Data reduction & analysis

Observational Astronomy

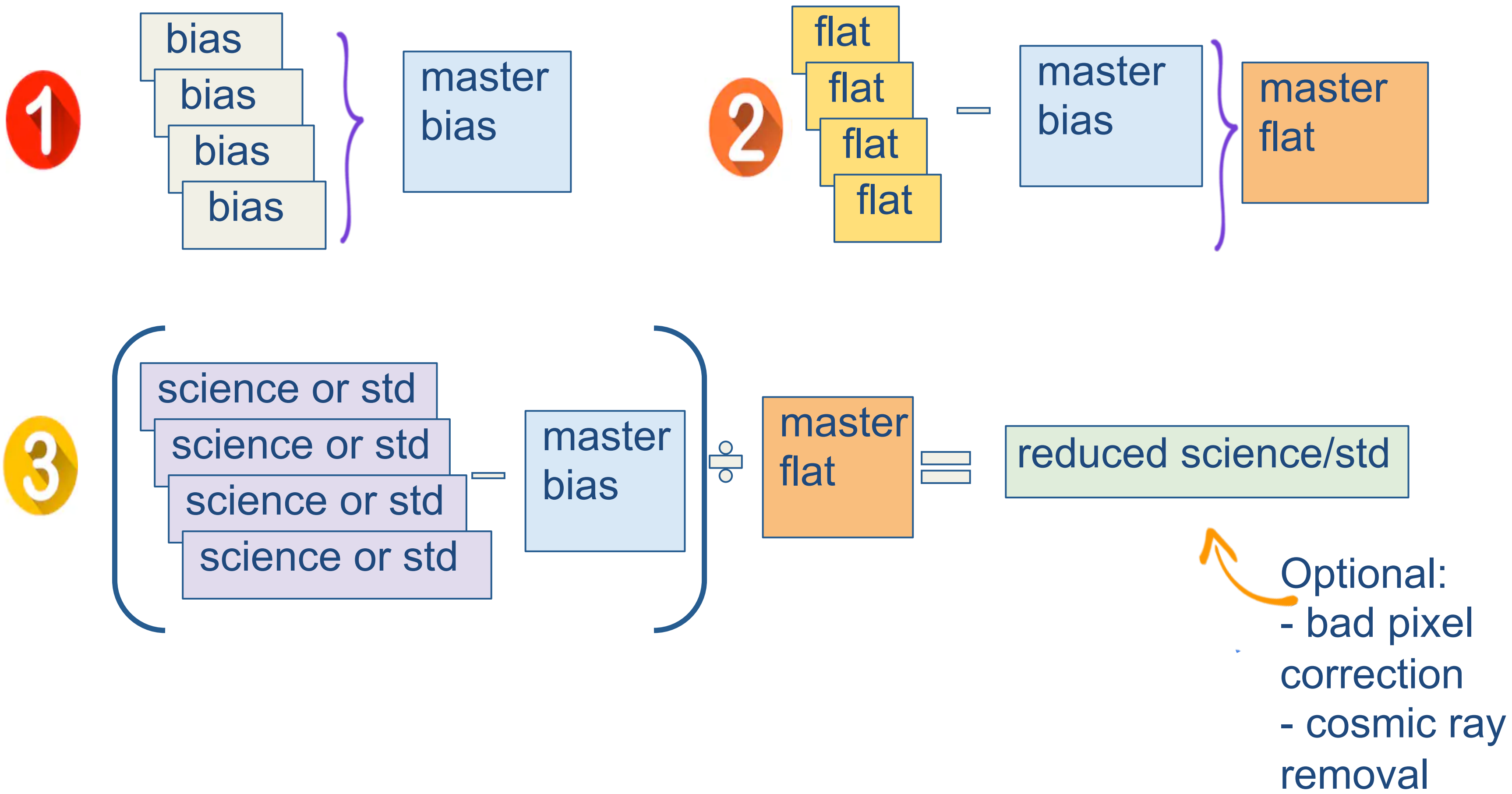
Laboratory of Astrophysics

Data reduction

- Reading/writing files
- Aligning & stacking
- Bias/dark & flat-field

Use python/astropy.io.fits

Data reduction - summary

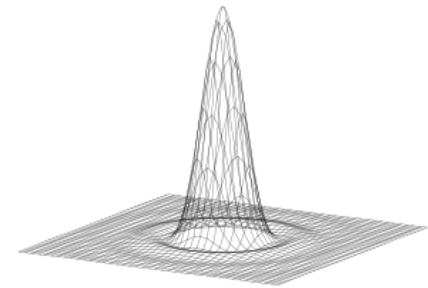


Data analysis: some basics

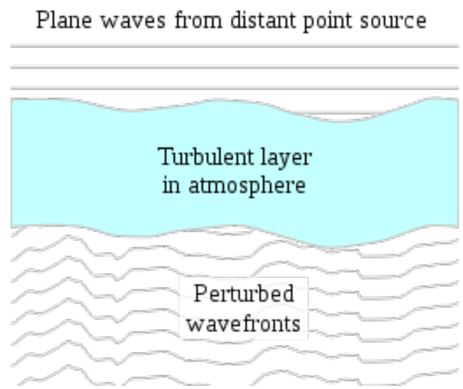
- Always estimate errors and propagate them!!!!
- Do not fake data even if your data is crappy. Instead calculate the errors properly!
- Statistics are primordial. Investigate and learn how to do things well.

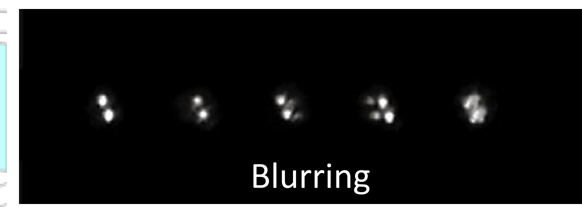
Seeing and FWHM

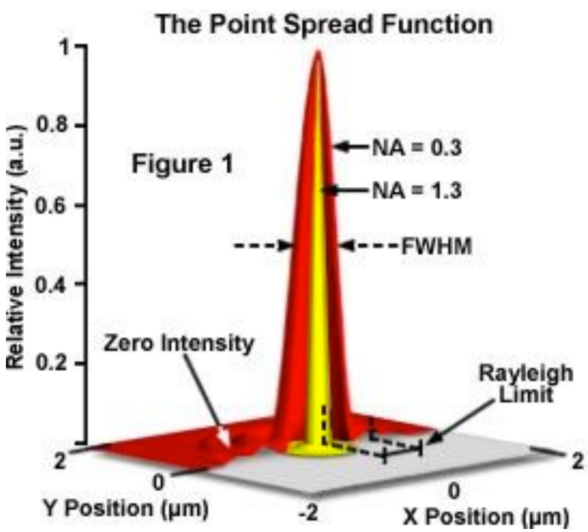
Airy pattern: how star looks like without atmosphere (diffraction), related to angular resolution (Rayleigh criterion)



Seeing: atmospheric turbulence





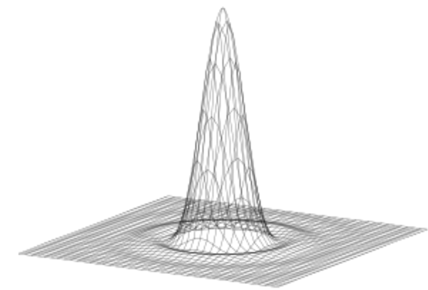


Point spread function (PSF): response of the imaging system to a point source, wider than Airy function

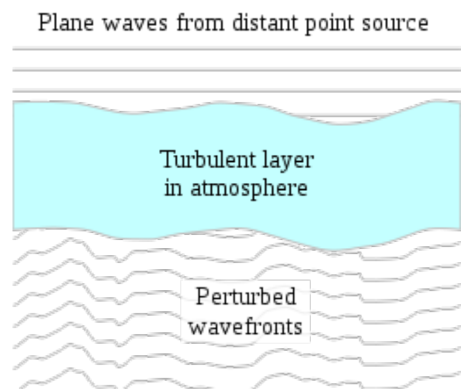
Full width half-maximum (FWHM): diameter of seeing disk (arcsec). Measure as width at half flux

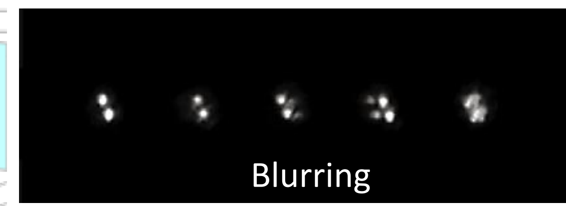
Seeing and FWHM

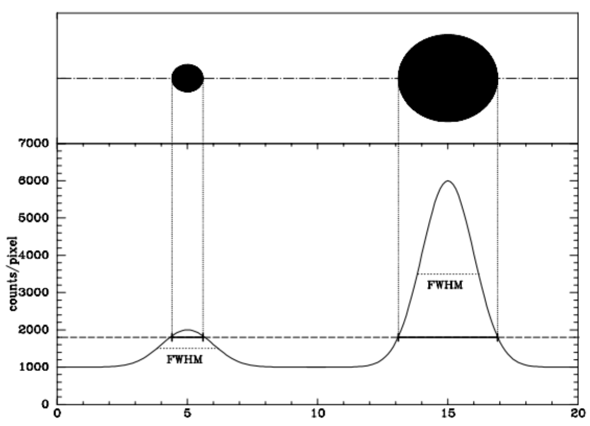
Airy pattern: how star looks like without atmosphere (diffraction), related to angular resolution (Rayleigh criterion)



