Assembly of Massive Elliptical Galaxies

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Mon. Not. Roy. Astron. Soc. 2005, 2006
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Massive Galaxies Over Cosmic Time 2

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How important are gas-poor mergers for building massive elliptical galaxies?

- Expected in current galaxy formation models embedded in LCDM simulations
- Help explain dichotomy between bright and faint ellipticals
- Have been observed
- Tension with evolution of galaxy luminosity functions?
- Consistency with tight observed scaling relations?

Merger Simulations

- Model elliptical galaxy as Hernquist stellar bulge + NFW dark matter halo w/ and w/o adiabatic contraction) - no black holes, no gas

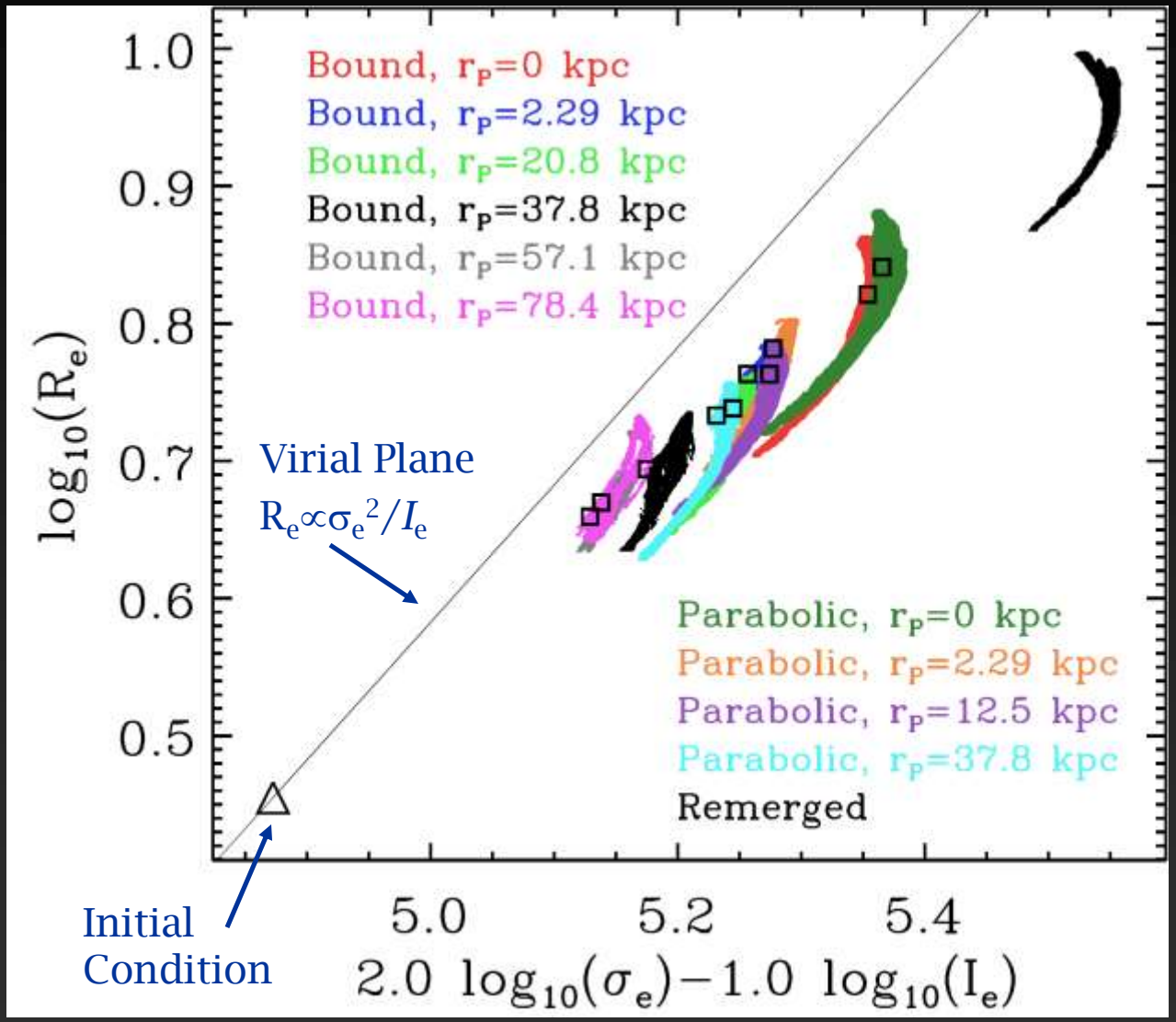
  important: $\Delta E_{☞} \neq 0$

- Simulate mass ratios of 1:1, 1:3

- Use distribution of orbits seen in cosmological dark matter simulations

- over 10^6 particles per simulation; run using GADGET

Fundamental Plane



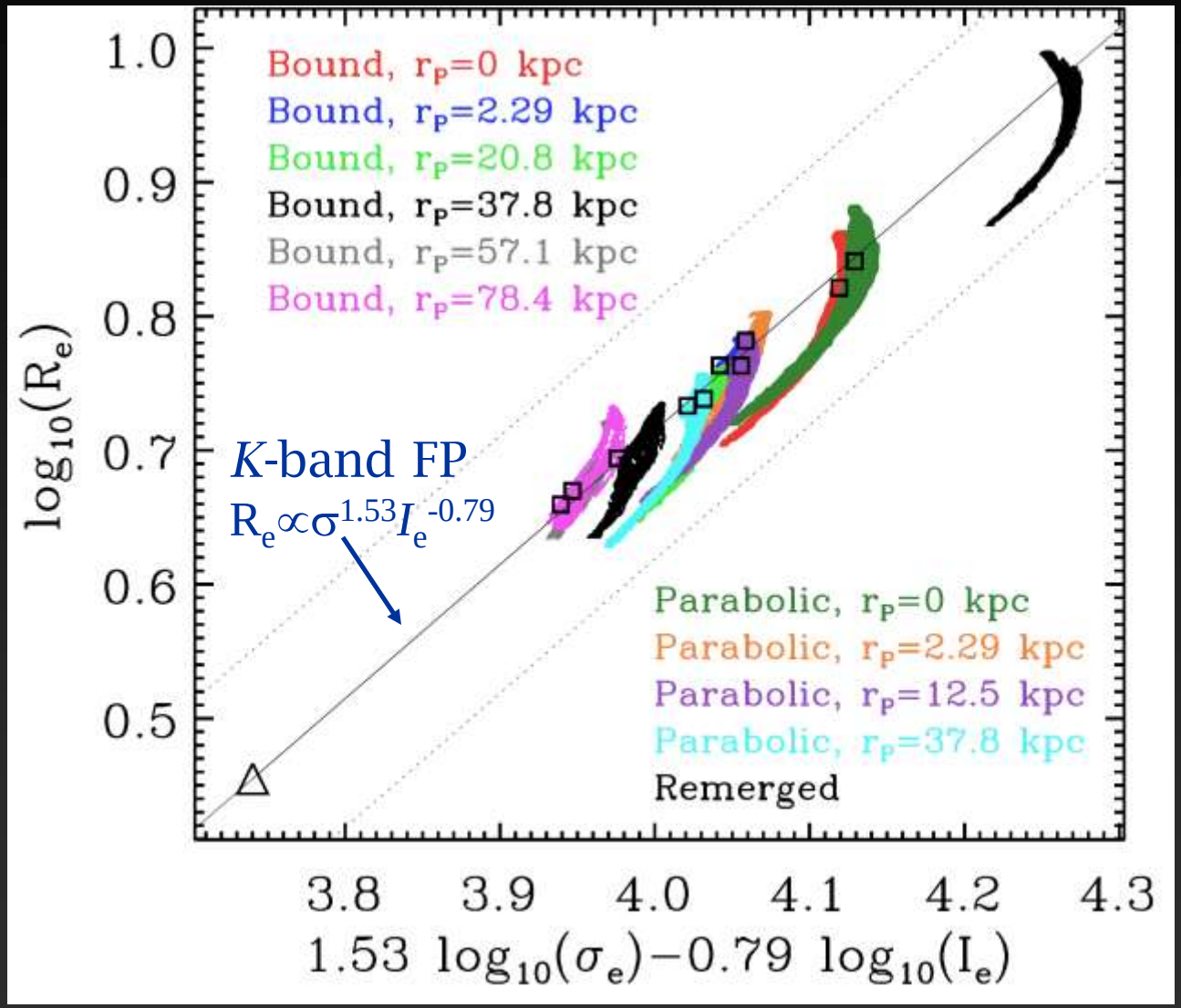
Virial Theorem:

