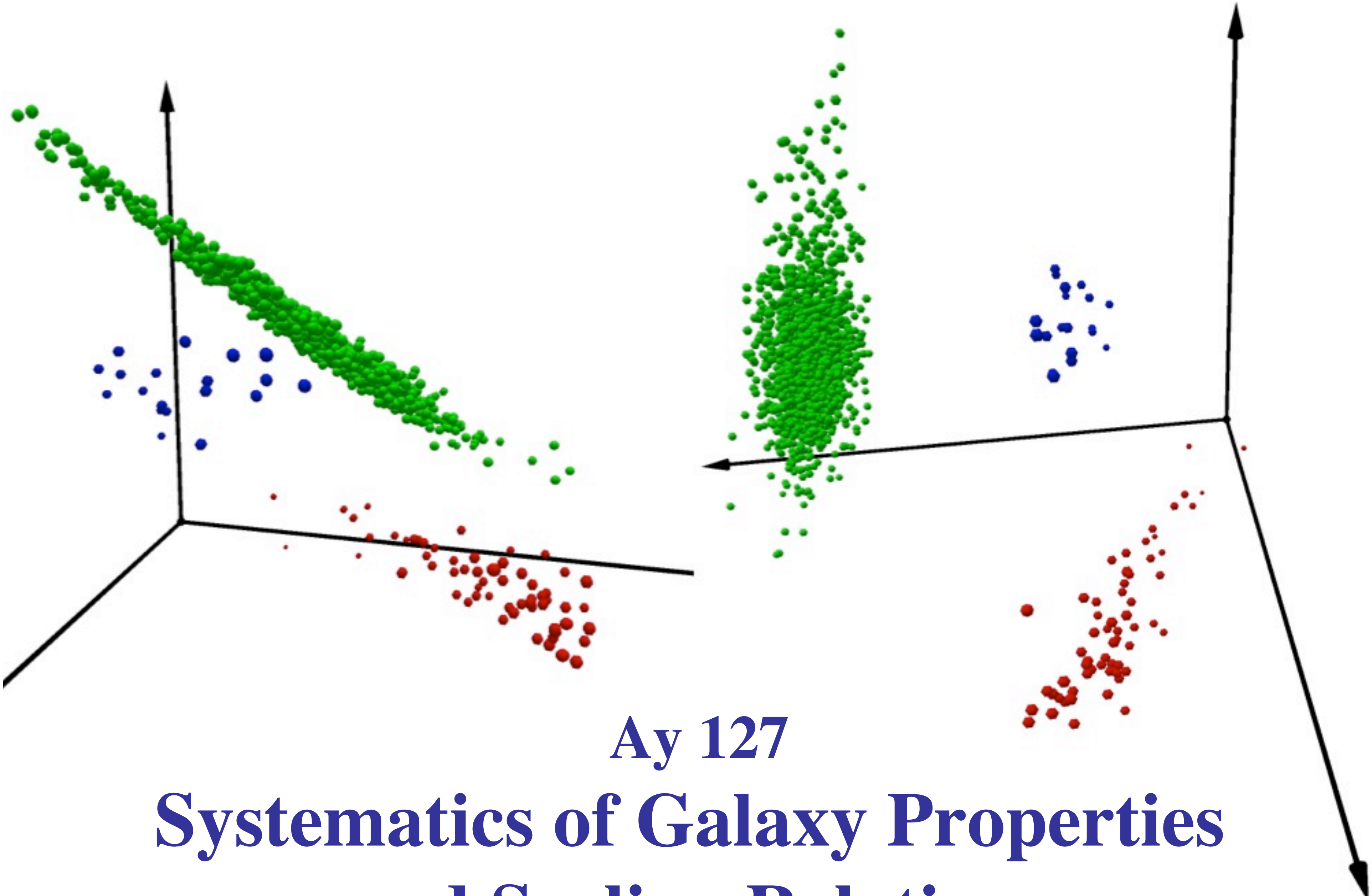


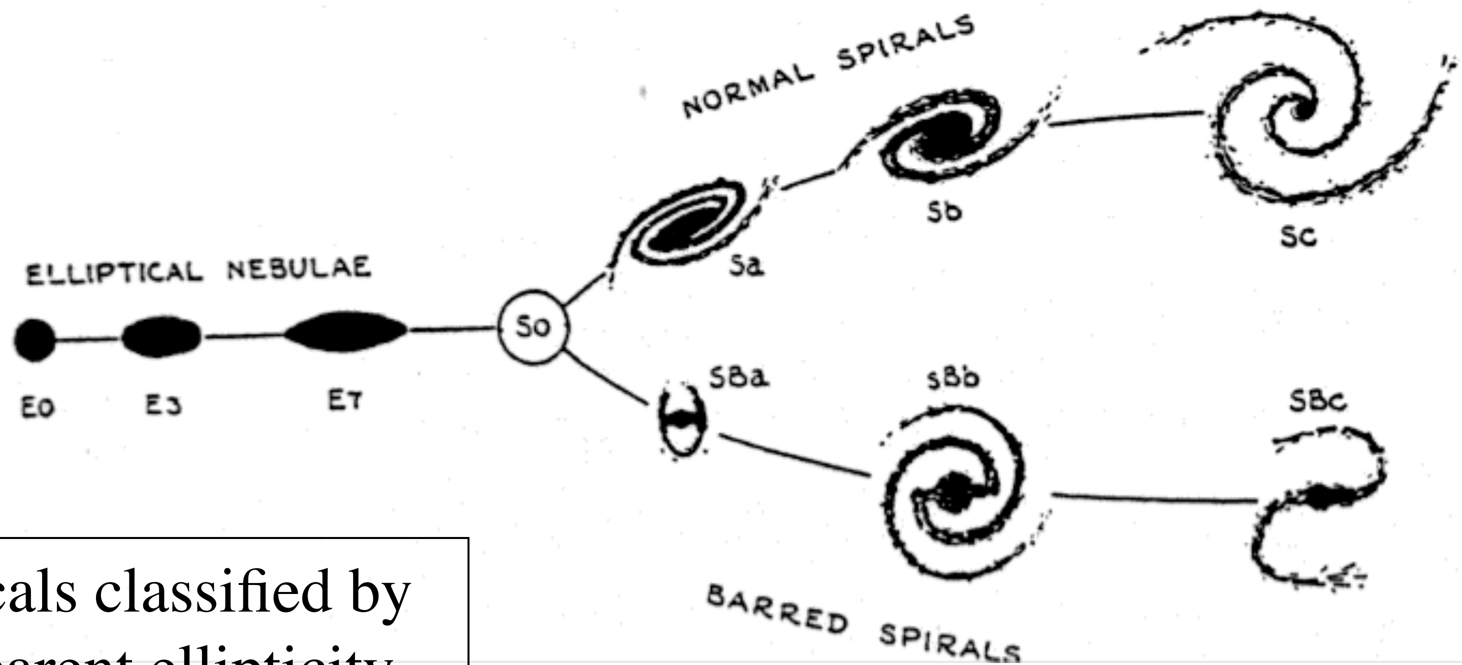
Ay 127

Systematics of Galaxy Properties and Scaling Relations

Morphological Classification and Galaxy Types

- The first step in any empirical science: look for patterns and trends, then try to understand the underlying physics
  - Hubble proposed a scheme for classifying galaxies (the "tuning fork" diagram) in his 1936 book, *The Realm of the Nebulae*
  - Subsequent refinements proposed by de Vaucouleurs (T-types), van den Bergh, and others - but not any fundamental change
- Nowadays we seek to define galaxy families through their physical properties and fundamental correlations - which reflect their physics and formative histories
- A better approach may be to look at the properties of *subsystems* within galaxies (e.g., disks, spheroids, halos, etc.), and deduce their origins and evolution

Hubble's Classification Scheme



Ellipticals classified by the apparent ellipticity

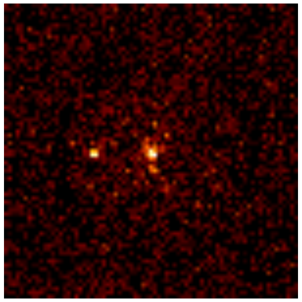
Spirals classified by the prominence of the spiral arms, and the presence of bars

Hubble thought (incorrectly) this was an evolutionary sequence, so ellipticals are called "early-type" and spirals "late-type" galaxies

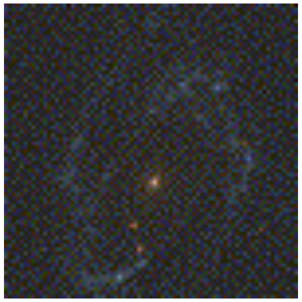
Problems With Traditional Galaxy Classification

Appearance of galaxies is strongly dependent on **which wavelength** the observations are made in.

e.g., the nearby galaxy M81:



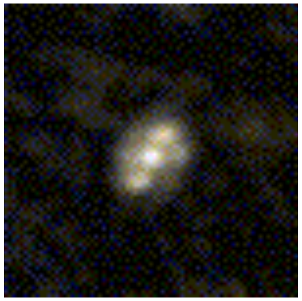
X-ray



UV

Visible

Near-IR



Far-IR

Note: large change in appearance between the UV and the near infrared images.

Galaxies look "clumpier" in the UV, and increasingly smooth as we go to the visible and longer wavelengths.

Problems With Traditional Galaxy Classification

Subjective - *especially for spiral galaxies*

However, there are automated, objective schemes to classify galaxies, using measured image parameters.

Superficial - *based on appearance, not physical properties*

Galaxy types or families can be defined in a parameter space of various measured/physical quantities. Different galaxy families follow different correlations.

Incomplete - *misses the major dichotomy of dwarfs and giants* (not separated in the traditional Hubble sequence)

Dwarfs also exist in gas rich / gas poor, star forming or not, and perhaps other varieties

The Meaning of Galaxy Classification

- *Galaxy morphologies and other properties reflect different formative and evolutionary histories*
- Much can be explained by considering galaxies as composites made of two dominant visible components:
  1. Old, pressure supported bulges, where most of the star formation occurred early on
  2. Young(er), rotationally supported disks, where star formation happened gradually and is still going on
- Note that we do not involve in this the dominant mass component - the dark matter

  … and that spiral arms may be mainly ornamental …
- Nevertheless, there are some important and meaningful trends along the Hubble sequence

Galaxy Properties and the Hubble Sequence

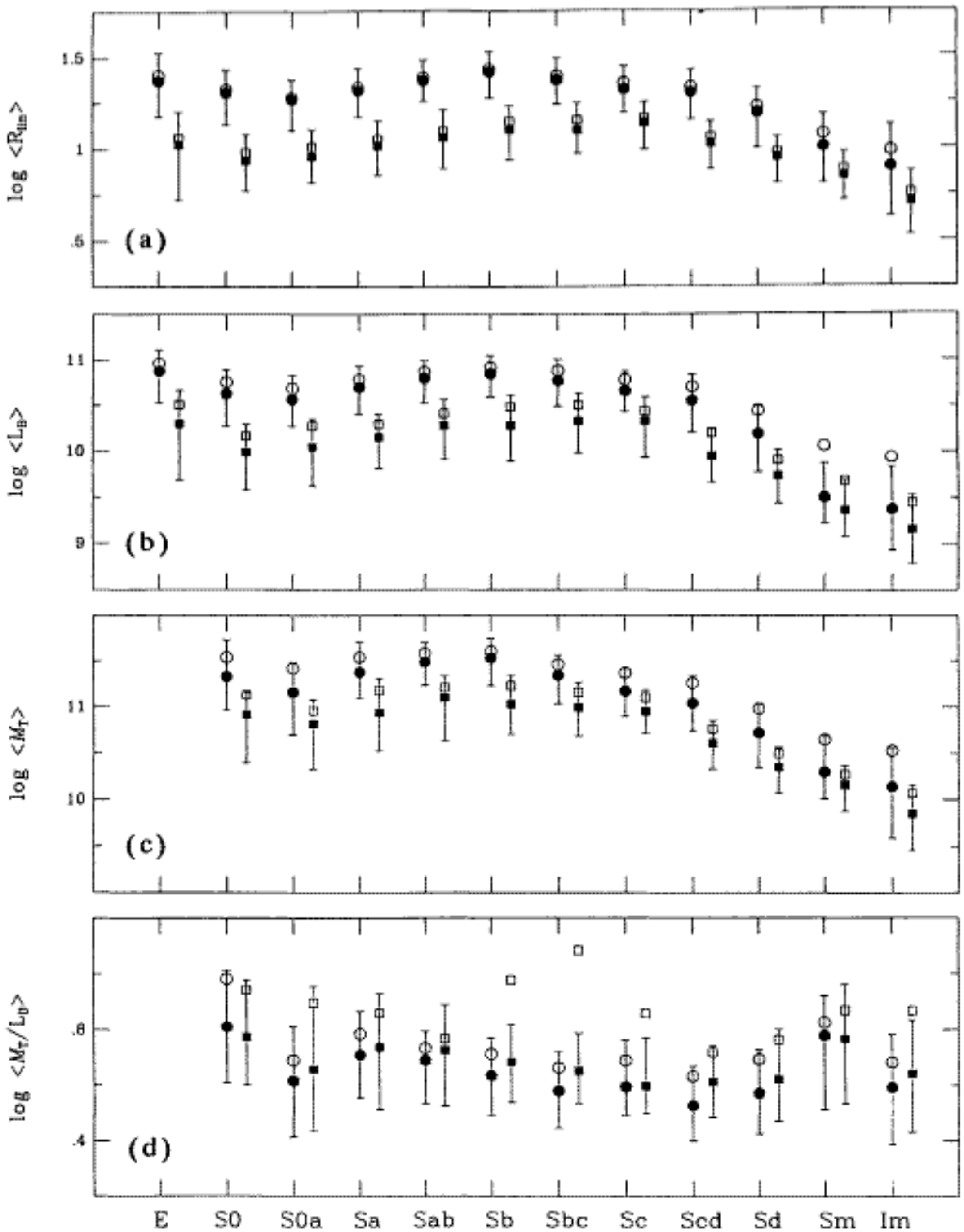
Hubble sequence turned out to be surprisingly robust: many, but not all, physical properties of galaxies correlate with the classification morphology:

E S0 Sa Sb Sc Sdm/Irr →

Pressure support ➞ Rotational support
Passive ➞ Actively star forming
Red colors ➞ Blue colors
Hot gas ➞ Cold gas and dust
Old ➞ Still forming
High luminosity density ➞ Low lum. dens.

… etc.

But, for example, masses, luminosities, sizes, etc., do not correlate well with the Hubble type: at every type there is a large spread in these fundamental properties.



