ON
OBSERVATÓRIO NACIONAL

Divisão de Programas
de Pós-graduação

XIII Ciclo de Cursos Especiais

27 a 31 de outubro de 2008

Lecture 4 - Galaxy Formation Theory: Semi-Analytic Models

Joel Primack, UCSC

Semi-Analytic Models are currently the best way to understand the formation of galaxies and clusters within the cosmic web dark matter gravitational skeleton. This lecture will discuss the current state of the art in galaxy formation, and describe the successes and challenges for the best current ΛCDM models of the roles of baryonic physics and supermassive black holes in the formation of galaxies. I thank my collaborators Avishai Dekel, Sandra Faber, and Rachel Somerville for some of the slides used in this lecture.

What We Know About Galaxy Formation

- Initial Conditions: WMAP5 cosmology

CMB + galaxy P(k) + Type Ia SNe $\rightarrow$

Ω_Λ=0.72, Ω_m=0.28, Ω_b=0.046, H_0=70 km/s/Mpc, σ_8=0.82

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxy properties

    Well-studied in Milky Way and nearby galaxies

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxies
- Integral Constraints: Cosmological quantities

  Star Formation Rate Density (SFRD) vs. redshift ($M_{\odot}/yr/Mpc^3$) - Madau plot

  Stellar Mass Density (SMD) vs. redshift ($M_{\odot}/Mpc^3$) - Dickinson plot

  SMD should = integrated SFRD: $\rho_*(t) = \int_0^t dt\, d\rho_*/dt$

  Extragalactic Background Light (EBL) - constrains integrated SFRD

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxies
- Integral Constraints: Cosmological quantities
- Well-studied galaxy evolution at z<1

    SDSS clarified galaxy scaling relations, galaxy color bimodality

    COMBO-17, DEEP, COSMOS surveys measuring star formation rates, etc.

What We Know About Galaxy Formation

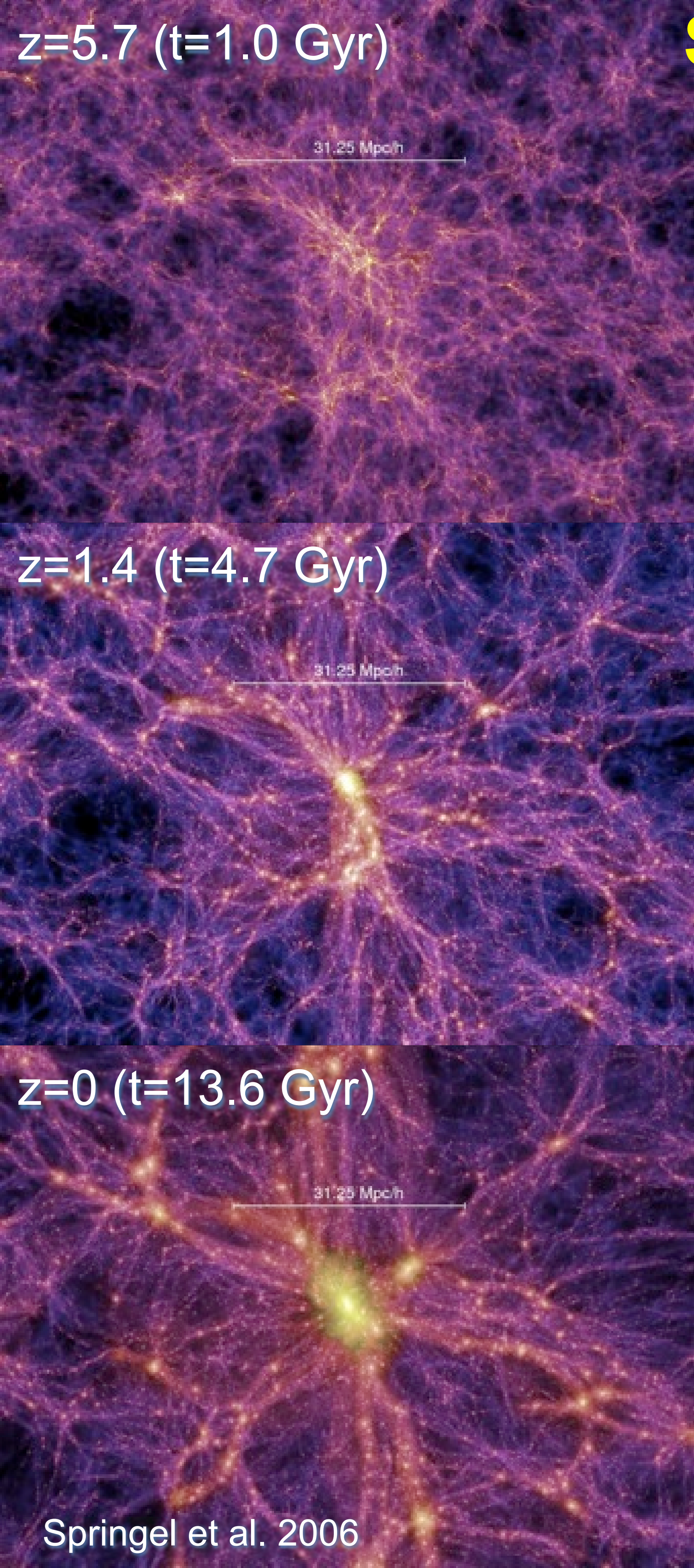
- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxies
- Integral Constraints: Cosmological quantities
- Well-studied galaxy evolution at $z<1$
- Galaxy Zoo Identified at $z=2$-3

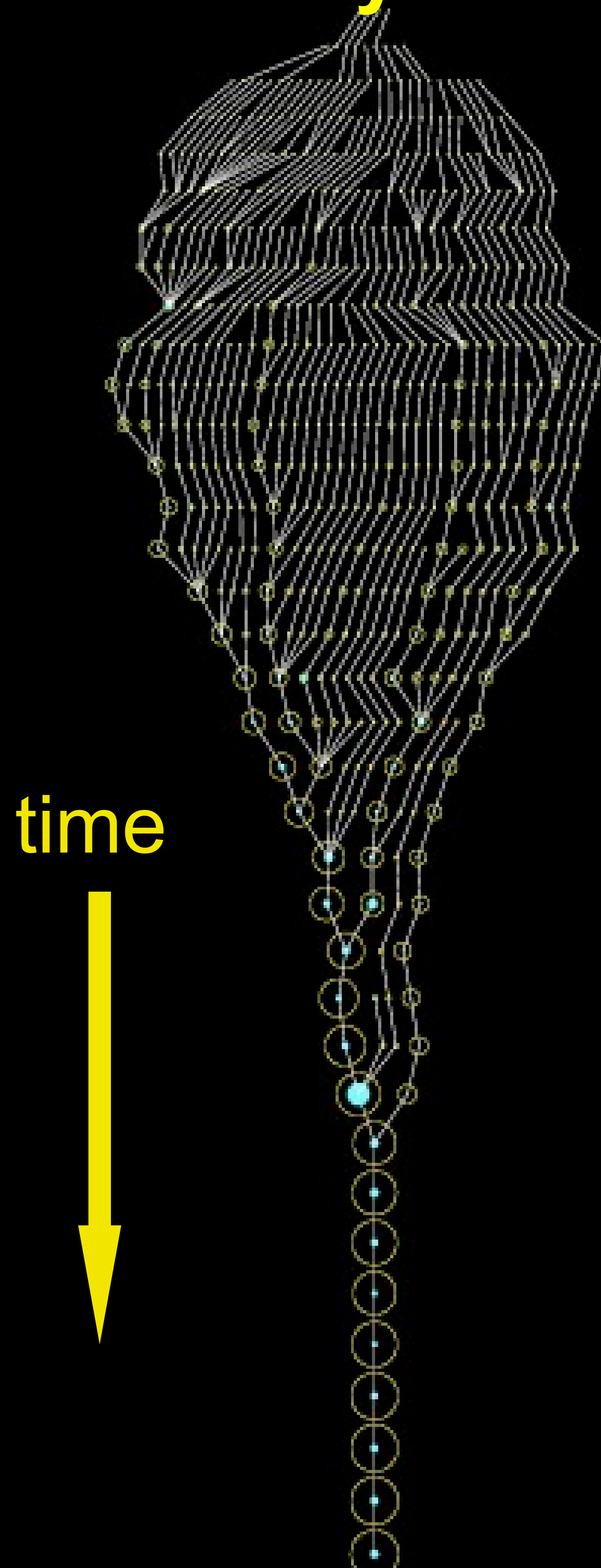
Lyman break galaxies, Lyman alpha emitters, Distant red galaxies, Active Galactic Nuclei, Damped Lyman alpha systems, Submillimeter galaxies

However: Evolutionary sequence unclear. Which (if any) are progenitors of typical galaxies like the Milky Way?

with thanks to Eric Gawiser

Semi-Analytic Models of Galaxy Formation



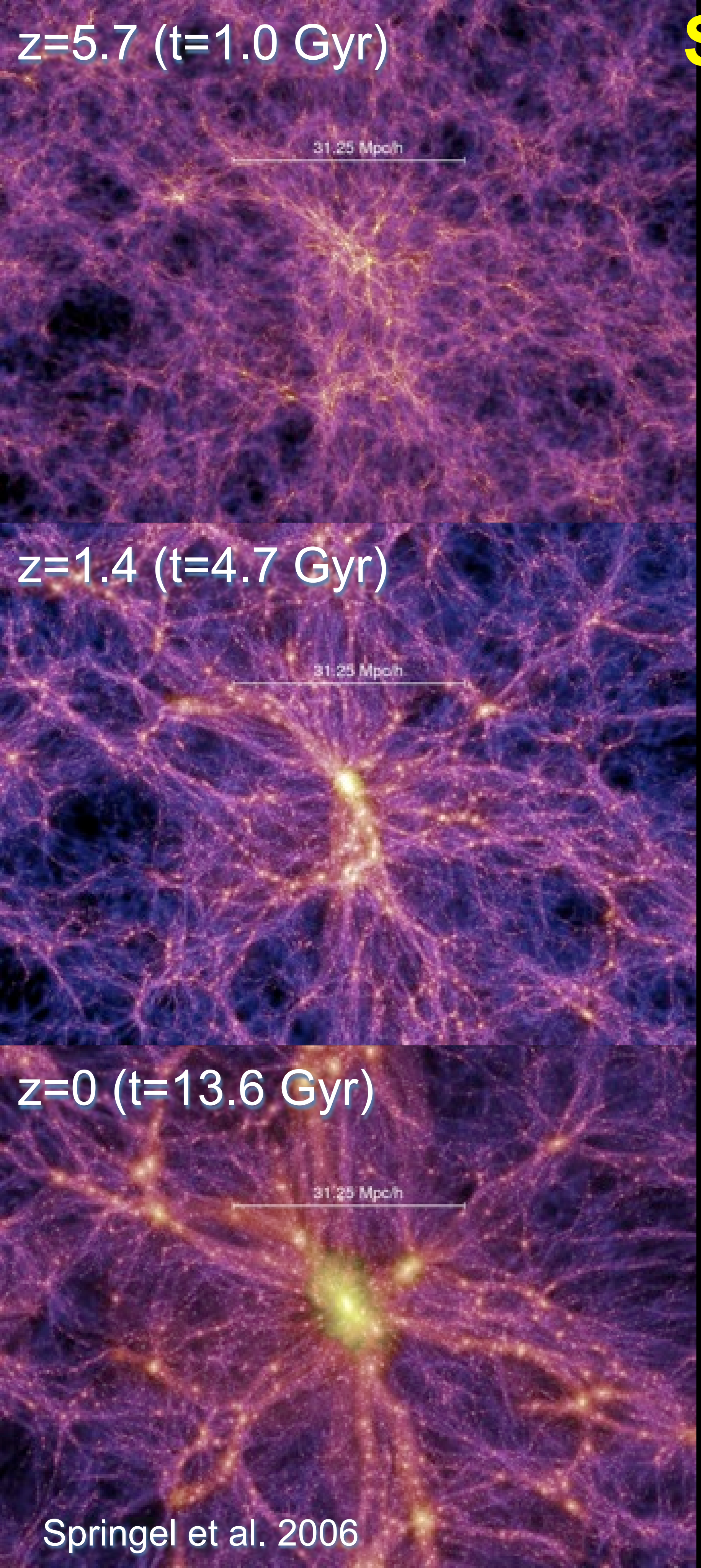


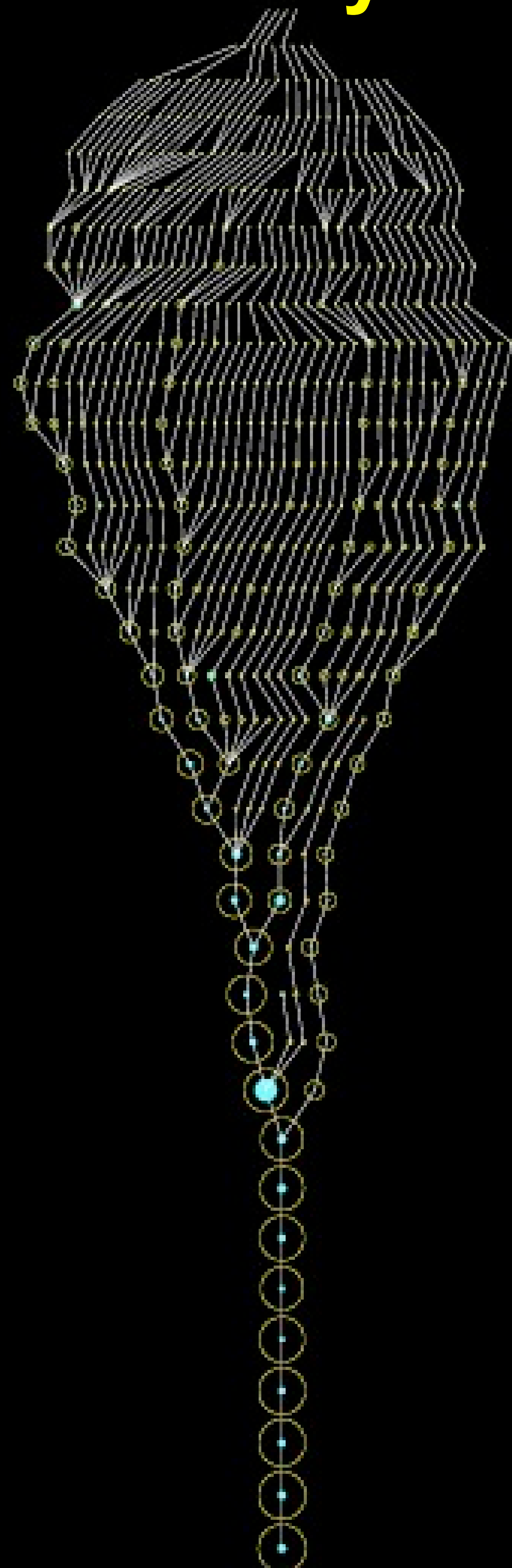
Wechsler et al. 2002

Present status of ΛCDM "Double Dark" theory:

- cosmological parameters are now well constrained by observations
- structure formation in dominant dark matter component accurately quantified
- mass accretion history of dark matter halos is represented by 'merger trees' like the one at left

Semi-Analytic Models of Galaxy Formation

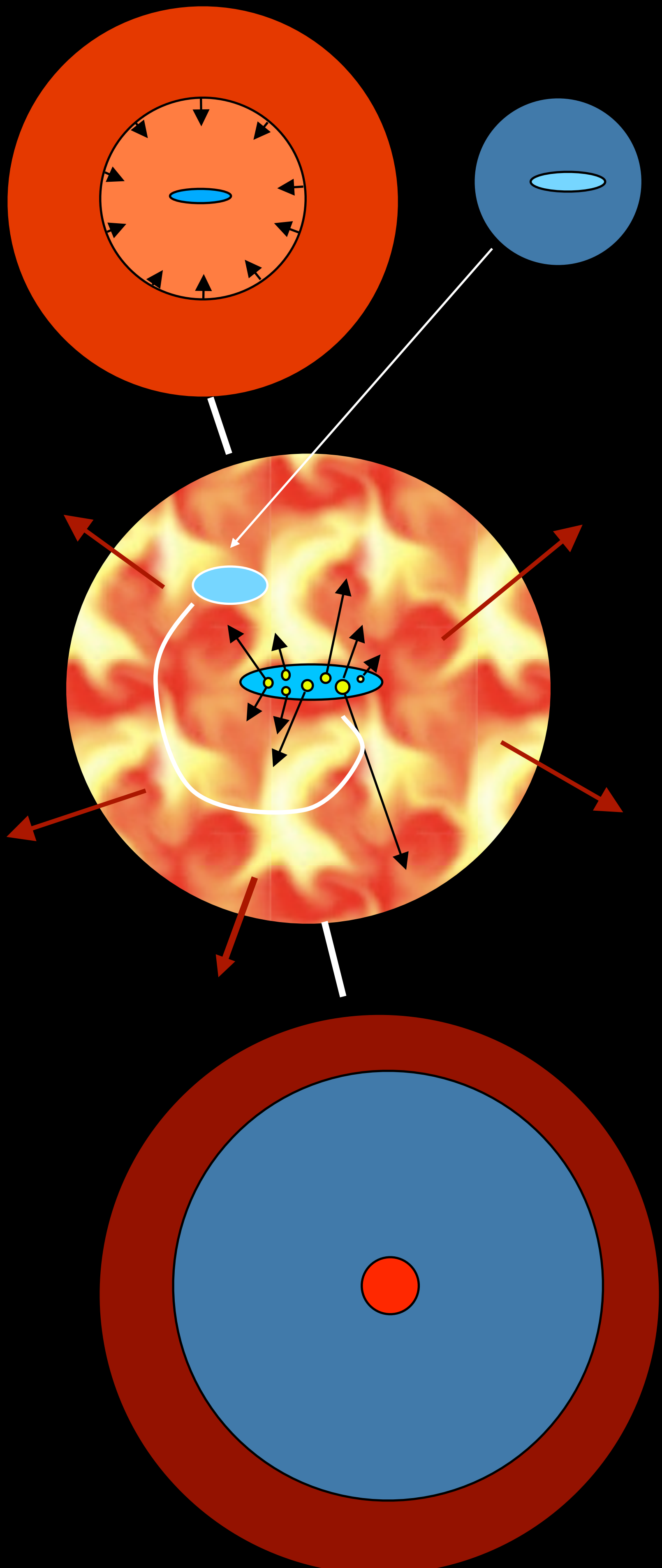




Astrophysical processes modeled:

- shock heating & radiative cooling
- photoionization squelching
- merging
- star formation (quiescent & burst)
- SN heating & SN-driven winds
- AGN accretion and feedback
- chemical evolution
- stellar populations & dust

Semi-Analytic Models of Galaxy Formation



- gas is collisionally heated when perturbations ‘turn around’ and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law)
- massive stars and SNae reheat (and expel?) cold gas and some metals
- galaxy mergers trigger bursts of star formation; ‘major’ mergers transform disks into spheroids

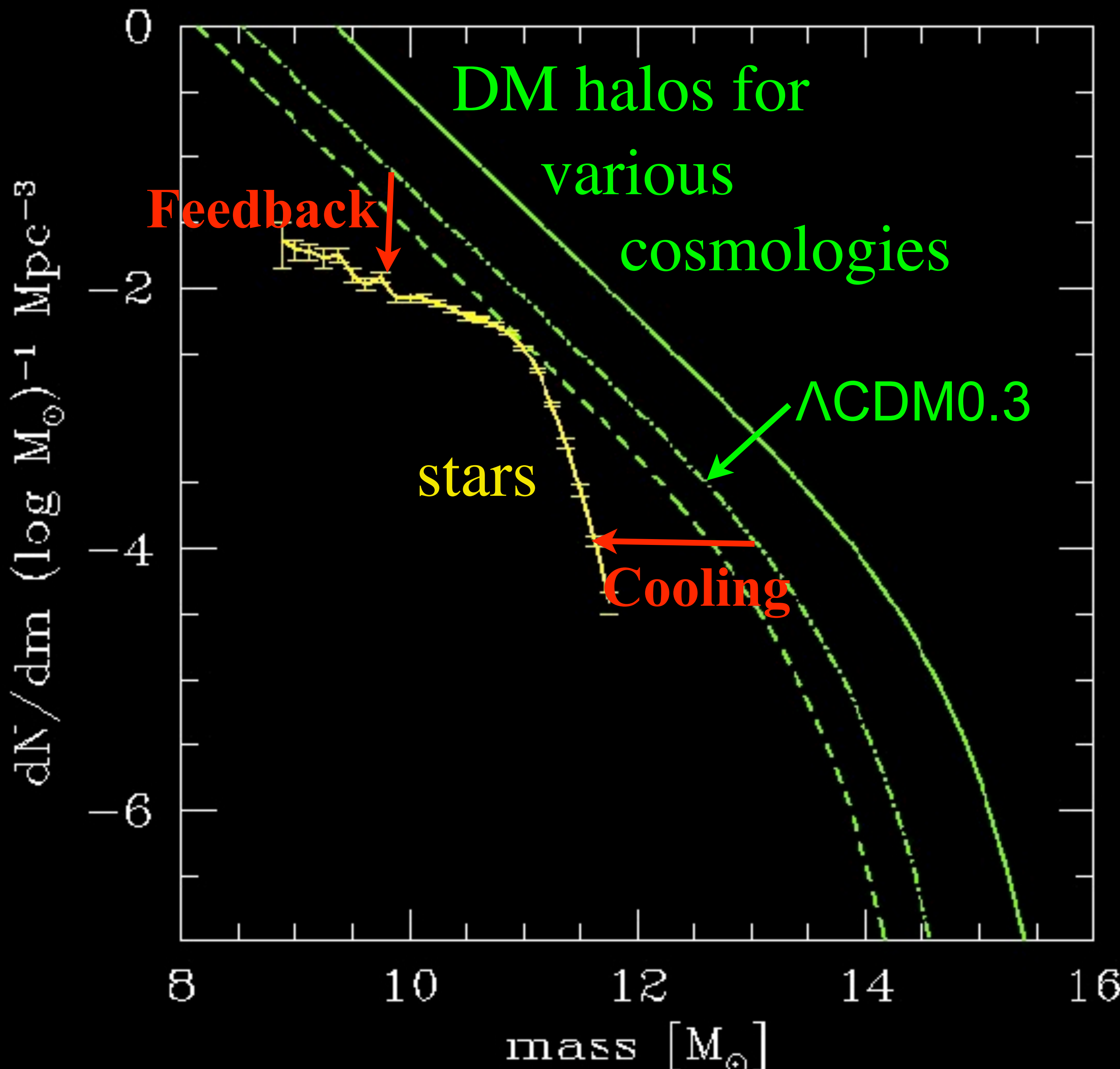
White & Frenk 1991; Kauffmann et al. 93; Cole et al. 94; Somerville & Primack 99; Cole et al. 2000; Somerville, Primack, & Faber 01; Croton et al. 06; De Lucia & Blaizot 06; Cattaneo et al. 07; Somerville et al. 08

New Improved Semi-Analytic Models Work!

- Earlier CDM-based galaxy formation models suffered from a set of interlinked problems
  - overcooling/cooling flow problems in galaxies and clusters
  - failure to produce observed color bimodality
- ‘Bright mode’ AGN feedback may regulate BH formation & temporarily quench star formation, but is not a viable ‘maintenance’ mechanism
- Low-accretion rate ‘radio mode’ feedback is a promising mechanism for counteracting cooling flows over long time scales
- New self-consistent ‘hybrid’ models based on physical scaling from numerical simulations and calibrated against empirical constraints now enable us to predict/ interpret the relationship between galaxies, BH, and AGN across cosmic history

-- Rachel Somerville

Baryons in Dark Matter Halos

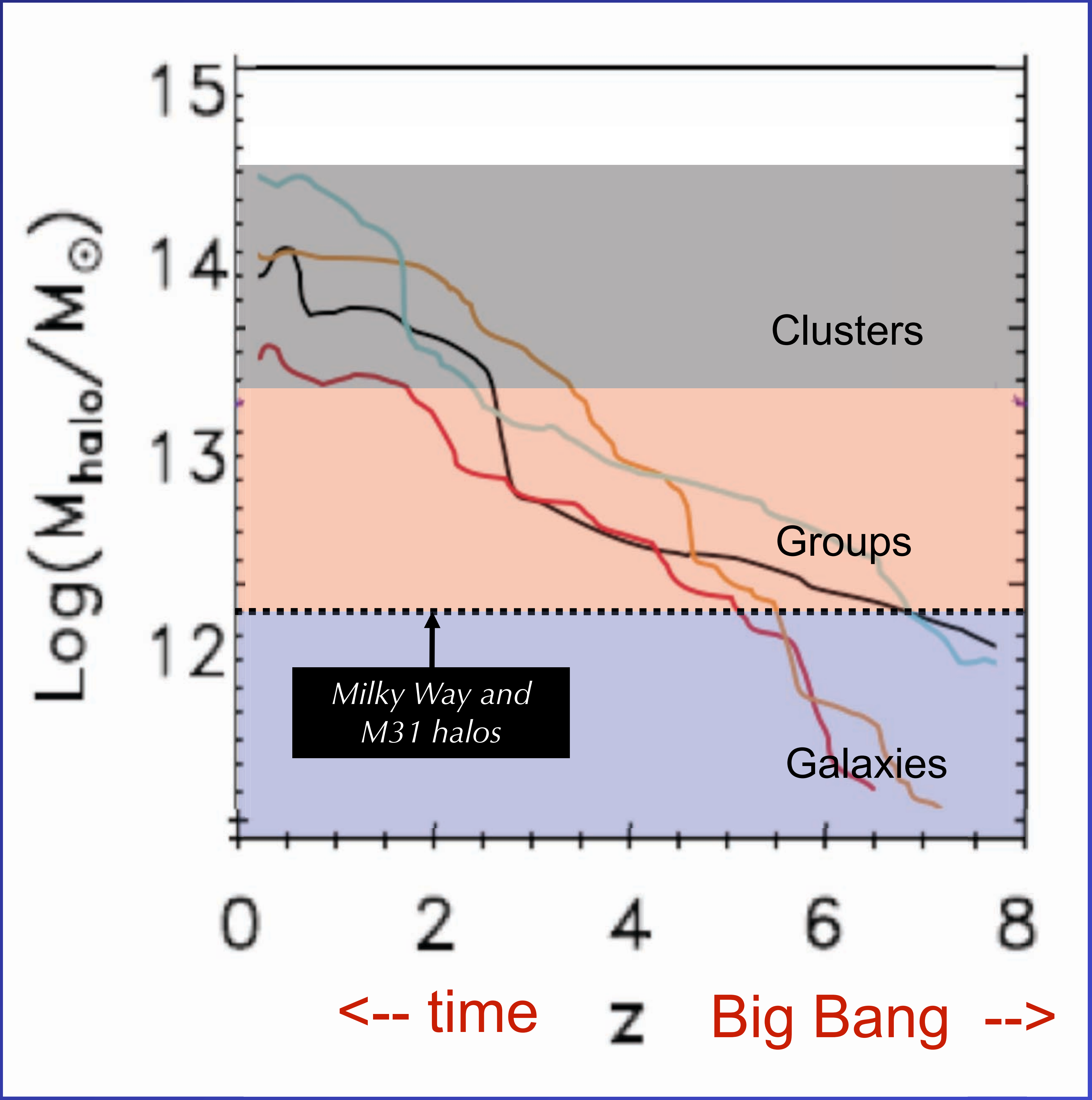


- in order to reconcile CDM (sub)halo mass function with galaxy LF or stellar MF, cooling/star formation must be inefficient overall, most efficient at $M_{halo} \sim 10^{11}\ M_{sun}$
- baryon/DM ratio must be a strongly non-linear (& non-monotonic) function of halo mass

