Introduction to photometry II – Galaxies

Mehmet Alpaslan
Center for Cosmology and Particle Physics, New York University

Tuesday, January 23rd

OUTLINE

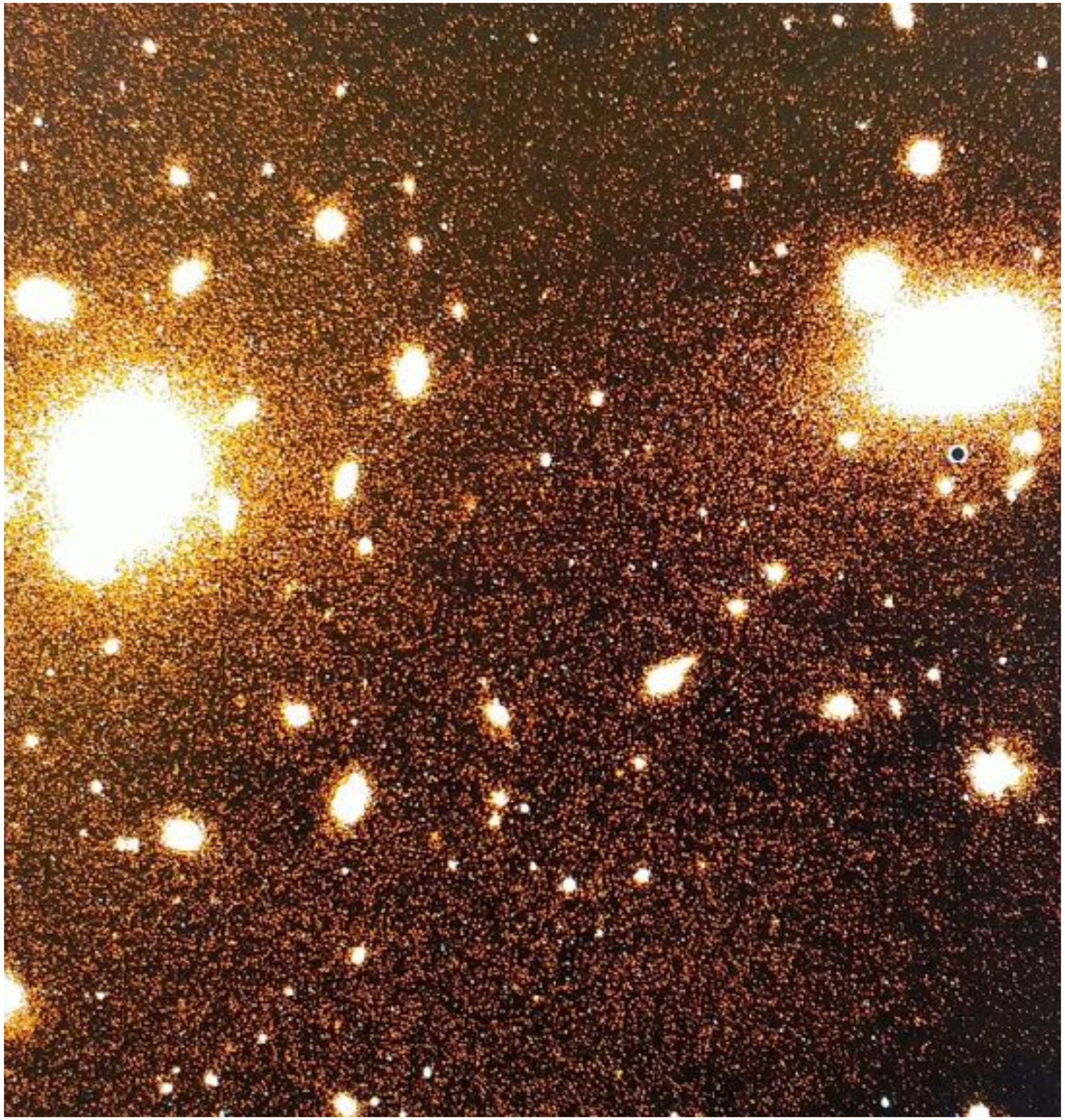
- The very basics of galaxy photometry.
- So what exactly do we measure?
- Filters, bandpasses, and more!
- Dust, PSFs, and other headache inducers.
- Apertures & profiles.
- **Surface photometry.**

WHAT EXACTLY ARE WE MEASURING?

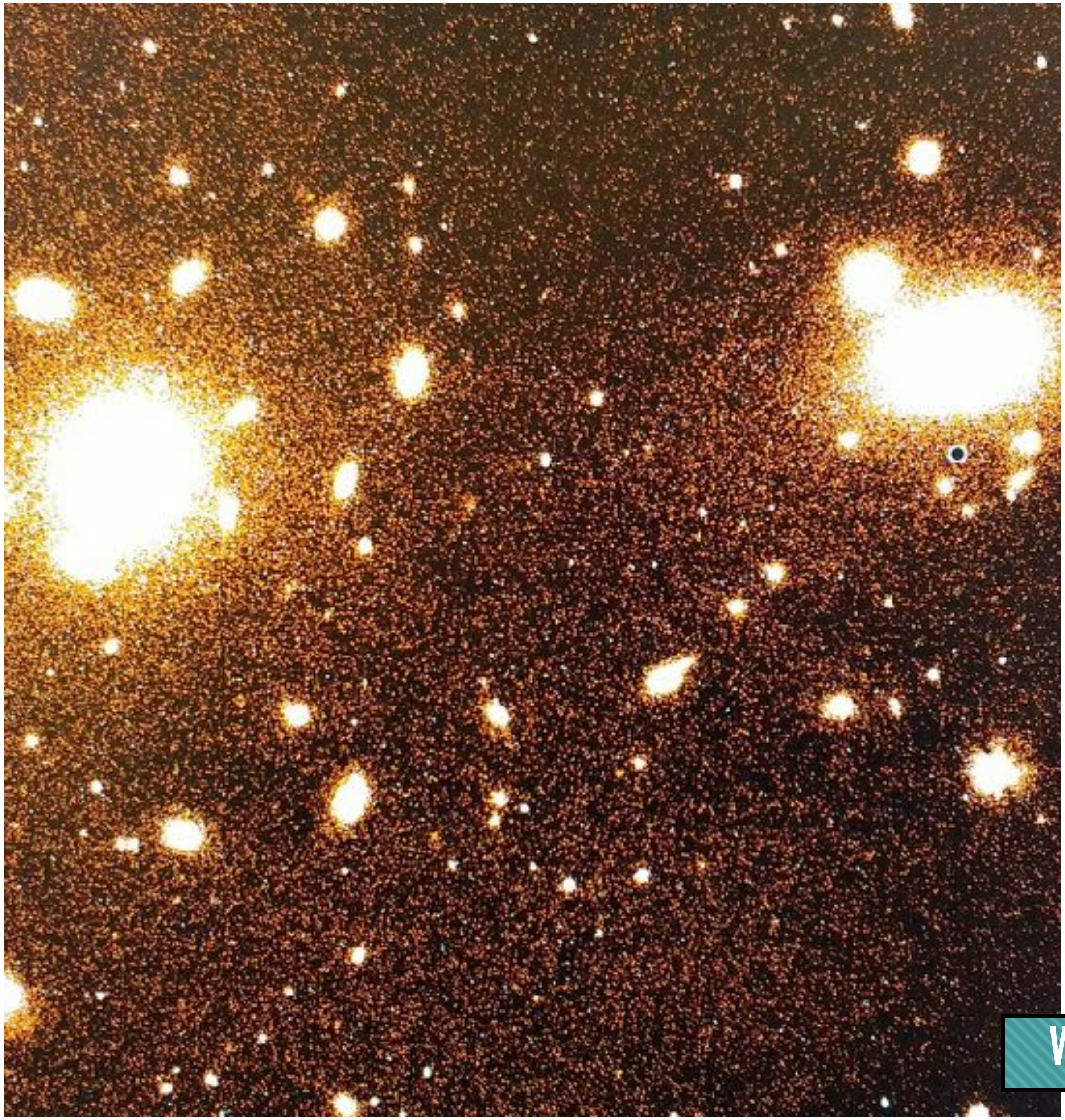
WHAT EXACTLY ARE WE MEASURING?

HOW WOULD YOU DO PHOTOMETRY ON THIS?

WHAT EXACTLY ARE WE MEASURING?



WHAT EXACTLY ARE WE MEASURING?



WHAT ABOUT THIS?

WHAT EXACTLY ARE WE MEASURING?

- Fundamentally, galaxy photometry is the practice of counting photons across a two dimensional aperture.
- Things get more complicated when considering which photons to count, and how to count them!
  - How far out from the galaxy's center should I stop counting?
  - Do I count in concentric circles? Ellipses? What about irregular galaxies?
  - (Actually, how do I define the galaxy's center?)
  - Am I interested in all the photons from the galaxy, or only the ones emitted from stars? What about dust?
  - Wait, what about dust in the foreground?
  - What about the Earth's atmosphere?!

FLUXES AND MAGNITUDES

- Magnitudes are defined from relative fluxes (e.g. two stars, or two galaxies).

$$m_1 - m_2 = -2.5 \log \frac{F_1}{F_2}$$

- In practice…

$$m = -2.5 \log \left(\int_0^\infty T_\lambda F_\lambda d\lambda \right)$$

FLUXES AND MAGNITUDES

- Magnitudes are defined from relative fluxes (e.g. two stars, or two galaxies).

$$m_1 - m_2 = -2.5 \log \frac{F_1}{F_2}$$

- In practice…

$$m = -2.5 \log \left(\int_0^\infty T_\lambda F_\lambda d\lambda \right)$$

where T refers to the filter response function.

FLUXES AND MAGNITUDES

- Tying magnitudes to a physical flux scale has historically used the star Vega, which is defined to have m = 0 across all passbands.

$$m_1 - m_2 = -2.5 \log \frac{F_\lambda}{F_V} = -2.5 \log F_\lambda + 2.5 \log F_\lambda, V$$

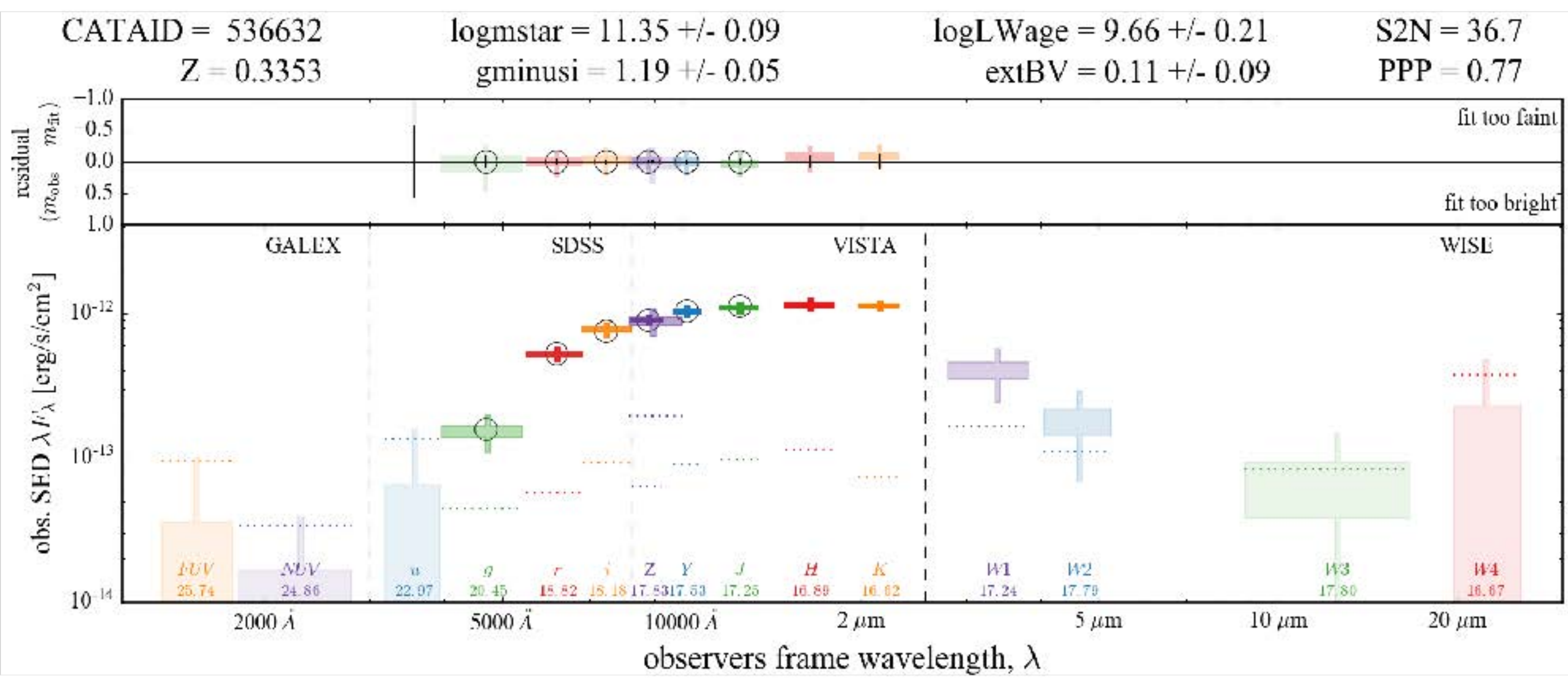
- $F_{\lambda,V}$ is referred to as the zeropoint in the Vega magnitude system. Generally speaking, all photometric observations of galaxies are calibrated to a given zeropoint.

- Most extragalactic observations use the AB magnitude system (Oke & Gunn, 1983). Based on flat reference spectrum chosen such that the V-band magnitude of Vega is 0.

FILTERS & BANDPASSES

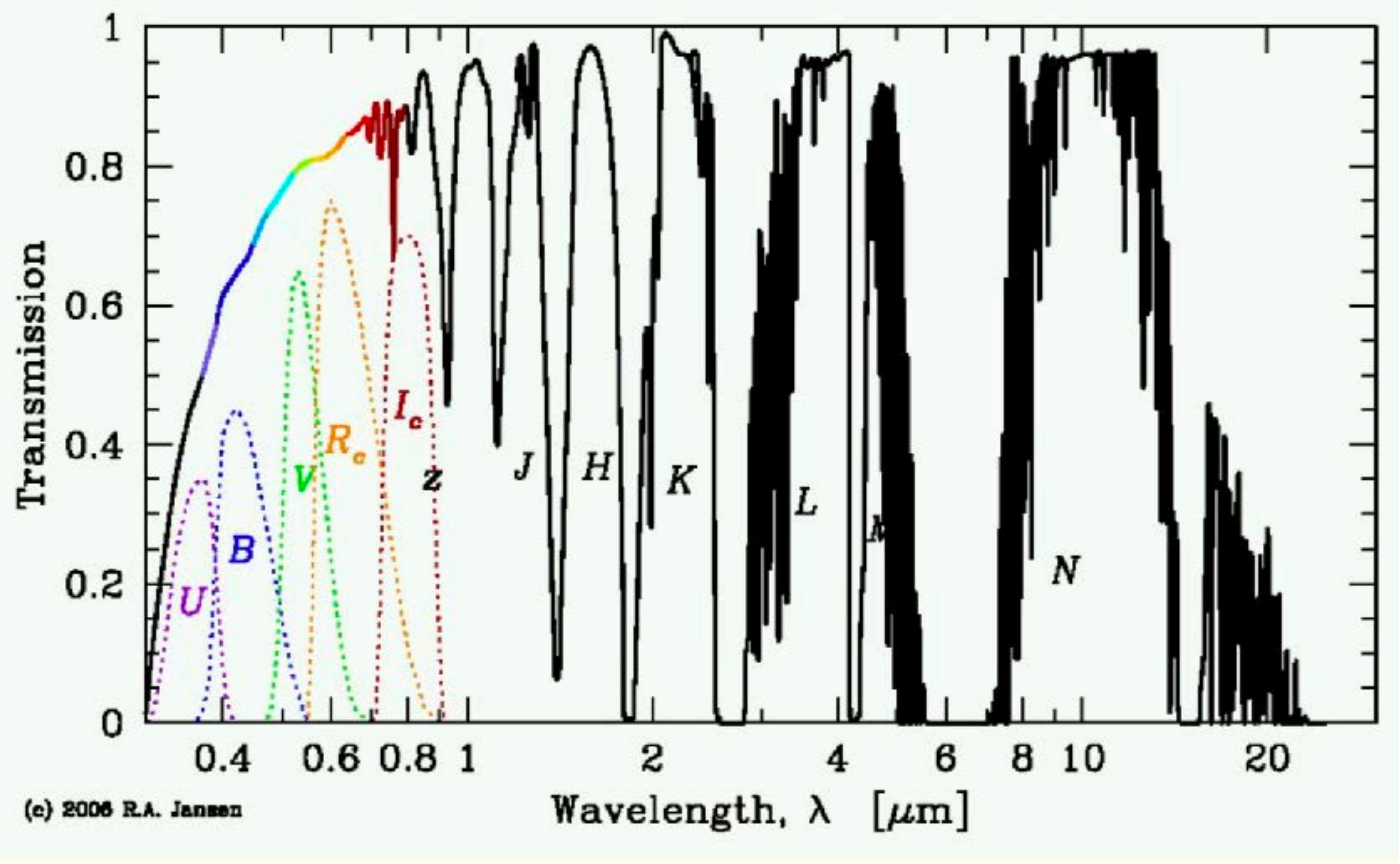
- Many filter systems have been developed. Lots of history to this.
  - Sloan *ugriz*: Minimal overlap between filters, with few gaps. Ideal filters for optical photometry.
  - 2MASS *JHK*: Infrared filters designed to measure thermal emission from dust.
- As instruments and surveys become more detailed, newer filters are released (e.g. VISTA VIKING *ZYJHK*).
  - These are almost always described in *excruciating* detail in the proposer's handbook for an instrument. Useful to know!
- A galaxy's color is defined as the relative magnitude difference of its flux when observed across two different filters.

