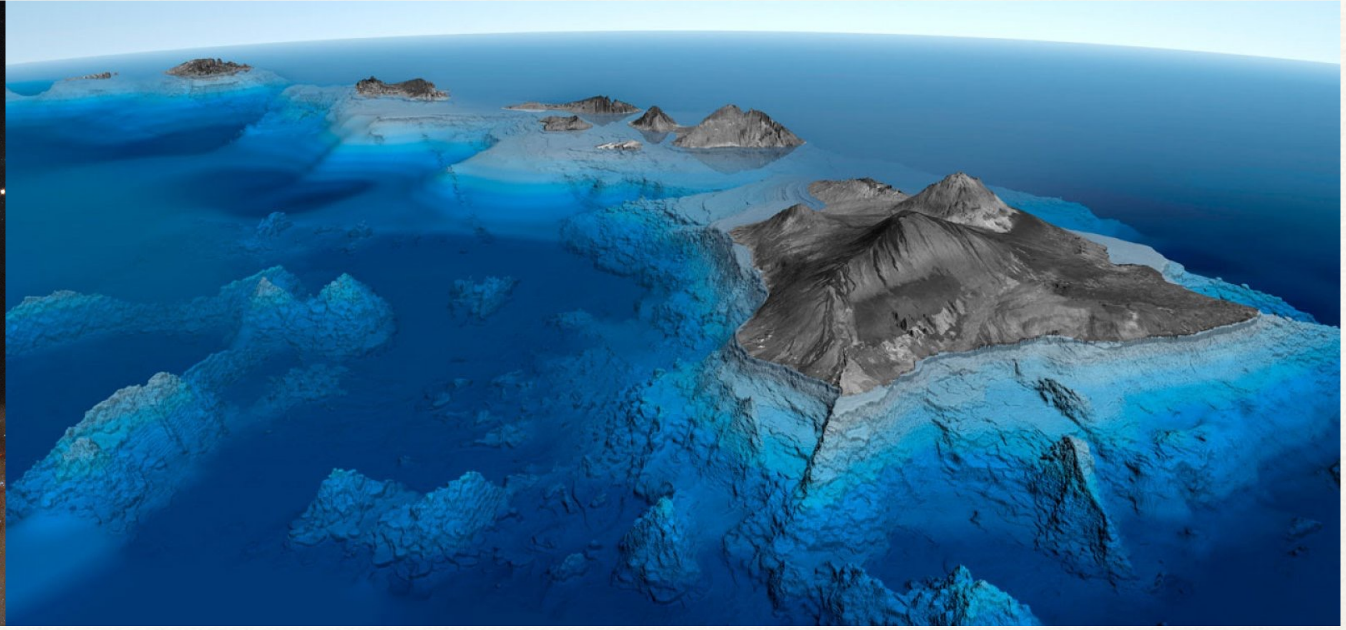


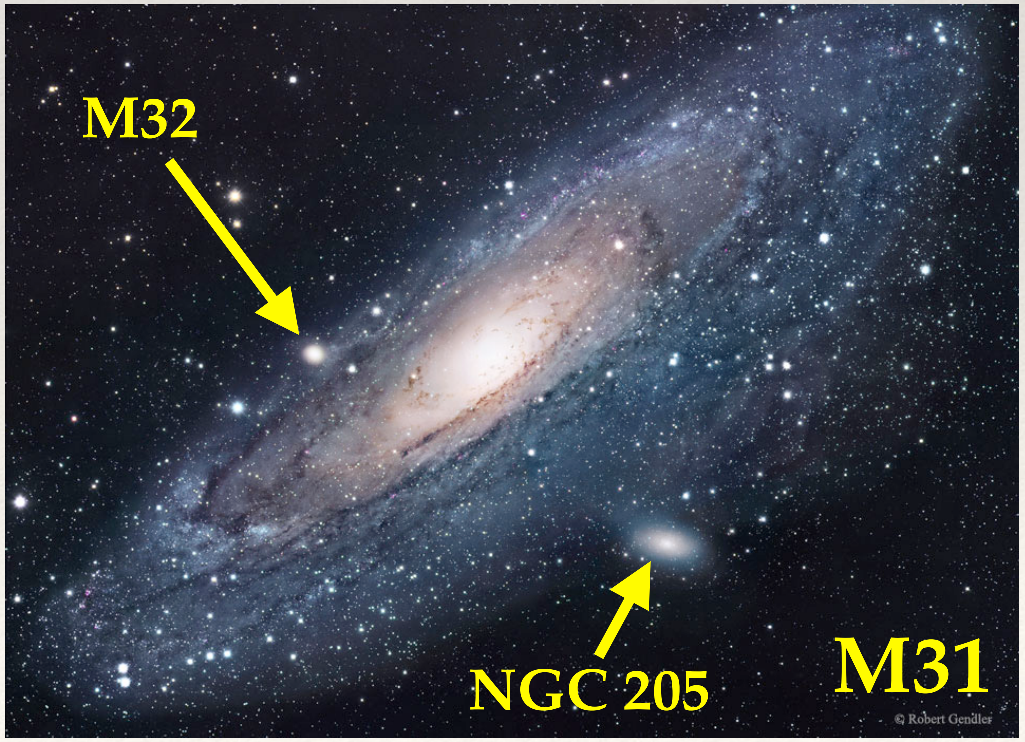
Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. on oltzman

Warm-up

- **Write for 2 minutes**:
    - Make a chart with the main classes of ellipticals and list some key properties for each.
    - M32 is sometimes classified as a compact dE while NGC205 is a dSph (aka a diffuse dE).
        - What would you expect the Sersic *n* to be for each galaxy?
        - Sketch the inner profile you would expect for M32.



https://apod.nasa.gov/apod/ap150830.html

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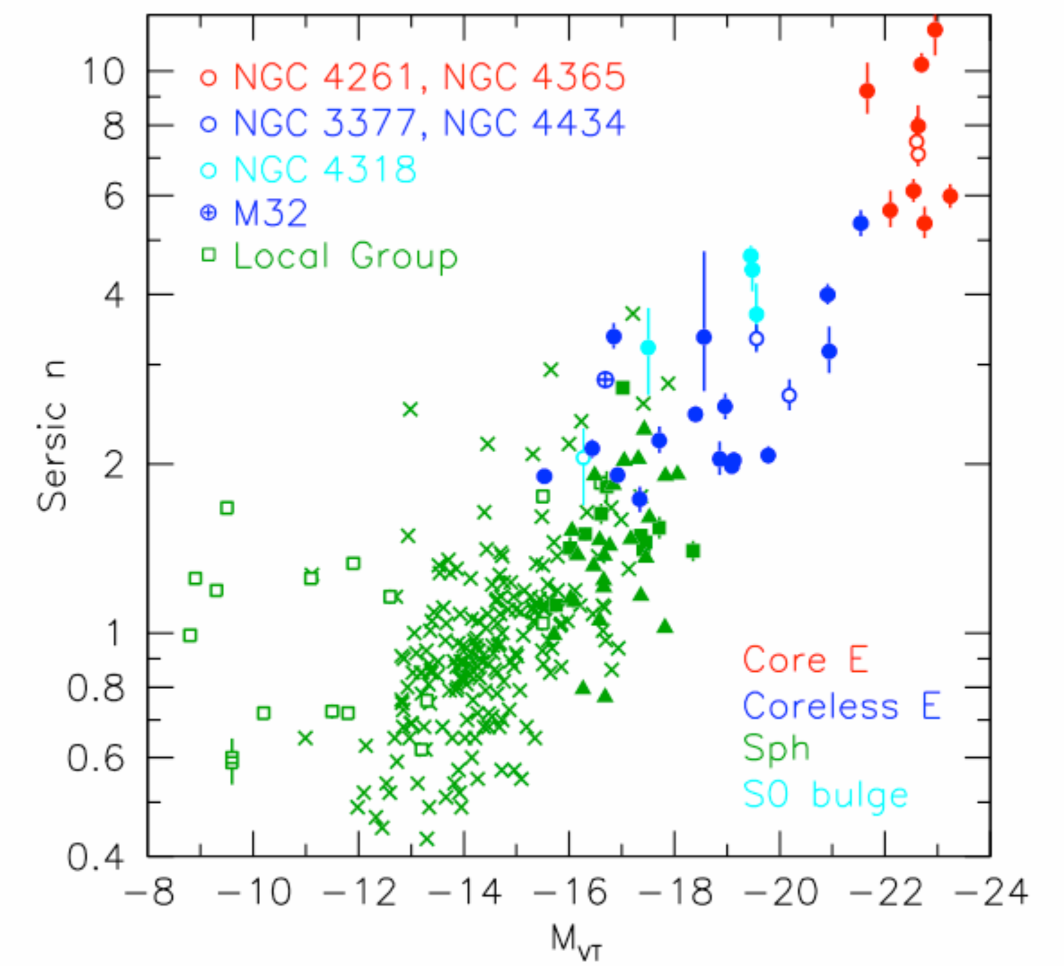
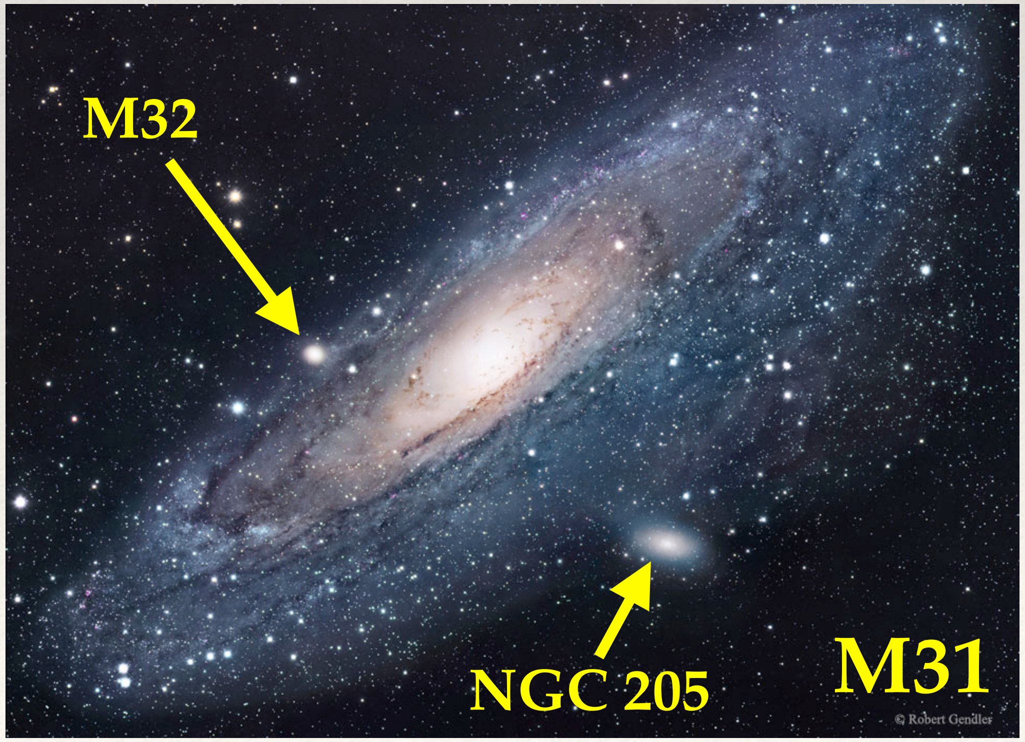


Kormendy 2006



https://apod.nasa.gov/apod/ap150830.html

Ellipticals/Spheroids

- **Low Luminosity — Spheroidals: (**diffuse dEs and dSph**)**
  - more like disks in profiles **(**n ~ **1),** size**,** brightness**,** surface brightness**,** multiple age stellar populations
  - Possibly gas stripped/tidally shaken dwarf irregular **(**dIrr**)** and dwarf spiral **(**dS**)** galaxies
- **Medium Luminosity — Coreless Ellipticals:**
  - central profiles show steep power law to the smallest radii, medium luminosity, high central surface brightness; outer Sersic profiles intermediate n
  - disky isophotes
  - possibly oblate spheroids
  - may have formed from "wet" mergers, gas moves to center to form new stars
- **High Luminosity — Core Ellipticals:**
  - central profiles break to shallower slope, luminous, but lower central brightness; outer profiles n~4
  - boxy isophotes
  - triaxial
  - May have formed from dry mergers of other ellipticals (no gas dissipation), with binary black holes "scouring out" central regions, leaving a flatter core
- There is overlap in luminosity between these groups, and some question about whether they are distinct groups or form a continuous sequence

Outline for Today

- Galaxy Population - Ellipticals/Spheroids:
  - Kinematics
  - Scaling Relations

NGC4636

Galaxy Population - Ellipticals/Spheroids: Kinematics

- Elliptical galaxies are kinematically **“hot”**:
  - Random motions of stars are large compared to organized rotational motion
- Basic kinematic observable is line-of-sight **velocity dispersion σ**:
  - often characterized by central velocity dispersion **σ_0**
  - can vary with radius
  - actual 3D velocity dispersion described as **velocity ellipsoid**

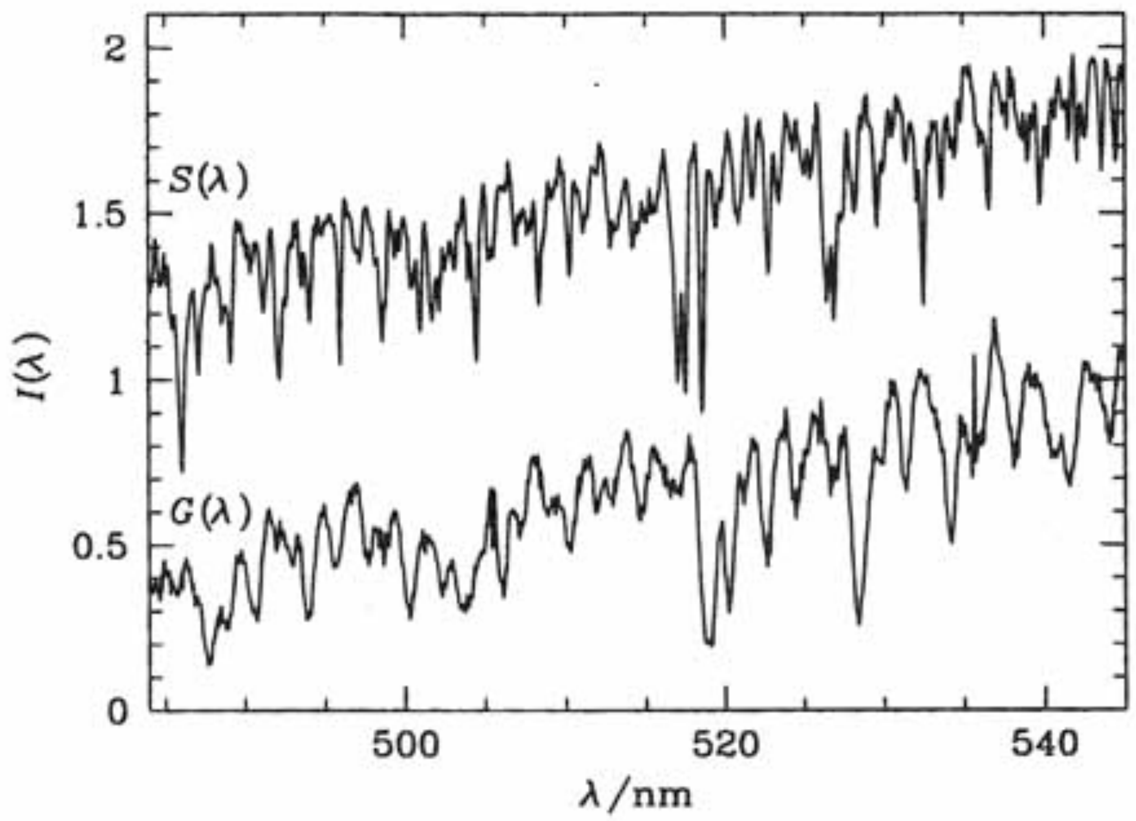


Figure 11.1 Spectra of a K0 giant star (S) and the center of the lenticular galaxy NGC 2549 (G). These data cover a small part of the optical spectrum around the strong Mg b absorption feature at 518 nm.

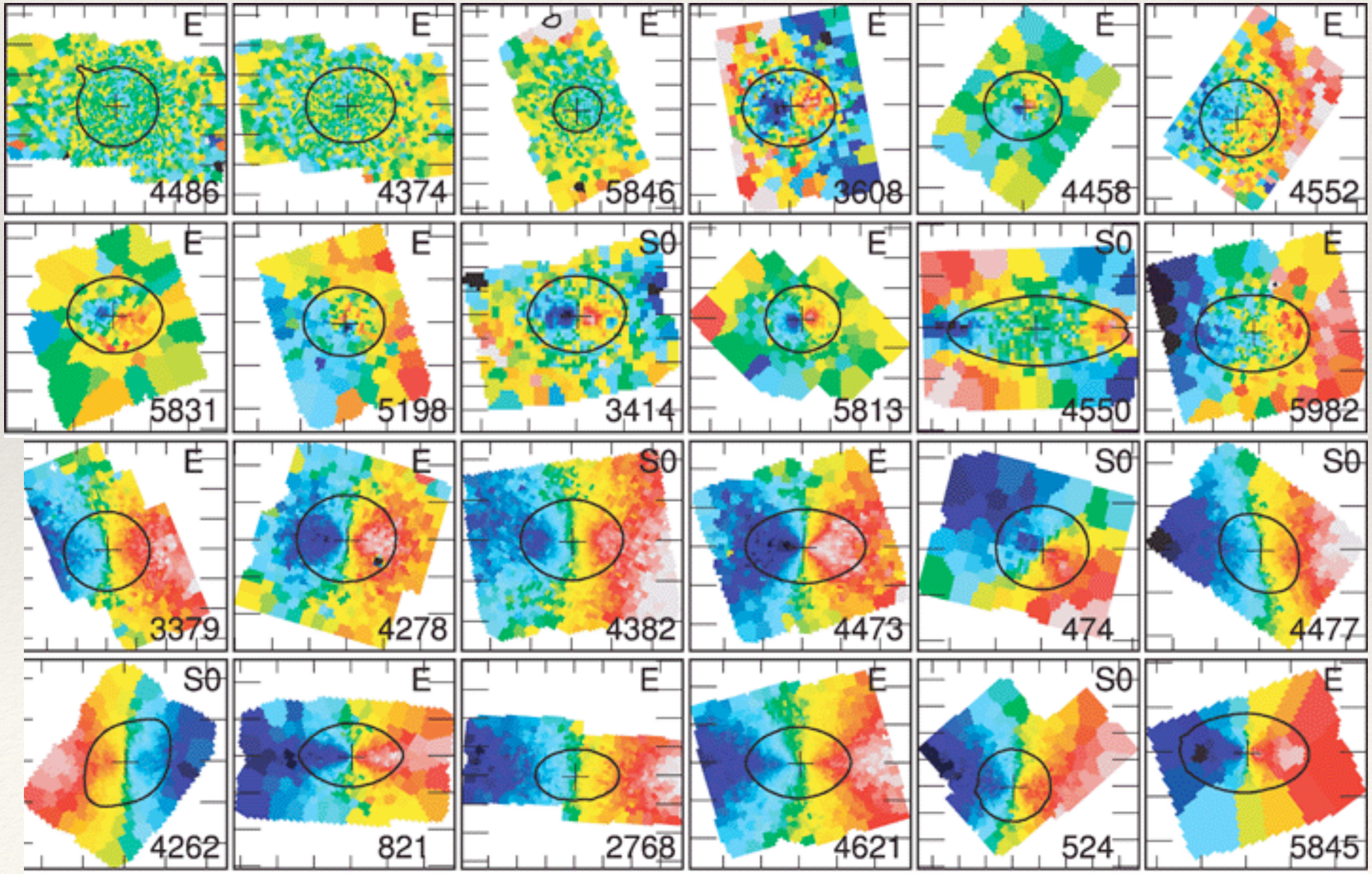
Thought Question

- Integral field spectroscopy (IFS) provides a spectrum at every pixel in a 2D image of the source. Suppose you observed an elliptical and a spiral galaxy using IFS:
  - What would you expect the 2D velocity field (i.e., a map of the measured radial velocity at every pixel) to look like in each case? Make a sketch.

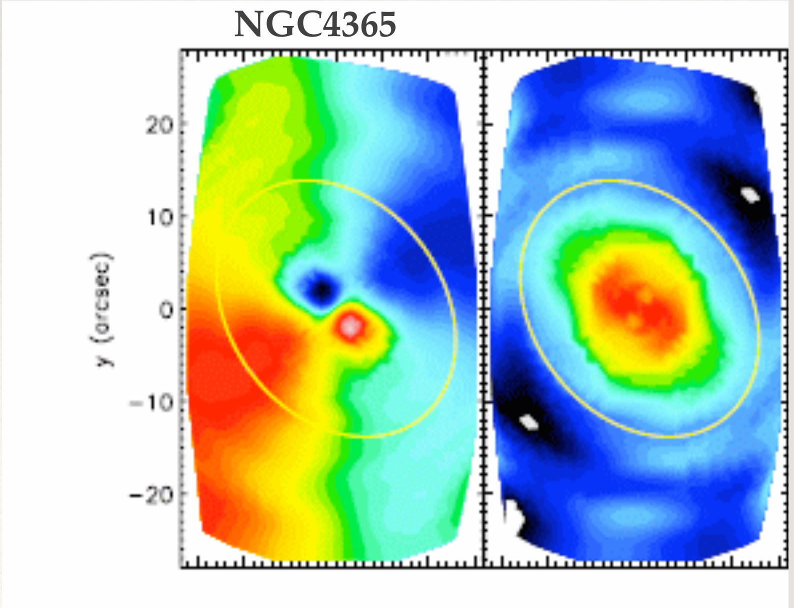
Galaxy Population - Ellipticals/Spheroids: Kinematics

- SAURON & ATLAS-3D surveys of elliptical galaxies revealed a diversity of kinematics!

Emsellem et al. 2007



- Significant fraction have dynamical subcomponents, e.g., “kinematically decoupled cores”



Galaxy Population - Elliptical

- Relative importance of organized vs. random motion characterized by:

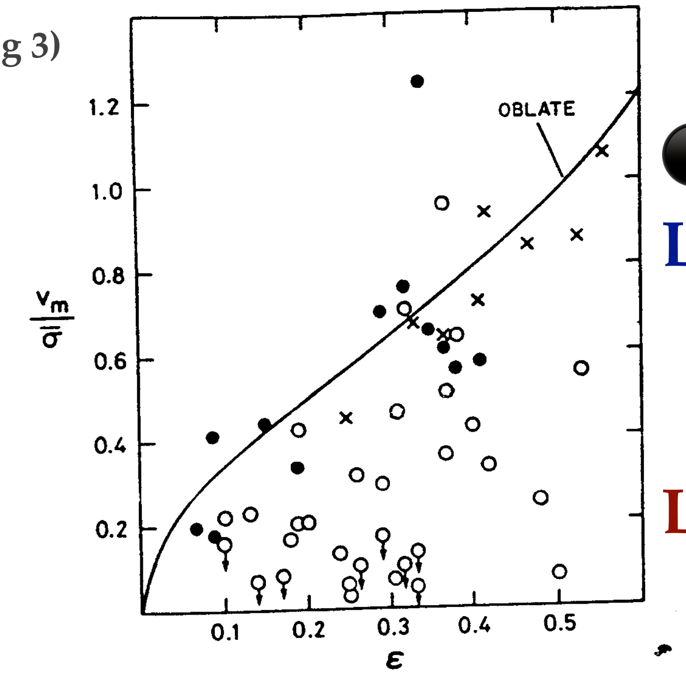
$$v_{rot}/\sigma$$

- More recent work uses λR parameter—specific angular momentum (normalized by mass)
- shape expected to be affected by rotation:
    - e.g., oblate model with isotropic velocity distribution flattened only by rotation:

$$v_{rot}/\sigma = \sqrt{\epsilon/(1-\epsilon)}$$

- Trends with luminosity / inner profile

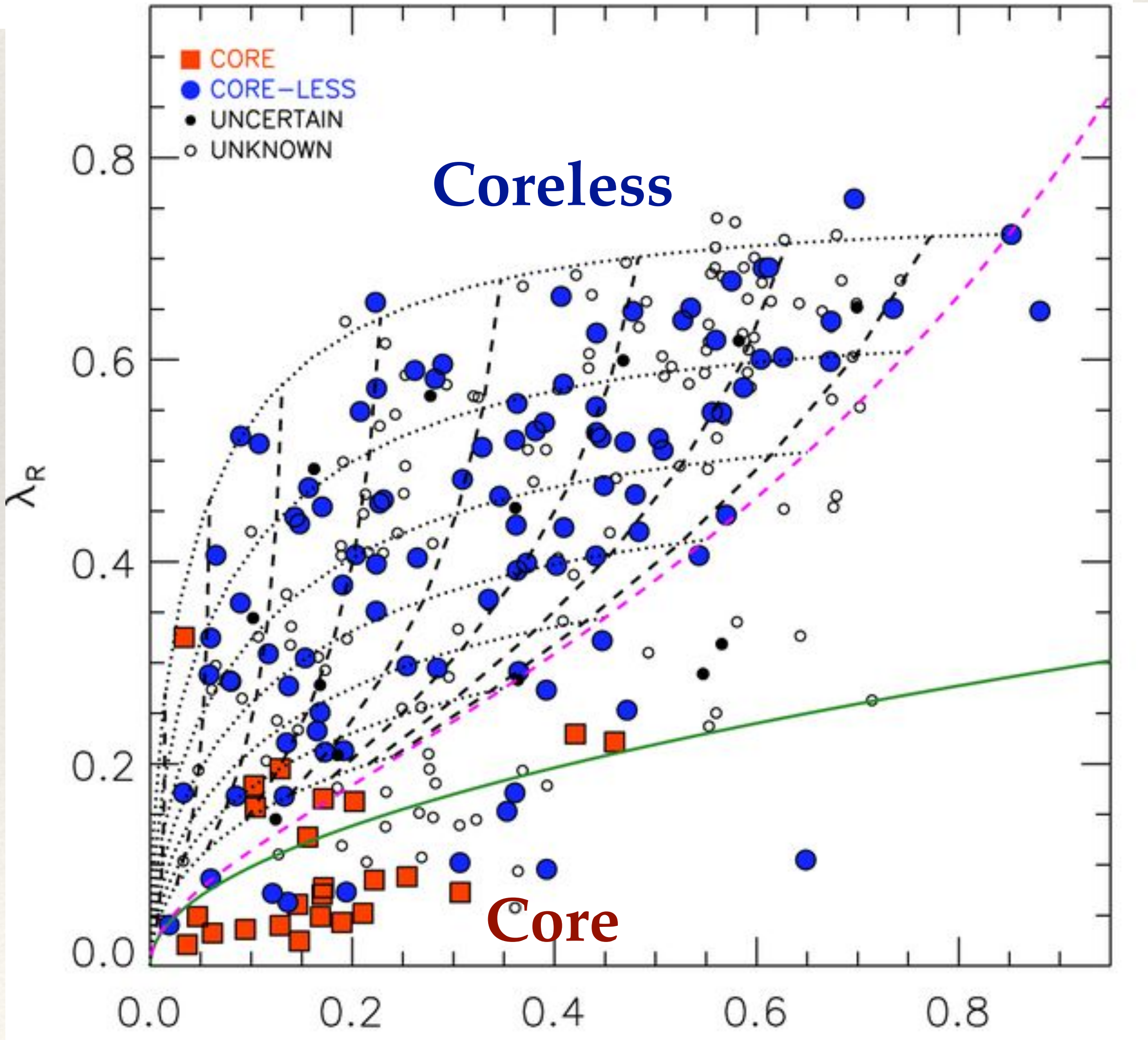
de Zeeuw (Fig 3)



● Medium Luminosity

○ High Luminosity

Figure 3: *Peak line-of-sight rotation velocity v_m divided by the mean velocity dispersion $\bar{\sigma}$ in the central region, as a function of apparent ellipticity ϵ. Open circles are luminous ellipticals with $M_B < -20^m.5$, filled circles are lower luminosity ellipticals and crosses are the bulges of spiral galaxies (Davies 1987). The solid curve is the mean line for oblate isotropic galaxies flattened by rotation.*



Krajnović et al. 2013

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- Deviations from elliptical shape correlated with dynamics:
  - slower rotators ~> **boxy**
  - faster rotators ~> **disky**
- Inner profile properties are correlated too!:
  - Coreless/Power-law galaxies ~> disky, rotating
  - Core galaxies ~> boxy, slow rotators

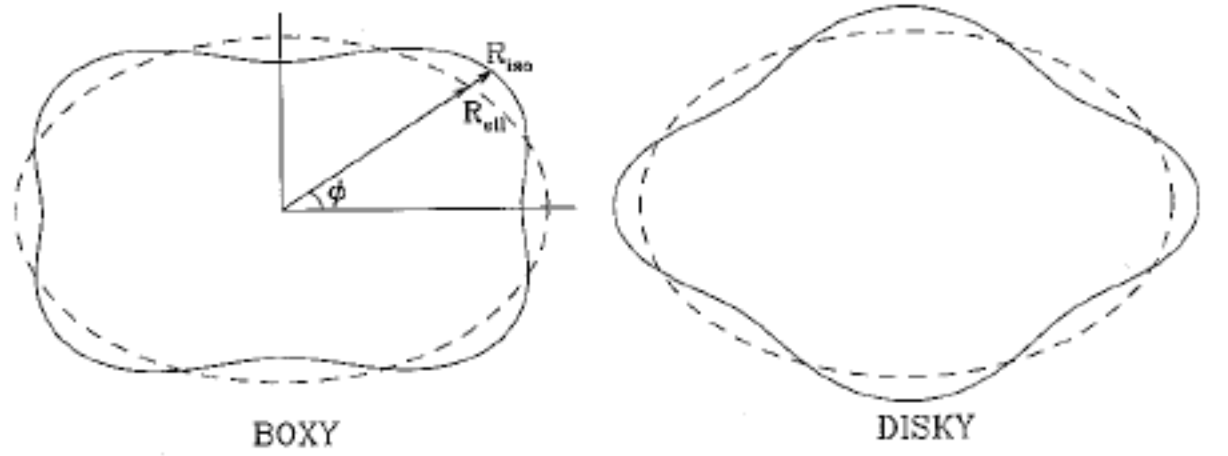
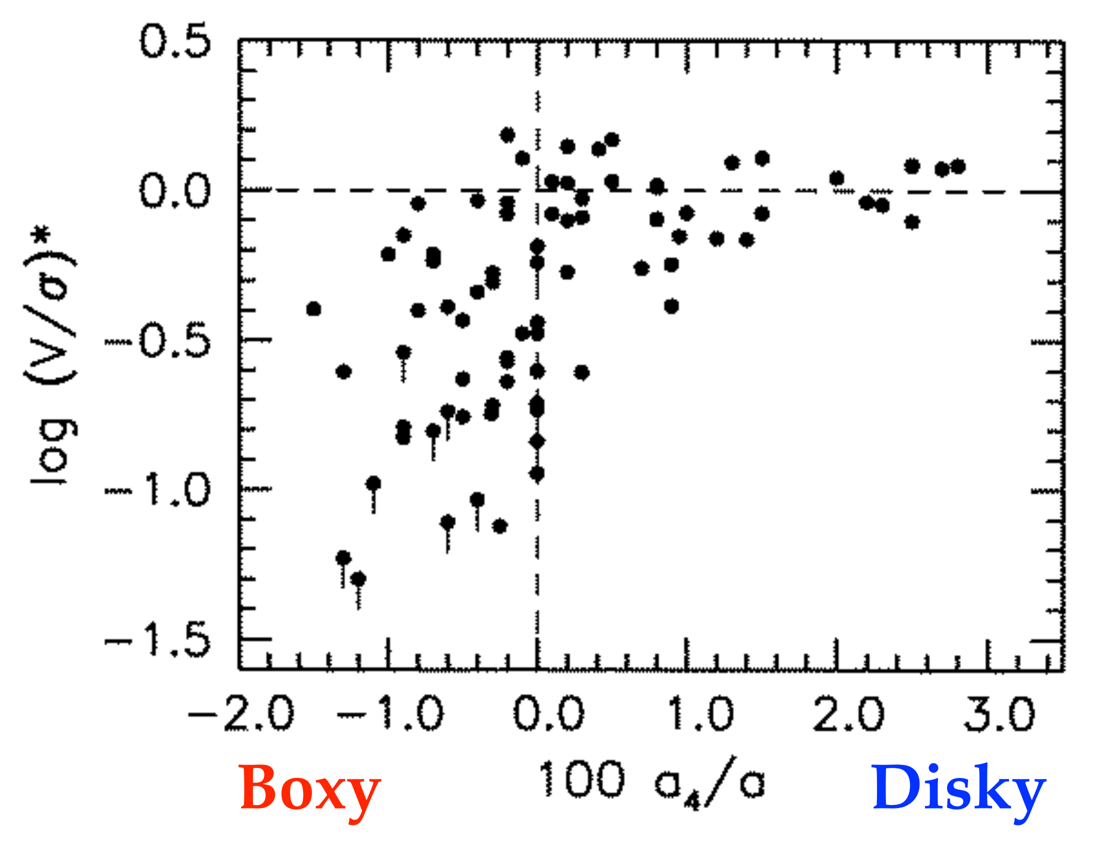


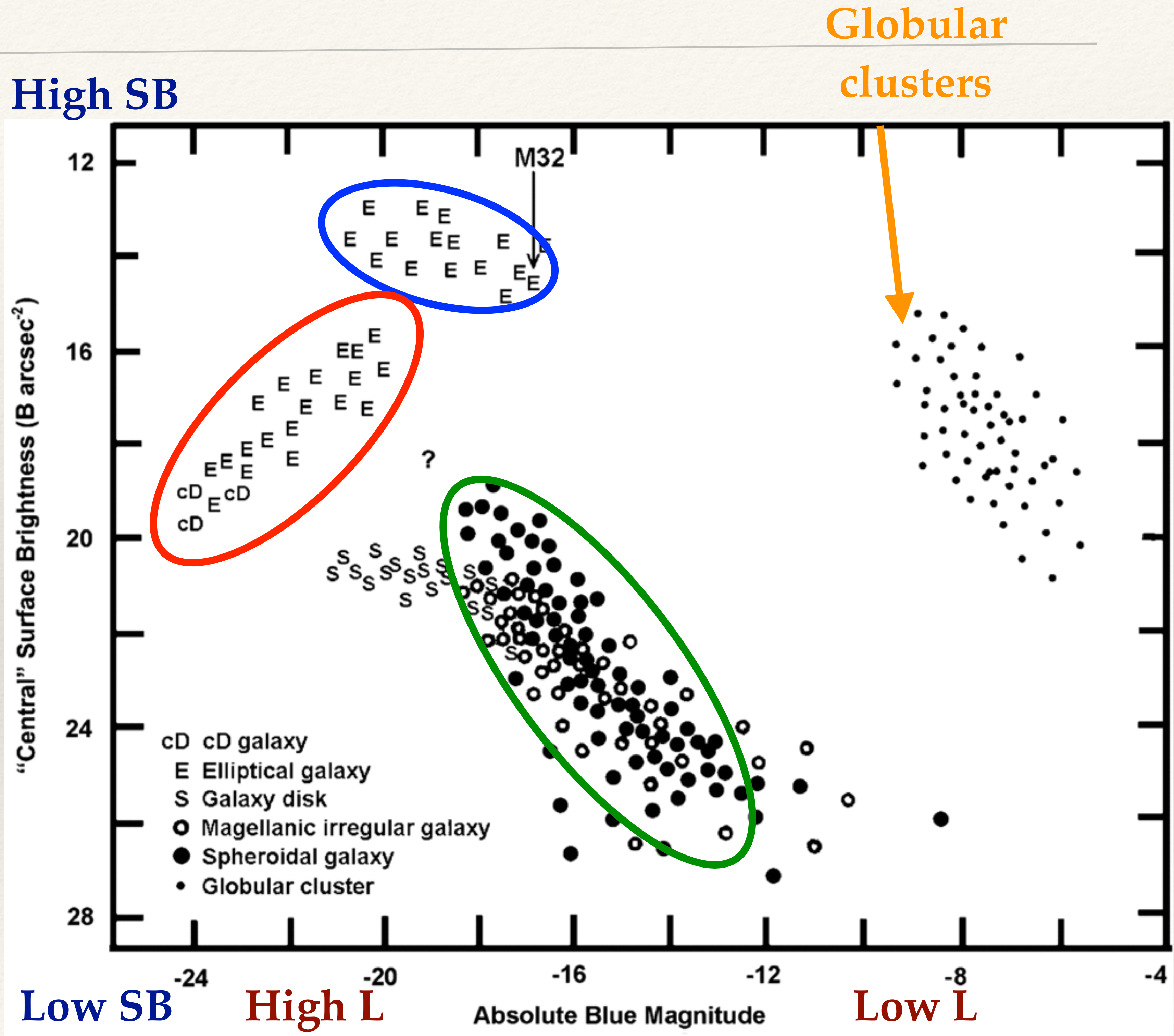
Fig. 2.15. An illustration of boxy and disky isophotes (solid curves). The dashed curves are the corresponding best-fit ellipses.



Kormendy & Bender (Fig 2)

Galaxy Population - Ellipticals/Spheroids: Classes

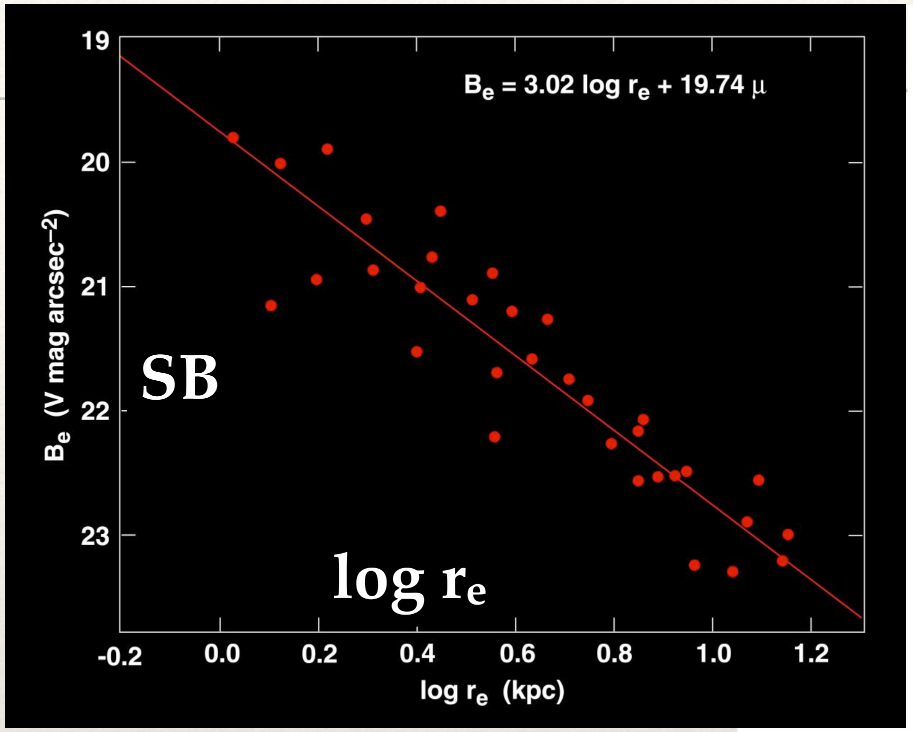
- **Low Luminosity — Spheroidals**: (diffuse dEs and dSph)
    - slow rotators for their ellipticity, radially anisotropic
- **Medium Luminosity — Coreless Ellipticals**:
    - significant rotation, nearly isotropic oblate spheroids
    - disky isophotes
- **High Luminosity — Core Ellipticals:**
    - non-rotating, radially anisotropic, triaxial
    - boxy isophotes



Kormendy 2009

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- Overall ellipticals obey relatively simple scaling relations:
  - **Kormendy Relations**:
    - surface brightness vs. size
    - surface brightness vs. luminosity relations
- Profile shape (e.g. Sersic index) vs. luminosity



Kormendy 1977 (PhD Thesis)

Kormendy 2009

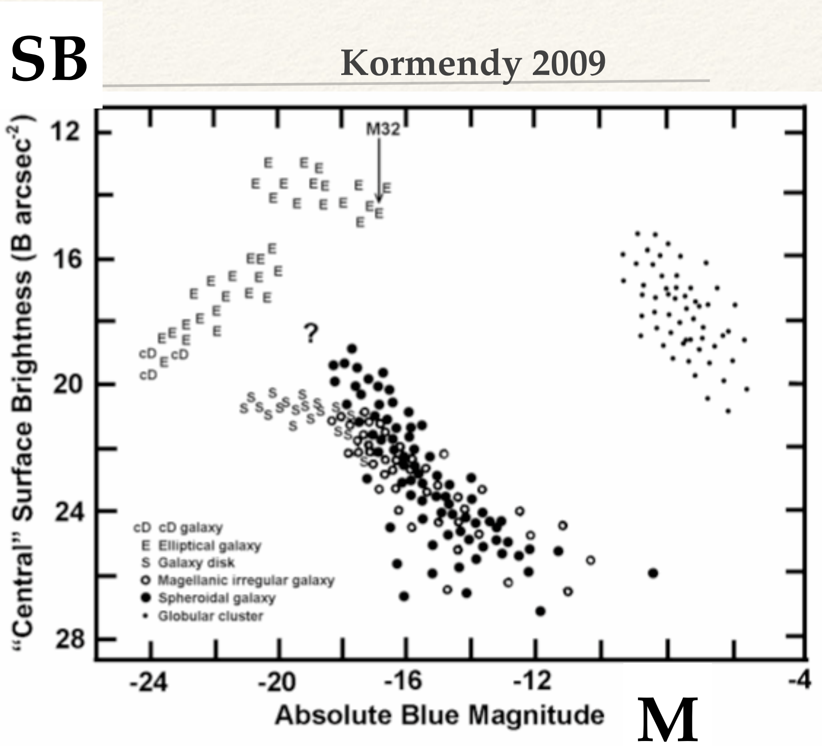
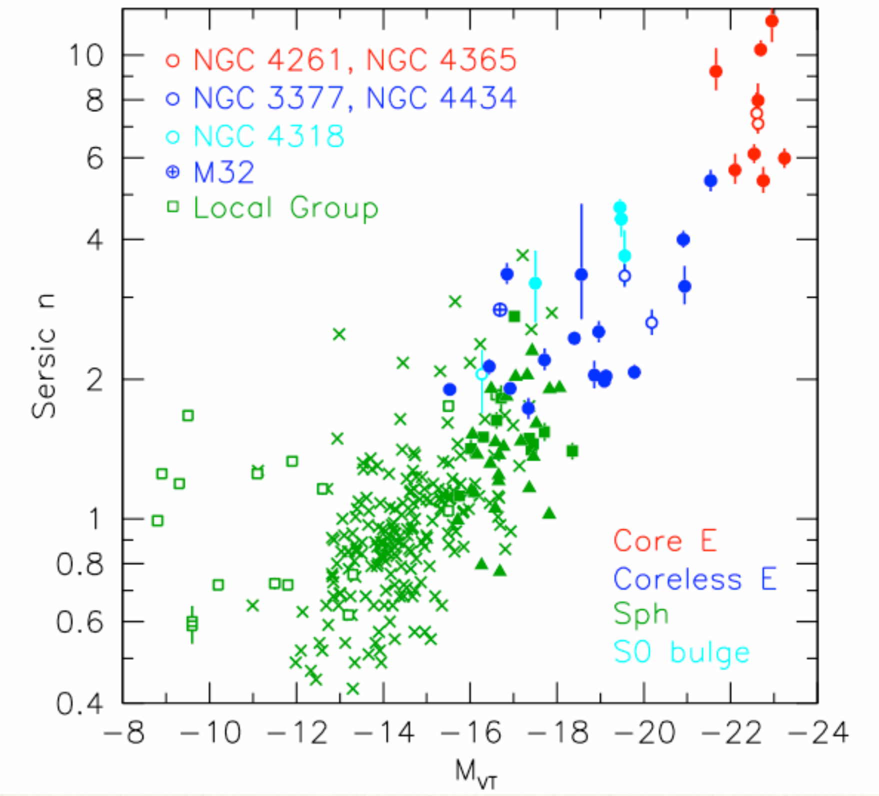


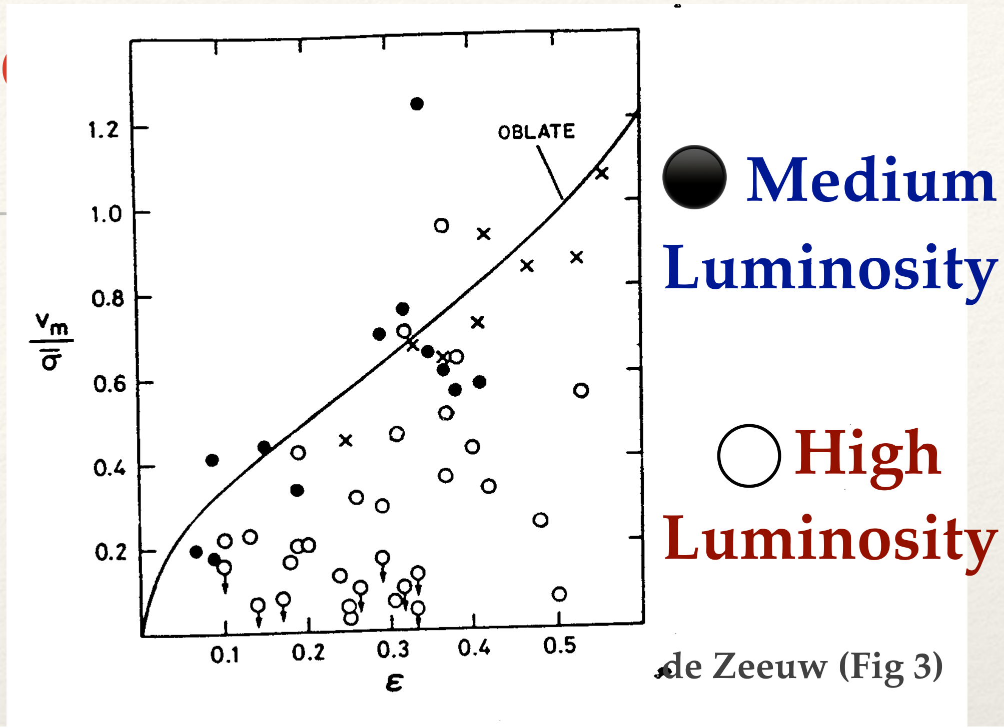
FIG. 1.— Schematic illustration of the dichotomies discussed in this paper. The figure sketches the correlation be ibsolute magnitu
brightness (for spheroidal and irregular galaxies, galaxy disks, and globular clusters) or the highest surface brightness resolved by the *Hubble*
elliptical and cD galaxies). Surface brightnesses apply to the main bodies of the galaxies; that is, nuclear star clusters and active galactic nu
figure is adapted from Binggeli (1994) but with the dichotomy between "core" and "power law" ellipticals – i.e., the discontinuity in E points a
from Faber et al. (1997). M 32 is one of the lowest-luminosity true ellipticals; the arrow points from the maximum surface brightness observ
Mpc to the lower limit that would be observed if the galaxy were moved to the Virgo cluster. M 32 resembles the faintest ellipticals in Virgo. T
ph and S+Im galaxies have similar global parameters at low luminosities, but the most
ırd higher surface brightness. Spheroidals with $M_B \lesssim -18$ are rare, so the degree to wh
mark). Note: Binggeli (1994) and some other authors call spheroidal galaxies "dwarf
igure and in Figures 34 – 38 and 41, as well as the considerations discussed in § 2.1 and
elated to late-type galaxies.

Kormendy 2006

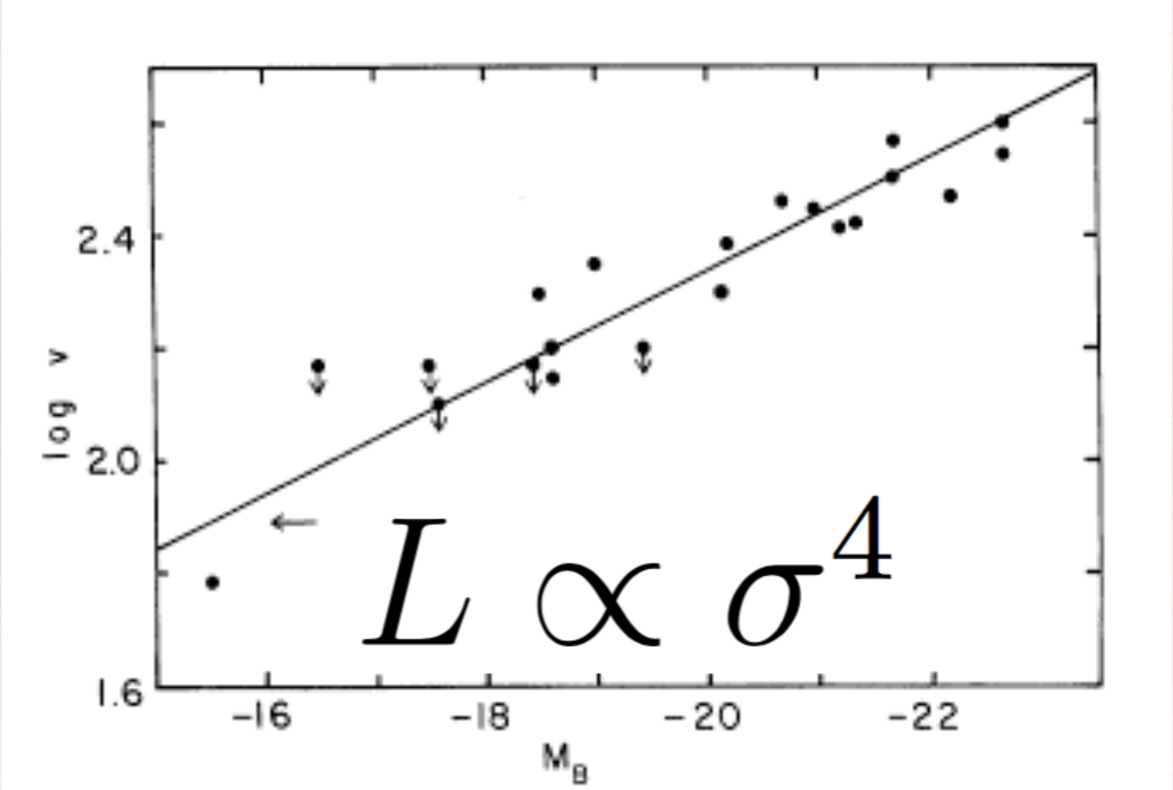


Galaxy Population - Ellipticals/Spher

- More luminous galaxies have less rotation
- **Faber-Jackson Relation**:
  - More luminous galaxies have higher velocity dispersions
- Clear scaling relations yet lots of scatter:
  - Correlation between residuals of relations with other parameters
  - **Suggests a more fundamental relationship…**



de Zeeuw (Fig 3)



$$L \propto \sigma^4$$

FIG. 16.—Line-of-sight velocity dispersions versus absolute magnitude from Table 1. The point with smallest velocity corresponds to M32, for which the velocity dispersion (60 km s^{-1}) was taken from Richstone and Sargent (1972).

Faber & Jackson 1976

Thought Questions

- Consider a stable, spherical, self-gravitating system in equilibrium:
    - How are the kinetic and potential energy of the system related?
    - What relevant quantities can we actually observe from a real galaxy?

Virial theorem:

$$-<U>=2<K>$$

$$\frac{GM}{<R>}=<v^2>$$

We do not have the information to average over all the particles, however, we have measurements of R_e, I_e and σ_0. Assume scaling relations:

$$R_e = k_R <R>$$

$$\sigma_0^2 = k_v <V^2>$$

$$L = k_L I_e R_e^2$$

where k_R, k_v, k_L represent density, kinematic, and luminosity structure of the galaxy, i.e., all the details!

Therefore we have

$$\frac{GMk_R}{R_e} = \frac{\sigma_0^2}{k_V}$$

$$L = k_L I_e R_e^2$$

With a mass-to-light ratio:

$$M = L(M/L)$$

We then derive:

$$R_e = Gk_R k_V k_L (\frac{M}{L})^{-1} \sigma_0^2 I_e^{-1}$$

If we were to have k_R, k_V, k_L, and M/L the same across a set of galaxies ("homology"), then we would expect a relation of this form. We already know that they don't (Sersic index variations, v/sigma variations!

Conversely, deviations from this relation indicate that some of these quantities vary across the population.

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- Expect fundamental relationship if Ellipticals:
    - are in Virial equilibrium
    - form a “homologous” family, e.g., with similar profiles, or that vary smoothly with other parameters
    - M/L constant or varies systematically with luminosity

$$r_e = \mathbf{k}\left(\frac{M}{L}\right)^{-1}\sigma_0^2 I_e^{-1}$$

- Note: “constants” **k** have to do with galaxy shape, structure, and other pesky details, and very well may not be constant across the population!

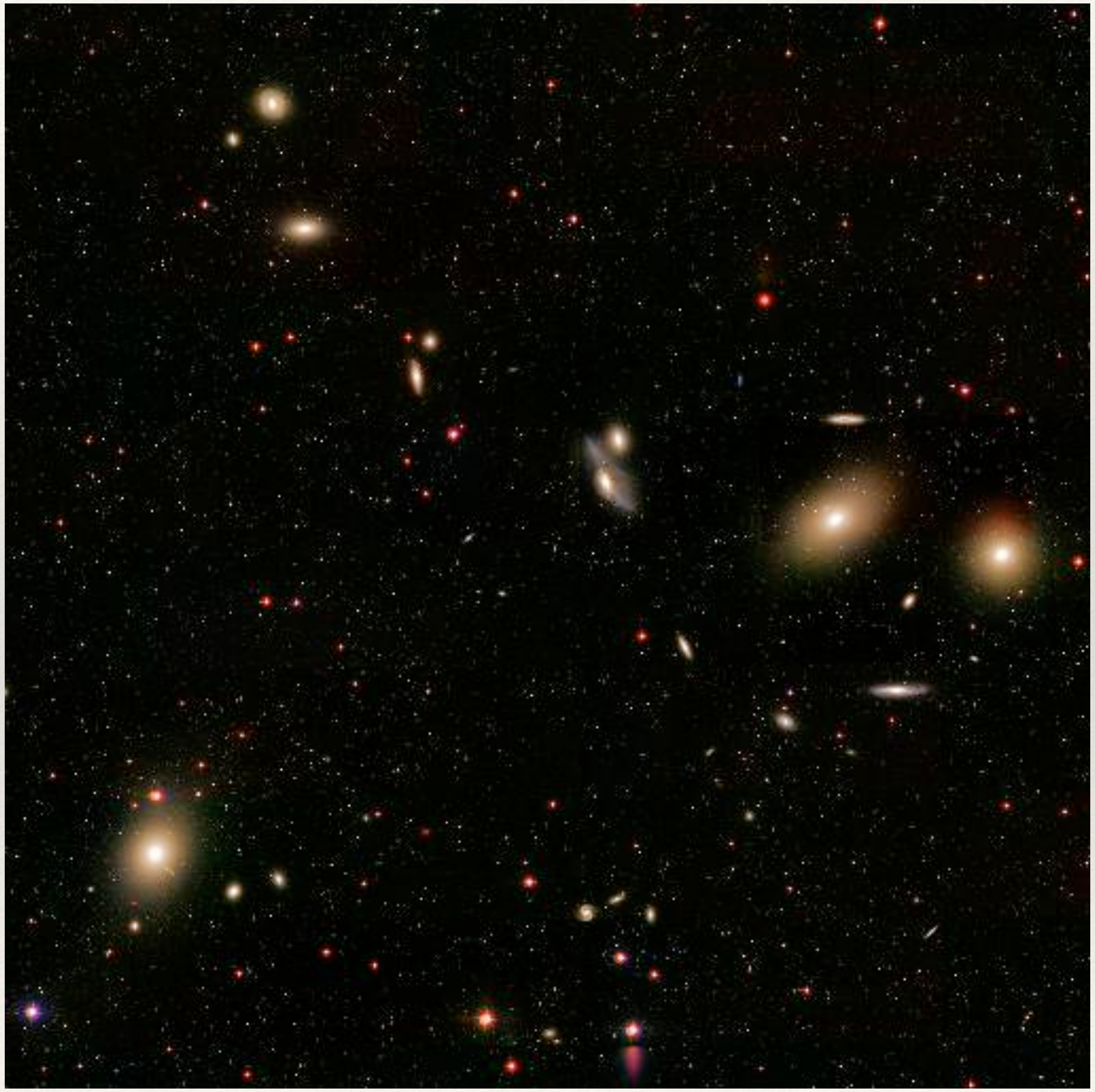
Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- Expected relation:

$$r_e = \mathbf{k} \left(\frac{M}{L}\right)^{-1} \sigma_0^2 I_e^{-1}$$

- Early observed relation for ellipticals in the Virgo Cluster:

$$r_e \propto (\sigma_0^2)^{0.7} I_e^{-0.85}$$



Virgo Cluster (SDSS)

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- **Fundamental Plane of Elliptical Galaxies**:
  - relationship between surface brightness (or luminosity), size, and velocity dispersion
  - Faber-Jackson and Kormendy relations are projections

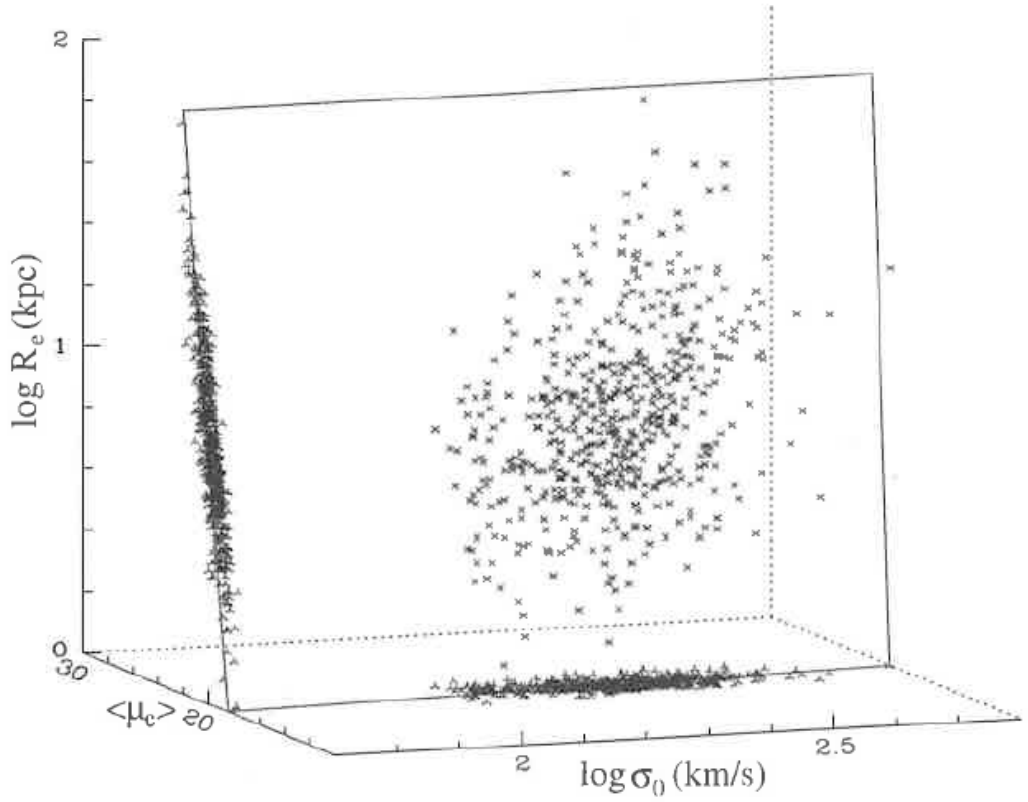
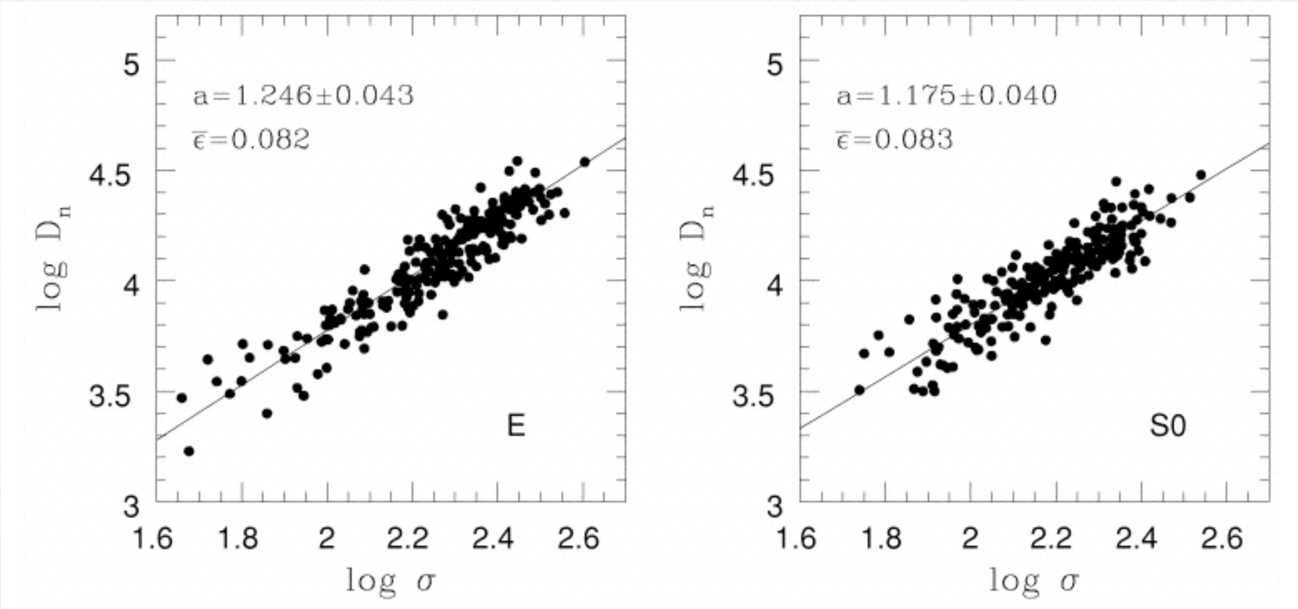


Fig. 2.18. The fundamental plane of elliptical galaxies in the $\log R_e$-$\log \sigma_0$-$\langle \mu \rangle_e$ space (σ_0 is the central velocity dispersion, and $\langle \mu \rangle_e$ is the mean surface brightness within R_e expressed in magnitudes per square arcsecond). [Plot kindly provided by R. Saglia, based on data published in Saglia et al. (1997) and Wegner et al. (1999)]

Mo, van den Bosch, & White; Fig 2.18

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- **Fundamental Plane of Elliptical Galaxies**:
    - can represent plane in 2D by appropriate combination of parameters, for example:
    - D_n- $\boldsymbol{\sigma}$ relation (Dressler 1987) effectively views the Fundamental Plane edge-on
        - D_n = diameter of the B=20.75 mag/arcsec^2 isophote
        - combines R_e and I_e



Bernardi et al. 2002

Quick Question

- How can we use the Faber-Jackson and D_n- σ relations to find distances to galaxies?

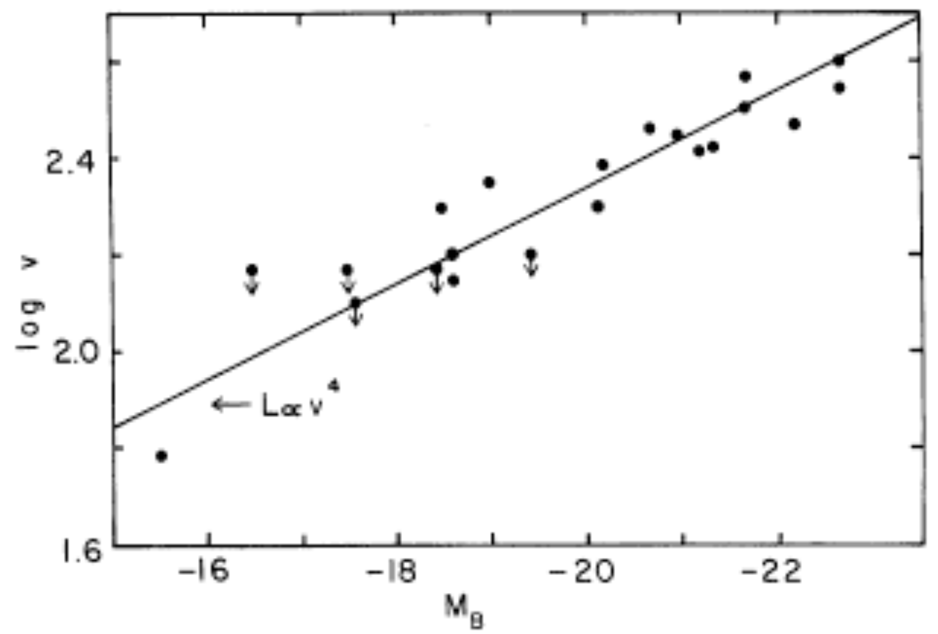
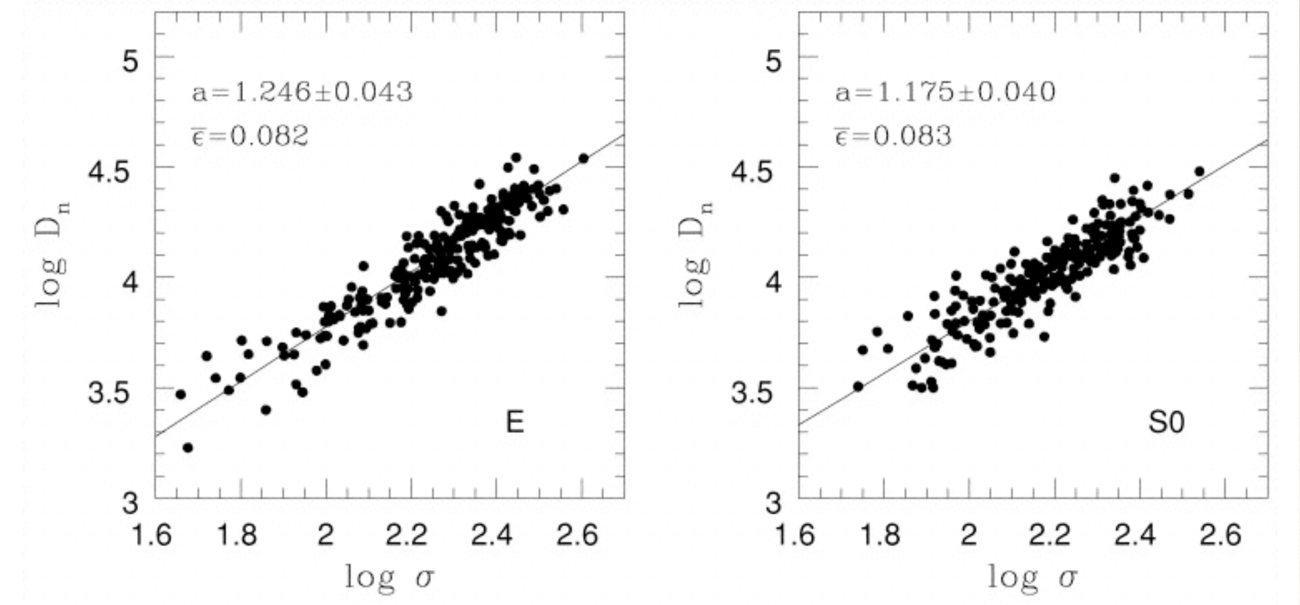


FIG. 16.—Line-of-sight velocity dispersions versus absolute magnitude from Table 1. The point with smallest velocity corresponds to M32, for which the velocity dispersion (60 km s^{-1}) was taken from Richstone and Sargent (1972).

Faber & Jackson 1976



Bernardi et al. 2002

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- Fundamental Plane from 93,000 ellipticals in SDSS
- Very small scatter! — **what does that imply?**
    - assumptions are reasonably valid over a large range of elliptical properties
    - significant regularities in the galaxy formation process

Often combine two parameters with appropriate coefficients to plot in 2D

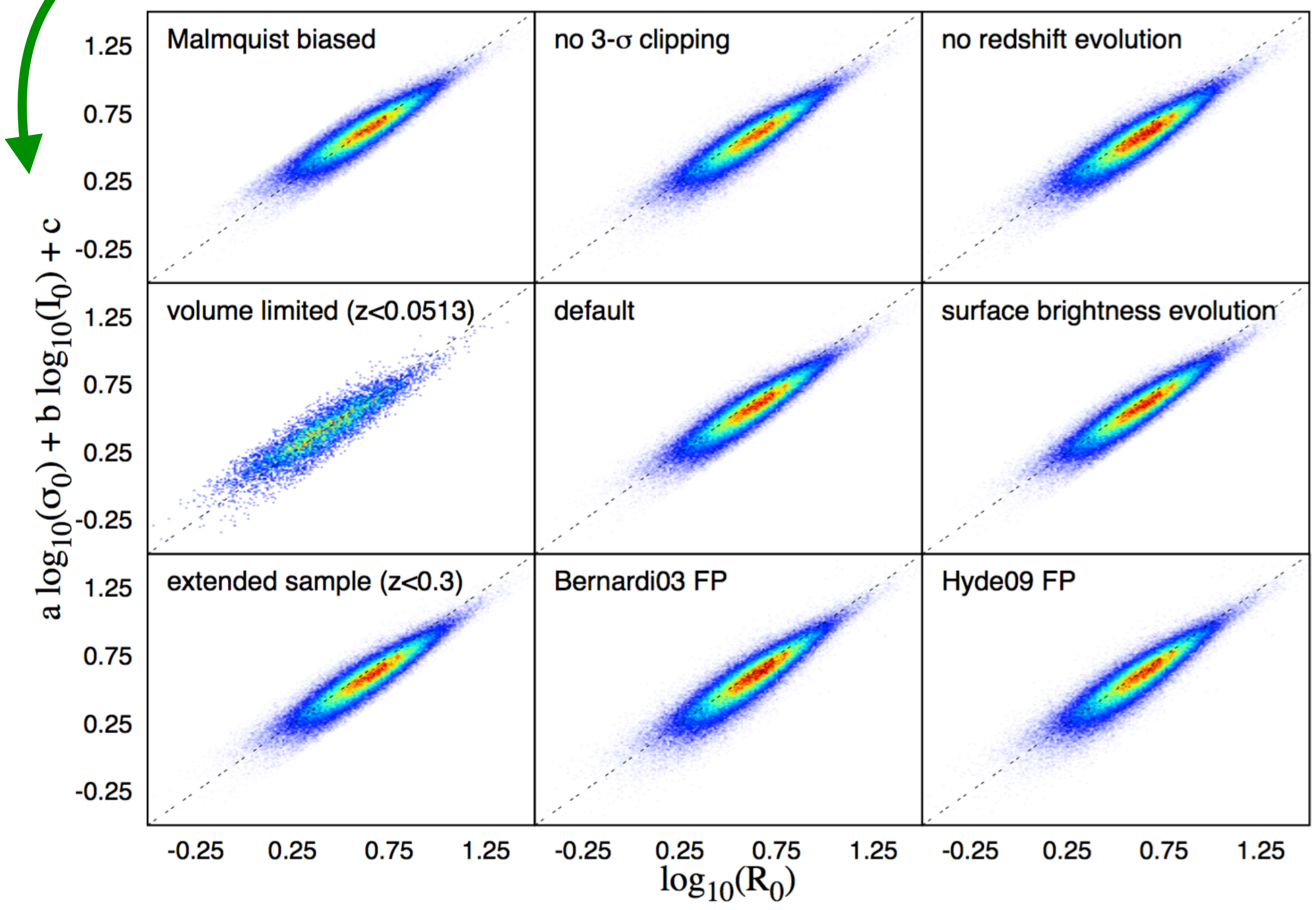


Figure 17. Results for the fundamental plane in the i band for the dV model using our alternatives fits. The plot in the top-left panel does not include the Malmquist bias. We did not perform a 3-σ clipping for the plot in the top-middle panel. The plot in the top-right panel excludes the redshift evolution. The results of the volume-limited sample ($z < 0.0513$) can be found in the central-left panel. The central-middle panel contains a plot of the default i band fit for the dV model for comparison. We are considering the surface brightness evolution instead of the redshift evolution derived form galaxy number densities in the central-right panel. In the bottom-left panel, the results are shown for an extended sample up to $z = 0.3$. The fundamental plane plotted using the coefficients of Bernardi et al. (2003c), but with our sample data is displayed in the bottom-middle panel. A similar plot using the coefficients of Hyde & Bernardi (2009) can be found in the bottom-right panel.

Saulder+2013, A&A

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- Expected relation:

$$r_e = \mathbf{k} \left(\frac{M}{L}\right)^{-1} \sigma_0^2 I_e^{-1}$$

- Saulder+2013 results (SDSS):
  - $r_e \sim \sigma^{1.126}\, I_e^{-0.688}$
- Clear departure from "homologous" Fundamental Plane — it has a "tilt"!

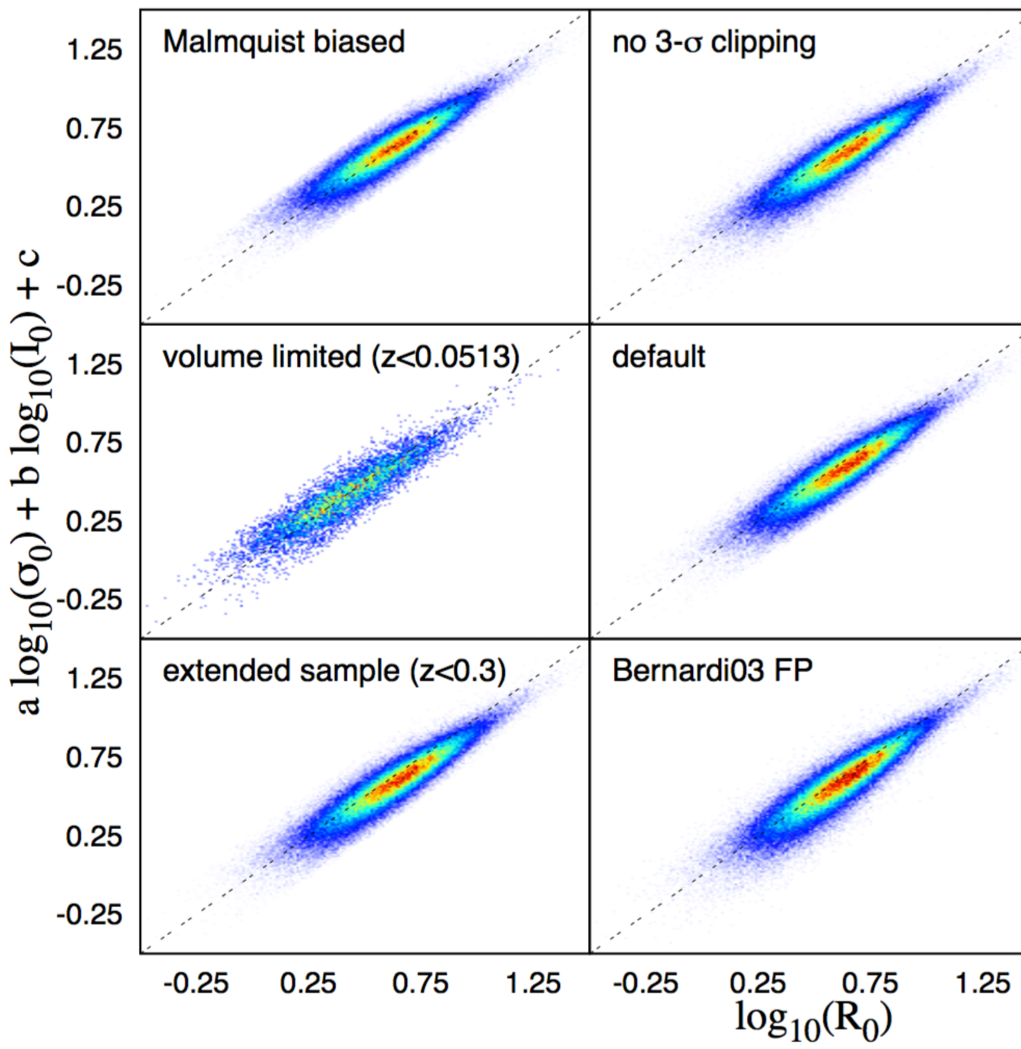
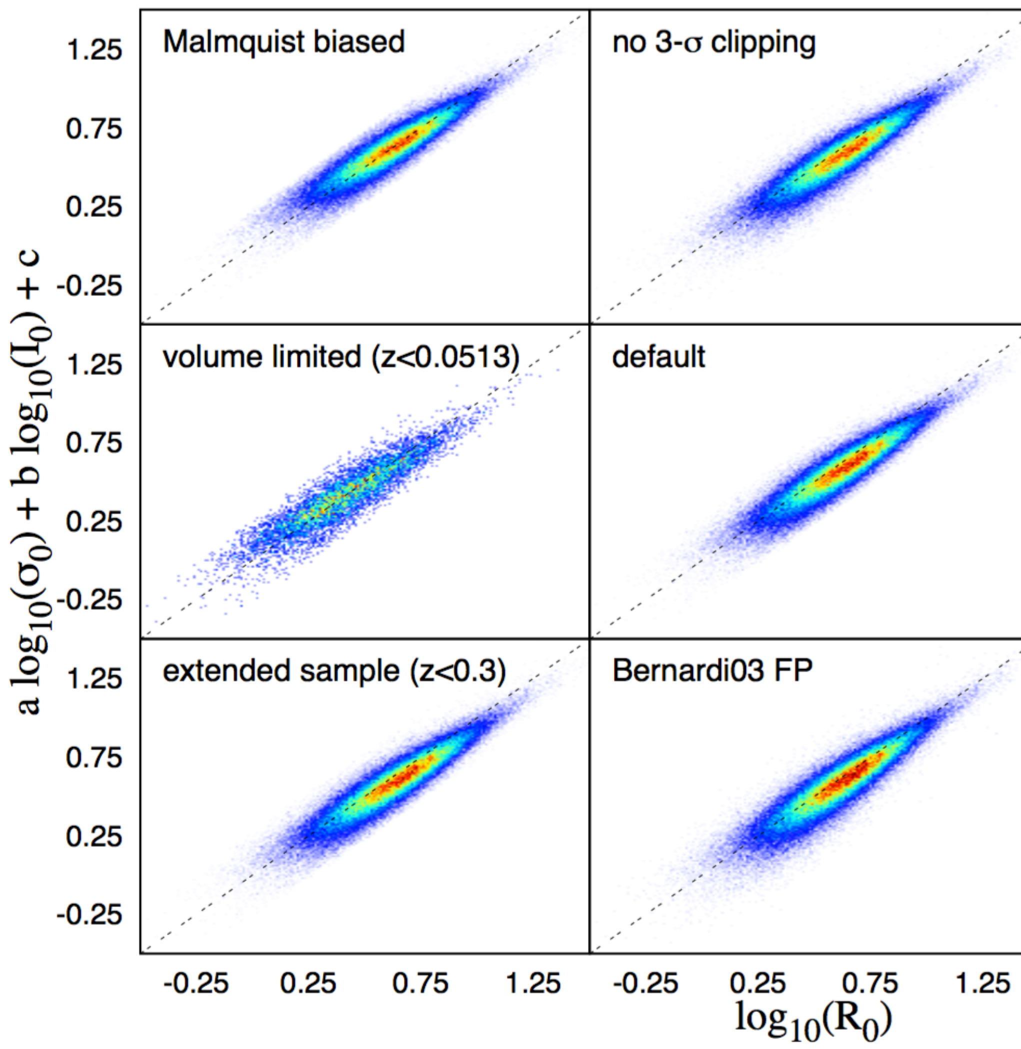


Figure 17. Results for the fundamental plane in the i band for the dV model using our alternatives the Malmquist bias. We did not perform a 3-σ clipping for the plot in the top-middle panel. Th evolution. The results of the volume-limited sample ($z < 0.0513$) can be found in the central-left the default i band fit for the dV model for comparison. We are considering the surface brightness form galaxy number densities in the central-right panel. In the bottom-left panel, the results are fundamental plane plotted using the coefficients of Bernardi et al. (2003c), but with our sample similar plot using the coefficients of Hyde & Bernardi (2009) can be found in the bottom-right p

Saulder+2013, A&A

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- “Tilt” could be from:
  - non-homology in surface brightness profiles or kinematics
  - varying M/L
    - stellar population properties
    - dark matter fraction
  - effects of gas dissipation



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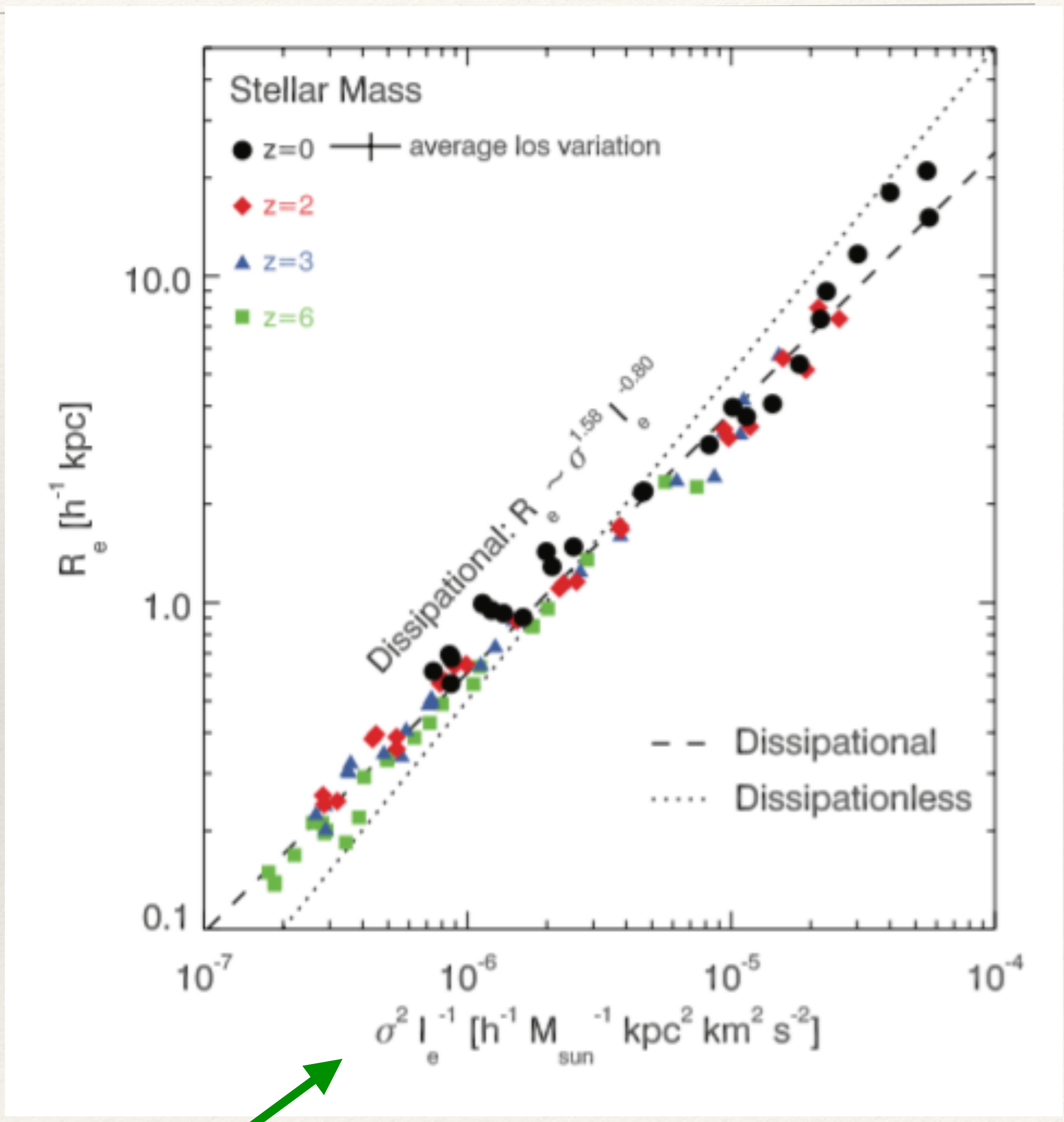
Saulder+2013, A&A

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- Simulations suggest that gas may be important:
  - Without gas dissipation, galaxies stay on the virial plane even after collisions.
  - Collisions and gas dissipation change the dynamics, particularly at low masses, leading to "tilt".



Robertson+2006

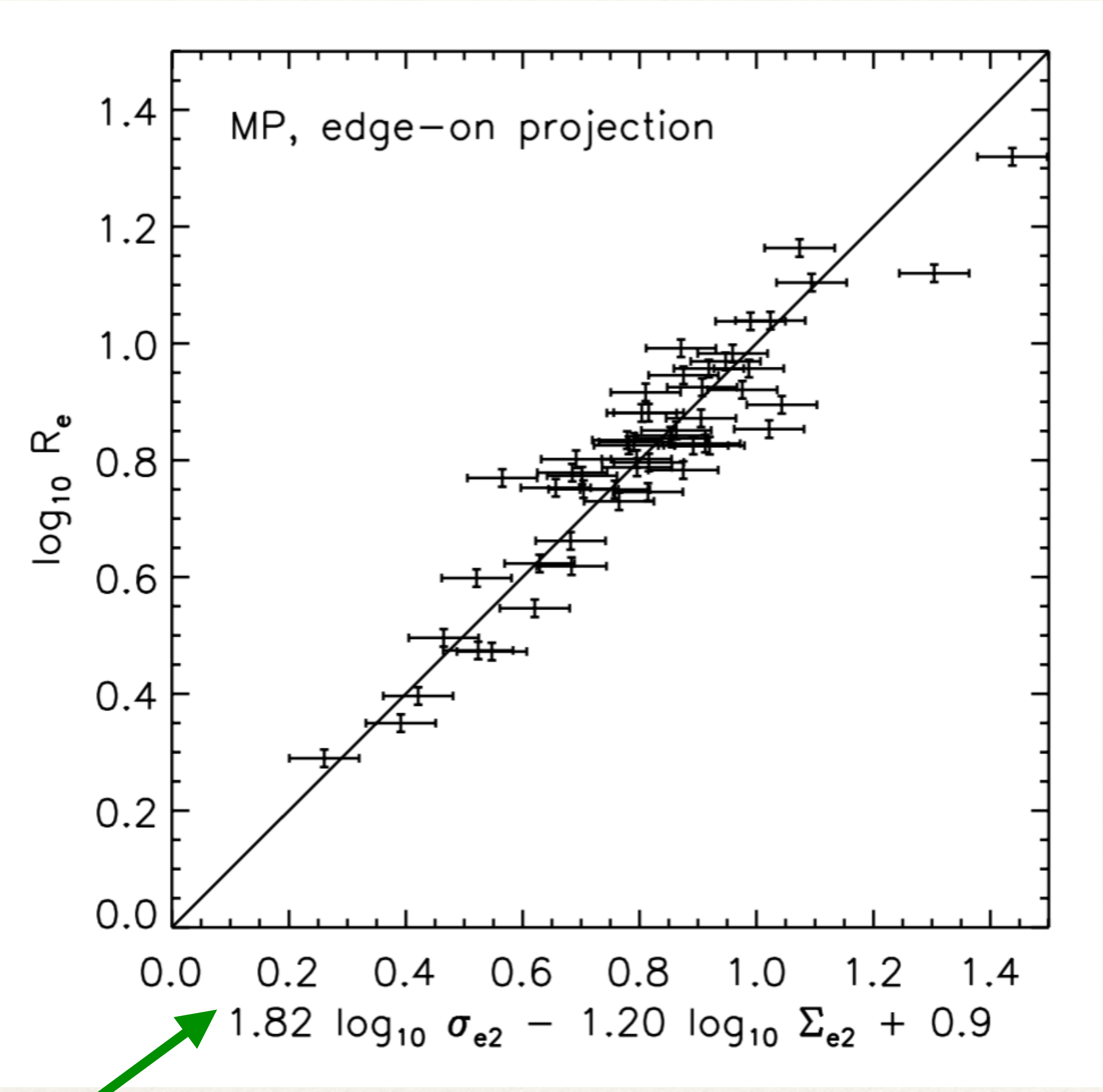
Often combine two parameters with appropriate coefficients to plot in 2D

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- Homologous Fundamental Plane:

$$r_e = \mathbf{k}\left(\frac{M}{L}\right)^{-1}\sigma_0^2 I_e^{-1}$$

- Bolton et al. 2007 use Σ (surface mass density of stars + dark matter) as measured from strong lensing to plot "Mass Plane" (MP):
    - $r_e \sim \sigma^{1.77}\,\Sigma^{-1.16}$
- "Tilt" is reduced and residuals smaller:
    - Variable (M/L)?

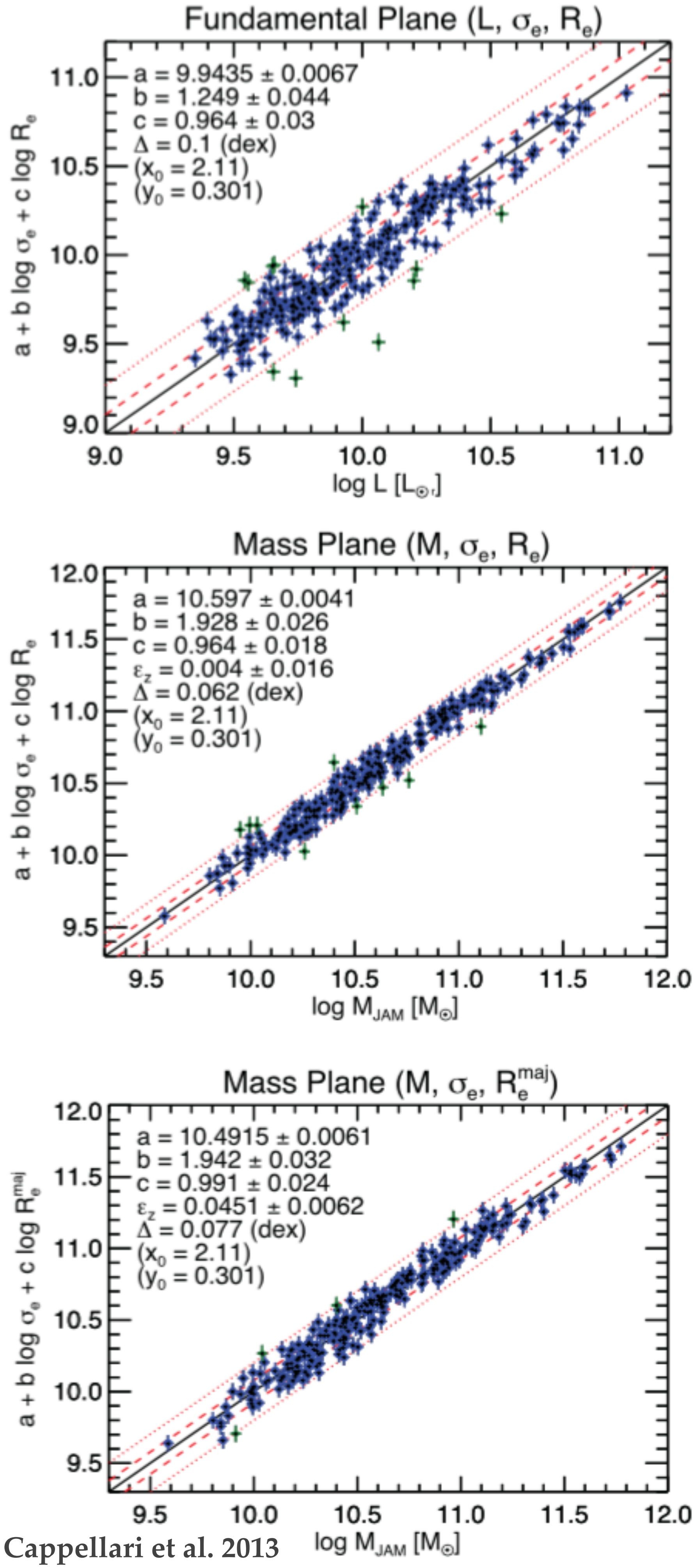


Bolton et al. 2008

Often combine two parameters with appropriate coefficients to plot in 2D

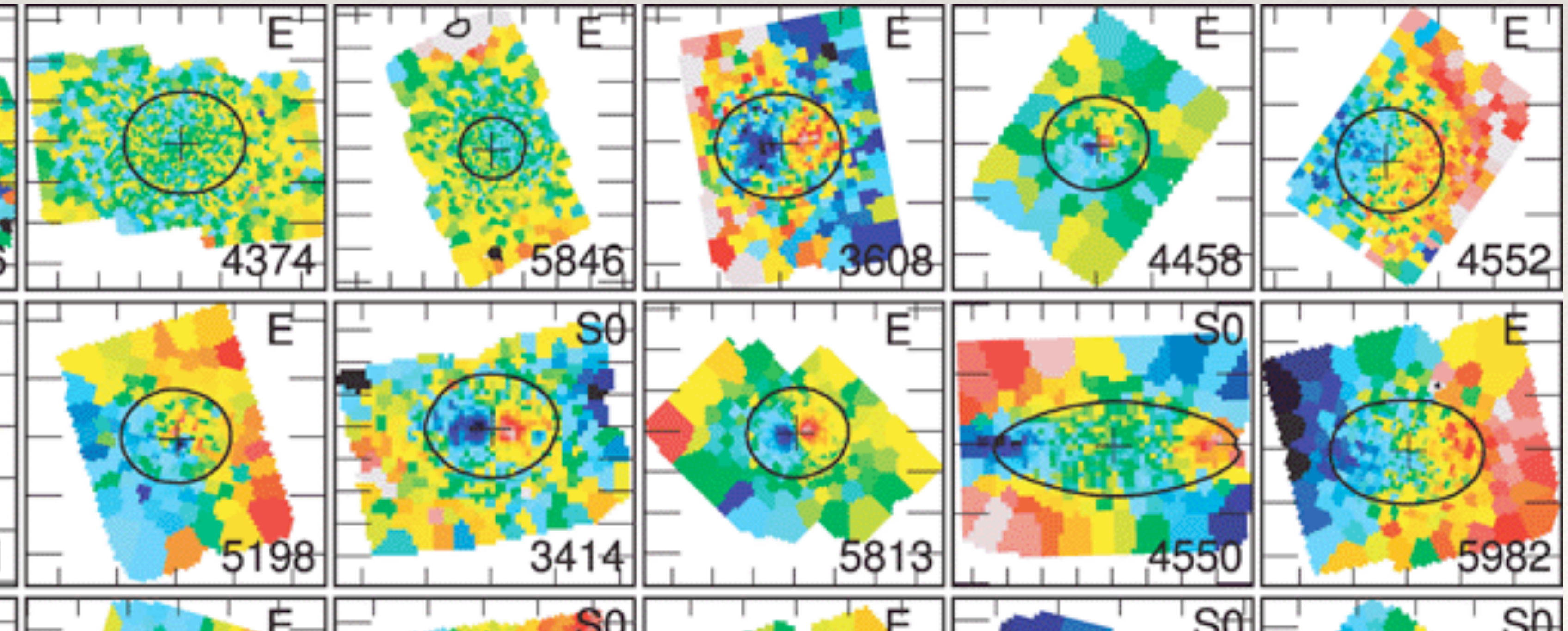
Galaxy Population - Ellipticals/Spheroid

- IFS data allows for detailed mass modeling with fewer assumptions
- Ellipticals seem to follow tight "Mass Plane" (MP) between M, $\boldsymbol{\sigma}$, and R_e^{maj}
- Fundamental Plane may be explained by Viral equilibrium plus systematic M/L variations

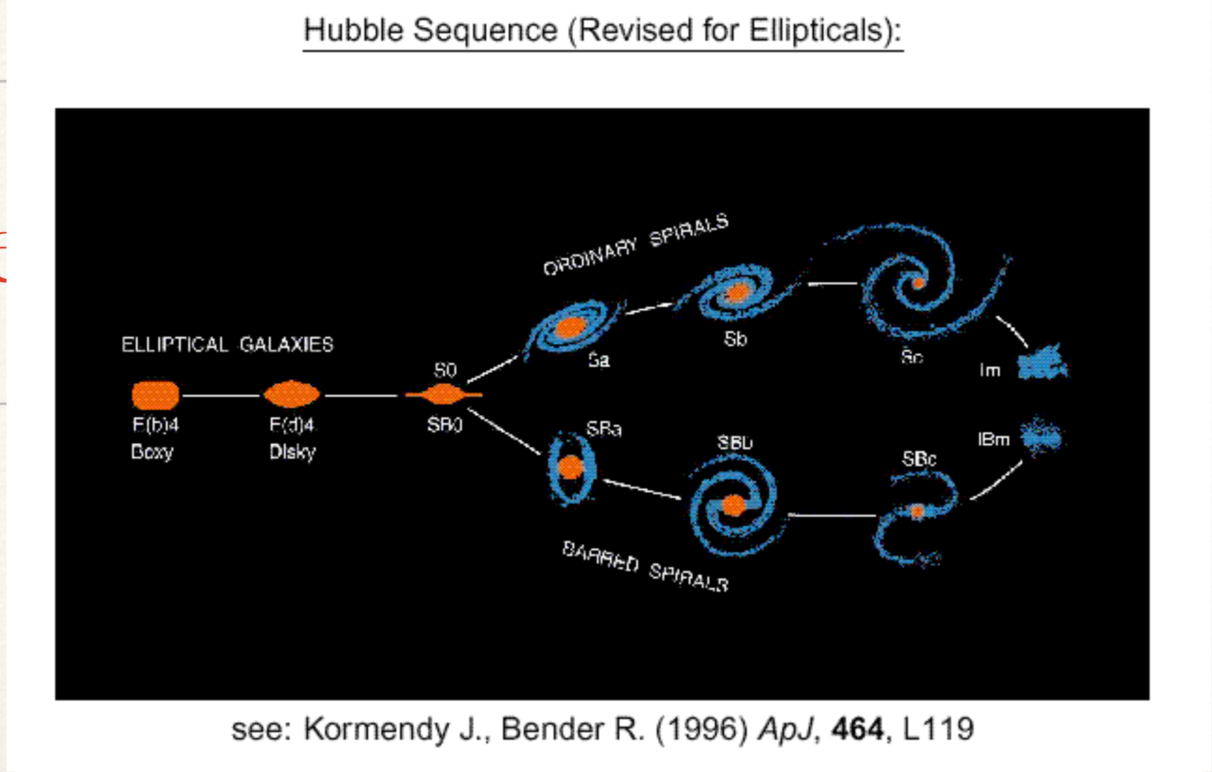


Cappellari et al. 2013

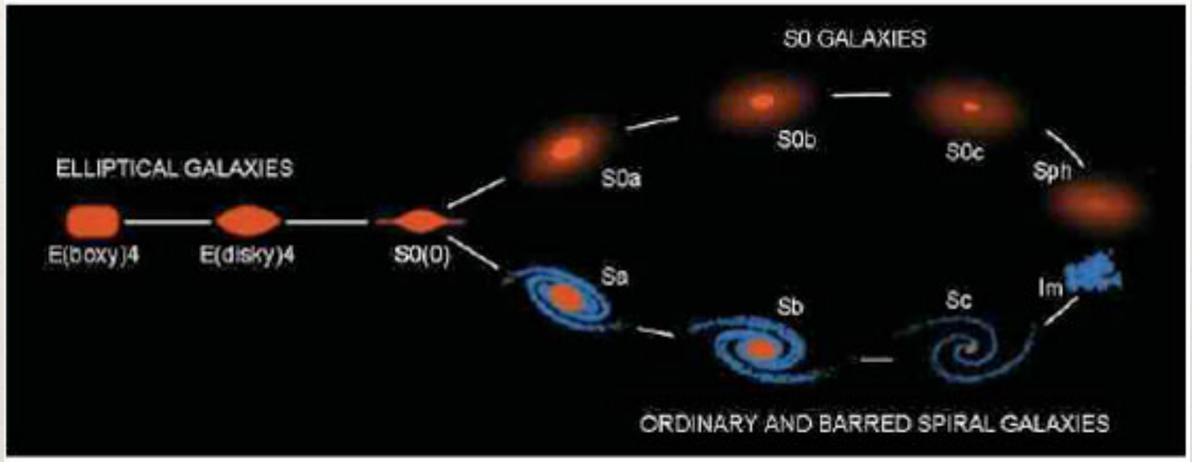
Emsellem et al. 2007



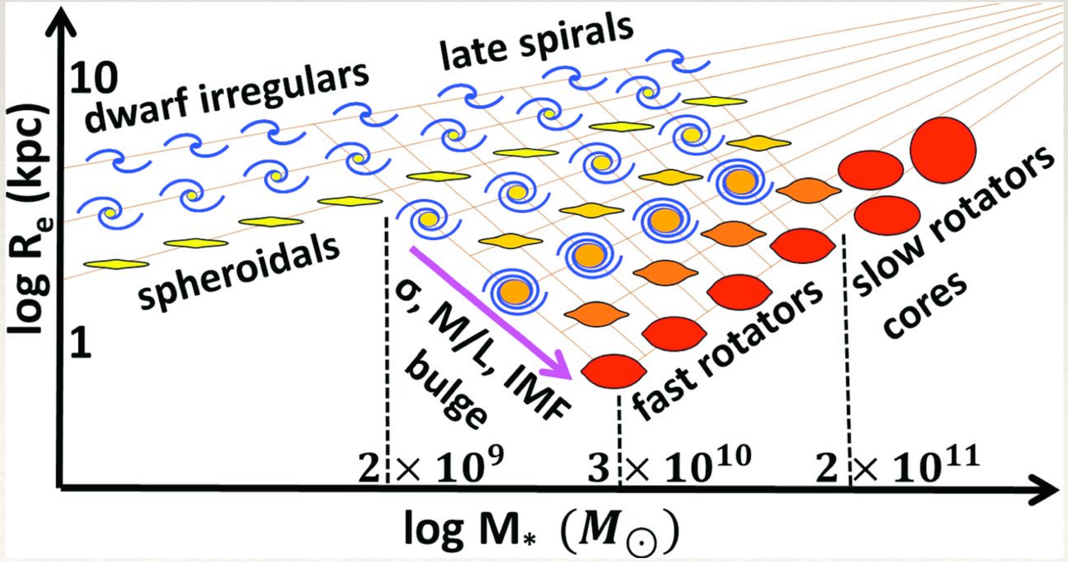
Ellipticals/Spheroids: Scaling Re



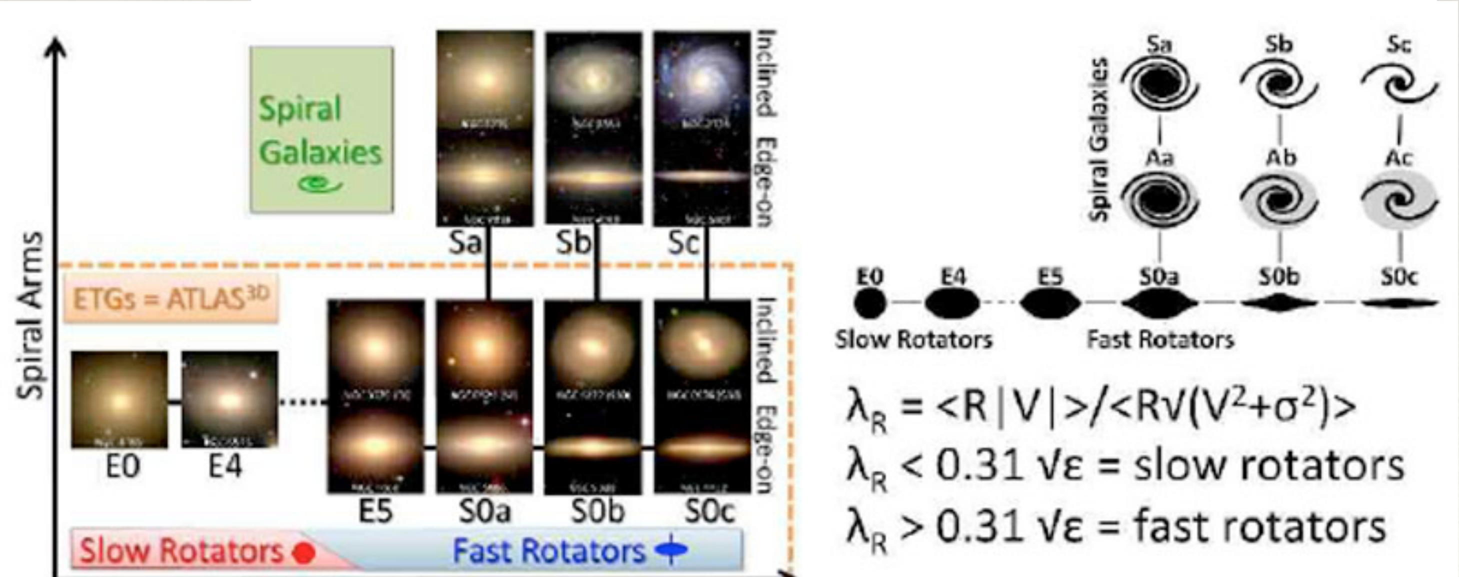
Kormendy & Bender (2012)



- Fundamental Plane is an important tool for understanding evolution of elliptical galaxies
- Emerging consensus on importance of considering kinematics (not just morphology) in classifying galaxies



Cappellari et al. 2013



$\lambda_R = \langle R|V|\rangle / \langle R\sqrt{V^2+\sigma^2}\rangle$

$\lambda_R < 0.31\sqrt{\varepsilon}$ = slow rotators

$\lambda_R > 0.31\sqrt{\varepsilon}$ = fast rotators

Cappellari et al. 2011

Galaxy Population - Ellipticals/Spheroids: Scaling Relations

- Galaxies do not fully populate the entire plane
- Observables relate to physical properties, e.g., surface brightness-**σ** plane related to density and virial temperature
- Physics of galaxy formation must restrict the parameter space in which we can find galaxies

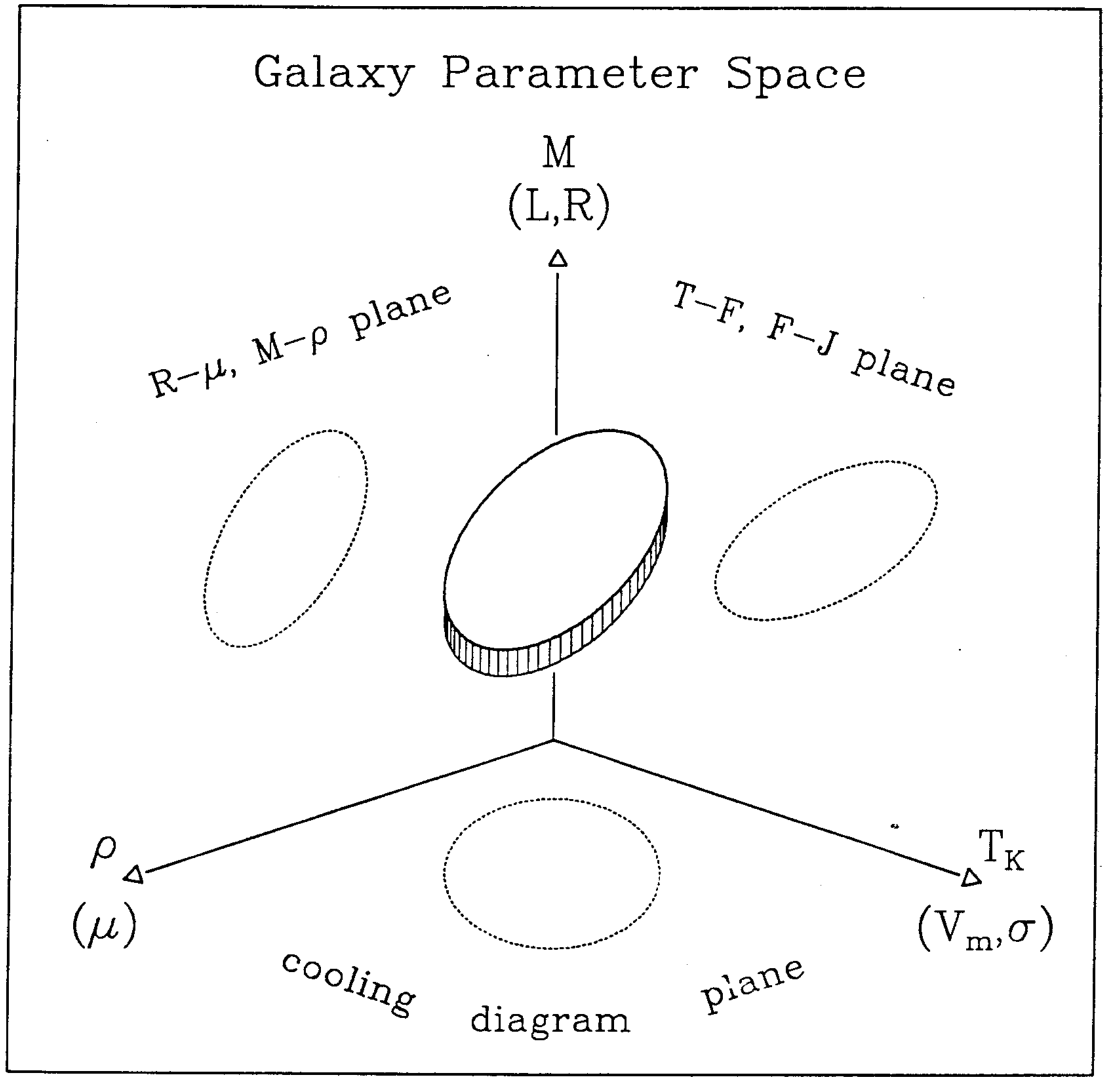


Figure 2. A schematic representation of the galaxy parameter space. Galaxies of a given family (ellipticals or spirals, and probably dwarfs as well) occupy two-dimensional regions (thickened in the third dimension mainly by the measurement errors) in a parameter space whose axes can be called size (mass, luminosity, or radius), density (or surface brightness), and temperature (i.e., kinetic energy per unit mass, typically the maximum rotational velocity for cold disks, or the central velocity dispersion for pressure-supported systems). The particular choice of axes depends on the application and available observables, but the basic picture remains unchanged. The coordinate planes thus defined are some of the well-known diagrams in extragalactic astronomy and cosmology; however, none of them contains all the information, only the oblique projections of the galaxy manifolds.

Djorgovski Fig 2