Lecture II: fundamental photometric parameters and quantitative morphology

Astrophysics of Galaxies 2019-2020

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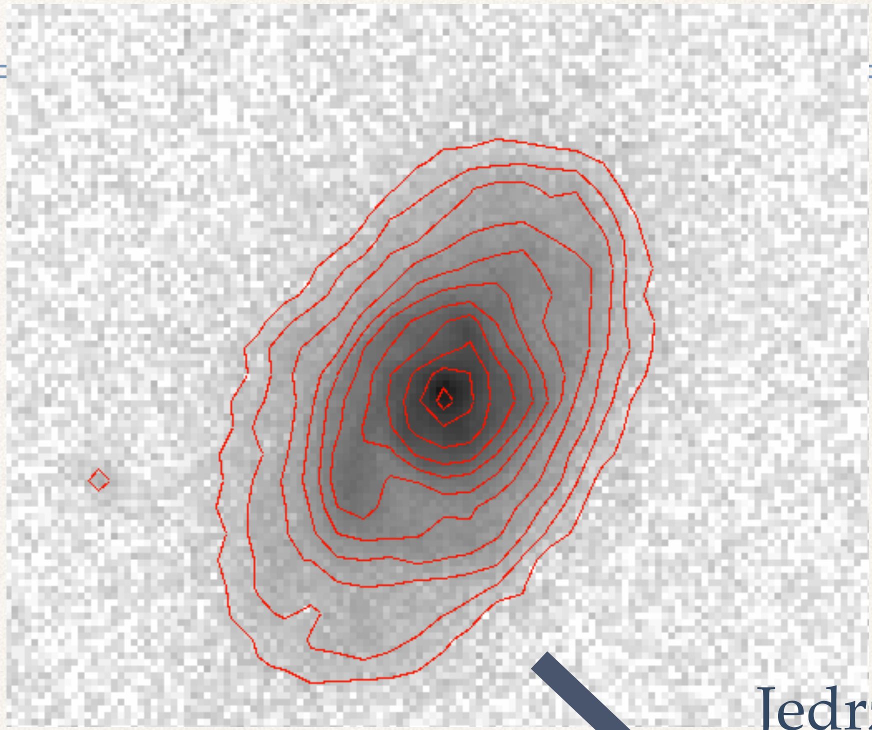
Summary

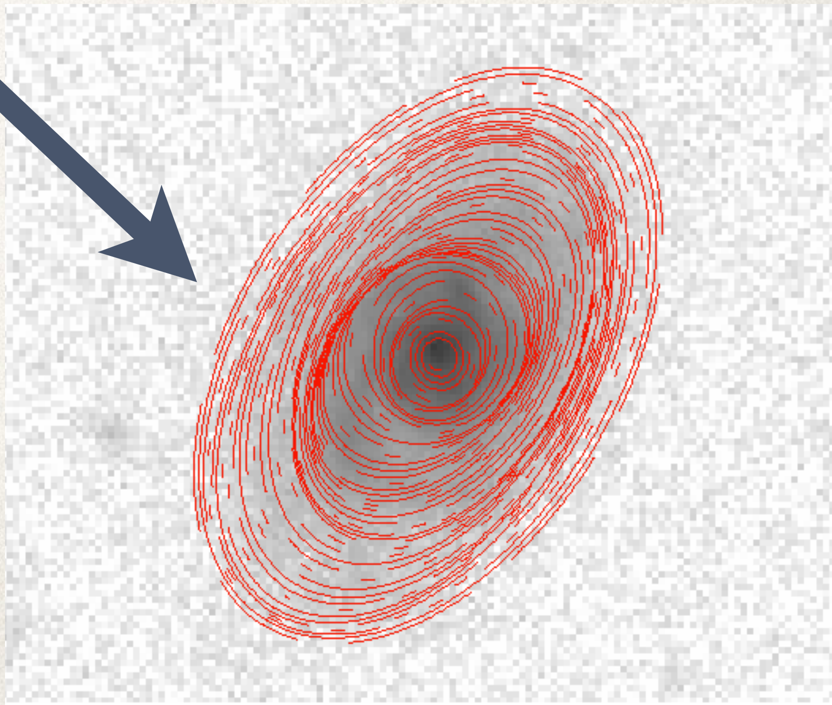
- Different structural components are charcterized by different SB profiles
- Use SB profile measurements to decompose galaxy structure
- Morphology *is* galaxy structure after all: use structure decomposition to infer morphology
- Why is morphology (still) so relevant? correlations with many physical properties
- Modern efforts towards an objective/automated morphological classification

Surface brightness profiles



“anonymous” SDSS galaxy

IRAF-STSAS-*ellipse*
Jedrzejewski (1987), Busko (1996)



- Isophotes
- Isophote ellipse fitting
- Azimuthally averaged profiles
- Profile fitting...

Various analytical profiles

- Exponential

$$I(R) = I(0)\, exp\,(-R/R_d)$$
$$\mu(R) = \mu(0) + 1.086\,(R/R_d)$$
$$R_e = 1.678 R_d$$

Classical → Disks

- de Vaucoluleuers (or r$^{1/4}$)

$$\mu(R) = \mu(0) + 8.325\,(R/R_e)^{1/4}$$
$$= \mu(R_e) + 8.325\left[\,(R/R_e)^{1/4} - 1\,\right]$$

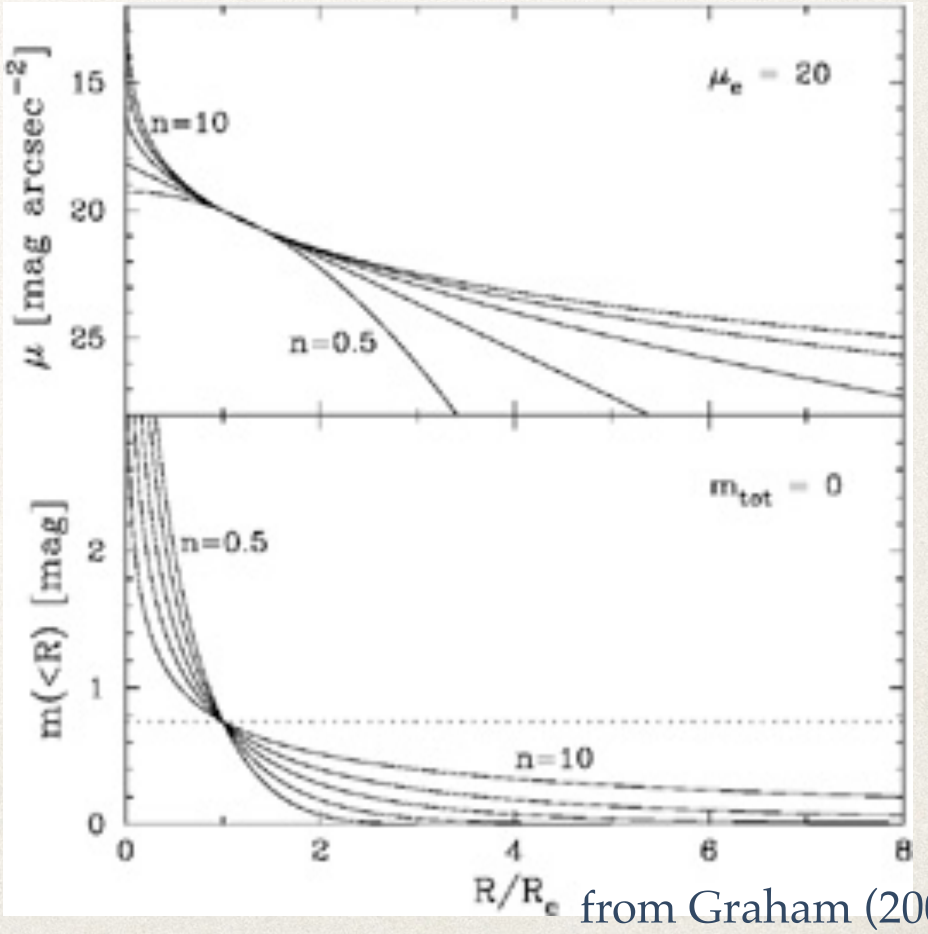
Classical → Ellipticals Bulges

- generalized Sersic

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

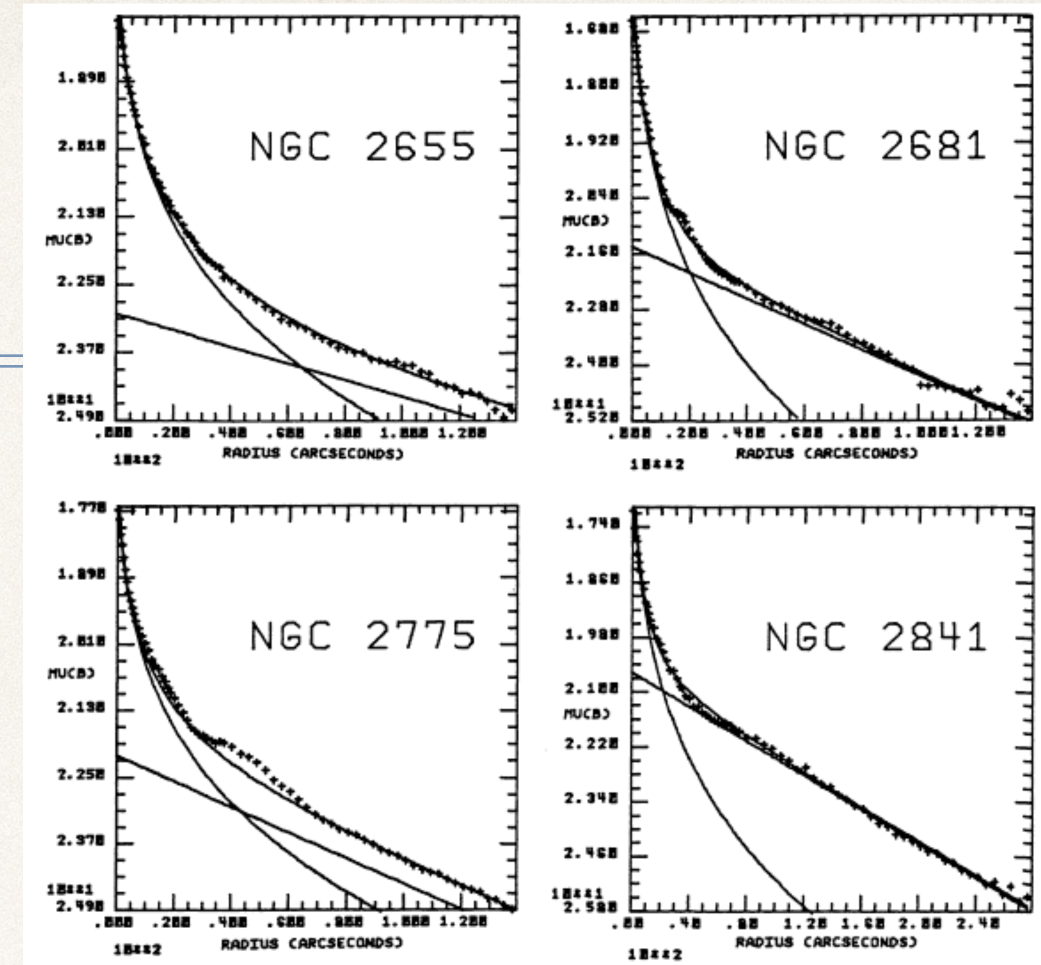
R_e effective radius, i.e. radius containing half of the total light

$\mu(R_e) \neq \langle\mu\rangle_e \equiv \mu_e$



from Graham (2005)

"Hybrid" profiles



- B+D profiles: exp+deV or exp+Sersic
- Truncated

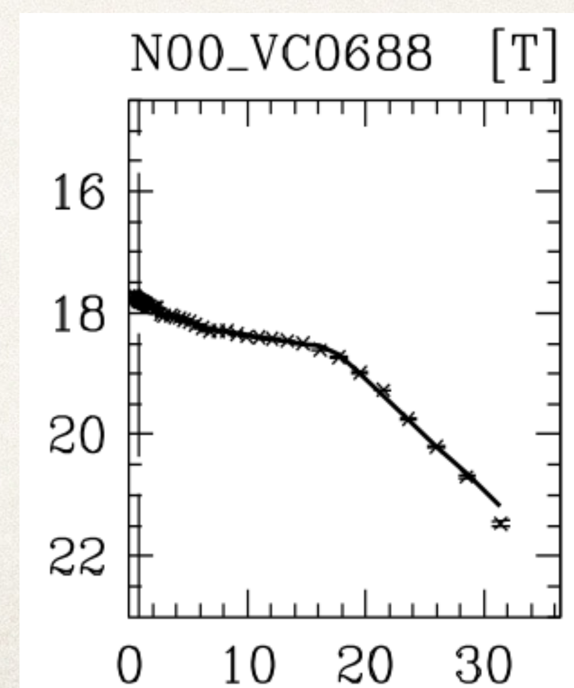
$$I(r) = c_1 \cdot \exp\left[-\frac{1}{c_2}(r - r_{\rm t} - |r - r_{\rm t}|)\right]$$

$$\times \exp\left[-\frac{1}{c_3}(r - r_{\rm t} + |r - r_{\rm t}|\right] \text{ (Truncated exponential)}$$

$$I(r) = c_1 \cdot \exp\left[-\frac{1}{c_2}(r^{1/4} - r_{\rm t}^{1/4} - |r^{1/4} - r_{\rm t}^{1/4}|)\right]$$

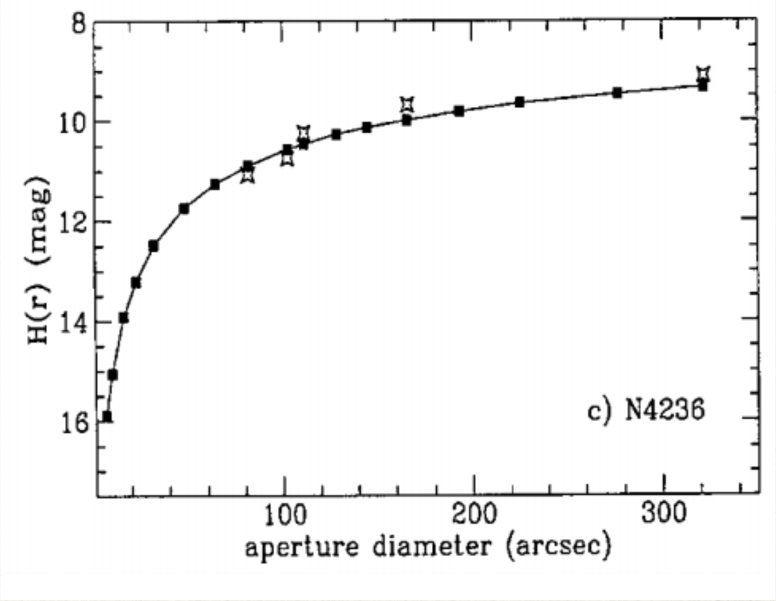
$$\times \exp\left[-\frac{1}{c_3}(r - r_{\rm t} + |r - r_{\rm t}|\right] \text{ (Tr. DeVaucouleurs).}$$

Gavazzi, SZ et al. (2001)



Profile parameters and the size(s) of galaxies

- Galaxies have no boundaries: need to define a "size".
  Different options
- Isophotal diameter (eg. 25 mag/arcsec^2 in B)
- Some scale-length from the analytical fit
- Growth curve: radius enclosing a given fraction of the "total" luminosity
- Kron (1980)
- Petrosian radius (SDSS standard!)



from Pierini et al. (1997)

Kron radius and flux

- Kron (1980)
- First moment of light distribution $$R_1(R) = \frac{2\pi \int_0^R I(x) x^2 \mathrm{d}x}{2\pi \int_0^R I(x) x \mathrm{d}x}.$$
- R_1 is a function of R. However for R "large enough", R_1 converges quickly and R_1 well defined independent of the exact choice of R.
- The Kron radius is defined as N times R_1. Standard in source extraction softwares, like SExtractor (default R_{Kron}=2.5R_1).
- Used to define standard aperture to integrate flux.

Petrosian quantities

- Not straightforward definition by Petrosian (1976)
- Petrosian ratio R_P: $$\mathscr{R}_P(r) \equiv \frac{\int_{0.8r}^{1.25r} dr'\, 2\pi r' I(r') / [\pi(1.25^2 - 0.8^2)r^2]}{\int_0^r dr'\, 2\pi r' I(r') / (\pi r^2)} ,$$
- Petrosian radius r_P: where $R_P(r_P)$ equals a given number (0.2 for SDSS)
- Petrosian aperture= N_P*r_P (N_P=2 for SDSS)
- Petrosian flux
- $R_{50,petro} \neq r_P$

$$F_P \equiv \int_0^{N_P r_P} 2\pi r'\, dr'\, I(r') .$$

Petrosian quantities: why?

- Robust
- Independent of surface brightness dimming, as the petrosian ratio is a ratio of two surface brightnesses
- Cosmological surface brightness dimming (see supplemental material "notes_Weinberg_cosmology.pdf")
  - The apparent angular size $d\gamma$ of a galaxy of proper dimension dl scales with the angular diameter distance D_A:

$$D_A = \frac{dl}{d\gamma}$$

  - The bolometric flux scales with the luminosity distance squared D_L^2 as:

$$F = \frac{L}{4\pi D_L^2}$$

$$D_L = (1+z)^2 D_A$$

  - Hence the bolometric surface brightness observed now (z=0) scales as:

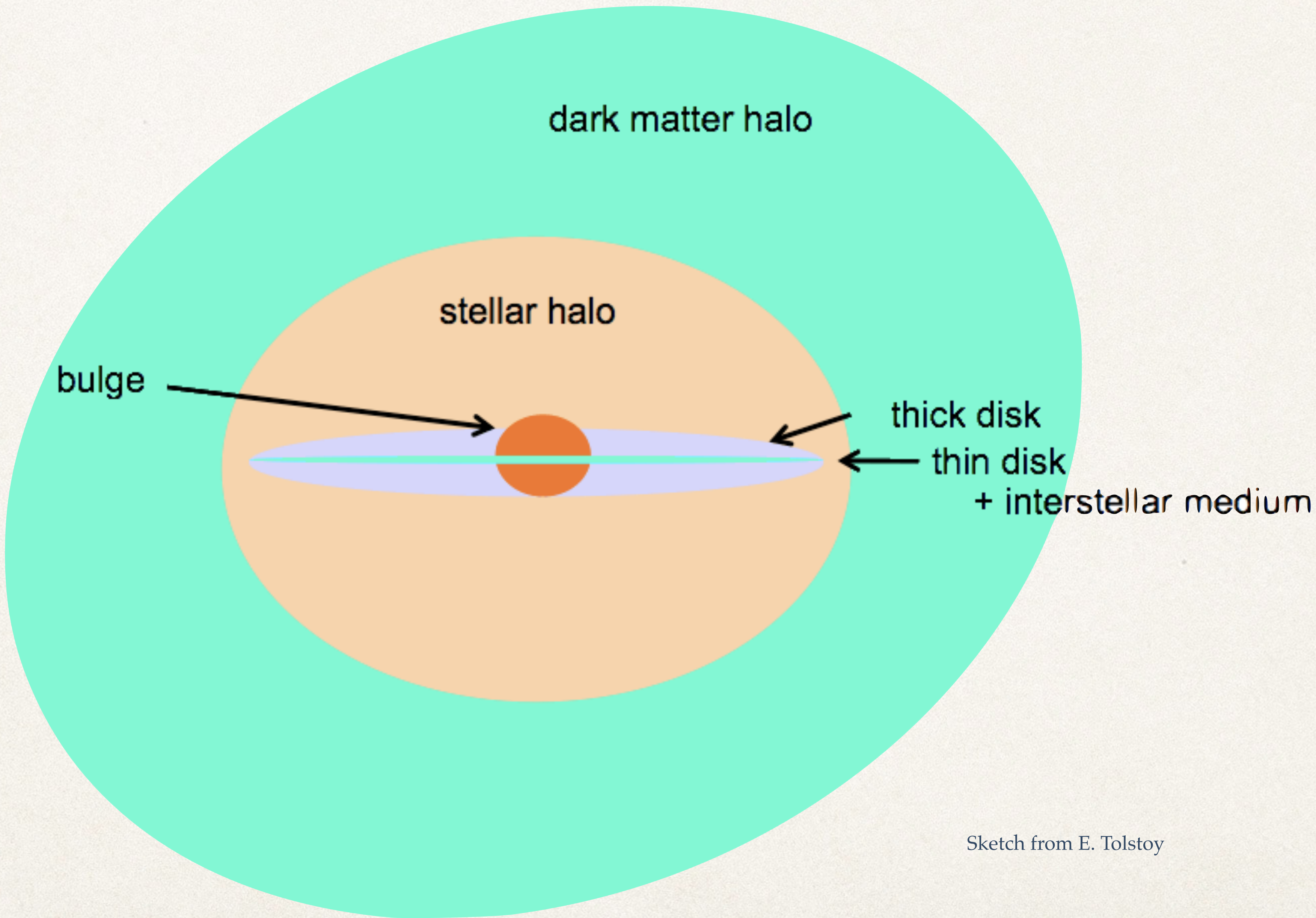
$$I_0 \equiv \frac{F}{\Omega} = \frac{L}{4\pi D_L^2}\frac{D_A^2}{A} = \frac{L}{4\pi A}\frac{1}{(1+z)^4} = \frac{I_e}{(1+z)^4}$$

$$\Omega = A/D_A^2$$

“Total” luminosities

- Rely on extrapolation to infinity
  - growth curve
  - analytical profile extrapolation
- For any definition of aperture, the amount of integrated flux with respect to the “total” depends on the shape of the profile, hence on the morphology.
  - This introduces a morphological bias when estimating galaxy luminosities from aperture photometry
  - On the other hand, extrapolation is risky!

