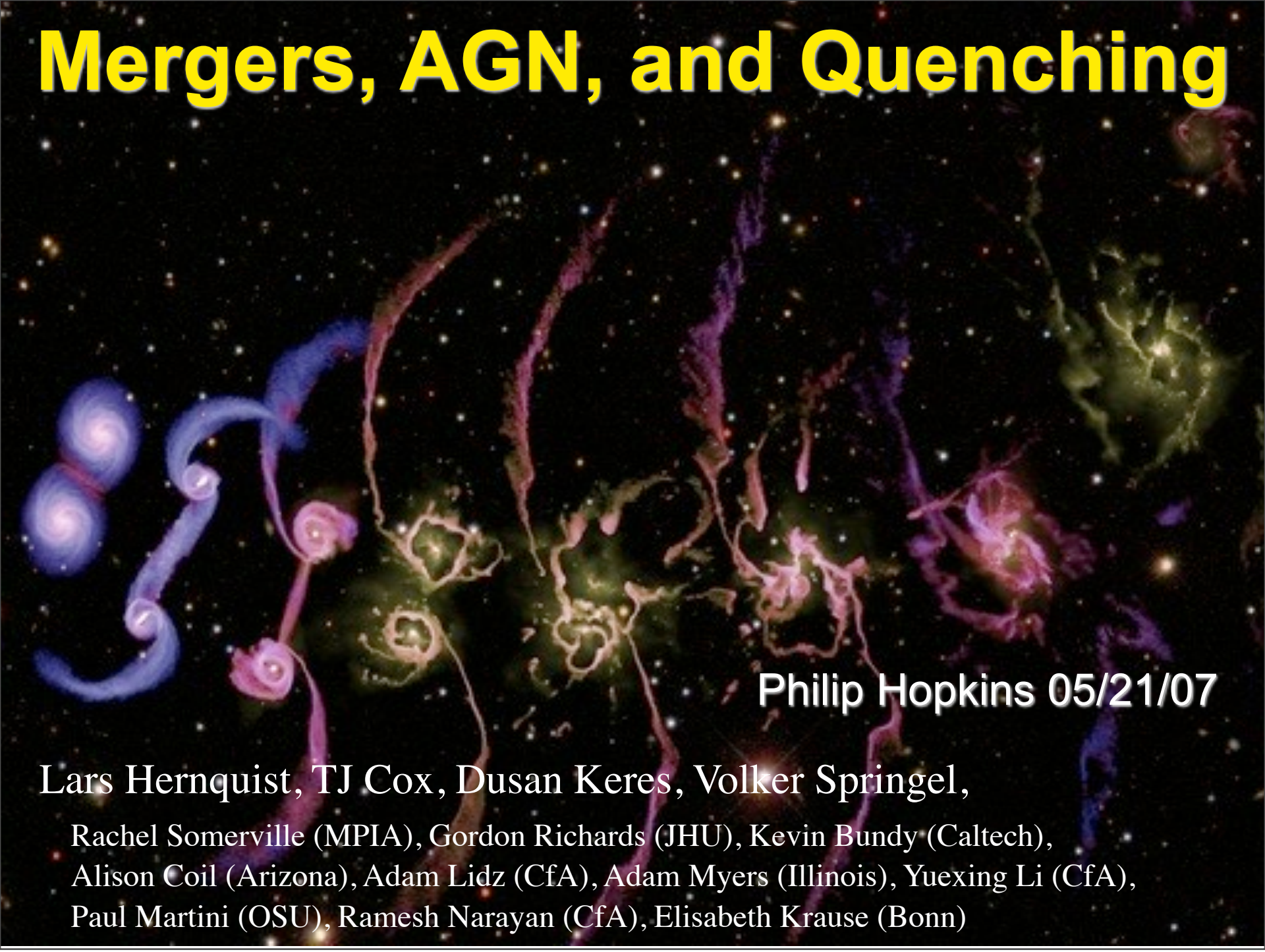
Mergers, AGN, and Quenching



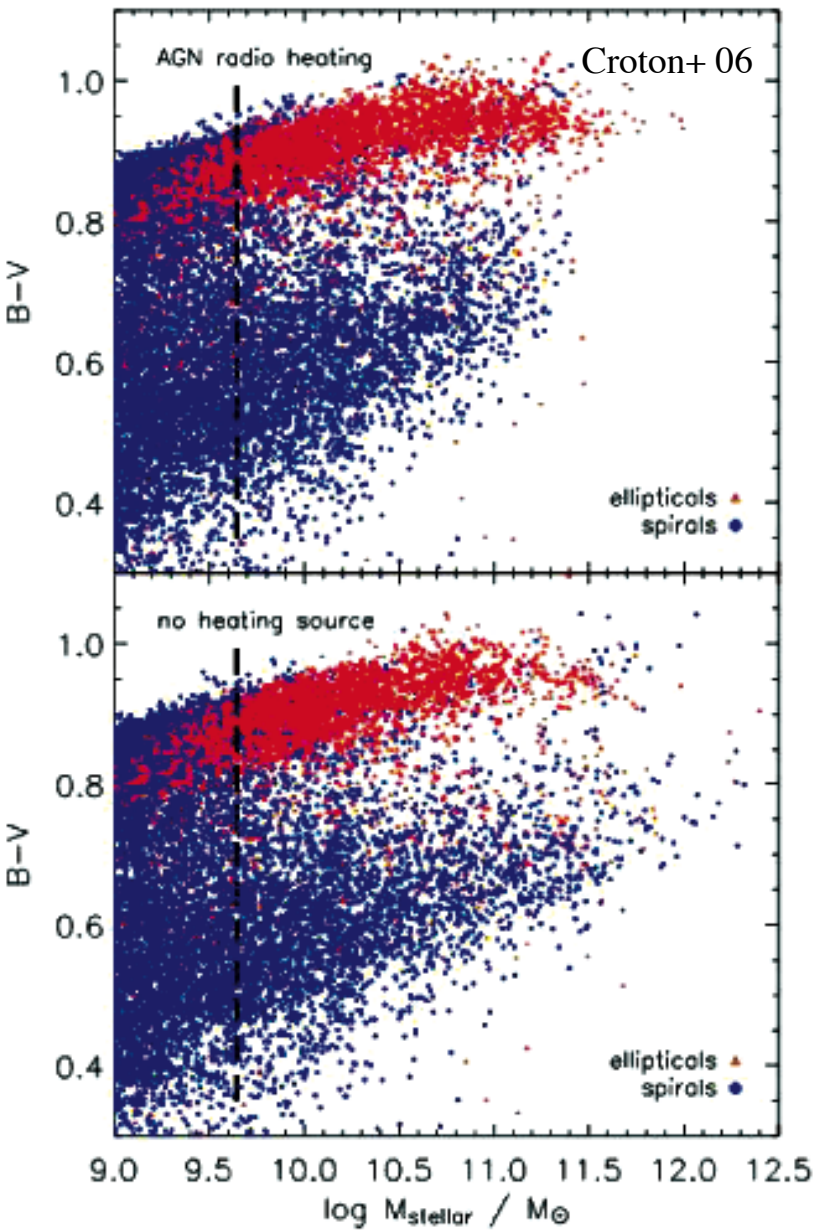
Philip Hopkins 05/21/07

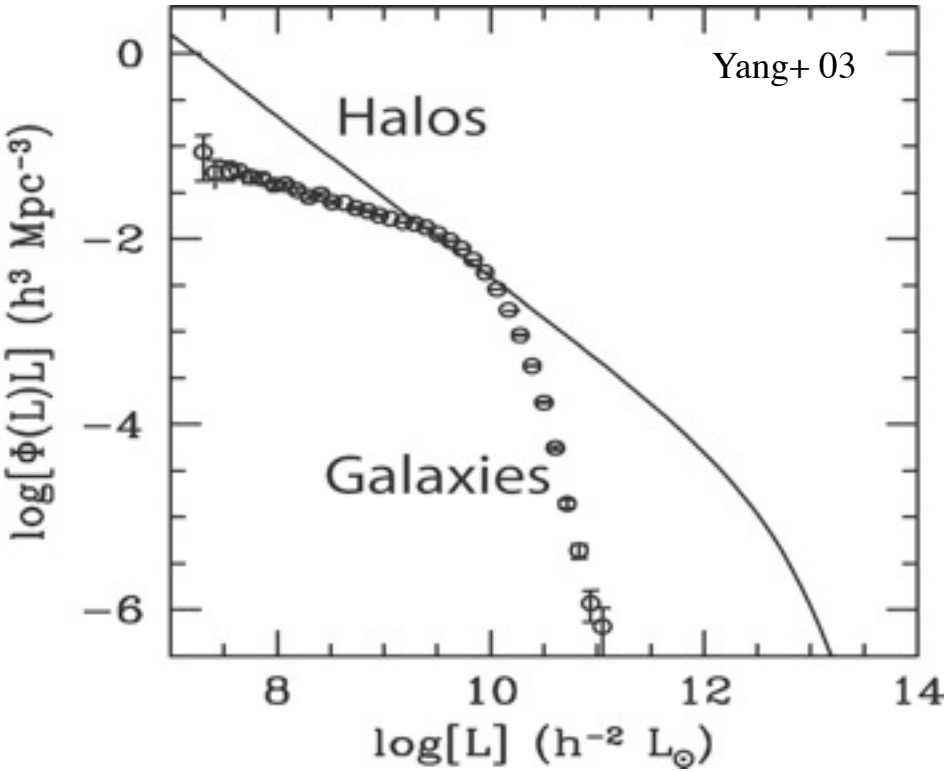
Lars Hernquist, TJ Cox, Dusan Keres, Volker Springel,

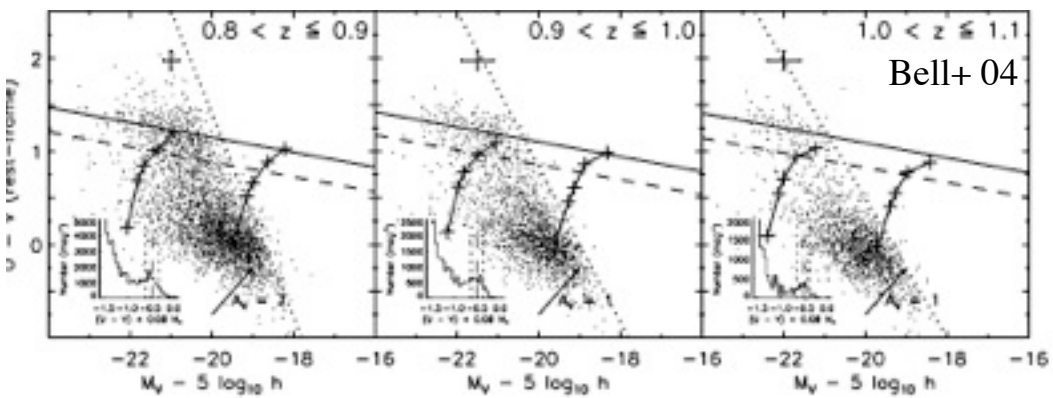
Rachel Somerville (MPIA), Gordon Richards (JHU), Kevin Bundy (Caltech),
Alison Coil (Arizona), Adam Lidz (CfA), Adam Myers (Illinois), Yuexing Li (CfA),
Paul Martini (OSU), Ramesh Narayan (CfA), Elisabeth Krause (Bonn)