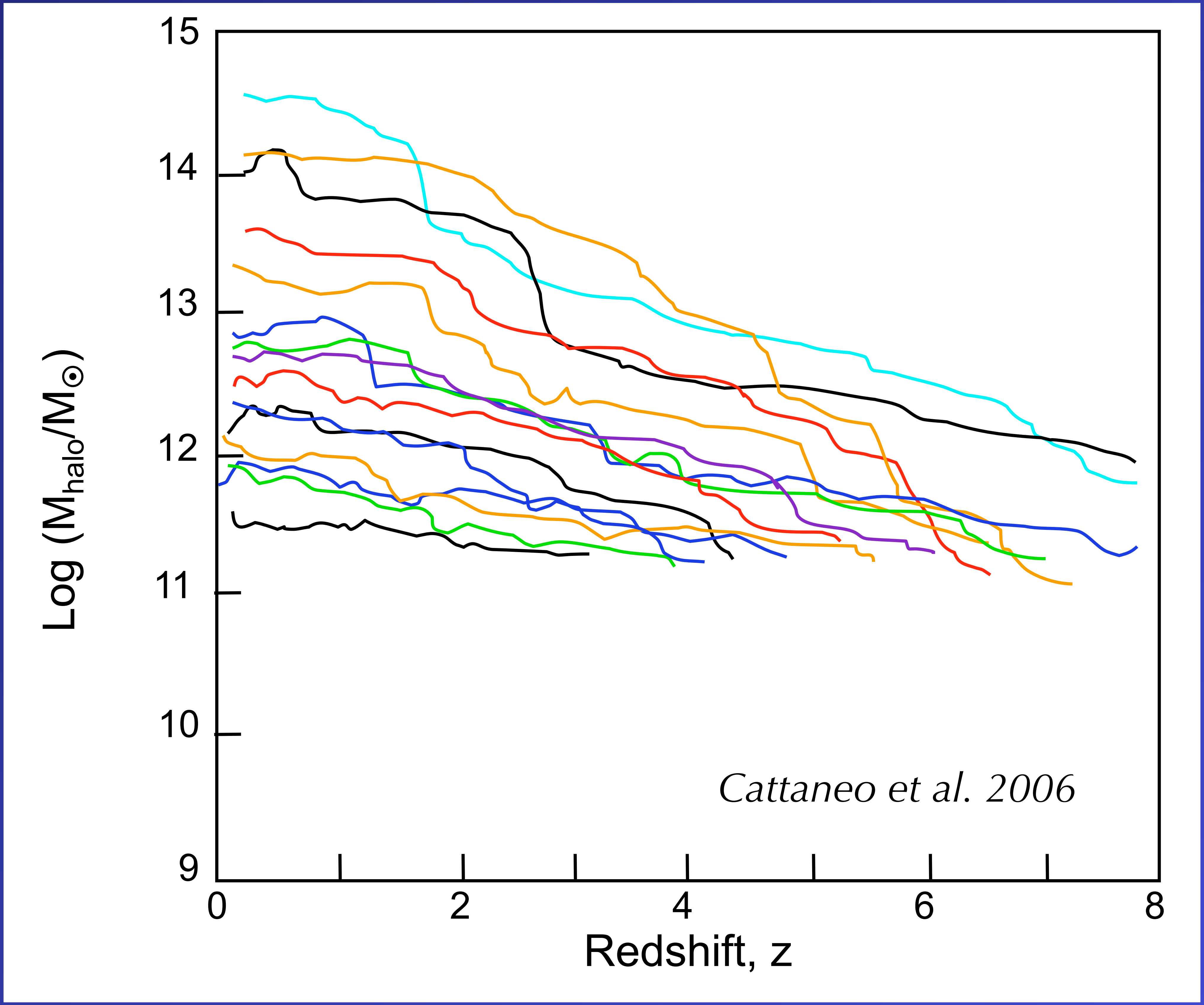
Somerville & Primack 1999; cf. Benson et al. 2003

Dark halo mass growth vs. time: 4 clusters

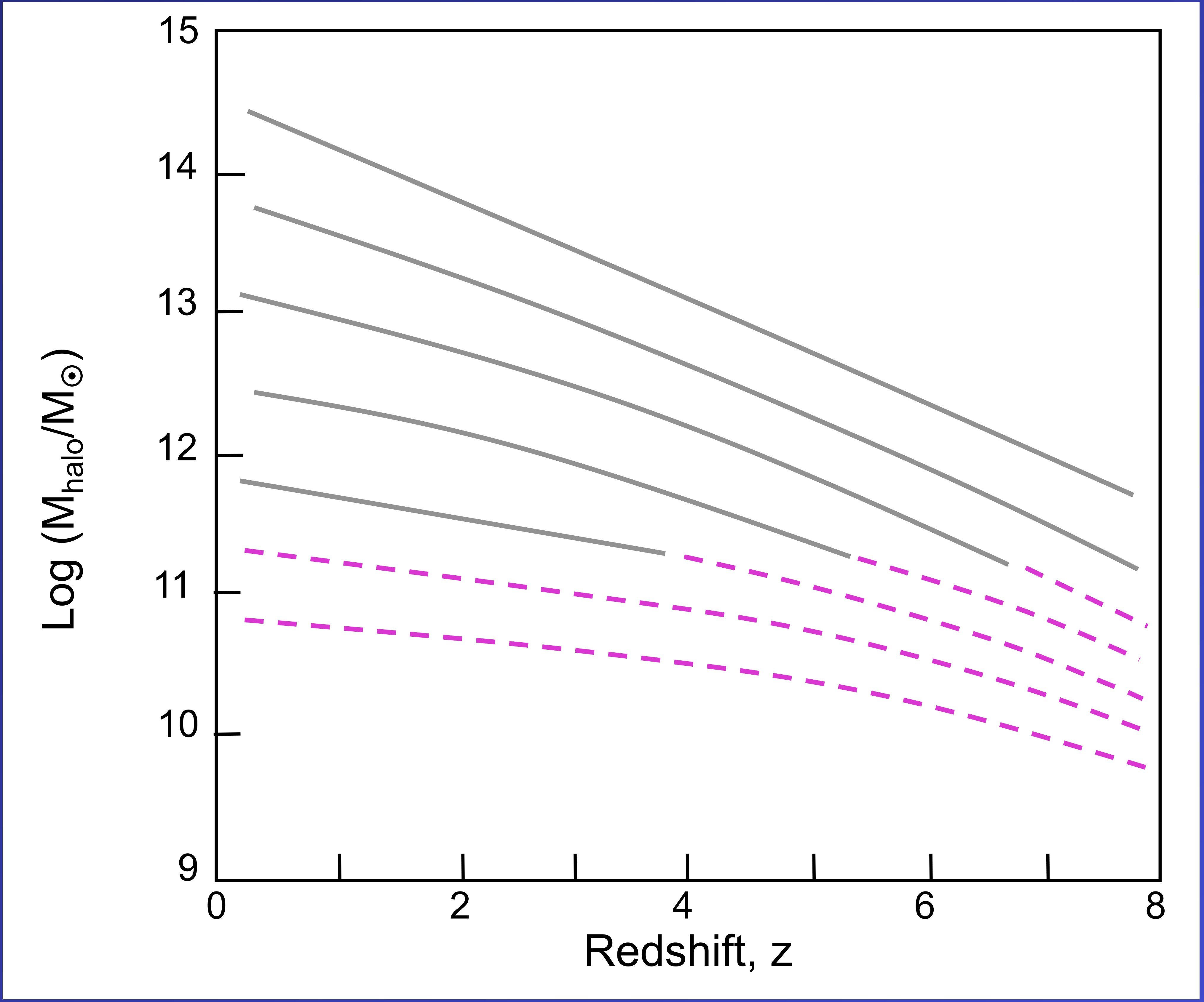
GALics DM halos by Cattaneo et al. 2006



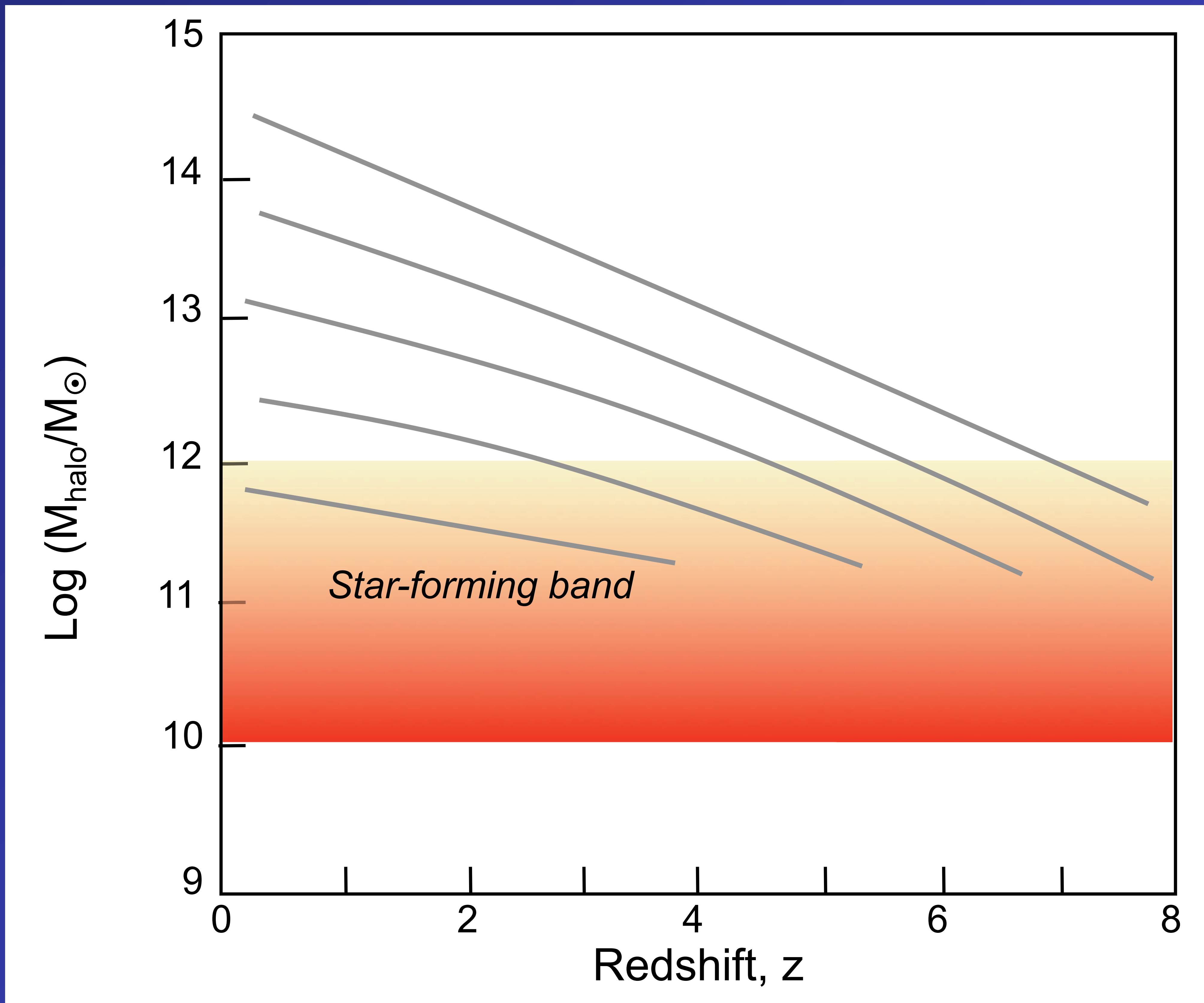
Dark halos of progressively smaller mass



A schematic model of average halo mass growth



Key assumption: ***star-forming band*** in dark-halo mass



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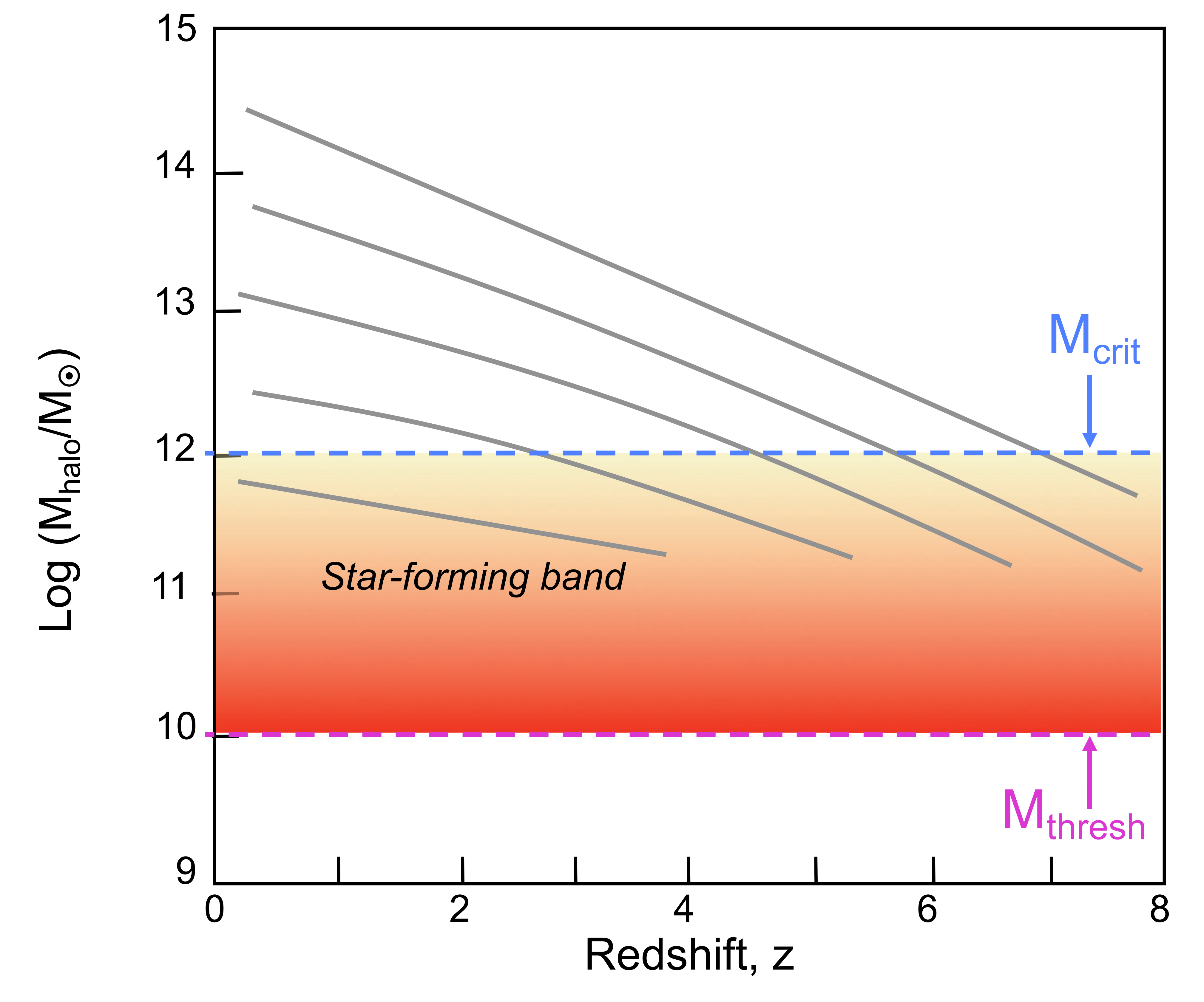
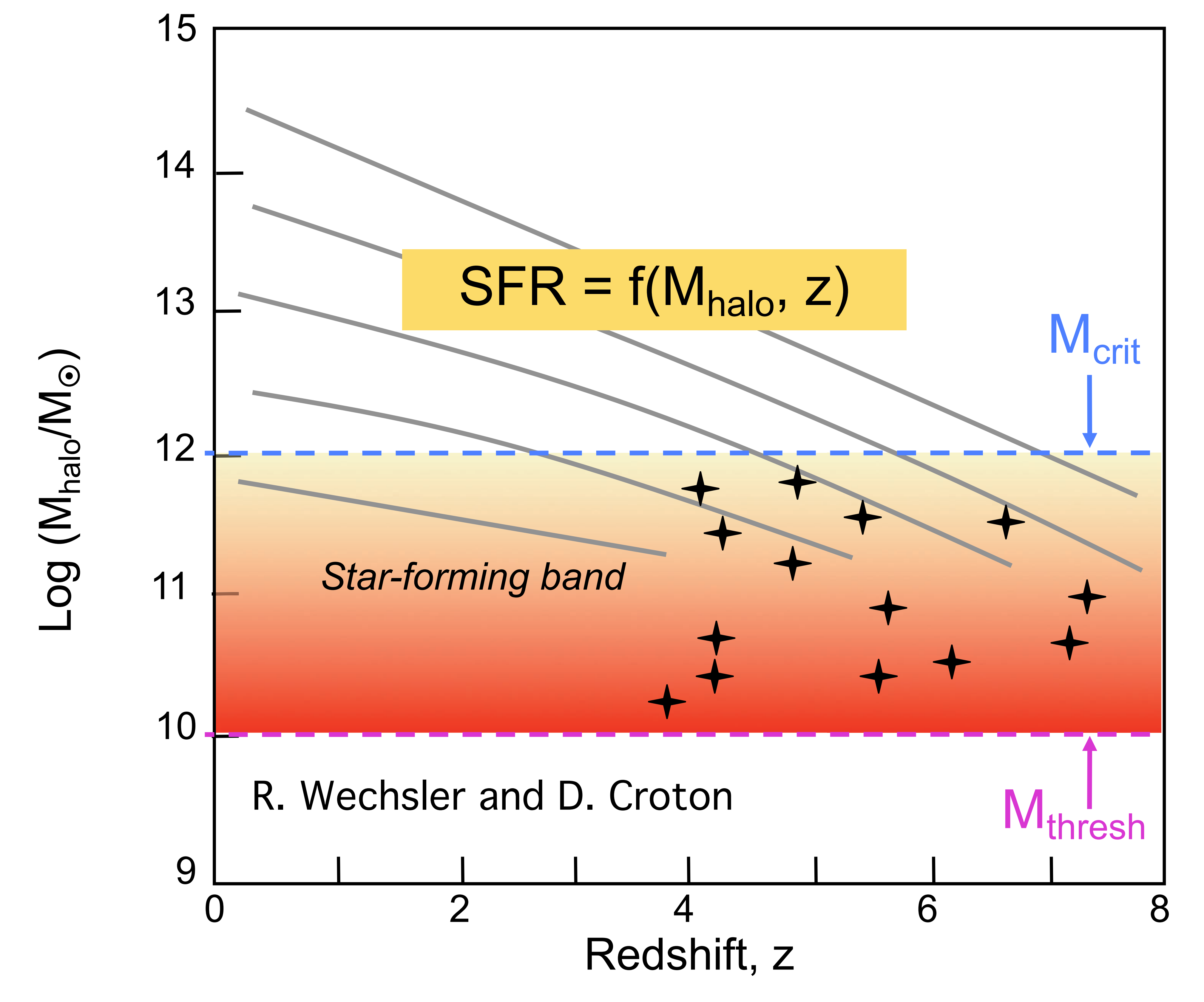
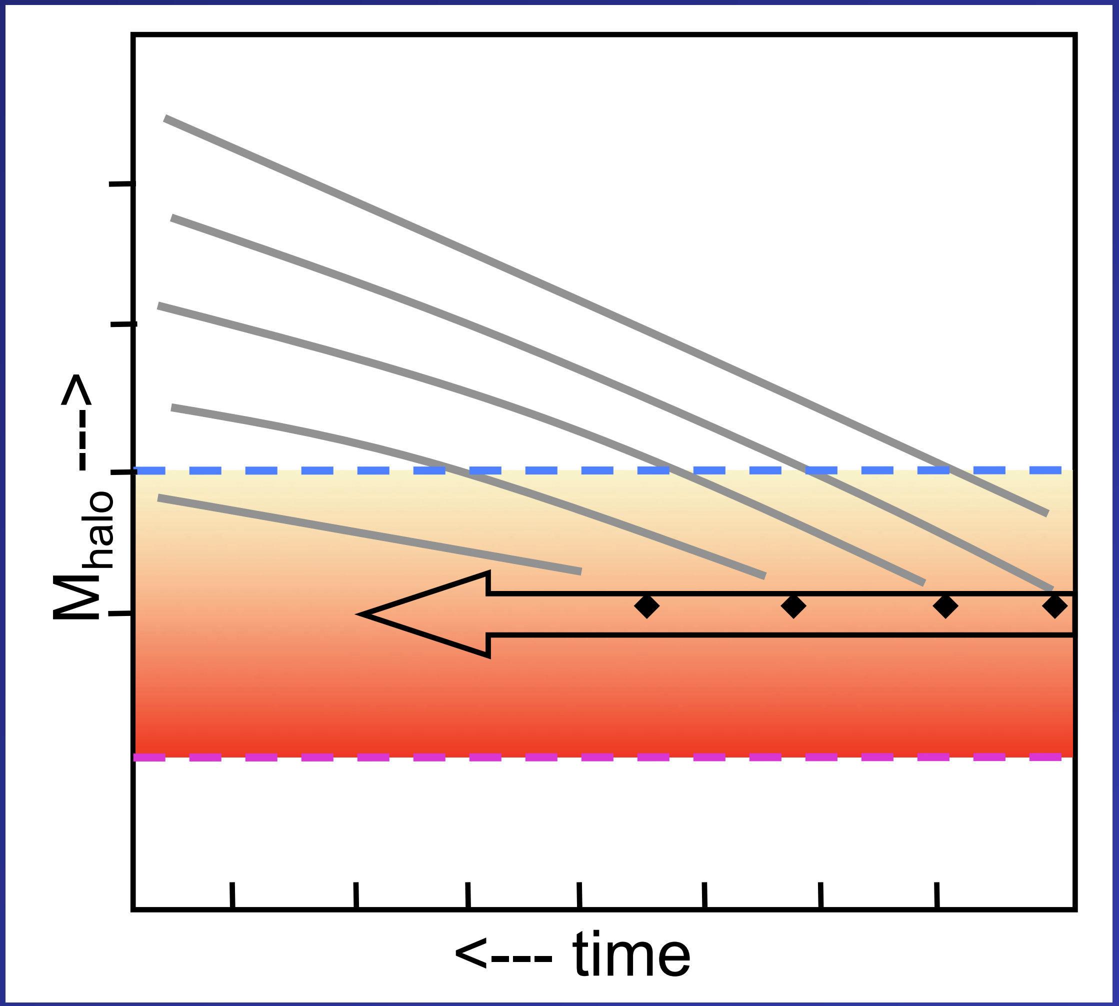


Key assumption: ***star-forming band*** in dark-halo mass



Implications and Predictions of the Model



1) Each halo has a unique dark-matter growth path and associated stellar mass growth path.

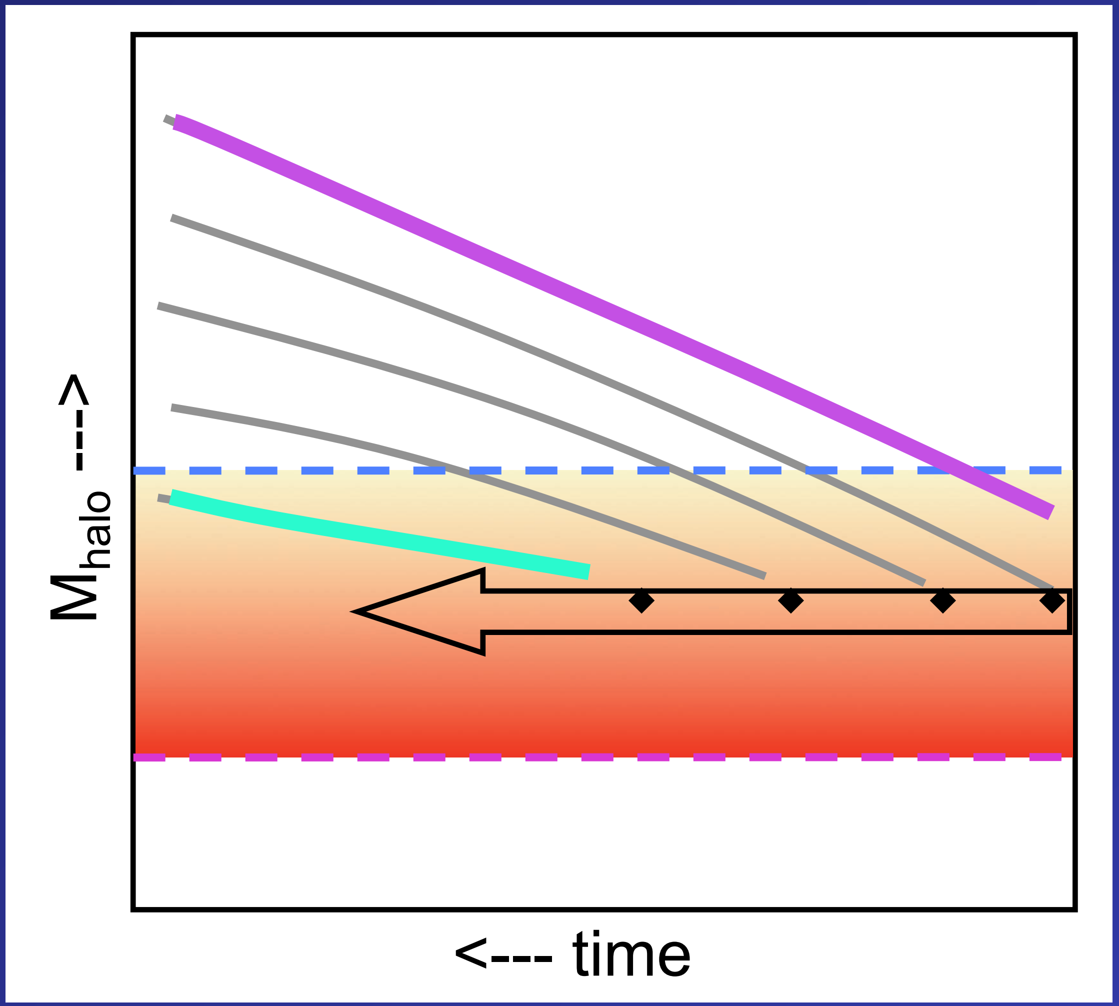
2) Stellar mass follows halo mass until M_{halo} crosses M_{crit}.

SAMs: $M_{star} \sim 0.05\ M_{halo}$

3) A ***mass sequence*** comes from the fact that different halo masses enter the star-forming band at different times. A galaxy's position is determined by its ***entry redshift*** into the band. More massive galaxies enter earlier. Thus:

z_{entry} <--> M_{halo} <--> M_{star}

Implications and Predictions of the Model



Massive galaxies:

- Started forming stars early.
- Shut down early.
- Are red today.
- Populate dark halos that are much more massive than their stellar mass.

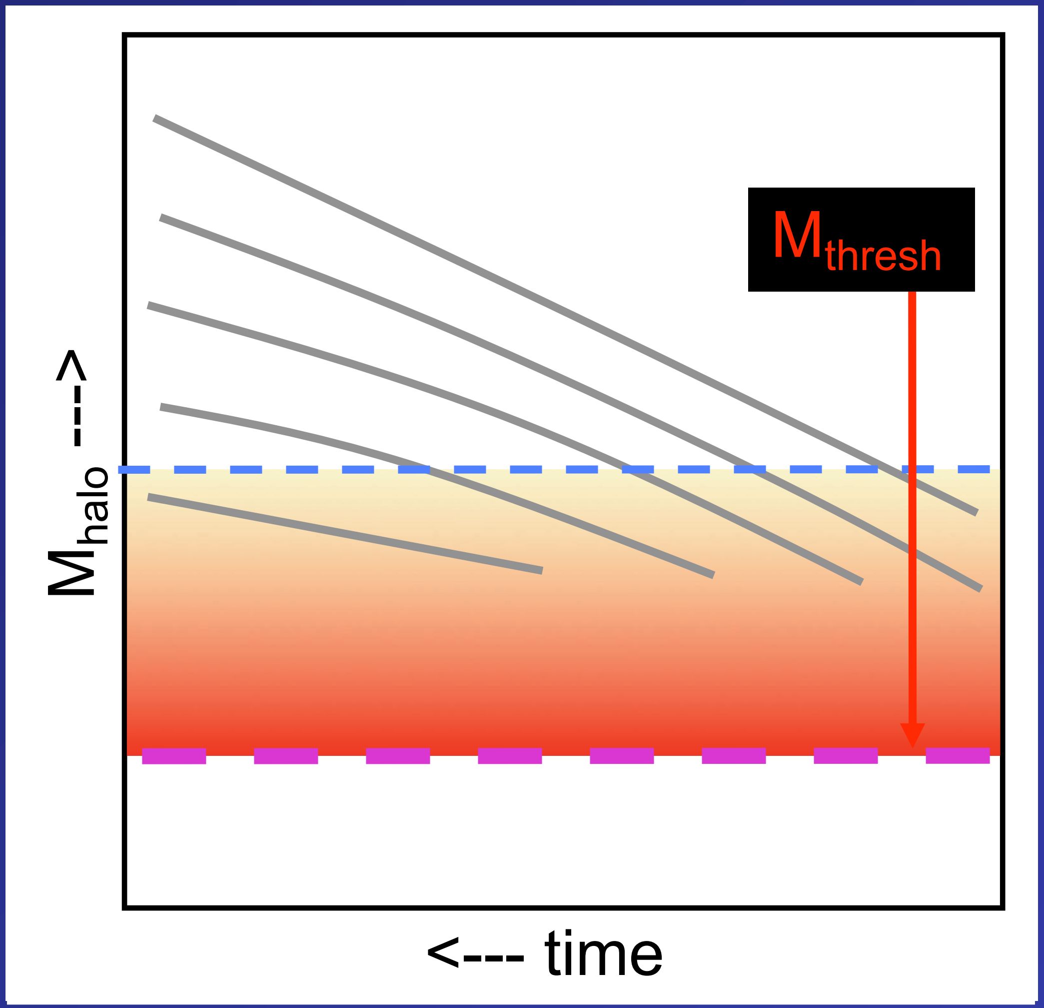
Small galaxies:

- Started forming stars late.
- Are still making stars today.
- Are blue today.
- Populate dark halos that match their stellar mass.

"Downsizing"

Star formation is a wave that started in the largest galaxies and swept down to smaller masses later (Cowie et al. 1996).

Theories for the ***lower*** halo star-formation boundary



M_{thresh} is the halo mass at the LOWER edge of the star-formation band, roughly 10^{10} $M_{\odot}$.