$R \propto \sigma^{-2} M_{dyn}$

$R \propto \sigma^{-2} (M_{dyn}/L) L$

MBK, Ma, & Quataert (MNRAS, 2006)

Fundamental Plane



MBK, Ma, & Quataert (MNRAS, 2006)

K-band FP:

$R_e \propto \sigma^{1.53 \pm 0.08} I_e^{-0.79 \pm 0.03}$

(Pahre et al. 1998)

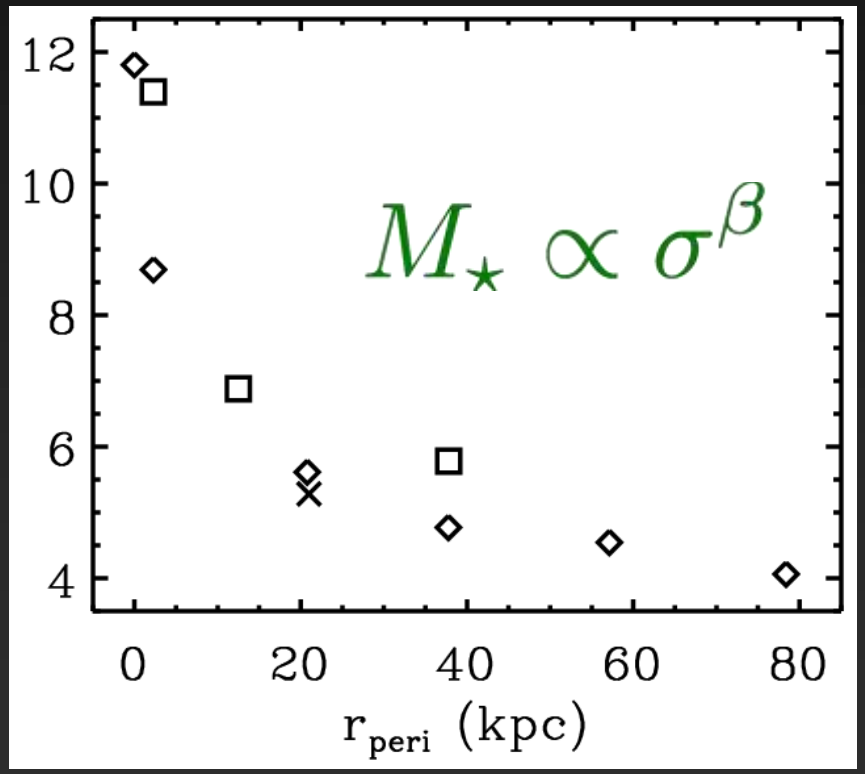
$M_{dyn}/L \propto R_e^{0.21}$

Tilt due to increasing dark matter fraction in with increasing R_e

See also Capelato et al. 1995, Nipoti et al. 2003, Robertson et al. 2006

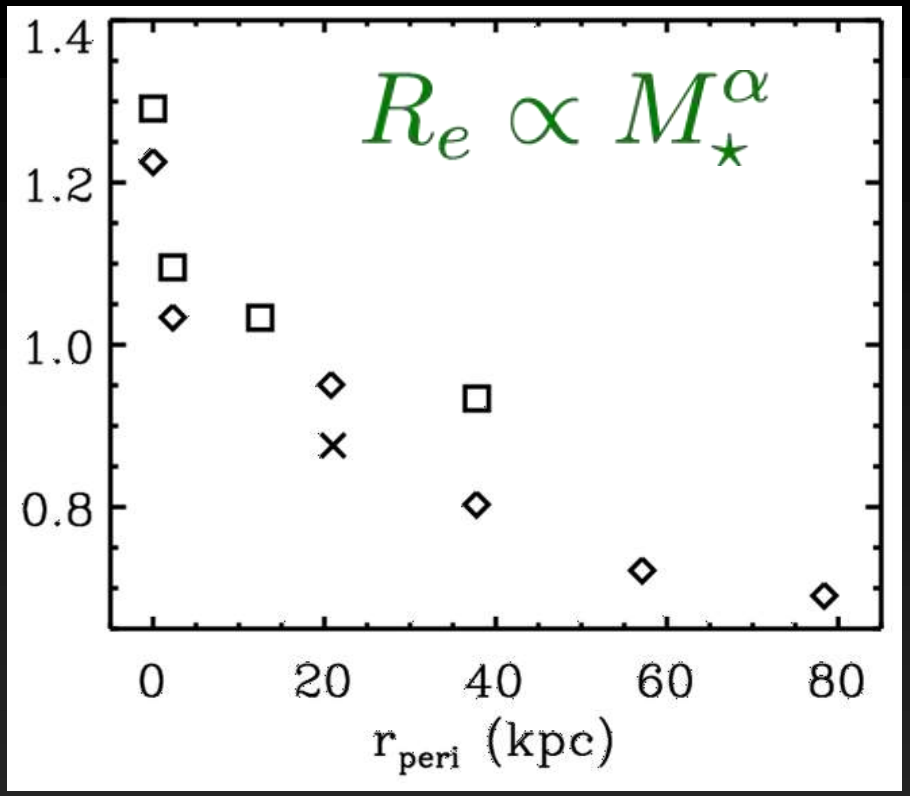
$M_\star$-σ and R_e-$M_\star$ relations

MBK, Ma, & Quataert (MNRAS, 2006)



β

Angular momentum



α

Full elliptical galaxy population:

$L \propto \sigma^4$

$R_e \propto L^{0.6\text{-}0.7}$

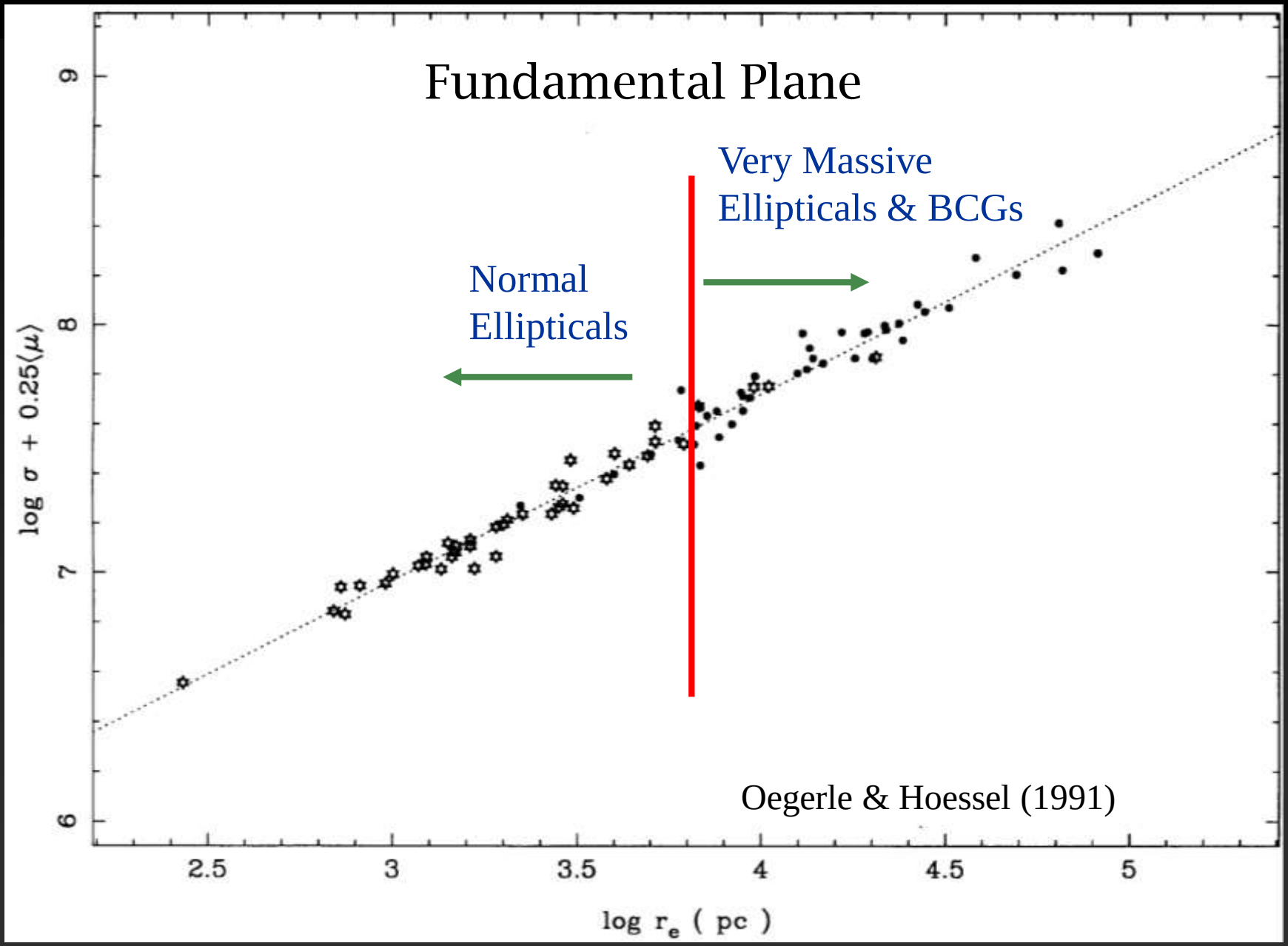
Brightest Cluster Galaxies

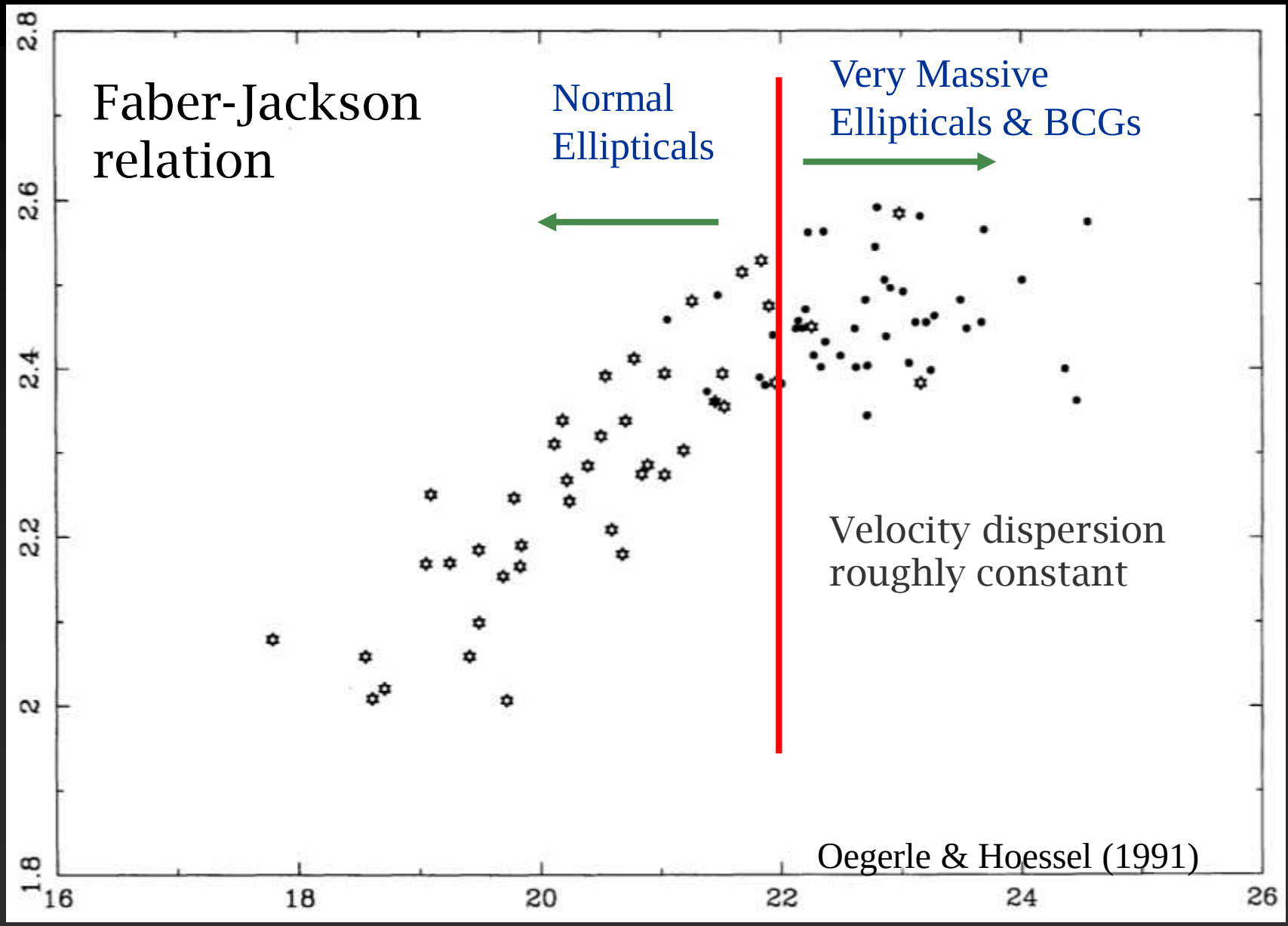
- Clusters form at intersections of filaments ⇒ natural preferred direction for merging

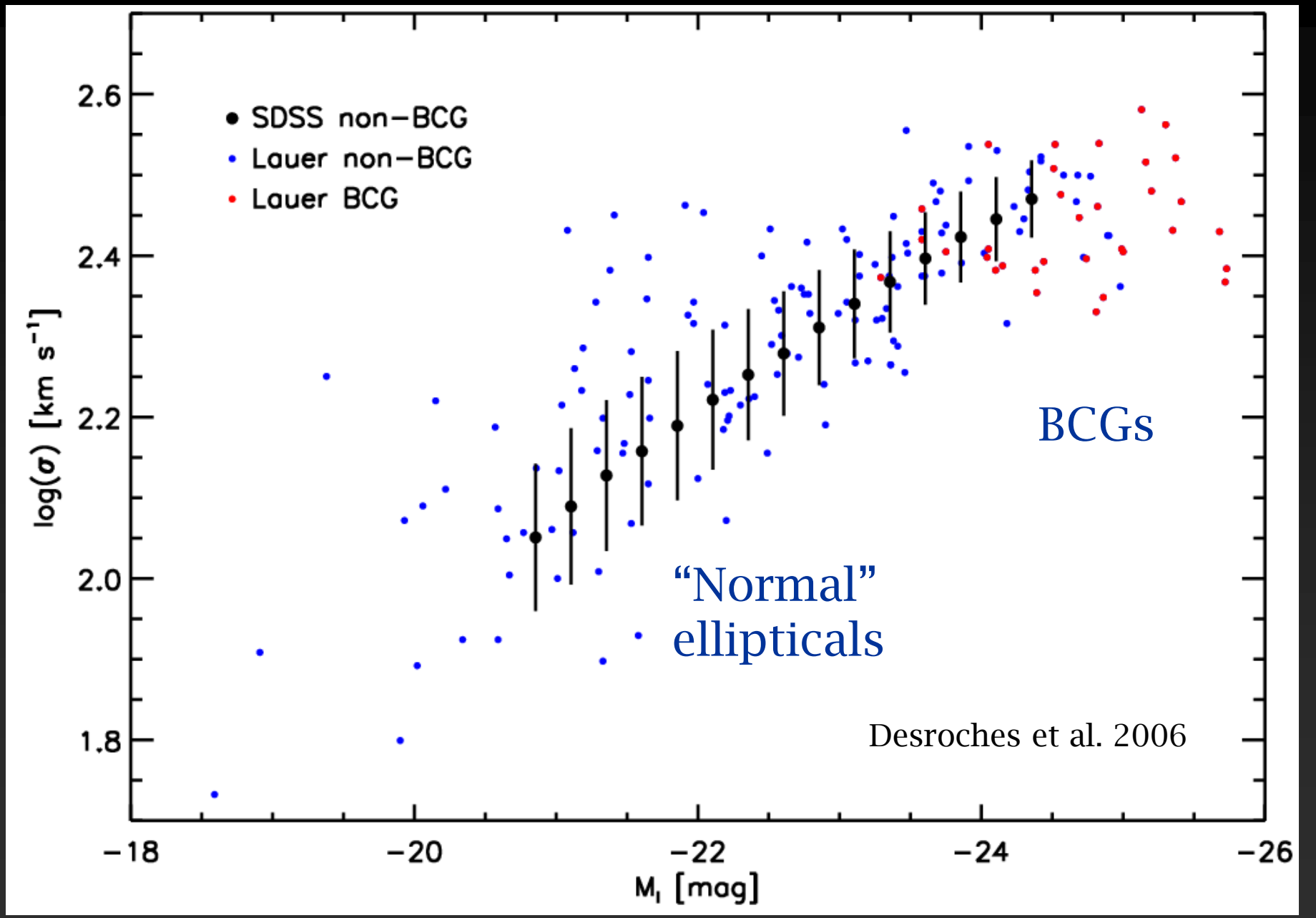
⇒If BCGs are assembled by dissipationless mergers during cluster formation, orbits should be preferentially radial.

