Photometric Properties of Galaxies

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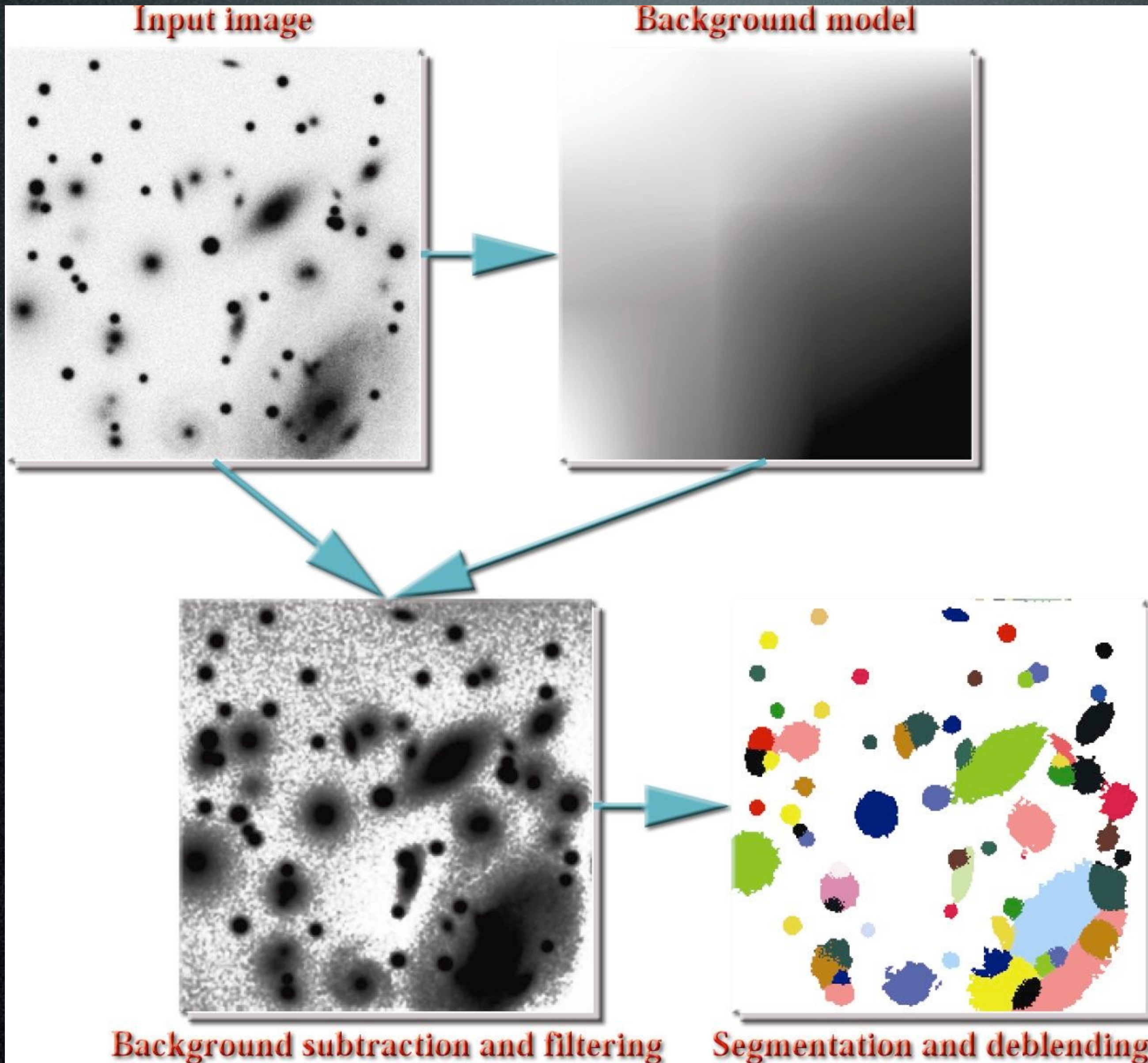
How is a galaxy defined on an image?

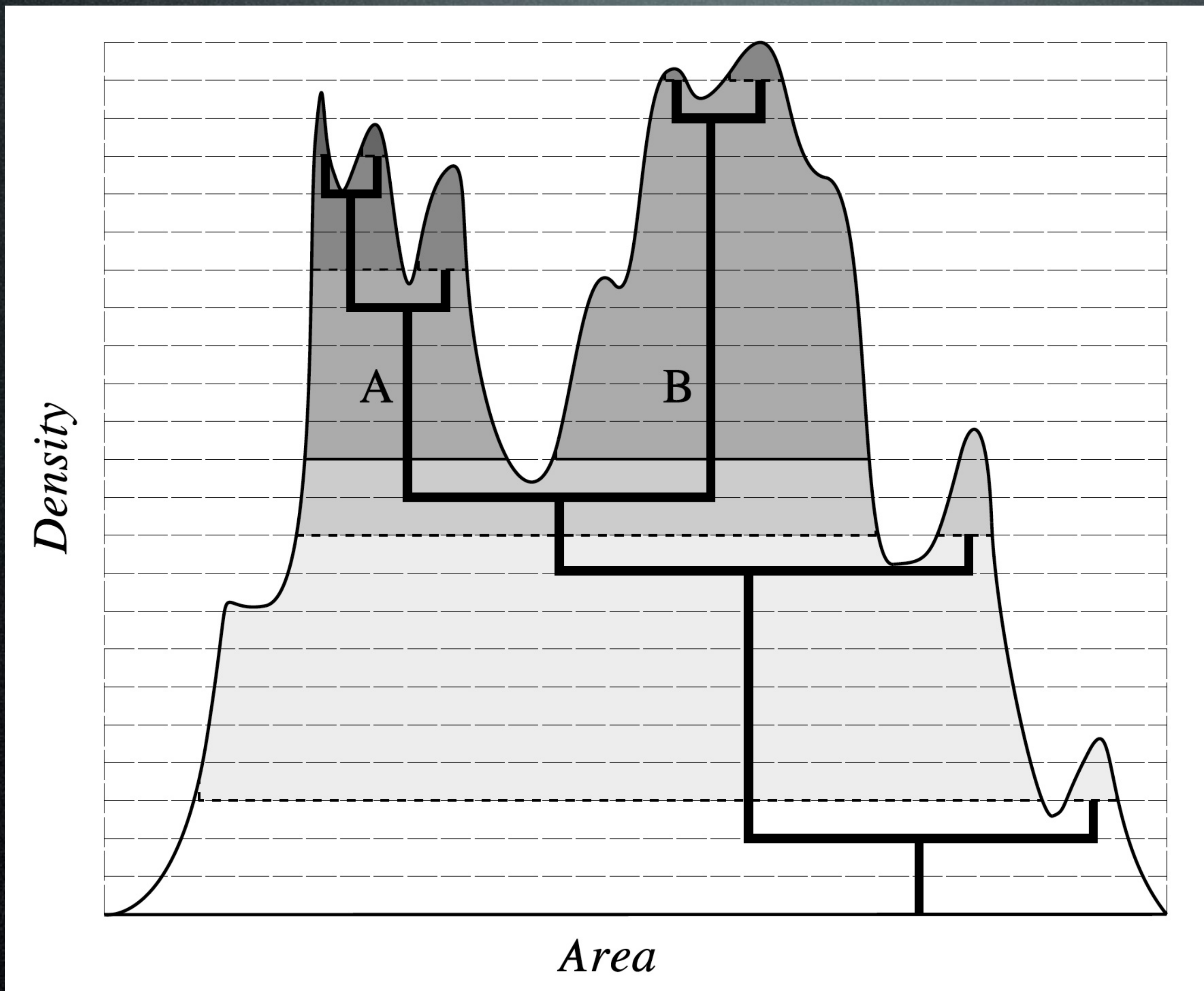


Pixels in image must be assigned to different objects as well as the sky using a “segmentation image”

