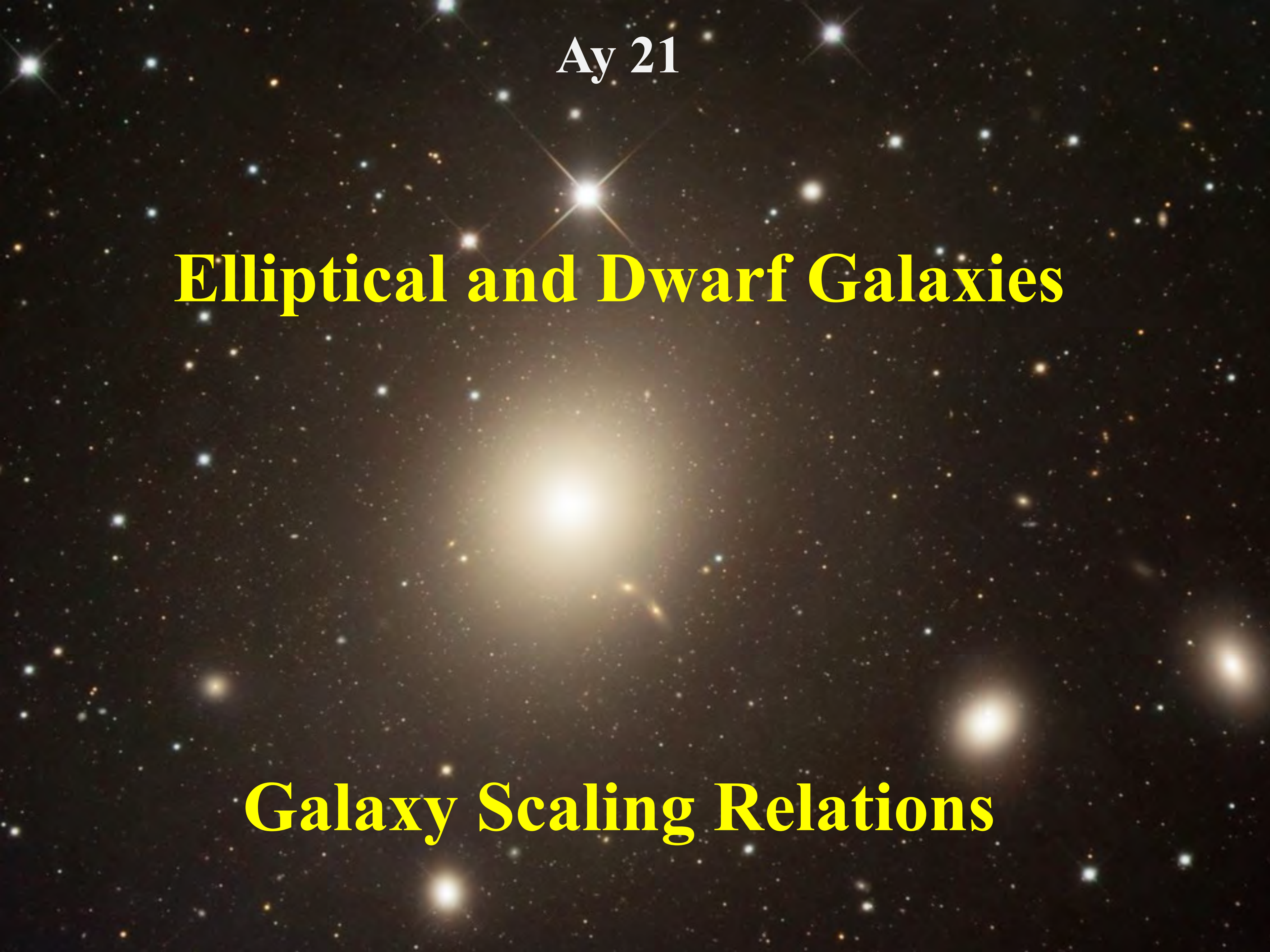


Ay 21

Elliptical and Dwarf Galaxies

Galaxy Scaling Relations

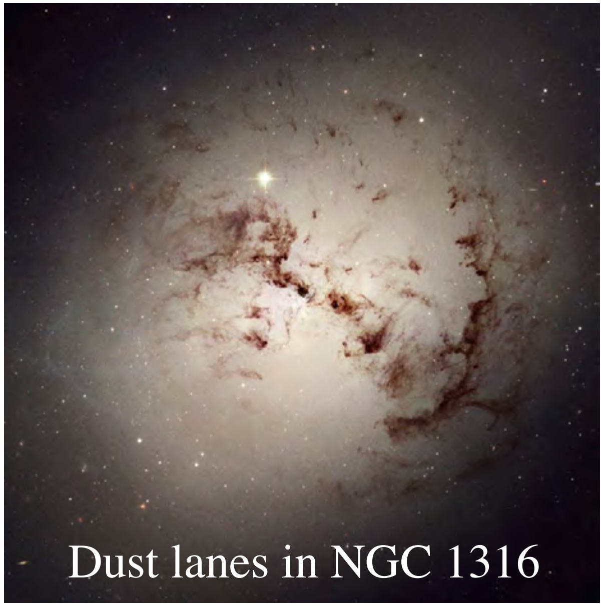
Elliptical Galaxies

Old view: ellipticals are boring, simple systems

- Ellipticals contain no gas & dust
- Ellipticals are composed of old stars
- Ellipticals formed in a monolithic collapse, which induced violent relaxation of the stars, stars are in an equilibrium state

Modern view:

- Most/all ellipticals have hot x-ray gas, some have dust, even cold gas
- Ellipticals do rotate, but most of the kinetic energy support (and galaxy shapes) come from an anisotropic velocity dispersion
- Some contain decoupled (counter-rotating) cores, or other complex kinematics
- Some have weak stellar disks
- Ellipticals formed by mergers of two spirals, or hierarchical clustering of smaller galaxies



Elliptical Galaxies: Surface Photometry

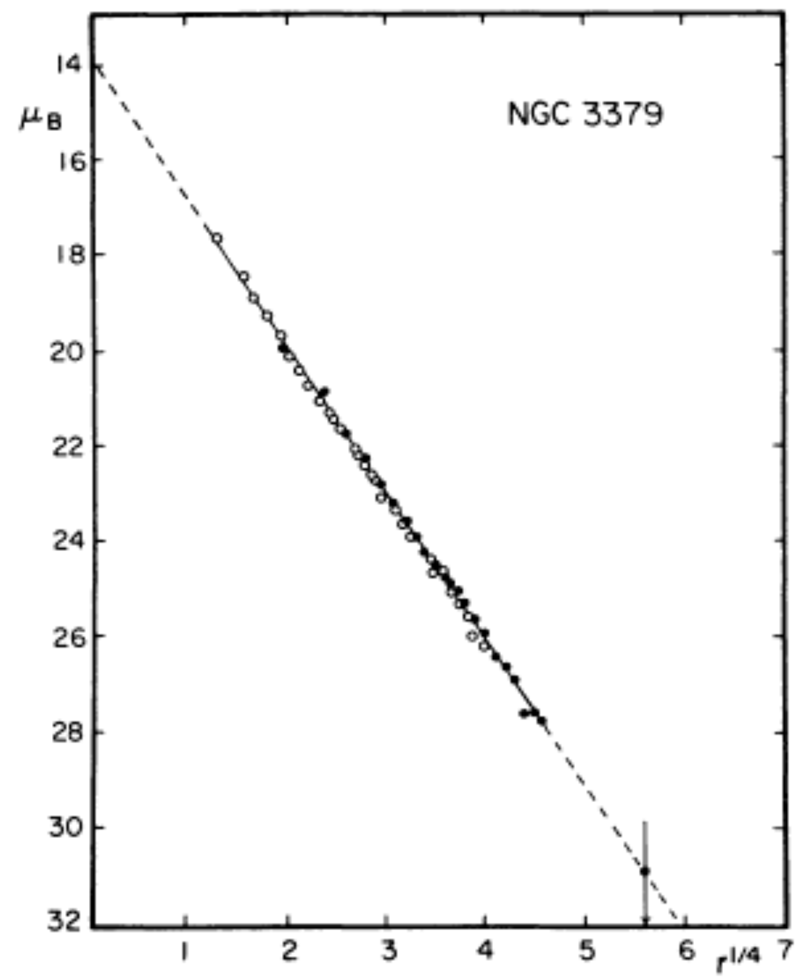
Surface brightness = projected luminosity density of elliptical galaxies falls off smoothly with radius. Measured (for example) along the major axis of the galaxy, the profile is normally well represented by the $R^{1/4}$ *or de Vaucouleurs law*:

$$I(R) = I(0)\, e^{-kR^{1/4}}$$

where k is a constant. This can be rewritten as:

$$I(R) = I_e\, e^{\left\{-7.67\left[\left(R/R_e\right)^{0.25}-1\right]\right\}}$$

where R_e is the ***effective radius*** - the radius of the isophote containing half of the total luminosity, typically a few kpc. $\boldsymbol{I_e}$ is the surface brightness at the effective radius.



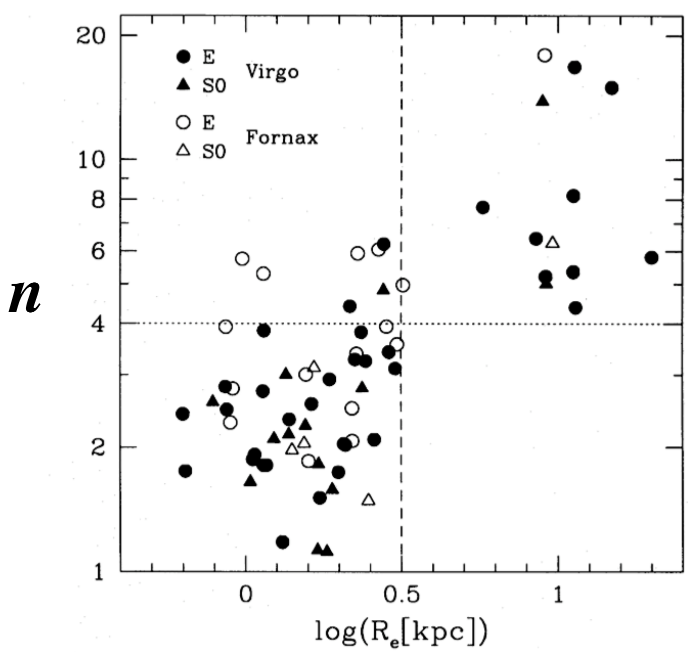
Elliptical Galaxies: Surface Photometry

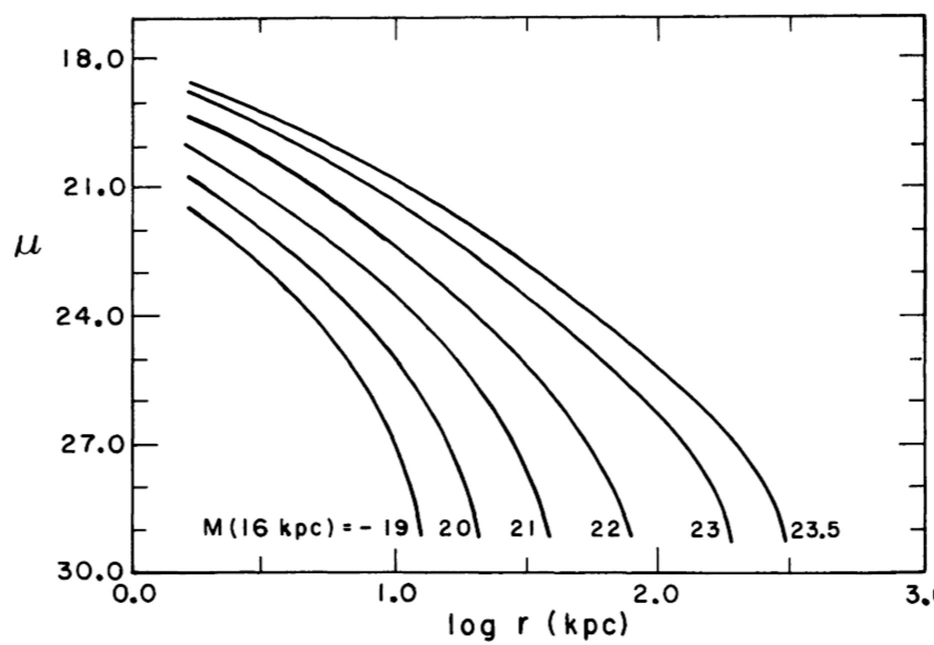
More generally, it is the Sersic profile:

$$\Sigma(r) = \Sigma_0 \exp\left\{-b_n\left[(r/r_e)^{1/n}\right]\right\}$$

where Σ is the surface brightness in linear units (not magnitudes), $\mathbf{b_n}$ is chosen such that half the luminosity comes from $R < R_e$. This law becomes de Vaucouleurs for $n = 4$, and exponential for $n = 1$.