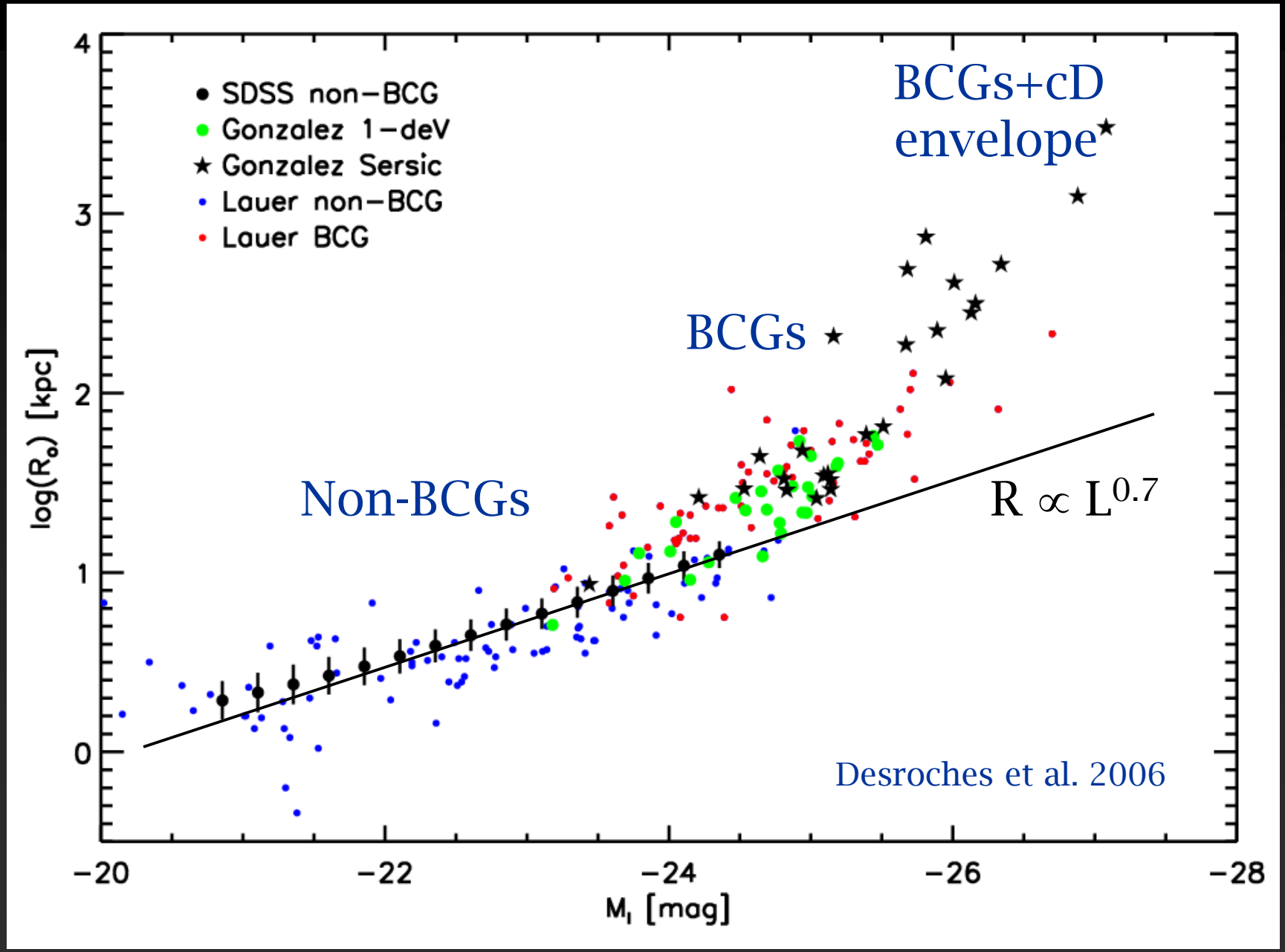
⇒This radial merging will preserve the fundamental plane but lead to deviations in $M_{\text{☞}} \propto \sigma^{\beta}$ and $R \propto M_{\text{☞}}^{\alpha}$:

$\beta > 4$, $\alpha > 0.6$


Fundamental Plane
Very Massive
Ellipticals & BCGs
Normal
Ellipticals
Oegerle & Hoessel (1991)
log σ + 0.25⟨μ⟩
log r_e (pc)
6
7
8
9
2.5
3
3.5
4
4.5
5


Faber-Jackson relation
Normal Ellipticals
Very Massive Ellipticals & BCGs
Velocity dispersion roughly constant
Oegerle & Hoessel (1991)
log(σ)
-M_r
2.8
2.6
2.4
2.2
2
1.8
16
18
20
22
24
26


SDSS non−BCG
Lauer non−BCG
Lauer BCG
2.6
2.4
2.2
2.0
1.8
log(σ) [km s⁻¹]
−18
−20
−22
−24
−26
M_I [mag]
BCGs
"Normal" ellipticals
Desroches et al. 2006

