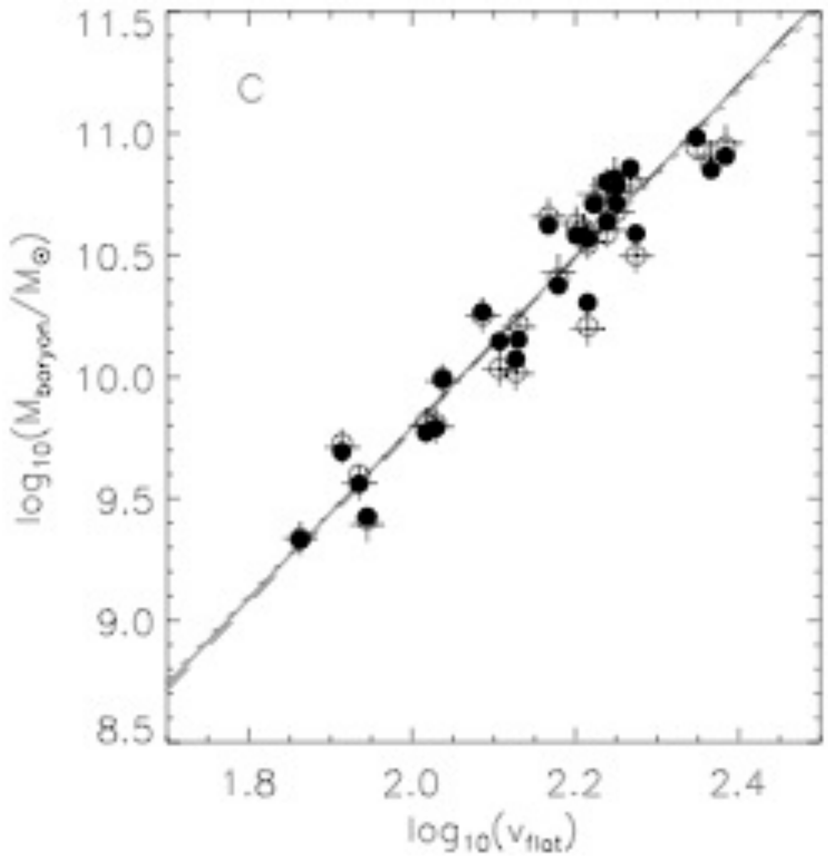
Redshift Evolution in Galaxy Scaling Laws

"Fundamental Planes" part 2.1

Recall, TF follows (to lowest order) from halo scalings:

at fixed M:

v~v_halo~$(1+z)^{1/2}$

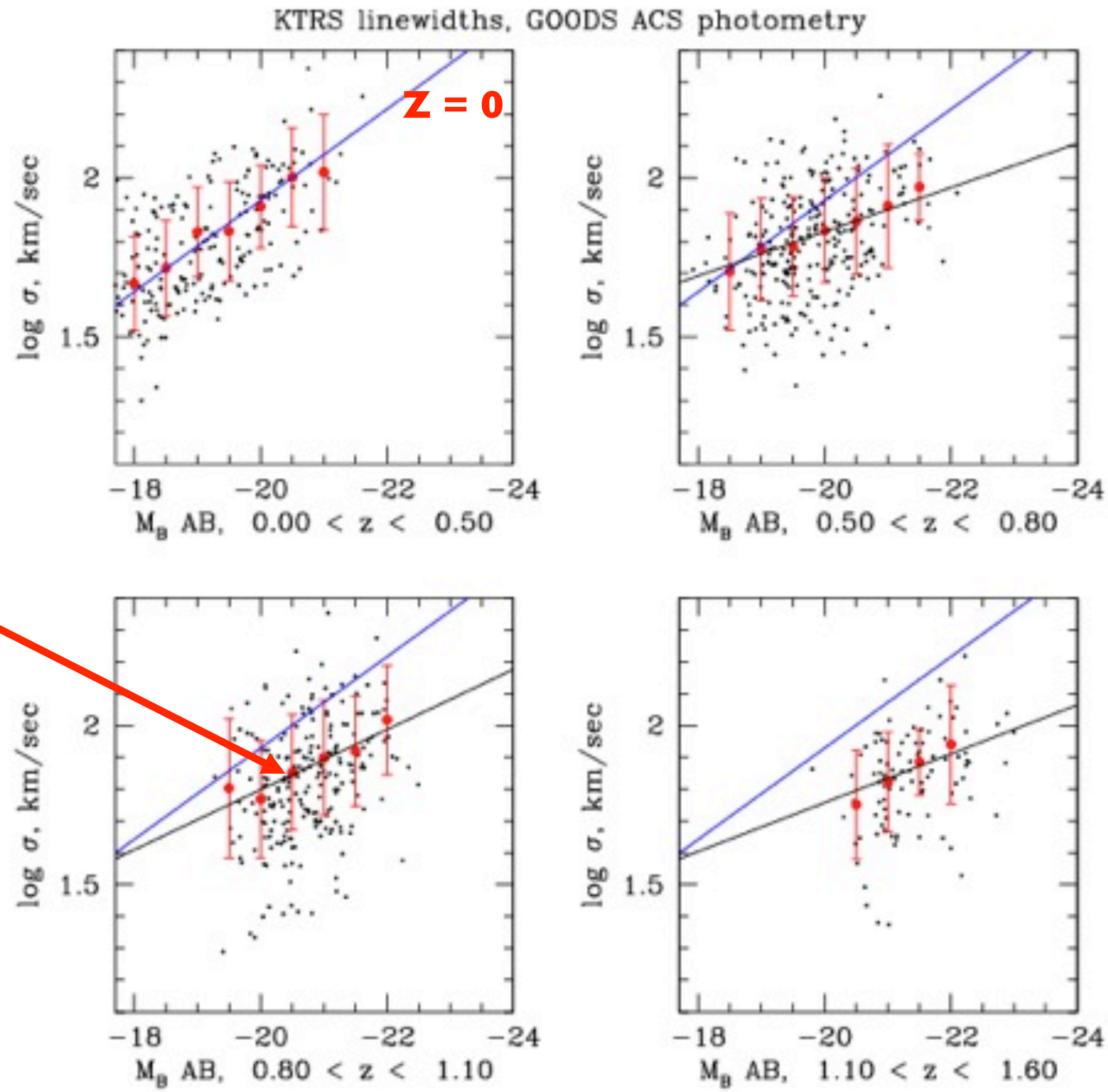


Redshift Evolution

THE TULLY-FISHER RELATION

DEEP2: See significant evolution in TF

Zeropoint offset of ~1.5 magnitude at z = 1

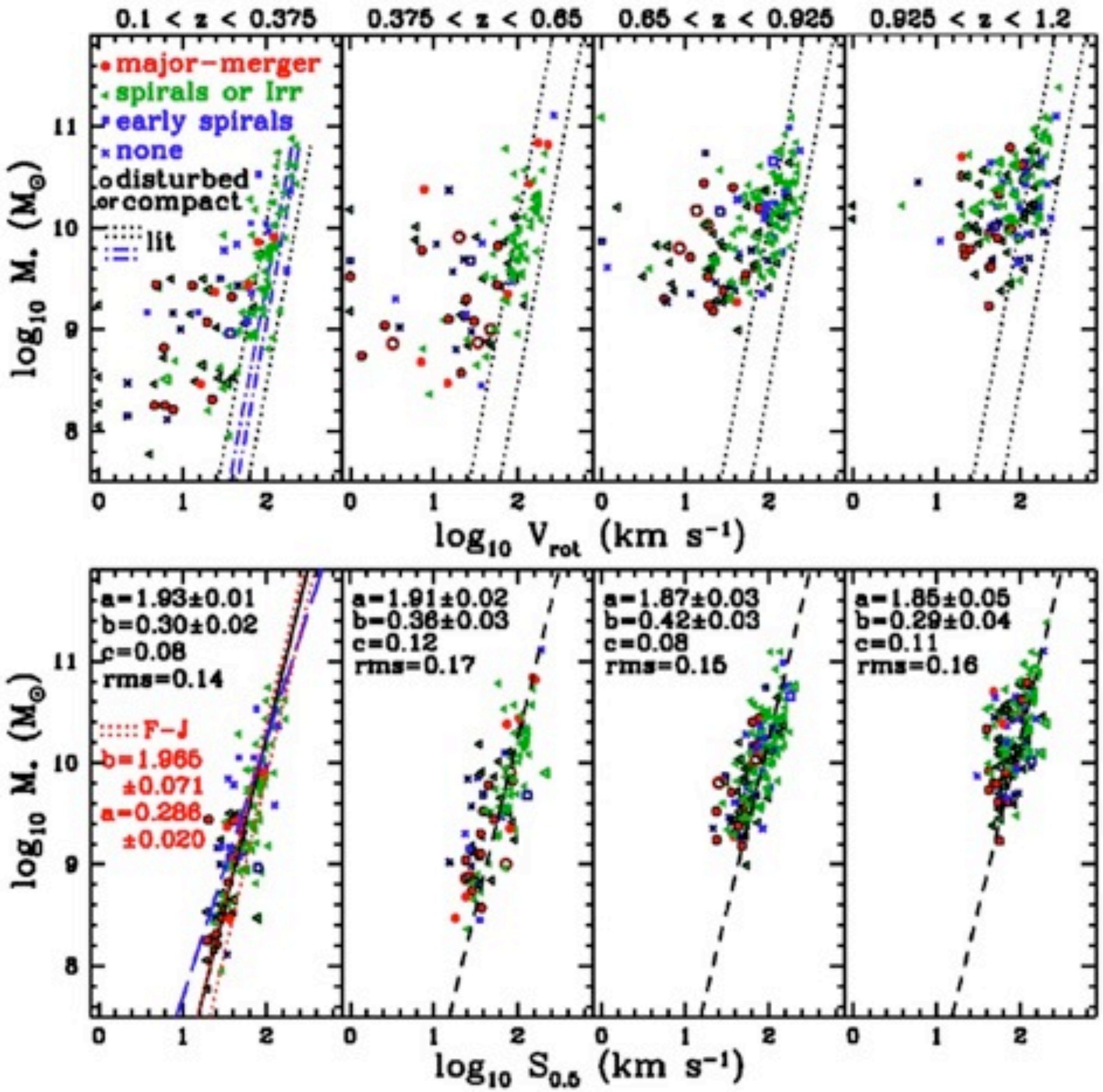


Weiner et al. 2004

Redshift Evolution

THE TULLY-FISHER RELATION

- But *baryonic* TF:

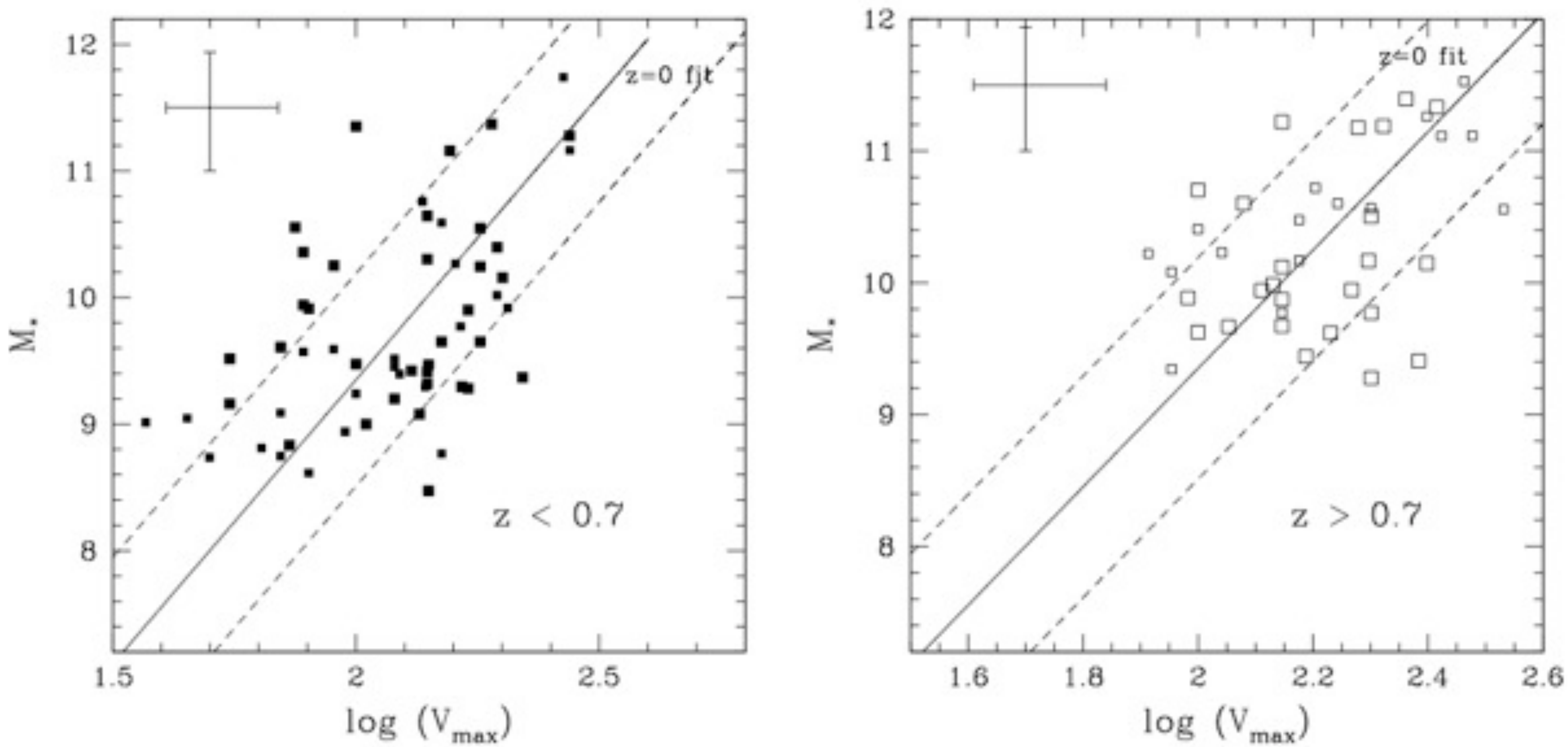


Kassin et al. 2007

Redshift Evolution

THE TULLY-FISHER RELATION

Conselice et al. 2006

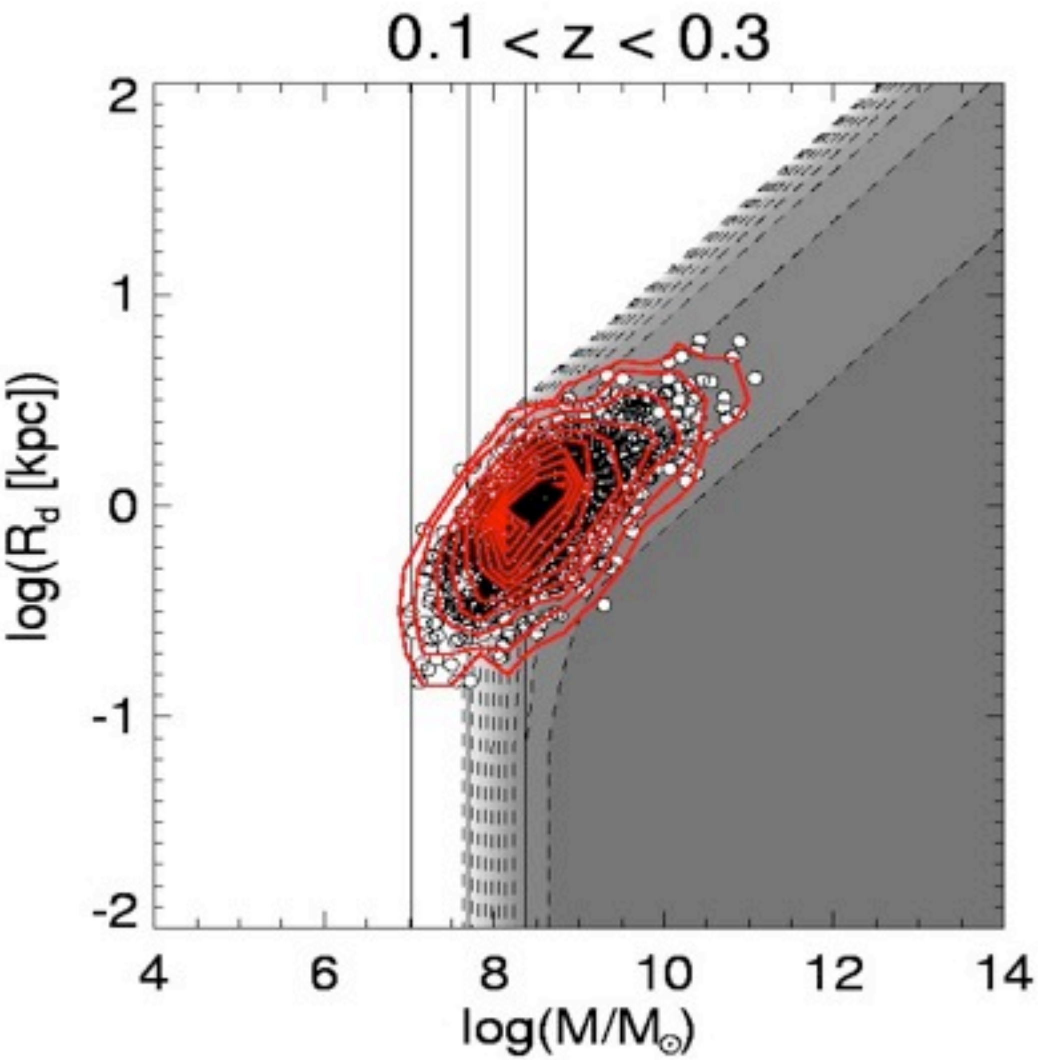


- Bouche et al. 2007: appears to hold out to z ~ 2-3

Redshift Evolution

SIZE-MASS RELATIONS

- TF doen't evolve: doesn't mean projections (e.g. size-mass) don't



Disk galaxies: naively assume (Mo, Mao, & White)

Rd ~ M/v^2

v~v_halo

Rd ~ 1/H(z)

Weiner et al. 2005

Redshift Evolution
SIZE-MASS RELATIONS

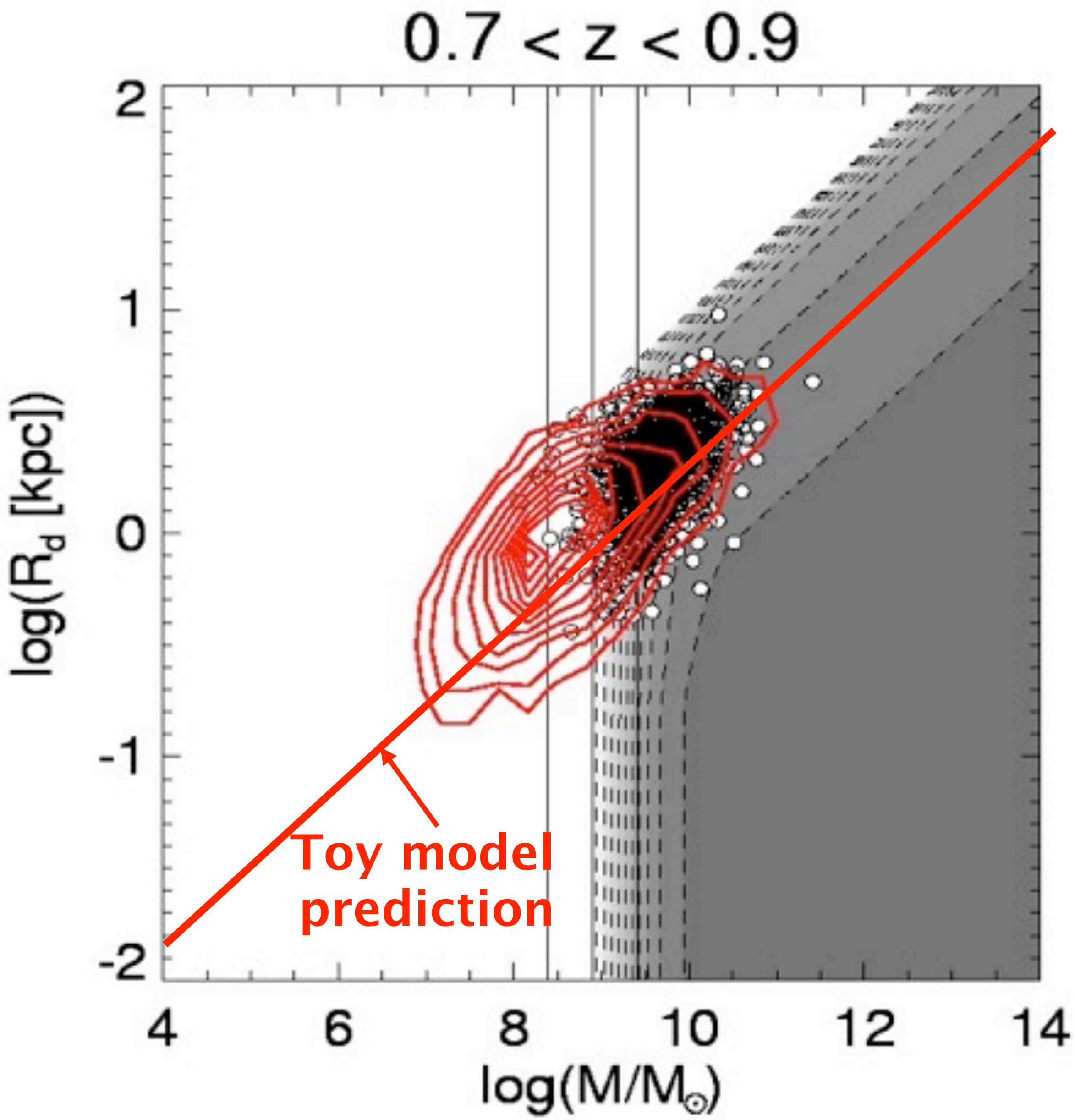
- FP and TF don't evolve: doesn't mean projections (e.g. size-mass) don't

COMBO-17:

Disk galaxies

Mass-radius relation

No shift in zeropoint vs. time

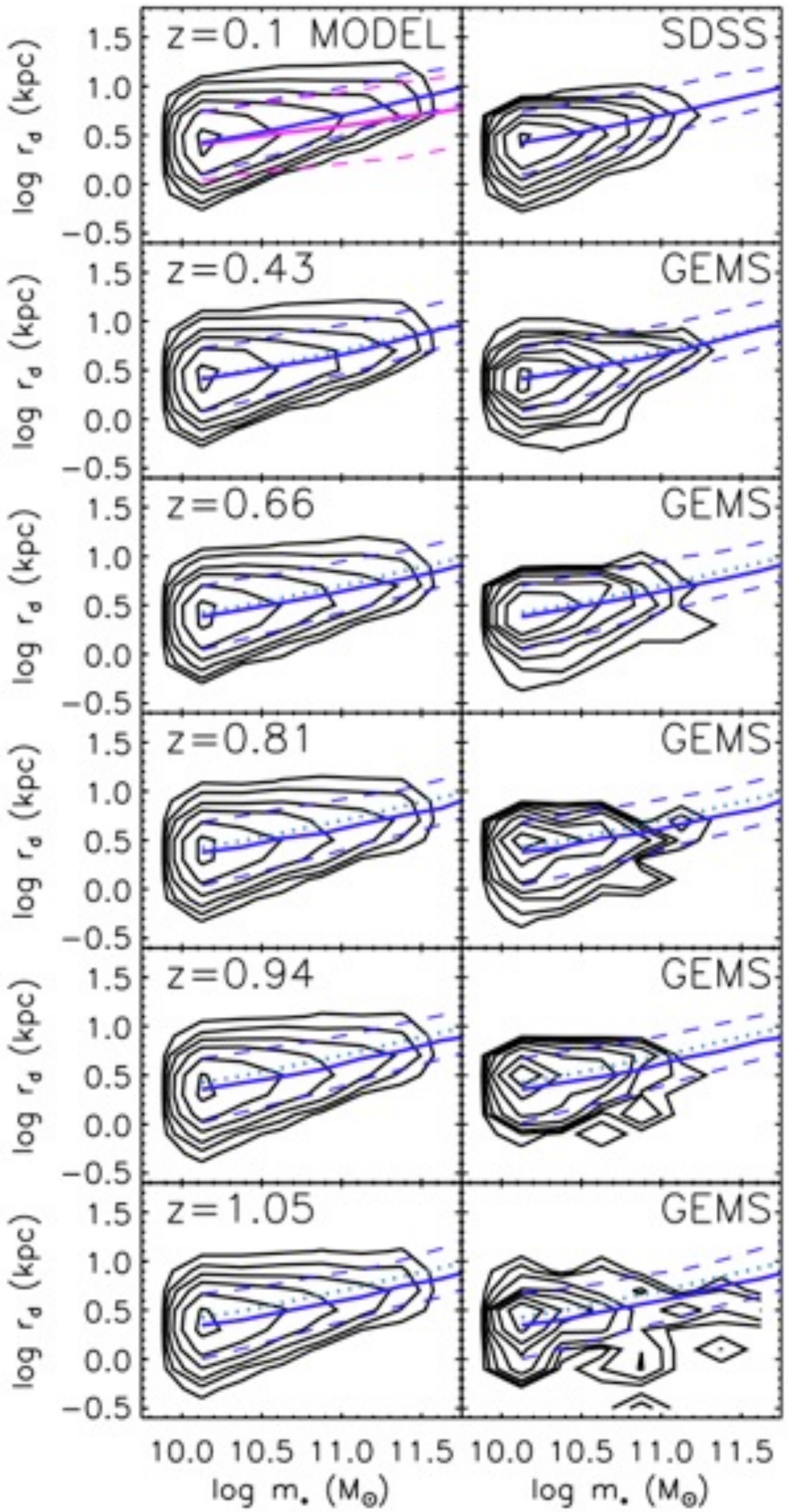


Redshift Evolution

SIZE-MASS RELATIONS

GEMs sees the same:

weak evolution in disk size-mass relation

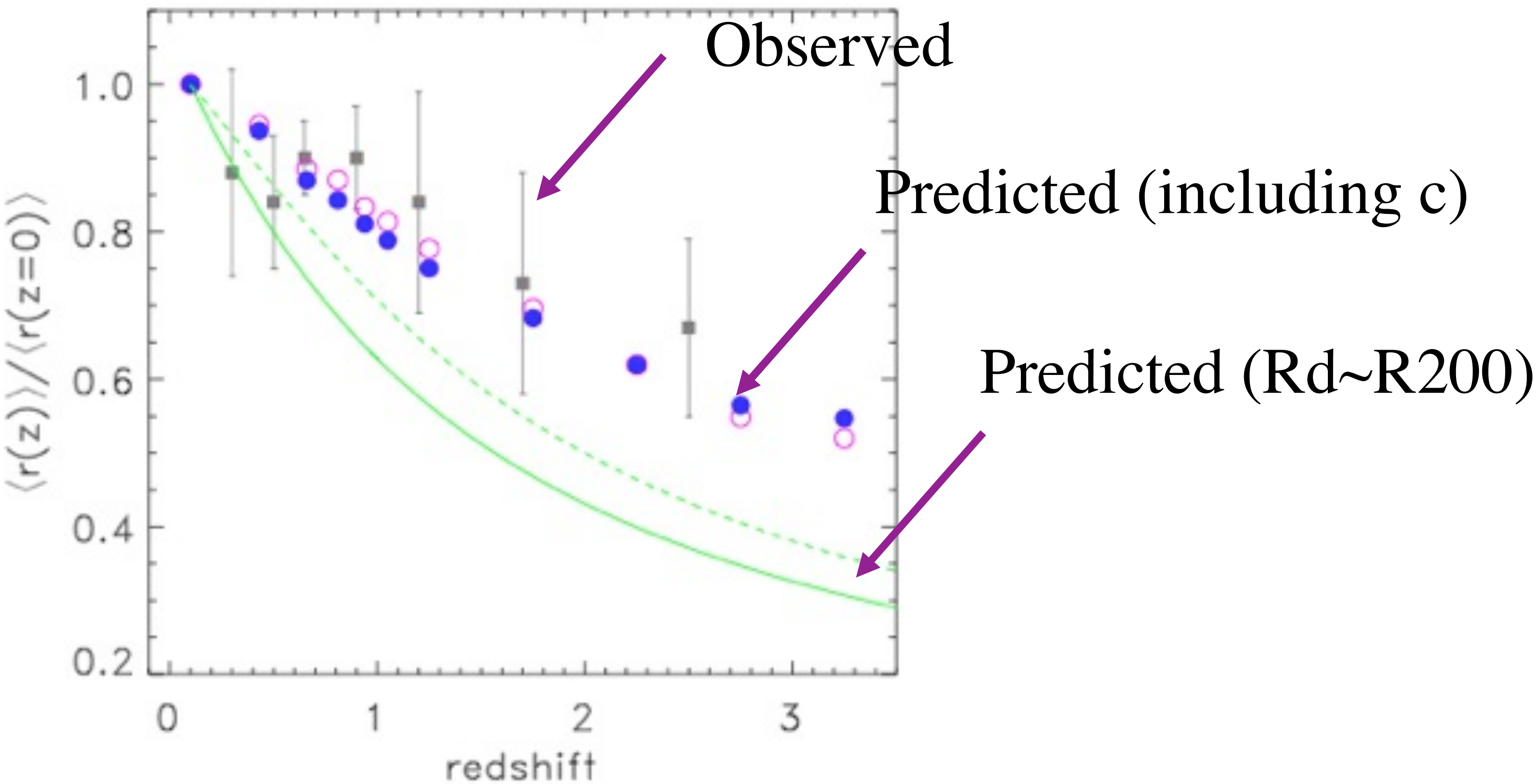


Somerville et al. 2007

Redshift Evolution

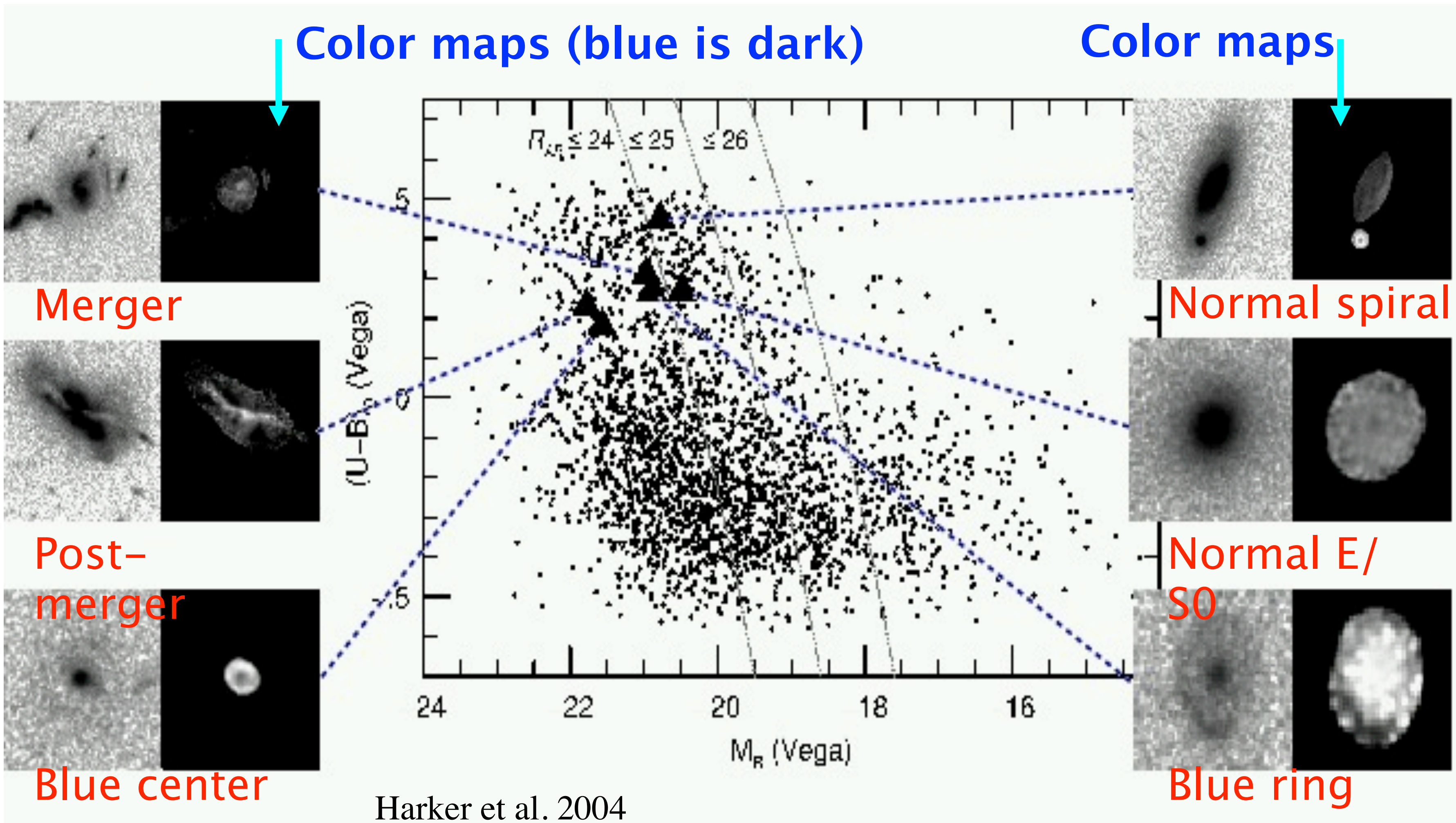
SIZE-MASS RELATIONS

- Weak disk size-mass evolution: why?
  - Rd ~ R_c (break radius of halo profile), not R_200 (most mass in R_c, so V^2 ~ M / R_c)
  - R_c = R_200 / c   (concentration)
  - c ~ 1 / (1 + z)   --- cancels most predicted evolution!

