LAB-EXERCISE

PHOTOMETRIC DECOMPOSITIONS

Groups of 3 people

Main Objectives of this Lab Exercise

- Understand and measure the basic properties of real astronomical images
  gain, readout noise, sky levels, noise
- Understand and measure nuisance effects of galaxy images
  PSF
- Basics of galaxy surface brightness measurements
  azimuthally averaged profiles, photometric calibrations
- Basics on two-dimensional photometric decompositions
  bulge+disk decomposition of a real galaxy
- Understanding the outputs from photometric decompositions
  Conversion to physical units

Basic properties of real (CCD) astronomical images

Gain: In CCD imaging, gain refers to the magnitude of amplification a given system will produce. Gain is reported in terms of electrons/ADU (analog-to-digital unit). A gain of 8 means that the camera digitizes the CCD signal so that each ADU corresponds to 8 photoelectrons.

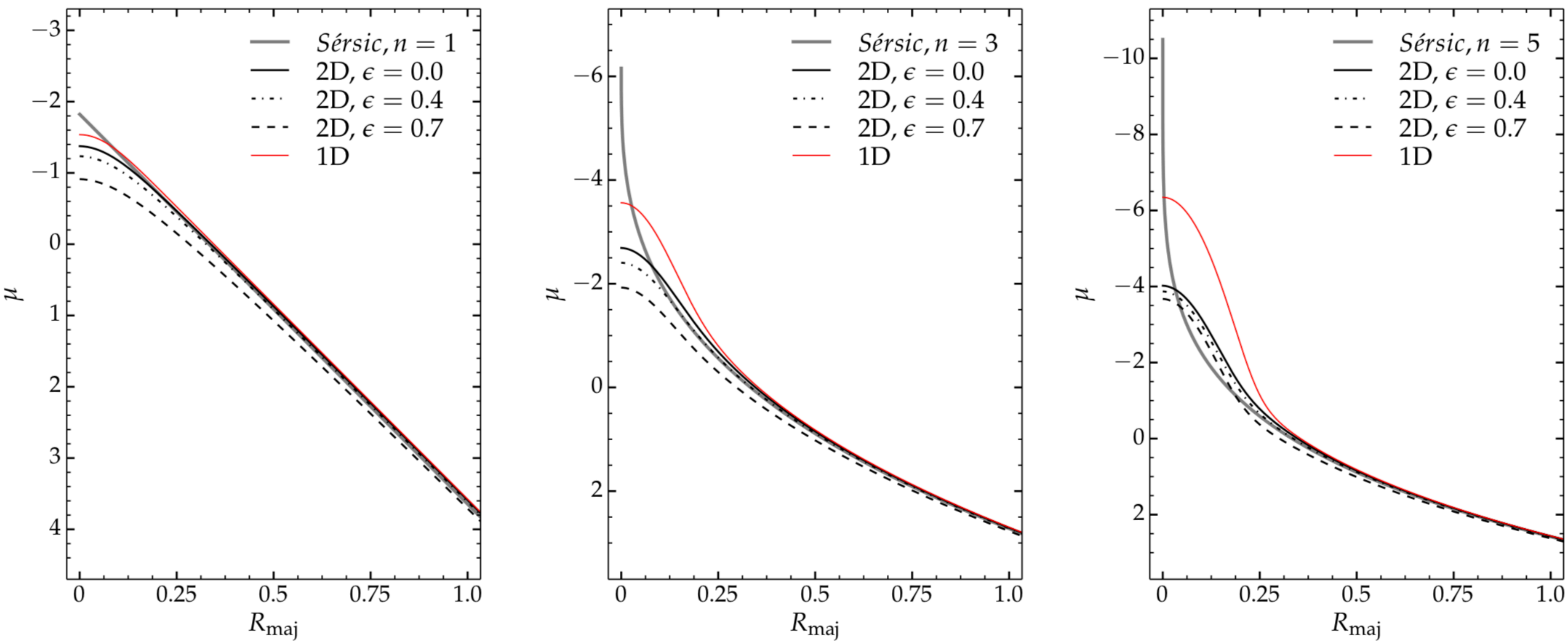
Sky Level: Extra light coming for non-astronomical sources. This light adds-up to the target light and must be accounted for when computing the noise.

Noise: It is a combination of different factors.

Photon noise - Poissonian noise due to photons from our targets hitting the detector
Sky noise - Another poissonian due to photons from sky hitting the detector
Thermal noise - ‘Dark Current’ Thermal random noise due to spontaneous electrons in the detector
Readout noise - noise of the on-chip amplifier which converts the charge (i.e the electrons) into a change in analogue voltage.