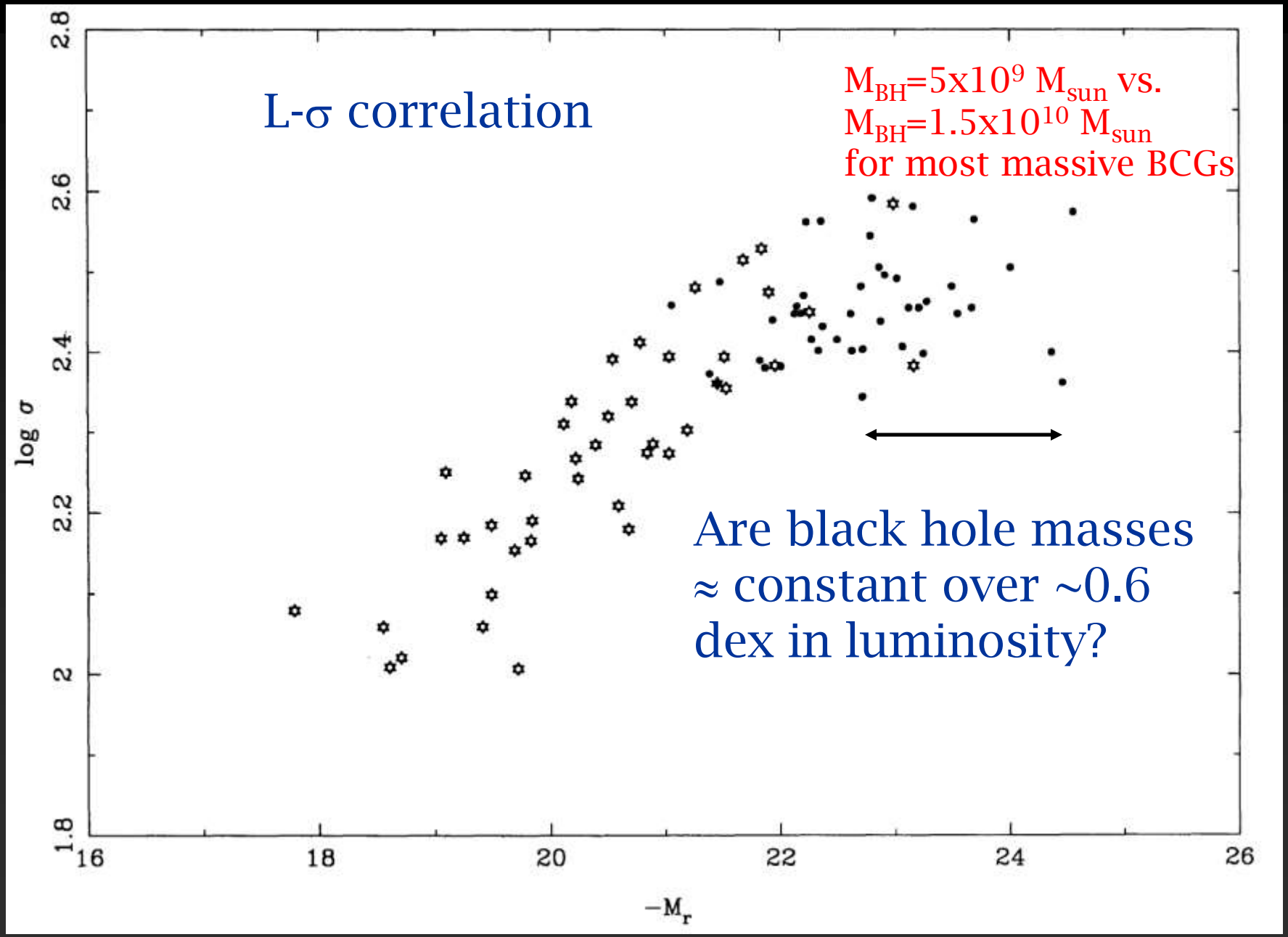

SDSS non−BCG
Gonzalez 1−deV
Gonzalez Sersic
Lauer non−BCG
Lauer BCG
BCGs+cD envelope
BCGs
Non-BCGs
R ∝ L^0.7
Desroches et al. 2006
log(R_e) [kpc]
M_I [mag]
4
3
2
1
0
−20
−22
−24
−26
−28

What About Black Holes?

- Dry assembly of BCGs / massive ellipticals: BH growth comes from mergers

  Dry merger predictions for BCGs:
  - Black hole mass traces galaxy stellar mass: $M_{BH} \propto M_{*}$
  - Different M_{*}-σ relation: $M_{*} \propto \sigma^{\beta}$ with $\beta>4$

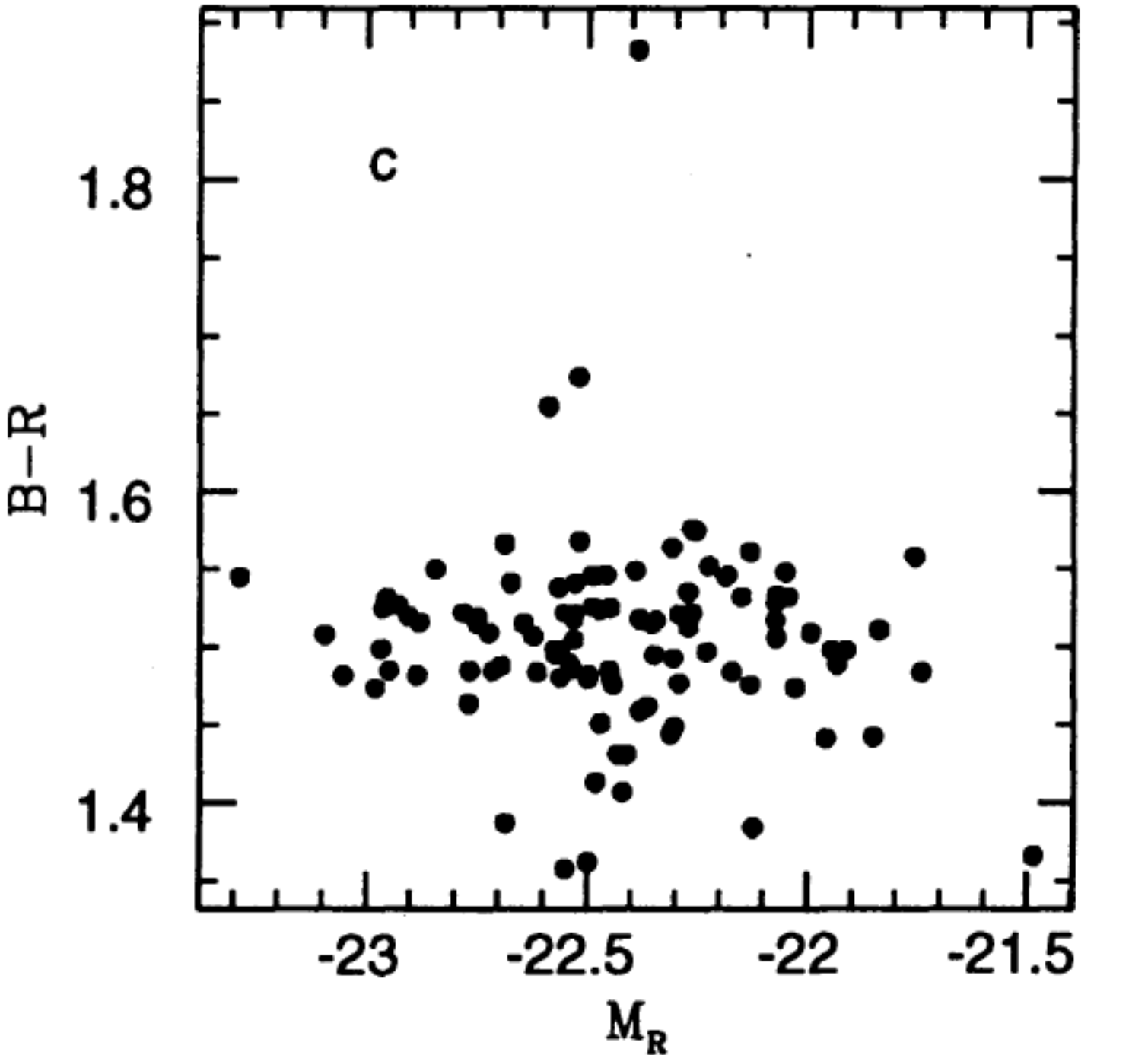
$\Rightarrow$ M_{BH}-σ^{β} relation changes to $\beta>4$



(see also Lauer et al. 2006, Bernardi et al. 2006)

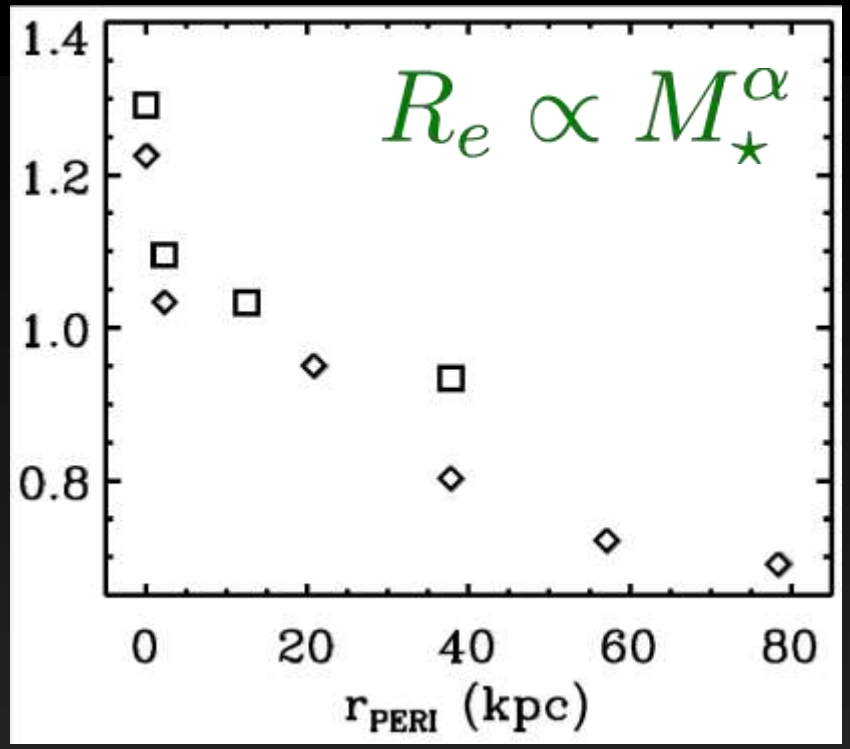
Conclusions

- The fundamental plane is preserved by dry merging under a variety of orbital configurations and mass ratios
- The FP projections *do show dependence* on merger orbit, a result of dynamical friction energy loss
- Radial merging along filaments is a well-motivated mechanism for producing BCGs; should lead to *BCGs following different FP projections* from normal ellipticals (now observed)
- Change in L-σ relation for massive galaxies means using standard black hole mass predictor ($M_{BH} \propto \sigma^4$) *may underestimate black hole masses*: BCGs could host black holes of $>10^{10}$ M_{sun}