Radius

Luminosity

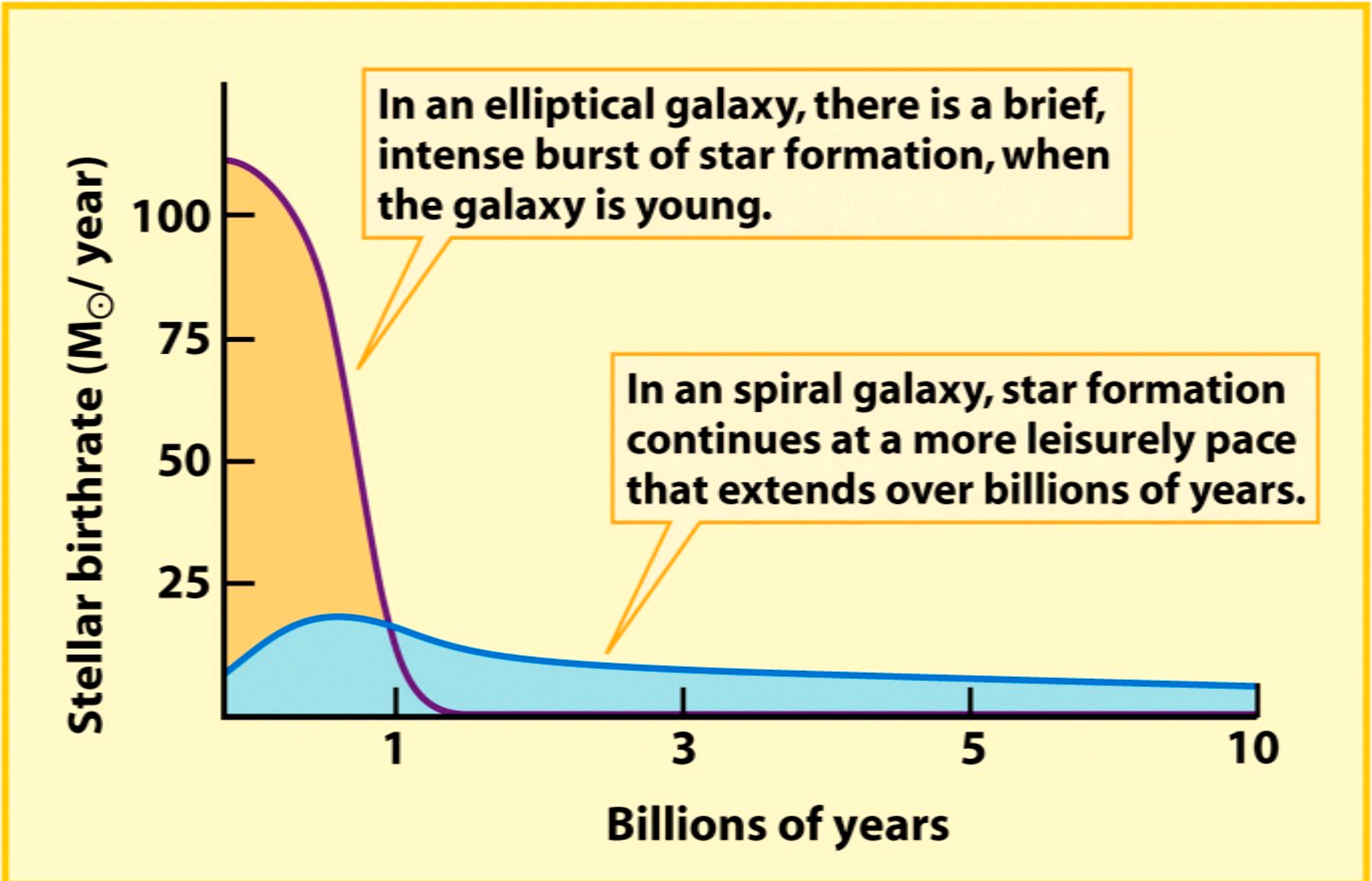
Mass

(M/L)

Interpreting the Trends Along the Hubble Sequence

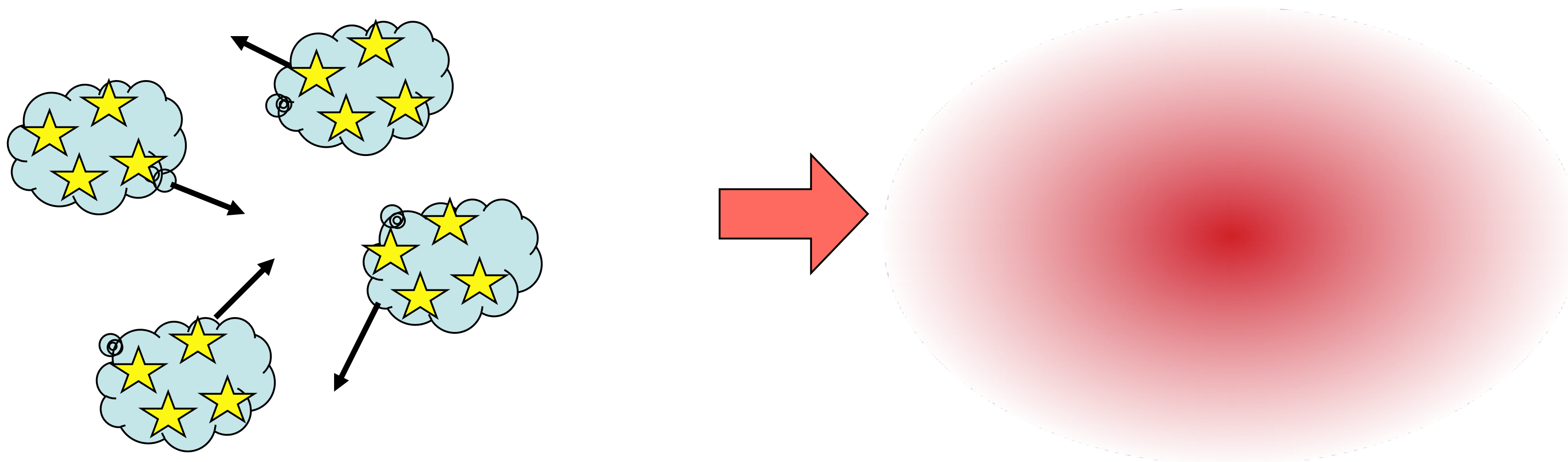
- Probably the best interpretation of many of these is ***a trend in star formation histories:***
  - Ellipticals and early type spirals formed most of their stars early on (used up their gas, have older/redder stars)
  - Late type spirals have substantial on-going star-formation, didn't form as many stars early-on (and thus lots of gas left)
  - Spirals are forming stars at a few $M_\odot$ per year, and we know that there is ~ a few x $10^9 M_\odot$ of HI mass in a typical spiral
    - How long can spirals keep forming stars?? It seems that some gas infall/resupply is needed

Star Formation History in Galaxies



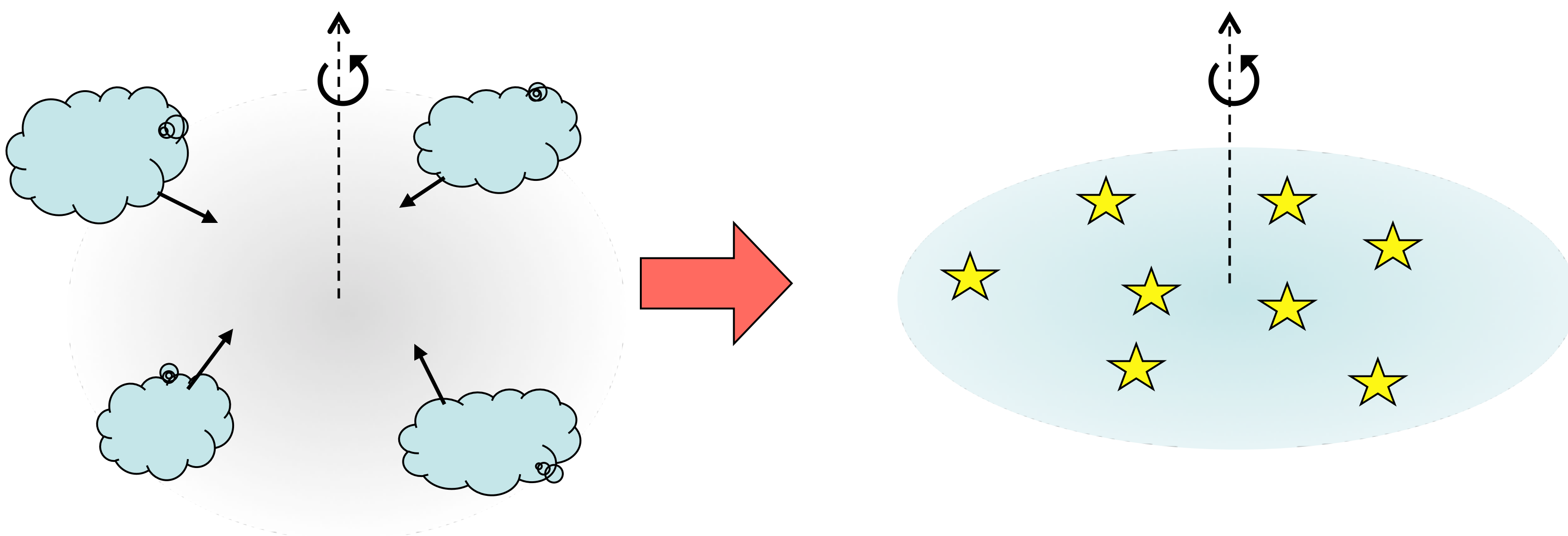
The stellar birthrate in galaxies

Formation of Galaxy Spheroids and Dynamics of Stellar Populations



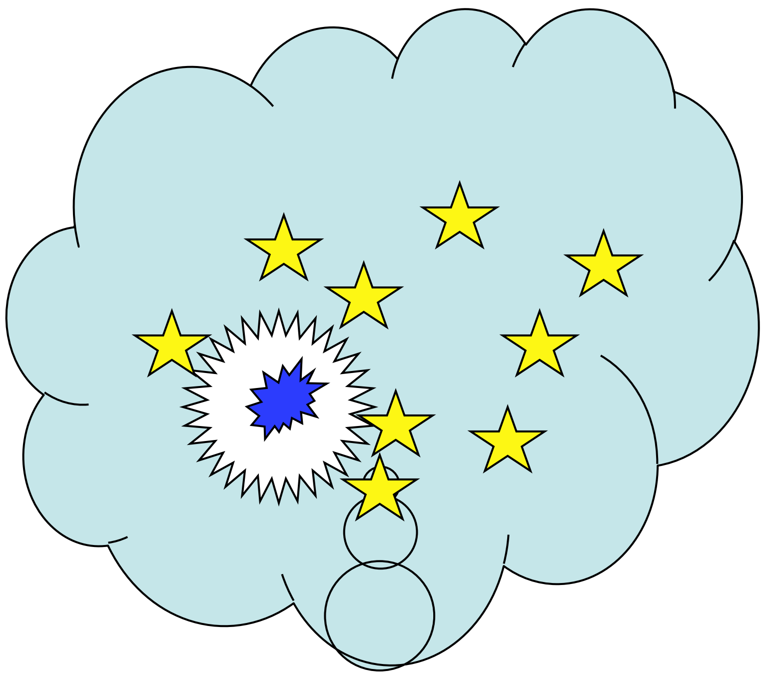
Stars "remember" the dynamics of their orbits at the time of formation, since dynamics of stellar systems is dissipationless. If stars form in dwarf protogalactic fragments which then merge, this will result in a pressure-supported system, *i.e.*, a spheroid (bulge or halo, or an elliptical galaxy). Their metallicities will reflect the abundances in their parent systems.

Formation of Galaxy Disks and Dynamics of Stellar Populations

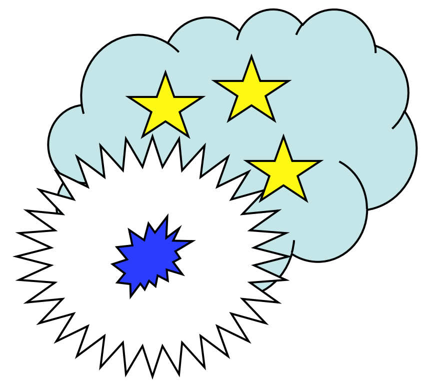


If protogalactic clouds merge dissipatively in a potential well of a dark halo, they will settle in a thin, rotating disk = the minimum energy configuration for a given angular momentum. If gas settles into a (dynamically cold) disk before stars form, then stars formed in that disk will inherit the motions of the gas (mainly an ordered rotation).

Chemical Self-Enrichment in Young Stellar Systems



In a massive system, supernova ejecta are retained, and reused for subsequent generations of stars, which achieve ever higher metallicities.



In a low-mass system, supernova shocks and star winds from massive young stars expell the enriched gas and may supress any subsequent star formation. The system retains its initial (low) metallicity.

