Demonstration on surface photometry and structural decomposition of galaxies

Physics of galaxy formation course (demo session)

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The photometric system

The magnitude system is logarithmic

A 5 mag difference means a factor of 100 in brightness.

$m_1 - m_2 = -2.5 \log_{10}(F_1 / F_2)$

$m = -2.5 \log_{10}(F) + ZP$

F = measured flux; ZP = flux calibration zeropoint

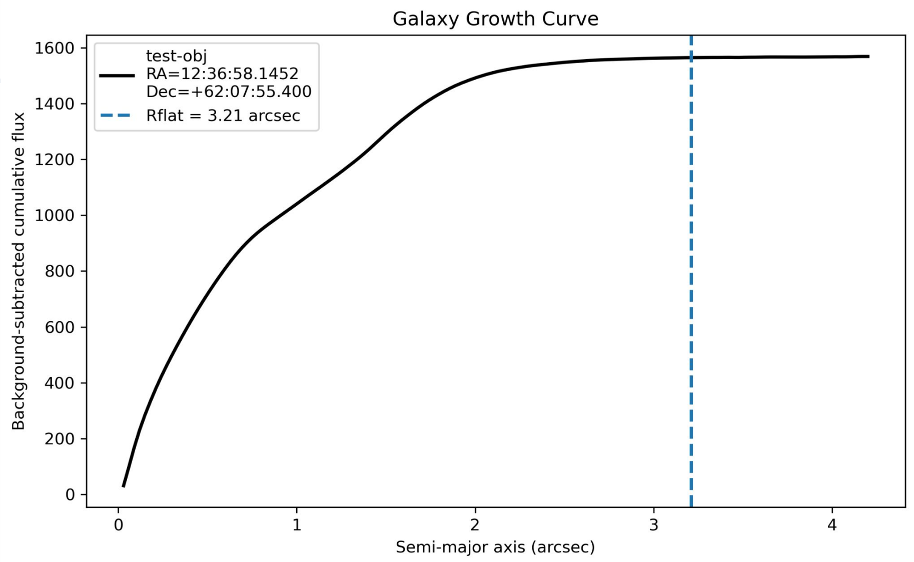
In AB magnitude system: 0 mag = 3631 Jansky

Take care to check whether the values are AB, Vega or any other system.

Measuring fluxes

Curve of growth

Measure flux in progressively larger apertures and obtain cumulative flux curve using concentric apertures.
Sensitive to sky estimate and object crowding.



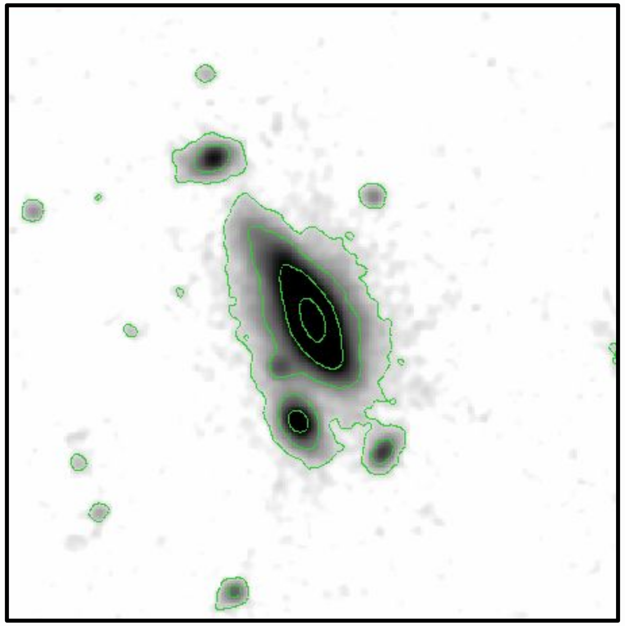
Fixed aperture photometry

Aperture photometry: excellent for stars, due to well-behaved light distribution, but galaxies are extended with diverse light profiles and blended neighbours adds to the complexity.

That is why galaxy photometry needs a little more care.

Isophotal photometry

Better for extended sources but depends on the threshold and again affected by crowding. Also it can miss the faint outskirts of galaxies.