Structural components of (spiral) galaxies



Sketch from E. Tolstoy

Structural components: I. the (exponential) disk

de Vaucouleurs (1959)

Freeman (1970)

Almost every disklike galaxy with measured $I(R)$ shows an *exponential* disk (see de Vaucouleurs 1959*a* and the references for Table 1). This disk is probably the most general property of these galaxies, and its origin is certainly a significant cosmogonic problem. It seems surprising that this problem has been almost ignored so far, whereas there is an extensive literature on the $I(R)$ distribution for elliptical galaxies. The problem of the exponential disk is the subject of this paper.

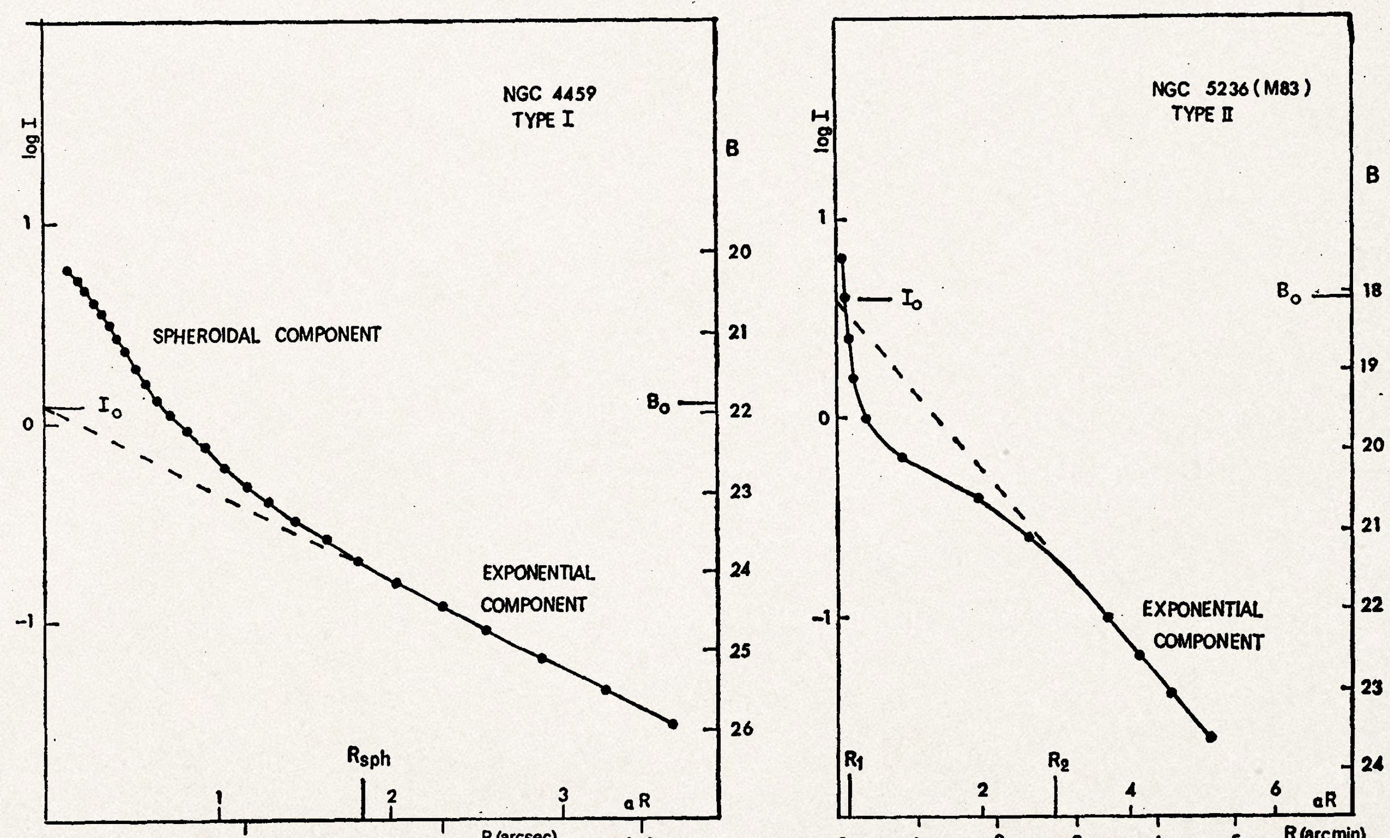
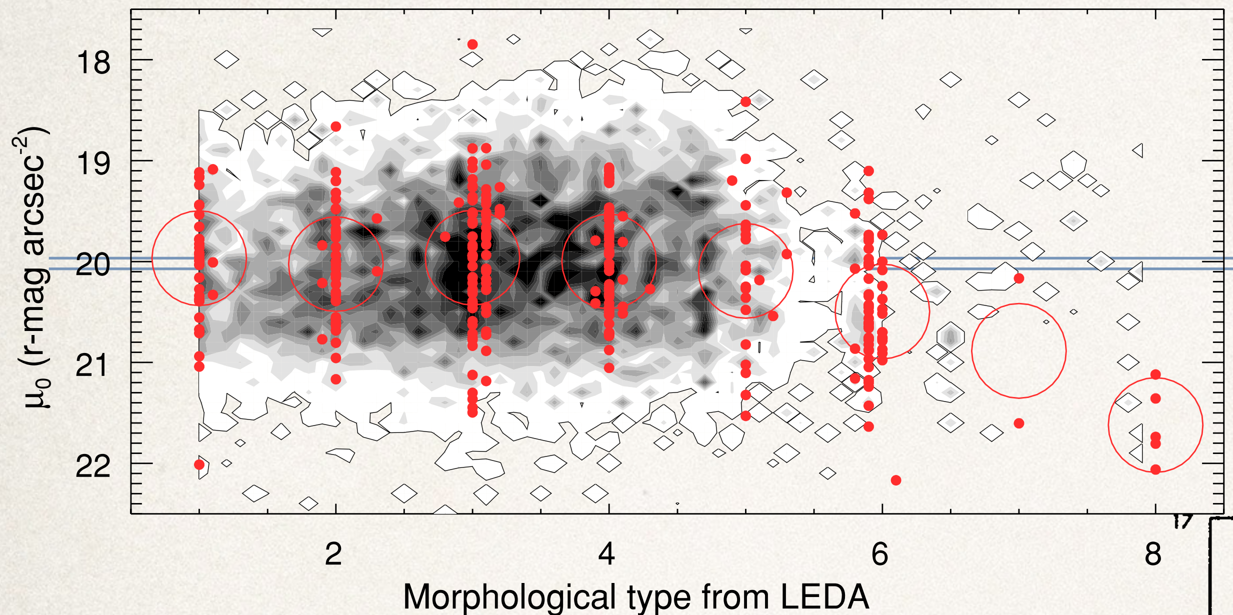


FIG. 1.—Radial luminosity distributions for NGC 4459 and M83. I is the surface brightness. Ordinates are log I and I in B-mag per square second of arc. R is distance from the nucleus along the major axis; the dimensionless radius αR is also shown. I_0, B_0 are the surface-brightness scale for the exponential disk, uncorrected for inclination and galactic absorption. R_1, R_2, and R_{sph} are defined in § III. *Filled circles*, observed points.

The Freeman Law

REVISITING THE SCALE LENGTH–μ_0 PLANE AND THE FREEMAN LAW



Fathi et al. (2010)

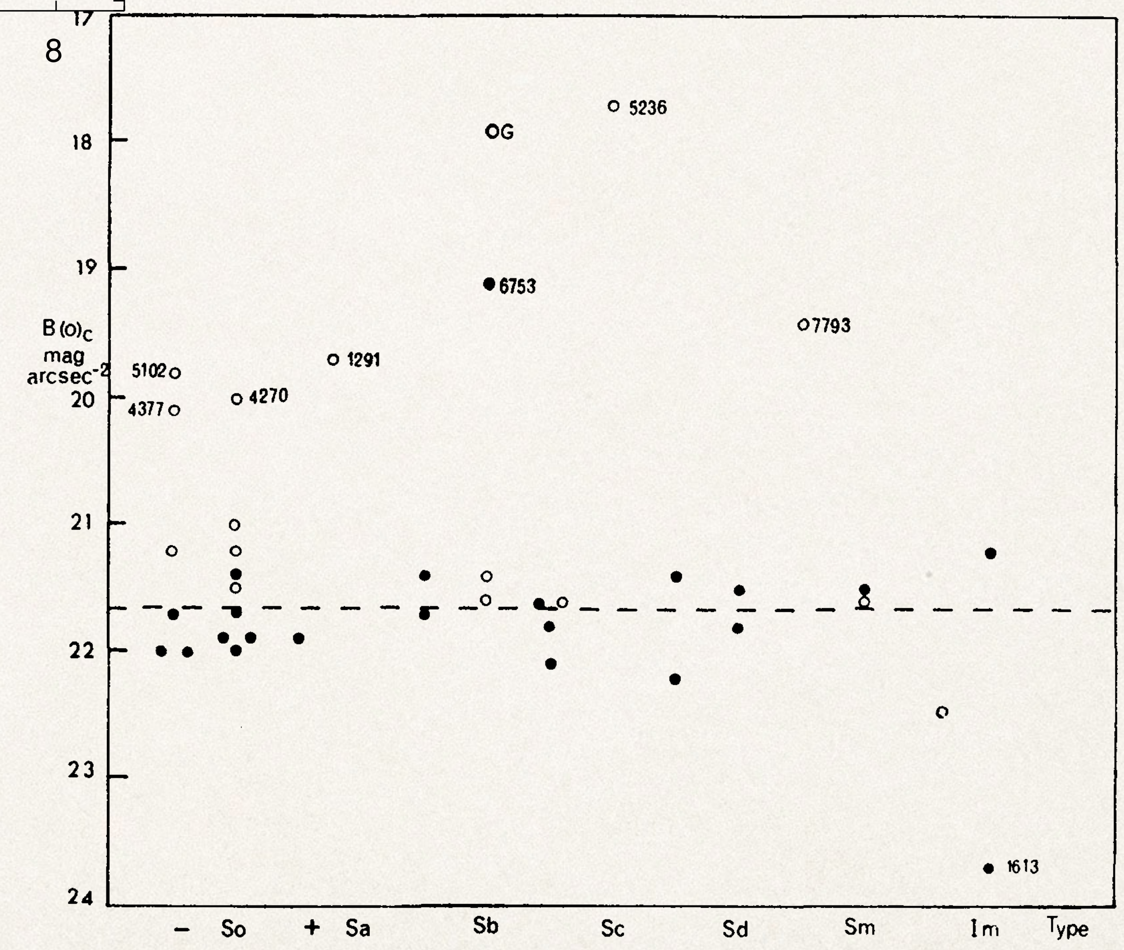


FIG. 5.—Intrinsic distance-independent blue-light luminosity scale $B(0)_c$ for the exponential disks of thirty-six galaxies against their morphological type. Broken line at $B(0)_c = 21.65$ is the mean for twenty-eight galaxies. NGC numbers are shown for the other eight. G denotes an estimate for the Galaxy. *Filled circles*, Type I luminosity profile; *open circles*, Type II luminosity profile (see Fig. 1).

Why are disks exponential?

ref. Dutton (2009)

- NOT obvious
- Key: Angular Momentum Distribution (AMD)
  - **specific AMD** of exp disk similar to solid sphere (Mestel 1963), but if you put material with such an AMD in a DM halo, central concentration goes up and truncation arises (Dalcanton+1997)
  - **viscosity** is often invoked as the key mechanism to redistribute AM (and mass), but enhances central concentration over initial conditions (LambdaCDM), so it's impossible to have bulgeless disks
- **possible solution**: SN-driven outflows and density dependent star formation, i.e. "dirty physics"

ERWIN, POHLEN, & BECKMAN (2008, AJ)

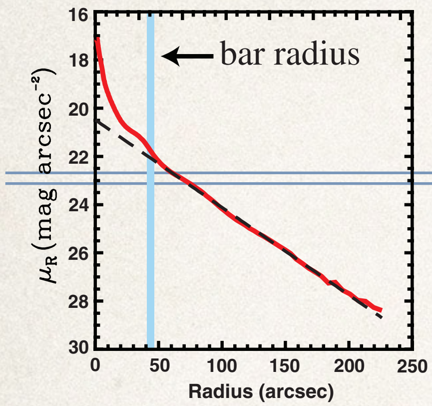
Are disks really exponential?

- Truncations and anti-truncations are often observed

- Dynamical interplay and overlapping of different components

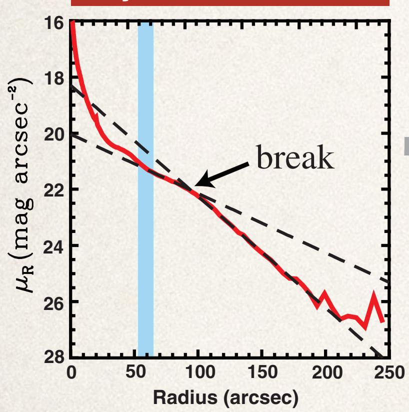
Type I

Single exponential



Type II

Profile "bends down" (becomes steeper) beyond break radius



Type II.i

Break at R ≤ bar radius

Type II.o

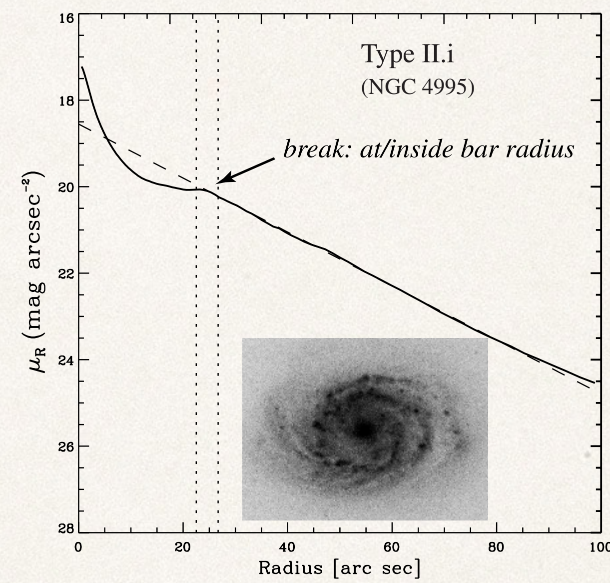
Break at R > bar radius

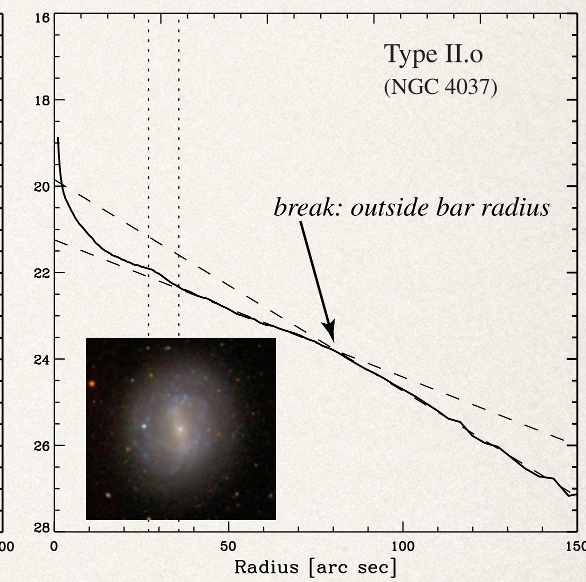
Type II.o-OLR

Break associated with outer ring (=*Outer Lindblad Resonance* of Bar)

Type II.o-CT

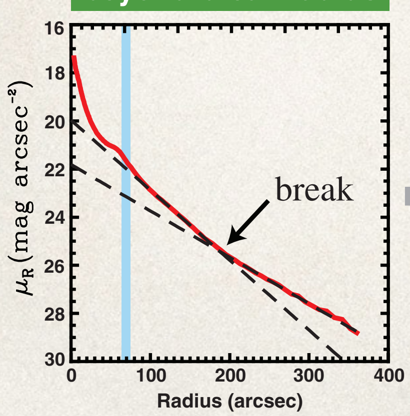
Break outside outer ring or probable OLR; possible "*classical truncation*" of SF





Type III

Profile "bends up" (becomes shallower) beyond break radius

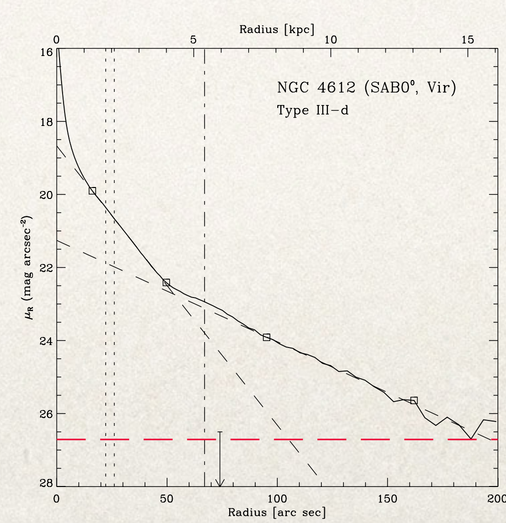


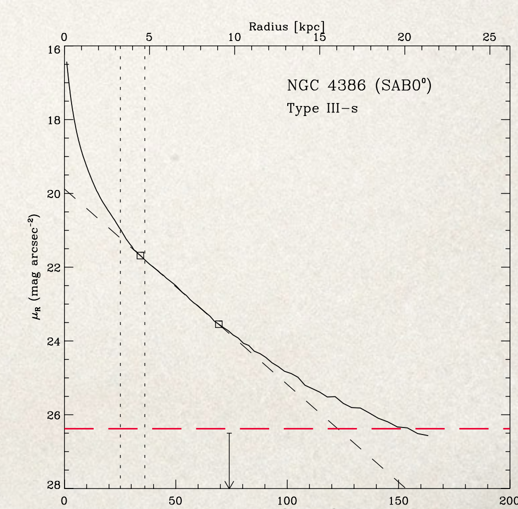
Type III-d

Outer profile is part of disk

Type III-s

Outer profile is part of spheroid

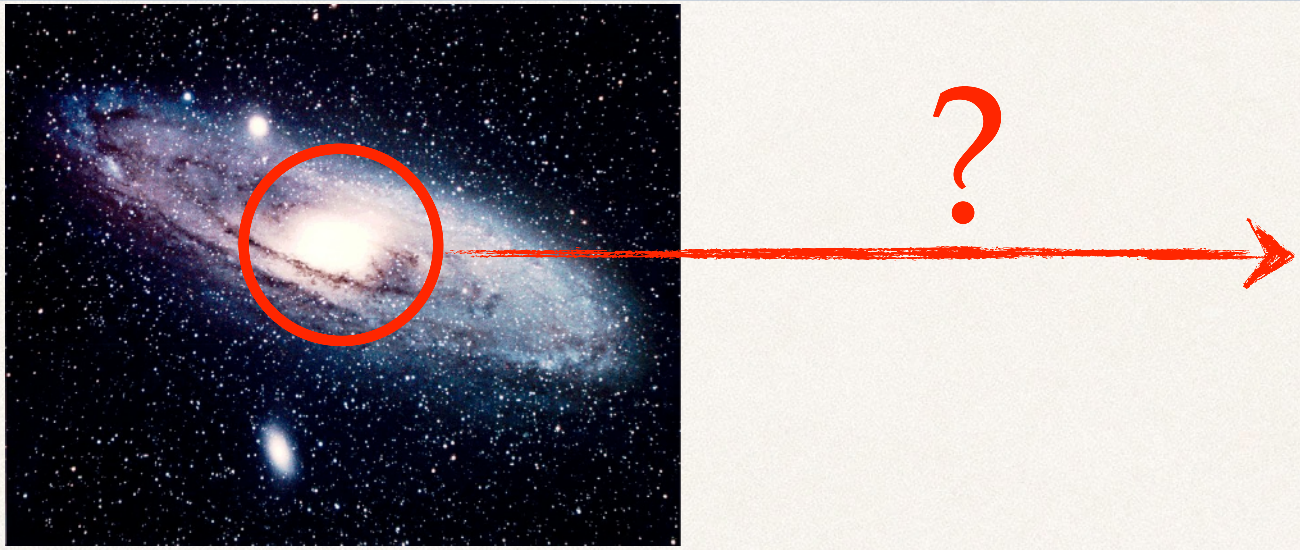




Canonical disk properties

- Rotationally supported dynamics
- Flatness, typically h~0.1 r_{exp} for the thin disk component
- Variety of stellar populations, most remarkably young and new-born stars are found here
- ISM (gas, neutral and ionized, and dust), 10 to 70-80% of baryonic mass
- Star forming regions

Structural components: II. the central spheroid or bulge



- Renzini (1999), canonical interpretation of Hubble-Sandage-de Vaucouleurs classifications: “It appears legitimate to look at bulges as ellipticals that happen to have a prominent disk around them [and] ellipticals as bulges that for some reason have missed the opportunity to acquire or maintain a prominent disk.”

- However, as observations improve, we discover more and more features that make it difficult to interpret every example of what we used to call a bulge as an elliptical living in the middle of a disk. This leads authors to agonize: “Are bulges of early-type and late-type spirals different? Are their formation scenarios different? Can we talk about bulges in the same way for different types of galaxies?” (Fathi & Peletier 2003).