FILTERS & BANDPASSES

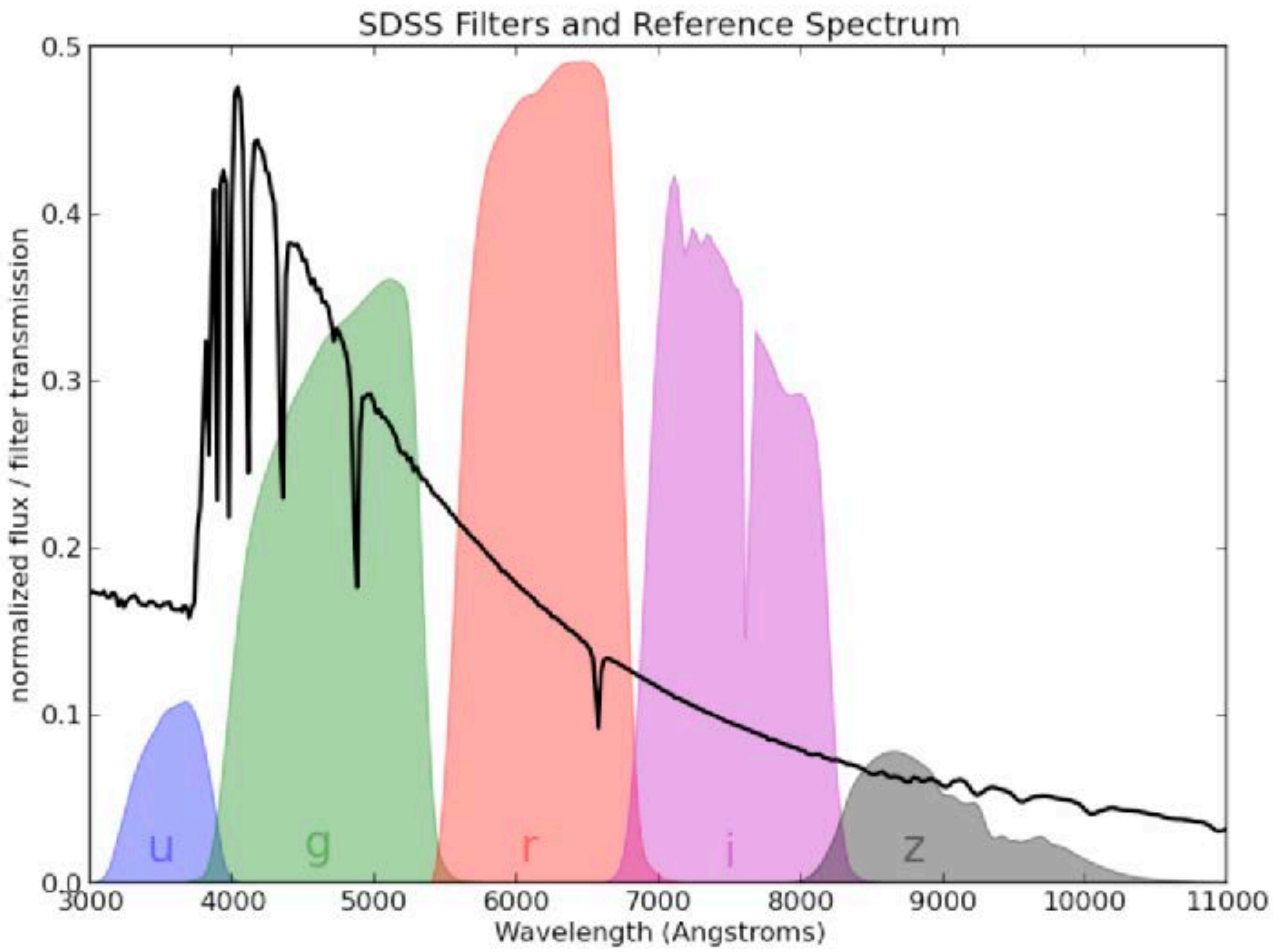


- A galaxy's color is defined as the relative magnitude difference of its flux when observed across two different filters.

FLUXES AND MAGNITUDES

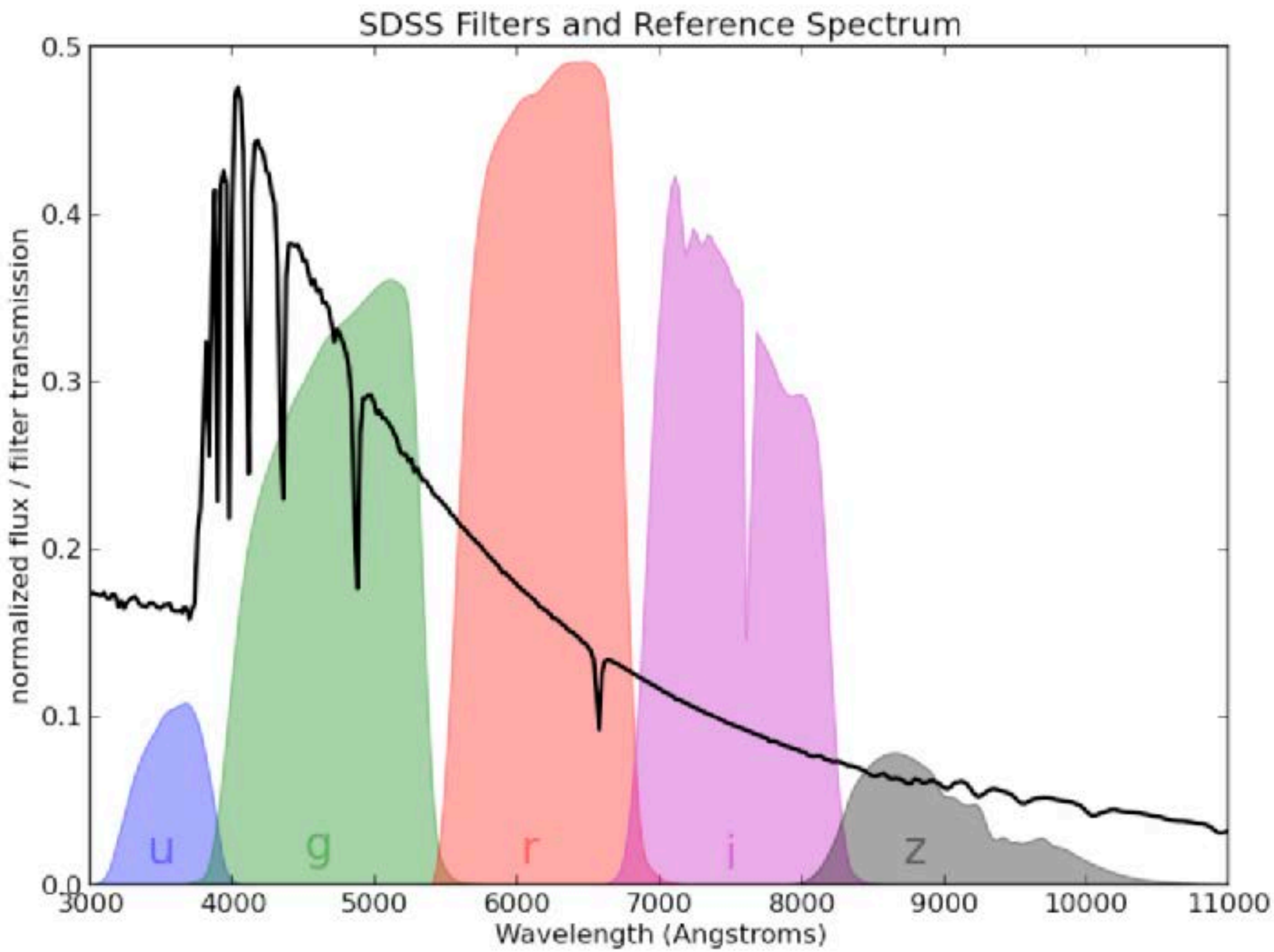


FLUXES AND MAGNITUDES



FLUXES AND MAGNITUDES

WHICH SDSS BAND DO YOU EXPECT TO HAVE THE LOWEST S/N?



FLUXES AND MAGNITUDES

- When dealing with galaxies, absolute magnitude is a key parameter.

$$m - M = 5\log(d) - 5 + A_V + K_V$$

Distance (in pc)

Foreground dust extinction
(strongly dependent on filter!)

K-correction

- M is very closely tied to the physical parameters of a galaxy, but it requires a distance (i.e. a redshift, or spectrum) to obtain.

DUST & K-CORRECTIONS

- Dust extinction in both the foreground (i.e. within the Milky Way) and in the background (i.e. within the galaxy being observed) leads to a net decrease in observed optical photons.
- Correcting for foreground emission is relatively easy – detailed maps of the distribution of dust in the Galaxy are readily available (e.g. Schlegel et al. 1998).
- Correcting for background emission is much more complicated, and requires a model of the distribution of dust in the galaxy being observed. This distribution can vary by galaxy morphology; mass; redshift (e.g. Grootes et al. 2013).

DUST & K-CORRECTIONS

- At higher redshifts, photometric emission from galaxies is influenced by the cosmological expansion of the Universe. This leads to a redshifting effect in photometry as well.

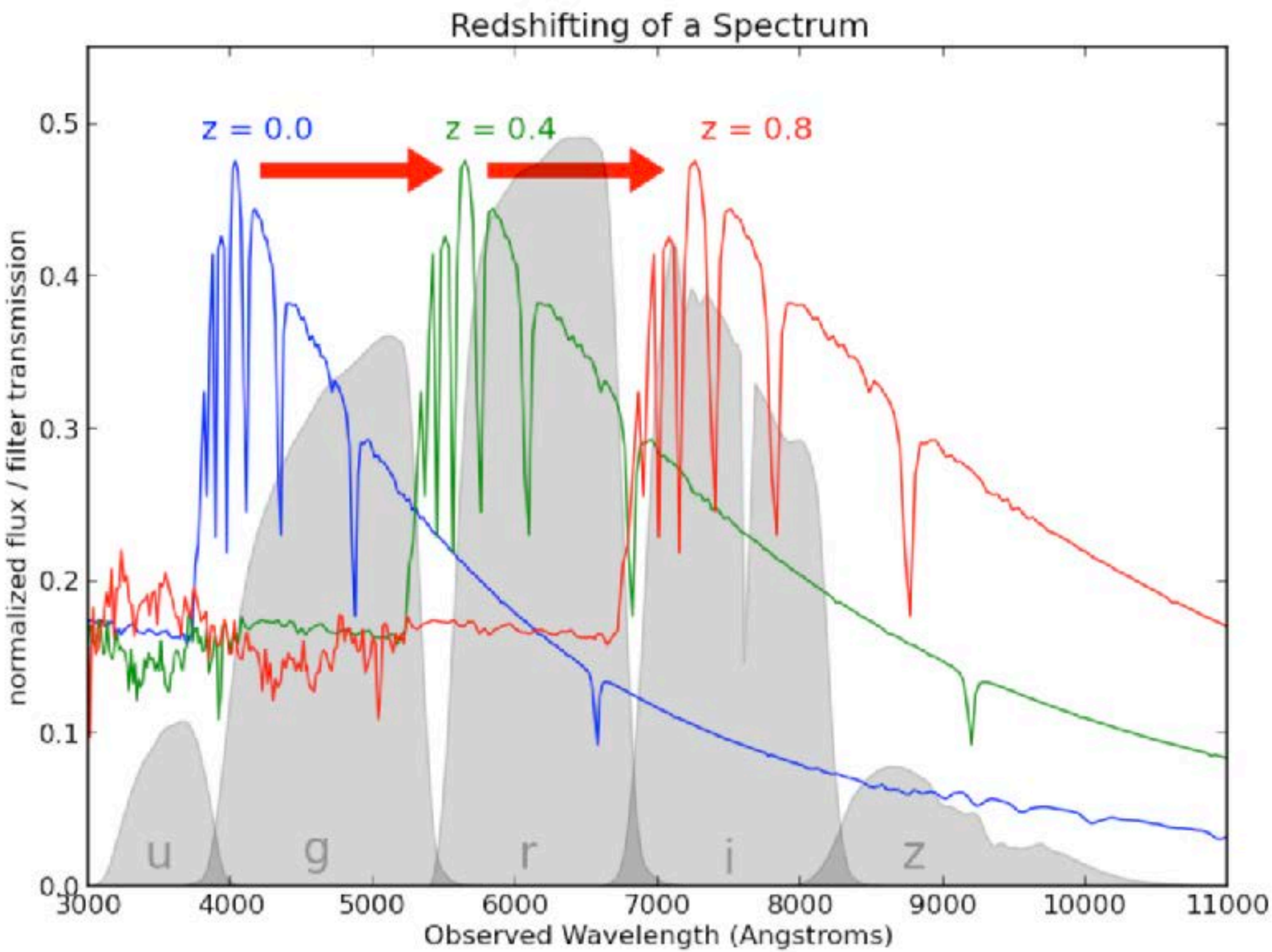
$$\lambda_{\mathrm{obs}} = \lambda_{\mathrm{em}}(1+z)$$

- Correction for this is referred to as the k-correction, and it is crucial for the correct interpretation of galaxy photometry.