Motivation

QUASARS AND SPHEROID FORMATION

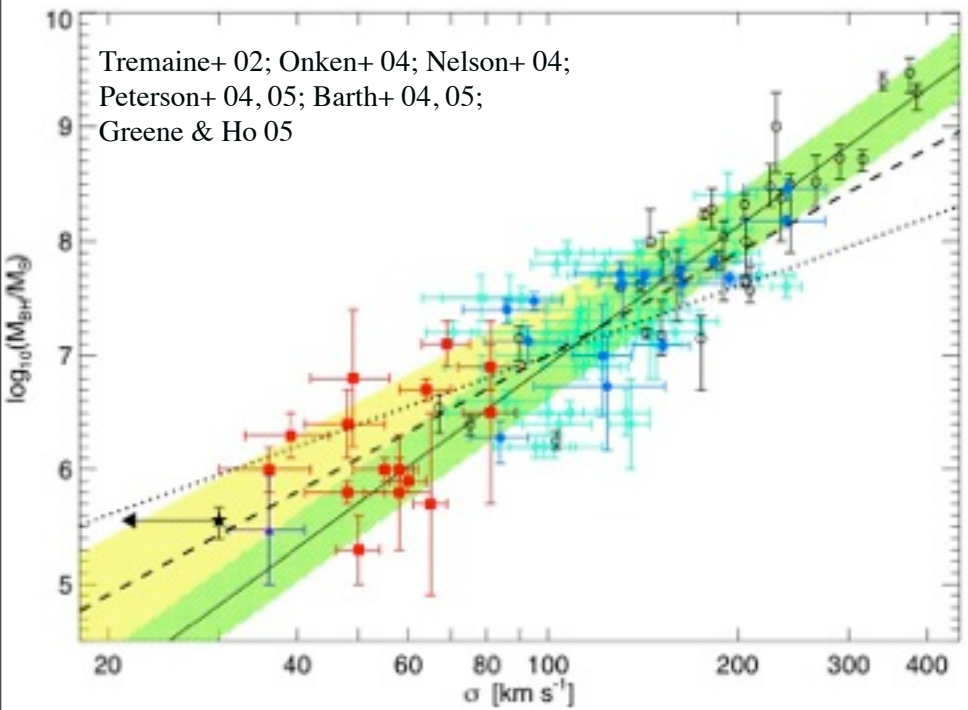


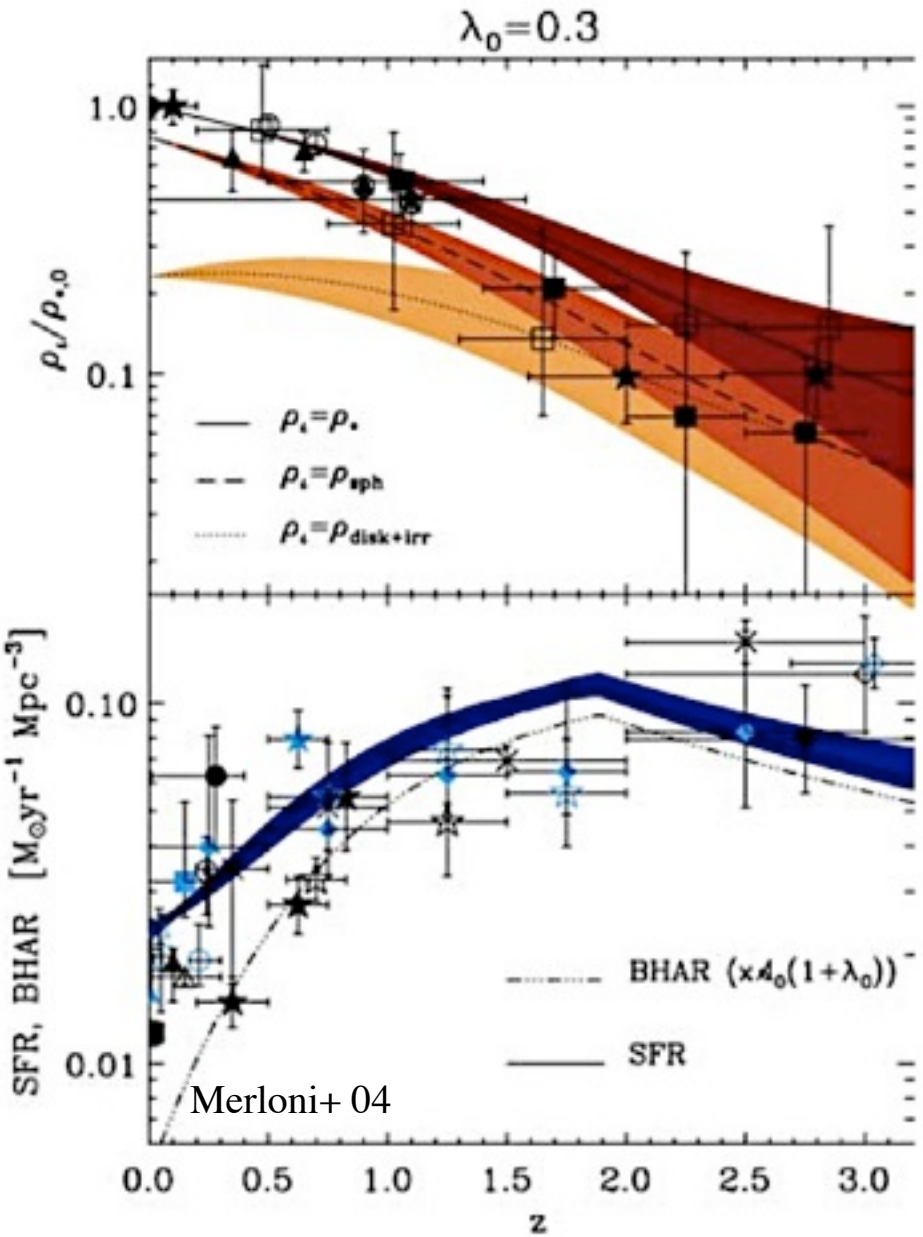




Motivation

CIRCUMSTANTIAL EVIDENCE

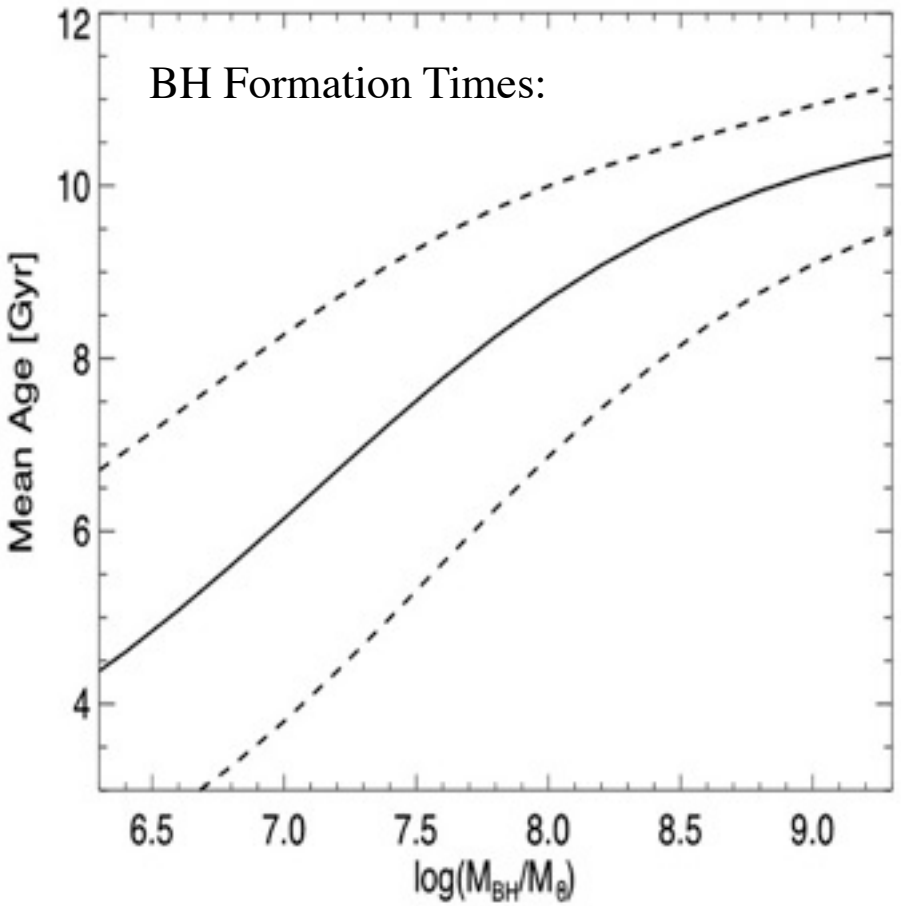


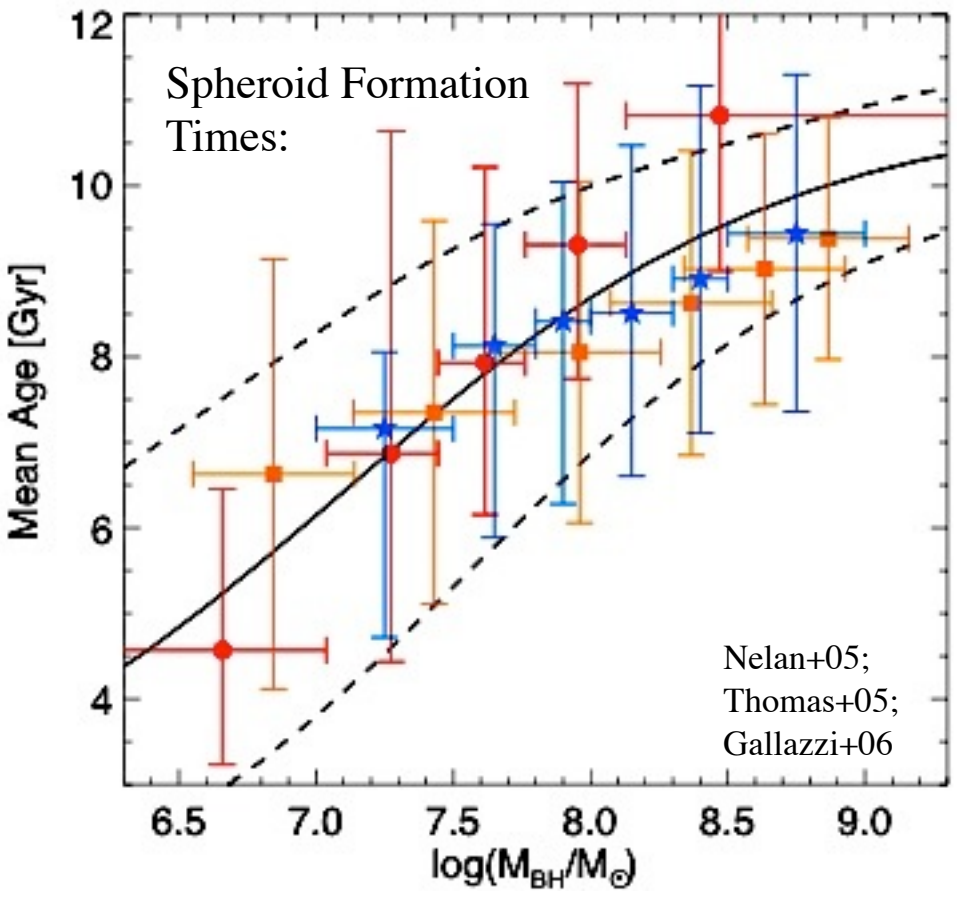


Motivation

CIRCUMSTANTIAL EVIDENCE

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

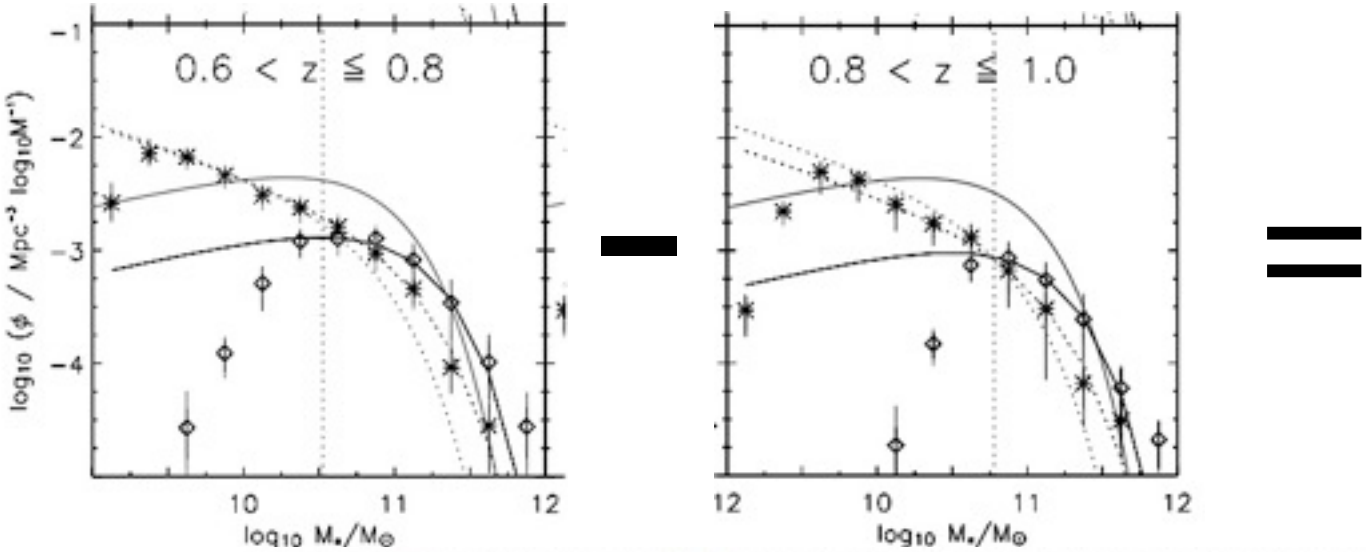


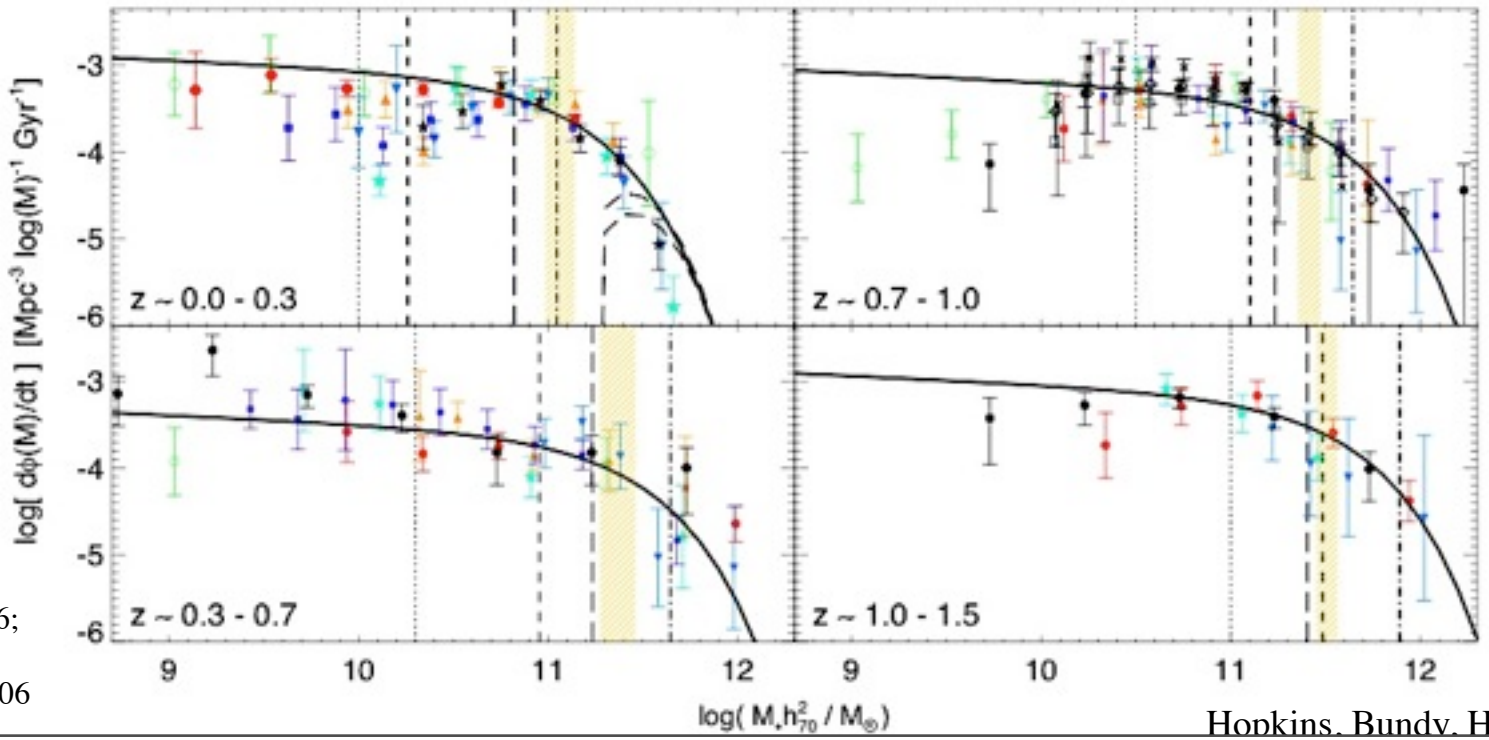


Hopkins, Lidz, Hernquist, Coil, et al. 2007

Motivation

CIRCUMSTANTIAL EVIDENCE





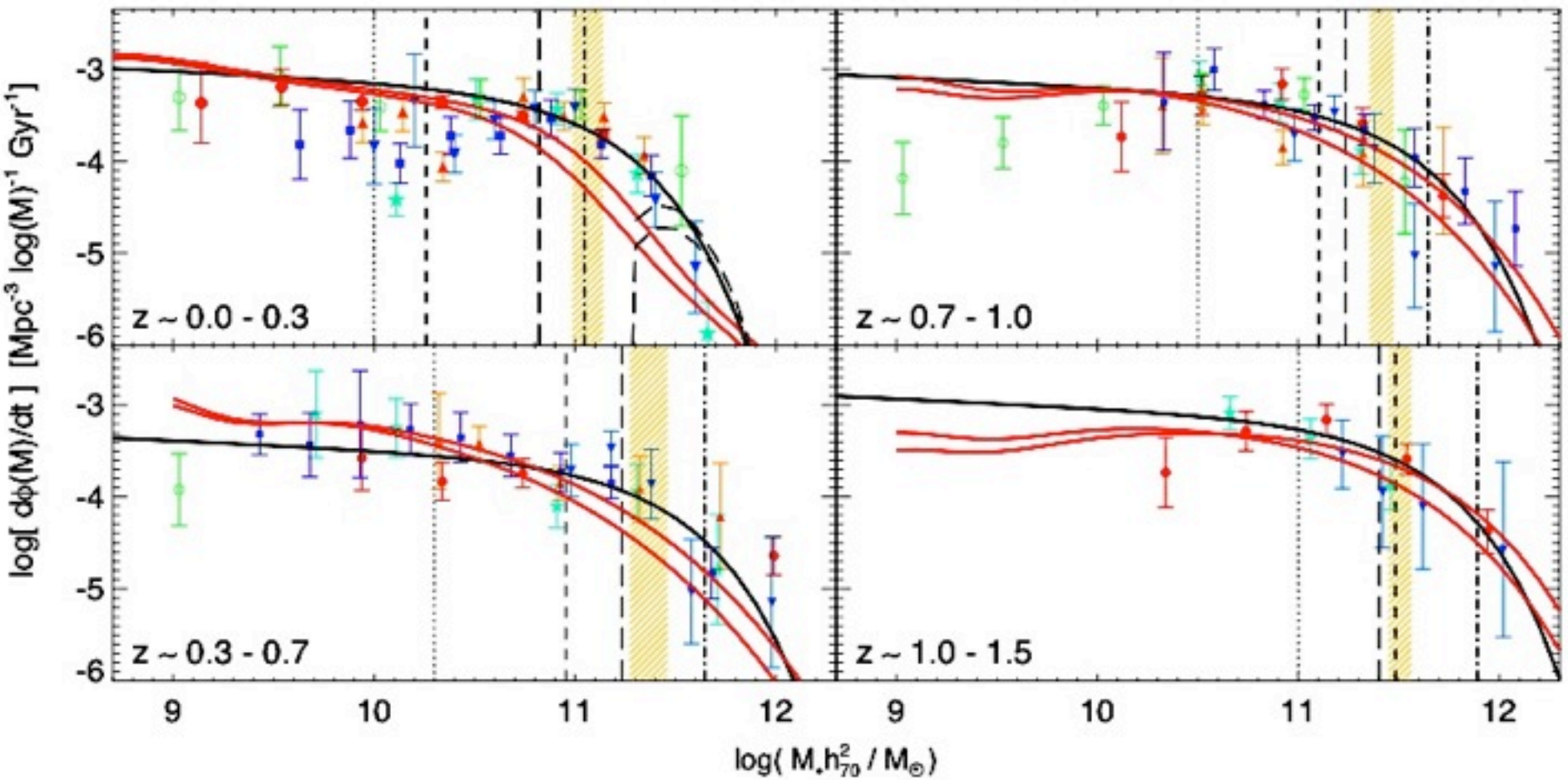
Borch+06;
Bundy+06;
Fontana+04,06;
Pannella+06;
Franceschini+06

Hopkins, Bundy, Hernquist+ 06

Motivation

CIRCUMSTANTIAL EVIDENCE

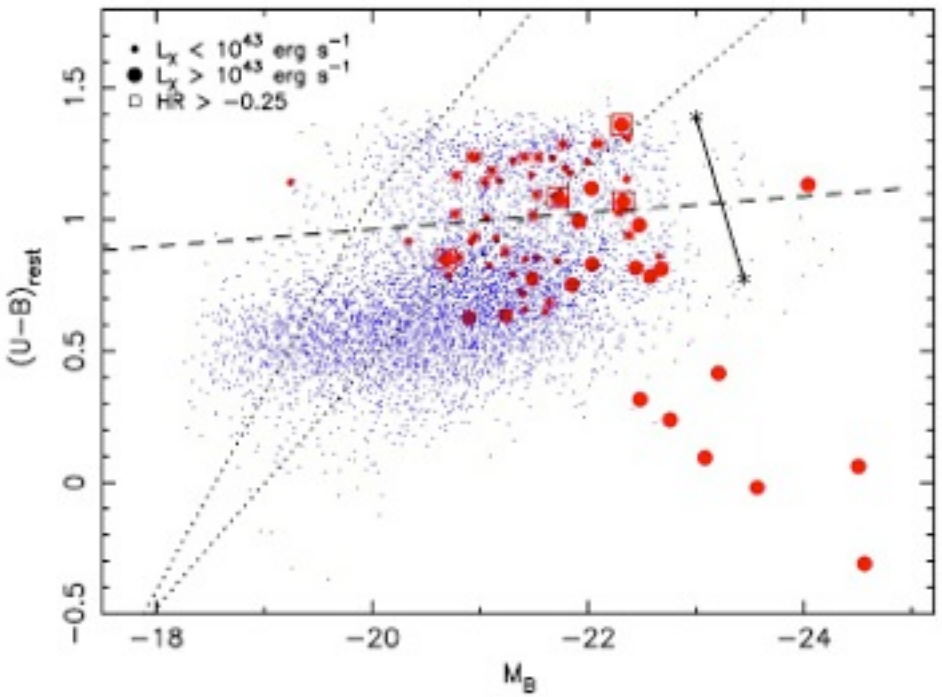
- Observed RS Buildup to z>~1 = Expectation if *all* new mass to the RS "transitions" in a quasar-producing merger



Hopkins, Bundy, Hernquist+ 06

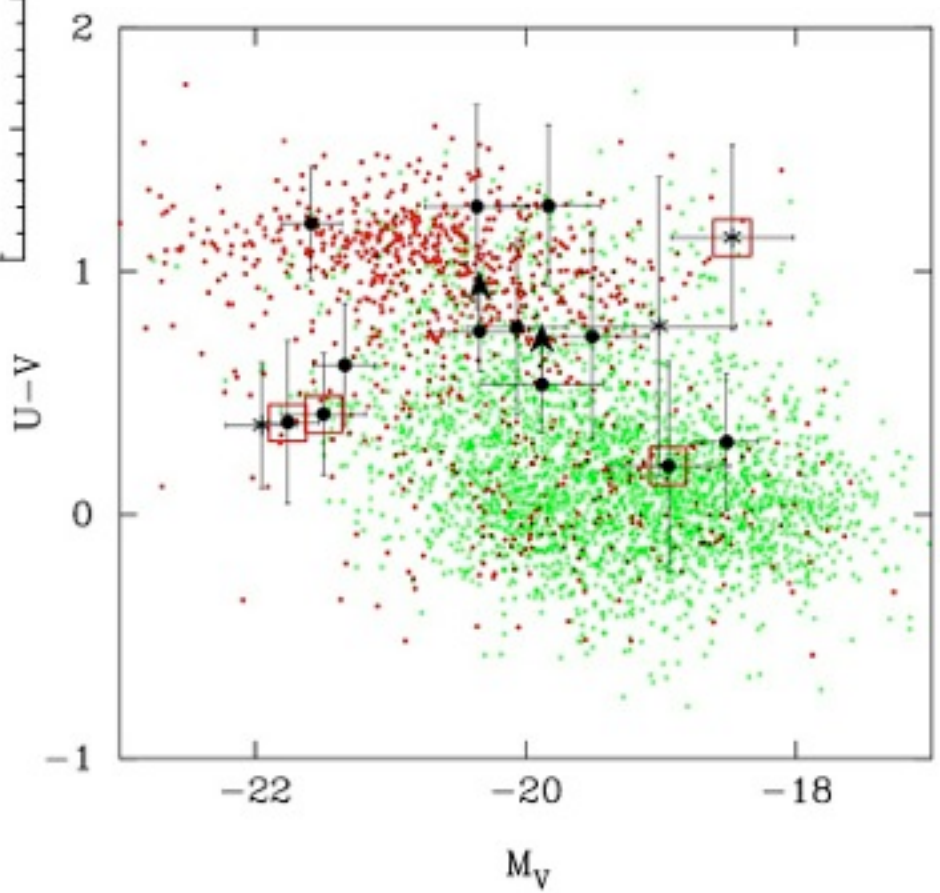
Motivation

CIRCUMSTANTIAL EVIDENCE



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

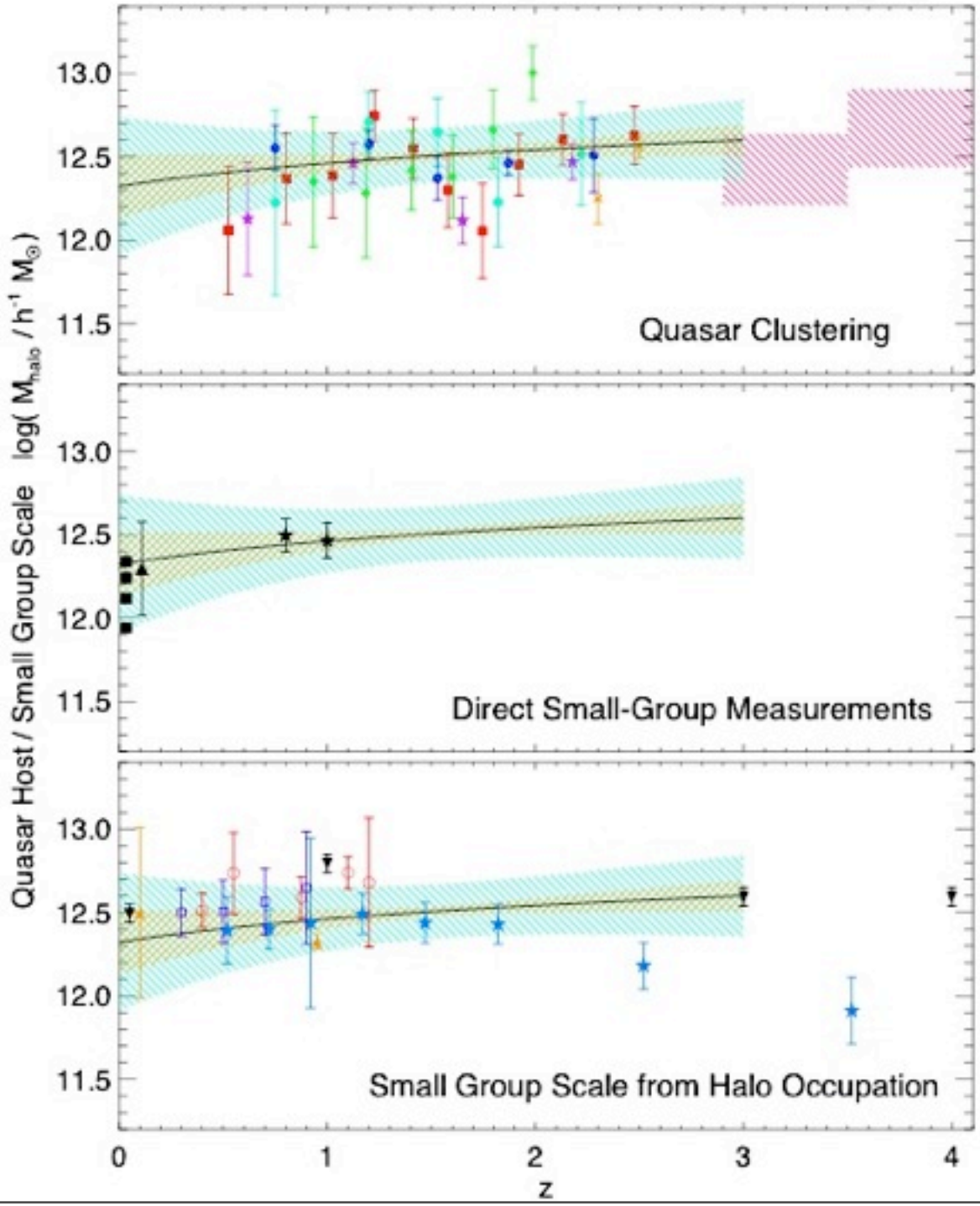
(also, Kauffmann+ 03;
local SDSS hosts)



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

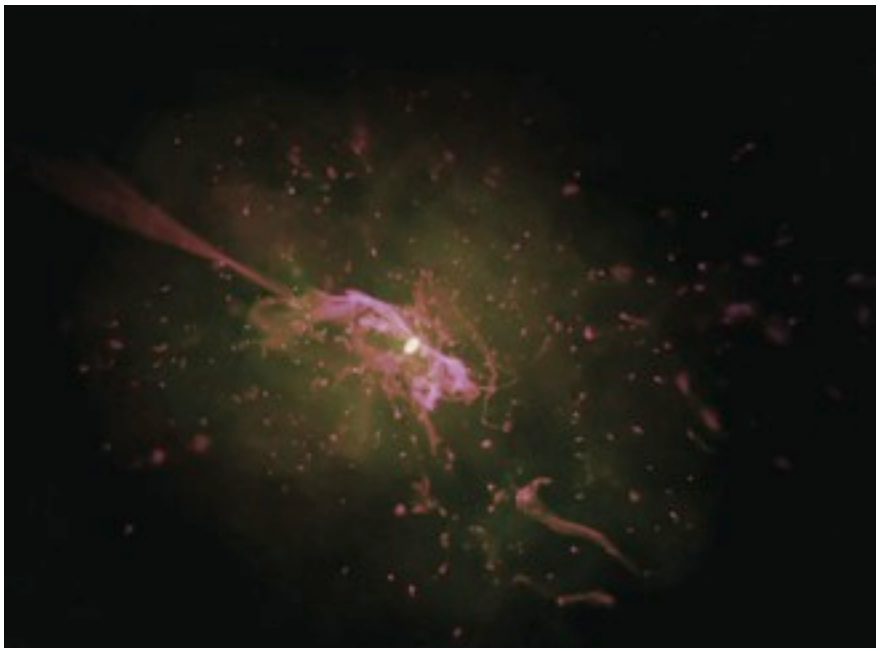
Motivation

CIRCUMSTANTIAL EVIDENCE



“Transition”:

- 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



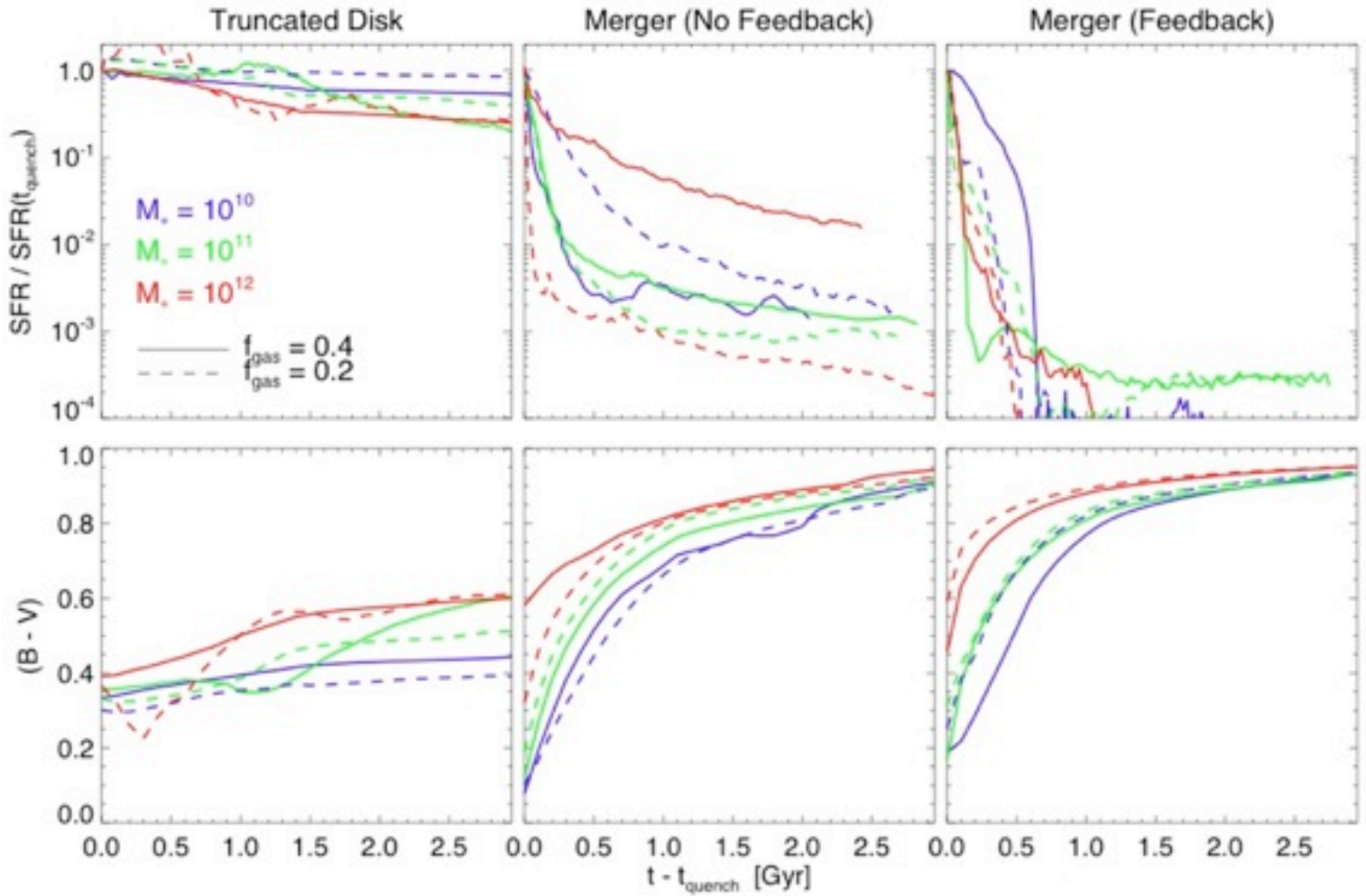
Motivation

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	Seyfert? stellar winds
timescales:	short (<Gyr)	~Hubble time	~Gyr?

Motivation

MERGERS AND THE BLUE-RED TRANSITION



The Model

MERGERS IN A COSMOLOGICAL CONTEXT

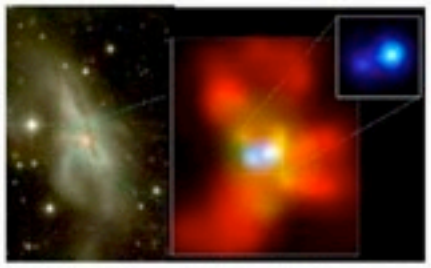
- Unfortunately, details of the transition are unclear:
  - What are the dominant feedback mechanisms?
  - How do they couple?

- Construct a generic model of merger-driven quenching to test:
  - populate halo+subhalo MFs (from cosmological simulations) with “initial” blue galaxies (according to HOD or simple prescriptions)
  - let them grow (star formation & accretion)
  - let them merge:
    - assume major, gas-rich merger = quenching (all baryons to stars, and no further star formation)
    - not testing *how* mergers might quench future SF, simply *whether or not* they do

(c) Interaction/"Merger"

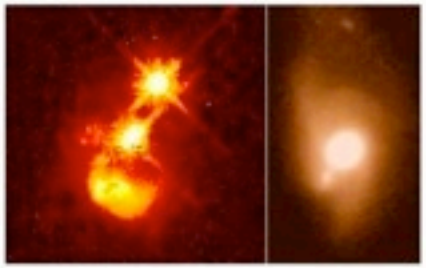
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

(d) Coalescence/(U)LIRG



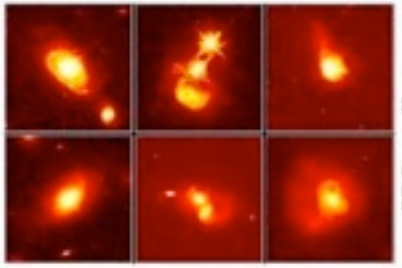
- galaxies coalesce: violent relaxation in core
- gas inflows to center: starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small

(e) "Blowout"



- 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

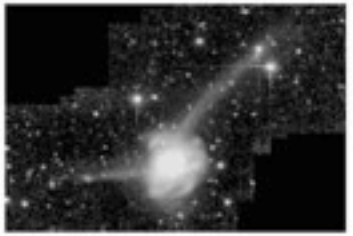


- dust removed: now a "traditional" QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

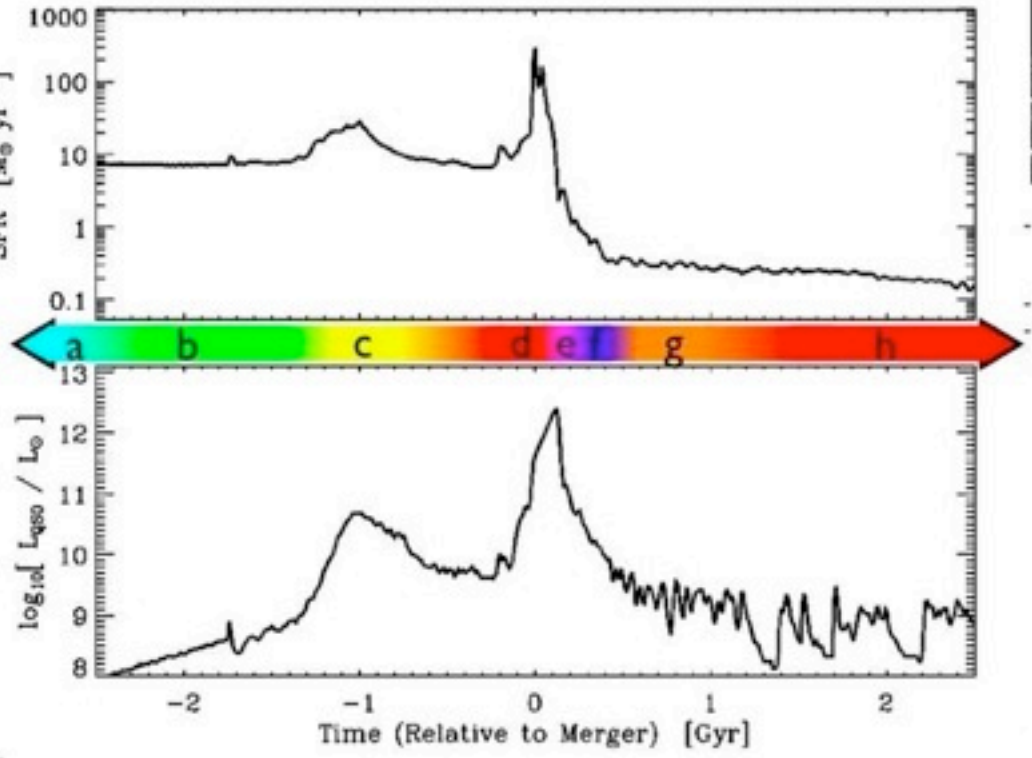
(b) "Small Group"

