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# **imcascade**

*Release 0.1*

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**Sep 03, 2023**



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Welcome to the documentation for `imcascade`. It is a non-parametric framework for fitting astronomical images to study the morphological properties of galaxies and other objects. This is accomplished by modelling them as a series (or cascade) of Gaussians

If you are planning on using `imcascade`, it is strongly recommended to read the paper describing the method, available [here](#)



## INSTALLATION

The source code for `imcascade` is stored on [github](#)

To install `imcascade` simply clone the github repo and run the `setup.py` install script. This is the best way to make sure you are using the most up to date version.

```
$ cd < Directory where imcascade will be installed >
$ git clone https://github.com/tbmiller-astro/imcascade
$ cd imcascade
$ python setup.py install
```

We have also uploaded our code to PyPI so you can install `imcascade` with `pip`

```
$ pip install imcascade
```

### 1.1 Dependencies

`imcascade` is written purely in Python and requires the following packages, all of which can be installed using either `pip install` or `conda install`

- `numpy`
- `scipy`
- `matplotlib`
- `astropy`
- `numba`
- `sep`
- `dyensty`
- `asdf`

Optionally, you can also install `jax`, this speeds up the express sampling by a decent margin. It is left as optional as it cannot currently be installed easily on all systems. To install `jax` follow the instructions [here](#).

`imcascade` was developed and tested using Python 3, but it may also work in Python 2 if the required packages can be installed, but be careful that it has not been properly vetted.



## QUICKSTART GUIDE

`imcascade` is a method to fit sources in astronomical images. This is accomplished using the multi-Gaussian expansion method which models the galaxy as a mixture of Gaussians. For more details please read the in-depth example. What follows is a (very) brief introduction to the basic usage of `imcascade`.

In this short example we will fit an analytic, circular, Sersic profile with  $n = 1.5$ ,  $r_e = 6$  and total flux,  $F = 250$ , we have convolved the profile with a Moffat PSF with  $\alpha = 3$  and  $\gamma = 3$  and added purely Gaussian noise.

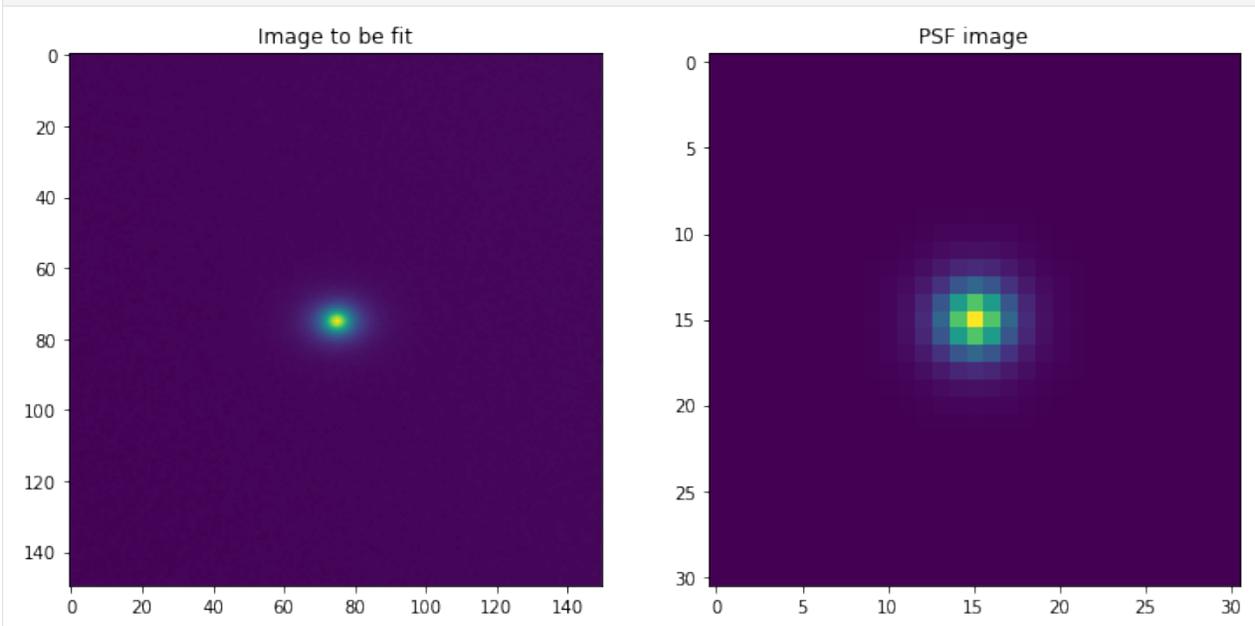
In a hidden cell I have initialized the cutout in the 2D array `sci` and the pixelized PSF saved in the 2D array `psf`. Below I show to 2D images of each

```
[2]: fig,(ax1,ax2) = plt.subplots(1,2, figsize = (12,6))
```

```
ax1.imshow(sci)  
ax1.set_title('Image to be fit')
```

```
ax2.imshow(psf)  
ax2.set_title('PSF image')
```

```
plt.show()
```



The `initialize_fitter` function is designed to take a pixelized science images (as 2D arrays or fits files) and help initialize a `Fitter` instance which will be used below to fit galaxies. This function is designed to help users get started

using our experiences to help guide some of the decisions, which may not be applicable in all situations. For more details about these choices or other options please see [the in depth example](#) for a longer discussion about all possibilities.

```
[3]: from imcascade.fitter import initialize_fitter

fitter = initialize_fitter(sci,psf)

2022-07-12 17:48:19,219 - Fit PSF with 4 components
2022-07-12 17:48:19,220 - Widths: 1.2,1.81,5.28,2.93
2022-07-12 17:48:19,221 - Fluxes: 0.27,0.51,0.03,0.19
2022-07-12 17:48:19,231 - Using 9 components with logarithmically spaced widths to fit
↳galaxy
2022-07-12 17:48:19,232 - 0.91, 1.52, 2.55, 4.27, 7.15, 11.97, 20.04, 33.54, 56.15
2022-07-12 17:48:19,233 - No mask was given, deriving one using sep
2022-07-12 17:48:19,246 - Using sep rms map to calculate pixel weights
```

This function uses the `psf_fitter` module to fit the given pixelized psf with a sum of Gaussians, which is required for our method. Next it estimates the effective radius and uses nine logarithmically spaced widths for the Gaussian components ranging from the PSF HWHM to  $10 \times r_e$ . It then derives pixel weights and masks using `sep` (or the gain, exposure time and readnoise to calculate the rms). There are also options to use pre-calculated version of these if the user has them.

Now we will run our least-squares minimization routine

```
[4]: opt_param = fitter.run_ls_min()
print (opt_param)

2022-07-12 17:48:21,366 - Running least squares minimization
2022-07-12 17:48:47,347 - Finished least squares minimization

[ 7.60051373e+01  7.50005090e+01  6.87265676e-01  1.57715338e+00
 1.42502826e+00 -2.57490313e+00  1.53411116e+00  1.81786238e+00
 1.87217228e+00  1.63625068e+00  7.22478506e-01 -1.31211431e+00
 4.65480859e-01 -2.74388677e-05 -9.73687762e-05  1.91394558e-04]
```

We have printed out the parameters that describe the best fit model. The first four are the structural parameters (x position, y position, axis ratio and position angle) then the next nine represent the fluxes or weights of the nine components (in logarithmic space) and the final three parameters for the tilted-plane sky model.

Obviously this is non-trivial to parse, which is why we will use our `results` module and the `ImcascadeResults` class to help us analyze the results

```
[7]: from imcascade.results import ImcascadeResults
res_class = ImcascadeResults(fitter)
res_class.run_basic_analysis()

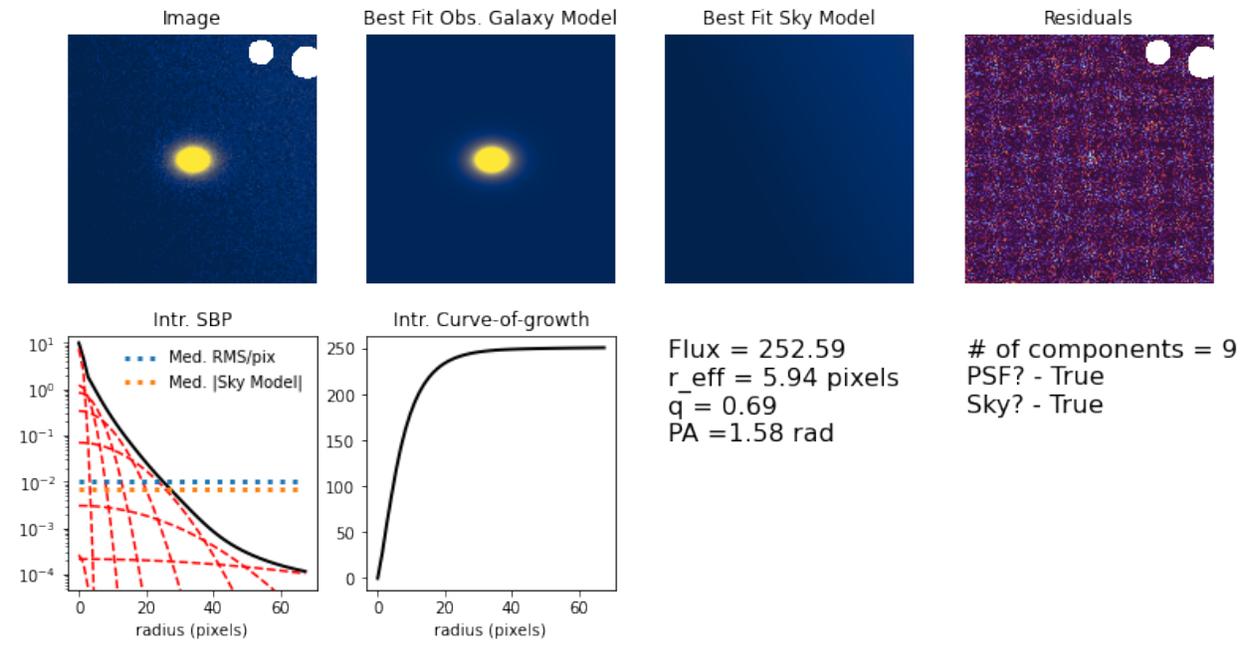
[7]: {'flux': 252.58989931777214,
      'r20': 2.305274076411796,
      'r50': 5.940674533616872,
      'r80': 12.340978912963354,
      'r90': 17.43337150701717,
      'C80_20': 5.353367323755417,
      'C90_50': 2.934577783779577}
```

The function `.run_basic_analysis()` calculates some basic morphological quantities like the total flux and half-light radius. We can see that the best fit parameters match the inputs pretty well!

Another very useful function is the `.make_diagnostic_fig()` this makes a figure which helps inspect the fit

```
[8]: fig = res_class.make_diagnostic_fig()
```

```
/mnt/c/Users/timbl/Documents/files/research/packages/imcascade/imcascade/results.py:707:
↳ RuntimeWarning: divide by zero encountered in true_divide
rms_med = np.median(1./np.sqrt(fitter.weight) )
```



This makes it easier to see if the fit went catastrophically wrong. This fit looks pretty good! Some examples of issues are if the curve-of-growth does not converge or if there are systematic issues in the residuals. To remedy this one could try using a different set of widths for the components, altering the initial guesses or making sure all the input data is correct.