Seeing: atmospheric turbulence







Point spread function (PSF): response of the imaging system to a point source, wider than Airy function

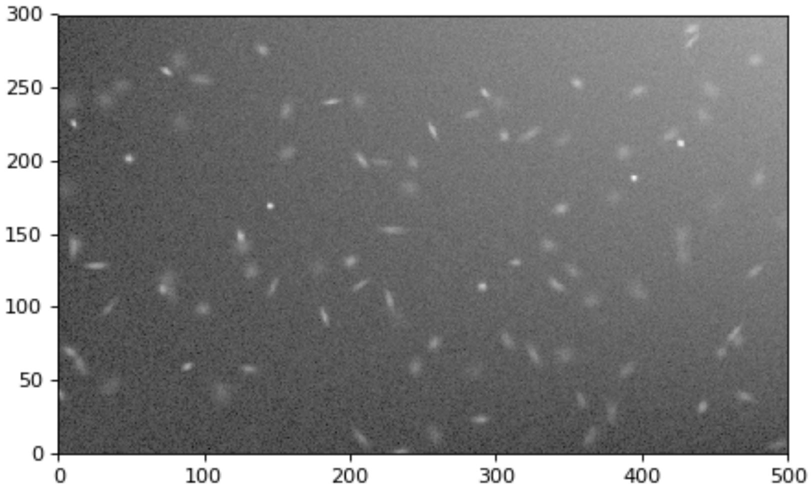
Full width half-maximum (FWHM): diameter of seeing disk (arcsec). Measure as width at half flux

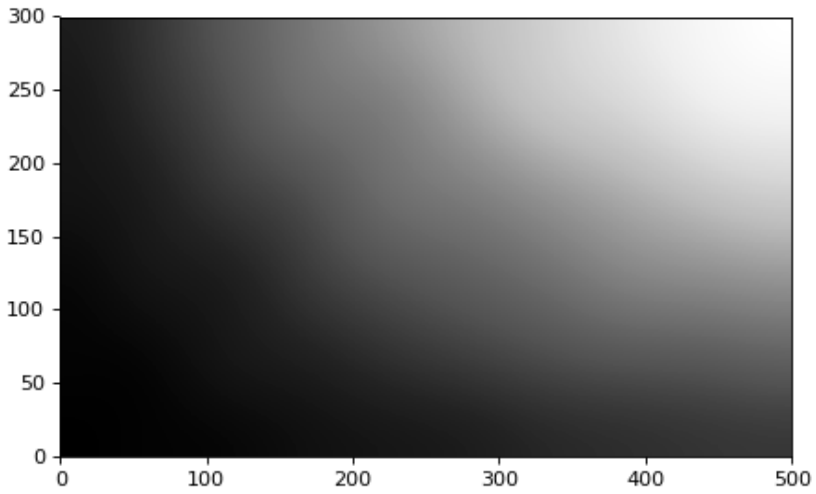
Background and noise

- ❑ Background level: from sky and/or detector
- ❑ Background noise: errors

Methods:

- ❖ Sky median and stddev *but* real sources are there
- ❖ Robust statistics: biweight location and median absolute deviation (MAD)
- ❖ Sigma clipping
- ❖ Mask sources





Calculate with python/photutils: background, Background2D

Data analysis in astronomy

- **Astrometry**
- **Photometry**
- Spectroscopy
- Polarimetry

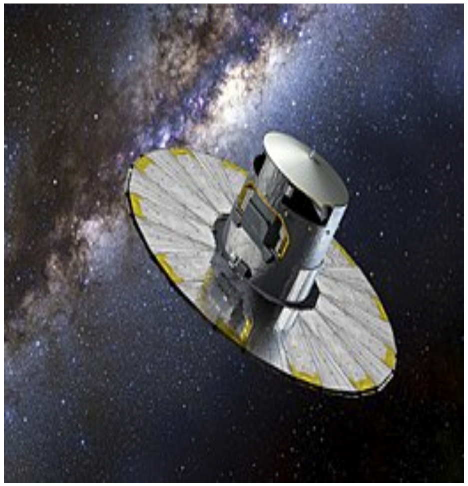
Astrometry

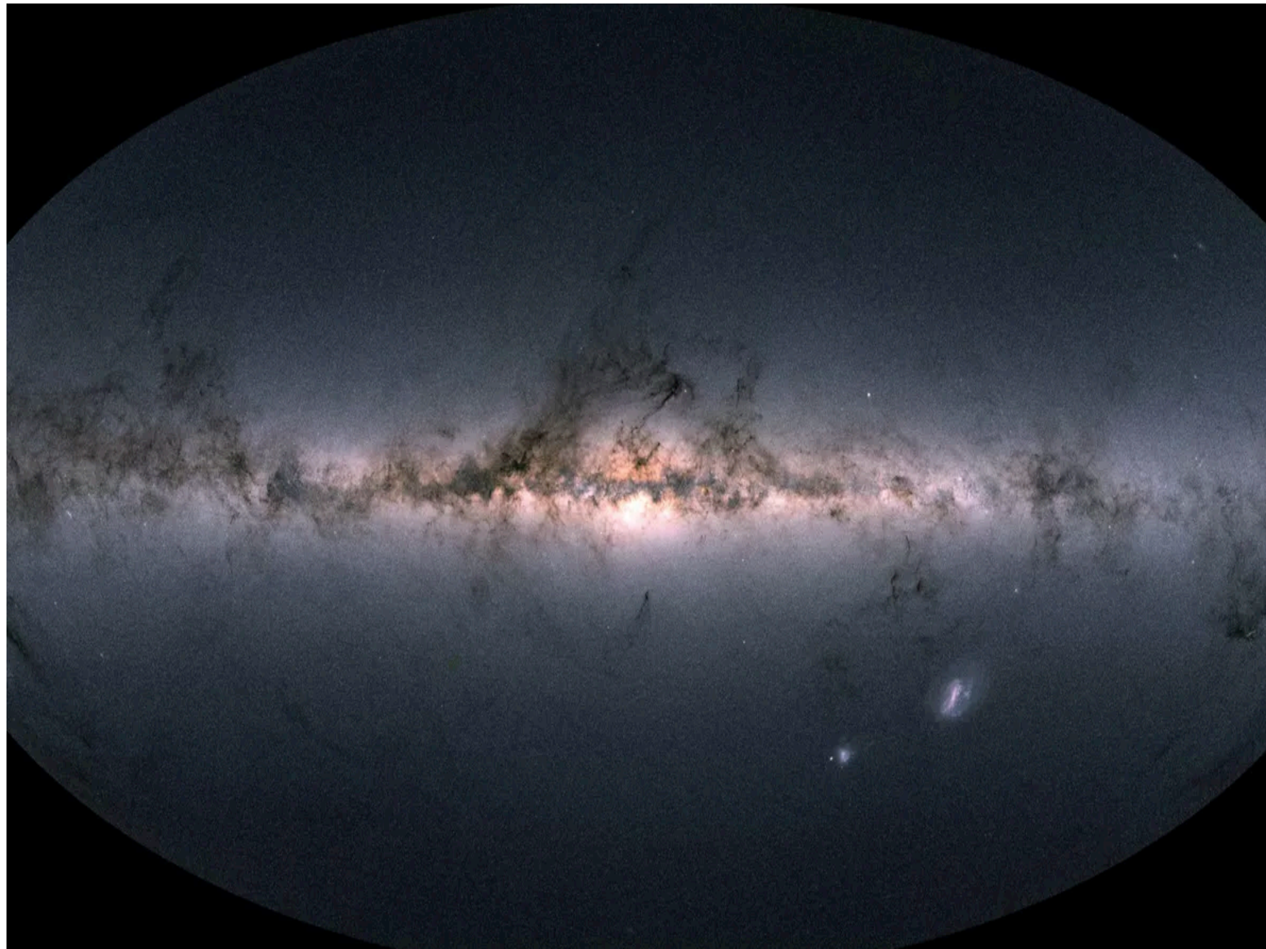
Precise measurement of positions and velocities of celestial objects

Astrometric solution: a world coordinate system (WCS) for the whole image using star catalogs and non-linear geometrical transformations

Use
Astrometry.net

Astrometry: Gaia



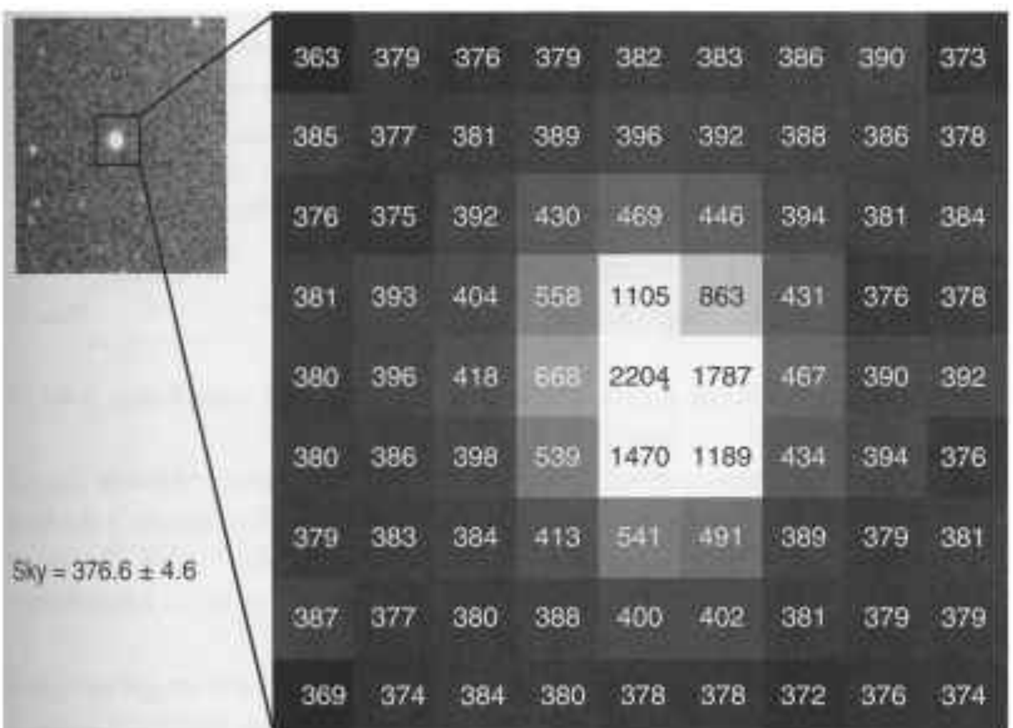


Precise positions, proper motions and parallaxes for > 1 billion stars

Launched in 2013 Expected end: 2022

Centroid

It is the barycenter (center of mass) of the image: use to calculate star center



Error on centroid:

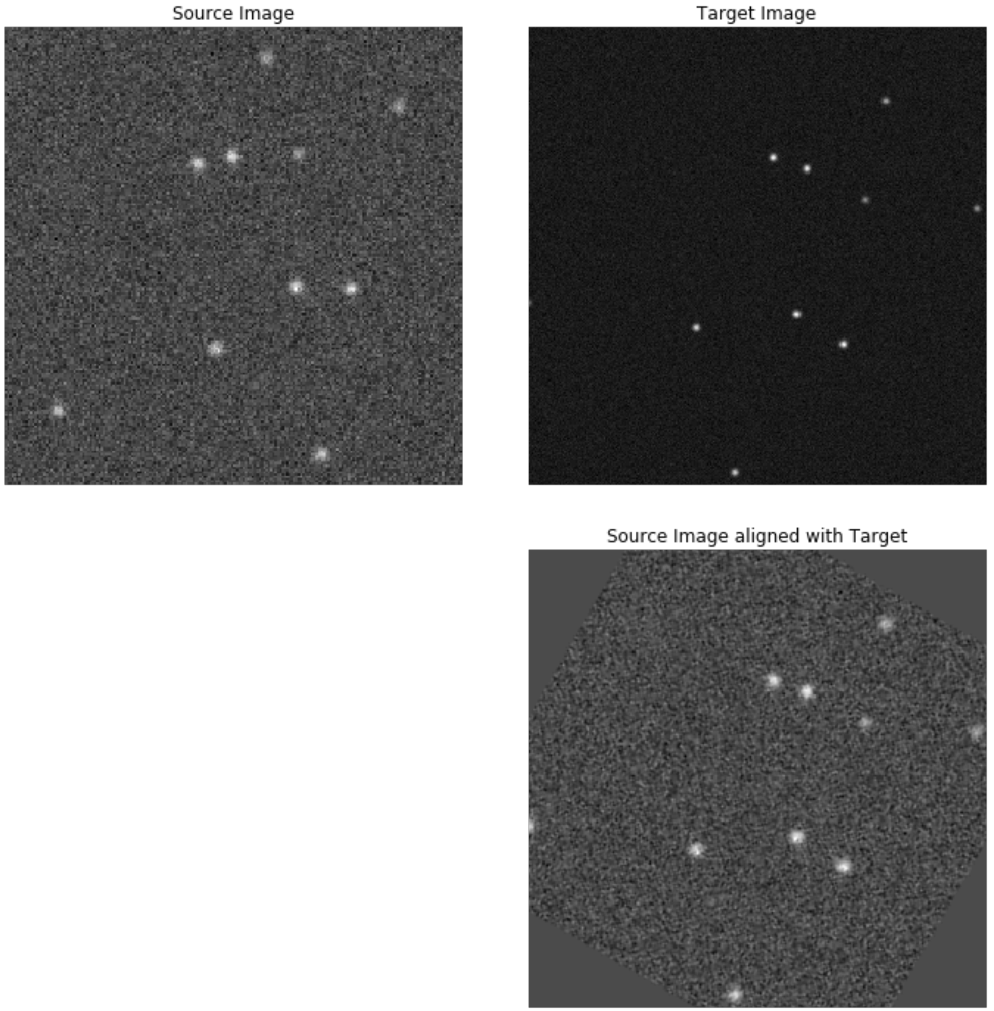
- from function used and noise
- from several images
- from different techniques

Calculate with ds9 or python/ photutils: centroid_com,centroid_2dg

Aligning images

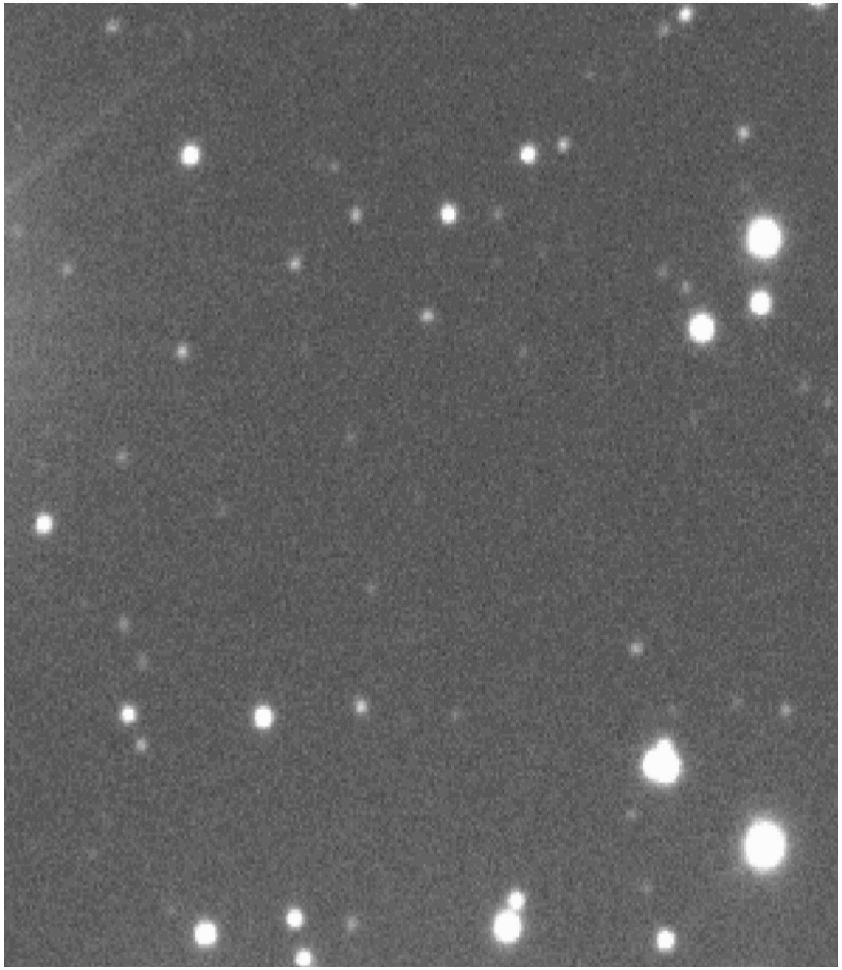
Two images that are not perfectly aligned need to be matched:

- simple shift based on centroids
- simple shift based on astrometric solution
- more advanced algorithm that takes into account rotations, deformations, etc.



Use python/astroalign

Object detection



How do we (mathematically) define when there is an object?

Define a detection threshold and area: if there are N pixels above the threshold in the area ⟶ that's an object

Use python/photutils (starfinder)

Stellar cluster: membership

Stars in an image might be from the cluster of foreground/background stars.
What observables characterizes the stars of the cluster?

- Distance
- Proper motion

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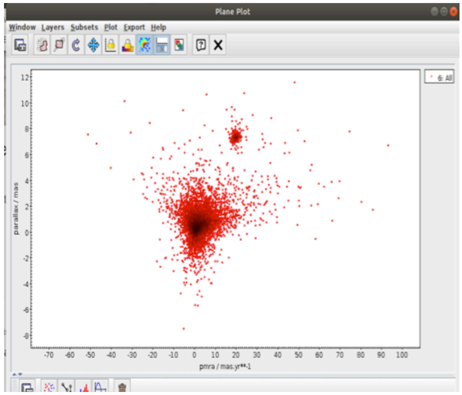
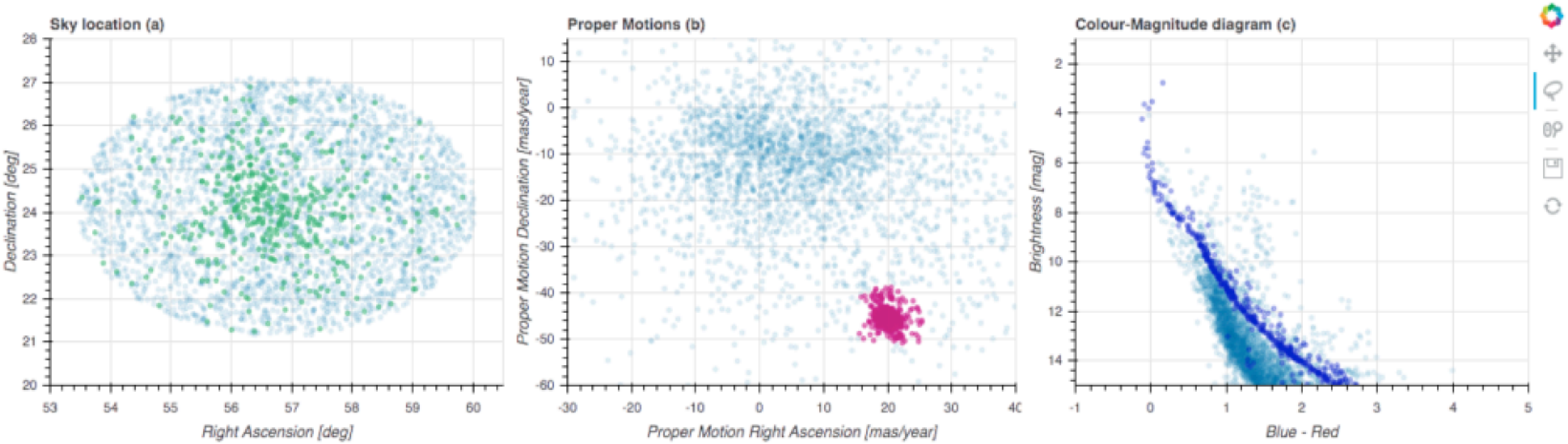