There is a systematic trend that the n is larger, i.e., the profiles are shallower with the increasing luminosity:





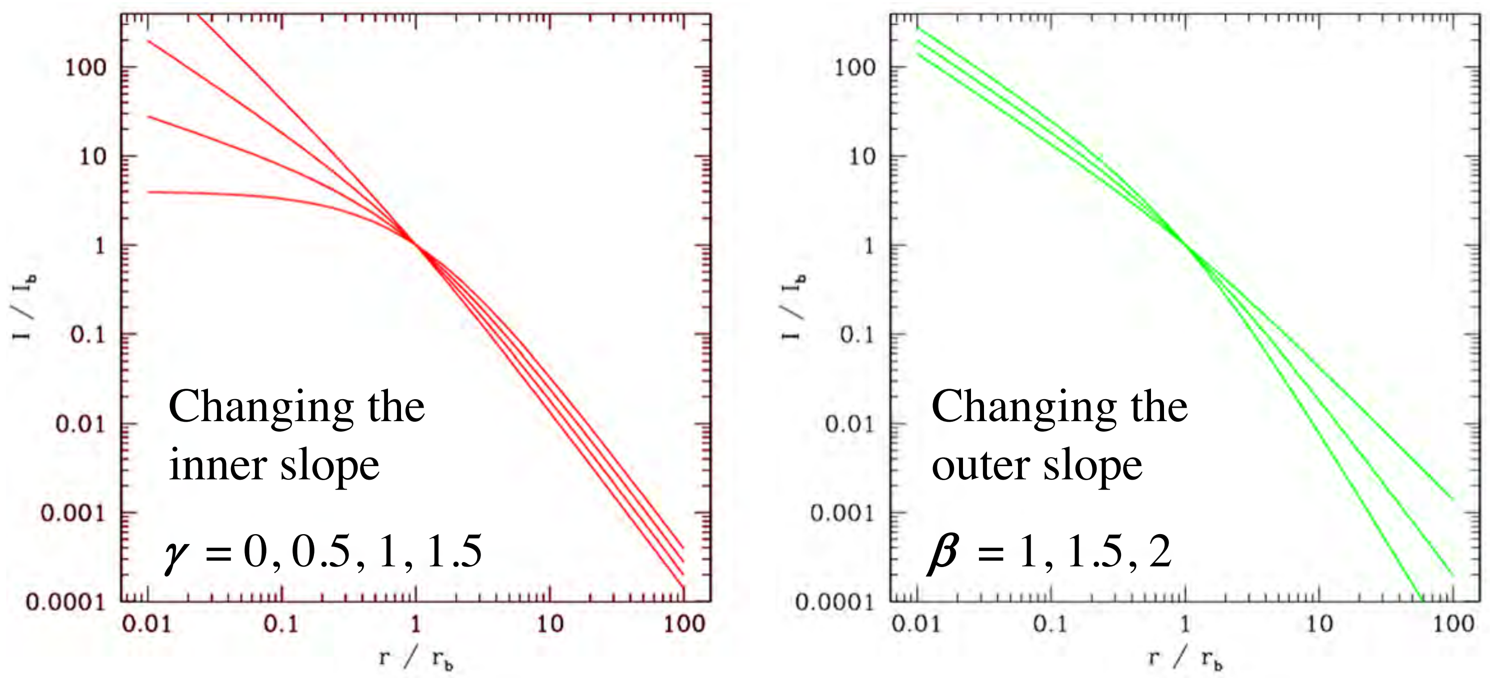
The Cores and Nuclei of Ellipticals

Close to the center profiles deviate from the $R^{1/4}$ law:

- More luminous ellipticals tend to have **cores** - region where the surface brightness flattens and is ~ constant
- Less luminous ellipticals tend to have power law **cusps** – surface brightness rises steeply towards the center

This is described by a more general "Nuker" profile:

$$I(R) = I_b 2^{(\beta-\gamma)/\alpha} \left(\frac{R}{R_b}\right)^{-\gamma} \left[1 + \left(\frac{R}{R_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

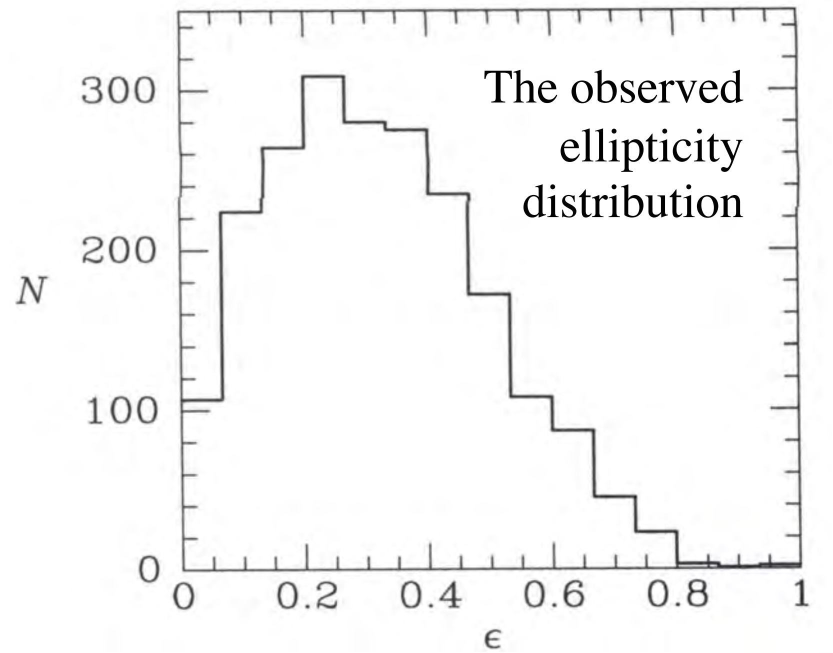


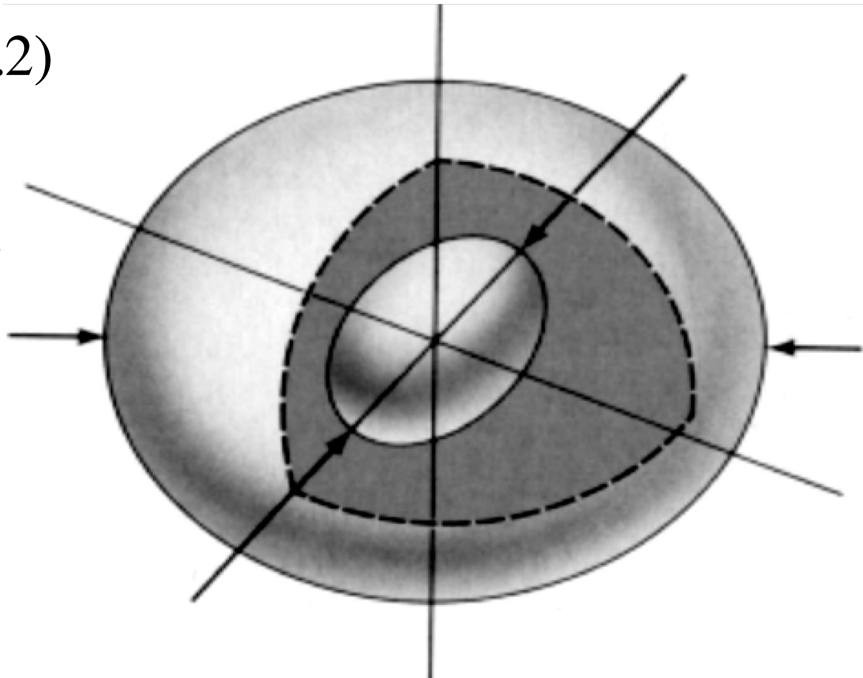
Shapes of Ellipticals

- Ellipticals are defined by E*n*, where *n=10ε*, and *ε=1-b/a* is the ellipticity, *as projected on the sky*
- More generally, we believe that they are mildly ***triaxial ellipsoids***, defined by three axes, *a*, *b*, and *c*, typically

  a:b:c ~ 1 : 0.95 : 0.65 (dispersion ~ 0.2)

- Triaxiality produces *isophotal twists* (would not see these if galaxies were purely oblate or prolate)
- It is due to the ***anisotropic velocity dispersions***, which stretch the galaxies in proportion along their 3 principal axes

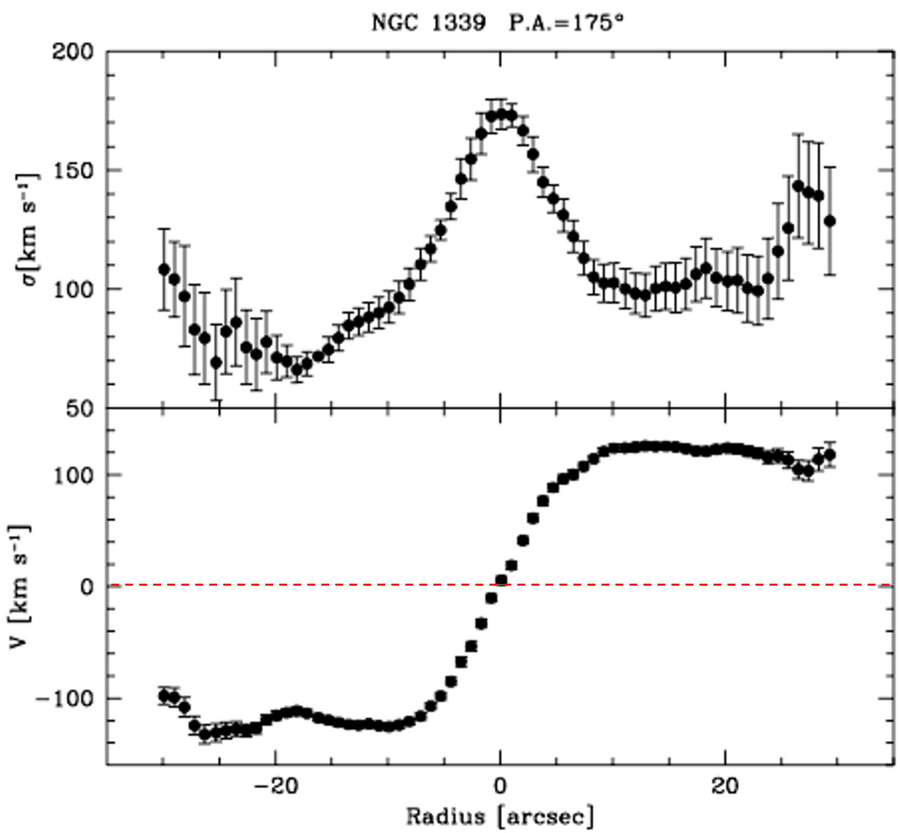


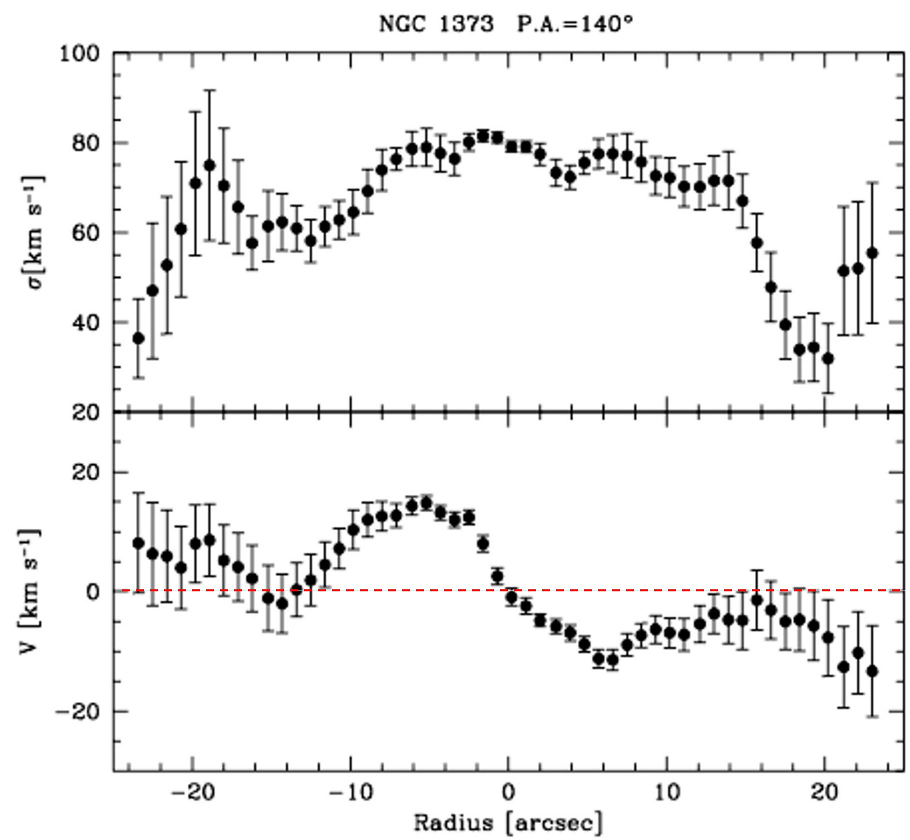


(from Binney & Merrifield)

The Kinematics of Elliptical Galaxies

Stars in E galaxies have some ordered motions (e.g., rotation), but most of their kinetic energy is in the form of random motions. Thus, we say that ellipticals are ***pressure-supported systems***





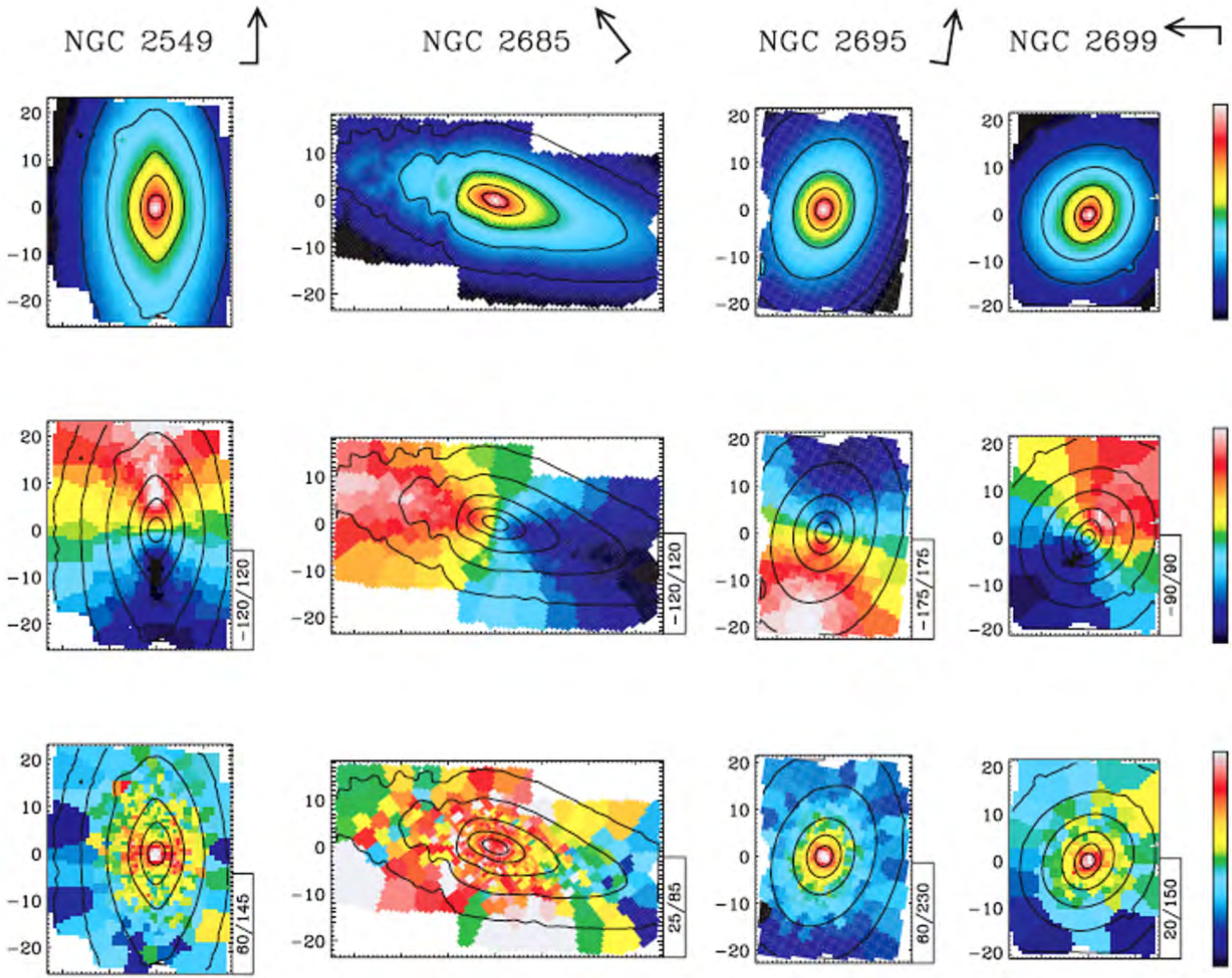
We use the kinematical and surface brightness profiles to determine the ***internal density and dynamical structure*** of ellipticals

2-Dimensional Kinematics of E-Gal’s

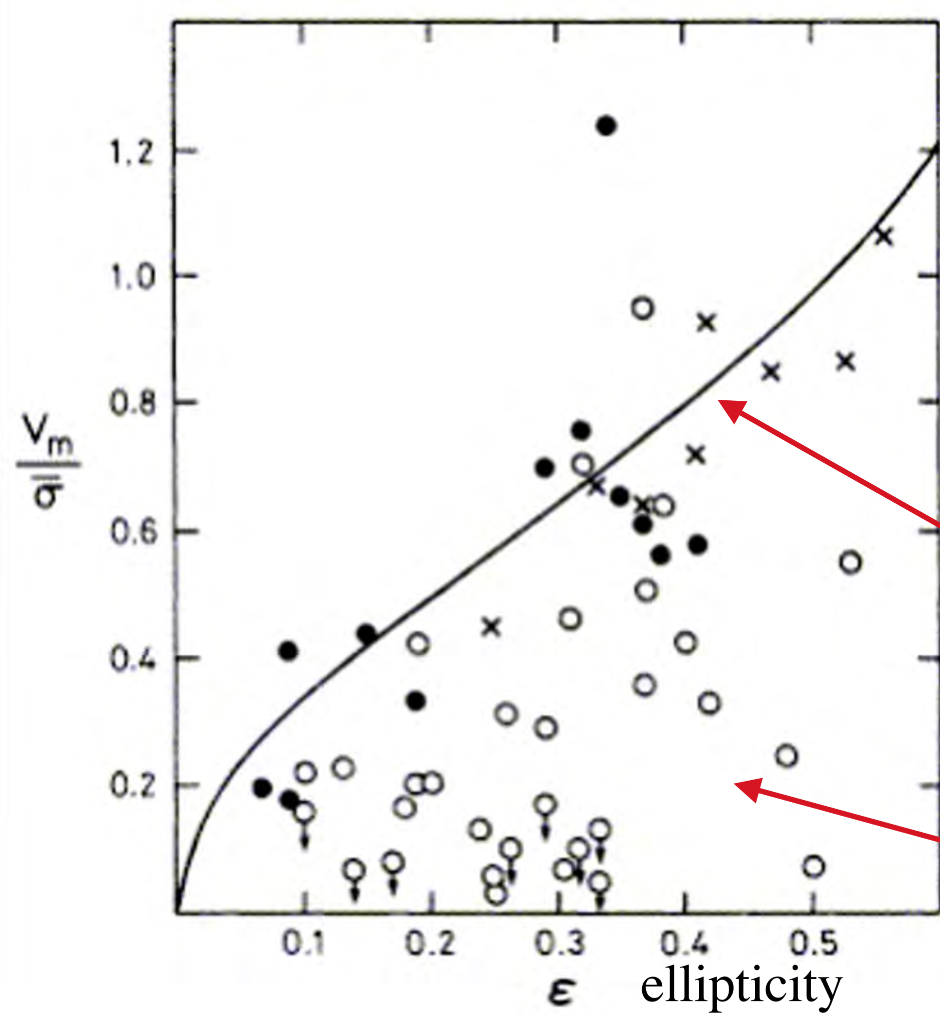
Intensity (surface brightness)

Rotation velocity

Velocity dispersion



Velocity Anisotropy in Elliptical Galaxies



The ratio of the maximum rotational velocity V_m and the mean velocity dispersion σ indicates whether the observed shapes of E' s are due to rotation or anisotropic pressure

Galaxies on this line are flattened by rotation

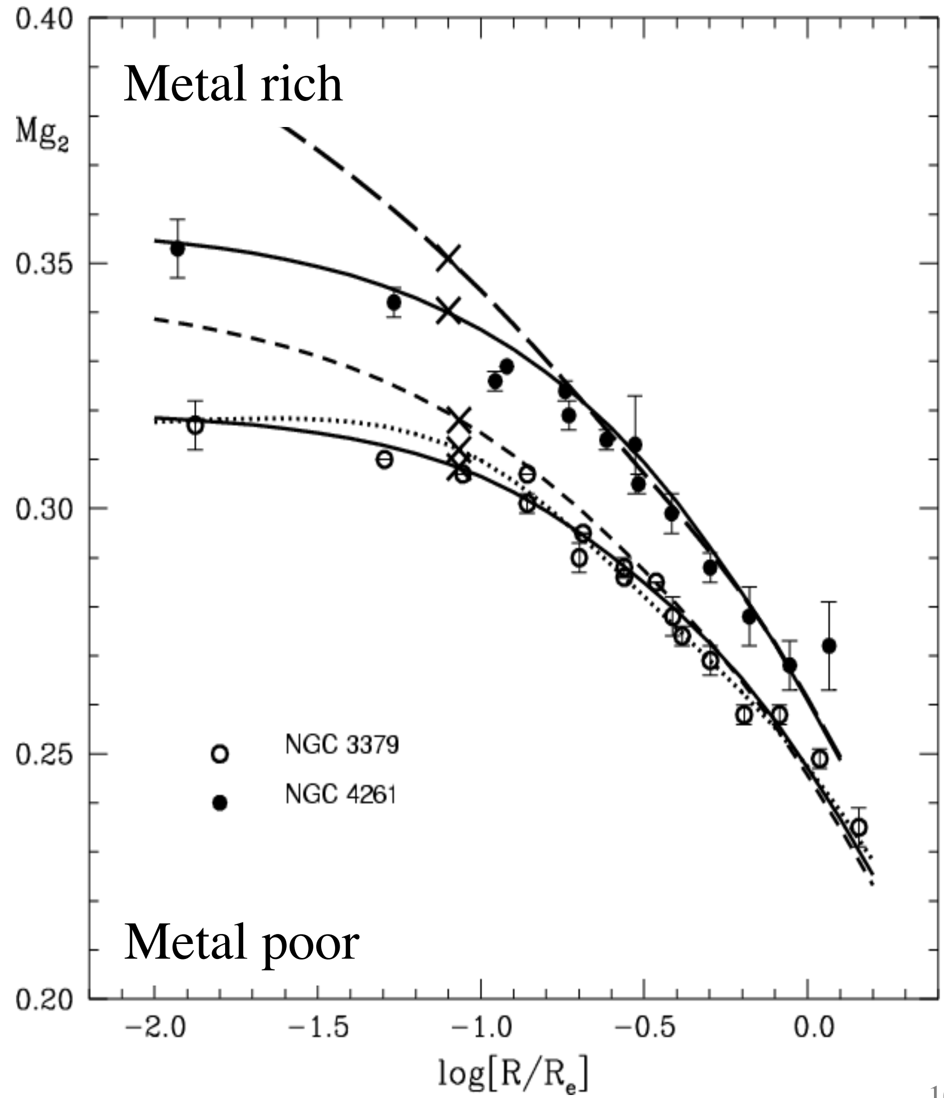
Galaxies below it are flattened by anisotropy

More luminous ellipticals also tend to be *more anisotropic*
This can be understood as *consequence of merging*

Stellar Populations in Ellipticals

- Ellipticals are made mostly from *old stars*, ages > 1 Gyr and generally ~ 10 Gyr
- They have *a broad range of metallicities* (which indicate the degree of chemical evolution), *up to 10 times Solar*!
- *More metal rich stars are found closer to the center*
- This is observed as line strength gradients, or as color gradients (more metal-rich stars are redder)

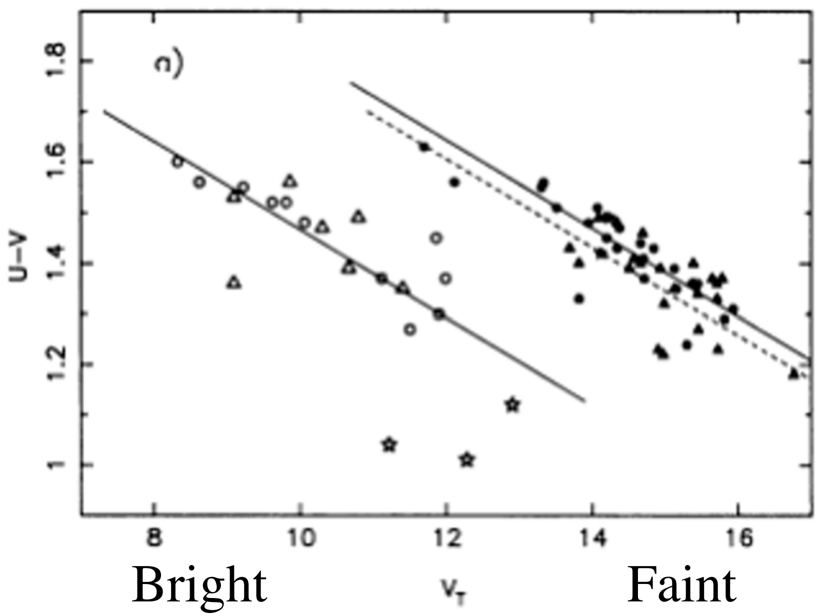
Mg line strength gradients vs. radius

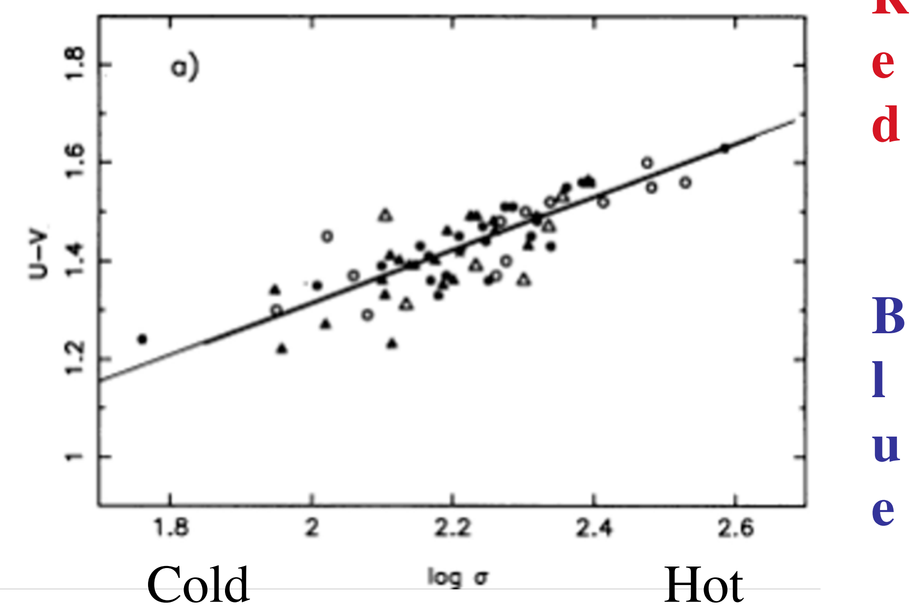


Metallicity-Luminosity Relation

also known as the Color-Magnitude Relation

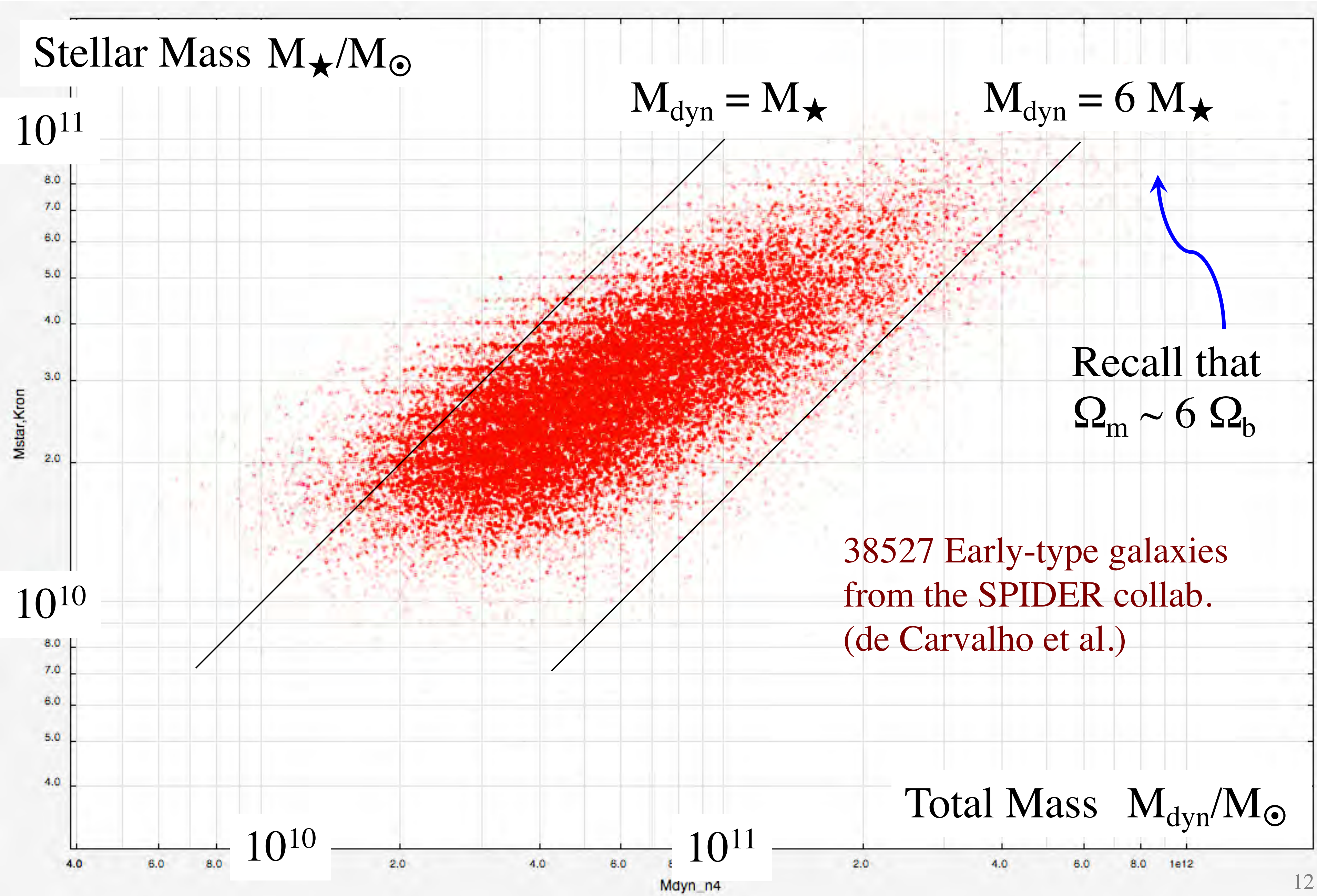
There is a relation between the color (a metallicity indicator) and the total luminosity or velocity dispersion for E galaxies:





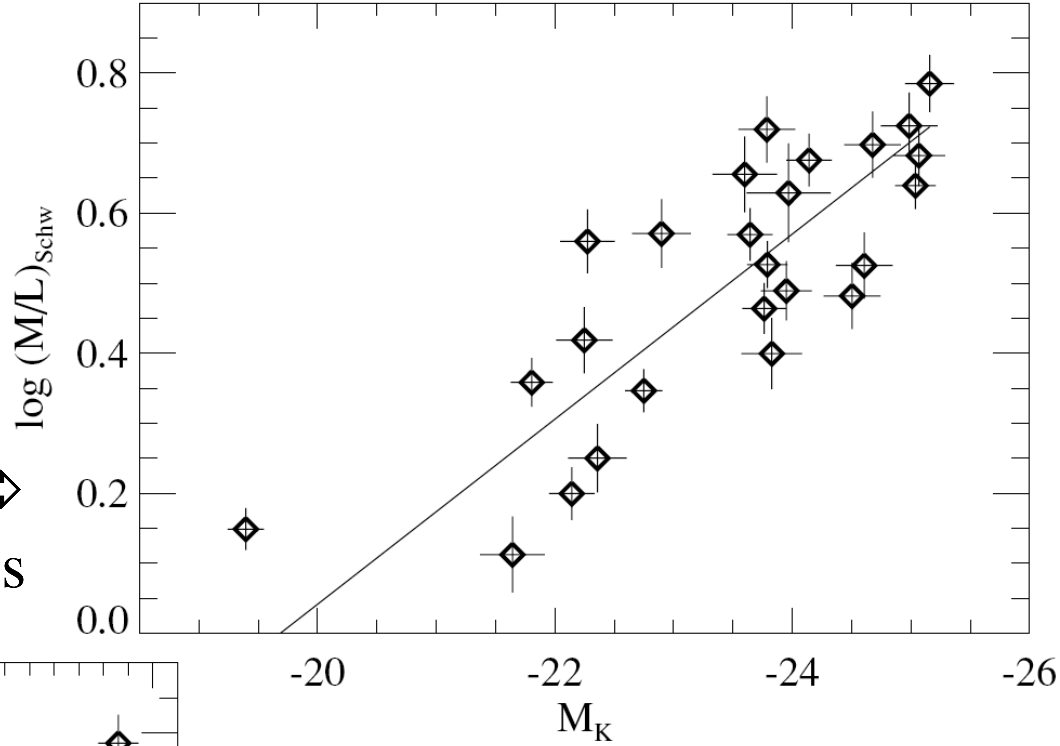
Brighter and dynamically hotter galaxies are redder. This could be explained if smaller E galaxies were younger or more metal-poor than the large ones. *More massive galaxies could be more effective in retaining and recycling their supernova ejecta.*

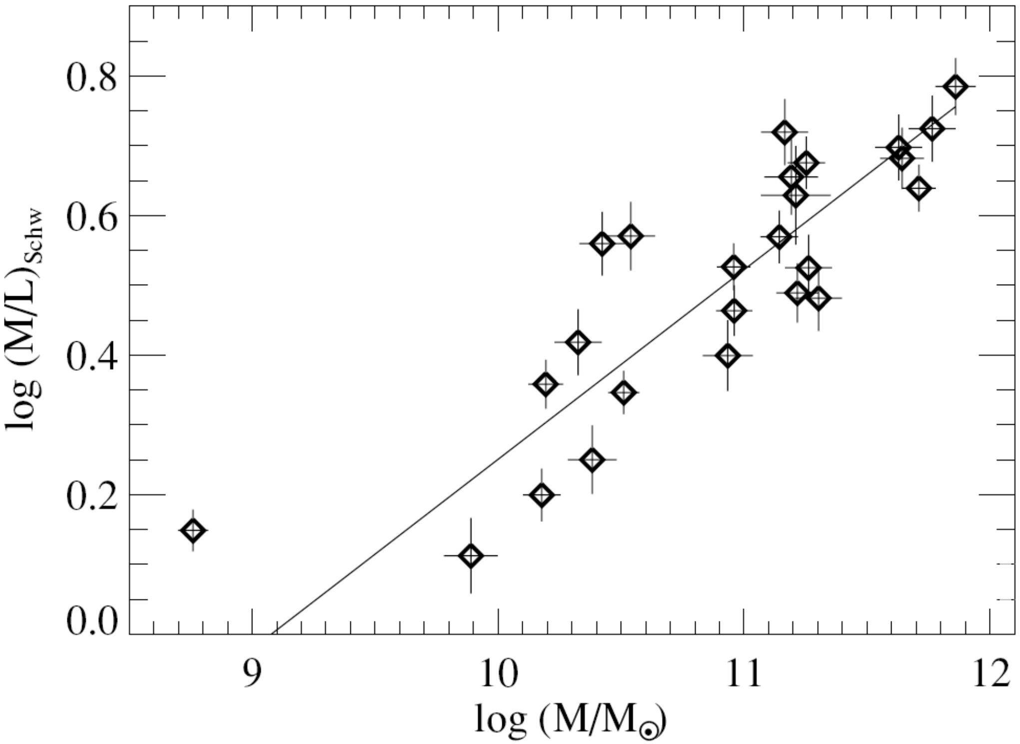
Stellar vs. Dynamical Mass



More Massive Galaxies Have Larger (M/L)

(M/L) vs. Luminosity ⇨
~ Stellar mass



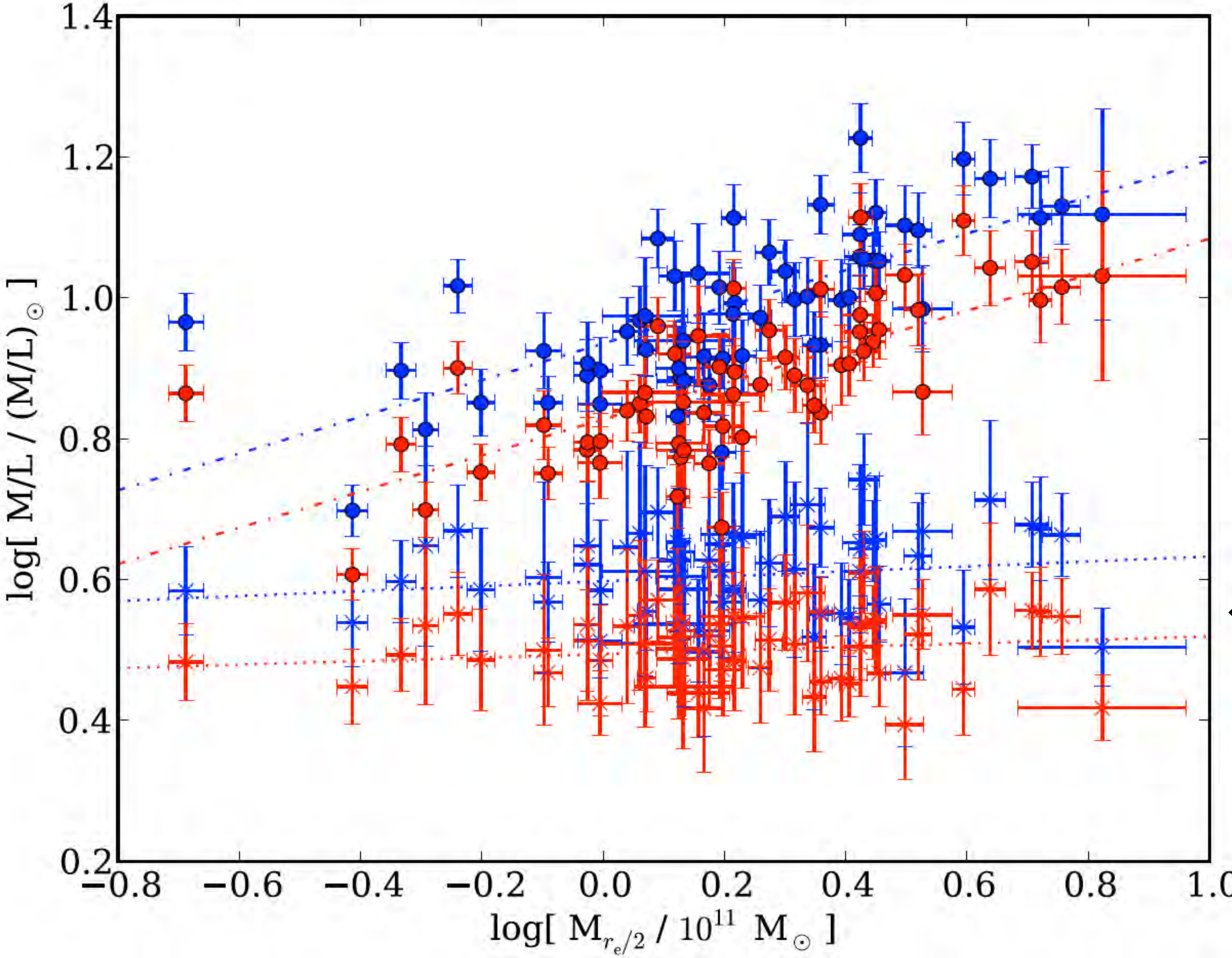


⇦ (M/L) vs. Total Mass

$$(M/L)_{\text{vir}} \propto L^{0.27\pm0.04}$$

(Cappellari et al. 2006)

(M/L) vs. Mass From Gravitational Lensing



$(M/L)_{total}$

Dark matter increasingly dominant for more massive galaxies

$(M/L)_{luminous}$

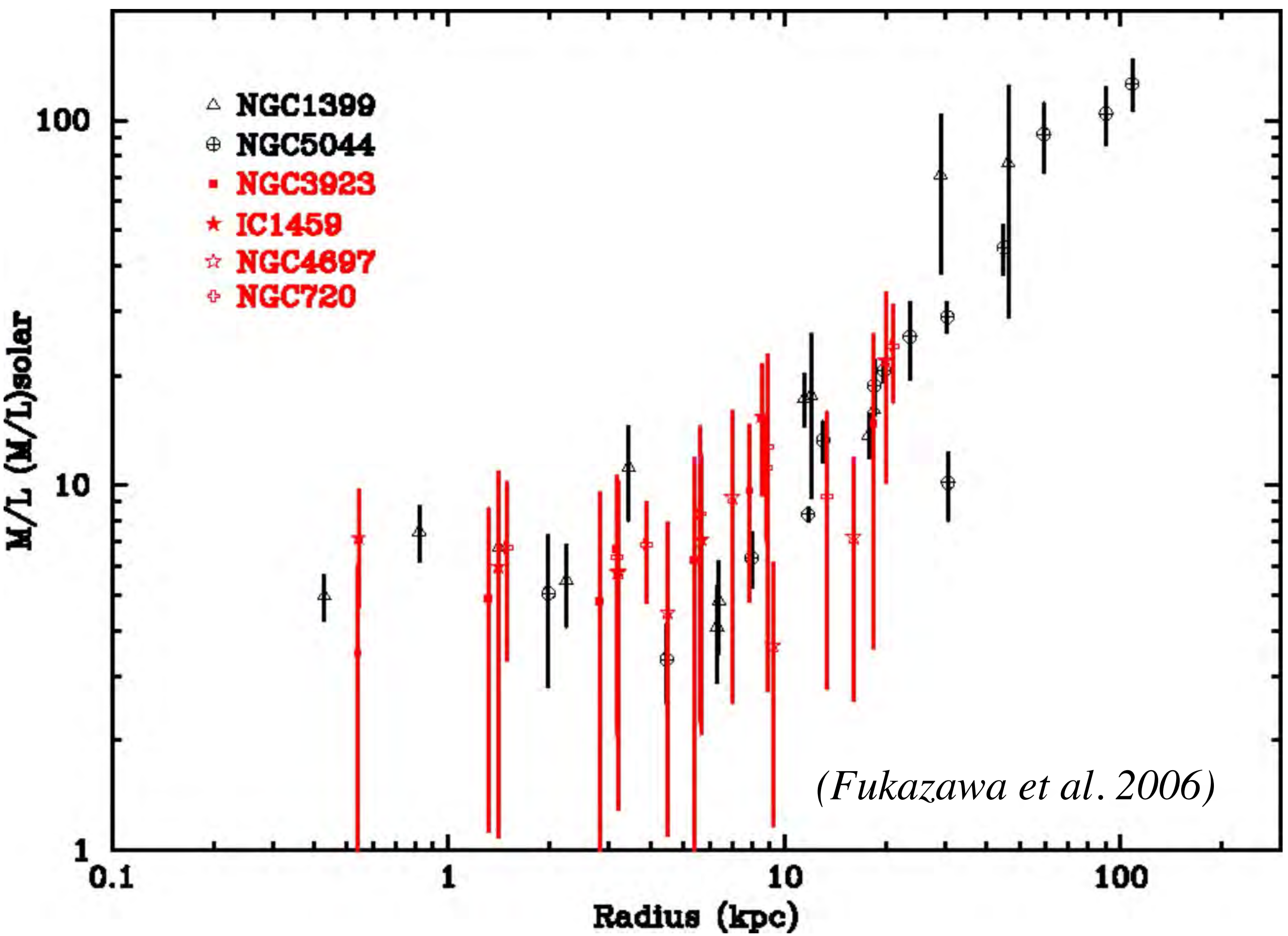
Uniform stellar populations

red = V band, **blue** = B band

(Auger et al. 2010, the SLACS collab.)

(M/L) Increases With Radius

(M/L) From the X-ray profiles and modeling



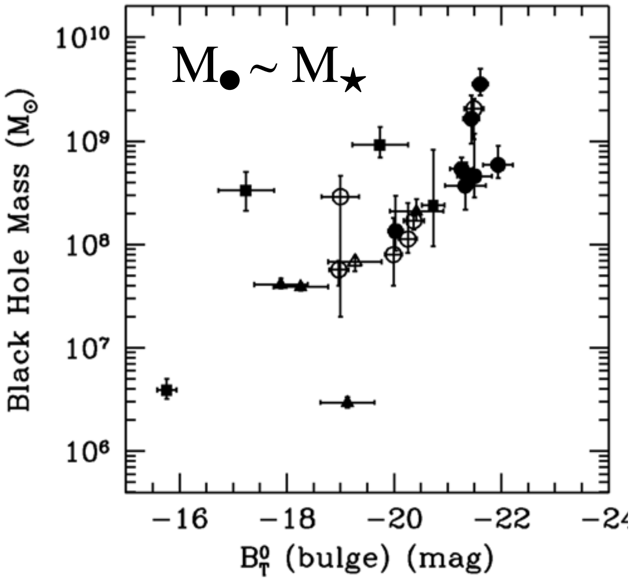
Dark halos dominant at larger radii (just like for the spirals)

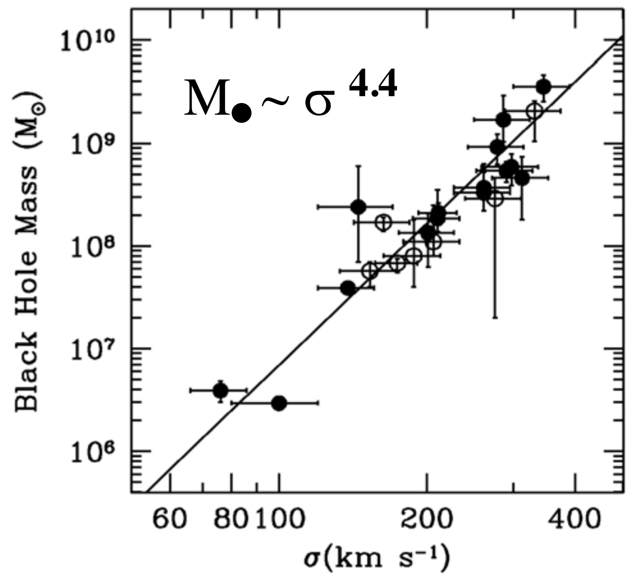
Fully consistent with the dynamical modeling of optical data

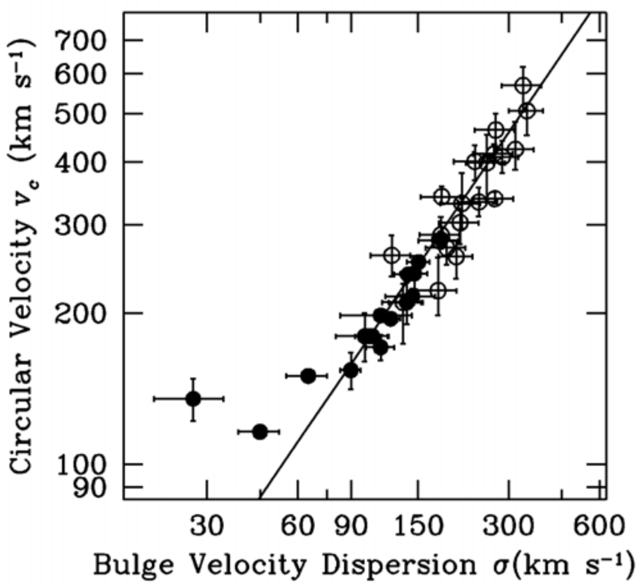
Massive Black Holes in Galactic Nuclei

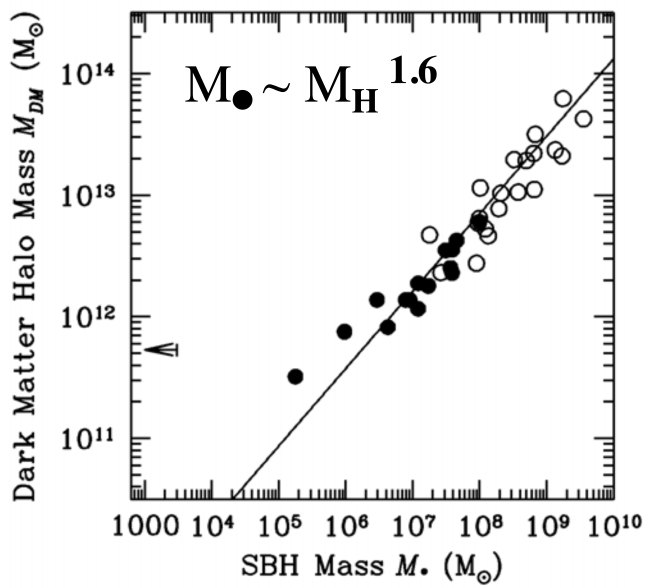
- It turns out that they are ***ubiquitous***: nearly every non-dwarf galaxy seems to have one, but only a small fraction are active today; these super-massive black holes (SMBH) are believed to be the central engines of quasars or other AGN
- They are detected through central velocity dispersion or rotation cusps near the center - requiring more mass than can be reasonably provided by stars
- ***Their masses correlate very well with many of their host galaxy properties***, suggesting a co-formation and/or co-evolution of galaxies (or at least their old stellar spheroid components) and the SMBHs they contain
- Understanding of this connection is still not complete, but dissipative mergers can both drive starbursts and fuel/grow SMBHs

The SMBH - Host Galaxy Correlations









Formation and growth of the central black holes are closely coupled with those of their host galaxies

Possible reasons:

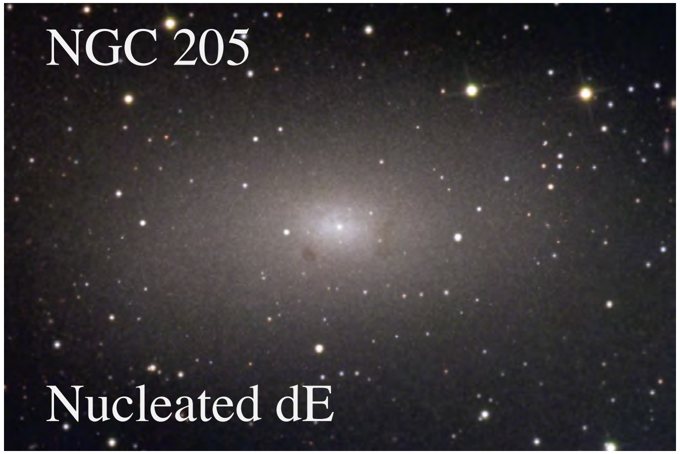
1. The same growth and formation mechanisms
2. Feedback

Elliptical Galaxies: Key Points

- Elliptical galaxies and bulges contain *old, metal-rich stellar populations*, and some show signs of recent merging
- They are supported against their self gravity by *random motions of stars*, with little or no rotation, and their shapes are *triaxial ellipsoids due to the anisotropic velocity dispersion*
- There is some variety in their radial density profiles, with larger galaxies being less concentrated
- Their stellar populations are *redder and more metal-rich closer to their centers*, indicative of a chemical self-enrichment
- More massive ellipticals have larger mass-to-light ratios, which can have multiple physical causes
- *Most (all?) contain supermassive black holes* in their centers, whose masses are correlated with the host galaxy properties, indicating a *shared formation mechanism*

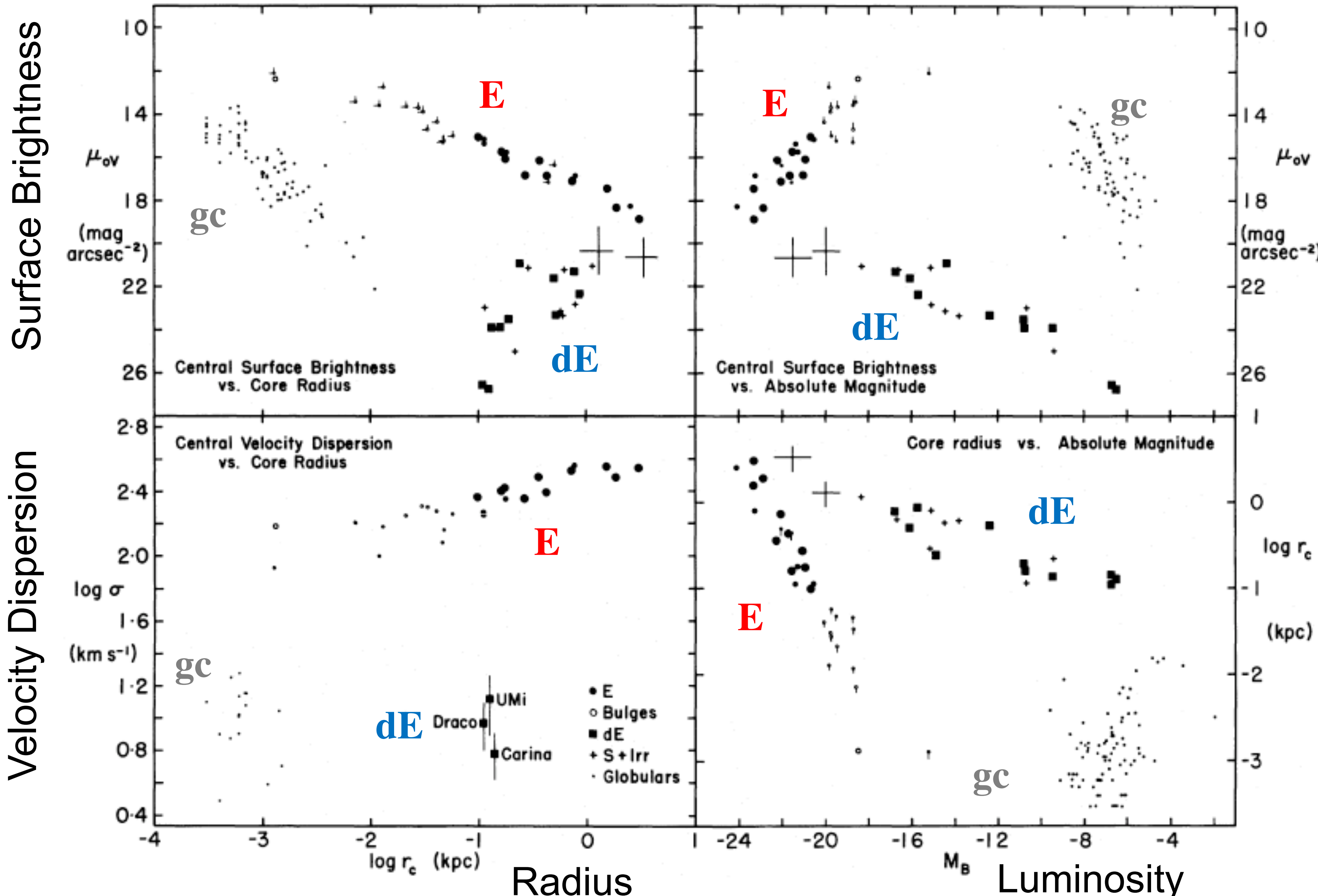
Dwarf Galaxies

- Dwarf ellipticals (dE) and dwarf spheroidals (dSph) are different families of objects from normal ellipticals – they are not just small E's



- 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
- 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

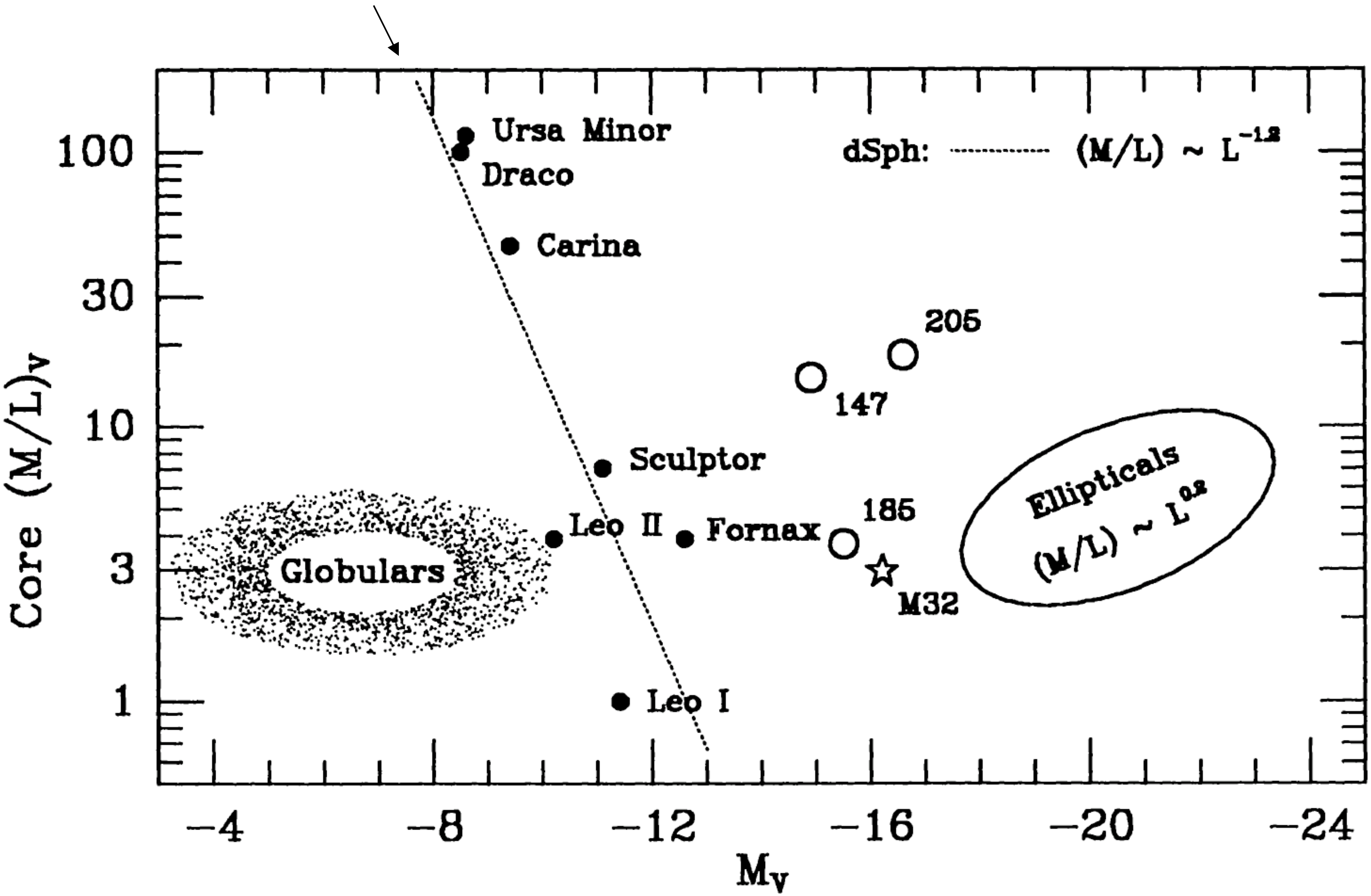
Parameter Correlations



Kormendy 1985

Mass to Light Ratios

Dwarf Spheroidals are Dark Matter Dominated



Galaxy Scaling Laws

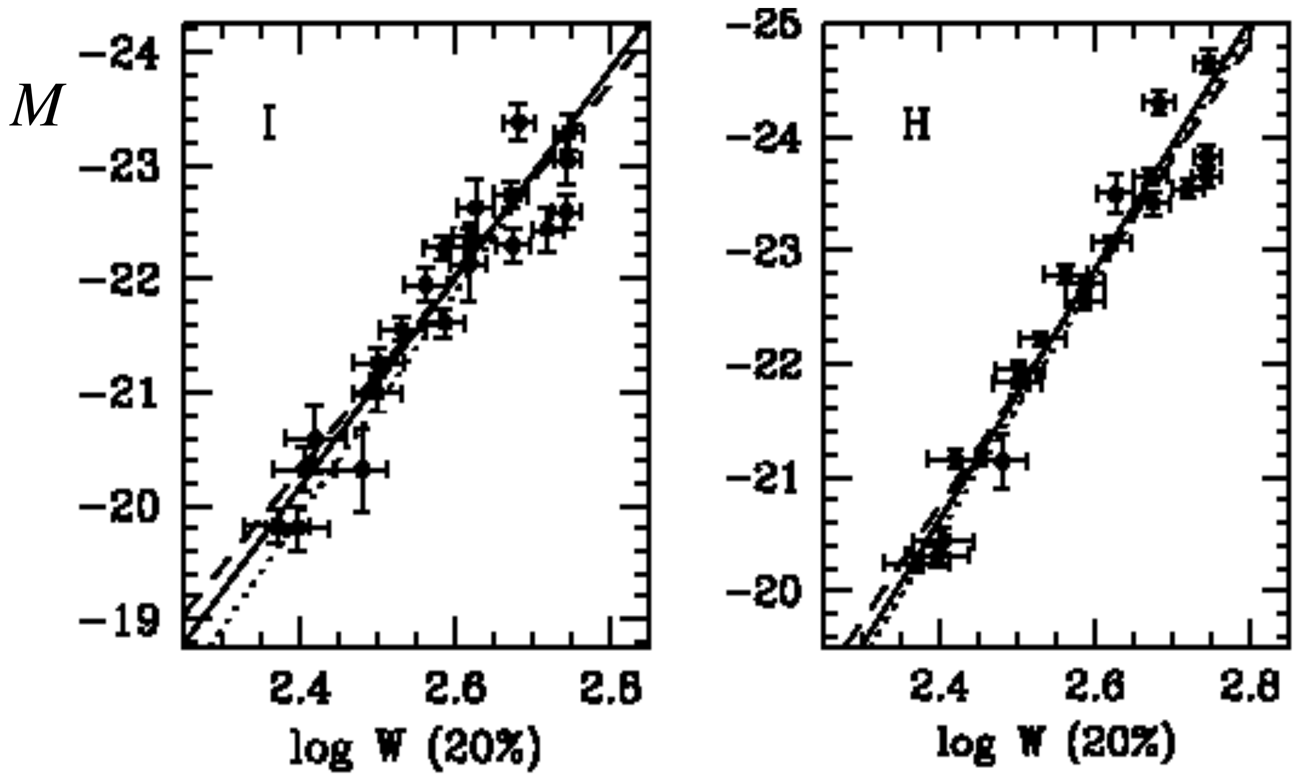
- When correlated, global properties of galaxies tend to do so as power-laws; thus "scaling laws"
- They provide a ***quantitative means of examining physical properties of galaxies and their systematics***
- They ***reflect the internal physics of galaxies, and are a product of the formative and evolutionary 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., the possible environmental dependences

The Tully-Fisher Relation

- A well-defined luminosity vs. maximum rotational speed relation for spirals:

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

The slope 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



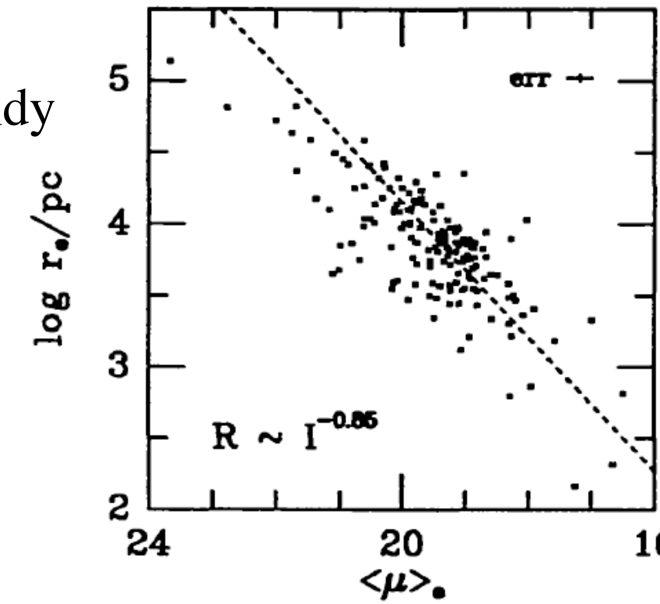
- Scatter can be as low as ~ 10%, better in the redder bands

Why is the TFR So Remarkable?

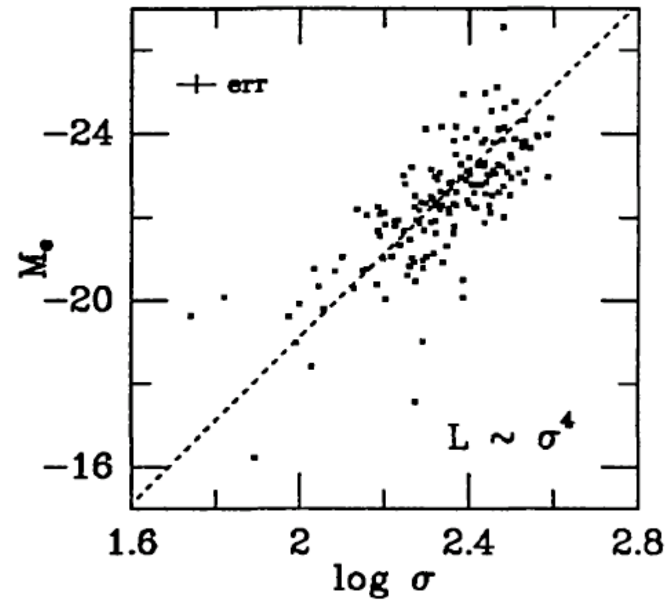
- Because it connects a property of the dark halo - the maximum circular speed - with the product of the net integrated star formation history, i.e., the luminosity of the disk
- Suggests a halo-regulated galaxy formation/evolution?
- The scatter is remarkably low - even though the conditions for this to happen are known not to be satisfied (e.g., a large spread in surface brightness and M/L ratios at any given luminosity)
- 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

Scaling Relations for Ellipticals

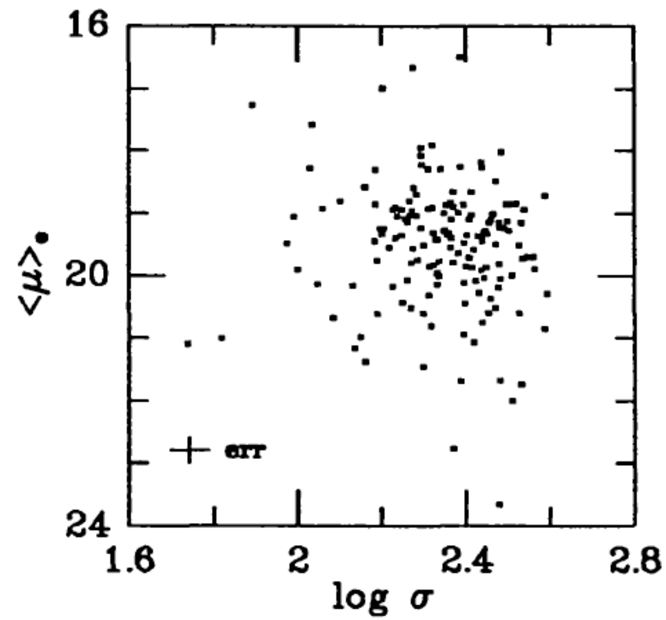
Kormendy rel' n



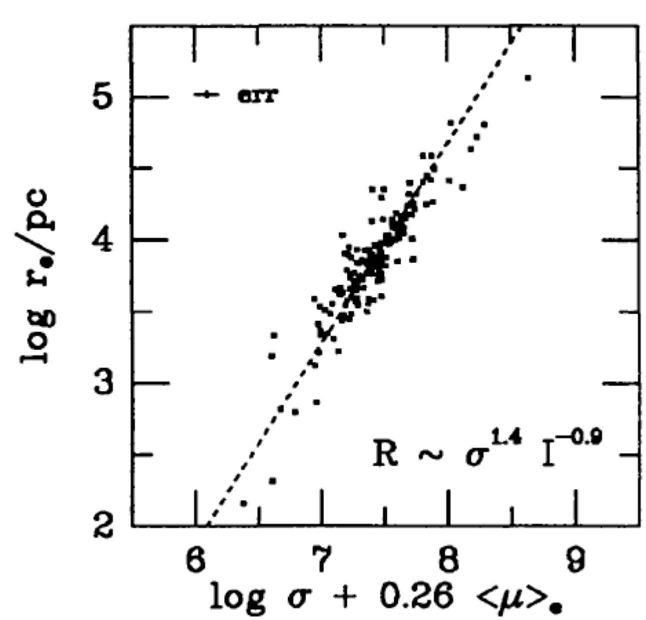
Faber-Jackson rel' n



Cooling diagram

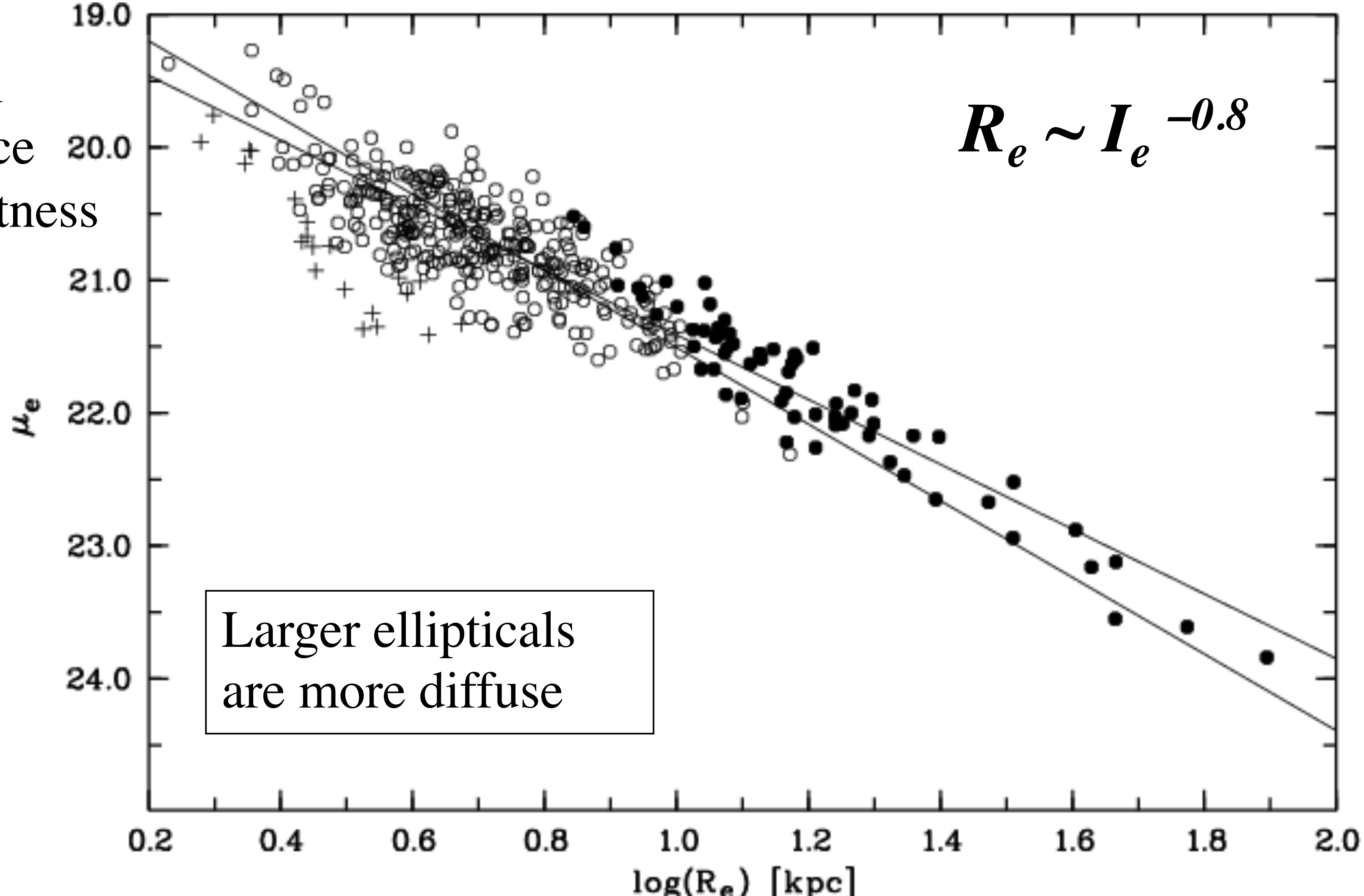


Fundam. Plane



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 $R \sim I^{\,-1}$

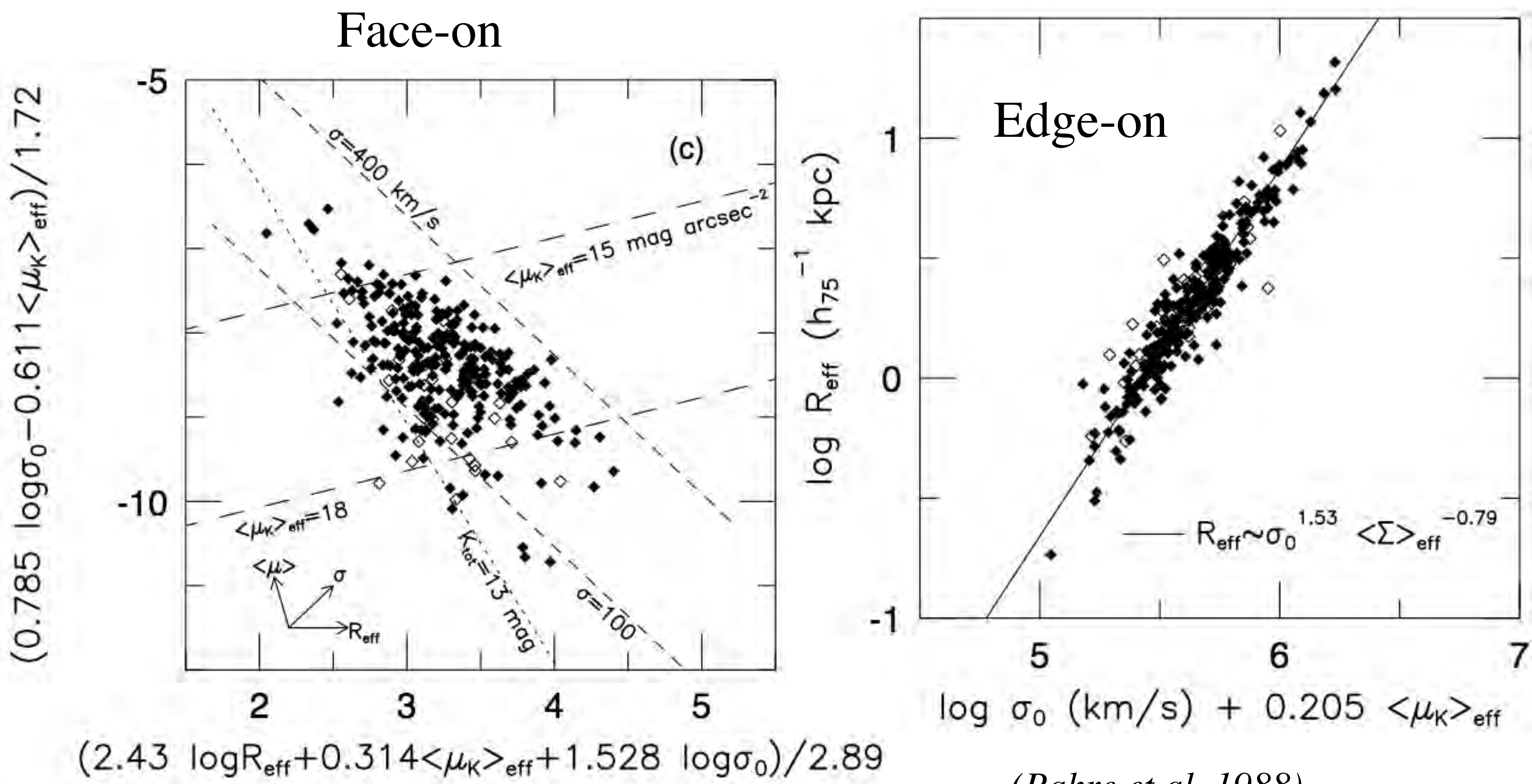
If, on the other hand, ellipticals form via **dissipative collapse**, then $M = const.$, surface brightness $I \sim M\,R^{\,-2}$, and thus we would predict the scaling to be $R \sim I^{\,-0.5}$

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.



(Pahre et al. 1988)

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:

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

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

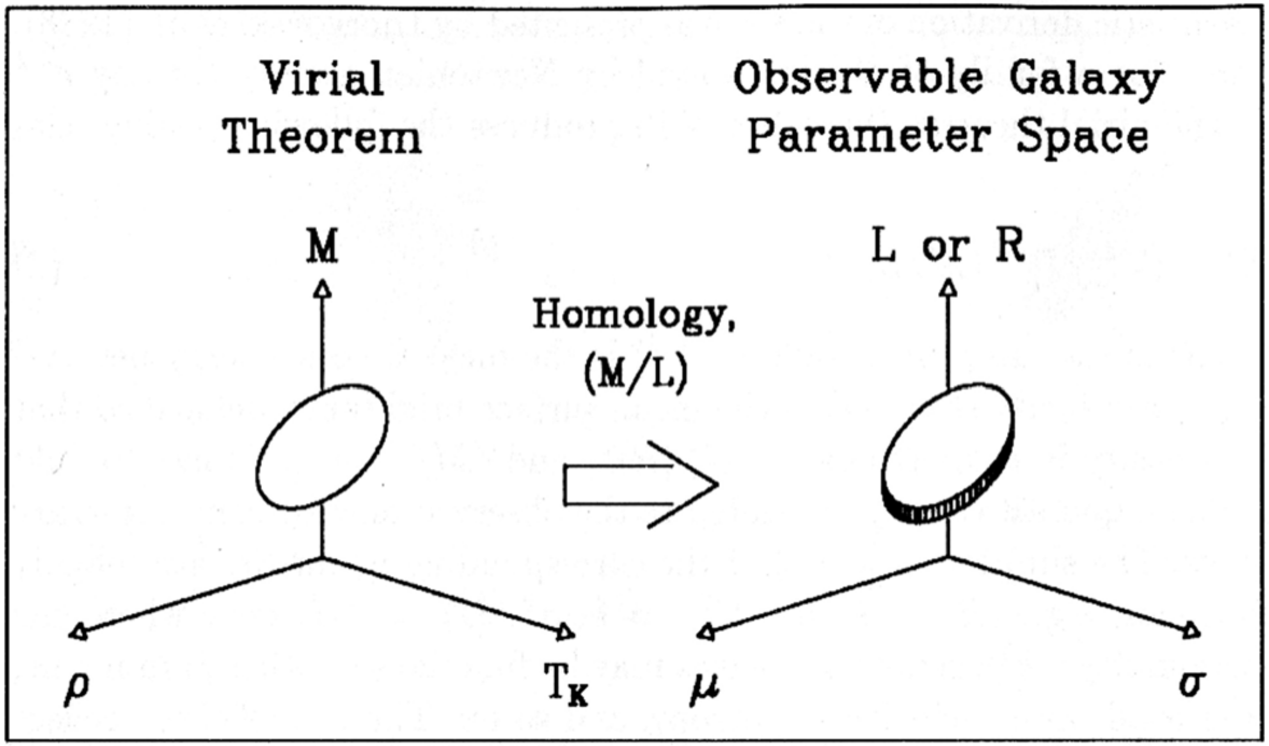
Where the "structure" coefficients are:

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

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

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



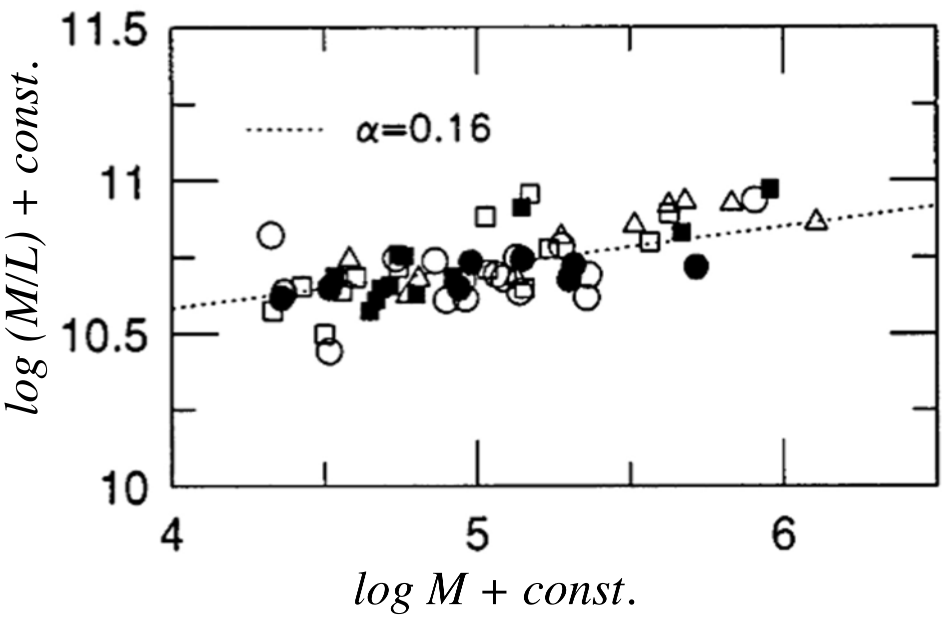
Virial Theorem connects mass, density, and kinetic temperature, and is thus an equation of a plane in that (theoretical) parameter space. Assumptions about the dynamical structure of ellipticals and their (M/L) ratios then map the VT into the tilted FP in the observable parameter space of measured quantities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

