

# Documentation for PopSyCLE

Population Synthesis for Compact object Lensing Events

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# 1 Installation

PopSyCLE has several dependencies. In addition to installing PopSyCLE, the user will need Galaxia, PopStar, and several Python libraries.

## 1.1 Installing Galaxia

### 1.1.1 Installation

Note there are also instructions from the creators of Galaxia at <http://galaxia.sourceforge.net/Galaxia3pub.html>; what follows is a super pedantic version of that.

1. Go to <https://sourceforge.net/projects/galaxia/files/> and download Galaxia by clicking the big green button.
2. Go to your Downloads folder and untar the file by double-clicking it.
3. Move the untar'd folder (which should be called something like `galaxia-0.7.2`) to your home directory. (That's the directory where you get sent if you `cd` and don't put a location. On my laptop, it's `/Users/casey/`).
4. In your home directory, make a directory called `GalaxiaData` (i.e. `mkdir GalaxiaData`).
5. Move to the `galaxia-0.7.2` directory (i.e. `cd galaxia-0.7.2`), and in there, do the following (replacing `/Users/casey/` with your home directory as appropriate):

- `./configure --datadir=/Users/casey/GalaxiaData/`
- `make`
- `sudo make install`
- `cp -r GalaxiaData/ /Users/casey/GalaxiaData/`

6. Move back into your home directory (i.e. `cd`), then run the following:

- `galaxia -s warp`

That should be it! You don't have to install `ebf` if you just download PopSyCLE!

NOTE: the instructions in step 5 are assuming a root install. If you want to do a local install, you need to have a folder for the software to be installed in. For example, in my home directory I made a `sw` directory (`/Users/casey/sw`) for `galaxia` to be installed in. Then I ran the following instead:

- `./configure --prefix=/Users/casey/sw --datadir=/Users/casey/GalaxiaData/`
- `make`
- `make install`
- `cp -r GalaxiaData/ /Users/casey/GalaxiaData/`

Also, you need to export `galaxia` to your path. In your `.bash_profile`, add the line `export PATH=$PATH:/Users/casey/sw/bin`. Then proceed with step 6 in the installation instructions.

### 1.1.2 Uninstallation

You need to remove the compiled `galaxia` code (you can find where it is by typing `which galaxia` in the terminal), the `GalaxiaData` directory, and you might as well remove the `galaxia-0.7.2` directory also. When you do `which galaxia` nothing should be returned.

### 1.1.3 Parameter modification

Suppose you want to change the pattern speed in `Galaxia`. To do this, follow the installation instructions up to and including step 4. Then do the following:

1. Move to the `galaxia-0.7.2/src` directory.
2. Open the `Population.h` file with your favorite text editor.
3. Find the pattern speed (in this case by searching for 71.62) and replace with your desired value (in this case 40.00).
4. Save the change.

Now return to step 5 in the installation instruction and proceed as instructed.

## 1.2 Installing PopStar

PopStar can be installed by cloning the repository from <https://github.com/astropy/PopStar>.

## 1.3 Installing Python libraries

We recommend the Anaconda distribution. In particular, numpy v1.13 or higher is required, along with Astropy and H5py.

## 2 Reading files

PopSyCLE use all sorts of different file formats. It can easily get confusing, so here is a short guide to the basics.

### 2.1 How to read HDF5 files

Within the HDF5 file are datasets that store the information. It is kind of like a dictionary in python– the dataset can be manipulated just like a numpy array.

First, go to the directory containing the HDF5 file you want to open. Next, start ipython. Then type the following:

```
import h5py

hf = h5py.File('filename.h5', 'r').
```

If you want to see the names of all the datasets in an HDF5 file, type the following:

```
list(hf.keys()).
```

Suppose you want to work with the dataset named `dname`. To access the dataset, type:

```
dset = hf['dname'].
```

Note that only one person at a time can work on an open HDF5 file. Thus, at the end, you need to close the file:

```
hf.close().
```

### 2.2 How to read EBF files

The EBF file is basically a dictionary in python. The output of `Galaxia` is in the EBF format.