There is NOT a unique way of building a segmentation image …

Bertin, E., Sextractor manual

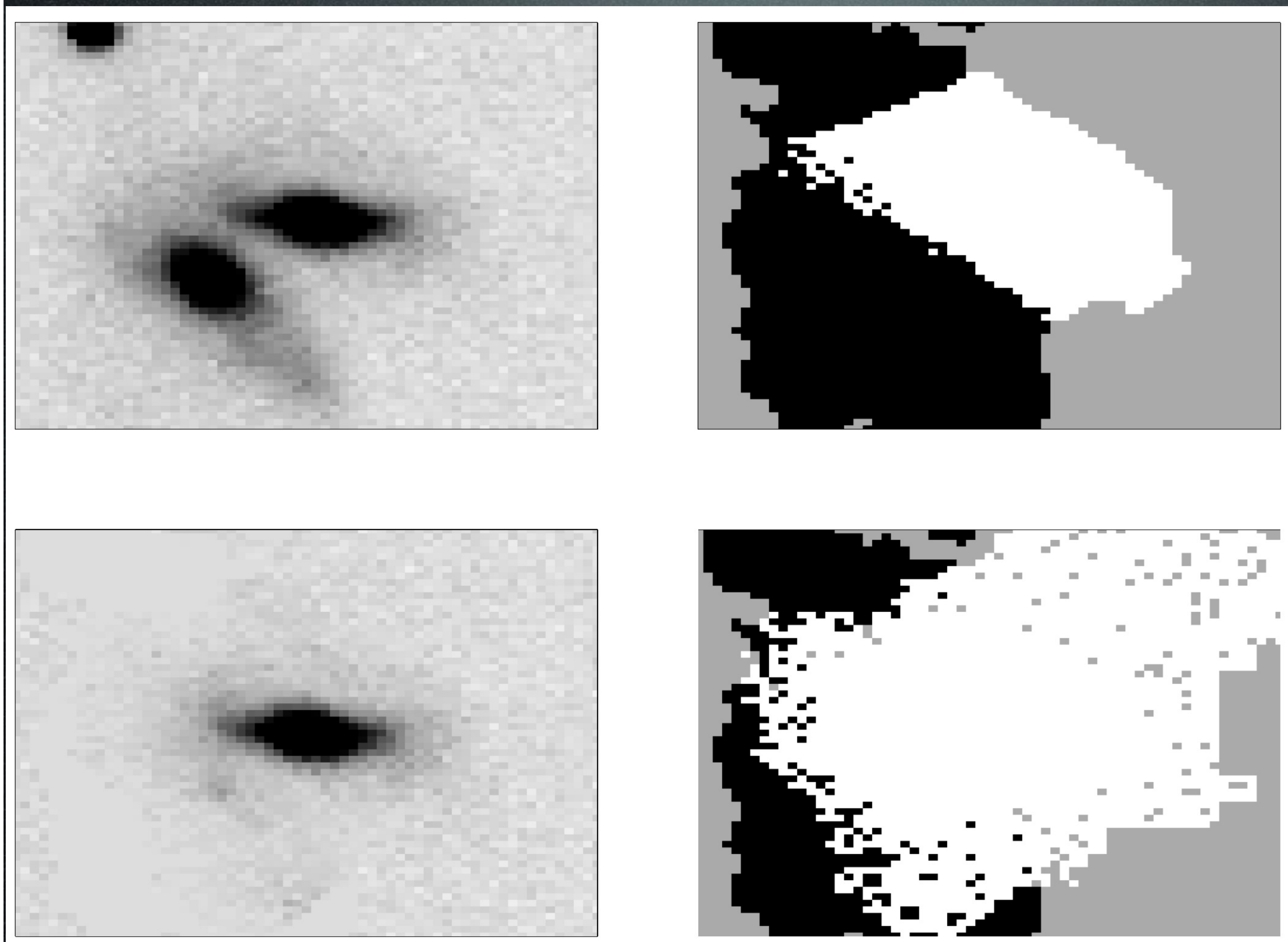
How is a segmentation image built?



Flux thresholding as done by SExtractor galaxy photometry package – the key parameter is the "deblending contrast"

Bertin, E., Sextractor manual

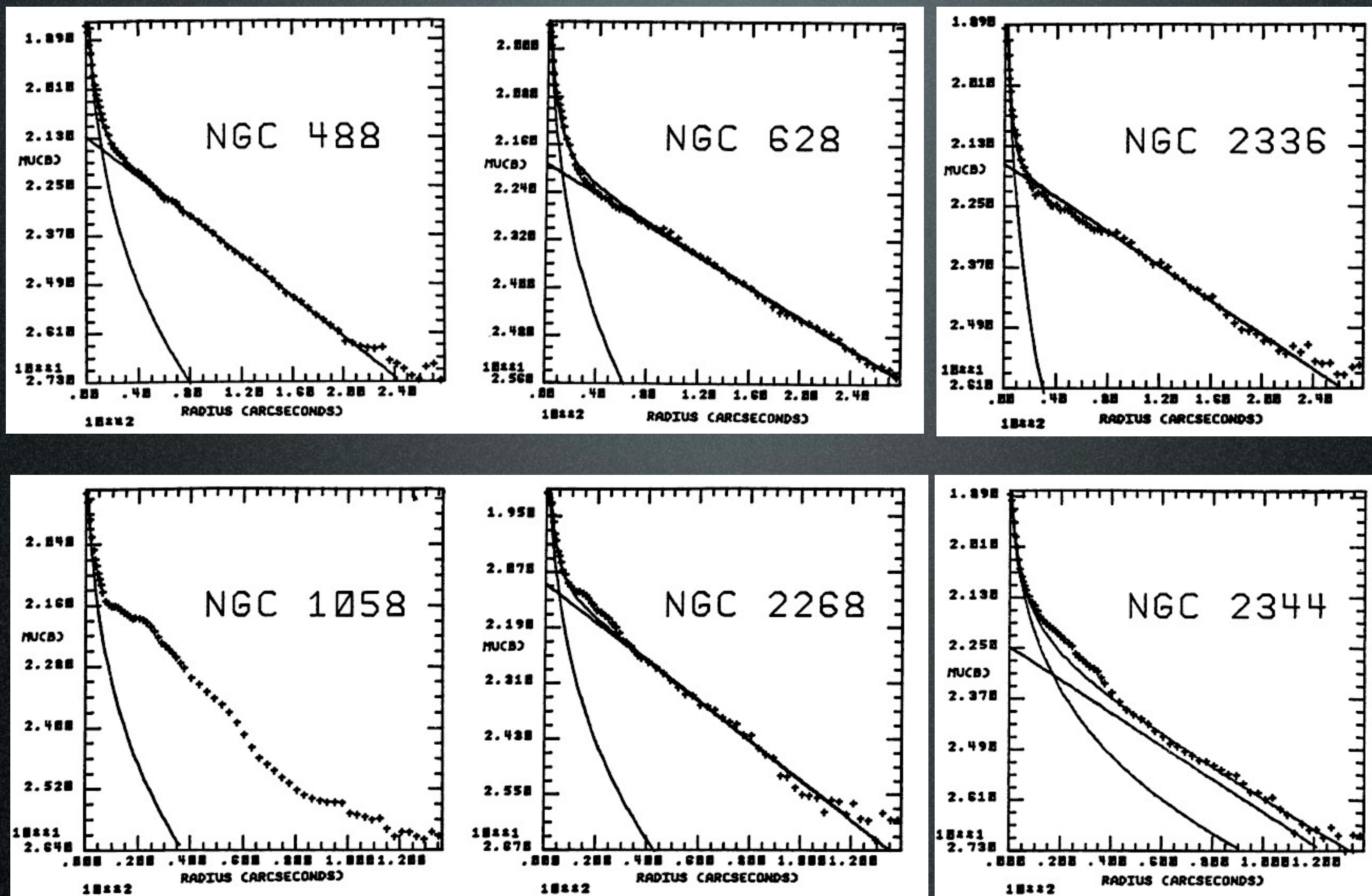
Effect of Crowding on Segmentation



Segmentation image for a close pair of galaxies in SDSS

Simard et al. 2011, ApJS, 196, 11

Radial Light Profiles

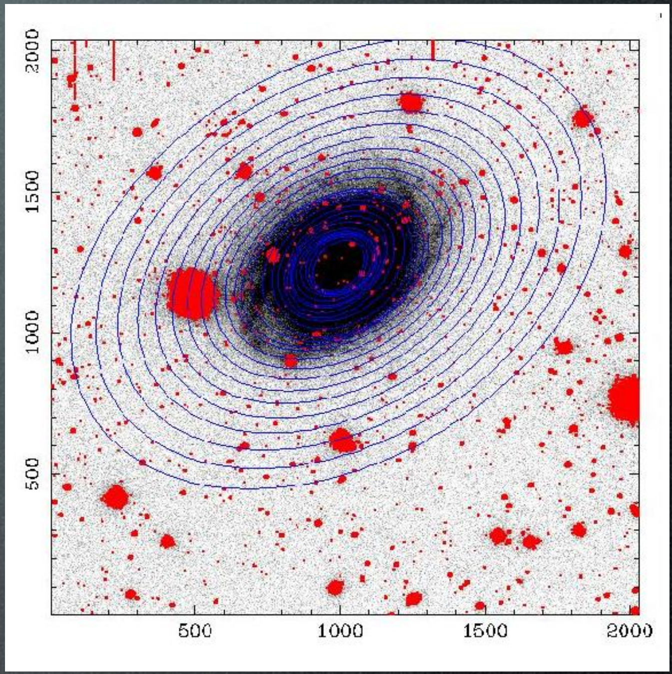


WARNING: Photometry ≠ Kinematics!!

Boroson et al. 1981, ApJS, 46, 177

Galaxy Curves-of-Growth

The curve of growth *C(R)* of an astronomical object with a light profile I(r) is given by:



$$C(R) = 2\pi \int_0^R I(r) r dr$$

In practice, the actual calculation from an image is:

$$C(R) = 2\pi \int_0^R [I_{raw}(r) - B_{sky}] r dr$$

IF the sky background B_{sky} has been accurately determined, then *C(R)* will asymptotically converge to the true total flux of the galaxy, i.e., *C(R)* should become flat at large radii

Galaxy Curves-of-Growth

Some important considerations:

- Are your apertures circular or elliptical?
- How should you deal with missing flux due to neighbor galaxies?
- Sky background is the dominant source of systematic error
- Going out to large radii decreases the overall signal-to-noise ratio of your total magnitude measurement
- Do you need to correct for seeing effects?
- Curves of growth are really hard to compute for all types of galaxies but especially those with a lot of light in the wings of their profile

Petrosian Radius

(Petrosian, V. 1976, ApJ, 209, L1)

The Petrosian radius is a definition of galaxy size that is independent of galaxy distance.