Kormendy & Kennicutt (2004)

Classical Bulges/Ellipticals

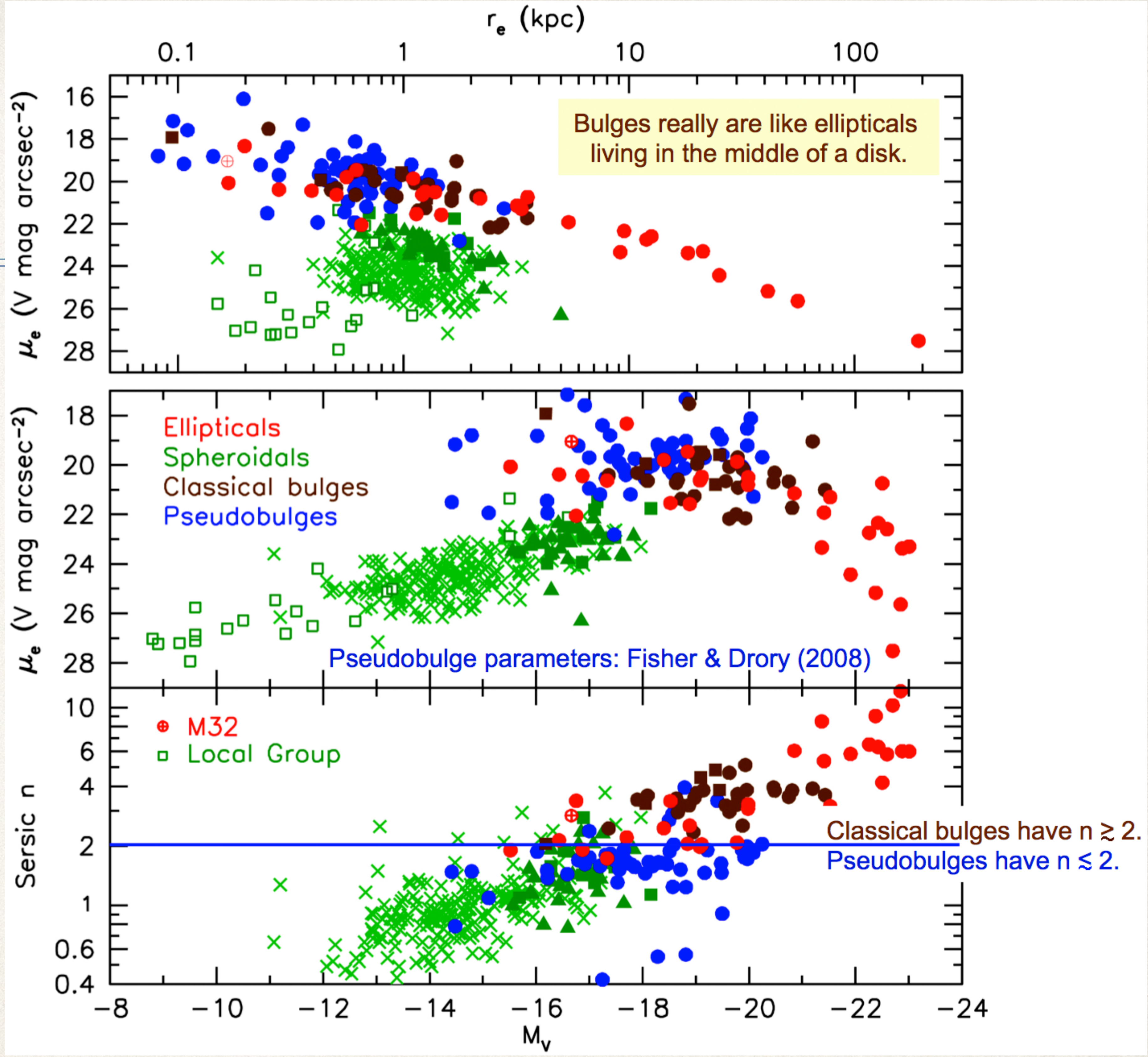
- Smooth stellar distribution, ~homogeneous old ages
- Little dust and neutral ISM
- Velocity dispersion ~dominates the dynamics (but ordered motions can be very important as well!)
- de Vaucouleurs or high-n Sersic profile

Pseudo Bulges

- Pseudobulges: dense central components in disk galaxies that look like classical, merger-built bulges but that were made slowly out of disk gas.
- Observations show that pseudo- bulges retain a memory of their disky origin. That is, they have one or more characteristics of disks:
  (a) flatter shapes than those of classical bulges
  (b) correspondingly large ratios of ordered to random velocities
  (c) small velocity dispersions σ with respect to the Faber-Jackson correlation between σ and bulge luminosity
  (d) spiral structure or nuclear bars in the "bulge" part of the light profile
  (e) nearly exponential brightness profiles
  (f) starbursts.
- All these structures occur preferentially in barred and oval galaxies, where secular evolution should be most rapid.

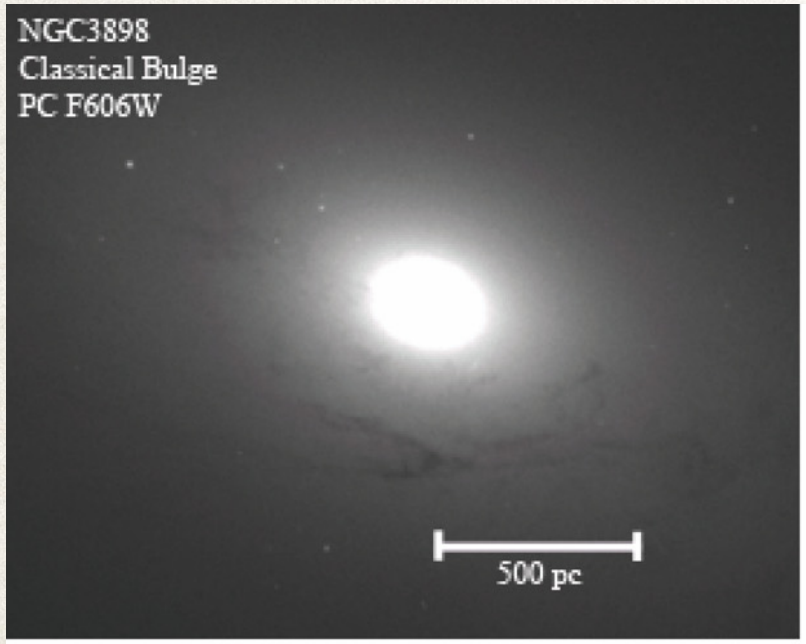
Kormendy & Kennicutt (2004)

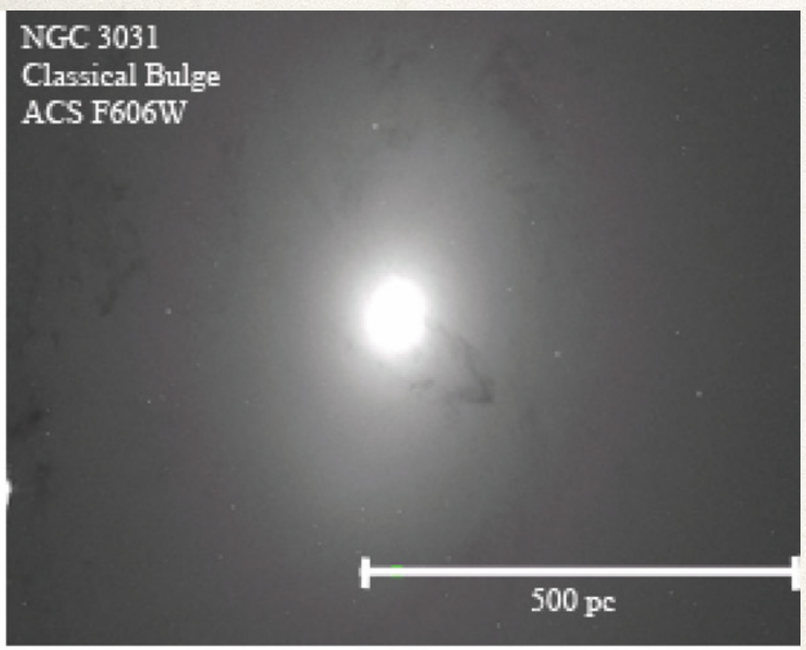
E/Classical bulges vs. PseudoBulges



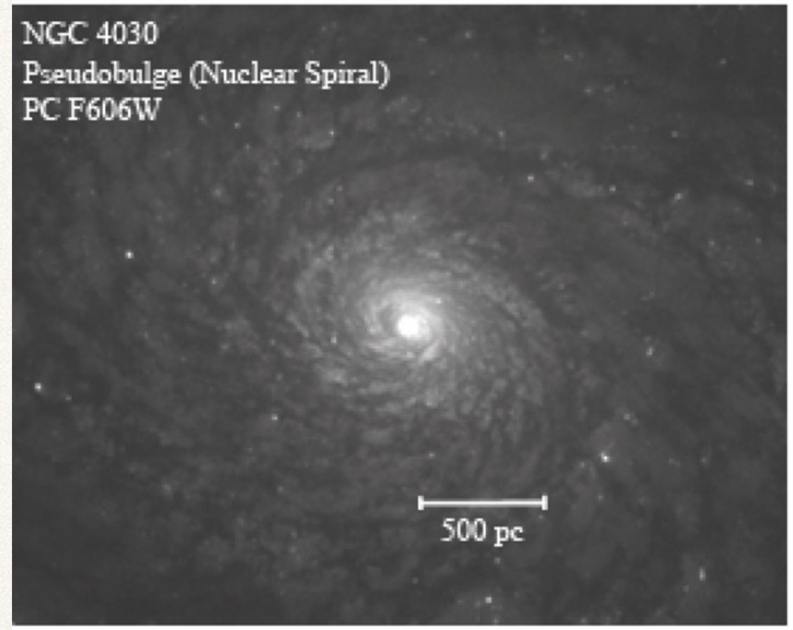
Kormendy & Fisher (2008)

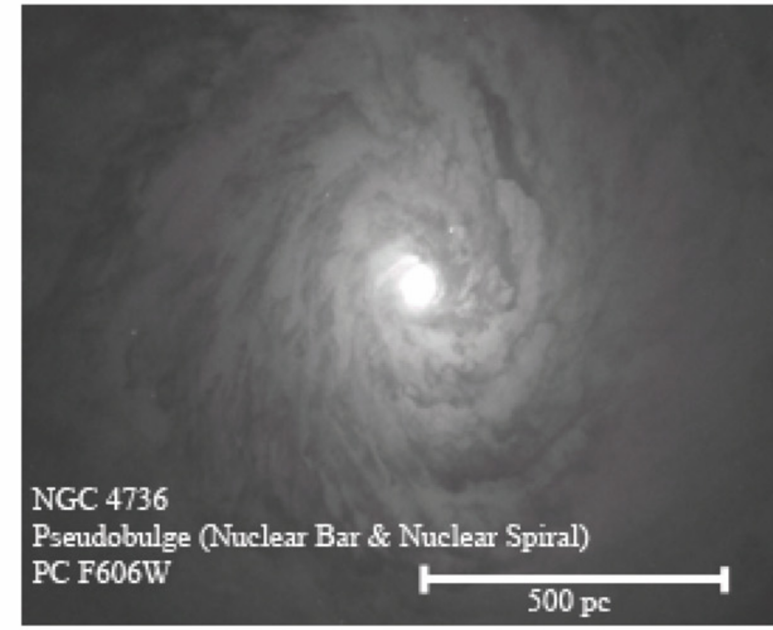
Classical bulges

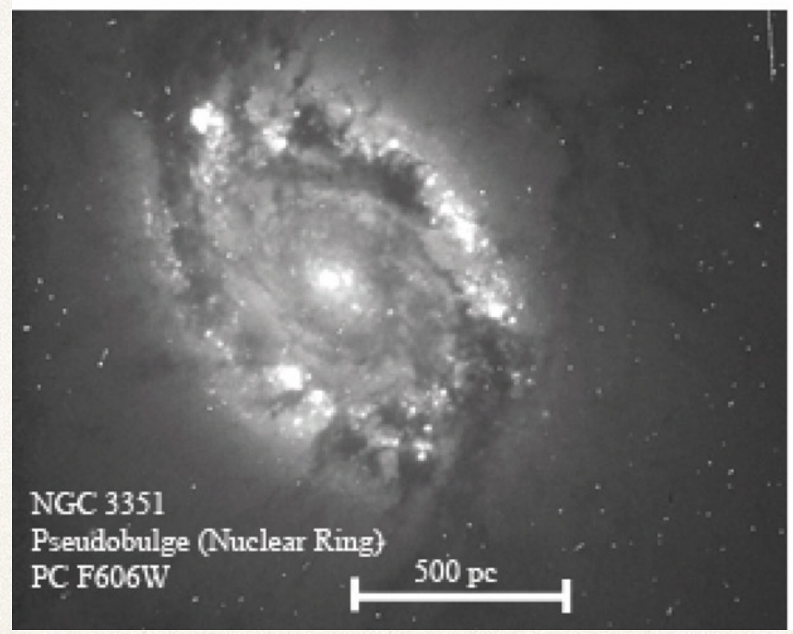


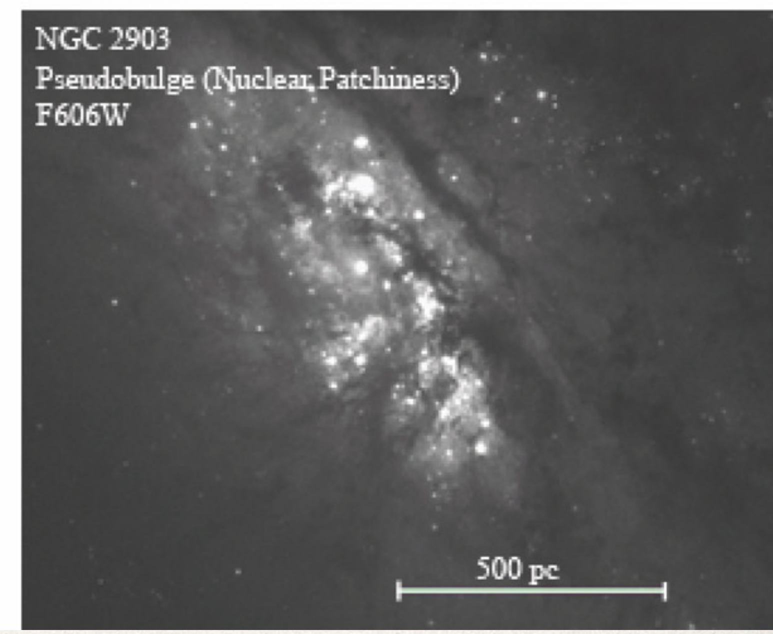


Pseudo-bulges



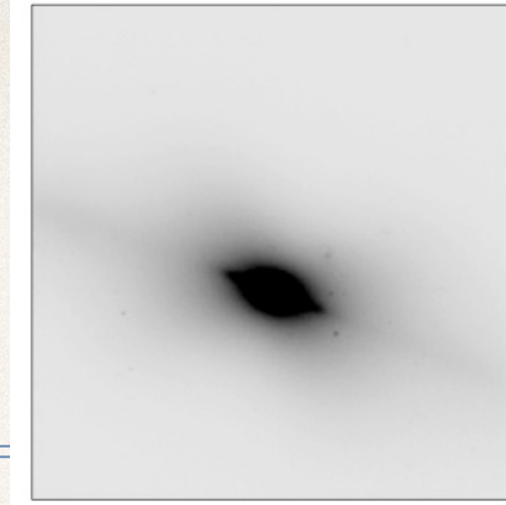


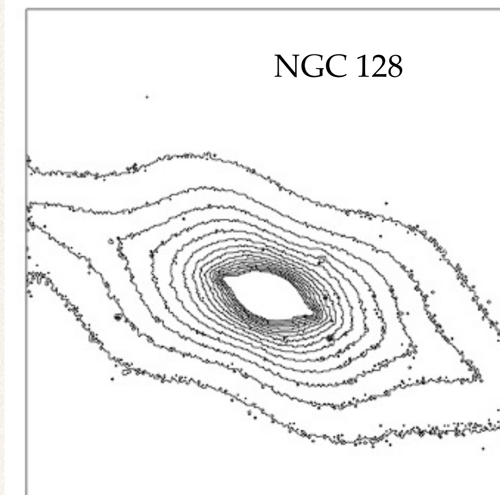




Fisher & Drory 2010

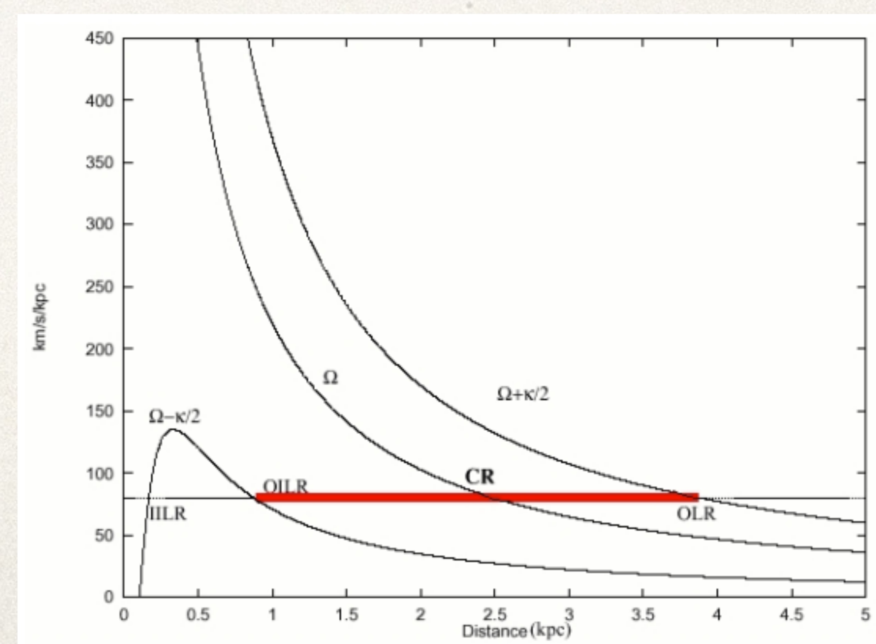
Structural components: III. bars



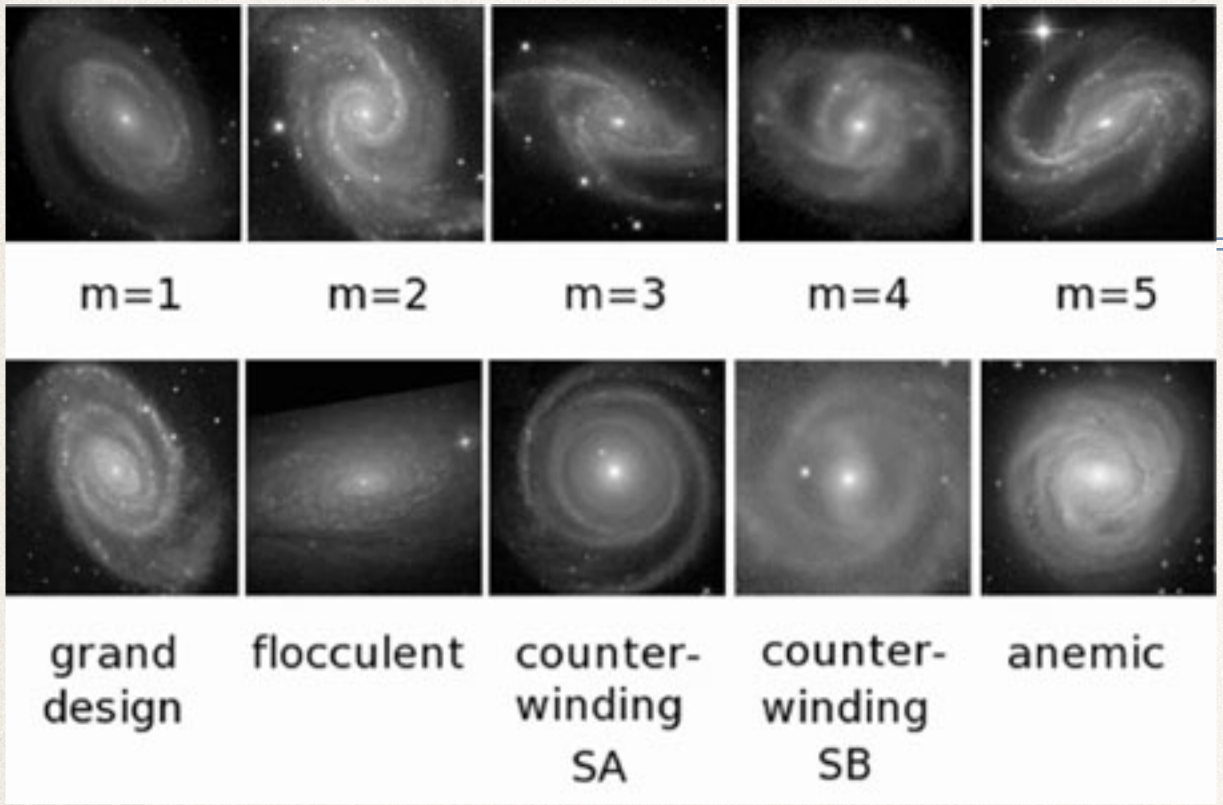


from the web, Josh Barnes

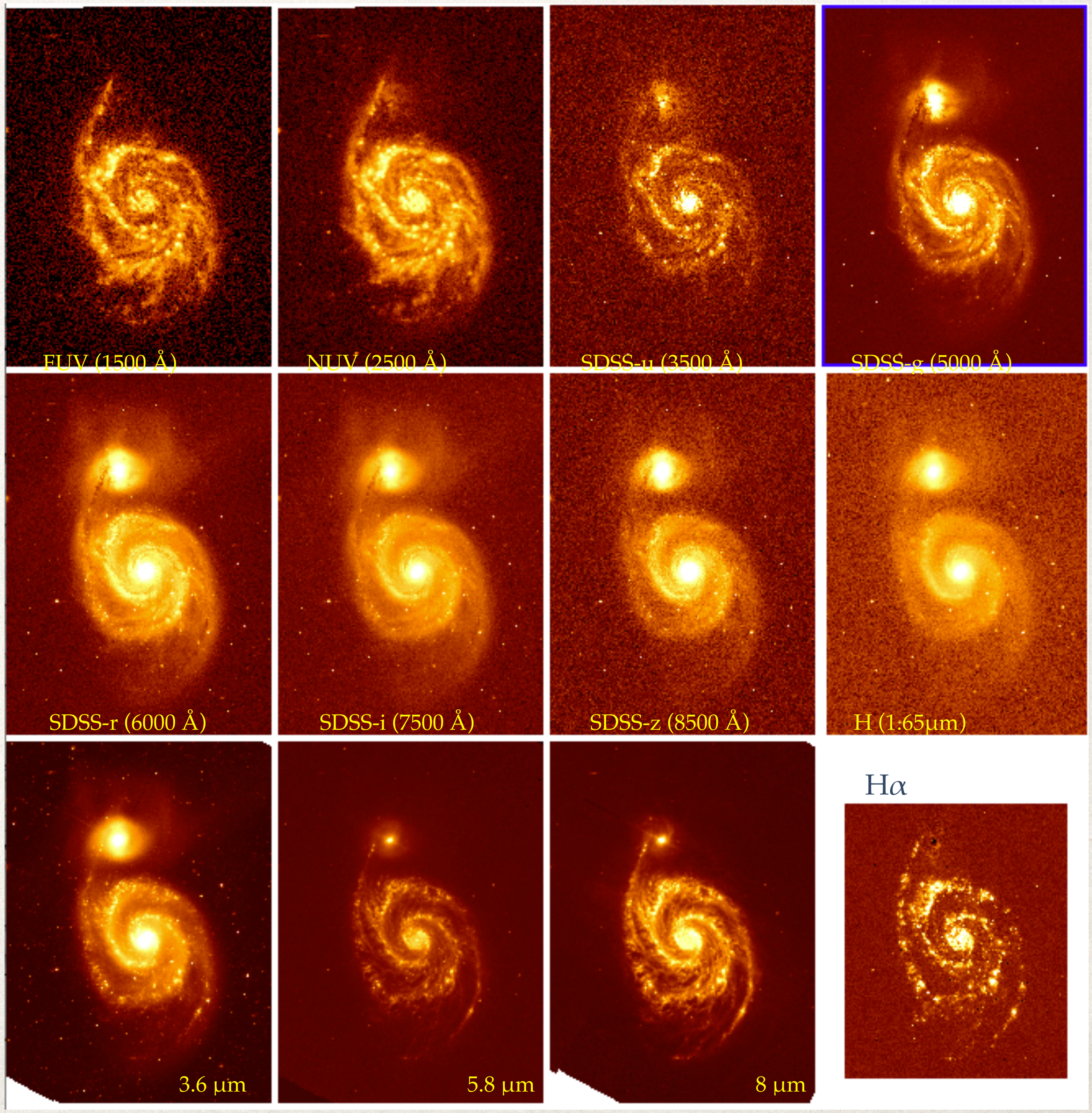
- Main disk perturbation
  - important role in redistributing gas, stars, angular momentum
  - resonances (co-rotation, ILR, OLR)