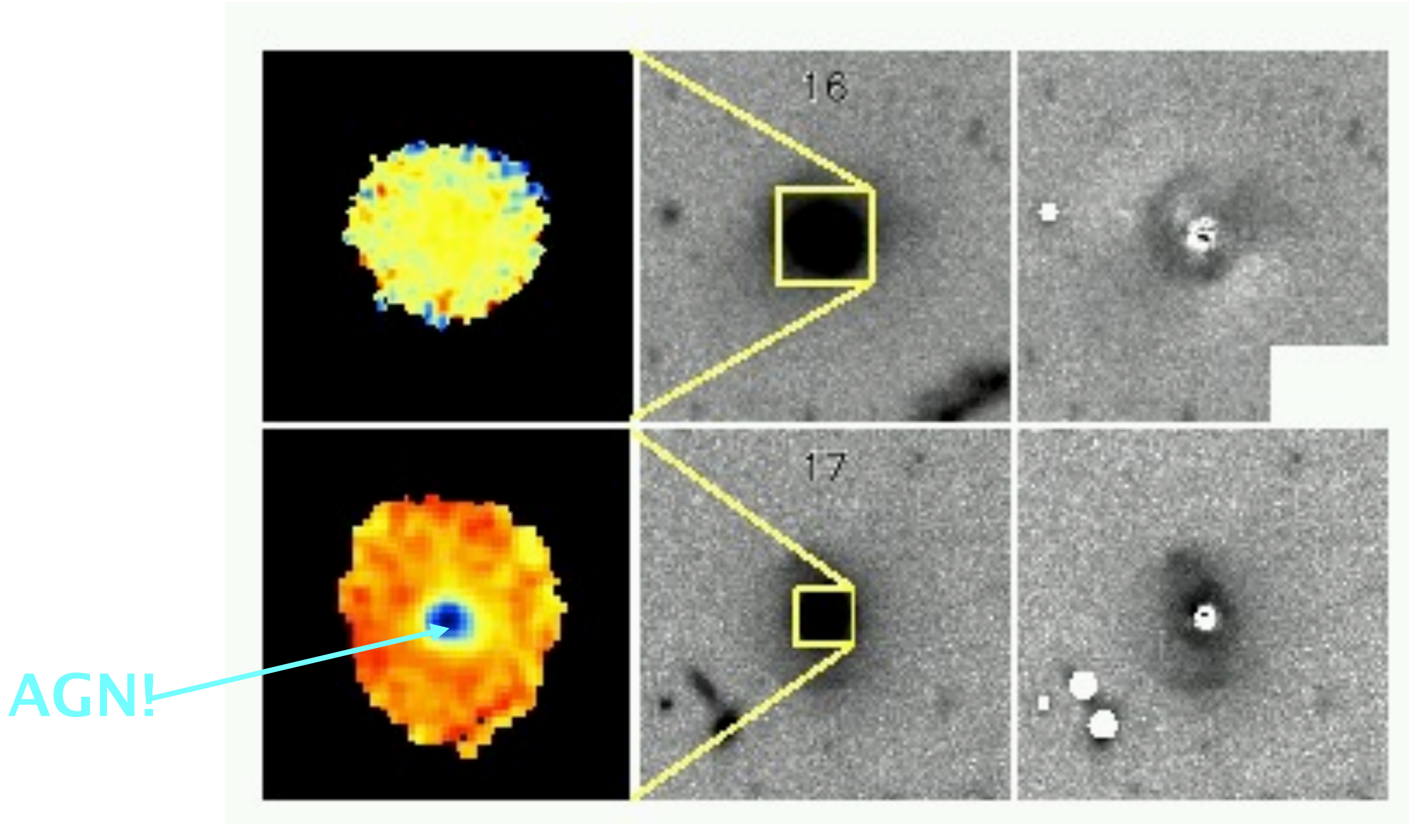


Disks are weakly evolving:
do we expect to see the same in ellipticals?

Caution: The red sequence at z~1 contains a wide range of morphologies



Many ellipticals being/recently formed: even normal E/S0s are often disturbed



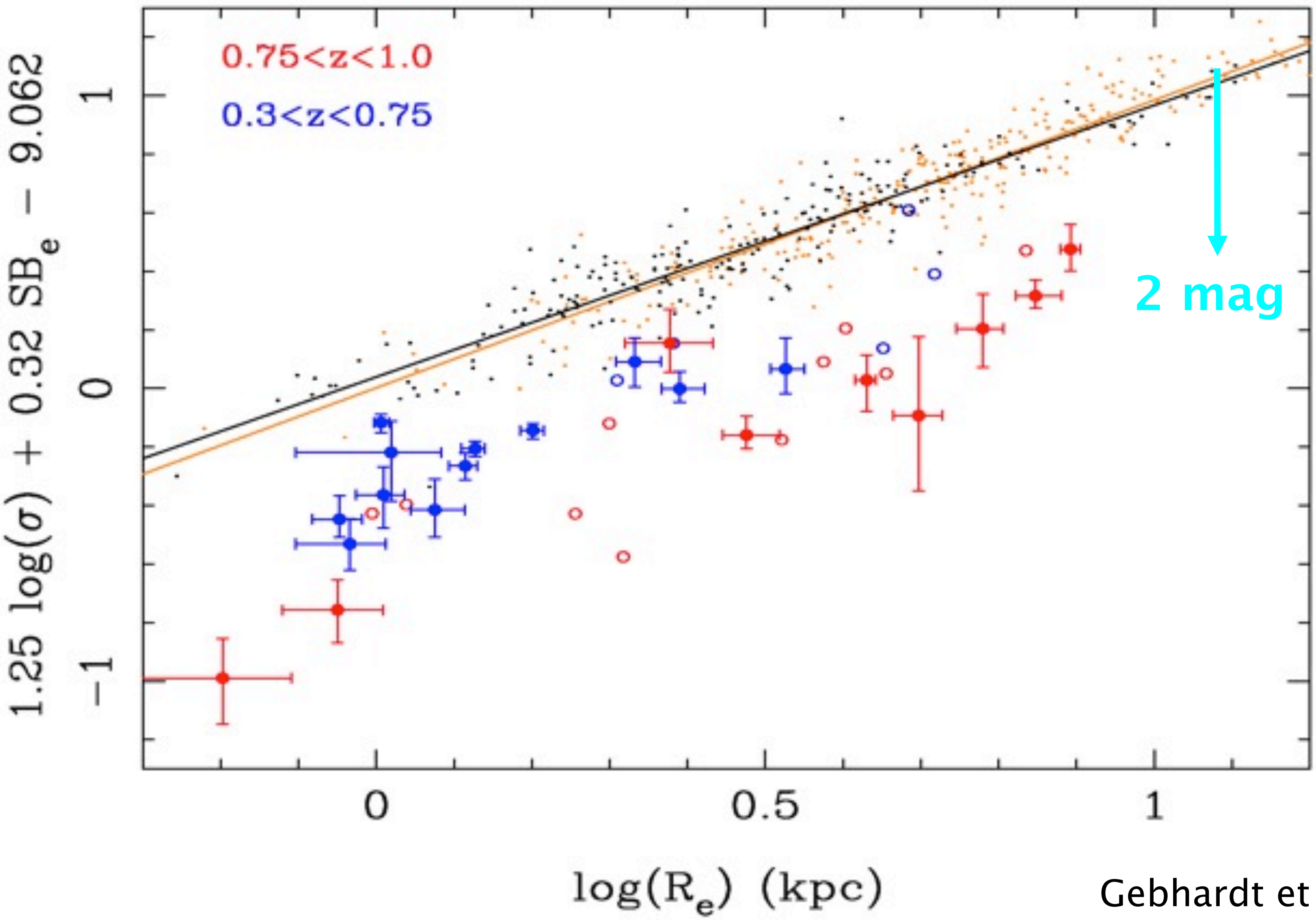
Van Dokkum & Ellis 2003

Red-sequence E/S0 galaxies in HDF-N. 40% of all spheroidal galaxies to 23 R mag are disturbed. Roughly 1/3 of these show blue centers and are also candidate AGNs.

Redshift Evolution

THE FUNDAMENTAL PLANE

- See an offset in magnitude in the FP



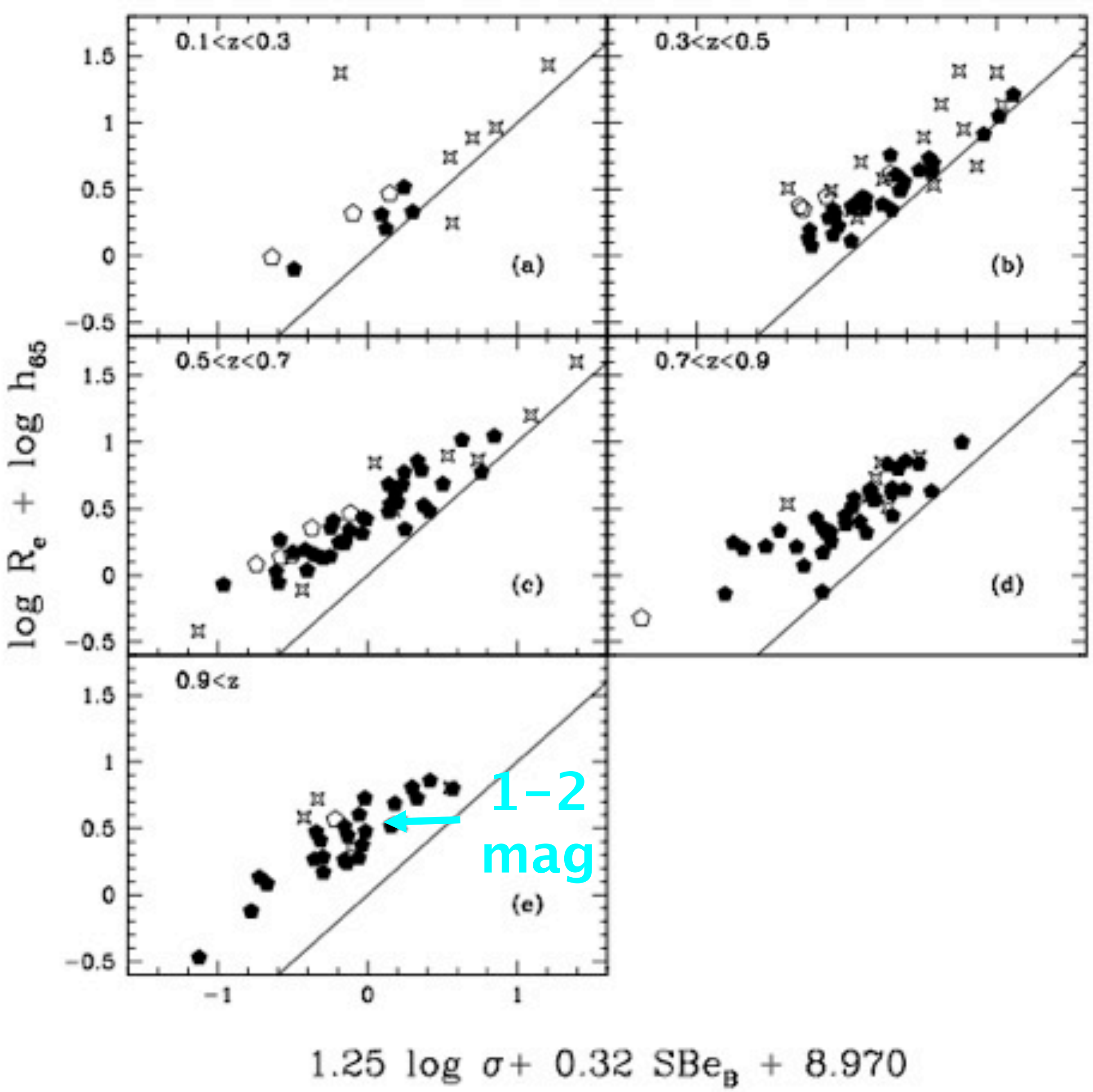
Gebhardt et al. 2003

(Field)

Redshift Evolution

THE FUNDAMENTAL PLANE

- See an offset in magnitude in the FP



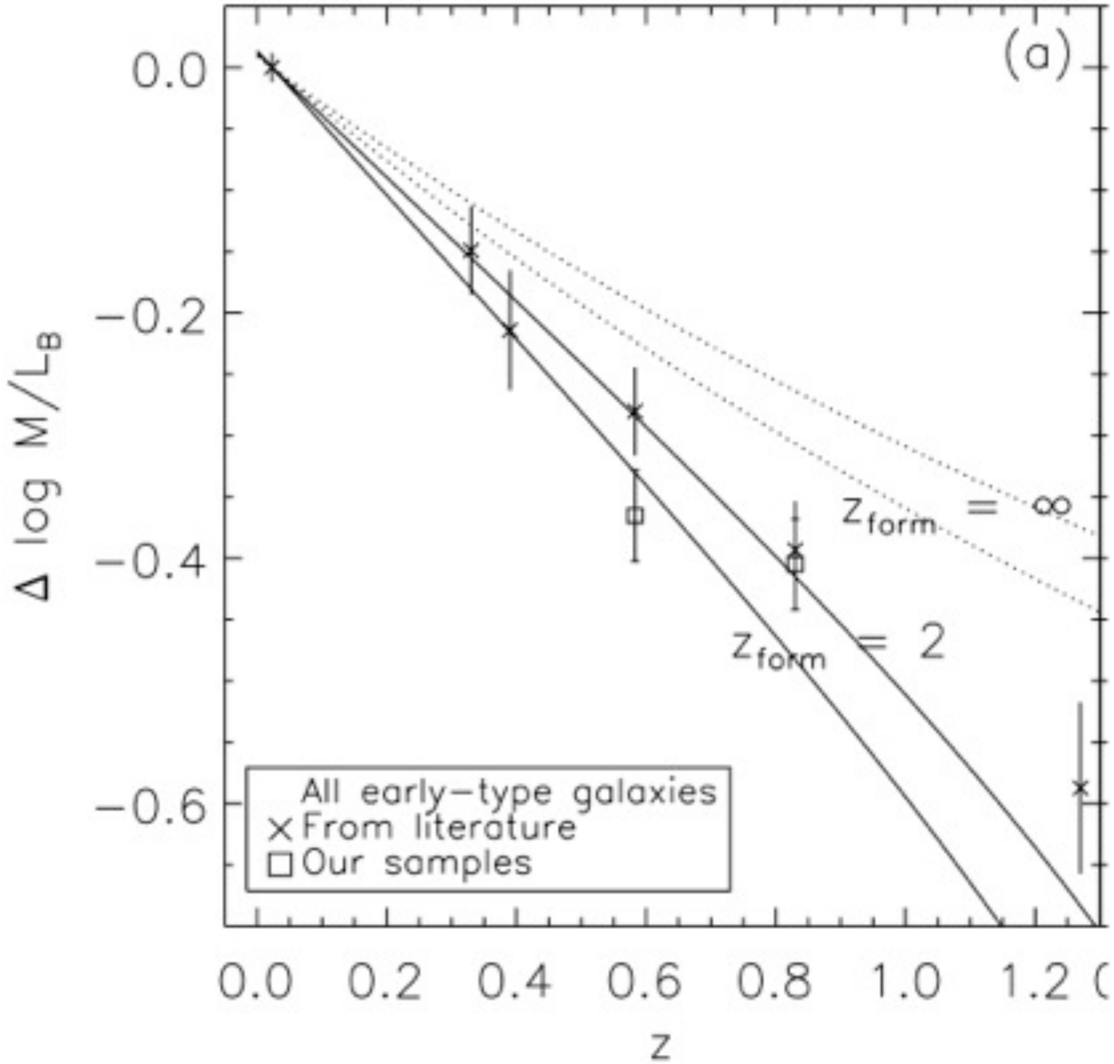
Treu et al.

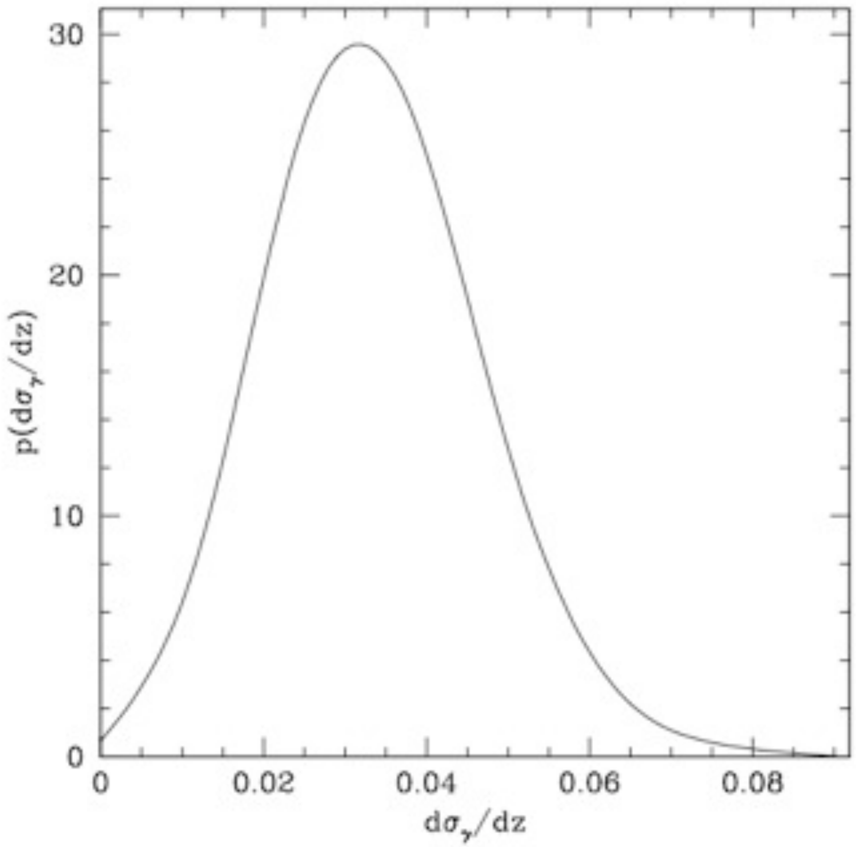
(Clusters)

Redshift Evolution

THE FUNDAMENTAL PLANE

- But again, evolution consistent with stellar population fading



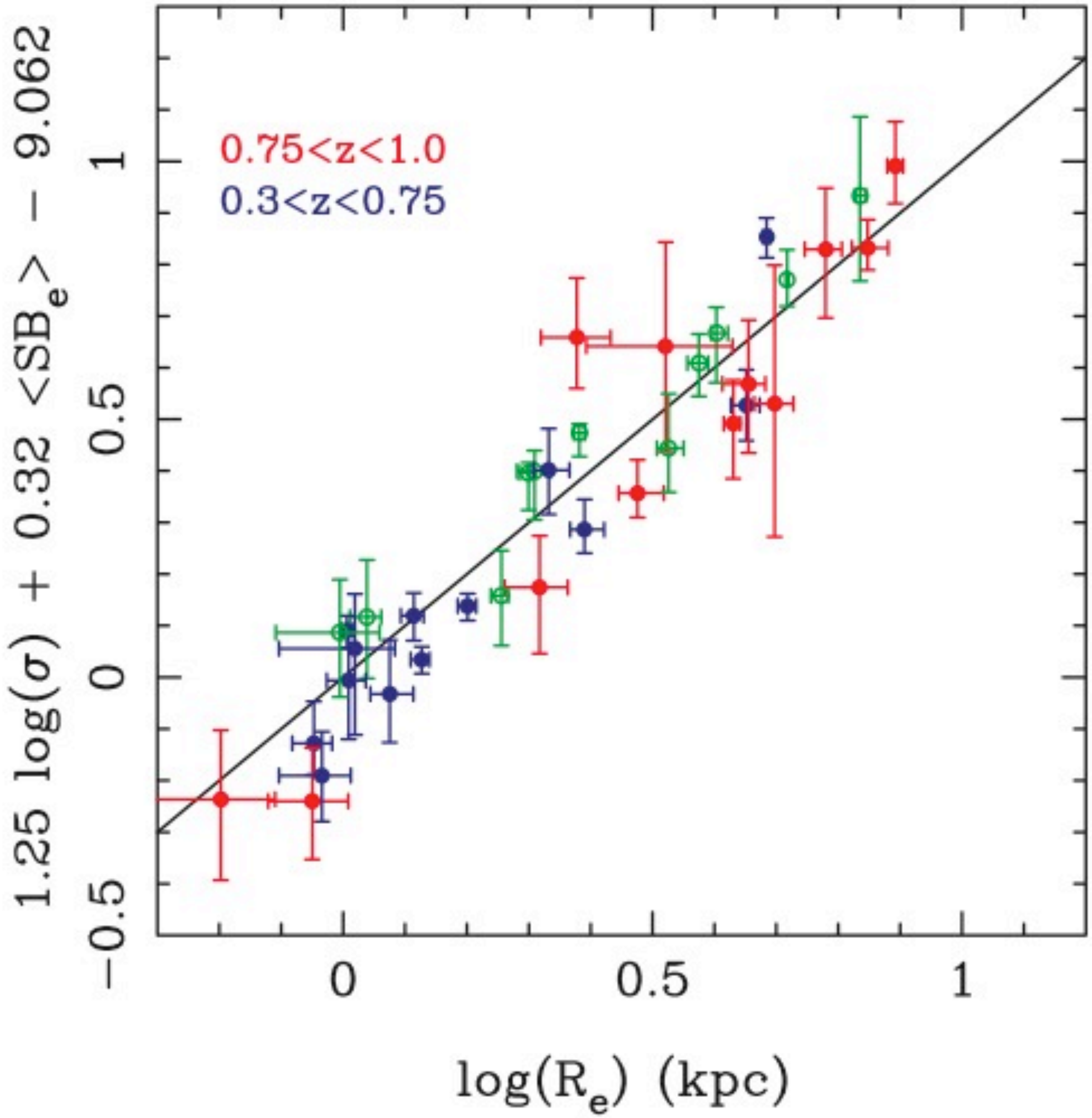


- And scatter remains small

Redshift Evolution

THE FUNDAMENTAL PLANE

- Given weak disk evolution, and that this is (to lowest order) the virial relation, perhaps we should not be surprised

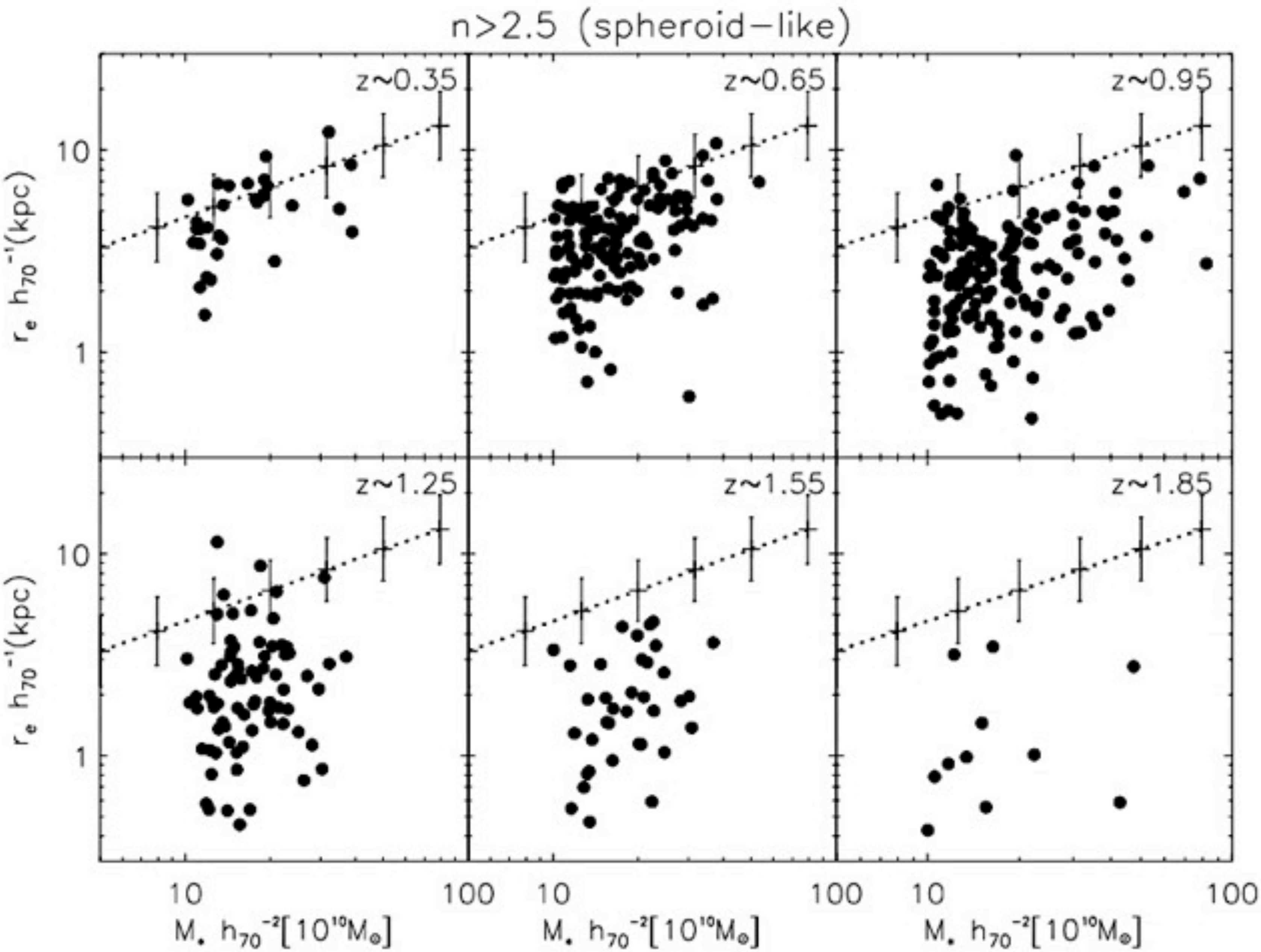


Redshift Evolution

SIZE-MASS RELATIONS

Trujillo et al. 2007

- What about spheroid sizes?

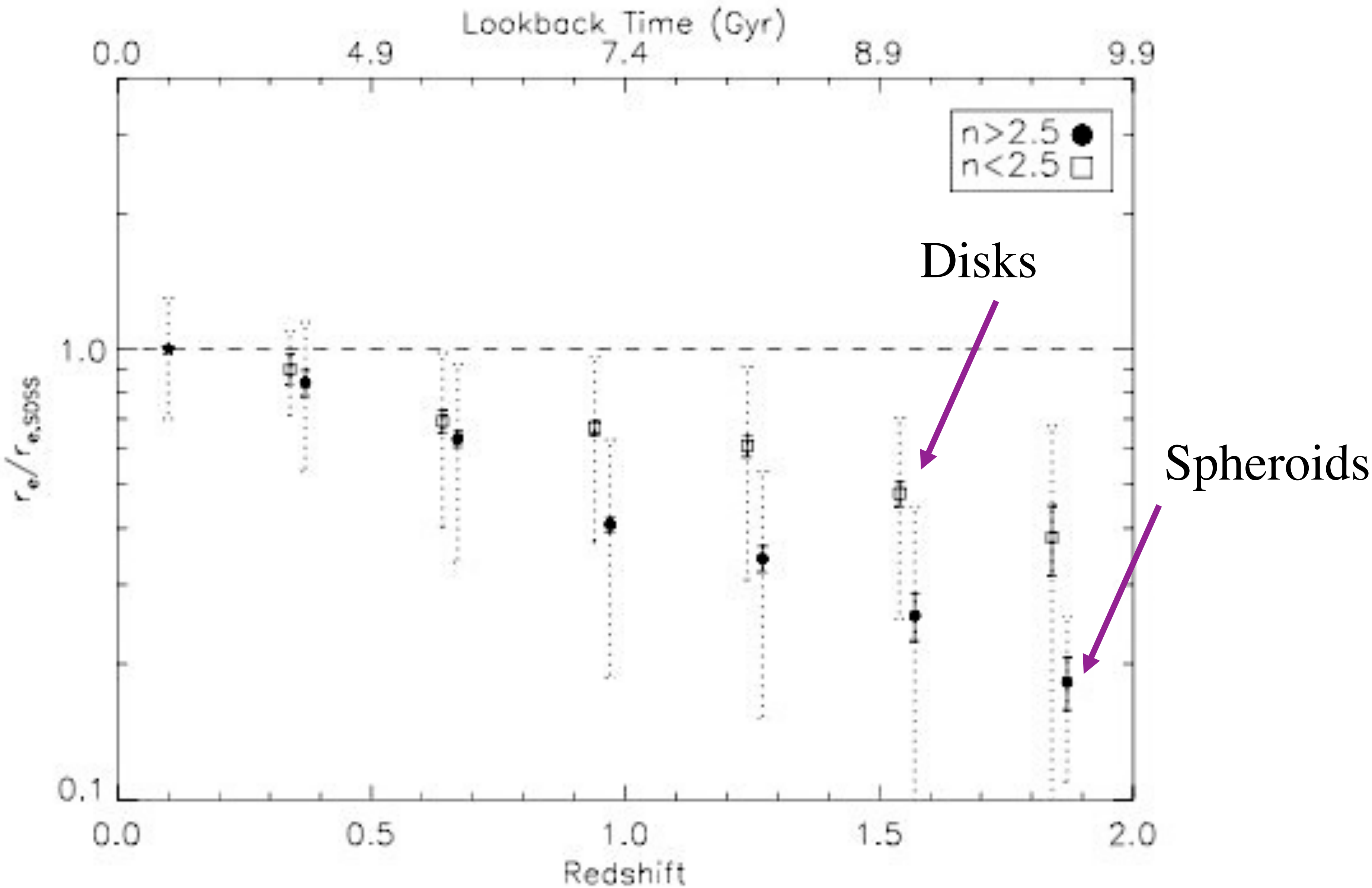


Redshift Evolution

SIZE-MASS RELATIONS

Trujillo et al. 2007

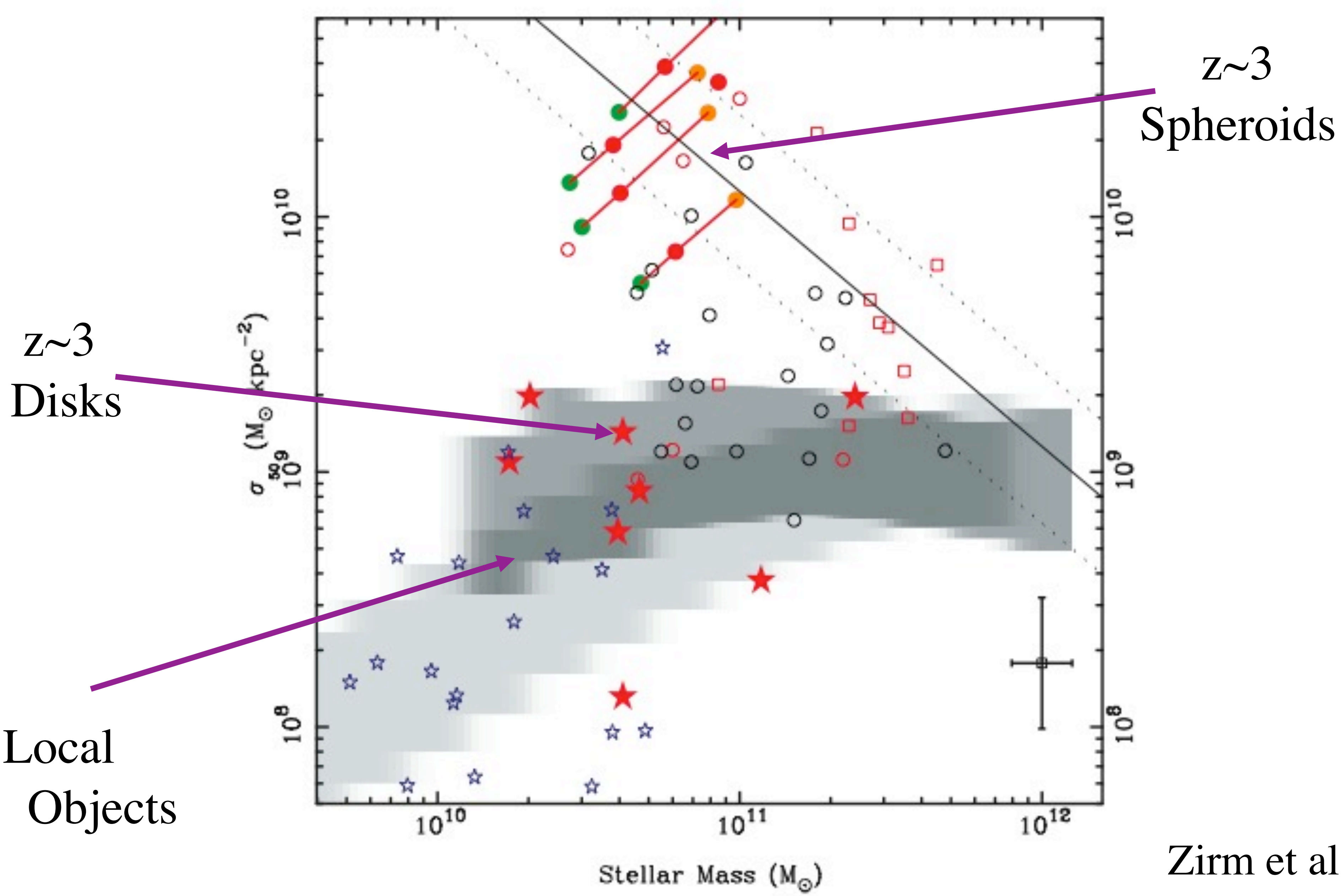
- Spheroids are getting smaller >2x as quickly as disks!