Consider a galaxy with a light profile given by *I(r)*. The average intensity with a radius R is then given by:

$$I_a(R) = \frac{\int_0^R I(r) 2\pi r dr}{\pi R^2}$$

At the Petrosian radius R_p, *we have*

$$I(R_p) = \eta \left(\frac{\int_0^{R_p} I(r) 2\pi r dr}{\pi R_p^2} \right)$$

Note that η is not necessarily 1 due to things like seeing. Its value is actually closer to 0.2 in real data.

Disk Light Profile

Disk radial profile follows:

$$\Sigma(r) = \Sigma_0 \exp(-r/r_d)$$

The total disk luminosity is obtained by integrating:

$$L_{tot} = 2\pi \int_0^\infty \Sigma_0 \exp(-r/r_d) r dr$$

which gives:

$$L_{tot} = 2\pi r_d^2 \Sigma_0$$

Disk Light Profile

Disk radial profile follows:

Disk Central Surface Brightness

Disk Scale Length (often simply called "size", also denoted as "h" in literature)

$$\Sigma(r) = \Sigma_0 \exp(-r/r_d)$$

The total disk luminosity is obtained by integrating:

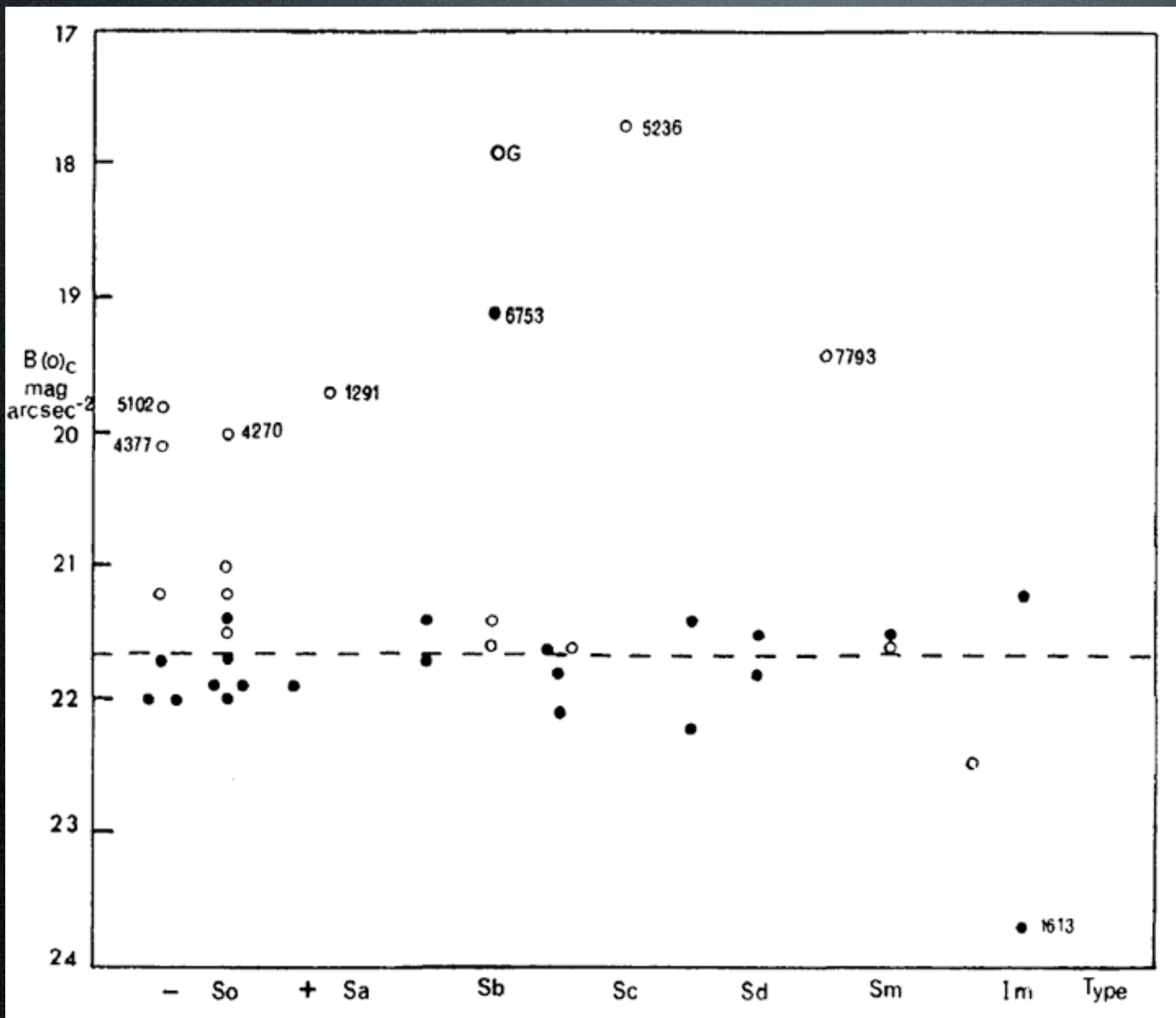
$$L_{tot} = 2\pi \int_0^\infty \Sigma_0 \exp(-r/r_d) r dr$$

Infinite disks are of course not real!

which gives:

$$L_{tot} = 2\pi r_d^2 \Sigma_0$$

Freeman's Law for Galaxy Disks

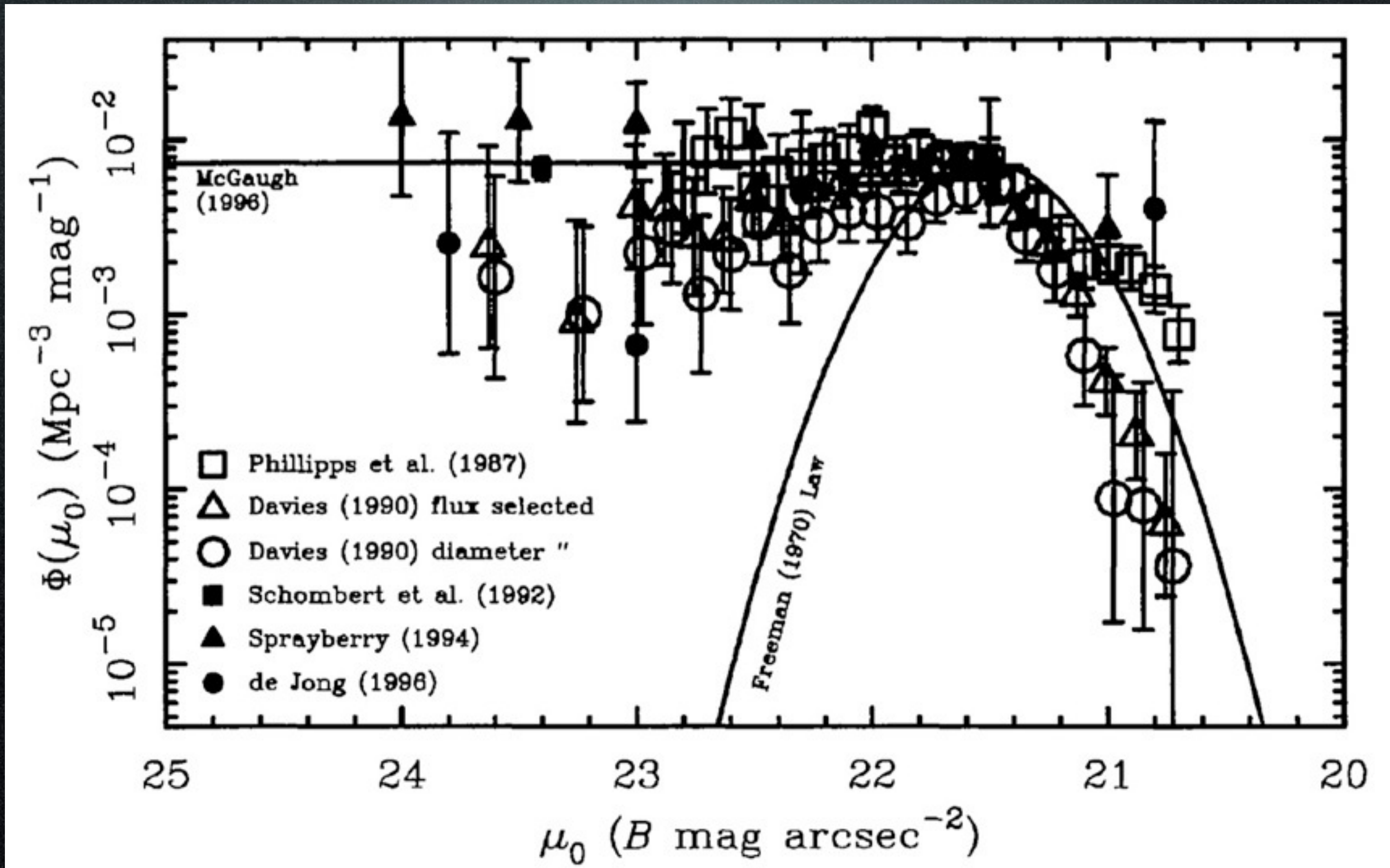


B-band central surface brightness of "Type I" disks is constant with

$\mu_B(0) \sim 21.65$ mag / arcsec^2

Freeman 1970, ApJ,, 160, 811

Caution: Low Surface Brightness Disks!