Galaxy Scaling Laws

- When correlated, global properties of galaxies tend to do so as power-laws; thus "scaling laws"
- They provide a quantitative means of examining physical properties of galaxies and their systematics
- They reflect the internal physics of galaxies, and are a product of the formative and evolutionary histories
  - Thus, they could be (and are) different for different galaxy families
  - We can use them as a fossil evidence of galaxy formation
- When expressed as correlations between distance-dependent and distance-independent quantities, they can be used to measure relative distances of galaxies and peculiar velocities: thus, it is really important to understand their intrinsic limitations of accuracy, e.g., environmental dependences

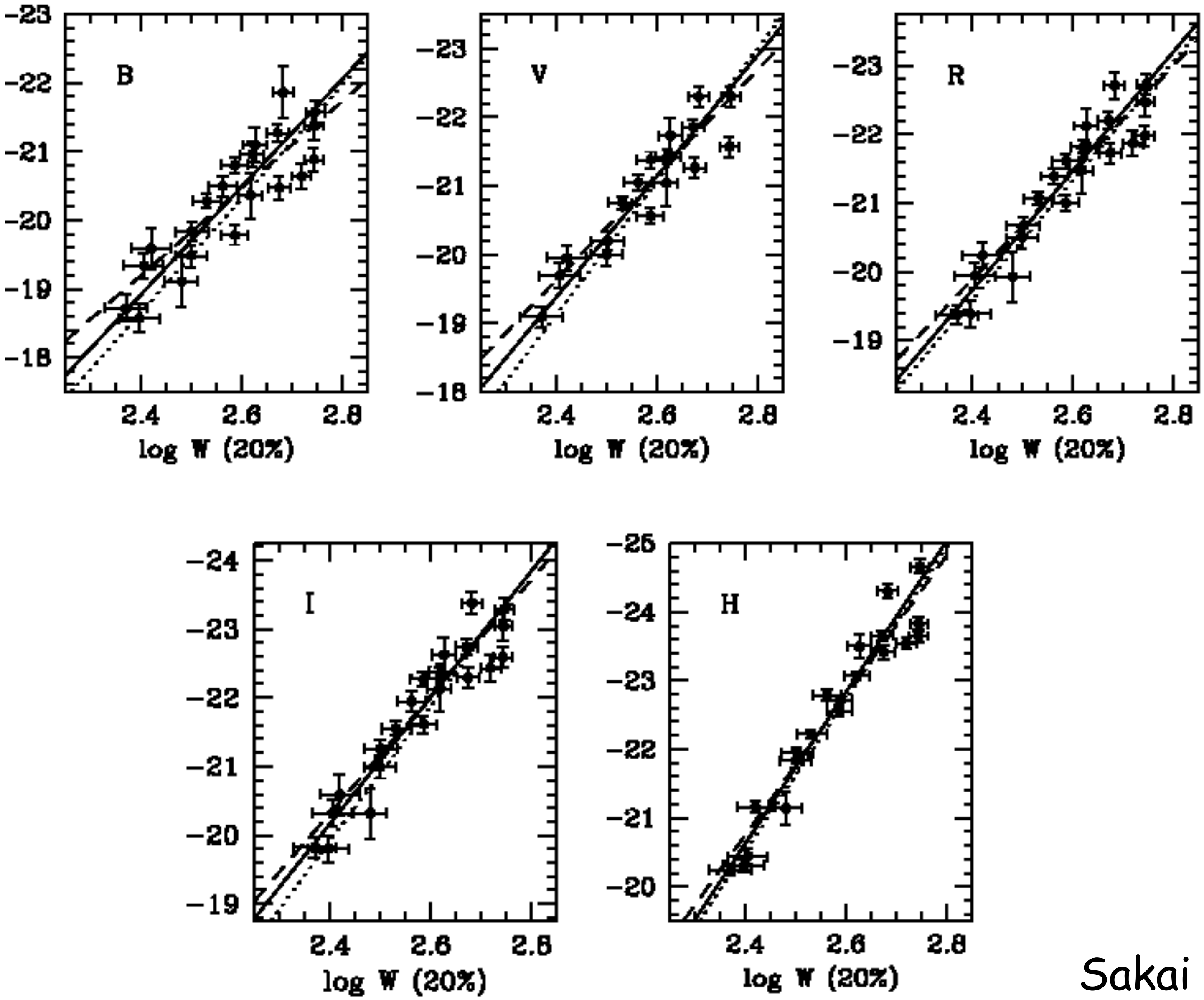
The Tully-Fisher Relation

- A well-defined luminosity vs. rotational speed (often measured as a H I 21 cm line width) relation for spirals:

$$\boldsymbol{L \sim V_{\mathbf{rot}}}^{\gamma}, \gamma \approx 4, \text{ varies with wavelength}$$

  Or: $M = b \log(W) + c$, where:
  - M is the absolute magnitude
  - W is the Doppler broadened line width, typically measured using the HI 21cm line, corrected for inclination $W_{true} = W_{obs} / \sin(i)$
  - Both the slope b and the zero-point c can be measured from a set of nearby spiral galaxies with well-known distances
  - The slope b can be also measured from any set of galaxies with roughly the same distance - e.g., galaxies in a cluster - even if that distance is not known
- Scatter is ~ 10-20% at best, better in the redder bands

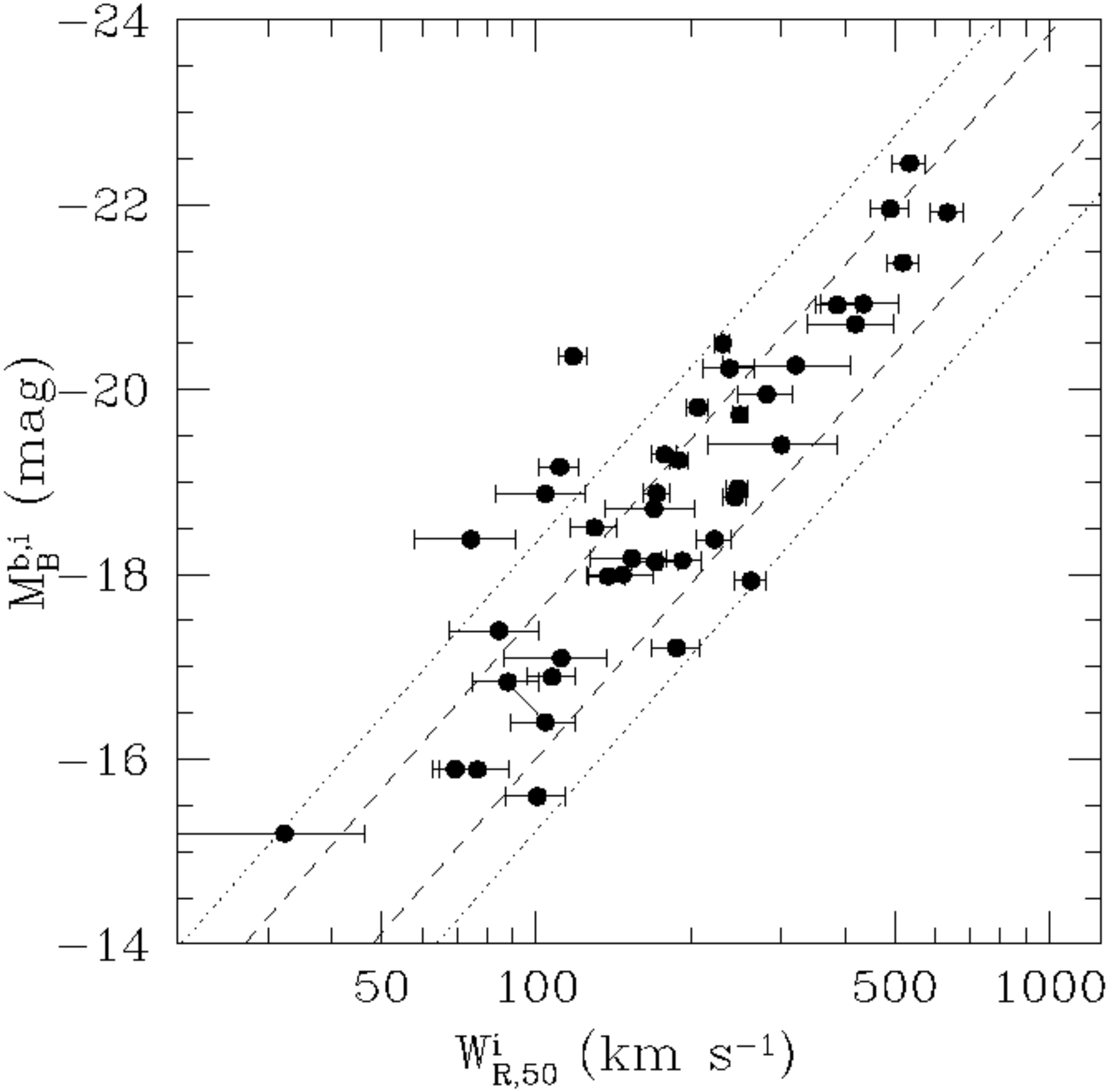
Tully-Fisher Relation in Diferent Bands



Sakai et al 1999

Why is the TFR So Remarkable?

- Because it connects a property of the dark halo - the maximum circular speed - with the product of the net integrated star formation history, i.e., the luminosity of the disk
- Halo-regulated galaxy formation/evolution?
- The scatter is remarkably low - even though the conditions for this to happen are known not to be satisfied
- There is some important feedback mechanism involved, which we do not understand yet
- Thus, the TFR offers some important insights into the physics of disk galaxy formation

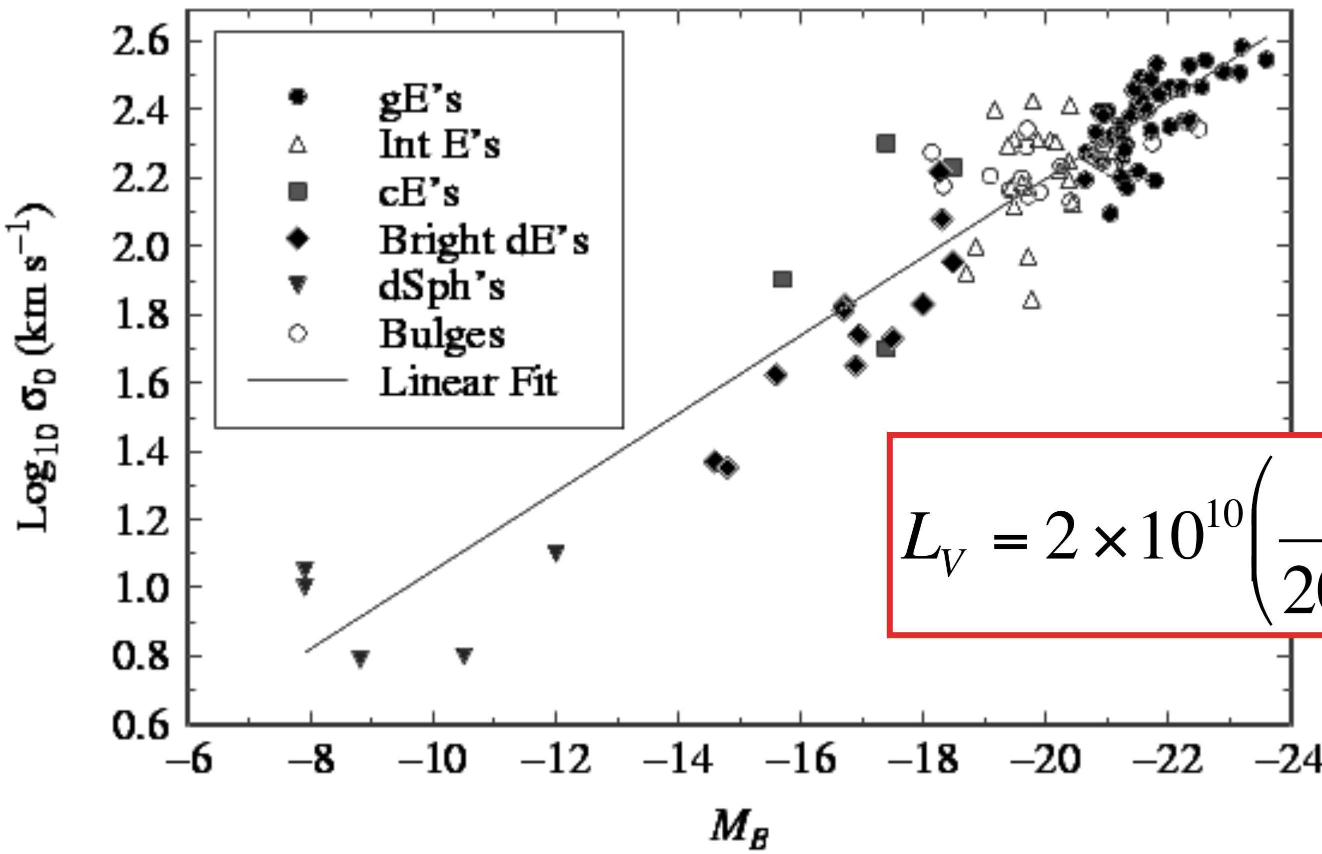


Low surface brightness galaxies follow the <u>same</u> TF law as the regular spirals: so it is really relating the baryonic mass to the dark halo

Zwaan et al. 1995

The Faber-Jackson Relation for Ellipticals

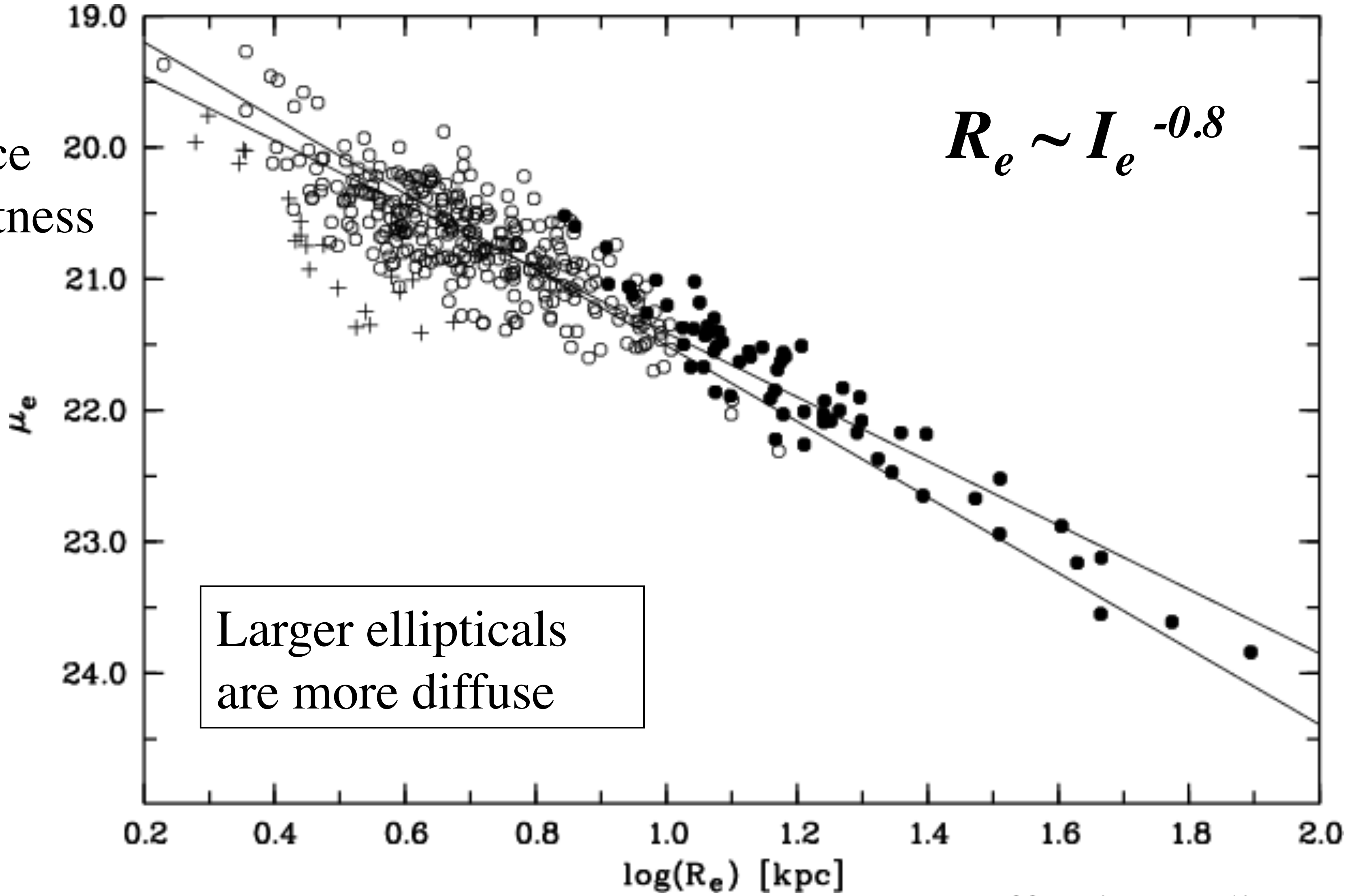
Analog of the Tully-Fisher relation for spirals, but instead of the peak rotation speed V_{max}, measure the velocity dispersion. This is correlated with the total luminosity:



$$L_V = 2\times 10^{10}\left(\frac{\sigma}{200\ \mathrm{kms^{-1}}}\right)^4 L_{sun}$$

The Kormendy Relation for Ellipticals

Mean
surface
brightness



Effective radius

Can We Learn Something About the Formation of Ellipticals From the Kormendy Relation?