Next we will explore the Posterior distribution using Dynesty. Specifically we will use the ‘express’ method which uses pre-rendered images to help speed up the run time. The code also automatically checks to see if the package jax is installed. This additionally helps to speed up the computation if available.

```
[ ]: post = fitter.run_dynesty(method = 'express')
```

Now if we re-initialize the results class, we can calculate uncertainties on the morphological values.

```
[9]: res_class_w_post = ImcascadeResults(fitter)
res_class_w_post.run_basic_analysis()
```

```
[9]: {'flux': array([249.31304659,  1.36354565,  1.27251959]),
'r20': array([2.3907311,  0.01458799,  0.01400204]),
'r50': array([5.88510278,  0.03870749,  0.03532017]),
'r80': array([12.00401554,  0.13302446,  0.1238212 ]),
'r90': array([16.70281417,  0.28503741,  0.2769434 ]),
'C80_20': array([5.0199006,  0.03832022,  0.03772956]),
'C90_50': array([2.83774779,  0.03312112,  0.03330771])}
```



## IN-DEPTH EXAMPLE

In this notebook we will be going through an example of running `imcascade` in a realistic setting and discussing issues along the way

```
[1]: #Load all necessary packages
import numpy as np
import matplotlib.pyplot as plt
import time
import sep

import astropy.units as u
from astropy.coordinates import SkyCoord
```

For this example we will be running `imcascade` on HSC data on a MW mass galaxy at  $z=0.25$ . The data is attained in the cell below and is retrieved using the `unagi` python package available [here](#), written by Song Huang. The cell below is used to download the data and the PSF

```
[2]: from unagi import hsc
from unagi.task import hsc_psf, hsc_cutout
pdr2 = hsc.Hsc(dr='pdr2', rerun = 'pdr2_wide')

#Downloaded from HSC archive, this a MW mass galaxy at z~0.25 at the sky location below
ra, dec = 219.36054754*u.deg, -0.40994375*u.deg
examp_coord = SkyCoord(ra = ra, dec = dec)
cutout = hsc_cutout(examp_coord, cutout_size=20*u.arcsec, filters='i', archive = pdr2,
↳ dr = 'pdr2', verbose=True, variance=True, mask=True, save_output = False)
psf = hsc_psf(examp_coord, filters='i', archive=pdr2, save_output = False)

#Retrieve science and variance images
img = cutout[1].data.byteswap().newbyteorder()
var = cutout[3].data.byteswap().newbyteorder()
psf_data = psf[0].data

# Get table list from /home/tbm/anaconda3/envs/py3/lib/python3.8/site-packages/unagi/
↳ data/pdr2_wide/pdr2_wide_tables.fits
# Retrieving cutout image in filter: i
# Retrieving coadd PSF model in filter: i
```

## 3.1 Setting up

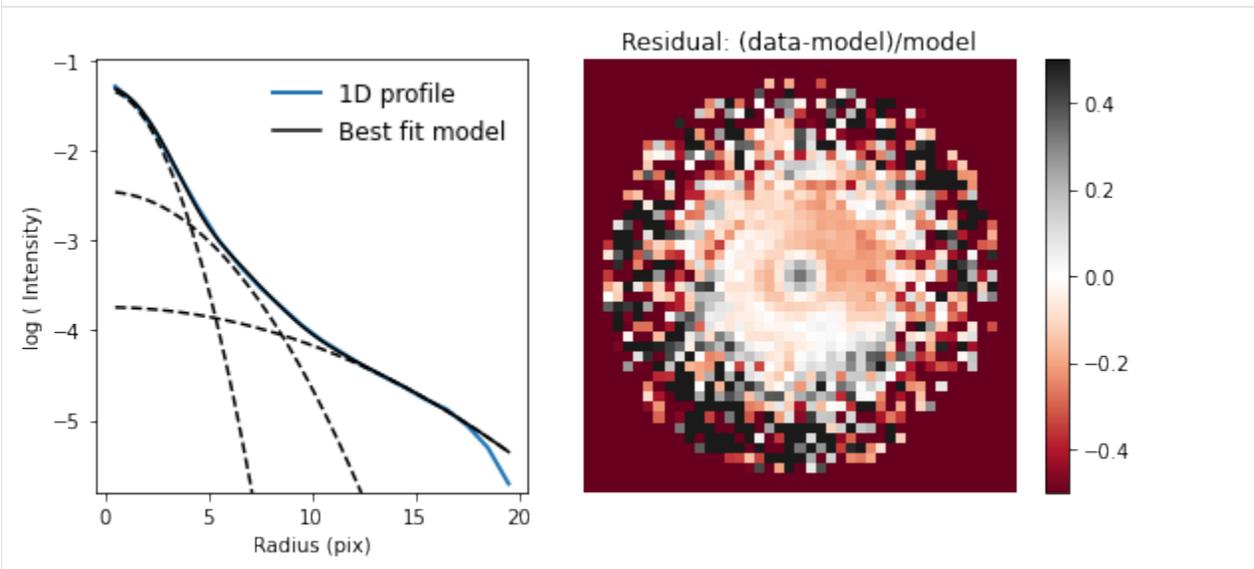
### 3.1.1 Modelling the PSF

To use `imcascade` while accounting for the PSF, you need to have a Gaussian decomposition of the PSF. While this is available for some surveys, you can use the `imcascade.psf_fitter` module to help if you have a pixelized version.

The following function first fits the PSF profile in 1D to decide what the best widths are. Then a 2D fit is used to find the correct weights

```
[3]: from imcascade.psf_fitter import PSFFitter
psf_fitter = PSFFitter(psf_data)
psf_sig,psf_a,chi2, fig = psf_fitter.fit_N(3, plot = True) # Can choose number
print (psf_sig,psf_a)
plt.show()
```

```
[1.56676938  3.15624179  7.16928138] [0.72289466  0.21654144  0.05830564]
```

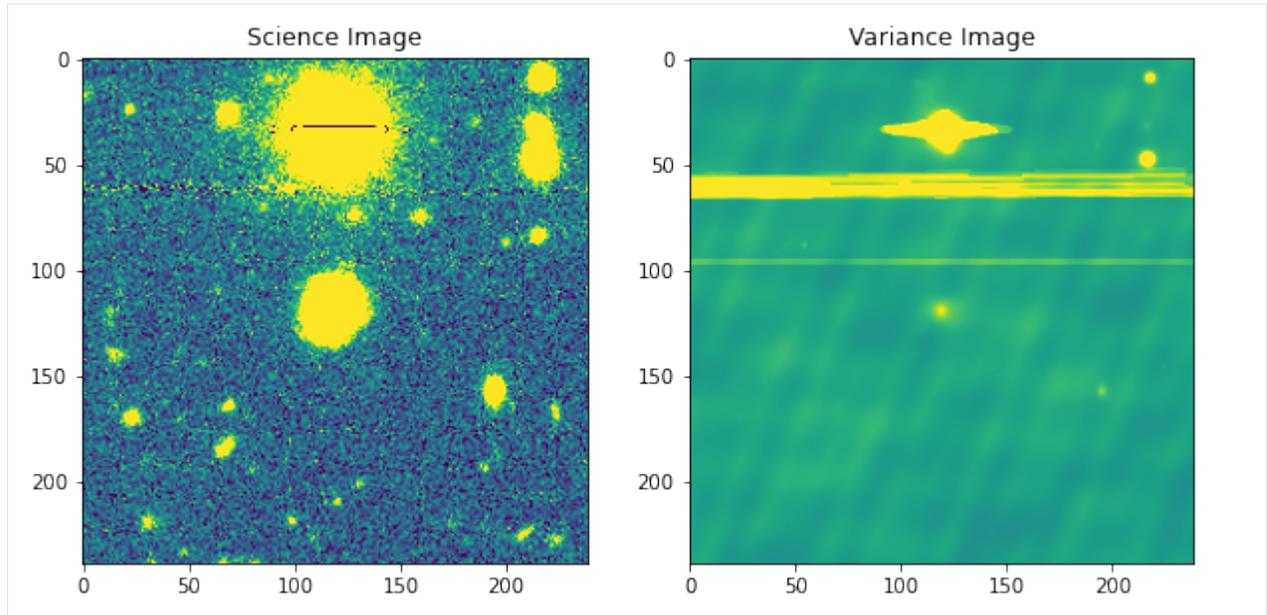


We can see that a model with three gaussians provides a pretty good fit! Generally we find 2-3 components works well for standard ground based telescopes and for more complicated PSFs, like HST WFC3, we find 4 works well. There is some incentive to use a small number of gaussians to define the PSF as it decreases the time to render a model image. Additionally it is good to check that the sum of the weights, `psf_a`, is close to one. This ensures the PSF, and the fit are properly normalized

### 3.1.2 Organizing all the inputs

First let's take a quick look at the science and variance images. We will be fitting a model to the science image and the inverse of the variance image will be used as the pixel weights when fitting

```
[4]: fig, (ax1,ax2) = plt.subplots(1,2, figsize = (10,5))
ax1.imshow(img, vmin = -0.1, vmax = 0.2)
ax1.set_title('Science Image')
ax2.imshow(var,vmin = 0, vmax = 0.005)
ax2.set_title('Variance Image')
plt.show()
```

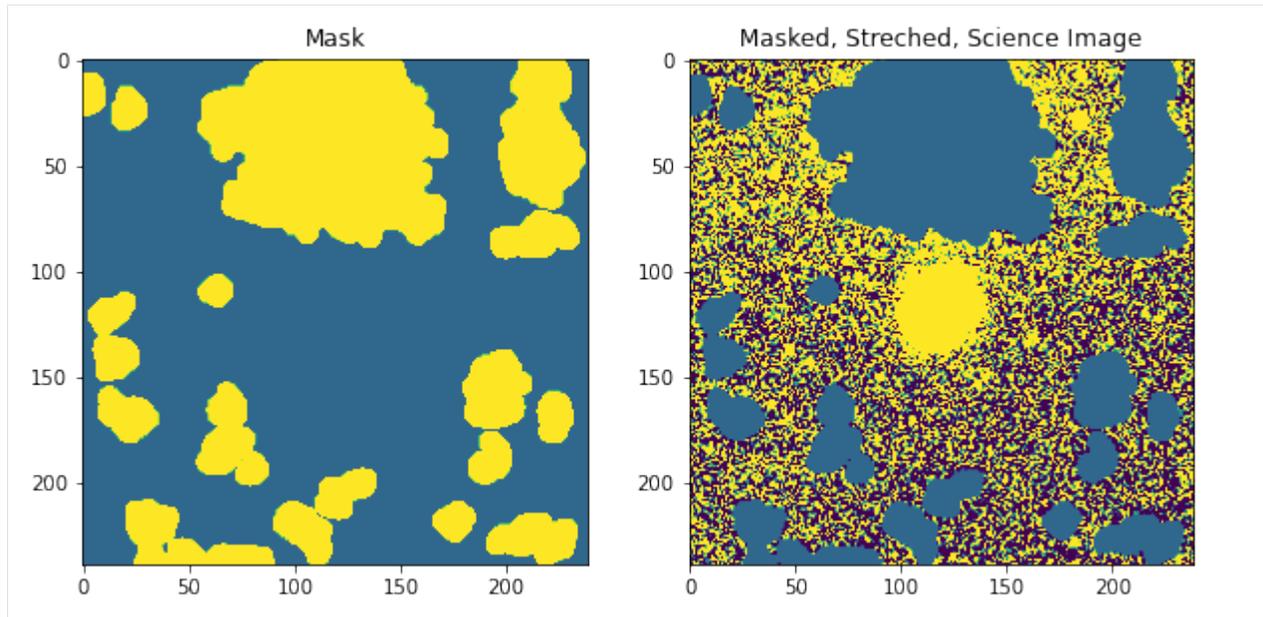


Additionally we will be building a mask to mask contaminating sources that we don't want affecting the fit

```
[5]: # Use sep to detect sources
bkg = sep.Background(img)
x_cent,y_cent = int(img.shape[0]/2.) , int(img.shape[1]/2.)
obj,seg = sep.extract(img - bkg.back(), 1.5, err = np.sqrt(var), deblend_cont = 0.005,
↳segmentation_map = True)
seg[np.where(seg == seg[x_cent,y_cent])] = 0
mask_raw = seg > 0

#Convolve mask with a gaussian to expand it and make sure that all low-SB emission is
↳masked
from imcascade.utils import expand_mask
mask = expand_mask(mask_raw, radius = 1.5)
mask = np.array(mask, dtype = bool)

fig, (ax1,ax2) = plt.subplots(1,2, figsize = (10,5))
ax1.imshow(mask, vmin = -0.1, vmax = 0.2)
ax1.set_title('Mask')
ax2.imshow(img*np.logical_not(mask),vmin = -0.01, vmax = 0.02)
ax2.set_title('Masked, Stretched, Science Image')
plt.show()
```



### 3.1.3 Choosing the widths for the Gaussian components

The next major decision is what set of widths to use for the Gaussian components. In general we recommend logarithmically spaced widths. This means there are more components at smaller radii where the signal is the largest and the profile changes the quickest. asinh scaling can also work.