Bothun 1997, PASP, 109, 745

Bulge Light Profile

Bulge radial profile follows:

$$\Sigma(r) = \Sigma_e \exp\{-k[(r/r_e)^{1/n} - 1]\}$$

This is known as the Sérsic profile. The special case $n = 4$ is the well-known de Vaucouleurs profile

The total bulge luminosity is given by

$$L_{tot} = 2\pi n e^k k^{-2n} r_e^2 \Gamma(n) \Sigma_e$$

Bulge Light Profile

Bulge radial profile follows:

Sérsic index

$$\Sigma(r) = \Sigma_e \exp\{-k[(r/r_e)^{1/n} - 1]\}$$

Bulge effective
Surface Brightness

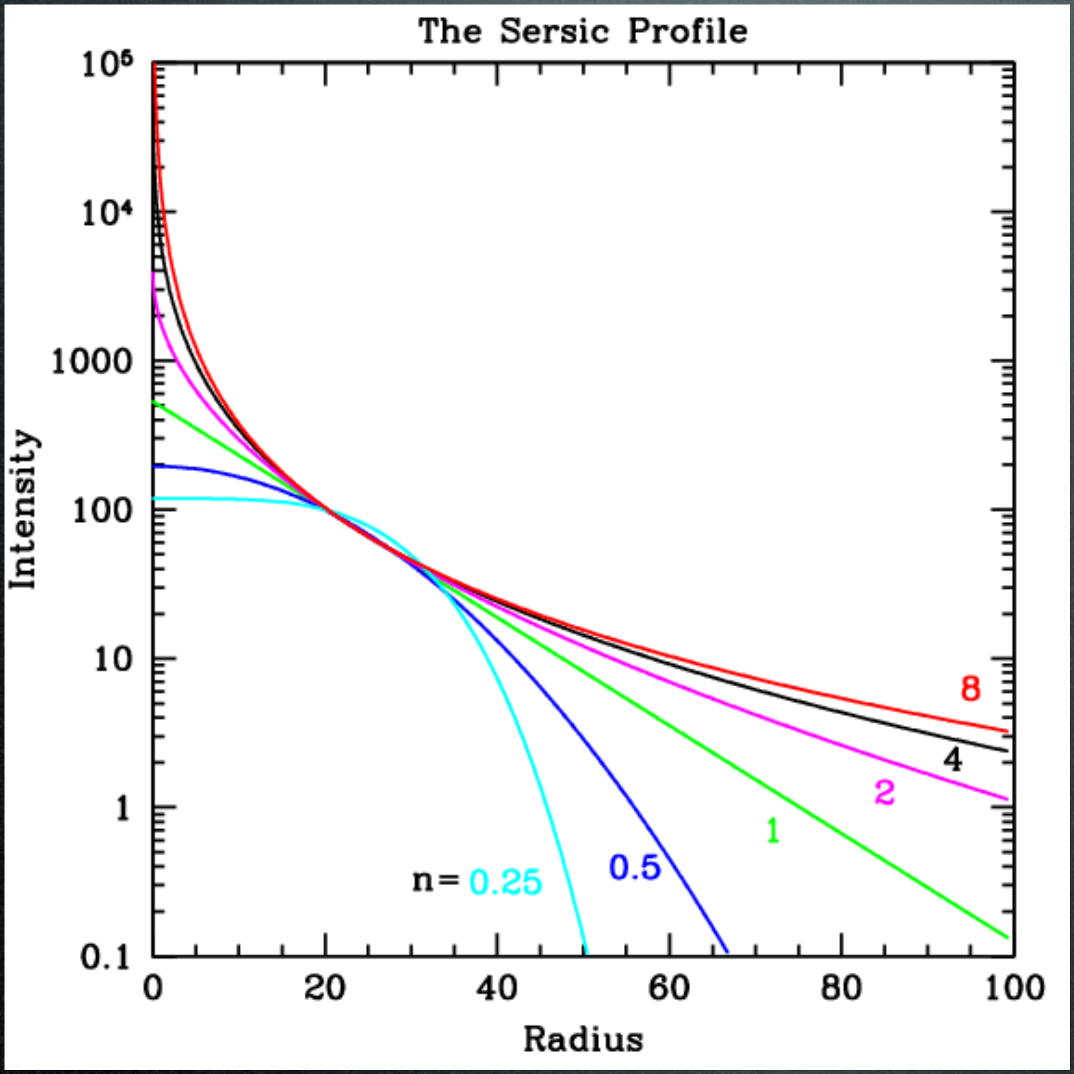
Bulge effective
radius

This is known as the Sérsic profile. The special case $n = 4$ is the well-known de Vaucouleurs profile

The total bulge luminosity is given by

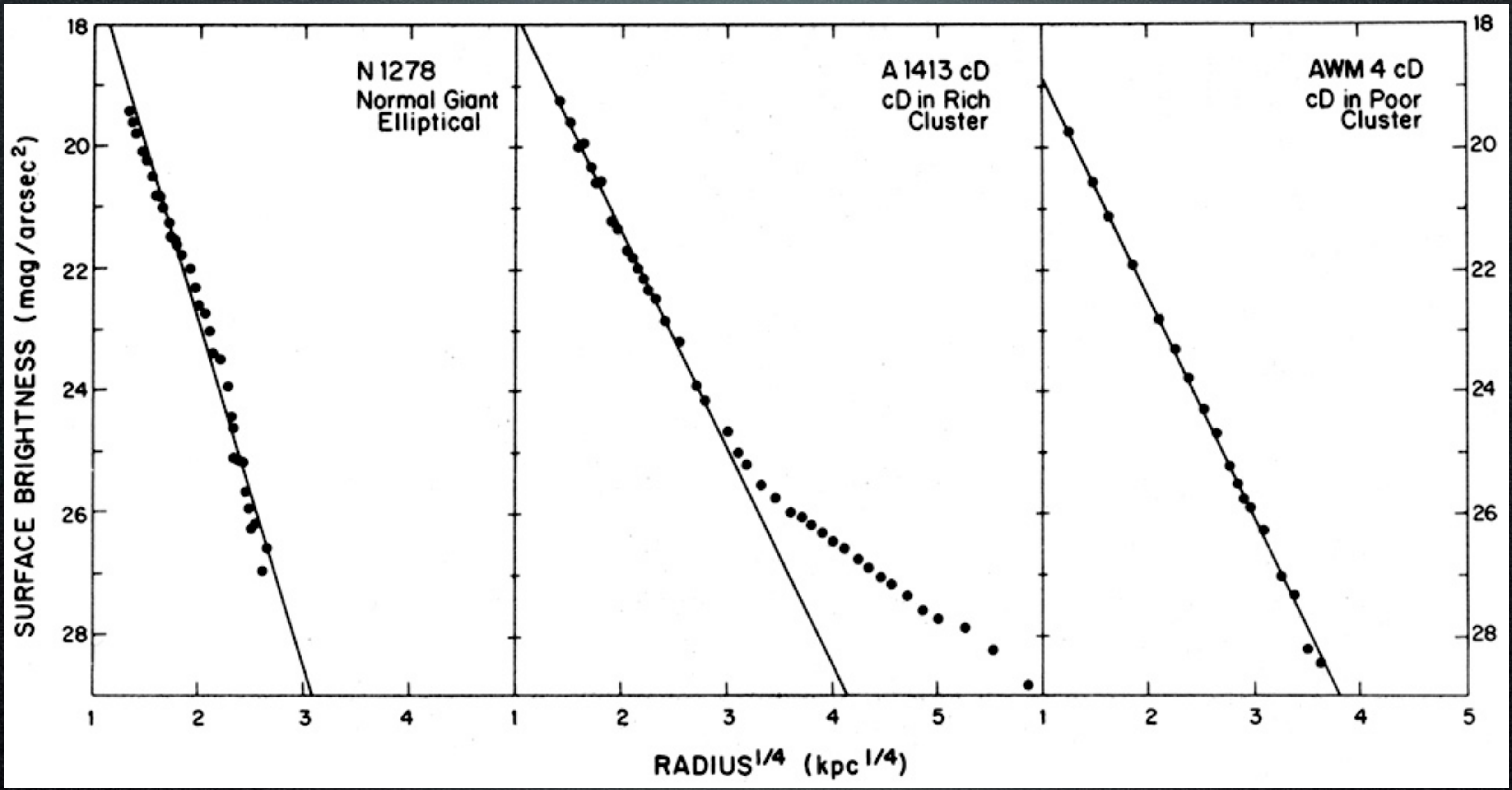
$$L_{tot} = 2\pi n e^k k^{-2n} r_e^2 \Gamma(n) \Sigma_e$$

Bulge Light Profile – Shape as a function of n



Note concentrated core with large wings at high *n* values – they make photometry very difficult!!