Use Gaia catalogs and astropy for matching

Data analysis in astronomy

- **Astrometry**: precise measurement of positions and velocities of celestial objects
- **Photometry:** measurement of flux through CCD (and passbands)

Photometry

Measure of flux through CCD (and passbands)

- **Aperture/PSF photometry:** for point sources
- **Surface photometry**: measure surface brightness distribution of extended sources

How you calibrate it:

- **Absolute photometry**: with respect to a standard star
- **Differential photometry**: compare main target's brightness with reference stars in same field

Aperture photometry

Since PSF is wide, we need to integrate several pixels to obtain the light of the star. But this contains sky background and contamination from other sources.

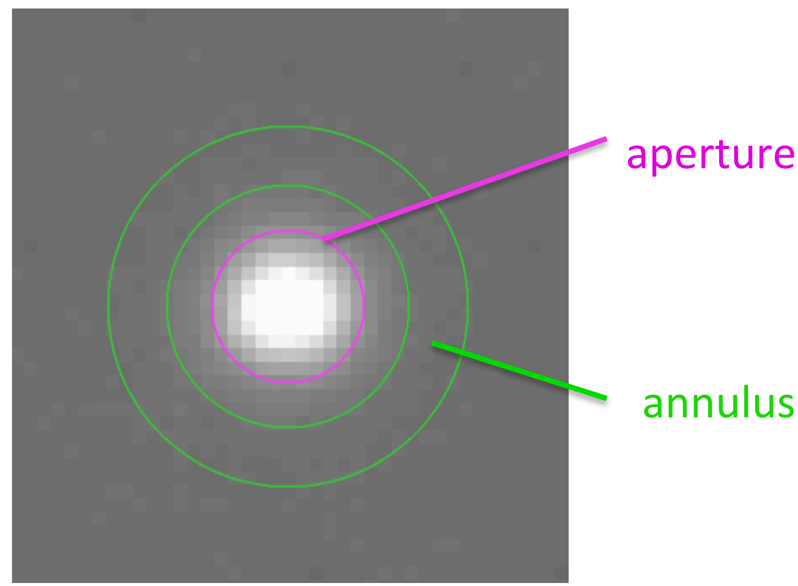
$$S = S_* + A \times B$$

Measured signal inside aperture

Star signal

Aperture area (πr^2)

Background (per area)



$$B = S_{ann} / A_{ann}$$

Aperture photometry

Since PSF is wide, we need to integrate several pixels to obtain the light of the star. But this contains sky background and contamination from other sources.

$S = \sum_i s_i$ Sum over all pixels

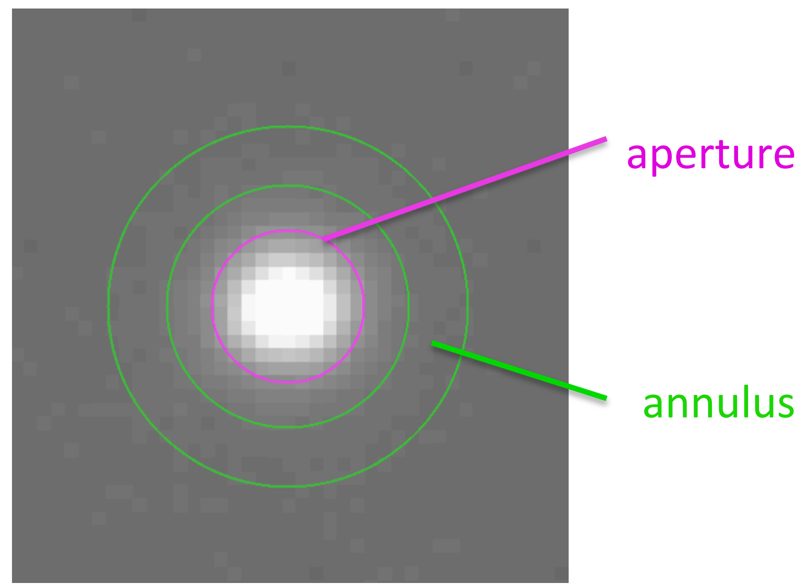
$$S = S_* + A \times B$$

Measured signal inside aperture

Star signal

Aperture area (πr^2)

Background (per area)

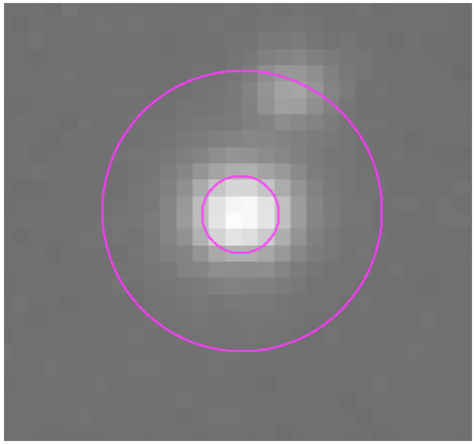


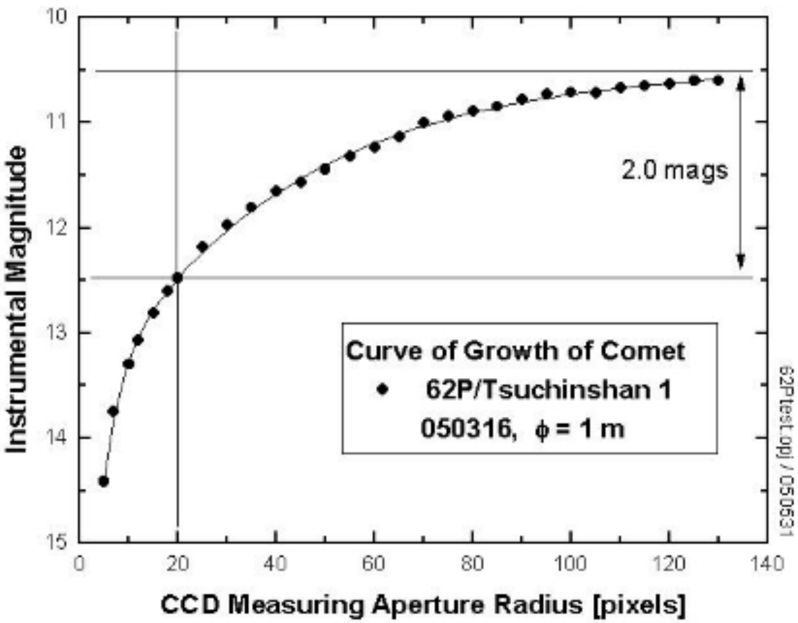
$$B = \sum_i b_i / A_B$$

Aperture photometry

What is the optimal radius size?

- As PSF is wide, light is spread over many pixels
- As radius is larger, sky also gets larger
- As radius is larger, more contamination from other sources





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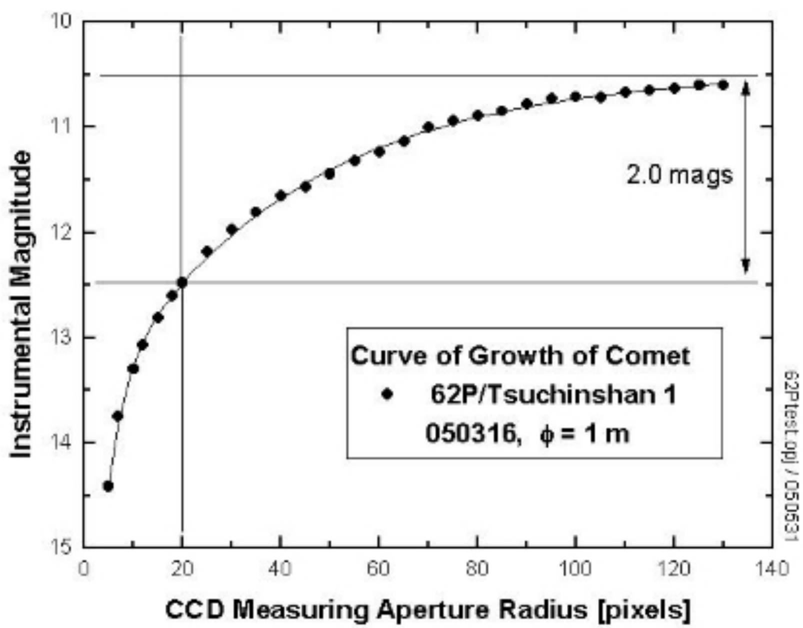