From the Virial Theorem, $m\sigma^2 \sim GmM/R$

Thus, the dynamical mass scales as $M \sim R\sigma^2$

Luminosity $L \sim I\,R^2$, where I is the mean surface brightness

Assuming $(M/L) = const.$, $M \sim I\,R^2 \sim R\sigma^2$ and $I\,R \sim \sigma^2$

Now, if ellipticals form via dissipationless merging, the kinetic energy per unit mass $\sim \sigma^2 \sim const.$, and thus we would predict the scaling to be $R \sim I^{-1}$

If, on the other hand, ellipticals form via dissipative collapse, then $M = const.$, surface brightness $I \sim M\,R^{-2}$, and thus we would predict the scaling to be $R \sim I^{-0.5}$

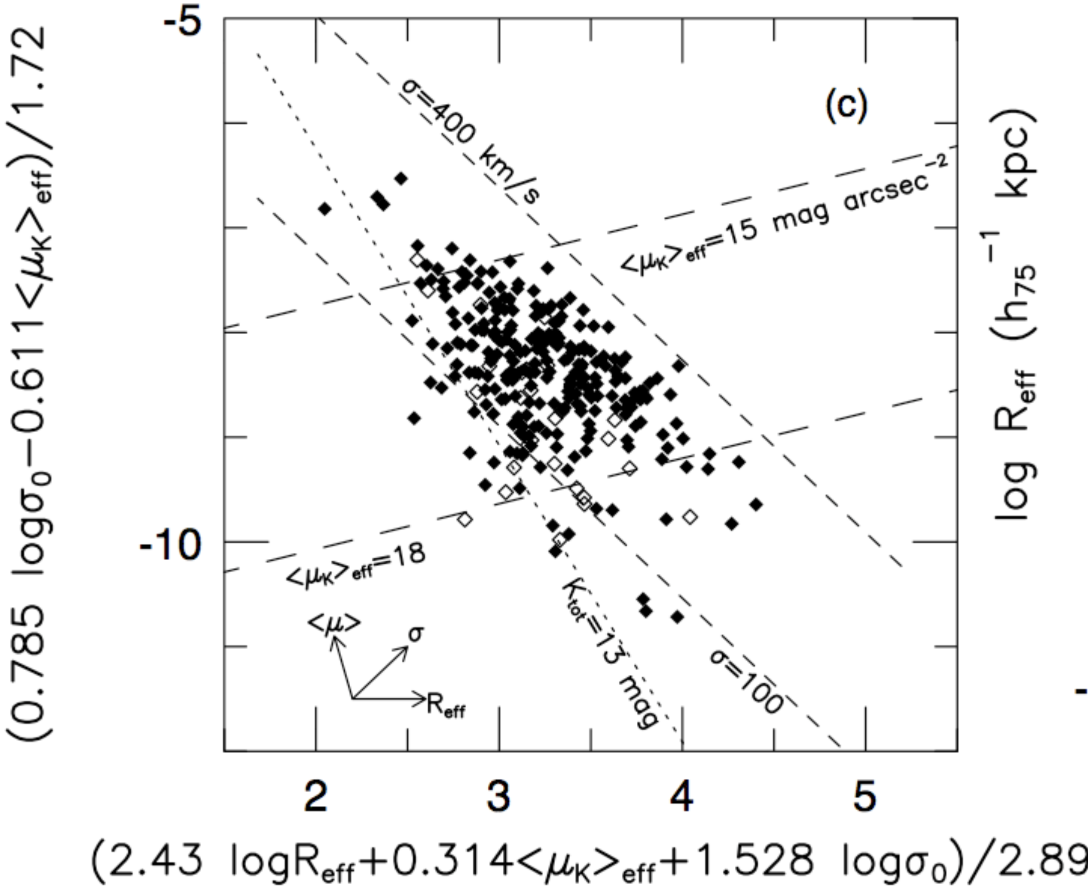
The observed scaling is $R \sim I^{-0.8}$. Thus, ***both*** dissipative collapse and dissipationless merging probably play a role

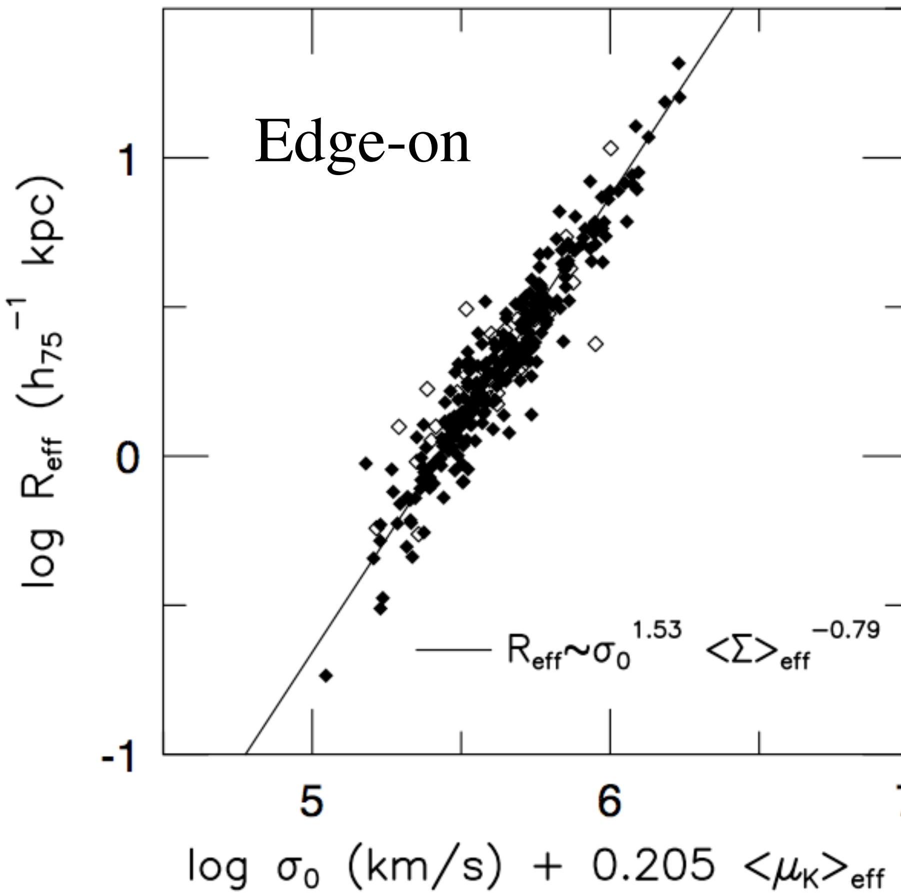
Fundamental Plane of Elliptical Galaxies

Commonly expressed as a bivariate scaling relation $\boldsymbol{R \sim \sigma^{1.4} I^{-0.8}}$

Where $\boldsymbol{R}$ is the radius, $\boldsymbol{I}$ the mean surf. brightness, $\boldsymbol{\sigma}$ the velocity disp.

Face-on

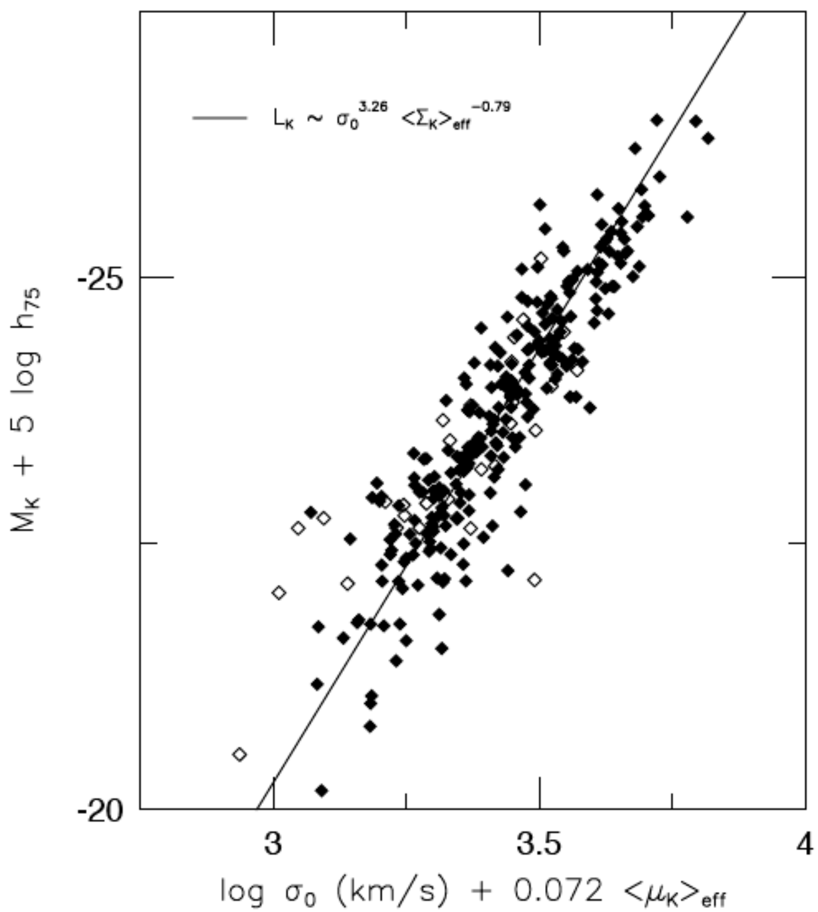




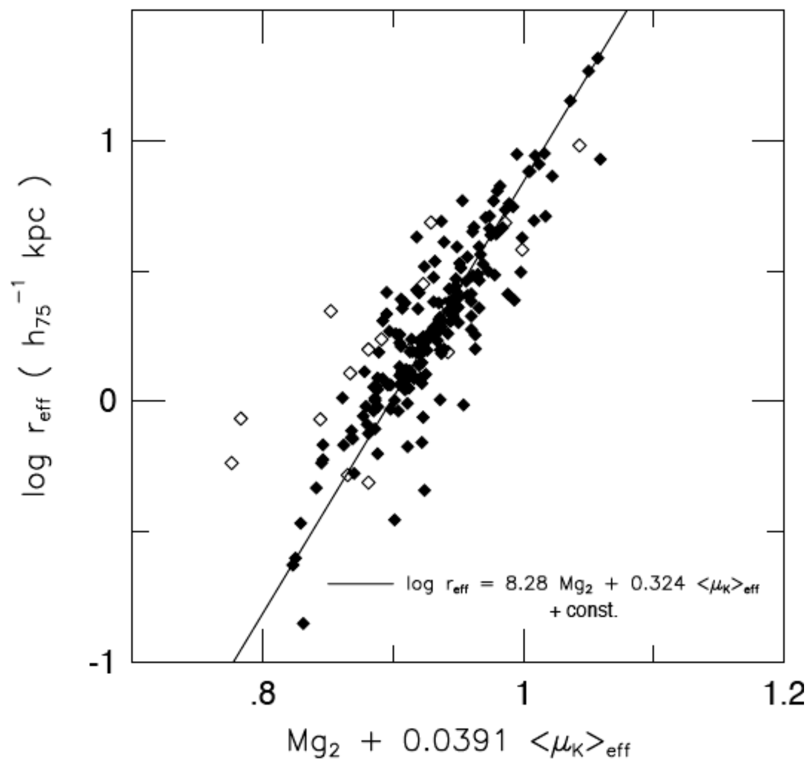
(Pahre et al. 1988)

Different Views of the FP

Luminosity instead of radius



Mg abs. line strength index (a measure of metallicity) instead of velocity dispersion



FP connects star formation histories and chemical evolution of stellar populations with dynamical and structural parameters of ellipticals

Deriving the Scaling Relations

Start with the Virial Theorem:

$$\frac{GM}{\langle R \rangle} = k_E \frac{\langle V^2 \rangle}{2}$$

Now relate the observable values of ***R*, *V*** (or ***σ***), ***L***, etc., to their "true" mean 3-dim. values by simple scalings:

$$R = k_R \langle R \rangle \qquad V^2 = k_V \langle V^2 \rangle \qquad L = k_L I R^2$$

One can then derive the "virial" versions of the FP and the TFR:

$$R = K_{SR} V^2 I^{-1} (M/L)^{-1}$$

$$L = K_{SL} V^4 I^{-1} (M/L)^{-2}$$

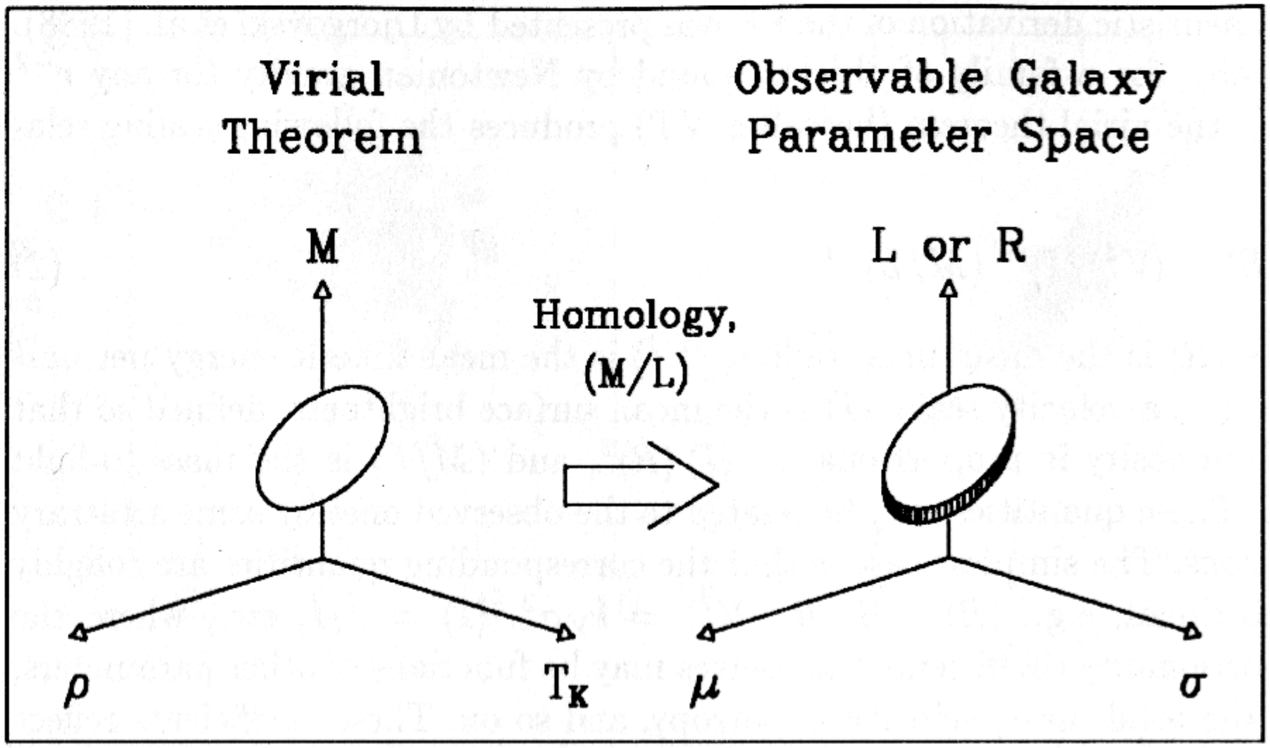
Where the "structure" coefficients are:

$$K_{SR} = \frac{k_E}{2G k_R k_L k_V}$$

$$K_{SL} = \frac{k_E^2}{4G^2 k_R^2 k_L k_V^2}$$

Deviations of the observed relations from these scalings must indicate that either some ***k'***s and/or the ***(M/L)*** are changing

