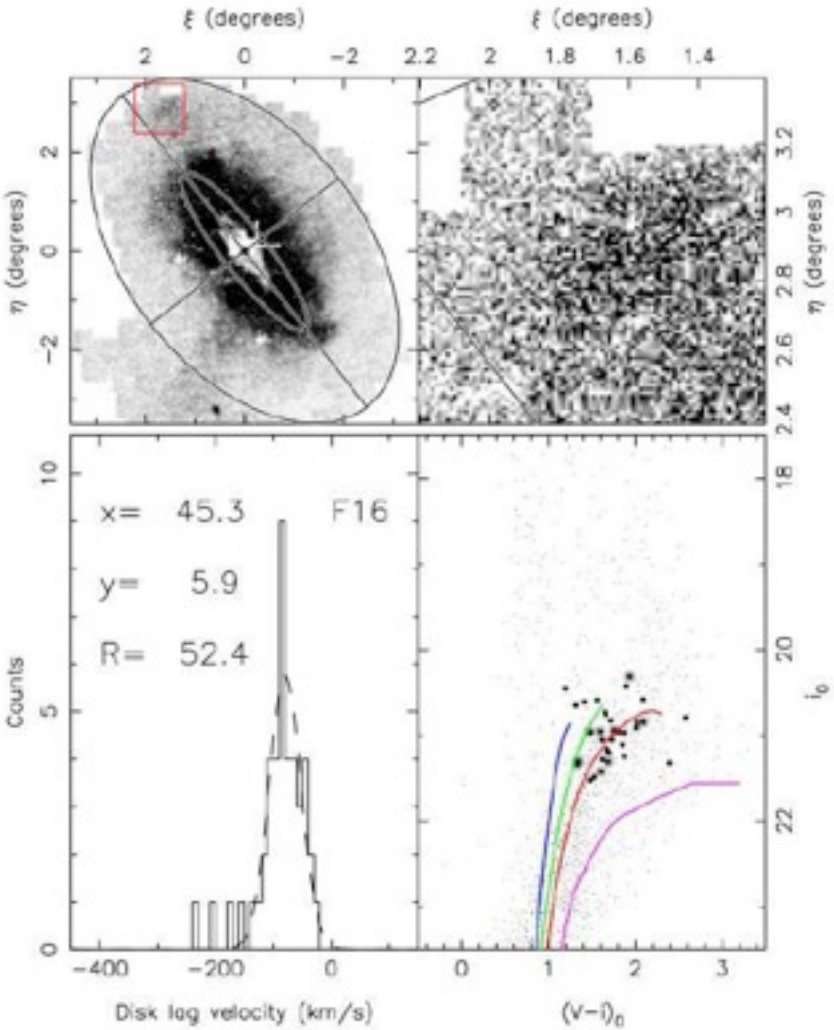
“Fundamental Planes” and Galaxy Formation

Philip Hopkins, NoviCosmo 2007

“Fundamental Planes” = Scaling Laws Obeyed by Galaxies



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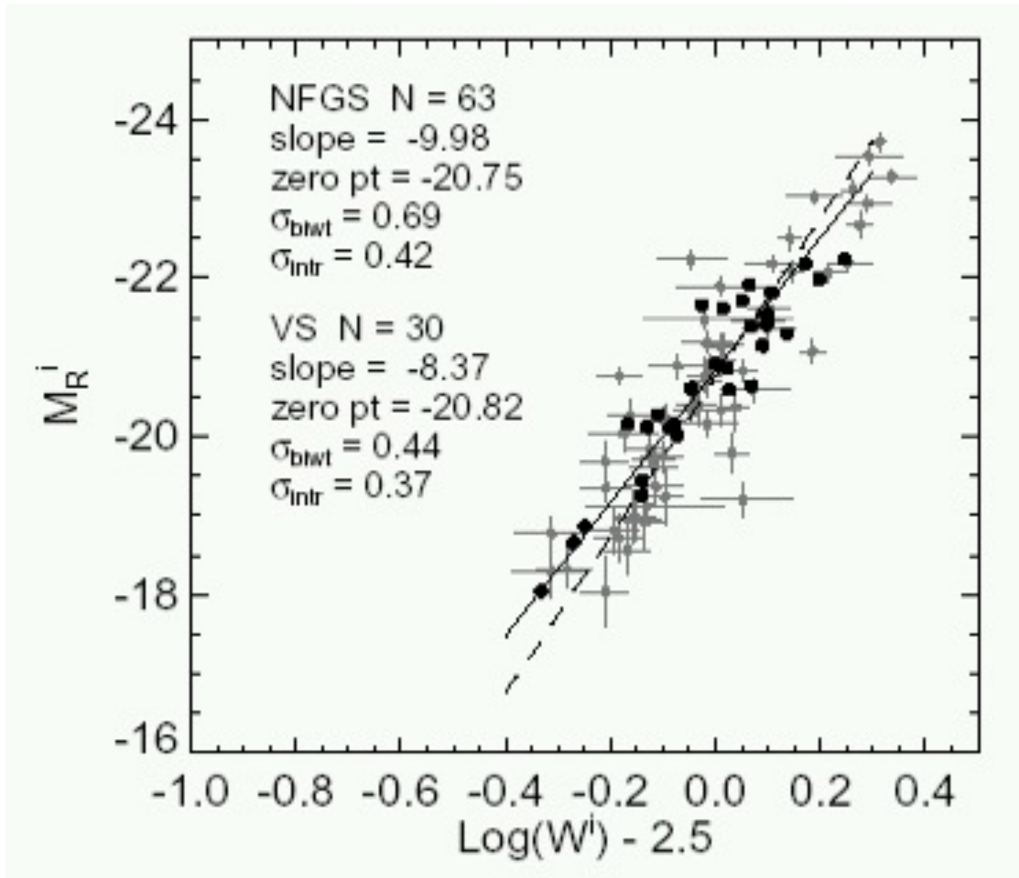


- Origin of scaling laws:
- Ideally, we’d understand every galaxy as an individual: but, “every galaxy is peculiar” if you look at it in enough detail
- Galaxies obey remarkable (and often puzzling) regularity

“Fundamental Planes” = Scaling Laws Obeyed by Galaxies

- Broadly speaking, the few most relevant categories:

- Disk scalings
  - Tully Fisher & size-mass relations: 1977+

- Bulge/Elliptical scalings
  - Faber-Jackson & size-mass :: 1976+
  - Fundamental Plane :: 1986+

- Black Holes
  - BH - Host L or M :: 1995+
  - M-sigma :: 2000+

Scaling Laws and Galaxy Properties

WHAT CAN BE MEASURED?

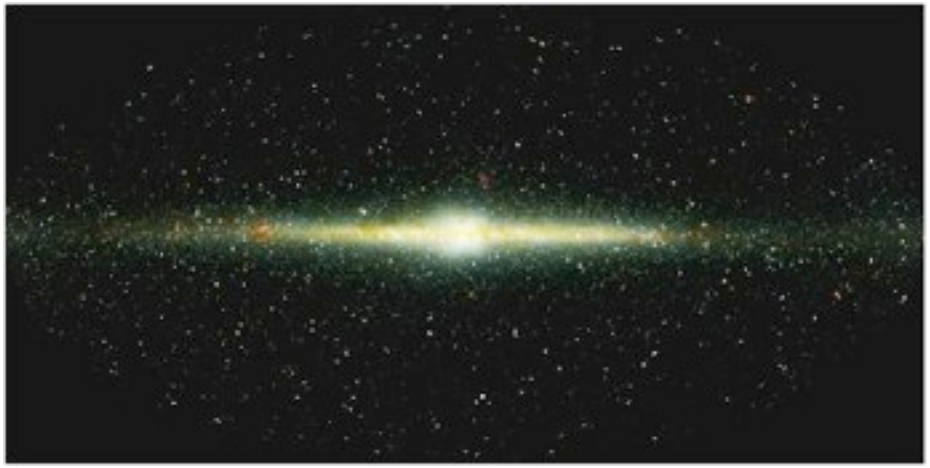
Luminosities → Stellar Mass, Stellar Populations

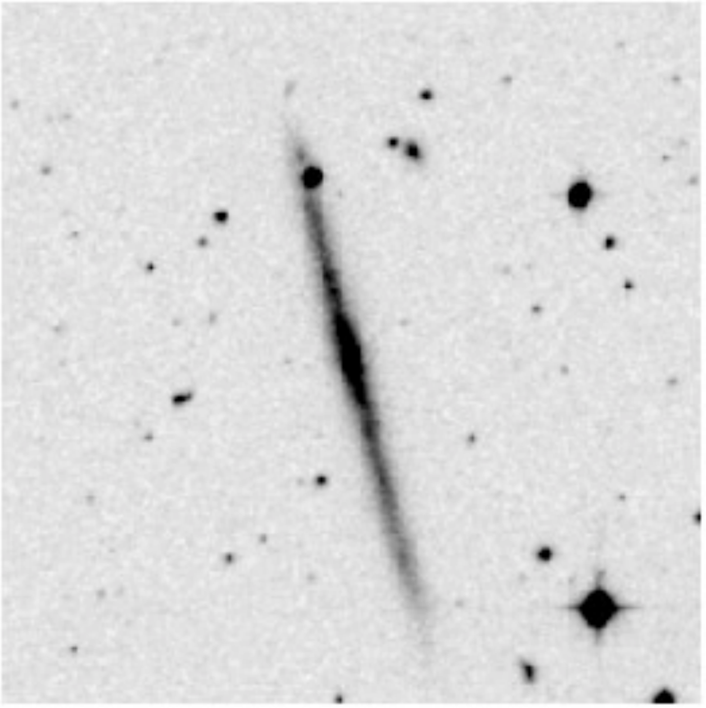
Line Indices → Stellar Populations, Star Formation Rates

Velocities → Rotation (V_c, V_max), Dispersion (sigma)

Light Profiles → Sizes, Shape/Morphology

Galactic disks





The disk is the defining stellar component of late-type galaxies.

It is the end product of the dissipation of most of the baryons, and contains **almost all of the baryonic angular momentum**

Endpoint of "quiescent" galaxy formation

Disks have a roughly exponential light distribution in R and z

$$I(R,z) = I_o \exp(-R/h_R) \exp(-z/h_z)$$

$$\text{or} \qquad I_o \exp(-R/h_R)\, \text{sech}^2(z/z_o)$$

out to $R = (3 \text{ to } 5)\, h_R$, then often truncated

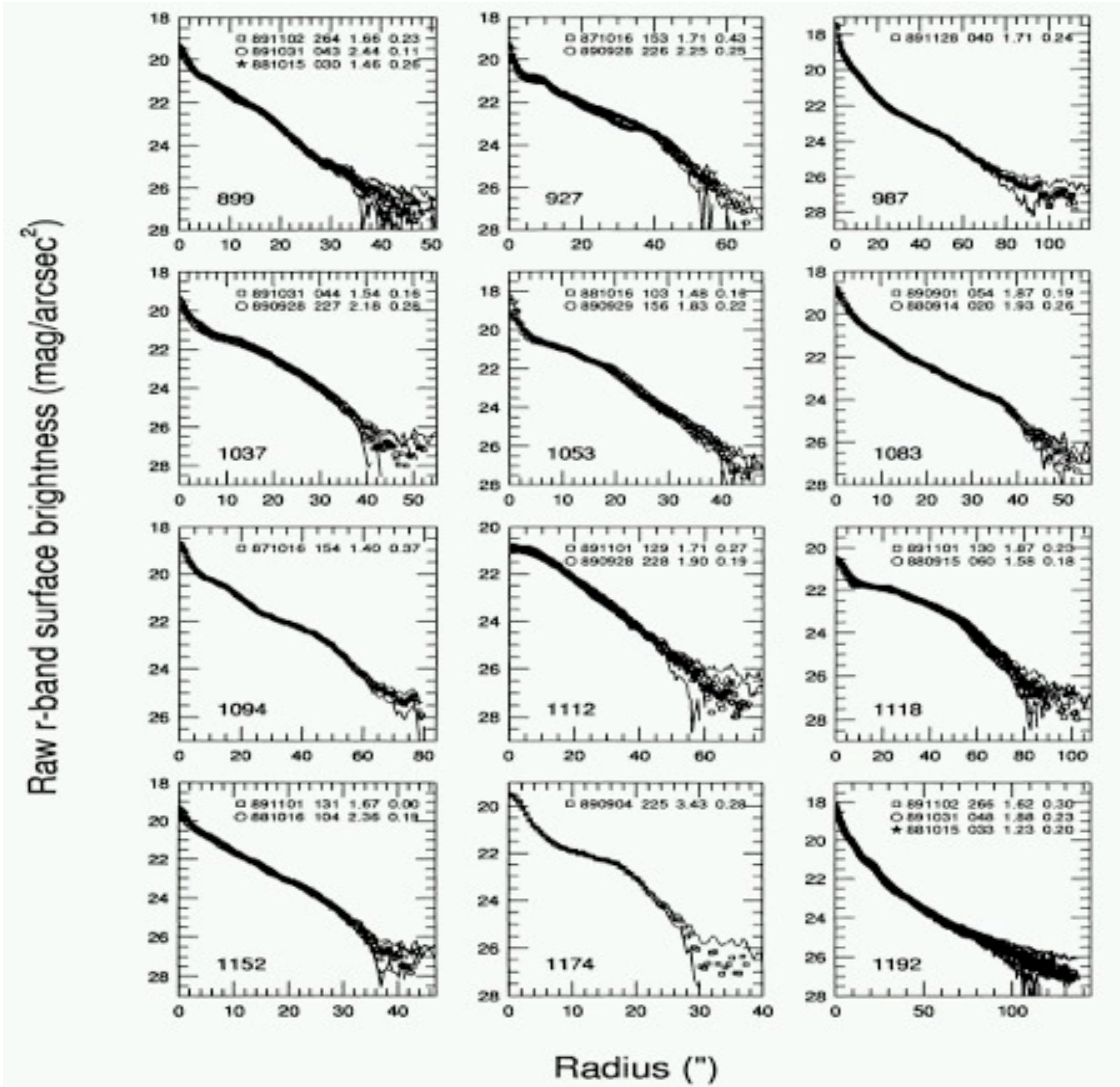
van der Kruit 1979, van der Kruit & Searle 1981-1982

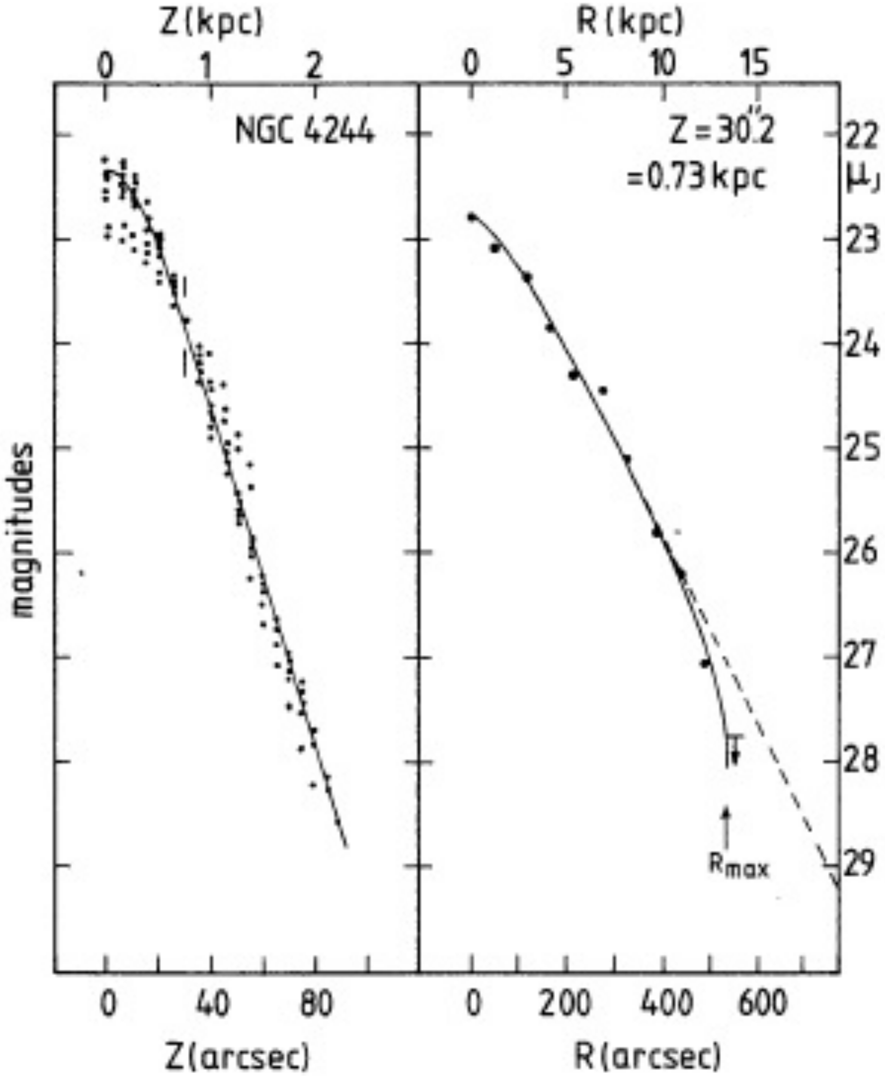
Galaxy Disks

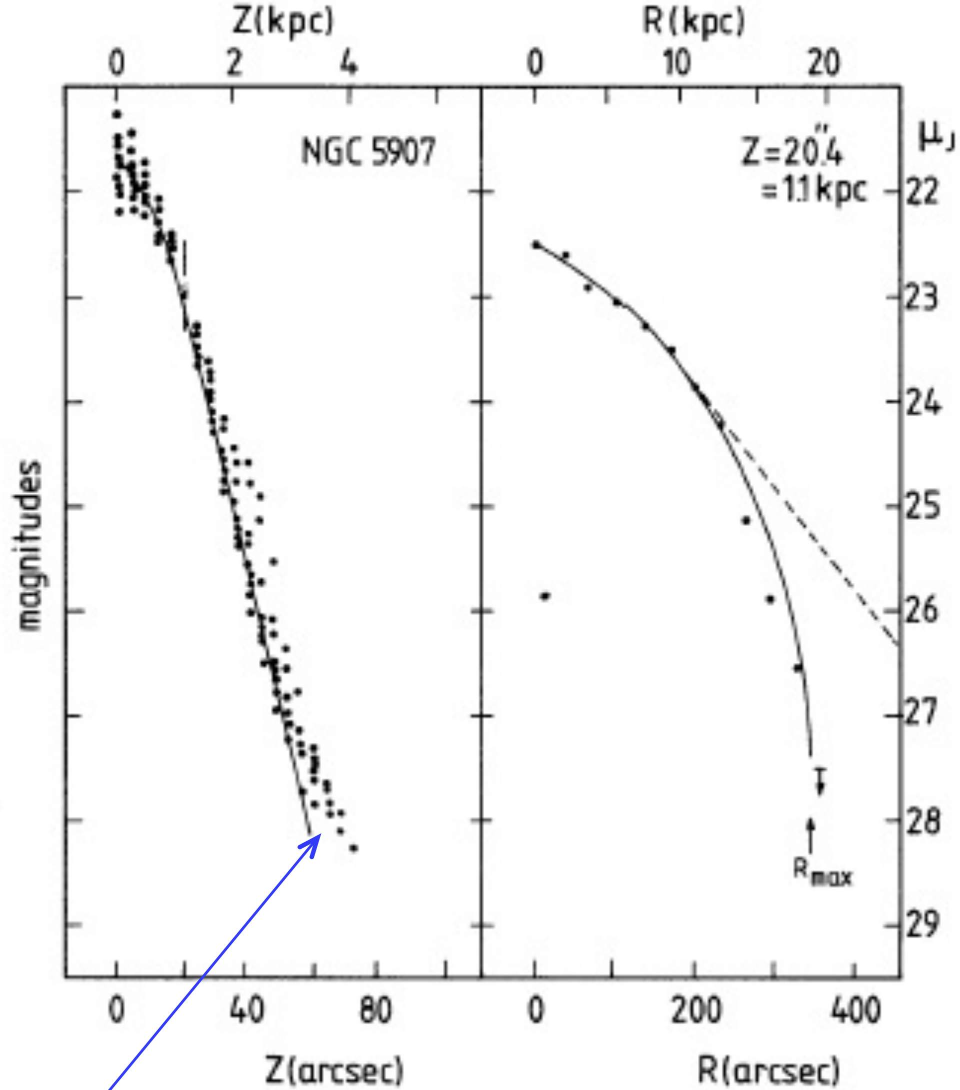
THE SEARCH FOR REGULARITY

Pure exponentials would be straight lines.

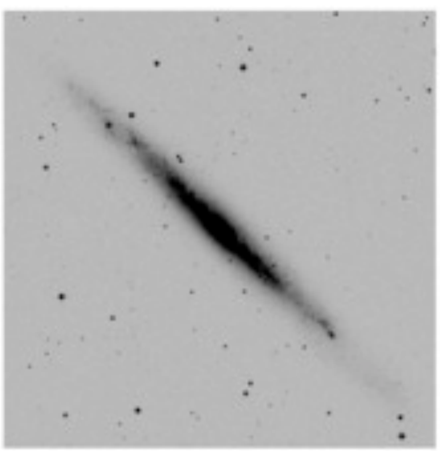
The exponential scale length α is a measure of the size of the baryonic disk.







Hint of a thick disk

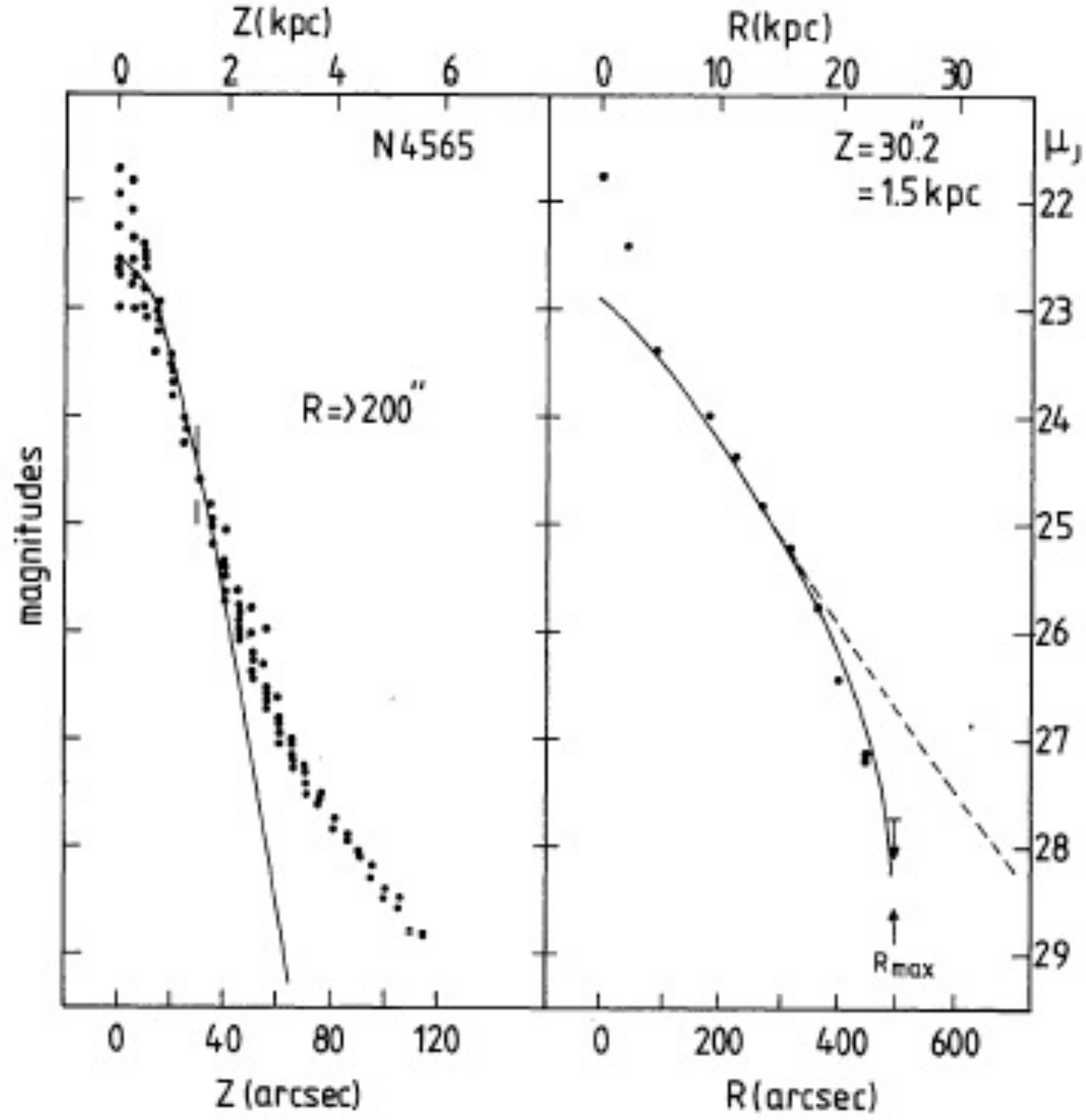


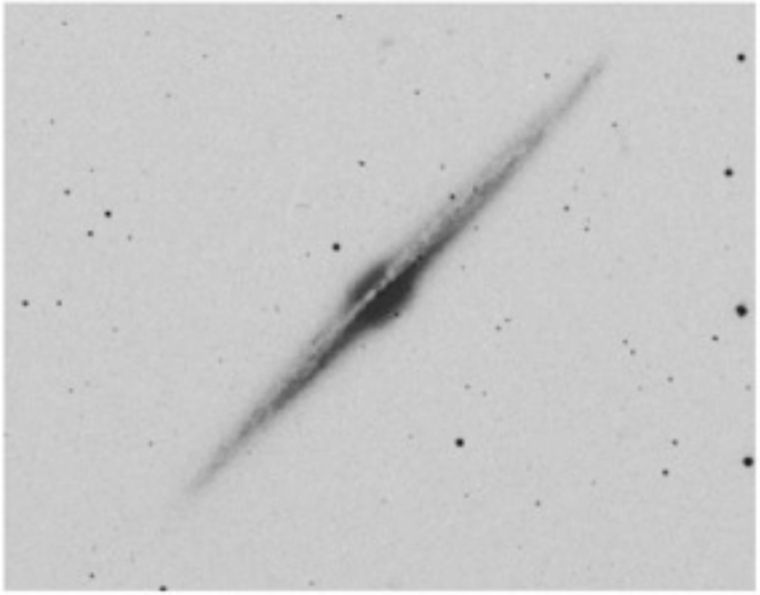
Two pure disk galaxies

NGC 4244

NGC 5907

vdK&S





NGC 4656: small bulge and prominent thick disk

vdK&S

Reason for the form of the exponential radial light distribution is not well understood : extreme options are

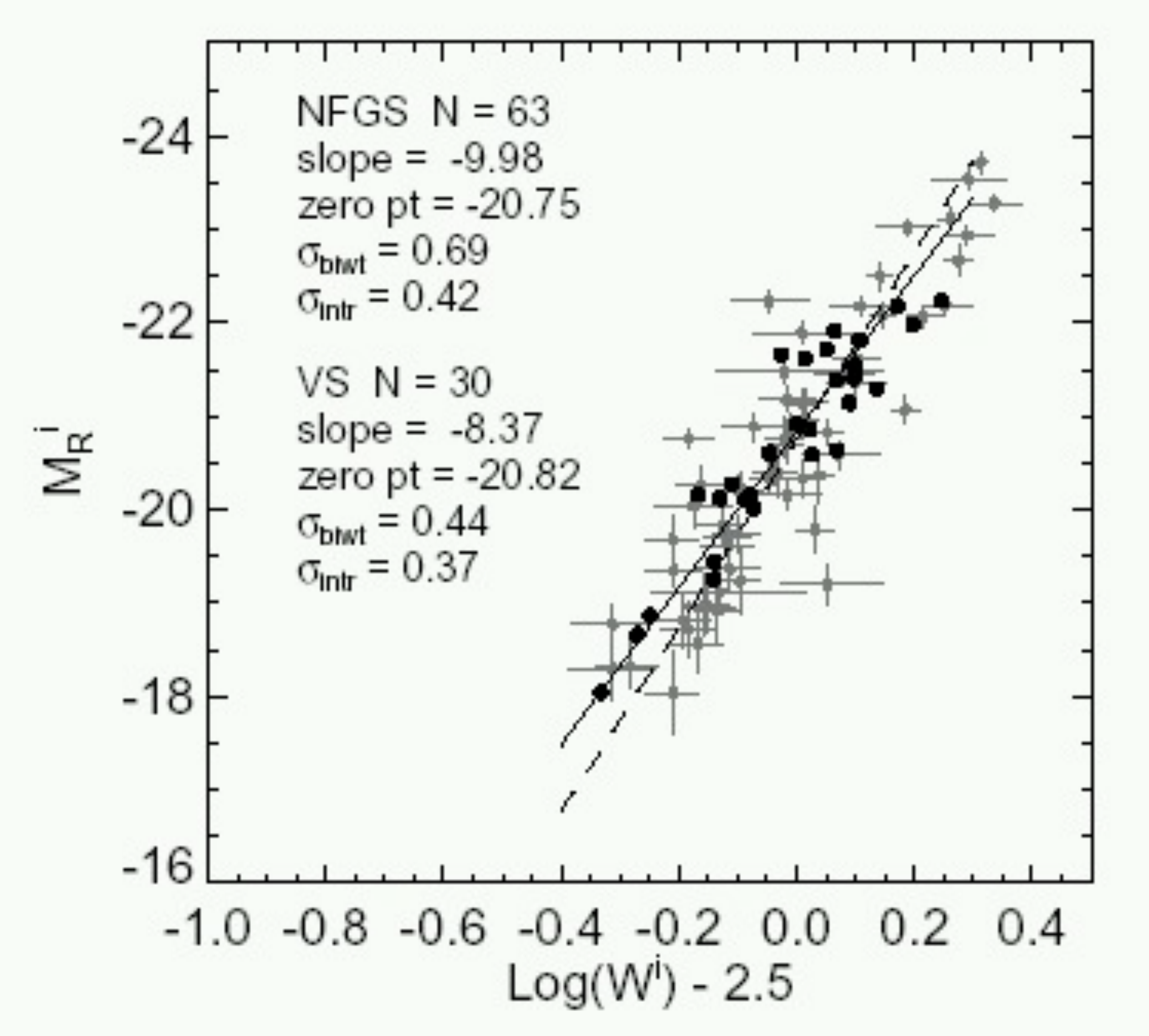
1. collapse of a torqued gas cloud within dark halo with the right internal angular momentum distribution M(j), conserving M(j) -> exponential gas disk, in place before star formation

2. gas in disk is radially redistributed by viscous torques: tends to an exponential disk if star formation timescale ≈ viscous timescale

Disk Galaxies

TULLY-FISHER

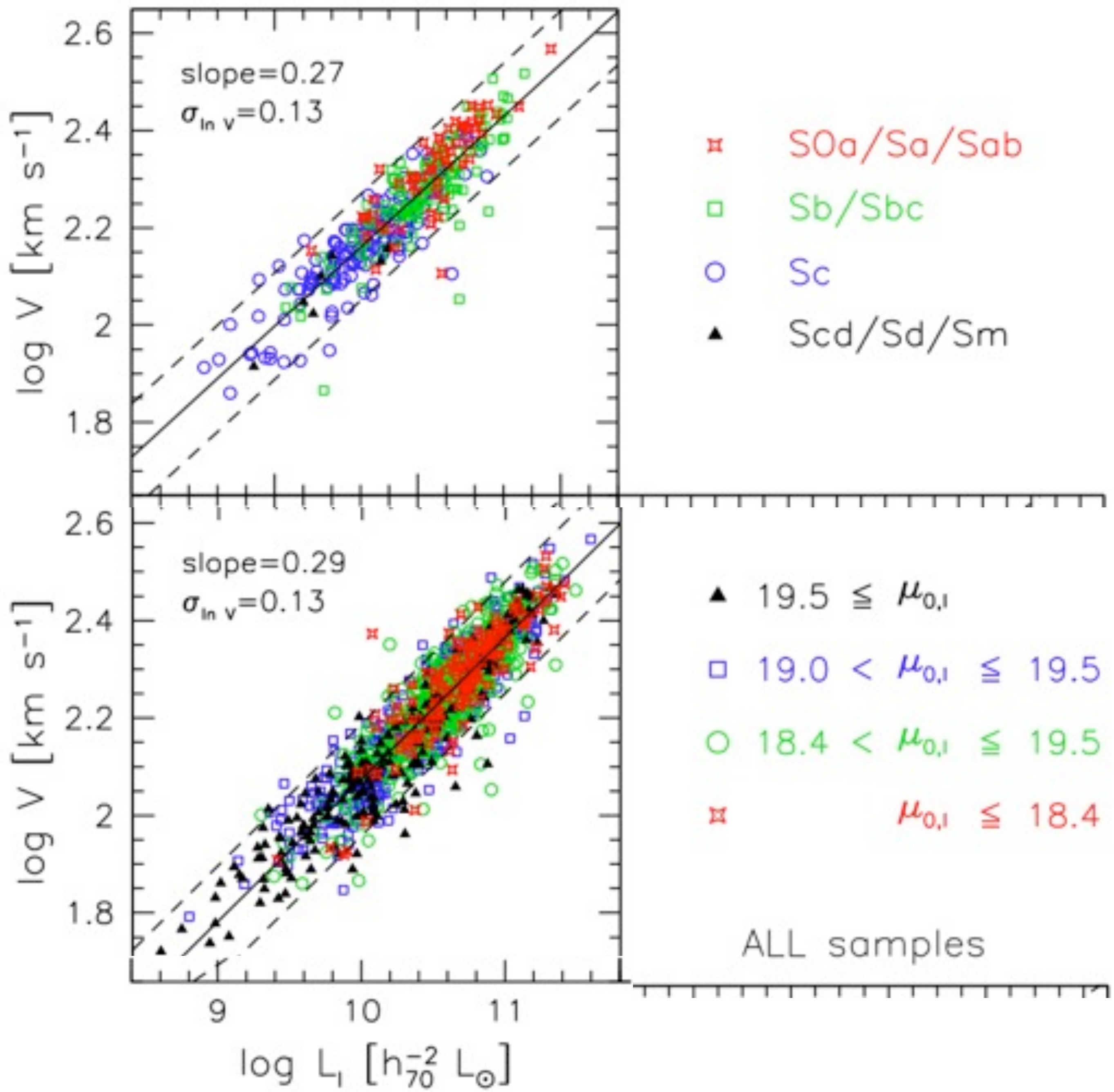
Tully & Fisher (1977)



The Tully-Fisher relation is the correlation between rotation speed and absolute magnitude for disk galaxies.

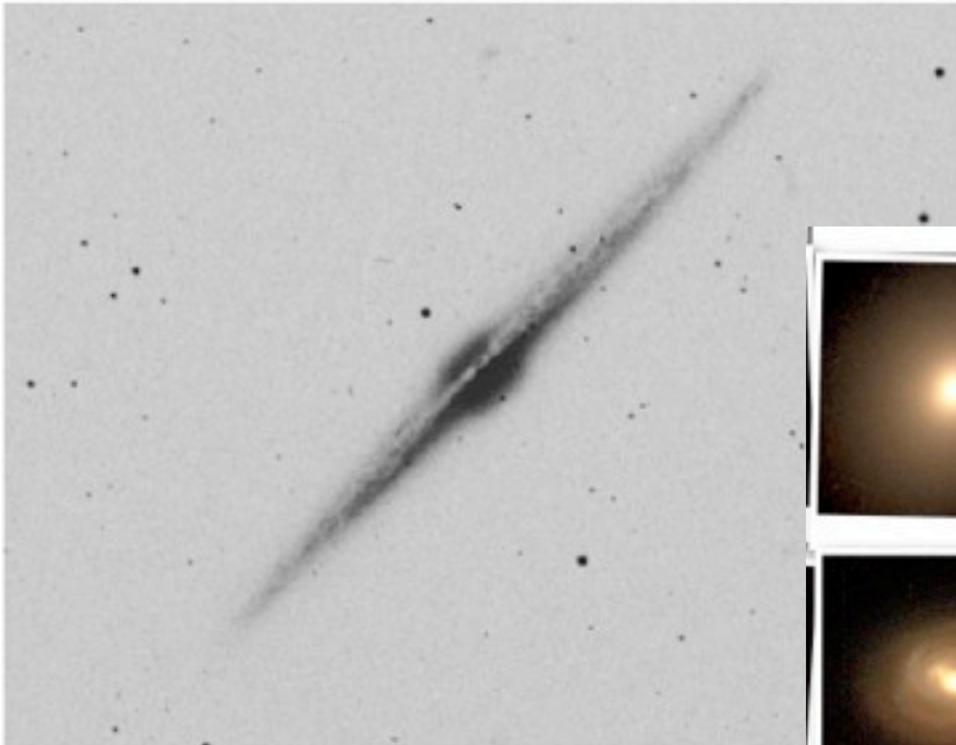
Disk Galaxies

TULLY-FISHER: SECONDARY VARIABLES?



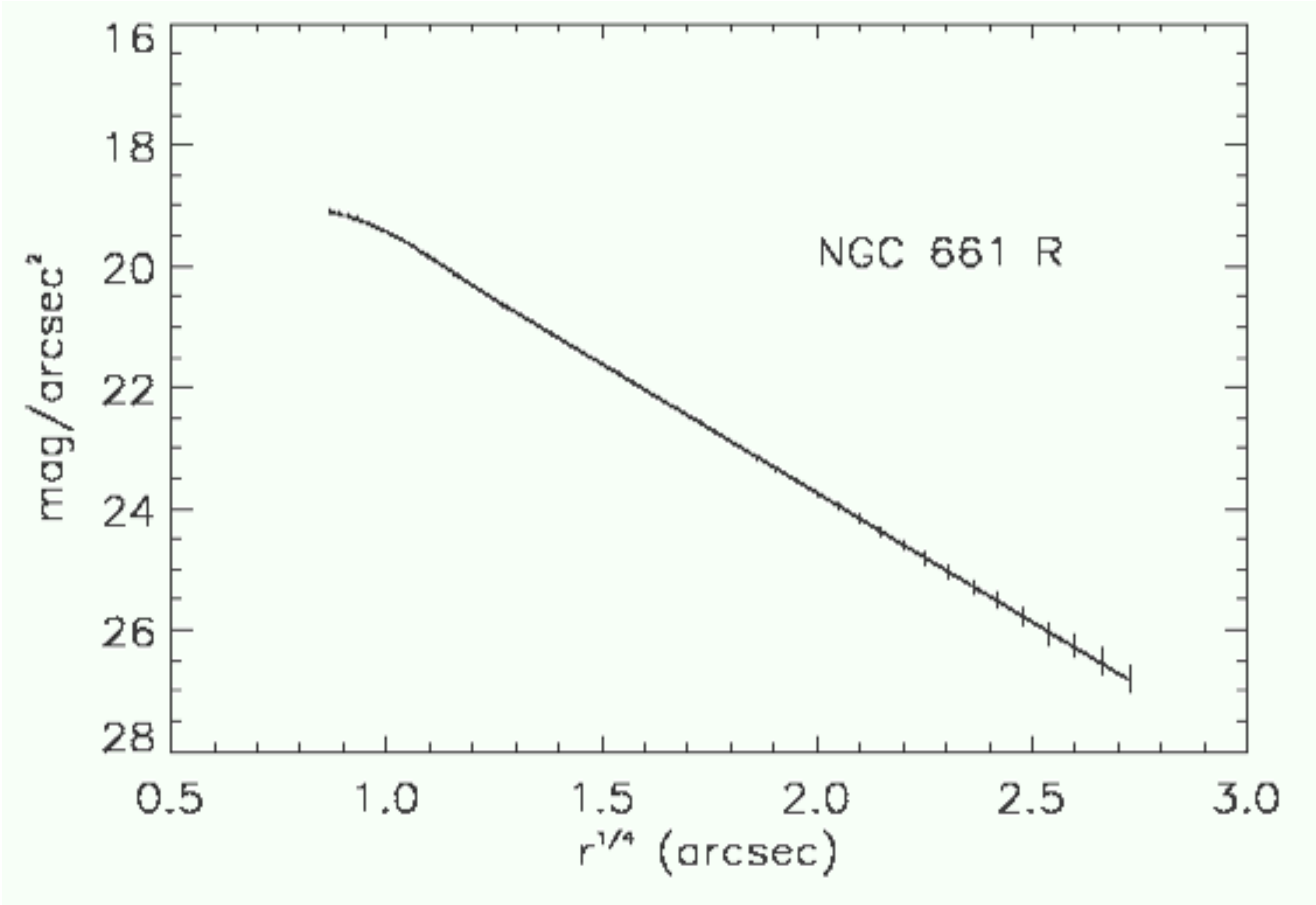
Courteau et al. 2007

What about the spheroidal components of galaxies?



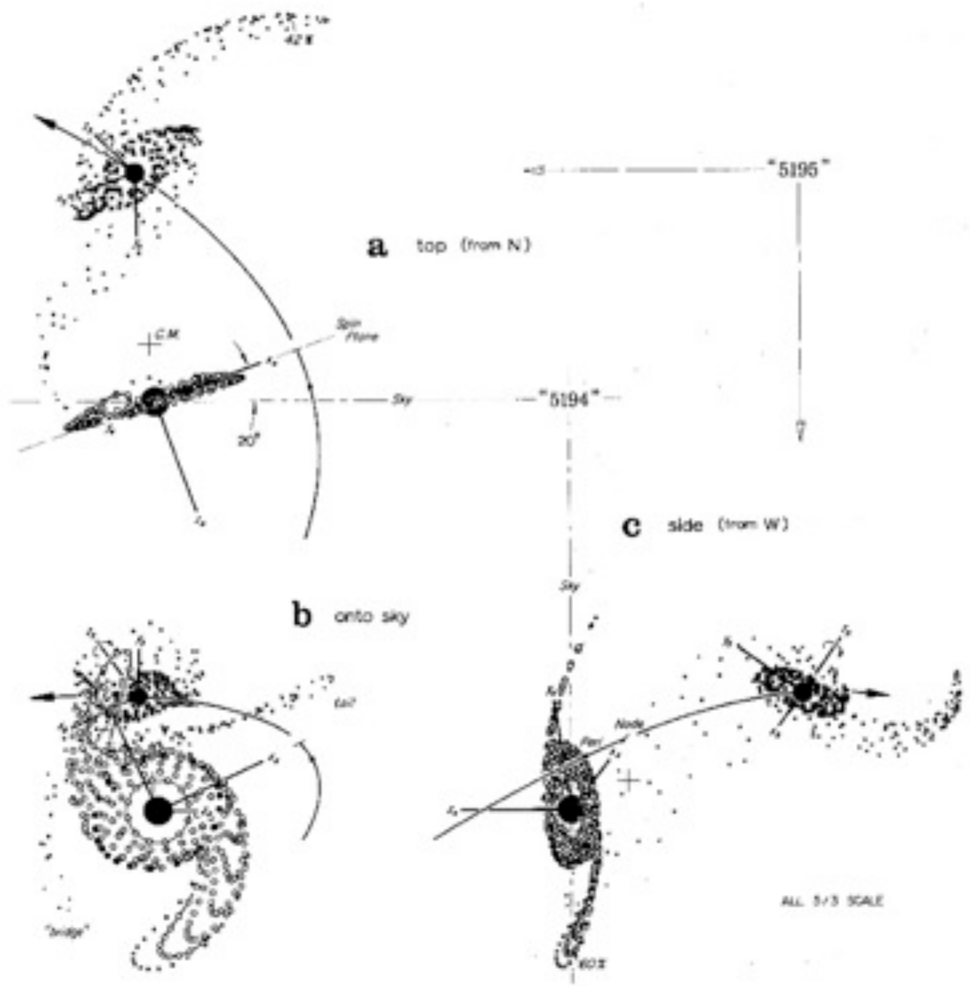
De Vaucouleurs (1948): Spheroids follow an r^1/4 law

$I(R) = I_o$ exp (-b [R/R_e]^{1/4})



Ellipticals & Bulges

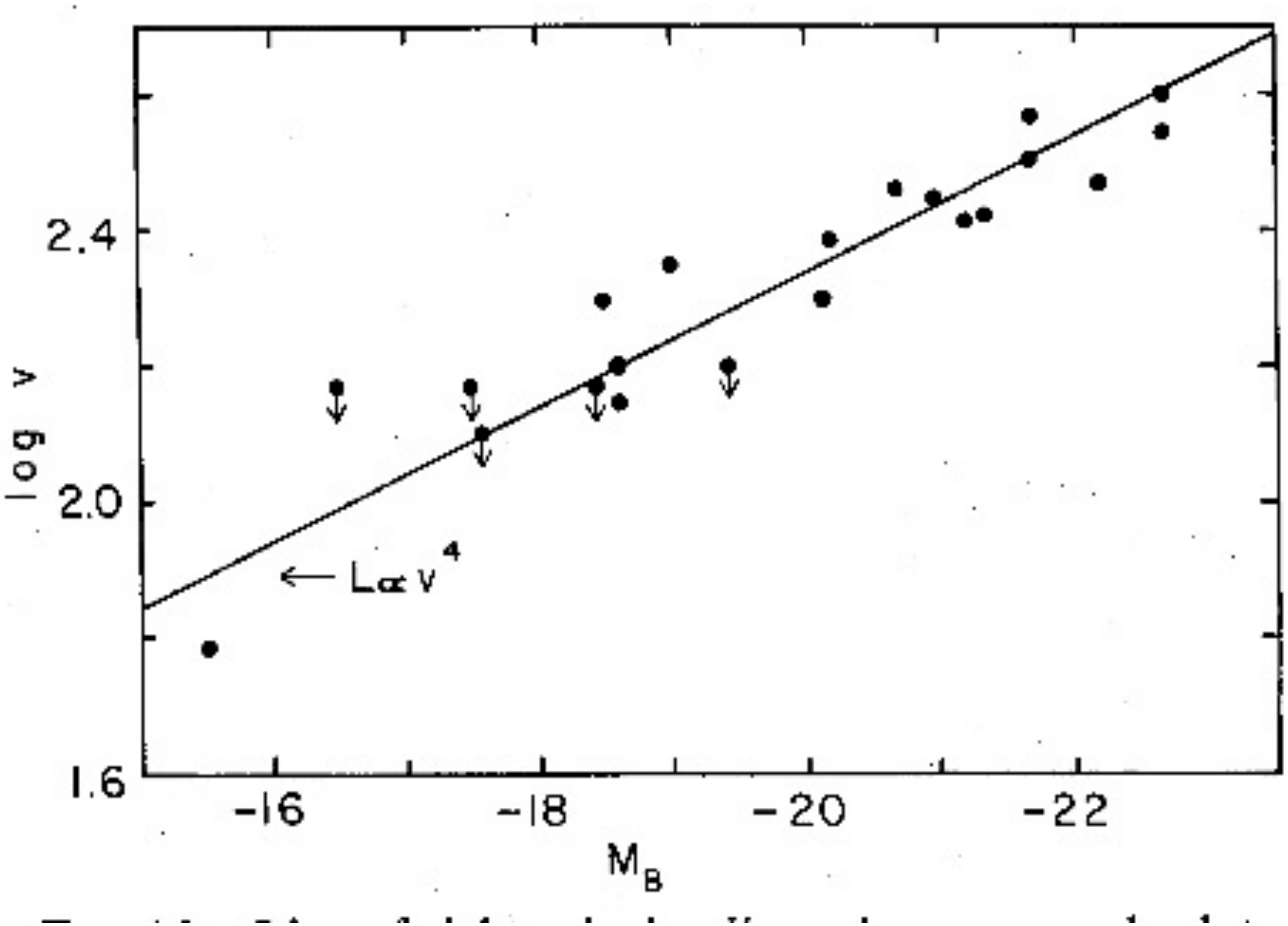
- r^1/4 law is (somewhat) better understood
  - Violent Relaxation (Lynden-Bell 1967)



Structure in Elliptical Light Profiles

THEIR SCALING LAWS

Faber & Jackson (1976)

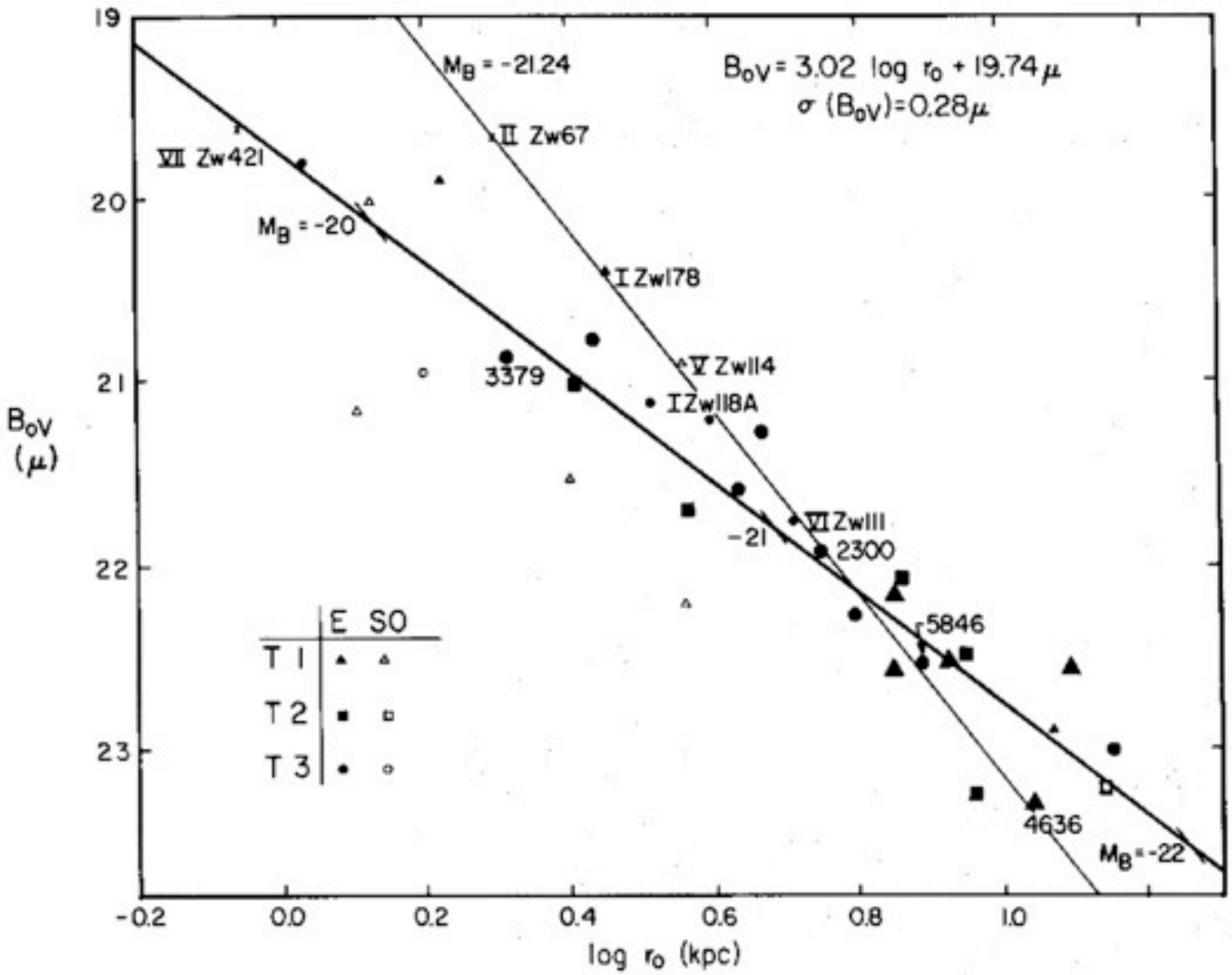


Faber-Jackson relation: the spheroid analogue of Tully-Fisher

Structure in Elliptical Light Profiles

THEIR SCALING LAWS

Kormendy (1977)



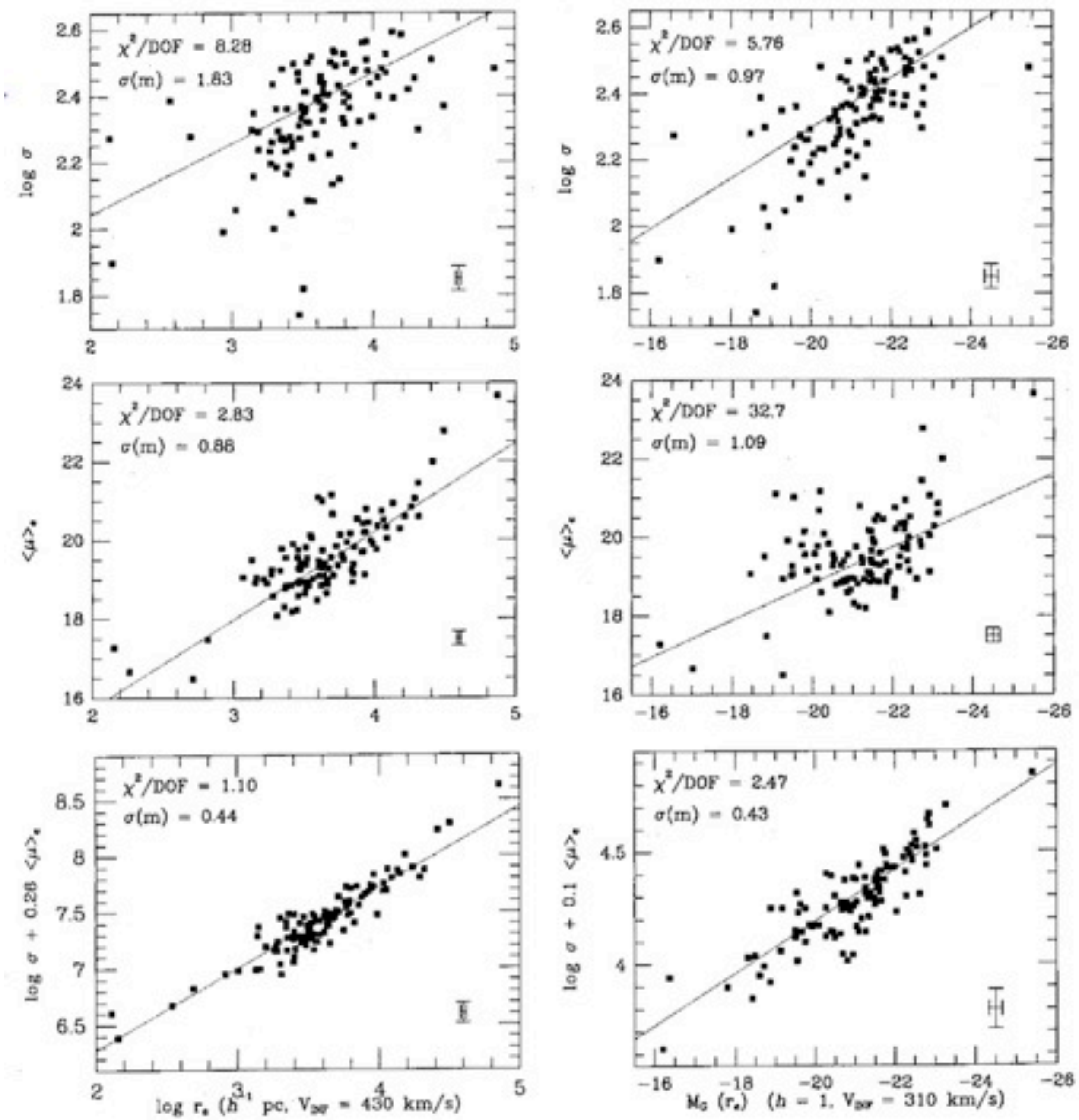
Essentially a size-luminosity relation

Structure in Elliptical Light Profiles

THEIR SCALING LAWS: SECONDARY VARIABLES?

Is a significant secondary variable, unlike disks

Djorgovski & Davis (1987)

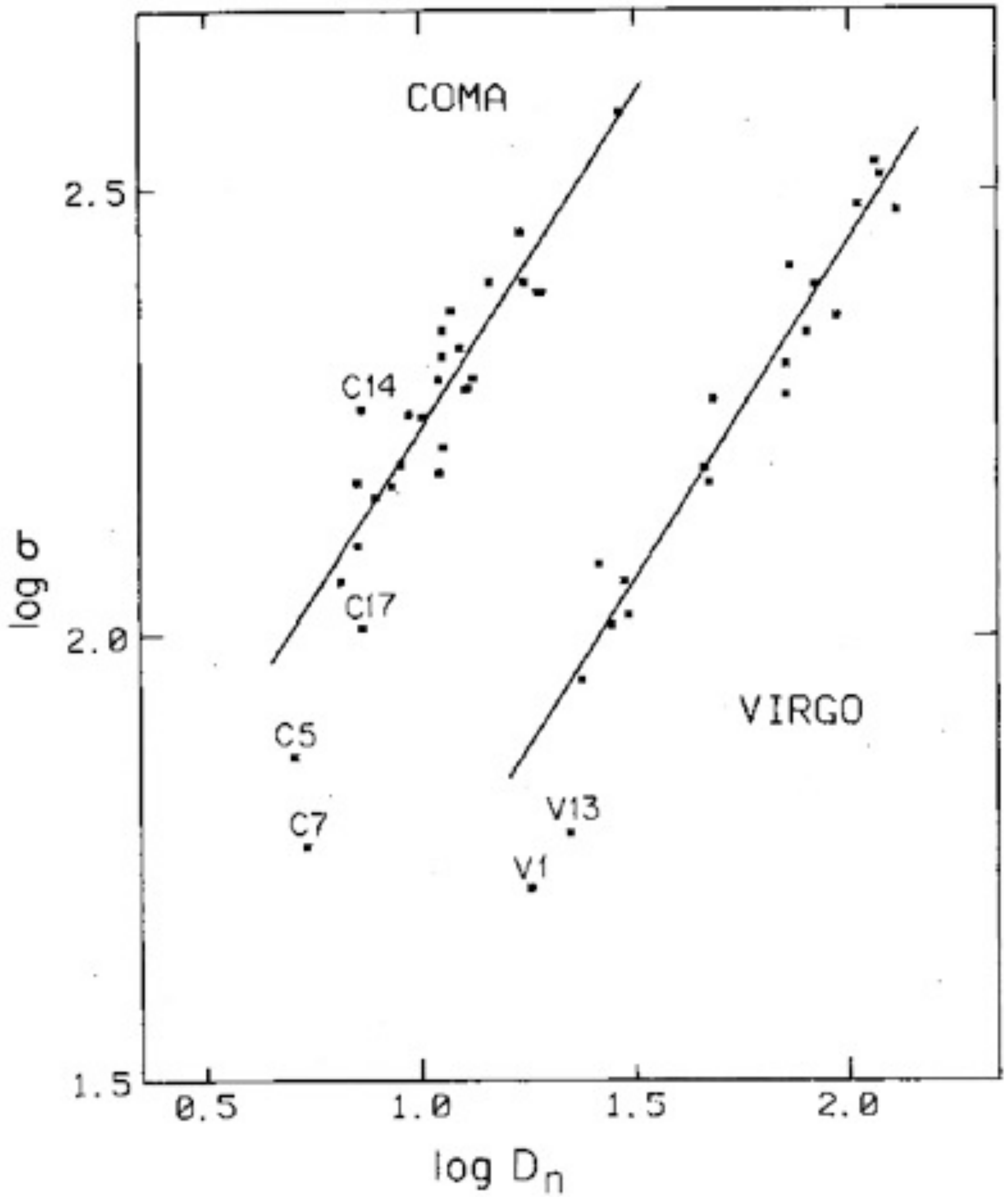


Structure in Elliptical Light Profiles

THEIR SCALING LAWS: SECONDARY VARIABLES?

Originally, intended as a distance indicator

Dressler (1987)

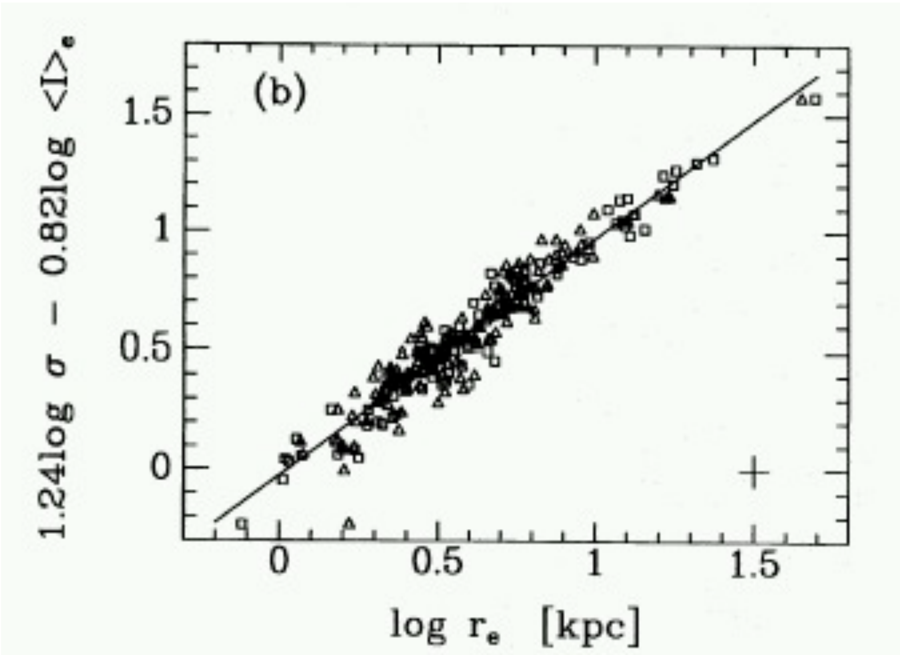


Structure in Elliptical Light Profiles

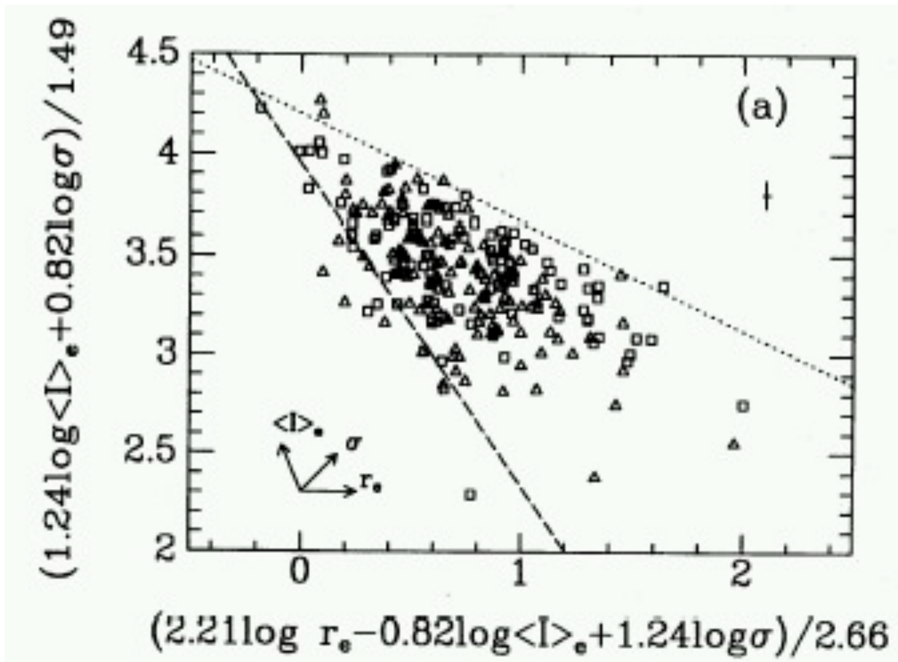
THEIR SCALING LAWS: SECONDARY VARIABLES?

The Fundamental Plane correlates R_e, surface brightness, and σ for elliptical galaxies.

The Fundamental Plane for Coma and other nearby cluster ellipticals:



Fundamental Plane edge on

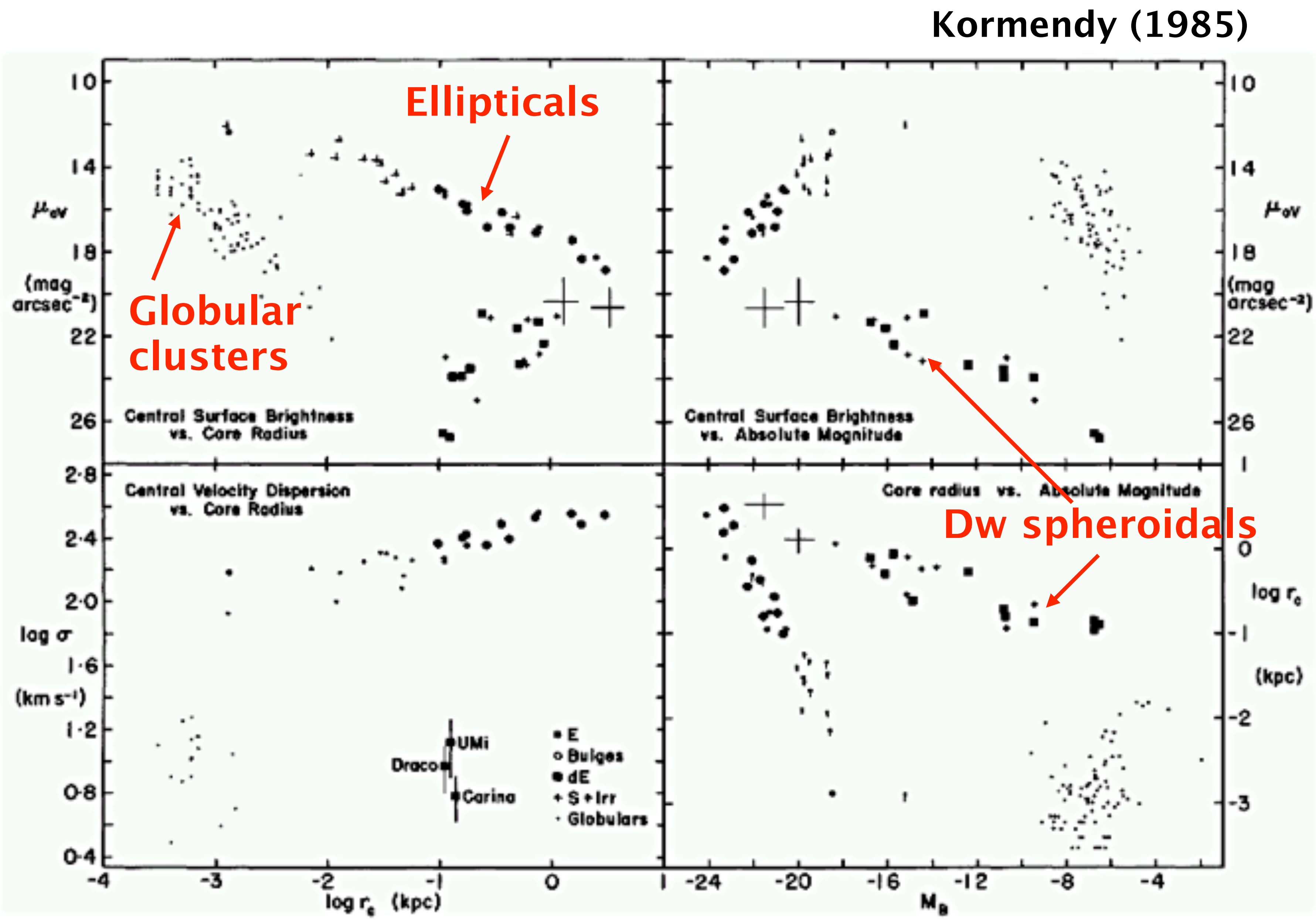


Fundamental Plane face on

Jorgensen 1996

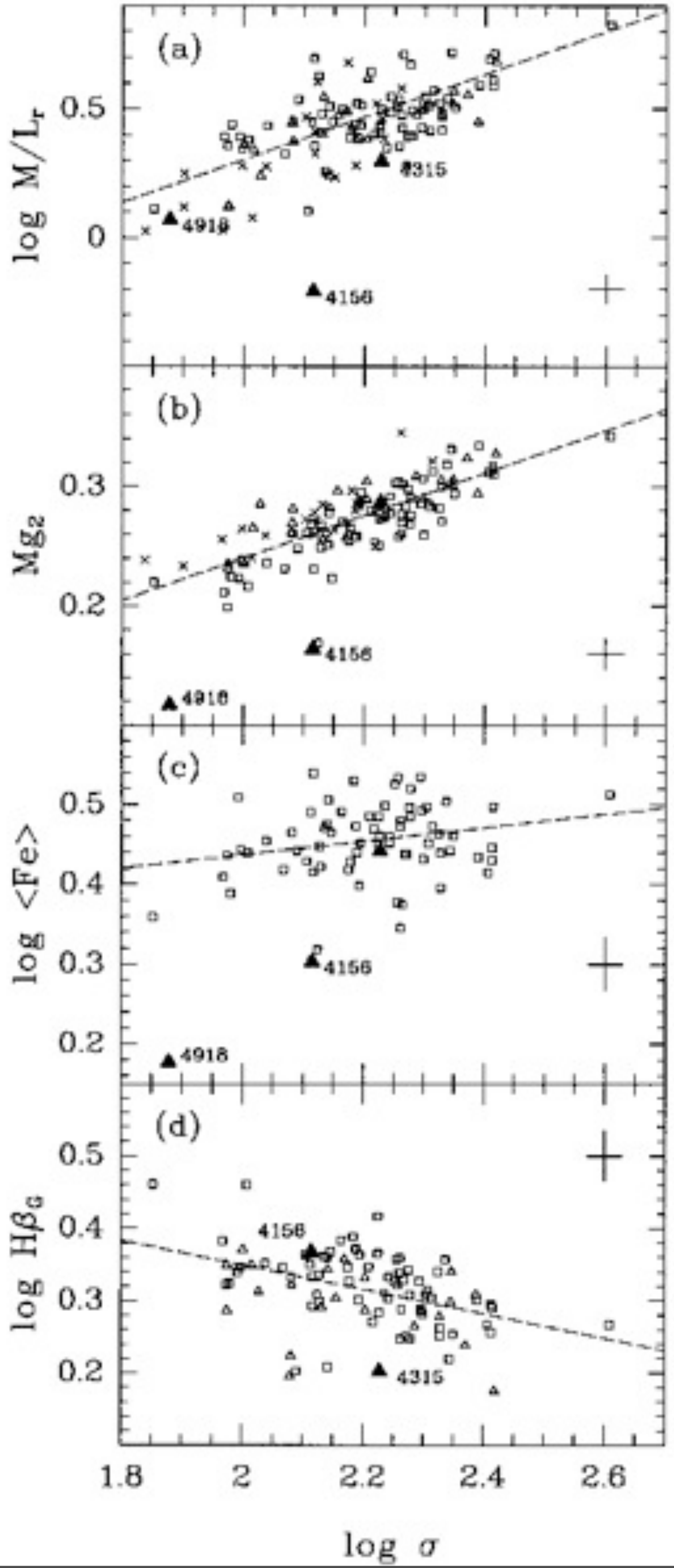
Structure in Elliptical Light Profiles

SEPARATION OF DIFFERENT POPULATIONS IN THESE CORRELATIONS



Structure in Ellipticals

- Line Indices tightly correlate with velocity dispersion
  - Some systematic variation in stellar populations with galaxy mass



Tuesday, December 25, 12

Black Holes

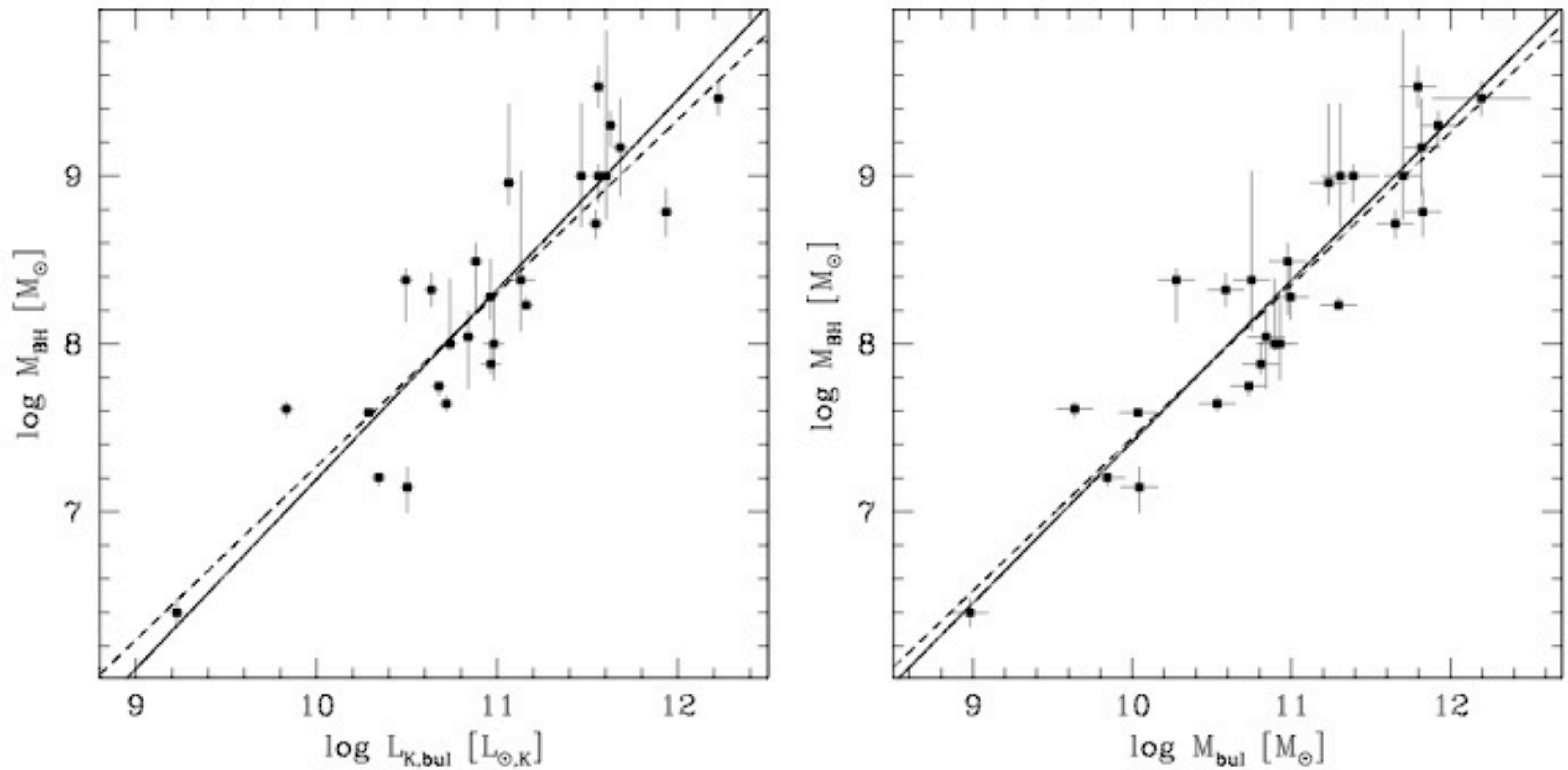
NEWCOMERS TO THE CORRELATIONS

Only recently (~1995+) has it become clear: every massive spheroid hosts a supermassive black hole (BH)

More surprising, those BH properties are tightly correlated with those of their host spheroids

Kormendy et al. (1995) & Magorrian (1998)

BH mass - galaxy luminosity / mass correlation



Marconi & Hunt (2003)

Black Holes

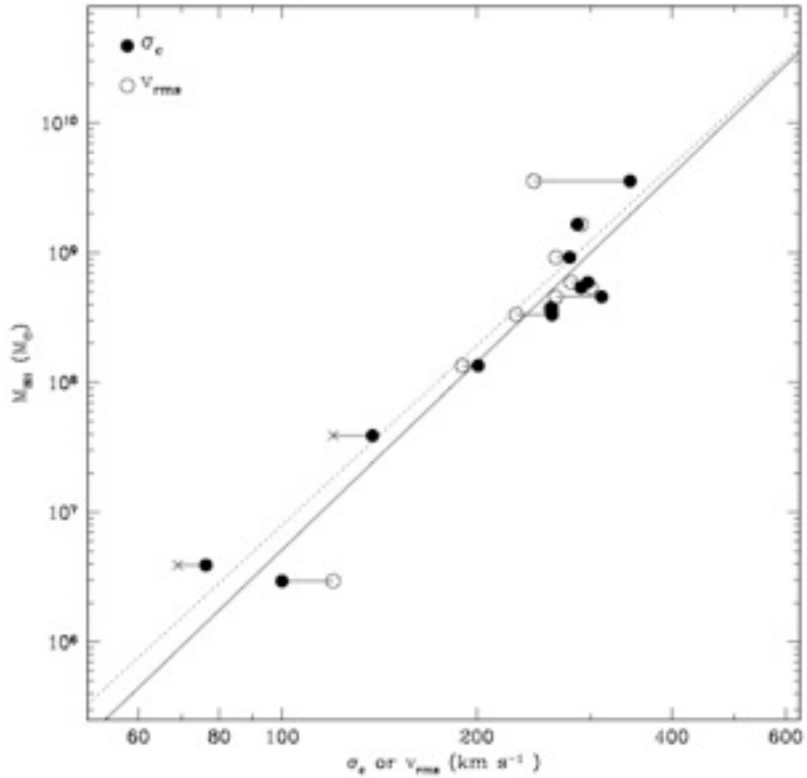
NEWCOMERS TO THE CORRELATIONS

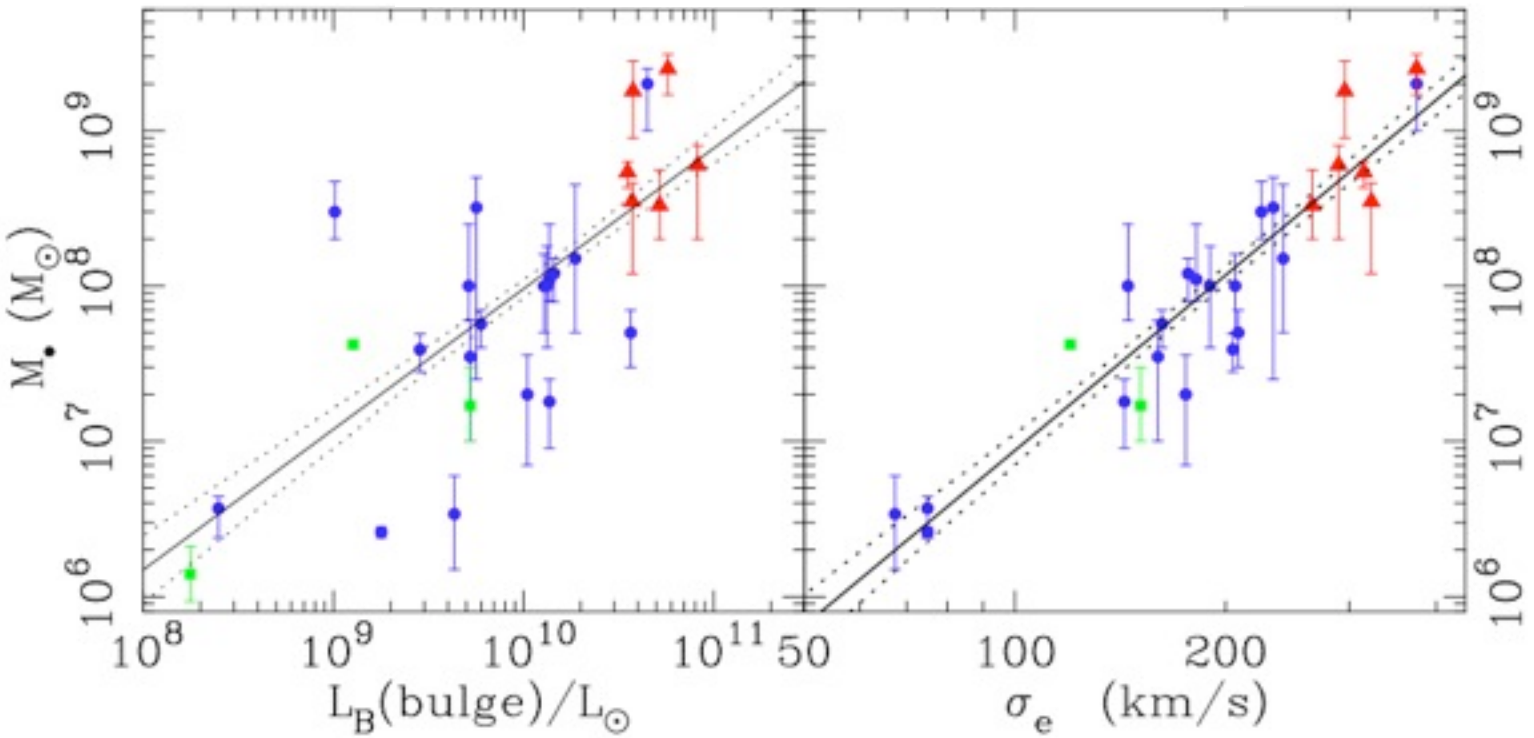
Ferrarese & Merritt (2000)

and

Gebhardt et al. 2000:

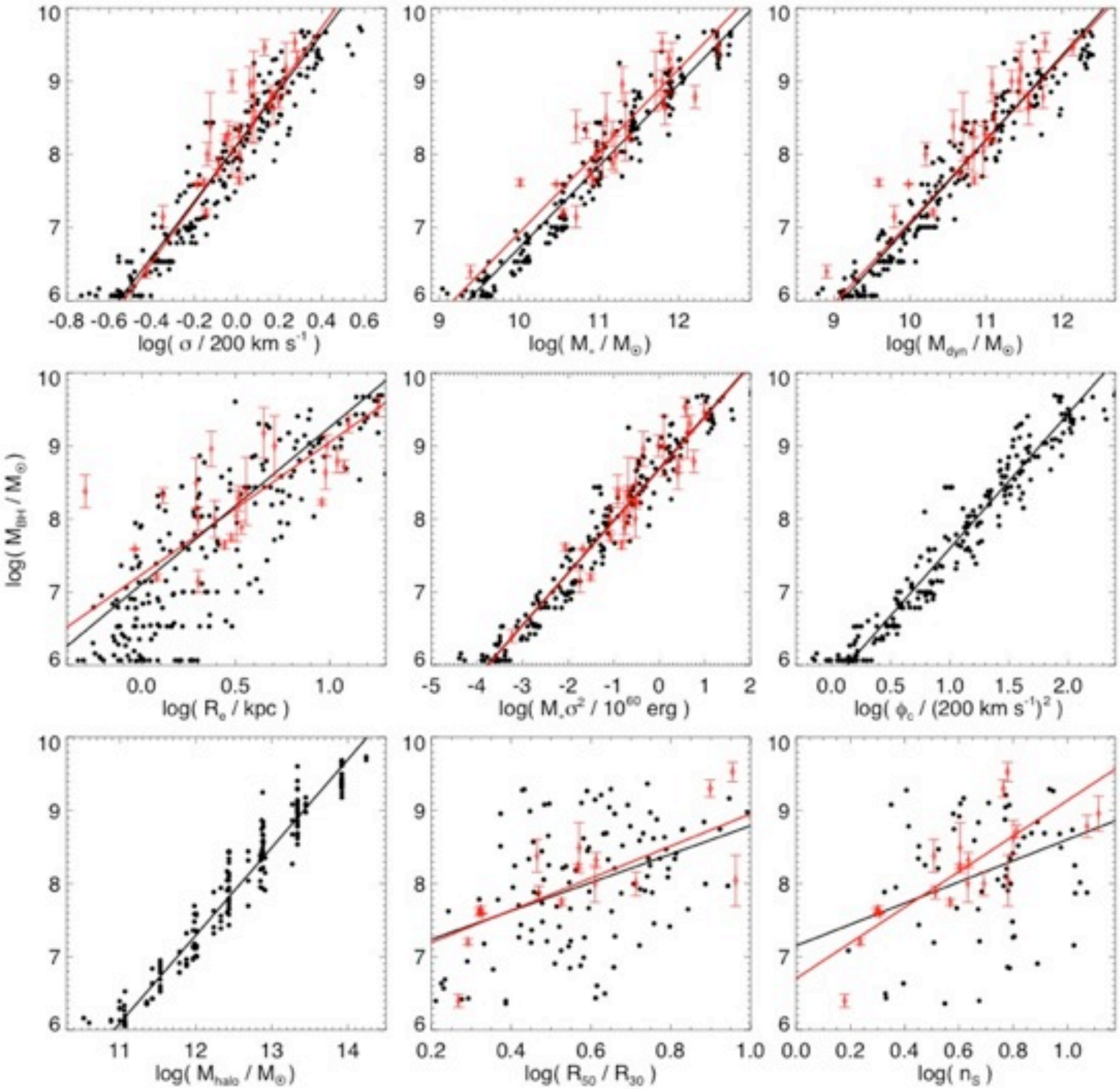
Mbh ~ sigma^4.x





Black Holes

NEWCOMERS TO THE CORRELATIONS

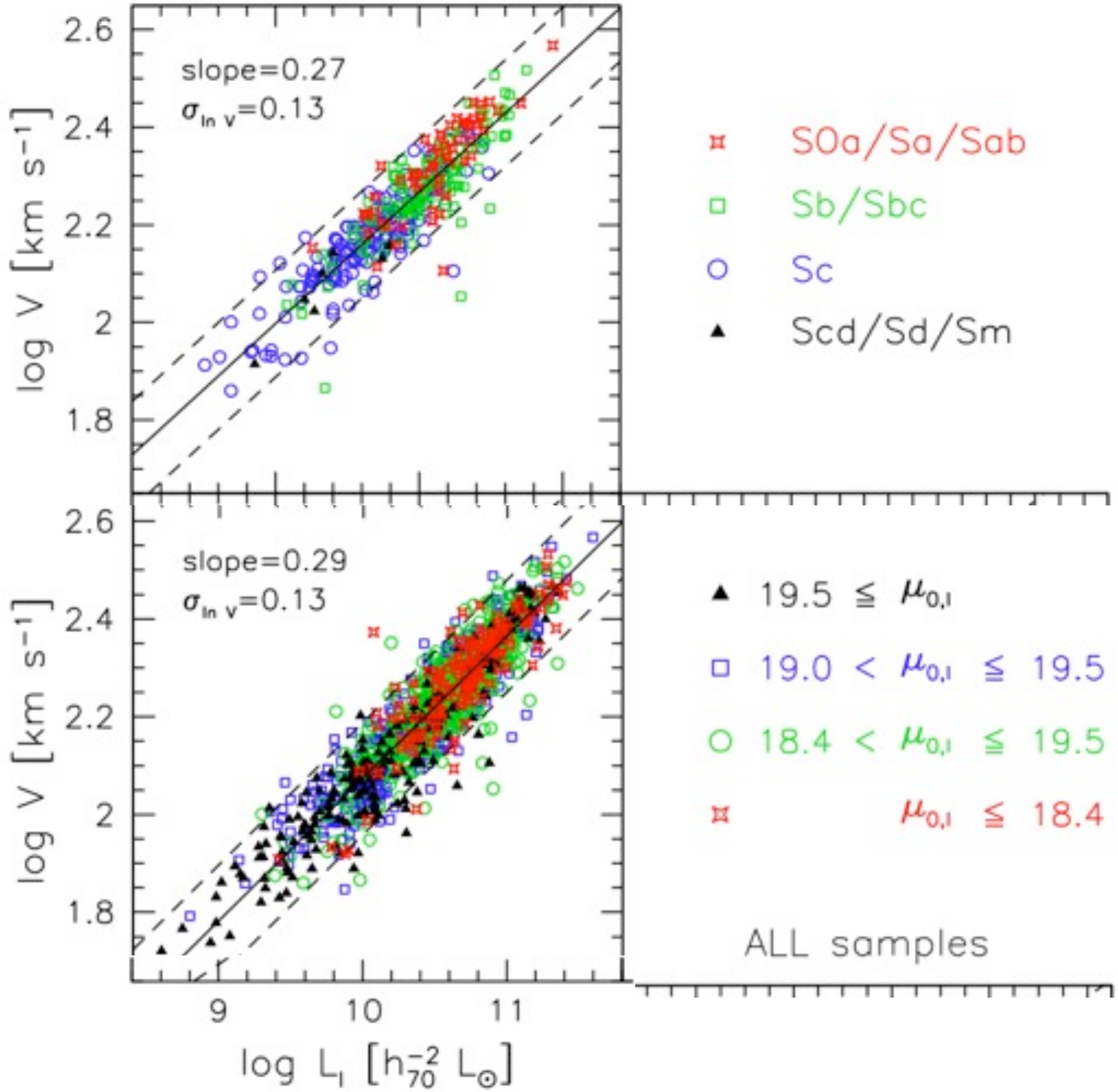


"Fundamental Planes" = Scaling Laws Obeyed by Galaxies

- Large degree of regularity in galaxy formation: need to get at what these correlations really "mean":
  - How do these observed correlations relate to physical properties of the galaxies?
  - How do other variables enter into them?
  - How do they evolve?
  - How do they arise?

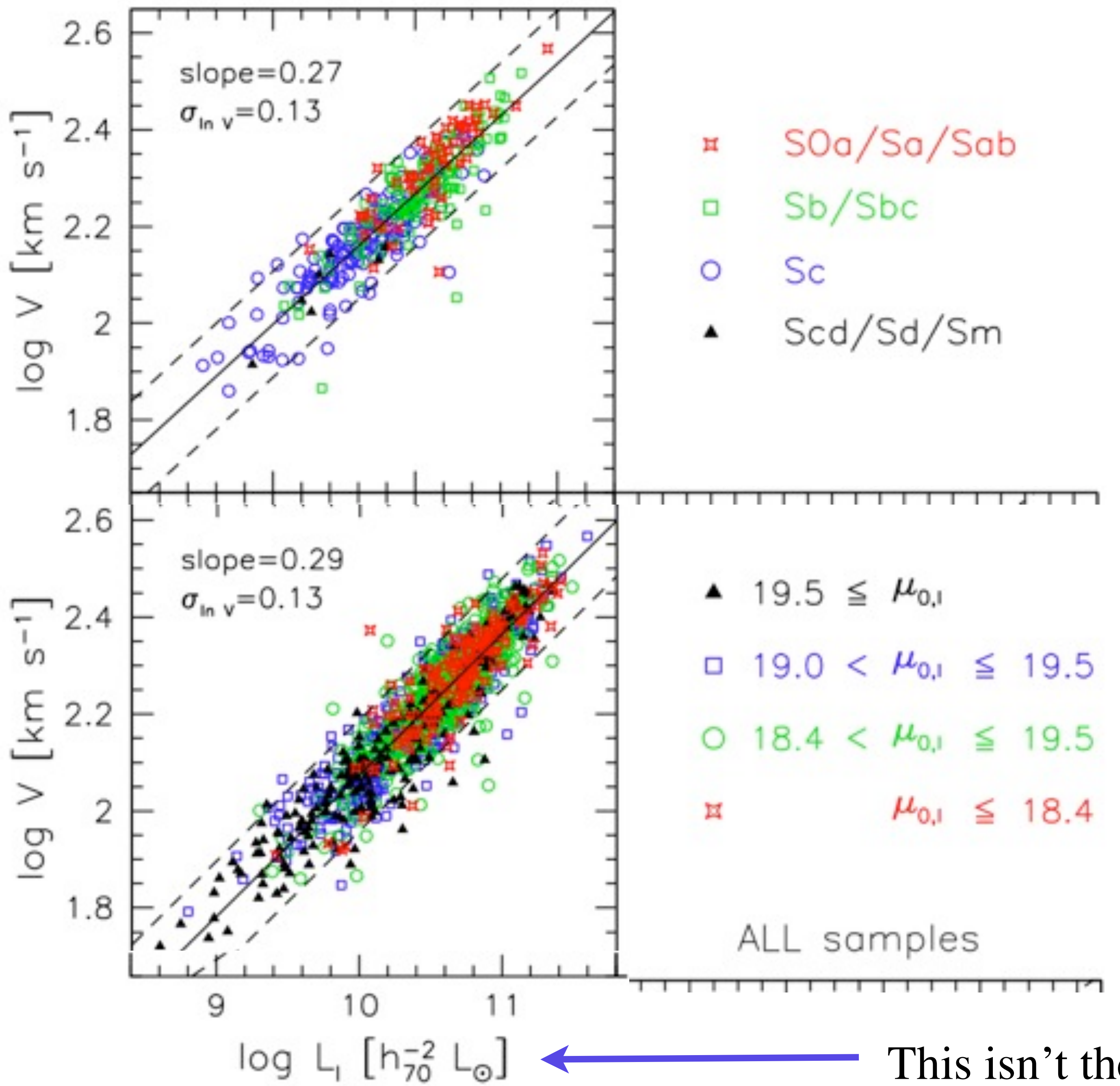
Understanding the Origins and Physical Meaning of Local Galaxy Scaling Laws

Return to the Tully-Fisher Relation:



Courteau et al. 2007

Return to the Tully-Fisher Relation:



This isn't the number we want!

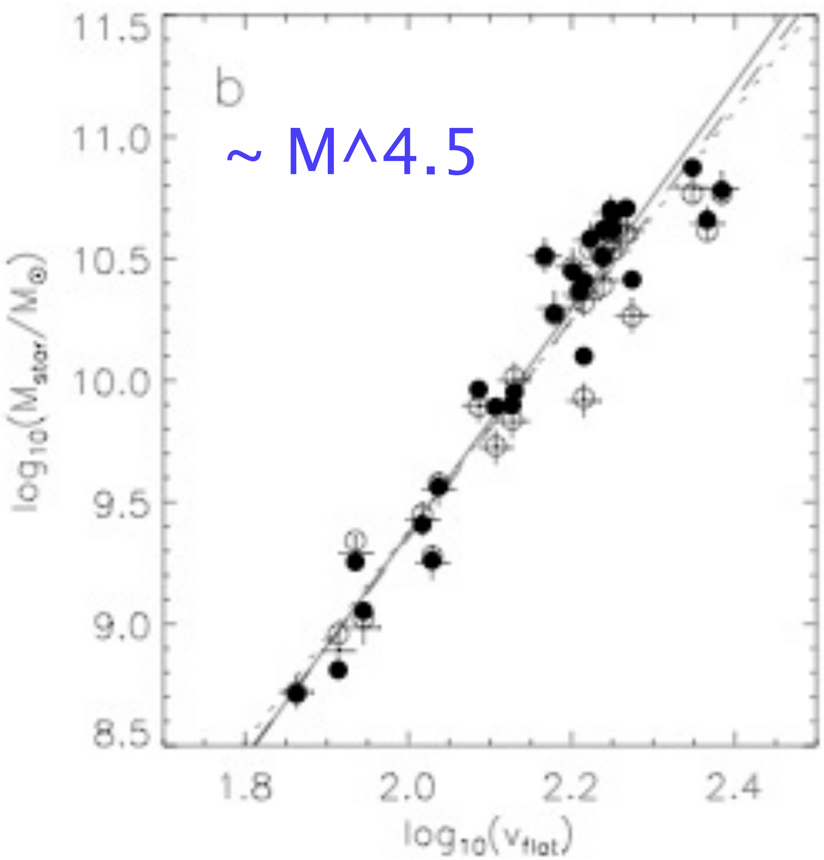
Return to the Tully-Fisher Relation:

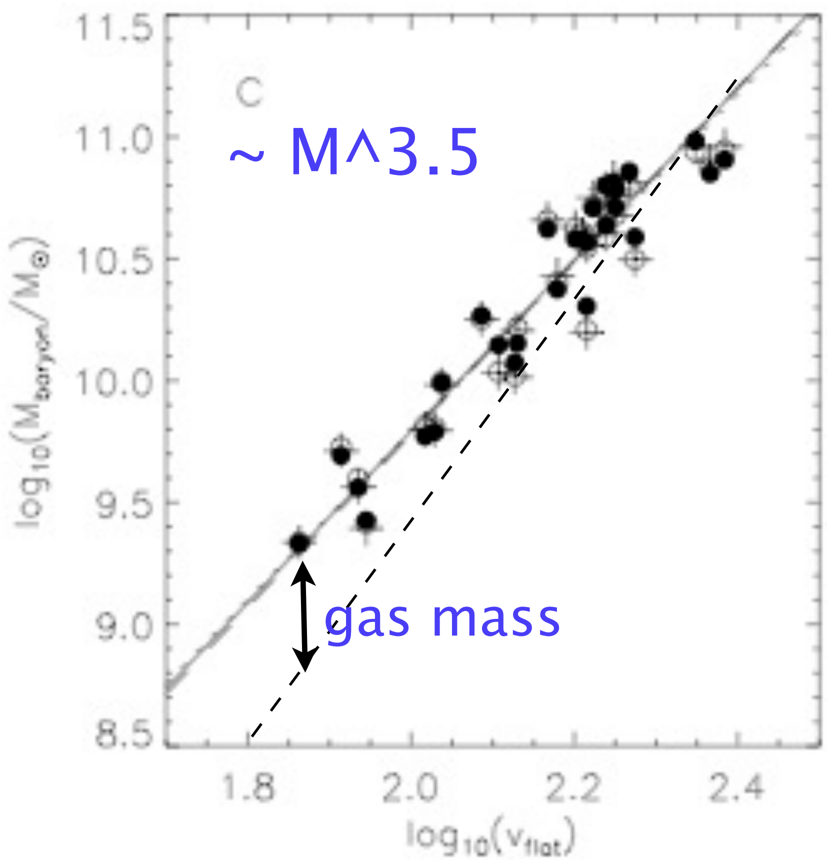
- Optical luminosity =
  stellar mass + age + metallicity + dust + star formation

  - Near-IR better -- get to stellar-mass Tully Fisher

  - Combine with gas mass & get
    Baryonic Tully-Fisher Relation

Bell & de Jong 2000

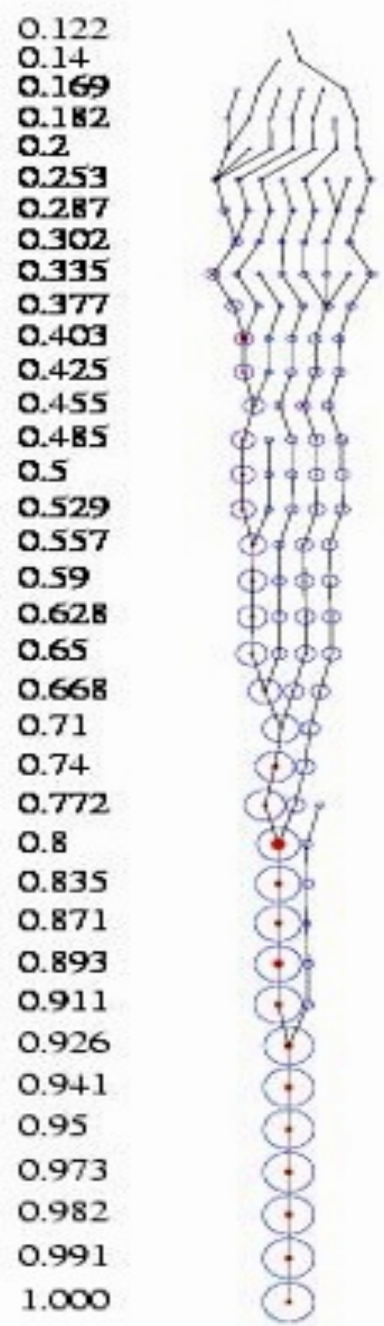




Structure in Disk Light Profiles

UNDERSTANDING THE TULLY-FISHER RELATION

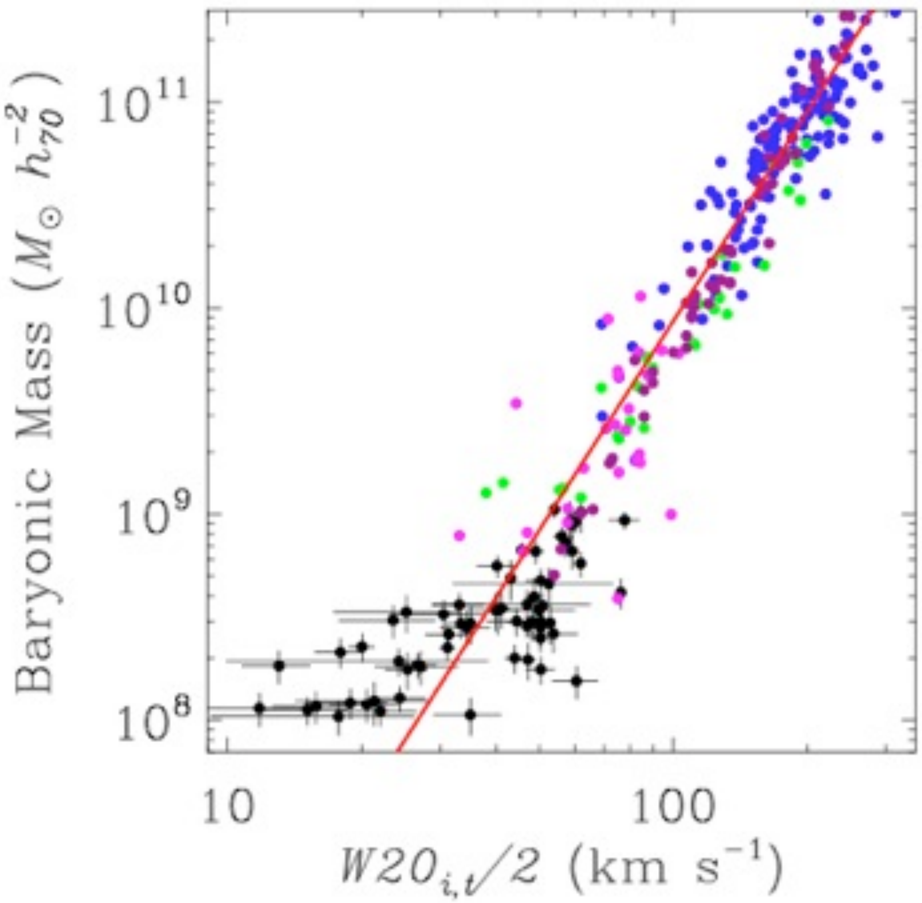
- Origin of scaling laws:
  - Halos collapse to the virial overdensity:
  - r_halo ~ 180 r_matter ~ CONSTANT at a given z
  - r ~ M^1/3
  - v ~ (GM/r)^1/2 ~ M^1/3

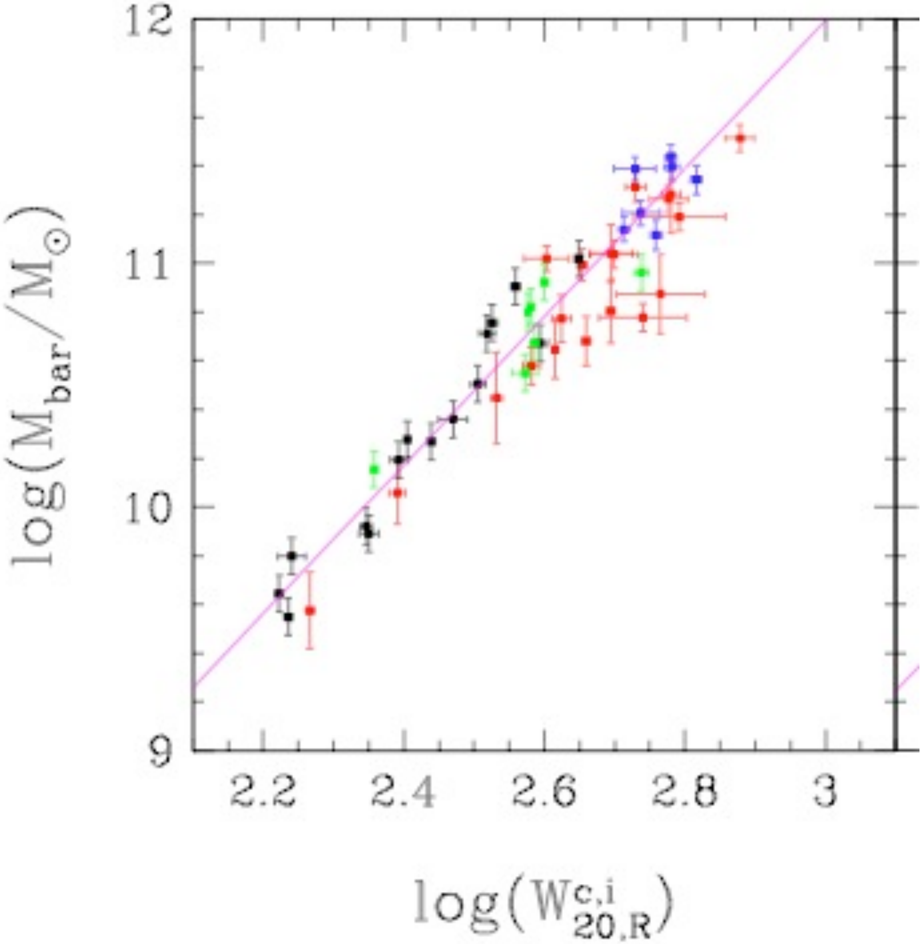


Structure in Disk Light Profiles

UNDERSTANDING THE TULLY-FISHER RELATION

- Roughly holds over a very large dynamic range: V~ 30 - 500 km/s





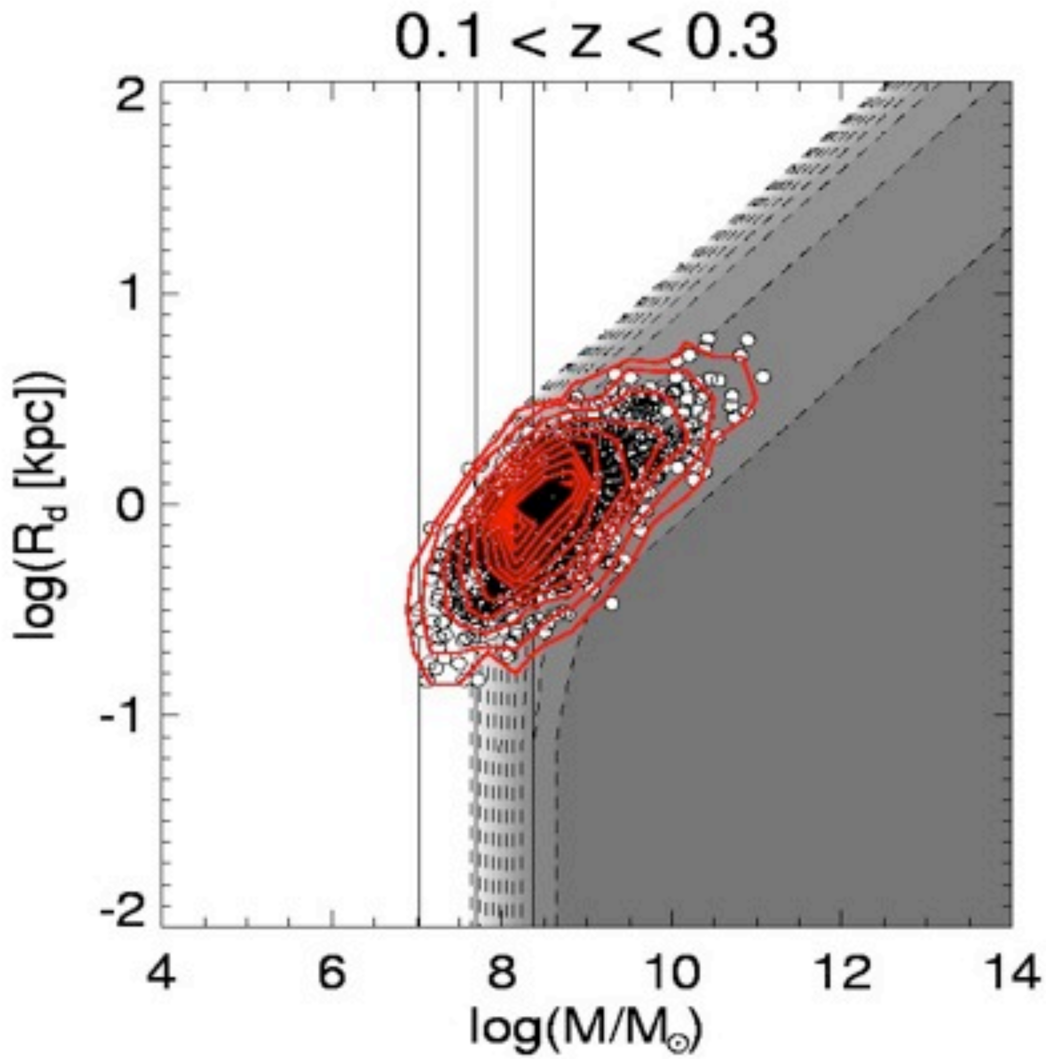
- Likewise, size-mass relation: but this doesn't enter into the TF relation

COMBO-17:

Disk galaxies

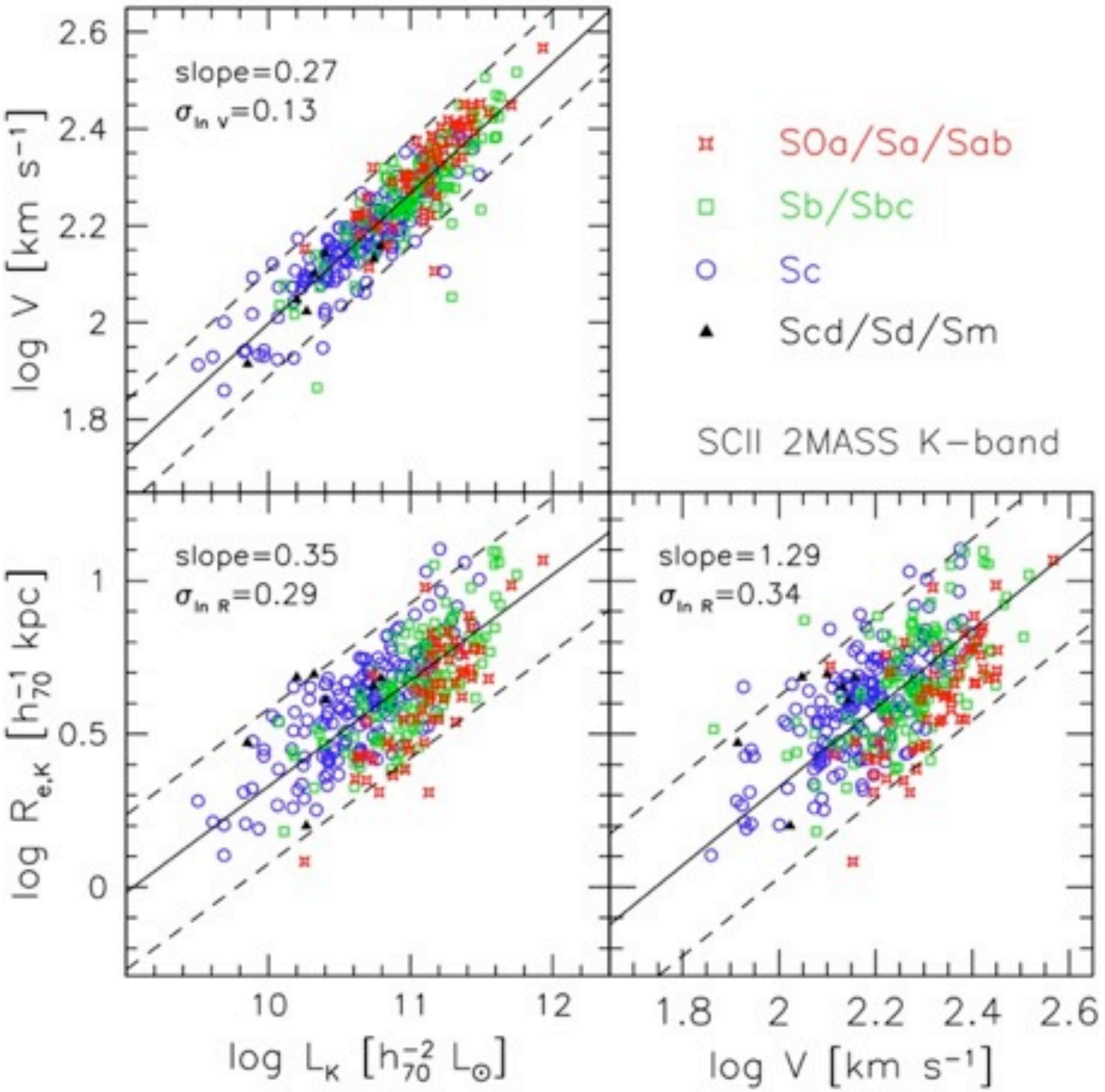
Mass-radius relation

Stellar Mass vs Size



Structure in Disk Light Profiles

UNDERSTANDING THE TULLY-FISHER RELATION



- Earlier types: compact central mass -- smaller R at fixed M

Structure in Disk Light Profiles

UNDERSTANDING THE TULLY-FISHER RELATION

- Systematic difference in e.g. B-band and stellar mass TF slopes are interesting:
  - L_B ~ v^3 :: v ~ L_B^1/3
  - M_star ~ v^4.5
  - (L_B/M_star) ~ M_star^-1/3

- M_baryon ~ V^{3.5 - 4.0} --- actually < 1/3 at high significance:
  - M_baryon/M_halo not constant
  - v isn't exactly v_halo
  - halo concentration scales with mass

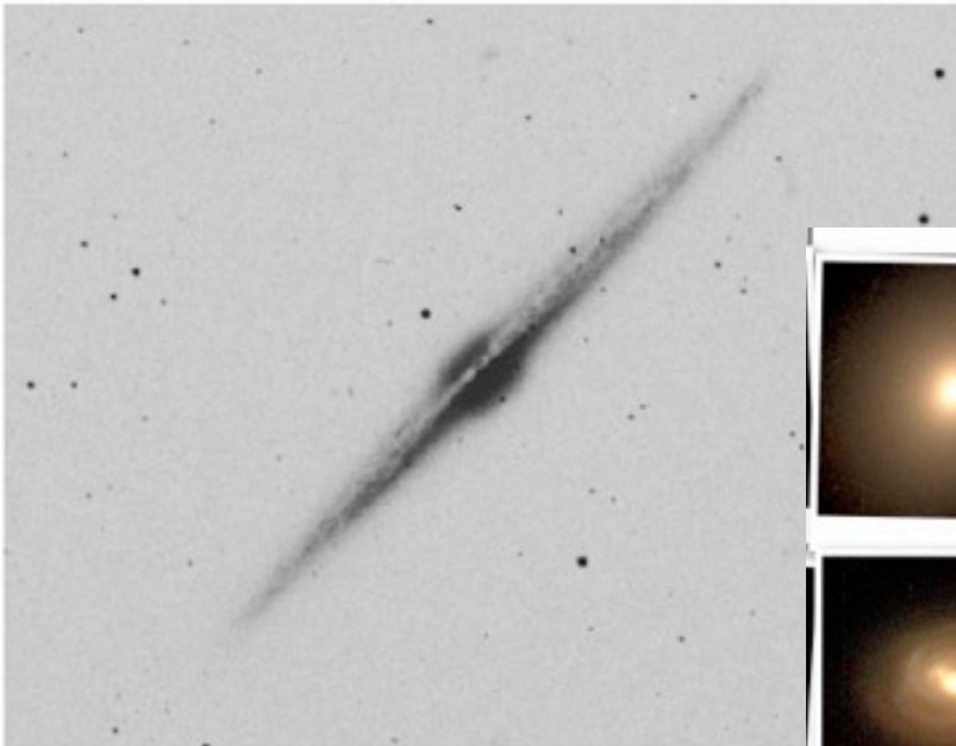
- Mo, Mau & White (1996) -- disk size set by conservation of specific angular momentum, with "stability criterion"

Structure in Disk Light Profiles

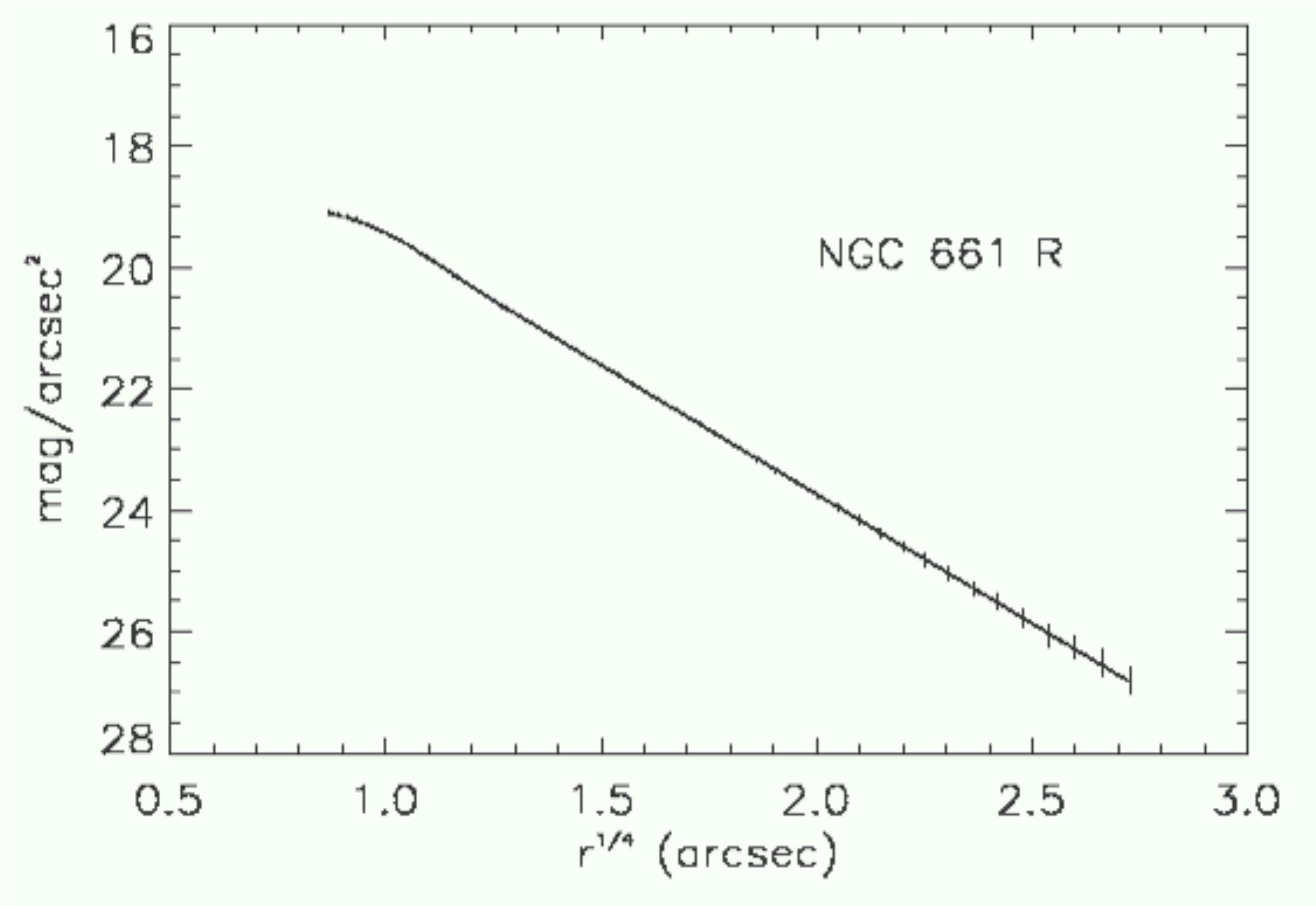
UNDERSTANDING THE TULLY-FISHER RELATION

- There is still a zero-point problem: most models can't simultaneously fit the zero-points of the Tully-Fisher and size-mass relations (model disks are too small)
- But, we think we (more or less) understand the slopes/scalings themselves

What about the spheroidal components of galaxies?



Ellipticals & Bulges

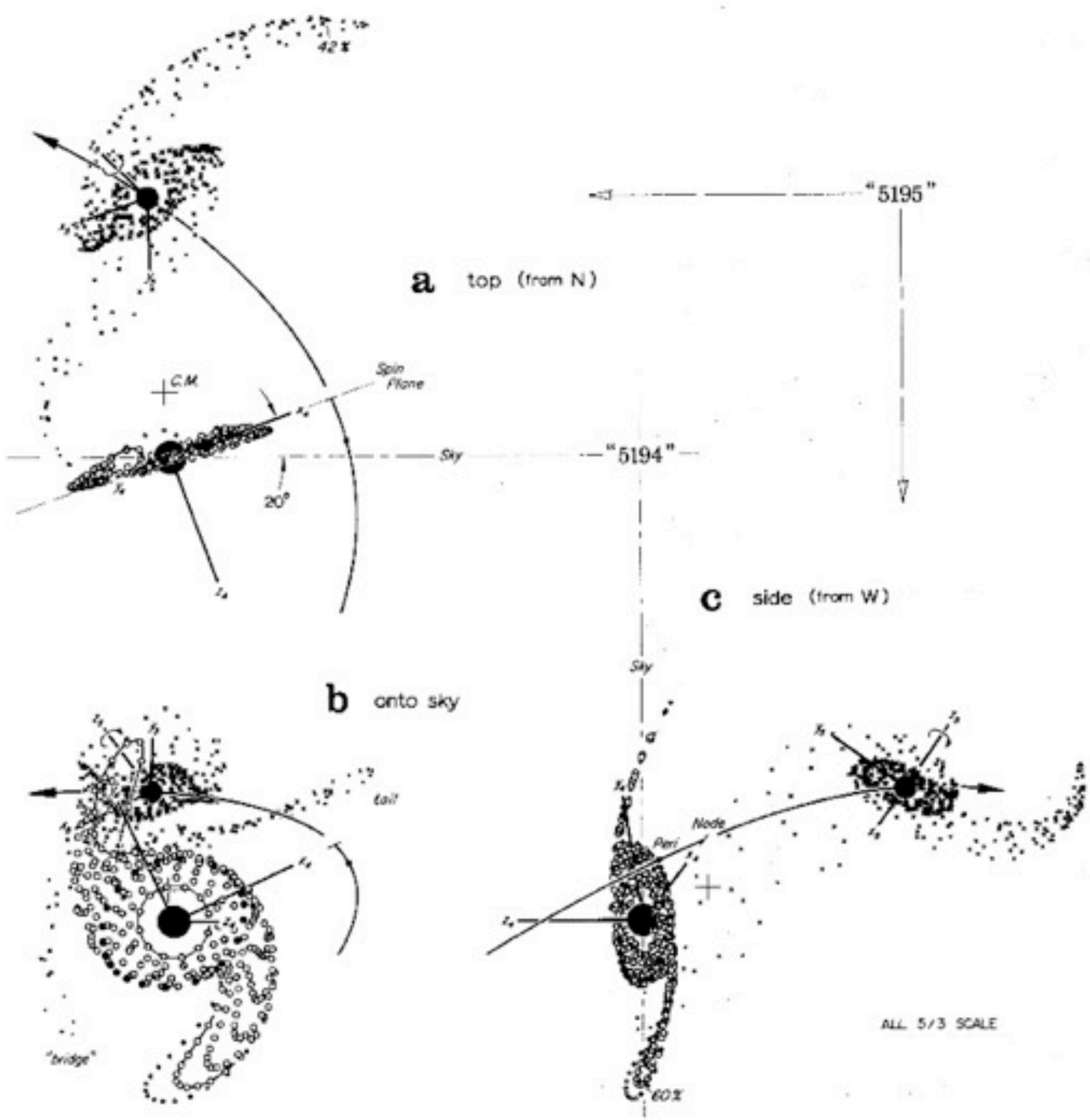


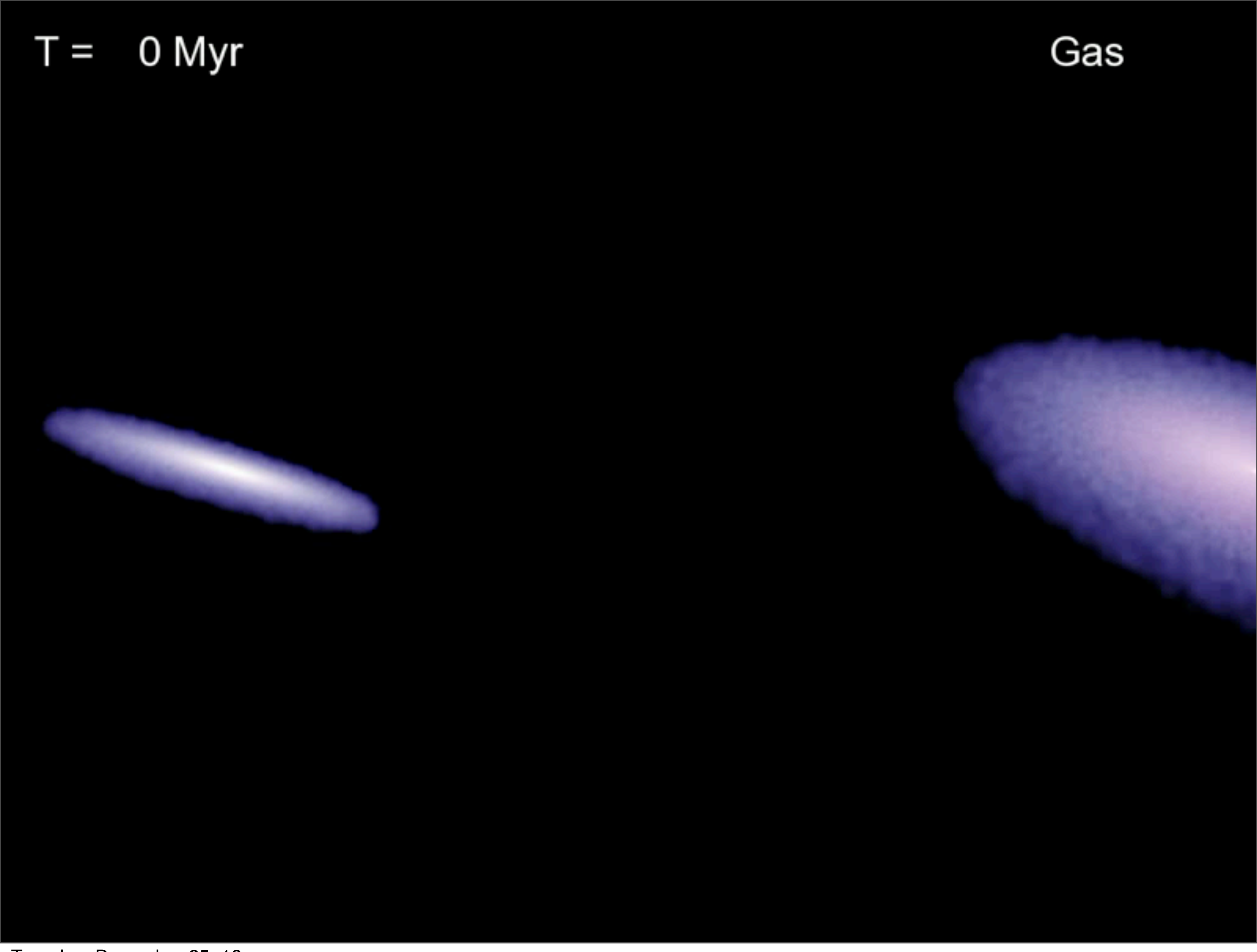
- Violent relaxation: rapidly changing potential: stars scatter off the changing potential, mixing their orbits and energies

Ellipticals & Bulges

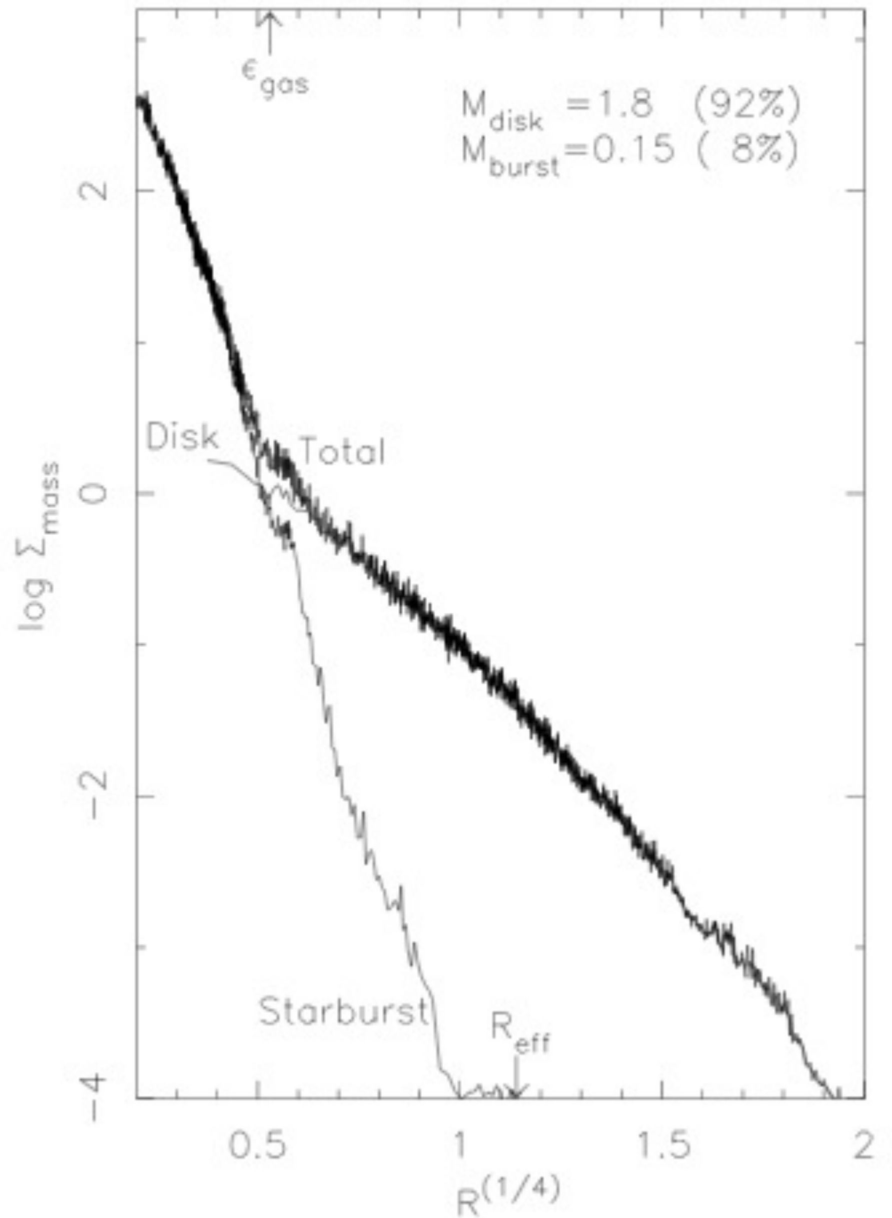
Toomre & Toomre (1972) ::
the "merger hyphothesis"

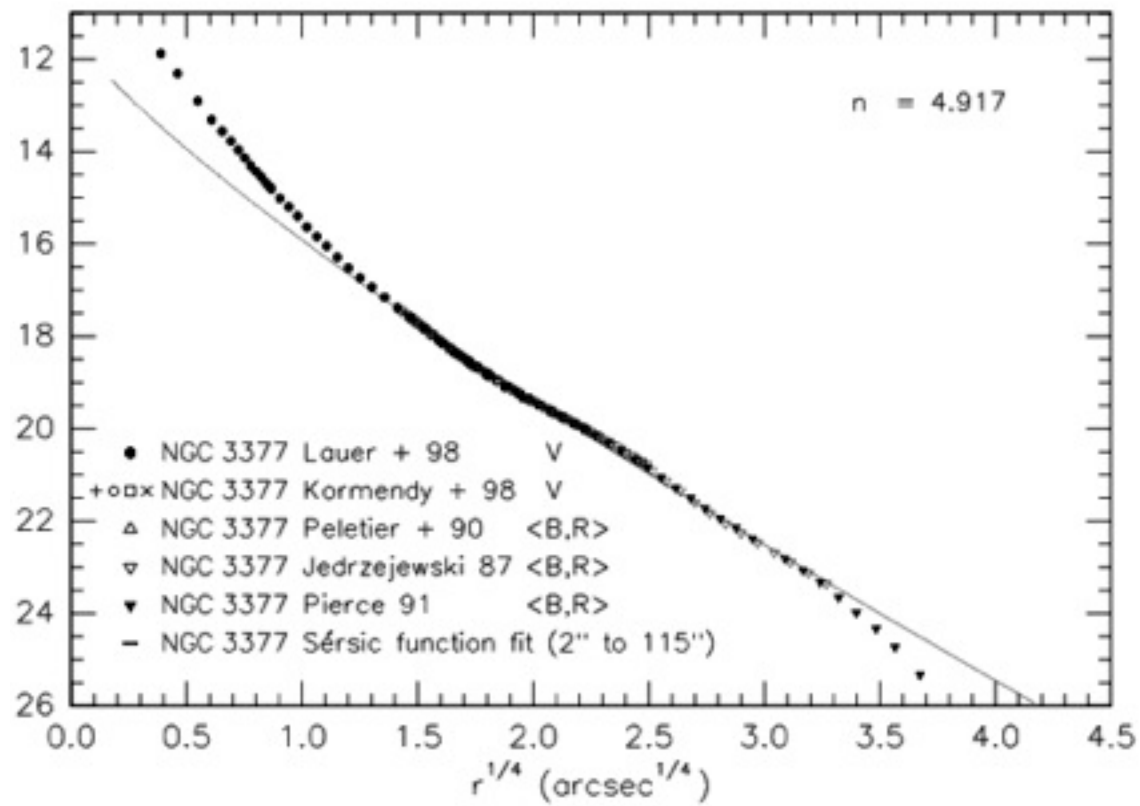
ellipticals are made by the collision and merger of spirals




T =   0 Myr
Gas

Structure in Elliptical Light Profiles

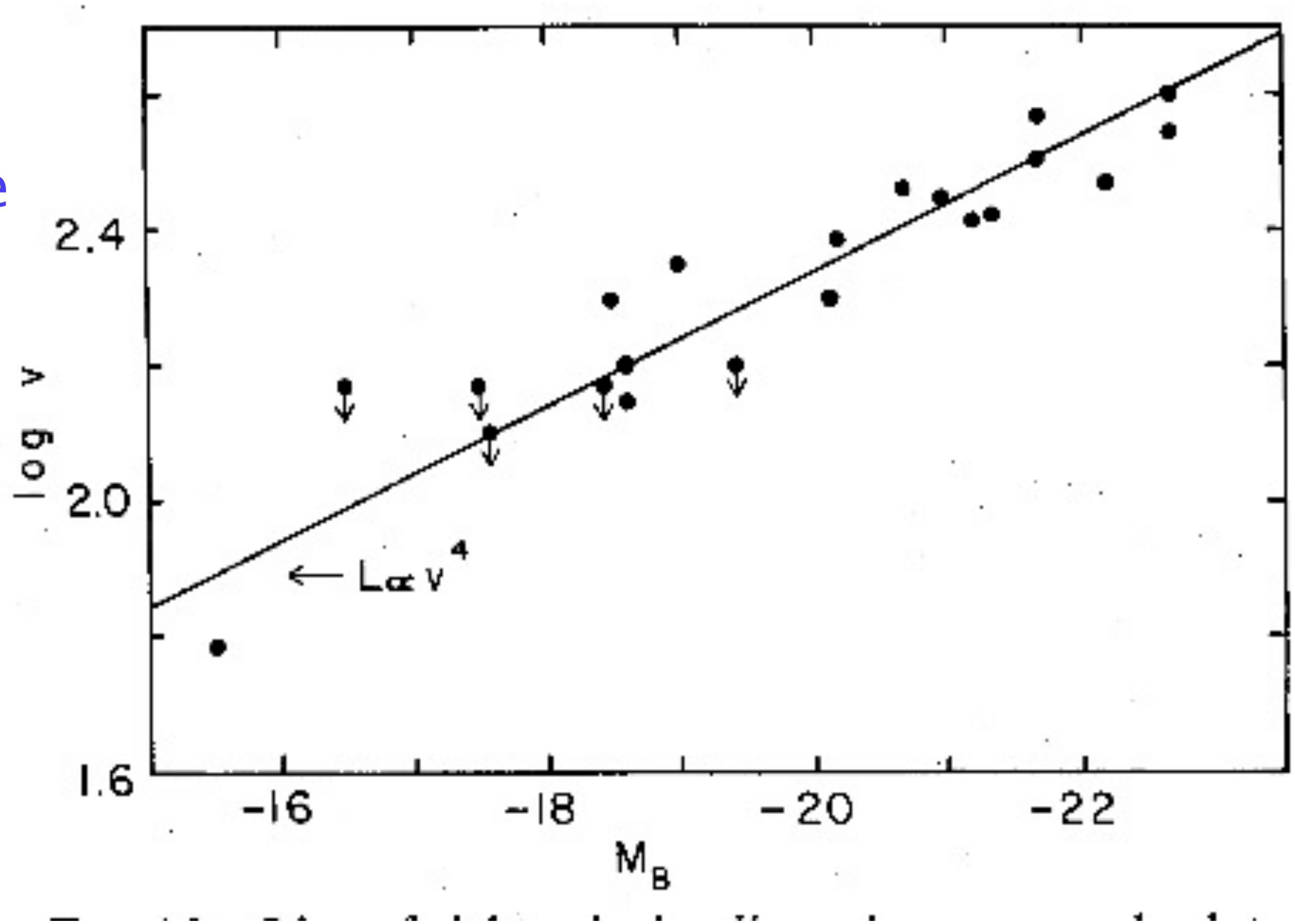




Structure in Elliptical Light Profiles

THEIR SCALING LAWS

Faber & Jackson (1976)



So, how does the Faber–Jackson relation arise?

Structure in Elliptical Light Profiles

THEIR SCALING LAWS

- Faber-Jackson:
  - Convert v_c to sigma (randomize the velocities)

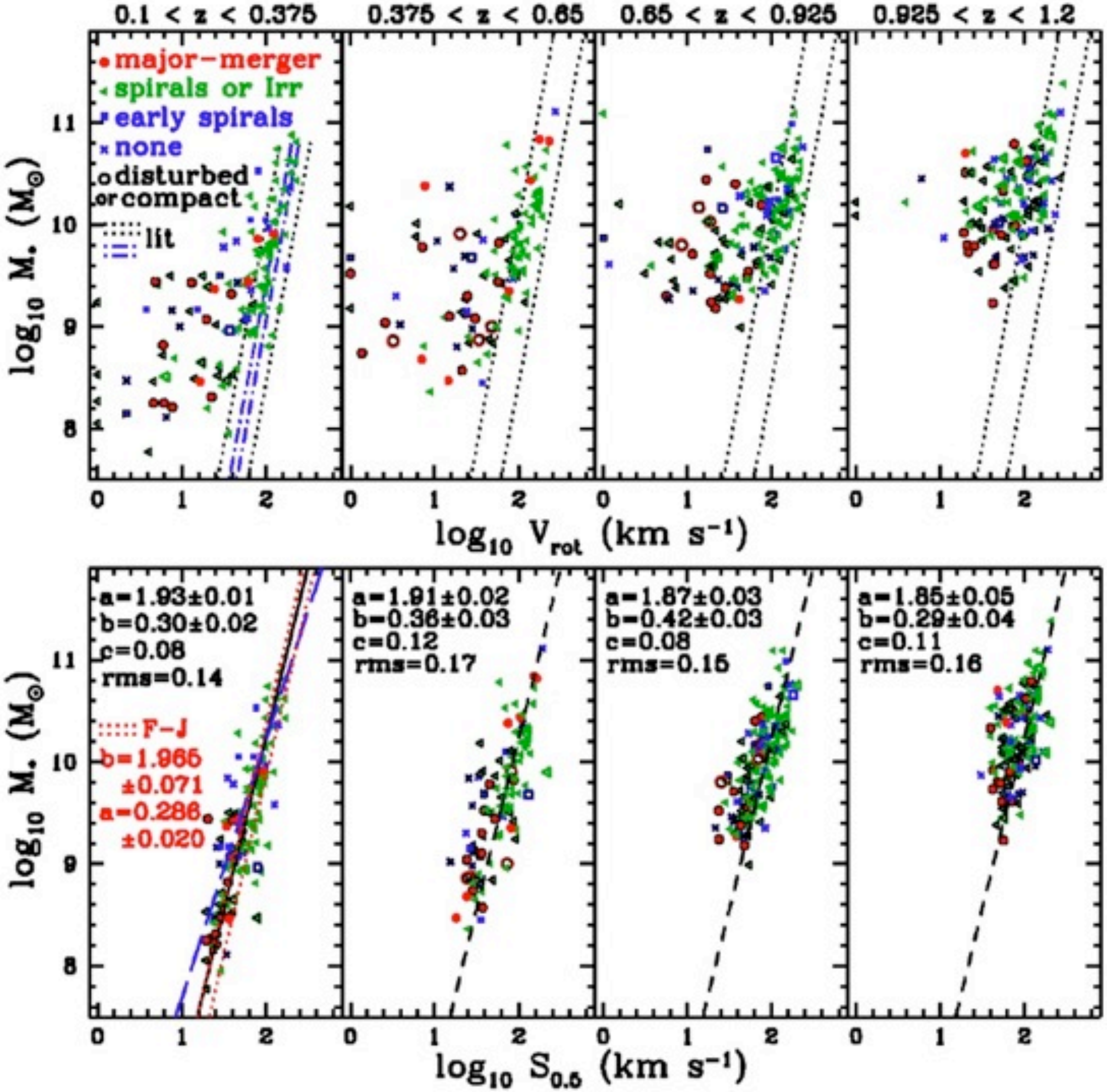
  - Tully-Fisher: M_baryon ~ 10^9.8 (V/100)^{3.5-4.0}
  - if ell M_baryon ~ M_stellar
  - Faber-Jackson: M_baryon ~ 10^{9.6-9.9} (sigma/100)^{3.5-4.0}

  - B-band differences owe to difference in (L_B/M_stellar) in ellipticals and disks

  - appear different in B, m_stellar, etc.

Structure in Elliptical Light Profiles

THEIR SCALING LAWS

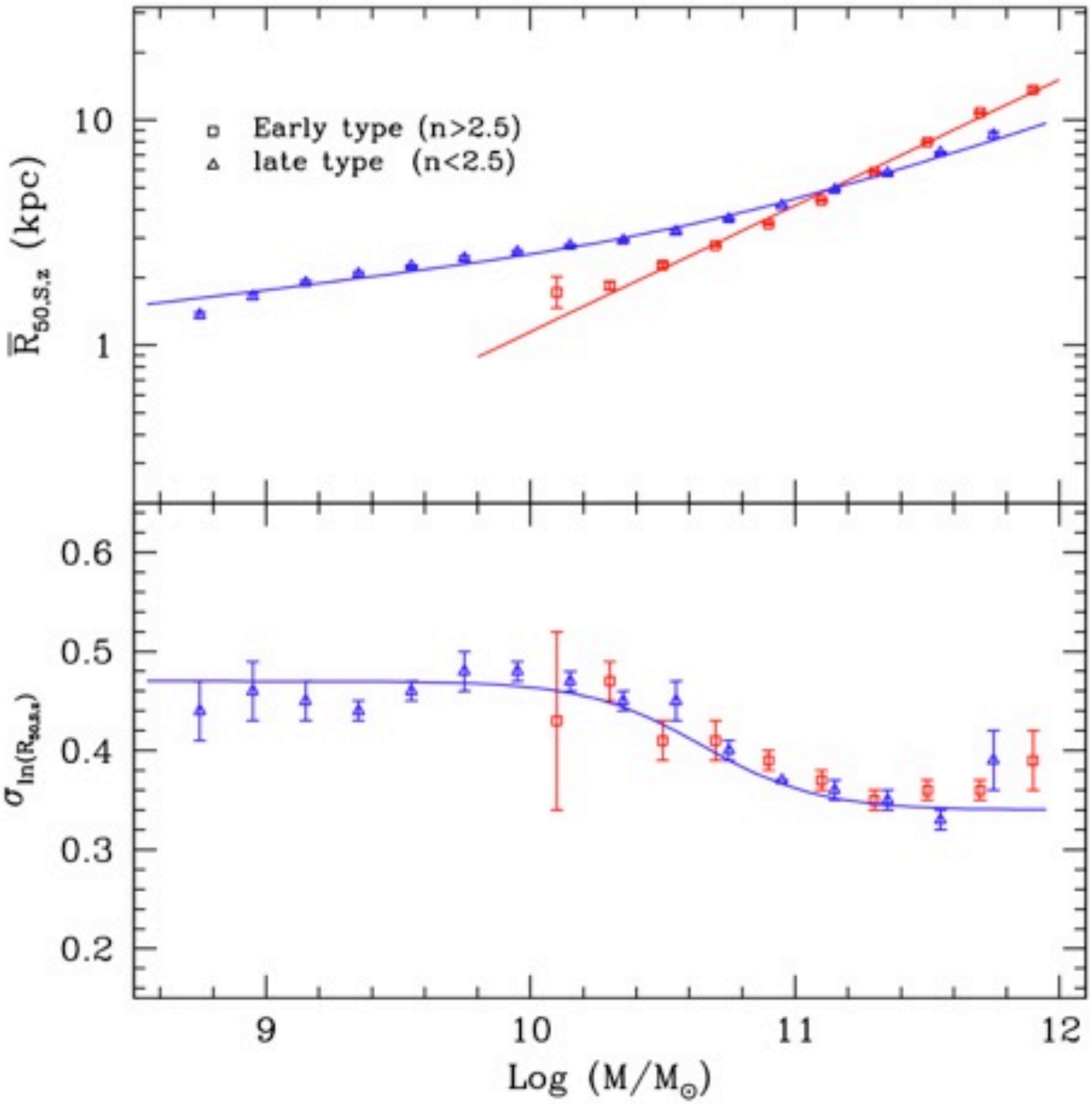


Kassin et al. 2007

Structure in Elliptical Light Profiles

THEIR SCALING LAWS

- Size-Mass Relation: R ~ M^0.56 (Shen et al. 2003)



Structure in Elliptical Light Profiles

THEIR SCALING LAWS

- Size-Mass Relation:
  R ~ M^1/2

- if:
  M ~ sigma^4 (Faber-Jackson)
  and virial theorem:
  R ~ M / sigma^2

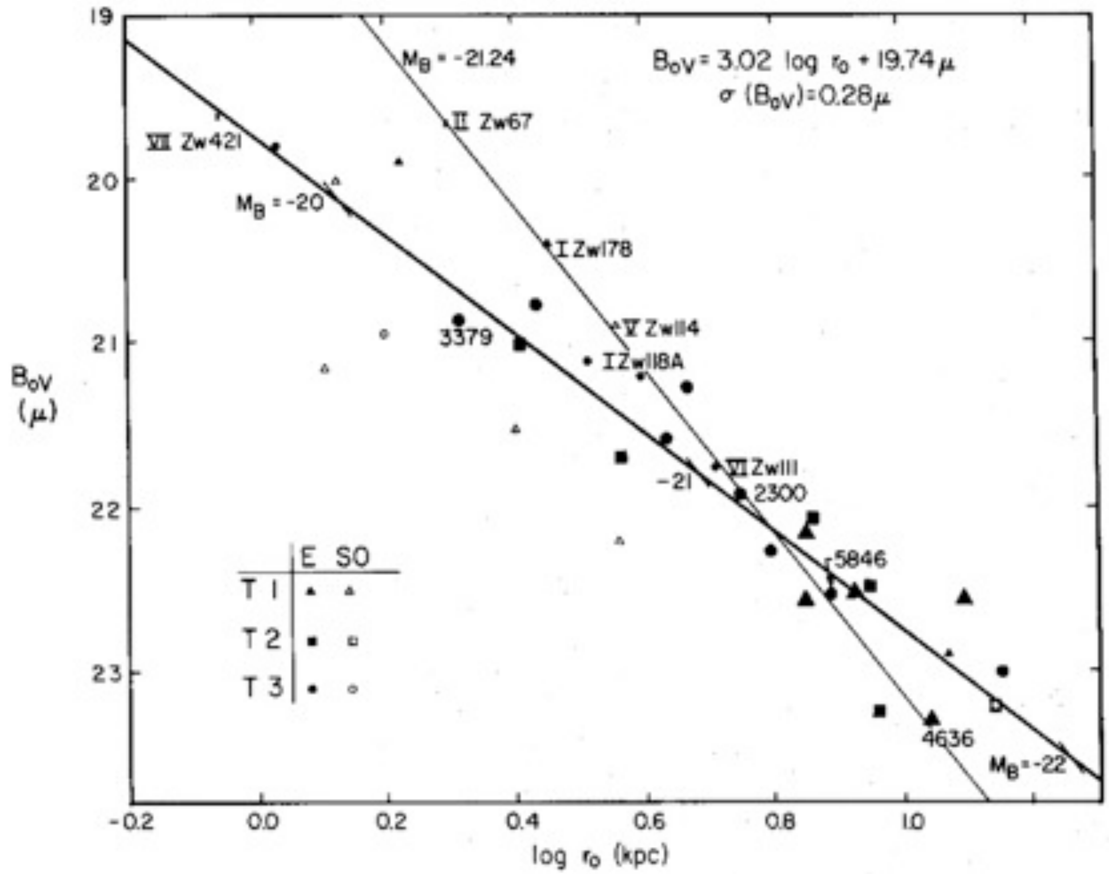
  then get R ~ M^1/2

- Both Faber-Jackson or Size-Mass relation have sufficient scatter that its unclear if anything “more accurate” for a mean relation is appropriate

Structure in Elliptical Light Profiles

THEIR SCALING LAWS

- Kormendy:
  - mu - R relation
  - Just a re-statement of the size-mass relation



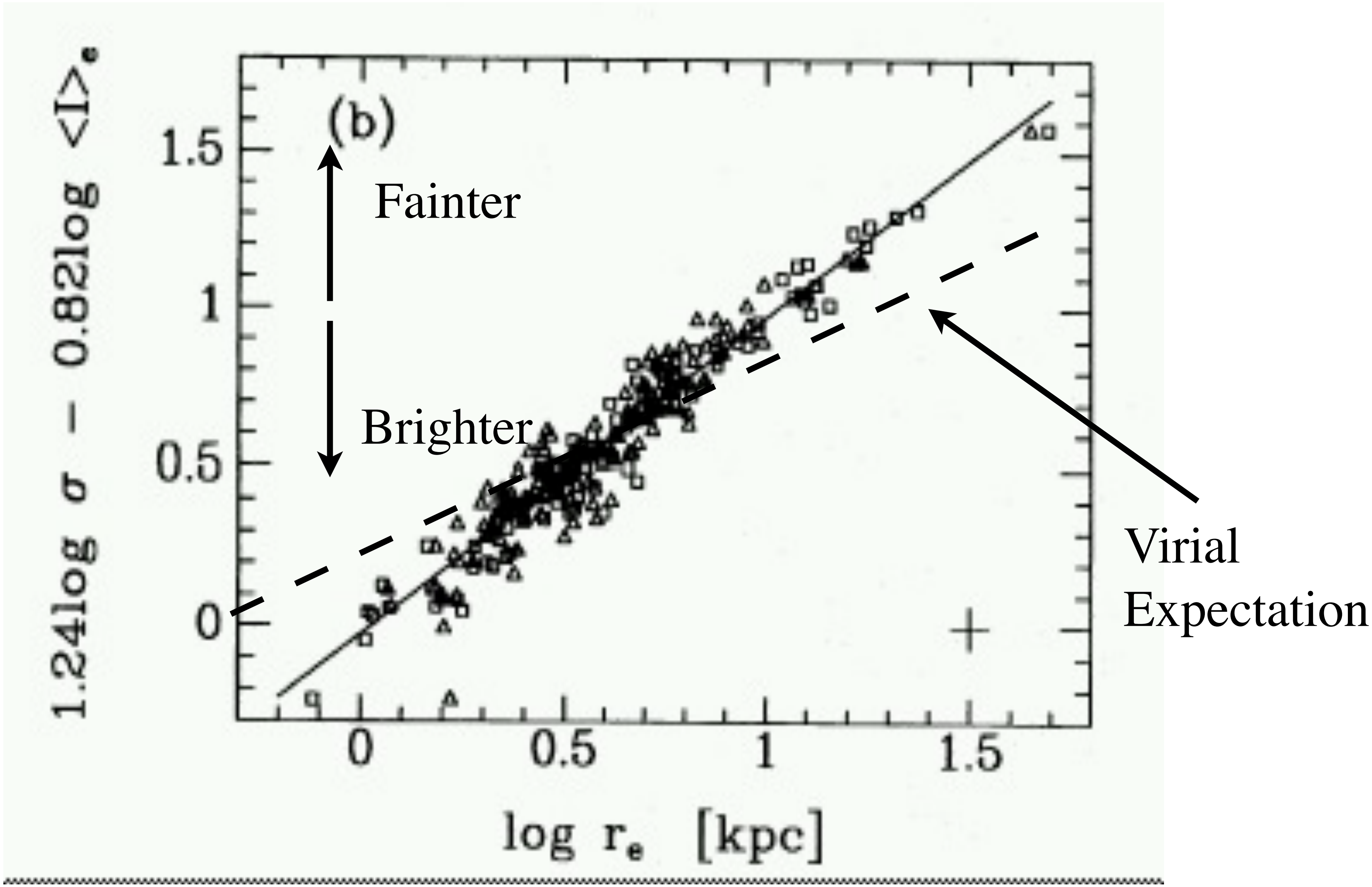
Structure of Spheroids

UNDERSTANDING THE FUNDAMENTAL PLANE

- If ellipticals were all homologous (self-similar), and L traced M reliably, then they would obey the virial relation:
  - sigma^2 = k G M / R_e ~ L / R_e,
    or
    M_dyn == sigma^2 R_e / G ~ L
  - k depends on the shape of the mass profile and the velocity structure (e.g. orbital anisotropy)

Fundamental Plane Tilt

STELLAR POPULATION VARIATION



- (L/M) decreases with mass: older, more metal rich?

Structure of Spheroids

UNDERSTANDING THE FUNDAMENTAL PLANE

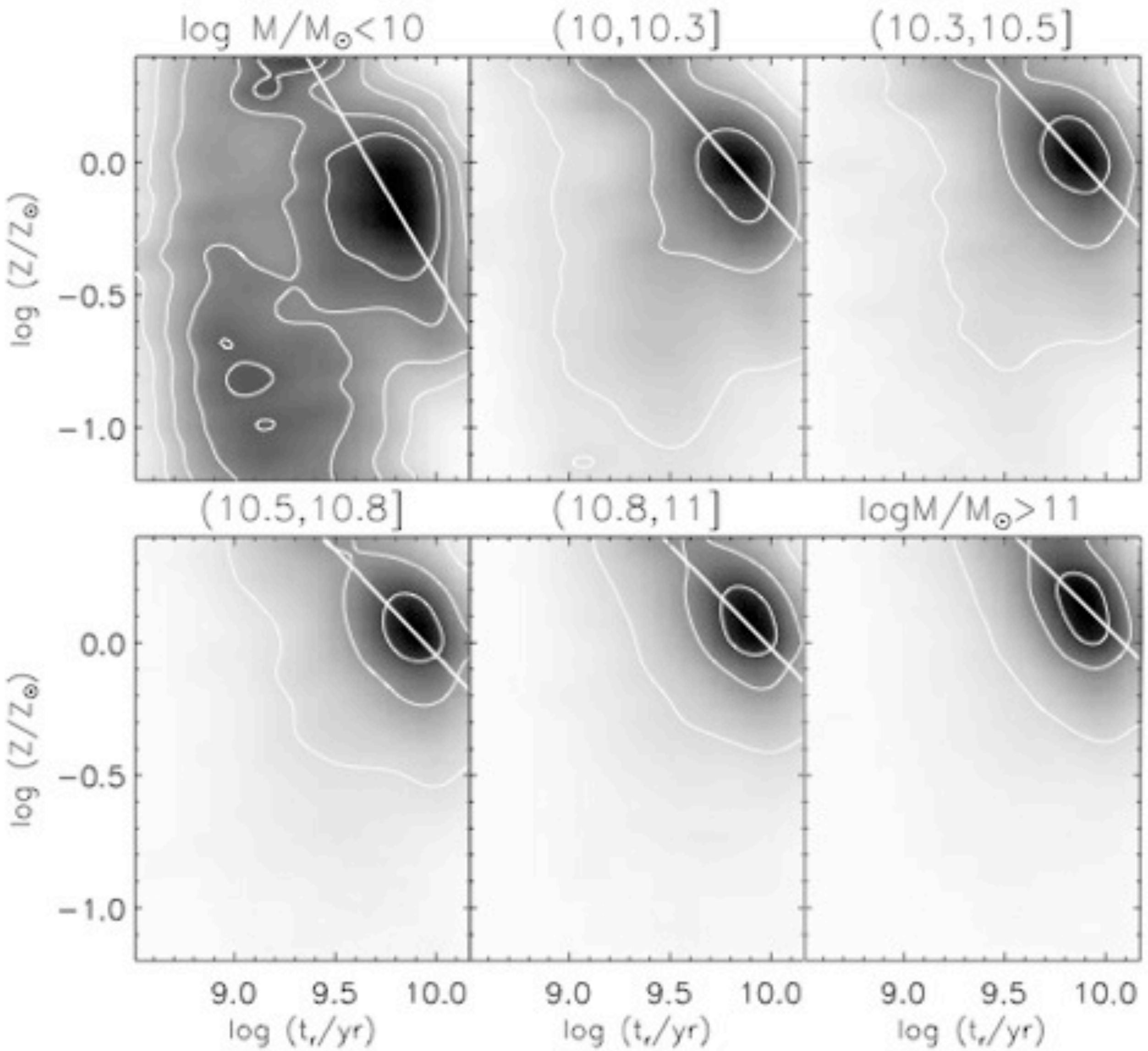
- Instead, the FP is "tilted":
  - (L / M_dyn) ~ M^{0.1-0.3, depending on the band}
  - three possible explanations:
  - stellar population variation:

    M_dyn ~ M_stellar holds, but (L/M_stellar) varies with L
  - kinematic non-homology:
    - velocity fields change
  - structural non-homology:
    - profile shape changes with mass
    - stellar-to-dark-matter mass ratio changes (can be the same as the above, or different)

Fundamental Plane Tilt

STELLAR POPULATION VARIATION

- Indeed, there are very significant stellar population trends as a function of elliptical mass:

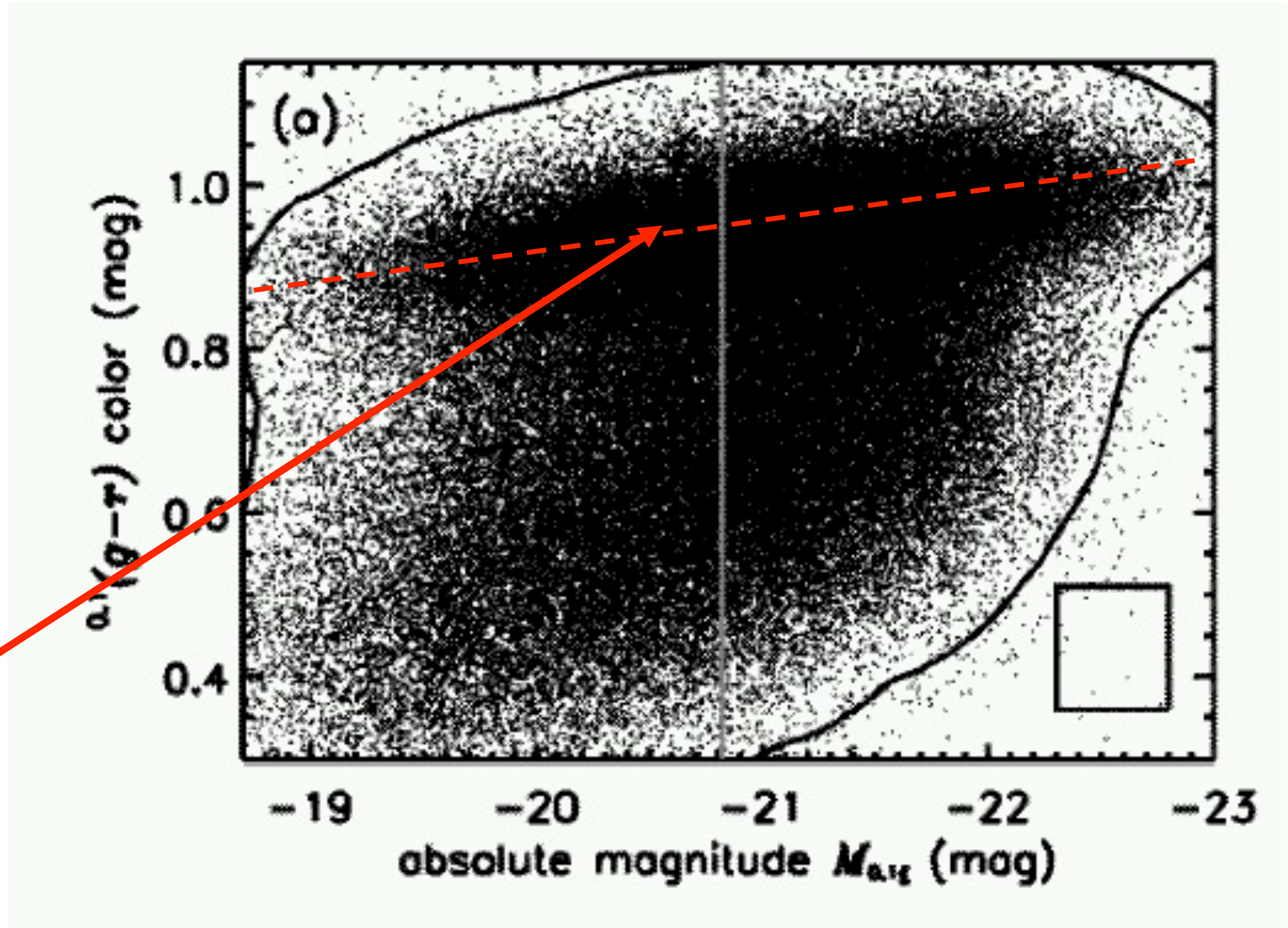


Fundamental Plane Tilt

STELLAR POPULATION VARIATION

The color-magnitude diagram from SDSS

The color-magnitude sequence of early-type galaxies.

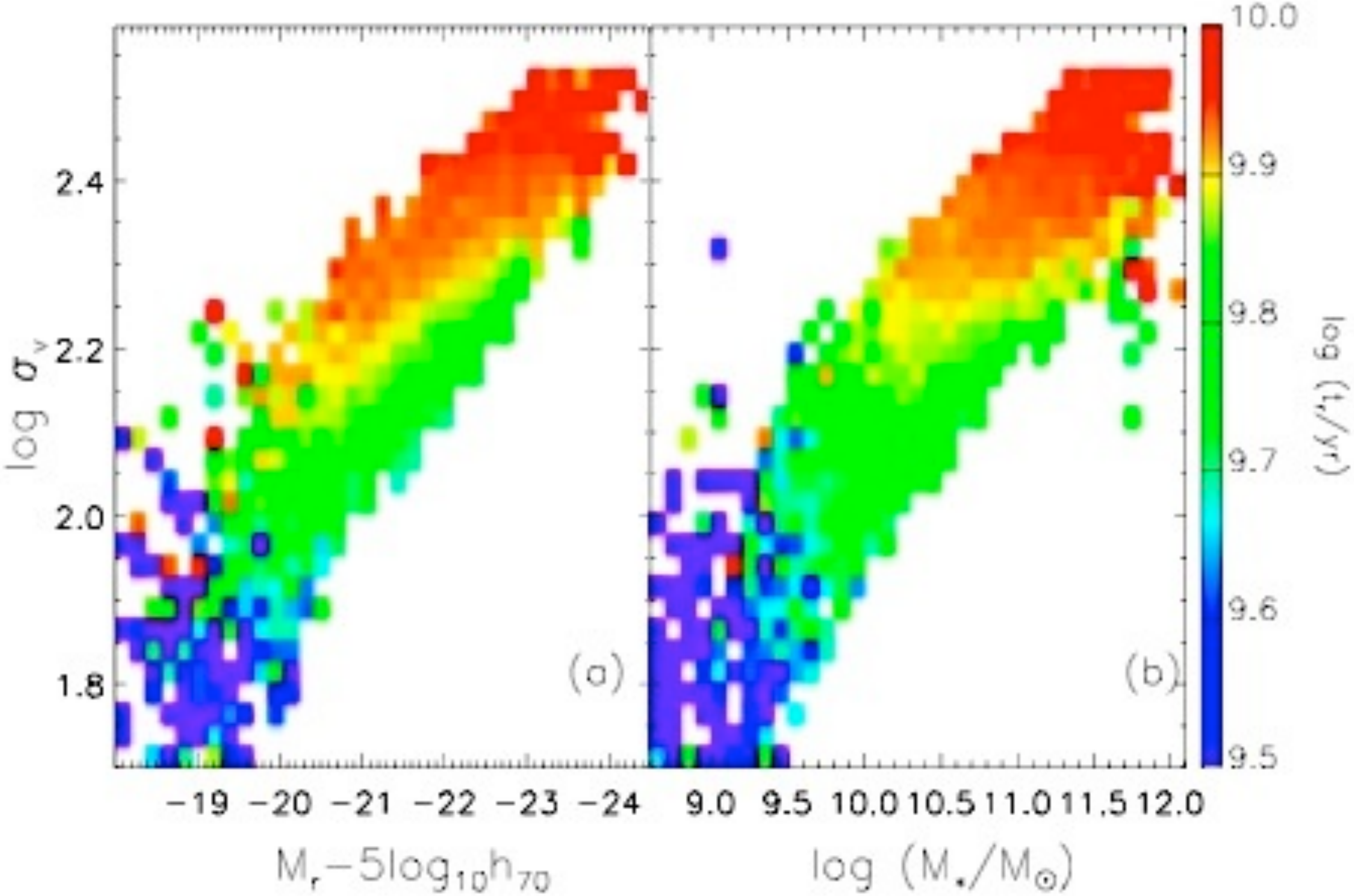


Hogg et al.,

Fundamental Plane Tilt

STELLAR POPULATION VARIATION

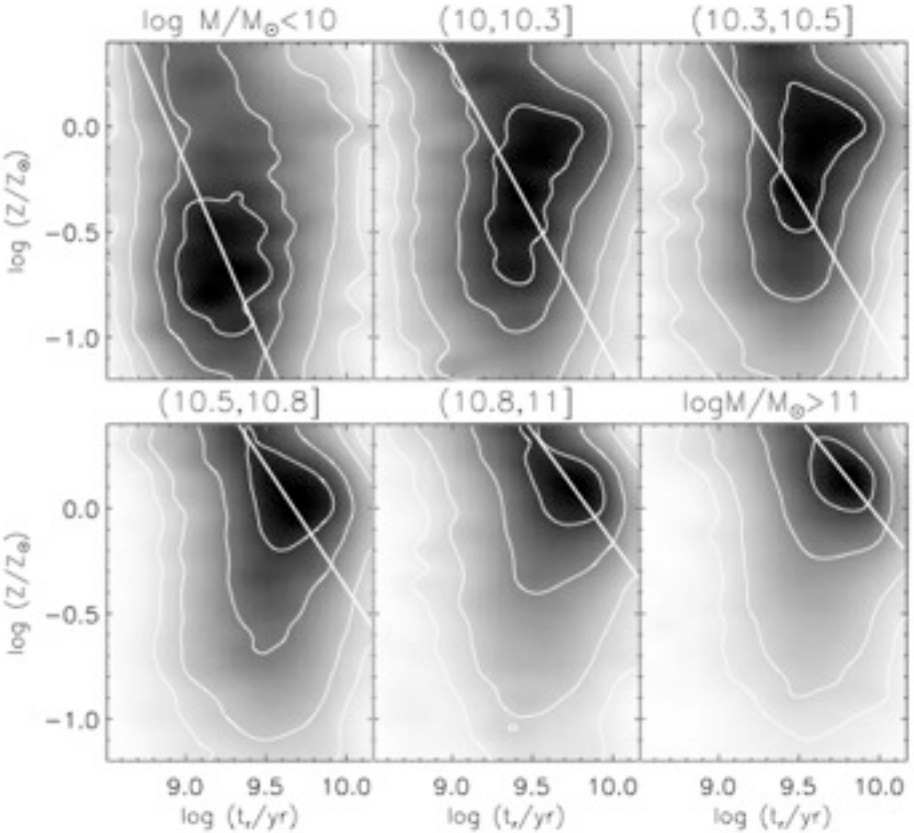
- Indeed, there are very significant stellar population trends as a function of elliptical mass:

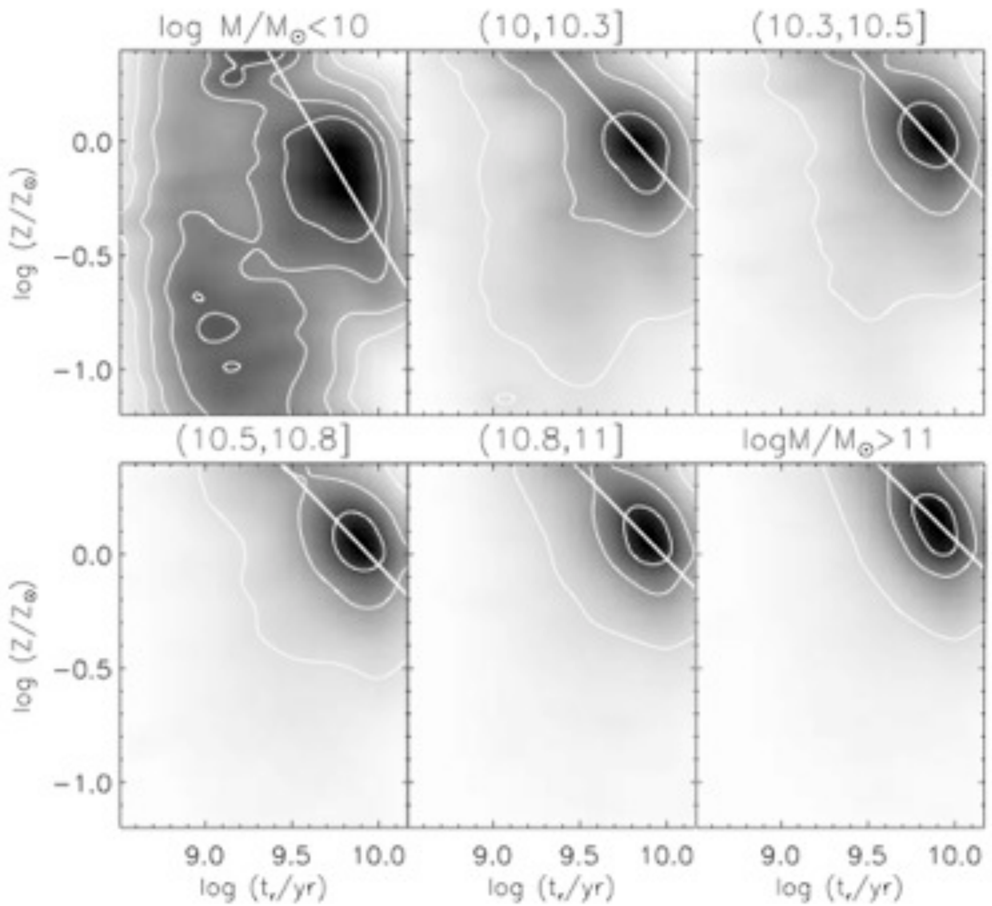


Fundamental Plane Tilt

STELLAR POPULATION VARIATION

- Where do these come from?





Fundamental Plane Tilt

STELLAR POPULATION VARIATION

- These *do* explain much of the optical fundamental plane tilt:

  but do they explain it all?

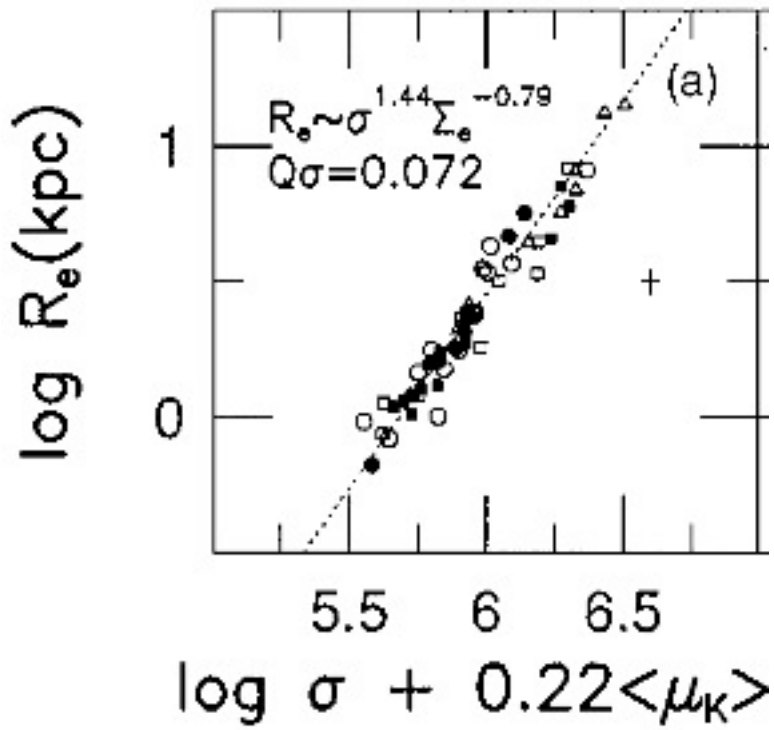
short answer: No

Fundamental Plane Tilt

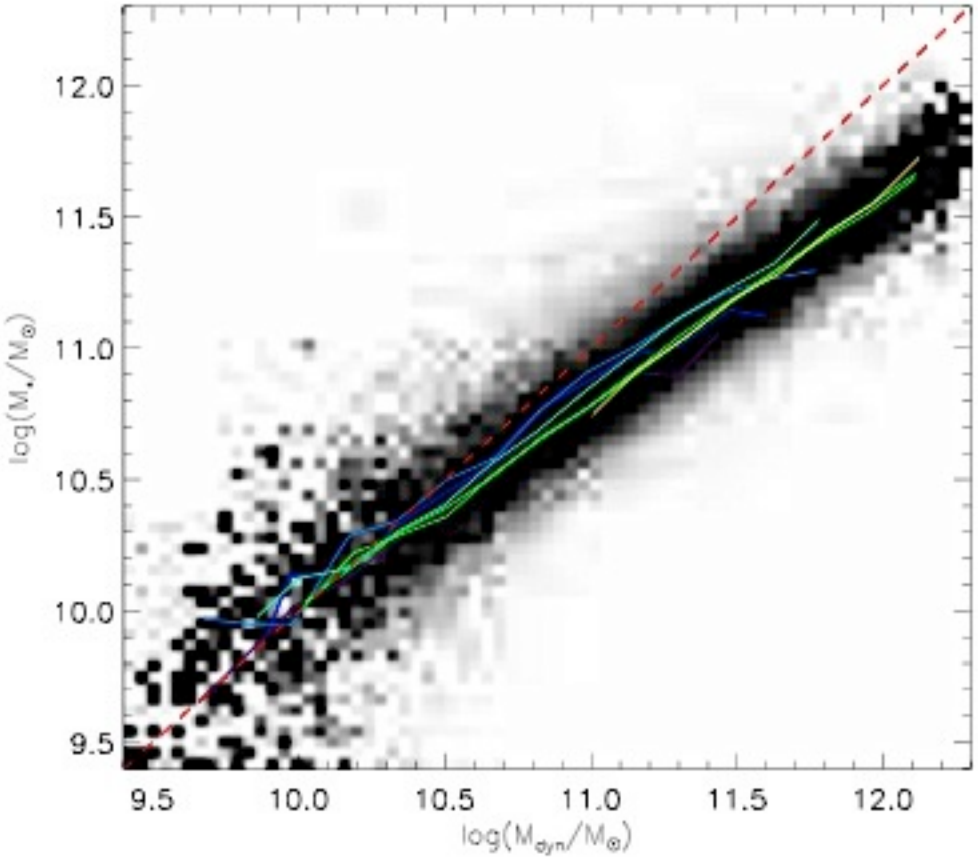
STELLAR POPULATION VARIATION

- These *do* explain much of the optical fundamental plane tilt:

  but do they explain it all?



Pahre et al. 1998

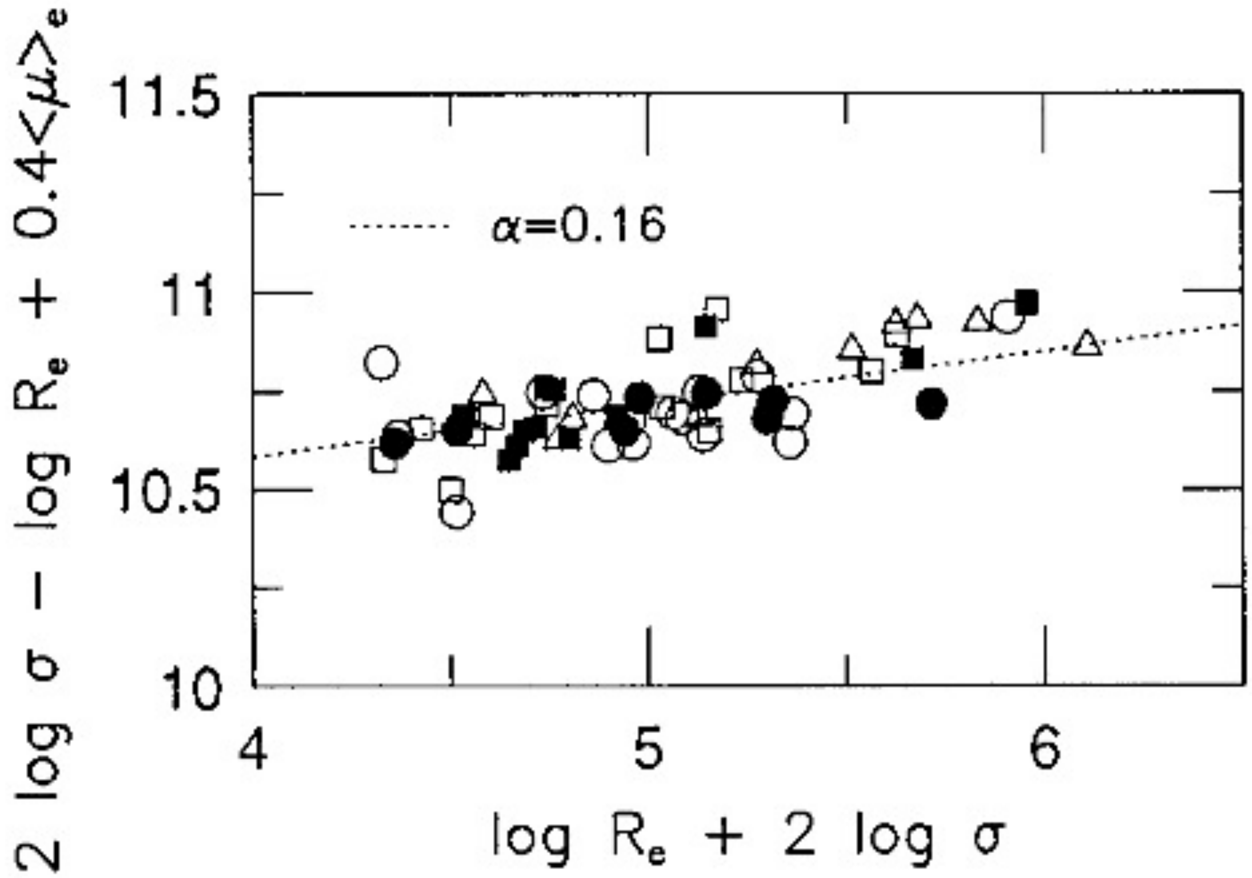


Gallazzi et al. 2007

Fundamental Plane Tilt

NON-HOMOLOGY

- M_dyn / M_stellar is an increasing function of either M



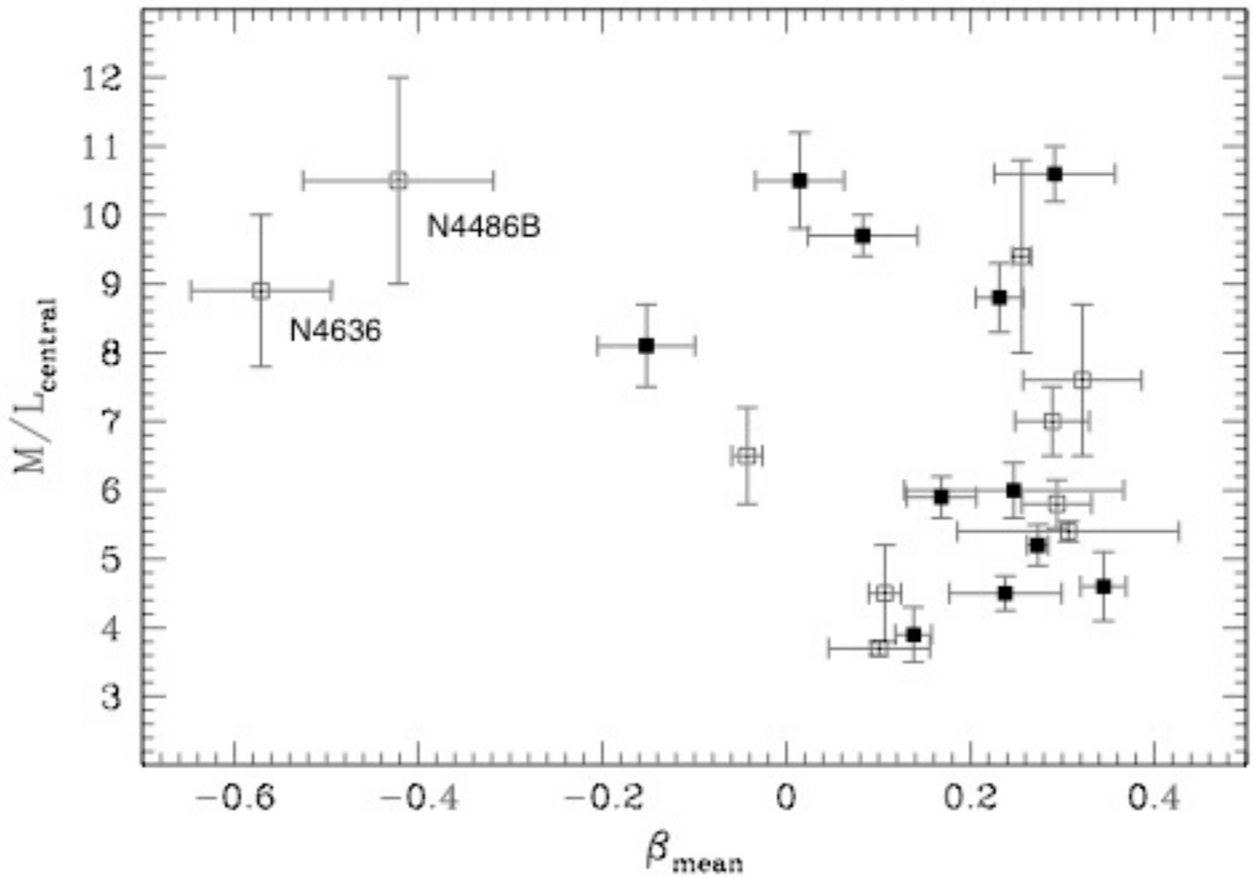
- SOME non-homology in ellipticals

Pahre et al. 1998

Fundamental Plane Tilt

KINEMATIC NON-HOMOLOGY

- Is sigma_obs systematically higher than it “should” be in high-mass systems?



- Inclusion of circular velocity in low-mass ellipticals should actually bias you the *opposite* way

Fundamental Plane Tilt

STRUCTURAL NON-HOMOLOGY

- How do you get more baryons inside R_e?
- R_e is R_e of the stellar mass -- so this is equivalent to the question: how do you shrink R_e relative to the dark matter?

- Problem: dissipationless systems cannot increase their phase space density f

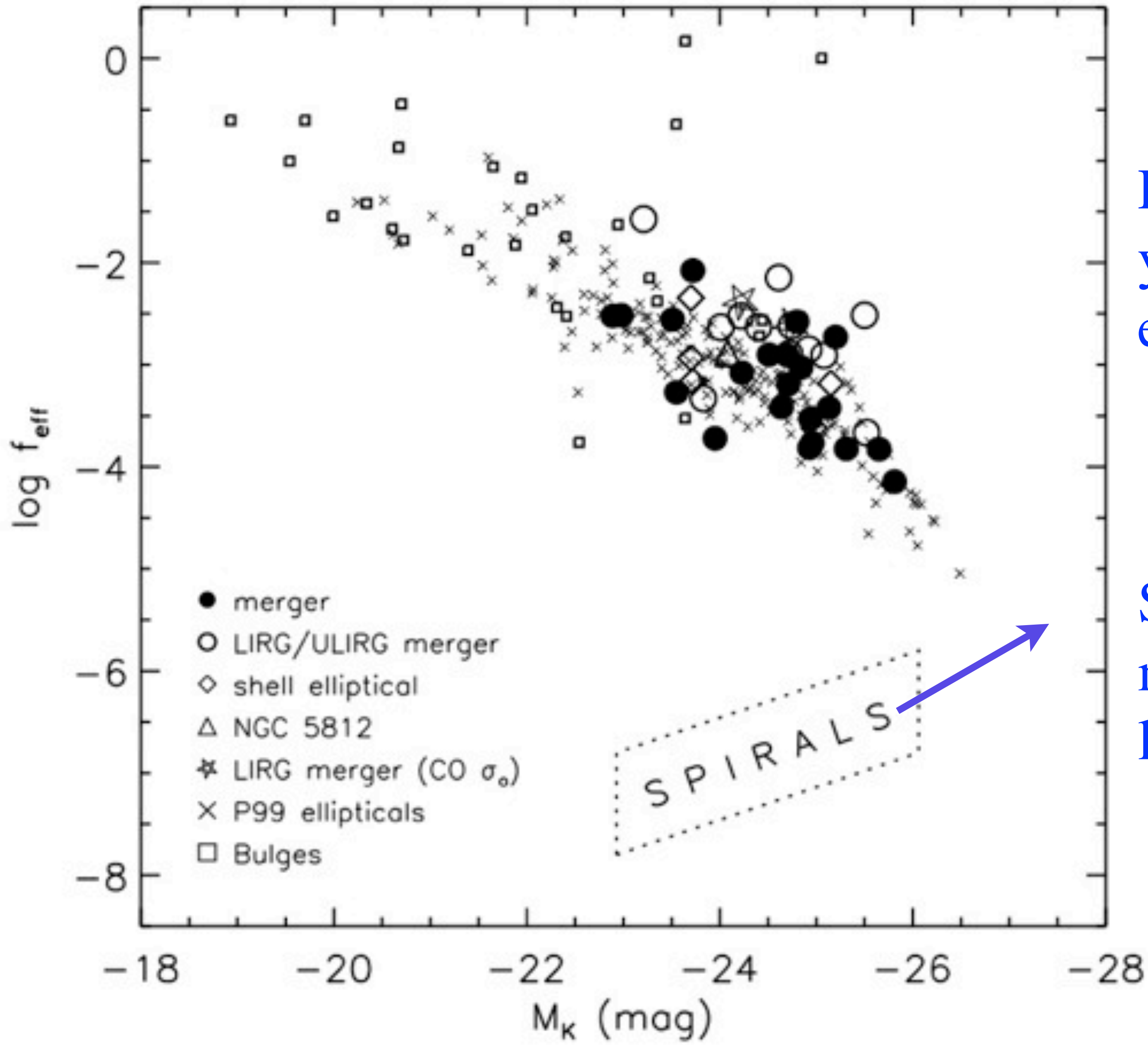
$$d M = f * dx\ dy\ dz\ dvx\ dvy\ dvz$$

- f ~ M / (r^3 * v^3) ~ 1 / (v * r^2)

Fundamental Plane Tilt

STRUCTURAL NON-HOMOLOGY

- f ~ M / (r^3 * v^3) ~ 1 / (v * r^2)



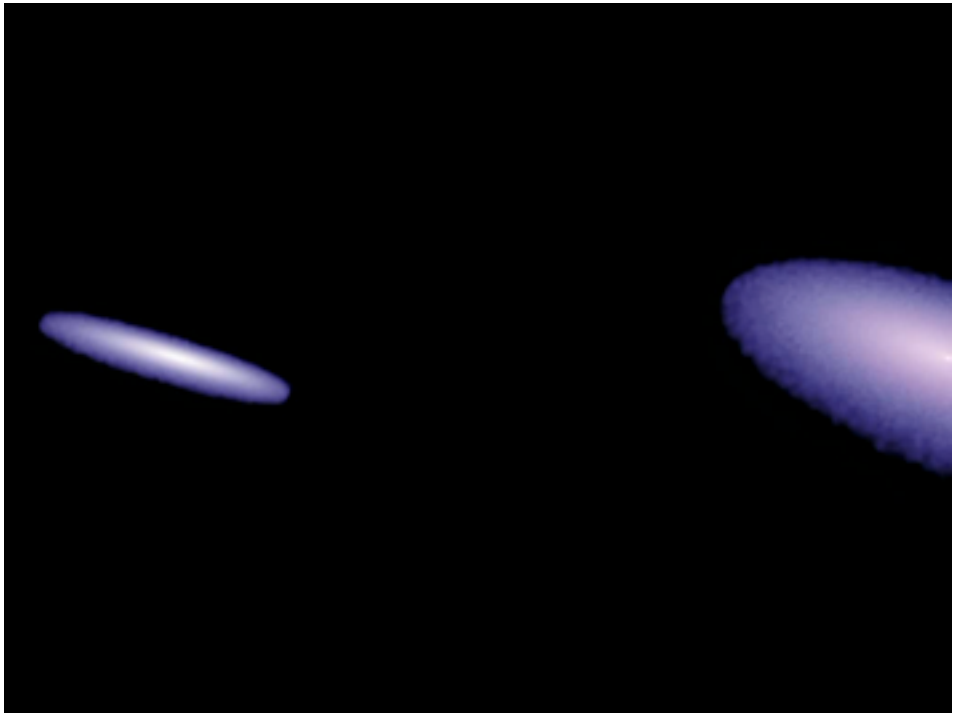
Direct merging can get you to the most massive ellipticals
(recall, where
Mdyn/M_stellar is large)

Stellar light needs to be made more dense in the low mass systems

Fundamental Plane Tilt

STRUCTURAL NON-HOMOLOGY

Solution: Gas dissipation



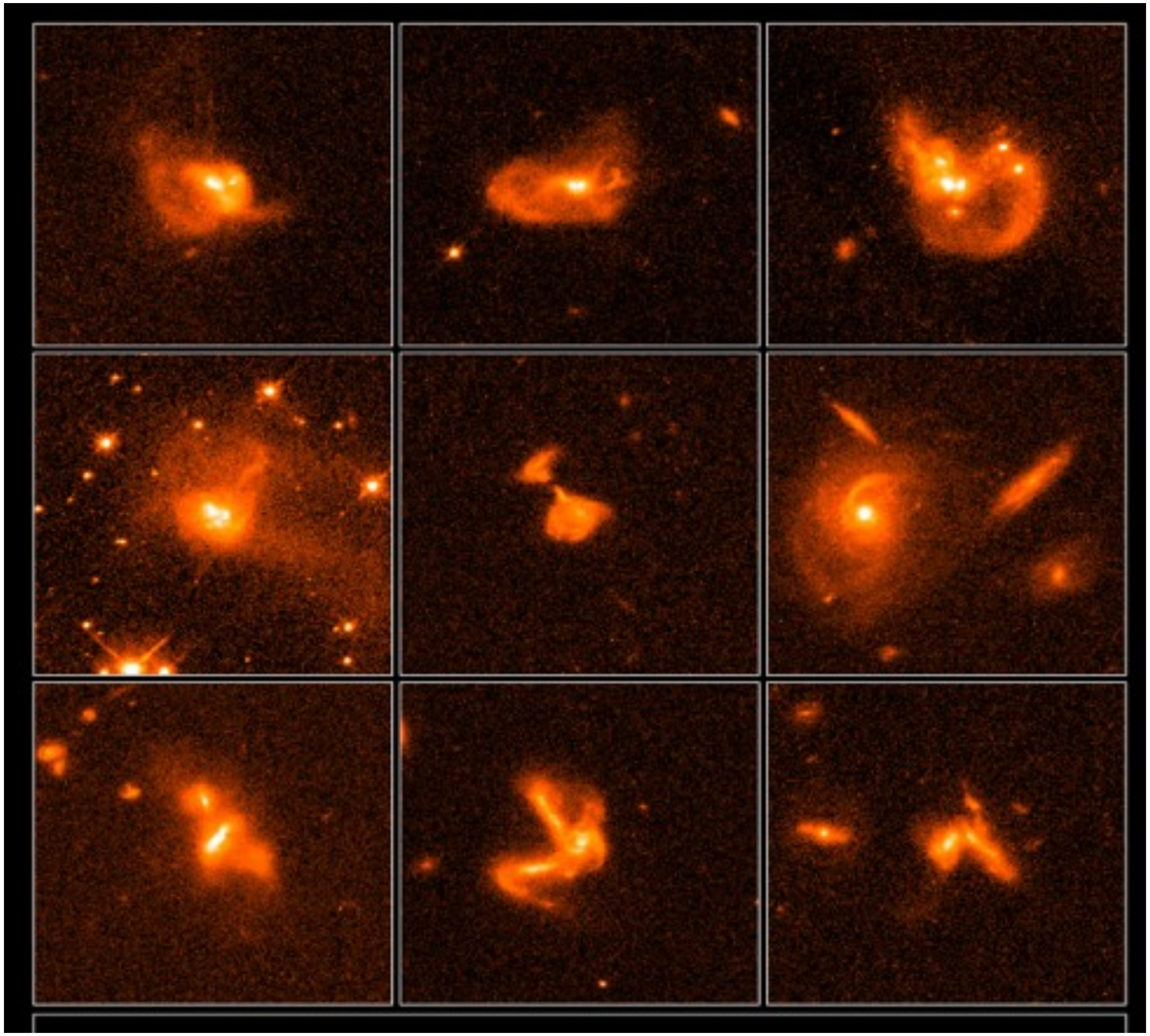
Fundamental Plane Tilt

STRUCTURAL NON-HOMOLOGY

Look at late-stage merger remnants

Bright ULIRGs make stars at a rate of >100 $M_\odot$/yr.

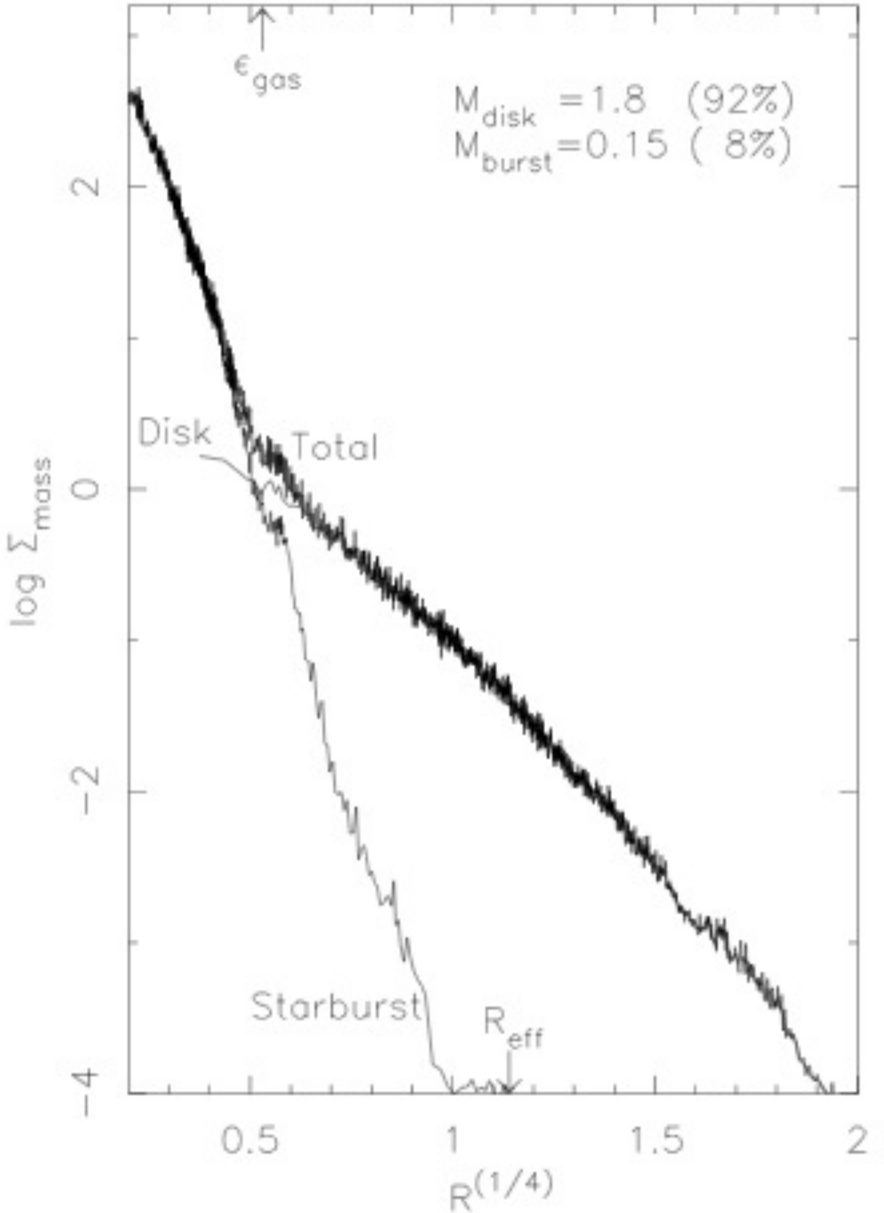
Extremely compact (<kpc scales)

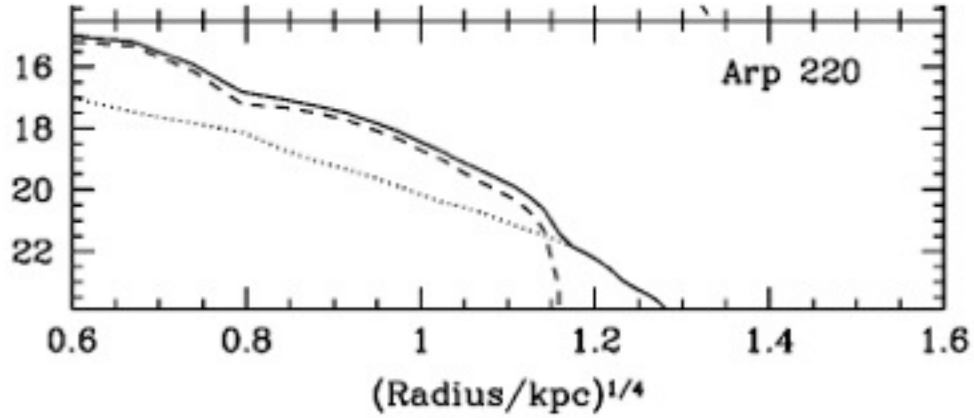


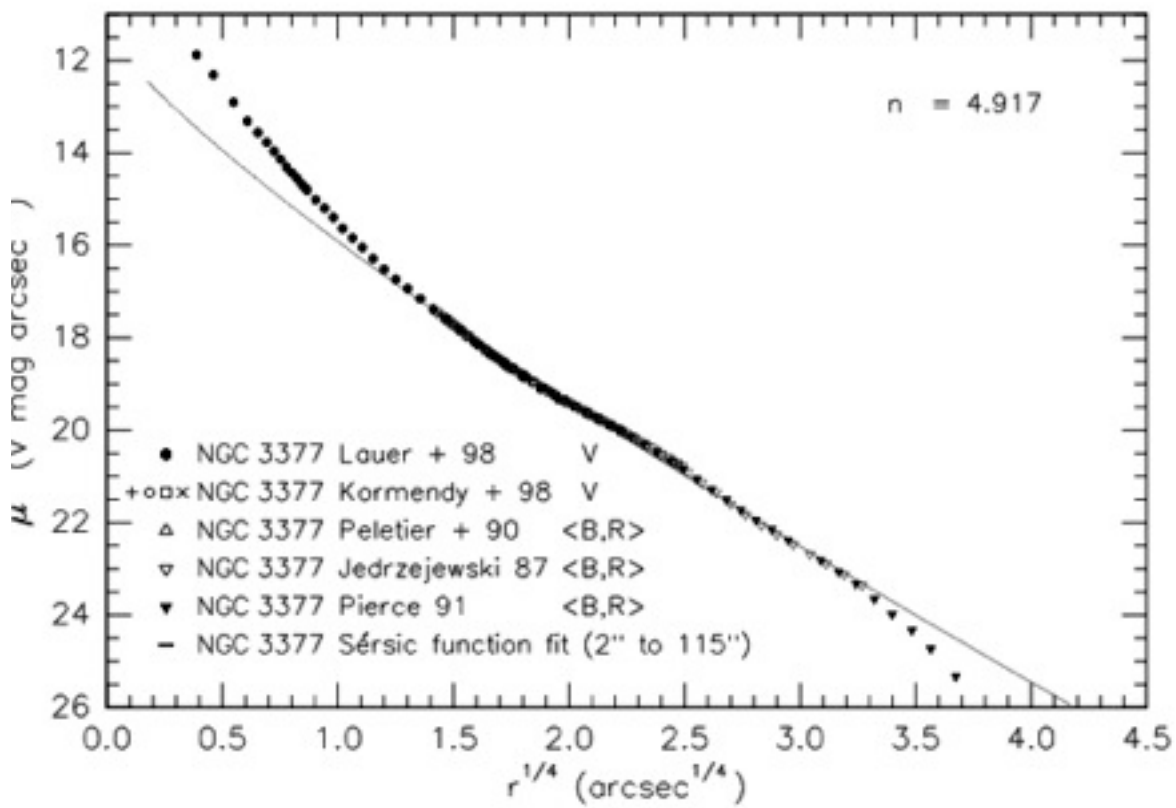
Borne et al., 2000

Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS



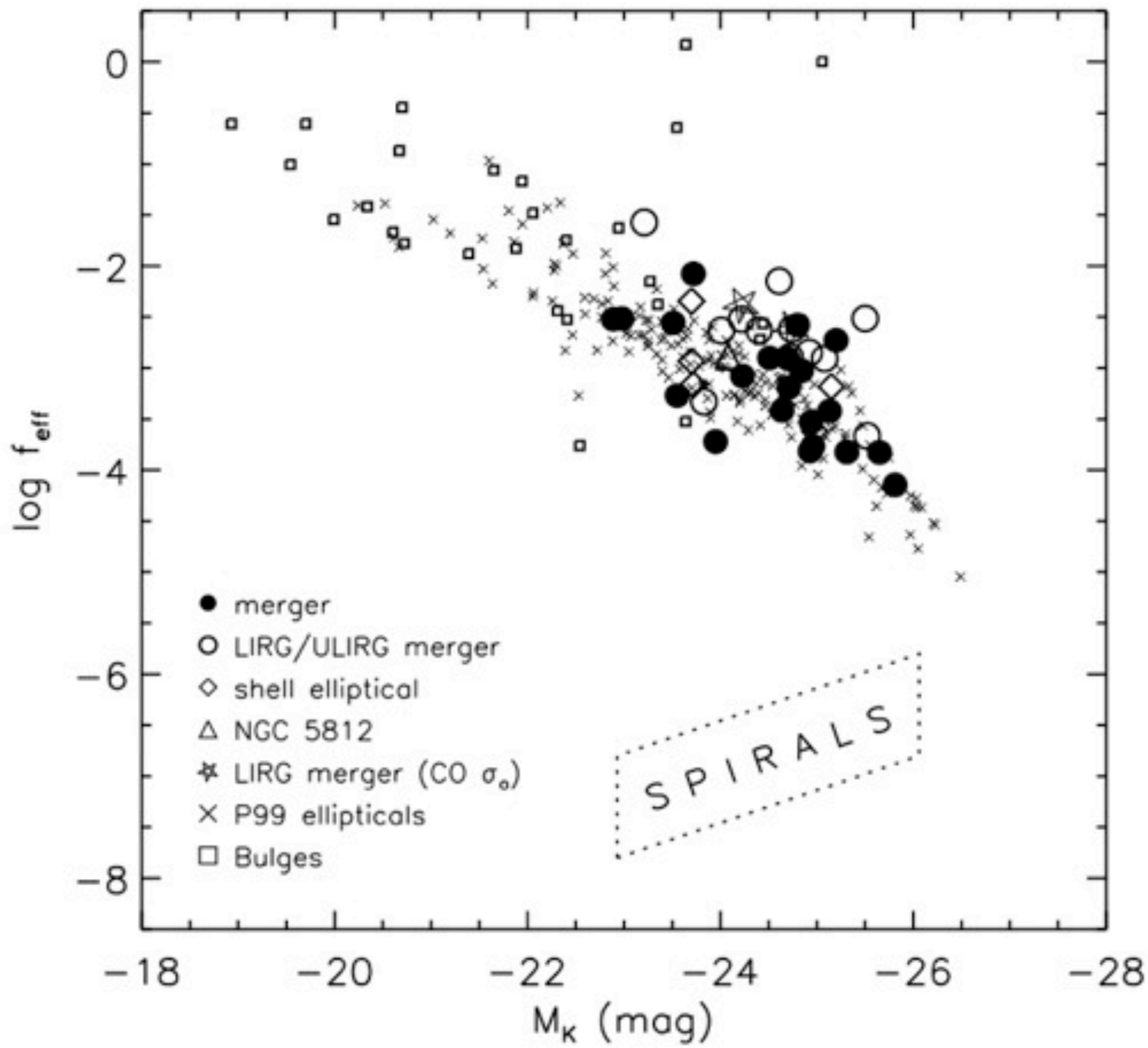




Structure in Elliptical Light Profiles

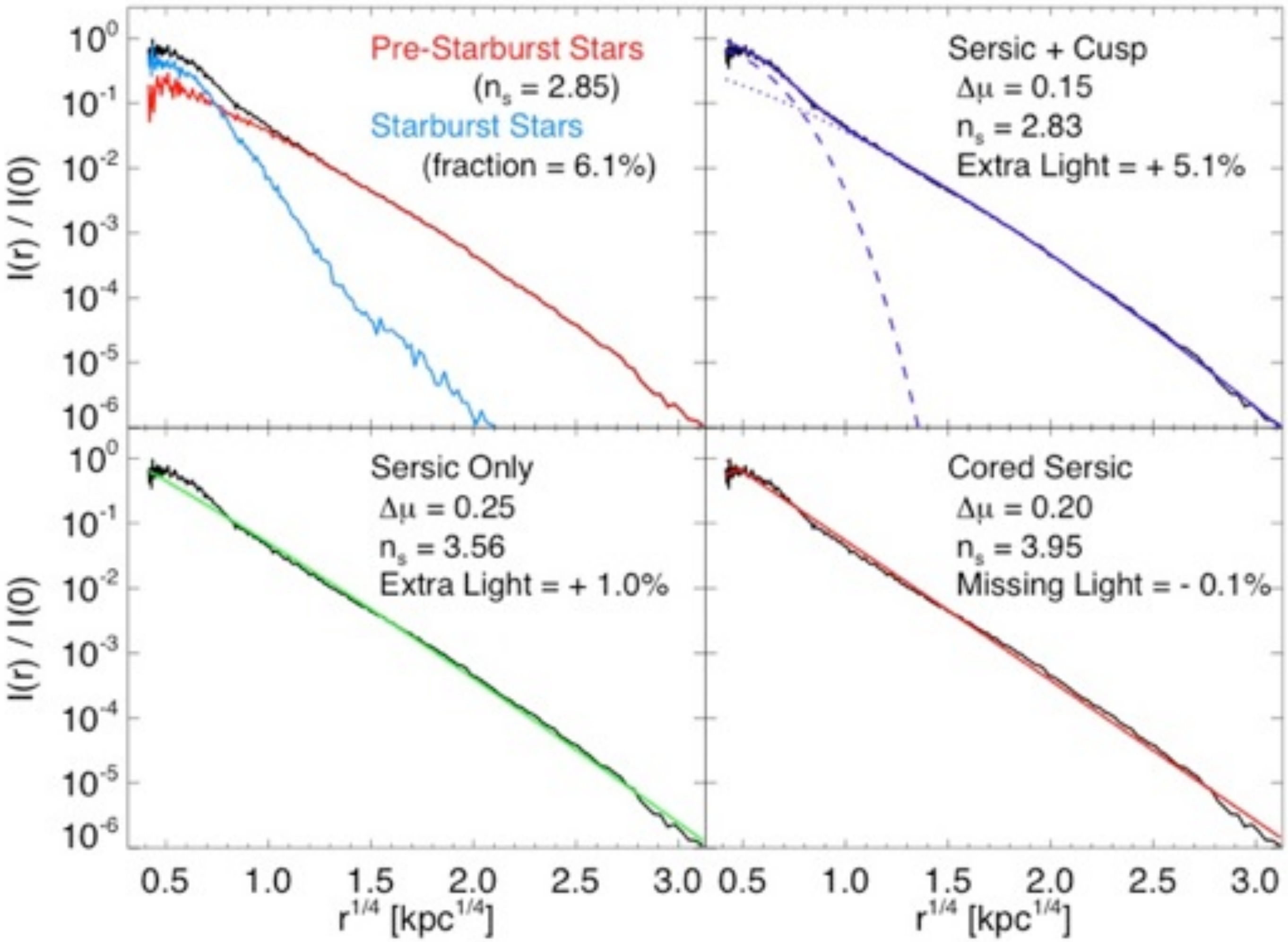
RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

- Mergers *have* solved this problem: we just need to understand it



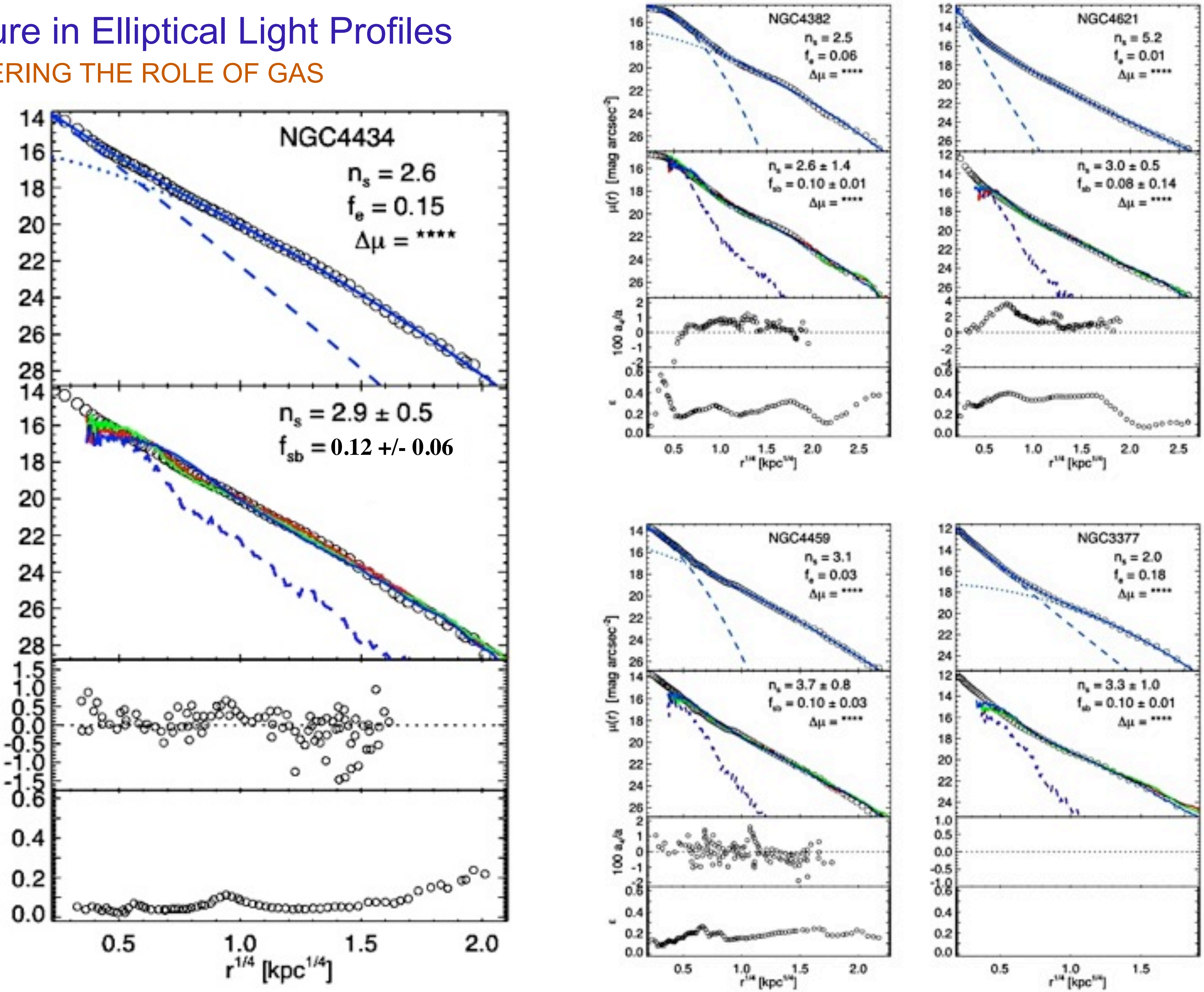
Structure in Elliptical Light Profiles

RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS



Structure in Elliptical Light Profiles

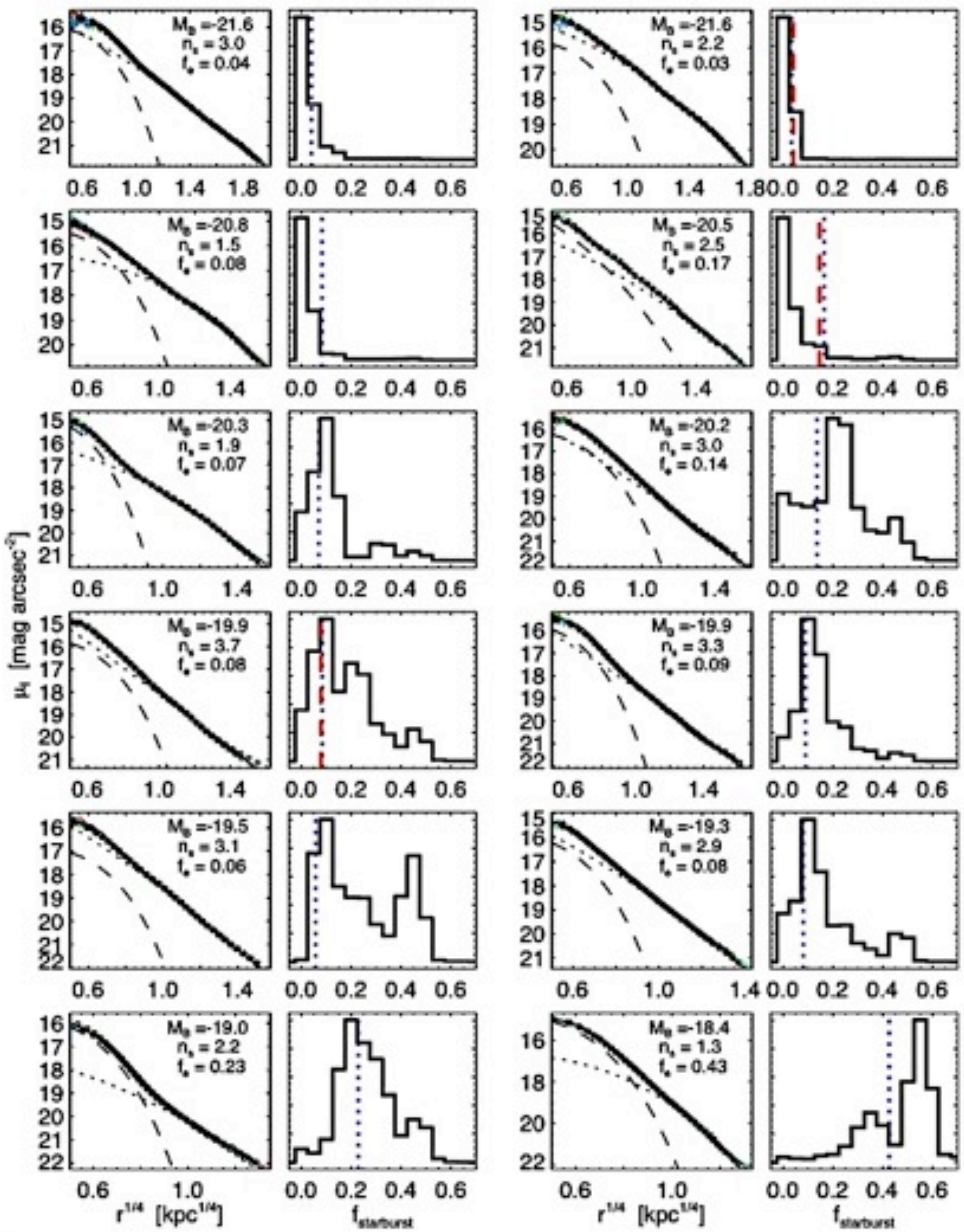
RECOVERING THE ROLE OF GAS

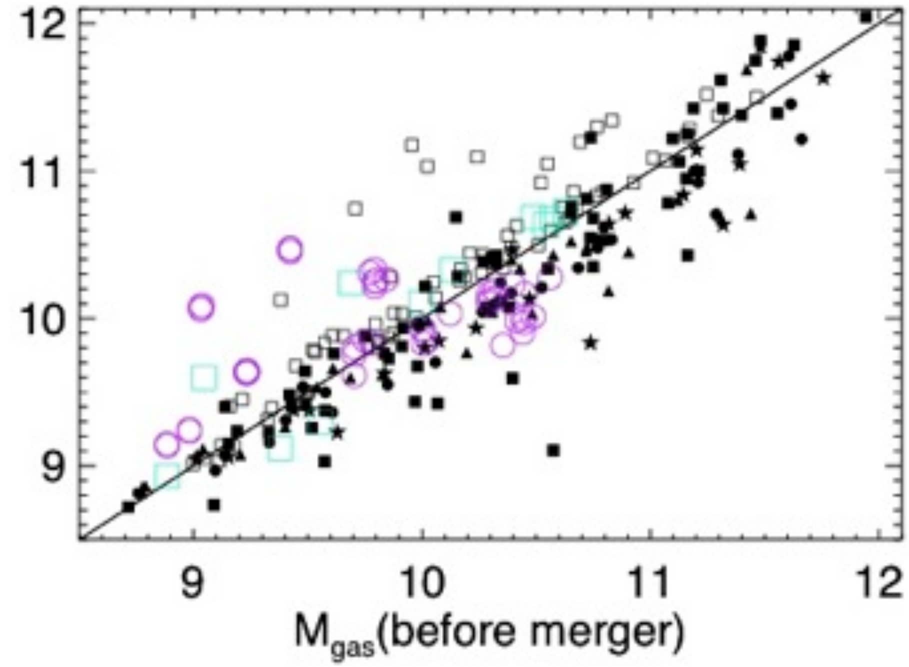


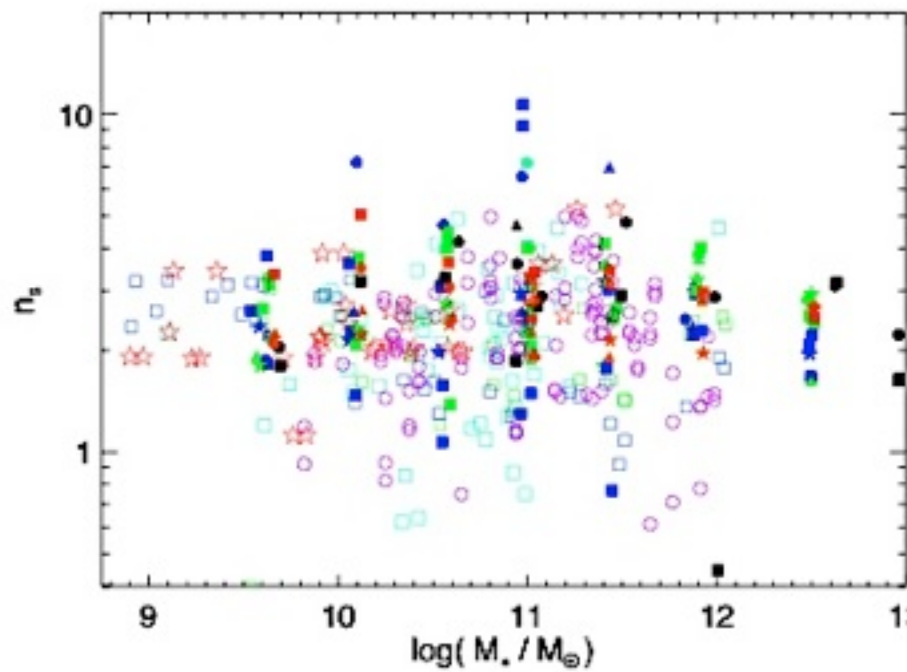
Tuesday, December 25, 12

Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS



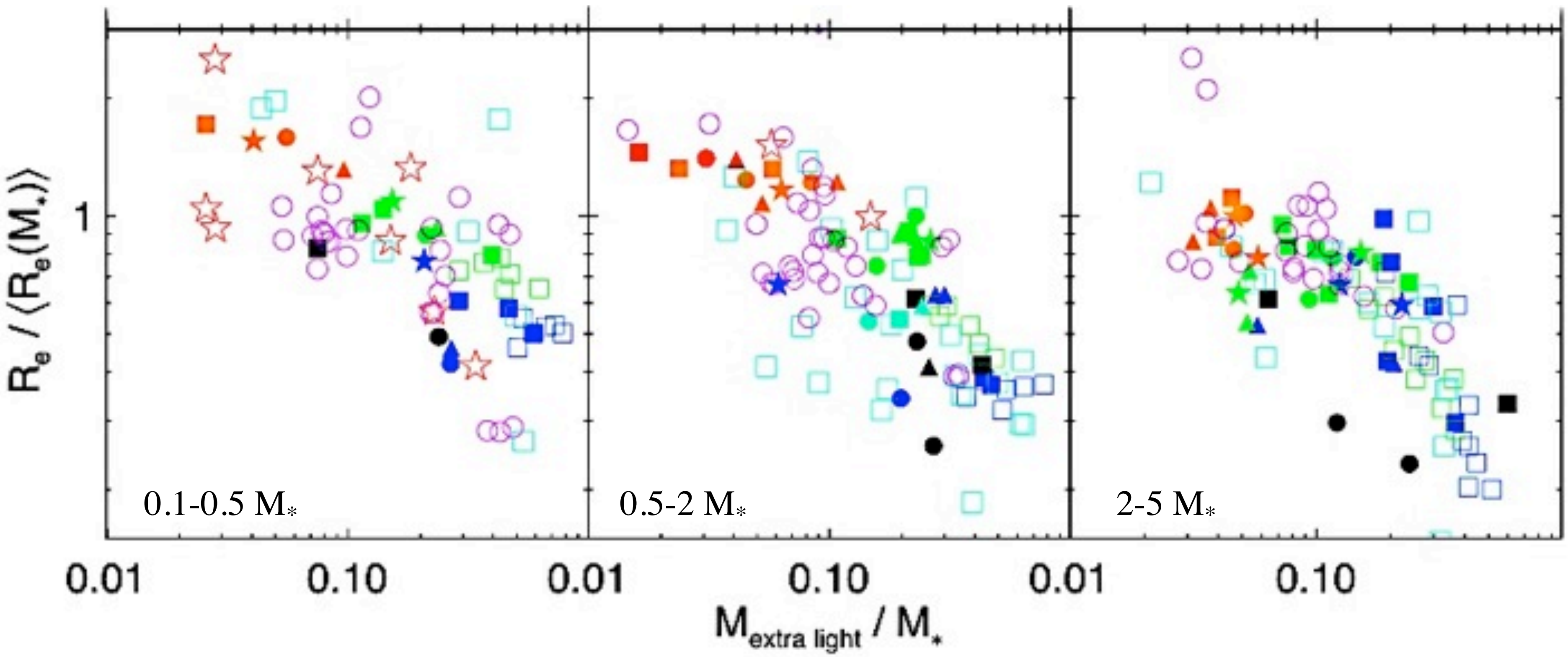




Structure in Elliptical Light Profiles

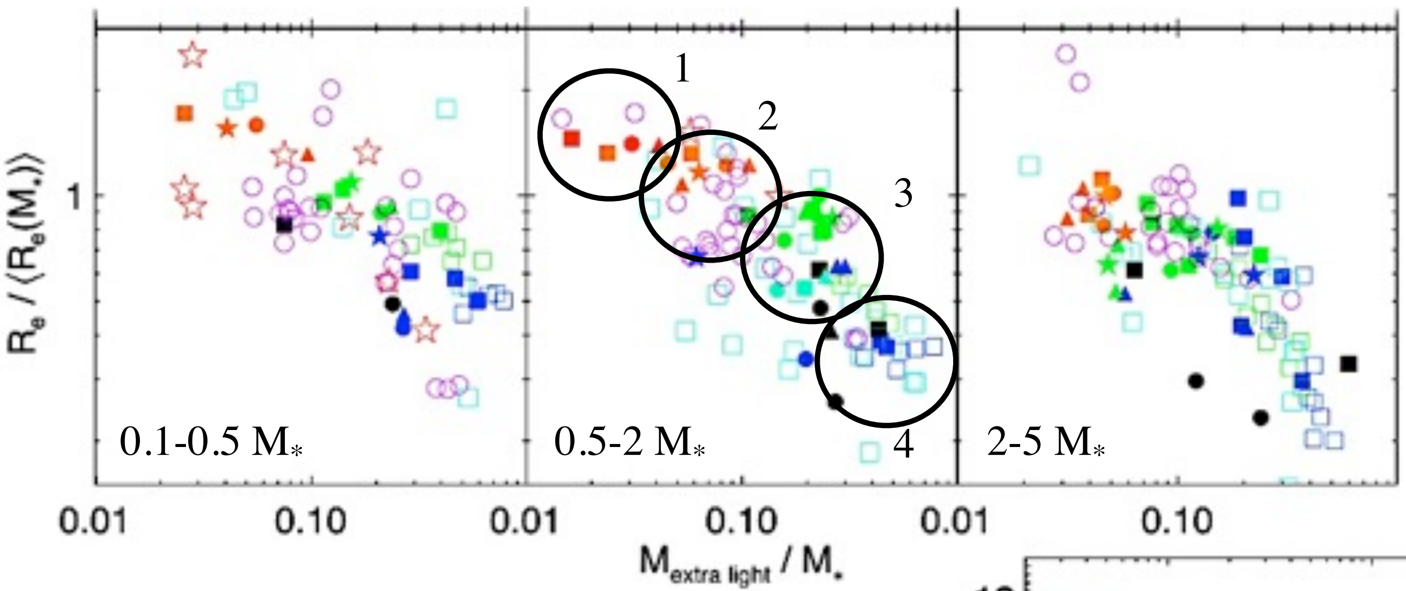
RECOVERING THE ROLE OF GAS

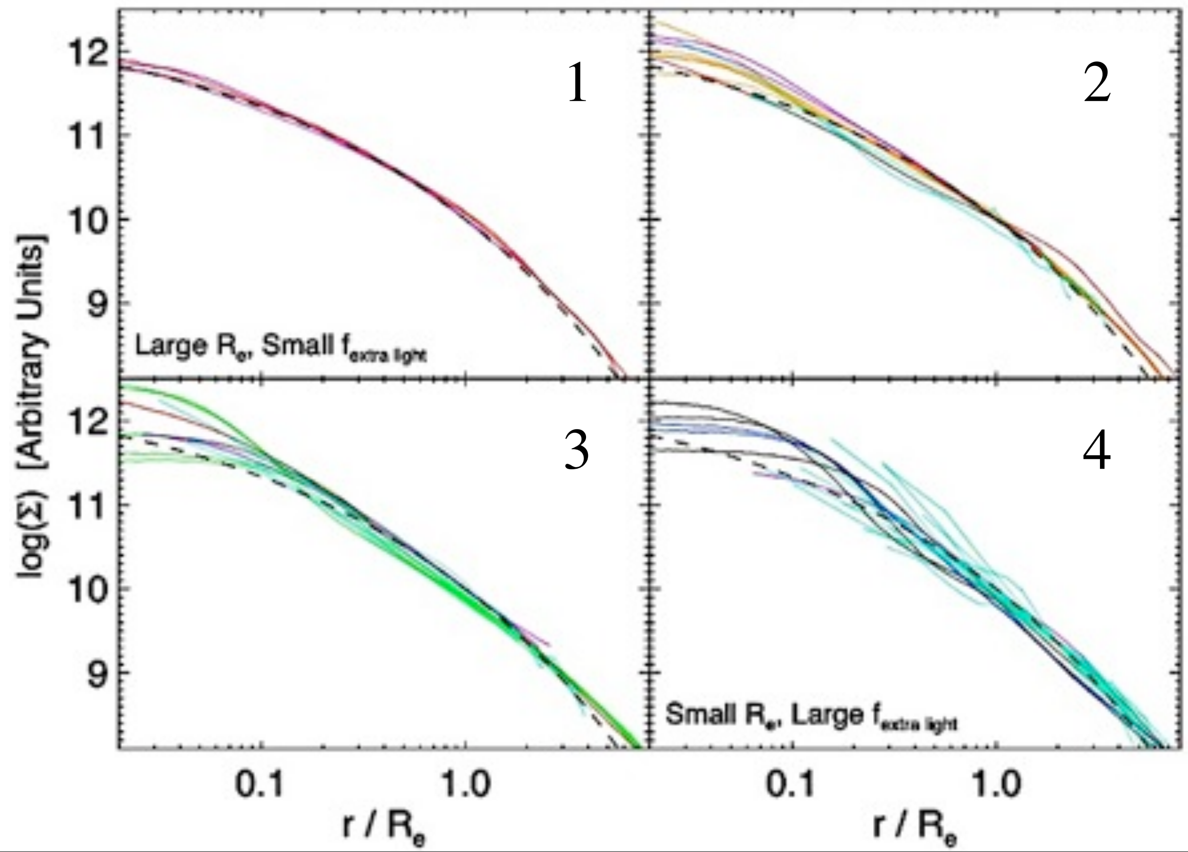
- Put more mass into a central dissipational component:
  - moves R_e inward
  - more of the mass inside R_e is this (totally baryon-dominated)
    - central cusp



Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

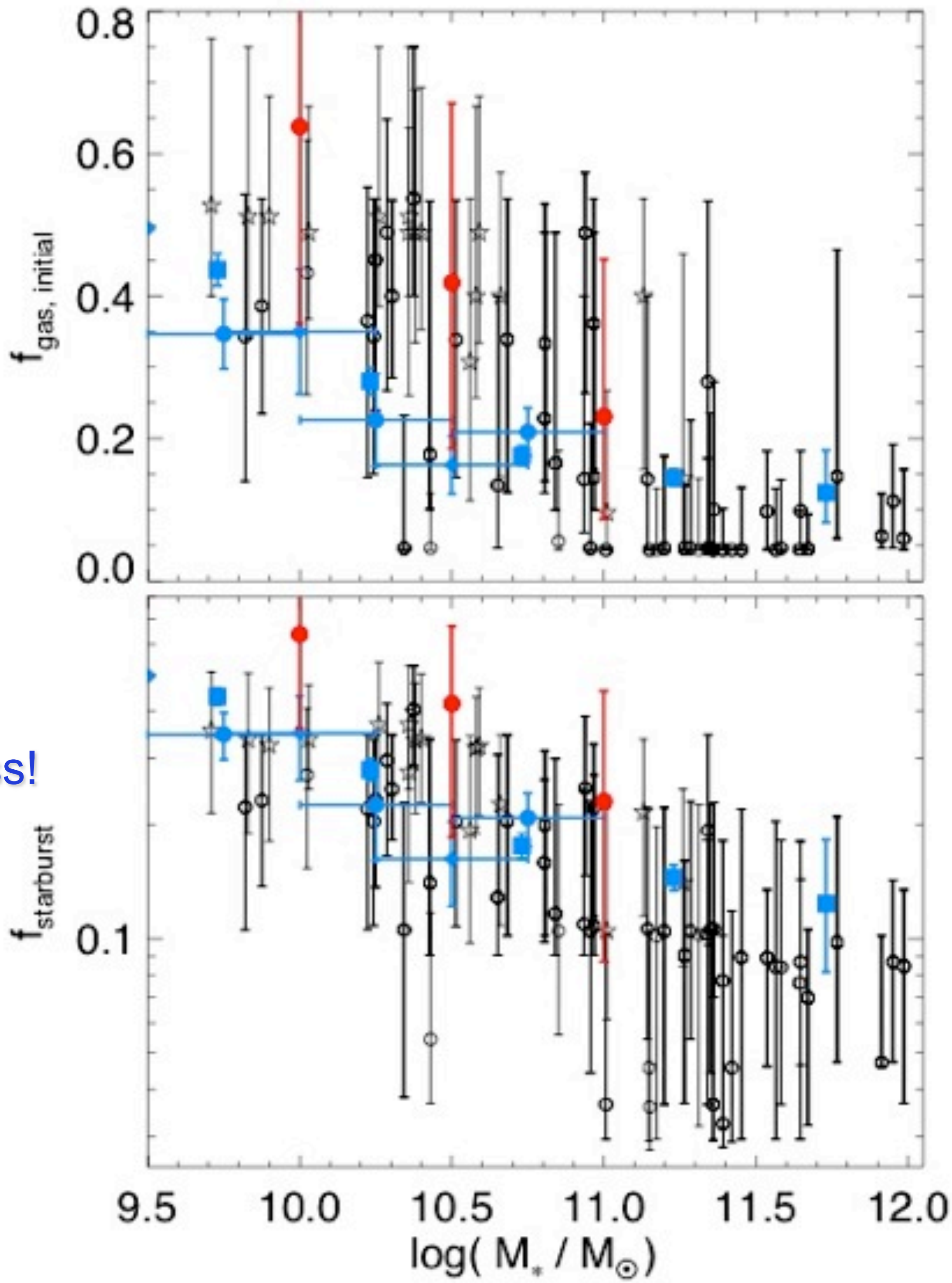




Structure in Elliptical Light Profiles

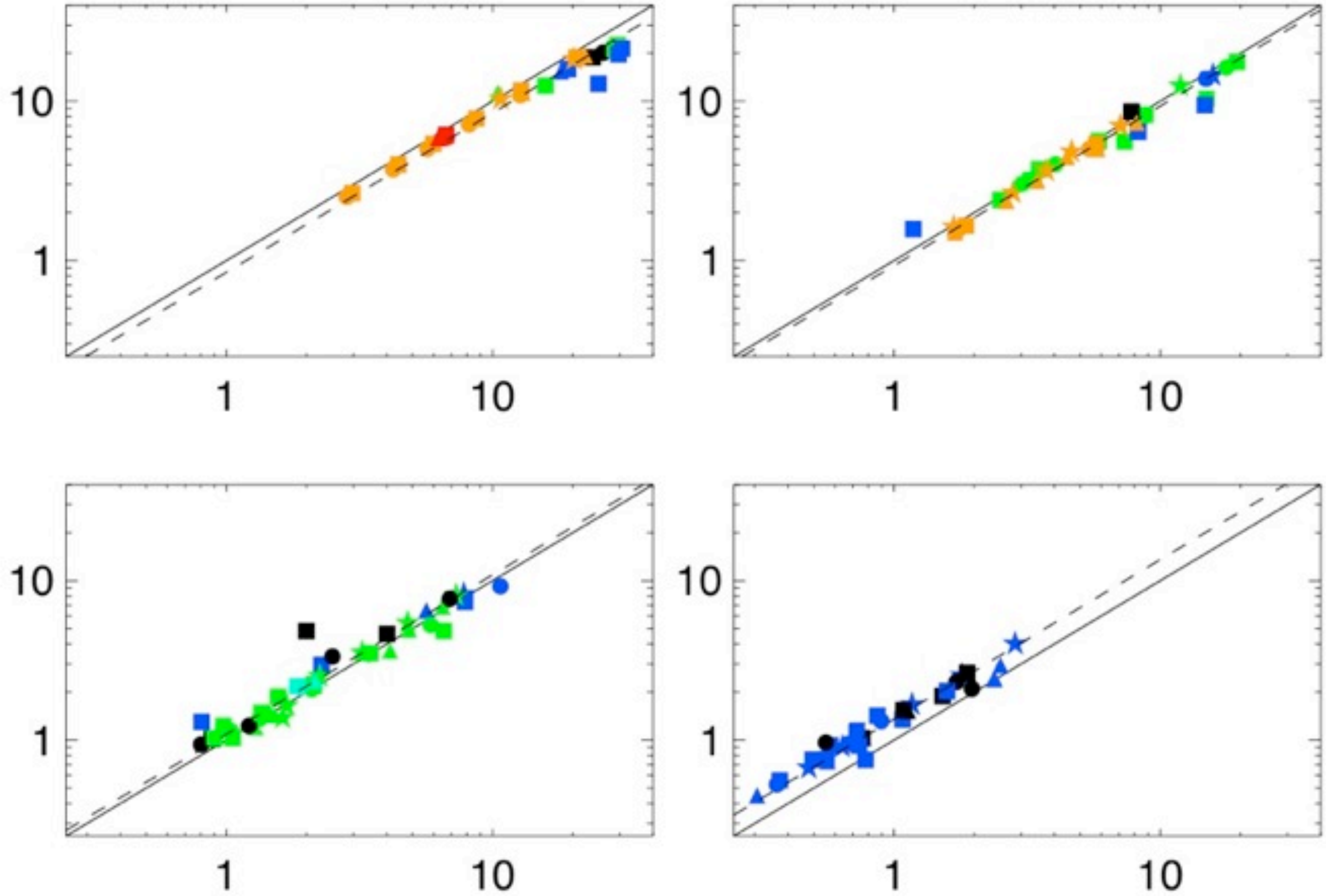
RECOVERING THE ROLE OF GAS

- Can match all (cusp) ellipticals with simple gas-rich merger remnants
- NEED systematically higher gas content in the progenitors at lower masses to explain the observed profile shapes
- This just recovers the *observed* dependence of f_gas on disk mass!



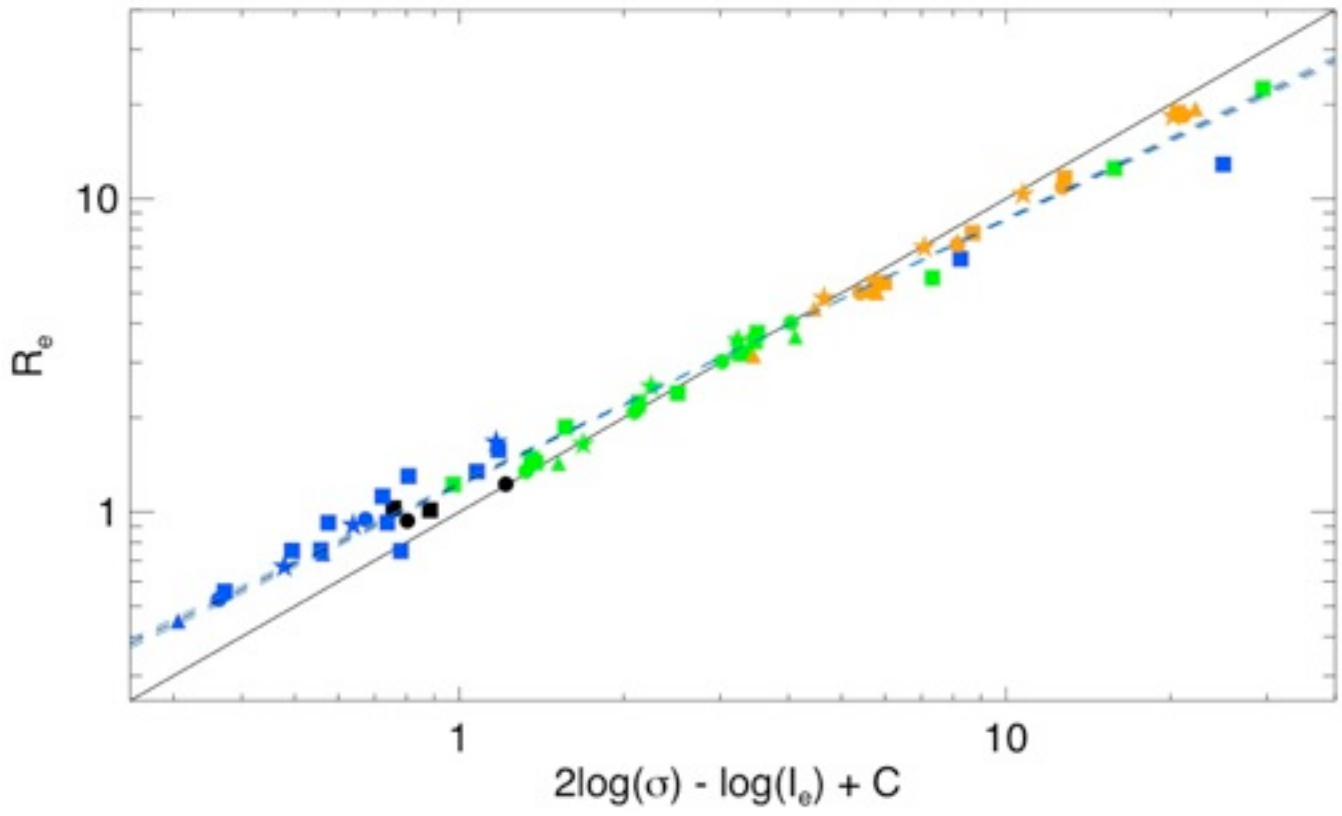
Structure in Elliptical Light Profiles

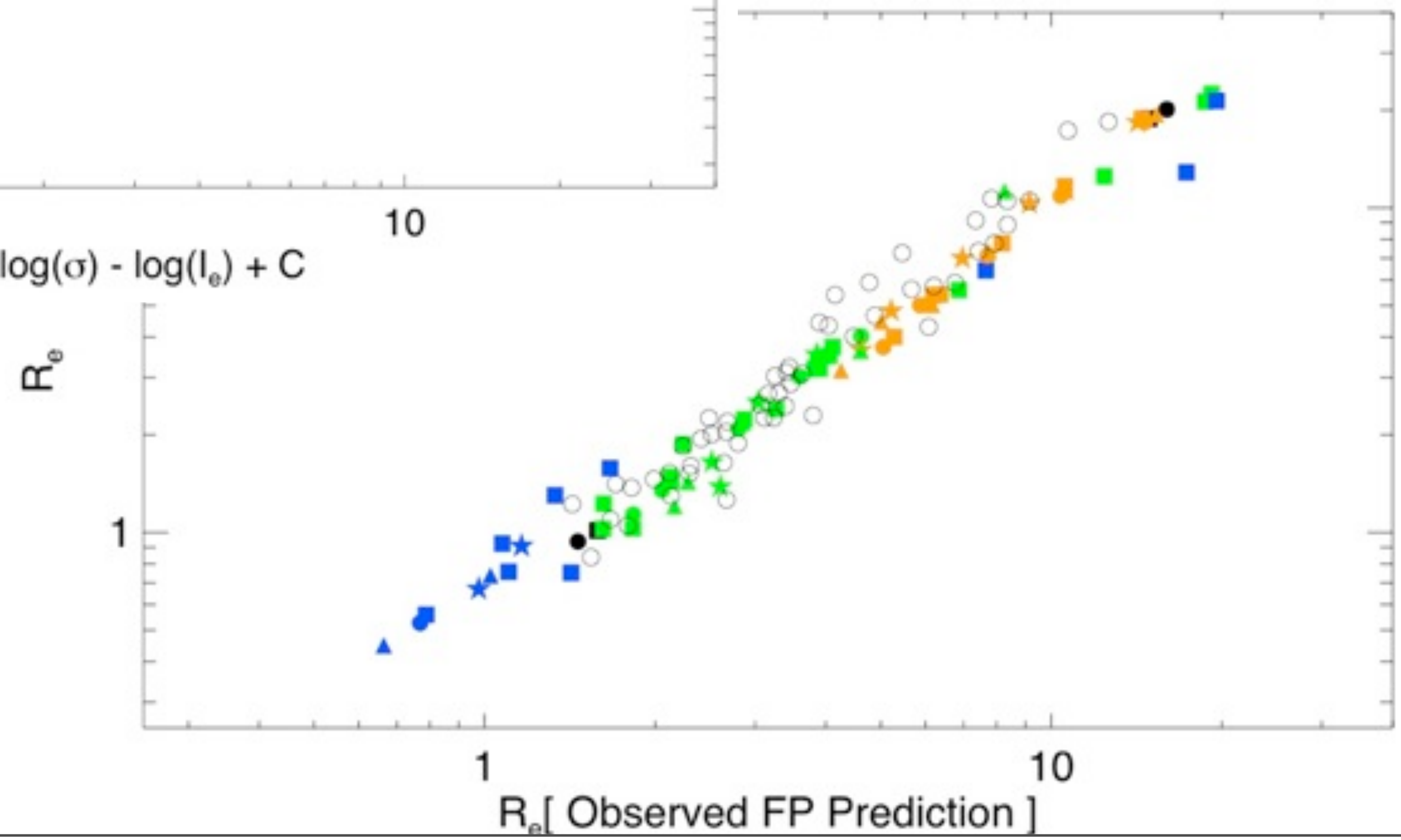
RECOVERING THE ROLE OF GAS



Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS





Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS

- Emerging evidence that the FP reflects a sequence in dissipation in the formation of ellipticals

- Need more evidence:
  - velocities
  - kinematic substructure
  - stellar populations
  - orbital structure

Structure in Elliptical Light Profiles

RECOVERING THE ROLE OF GAS