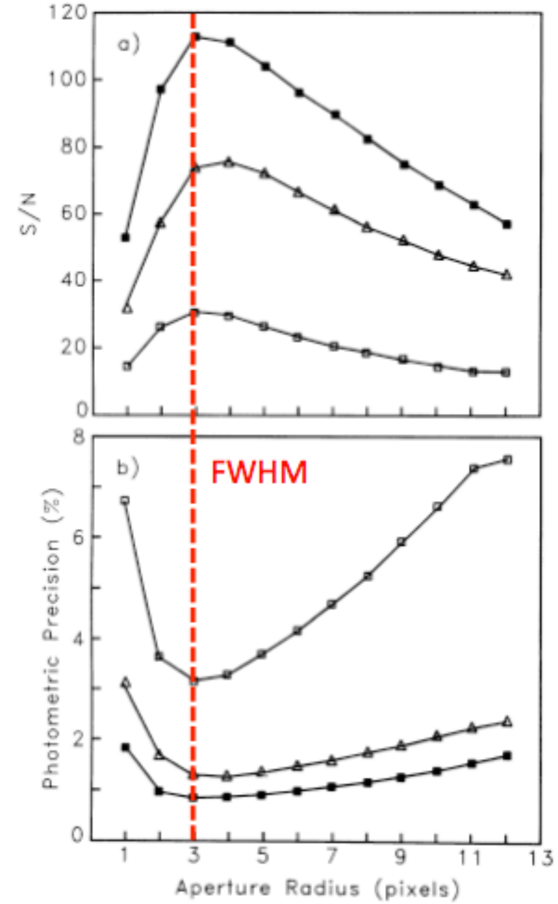

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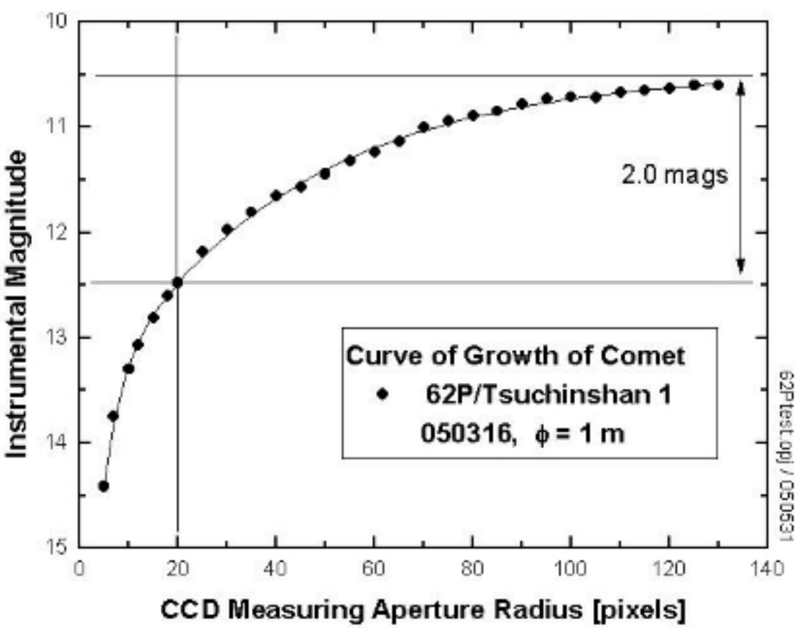
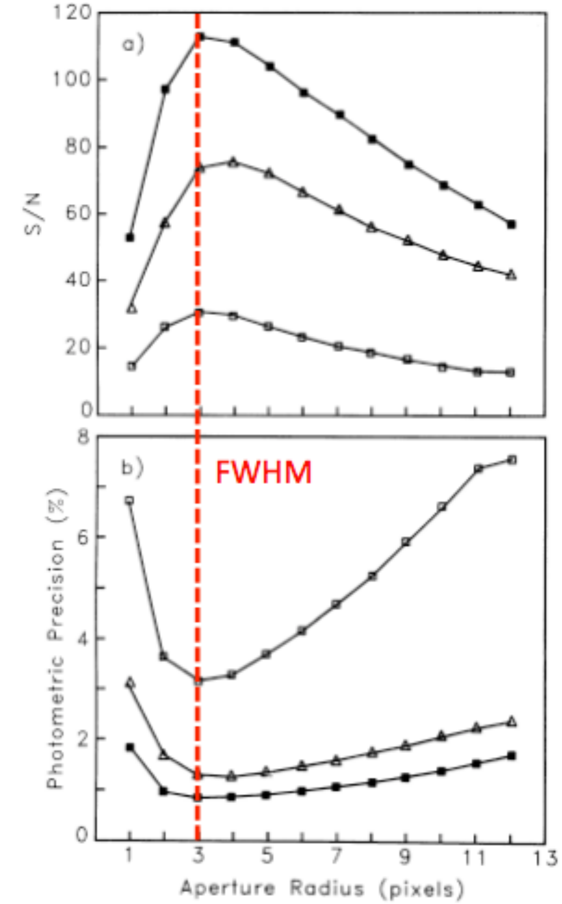
Optimal aperture size

$$r \approx 1.59 \times FWHM$$





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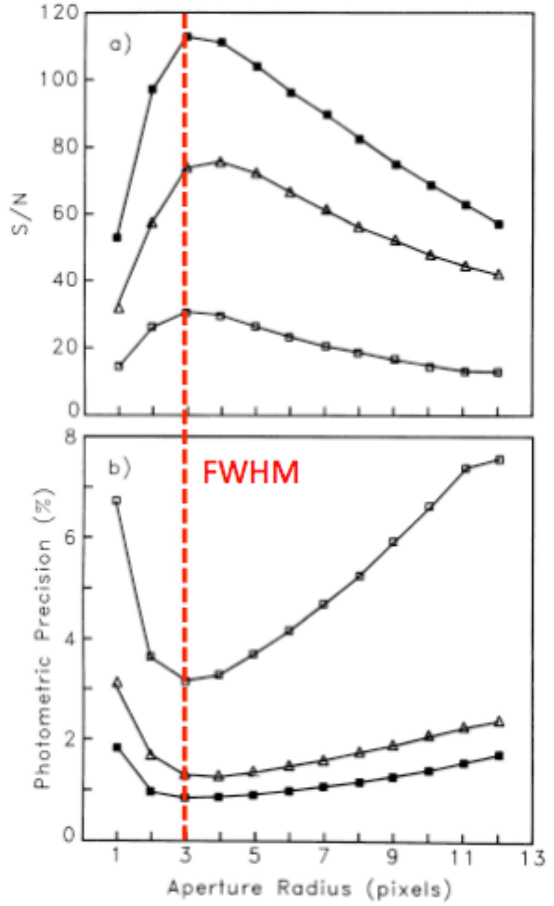


Optimal aperture size

$$r \approx 1.59 \times FWHM$$

Error on photometry:

- from function used and noise
- from different apertures/PSF
- from different techniques

Use
python/photutils:
CircularAperture, CircularAnnulus,
aperture_photometry

Aperture photometry

What to do about missing light?

1. Ok not to measure all flux as long as you measure same percentage for all stars and standard stars calibrators (all stars in same field have the same PSF)
2. Use the curve of growth of a bright star. Use this well-established curve (that should be the same for all stars) to correct the faint stars with an aperture correction:

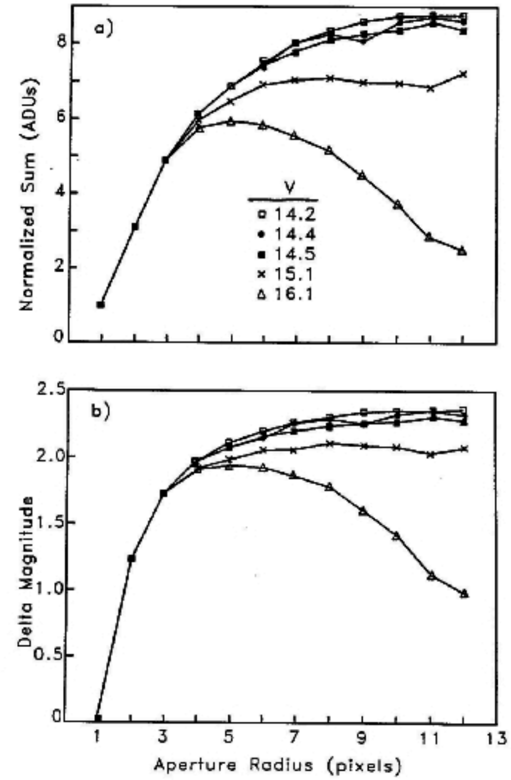
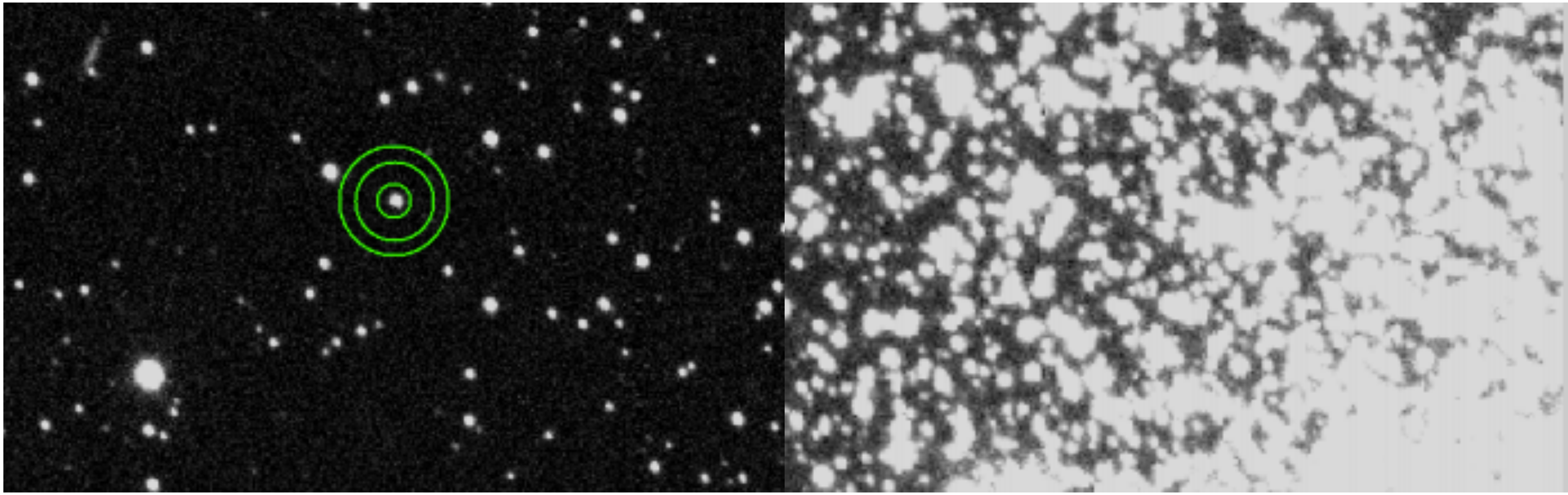


