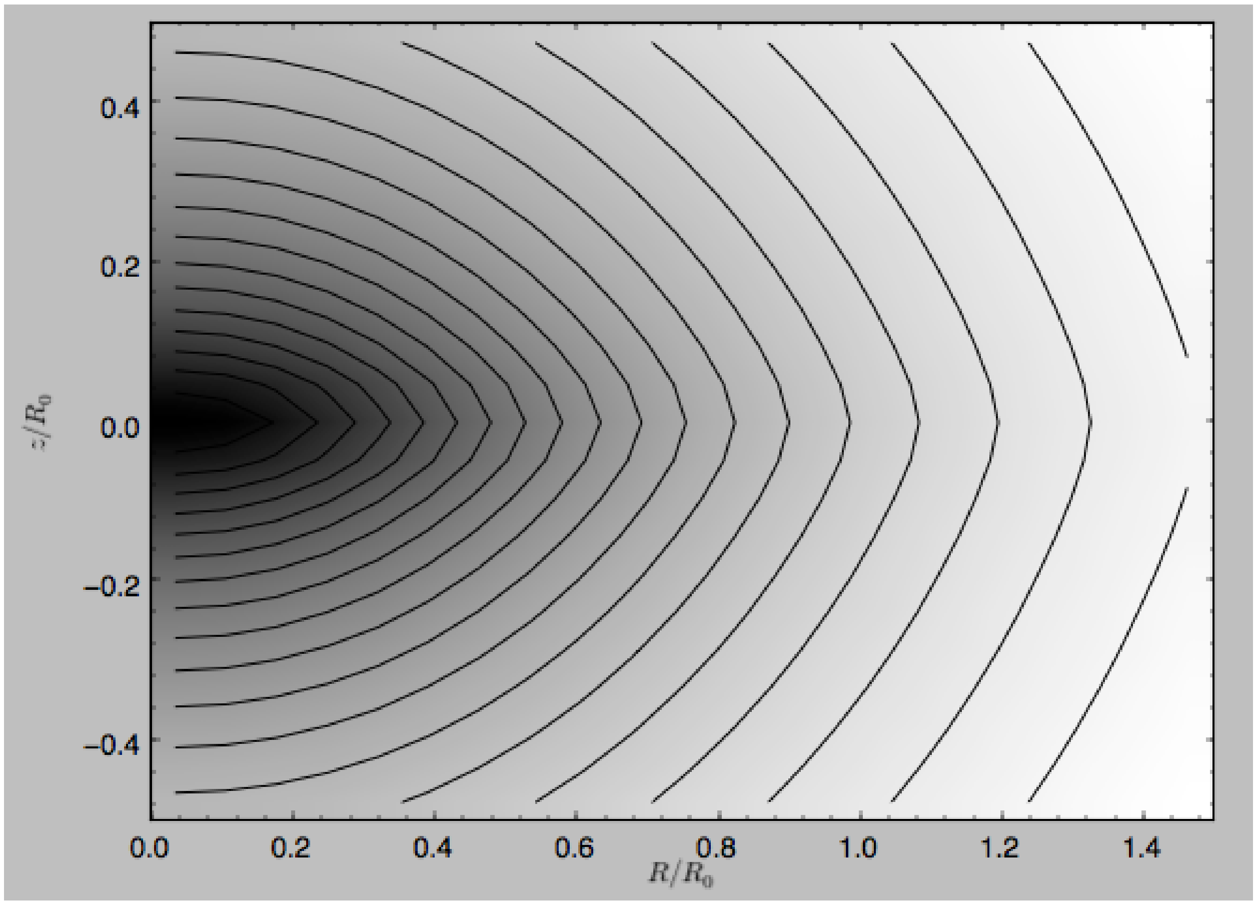
and we can evaluate the potential by using the `evaluatePotentials` function

```
>>> from galpy.potential import evaluatePotentials
>>> evaluatePotentials(1.,0.,MWPotential2014)
-1.3733506513947895
```

We can plot the potential of axisymmetric potentials (or of non-axisymmetric potentials at phi=0) using the `plot` member function

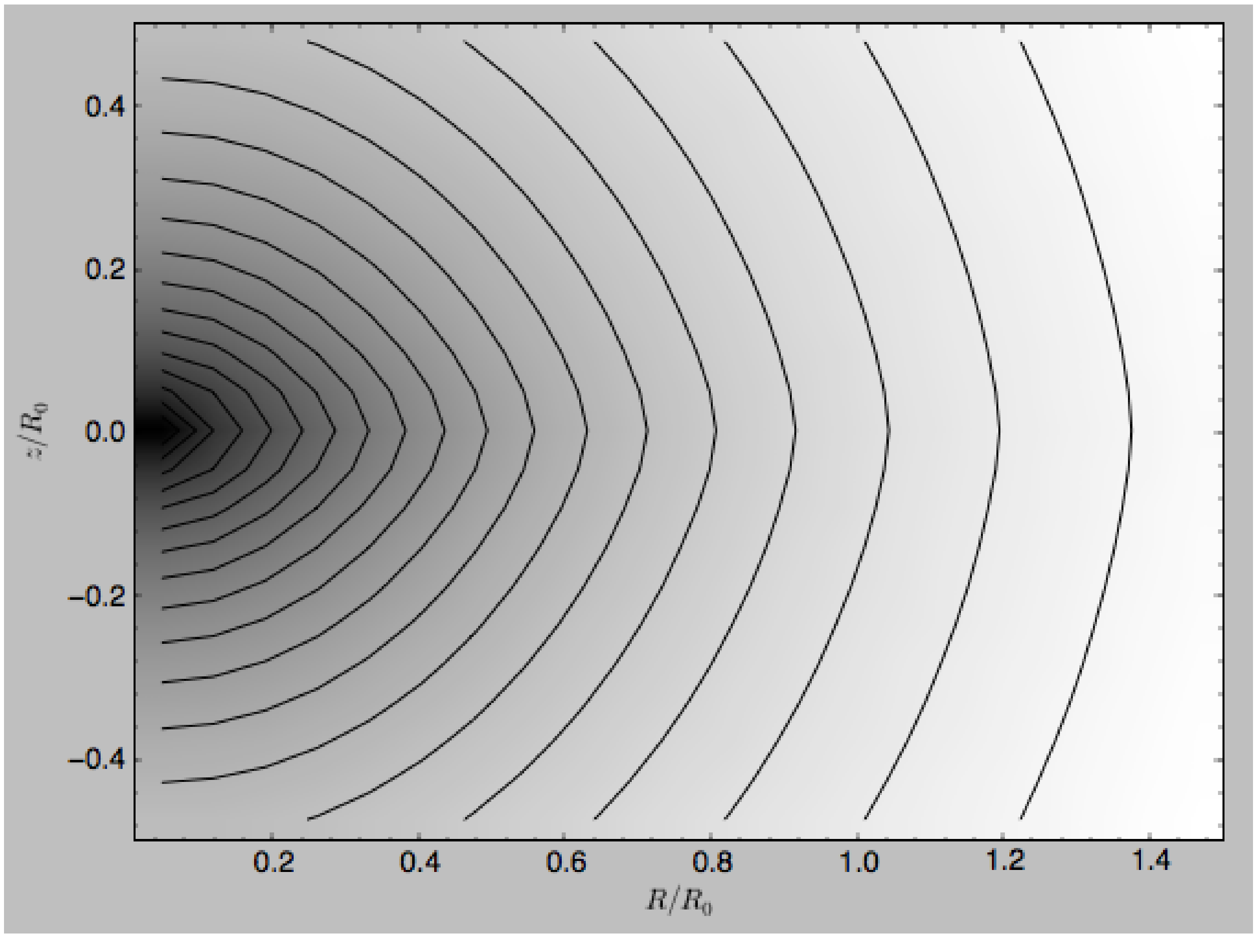
```
>>> mp.plot()
```

which produces the following plot



Similarly, we can plot combinations of Potentials using `plotPotentials`, e.g.,

```
>>> from galpy.potential import plotPotentials
>>> plotPotentials(MWPotential2014,rmin=0.01)
```



These functions have arguments that can provide custom `R` and `z` ranges for the plot, the number of grid points, the number of contours, and many other parameters determining the appearance of these figures.

galpy also allows the forces corresponding to a gravitational potential to be calculated. Again for the Miyamoto-Nagai Potential instance from above

```
>>> mp.Rforce(1.,0.)
-1.0
```

This value of -1.0 is due to the normalization of the potential such that the circular velocity is 1. at R=1. Similarly, the vertical force is zero in the mid-plane

```
>>> mp.zforce(1.,0.)
-0.0
```

but not further from the mid-plane

```
>>> mp.zforce(1.,0.125)
-0.53488743705310848
```

As explained in *Units in galpy*, these forces are in standard galpy units, and we can convert them to physical units using methods in the `galpy.util.bovy_conversion` module. For example, assuming a physical circular velocity of 220 km/s at R=8 kpc

```
>>> from galpy.util import bovy_conversion
>>> mp.zforce(1.,0.125)*bovy_conversion.force_in_kmsMyr(220.,8.)
-3.3095671288657584 #km/s/Myr
>>> mp.zforce(1.,0.125)*bovy_conversion.force_in_2piGmsolpc2(220.,8.)
-119.72021771473301 #2 \pi G Msol / pc^2
```

Again, there are functions in `galpy.potential` that allow for the evaluation of the forces for lists of Potential instances, such that

```
>>> from galpy.potential import evaluateRforces
>>> evaluateRforces(1.,0.,MWPotential2014)
-1.0
>>> from galpy.potential import evaluatezforces
>>> evaluatezforces(1.,0.125,MWPotential2014)*bovy_conversion.force_in_
↪2piGmsolpc2(220.,8.)
>>> -69.680720137571114 #2 \pi G Msol / pc^2
```

We can evaluate the flattening of the potential as $\sqrt{|z\,F_R/R\,F_Z|}$ for a Potential instance as well as for a list of such instances

```
>>> mp.flattening(1.,0.125)
0.4549542914935209
>>> from galpy.potential import flattening
>>> flattening(MWPotential2014,1.,0.125)
0.61231675305658628
```

1.3.2 Densities

galpy can also calculate the densities corresponding to gravitational potentials. For many potentials, the densities are explicitly implemented, but if they are not, the density is calculated using the Poisson equation (second derivatives of the potential have to be implemented for this). For example, for the Miyamoto-Nagai potential, the density is explicitly implemented

```
>>> mp.dens(1.,0.)
1.1145444383277576
```

and we can also calculate this using the Poisson equation

```
>>> mp.dens(1.,0.,forcepoisson=True)
1.1145444383277574
```

which are the same to machine precision

```
>>> mp.dens(1.,0.,forcepoisson=True)-mp.dens(1.,0.)
-2.2204460492503131e-16
```

Similarly, all of the potentials in `galpy.potential.MWPotential2014` have explicitly-implemented densities, so we can do

```
>>> from galpy.potential import evaluateDensities
>>> evaluateDensities(1.,0.,MWPotential2014)
0.57508603122264867
```

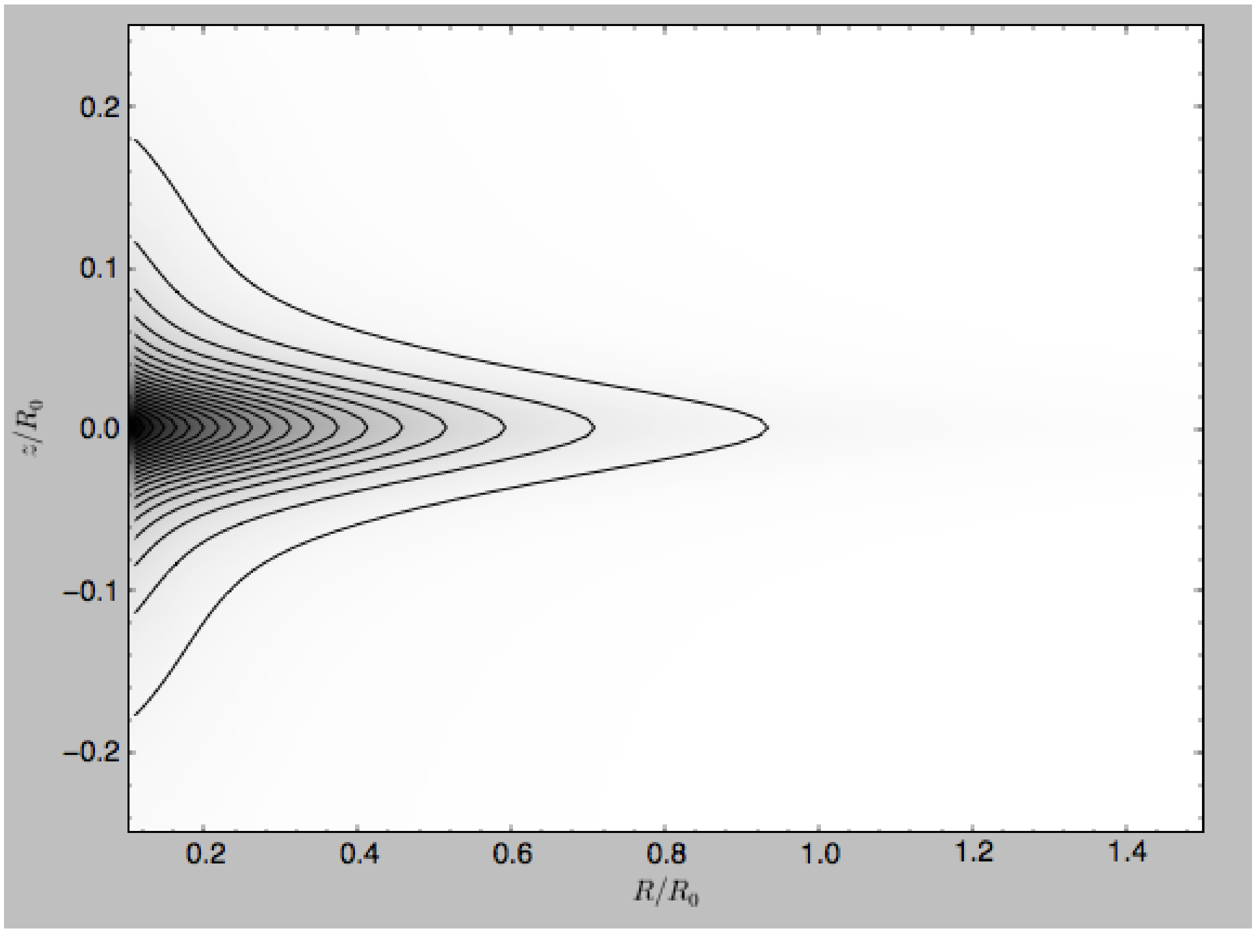
In physical coordinates, this becomes

```
>>> evaluateDensities(1.,0.,MWPotential2014)*bovy_conversion.dens_in_msolpc3(220.,8.)
0.1010945632524705 #Msol / pc^3
```

We can also plot densities

```
>>> from galpy.potential import plotDensities
>>> plotDensities(MWPotential2014,rmin=0.1,zmax=0.25,zmin=-0.25,nrs=101,nzs=101)
```

which gives



Another example of this is for an exponential disk potential

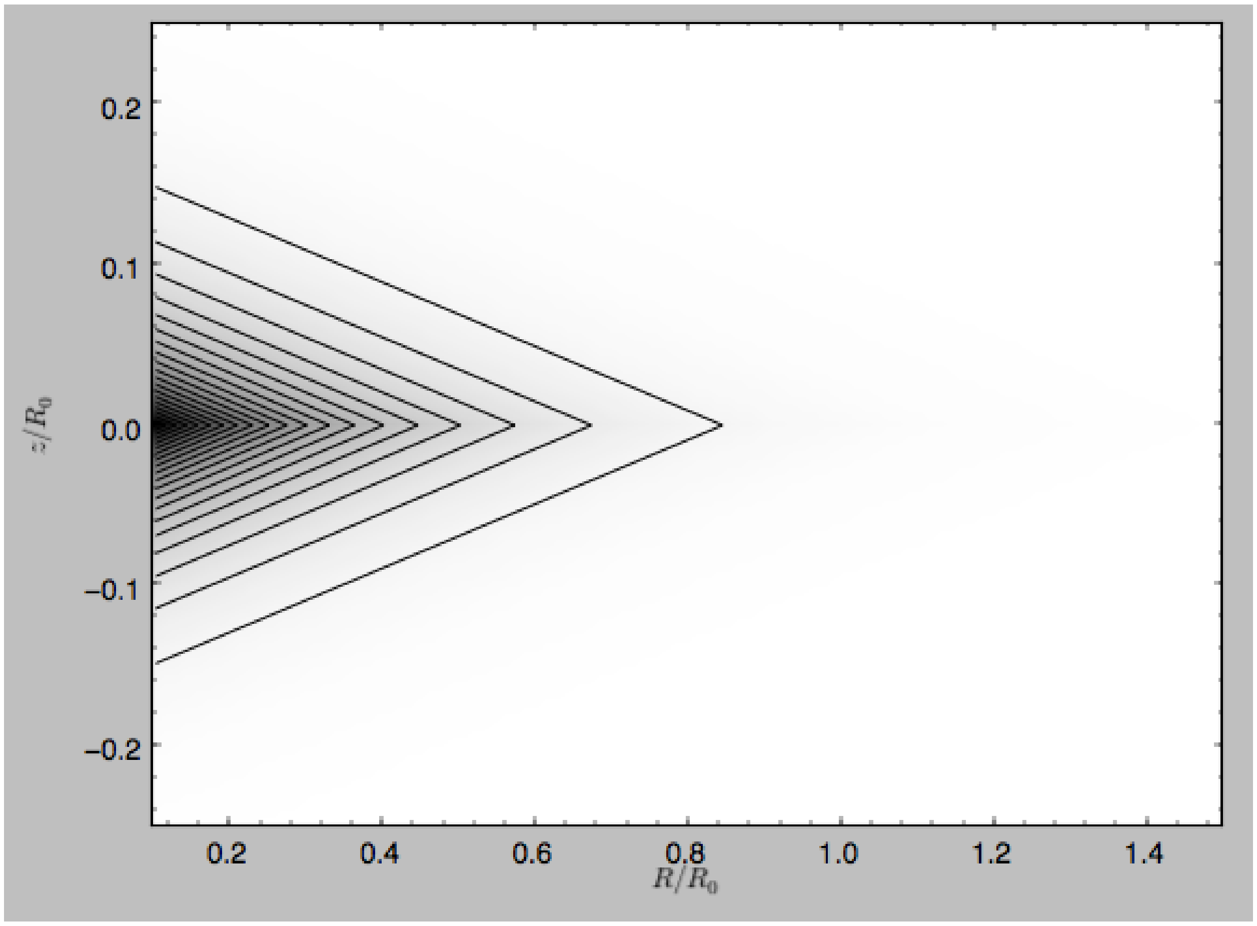
```
>>> from galpy.potential import DoubleExponentialDiskPotential
>>> dp= DoubleExponentialDiskPotential(hr=1./4.,hz=1./20.,normalize=1.)
```

The density computed using the Poisson equation now requires multiple numerical integrations, so the agreement between the analytical density and that computed using the Poisson equation is slightly less good, but still better than a percent

```
>>> (dp.dens(1.,0.,forcepoisson=True)-dp.dens(1.,0.))/dp.dens(1.,0.)
0.0032522956769123019
```

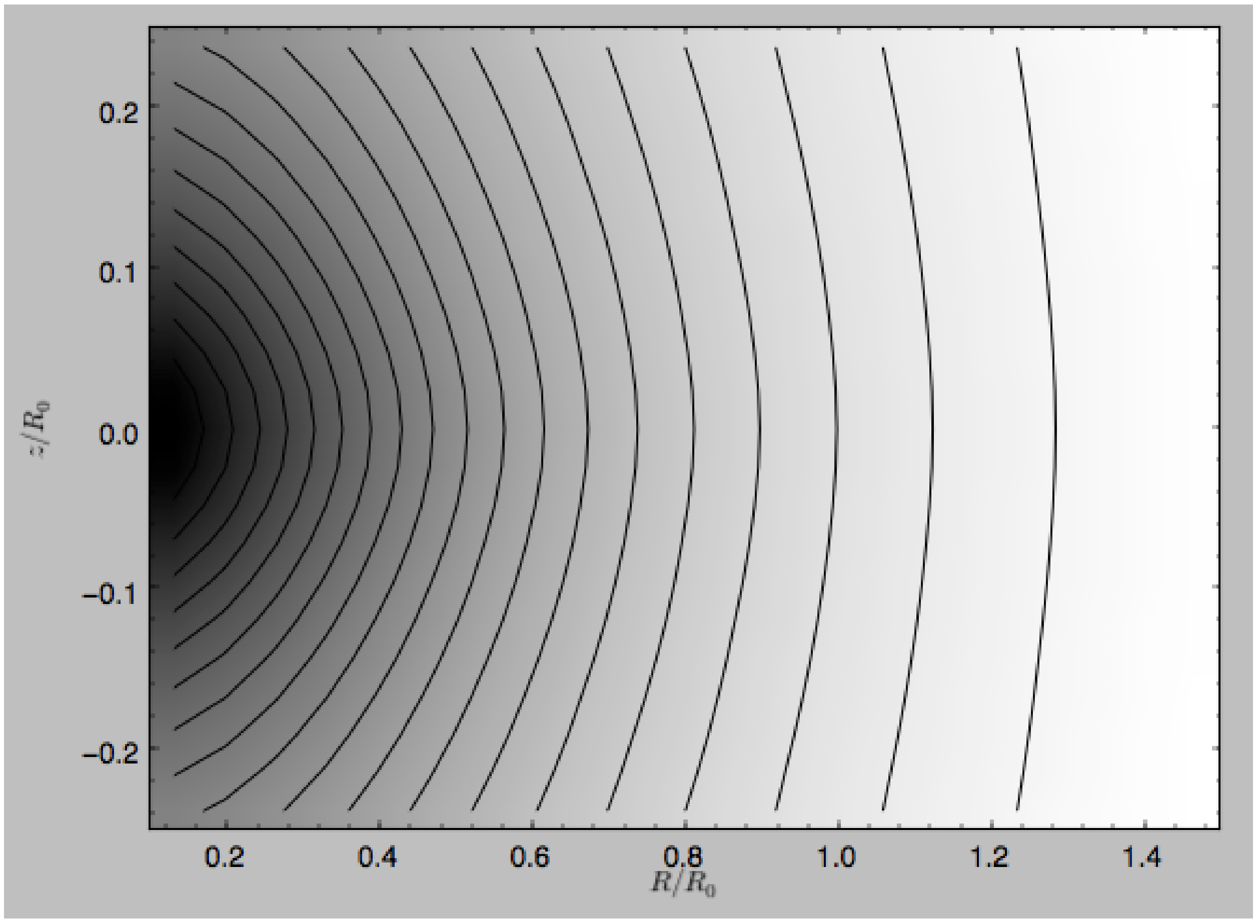
The density is

```
>>> dp.plotDensity(rmin=0.1,zmax=0.25,zmin=-0.25,nrs=101,nzs=101)
```



and the potential is

```
>>> dp.plot(rmin=0.1,zmin=-0.25,zmax=0.25)
```



Clearly, the potential is much less flattened than the density.

1.3.3 Close-to-circular orbits and orbital frequencies

We can also compute the properties of close-to-circular orbits. First of all, we can calculate the circular velocity and its derivative

```
>>> mp.vcirc(1.)
1.0
>>> mp.dvcircdR(1.)
-0.163777427566978
```

or, for lists of Potential instances

```
>>> from galpy.potential import vcirc
>>> vcirc(MWPotential2014,1.)
1.0
>>> from galpy.potential import dvcircdR
>>> dvcircdR(MWPotential2014,1.)
-0.10091361254334696
```

We can also calculate the various frequencies for close-to-circular orbits. For example, the rotational frequency

```
>>> mp.omegac(0.8)
1.2784598203204887
```

(continues on next page)

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```
>>> from galpy.potential import omegac
>>> omegac(MWPotential2014,0.8)
1.2733514576122869
```

and the epicycle frequency

```
>>> mp.epifreq(0.8)
1.7774973530267848
>>> from galpy.potential import epifreq
>>> epifreq(MWPotential2014,0.8)
1.7452189766287691
```

as well as the vertical frequency

```
>>> mp.verticalfreq(1.0)
3.7859388972001828
>>> from galpy.potential import verticalfreq
>>> verticalfreq(MWPotential2014,1.)
2.7255405754769875
```

For close-to-circular orbits, we can also compute the radii of the Lindblad resonances. For example, for a frequency similar to that of the Milky Way's bar

```
>>> mp.lindbladR(5./3.,m='corotation') #args are pattern speed and m of pattern
0.6027911166042229 #~ 5kpc
>>> print mp.lindbladR(5./3.,m=2)
None
>>> mp.lindbladR(5./3.,m=-2)
0.9906190683480501
```

The `None` here means that there is no inner Lindblad resonance, the `m=-2` resonance is in the Solar neighborhood (see the section on the *Hercules stream* in this documentation).

1.3.4 Using interpolations of potentials

`galpy` contains a general `Potential` class `interpRZPotential` that can be used to generate interpolations of potentials that can be used in their stead to speed up calculations when the calculation of the original potential is computationally expensive (for example, for the `DoubleExponentialDiskPotential`). Full details on how to set this up are given *here*. Interpolated potentials can be used anywhere that general three-dimensional galpy potentials can be used. Some care must be taken with outside-the-interpolation-grid evaluations for functions that use `C` to speed up computations.

1.3.5 NEW: The potential of N-body simulations

`galpy` can setup and work with the frozen potential of an N-body simulation. This allows us to study the properties of such potentials in the same way as other potentials in `galpy`. We can also investigate the properties of orbits in these potentials and calculate action-angle coordinates, using the `galpy` framework. Currently, this functionality is limited to axisymmetrized versions of the N-body snapshots, although this capability could be somewhat straightforwardly expanded to full triaxial potentials. The use of this functionality requires pynbody to be installed; the potential of any snapshot that can be loaded with `pynbody` can be used within `galpy`.

As a first, simple example of this we look at the potential of a single simulation particle, which should correspond to galpy's `KeplerPotential`. We can create such a single-particle snapshot using `pynbody` by doing

```
>>> import pynbody
>>> s= pynbody.new(star=1)
>>> s['mass']= 1.
>>> s['eps']= 0.
```

and we get the potential of this snapshot in `galpy` by doing

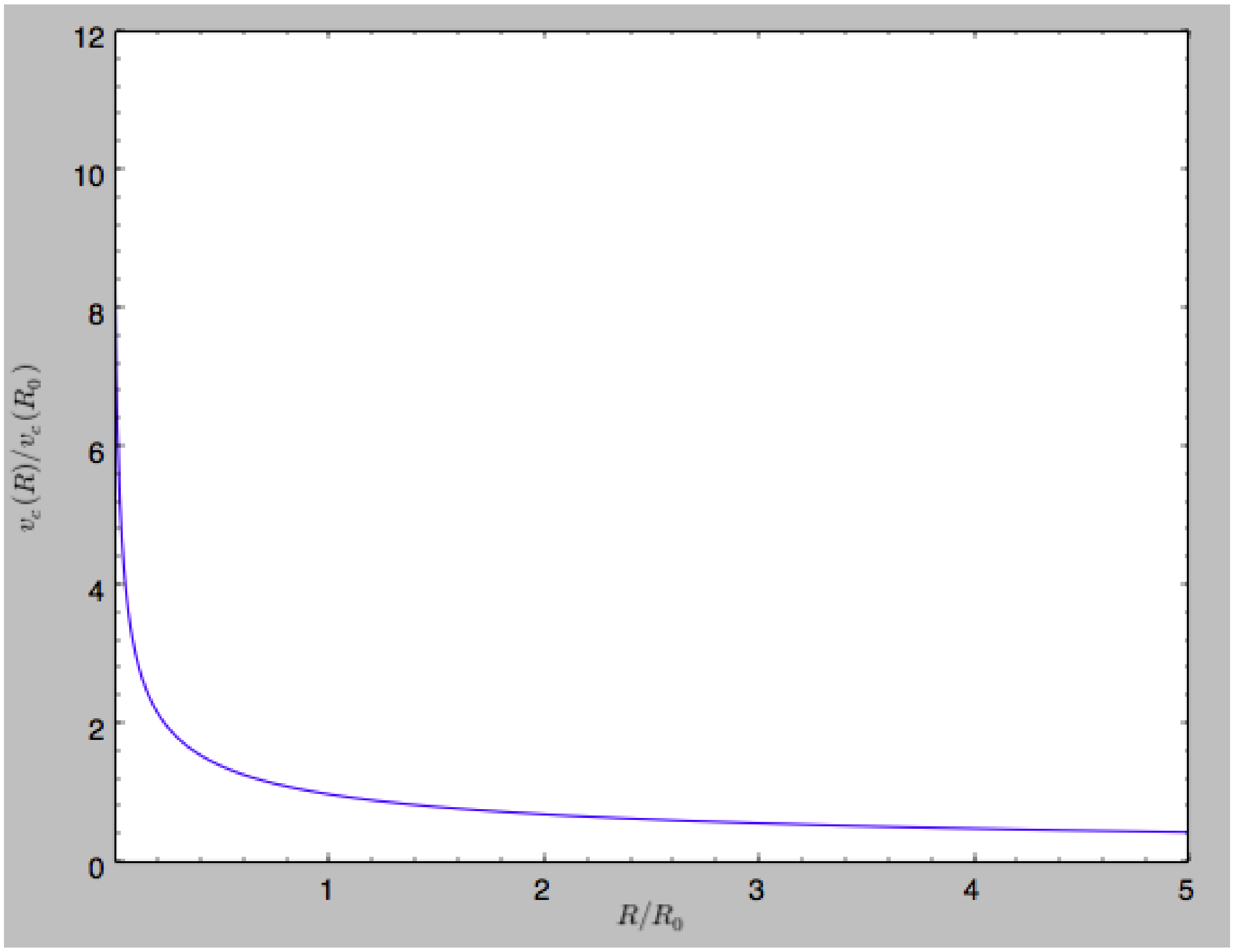
```
>>> from galpy.potential import SnapshotRZPotential
>>> sp= SnapshotRZPotential(s,num_threads=1)
```

With these definitions, this snapshot potential should be the same as `KeplerPotential` with an amplitude of one, which we can test as follows

```
>>> from galpy.potential import KeplerPotential
>>> kp= KeplerPotential(amp=1.)
>>> print(sp(1.1,0.),kp(1.1,0.),sp(1.1,0.)-kp(1.1,0.))
(-0.90909090909090906, -0.9090909090909091, 0.0)
>>> print(sp.Rforce(1.1,0.),kp.Rforce(1.1,0.),sp.Rforce(1.1,0.)-kp.Rforce(1.1,0.))
(-0.82644628099173545, -0.8264462809917353, -1.1102230246251565e-16)
```

`SnapshotRZPotential` instances can be used wherever other `galpy` potentials can be used (note that the second derivatives have not been implemented, such that functions depending on those will not work). For example, we can plot the rotation curve

```
>>> sp.plotRotcurve()
```



Because evaluating the potential and forces of a snapshot is computationally expensive, most useful applications of frozen N-body potentials employ interpolated versions of the snapshot potential. These can be setup in `galpy` using an `InterpSnapshotRZPotential` class that is a subclass of the `interpRZPotential` described above and that can be used in the same manner. To illustrate its use we will make use of one of `pynbody`'s example snapshots, `g15784`. This snapshot is used here to illustrate `pynbody`'s use. Please follow the instructions there on how to download this snapshot.

Once you have downloaded the `pynbody` testdata, we can load this snapshot using

```
>>> s = pynbody.load('testdata/g15784.lr.01024.gz')
```

(please adjust the path according to where you downloaded the `pynbody` testdata). We get the main galaxy in this snapshot, center the simulation on it, and align the galaxy face-on using

```
>>> h = s.halos()
>>> h1 = h[1]
>>> pynbody.analysis.halo.center(h1,mode='hyb')
>>> pynbody.analysis.angmom.faceon(h1, cen=(0,0,0),mode='ssc')
```

we also convert the simulation to physical units, but set *G=1* by doing the following

```
>>> s.physical_units()
>>> from galpy.util.bovy_conversion import _G
>>> g= pynbody.array.SimArray(_G/1000.)
```

(continues on next page)

(continued from previous page)

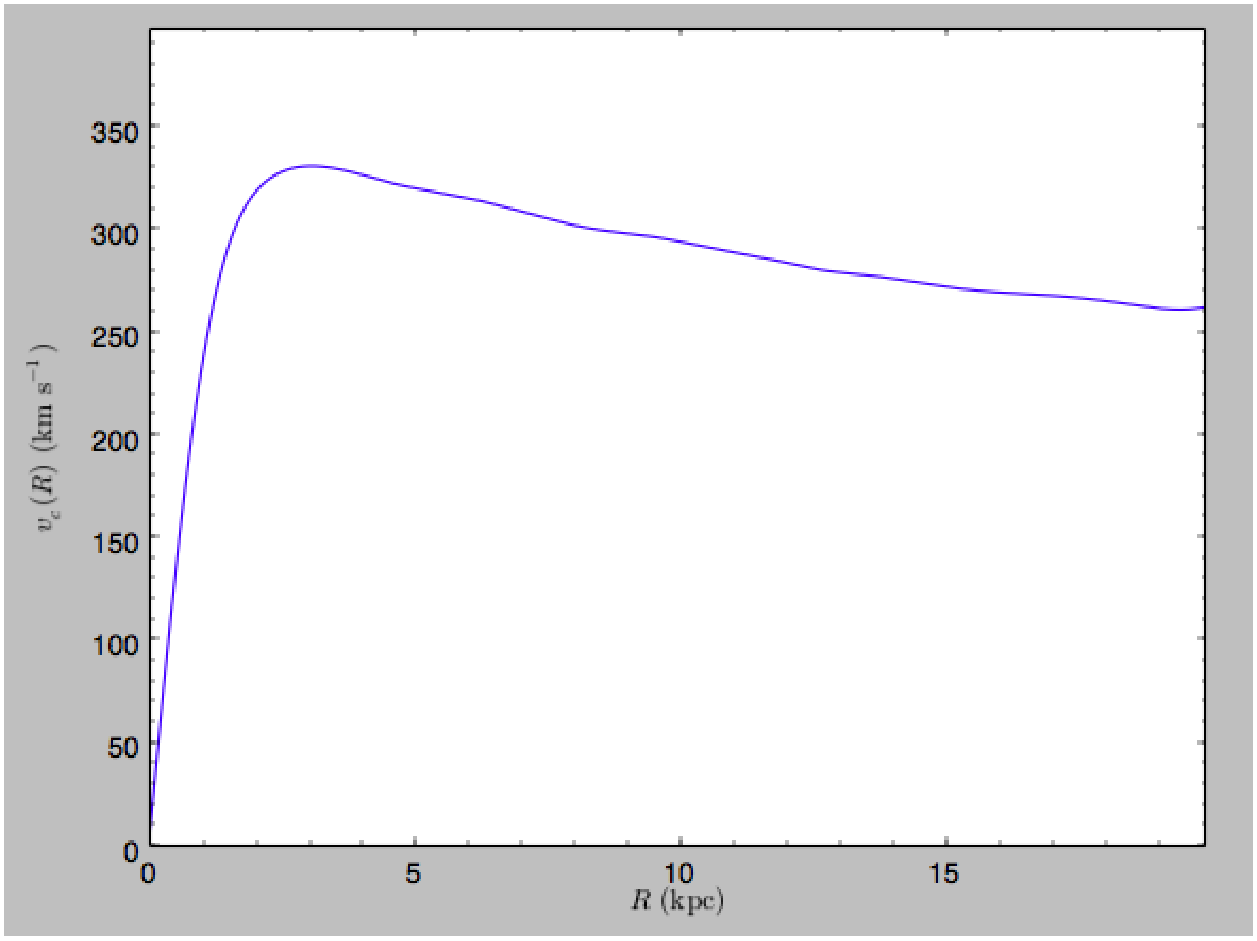
```
>>> g.units= 'kpc Msol**-1 km**2 s**-2 G**-1'
>>> s._arrays['mass']= s._arrays['mass']*g
```

We can now load an interpolated version of this snapshot's potential into `galpy` using

```
>>> from galpy.potential import InterpSnapshotRZPotential
>>> spi= InterpSnapshotRZPotential(h1,rgrid=(numpy.log(0.01),numpy.log(20.),101),
↪logR=True,zgrid=(0.,10.,101),interpPot=True,zsym=True)
```

where we further assume that the potential is symmetric around the mid-plane (*z=0*). This instantiation will take about ten to fiteen minutes. This potential instance has *physical* units (and thus the `rgrid=` and `zgrid=` inputs are given in kpc if the simulation's distance unit is kpc). For example, if we ask for the rotation curve, we get the following:

```
>>> spi.plotRotcurve(Rrange=[0.01,19.9],xlabel=r'$R\,(\mathrm{kpc})$',ylabel=r'$v_
↪c(R)\,(\mathrm{km\,s}^{-1})$')
```



This can be compared to the rotation curve calculated by `pynbody`, see here.

Because `galpy` works best in a system of *natural units* as explained in *Units in galpy*, we will convert this instance to natural units using the circular velocity at *R=10* kpc, which is

```
>>> spi.vcirc(10.)
294.62723076942245
```

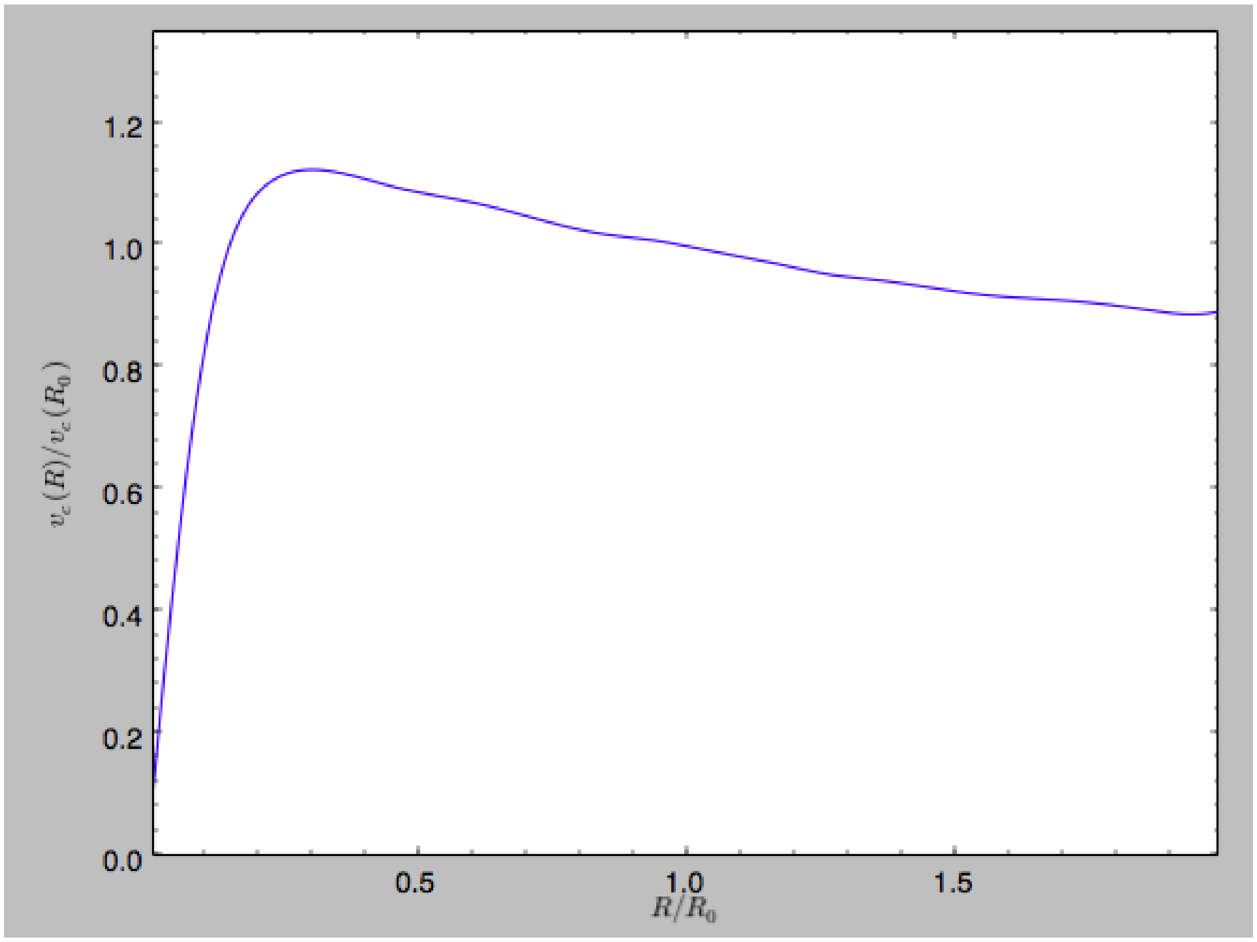
To convert to *natural units* we do

```
>>> spi.normalize(R0=10.)
```

We can then again plot the rotation curve, keeping in mind that the distance unit is now R_0

```
>>> spi.plotRotcurve(Rrange=[0.01,1.99])
```

which gives

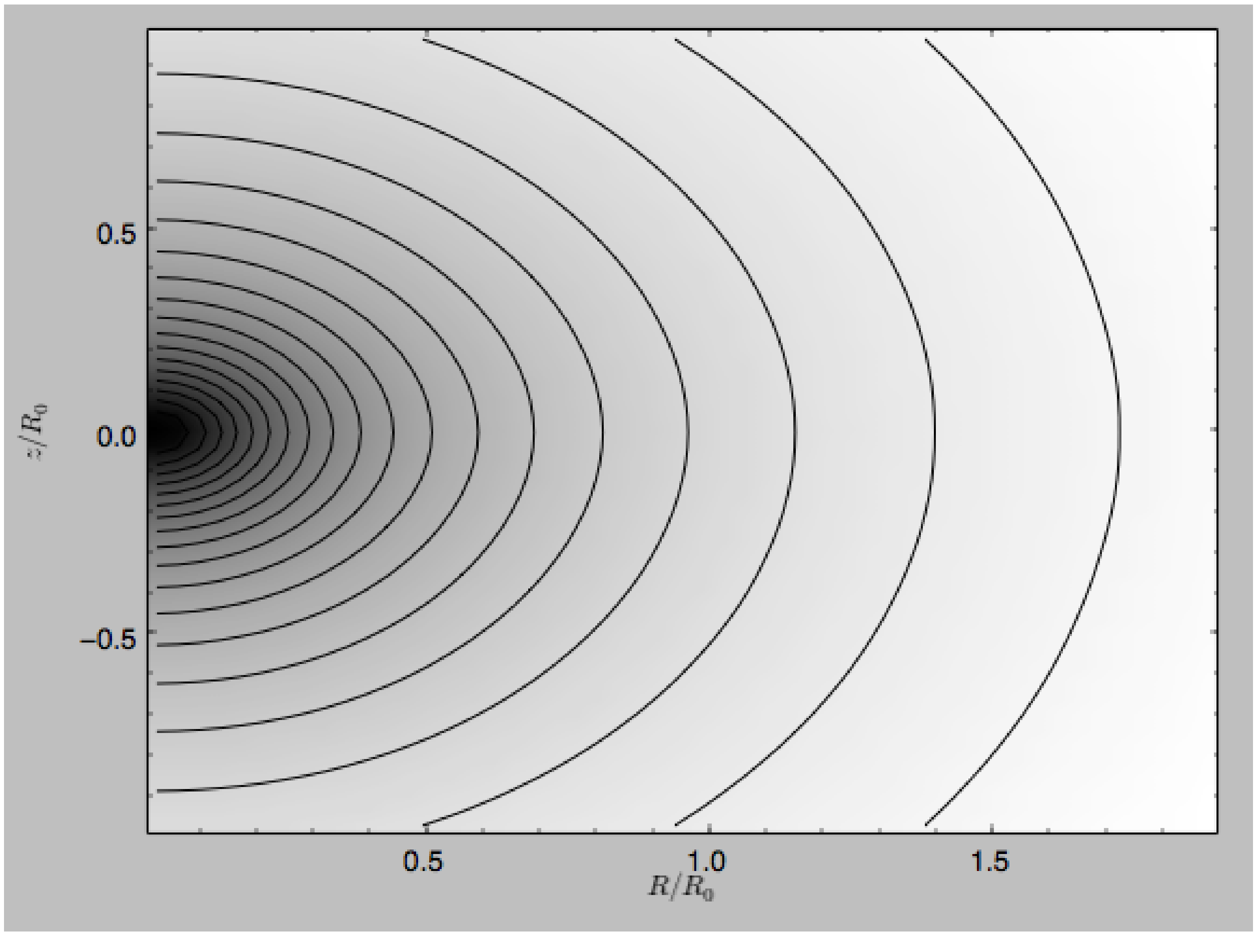


in particular

```
>>> spi.vcirc(1.)
1.0000000000000002
```

We can also plot the potential

```
>>> spi.plot(rmin=0.01,rmax=1.9,nrs=51,zmin=-0.99,zmax=0.99,nzs=51)
```



Clearly, this simulation's potential is quite spherical, which is confirmed by looking at the flattening

```
>>> spi.flattening(1.,0.1)
0.86675711023391921
>>> spi.flattening(1.5,0.1)
0.94442750306256895
```

The epicyle and vertical frequencies can also be interpolated by setting the `interpepifreq=True` or `interpverticalfreq=True` keywords when instantiating the `InterpSnapshotRZPotential` object.

1.3.6 NEW: Conversion to NEMO potentials

NEMO is a set of tools for studying stellar dynamics. Some of its functionality overlaps with that of `galpy`, but many of its programs are very complementary to `galpy`. In particular, it has the ability to perform N-body simulations with a variety of poisson solvers, which is currently not supported by `galpy` (and likely will never be directly supported). To encourage interaction between `galpy` and NEMO it is quite useful to be able to convert potentials between these two frameworks, which is not completely trivial. In particular, NEMO contains Walter Dehnen's fast collisionless `gyrfalcON` code (see 2000ApJ…536L..39D and 2002JCoPh.179…27D) and the discussion here focuses on how to run N-body simulations using external potentials defined in `galpy`.

Some `galpy` potential instances support the functions `nemo_accname` and `nemo_accpars` that return the name of the NEMO potential corresponding to this `galpy` Potential and its parameters in NEMO units. These functions assume that you use NEMO with WD_units, that is, positions are specified in kpc, velocities in kpc/Gyr, times in Gyr, and G=1. For the Miyamoto-Nagai potential above, you can get its name in the NEMO framework as

```
>>> mp.nemo_accname()
'MiyamotoNagai'
```

and its parameters as

```
>>> mp.nemo_accpars(220.,8.)
'0,592617.11132,4.0,0.3'
```

assuming that we scale velocities by `vo=220` km/s and positions by `ro=8` kpc in galpy. These two strings can then be given to the `gyrfalcON` `accname=` and `accpars=` keywords.

We can do the same for lists of potentials. For example, for `MWPotential2014` we do

```
>>> from galpy.potential import nemo_accname, nemo_accpars
>>> nemo_accname(MWPotential2014)
'PowSphwCut+MiyamotoNagai+NFW'
>>> nemo_accpars(MWPotential2014,220.,8.)
'0,1001.79126907,1.8,1.9#0,306770.418682,3.0,0.28#0,16.0,162.958241887'
```

Therefore, these are the `accname=` and `accpars=` that one needs to provide to `gyrfalcON` to run a simulation in `MWPotential2014`.

Note that the NEMO potential `PowSphwCut` is *not* a standard NEMO potential. This potential can be found in the nemo/ directory of the `galpy` source code; this directory also contains a Makefile that can be used to compile the extra NEMO potential and install it in the correct NEMO directory (this requires one to have NEMO running, i.e., having sourced nemo_start).

You can use the `PowSphwCut.cc` file in the nemo/ directory as a template for adding additional potentials in `galpy` to the NEMO framework. To figure out how to convert the normalized `galpy` potential to an amplitude when scaling to physical coordinates (like kpc and kpc/Gyr), one needs to look at the scaling of the radial force with R. For example, from the definition of MiyamotoNagaiPotential, we see that the radial force scales as R^{-2}. For a general scaling $R^{-\alpha}$, the amplitude will scale as $V_0^2\,R_0^{\alpha-1}$ with the velocity V_0 and position R_0 of the `v=1` at `R=1` normalization. Therefore, for the MiyamotoNagaiPotential, the physical amplitude scales as $V_0^2\,R_0$. For the LogarithmicHaloPotential, the radial force scales as R^{-1}, so the amplitude scales as V_0^2.

Currently, only the `MiyamotoNagaiPotential`, `NFWPotential`, `PowerSphericalPotentialwCutoff`, `PlummerPotential`, `MN3ExponentialDiskPotential`, and the `LogarithmicHaloPotential` have this NEMO support. Combinations of the first three are also supported (e.g., `MWPotential2014`); they can also be combined with spherical `LogarithmicHaloPotentials`. Because of the definition of the logarithmic potential in NEMO, it cannot be flattened in `z`, so to use a flattened logarithmic potential, one has to flip `y` and `z` between `galpy` and NEMO (one can flatten in `y`).

1.3.7 Adding potentials to the galpy framework

Potentials in galpy can be used in many places such as orbit integration, distribution functions, or the calculation of action-angle variables, and in most cases any instance of a potential class that inherits from the general `Potential` class (or a list of such instances) can be given. For example, all orbit integration routines work with any list of instances of the general `Potential` class. Adding new potentials to galpy therefore allows them to be used everywhere in galpy where general `Potential` instances can be used. Adding a new class of potentials to galpy consists of the following series of steps (some of these are also given in the file `README.dev` in the galpy distribution):

1. Implement the new potential in a class that inherits from `galpy.potential.Potential`. The new class should have an `__init__` method that sets up the necessary parameters for the class. An amplitude parameter `amp=` should be taken as an argument for this class and before performing any other setup, the `galpy.potential.Potential.__init__(self,amp=amp)` method should be called to setup the amplitude.

To add support for normalizing the potential to standard galpy units, one can call the `galpy.potential.Potential.normalize` function at the end of the __init__ function.

The new potential class should implement some of the following functions:

- `_evaluate(self,R,z,phi=0,t=0)` which evaluates the potential itself (*without* the amp factor, which is added in the `__call__` method of the general Potential class).
- `_Rforce(self,R,z,phi=0.,t=0.)` which evaluates the radial force in cylindrical coordinates (-d potential / d R).
- `_zforce(self,R,z,phi=0.,t=0.)` which evaluates the vertical force in cylindrical coordinates (-d potential / d z).
- `_R2deriv(self,R,z,phi=0.,t=0.)` which evaluates the second (cylindrical) radial derivative of the potential (d^2 potential / d R^2).
- `_z2deriv(self,R,z,phi=0.,t=0.)` which evaluates the second (cylindrical) vertical derivative of the potential (d^2 potential / d z^2).
- `_Rzderiv(self,R,z,phi=0.,t=0.)` which evaluates the mixed (cylindrical) radial and vertical derivative of the potential (d^2 potential / d R d z).
- `_dens(self,R,z,phi=0.,t=0.)` which evaluates the density. If not given, the density is computed using the Poisson equation from the first and second derivatives of the potential (if all are implemented).
- `_mass(self,R,z=0.,t=0.)` which evaluates the mass. For spherical potentials this should give the mass enclosed within the spherical radius; for axisymmetric potentials this should return the mass up to `R` and between `-Z` and `Z`. If not given, the mass is computed by integrating the density (if it is implemented or can be calculated from the Poisson equation).
- `_phiforce(self,R,z,phi=0.,t=0.)`: the azimuthal force in cylindrical coordinates (assumed zero if not implemented).
- `_phi2deriv(self,R,z,phi=0.,t=0.)`: the second azimuthal derivative of the potential in cylindrical coordinates (d^2 potential / d phi^2; assumed zero if not given).
- `_Rphideriv(self,R,z,phi=0.,t=0.)`: the mixed radial and azimuthal derivative of the potential in cylindrical coordinates (d^2 potential / d R d phi; assumed zero if not given).

If you want to be able to calculate the concentration for a potential, you also have to set self._scale to a scale parameter for your potential.

The code for `galpy.potential.MiyamotoNagaiPotential` gives a good template to follow for 3D axisymmetric potentials. Similarly, the code for `galpy.potential.CosmphiDiskPotential` provides a good template for 2D, non-axisymmetric potentials.

After this step, the new potential will work in any part of galpy that uses pure python potentials. To get the potential to work with the C implementations of orbit integration or action-angle calculations, the potential also has to be implemented in C and the potential has to be passed from python to C.

The `__init__` method should be written in such a way that a relevant object can be initialized using `Classname()` (i.e., there have to be reasonable defaults given for all parameters, including the amplitude); doing this allows the nose tests for potentials to automatically check that your Potential's potential function, force functions, second derivatives, and density (through the Poisson equation) are correctly implemented (if they are implemented). The continuous-integration platform that builds the galpy codebase upon code pushes will then automatically test all of this, streamlining push requests of new potentials.

2. To add a C implementation of the potential, implement it in a .c file under `potential_src/potential_c_ext`. Look at `potential_src/potential_c_ext/LogarithmicHaloPotential.c` for the right format for 3D, axisymmetric potentials, or at

`potential_src/potential_c_ext/LopsidedDiskPotential.c` for 2D, non-axisymmetric potentials.

For orbit integration, the functions such as:

- double LogarithmicHaloPotentialRforce(double R,double Z, double phi,double t,struct potentialArg * potentialArgs)
- double LogarithmicHaloPotentialzforce(double R,double Z, double phi,double t,struct potentialArg * potentialArgs)

are most important. For some of the action-angle calculations

- double LogarithmicHaloPotentialEval(double R,double Z, double phi,double t,struct potentialArg * potentialArgs)

is most important (i.e., for those algorithms that evaluate the potential). The arguments of the potential are passed in a `potentialArgs` structure that contains `args`, which are the arguments that should be unpacked. Again, looking at some example code will make this clear. The `potentialArgs` structure is defined in `potential_src/potential_c_ext/galpy_potentials.h`.

3. Add the potential's function declarations to `potential_src/potential_c_ext/galpy_potentials.h`

4. (4. and 5. for planar orbit integration) Edit the code under `orbit_src/orbit_c_ext/integratePlanarOrbit.c` to set up your new potential (in the **parse_leapFuncArgs** function).

5. Edit the code in `orbit_src/integratePlanarOrbit.py` to set up your new potential (in the **_parse_pot** function).

6. Edit the code under `orbit_src/orbit_c_ext/integrateFullOrbit.c` to set up your new potential (in the **parse_leapFuncArgs_Full** function).

7. Edit the code in `orbit_src/integrateFullOrbit.py` to set up your new potential (in the **_parse_pot** function).

8. (for using the actionAngleStaeckel methods in C) Edit the code in `actionAngle_src/actionAngle_c_ext/actionAngle.c` to parse the new potential (in the **parse_actionAngleArgs** function).

9. Finally, add `self.hasC= True` to the initialization of the potential in question (after the initialization of the super class, or otherwise it will be undone). If you have implemented the necessary second derivatives for integrating phase-space volumes, also add `self.hasC_dxdv=True`.

After following the relevant steps, the new potential class can be used in any galpy context in which C is used to speed up computations.

1.4 Two-dimensional disk distribution functions

galpy contains various disk distribution functions, both in two and three dimensions. This section introduces the two-dimensional distribution functions, useful for studying the dynamics of stars that stay relatively close to the mid-plane of a galaxy. The vertical motions of these stars may be approximated as being entirely decoupled from the motion in the plane.

1.4.1 Types of disk distribution functions

galpy contains the following distribution functions for razor-thin disks: `galpy.df.dehnendf` and `galpy.df.shudf`. These are the distribution functions of Dehnen (1999AJ....118.1201D) and Shu (1969ApJ...158..505S). Everything shown below for `dehnendf` can also be done for `shudf`.

These disk distribution functions are functions of the energy and the angular momentum alone. They can be evaluated for orbits, or for a given energy and angular momentum. At this point, only power-law rotation curves are supported. A `dehnendf` instance is initialized as follows

```
>>> from galpy.df import dehnendf
>>> dfc= dehnendf(beta=0.)
```

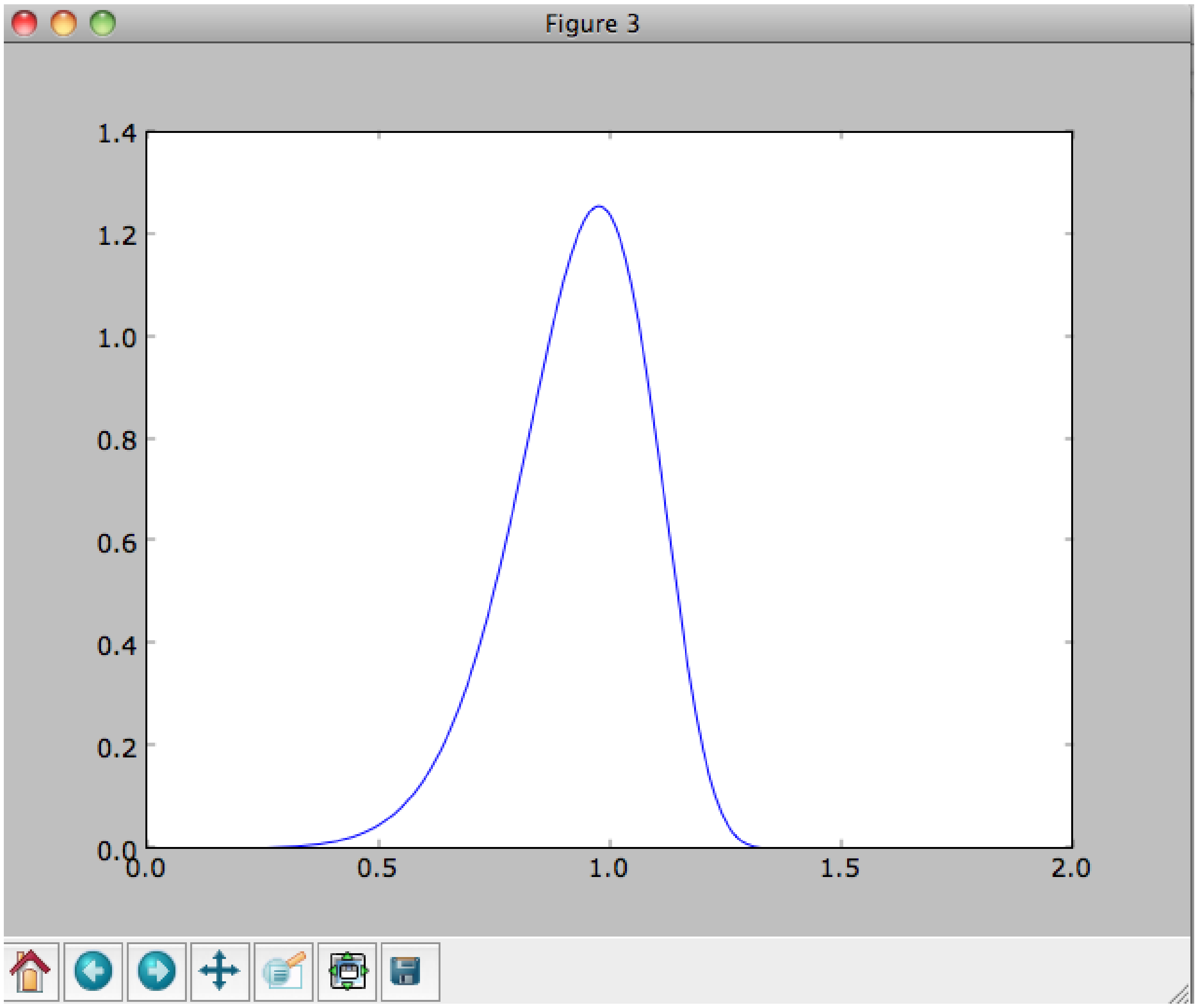
This initializes a `dehnendf` instance based on an exponential surface-mass profile with scale-length 1/3 and an exponential radial-velocity-dispersion profile with scale-length 1 and a value of 0.2 at R=1. Different parameters for these profiles can be provided as an initialization keyword. For example,

```
>>> dfc= dehnendf(beta=0.,profileParams=(1./4.,1.,0.2))
```

initializes the distribution function with a radial scale length of 1/4 instead.

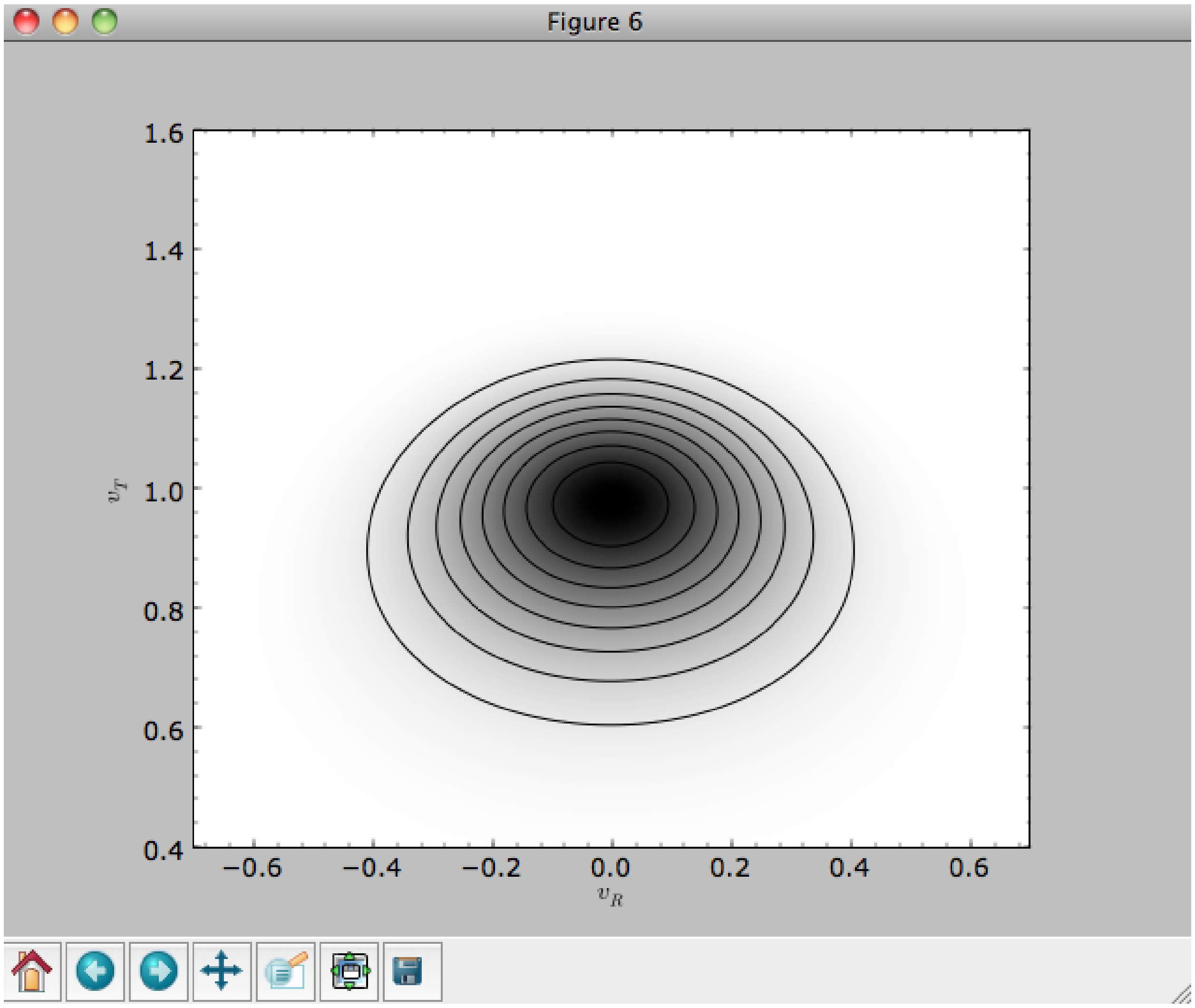
We can show that these distribution functions have an asymmetric drift built-in by evaluating the DF at R=1. We first create a set of orbit-instances and then evaluate the DF at them

```
>>> from galpy.orbit import Orbit
>>> os= [Orbit([1.,0.,1.+-0.9+1.8/1000*ii]) for ii in range(1001)]
>>> dfro= [dfc(o) for o in os]
>>> plot([1.+-0.9+1.8/1000*ii for ii in range(1001)],dfro)
```



Or we can plot the two-dimensional density at R=1.