From Virial Theorem to FP



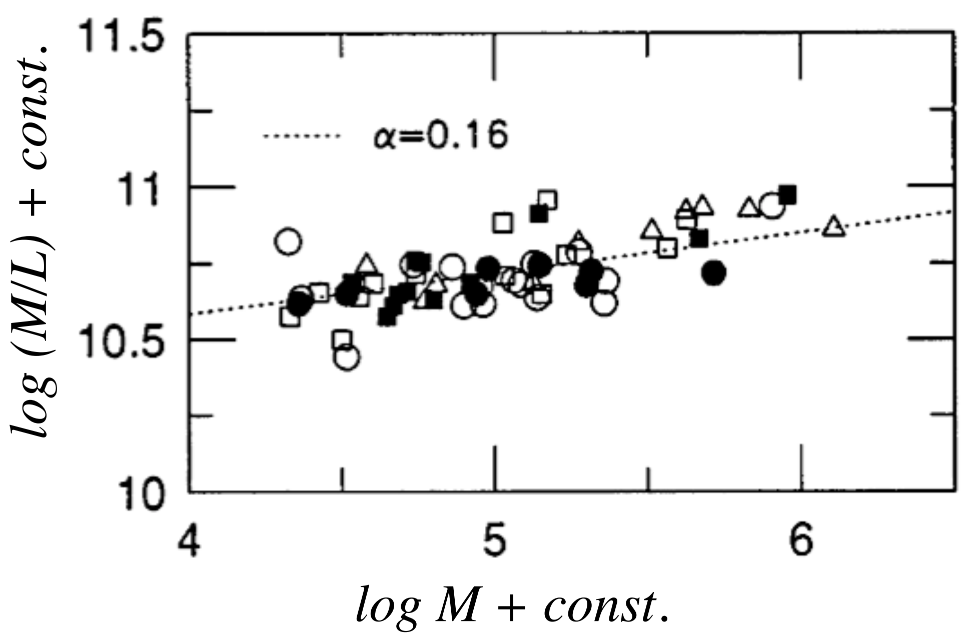
Virial Theorem connects mass, density, and kinetic temperature, and is thus an equation of a plane in that (theoretical) parameter space. Assumptions about the dynamical structure of ellipticals and their (M/L) ratios then map the VT into the tilted FP in the observable parameter space of measured quantities such as ***R*, *σ* , *I*, *L*, …**

Fundamental Plane and M/L Ratios

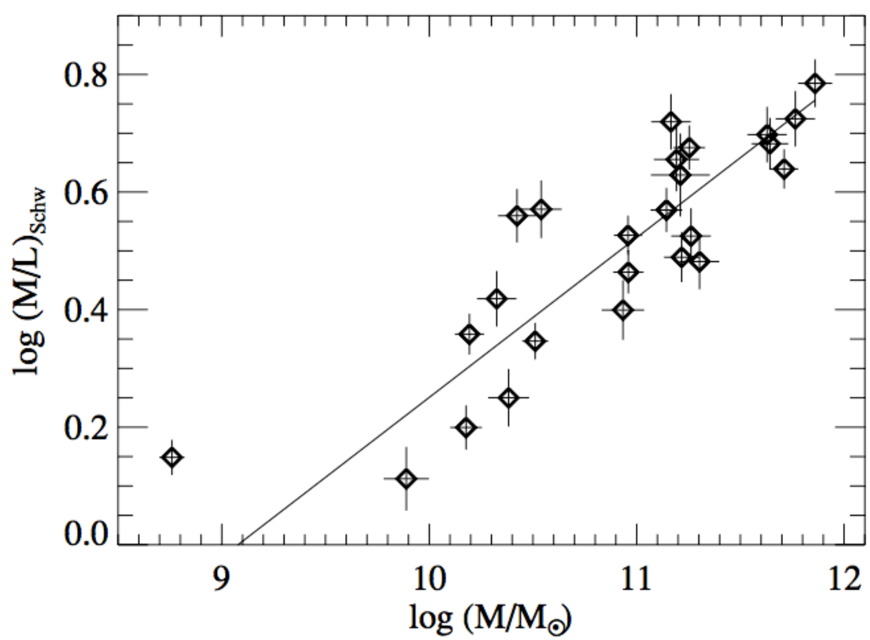
If we *assume* homology and attribute all of the FP tilt to the changes in ***(M/L)*** , $(M/L) \sim L^{\alpha}$, $\alpha \sim 0.2$ (vis) or ~ 0.1 (IR)

Possible causes: systematic changes in $M_{visible}/M_{dark}$, or in their relative concentrations; or in the stellar IMF

Pahre et al. 1995: K-band FP

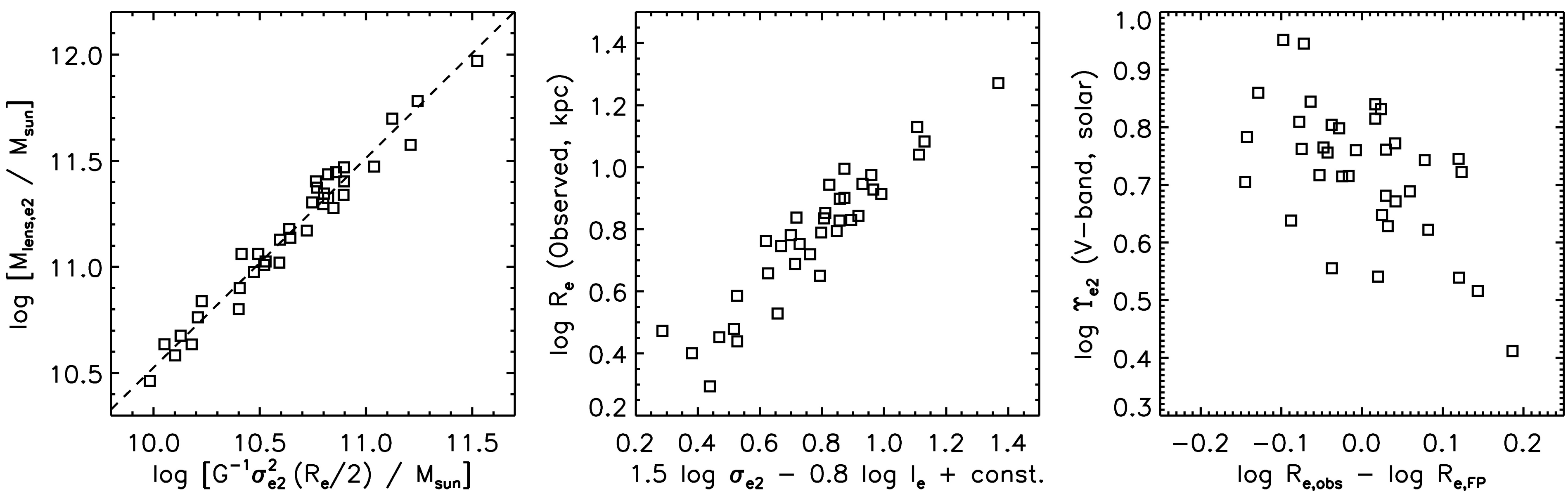


Cappellaro et al. 2006: SAURON dynamical modeling



Mass-Based Fundamental Plane

The use of lensing galaxies allows for the determination of their ***mass-based*** structural parameters *(Bolton et al. 2007)*



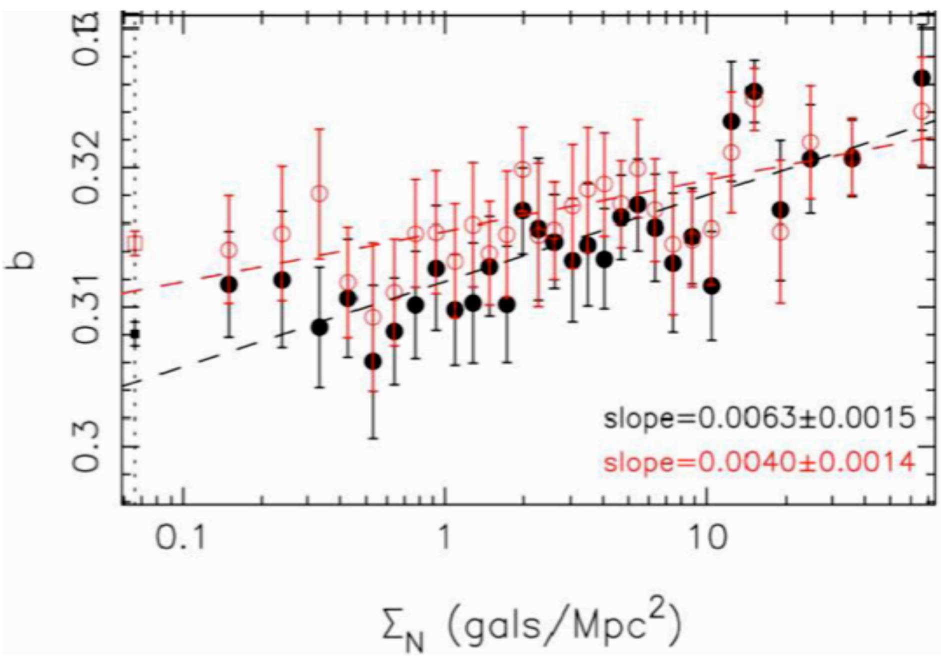
Replacing the surface brightness ***I*** with the *projected mass density* $\boldsymbol{\Sigma}$ gives a "mass plane" scaling: $R \sim \sigma^{1.8 \pm 0.2}\, \Sigma^{-1 \pm 0.2}$, consistent with the Virial Theorem, and with a smaller scatter!

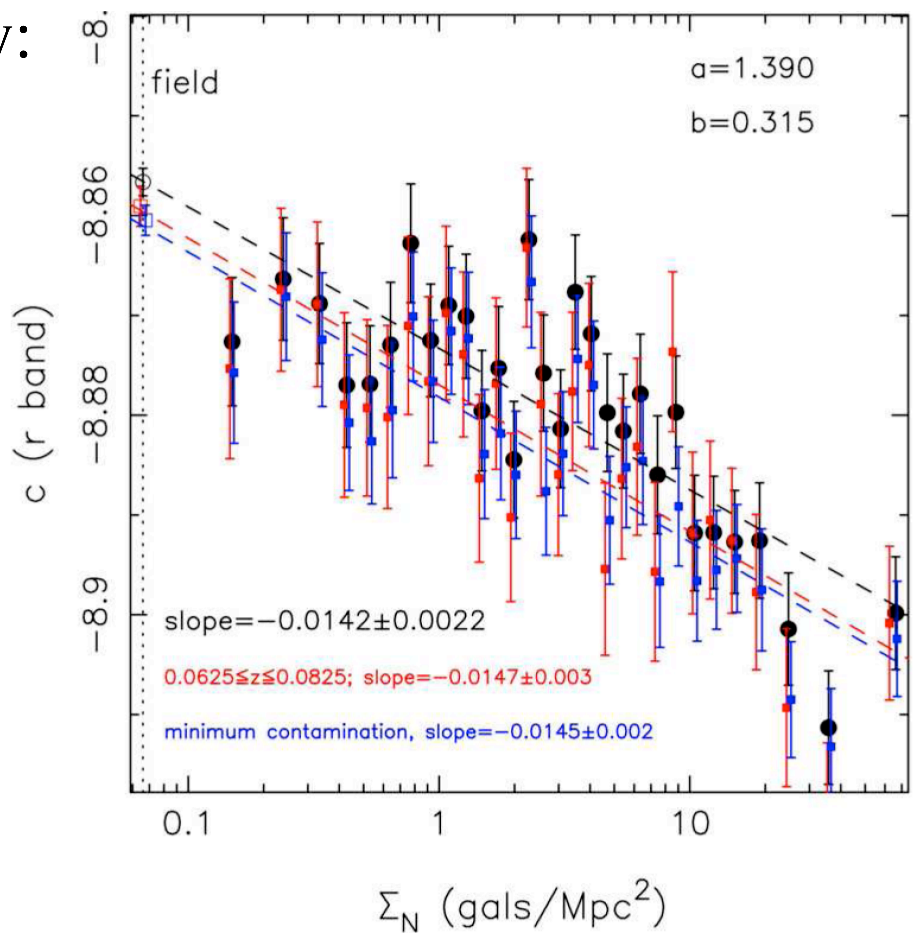
This implies *a homology of mass* (if not light) structures of E's

FP Dependence On Environment

$$\log R_e = a \log \sigma_0 + b < \mu >_e + c$$

Both surface brightness slope ***b*** and the intercept ***c*** depend weakly (at a few % level) on the projected galaxy surface density:





(La Barbera et al.)

