# The Role of Dissipation in Spheroid Formation

Philip Hopkins 12/03/07

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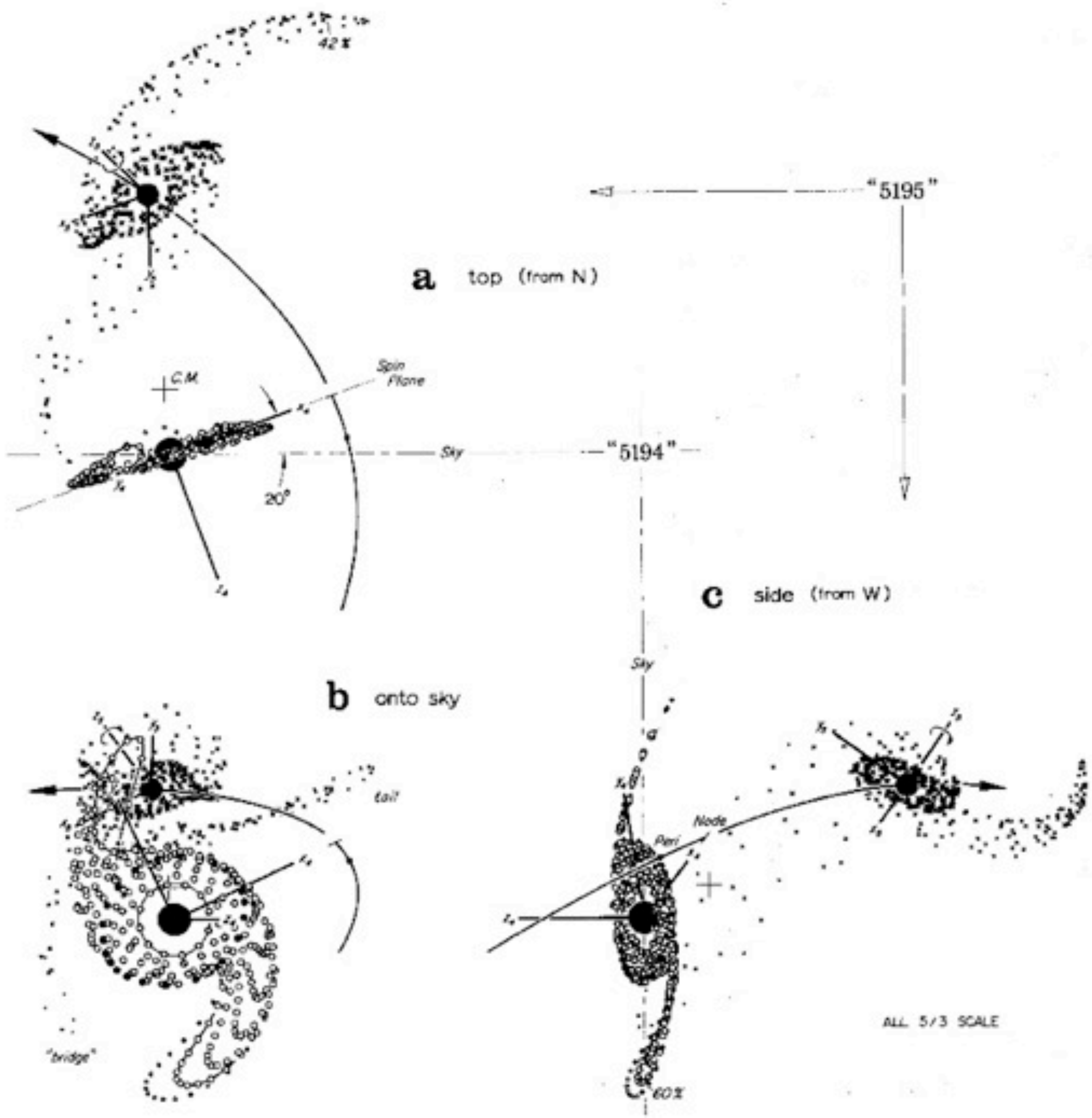
# Ellipticals & Bulges: Formation in Mergers?

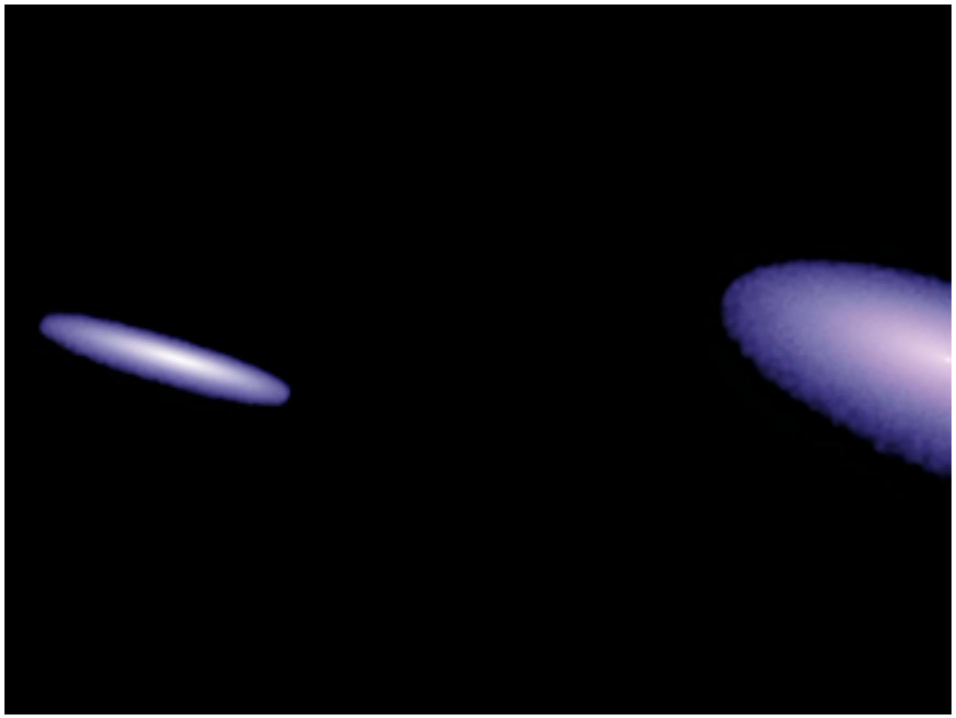
Toomre & Toomre (1972) ::
the "merger hypothesis"

ellipticals are made by the collision and merger of spirals



# Fundamental Plane Tilt

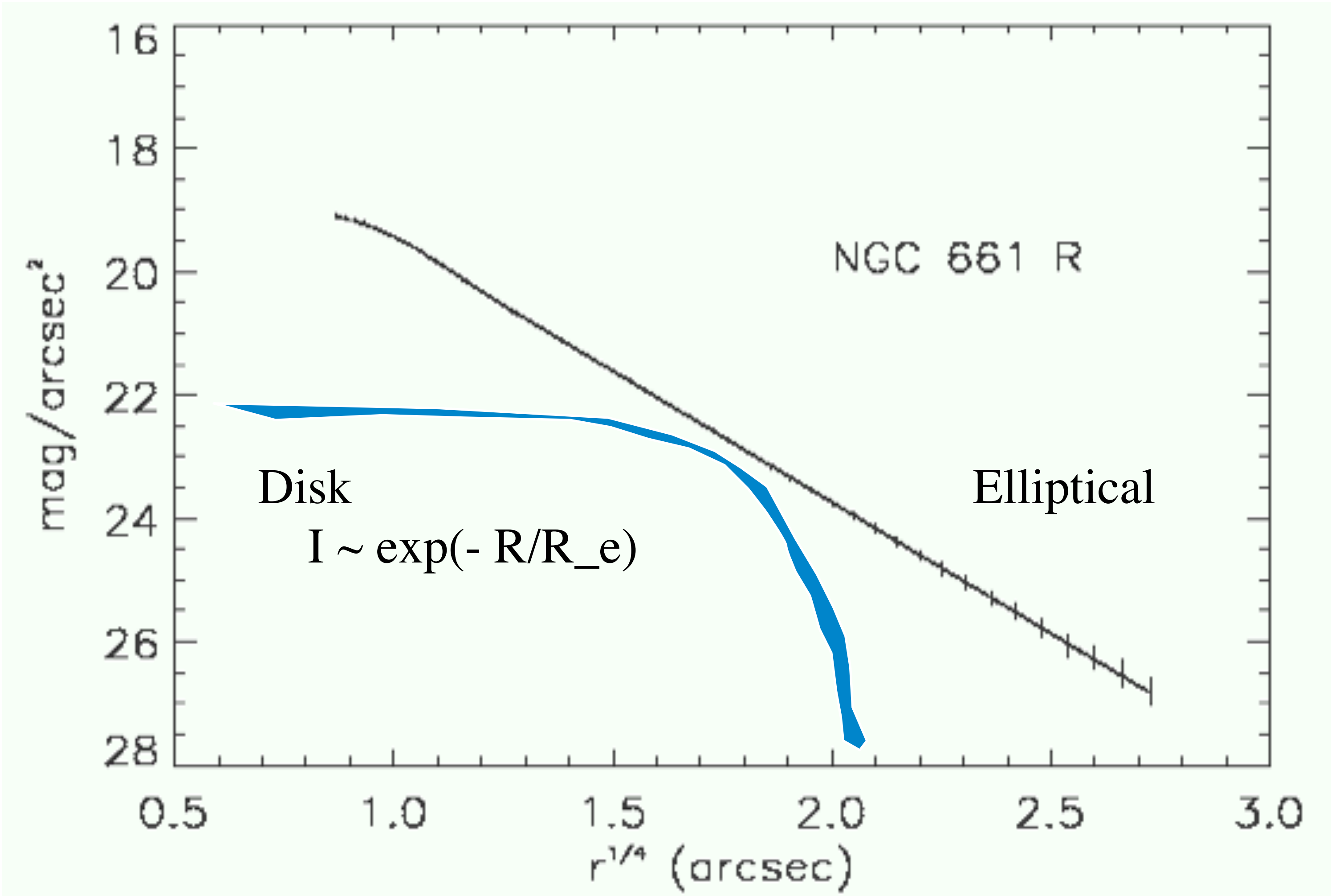
## STRUCTURAL NON-HOMOLOGY



# Ellipticals & Bulges: Formation in Mergers?

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

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



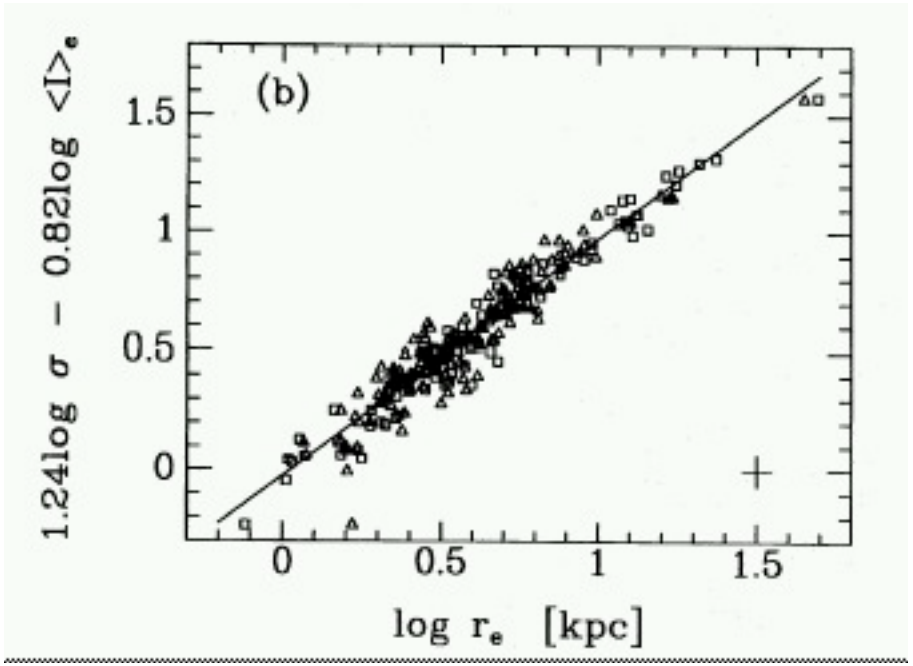

- Lynden-Bell: violent relaxation: rapidly changing potential: stars scatter off the changing potential, mixing their orbits and energies

## The Problem:

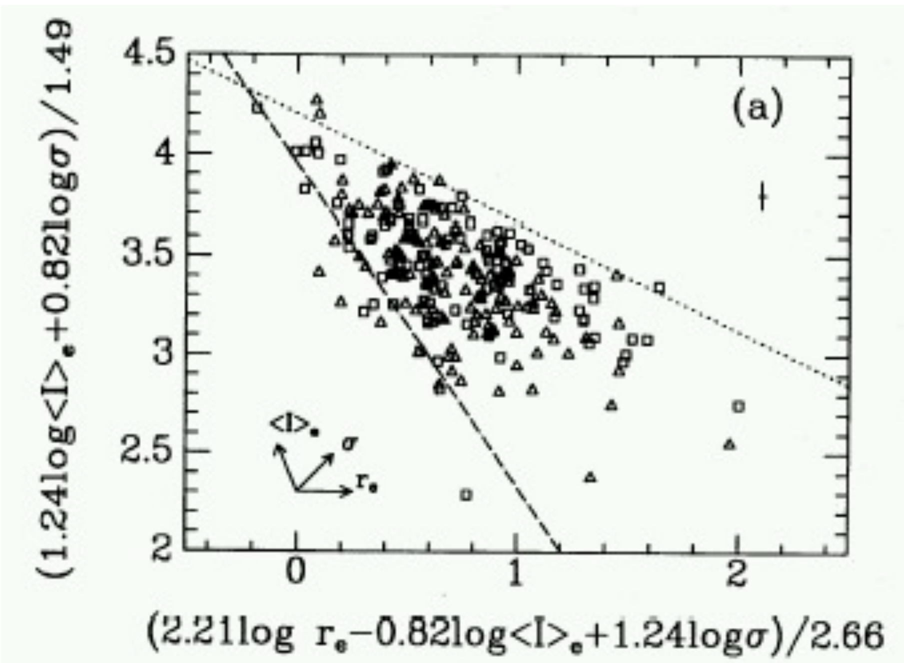
The Fundamental Plane correlates $R_e$, surface brightness, and $\sigma$ for elliptical galaxies.

Faber-Jackson & Kormendy relations link size or dispersion to luminosity or stellar mass:

Ellipticals are much more dense than spirals of the same mass!




Fundamental Plane edge on



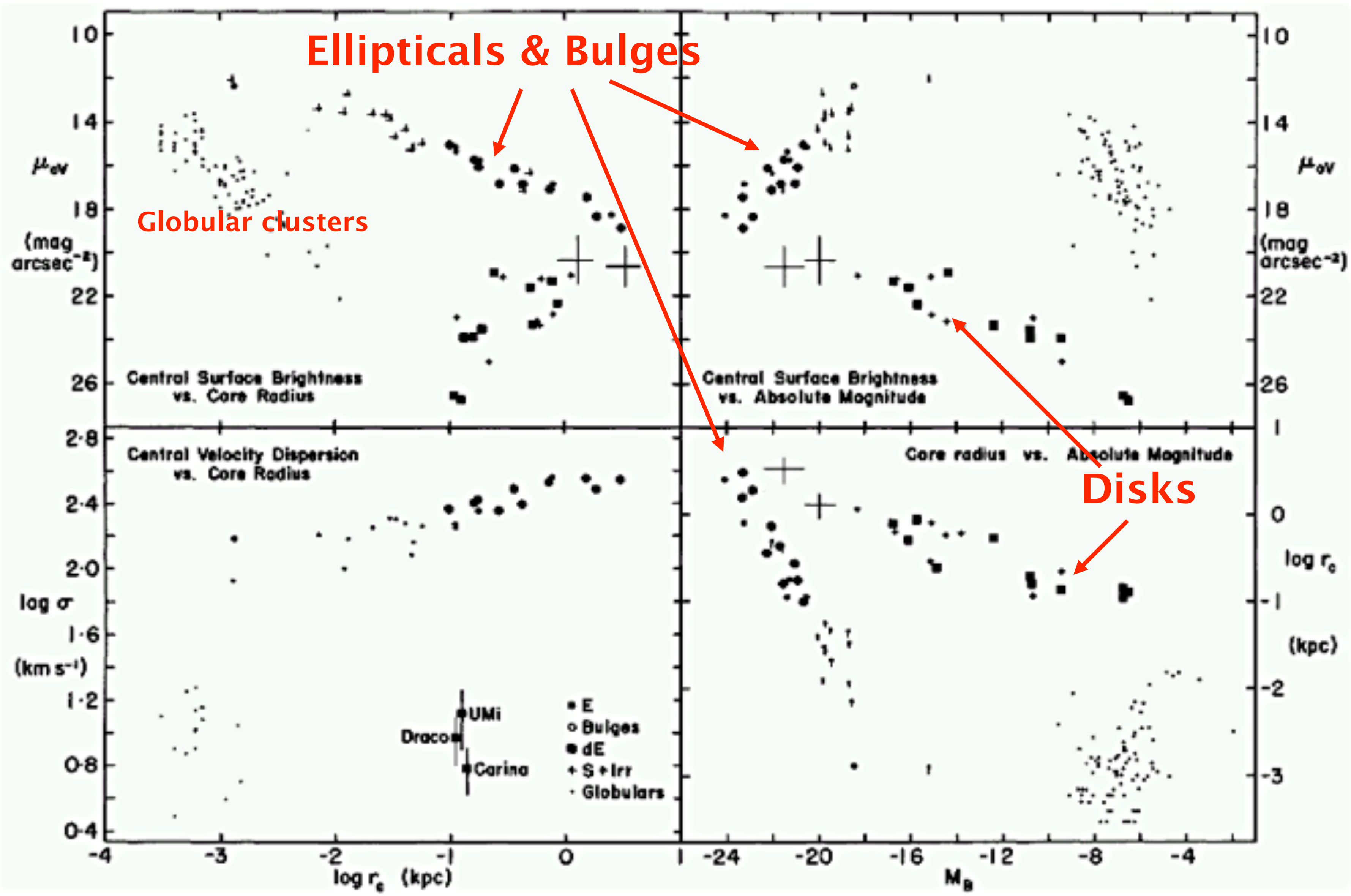

Fundamental Plane face on

Jorgensen 1996

# The Problem

## FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

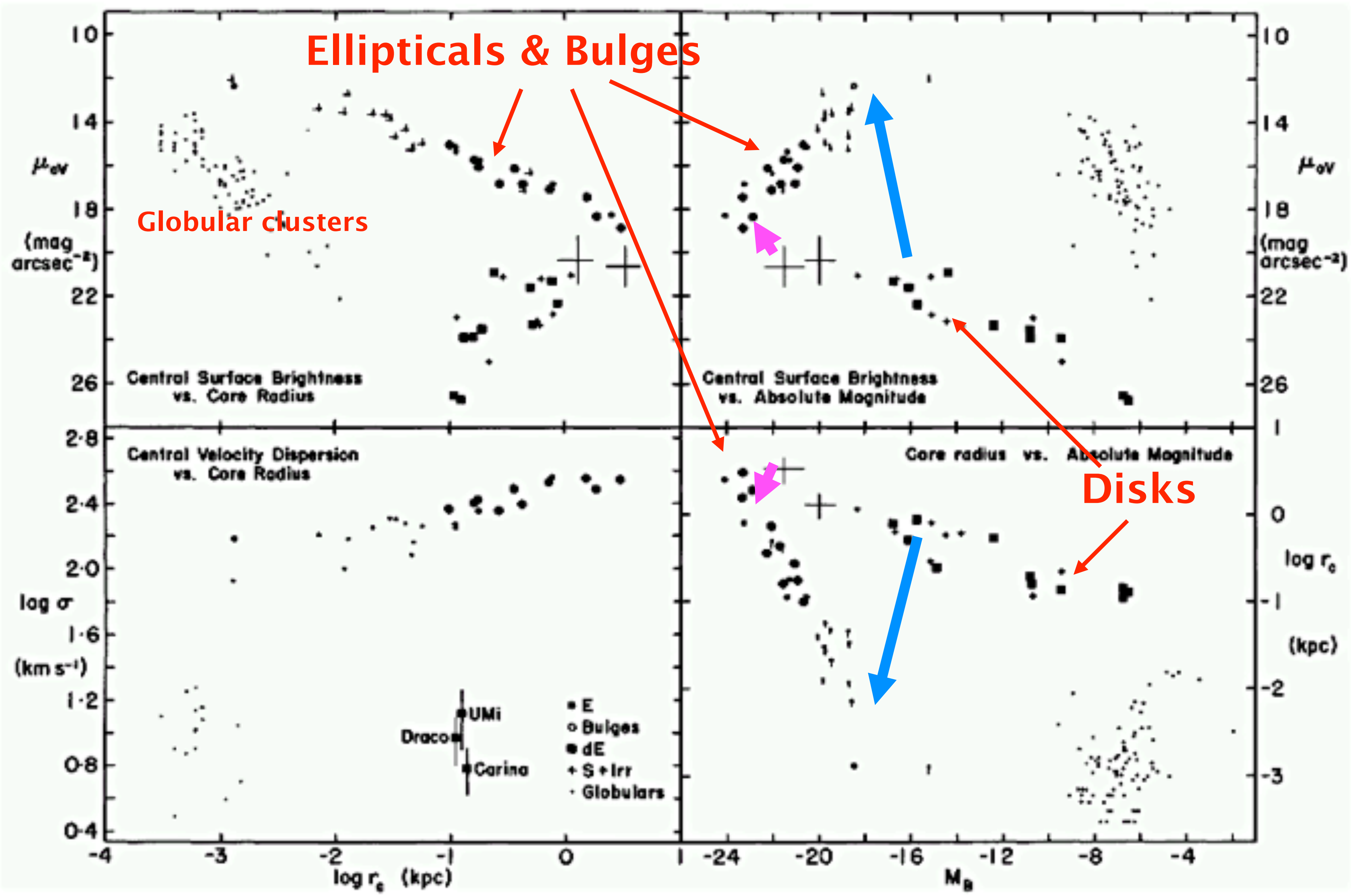
Kormendy (1985)



# The Problem

## FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

Kormendy (1985)



# The Problem

## FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

Louisville's Theorem: cannot increase phase space density in collisionless mergers

Solution 1: High-z mergers from more compact disks

but...

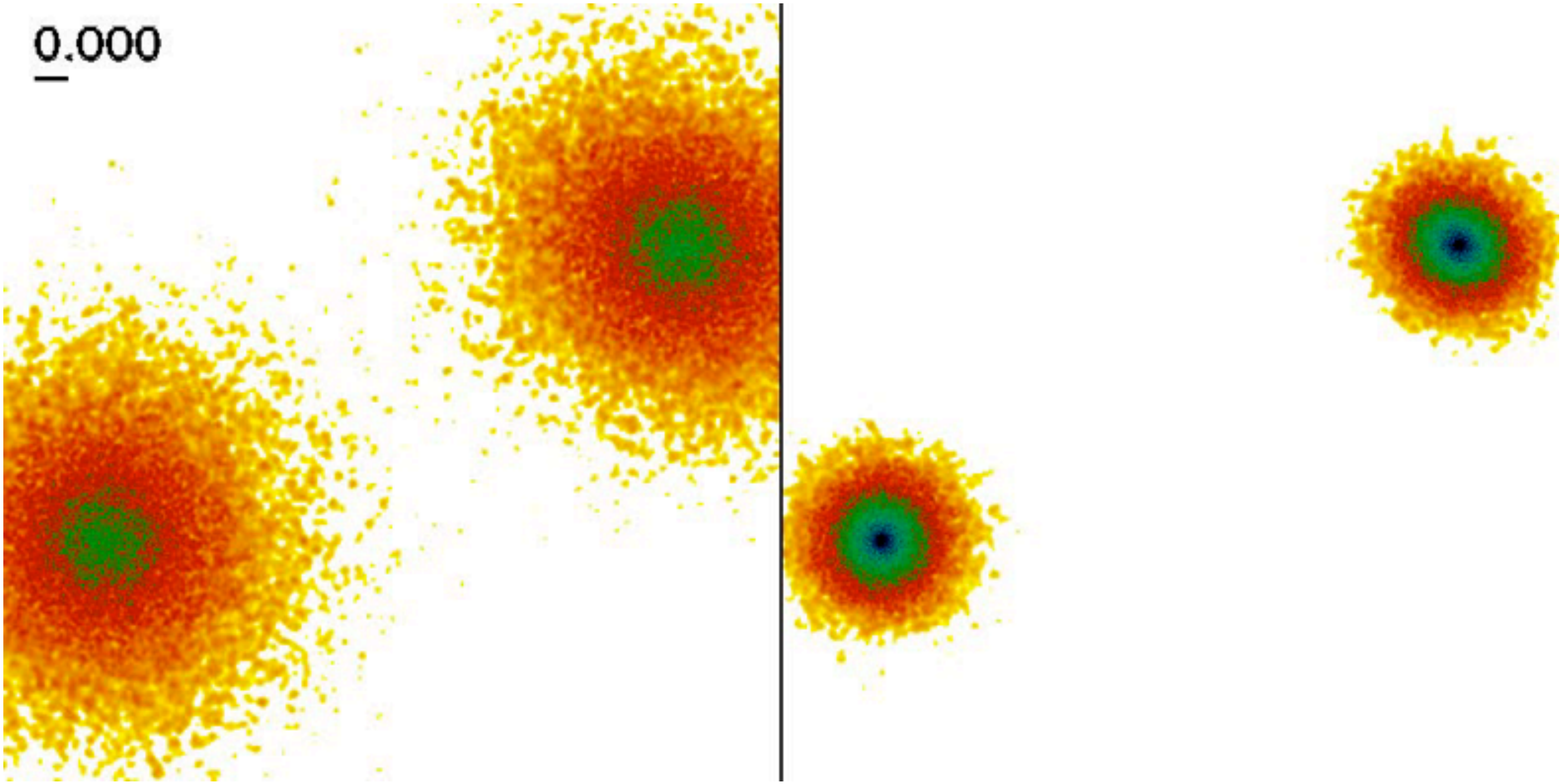
- many low-mass ellipticals formed at $z<1$
- observed evolution is relatively weak

Solution 2: Gas dissipation

# The Problem

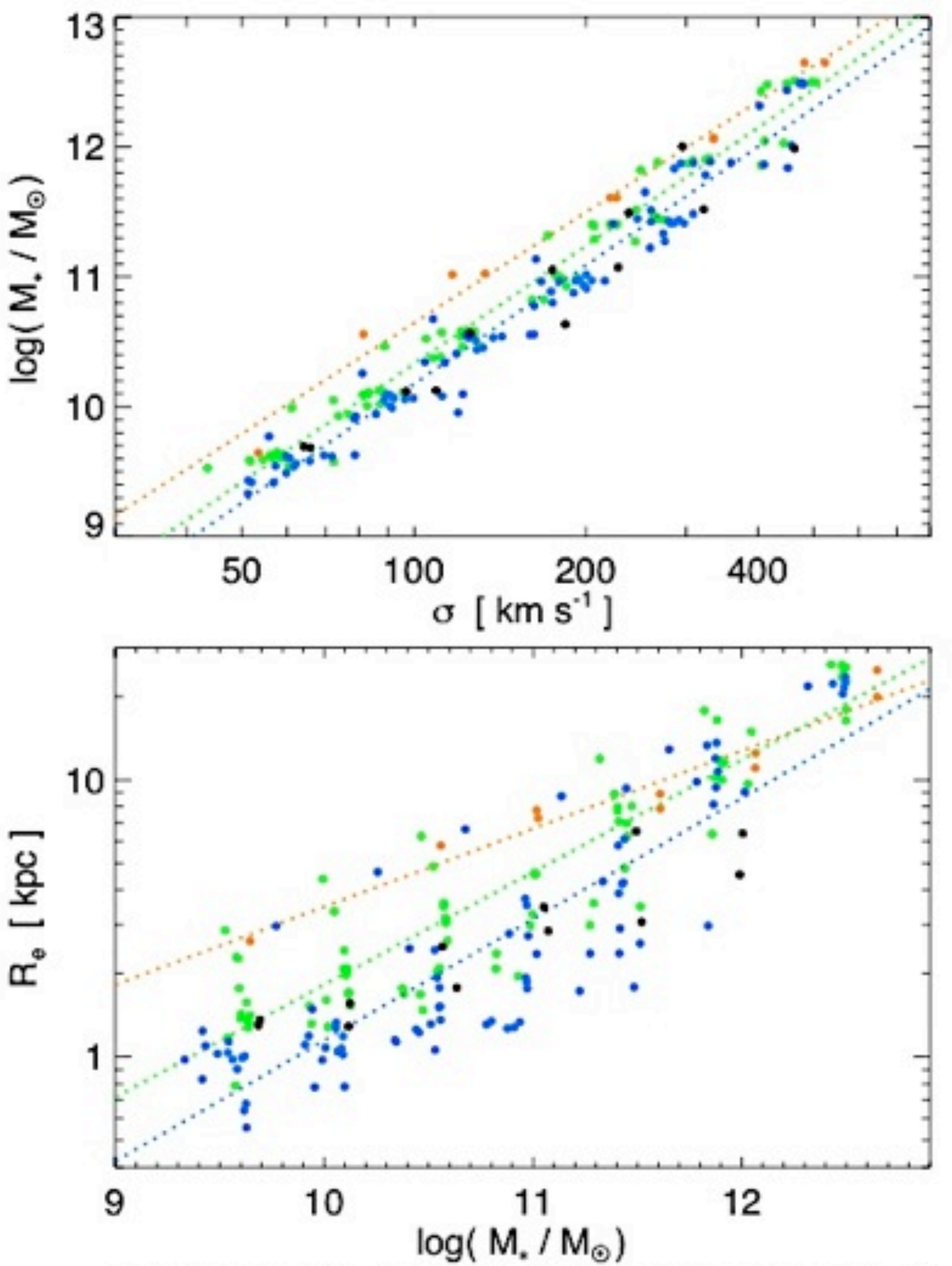
## FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS

- Why are ellipticals so much smaller than disks?
  Gas dissipation allows them to collapse to small scales!