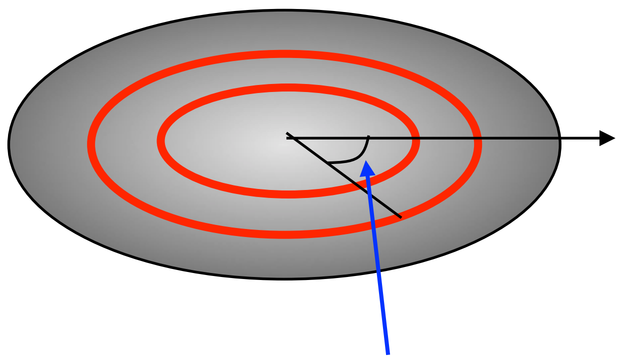
Total Noise = sqrt(Photons(Target) *npix+ Photons(Sky)*npix + Photons (Thermal)*npix + (readnoise)^2*npix)

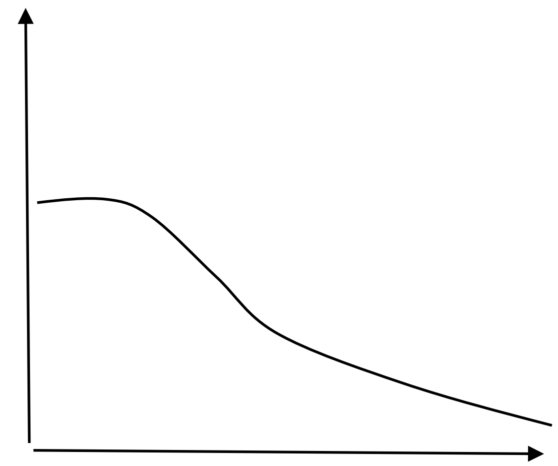
Point Spread Function



- Measured using a non-resolved source in the image, generally a star.
- It can change during the night.
- It depends on the wavelength band.
- It can vary across the image.

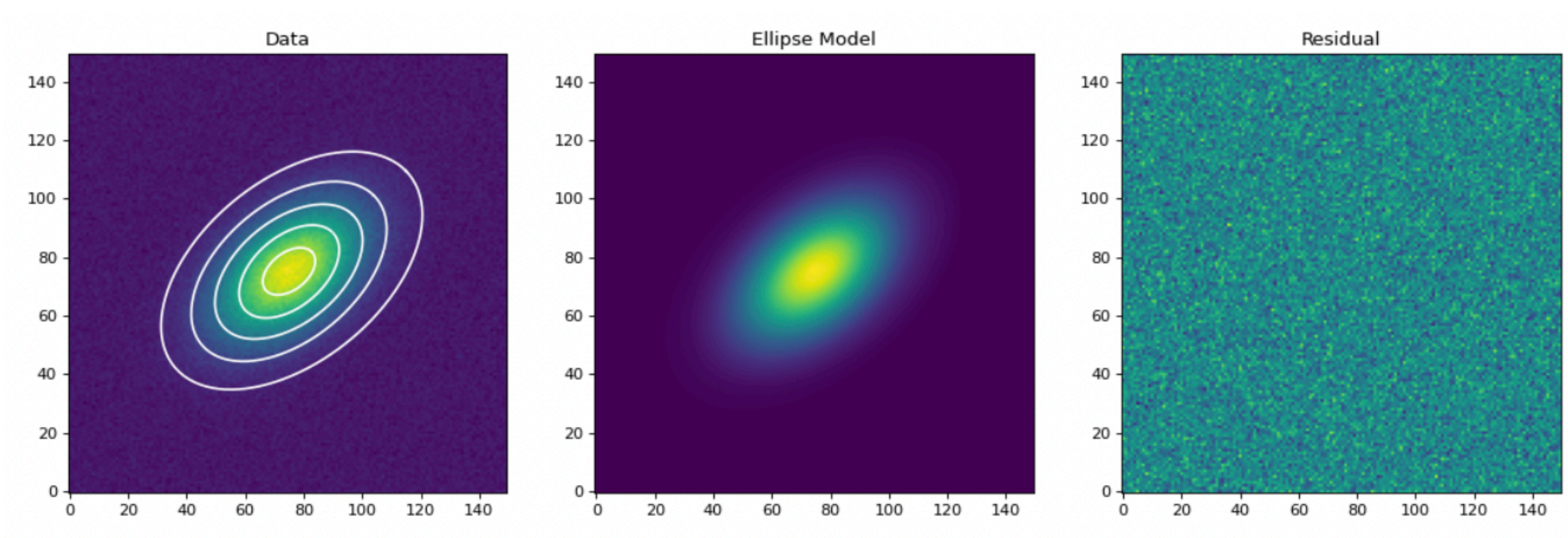
Basics of galaxy surface brightness measurements





Python routine to perform ellipse fitting of galaxy isophotes

https://photutils.readthedocs.io/en/stable/isophote.html



Basics on two-dimensional photometric decompositions

We will follow the IMFIT code to perform the 2D decomposition

We will download the executable code from here
https://www.mpe.mpg.de/~erwin/code/imfit/index.html#downloads

You can find an extensive manual of use here
https://www.mpe.mpg.de/~erwin/resources/imfit/imfit_howto.pdf

Example of IMFIT at work

How to Fit Your First Image?

Imfit requires, as a minimum, two things:

1. An image in FITS format containing the data to be fit;
2. A configuration file describing the model you want to fit to the data.