For any elliptical galaxy today, big or small,

Just Two Numbers

determine *to within a few percent or less*:

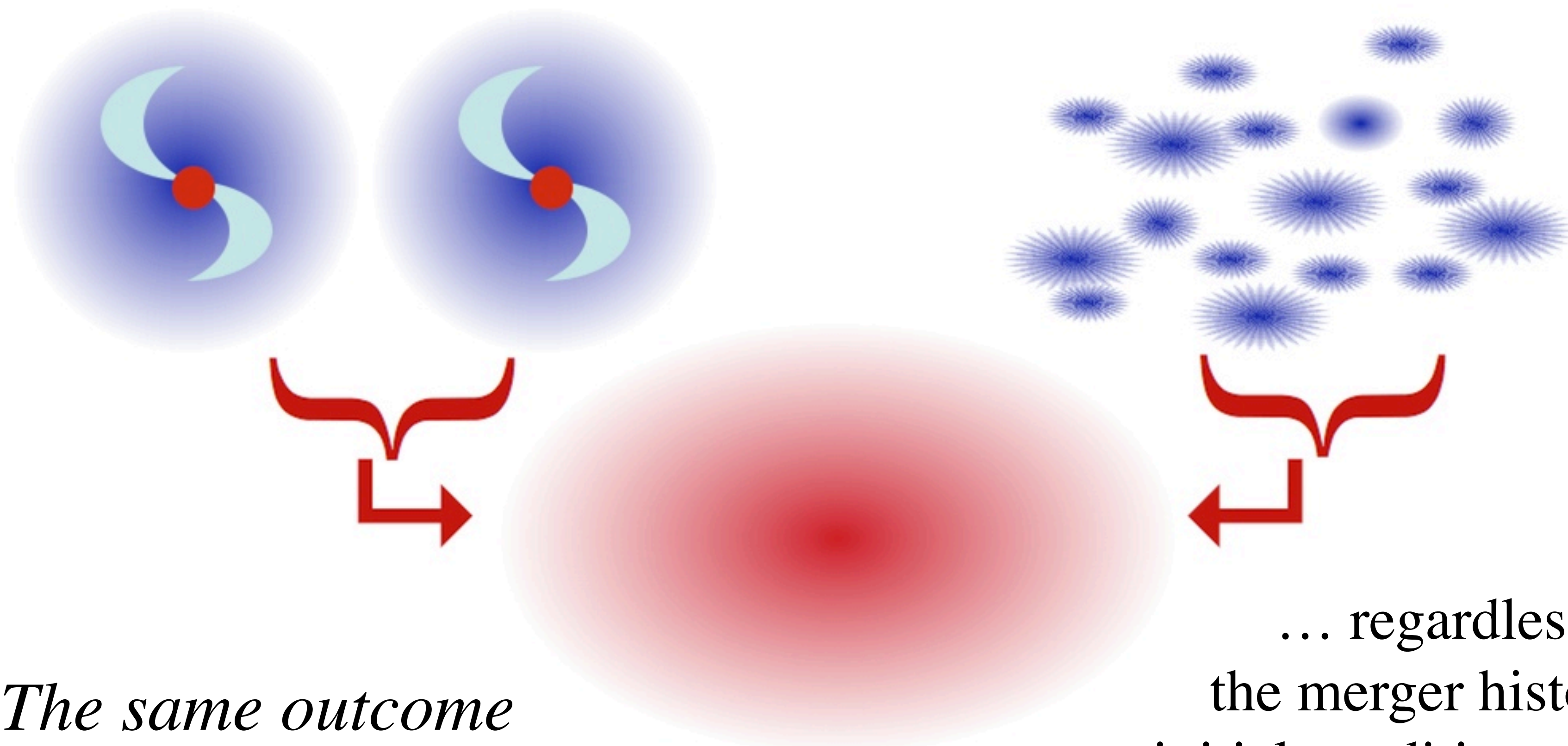
- Mass, luminosity (in any OIR band),
- Any consistently defined radius
- Surface brightness or projected mass density
- Derived 3-d luminosity, mass, or phase-space density
- Central projected radial velocity dispersion
- OIR colors, line strengths, and metallicity
- Mass of the central black hole
- … and maybe other things as well

And they do so regardless of the:

- Star formation and merging formative/evolutionary history
- Large-scale environment (to within a few %)
- Details of the internal structure and dynamics (including S0's)
- Projection effects (the direction we are looking from)

Many Paths Towards Building of an Elliptical Galaxy

Merger of 2 grand-design spirals … … or 100’s of dwarfs

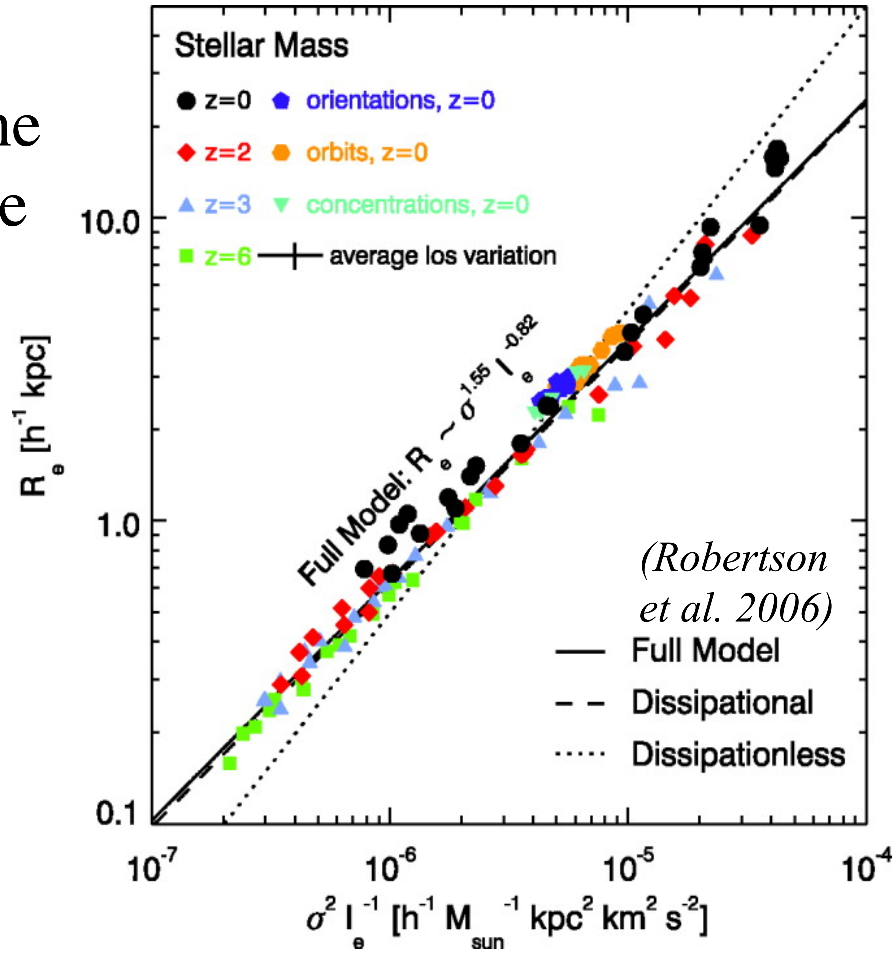


The same outcome is produced …

… regardless of the merger history, initial conditions, the amount of dissipation, etc.

How Can This Be?

- The intrinsic scatter of the FP is at most a few %, and could be 0
- The implication is that elliptical galaxies occupy only a small, naturally selected, subset of all dynamical structures which are in principle open to them
- Numerical sim's can *reproduce* the observed structures of E's, and the FP, but they *do not explain* them
- Understanding of the origin of the small scatter of the FP (or, equivalently, the narrow range of their dynamical structures) is ***an outstanding problem***



(Robertson et al. 2006)

Fundamental Corrrelations Between SMBH Masses and Their Host Galaxy Properties

53

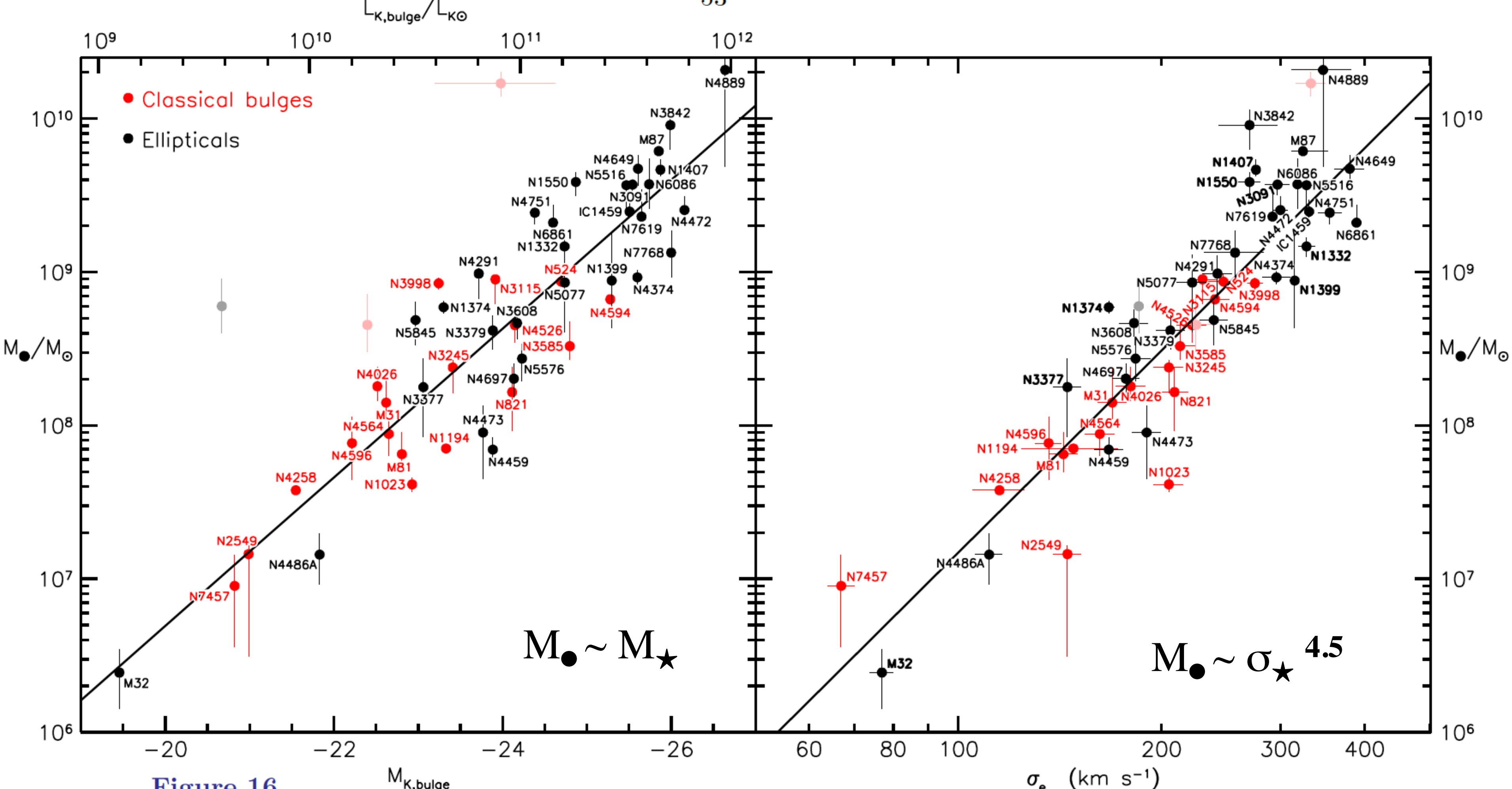


Figure 16

Correlation of dynamically measured BH mass $M_\bullet$ with (*left*) K-band absolute magnitude $M_{K,bulge}$ and luminosity $L_{K,bulge}$ and (*right*) velocity dispersion σ_e for (*red*) classical bulges and (*black*) elliptical galaxies. The lines are symmetric least-squares fits to all the points except the monsters (*points in light colors*), NGC 3842, and NGC 4889. **Figure 17** shows this fit with 1-σ error bars.

(Kormendy & Ho 2013)

Local SMBH Demographics and Comoving Mass Density

Relative fraction of SMBH mass:

$\mathbf{x = M_\bullet / M_{bulge} \sim 0.13\%}$

(*Ferrarese & Merritt 2001*)

Local mass density in bulges/E's:

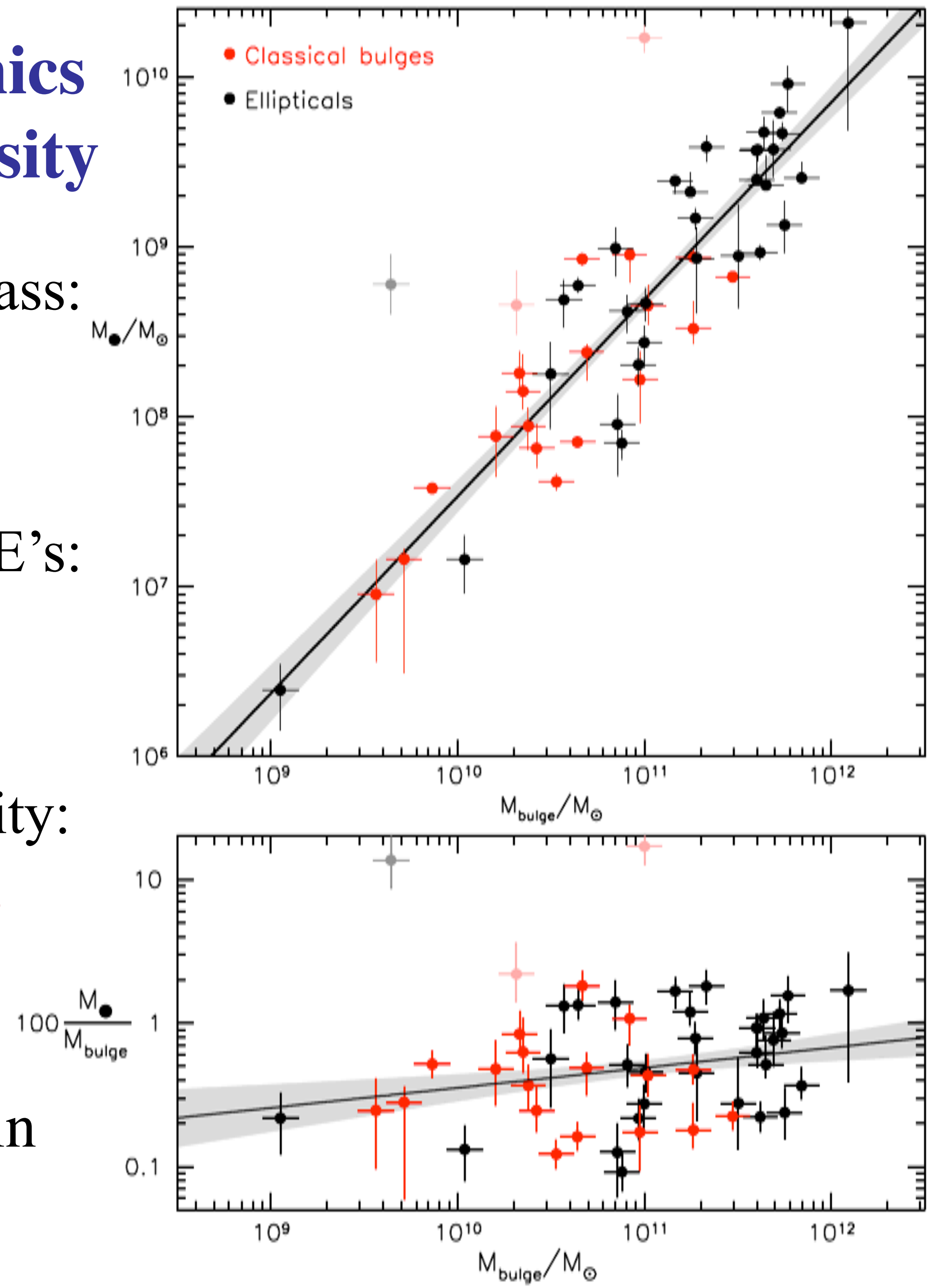
$\boldsymbol{\rho_{bulge} \sim 3.7 \times 10^8\ M_\odot\ \mathrm{Mpc}}$

(*Fukugita et al. 1998*)

Thus, local SMBH mass density:

$\boldsymbol{\rho_\bullet \sim 4.9 \times 10^5\ M_\odot\ \mathrm{Mpc}^{-3}}$

Since $\phi_* \sim 10^{-2}$ Mpc^{-3}, an average galaxy should contain a $\mathbf{\sim 10^7\ M_\odot}$ black hole!