# Redshift Evolution

## SIZE-MASS RELATIONS




- Faber-Jackson & size-mass vs. disk gas content

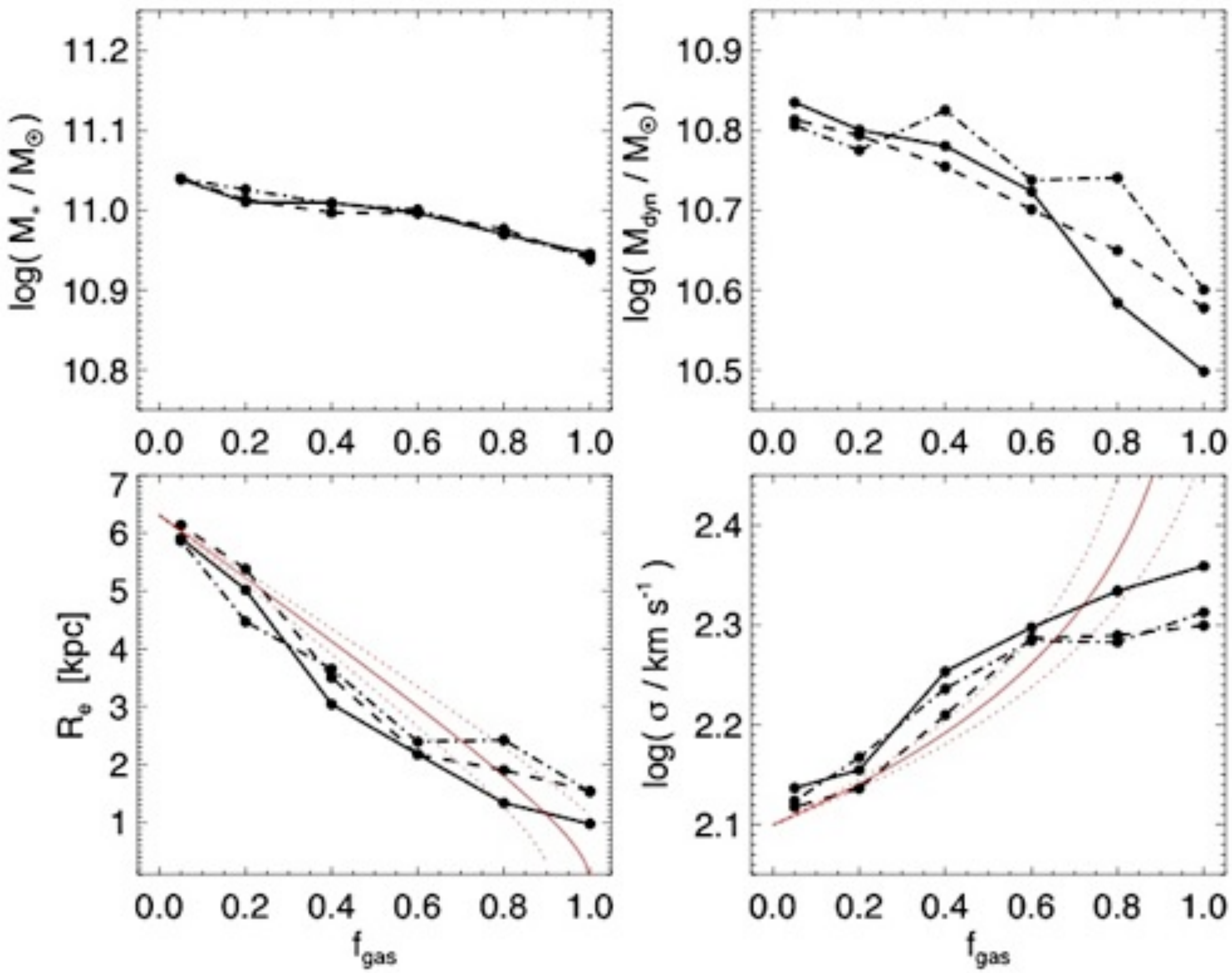
fgas = 0.1

fgas = 0.4

fgas = 0.8

# The Problem

## FUNDAMENTAL PLANE CORRELATIONS & THE DENSITY OF ELLIPTICALS



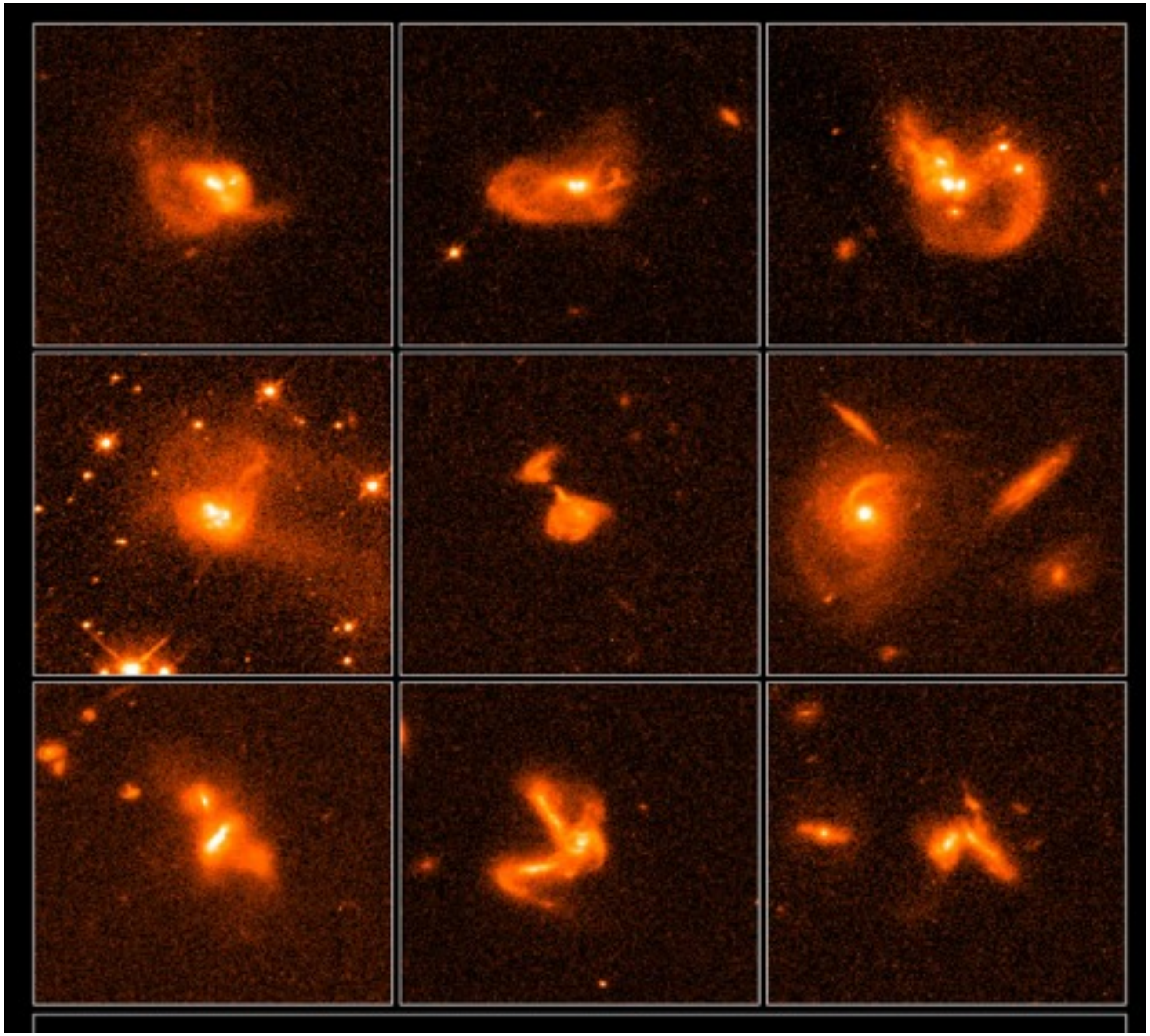

- Increased dissipation >> smaller, more compact remnants (Cox et al.; Robertson et al.)
- Deepens the central potential

# The Solution: Gas Dissipation?

Look at late-stage merger remnants

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

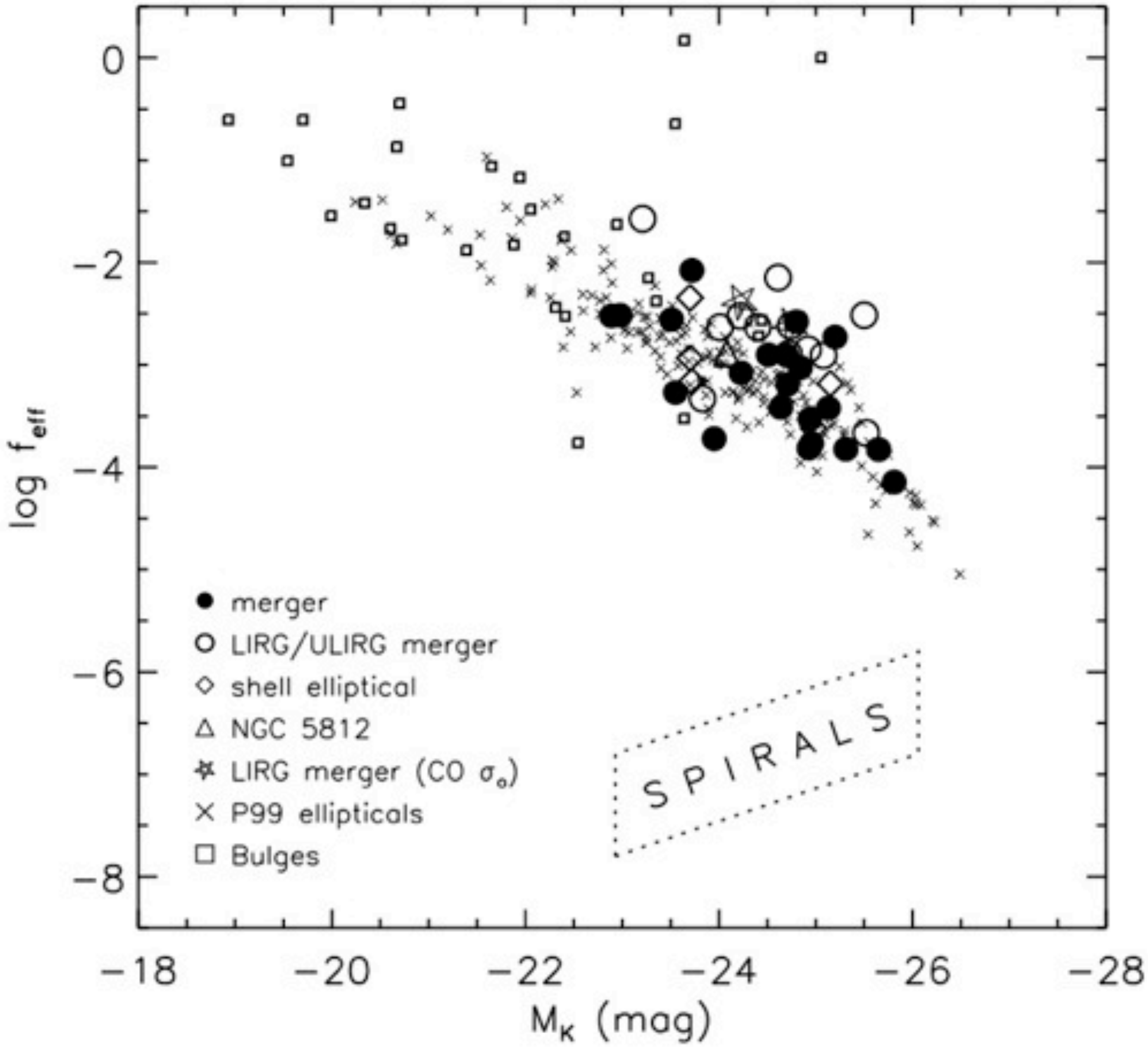
Extremely compact (<kpc scales)



**Borne et al., 2000**

# The Solution: Gas Dissipation?

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

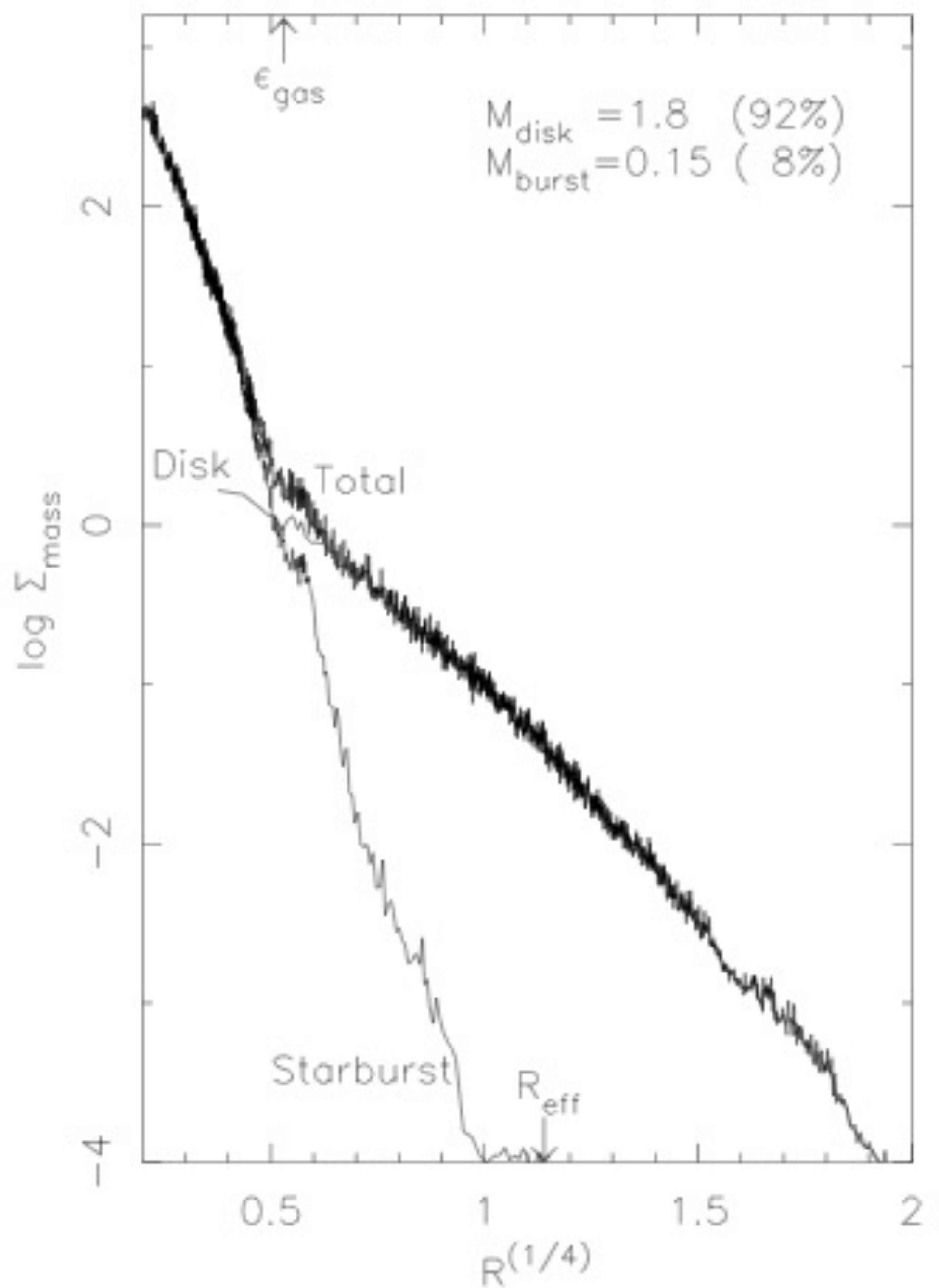


# Starburst Stars in Simulations Leave an "Imprint" on the Profile



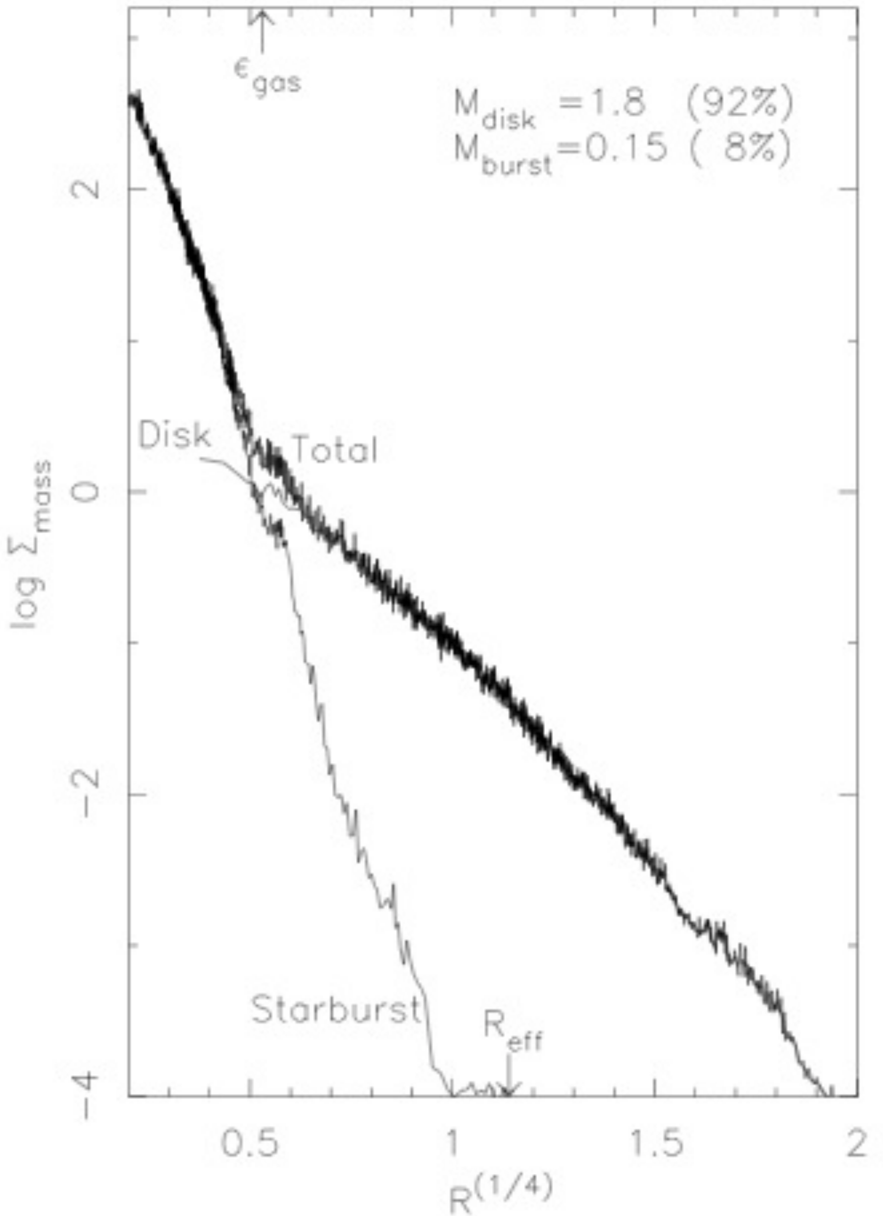
Separate stars into 3 populations:

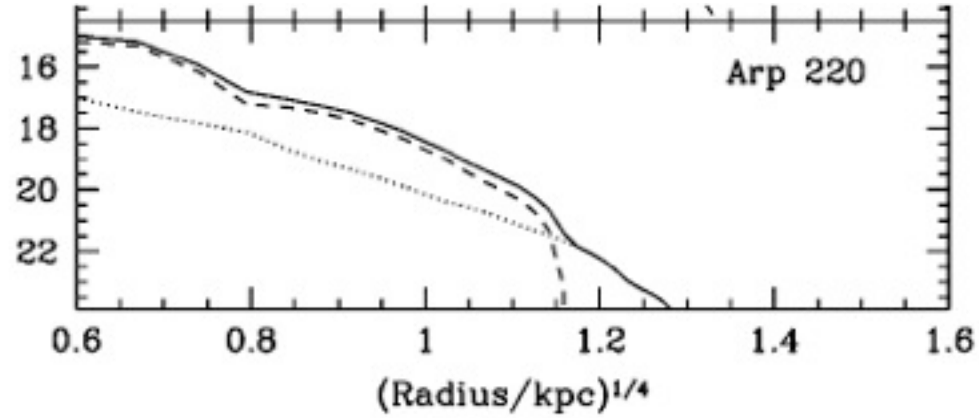
1. Disk/pre-starburst
2. Starburst
3. Post-starburst
   (embedded kinematic subsystems)