Next we have to choose start and end points. This should be 0.75-1 pixel (or half the PSF width) to roughly 8-10 times the effective radius. The estimate of the effective radius does not need to be perfect, for example the Kron radius for sep or SExtractor works well. This should help decide the size of the cutout. In order to properly model the sky the cutout size should be at least 3-4 times larger than the largest width, so 30-40 times the effective radius.

Finally we have to choose the number of components. In our testing somewhere around 9-11 seems to work.

---

**Note:** These decisions are not trivial and can affect on the outcome of an `imcascade` fit. However reasonable changes within the confines discussed here shouldn't greatly affect the results. You should run tests to ensure you have chosen a reliable set of widths. If the results are very sensitive to the choice of widths, you should be wary and there may be other issues at play.

---

In this example we estimate the effective radius to be roughly 6 pixels so we use 9 components with logarithmically spaced widths from 1 pixels to 60 pixels ( $\sim 10 \times r_{\text{eff}}$ ) and use a cutout size of 240 pixels, roughly 40 times the effective radius.

```
[6]: sig = np.logspace(np.log10(1), np.log10(60), num = 9)
```

We can also specify initial conditions to help make initial guesses. Here we specify the estimated half light radii and total flux. The code makes some intelligent guesses on the initial conditions and the bounds but this may help ensure a quick and reliable fit. It is also possible to specify guesses and bounds for individual components, sky values etc. but this is more involved. See the user's guide for more details

```
[7]: init_dict = {'re': 6., 'flux': 1000.}
```

## 3.2 Running imcascade

### 3.2.1 Least squares-minimization

To run imcascade we first need to initialize a `Fitter` instance with all the inputs discussed above. This class organizes all the data and contains all the methods used to fit the image

```
[8]: from imcascade import Fitter
fitter = Fitter(img,sig, psf_sig, psf_a, weight = 1./var, mask = mask, init_dict = init_
↳dict)
```

Now we can run least squares minimization using the command below

```
[9]: min_res = fitter.run_ls_min()
2022-06-22 12:30:26,609 - Running least squares minimization
2022-06-22 12:30:53,368 - Finished least squares minimization
```

```
[10]: print (min_res)
[ 1.20224028e+02  1.18955019e+02  9.11389758e-01  2.29047642e+00
  2.20703755e+00 -1.99999486e+00  2.13014635e+00  2.55804376e+00
  2.85067400e+00 -1.99999840e+00  1.44969096e+00 -1.99999947e+00
 -1.99999996e+00  7.17048936e-03 -1.24392340e-04 -2.20482392e-05]
```

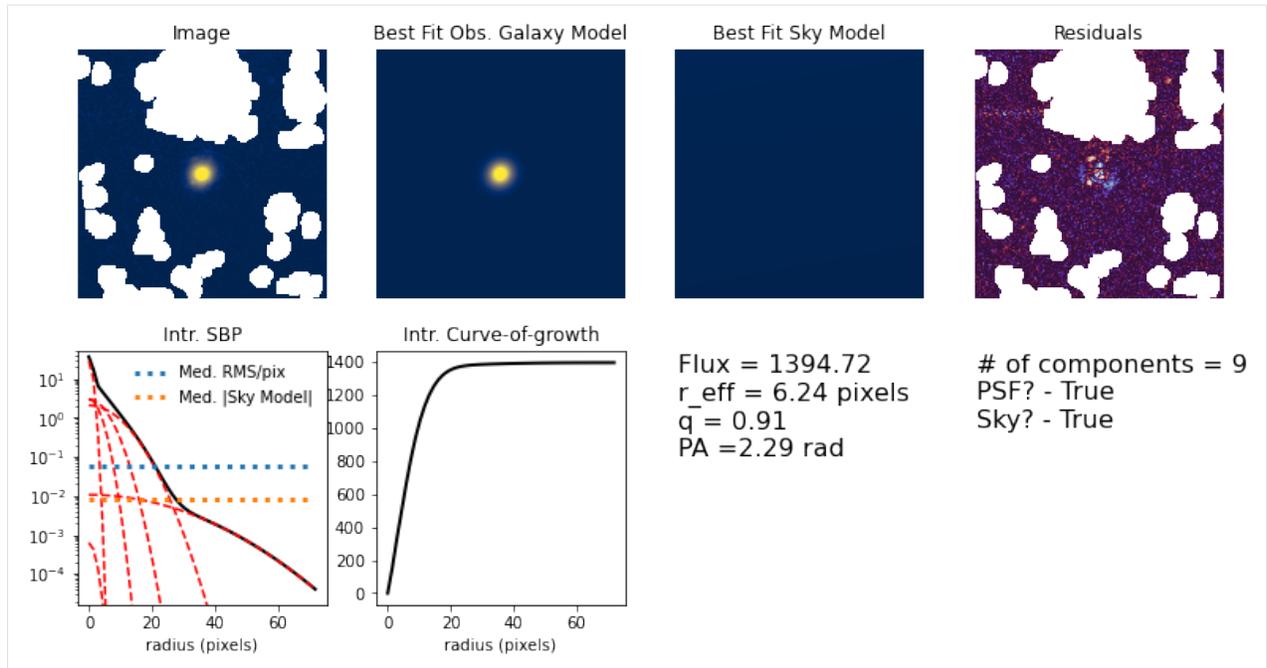
Here we have printed out the best-fit parameters. They are, in order,  $x_0, y_0$ , axis ratio and position angle. Then the next 9 values are the best fit weights for the Gaussian components. Note that by default imcascade explores these in log scale. This can be changed by passing the option `log_weight_scale = False` when initializing. The final three parameters describe the best fit tilted-plane sky model. They can also be disabled when initializing with `sky_model = False` or can be set to a flat sky model with `sky_type = 'flat'`.

These aren't super easy to parse as is, which is why we use the `ImcascadeResults` class, described below

```
[11]: from imcascade import ImcascadeResults

#Initialized using `imcascade.Fitter.fitter` instance
res_class = ImcascadeResults(fitter)
fig = res_class.make_diagnostic_fig()

/mnt/c/Users/timbl/Documents/files/research/packages/imcascade/imcascade/results.py:697:
↳RuntimeWarning: divide by zero encountered in true_divide
  rms_med = np.median(1./np.sqrt(fitter.weight) )
```



Here we have used the `make_diagnostic_fig()` function to help diagnose the fit. This figure shows the (masked) observed image, best fit model, sky and residuals. Along with some facts about the fit and the intrinsic surface brightness profile and curve-of-growth. From this it is easy to diagnose if something has gone catastrophically wrong. Such as: Major source not masked properly, poor convergence on fit, or the COG not asymptoting. Here we can see the fit performs pretty well, with no major issues!

### 3.2.2 Posterior estimation

Below we show the commands that could be used to use Bayesian techniques to explore the posterior distributions. Specifically we are using the “express” method discussed in the paper based on pre-rendered images. There are additional options when running `dynesty` using `imcascade`. Specifically we offer two choices of priors, the default is based on the results of the least-squares minimization, the other being uniform priors. We found the former runs quicker and more reliably as the priors are not as broad. It is also possible to set your own priors, see the Advanced section for more details.

```
> fitter.run_dynesty(method = 'express')
> fitter.save_results('./examp_results.asdf')
```

This is much quicker than the traditional method. However it still took about 15 min to run on my laptop. So I have run it previously and we will load the saved data.

### 3.3 Analyzing the results

Since when using `imcascade` the parameters that are fit are the fluxes of each Gaussian component, the analysis is more involved than other parameterized models, which fit directly for the total flux, radius etc. To assist in this we have written the `results` module and the `ImcascadeResults` class. This class can be initialized multiple ways. First you can pass it a `Fitter` instance after running `run_ls_min()` and/or `run_dynesty()`. Alternatively it can be passed a string which denotes the location of an ASDF file of the saved results

```
[12]: #Initialized with saved file
res_class_w_post = ImcascadeResults('examp_results.asdf')
```

`ImcascadeResults` will default to using the posterior to derive morphological parameters if it is available.

There are a number of functions we have written to calculate various morphological quantities, please see the API reference for all functions. For a lot of applications, one can simply run `run_basic_analysis()` which calculates a series of common morphological quantities

```
[13]: #we can also specify the percentiles used to calculate the error bars, here we use the
      ↪ 5th-95th percentile
res_class_w_post.run_basic_analysis(zpt = 27, errp_lo = 5, errp_hi = 95)
```

```
[13]: {'flux': array([1392.30063682,  8.20183351,  8.24031006]),
      'mag': array([1.91406674e+01, 6.40697201e-03, 6.41482156e-03]),
      'r20': array([2.45196295, 0.01713131, 0.01708627]),
      'r50': array([6.22617613, 0.03933737, 0.04009991]),
      'r80': array([11.42789865, 0.11402678, 0.11763424]),
      'r90': array([14.71073612, 0.22744139, 0.23404145]),
      'C80_20': array([4.66096268, 0.02856234, 0.02881198]),
      'C90_50': array([2.36285489, 0.02340729, 0.02374323])}
```

In addition to these integrated quantities, we can calculate the surface brightness profile and curve-of-growth as a function of semi-major axis

```
[14]: #Set of radii to calculate profiles at
rplot = np.linspace(0, 50, num = 100)

#Here we will calculate the posterior distribution of the surface_brightness profile
sbp_all = res_class_w_post.calc_sbp(rplot)
print (sbp_all.shape)

#Here we calculate the curve-of-growth for the posterior
cog_all = res_class_w_post.calc_cog(rplot)

(100, 29206)
```

If you use `res_class_w_post` where the posterior distribution is available it will return a 2D array containing the SBP of each sample of the posterior.

Now we plot many grey lines which show individual samples from the posterior

```
[15]: fig, (ax1,ax2) = plt.subplots(1,2, figsize = (12,5))
ax1.plot(rplot, sbp_all[:,::100], 'k-', alpha = 0.05)

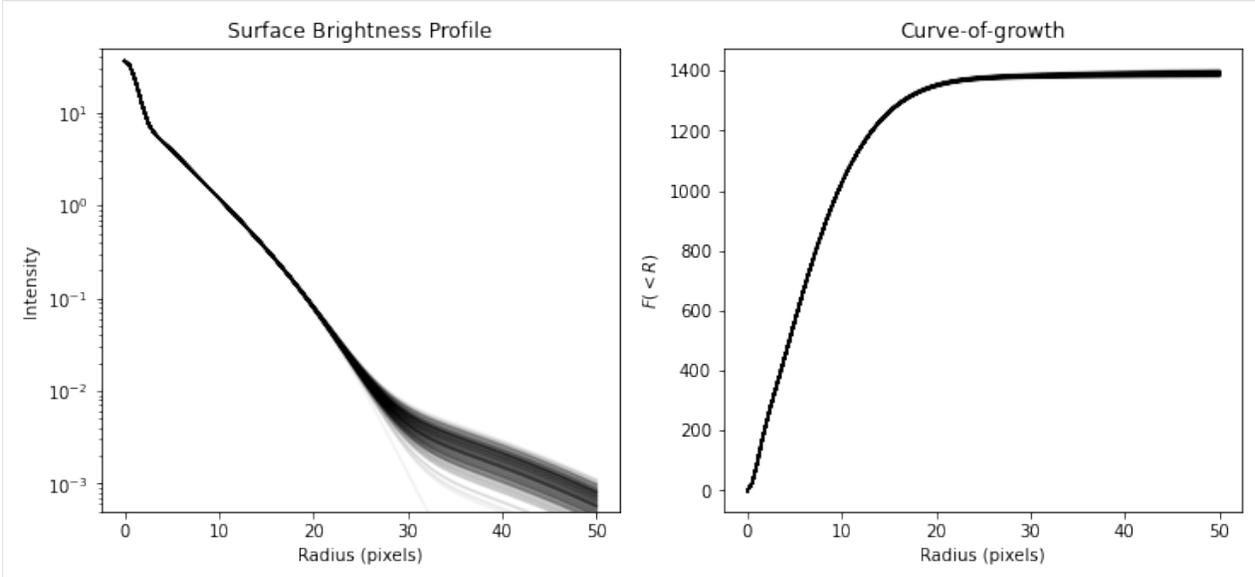
ax1.set_yscale('log')
ax1.set_ylim([5e-4,5e1])
```

(continues on next page)