```
>>> dfro= [[dfc(Orbit([1.,-0.7+1.4/200*jj,1.-0.6+1.2/200*ii])) for jj in␣
↪range(201)]for ii in range(201)]
>>> dfro= numpy.array(dfro)
>>> from galpy.util.bovy_plot import bovy_dens2d
>>> bovy_dens2d(dfro,origin='lower',cmap='gist_yarg',contours=True,xrange=[-0.7,0.7],
↪yrange=[0.4,1.6],xlabel=r'$v_R$',ylabel=r'$v_T$')
```



1.4.2 Evaluating moments of the DF

galpy can evaluate various moments of the disk distribution functions. For example, we can calculate the mean velocities (for the DF with a scale length of 1/3 above)

```
>>> dfc.meanvT(1.)
0.91715276979447324
>>> dfc.meanvR(1.)
0.0
```

and the velocity dispersions

```
>>> numpy.sqrt(dfc.sigmaR2(1.))
0.19321086259083936
>>> numpy.sqrt(dfc.sigmaT2(1.))
0.15084122011271159
```

and their ratio

```
>>> dfc.sigmaR2(1.)/dfc.sigmaT2(1.)
1.6406766813028968
```

In the limit of zero velocity dispersion (the epicycle approximation) this ratio should be equal to 2, which we can check as follows

```
>>> dfccold= dehnendf(beta=0.,profileParams=(1./3.,1.,0.02))
>>> dfccold.sigmaR2(1.)/dfccold.sigmaT2(1.)
1.9947493895454664
```

We can also calculate higher order moments

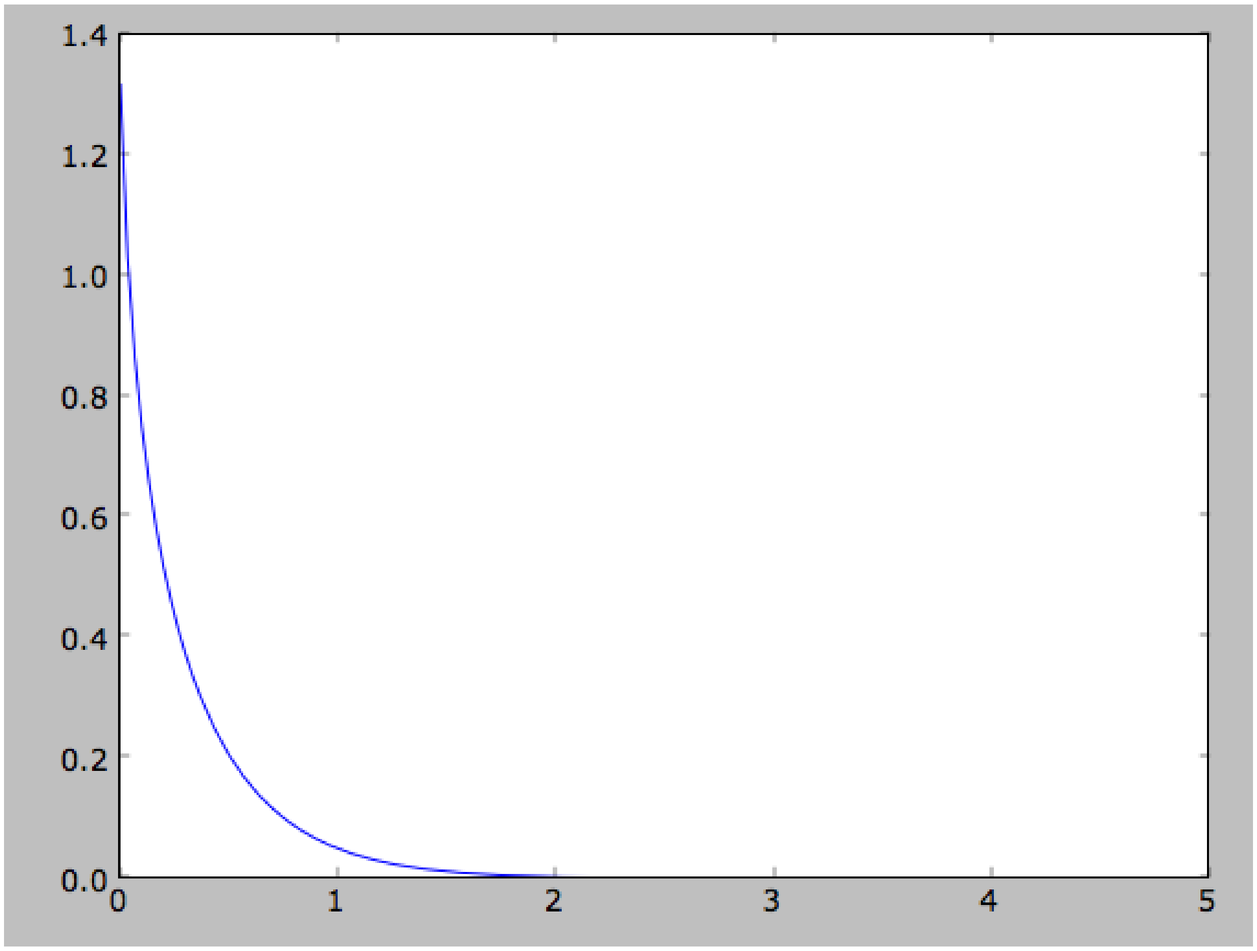
```
>>> dfc.skewvT(1.)
-0.48617143862047763
>>> dfc.kurtosisvT(1.)
0.13338978593181494
>>> dfc.kurtosisvR(1.)
-0.12159407676394096
```

We already saw above that the velocity dispersion at R=1 is not exactly equal to the input velocity dispersion (0.19321086259083936 vs. 0.2). Similarly, the whole surface-density and velocity-dispersion profiles are not quite equal to the exponential input profiles. We can calculate the resulting surface-mass density profile using `surfacemass`, `sigmaR2`, and `sigma2surfacemass`. The latter calculates the product of the velocity dispersion squared and the surface-mass density. E.g.,

```
>>> dfc.surfacemass(1.)
0.050820867101511534
```

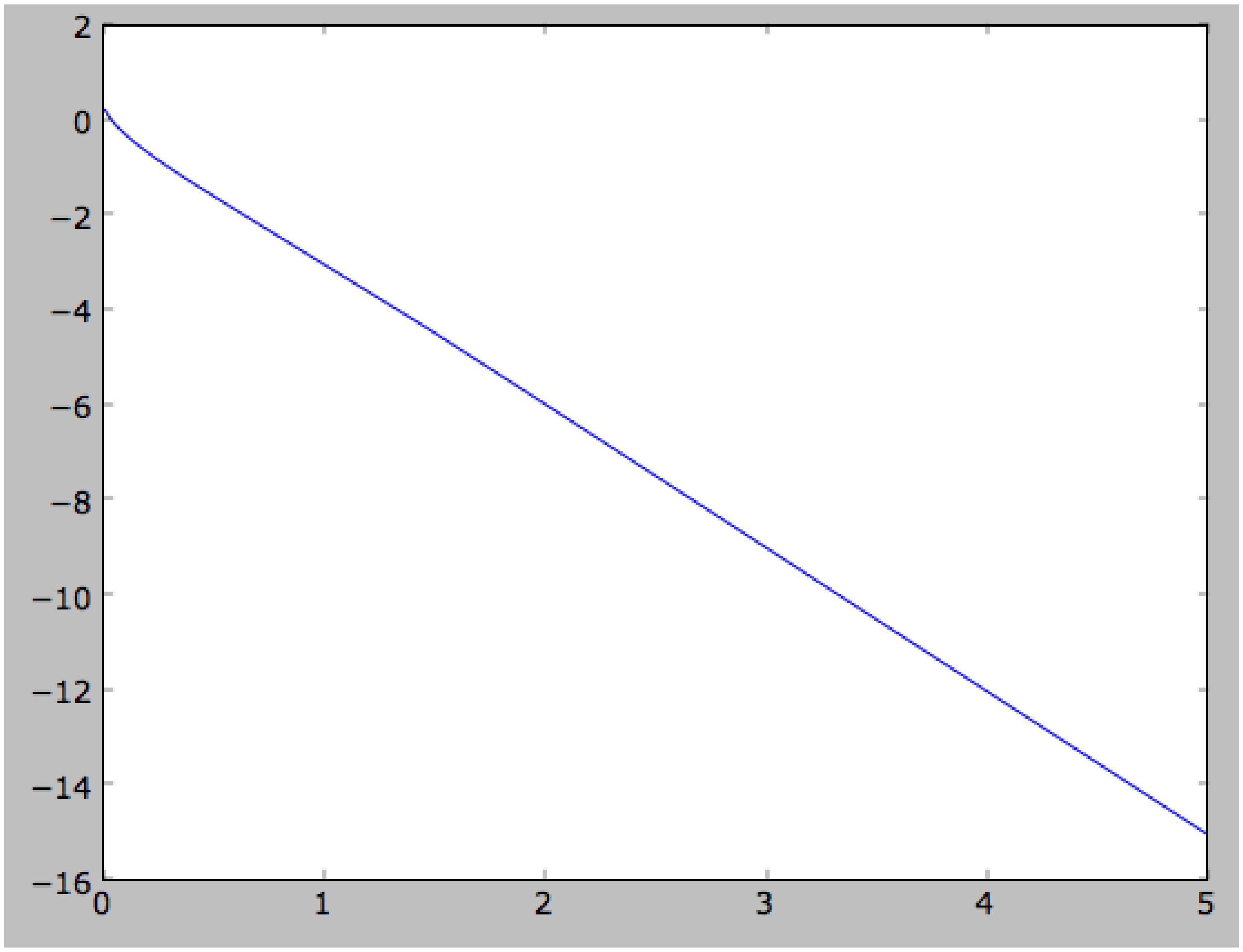
We can plot the surface-mass density as follows

```
>>> Rs= numpy.linspace(0.01,5.,151)
>>> out= [dfc.surfacemass(r) for r in Rs]
>>> plot(Rs, out)
```



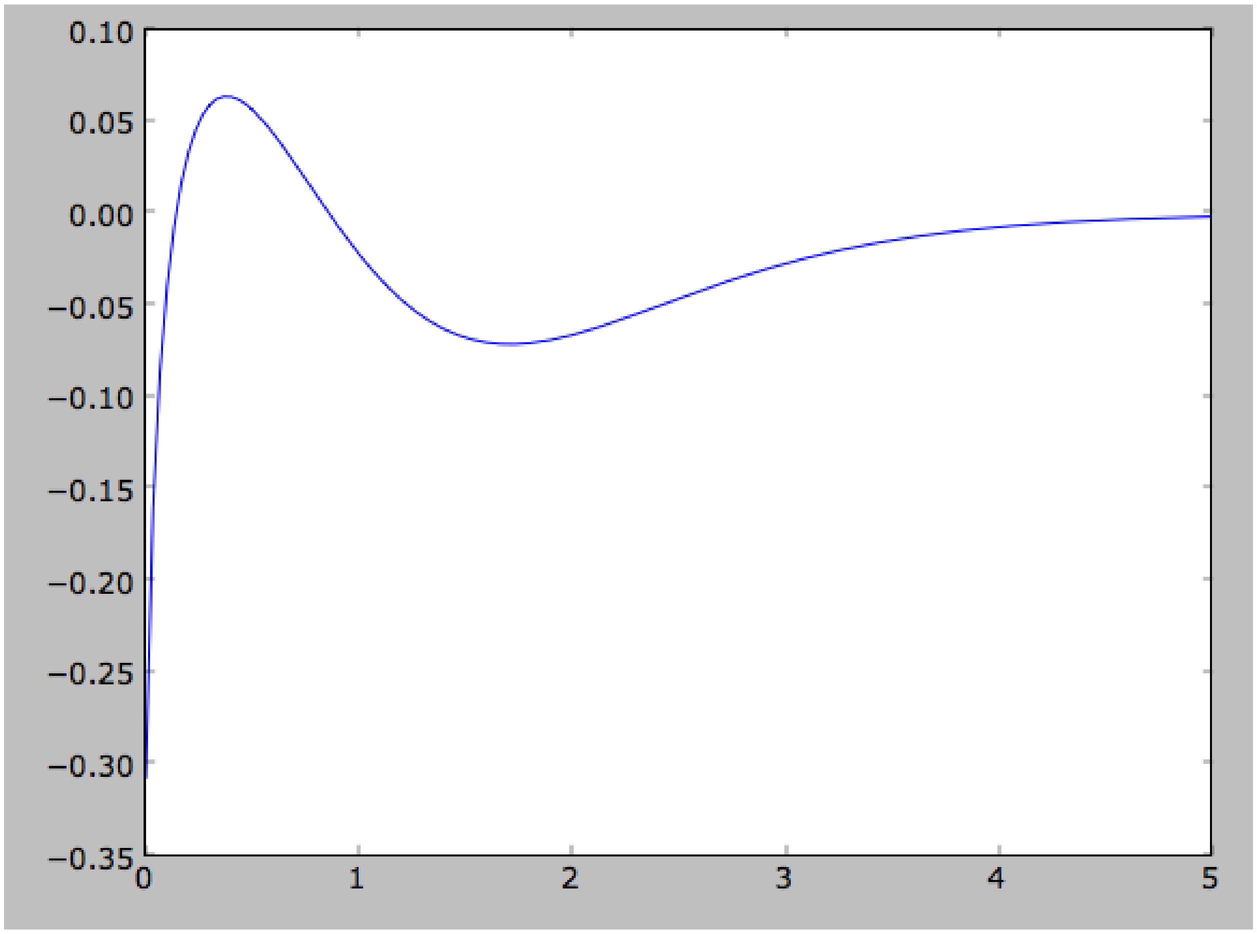
or

```
>>> plot(Rs,numpy.log(out))
```



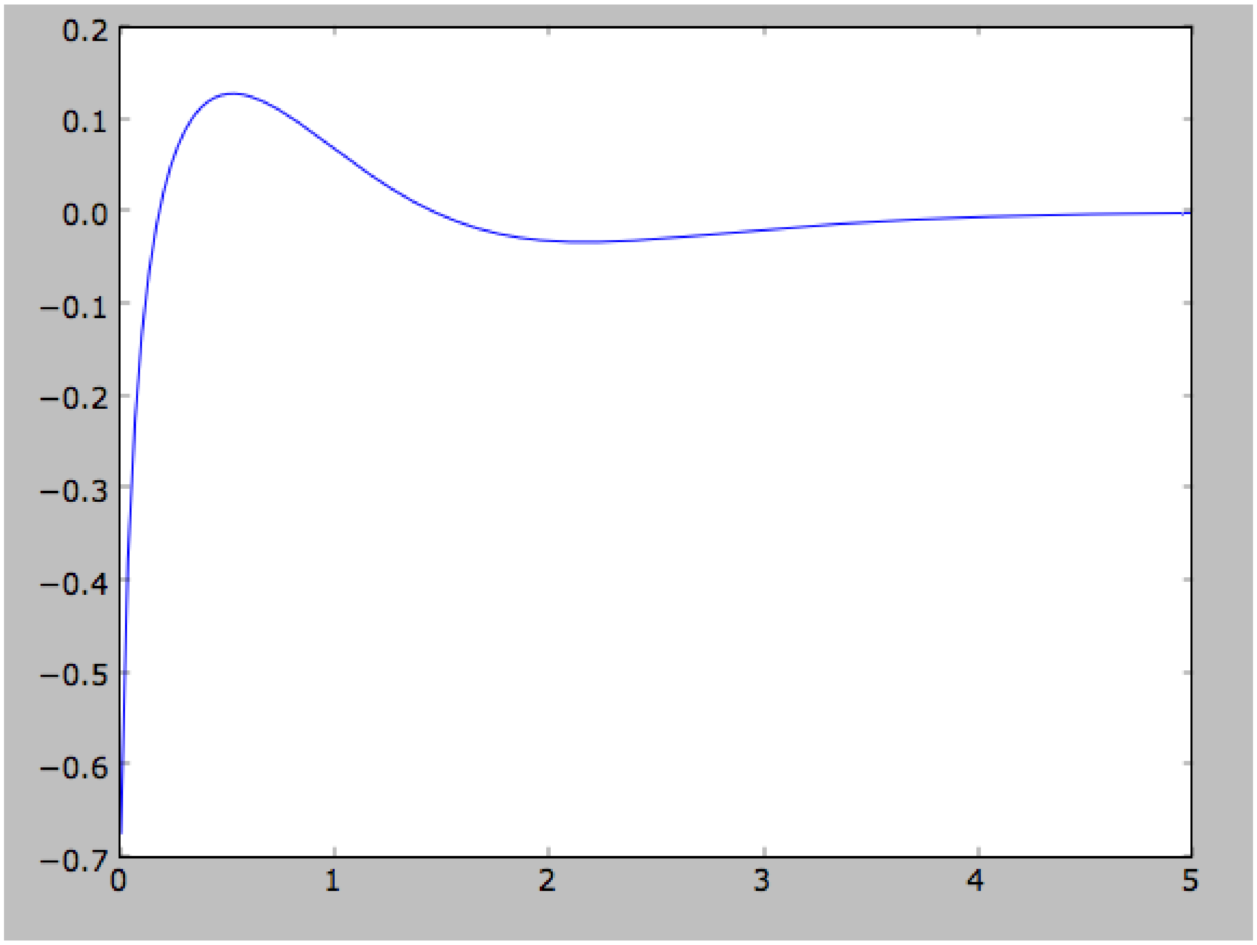
which shows the exponential behavior expected for an exponential disk. We can compare this to the input surface-mass density

```
>>> input_out= [dfc.targetSurfacemass(r) for r in Rs]
>>> plot(Rs,numpy.log(input_out)-numpy.log(out))
```



which shows that there are significant differences between the desired surface-mass density and the actual surface-mass density. We can do the same for the velocity-dispersion profile

```
>>> out= [dfc.sigmaR2(r) for r in Rs]
>>> input_out= [dfc.targetSigma2(r) for r in Rs]
>>> plot(Rs,numpy.log(input_out)-numpy.log(out))
```



That the input surface-density and velocity-dispersion profiles are not the same as the output profiles, means that estimates of DF properties based on these profiles will not be quite correct. Obviously this is the case for the surface-density and velocity-dispersion profiles themselves, which have to be explicitly calculated by integration over the DF rather than by evaluating the input profiles. This also means that estimates of the asymmetric drift based on the input profiles will be wrong. We can calculate the asymmetric drift at R=1 using the asymmetric drift equation derived from the Jeans equation (eq. 4.228 in Binney & Tremaine 2008), using the input surface-density and velocity dispersion profiles

```
>>> dfc.asymmetricdrift(1.)
0.090000000000000024
```

which should be equal to the circular velocity minus the mean rotational velocity

```
>>> 1.-dfc.meanvT(1.)
0.082847230205526756
```

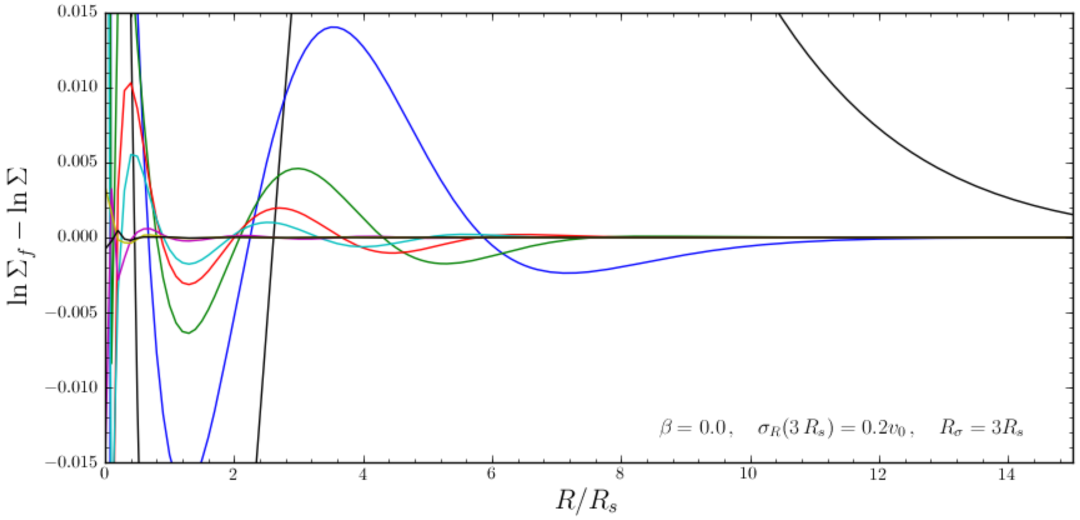
These are not the same in part because of the difference between the input and output surface-density and velocity-dispersion profiles (and because the `asymmetricdrift` method assumes that the ratio of the velocity dispersions squared is two using the epicycle approximation; see above).

1.4.3 Using corrected disk distribution functions

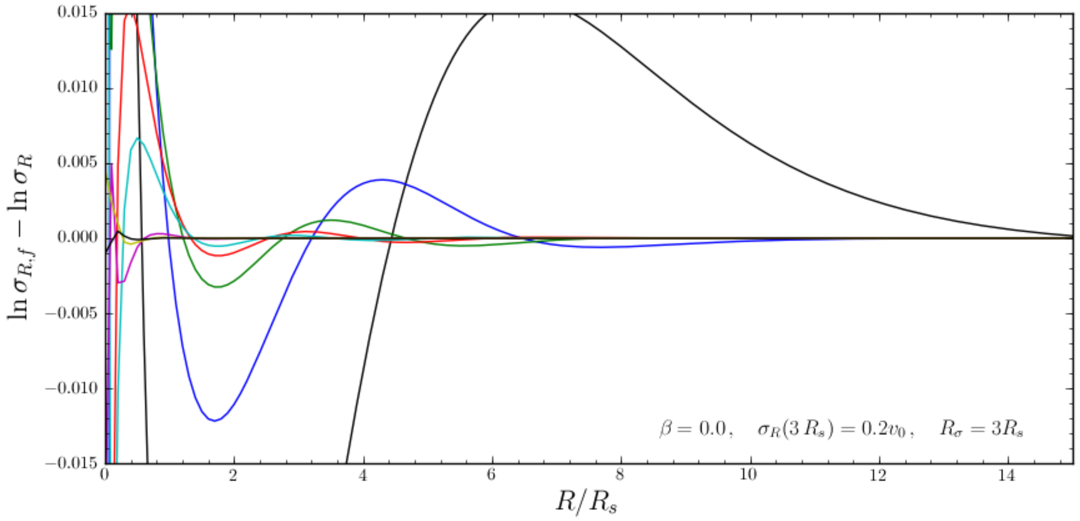
As shown above, for a given surface-mass density and velocity dispersion profile, the two-dimensional disk distribution functions only do a poor job of reproducing the desired profiles. We can correct this by calculating a set of *corrections* to the input profiles such that the output profiles more closely resemble the desired profiles (see 1999AJ....118.1201D). galpy supports the calculation of these corrections, and comes with some pre-calculated corrections (these can be found here). For example, the following initializes a `dehnendf` with corrections up to 20th order (the default)

```
>>> dfc= dehnendf(beta=0.,correct=True)
```

The following figure shows the difference between the actual surface-mass density profile and the desired profile for 1, 2, 3, 4, 5, 10, 15, and 20 iterations



and the same for the velocity-dispersion profile



galpy will automatically save any new corrections that you calculate.

All of the methods for an uncorrected disk DF can be used for the corrected DFs as well. For example, the velocity dispersion is now

```
>>> numpy.sqrt(dfc.sigmaR2(1.))
0.19999985069451526
```

and the mean rotation velocity is

```
>>> dfc.meanvT(1.)
0.90355161181498711
```

and (correct) asymmetric drift

```
>>> 1.-dfc.meanvT(1.)
0.09644838818501289
```

That this still does not agree with the simple `dfc.asymmetricdrift` estimate is because of the latter's using the epicycle approximation for the ratio of the velocity dispersions.

1.4.4 Oort constants and functions

galpy also contains methods to calculate the Oort functions for two-dimensional disk distribution functions. These are known as the *Oort constants* when measured in the solar neighborhood. They are combinations of the mean velocities and derivatives thereof. galpy calculates these by direct integration over the DF and derivatives of the DF. Thus, we can calculate

```
>>> dfc= dehnendf(beta=0.)
>>> dfc.oortA(1.)
0.43190780889218749
>>> dfc.oortB(1.)
-0.48524496090228575
```

The K and C Oort constants are zero for axisymmetric DFs

```
>>> dfc.oortC(1.)
0.0
>>> dfc.oortK(1.)
0.0
```

In the epicycle approximation, for a flat rotation curve A =- B = 0.5. The explicit calculates of A and B for warm DFs quantify how good (or bad) this approximation is

```
>>> dfc.oortA(1.)+dfc.oortB(1.)
-0.053337152010098254
```

For the cold DF from above the approximation is much better

```
>>> dfccold= dehnendf(beta=0.,profileParams=(1./3.,1.,0.02))
>>> dfccold.oortA(1.), dfccold.oortB(1.)
(0.49917556666144003, -0.49992824742490816)
```

1.4.5 Sampling data from the DF

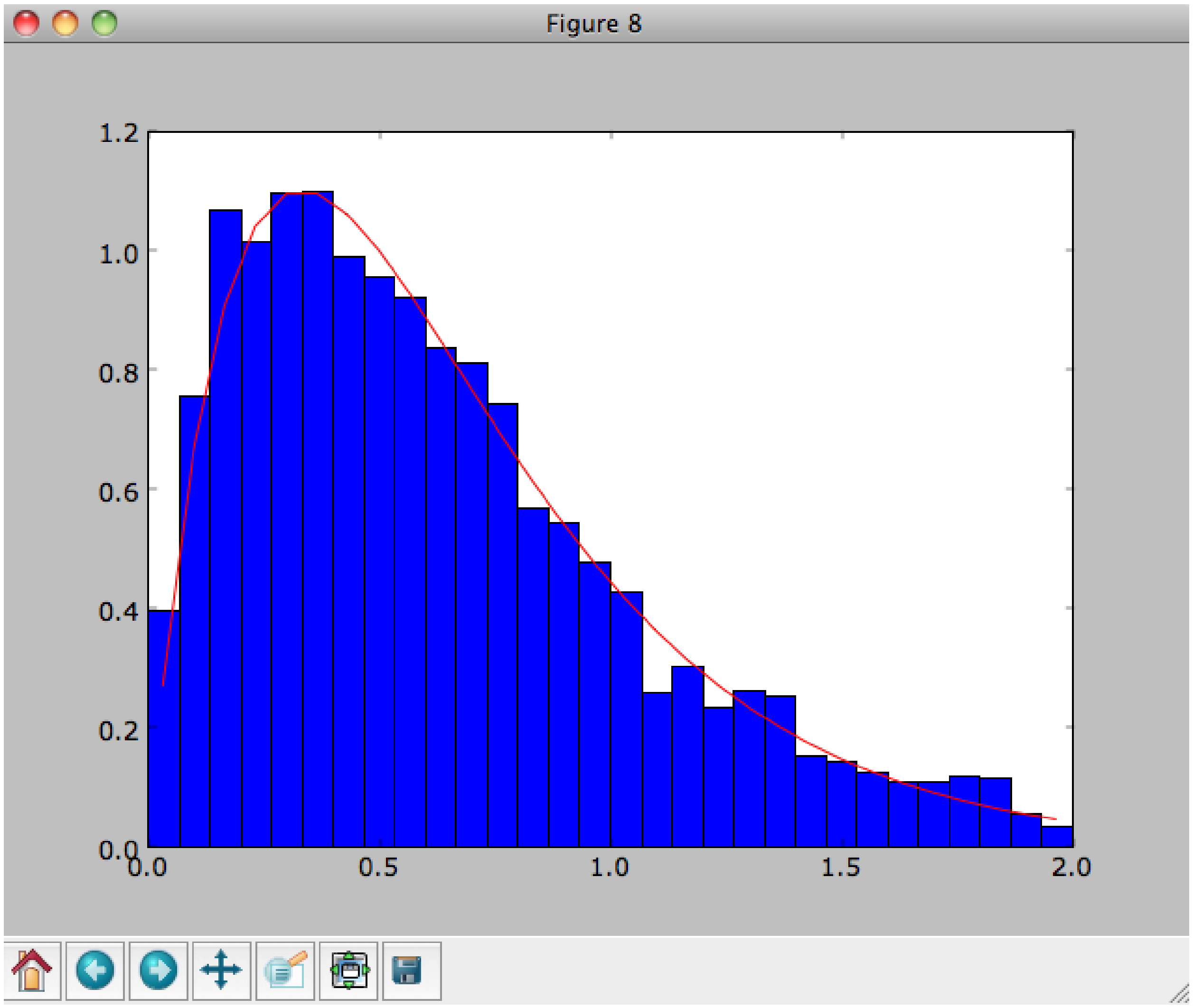
We can sample from the disk distribution functions using `sample`. `sample` can return either an energy–angular-momentum pair, or a full orbit initialization. We can sample 4000 orbits for example as (could take two minutes)

```
>>> o= dfc.sample(n=4000,returnOrbit=True,nphi=1)
```

We can then plot the histogram of the sampled radii and compare it to the input surface-mass density profile

```
>>> Rs= [e.R() for e in o]
>>> hists, bins, edges= hist(Rs,range=[0,2],normed=True,bins=30)
>>> xs= numpy.array([(bins[ii+1]+bins[ii])/2. for ii in range(len(bins)-1)])
>>> plot(xs, xs*exp(-xs*3.)*9.,'r-')
```

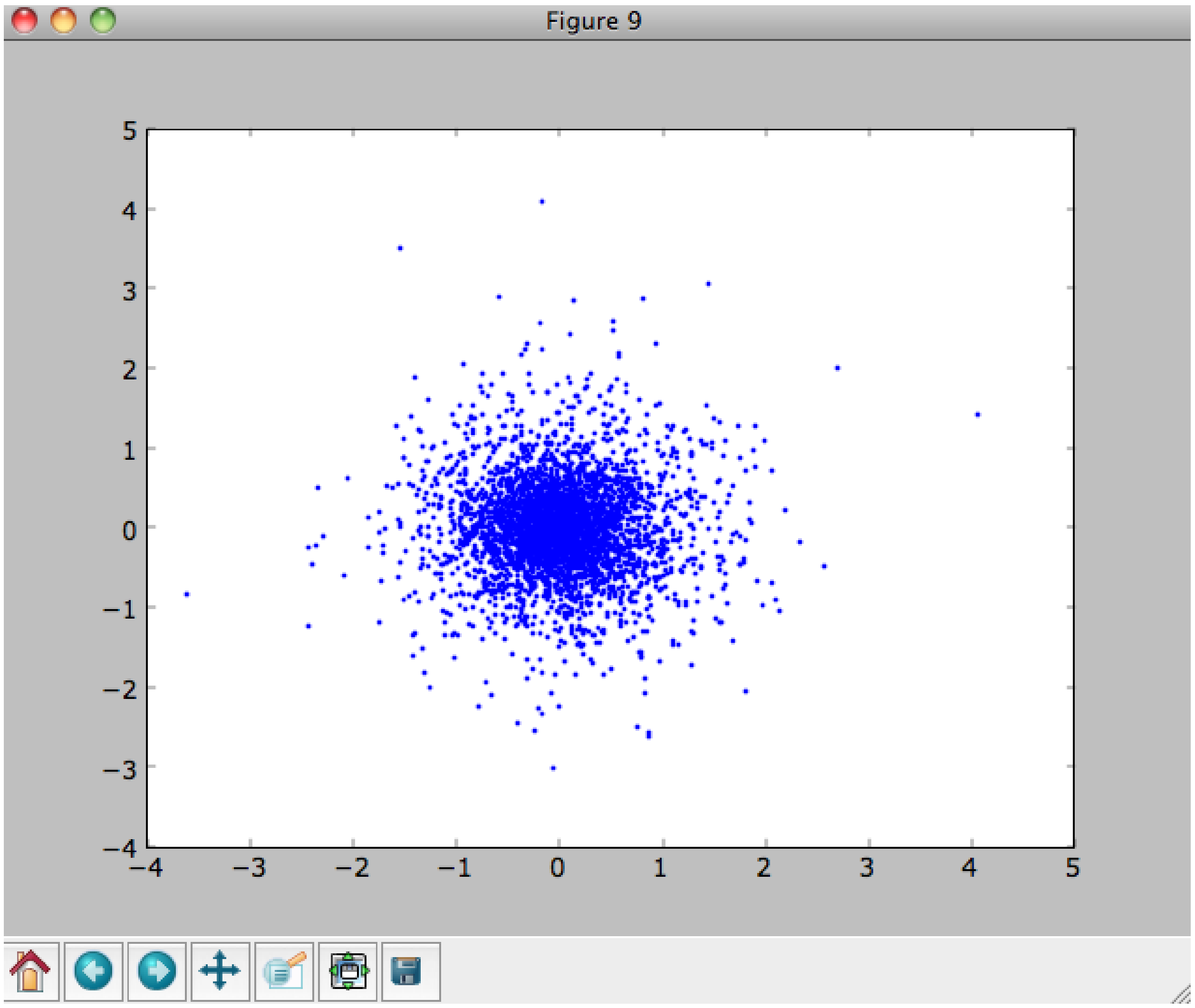
E.g.,



We can also plot the spatial distribution of the sampled disk

```
>>> xs= [e.x() for e in o]
>>> ys= [e.y() for e in o]
>>> figure()
>>> plot(xs,ys,',')
```

E.g.,

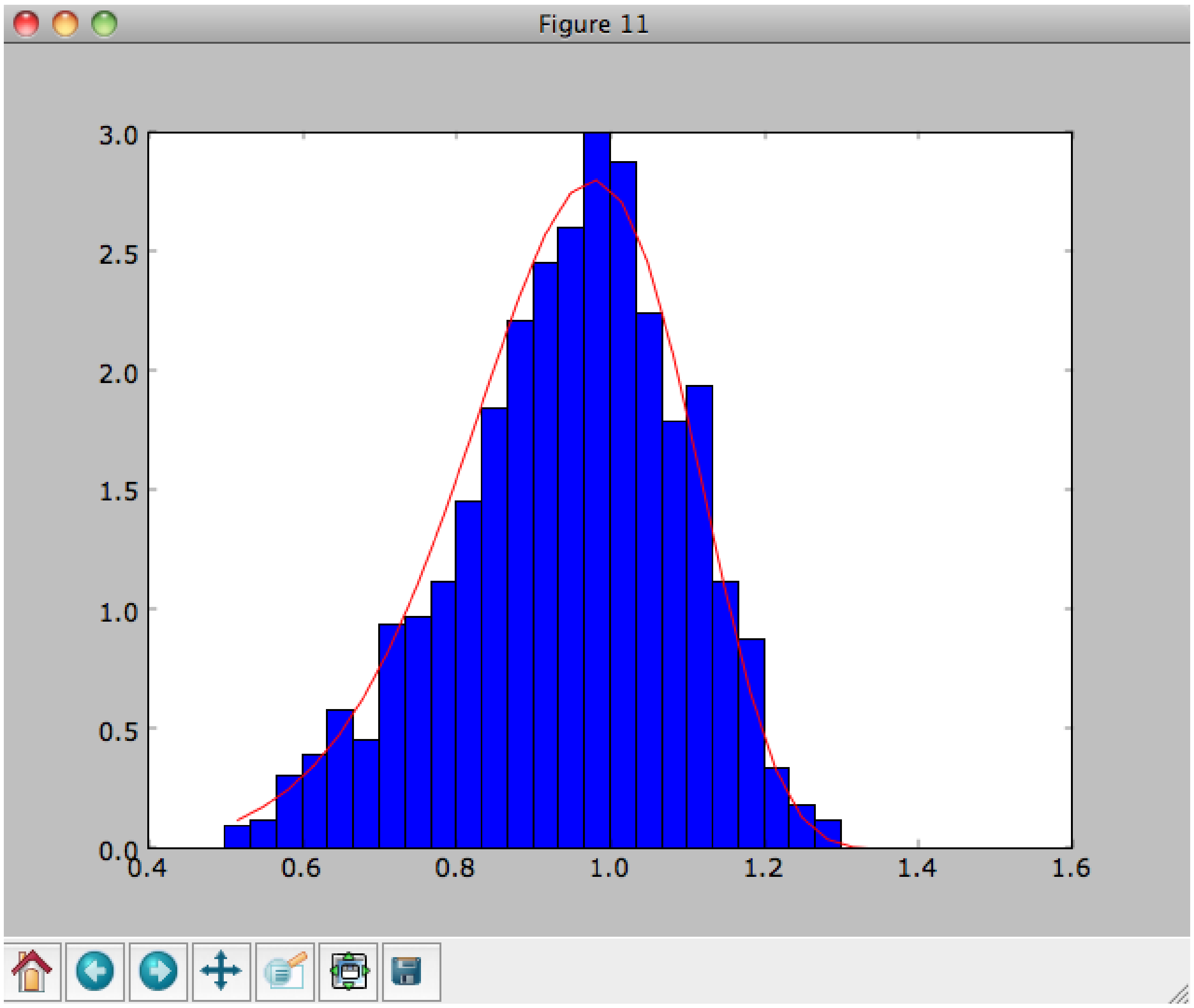


We can also sample points in a specific radial range (might take a few minutes)

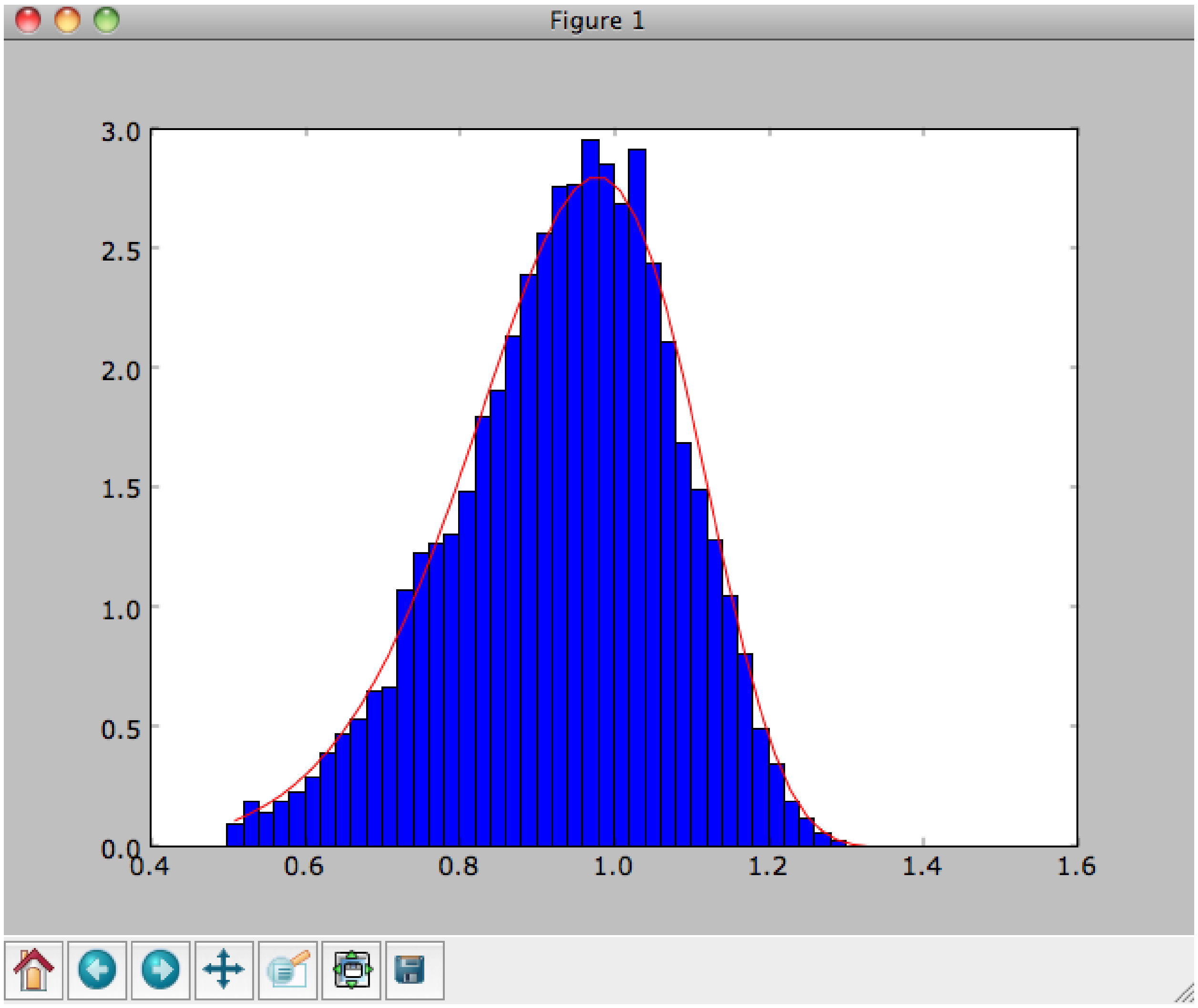
```
>>> o= dfc.sample(n=1000,returnOrbit=True,nphi=1,rrange=[0.8,1.2])
```

and we can plot the distribution of tangential velocities

```
>>> vTs= [e.vxvv[2] for e in o]
>>> hists, bins, edges= hist(vTs,range=[.5,1.5],normed=True,bins=30)
>>> xs= numpy.array([(bins[ii+1]+bins[ii])/2. for ii in range(len(bins)-1)])
>>> dfro= [dfc(Orbit([1.,0.,x]))/9./numpy.exp(-3.) for x in xs]
>>> plot(xs,dfro,'r-')
```

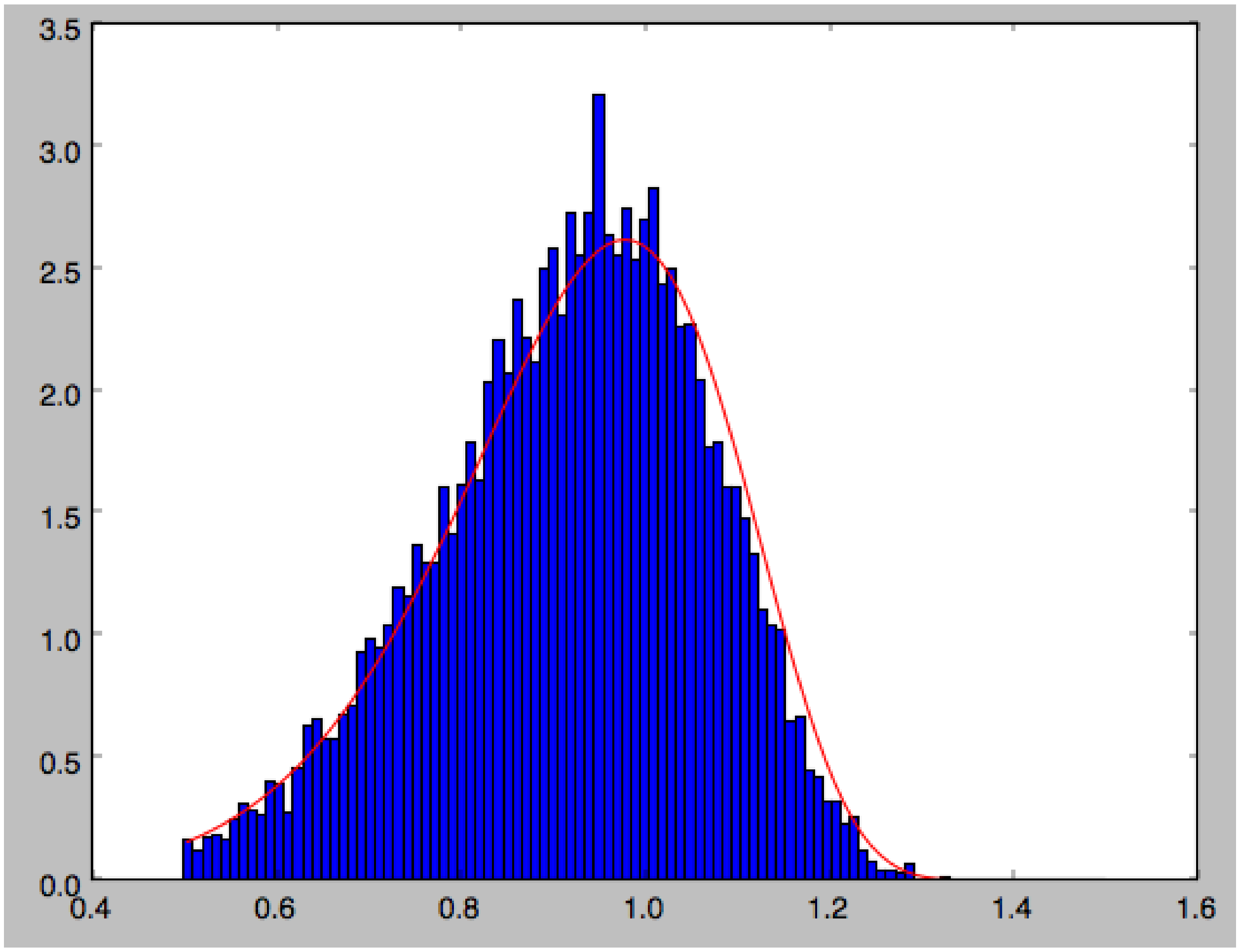


The agreement between the sampled distribution and the theoretical curve is not as good because the sampled distribution has a finite radial range. If we sample 10,000 points in `rrange=[0.95,1.05]` the agreement is better (this takes a long time):



We can also directly sample velocities at a given radius rather than in a range of radii. Doing this for a correct DF gives

```
>>> dfc= dehnendf(beta=0.,correct=True)
>>> vrvt= dfc.sampleVRVT(1.,n=10000)
>>> hists, bins, edges= hist(vrvt[:,1],range=[.5,1.5],normed=True,bins=101)
>>> xs= numpy.array([(bins[ii+1]+bins[ii])/2. for ii in range(len(bins)-1)])
>>> dfro= [dfc(Orbit([1.,0.,x])) for x in xs]
>>> plot(xs,dfro/numpy.sum(dfro)/(xs[1]-xs[0]),'r-')
```



galpy further has support for sampling along a given line of sight in the disk, which is useful for interpreting surveys consisting of a finite number of pointings. For example, we can sampled distances along a given line of sight

```
>>> ds= dfc.sampledSurfacemassLOS(30./180.*numpy.pi,n=10000)
```

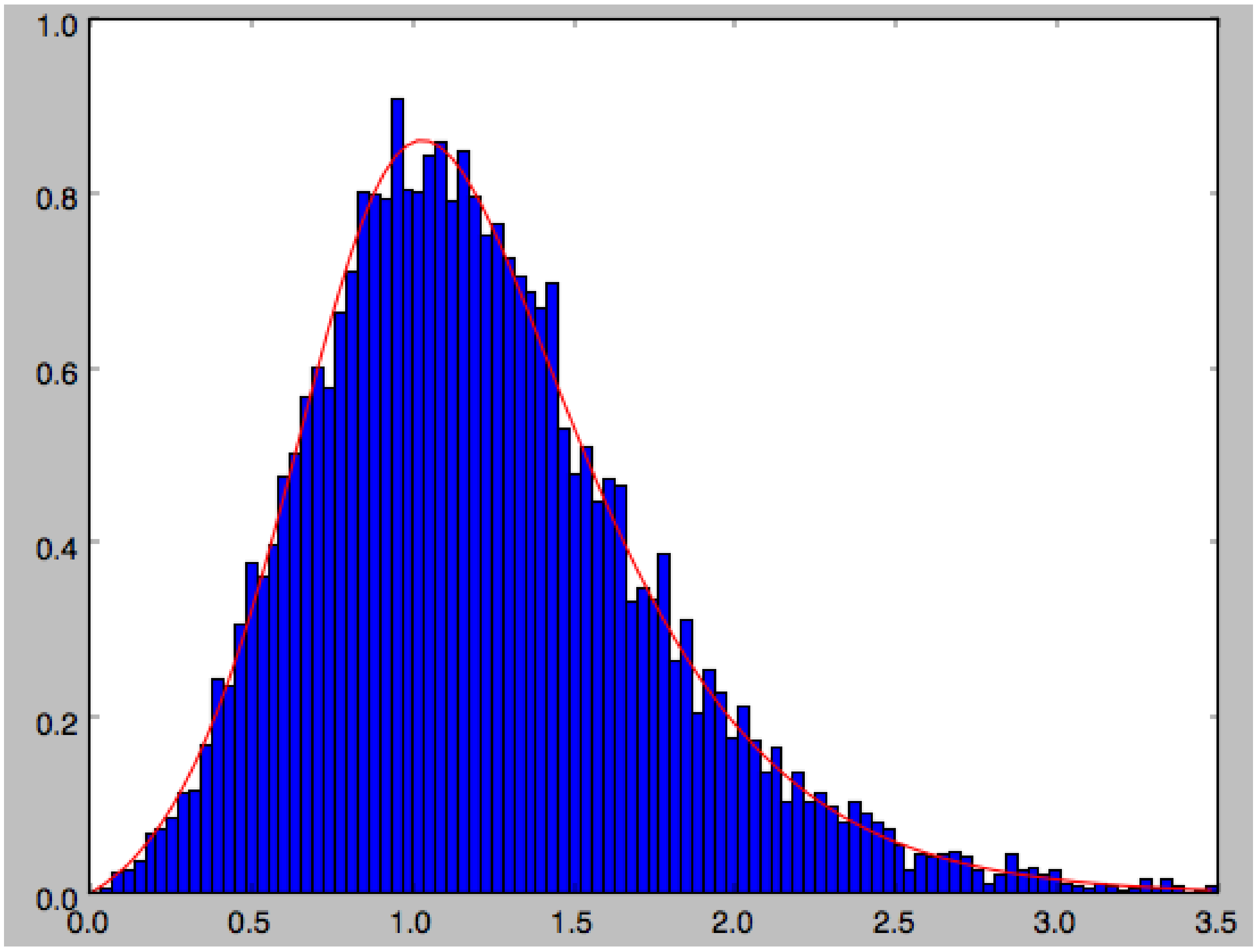
which is very fast. We can histogram these

```
>>> hists, bins, edges= hist(ds,range=[0.,3.5],normed=True,bins=101)
```

and compare it to the predicted distribution, which we can calculate as

```
>>> xs= numpy.array([(bins[ii+1]+bins[ii])/2. for ii in range(len(bins)-1)])
>>> fd= numpy.array([dfc.surfacemassLOS(d,30.) for d in xs])
>>> plot(xs,fd/numpy.sum(fd)/(xs[1]-xs[0]),'r-')
```

which shows very good agreement with the sampled distances



galpy can further sample full 4D phase–space coordinates along a given line of sight through `dfc.sampleLOS`.

1.4.6 Non-axisymmetric, time-dependent disk distribution functions

`galpy` also supports the evaluation of non-axisymmetric, time-dependent two-dimensional DFs. These specific DFs are constructed by assuming an initial axisymmetric steady state, described by a DF of the family discussed above, that is then acted upon by a non-axisymmetric, time-dependent perturbation. The DF at a given time and phase-space position is evaluated by integrating the orbit backwards in time in the non-axisymmetric potential until the time of the initial DF is reached. From Liouville's theorem, which states that phase-space volume is conserved along the orbit, we then know that we can evaluate the non-axisymmetric DF today as the initial DF at the initial point on the orbit. This procedure was first used by Dehnen (2000).

This is implemented in `galpy` as `galpy.df.evolveddiskdf`. Such a DF is setup by specifying the initial DF, the non-axisymmetric potential, and the time of the initial state. For example, we can look at the effect of an elliptical perturbation to the potential like that described by Kuijken & Tremaine. To do this, we set up an elliptical perturbation to a logarithmic potential that is grown slowly to minimize non-adiabatic effects

```
>>> from galpy.potential import LogarithmicHaloPotential, EllipticalDiskPotential
>>> lp= LogarithmicHaloPotential(normalize=1.)
>>> ep= EllipticalDiskPotential(twophio=0.05,phib=0.,p=0.,tform=-150.,tsteady=125.)
```

This perturbation starts to be grown at `tform=-150` over a time period of `tsteady=125` time units. We will consider the effect of this perturbation on a very cold disk (velocity dispersion $\sigma_R = 0.0125\,v_c$) and a warm disk ($\sigma_R = 0.15\,v_c$). We set up these two initial DFs

```
>>> idfcold= dehnendf(beta=0.,profileParams=(1./3.,1.,0.0125))
>>> idfwarm= dehnendf(beta=0.,profileParams=(1./3.,1.,0.15))
```

and then set up the `evolveddiskdf`

```
>>> from galpy.df import evolveddiskdf
>>> edfcold= evolveddiskdf(idfcold,[lp,ep],to=-150.)
>>> edfwarm= evolveddiskdf(idfwarm,[lp,ep],to=-150.)
```

where we specify that the initial state is at `to=-150`.

We can now use these `evolveddiskdf` instances in much the same way as `diskdf` instances. One difference is that there is much more support for evaluating the DF on a grid (to help speed up the rather slow computations involved). Thus, we can evaluate the mean radial velocity at `R=0.9`, `phi=22.5` degree, and `t=0` by using a grid

```
>>> mvrcold, gridcold= edfcold.meanvR(0.9,phi=22.5,deg=True,t=0.,grid=True,
↪returnGrid=True,gridpoints=51,nsigma=6.)
>>> mvrwarm, gridwarm= edfcold.meanvR(0.9,phi=22.5,deg=True,t=0.,grid=True,
↪returnGrid=True,gridpoints=51)
>>> print mvrcold, mvrwarm
-0.0358753028951 -0.0294763627935
```

The cold response agrees well with the analytical calculation, which predicts that this is $-0.05/\sqrt{2}$:

```
>>> print mvrcold+0.05/sqrt(2.)
-0.000519963835811
```

The warm response is slightly smaller in amplitude

```
>>> print mvrwarm/mvrcold
0.821633837619
```

although the numerical uncertainty in `mvrwarm` is large, because the grid is not sufficiently fine.

We can then re-use this grid in calculations of other moments of the DF, e.g.,

```
>>> print edfcold.meanvT(0.9,phi=22.5,deg=True,t=0.,grid=gridcold)
0.965058551359
>>> print edfwarm.meanvT(0.9,phi=22.5,deg=True,t=0.,grid=gridwarm)
0.915397094614
```

which returns the mean rotational velocity, and

```
>>> print edfcold.vertexdev(0.9,phi=22.5,deg=True,t=0.,grid=gridcold)
3.21160878582
>>> print edfwarm.vertexdev(0.9,phi=22.5,deg=True,t=0.,grid=gridwarm)
4.23510254333
```

which gives the vertex deviation. The reason we have to calculate the grid out to `6nsigma` for the cold response is that the response is much bigger than the velocity dispersion of the population. This velocity dispersion is used to automatically to set the grid edges, but sometimes has to be adjusted to contain the full DF.

`evolveddiskdf` can also calculate the Oort functions, by directly calculating the spatial derivatives of the DF. These can also be calculated on a grid, such that we can do

```
>>> oortacold, gridcold, gridrcold, gridphicold= edfcold.oortA(0.9,phi=22.5,deg=True,
↪t=0.,returnGrids=True,gridpoints=51,derivGridpoints=51,grid=True,derivphiGrid=True,
↪derivRGrid=True,nsigma=6.)
>>> oortawarm, gridwarm, gridrwarm, gridphiwarm= edfwarm.oortA(0.9,phi=22.5,deg=True,
↪t=0.,returnGrids=True,gridpoints=51,derivGridpoints=51,grid=True,derivphiGrid=True,
↪derivRGrid=True)
>>> print oortacold, oortawarm
0.575494559999 0.526389833249
```

It is clear that these are quite different. The cold calculation is again close to the analytical prediction, which says that $A = A_{\mathrm{axi}} + 0.05/(2\sqrt{2})$ where $A_{\mathrm{axi}} = 1/(2 \times 0.9)$ in this case:

```
>>> print oortacold-(0.5/0.9+0.05/2./sqrt(2.))
0.0022613349141670236
```

These grids can then be re-used for the other Oort functions, for example,

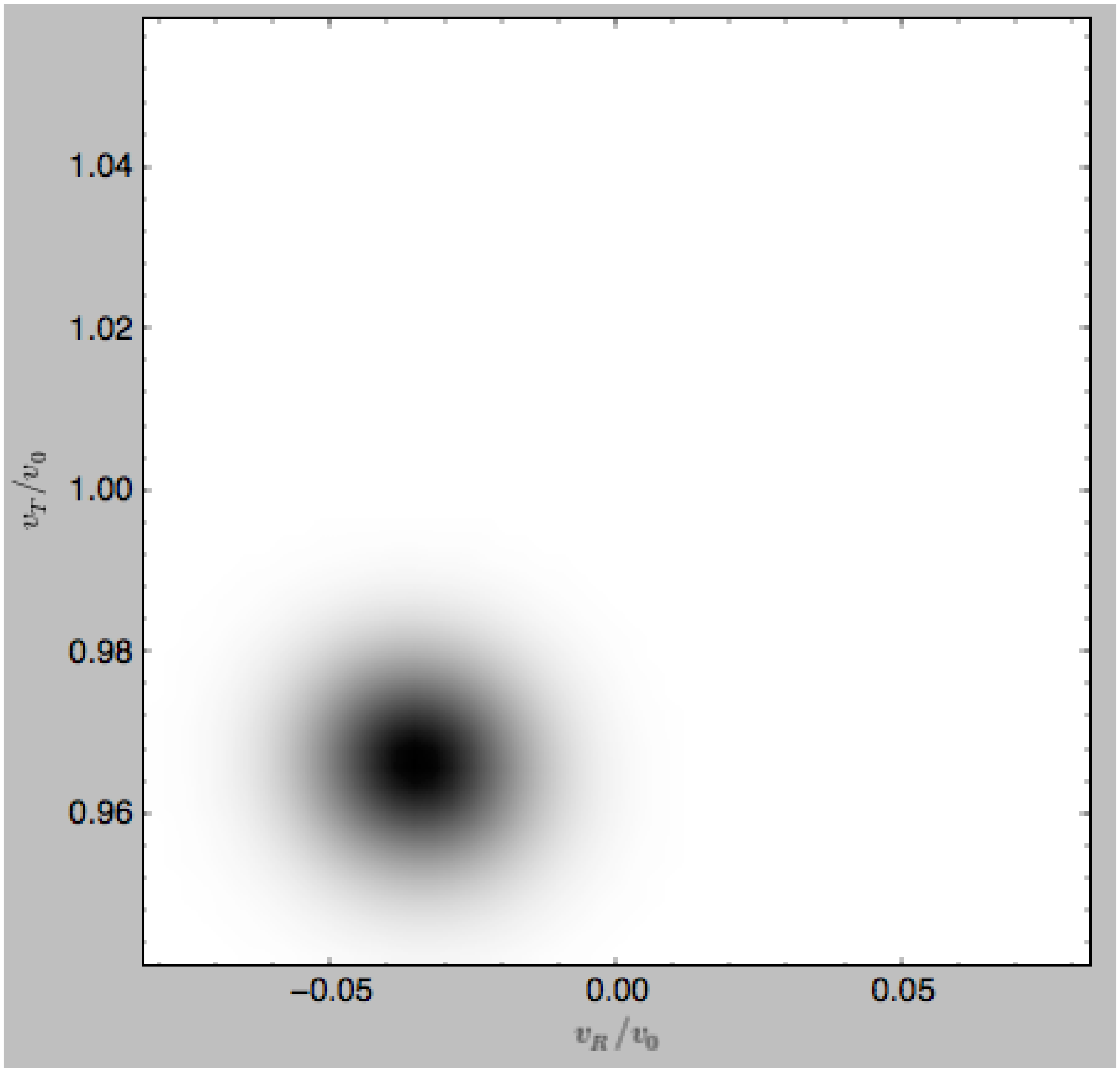
```
>>> print edfcold.oortB(0.9,phi=22.5,deg=True,t=0.,grid=gridcold,
↪derivphiGrid=gridphicold,derivRGrid=gridrcold)
-0.574674310521
>>> print edfwarm.oortB(0.9,phi=22.5,deg=True,t=0.,grid=gridwarm,
↪derivphiGrid=gridphiwarm,derivRGrid=gridrwarm)
-0.555546911144
```

and similar for `oortC` and `oortK`. These warm results should again be considered for illustration only, as the grid is not sufficiently fine to have a small numerical error.

The grids that have been calculated can also be plotted to show the full velocity DF. For example,

```
>>> gridcold.plot()
```

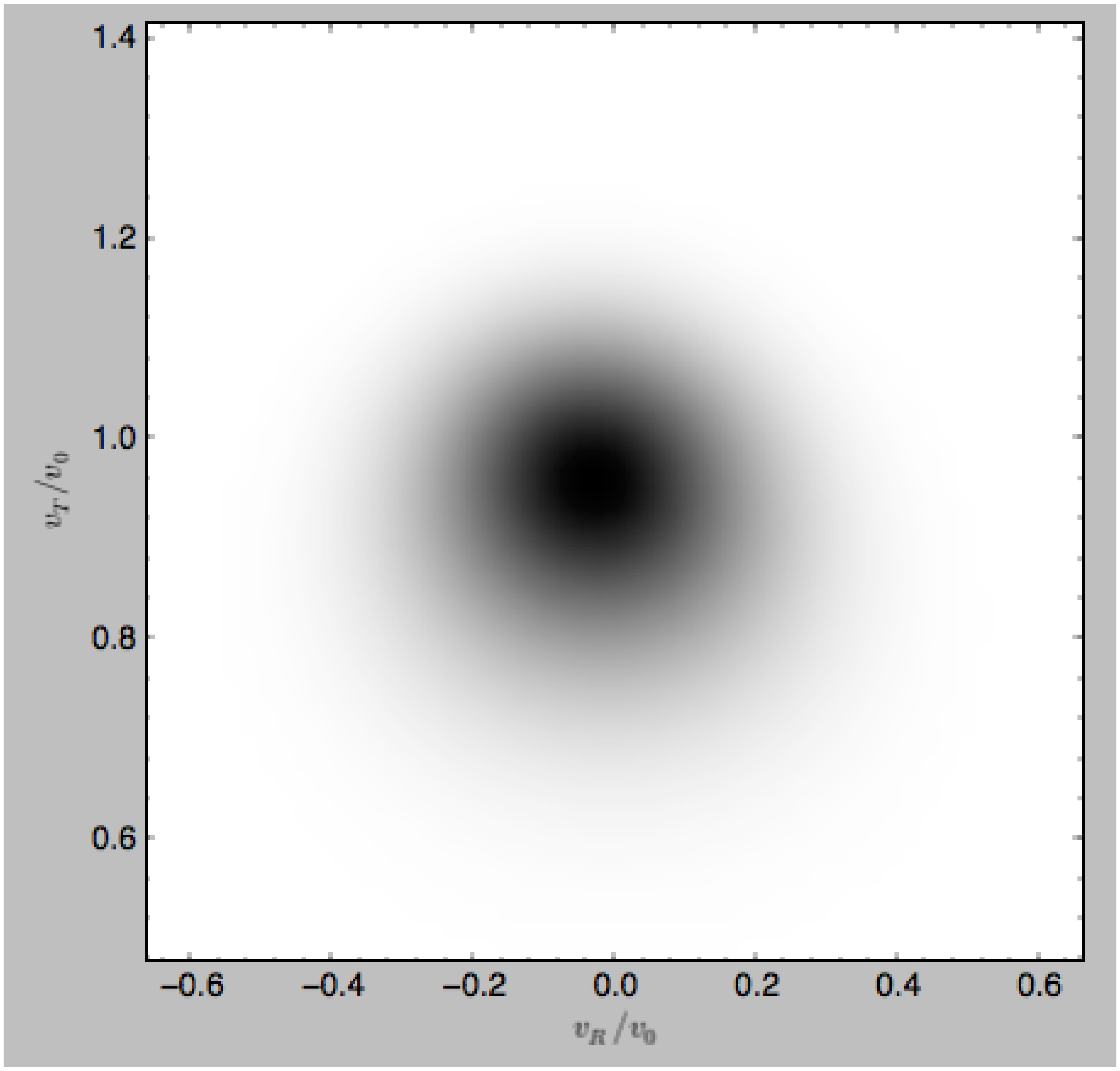
gives



which demonstrates that the DF is basically the initial DF that has been displaced (by a significant amount compared to the velocity dispersion). The warm velocityd distribution is given by

```
>>> gridwarm.plot()
```

which returns



The shift of the smooth DF here is much smaller than the velocity dispersion.

1.4.7 Example: The Hercules stream in the Solar neighborhood as a result of the Galactic bar

We can combine the orbit integration capabilities of galpy with the provided distribution functions and see the effect of the Galactic bar on stellar velocities. By backward integrating orbits starting at the Solar position in a potential that includes the Galactic bar we can evaluate what the velocity distribution is that we should see today if the Galactic bar stirred up a steady-state disk. For this we initialize a flat rotation curve potential and Dehnen's bar potential

```
>>> from galpy.potential import LogarithmicHaloPotential, DehnenBarPotential
>>> lp= LogarithmicHaloPotential(normalize=1.)
>>> dp= DehnenBarPotential()
```

The Dehnen bar potential is initialized to start bar formation four bar periods before the present day and to have completely formed the bar two bar periods ago. We can integrate back to the time before bar-formation:

```
>>> ts= numpy.linspace(0,dp.tform(),1000)
```

where `dp.tform()` is the time of bar-formation (in the usual time-coordinates).

We initialize orbits on a grid in velocity space and integrate them

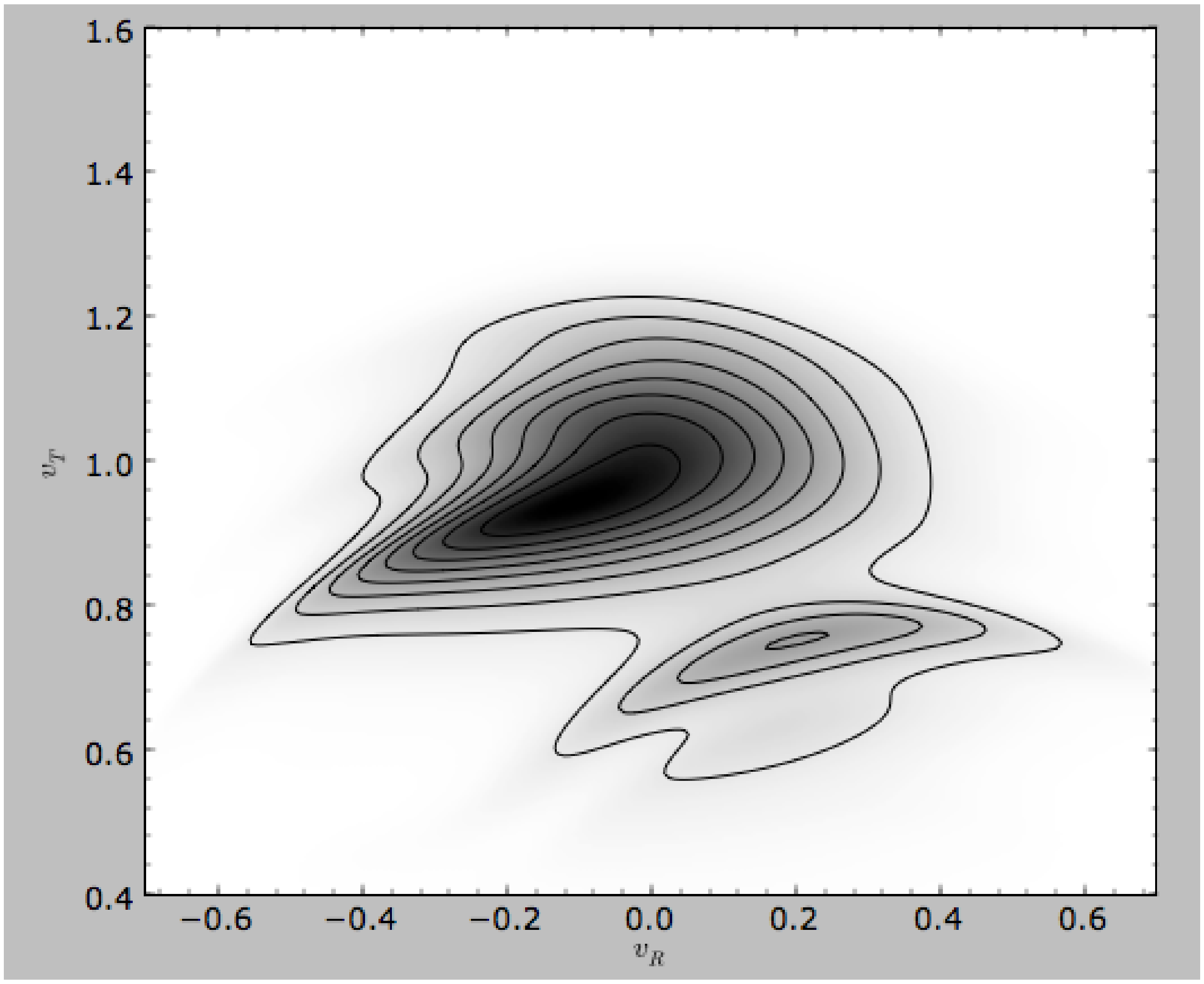
```
>>> ins=[[Orbit([1.,-0.7+1.4/100*jj,1.-0.6+1.2/100*ii,0.]) for jj in range(101)] for␣
↪ii in range(101)]
>>> int=[[o.integrate(ts,[lp,dp]) for o in j] for j in ins]
```

We can then evaluate the weight of these orbits by assuming that the disk was in a steady-state before bar-formation with a Dehnen distribution function. We evaluate the Dehnen distribution function at `dp.tform()` for each of the orbits

```
>>> dfc= dehnendf(beta=0.,correct=True)
>>> out= [[dfc(o(dp.tform())) for o in j] for j in ins]
>>> out= numpy.array(out)
```

This gives

```
>>> from galpy.util.bovy_plot import bovy_dens2d
>>> bovy_dens2d(out,origin='lower',cmap='gist_yarg',contours=True,xrange=[-0.7,0.7],
↪yrange=[0.4,1.6],xlabel=r'$v_R$',ylabel=r'$v_T$')
```

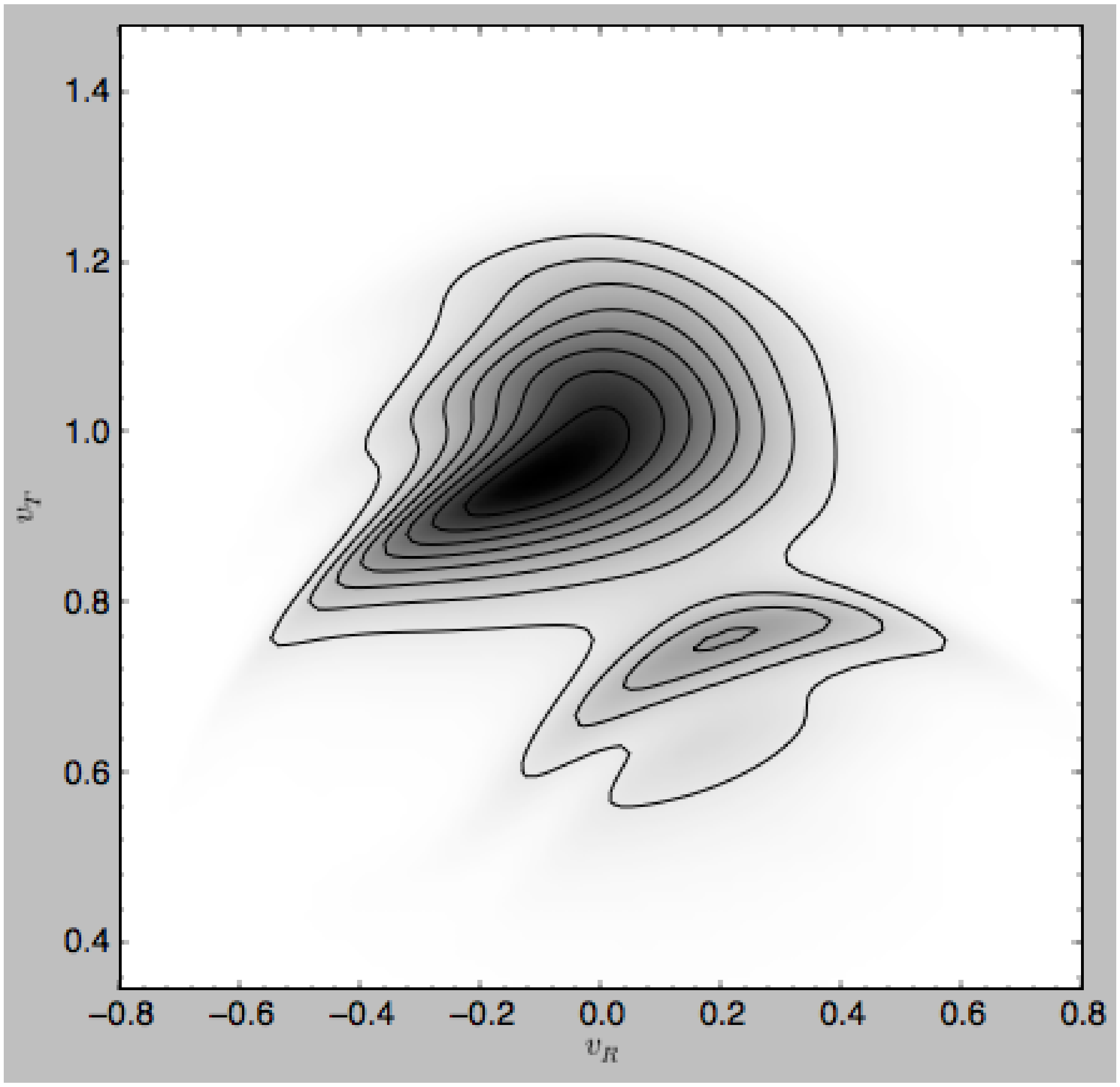


Now that galpy contains the evolveddiskdf described above, this whole calculation is encapsulated in this module and can be done much more easily as

```
>>> edf= evolveddiskdf(dfc,[lp,dp],to=dp.tform())
>>> mvr, grid= edf.meanvR(1.,grid=True,gridpoints=101,returnGrid=True)
```

The gridded DF can be accessed as grid.df, which we can plot as before

```
>>> bovy_dens2d(grid.df.T,origin='lower',cmap='gist_yarg',contours=True,xrange=[grid.
↪vRgrid[0],grid.vRgrid[-1]],yrange=[grid.vTgrid[0],grid.vTgrid[-1]],xlabel=r'$v_R$',
↪ylabel=r'$v_T$')
```



For more information see 2000AJ....119..800D and 2010ApJ...725.1676B. Note that the x-axis in the Figure above is defined as minus the x-axis in these papers.

1.5 A closer look at orbit integration

1.5.1 Orbit initialization

Standard initialization

Orbits can be initialized in various coordinate frames. The simplest initialization gives the initial conditions directly in the Galactocentric cylindrical coordinate frame (or in the rectangular coordinate frame in one dimension). `Orbit()` automatically figures out the dimensionality of the space from the initial conditions in this case. In three dimensions initial conditions are given either as `vxvv=[R,vR,vT,z,vz,phi]` or one can choose not to specify the azimuth of the orbit and initialize with `vxvv=[R,vR,vT,z,vz]`. Since potentials in galpy are easily initialized to have a circular velocity of one at a radius equal to one, initial coordinates are best given as a fraction of the radius at which one specifies the circular velocity, and initial velocities are best expressed as fractions of this circular velocity. For example,

```
>>> o= Orbit(vxvv=[1.,0.1,1.1,0.,0.1,0.])
```

initializes a fully three-dimensional orbit, while

```
>>> o= Orbit(vxvv=[1.,0.1,1.1,0.,0.1])
```

initializes an orbit in which the azimuth is not tracked, as might be useful for axisymmetric potentials.

In two dimensions, we can similarly specify fully two-dimensional orbits `o=Orbit(vxvv=[R,vR,vT,phi])` or choose not to track the azimuth and initialize with `o= Orbit(vxvv=[R,vR,vT])`.

In one dimension we simply initialize with `o= Orbit(vxvv=[x,vx])`.

Initialization with physical scales

Orbits are normally used in galpy's *natural coordinates*. When Orbits are initialized using a distance scale `ro=` and a velocity scale `vo=`, then many Orbit methods return quantities in physical coordinates. Specifically, physical distance and velocity scales are specified as

```
>>> op= Orbit(vxvv=[1.,0.1,1.1,0.,0.1,0.],ro=8.,vo=220.)
```

All output quantities will then be automatically be specified in physical units: kpc for positions, km/s for velocities, (km/s)^2 for energies and the Jacobi integral, km/s kpc for the angular momentum o.L() and actions, 1/Gyr for frequencies, and Gyr for times and periods. See below for examples of this.

Physical units are only used for outputs: internally natural units are still used and inputs have to also be specified in natural units (for example, integration times or the time at which an output is requested must be specified in natural units). If for any output you do *not* want the output in physical units, you can specify this by supplying the keyword argument `use_physical=False`.

Initialization from observed coordinates

For orbit integration and characterization of observed stars or clusters, initial conditions can also be specified directly as observed quantities when `radec=True` is set. In this case a full three-dimensional orbit is initialized as `o= Orbit(vxvv=[RA,Dec,distance,pmRA,pmDec,Vlos],radec=True)` where RA and Dec are expressed in degrees, the distance is expressed in kpc, proper motions are expressed in mas/yr (pmra = pmra' * cos[Dec]), and `Vlos` is the heliocentric line-of-sight velocity given in km/s. The observed epoch is currently assumed to be J2000.00. These observed coordinates are translated to the Galactocentric cylindrical coordinate frame by assuming a Solar motion that can be specified as either `solarmotion=hogg` (default; 2005ApJ...629..268H), `solarmotion=dehnen` (1998MNRAS.298..387D) or `solarmotion=shoenrich` (2010MNRAS.403.1829S). A circular velocity can be specified as `vo=220` in km/s and a value for the distance between the Galactic center and the Sun can be given as `ro=8.0` in kpc (e.g., 2012ApJ...759..131B). While the inputs are given in physical units, the orbit is initialized assuming a circular velocity of one at the distance of the Sun (that is, the orbit's position and velocity is scaled to galpy's *natural* units after converting to the Galactocentric coordinate frame, using the specified `ro=` and `vo=`). The parameters of the coordinate transformations are stored internally, such that they are automatically used for relevant outputs (for example, when the RA of an orbit is requested). An example of all of this is:

```
>>> o= Orbit(vxvv=[20.,30.,2.,-10.,20.,50.],radec=True,ro=8.,vo=220.)
```

However, the internally stored position/velocity vector is

```
>>> print o.vxvv
[1.1476649101960512, 0.20128601278731811, 1.8303776114906387, -0.13107066602923434, 0.
↪58171049004255293, 0.14071341020496472]
```

and is therefore in *natural* units.

Similarly, one can also initialize orbits from Galactic coordinates using `o= Orbit(vxvv=[glon,glat, distance,pmll,pmbb,Vlos],lb=True)`, where glon and glat are Galactic longitude and latitude expressed in degrees, and the proper motions are again given in mas/yr ((pmll = pmll' * cos[glat]):

```
>>> o= Orbit(vxvv=[20.,30.,2.,-10.,20.,50.],lb=True,ro=8.,vo=220.)
>>> print o.vxvv
[0.79998509943955398, 0.075939950035477488, 0.52838231795389867, 0.12812499999999999,␣
↪0.89052135379600328, 0.092696334097541536]
```

When `radec=True` or `lb=True` is set, velocities can also be specified in Galactic coordinates if `UVW=True` is set. The input is then `vxvv=[RA,Dec,distance,U,V,W]`, where the velocities are expressed in km/s. U is, as usual, defined as -vR (minus vR).

When orbits are initialized using `radec=True` or `lb=True`, physical scales `ro=` and `vo=` are automatically specified (because they have defaults of `ro=8` and `vo=220`). Therefore, all output quantities will be specified in physical units (see above). If you do want to get outputs in galpy's natural coordinates, you can turn this behavior off by doing

```
>>> o.turn_physical_off()
```

All outputs will then be specified in galpy's natural coordinates.

1.5.2 Orbit integration

After an orbit is initialized, we can integrate it for a set of times `ts`, given as a numpy array. For example, in a simple logarithmic potential we can do the following

```
>>> from galpy.potential import LogarithmicHaloPotential
>>> lp= LogarithmicHaloPotential(normalize=1.)
>>> o= Orbit(vxvv=[1.,0.1,1.1,0.,0.1,0.])
>>> import numpy
>>> ts= numpy.linspace(0,100,10000)
>>> o.integrate(ts,lp)
```

to integrate the orbit from `t=0` to `t=100`, saving the orbit at 10000 instances.

If we initialize the Orbit using a distance scale `ro=` and a velocity scale `vo=`, then Orbit plots and outputs will use physical coordinates (currently, times, positions, and velocities)

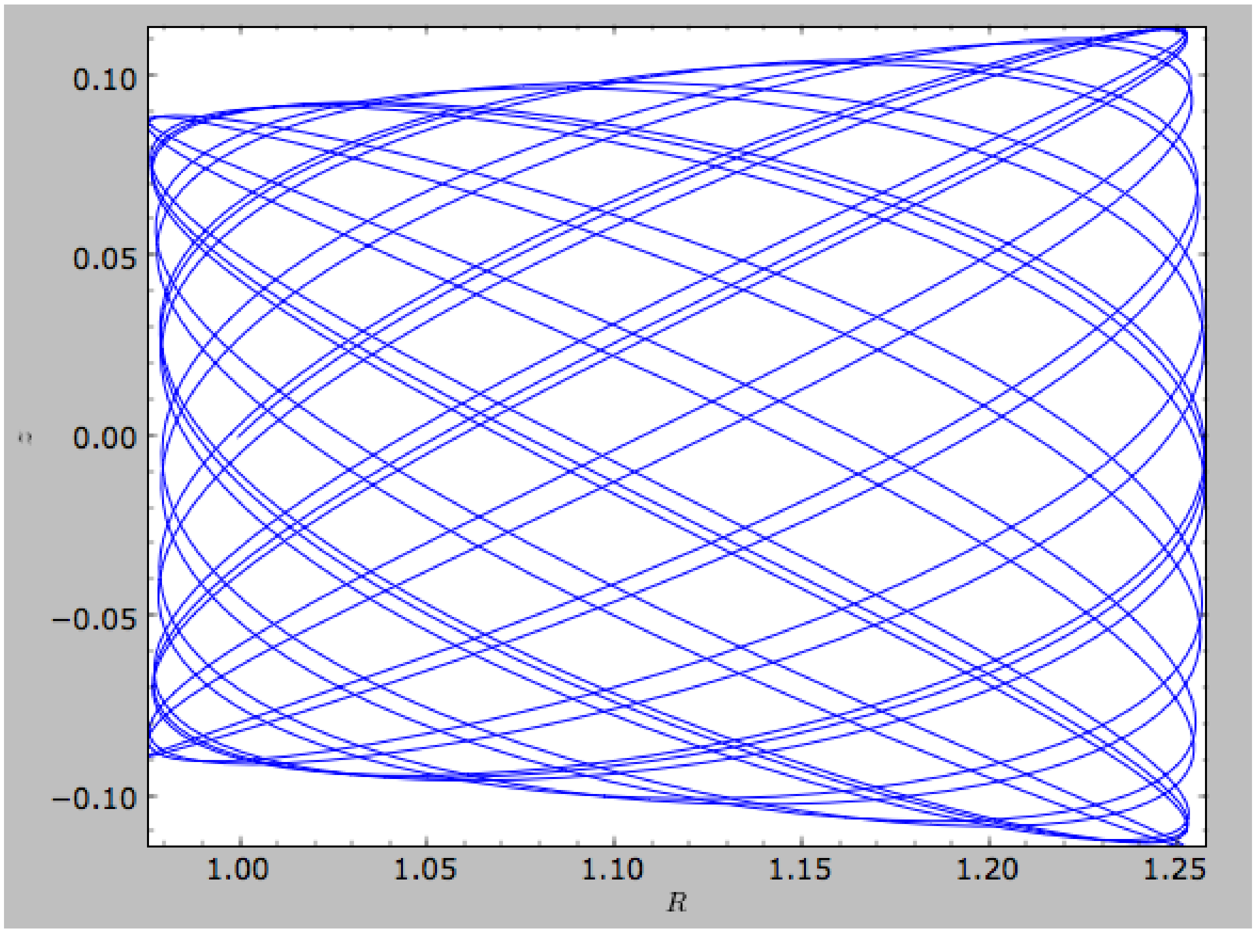
```
>>> op= Orbit(vxvv=[1.,0.1,1.1,0.,0.1,0.],ro=8.,vo=220.) #Use Vc=220 km/s at R= 8 kpc␣
↪as the normalization
>>> op.integrate(ts,lp) #times are still specified in natural coordinates
```

1.5.3 Displaying the orbit

After integrating the orbit, it can be displayed by using the `plot()` function. The quantities that are plotted when `plot()` is called depend on the dimensionality of the orbit: in 3D the (R,z) projection of the orbit is shown; in 2D either (X,Y) is plotted if the azimuth is tracked and (R,vR) is shown otherwise; in 1D (x,vx) is shown. E.g., for the example given above,

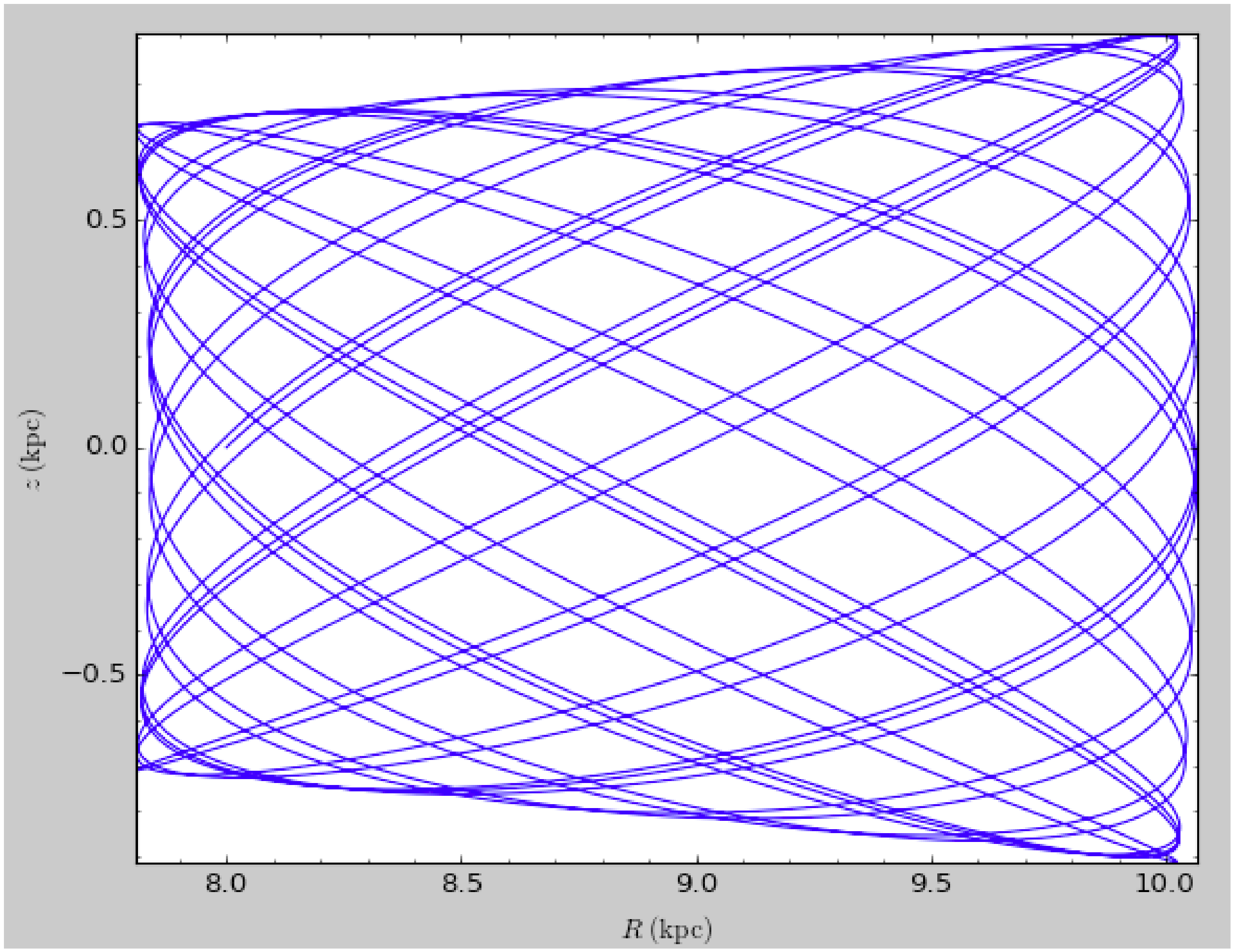
```
>>> o.plot()
```

gives



If we do the same for the Orbit that has physical distance and velocity scales associated with it, we get the following

```
>>> op.plot()
```

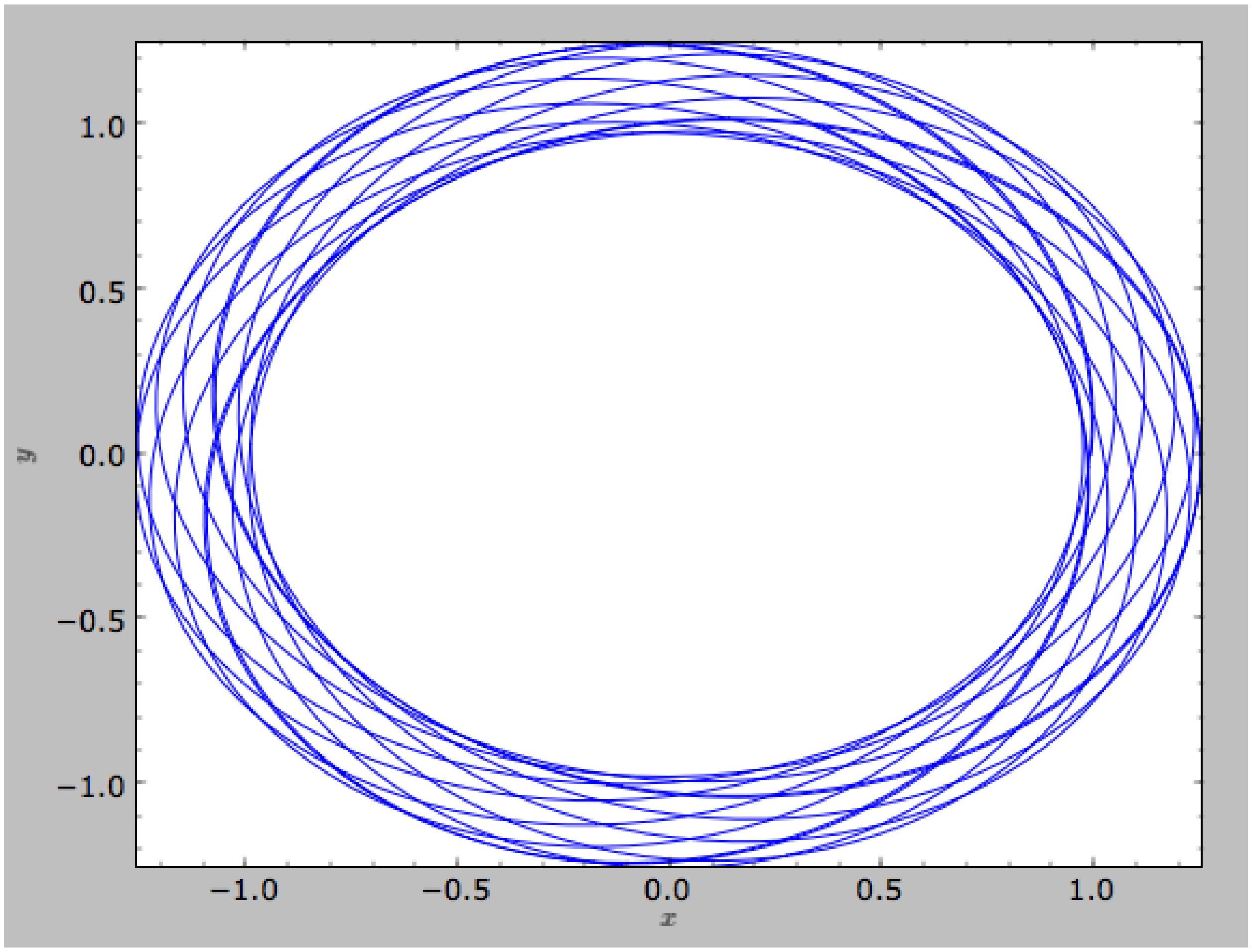


If we call `op.plot(use_physical=False)`, the quantities will be displayed in natural galpy coordinates.

Other projections of the orbit can be displayed by specifying the quantities to plot. E.g.,

```
>>> o.plot(d1='x',d2='y')
```

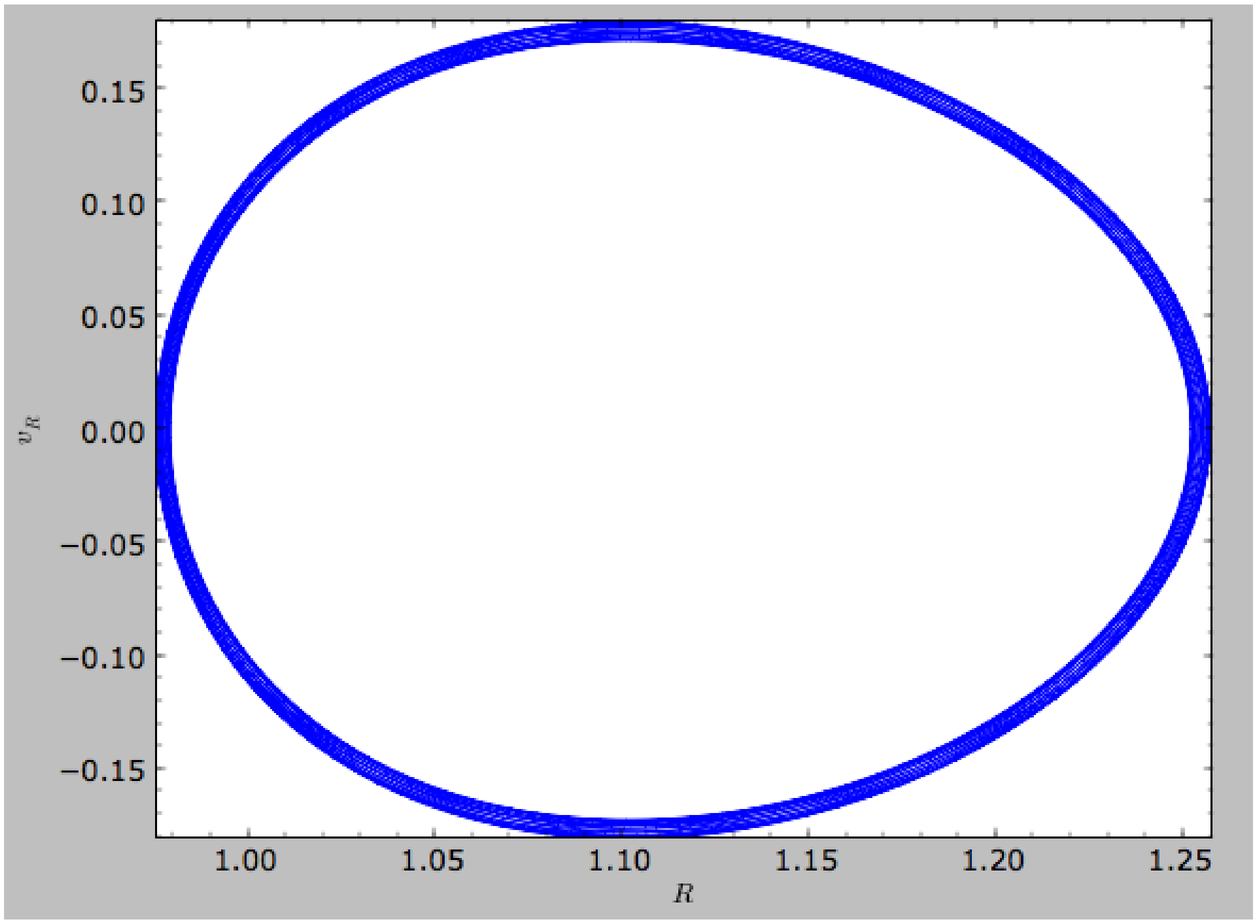
gives the projection onto the plane of the orbit:



while

```
>>> o.plot(d1='R',d2='vR')
```

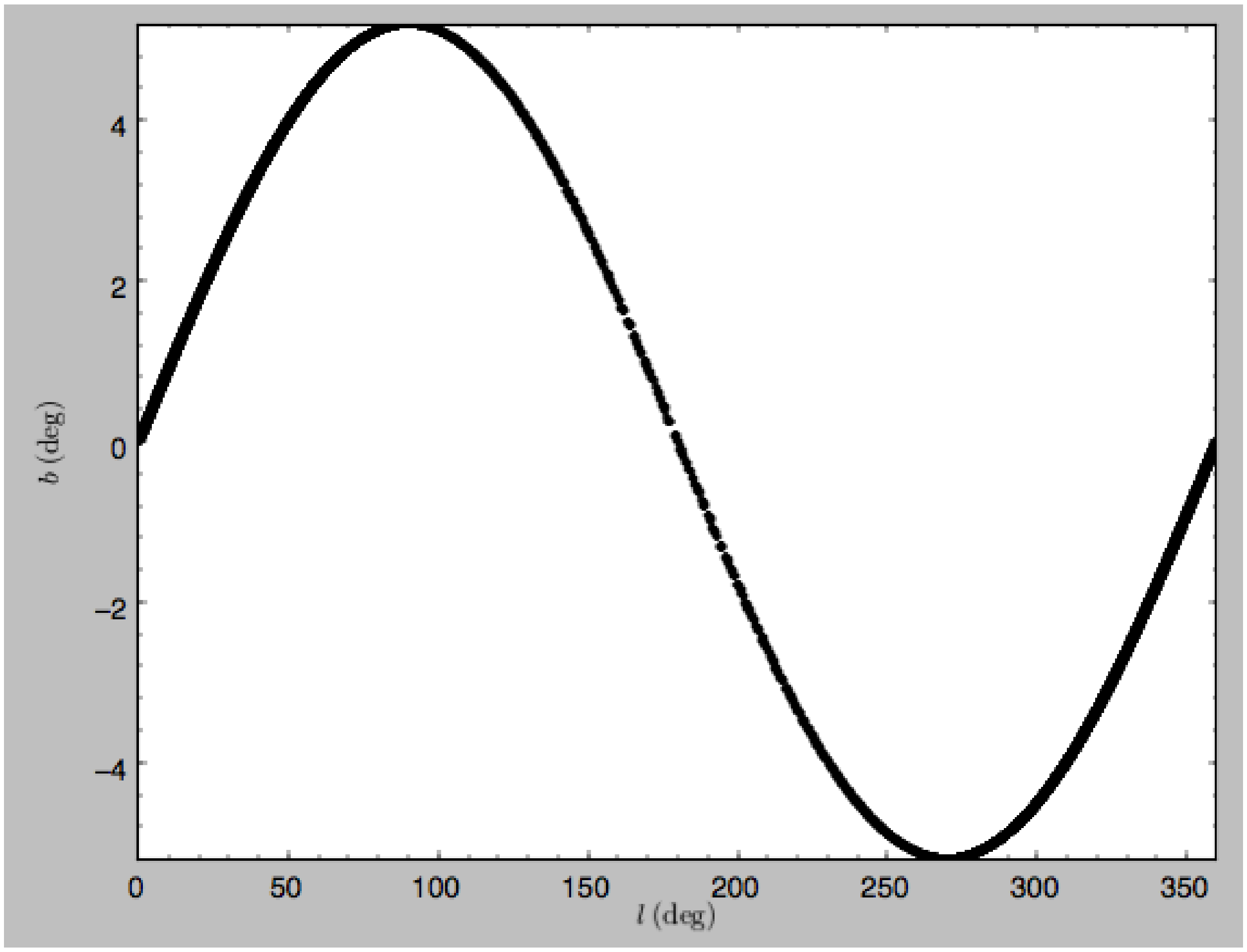
gives the projection onto (R,vR):



We can also plot the orbit in other coordinate systems such as Galactic longitude and latitude

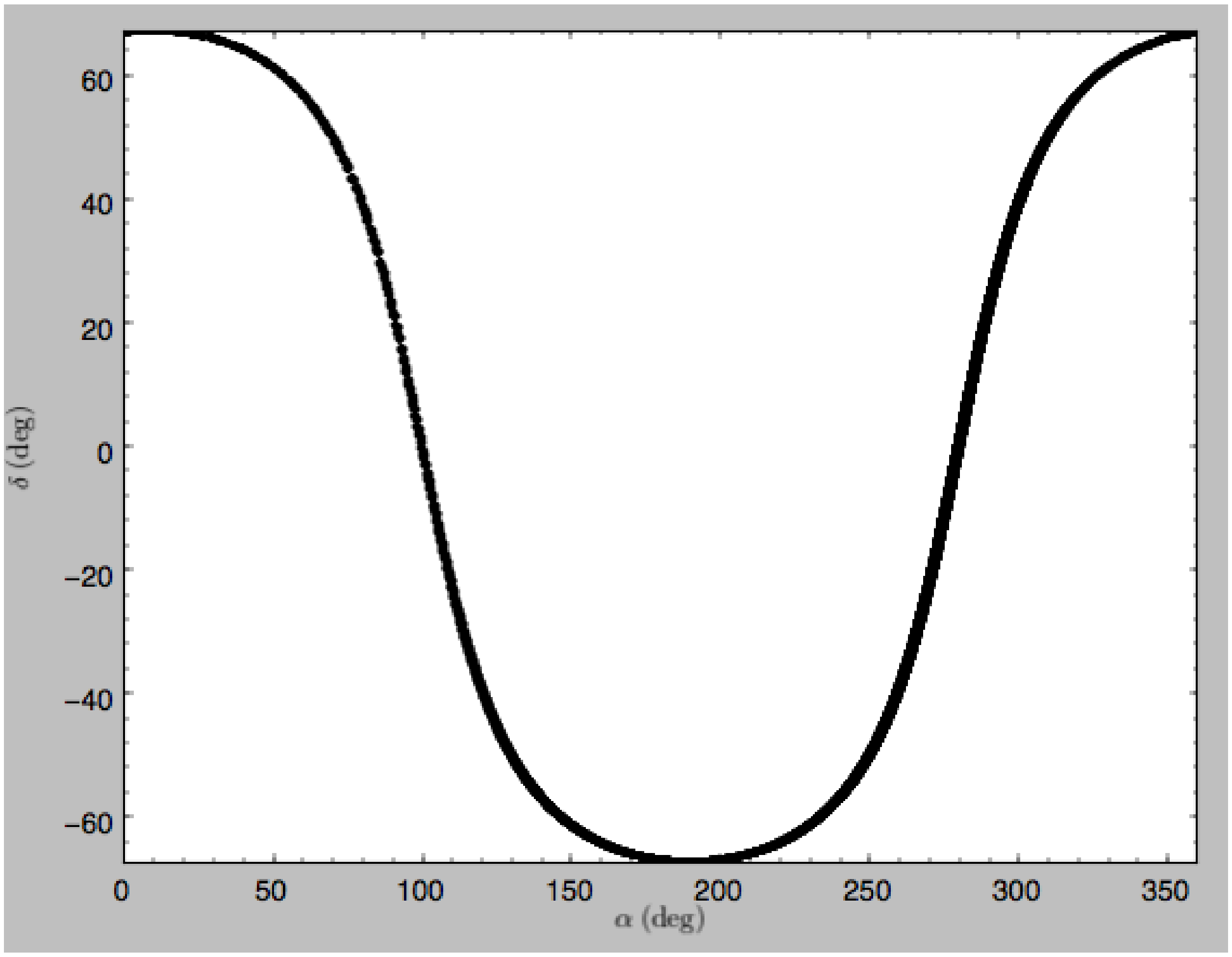
```
>>> o.plot('k.',d1='ll',d2='bb')
```

which shows



or RA and Dec

```
>>> o.plot('k.',d1='ra',d2='dec')
```



See the documentation of the o.plot function and the o.ra(), o.ll(), etc. functions on how to provide the necessary parameters for the coordinate transformations.

1.5.4 Orbit characterization

The properties of the orbit can also be found using galpy. For example, we can calculate the peri- and apocenter radii of an orbit, its eccentricity, and the maximal height above the plane of the orbit

```
>>> o.rap(), o.rperi(), o.e(), o.zmax()
(1.2581455175173673,0.97981663263371377,0.12436710999105324,0.11388132751079502)
```

We can also calculate the energy of the orbit, either in the potential that the orbit was integrated in, or in another potential:

```
>>> o.E(), o.E(pot=mp)
(0.6150000000000001, -0.67390625000000015)
```

where `mp` is the Miyamoto-Nagai potential of *Introduction: Rotation curves*.

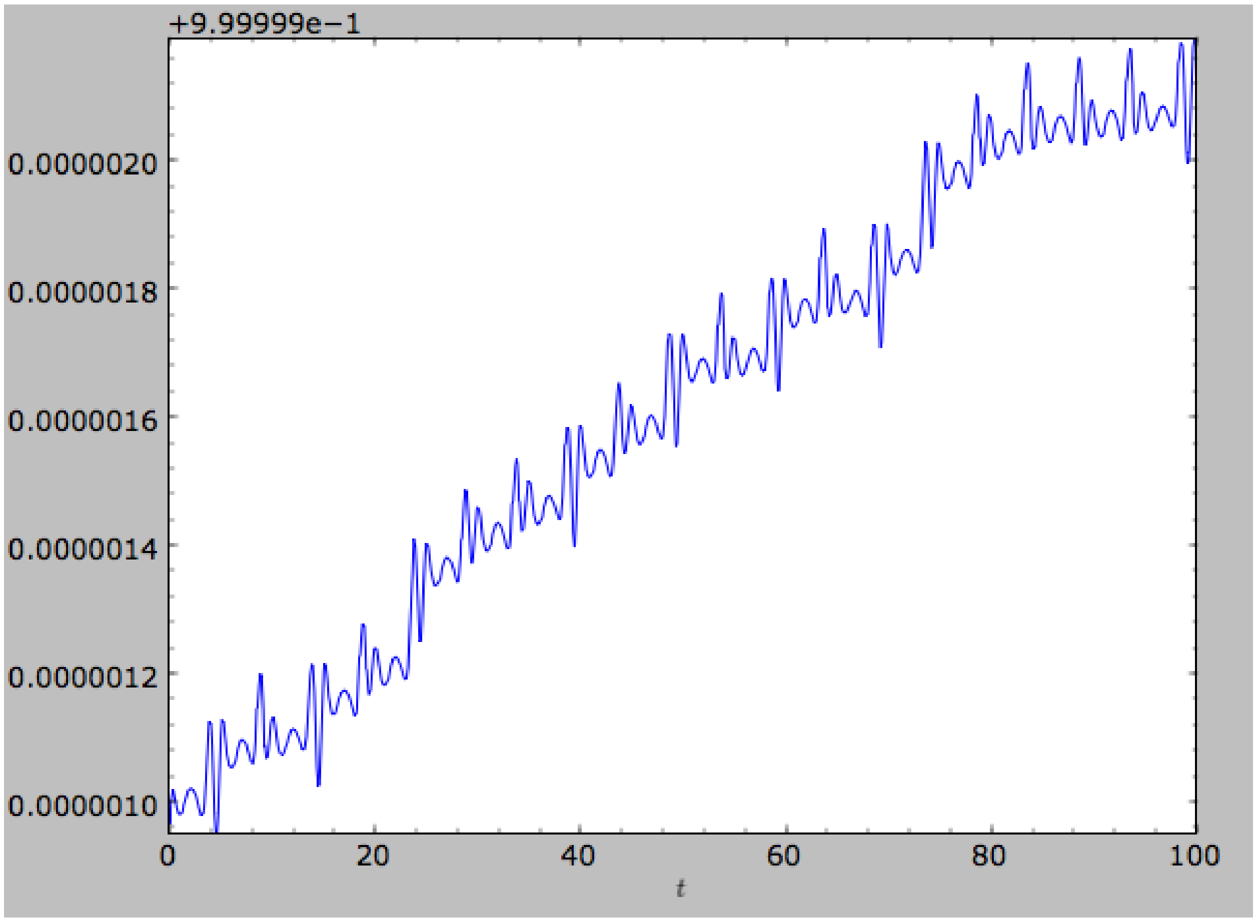
For the Orbit `op` that was initialized above with a distance scale `ro=` and a velocity scale `vo=`, these outputs are all in physical units

```
>>> op.rap(), op.rperi(), op.e(), op.zmax()
(10.065158988860341,7.8385312810643057,0.12436696983841462,0.91105035688072711) #kpc
>>> op.E(), op.E(pot=mp)
(29766.000000000004, -32617.062500000007) #(km/s)^2
```

We can also show the energy as a function of time (to check energy conservation)

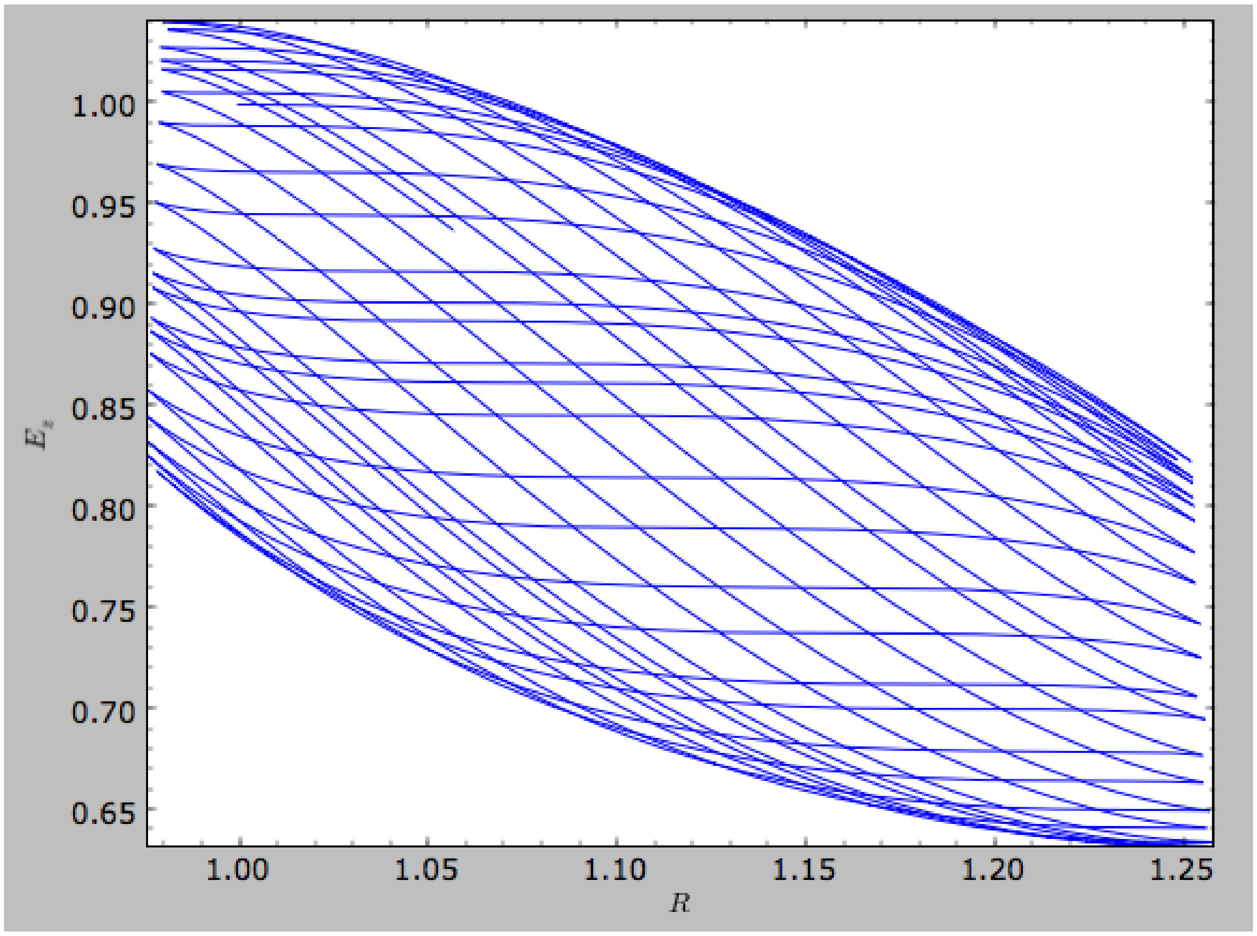
```
>>> o.plotE(normed=True)
```

gives



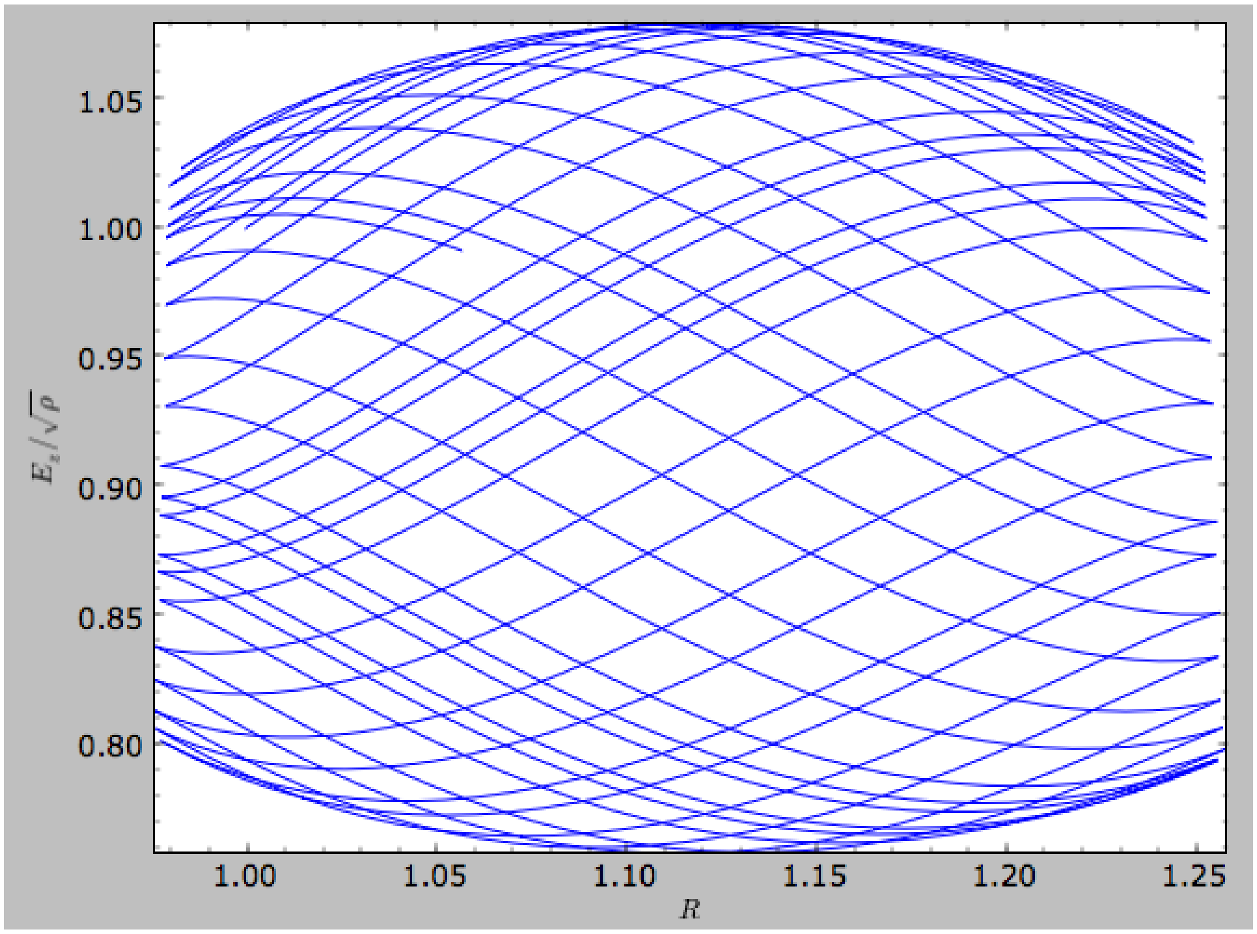
We can specify another quantity to plot the energy against by specifying `d1=`. We can also show the vertical energy, for example, as a function of R

```
>>> o.plotEz(d1='R',normed=True)
```



Often, a better approximation to an integral of the motion is given by Ez/sqrt(density[R]). We refer to this quantity as `EzJz` and we can plot its behavior

```
>>> o.plotEzJz(d1='R',normed=True)
```



1.5.5 Accessing the raw orbit

The value of `R`, `vR`, `vT`, `z`, `vz`, `x`, `vx`, `y`, `vy`, `phi`, and `vphi` at any time can be obtained by calling the corresponding function with as argument the time (the same holds for other coordinates `ra`, `dec`, `pmra`, `pmdec`, `vra`, `vdec`, `ll`, `bb`, `pmll`, `pmbb`, `vll`, `vbb`, `vlos`, `dist`, `helioX`, `helioY`, `helioZ`, `U`, `V`, and `W`). If no time is given the initial condition is returned, and if a time is requested at which the orbit was not saved spline interpolation is used to return the value. Examples include

```
>>> o.R(1.)
1.1545076874679474
>>> o.phi(99.)
88.105603035901169
>>> o.ra(2.,obs=[8.,0.,0.],ro=8.)
array([ 285.76403985])
>>> o.helioX(5.)
array([ 1.24888927])
>>> o.pmll(10.,obs=[8.,0.,0.,0.,245.,0.],ro=8.,vo=230.)
array([-6.45263888])
```

For the Orbit `op` that was initialized above with a distance scale `ro=` and a velocity scale `vo=`, the first of these would be

```
>>> op.R(1.)
9.2360614837829225 #kpc
```

which we can also access in natural coordinates as

```
>>> op.R(1.,use_physical=False)
1.1545076854728653
```

We can also specify a different distance or velocity scale on the fly, e.g.,

```
>>> op.R(1.,ro=4.) #different velocity scale would be vo=
4.6180307418914612
```

We can also initialize an `Orbit` instance using the phase-space position of another `Orbit` instance evaluated at time t. For example,

```
>>> newOrbit= o(10.)
```

will initialize a new Orbit instance with as initial condition the phase-space position of orbit `o` at `time=10.`.

The whole orbit can also be obtained using the function `getOrbit`

```
>>> o.getOrbit()
```

which returns a matrix of phase-space points with dimensions [ntimes,ndim].

1.5.6 Fast orbit integration

The standard orbit integration is done purely in python using standard scipy integrators. When fast orbit integration is needed for batch integration of a large number of orbits, a set of orbit integration routines are written in C that can be accessed for most potentials, as long as they have C implementations, which can be checked by using the attribute `hasC`

```
>>> mp= MiyamotoNagaiPotential(a=0.5,b=0.0375,amp=1.,normalize=1.)
>>> mp.hasC
True
```

Fast C integrators can be accessed through the `method=` keyword of the `orbit.integrate` method. Currently available integrators are

- rk4_c
- rk6_c
- dopr54_c

which are Runge-Kutta and Dormand-Prince methods. There are also a number of symplectic integrators available

- leapfrog_c
- symplec4_c
- symplec6_c

The higher order symplectic integrators are described in Yoshida (1993).

For most applications I recommend `dopr54_c`. For example, compare

```
>>> o= Orbit(vxvv=[1.,0.1,1.1,0.,0.1])
>>> timeit(o.integrate(ts,mp))
1 loops, best of 3: 553 ms per loop
>>> timeit(o.integrate(ts,mp,method='dopr54_c'))
```

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```
galpyWarning: Using C implementation to integrate orbits
10 loops, best of 3: 25.6 ms per loop
```

As this example shows, galpy will issue a warning that C is being used. Speed-ups by a factor of 20 are typical.

1.5.7 Integration of the phase-space volume

`galpy` further supports the integration of the phase-space volume through the method `integrate_dxdv`, although this is currently only implemented for two-dimensional orbits (`planarOrbit`). As an example, we can check Liouville's theorem explicitly. We initialize the orbit

```
>>> o= Orbit(vxvv=[1.,0.1,1.1,0.])
```

and then integrate small deviations in each of the four phase-space directions

```
>>> ts= numpy.linspace(0.,28.,1001) #~1 Gyr at the Solar circle
>>> o.integrate_dxdv([1.,0.,0.,0.],ts,mp,method='dopr54_c',rectIn=True,rectOut=True)
>>> dx= o.getOrbit_dxdv()[-1,:] # evolution of dxdv[0] along the orbit
>>> o.integrate_dxdv([0.,1.,0.,0.],ts,mp,method='dopr54_c',rectIn=True,rectOut=True)
>>> dy= o.getOrbit_dxdv()[-1,:]
>>> o.integrate_dxdv([0.,0.,1.,0.],ts,mp,method='dopr54_c',rectIn=True,rectOut=True)
>>> dvx= o.getOrbit_dxdv()[-1,:]
>>> o.integrate_dxdv([0.,0.,0.,1.],ts,mp,method='dopr54_c',rectIn=True,rectOut=True)
>>> dvy= o.getOrbit_dxdv()[-1,:]
```

We can then compute the determinant of the Jacobian of the mapping defined by the orbit integration from time zero to the final time

```
>>> tjac= numpy.linalg.det(numpy.array([dx,dy,dvx,dvy]))
```

This determinant should be equal to one

```
>>> print tjac
0.999999991189
>>> numpy.fabs(tjac-1.) < 10.**-8.
True
```

The calls to `integrate_dxdv` above set the keywords `rectIn=` and `rectOut=` to True, as the default input and output uses phase-space volumes defined as (dR,dvR,dvT,dphi) in cylindrical coordinates. When `rectIn` or `rectOut` is set, the in- or output is in rectangular coordinates ([x,y,vx,vy] in two dimensions).

Implementing the phase-space integration for three-dimensional `FullOrbit` instances is straightforward and is part of the longer term development plan for `galpy`. Let the main developer know if you would like this functionality, or better yet, implement it yourself in a fork of the code and send a pull request!

1.5.8 Example: The eccentricity distribution of the Milky Way's thick disk

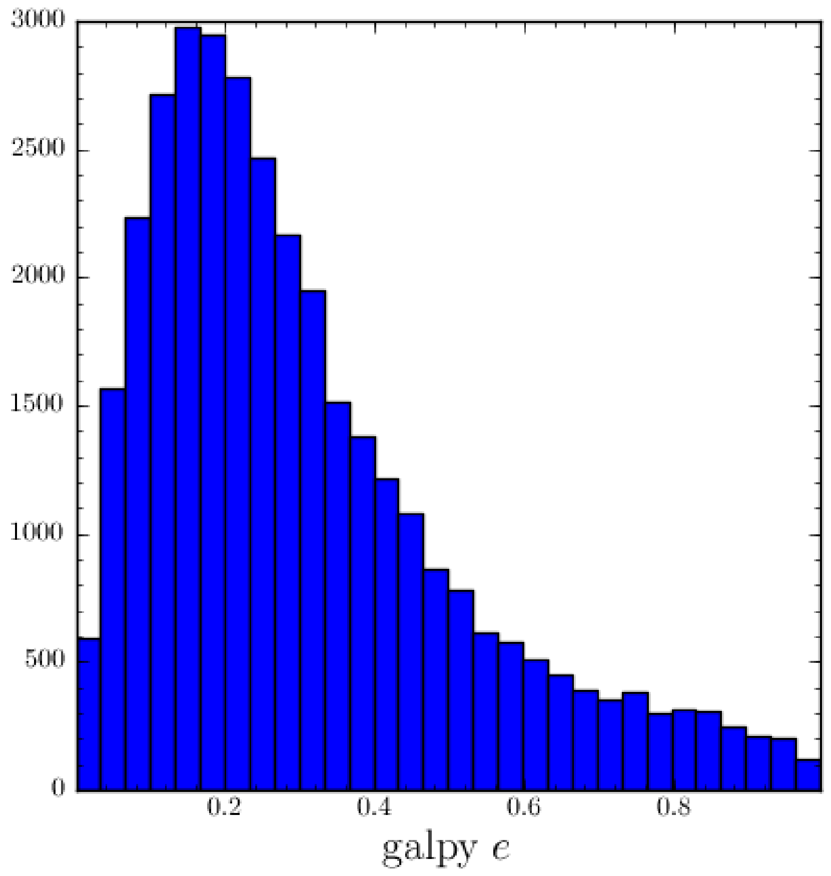
A straightforward application of galpy's orbit initialization and integration capabilities is to derive the eccentricity distribution of a set of thick disk stars. We start by downloading the sample of SDSS SEGUE (2009AJ....137.4377Y) thick disk stars compiled by Dierickx et al. (2010arXiv1009.1616D) at

http://www.mpia-hd.mpg.de/homes/rix/Data/Dierickx-etal-tab2.txt

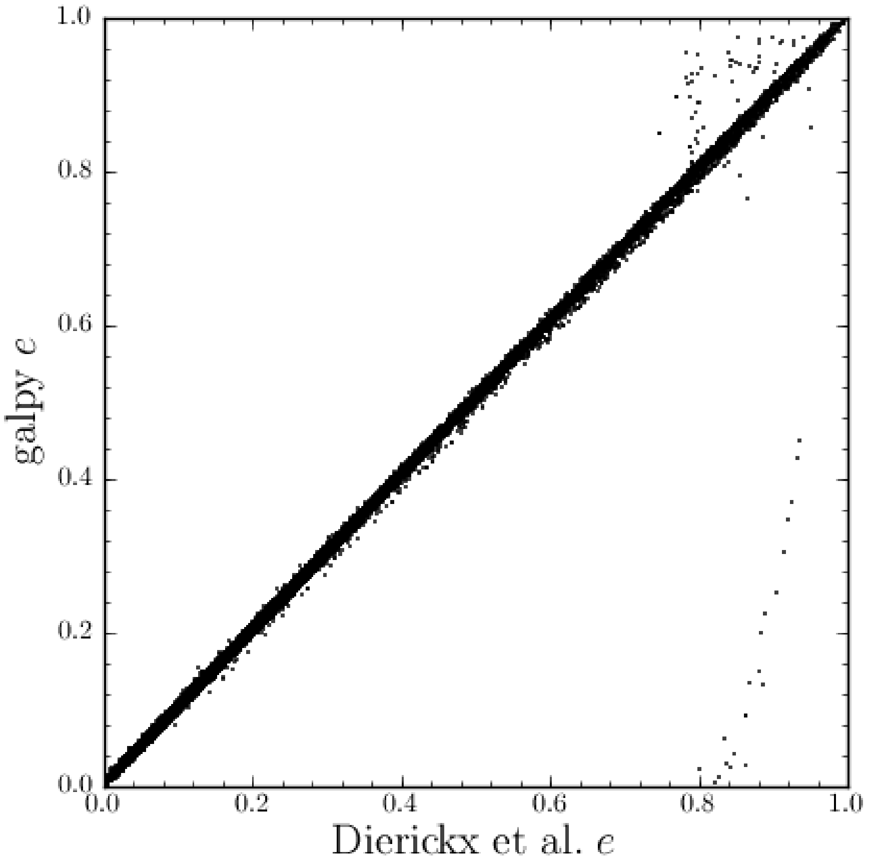
After reading in the data (RA,Dec,distance,pmRA,pmDec,vlos; see above) as a vector `vxvv` with dimensions [6,ndata] we (a) define the potential in which we want to integrate the orbits, and (b) integrate each orbit and save its eccentricity (running this for all 30,000-ish stars will take about half an hour)

```
>>> lp= LogarithmicHaloPotential(normalize=1.)
>>> ts= nu.linspace(0.,20.,10000)
>>> mye= nu.zeros(ndata)
>>> for ii in range(len(e)):
...         o= Orbit(vxvv[ii,:],radec=True,vo=220.,ro=8.) #Initialize
...         o.integrate(ts,lp) #Integrate
...         mye[ii]= o.e() #Calculate eccentricity
```

We then find the following eccentricity distribution



The eccentricity calculated by galpy compare well with those calculated by Dierickx et al., except for a few objects



The script that calculates and plots everything can be downloaded `here`.

1.6 Action-angle coordinates

galpy can calculate actions and angles for a large variety of potentials (any time-independent potential in principle). These are implemented in a separate module `galpy.actionAngle`, and the preferred method for accessing them is through the routines in this module. There is also some support for accessing the actionAngle routines as methods of the `Orbit` class.

Action-angle coordinates can be calculated for the following potentials/approximations:

- Isochrone potential
- Spherical potentials
- Adiabatic approximation
- Staeckel approximation
- A general orbit-integration-based technique

There are classes corresponding to these different potentials/approximations and actions, frequencies, and angles can typically be calculated using these three methods:

- __call__: returns the actions

- actionsFreqs: returns the actions and the frequencies
- actionsFreqsAngles: returns the actions, frequencies, and angles

These are not all implemented for each of the cases above yet.

The adiabatic and Staeckel approximation have also been implemented in C and using grid-based interpolation, for extremely fast action-angle calculations (see below).

1.6.1 Action-angle coordinates for the isochrone potential

The isochrone potential is the only potential for which all of the actions, frequencies, and angles can be calculated analytically. We can do this in galpy by doing

```
>>> from galpy.potential import IsochronePotential
>>> from galpy.actionAngle import actionAngleIsochrone
>>> ip= IsochronePotential(b=1.,normalize=1.)
>>> aAI= actionAngleIsochrone(ip=ip)
```

`aAI` is now an instance that can be used to calculate action-angle variables for the specific isochrone potential `ip`. Calling this instance returns (J_R, L_Z, J_Z)

```
>>> aAI(1.,0.1,1.1,0.1,0.) #inputs R,vR,vT,z,vz
(array([ 0.00713759]), array([ 1.1]), array([ 0.00553155]))
```

or for a more eccentric orbit

```
>>> aAI(1.,0.5,1.3,0.2,0.1)
(array([ 0.13769498]), array([ 1.3]), array([ 0.02574507]))
```

Note that we can also specify `phi`, but this is not necessary

```
>>> aAI(1.,0.5,1.3,0.2,0.1,0.)
(array([ 0.13769498]), array([ 1.3]), array([ 0.02574507]))
```

We can likewise calculate the frequencies as well

```
>>> aAI.actionsFreqs(1.,0.5,1.3,0.2,0.1,0.)
(array([ 0.13769498]),
 array([ 1.3]),
 array([ 0.02574507]),
 array([ 1.29136096]),
 array([ 0.79093738]),
 array([ 0.79093738]))
```

The output is $(J_R, L_Z, J_Z, \Omega_R, \Omega_\phi, \Omega_Z)$. For any spherical potential, $\Omega_\phi = \mathrm{sgn}(L_Z)\Omega_Z$, such that the last two frequencies are the same.