Not yet well understood

1. Supernova feedback (Dekel & Silk 1985):

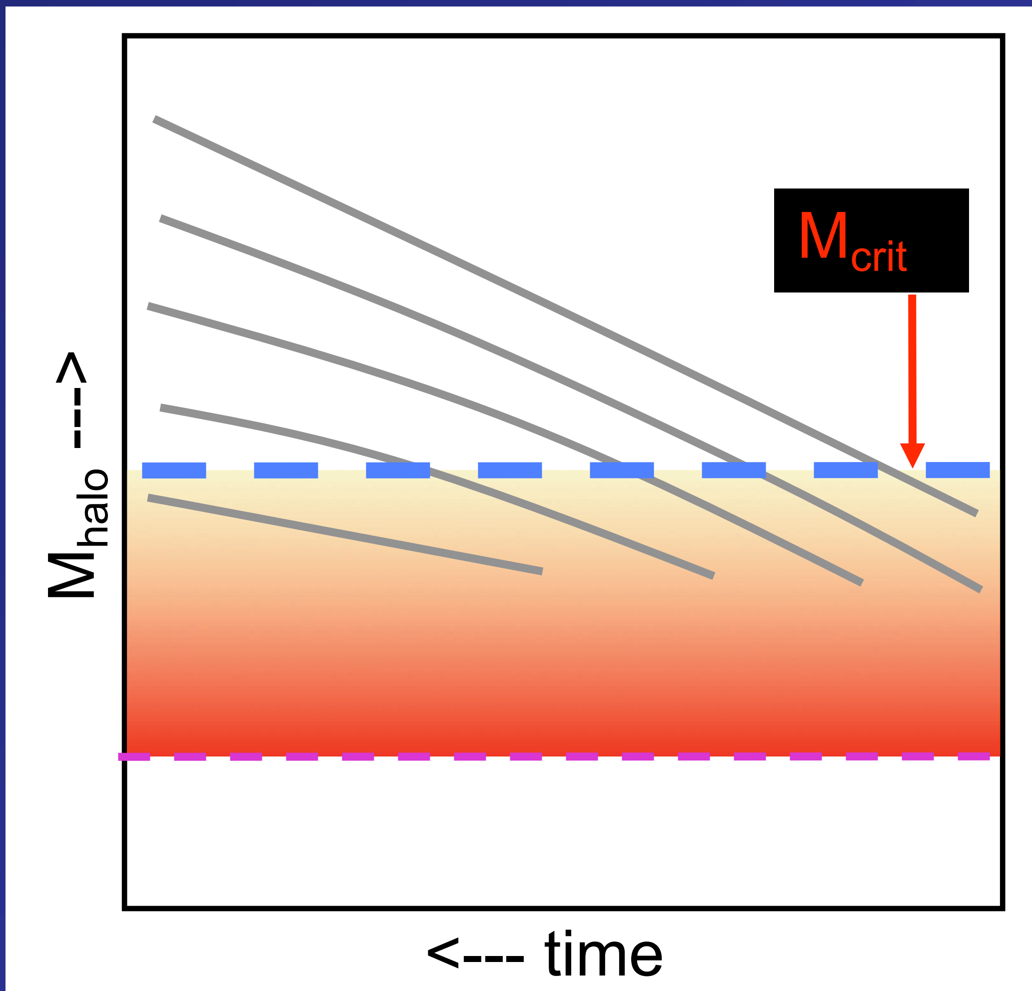
   $v_{lim} < 100$ km/sec

2. Early Universe reionization (e.g., Somerville 2002):

   $v_{lim} < 30$ km/sec

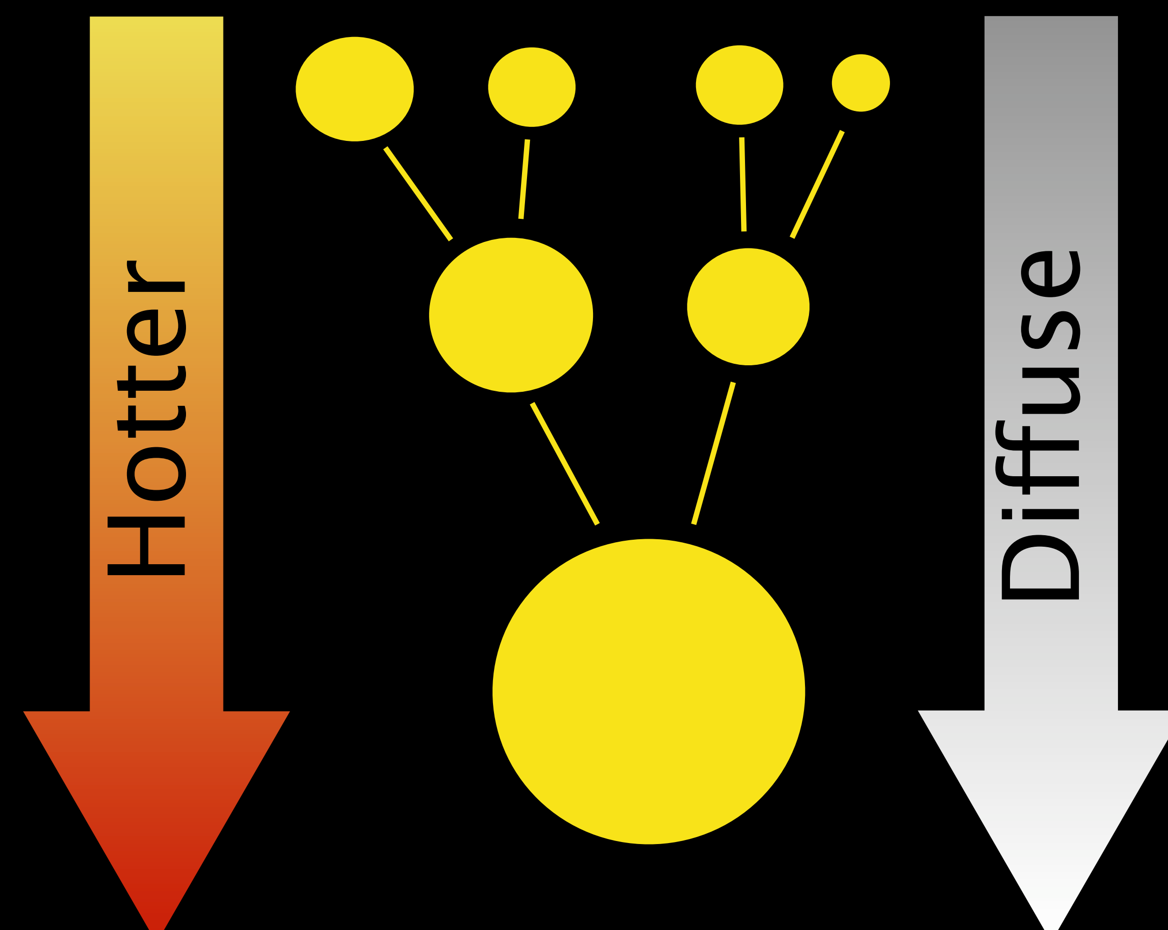
3. Plus tidal destruction!

Theories for the ***upper*** halo star-formation boundary

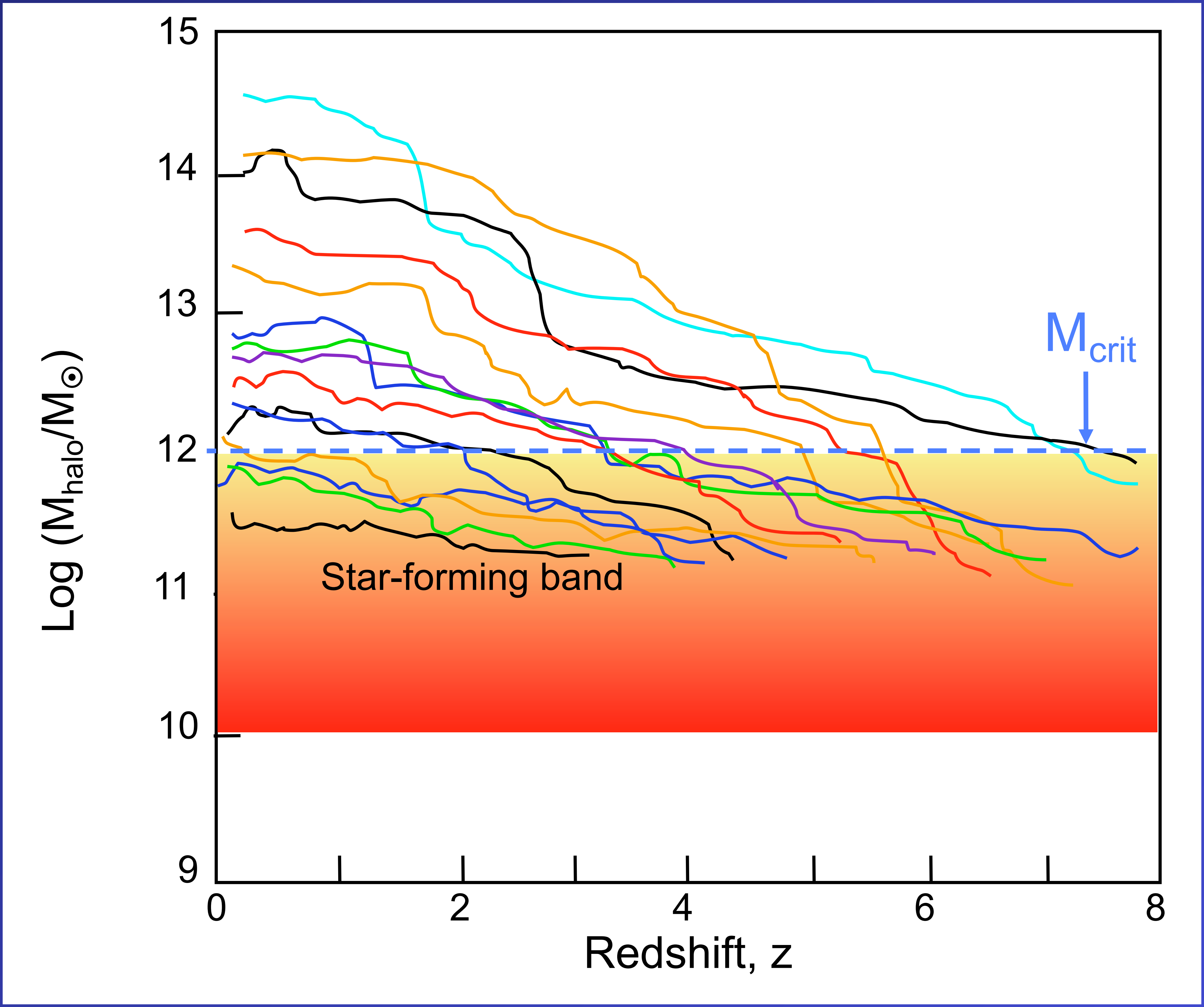


M_{crit} is the halo mass at the UPPER edge of the star-formation band, roughly 10^{12} M_X.

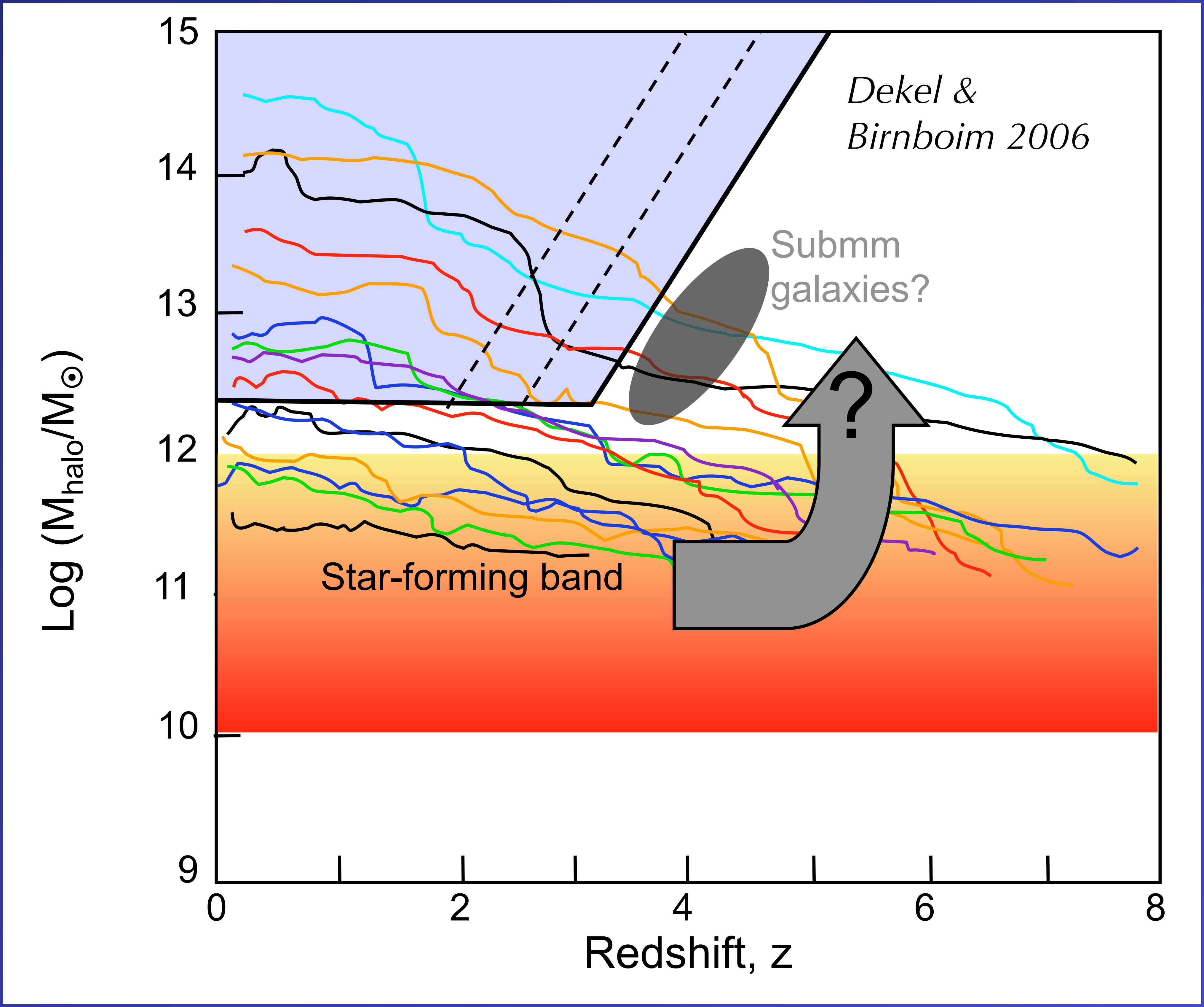
1 Gas in halos above the critical halo mass $M_{crit} \sim 10^{12}$ $M_\odot$ cannot cool (Ostriker & Rees 1978, Blumenthal et al. 1984, Dekel & Birnboim 2007).



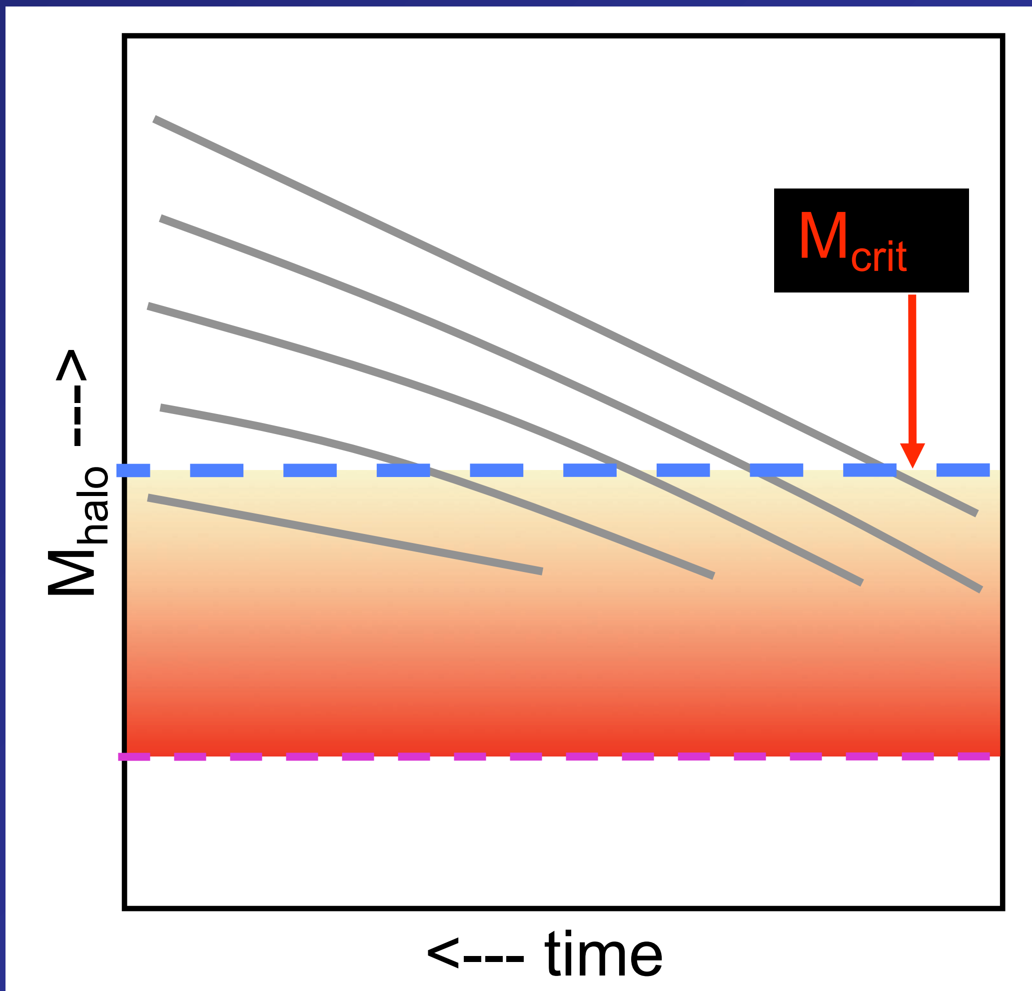
More realistic model of halo-cooling boundary



More realistic model of halo-cooling boundary

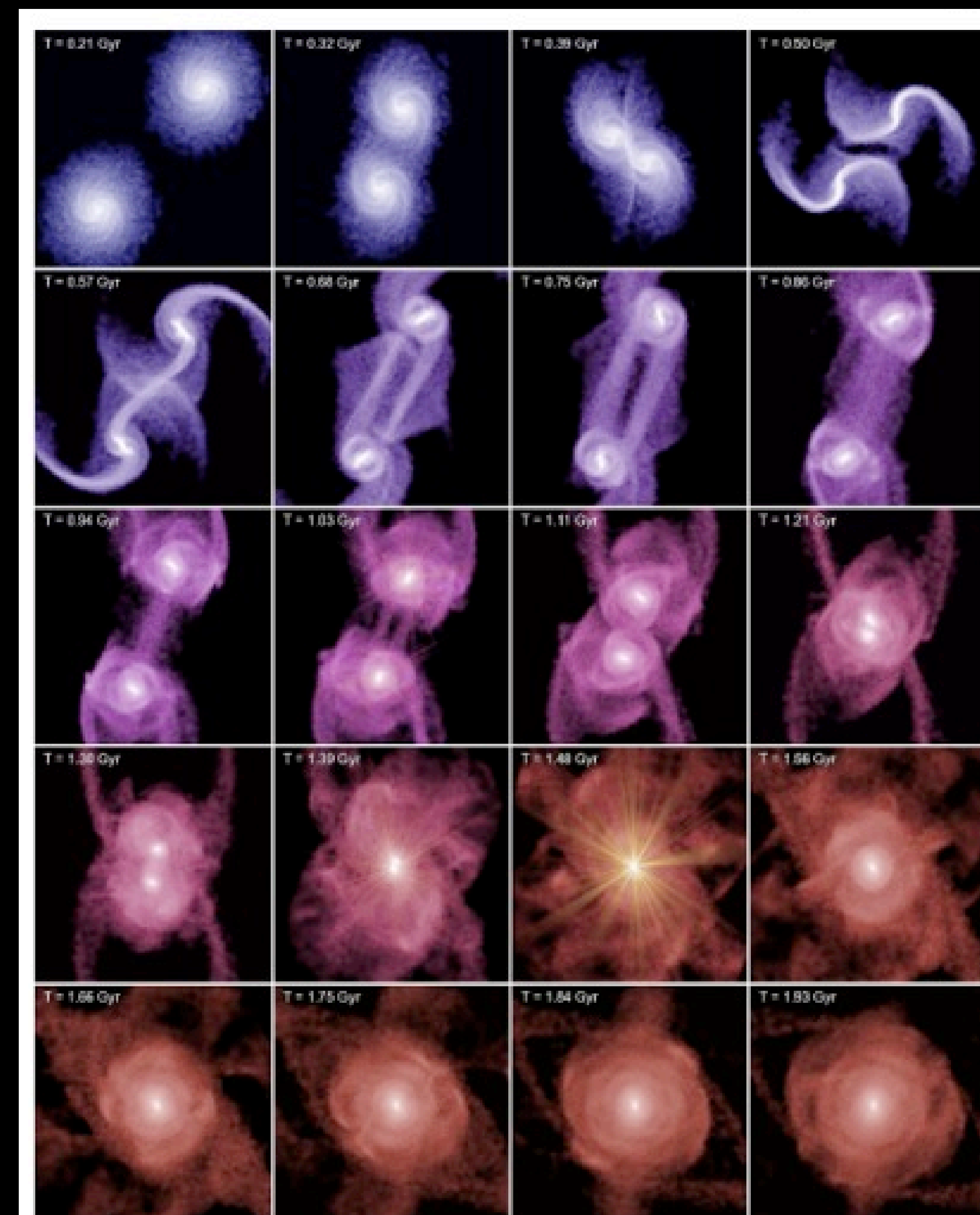


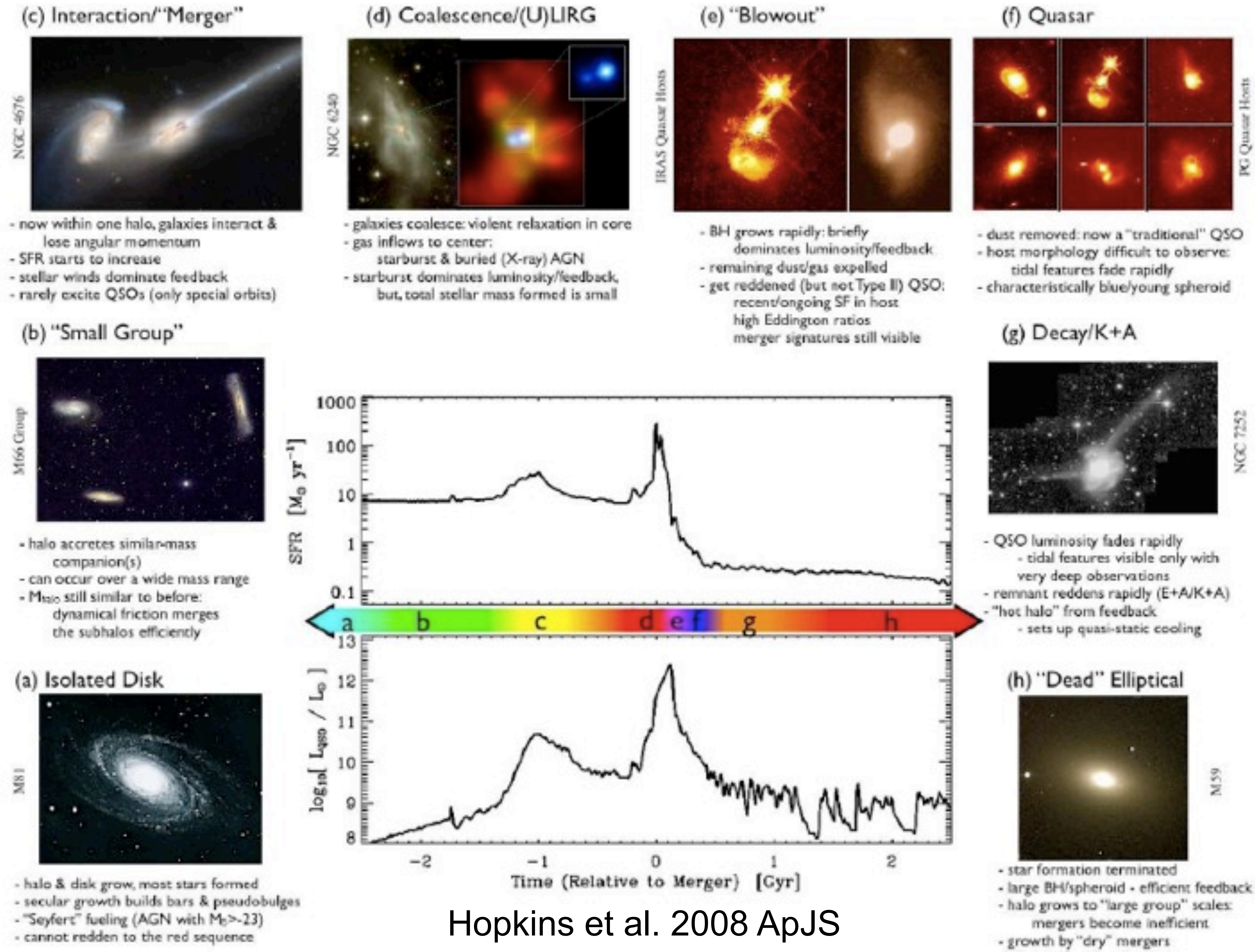
Theories for the *upper* halo star-formation boundary



M_{crit} is the halo mass at the UPPER edge of the star-formation band, roughly 10^{12} M_X.