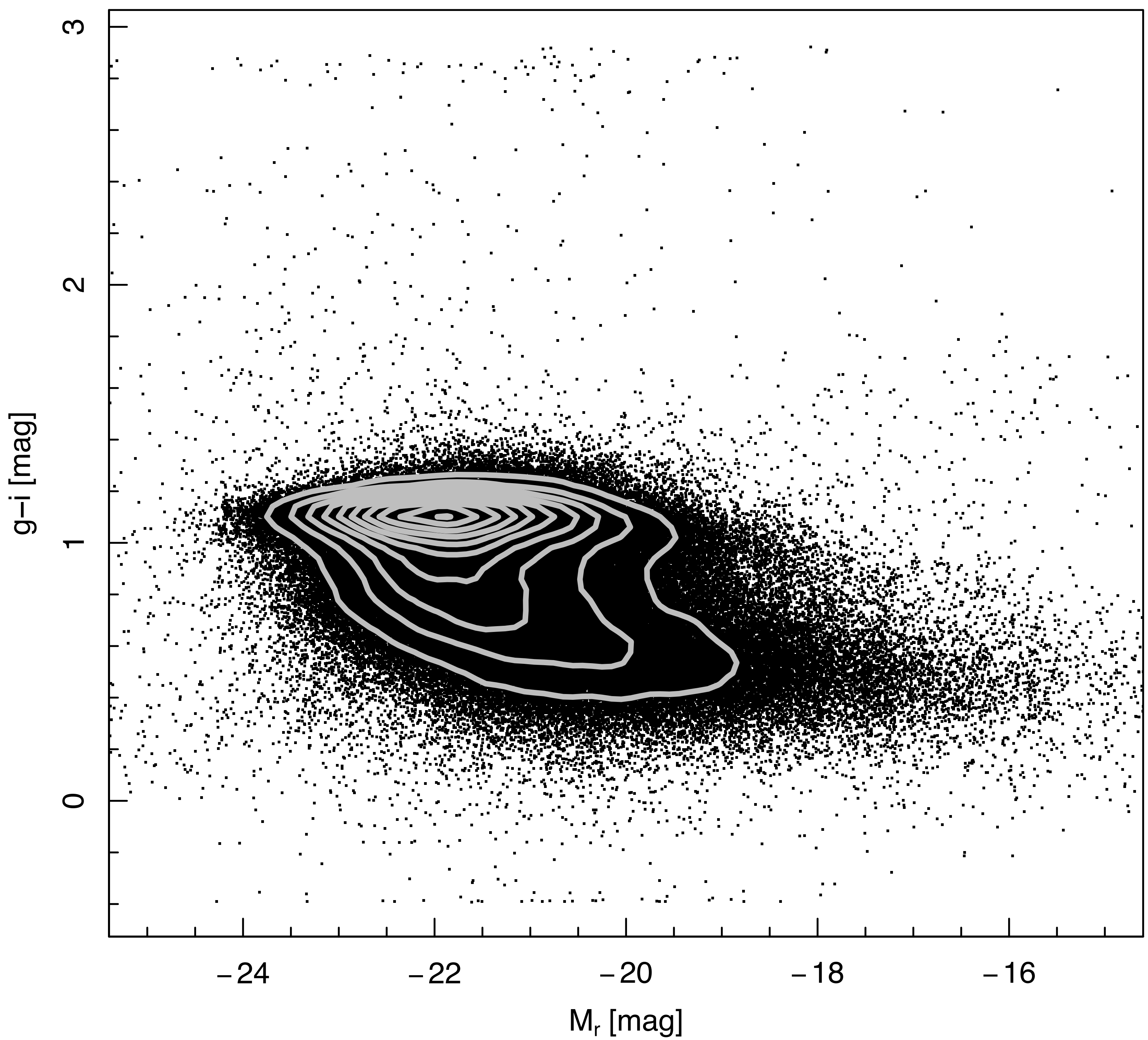
$$K = k + 2.5\log(1+z)$$

Varies as a function of redshift, morphology, luminosity function…

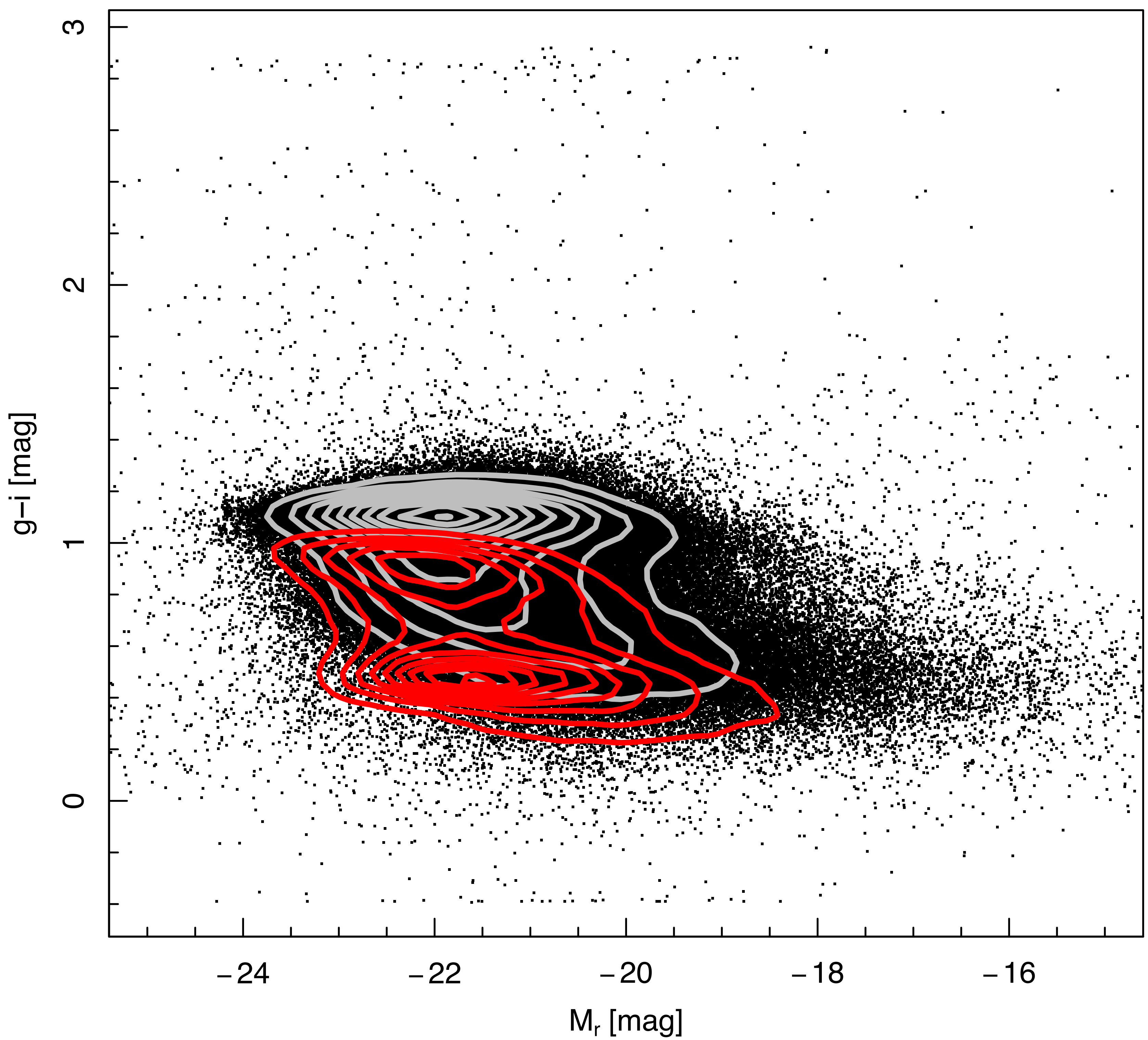
DUST & K-CORRECTIONS



DUST & K-CORRECTIONS

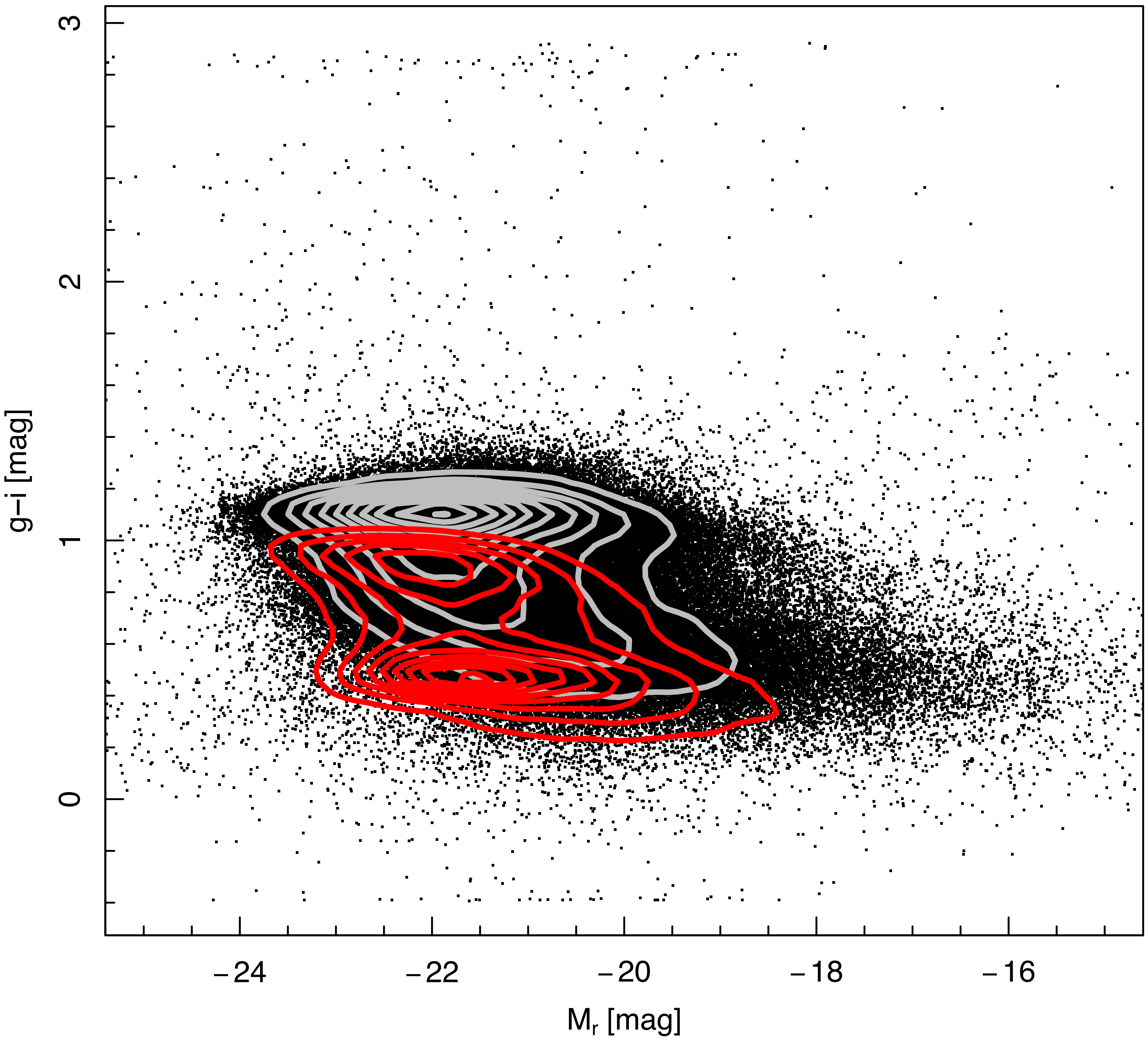


DUST & K-CORRECTIONS



DUST & K-CORRECTIONS

HOW WILL THIS DISTRIBUTION CHANGE AFTER CORRECTIONS?



SURFACE PHOTOMETRY

- Surface photometry refers to measuring the brightness per unit area of an extended object in the sky.
- Used to study the global morphologies of galaxies, their internal components, distances, stellar populations, distribution of dust…
- Surface brightness: $I =\propto \frac{f}{\Lambda\Omega}$

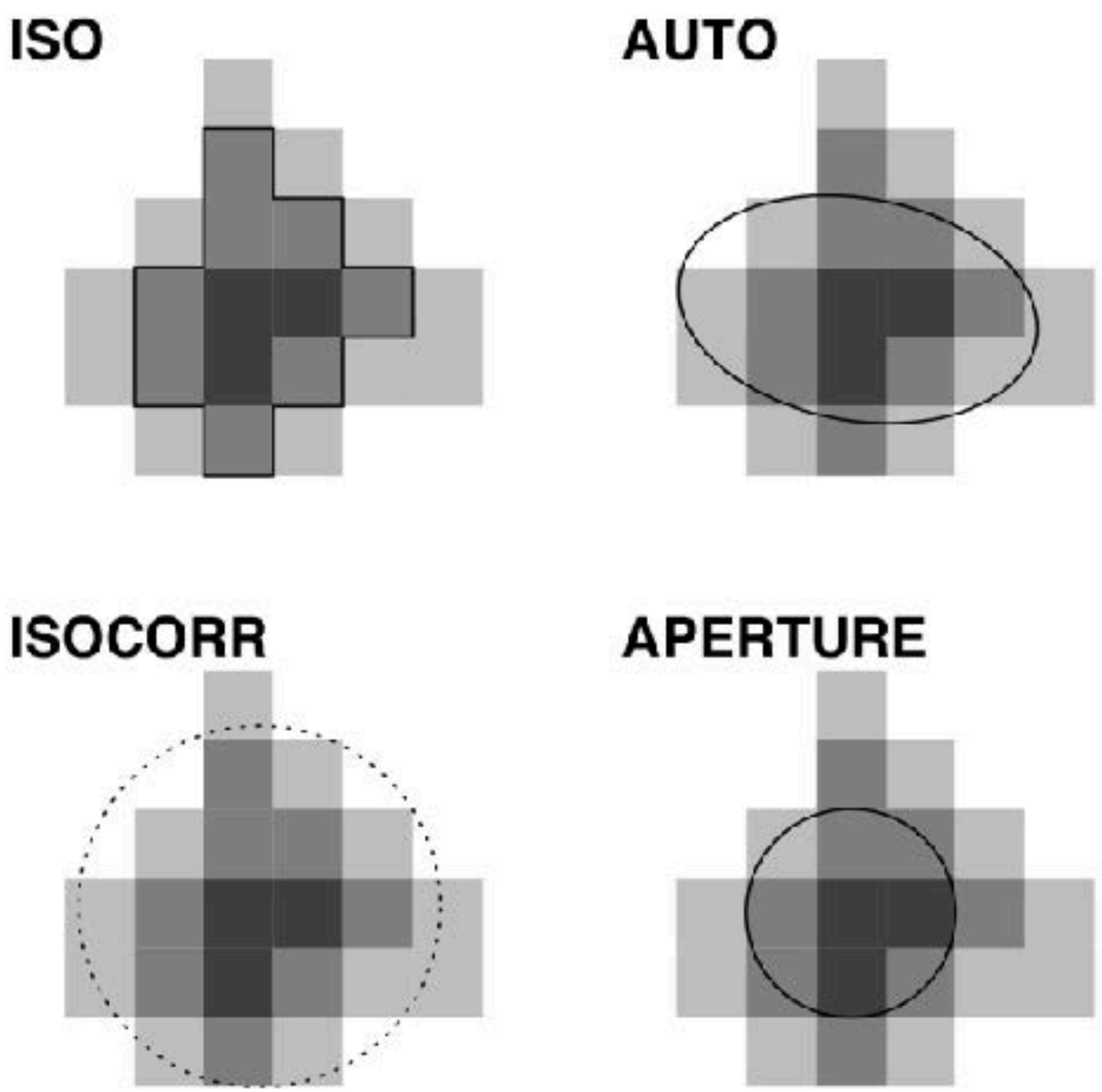
$$\mu = -2.5 \log I + C$$

magnitudes per arcsecond

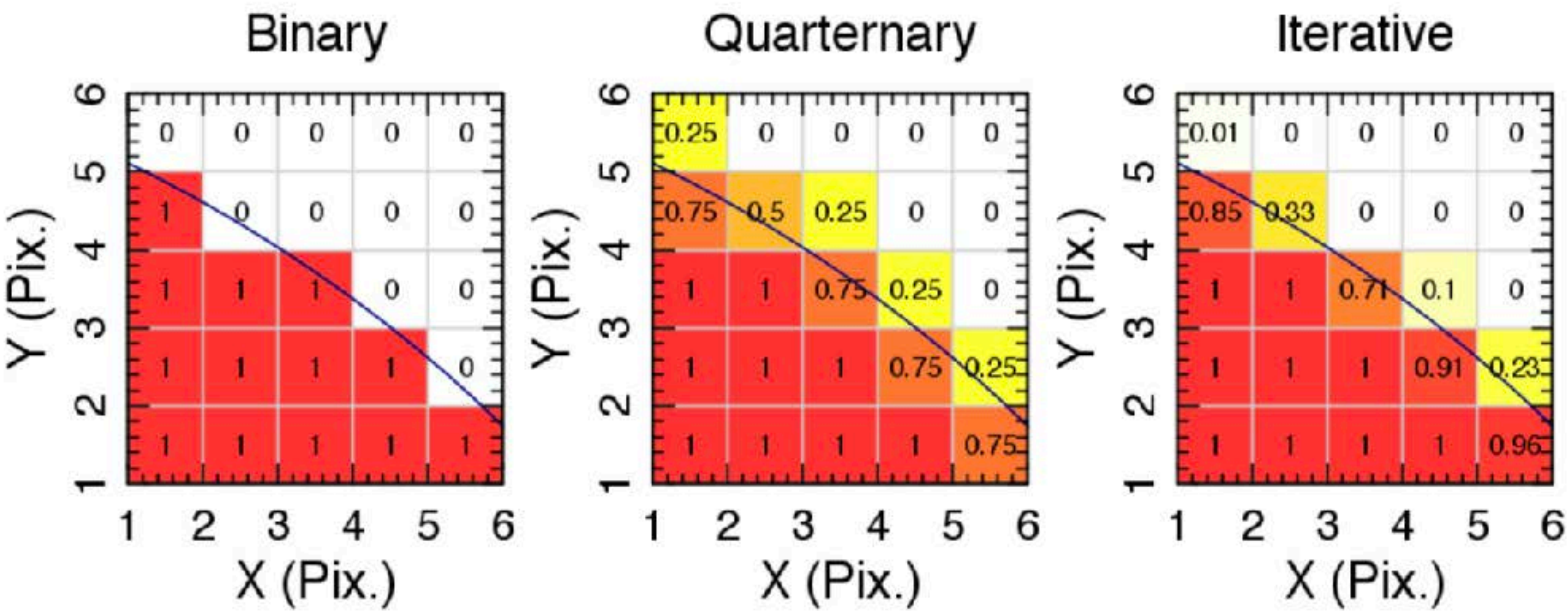
SURFACE PHOTOMETRY

- Different photometric measurements of galaxies are possible.
  - Aperture magnitudes: flux within a given aperture placed over a galaxy.
  - Isophotal magnitudes: total light above a given surface brightness level.
  - Total magnitudes: extrapolated estimates of total galaxy light; e.g. Kron magnitude (estimate r_e and double the emission within it).