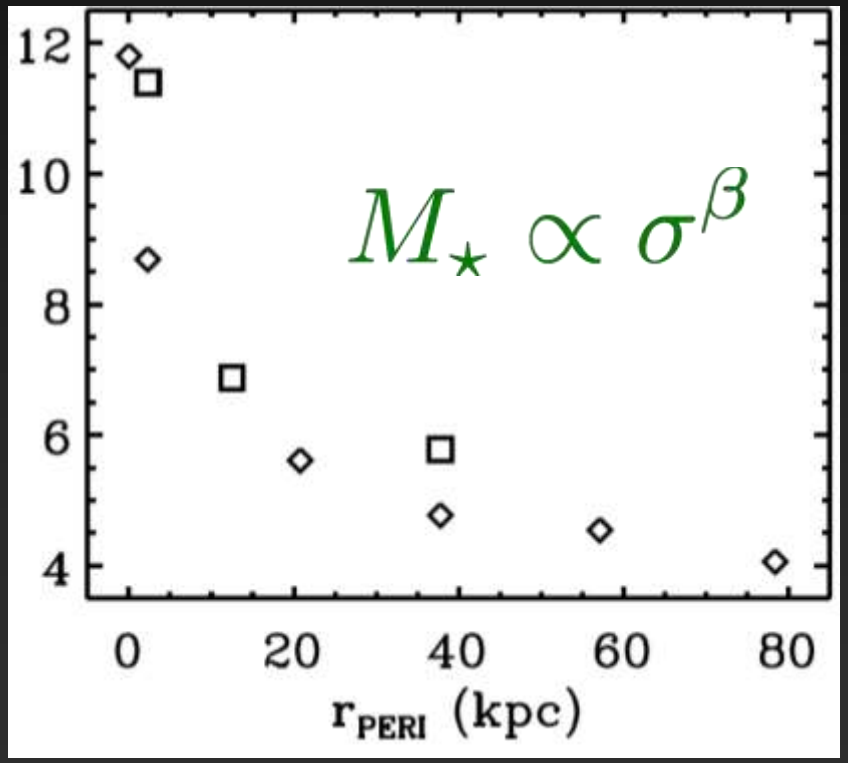

c
1.8
1.6
1.4
B−R
-23
-22.5
-22
-21.5
M_R

Fundamental Plane Projections

MBK, Ma, & Quataert (MNRAS, 2006)



α



β

Angular momentum

observed:

$M \propto \sigma^4$

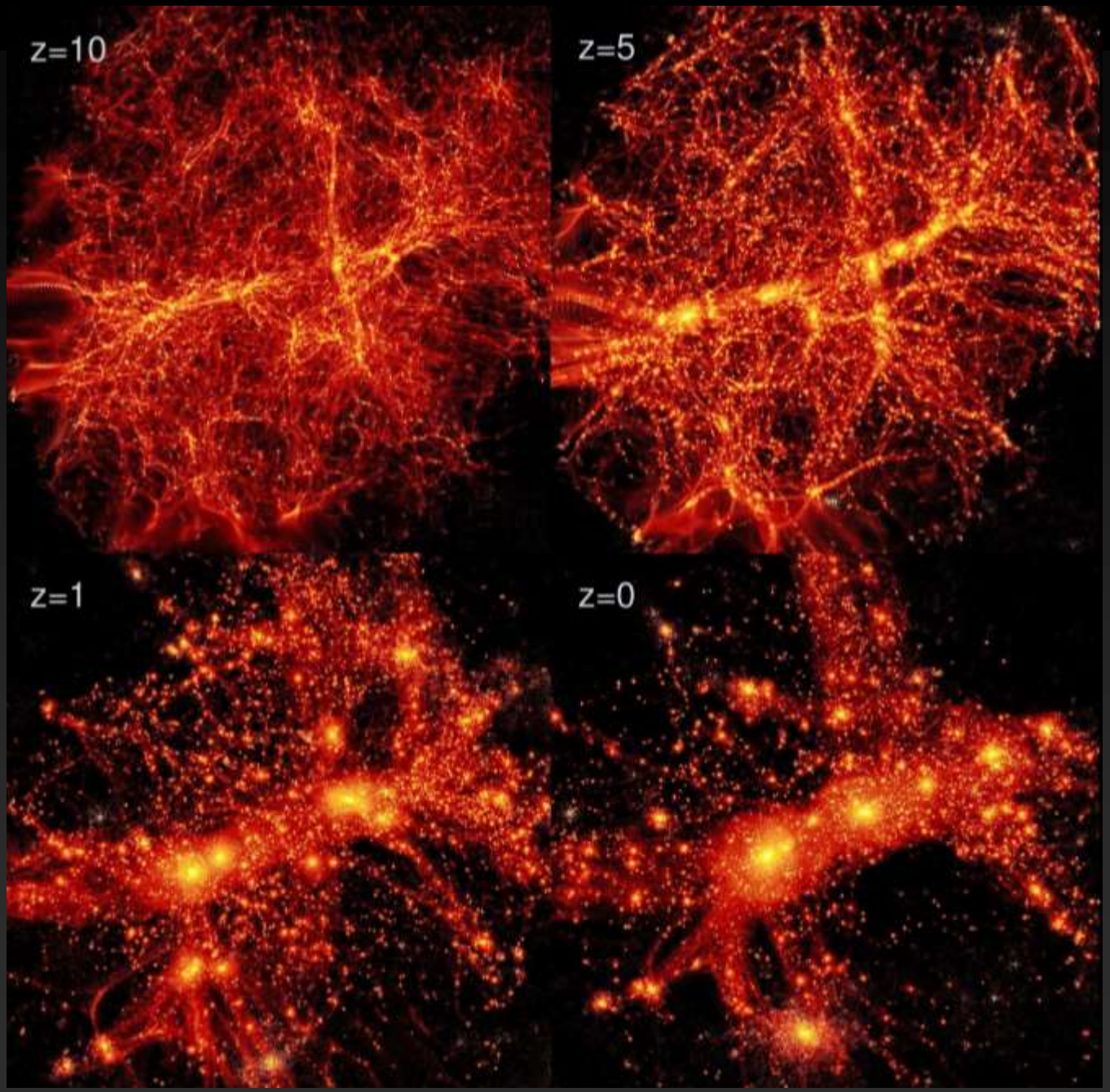
$R_e \propto L^{0.6\text{-}0.7}$

⇒ scaling relations depend on energy and angular momentum of orbit

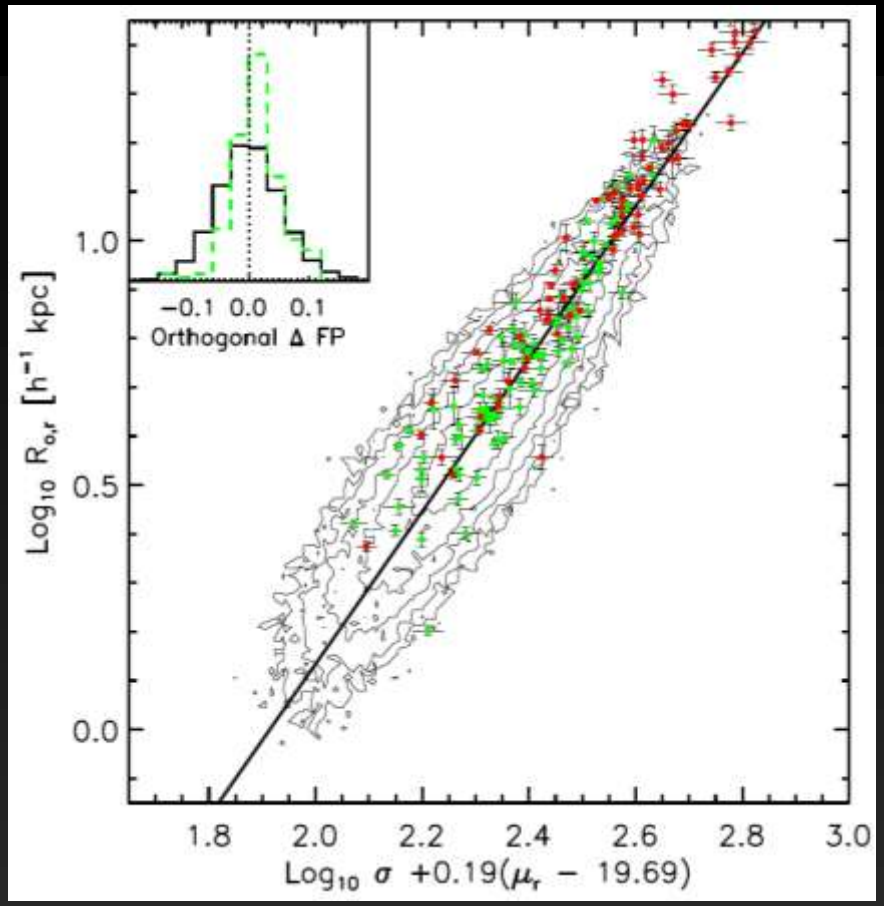
Predictions

- Dry mergers will preserve the fundamental plane
- If the mergers are on typical orbits (significant angular momentum), they will also preserve projections of the FP
- More radial mergers will lead to deviations in projections of the FP

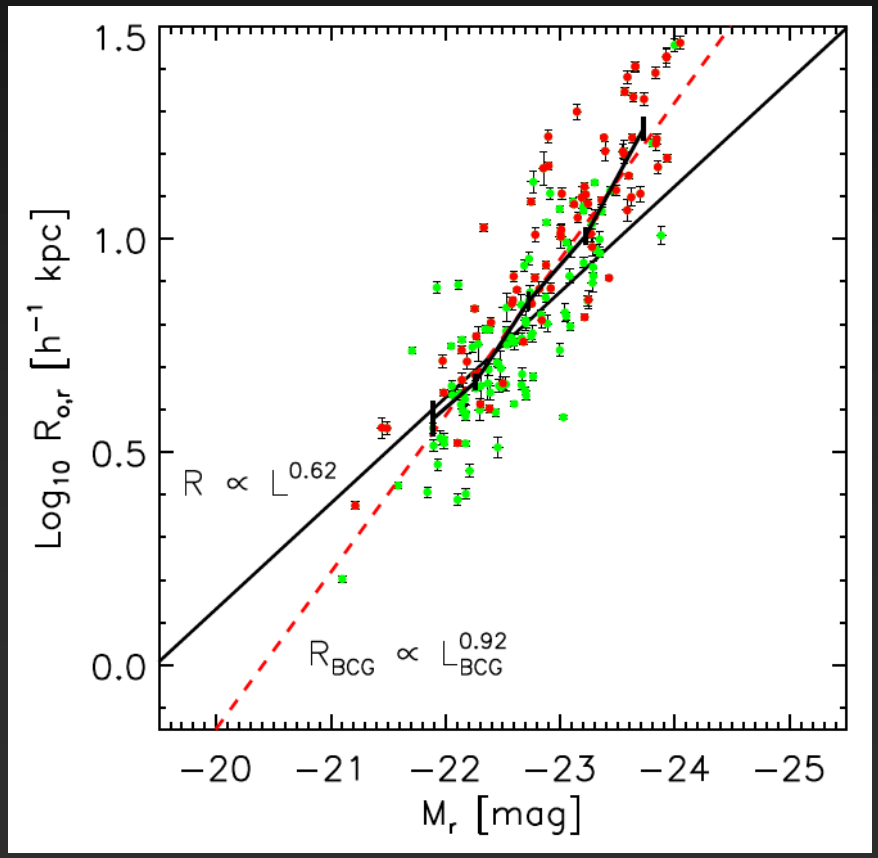
Q: when (if ever) are low angular momentum mergers expected?



B. Moore



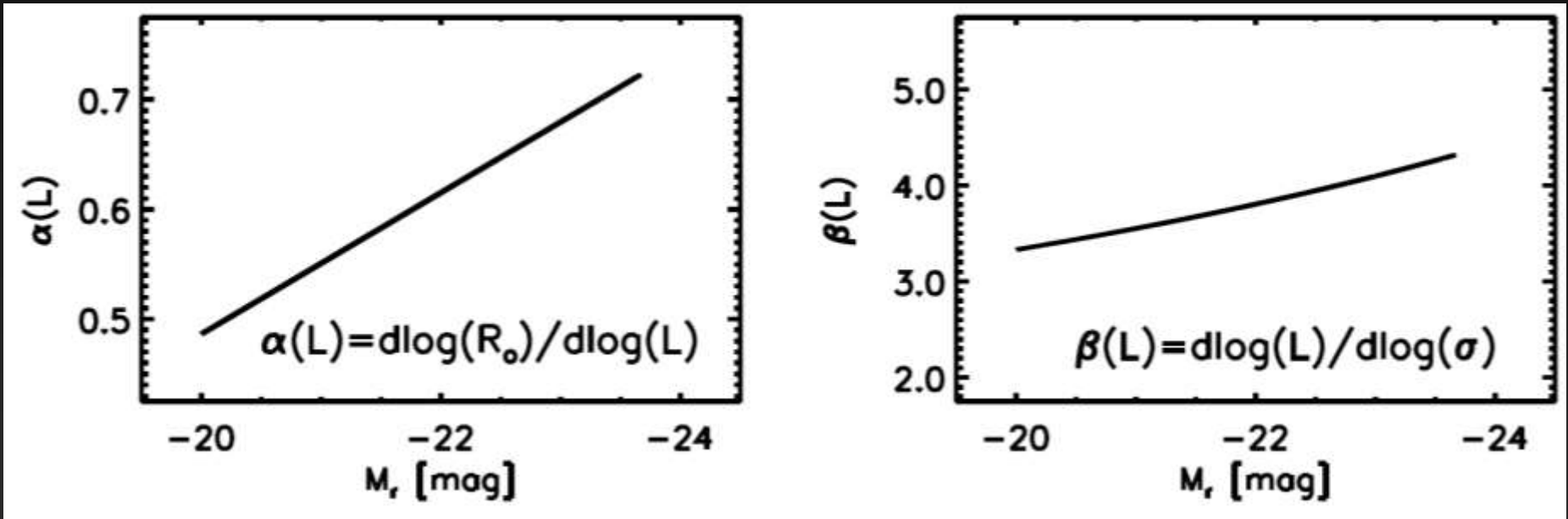
← Fundamental Plane



R vs. L →

Bernardi et al. 2006; also Lauer et al. 2006

Deviations also seen for other massive ellipticals (Desroches, Quataert, Ma, and West 2006)



Constraints on Galaxy Assembly

fundamental plane connects ellipticals' half-light radii (R_e), luminosities (L), and velocity dispersions (σ):
(Djorgovski & Davis 1987, Dressler et al. 1987)

$R_e \propto \sigma^{1.53\pm0.08} I_e^{-0.79\pm0.03} \Rightarrow R_e \propto \sigma^{-3} L^{3/2}$
Pahre et al. 1998 (K-band)

virial theorem connects R, σ, and M

$R \propto \sigma^{-2} M \Rightarrow R \propto \sigma^{-2} (M/L) L$

$\Rightarrow$ require $(M/L) \propto L^{1/2} \sigma^{-1}$ or (tilt)