2 Merging galaxies trigger BH growth. AGN feedback drives out galaxy gas (Hopkins et al 2006).

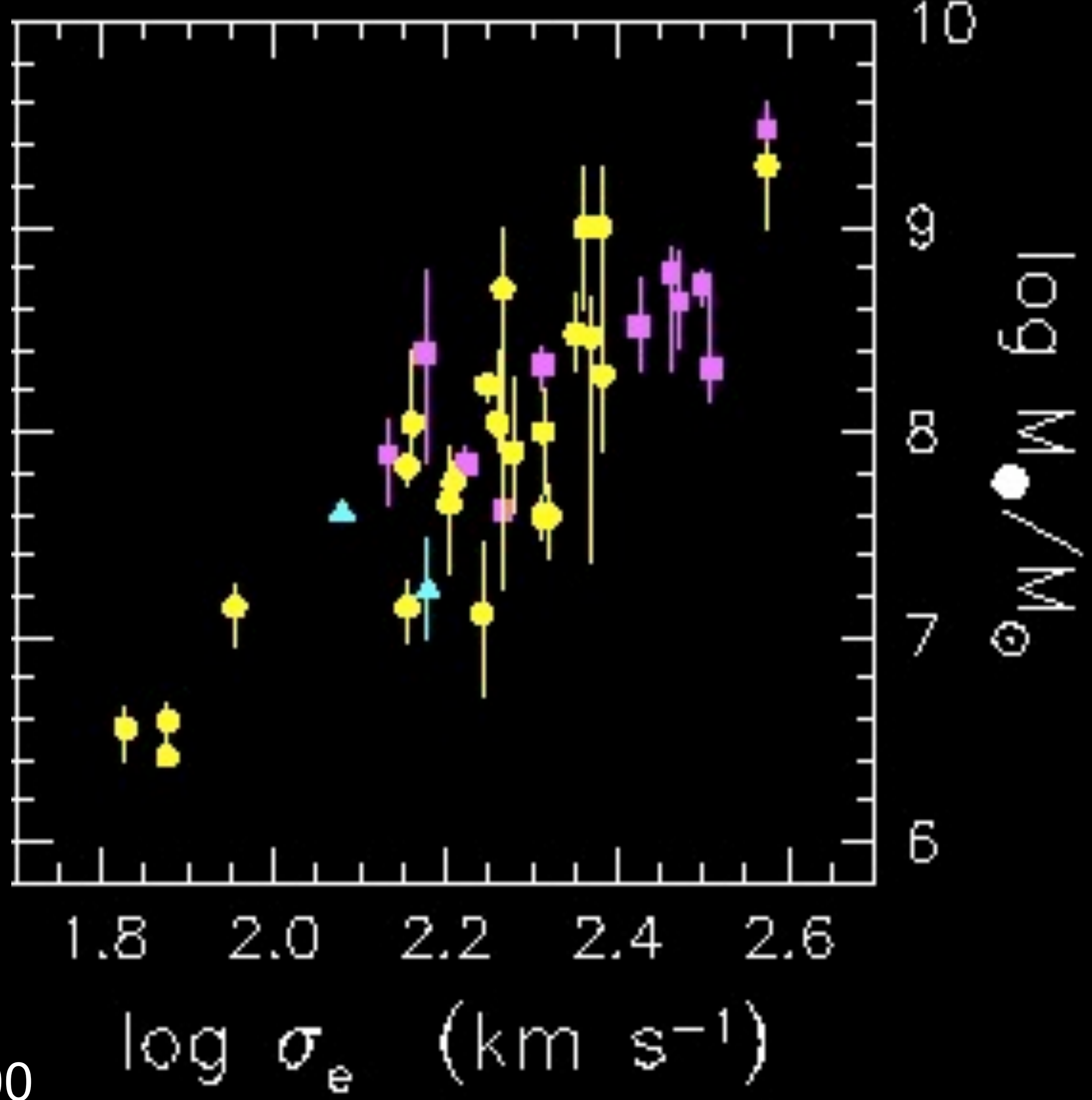




Hopkins et al. 2008 ApJS

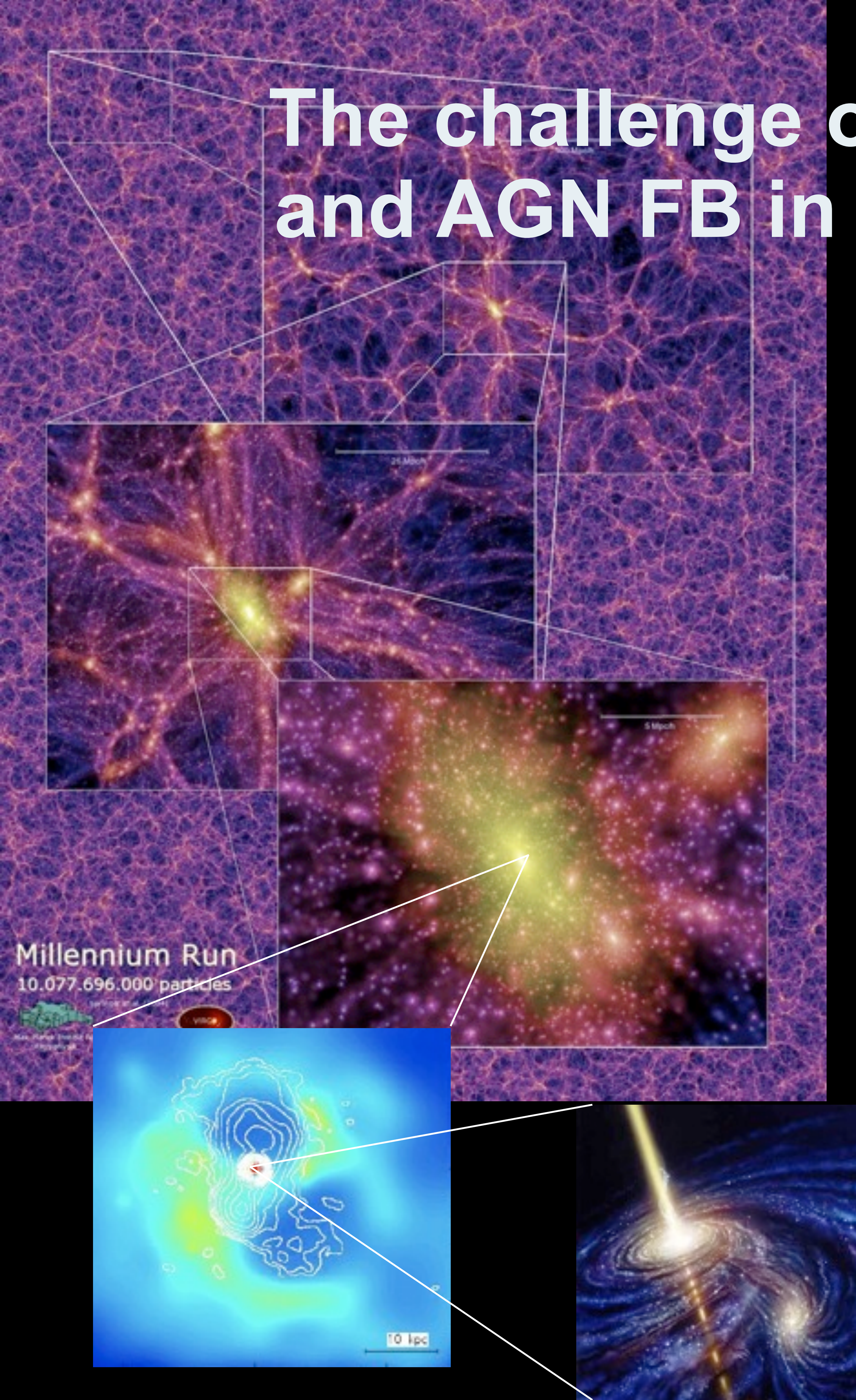
Why AGN Feedback Can Make Massive Galaxies Red/Dead

- Need mechanism to
  - quench star formation in massive galaxies
  - stop cooling in clusters
- SN feedback inadequate: not enough energy, little star formation in red galaxies
- BH mass closely connected with host galaxy's spheroid mass
- Bigger BH $\Rightarrow$ more energy ($L_{max} \sim L_{Edd} \sim M_{BH}$)



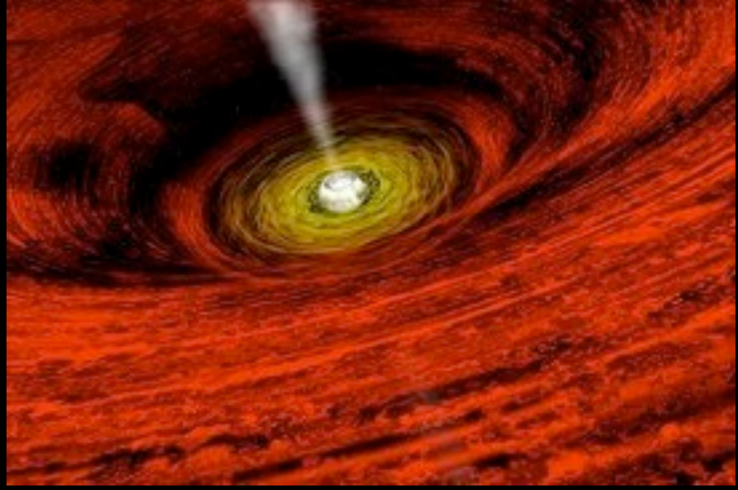
Magorrian et al. 1998;
Gebhardt et al. 2000,
Ferrarese & Merritt 2000

The challenge of simulating BH growth and AGN FB in a cosmological context



- dynamic range:
  - Gpc (luminous QSO)
  - few 100 Mpc (LSS)
  - 10’s of kpc (ICM, jets)
  - sub-kpc (star formation, stellar FB)
  - few 100 pc (nuclear gas inflows, starbursts, AGN feeding, winds)
  - pc & sub-pc (accretion disk, BH mergers, etc)
- poorly understood physics (B-fields, conduction, cosmic ray pressure, turbulence, feeding problem, ...)

AGN feedback 1: bright mode

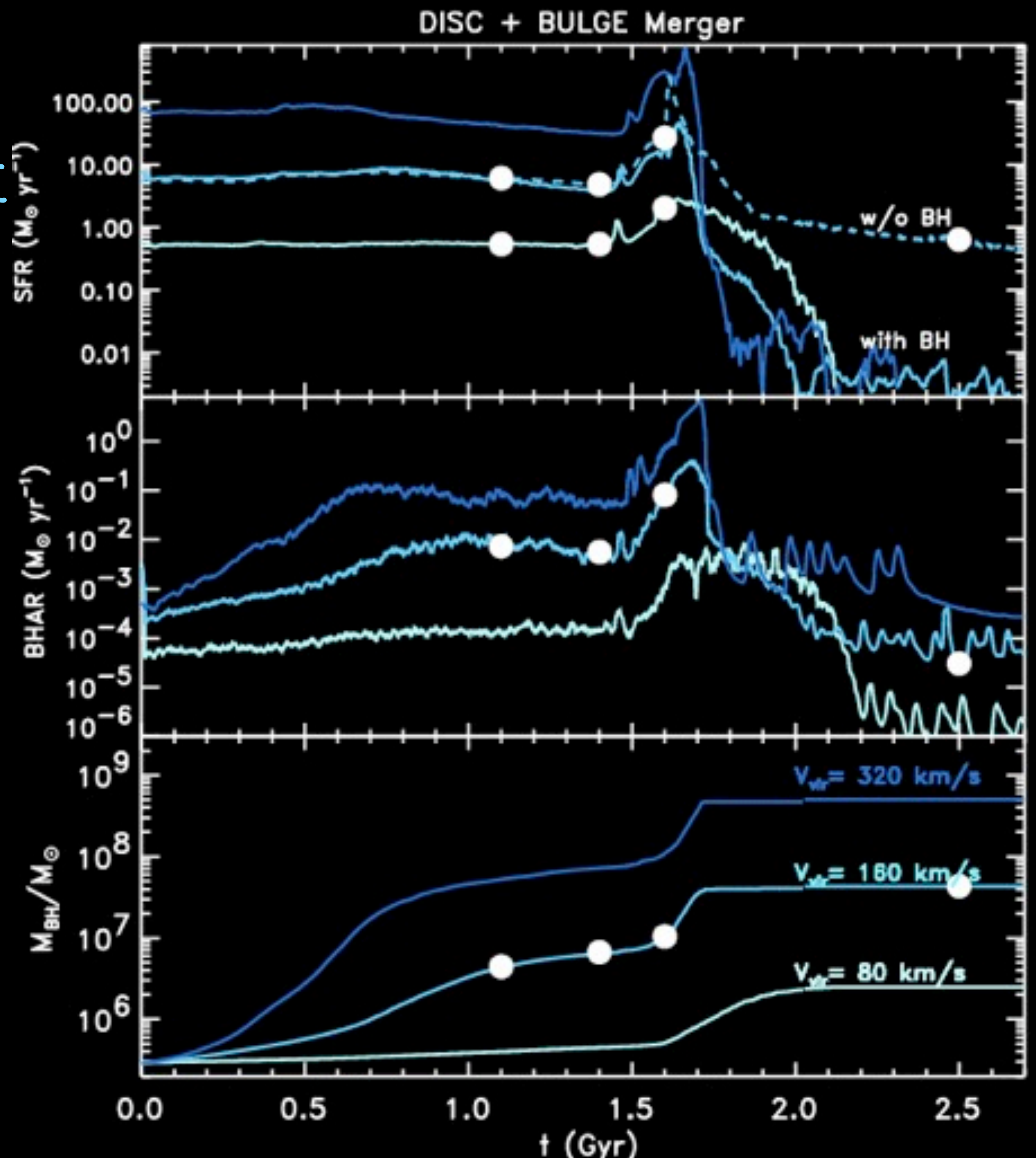


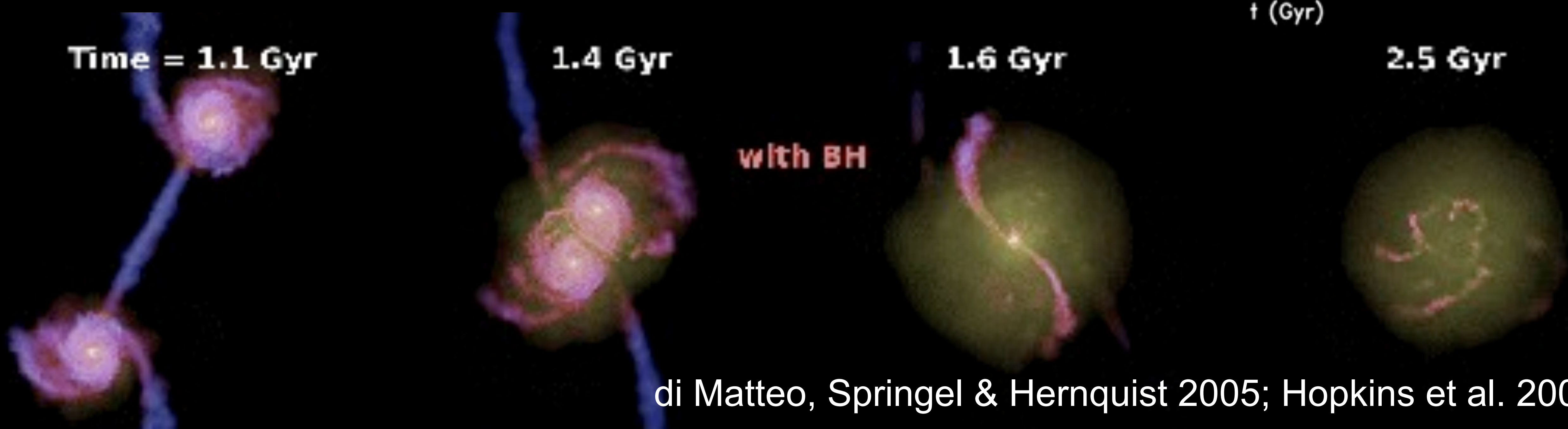
- optical/X-ray luminous AGN/QSO, produced during periods of efficient feeding (mergers?)
- high accretion rates (0.1-1 L_{Edd}), fueled by cold gas via thin accretion disk --> BH grows rapidly
- rare-->duty cycle short
- thermal coupling of AGN energy with ISM is probably fairly weak (<5%)

Di Matteo, Springel & Hernquist 2005

Hydrodynamic simulations of galaxy mergers including black hole growth and feedback

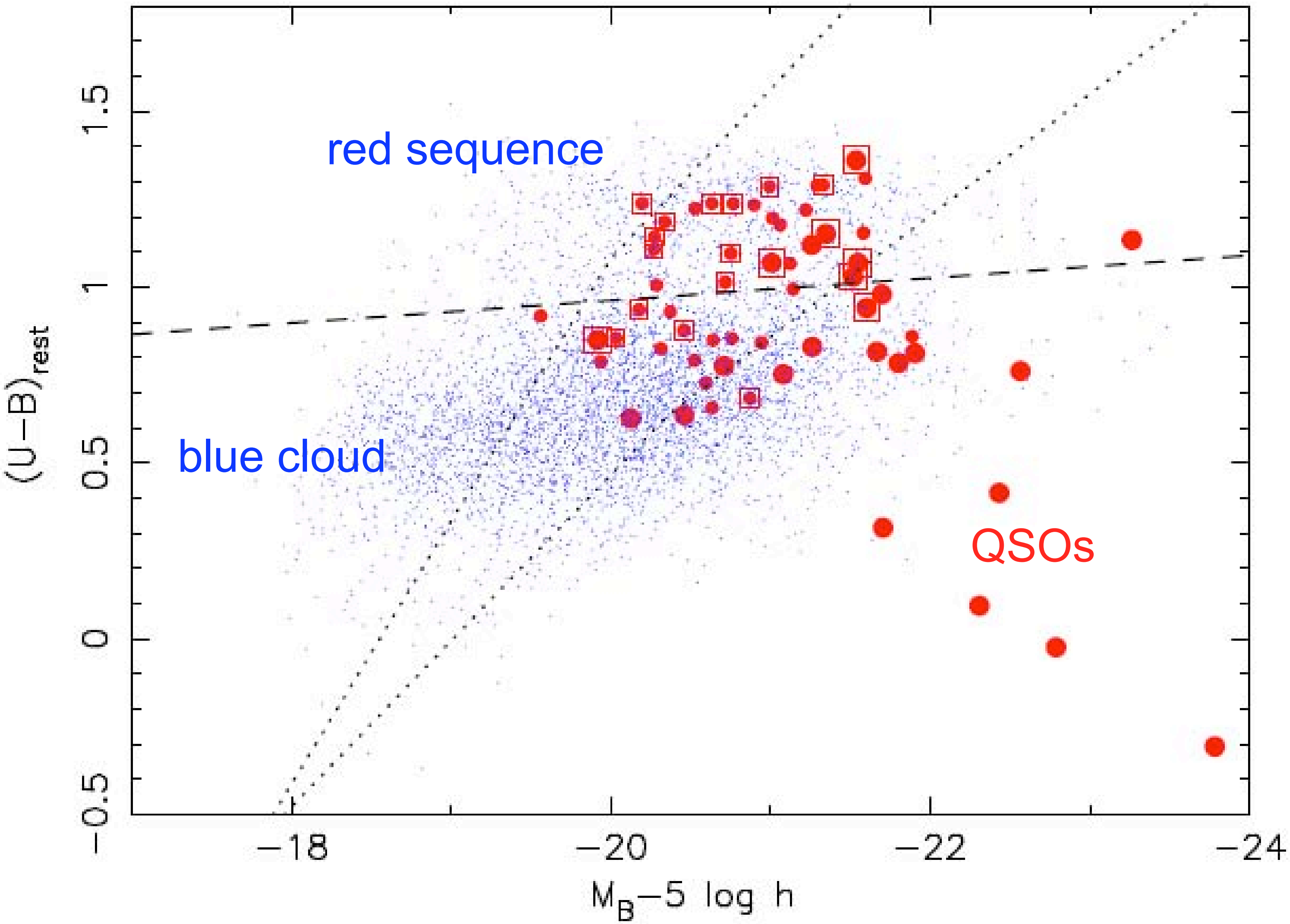
- self-regulated BH growth, reproducing M_{BH}-σ relation (di Matteo et al. 2004)
- AGN-driven wind removes residual cold gas at the end of the merger, leading to lower SFR and redder colors in the spheroidal remnant (Springel et al. 2004)





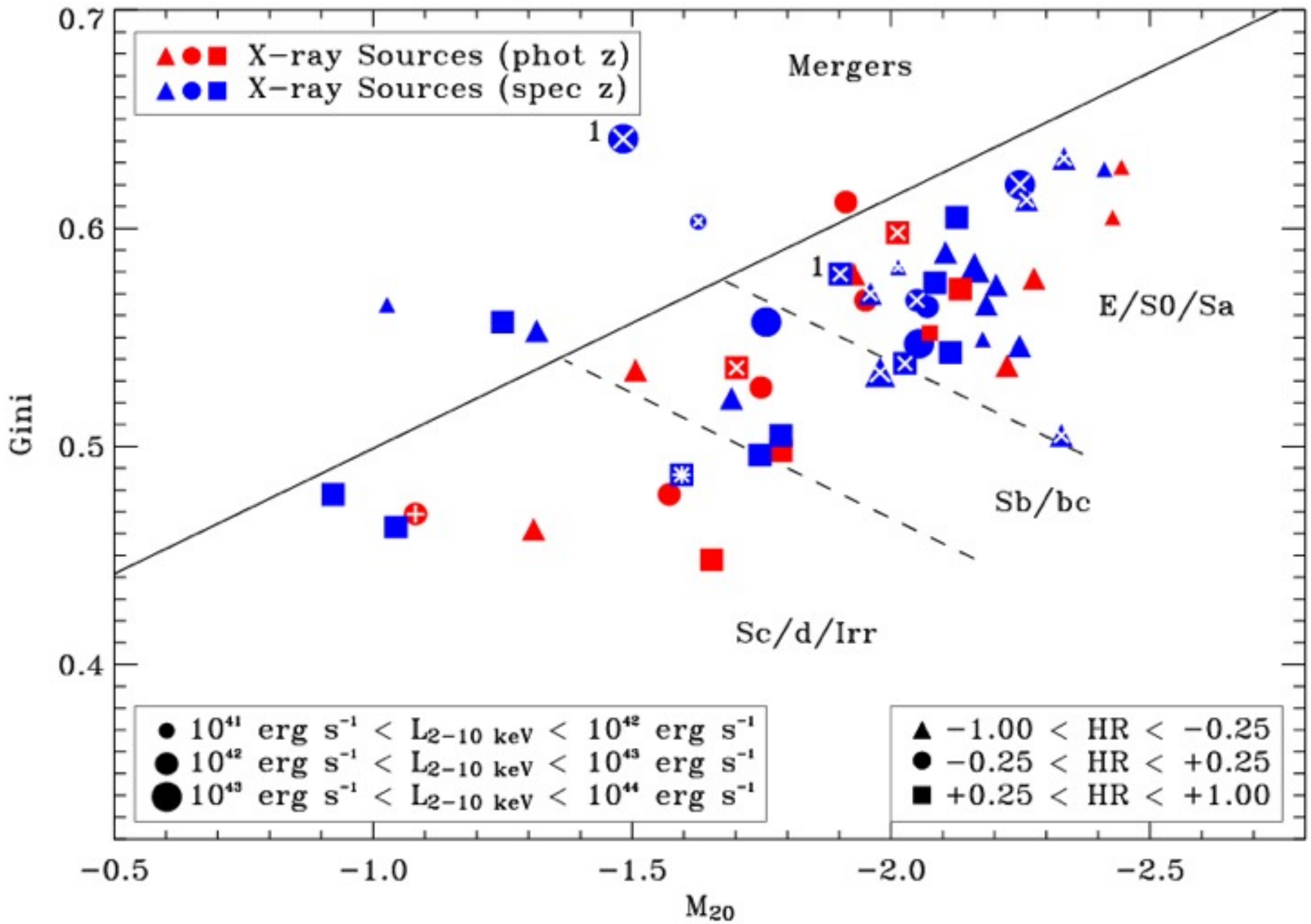
di Matteo, Springel & Hernquist 2005; Hopkins et al. 2006-

Color-Magnitude Diagram of EGS X-ray selected AGN

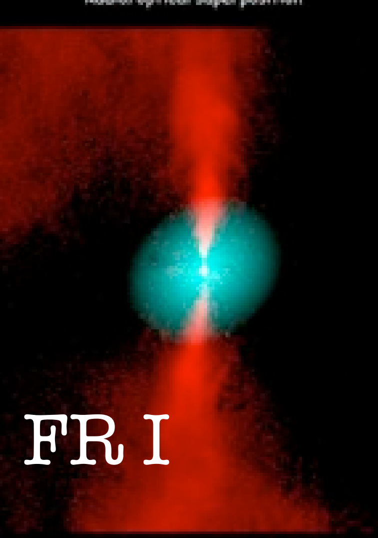


Rest-frame U-B colour is plotted against the B-band absolute magnitude for DEEP2 comparison galaxies (small blue dots) and X-ray sources (filled red circles) in the EGS in the range $0.7 < z < 1.4$. Squares around the symbols indicate hard X-ray sources, and more luminous systems ($L_X > 10^{43}$ erg s^{-1}) are plotted with larger symbols. The dashed line separates red and blue galaxies, and the dotted lines show the DEEP2 completeness limits at $z = 1.0$ and $z = 1.4$. (Nandra et al., ApJ Letters, 2007.)

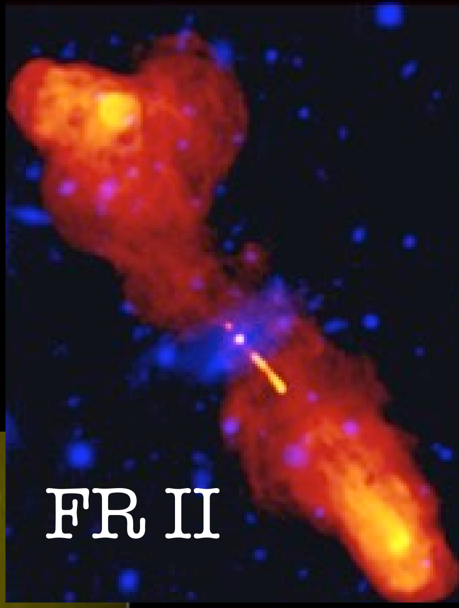
Morphological distribution of EGS X-ray selected AGN



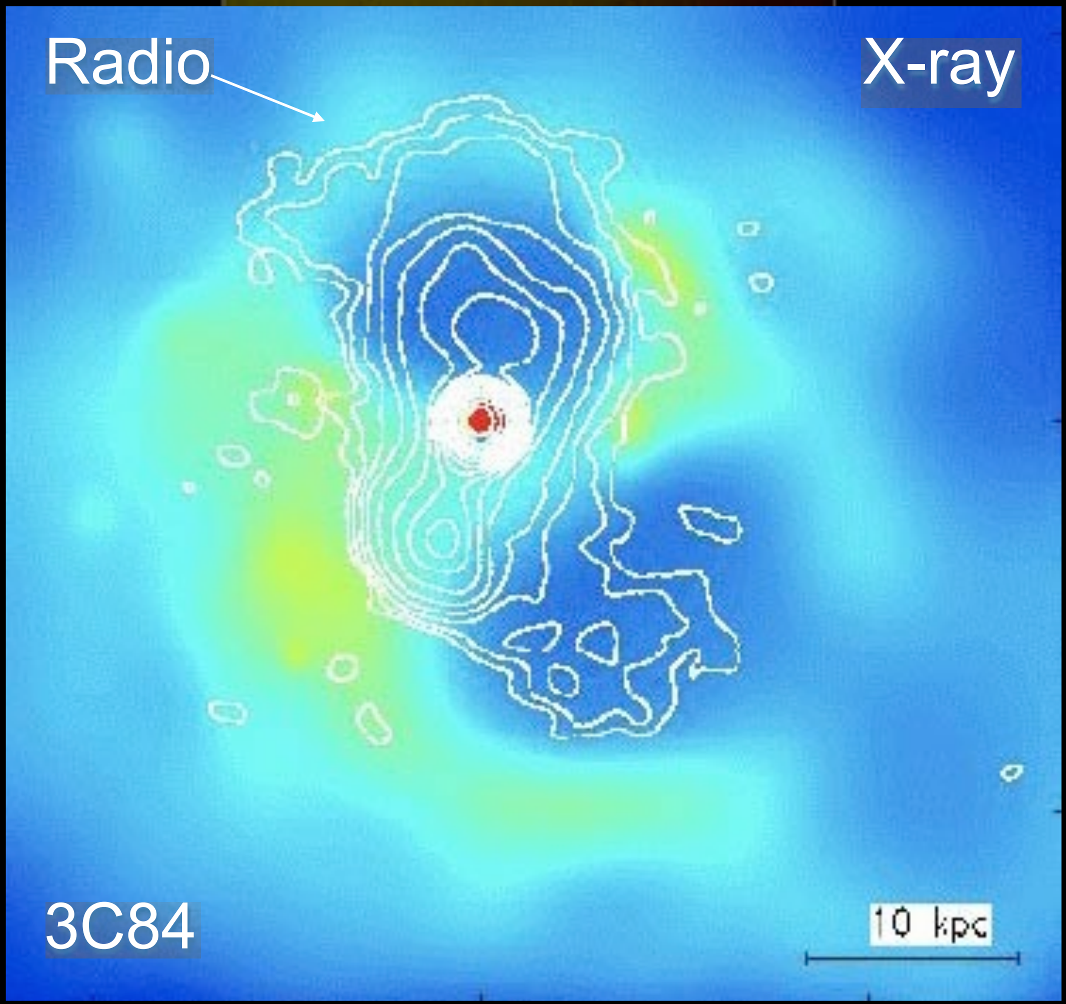
The highest fraction of EGS galaxies hosting AGN are early-types, not mergers. This suggests that the AGN activity is delayed, rather than occurring mainly during and immediately following mergers as the Hopkins et al. simulations predicted. (Christy Pierce et al., ApJ Letters, May 2007).