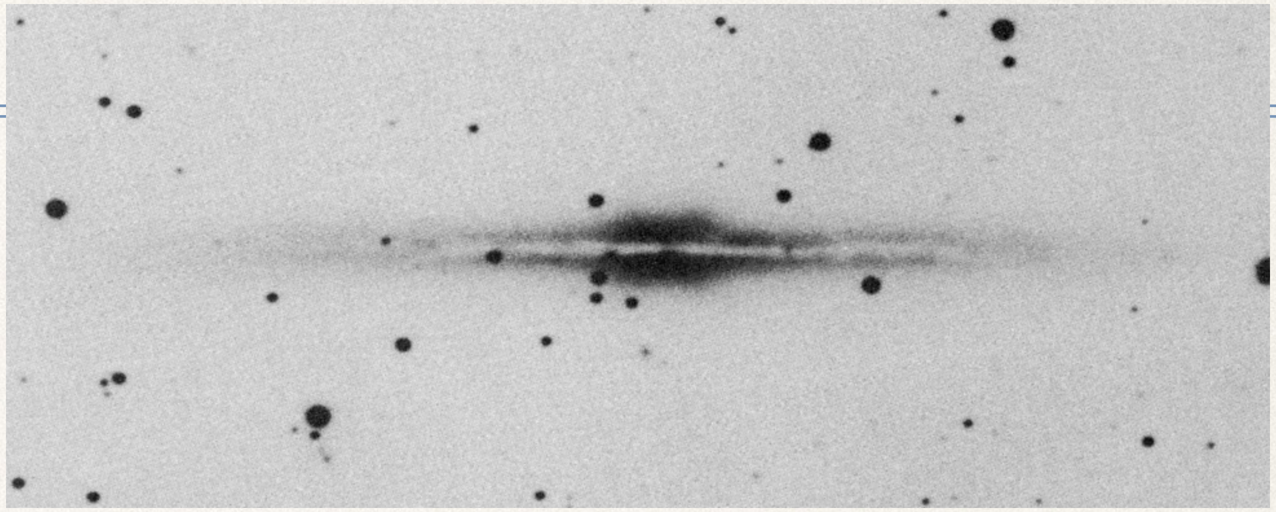
Structural components: IV. spiral arms



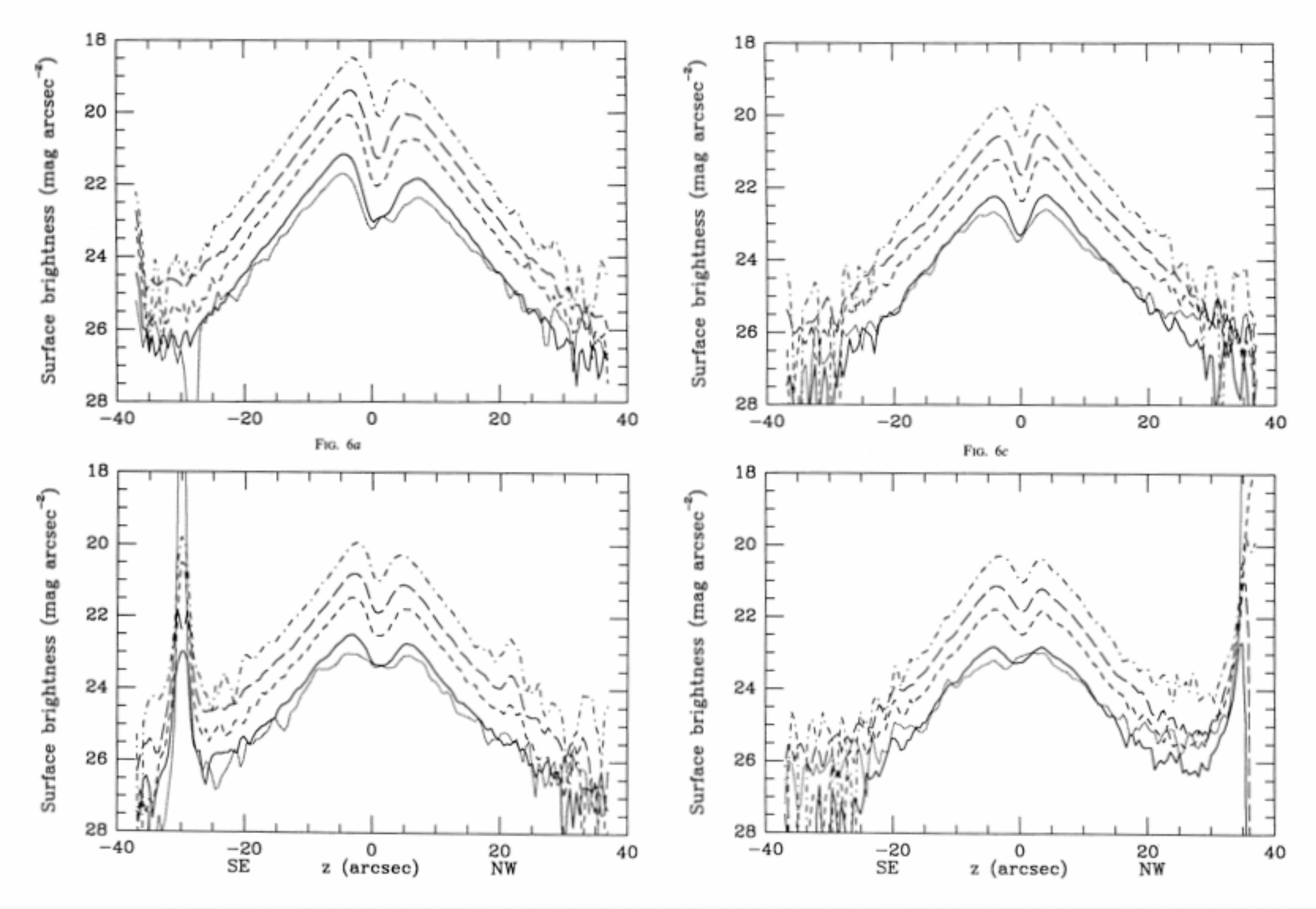
- what are they?
- Grand design vs flocculent mechanical waves vs stochastic SF propagation
- how do they look like at different lambda (see next lecture)



Structural components: V. thick disk



from Wainscoat, Freeman & Hyland 1989



- Vertical structure of the disk

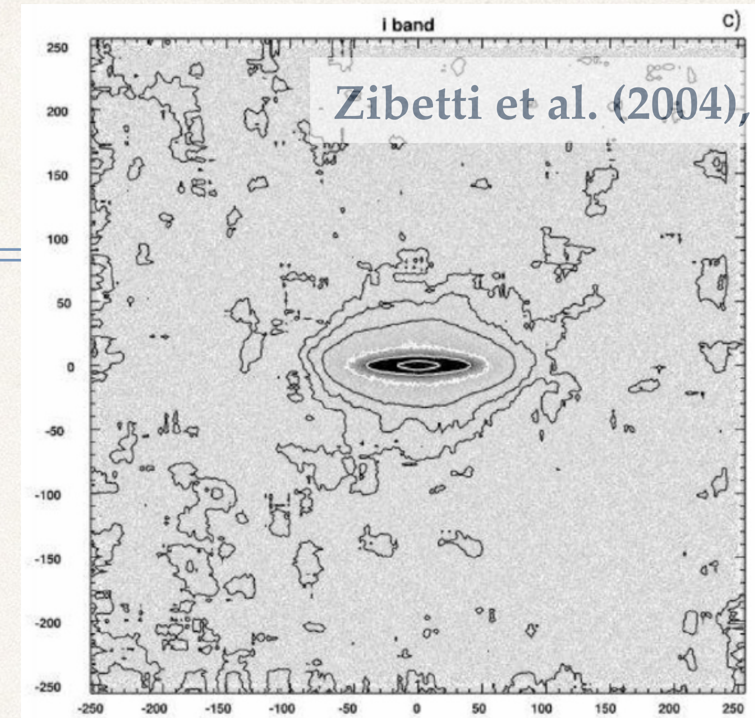
$$I(z) = I(0)\, exp\,(-|z|/z_o)$$

- Heated old stars?

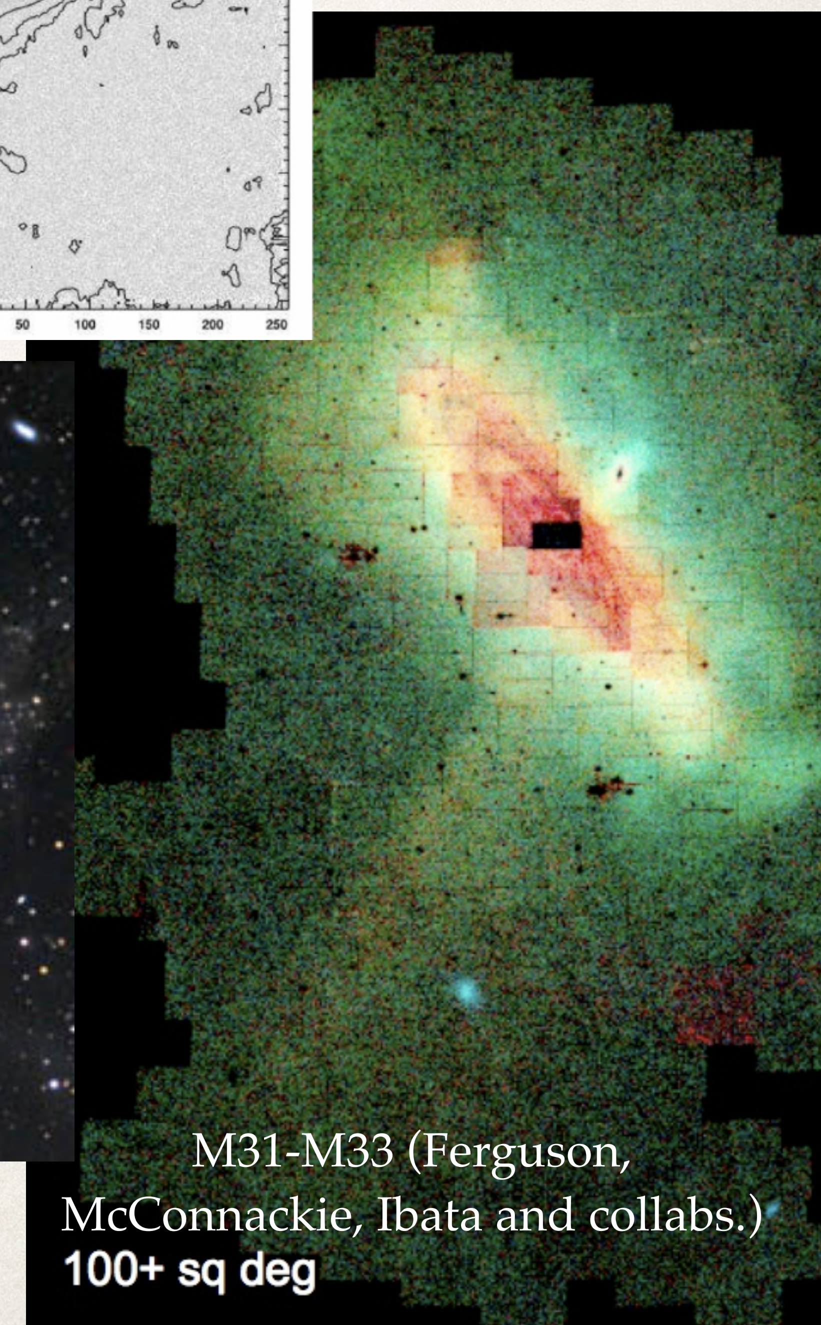
Structural components: VI. the stellar halo

- smooth outer spheroid of old low-metallicity stars?

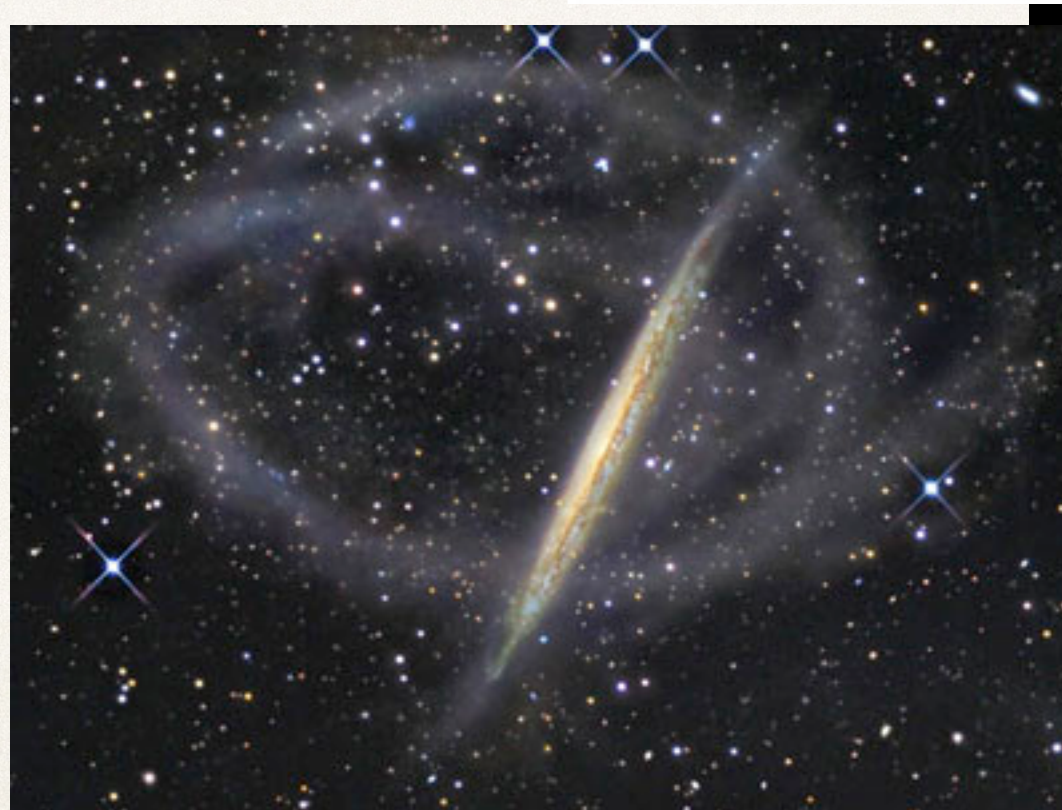
- streams, shells etc... the halo is the interface of a galaxy with the cosmic web and keeps records of accretions, mergers and interactions

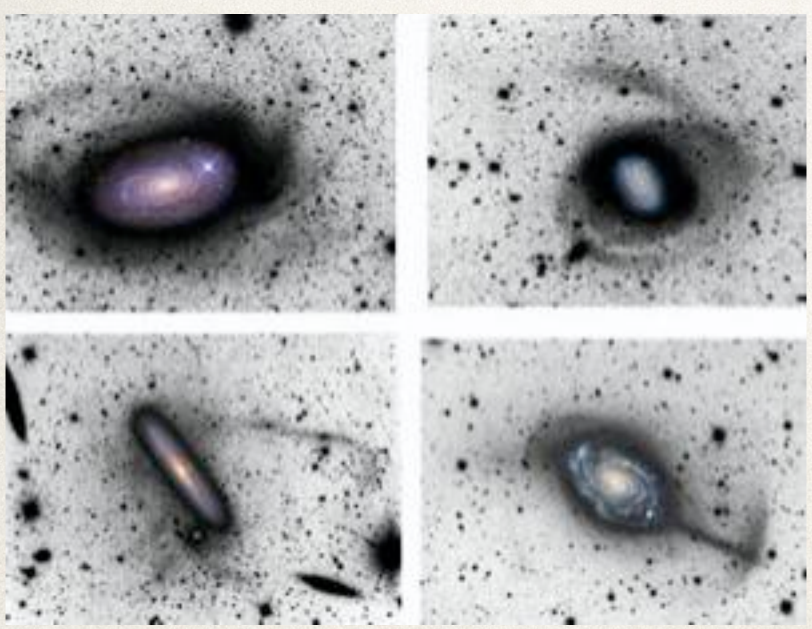


Zibetti et al. (2004), stacking of >1000 gals.



M31-M33 (Ferguson, McConnackie, Ibata and collabs.)





Martinez-Delgado et al. (2010)

Structural components:
VII. “other”: nuclei, rings, and more oddities...

- Signposts of secular evolution and environmental interactions

- warps (from Kuijken 2000)

Bosma's Laws (Bosma 1991, on overall statistics of warps)

1. At least half of all galaxies are warped
   Implication: Warps are long-lived or continuously generated
2. Galaxies with small dark halo core radii (as determined from a rotation curve decomposition) are less likely to be warped
   Implication: Link between warps and the dark halo potential

Briggs's Laws (Briggs 1990, on structure of individual warps)

3. Disks are generally flat inside radius R_{25}. Out to radius $R_{26.5}$ the line of nodes of a warp is straight
   Implication: Self-gravity of the disk is important (it keeps the different parts of the disk precessing synchronously and hence the line of nodes straight - cf. the winding problem of spiral waves)
4. The outer line of nodes advances in the direction of galactic rotation
   Implication: Warps are not quite in equilibrium at large radii. This points to a link to the environment, or to very long timescales

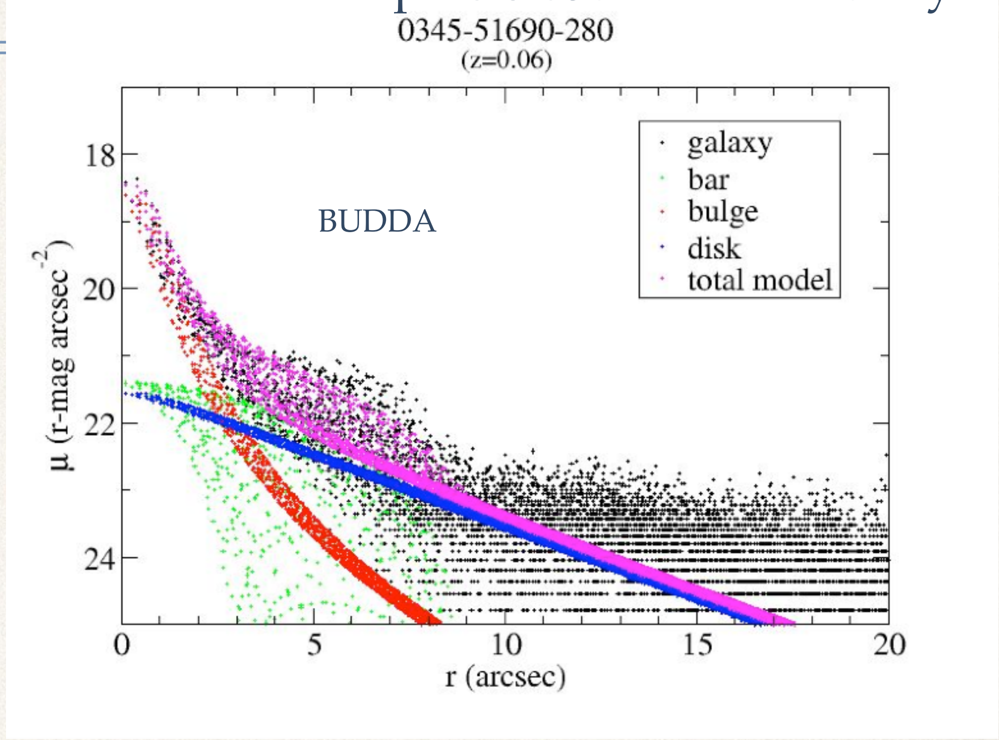
- lopsidedness, asymmetries, streamers etc are signs of possible interactions with larger potential, other galaxies or even merger events

Structural (de)composition of galaxies

- Phenomena and reality
    - effects of observing conditions
    - stellar populations
    - dust
- Should one look at stellar MASS distribution instead?
- 1D azimuthally averaged profiles (see above): reduces to curve fitting
- 2D SB distributions: techniques and examples

2D galaxy decomposition

Note: at any given radius many pixels count individually!

