Astronomy 233 Spring 2011

Physical Cosmology

Week 9

Galaxies & Inflation

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Astro 233 - Spring 2011

Physical Cosmology

Week	Topics
1	Introduction
2	General Relativistic Cosmology
3	Big Bang Nucleosynthesis
4	Recombination, Dark Matter (DM)
5	DM Detection, Cosmic Microwave Background
6	Structure Formation
7	(Reminder: no lectures May 10 & 12)
8	Galaxy Formation
9	Galaxies; Cosmic Inflation and Before
10	After Inflation: Baryogenesis, Strings, ...
11	Student Presentations of Term Projects

small scale issues

Cusps

The triaxial nature of dark matter halos plus observational biases suggest that observed velocity structure of LSB and dSpiral galaxies may be consistent with cuspy ΛCDM halos. Baryonic physics may soften the central cusp.

Angular momentum

ΛCDM simulations are increasingly able to form realistic spiral galaxies, as resolution improves and feedback becomes more realistic.

Satellites

The discovery of many faint Local Group dwarf galaxies is consistent with ΛCDM predictions. Reionization, lensing, satellites, and Lyα forest data imply that WDM must be Tepid or Cooler.

CHALLENGES TO CDM

- ANGULAR MOMENTUM ISSUES

Catastrophic loss of angular momentum due to overcooling in hydrodynamic simulations (Navarro, Steinmetz). Spiral galaxies would be hard to form if ordinary matter has the same specific angular momentum distribution as dark matter (Bullock). How do the disk baryons get the right angular momentum?

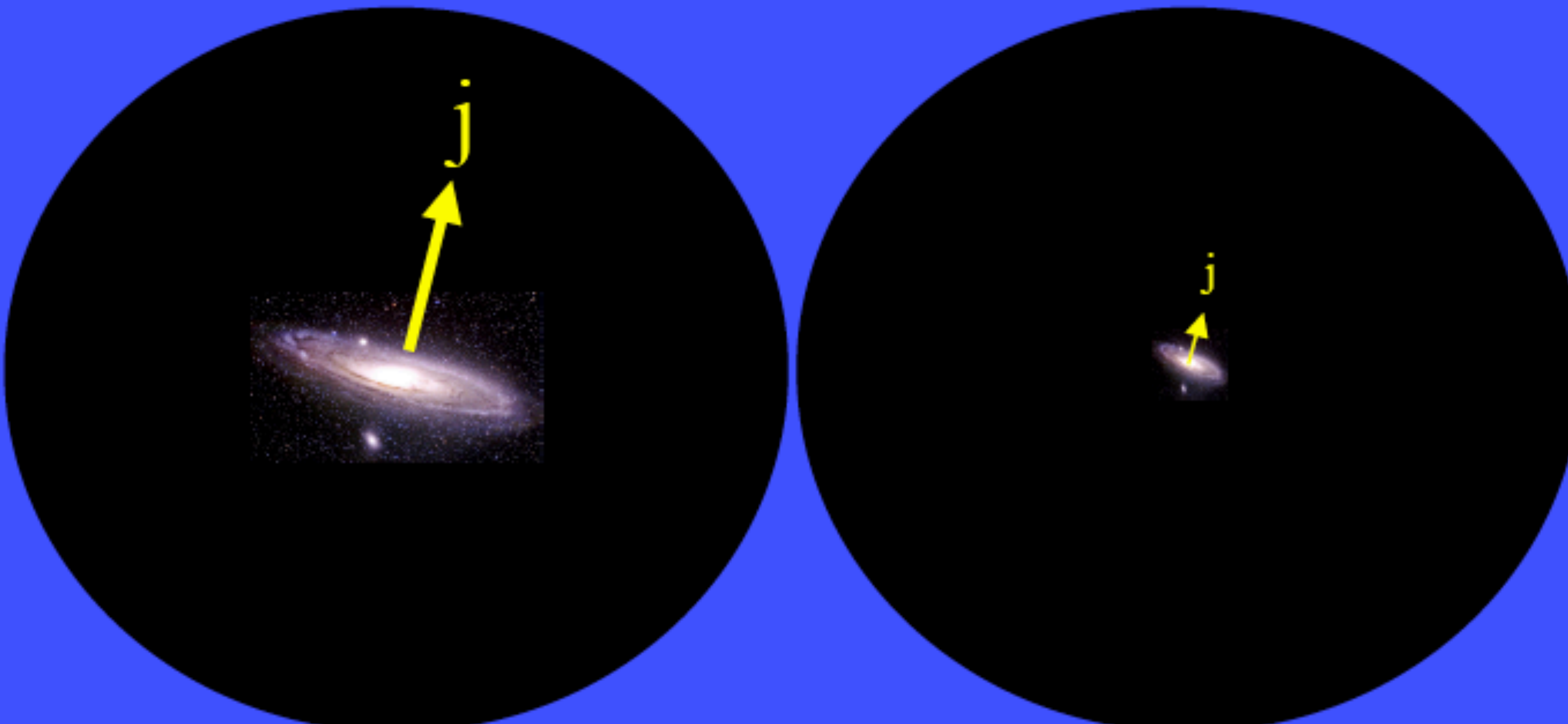
Mergers give halos angular momentum – too little for halos that host disks, too much for halos that host spheroids? Role of AGN and other energy inputs? Role of cold inflows (Birnboim & Dekel; Keres+…)?