- 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



- 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



(a) Isolated Disk

- halo & disk grow, most stars formed
- secular growth builds bars & pseudobulges
- "Seyfert" fueling (AGN with M_B>-23)
- cannot redden to the red sequence

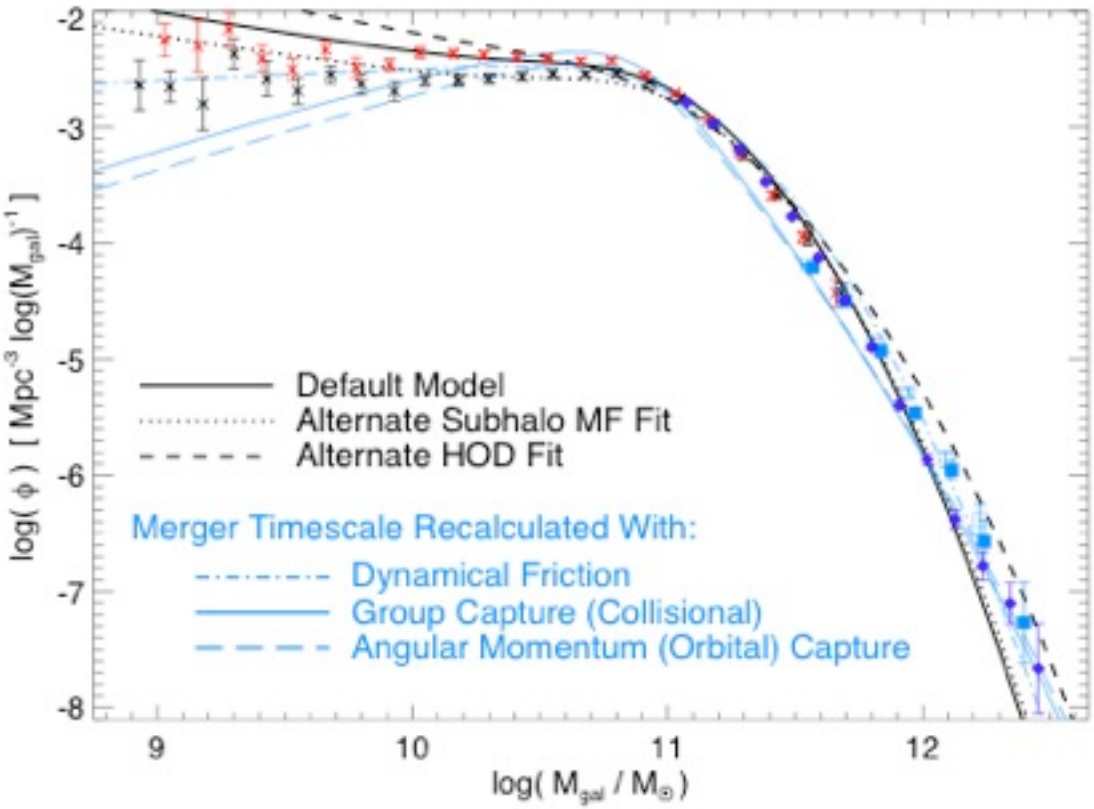
(h) "Dead" Elliptical

- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to "large group" scales: mergers become inefficient
- growth by "dry" mergers

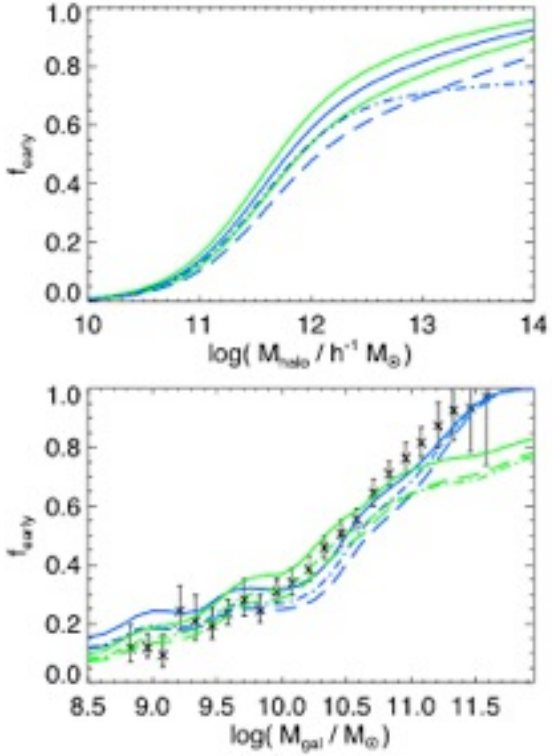
The Model

PREDICTIONS

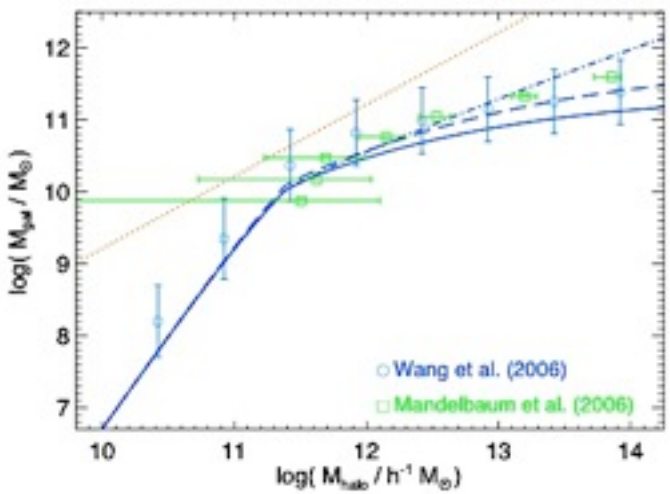
- z=0 mass functions



- red fractions:



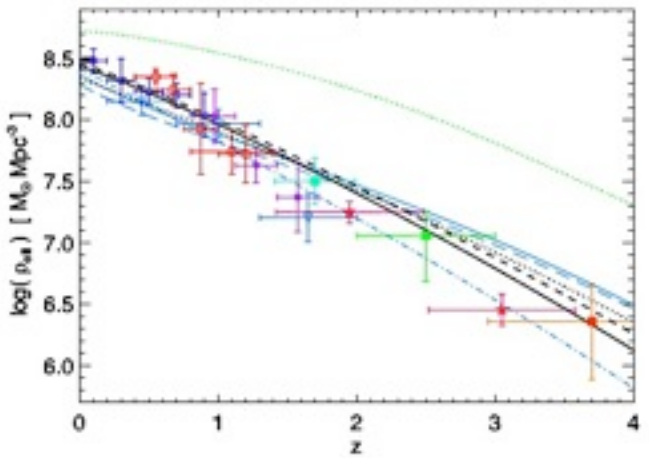
- M/L vs. M_halo



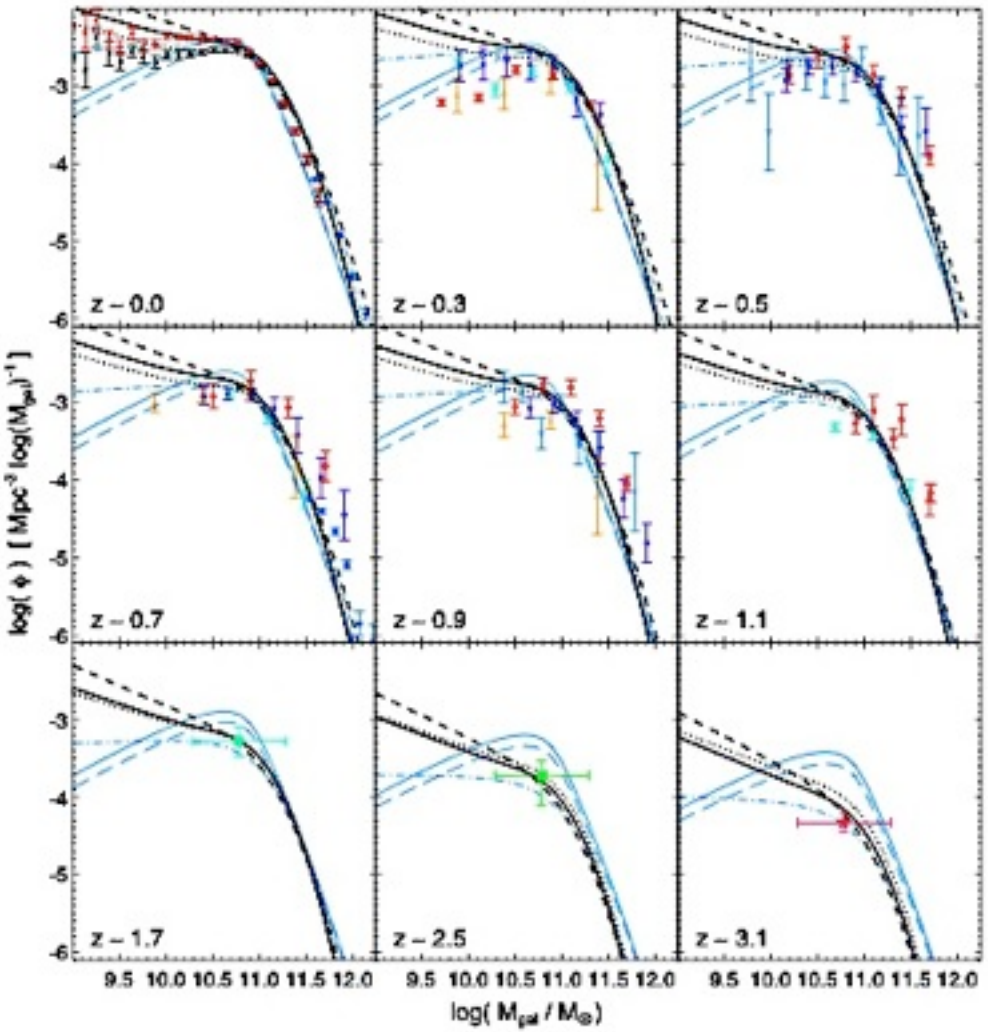
The Model

PREDICTIONS

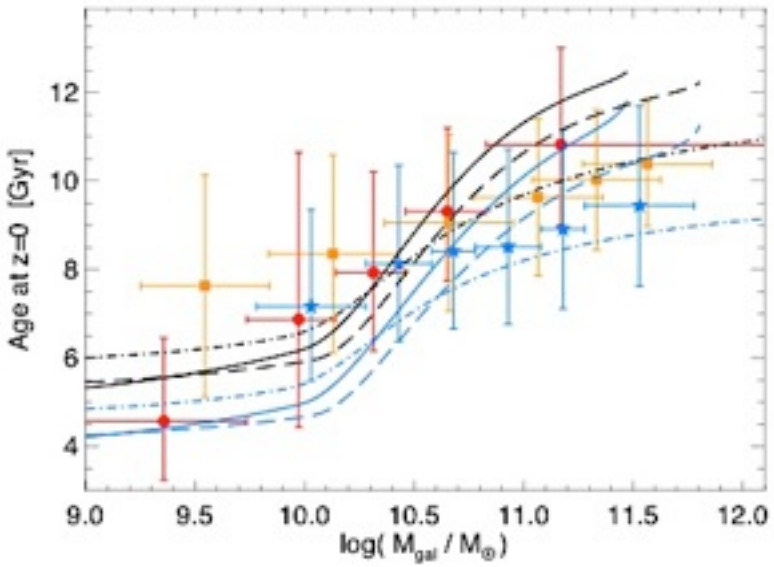
- mass density:



- mass function redshift evolution:



- age vs. mass:



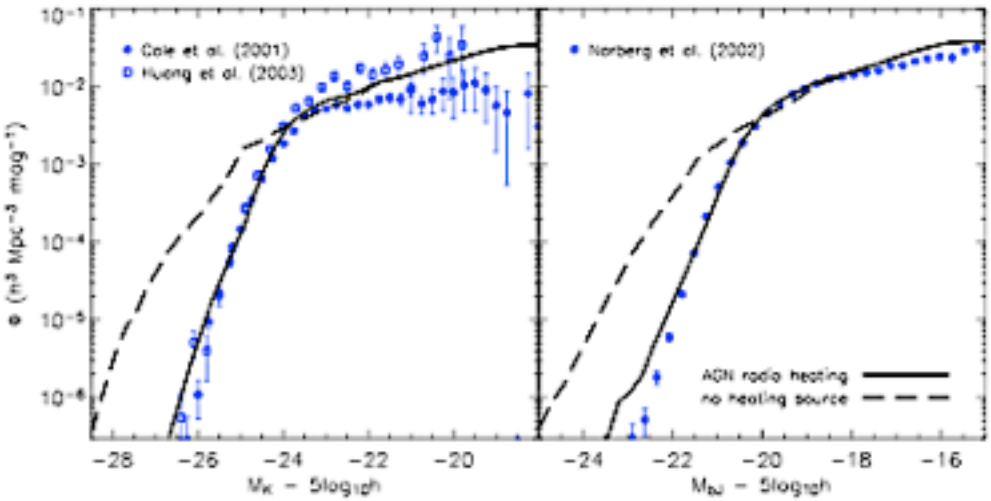
Great!

....BUT....

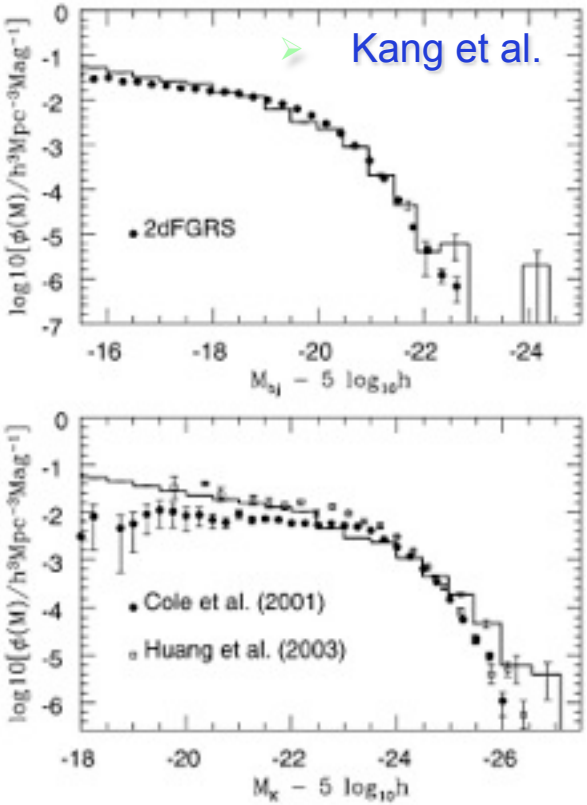
Great!

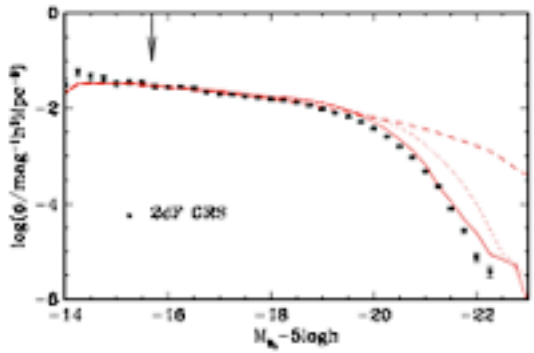
....BUT....

Croton et al.

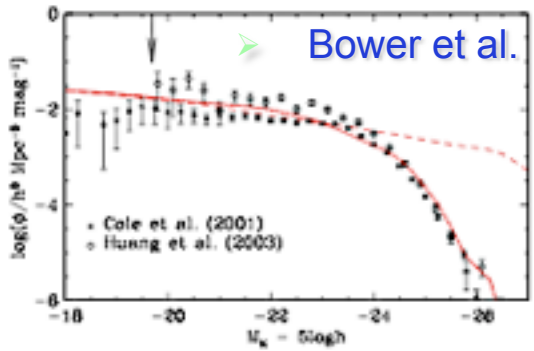


Kang et al.

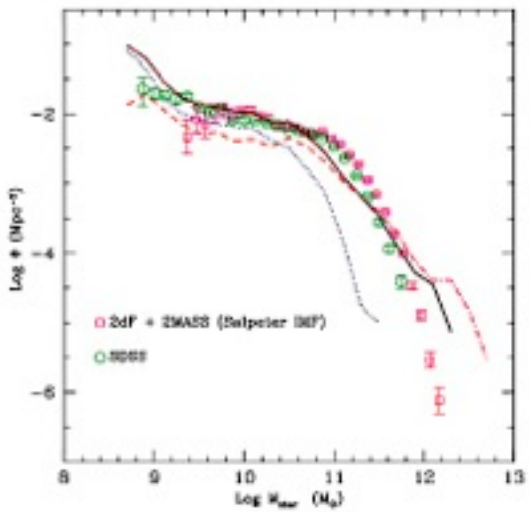




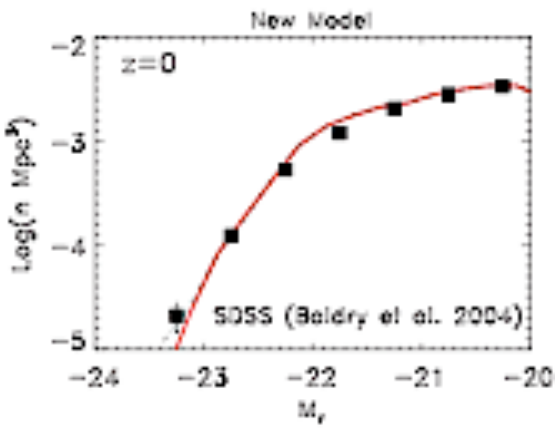
Bower et al.



Monaco et al.



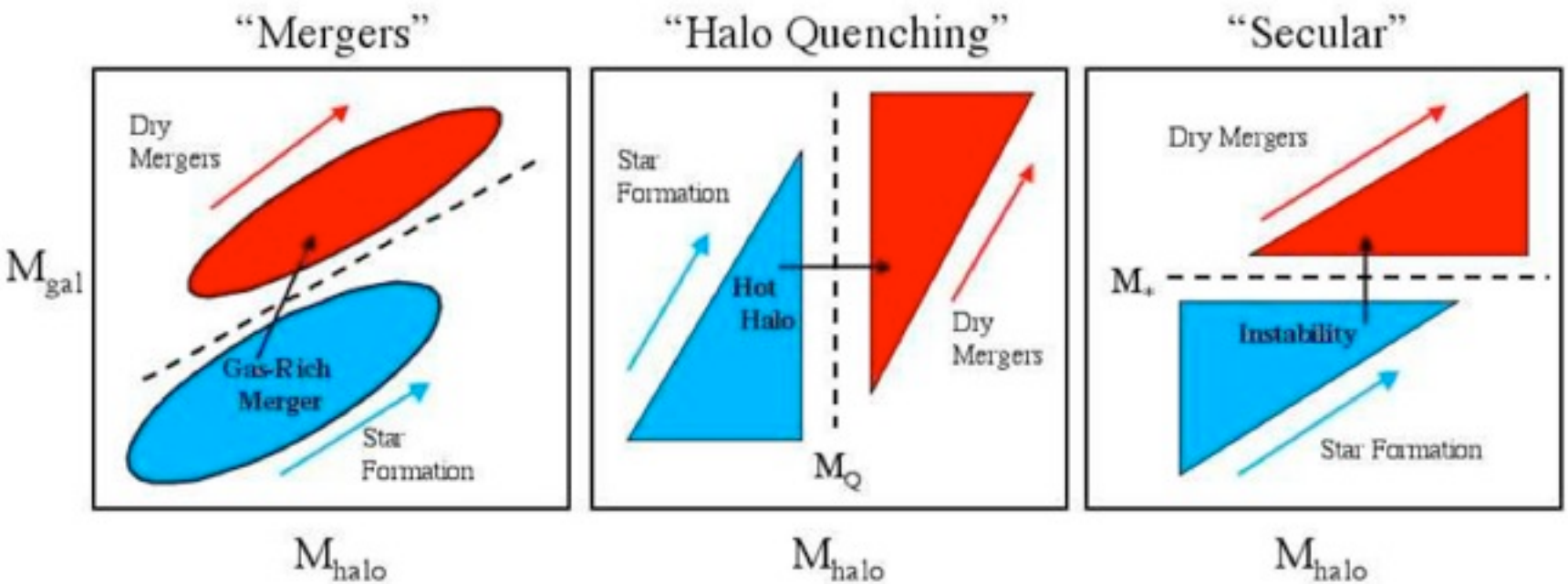
Cattaneo et al.



Lowest-Order Predictions are Fundamentally Non-Unique:

HOW DO WE BREAK THE DEGENERACIES?

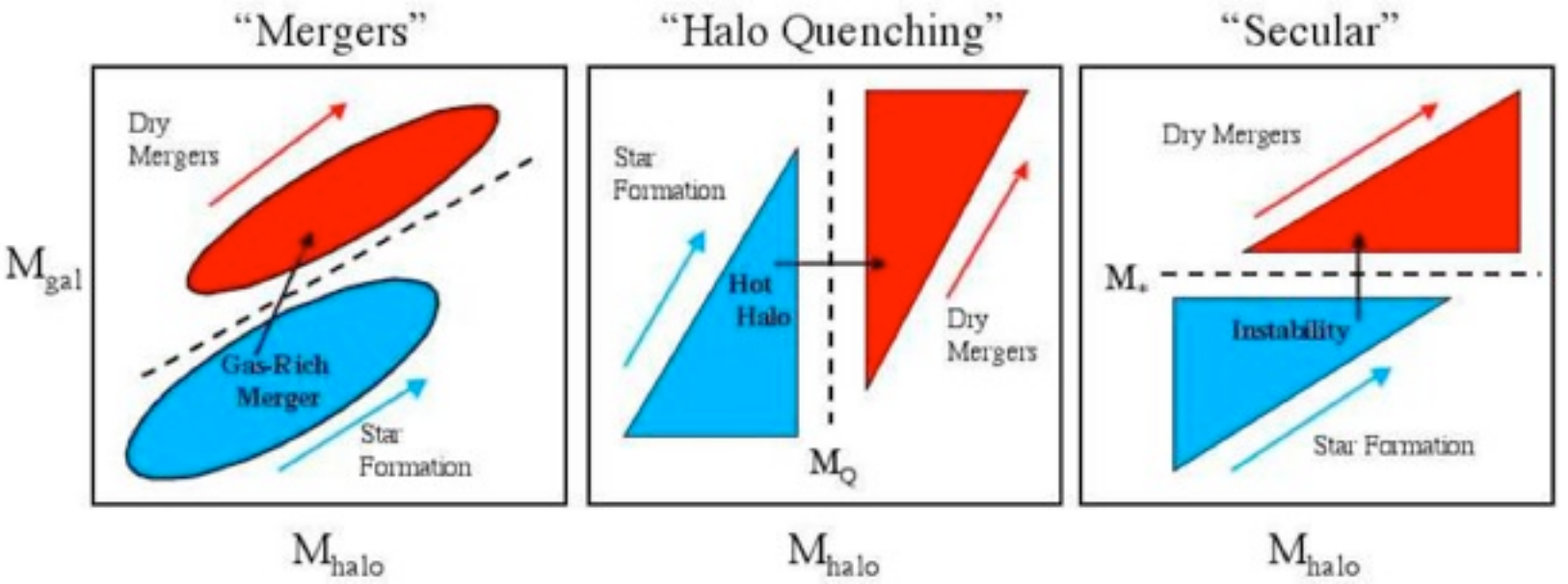
- Identify broad classes of quenching models:

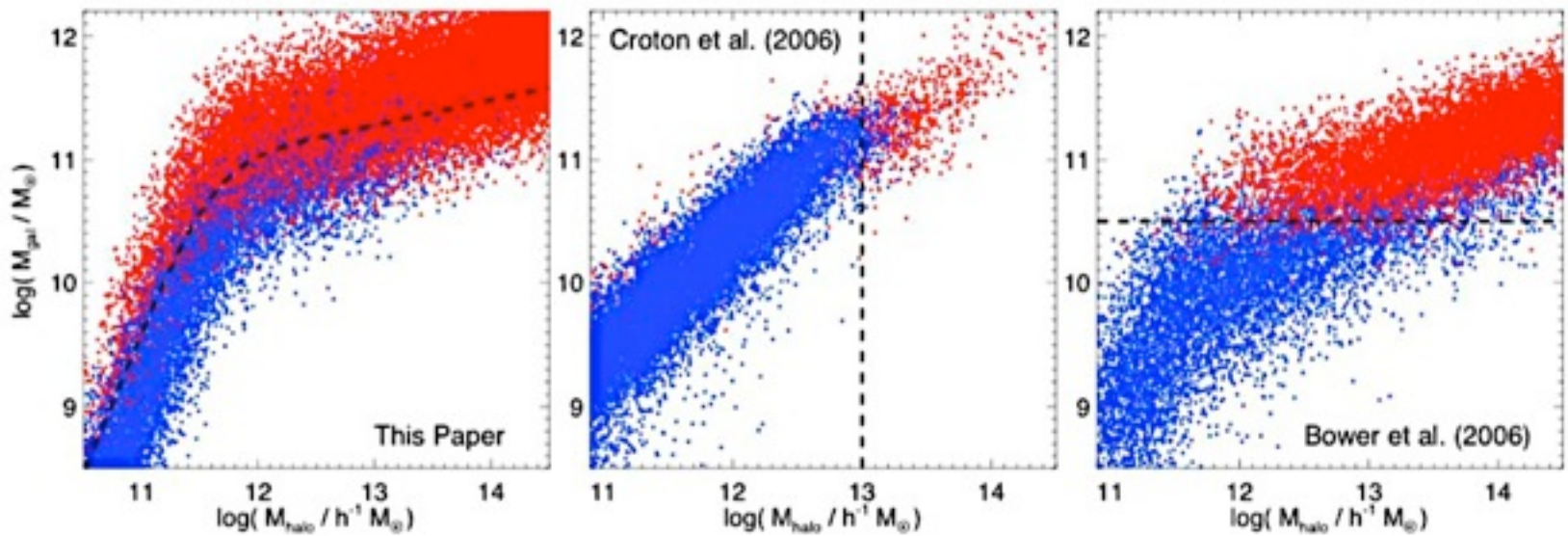


- What are the *unique* predictions of a model in which mergers/ spheroid formation/quasar modes are a key agent in quenching?