Fig. 5.7. Growth curves for five stars on a single CCD frame. The three brightest stars follow the same curve, which is very similar to the theoretical expectation as shown in Figure 5.5. The two faint stars start out in a similar manner, but eventually the background level is sufficient to overtake their PSF in the wings and they deviate strongly from the other three. Corrections, based on the bright stars, can be applied to these curves to obtain good estimates of their true brightnesses. The top panel presents growth curves as a function of normalized aperture sums while the bottom panel shows the curves as a function of magnitude differences within each successive aperture. The relative magnitudes of the point sources are given in the top panel and the image scale is the same as in Figure 5.6. From Howell (1989).

Aperture correction

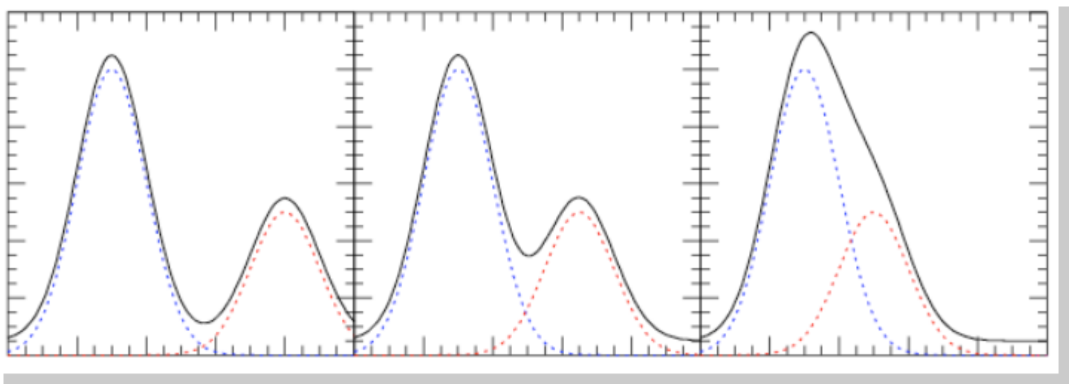
$$\Delta = m_{a2} - m_{a1}$$

PSF photometry

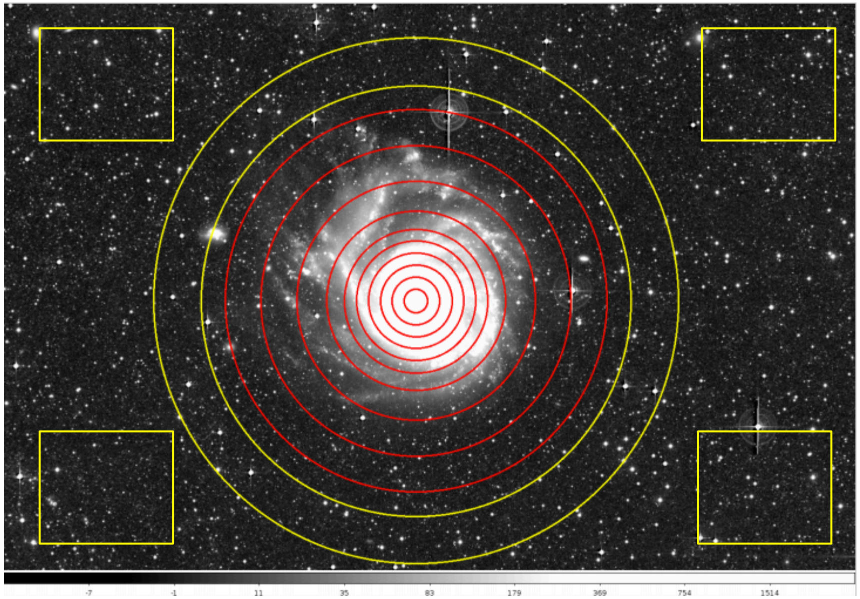


- Model point spread function (PSF) with bright stars
- Fit to individual stars with brightness as free parameter

Use
python/
photutils.psf



Surface photometry



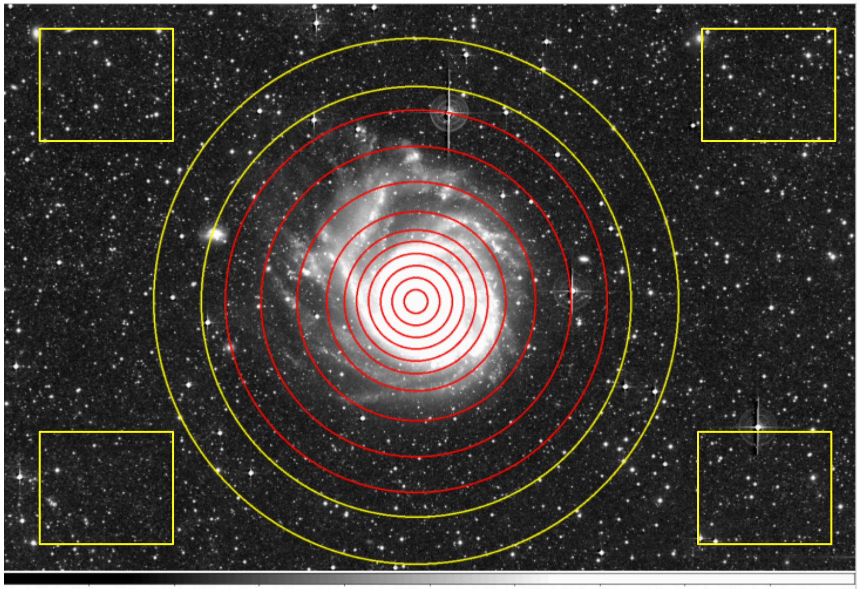
Light of a galaxy may be really extended:
use other regions to measure the sky

Brightness per area

Integrated photometry:
Galaxy and sky apertures

You can **bin** data to
increase S/N

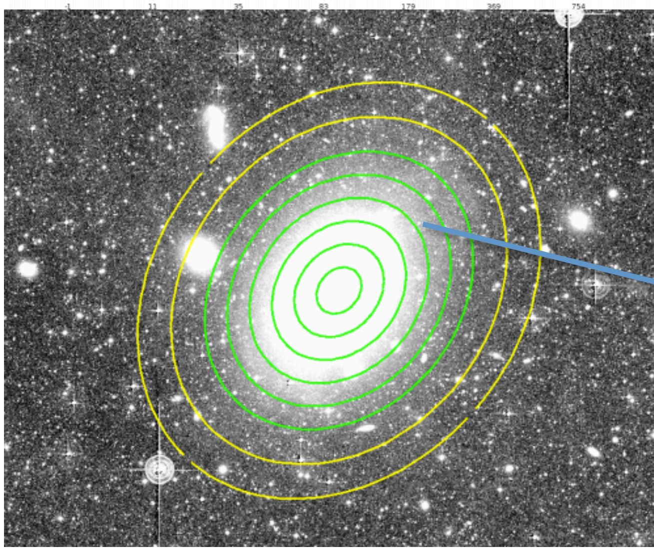
Surface photometry



Brightness per area

Integrated photometry:
Galaxy and sky apertures

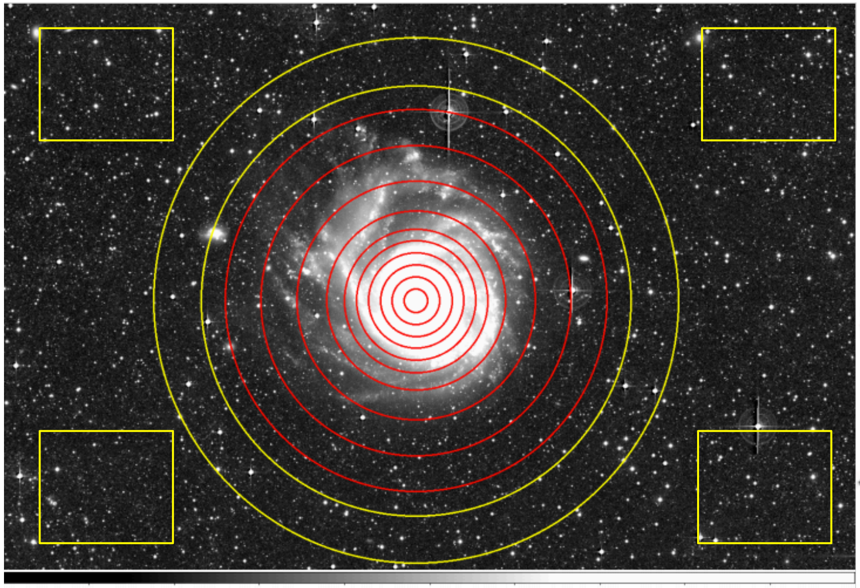
Instead of using circular apertures, use isophotes: regions of equal flux