SURFACE PHOTOMETRY



SURFACE PHOTOMETRY



THE POINT SPREAD FUNCTION

- Varying temperature and humidity levels, as well as turbulence in the upper layers of the atmosphere blurs astronomical images. This is commonly referred to as seeing.

- The effect of seeing can be quantified as follows:

$$I_{\rm eff}(R) = \int d^2R' P(R - R') I_{\rm obs}(R')$$

Effective seeing at R

Point Spread Function

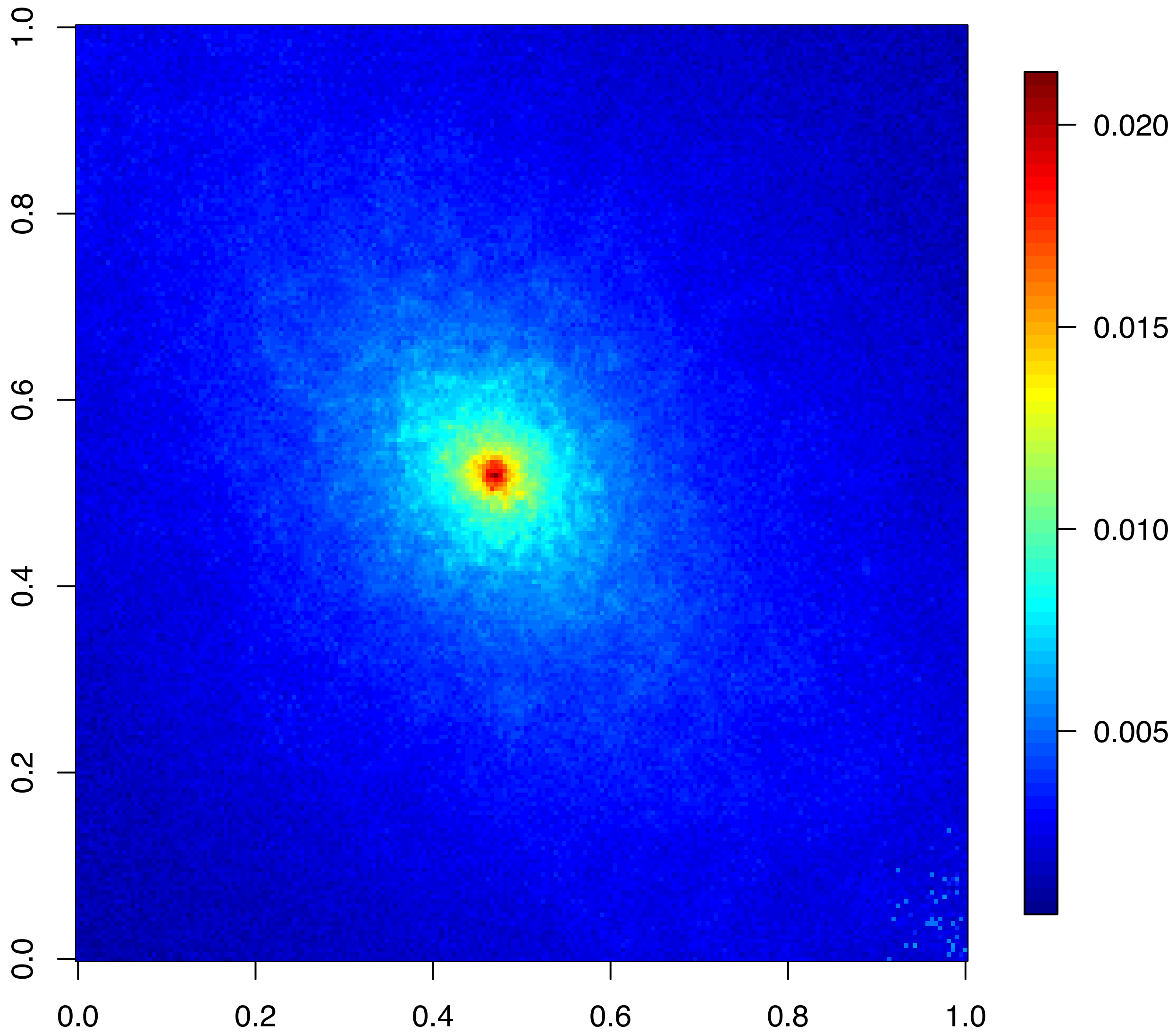
Surface brightness at R′ assuming no seeing.

THE POINT SPREAD FUNCTION

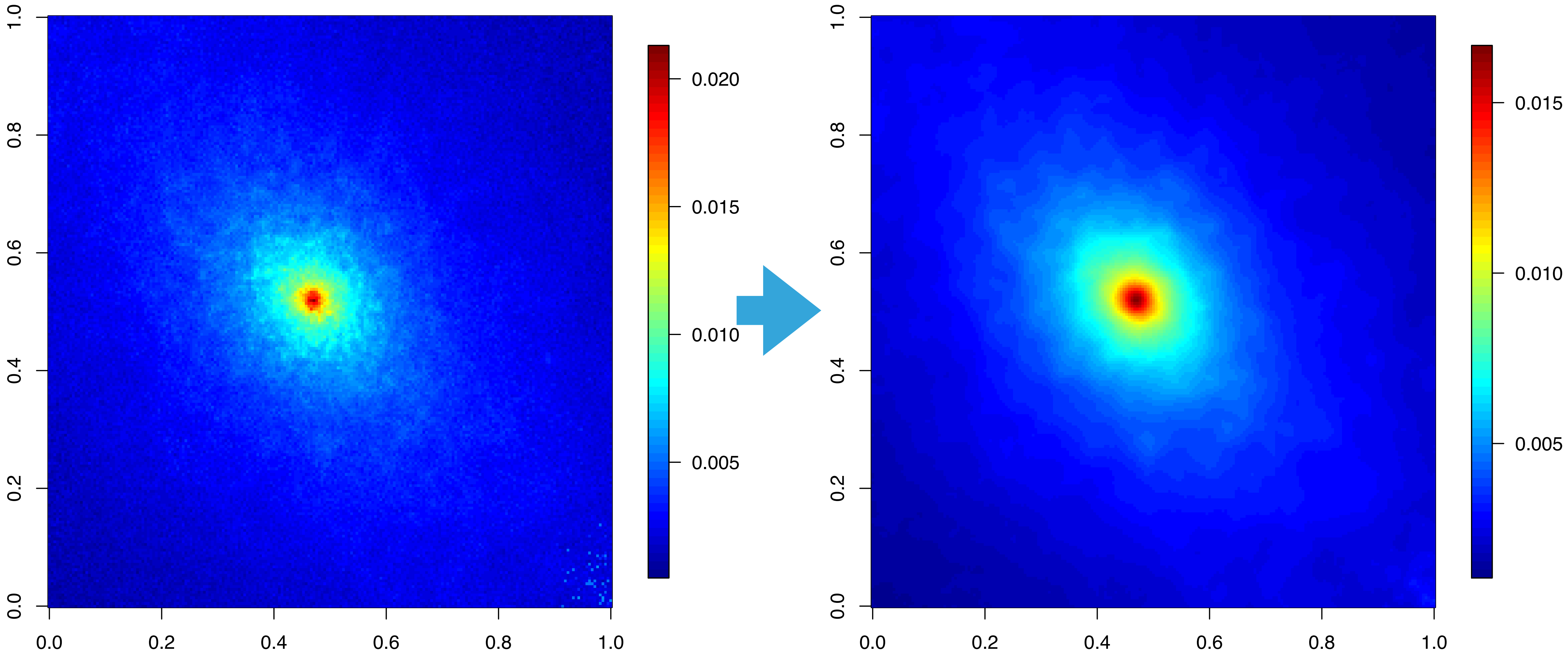
- The shape of a point source on a given detector at a given location, and given atmospheric conditions is known as the point spread function. In other words, the PSF transforms a point source into an extended object as a function of various external parameters.
- A very simple example of a PSF is a circular Gaussian:

$$P(d) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{d^2}{2\sigma^2}\right)$$