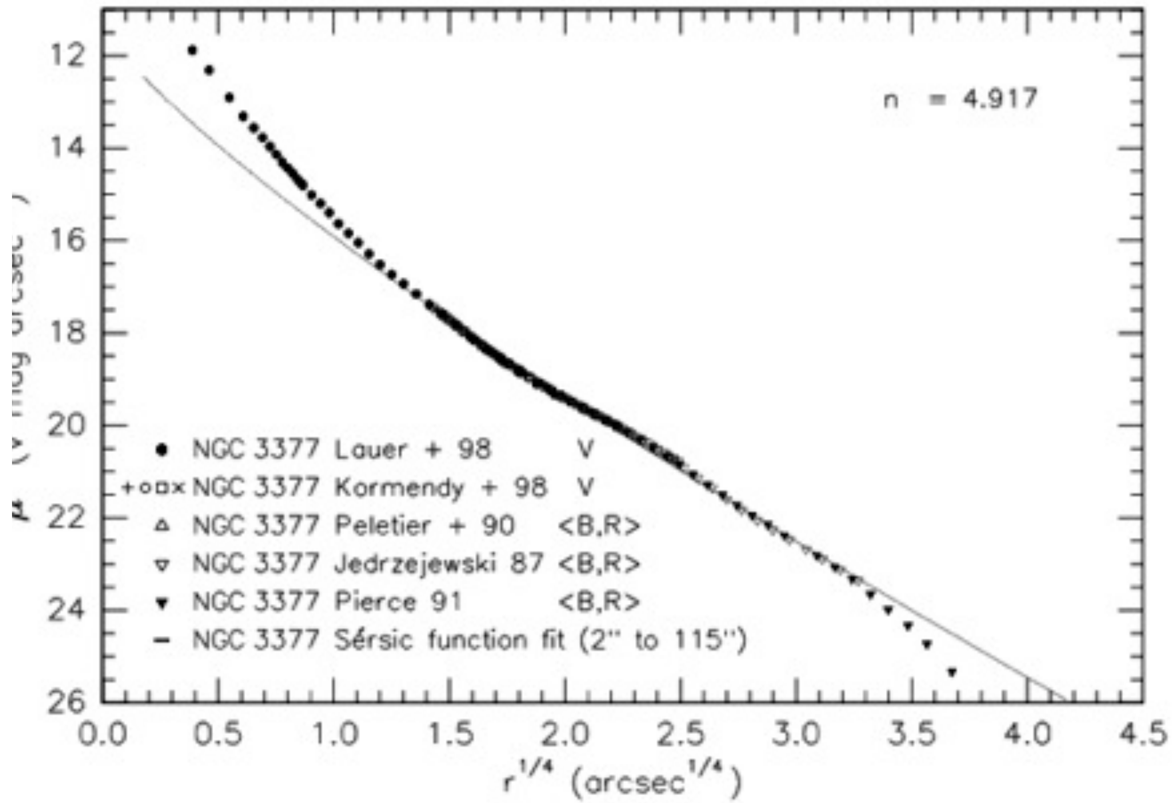


# Starburst Stars in Simulations Leave an “Imprint” on the Profile

## RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS



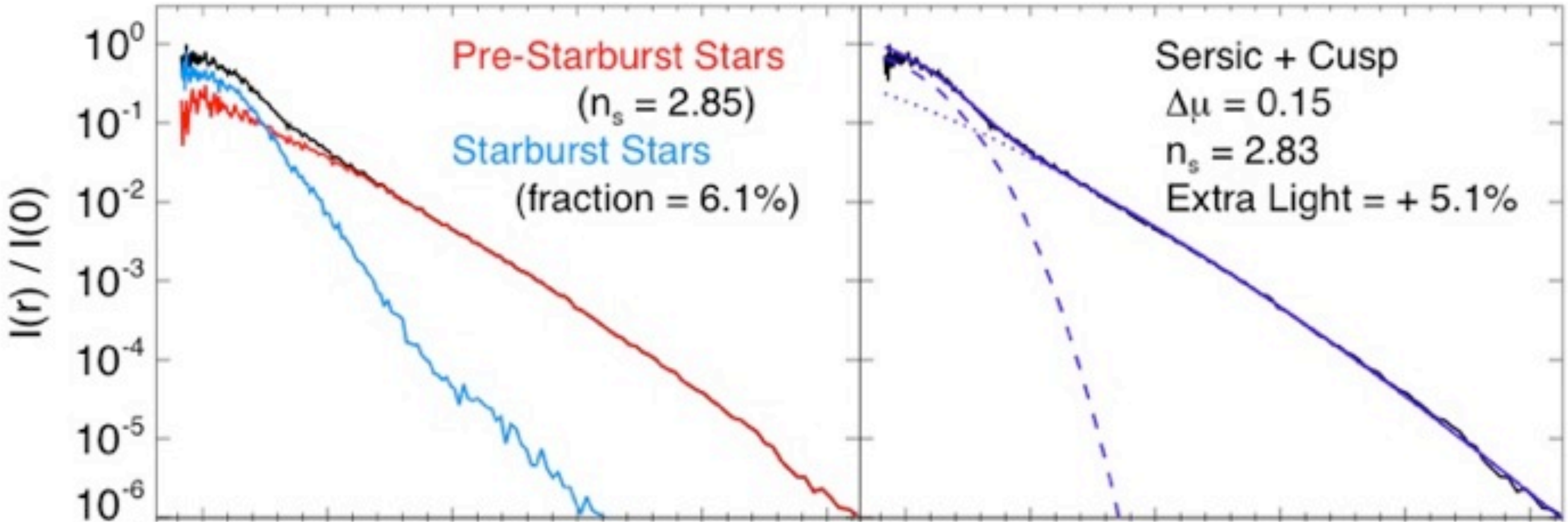



# Structure in Elliptical Light Profiles

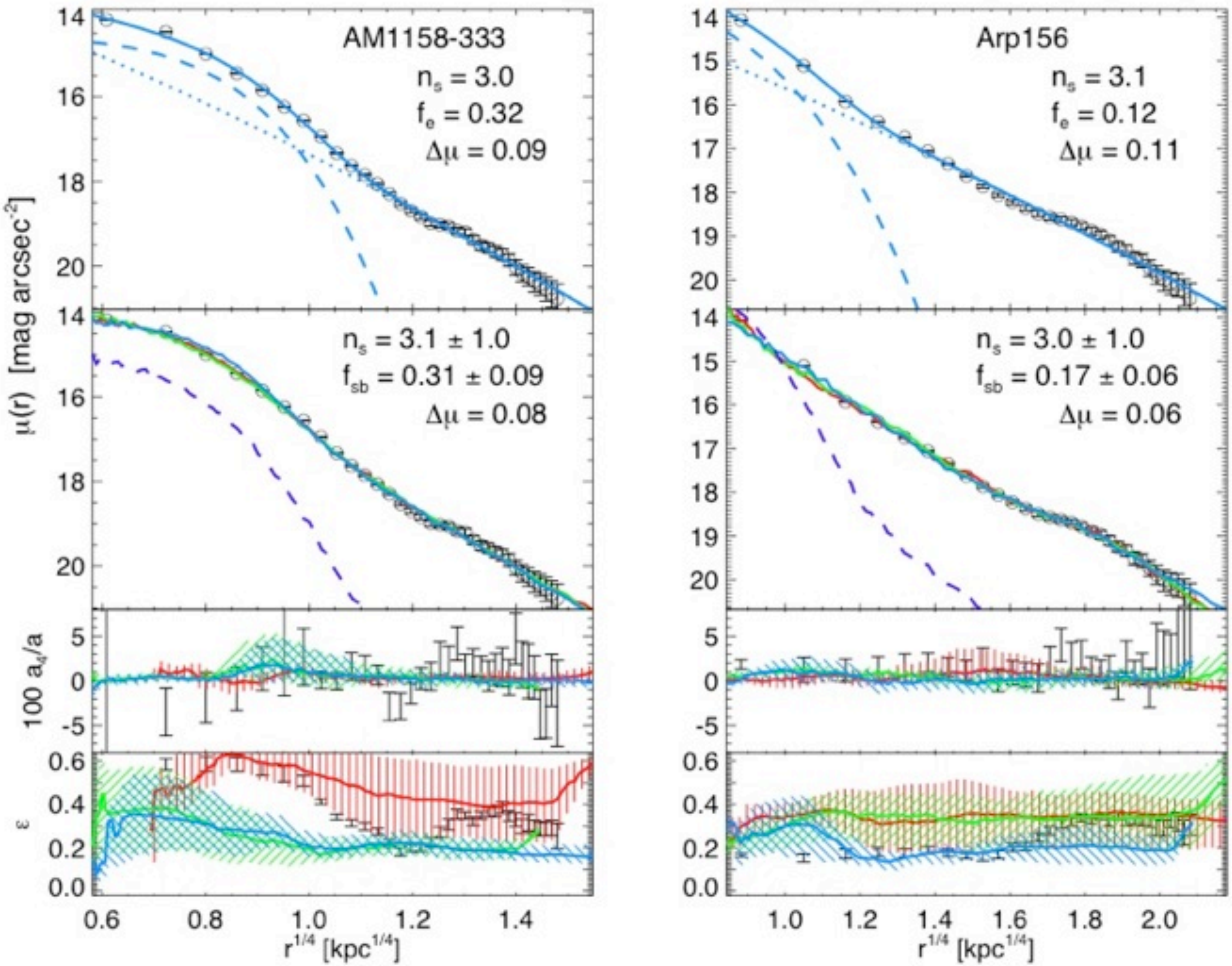
## RECOVERING THE GASEOUS HISTORY OF ELLIPTICALS

Q: Can we design a decomposition that separates disk/starburst stars in the final profile?



# Application: Merger Remnants

## RECOVERING THE ROLE OF GAS

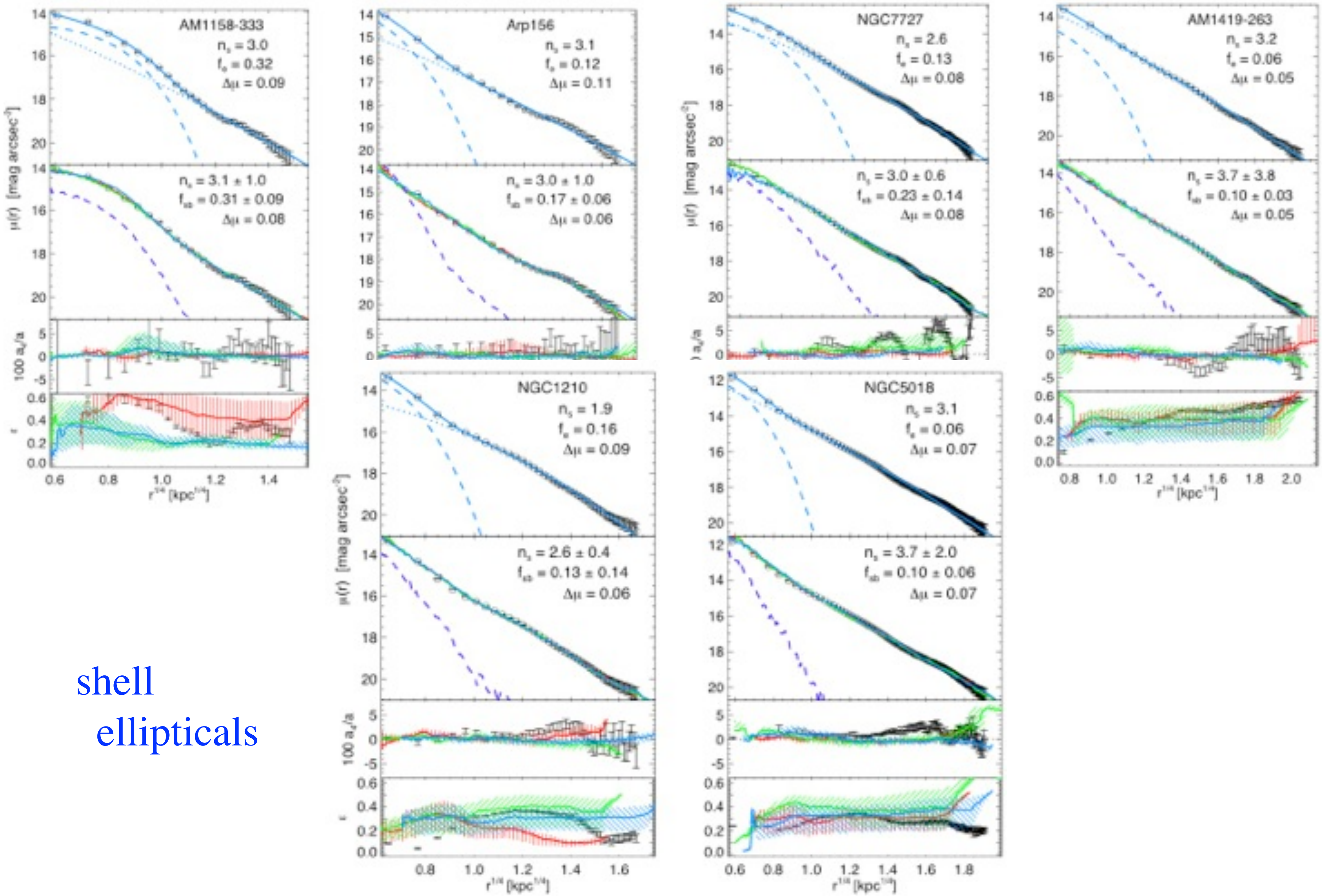


# Application: Merger Remnants

## RECOVERING THE ROLE OF GAS

bright, young mergers

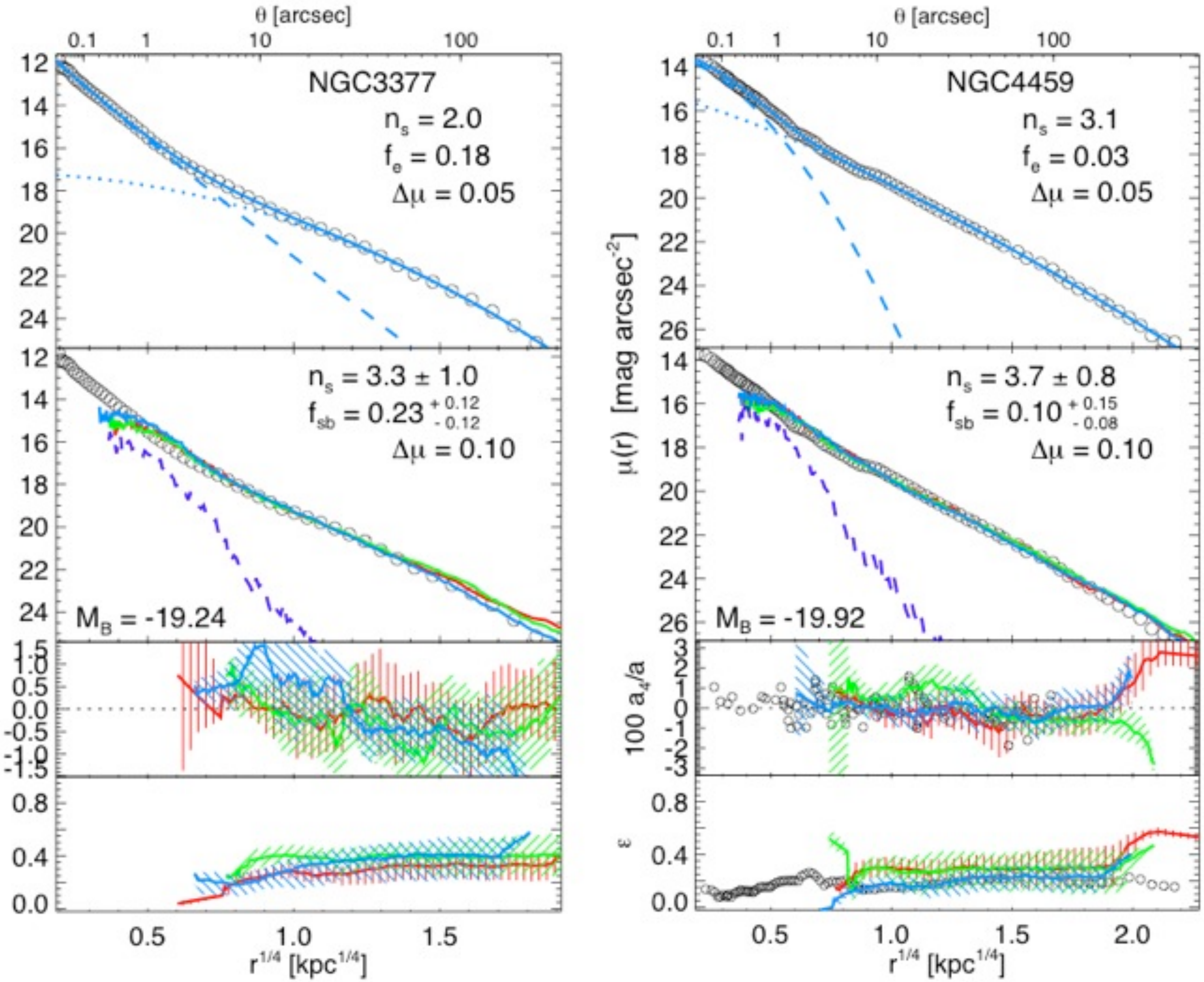
low-luminosity, relaxed mergers




shell
ellipticals

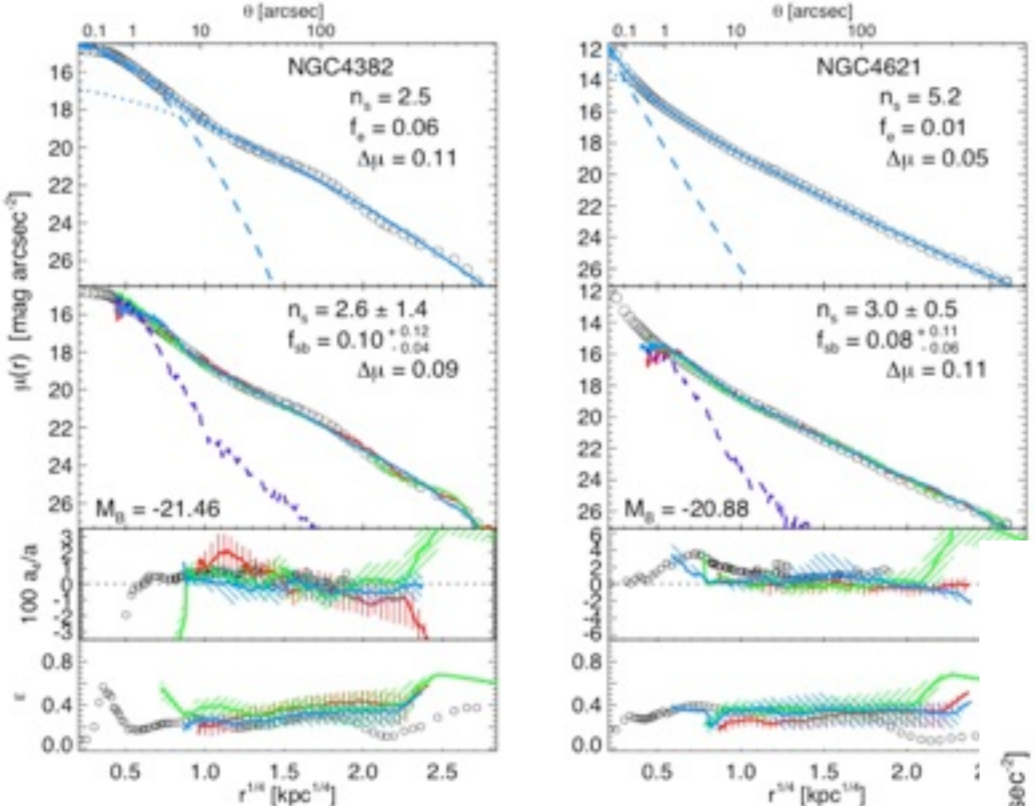
# Application: "Cusp" Ellipticals

## RECOVERING THE ROLE OF GAS

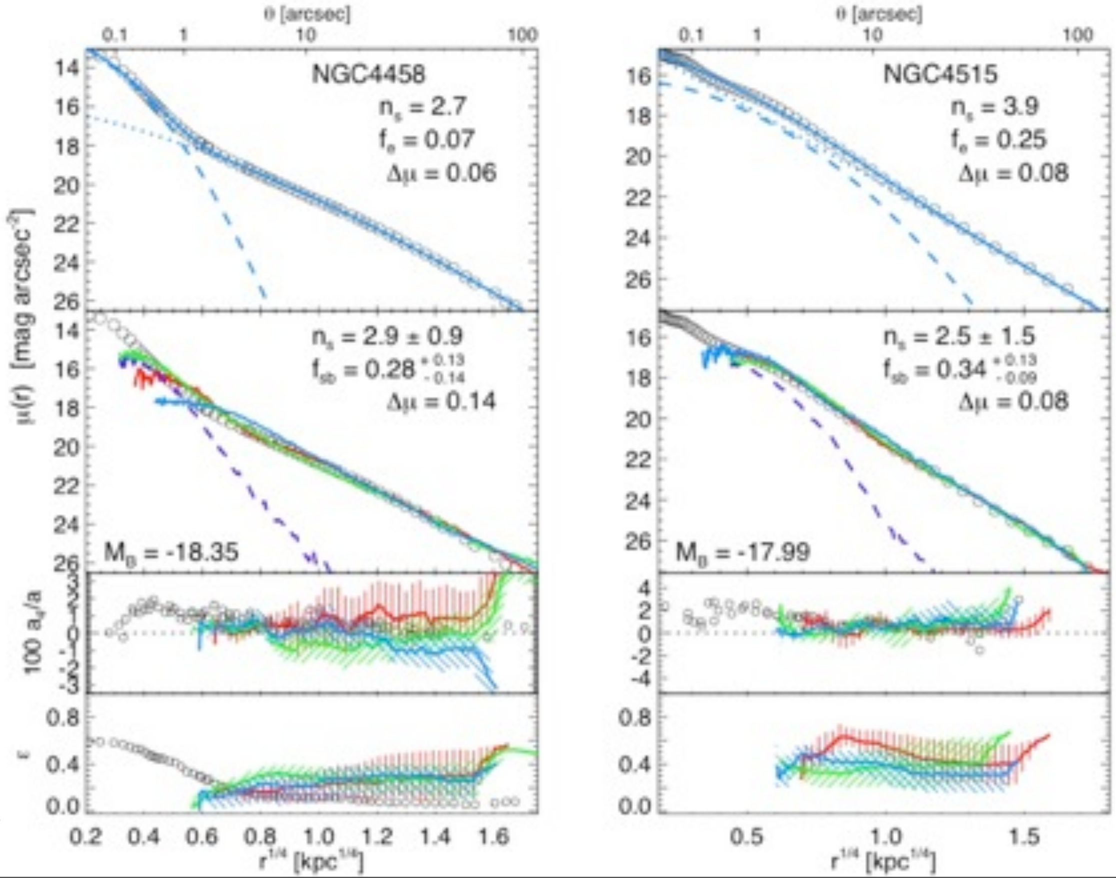


# Application: “Cusp” Ellipticals

## RECOVERING THE ROLE OF GAS



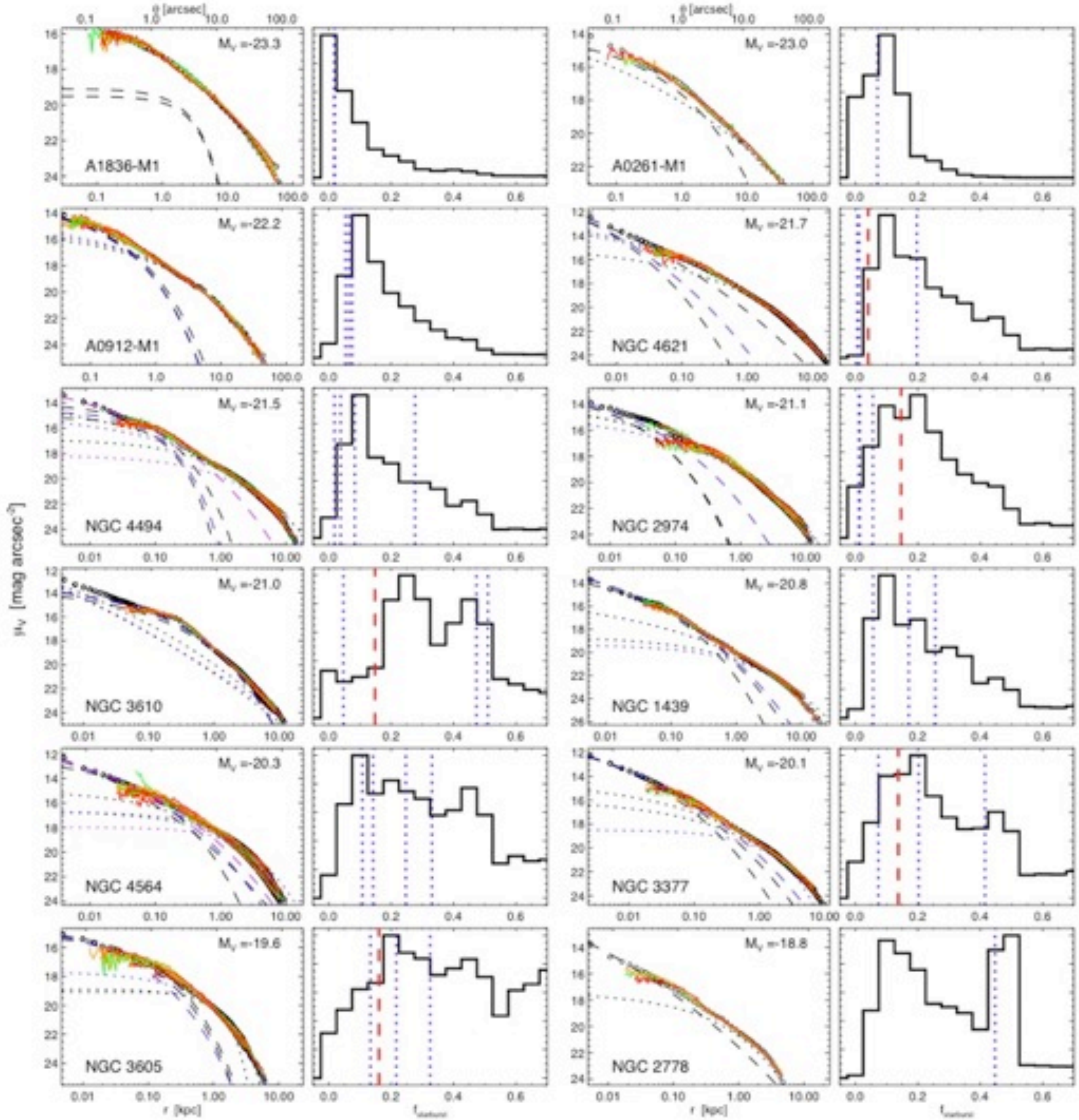

L > L* ellipticals




L < 0.1 L* ellipticals

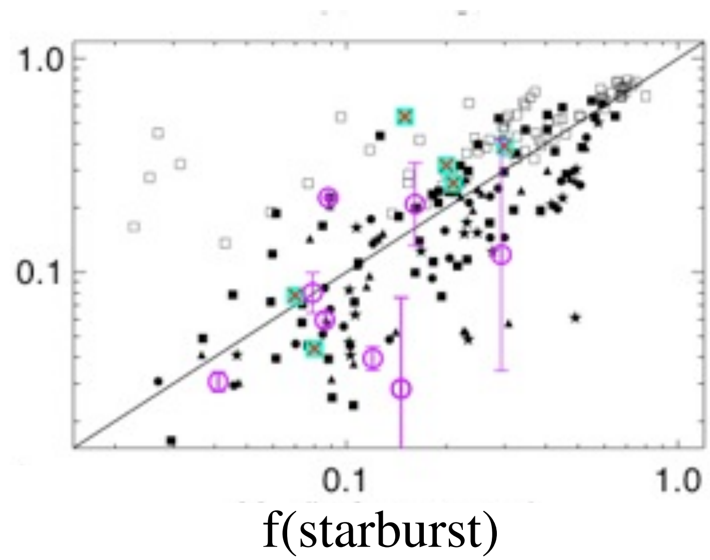
# Application: “Cusp” Ellipticals

## RECOVERING THE ROLE OF GAS



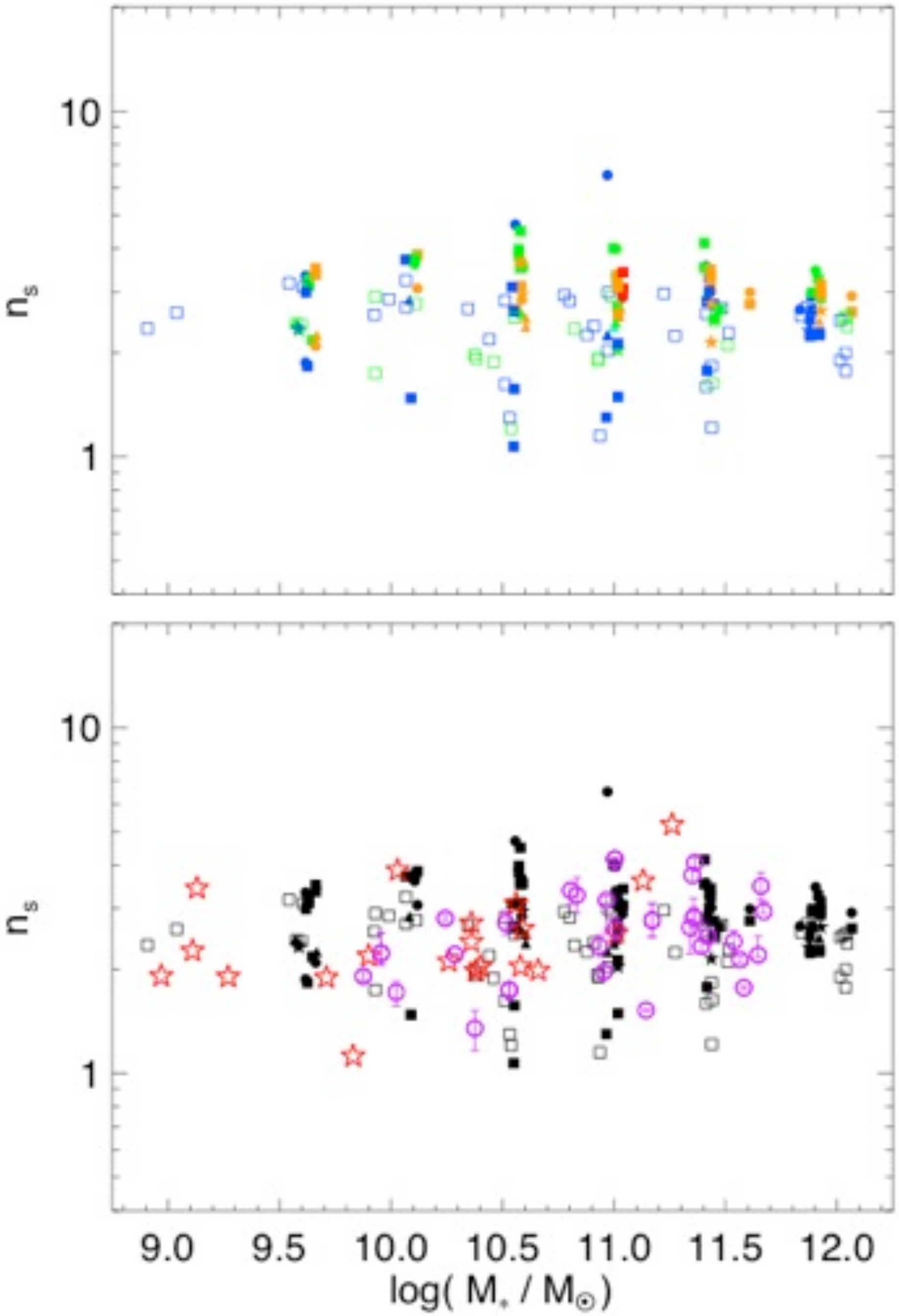

Compare:

- Parametric fitting
- Direct simulation fitting
- Stellar population models



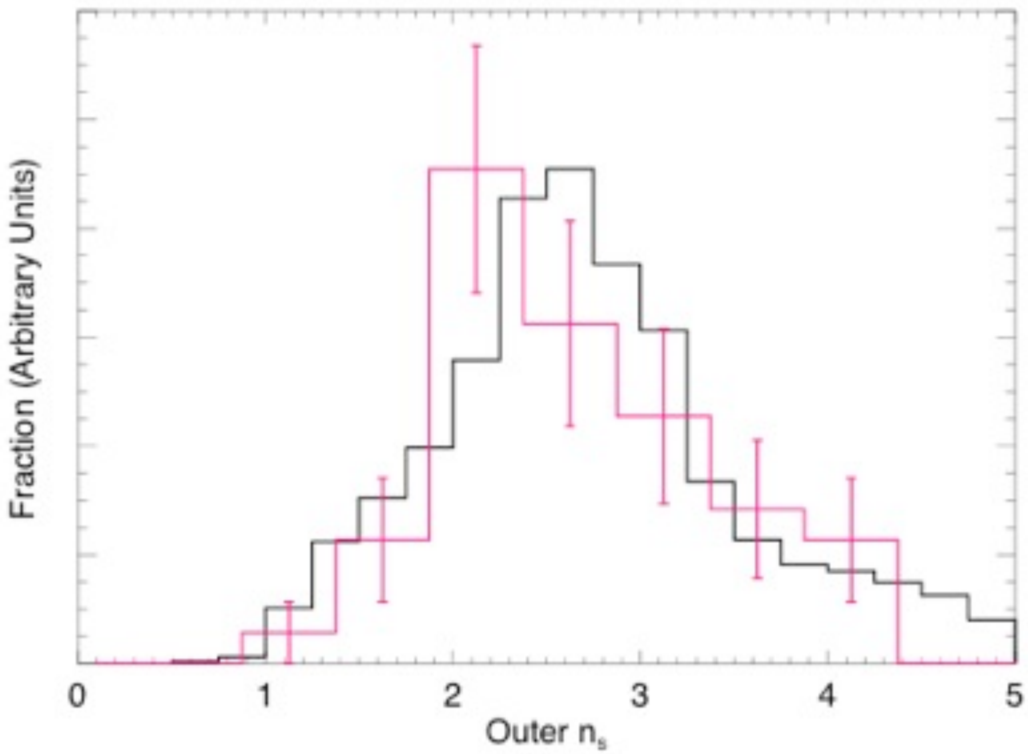
# Application: “Cusp” Ellipticals

## RECOVERING THE ROLE OF GAS



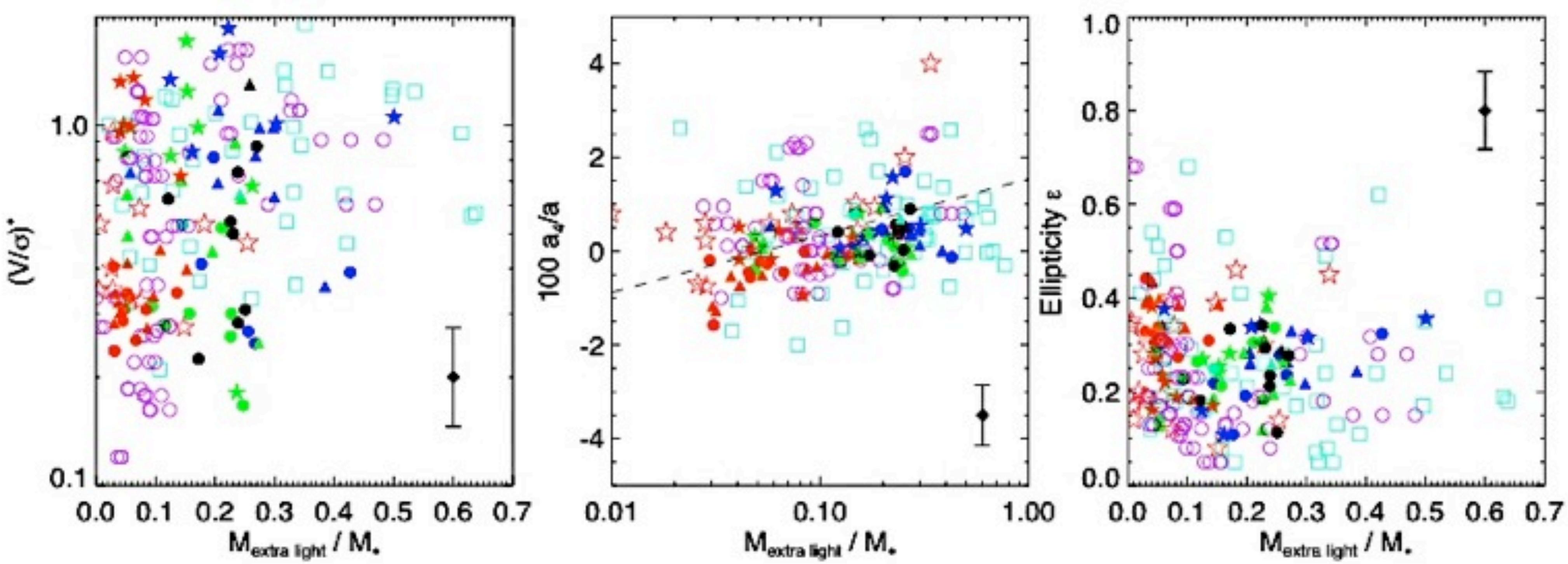

*OUTER* Sersic index is independent of mass, radius, etc.

--- gravity is self-similar



# Structure in Elliptical Light Profiles

## RECOVERING THE ROLE OF GAS

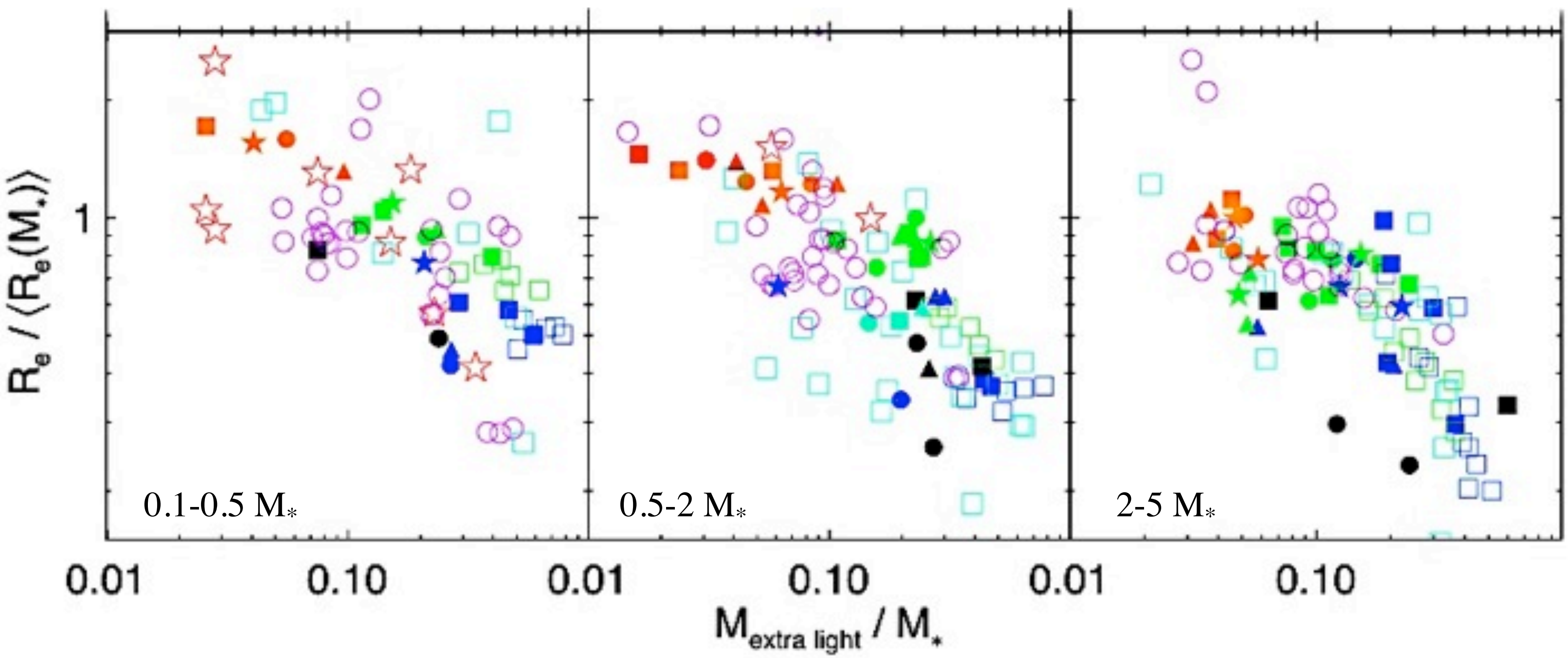


# Structure in Elliptical Light Profiles

## RECOVERING THE ROLE OF GAS

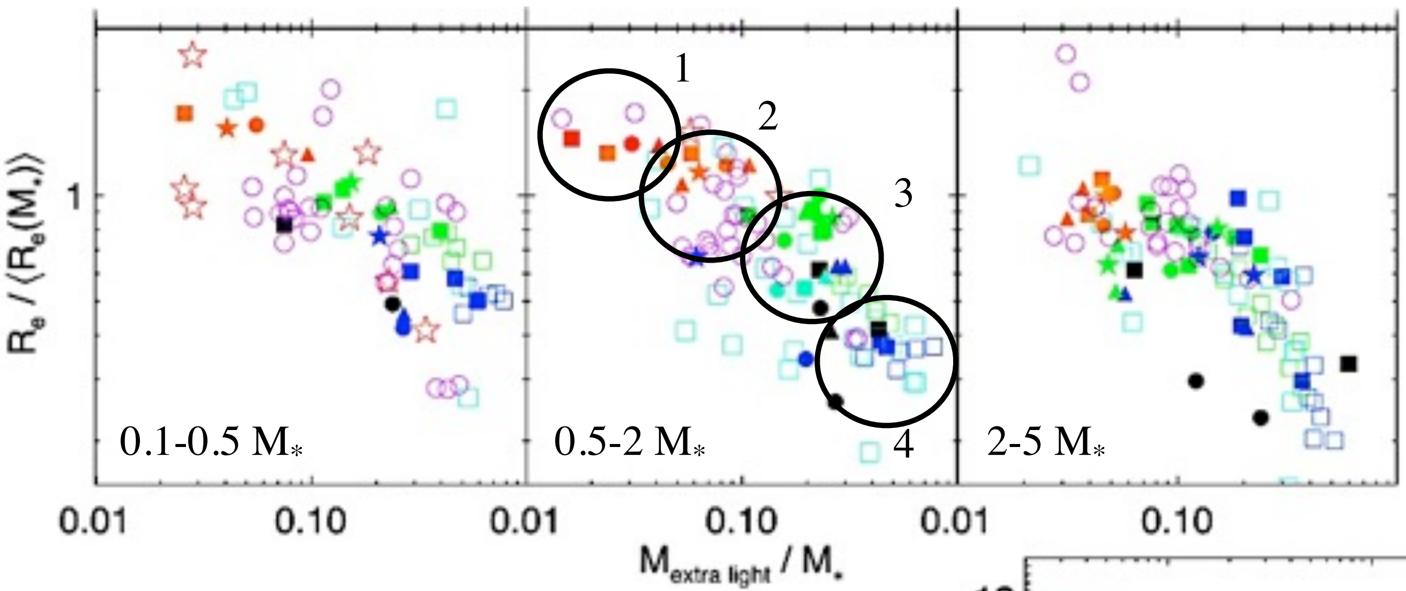
- Systems with more “extra light” are smaller

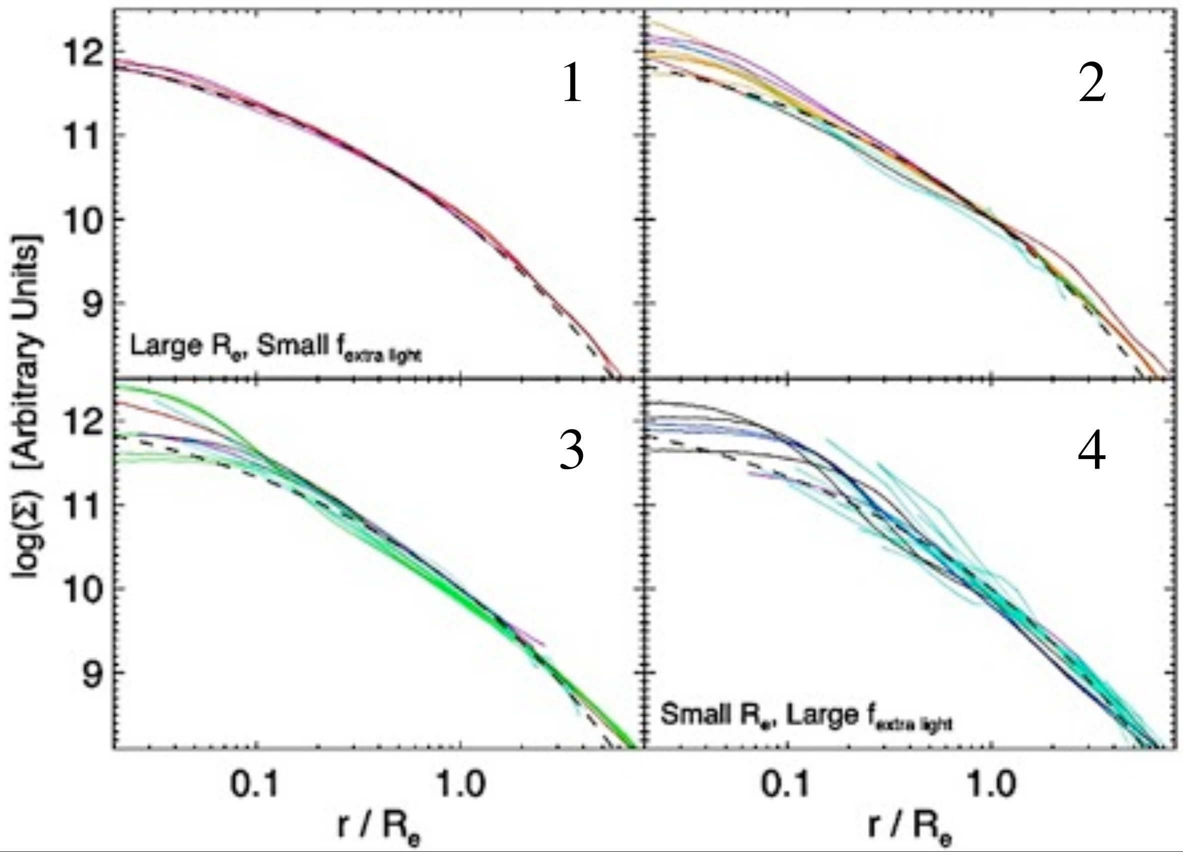
- Put more mass into a central dissipational component:
  moves R_e inward
  more of the mass inside R_e is this (totally baryon-dominated)
  central cusp



# Structure in Elliptical Light Profiles

## RECOVERING THE ROLE OF GAS

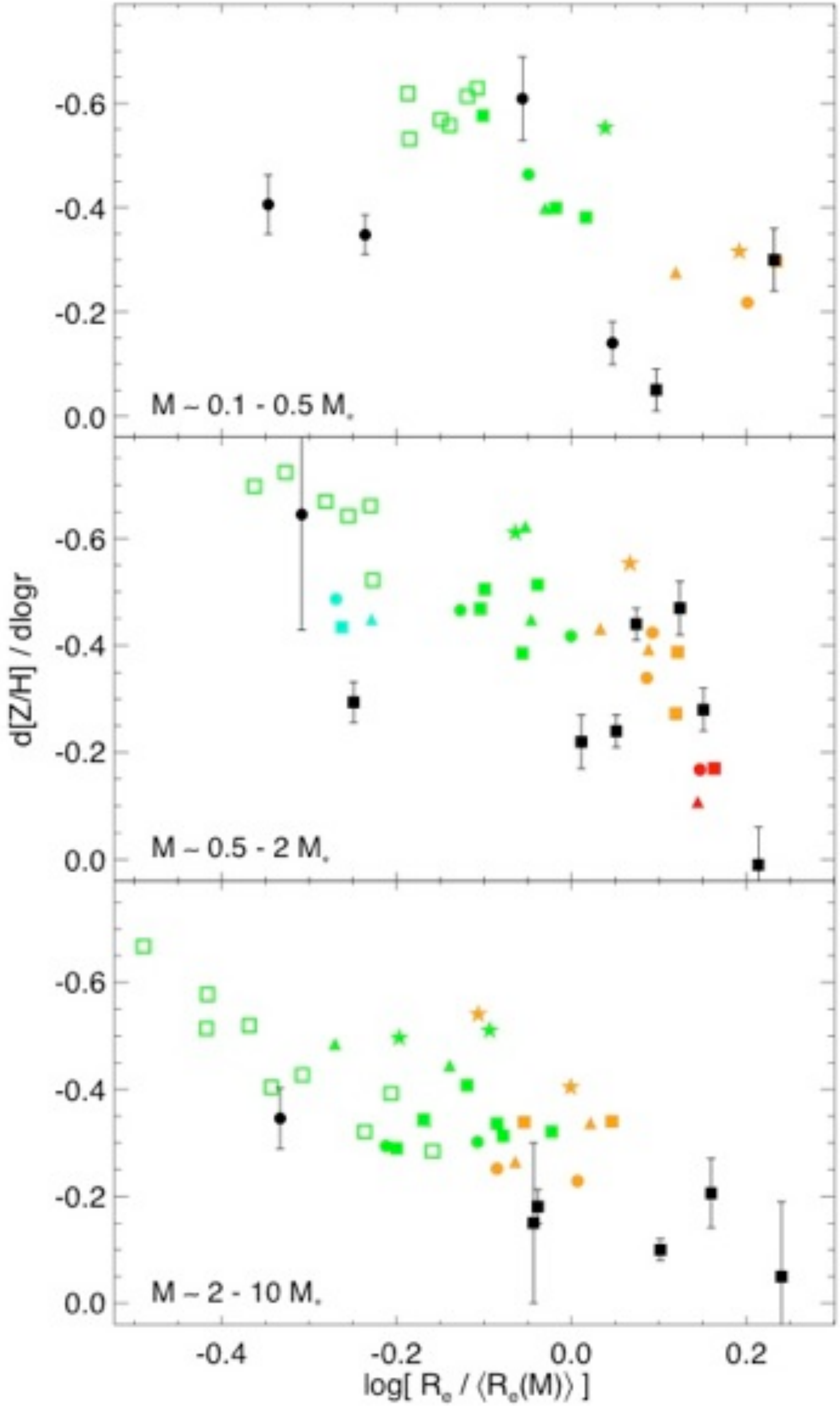


# Structure in Elliptical Light Profiles

## RECOVERING THE ROLE OF GAS

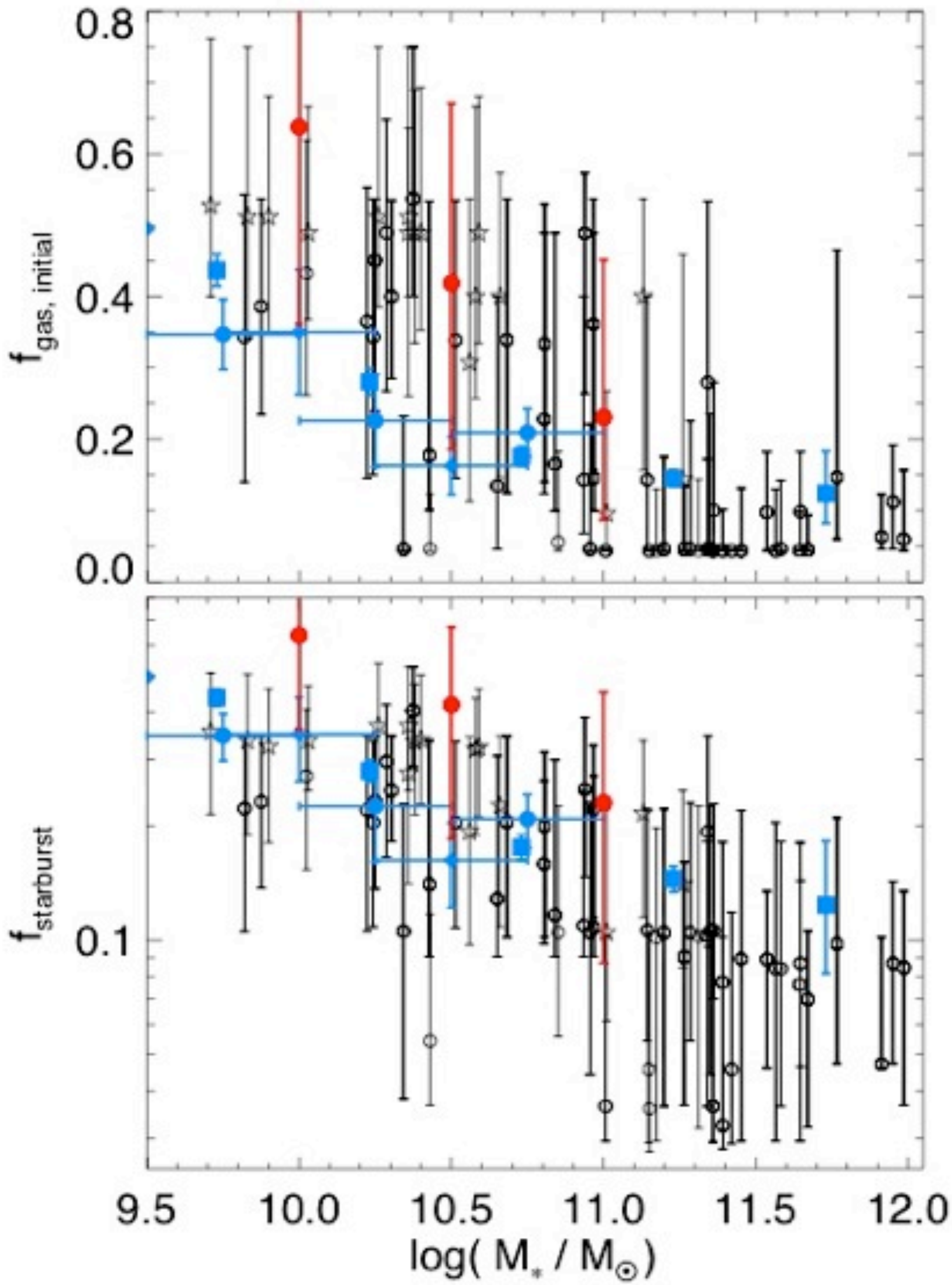
- Get accompanying predictions for how stellar populations & their gradients should scale with size, luminosity, etc.