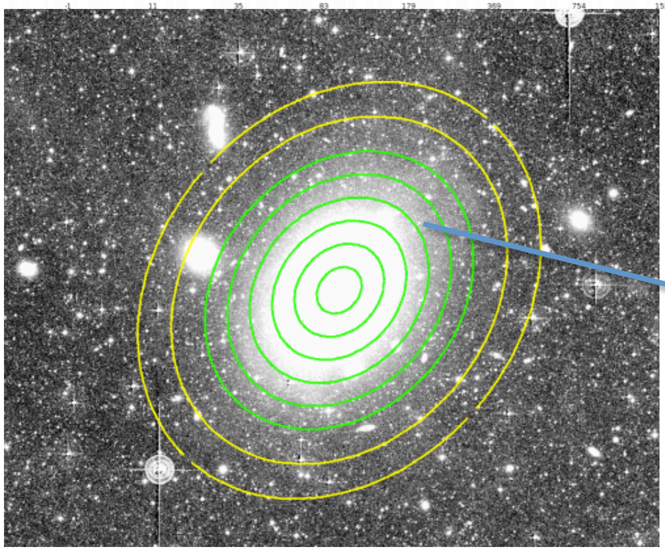


Isophotal surfaces

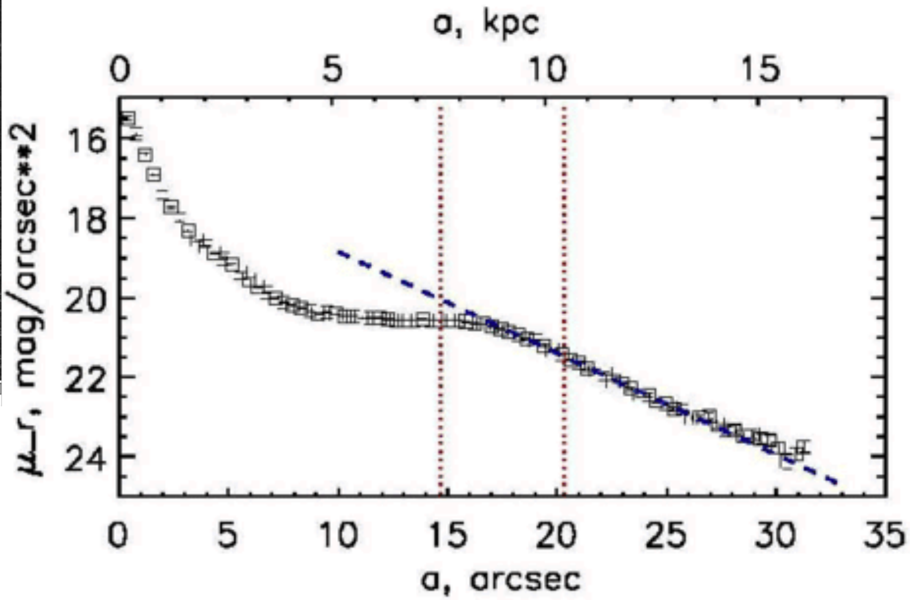
Use
python/photutils.isophote

Surface photometry





Isophotal surfaces



Sersic profiles (can be used to extend to large radii)

Use
python/photutils.isophote

Calibrate (absolute) photometry: standard stars

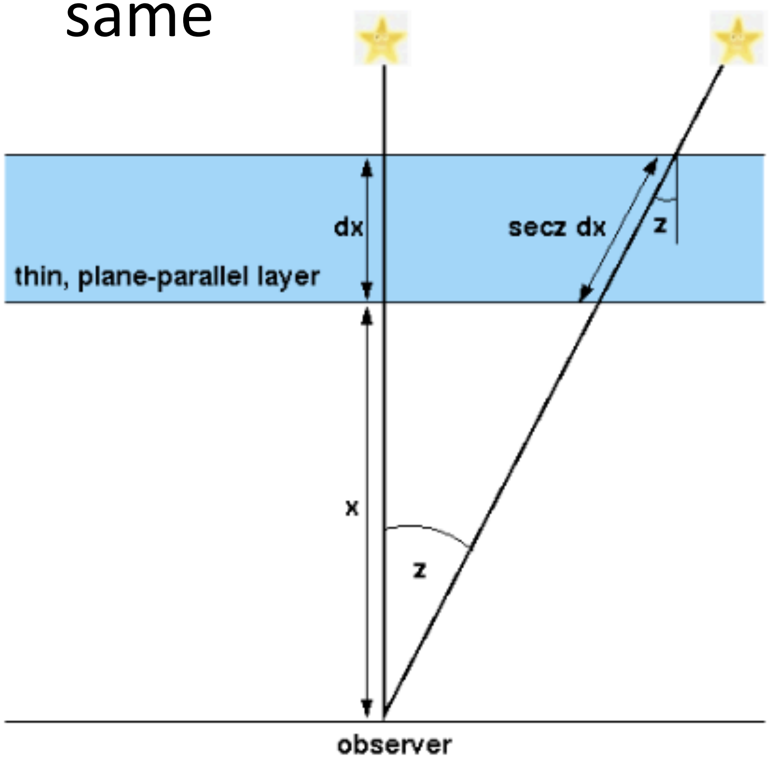
- **Instrumental magnitude** (arbitrary units): $m_{inst} = -2.5\log\left(\frac{flux}{t_{\exp}}\right)$

Science and standard star may not have same exposure!

Calibrate (absolute) photometry: standard stars

- **Instrumental magnitude** (arbitrary units): $m_{inst} = -2.5\log\left(\frac{flux}{t_{exp}}\right)$
- **Atmospheric extinction** correction: if target and standard stars are not in the same field, i.e. have different airmass – atmospheric extinction is not the same

$$m_{inst} = m_{inst,0} + k\sec z$$



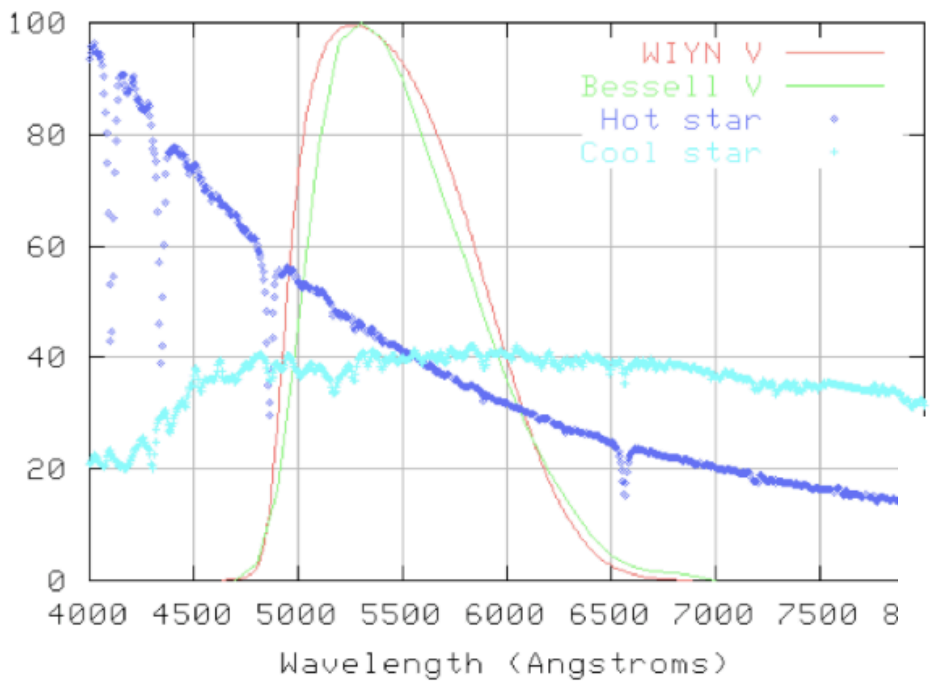
Filter	λ_{eff} (nm)	k (mags/airmass)	m_{sky} (mags/arcsec^2)		
			Dark	Grey	Bright
U	360	0.55	22.0	20.0	17.7
B	430	0.25	22.7	20.7	18.4
V	550	0.15	21.9	19.9	17.6
R	650	0.09	21.0	19.7	17.5
I	820	0.06	20.0	18.9	16.7

Absolute photometry: standard stars

- **Instrumental magnitude**: $$m_{inst} = -2.5\log\left(\frac{flux}{t_{\exp}}\right)$$
- **Atmospheric extinction** correction: if target and standard stars are not in the same field $$m_{inst} = m_{inst,0} + k\sec z$$
- **Standard star**: compare to literature value $$m_{ZP} = m_{std} - m_{std,0}$$
- **Zero-point (ZP)** depends on telescope/instrument used
- **Calibrated magnitude of targets**: $$m_{calib} = m_{inst,0} + m_{ZP}$$