We obtain the angles as well by calling

```
>>> aAI.actionsFreqsAngles(1.,0.5,1.3,0.2,0.1,0.)
(array([ 0.13769498]),
 array([ 1.3]),
 array([ 0.02574507]),
 array([ 1.29136096]),
 array([ 0.79093738]),
 array([ 0.79093738]),
```

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```
array([ 0.57101518]),
array([ 5.96238847]),
array([ 1.24999949]))
```

The output here is $(J_R, L_Z, J_Z, \Omega_R, \Omega_\phi, \Omega_Z, \theta_R, \theta_\phi, \theta_Z)$.

To check that these are good action-angle variables, we can calculate them along an orbit

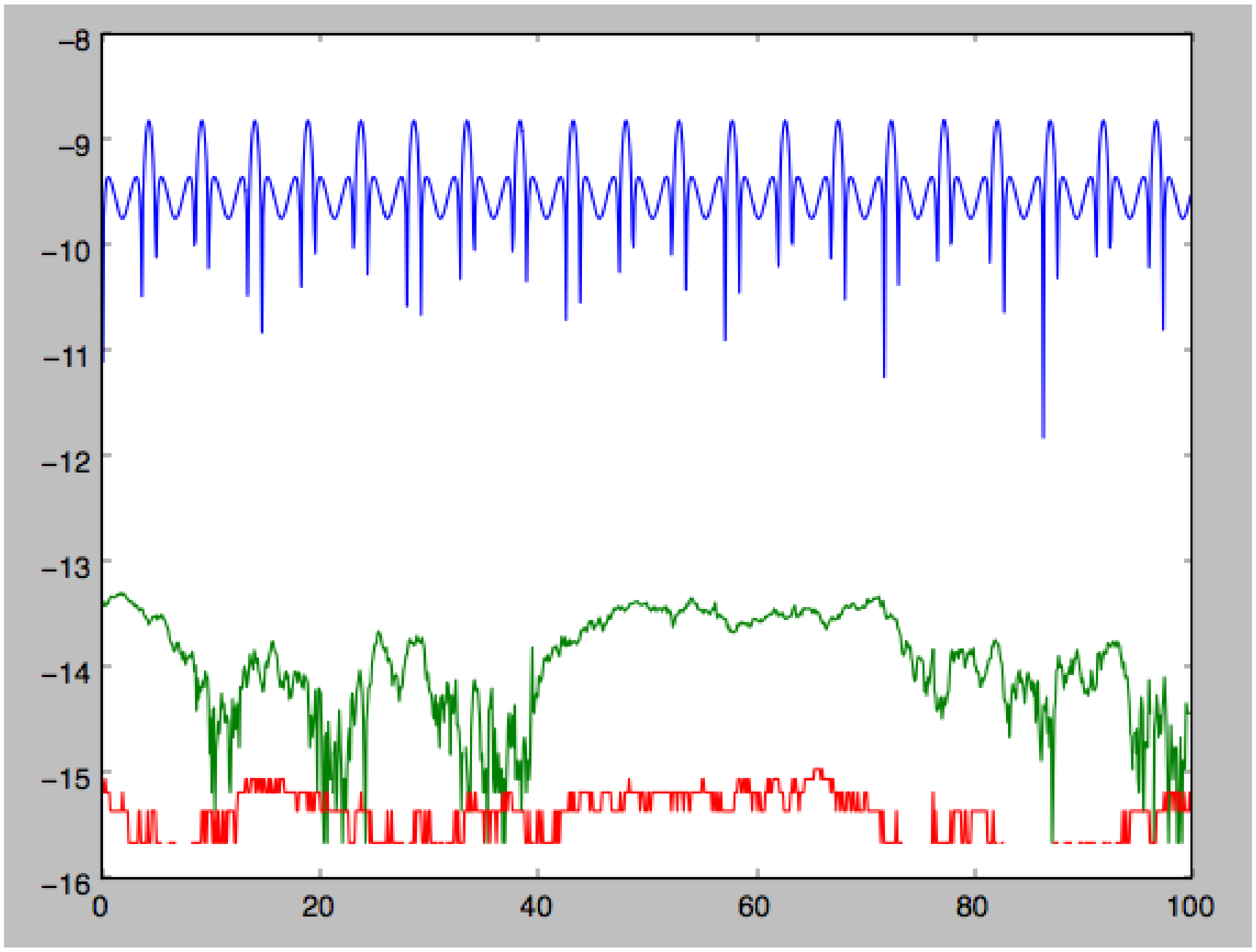
```
>>> from galpy.orbit import Orbit
>>> o= Orbit([1.,0.5,1.3,0.2,0.1,0.])
>>> ts= numpy.linspace(0.,100.,1001)
>>> o.integrate(ts,ip)
>>> jfa= aAI.actionsFreqsAngles(o.R(ts),o.vR(ts),o.vT(ts),o.z(ts),o.vz(ts),o.phi(ts))
```

which works because we can provide arrays for the `R` etc. inputs.

We can then check that the actions are constant over the orbit

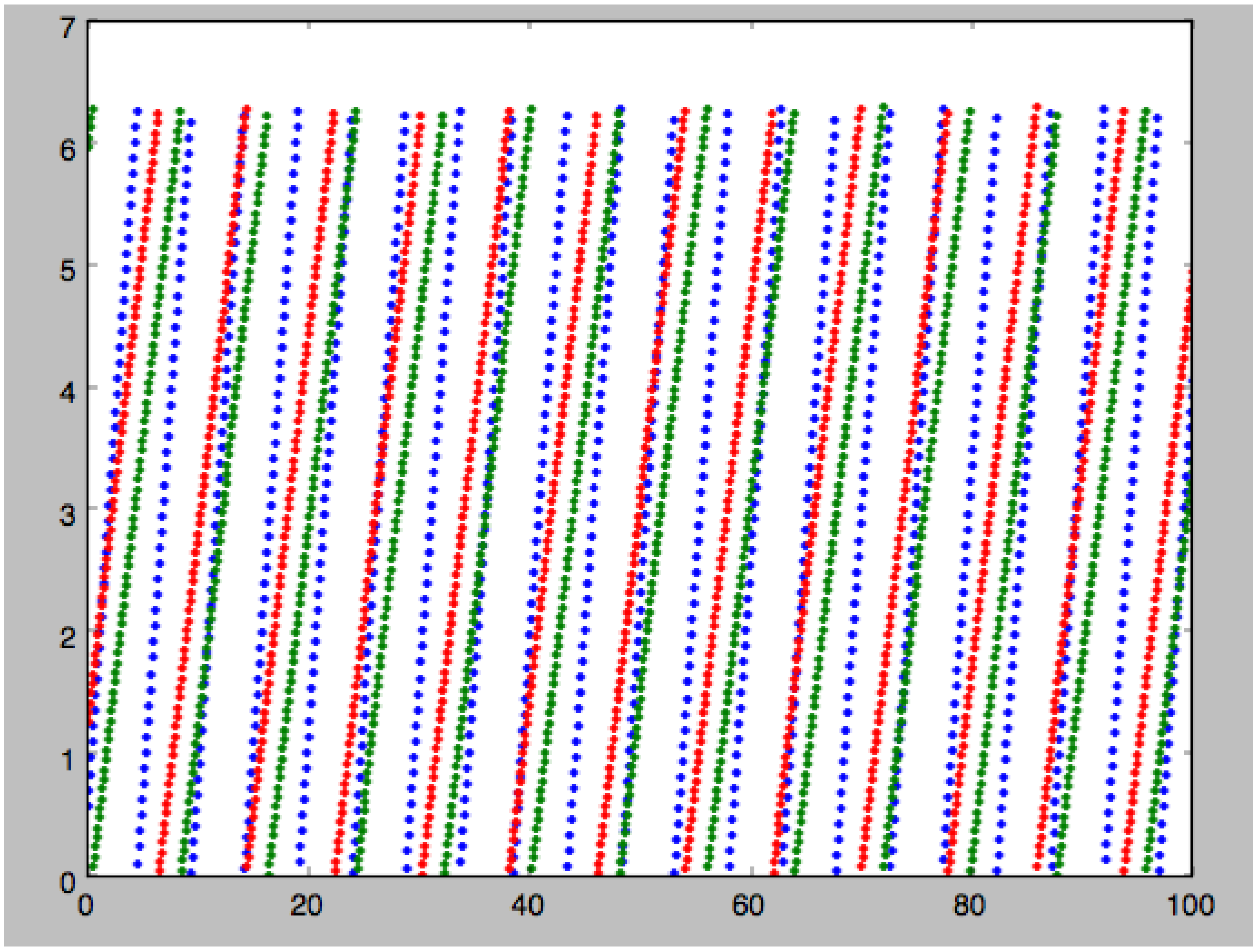
```
>>> plot(ts,numpy.log10(numpy.fabs((jfa[0]-numpy.mean(jfa[0])))))
>>> plot(ts,numpy.log10(numpy.fabs((jfa[1]-numpy.mean(jfa[1])))))
>>> plot(ts,numpy.log10(numpy.fabs((jfa[2]-numpy.mean(jfa[2])))))
```

which gives



The actions are all conserved. The angles increase linearly with time

```
>>> plot(ts,jfa[6],'b.')
>>> plot(ts,jfa[7],'g.')
>>> plot(ts,jfa[8],'r.')
```



1.6.2 Action-angle coordinates for spherical potentials

Action-angle coordinates for any spherical potential can be calculated using a few orbit integrations. These are implemented in galpy in the `actionAngleSpherical` module. For example, we can do

```
>>> from galpy.potential import LogarithmicHaloPotential
>>> lp= LogarithmicHaloPotential(normalize=1.)
>>> from galpy.actionAngle import actionAngleSpherical
>>> aAS= actionAngleSpherical(pot=lp)
```

For the same eccentric orbit as above we find

```
>>> aAS(1.,0.5,1.3,0.2,0.1,0.)
(array([ 0.22022112]), array([ 1.3]), array([ 0.02574507]))
>>> aAS.actionsFreqs(1.,0.5,1.3,0.2,0.1,0.)
(array([ 0.22022112]),
 array([ 1.3]),
 array([ 0.02574507]),
 array([ 0.87630459]),
```

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```
 array([ 0.60872881]),
 array([ 0.60872881]))
>>> aAS.actionsFreqsAngles(1.,0.5,1.3,0.2,0.1,0.)
(array([ 0.22022112]),
 array([ 1.3]),
 array([ 0.02574507]),
 array([ 0.87630459]),
 array([ 0.60872881]),
 array([ 0.60872881]),
 array([ 0.40443857]),
 array([ 5.85965048]),
 array([ 1.1472615]))
```

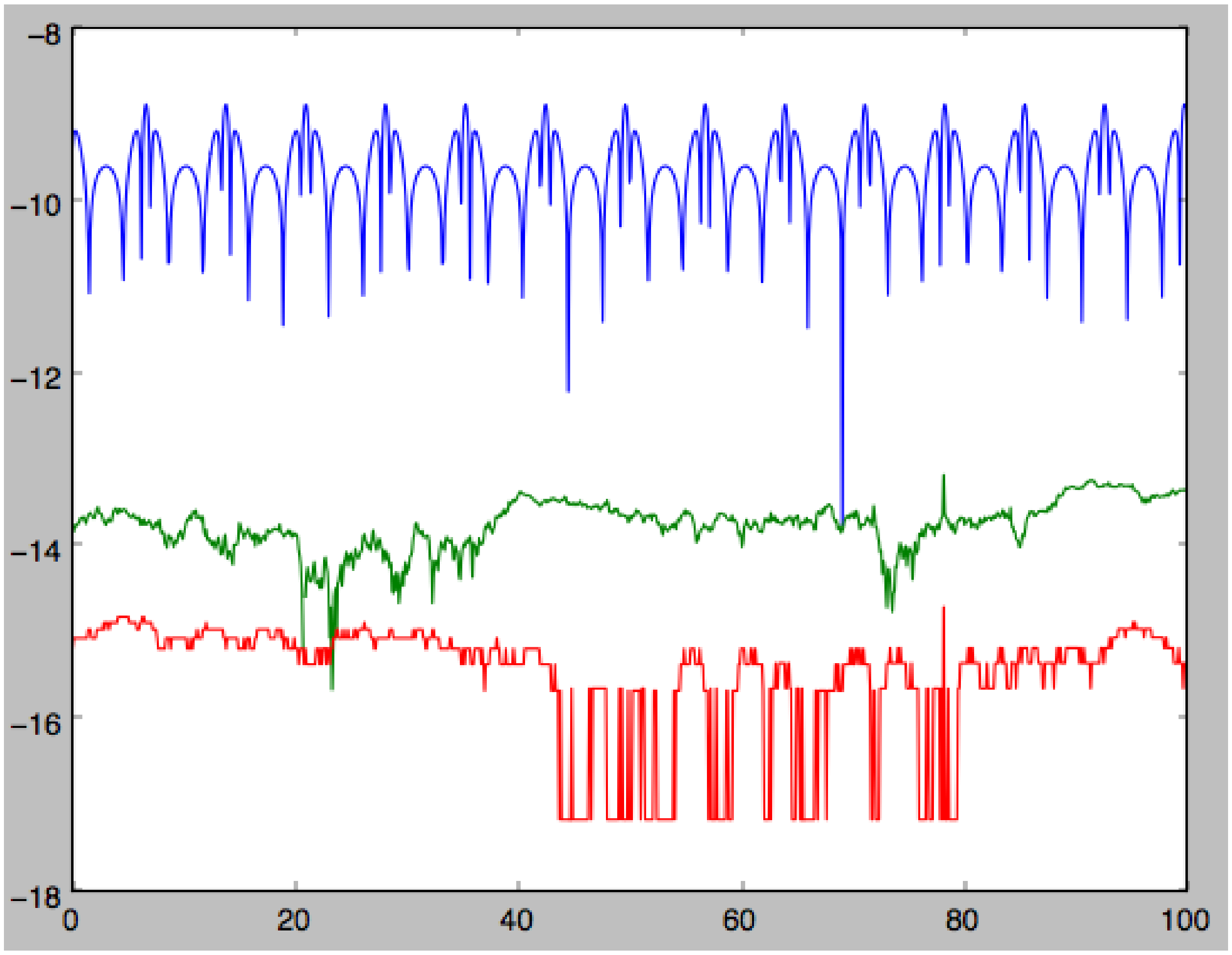
We can again check that the actions are conserved along the orbit and that the angles increase linearly with time:

```
>>> o.integrate(ts,lp)
>>> jfa= aAS.actionsFreqsAngles(o.R(ts),o.vR(ts),o.vT(ts),o.z(ts),o.vz(ts),o.phi(ts),
↪fixed_quad=True)
```

where we use `fixed_quad=True` for a faster evaluation of the required one-dimensional integrals using Gaussian quadrature. We then plot the action fluctuations

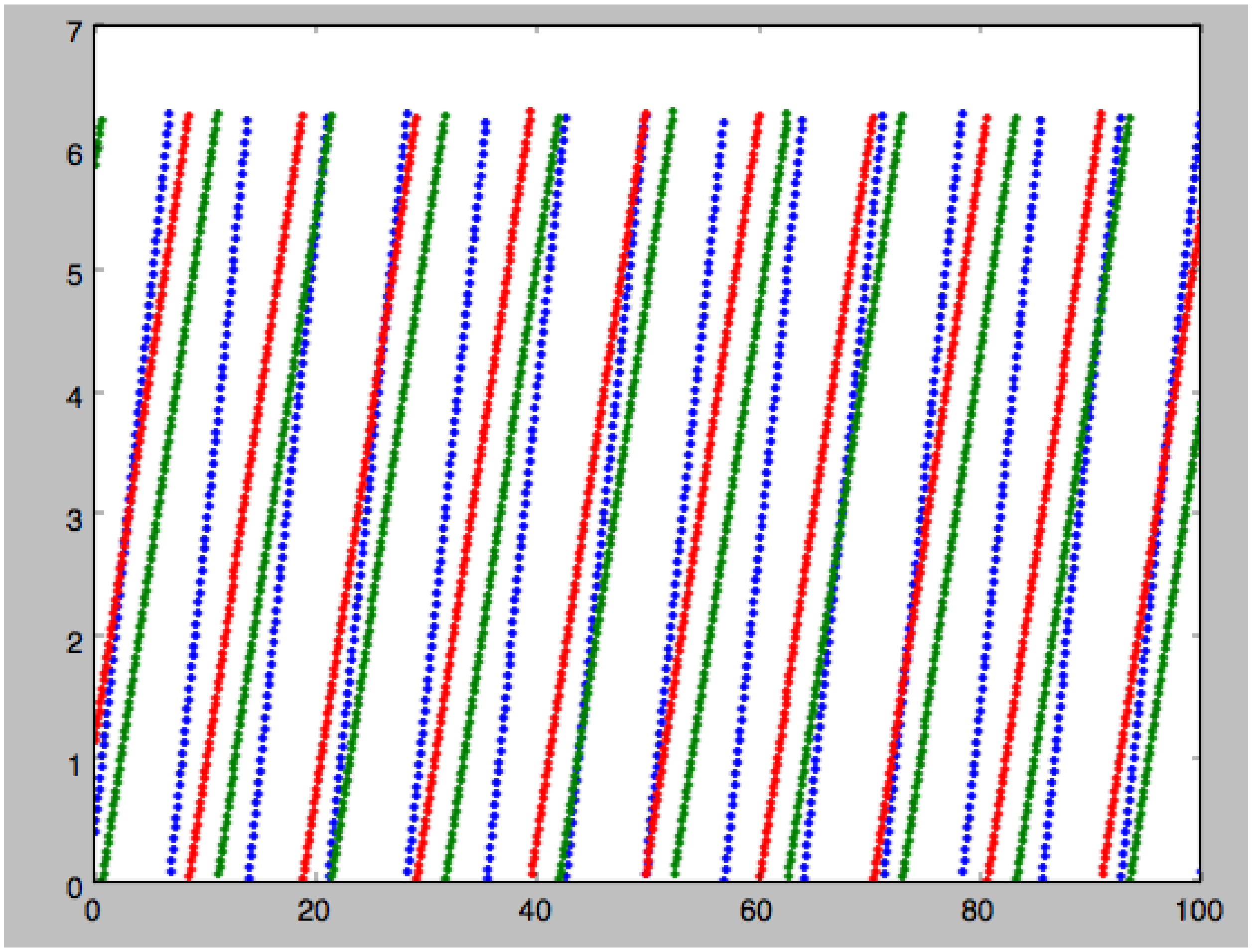
```
>>> plot(ts,numpy.log10(numpy.fabs((jfa[0]-numpy.mean(jfa[0])))))
>>> plot(ts,numpy.log10(numpy.fabs((jfa[1]-numpy.mean(jfa[1])))))
>>> plot(ts,numpy.log10(numpy.fabs((jfa[2]-numpy.mean(jfa[2])))))
```

which gives



showing that the actions are all conserved. The angles again increase linearly with time

```
>>> plot(ts,jfa[6],'b.')
>>> plot(ts,jfa[7],'g.')
>>> plot(ts,jfa[8],'r.')
```



We can check the spherical action-angle calculations against the analytical calculations for the isochrone potential. Starting again from the isochrone potential used in the previous section

```
>>> ip= IsochronePotential(b=1.,normalize=1.)
>>> aAI= actionAngleIsochrone(ip=ip)
>>> aAS= actionAngleSpherical(pot=ip)
```

we can compare the actions, frequencies, and angles computed using both

```
>>> aAI.actionsFreqsAngles(1.,0.5,1.3,0.2,0.1,0.)
(array([ 0.13769498]),
 array([ 1.3]),
 array([ 0.02574507]),
 array([ 1.29136096]),
 array([ 0.79093738]),
 array([ 0.79093738]),
 array([ 0.57101518]),
 array([ 5.96238847]),
 array([ 1.24999949]))
>>> aAS.actionsFreqsAngles(1.,0.5,1.3,0.2,0.1,0.)
(array([ 0.13769498]),
 array([ 1.3]),
 array([ 0.02574507]),
 array([ 1.29136096]),
 array([ 0.79093738]),
```

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```
 array([ 0.79093738]),
 array([ 0.57101518]),
 array([ 5.96238838]),
 array([ 1.2499994]))
```

or more explicitly comparing the two

```
>>> [r-s for r,s in zip(aAI.actionsFreqsAngles(1.,0.5,1.3,0.2,0.1,0.),aAS.
→actionsFreqsAngles(1.,0.5,1.3,0.2,0.1,0.))]
[array([  6.66133815e-16]),
 array([ 0.]),
 array([ 0.]),
 array([ -4.53851845e-10]),
 array([  4.74775219e-10]),
 array([  4.74775219e-10]),
 array([ -1.65965242e-10]),
 array([  9.04759645e-08]),
 array([  9.04759649e-08])]
```

1.6.3 Action-angle coordinates using the adiabatic approximation

For non-spherical, axisymmetric potentials galpy contains multiple methods for calculating approximate action–angle coordinates. The simplest of those is the adiabatic approximation, which works well for disk orbits that do not go too far from the plane, as it assumes that the vertical motion is decoupled from that in the plane (e.g., 2010MNRAS.401.2318B).

Setup is similar as for other actionAngle objects

```
>>> from galpy.potential import MWPotential2014
>>> from galpy.actionAngle import actionAngleAdiabatic
>>> aAA= actionAngleAdiabatic(pot=MWPotential2014)
```

and evaluation then proceeds similarly as before

```
>>> aAA(1.,0.1,1.1,0.,0.05)
(0.01351896260559274, 1.1, 0.0004690133479435352)
```

We can again check that the actions are conserved along the orbit

```
>>> from galpy.orbit import Orbit
>>> ts=numpy.linspace(0.,100.,1001)
>>> o= Orbit([1.,0.1,1.1,0.,0.05])
>>> o.integrate(ts,MWPotential2014)
>>> js= aAA(o.R(ts),o.vR(ts),o.vT(ts),o.z(ts),o.vz(ts))
```

This takes a while. The adiabatic approximation is also implemented in C, which leads to great speed-ups. Here is how to use it

```
>>> timeit(aAA(1.,0.1,1.1,0.,0.05))
10 loops, best of 3: 73.7 ms per loop
>>> aAA= actionAngleAdiabatic(pot=MWPotential2014,c=True)
>>> timeit(aAA(1.,0.1,1.1,0.,0.05))
1000 loops, best of 3: 1.3 ms per loop
```

or about a *50 times* speed-up. For arrays the speed-up is even more impressive

```
>>> s= numpy.ones(100)
>>> timeit(aAA(1.*s,0.1*s,1.1*s,0.*s,0.05*s))
10 loops, best of 3: 37.8 ms per loop
>>> aAA= actionAngleAdiabatic(pot=MWPotential2014) #back to no C
>>> timeit(aAA(1.*s,0.1*s,1.1*s,0.*s,0.05*s))
1 loops, best of 3: 7.71 s per loop
```

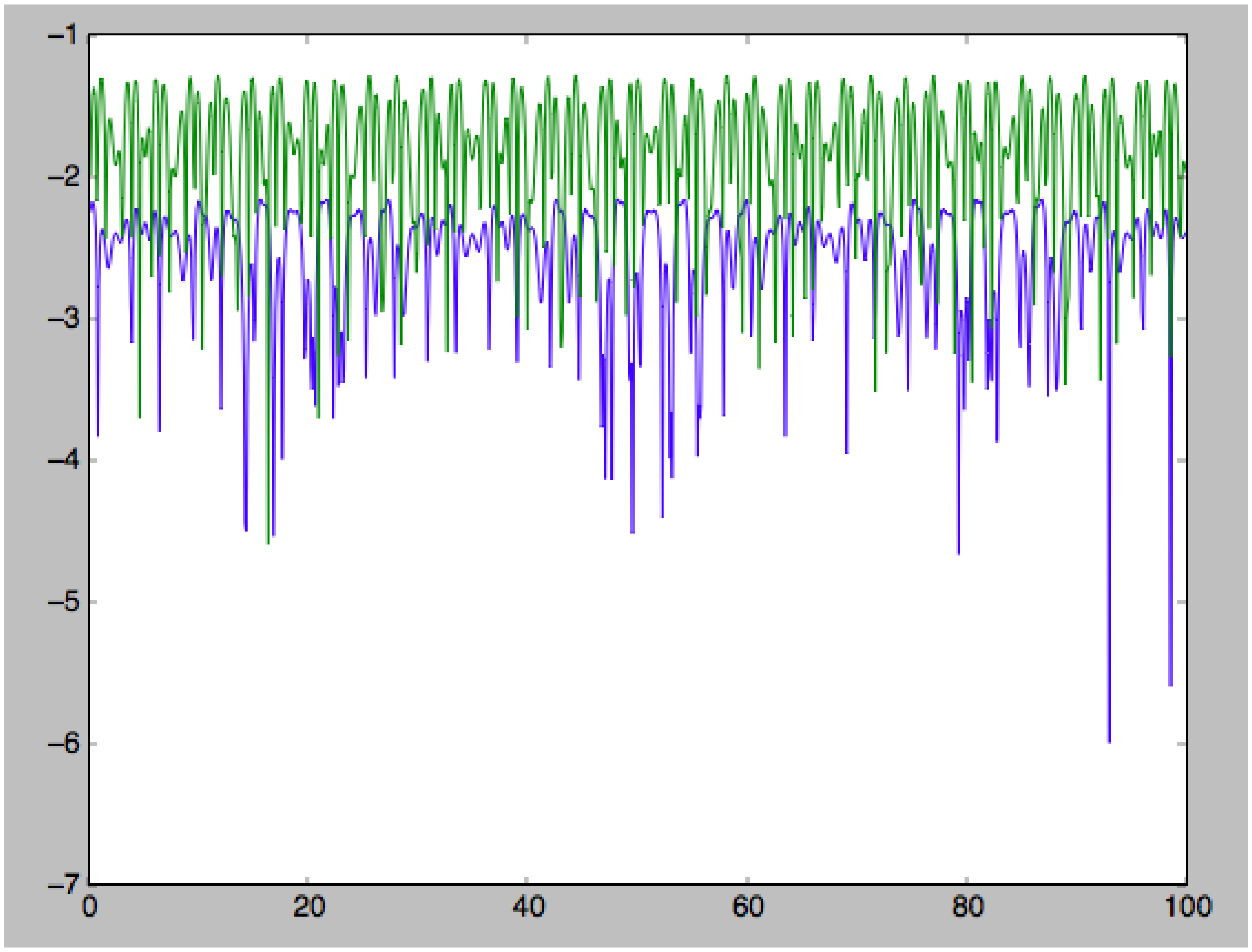
or a speed-up of 200! Back to the previous example, you can run it with `c=True` to speed up the computation

```
>>> aAA= actionAngleAdiabatic(pot=MWPotential2014,c=True)
>>> js= aAA(o.R(ts),o.vR(ts),o.vT(ts),o.z(ts),o.vz(ts))
```

We can plot the radial- and vertical-action fluctuation as a function of time

```
>>> plot(ts,numpy.log10(numpy.fabs((js[0]-numpy.mean(js[0]))/numpy.mean(js[0]))))
>>> plot(ts,numpy.log10(numpy.fabs((js[2]-numpy.mean(js[2]))/numpy.mean(js[2]))))
```

which gives



The radial action is conserved to about half a percent, the vertical action to two percent.

Another way to speed up the calculation of actions using the adiabatic approximation is to tabulate the actions on a grid in (approximate) integrals of the motion and evaluating new actions by interpolating on this grid. How this is done in practice is described in detail in the galpy paper. To setup this grid-based interpolation method, which is contained in `actionAngleAdiabaticGrid`, do

```
>>> from galpy.actionAngle import actionAngleAdiabaticGrid
>>> aAG= actionAngleAdiabaticGrid(pot=MWPotential2014,nR=31,nEz=31,nEr=51,nLz=51,
↪c=True)
```

where `c=True` specifies that we use the C implementation of `actionAngleAdiabatic` for speed. We can now evaluate in the same was as before, for example

```
>>> aAA(1.,0.1,1.1,0.,0.05), aAG(1.,0.1,1.1,0.,0.05)
((array([ 0.01352523]), array([ 1.1]), array([ 0.00046909])),
 (0.013527010324238781, 1.1, 0.00047747359874375148))
```

which agree very well. To look at the timings, we first switch back to not using C and then list all of the relevant timings:

```
>>> aAA= actionAngleAdiabatic(pot=MWPotential2014,c=False)
# Not using C, direct calculation
>>> timeit(aAA(1.*s,0.1*s,1.1*s,0.*s,0.05*s))
1 loops, best of 3: 9.05 s per loop
>>> aAA= actionAngleAdiabatic(pot=MWPotential2014,c=True)
# Using C, direct calculation
>>> timeit(aAA(1.*s,0.1*s,1.1*s,0.*s,0.05*s))
10 loops, best of 3: 39.7 ms per loop
# Grid-based calculation
>>> timeit(aAG(1.*s,0.1*s,1.1*s,0.*s,0.05*s))
1000 loops, best of 3: 1.09 ms per loop
```

Thus, in this example (and more generally) the grid-based calculation is significantly faster than even the direct implementation in C. The overall speed up between the direct Python version and the grid-based version is larger than 8,000; the speed up between the direct C version and the grid-based version is 36. For larger arrays of input phase-space positions, the latter speed up can increase to 150. For simpler, fully analytical potentials the speed up will be slightly less, but for `MWPotential2014` and other more complicated potentials (such as those involving a double-exponential disk), the overhead of setting up the grid is worth it when evaluating more than a few thousand actions.

The adiabatic approximation works well for orbits that stay close to the plane. The orbit we have been considering so far only reaches a height two percent of R_0, or about 150 pc for $R_0 = 8$ kpc.

```
>>> o.zmax()*8.
0.17903686455491979
```

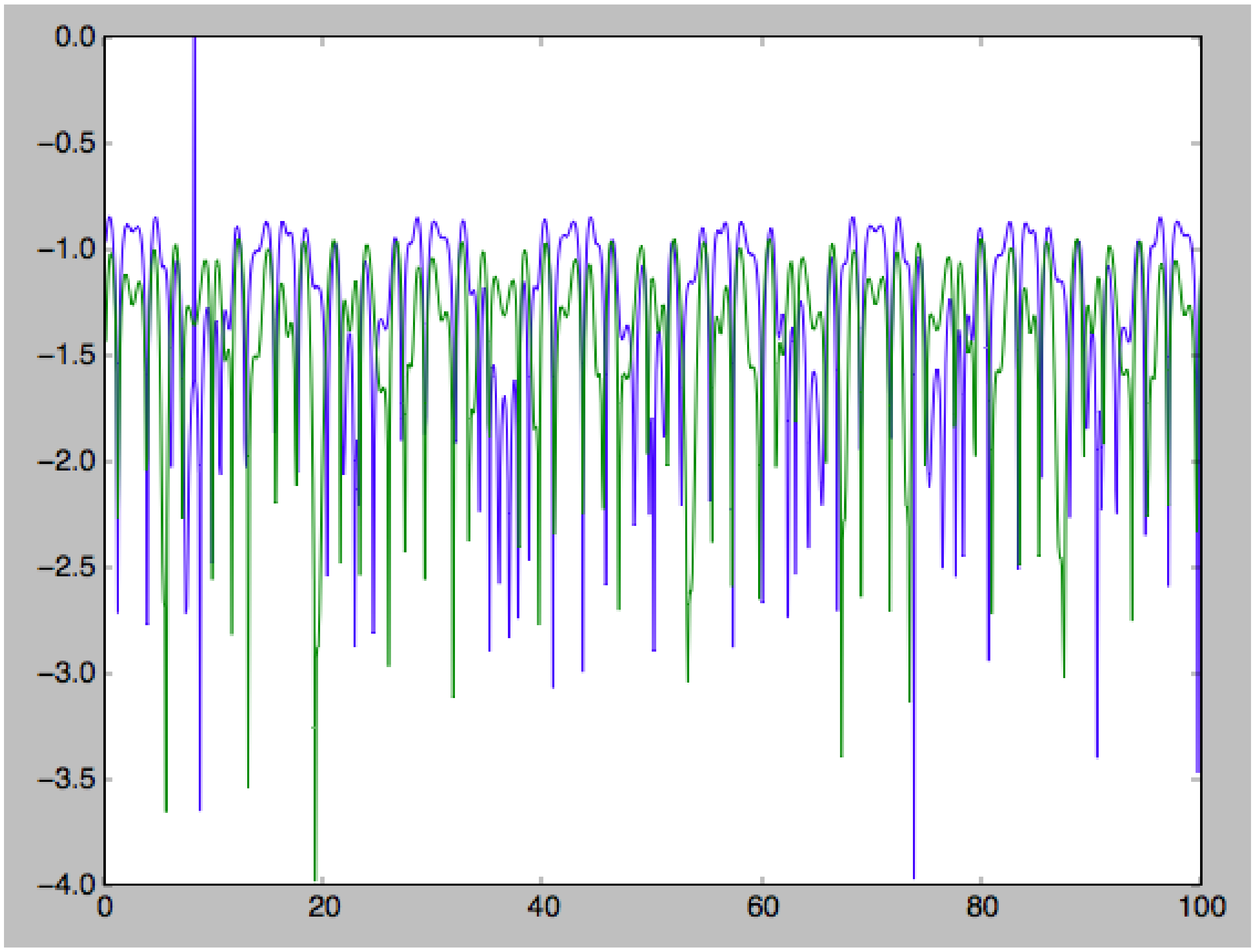
For orbits that reach distances of a kpc and more from the plane, the adiabatic approximation does not work as well. For example,

```
>>> o= Orbit([1.,0.1,1.1,0.,0.25])
>>> o.integrate(ts,MWPotential2014)
>>> o.zmax()*8.
1.3506059038621048
```

and we can again calculate the actions along the orbit

```
>>> js= aAA(o.R(ts),o.vR(ts),o.vT(ts),o.z(ts),o.vz(ts))
>>> plot(ts,numpy.log10(numpy.fabs((js[0]-numpy.mean(js[0]))/numpy.mean(js[0]))))
>>> plot(ts,numpy.log10(numpy.fabs((js[2]-numpy.mean(js[2]))/numpy.mean(js[2]))))
```

which gives



The radial action is now only conserved to about ten percent and the vertical action to approximately five percent.

Warning: Frequencies and angles using the adiabatic approximation are not implemented at this time.

1.6.4 Action-angle coordinates using the Staeckel approximation

A better approximation than the adiabatic one is to locally approximate the potential as a Staeckel potential, for which actions, frequencies, and angles can be calculated through numerical integration. galpy contains an implementation of the algorithm of Binney (2012; 2012MNRAS.426.1324B), which accomplishes the Staeckel approximation for disk-like (i.e., oblate) potentials without explicitly fitting a Staeckel potential. For all intents and purposes the adiabatic approximation is made obsolete by this new method, which is as fast and more precise. The only advantage of the adiabatic approximation over the Staeckel approximation is that the Staeckel approximation requires the user to specify a *focal length* Δ to be used in the Staeckel approximation. However, this focal length can be easily estimated from the second derivatives of the potential (see Sanders 2012; 2012MNRAS.426..128S).

Starting from the second orbit example in the adiabatic section above, we first estimate a good focal length of the `MWPotential2014` to use in the Staeckel approximation. We do this by averaging (through the median) estimates at positions around the orbit (which we integrated in the example above)

```
>>> from galpy.actionAngle import estimateDeltaStaeckel
>>> estimateDeltaStaeckel(o.R(ts),o.z(ts),pot=MWPotential2014)
0.40272708556203662
```

We will use $\Delta = 0.4$ in what follows. We set up the `actionAngleStaeckel` object

```
>>> from galpy.actionAngle import actionAngleStaeckel
>>> aAS= actionAngleStaeckel(pot=MWPotential2014,delta=0.4,c=False) #c=True is the␣
↪default
```

and calculate the actions

```
>>> aAS(o.R(),o.vR(),o.vT(),o.z(),o.vz())
(0.019212848866725911, 1.1000000000000001, 0.015274597971510892)
```

The adiabatic approximation from above gives

```
>>> aAA(o.R(),o.vR(),o.vT(),o.z(),o.vz())
(array([ 0.01686478]), array([ 1.1]), array([ 0.01590001]))
```

The actionAngleStaeckel calculations are sped up in two ways. First, the action integrals can be calculated using Gaussian quadrature by specifying `fixed_quad=True`

```
>>> aAS(o.R(),o.vR(),o.vT(),o.z(),o.vz(),fixed_quad=True)
(0.01922167296633687, 1.1000000000000001, 0.015276825017286706)
```

which in itself leads to a ten times speed up

```
>>> timeit(aAS(o.R(),o.vR(),o.vT(),o.z(),o.vz(),fixed_quad=False))
10 loops, best of 3: 129 ms per loop
>>> timeit(aAS(o.R(),o.vR(),o.vT(),o.z(),o.vz(),fixed_quad=True))
100 loops, best of 3: 10.3 ms per loop
```

Second, the actionAngleStaeckel calculations have also been implemented in C, which leads to even greater speed-ups, especially for arrays

```
>>> aAS= actionAngleStaeckel(pot=MWPotential2014,delta=0.4,c=True)
>>> s= numpy.ones(100)
>>> timeit(aAS(1.*s,0.1*s,1.1*s,0.*s,0.05*s))
10 loops, best of 3: 35.1 ms per loop
>>> aAS= actionAngleStaeckel(pot=MWPotential2014,delta=0.4,c=False) #back to no C
>>> timeit(aAS(1.*s,0.1*s,1.1*s,0.*s,0.05*s,fixed_quad=True))
1 loops, best of 3: 496 ms per loop
```

or a fifteen times speed up. The speed up is not that large because the bulge model in `MWPotential2014` requires expensive special functions to be evaluated. Computations could be sped up ten times more when using a simpler bulge model.

Similar to `actionAngleAdiabaticGrid`, we can also tabulate the actions on a grid of (approximate) integrals of the motion and interpolate over this look-up table when evaluating new actions. The details of how this look-up table is setup and used are again fully explained in the galpy paper. To use this grid-based Staeckel approximation, contained in `actionAngleStaeckelGrid`, do

```
>>> from galpy.actionAngle import actionAngleStaeckelGrid
>>> aASG= actionAngleStaeckelGrid(pot=MWPotential2014,delta=0.4,nE=51,npsi=51,nLz=61,
↪c=True)
```

where `c=True` makes sure that we use the C implementation of the Staeckel method to calculate the grid. Because this is a fully three-dimensional grid, setting up the grid takes longer than it does for the adiabatic method (which only uses two two-dimensional grids). We can then evaluate actions as before

```
>>> aAS(o.R(),o.vR(),o.vT(),o.z(),o.vz()), aASG(o.R(),o.vR(),o.vT(),o.z(),o.vz())
((0.019212848866725911, 1.1000000000000001, 0.015274597971510892),
 (0.019221119033345408, 1.1000000000000001, 0.015022528662310393))
```

These actions agree very well. We can compare the timings of these methods as above

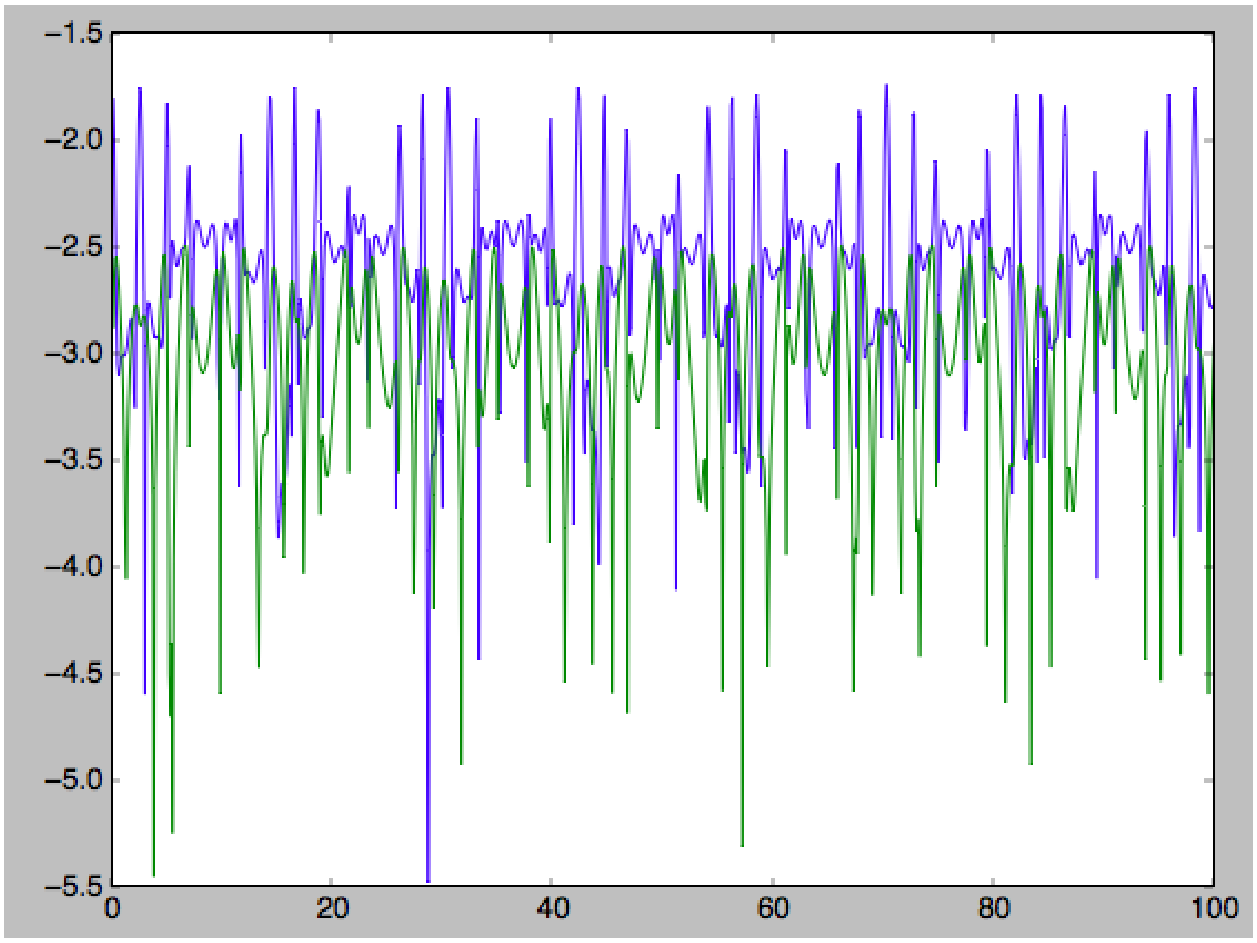
```
>>> timeit(aAS(1.*s,0.1*s,1.1*s,0.*s,0.05*s,fixed_quad=True))
1 loops, best of 3: 576 ms per loop # Not using C, direct calculation
>>> aAS= actionAngleStaeckel(pot=MWPotential2014,delta=0.4,c=True)
>>> timeit(aAS(1.*s,0.1*s,1.1*s,0.*s,0.05*s))
100 loops, best of 3: 17.8 ms per loop # Using C, direct calculation
>>> timeit(aASG(1.*s,0.1*s,1.1*s,0.*s,0.05*s))
100 loops, best of 3: 3.45 ms per loop # Grid-based calculation
```

This demonstrates that the grid-based interpolation again leeds to a significant speed up, even over the C implementation of the direct calculation. This speed up becomes more significant for larger array input, although it saturates at about 25 times (at least for `MWPotential2014`).

We can now go back to checking that the actions are conserved along the orbit (going back to the `c=False` version of `actionAngleStaeckel`)

```
>>> aAS= actionAngleStaeckel(pot=MWPotential2014,delta=0.4,c=False)
>>> js= aAS(o.R(ts),o.vR(ts),o.vT(ts),o.z(ts),o.vz(ts),fixed_quad=True)
>>> plot(ts,numpy.log10(numpy.fabs((js[0]-numpy.mean(js[0]))/numpy.mean(js[0]))))
>>> plot(ts,numpy.log10(numpy.fabs((js[2]-numpy.mean(js[2]))/numpy.mean(js[2]))))
```

which gives



The radial action is now conserved to better than a percent and the vertical action to only a fraction of a percent. Clearly, this is much better than the five to ten percent errors found for the adiabatic approximation above.

For the Staeckel approximation we can also calculate frequencies and angles through the `actionsFreqs` and `actionsFreqsAngles` methods.

Warning: Frequencies and angles using the Staeckel approximation are *only* implemented in C. So use `c=True` in the setup of the actionAngleStaeckel object.

Warning: Angles using the Staeckel approximation in galpy are such that (a) the radial angle starts at zero at pericenter and increases then going toward apocenter; (b) the vertical angle starts at zero at *z=0* and increases toward positive zmax. The latter is a different convention from that in Binney (2012), but is consistent with that in actionAngleIsochrone and actionAngleSpherical.

```
>>> aAS= actionAngleStaeckel(pot=MWPotential2014,delta=0.4,c=True)
>>> o= Orbit([1.,0.1,1.1,0.,0.25,0.]) #need to specify phi for angles
>>> aAS.actionsFreqsAngles(o.R(),o.vR(),o.vT(),o.z(),o.vz(),o.phi())
(array([ 0.01922167]),
 array([ 1.1]),
 array([ 0.01527683]),
 array([ 1.11317796]),
```

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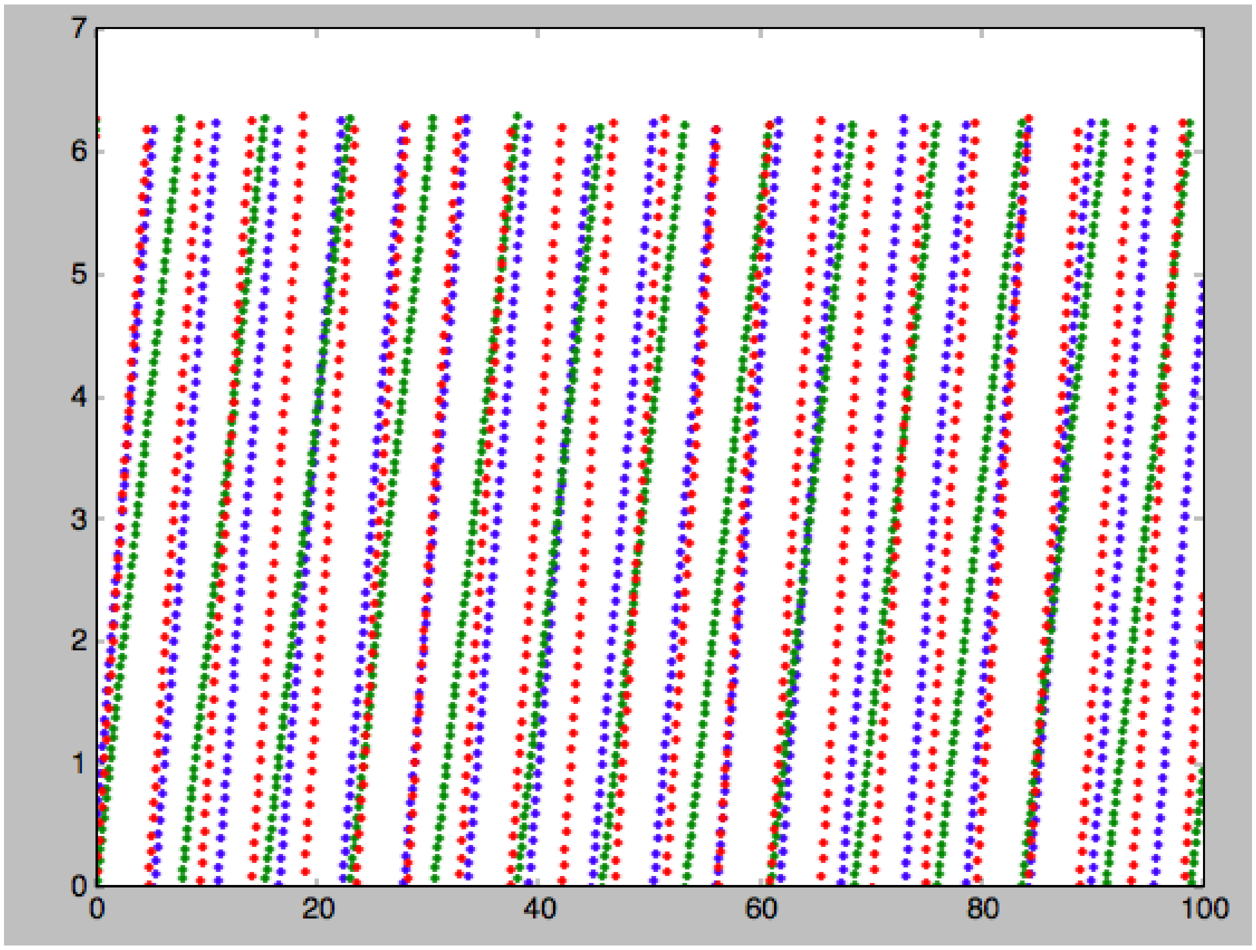
```
 array([ 0.82538032]),
 array([ 1.34126138]),
 array([ 0.37758087]),
 array([ 6.17833493]),
 array([ 6.13368239]))
```

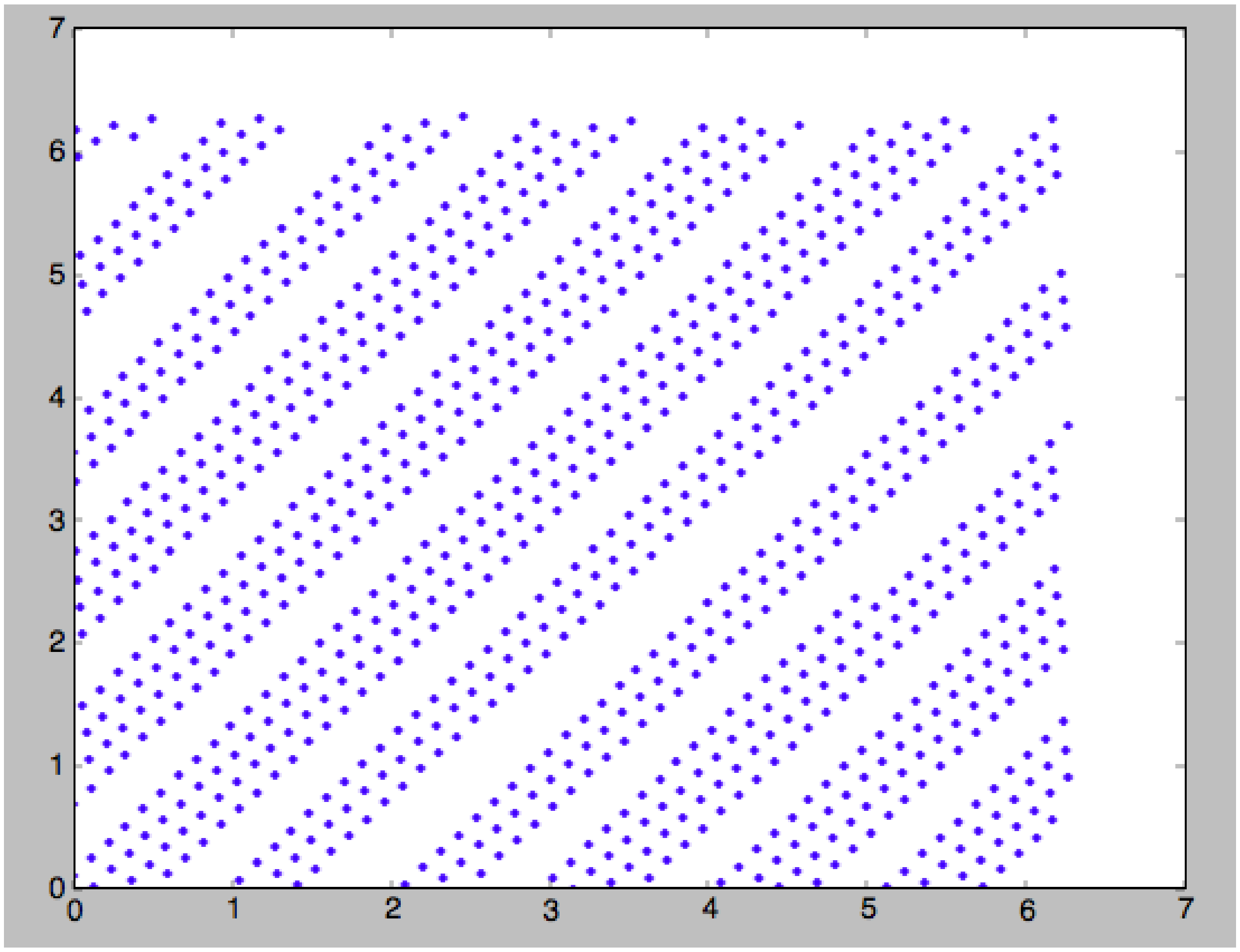
and we can check that the angles increase linearly along the orbit

```
>>> o.integrate(ts,MWPotential2014)
>>> jfa= aAS.actionsFreqsAngles(o.R(ts),o.vR(ts),o.vT(ts),o.z(ts),o.vz(ts),o.phi(ts))
>>> plot(ts,jfa[6],'b.')
>>> plot(ts,jfa[7],'g.')
>>> plot(ts,jfa[8],'r.')
```



or

```
>>> plot(jfa[6],jfa[8],'b.')
```



1.6.5 Action-angle coordinates using an orbit-integration-based approximation

The adiabatic and Staeckel approximations used above are good for stars on close-to-circular orbits, but they break down for more eccentric orbits (specifically, orbits for which the radial and/or vertical action is of a similar magnitude as the angular momentum). This is because the approximations made to the potential in these methods (that it is separable in R and z for the adiabatic approximation and that it is close to a Staeckel potential for the Staeckel approximation) break down for such orbits. Unfortunately, these methods cannot be refined to provide better approximations for eccentric orbits.

galpy contains a new method for calculating actions, frequencies, and angles that is completely general for any static potential. It can calculate the actions to any desired precision for any orbit in such potentials. The method works by employing an auxiliary isochrone potential and calculates action-angle variables by arithmetic operations on the actions and angles calculated in the auxiliary potential along an orbit (integrated in the true potential). Full details can be found in Appendix A of Bovy (2014).

We setup this method for a logarithmic potential as follows

```
>>> from galpy.actionAngle import actionAngleIsochroneApprox
>>> from galpy.potential import LogarithmicHaloPotential
>>> lp= LogarithmicHaloPotential(normalize=1.,q=0.9)
>>> aAIA= actionAngleIsochroneApprox(pot=lp,b=0.8)
```

`b=0.8` here sets the scale parameter of the auxiliary isochrone potential; this potential can also be specified as an

IsochronePotential instance through `ip=`). We can now calculate the actions for an orbit similar to that of the GD-1 stream

```
>>> obs= numpy.array([1.56148083,0.35081535,-1.15481504,0.88719443,-0.47713334,0.
↪12019596]) #orbit similar to GD-1
>>> aAIA(*obs)
(array([ 0.16605011]), array([-1.80322155]), array([ 0.50704439]))
```

An essential requirement of this method is that the angles calculated in the auxiliary potential go through the full range $[0, 2\pi]$. If this is not the case, galpy will raise a warning

```
>>> aAIA= actionAngleIsochroneApprox(pot=lp,b=10.8)
>>> aAIA(*obs)
galpyWarning: Full radial angle range not covered for at least one object; actions␣
↪are likely not reliable
(array([ 0.08985167]), array([-1.80322155]), array([ 0.50849276]))
```

Therefore, some care should be taken to choosing a good auxiliary potential. galpy contains a method to estimate a decent scale parameter for the auxiliary scale parameter, which works similar to `estimateDeltaStaeckel` above except that it also gives a minimum and maximum b if multiple R and z are given

```
>>> from galpy.actionAngle import estimateBIsochrone
>>> from galpy.orbit import Orbit
>>> o= Orbit(obs)
>>> ts= numpy.linspace(0.,100.,1001)
>>> o.integrate(ts,lp)
>>> estimateBIsochrone(o.R(ts),o.z(ts),pot=lp)
(0.78065062339131952, 1.2265541473461612, 1.4899326335155412) #bmin,bmedian,bmax over␣
↪the orbit
```

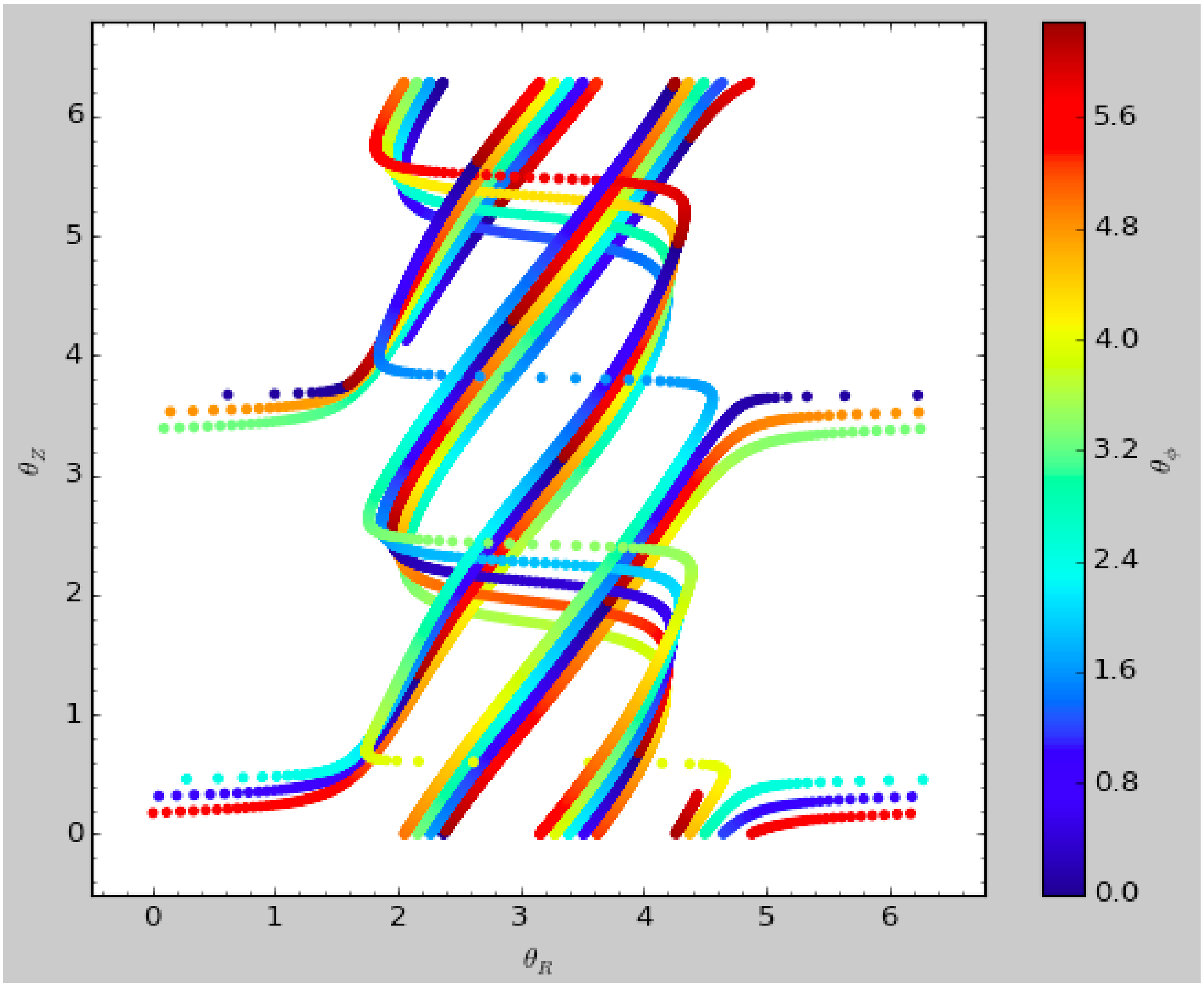
Experience shows that a scale parameter somewhere in the range returned by this function makes sure that the angles go through the full $[0, 2\pi]$ range. However, even if the angles go through the full range, the closer the angles increase to linear, the better the converenge of the algorithm is (and especially, the more accurate the calculation of the frequencies and angles is, see below). For example, for the scale parameter at the upper and of the range

```
>>> aAIA= actionAngleIsochroneApprox(pot=lp,b=1.5)
>>> aAIA(*obs)
(array([ 0.01120145]), array([-1.80322155]), array([ 0.50788893]))
```

which does not agree with the previous calculation. We can inspect how the angles increase and how the actions converge by using the `aAIA.plot` function. For example, we can plot the radial versus the vertical angle in the auxiliary potential

```
>>> aAIA.plot(*obs,type='araz')
```

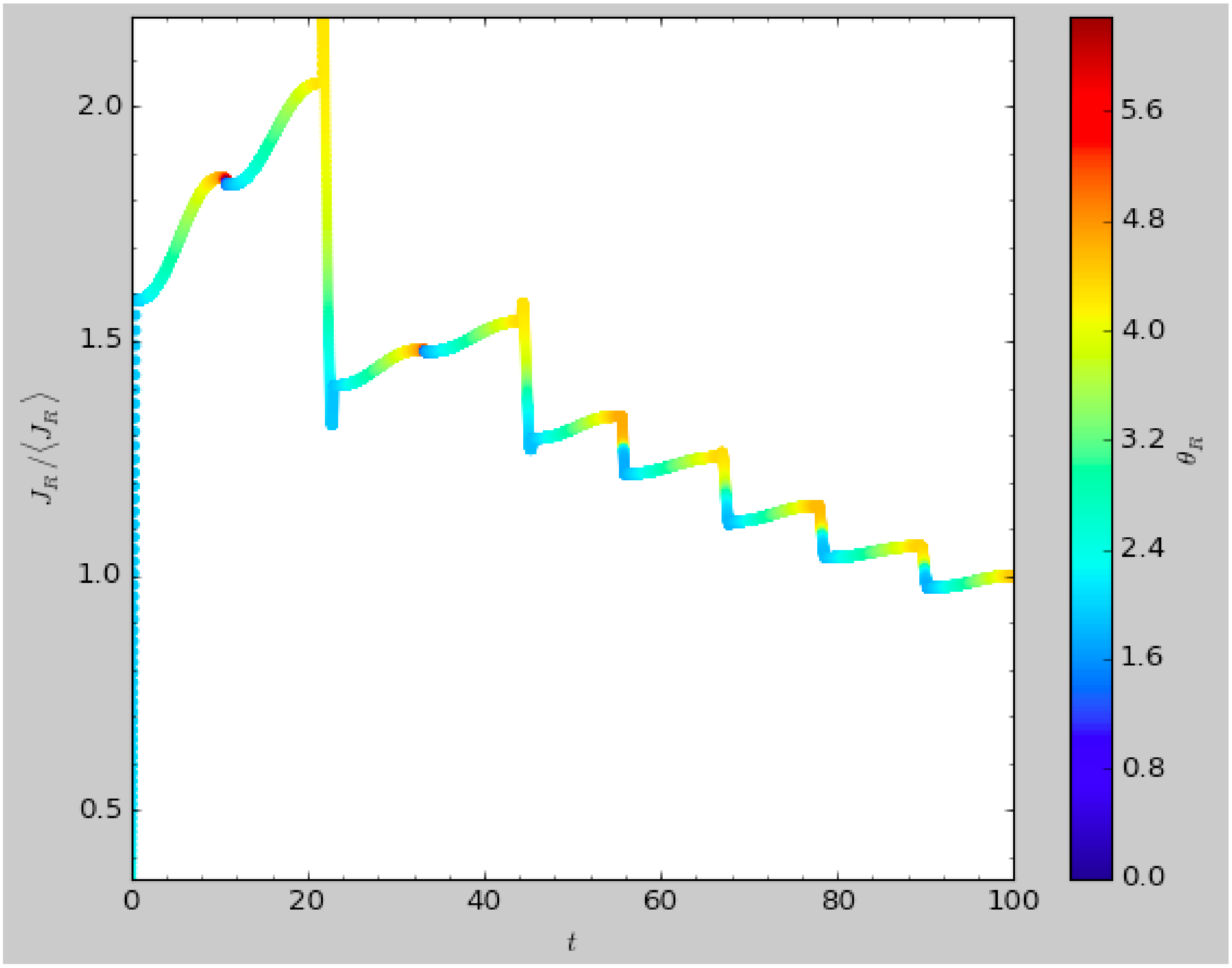
which gives



and this clearly shows that the angles increase *very* non-linearly, because the auxiliary isochrone potential used is too far from the real potential. This causes the actions to converge only very slowly. For example, for the radial action we can plot the converge as a function of integration time

```
>>> aAIA.plot(*obs,type='jr')
```

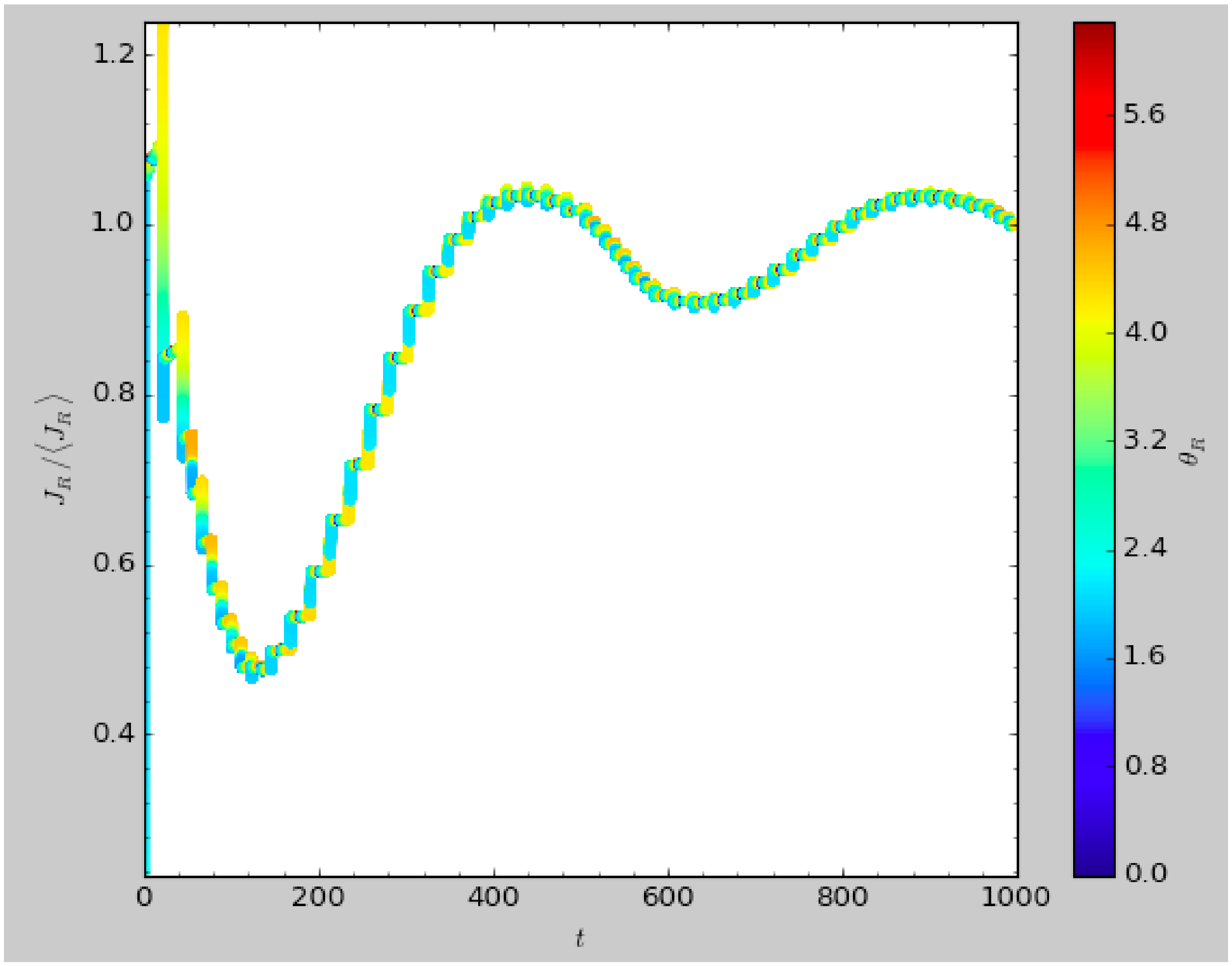
which gives



This Figure clearly shows that the radial action has not converged yet. We need to integrate *much* longer in this auxiliary potential to obtain convergence and because the angles increase so non-linearly, we also need to integrate the orbit much more finely:

```
>>> aAIA= actionAngleIsochroneApprox(pot=lp,b=1.5,tintJ=1000,ntintJ=800000)
>>> aAIA(*obs)
(array([ 0.01711635]), array([-1.80322155]), array([ 0.51008058]))
>>> aAIA.plot(*obs,type='jr')
```

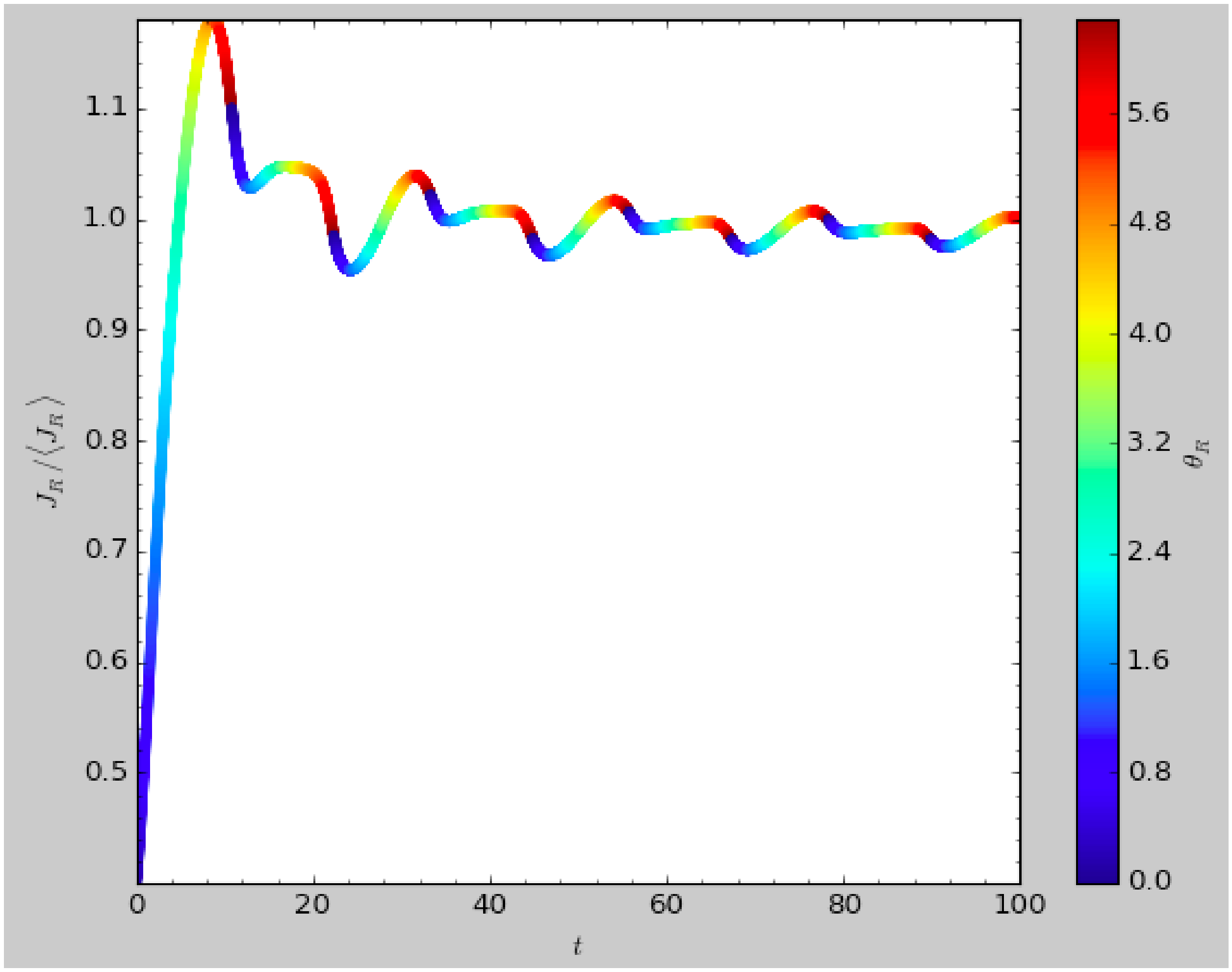
which shows slow convergence



Finding a better auxiliary potential makes convergence *much* faster and also allows the frequencies and the angles to be calculated by removing the small wiggles in the auxiliary angles vs. time (in the angle plot above, the wiggles are much larger, such that removing them is hard). The auxiliary potential used above had `b=0.8`, which shows very quick converenge and good behavior of the angles

```
>>> aAIA= actionAngleIsochroneApprox(pot=lp,b=0.8)
>>> aAIA.plot(*obs,type='jr')
```

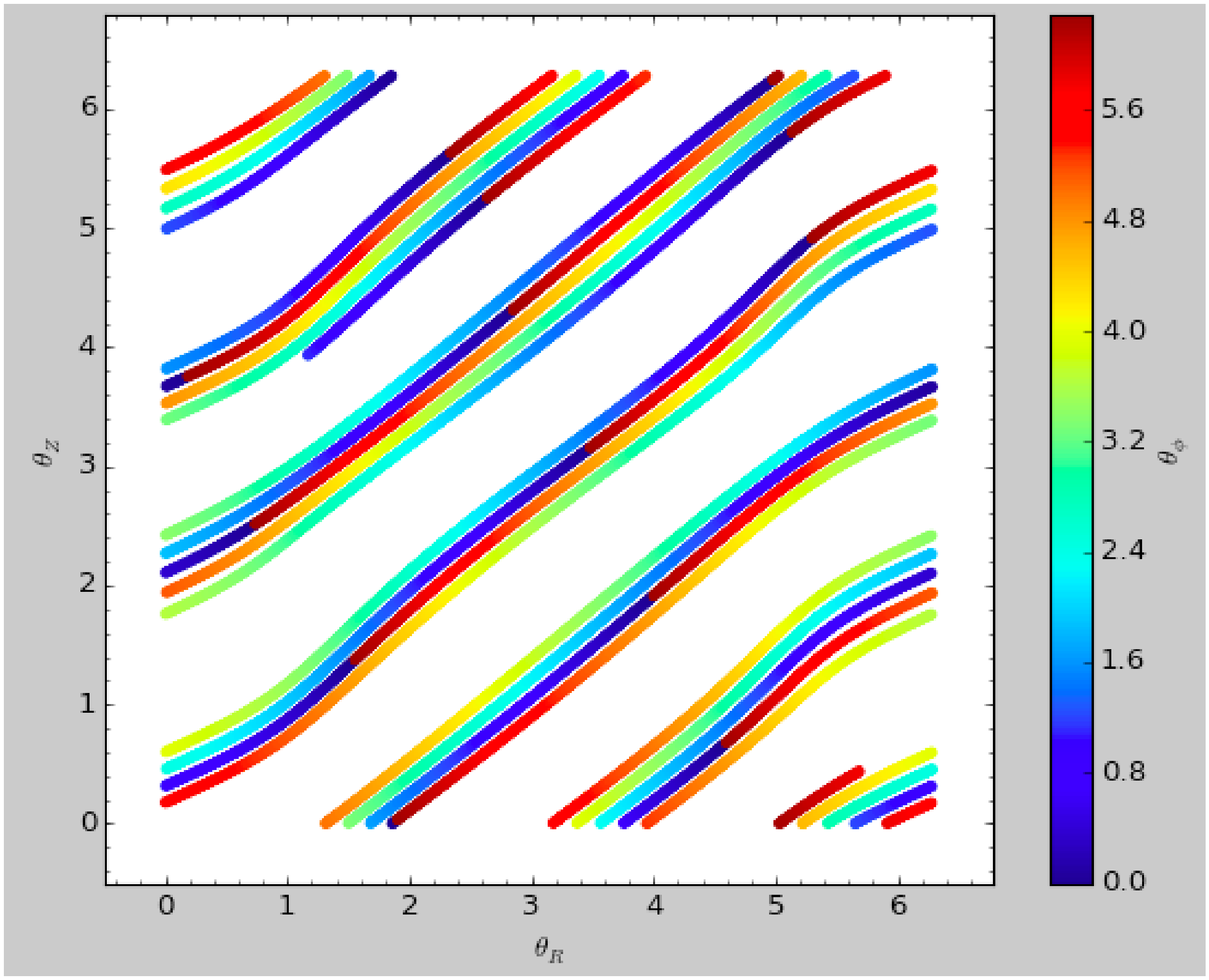
gives



and

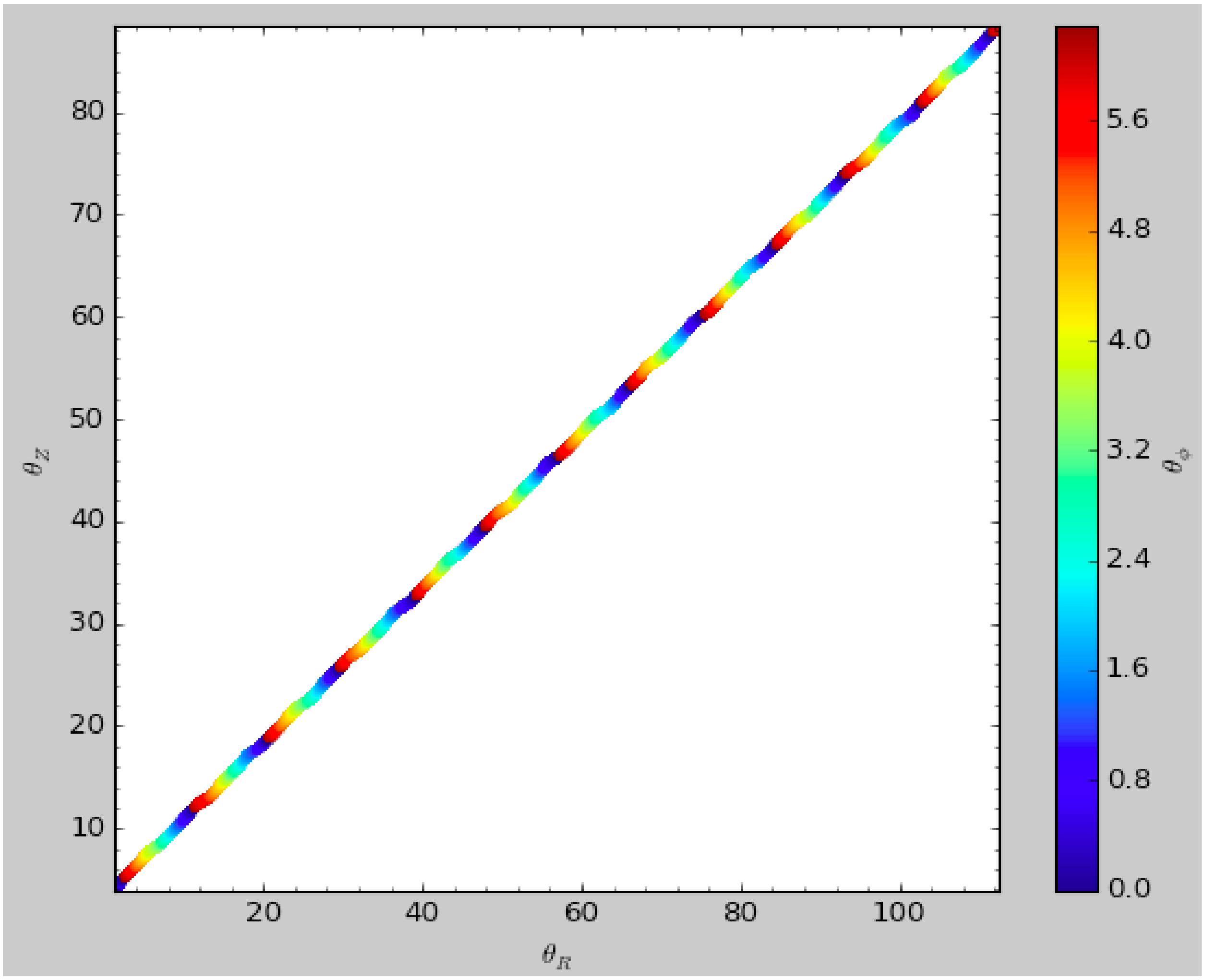
```
>>> aAIA.plot(*obs,type='araz')
```

gives



We can remove the periodic behavior from the angles, which clearly shows that they increase close-to-linear with time

```
>>> aAIA.plot(*obs,type='araz',deperiod=True)
```



We can then calculate the frequencies and the angles for this orbit as

```
>>> aAIA.actionsFreqsAngles(*obs)
(array([ 0.16392384]),
 array([-1.80322155]),
 array([ 0.50999882]),
 array([ 0.55808933]),
 array([-0.38475753]),
 array([ 0.42199713]),
 array([ 0.18739688]),
 array([ 0.3131815]),
 array([ 2.18425661]))
```

This function takes as an argument `maxn=` the maximum *n* for which to remove sinusoidal wiggles. So we can raise this, for example to 4 from 3

```
>>> aAIA.actionsFreqsAngles(*obs,maxn=4)
(array([ 0.16392384]),
 array([-1.80322155]),
 array([ 0.50999882]),
 array([ 0.55808776]),
 array([-0.38475733]),
 array([ 0.4219968]),
```

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```
array([ 0.18732009]),
array([ 0.31318534]),
array([ 2.18421296]))
```

Clearly, there is very little change, as most of the wiggles are of low n.

Warning: While the orbit-based actionAngle technique in principle works for triaxial potentials, angles and frequencies for non-axisymmetric potentials are not implemented yet.

This technique also works for triaxial potentials, but using those requires the code to also use the azimuthal angle variable in the auxiliary potential (this is unnecessary in axisymmetric potentials as the z component of the angular momentum is conserved). We can calculate actions for triaxial potentials by specifying that `nonaxi=True`:

```
>>> aAIA(*obs,nonaxi=True)
(array([ 0.16605011]), array([-1.80322155]), array([ 0.50704439]))
```

galpy currently does not contain any triaxial potentials, so we cannot illustrate this here with any real triaxial potentials.

1.6.6 Accessing action-angle coordinates for Orbit instances

While the recommended way to access the actionAngle routines is through the methods in the `galpy.actionAngle` modules, action-angle coordinates can also be cacluated for `galpy.orbit.Orbit` instances. This is illustrated here briefly. We initialize an Orbit instance

```
>>> from galpy.orbit import Orbit
>>> from galpy.potential import MWPotential2014
>>> o= Orbit([1.,0.1,1.1,0.,0.25,0.])
```

and we can then calculate the actions (default is to use the adiabatic approximation)

```
>>> o.jr(MWPotential2014), o.jp(MWPotential2014), o.jz(MWPotential2014)
(0.01685643005901713, 1.1, 0.015897730620467752)
```

`o.jp` here gives the azimuthal action (which is the z component of the angular momentum for axisymmetric potentials). We can also use the other methods described above, but note that these require extra parameters related to the approximation to be specified (see above):

```
>>> o.jr(MWPotential2014,type='staeckel',delta=0.4), o.jp(MWPotential2014,type=
↪'staeckel',delta=0.4), o.jz(MWPotential2014,type='staeckel',delta=0.4)
(array([ 0.01922167]), array([ 1.1]), array([ 0.01527683]))
>>> o.jr(MWPotential2014,type='isochroneApprox',b=0.8), o.jp(MWPotential2014,type=
↪'isochroneApprox',b=0.8), o.jz(MWPotential2014,type='isochroneApprox',b=0.8)
(array([ 0.01906609]), array([ 1.1]), array([ 0.01528049]))
```

These two methods give very precise actions for this orbit (both are converged to about 1%) and they agree very well

```
>>> (o.jr(MWPotential2014,type='staeckel',delta=0.4)-o.jr(MWPotential2014,type=
↪'isochroneApprox',b=0.8))/o.jr(MWPotential2014,type='isochroneApprox',b=0.8)
array([ 0.00816012])
>>>  (o.jz(MWPotential2014,type='staeckel',delta=0.4)-o.jz(MWPotential2014,type=
↪'isochroneApprox',b=0.8))/o.jz(MWPotential2014,type='isochroneApprox',b=0.8)
array([-0.00024])
```

Warning: Once an action, frequency, or angle is calculated for a given type of calculation (e.g., staeckel), the parameters for that type are fixed in the Orbit instance. Call o.resetaA() to reset the action-angle instance used when using different parameters (i.e., different `delta=` for staeckel or different `b=` for isochroneApprox.

We can also calculate the frequencies and the angles. This requires using the Staeckel or Isochrone approximations, because frequencies and angles are currently not supported for the adiabatic approximation. For example, the radial frequency

```
>>> o.Or(MWPotential2014,type='staeckel',delta=0.4)
1.1131779637307115
>>> o.Or(MWPotential2014,type='isochroneApprox',b=0.8)
1.1134635974560649
```

and the radial angle

```
>>> o.wr(MWPotential2014,type='staeckel',delta=0.4)
0.37758086786371969
>>> o.wr(MWPotential2014,type='isochroneApprox',b=0.8)
0.38159809018175395
```

which again agree to 1%. We can also calculate the other frequencies, angles, as well as periods using the functions `o.Op`, `o.oz`, `o.wp`, `o.wz`, `o.Tr`, `o.Tp`, `o.Tz`.

1.6.7 Example: Evidence for a Lindblad resonance in the Solar neighborhood

We can use galpy to calculate action-angle coordinates for a set of stars in the Solar neighborhood and look for unexplained features. For this we download the data from the Geneva-Copenhagen Survey (2009A&A...501..941H; data available at viZier). Since the velocities in this catalog are given as U,V, and W, we use the `radec` and `UVW` keywords to initialize the orbits from the raw data. For each object `ii`

```
>>> o= Orbit(vxvv[ii,:],radec=True,uvw=True,vo=220.,ro=8.)
```

We then calculate the actions and angles for each object in a flat rotation curve potential

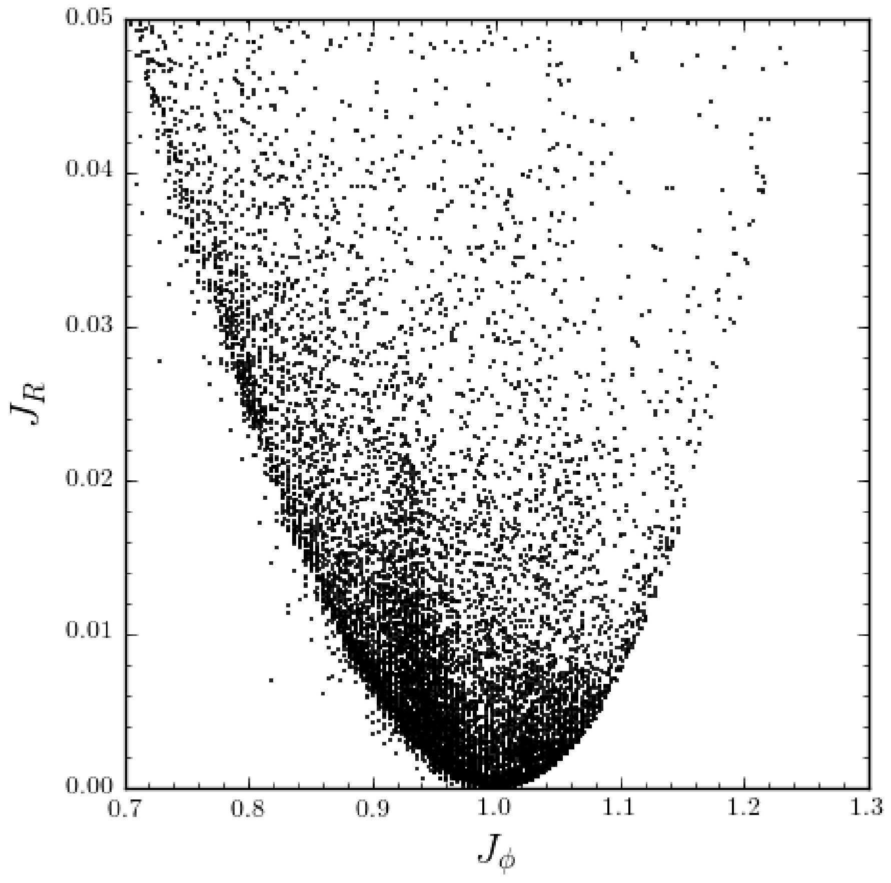
```
>>> lp= LogarithmicHaloPotential(normalize=1.)
>>> myjr[ii]= o.jr(lp)
```

etc.

Plotting the radial action versus the angular momentum

```
>>> plot.bovy_plot(myjp,myjr,'k.',ms=2.,xlabel=r'$J_{\phi}$',ylabel=r'$J_R$',
↪xrange=[0.7,1.3],yrange=[0.,0.05])
```

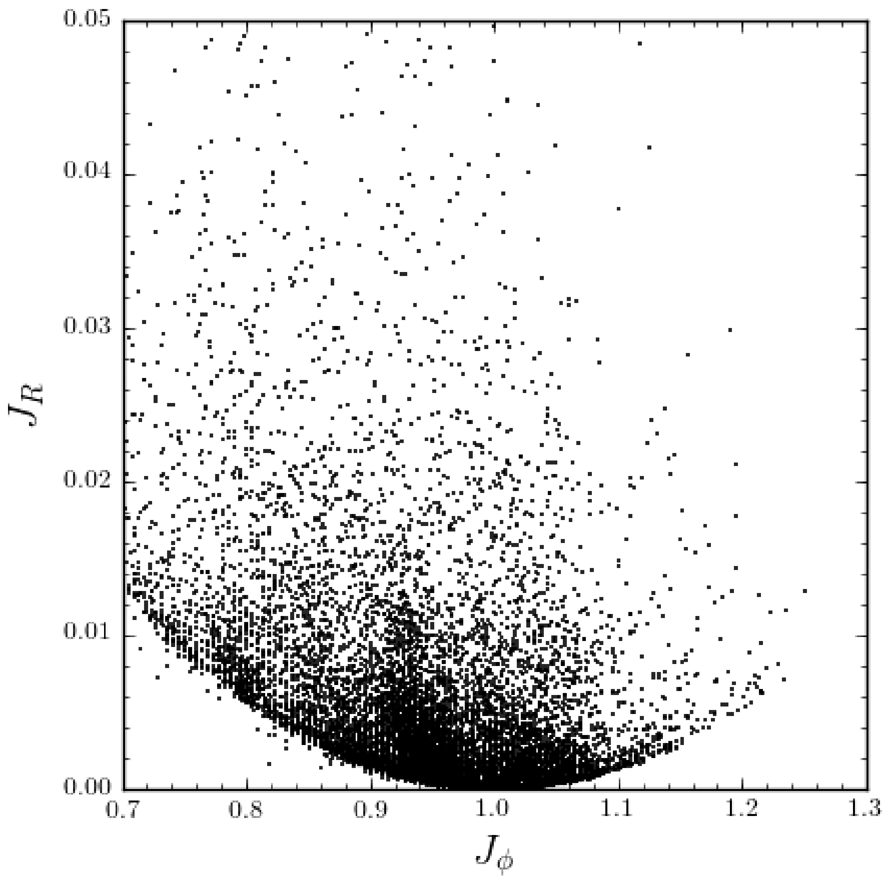
shows a feature in the distribution



If instead we use a power-law rotation curve with power-law index 1

```
>>> pp= PowerSphericalPotential(normalize=1.,alpha=-2.)
>>> myjr[ii]= o.jr(pp)
```

We find that the distribution is stretched, but the feature remains



Code for this example can be found `here` (note that this code uses a particular download of the GCS data set; if you use your own version, you will need to modify the part of the code that reads the data). For more information see 2010MNRAS.409..145S.

1.6.8 NEW: Example: actions in an N-body simulation

To illustrate how we can use `galpy` to calculate actions in a snapshot of an N-body simulation, we again look at the `g15784` snapshot in the `pynbody` test suite, discussed in *The potential of N-body simulations*. Please look at that section for information on how to setup the potential of this snapshot in `galpy`. One change is that we should set `enable_c=True` in the instantiation of the `InterpSnapshotRZPotential` object

```
>>> spi= InterpSnapshotRZPotential(h1,rgrid=(numpy.log(0.01),numpy.log(20.),101),
↪logR=True,zgrid=(0.,10.,101),interpPot=True,zsym=True,enable_c=True)
>>> spi.normalize(R0=10.)
```

where we again normalize the potential to use galpy's *natural units*.

We first load a pristine copy of the simulation (because the normalization above leads to some inconsistent behavior in pynbody)

```
>>> sc = pynbody.load('Repos/pynbody-testdata/g15784.lr.01024.gz'); hc = sc.halos();␣
↪hc1= hc[1]; pynbody.analysis.halo.center(hc1,mode='hyb'); pynbody.analysis.angmom.
↪faceon(hc1, cen=(0,0,0),mode='ssc'); sc.physical_units()
```

and then select particles near *R=8* kpc by doing

```
>>> sn= pynbody.filt.BandPass('rxy','7 kpc','9 kpc')
>>> R,vR,vT,z,vz = [numpy.ascontiguousarray(hc1.s[sn][x]) for x in ('rxy','vr','vt','z
↪','vz')]
```

These have physical units, so we normalize them (the velocity normalization is the circular velocity at *R=10* kpc, see *here*).

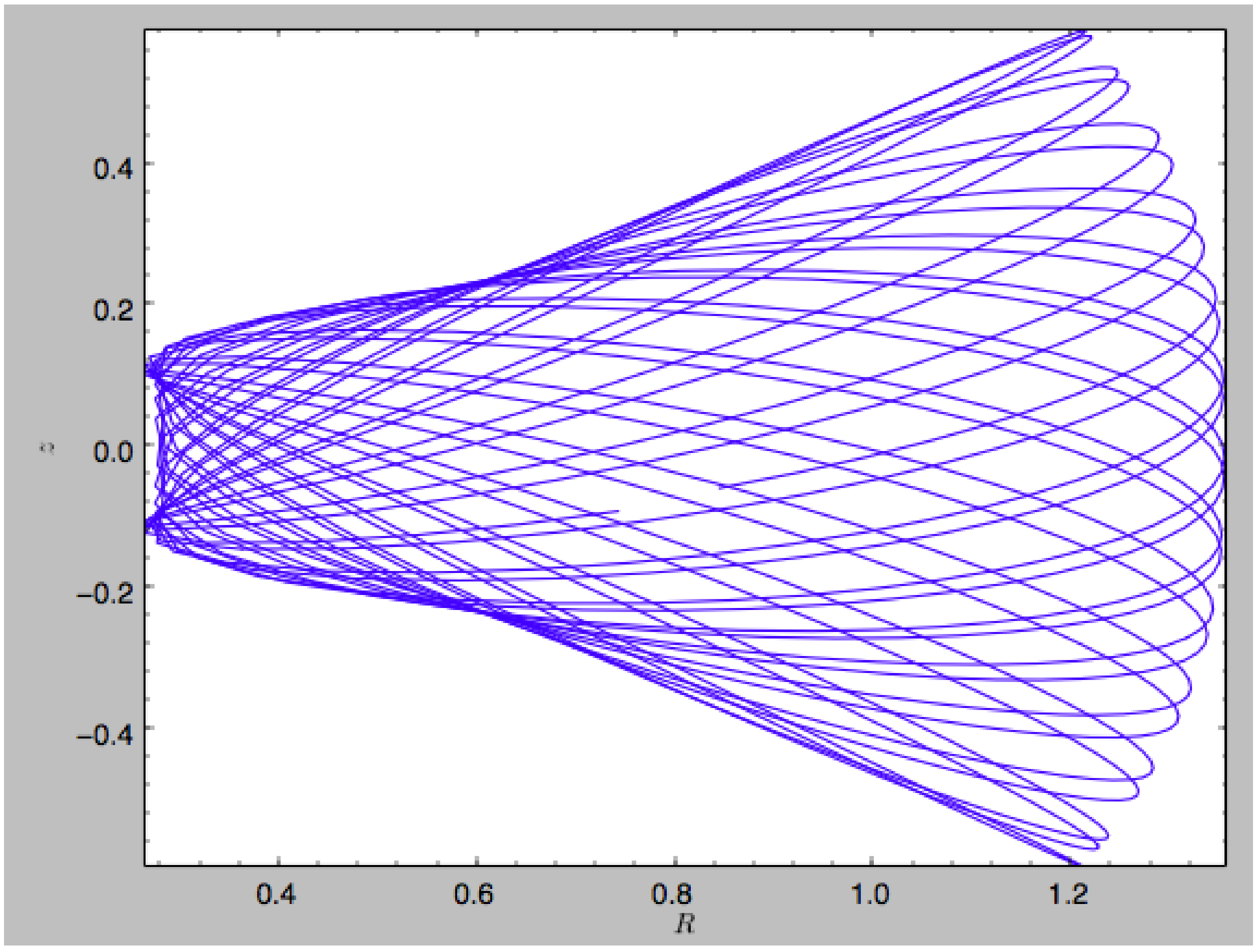
```
>>> ro, vo= 10., 294.62723076942245
>>> R/= ro
>>> z/= ro
>>> vR/= vo
>>> vT/= vo
>>> vz/= vo
```

We will calculate actions using `actionAngleStaeckel` above. We can first integrate a random orbit in this potential

```
>>> from galpy.orbit import Orbit
>>> numpy.random.seed(1)
>>> ii= numpy.random.permutation(len(R))[0]
>>> o= Orbit([R[ii],vR[ii],vT[ii],z[ii],vz[ii]])
>>> ts= numpy.linspace(0.,100.,1001)
>>> o.integrate(ts,spi)
```

This orbit looks like this

```
>>> o.plot()
```



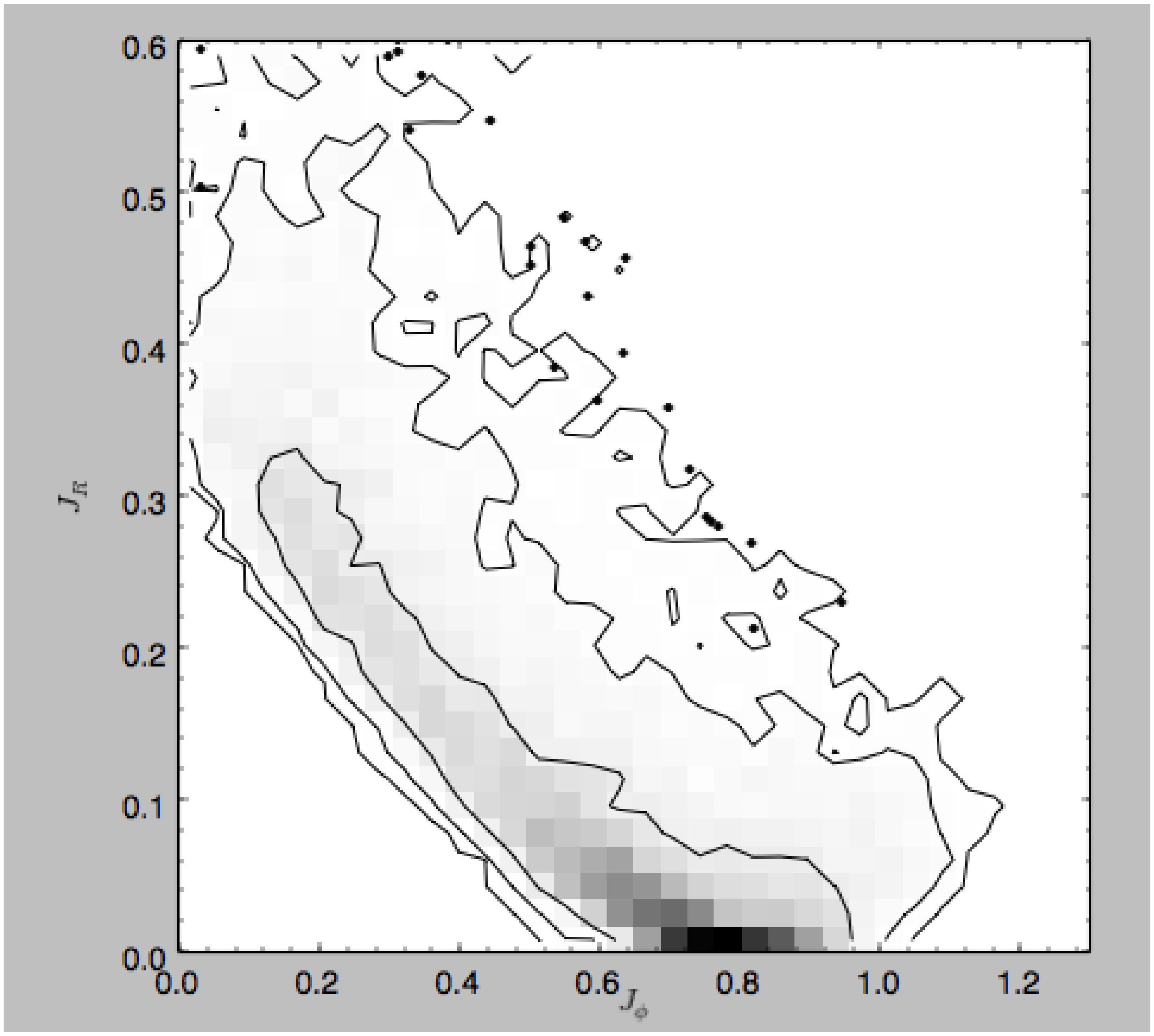
We can now calculate the actions by doing

```
>>> from galpy.actionAngle import actionAngleStaeckel
>>> aAS= actionAngleStaeckel(pot=spi,delta=0.45,c=True)
>>> jr,lz,jz= aAS(R,vR,vT,z,vz)
```

These actions are also in *natural units*; you can obtain physical units by multiplying with *ro*vo*. We can now plot these actions

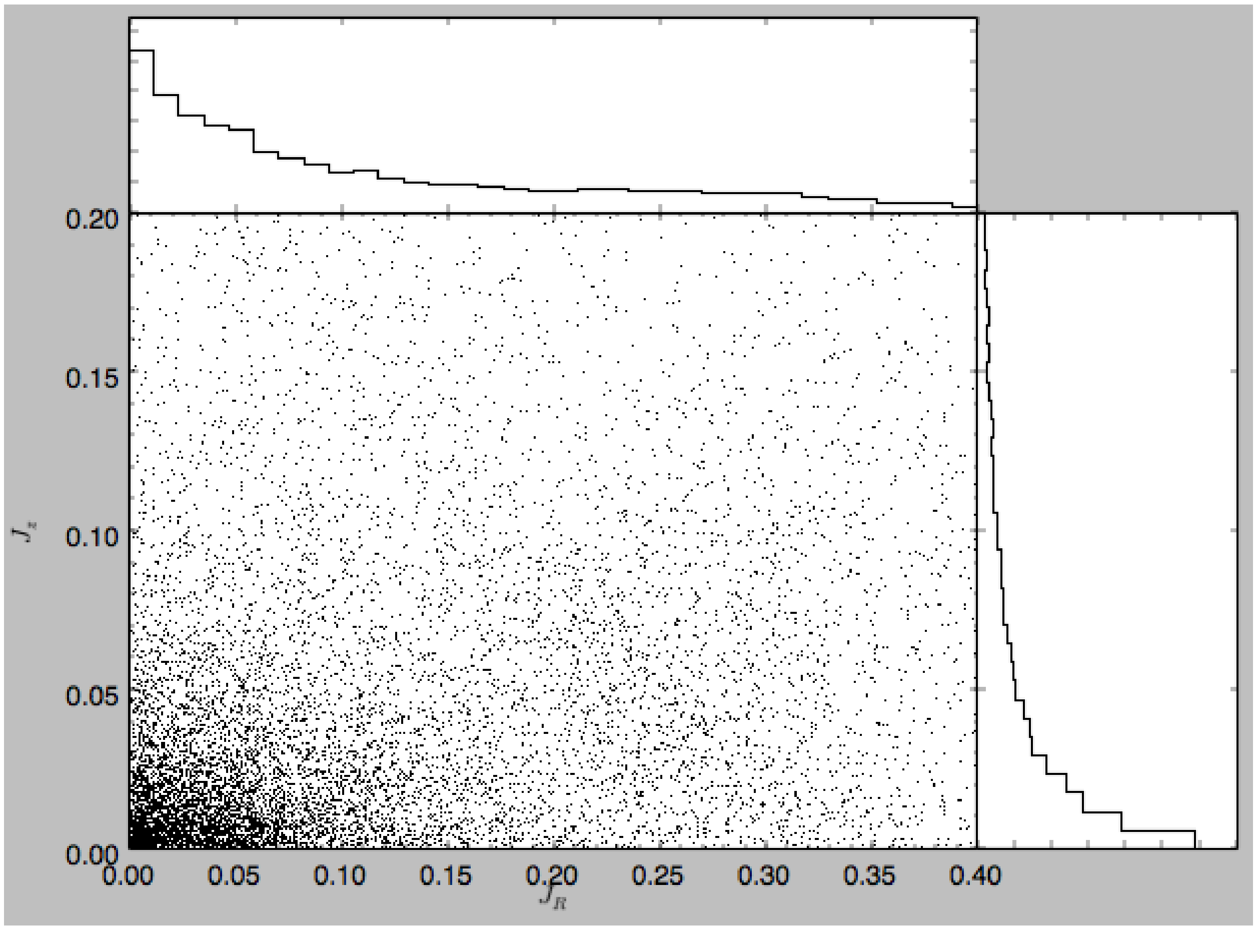
```
>>> from galpy.util import bovy_plot
>>> bovy_plot.scatterplot(lz,jr,'k.',xlabel=r'$J_\phi$',ylabel=r'$J_R$',xrange=[0.,1.
↪3],yrange=[0.,.6])
```

which gives



Note the similarity between this figure and the GCS figure above. The curve shape is due to the selection (low angular momentum stars can only enter the selected radial ring if they are very elliptical and therefore have large radial action) and the density gradient in angular momentum is due to the falling surface density of the disk. We can also look at the distribution of radial and vertical actions.

```
>>> bovy_plot.bovy_plot(jr,jz,'k,',xlabel=r'$J_R$',ylabel=r'$J_z$',xrange=[0.,.4],
↪yrange=[0.,0.2],onedhists=True)
```



With the other methods in the actionAngle module we can also calculate frequencies and angles.

1.7 Three-dimensional disk distribution functions

galpy contains a fully three-dimensional disk distribution: `galpy.df.quasiisothermaldf`, which is an approximately isothermal distribution function expressed in terms of action–angle variables (see 2010MNRAS.401.2318B and 2011MNRAS.413.1889B). Recent research shows that this distribution function provides a good model for the DF of mono-abundance sub-populations (MAPs) of the Milky Way disk (see 2013MNRAS.434..652T and 2013ApJ…779..115B). This distribution function family requires action-angle coordinates to evaluate the DF, so `galpy.df.quasiisothermaldf` makes heavy use of the routines in `galpy.actionAngle` (in particular those in `galpy.actionAngleAdiabatic` and `galpy.actionAngle.actionAngleStaeckel`).

1.7.1 Setting up the DF and basic properties

The quasi-isothermal DF is defined by a gravitational potential and a set of parameters describing the radial surface-density profile and the radial and vertical velocity dispersion as a function of radius. In addition, we have to provide an instance of a `galpy.actionAngle` class to calculate the actions for a given position and velocity. For example, for a `galpy.potential.MWPotential2014` potential using the adiabatic approximation for the actions, we import and define the following

```
>>> from galpy.potential import MWPotential2014
>>> from galpy.actionAngle import actionAngleAdiabatic
>>> from galpy.df import quasiisothermaldf
>>> aA= actionAngleAdiabatic(pot=MWPotential2014,c=True)
```

and then setup the `quasiisothermaldf` instance

```
>>> qdf= quasiisothermaldf(1./3.,0.2,0.1,1.,1.,pot=MWPotential2014,aA=aA,
↪cutcounter=True)
```

which sets up a DF instance with a radial scale length of $R_0/3$, a local radial and vertical velocity dispersion of $0.2\,V_c(R_0)$ and $0.1\,V_c(R_0)$, respectively, and a radial scale lengths of the velocity dispersions of R_0. `cutcounter=True` specifies that counter-rotating stars are explicitly excluded (normally these are just exponentially suppressed). As for the two-dimensional disk DFs, these parameters are merely input (or target) parameters; the true density and velocity dispersion profiles calculated by evaluating the relevant moments of the DF (see below) are not exactly exponential and have scale lengths and local normalizations that deviate slightly from these input parameters. We can estimate the DF's actual radial scale length near R_0 as

```
>>> qdf.estimate_hr(1.)
0.32908034635647182
```

which is quite close to the input value of 1/3. Similarly, we can estimate the scale lengths of the dispersions

```
>>> qdf.estimate_hsr(1.)
1.1913935820372923
>>> qdf.estimate_hsz(1.)
1.0506918075359255
```

The vertical profile is fully specified by the velocity dispersions and radial density / dispersion profiles under the assumption of dynamical equilibrium. We can estimate the scale height of this DF at a given radius and height as follows

```
>>> qdf.estimate_hz(1.,0.125)
0.021389597757156088
```

Near the mid-plane this vertical scale height becomes very large because the vertical profile flattens, e.g.,

```
>>> qdf.estimate_hz(1.,0.125/100.)
1.006386030587223
```

or even

```
>>> qdf.estimate_hz(1.,0.)
187649.98447377066
```

which is basically infinity.

1.7.2 Evaluating moments

We can evaluate various moments of the DF giving the density, mean velocities, and velocity dispersions. For example, the mean radial velocity is again everywhere zero because the potential and the DF are axisymmetric

```
>>> qdf.meanvR(1.,0.)
0.0
```

Likewise, the mean vertical velocity is everywhere zero

```
>>> qdf.meanvz(1.,0.)
0.0
```

The mean rotational velocity has a more interesting dependence on position. Near the plane, this is the same as that calculated for a similar two-dimensional disk DF (see *Evaluating moments of the DF*)

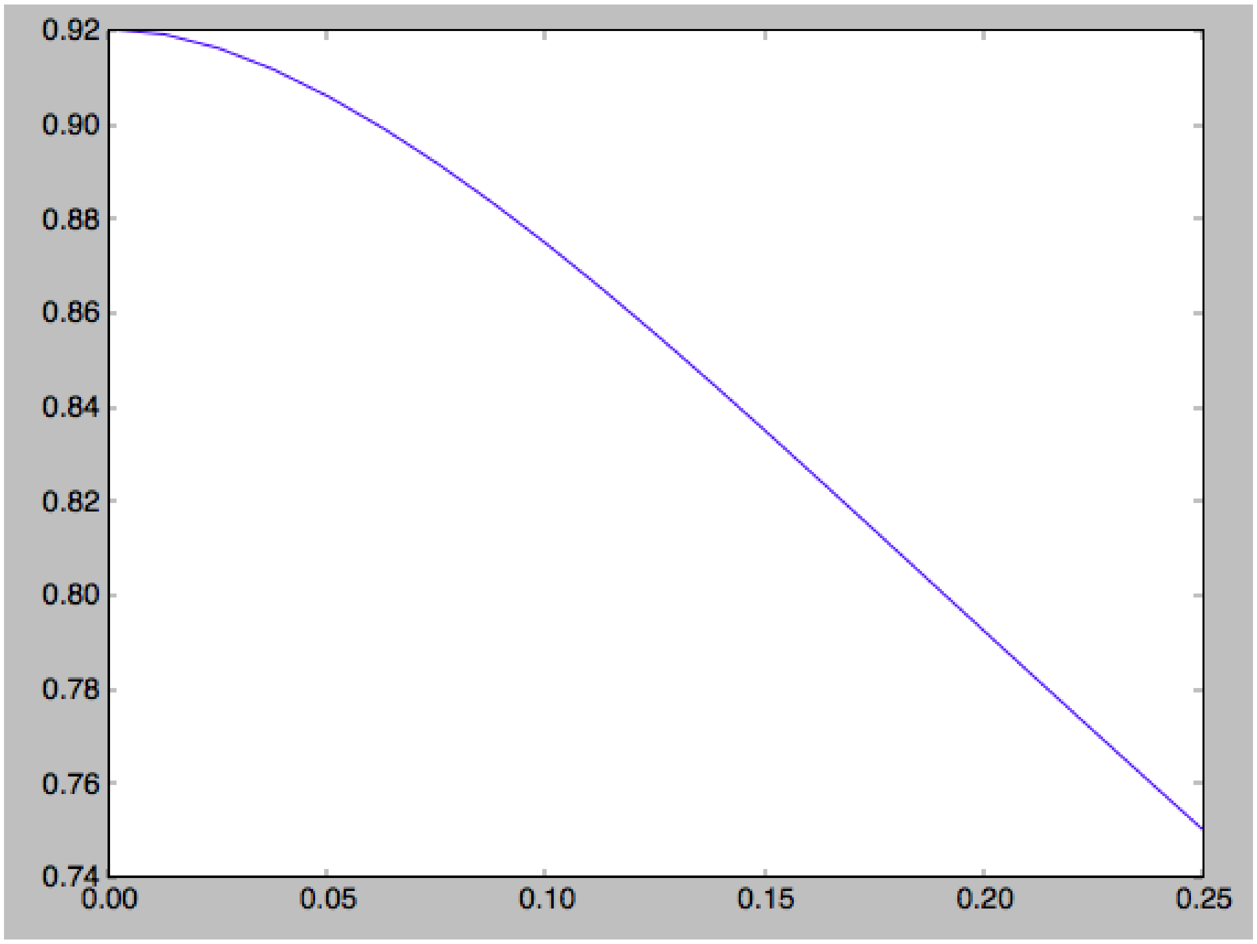
```
>>> qdf.meanvT(1.,0.)
0.91988346380781227
```

However, this value decreases as one moves further from the plane. The `quasiisothermaldf` allows us to calculate the average rotational velocity as a function of height above the plane. For example,

```
>>> zs= numpy.linspace(0.,0.25,21)
>>> mvts= numpy.array([qdf.meanvT(1.,z) for z in zs])
```

which gives

```
>>> plot(zs,mvts)
```



We can also calculate the second moments of the DF. We can check whether the radial and velocity dispersions at R_0 are close to their input values

```
>>> numpy.sqrt(qdf.sigmaR2(1.,0.))
0.20807112565801389
```

(continues on next page)

(continued from previous page)

```
>>> numpy.sqrt(qdf.sigmaz2(1.,0.))
0.090453510526130904
```

and they are pretty close. We can also calculate the mixed *R* and *z* moment, for example,

```
>>> qdf.sigmaRz(1.,0.125)
0.0
```

or expressed as an angle (the *tilt of the velocity ellipsoid*)

```
>>> qdf.tilt(1.,0.125)
0.0
```

This tilt is zero because we are using the adiabatic approximation. As this approximation assumes that the motions in the plane are decoupled from the vertical motions of stars, the mixed moment is zero. However, this approximation is invalid for stars that go far above the plane. By using the Staeckel approximation to calculate the actions, we can model this coupling better. Setting up a `quasiisothermaldf` instance with the Staeckel approximation

```
>>> from galpy.actionAngle import actionAngleStaeckel
>>> aAS= actionAngleStaeckel(pot=MWPotential2014,delta=0.45,c=True)
>>> qdfS= quasiisothermaldf(1./3.,0.2,0.1,1.,1.,pot=MWPotential2014,aA=aAS,
↪cutcounter=True)
```

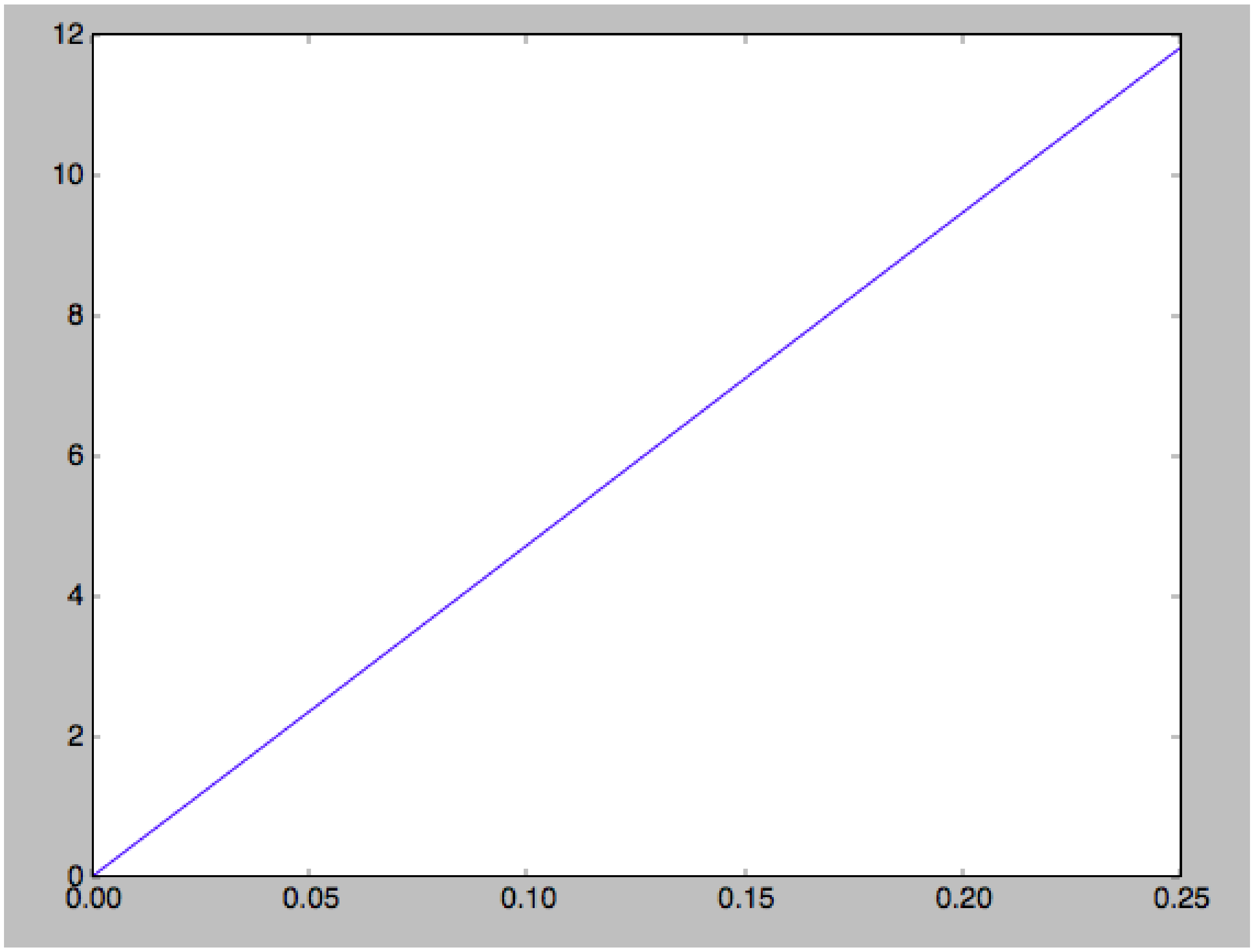
we can similarly calculate the tilt

```
>>> qdfS.tilt(1.,0.125)
5.9096430410862419
```

or about 5 degrees. As a function of height, we find

```
>>> tilts= numpy.array([qdfS.tilt(1.,z) for z in zs])
>>> plot(zs,tilts)
```

which gives



We can also calculate the density and surface density (the zero-th velocity moments). For example, the vertical density

```
>>> densz= numpy.array([qdf.density(1.,z) for z in zs])
```

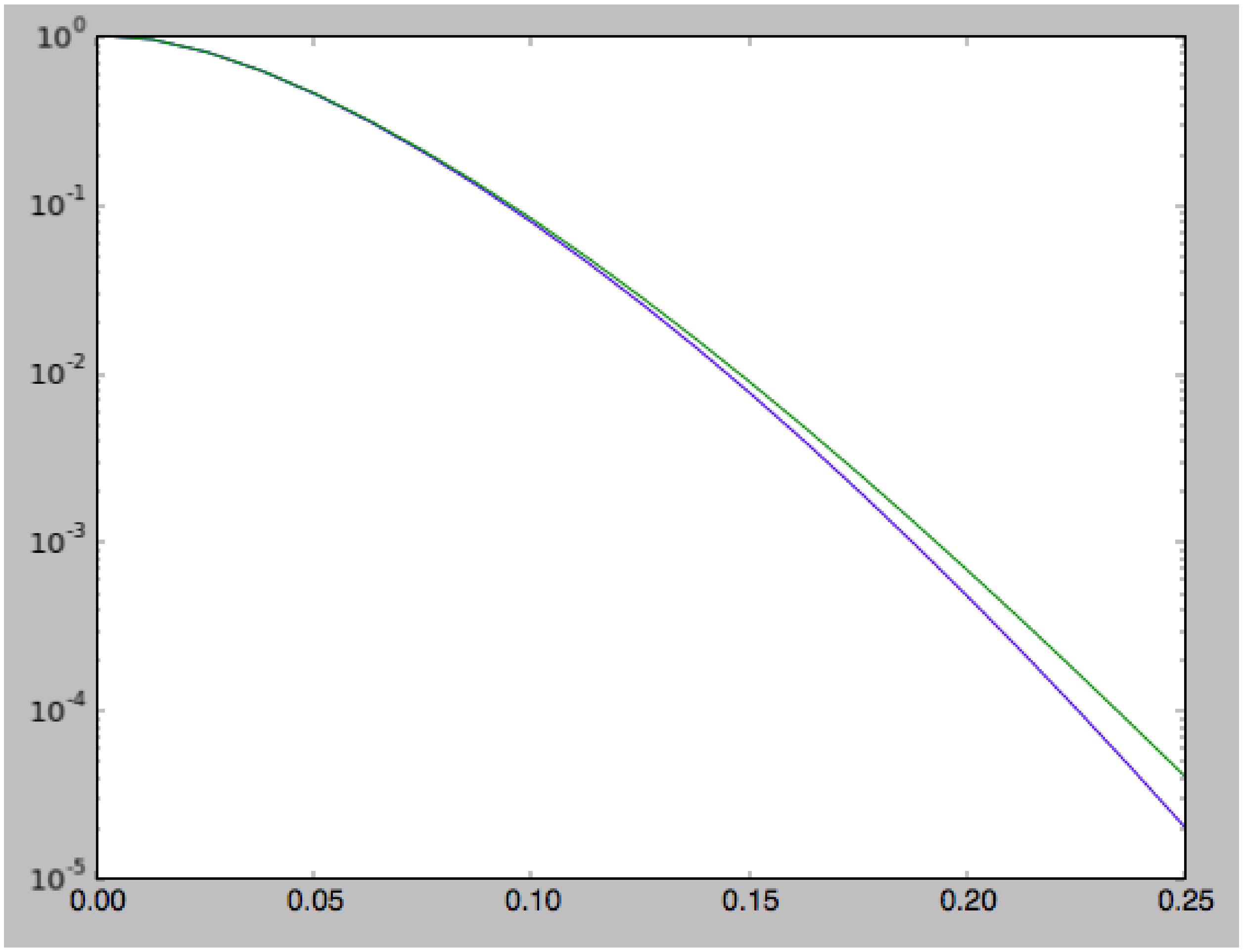
and

```
>>> denszS= numpy.array([qdfS.density(1.,z) for z in zs])
```

We can compare the vertical profiles calculated using the adiabatic and Staeckel action-angle approximations

```
>>> semilogy(zs,densz/densz[0])
>>> semilogy(zs,denszS/denszS[0])
```

which gives



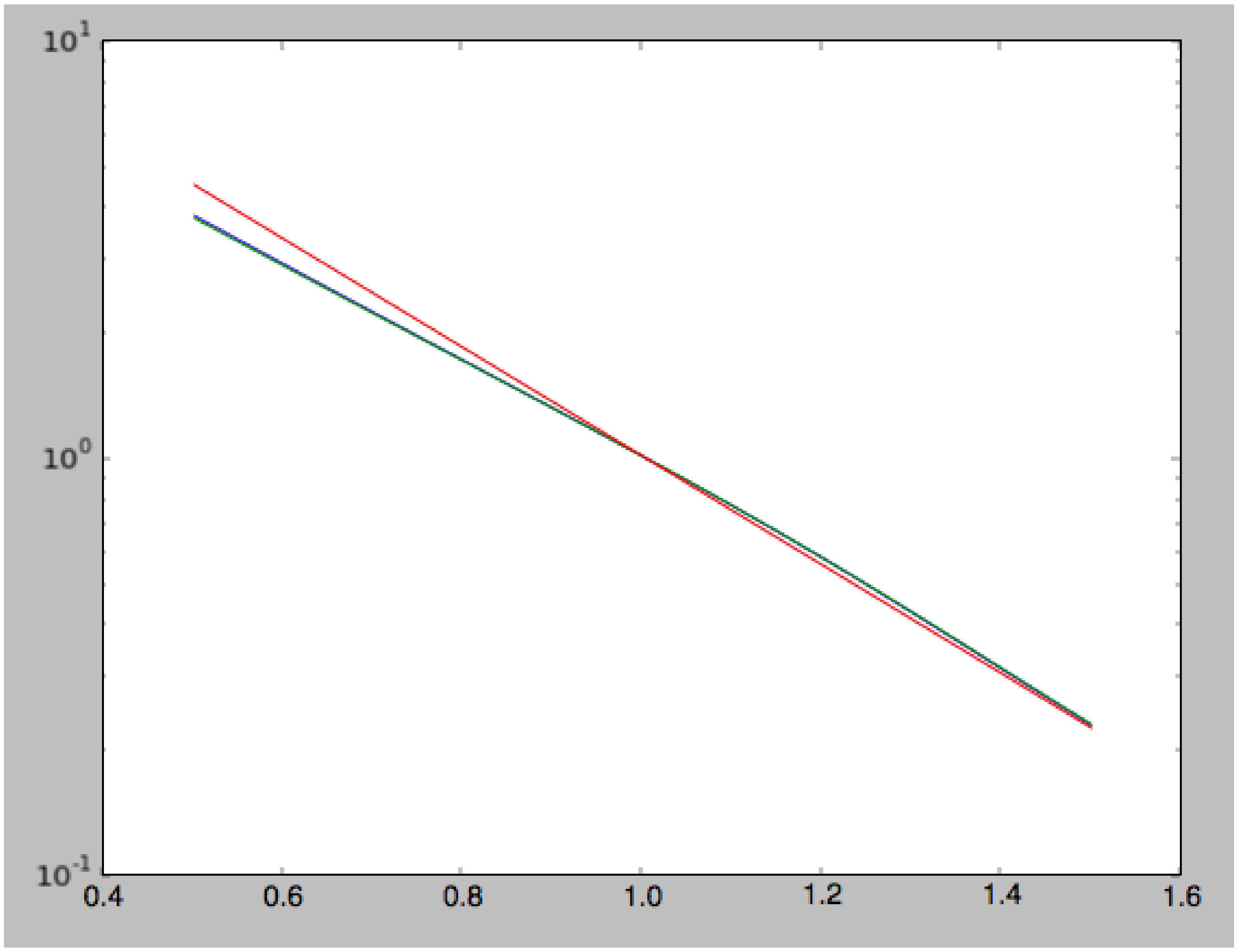
Similarly, we can calculate the radial profile of the surface density

```
>>> rs= numpy.linspace(0.5,1.5,21)
>>> surfr= numpy.array([qdf.surfacemass_z(r) for r in rs])
>>> surfrS= numpy.array([qdfS.surfacemass_z(r) for r in rs])
```

and compare them with each other and an exponential with scale length 1/3

```
>>> semilogy(rs,surfr/surfr[10])
>>> semilogy(rs,surfrS/surfrS[10])
>>> semilogy(rs,numpy.exp(-(rs-1.)/(1./3.)))
```

which gives



The two radial profiles are almost indistinguishable and are very close, if somewhat shallower, than the pure exponential profile.

General velocity moments, including all higher order moments, are implemented in `quasiisothermaldf.vmomentdensity`.