So to start off, we'll try fitting the image file ic3478rss_256.fits (a 256 x 256-pixel cutout from a DR7 SDSS r-band image of the dwarf elliptical galaxy IC 3478) with a simple exponential model, which is described in the configuration file config_exponential_ic3478_256.dat. To do the fit, just type (all on one line):

imfit ic3478rss_256.fits -c config_exponential_ic3478_256.dat - -sky=130.14

The --sky=130.14 is a note to Imfit that the image had a background sky level of 130.14 counts/pixel which was previously subtracted; if we don't include this, Imfit will get confused by the fact that some of the pixels in the image have slightly negative values. (Note that you can use = or a space to connect an option with its argument on the command line.)

Imfit will print some preliminary information, confirming which files are being used, the size of the image being fit, the image functions used in the model, and so forth. It will then call the minimization routine, which prints a minimal set of updates for each iteration. At the end, a summary of the fit is printed (final $\chi 2$, etc.), along with the best-fitting parameters of the model and some crude estimates of the uncertainties for each parameter. These parameters are also saved in a text file: "bestfit_parameters_imfit.dat", which includes a record of how imfit was called and a short summary of the fit. (You can specify a different name for this output file via the --save-params option.)

Reduced Chi^2 = 0.450366
AIC = 29524.514967, BIC = 29579.055814

X0 128.8530 # +/- 0.0517
Y0 129.1035 # +/- 0.0633
FUNCTION Exponential
PA 19.7364 # +/- 0.467417
ell 0.231428 # +/- 0.00333939
I_0 315.173 # +/- 1.33252
h 20.5726 # +/- 0.0748152

Example of IMFIT at work

Inspecting the Fit: Model Images and Residuals

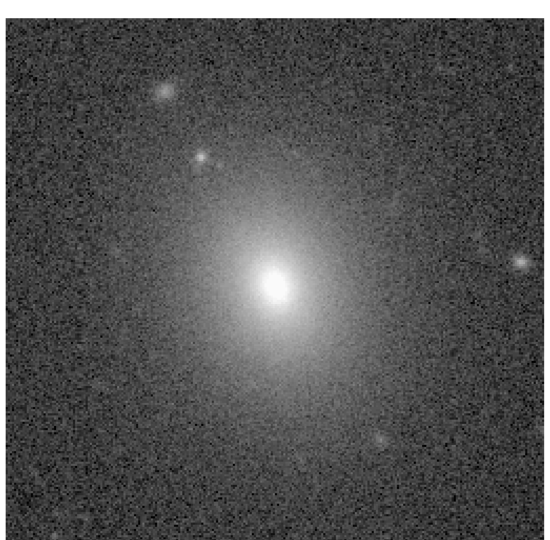
So what kind of fit did we get, and how good was it? When you run imfit, you can tell it to save the best-fitting model image, and the residual image (data - model) as well, using the --save-model and --save-residual commandline options:

imfit ic3478rss_256.fits -c config_exponential_ic3478_256.dat --sky=130.14 --save-model=model.fits —save-residual=resid.fits

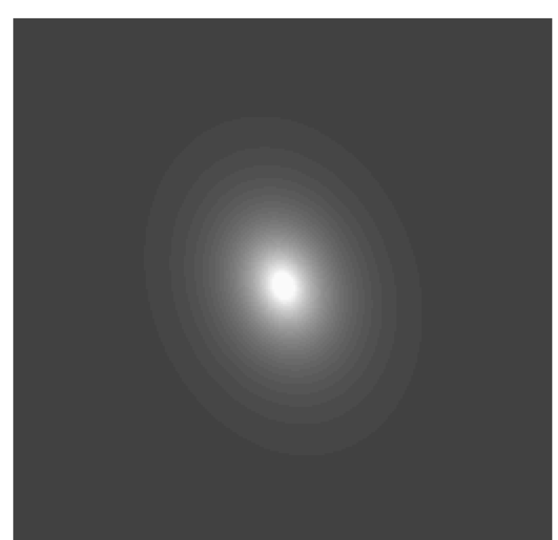
These are FITS files with the same dimensions as the data image.
You can use an image visualisation tools such as ds9

If you look at the residual image (below, right), you can see it's systematically bright in the center, with an oval region of negative pixels outside. This is a pretty good indication that the exponential model isn't actually a good match to the data, something we'll try to address in a bit.

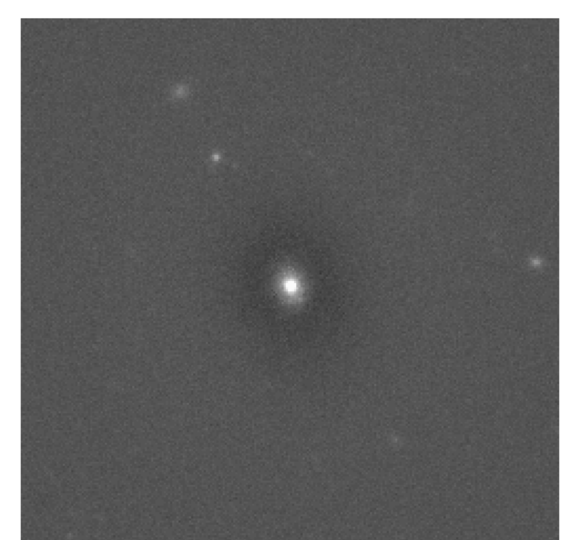
Image



Model



Residual



Example of IMFIT at work

Improving the fit

Leaving aside the question of mismatches between an exponential model and the actual galaxy, this isn't the best possible fit yet for our model. (You may have noticed that imfit reported a reduced χ2 value of ~ 0.45, which is a sign something odd is going on.) For one thing, we've deceived imfit about the nature of the data. The default χ2 minimization process that imfit uses is based on the Gaussian approximation to Poisson statistics, and assumes that the pixel values in the image are detected photoelectrons (or N-body particles, or something else that obeys Poisson statistics). In reality, our image deviates from this ideal in three ways:

1. There was a sky background that was previously subtracted from the image;
2. The pixel values are counts (ADUs), not detected photoelectrons;
3. The image has some Gaussian read noise.

To fix this, we can tell imfit three things:

1. The original background level (which we're already doing, via the --sky option);
2. The A/D gain in electrons/count, via the --gain option;
3. The read noise value (in electrons), via the --readnoise option

In the case of this SDSS image, the corresponding tsField FITS table (from the SDSS DR7 archive) has information about the A/D gain and the read noise (or "dark variance") and tells us that the gain and read noise are 4.725 and 4.3 electrons, respectively, for the r-band image.
So we can re-run the fit with the following command:

imfit ic3478rss_256.fits -c config_exponential_ic3478_256.dat --sky=130.14 --gain=4.725 readnoise=4.3

Now the reduced χ2 is about 2.1, which isn't necessarily that good, but is at least statistically plausible!

Reduced Chi^2 = 2.082564
AIC = 136482.400611, BIC = 136536.941458

X0 128.8540 # +/- 0.0239
Y0 129.1028 # +/- 0.0293
FUNCTION Exponential
PA 19.7266 # +/- 0.217212
ell 0.23152 # +/- 0.00155236
I_0 316.313 # +/- 0.619616
h 20.522 # +/- 0.0346742

$$\boxed{\chi^2 = \frac{1}{N_{\rm dof}} \sum_{x=1}^{N} \sum_{y=1}^{M} \frac{\left[I_{\rm m}(x,\, y) - I_{\rm g}(x,\, y)\right]^2}{\sigma^2}}$$

Example of IMFIT at work

Using mask to avoid pixels in the fitting

If you look at the image (e.g., with SAOimage DS9 or another FITS-displaying program), you can see features that most likely aren't part of the galaxy -- for example, there are certainly three (and possibly five) distinct, small objects near the galaxy which are probably foreground stars or background galaxies. Since they're relatively bright compared to the outer parts of the galaxy, they will bias the fit.
To prevent this from happening, you can mask out parts of an image. This is done with a separate mask image: an image of the same size as the data, but with pixel values = 0 for all the "good" pixels and >= 1 for all the "bad" pixels (i.e., those pixels you want Imfit to ignore).
The file ic3478rss_256_mask.fits in the examples directory is a mask image. You can use it in the fit with the "--mask" option:

imfit ic3478rss_256.fits -c config_exponential_ic3478_256.dat --mask ic3478rss_256_mask.fits --sky=130.14 --gain=4.725 --readnoise=4.3

(Again, note that options can be linked to their targets with "=" or with just a space, whichever make more sense to you.)
The reduced $\chi 2$ is slightly smaller; in addition, the position angle, ellipticity, and scale length of the best-fitting model have changed slightly (the smaller scale length is because imfit is no longer trying to account for the excess light from the other sources by radially stretching the exponential).

Reduced Chi^2 = 1.964467
AIC = 124602.443320, BIC = 124656.787960

X0 128.8793 # +/- 0.0237
Y0 129.0589 # +/- 0.0289
FUNCTION Exponential
PA 18.7492 # +/- 0.23086
ell 0.220646 # +/- 0.00159077
I_0 321.631 # +/- 0.634224
h 20.0684 # +/- 0.034584

Example of IMFIT at work

More Correct Fits: PSF Convolution

Astronomical images obtained with telescopes are almost always affected by telescope optics, atmospheric seeing, and so forth, so that the actual recorded image -- what we're trying to model -- is really the convolution of an idealized "true" image with a point-spread function (PSF).
You can simulate this process in Imfit by providing a PSF image in FITS format, using the --psf option. This can be any square, centered image, based on observed stellar PSFs, produced by telescope modeling software, etc. Imfit will then convolve the internally generated model image with the PSF image before comparing the model with the data.
Here, we use a pre-generated 51 x 51-pixel PSF image which approximates the seeing in the SDSS image using a circular Moffat function:

imfit ic3478rss_256.fits -c config_exponential_ic3478_256.dat --mask ic3478rss_256_mask.fits --gain=4.725 --readnoise=4.3 --sky=130.14 --psf psf_moffat_51.fits

Reduced Chi^2 = 2.002440
AIC = 127010.744960, BIC = 127065.089600

```
X0          128.8745 # +/- 0.0241
Y0          129.0573 # +/- 0.0293
FUNCTION Exponential
PA          18.7601 # +/- 0.23154
ell         0.221974 # +/- 0.0016039
I_0          322.35 # +/- 0.64072
h           20.0595 # +/- 0.034806
```

Example of IMFIT at work

Better Fits: Trying Different Models

As noted above, it looks like the exponential model is not a good match to the galaxy. You can see the available model components ("image functions") by calling imfit with the --list-functions option:

imfit —list-functions

You can also see the full set of parameters for each image function using the --list-parameters option:

imfit —list-parameters

A model fit to an image can consist of multiple image functions (and multiple copies of each image function), but for now let's just try a Sérsic function with elliptical isophotes. This is encoded in the "config_sersic_ic3478_256.dat" file.