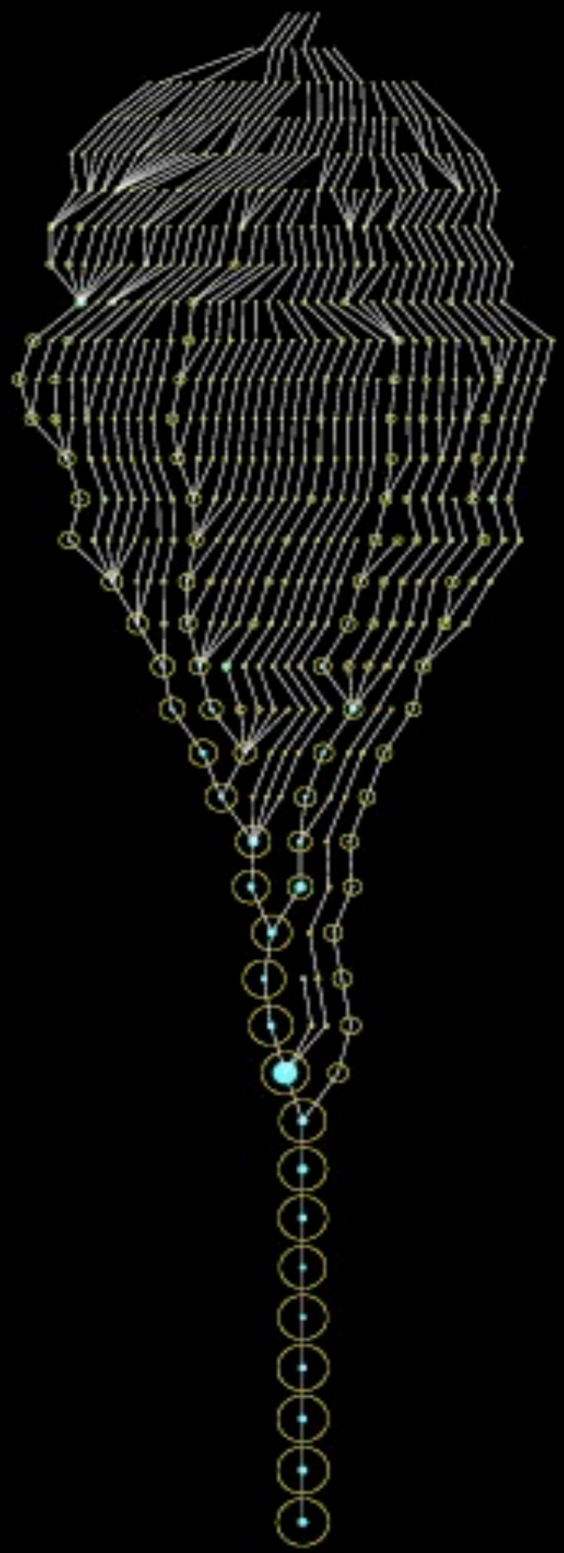
AGN feedback 2: Radio Mode



- some massive galaxies are 'radio loud'
- radio activity believed to be associated with BH's in 'low accretion state' (low Eddington ratio, $<10^{-3}$)
- jets often associated with cavities visible in X-ray images
- coupling of jet energy with hot gas very efficient



NEW Self-Consistent Model for the Co-Evolution of Galaxies, Black Holes, and AGN

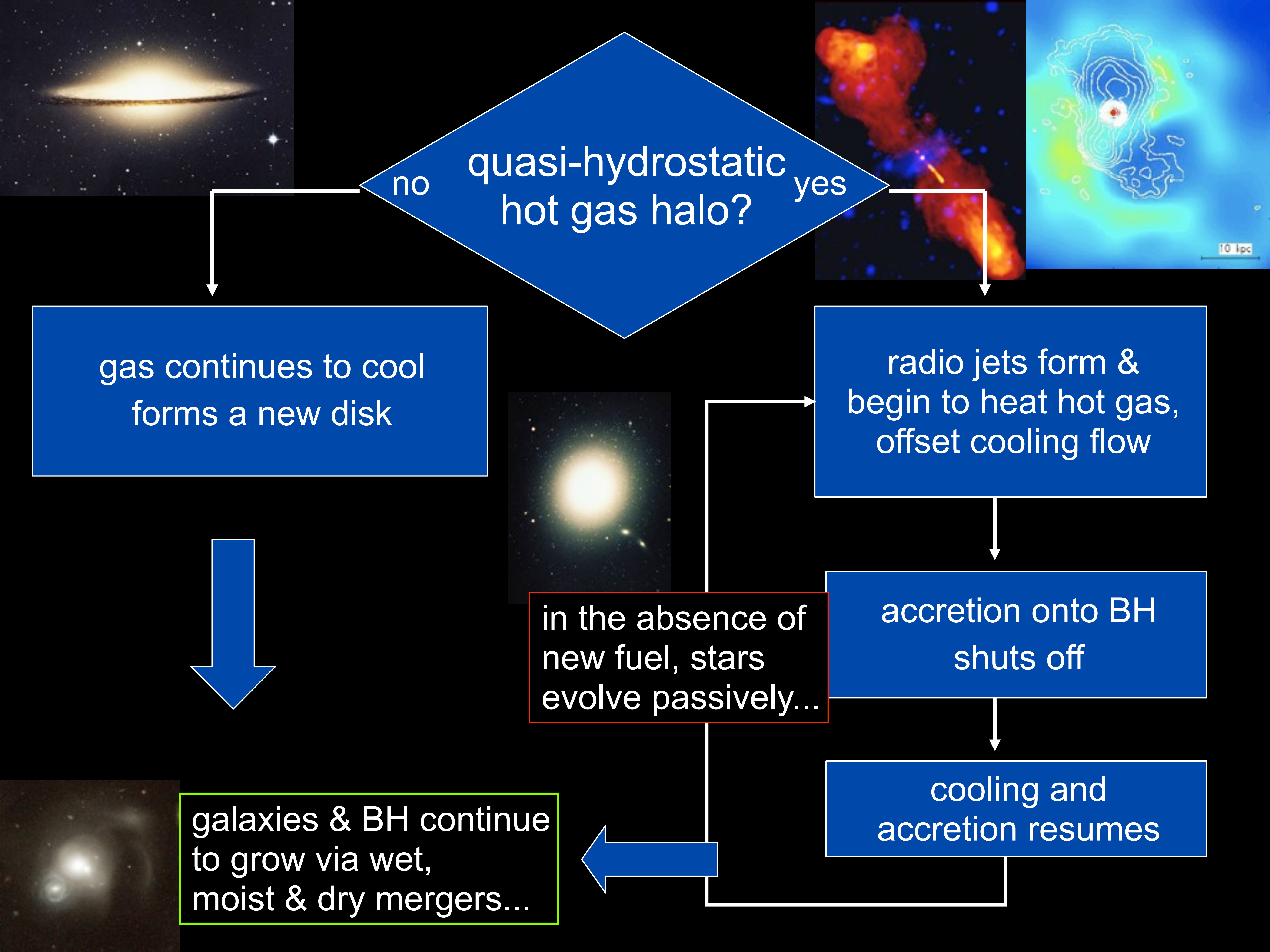


- Top-level halos start with a ~100 M_{sun} seed BH
- Mergers trigger bursts of star formation and accretion onto BH; efficiency and timescale parameterized based on hydrodynamical merger simulations (μ, B/T, V_c, f_g, z; Cox et al., Robertson et al.)
- BH accrete at Eddington rate until they reach 'critical mass', then enter 'blowout' (power-law decline) phase

$$dm_{acc}/dt = \dot{m}_{Edd}/[1+(t/t_Q)^{\beta}]$$

- Energy released by accretion drives a wind
- BH merge when their galaxies merge; mass is conserved

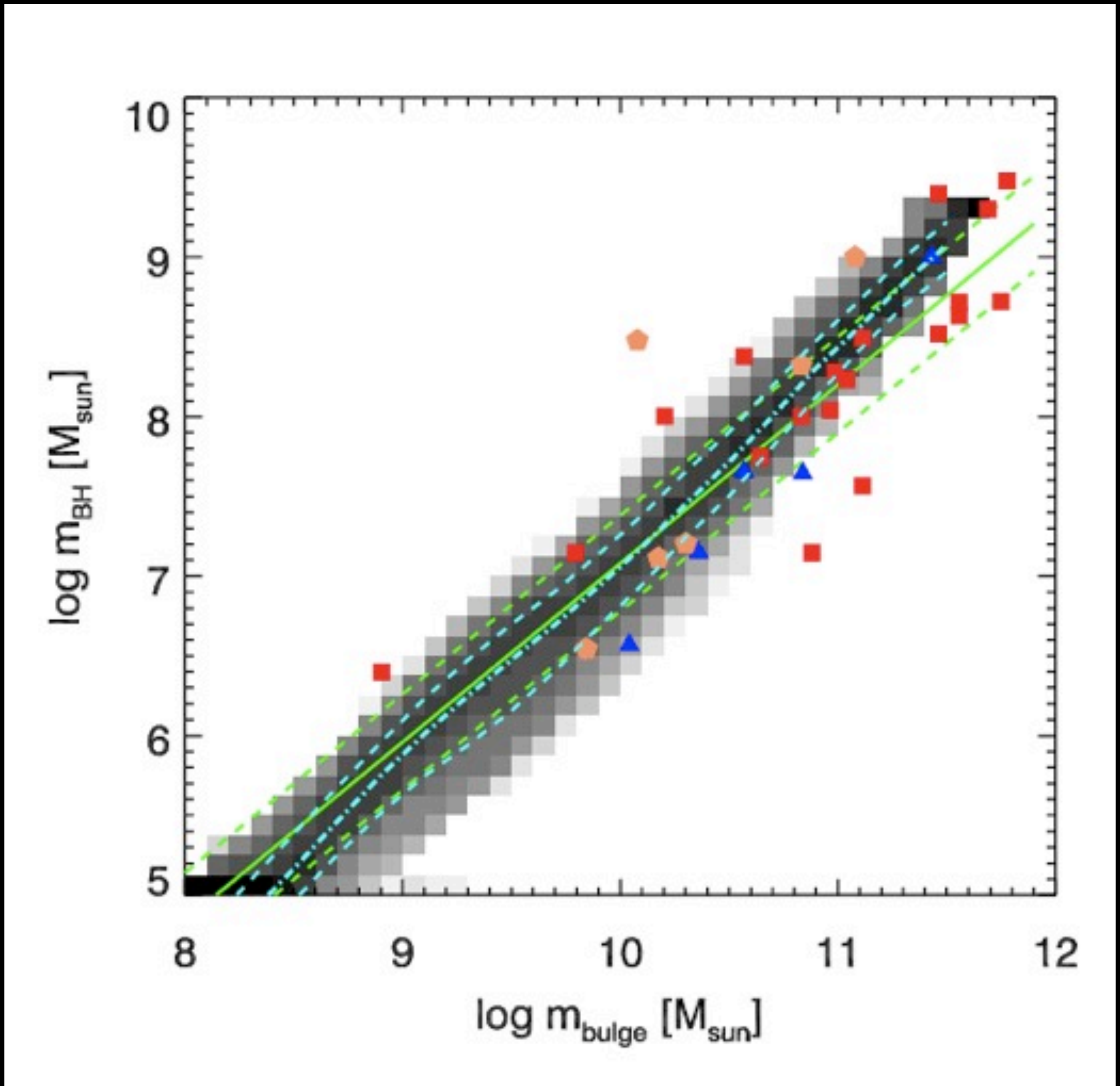
Somerville, Hopkins, Cox, et al. 2008 MN



quasi-hydrostatic hot gas halo?
no
yes
gas continues to cool forms a new disk
radio jets form & begin to heat hot gas, offset cooling flow
accretion onto BH shuts off
cooling and accretion resumes
in the absence of new fuel, stars evolve passively...
galaxies & BH continue to grow via wet, moist & dry mergers...

Predicted M_{BH}-M_{bulge} relationship

in Somerville+08 model, arises from 'bright mode' feedback



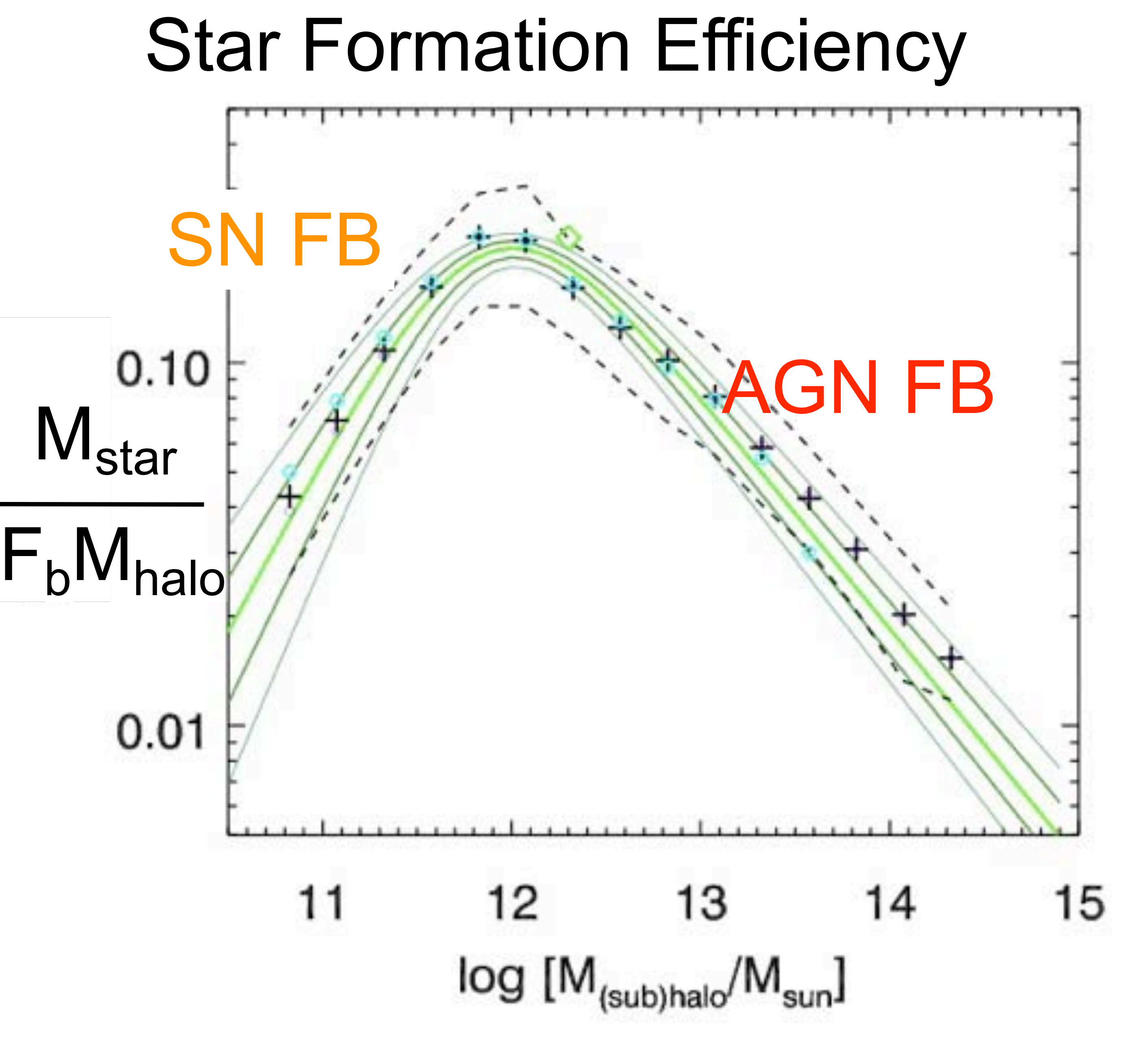
matches slope & scatter of observed relation

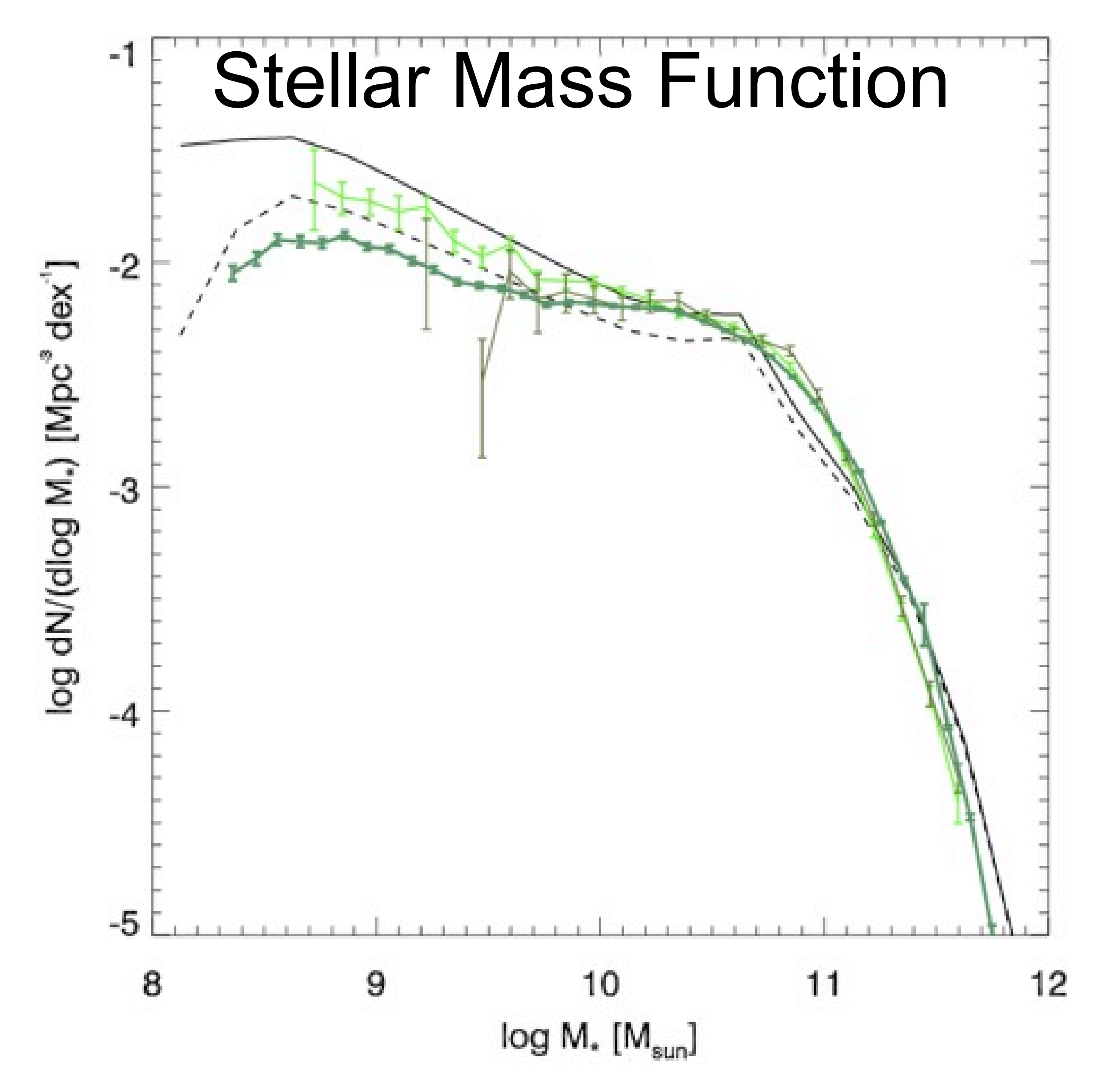
large symbols:
Haering & Rix data
green: H&R fit + scatter
intrinsic scatter: 0.3 dex

cyan: predicted median,
10th, & 90th percentile
predicted scatter:
~0.15 dex

Somerville et al. 2008

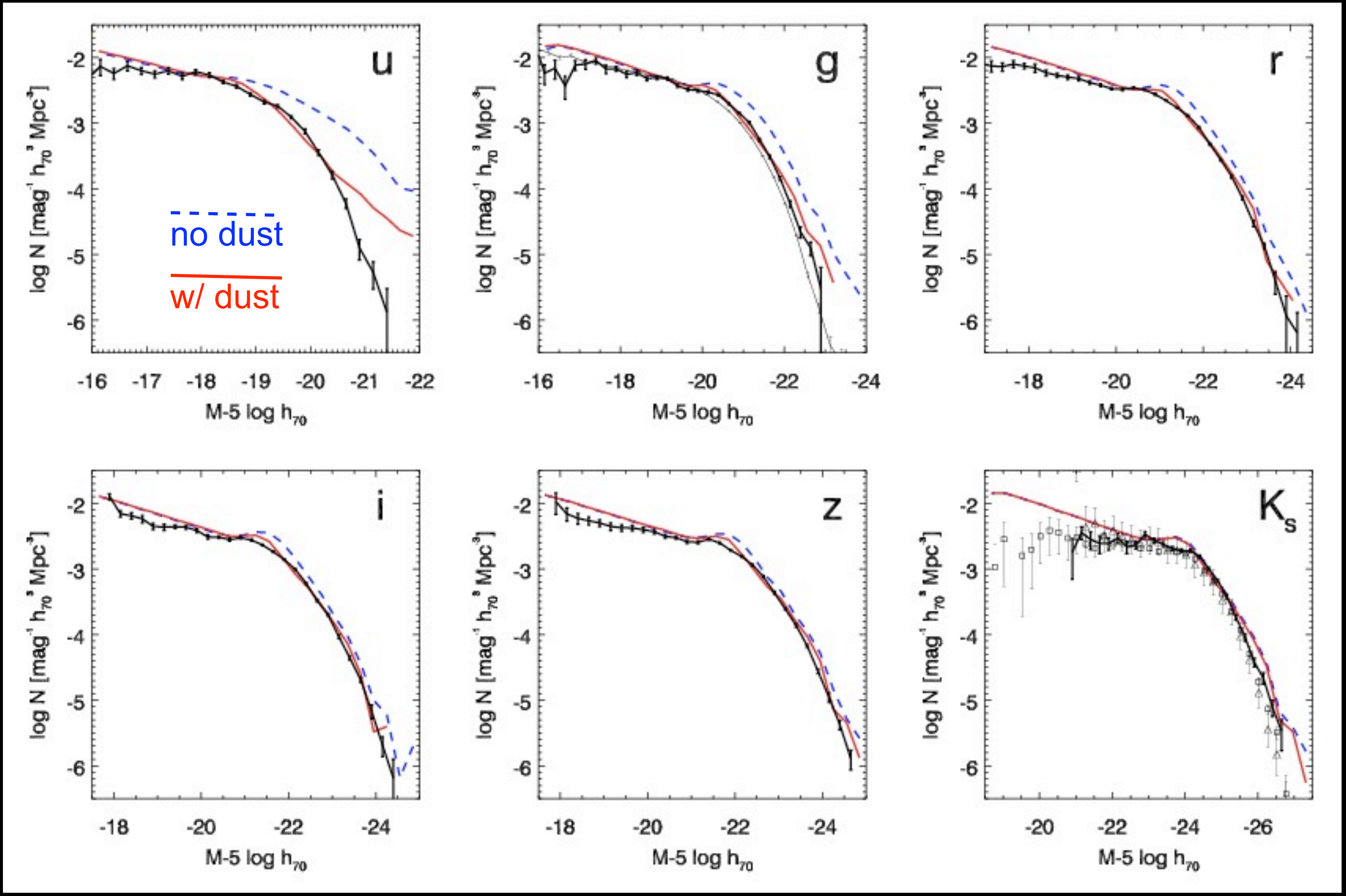
AGN Heating Leads to Galaxy Mass Functions at z~0 in Agreement with Observations





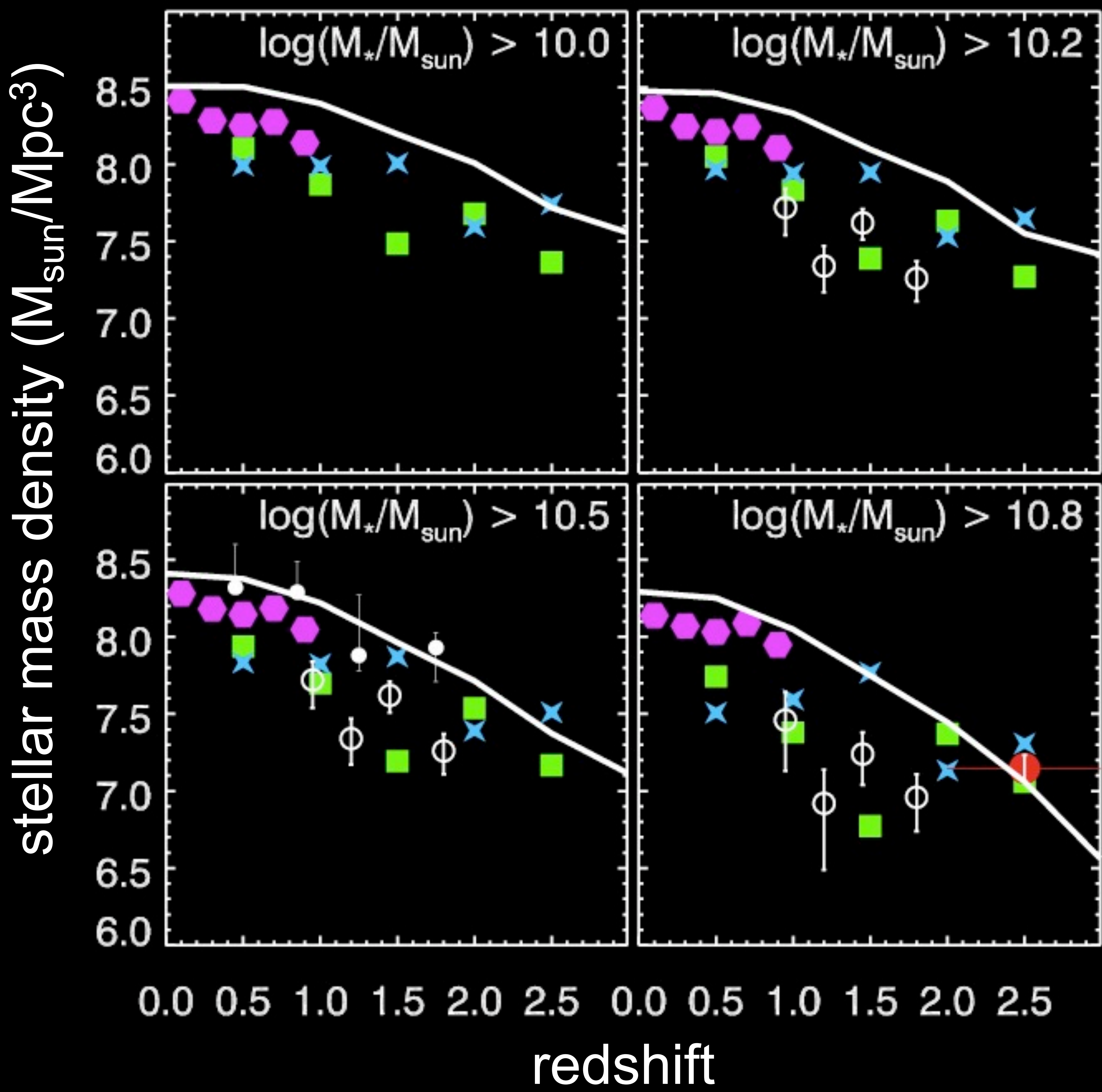
Somerville et al. 2008

Luminosity Functions



Somerville et al. 2008

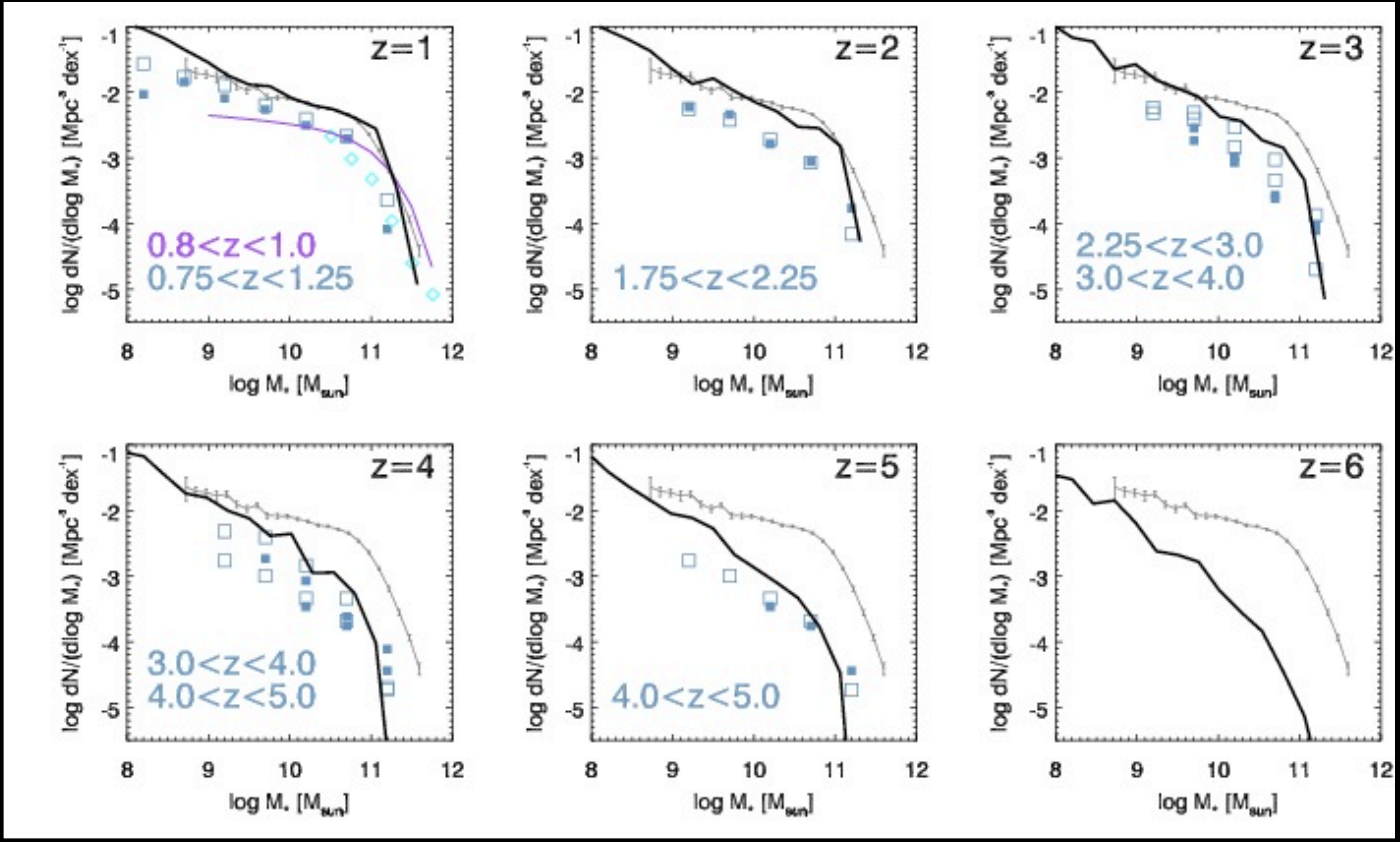
Model produces enough massive galaxies at high redshift



observations:
Borch et al. (COMBO-17)
Drory et al. (GOODS)
Glazebrook et al. (GDDS)
Fontana et al. (K20)
Papovich et al. (GOODS DRGs)

Somerville et al. 2008;
see also Bower et al.2006;
Kitzblicher & White 2006

Stellar Mass Function Evolution



data from Borch et al. (COMBO-17);
Drory et al. (MUNICS, GOODS, FDF)

Somerville et al. in prep

A Physical Model for Predicting the Properties of Spheroidal Remnants of Binary Mergers of Gas Rich Disk Galaxies

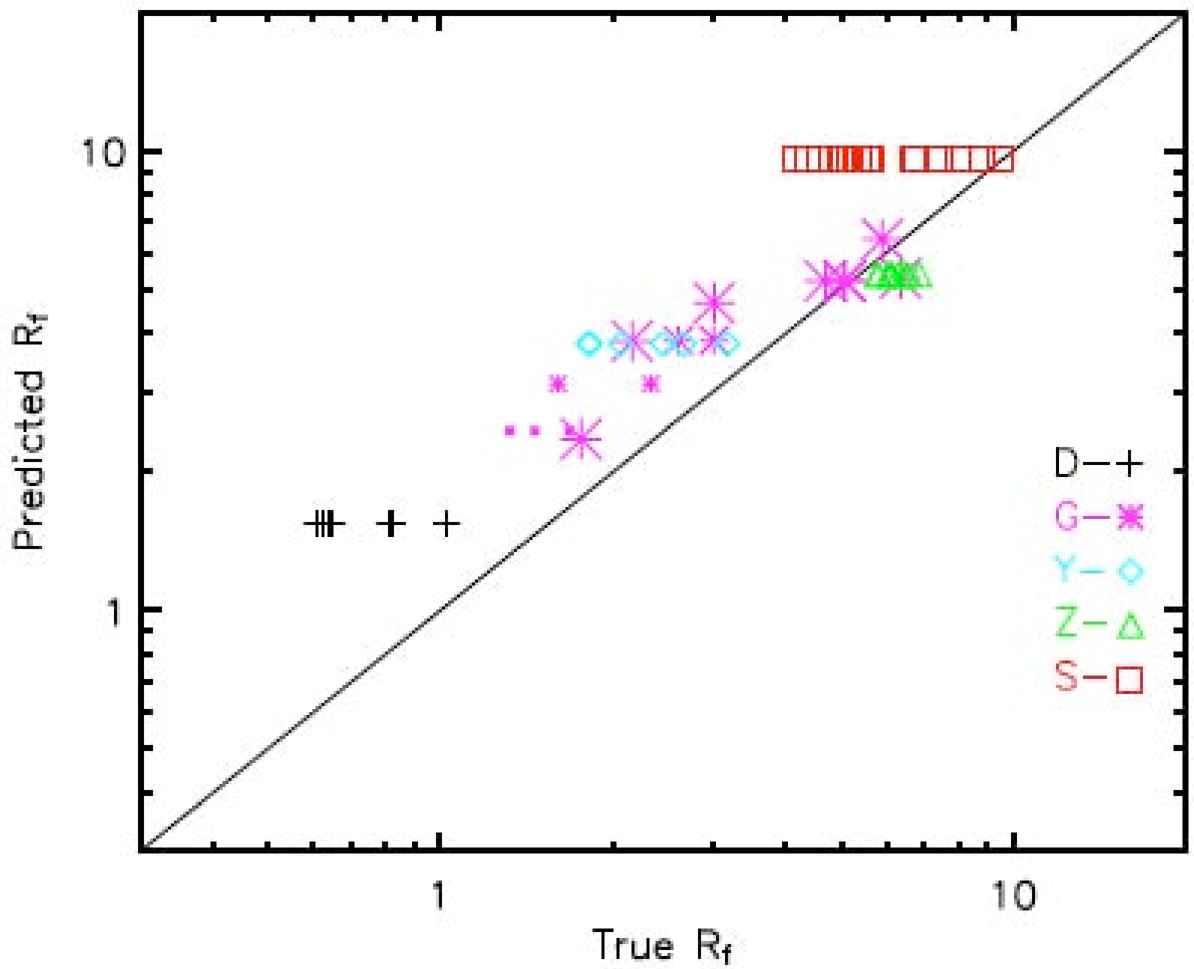
We might expect that a more energetic encounter will cause increased tidal stripping and puff up the remnant.