Accurate absolute photometry: standard stars & color terms

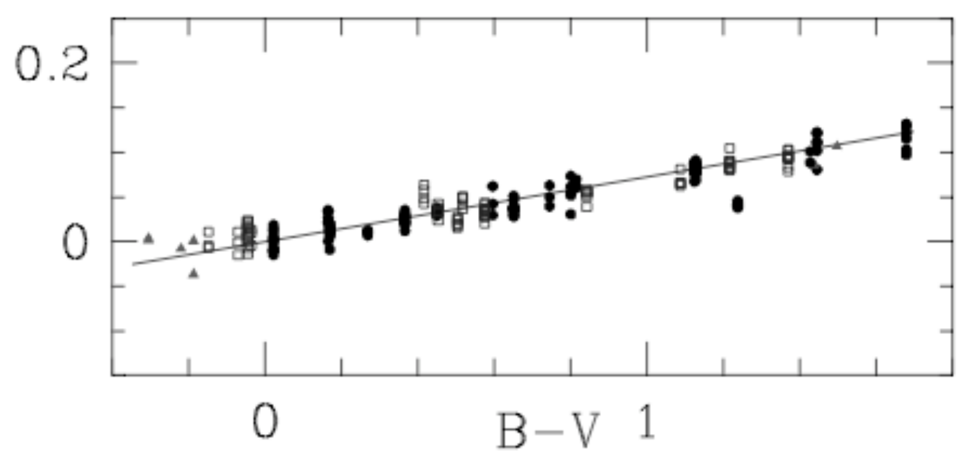
Filter definitions change from instrument to instrument! So filter set used in standard star system and target star differ!



$$m_{ZP} = m_{std} - m_{std,0}$$

- Corrections of stars depend on color!
- Color term depending on filter system

$$m_{std} - m_{std,0} - m_{ZP} = ct \times (B - V)$$



Fitting models to data

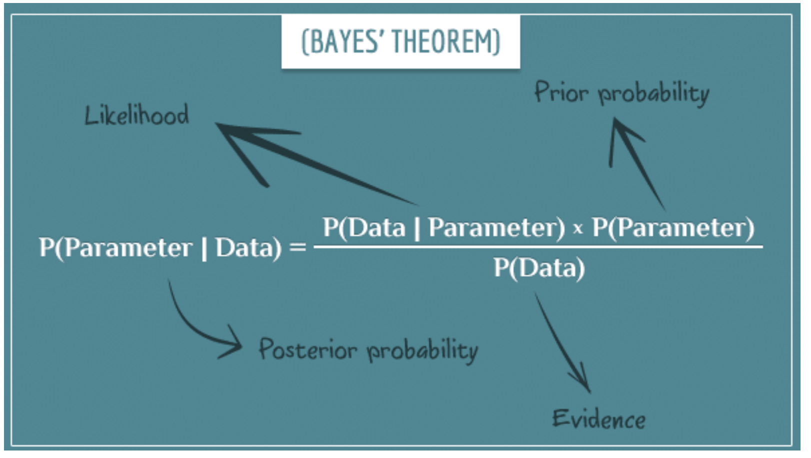
Fitting is hypothesis testing

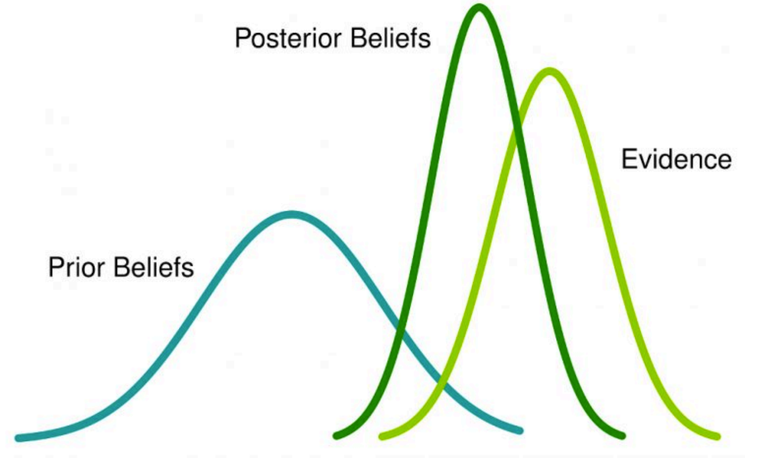
- **Frequentist** approach:
  - Probability is long-term frequency
  - Predicts an optimum point of a parameter
  - Uncertainty in the parameter poorly constrained

Fitting models to data

Fitting is hypothesis testing

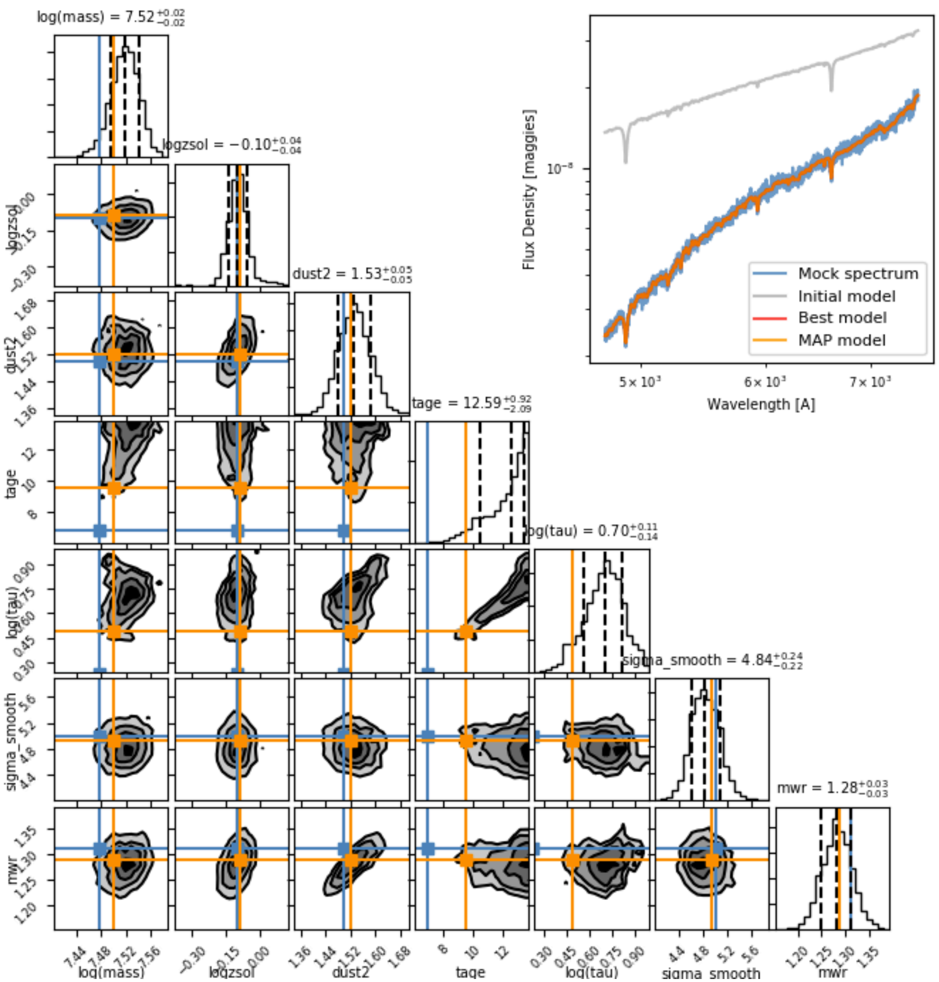
- **Bayesian** approach:
  - Probability is degree of belief
  - An initial belief (prior) gets updated with new information
  - Predicts a full posterior distribution for a parameter
  - Computationally more expensive





Fitting models to data

Example



Use

Frequentist optimization:

python/scipy.optimize

Bayesian:

python/emcee

Data reduction & analysis

- Reading/writing files
- Stacking
- Bias/dark & flat-field

- Astrometry (not necessary?) and alignment → relative positions
- Photometry: point-source (aperture/PSF) or surface: calibrate the photometry
- Analysis & model fitting (isochrones/ Sersic profiles)
- Remember: color composite of your extended target.

Use: Python/astropy.visualization

Hands-on!

Data reduction & analysis

Codes you can use: IDL, IRAF, Python, R, etc.

Python:

python, ipython, jupyter notebook, pycharm

Some basic examples with python: notebook

Writing a paper

Writing a paper: general rules

- Do not copy (even yourself), it is plagiarism and ruins careers!
- Investigate literature and cite!
- Check your English: keep it simple and flowing like a story, avoid repetitions of words

  Interesting tool: expresso-app.org
- Figures and visualization are fundamental! Make appealing and clear plots.

Paper content

You have freedom but generally:

- **Title**: you can be creative
- **Abstract** (a must): catchy summary of what is done, especially on the findings
- **Introduction**: a summarized state of the art on the subject motivating its importance
- **Observations & data**: Presentation of the data, how it was taken (instrument) with brief explanation of reduction steps
- **Analysis**: Processes/methods applied to reduced data like model fits, relevant figures, constraints, results.
- **Discussion**: Physical interpretation of results: what do they mean? How do they compare with others? How can they be improved?
- **Summary/conclusions**: Brief summary of the paper and its relevance with possible future outlook