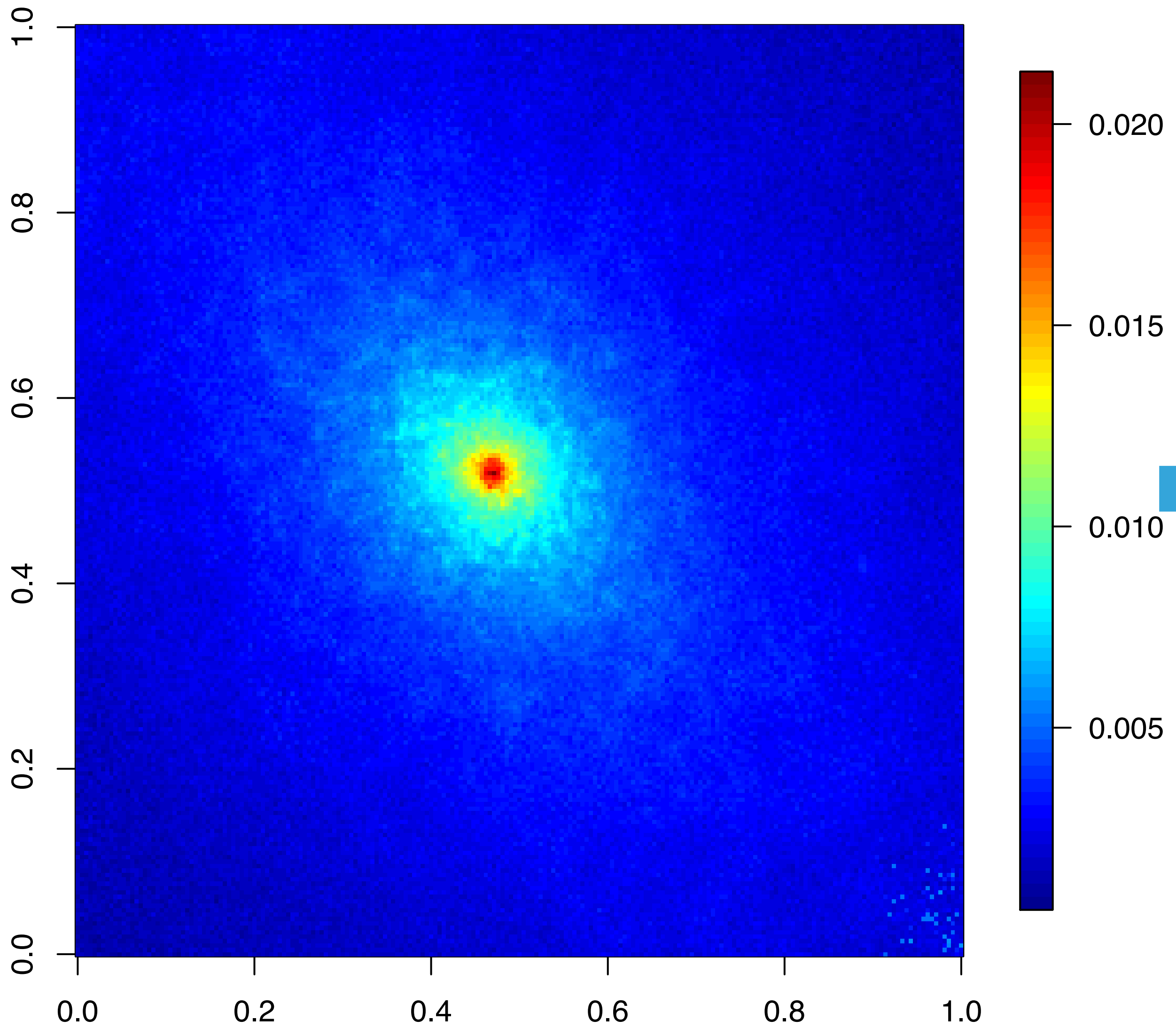
THE POINT SPREAD FUNCTION

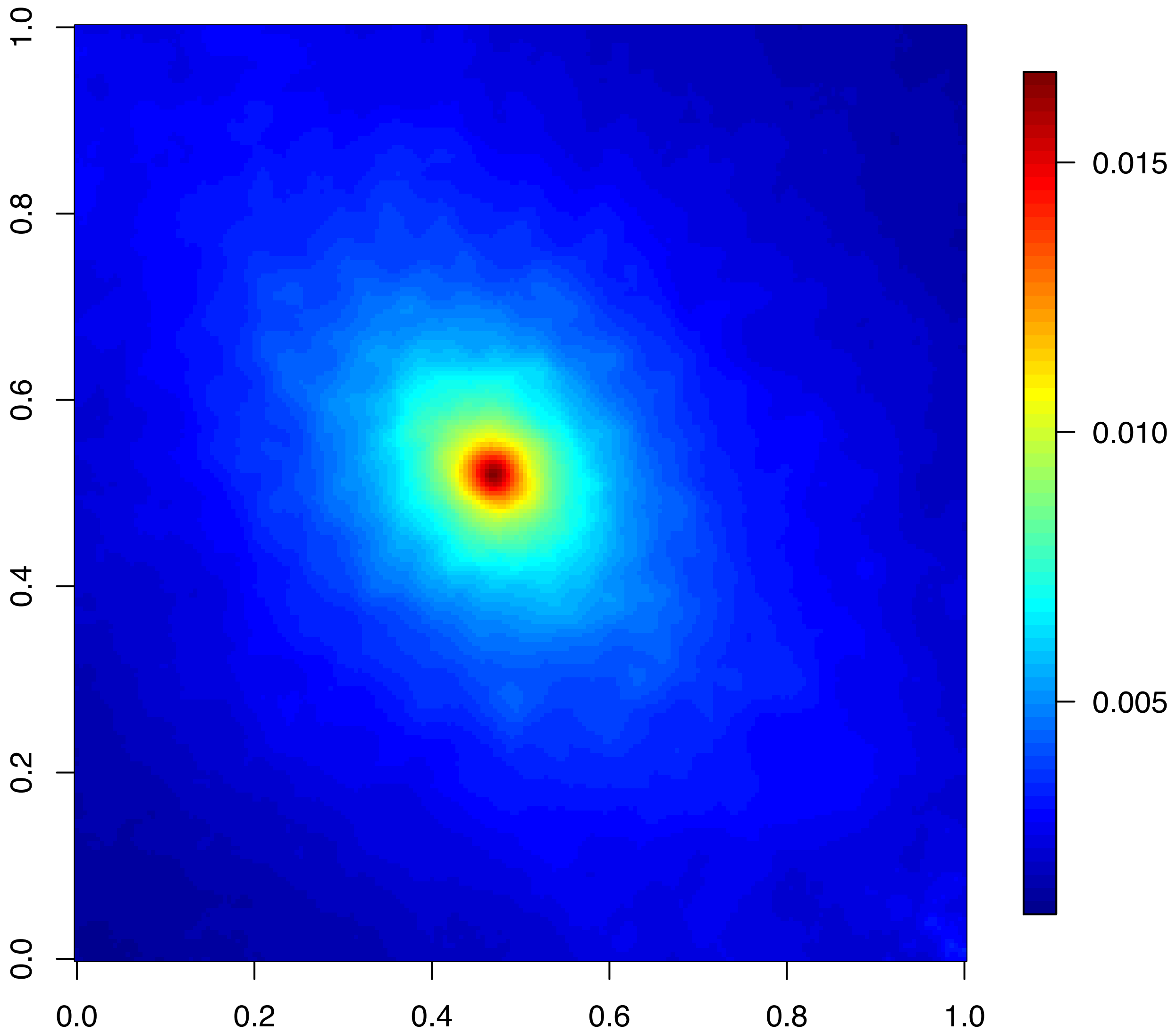


THE POINT SPREAD FUNCTION



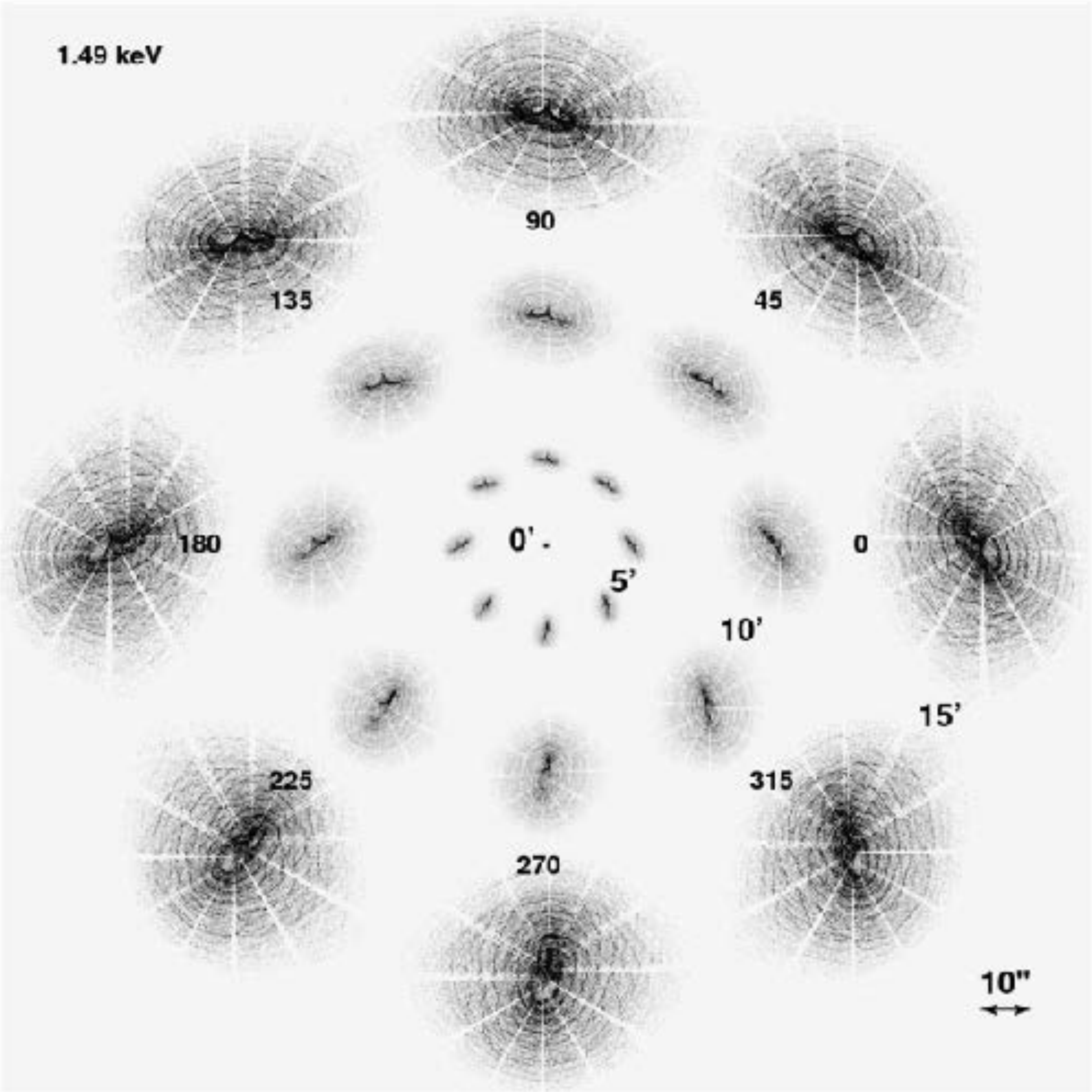
THE POINT SPREAD FUNCTION



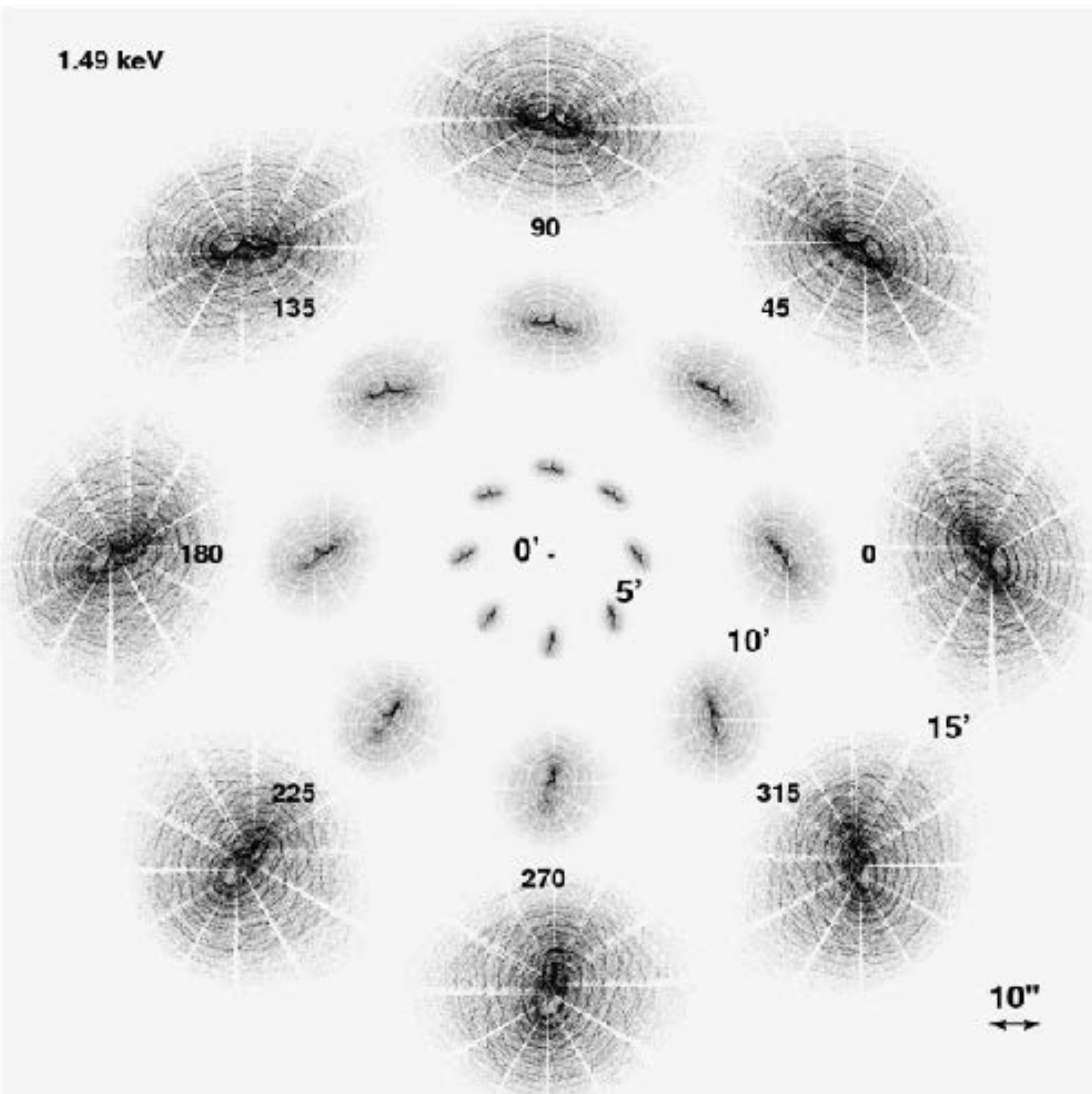


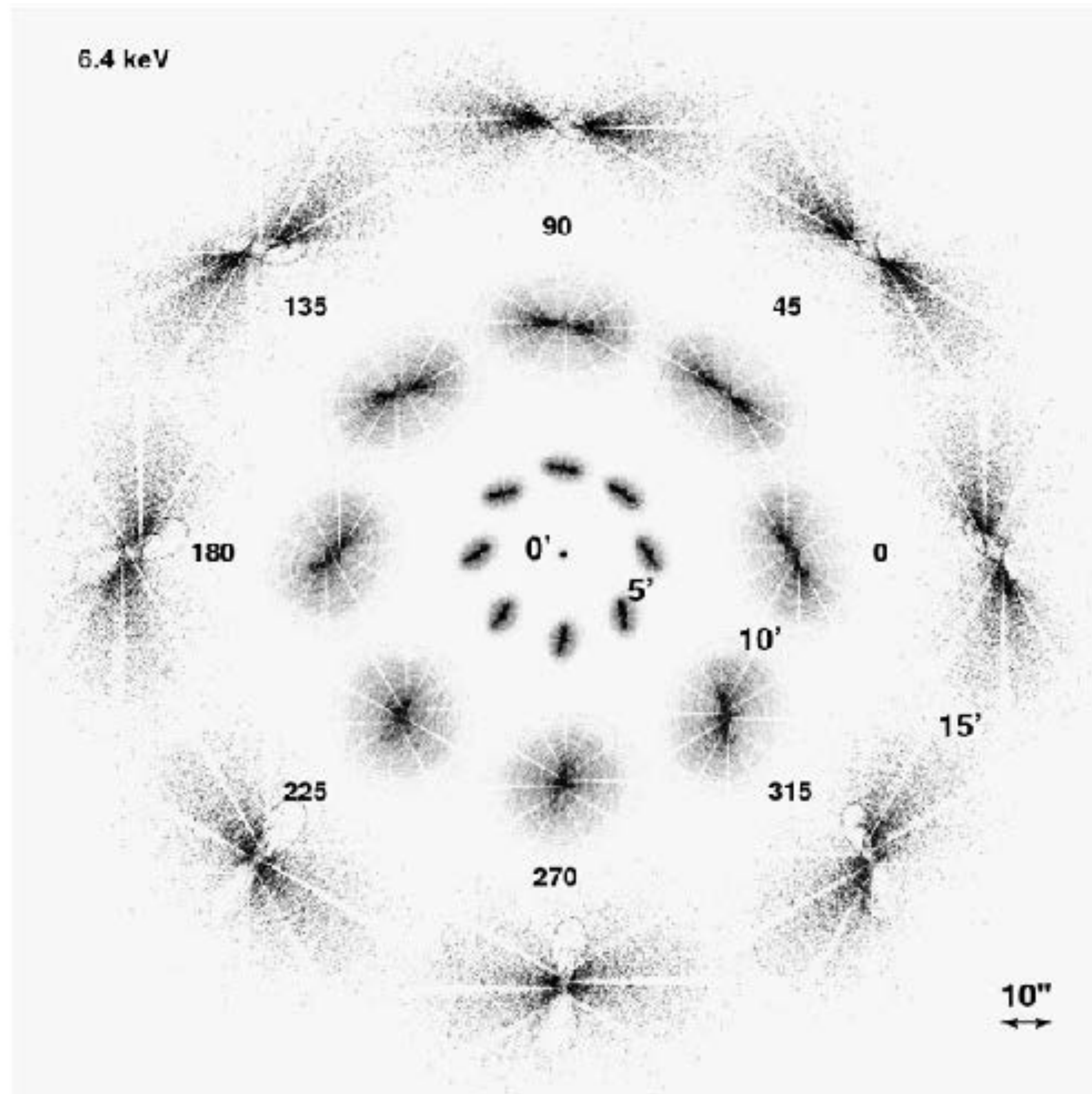
WHAT DERIVED GALAXY PROPERTIES WILL THIS AFFECT?

THE POINT SPREAD FUNCTION… IS RARELY THAT SIMPLE.



THE POINT SPREAD FUNCTION… IS RARELY THAT SIMPLE.





SIZE MEASUREMENTS

- Galaxy sizes are generally defined via convention, as it can be subjective to define where the 'edge' of a galaxy is.
  - The effective radius r_e is the radius contains 50% of the total emission from the galaxy.
  - The Petrosian radius r_p is the radius at which the Petrosian index of a galaxy is equal to some pre-defined value (5 in the SDSS pipeline). Not sensitive to distance!
  - The Petrosian index is defined as the ratio between the average intensity of light $<I_R>$ from a galaxy within a projected radius R and the projected intensity at that radius I(R).

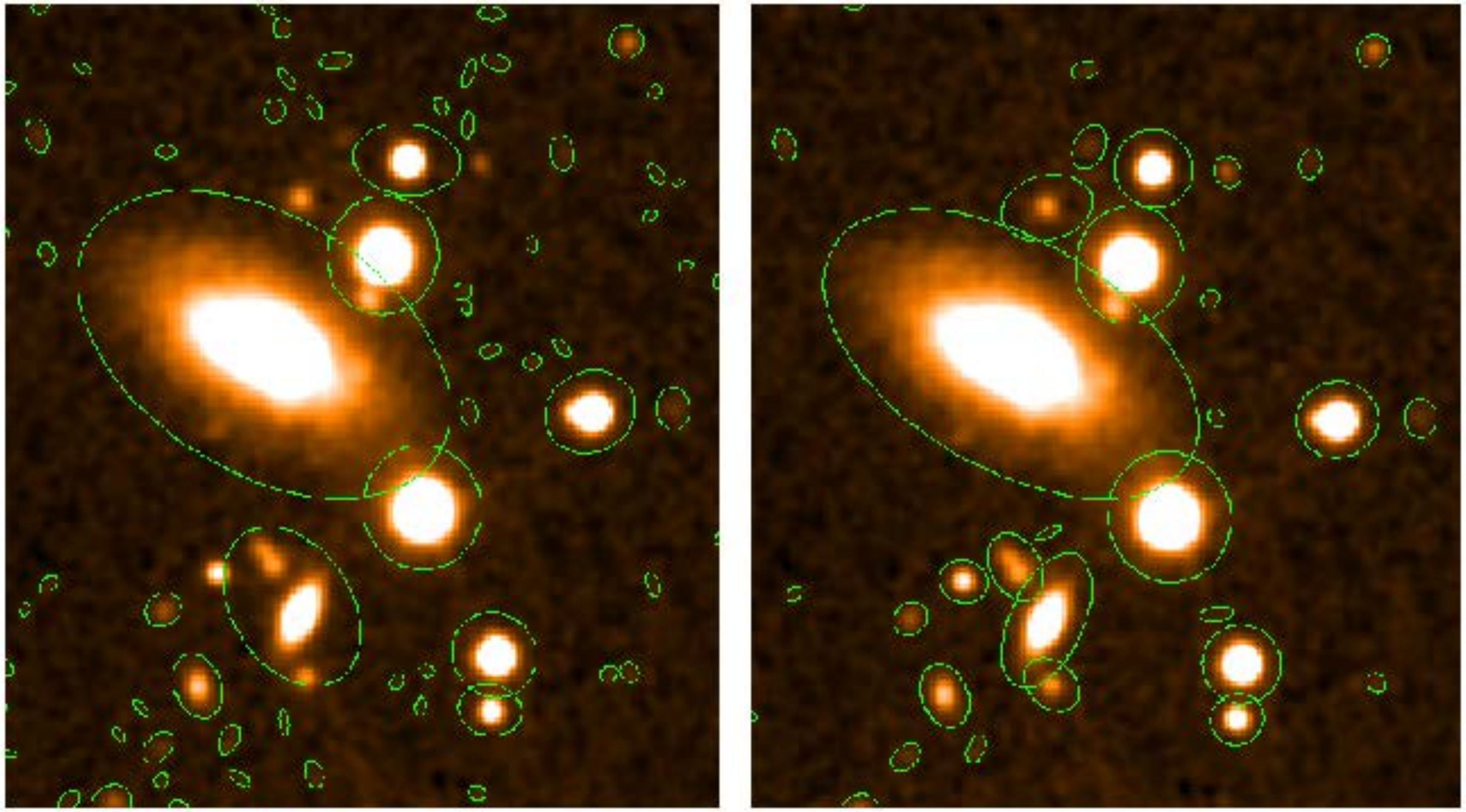
$$\eta(R) = \frac{L(< R)}{\pi R^2 I(R)} = \frac{\langle I \rangle_R}{I(R)}$$

DEBLENDING

- Deblending is an integral part of object detection, and refers to the separation of overlapping objects into separate apertures.