Can simulated disks agree with observed Tully-Fisher relation and Luminosity Function at all redshifts? Recent simulations (Governato+; Guedes+) are encouraging.

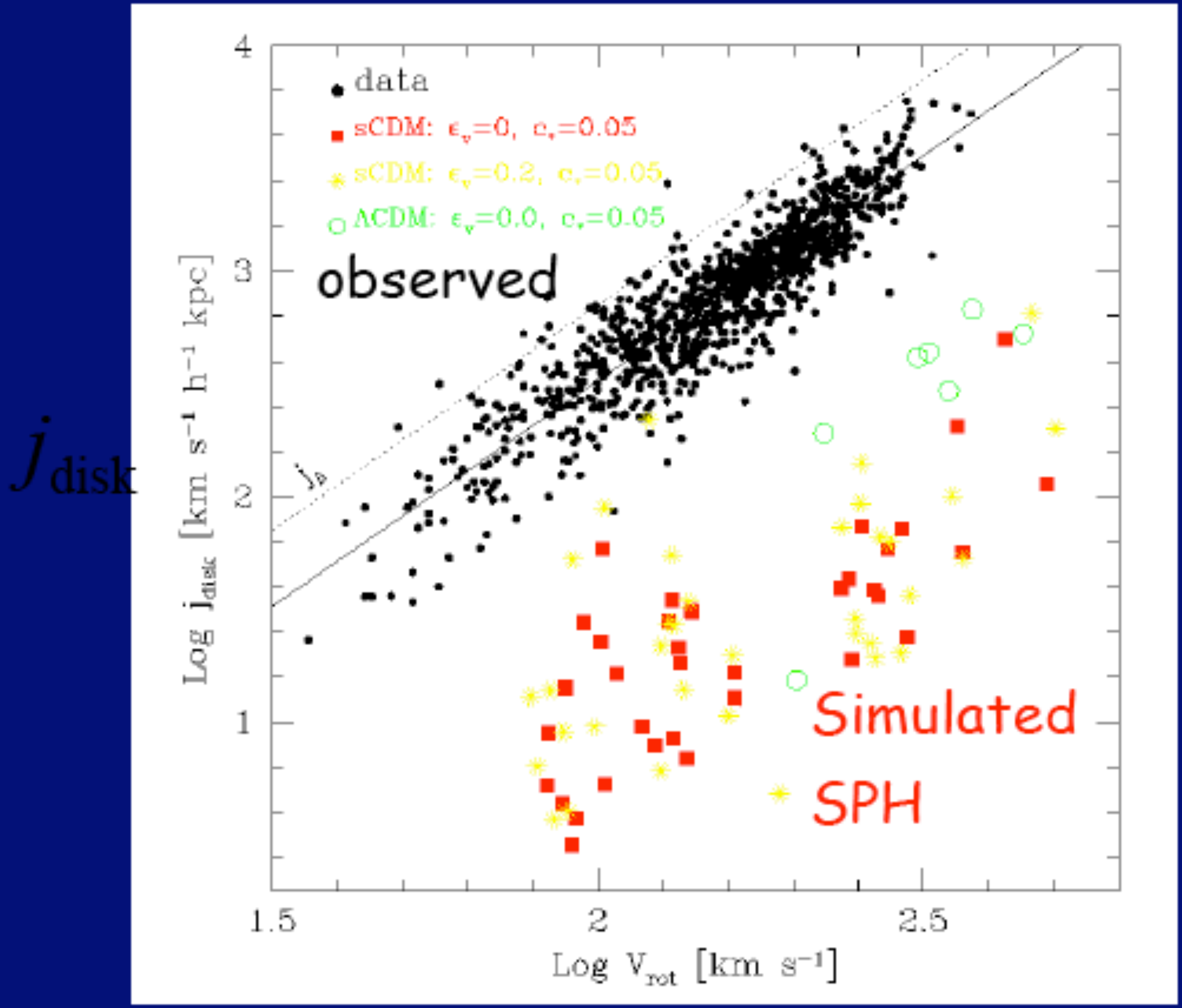
The Spin Catastrophe

Navarro & Steinmetz et al.