# Structure in Elliptical Light Profiles

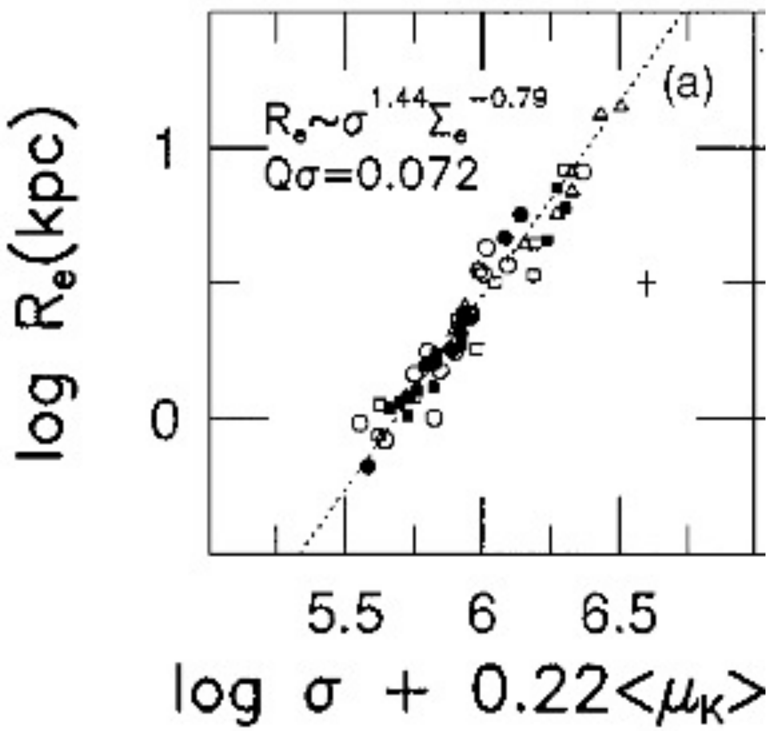
## RECOVERING THE ROLE OF GAS

- 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
- Recover the *observed* dependence of f_gas on disk mass

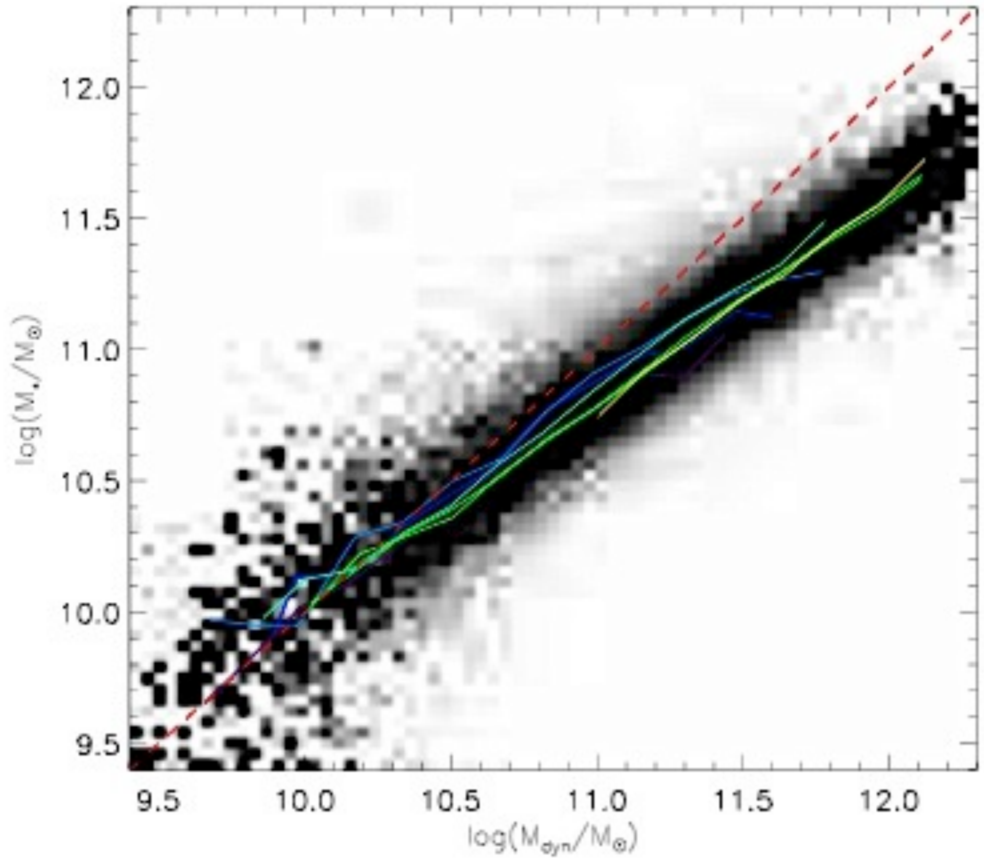


# Fundamental Plane Tilt

## WHERE DOES IT COME FROM?




Pahre et al. 1998

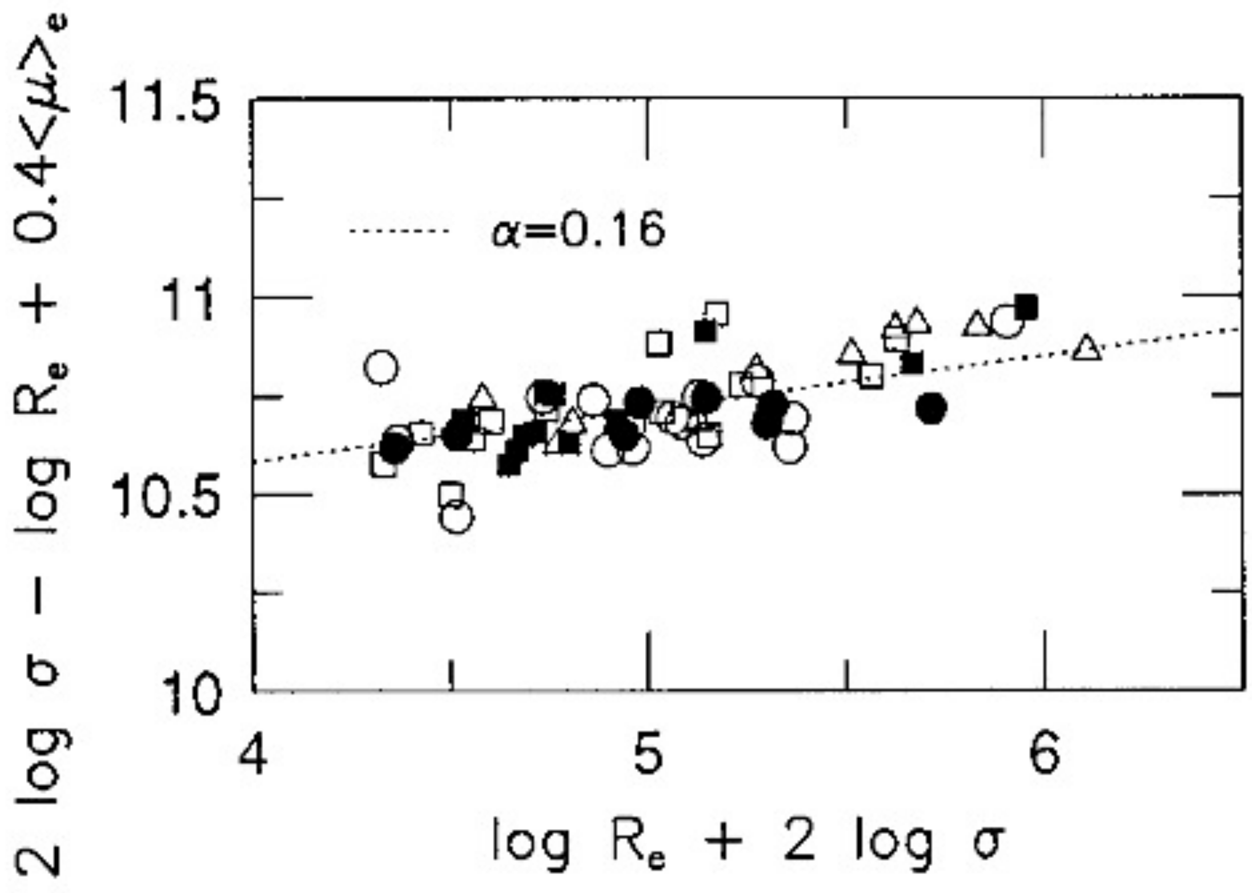



Gallazzi et al. 2007

# Fundamental Plane Tilt

## WHERE DOES IT COME FROM?

- M_dyn / M_stellar is an increasing function of either M




- SOME non-homology in ellipticals

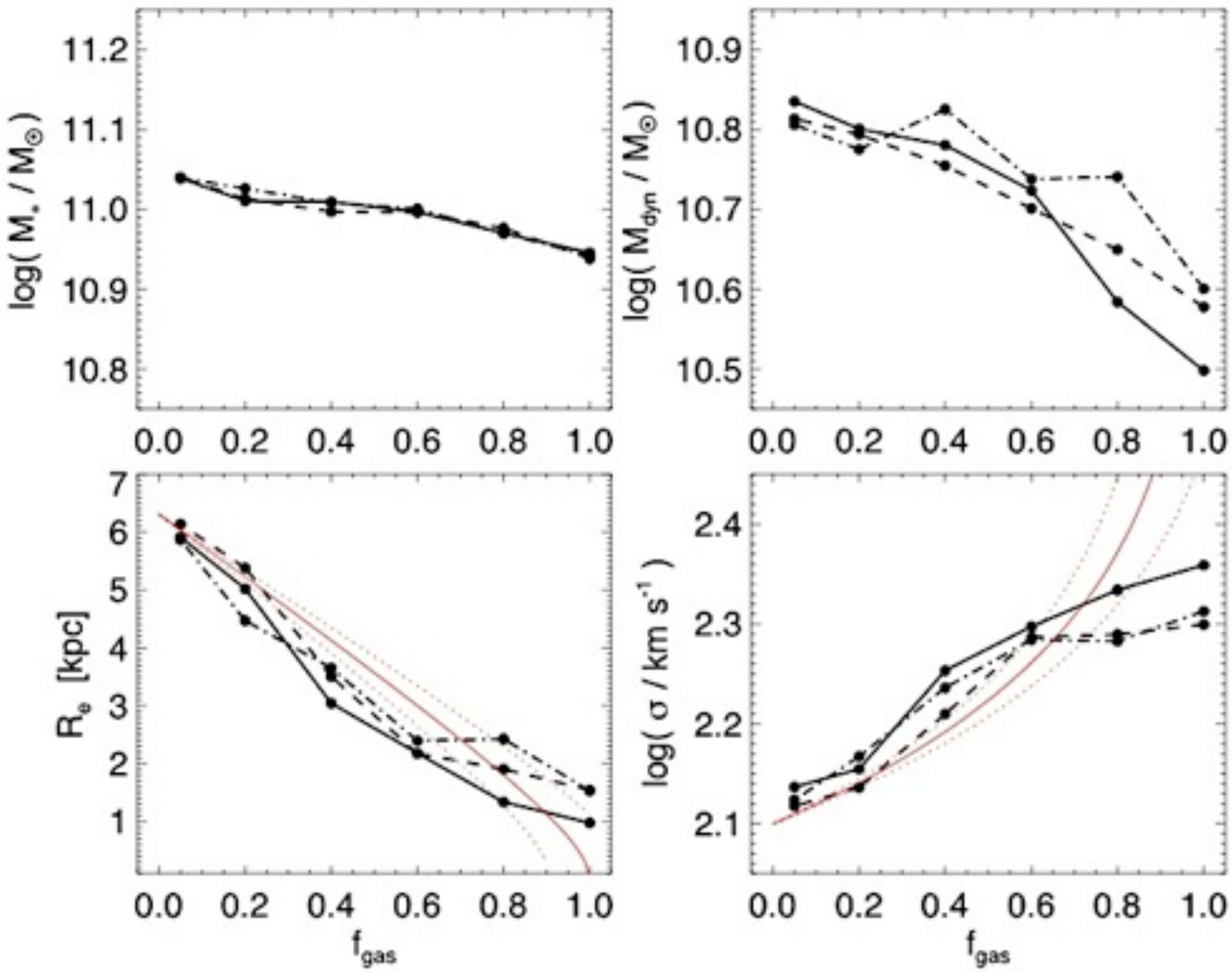
Pahre et al. 1998

# Fundamental Plane Tilt

## WHERE DOES IT COME FROM?

- Recall: more dissipation moves R_e in, to where the system is more baryon-dominated:

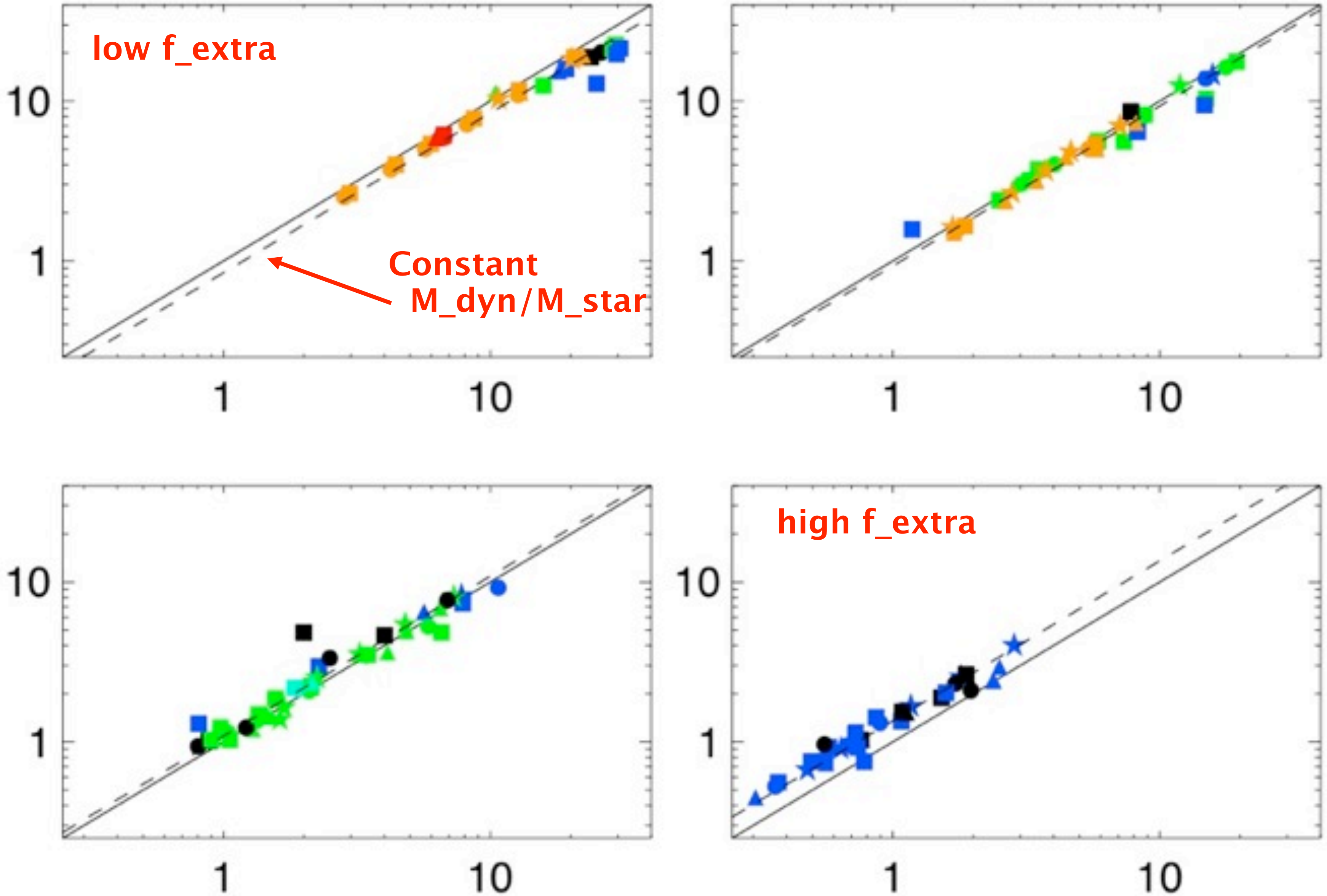
  lowers M_dyn / M_stellar



# Fundamental Plane Tilt

## WHERE DOES IT COME FROM?

- Look at systems with the *same* extra light mass::



# Fundamental Plane Tilt

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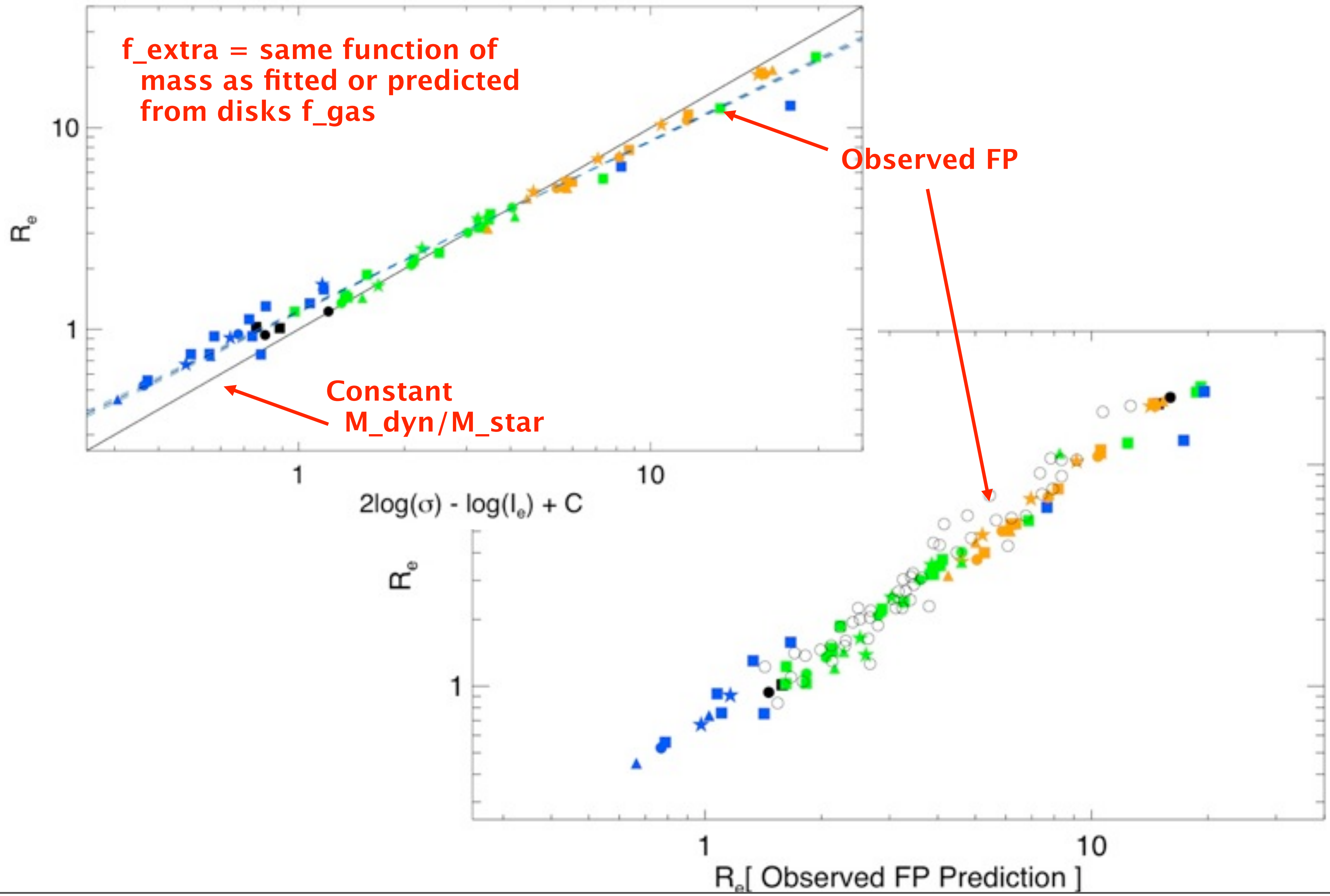
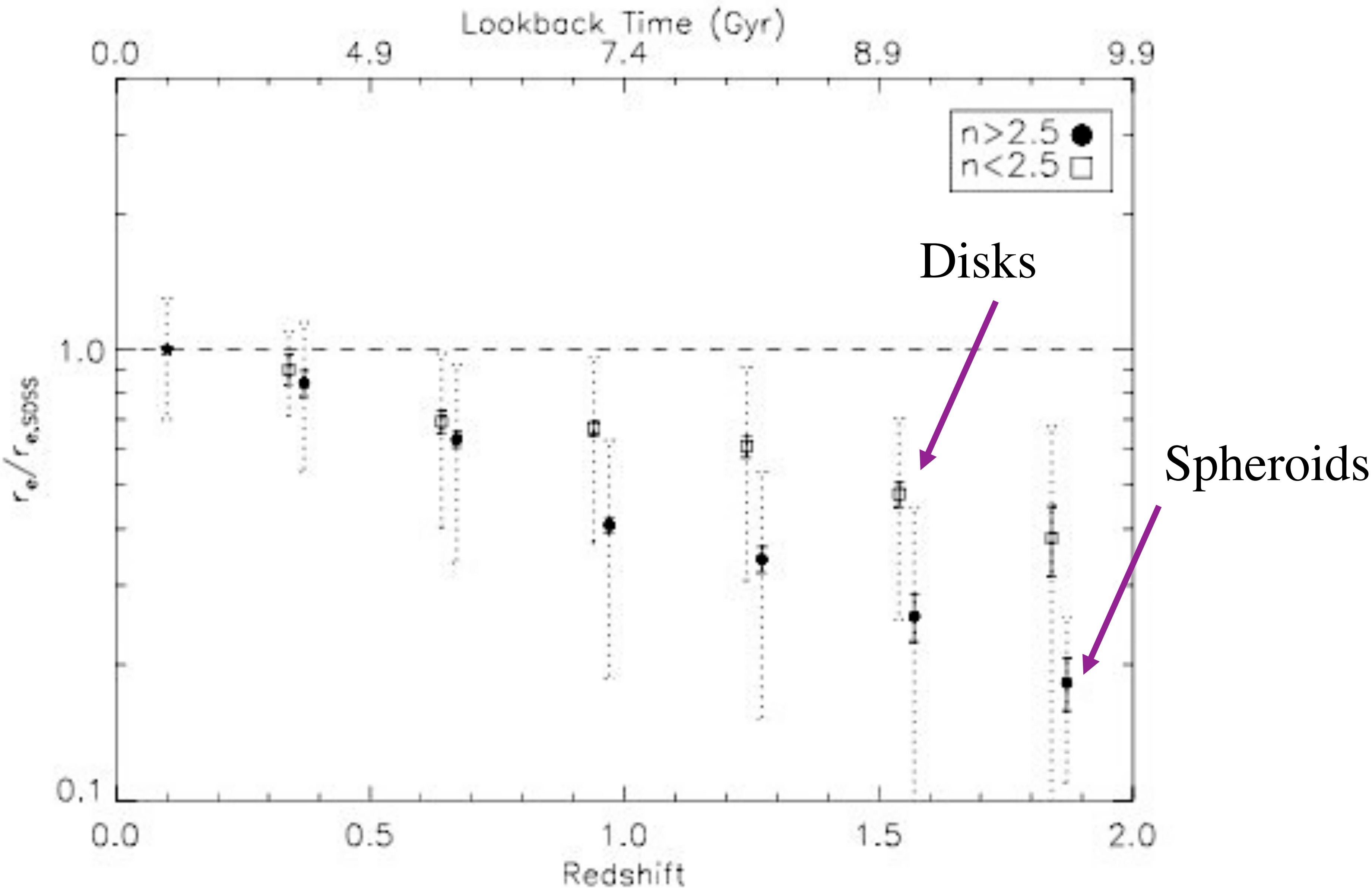


# Redshift Evolution
## SIZE-MASS RELATIONS

Trujillo et al. 2007

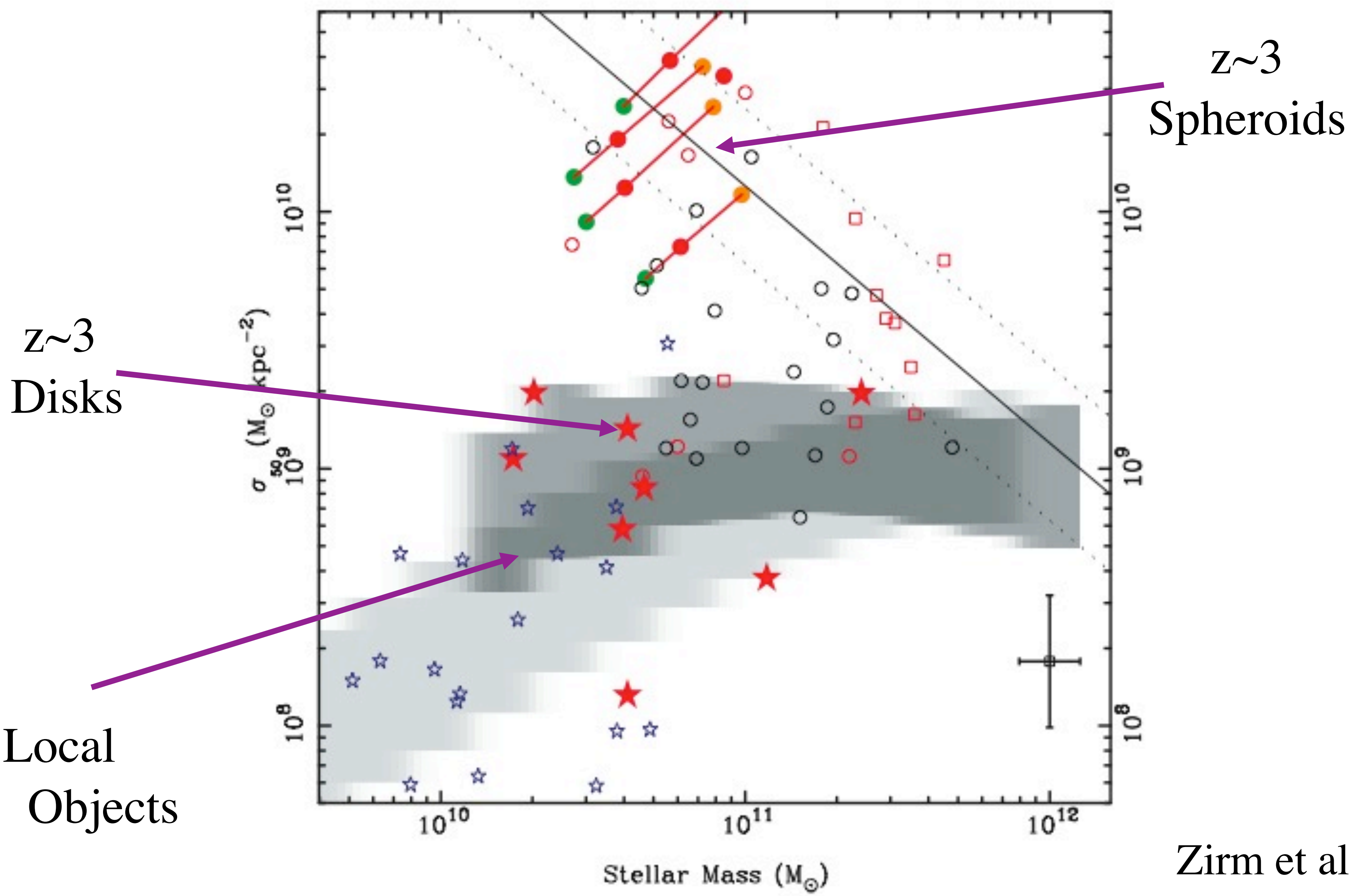
- Spheroids are getting smaller >2x as quickly as disks!