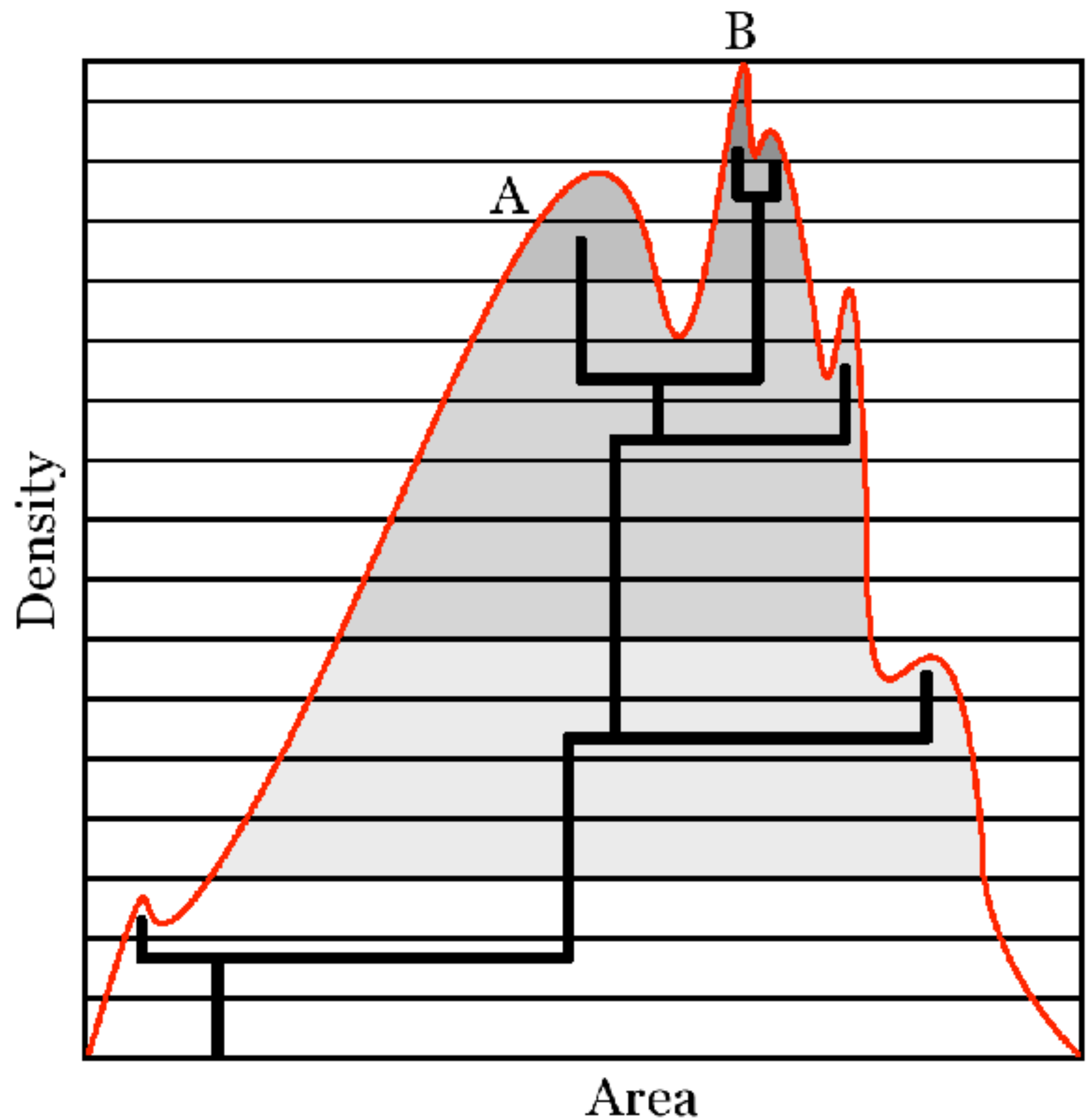
DEBLENDING

- Deblending is an integral part of object detection, and refers to the separation of overlapping objects into separate apertures.



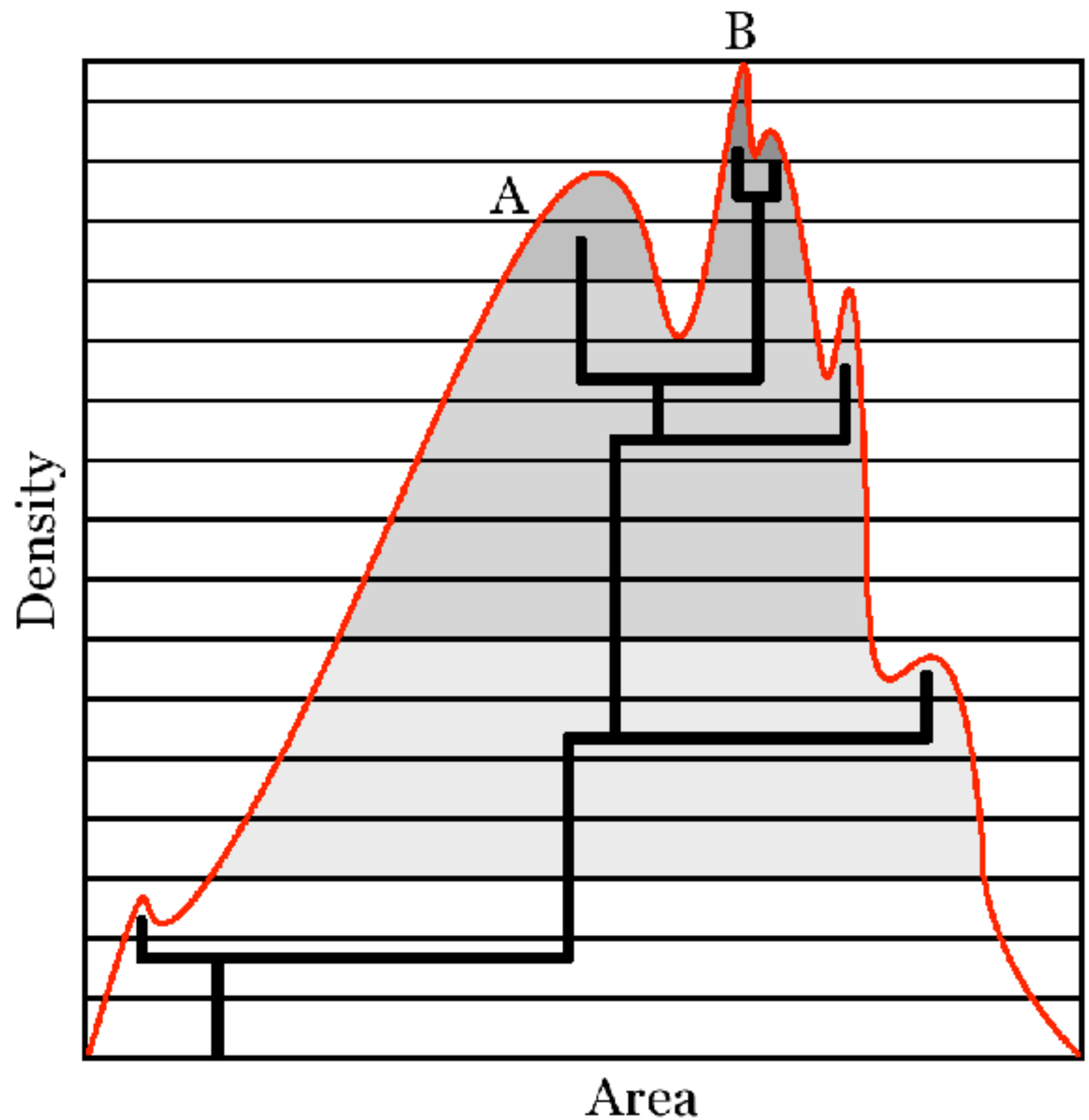
Default settings. IOTA settings.

DEBLENDING



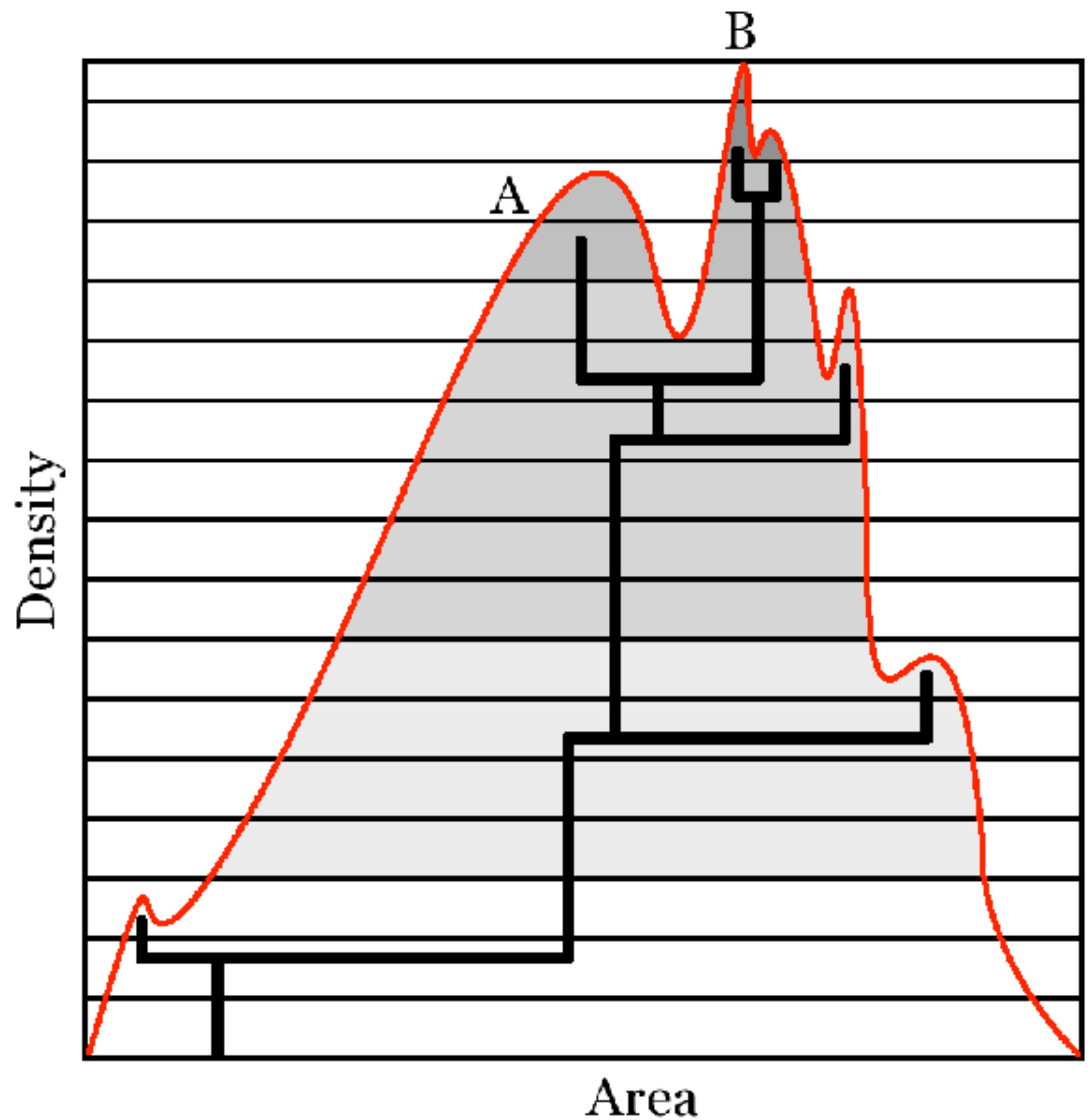
DEBLENDING

- Traditionally, deblending depends on a detection threshold, and the number of levels between that threshold and the maximum flux in the image.



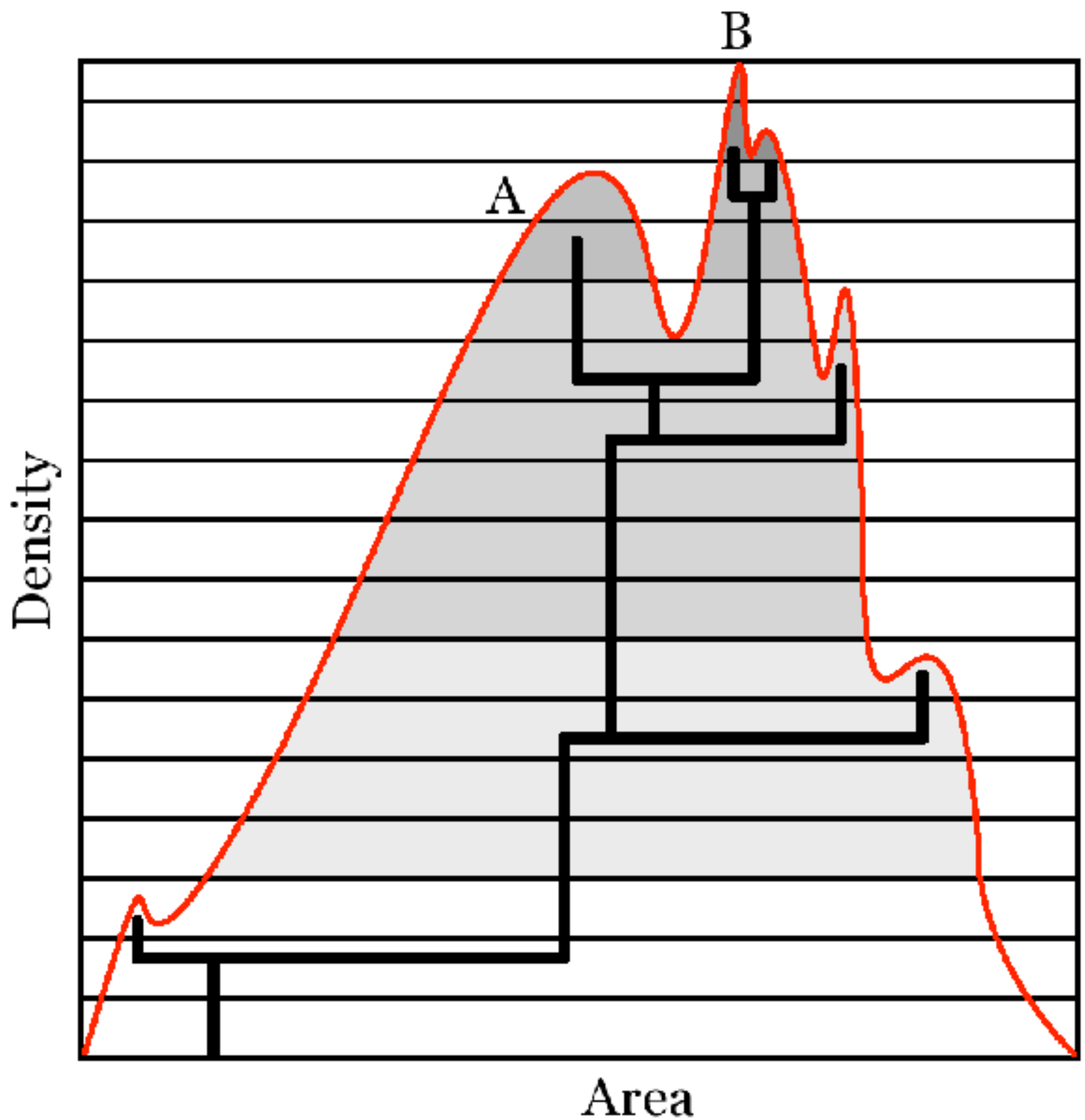
DEBLENDING

- Traditionally, deblending depends on a detection threshold, and the number of levels between that threshold and the maximum flux in the image.
- An object is then a collection of adjacent pixels whose flux value is above the minimum detection threshold.