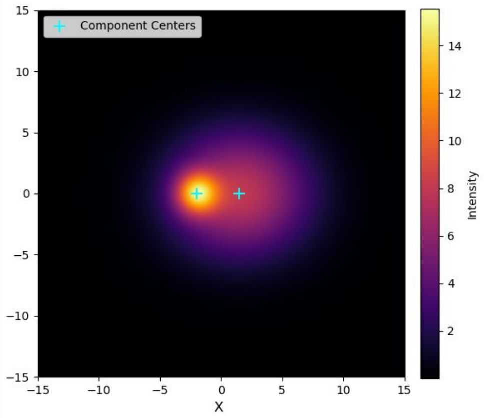
Parametric models (?) Beyond integrated fluxes

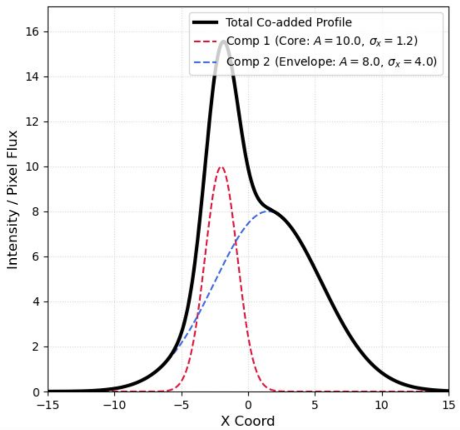
Why parametric models help?

Parametric models describe a galaxy with physically meaningful components rather than just summed pixels.

They are especially useful in crowded fields, for multi-component systems, and when we want component magnitudes, sizes, orientations, etc.

Example: Two gaussians blended together. With parametric models we obtain total model fluxes along with consistent size measurements for comparison (e.g. FWHM)

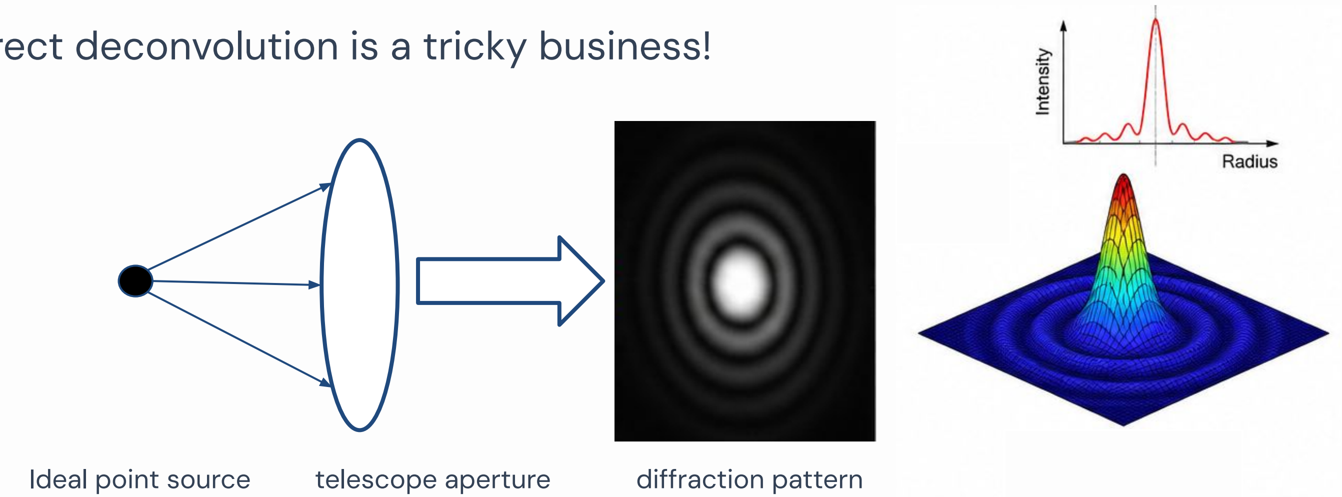




Importantly, the effect of **point spread function (PSF)** can be taken into account fairly well.