First, go to the directory containing the EBF file you want to open. Next, start ipython. Then type the following:

```
import ebf

ef = ebf.read('filename.ebf', '/').
```

If you want to see the names of all the keys in the EBF file, type the following:

```
ef.keys().
```

Suppose you want to work with the key `xkey`. To access that part of the file, type:

```
x = ef['xkey'].
```

Now `x` is just a numpy array and can be manipulated as such.

## 2.3 How to read FITS table files

First, go to the directory containing the fits file you want to open. Next, start ipython, Then type the following:

```
from astropy.table import Table  
  
tab = Table.read('table.fits')
```

To view the entire table, just type `tab`. The table works similar to a python dictionary. The column names are the keys of the dictionary, and the dictionary name in this case is `tab`.

To view the header information/metadata, type

```
tab.meta.
```

### 3 Description of Pipeline

First, run `Galaxia` to create an EBF file, which produces a synthetic survey, i.e. a bunch of stars. Next, run population synthesis (`perform_pop_syn`) to inject compact objects into the synthetic survey; both the compact objects and stars are saved in an HDF5 file. Then run a synthetic survey (`calc_events` and `refine_events`) that will produce a list of microlensing events, which are listed in a FITS file.

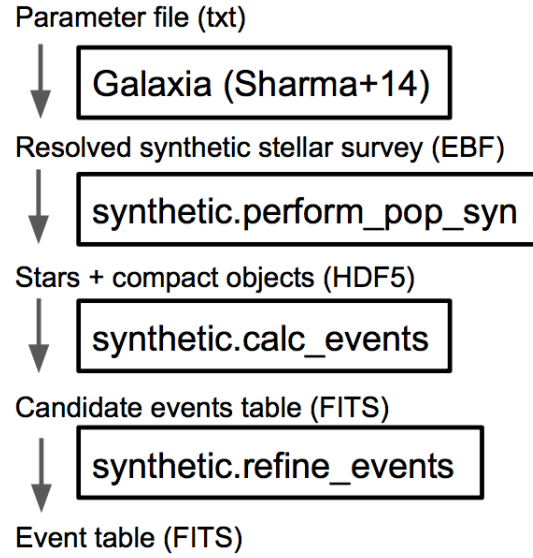


Figure 1: Flowchart of pipeline.

## 4 Outputs

In addition to the outputs about to be described, each function produces a text log file that lists the input parameters.

### 4.1 perform\_pop\_syn

#### 4.1.1 Label/summary file (Astropy FITS table)

- file\_name is the name of the dataset for the HDF5 file.
- long\_start and long\_end are the edges of the longitude bin.
- lat\_start and lat\_end are the edges of the latitude bin.
- objects is the number of objects in that latitude/longitude bin.
- N\_stars, N\_WD, N\_NS, and N\_BH are the number of stars, white dwarfs, neutron stars, and black holes, respectively, in that latitude/longitude bin. The sum of these should be equal to the total number of objects.

Total white dwarfs is equal to adding the numbers of WDs made from MIST and the IFMR. WDs from the MIST models have photometry (they're bright), while WDs from the IFMR and are dark (roughly 30th magnitude and below, so we assign them a value of `nan` for their magnitude.)