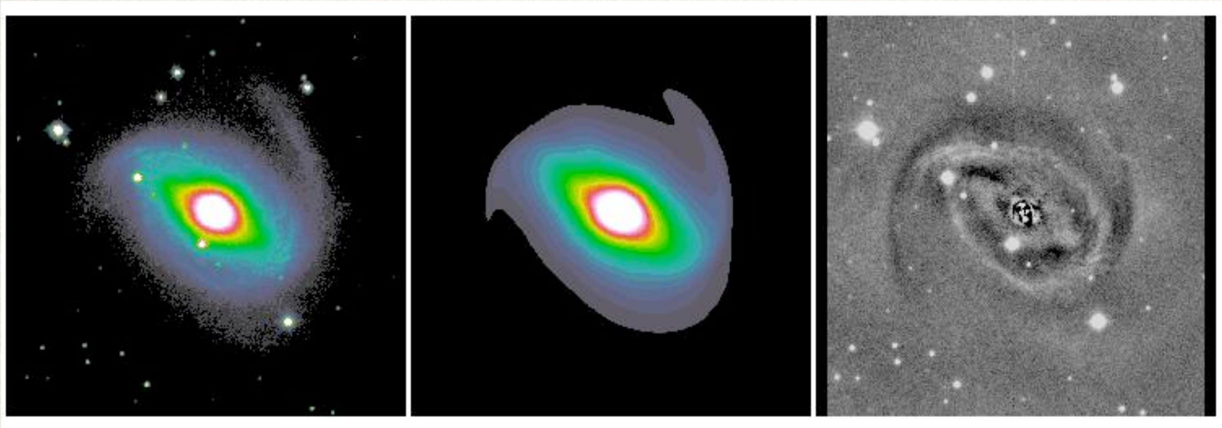


- Avoid azimuthal averaging
- directly take PSF into account
- many more degrees of freedom!
  - variable centers, ellipticity and PA for different components
  - can reproduce non-axissymmetric shapes
- 1st generation: only elliptical symmetry
  - GIM2D https://www.astrosci.ca/users/GIM2D/ essentially 2D bulge-disk decomposition optimized for marginally resolved galaxies (Simard 2002)
  - GALFIT v<2
  - BUlgeDiskDecompositionAnalysis http://www.sc.eso.org/~dgadotti/budda (de Souza, Gadotti & dos Anjos 2004) introduces special treatment for bars
- 2nd generation:
  - generalized ellipses
  - general functions (e.g. GALFIT v>=3, Peng et al. 2010; Imfit, Erwin et al. 2015)

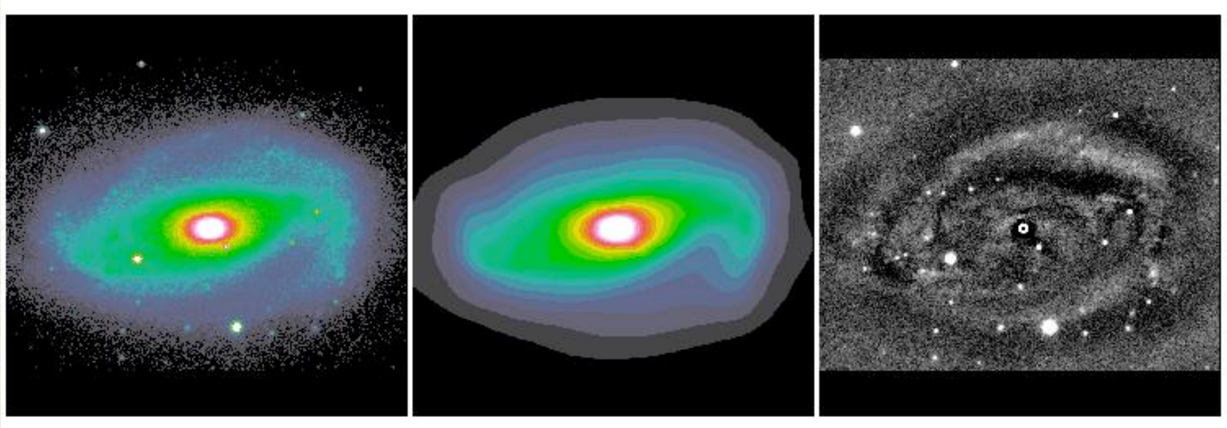
GALFIT v.3 (Peng et al. 2010)

http://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html

- improves on previous 2D fitting algorithms by allowing for **irregular, curved, logarithmic and power-law spirals, ring, and truncated shapes** in otherwise traditional **parametric functions** like the Sersic, Moffat, King, Ferrer, etc., profiles.
- One can mix and match these new shape features freely, with or without constraints, and apply them to an arbitrary number of model components of numerous profile types, so as to produce realistic-looking galaxy model images.
- Yet, despite the potential for extreme complexity, the meaning of the key parameters like the Sersic index, effective radius, or luminosity remains intuitive and essentially unchanged.
- The new features have an interesting potential for use to quantify the degree of asymmetry of galaxies, to quantify low surface brightness tidal features beneath and beyond luminous galaxies, to allow more realistic decompositions of galaxy subcomponents in the presence of strong rings and spiral arms, and to enable ways to gauge the uncertainties when decomposing galaxy subcomponents.



5 components fitted: bulge, spiral, disk, and 2 nuclear components composed of a nuclear bar and a nuclear disk.



Structural decomposition

- Large degeneracies, both in 1D and 2D
  - often crucial to provide good initial guesses based on some raw but robust analysis
- As always, adding degrees of freedom helps ONLY IF:
  - data quality is good: low noise and **systematics**
  - you know what you are doing: one can fit anything, but not necessarily meaningful!
- Weighing scheme is crucial. The simple photon noise is rarely the best choice, unless the model is GOOD in a chisquared sense

Physical decomposition of galaxies?

- Different content in different structure
- Different dynamics: the “family of orbits” view

Physical properties vs Morphology i.e. why is morphology still so popular? or are physical parameters just "proxies"?

- B/T (concentration) vs morphology
- color vs morphology
- (s)SFR vs morphology
- kinematics vs morphology
- mass vs morphology
- environment vs morphology (see following lectures)

Going to high redshift: the end of "classical morphology"?

- Galaxies that can be classifies within the classic Hubble-Sandage-deVaucoulers scheme become more and more rare moving to high-z
- Fraction of irregular grows
- New types appear

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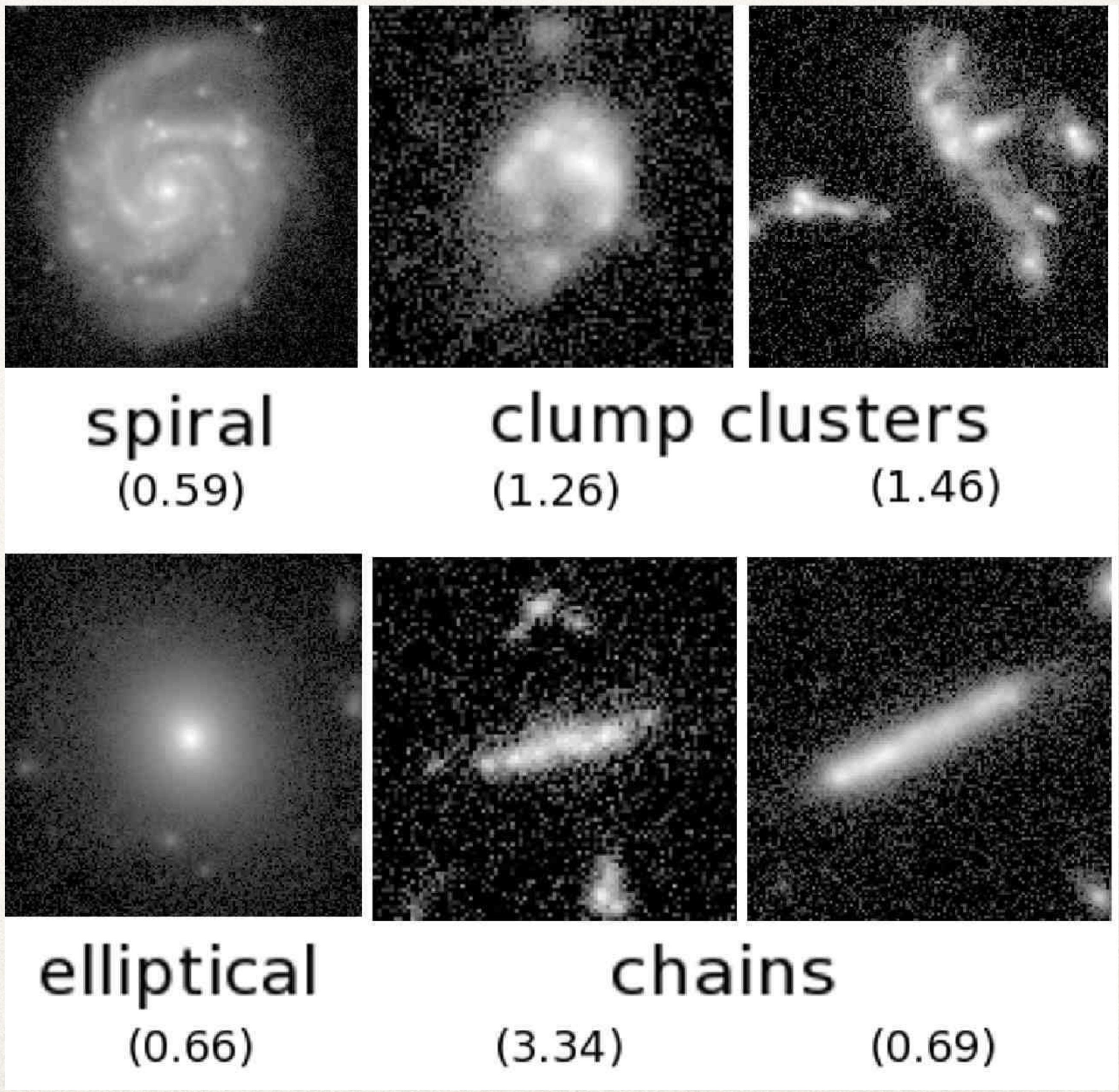
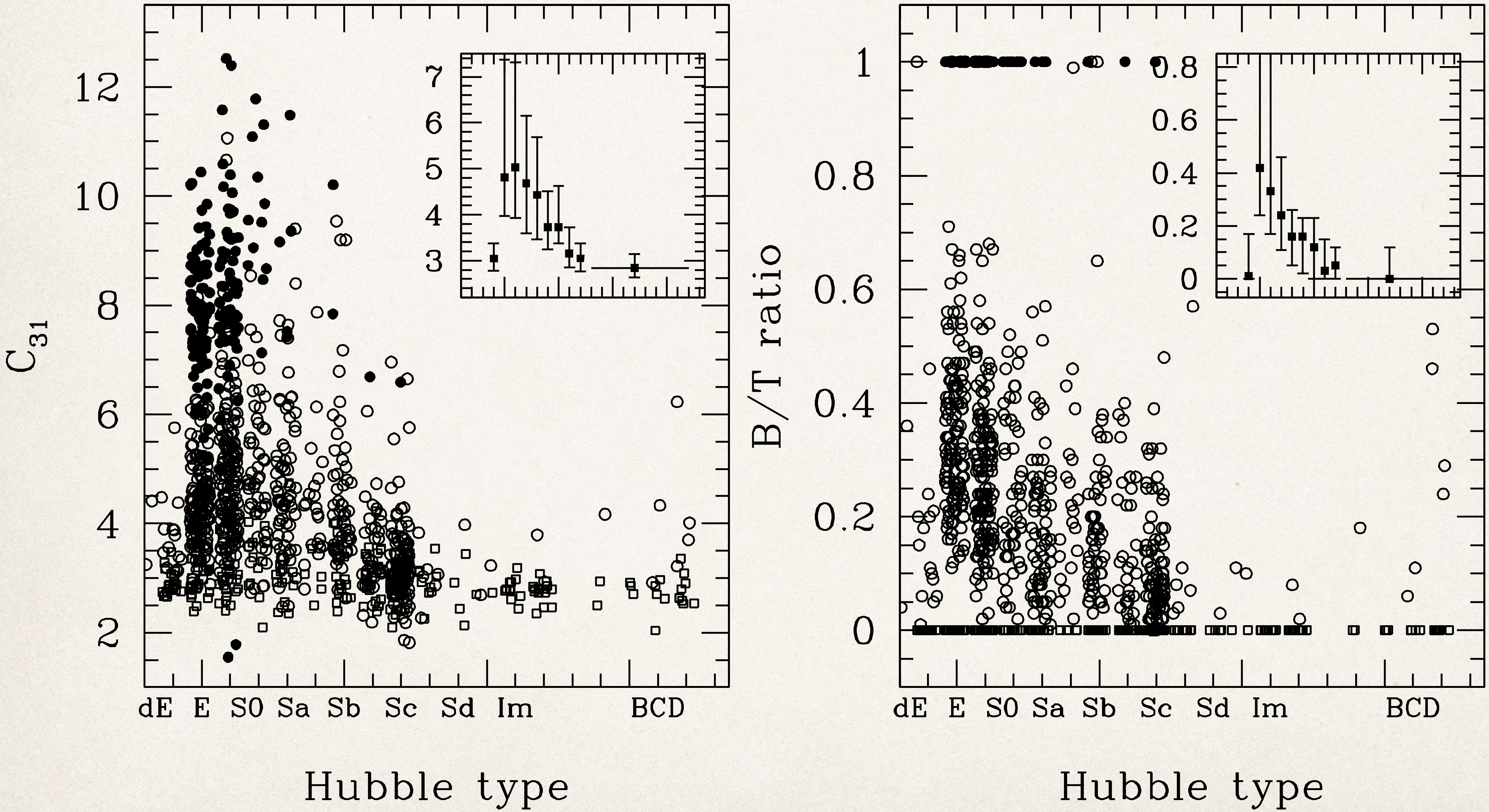


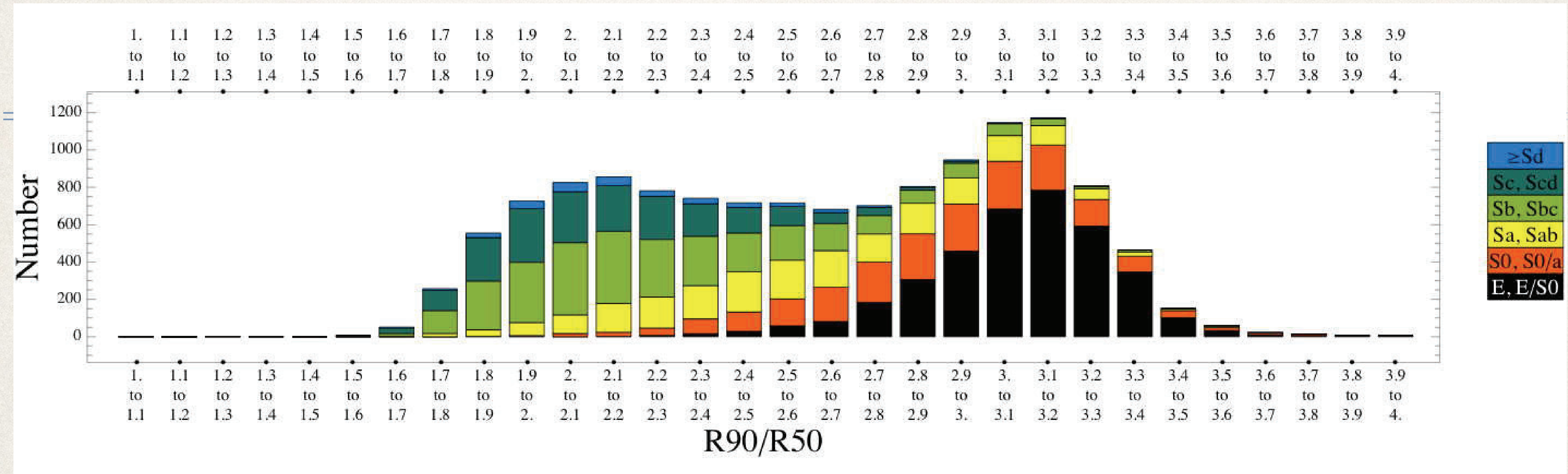
Fig. 2.83. Several high-redshift morphological categories, from B13 and references therein. The number in parentheses is the redshift.

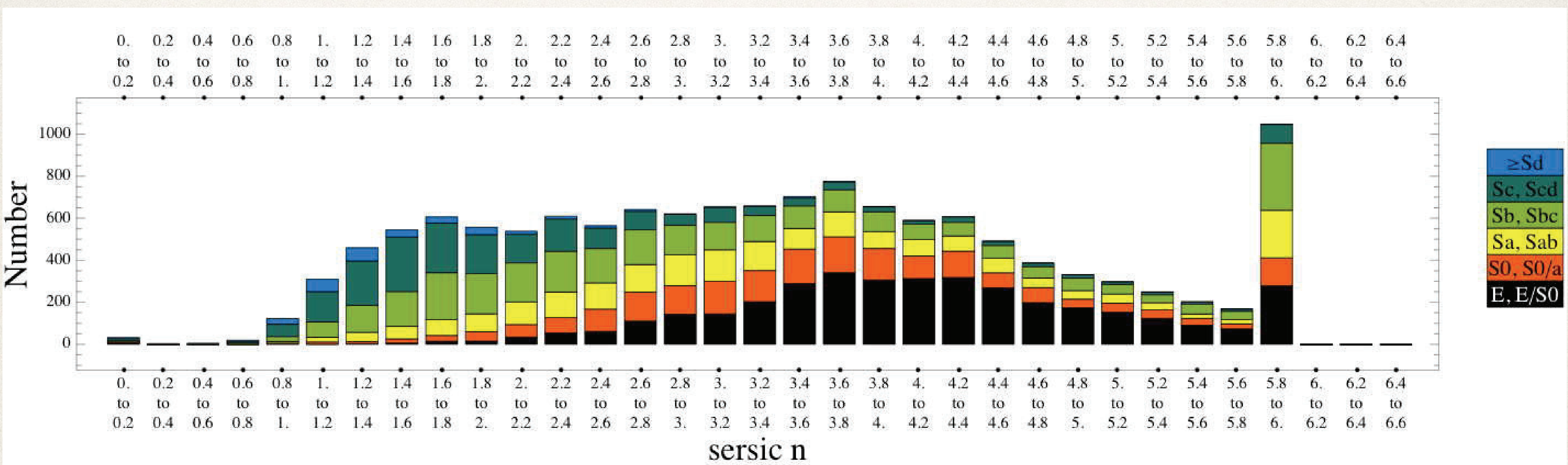
B/T [concentration] vs morphology



Scodeggio et al. (2002)