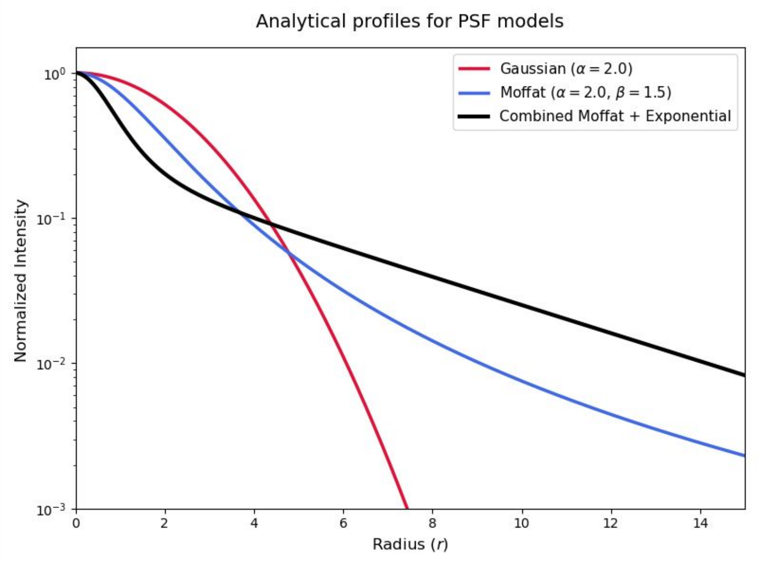
Everything we see is convolved with the PSF of the observing instrument.

Direct deconvolution is a tricky business!