Comparing Quenching Models

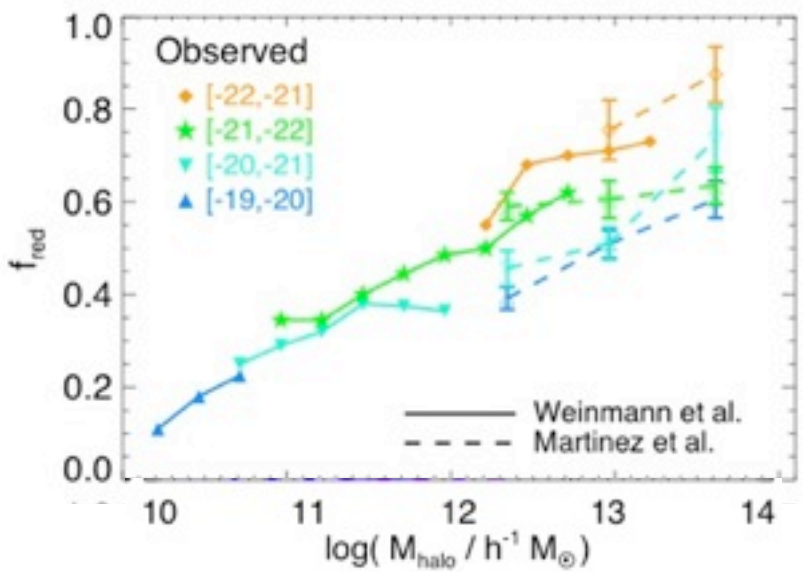
HOW DO WE BREAK THE DEGENERACIES?





Comparing Quenching Models

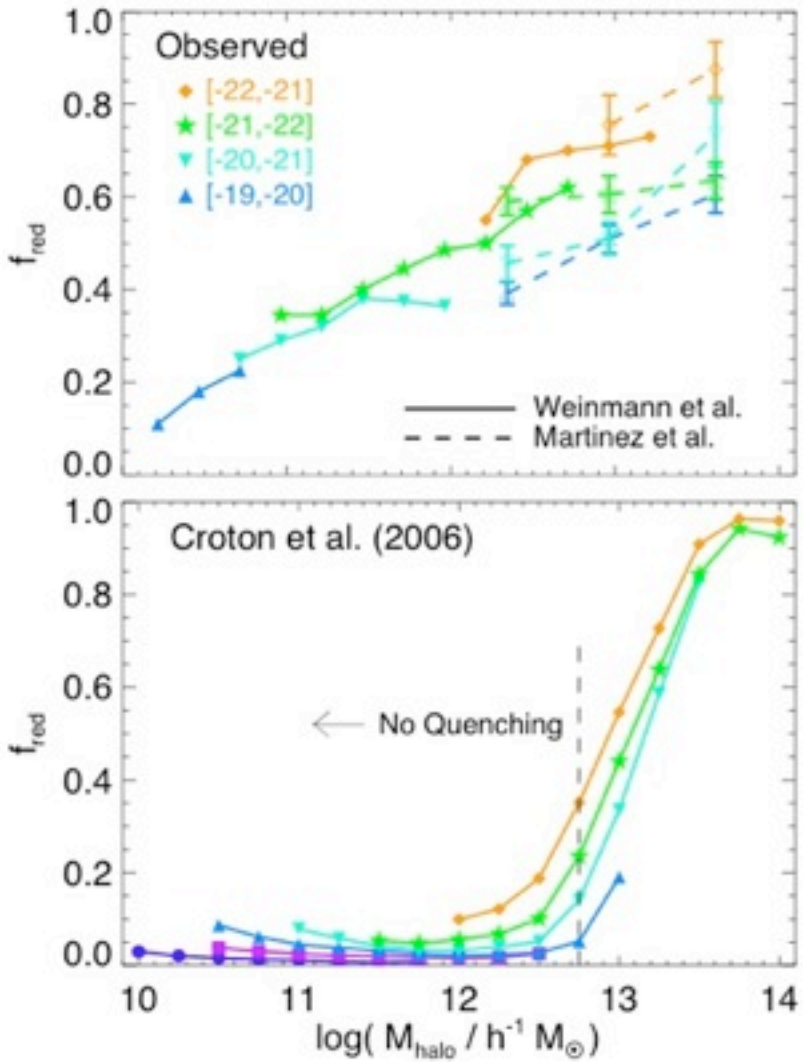
HOW DO WE BREAK THE DEGENERACIES?



- 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

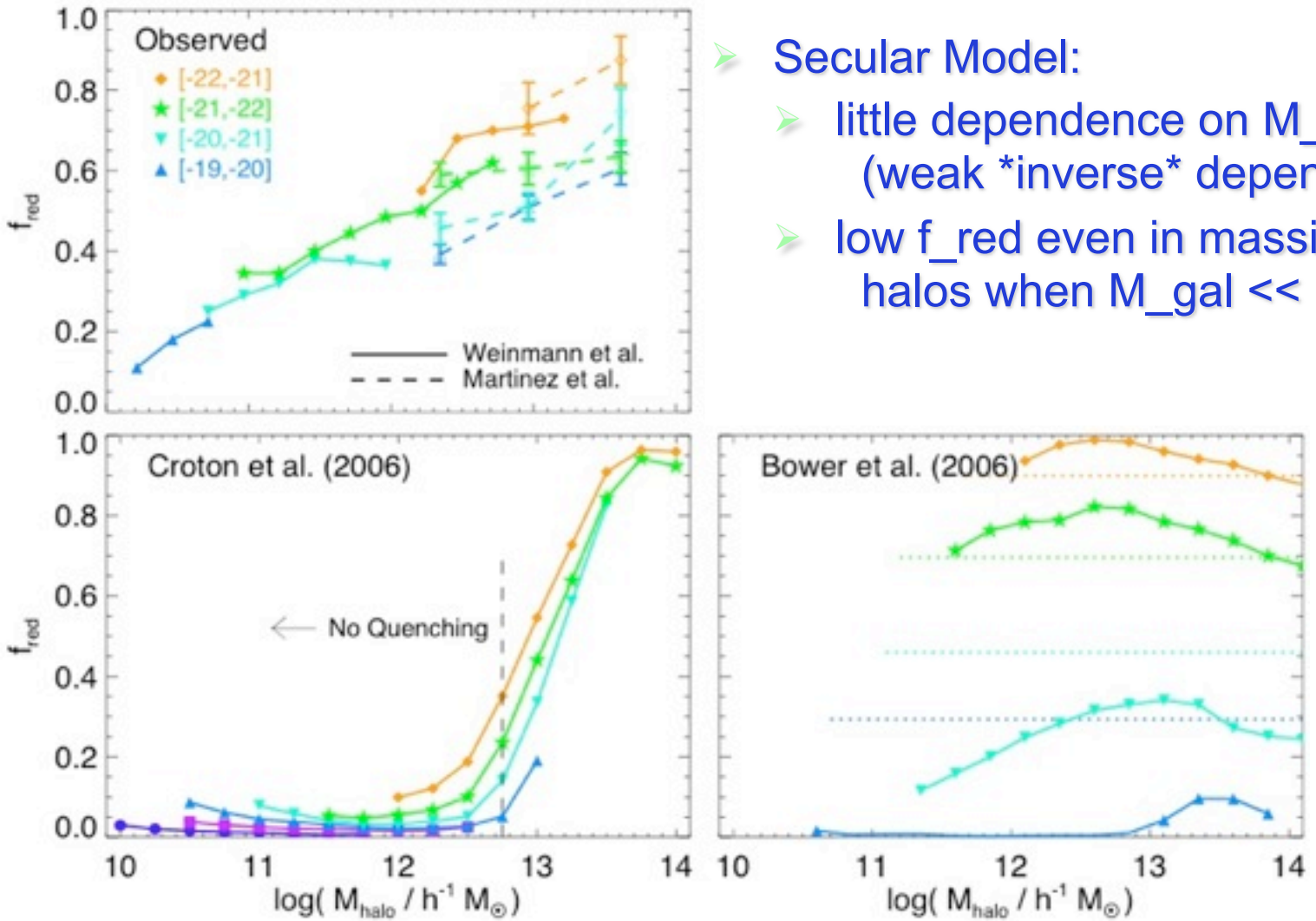
HOW DO WE BREAK THE DEGENERACIES?



- "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?

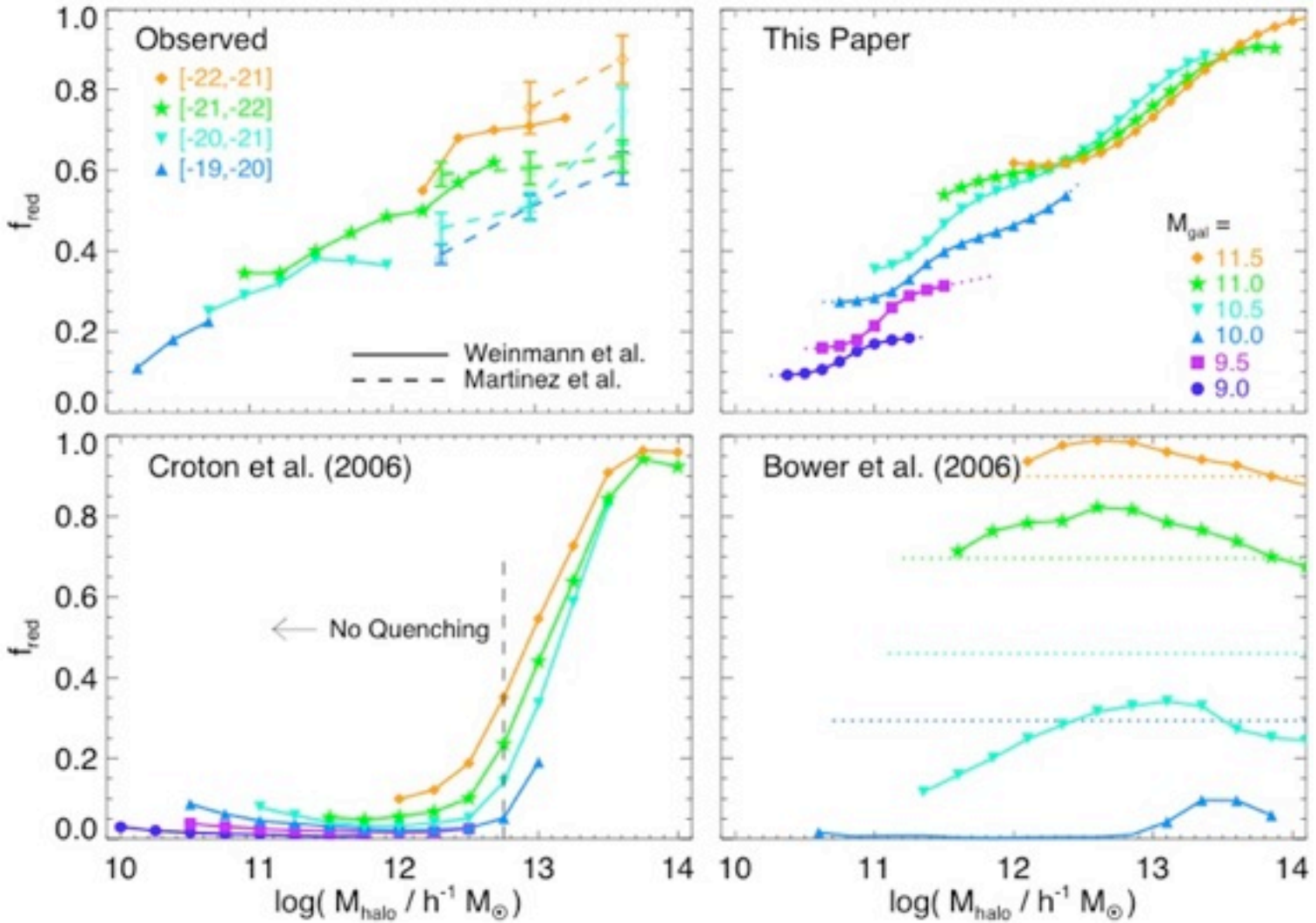


- Secular Model:
  - little dependence on M_halo (weak *inverse* dependence)
  - low f_red even in massive halos when M_gal << M*

Comparing Quenching Models

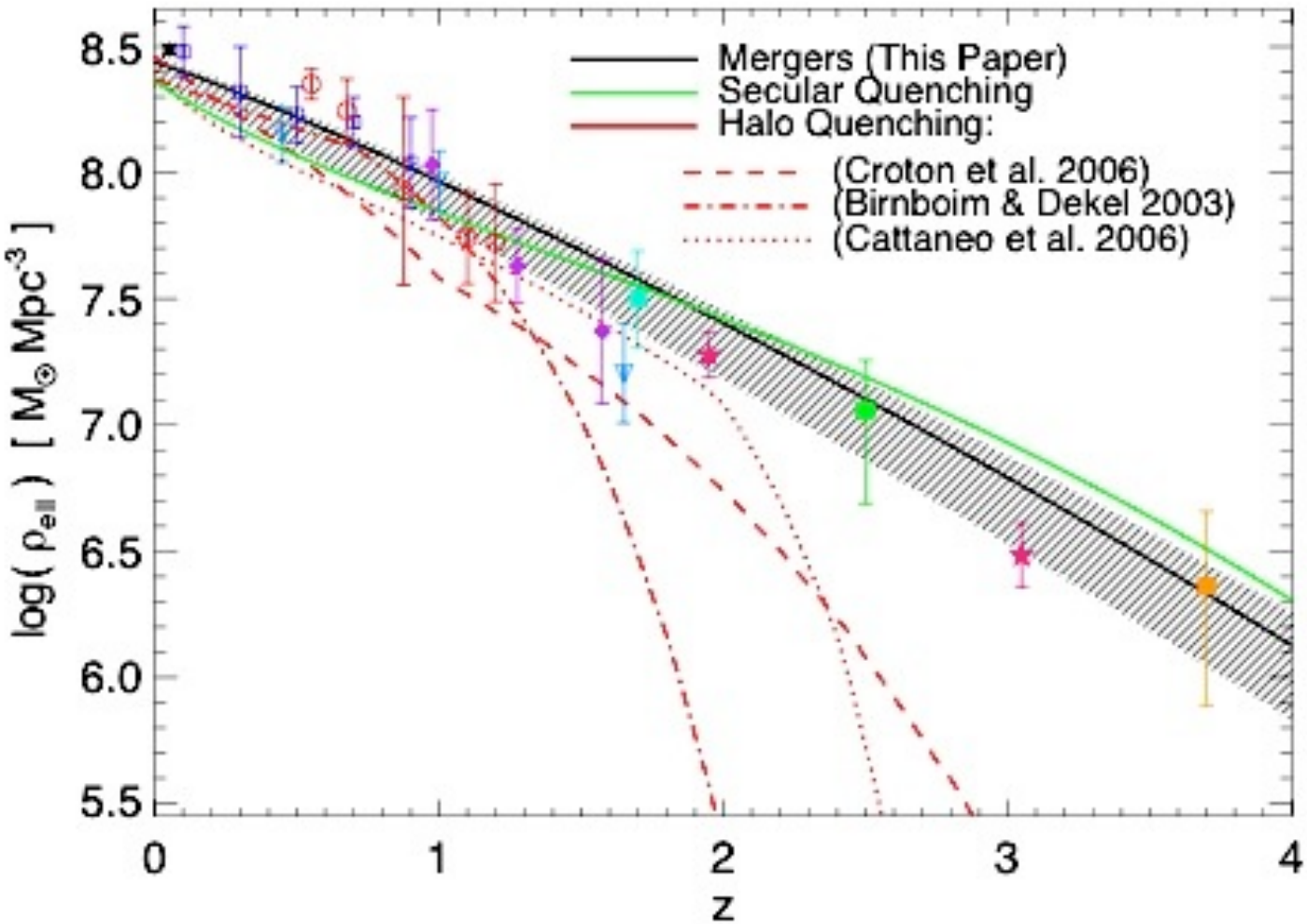
HOW DO WE BREAK THE DEGENERACIES?