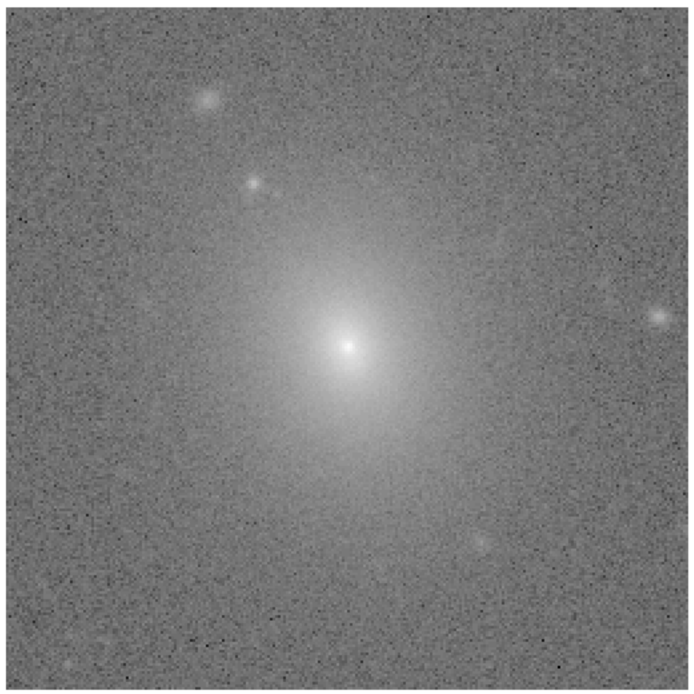
imfit ic3478rss_256.fits -c config_sersic_ic3478_256.dat --mask ic3478rss_256_mask.fits --gain=4.725 --readnoise=4.3 --sky=130.14 --psf psf_moffat_51.fits --save-model=model.fits —save-residual=resid.fits

The result is a significantly better fit:
Reduced Chi^2 = 1.055366
AIC = 66946.393806, BIC = 67009.795665

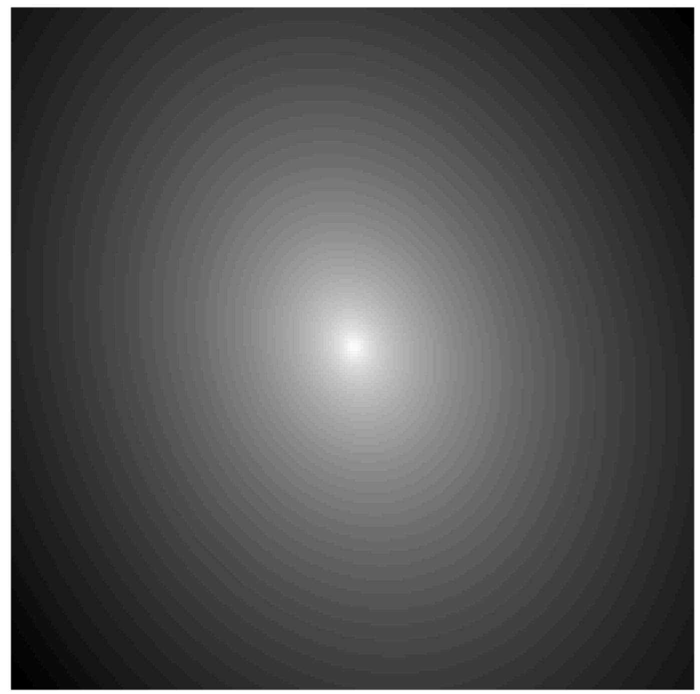
X0 128.9321 # +/- 0.0130
Y0 129.0983 # +/- 0.0155
FUNCTION Sersic
PA 19.0449 # +/- 0.247618
ell 0.221656 # +/- 0.00171861
n 2.3108 # +/- 0.00818546
I_e 22.1351 # +/- 0.163568
r_e 56.2217 # +/- 0.256568