1.7.3 Evaluating and sampling the full probability distribution function

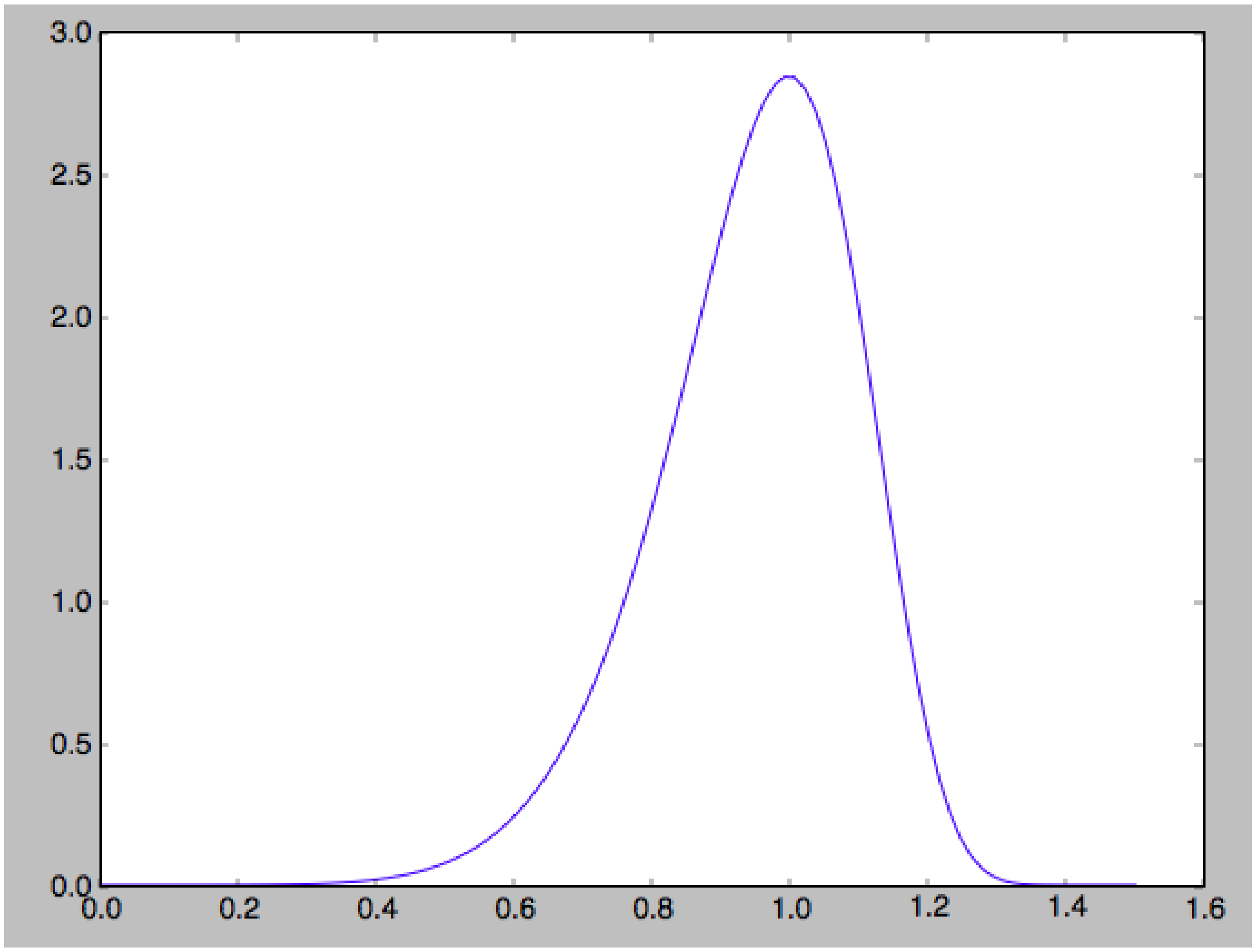
We can evaluate the distribution itself by calling the object, e.g.,

```
>>> qdf(1.,0.1,1.1,0.1,0.) #input: R,vR,vT,z,vz
array([ 16.86790643])
```

or as a function of rotational velocity, for example in the mid-plane

```
>>> vts= numpy.linspace(0.,1.5,101)
>>> pvt= numpy.array([qdfS(1.,0.,vt,0.,0.) for vt in vts])
>>> plot(vts,pvt/numpy.sum(pvt)/(vts[1]-vts[0]))
```

which gives



This is, however, not the true distribution of rotational velocities at R =0 and z =0, because it is conditioned on zero radial and vertical velocities. We can calculate the distribution of rotational velocities marginalized over the radial and vertical velocities as

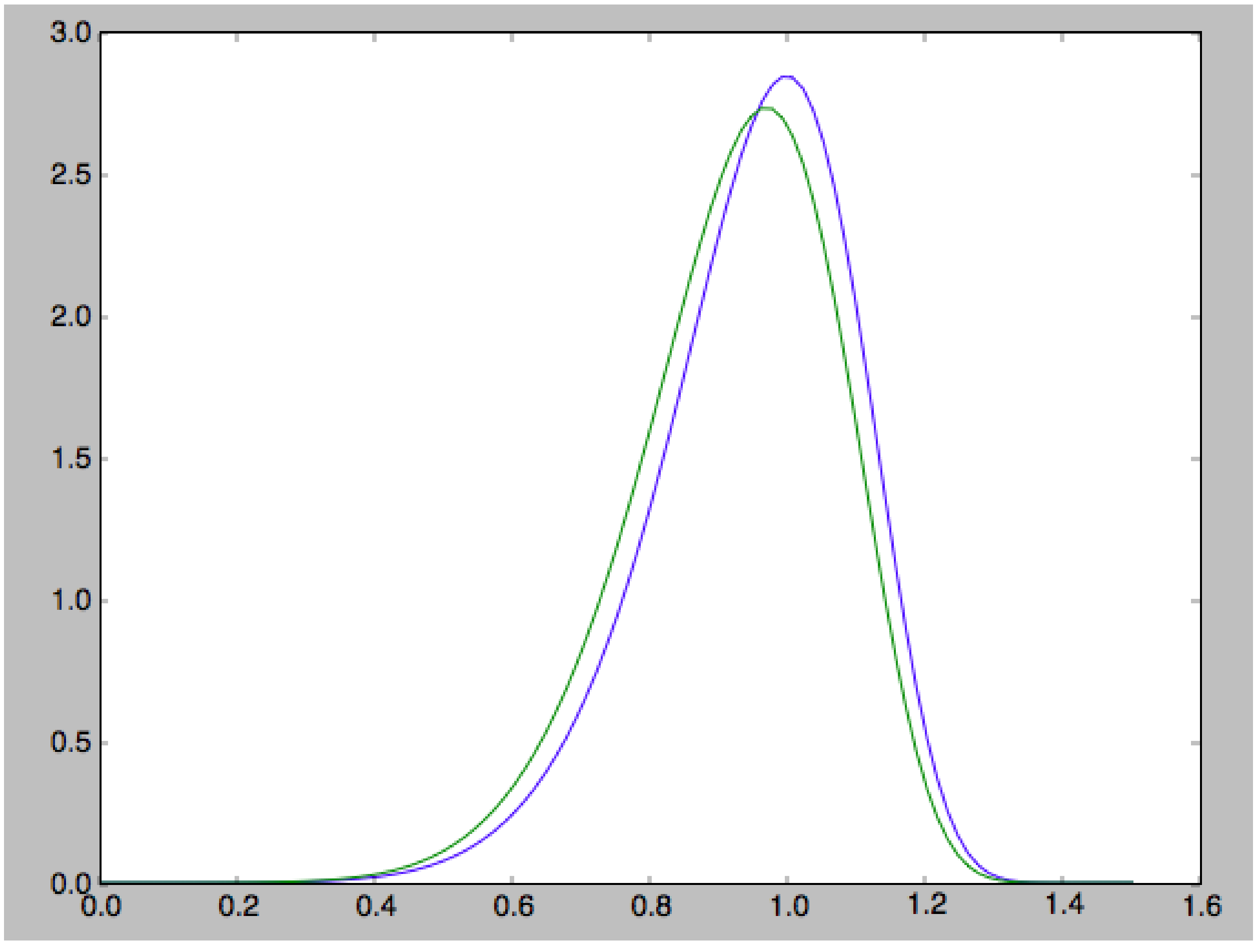
```
>>> qdfS.pvT(1.,1.,0.) #input vT,R,z
14.677231196899195
```

or as a function of rotational velocity

```
>>> pvt= numpy.array([qdfS.pvT(vt,1.,0.) for vt in vts])
```

overplotting this over the previous distribution gives

```
>>> plot(vts,pvt/numpy.sum(pvt)/(vts[1]-vts[0]))
```

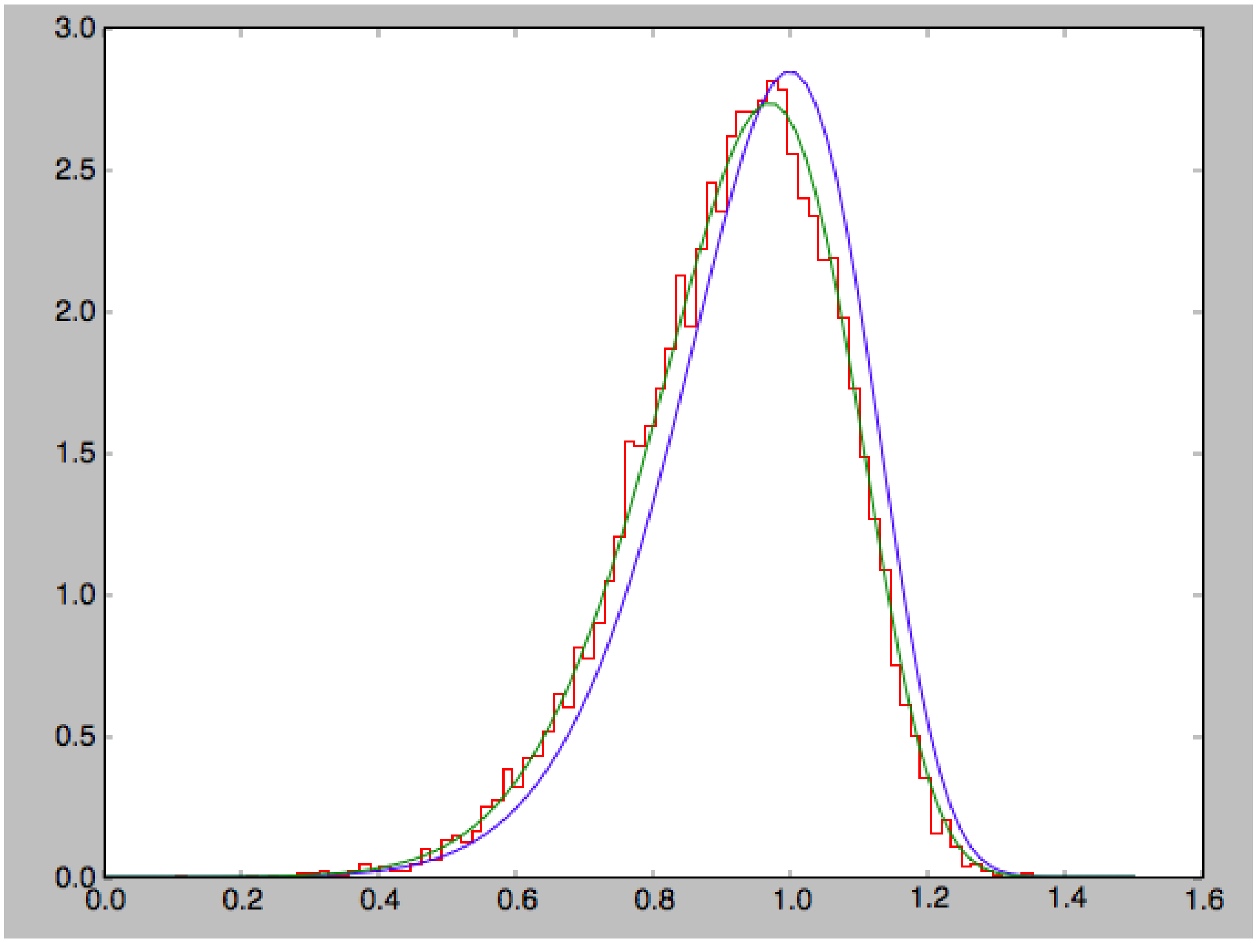


which is slightly different from the conditioned distribution. Similarly, we can calculate marginalized velocity probabilities `pvR, pvz, pvRvT, pvRvz, and pvTvz. These are all multiplied with the density, such that marginalizing these over the remaining velocity component results in the density.

We can sample velocities at a given location using quasiisothermaldf.sampleV (there is currently no support for sampling locations from the density profile, although that is rather trivial):

```
>>> vs= qdfS.sampleV(1.,0.,n=10000)
>>> hist(vs[:,1],normed=True,histtype='step',bins=101,range=[0.,1.5])
```

gives



which shows very good agreement with the green (marginalized over *vR* and *vz*) curve (as it should).

CHAPTER 2

Tutorials

2.1 Dynamical modeling of tidal streams

galpy contains tools to model the dynamics of tidal streams, making extensive use of action-angle variables. As an example, we can model the dynamics of the following tidal stream (that of Bovy 2014; 2014ApJ. . . 795. . . 95B). This movie shows the disruption of a cluster on a GD-1-like orbit around the Milky Way:

The blue line is the orbit of the progenitor cluster and the black points are cluster members. The disruption is shown in an approximate orbital plane and the movie is comoving with the progenitor cluster.

Streams can be represented by simple dynamical models in action-angle coordinates. In action-angle coordinates, stream members are stripped from the progenitor cluster onto orbits specified by a set of actions (J_R, J_ϕ, J_Z), which remain constant after the stars have been stripped. This is shown in the following movie, which shows the generation of the stream in action space

The color-coding gives the angular momentum J_ϕ and the black dot shows the progenitor orbit. These actions were calculated using `galpy.actionAngle.actionAngleIsochroneApprox`. The points move slightly because of small errors in the action calculation (these are correlated, so the cloud of points moves coherently because of calculation errors). The same movie that also shows the actions of stars in the cluster can be found here. This shows that the actions of stars in the cluster are not conserved (because the self-gravity of the cluster is important), but that the actions of stream members freeze once they are stripped. The angle difference between stars in a stream and the progenitor increases linearly with time, which is shown in the following movie:

where the radial and vertical angle difference with respect to the progenitor (co-moving at $(\theta_R, \theta_\phi, \theta_Z) = (\pi, \pi, \pi)$) is shown for each snapshot (the color-coding gives θ_ϕ).

One last movie provides further insight in how a stream evolves over time. The following movie shows the evolution of the stream in the two dimensional plane of frequency and angle along the stream (that is, both are projections of the three dimensional frequencies or angles onto the angle direction along the stream). The points are color-coded by the time at which they were removed from the progenitor cluster.

It is clear that disruption happens in bursts (at pericenter passages) and that the initial frequency distribution at the time of removal does not change (much) with time. However, stars removed at larger frequency difference move away from the cluster faster, such that the end of the stream is primarily made up of stars with large frequency differences with respect to the progenitor. This leads to a gradient in the typical orbit in the stream, and the stream is on average *not* on a single orbit.

2.1.1 Modeling streams in galpy

In galpy we can model streams using the tools in `galpy.df.streamdf`. We setup a streamdf instance by specifying the host gravitational potential `pot=`, an actionAngle method (typically `galpy.actionAngle.actionAngleIsochroneApprox`), a `galpy.orbit.Orbit` instance with the position of the progenitor, a parameter related to the velocity dispersion of the progenitor, and the time since disruption began. We first import all of the necessary modules

```
>>> from galpy.df import streamdf
>>> from galpy.orbit import Orbit
>>> from galpy.potential import LogarithmicHaloPotential
>>> from galpy.actionAngle import actionAngleIsochroneApprox
>>> from galpy.util import bovy_conversion #for unit conversions
```

setup the potential and actionAngle instances

```
>>> lp= LogarithmicHaloPotential(normalize=1.,q=0.9)
>>> aAI= actionAngleIsochroneApprox(pot=lp,b=0.8)
```

define a progenitor Orbit instance

```
>>> obs= Orbit([1.56148083,0.35081535,-1.15481504,0.88719443,-0.47713334,0.12019596])
```

and instantiate the streamdf model

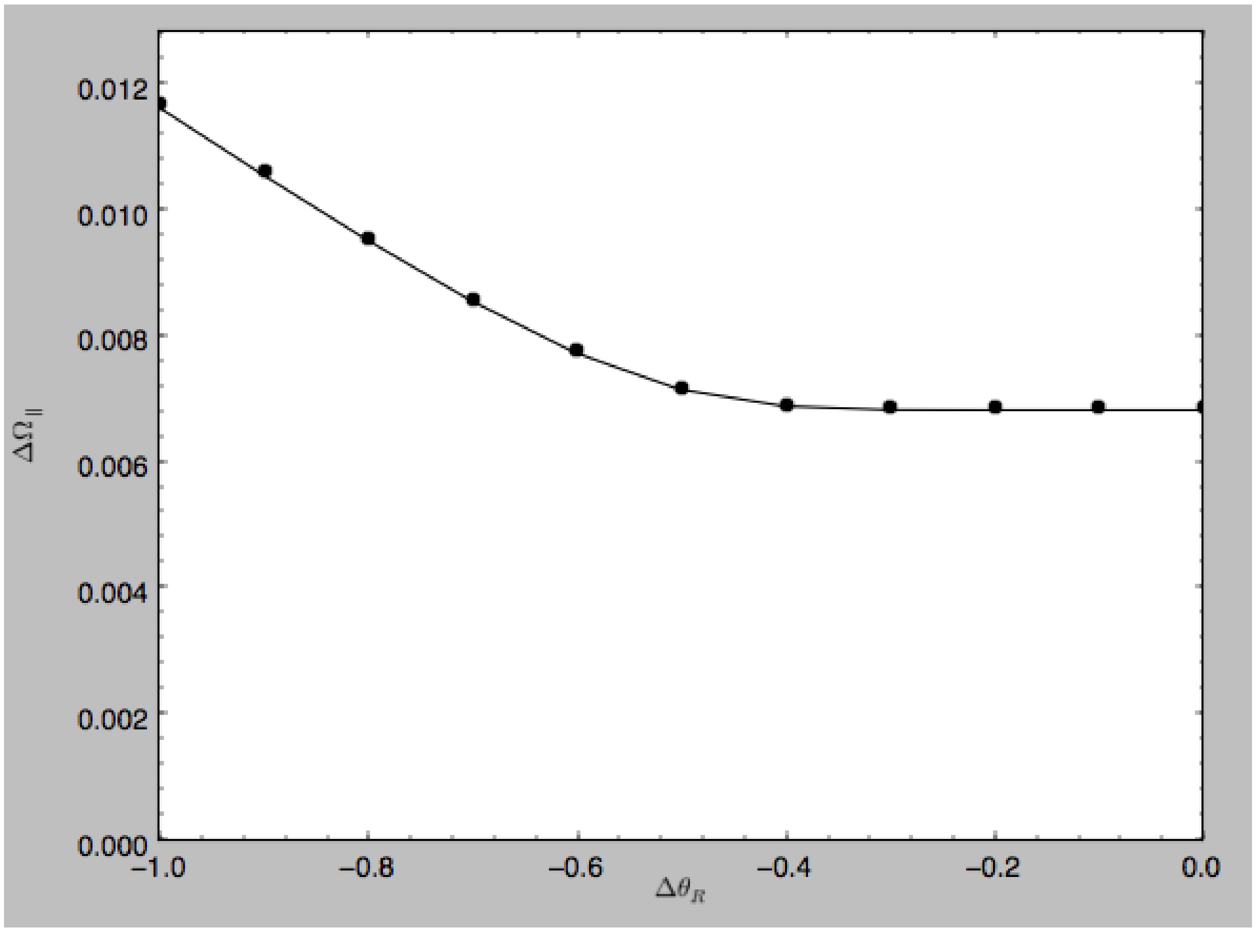
```
>>> sigv= 0.365 #km/s
>>> sdf= streamdf(sigv/220.,progenitor=obs,pot=lp,aA=aAI,leading=True,nTrackChunks=11,
↪tdisrupt=4.5/bovy_conversion.time_in_Gyr(220.,8.))
```

for a leading stream. This runs in about half a minute on a 2011 Macbook Air.

Bovy (2014) discusses how the calculation of the track needs to be iterated for potentials where there is a large offset between the track and a single orbit. One can increase the default number of iterations by specifying `nTrackIterations=` in the streamdf initialization (the default is set based on the angle between the track's frequency vector and the progenitor orbit's frequency vector; you can access the number of iterations used as `sdf.nTrackIterations`). To check whether the track is calculated accurately, one can use the following

```
>>> sdf.plotCompareTrackAAModel()
```

which in this case gives



This displays the stream model's track in frequency offset (y axis) versus angle offset (x axis) as the solid line; this is the track that the model should have if it is calculated correctly. The points are the frequency and angle offset calculated from the calculated track's $(\mathbf{x}, \mathbf{v})$. For a properly computed track these should line up, as they do in this figure. If they do not line up, increasing `nTrackIterations` is necessary.

We can calculate some simple properties of the stream, such as the ratio of the largest and second-to-largest eigenvalue of the Hessian $\partial\mathbf{\Omega}/\partial\mathbf{J}$

```
>>> sdf.freqEigvalRatio(isotropic=True)
34.450028399901434
```

or the model's ratio of the largest and second-to-largest eigenvalue of the model frequency variance matrix

```
>>> sdf.freqEigvalRatio()
29.625538344985291
```

The fact that this ratio is so large means that an approximately one dimensional stream will form.

Similarly, we can calculate the angle between the frequency vector of the progenitor and of the model mean frequency vector

```
>>> sdf.misalignment()
-0.49526013844831596
```

which returns this angle in degrees. We can also calculate the angle between the frequency vector of the progenitor and the principal eigenvector of $\partial\mathbf{\Omega}/\partial\mathbf{J}$

```
>>> sdf.misalignment(isotropic=True)
 1.2825116841963993
```

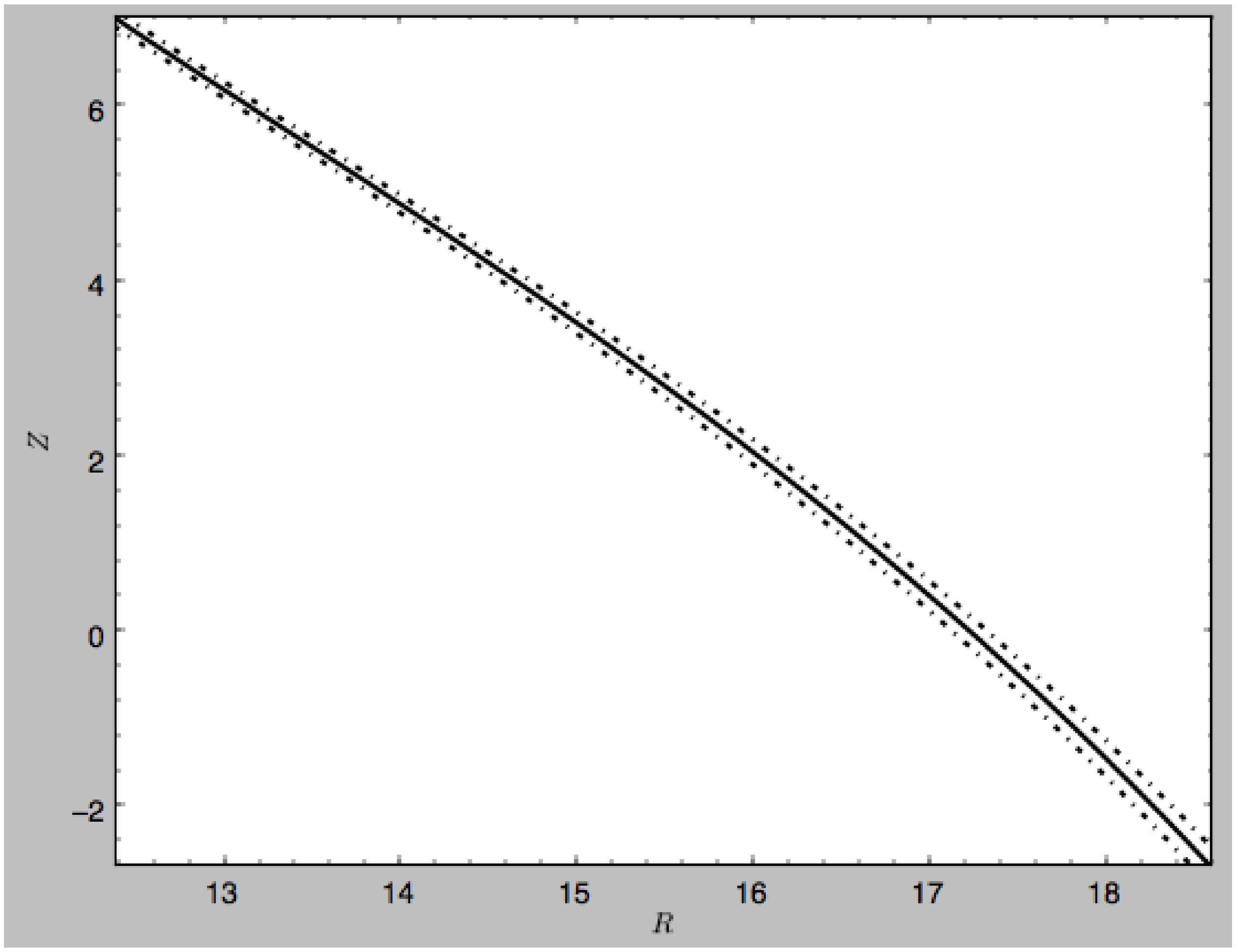
(the reason these are obtained by specifying `isotropic=True` is that these would be the ratio of the eigenvalues or the angle if we assumed that the disrupted materials action distribution were isotropic).

2.1.2 Calculating the average stream location (track)

We can display the stream track in various coordinate systems as follows

```
>>> sdf.plotTrack(d1='r',d2='z',interp=True,color='k',spread=2,overplot=False,lw=2.,
↪scaleToPhysical=True)
```

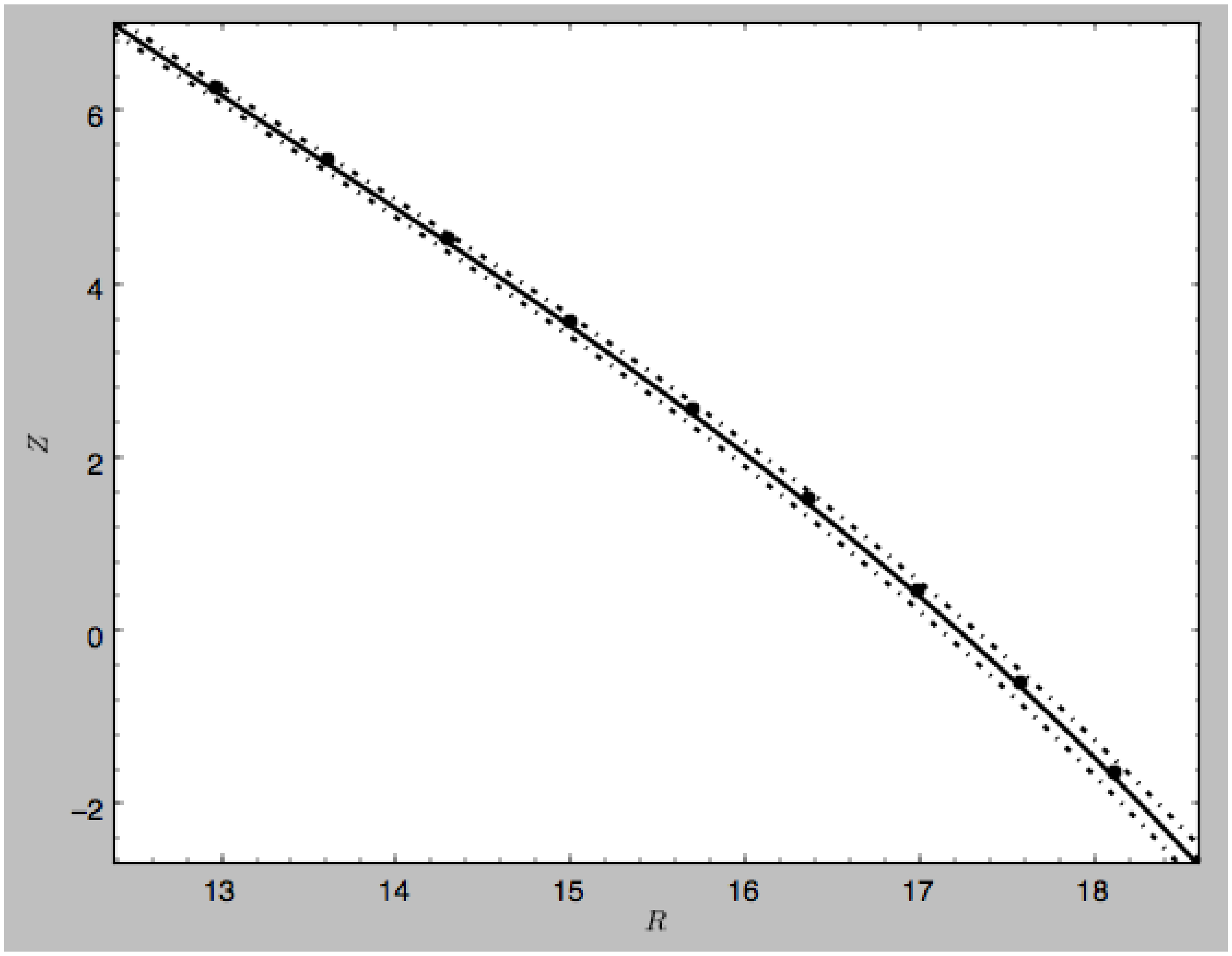
which gives



which shows the track in Galactocentric *R* and *Z* coordinates as well as an estimate of the spread around the track as the dash-dotted line. We can overplot the points along the track along which the $(\mathbf{x}, \mathbf{v}) \rightarrow (\mathbf{\Omega}, \boldsymbol{\theta})$ transformation and the track position is explicitly calculated, by turning off the interpolation

```
>>> sdf.plotTrack(d1='r',d2='z',interp=False,color='k',spread=0,overplot=True,ls='none
↪',marker='o',scaleToPhysical=True)
```

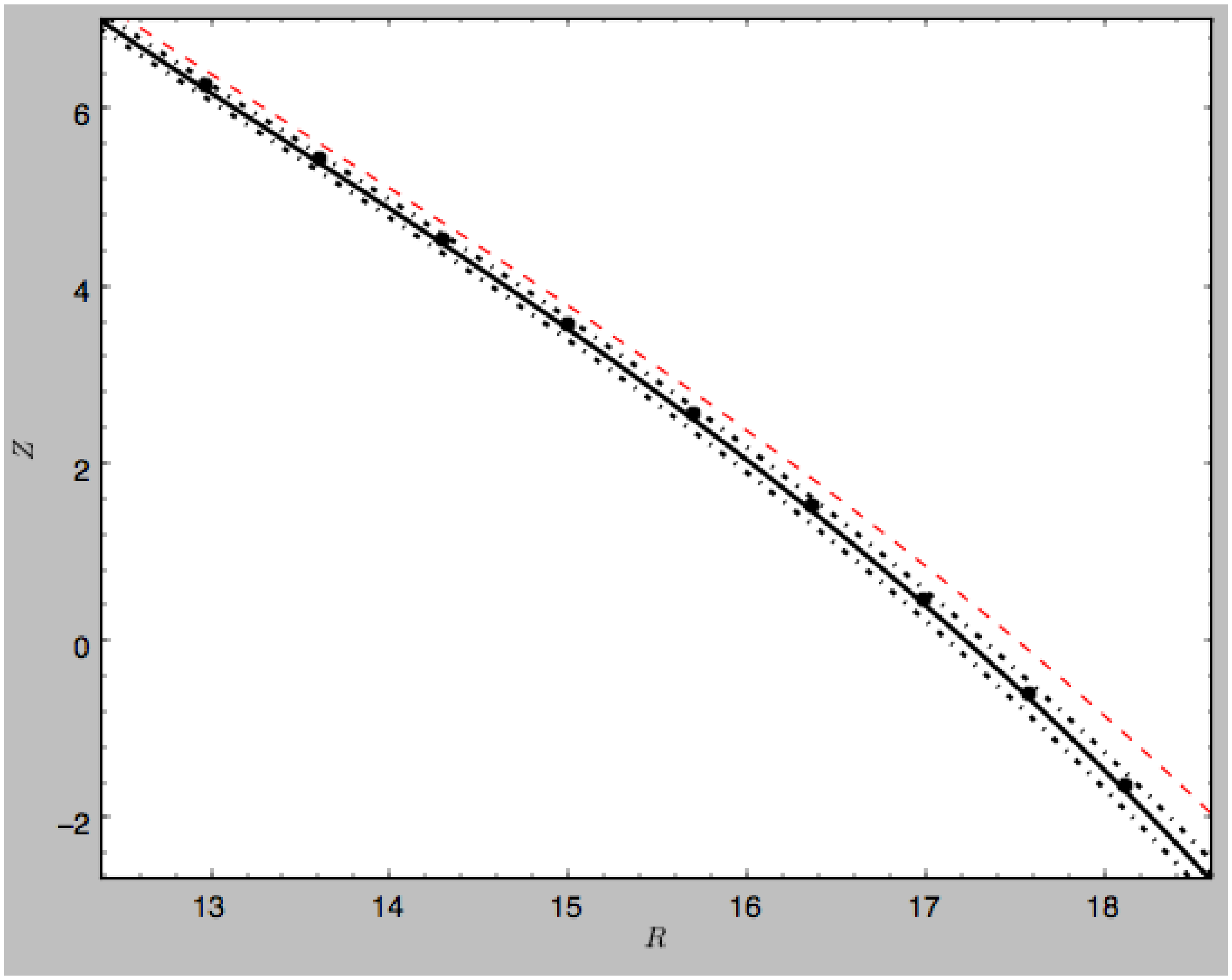
which gives



We can also overplot the orbit of the progenitor

```
>>> sdf.plotProgenitor(d1='r',d2='z',color='r',overplot=True,ls='--',
↪scaleToPhysical=True)
```

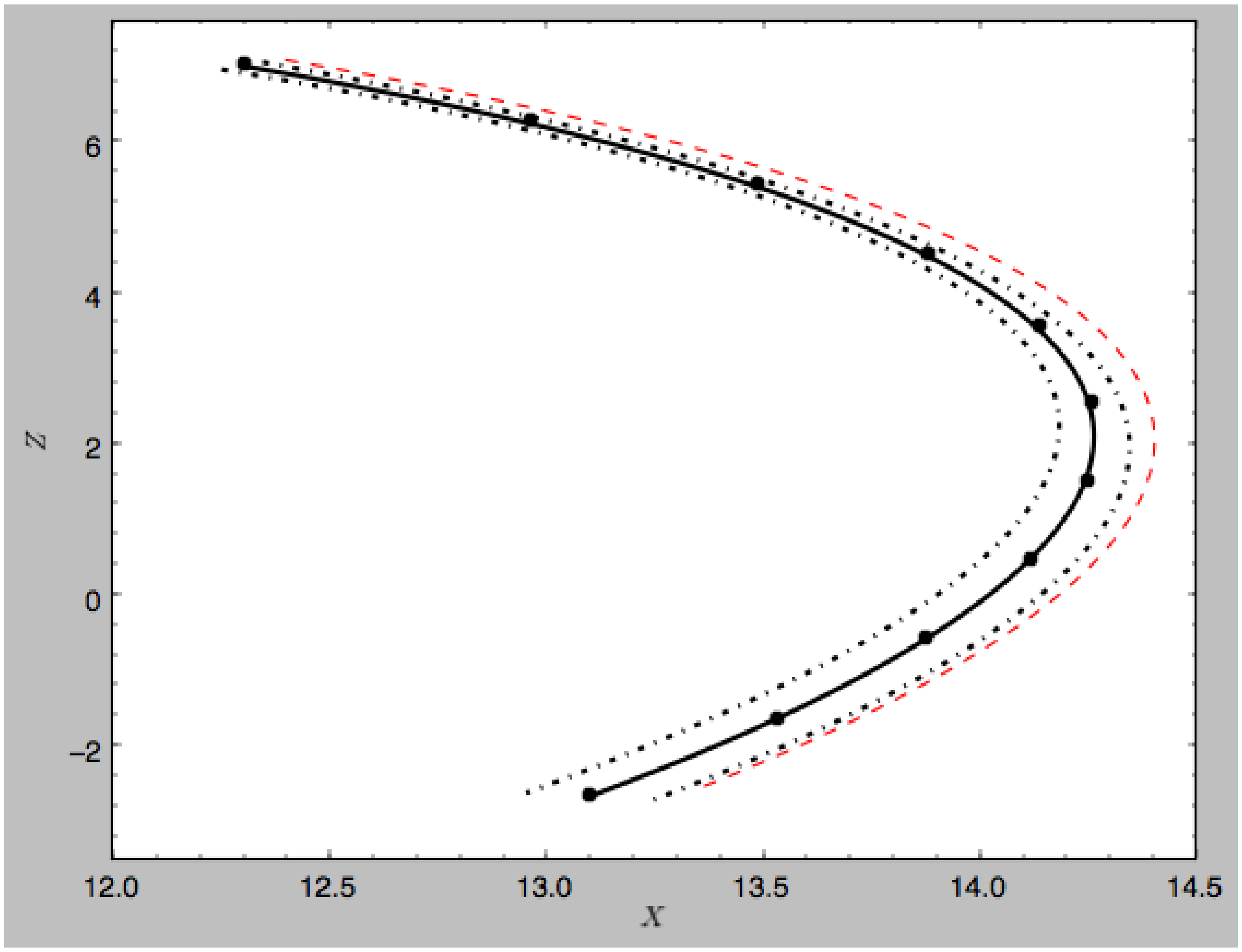
to give



We can do the same in other coordinate systems, for example *X* and *Z* (as in Figure 1 of Bovy 2014)

```
>>> sdf.plotTrack(d1='x',d2='z',interp=True,color='k',spread=2,overplot=False,lw=2.,
↪scaleToPhysical=True)
>>> sdf.plotTrack(d1='x',d2='z',interp=False,color='k',spread=0,overplot=True,ls='none
↪',marker='o',scaleToPhysical=True)
>>> sdf.plotProgenitor(d1='x',d2='z',color='r',overplot=True,ls='--',
↪scaleToPhysical=True)
>>> xlim(12.,14.5); ylim(-3.5,7.6)
```

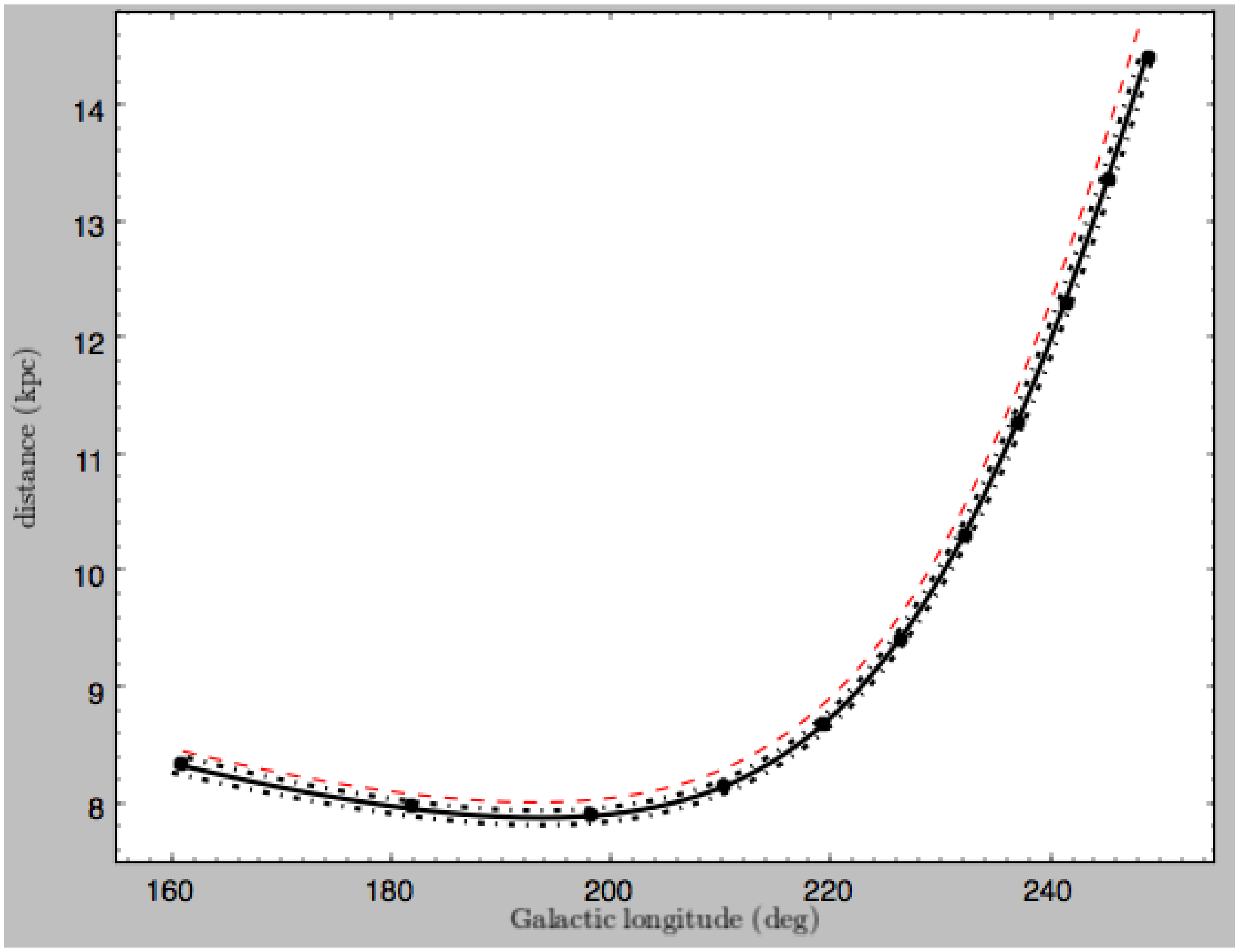
which gives



or we can calculate the track in observable coordinates, e.g.,

```
>>> sdf.plotTrack(d1='ll',d2='dist',interp=True,color='k',spread=2,overplot=False,
↪lw=2.)
>>> sdf.plotTrack(d1='ll',d2='dist',interp=False,color='k',spread=0,overplot=True,ls=
↪'none',marker='o')
>>> sdf.plotProgenitor(d1='ll',d2='dist',color='r',overplot=True,ls='--')
>>> xlim(155.,255.); ylim(7.5,14.8)
```

which displays



Coordinate transformations to physical coordinates are done using parameters set when initializing the `sdf` instance. See the help for `?streamdf` for a complete list of initialization parameters.

2.1.3 Mock stream data generation

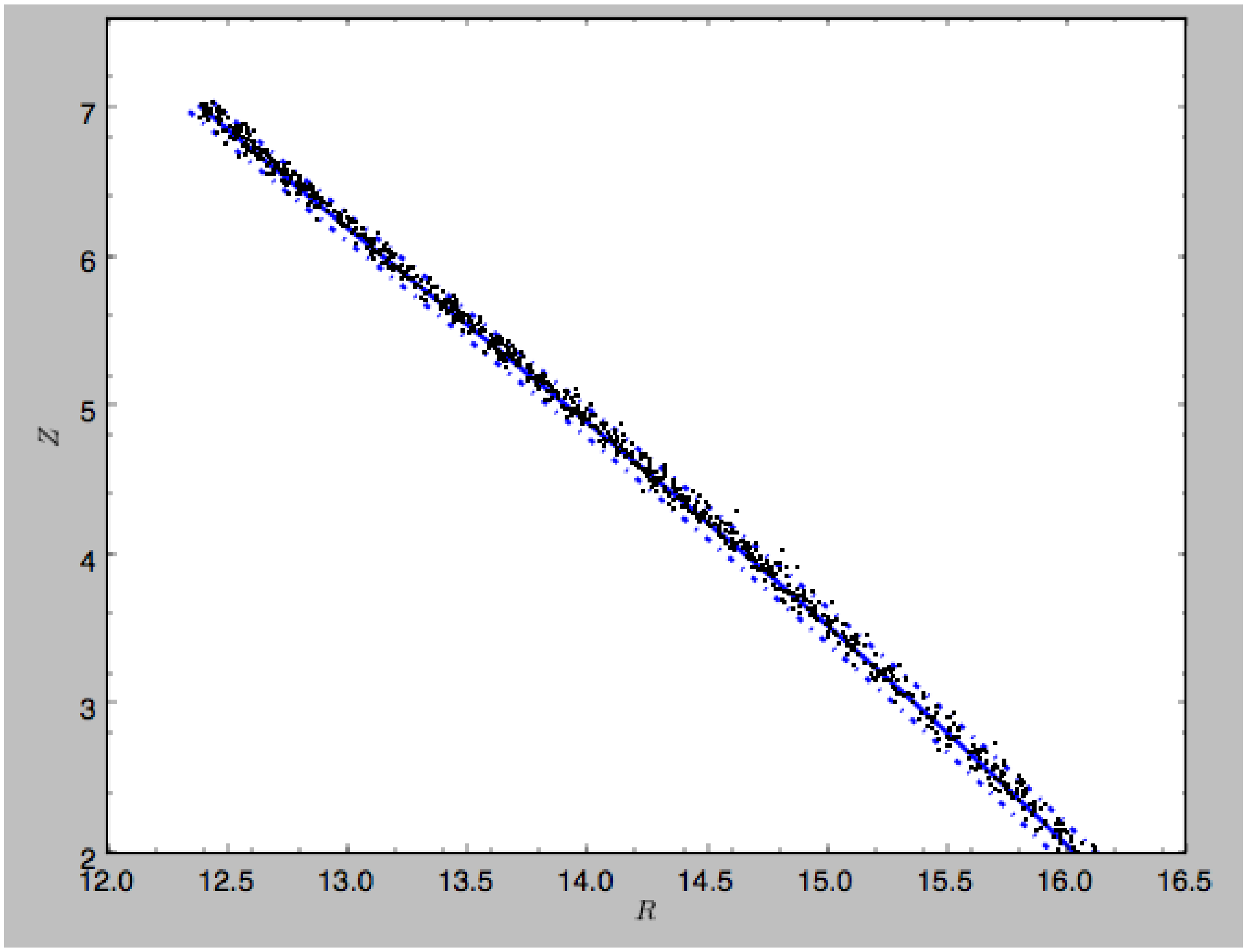
We can also easily generate mock data from the stream model. This uses `streamdf.sample`. For example,

```
>>> RvR= sdf.sample(n=1000)
```

which returns the sampled points as a set $(R, v_R, v_T, Z, v_Z, \phi)$ in natural galpy coordinates. We can plot these and compare them to the track location

```
>>> sdf.plotTrack(d1='r',d2='z',interp=True,color='b',spread=2,overplot=False,lw=2.,
↪scaleToPhysical=True)
>>> plot(RvR[0]*8.,RvR[3]*8.,'k.',ms=2.) #multiply by the physical distance scale
>>> xlim(12.,16.5); ylim(2.,7.6)
```

which gives



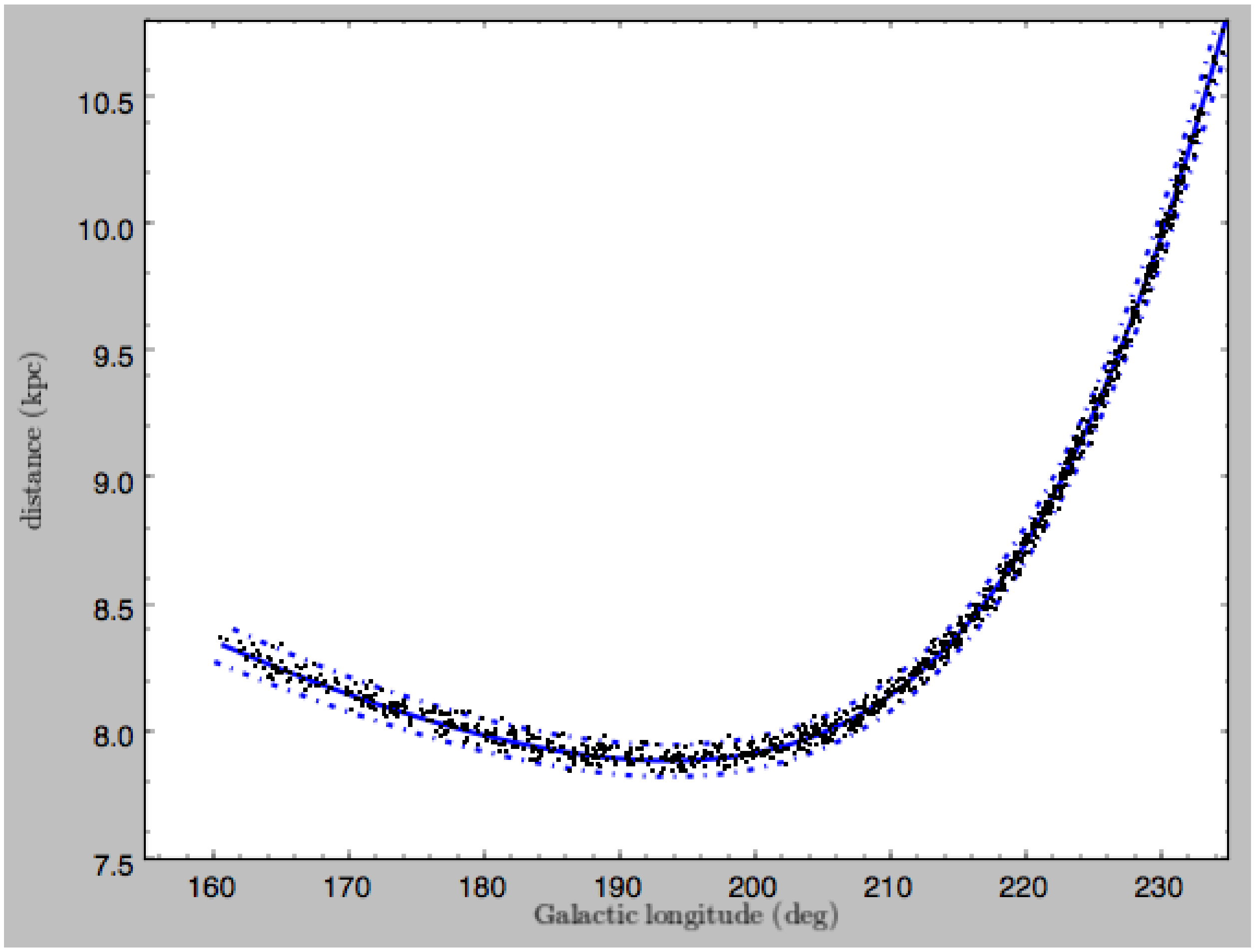
Similarly, we can generate mock data in observable coordinates

```
>>> lb= sdf.sample(n=1000,lb=True)
```

and plot it

```
>>> sdf.plotTrack(d1='ll',d2='dist',interp=True,color='b',spread=2,overplot=False,
↪lw=2.)
>>> plot(lb[0],lb[2],'k.',ms=2.)
>>> xlim(155.,235.); ylim(7.5,10.8)
```

which displays

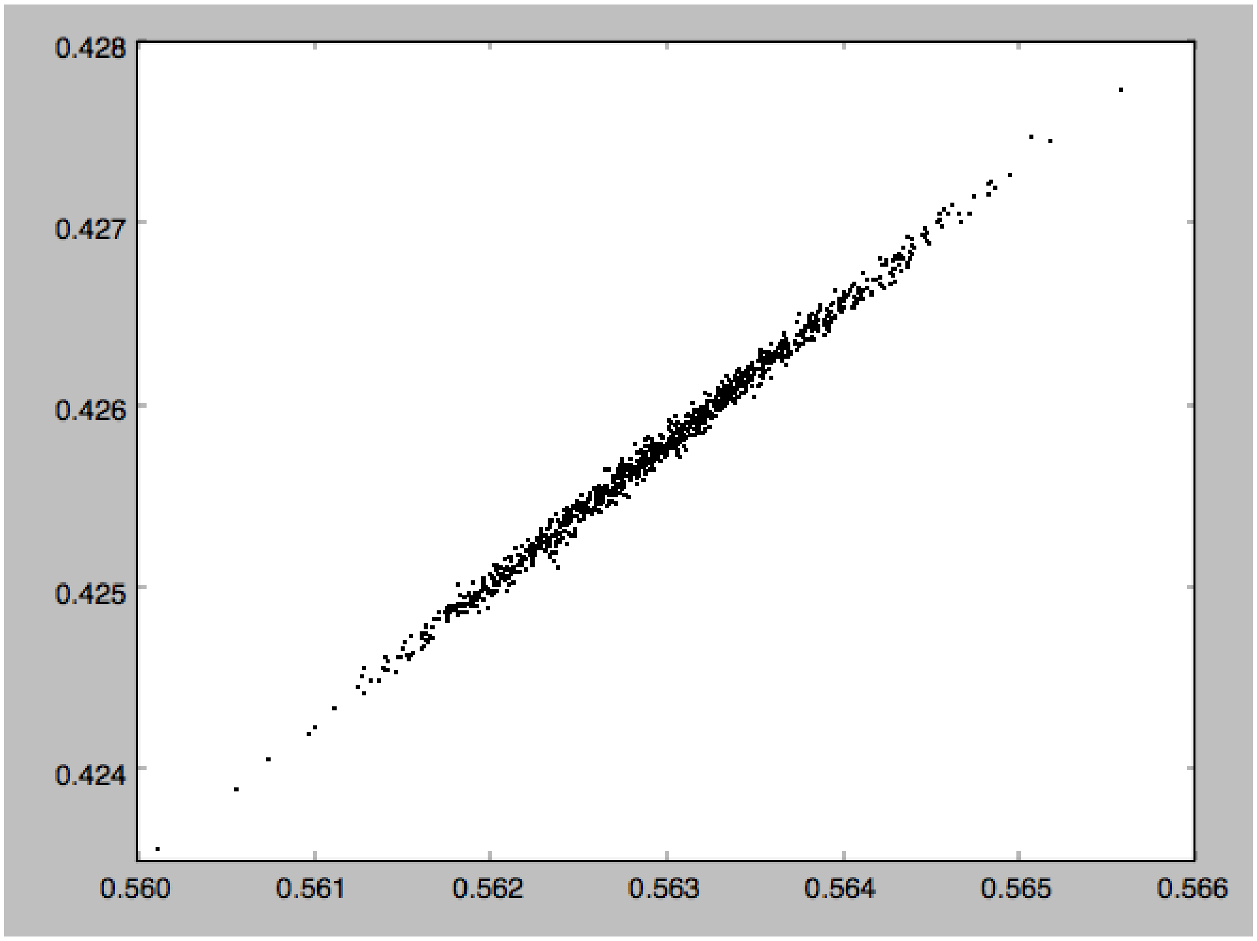


We can also just generate mock stream data in frequency-angle coordinates

```
>>> mockaA= sdf.sample(n=1000,returnaAdt=True)
```

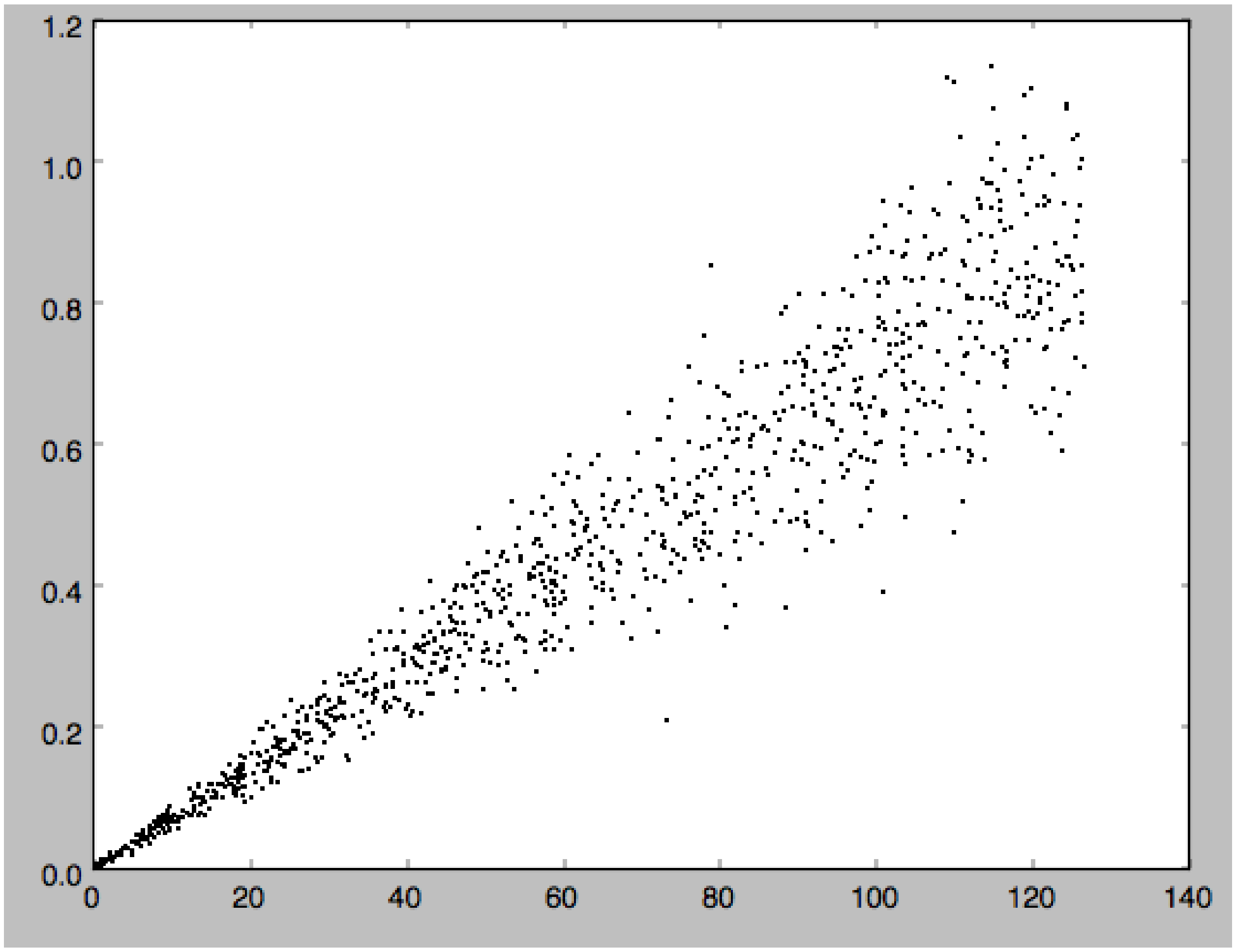
which returns a tuple with three components: an array with shape [3,N] of frequency vectors $(\Omega_R, \Omega_\phi, \Omega_Z)$, an array with shape [3,N] of angle vectors $(\theta_R, \theta_\phi, \theta_Z)$ and t_s, the stripping time. We can plot the vertical versus the radial frequency

```
>>> plot(mockaA[0][0],mockaA[0][2],'k.',ms=2.)
```



or we can plot the magnitude of the angle offset as a function of stripping time

```
>>> plot(mockaA[2],numpy.sqrt(numpy.sum((mockaA[1]-numpy.tile(sdf._progenitor_angle,
↪(1000,1)).T)**2.,axis=0)),'k.',ms=2.)
```



2.1.4 Evaluating and marginalizing the full PDF

We can also evaluate the stream PDF, the probability of a $(\mathbf{x},\mathbf{v})$ phase-space position in the stream. We can evaluate the PDF, for example, at the location of the progenitor

```
>>> sdf(obs.R(),obs.vR(),obs.vT(),obs.z(),obs.vz(),obs.phi())
array([-33.16985861])
```

which returns the natural log of the PDF. If we go to slightly higher in Z and slightly smaller in R, the PDF becomes zero

```
>>> sdf(obs.R()-0.1,obs.vR(),obs.vT(),obs.z()+0.1,obs.vz(),obs.phi())
array([-inf])
```

because this phase-space position cannot be reached by a leading stream star. We can also marginalize the PDF over unobserved directions. For example, similar to Figure 10 in Bovy (2014), we can evaluate the PDF $p(X|Z)$ near a point on the track, say near Z =2 kpc (=0.25 in natural units. We first find the approximate Gaussian PDF near this point, calculated from the stream track and dispersion (see above)

```
>>> meanp, varp= sdf.gaussApprox([None,None,2./8.,None,None,None])
```

where the input is a array with entries [X,Y,Z,vX,vY,vZ] and we substitute None for directions that we want to establish the approximate PDF for. So the above expression returns an approximation to $p(X,Y,v_X,v_Y,v_Z|Z)$. This approximation allows us to get a sense of where the PDF peaks and what its width is

```
>>> meanp[0]*8.
14.267559400127833
>>> numpy.sqrt(varp[0,0])*8.
0.04152968631186698
```

We can now evaluate the PDF $p(X|Z)$ as a function of X near the peak

```
>>> xs= numpy.linspace(-3.*numpy.sqrt(varp[0,0]),3.*numpy.sqrt(varp[0,0]),21)+meanp[0]
>>> logps= numpy.array([sdf.callMarg([x,None,2./8.,None,None,None]) for x in xs])
>>> ps= numpy.exp(logps)
```

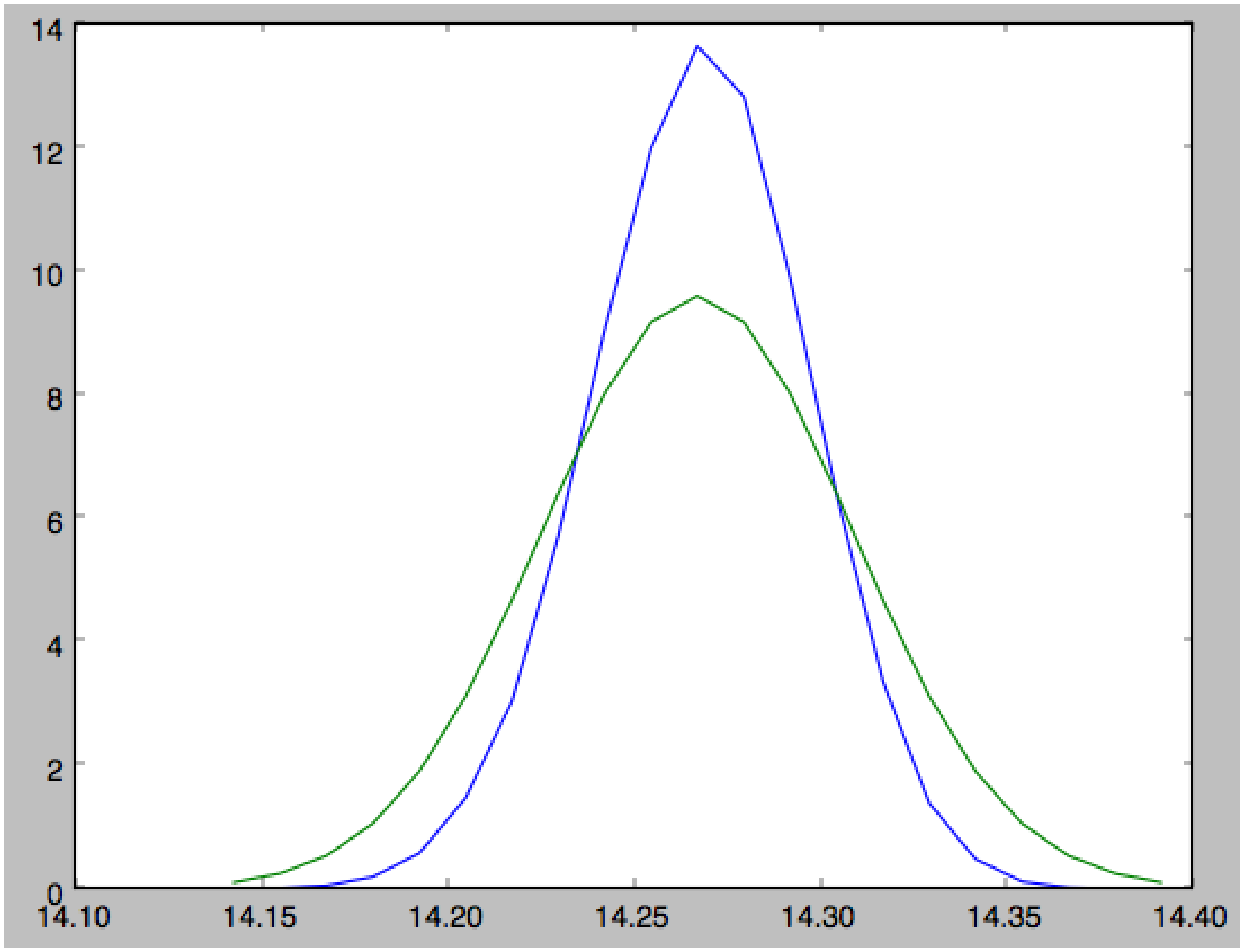
and we normalize the PDF

```
>>> ps/= numpy.sum(ps)*(xs[1]-xs[0])*8.
```

and plot it together with the Gaussian approximation

```
>>> plot(xs*8.,ps)
>>> plot(xs*8.,1./numpy.sqrt(2.*numpy.pi)/numpy.sqrt(varp[0,0])/8.*numpy.exp(-0.5*(xs-
↪meanp[0])**2./varp[0,0]))
```

which gives



Sometimes it is hard to automatically determine the closest point on the calculated track if only one phase-space coordinate is given. For example, this happens when evaluating $p(Z|X)$ for X > 13 kpc here, where there are two branches of the track in Z (see the figure of the track above). In that case, we can determine the closest track point on one of the branches by hand and then provide this closest point as the basis of PDF calculations. The following example shows how this is done for the upper Z branch at X = 13.5 kpc, which is near Z =5 kpc (Figure 10 in Bovy 2014).

```
>>> cindx= sdf.find_closest_trackpoint(13.5/8.,None,5.32/8.,None,None,None,xy=True)
```

gives the index of the closest point on the calculated track. This index can then be given as an argument for the PDF functions:

```
>>> meanp, varp= meanp, varp= sdf.gaussApprox([13.5/8.,None,None,None,None,None],
↪cindx=cindx)
```

computes the approximate $p(Y, Z, v_X, v_Y, v_Z|X)$ near the upper Z branch. In Z, this PDF has mean and dispersion

```
>>> meanp[1]*8.
5.4005530328542077
>>> numpy.sqrt(varp[1,1])*8.
0.05796023309510244
```

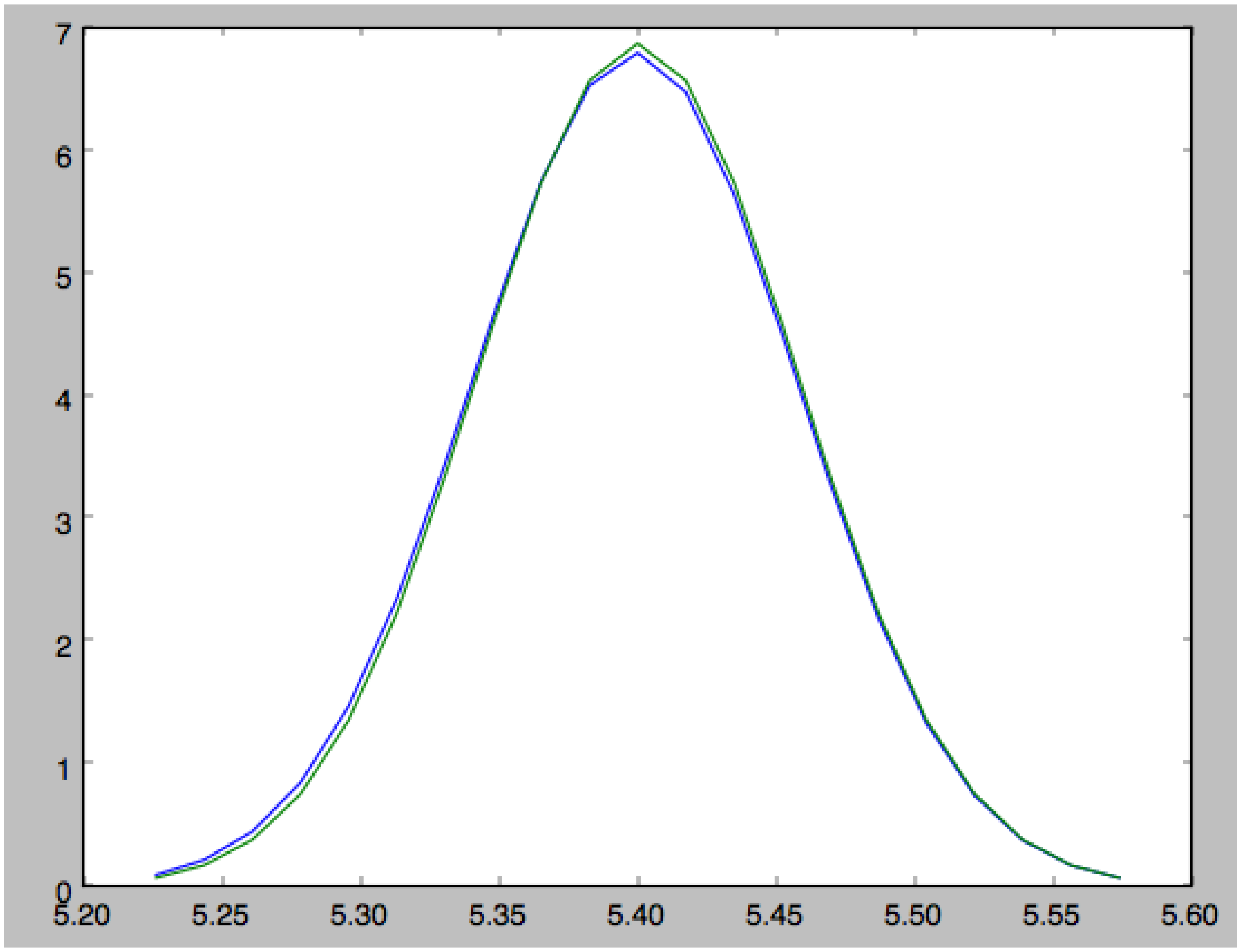
We can then evaluate $p(Z|X)$ for the upper branch as

```
>>> zs= numpy.linspace(-3.*numpy.sqrt(varp[1,1]),3.*numpy.sqrt(varp[1,1]),21)+meanp[1]
>>> logps= numpy.array([sdf.callMarg([13.5/8.,None,z,None,None,None],cindx=cindx) for␣
↪z in zs])
>>> ps= numpy.exp(logps)
>>> ps/= numpy.sum(ps)*(zs[1]-zs[0])*8.
```

and we can again plot this and the approximation

```
>>> plot(zs*8.,ps)
>>> plot(zs*8.,1./numpy.sqrt(2.*numpy.pi)/numpy.sqrt(varp[1,1])/8.*numpy.exp(-0.5*(zs-
↪meanp[1])**2./varp[1,1]))
```

which gives



The approximate PDF in this case is very close to the correct PDF. When supplying the closest track point, care needs to be taken that this really is the closest track point. Otherwise the approximate PDF will not be quite correct.