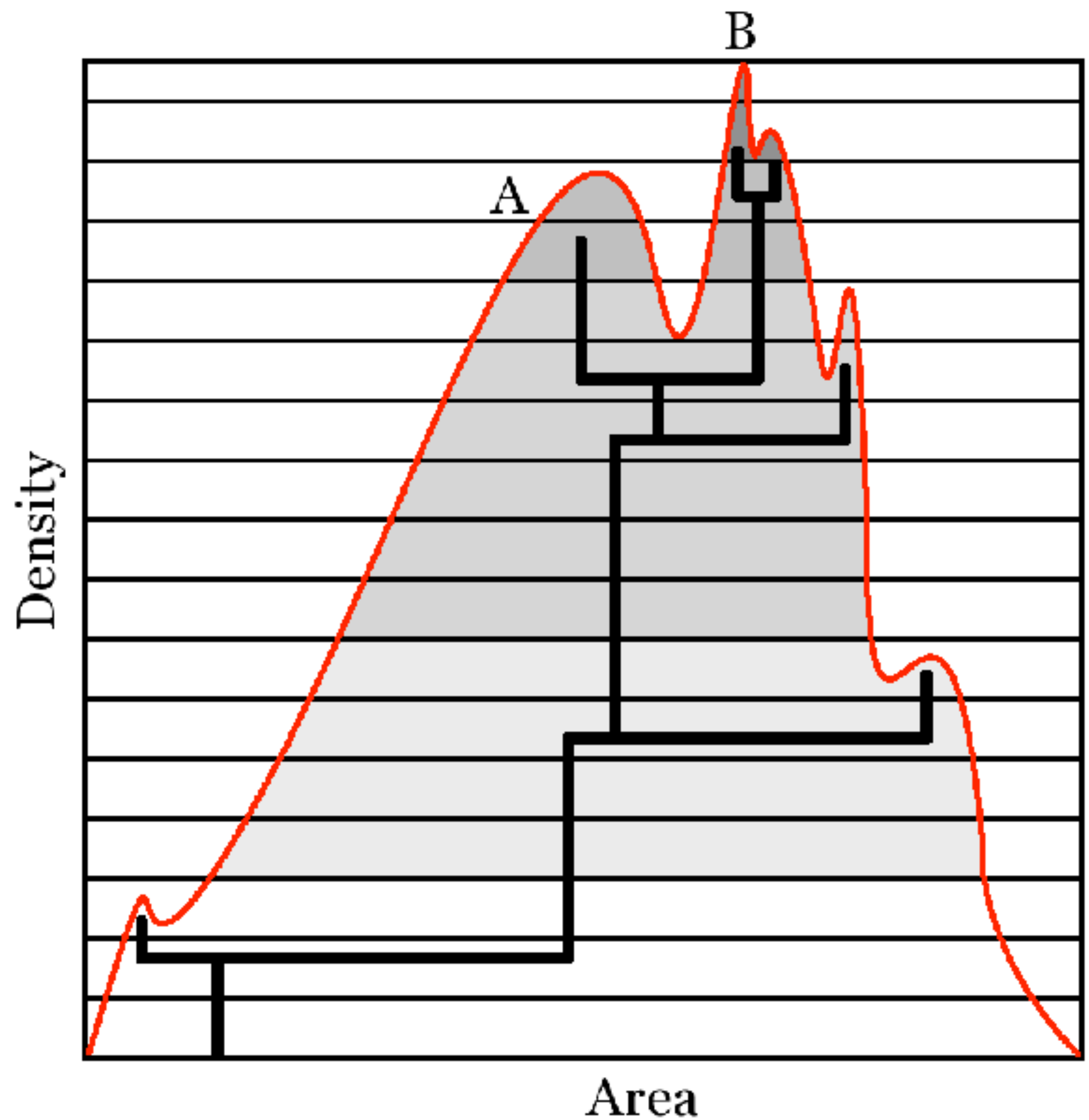


DEBLENDING

- Traditionally, deblending depends on a detection threshold, and the number of levels between that threshold and the maximum flux in the image.
- An object is then a collection of adjacent pixels whose flux value is above the minimum detection threshold.
- 1D representation on the right.

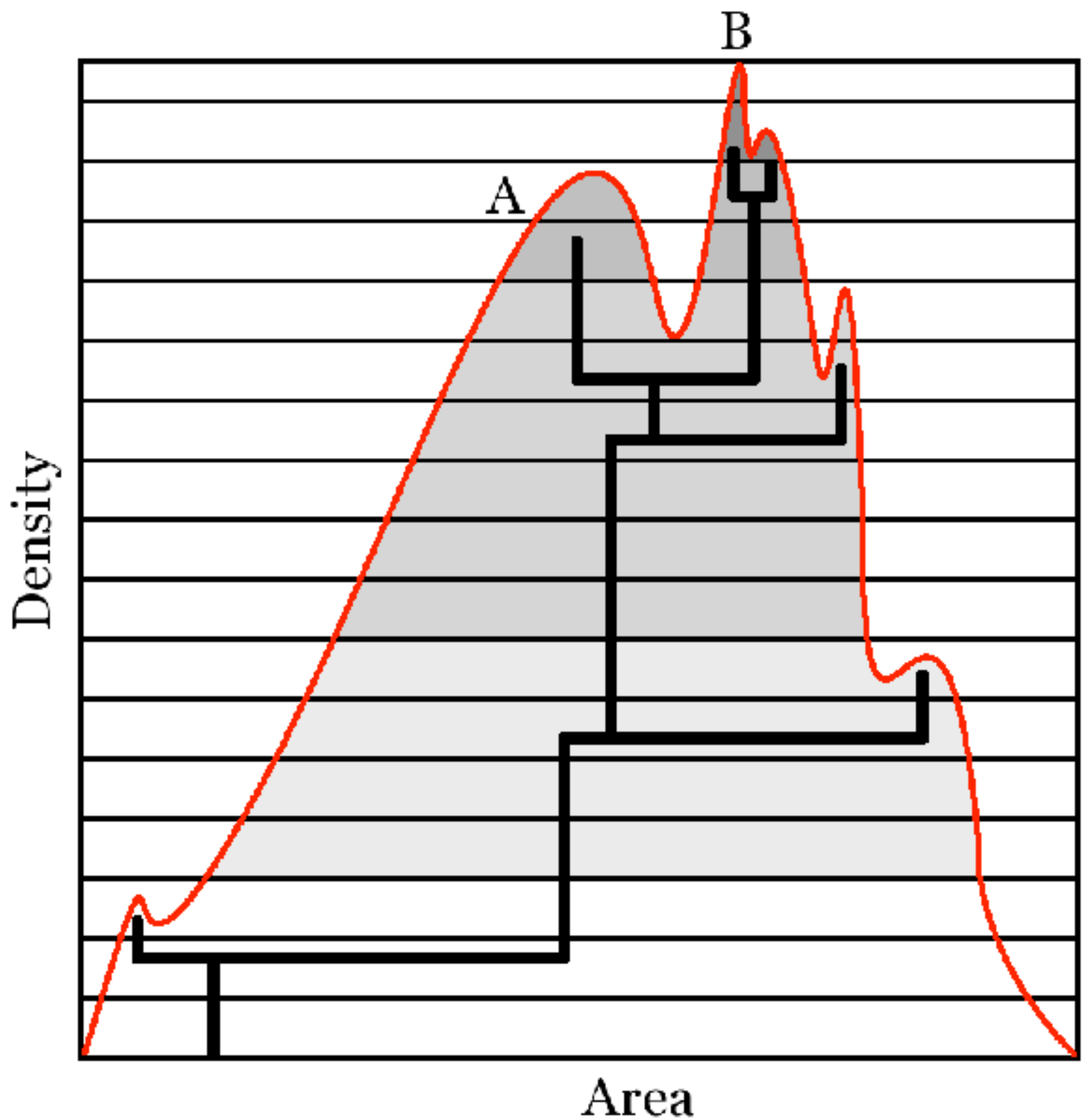


DEBLENDING



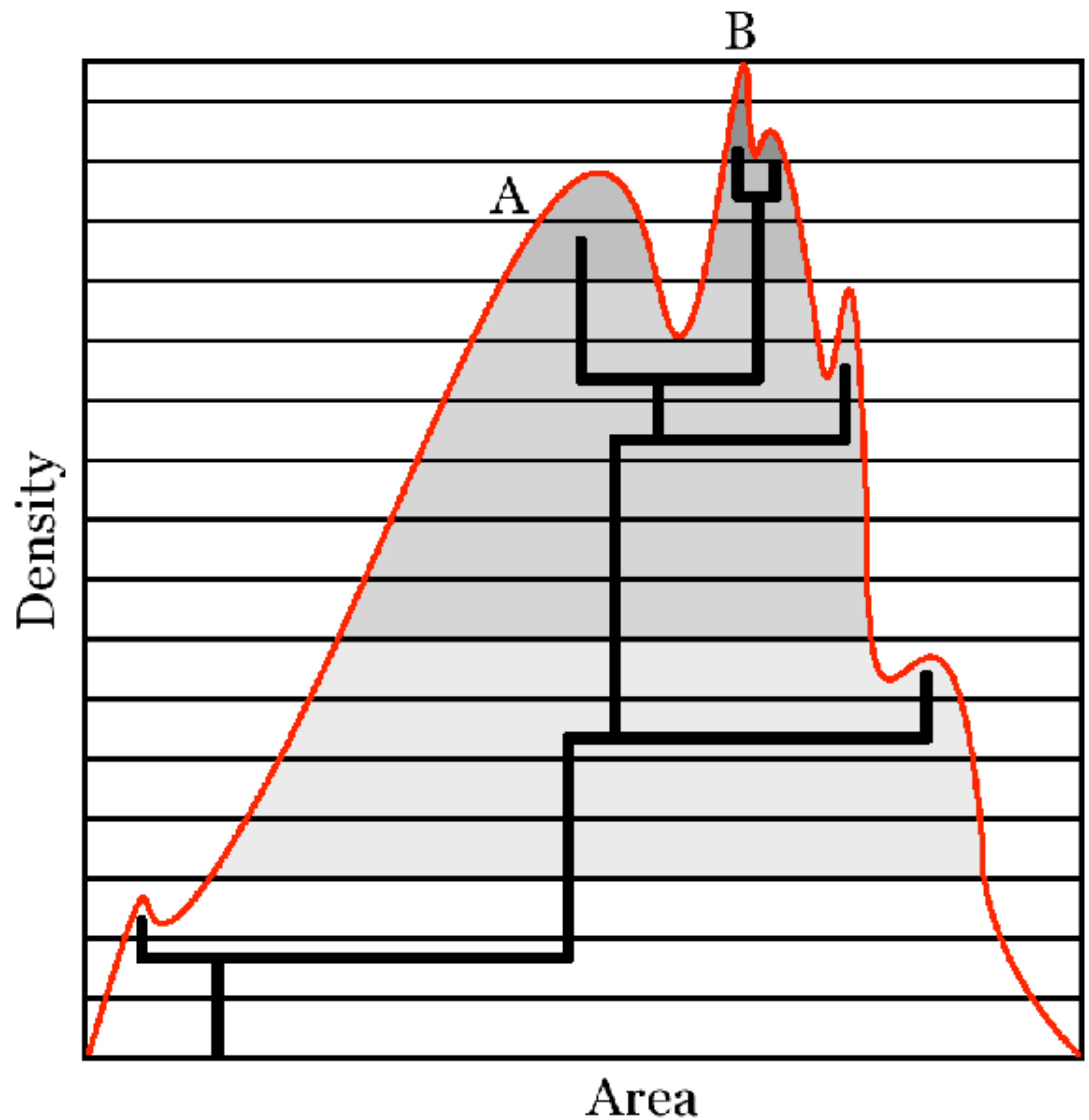
DEBLENDING

- Conservative deblending leads to multiple objects being grouped together – missing flux!



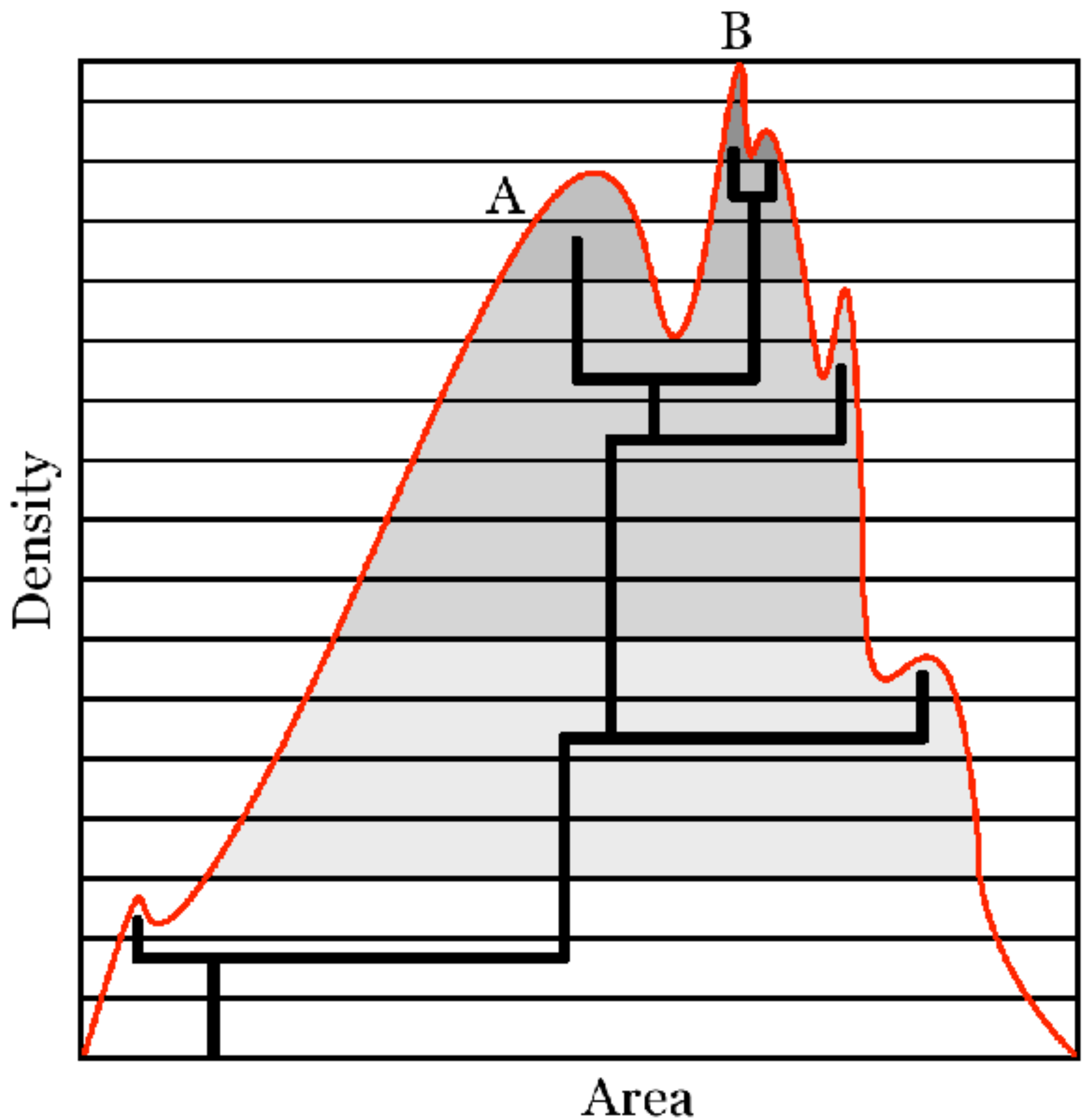
DEBLENDING

- Conservative deblending leads to multiple objects being grouped together – missing flux!
- Cavalier deblending leads to individual galaxies being broken into parts.