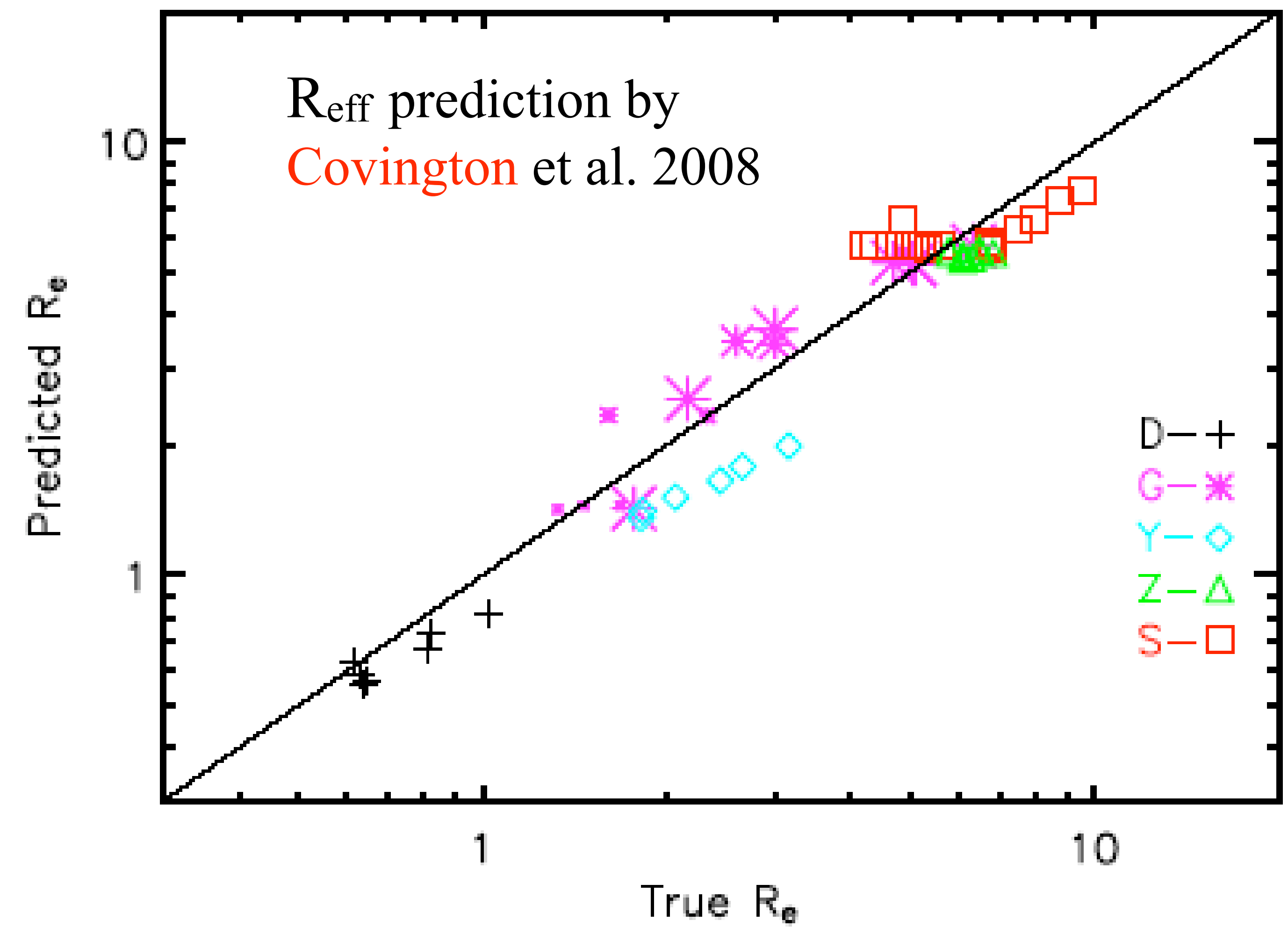
NO! For our simulations, more energetic encounters create more compact remnants.

Why? Dissipative effects cause more energetic encounters to result in smaller remnants. The greater the impulse, the more the gas is disturbed, therefore the more it can radiate and form stars.

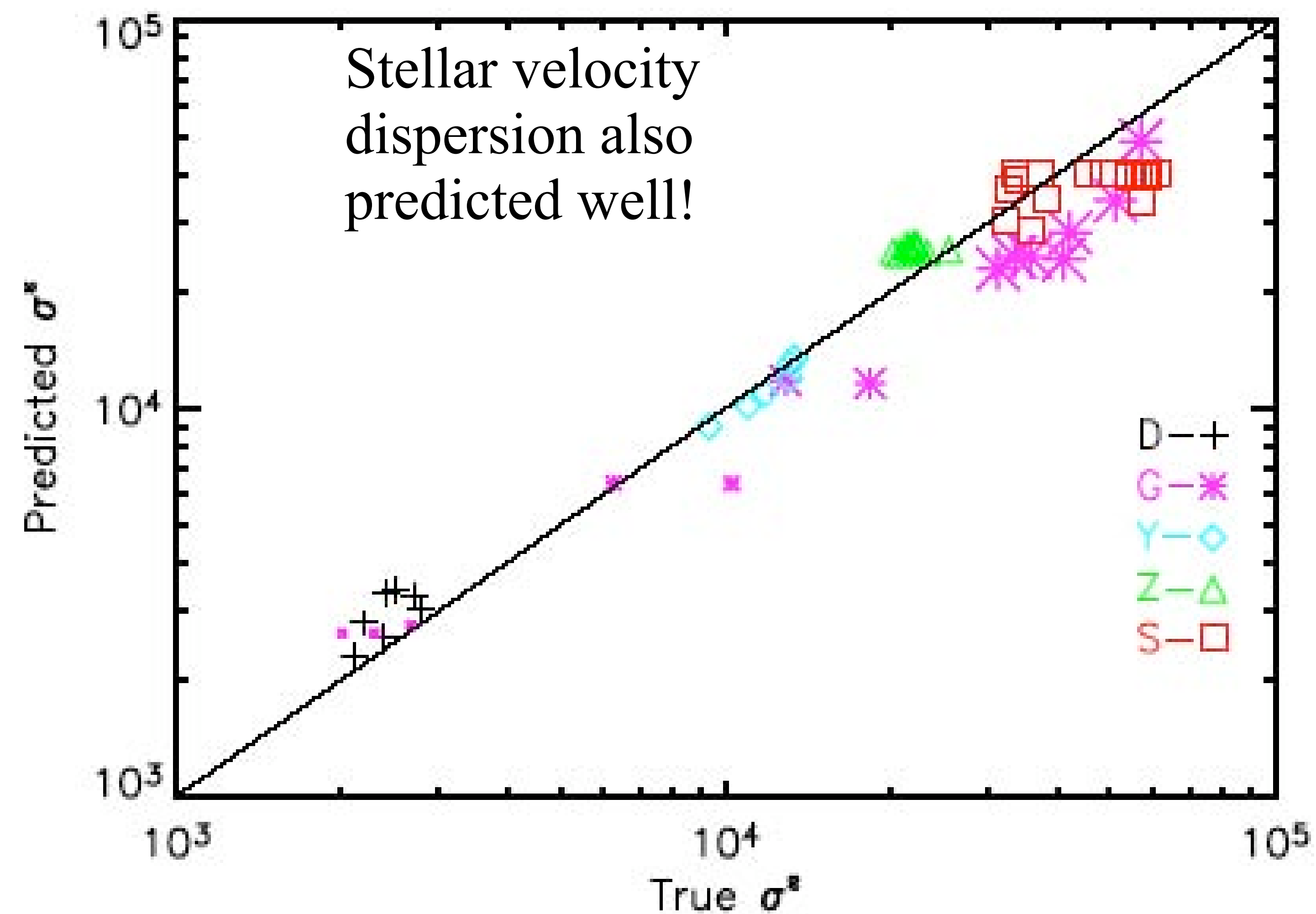
A number of physical mechanisms conspire to make this so (e.g., greater tidal effects, lower angular momentum, and more gas disk overlap).

Matt Covington, Cox, Dekel, & Primack MNRAS 2008



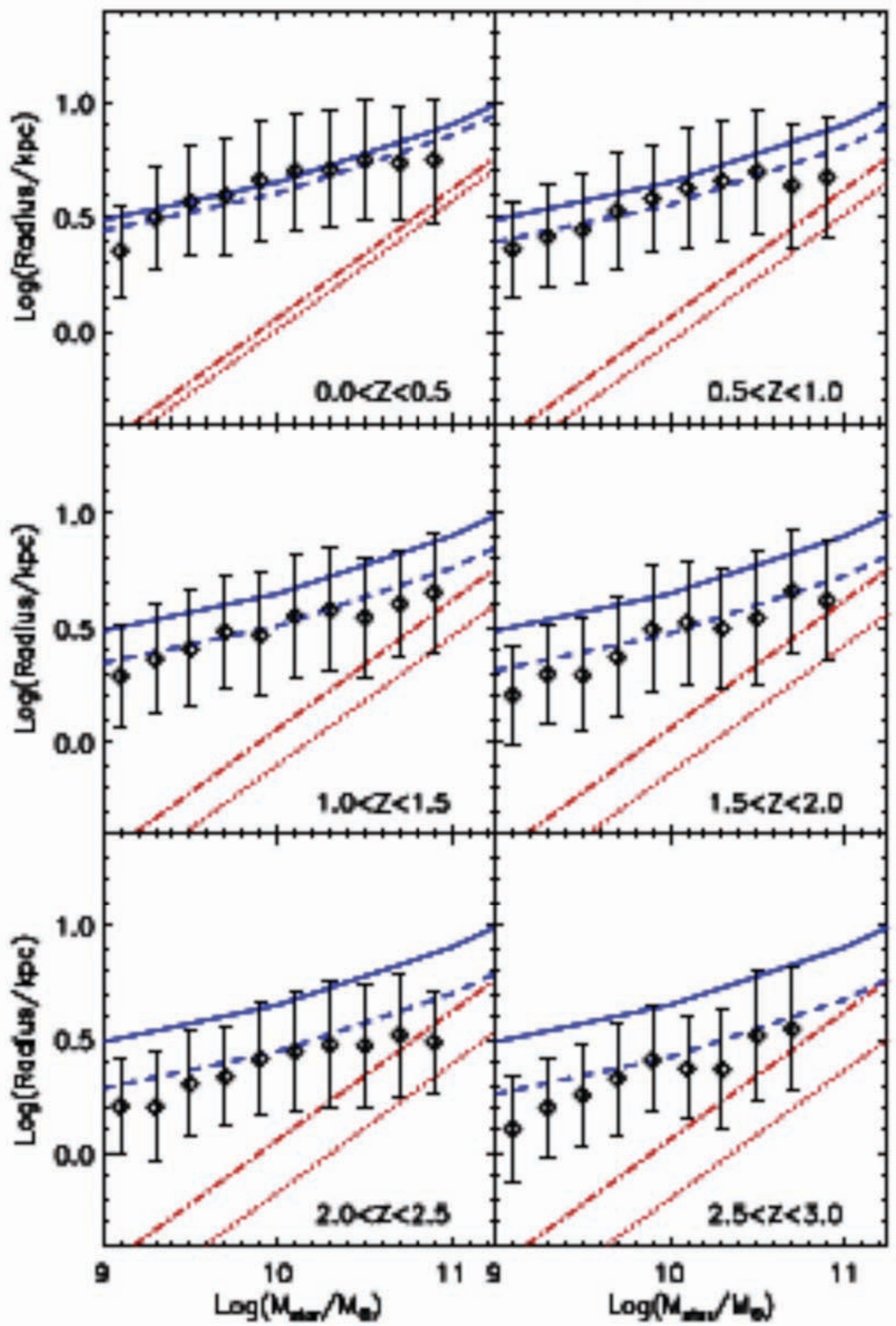


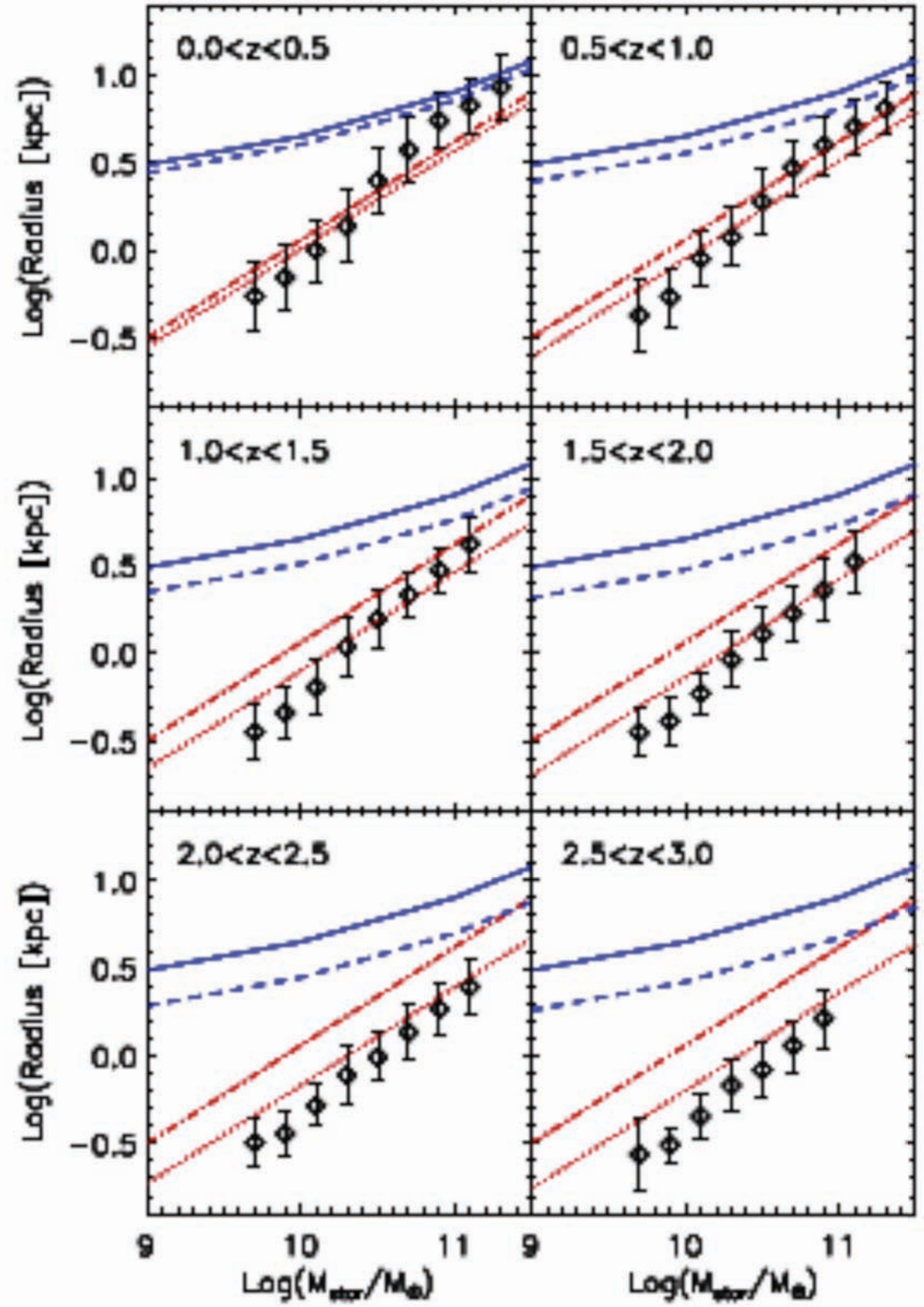
R_{eff} prediction by
Cole et al. 2000
dissipationless model,
best for dry merging



Covington et al. 2008 model takes dissipation into account, also works well for dry and non-equal mass mergers, including minor mergers!

Somerville+08 SAM + Mergers Predict Observed Size-Mass





DISKS

——— z ~ 0 observations SDSS

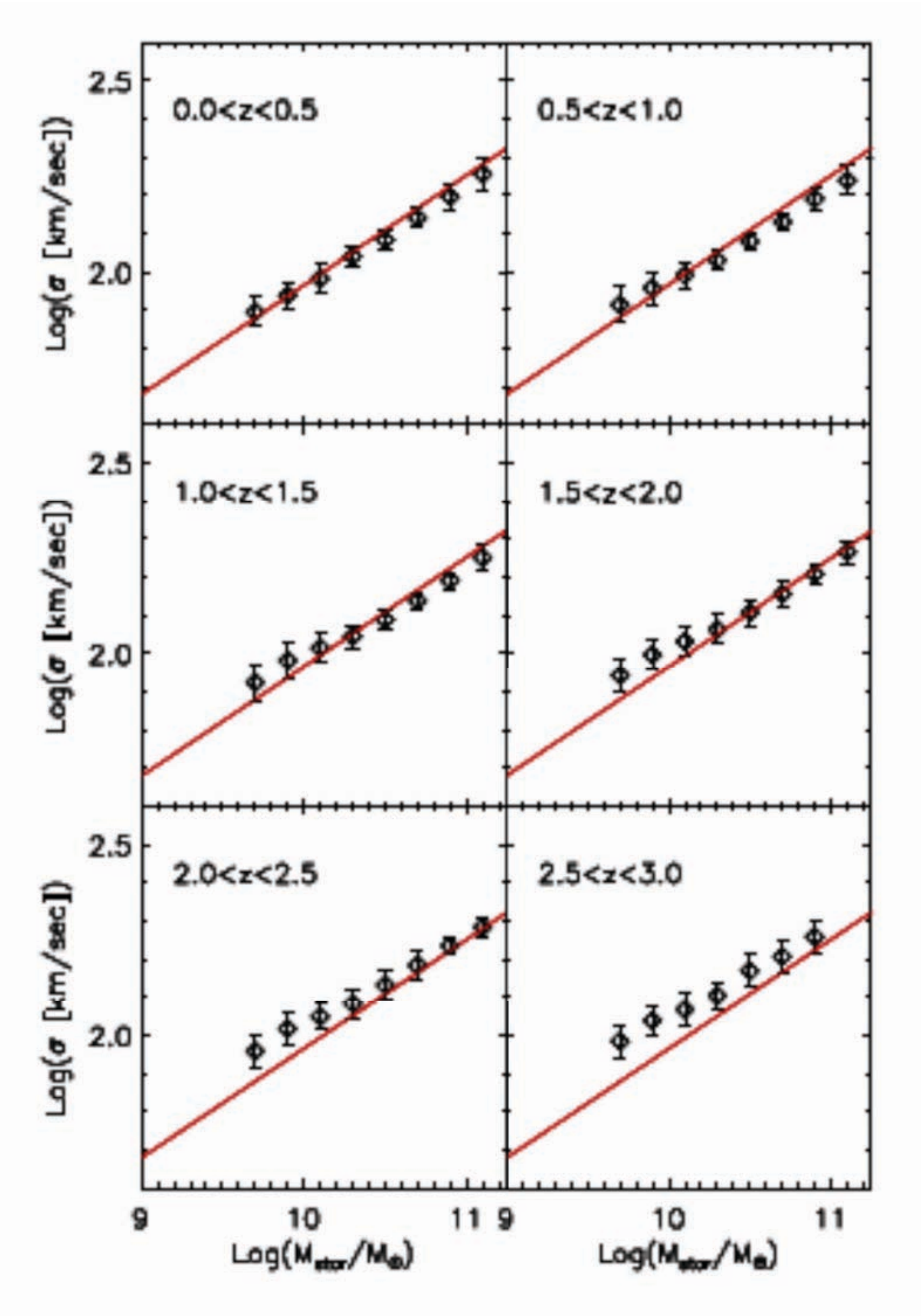
- - - - - - - - higher z data Trujillo+06

SPHEROIDS

——— z ~ 0 observations SDSS

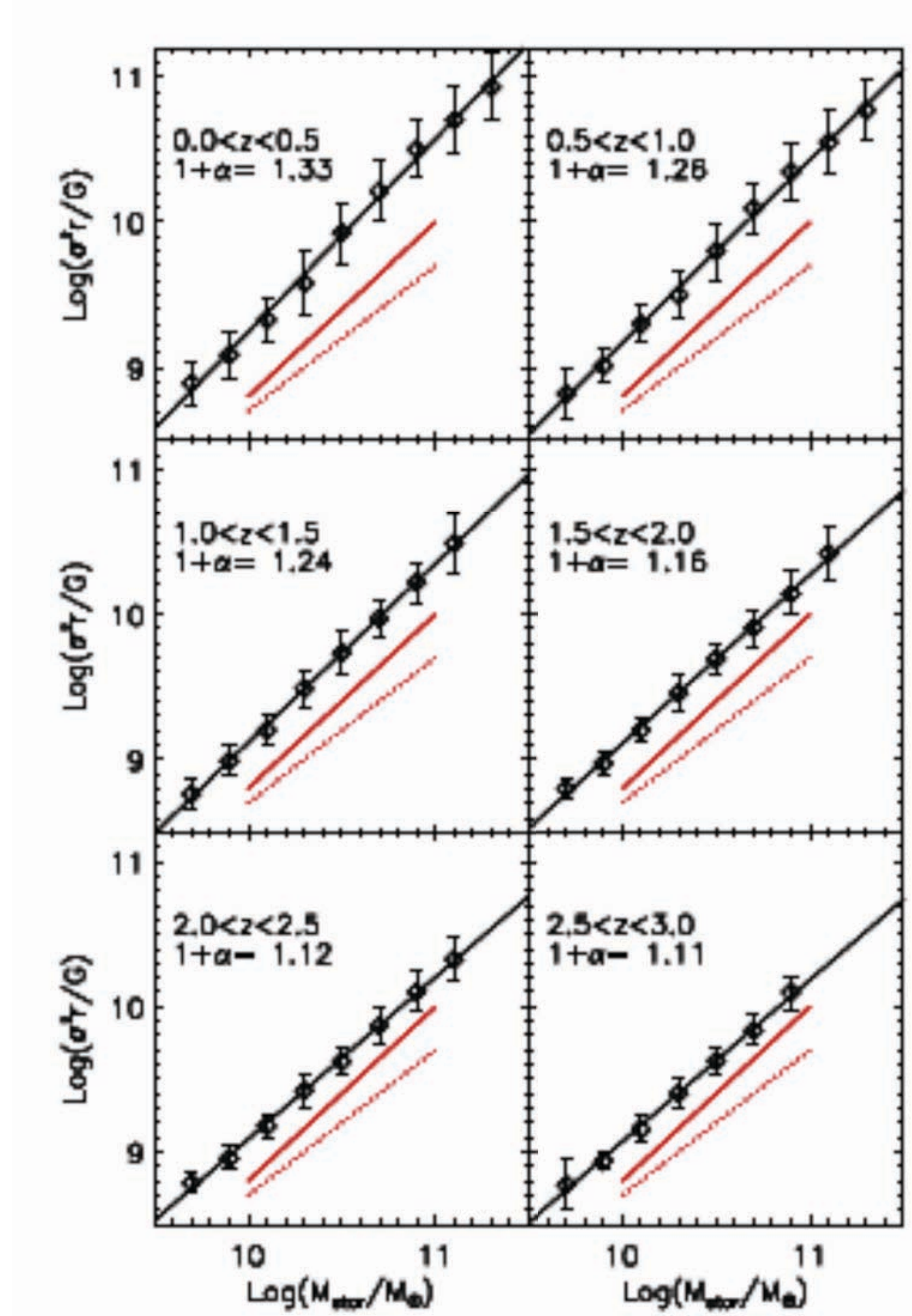
- - - - - - - - higher z data Trujillo+06

Faber-Jackson relations for the remnants in the S08 SAM, binned by redshift. **Model predicts little F-J evolution.**



Red line is the observed relation at low redshift (Gallazzi et al., 2006).