Redshift Evolution

SIZE-MASS RELATIONS

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



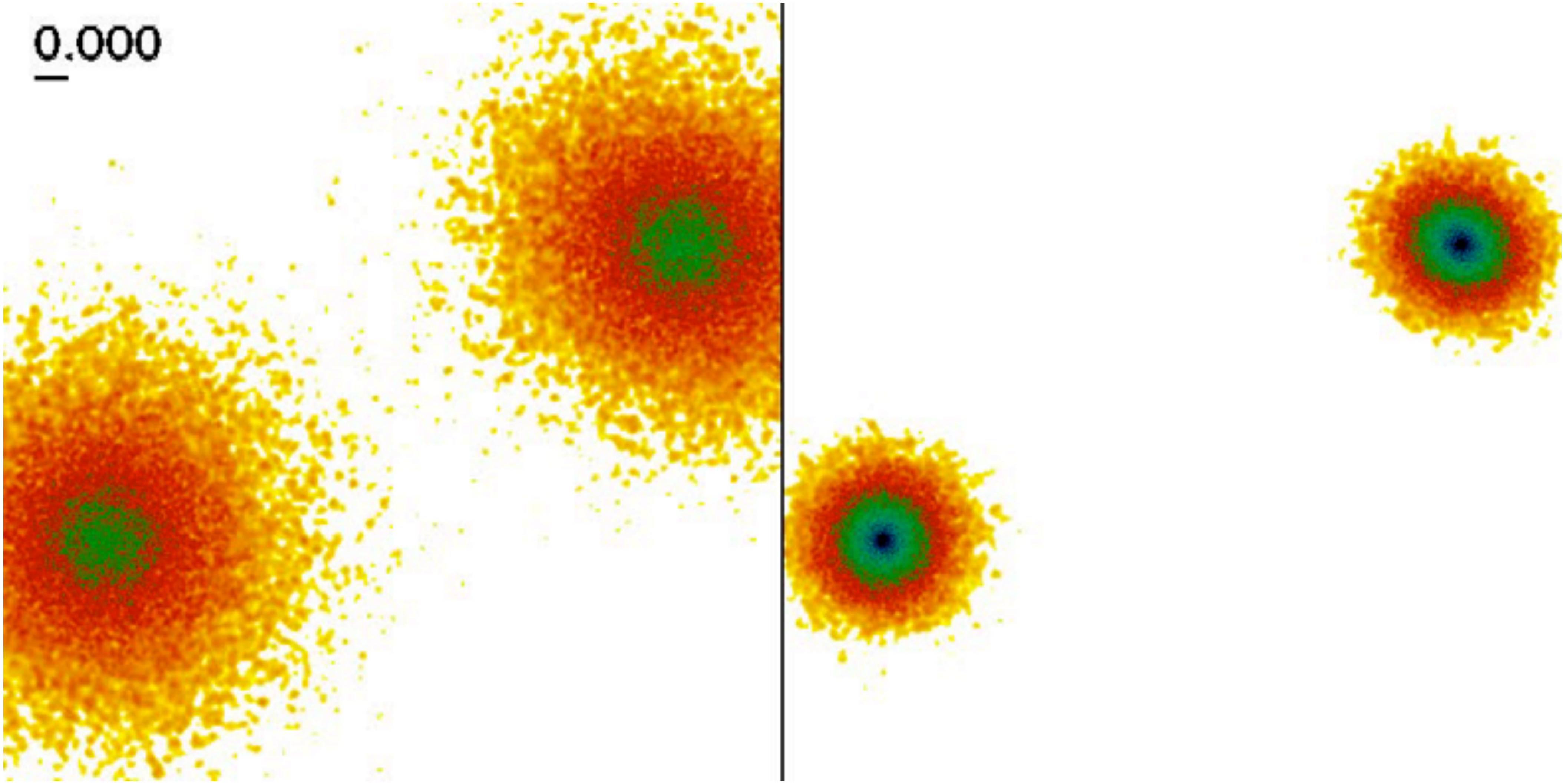
Zirm et al.

Redshift Evolution

SIZE-MASS RELATIONS

- Why are ellipticals so much smaller than disks at high-z?

Same answer as at low-z: gas. just more of it



Redshift Evolution

SIZE-MASS RELATIONS

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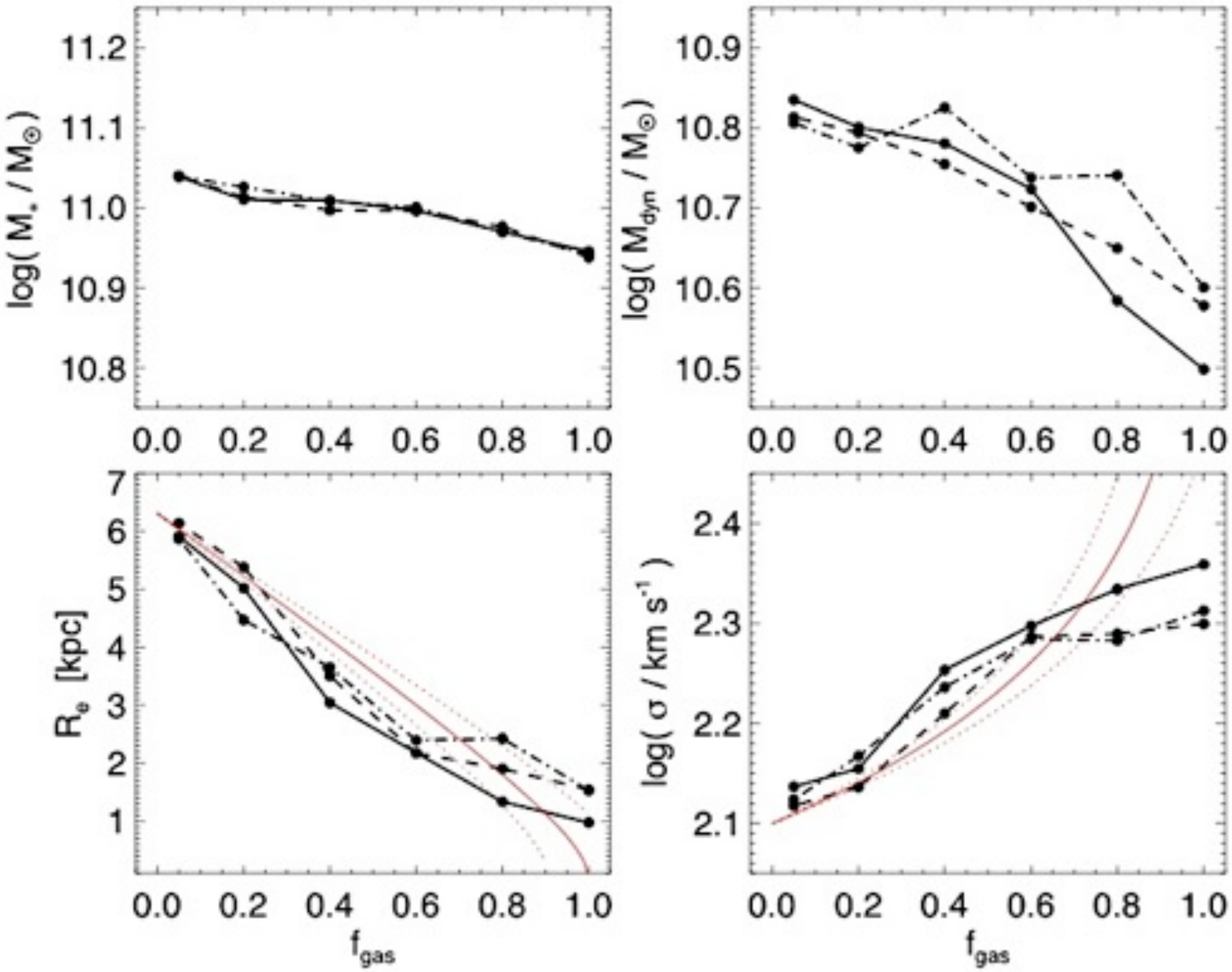
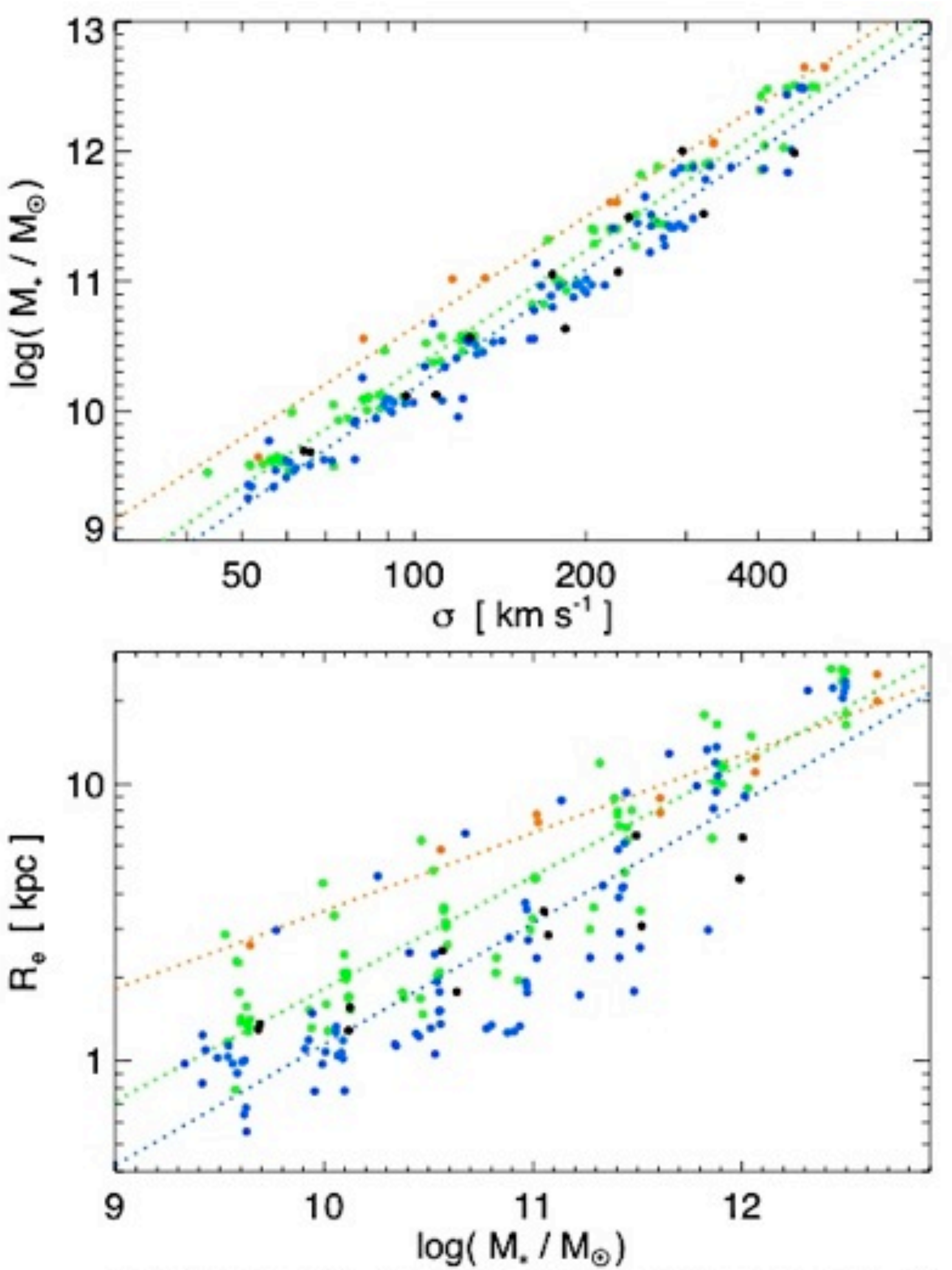


- Increased dissipation >> smaller, more compact remnants (Cox et al.; Robertson et al.)

Redshift Evolution

SIZE-MASS RELATIONS



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

fgas = 0.1

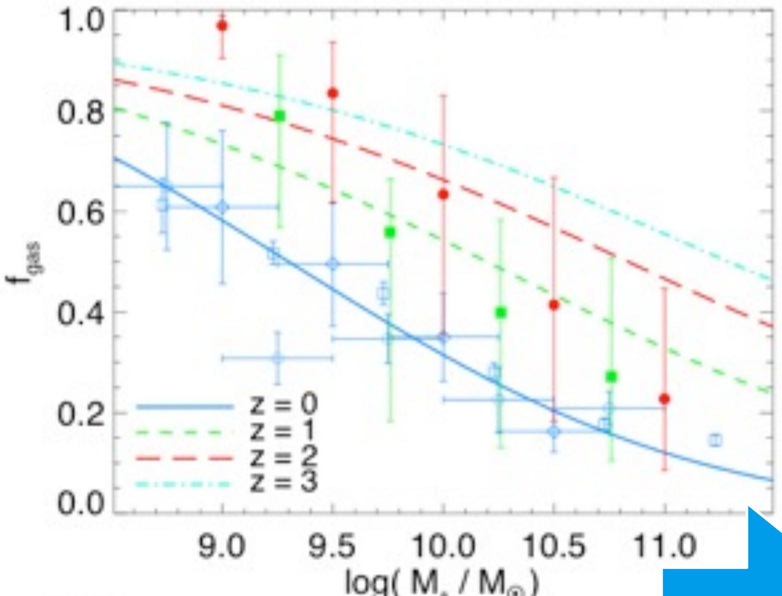
fgas = 0.4

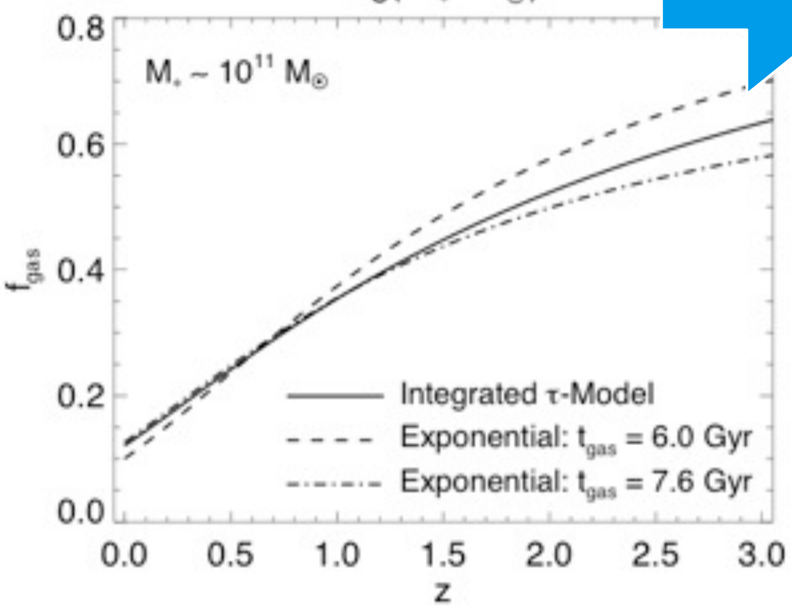
fgas = 0.8

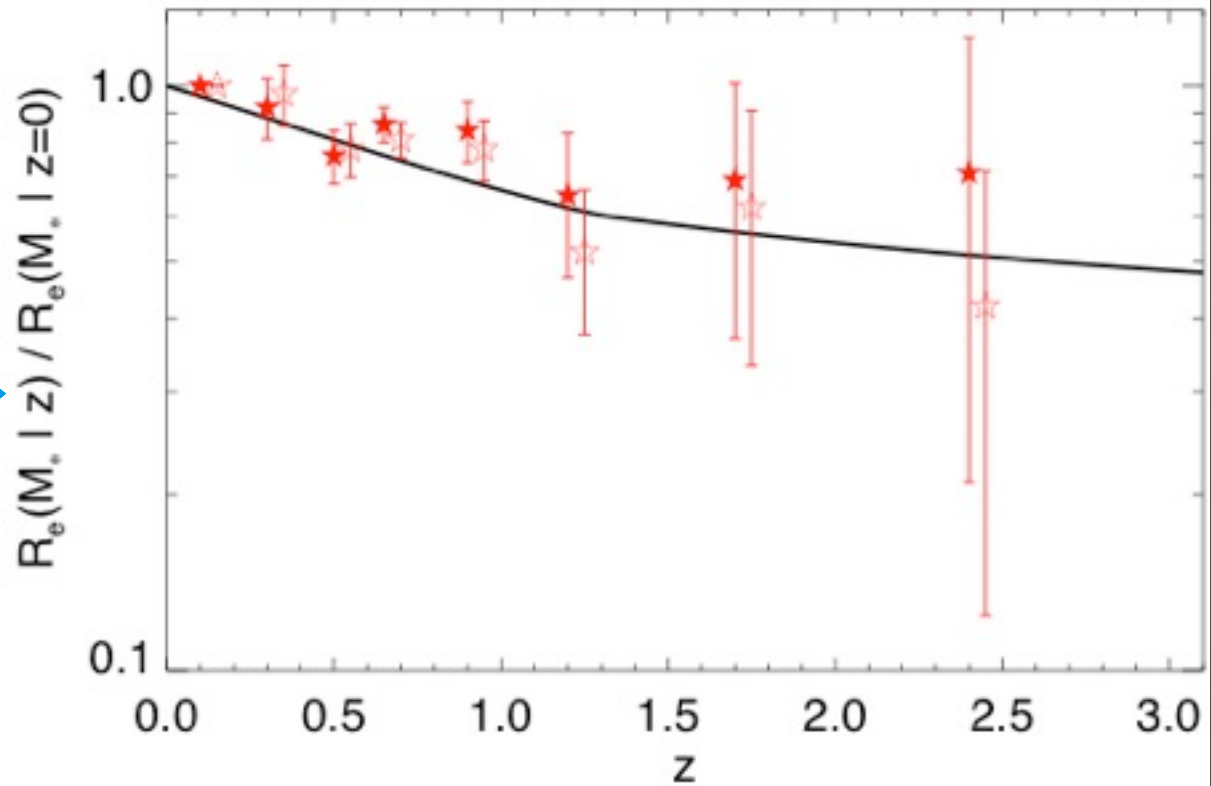
Redshift Evolution

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

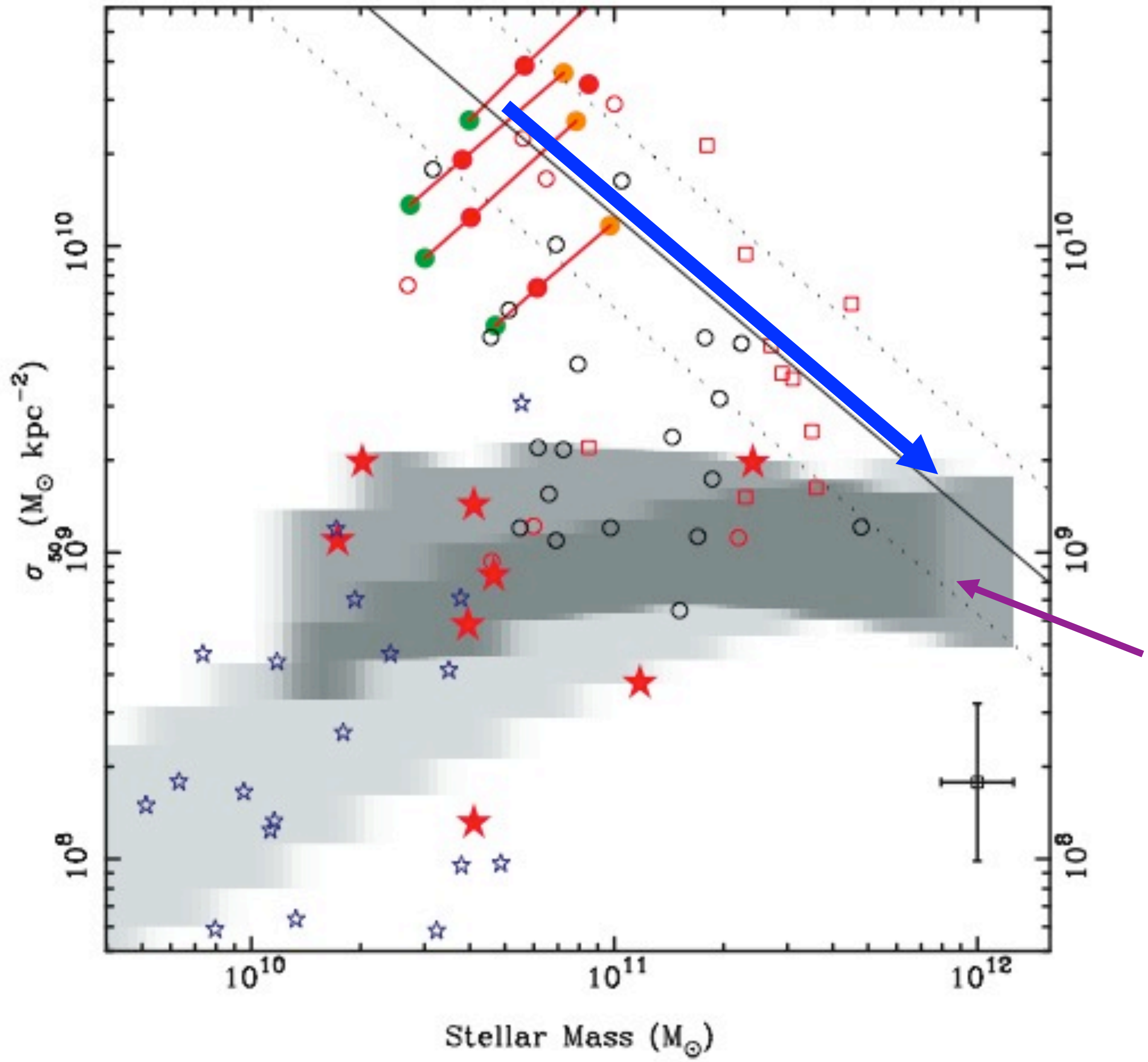
- Relative to the slope of the size mass relation (R ~ M^1/2), you're rapidly moving up (increasing R)

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

Redshift Evolution

SIZE-MASS RELATIONS

Direction dry mergers move you



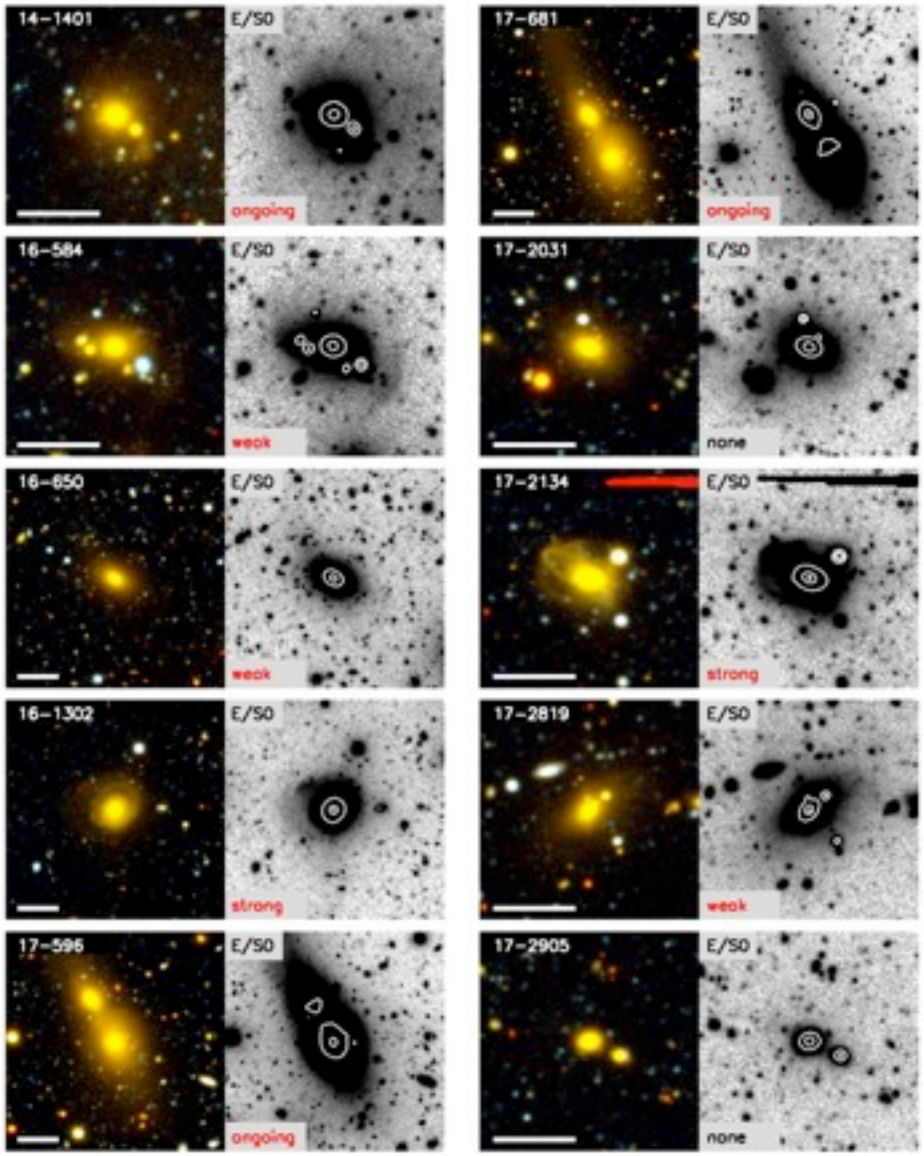
these z~3 galaxies are the most massive galaxies today

Redshift Evolution

SIZE-MASS RELATIONS

- But....

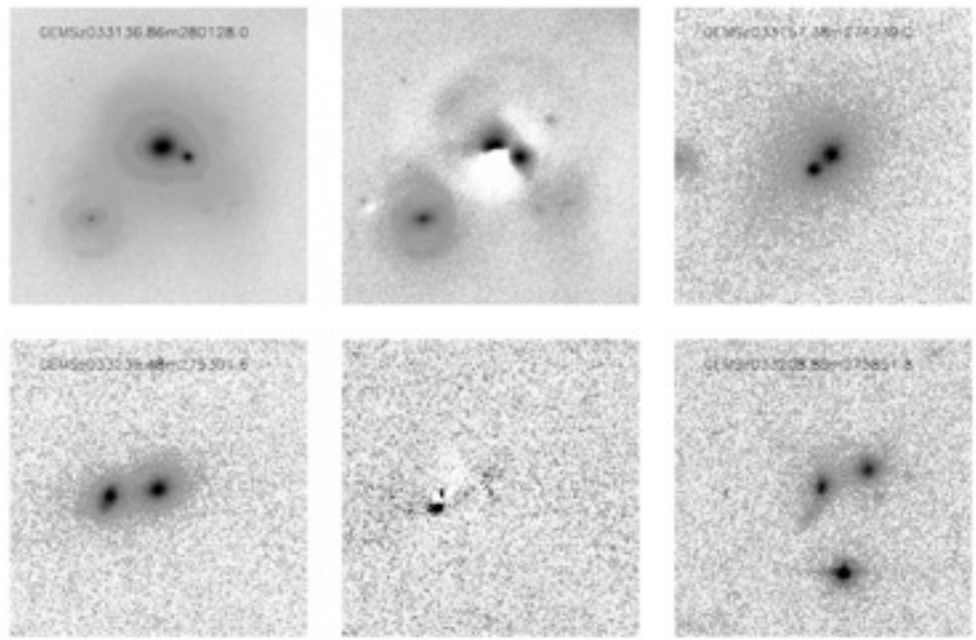
unclear how much room there is for dry mergers in the most massive galaxies



Van Dokkum et al. (2005)

- We see them happening...