Example of IMFIT at work

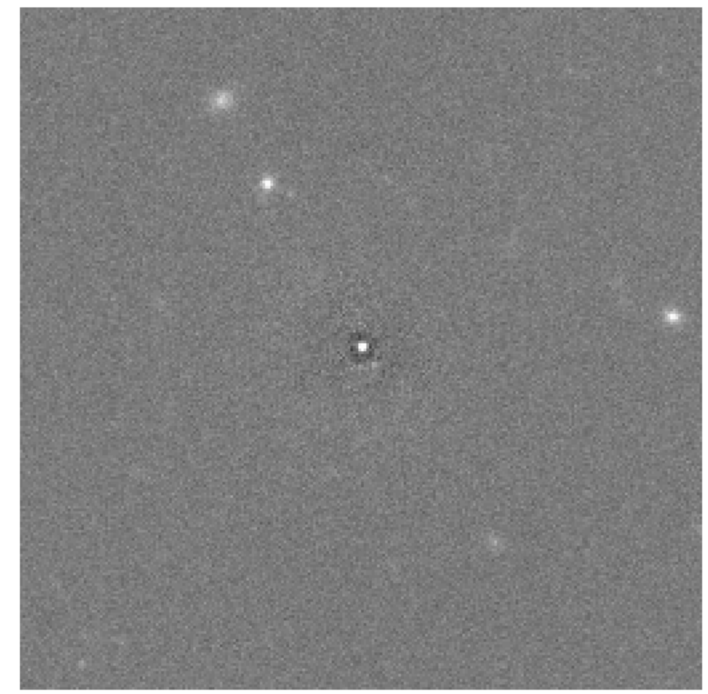
Image



Model



Residual



Example of IMFIT at work

Better Fits: Fitting Multiple Models

Many galaxies cannot be reproduced with single functions and multiple components need to be fitted simultaneously. We can do this by modifying the ‘config’ file adding different components one after the other. For instance, a combined Sersic+ Exponential model will look like

```
# This is an example of a configuration file for Imfit.
# More specifically, it specifies a Sersic model for use in fitting a
# 256x256-pixel SDSS r-band cutout image of the galaxy IC 3478.

X0   129.0    125,135
Y0   129.0    125,135
FUNCTION Sersic
PA    18.0    0,90
ell    0.2    0,1
n      1.5    0,5
I_e    15     0,500
r_e    25     0,100
FUNCTION Exponential
PA    18.0    0,90
ell    0.2    0,1
I_0    100    0,500
h      25     0,100
```

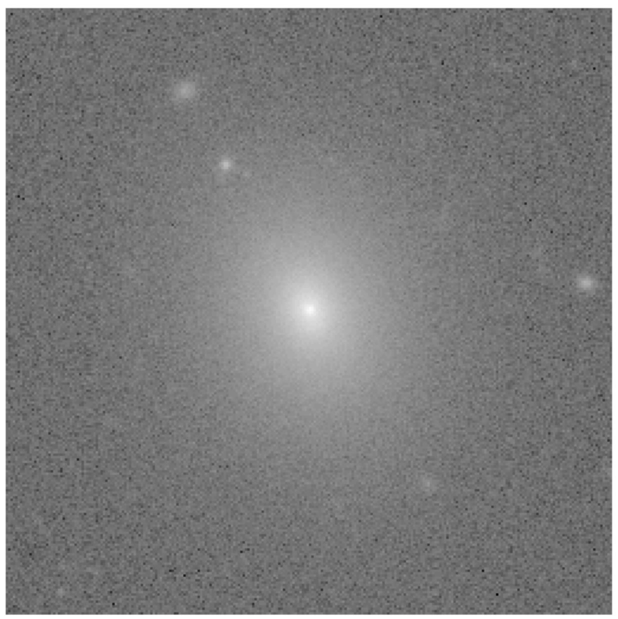
Then we can run again imfit with the corresponding config file

imfit ic3478rss_256.fits -c config_sersicexp_ic3478_256.dat --mask ic3478rss_256_mask.fits --gain=4.725 --readnoise=4.3 --sky=130.14 --psf psf_moffat_51.fits --save-model=model.fits —save-residual=resid.fits

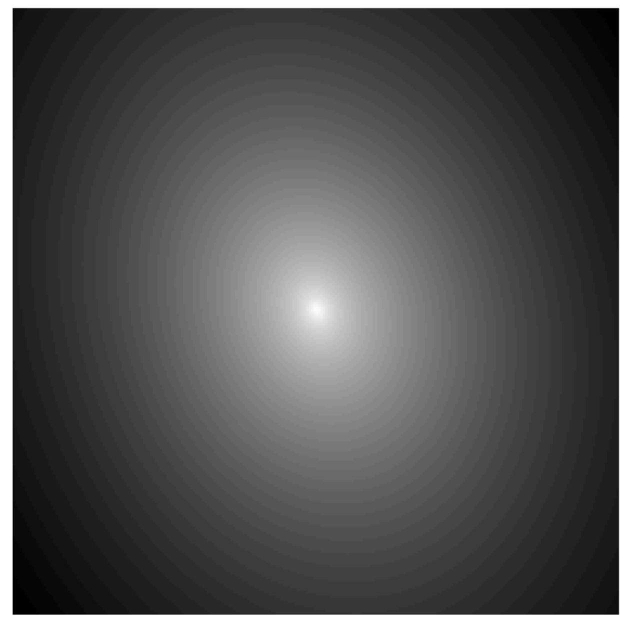
```
Reduced Chi^2 = 1.062989
AIC = 67433.569887, BIC = 67533.199992

X0              128.9257 # +/- 0.0145
Y0              129.0814 # +/- 0.0167
FUNCTION Sersic
PA              17.0369 # +/- 0.71238
ell             0.250777 # +/- 0.0055691
n                3.3454 # +/- 0.057037
I_e             8.85099 # +/- 0.4976
r_e             78.0184 # +/- 2.2964
FUNCTION Exponential
PA              27.2254 # +/- 2.7091
ell             0.17207 # +/- 0.014905
I_0             68.9615 # +/- 2.9409
h               23.6199 # +/- 0.42582
```