Fundamental Plane plotted as M_* vs. M_{dyn} for the remnants in the S08 SAM, binned by redshift. **Model reproduces observed tilt of the Fundamental Plane.**



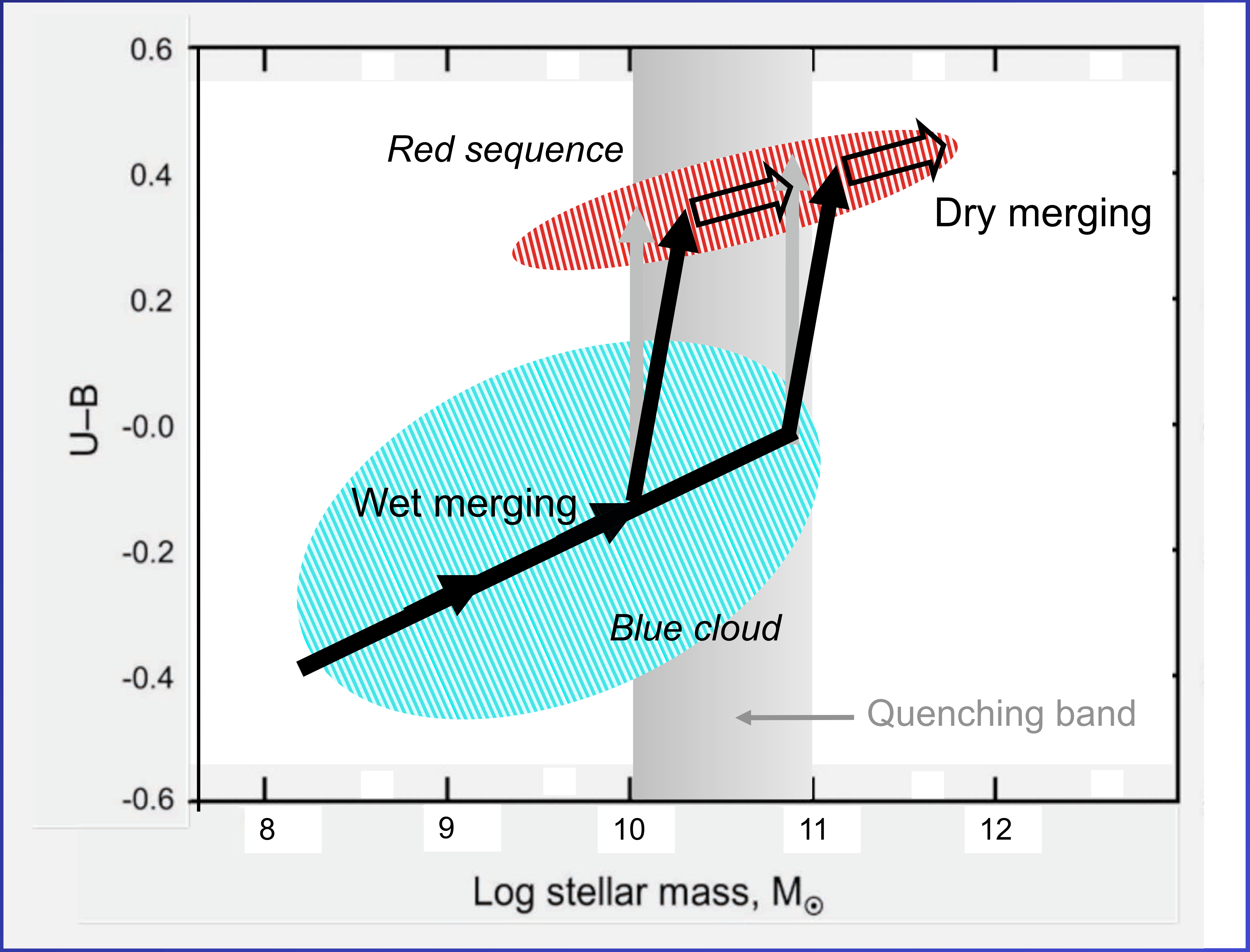
observed scaling $M_{dyn} \propto M_*^{1.2}$

virial scaling

Matt Covington dissertation 08

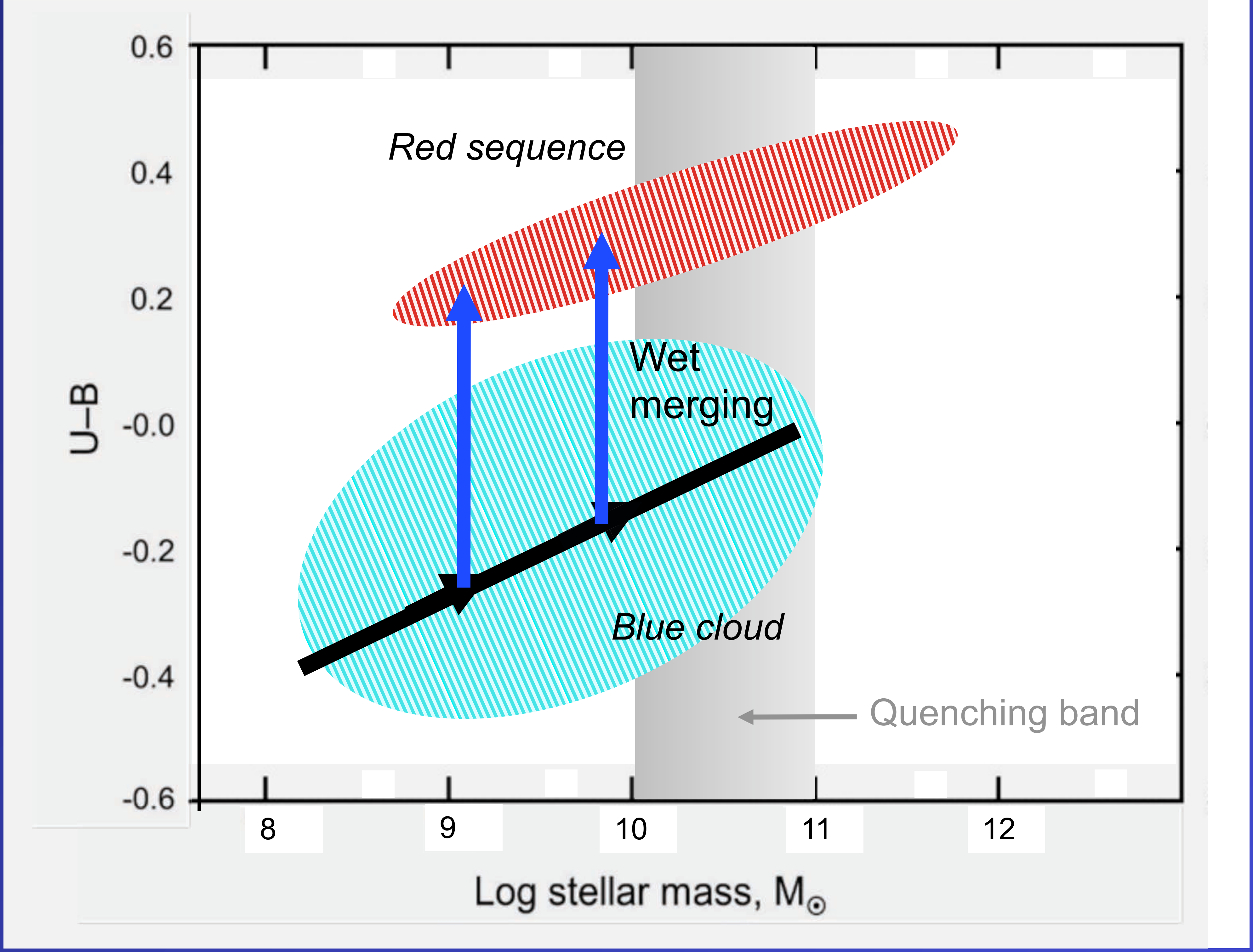
The black line is fit to the SAM remnants with $M_{dyn} \propto M_*^{1+\alpha}$ (1 + α is shown on the figure). **Covington et al. in prep.**

Flow through the color-mass diagram for "central" galaxies



Sandra Faber

Flow through the color-mass diagram for "satellite" galaxies



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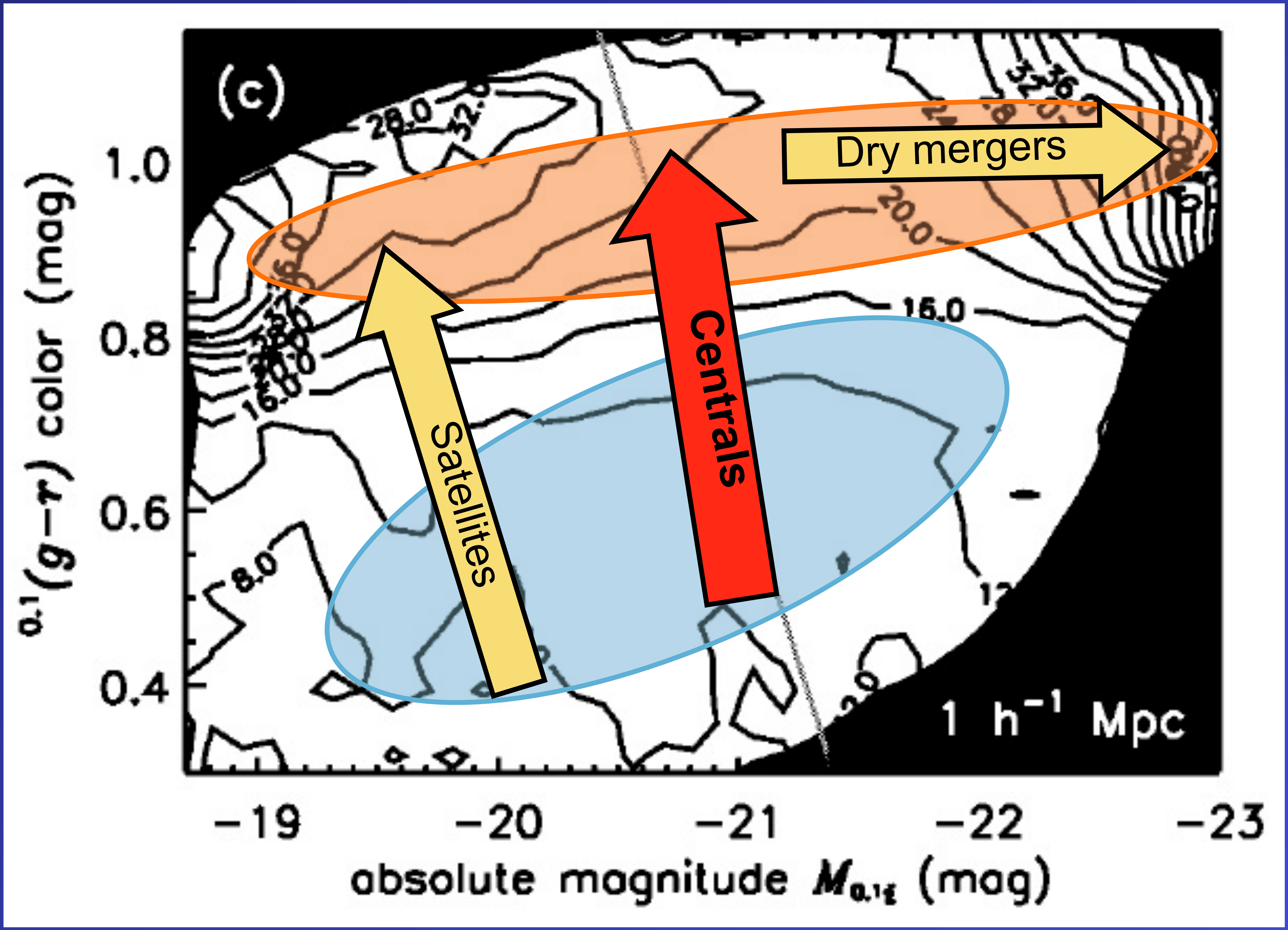
Flow through the CM diagram versus environment



Hogg et al. 2003: Sloan Survey

All formed by environment

BH not avail?

$M_i^{0.1}$ = -19.3

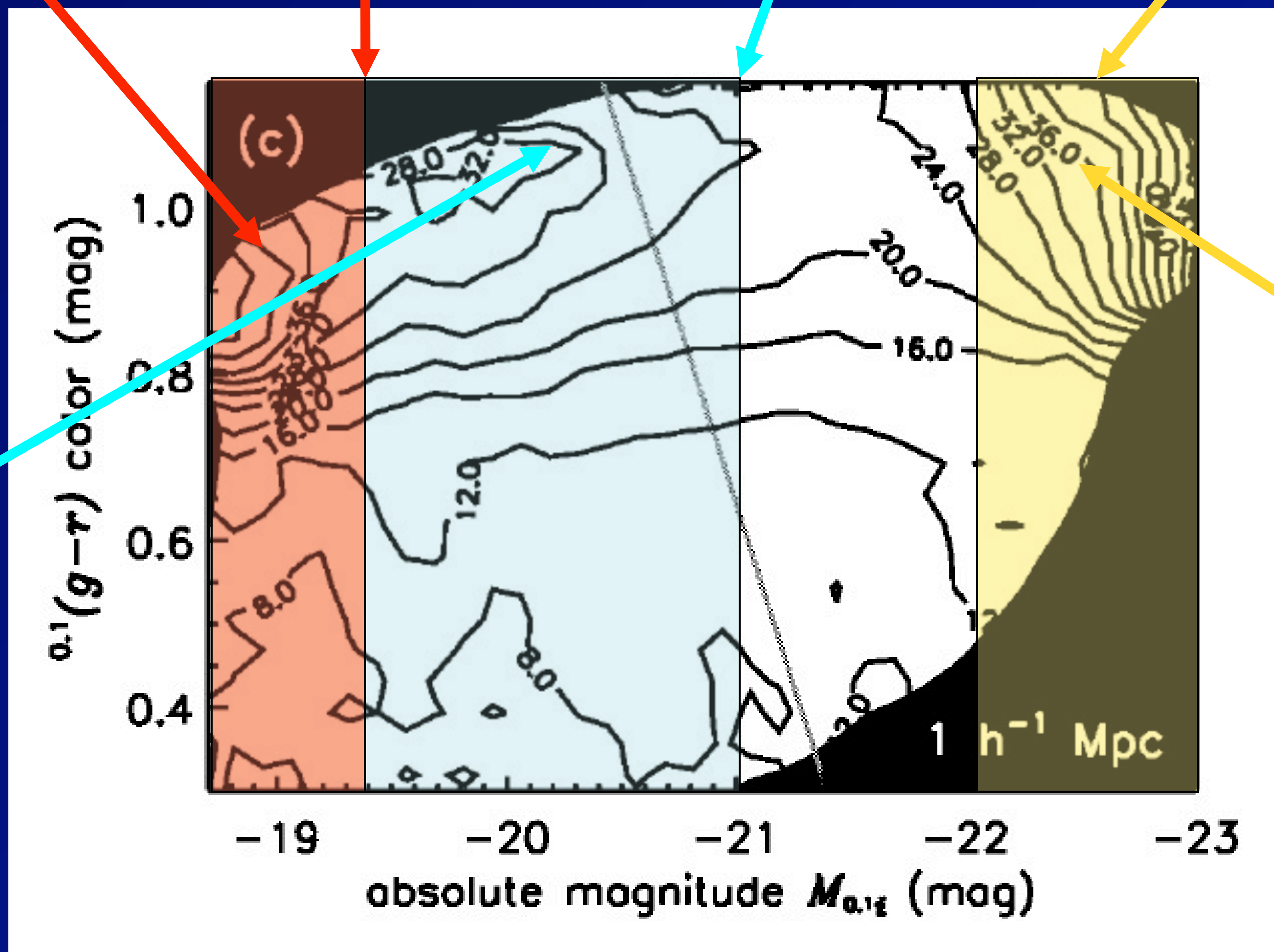
Transition mass
$3 \times 10^{10}\ M_\odot$

$M_i^{0.1}$ ~ -21.0

Satellite/Central
wet/dry transition

$M_i^{0.1}$ > -22.1

All boxy/dry



All by dry mergers

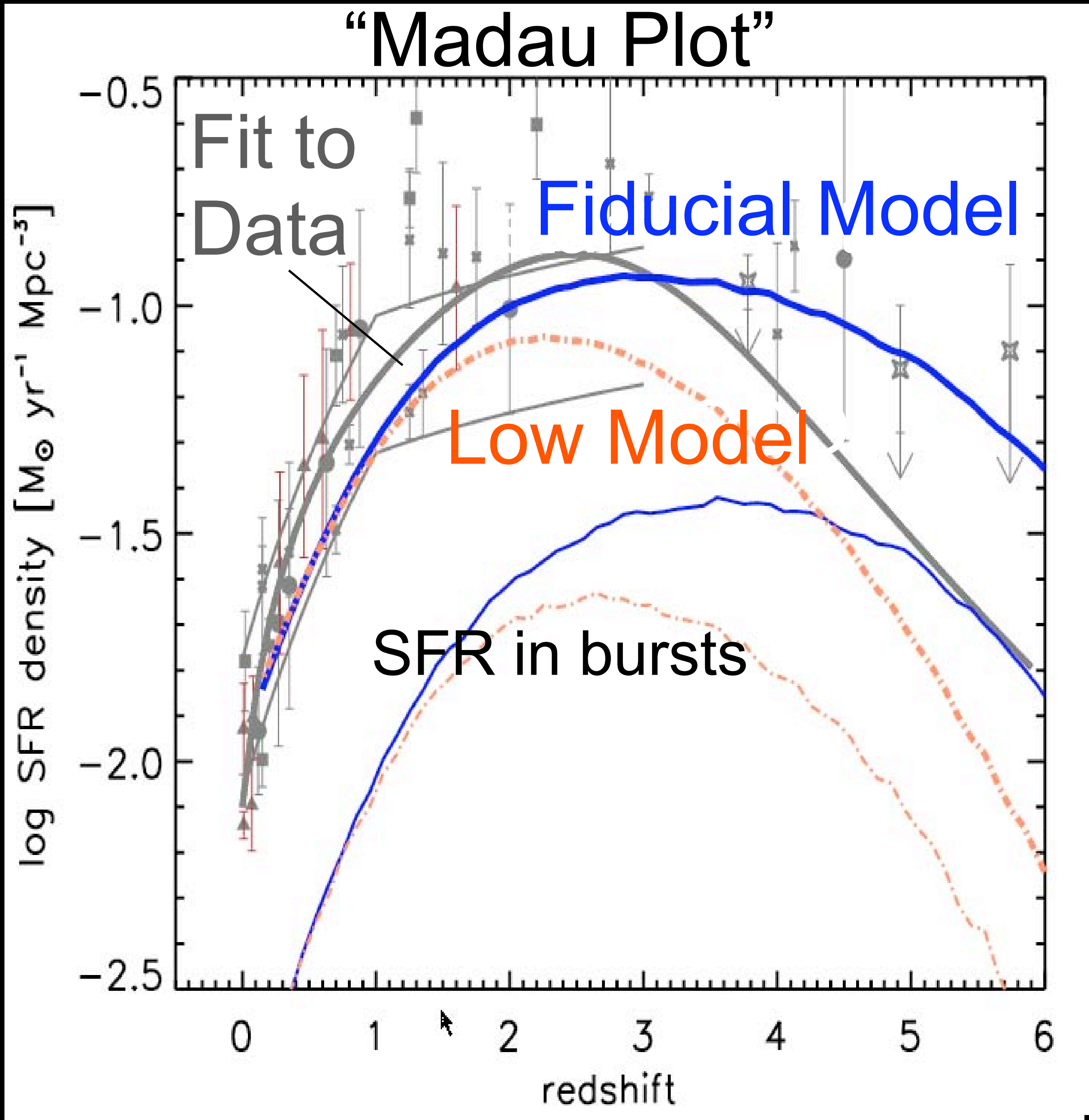
Some by env, some by wet mergers

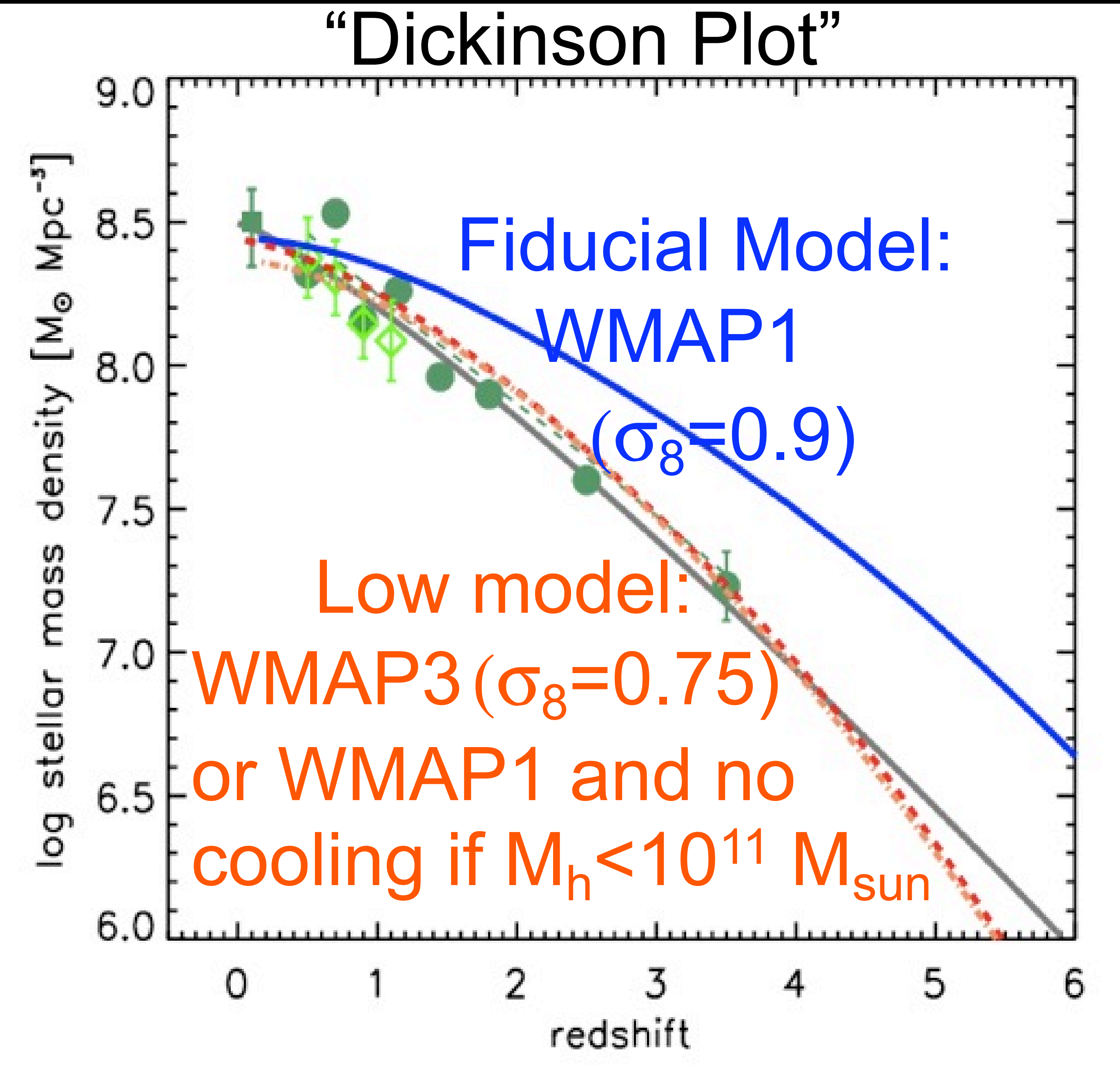
Sandra Faber

History of Star Formation and Stellar Mass Build-up

Star Formation History

Stellar Mass Build-up





Discrepancy: SFR indicators or IMF evolution?

Somerville et al. 2008

SFR tracers available for large numbers of galaxies at z~1:

1) Thermal IR 24mum + UV continuum :

Advantage: In principle, self-correcting for extinction

Problems: Obscured AGN posing as SF (Daddi et al. 2007)

Are local IR SED templates correct at z>~1?

Hope: longer λ data (FIDEL, Herschel, LMT, ALMA)

2) UV continuum

Advantage: widely available from broad-band imaging to high z

Problems: extinction correction (UV slope, ...) uncertain

Hope: SED fits (Salim et al.), calib from other tracers

3) Emission lines (Balmer, OII, OIII)

Advantage: Robust extinction correction from Balmer decrement

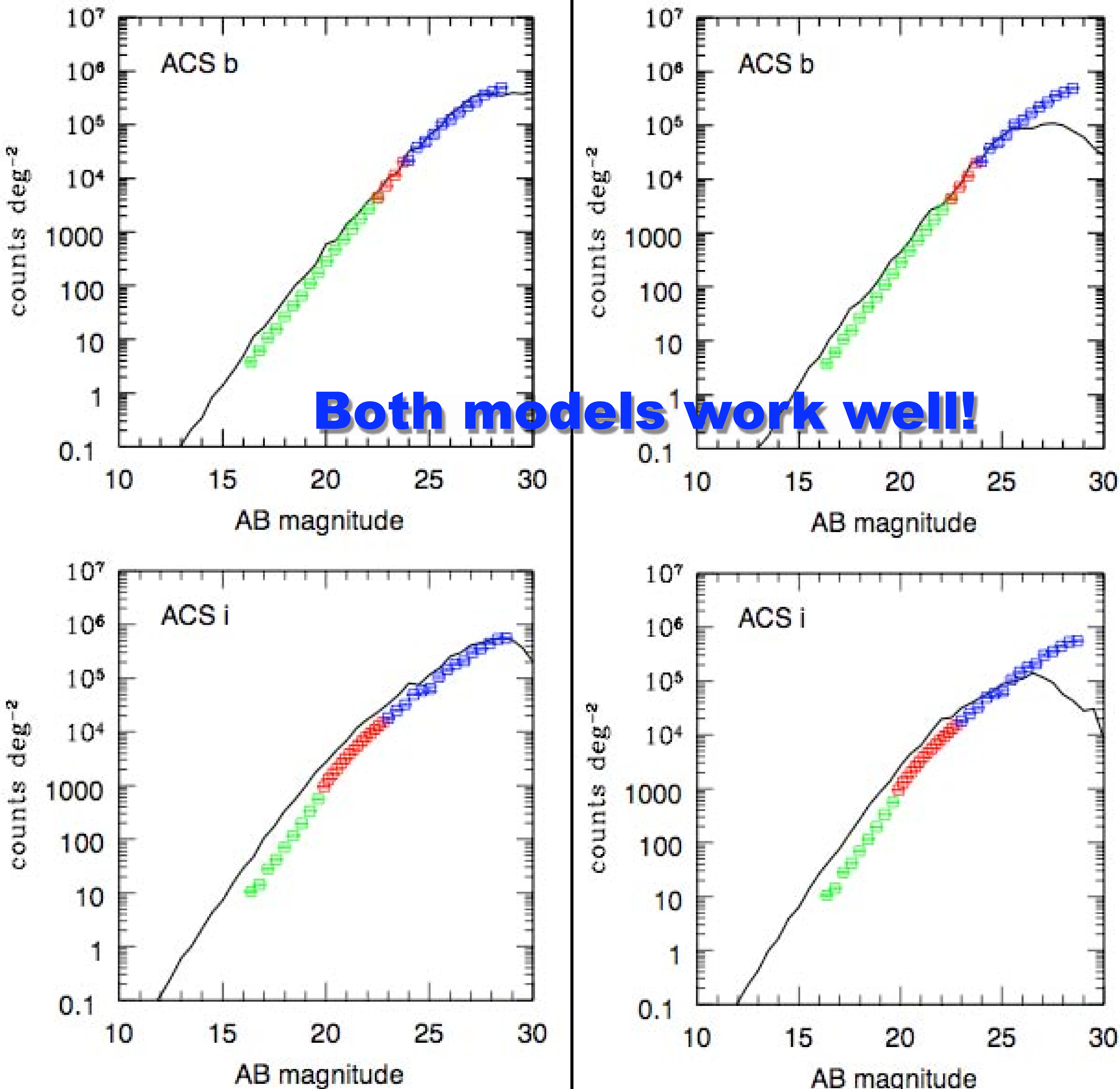
Problems: Balmer lines need NIR spectroscopy at z~1