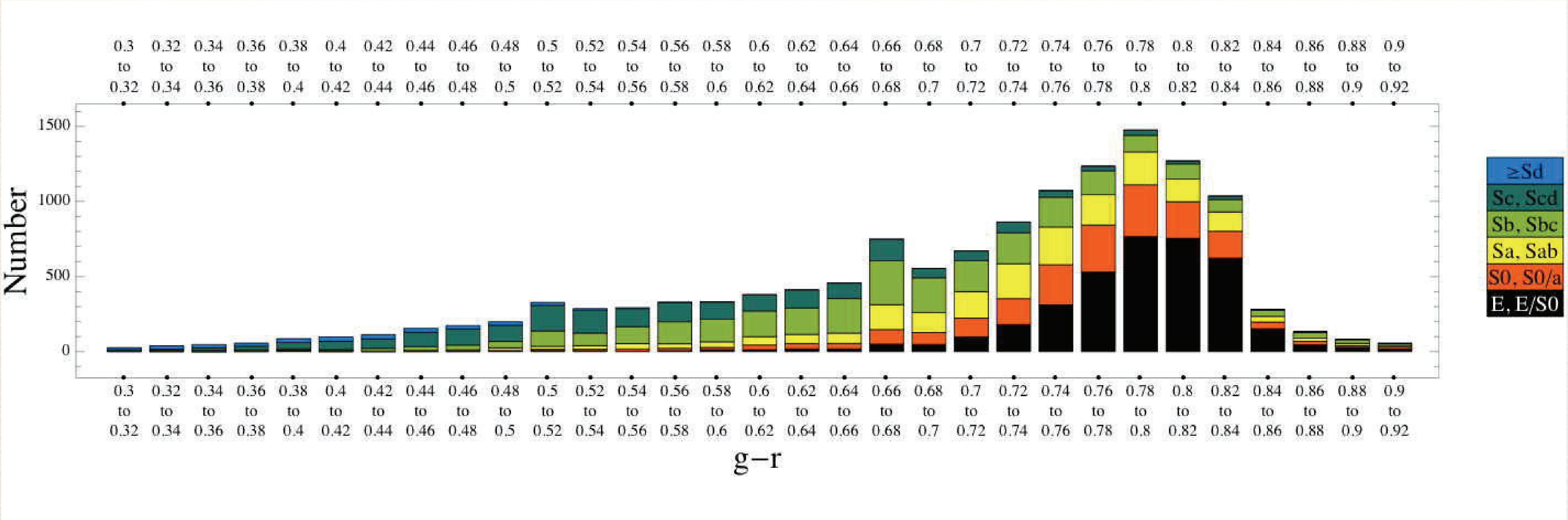
Concentration vs Morphology





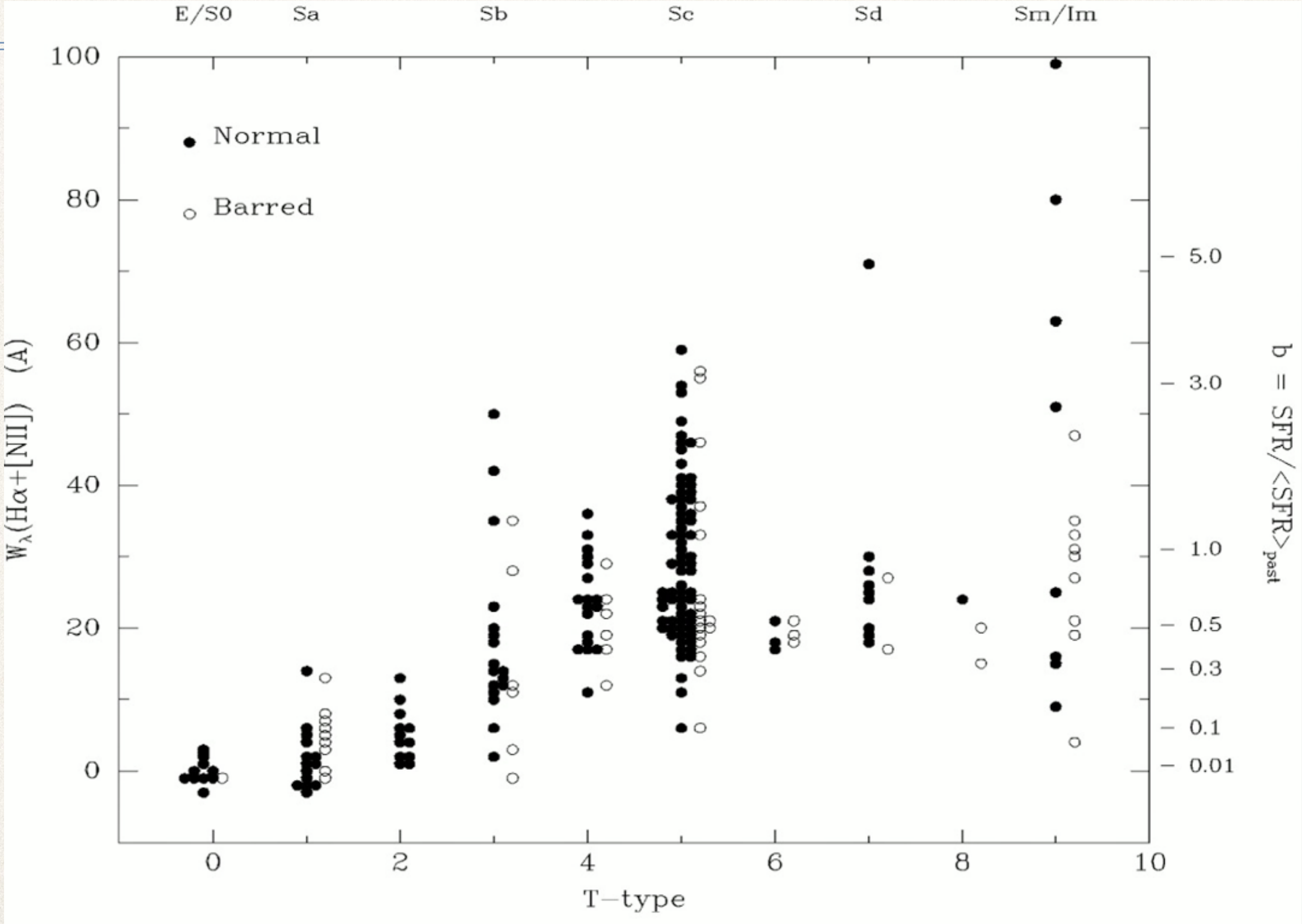
Nair & Abraham (2010)

Color vs Morphology



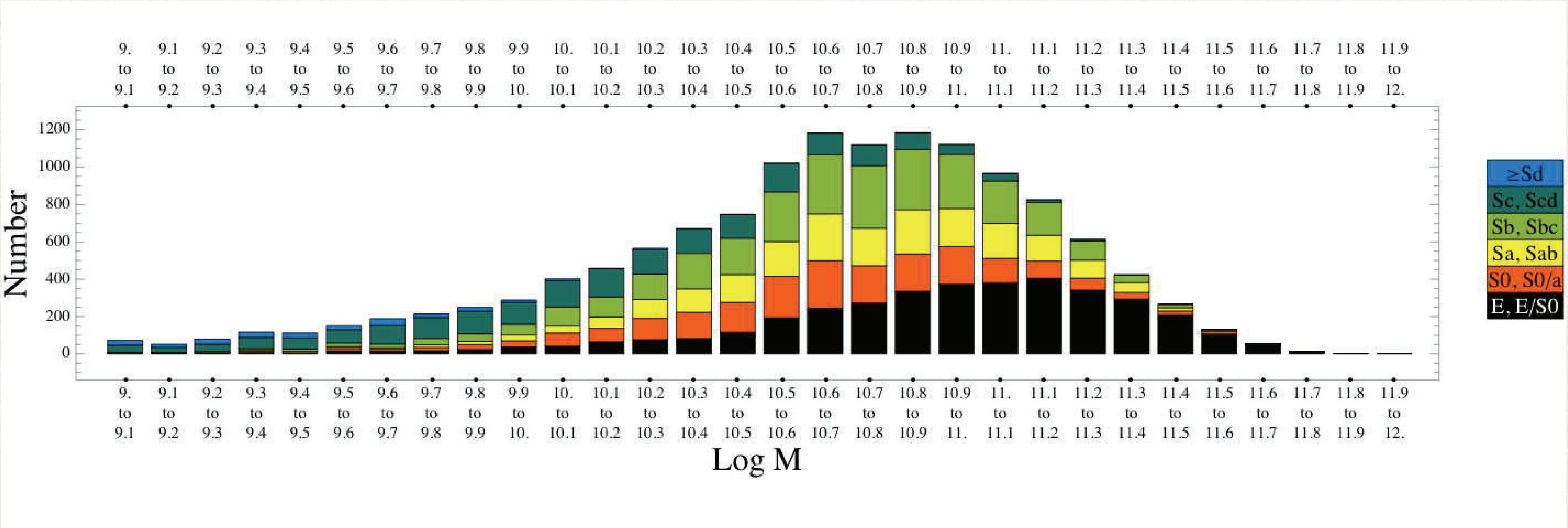
Nair & Abraham (2010)

sSFR vs Morphology

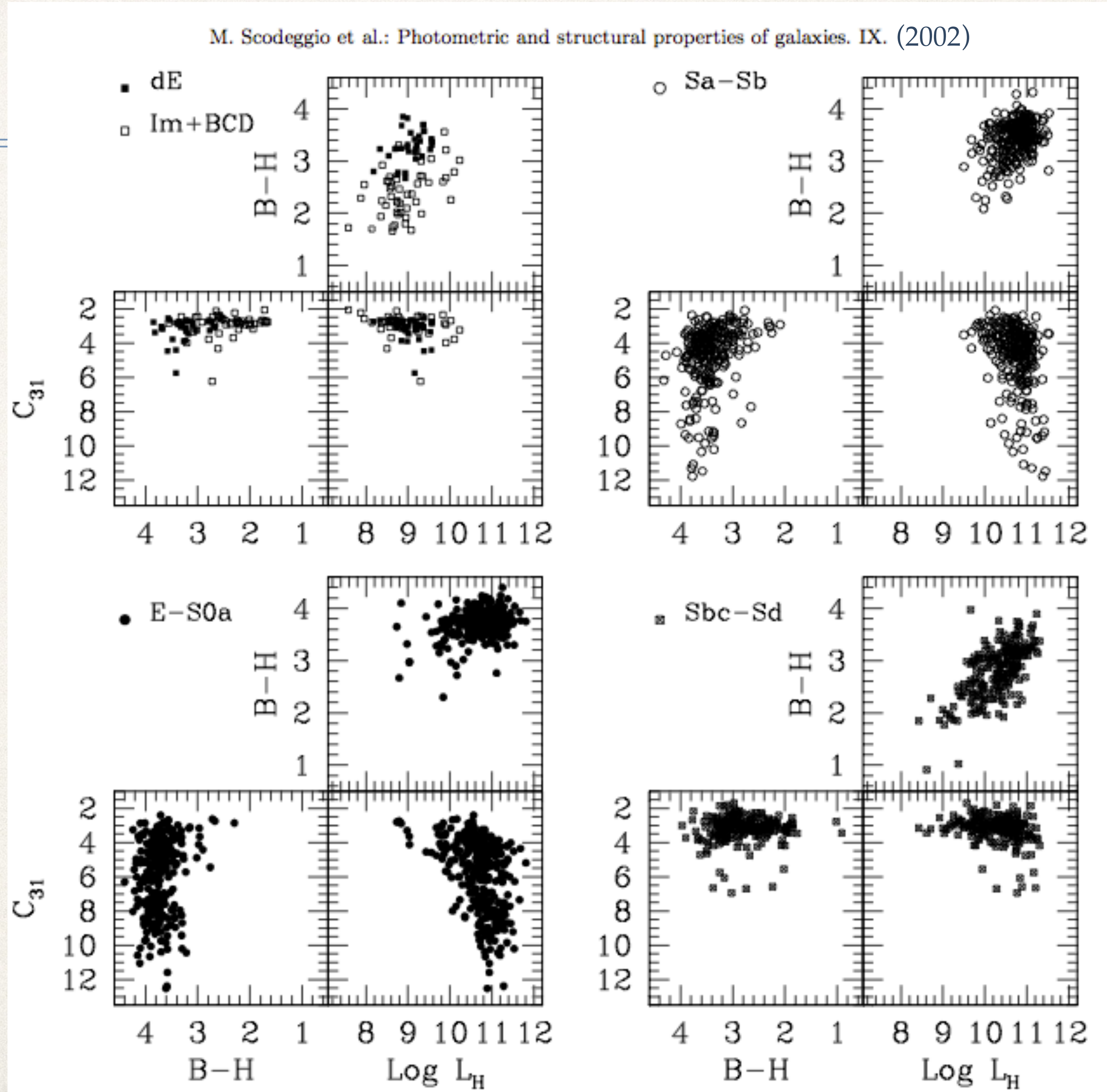


Kennicutt (1998)

Mass vs Morphology

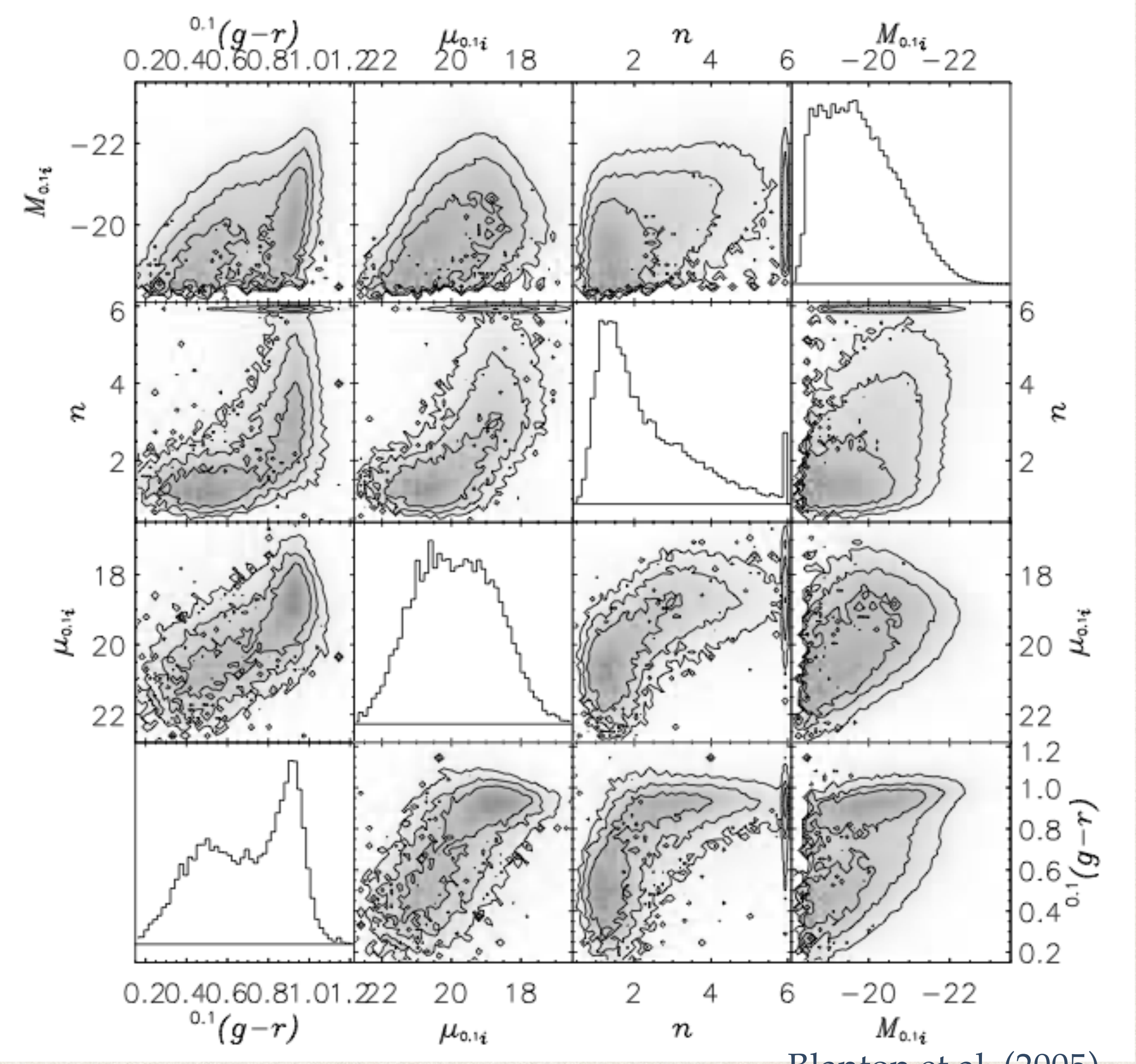


Color-Concentration-L(H) cube



Is bimodality the key? Or, what do we need morphology for?

- Morphology should be defined in relation to what one looks for: if you only care about a rough early-late type distinction, fine classification makes no sense
- Although "natura non facit saltus", clear bimodalities in structure and physical properties of galaxies are clear and appear to be key to understand galaxy evolution
- Linking these bimodal distribution to physical parameters, environment, signs of evolutionary mechanisms (possibly highlighted by morphological signatures) is a powerful way to make progress

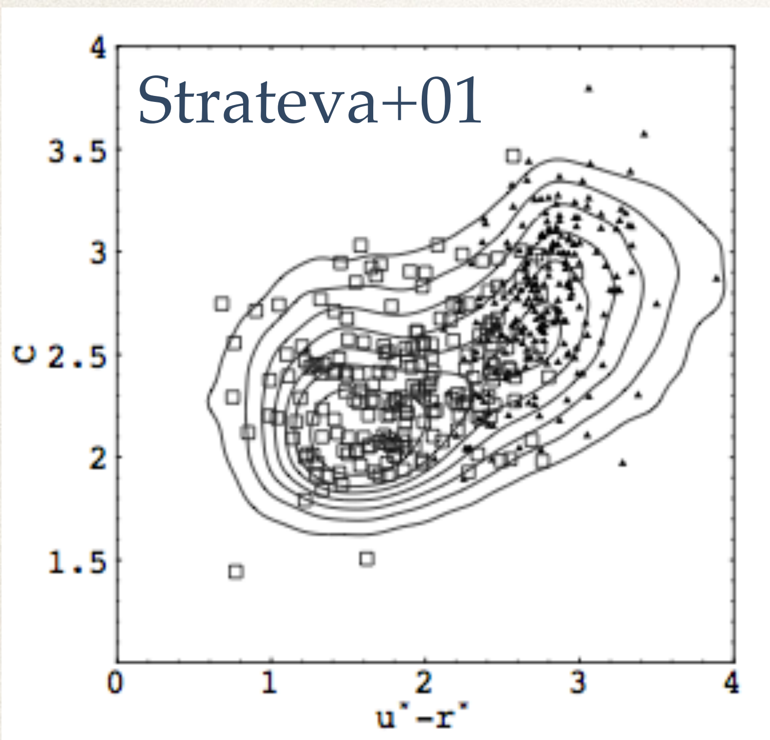


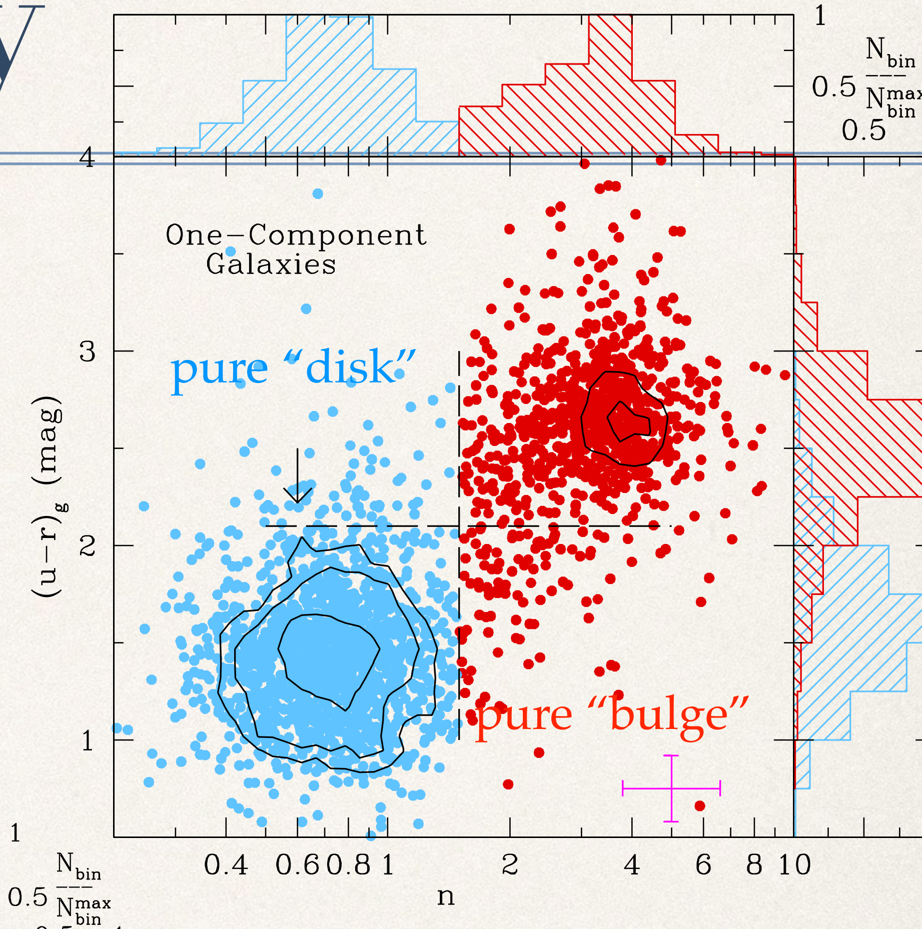
Blanton et al. (2005)

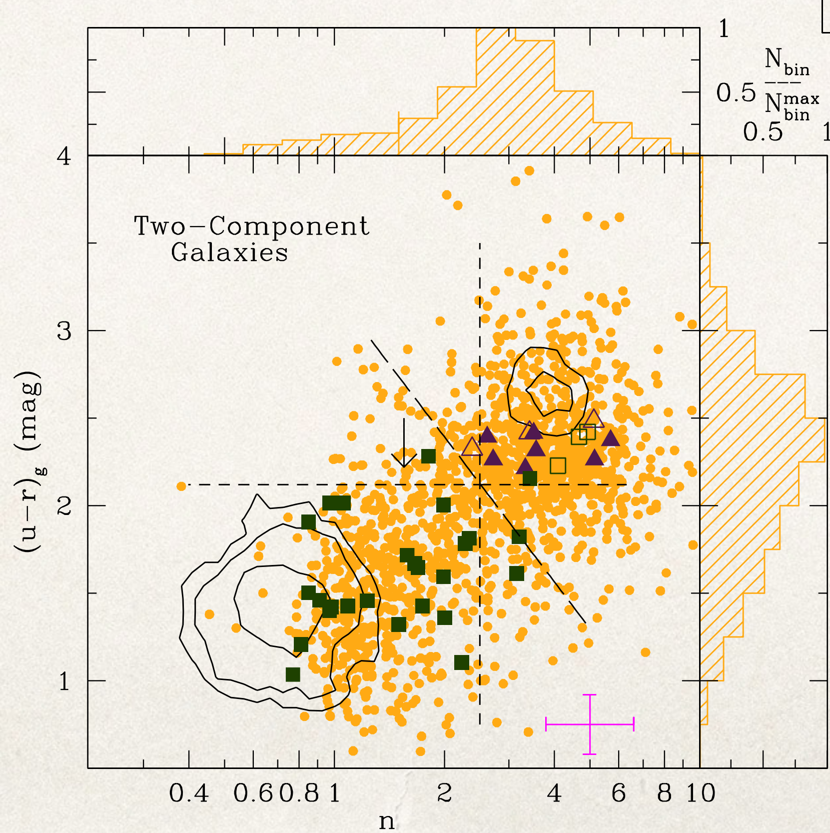
"Objective" and "quantitative" morphological classifications