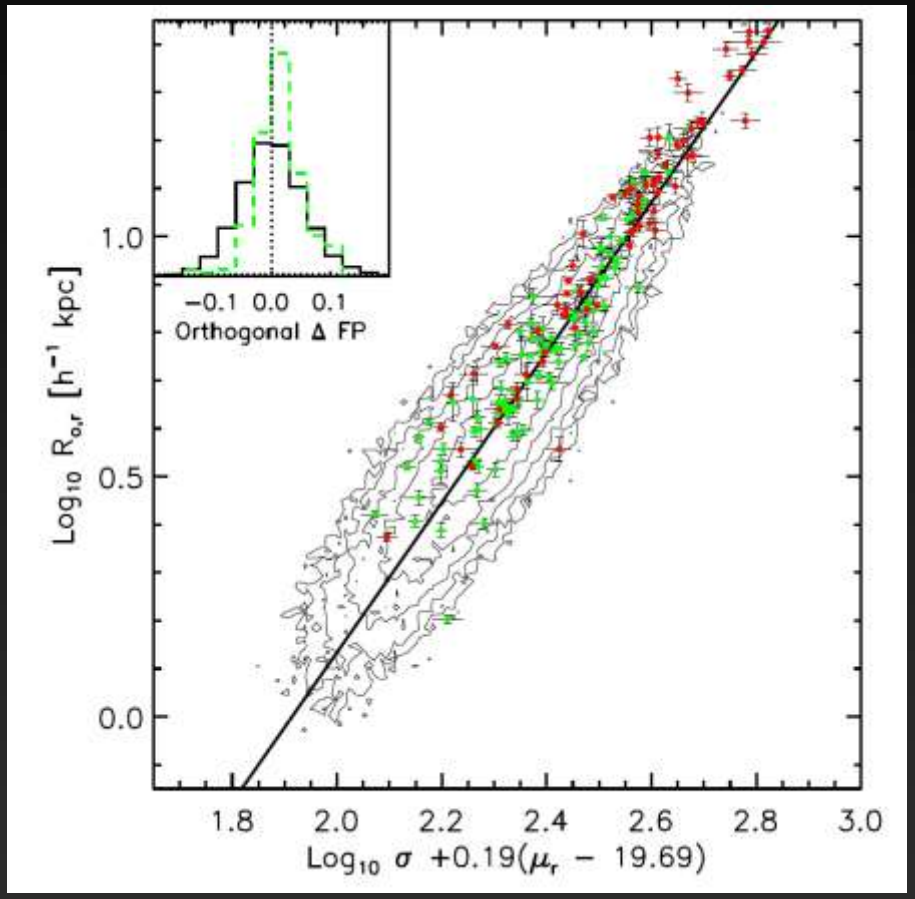
Locations in : $L \propto \sigma^4$ (Faber-Jackson), $R \propto L^{0.7}$
contain more information than plane itself

Future Work

- Reproducing scaling relations is only one piece of the puzzle: need to understand if dry merging works in other ways too
- Need to embed merger simulations into cosmological environment: multiple mergers, realistic merging sequence
- Make predictions for black hole mass function and its evolution - implications for galaxy formation at higher redshifts?
- Observations: measure more black hole masses in BIG galaxies (using adaptive optics) to get better statistics

Example: Virgo Cluster / M87

- Virgo / M87
  - $M_{☞} \approx 6 \times 10^{11} M_{sun}$
  - $\sigma_{M87} \approx 340$ km s^{-1}
  - $M_{BH} = 3.0 \times 10^{9} M_{sun}$
- Massive clusters:
  - $M_{☞,\,BCG} \approx 1\text{-}3 \times 10^{12} M_{sun}$ (or more?)
  - maximum $\sigma \approx 400$ km s^{-1}
  - gives:
    - $M_{BH} = 5.8 \times 10^{9} M_{sun}$ (using M_{BH}-σ)
    - $M_{BH} = 2 \times 10^{10} M_{sun}$ (using M_{BH}-$M_{☞}$)



SDSS: Bernardi et al. 2006

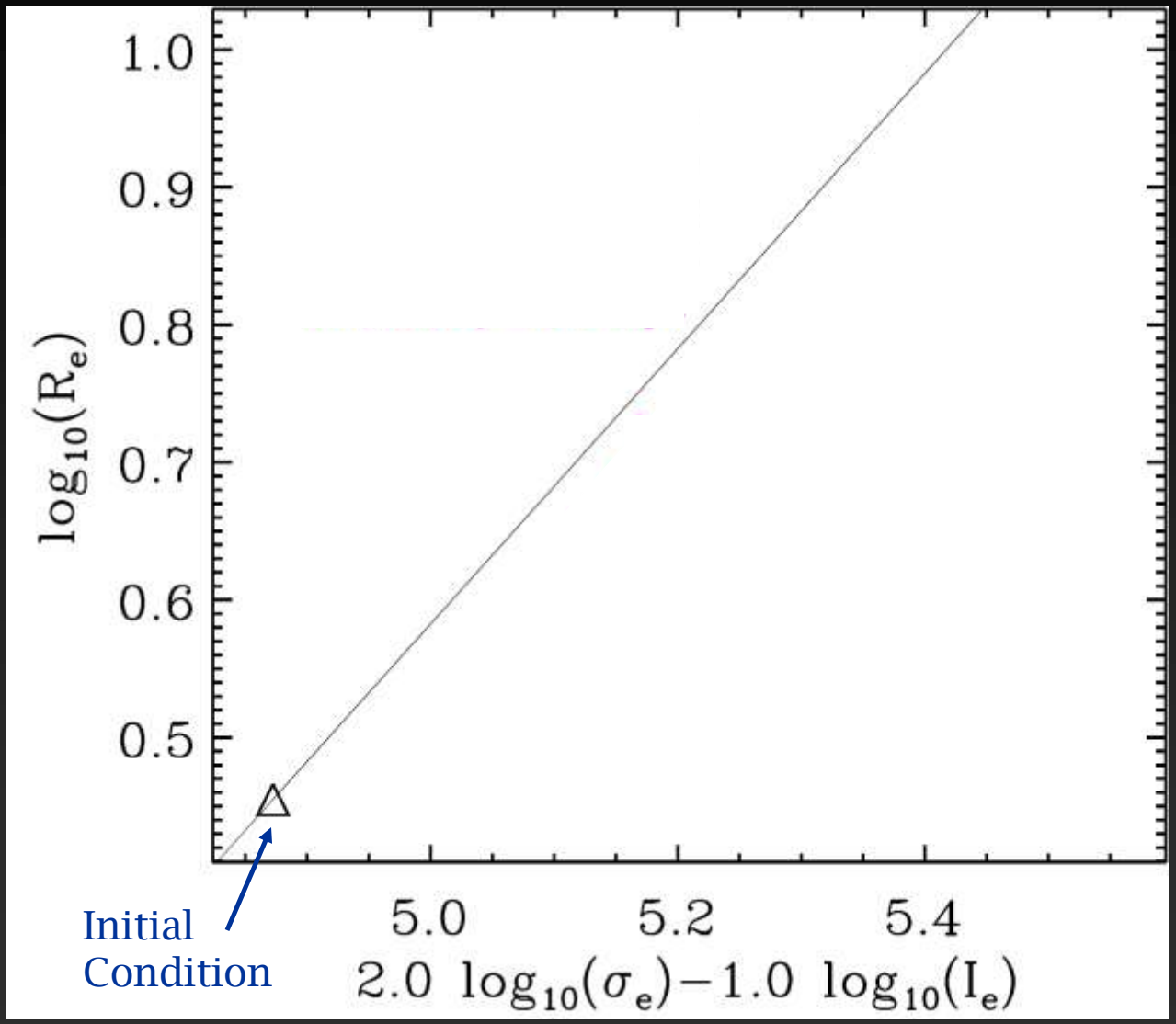
Projections:

$L \propto \sigma^4$ (Faber-Jackson)

$R \propto L^{0.7}$

Projections carry more information than plane itself

Fundamental Plane



Solid Line:
Virial theorem prediction

MBK, Ma, & Quataert (MNRAS, 2006)