<Table length=36>									
file_name	long_start	long_end	lat_start	lat_end	objects	N_stars	N_WD	N_NS	N_BH
bytes4	float64	float64	float64	float64	int64	int64	int64	int64	int64
10b0	0004.938	0004.959	001.938	001.959	0	0	0	0	0
10b1	0004.938	0004.959	001.959	001.979	38758	36313	2318	96	31
10b2	0004.938	0004.959	001.979	002.000	98252	92115	5761	240	136
10b3	0004.938	0004.959	002.000	002.021	98131	91989	5794	228	120
10b4	0004.938	0004.959	002.021	002.041	38538	36115	2274	100	49
10b5	0004.938	0004.959	002.041	002.062	0	0	0	0	0
11b0	0004.959	0004.979	001.938	001.959	37973	35635	2196	102	40
11b1	0004.959	0004.979	001.959	001.979	146343	137172	8605	388	178
11b2	0004.959	0004.979	001.979	002.000	146929	137769	8616	351	193
11b3	0004.959	0004.979	002.000	002.021	146109	136923	8587	395	204
11b4	0004.959	0004.979	002.021	002.041	143826	134865	8427	368	166
11b5	0004.959	0004.979	002.041	002.062	37739	35391	2206	83	59
12b0	0004.979	0005.000	001.938	001.959	97024	90831	5836	232	125
12b1	0004.979	0005.000	001.959	001.979	146781	137554	8635	392	200
12b2	0004.979	0005.000	001.979	002.000	146107	136876	8685	363	183
12b3	0004.979	0005.000	002.000	002.021	145358	136289	8503	366	200
12b4	0004.979	0005.000	002.021	002.041	144969	135597	8828	374	170
12b5	0004.979	0005.000	002.041	002.062	96090	89816	5904	249	121
13b0	0005.000	0005.021	001.938	001.959	97227	91158	5710	240	119
13b1	0005.000	0005.021	001.959	001.979	145371	136211	8609	363	188
13b2	0005.000	0005.021	001.979	002.000	145038	135760	8671	395	212
13b3	0005.000	0005.021	002.000	002.021	144262	135128	8564	368	202
13b4	0005.000	0005.021	002.021	002.041	143560	134530	8494	365	171
13b5	0005.000	0005.021	002.041	002.062	94873	88947	5598	217	111
14b0	0005.021	0005.041	001.938	001.959	37743	35294	2304	94	51
14b1	0005.021	0005.041	001.959	001.979	144179	135039	8618	332	190
14b2	0005.021	0005.041	001.979	002.000	143802	134786	8474	351	191
14b3	0005.021	0005.041	002.000	002.021	143790	134876	8383	355	176
14b4	0005.021	0005.041	002.021	002.041	141147	132257	8346	365	179
14b5	0005.021	0005.041	002.041	002.062	37238	34878	2232	90	38
15b0	0005.041	0005.062	001.938	001.959	0	0	0	0	0
15b1	0005.041	0005.062	001.959	001.979	37987	35590	2232	102	63
15b2	0005.041	0005.062	001.979	002.000	95712	89565	5769	247	131
15b3	0005.041	0005.062	002.000	002.021	95154	89039	5759	231	125
15b4	0005.041	0005.062	002.021	002.041	37353	35027	2174	99	53
15b5	0005.041	0005.062	002.041	002.062	0	0	0	0	0



#### 4.1.2 Stars and compact objects (HDF5)

The data output contained in the HDF5 datasets are a combination of outputs that come directly from Galaxia, and outputs we ourselves have calculated or defined.

Index	Tag name	Brief Description	Units
[0]	zams_mass	ZAMS mass	$M_{\odot}$
[1]	rem_id	Integer indicating the remnant object type (more details in tag description)	N/A
[2]	mass	Current mass	$M_{\odot}$
[3]	px	Heliocentric x position	kpc
[4]	py	Heliocentric y position	kpc
[5]	pz	Heliocentric z position	kpc
[6]	vx	Heliocentric x velocity	km/s
[7]	vy	Heliocentric y velocity	km/s
[8]	vz	Heliocentric z velocity	km/s
[9]	rad	Galactic radial distance	kpc
[10]	glat	Galactic latitude	deg
[11]	glon	Galactic longitude	deg
[12]	vr	Galactic radial velocity	km/s
[13]	mu_b	Galactic proper motion, b component	mas/yr
[14]	mu_lcosb	Galactic proper motion, l component	mas/yr
[15]	age	Age	log(age/yr)
[16]	popid	Population ID– integer indicating the population type ranging from 0 to 9	N/A
[17]	ubv_k	UBV photometric system, K-band absolute magnitude	mag
[18]	ubv_i	UBV photometric system, I-band absolute magnitude	mag
[19]	exbv	Extinction E(B-V) at the location of star given by 3-D Schlegel extinction maps	mag
[20]	obj_id	Object ID– unique integer to identify star/compact object	N/A
[21] – [26]	ubv_j, u, r, b, h, v	UBV photometric system, J, U, R, B, H, V absolute magnitude (in this order)	mag

Table 1: Note that the tag names are NOT used in the HDF5 files. They are just listed here to show the direct correspondence between the HDF5 outputs and the Astropy table of candidate events (next section.)