- Entering the epoch of large survey: more statistics, less detail
- Parameter proxies and profile/image decomposition: B/T, concentration (R90/R50, c31), color, best fitting profile (exp vs deV)
- Concentration-Asymmetry-clumpinesS (Conselice 2003)
- M20, Gini, elongation + PCA (ZEST, Scarlata et al. 2007)
- Shapelet decomposition and PCA
- Artificial Neural Networks (eg Ball et al. 2004)

Structure-color **bimodality** as a proxy for morphology







Cameron+09, Millennium Galaxy Catalog

The CAS proxy (Conselice 2003)

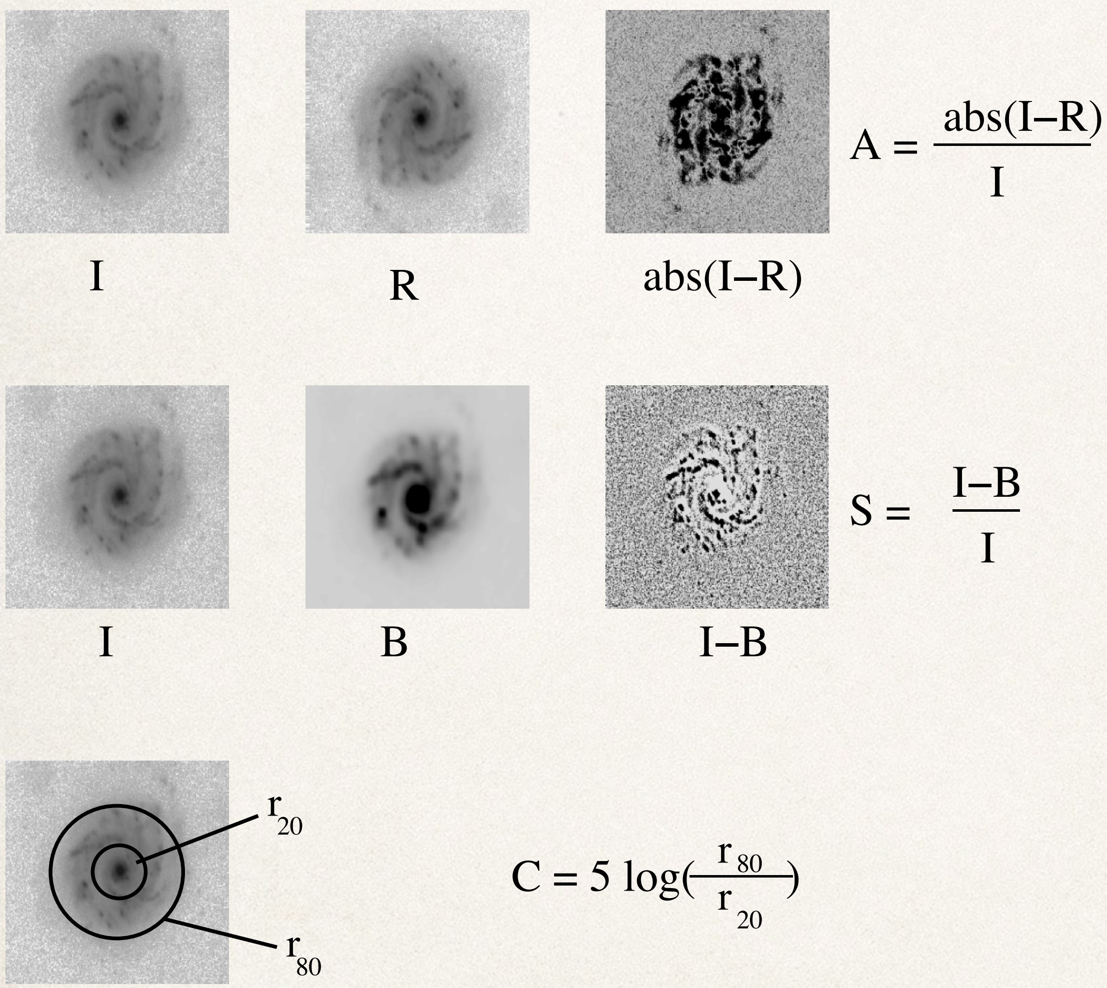
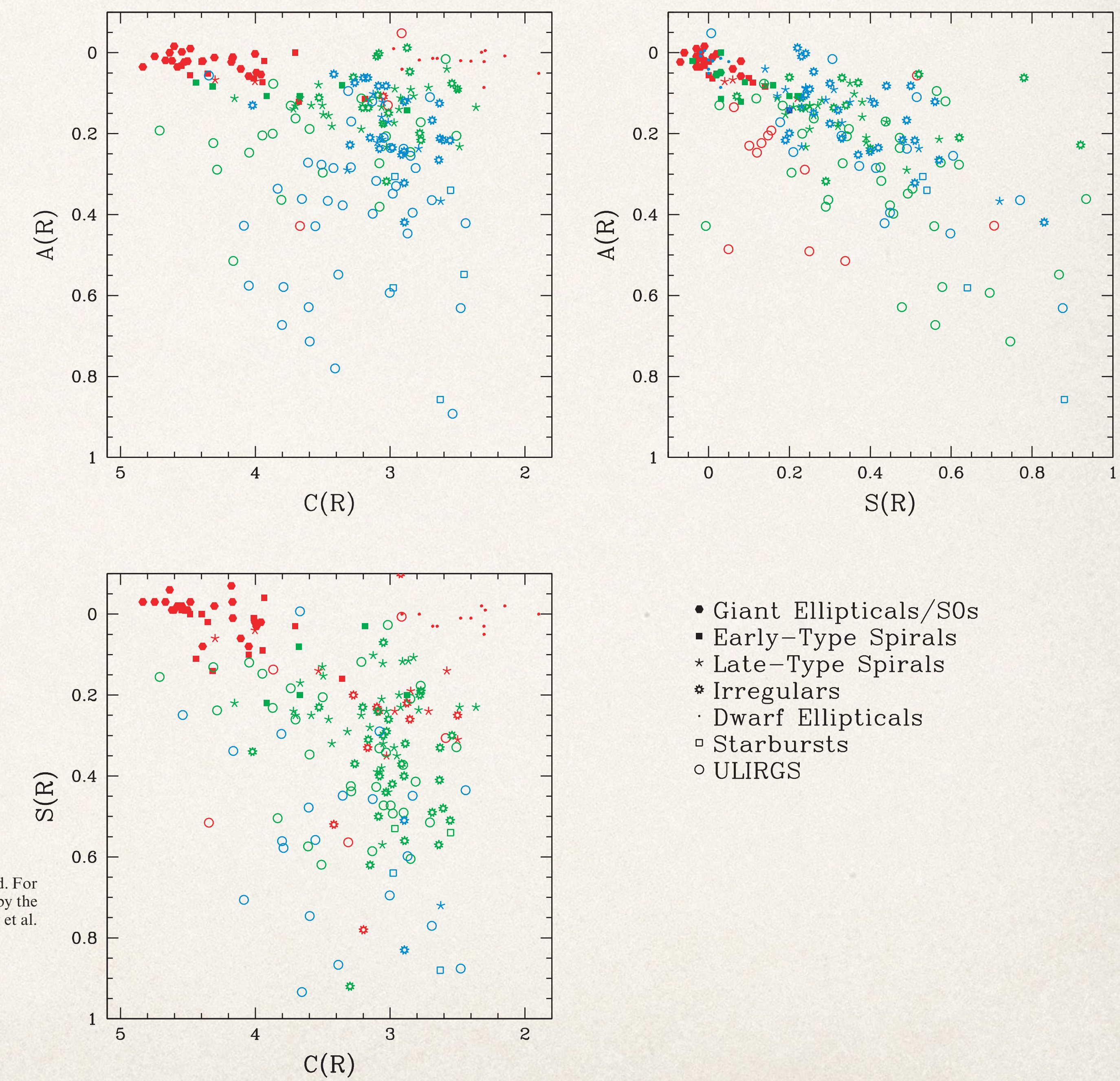


FIG. 3.—Graphical representation of how the three parameters used in this paper, asymmetry (A), clumpiness (S), and concentration (C) are measured. For the measurements of A and S, I is the original galaxy image, R is this image rotated by 180°, while B is the image after it has been smoothed (blurred) by the factor $0.3 \times r(\eta = 0.2)$. The details of these measurements are not shown here but can be found in Conselice et al. (2000b) for asymmetry, A, Bershady et al. (2000) for concentration, C, and this paper for the clumpiness index, S.



Gini coefficient

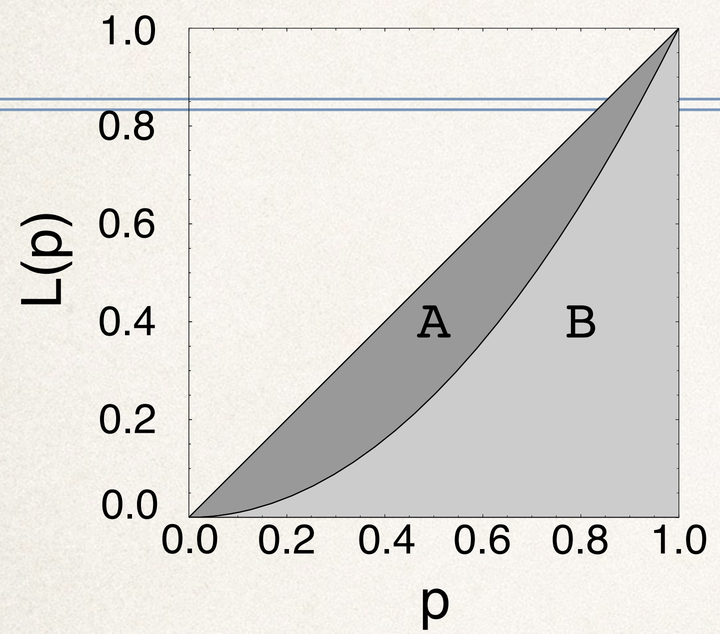


FIG. 1.—Geometric interpretation of the Gini coefficient based on the Lorenz curve. The x-axis corresponds to the quantile of the distribution, and the y-axis corresponds to the cumulative proportion. The Lorenz curve for a perfectly equal distribution corresponds to the diagonal line of equality. In the figure, a schematic Lorenz curve divides the area beneath the line of equality into two areas, A and B. The greater the deviation of a measured Lorenz curve from the line of equality, the greater the inequality. The Gini coefficient corresponds to the ratio of area A to the total area under the diagonal A + B.

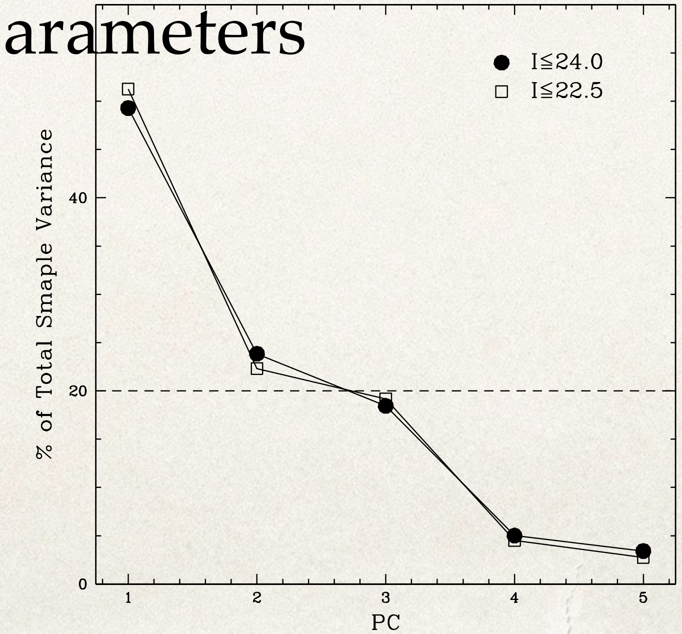
Abraham et al. (2003)

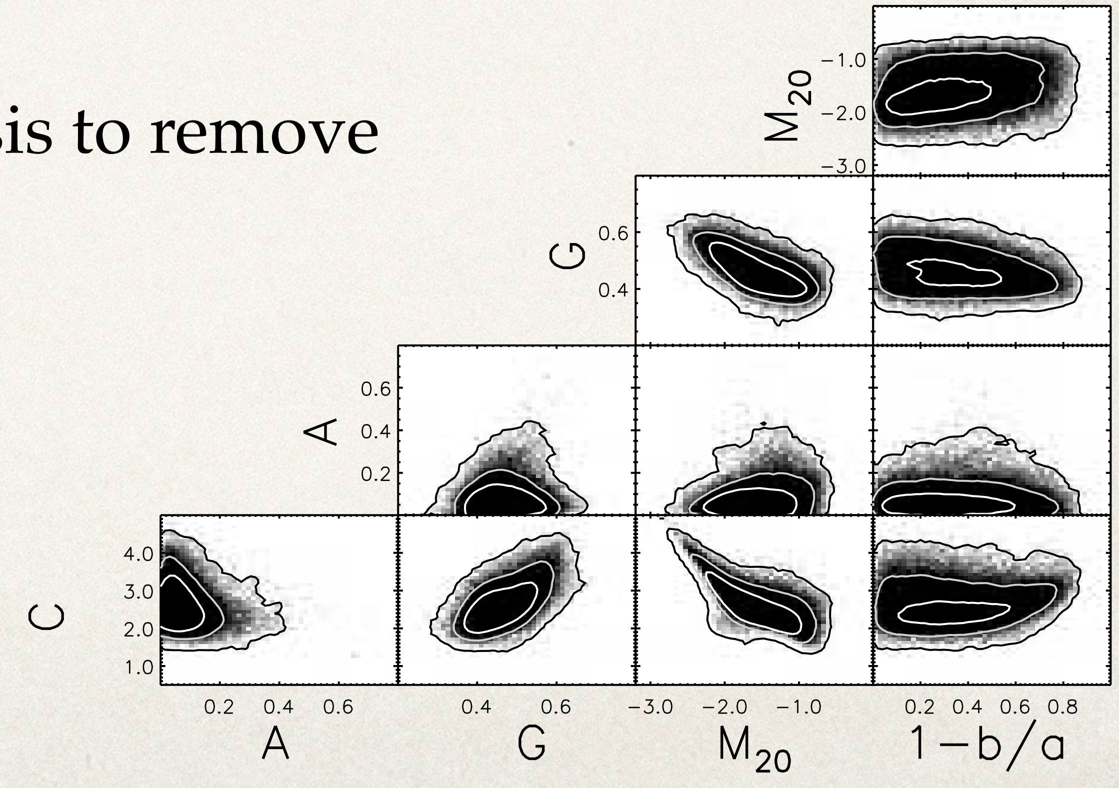
- **Gini**: how much of the light goes into the brightest pixels
- Lorentz curve:
  - sort pixels by intensity: $f_{i+1} \geq f_i$
  - $$L(p \equiv n/N_{tot}) = \frac{\sum_{i=1}^{n} f_i}{\sum_{i=1}^{N_{tot}} f_i}$$
  - For a uniform population $L(p)$ is the diagonal
  - The less uniform the distribution, the more the curve deviates from the diagonal
- Gini coefficient measures this deviation

“Bonus” material

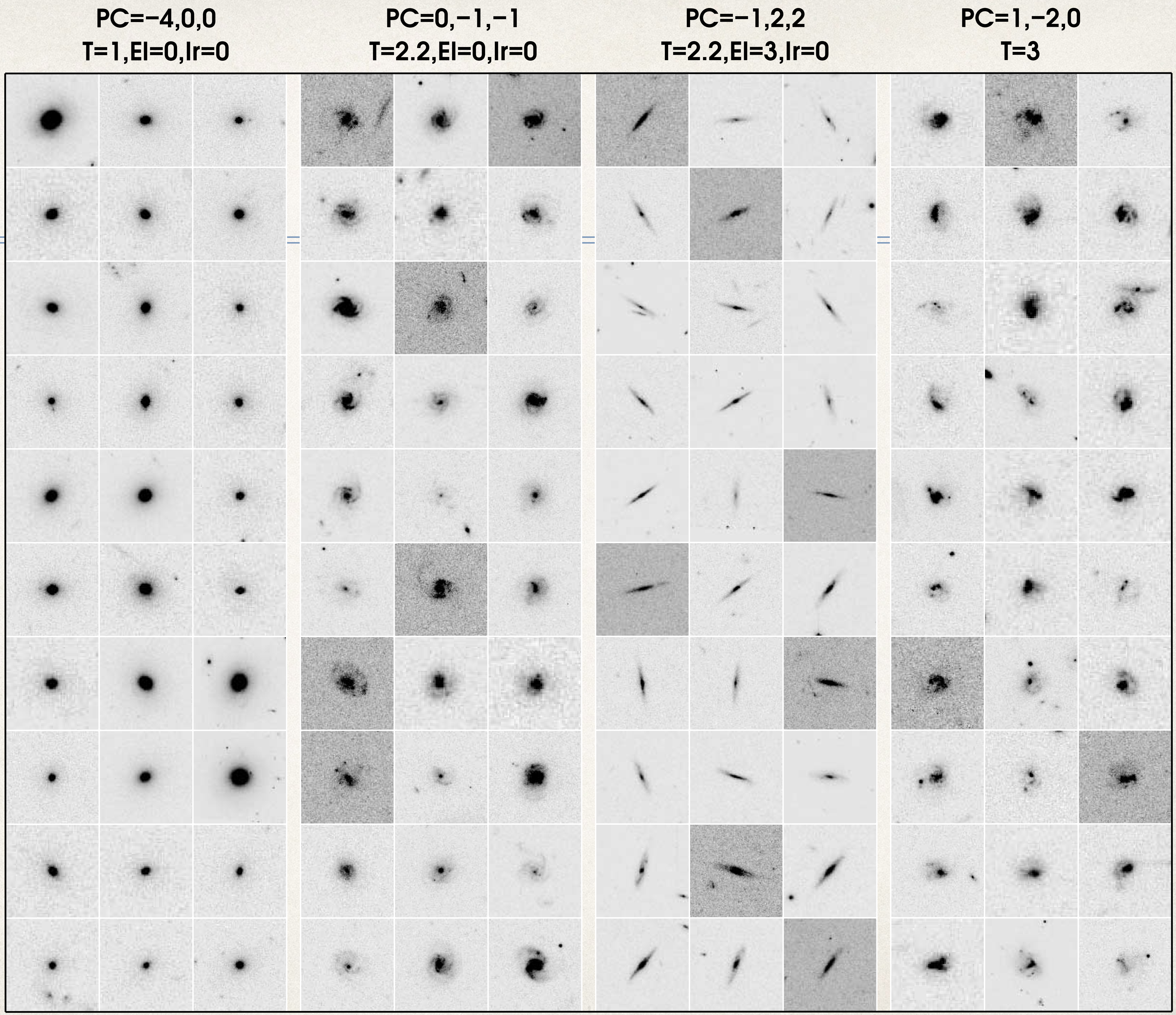
Multiparameter+PCA approach the ZEST example (Zurich Estimator of Structural Types, Scarlata et al. 2007)

- Set of 4 non-parametric indices of light distribution plus ellipticity
  - Concentration C
  - Asymmetry A
  - Gini G
  - M20 (how much the second moment of the 20% brightest pixels deviates from the overall second moment)
  - ellipticity
- Combine with Principal Component Analysis to remove correlation among parameters