Bell et al. (2006)



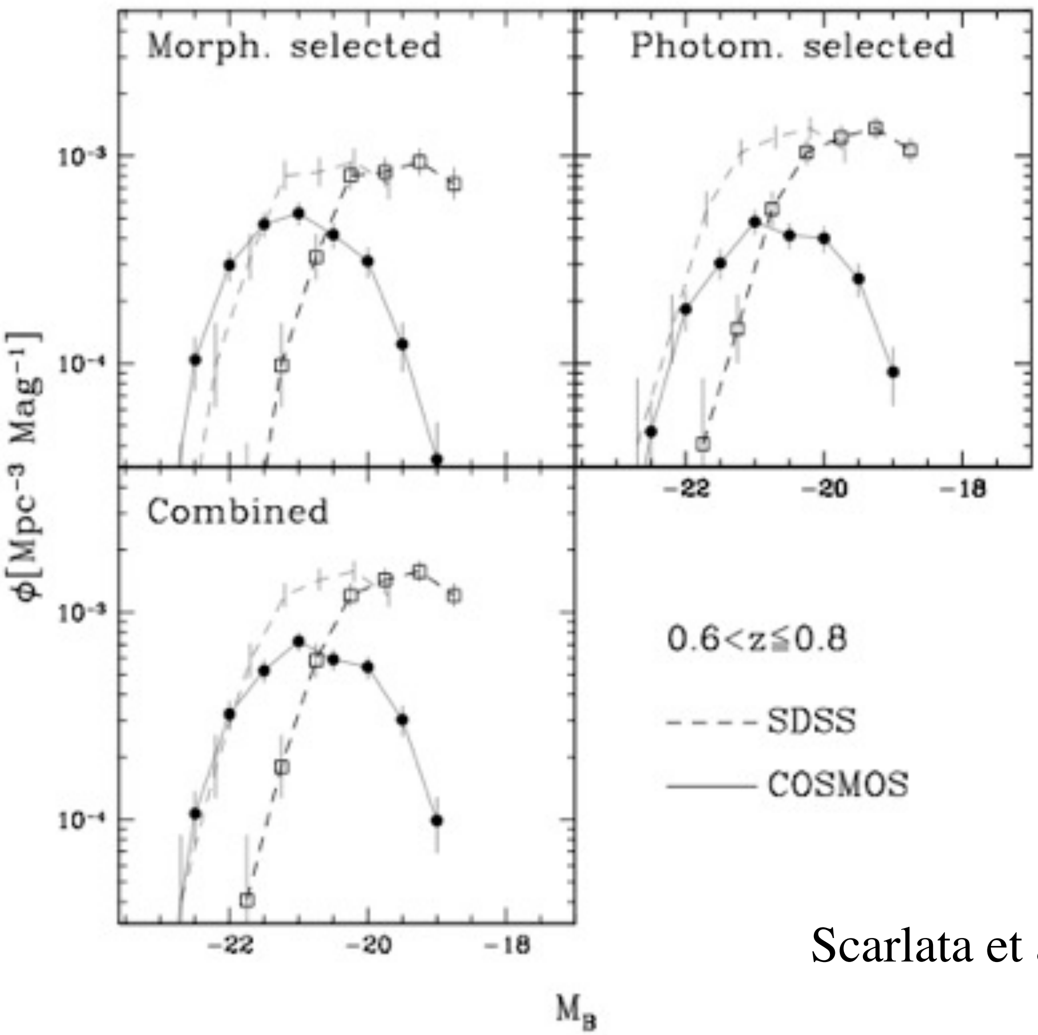
Redshift Evolution

SIZE-MASS RELATIONS

- But....

  unclear how much room there is for dry mergers in the most massive galaxies

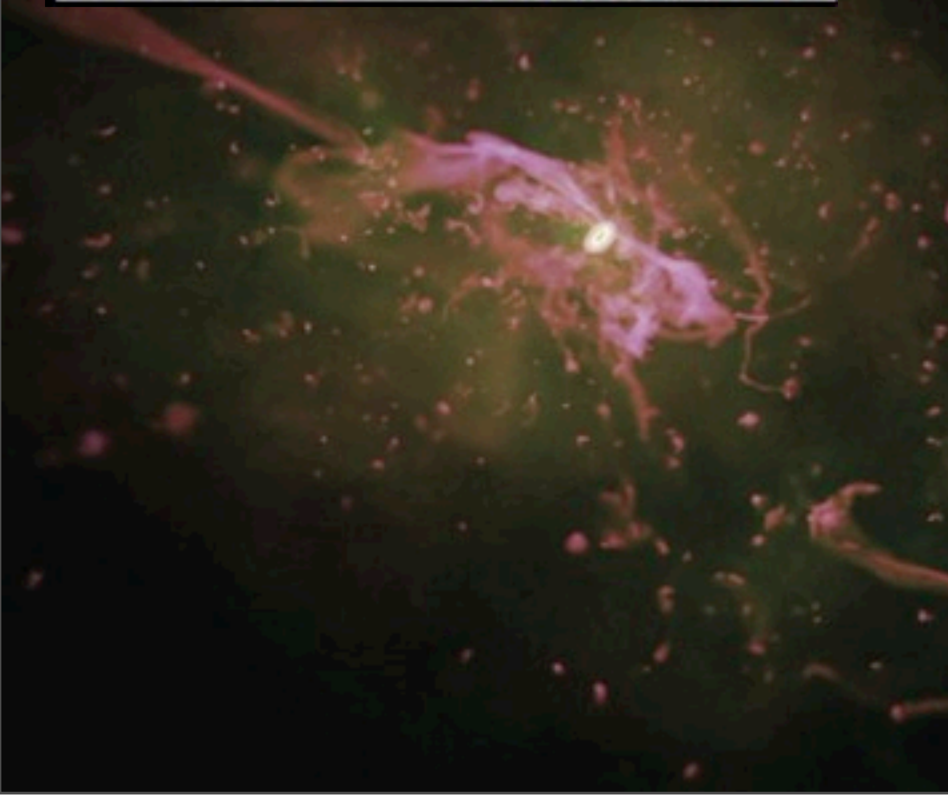
- But others argue even ~1 is too many for a massive galaxy

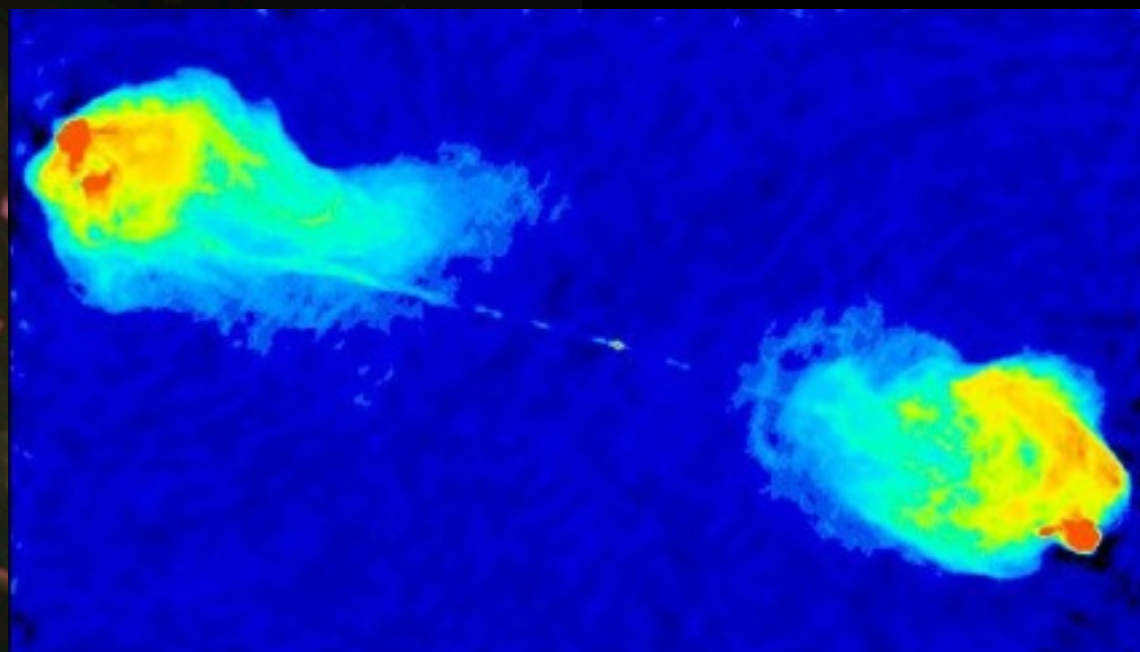


- Major caveat: our knowledge of stellar populations
  - Maraston: M/L is much lower *when galaxies are younger*

Scarlata et al. (2007)

Red galaxies: How do we determine how galaxies shut down?

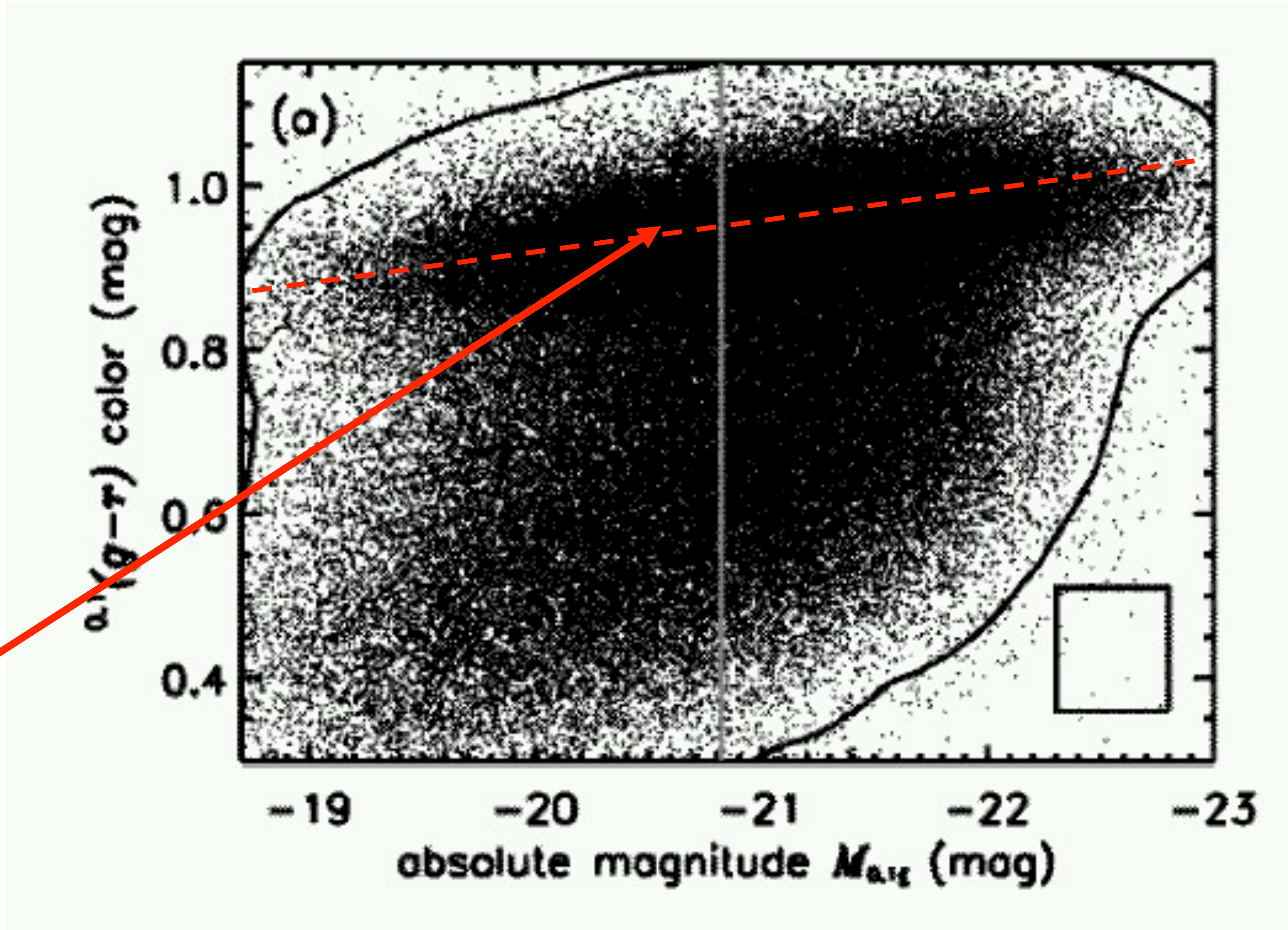




Fundamental Plane Tilt

STELLAR POPULATION VARIATION

The color-magnitude diagram from SDSS



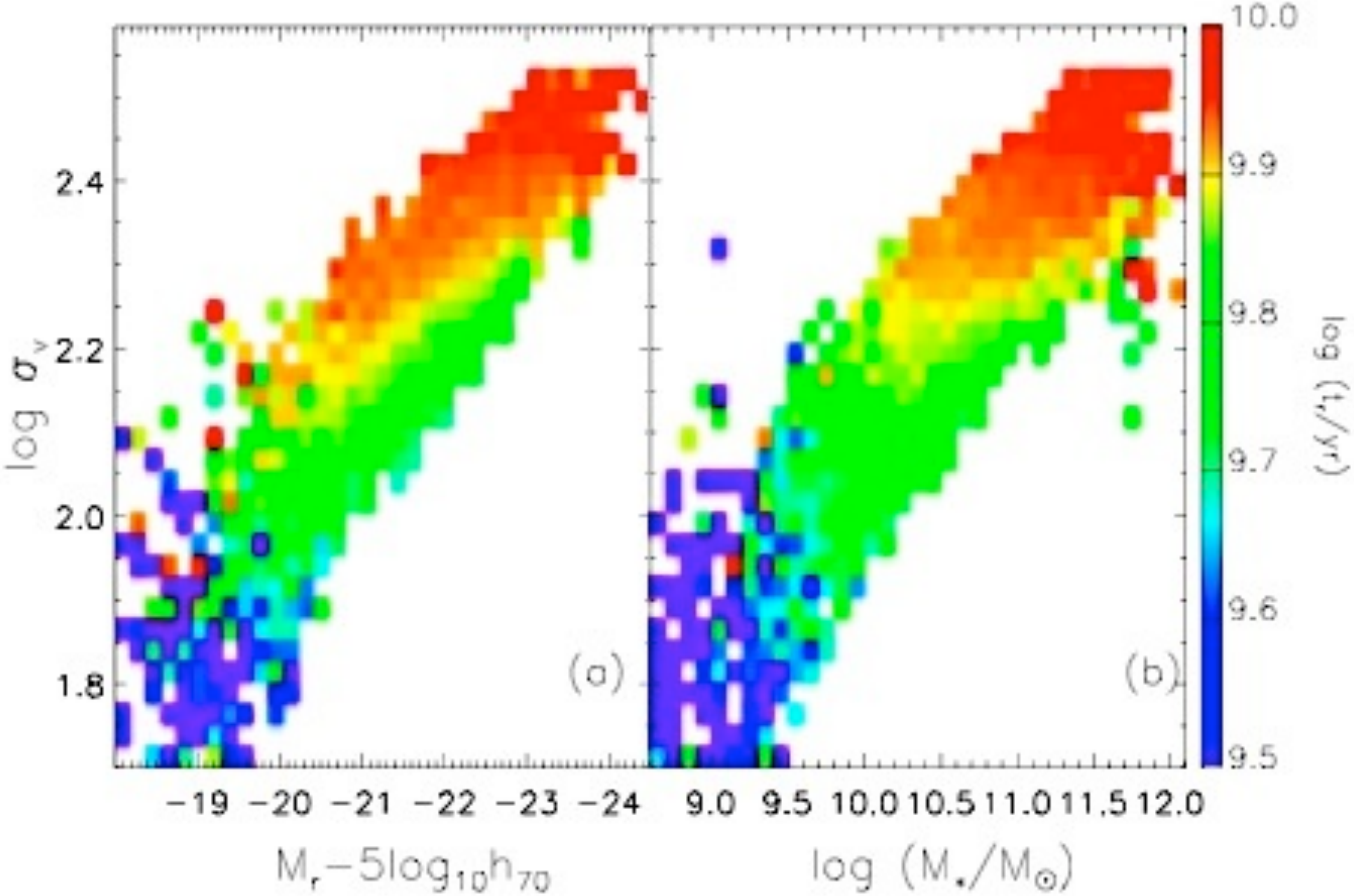
The color-magnitude sequence of early-type galaxies.

Hogg et al.,

Fundamental Plane Tilt

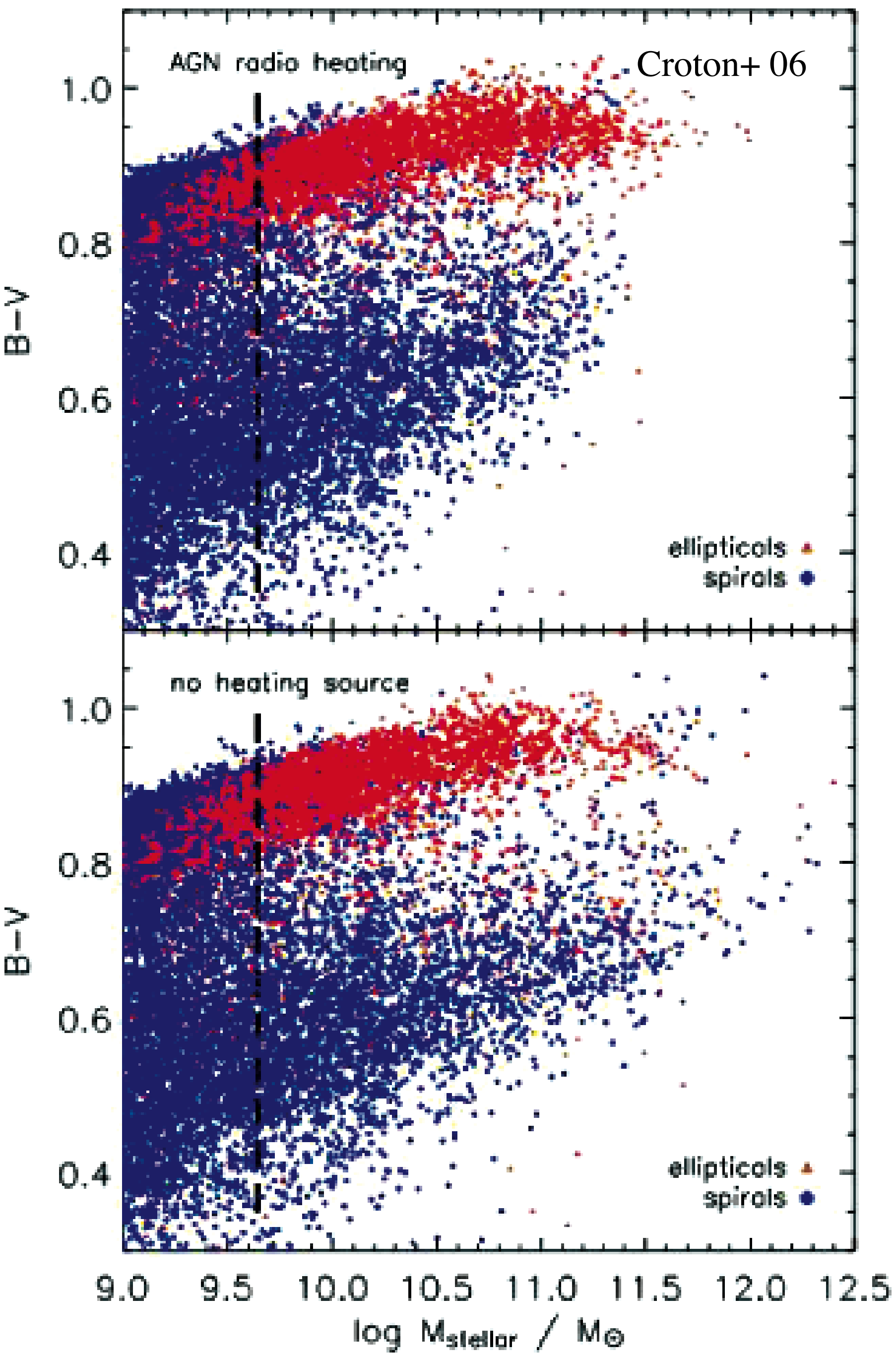
STELLAR POPULATION VARIATION

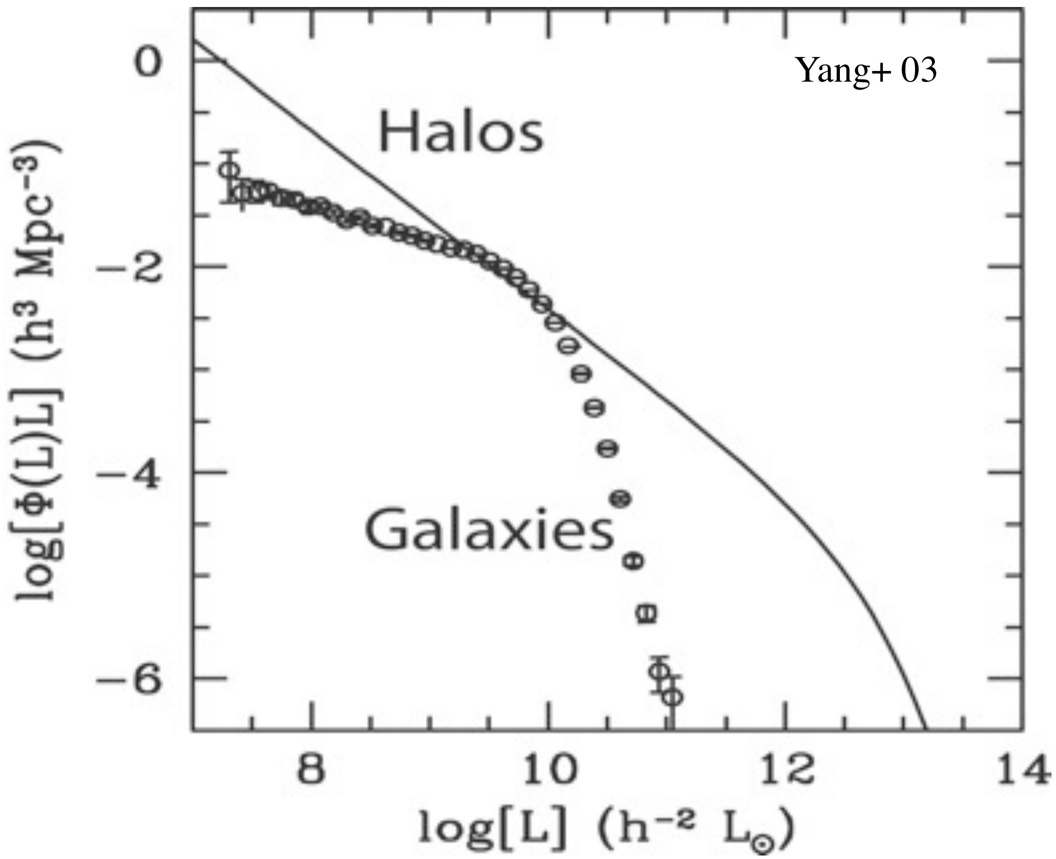
- Indeed, there are very significant stellar population trends as a function of elliptical mass:

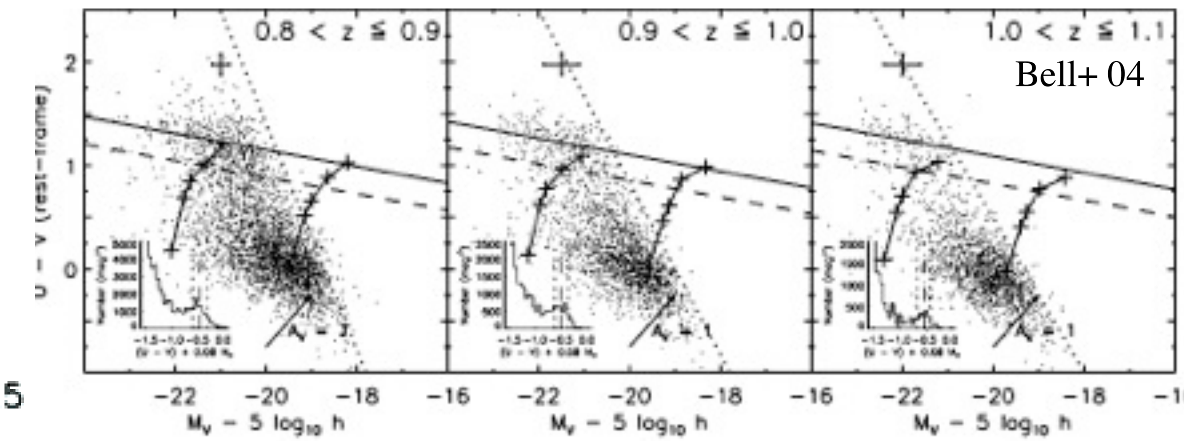


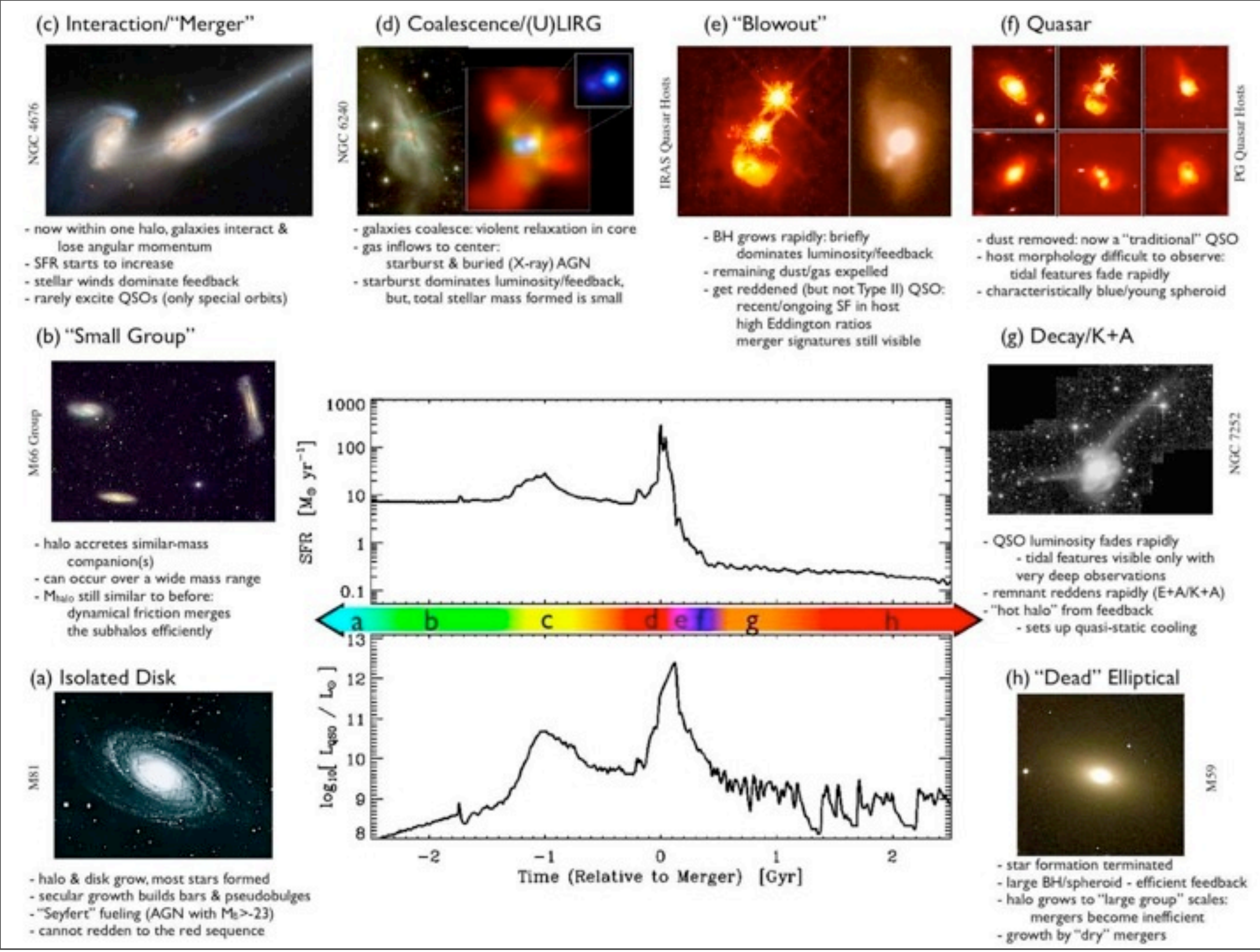
Motivation

QUASARS AND SPHEROID FORMATION





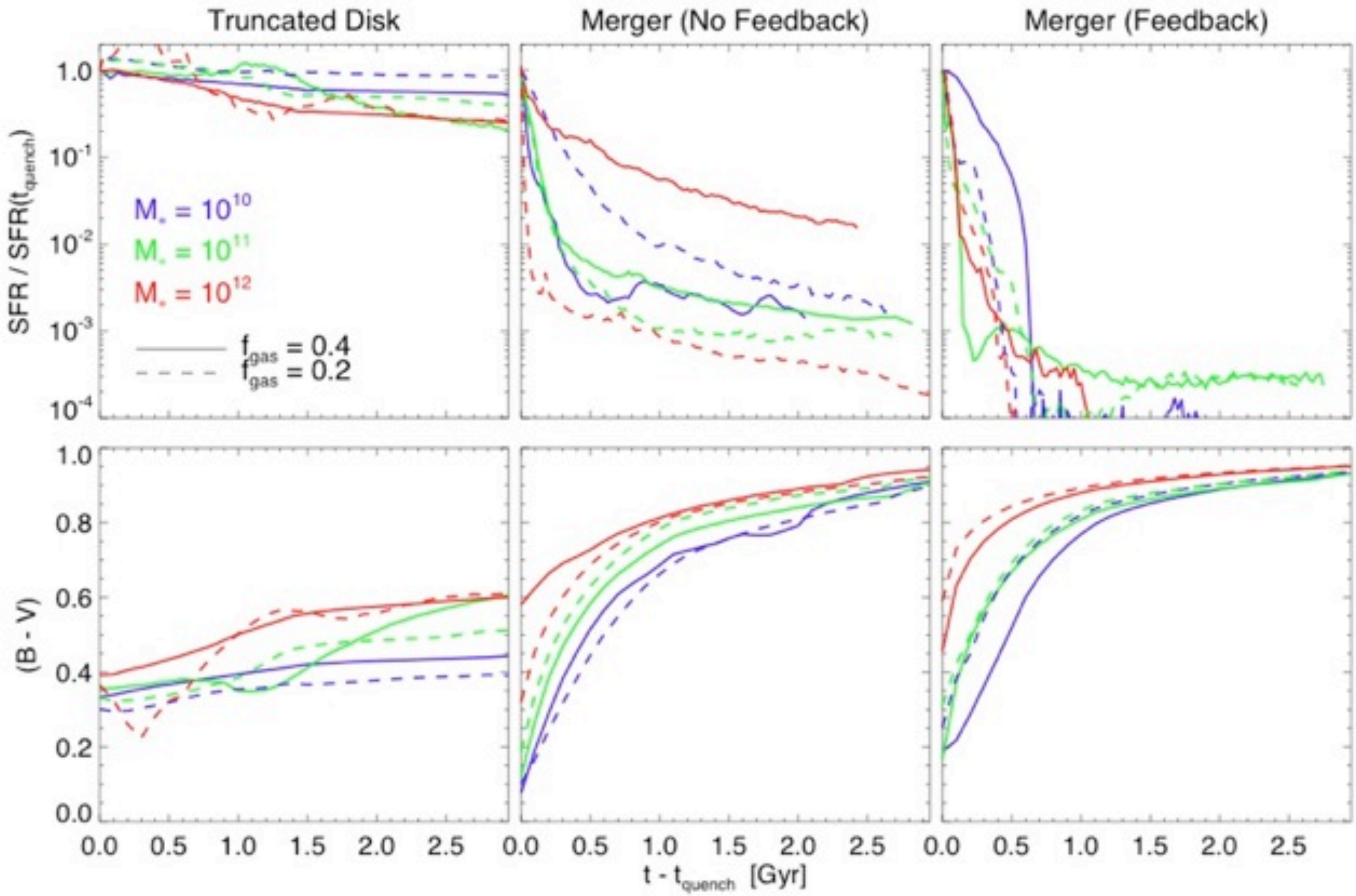




(c) Interaction/"Merger"
NGC 4676
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)
(d) Coalescence/(U)LIRG
NGC 6240
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small
(e) "Blowout"
IRAS Quasar Hosts
- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host high Eddington ratios merger signatures still visible
(f) Quasar
PG Quasar Hosts
- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid
(b) "Small Group"
M66 Group
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- M_{halo} still similar to before: dynamical friction merges the subhalos efficiently
(g) Decay/K+A
NGC 7252
- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant reddens rapidly (E+A/K+A)
- "hot halo" from feedback
- sets up quasi-static cooling
SFR [$M_\odot$ yr^{-1}]
1000
100
10
1
0.1
a b c d e f g h
$\log_{10}[L_{QSO} / L_\odot]$
13
12
11
10
9
8
−2
−1
0
1
2
Time (Relative to Merger) [Gyr]
(a) Isolated Disk
M81
- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with M_B>-23)
- cannot redden to the red sequence
(h) "Dead" Elliptical
M59
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers

Motivation

MERGERS AND THE BLUE-RED TRANSITION



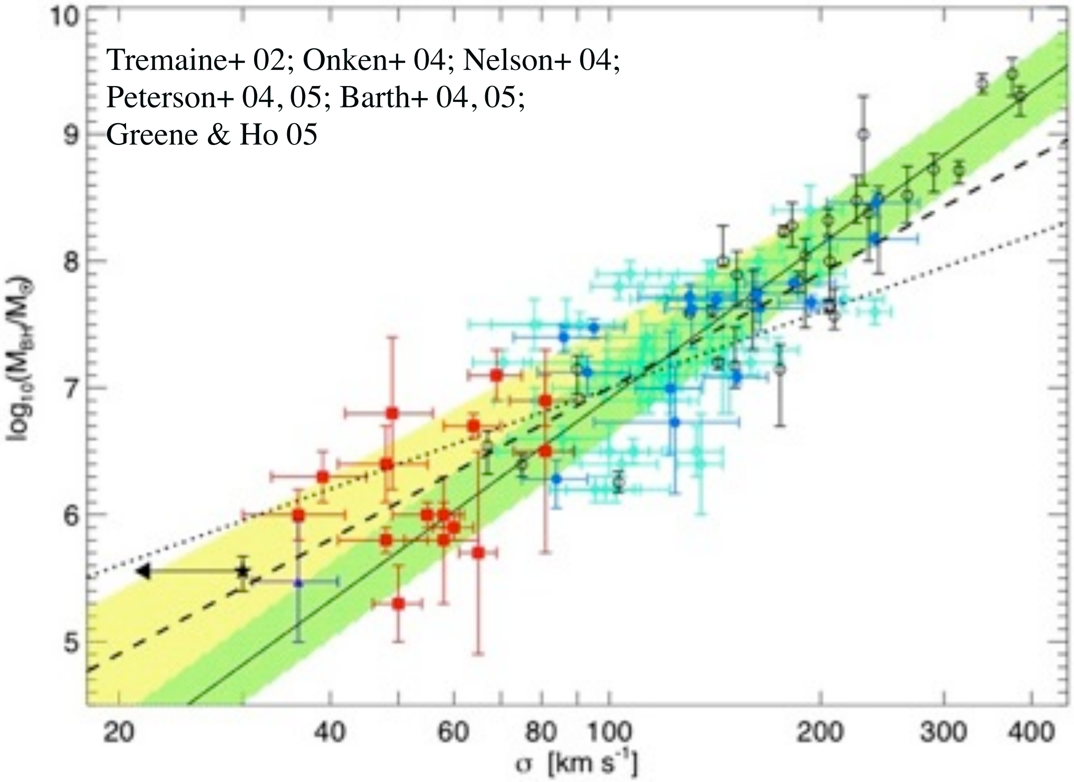
- Woo et al.: Disks aren't "turned off" (red = bulge)?