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```
ax1.set_title('Surface Brightness Profile')
ax1.set_xlabel('Radius (pixels)')
ax1.set_ylabel('Intensity')

ax2.plot(rplot,cog_all[:,::100], 'k-', alpha = 0.05)
ax2.set_title('Curve-of-growth')
ax2.set_xlabel('Radius (pixels)')
ax2.set_ylabel(r'$F(<R)$')
plt.show()
```



If you are interested in morphological quantity that is not included, it is likely that it will be easy to calculate and code up, so please contact us!

## ADVANCED

A guide of more advanced and in-depth features and possibilities when running *imcascade*. Currently in progress of being written

If you have additional questions please feel free to reach out to me or raise an issue on github!

### 4.1 Adjusting initial values and bounds

By default *imcascade* attempts to make “smart” guesses for the initial values and bounds based on the input variables. These can be easily changed by using the `init_dict` or `bounds_dict` arguments when initializing a `Fitter` instance. These are both dictionaries, with matching keys, that will be discussed below, where each key should match to a float for `init_dict` and 2 length tuple or list for `bounds_dict`.

- `x0` and `y0` - The central location of the object. By default this initial value is the center of the image and the bounds are +/- 10 pixels
- `phi` - The position angle in radians, default is  $\pi/2$  with bounds 0 to  $\pi$
- `q` - The axis ratio initial value is 0.5 and bounds are 0 to 1

The initial values and bounds for the fluxes of each gaussian components can be adjusted in several ways. The easiest is to specify ‘re’ and ‘flux’ in `init_dict`. This uses a polynomial fit to the exponential relationship derived in [Hogg & Lang \(2013\)](#) to guess the initial values. This lower bounds on the flux of each component is then  $flux/10^5$  (or 0 if using linear weight scaling) and the upper bound is the `flux` value.

You can also specify using the keys `a_max` and `a_min` in `bounds_dict` to directly specify the upper and lower bound for the flux of every component. Note that these need to be specified in logarithmic scale if exploring the fluxes in log scale. These will override the bounds discussed above.

Finally you can specify `a_i`, where `i` is the component of interest, in `init_dict` and `bounds_dict` to make changes to specific components.

Again these will need to be in logarithmic scale if using `log_weight_scale = True`

If you are using the tilted plane sky model, you can additionally specify those parameters

- `sky0` - Overall sky background, estimated as the median of the image
- `sky1` - X slope of sky, estimated using the edges of the image
- `sky2` - Y slope of sky, estimated using the edges of the image

## 4.2 Fitting options

imcascade utilized previously written routines for the optimization procedures. For the least squares minimization we use the `scipy.optimize.least_squares` routine. when using `run_ls_min()` the `ls_kwargs` input can be used to specify keywords to be passed to the `least_squares` function.

Similarly we implemented `dynesty` for Bayesian inference. You can pass arguments through `run_dynesty()` for when defining the sampler using `sampler_kwargs` or running the nested sampling using `run_nested_kwargs()`. Both of these should be dictionaries.

We have found the default options for both these packages work fairly well however performance can likely be increased by tweaking one or more parameters when using these packages.

## 4.3 Model averaging

As discussed in our paper, a powerful extension of imcascade is to run Bayesian inference on a galaxy multiple times with different using different set of widths. These can then be combined using a Bayesian model averaging approach. For ease of use we have written a class `MultiResults` in the `results` module. The input for this class is a list of `ImcascadeResuts` instances which are meant to be combined. It contains some (but not all) function contained in `ImcascadeResuts` and calculates the joint posterior distribution of these quantities by weighting each model (i.e. set of widths) by their relative evidence. It is important to make sure you are using results run on the same images etc. or else it will produce non-sensical results.

## 4.4 Non-circular PSF

As a extension to the normal mode with a circular PSF, we have implemented the ability to specify a non-circular PSF. To do this use the parameter `PSF_shape` when initializing a `Fitter` instance. This should be a dictionary with the keys `q` for the axis ratio and `phi` for the position angle. Currently all components of the psf must have the same shape parameters

This increases the time to render a model as no each individual component in the observed profile must be rotated individually as they will have different position angles. **It has also not been thoroughly tested so use with caution!**

## 4.5 Changing the Likelihood function

In our implementation of imcascade we have assumed Gaussian statistics and errors when using the usual  $\chi^2$  method. However, In some use cases (or just in general, see [Erwin \(2015\)](#) ) it is preferable to assume Poisson statistics and use the Cash statistic as the likelihood ([Cash \(1979\)](#)). For the “express” method the function that gets called to calculate the likelihood is `log_like_express`, we can simply re-assign the to a function of our choosing, using the `setattr` method built in to python. First we have initialized a `Fitter` instance under the name `fitter_cash` as usual (but with the pixel weights equal to one) and then we run the following code block

```
fitter_cash = initialize_fitter(img, psf, sky_model = False, err = np.ones(img.shape))

def log_like_cash(self, exp_params):
    "log likelihood using the Cash statistic"

    #Use this function to generate model
    model = self.make_express_model(exp_params)
```

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```
#Employing the Cash statistic  
return -1.*np.sum( self.weight *(model - self.img*np.log(model)) )  
  
setattr(fitter_cash, 'log_like_express', log_like_cash)
```

In this example we have written our own function to replace the original function. Now when we use `run_dynesty` it will call our new function instead. The function `self.make_express_model` generates the model image and the `self.weight` variable contains the pixel weights (which we have set to 1.) and any mask we have supplied. `self.img` contains the input science cutout.

Using this example as a blueprint, it is possible to change the likelihood function to anything your heart desires! It is important to test whatever function you have used to make sure the answer is what you expect.

## 4.6 Changing the Priors



## API REFERENCE

This page contains auto-generated API reference documentation<sup>1</sup>.

### 5.1 imcascade

imcascade: Fitting astronomical images using a ‘cascade’ of Gaussians

#### 5.1.1 Submodules

`imcascade.fitter`

##### Module Contents

##### Classes

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<i>Fitter</i>	A Class used fit images with MultiGaussModel
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##### Functions

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<i>initialize_fitter</i> (im, psf[, mask, err, x0, y0, re, ...])	Function used to help Initialize Fitter instance from simple inputs
<i>fitter_from_ASDF</i> (file_name[, init_dict, bounds_dict])	Function used to initialize a fitter from a saved asdf file

---

---

<sup>1</sup> Created with sphinx-autoapi

## Attributes

---

*log2pi*

---

`imcascade.fitter.log2pi`

`imcascade.fitter.initialize_fitter`(*im, psf, mask=None, err=None, x0=None, y0=None, re=None, flux=None, psf\_oversamp=1, sky\_model=True, log\_file=None, readnoise=None, gain=None, exp\_time=None, num\_components=None, component\_widths=None, log\_weight\_scale=True*)

Function used to help Initialize Fitter instance from simple inputs

### Parameters

- **im** (*str or 2D Array*) – The image or cutout to be fit with imcascade. If a string is given, it is interpreted as the location of a fits file with the cutout in it's first HDU. Otherwise is a 2D numpy array of the data to be fit
- **psf** (*str, 2D Array or None*) – Similar to above but for the PSF. If not using a PSF, the use None
- **mask** (*2D array (optional)*) – Sources to be masked when fitting, if none is given then one will be derived
- **err** (*2D array (optional)*) – Pixel errors used to calculate the weights when fitting. If none is given will use readnoise, gain and exp\_time if given, or default to sep derived rms
- **x0** (*float (optional)*) – Inital guess at x position of center, if not will assume the center of the image
- **y0** (*float (optional)*) – Inital guess at y position of center, if not will assume the center of the image
- **re** (*float (optional)*) – Inital guess at the effective radius of the galaxy, if not given will estimate using sep kron radius
- **flux** (*float (optional)*) – Inital guess at the flux of the galaxy, if not given will estimate using sep flux
- **psf\_oversamp** (*float (optional)*) – Oversampling of PSF given, default is 1
- **sky\_model** (*boolean (optional)*) – Whether or not to model sky as tilted-plane, default is True
- **log\_file** (*str (optional)*) – Location of log file
- **readnoise, gain, exp\_time** (*float, float, float (all optional)*) – The read noise (in electrons), gain and exposure time of image that is used to calculate the errors and therefore pixel weights. Only used if **err** = None. If these parameters are also None, then will estimate pixel errors using sep rms map.

**Returns Fitter** – Returns intialized instance of `imcascade.fitter.Fitter` which can then be used to fit galaxy and analyze results.

**Return type** *imcascade.fitter.Fitter*

`imcascade.fitter.fitter_from_ASDF`(*file\_name, init\_dict={}, bounds\_dict={}*)

Function used to initalize a fitter from a saved asdf file

This can be useful for re-running or for initializing a series of galaxies beforehand and then transferring to somewhere else or running in parallel

### Parameters

- **file\_name** (*str*) – location of asdf file containing saved data. Often this is a file created by `Fitter.save_results`
- **init\_dict** (*dict (optional)*) – Dictionary specifying initial guesses for least\_squares fitting to be passed to Fitter instance.
- **bounds\_dict** (*dict (optional)*) – Dictionary specifying bounds for least\_squares fitting to be passed to Fitter instance.

```
class imcascade.fitter.Fitter(img, sig, psf_sig, psf_a, weight=None, mask=None, sky_model=True,
                             sky_type='tilted-plane', render_mode='hybrid', log_weight_scale=True,
                             verbose=True, psf_shape=None, init_dict={}, bounds_dict={},
                             log_file=None)
```

Bases: `imcascade.mgm.MultiGaussModel`

A Class used fit images with MultiGaussModel

This is the main class used to fit imcascade models

### Parameters

- **img** (*2D Array*) – Data to be fit, it is assumed to be a cutout with the object of interest in the center of the image
- **sig** (*1D Array*) – Widths of Gaussians to be used in MultiGaussModel
- **psf\_sig** (*1D array, None*) – Width of Gaussians used to approximate psf
- **psf\_a** (*1D array, None*) – Weights of Gaussians used to approximate psf If both `psf_sig` and `psf_a` are `None` then will run in Non-psf mode
- **weight** (*2D Array, optional*) – Array of pixel by pixel weights to be used in fitting. Must be same shape as ‘img’ If `None`, all the weights will be set to 1.
- **mask** (*2D Array, optional*) – Array with the same shape as ‘img’ denoting which, if any, pixels to mask during fitting process. Values of ‘1’ or ‘True’ values for the pixels to be masked. If set to ‘None’ then will not mask any pixels. In practice, the weights of masked pixels is set to ‘0’.
- **sky\_model** (*bool, optional*) – If True will incorporate a tilted plane sky model. Recommended to be set to True
- **sky\_type** (*str, 'tilted-plane' or 'flat'*) – Function used to model sky. Default is tilted plane with 3 parameters, const bkg and slopes in each directin. ‘flat’ uses constant background model with 1 parameter.
- **render\_mode** (*'hybrid', 'erf' or 'gauss'*) – Option to decide how to render models. ‘erf’ analytically computes the integral over the pixel of each profile therefore is more accurate but more computationally intensive. ‘gauss’ assumes the center of a pixel provides a reasonable estimate of the average flux in that pixel. ‘gauss’ is faster but far less accurate for objects which vary on  $O(\text{pixel size})$ , so use with caution. ‘hybrid’ is the default, uses ‘erf’ for components with width  $< 5$  to ensure accuracy and uses ‘gauss’ otherwise as it is accurate enough and faster. Also assumes all flux  $> 5$  sigma for components is 0.
- **log\_weight\_scale** (*bool, optional*) – Wether to treat weights as log scale, Default True
- **verbose** (*bool, optional*) – If true will log and print out errors

- **psf\_shape** (*dict, Optional*) – Dictionary containing at ‘q’ and ‘phi’ that define the shape of the PSF. Note that this slows down model rendering significantly so only recommended if necessary.
- **init\_dict** (*dict, Optional*) – Dictionary specifying initial guesses for least\_squares fitting. The code is designed to make ‘intelligent’ guesses if none are provided
- **bounds\_dict** (*dict, Optional*) – Dictionary specifying bounds for least\_squares fitting and priors. The code is designed to make ‘intelligent’ guesses if none are provided

**resid\_1d**(*params*)

Given a set of parameters returns the 1-D flattened residuals when compared to the Data, to be used in `run_ls_min` Function

**Parameters** **params** (*Array*) – List of parameters to define model

**Returns** **resid\_flatten** – 1-D array of the flattened residuals

**Return type** array

**run\_ls\_min**(*ls\_kwargs={}*)

Function to run a least\_squares minimization routine using pre-determined initial guesses and bounds.