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



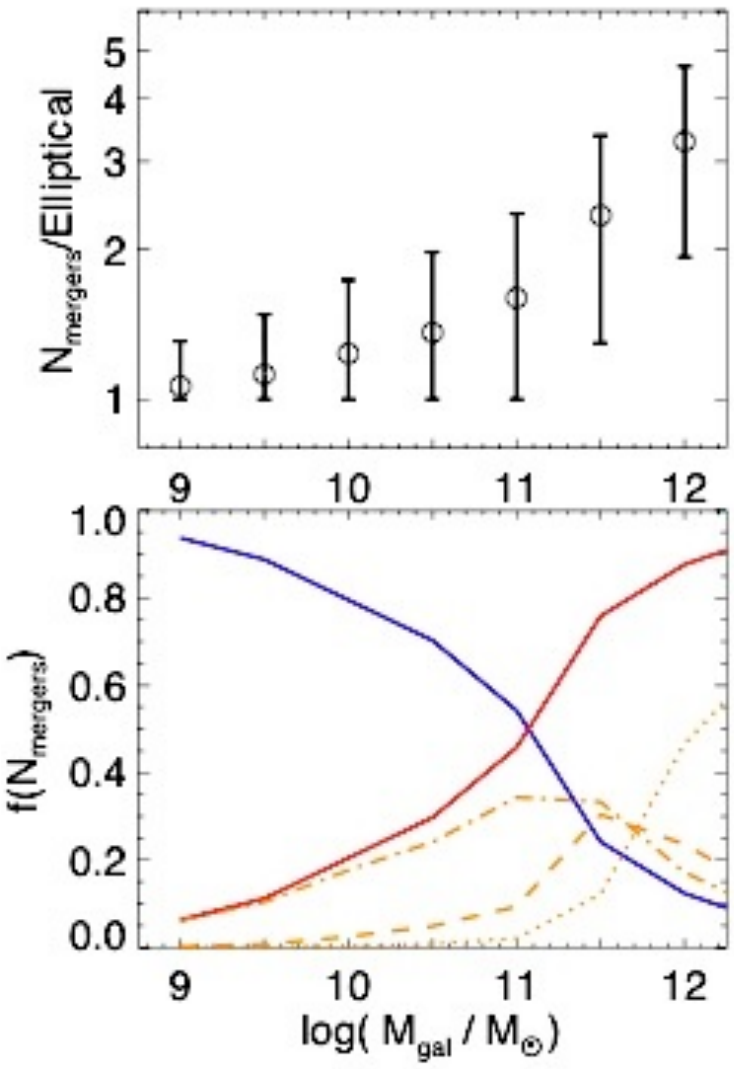
Comparing Quenching Models

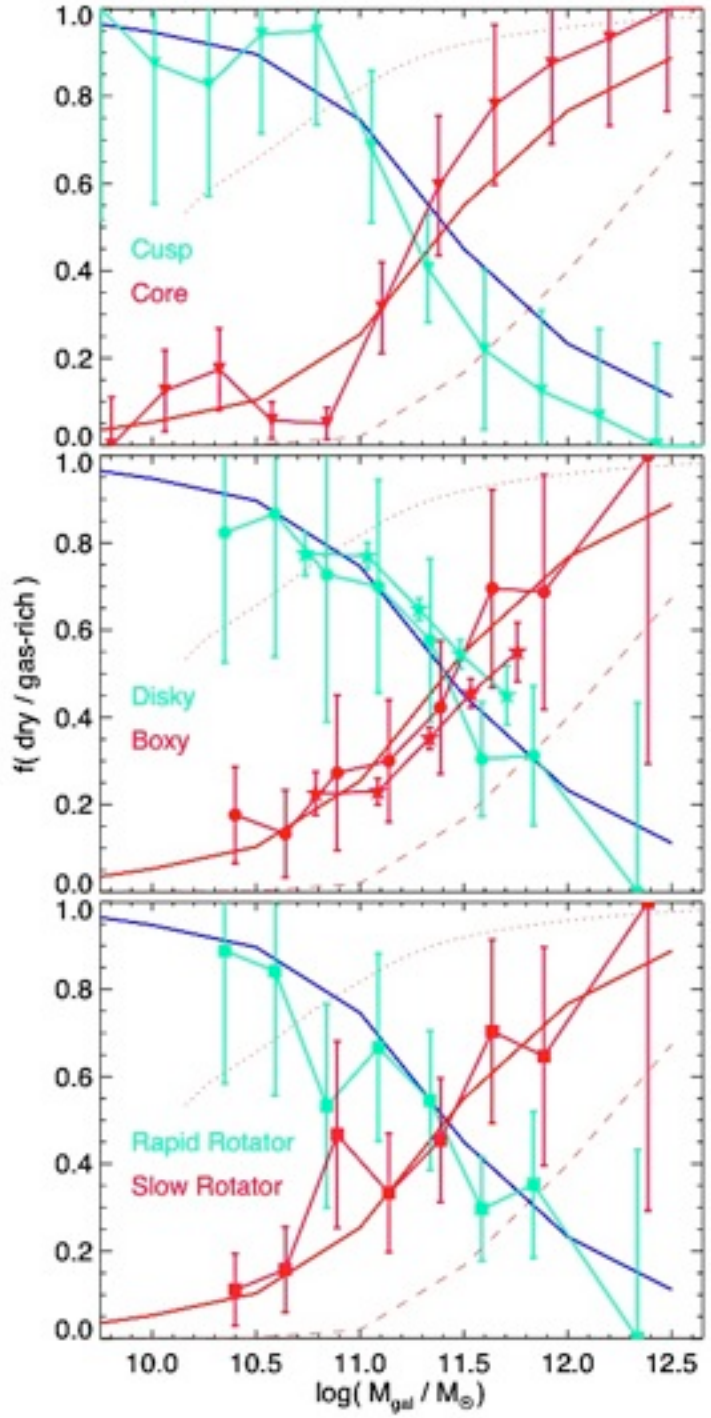
HIGH-REDSHIFT PASSIVE GALAXIES



Comparing Quenching Models

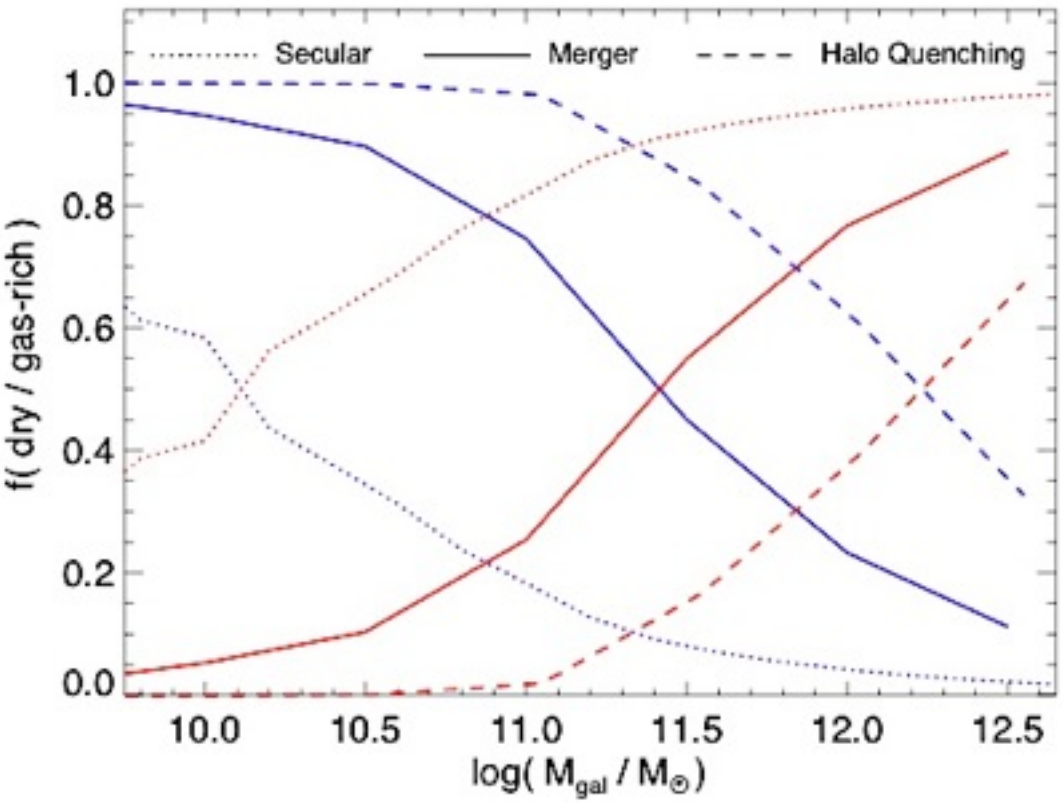
DICHOTOMY IN ELLIPTICAL KINEMATICS

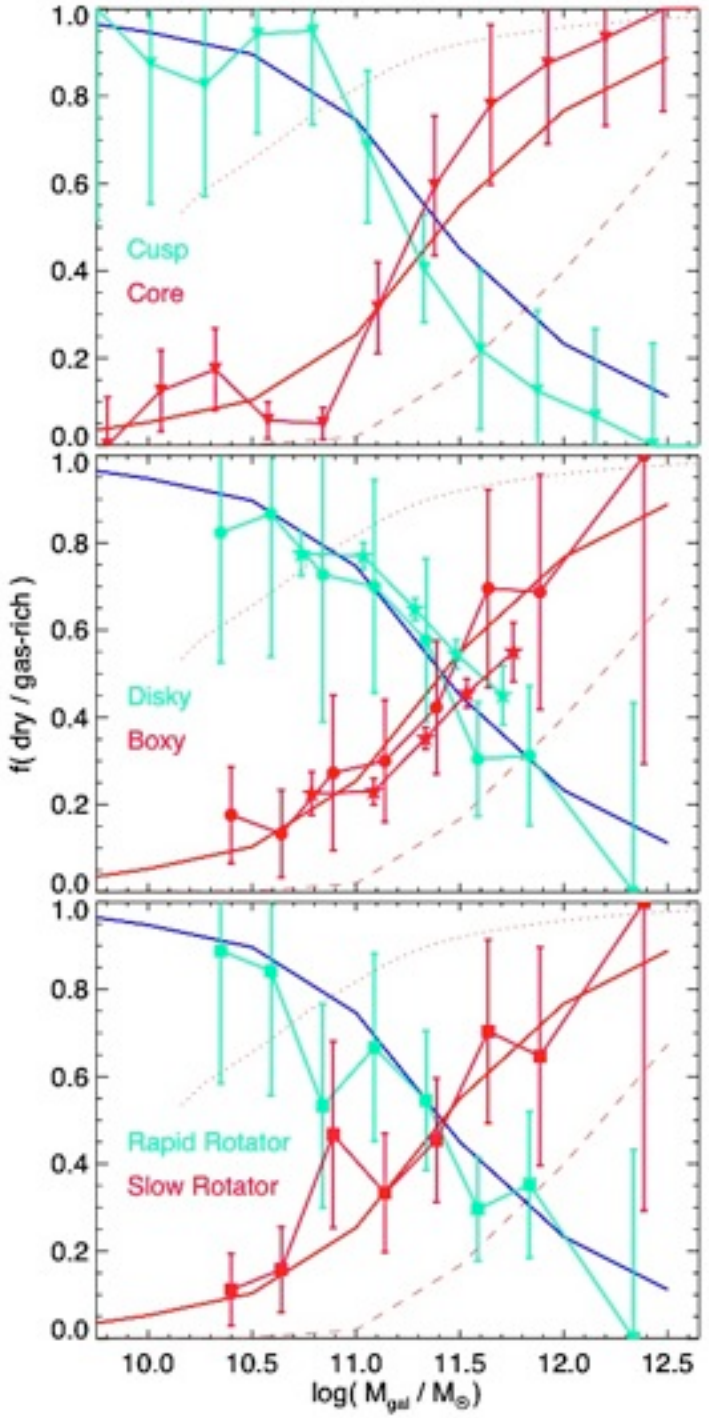




Comparing Quenching Models

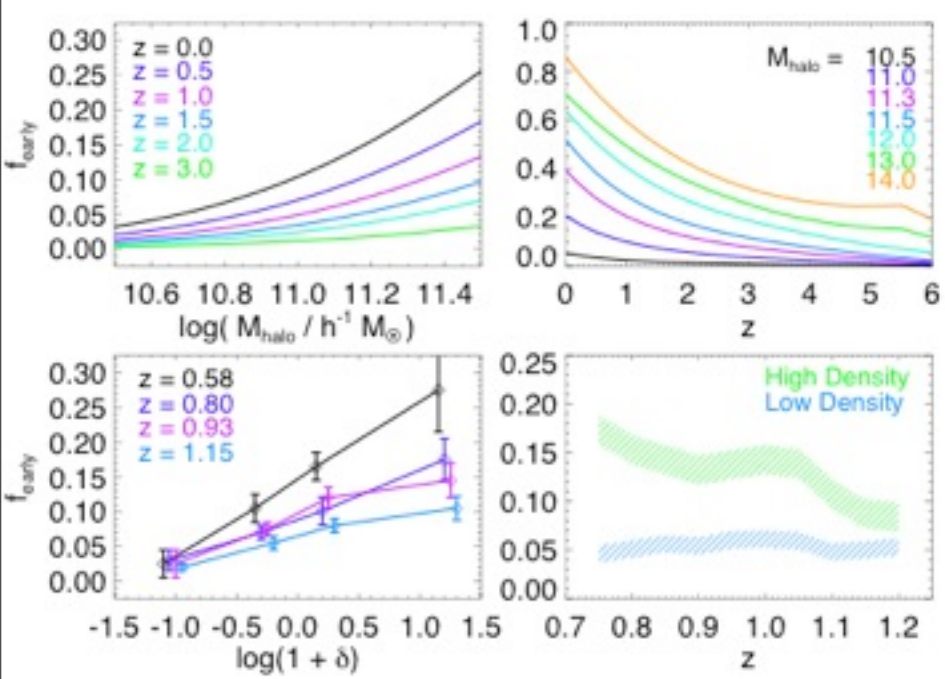
DICHOTOMY IN ELLIPTICAL KINEMATICS

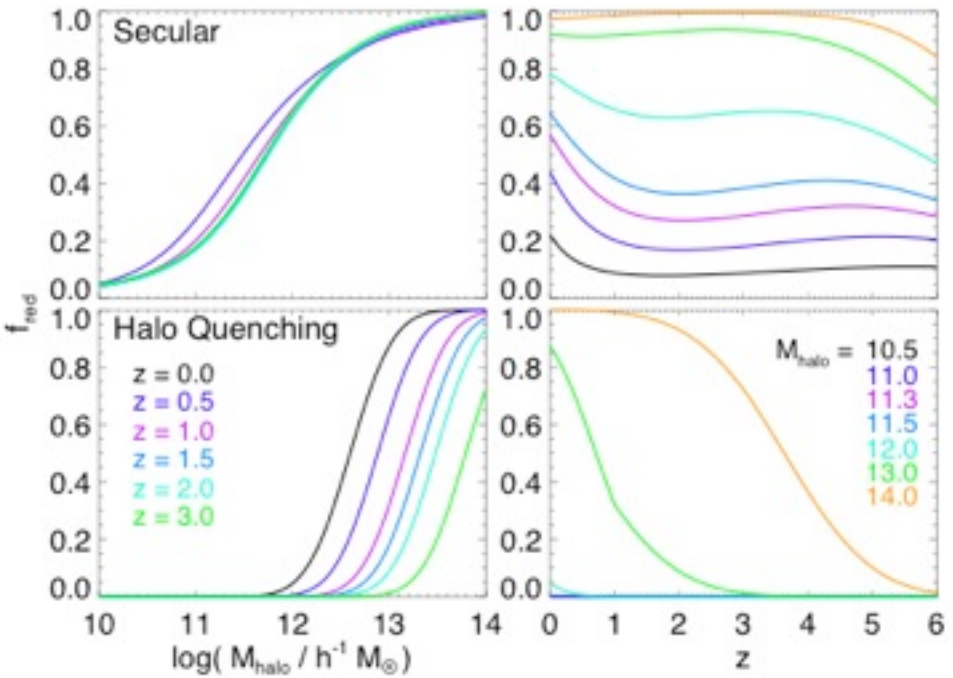




Comparing Quenching Models

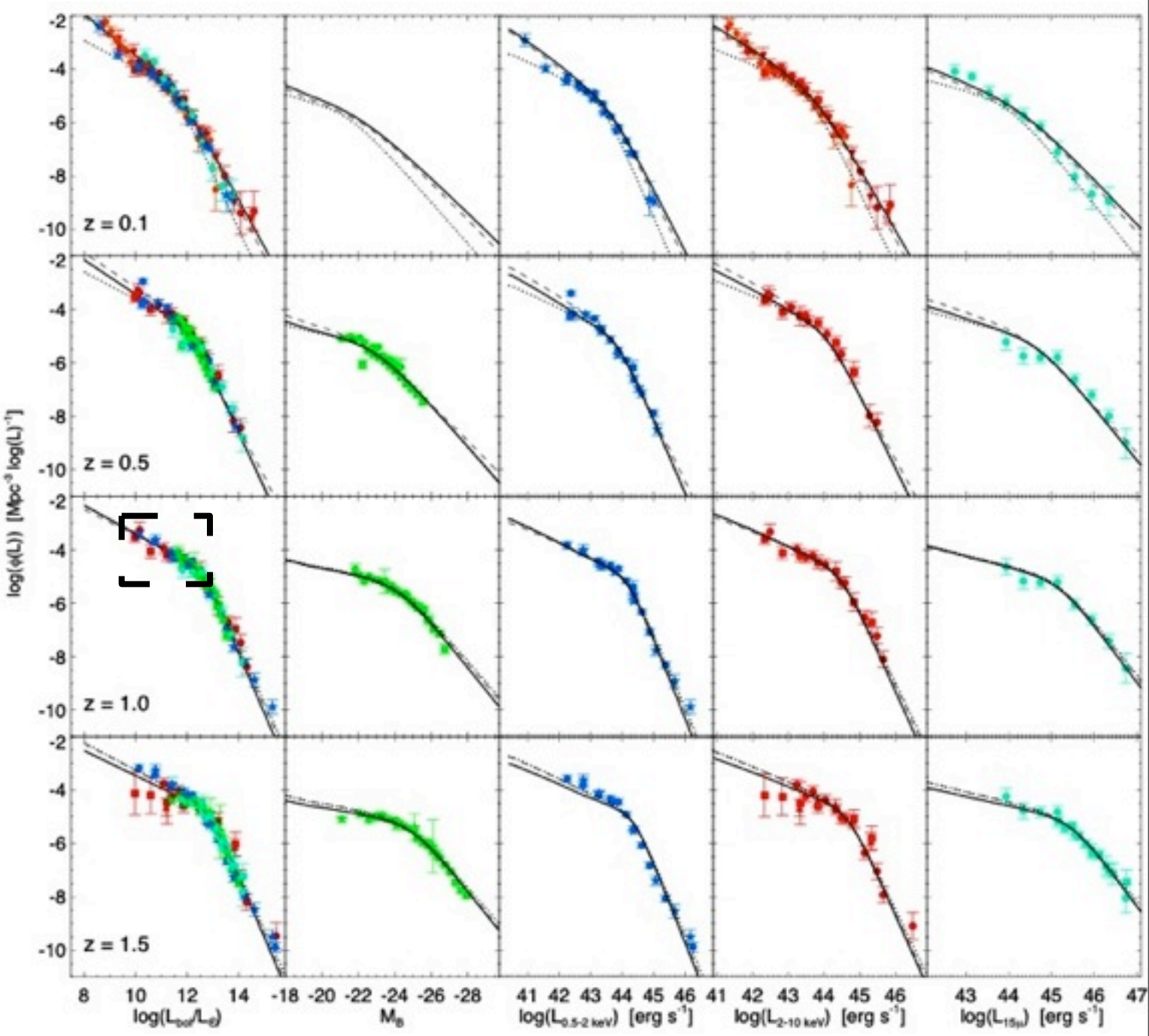
COLOR-MORPHOLOGY-DENSITY RELATION EVOLUTION





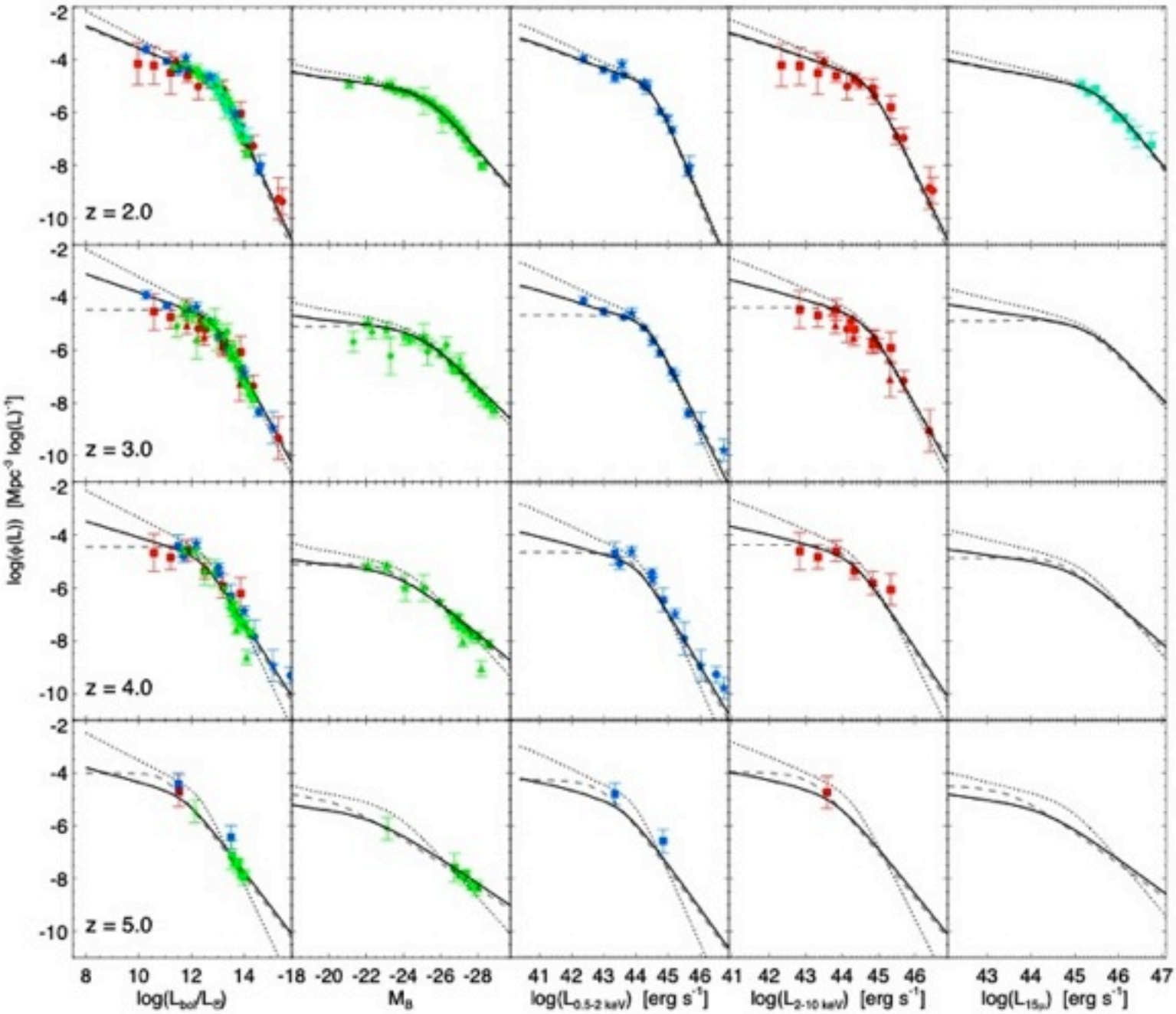
LF vs. Redshift

UV THROUGH IR



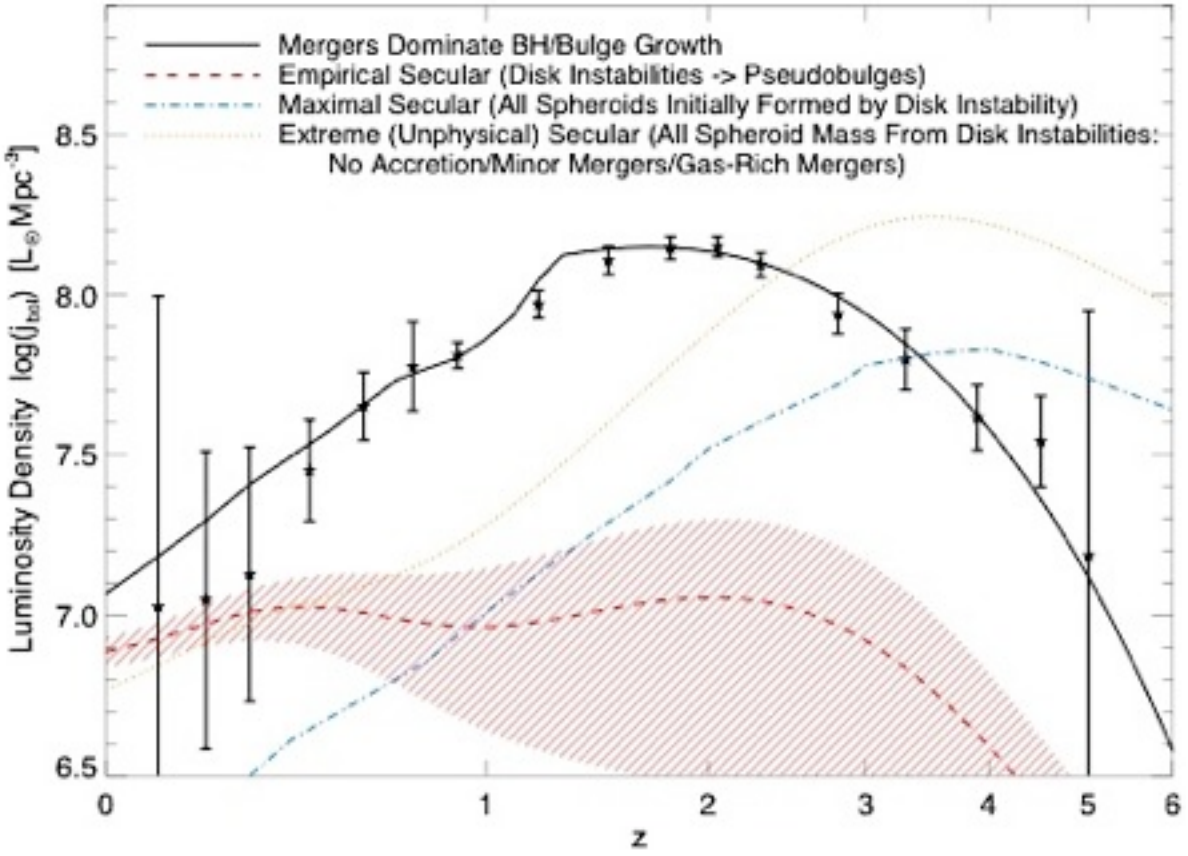
LF vs. Redshift

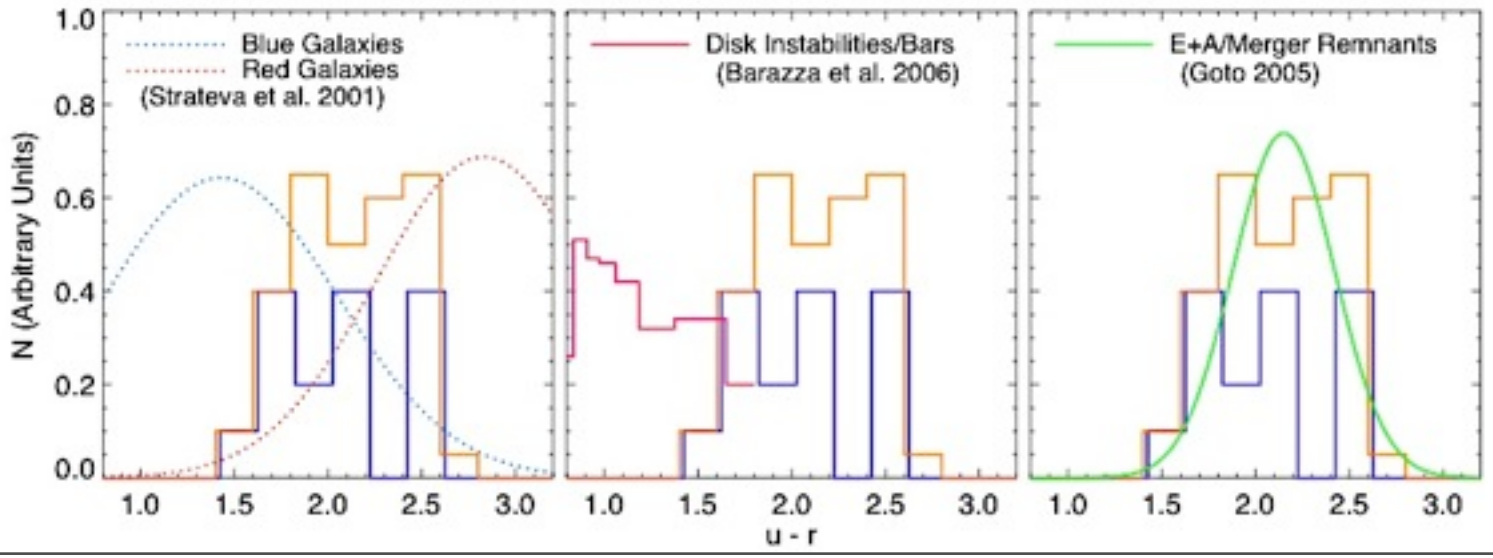
UV THROUGH IR



LF vs. Redshift

UV THROUGH IR





Comparing Quenching Models

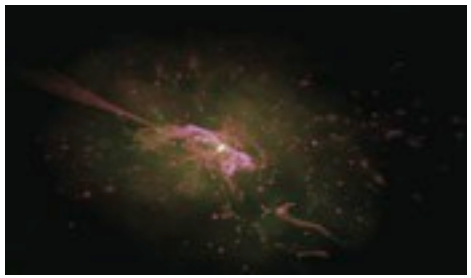
SUMMARY

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

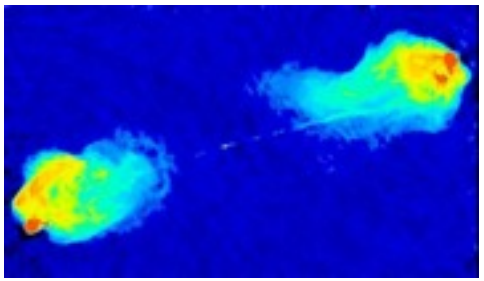
- But, how is quenching over a Hubble time accomplished by a single, potentially high redshift gas-rich major merger?

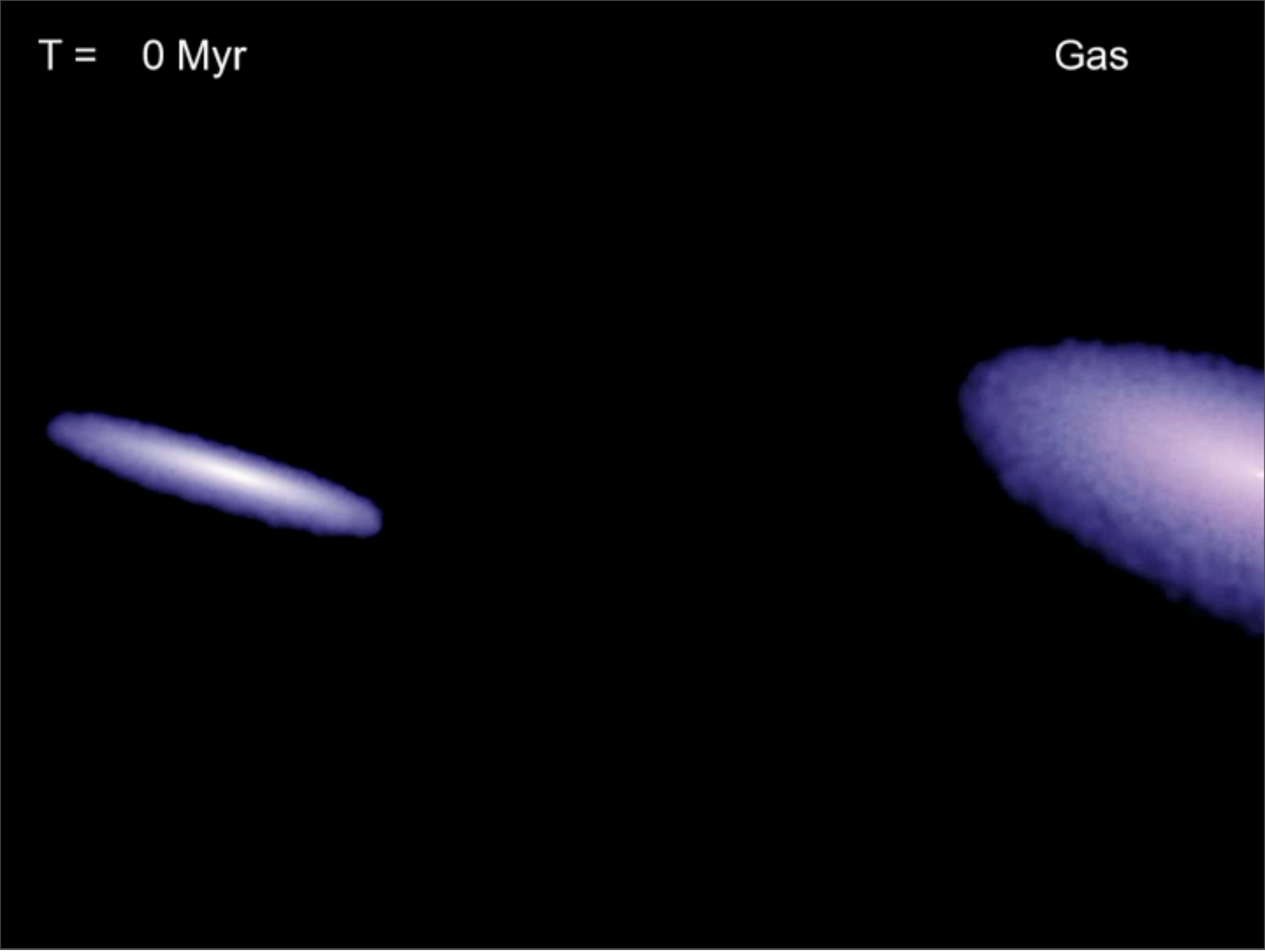
“Transition” vs. “Maintenance”

- 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?

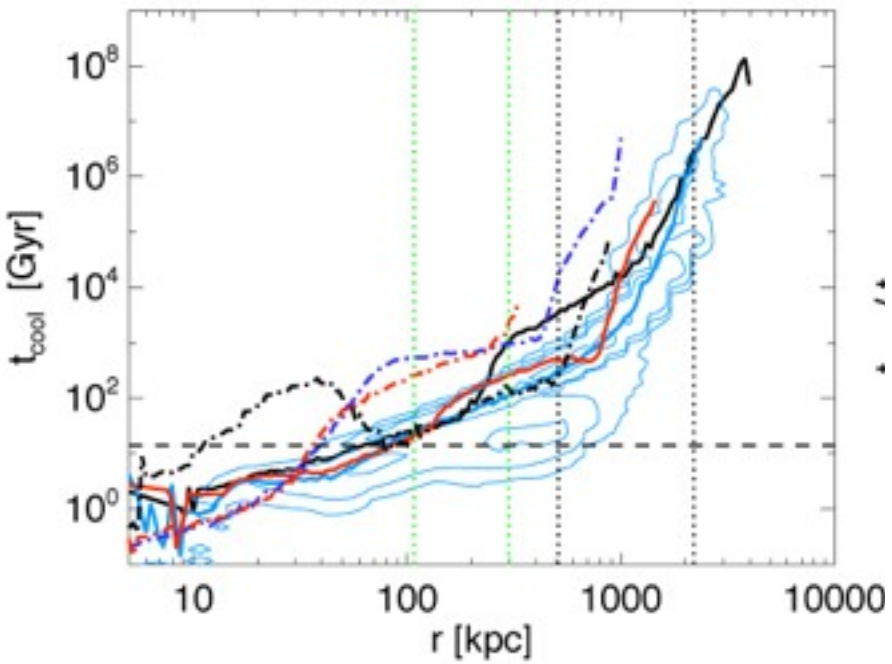



T = 0 Myr
Gas

How Could Mergers Be Associated with “Maintenance”?