For stars (which are generated by Galaxia), the following outputs are taken directly from Galaxia and just reformatted into the HDF5 format; parenthetical names correspond to the tag name from Galaxia, if different: zams\_mass (smass), mass (mact), px, py, pz, vx, vy, vz, age, popid, ubv\_k, ubv\_i, ubv\_u, ubv\_b, ubv\_v, ubv\_r, ubv\_j, ubv\_h, exbv (exbv\_schlegel). For compact objects (which we generated with our population synthesis code), we must assign these values ourselves. For both stars and compact objects, the following are things we have directly calculated or assigned ourselves: rem\_id, rad, glat, glon, vr, mu\_b, mu\_lcosb, obj\_id.<sup>1</sup>

<sup>1</sup>For reasons relating to managing RAM, we calculate rad, glat, and glon although they are an output given directly from Galaxia, and we could have just read in the value. However, it can be calculated directly from knowledge of px, py, and pz.

## 4.2 calc\_events

### 4.2.1 Event candidates table (Astropy FITS table)

The event candidates table is very similar to the HDF5 file created in `perform_pop_syn`. (In fact, the top part is completely duplicated; it's here for completeness.) However, the main difference is that there is a LOT less of the output, so instead of writing it in arrays in an HDF5 file, we use an Astropy table.

Tag name	Brief Description	Units
zams_mass (L, S)	ZAMS mass	$M_{\odot}$
rem_id (L, S)	Remnant ID– integer indicating the remnant object type ranging from 0 to 3	N/A
mass (L, S)	Current mass	$M_{\odot}$
px (L, S)	Heliocentric x position	kpc
py (L, S)	Heliocentric y position	kpc
pz (L, S)	Heliocentric z position	kpc
vx (L, S)	Heliocentric x velocity	km/s
vy (L, S)	Heliocentric y velocity	km/s
vz (L, S)	Heliocentric z velocity	km/s
rad (L, S)	Galactic radial distance	kpc
glat (L, S)	Galactic latitude b	deg
glon (L, S)	Galactic longitude l	deg
vr (L, S)	Galactic radial velocity	km/s
mu_b (L, S)	Galactic proper motion, b component	mas/yr
mu_lcosb (L, S)	Galactic proper motion, l component	mas/yr
age (L, S)	Age	$\log(\text{age/yr})$
popid (L, S)	Population ID– integer indicating the population type ranging from 0 to 9	N/A
ubv_u, b, v, i, r, j, h, k (L, S)	UBV photometric system absolute magnitudes	mag
exbv (L, S)	Extinction E(B-V) at the location of star given by 3-D Schlegel extinction maps	mag
obj_id (L, S)	Object ID– unique integer to identify star/compact object	N/A
theta_E	(Angular) Einstein radius	mas
mu_rel	Relative source-lens proper motion	mas/yr
u0	(Unitless) minimum source-lens separation, <i>during</i> the survey	dim'less (normalized to $\theta_E$ )
t0	Time at which minimum source-lens separation occurs	days

Tag names ARE used for the Astropy table. You will see a lot of the tag names have a parenthetical after (L, S). That is to indicate there is one tag for the lens (L) and one for the source (S), since for a given event, you need to have both a lens and a source, and each of these things has a mass, a velocity, a position, etc. For example, `zams_mass.L` is the ZAMS mass of the lens, and `age.S` is the  $\log(\text{age/yr})$  of the source.

#### 4.2.2 Blends table (Astropy FITS table)

For each candidate microlensing event, associated with it are blended stars, which we call neighbors. Given the blend radius chosen when running `calc_events`, the blend table saves all neighbor stars that fall within that distance from the lenses in the candidate events table. The blends table is again almost identical to the HDF5 output, but is has three additional items. For each neighbor star, it lists the object ID of the lens and source it is associated with, and the distance between itself and the lens. Note that there can be multiple neighbor stars associated with a single lens and source (microlensing event).