CHAPTER 3

Library reference

3.1 Orbit

See *Orbit initialization* for a detailed explanation on how to set up Orbit instances.

3.1.1 Class

galpy.orbit.Orbit

3.1.2 Methods

galpy.orbit.Orbit.__add__

galpy.orbit.Orbit.__call__

galpy.orbit.Orbit.bb

galpy.orbit.Orbit.dec

galpy.orbit.Orbit.dist

galpy.orbit.Orbit.E

galpy.orbit.Orbit.e

galpy.orbit.Orbit.ER

galpy.orbit.Orbit.Ez

galpy.orbit.Orbit.fit

galpy.orbit.Orbit.flip

galpy.orbit.Orbit.integrate

galpy.orbit.Orbit.integrate_dxdv

Currently only supported for `planarOrbit` instances.

galpy.orbit.Orbit.getOrbit

galpy.orbit.Orbit.getOrbit_dxdv

`integrate_dxdv` is currently only supported for `planarOrbit` instances. `getOrbit_dxdv` is therefore also only supported for those types of `Orbit`.

galpy.orbit.Orbit.helioX

galpy.orbit.Orbit.helioY

galpy.orbit.Orbit.helioZ

galpy.orbit.Orbit.Jacobi

galpy.orbit.Orbit.jp

galpy.orbit.Orbit.jr

galpy.orbit.Orbit.jz

galpy.orbit.Orbit.ll

galpy.orbit.Orbit.L

galpy.orbit.Orbit.Op

galpy.orbit.Orbit.Or

galpy.orbit.Orbit.Oz

galpy.orbit.Orbit.phi

galpy.orbit.Orbit.plot

galpy.orbit.Orbit.plot3d

galpy.orbit.Orbit.plotE

galpy.orbit.Orbit.plotER

galpy.orbit.Orbit.plotEz

galpy.orbit.Orbit.plotEzJz

galpy.orbit.Orbit.plotphi

galpy.orbit.Orbit.plotR

galpy.orbit.Orbit.plotvR

galpy.orbit.Orbit.plotvT

galpy.orbit.Orbit.plotvx

galpy.orbit.Orbit.plotvy

galpy.orbit.Orbit.plotvz

galpy.orbit.Orbit.plotx

galpy.orbit.Orbit.ploty

galpy.orbit.Orbit.plotz

galpy.orbit.Orbit.pmbb

galpy.orbit.Orbit.pmdec

galpy.orbit.Orbit.pmll

galpy.orbit.Orbit.pmra

galpy.orbit.Orbit.R

galpy.orbit.Orbit.ra

galpy.orbit.Orbit.rap

galpy.orbit.Orbit.resetaA

galpy.orbit.Orbit.rperi

galpy.orbit.Orbit.setphi

galpy.orbit.Orbit.time

galpy.orbit.Orbit.toLinear

galpy.orbit.Orbit.toPlanar

galpy.orbit.Orbit.Tp

galpy.orbit.Orbit.Tr

galpy.orbit.Orbit.TrTp

galpy.orbit.Orbit.turn_physical_off

galpy.orbit.Orbit.Tz

galpy.orbit.Orbit.U

galpy.orbit.Orbit.V

galpy.orbit.Orbit.vbb

galpy.orbit.Orbit.vdec

galpy.orbit.Orbit.vll

galpy.orbit.Orbit.vlos

galpy.orbit.Orbit.vphi

galpy.orbit.Orbit.vR

galpy.orbit.Orbit.vra

galpy.orbit.Orbit.vT

galpy.orbit.Orbit.vx

galpy.orbit.Orbit.vy

galpy.orbit.Orbit.vz

galpy.orbit.Orbit.W

galpy.orbit.Orbit.wp

galpy.orbit.Orbit.wr

galpy.orbit.Orbit.wz

galpy.orbit.Orbit.x

galpy.orbit.Orbit.y

galpy.orbit.Orbit.z

galpy.orbit.Orbit.zmax

3.2 Potential

3.2.1 3D potentials

General instance routines

Use as `Potential-instance.method(...)`

galpy.potential.Potential.__call__

`Potential.__call__`(*R*, *z*, *phi=0.0*, *t=0.0*, *dR=0*, *dphi=0*)

NAME: __call__

PURPOSE: evaluate the potential at (R,z,phi,t)

INPUT: R - Cylindrical Galactocentric radius

z - vertical height

phi - azimuth (optional)

t - time (optional)

dR= dphi=, if set to non-zero integers, return the dR, dphi't derivative instead

OUTPUT: Phi(R,z,t)

HISTORY: 2010-04-16 - Written - Bovy (NYU)

galpy.potential.Potential.dens

`Potential.dens`(*R*, *z*, *phi=0.0*, *t=0.0*, *forcepoisson=False*)

NAME:

dens

PURPOSE:

evaluate the density rho(R,z,t)

INPUT:

R - Cylindrical Galactocentric radius

z - vertical height

phi - azimuth (optional)

t - time (optional)

KEYWORDS:

forcepoisson= if True, calculate the density through the Poisson equation, even if an explicit expression for the density exists

OUTPUT:

rho (R,z,phi,t)

HISTORY:

2010-08-08 - Written - Bovy (NYU)

galpy.potential.Potential.dvcircdR

Potential.**dvcircdR**(*R*)

NAME:

dvcircdR

PURPOSE:

calculate the derivative of the circular velocity at R wrt R in this potential

INPUT:

R - Galactocentric radius

OUTPUT:

derivative of the circular rotation velocity wrt R

HISTORY:

2013-01-08 - Written - Bovy (IAS)

galpy.potential.Potential.epifreq

Potential.**epifreq**(*R*)

NAME:

epifreq

PURPOSE:

calculate the epicycle frequency at R in this potential

INPUT:

R - Galactocentric radius

OUTPUT:

epicycle frequency

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.Potential.flattening

Potential.**flattening**(*R*, *z*)

NAME:

flattening

PURPOSE:

calculate the potential flattening, defined as sqrt(**|z/R F_R/F_z|**)

INPUT:

R - Galactocentric radius

z - height

OUTPUT:

flattening

HISTORY:

2012-09-13 - Written - Bovy (IAS)

galpy.potential.Potential.lindbladR

`Potential.`**`lindbladR`**(*OmegaP*, *m=2*, ***kwargs*)

NAME:

lindbladR

PURPOSE:

calculate the radius of a Lindblad resonance

INPUT:

OmegaP - pattern speed

m= order of the resonance (as in m(O-Op)=kappa (negative m for outer) use m='corotation' for corotation +scipy.optimize.brentq xtol,rtol,maxiter kwargs

OUTPUT:

radius of Linblad resonance, None if there is no resonance

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.Potential.mass

`Potential.`**`mass`**(*R*, *z=None*, *t=0.0*, *forceint=False*)

NAME:

mass

PURPOSE:

evaluate the mass enclosed

INPUT:

R - Cylindrical Galactocentric radius

z= (None) vertical height

t - time (optional)

KEYWORDS:

forceint= if True, calculate the mass through integration of the density, even if an explicit expression for the mass exists

OUTPUT:

1) for spherical potentials: M(<R) [or if z is None], when the mass is implemented explicitly, the mass enclosed within r = sqrt(R^2+z^2) is returned when not z is None; forceint will integrate between -z and z, so the two are inconsistent (If you care to have this changed, raise an issue on github)

2) for axisymmetric potentials: M(<R,<|Z|)

HISTORY:

2014-01-29 - Written - Bovy (IAS)

galpy.potential.Potential.nemo_accname

`Potential.`**`nemo_accname`**`()`

NAME:

nemo_accname

PURPOSE:

return the accname potential name for use of this potential with NEMO

INPUT:

(none)

OUTPUT:

Acceleration name

HISTORY:

2014-12-18 - Written - Bovy (IAS)

galpy.potential.Potential.nemo_accpars

`Potential.`**`nemo_accpars`**`(`*vo*, *ro*`)`

NAME:

nemo_accpars

PURPOSE:

return the accpars potential parameters for use of this potential with NEMO

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

accpars string

HISTORY:

2014-12-18 - Written - Bovy (IAS)

galpy.potential.Potential.omegac

`Potential.`**`omegac`**`(`*R*`)`

NAME:

omegac

PURPOSE:

calculate the circular angular speed at R in this potential

INPUT:

R - Galactocentric radius

OUTPUT:

circular angular speed

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.Potential.phiforce

`Potential.phiforce(R, z, phi=0.0, t=0.0)`

NAME:

phiforce

PURPOSE:

evaluate the azimuthal force F_phi (R,z,phi,t)

INPUT:

R - Cylindrical Galactocentric radius

z - vertical height

phi - azimuth (rad)

t - time (optional)

OUTPUT:

F_phi (R,z,phi,t)

HISTORY:

2010-07-10 - Written - Bovy (NYU)

galpy.potential.Potential.phi2deriv

`Potential.phi2deriv(R, Z, phi=0.0, t=0.0)`

NAME:

phi2deriv

PURPOSE:

evaluate the second azimuthal derivative

INPUT:

R - Galactocentric radius

Z - vertical height

phi - Galactocentric azimuth

t - time

OUTPUT:

d2Phi/dphi2

HISTORY:

2013-09-24 - Written - Bovy (IAS)

galpy.potential.Potential.plot

Potential.**plot**(*t=0.0*, *rmin=0.0*, *rmax=1.5*, *nrs=21*, *zmin=-0.5*, *zmax=0.5*, *nzs=21*, *effective=False*, *Lz=None*, *xrange=None*, *yrange=None*, *justcontours=False*, *ncontours=21*, *savefilename=None*)

NAME:

plot

PURPOSE:

plot the potential

INPUT:

t= time tp plot potential at

rmin= minimum R at which to calculate

rmax= maximum R

nrs= grid in R

zmin= minimum z

zmax= maximum z

nzs= grid in z

effective= (False) if True, plot the effective potential Phi + Lz^2/2/R^2

Lz= (None) angular momentum to use for the effective potential when effective=True

ncontours - number of contours

justcontours= (False) if True, just plot contours

savefilename - save to or restore from this savefile (pickle)

xrange, yrange= can be specified independently from rmin,zmin, etc.

OUTPUT:

plot to output device

HISTORY:

2010-07-09 - Written - Bovy (NYU)

2014-04-08 - Added effective= - Bovy (IAS)

galpy.potential.Potential.plotDensity

Potential.**plotDensity**(*rmin=0.0*, *rmax=1.5*, *nrs=21*, *zmin=-0.5*, *zmax=0.5*, *nzs=21*, *ncontours=21*, *savefilename=None*, *aspect=None*, *log=False*, *justcontours=False*)

NAME: plotDensity

PURPOSE: plot the density of this potential

INPUT:

rmin= minimum R

rmax= maximum R

nrs= grid in R

zmin= minimum z

zmax= maximum z

nzs= grid in z

ncontours= number of contours

justcontours= (False) if True, just plot contours

savefilename= save to or restore from this savefile (pickle)

log= if True, plot the log density

OUTPUT: plot to output device

HISTORY: 2014-01-05 - Written - Bovy (IAS)

galpy.potential.Potential.plotEscapecurve

`Potential.`**`plotEscapecurve`**`(`**args*, ***kwargs*`)`

NAME:

plotEscapecurve

PURPOSE:

plot the escape velocity curve for this potential (in the z=0 plane for non-spherical potentials)

INPUT:

Rrange - range

grid= number of points to plot

savefilename= save to or restore from this savefile (pickle)

+bovy_plot(*args,**kwargs)

OUTPUT:

plot to output device

HISTORY:

2010-08-08 - Written - Bovy (NYU)

galpy.potential.Potential.plotRotcurve

`Potential.`**`plotRotcurve`**`(`**args*, ***kwargs*`)`

NAME:

plotRotcurve

PURPOSE:

plot the rotation curve for this potential (in the z=0 plane for non-spherical potentials)

INPUT:

Rrange - range

grid= number of points to plot

savefilename=- save to or restore from this savefile (pickle)

+bovy_plot(*args,**kwargs)

OUTPUT:

plot to output device

HISTORY:

2010-07-10 - Written - Bovy (NYU)

galpy.potential.Potential.R2deriv

`Potential.R2deriv(R, Z, phi=0.0, t=0.0)`

NAME:

R2deriv

PURPOSE:

evaluate the second radial derivative

INPUT:

R - Galactocentric radius

Z - vertical height

phi - Galactocentric azimuth

t - time

OUTPUT:

d2phi/dR2

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.Potential.Rzderiv

`Potential.Rzderiv(R, Z, phi=0.0, t=0.0)`

NAME:

Rzderiv

PURPOSE:

evaluate the mixed R,z derivative

INPUT:

R - Galactocentric radius

Z - vertical height

phi - Galactocentric azimuth

t - time

OUTPUT:

d2phi/dz/dR

HISTORY:

2013-08-26 - Written - Bovy (IAS)

galpy.potential.Potential.Rforce

`Potential.`**`Rforce`**(*R*, *z*, *phi=0.0*, *t=0.0*)

NAME:

Rforce

PURPOSE:

evaluate radial force F_R (R,z)

INPUT:

R - Cylindrical Galactocentric radius

z - vertical height

phi - azimuth (optional)

t - time (optional)

OUTPUT:

F_R (R,z,phi,t)

HISTORY:

2010-04-16 - Written - Bovy (NYU)

galpy.potential.Potential.rl

`Potential.`**`rl`**(*lz*)

NAME:

rl

PURPOSE:

calculate the radius of a circular orbit of Lz

INPUT:

lz - Angular momentum

OUTPUT:

radius

HISTORY:

2012-07-30 - Written - Bovy (IAS@MPIA)

NOTE:

seems to take about ~0.5 ms for a Miyamoto-Nagai potential; ~0.75 ms for a MWPotential

galpy.planar.Potential.toPlanar

`Potential.toPlanar()`

NAME: toPlanar

PURPOSE: convert a 3D potential into a planar potential in the mid-plane

INPUT: (none)

OUTPUT: planarPotential

HISTORY

galpy.potential.Potential.toVertical

`Potential.toVertical(R)`

NAME: toVertical

PURPOSE: convert a 3D potential into a linear (vertical) potential at R

INPUT: R - Galactocentric radius at which to create the vertical potential

OUTPUT: linear (vertical) potential

HISTORY

galpy.potential.Potential.vcirc

`Potential.vcirc(R)`

NAME:

vcirc

PURPOSE:

calculate the circular velocity at R in this potential

INPUT:

R - Galactocentric radius

OUTPUT:

circular rotation velocity

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.Potential.verticalfreq

`Potential.verticalfreq(R)`

NAME:

verticalfreq

PURPOSE:

calculate the vertical frequency at R in this potential

INPUT:

R - Galactocentric radius

OUTPUT:

vertical frequency

HISTORY:

2012-07-25 - Written - Bovy (IAS@MPIA)

galpy.potential.Potential.vesc

`Potential.`**`vesc`**`(`*R*`)`

NAME:

vesc

PURPOSE:

calculate the escape velocity at R for this potential

INPUT:

R - Galactocentric radius

OUTPUT:

escape velocity

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.Potential.vterm

`Potential.`**`vterm`**`(`*l*, *deg=True*`)`

NAME:

vterm

PURPOSE:

calculate the terminal velocity at l in this potential

INPUT:

l - Galactic longitude [deg/rad]

deg= if True (default), l in deg

OUTPUT:

terminal velocity

HISTORY:

2013-05-31 - Written - Bovy (IAS)

galpy.potential.Potential.z2deriv

`Potential.`**`z2deriv`**(*R*, *Z*, *phi=0.0*, *t=0.0*)

NAME:

z2deriv

PURPOSE:

evaluate the second vertical derivative

INPUT:

R - Galactocentric radius

Z - vertical height

phi - Galactocentric azimuth

t - time

OUTPUT:

d2phi/dz2

HISTORY:

2012-07-25 - Written - Bovy (IAS@MPIA)

galpy.potential.Potential.zforce

`Potential.`**`zforce`**(*R*, *z*, *phi=0.0*, *t=0.0*)

NAME:

zforce

PURPOSE:

evaluate the vertical force F_z (R,z,t)

INPUT:

R - Cylindrical Galactocentric radius

z - vertical height

phi - azimuth (optional)

t - time (optional)

OUTPUT:

F_z (R,z,phi,t)

HISTORY:

2010-04-16 - Written - Bovy (NYU)

In addition to these, the `NFWPotential` also has methods to calculate virial quantities

galpy.potential.Potential.conc

`Potential.conc`(*vo*, *ro*, *H=70.0*, *Om=0.3*, *overdens=200.0*, *wrtcrit=False*)

NAME:

conc

PURPOSE:

return the concentration

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

H= (default: 70) Hubble constant in km/s/Mpc

Om= (default: 0.3) Omega matter

overdens= (200) overdensity which defines the virial radius

wrtcrit= (False) if True, the overdensity is wrt the critical density rather than the mean matter density

OUTPUT:

concentration (scale/rvir)

HISTORY:

2014-04-03 - Written - Bovy (IAS)

galpy.potential.Potential.mvir

`Potential.mvir`(*vo*, *ro*, *H=70.0*, *Om=0.3*, *overdens=200.0*, *wrtcrit=False*, *forceint=False*)

NAME:

mvir

PURPOSE:

calculate the virial mass

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

H= (default: 70) Hubble constant in km/s/Mpc

Om= (default: 0.3) Omega matter

overdens= (200) overdensity which defines the virial radius

wrtcrit= (False) if True, the overdensity is wrt the critical density rather than the mean matter density

KEYWORDS:

forceint= if True, calculate the mass through integration of the density, even if an explicit expression for the mass exists

OUTPUT:

M(<rvir)

HISTORY:

2014-09-12 - Written - Bovy (IAS)

galpy.potential.NFWPotential.rvir

`NFWPotential.`**`rvir`**(*vo*, *ro*, *H=70.0*, *Om=0.3*, *overdens=200.0*, *wrtcrit=False*)

NAME:

rvir

PURPOSE:

calculate the virial radius for this density distribution

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

H= (default: 70) Hubble constant in km/s/Mpc

Om= (default: 0.3) Omega matter

overdens= (200) overdensity which defines the virial radius

wrtcrit= (False) if True, the overdensity is wrt the critical density rather than the mean matter density

OUTPUT:

virial radius in natural units

HISTORY:

2014-01-29 - Written - Bovy (IAS)

General 3D potential routines

Use as `method(...)`

galpy.potential.dvcircdR

`galpy.potential.`**`dvcircdR`**(*Pot*, *R*)

NAME:

dvcircdR

PURPOSE:

calculate the derivative of the circular velocity wrt R at R in potential Pot

INPUT:

Pot - Potential instance or list of such instances

R - Galactocentric radius

OUTPUT:

derivative of the circular rotation velocity wrt R

HISTORY:

2013-01-08 - Written - Bovy (IAS)

galpy.potential.epifreq

galpy.potential.**epifreq**(*Pot*, *R*)

NAME:

epifreq

PURPOSE:

calculate the epicycle frequency at R in the potential Pot

INPUT:

Pot - Potential instance or list thereof

R - Galactocentric radius

OUTPUT:

epicycle frequency

HISTORY:

2012-07-25 - Written - Bovy (IAS)

galpy.potential.evaluateDensities

galpy.potential.**evaluateDensities**(*R*, *z*, *Pot*, *phi=0.0*, *t=0.0*, *forcepoisson=False*)

NAME:

evaluateDensities

PURPOSE:

convenience function to evaluate a possible sum of densities

INPUT:

R - cylindrical Galactocentric distance

z - distance above the plane

Pot - potential or list of potentials

phi - azimuth

t - time

forcepoisson= if True, calculate the density through the Poisson equation, even if an explicit expression for the density exists

OUTPUT:

rho(R,z)

HISTORY:

2010-08-08 - Written - Bovy (NYU)

2013-12-28 - Added forcepoisson - Bovy (IAS)

galpy.potential.evaluatephiforces

galpy.potential.**evaluatephiforces**(*R*, *z*, *Pot*, *phi=0.0*, *t=0.0*)

NAME:

evaluatephiforces

PURPOSE:

convenience function to evaluate a possible sum of potentials

INPUT: R - cylindrical Galactocentric distance

z - distance above the plane

Pot - a potential or list of potentials

phi - azimuth (optional)

t - time (optional)

OUTPUT:

F_phi(R,z,phi,t)

HISTORY:

2010-04-16 - Written - Bovy (NYU)

galpy.potential.evaluatePotentials

galpy.potential.**evaluatePotentials**(*R*, *z*, *Pot*, *phi=0.0*, *t=0.0*, *dR=0*, *dphi=0*)

NAME: evaluatePotentials

PURPOSE: convenience function to evaluate a possible sum of potentials

INPUT: R - cylindrical Galactocentric distance

z - distance above the plane

Pot - potential or list of potentials

phi - azimuth

t - time

dR= dphi=, if set to non-zero integers, return the dR, dphi't derivative instead

OUTPUT: Phi(R,z)

HISTORY: 2010-04-16 - Written - Bovy (NYU)

galpy.potential.evaluateR2derivs

galpy.potential.**evaluateR2derivs**(*R*, *z*, *Pot*, *phi=0.0*, *t=0.0*)

NAME: evaluateR2derivs

PURPOSE: convenience function to evaluate a possible sum of potentials

INPUT: R - cylindrical Galactocentric distance

z - distance above the plane

Pot - a potential or list of potentials

phi - azimuth (optional)

t - time (optional)

OUTPUT: d2Phi/d2R(R,z,phi,t)

HISTORY: 2012-07-25 - Written - Bovy (IAS)

galpy.potential.evaluateRzderivs

`galpy.potential.evaluateRzderivs(R, z, Pot, phi=0.0, t=0.0)`

NAME: evaluateRzderivs

PURPOSE: convenience function to evaluate a possible sum of potentials

INPUT: R - cylindrical Galactocentric distance

z - distance above the plane

Pot - a potential or list of potentials

phi - azimuth (optional)

t - time (optional)

OUTPUT: d2Phi/dz/dR(R,z,phi,t)

HISTORY: 2013-08-28 - Written - Bovy (IAS)

galpy.potential.evaluateRforces

`galpy.potential.evaluateRforces(R, z, Pot, phi=0.0, t=0.0)`

NAME: evaluateRforce

PURPOSE: convenience function to evaluate a possible sum of potentials

INPUT: R - cylindrical Galactocentric distance

z - distance above the plane

Pot - a potential or list of potentials

phi - azimuth (optional)

t - time (optional)

OUTPUT: F_R(R,z,phi,t)

HISTORY: 2010-04-16 - Written - Bovy (NYU)

galpy.potential.evaluatez2derivs

`galpy.potential.`**`evaluatez2derivs`**(*R*, *z*, *Pot*, *phi=0.0*, *t=0.0*)

NAME: evaluatez2derivs

PURPOSE: convenience function to evaluate a possible sum of potentials

INPUT: R - cylindrical Galactocentric distance

z - distance above the plane

Pot - a potential or list of potentials

phi - azimuth (optional)

t - time (optional)

OUTPUT: d2Phi/d2z(R,z,phi,t)

HISTORY: 2012-07-25 - Written - Bovy (IAS)

galpy.potential.evaluatezforces

`galpy.potential.`**`evaluatezforces`**(*R*, *z*, *Pot*, *phi=0.0*, *t=0.0*)

NAME:

evaluatezforces

PURPOSE:

convenience function to evaluate a possible sum of potentials

INPUT:

R - cylindrical Galactocentric distance

z - distance above the plane

Pot - a potential or list of potentials

phi - azimuth (optional)

t - time (optional)

OUTPUT:

F_z(R,z,phi,t)

HISTORY:

2010-04-16 - Written - Bovy (NYU)

galpy.potential.flattening

`galpy.potential.`**`flattening`**(*Pot*, *R*, *z*)

NAME:

flattening

PURPOSE:

calculate the potential flattening, defined as sqrt(**|z/R F_R/F_z|**)

INPUT:

Pot - Potential instance or list thereof

R - Galactocentric radius

z - height

OUTPUT:

flattening

HISTORY:

2012-09-13 - Written - Bovy (IAS)

galpy.potential.lindbladR

`galpy.potential.lindbladR`(*Pot*, *OmegaP*, *m=2*, ***kwargs*)

NAME:

lindbladR

PURPOSE:

calculate the radius of a Lindblad resonance

INPUT:

Pot - Potential instance or list of such instances

OmegaP - pattern speed

m= order of the resonance (as in m(O-Op)=kappa (negative m for outer) use m='corotation' for corotation

+scipy.optimize.brentq xtol,rtol,maxiter kwargs

OUTPUT:

radius of Linblad resonance, None if there is no resonance

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.nemo_accname

`galpy.potential.nemo_accname`(*Pot*)

NAME:

nemo_accname

PURPOSE:

return the accname potential name for use of this potential or list of potentials with NEMO

INPUT:

Pot - Potential instance or list of such instances

OUTPUT:

Acceleration name in the correct format to give to accname=

HISTORY:

2014-12-18 - Written - Bovy (IAS)

galpy.potential.nemo_accpars

`galpy.potential.nemo_accpars`(*Pot*, *vo*, *ro*)

NAME:

nemo_accpars

PURPOSE:

return the accpars potential parameters for use of this potential or list of potentials with NEMO

INPUT:

Pot - Potential instance or list of such instances

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

accpars string in the corrct format to give to accpars

HISTORY:

2014-12-18 - Written - Bovy (IAS)

galpy.potential.omegac

`galpy.potential.omegac`(*Pot*, *R*)

NAME:

omegac

PURPOSE:

calculate the circular angular speed velocity at R in potential Pot

INPUT:

Pot - Potential instance or list of such instances

R - Galactocentric radius

OUTPUT:

circular angular speed

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.plotDensities

`galpy.potential.plotDensities`(*Pot*, *rmin=0.0*, *rmax=1.5*, *nrs=21*, *zmin=-0.5*, *zmax=0.5*, *nzs=21*, *ncontours=21*, *savefilename=None*, *aspect=None*, *log=False*, *justcontours=False*)

NAME:

plotDensities

PURPOSE:

plot the density a set of potentials

INPUT:

Pot - Potential or list of Potential instances

rmin= minimum R

rmax= maximum R

nrs= grid in R

zmin= minimum z

zmax= maximum z

nzs= grid in z

ncontours= number of contours

justcontours= (False) if True, just plot contours

savefilename= save to or restore from this savefile (pickle)

log= if True, plot the log density

OUTPUT: plot to output device

HISTORY: 2013-07-05 - Written - Bovy (IAS)

galpy.potential.plotEscapecurve

`galpy.potential.`**`plotEscapecurve`**`(`*Pot*, **args*, ***kwargs*`)`

NAME:

plotEscapecurve

PURPOSE:

plot the escape velocity curve for this potential (in the z=0 plane for non-spherical potentials)

INPUT:

Pot - Potential or list of Potential instances

Rrange= Range in R to consider

grid= grid in R

savefilename= save to or restore from this savefile (pickle)

+bovy_plot.bovy_plot args and kwargs

OUTPUT:

plot to output device

HISTORY:

2010-08-08 - Written - Bovy (NYU)

galpy.potential.plotPotentials

`galpy.potential.plotPotentials`(*Pot*, *rmin=0.0*, *rmax=1.5*, *nrs=21*, *zmin=-0.5*, *zmax=0.5*, *nzs=21*, *ncontours=21*, *savefilename=None*, *aspect=None*, *justcontours=False*)

NAME:

plotPotentials

PURPOSE:

plot a set of potentials

INPUT:

Pot - Potential or list of Potential instances

rmin= minimum R

rmax= maximum R

nrs= grid in R

zmin= minimum z

zmax= maximum z

nzs= grid in z

ncontours= number of contours

justcontours= (False) if True, just plot contours

savefilename= save to or restore from this savefile (pickle)

OUTPUT:

plot to output device

HISTORY:

2010-07-09 - Written - Bovy (NYU)

galpy.potential.plotRotcurve

`galpy.potential.plotRotcurve`(*Pot*, **args*, ***kwargs*)

NAME:

plotRotcurve

PURPOSE:

plot the rotation curve for this potential (in the z=0 plane for non-spherical potentials)

INPUT:

Pot - Potential or list of Potential instances

Rrange - Range in R to consider

grid= grid in R

savefilename= save to or restore from this savefile (pickle)

+bovy_plot.bovy_plot args and kwargs

OUTPUT:

plot to output device

HISTORY:

2010-07-10 - Written - Bovy (NYU)

galpy.potential.rl

`galpy.potential.rl(Pot, lz)`

NAME:

rl

PURPOSE:

calculate the radius of a circular orbit of Lz

INPUT:

Pot - Potential instance or list thereof

lz - Angular momentum

OUTPUT:

radius

HISTORY:

2012-07-30 - Written - Bovy (IAS@MPIA)

NOTE:

seems to take about ~0.5 ms for a Miyamoto-Nagai potential; ~0.75 ms for a MWPotential

galpy.potential.vcirc

`galpy.potential.vcirc(Pot, R)`

NAME:

vcirc

PURPOSE:

calculate the circular velocity at R in potential Pot

INPUT:

Pot - Potential instance or list of such instances

R - Galactocentric radius

OUTPUT:

circular rotation velocity

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.verticalfreq

`galpy.potential.verticalfreq(Pot, R)`

NAME:

verticalfreq

PURPOSE:

calculate the vertical frequency at R in the potential Pot

INPUT:

Pot - Potential instance or list thereof

R - Galactocentric radius

OUTPUT:

vertical frequency

HISTORY:

2012-07-25 - Written - Bovy (IAS@MPIA)

galpy.potential.vesc

`galpy.potential.vesc(Pot, R)`

NAME:

vesc

PURPOSE:

calculate the escape velocity at R for potential Pot

INPUT:

Pot - Potential instances or list thereof

R - Galactocentric radius

OUTPUT:

escape velocity

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.vterm

`galpy.potential.vterm(Pot, l, deg=True)`

NAME:

vterm

PURPOSE:

calculate the terminal velocity at l in this potential

INPUT:

Pot - Potential instance

l - Galactic longitude [deg/rad]

deg= if True (default), l in deg

OUTPUT:

terminal velocity

HISTORY:

2013-05-31 - Written - Bovy (IAS)

Specific potentials

Burkert potential

class galpy.potential.**BurkertPotential**(*amp=1.0*, *a=2.0*, *normalize=False*)

BurkertPotential.py: Potential with a Burkert density

$$\rho(r) = \frac{\mathrm{amp}}{(1+r/a)\,(1+[r/a]^2)}$$

__init__(*amp=1.0*, *a=2.0*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a Burkert-density potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

a = scale radius

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2013-04-10 - Written - Bovy (IAS)

Double exponential disk potential

class galpy.potential.**DoubleExponentialDiskPotential**(*amp=1.0*, *hr=0.3333333333333333*, *hz=0.0625*, *maxiter=20*, *tol=0.001*, *normalize=False*, *new=True*, *kmaxFac=2.0*, *glorder=10*)

Class that implements the double exponential disk potential

$$\rho(R,z) = \mathrm{amp}\,\exp\left(-R/h_R - |z|/h_z\right)$$

__init__(*amp=1.0*, *hr=0.3333333333333333*, *hz=0.0625*, *maxiter=20*, *tol=0.001*, *normalize=False*, *new=True*, *kmaxFac=2.0*, *glorder=10*)

NAME:

__init__

PURPOSE:

initialize a double-exponential disk potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

hr - disk scale-length

hz - scale-height

tol - relative accuracy of potential-evaluations

maxiter - scipy.integrate keyword

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

DoubleExponentialDiskPotential object

HISTORY:

2010-04-16 - Written - Bovy (NYU)

2013-01-01 - Re-implemented using faster integration techniques - Bovy (IAS)

Double power-law density spherical potential

class galpy.potential.**TwoPowerSphericalPotential**(*amp=1.0*, *a=5.0*, *alpha=1.5*, *beta=3.5*, *normalize=False*)

Class that implements spherical potentials that are derived from two-power density models

$$\rho(r) = \frac{\mathrm{amp}}{4\,\pi\,a^3}\,\frac{1}{(r/a)^{\alpha}\,(1+r/a)^{\beta-\alpha}}$$

__init__(*amp=1.0*, *a=5.0*, *alpha=1.5*, *beta=3.5*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a two-power-density potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

a - “scale” (in terms of Ro)

alpha - inner power

beta - outer power

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2010-07-09 - Started - Bovy (NYU)

Jaffe potential

class galpy.potential.**JaffePotential**(*amp=1.0*, *a=1.0*, *normalize=False*)

Class that implements the Jaffe potential

$$\rho(r) = \frac{\mathrm{amp}}{4\,\pi\,a^3}\,\frac{1}{(r/a)^2\,(1+r/a)^2}$$

__init__(*amp=1.0*, *a=1.0*, *normalize=False*)

NAME:

__init__

PURPOSE:

Initialize a Jaffe potential

INPUT:

amp - amplitude to be applied to the potential

a - “scale” (in terms of Ro)

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2010-07-09 - Written - Bovy (NYU)

Flattened Power-law potential

Flattening is in the potential as in Evans (1994) rather than in the density

class galpy.potential.**FlattenedPowerPotential**(*amp=1.0*, *alpha=0.5*, *q=0.9*, *core=1e-08*, *normalize=False*)

Class that implements a power-law potential that is flattened in the potential (NOT the density)

$$\Phi(R,z) = -\frac{\mathrm{amp}}{\alpha\,\left(R^2+(z/q)^2+\mathrm{core}^2\right)^{\alpha/2}}$$

and the same as LogarithmicHaloPotential for $\alpha=0$

See Figure 1 in Evans (1994) for combinations of alpha and q that correspond to positive densities

__init__(*amp=1.0*, *alpha=0.5*, *q=0.9*, *core=1e-08*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a flattened power-law potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

alpha - power

q - flattening

core - core radius

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2013-01-09 - Written - Bovy (IAS)

Hernquist potential

class galpy.potential.**HernquistPotential**(*amp=1.0*, *a=1.0*, *normalize=False*)

Class that implements the Hernquist potential

$$\rho(r) = \frac{\mathrm{amp}}{4\,\pi\,a^3}\,\frac{1}{(r/a)\,(1+r/a)^3}$$

__init__(*amp=1.0*, *a=1.0*, *normalize=False*)

NAME:

__init__

PURPOSE:

Initialize a Hernquist potential

INPUT:

amp - amplitude to be applied to the potential

a - “scale” (in terms of Ro)

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2010-07-09 - Written - Bovy (NYU)

Interpolated axisymmetric potential

The `interpRZPotential` class provides a general interface to generate interpolated instances of general three-dimensional, axisymmetric potentials or lists of such potentials. This interpolated potential can be used in any function where other three-dimensional galpy potentials can be used. This includes functions that use `C` to speed up calculations, if the `interpRZPotential` instance was set up with `enable_c=True`. Initialize as

```
>>> from galpy import potential
>>> ip= potential.interpRZPotential(potential.MWPotential,interpPot=True)
```

which sets up an interpolation of the potential itself only. The potential and all different forces and functions (`dens`,``vcirc``, `epifreq`, `verticalfreq`, `dvcircdR`) are interpolated separately and one needs to specify that these need to be interpolated separately (so, for example, one needs to set `interpRforce=True` to interpolate the radial force, or `interpvcirc=True` to interpolate the circular velocity).

When points outside the grid are requested within the python code, the instance will fall back on the original (non-interpolated) potential. However, when the potential is used purely in `C`, like during orbit integration in `C` or during action–angle evaluations in `C`, there is no way for the potential to fall back onto the original potential and nonsense or NaNs will be returned. Therefore, when using `interpRZPotential` in `C`, one must make sure that the whole relevant part of the `(R,z)` plane is covered. One more time:

Warning: When an interpolated potential is used purely in `C`, like during orbit integration in `C` or during action–angle evaluations in `C`, there is no way for the potential to fall back onto the original potential and nonsense or NaNs will be returned. Therefore, when using `interpRZPotential` in `C`, one must make sure that the whole relevant part of the `(R,z)` plane is covered.

class galpy.potential.**interpRZPotential**(*RZPot=None*, *rgrid=(-4.605170185988091*, *2.995732273553991*, *101)*, *zgrid=(0.0*, *1.0*, *101)*, *logR=True*, *interpPot=False*, *interpRforce=False*, *interpzforce=False*, *interpDens=False*, *interpvcirc=False*, *interpdvcircdr=False*, *interpepifreq=False*, *interpverticalfreq=False*, *use_c=False*, *enable_c=False*, *zsym=True*, *numcores=None*)

Class that interpolates a given potential on a grid for fast orbit integration

__init__(*RZPot=None*, *rgrid=(-4.605170185988091*, *2.995732273553991*, *101)*, *zgrid=(0.0*, *1.0*, *101)*, *logR=True*, *interpPot=False*, *interpRforce=False*, *interpzforce=False*, *interpDens=False*, *interpvcirc=False*, *interpdvcircdr=False*, *interpepifreq=False*, *interpverticalfreq=False*, *use_c=False*, *enable_c=False*, *zsym=True*, *numcores=None*)

NAME:

__init__

PURPOSE:

Initialize an interpRZPotential instance

INPUT:

RZPot - RZPotential to be interpolated

rgrid - R grid to be given to linspace as in rs= linspace(*rgrid)

zgrid - z grid to be given to linspace as in zs= linspace(*zgrid)

logR - if True, rgrid is in the log of R so logrs= linspace(*rgrid) interpPot, interpRforce, interpzforce, interpDens,interpvcirc, interpepifreq, interpverticalfreq, interpdvcircdr= if True, interpolate these functions

use_c= use C to speed up the calculation of the grid

enable_c= enable use of C for interpolations

zsym= if True (default), the potential is assumed to be symmetric around z=0 (so you can use, e.g., zgrid=(0.,1.,101)).

numcores= if set to an integer, use this many cores (only used for vcirc, dvcircdR, epifreq, and verticalfreq; NOT NECESSARILY FASTER, TIME TO MAKE SURE)

OUTPUT:

instance

HISTORY:

2010-07-21 - Written - Bovy (NYU)

2013-01-24 - Started with new implementation - Bovy (IAS)

Interpolated SnapshotRZ potential

This class is built on the `interpRZPotential` class; see the documentation of that class *here* for additional information on how to setup objects of the `InterpSnapshotRZPotential` class.

class galpy.potential.**InterpSnapshotRZPotential**(*s*, *rgrid=(-4.605170185988091, 2.995732273553991, 101)*, *zgrid=(0.0, 1.0, 101)*, *interpepifreq=False*, *interpverticalfreq=False*, *interpPot=True*, *enable_c=True*, *logR=True*, *zsym=True*, *numcores=None*, *nazimuths=4*, *use_pkdgrav=False*)

Interpolated axisymmetrized potential extracted from a simulation output (see `interpRZPotential` and `SnapshotRZPotential`)

__init__(*s*, *rgrid=(-4.605170185988091, 2.995732273553991, 101)*, *zgrid=(0.0, 1.0, 101)*, *interpepifreq=False*, *interpverticalfreq=False*, *interpPot=True*, *enable_c=True*, *logR=True*, *zsym=True*, *numcores=None*, *nazimuths=4*, *use_pkdgrav=False*)

NAME:

__init__

PURPOSE:

Initialize an InterpSnapshotRZPotential instance

INPUT:

s - a simulation snapshot loaded with pynbody

rgrid - R grid to be given to linspace as in rs= linspace(*rgrid)

zgrid - z grid to be given to linspace as in zs= linspace(*zgrid)

logR - if True, rgrid is in the log of R so logrs= linspace(*rgrid)

interpPot, interpepifreq, interpverticalfreq= if True, interpolate these functions (interpPot=True also interpolates the R and zforce)

enable_c= enable use of C for interpolations zsym= if True (default), the potential is assumed to be symmetric around z=0 (so you can use, e.g., zgrid=(0.,1.,101)).

numcores= if set to an integer, use this many cores

nazimuths= (4) number of azimuths to average over

use_pkdgrav= (False) use PKDGRAV to calculate the snapshot's potential and forces (CURRENTLY NOT IMPLEMENTED)

OUTPUT:

instance

HISTORY:

2013 - Written - Rok Roskar (ETH)

2014-11-24 - Edited for merging into main galpy - Bovy (IAS)

Isochrone potential

class galpy.potential.**IsochronePotential**(*amp=1.0*, *b=1.0*, *normalize=False*)

Class that implements the Isochrone potential

$$\Phi(r) = -\frac{\mathrm{amp}}{b+\sqrt{b^2+r^2}}$$

__init__(*amp=1.0*, *b=1.0*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize an isochrone potential

INPUT:

amp= amplitude to be applied to the potential (default: 1)

b= scale radius of the isochrone potential

normalize= if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2013-09-08 - Written - Bovy (IAS)

Kepler potential

class galpy.potential.**KeplerPotential**(*amp=1.0*, *normalize=False*)

Class that implements the Kepler potential

$$\Phi(r) = -\frac{\mathrm{amp}}{r}$$

__init__(*amp=1.0*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a Kepler potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

alpha - inner power

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2010-07-10 - Written - Bovy (NYU)

Kuzmin-Kutuzov Staeckel potential

class galpy.potential.**KuzminKutuzovStaeckelPotential**(*amp=1.0*, *ac=5.0*, *Delta=1.0*, *normalize=False*)

Class that implements the Kuzmin-Kutuzov Staeckel potential

$$\Phi(R,z) = -\frac{\mathrm{amp}}{\sqrt{\lambda}+\sqrt{\nu}}$$

__init__(*amp=1.0*, *ac=5.0*, *Delta=1.0*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a Kuzmin-Kutuzov Staeckel potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

ac - axis ratio of the coordinate surfaces; (a/c) = sqrt(-alpha) / sqrt(-gamma) (default: 5.)

Delta - focal distance that defines the spheroidal coordinate system (default: 1.); Delta=sqrt(gamma-alpha)

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2015-02-15 - Written - Trick (MPIA)

Logarithmic halo potential

class galpy.potential.**LogarithmicHaloPotential**(*amp=1.0*, *core=1e-08*, *q=1.0*, *normalize=False*)

Class that implements the logarithmic halo potential

$$\Phi(R,z) = \frac{\mathrm{amp}}{2}\,\ln\left(R^2+(z/q)^2+\mathrm{core}^2\right)$$

__init__(*amp=1.0*, *core=1e-08*, *q=1.0*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a Logarithmic Halo potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

core - core radius at which the logarithm is cut

q - potential flattening (z/q)**2.

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2010-04-02 - Started - Bovy (NYU)

Miyamoto-Nagai potential

class galpy.potential.**MiyamotoNagaiPotential**(*amp=1.0*, *a=1.0*, *b=0.1*, *normalize=False*)

Class that implements the Miyamoto-Nagai potential

$$\Phi(R,z) = -\frac{\mathrm{amp}}{\sqrt{R^2+(a+\sqrt{z^2+b^2})^2}}$$

__init__(*amp=1.0*, *a=1.0*, *b=0.1*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a Miyamoto-Nagai potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

a - “disk scale” (in terms of Ro)

b - “disk height” (in terms of Ro)

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2010-07-09 - Started - Bovy (NYU)

Three Miyamoto-Nagai disk approximation to an exponential disk

class galpy.potential.**MN3ExponentialDiskPotential**(*amp=1.0*, *hr=0.3333333333333333*, *hz=0.0625*, *sech=False*, *posdens=False*, *normalize=False*)

class that implements the three Miyamoto-Nagai approximation to a radially-exponential disk potential of Smith et al. 2015

$$\rho(R,z) = \mathrm{amp}\,\exp\left(-R/h_R - |z|/h_z\right)$$

or

$$\rho(R,z) = \mathrm{amp}\,\exp\left(-R/h_R\right)\mathrm{sech}^2\left(-|z|/h_z\right)$$

depending on whether sech=True or not. This density is approximated using three Miyamoto-Nagai disks

__init__(*amp=1.0*, *hr=0.3333333333333333*, *hz=0.0625*, *sech=False*, *posdens=False*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a 3MN approximation to an exponential disk potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

hr - disk scale-length

hz - scale-height

sech= (False) if True, hz is the scale height of a sech vertical profile (default is exponential vertical profile)

posdens= (False) if True, allow only positive density solutions (Table 2 in Smith et al. rather than Table 1)

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

MN3ExponentialDiskPotential object

HISTORY:

2015-02-07 - Written - Bovy (IAS)

Moving object potential

class galpy.potential.**MovingObjectPotential**(*orbit*, *amp=1.0*, *GM=0.06*, *softening=None*, *softening_model='plummer'*, *softening_length=0.01*)

Class that implements the potential coming from a moving object

$$\Phi(R,z,\phi,t) = -\mathrm{amp}\,GM\,S(d)$$

where d is the distance between (R,z,ϕ) and the moving object at time t and $S(\cdot)$ is a softening kernel. In the case of Plummer softening, this kernel is

$$S(d) = \frac{1}{\sqrt{d^2+\mathrm{softening\_length}^2}}$$

Plummer is currently the only implemented softening.

__init__(*orbit*, *amp=1.0*, *GM=0.06*, *softening=None*, *softening_model='plummer'*, *softening_length=0.01*)

NAME:

__init__

PURPOSE:

initialize a MovingObjectPotential

INPUT:

orbit - the Orbit of the object (Orbit object)

amp= - amplitude to be applied to the potential (default: 1)

GM - 'mass' of the object (degenerate with amp)

Softening: either provide

a) softening= with a ForceSoftening-type object

b) softening_model= type of softening to use ('plummer')

softening_length= (optional)

OUTPUT:

(none)

HISTORY:

2011-04-10 - Started - Bovy (NYU)

NFW potential

class galpy.potential.**NFWPotential**(*amp=1.0*, *a=1.0*, *normalize=False*, *conc=None*, *mvir=None*, *vo=220.0*, *ro=8.0*, *H=70.0*, *Om=0.3*, *overdens=200.0*, *wrtcrit=False*)

Class that implements the NFW potential

$$\rho(r) = \frac{\mathrm{amp}}{4\,\pi\,a^3}\,\frac{1}{(r/a)\,(1+r/a)^2}$$

__init__(*amp=1.0*, *a=1.0*, *normalize=False*, *conc=None*, *mvir=None*, *vo=220.0*, *ro=8.0*, *H=70.0*, *Om=0.3*, *overdens=200.0*, *wrtcrit=False*)

NAME:

__init__

PURPOSE:

Initialize a NFW potential

INPUT:

amp - amplitude to be applied to the potential

a - “scale” (in terms of Ro)

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

Alternatively, NFW potentials can be initialized using

conc= concentration

mvir= virial mass in 10^12 Msolar

in which case you also need to supply the following keywords

vo= (220.) velocity unit in km/s

ro= (8.) length unit in kpc

H= (default: 70) Hubble constant in km/s/Mpc

Om= (default: 0.3) Omega matter

overdens= (200) overdensity which defines the virial radius

wrtcrit= (False) if True, the overdensity is wrt the critical density rather than the mean matter density

OUTPUT:

(none)

HISTORY:

2010-07-09 - Written - Bovy (NYU)

2014-04-03 - Initialization w/ concentration and mass - Bovy (IAS)

Plummer potential

class galpy.potential.**PlummerPotential**(*amp=1.0*, *b=0.8*, *normalize=False*)

Class that implements the Plummer potential

$$\Phi(R,z) = -\frac{\mathrm{amp}}{\sqrt{R^2+z^2+b^2}}$$

__init__(*amp=1.0*, *b=0.8*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a Plummer potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

b - scale parameter

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2015-06-15 - Written - Bovy (IAS)

Power-law density spherical potential

class galpy.potential.**PowerSphericalPotential**(*amp=1.0*, *alpha=1.0*, *normalize=False*)

Class that implements spherical potentials that are derived from power-law density models

$$\rho(r) = \mathrm{amp}\,\frac{3-\alpha}{4\,\pi}\,r^{-\alpha}$$

__init__(*amp=1.0*, *alpha=1.0*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a power-law-density potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

alpha - inner power

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2010-07-10 - Written - Bovy (NYU)

Power-law density spherical potential with an exponential cut-off

class galpy.potential.**PowerSphericalPotentialwCutoff**(*amp=1.0*, *alpha=1.0*, *rc=1.0*, *normalize=False*)

Class that implements spherical potentials that are derived from power-law density models

$$\rho(r) = \frac{\mathrm{amp}}{r^\alpha}\,\exp\left(-(r/rc)^2\right)$$

__init__(*amp=1.0*, *alpha=1.0*, *rc=1.0*, *normalize=False*)

NAME:

__init__

PURPOSE:

initialize a power-law-density potential

INPUT:

amp= amplitude to be applied to the potential (default: 1)

alpha= inner power

rc= cut-off radius

normalize= if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

(none)

HISTORY:

2013-06-28 - Written - Bovy (IAS)

Razor-thin exponential disk potential

class galpy.potential.**RazorThinExponentialDiskPotential**(*amp=1.0*, *ro=1.0*, *hr=0.3333333333333333*, *maxiter=20*, *tol=0.001*, *normalize=False*, *new=True*, *glorder=100*)

Class that implements the razor-thin exponential disk potential

$$\rho(R,z) = \mathrm{amp}\,\exp\left(-R/h_R\right)\,\delta(z)$$

__init__(*amp=1.0*, *ro=1.0*, *hr=0.3333333333333333*, *maxiter=20*, *tol=0.001*, *normalize=False*, *new=True*, *glorder=100*)

NAME:

__init__

PURPOSE:

initialize a razor-thin-exponential disk potential

INPUT:

amp - amplitude to be applied to the potential (default: 1)

hr - disk scale-length in terms of ro

tol - relative accuracy of potential-evaluations

maxiter - scipy.integrate keyword

normalize - if True, normalize such that vc(1.,0.)=1., or, if given as a number, such that the force is this fraction of the force necessary to make vc(1.,0.)=1.

OUTPUT:

RazorThinExponentialDiskPotential object

HISTORY:

2012-12-27 - Written - Bovy (IAS)

Axisymmetrized N-body snapshot potential

class galpy.potential.**SnapshotRZPotential**(*s*, *num_threads=None*, *nazimuths=4*)

Class that implements an axisymmetrized version of the potential of an N-body snapshot (requires pynbody)

_evaluate, *_Rforce*, and *_zforce* calculate a hash for the array of points that is passed in by the user. The hash and corresponding potential/force arrays are stored – if a subsequent request matches a previously computed hash, the previous results are returned and not recalculated.

__init__(*s*, *num_threads=None*, *nazimuths=4*)

NAME:

__init__

PURPOSE:

Initialize a SnapshotRZ potential object

INPUT:

s - a simulation snapshot loaded with pynbody

num_threads= (4) number of threads to use for calculation

nazimuths= (4) number of azimuths to average over

OUTPUT:

instance

HISTORY:

2013 - Written - Rok Roskar (ETH)

2014-11-24 - Edited for merging into main galpy - Bovy (IAS)

In addition to these classes, a simple Milky-Way-like potential fit to data on the Milky Way is included as `galpy.potential.MWPotential2014` (see the `galpy` paper for details). This potential is defined as

```
>>> bp= PowerSphericalPotentialwCutoff(alpha=1.8,rc=1.9/8.,normalize=0.05)
>>> mp= MiyamotoNagaiPotential(a=3./8.,b=0.28/8.,normalize=.6)
>>> np= NFWPotential(a=16/8.,normalize=.35)
>>> MWPotential2014= [bp,mp,np]
```

and can thus be used like any list of `Potentials`. If one wants to add the supermassive black hole at the Galactic center, this can be done by

```
>>> from galpy.potential import KeplerPotential
>>> from galpy.util import bovy_conversion
>>> MWPotential2014.append(KeplerPotential(amp=4*10**6./bovy_conversion.mass_in_
↪msol(220.,8.)))
```

for a black hole with a mass of $4 \times 10^6\ M_\odot$.

As explained in *this section*, *without* this black hole `MWPotential2014` can be used with Dehnen's gyrfalcON code using `accname=PowSphwCut+MiyamotoNagai+NFW` and `accpars=0,1001.79126907,1.8,1.9#0,306770.418682,3.0,0.28#0,16.0,162.958241887`.

An older version `galpy.potential.MWPotential` of a similar potential that was *not* fit to data on the Milky Way is defined as

```
>>> mp= MiyamotoNagaiPotential(a=0.5,b=0.0375,normalize=.6)
>>> np= NFWPotential(a=4.5,normalize=.35)
>>> hp= HernquistPotential(a=0.6/8,normalize=0.05)
>>> MWPotential= [mp,np,hp]
```

`galpy.potential.MWPotential2014` supersedes `galpy.potential.MWPotential`.

3.2.2 2D potentials

General instance routines

Use as `Potential-instance.method(...)`

galpy.potential.planarPotential.__call__

`planarPotential.`**`__call__`**(*R*, *phi=0.0*, *t=0.0*, *dR=0*, *dphi=0*)

NAME:

__call__

PURPOSE:

evaluate the potential

INPUT:

R - Cylindrica radius

phi= azimuth (optional)

t= time (optional)

dR=, dphi= if set to non-zero integers, return the dR,dphi't derivative

OUTPUT:

Phi(R(,phi,t)))

HISTORY:

2010-07-13 - Written - Bovy (NYU)

galpy.potential.planarPotential.phiforce

`planarPotential.`**`phiforce`**(*R*, *phi=0.0*, *t=0.0*)

NAME:

phiforce

PURPOSE:

evaluate the phi force

INPUT:

R - Cylindrical radius

phi= azimuth (optional)

t= time (optional)

OUTPUT:

F_phi(R,(phi,t)))

HISTORY:

2010-07-13 - Written - Bovy (NYU)

galpy.potential.planarPotential.Rforce

`planarPotential.`**`Rforce`**`(`*R*, *phi=0.0*, *t=0.0*`)`

NAME:

Rforce

PURPOSE:

evaluate the radial force

INPUT:

R - Cylindrical radius

phi= azimuth (optional)

t= time (optional)

OUTPUT:

F_R(R,(phi,t)))

HISTORY:

2010-07-13 - Written - Bovy (NYU)

General axisymmetric potential instance routines

Use as `Potential-instance.method(...)`

galpy.potential.planarAxiPotential.epifreq

`Potential.`**`epifreq`**`(`*R*`)`

NAME:

epifreq

PURPOSE:

calculate the epicycle frequency at R in this potential

INPUT:

R - Galactocentric radius

OUTPUT:

epicycle frequency

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.planarAxiPotential.lindbladR

`Potential.`**`lindbladR`**`(`*OmegaP*, *m=2*, ***kwargs*`)`

NAME:

lindbladR

PURPOSE:

calculate the radius of a Lindblad resonance

INPUT:

OmegaP - pattern speed

m= order of the resonance (as in m(O-Op)=kappa (negative m for outer) use m='corotation' for corotation +scipy.optimize.brentq xtol,rtol,maxiter kwargs

OUTPUT:

radius of Linblad resonance, None if there is no resonance

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.planarAxiPotential.omegac

`Potential.`**`omegac`**`(`*R*`)`

NAME:

omegac

PURPOSE:

calculate the circular angular speed at R in this potential

INPUT:

R - Galactocentric radius

OUTPUT:

circular angular speed

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.planarAxiPotential.plot

`planarAxiPotential.`**`plot`**`(`**args*, ***kwargs*`)`

NAME: plot

PURPOSE: plot the potential

INPUT: Rrange - range grid - number of points to plot savefilename - save to or restore from this savefile (pickle) +bovy_plot(*args,**kwargs)

OUTPUT: plot to output device

HISTORY: 2010-07-13 - Written - Bovy (NYU)

galpy.potential.planarAxiPotential.plotEscapecurve

`planarAxiPotential.`**`plotEscapecurve`**`(`**args*, ***kwargs*`)`

NAME:

plotEscapecurve

PURPOSE:

plot the escape velocity curve for this potential

INPUT:

Rrange - range

grid - number of points to plot

savefilename - save to or restore from this savefile (pickle)

+bovy_plot(*args,**kwargs)

OUTPUT:

plot to output device

HISTORY:

2010-07-13 - Written - Bovy (NYU)

galpy.potential.planarAxiPotential.plotRotcurve

`planarAxiPotential.`**`plotRotcurve`**`(`**args*, ***kwargs*`)`

NAME:

plotRotcurve

PURPOSE:

plot the rotation curve for this potential

INPUT:

Rrange - range

grid - number of points to plot

savefilename - save to or restore from this savefile (pickle)

+bovy_plot(*args,**kwargs)

OUTPUT:

plot to output device

HISTORY:

2010-07-13 - Written - Bovy (NYU)

galpy.potential.planarAxiPotential.vcirc

`Potential.vcirc(R)`

NAME:

vcirc

PURPOSE:

calculate the circular velocity at R in this potential

INPUT:

R - Galactocentric radius

OUTPUT:

circular rotation velocity

HISTORY:

2011-10-09 - Written - Bovy (IAS)

galpy.potential.planarAxiPotential.vesc

`Potential.vesc(R)`

NAME:

vesc

PURPOSE:

calculate the escape velocity at R for this potential

INPUT:

R - Galactocentric radius

OUTPUT:

escape velocity

HISTORY:

2011-10-09 - Written - Bovy (IAS)

General 2D potential routines

Use as `method(...)`

galpy.potential.evaluateplanarphiforces

`galpy.potential.evaluateplanarphiforces(R, Pot, phi=None, t=0.0)`

NAME:

evaluateplanarphiforces

PURPOSE:

evaluate the phiforce of a (list of) planarPotential instance(s)

INPUT:

R - Cylindrical radius

Pot - (list of) planarPotential instance(s)

phi= azimuth (optional)

t= time (optional)

OUTPUT:

F_phi(R(,phi,t))

HISTORY:

2010-07-13 - Written - Bovy (NYU)

galpy.potential.evaluateplanarPotentials

`galpy.potential.`**`evaluateplanarPotentials`**(*R*, *Pot*, *phi=None*, *t=0.0*, *dR=0*, *dphi=0*)

NAME:

evaluateplanarPotentials

PURPOSE:

evaluate a (list of) planarPotential instance(s)

INPUT:

R - Cylindrical radius

Pot - (list of) planarPotential instance(s)

phi= azimuth (optional)

t= time (optional)

dR=, dphi= if set to non-zero integers, return the dR,dphi't derivative instead

OUTPUT:

Phi(R(,phi,t))

HISTORY:

2010-07-13 - Written - Bovy (NYU)

galpy.potential.evaluateplanarRforces

`galpy.potential.`**`evaluateplanarRforces`**(*R*, *Pot*, *phi=None*, *t=0.0*)

NAME:

evaluateplanarRforces

PURPOSE:

evaluate the Rforce of a (list of) planarPotential instance(s)

INPUT:

R - Cylindrical radius

Pot - (list of) planarPotential instance(s)

phi= azimuth (optional)

t= time (optional)

OUTPUT:

F_R(R(,phi,t))

HISTORY:

2010-07-13 - Written - Bovy (NYU)

galpy.potential.evaluateplanarR2derivs

`galpy.potential.`**`evaluateplanarR2derivs`**(*R*, *Pot*, *phi=None*, *t=0.0*)

NAME:

evaluateplanarR2derivs

PURPOSE:

evaluate the second radial derivative of a (list of) planarPotential instance(s)

INPUT:

R - Cylindrical radius

Pot - (list of) planarPotential instance(s)

phi= azimuth (optional)

t= time (optional)

OUTPUT:

F_R(R(,phi,t))

HISTORY:

2010-10-09 - Written - Bovy (IAS)

galpy.potential.LinShuReductionFactor

`galpy.potential.`**`LinShuReductionFactor`**(*axiPot*, *R*, *sigmar*, *nonaxiPot=None*, *k=None*, *m=None*, *OmegaP=None*)

NAME:

LinShuReductionFactor

PURPOSE:

Calculate the Lin & Shu (1966) reduction factor: the reduced linear response of a kinematically-warm stellar disk to a perturbation

INPUT:

axiPot - The background, axisymmetric potential

R - Cylindrical radius

sigmar - radial velocity dispersion of the population

Then either provide:

1) m= m in the perturbation's m x phi (number of arms for a spiral)

   k= wavenumber (see Binney & Tremaine 2008)

   OmegaP= pattern speed

2) nonaxiPot= a non-axisymmetric Potential instance (such as SteadyLogSpiralPotential) that has functions that return OmegaP, m, and wavenumber

OUTPUT:

reduction factor

HISTORY:

2014-08-23 - Written - Bovy (IAS)

galpy.potential.plotplanarPotentials

galpy.potential.**plotplanarPotentials**(*Pot*, **args*, ***kwargs*)

NAME:

plotplanarPotentials

PURPOSE:

plot a planar potential

INPUT:

Rrange - range

xrange, yrange - if relevant

grid, gridx, gridy - number of points to plot

savefilename - save to or restore from this savefile (pickle)

ncontours - number of contours to plot (if applicable)

+bovy_plot(*args,**kwargs) or bovy_dens2d(**kwargs)

OUTPUT:

plot to output device

HISTORY:

2010-07-13 - Written - Bovy (NYU)

Specific potentials

All of the 3D potentials above can be used as two-dimensional potentials in the mid-plane.

galpy.potential.RZToplanarPotential

galpy.potential.**RZToplanarPotential**(*RZPot*)

NAME:

RZToplanarPotential

PURPOSE:

convert an RZPotential to a planarPotential in the mid-plane (z=0)

INPUT:

RZPot - RZPotential instance or list of such instances (existing planarPotential instances are just copied to the output)

OUTPUT:

planarPotential instance(s)

HISTORY:

2010-07-13 - Written - Bovy (NYU)

In addition, a two-dimensional bar potential and a two spiral potentials are included

Dehnen bar potential

class galpy.potential.**DehnenBarPotential**(*amp=1.0*, *omegab=None*, *rb=None*, *chi=0.8*, *rolr=0.9*, *barphi=0.4363323129985824*, *tform=-4.0*, *tsteady=None*, *beta=0.0*, *alpha=0.01*, *Af=None*)

Class that implements the Dehnen bar potential (Dehnen 2000)

$$\Phi(R,\phi) = A_b(t)\,\cos\left(2\,(\phi-\Omega_b\,t)\right)) \times \begin{cases} -(R_b/R)^3\,, & \text{for } R \geq R_b \\ (R/R_b)^3-2\,, & \text{for } R \leq R_b. \end{cases}$$

where

$$A_b(t) = \frac{\alpha}{3\,R_b^3}\left(\frac{3}{16}\xi^5-\frac{5}{8}\xi^3+\frac{15}{16}\xi+\frac{1}{2}\right),\xi = 2\frac{t/T_b-t_{\mathrm{form}}}{T_{\mathrm{steady}}}-1\,,\ \mathrm{if}\ t_{\mathrm{form}} \leq \frac{t}{T_b} \leq t_{\mathrm{form}}+T_{\mathrm{steady}}$$

and

$$A_b(t) = \begin{cases} 0\,, & \frac{t}{T_b} < t_{\mathrm{form}} \\ \frac{\alpha}{3\,R_b^3}\,, & \frac{t}{T_b} > t_{\mathrm{form}}+T_{\mathrm{steady}} \end{cases}$$

where

$$T_b = \frac{2\pi}{\Omega_b}$$

is the bar period.