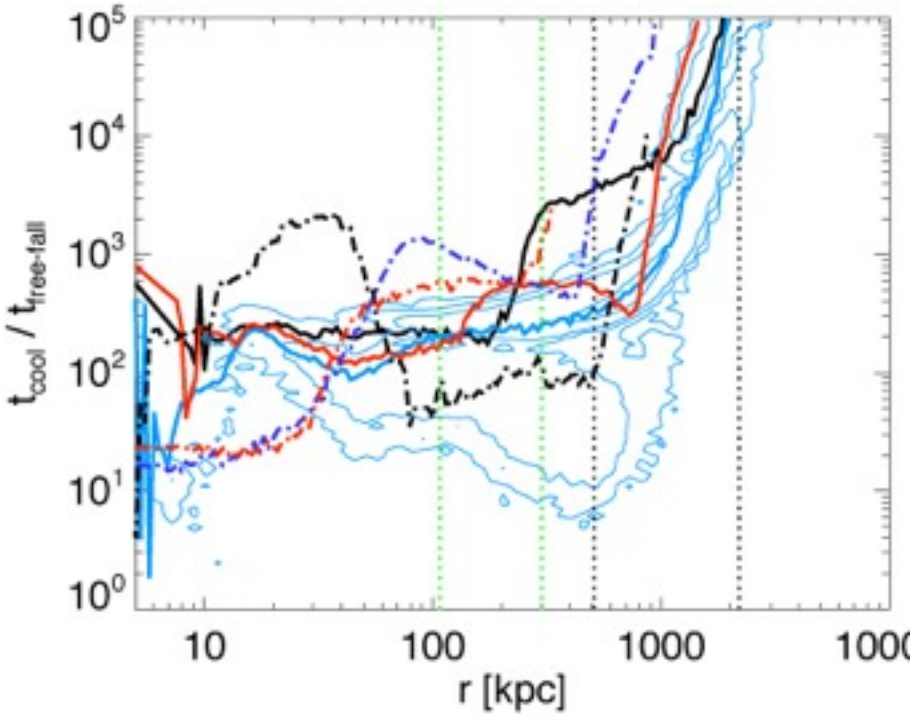
- (1) “Complete” quenching from a single event
  - energetics might be ok...
  - high redshifts: densities larger, cooling in filaments
  - can it really work for a Hubble time?

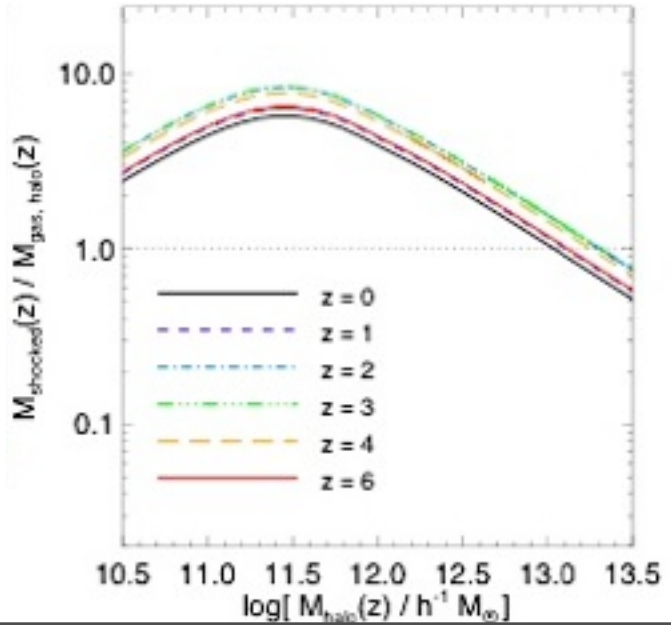
- (2) Buying time
  - expel cold gas at the end of the merger
  - heat remaining gas to much larger t_cool
  - only need ~couple Gyr to “naturally” develop a hot halo
  - still needs “radio mode” when that hot halo is formed



How Could Mergers Be Associated with “Maintenance”?

- (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
  - just gives a “head start” to the traditional hot halo accretion shock





Summary

- Models where merger history drives 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

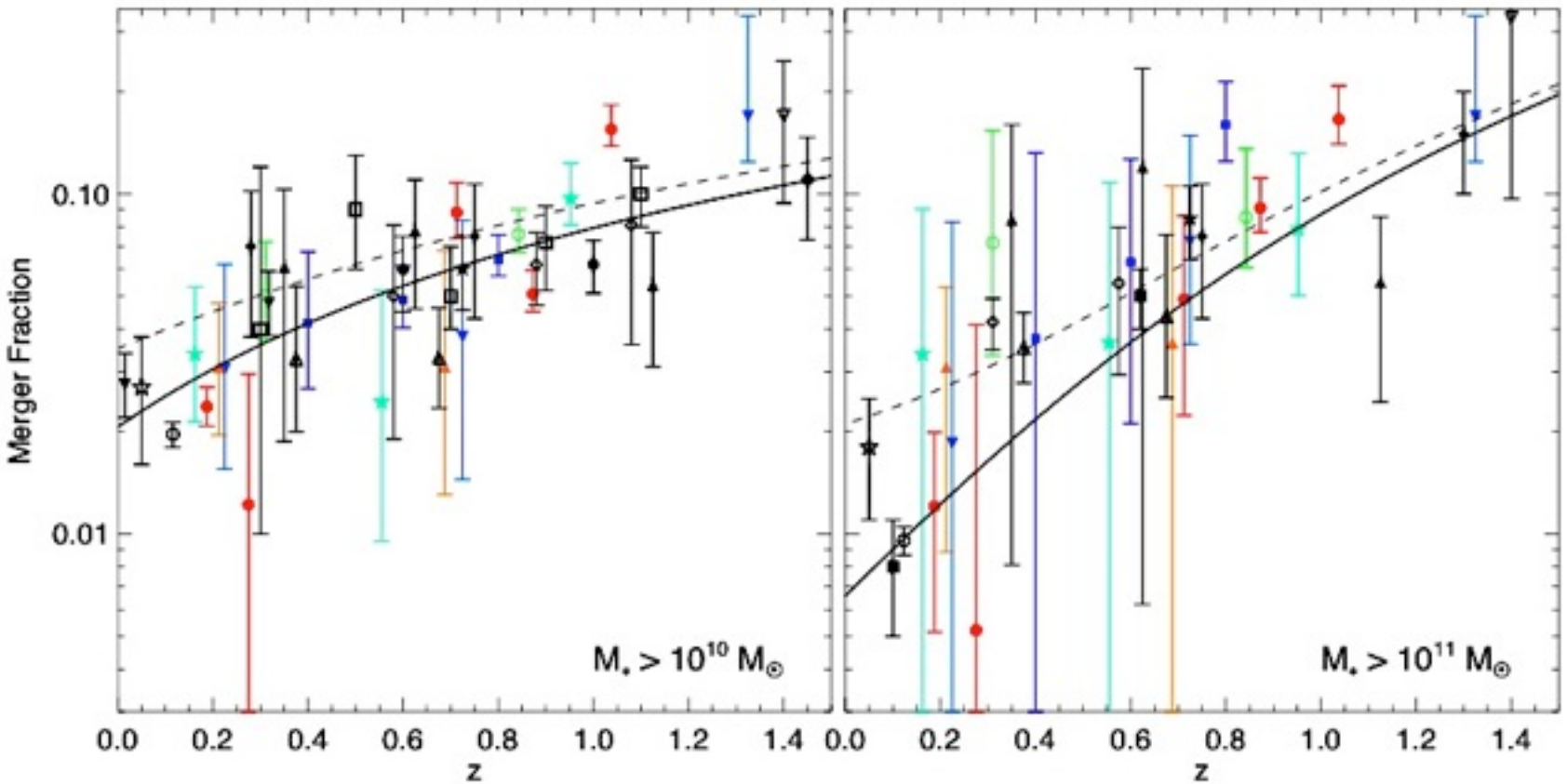
- Mergers work *with* hot halos
  - Buy time for hot halos to develop
  - Directly shock low-mass systems to “hot halo” mode

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

Motivation

CIRCUMSTANTIAL EVIDENCE

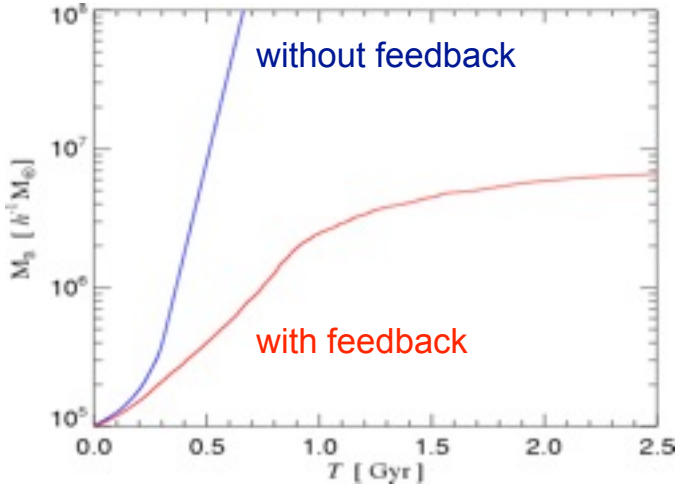
Bell+06; Lotz+06; Lin+04;
Patton+02; Conselice+03



Hopkins, Bundy+ 06

The Role of "Quasar" Feedback

CORRELATION VS. CAUSALITY?

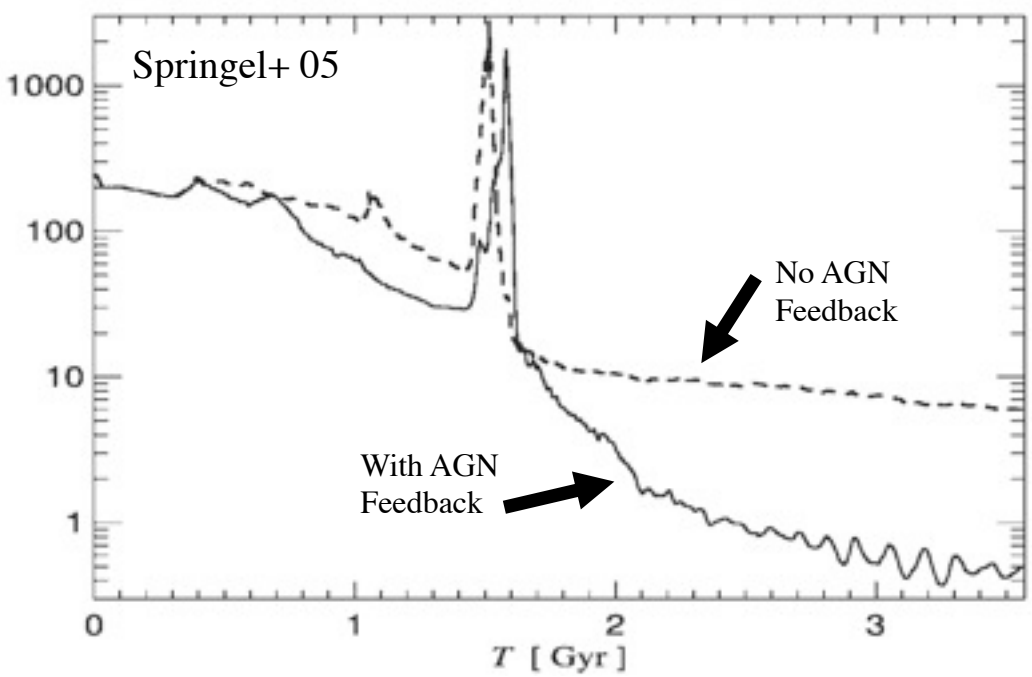


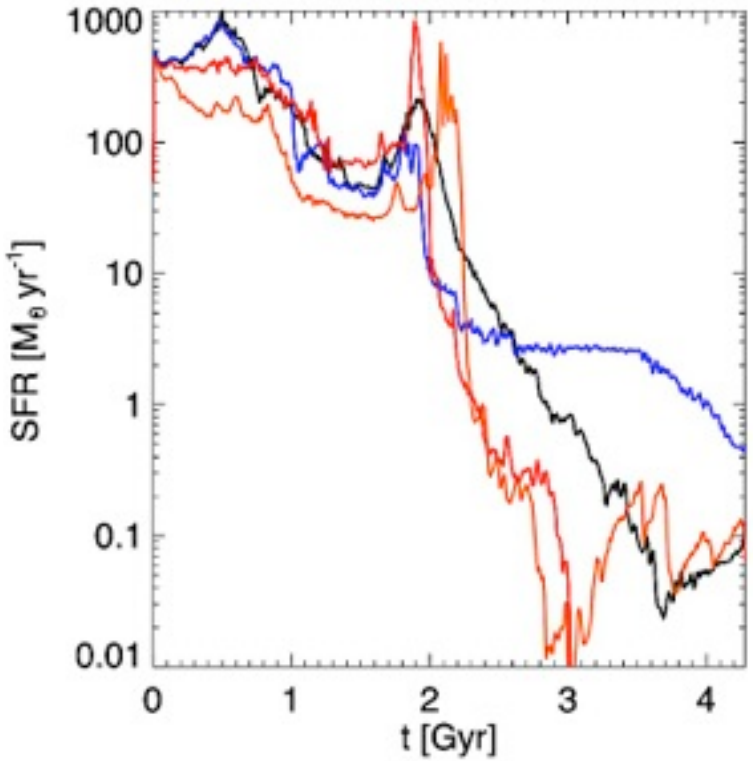
(see also Fontanot+ 06; Volonteri+ 06)

"Quasar" feedback *must* exist...

...and it *does* exist

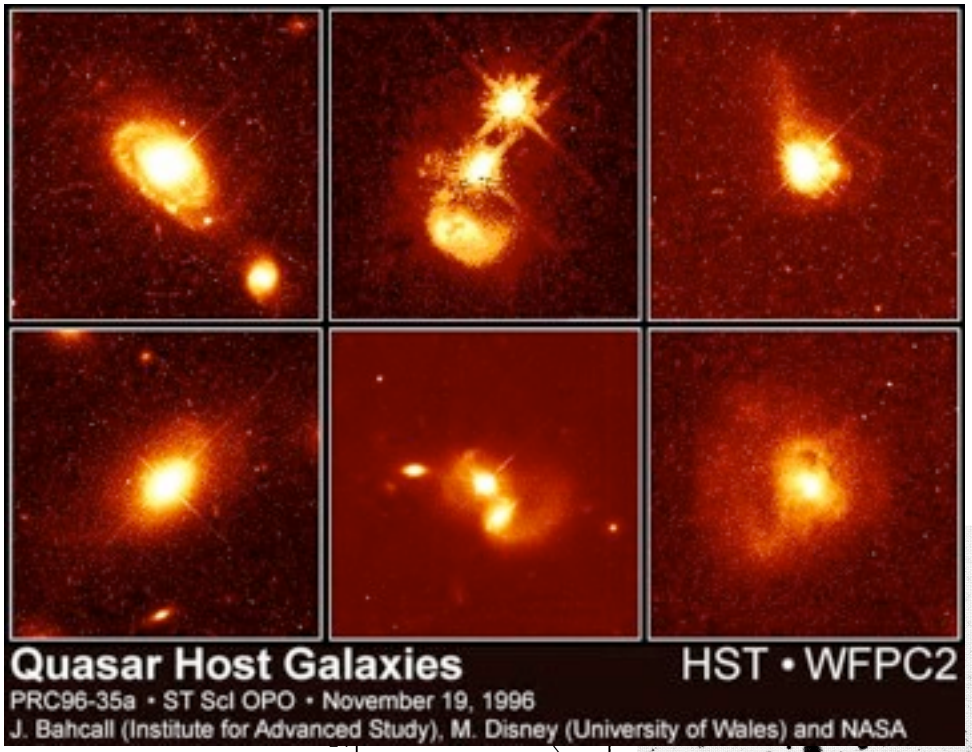
(but on what level?)





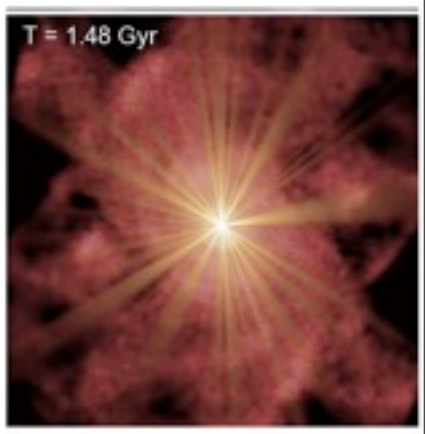
Feedback Reveals the Brightest Quasars

GAS IS HEATED AND EXPELLED IN BLOWOUT, REVEALING A BRIEF, BRIGHT QUASAR

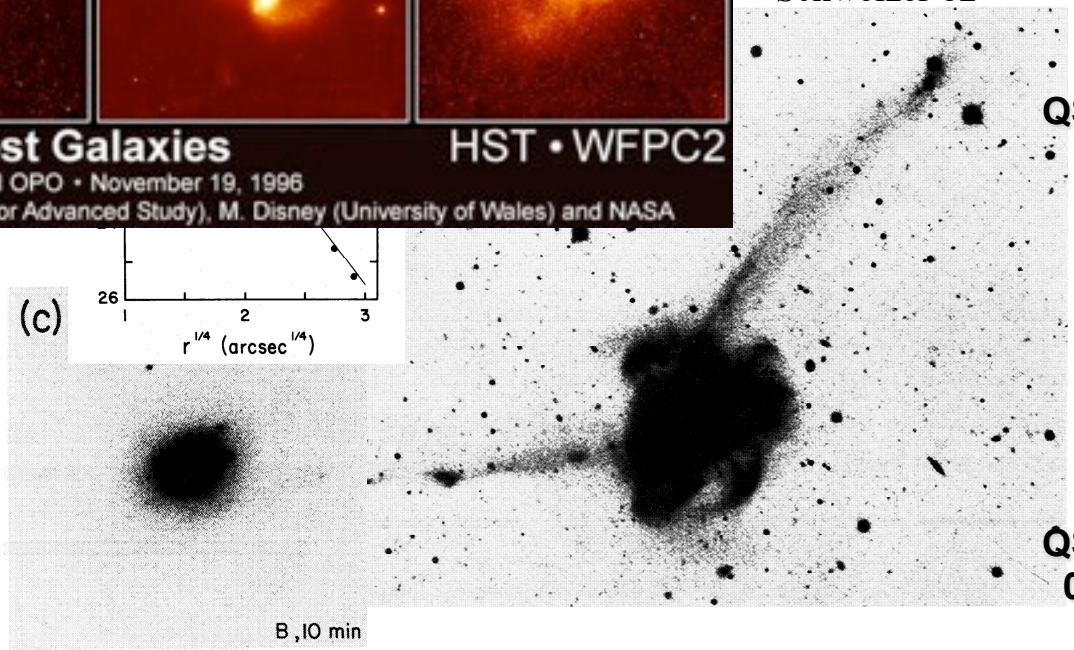


Bahcall+ 97

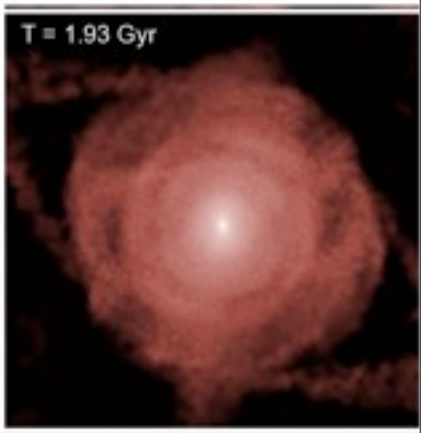
QSO = 1000xHost



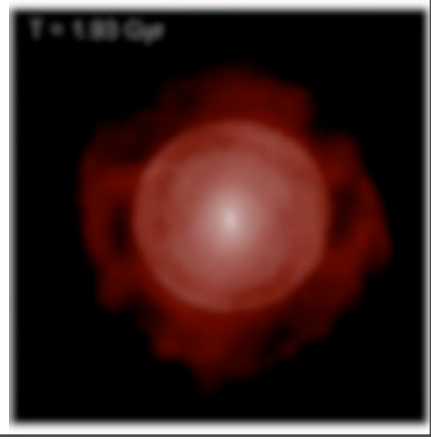
Schweizer 82



QSO = Host



QSO = 0.1xHost

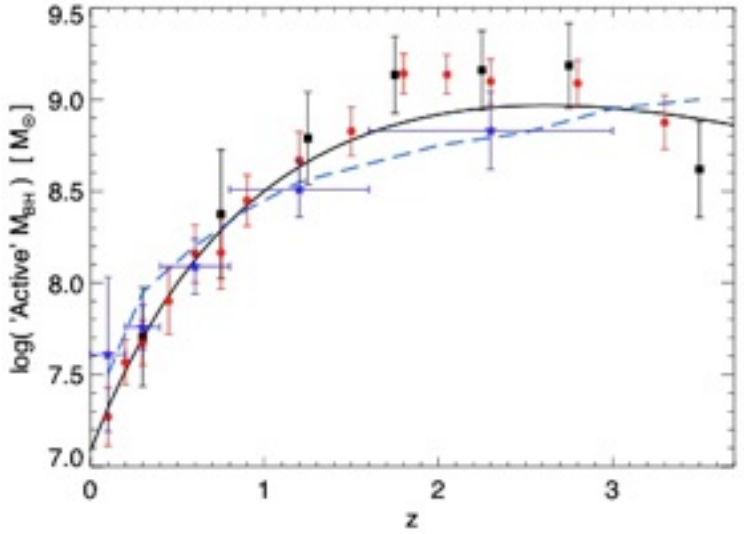


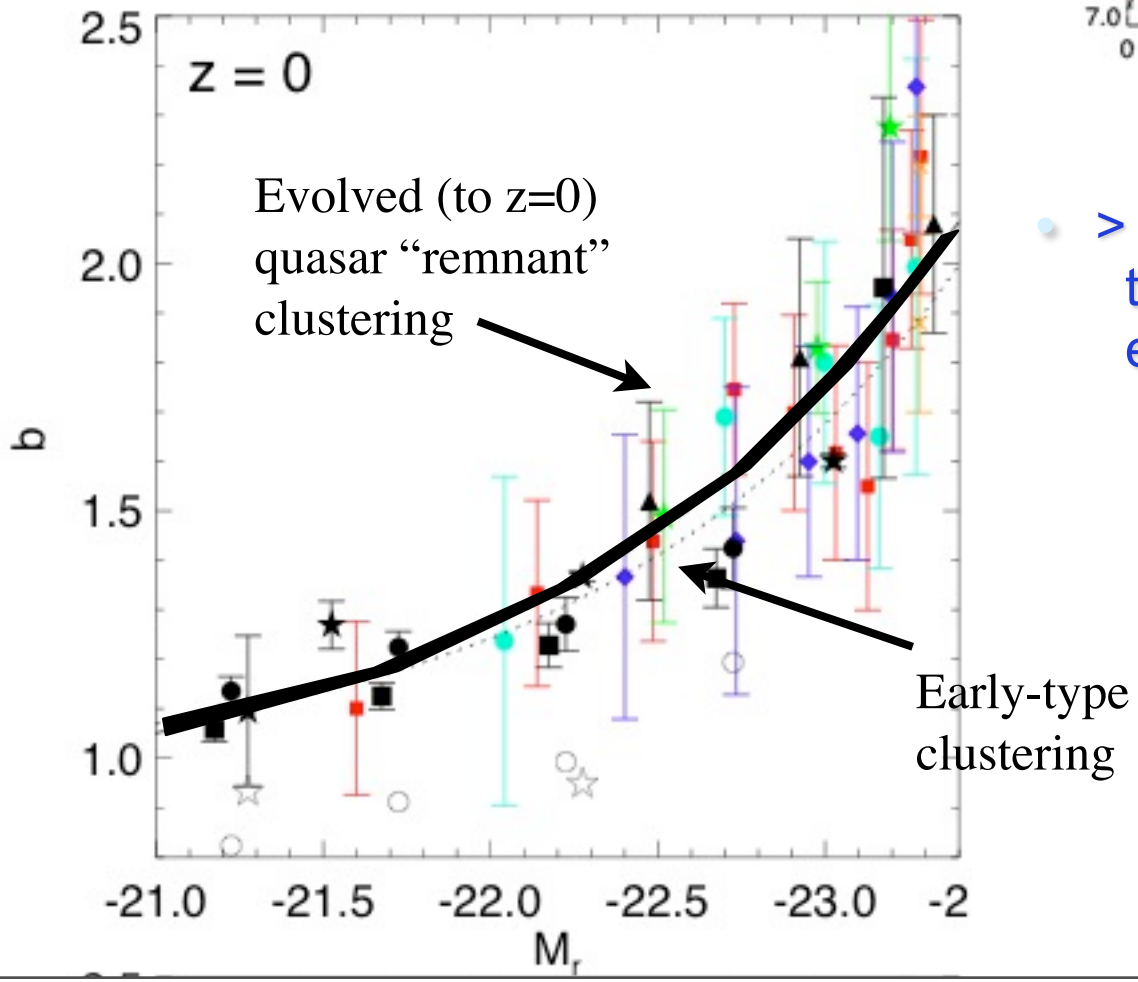
- Why can't we just look for the mergers? (see Jennifer Lotz's talk also!)

What Do We Learn?

WHAT DOES THIS TELL US ABOUT MASSIVE GALAXY FORMATION?