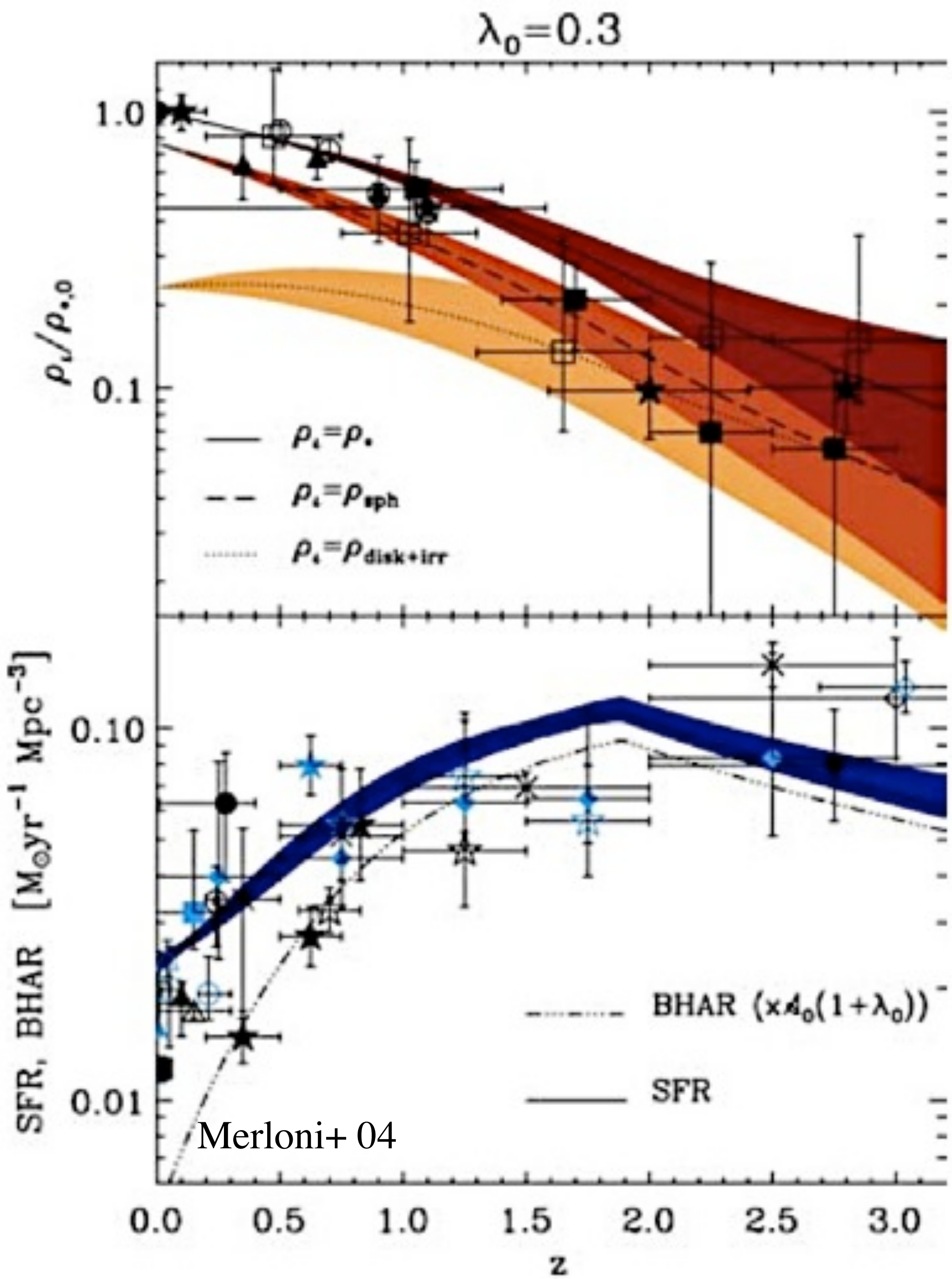
Sbc201a-n4
Zsolar-imf2.35

urz color

Motivation

CIRCUMSTANTIAL EVIDENCE

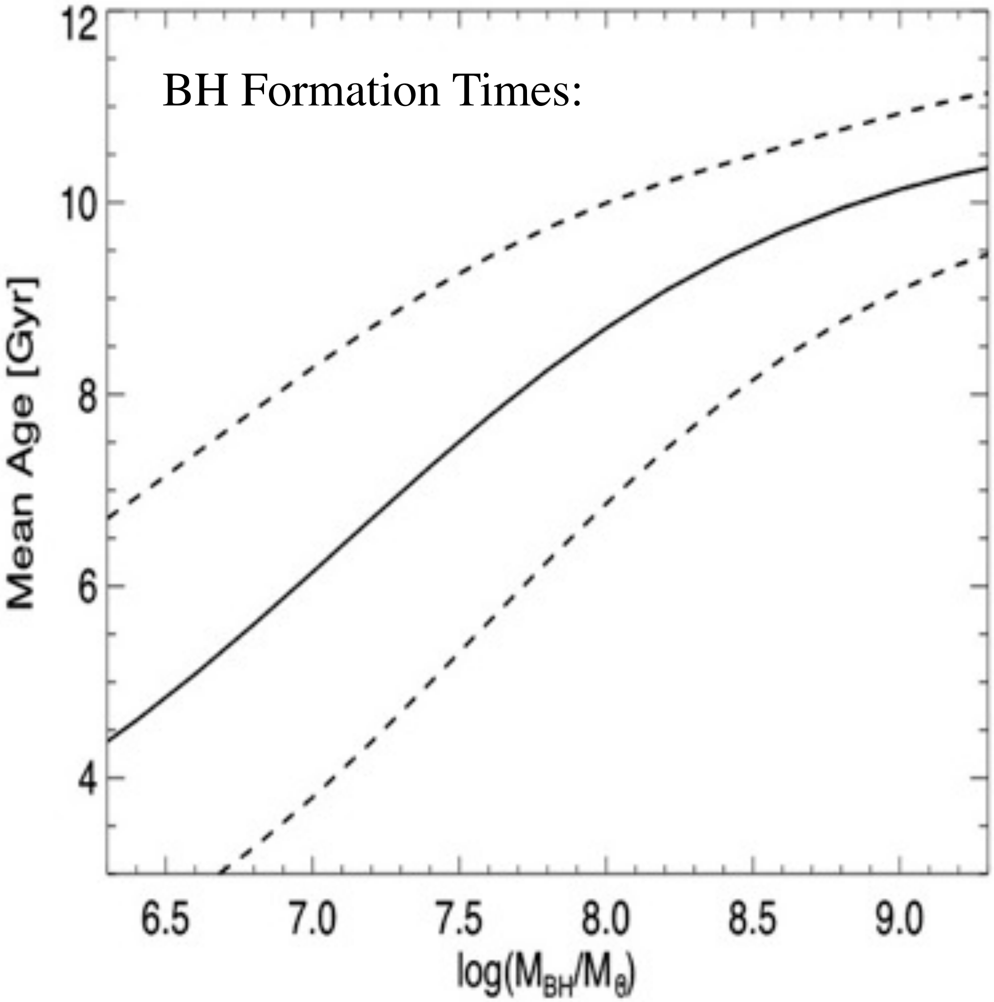


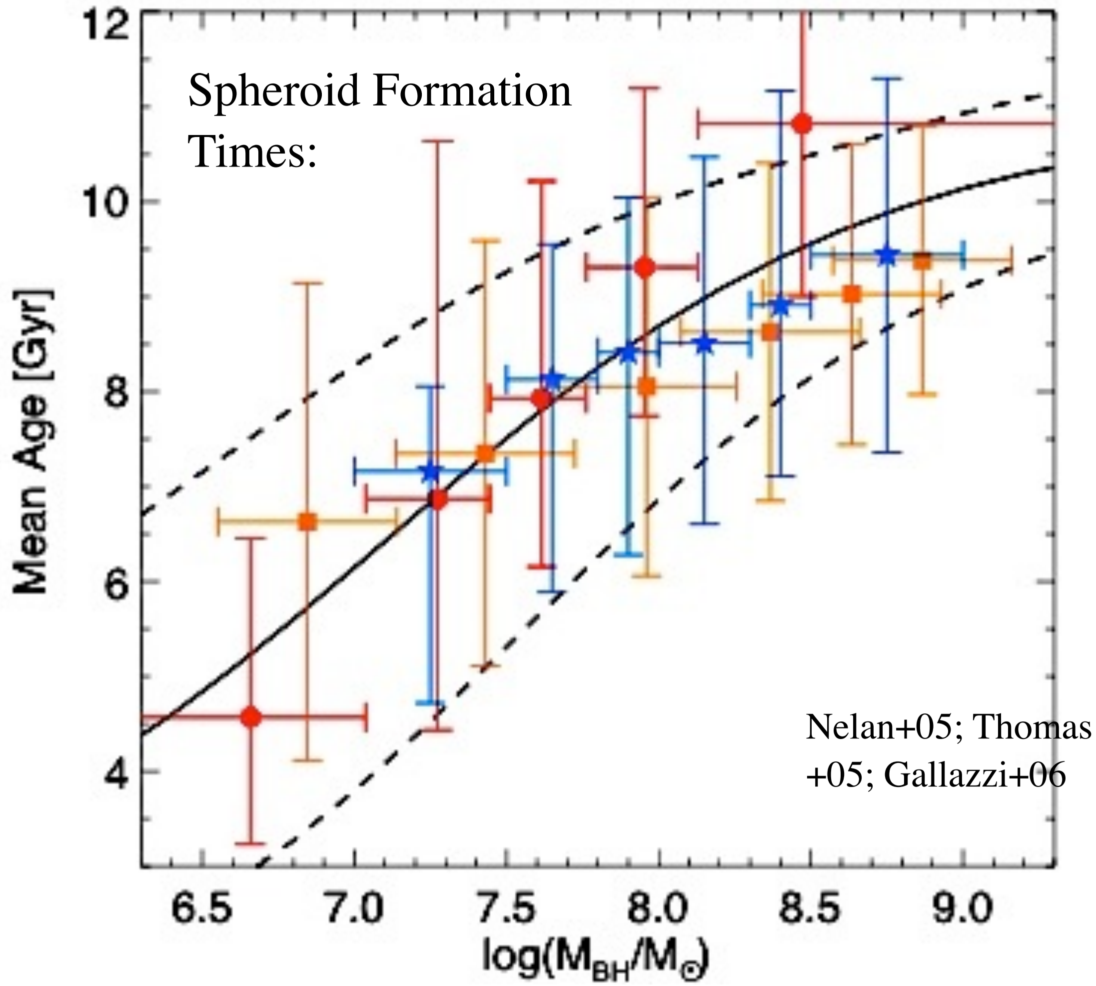


Motivation

CIRCUMSTANTIAL EVIDENCE

- Quasars were active/BHs formed when SF shut down...

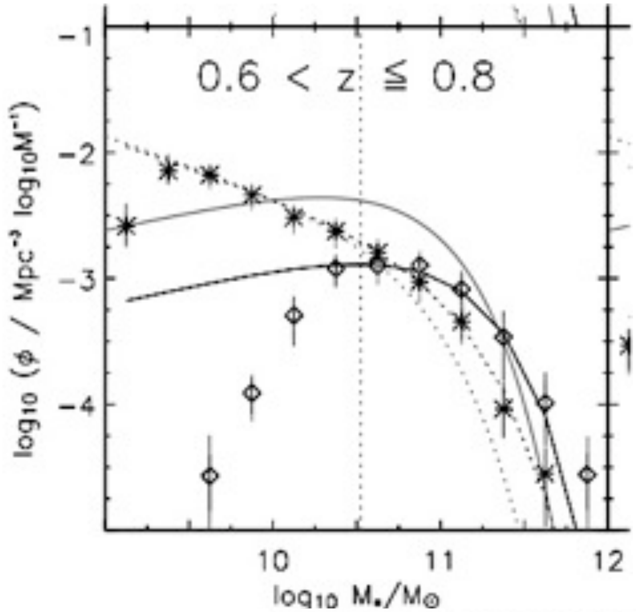




Hopkins, Lidz, Hernquist, Coil, et al. 2007

Motivation

CIRCUMSTANTIAL EVIDENCE



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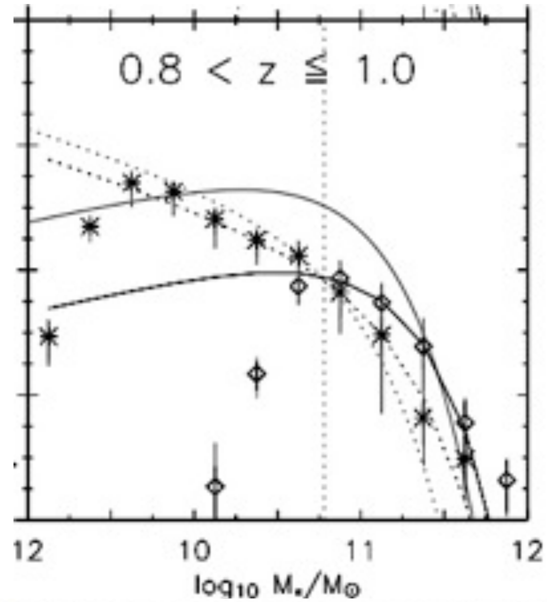

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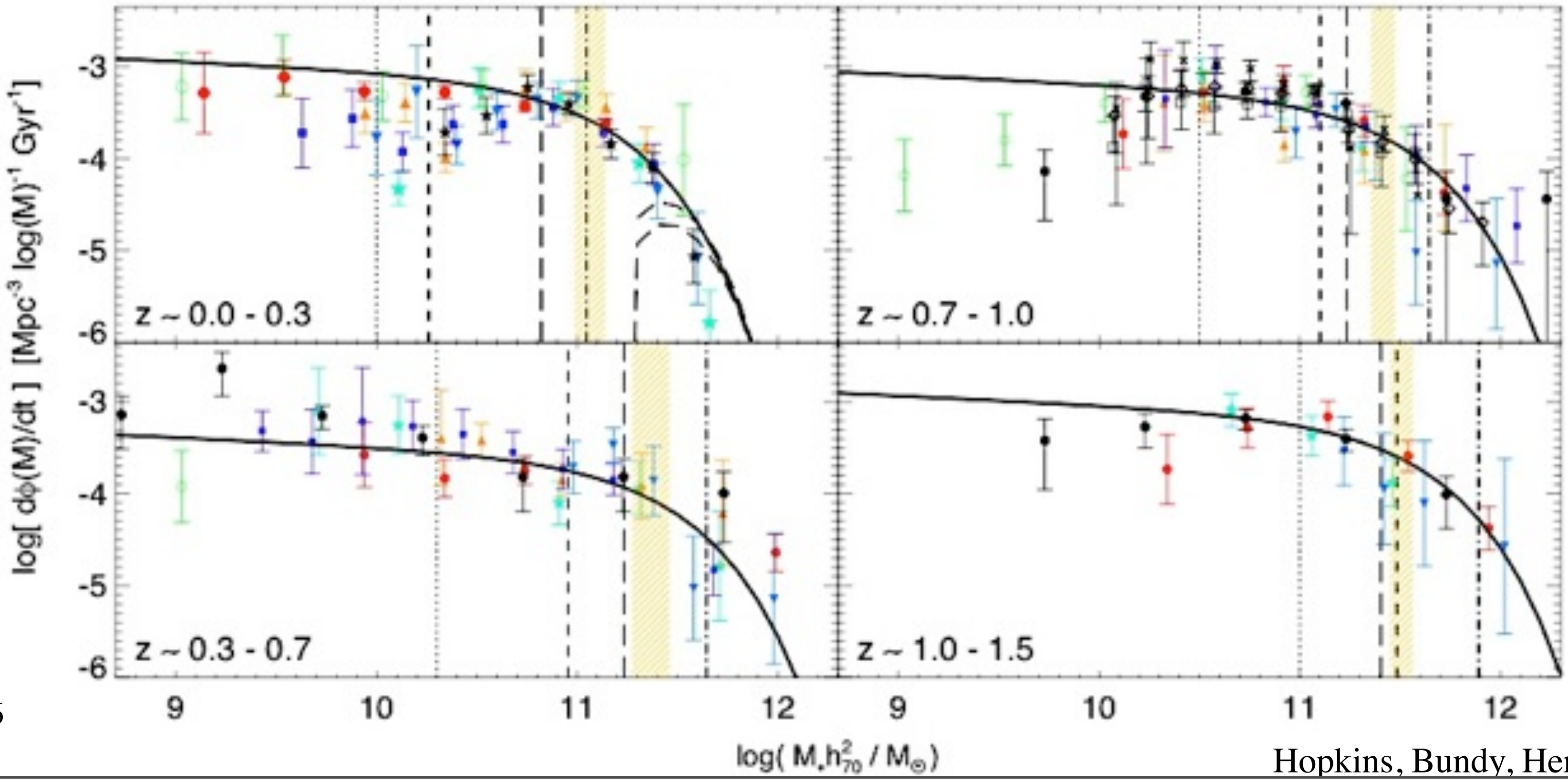


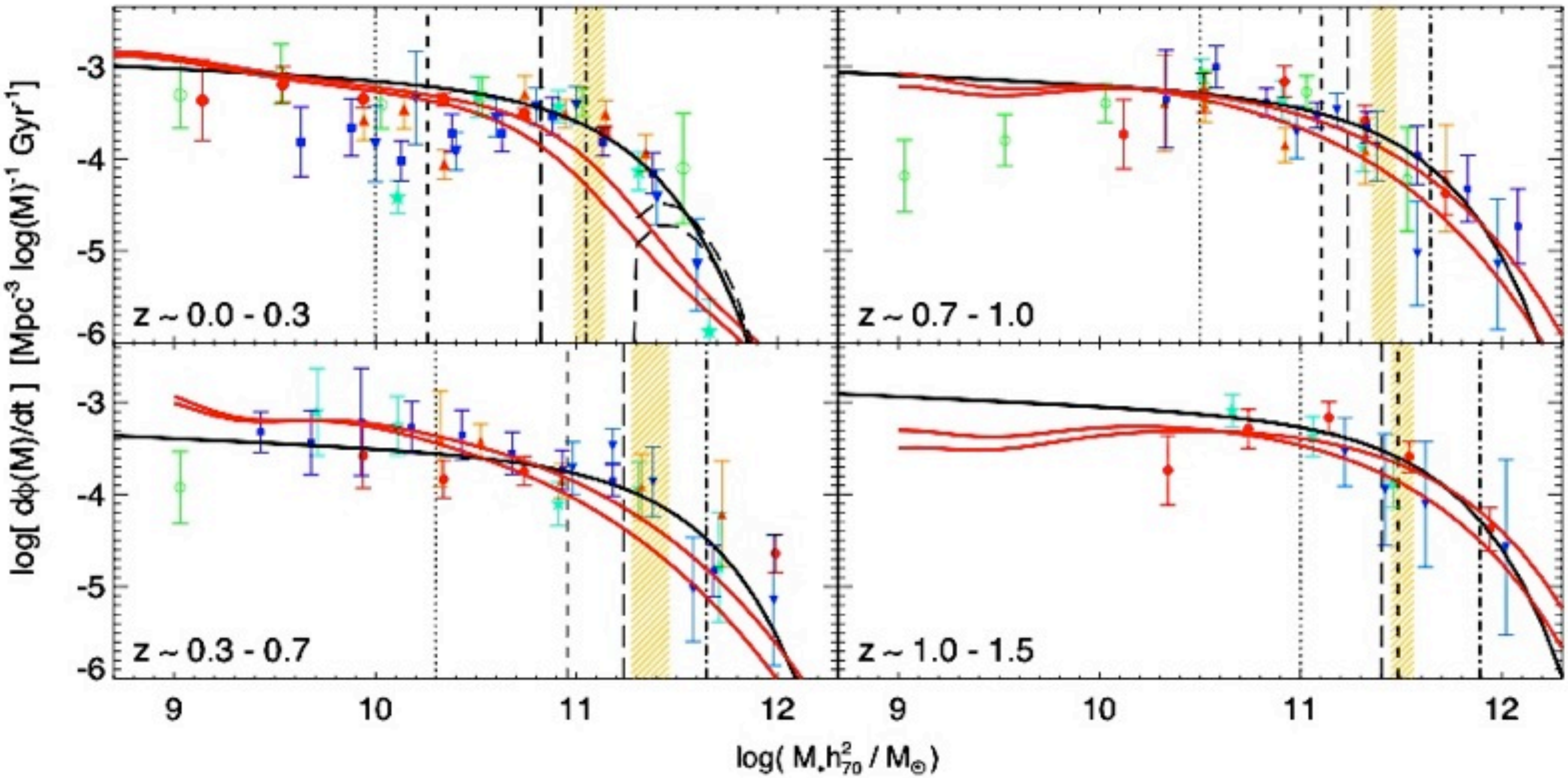
Borch+06;
Bundy+06;
Fontana+04,06;
Pannella+06;
Franceschini+06

Hopkins, Bundy, Hernquist+ 06

Motivation

CIRCUMSTANTIAL EVIDENCE

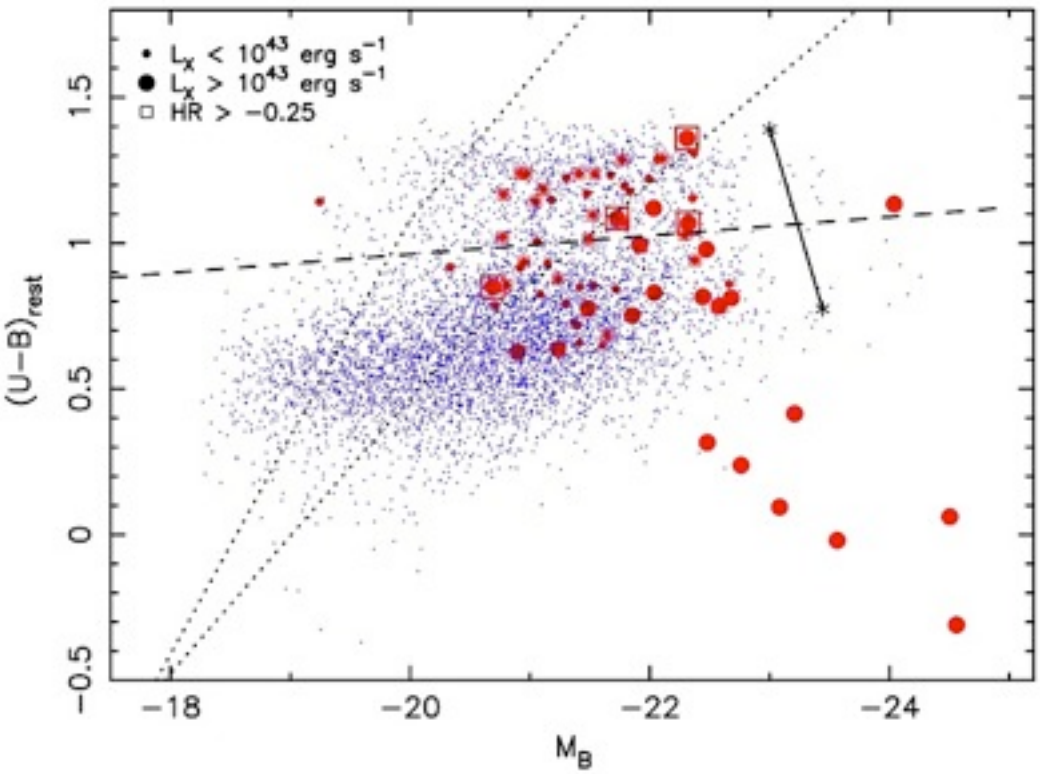
- Observed RS Buildup to z>~1 = Expectation if *all* new mass to the RS "transitions" in a quasar-producing merger



Hopkins, Bundy, Hernquist+ 06

Motivation

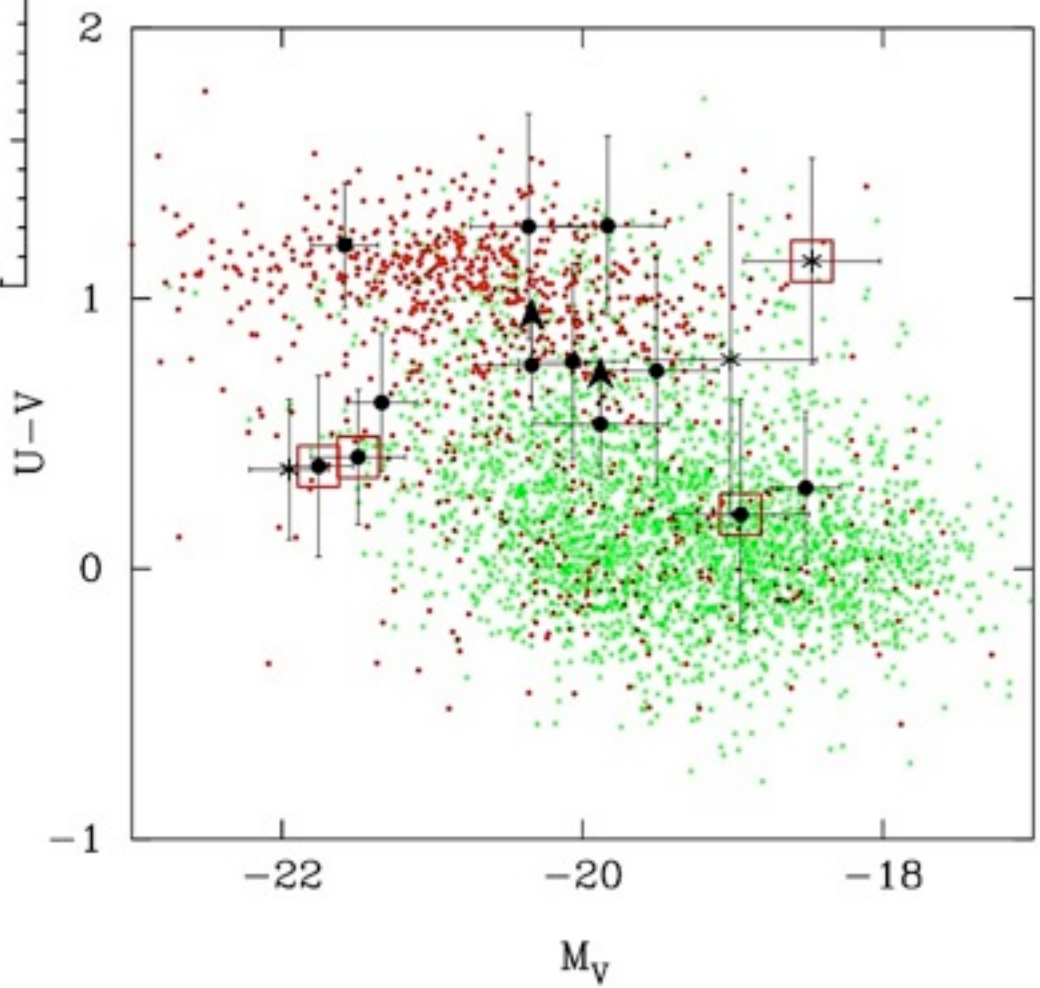
CIRCUMSTANTIAL EVIDENCE



Sanchez+ '05
GEMS
0.5 < z < 1.1
Optical QSOs

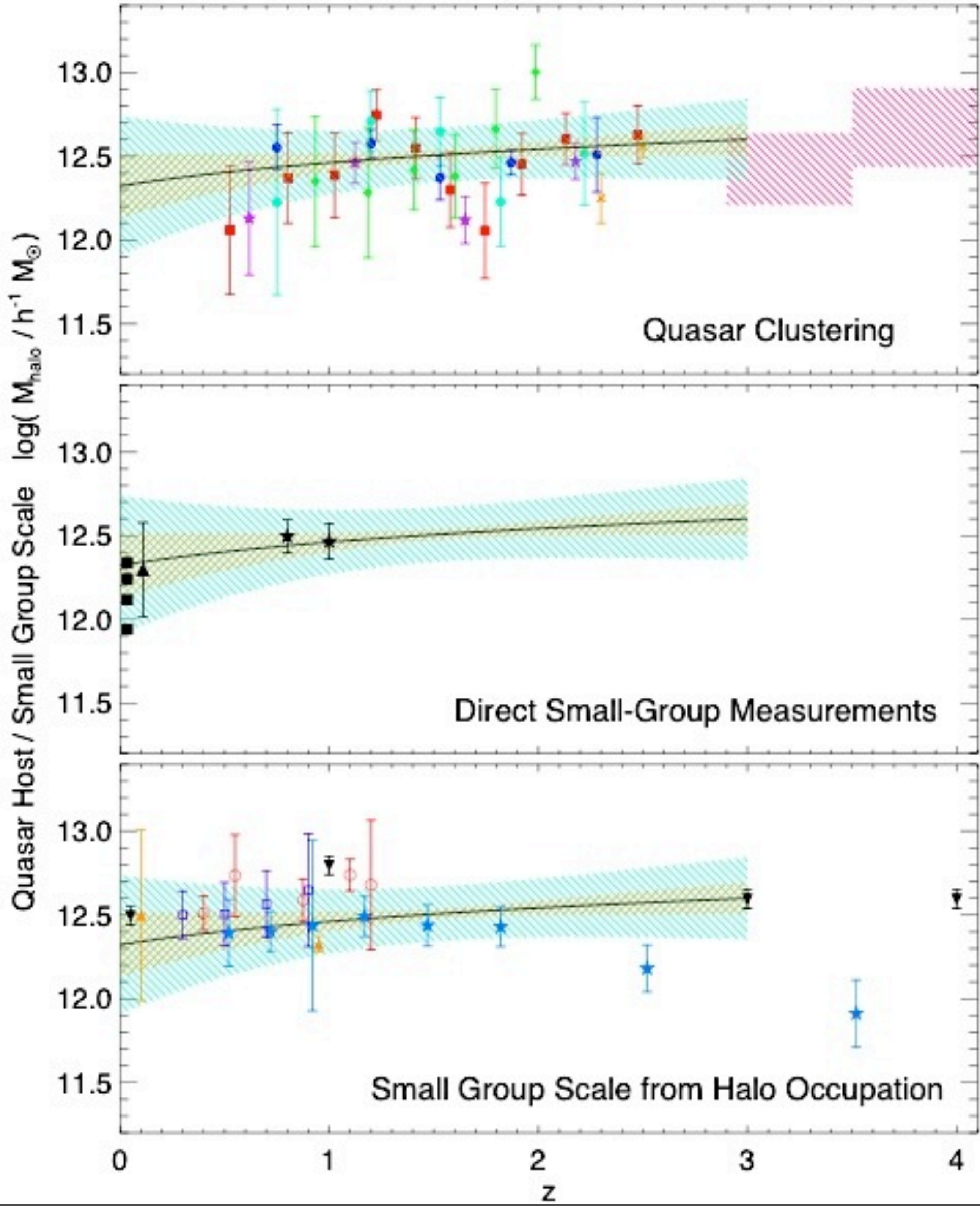
(also, Kauffmann+ 03;
local SDSS hosts)