An even more fundamental relation?

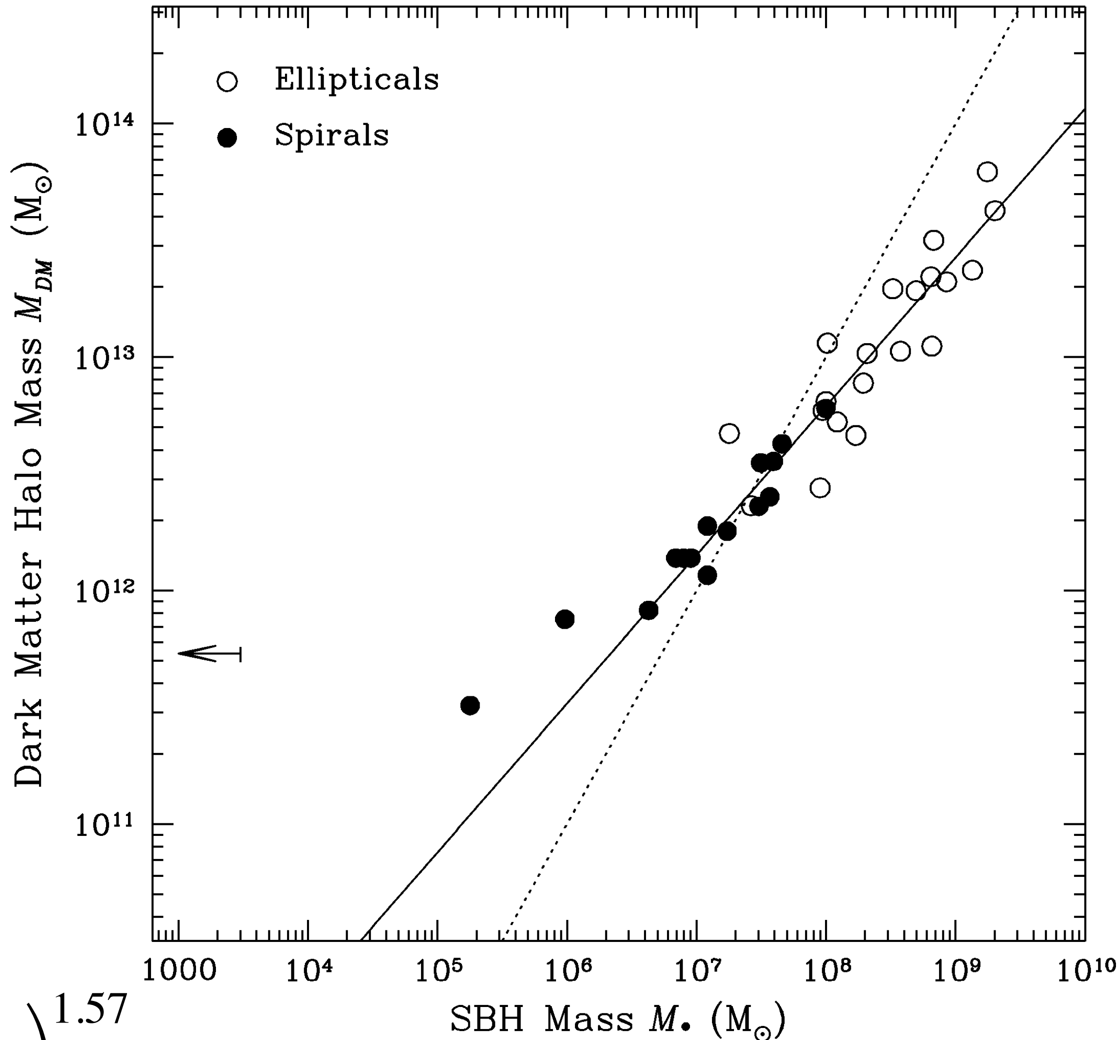
Dark halo mass
vs. SMBH mass

(Ferrarese 2002)

(However, its significance has been disputed by Kormendy et al.)

Note the nonlinearity (unlike the correlation with the stellar mass):

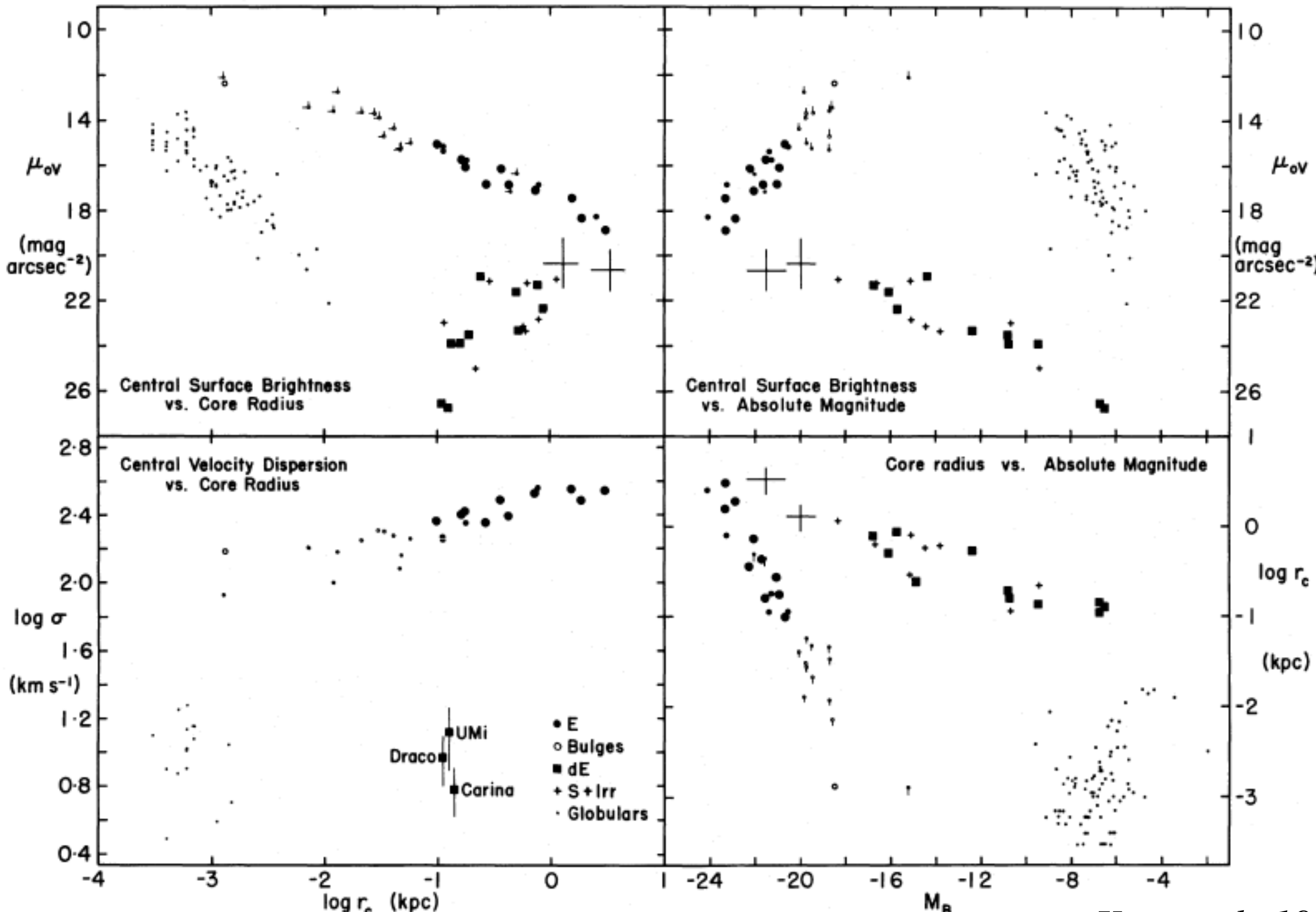
$$\frac{M_\bullet}{10^8 M_\odot} \sim 0.046 \left(\frac{M_{DM}}{10^{12} M_\odot}\right)^{1.57}$$



Dwarf Galaxies

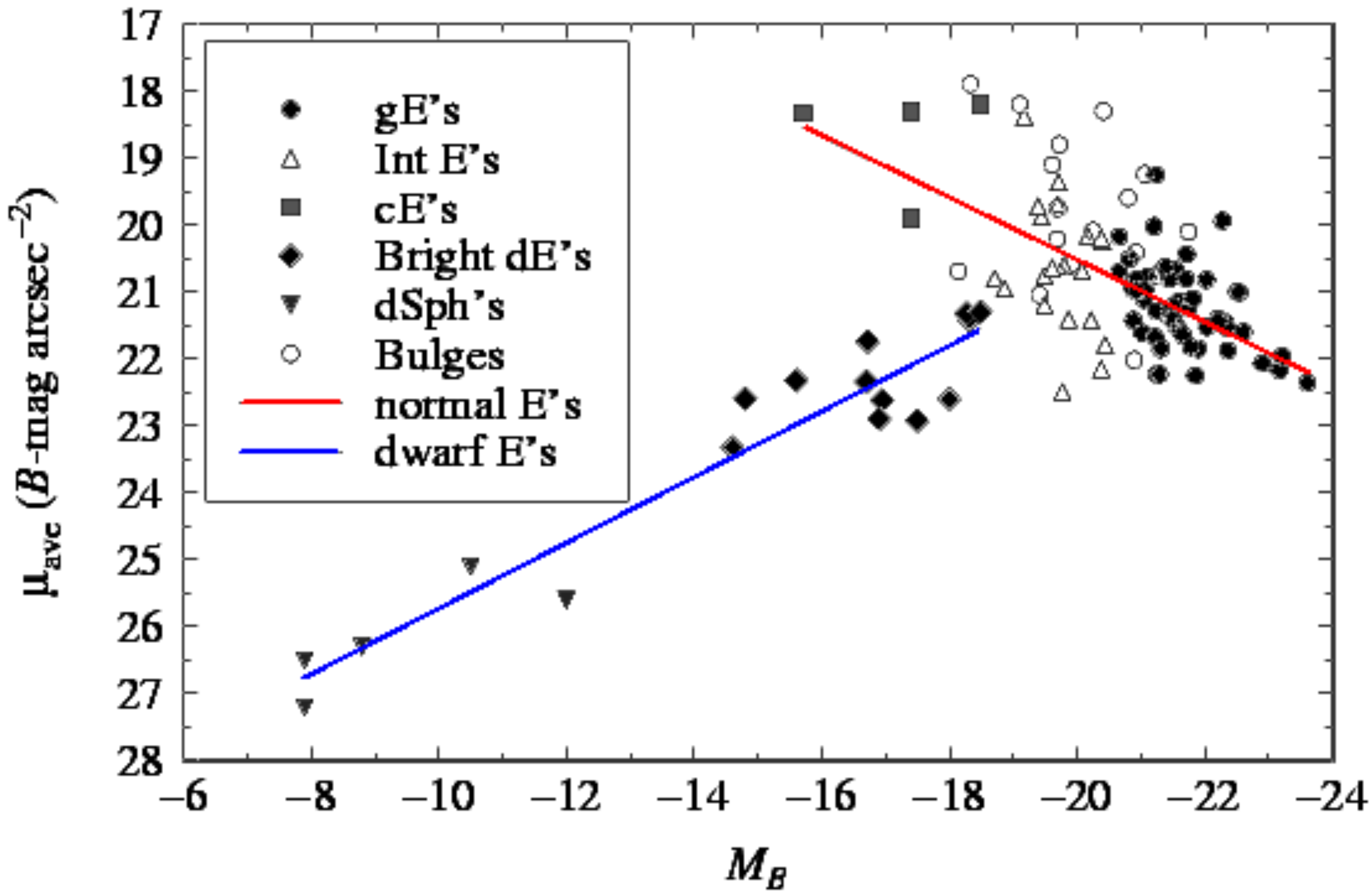
- Dwarf ellipticals (dE) and dwarf spheroidals (dSph) are a completely different family of objects from normal ellipticals - they are not just small E’s
- In fact, there may be more than one family of gas-poor dwarf galaxies …
- Dwarfs follow completely different correlations from giant galaxies, suggestive of different formative mechanisms
- They are generally dark matter (DM) dominated, especially at the faint end of the sequence
- One possible scenario is that supernova (SN) winds can remove baryons from these low-mass systems, while leaving the DM, while the more massive galaxies retain and recycle their SN ejecta