Utilizes the scipy least\_squares routine ([https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.least\\_squares.html](https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.least_squares.html))

**Parameters** **ls\_kwargs** (*dict, optional*) – Optional list of arguments to be passed to least\_squares routine

**Returns** **min\_param** – Returns a 1D array containing the optimized parameters that describe the best fit model.

**Return type** 1D array

**set\_up\_express\_run**(*set\_params=None*)

Function to set up ‘express’ run using pre-rendered images with a fixed x0,y0, phi and q. Sets class attribute ‘express\_gauss\_arr’ which is needed to run dynesty or emcee in express mode

**Parameters** **set\_params** (*len(4) array-like, optional*) – Parameters (x0,y0,q,phi) to use to pre-render images. If None will call `run_ls_min()` or use stored `min_res` to find parameters.

**Returns** **express\_gauss\_arr** – Returns a 3-D with pre-rendered images based on input parameters

**Return type** array (shape[0],shape[1], N dof\_gauss)

**make\_express\_model**(*exp\_params*)

Function to generate a model for a given set of parameters, specifically using the pre-rendered model for the ‘express’ mode

**Parameters** **exo\_params** (*Array*) – List of parameters to define model. Length is N dof\_gauss + N dof\_sky since the structural parameters (x0,y0,q, PA) are set

**Returns** **model** – Model image based on input parameters

**Return type** 2D-array

**chi\_sq**(*params*)

Function to calculate chi\_sq for a given set of parameters

**Parameters** **params** (*Array*) – List of parameters to define model

**Returns** **chi^2** – Chi squared statistic for the given set of parameters

**Return type** float

**log\_like**(*params*)

Function to calculate the log likelihood for a given set of paramters

**Parameters** *params* (*Array*) – List of parameters to define model

**Returns** **log likelihood** – log likelihood for a given set of paramters, defined as  $-0.5*\chi^2$

**Return type** float

**ptform**(*u*)

Prior transformation function to be used in dynesty ‘full’ mode

**Parameters** *u* (*array*) – array of random numbers from 0 to 1

**Returns** *x* – array containing distribution of parameters from prior

**Return type** array

**log\_like\_exp**(*exp\_params*)

Function to calculate the log likelihood for a given set of paramters, specifically using the pre-rendered model for the ‘express’ mode

**Parameters** *exo\_params* (*Array*) – List of parameters to define model. Length is `Ndof_gauss + Ndof_sky` since the structural parameters (`x0,y0,q, PA`) are set

**Returns** **log likelihood** – log likelihood for a given set of paramters, defined as  $-0.5*\chi^2$

**Return type** float

**ptform\_exp\_ls**(*u*)

Prior transformation function to be used in dynesty ‘express’ mode using gaussian priors defined by the results of the least\_squares minimization

**Parameters** *u* (*array*) – array of random numbers from 0 to 1

**Returns** *x* – array containing distribution of parameters from prior

**Return type** array

**ptform\_exp\_lin\_cauchy**(*u*)

Prior transformation function to be used in dynesty ‘express’ mode using gaussian priors defined by the results of the least\_squares minimization

**Parameters** *u* (*array*) – array of random numbers from 0 to 1

**Returns** *x* – array containing distribution of parameters from prior

**Return type** array

**ptform\_exp\_unif**(*u*)

Prior transformation function to be used in dynesty ‘express’ mode using unifrom priors defined by `self.lb` and `self.ub`

**Parameters** *u* (*array*) – array of random numbers from 0 to 1

**Returns** *x* – array containing distribution of parameters from prior

**Return type** array

**run\_dynesty**(*method='full', sampler\_kwargs={}, run\_nested\_kwargs={}, prior='min\_results'*)

Function to run dynesty to sample the posterior distribution using either the ‘full’ methods which explores all paramters, or the ‘express’ method which sets the structural parameters.

**Parameters**

- **method** (*str*: 'full' or 'express') – Which method to use to run dynesty
- **sampler\_kwargs** (*dict*) – set of keyword arguments to pass the the dynesty `DynamicNestedSampler` call, see: <https://dynesty.readthedocs.io/en/latest/api.html#dynesty.dynesty.DynamicNestedSampler>
- **run\_nested\_kwargs** (*dict*) – set of keyword arguments to pass the the dynesty `run_nested` call, see: [https://dynesty.readthedocs.io/en/latest/api.html#dynesty.dynamicsampler.DynamicSampler.run\\_nested](https://dynesty.readthedocs.io/en/latest/api.html#dynesty.dynamicsampler.DynamicSampler.run_nested)
- **prior** ('min\_results' or 'uniform') – Which of the two choices of priors to use. The *min\_results* priors are Gaussian, with centers defined by the best fit paramters and variance equal to 4 times the variance estimated using the Hessian matrix from the `run_ls_min()` run. *uniform* is what it sounds like, uniform priors based on the the lower and upper bounds. Default is *min\_results*

**Returns Posterior** – posterior distribution derived. If method is 'express', the first 4 columns, containing *x0*, *y0*, *PA* and *q*, are all the same and equal to values used to pre-render the images

**Return type** Array

**save\_results**(*file\_name*)

Function to save results after `run_ls_min`, `run_dynesty` and/or `run_emcee` is performed. Will be saved as an ASDF file.

**Parameters** **file\_name** (*str*) – Str defining location of where to save data

**Returns** **dict\_saved** – Dictionary containing all the save quantities

**Return type** dict

imcascade.mgm

## Module Contents

### Classes

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<i>MultiGaussModel</i>	A class used to generate models based series of Gaussians
------------------------	---

---

### Functions

---

<i>rot_im_jax_exp</i> (img, phi, x0, y0)	Experimental, do not use yet!
<i>rot_im</i> (img, phi, x0, y0)	Function to rotate image around a given point
<i>get_ellip_conv_params</i> (var_all, q, phi, psf_var_all, ...)	Function used to derive the observed Gaussian Parameters for a non-circular PSF
<i>_erf_approx</i> (x)	Approximate erf function for use with numba
<i>_get_hybrid_stack</i> (x0, y0, final_q, final_a, final_var, ...)	Wrapper Function used to calculate render model using the hybrid method

---

```
class imcascade.mgm.MultiGaussModel(shape, sig, psf_sig, psf_a, verbose=True, sky_model=True,
                                   sky_type='tilted-plane', render_mode='hybrid',
                                   log_weight_scale=True, psf_shape=None)
```

A class used to generate models based series of Gaussians

**Parameters**

- **shape** (*2x1 array\_like*) – Size of model image to generate
- **sig** (*1-D array*) – Widths of Gaussians used to generate model
- **psf\_sig** (*1-D array, None*) – Width of Gaussians used to approximate psf
- **psf\_a** (*1-D array, None*) – Weights of Gaussians used to approximate psf, must be same length as ‘psf\_sig’. If both psf\_sig and psf\_a are None then will run in Non-psf mode
- **verbose** (*bool, optional*) – If true will print out errors
- **sky\_model** (*bool, optional*) – If True will incorporate a tilted plane sky model
- **render\_mode** (*‘gauss’ or ‘erf’*) – Option to decide how to render models. Default is ‘erf’ as it computes the integral over the pixel of each profile therefore is more accurate but more computationally intensive. ‘gauss’ assumes the center of a pixel provides a reasonable estimate of the average flux in that pixel. ‘gauss’ is faster but far less accurate for objects with size  $O(\text{pixel size})$ , so use with caution.
- **log\_weight\_scale** (*bool, optional*) – Whether to treat weights as log scale, Default True

**get\_gauss\_stack**(*x0, y0, q\_arr, a\_arr, var\_arr*)

Function used to calculate render model using the ‘Gauss’ method

**Parameters**

- **x0** (*float*) – x position of center
- **y0** (*float*) – y position of center
- **q\_arr** (*Array*) – Array of axis ratios
- **a\_arr** – Array of Gaussian Weights
- **var\_arr** – Array of Gaussian widths, note this the variance so  $\text{sig}^2$

**Returns Gauss\_model** – Array representing the model image, same shape as ‘shape’

**Return type** array

**get\_erf\_stack**(*x0, y0, final\_q, final\_a, final\_var*)

Function used to calculate render model using the ‘erf’ method

**Parameters**

- **x0** (*float*) – x position of center
- **y0** (*float*) – y position of the center
- **final\_q** (*Array*) – Array of axis ratios
- **final\_a** (*Array*) – Array of Gaussian Weights
- **final\_var** (*Array*) – Array of Gaussian widths, note this the variance so  $\text{sig}^2$

**Returns erf\_model** – Array representing each rendered component

**Return type** array

**get\_hybrid\_stack**(*x0, y0, final\_q, final\_a, final\_var*)

Function used to calculate render model using the hybrid method, which uses erf where necessary to ensure accurate integration and gauss otherwise. Also set everything  $>5$  sigma away to 0.

**Parameters**

- **x0** (*float*) – x position of center
- **y0** (*float*) – y position of the center
- **final\_q** (*Array*) – Array of axis ratios
- **final\_a** (*Array*) – Array of Gaussian Weights
- **final\_var** (*Array*) – Array of Gaussian widths, note this the variance so sig<sup>2</sup>

**Returns** **erf\_model** – Array representing each rendered component

**Return type** 3D array

**make\_model**(*param, return\_stack=False*)

Function to generate model image based on given paramters array. This version assumaes the gaussian weights are given in linear scale

**Parameters** **param** (*array*) – 1-D array containing all the Parameters

**Returns** **model\_image** – Generated model image as the sum of all components plus sky, if included

**Return type** 2D Array

**get\_sky\_model\_flat**(*args*)

Function used to calculate flat sky model

**Parameters**

args: (a,) (*float*),)

**Returns** **sky\_model** – Model for sky background based on given parameters, same shape as ‘shape’

**Return type** 2D Array

**get\_sky\_model\_tp**(*args*)

Function used to calculate tilted-plane sky model

**Parameters**

- **args** ((*a, b, c*) (*float, float, float*)) –
- - **overall normalization** (*a*) –
- - **slope in x direction** (*b*) –
- - **slope in y direction** (*c*) –

**Returns** **sky\_model** – Model for sky background based on given parameters, same shape as ‘shape’

**Return type** 2D Array

`imcascade.mgm.rot_im_jax_exp`(*img, phi, x0, y0*)

Experimental, do not use yet!

`imcascade.mgm.rot_im`(*img, phi, x0, y0*)

Function to rotate image around a given point

**Parameters**

- **img** (*2D array*) – Image to be rotated
- **phi** (*Float*) – angle to rotate image
- **x0** (*Float*) – x coordinate to rotate image around

- **y0** (*Float*) – y coordinate to rotate image around

**Returns** rotated image

**Return type** 2D array

`imcascade.mgm.get_ellip_conv_params`(*var\_all, q, phi, psf\_var\_all, psf\_q, psf\_phi*)

Function used to derive the observed Gaussian Parameters for a non-circular PSF

**Parameters**

- **var** (*array*) – Variances of Gaussian components
- **q** (*Float*) – Axis ratio of Galaxy
- **phi** (*Float*) – PA of galaxy
- **psf\_var\_all** (*array*) – Variances of PSF gaussian decomposition
- **psf\_q** (*float*) – Axis ratio of PSF
- **psf\_phi** (*PA of PSF*) –

**Returns**

- **obs\_var** (*array*) – Array of variances for the components of the convolved gaussian model
- **obs\_phi** (*array*) – Array of position angles for the components of the convolved gaussian model
- **obs\_q** (*array*) – Array of axis ratios for the components of the convolved gaussian model

`imcascade.mgm._erf_approx`(*x*)

Approximate erf function for use with numba

**Parameters** **x** (*scalar*) – value

**Returns**

**Return type** Approximation of erf(x)

`imcascade.mgm._get_hybrid_stack`(*x0, y0, final\_q, final\_a, final\_var, im\_args*)

Wrapper Function used to calculate render model using the hybrid method

**Parameters**

- **x0** (*float*) – x position of center
- **y0** (*float*) – y position of the center
- **final\_q** (*Array*) – Array of axis ratios
- **final\_a** – Array of Gaussian Weights
- **final\_var** – Array of Gassian widths, note this the variance so sig<sup>2</sup>
- **return\_stack** (*Bool, optional*) – If True returns an image for each individual gaussian

**Returns** **erf\_model** – Array representing the model image, same shape as ‘shape’

**Return type** array

`imcascade.psf_fitter`

## Module Contents

### Classes

---

*PSFFitter*A Class used to fit Gaussian models to a PSF image

---

**class** `imcascade.psf_fitter.PSFFitter`(*psf\_img*, *oversamp=1.0*)

A Class used to fit Gaussian models to a PSF image

**Parameters**

- **psf\_img** (*str or 2D array*) – PSF data to be fit. If a string is given will assume it is a fits file and load the Data in the first HDU. If it is an array then will use as the PSF image. Either way it is assumed the PSF is centered and image is square.
- **oversamp** (*Float, optional*) – Factor by which the PSF image is oversampled. Default is 1.