Nandra+ '06
DEEP2
0.7 < z < 1.4
X-ray QSOs



Motivation

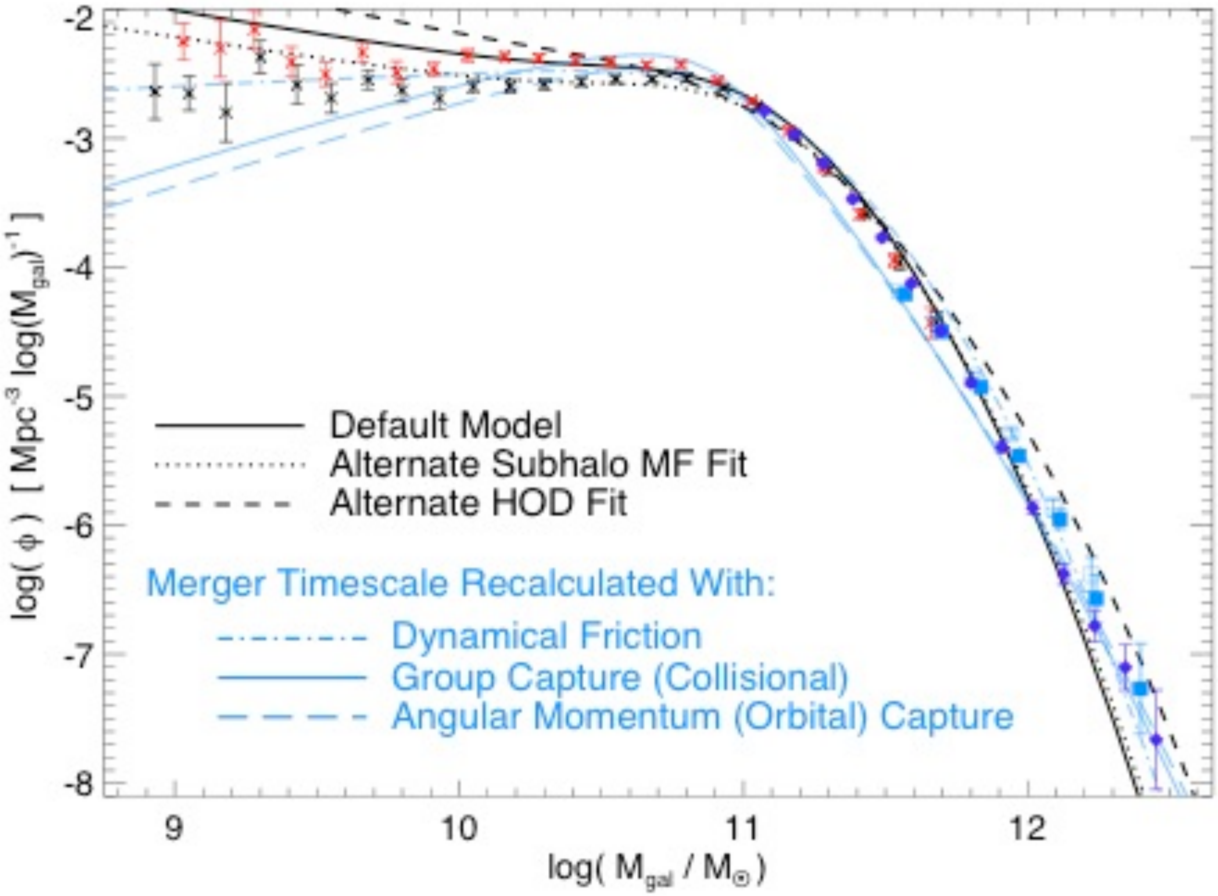
CIRCUMSTANTIAL EVIDENCE



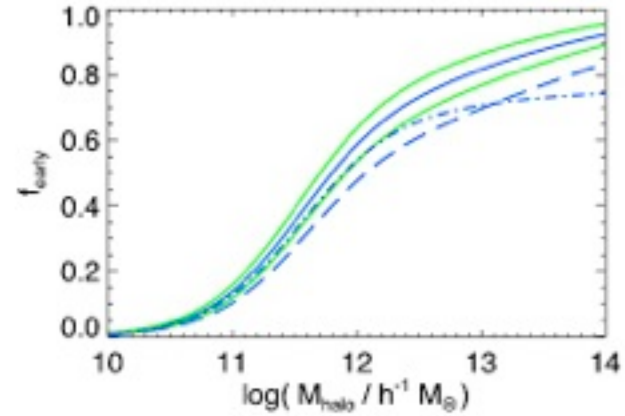
The Model

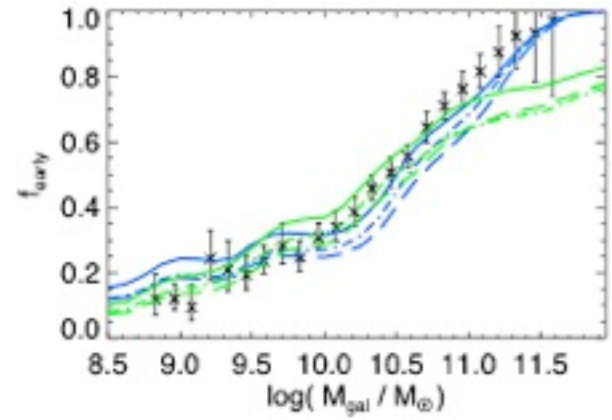
PREDICTIONS

- z=0 mass functions

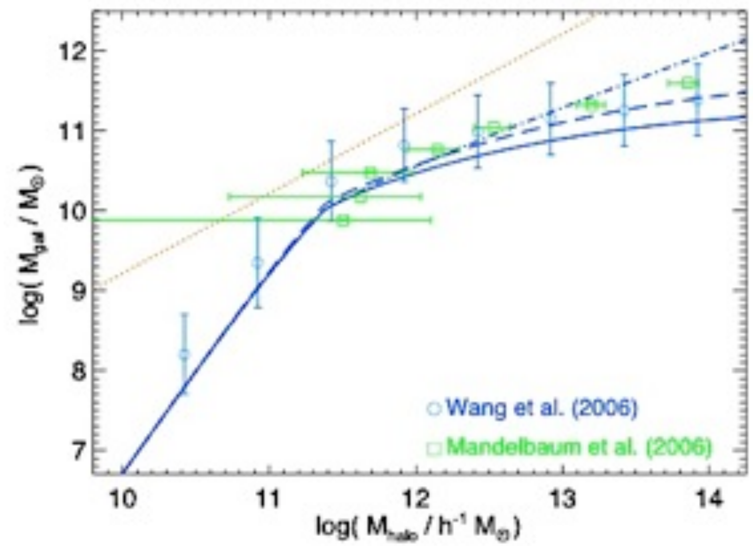


- red fractions:





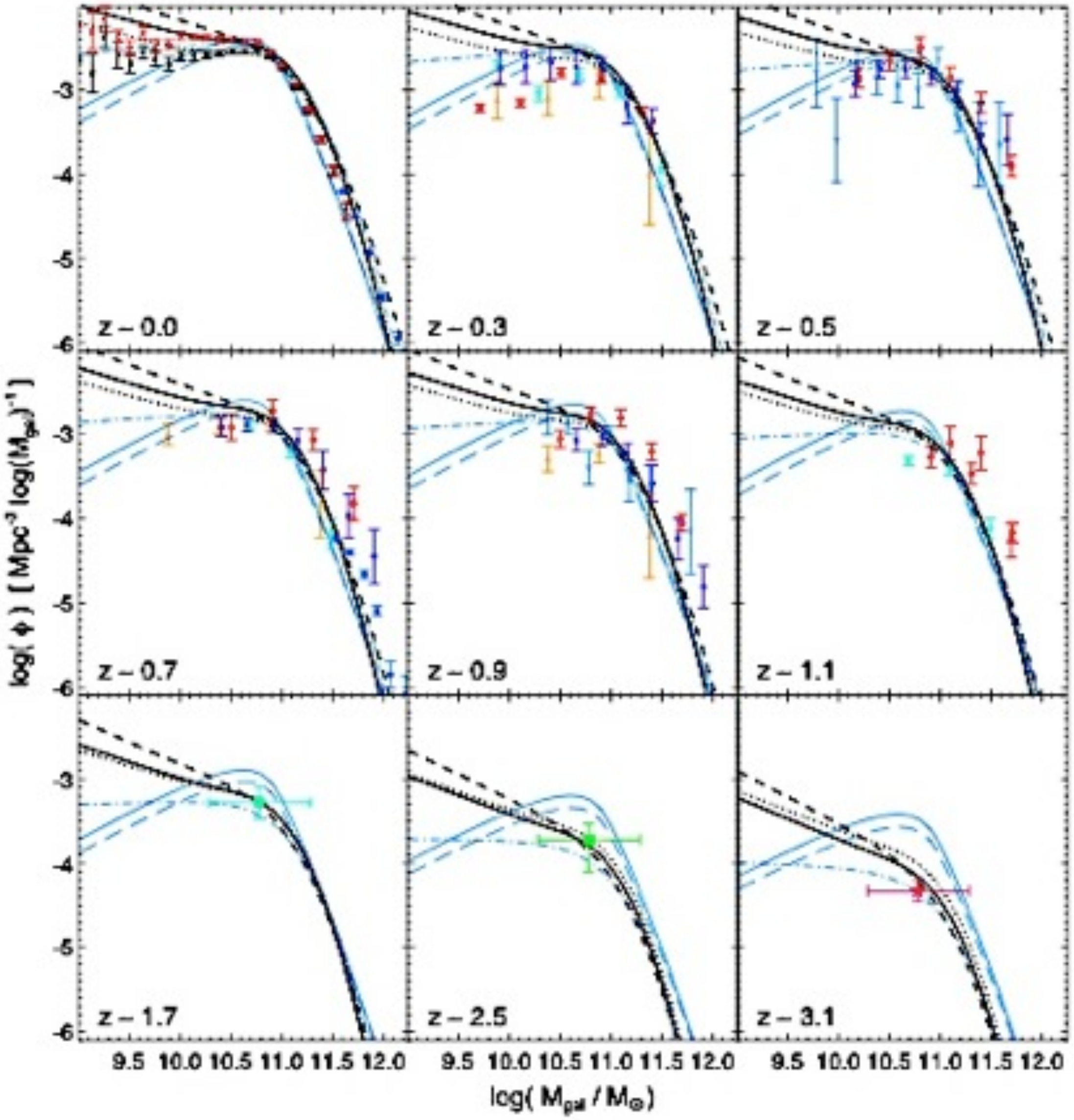
- M/L vs. M_halo



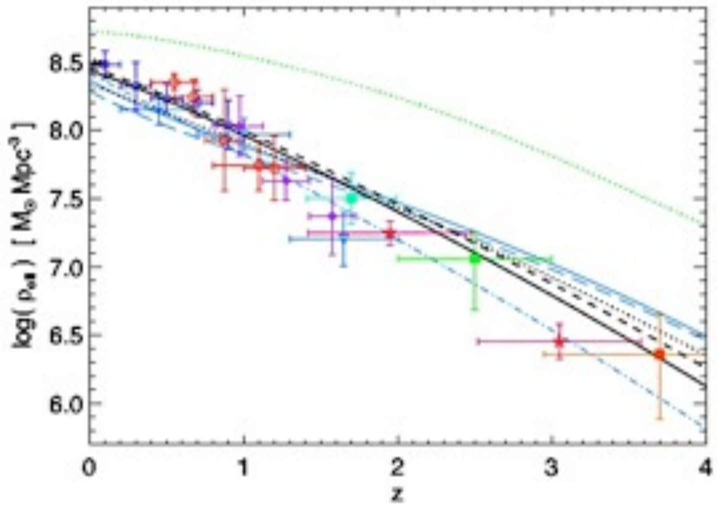
The Model

PREDICTIONS

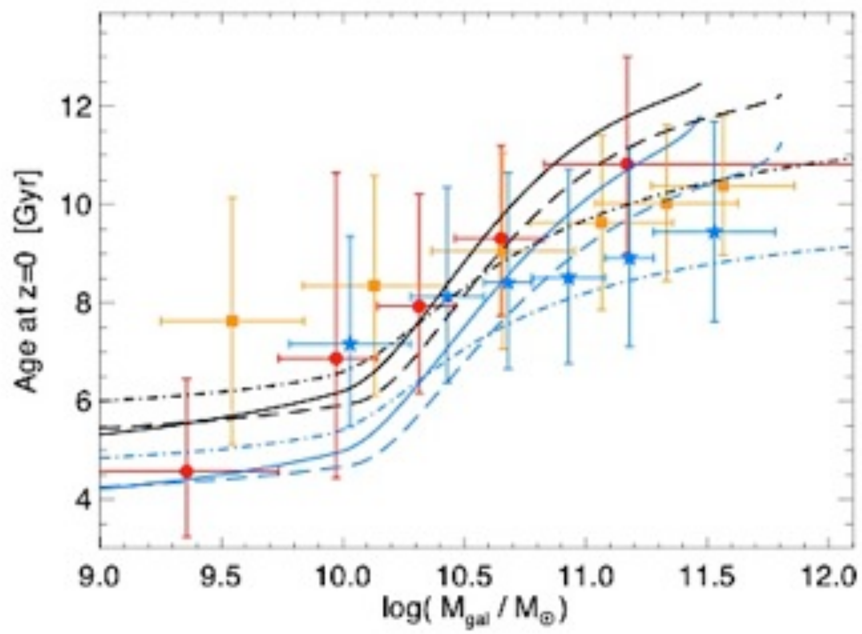
- mass function redshift evolution:



- mass density:



- age vs. mass:



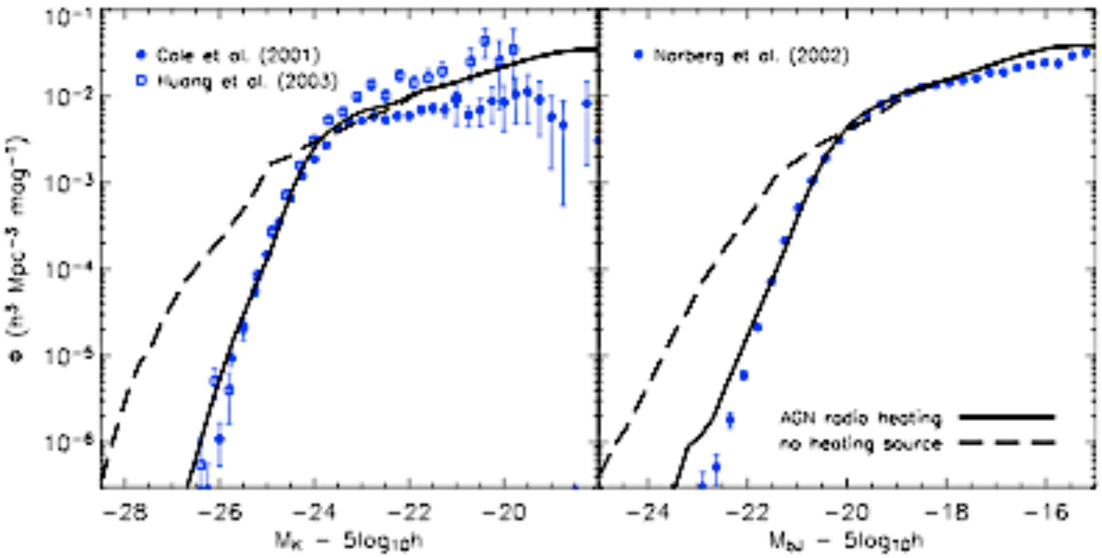
Great!

....BUT....

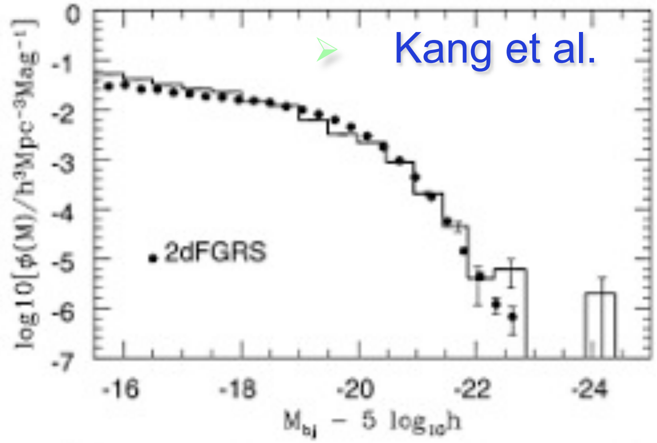
Great!

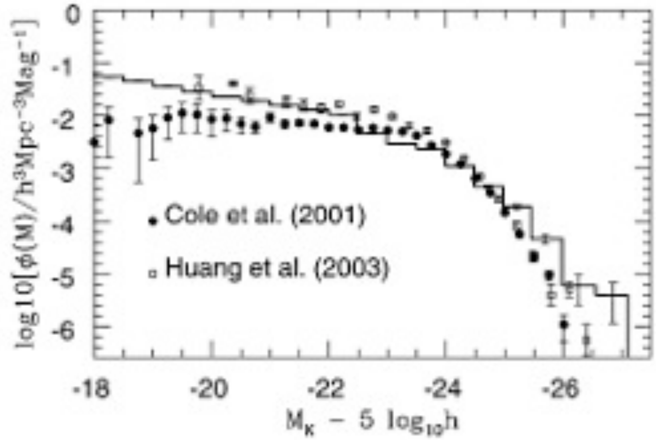
....BUT....

Croton et al.

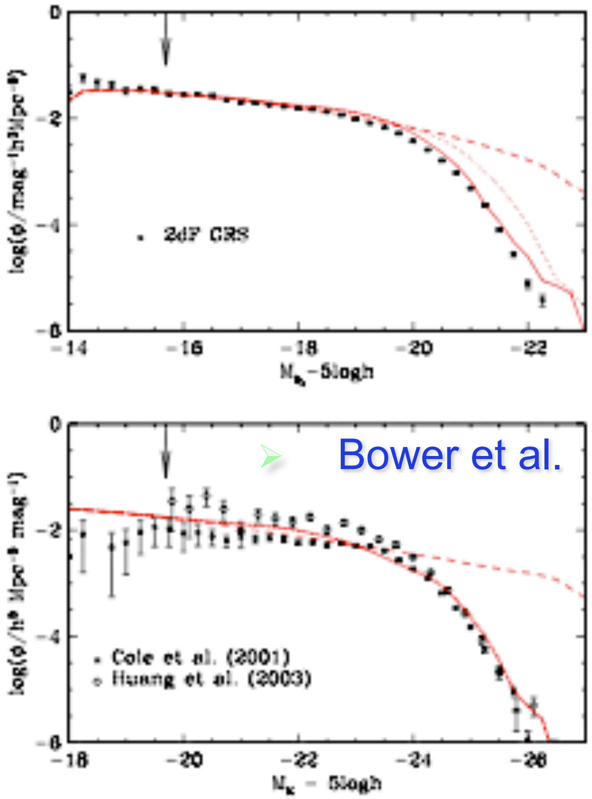


Kang et al.

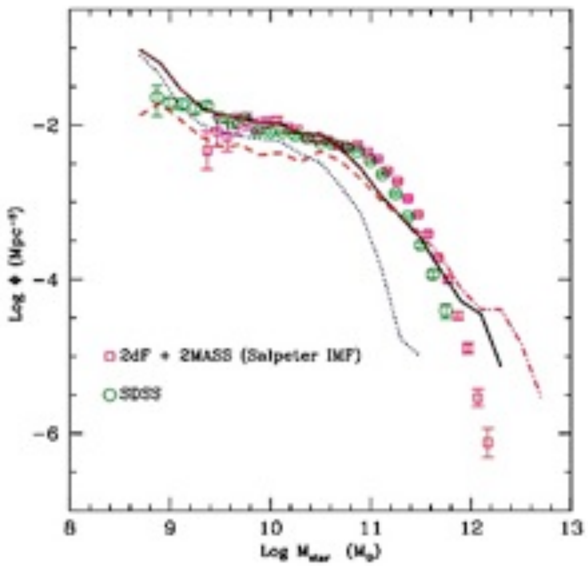




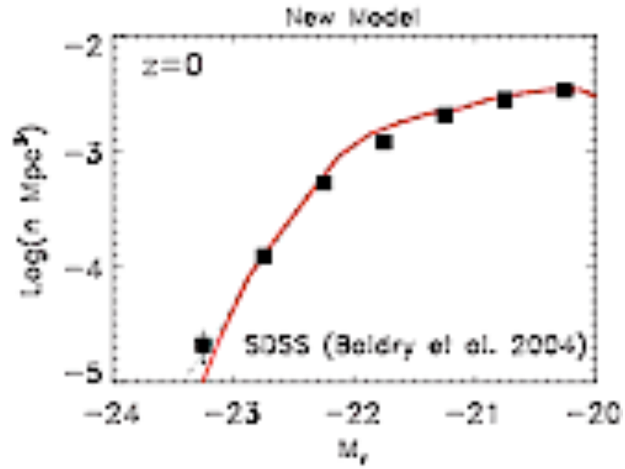
Bower et al.



Monaco et al.



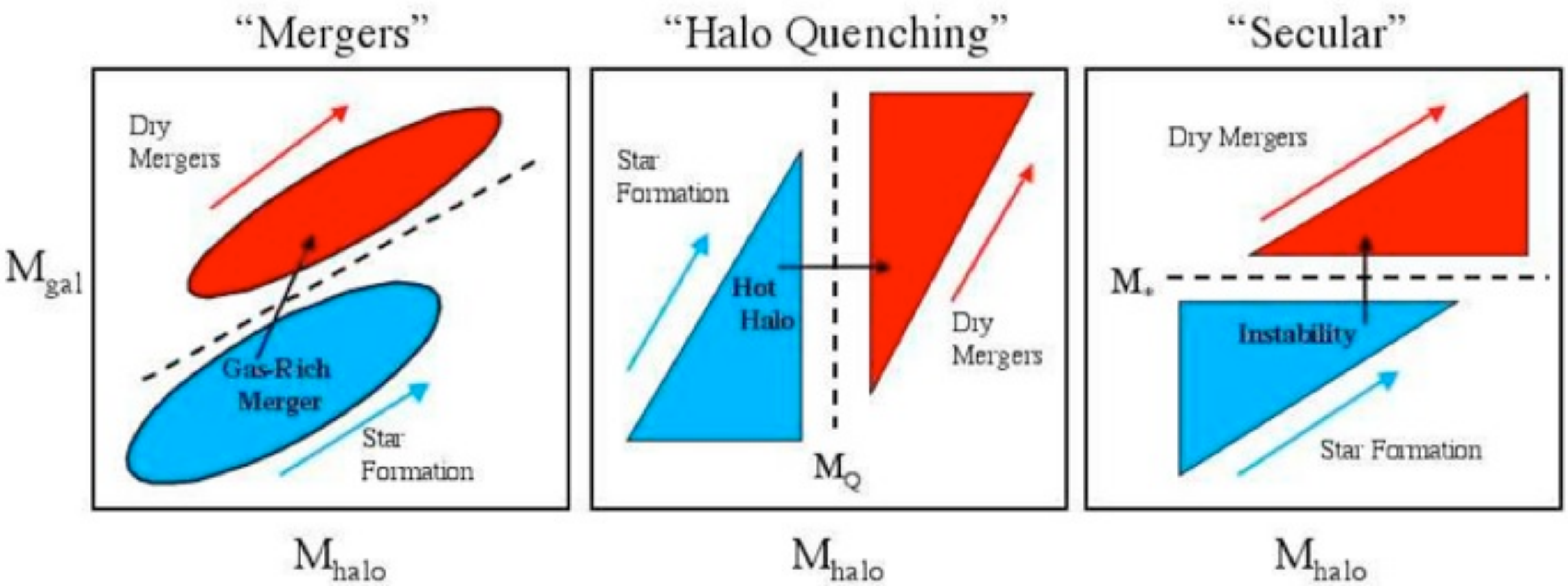
Cattaneo et al.



Lowest-Order Predictions are Fundamentally Non-Unique:

HOW DO WE BREAK THE DEGENERACIES?

- Identify broad classes of quenching models:

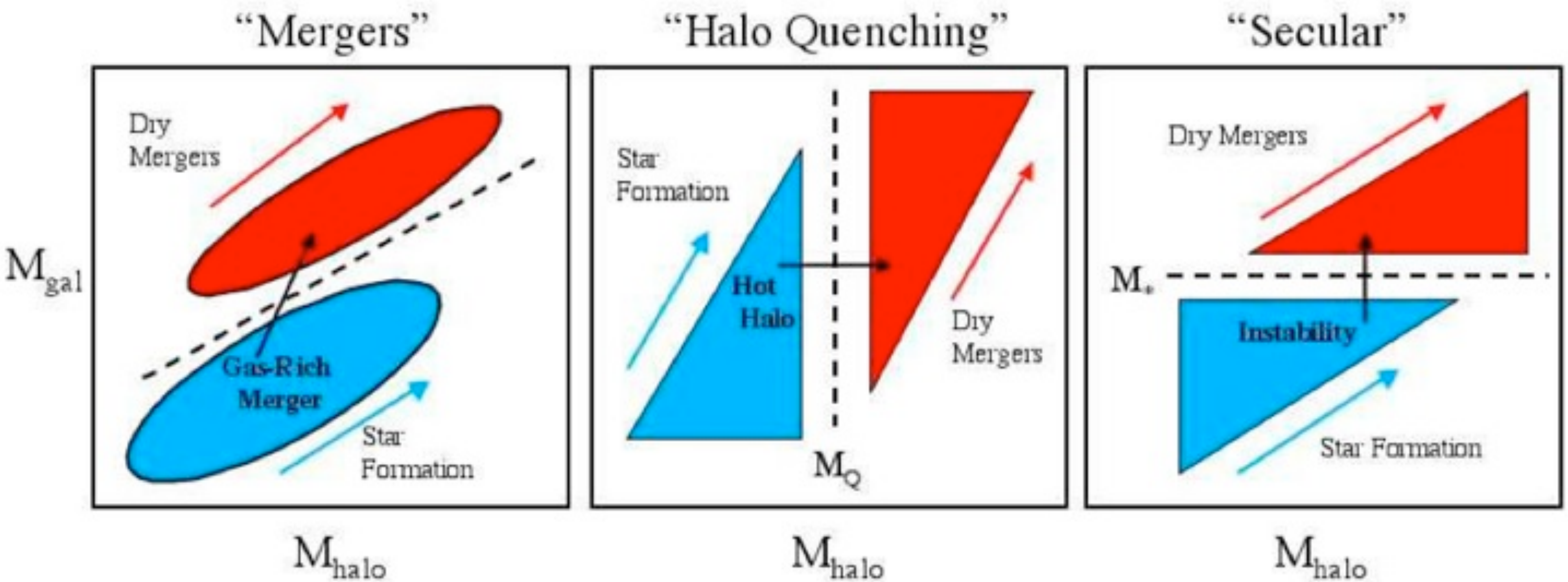


- Are there unique, robust predictions of the different classes of quenching mechanisms?

Lowest-Order Predictions are Fundamentally Non-Unique:

HOW DO WE BREAK THE DEGENERACIES?

- Identify broad classes of quenching models:



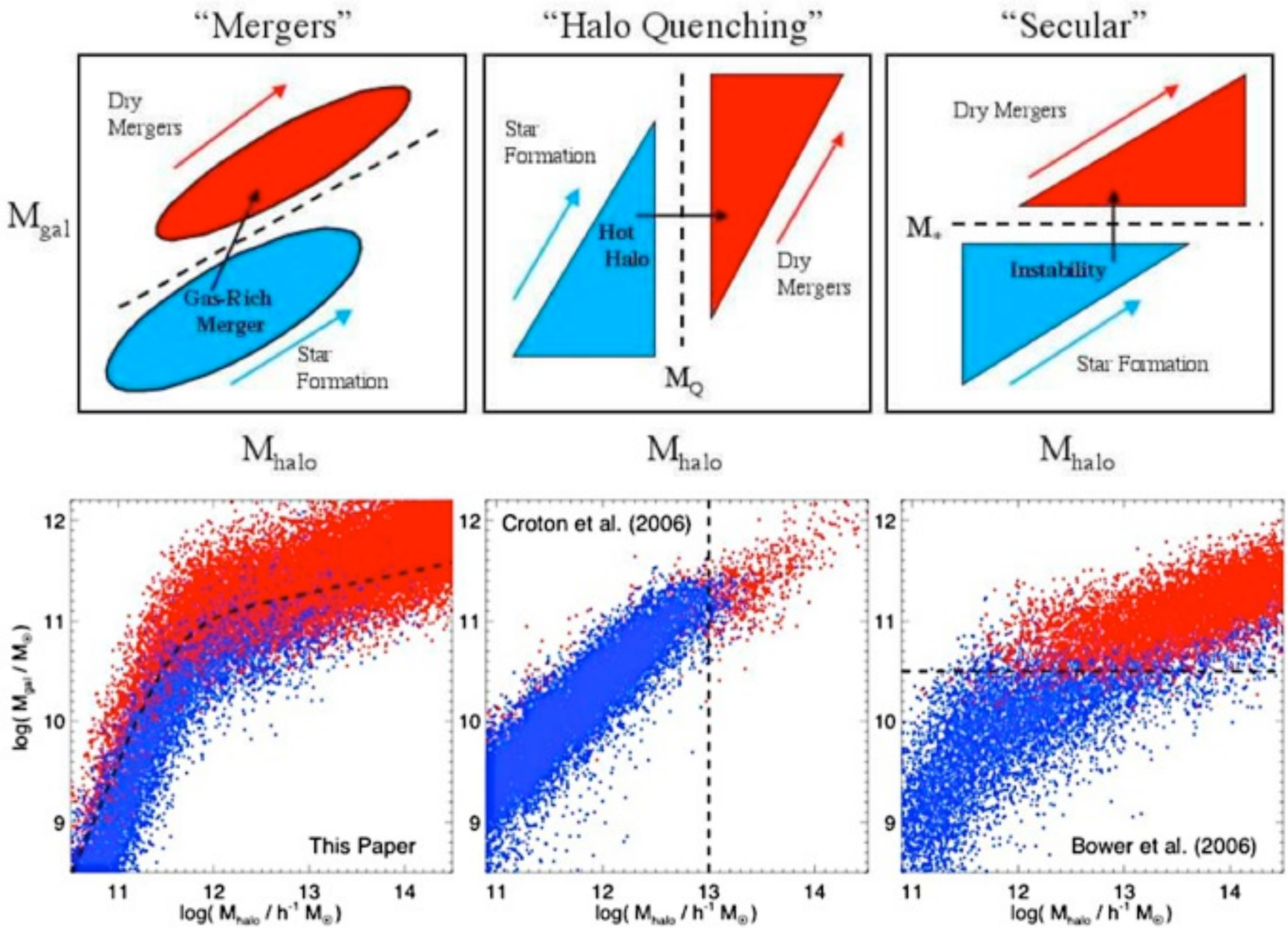
Khochfar & Silk (w. Naab et al.)
Cattaneo et al. (alt)
Somerville et al. (new)
Hopkins et al. (too many)

Croton et al.
De Lucia et al.
Bower et al.
Cattaneo et al. (standard)
Kang et al.
Monaco et al. (no QSO)

Bower et al. (sometimes)
Noeske et al.

Comparing Quenching Models

HOW DO WE BREAK THE DEGENERACIES?



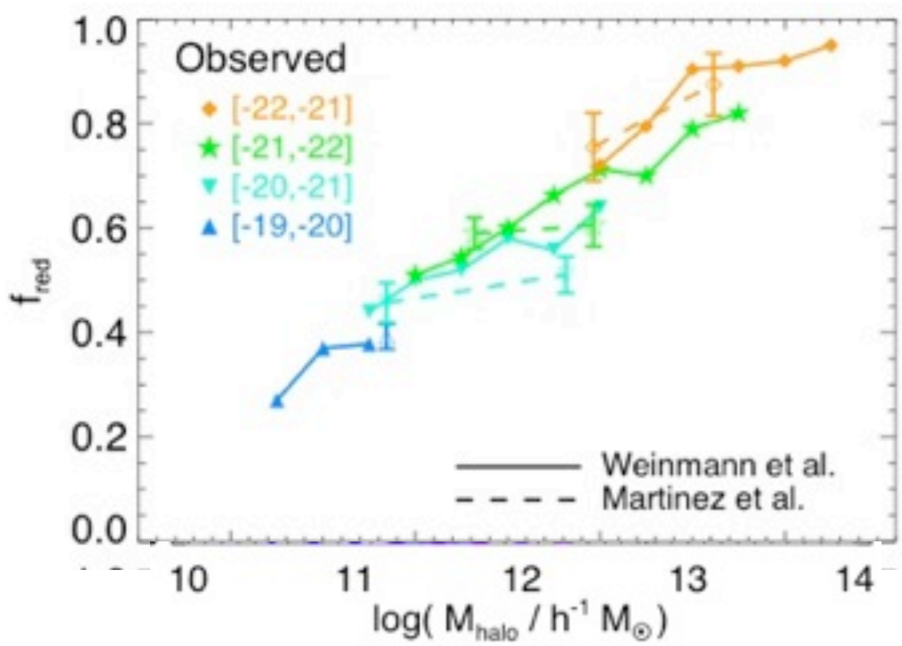
Motivation

WHAT DO WE KNOW?

	Mergers	Hot Halos	Secular
morphology:	classical bulges/ spheroids	little effect	“pseudobulges”
BH/AGN:	*quasar & remnant massive BH	*little BH growth *fuel for low Mdot modes?	*Seyferts? *small (<10^7 M_sun) BHs
feedback:	*kinematic *quasar *starburst	*accretion shocks *gravitational	*Seyfert? *stellar winds
timescales:	short (<Gyr)	~Hubble time	~Gyr?