# Redshift Evolution

## SIZE-MASS RELATIONS

- By z~3, massive ellipticals are little bigger than a starburst (~kpc)

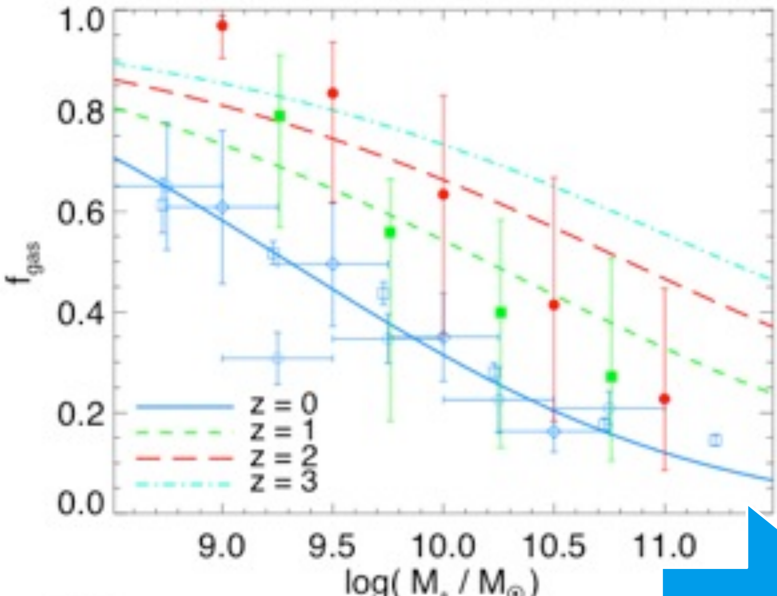


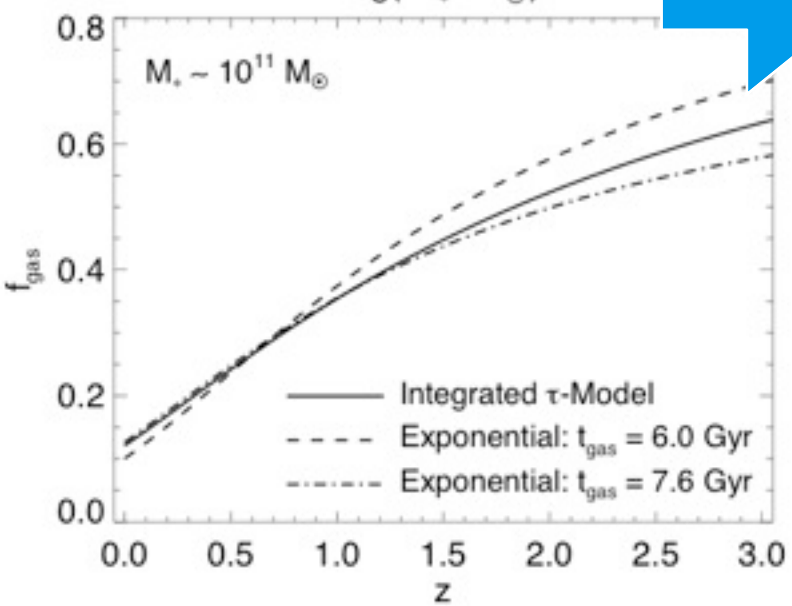

Zirm et al.

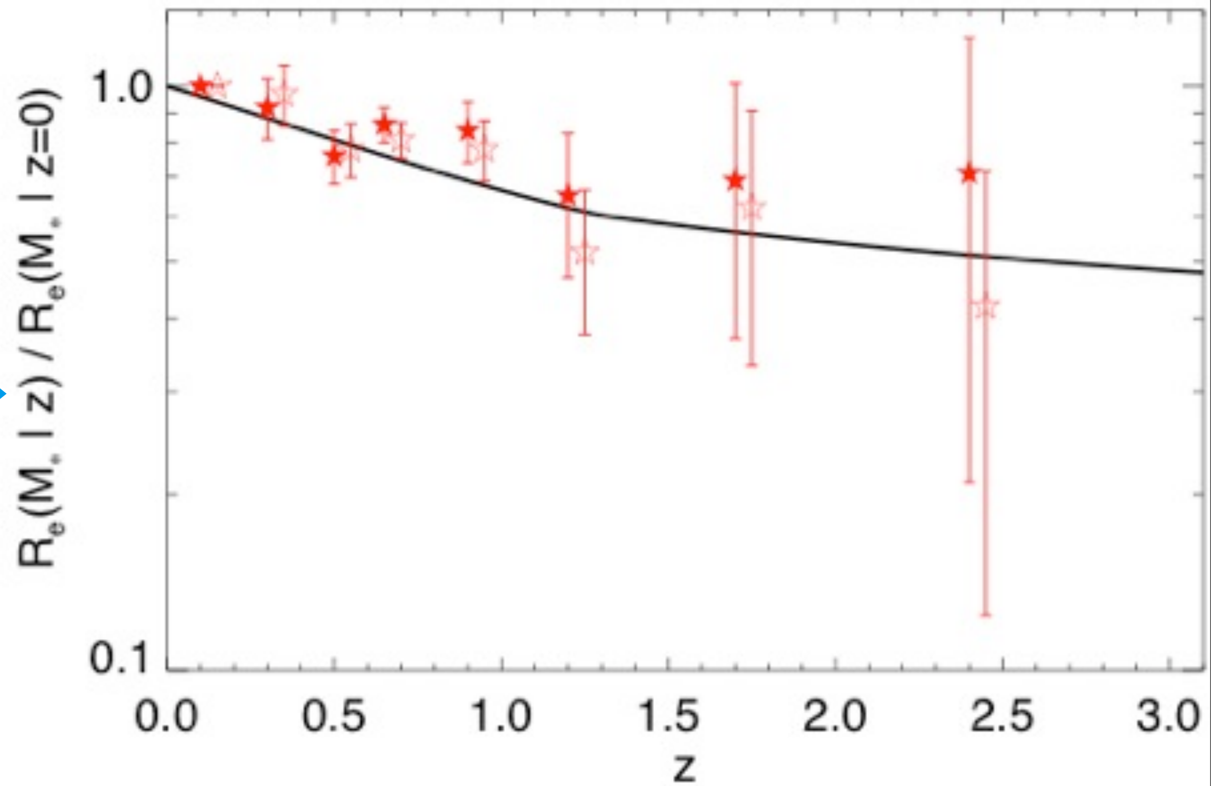
# Redshift Evolution

## SIZE-MASS RELATIONS

- High-z galaxies are more gas-rich:
  - Expect more compact remnants (see also Khochfar & Silk)



# Redshift Evolution

## SIZE-MASS RELATIONS

- Where are they now?

- Dry (spheroid-spheroid) merger:

  Typical orbits weakly bound -- E_final = E_initial = 2 ( M_i * sigma_i^2)

  M_f = 2 M_i -- so sigma_f = sigma_i

  virial theorem -- R_f = 2 * R_i

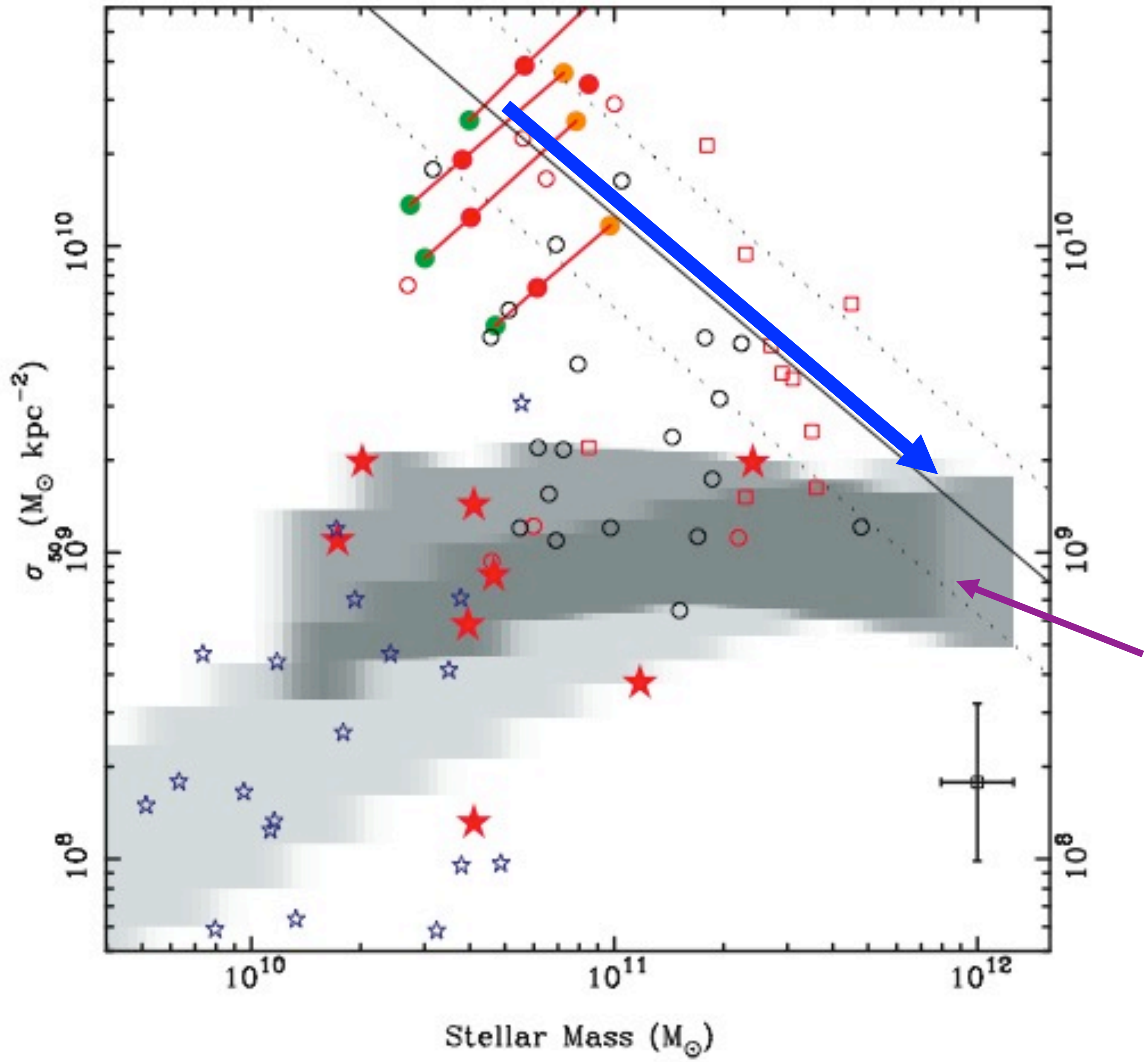
- Relative to the slope of the size mass relation (R ~ M^1/2), you're rapidly moving up (increasing R)

- High-z early mergers are *exactly* the systems expected to have more dry mergers

## Redshift Evolution

SIZE-MASS RELATIONS

Direction dry mergers move you

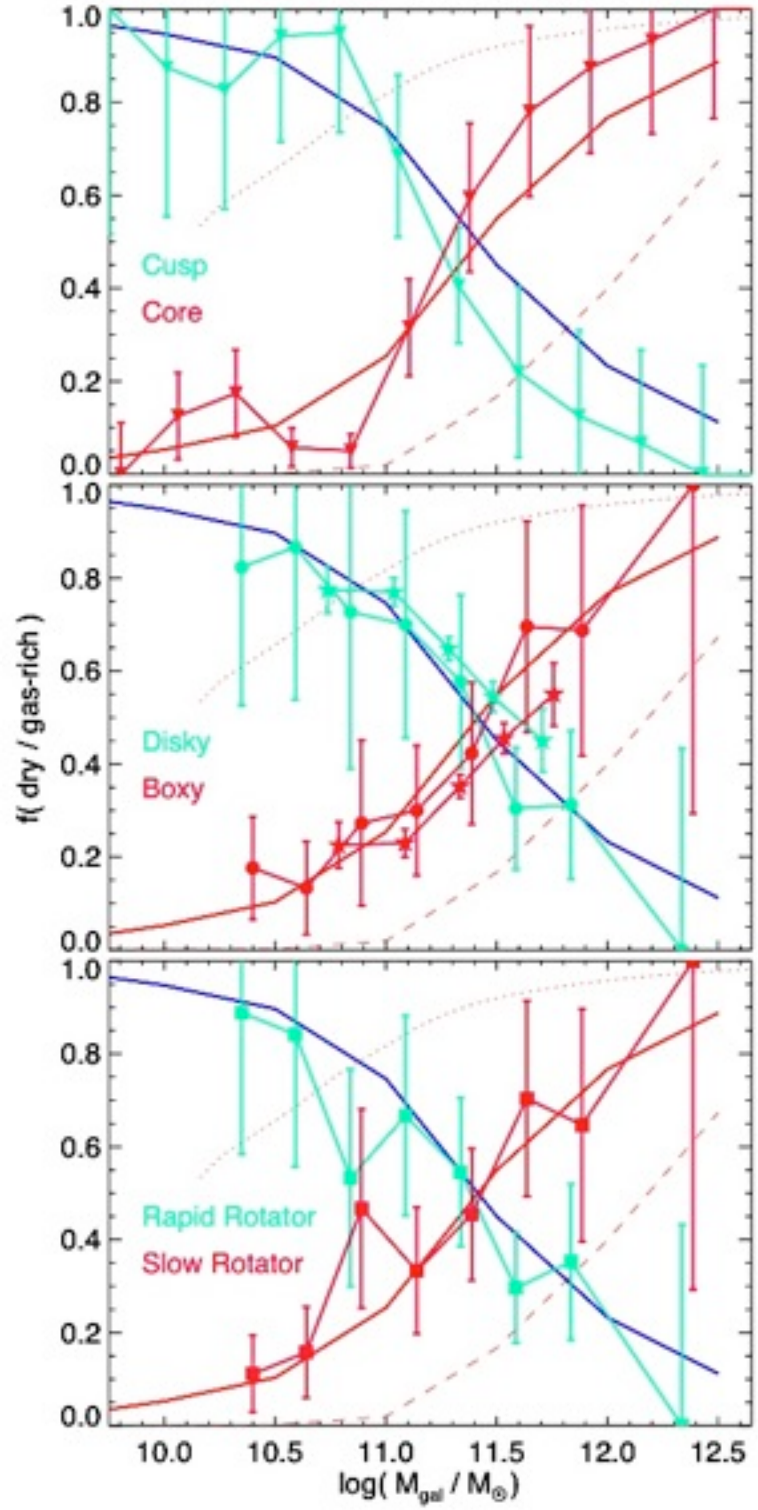



these z~3 galaxies are the most massive galaxies today

# What about the "Cores"?

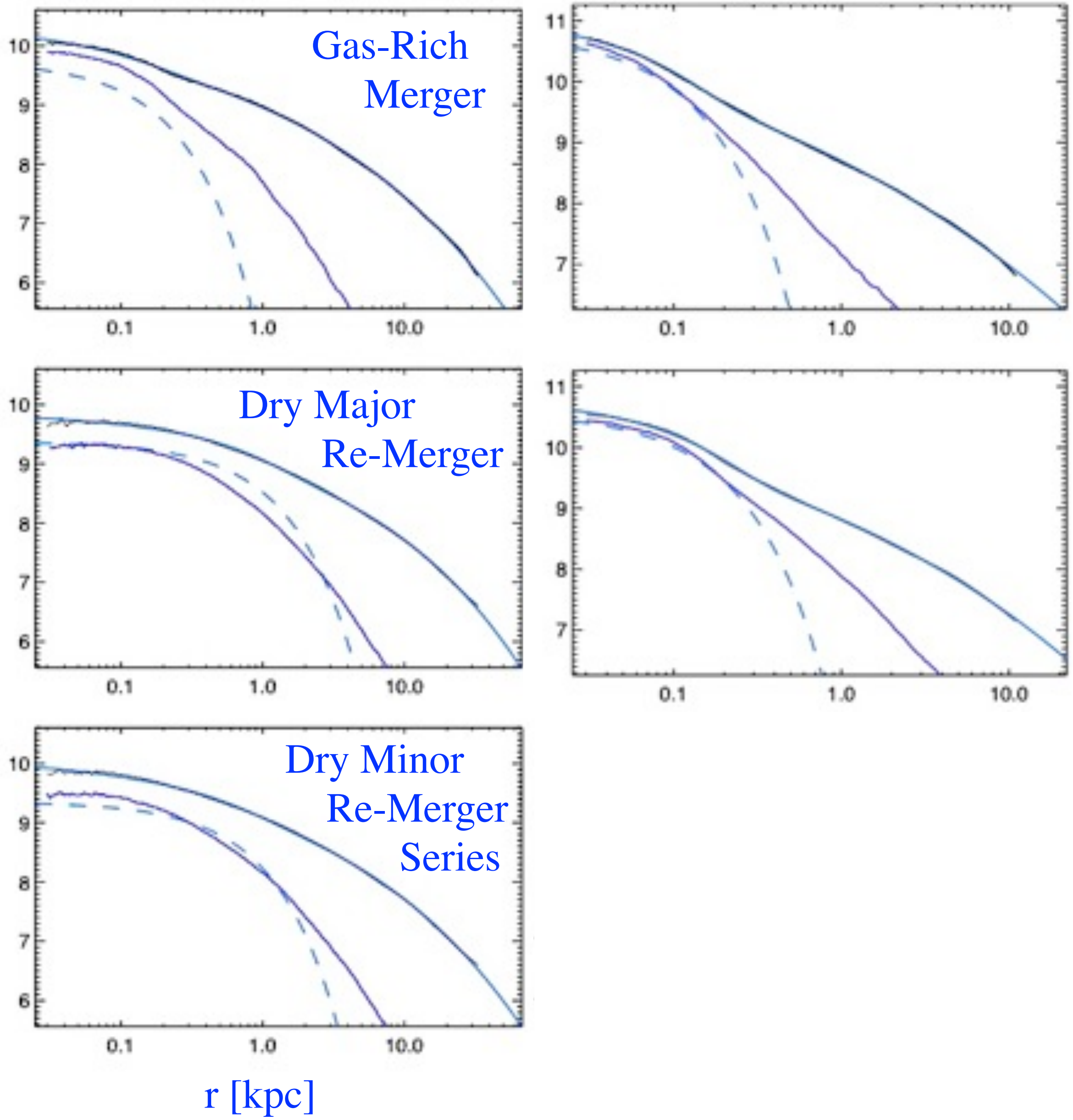
CAN THIS BE EXTENDED TO THE MOST MASSIVE ELLIPTICALS?

- Massive ellipticals tend to have "cores" or flattening in their centers (central ~10-30pc)
  - Typically associated with BH "scouring" in subsequent gas-poor re-mergers ("dry mergers")
  - But now it is typically claimed that they are "missing" up to ~a few % of their light (~10-50x M_bh) out to ~100-500 pc
  - What happened to all that "extra light"?



# What about the "Cores"?

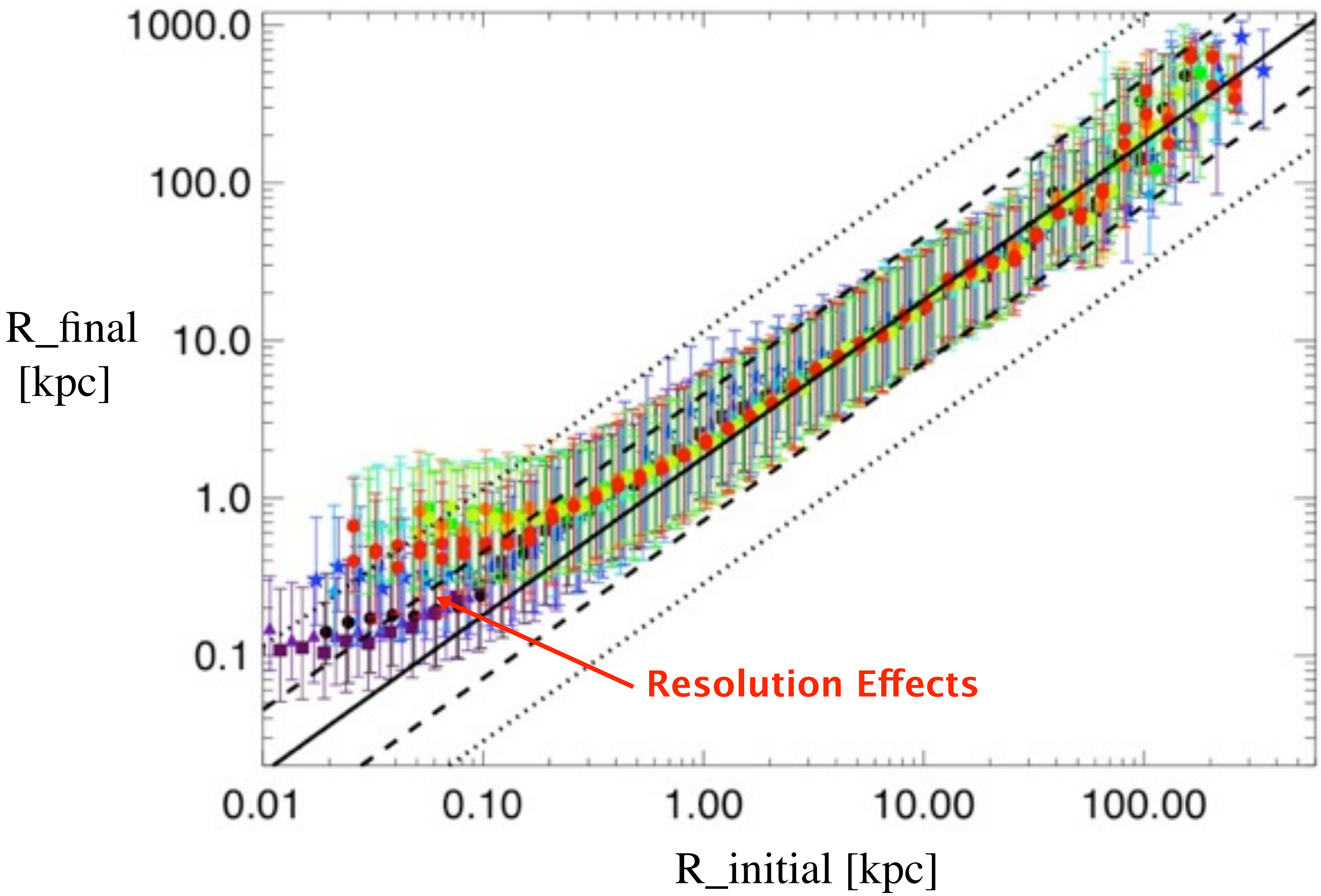
## CAN THIS BE EXTENDED TO THE MOST MASSIVE ELLIPTICALS?