- > Know quasar clustering(z) & z=0 hosts of these BHs:

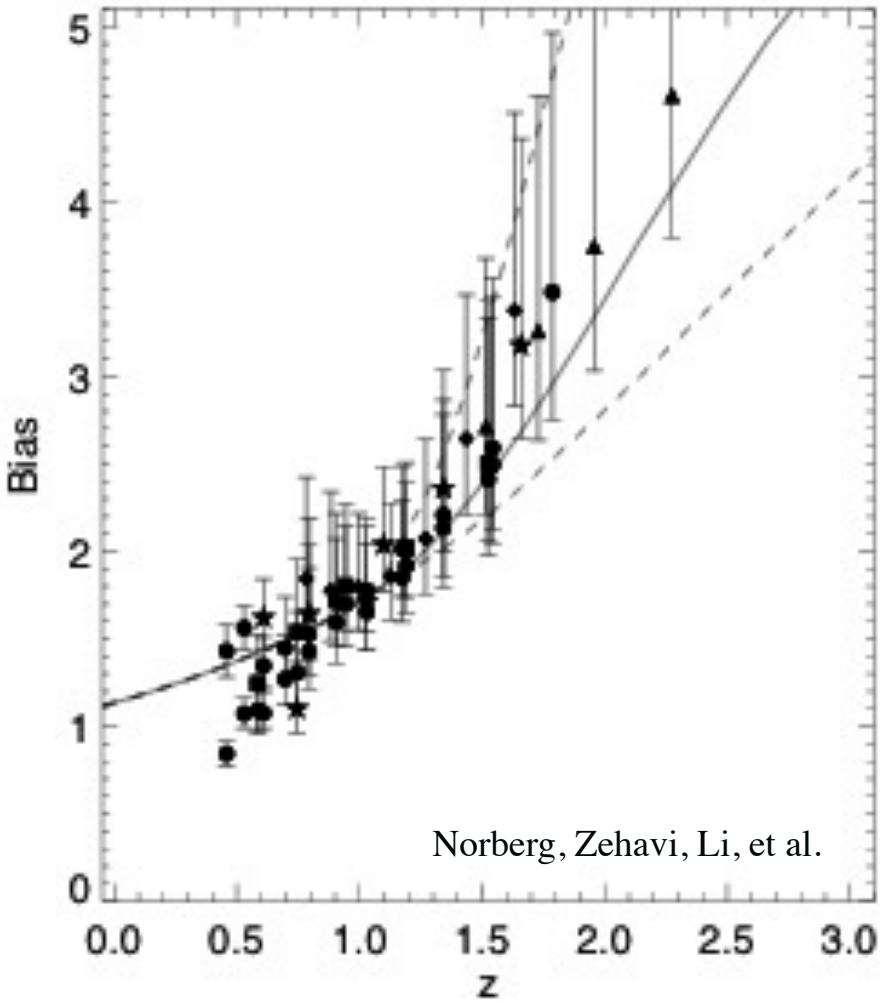




- > Quasars really *are* the progenitors of local early-type galaxies

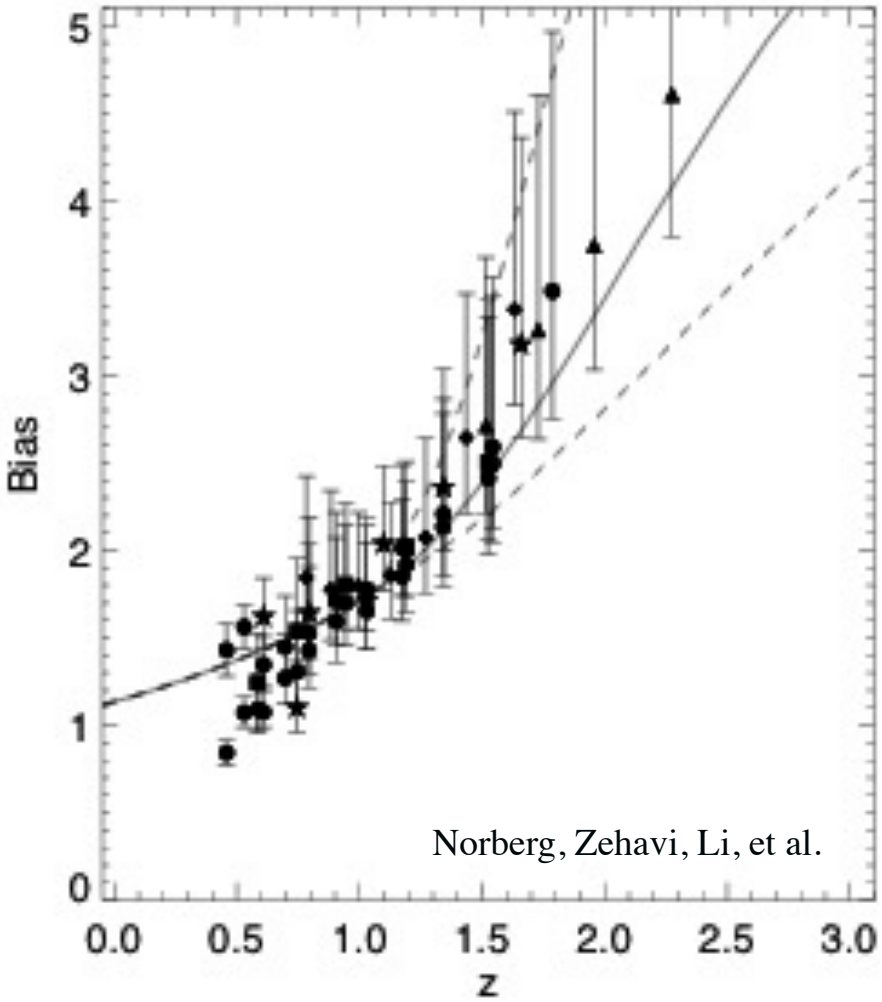
Hopkins, Coil, Myers, Lidz, et al.

Is the “Quasar” Epoch Really Coincident with the End of Star Formation?

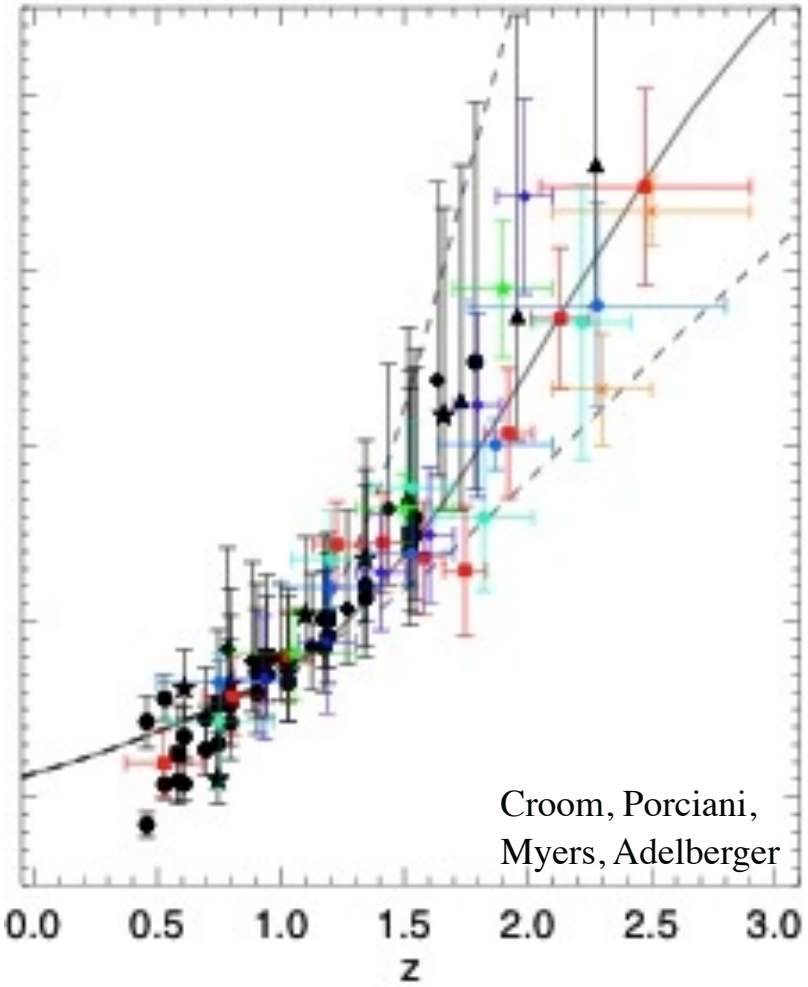


Local Early-Type Clustering, Extrapolated to the Star-Formation Time for each M_gal

Is the “Quasar” Epoch Really Coincident with the End of Star Formation?



Local Early-Type Clustering, Extrapolated to the Star-Formation Time for each M_gal

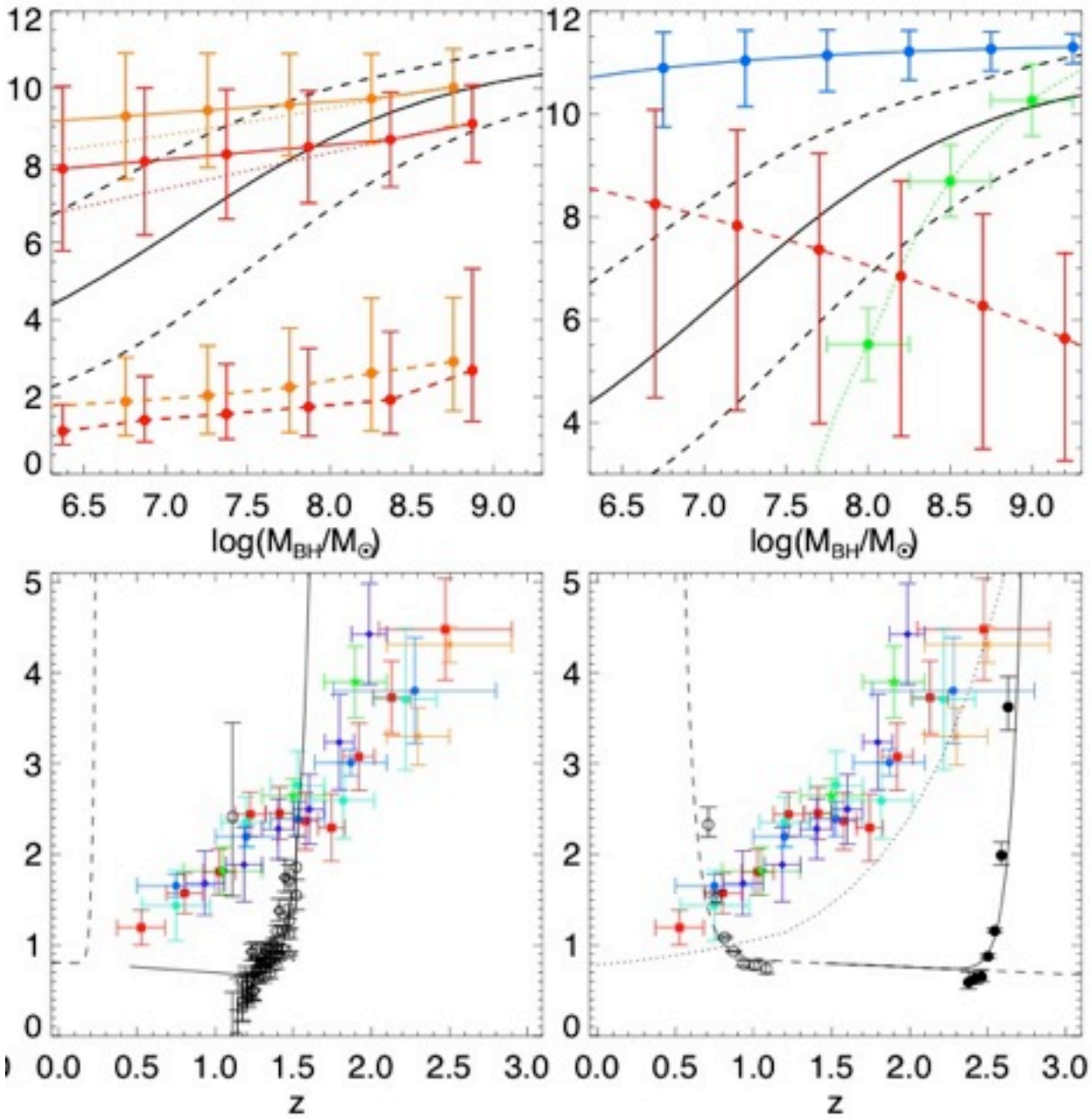


Observed Quasar Clustering at each z

Where Is This Happening?

EMPIRICAL TESTS OF QUASAR FUELING MECHANISMS

Doesn't *generically* trace star formation



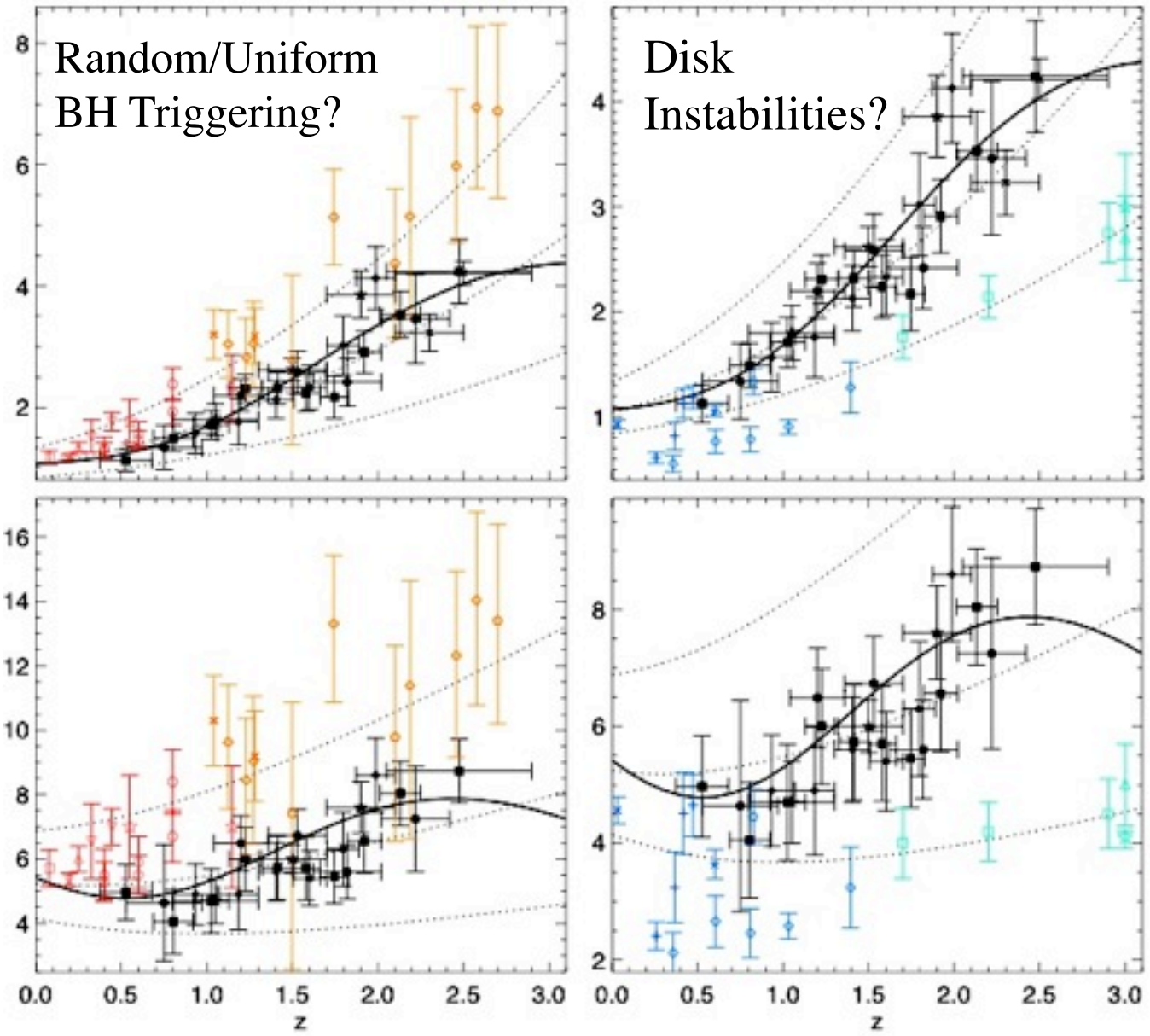
or halo formation

Where Is This Happening?

EMPIRICAL TESTS OF QUASAR FUELING MECHANISMS

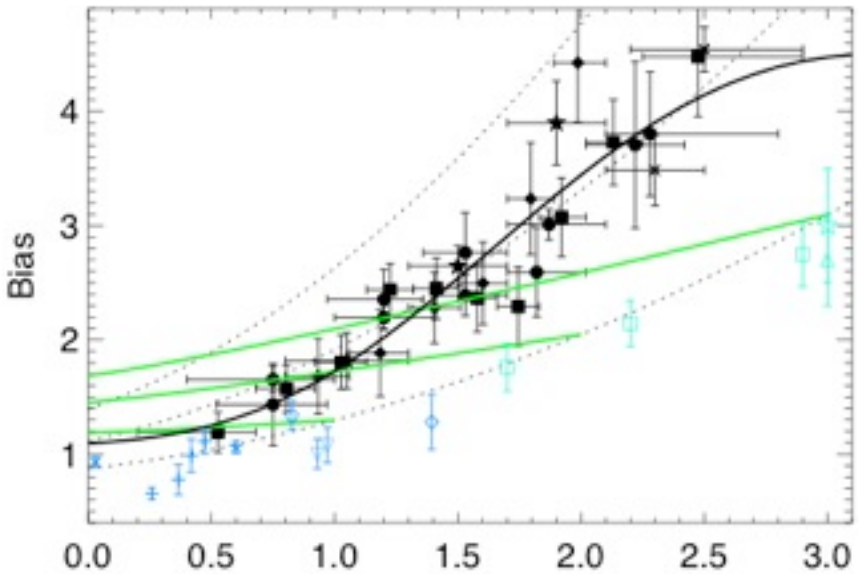
b(z)

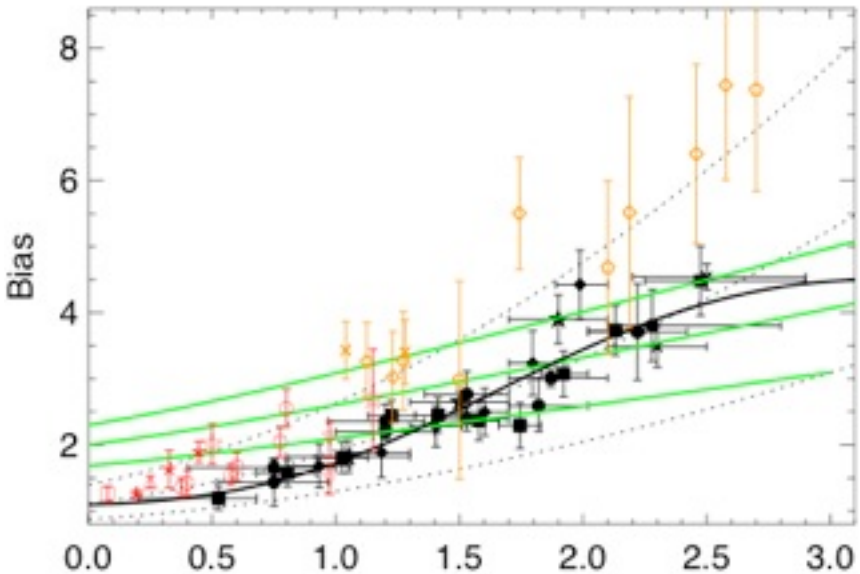
r_0(z)

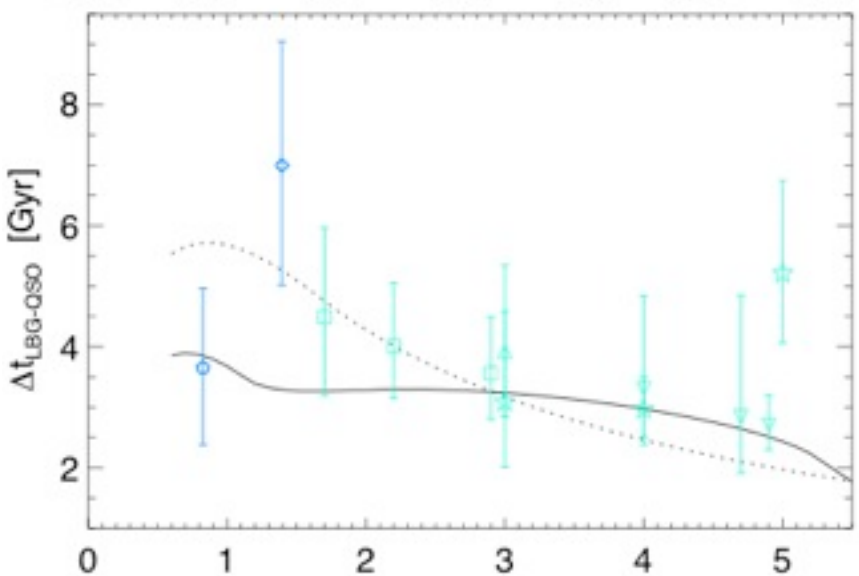


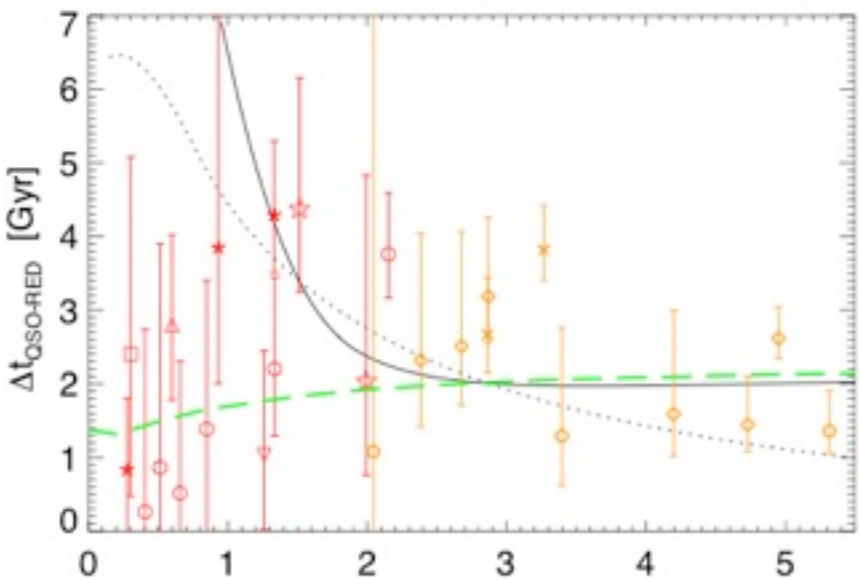
A “Generic” Sequence?