Example of IMFIT at work

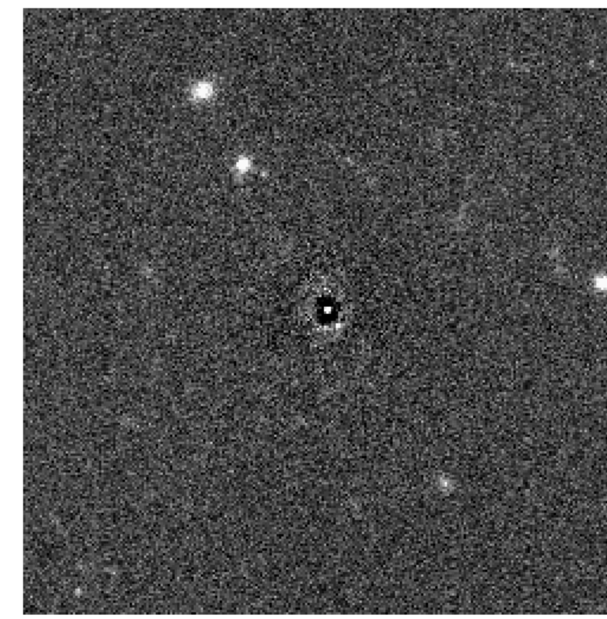
Image



Model



Residual



How to choose the best model

Single Sérsic

```
Reduced Chi^2 = 1.055366
AIC = 66946.393806, BIC = 67009.795665

X0      128.9321 # +/- 0.0130
Y0      129.0983 # +/- 0.0155
FUNCTION Sersic
PA      19.0449 # +/- 0.247618
ell     0.221656 # +/- 0.00171861
n       2.3108 # +/- 0.00818546
I_e     22.1351 # +/- 0.163568
r_e     56.2217 # +/- 0.256568
```

Sérsic + Exponential

```
Reduced Chi^2 = 1.062989
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X0              128.9257 # +/- 0.0145
Y0              129.0814 # +/- 0.0167
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How to choose the best model

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ell            0.250777 # +/- 0.0055691
n               3.3454 # +/- 0.057037
I_e            8.85099 # +/- 0.4976
r_e            78.0184 # +/- 2.2964
FUNCTION Exponential
PA             27.2254 # +/- 2.7091
ell            0.17207 # +/- 0.014905
I_0            68.9615 # +/- 2.9409
h              23.6199 # +/- 0.42582
```

The Chi^2 closer to one would represent a better a fit, but
be aware of the number of free parameters included in the fit

How to choose the best model

Single Sérsic

```
Reduced Chi^2 = 1.055366
AIC = 66946.393806, BIC = 67009.795665

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I_e           8.85099 # +/- 0.4976
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FUNCTION Exponential
PA            27.2254 # +/- 2.7091
ell           0.17207 # +/- 0.014905
I_0           68.9615 # +/- 2.9409
h             23.6199 # +/- 0.42582
```