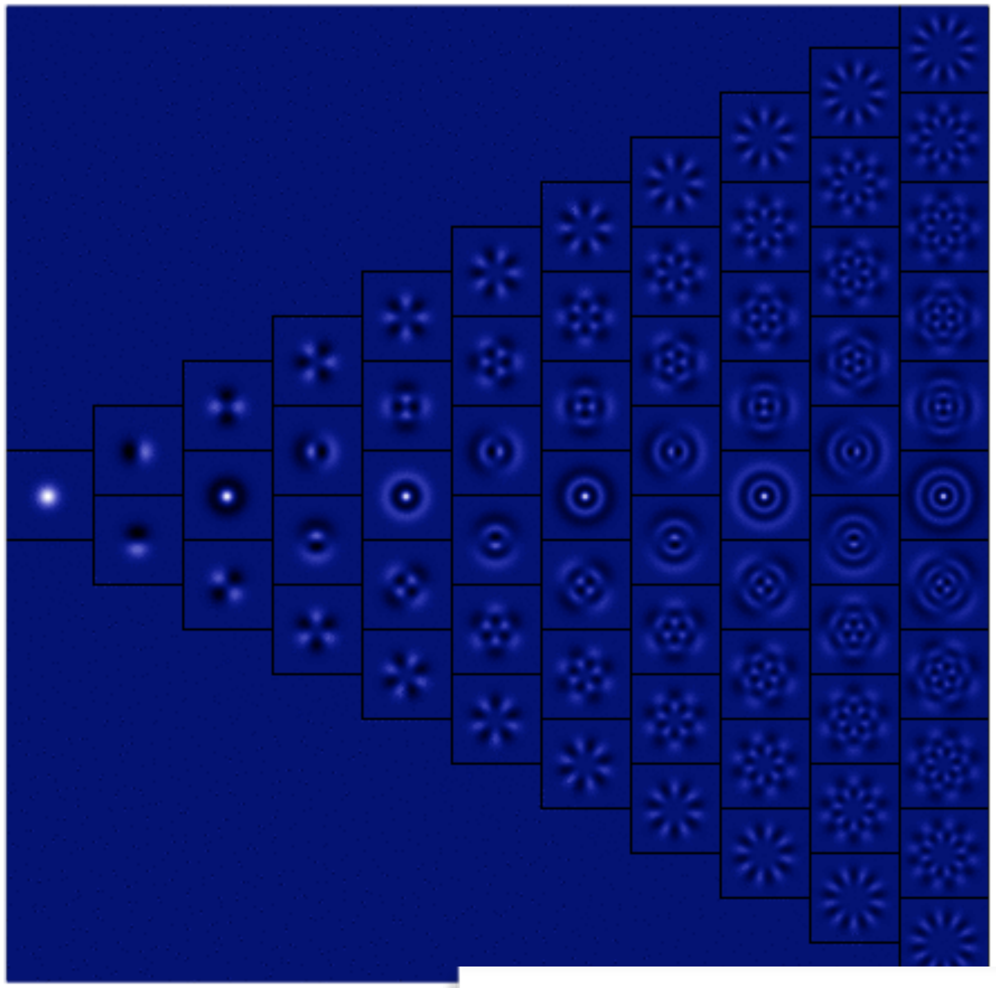
ZEST

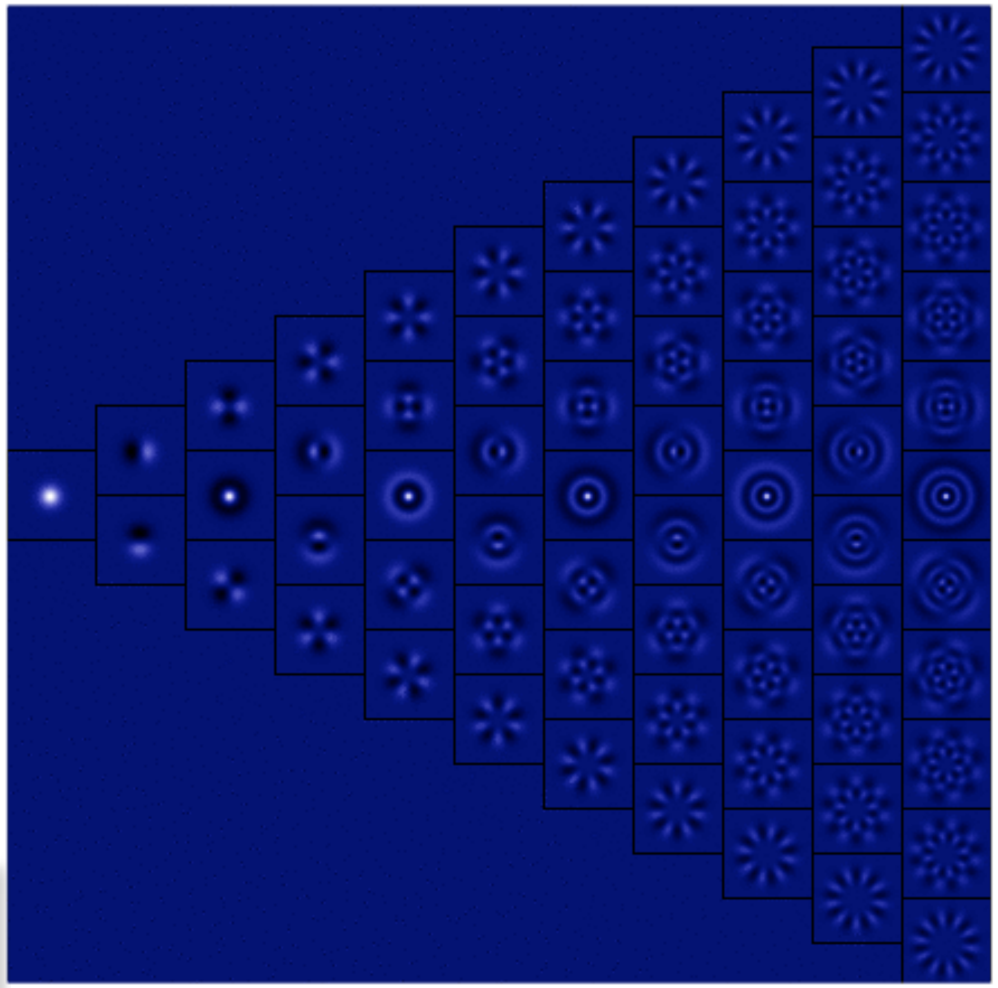


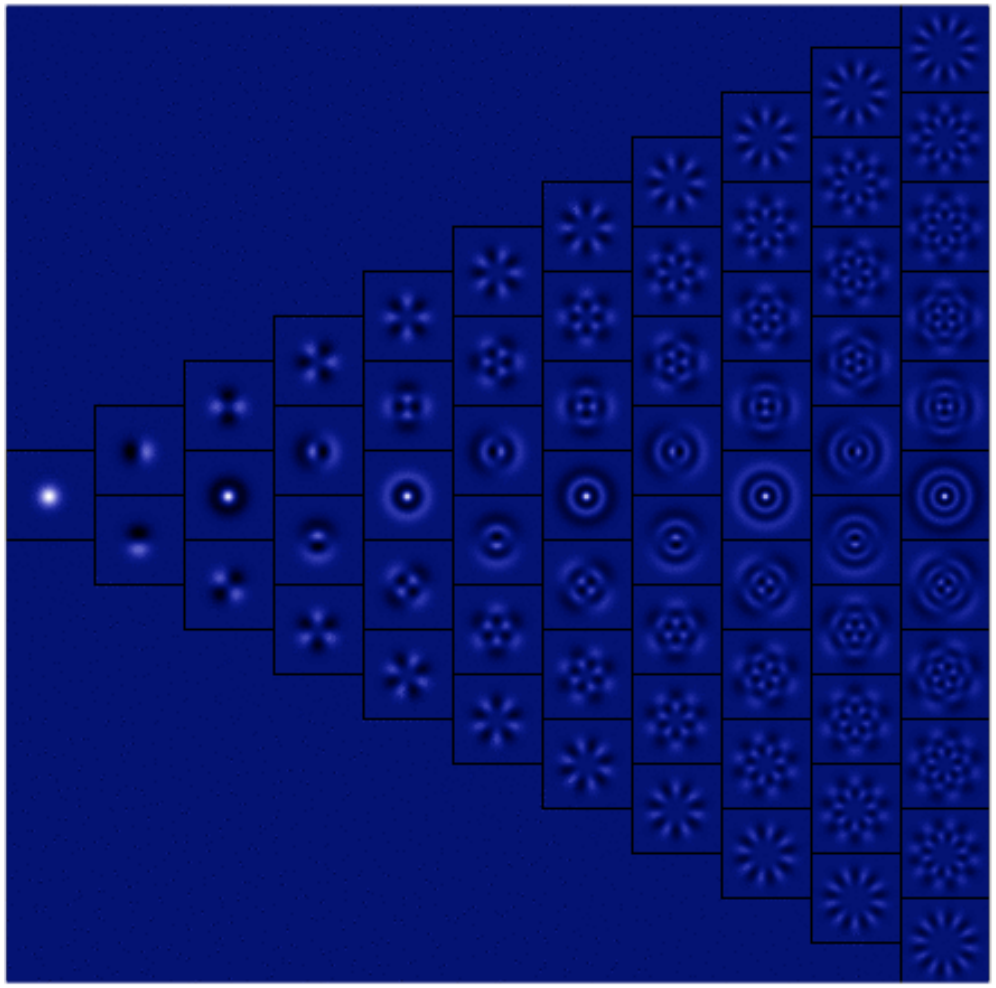
Shapelet (non-parametric) decomposition

- Base of "shapes" to decompose galaxies as linear combination, just like a vectorial space
- Large dimensionality, need to compress data --> e.g. PCA
- Usual problem with PCA: what's the physical meaning of the PCs??
- http://www.astro.caltech.edu/~rjm/shapelets/
- Wavelet decomposition: Refregier (2003), Massey & Refregier (2005), Bosch (2010) elliptical shapelets
- Kelly & McKay (2004): application to SDSS morphology

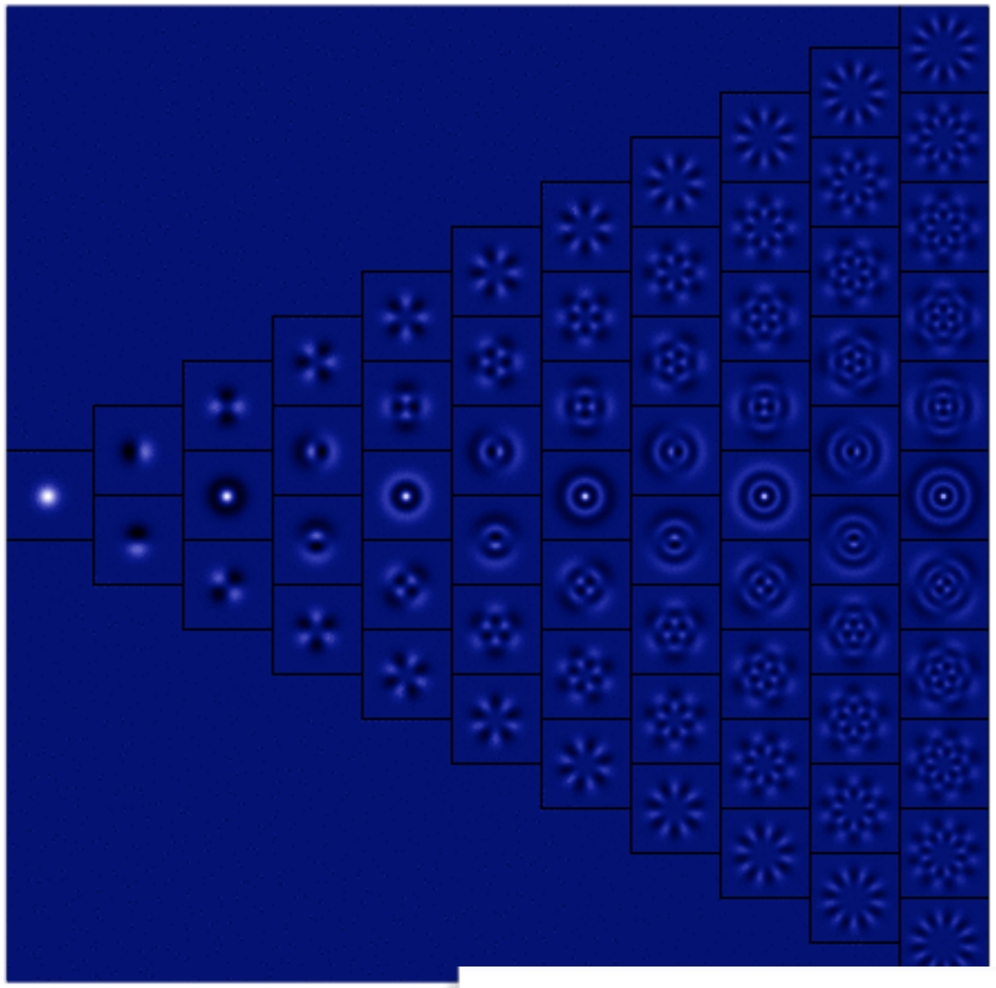
http://www.astro.caltech.edu/~rjm/shapelets/anims.php

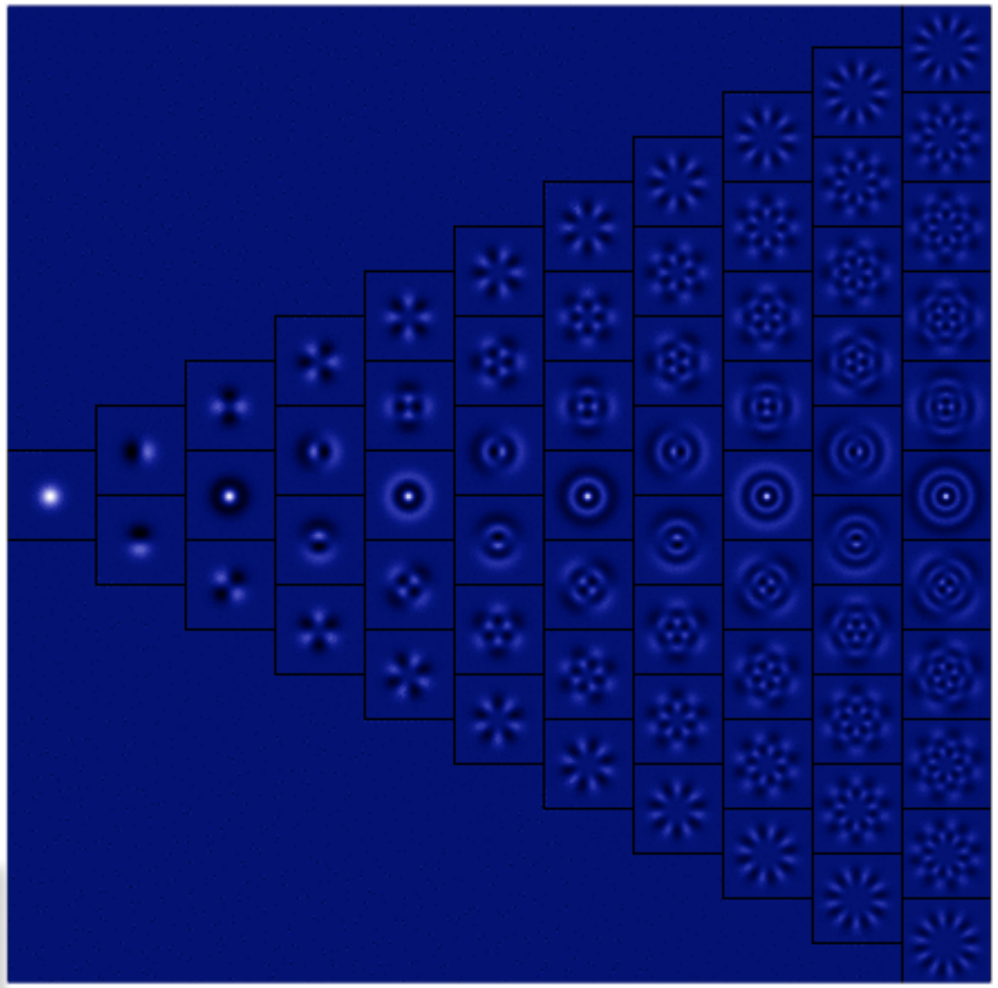


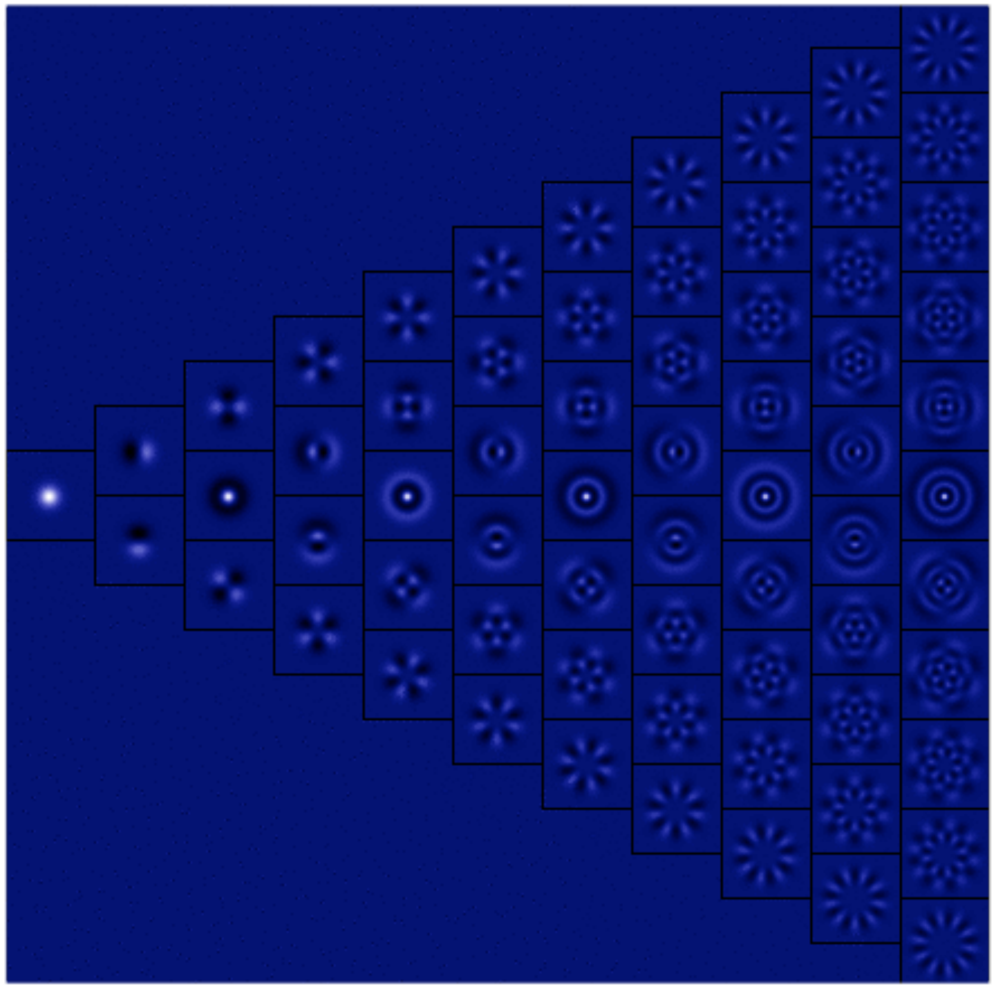




http://www.astro.caltech.edu/~rjm/shapelets/anims.php



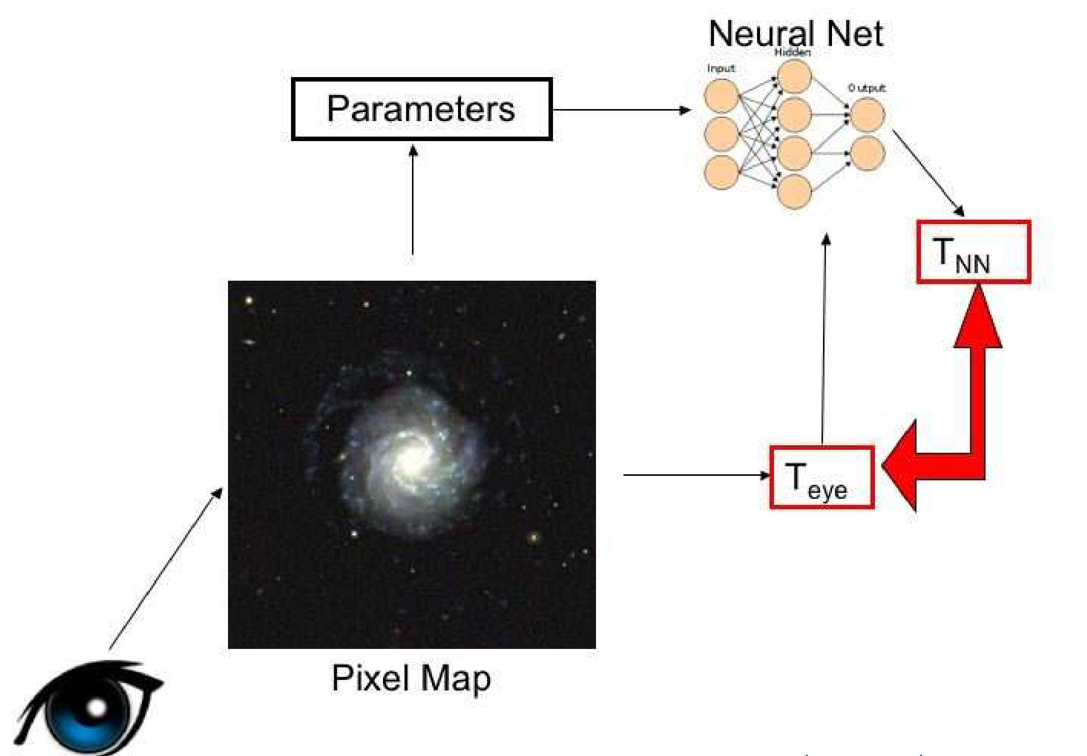




Artificial Neural Networks

- e.g. Ball et al. (2004), https://sites.google.com/site/nickballastronomer/research/ann_morph

The supervised ANN takes parameters as input and maps them on to one or more outputs. A set of vectors of parameters, each vector representing a galaxy and corresponding to a desired output, or target, is presented. The network is trained and is then able to assign an output to an unseen parameter vector.



Banerji et al. (2010)

In general the neurons could be connected in any topology, but a commonly used form is to have an $a : b_1 : b_2 : \ldots : b_n : c$ arrangement, where a is the number of input parameters, $b_{1\ldots n}$ are the number of neurons in each of n one dimensional 'hidden' layers and c is the number of neurons in the final layer, equal to the number of outputs. Here we have one output, $c = 1$. Multiple outputs can give Bayesian *a posteriori* probabilities that the output is of that class given the values of the input parameters. (This is classification, whereas a single output, $c = 1$, is strictly regression.) Each neuron is connected to every neuron in adjacent layers but not to any others.

Following Lahav et al. (1996), each neuron j in layer s receives the N outputs $x_i^{(s-1)}$ from the previous layer $s-1$ and gives a linear weighted sum over the outputs,

$$I_j^{(s)} = \sum_{i=0}^{N} w_{ij}^{(s)} x_i^{(s-1)}. \quad (9)$$

Citizen science classification GalaxyZoo

www.galaxyzoo.org