Tag name	Brief Description	Units
zams_mass_N	ZAMS mass	$M_{\odot}$
rem_id_N	Remnant ID– integer indicating the remnant object type ranging from 0 to 3	N/A
mass_N	Current mass	$M_{\odot}$
px_N	Heliocentric x position	kpc
py_N	Heliocentric y position	kpc
pz_N	Heliocentric z position	kpc
vx_N	Heliocentric x velocity	km/s
vy_N	Heliocentric y velocity	km/s
vz_N	Heliocentric z velocity	km/s
rad_N	Galactic radial distance	kpc
glat_N	Galactic latitude b	deg
glon_N	Galactic longitude l	deg
vr_N	Galactic radial velocity	km/s
mu_b_N	Galactic proper motion, b component	mas/yr
mu_lcosb_N	Galactic proper motion, l component	mas/yr
age_N	Age	log(age/yr)
popid_N	Population ID– integer indicating the population type ranging from 0 to 9	N/A
ubv_u, b, v, i, r, j, h, k_N	UBV photometric system absolute magnitudes	mag
exbv_N	Extinction E(B-V) at the location of star given by 3-D Schlegel extinction maps	mag
obj_id_N	Object ID– unique integer to identify star/compact object	N/A
obj_id_L	Object ID of the lens	N/A
obj_id_S	Object ID of the source	N/A
sep_LN	Separation between lens and neighbor	arcsec

### 4.3 refine\_events

#### 4.3.1 Events table (Astropy FITS table)

The output here is very similar to the candidate events table. In fact, part of it is completely duplicated. All tags listed in the event candidates table are also part of the events table. However, the following columns are also appended. NOTE: the entries for `u0` and `t0` are *overwritten*; the values for `u0` and `t0` returned from `calc_events` is different from that returned in `refine_events`. Each `refine_events` file requires you to choose a filter and extinction law; in this table we suppose filter  $x$  is chosen.

Tag name	Brief Description	Units
<code>u0</code>	(Unitless) minimum source-lens separation, <i>during</i> the survey	dim'less
<code>t0</code>	Time at which minimum source-lens separation occurs	days
<code>delta_m_x</code>	Bump amplitude (difference in baseline and maximum magnification magnitude) in $x$ -band	mag
<code>pi_rel</code>	Relative parallax	mas
<code>pi_E</code>	Microlensing parallax	dim'less
<code>t_E</code>	Einstein crossing time	days
<code>ubv_x_app (L, S)</code>	UBV photometric system, $x$ -band apparent magnitude, with extinction	mag
<code>ubv_x_LSN</code>	Blended magnitude in $x$ band (Apparent magnitude of source + lens + neighbors)	mag
<code>f_blend_x</code>	Source flux fraction (unlensed source flux divided by baseline) in $x$ -band	dim'less
<code>cent_glon_x_N</code>	Galactic longitude $l$ of neighbor stars' centroid	deg
<code>cent_glat_x_N</code>	Galactic latitude $b$ of neighbor stars' centroid	deg
<code>ubv_x_app_N</code>	Apparent magnitude of neighbor stars, $x$ -band apparent magnitude	mag

## 4.4 Additional descriptions of tags

**rem\_id** These label the different types of remnant objects (star, black hole, neutron star, or white dwarf.) They are identified as following:

- 0: Star
- 101: WD
- 102: NS
- 103: BH

**popid** Describes which population is generated.<sup>2</sup> They are identified as following:

- 0: Thin disk,  $\leq 0.15$  Gyr
- 1: Thin disk, 0.15-1 Gyr
- 2: Thin disk, 1-2 Gyr
- 3: Thin disk, 2-3 Gyr
- 4: Thin disk, 3-5 Gyr
- 5: Thin disk, 5-7 Gyr
- 6: Thin disk, 7-10 Gyr
- 7: Thick disk, 11 Gyr (single-age)
- 8: Stellar halo, 14 Gyr (single-age)
- 9: Bulge, 10 Gyr (single-age)

**px, py, pz; vx, vy, vz** These are given in heliocentric coordinates (i.e. Cartesian coordinates with the sun at the origin.) See subsection on coordinate systems for more information.