**psf\_data**

pixelized PSF data to be fit

**Type** 2D array**intens**

1D sbp of PSF

**Type** 1D array**radii**

Radii corresponding to intens

**Type** 1D array**calc\_profile()**

Calculates the 1-D PSF profile in 1 pixel steps assuming it is circular

**Returns**

- **intens** (*1D array*) – Intensity profile.
- **radius** (*1D array*) – radii at which the intensity measurements are made.

**multi\_gauss\_1d**(*r*, *\*params*, *mu=0*)

Function used to evaluate a 1-D multi Gaussian model with any number of components

**Parameters**

- **params** (*1D array*) – List of parameters to define model. The length should be twice the number of components in the following pattern: [ a<sub>1</sub>, sig<sub>1</sub>, a<sub>2</sub>, sig<sub>2</sub>, ... ] where a<sub>i</sub> is the weight of the i'th component and sig<sub>i</sub> is the width of the i'th component.
- **r** (*float, array*) – Radii at which the profile is to be evaluated
- **mu** (*float, optional*) – The centre of the gaussian distribution, default is 0

**Returns** The multi-gaussian profile evaluated at 'r'**Return type** 1D array**multi\_gauss\_1d\_ls**(*\*params*, *x\_data=np.zeros(10)*, *y\_data=np.zeros(10)*, *mu=0*)

Wrapper for multi\_gauss\_1d function, to be used in fitting the profile

**Parameters**

- **params** (*1D Array*) – List of parameters to define model. The length should be twice the number of components in the following pattern: [ a\_1, sig\_1, a\_2,sig\_2, ...]. Here a\_i is the weight of the i'th component and sig\_i is the width of the i'th component.
- **x\_data** (*1-D array*) – x\_data to be fit, generally self.radius.
- **y\_data** (*1-D array*) – y\_data to be fit, generally self.intens
- **mu** (*float, optional*) – The centre of the gaussian distribution, default is 0.

**Returns resid** – log scale residuals between the models specified by 'params' and the given y\_data

**Return type** 1D array

**fit\_N**(*N, frac\_cutoff=0.0001, plot=False*)

'Fully' Fit a Multi Gaussian Model with a given number of gaussians to the psf profile. Start with 1D to find the best fit widths and then us evaluate chi2 in 2D

**Parameters**

- **N** (*Int*) – Number of gaussian to us in fit
- **frac\_cutoff** (*float, optional*) – Fraction of max, below which to not fit. This is done to focus on the center of the PSF and not the edges. Important because we using the log-residuals
- **plot** (*bool*) – Whether or not to show summary plot

**Returns**

- **a\_fit** (*1-D array*) – Best fit Weights, corrected for oversampling
- **sig\_fit** (*1-D array*) – Best fit widths, corrected for oversampling
- **Chi2** (*Float*) – The overall chi squared of the fit, computed using the best fit 2D model

**fit\_1D**(*N, init\_guess=None, frac\_cutoff=0.0001*)

Fit a 1-D Multi Gaussian Model to the psf profile

**Parameters**

- **N** (*Int*) – Number of gaussian to us in fit
- **guess** (*Int*) – Initial guess at parameters, if None will set Default based on N
- **frac\_cutoff** (*float*) – Fraction of max, below which to not fit. This is done to focus on the center of the PSF and not the edges. Important because we using the log-residuals

**Returns**

- **a\_fit** (*1-D array*) – Best fit Weights, Not corrected for oversampling
- **sig\_fit** (*1-D array*) – Best fit widths, Not corrected for oversampling
- **Chi2** (*Float*) – The overall chi squared of the fit

**auto\_fit**(*N\_max=5, frac\_cutoff=0.0001, norm\_a=True*)

Function used for automatic fitting of PSF. First using a 1-D fit to find the smallest acceptable number of Gaussians and the corresponding widths, then using these widths to fit in 2D and find the weights.

**Parameters**

- **N** (*Int*) – Number of gaussian to us in fit

- **frac\_cutoff** (*float*) – Fraction of max, below which to not fit. This is done to focus on the center of the PSF and not the edges. Important because we using the log-residuals
- **norm\_a** (*Bool*) – Wheter or not to normalize the resulting weight so that the sum is unity

**Returns**

- **a\_fit** (*1-D array*) – Best fit Weights
- **sig\_fit** (*1-D array*) – Best fit widths

**calc\_fwhm()**

Function to estimate the FWHM of the PSF, by interpolating the measured profile

**Returns** **FWHM** – Estimate of the FWHM in pixels

**Return type** float

**imcascade.results**

**Module Contents**

**Classes**

<i>ImcascadeResults</i>	A class used for collating imcascade results and performing analysis
<i>MultiResults</i>	A Class to analyze and combine multiple ImcascadeResults classes using evidence weighting

**Functions**

<i>calc_flux_input(weights, sig[, cutoff])</i>
<i>r_root_func(r, f_L, weights, sig, cutoff)</i>

`imcascade.results.calc_flux_input(weights, sig, cutoff=None)`

`imcascade.results.r_root_func(r, f_L, weights, sig, cutoff)`

**class** `imcascade.results.ImcascadeResults(Obj, thin_posterior=1)`

A class used for collating imcascade results and performing analysis

**Parameters**

- **Obj** (*imcascade.fitter.Fitter class, dictionary or str*) – Object which contains the data to be analyzed. Can be a Fitter object once the run\_(ls\_min,dynesty, emcee) has been ran. If it is a dictionay needs to contain, at bare minmum the variables sig, Ndof, Ndof\_sky, Ndof\_gauss, log\_weight\_scale and either min\_param or posterior. If a string is passed it will be interreted as a file locations with an ASDF file containing the necessary information.
- **thin\_posterior** (*int (optional)*) – Factor by which to thin the posterior distribution by. While one wants to ensure the posterior is large enough, some of this analysis can take time if you have >10^6 samples so this is one way to speed up this task but use with caution.

**calc\_flux**(*cutoff=None*)

Calculate flux of given results

**Parameters** **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** **Flux** – Total flux of best fit model

**Return type** float or Array

**\_min\_calc\_rX**(*X, cutoff=None*)

Old and slow Function to calculate the radius containing X percent of the light

**Parameters**

- **X** (*float*) – Fractional radius of interest to calculate. if  $X < 1$  will take as a fraction, else will interpret as percent and divide X by 100. i.e. to calculate the radius containing 20% of the light, once can either pass  $X = 20$  or 0.2
- **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width used

**Returns** **r\_X** – The radius containing X percent of the light

**Return type** float or Array

**calc\_rX**(*X, cutoff=None*)

Function to calculate the radius containing X percent of the light

**Parameters**

- **X** (*float*) – Fractional radius of interest to calculate. if  $X < 1$  will take as a fraction, else will interpret as percent and divide X by 100. i.e. to calculate the radius containing 20% of the light, once can either pass  $X = 20$  or 0.2
- **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width used

**Returns** **r\_X** – The radius containing X percent of the light

**Return type** float or Array

**calc\_r90**(*cutoff=None*)

Wrapper function to calculate the radius containing 90% of the light

**Parameters** **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** **r\_90** – The radius containing 90 percent of the light

**Return type** float or Array

**calc\_r80**(*cutoff=None*)

Wrapper function to calculate the radius containing 80% of the light

**Parameters** **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** **r\_80** – The radius containing 80 percent of the light

**Return type** float or Array

**calc\_r50**(*cutoff=None*)

Wrapper function to calculate the radius containing 50% of the light, or the effective radius

**Parameters** `cutoff` (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** `r_50` – The radius containing 50 percent of the light

**Return type** float or Array

`calc_r20`(*cutoff=None*)

Wrapper function to calculate the radius containing 20% of the light

**Parameters** `cutoff` (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** `r_20` – The radius containing 20 percent of the light

**Return type** float or Array

`calc_sbp`(*r, return\_ind=False*)

Function to calculate surface brightness profiles for the given results

**Parameters**

- `r` (*float or array*) – Radii (in pixels) at which to evaluate the surface brightness profile
- `return_ind` (*bool (optional)*) – If False will only return the sum of all gaussian, i.e. the best fit profile. If true will return an array with +1 dimensions containing the profiles of each individual gaussian component

**Returns** `SBP` – Surface brightness profiles evaluated at ‘r’. If ‘return\_ind = True’, returns the profile of each individual gaussian component

**Return type** array

`calc_obs_sbp`(*r, return\_ind=False*)

Function to calculate the observed surface brightness profiles, i.e. convolved with the PSF for the given results

**Parameters**

- `r` (*float or array*) – Radii (in pixels) at which to evaluate the surface brightness profile
- `return_ind` (*bool (optional)*) – If False will only return the sum of all gaussian, i.e. the best fit profile. If true will return an array with +1 dimensions containing the profiles of each individual gaussian component

**Returns** `observed SBP` – Observed surface brightness profiles evaluated at ‘r’. If ‘return\_ind = True’, returns the profile of each individual gaussian component

**Return type** array

`calc_cog`(*r, return\_ind=False, norm=False, cutoff=None*)

Function to calculate curves-of-growth for the given results

**Parameters**

- `r` (*float or array*) – Radii (in pixels) at which to evaluate the surface brightness profile
- `return_ind` (*bool (optional)*) – If False will only return the sum of all gaussian, i.e. the best fit profile. If true will return an array with +1 dimensions containing the profiles of each individual gaussian component
- `norm` (*Bool (optional)*) – Whether to normalize curves-of-growth to total flux, calculated using ‘self.calc\_flux’. Does nothing if ‘return\_ind = True’
- `cutoff` (*Float (optional)*) – Cutoff radius used in ‘self.calc\_flux’, only is used if ‘norm’ is True

**Returns COG** – curves-of-growth evaluated at ‘r’. If ‘return\_ind = True’, returns the profile of each individual gaussian component

**Return type** array

**calc\_obs\_cog**(*r*, *return\_ind=False*, *norm=False*, *cutoff=None*)

Function to calculate the observed curve of growth, i.e. convolved with the PSF for the given results

**Parameters**

- **r** (*float or array*) – Radii (in pixels) at which to evaluate the surface brightness profile
- **return\_ind** (*bool (optional)*) – If False will only return the sum of all gaussian, i.e. the best fit profile. If true will return an array with +1 dimensions containing the profiles of each individual gaussian component
- **norm** (*Bool (optional)*) – Wether to normalize curves-of-growth to total flux, calculated using ‘self.calc\_flux’. Does nothing if ‘return\_ind = True’
- **cutoff** (*Float (optional)*) – Cutoff radius used in ‘self.calc\_flux’, only is used if ‘norm’ is True

**Returns observed COG** – curves-of-growth evaluated at ‘r’. If ‘return\_ind = True’, returns the profile of each individual gaussian component

**Return type** array

**run\_basic\_analysis**(*zpt=None*, *cutoff=None*, *errp\_lo=16*, *errp\_hi=84*, *save\_results=False*, *save\_file='./imcascade\_results.asdf'*)

Function to calculate a set of common variables and save the save the results

**Parameters**

- **zpt** (*float (optional)*) – photometric zeropoint for the data. if not ‘None’, will also calculate magnitude
- **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use
- **errp\_lo,hi** (*float (optional)*) – percentiles to be used to calculate the lower and upper error bars from the posterior distribution. Default is 16 and 84, corresponding to 1-sigma for a gaussian distribtuion
- **save\_results** (*bool (optional)*) – If true will save results to file. If input is a file, will add to given file, else will save to file denoted by ‘save\_file’ (see below)
- **save\_file** (*str*) – String to describe where to save file, only applicaple if the input is not a file.