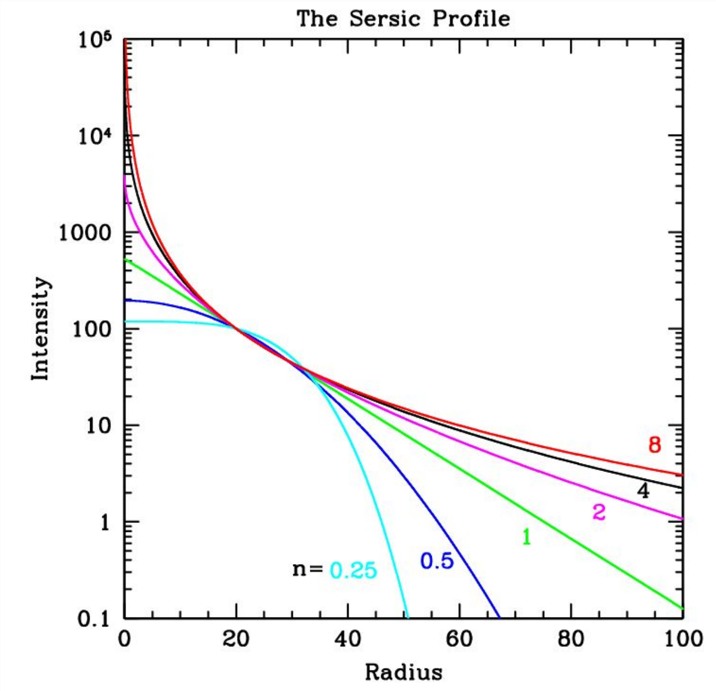


Different parametric profiles

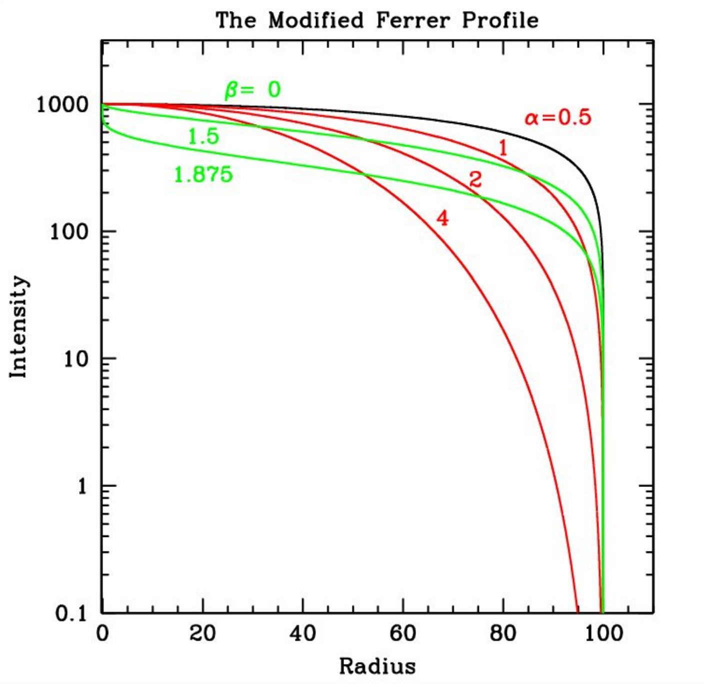
PSF profiles



General galaxy profiles (Ellipticals, bulges, bars, disks)



Stellar bar profiles



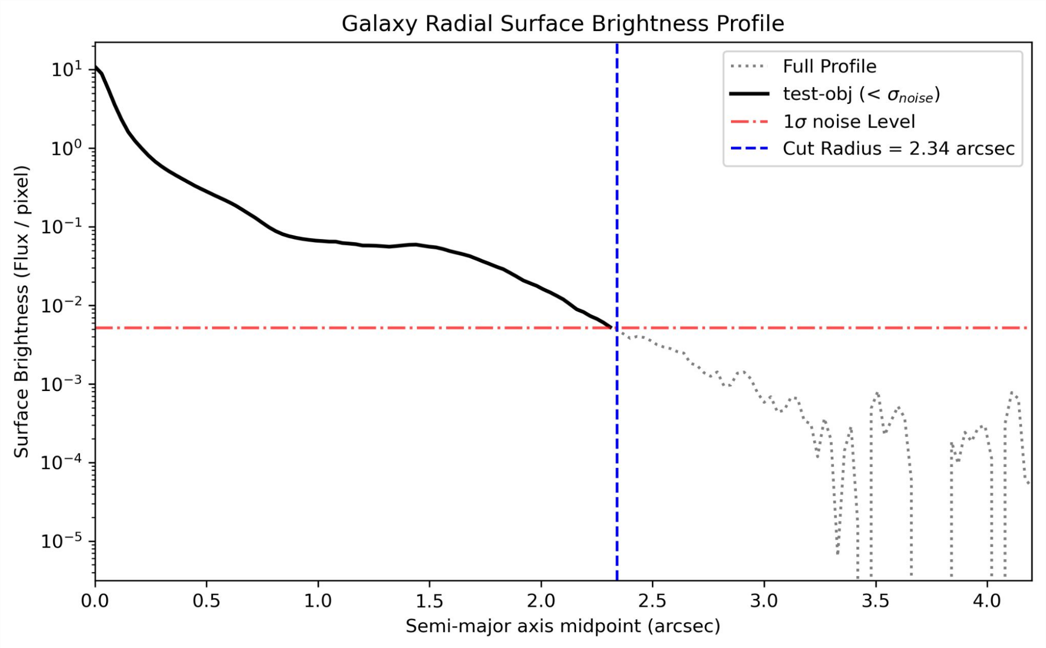
Surface photometry

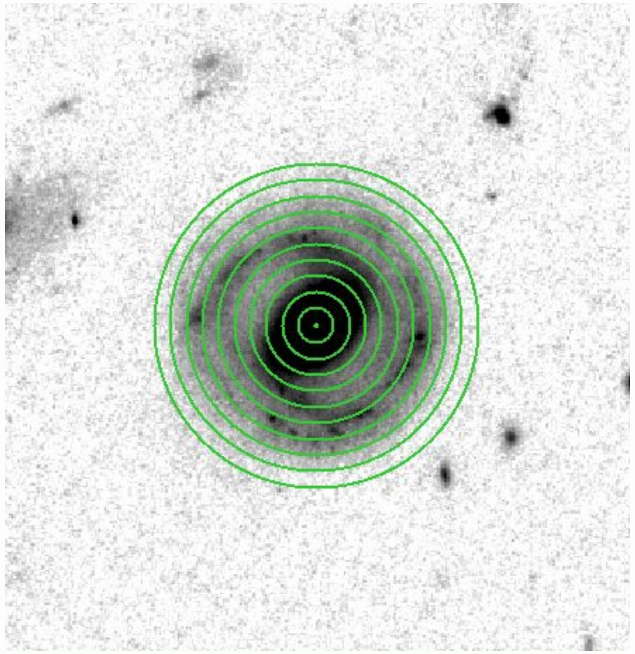
Surface brightness is the flux per unit area, usually written in mag arcsec^{-2}.