Bulge Light Profile – Deviations from $r^{1/4}$



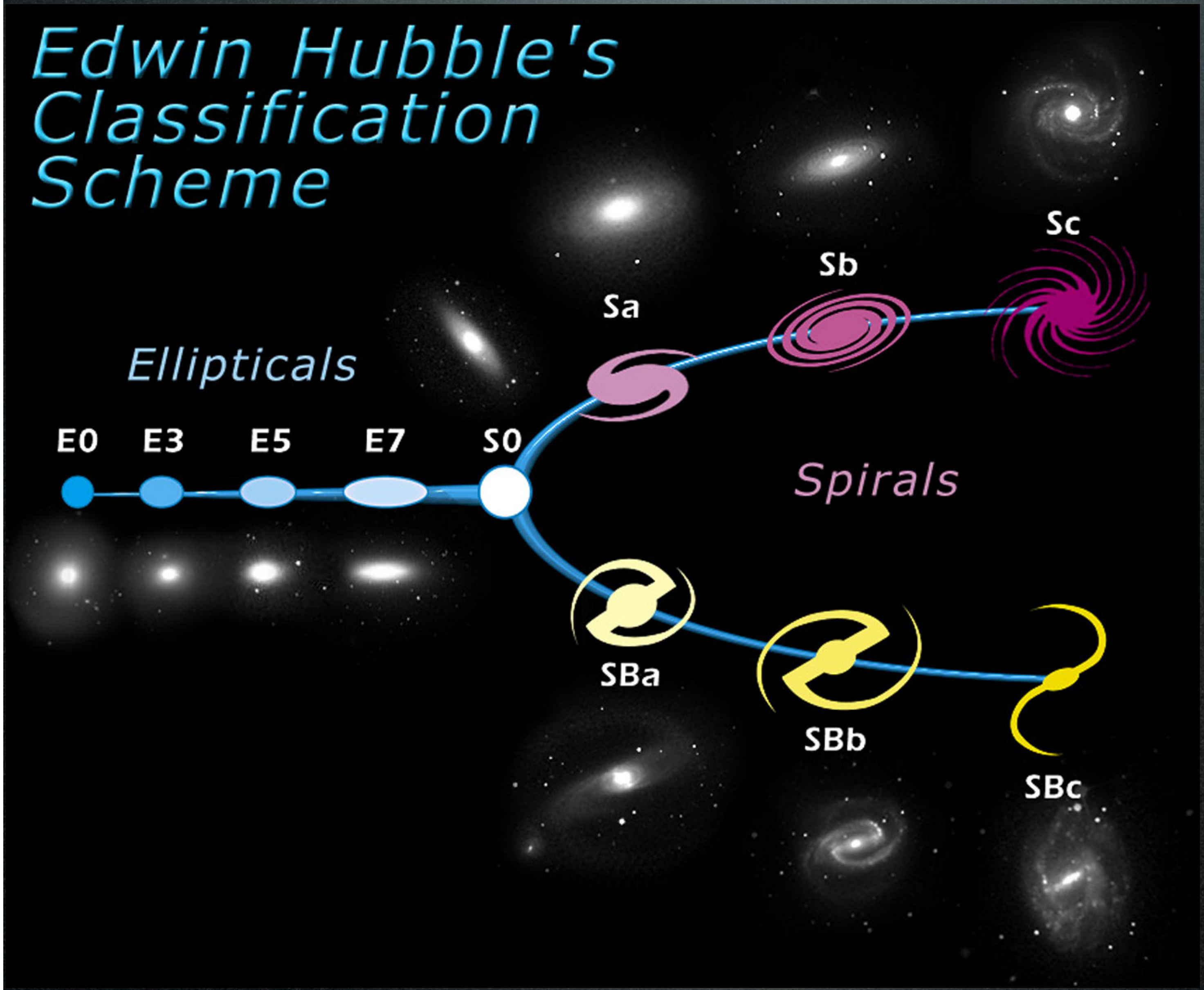
Note what is being plotted on x-axis!

The Pitfalls of Galaxy Photometry Nomenclature – An Example: The effective radius

Papers in the literature have used the *same* symbol, r_e, for very different quantities. It has been used for:

- The half-light radius measured from circular apertures
- The semi-major axis radius of elliptical isophotes
- A circularized radius corresponding to the area of an ellipse $A = \pi ab = \pi r_e^2$
- The effective radius from a *circular* deVaucouleurs model fitted to *every* galaxy (late and early types!) in the sample

Visual Classification of Galaxies



Ellipticals are also called "Early Type", and spirals are also called "Late Type"

Edwin Hubble believed his classification scheme to be time series.

Rationale for Quantitative Morphology

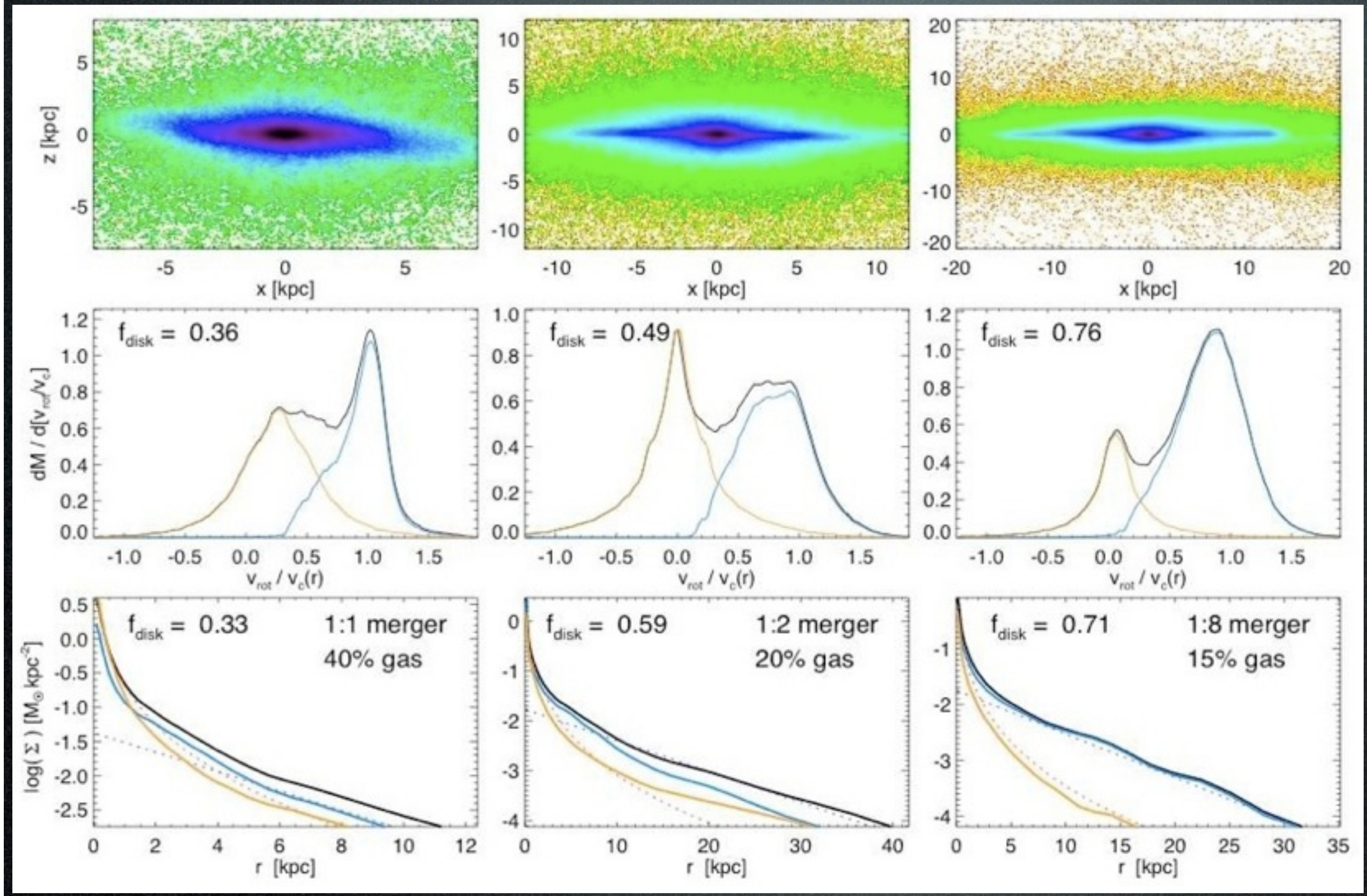
Pros:

- Can be automated for large surveys
- Reproducible in its successes *and* its failures
- Can be linked to numerical simulations

Caveats:

- Analysis tools should not be treated as “black boxes”
- Systematics dominate (sky, sky and sky)
- Catalogs should not be “over-interpreted”

Quantitative Morphology can be linked to models



Significant disk component in mergers (f_{disk} = 0.76)

Hopkins et al. 2008

Bulge + Disk Decompositions

The full, 2D bulge+disk model is:

$$\Sigma_{obs}(x,y) = (\Sigma_{bulge}(x,y) + \Sigma_{disk}(x,y)) * PSF(x,y)$$

where *PSF(x,y)* is the Point-Spread-Function

The list of fitting parameters includes:

- Total flux
- Bulge fraction *B/T*
- Bulge effective radius r_e, ellipticity *e* and position angle ϕ_b
- Disk scale length r_d, inclination *i* and position angle ϕ_d
- Bulge Sérsic index *n*

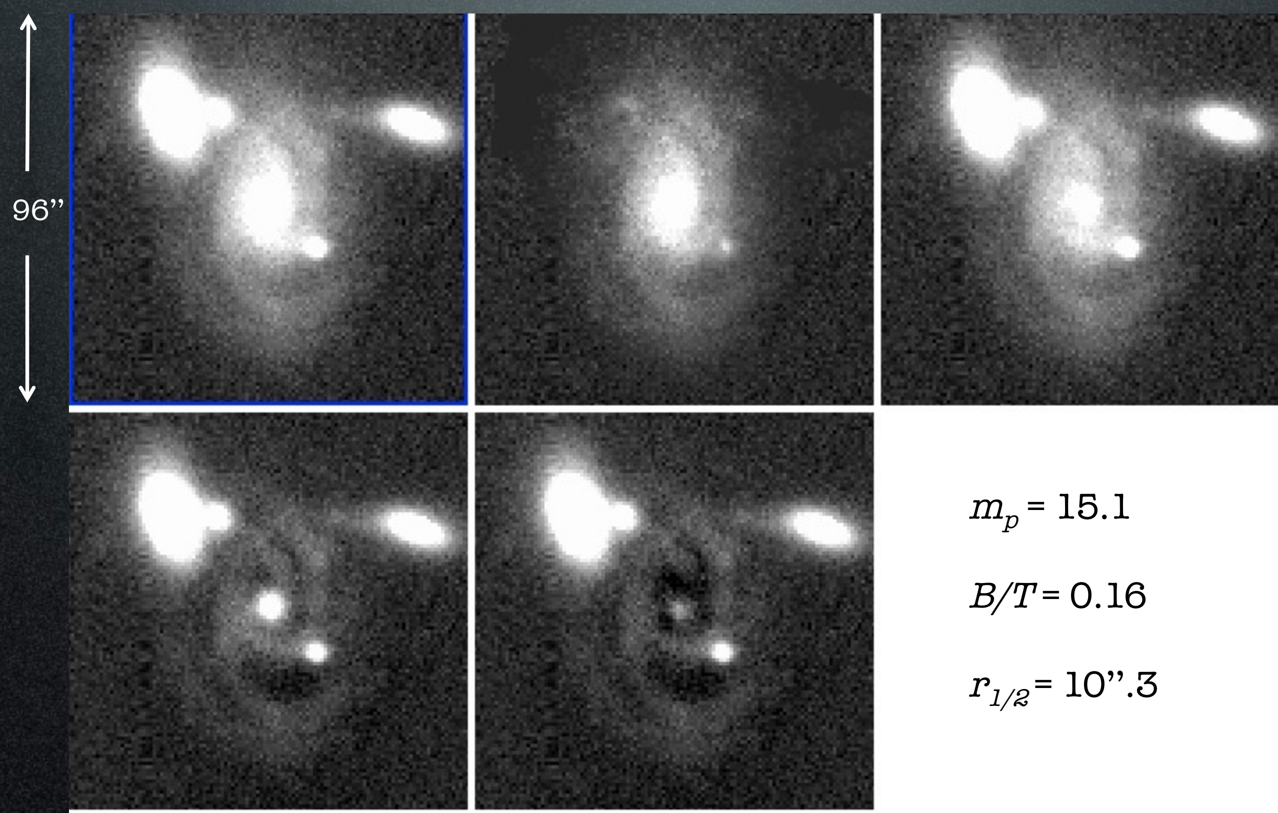
This is a very complex non-linear optimization problem which requires powerful algorithms – my choice is the Metropolis algorithm (1953)!