$$\mathrm{AIC_c} = -2\ln\mathcal{L} + 2k + \frac{2k(k+1)}{n-k-1}$$

Akaike Information Criteria

$$\mathrm{BIC} = -2\ln\mathcal{L} + k\ln n$$

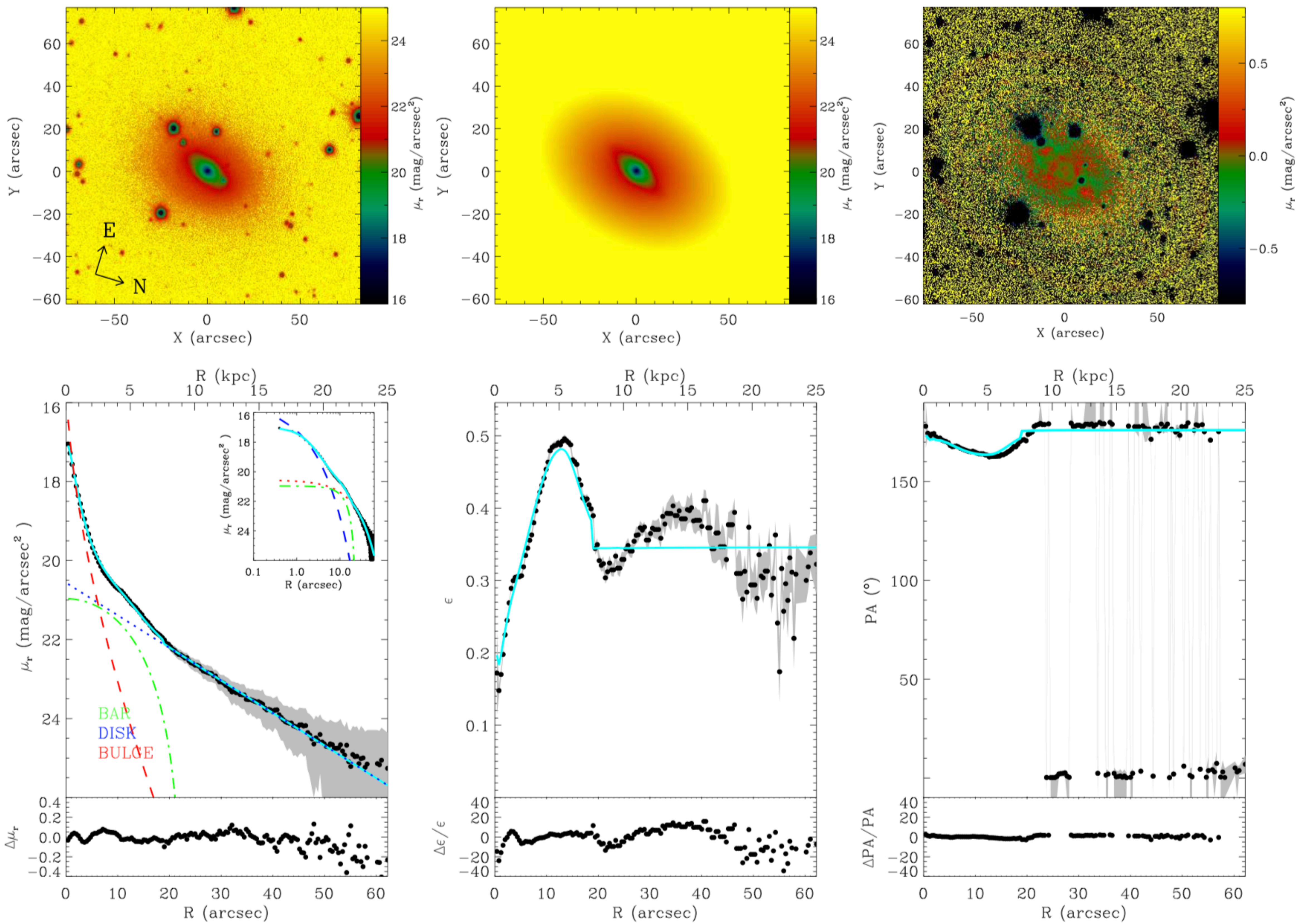
Bayesian Information Criteria

Free parameters

Data points

When two or more models fit to the same data are compared, the model with the lowest AIC (or BIC) is preferred, though a difference ΔAIC or ΔBIC of at least ~ 6 is usually required before one model can be deemed clearly superior (or inferior); see, e.g., Takeuchi (2000) and Liddle (2007) for discussions of AIC and BIC in astronomical contexts, and Burnham & Anderson (2002) for more general background. Needless to say, all models being compared in this manner should be fit by minimizing the same fit statistic.

How the final best fit should looks like?



What do you have to do now?

Repeat the steps described during this lab for a galaxy in the list

https://drive.google.com/drive/folders/1JtpndXzqOj90W2LOjFncJYGNjEDJGhA7?usp=sharing

- Fill the GalaxyTable.docx with your names on your favourite galaxy
- galaxy_i.fits is the file containing the image of your galaxy
- galaxy_mask2D_new.fits is the file containing the mask for your galaxy
- phot_pars_lab1.docx is a file with information about the sky counts and calibration of the images
- SKY_PSF.docx is a file with information about the PSF of the images.

What do you have to do now?

Repeat the steps described during this lab for a galaxy in the list

- Perform the 2D photometric decomposition (search for the best fit model). Use as many components as necessary and take into account all the information to perform a good fit.
- Create a table with the main results (best fit parameters (in observed and physical units), derive other parameters such as total magnitude of the components and B/T).
- Create 2D maps of galaxy, models and residuals. Plot 1D profiles of the galaxy with best fit models —Sérsic+Exponential- overplotted. Use physical scales whenever possible.
- Include all this information in the report in the correct sections.

Tricks and Tips

- The initial conditions are fundamental to obtain a physically meaningful fit.
- Always check the results…do not fully trust the results just because the code converges. Use the 1D profiles to check the fits.
- Remember the noise! Use properly the sky, readout noise and gain.
- Remember the PSF.
- Use a mask whenever there are other sources in the image.
- Remember there is a difference between calibrate a magnitude (mag) and a surface brightness (mag/arcsec^2). There is a factor to account for the area (tip: pixel scale)
- Use the redshift (or the recessional velocity) to compute distances. Remember the Hubble law.
- Use the angular size to transform arcsec -> kpc.

Final Report

Abstract: Structured summary of the exercise
Introduction: Importance of photometric decomposition to understand galaxy structure
Methodology: How did you get to the best fit? Use of image parameter (gain, RON, sky, PSF), test with different components, finding the best fit
Results: Best fit 2D image and residuals, plot the 1D radial profiles with the best fit over plotted. Compute B/T
Discussion: Discuss your results in terms of what is already known about the subject
Conclusions: Ordered summary of main results and discussions
References: