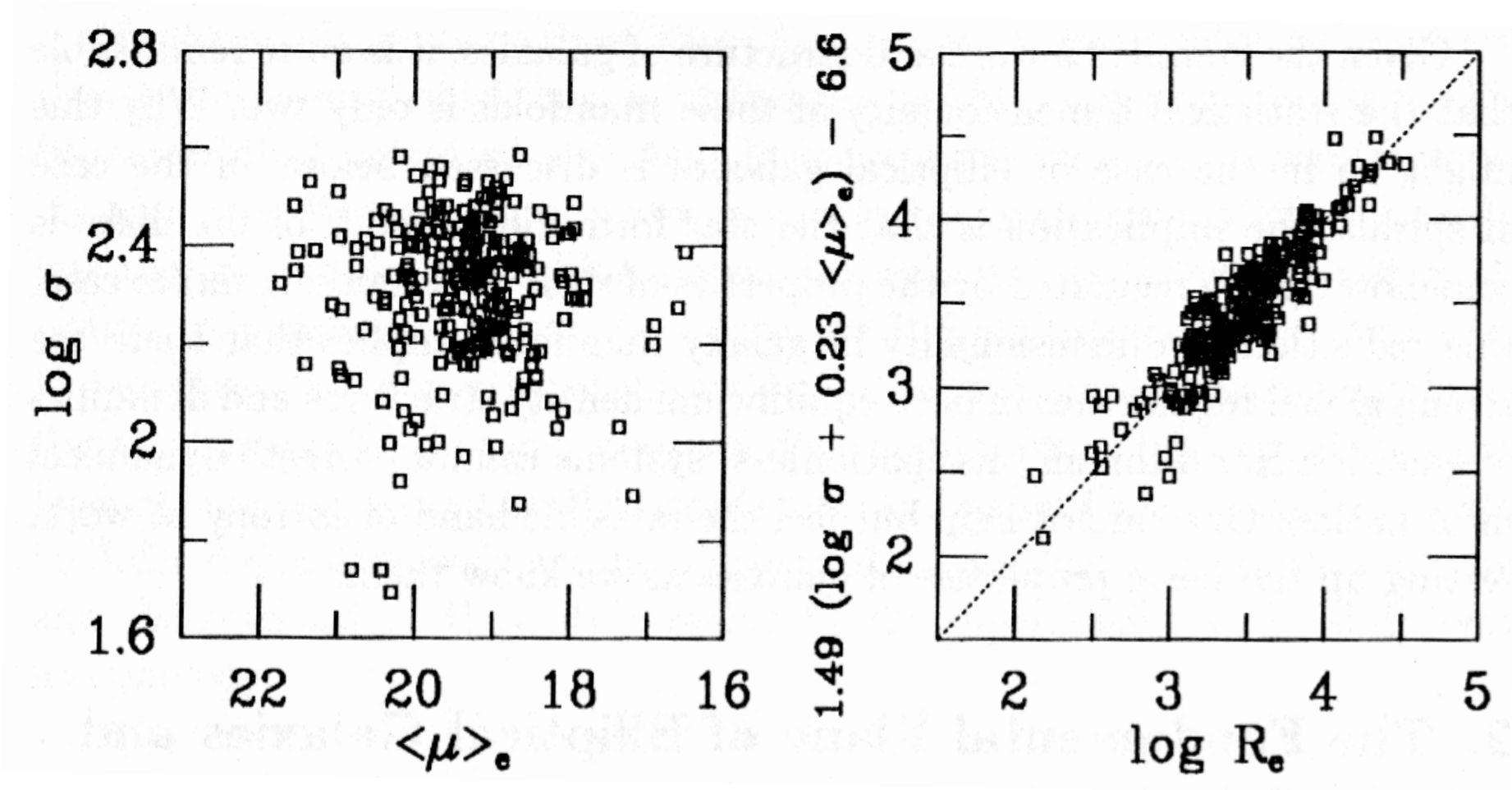
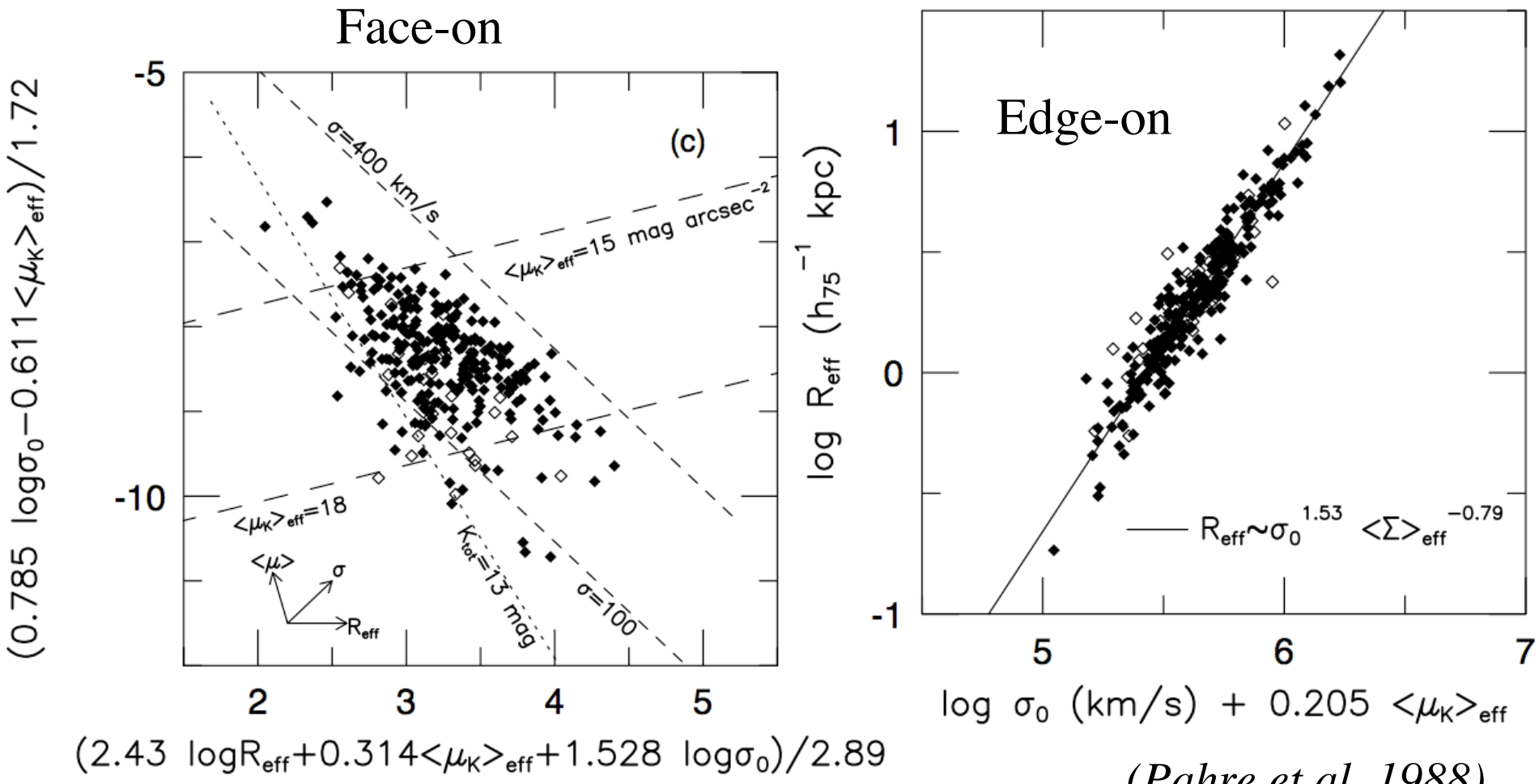
Galaxy Scaling Relations
Part II



Fundamental Plane of Elliptical Galaxies

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

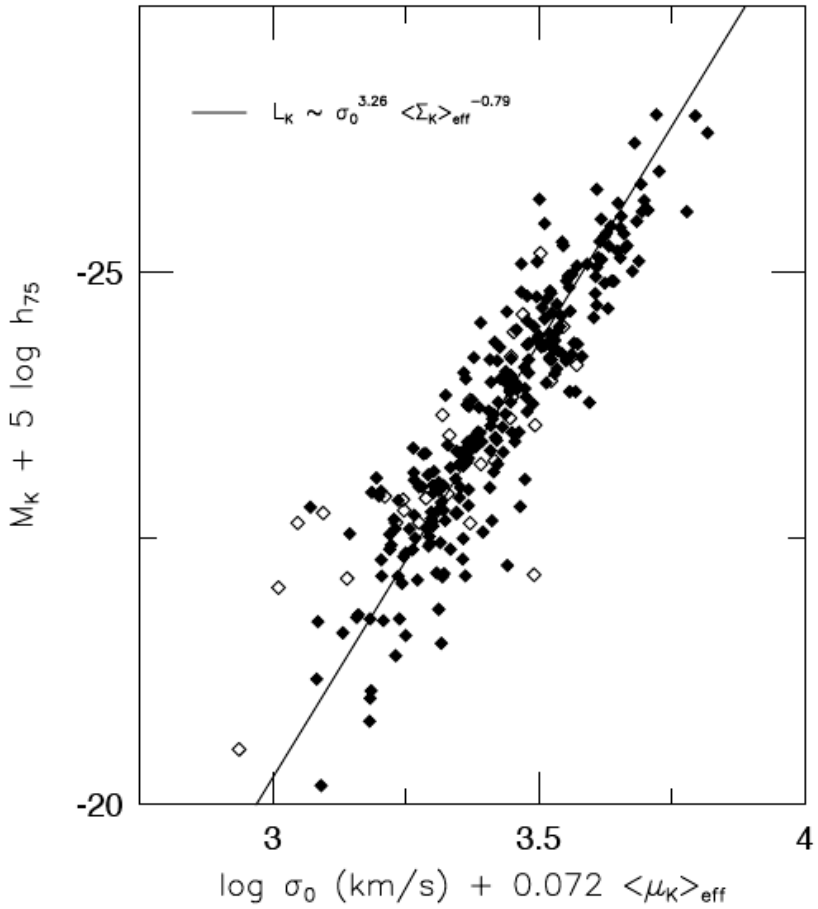
Where R is the radius, I the mean surf. brightness, σ the velocity disp.



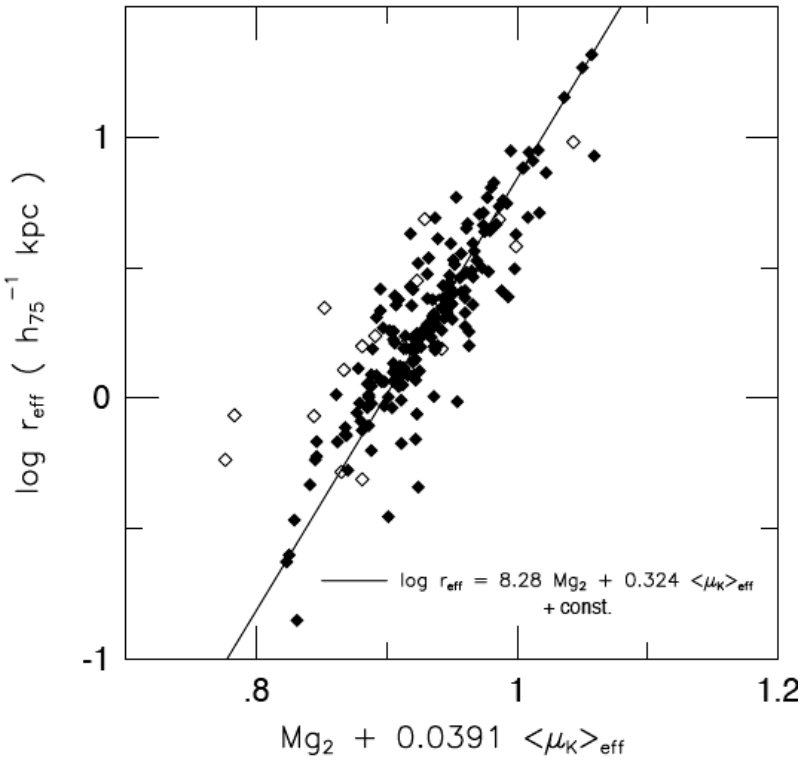
(Pahre et al. 1988)

Different Views of the FP

Luminosity instead of radius

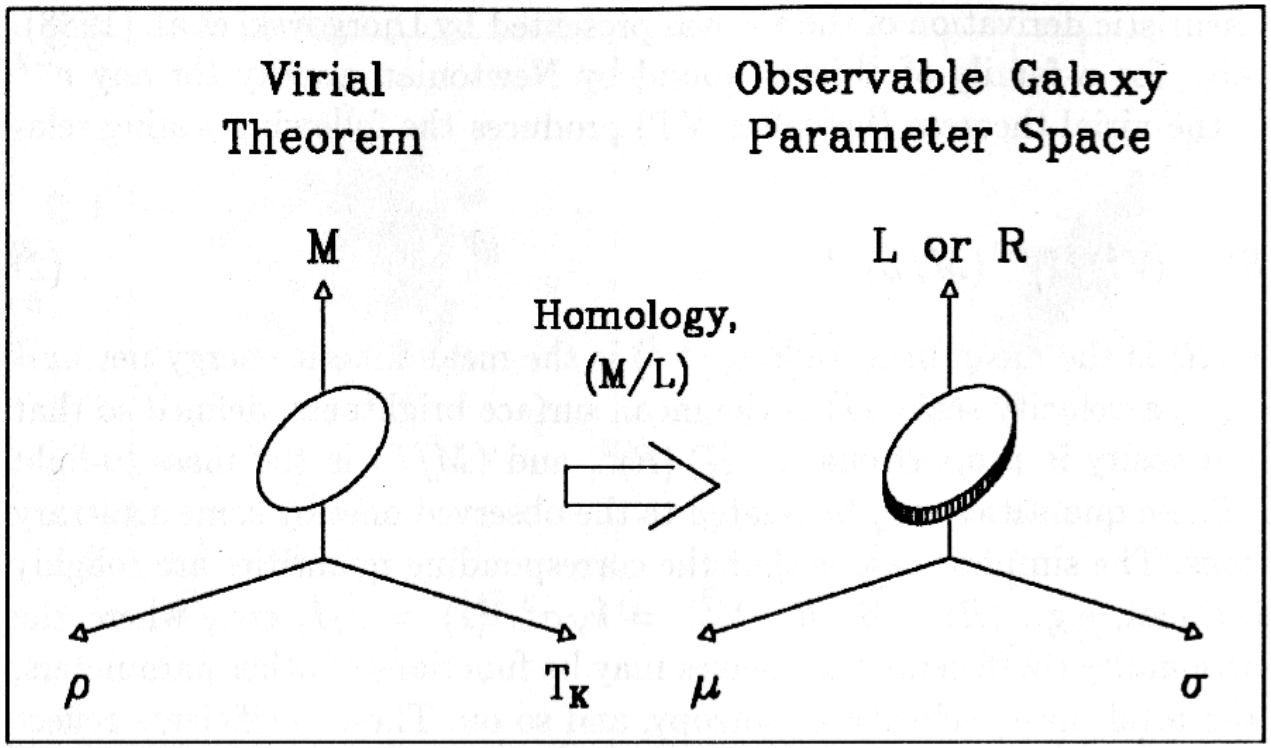


Mg abs. line strength index (a measure of metallicity) instead of velocity dispersion



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

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 $R, \sigma, I, L, \ldots$

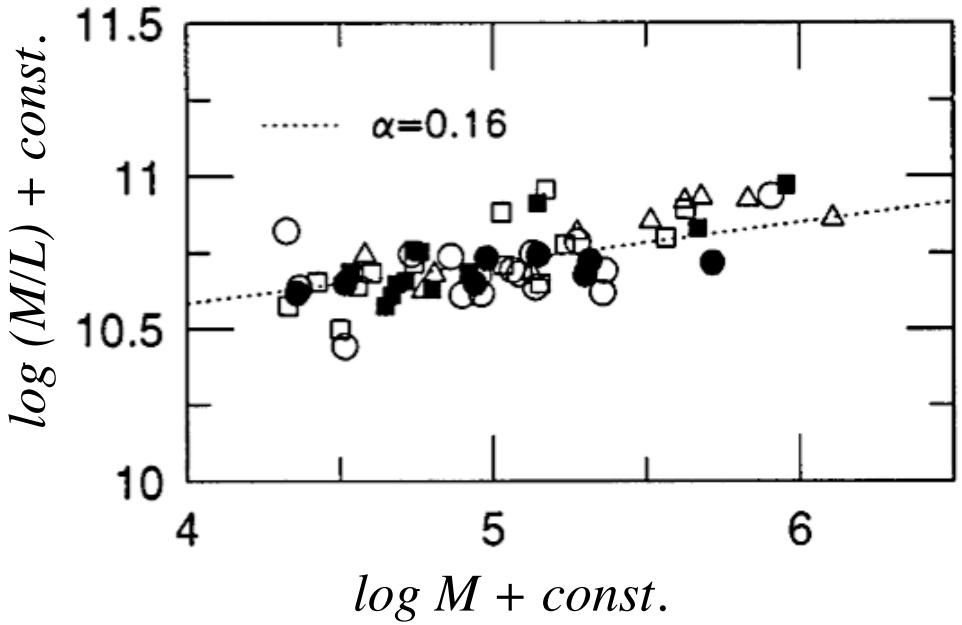
Fundamental Plane and M/L Ratios

If we *assume* homology and attribute all of the FP tilt to the changes in ***(M/L)*** ,

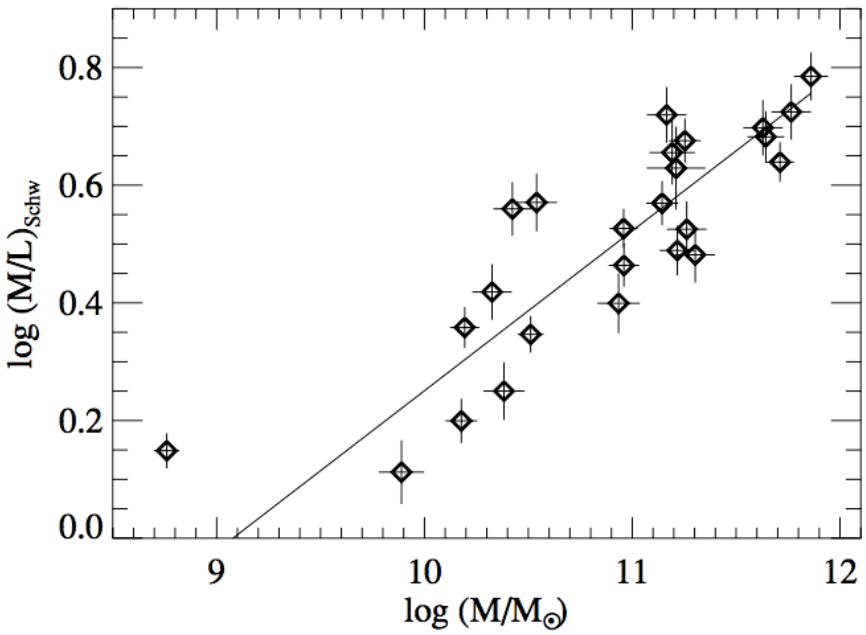
$$(M/L) \sim L^{\alpha}, \quad \alpha \sim 0.2 \text{ (vis) or } \sim 0.1 \text{ (IR)}$$

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

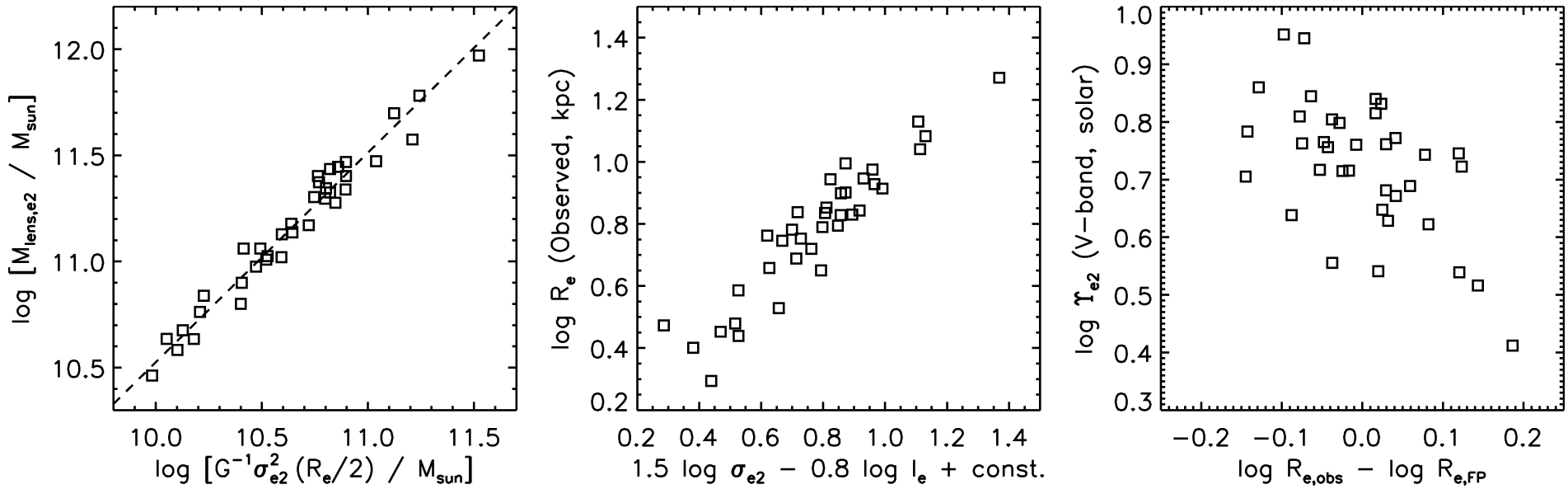


Cappellaro et al. 2006: SAURON dynamical modeling



Mass-Based Fundamental Plane

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



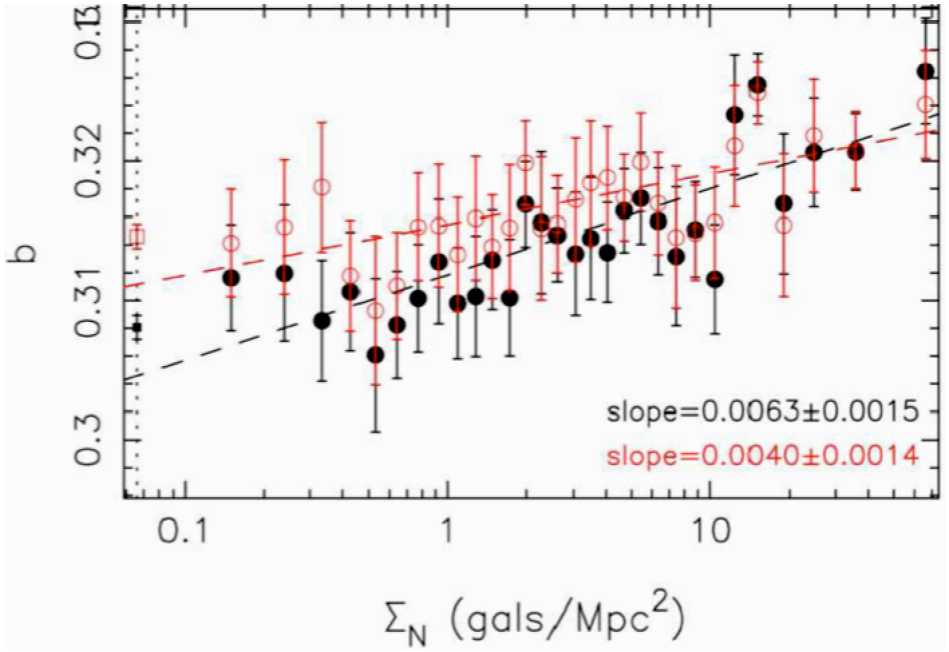
Replacing the surface brightness ***I*** with the *projected mass density* $\boldsymbol{\Sigma}$ gives a "mass plane" scaling: $\boldsymbol{R \sim \sigma^{1.8 \pm 0.2}\ \Sigma^{-1 \pm 0.2}}$, consistent with the Virial Theorem, and with a smaller scatter!

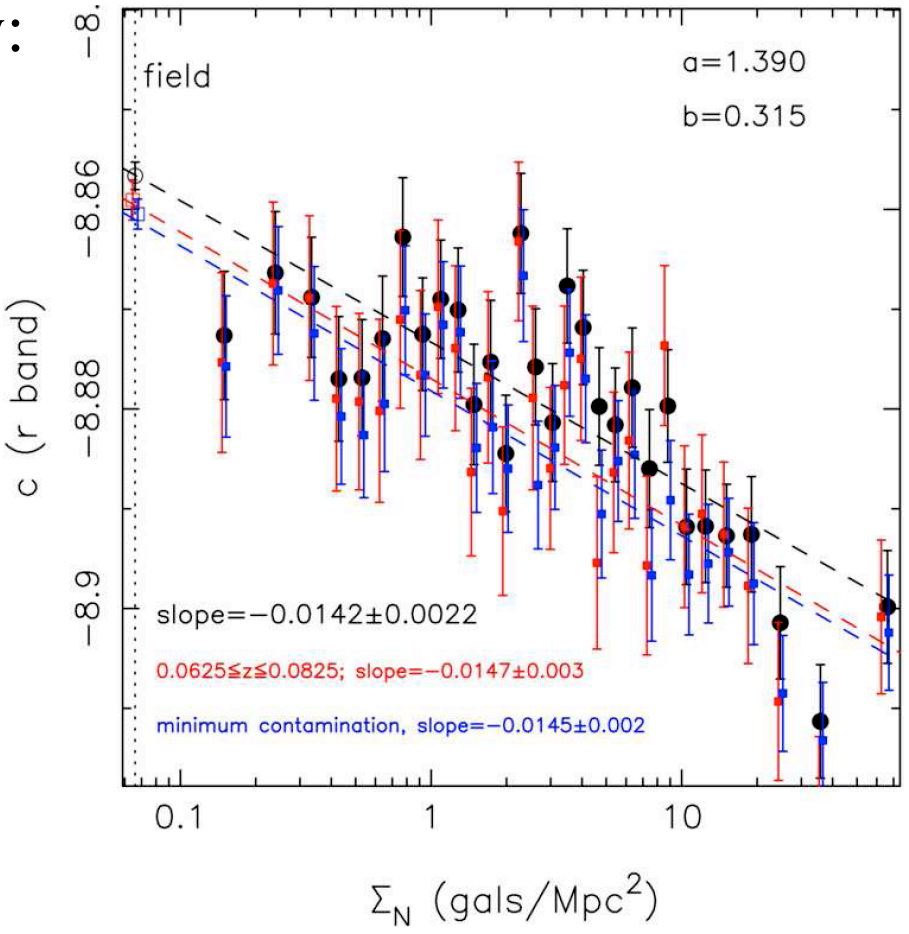
This implies *a homology of mass* (if not light) structures of E's

FP Dependence On Environment

$$\log R_{\rm e} = a \log \sigma_0 + b < \mu >_{\rm e} + c$$

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*:

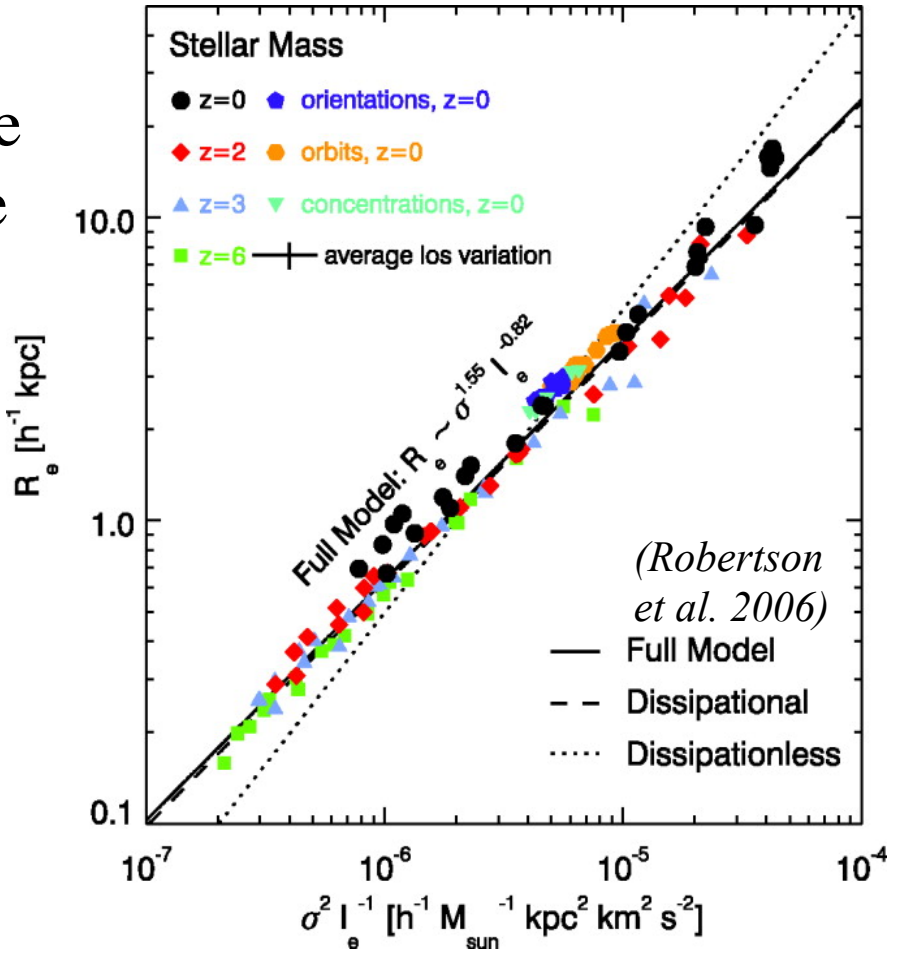
- Mass, luminosity (in any OIR band),
- Any consistently defined radius
- Surface brightness or projected mass density
- Derived 3-d luminosity, mass, or phase-space density
- Central projected radial velocity dispersion
- OIR colors, line strengths, and metallicity
- Mass of the central black hole
-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

And they do so regardless of the:

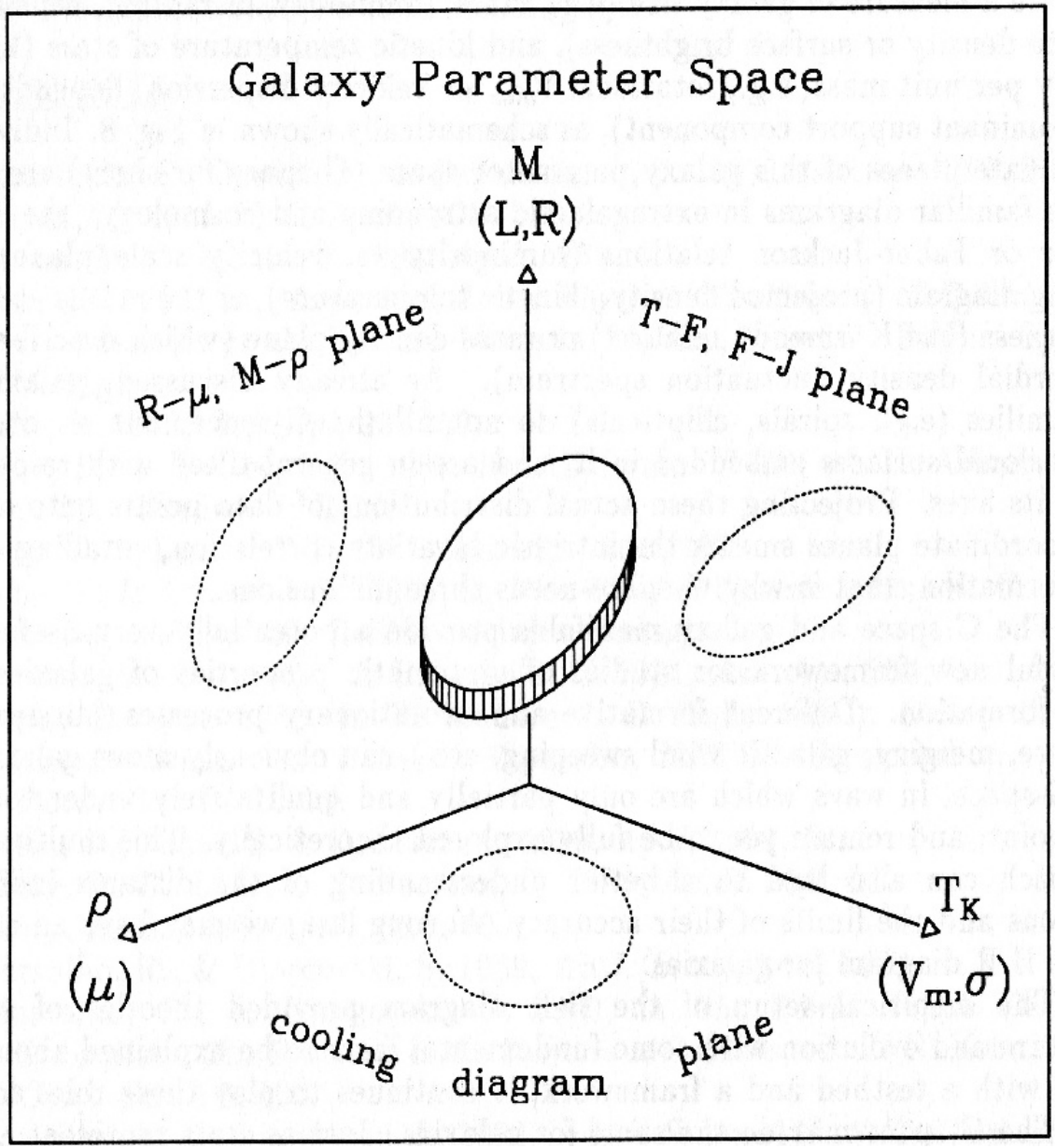
- Star formation and merging formative/evolutionary history
- Large-scale environment (to within a few %)
- Details of the internal structure and dynamics (including S0's)
- Projection effects (the direction we are looking from)

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***



The Galaxy Parameter Space



A more general picture

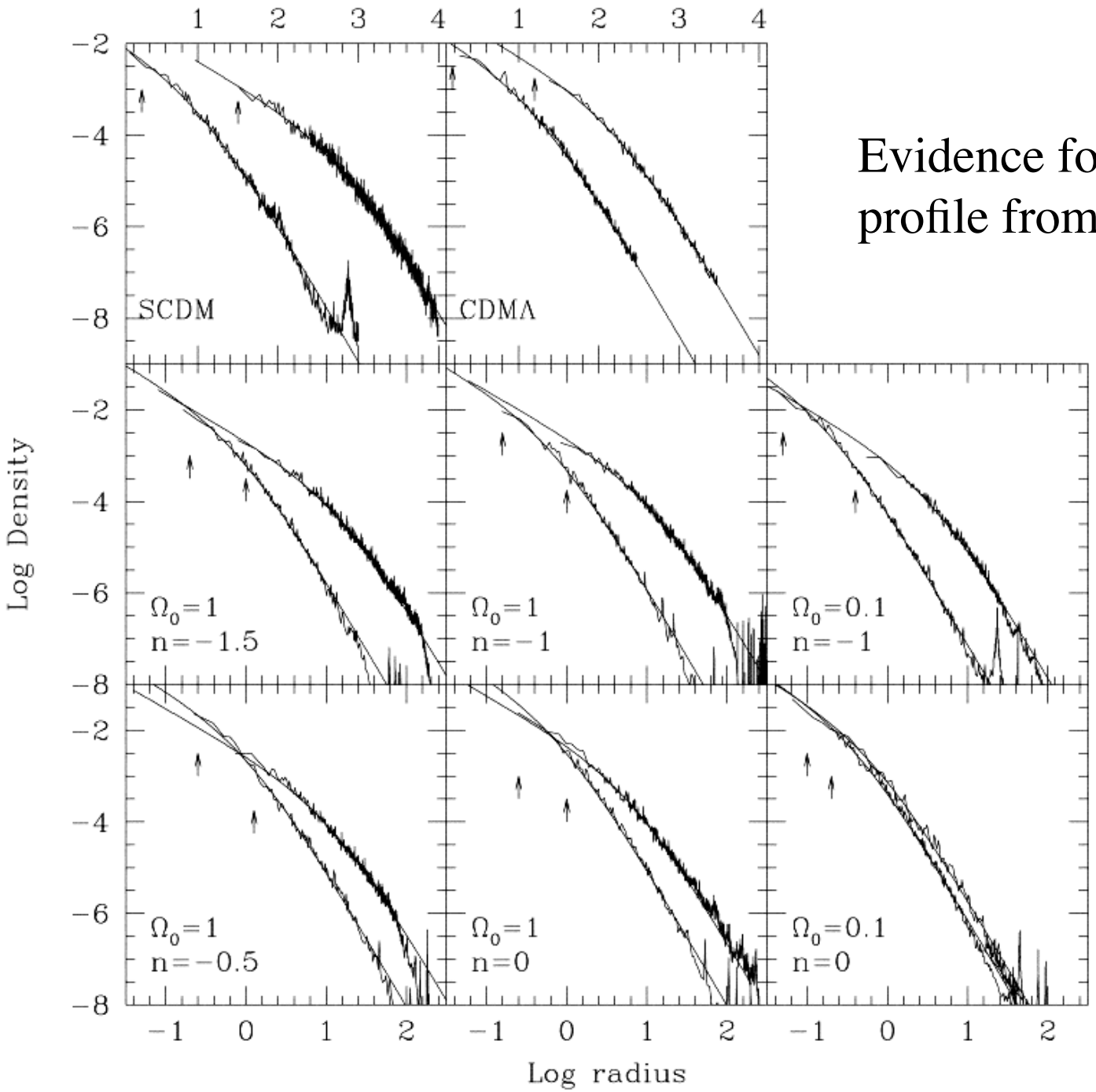
Galaxies of different families form 2-dim. sequences in a 3+ dimensional parameter space of physical properties, much like stars form 1-dim. sequences in a 2-dim. parameter space of {L,T} - this is an equivalent of the H-R diagram, but for galaxies

The Dark Halos

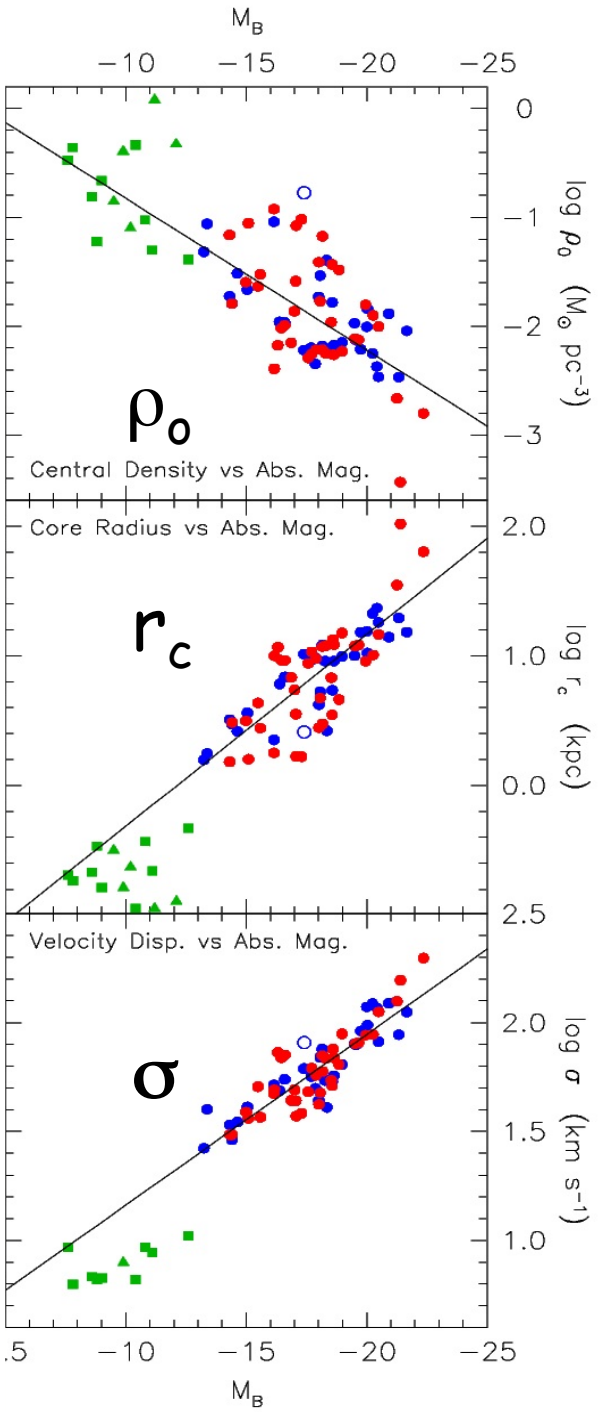
- Many of galaxy scaling relations may be driven by the properties of their dark halos
- It is possible to infer their properties from detailed dynamical profiles of galaxies and some modeling
- Numerical simulations suggest a universal form of the dark halo density profile (NFW = Navarro, Frenk & White):

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

(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)

$\sigma \sim L_B^{0.20}$

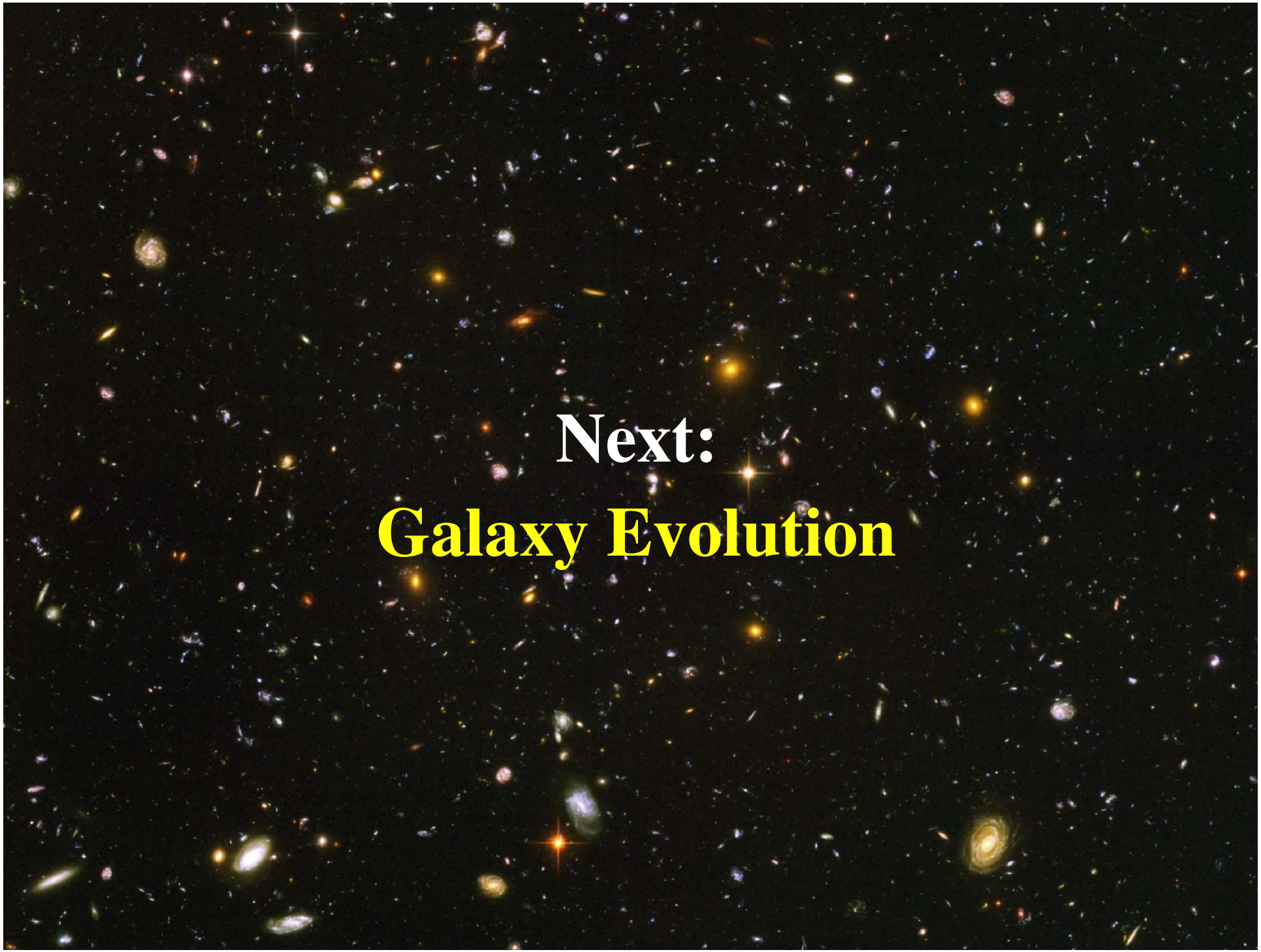
■ ▲ are dSph, dIrr

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


Next:
Galaxy Evolution