observations simulations



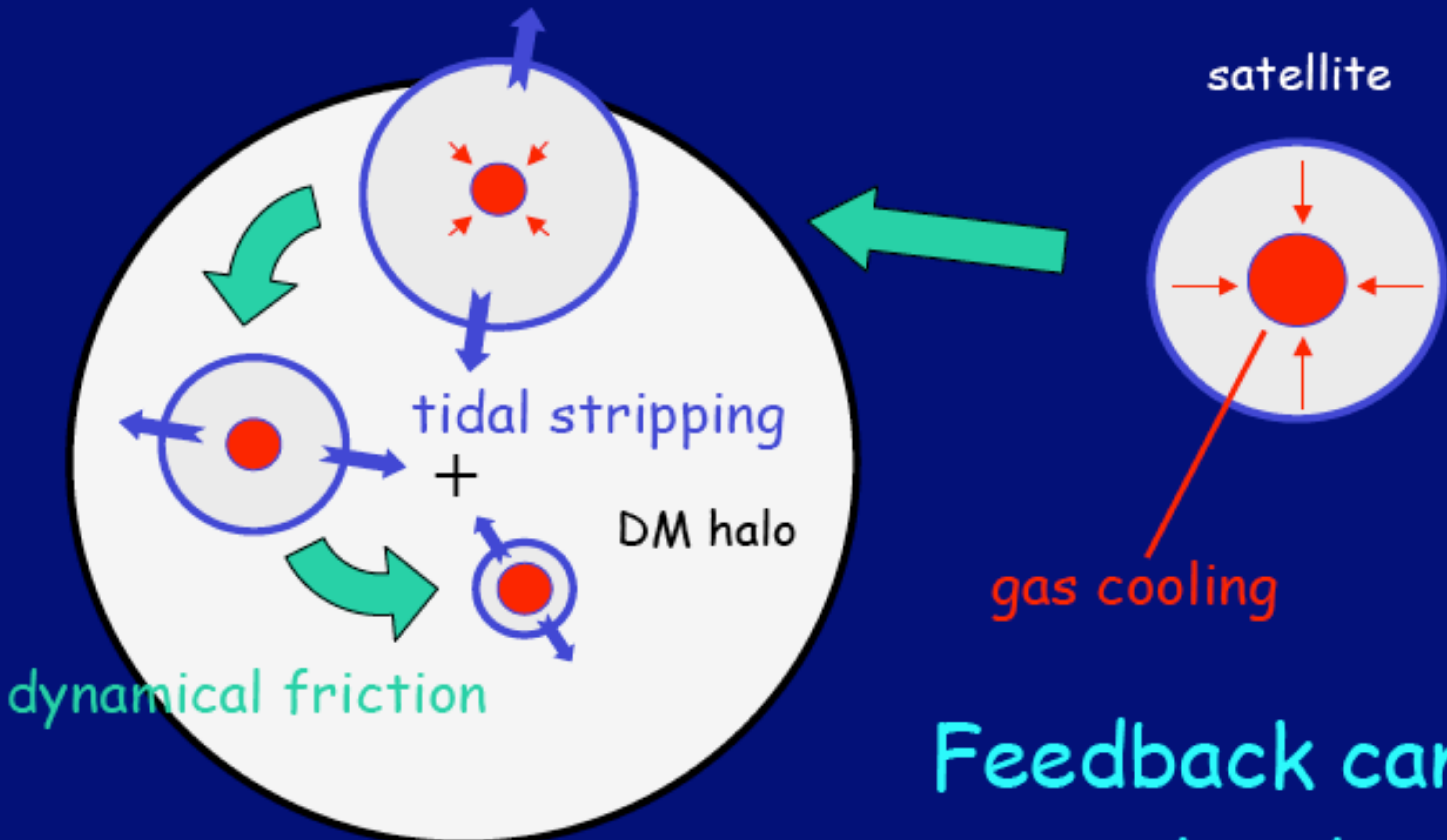
The spin catastrophe



Steinmetz, Navarro, et al.

Over-cooling → spin catastrophe

Maller & Dekel 02



Feedback can save the day

FORMING REALISTIC LATE-TYPE SPIRALS IN A ΛCDM UNIVERSE: THE ERIS SIMULATION

JAVIERA GUEDES[1], SIMONE CALLEGARI[2], PIERO MADAU[1], & LUCIO MAYER[2]

Simulations of the formation of late-type spiral galaxies in a cold dark matter (ΛCDM) universe have traditionally failed to yield realistic candidates. Here we report a new cosmological N-body/smooth particle hydrodynamic (SPH) simulation of extreme dynamic range in which a close analog of a Milky Way disk galaxy arises naturally. Termed "Eris", the simulation follows the assembly of a galaxy halo of mass $M_{\rm vir} = 7.9 \times 10^{11}$ $M_{\odot}$ with a total of $N = 18.6$ million particles (gas + dark matter + stars) within the final virial radius, and a force resolution of 120 pc. It includes radiative cooling, heating from a cosmic UV field and supernova explosions (blastwave feedback), a star formation recipe based on a high gas density threshold ($n_{\rm SF} = 5$ atoms cm^{-3} rather than the canonical $n_{\rm SF} = 0.1$ atoms cm^{-3}), and neglects any feedback from an active galactic nucleus. Artificial images are generated to correctly compare simulations with observations. At the present epoch, the simulated galaxy has an extended rotationally-supported disk with a radial scale length $R_d = 2.5$ kpc, a gently falling rotation curve with circular velocity at 2.2 disk scale lengths of $V_{2.2} = 214$ km