$\mu = -2.5 \log_{10}(F / \text{area}) + \text{zeropoint}$ (area = number of pixels * pixel scale)

We can use concentric annuli to obtain the radial profile of a galaxy.

Example: Plot of average flux per pixel.

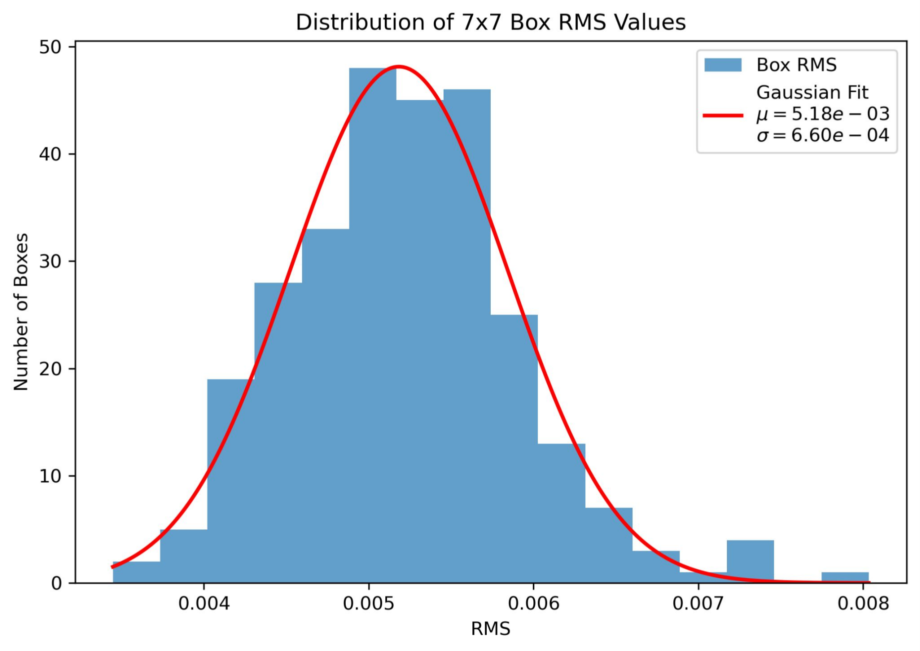




Reliability of observed profile: until it hits the noise/errors become large (?)

Sky background/noise estimates

Example:



**Sometimes noise map comes bundled with the data

signal-to-noise within an region

$$\mathrm{SNR} = S_{object} \,/\, \sqrt{(\sigma_{sky}{}^2 + S_{object} + S_{sky} + \text{read noise})}$$

$$mag_{err} \sim 1/\mathrm{SNR}$$

Isophotal analysis and 1D profile extraction

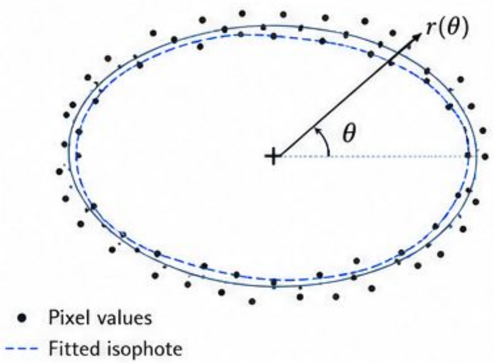
Ellipses are often better than circles because they allow for variation in ellipticity and position angle.

Nearby objects should be cleaned off or masked before proceeding.

A sequence of elliptical isophotes are fit.

We get average intensity, ellipticity, position-angles, centers etc. as a function of the radial distance.

HOW AN ISOPHOTE IS FIT



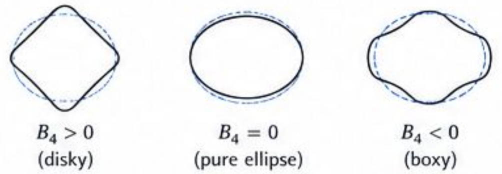
The ellipse parameters are adjusted to minimize the intensity residuals around the isophote.

INTENSITY AS A FOURIER SERIES

Along a fitted isophote of semi-major axis a, the intensity variation is described by:

$$I(\theta) = I_0(a) + \sum_{n=1}^{N} \left[A_n(a)\sin(n\theta) + B_n(a)\cos(n\theta)\right]$$

I_0 = mean intensity on the isophote
A_n, B_n = Fourier coefficients $(n = 1, 2, \ldots)$
A_4, B_4 indicate deviations from pure ellipses (disky/boxy isophotes)



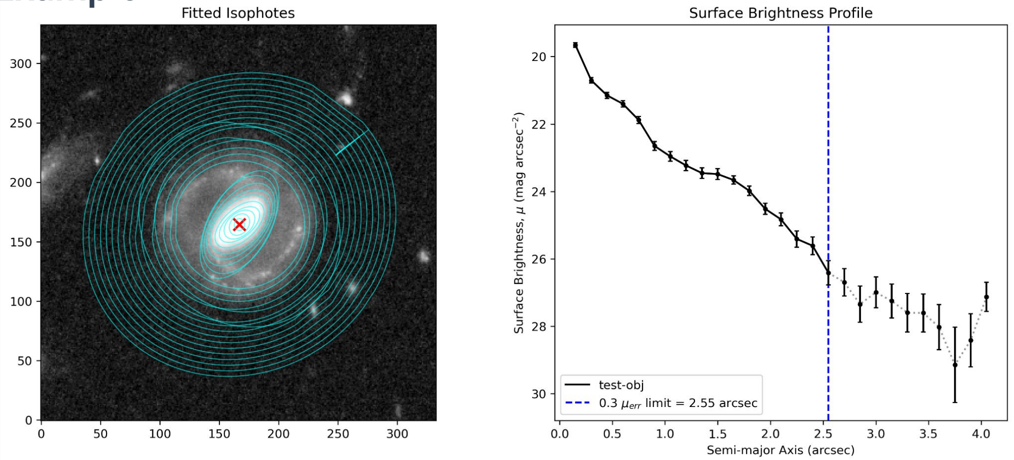
User Guide > Elliptical Isophote Analysis (`photutils.isophote`)

Elliptical Isophote Analysis (`photutils.isophote`)

Introduction

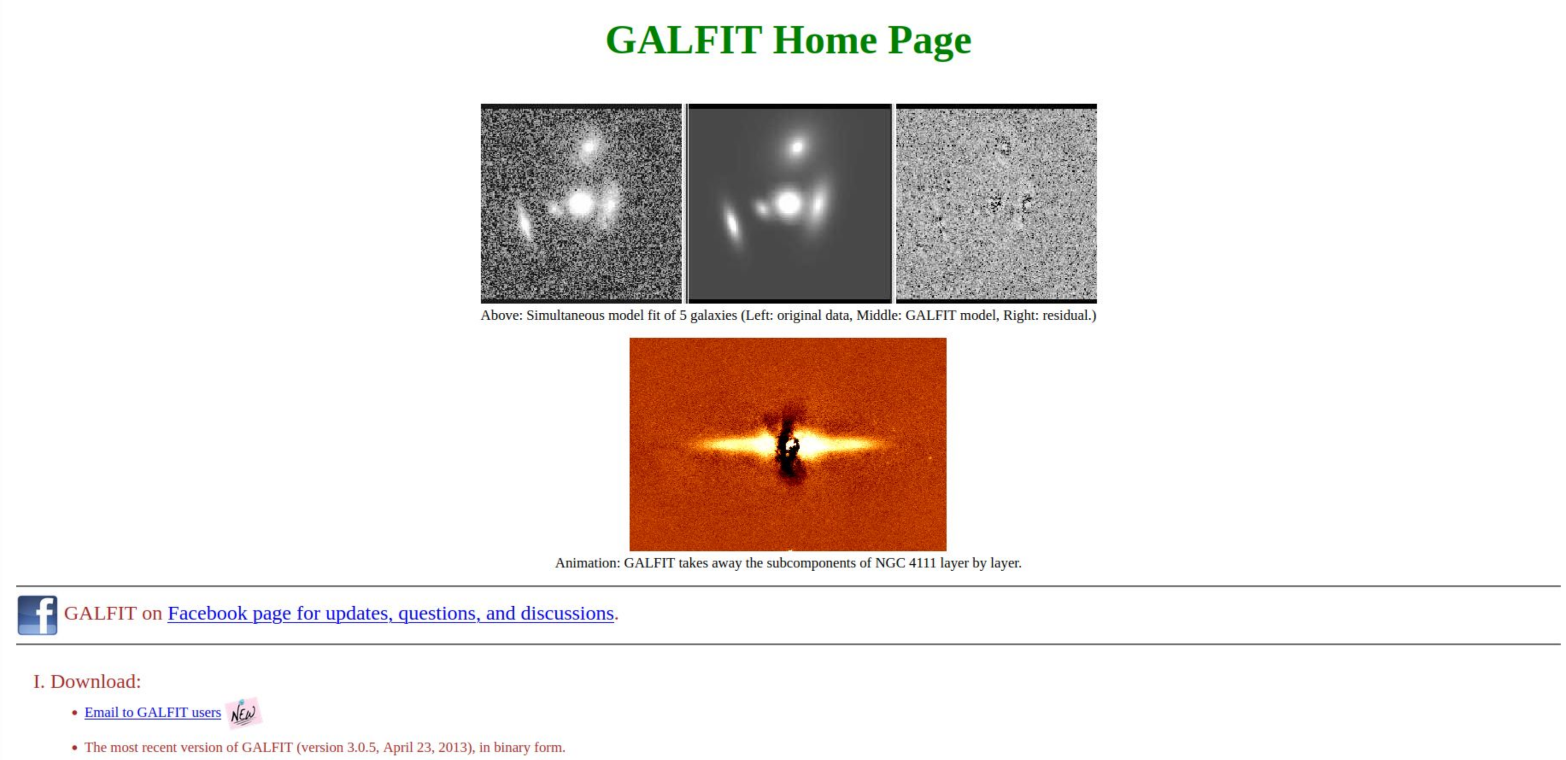
The `isophote` package provides tools to fit elliptical isophotes to a galaxy image. The isophotes in the image are measured using an iterative method described by Jedrzejewski (1987; MNRAS 226, 747). See the documentation of the `Ellipse` class for details about the algorithm. Please also see the Isophote Frequently Asked Questions.

Example



Can fit parametric 1D profiles and perform galaxy decomposition. 1D profiles are useful for deciding on initial guesses.

GALFIT and 2D modelling



[Original paper on GALFIT](#) (Peng et al. 2002, Astro*nomical* Journal (AJ), 124, 266)

2D image provides more information and allows for better decomposition choices.

GALFIT is a 2D fitting code allows to fit a variety parametric models via χ^2 minimisation.

PSF, bulges, disks, bars, rings, spiral arms, even irregular galaxies (more info in the relevant papers by *Peng et al.*)

2D surface photometry with GALFIT

Preparation:

- science image
- 2D PSF
- sigma image
- mask image

Importantly, configure the feedme file.

```

===============================================================================
# IMAGE and GALFIT CONTROL PARAMETERS
A) jwst-example-cutout.fits[1]   #  Sersic index n (de Vaucouleurs n=4)
B) model-output.fits   # Output data image block
C) obj-rms.fits               # Sigma image name (made from data if blank or "none")
D) jwst_f150w_psf.fits           # Input PSF image and (optional) diffusion kernel
E) 1                    # PSF fine sampling factor relative to data
F) obj-mask.fits        # Bad pixel mask (FITS image or ASCII coord list)
G) constraints.txt                # File with parameter constraints (ASCII file)
H) 61 262 67 268 # Image region to fit (xmin xmax ymin ymax)
I) 161  161        # Size of the convolution box (x y)
J) 28.0  # Magnitude photometric zeropoint
K) 0.03  0.03        # Plate scale (dx dy)    [arcsec per pixel]
O) regular              # Display type (regular, curses, both)
P) 0                    # Choose: 0=optimize, 1=model, 2=imgblock, 3=subcomps

# INITIAL FITTING PARAMETERS
#
#   For object type, the allowed functions are:
#       nuker, sersic, expdisk, devauc, king, psf, gaussian, moffat,
#       ferrer, powsersic, sky, and isophote.
#
#   Hidden parameters will only appear when they're specified:
#       C0 (diskyness/boxyness),
#       Fn (n=integer, Azimuthal Fourier Modes),
#       R0-R10 (PA rotation, for creating spiral structures).
#
# -----------------------------------------------------------------------------
#   par)    par value(s)    fit toggle(s)    # parameter description
# -----------------------------------------------------------------------------



================================================================================

# Component number: 1
0) sersic                    #  Component type
1) 167  167   1 1  #  Position x, y
3) 22.0 1           #  Integrated magnitude
4) 5   1          #  R_e (effective radius)   [pix]
5) 2   1          #  Sersic index n (de Vaucouleurs n=4)
 6) 0.0000      0          #     -----
 7) 0.0000      0          #     -----
 8) 0.0000      0          #     -----
9) 0.9     1          #  Axis ratio (b/a)
10) -10    1          #  Position angle (PA) [deg: Up=0, Left=90]
```

The GALFIT workflow

Crop and clean postage stamp around the target (there should be sufficient sky as well).

Mask neighbours, and defects or use a mask image. Proper PSF is a must, especially in case of compact objects.

Derive initial guesses from the image or from a 1D profile.

Fit the simplest model first, then add components only when the residuals justify it.

Re-run with small changes to check stability.

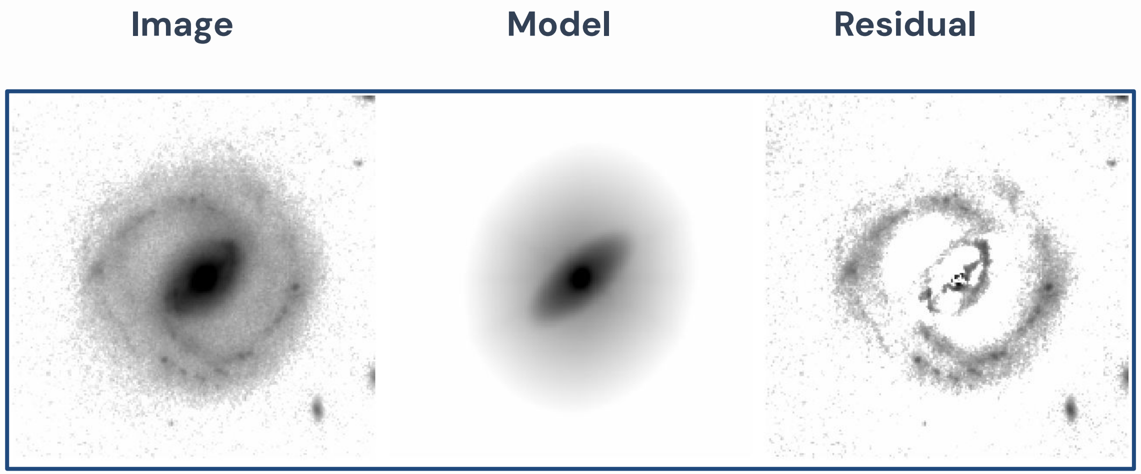
Optimization goals

χ^2 is a good metric, but not always sufficient!
The fit must also be visually and physically reasonable.

Separate the galaxy light distribution into physically meaningful components such as bulge, disk, bar, nucleus, etc.

Can go on adding models arbitrarily to obtain a numerically good fit but can be physically absurd!

Modelling becomes challenging as sizes grow smaller and reach closer to the PSF regime.



Summary

- Basic photometry and ways to measure fluxes.
- Surface photometry to extract galaxy profiles.
- Using GALFIT to perform full 2D decomposition.
- The best model is the one that is stable, interpretable, and consistent with the residuals.