**Returns res\_dict** – Dictionary contining the results of the analysis

**Return type** dictionary

**calc\_iso\_r**(*I*, *zpt=None*, *pix\_scale=None*)

Function to calculate the isophotal radius

**Parameters**

- **I** (*float*) – Surface brightness target to define the isophotal radii. By default this should be in image units unless both zpt and pix\_scale are given, then I is interpreted as mag per arcsec<sup>2</sup>.
- **zpt** (*float (optional)*) – zeropoint magnitude of image, used to convert I to mag per arcsec<sup>2</sup>

- **pix\_scale** (*float (optional)*) – pixel scale in units of arcseconds/pixel, used to convert I to mag per arcsec<sup>2</sup>

**Returns** **r\_I** – The radius, in pixel units, where the surface brightness profile matches I

**Return type** float or Array

**calc\_petro\_r**(*P\_ratio=0.2, r\_fac\_min=0.8, r\_fac\_max=1.25*)

Function to calculate the petrosian radii of a galaxy

**Parameters**

- **P\_ratio** (*float (optional)*) – The Petrosian ratio which defines the Petrosian radii, default is 0.2
- **r\_fac\_min** (*float (optional)*) – lower multiplicative factor which is used to integrate flux, default 0.8
- **r\_fac\_max** (*float (optional)*) – higher multiplicative factor which is used to integrate flux, default 1.25

**Returns** **r\_I** – The radius, in pixel units, where the surface brightness profile matches I

**Return type** float or Array

**make\_diagnostic\_fig**()

Function which generates a diagnostic figure to assess fit

**Returns** **fig** – matplotlib figure object

**Return type** matplotlib figure

**class** `imcascade.results.MultiResults`(*lofr*)

A Class to analyze and combine multiple ImcascadeResults classes using evidence weighting

**calc\_cog**(*r, num=1000*)

**calc\_obs\_cog**(*r, num=1000*)

**calc\_sbp**(*r, num=1000*)

**calc\_obs\_sbp**(*r, num=1000*)

**calc\_flux**(*cutoff=None, num=1000*)

**calc\_rX**(*X, cutoff=None, num=1000*)

## imcascade.utils

### Module Contents

#### Functions

<a href="#"><i>guess_weights</i></a> (sig, re, flux)	Method to guess the weights of gaussian componenets given an re and flux.
<a href="#"><i>expand_mask</i></a> (mask[, radius, threshold])	Expands mask by convolving it with a Gaussians
<a href="#"><i>asinh_scale</i></a> (start, end, num)	Simple wrapper to generate list of numbers equally spaced in asinh space
<a href="#"><i>log_scale</i></a> (start, end, num)	Simple wrapper to generate list of numbers equally spaced in logspace

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Table 9 – continued from previous page

<code>dict_add(dict_use, key, obj)</code>	Simple wrapper to add obj to dictionary if it doesn't exist. Used in <code>fitter.Fitter</code> when defining defaults
<code>get_med_errors(arr[, lo, hi])</code>	Simple function to find percentiles from distribution
<code>b(n)</code>	Simple function to approximate <code>b(n)</code> when evaluating a Sersic profile
<code>sersic(r, n, re, Ltot)</code>	Calculates the surface brightness profile for a Sersic profile
<code>min_diff_array(arr)</code>	Function used to calculate the minimum difference between any two elements

## Attributes

---

`vars_to_use`

---

`imcascade.utils.vars_to_use = ['img', 'weight', 'mask', 'sig', 'Ndof', 'Ndof_sky', 'Ndof_gauss', 'has_psf', 'psf_a', ...]`

`imcascade.utils.guess_weights(sig, re, flux)`

Method to guess the weights of gaussian componenets given an `re` and `flux`. Based on a polynomial fit to the exp fits of Hogg & Lang 2013

### Parameters

- **sig** (*array*) – List of gaussian widths for imcascade model
- **re** (*Float*) – Estimate of effective radius
- **flux** – Estimate of flux

**Returns** `a_i` – Inital estimate of weights based on `re` and `flux`

**Return type** `Array`

`imcascade.utils.expand_mask(mask, radius=5, threshold=0.001)`

Expands `mask` by convolving it with a Gaussians

### Parameters

- **Mask** (*2D array*) – inital mask with masked pixels equal to 1
- **radius** (*Float*) – width of gaussian used to convolve mask. default 5, set larger for more aggressive masking
- **threshold** (*Float*) – threshold to generate new mask from convolved mask. Default is 1e-3, set lower for more aggressive mask

**Returns** `new_mask` – New, expanded mask

**Return type** `2D-Array`

`imcascade.utils.asinh_scale(start, end, num)`

Simple wrapper to generate list of numbers equally spaced in asinh space

### Parameters

- **start** (*float*) – Inital number
- **end** (*Float*) – Final number

- **num** (*Float*) – Number of number in the list

**Returns list** – List of number spanning start to end, equally space in asinh space

**Return type** 1d array

`imcascade.utils.log_scale(start, end, num)`

Simple wrapper to generate list of numbers equally spaced in logspace

**Parameters**

- **start** (*float*) – Inital number
- **end** (*Float*) – Final number
- **num** (*Float*) – Number of number in the list

**Returns list** – List of number spanning start to end, equally space in log space

**Return type** 1d array

`imcascade.utils.dict_add(dict_use, key, obj)`

Simple wrapper to add obj to dictionary if it doesn't exist. Used in `fitter.Fitter` when defining defaults

**Parameters**

- **dict\_use** (*Dictionary*) – dictionary to be, possibly, updated
- **key** (*str*) – key to update, only updated if the key doesn't exist in dict\_use already
- **obj** (*Object*) – Object to be added to dict\_use under key

**Returns dict\_add** – updated dictionary

**Return type** Dictionary

`imcascade.utils.get_med_errors(arr, lo=16, hi=84)`

Simple function to find percentiles from distribution

**Parameters**

- **arr** (*array*) – Array containing in the distribution of interest
- **lo** (*float (optional)*) – percentile to define lower error bar, Default 16
- **hi** (*float (optional)*) – percentile to define upper error bar, Default 84

**Returns (med,err\_lo,err\_hi)** – Array containg the median and errorbars of the distribution

**Return type** array

`imcascade.utils.b(n)`

Simple function to approximate  $b(n)$  when evaluating a Sersic profile following Capaccioli (1989). Valid for  $0.5 < n < 10$

**Parameters n** (*float or array*) – Sersic index

**Returns b(n)** – Approximation to  $\Gamma(2n) = 2 \gamma(2n, b(n))$

**Return type** float or array

`imcascade.utils.sersic(r, n, re, Ltot)`

Calculates the surface brightness profile for a Sersic profile

**Parameters**

- **r** (*array*) – Radii at which to evaluate surface brightness profile
- **n** (*float*) – Sersic index of profile

- **re** (*float*) – Half-light radius of profile
- **Ltot** (*float*) – Total flux of Sersic profile

**Returns** Surface brightness profile evaluate along the semi-major axis at ‘r’

**Return type** float or array

`imcascade.utils.min_diff_array(arr)`

Function used to calculate the minimum difference between any two elements in a given array\_like :param arr: Array to be searched :type arr: 1-D array

**Returns** `min_diff` – The minimum difference between any two elements of the given array

**Return type** Float

## 5.1.2 Package Contents

### Classes

<i>Fitter</i>	A Class used fit images with MultiGaussModel
<i>ImcascadeResults</i>	A class used for collating imcascade results and performing analysis

### Attributes

`__version__`

`imcascade.__version__ = '1.0'`

```
class imcascade.Fitter(img, sig, psf_sig, psf_a, weight=None, mask=None, sky_model=True,
                      sky_type='tilted-plane', render_mode='hybrid', log_weight_scale=True,
                      verbose=True, psf_shape=None, init_dict={}, bounds_dict={}, log_file=None)
```

Bases: `imcascade.mgm.MultiGaussModel`

A Class used fit images with MultiGaussModel

This is the main class used to fit imcascade models

#### Parameters

- **img** (*2D Array*) – Data to be fit, it is assumed to be a cutout with the object of interest in the center of the image
- **sig** (*1D Array*) – Widths of Gaussians to be used in MultiGaussModel
- **psf\_sig** (*1D array, None*) – Width of Gaussians used to approximate psf
- **psf\_a** (*1D array, None*) – Weights of Gaussians used to approximate psf If both `psf_sig` and `psf_a` are `None` then will run in Non-psf mode
- **weight** (*2D Array, optional*) – Array of pixel by pixel weights to be used in fitting. Must be same shape as ‘img’ If `None`, all the weights will be set to 1.
- **mask** (*2D Array, optional*) – Array with the same shape as ‘img’ denoting which, if any, pixels to mask during fitting process. Values of ‘1’ or ‘True’ values for the pixels to be

masked. If set to 'None' then will not mask any pixels. In practice, the weights of masked pixels is set to '0'.

- **sky\_model** (*bool, optional*) – If True will incorporate a tilted plane sky model. Recommended to be set to True
- **sky\_type** (*str, 'tilted-plane' or 'flat'*) – Function used to model sky. Default is tilted plane with 3 parameters, const bkg and slopes in each directin. 'flat' uses constant background model with 1 parameter.
- **render\_mode** (*'hybrid', 'erf' or 'gauss'*) – Option to decide how to render models. 'erf' analytically computes the integral over the pixel of each profile therefore is more accurate but more computationally intensive. 'gauss' assumes the center of a pixel provides a reasonable estimate of the average flux in that pixel. 'gauss' is faster but far less accurate for objects which vary on O(pixel size), so use with caution. 'hybrid' is the default, uses 'erf' for components with width < 5 to ensure accuracy and uses 'gauss' otherwise as it is accurate enough and faster. Also assumes all flux > 5 sigma for components is 0.
- **log\_weight\_scale** (*bool, optional*) – Wether to treat weights as log scale, Default True
- **verbose** (*bool, optional*) – If true will log and print out errors
- **psf\_shape** (*dict, Optional*) – Dictionary containg at 'q' and 'phi' that define the shape of the PSF. Note that this slows down model rendering significantly so only reccomended if necessary.
- **init\_dict** (*dict, Optional*) – Dictionary specifying initial guesses for least\_squares fitting. The code is designed to make 'intelligent' guesses if none are provided
- **bounds\_dict** (*dict, Optional*) – Dictionary specifying boundss for least\_squares fitting and priors. The code is designed to make 'intelligent' guesses if none are provided

#### **resid\_1d**(*params*)

Given a set of parameters returns the 1-D flattened residuals when compared to the Data, to be used in run\_ls\_min Function

**Parameters** *params* (*Array*) – List of parameters to define model

**Returns** *resid\_flatten* – 1-D array of the flattened residuals

**Return type** array

#### **run\_ls\_min**(*ls\_kwargs={}*)

Function to run a least\_squares minimization routine using pre-determined inital guesses and bounds.

Utilizes the scipy least\_squares routine ([https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.least\\_squares.html](https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.least_squares.html))

**Parameters** *ls\_kwargs* (*dict, optional*) – Optional list of arguments to be passes to least\_squares routine

**Returns** *min\_param* – Returns a 1D array containing the optimized parameters that describe the best fit model.

**Return type** 1D array

#### **set\_up\_express\_run**(*set\_params=None*)

Function to set up 'express' run using pre-rendered images with a fixed x0,y0, phi and q. Sets class attribute 'express\_gauss\_arr' which is needed to run dynesty or emcee in express mode

**Parameters** `set_params` (*len(4) array-like, optional*) – Parameters (x0,y0,q,phi) to use to per-render images. If None will call `run_ls_min()` or use stored `min_res` to find parameters.