- Re-mergers in simulations preserve the extra light: applying our decomposition reliably extracts the "original" starburst stars

# Application: “Core” Ellipticals

## WHAT HAPPENS TO THE “EXTRA LIGHT”?

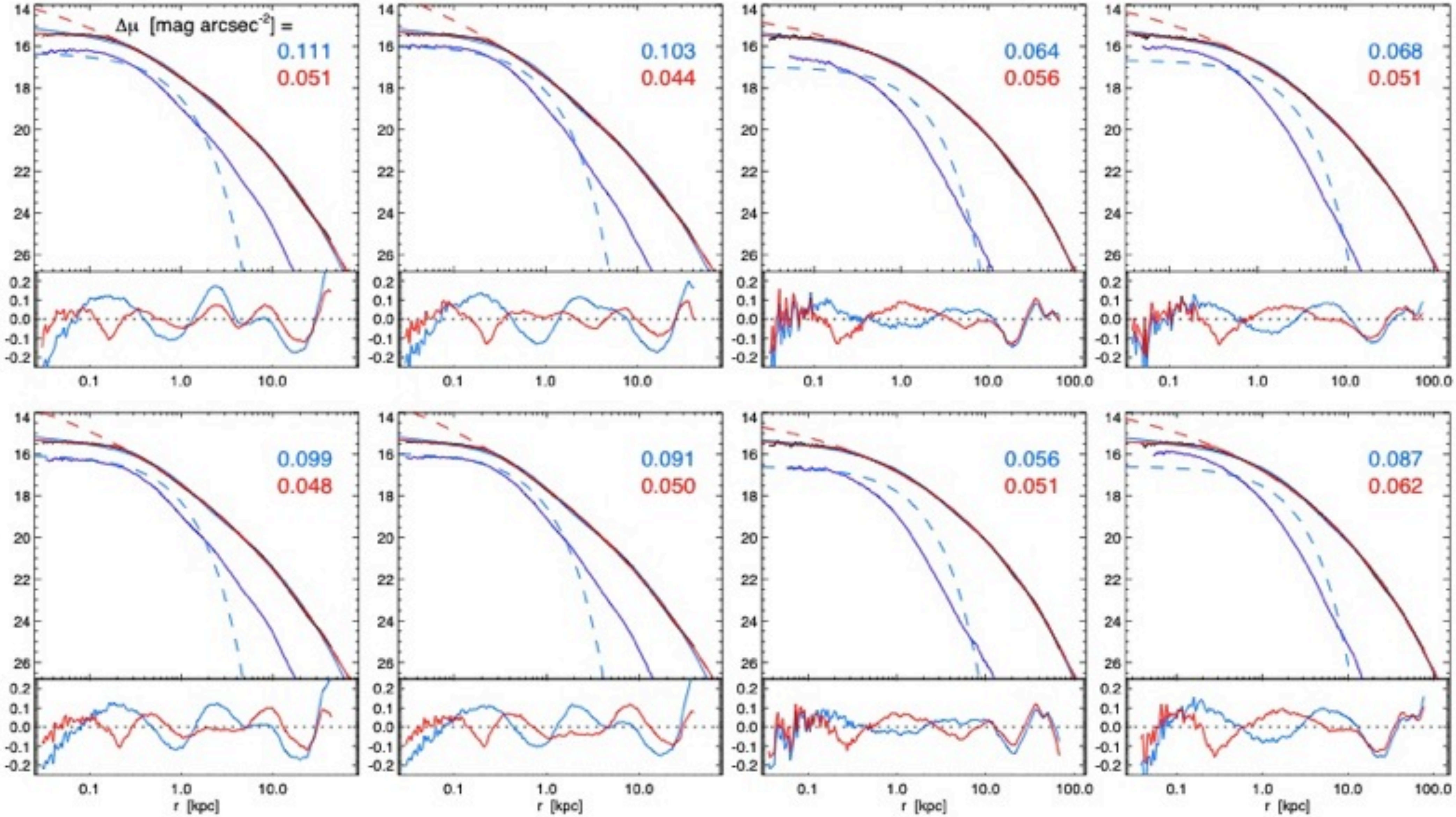



- Stars are puffed out, but preserve rank-ordering in radius (or binding energy)
  - Extra light is *NOT* destroyed in “dry mergers”

- However, there is significant (~0.4 dex) scattering :: the transition is “smoothed”

# Application: "Core" Ellipticals

## WHAT HAPPENS TO THE "EXTRA LIGHT"?

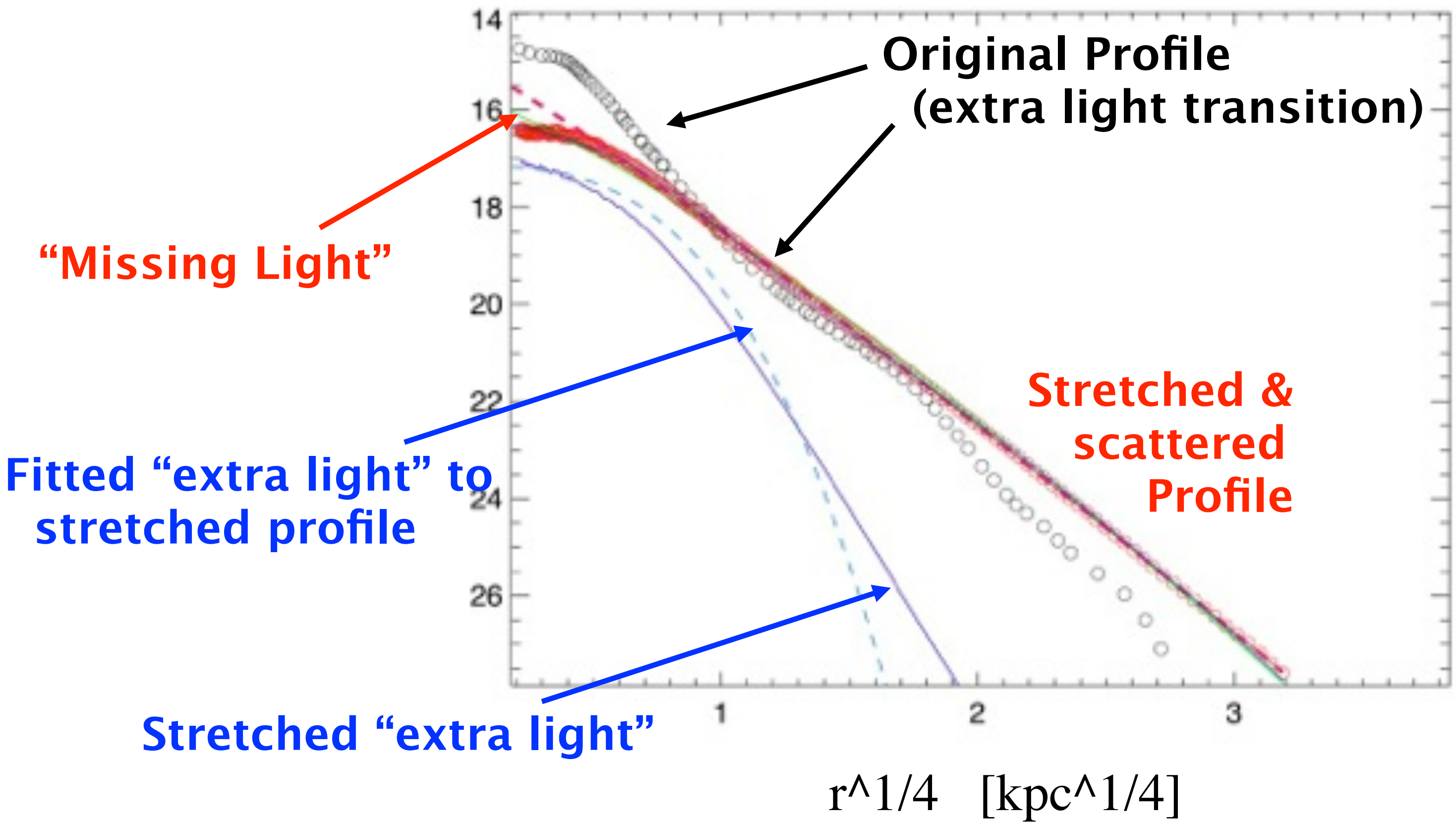



- Systems are now often better fit (technically) by a "core-Sersic" law with MISSING light in the center!

# Application: “Core” Ellipticals

## WHAT HAPPENS TO THE “EXTRA LIGHT”?

- Play the same game with the observed systems: stretch & scatter their stars



# Application: "Core" Ellipticals

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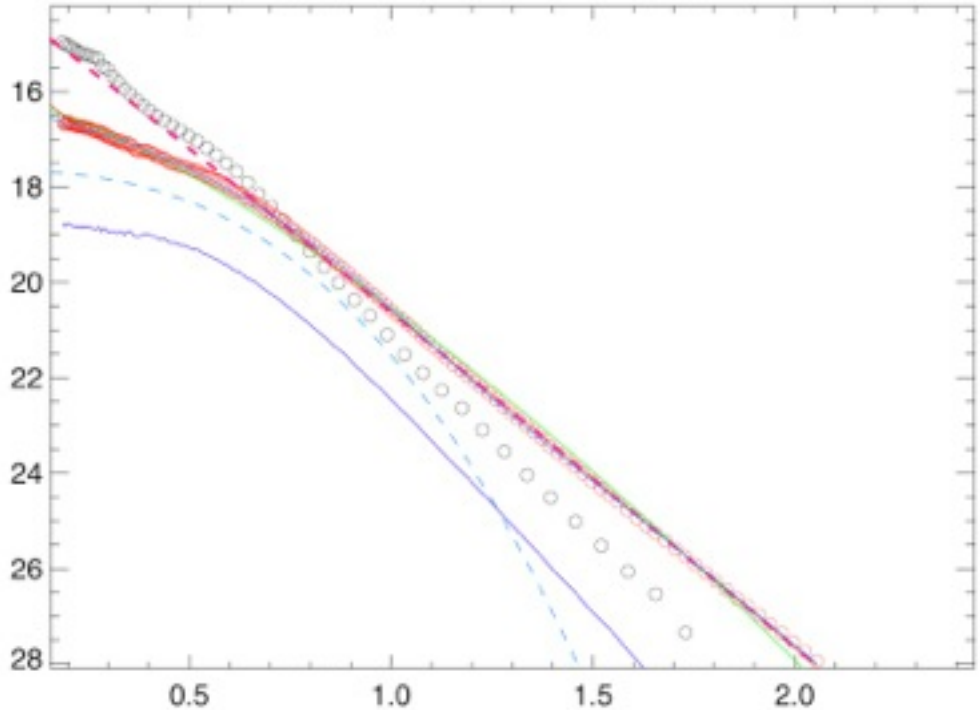
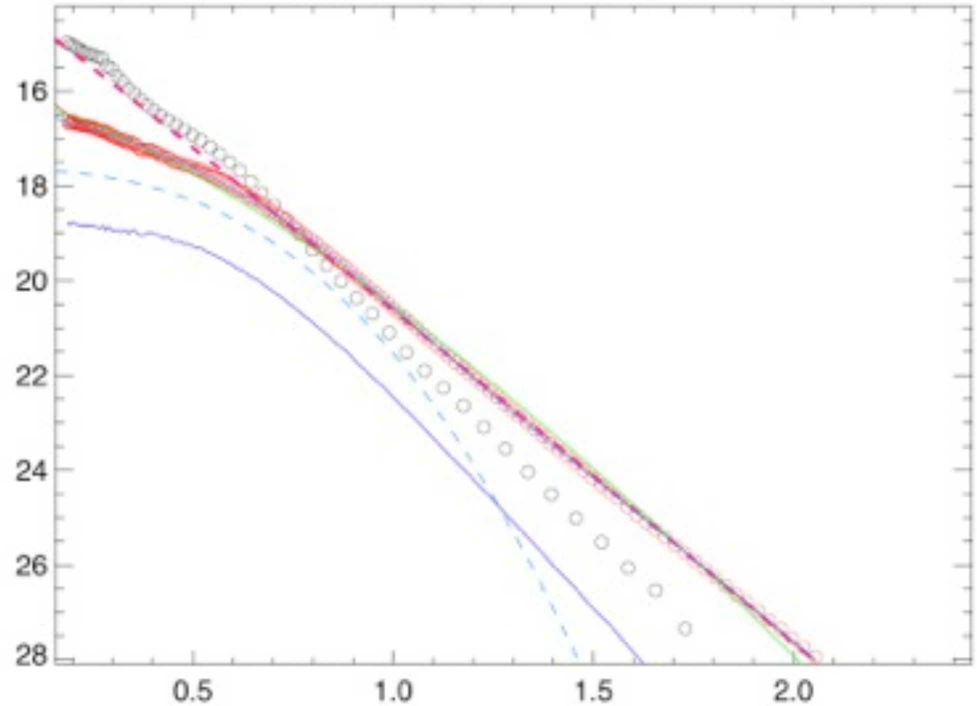



r^1/4 [kpc^1/4]




r^1/4 [kpc^1/4]

# Application: "Core" Ellipticals

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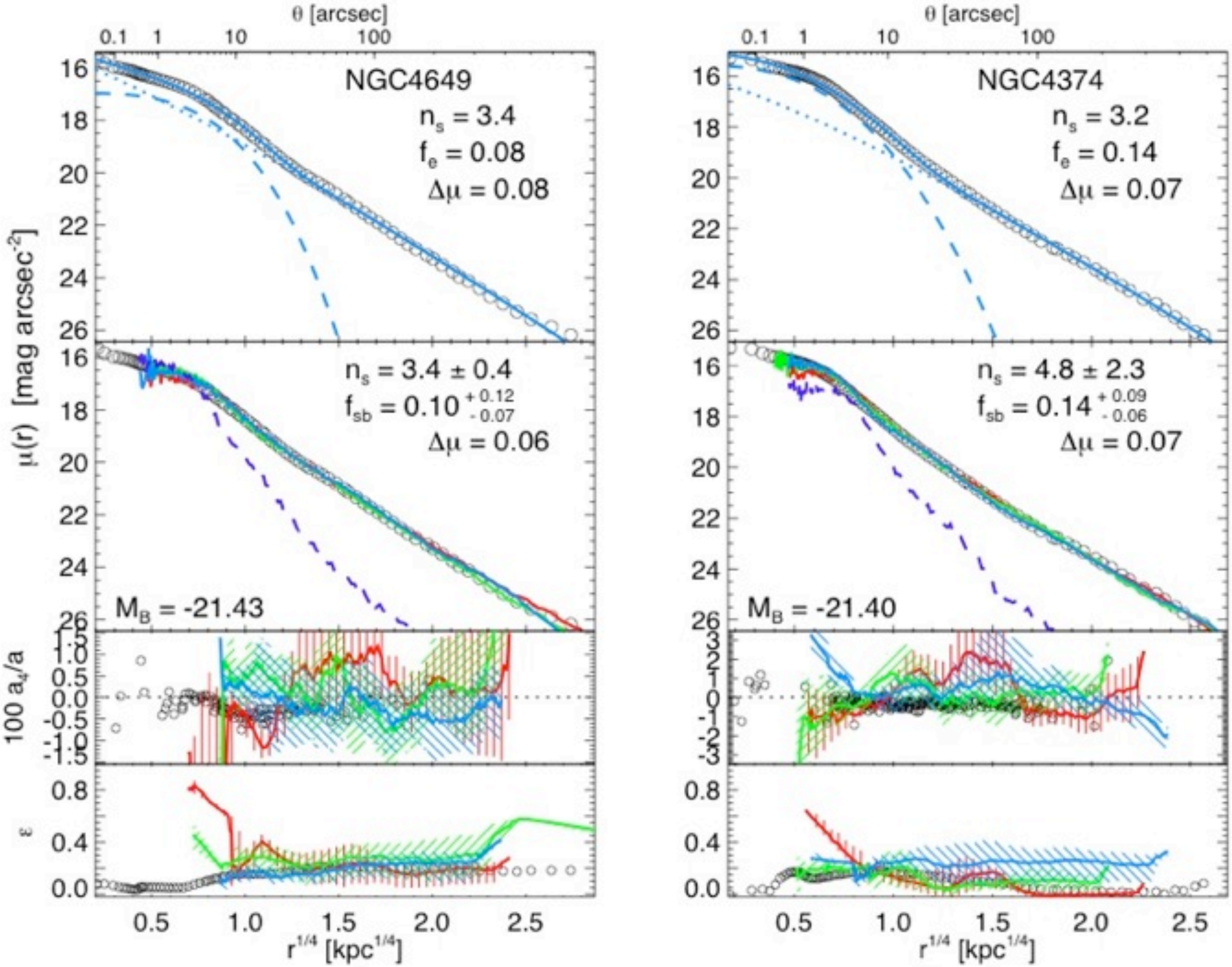

# Application: “Core” Ellipticals

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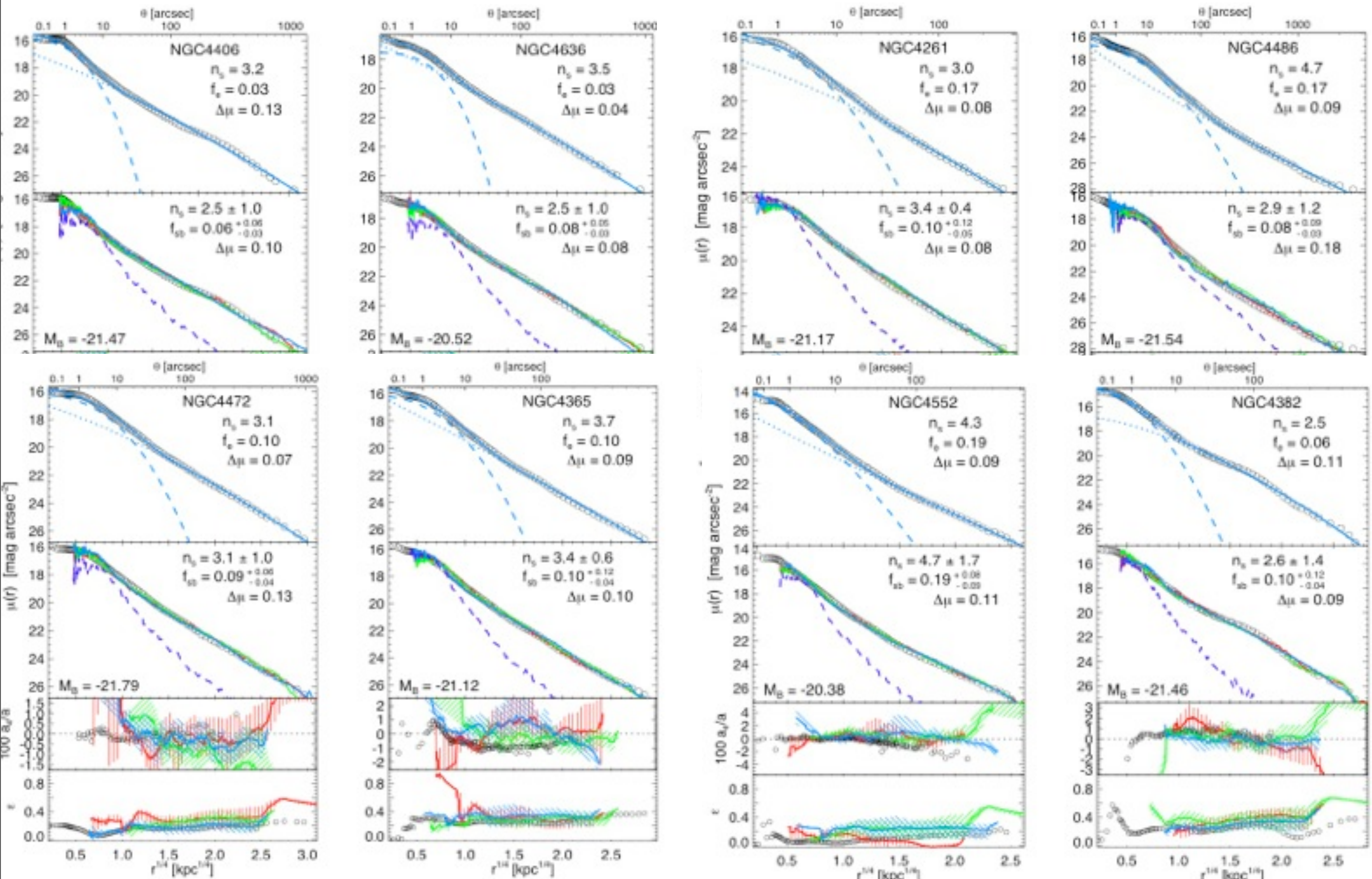

# Application: “Core” Ellipticals

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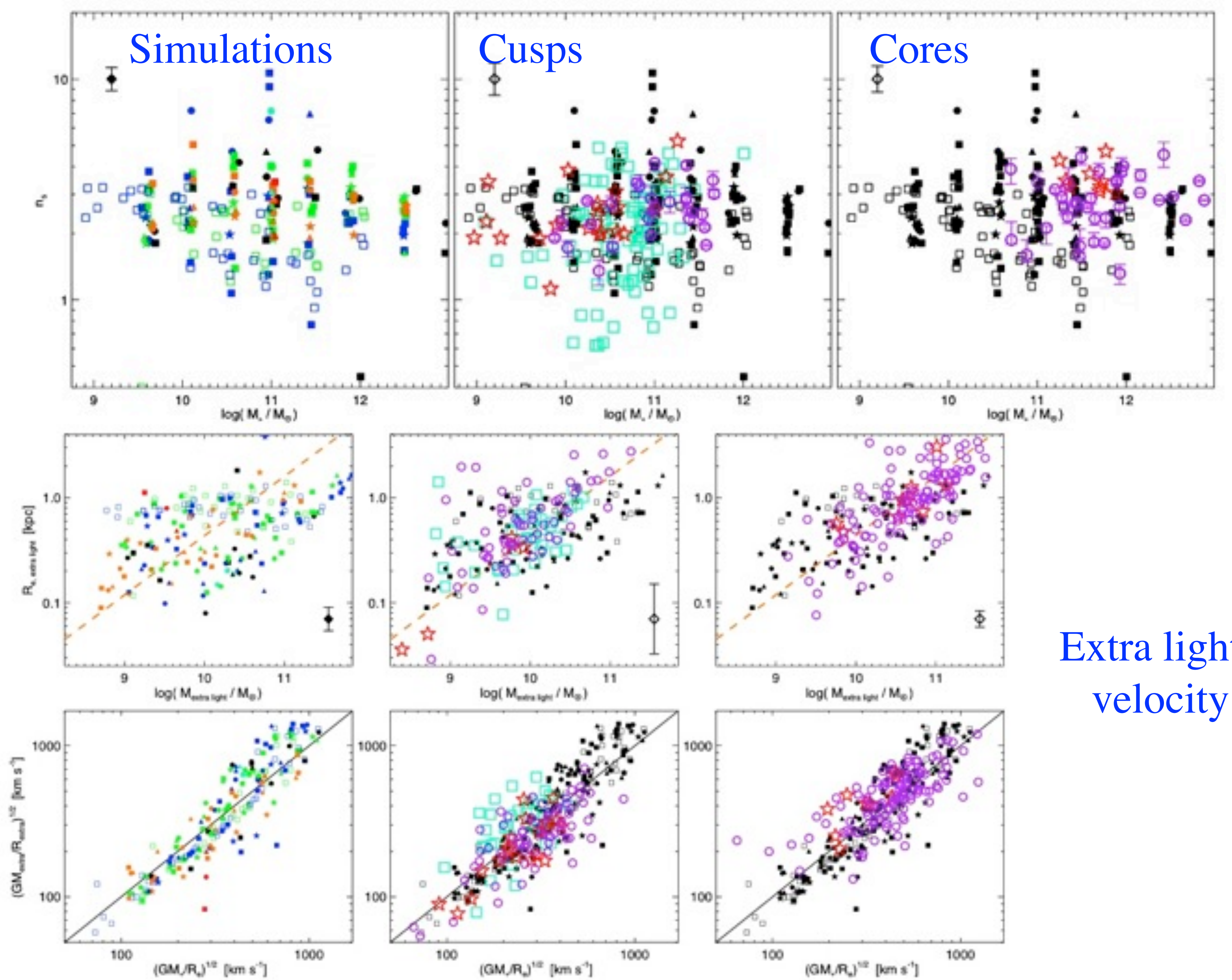
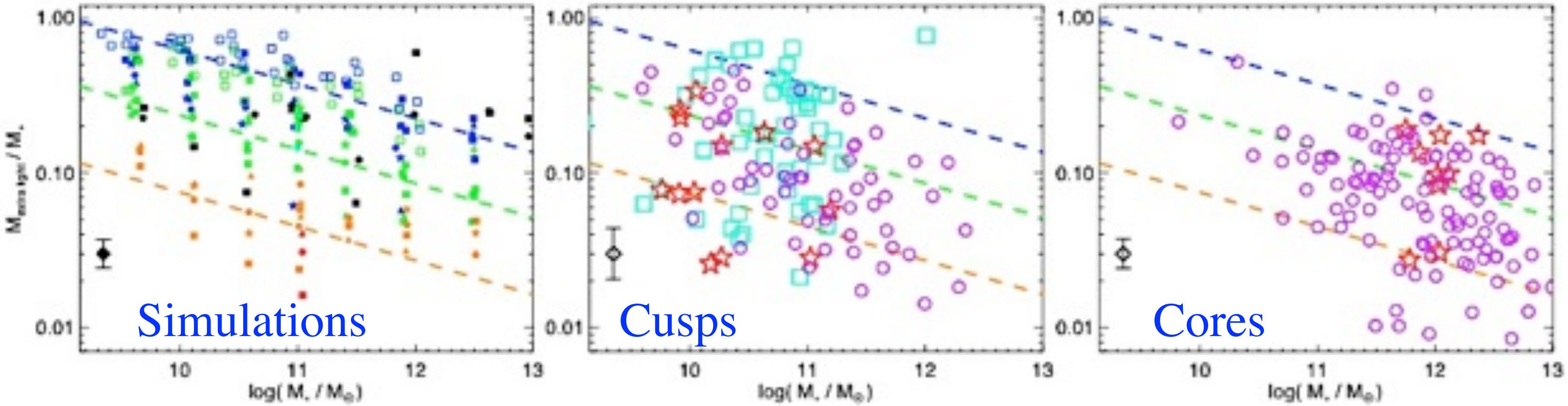



Outer Sersic index

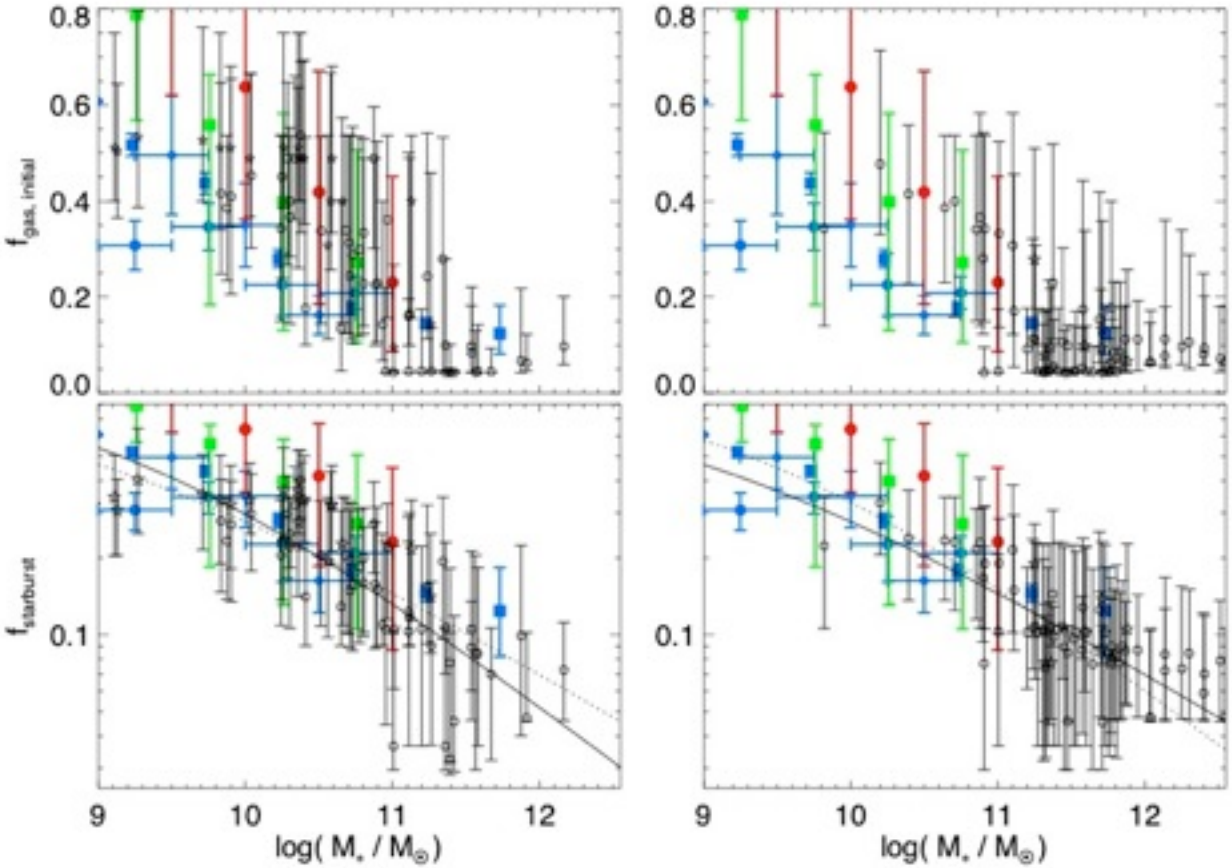
Extra light sizes/ velocity dispersions

# Application: “Core” Ellipticals

## WHAT HAPPENS TO THE “EXTRA LIGHT”?




Extra light mass fraction



# Summary

- All ellipticals have “extra light,” the remnants of the dissipational starburst from their formation event
  - Detailed observations can be separated into starburst light & violently relaxed populations
  - Extra light scales with mass: lower-mass systems had more dissipation