EMPIRICAL TESTS OF QUASAR FUELING MECHANISMS





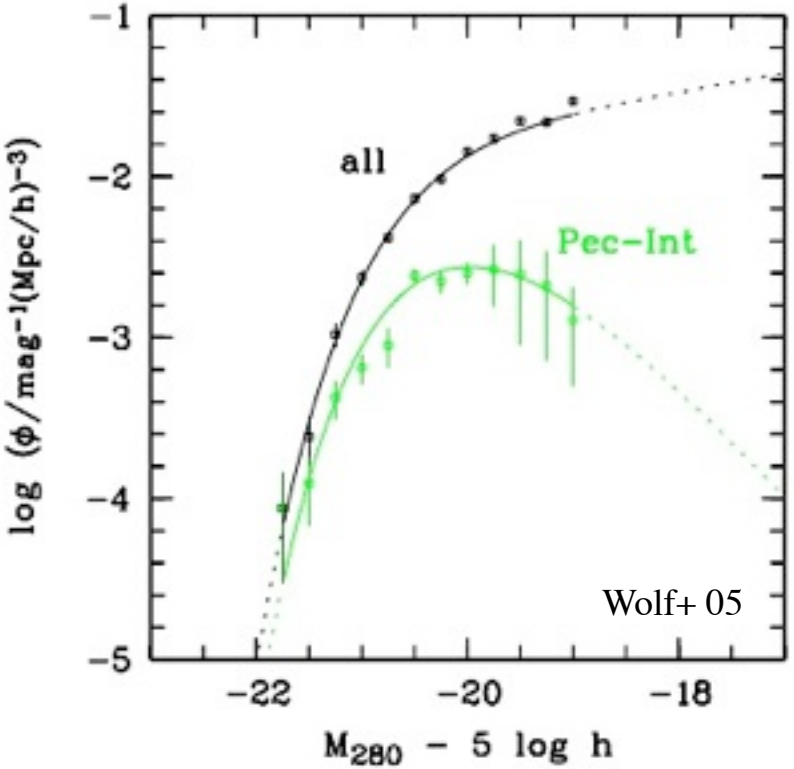




More Detailed Comparison

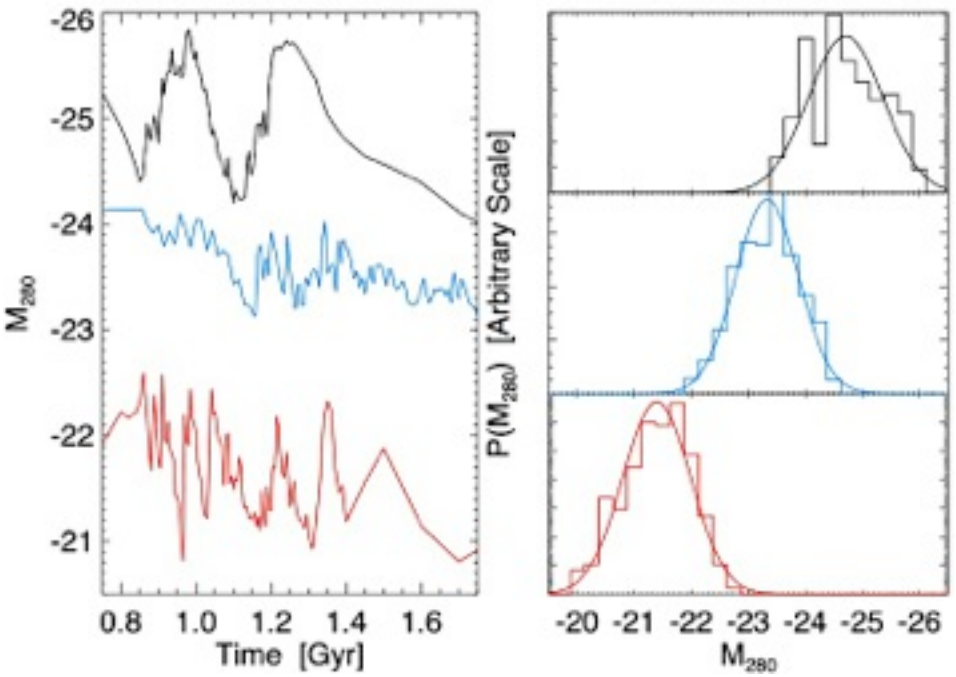
USING SIMULATIONS TO MAP QUASARS <> SPHEROIDS

Observed "Merger" MF



+

~500 Merger Simulations



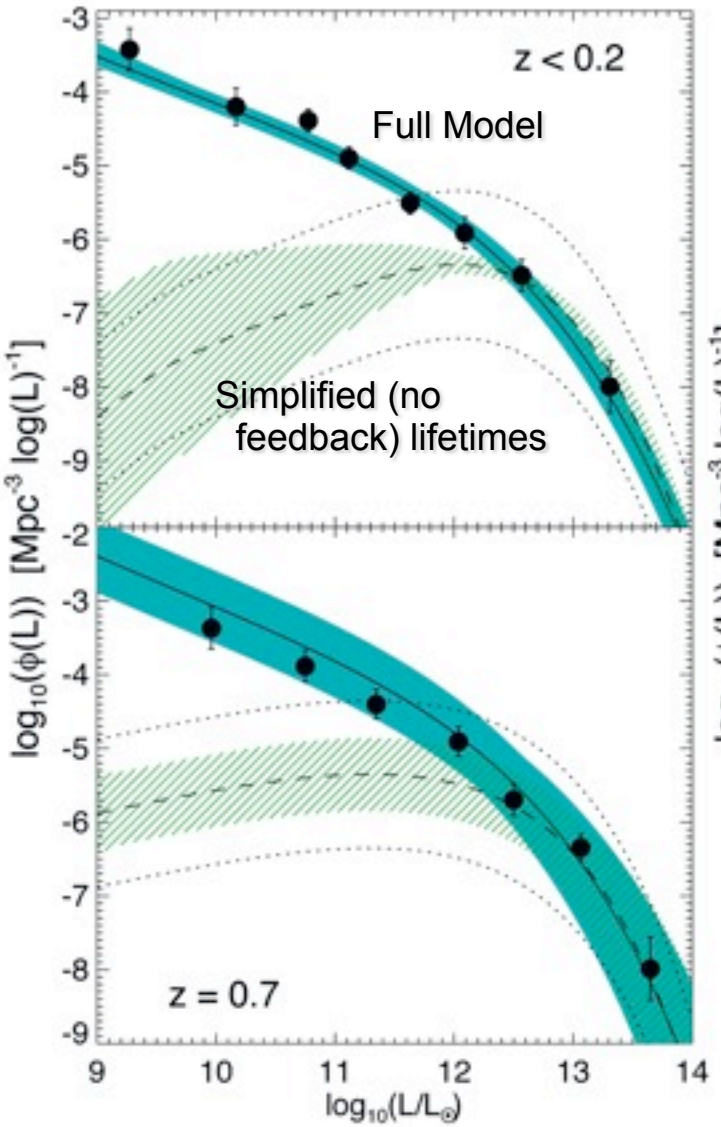
Hopkins, Somerville, Hernquist+ 06

More Detailed Comparison

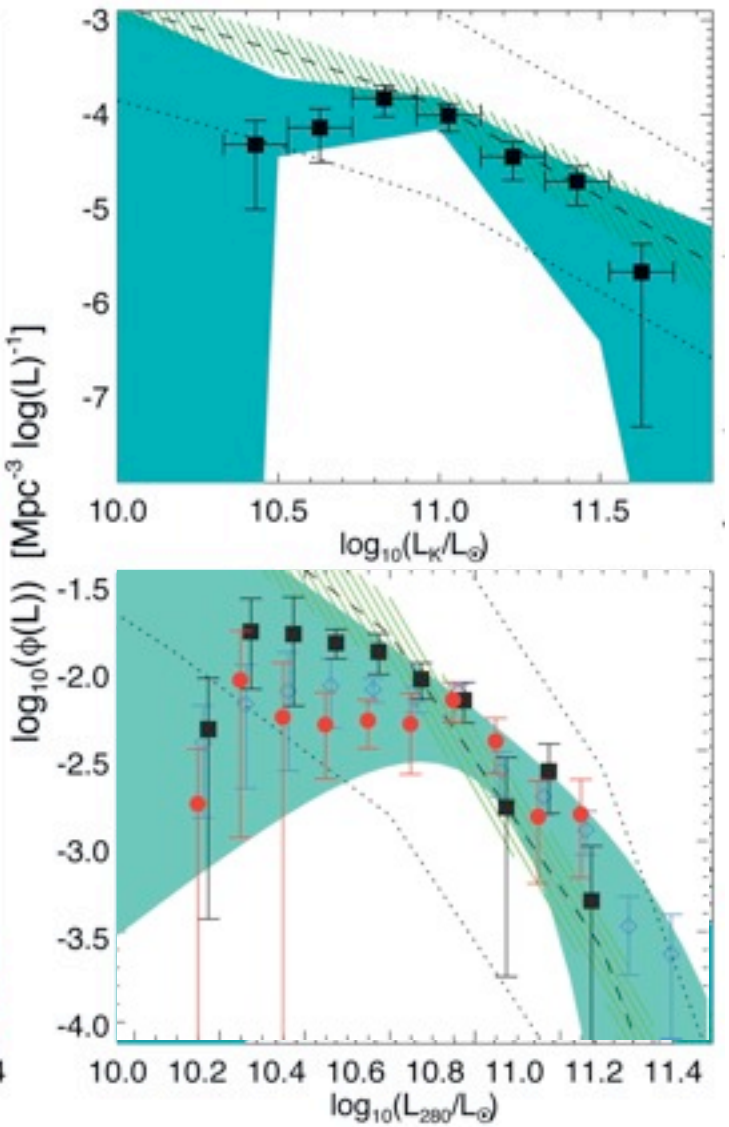
TEST STATISTICS OF QUASAR, RED GALAXY, & MERGER POPULATIONS

(see also Fontanot et al. 2006, Malbon et al. 2006, Volonteri et al. 2006)

Merger LF → Quasar LF



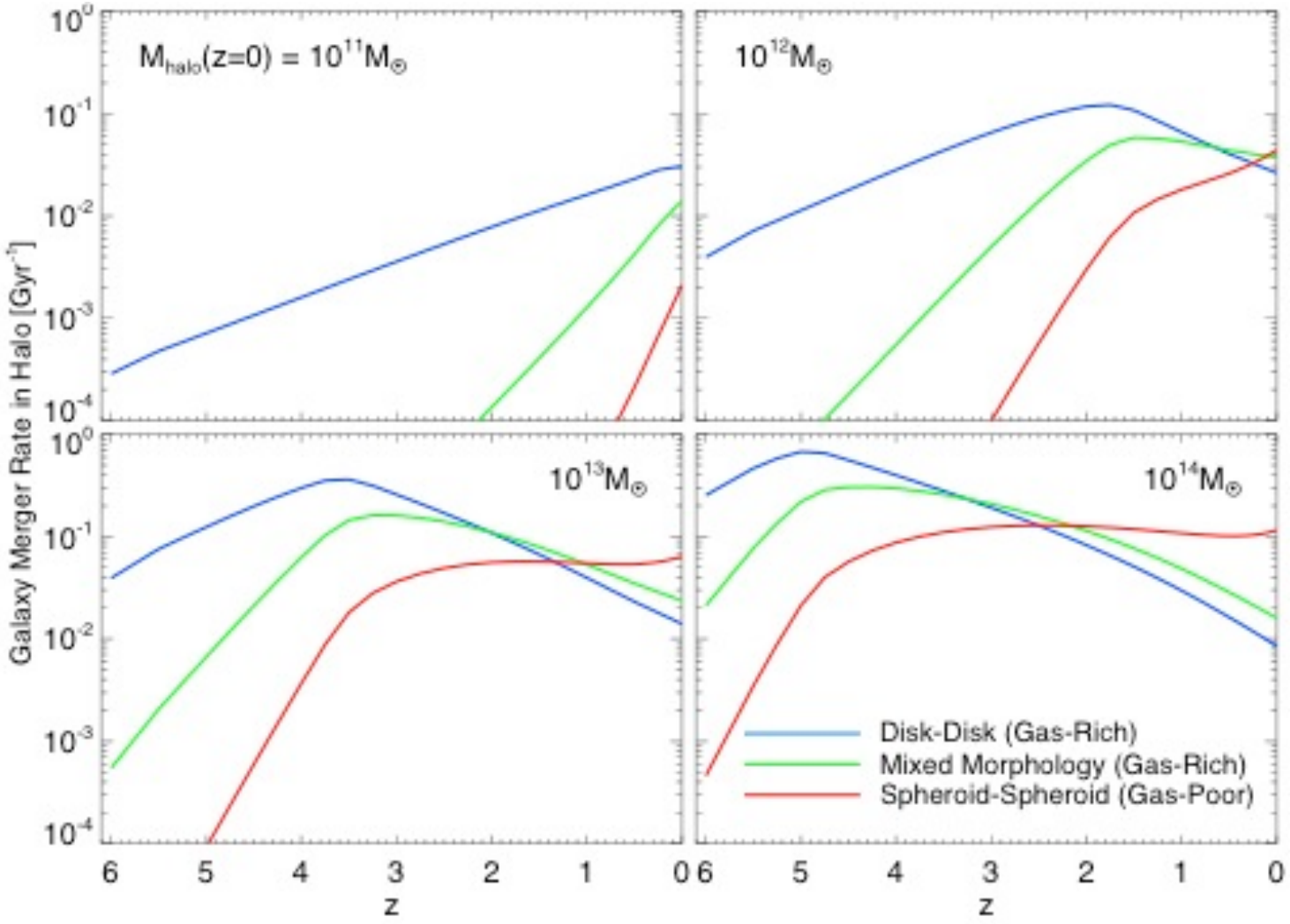
Quasar LF → Merger LF



Xu+;Wolf+; Ueda+

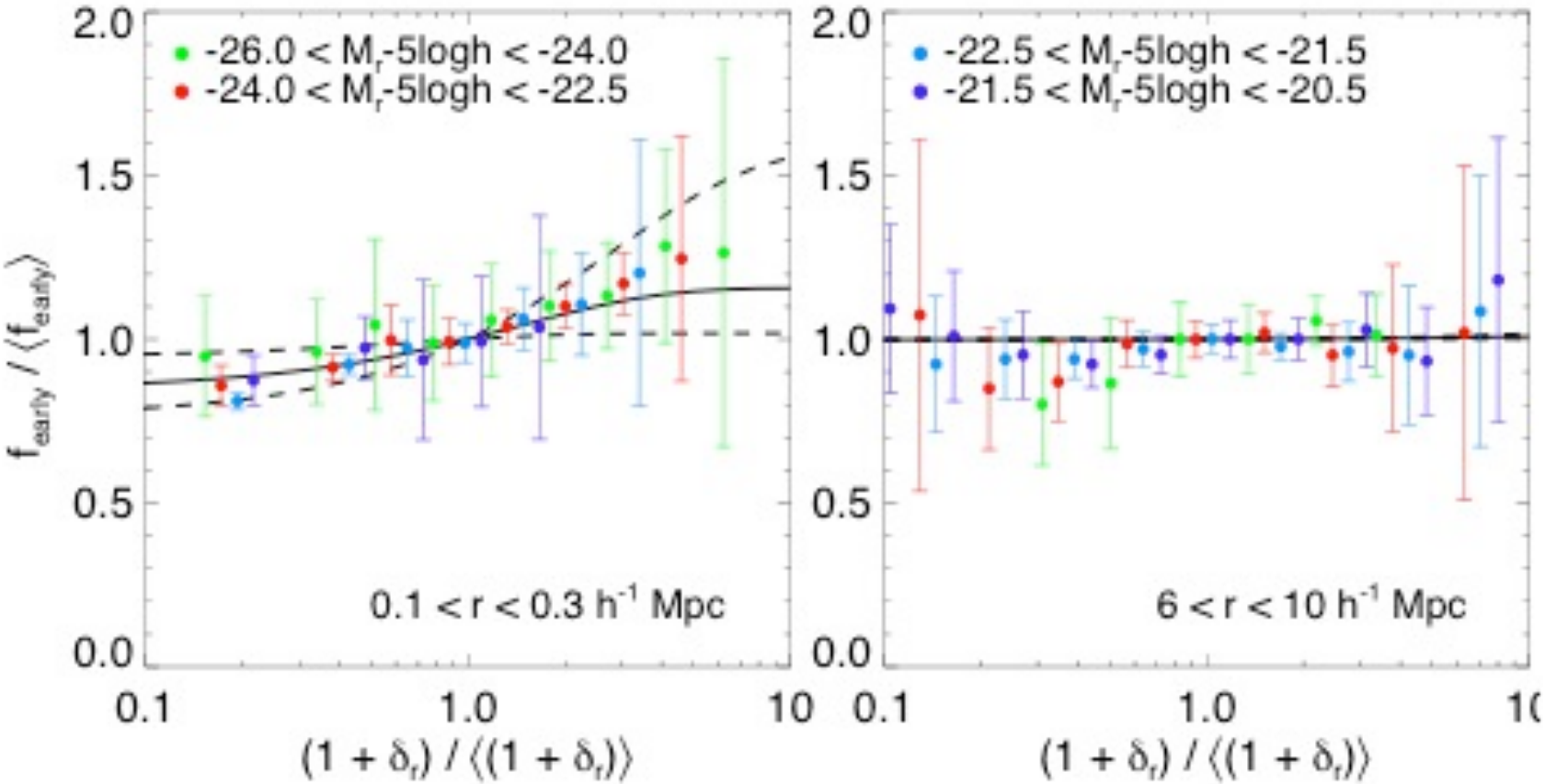
Comparing Quenching Models

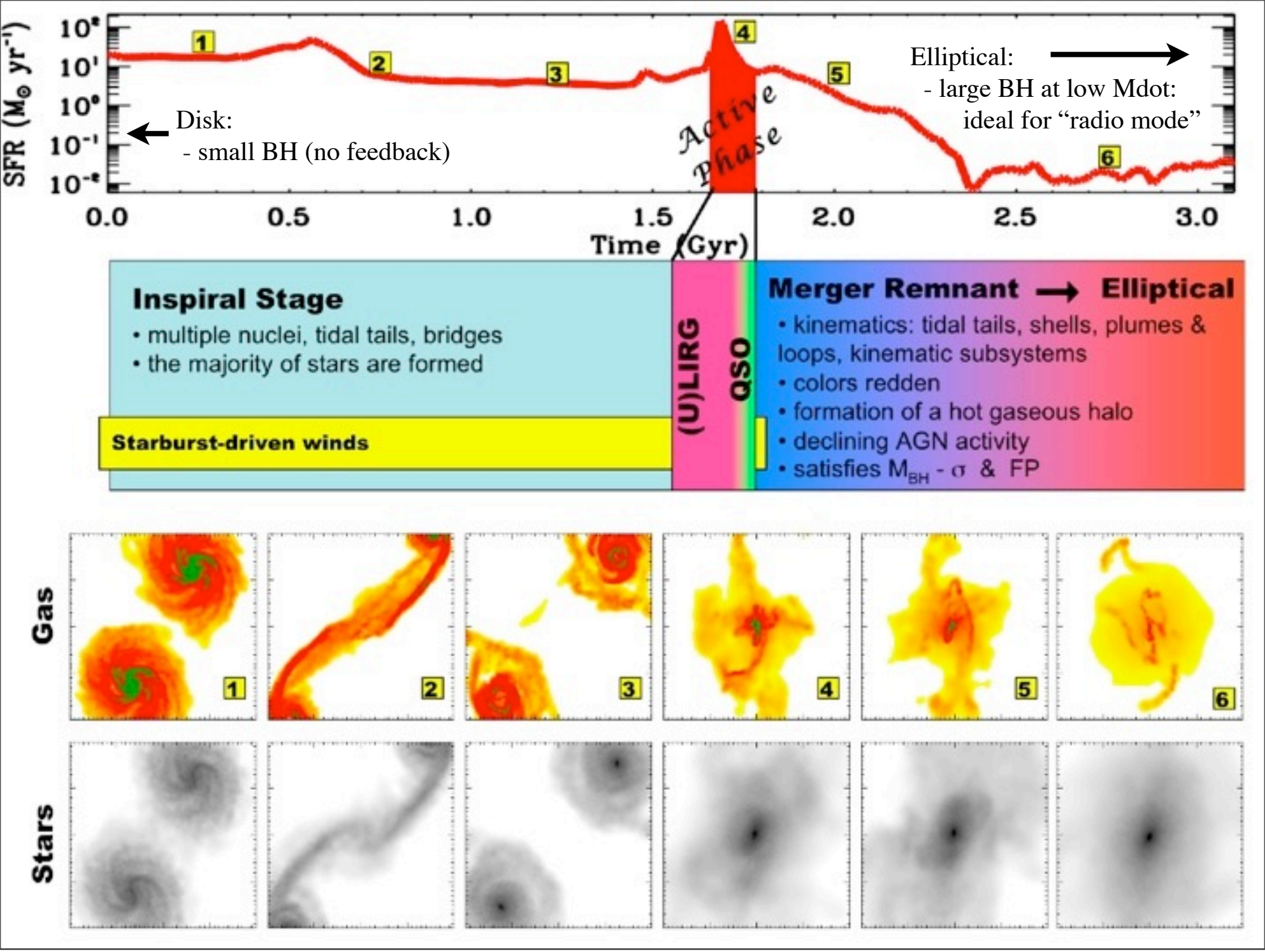
DICHOTOMY IN ELLIPTICAL KINEMATICS



Comparing Quenching Models

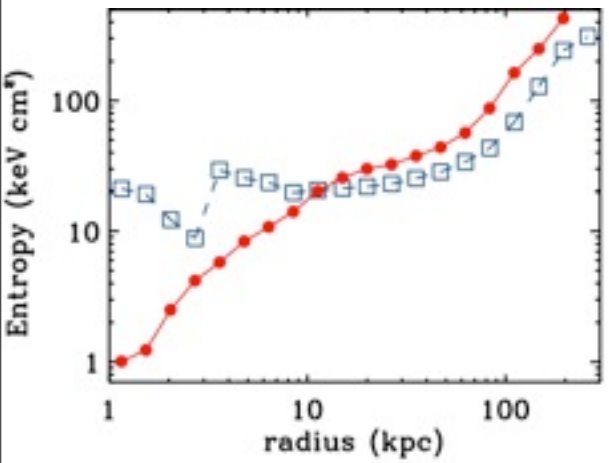
ENVIRONMENTAL DEPENDENCE OF EARLY-TYPE FRACTIONS

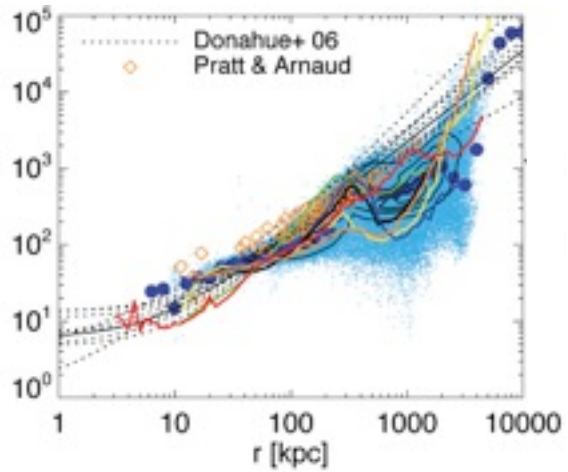


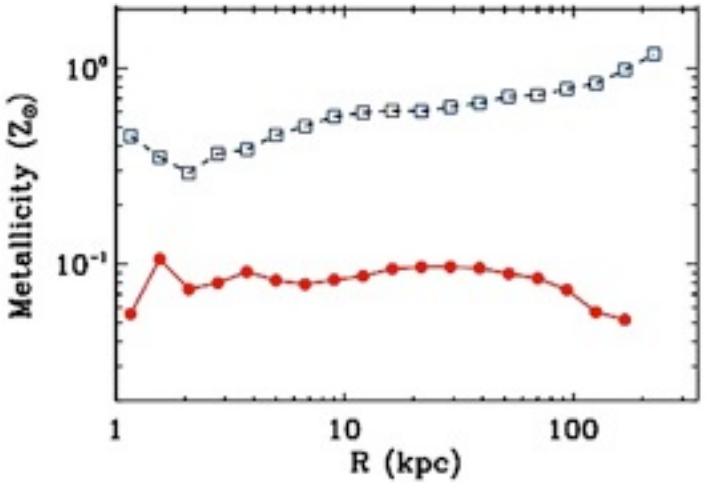

SFR ($M_\odot$ yr^{-1})
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
1
2
3
4
5
6
Active Phase
Disk:
- small BH (no feedback)
Elliptical:
- large BH at low Mdot:
ideal for "radio mode"
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time (Gyr)
Inspiral Stage
• multiple nuclei, tidal tails, bridges
• the majority of stars are formed
Starburst-driven winds
(U)LIRG
QSO
Merger Remnant → Elliptical
• kinematics: tidal tails, shells, plumes & loops, kinematic subsystems
• colors redden
• formation of a hot gaseous halo
• declining AGN activity
• satisfies M_{BH} - σ & FP
Gas
Stars

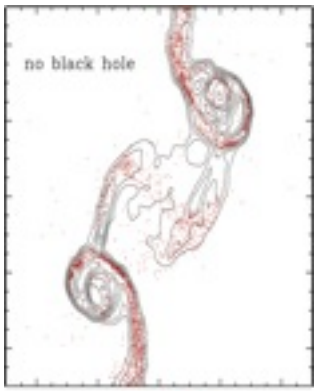
The Role of "Quasar" Feedback

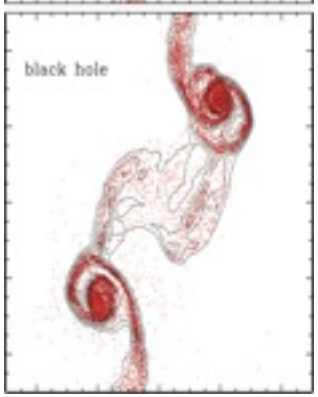
CORRELATION VS. CAUSALITY?

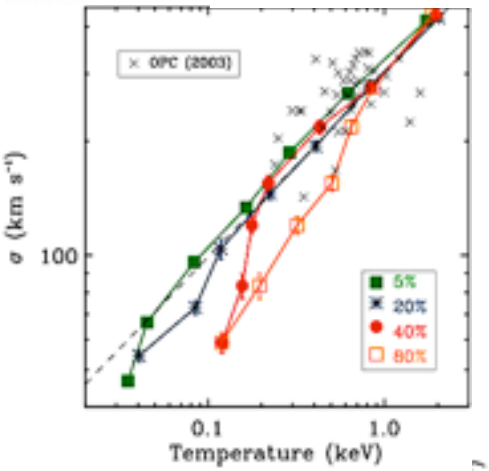


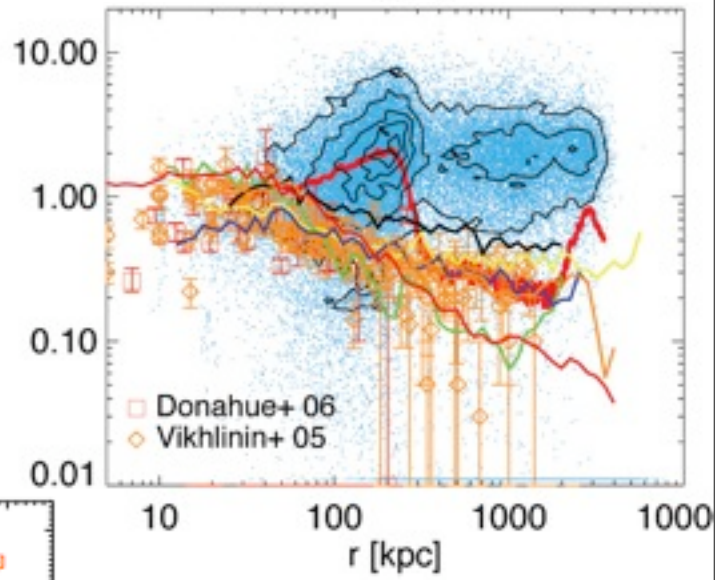


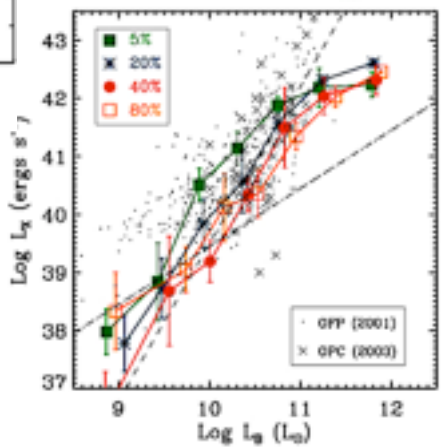


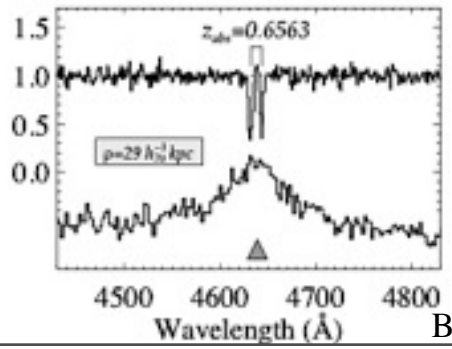












Cox+ 06

Hopkins+ 06 (in prep)

Bowen+ 06