Fundamental Plane and M/L Ratios

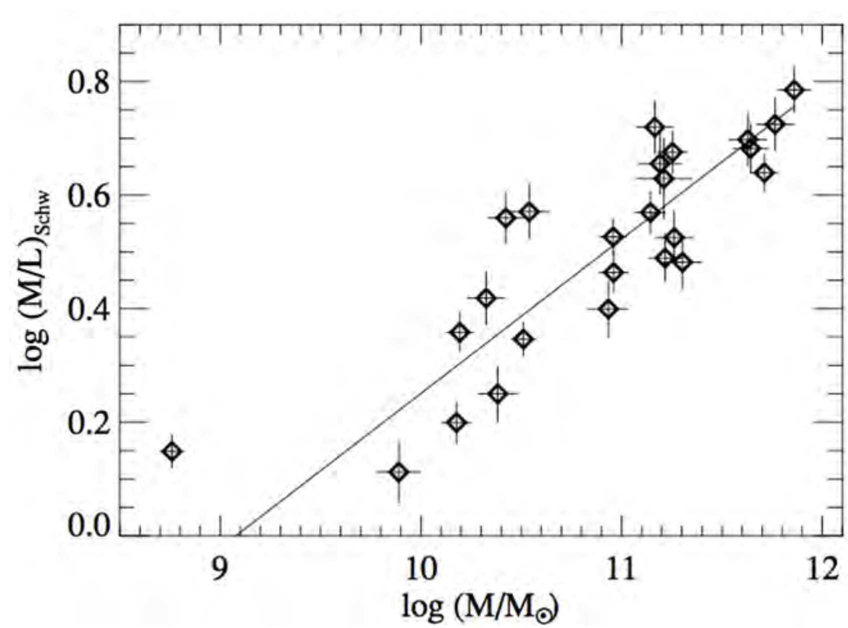
If we *assume* homology and attribute all of the FP tilt to the changes in ***(M/L)*** , $(M/L) \sim L^{\alpha}$, $\alpha \sim 0.2$ (vis) or ~ 0.1 (IR)

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



For any elliptical galaxy today, big or small,

Just Two Numbers

determine *to within a few percent or less*:

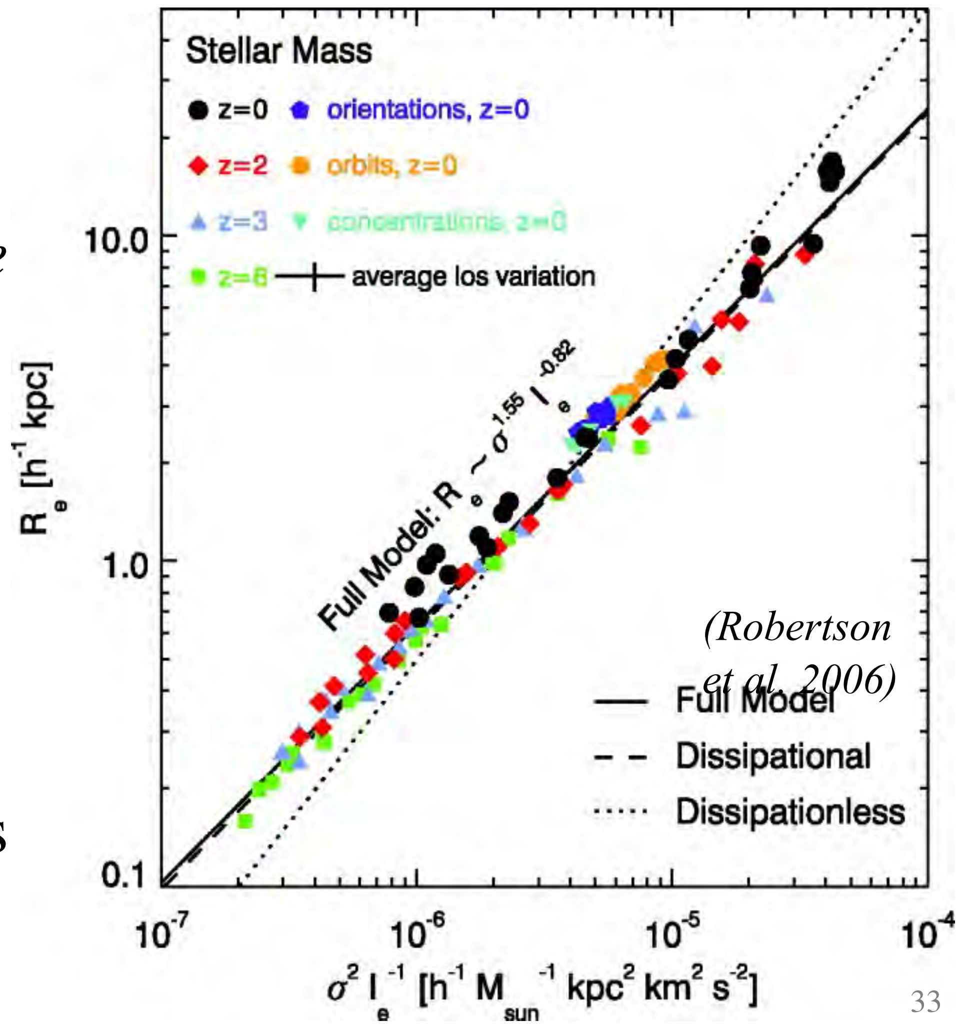
- Mass, luminosity (in any OIR band),
- Any consistently defined radius
- Surface brightness or projected mass density
- Derived 3-d luminosity, mass, or phase-space density
- Central projected radial velocity dispersion
- OIR colors, line strengths, and metallicity
- Mass of the central black hole
-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

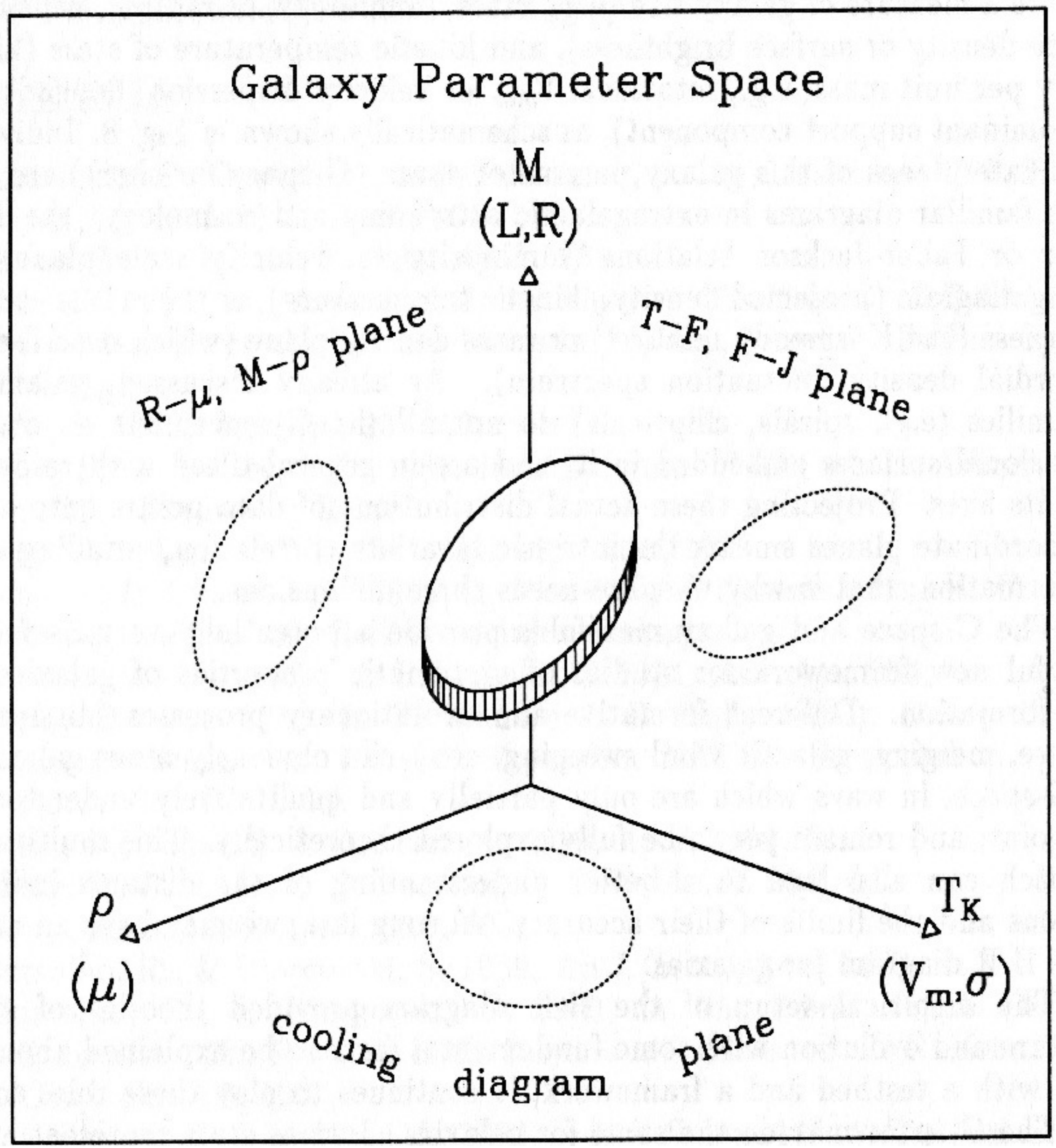
How Can This Be?

- 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)

The Galaxy Parameter Space



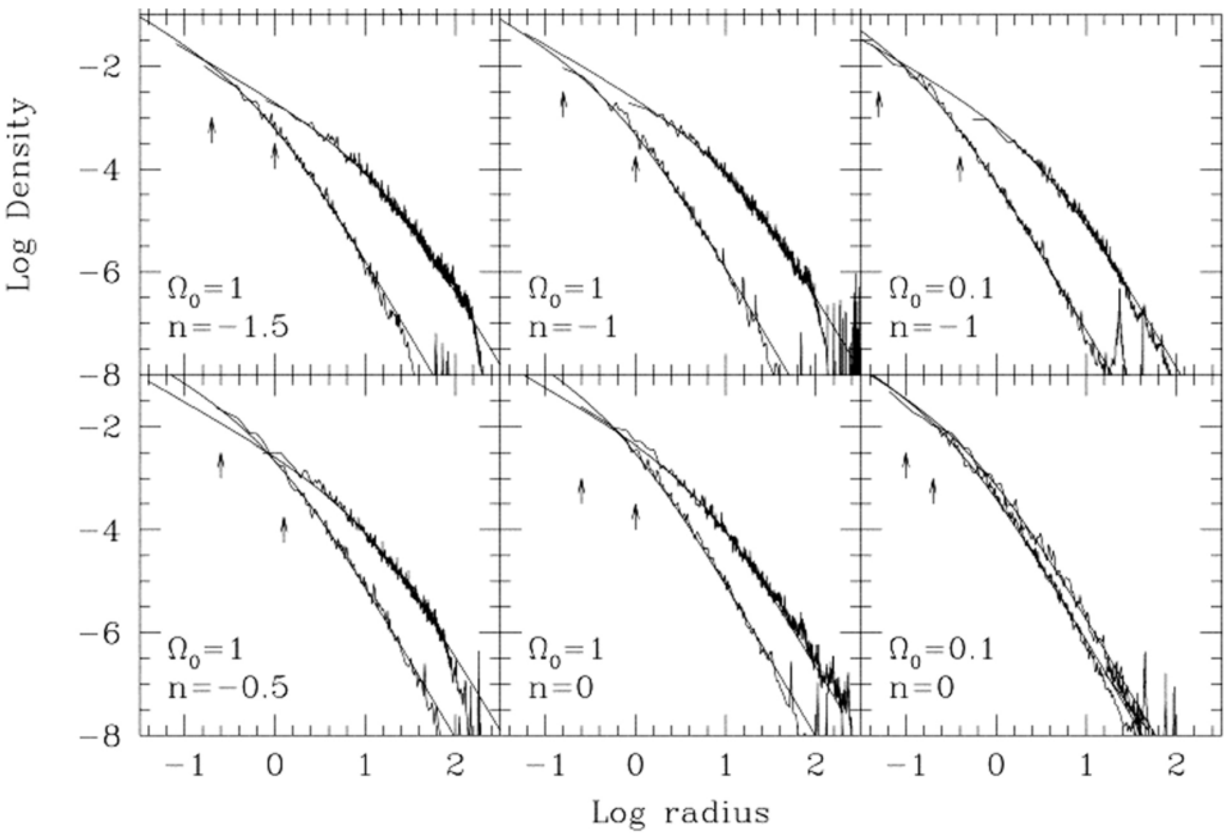
A more general picture

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, since they dominate the dynamics
- Numerical simulations suggest a ***universal form of the dark halo density profile*** (NFW = Navarro, Frenk & White):

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



This may help explain the uniformity of galaxian density and dynamical structures, and thus the small scatter of the scaling relations, but we still don't understand how.

Galaxy Scaling Laws: Key Points

- Many *fundamental properties of galaxies are correlated*, typically as *power laws (scaling relations)*, e.g., the Tully-Fisher relation for spirals and the Fundamental Plane relations for ellipticals
- These relations contain ***information about their formative and evolutionary histories***, and can sometimes be used as ***distance indicator relations***
- Their basic forms reflect the virial theorem (i.e., galaxies are self-gravitating systems), but ***the details and the small scatter are still not fully understood***
- These relations indicate a strong coupling between the galaxy dynamics and structure and their star formation history
- ***Dwarf galaxies obey different scaling relations*** from the large galaxies, indicative of different formation mechanisms