Comparing Quenching Models

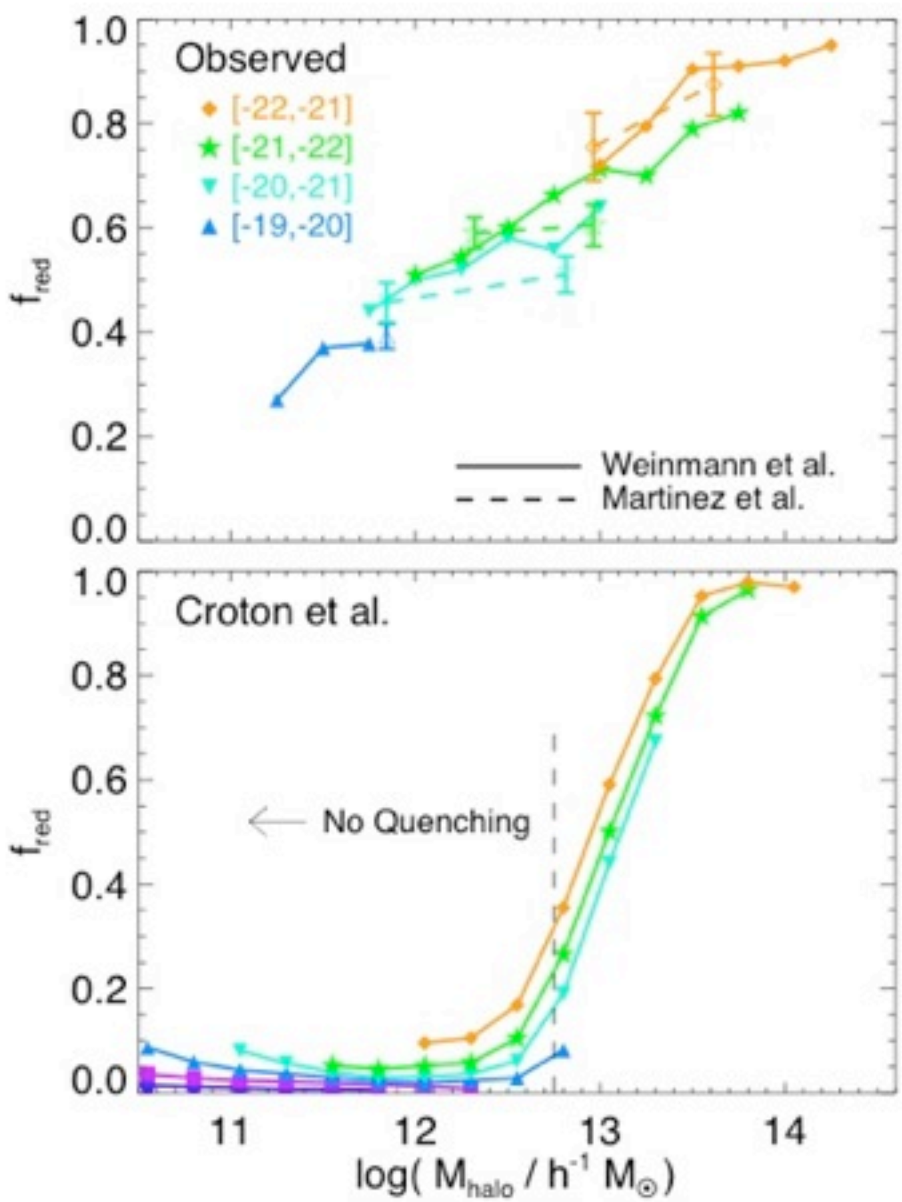
HOW DO WE BREAK THE DEGENERACIES?



- f_red vs. M_halo and M_gal:
  - smooth dependence on M_halo
  - no characteristic scale
  - high even in low M_halo (for massive galaxies)

Comparing Quenching Models

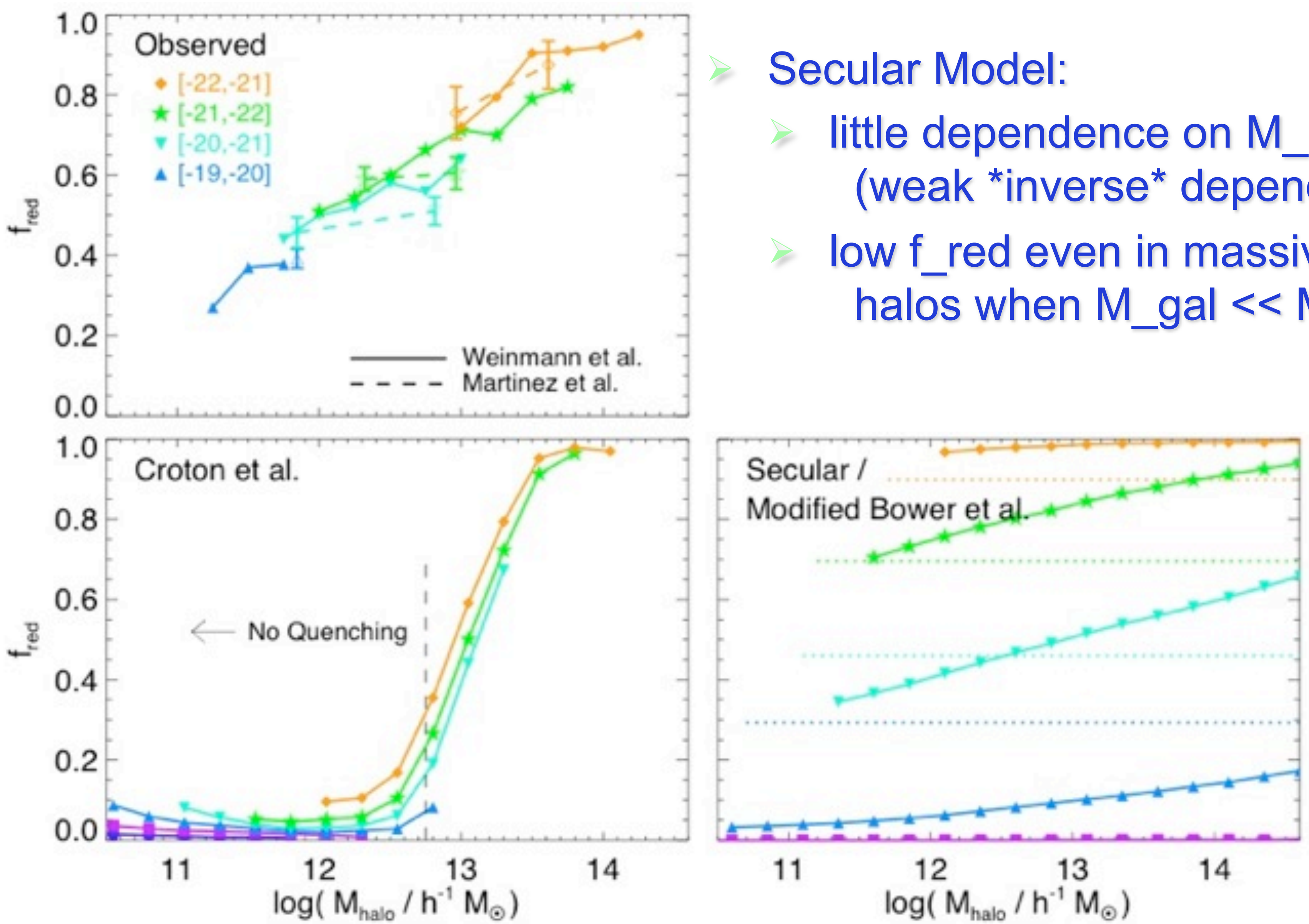
HOW DO WE BREAK THE DEGENERACIES?



- "Halo Quenching" Model:
  - step function in M_halo: strong characteristic scale
  - no residual M_gal dependence
  - no f_red in low M_halo

Comparing Quenching Models

HOW DO WE BREAK THE DEGENERACIES?

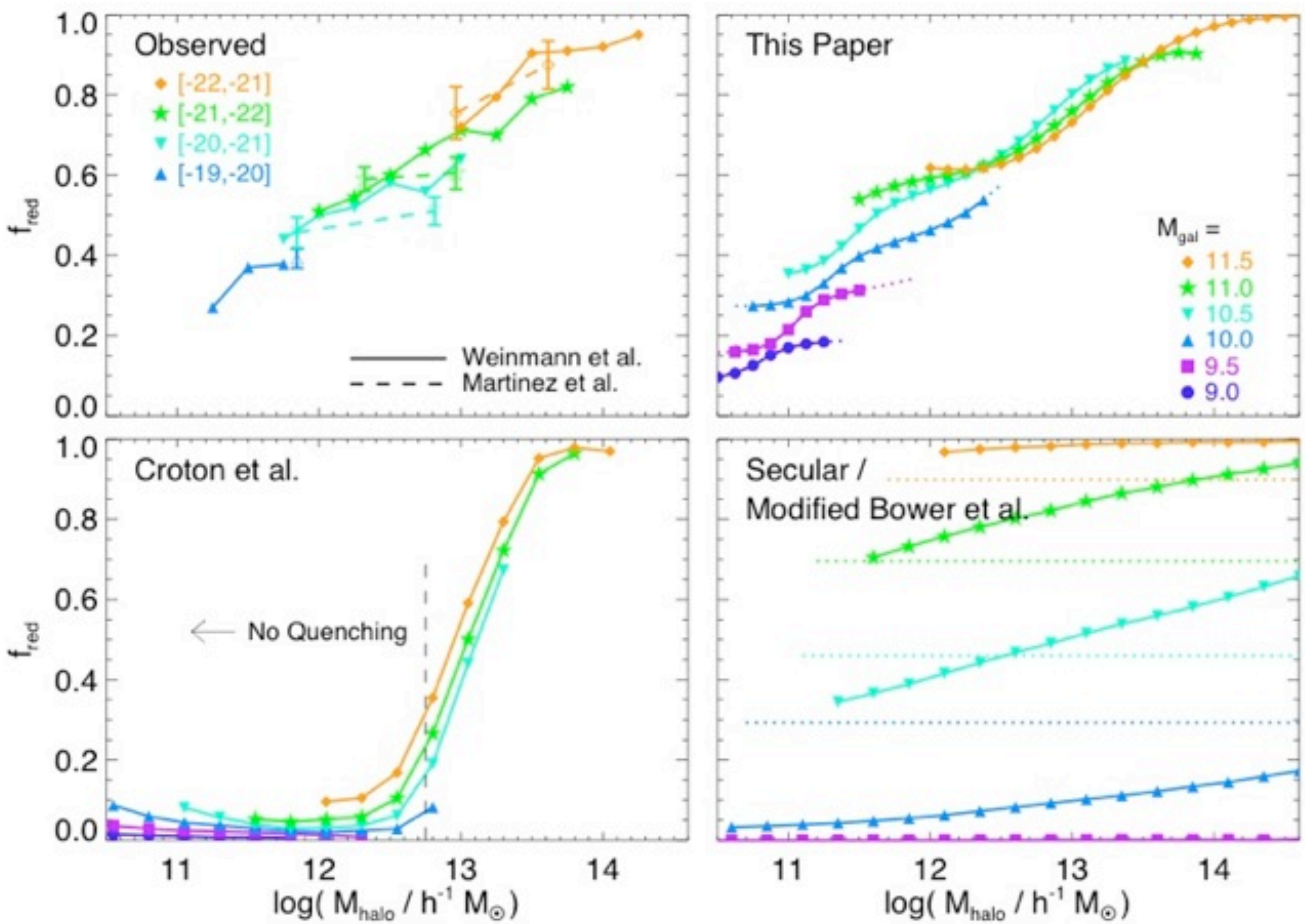


- Secular Model:
  - little dependence on M_halo (weak *inverse* dependence)
  - low f_red even in massive halos when M_gal << M*

Comparing Quenching Models

HOW DO WE BREAK THE DEGENERACIES?

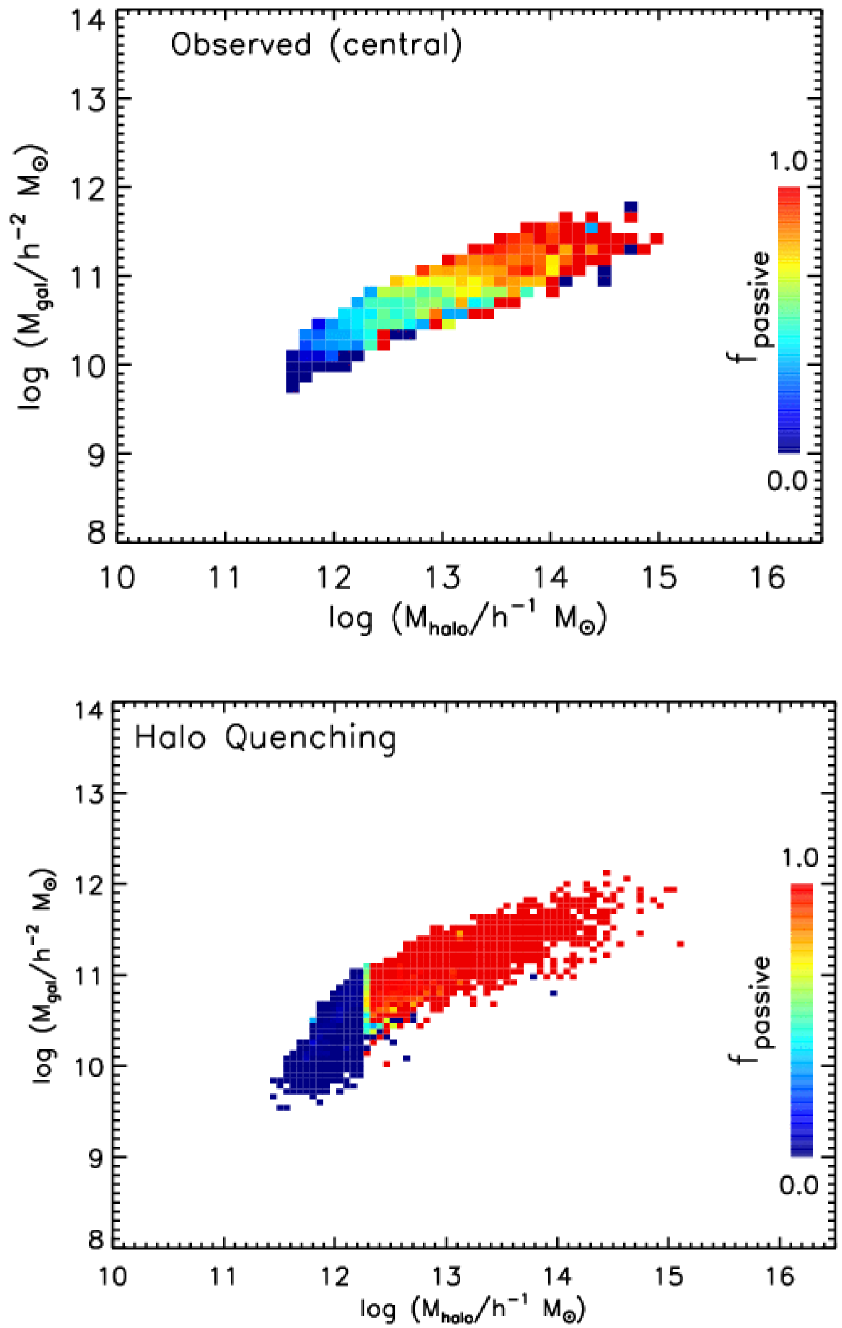
- Merger Model:
  - appropriate mixed dependence on M_halo and M_gal
  - no sharp scale in M_halo



Comparing Quenching Models

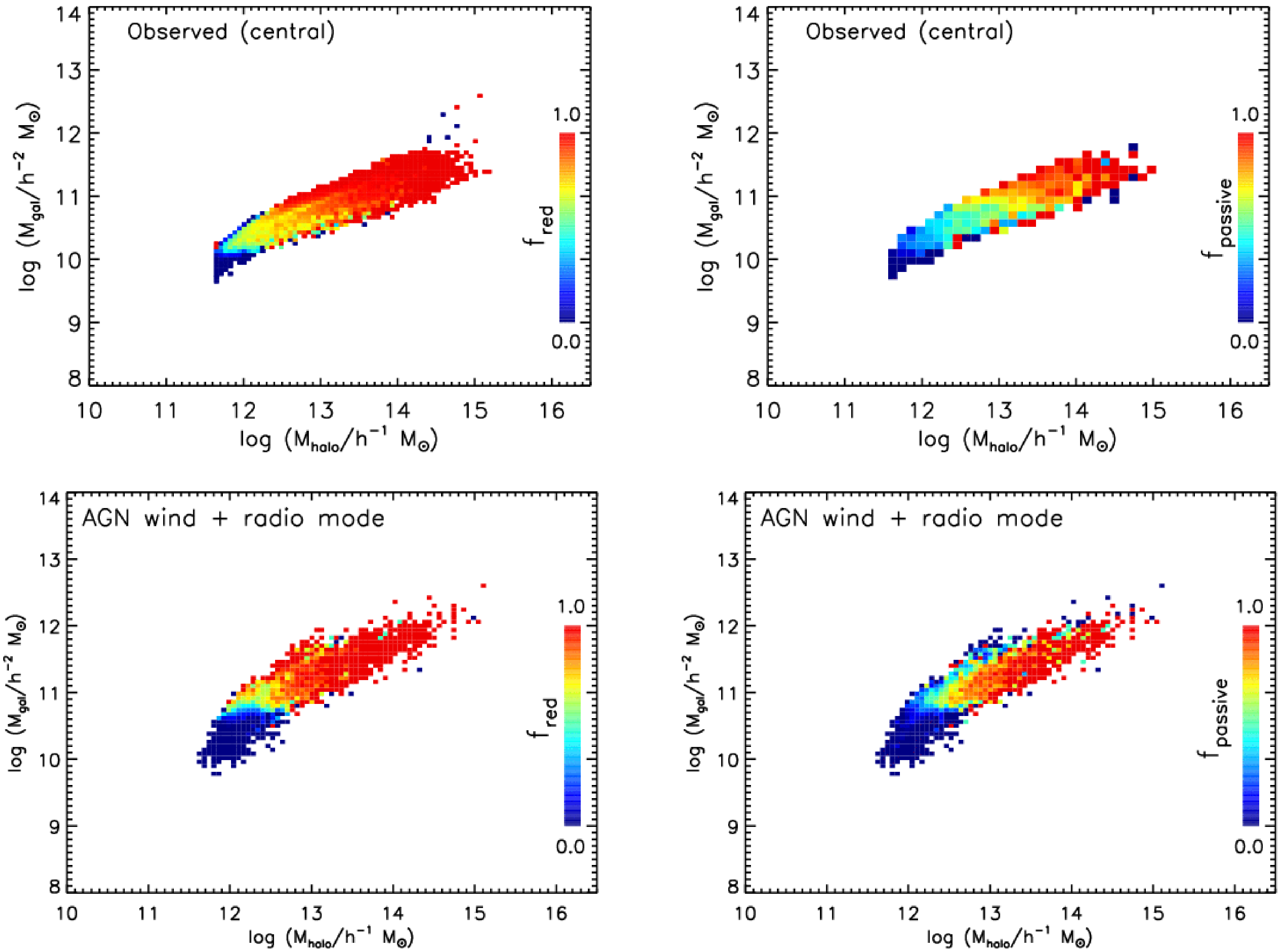
HOW DO WE BREAK THE DEGENERACIES?

- Passive (low SSFR) galaxies:
  - same trends
  - avoid dusty/metal-rich disk contamination



Comparing Quenching Models

HOW DO WE BREAK THE DEGENERACIES?

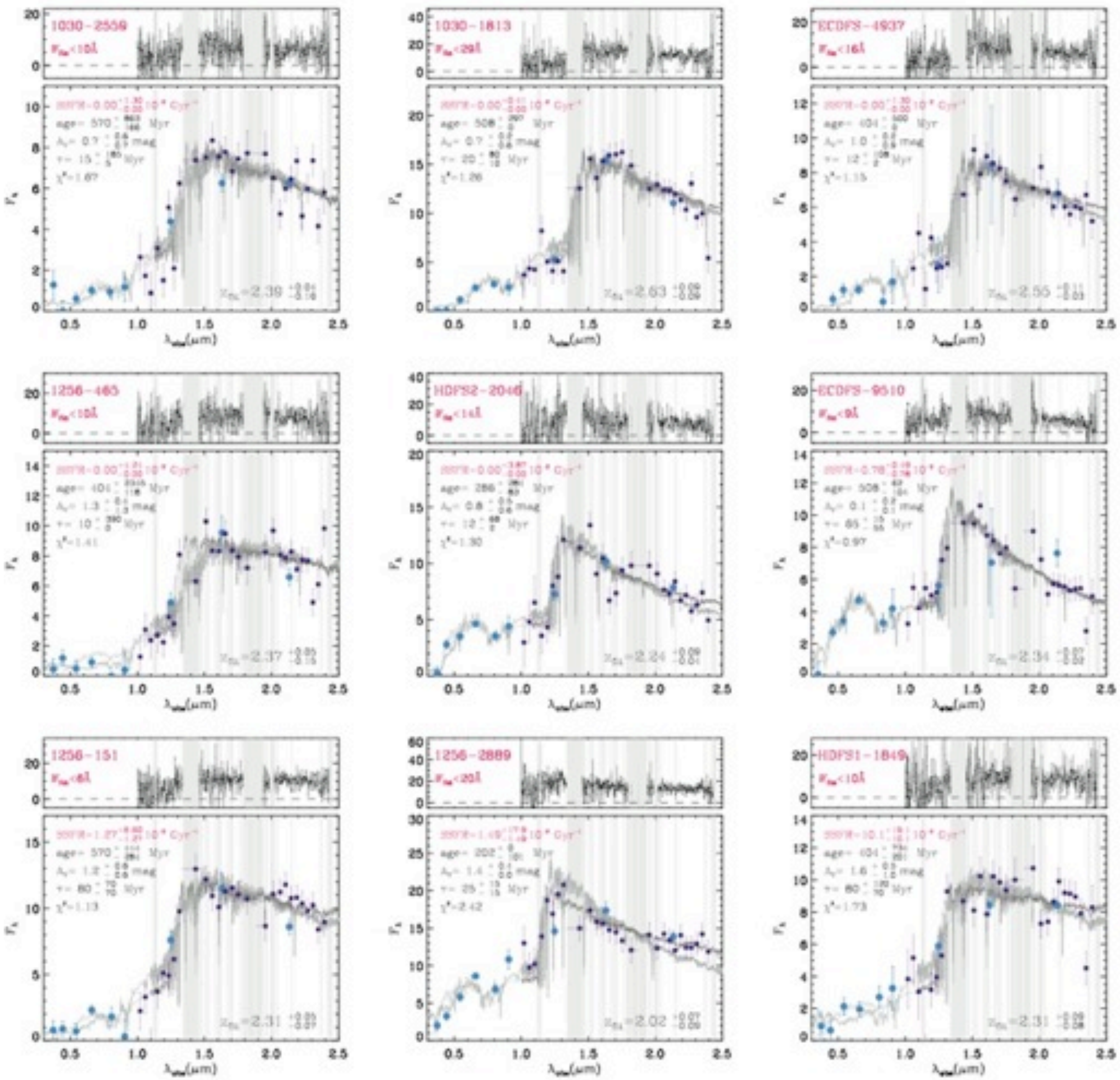


Comparing Quenching Models

HIGH-REDSHIFT PASSIVE GALAXIES

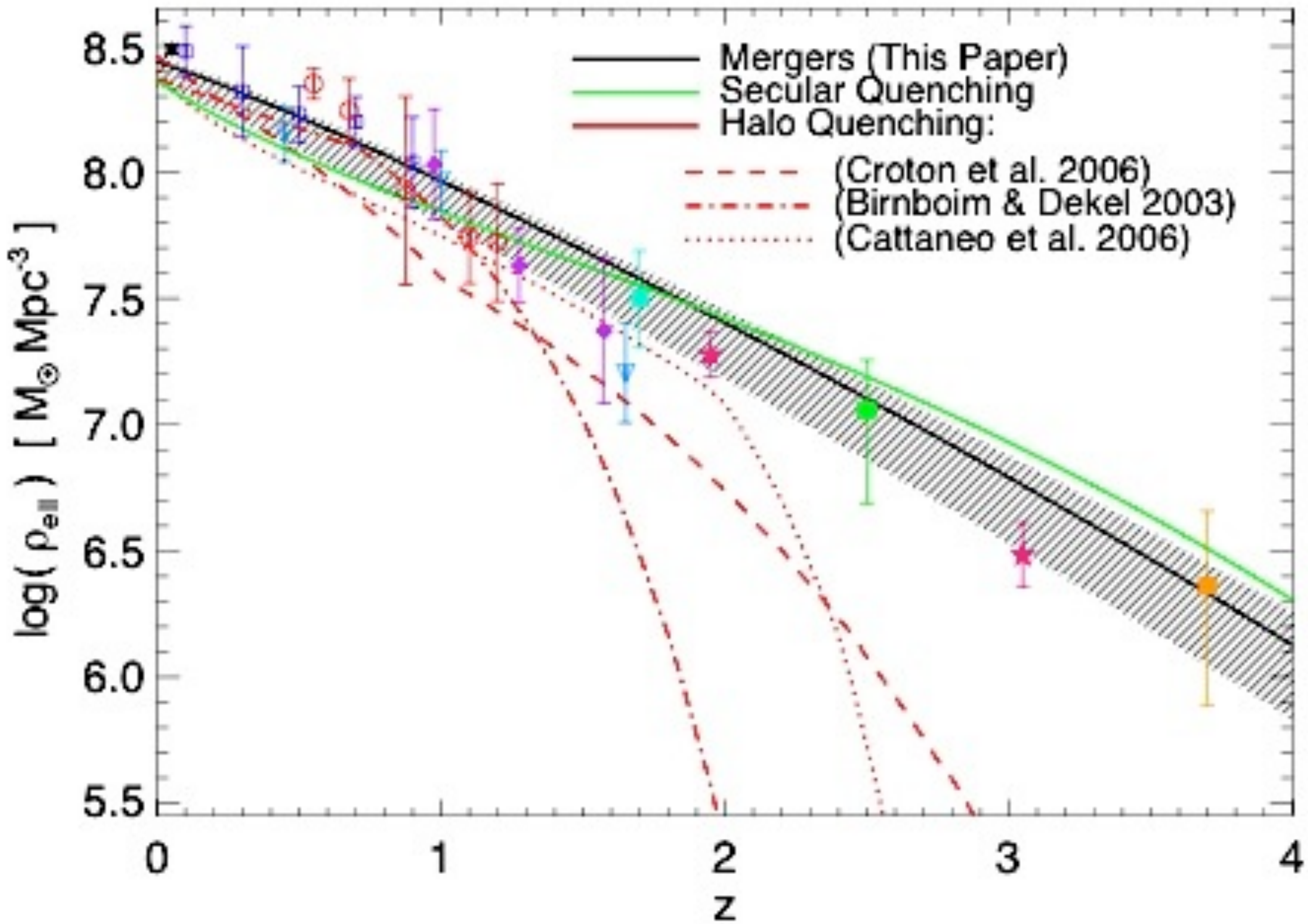
Kriek et al., Labbe et al., Zirm et al.

- High-z passive (low SSFR) galaxies:
  - z ~ 2 - 4
  - Very compact, n~4: Spheroids/Merger remnants
  - High (low-lum) AGN fraction



Comparing Quenching Models

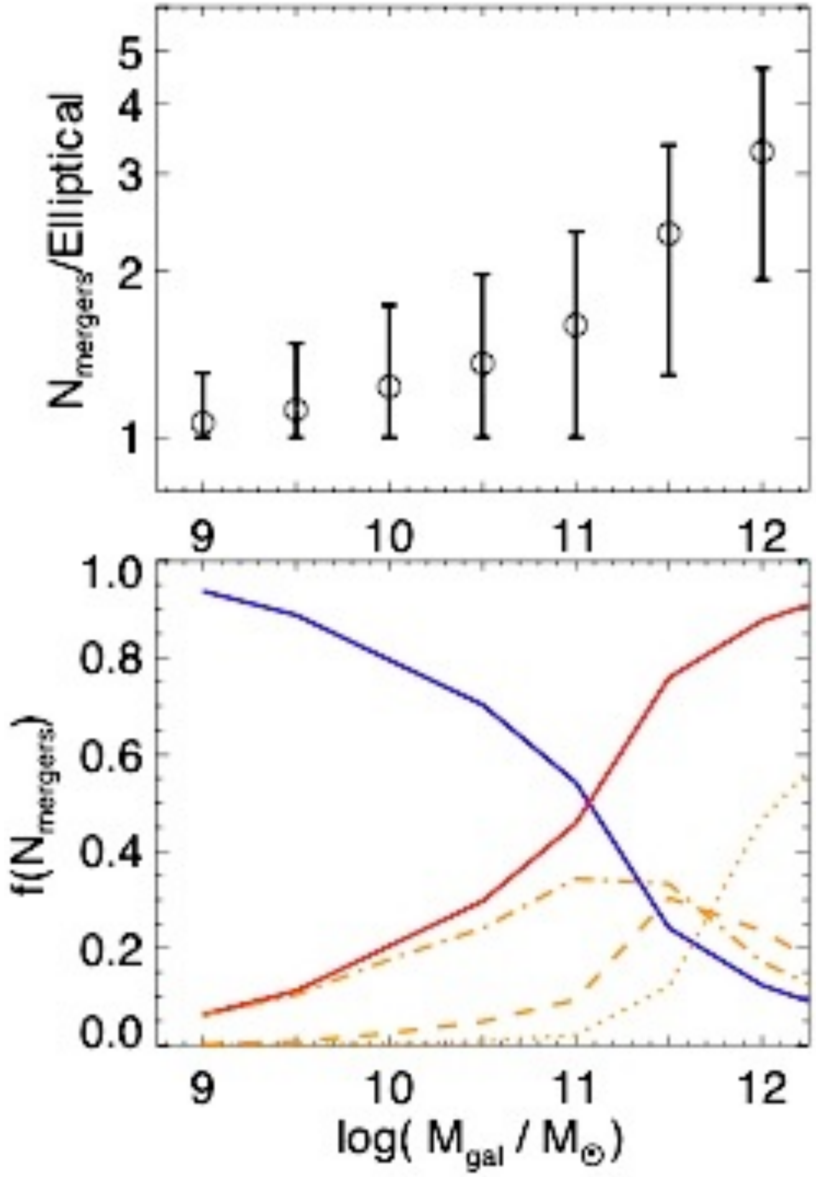
HIGH-REDSHIFT PASSIVE GALAXIES

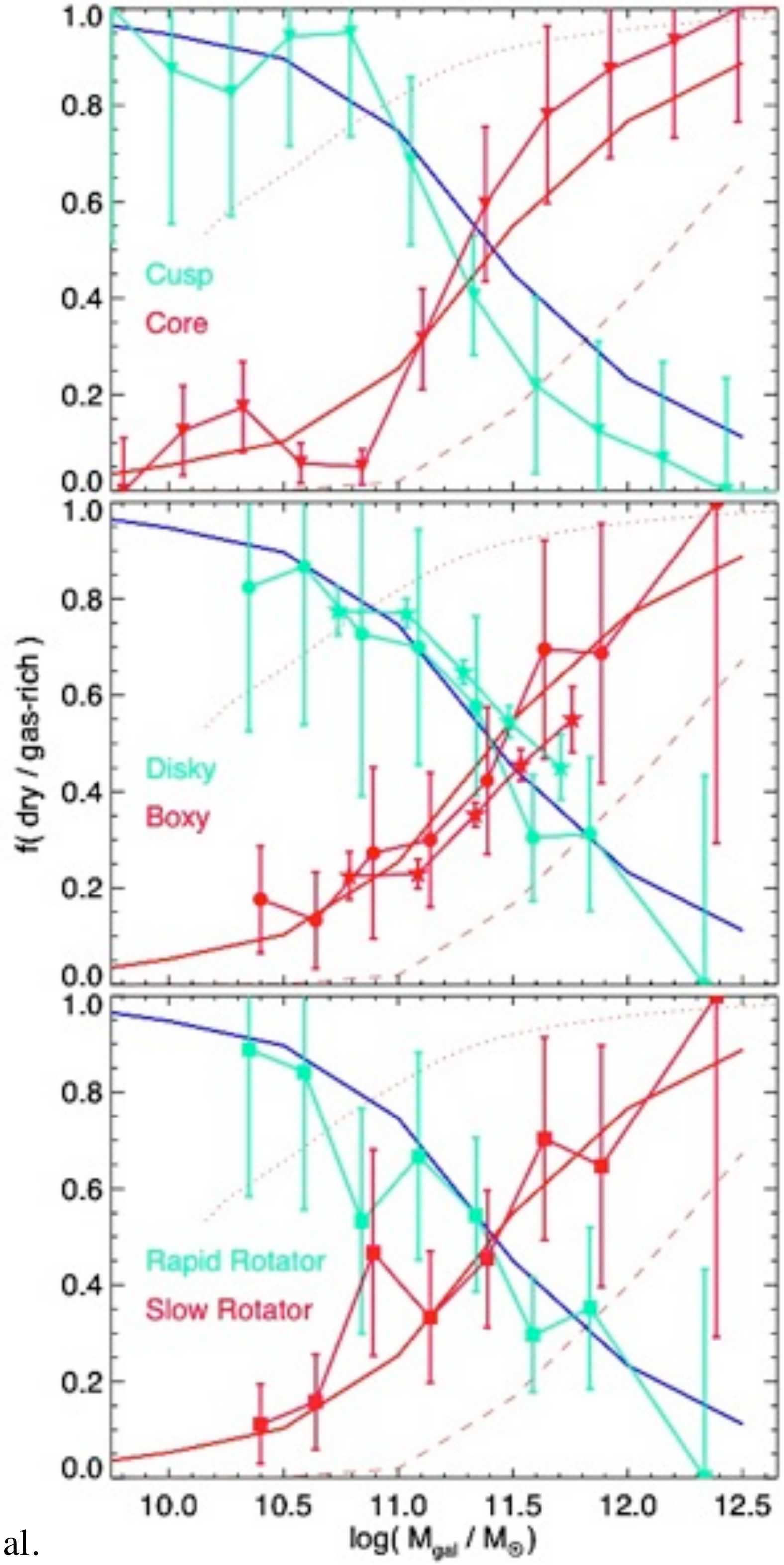


Kriek et al., Daddi et al.,
Grazian et al., Van Dokkum et al.