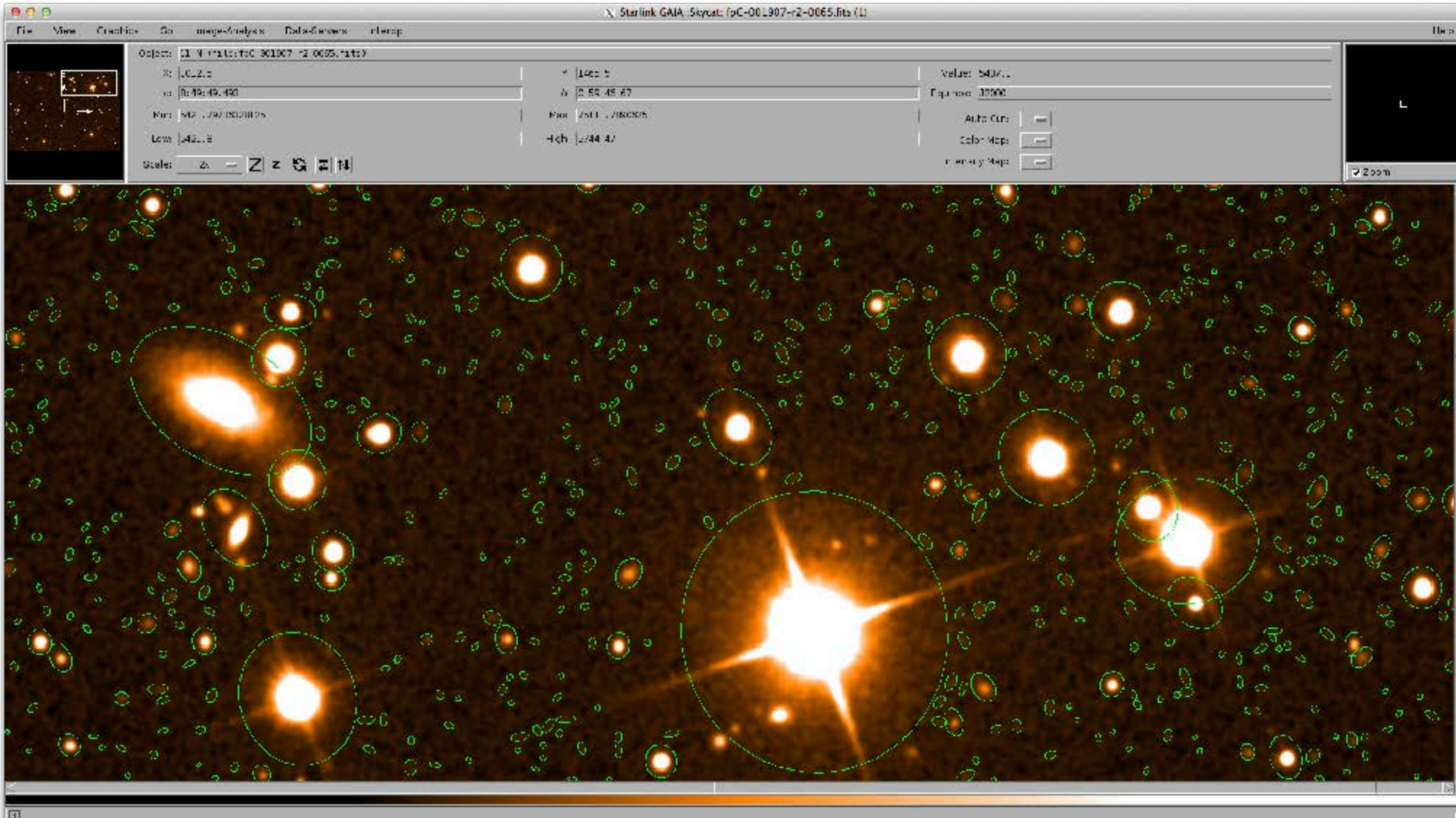


DEBLENDING

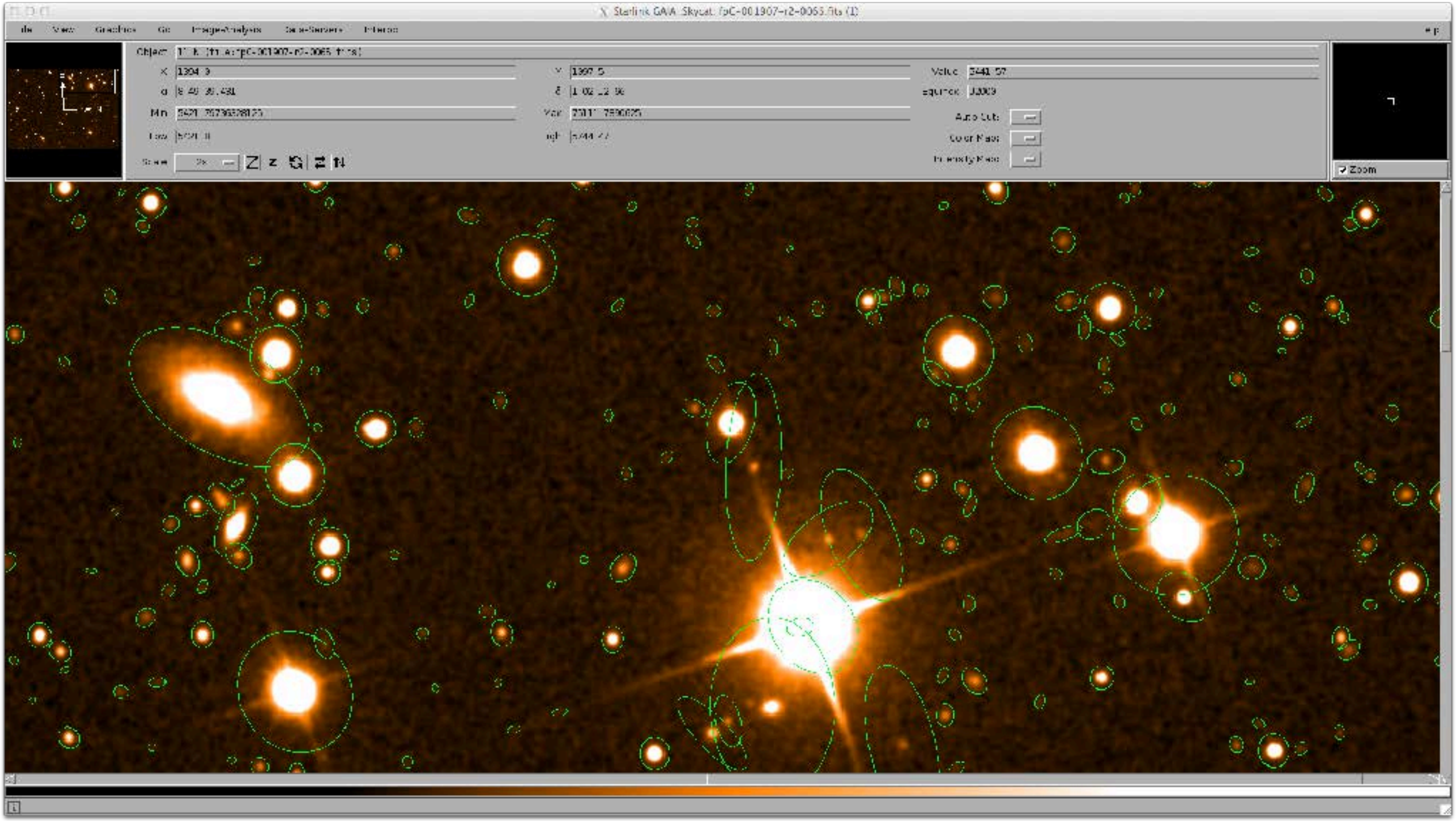
- Conservative deblending leads to multiple objects being grouped together – missing flux!
- Cavalier deblending leads to individual galaxies being broken into parts.
  - Also, lots of spurious detections.



DEBLENDING



DEBLENDING

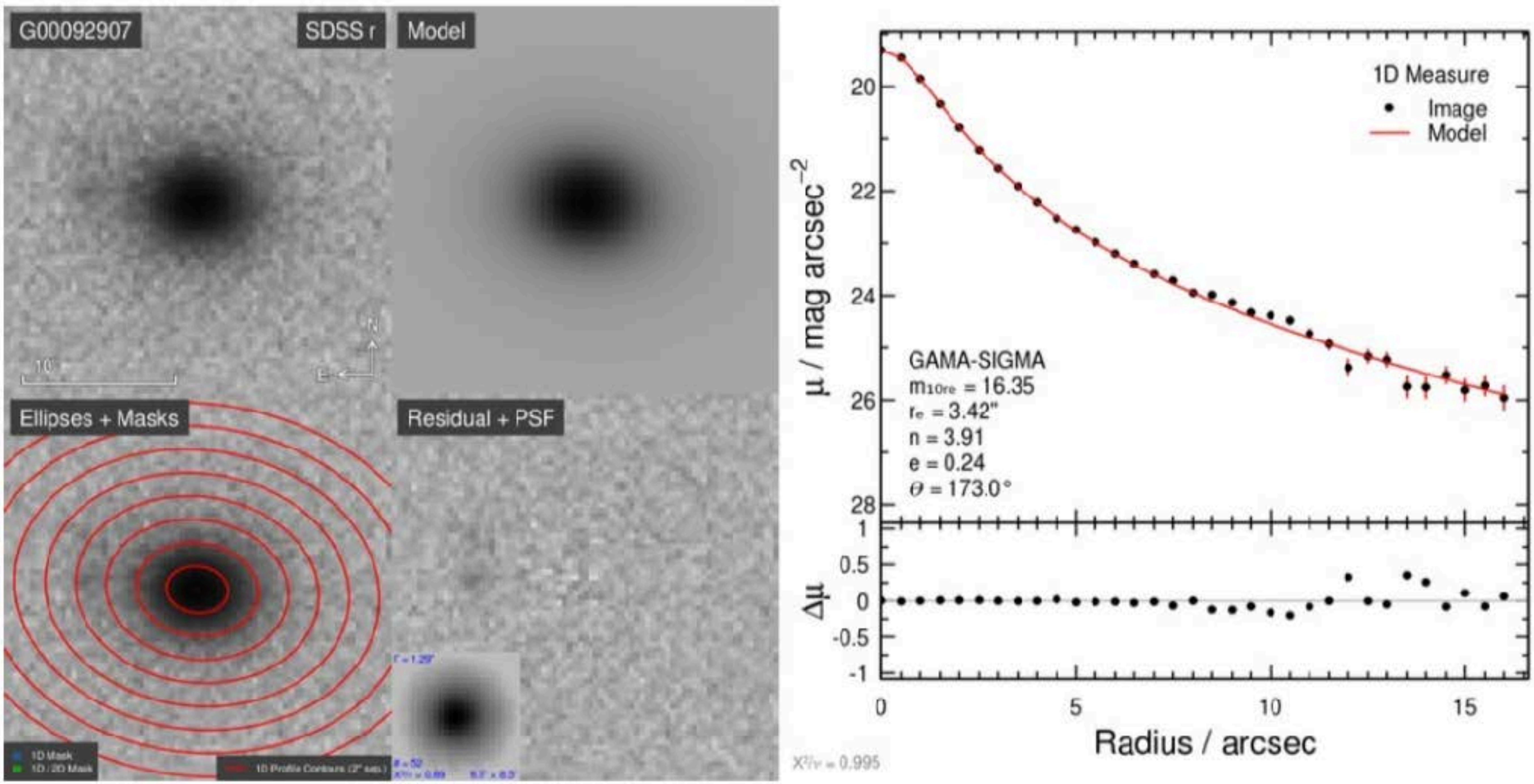


RADIAL PROFILES

RADIAL PROFILES

- Surface brightness profiles, or radial profiles, are computed by azimuthally averaging the flux along isophotes (lines of constant brightness).

RADIAL PROFILES



THE SERSIC PROFILE

- The Sérsic profile is given by

$$I(R) = I_0 \exp\left(-\frac{1}{k} r^{1/n}\right)$$

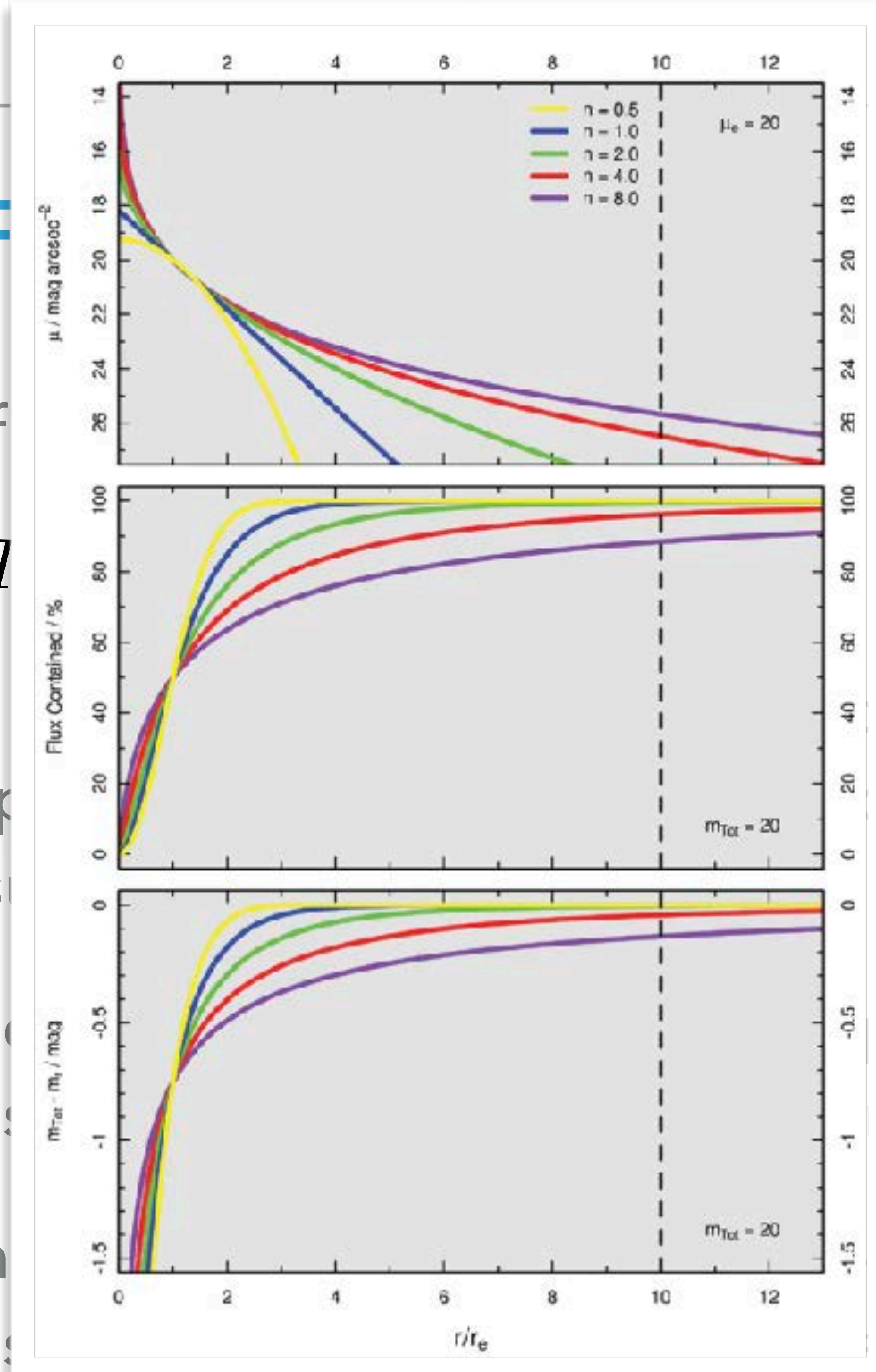
- Varying values of *n* are able to fit the radial profiles of *most* elliptical and spiral galaxies; so the Sérsic index is a very common measure of galaxy morphology.
    - Smaller n – less concentrated, steeper slope at large R. Generally associated with spiral galaxies (n=1).
    - Larger n – more concentrated, shallow slope at large R. Generally associated with elliptical galaxies (n=4).

THE SERSIC PROF

- The Sérsic prof

I

- Varying values … rofiles of *most* elliptical and sp … lex is a very common meas
  - Smaller n – l … be at large R. Generally as … n=1).
  - Larger n – m … be at large R. Generally as … s (n=4).



THE SERSIC PROFILE

- *k* can be decomposed into constants that make more sense.

$$I(R) = I_e \exp\left(-b\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right)$$

- R_e is the effective radius, and I_e is the intensity at that radius. b depends on *n*, and is generally given by a Gamma function
  - MacArthur, Courteau, & Holtzman 2003) gives, for n > 0.35:

$$b(n) = 2n - \frac{1}{3} + \frac{4}{405n} + \frac{46}{25515n^2} + \frac{131}{1148175n^3} - \frac{2194697}{30690717750n^4}$$

THINGS I HAVE NOT DISCUSSED…

- Errors!
- Bulge-disk decomposition.
- Galaxy luminosity functions.
- Galaxy colors as a proxy for clustering.
- More detail on galaxy colors.
- Photometric redshifts.
- Zodiacal light.
- Intracluster light.
- …!