__init__(*amp=1.0*, *omegab=None*, *rb=None*, *chi=0.8*, *rolr=0.9*, *barphi=0.4363323129985824*, *tform=-4.0*, *tsteady=None*, *beta=0.0*, *alpha=0.01*, *Af=None*)

NAME:

__init__

PURPOSE:

initialize a Dehnen bar potential

INPUT:

amp - amplitude to be applied to the potential (default: 1., see alpha or Ab below)

barphi - angle between sun-GC line and the bar's major axis (in rad; default=25 degree)

tform - start of bar growth / bar period (default: -4) tsteady - time from tform at which the bar is fully grown / bar period (default: -tform/2, st the perturbation is fully grown at tform/2)

tsteady - time at which the bar is fully grown / bar period (default: tform/2)

Either provide:

a) rolr - radius of the Outer Lindblad Resonance for a circular orbit

   chi - fraction R_bar / R_CR (corotation radius of bar)

   alpha - relative bar strength (default: 0.01)

   beta - power law index of rotation curve (to calculate OLR, etc.)

b) omegab - rotation speed of the bar

   rb - bar radius

   Af - bar strength

OUTPUT:

(none)

HISTORY:

2010-11-24 - Started - Bovy (NYU)

Cos(m phi) disk potential

Generalization of the *lopsided* and *elliptical* disk potentials to any m.

class galpy.potential.**CosmphiDiskPotential**(*amp=1.0*, *phib=0.4363323129985824*, *p=1.0*, *phio=0.01*, *m=1.0*, *tform=None*, *tsteady=None*, *cp=None*, *sp=None*)

Class that implements the disk potential

$$\Phi(R,\phi) = \phi_0\,R^p\,\cos\left(m\,(\phi-\phi_b)\right)$$

This potential can be grown between t_{form} and $t_{\mathrm{form}}+T_{\mathrm{steady}}$ in a similar way as DehnenBarPotential, but times are given directly in galpy time units

__init__(*amp=1.0*, *phib=0.4363323129985824*, *p=1.0*, *phio=0.01*, *m=1.0*, *tform=None*, *tsteady=None*, *cp=None*, *sp=None*)

NAME:

__init__

PURPOSE:

initialize an cosmphi disk potential

phi(R,phi) = phio (R/Ro)^p cos[m(phi-phib)]

INPUT:

amp= amplitude to be applied to the potential (default: 1.), see twophio below

tform= start of growth (to smoothly grow this potential

tsteady= time delay at which the perturbation is fully grown (default: 2.)

m= cos(m * (phi - phib))

p= power-law index of the phi(R) = (R/Ro)^p part

Either:

a) phib= angle (in rad; default=25 degree)

   phio= potential perturbation (in terms of phio/vo^2 if vo=1 at Ro=1)

b) cp, sp= m * phio * cos(m * phib), m * phio * sin(m * phib)

OUTPUT:

(none)

HISTORY:

2011-10-27 - Started - Bovy (IAS)

Elliptical disk potential

Like in Kuijken & Tremaine

class galpy.potential.**EllipticalDiskPotential**(*amp=1.0*, *phib=0.4363323129985824*, *p=1.0*, *twophio=0.01*, *tform=None*, *tsteady=None*, *cp=None*, *sp=None*)

Class that implements the Elliptical disk potential of Kuijken & Tremaine (1994)

$$\Phi(R,\phi) = \phi_0\,R^p\,\cos\left(2\,(\phi-\phi_b)\right)$$

This potential can be grown between t_{form} and $t_{\mathrm{form}}+T_{\mathrm{steady}}$ in a similar way as DehnenBarPotential, but times are given directly in galpy time units

__init__(*amp=1.0*, *phib=0.4363323129985824*, *p=1.0*, *twophio=0.01*, *tform=None*, *tsteady=None*, *cp=None*, *sp=None*)

NAME:

__init__

PURPOSE:

initialize an Elliptical disk potential

phi(R,phi) = phio (R/Ro)^p cos[2(phi-phib)]

INPUT:

amp= amplitude to be applied to the potential (default: 1.), see twophio below

tform= start of growth (to smoothly grow this potential

tsteady= time delay at which the perturbation is fully grown (default: 2.)

p= power-law index of the phi(R) = (R/Ro)^p part

Either:

a) phib= angle (in rad; default=25 degree)

   twophio= potential perturbation (in terms of 2phio/vo^2 if vo=1 at Ro=1)

b) cp, sp= twophio * cos(2phib), twophio * sin(2phib)

OUTPUT:

(none)

HISTORY:

2011-10-19 - Started - Bovy (IAS)

Lopsided disk potential

Like in Kuijken & Tremaine, but for m=1

class galpy.potential.**LopsidedDiskPotential**(*amp=1.0*, *phib=0.4363323129985824*, *p=1.0*, *phio=0.01*, *tform=None*, *tsteady=None*, *cp=None*, *sp=None*)

Class that implements the disk potential

$$\Phi(R,\phi) = \phi_0\,R^p\,\cos\left(\phi-\phi_b\right)$$

See documentation for CosmphiDiskPotential

__init__(*amp=1.0*, *phib=0.4363323129985824*, *p=1.0*, *phio=0.01*, *tform=None*, *tsteady=None*, *cp=None*, *sp=None*)

NAME:

__init__

PURPOSE:

initialize an cosmphi disk potential

phi(R,phi) = phio (R/Ro)^p cos[m(phi-phib)]

INPUT:

amp= amplitude to be applied to the potential (default: 1.), see twophio below

tform= start of growth (to smoothly grow this potential

tsteady= time delay at which the perturbation is fully grown (default: 2.)

m= cos(m * (phi - phib))

p= power-law index of the phi(R) = (R/Ro)^p part

Either:

a) phib= angle (in rad; default=25 degree)

phio= potential perturbation (in terms of phio/vo^2 if vo=1 at Ro=1)

b) cp, sp= m * phio * cos(m * phib), m * phio * sin(m * phib)

OUTPUT:

(none)

HISTORY:

2011-10-27 - Started - Bovy (IAS)

Steady-state logarithmic spiral potential

class galpy.potential.**SteadyLogSpiralPotential**(*amp=1.0*, *omegas=0.65*, *A=-0.035*, *alpha=-7.0*, *m=2*, *gamma=0.7853981633974483*, *p=None*, *tform=None*, *tsteady=None*)

Class that implements a steady-state spiral potential

$$\Phi(R,\phi) = \frac{\mathrm{amp}\times A}{\alpha}\,\cos\left(\alpha\,\ln R - m\,(\phi-\Omega_s\,t-\gamma)\right)$$

Can be grown in a similar way as the DehnenBarPotential, but using $T_s = 2\pi/\Omega_s$ to normalize t_{form} and T_{steady}.

__init__(*amp=1.0*, *omegas=0.65*, *A=-0.035*, *alpha=-7.0*, *m=2*, *gamma=0.7853981633974483*, *p=None*, *tform=None*, *tsteady=None*)

NAME:

__init__

PURPOSE:

initialize a logarithmic spiral potential

INPUT:

amp - amplitude to be applied to the potential (default: 1., A below)

gamma - angle between sun-GC line and the line connecting the peak of the spiral pattern at the Solar radius (in rad; default=45 degree)

A - force amplitude (alpha*potential-amplitude; default=0.035)

omegas= - pattern speed (default=0.65)

m= number of arms

Either provide:

a) alpha=

b) p= pitch angle (rad)

tform - start of spiral growth / spiral period (default: -Infinity)

tsteady - time from tform at which the spiral is fully grown / spiral period (default: 2 periods)

OUTPUT:

(none)

HISTORY:

2011-03-27 - Started - Bovy (NYU)

Transient logarithmic spiral potential

class galpy.potential.**TransientLogSpiralPotential**(*amp=1.0*, *omegas=0.65*, *A=-0.035*, *alpha=-7.0*, *m=2*, *gamma=0.7853981633974483*, *p=None*, *sigma=1.0*, *to=0.0*)

Class that implements a steady-state spiral potential

$$\Phi(R,\phi) = \frac{\mathrm{amp}(t)}{\alpha}\,\cos\left(\alpha\,\ln R - m\,(\phi-\Omega_s\,t-\gamma)\right)$$

where

$$\mathrm{amp}(t) = \mathrm{amp}\,\times A\,\exp\left(-\frac{[t-t_0]^2}{2\,\sigma^2}\right)$$

__init__(*amp=1.0*, *omegas=0.65*, *A=-0.035*, *alpha=-7.0*, *m=2*, *gamma=0.7853981633974483*, *p=None*, *sigma=1.0*, *to=0.0*)

NAME:

__init__

PURPOSE:

initialize a transient logarithmic spiral potential localized around to

INPUT:

amp - amplitude to be applied to the potential (default: 1., A below)

gamma - angle between sun-GC line and the line connecting the peak of the spiral pattern at the Solar radius (in rad; default=45 degree)

A - force amplitude (alpha*potential-amplitude; default=0.035)

omegas= - pattern speed (default=0.65)

m= number of arms

to= time at which the spiral peaks

sigma= "spiral duration" (sigma in Gaussian amplitude)

Either provide:

a) alpha=

b) p= pitch angle (rad)

OUTPUT:

(none)

HISTORY:

2011-03-27 - Started - Bovy (NYU)

3.2.3 1D potentials

General instance routines

Use as `Potential-instance.method(...)`

galpy.potential.linearPotential.__call__

`linearPotential.`**`__call__`**(*x*, *t=0.0*)

NAME: __call__

PURPOSE:

evaluate the potential

INPUT:

x - position

t= time (optional)

OUTPUT:

Phi(x,t)

HISTORY:

2010-07-12 - Written - Bovy (NYU)

galpy.potential.linearPotential.force

`linearPotential.force`(*x*, *t=0.0*)

NAME:

force

PURPOSE:

evaluate the force

INPUT:

x - position

t= time (optional)

OUTPUT:

F(x,t)

HISTORY:

2010-07-12 - Written - Bovy (NYU)

galpy.potential.linearPotential.plot

`linearPotential.plot`(*t=0.0*, *min=-15.0*, *max=15*, *ns=21*, *savefilename=None*)

NAME:

plot

PURPOSE:

plot the potential

INPUT:

t - time to evaluate the potential at

min - minimum x

max - maximum x

ns - grid in x

savefilename - save to or restore from this savefile (pickle)

OUTPUT:

plot to output device

HISTORY:

2010-07-13 - Written - Bovy (NYU)

General 1D potential routines

Use as `method(...)`

galpy.potential.evaluatelinearForces

`galpy.potential.`**`evaluatelinearForces`**(*x*, *Pot*, *t=0.0*)

NAME:

evaluatelinearForces

PURPOSE:

evaluate the forces due to a list of potentials

INPUT:

x - evaluate forces at this position

Pot - (list of) linearPotential instance(s)

t - time to evaluate at

OUTPUT:

force(x,t)

HISTORY:

2010-07-13 - Written - Bovy (NYU)

galpy.potential.evaluatelinearPotentials

`galpy.potential.`**`evaluatelinearPotentials`**(*x*, *Pot*, *t=0.0*)

NAME:

evaluatelinearPotentials

PURPOSE:

evaluate the sum of a list of potentials

INPUT:

x - evaluate potentials at this position

Pot - (list of) linearPotential instance(s)

t - time to evaluate at

OUTPUT:

pot(x,t)

HISTORY:

2010-07-13 - Written - Bovy (NYU)

galpy.potential.plotlinearPotentials

`galpy.potential.`**`plotlinearPotentials`**(*Pot*, *t=0.0*, *min=-15.0*, *max=15*, *ns=21*, *savefilename=None*)

NAME:

plotlinearPotentials

PURPOSE:

plot a combination of potentials

INPUT:

t - time to evaluate potential at

min - minimum x

max - maximum x

ns - grid in x

savefilename - save to or restore from this savefile (pickle)

OUTPUT:

plot to output device

HISTORY:

2010-07-13 - Written - Bovy (NYU)

Specific potentials

Vertical Kuijken & Gilmore potential

class galpy.potential.**KGPotential**(*K=1.15*, *F=0.03*, *D=1.8*, *amp=1.0*)

Class representing the Kuijken & Gilmore (1989) potential

$$\Phi(x) = \mathrm{amp}\,\left(K\,\left(\sqrt{x^2+D^2}-D\right)+F\,x^2\right)$$

__init__(*K=1.15*, *F=0.03*, *D=1.8*, *amp=1.0*)

NAME:

__init__

PURPOSE:

Initialize a KGPotential

INPUT:

K= K parameter

F= F parameter

D= D parameter

amp - an overall amplitude

OUTPUT:

instance

HISTORY:

2010-07-12 - Written - Bovy (NYU)

One-dimensional potentials can also be derived from 3D axisymmetric potentials as the vertical potential at a certain Galactocentric radius

galpy.potential.RZToverticalPotential

galpy.potential.**RZToverticalPotential**(*RZPot*, *R*)

NAME:

RZToverticalPotential

PURPOSE:

convert a RZPotential to a vertical potential at a given R

INPUT:

RZPot - RZPotential instance or list of such instances

R - Galactocentric radius at which to evaluate the vertical potential

OUTPUT:

(list of) linearPotential instance(s)

HISTORY:

2010-07-21 - Written - Bovy (NYU)

3.3 DF

3.3.1 Two-dimensional, axisymmetric disk distribution functions

Distribution function for orbits in the plane of a galactic disk.

General instance routines

galpy.df.diskdf.__call__

galpy.df.diskdf.asymmetricdrift

galpy.df.diskdf.kurtosisvR

galpy.df.diskdf.kurtosisvT

galpy.df.diskdf.meanvR

galpy.df.diskdf.meanvT

galpy.df.diskdf.oortA

galpy.df.diskdf.oortB

galpy.df.diskdf.oortC

galpy.df.diskdf.oortK

galpy.df.diskdf.sigma2surfacemass

galpy.df.diskdf.sigma2

galpy.df.diskdf.sigmaR2

galpy.df.diskdf.sigmaT2

galpy.df.diskdf.skewvR

galpy.df.diskdf.skewvT

galpy.df.diskdf.surfacemass

galpy.df.diskdf.surfacemassLOS

galpy.df.diskdf.targetSigma2

galpy.df.diskdf.targetSurfacemass

galpy.df.diskdf.targetSurfacemassLOS

galpy.df.diskdf.vmomentsurfacemass

Sampling routines

galpy.df.diskdf.sample

galpy.df.diskdf.sampledSurfacemassLOS

hhgalpy.df.diskdf.sampleLOS

galpy.df.diskdf.sampleVRVT

Specific distribution functions

Dehnen DF

Shu DF

3.3.2 Two-dimensional, non-axisymmetric disk distribution functions

Distribution function for orbits in the plane of a galactic disk in non-axisymmetric potentials. These are calculated using the technique of Dehnen 2000, where the DF at the current time is obtained as the evolution of an initially-axisymmetric DF at time `to` in the non-axisymmetric potential until the current time.

General instance routines

galpy.df.evolveddiskdf.__call__

The DF of a two-dimensional, non-axisymmetric disk

galpy.df.evolveddiskdf.meanvR

galpy.df.evolveddiskdf.meanvT

galpy.df.evolveddiskdf.oortA

galpy.df.evolveddiskdf.oortB

galpy.df.evolveddiskdf.oortC

galpy.df.evolveddiskdf.oortK

galpy.df.evolveddiskdf.sigmaR2

galpy.df.evolveddiskdf.sigmaRT

galpy.df.evolveddiskdf.sigmaT2

galpy.df.evolveddiskdf.vertexdev

galpy.df.evolveddiskdf.vmomentsurfacemass

3.3.3 Three-dimensional disk distribution functions

Distribution functions for orbits in galactic disks, including the vertical motion for stars reaching large heights above the plane. Currently only the *quasi-isothermal DF*.

General instance routines

galpy.df.quasiisothermaldf.__call__

galpy.df.quasiisothermaldf.density

galpy.df.quasiisothermaldf.estimate_hr

galpy.df.quasiisothermaldf.estimate_hsr

galpy.df.quasiisothermaldf.estimate_hsz

galpy.df.quasiisothermaldf.estimate_hz

galpy.df.quasiisothermaldf.jmomentdensity

galpy.df.quasiisothermaldf.meanjr

galpy.df.quasiisothermaldf.meanjz

galpy.df.quasiisothermaldf.meanlz

galpy.df.quasiisothermaldf.meanvR

galpy.df.quasiisothermaldf.meanvT

galpy.df.quasiisothermaldf.meanvz

galpy.df.quasiisothermaldf.pvR

galpy.df.quasiisothermaldf.pvRvT

galpy.df.quasiisothermaldf.pvRvz

galpy.df.quasiisothermaldf.pvT

galpy.df.quasiisothermaldf.pvTvz

galpy.df.quasiisothermaldf.pvz

galpy.df.quasiisothermaldf.sampleV

galpy.df.quasiisothermaldf.sigmaR2

galpy.df.quasiisothermaldf.sigmaRz

galpy.df.quasiisothermaldf.sigmaT2

galpy.df.quasiisothermaldf.sigmaz2

galpy.df.quasiisothermaldf.surfacemass_z

galpy.df.quasiisothermaldf.tilt

galpy.df.quasiisothermaldf.vmomentdensity

Specific distribution functions

Quasi-isothermal DF

3.3.4 The distribution function of a tidal stream

From Bovy 2014; see *Dynamical modeling of tidal streams*.

General instance routines

galpy.df.streamdf.__call__

The stream DF

galpy.df.streamdf.calc_stream_lb

galpy.df.streamdf.callMarg

galpy.df.streamdf.estimateTdisrupt

galpy.df.streamdf.find_closest_trackpoint

galpy.df.streamdf.find_closest_trackpointLB

galpy.df.streamdf.freqEigvalRatio

galpy.df.streamdf.gaussApprox

galpy.df.streamdf.meanangledAngle

galpy.df.streamdf.meanOmega

galpy.df.streamdf.meantdAngle

galpy.df.streamdf.misalignment

galpy.df.streamdf.pangledAngle

galpy.df.streamdf.plotCompareTrackAAModel

galpy.df.streamdf.plotProgenitor

galpy.df.streamdf.plotTrack

galpy.df.streamdf.ptdAngle

galpy.df.streamdf.sample

galpy.df.streamdf.sigangledAngle

galpy.df.streamdf.sigOmega

galpy.df.streamdf.sigtdAngle

3.4 actionAngle

3.4.1 General instance routines

Not necessarily supported for all different types of actionAngle calculations. These have extra arguments for different `actionAngle` modules, so check the documentation of the module-specific functions for more info (e.g., `?actionAngleIsochrone.__call__`)

galpy.actionAngle.actionAngle.__call__

`actionAngle.`**`__call__`**(**args*, ***kwargs*)

NAME: __call__

PURPOSE: evaluate the actions (jr,lz,jz)

INPUT:

Either:

a) R,vR,vT,z,vz[,phi]:

1) floats: phase-space value for single object (phi is optional)

2) numpy.ndarray: [N] phase-space values for N objects

b) Orbit instance: initial condition used if that's it, orbit(t) if there is a time given as well as the second argument

OUTPUT: (jr,lz,jz)

HISTORY: 2014-01-03 - Written for top level - Bovy (IAS)

galpy.actionAngle.actionAngle.actionsFreqs

galpy.actionAngle.actionAngle.actionsFreqsAngles

`actionAngle.`**`actionsFreqsAngles`**(**args*, ***kwargs*)

NAME: actionsFreqsAngles

PURPOSE: evaluate the actions, frequencies, and angles (jr,lz,jz,Omegar,Omegaphi,Omegaz,angler,anglephi,anglez)

INPUT:

Either:

a) R,vR,vT,z,vz,phi:

1) floats: phase-space value for single object (phi needs to be specified)

2) numpy.ndarray: [N] phase-space values for N objects

b) Orbit instance: initial condition used if that's it, orbit(t) if there is a time given as well as the second argument

OUTPUT: (jr,lz,jz,Omegar,Omegaphi,Omegaz,angler,anglephi,anglez)

HISTORY: 2014-01-03 - Written for top level - Bovy (IAS)

3.4.2 Specific actionAngle modules

actionAngleIsochrone

class galpy.actionAngle.**actionAngleIsochrone**(**args*, ***kwargs*)

Action-angle formalism for the isochrone potential, on the Jphi, Jtheta system of Binney & Tremaine (2008)

__init__(**args*, ***kwargs*)

NAME: __init__

PURPOSE: initialize an actionAngleIsochrone object

INPUT: Either:

b= scale parameter of the isochrone parameter

ip= instance of a IsochronePotential

OUTPUT: HISTORY:

2013-09-08 - Written - Bovy (IAS)

actionAngleSpherical

class galpy.actionAngle.**actionAngleSpherical**(**args*, ***kwargs*)

Action-angle formalism for spherical potentials

__init__(**args*, ***kwargs*)

NAME: __init__

PURPOSE: initialize an actionAngleSpherical object

INPUT: pot= a Spherical potential

OUTPUT: HISTORY:

2013-12-28 - Written - Bovy (IAS)

actionAngleAdiabatic

class galpy.actionAngle.**actionAngleAdiabatic**(**args*, ***kwargs*)

Action-angle formalism for axisymmetric potentials using the adiabatic approximation

__init__(**args*, ***kwargs*)

NAME: __init__

PURPOSE: initialize an actionAngleAdiabatic object

INPUT:

pot= potential or list of potentials (planarPotentials)

gamma= (default=1.) replace Lz by Lz+gamma Jz in effective potential

OUTPUT: HISTORY:

2012-07-26 - Written - Bovy (IAS@MPIA)

actionAngleAdiabaticGrid

class galpy.actionAngle.**actionAngleAdiabaticGrid**(*pot=None*, *zmax=1.0*, *gamma=1.0*, *Rmax=5.0*, *nR=16*, *nEz=16*, *nEr=31*, *nLz=31*, *numcores=1*, ***kwargs*)

Action-angle formalism for axisymmetric potentials using the adiabatic approximation, grid-based interpolation

__init__(*pot=None*, *zmax=1.0*, *gamma=1.0*, *Rmax=5.0*, *nR=16*, *nEz=16*, *nEr=31*, *nLz=31*, *numcores=1*, ***kwargs*)

NAME: __init__

PURPOSE: initialize an actionAngleAdiabaticGrid object

INPUT:

pot= potential or list of potentials

zmax= zmax for building Ez grid

Rmax = Rmax for building grids

gamma= (default=1.) replace Lz by Lz+gamma Jz in effective potential

nEz=, nEr=, nLz, nR= grid size

numcores= number of cpus to use to parallellize

c= if True, use C to calculate actions

+scipy.integrate.quad keywords

OUTPUT: HISTORY:

2012-07-27 - Written - Bovy (IAS@MPIA)

actionAngleStaeckel

class galpy.actionAngle.**actionAngleStaeckel**(**args*, ***kwargs*)

Action-angle formalism for axisymmetric potentials using Binney (2012)'s Staeckel approximation

__init__(**args*, ***kwargs*)

NAME: __init__

PURPOSE: initialize an actionAngleStaeckel object

INPUT: pot= potential or list of potentials (3D)

delta= focus

useu0 - use u0 to calculate dV (NOT recommended)

c= if True, always use C for calculations

OUTPUT: HISTORY:

2012-11-27 - Written - Bovy (IAS)

actionAngleStaeckelGrid

class galpy.actionAngle.**actionAngleStaeckelGrid**(*pot=None*, *delta=None*, *Rmax=5.0*, *nE=25*, *npsi=25*, *nLz=30*, *numcores=1*, ***kwargs*)

Action-angle formalism for axisymmetric potentials using Binney (2012)'s Staeckel approximation, grid-based interpolation

__init__(*pot=None*, *delta=None*, *Rmax=5.0*, *nE=25*, *npsi=25*, *nLz=30*, *numcores=1*, ***kwargs*)

NAME: __init__

PURPOSE: initialize an actionAngleStaeckelGrid object

INPUT: pot= potential or list of potentials

delta= focus of prolate confocal coordinate system

Rmax = Rmax for building grids

nE=, npsi=, nLz= grid size

numcores= number of cpus to use to parallellize

+scipy.integrate.quad keywords

OUTPUT: HISTORY:

2012-11-29 - Written - Bovy (IAS)

actionAngleIsochroneApprox

class galpy.actionAngle.**actionAngleIsochroneApprox**(**args*, ***kwargs*)

Action-angle formalism using an isochrone potential as an approximate potential and using a Fox & Binney (2014?) like algorithm to calculate the actions using orbit integrations and a torus-machinery-like angle-fit to get the angles and frequencies (Bovy 2014)

__init__(**args*, ***kwargs*)

NAME: __init__

PURPOSE: initialize an actionAngleIsochroneApprox object

INPUT:

Either:

b= scale parameter of the isochrone parameter

ip= instance of a IsochronePotential

aAI= instance of an actionAngleIsochrone

pot= potential to calculate action-angle variables for

tintJ= (default: 100) time to integrate orbits for to estimate actions

ntintJ= (default: 10000) number of time-integration points

integrate_method= (default: 'dopr54_c') integration method to use

OUTPUT: HISTORY:

2013-09-10 - Written - Bovy (IAS)

3.5 Utilities

3.5.1 galpy.util.bovy_plot

Various plotting routines:

galpy.util.bovy_plot.bovy_dens2d

`galpy.util.bovy_plot.`**`bovy_dens2d`**`(`*X*, ***kwargs*`)`

NAME:

bovy_dens2d

PURPOSE:

plot a 2d density with optional contours

INPUT:

first argument is the density

matplotlib.pyplot.imshow keywords (see http://matplotlib.sourceforge.net/api/axes_api.html#matplotlib.axes.Axes.imshow)

xlabel - (raw string!) x-axis label, LaTeX math mode, no $s needed

ylabel - (raw string!) y-axis label, LaTeX math mode, no $s needed

xrange

yrange

noaxes - don't plot any axes

overplot - if True, overplot

colorbar - if True, add colorbar

shrink= colorbar argument: shrink the colorbar by the factor (optional)

conditional - normalize each column separately (for probability densities, i.e., cntrmass=True)

Contours:

justcontours - if True, only draw contours

contours - if True, draw contours (10 by default)

levels - contour-levels

cntrmass - if True, the density is a probability and the levels are probability masses contained within the contour

cntrcolors - colors for contours (single color or array)

cntrlabel - label the contours

cntrlw, cntrls - linewidths and linestyles for contour

cntrlabelsize, cntrlabelcolors,cntrinline - contour arguments

cntrSmooth - use ndimage.gaussian_filter to smooth before contouring onedhists - if True, make one-d histograms on the sides

onedhistcolor - histogram color

retAxes= return all Axes instances

retCont= return the contour instance

OUTPUT:

plot to output device, Axes instances depending on input

HISTORY:

2010-03-09 - Written - Bovy (NYU)

galpy.util.bovy_plot.bovy_end_print

`galpy.util.bovy_plot.`**`bovy_end_print`**(*filename*, ***kwargs*)

NAME:

bovy_end_print

PURPOSE:

saves the current figure(s) to filename

INPUT:

filename - filename for plot (with extension)

OPTIONAL INPUTS:

format - file-format

OUTPUT:

(none)

HISTORY:

2009-12-23 - Written - Bovy (NYU)

galpy.util.bovy_plot.bovy_hist

`galpy.util.bovy_plot.`**`bovy_hist`**(*x*, *xlabel=None*, *ylabel=None*, *overplot=False*, ***kwargs*)

NAME:

bovy_hist

PURPOSE:

wrapper around matplotlib's hist function

INPUT:

x - array to histogram

xlabel - (raw string!) x-axis label, LaTeX math mode, no $s needed

ylabel - (raw string!) y-axis label, LaTeX math mode, no $s needed

yrange - set the y-axis range

+all pyplot.hist keywords

OUTPUT: (from the matplotlib docs: http://matplotlib.sourceforge.net/api/pyplot_api.html#matplotlib.pyplot.hist)

The return value is a tuple (n, bins, patches) or ([n0, n1, . . .], bins, [patches0, patches1,. . .]) if the input contains multiple data

HISTORY:

2009-12-23 - Written - Bovy (NYU)

galpy.util.bovy_plot.bovy_plot

galpy.util.bovy_plot.**bovy_plot**(**args*, ***kwargs*)

NAME:

bovy_plot

PURPOSE:

wrapper around matplotlib's plot function

INPUT:

see http://matplotlib.sourceforge.net/api/pyplot_api.html#matplotlib.pyplot.plot

xlabel - (raw string!) x-axis label, LaTeX math mode, no $s needed

ylabel - (raw string!) y-axis label, LaTeX math mode, no $s needed

xrange

yrange

scatter= if True, use pyplot.scatter and its options etc.

colorbar= if True, and scatter==True, add colorbar

crange - range for colorbar of scatter==True

clabel= label for colorbar

overplot=True does not start a new figure and does not change the ranges and labels

gcf=True does not start a new figure (does change the ranges and labels)

onedhists - if True, make one-d histograms on the sides

onedhistcolor, onedhistfc, onedhistec

onedhistxnormed, onedhistynormed - normed keyword for one-d histograms

onedhistxweights, onedhistyweights - weights keyword for one-d histograms

bins= number of bins for onedhists

semilogx=, semilogy=, loglog= if True, plot logs

OUTPUT:

plot to output device, returns what pyplot.plot returns, or 3 Axes instances if onedhists=True

HISTORY:

2009-12-28 - Written - Bovy (NYU)

galpy.util.bovy_plot.bovy_print

`galpy.util.bovy_plot.`**`bovy_print`**(*fig_width=5*, *fig_height=5*, *axes_labelsize=16*, *text_fontsize=11*, *legend_fontsize=12*, *xtick_labelsize=10*, *ytick_labelsize=10*, *xtick_minor_size=2*, *ytick_minor_size=2*, *xtick_major_size=4*, *ytick_major_size=4*)

NAME:

bovy_print

PURPOSE:

setup a figure for plotting

INPUT:

fig_width - width in inches

fig_height - height in inches

axes_labelsize - size of the axis-labels

text_fontsize - font-size of the text (if any)

legend_fontsize - font-size of the legend (if any)

xtick_labelsize - size of the x-axis labels

ytick_labelsize - size of the y-axis labels

xtick_minor_size - size of the minor x-ticks

ytick_minor_size - size of the minor y-ticks

OUTPUT:

(none)

HISTORY:

2009-12-23 - Written - Bovy (NYU)

galpy.util.bovy_plot.bovy_text

`galpy.util.bovy_plot.`**`bovy_text`**(**args*, ***kwargs*)

NAME:

bovy_text

PURPOSE:

thin wrapper around matplotlib's text and annotate

use keywords:

'bottom_left=True'

'bottom_right=True'

'top_left=True'

'top_right=True'

'title=True'

to place the text in one of the corners or use it as the title

INPUT:

see matplotlib's text (http://matplotlib.sourceforge.net/api/pyplot_api.html#matplotlib.pyplot.text)

OUTPUT:

prints text on the current figure

HISTORY:

2010-01-26 - Written - Bovy (NYU)

galpy.util.bovy_plot.scatterplot

`galpy.util.bovy_plot.scatterplot(x, y, *args, **kwargs)`

NAME:

scatterplot

PURPOSE:

make a 'smart' scatterplot that is a density plot in high-density regions and a regular scatterplot for outliers

INPUT:

x, y

xlabel - (raw string!) x-axis label, LaTeX math mode, no $s needed

ylabel - (raw string!) y-axis label, LaTeX math mode, no $s needed

xrange

yrange

bins - number of bins to use in each dimension

weights - data-weights

aspect - aspect ratio

conditional - normalize each column separately (for probability densities, i.e., cntrmass=True)

contours - if False, don't plot contours

justcontours - if True, only draw contours, no density

cntrcolors - color of contours (can be array as for bovy_dens2d)

cntrlw, cntrls - linewidths and linestyles for contour

cntrSmooth - use ndimage.gaussian_filter to smooth before contouring

levels - contour-levels; data points outside of the last level will be individually shown (so, e.g., if this list is descending, contours and data points will be overplotted)

onedhists - if True, make one-d histograms on the sides

onedhistx - if True, make one-d histograms on the side of the x distribution

onedhisty - if True, make one-d histograms on the side of the y distribution

onedhistcolor, onedhistfc, onedhistec

onedhistxnormed, onedhistynormed - normed keyword for one-d histograms

onedhistxweights, onedhistyweights - weights keyword for one-d histograms cmap= cmap for density plot

hist= and edges= - you can supply the histogram of the data yourself, this can be useful if you want to censor the data, both need to be set and calculated using scipy.histogramdd with the given range

retAxes= return all Axes instances

OUTPUT:

plot to output device, Axes instance(s) or not, depending on input

HISTORY:

2010-04-15 - Written - Bovy (NYU)

`galpy` also contains a new matplotlib projection `'galpolar'` that can be used when working with older versions of matplotlib like `'polar'` to create a polar plot in which the azimuth increases clockwise (like when looking at the Milky Way from the north Galactic pole). In newer versions of matplotlib, this does not work, but the `'polar'` projection now supports clockwise azimuths by doing, e.g.,

```
>>> ax= pyplot.subplot(111,projection='polar')
>>> ax.set_theta_direction(-1)
```

3.5.2 galpy.util.bovy_conversion

Utility functions that provide conversions between galpy's *natural* units and *physical* units. These can be used to translate galpy outputs in natural coordinates to physical units by multiplying with the appropriate function.

These could also be used to figure out the conversion between different units. For example, if you want to know how many $\mathrm{GeV\,cm^{-3}}$ correspond to $1\,M_\odot\,\mathrm{pc}^{-3}$, you can calculate

```
>>> from galpy.util import bovy_conversion
>>> bovy_conversion.dens_in_gevcc(1.,1.)/bovy_conversion.dens_in_msolpc3(1.,1.)
37.978342941703616
```

or $1\,M_\odot\,\mathrm{pc}^{-3} \approx 40\,\mathrm{GeV\,cm^{-3}}$.

Functions:

galpy.util.bovy_conversion.dens_in_criticaldens

`galpy.util.bovy_conversion.`**`dens_in_criticaldens`**(*vo*, *ro*, *H=70.0*)

NAME:

dens_in_criticaldens

PURPOSE:

convert density to units of the critical density

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

H= (default: 70) Hubble constant in km/s/Mpc

OUTPUT:

conversion from units where vo=1. at ro=1. to units of the critical density

HISTORY:

2014-01-28 - Written - Bovy (IAS)

galpy.util.bovy_conversion.dens_in_gevcc

`galpy.util.bovy_conversion.`**`dens_in_gevcc`**(*vo*, *ro*)

NAME:

dens_in_gevcc

PURPOSE:

convert density to GeV / cm^3

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1. to GeV/cm^3

HISTORY:

2014-06-16 - Written - Bovy (IAS)

galpy.util.bovy_conversion.dens_in_meanmatterdens

`galpy.util.bovy_conversion.`**`dens_in_meanmatterdens`**(*vo*, *ro*, *H=70.0*, *Om=0.3*)

NAME:

dens_in_meanmatterdens

PURPOSE:

convert density to units of the mean matter density

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

H= (default: 70) Hubble constant in km/s/Mpc

Om= (default: 0.3) Omega matter

OUTPUT:

conversion from units where vo=1. at ro=1. to units of the mean matter density

HISTORY:

2014-01-28 - Written - Bovy (IAS)

galpy.util.bovy_conversion.dens_in_msolpc3

`galpy.util.bovy_conversion.`**`dens_in_msolpc3`**`(`*vo*, *ro*`)`

NAME:

dens_in_msolpc3

PURPOSE:

convert density to Msolar / pc^3

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1. to Msolar/pc^3

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.force_in_2piGmsolpc2

`galpy.util.bovy_conversion.`**`force_in_2piGmsolpc2`**`(`*vo*, *ro*`)`

NAME:

force_in_2piGmsolpc2

PURPOSE:

convert a force or acceleration to 2piG x Msolar / pc^2

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.force_in_pcMyr2

`galpy.util.bovy_conversion.`**`force_in_pcMyr2`**`(`*vo*, *ro*`)`

NAME:

force_in_pcMyr2

PURPOSE:

convert a force or acceleration to pc/Myr^2

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.force_in_10m13kms2

`galpy.util.bovy_conversion.`**`force_in_10m13kms2`**`(`*vo*, *ro*`)`

NAME:

force_in_10m13kms2

PURPOSE:

convert a force or acceleration to 10^(-13) km/s^2

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2014-01-22 - Written - Bovy (IAS)

galpy.util.bovy_conversion.force_in_kmsMyr

`galpy.util.bovy_conversion.`**`force_in_kmsMyr`**`(`*vo*, *ro*`)`

NAME:

force_in_kmsMyr

PURPOSE:

convert a force or acceleration to km/s/Myr

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.freq_in_Gyr

`galpy.util.bovy_conversion.`**`freq_in_Gyr`**`(`*vo*, *ro*`)`

NAME:

freq_in_Gyr

PURPOSE:

convert a frequency to 1/Gyr

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.freq_in_kmskpc

`galpy.util.bovy_conversion.`**`freq_in_kmskpc`**`(`*vo*, *ro*`)`

NAME:

freq_in_kmskpc

PURPOSE:

convert a frequency to km/s/kpc

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.surfdens_in_msolpc2

`galpy.util.bovy_conversion.`**`surfdens_in_msolpc2`**`(`*vo*, *ro*`)`

NAME:

surfdens_in_msolpc2

PURPOSE:

convert a surface density to Msolar / pc^2

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.mass_in_msol

`galpy.util.bovy_conversion.`**`mass_in_msol`**`(`*vo*, *ro*`)`

NAME:

mass_in_msol

PURPOSE:

convert a mass to Msolar

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.mass_in_1010msol

`galpy.util.bovy_conversion.`**`mass_in_1010msol`**`(`*vo*, *ro*`)`

NAME:

mass_in_1010msol

PURPOSE:

convert a mass to 10^10 x Msolar

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.time_in_Gyr

`galpy.util.bovy_conversion.`**`time_in_Gyr`**(*vo*, *ro*)

NAME:

time_in_Gyr

PURPOSE:

convert a time to Gyr

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2013-09-01 - Written - Bovy (IAS)

galpy.util.bovy_conversion.velocity_in_kpcGyr

`galpy.util.bovy_conversion.`**`velocity_in_kpcGyr`**(*vo*, *ro*)

NAME:

velocity_in_kpcGyr

PURPOSE:

convert a velocity to kpc/Gyr

INPUT:

vo - velocity unit in km/s

ro - length unit in kpc

OUTPUT:

conversion from units where vo=1. at ro=1.

HISTORY:

2014-12-19 - Written - Bovy (IAS)

3.5.3 galpy.util.bovy_coords

Various coordinate transformation routines with fairly self-explanatory names:

galpy.util.bovy_coords.cov_dvrpmllbb_to_vxyz

`galpy.util.bovy_coords.`**`cov_dvrpmllbb_to_vxyz`**(*d*, *e_d*, *e_vr*, *pmll*, *pmbb*, *cov_pmllbb*, *l*, *b*, *plx=False*, *degree=False*)

NAME:

cov_dvrpmllbb_to_vxyz

PURPOSE:

propagate distance, radial velocity, and proper motion uncertainties to Galactic coordinates

INPUT:

d - distance [kpc, as/mas for plx]

e_d - distance uncertainty [kpc, [as/mas] for plx]

e_vr - low velocity uncertainty [km/s]

pmll - proper motion in l (*cos(b)) [[as/mas]/yr]

pmbb - proper motion in b [[as/mas]/yr]

cov_pmllbb - uncertainty covariance for proper motion

l - Galactic longitude

b - Galactic lattitude

KEYWORDS:

plx - if True, d is a parallax, and e_d is a parallax uncertainty

degree - if True, l and b are given in degree

OUTPUT:

cov(vx,vy,vz) [3,3] or [:,3,3]

HISTORY:

2010-04-12 - Written - Bovy (NYU)

galpy.util.bovy_coords.cov_pmrapmdec_to_pmllpmbb

galpy.util.bovy_coords.**cov_pmrapmdec_to_pmllpmbb**(*cov_pmradec*, *ra*, *dec*, *degree=False*, *epoch=2000.0*)

NAME:

cov_pmrapmdec_to_pmllpmbb

PURPOSE:

propagate the proper motions errors through the rotation from (ra,dec) to (l,b)

INPUT:

covar_pmradec - uncertainty covariance matrix of the proper motion in ra (multplied with cos(dec)) and dec [2,2] or [:,2,2]

ra - right ascension

dec - declination

degree - if True, ra and dec are given in degrees (default=False)

epoch - epoch of ra,dec (right now only 2000.0 and 1950.0 are supported)

OUTPUT:

covar_pmllbb [2,2] or [:,2,2]

HISTORY:

2010-04-12 - Written - Bovy (NYU)

galpy.util.bovy_coords.cyl_to_rect

`galpy.util.bovy_coords.`**`cyl_to_rect`**(*R*, *phi*, *Z*)

NAME:

cyl_to_rect

PURPOSE:

convert from cylindrical to rectangular coordinates

INPUT:

R, phi, Z - cylindrical coordinates

OUTPUT:

X,Y,Z

HISTORY:

2011-02-23 - Written - Bovy (NYU)

galpy.util.bovy_coords.cyl_to_rect_vec

`galpy.util.bovy_coords.`**`cyl_to_rect_vec`**(*vr*, *vt*, *vz*, *phi*)

NAME:

cyl_to_rect_vec

PURPOSE:

transform vectors from cylindrical to rectangular coordinate vectors

INPUT:

vr - radial velocity

vt - tangential velocity

vz - vertical velocity

phi - azimuth

OUTPUT:

vx,vy,vz

HISTORY:

2011-02-24 - Written - Bovy (NYU)

galpy.util.bovy_coords.dl_to_rphi_2d

`galpy.util.bovy_coords.`**`dl_to_rphi_2d`**(*d*, *l*, *degree=False*, *ro=1.0*, *phio=0.0*)

NAME:

dl_to_rphi_2d

PURPOSE:

convert Galactic longitude and distance to Galactocentric radius and azimuth

INPUT:

d - distance

l - Galactic longitude [rad/deg if degree]

KEYWORDS:

degree= (False): l is in degrees rather than rad

ro= (1) Galactocentric radius of the observer

phio= (0) Galactocentric azimuth of the observer [rad/deg if degree]

OUTPUT:

(R,phi); phi in degree if degree

HISTORY:

2012-01-04 - Written - Bovy (IAS)

galpy.util.bovy_coords.galcencyl_to_XYZ

galpy.util.bovy_coords.**galcencyl_to_XYZ**(*R*, *phi*, *Z*, *Xsun=1.0*, *Ysun=0.0*, *Zsun=0.0*)

NAME:

galcencyl_to_XYZ

PURPOSE:

transform cylindrical Galactocentric coordinates to XYZ coordinates (wrt Sun)

INPUT:

R, phi, Z - Galactocentric cylindrical coordinates

OUTPUT:

X,Y,Z

HISTORY:

2011-02-23 - Written - Bovy (NYU)

galpy.util.bovy_coords.galcencyl_to_vxvyvz

galpy.util.bovy_coords.**galcencyl_to_vxvyvz**(*vR*, *vT*, *vZ*, *phi*, *vsun=[0.0, 1.0, 0.0]*)

NAME:

galcencyl_to_vxvyvz

PURPOSE:

transform cylindrical Galactocentric coordinates to XYZ (wrt Sun) coordinates for velocities

INPUT:

vR - Galactocentric radial velocity

vT - Galactocentric tangential velocity

vZ - Galactocentric vertical velocity

phi - Galactocentric azimuth

vsun - velocity of the sun in the GC frame ndarray[3]

OUTPUT:

vx,vy,vz

HISTORY:

2011-02-24 - Written - Bovy (NYU)

galpy.util.bovy_coords.galcenrect_to_XYZ

`galpy.util.bovy_coords.`**`galcenrect_to_XYZ`**(*X*, *Y*, *Z*, *Xsun=1.0*, *Ysun=0.0*, *Zsun=0.0*)

NAME:

galcenrect_to_XYZ

PURPOSE:

transform rectangular Galactocentric to XYZ coordinates (wrt Sun) coordinates

INPUT:

X, Y, Z - Galactocentric rectangular coordinates

OUTPUT:

(X, Y, Z)

HISTORY:

2011-02-23 - Written - Bovy (NYU)

galpy.util.bovy_coords.galcenrect_to_vxvyvz

`galpy.util.bovy_coords.`**`galcenrect_to_vxvyvz`**(*vXg, vYg, vZg, vsun=[0.0, 1.0, 0.0]*)

NAME:

galcenrect_to_vxvyvz

PURPOSE:

transform rectangular Galactocentric coordinates to XYZ coordinates (wrt Sun) for velocities

INPUT:

vXg - Galactocentric x-velocity

vYg - Galactocentric y-velocity

vZg - Galactocentric z-velocity

vsun - velocity of the sun in the GC frame ndarray[3]

OUTPUT:

[:,3]= vx, vy, vz

HISTORY:

2011-02-24 - Written - Bovy (NYU)

galpy.util.bovy_coords.lb_to_radec

galpy.util.bovy_coords.**lb_to_radec**(*l*, *b*, *degree=False*, *epoch=2000.0*)

NAME:

lb_to_radec

PURPOSE:

transform from Galactic coordinates to equatorial coordinates

INPUT:

l - Galactic longitude

b - Galactic lattitude

degree - (Bool) if True, l and b are given in degree and ra and dec will be as well

epoch - epoch of target ra,dec (right now only 2000.0 and 1950.0 are supported)

OUTPUT:

ra,dec

For vector inputs [:,2]

HISTORY:

2010-04-07 - Written - Bovy (NYU)

2014-06-14 - Re-written w/ numpy functions for speed and w/ decorators for beauty - Bovy (IAS)

galpy.util.bovy_coords.lb_to_radec

galpy.util.bovy_coords.**lbd_to_XYZ**(*l*, *b*, *d*, *degree=False*)

NAME:

lbd_to_XYZ

PURPOSE:

transform from spherical Galactic coordinates to rectangular Galactic coordinates (works with vector inputs)

INPUT:

l - Galactic longitude (rad)

b - Galactic lattitude (rad)

d - distance (arbitrary units)

degree - (bool) if True, l and b are in degrees

OUTPUT:

[X,Y,Z] in whatever units d was in

For vector inputs [:,3]

HISTORY:

2009-10-24- Written - Bovy (NYU)

2014-06-14 - Re-written w/ numpy functions for speed and w/ decorators for beauty - Bovy (IAS)

galpy.util.bovy_coords.pmllpmbb_to_pmrapmdec

`galpy.util.bovy_coords.`**`pmllpmbb_to_pmrapmdec`**(*pmll*, *pmbb*, *l*, *b*, *degree=False*, *epoch=2000.0*)

NAME:

pmllpmbb_to_pmrapmdec

PURPOSE:

rotate proper motions in (l,b) into proper motions in (ra,dec)

INPUT:

pmll - proper motion in l (multplied with cos(b)) [mas/yr]

pmbb - proper motion in b [mas/yr]

l - Galactic longitude

b - Galactic lattitude

degree - if True, l and b are given in degrees (default=False)

epoch - epoch of ra,dec (right now only 2000.0 and 1950.0 are supported)

OUTPUT:

(pmra,pmdec), for vector inputs [:,2]

HISTORY:

2010-04-07 - Written - Bovy (NYU)

2014-06-14 - Re-written w/ numpy functions for speed and w/ decorators for beauty - Bovy (IAS)

galpy.util.bovy_coords.pmrapmdec_to_pmllpmbb

`galpy.util.bovy_coords.`**`pmrapmdec_to_pmllpmbb`**(*pmra*, *pmdec*, *ra*, *dec*, *degree=False*, *epoch=2000.0*)

NAME:

pmrapmdec_to_pmllpmbb

PURPOSE:

rotate proper motions in (ra,dec) into proper motions in (l,b)

INPUT:

pmra - proper motion in ra (multplied with cos(dec)) [mas/yr]

pmdec - proper motion in dec [mas/yr]

ra - right ascension

dec - declination

degree - if True, ra and dec are given in degrees (default=False)

epoch - epoch of ra,dec (right now only 2000.0 and 1950.0 are supported)

OUTPUT:

(pmll,pmbb) for vector inputs [:,2]

HISTORY:

2010-04-07 - Written - Bovy (NYU)

2014-06-14 - Re-written w/ numpy functions for speed and w/ decorators for beauty - Bovy (IAS)

galpy.util.bovy_coords.radec_to_lb

galpy.util.bovy_coords.**radec_to_lb**(*ra*, *dec*, *degree=False*, *epoch=2000.0*)

NAME:

radec_to_lb

PURPOSE:

transform from equatorial coordinates to Galactic coordinates

INPUT:

ra - right ascension

dec - declination

degree - (Bool) if True, ra and dec are given in degree and l and b will be as well

epoch - epoch of ra,dec (right now only 2000.0 and 1950.0 are supported)

OUTPUT:

l,b

For vector inputs [:,2]

HISTORY:

2009-11-12 - Written - Bovy (NYU)

2014-06-14 - Re-written w/ numpy functions for speed and w/ decorators for beauty - Bovy (IAS)

galpy.util.bovy_coords.rectgal_to_sphergal

galpy.util.bovy_coords.**rectgal_to_sphergal**(*X*, *Y*, *Z*, *vx*, *vy*, *vz*, *degree=False*)

NAME:

rectgal_to_sphergal

PURPOSE:

transform phase-space coordinates in rectangular Galactic coordinates to spherical Galactic coordinates (can take vector inputs)

INPUT:

X - component towards the Galactic Center (kpc)

Y - component in the direction of Galactic rotation (kpc)

Z - component towards the North Galactic Pole (kpc)

vx - velocity towards the Galactic Center (km/s)

vy - velocity in the direction of Galactic rotation (km/s)

vz - velocity towards the North Galactic Pole (km/s)

degree - (Bool) if True, return l and b in degrees

OUTPUT:

(l,b,d,vr,pmll,pmbb) in (rad,rad,kpc,km/s,mas/yr,mas/yr)

HISTORY:

2009-10-25 - Written - Bovy (NYU)

galpy.util.bovy_coords.rect_to_cyl

`galpy.util.bovy_coords.`**`rect_to_cyl`**(*X*, *Y*, *Z*)

NAME:

rect_to_cyl

PURPOSE:

convert from rectangular to cylindrical coordinates

INPUT:

X, Y, Z - rectangular coordinates

OUTPUT:

R,phi,z

HISTORY:

2010-09-24 - Written - Bovy (NYU)

galpy.util.bovy_coords.rect_to_cyl_vec

`galpy.util.bovy_coords.`**`rect_to_cyl_vec`**(*vx*, *vy*, *vz*, *X*, *Y*, *Z*, *cyl=False*)

NAME:

rect_to_cyl_vec

PURPOSE:

transform vectors from rectangular to cylindrical coordinates vectors

INPUT:

vx -

vy -

vz -

X - X

Y - Y

Z - Z

cyl - if True, X,Y,Z are already cylindrical

OUTPUT:

vR,vT,vz

HISTORY:

2010-09-24 - Written - Bovy (NYU)

galpy.util.bovy_coords.rphi_to_dl_2d

galpy.util.bovy_coords.**rphi_to_dl_2d**(*R*, *phi*, *degree=False*, *ro=1.0*, *phio=0.0*)

NAME:

rphi_to_dl_2d

PURPOSE:

convert Galactocentric radius and azimuth to distance and Galactic longitude

INPUT:

R - Galactocentric radius

phi - Galactocentric azimuth [rad/deg if degree]

KEYWORDS:

degree= (False): phi is in degrees rather than rad

ro= (1) Galactocentric radius of the observer

phio= (0) Galactocentric azimuth of the observer [rad/deg if degree]

OUTPUT:

(d,l); phi in degree if degree

HISTORY:

2012-01-04 - Written - Bovy (IAS)

galpy.util.bovy_coords.Rz_to_coshucosv

galpy.util.bovy_coords.**Rz_to_coshucosv**(*R*, *z*, *delta=1.0*)

NAME:

Rz_to_coshucosv

PURPOSE:

calculate prolate confocal cosh(u) and cos(v) coordinates from R,z, and delta

INPUT:

R - radius

z - height

delta= focus

OUTPUT:

(cosh(u),cos(v))

HISTORY:

2012-11-27 - Written - Bovy (IAS)

galpy.util.bovy_coords.Rz_to_uv

`galpy.util.bovy_coords.`**`Rz_to_uv`**(*R*, *z*, *delta=1.0*)

NAME:

Rz_to_uv

PURPOSE:

calculate prolate confocal u and v coordinates from R,z, and delta

INPUT:

R - radius

z - height

delta= focus

OUTPUT:

(u,v)

HISTORY:

2012-11-27 - Written - Bovy (IAS)

galpy.util.bovy_coords.sphergal_to_rectgal

`galpy.util.bovy_coords.`**`sphergal_to_rectgal`**(*l*, *b*, *d*, *vr*, *pmll*, *pmbb*, *degree=False*)

NAME:

sphergal_to_rectgal

PURPOSE:

transform phase-space coordinates in spherical Galactic coordinates to rectangular Galactic coordinates (can take vector inputs)

INPUT:

l - Galactic longitude (rad)

b - Galactic lattitude (rad)

d - distance (kpc)

vr - line-of-sight velocity (km/s)

pmll - proper motion in the Galactic longitude direction (mu_l*cos(b)) (mas/yr)

pmbb - proper motion in the Galactic lattitude (mas/yr)

degree - (bool) if True, l and b are in degrees

OUTPUT:

(X,Y,Z,vx,vy,vz) in (kpc,kpc,kpc,km/s,km/s,km/s)

HISTORY:

2009-10-25 - Written - Bovy (NYU)

galpy.util.bovy_coords.uv_to_Rz

galpy.util.bovy_coords.**uv_to_Rz**(*u*, *v*, *delta=1.0*)

NAME:

uv_to_Rz

PURPOSE:

calculate R and z from prolate confocal u and v coordinates

INPUT:

u - confocal u

v - confocal v

delta= focus

OUTPUT:

(R,z)

HISTORY:

2012-11-27 - Written - Bovy (IAS)

galpy.util.bovy_coords.vrpmllpmbb_to_vxvyvz

galpy.util.bovy_coords.**vrpmllpmbb_to_vxvyvz**(*vr*, *pmll*, *pmbb*, *l*, *b*, *d*, *XYZ=False*, *degree=False*)

NAME:

vrpmllpmbb_to_vxvyvz

PURPOSE:

Transform velocities in the spherical Galactic coordinate frame to the rectangular Galactic coordinate frame (can take vector inputs)

INPUT:

vr - line-of-sight velocity (km/s)

pmll - proper motion in the Galactic longitude (mu_l * cos(b))(mas/yr)

pmbb - proper motion in the Galactic lattitude (mas/yr)

l - Galactic longitude

b - Galactic lattitude

d - distance (kpc)

XYZ - (bool) If True, then l,b,d is actually X,Y,Z (rectangular Galactic coordinates)

degree - (bool) if True, l and b are in degrees

OUTPUT:

(vx,vy,vz) in (km/s,km/s,km/s)

For vector inputs [:,3]

HISTORY:

2009-10-24 - Written - Bovy (NYU)

2014-06-14 - Re-written w/ numpy functions for speed and w/ decorators for beauty - Bovy (IAS)

galpy.util.bovy_coords.vxvyvz_to_galcencyl

`galpy.util.bovy_coords.`**`vxvyvz_to_galcencyl`**(*vx, vy, vz, X, Y, Z, vsun=[0.0, 1.0, 0.0], galcen=False*)

NAME:

vxvyvz_to_galcencyl

PURPOSE:

transform velocities in XYZ coordinates (wrt Sun) to cylindrical Galactocentric coordinates for velocities

INPUT:

vx - U

vy - V

vz - W

X - X in Galactocentric rectangular coordinates

Y - Y in Galactocentric rectangular coordinates

Z - Z in Galactocentric rectangular coordinates

vsun - velocity of the sun in the GC frame ndarray[3]

galcen - if True, then X,Y,Z are in cylindrical Galactocentric coordinates rather than rectangular coordinates

OUTPUT:

vRg, vTg, vZg

HISTORY:

2010-09-24 - Written - Bovy (NYU)

galpy.util.bovy_coords.vxvyvz_to_galcenrect

`galpy.util.bovy_coords.`**`vxvyvz_to_galcenrect`**(*vx, vy, vz, vsun=[0.0, 1.0, 0.0]*)

NAME:

vxvyvz_to_galcenrect

PURPOSE:

transform velocities in XYZ coordinates (wrt Sun) to rectangular Galactocentric coordinates for velocities

INPUT:

vx - U

vy - V

vz - W

vsun - velocity of the sun in the GC frame ndarray[3]

OUTPUT:

[:,3]= vXg, vYg, vZg

HISTORY:

2010-09-24 - Written - Bovy (NYU)

galpy.util.bovy_coords.vxvyvz_to_vrpmllpmbb

`galpy.util.bovy_coords.`**`vxvyvz_to_vrpmllpmbb`**(*vx*, *vy*, *vz*, *l*, *b*, *d*, *XYZ=False*, *degree=False*)

NAME:

vxvyvz_to_vrpmllpmbb

PURPOSE:

Transform velocities in the rectangular Galactic coordinate frame to the spherical Galactic coordinate frame (can take vector inputs)

INPUT:

vx - velocity towards the Galactic Center (km/s)

vy - velocity in the direction of Galactic rotation (km/s)

vz - velocity towards the North Galactic Pole (km/s)

l - Galactic longitude

b - Galactic lattitude

d - distance (kpc)

XYZ - (bool) If True, then l,b,d is actually X,Y,Z (rectangular Galactic coordinates)

degree - (bool) if True, l and b are in degrees

OUTPUT:

(vr,pmll,pmbb) in (km/s,mas/yr,mas/yr); pmll = mu_l * cos(b)

For vector inputs [:,3]

HISTORY:

2009-10-24 - Written - Bovy (NYU)

2014-06-14 - Re-written w/ numpy functions for speed and w/ decorators for beauty - Bovy (IAS)

galpy.util.bovy_coords.XYZ_to_galcencyl

`galpy.util.bovy_coords.`**`XYZ_to_galcencyl`**(*X*, *Y*, *Z*, *Xsun=1.0*, *Ysun=0.0*, *Zsun=0.0*)

NAME:

XYZ_to_galcencyl

PURPOSE:

transform XYZ coordinates (wrt Sun) to cylindrical Galactocentric coordinates

INPUT:

X - X

Y - Y

Z - Z

OUTPUT:

R,phi,z

HISTORY:

2010-09-24 - Written - Bovy (NYU)

galpy.util.bovy_coords.XYZ_to_galcenrect

`galpy.util.bovy_coords.`**`XYZ_to_galcenrect`**(*X*, *Y*, *Z*, *Xsun=1.0*, *Ysun=0.0*, *Zsun=0.0*)

NAME:

XYZ_to_galcenrect

PURPOSE:

transform XYZ coordinates (wrt Sun) to rectangular Galactocentric coordinates

INPUT:

X - X

Y - Y

Z - Z

OUTPUT:

(Xg, Yg, Zg)

HISTORY:

2010-09-24 - Written - Bovy (NYU)

galpy.util.bovy_coords.XYZ_to_lbd

`galpy.util.bovy_coords.`**`XYZ_to_lbd`**(*X*, *Y*, *Z*, *degree=False*)

NAME:

XYZ_to_lbd

PURPOSE:

transform from rectangular Galactic coordinates to spherical Galactic coordinates (works with vector inputs)

INPUT:

X - component towards the Galactic Center (in kpc; though this obviously does not matter))

Y - component in the direction of Galactic rotation (in kpc)

Z - component towards the North Galactic Pole (kpc)

degree - (Bool) if True, return l and b in degrees

OUTPUT:

[l,b,d] in (rad or degree,rad or degree,kpc)

For vector inputs [:,3]

HISTORY:

2009-10-24 - Written - Bovy (NYU)

2014-06-14 - Re-written w/ numpy functions for speed and w/ decorators for beauty - Bovy (IAS)

3.5.4 galpy.util.bovy_ars.bovy_ars

`galpy.util.bovy_ars.`**`bovy_ars`**(*domain*, *isDomainFinite*, *abcissae*, *hx*, *hpx*, *nsamples=1*, *hxparams=()*, *maxn=100*)

bovy_ars: Implementation of the Adaptive-Rejection Sampling algorithm by Gilks & Wild (1992): Adaptive Rejection Sampling for Gibbs Sampling, Applied Statistics, 41, 337 Based on Wild & Gilks (1993), Algorithm AS 287: Adaptive Rejection Sampling from Log-concave Density Functions, Applied Statistics, 42, 701

Input:

domain - [.,.] upper and lower limit to the domain

isDomainFinite - [.,.] is there a lower/upper limit to the domain?

abcissae - initial list of abcissae (must lie on either side of the peak in hx if the domain is unbounded

hx - function that evaluates h(x) = ln g(x)

hpx - function that evaluates hp(x) = d h(x) / d x

nsamples - (optional) number of desired samples (default=1)

hxparams - (optional) a tuple of parameters for h(x) and h'(x)

maxn - (optional) maximum number of updates to the hull (default=100)

Output:

list with nsamples of samples from exp(h(x))

External dependencies:

math scipy scipy.stats

History: 2009-05-21 - Written - Bovy (NYU)

CHAPTER 4

Papers using galpy

`galpy` is described in detail in this publication:

- *galpy: A Python Library for Galactic Dynamics*, Jo Bovy (2015), *Astrophys. J. Supp.*, **216**, 29 (arXiv/1412.3451).

The following is a list of publications using `galpy`; please let me (bovy -at- ias.edu) know if you make use of `galpy` in a publication.

1. ***Tracing the Hercules stream around the Galaxy*, Jo Bovy (2010), *Astrophys. J.* 725, 1676 (2010ApJ...725.1676B):**
   Uses what later became the orbit integration routines and Dehnen and Shu disk distribution functions.
2. ***The spatial structure of mono-abundance sub-populations of the Milky Way disk*, Jo Bovy, Hans-Walter Rix, Chao Liu, et al.**
   Employs galpy orbit integration in `galpy.potential.MWPotential` to characterize the orbits in the SEGUE G dwarf sample.
3. ***On the local dark matter density*, Jo Bovy & Scott Tremaine (2012), *Astrophys. J.* 756, 89 (2012ApJ...756...89B):**
   Uses `galpy.potential` force and density routines to characterize the difference between the vertical force and the surface density at large heights above the MW midplane.
4. ***The Milky Way's circular velocity curve between 4 and 14 kpc from APOGEE data*, Jo Bovy, Carlos Allende Prieto, Timothy**
   Utilizes the Dehnen distribution function to inform a simple model of the velocity distribution of APOGEE stars in the Milky Way disk and to create mock data.
5. ***A direct dynamical measurement of the Milky Way's disk surface density profile, disk scale length, and dark matter profile at 4***
   Makes use of potential models, the adiabatic and Staeckel actionAngle modules, and the quasiisothermal DF to model the dynamics of the SEGUE G dwarf sample in mono-abundance bins.
6. ***The peculiar pulsar population of the central parsec*, Jason Dexter & Ryan M. O'Leary (2013), *Astrophys. J. Lett.*, 783, L7 (**
   Uses galpy for orbit integration of pulsars kicked out of the Galactic center.
7. ***Chemodynamics of the Milky Way. I. The first year of APOGEE data*, Friedrich Anders, Christina Chiappini, Basilio X. San**
   Employs galpy to perform orbit integrations in `galpy.potential.MWPotential` to characterize the orbits of stars in the APOGEE sample.
8. ***Dynamical modeling of tidal streams*, Jo Bovy (2014), *Astrophys. J.*, 795, 95 (2014ApJ...795...95B):**
   Introduces `galpy.df.streamdf` and `galpy.actionAngle.`

`actionAngleIsochroneApprox` for modeling tidal streams using simple models formulated in action-angle space (see the tutorial above).

9. ***The Milky Way Tomography with SDSS. V. Mapping the Dark Matter Halo*, Sarah R. Loebman, Zeljko Ivezic Thomas R. Qu**
   Uses `galpy.potential` functions to calculate the acceleration field of the best-fit potential in Bovy & Rix (2013) above.

10. ***The power spectrum of the Milky Way: Velocity fluctuations in the Galactic disk*, Jo Bovy, Jonathan C. Bird, Ana E. Garcia P**
    Uses `galpy.df.evolveddiskdf` to calculate the mean non-axisymmetric velocity field due to different non-axisymmetric perturbations and compares it to APOGEE data.

11. ***Generation of mock tidal streams*, Mark A. Fardal, Shuiyao Huang, & Martin D. Weinberg (2014), *Mon. Not. Roy. Astron.***
    Uses `galpy.potential` and `galpy.orbit` for orbit integration in creating a *particle-spray* model for tidal streams.

12. ***The nature and orbit of the Ophiuchus stream*, Branimir Sesar, Jo Bovy, Edouard J. Bernard, et al. (2015), *Astrophys. J.*, su**
    Uses the Orbit.fit routine in `galpy.orbit` to fit the orbit of the Ophiuchus stream to newly obtained observational data and the routines in `galpy.df.streamdf` to model the creation of the stream.

13. ***The LMC geometry and outer stellar populations from early DES data*, Eduardo Balbinot, B. X. Santiago, L. Girardi, et al. (**
    Employs `galpy.potential.MWPotential` as a mass model for the Milky Way to constrain the mass of the LMC.

14. ***Young Pulsars and the Galactic Center GeV Gamma-ray Excess*, Ryan M. O'Leary, Matthew D. Kistler, Matthew Kerr, & J**
    Uses galpy orbit integration and `galpy.potential.MWPotential2014` as part of a Monte Carlo simulation of the Galactic young-pulsar population.

CHAPTER 5

Acknowledging galpy

If you use galpy in a publication, please cite the following paper

- *galpy: A Python Library for Galactic Dynamics*, Jo Bovy (2015), *Astrophys. J. Supp.*, **216**, 29 (arXiv/1412.3451).

and link to `http://github.com/jobovy/galpy`. Please also send me a reference to the paper or send a pull request including your paper in the list of galpy papers on this page (this page is at doc/source/index.rst). Thanks!

When using the `galpy.actionAngle.actionAngleAdiabatic` and `galpy.actionAngle.actionAngleStaeckel` modules, please cite 2013ApJ…779..115B in addition to the papers describing the algorithm used. When using `galpy.actionAngle.actionAngleIsochroneApprox`, please cite 2014ApJ…795…95B, which introduced this technique.

CHAPTER 6

Indices and tables

- genindex
- modindex
- search

Index

Symbols