OII, OIII depend on T,O/H, calibration problematic

Hope: NIR, massively Multi-Object spectrographs

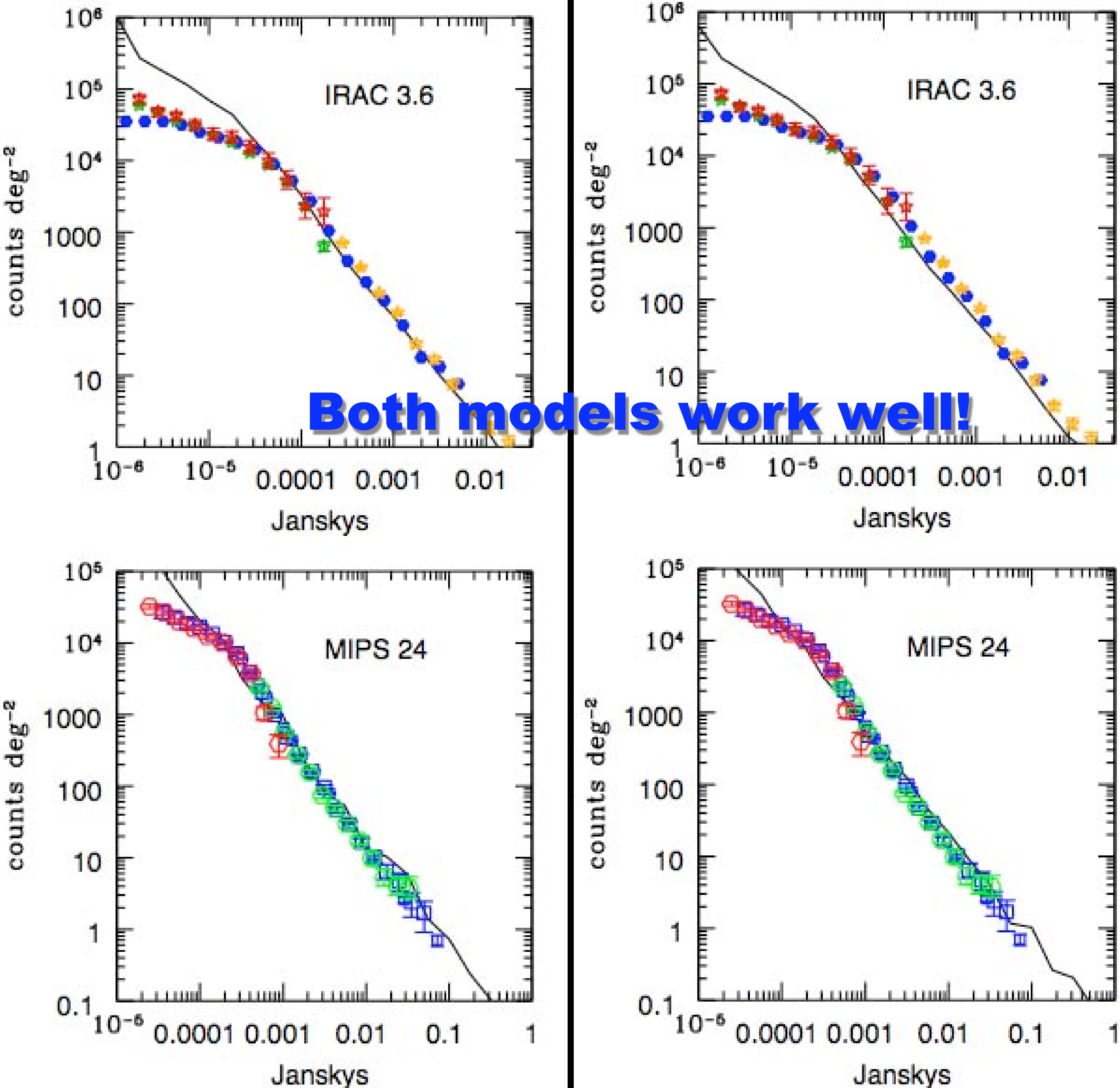
Kai Noeske

Fiducial Model | Low Model



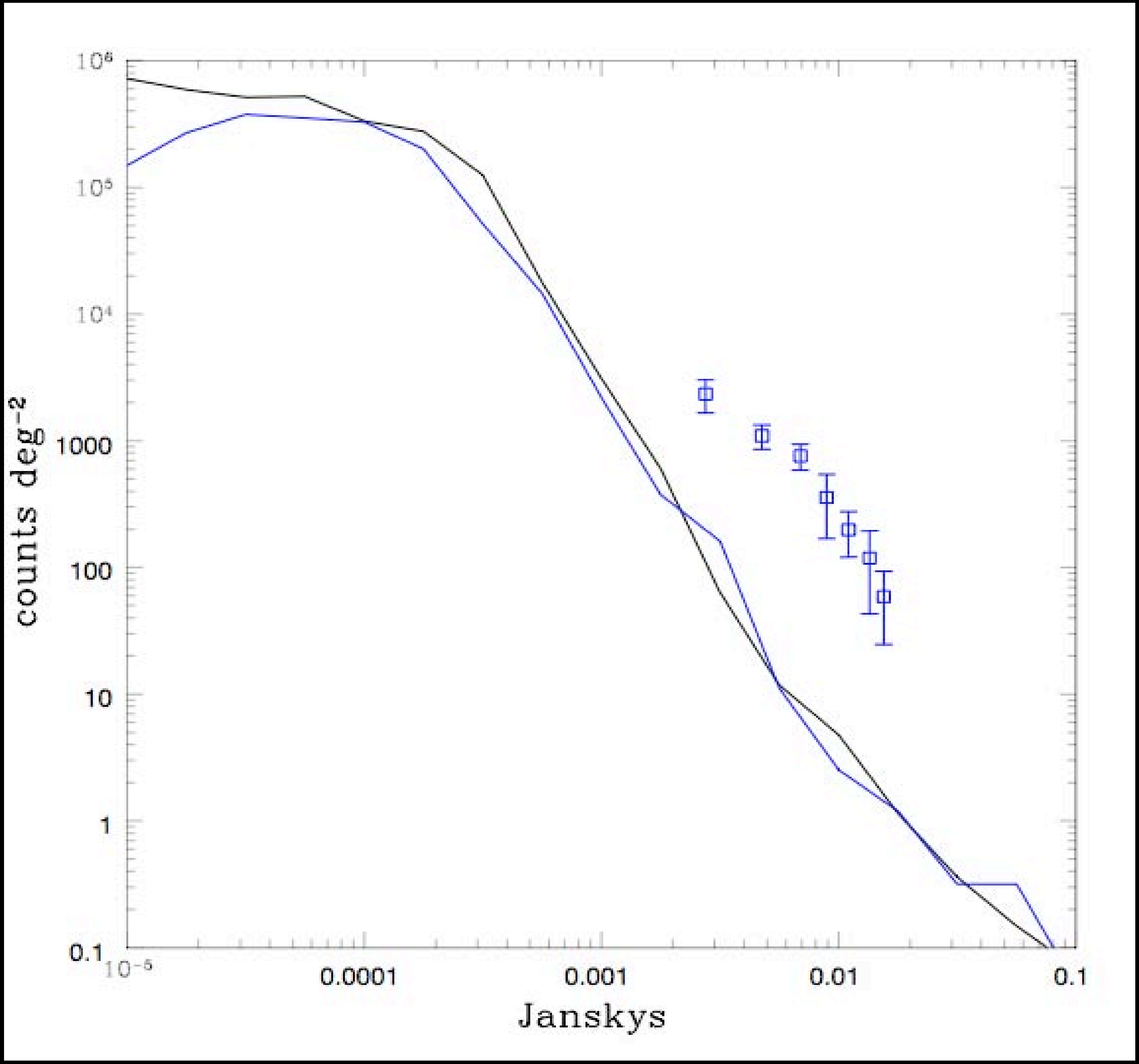
Both models work well!

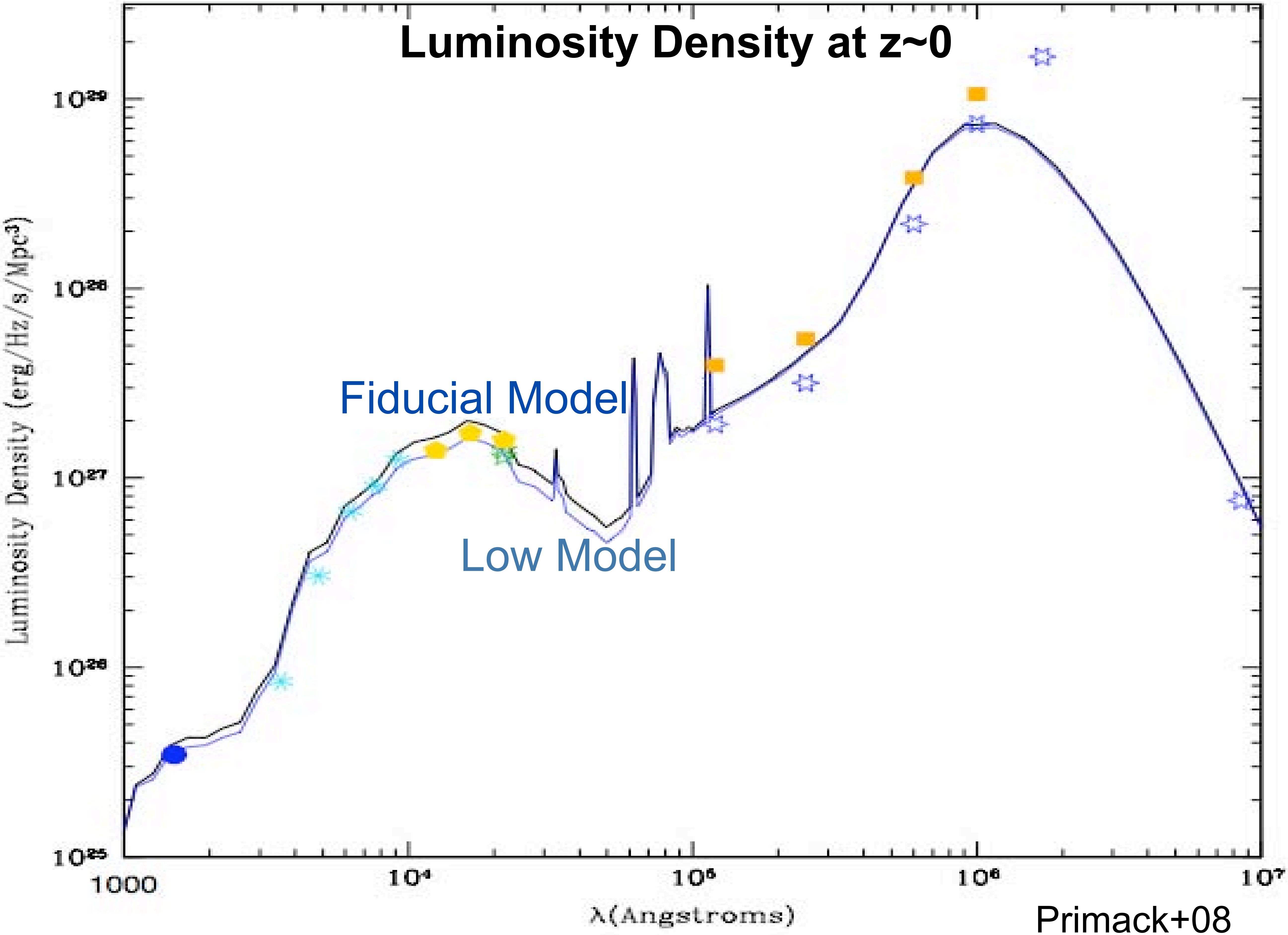
Fiducial Model | Low Model



Both models work well!

08SAM Fails to Predict Observed 850 μm Number Counts

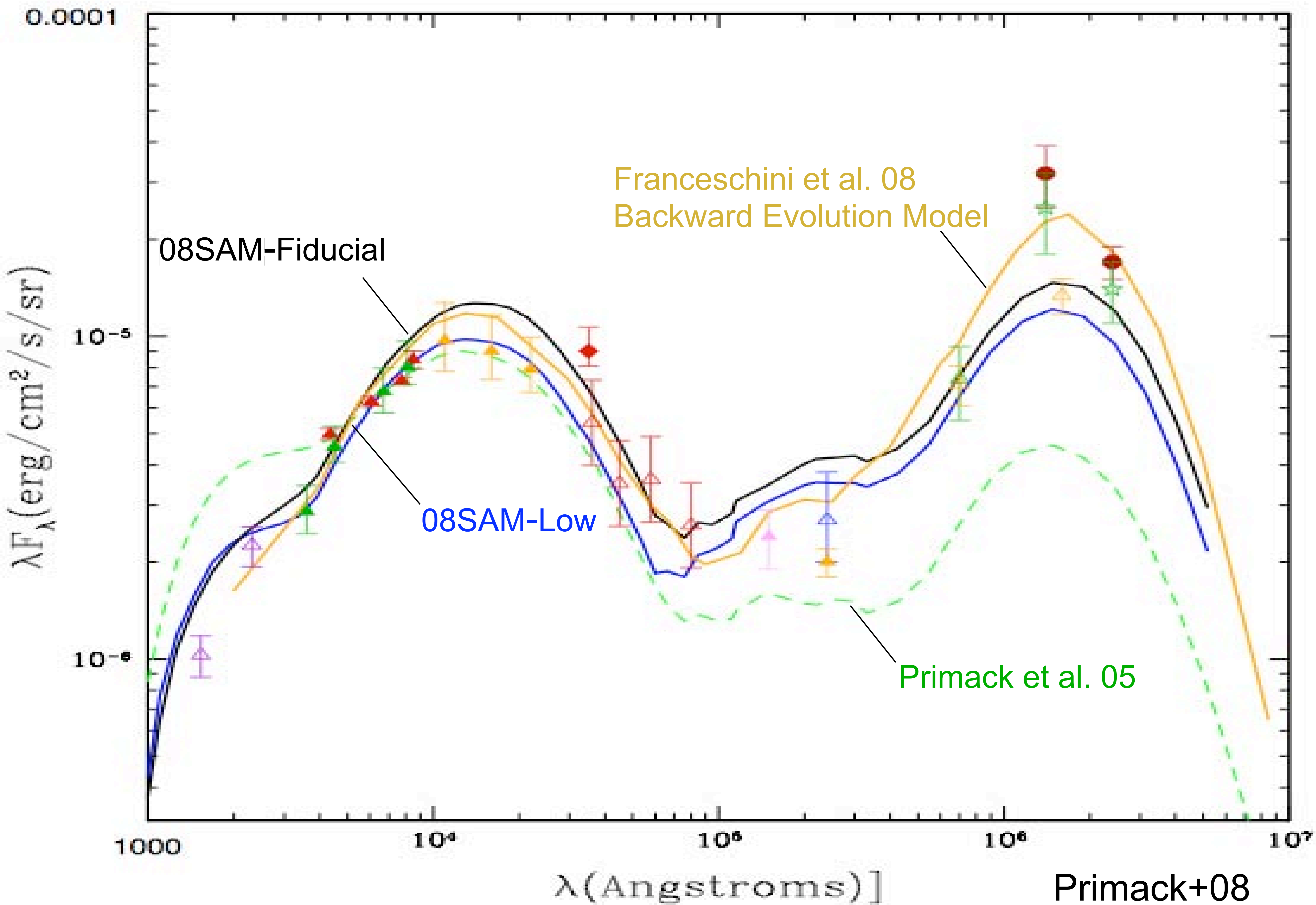




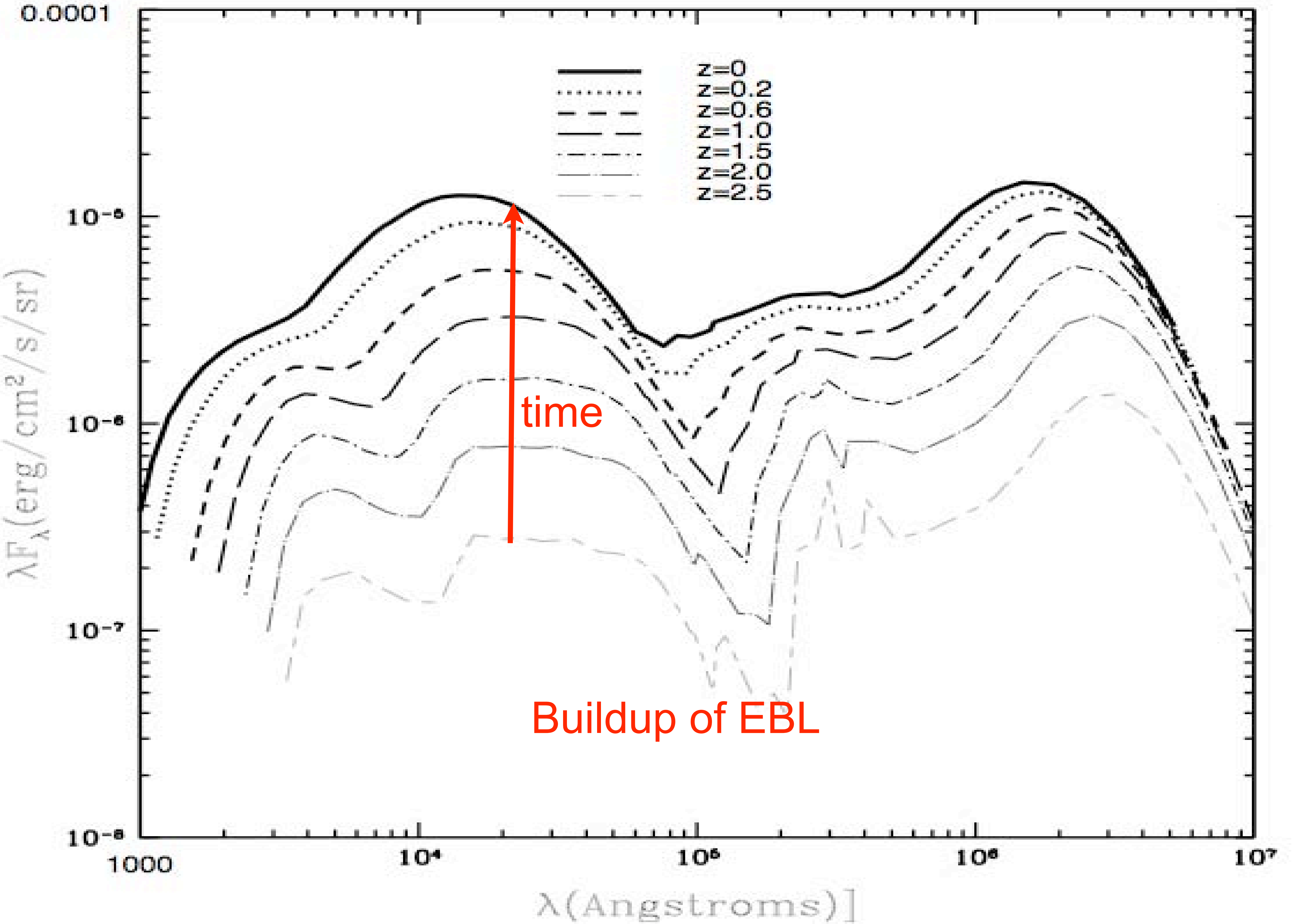
Luminosity Density at z~0
Fiducial Model
Low Model
Luminosity Density (erg/Hz/s/Mpc³)
λ(Angstroms)
1000
10⁴
10⁵
10⁶
10⁷
10²⁵
10²⁶
10²⁷
10²⁸
10²⁹

Primack+08

Extragalactic Background Light

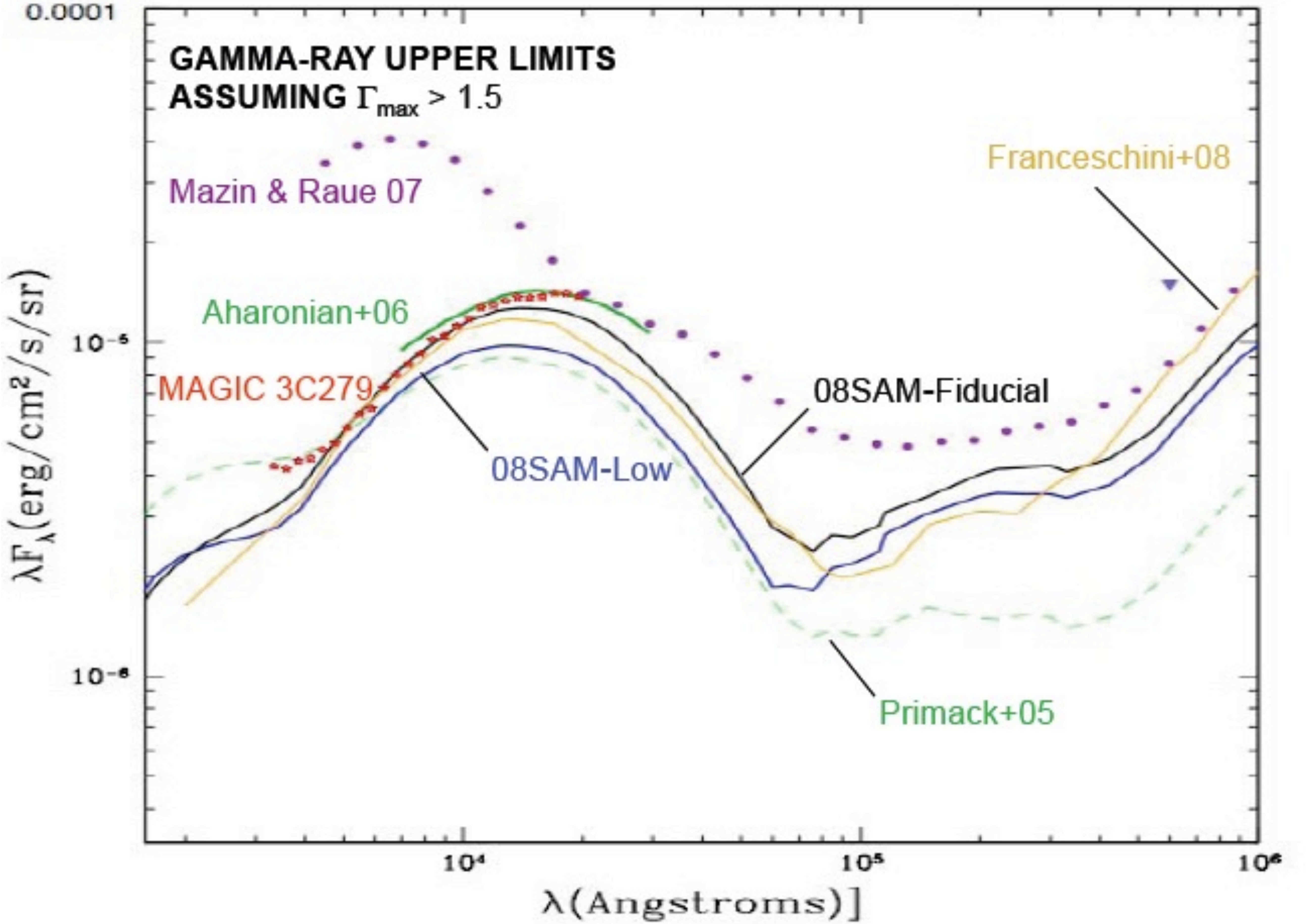


Primack+08

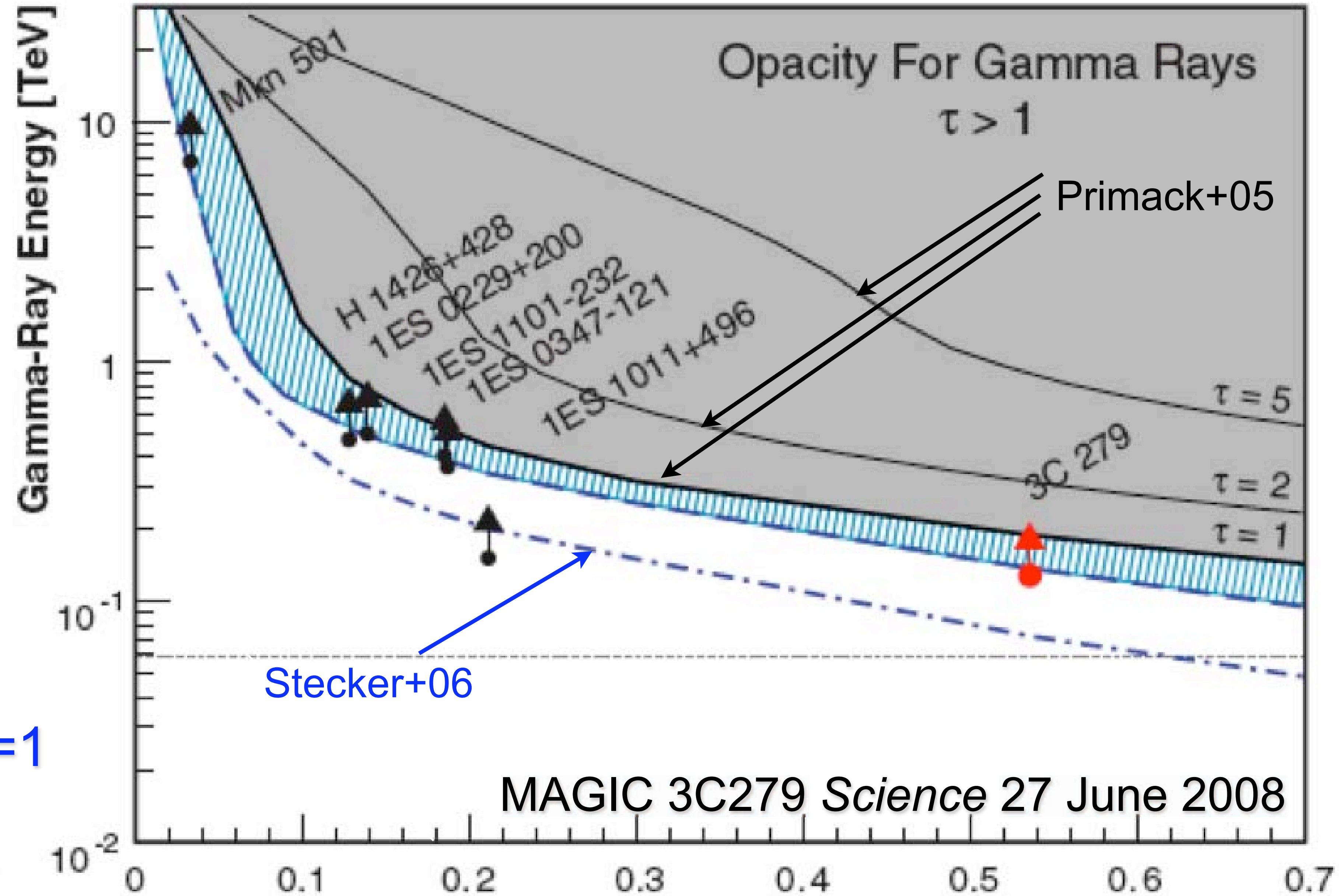


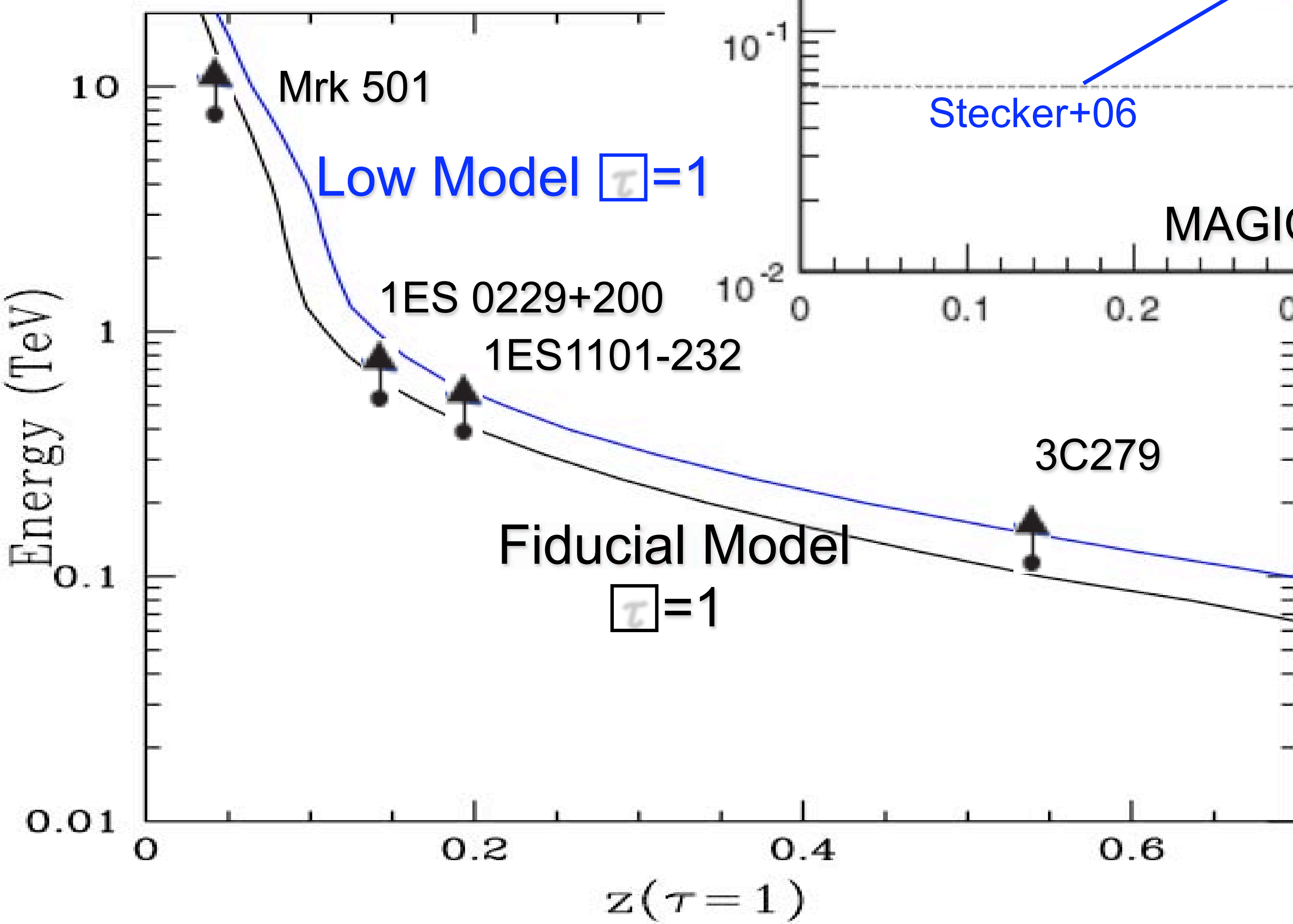
0.0001
10^{-5}
10^{-6}
10^{-7}
10^{-8}
1000
10^{4}
10^{5}
10^{6}
10^{7}
λF_λ(erg/cm^2/s/sr)
λ(Angstroms)]
z=0
z=0.2
z=0.6
z=1.0
z=1.5
z=2.0
z=2.5
time
Buildup of EBL

Upper Limits on EBL from z~0.2 Blazars and z=0.53 Quasar



Gamma Ray Attenuation Due to **Fiducial** and Low Models





Gilmore, Primack, Somerville 2009
Low Model is well within observational constraints

Fiducial Model also looks OK!

Conclusions

- High resolution DM simulations show halo substructure. New hydrodynamic simulations are increasingly able to explain galaxy formation. At z>2, even massive halos have cold streams bringing in gas that quickly forms stars. At z<2 this only happens for $M_{halo} < 10^{12}$.
- Spheroids from mergers have the observed size-mass relation and lie in the observed Fundamental Plane.
- New self-consistent semi-analytic galaxy formation models based on physical scaling from numerical simulations and calibrated against empirical constraints now enable us to predict and interpret the relationship between galaxies, BH, and AGN across cosmic history.
- Such models accurately predict number counts and luminosity functions in all spectral bands and all redshifts except for sub-mm galaxies.
- The predicted range of EBLs is consistent with the best estimates of EBL evolution inferred from observations.