**rad, glat, glon; vr, mu\_b, mu\_lcosb** These are given in galactic coordinates (i.e. spherical coordinates with the sun at the origin.) See subsection on coordinate systems for more information.

**ubv\_u, b, v, r, i, j, h, k; exbv** Photometry information is given in absolute magnitude. For NSs and BHs, all these values are **nan** to indicate they are dark.

**t0** Note that you can have a negative day (this just means time before the “zero” time, which is defined as the state of the system that is generated by Galaxia and the population synthesis. Since we are assuming everything moves in straight lines, we can propagate either forward or backwards.

---

<sup>2</sup>In **Galaxia** there is an option for a 10th population type; the Bullock and Johnston stellar halos. We have chosen not use it, and the code is not written to include it.

## 5 Coordinates Systems

There are two different coordinate systems used, Heliocentric and Galactic. Heliocentric coordinates are Cartesian coordinates with the sun at the origin. The positive  $x$  axis is pointing toward the Galactic Center, and the positive  $z$  axis is pointing toward the Galactic North Pole. Galactic coordinates are spherical coordinates with the sun at the origin. Longitude  $l$  is measuring the angular distance of an object eastward along the galactic equator from the galactic center, and latitude  $b$  is measuring the angle of an object north or south of the galactic equator (or midplane) as viewed from Earth; positive to the north, negative to the south. Radius  $r$  is the distance from the sun to the object.

The conversion between Heliocentric and Galactic is just the same as converting between rectangular to spherical coordinates, where  $\phi = l$  and  $\theta = -b + 90^\circ$ . Going from Galactic to Heliocentric (units are degrees):

$$\begin{aligned}x &= r \sin(-b + 90^\circ) \cos l = r \cos b \cos l \\y &= r \sin(-b + 90^\circ) \sin l = r \cos b \sin l \\z &= r \cos(-b + 90^\circ) = r \sin b\end{aligned}$$

Going from Heliocentric to Galactic (units are degrees):

$$\begin{aligned}r &= \sqrt{x^2 + y^2 + z^2} \\b &= -\cos^{-1}(z/r) + 90^\circ \\l &= \tan^{-1}(y/x)\end{aligned}$$

Note: be careful with the branch of arctangent. Practically, use `numpy.arctan2` if using Python.

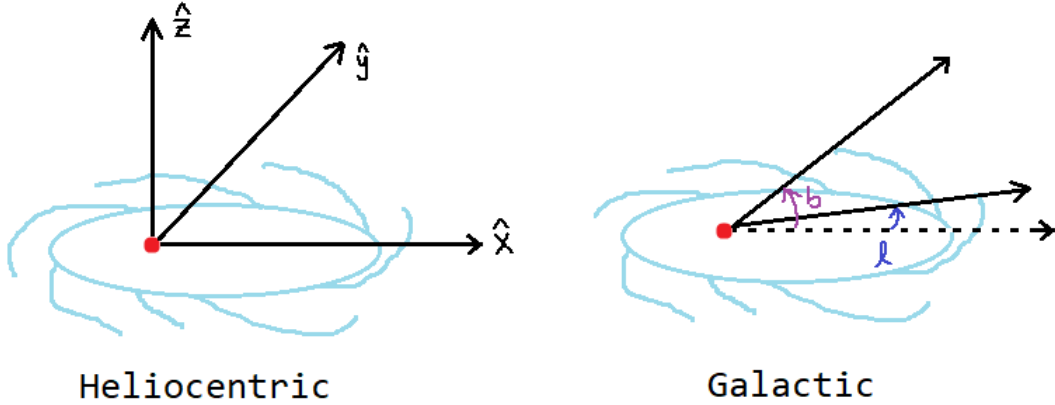


Figure 2: Diagram of Heliocentric and Galactic coordinate systems. The red dot is the sun.