**Returns** `express_gauss_arr` – Returns a 3-D with pre-rendered images based on input parameters

**Return type** array (shape[0],shape[1], Ndof\_gauss)

**make\_express\_model**(*exp\_params*)

Function to generate a model for a given set of paramters, specifically using the pre-rendered model for the ‘express’ mode

**Parameters** `exo_params` (*Array*) – List of parameters to define model. Length is Ndof\_gauss + Ndof\_sky since the structural parameters (x0,y0,q, PA) are set

**Returns** `model` – Model image based on input parameters

**Return type** 2D-array

**chi\_sq**(*params*)

Function to calculate chi\_sq for a given set of paramters

**Parameters** `params` (*Array*) – List of parameters to define model

**Returns** `chi^2` – Chi squared statistic for the given set of parameters

**Return type** float

**log\_like**(*params*)

Function to calculate the log likelihood for a given set of paramters

**Parameters** `params` (*Array*) – List of parameters to define model

**Returns** `log likelihood` – log likelihood for a given set of paramters, defined as  $-0.5 \cdot \text{chi}^2$

**Return type** float

**ptform**(*u*)

Prior transformation function to be used in dynesty ‘full’ mode

**Parameters** `u` (*array*) – array of random numbers from 0 to 1

**Returns** `x` – array containing distribution of parameters from prior

**Return type** array

**log\_like\_exp**(*exp\_params*)

Function to calculate the log likelihood for a given set of paramters, specifically using the pre-rendered model for the ‘express’ mode

**Parameters** `exo_params` (*Array*) – List of parameters to define model. Length is Ndof\_gauss + Ndof\_sky since the structural parameters (x0,y0,q, PA) are set

**Returns** `log likelihood` – log likelihood for a given set of paramters, defined as  $-0.5 \cdot \text{chi}^2$

**Return type** float

**ptform\_exp\_ls**(*u*)

Prior transformation function to be used in dynesty ‘express’ mode using gaussian priors defined by the results of the least\_squares minimization

**Parameters** `u` (*array*) – array of random numbers from 0 to 1

**Returns** `x` – array containing distribution of parameters from prior

**Return type** array

**ptform\_exp\_lin\_cauchy(*u*)**

Prior transformation function to be used in dynesty ‘express’ mode using gaussian priors defined by the results of the least\_squares minimization

**Parameters** *u* (*array*) – array of random numbers from 0 to 1

**Returns** *x* – array containing distribution of parameters from prior

**Return type** array

**ptform\_exp\_unif(*u*)**

Prior transformation function to be used in dynesty ‘express’ mode using unifrom priors defined by self.lb and self.ub

**Parameters** *u* (*array*) – array of random numbers from 0 to 1

**Returns** *x* – array containing distribution of parameters from prior

**Return type** array

**run\_dynesty(*method*='full', *sampler\_kwargs*={}, *run\_nested\_kwargs*={}, *prior*='min\_results')**

Function to run dynesty to sample the posterior distribution using either the ‘full’ methods which explores all paramters, or the ‘express’ method which sets the structural parameters.

**Parameters**

- **method** (*str*: ‘full’ or ‘express’) – Which method to use to run dynesty
- **sampler\_kwargs** (*dict*) – set of keyword arguments to pass the the dynesty DynamicNestedSampler call, see: <https://dynesty.readthedocs.io/en/latest/api.html#dynesty.dynesty.DynamicNestedSampler>
- **run\_nested\_kwargs** (*dict*) – set of keyword arguments to pass the the dynesty run\_nested call, see: [https://dynesty.readthedocs.io/en/latest/api.html#dynesty.dynamicsampler.DynamicSampler.run\\_nested](https://dynesty.readthedocs.io/en/latest/api.html#dynesty.dynamicsampler.DynamicSampler.run_nested)
- **prior** (‘min\_results’ or ‘uniform’) – Which of the two choices of priors to use. The *min\_results* priors are Gaussian, with centers defined by the best fit paramters and variance equal to 4 times the variance estimated using the Hessian matrix from the run\_ls\_min() run. *uniform* is what it sounds like, uniform priors based on the the lower and upper bounds Default is *min\_results*

**Returns** **Posterior** – posterior distribution derrived. If method is ‘express’, the first 4 columns, containg x0, y0, PA and q, are all the same and equal to values used to pre-render the images

**Return type** Array

**save\_results(*file\_name*)**

Function to save results after run\_ls\_min, run\_dynesty and/or run\_emcee is performed. Will be saved as an ASDF file.

**Parameters** **file\_name** (*str*) – Str defining location of where to save data

**Returns** **dict\_saved** – Dictionary containing all the save quantities

**Return type** dict

**class imcascade.ImcascadeResults(*Obj*, *thin\_posterior*=1)**

A class used for collating imcascade results and performing analysis

**Parameters**

- **Obj** (*imcascade.fitter.Fitter class, dictionary or str*) – Object which contains the data to be analyzed. Can be a Fitter object once the run\_(ls\_min,dynesty, emcee) has been ran. If it is a dictionay needs to contain, at bare minmum the variables sig, Ndof,

Ndof\_sky, Ndof\_gauss, log\_weight\_scale and either min\_param or posterior. If a string is passed it will be interpreted as a file locations with an ASDF file containing the necessary information.

- **thin\_posterior** (*int (optional)*) – Factor by which to thin the posterior distribution by. While one wants to ensure the posterior is large enough, some of this analysis can take time if you have  $>10^6$  samples so this is one way to speed up this task but use with caution.

#### **calc\_flux**(*cutoff=None*)

Calculate flux of given results

**Parameters** **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** **Flux** – Total flux of best fit model

**Return type** float or Array

#### **\_min\_calc\_rX**(*X, cutoff=None*)

Old and slow Function to calculate the radius containing X percent of the light

**Parameters**

- **X** (*float*) – Fractional radius of interest to calculate. if  $X < 1$  will take as a fraction, else will interpret as percent and divide X by 100. i.e. to calculate the radius containing 20% of the light, once can either pass  $X = 20$  or 0.2
- **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width used

**Returns** **r\_X** – The radius containing X percent of the light

**Return type** float or Array

#### **calc\_rX**(*X, cutoff=None*)

Function to calculate the radius containing X percent of the light

**Parameters**

- **X** (*float*) – Fractional radius of interest to calculate. if  $X < 1$  will take as a fraction, else will interpret as percent and divide X by 100. i.e. to calculate the radius containing 20% of the light, once can either pass  $X = 20$  or 0.2
- **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width used

**Returns** **r\_X** – The radius containing X percent of the light

**Return type** float or Array

#### **calc\_r90**(*cutoff=None*)

Wrapper function to calculate the radius containing 90% of the light

**Parameters** **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** **r\_90** – The radius containing 90 percent of the light

**Return type** float or Array

#### **calc\_r80**(*cutoff=None*)

Wrapper function to calculate the radius containing 80% of the light

**Parameters** **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** **r\_80** – The radius containing 80 percent of the light

**Return type** float or Array

**calc\_r50**(*cutoff=None*)

Wrapper function to calculate the radius containing 50% of the light, or the effective radius

**Parameters** **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** **r\_50** – The radius containing 50 percent of the light

**Return type** float or Array

**calc\_r20**(*cutoff=None*)

Wrapper function to calculate the radius containing 20% of the light

**Parameters** **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use

**Returns** **r\_20** – The radius containing 20 percent of the light

**Return type** float or Array

**calc\_sbp**(*r, return\_ind=False*)

Function to calculate surface brightness profiles for the given results

**Parameters**

- **r** (*float or array*) – Radii (in pixels) at which to evaluate the surface brightness profile
- **return\_ind** (*bool (optional)*) – If False will only return the sum of all gaussian, i.e. the best fit profile. If true will return an array with +1 dimensions containing the profiles of each individual gaussian component

**Returns** **SBP** – Surface brightness profiles evaluated at ‘r’. If ‘return\_ind = True’, returns the profile of each individual gaussian component

**Return type** array

**calc\_obs\_sbp**(*r, return\_ind=False*)

Function to calculate the observed surface brightness profiles, i.e. convolved with the PSF for the given results

**Parameters**

- **r** (*float or array*) – Radii (in pixels) at which to evaluate the surface brightness profile
- **return\_ind** (*bool (optional)*) – If False will only return the sum of all gaussian, i.e. the best fit profile. If true will return an array with +1 dimensions containing the profiles of each individual gaussian component

**Returns** **observed SBP** – Observed surface brightness profiles evaluated at ‘r’. If ‘return\_ind = True’, returns the profile of each individual gaussian component

**Return type** array

**calc\_cog**(*r, return\_ind=False, norm=False, cutoff=None*)

Function to calculate curves-of-growth for the given results

**Parameters**

- **r** (*float or array*) – Radii (in pixels) at which to evaluate the surface brightness profile

- **return\_ind** (*bool (optional)*) – If False will only return the sum of all gaussian, i.e. the best fit profile. If true will return an array with +1 dimensions containing the profiles of each individual gaussian component
- **norm** (*Bool (optional)*) – Wether to normalize curves-of-growth to total flux, calculated using 'self.calc\_flux'. Does nothing if 'return\_ind = True'
- **cutoff** (*Float (optional)*) – Cutoff radius used in 'self.calc\_flux', only is used if 'norm' is True

**Returns COG** – curves-of-growth evaluated at 'r'. If 'return\_ind = True', returns the profile of each individual gaussian component

**Return type** array

**calc\_obs\_cog**(*r, return\_ind=False, norm=False, cutoff=None*)

Function to calculate the observed curve of growth, i.e. convolved with the PSF for the given results

**Parameters**

- **r** (*float or array*) – Radii (in pixels) at which to evaluate the surface brightness profile
- **return\_ind** (*bool (optional)*) – If False will only return the sum of all gaussian, i.e. the best fit profile. If true will return an array with +1 dimensions containing the profiles of each individual gaussian component
- **norm** (*Bool (optional)*) – Wether to normalize curves-of-growth to total flux, calculated using 'self.calc\_flux'. Does nothing if 'return\_ind = True'
- **cutoff** (*Float (optional)*) – Cutoff radius used in 'self.calc\_flux', only is used if 'norm' is True

**Returns observed COG** – curves-of-growth evaluated at 'r'. If 'return\_ind = True', returns the profile of each individual gaussian component

**Return type** array

**run\_basic\_analysis**(*zpt=None, cutoff=None, errp\_lo=16, errp\_hi=84, save\_results=False, save\_file='./imcascade\_results.asdf*)

Function to calculate a set of common variables and save the save the results

**Parameters**

- **zpt** (*float (optional)*) – photometric zeropoint for the data. if not 'None', will also calculate magnitude
- **cutoff** (*float (optional)*) – Radius out to which to consider the profile. Generally this should be around the half-width of the image or the largest gaussian width use
- **errp\_lo,hi** (*float (optional)*) – percentiles to be used to calculate the lower and upper error bars from the posterior distribution. Default is 16 and 84, corresponding to 1-sigma for a gaussian distribuion
- **save\_results** (*bool (optional)*) – If true will save results to file. If input is a file, will add to given file, else will save to file denoted by 'save\_file' (see below)
- **save\_file** (*str*) – String to describe where to save file, only applicaple if the input is not a file.

**Returns res\_dict** – Dictionary contining the results of the analysis

**Return type** dictionary

**calc\_iso\_r**(*I, zpt=None, pix\_scale=None*)

Function to calculate the isophotal radius

**Parameters**

- **I** (*float*) – Surface brightness target to define the isophotal radii. By default this should be in image units unless both `zpt` and `pix_scale` are given, then I is interpreted as mag per arcsec<sup>2</sup>.
- **zpt** (*float (optional)*) – zeropoint magnitude of image, used to convert I to mag per arcsec<sup>2</sup>
- **pix\_scale** (*float (optional)*) – pixel scale in units of arcseconds/pixel, used to convert I to mag per arcsec<sup>2</sup>

**Returns** `r_I` – The radius, in pixel units, where the surface brightness profile matches I

**Return type** float or Array

**calc\_petro\_r**(*P\_ratio=0.2, r\_fac\_min=0.8, r\_fac\_max=1.25*)

Function to calculate the petrosian radii of a galaxy

**Parameters**

- **P\_ratio** (*float (optional)*) – The Petrosian ratio which defines the Petrosian radii, default is 0.2
- **r\_fac\_min** (*float (optional)*) – lower multiplicative factor which is used to integrate flux, default 0.8
- **r\_fac\_max** (*float (optional)*) – higher multiplicative factor which is used to integrate flux, default 1.25

**Returns** `r_I` – The radius, in pixel units, where the surface brightness profile matches I

**Return type** float or Array

**make\_diagnostic\_fig**()

Function which generates a diagnostic figure to assess fit

**Returns** `fig` – matplotlib figure object

**Return type** matplotlib figure

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