Parameter Correlations



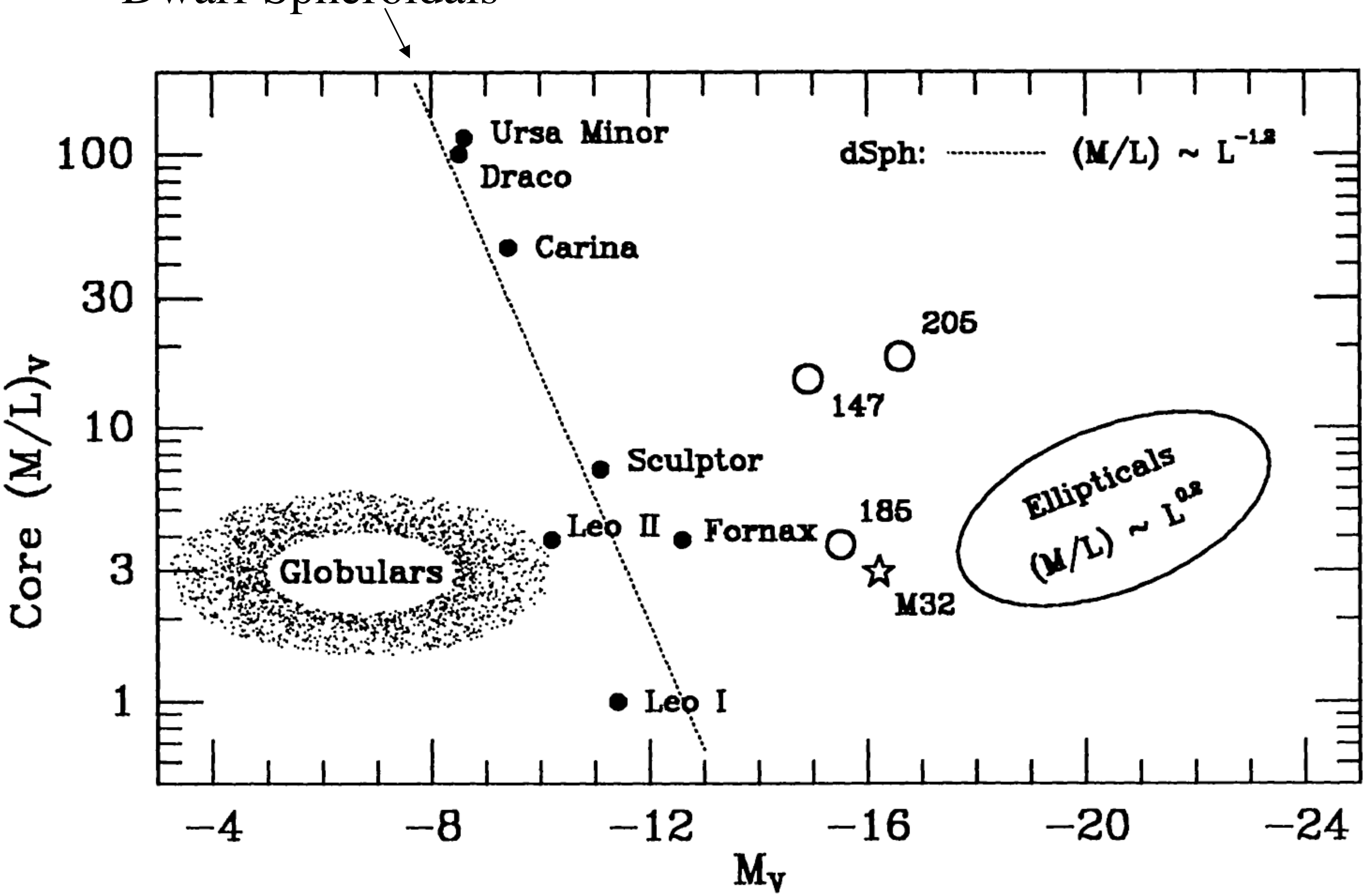
Kormendy 1985

Mean Surface Brightness vs. Absolute Mag.

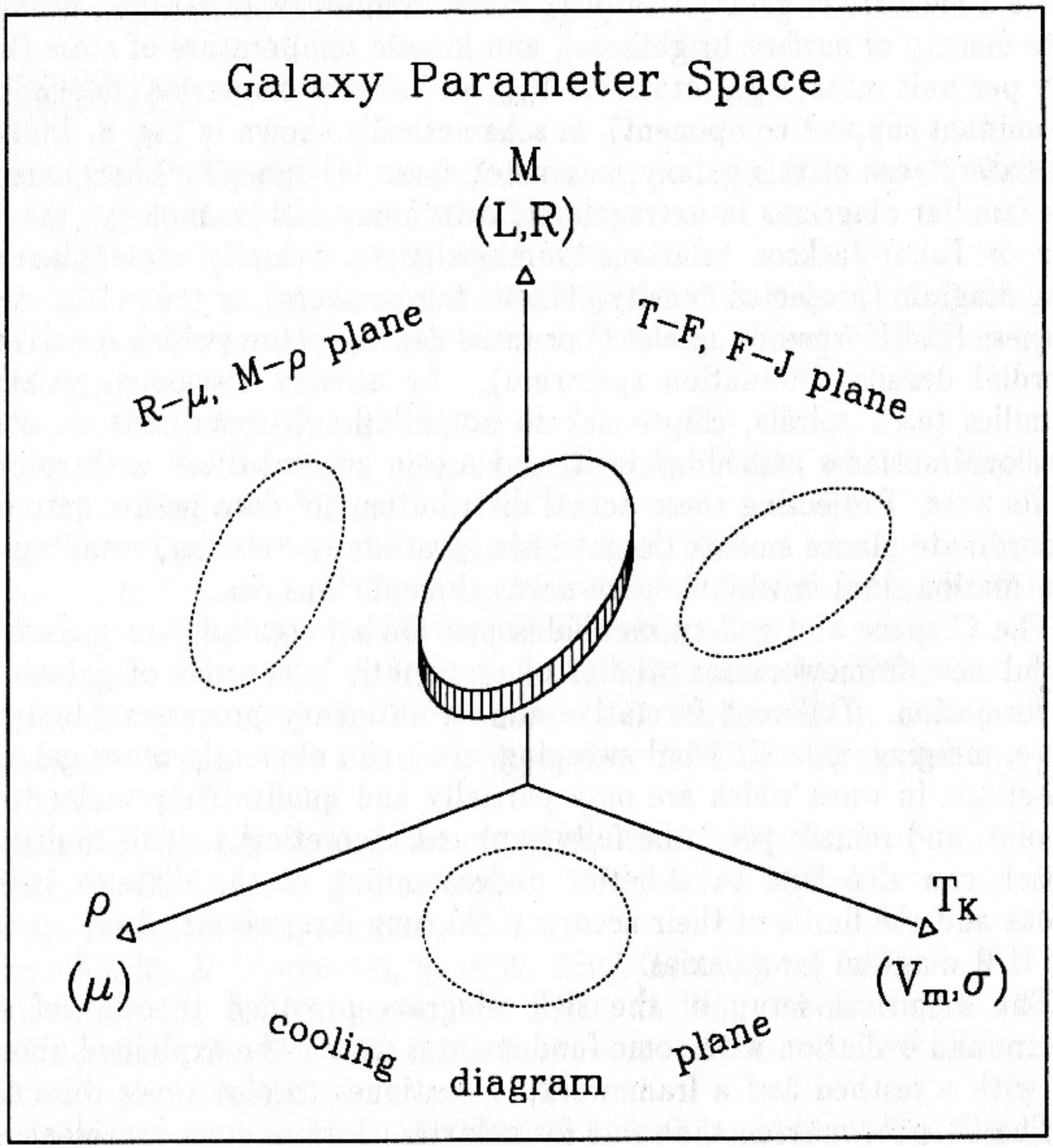


Mass to Light Ratios

Dwarf Spheroidals



The Galaxy Parameter Space



A more general picture

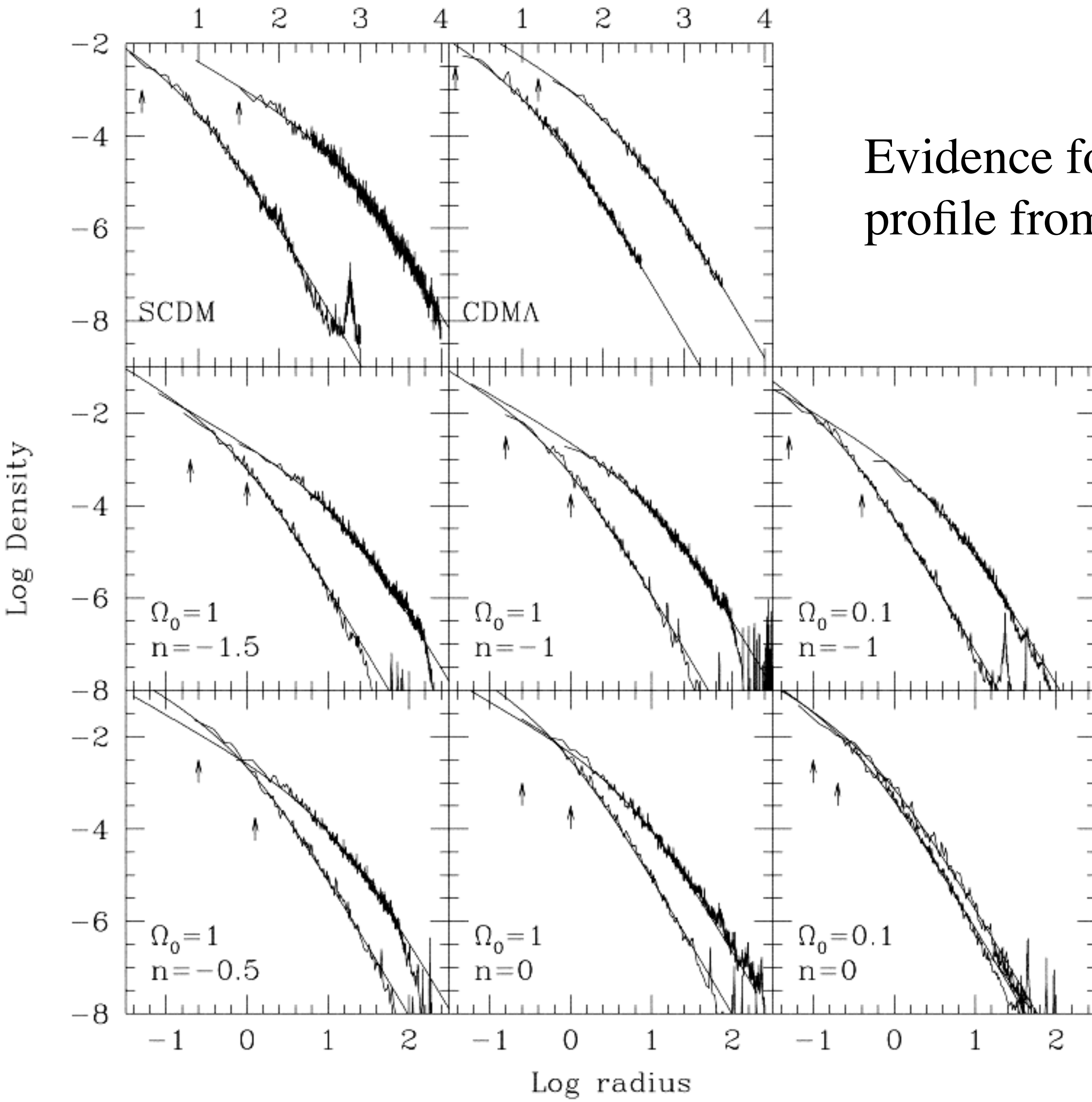
Galaxies of different families form 2-dim. sequences in a 3+ dimensional parameter space of physical properties, much like stars form 1-dim. sequences in a 2-dim. parameter space of {L,T} - this is an equivalent of the H-R diagram, but for galaxies

The Dark Halos

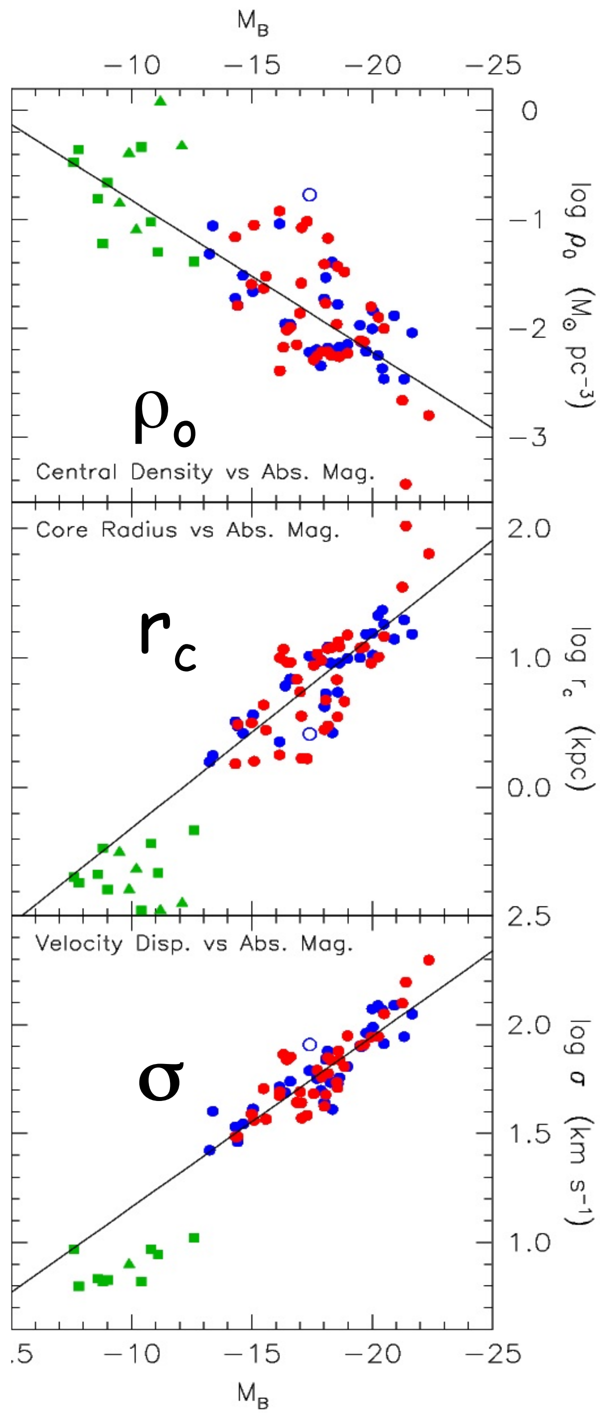
- Many of galaxy scaling relations may be driven by the properties of their dark halos
- It is possible to infer their properties from detailed dynamical profiles of galaxies and some modeling
- Numerical simulations suggest a universal form of the dark halo density profile (NFW = Navarro, Frenk & White):

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

(but one can also fit another formula, e.g., with a core radius and a finite central density)



Evidence for the NFW profile from simulations



Dark Halo Scaling Laws

$\rho_o \sim L_B^{-0.35}$

$r_c \sim L_B^{0.37}$ (fits to Sc-Im only)

$\sigma \sim L_B^{0.20}$

■ ▲ are dSph, dIrr

so expect the surface density

$\Sigma \sim \rho_o\, r_c$

to be ~ constant over this range of M_B, and it is

Kormendy & Freeman 2003

Key Points

- Correlations and scaling laws between galaxian properties (e.g., Tully-Fisher, Fundamental Plane, etc.) reflect processes of galaxy formation and evolution
- They define galaxy families in an objective manner
- They are important distance indicator relations; environmental dependence can cause systematics, but apparently it is not very strong
- They are the sharpest tools we have to study galaxy evolution
- The major outstanding issue is the small intrinsic scatter