Bulge+Disk Decompositions – A SDSS Example

Original r-band image

SDSS deblended image

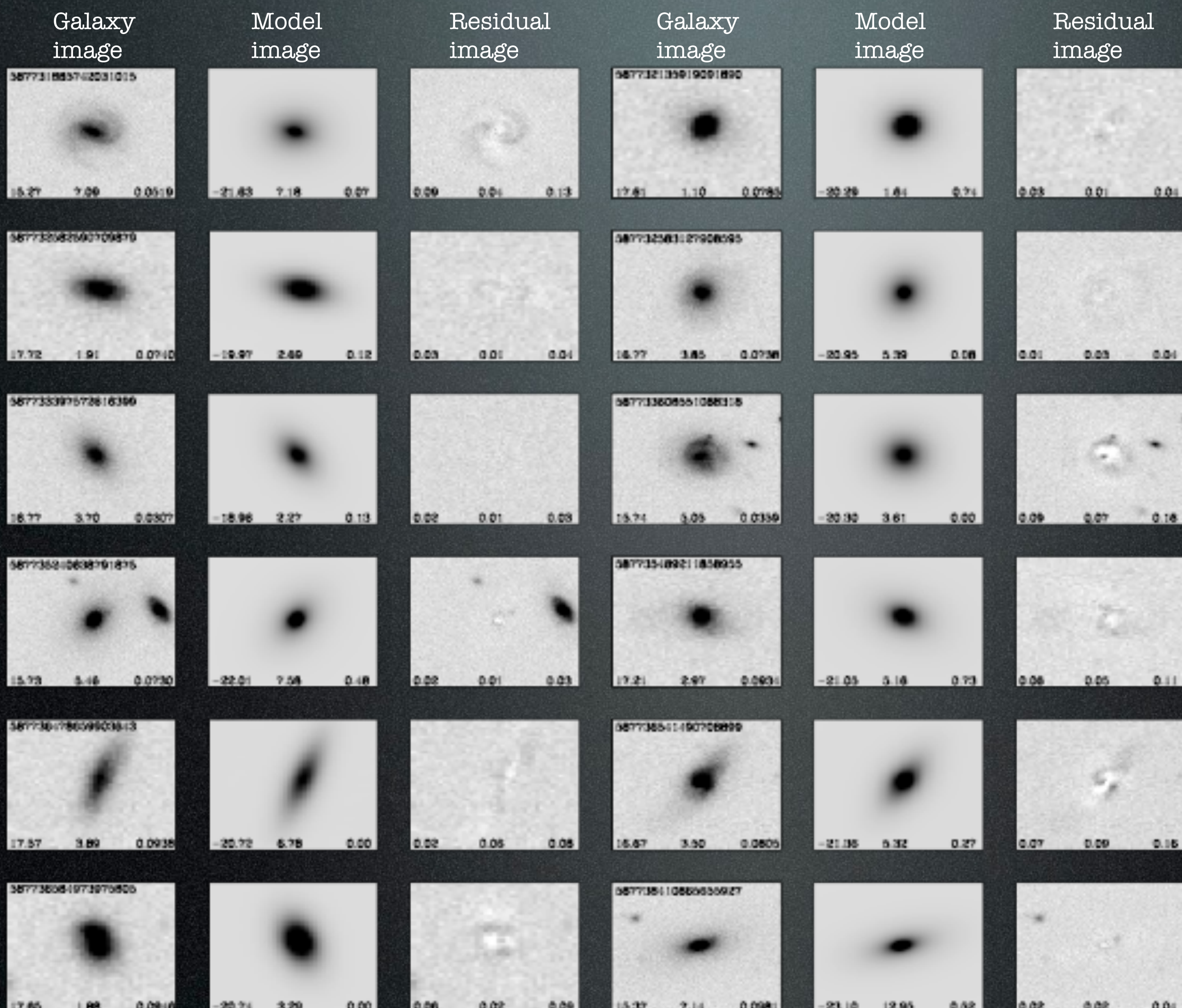
Bulge subtracted image



Disk subtracted image

Bulge+Disk subtracted image

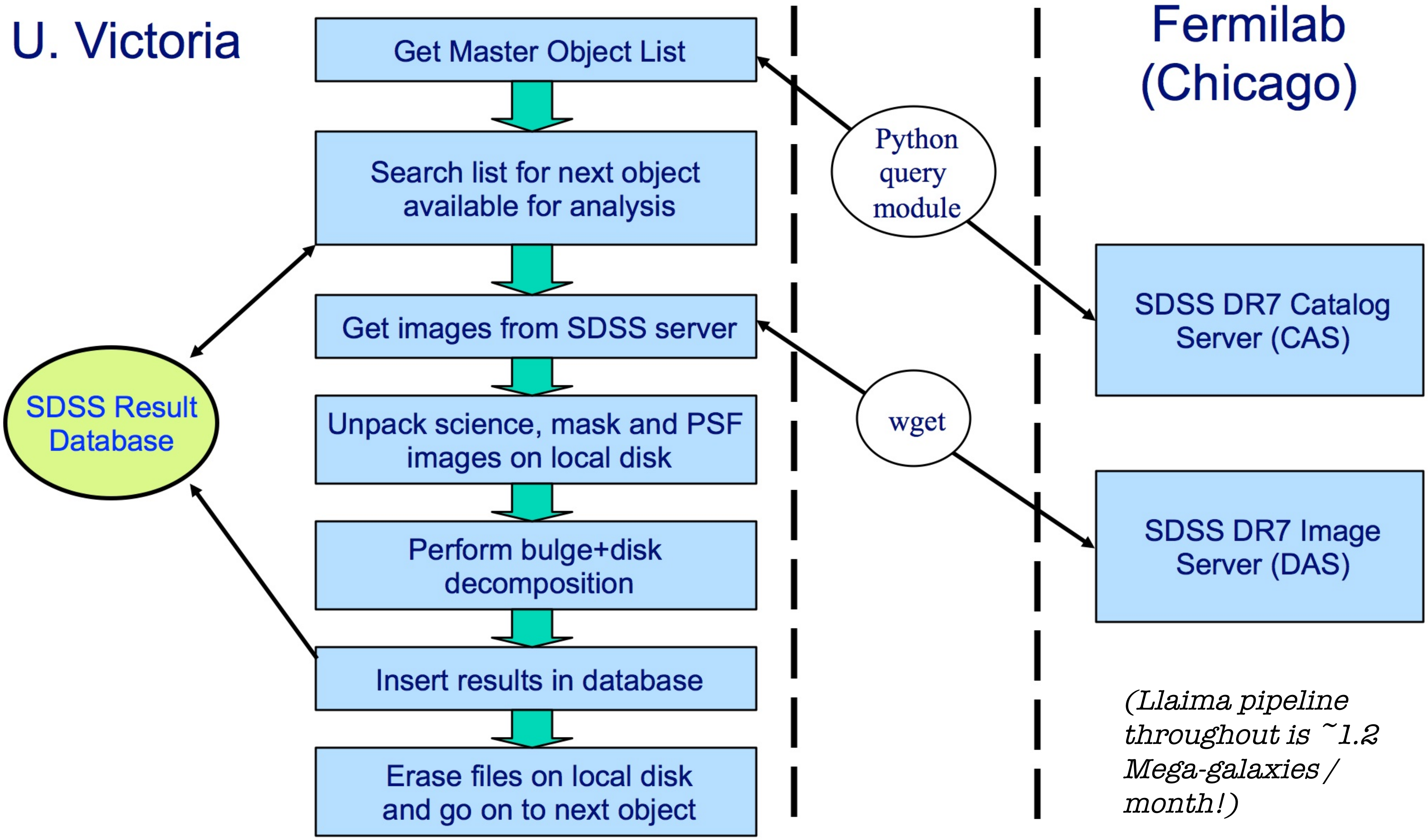
Bulge+Disk Decompositions –More Examples



Performed simultaneously in g- and r-band filters

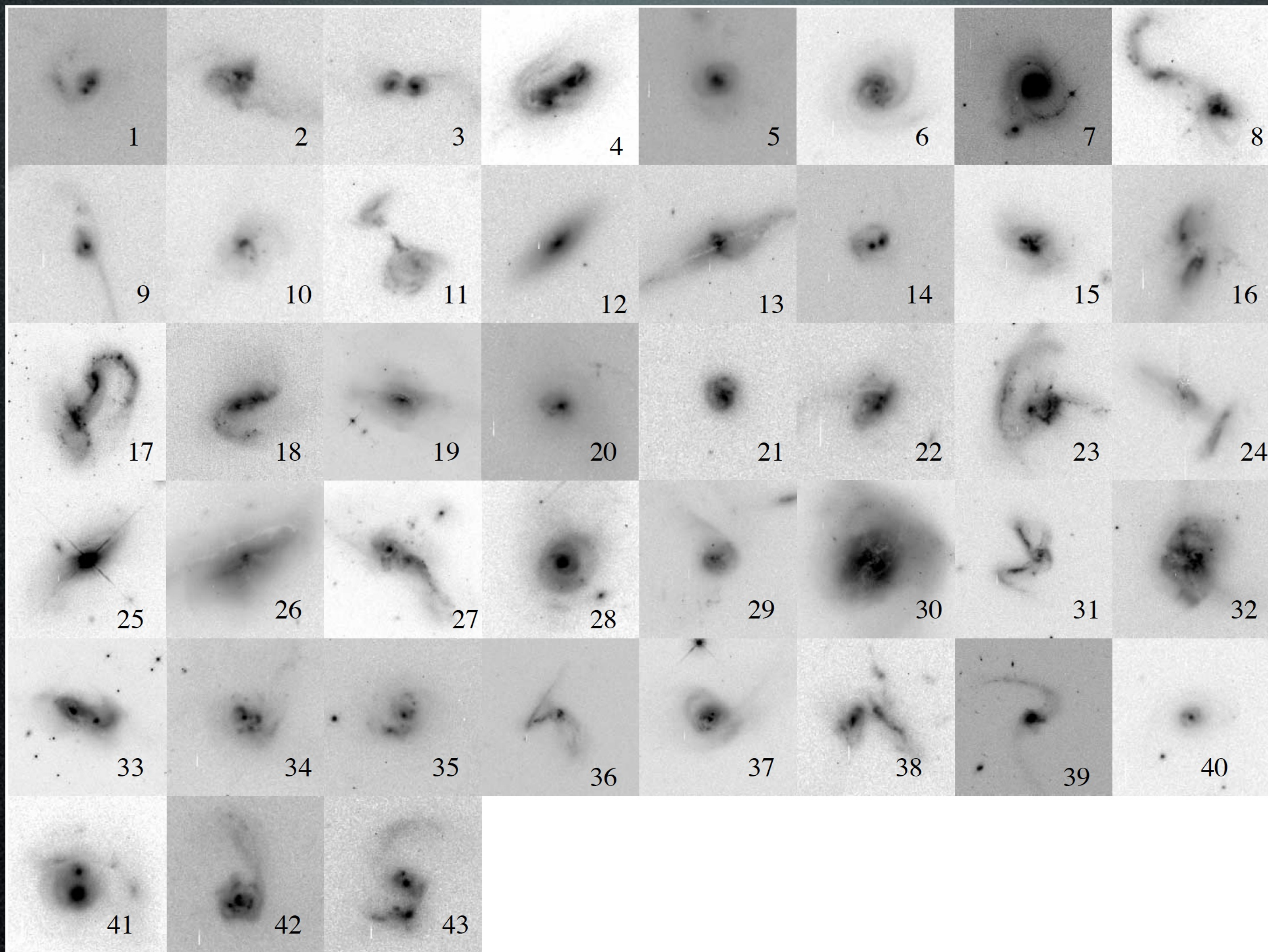
Simard et al. 2011, ApJS, 196, 11

Remote Data Mining in the SDSS



(Llaima pipeline throughout is ~1.2 Mega-galaxies / month!)

Galaxy Asymmetries



Conselice 2003, ApJS, 147, 1

Galaxy Asymmetries – CAS

(Conselice 2003, ApJS, 147, 1)

The CAS system is a *non-parametric* (i.e., not based on a fitting model) approach to characterizing the photometric properties of a galaxy. It stands for Concentration, Asymmetry and Smoothness.

Concentration:

$$C = 5\log(r_{80}/r_{20})$$

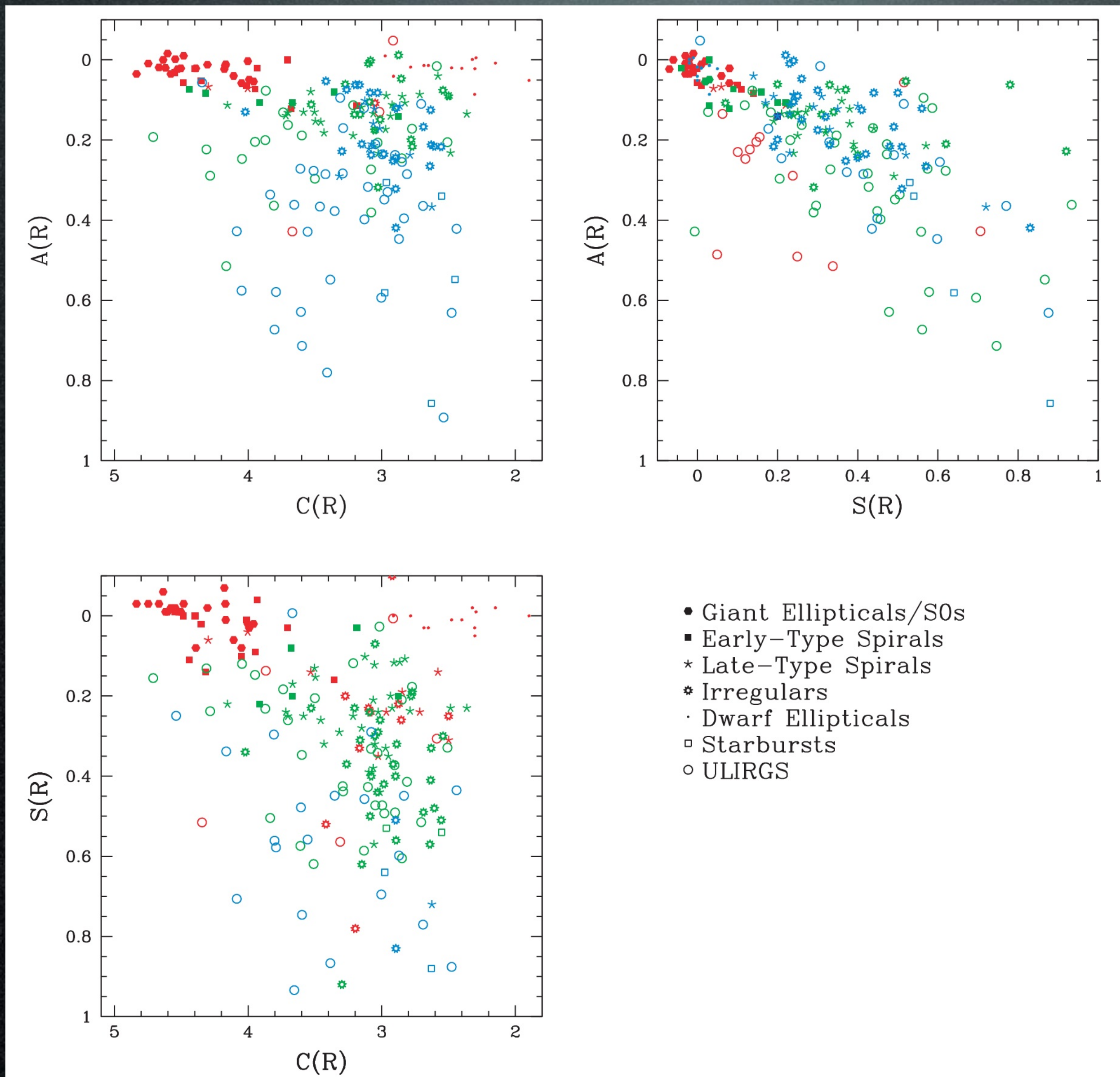
Asymmetry:

$$A = \min\left(\frac{\Sigma|I_o - I_\phi|}{\Sigma|I_o|}\right) - \min\left(\frac{\Sigma|B_o - B_\phi|}{\Sigma|I_o|}\right)$$

Smoothness (i.e., high-spatial frequency clumpiness):

$$S = 10 \times \Sigma_{x,y=1,1}^{N,N} \frac{(I_{x,y} - I_{x,y}^{\sigma}) - B_{x,y}}{I_{x,y}}$$

Galaxy Asymmetries - CAS



(Conselice 2003, ApJS, 147, 1)

Galaxy Asymmetries – Gini and M20

(Lotz et al. 2004, AJ, 128, 163)

The Gini coefficient *G* is actually from the world of economics – it was first used to simply characterize the fairness of the income distribution of a population.

In a completely egalitarian society, G is zero, and if one individual has all the wealth, *G* is unity.

In galaxy images, flux substitutes for money. *G* is then defined as:

$$G = \frac{1}{2\overline{X}n(n-1)} \sum_{i=1}^{n} \sum_{j=1}^{n} |X_i - X_j|$$

where *n* is the number of pixels in a galaxy image, $\bar{X}$ is the mean over all pixel flux values X_i

This concept is also another formulation of “image entropy” which is well-known in information theory.

Galaxy Asymmetries – Gini and M_{20}

(Lotz et al. 2004, AJ, 128, 163)

The M_{20} coefficient is defined as the normalized second-order moment of the bright 20% of the galaxy's flux:

$$M_{20} \equiv \log_{10}\left(\frac{\sum_i M_i}{M_{tot}}\right) \text{, while } \sum_i f_i < 0.2 f_{tot}$$

where f_{tot} is the total flux of the galaxy pixels identified by the segmentation map, and f_i are the the fluxes for each pixel i, ordered such that f_1 is the brightest pixel, f_2 is the second brightest and so on. M_{tot} is given by:

$$M_{tot} = \sum_i^n M_i = \sum_i^n f_i[(x_i - x_c)^2 + (y_i - y_c)^2]$$

where (x_c, y_c) are the coordinates for the center of the galaxy that minimize M_{tot}

Galaxy Asymmetries - Gini and M_{20}

(Lotz et al. 2004, AJ, 128, 163)

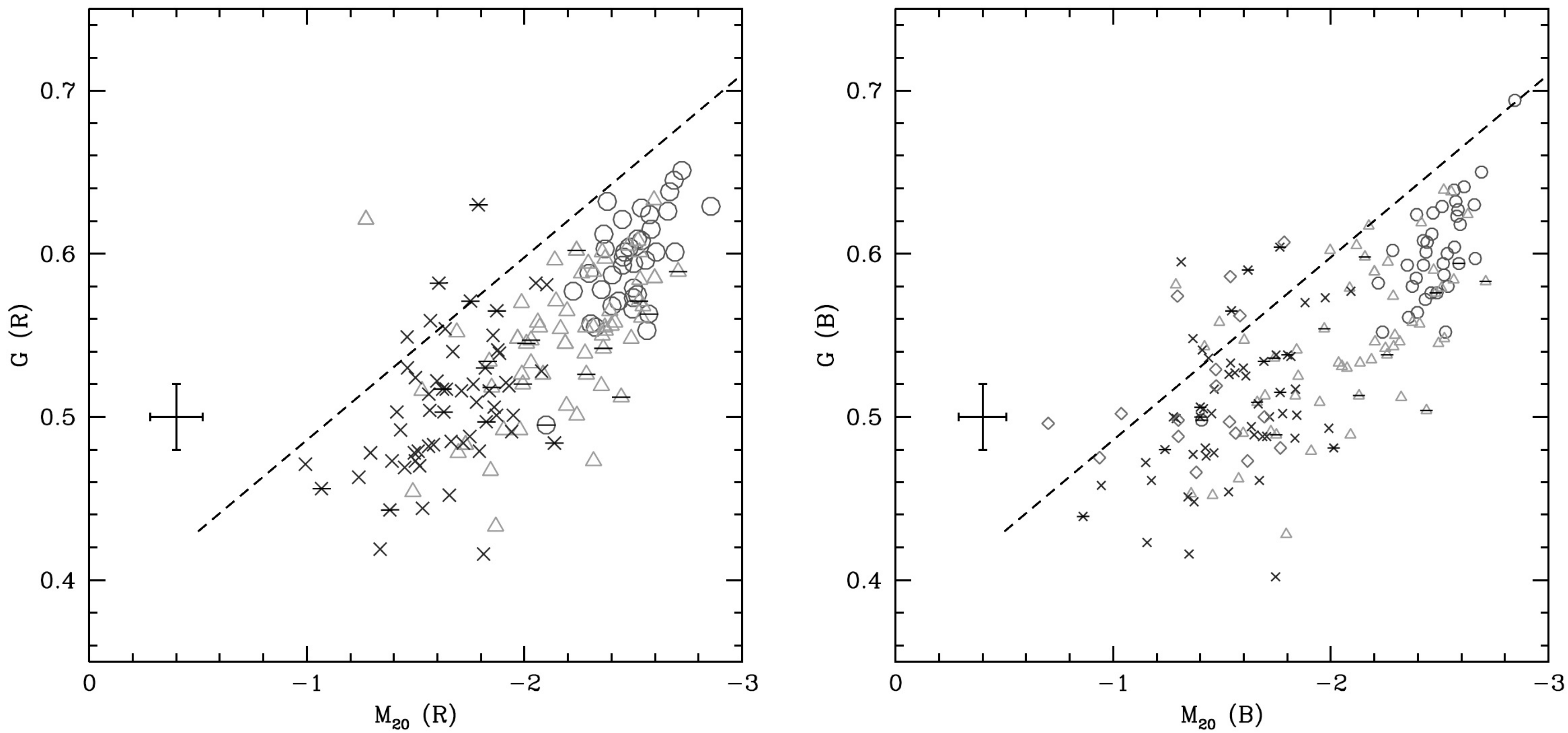


FIG. 9.—M_{20} vs. G for rest-frame ∼6500 Å (*left*) and 4400 Å (*right*) observations of local galaxies (*circles*: E/S0; *triangles*: Sa−Sbc; *crosses*: Sc−Sd; *diamonds*: dI; *bars*: edge-on spirals). The error bars are mean difference in G and M_{20} between SDSS r-band and Frei R/r observations of the same objects. Almost all the ‘‘normal’’ galaxies lie below the dashed line in the R-band plot. The outlying Sb galaxy NGC 5850 has a strong star-forming ring and is in a close pair with NGC 5846. Three of the outlying dI’s in the B-band plot are starbursting.

Paper Discussion