Comparing Quenching Models

DICHOTOMY IN ELLIPTICAL KINEMATICS

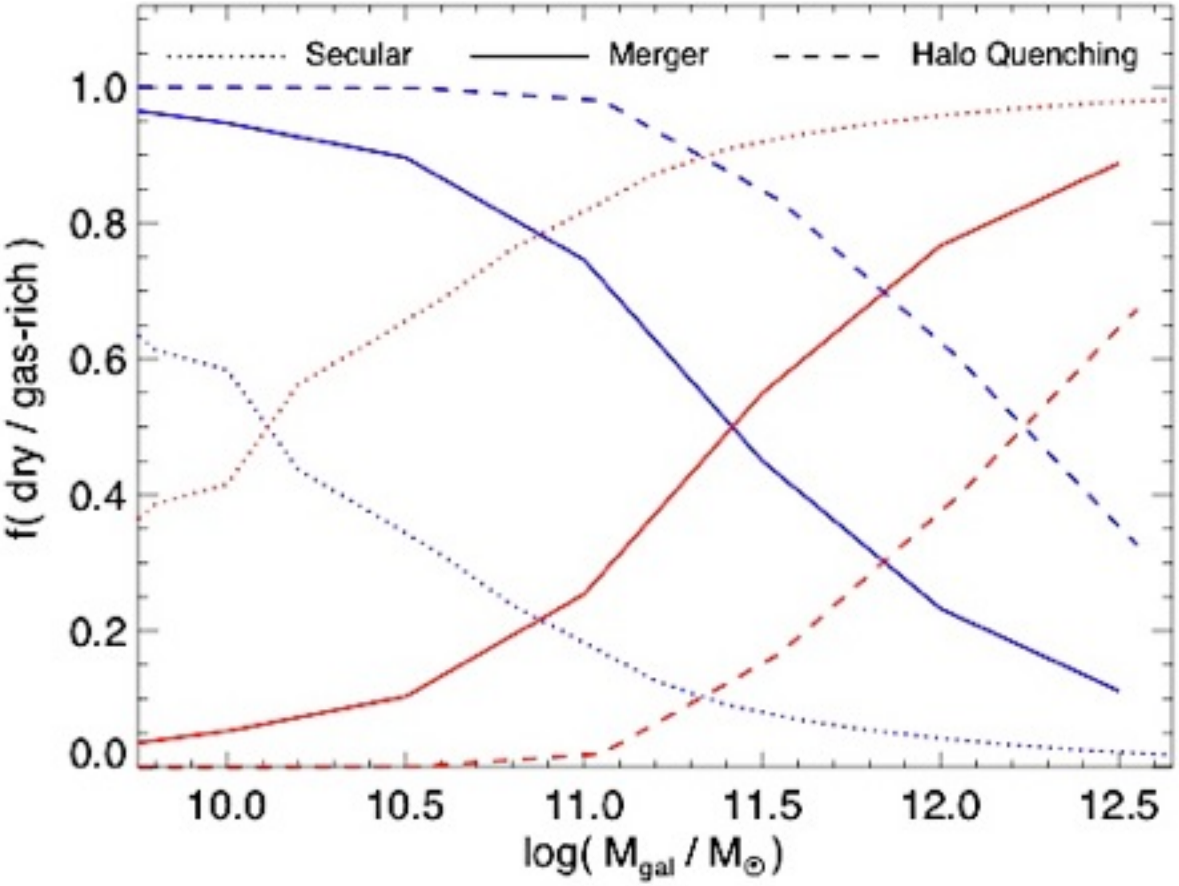


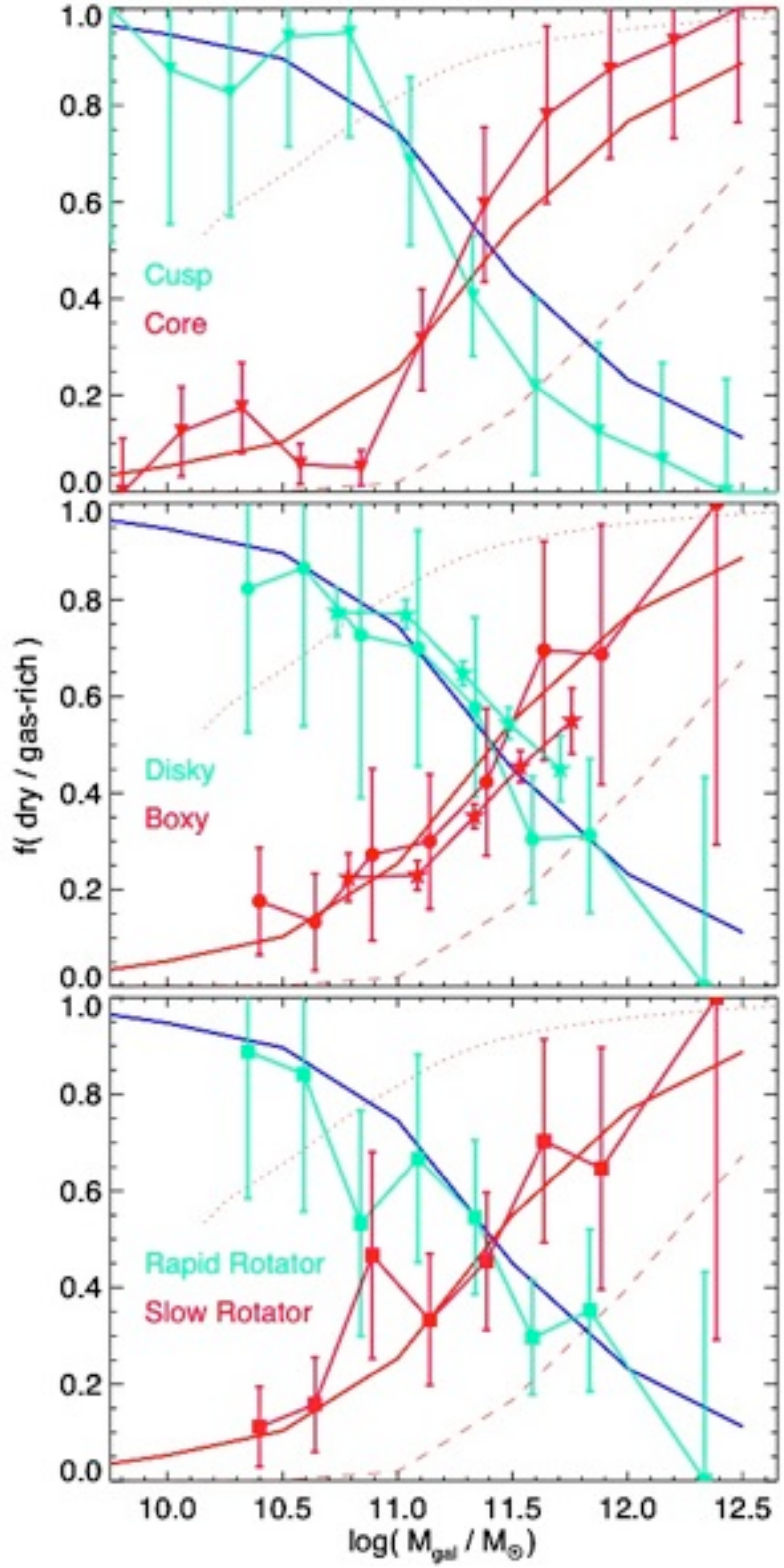


Lauer et al., Bender et al., Pasquali et al.

Comparing Quenching Models

DICHOTOMY IN ELLIPTICAL KINEMATICS

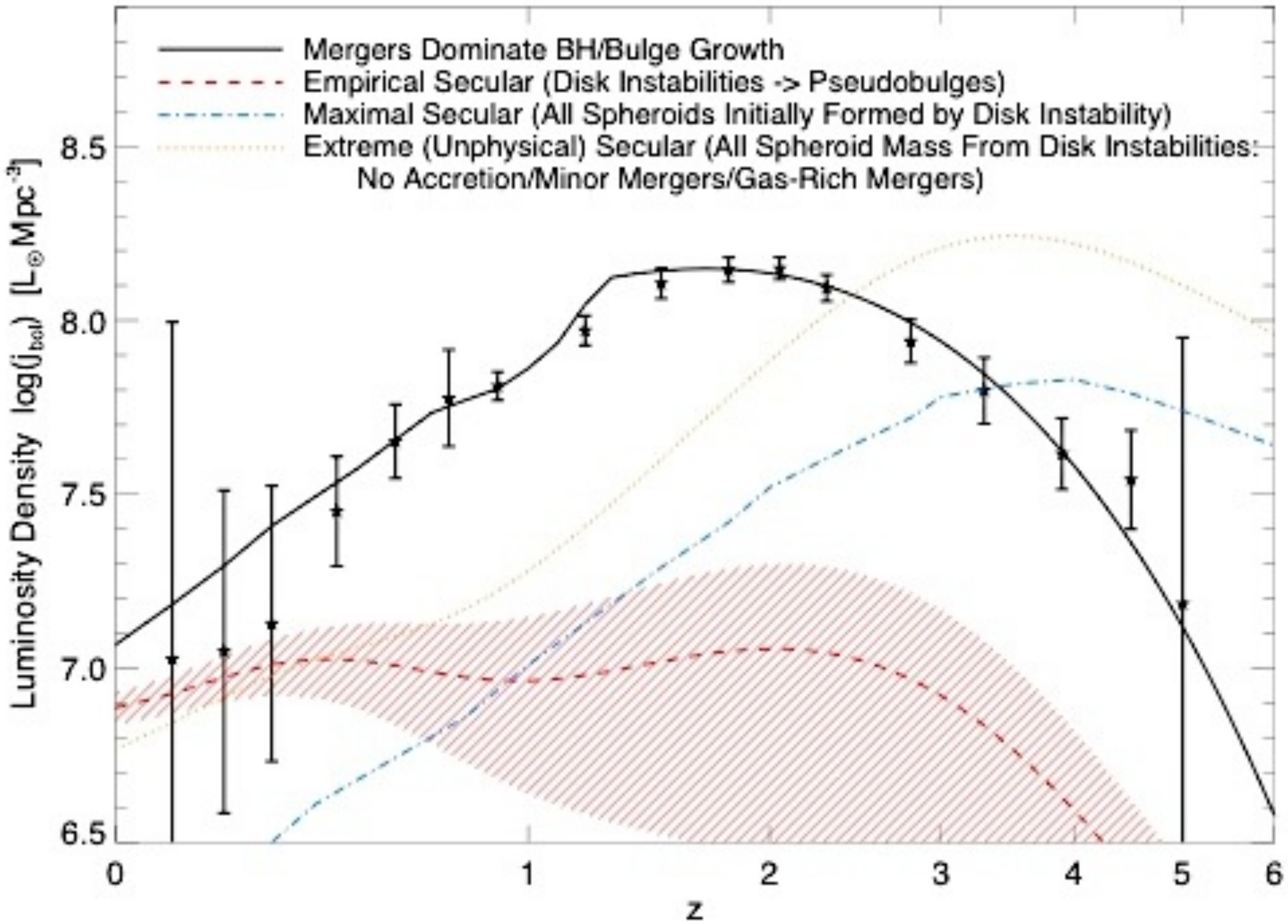


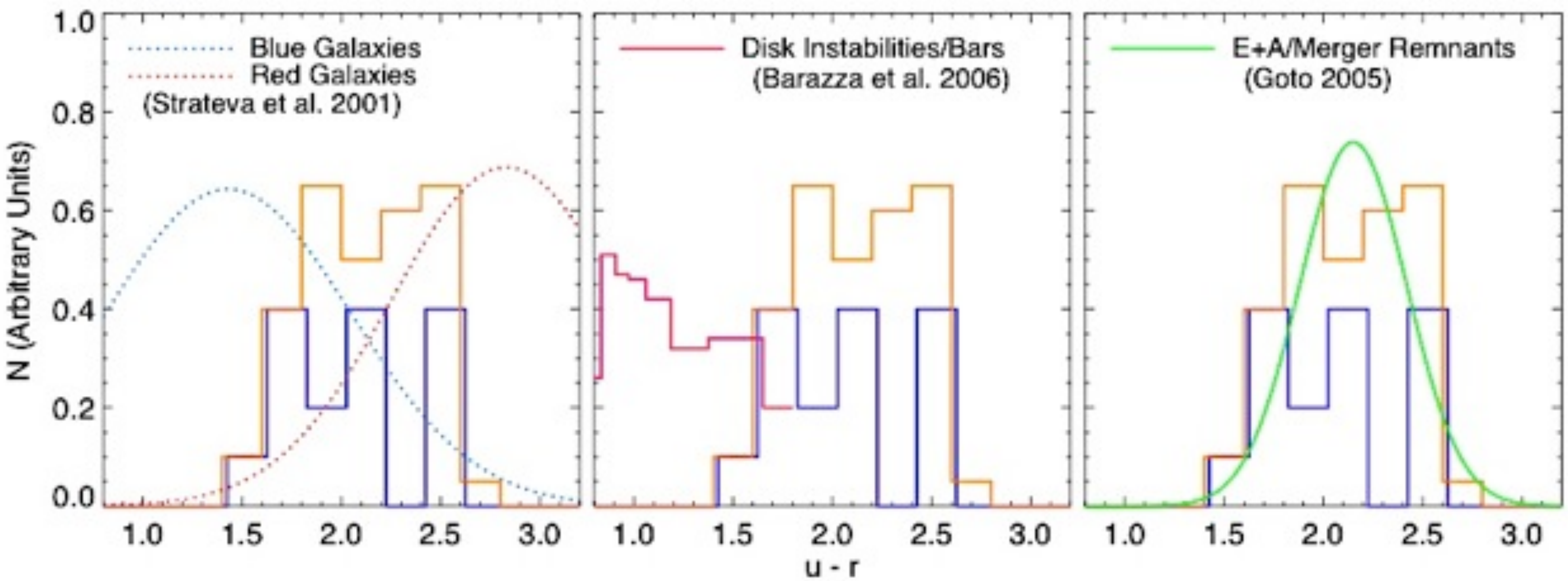


- See also Naab et al., Kang et al., Kochfar & Silk

LF vs. Redshift

UV THROUGH IR





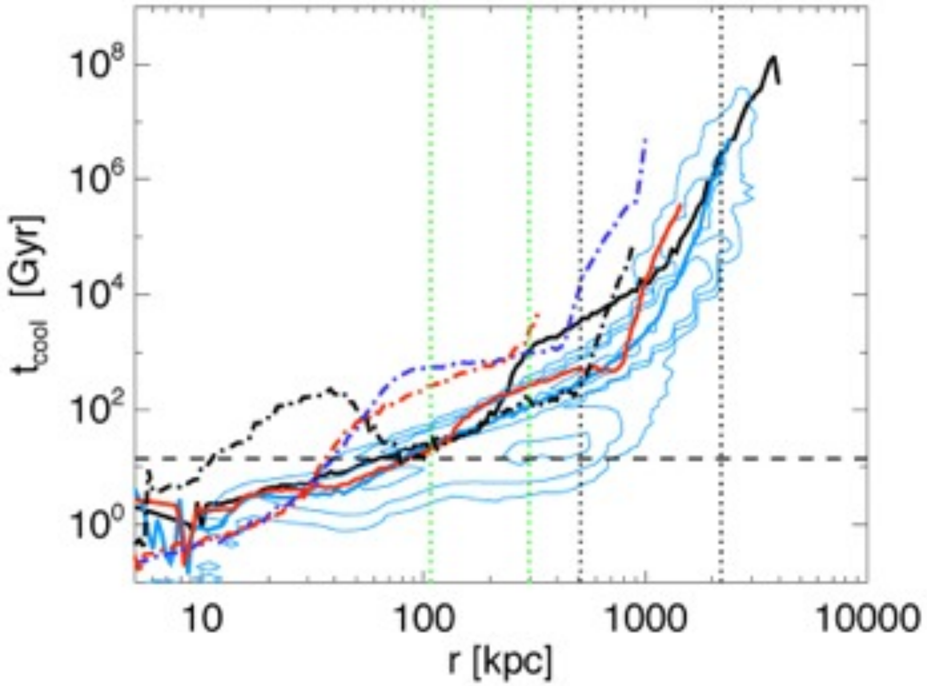
Comparing Quenching Models

SUMMARY

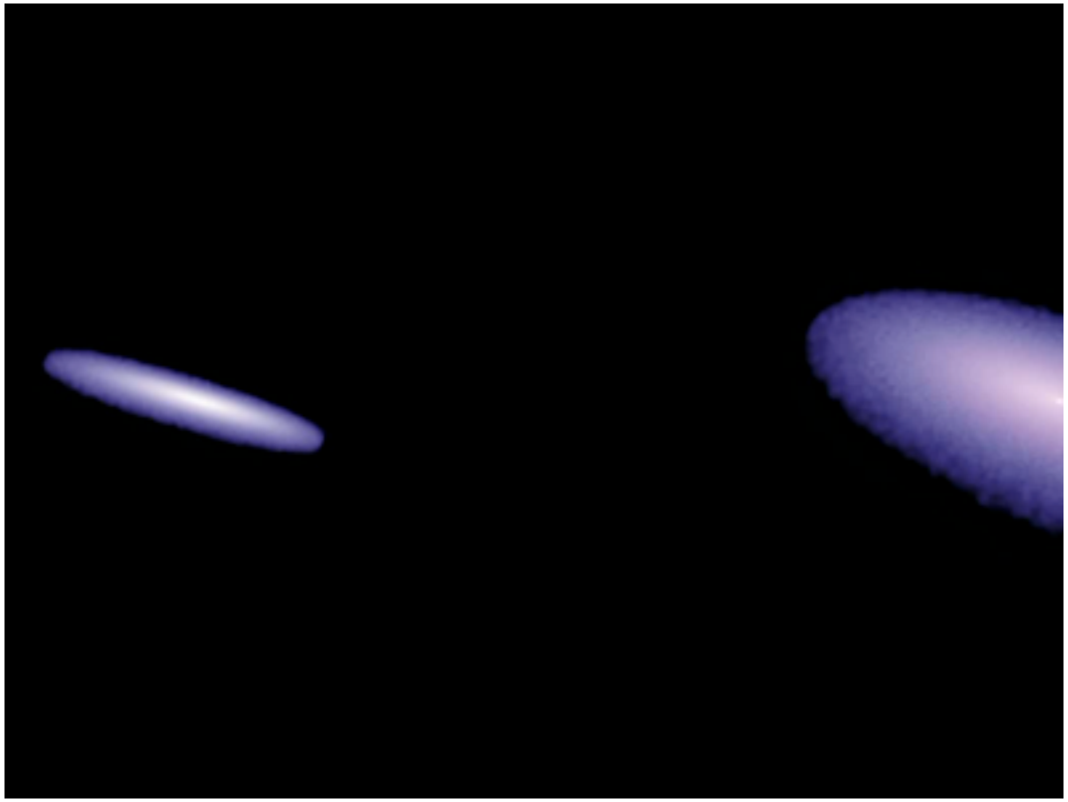
- Strong arguments for association between mergers, quasars, & blue-red transition:
  - clustering, number densities, merger fractions, morphologies, host colors/SFHs, LF evolution, kinematics, etc.

- But, how is quenching over a Hubble time accomplished by a single, potentially high redshift gas-rich major merger?

How Could Mergers Be Associated with “Maintenance”?

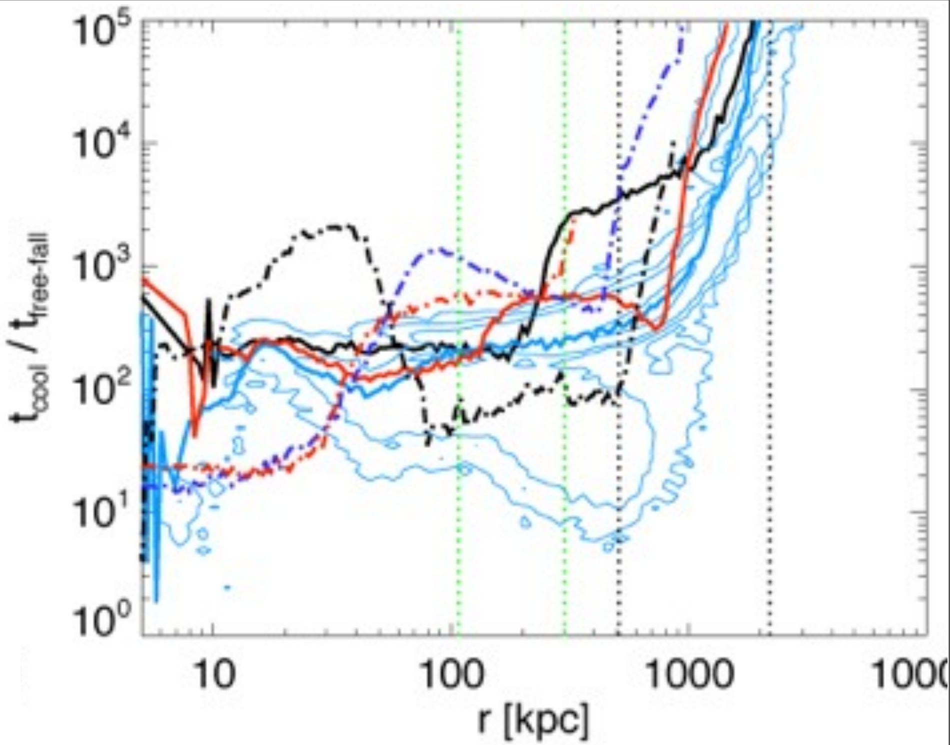


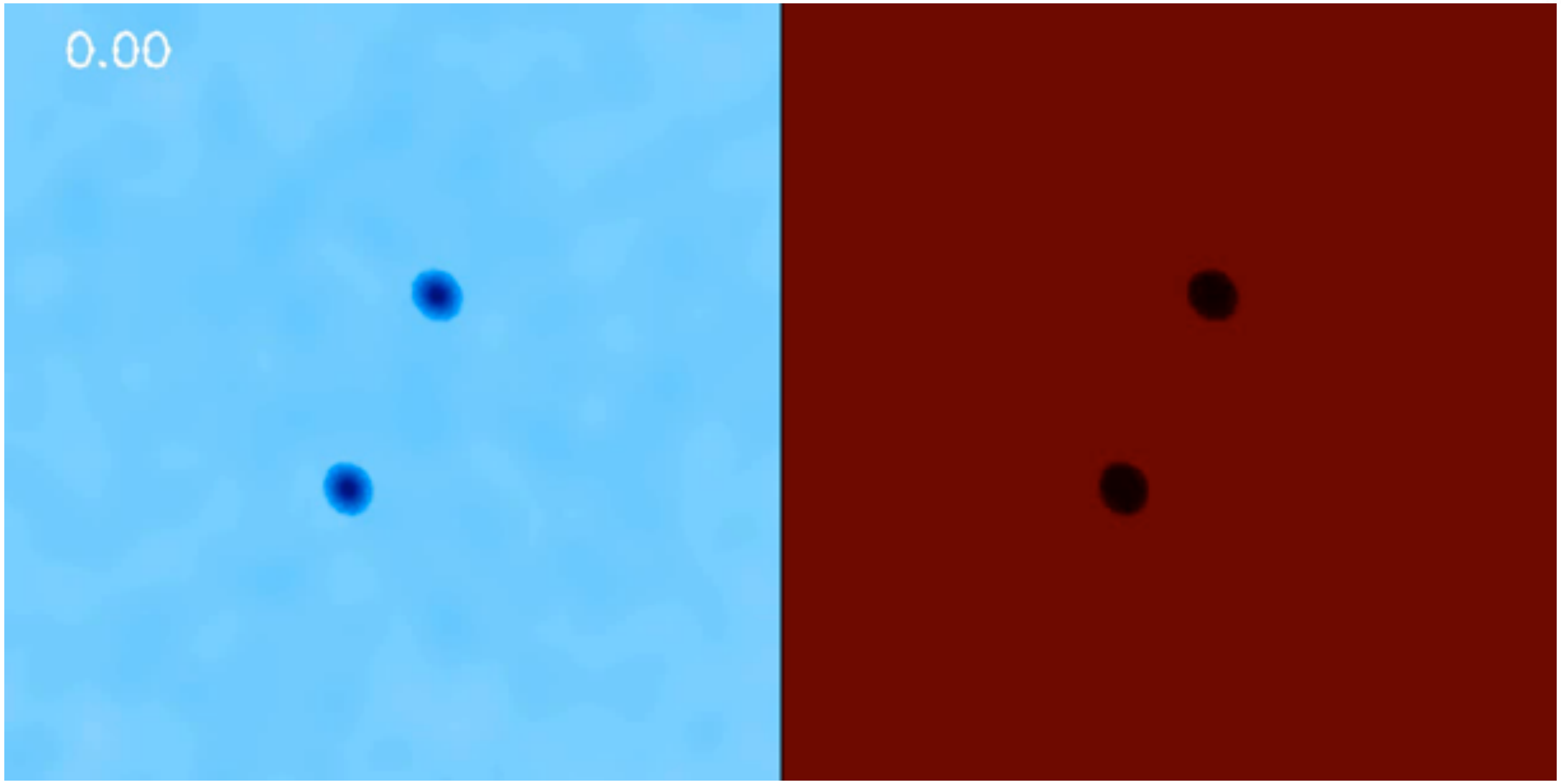
- (1) “Complete” quenching from a single event
  - energetics might be ok...
  - high redshifts: densities larger, cooling in filaments
  - can it really work for a Hubble time?



- (2) Buying time
  - expel cold gas at the end of the merger
  - heat remaining gas to much larger t_cool
  - only need ~couple Gyr to “naturally” develop a hot halo
  - still needs “radio mode” when that hot halo is formed

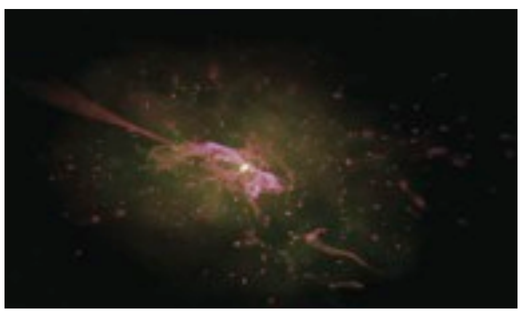
- (3) Hot halos from merger feedback
  - quasar/starburst heats gas to t_cool >> t_dyn
  - merger simulations end up with quasi-static, pressure supported gas equilibrium inside R_vir
  - new gas will shock: don't need to "pre-heat" everything



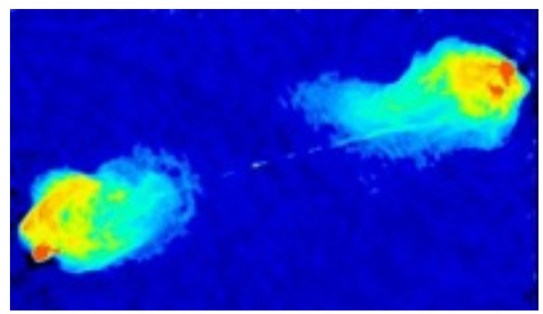


“Transition” vs. “Maintenance”

- Move mass from Blue to Red:
  Exhaust *all* cold gas
- Rapid (<~ Gyr)
- Small scales (~pc - kpc)
- “Quasar” mode (high mdot):
  Soltan: most BH mass
  short-lived (~10^7-10^8 yr)
- Morphological Transformation:
  Violent relaxation
  Classical spheroid formation
- Gas-rich/Dissipational Mergers



- Keep it Red:
  Prevent new cooling
- Long-lived (~Hubble time)
- Large (~R_vir) scales
- “Radio” mode (low mdot):
  small mass gain
  long-lived (~Hubble time)
- Subtle morphological change:
  (regular vs. giant ellipticals)
  “dry”/dissipationless mergers
- Halo Processes?



Summary

- Models where merger history supplements quenching make robust, qualitatively distinct predictions
  - Detailed observations can break degeneracies
  - Compared to models where a simple halo mass threshold or secular mechanisms set quenching, only the merger model appears to match these observations:
    - Bivariate red fraction (vs. M_halo & M_gal)
    - High-z passive populations
    - Elliptical dichotomy
    - Evolution of color-morphology-density relations

- Mergers work *with* hot halos
  - Buy time for hot halos to develop
  - Directly shock low-mass systems to “hot halo” mode

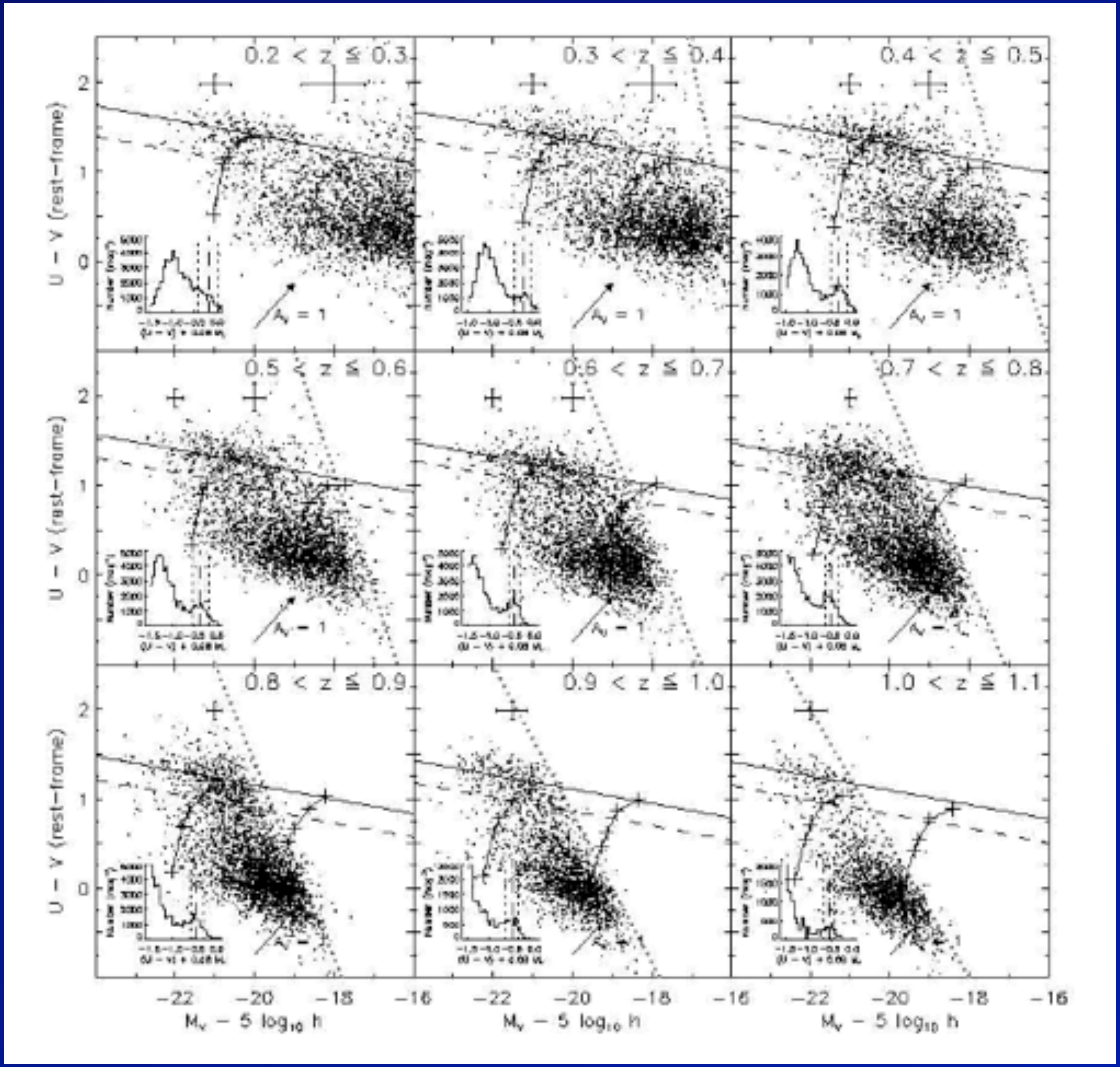
- Caveats:
  - Satellites
  - Secular AGN fueling & pseudobulge formation are probably important: M_bulge < 10^10 M_sun, M_bh <~ 10^7 M_sun

COMBO-17: Color bi-modality to z=1.1

25,000 galaxies

17-color photo z's

R-band selected to R = 24



Bell et al. 2004

COMBO-17:

Disk galaxies

Mass-radius relation

No shift in zeropoint vs. time