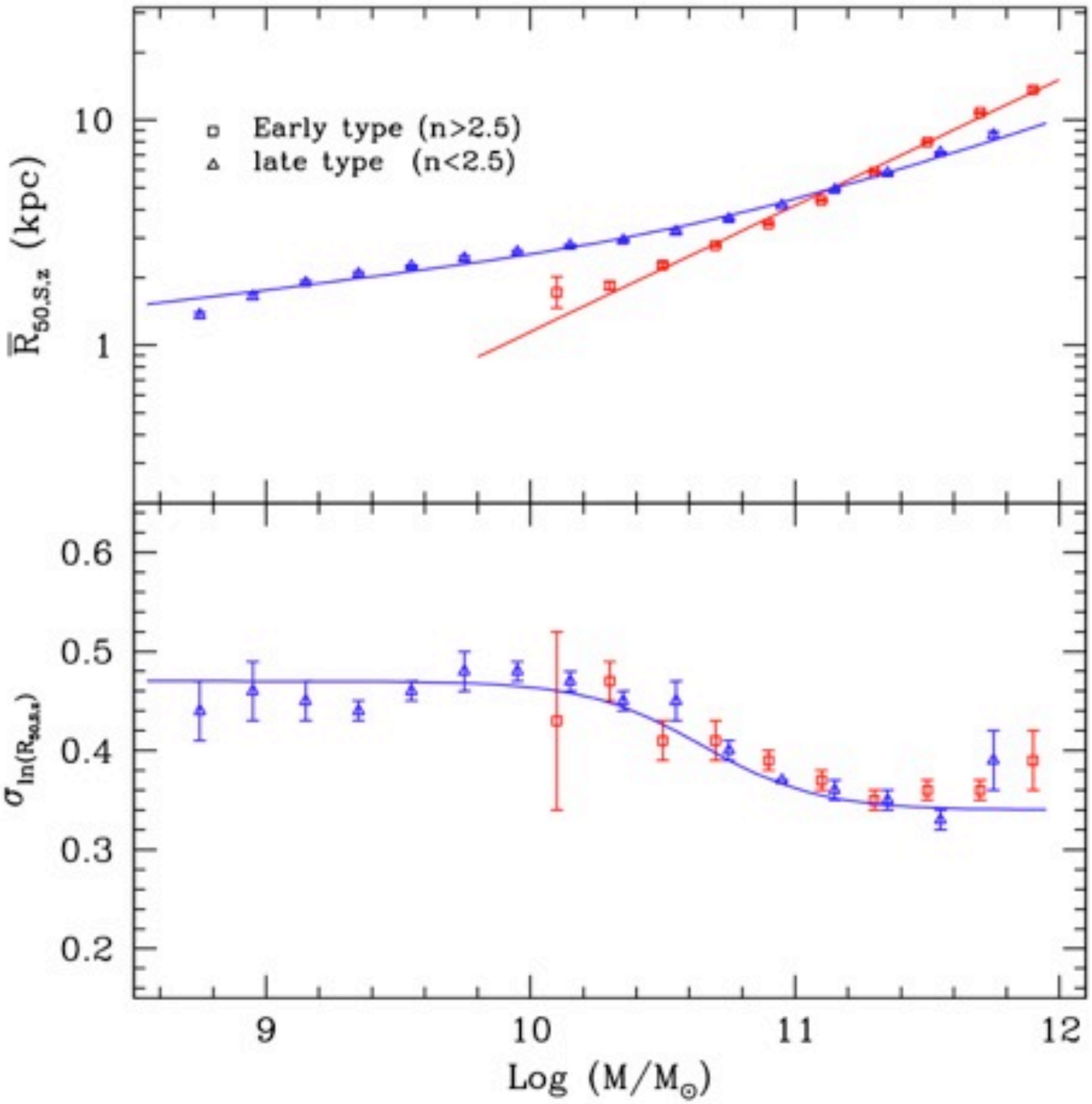
- This drives galaxies along the fundamental plane: more dissipation yields more compact remnants
  - This provides the first means to directly observationally test the idea that different degrees of dissipation produce the tilt in the FP

- While scouring may create “cores”, “missing light” is often an illusion caused by a particular choice of parametric fitting functions
  - Core ellipticals and cusp ellipticals have the same extra/starburst components: they both were formed *originally* in dissipational events

# Structure in Elliptical Light Profiles

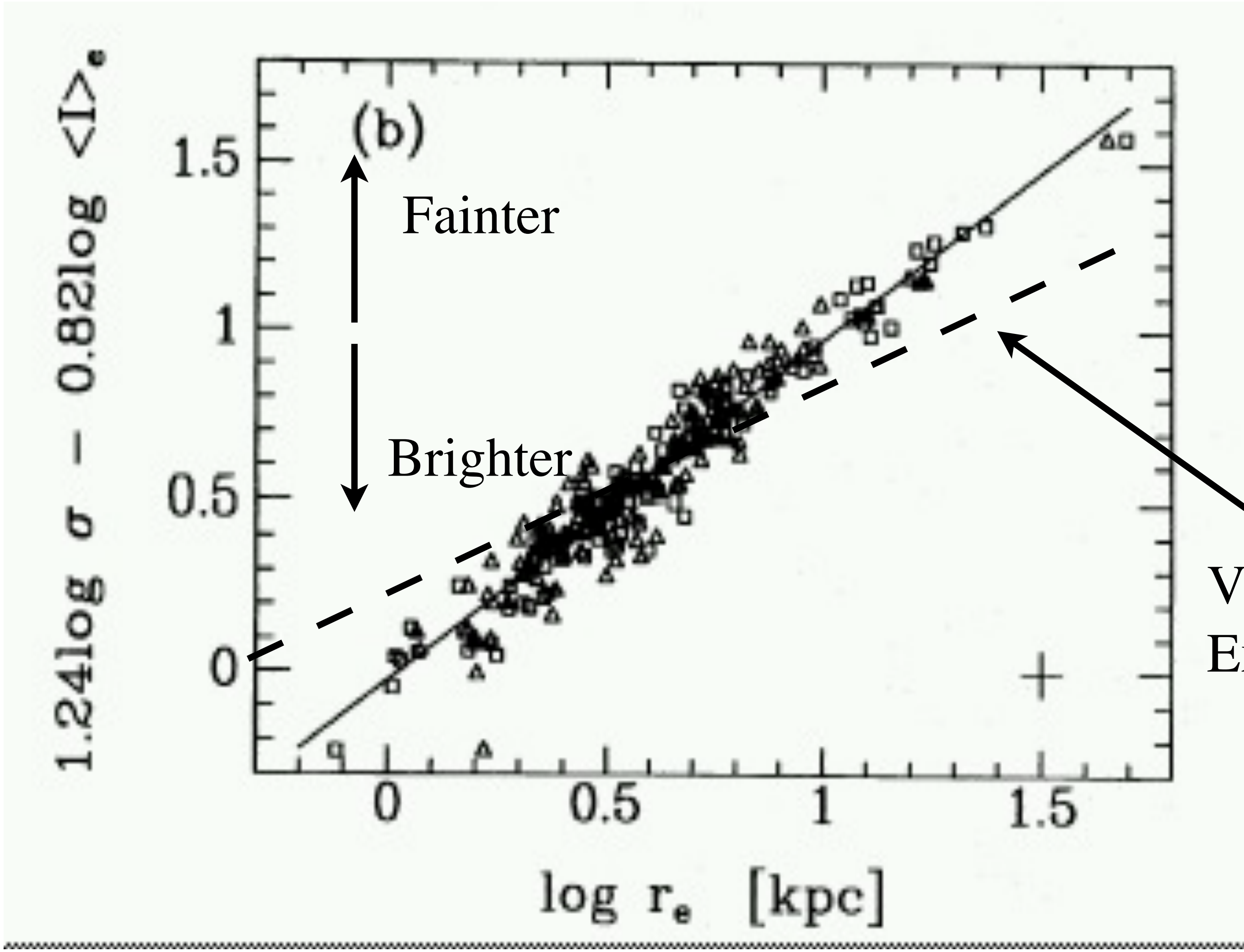
## THEIR SCALING LAWS

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



# Fundamental Plane Tilt

## STELLAR POPULATION VARIATION




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

# Structure of Spheroids

## UNDERSTANDING THE FUNDAMENTAL PLANE

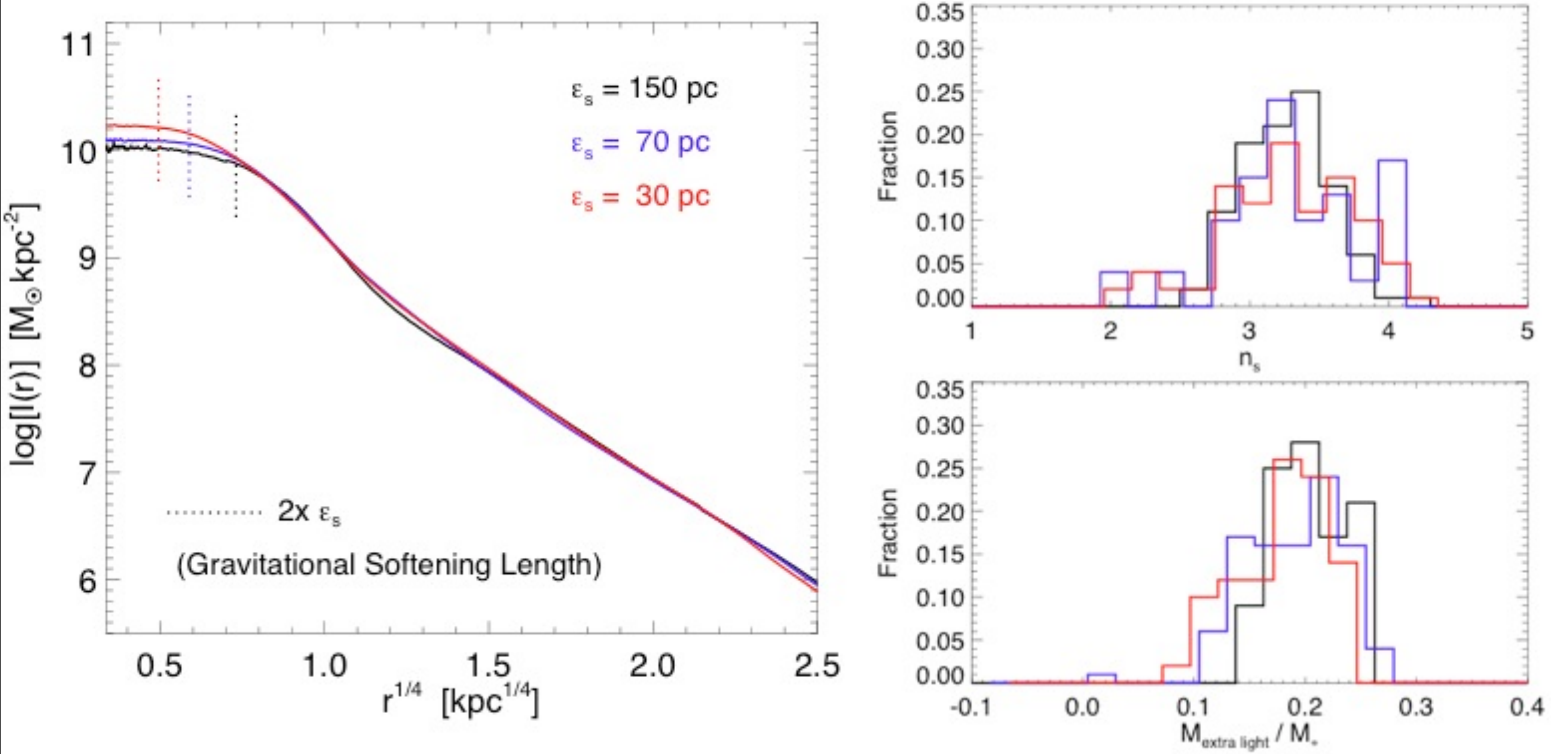
- Instead, the FP is “tilted”:
  - (L / M_dyn) ~ M^{0.1-0.3, depending on the band}
  - three possible explanations:
  - stellar population variation:

    M_dyn ~ M_stellar holds, but (L/M_stellar) varies with L

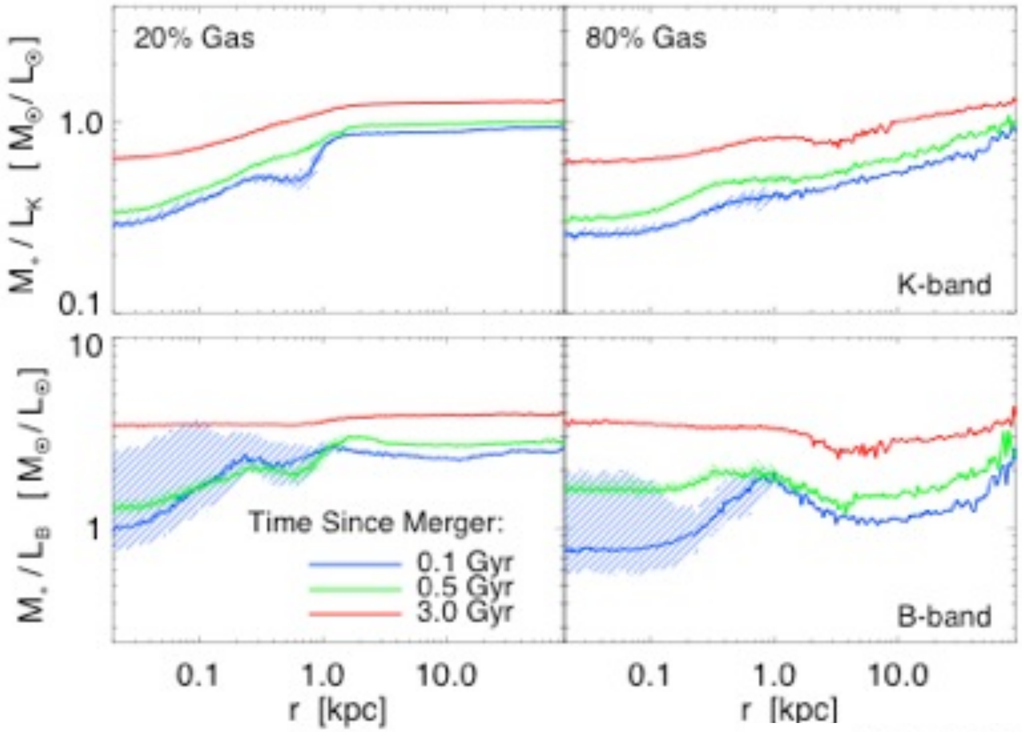
  - kinematic non-homology:
    - velocity fields change
  - structural non-homology:
    - profile shape changes with mass
    - stellar-to-dark-matter mass ratio changes (can be the same as the above, or different)

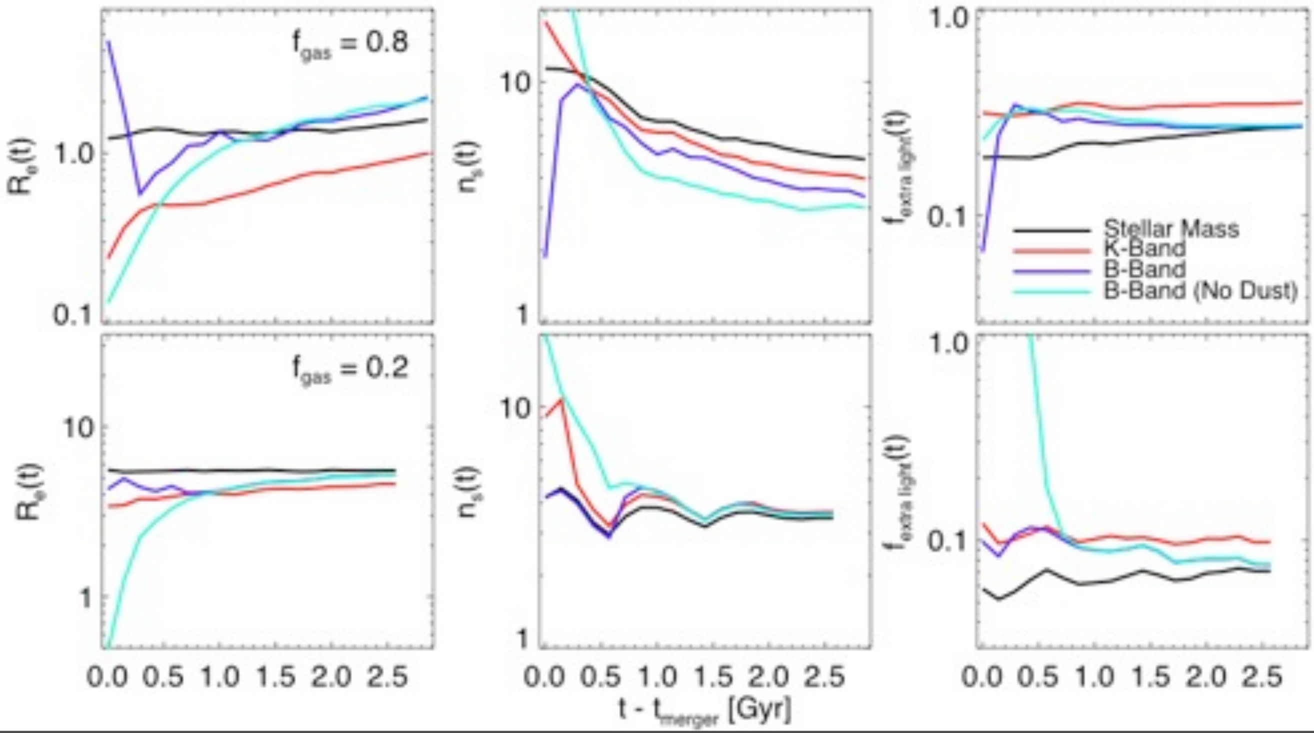
# Resolution Studies

## RECOVERING THE ROLE OF GAS



# Stellar Population Effects

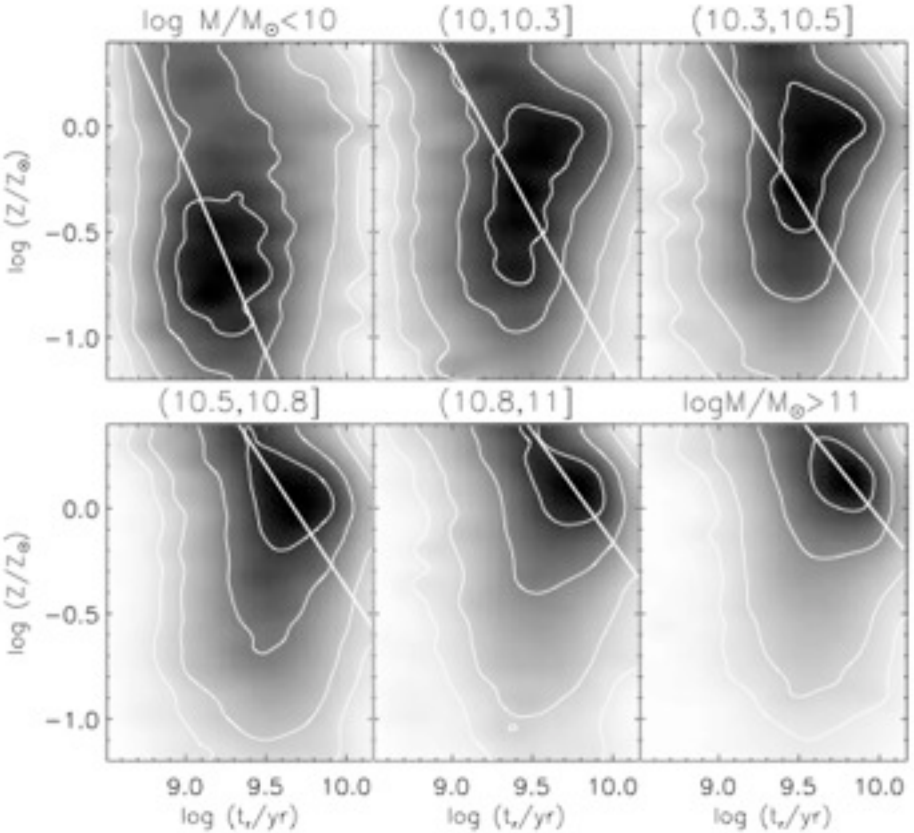


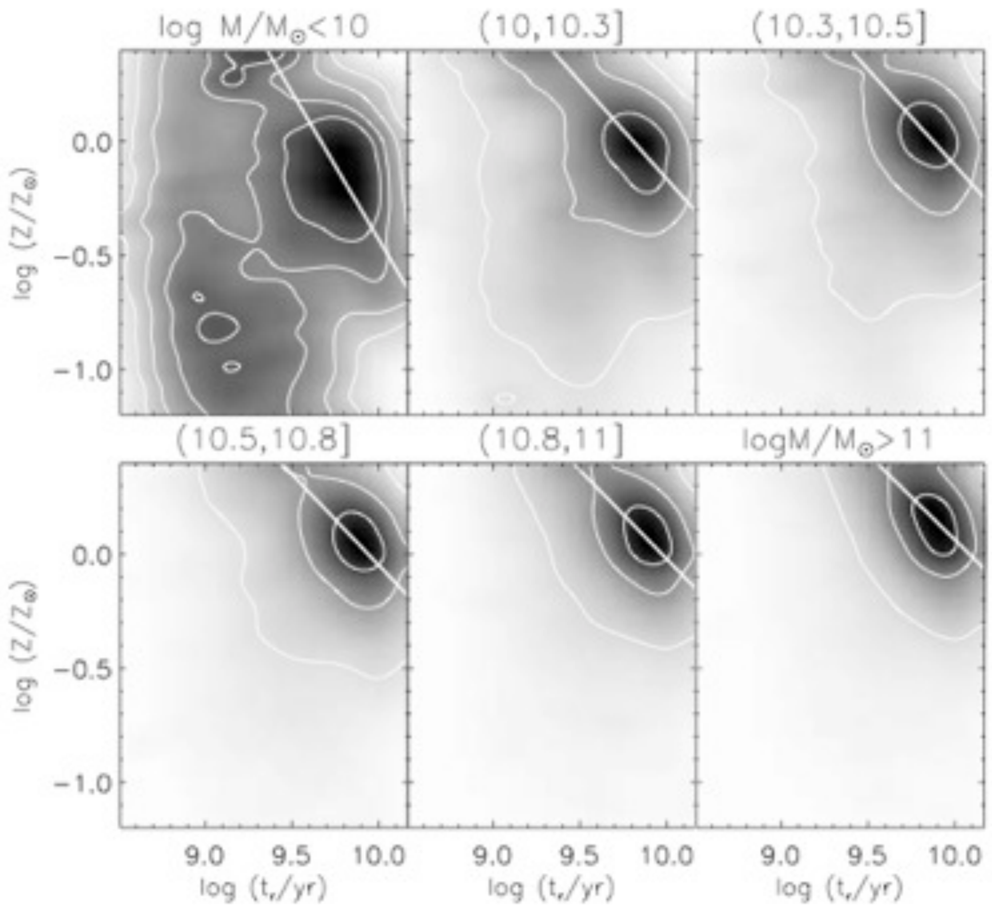



# Fundamental Plane Tilt

## STELLAR POPULATION VARIATION

- Where do these come from?

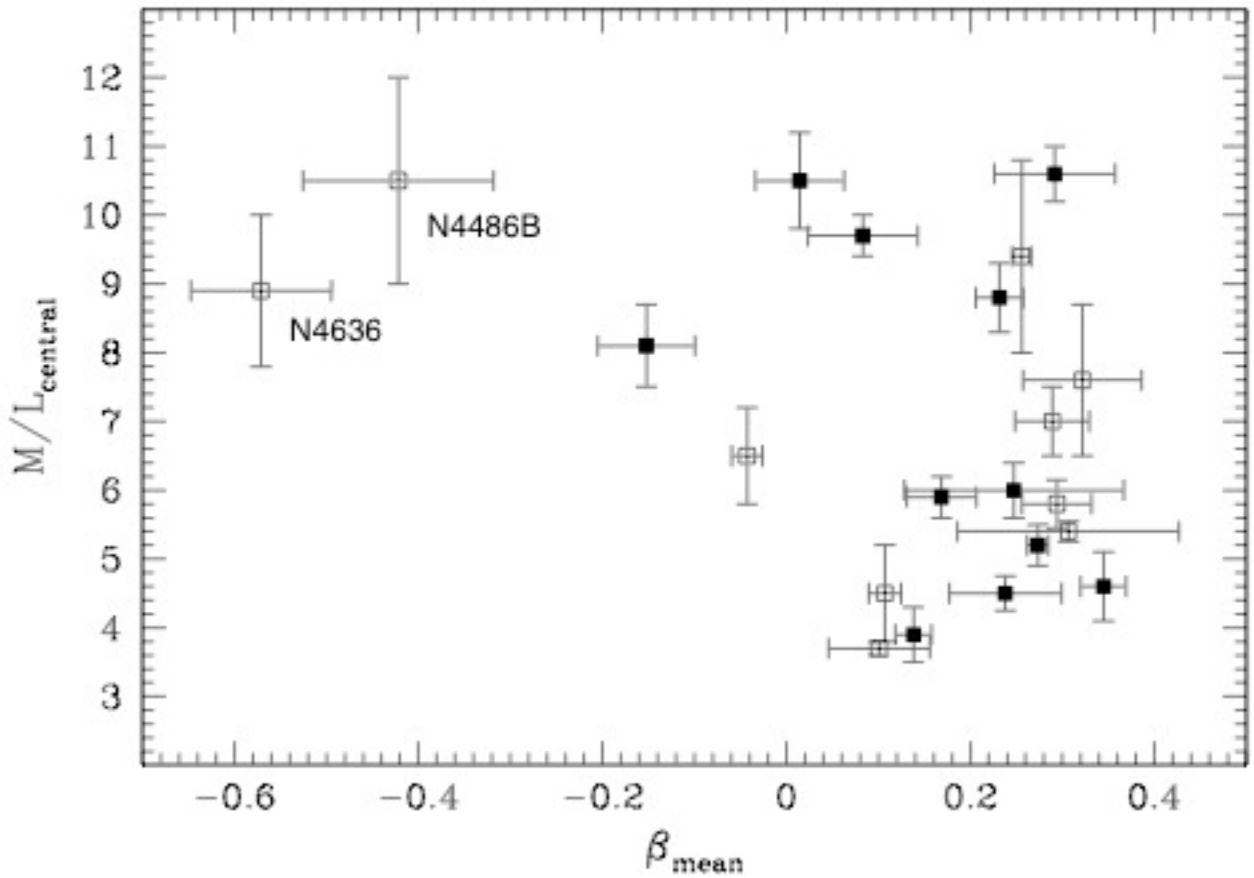


# Fundamental Plane Tilt

## 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