s^{-1}, an i-band bulge-to-disk ratio $B/D = 0.35$, and a baryonic mass fraction within the virial radius that is 30% below the cosmic value. The disk is thin, is forming stars in the region of the $\Sigma_{\rm SFR}$-$\Sigma_{\rm HI}$ plane occupied by spiral galaxies, and falls on the photometric Tully-Fisher and the stellar mass-halo virial mass relations. Hot ($T > 3 \times 10^5$ K), X-ray luminous halo gas makes only 26% of the universal baryon fraction and follows a "flattened" density profile $\propto r^{-1.13}$ out to $r = 100$ kpc. Eris appears then to be the first cosmological hydrodynamic simulation in which the galaxy structural properties, the mass budget in the various components, and the scaling relations between mass and luminosity are all consistent with a host of observational constraints. A twin simulation with a low star formation density threshold results in a galaxy with a more massive bulge and a much steeper rotation curve, as in previously published work. A high star formation threshold is therefore key in obtaining realistic late-type galaxies, as it enables the development of an inhomogeneous interstellar medium where star formation and heating by supernovae occur in a clustered fashion. The resulting outflows at high redshifts reduce the baryonic content of galaxies and preferentially remove low angular momentum gas, decreasing the mass of the bulge component.

The *Eris* N-body/SPH simulation of a massive late-type spiral galaxy in a *WMAP3* cosmology (Guedes, Callegari, Madau, & Mayer 2011). The simulation was performed with the *GASOLINE* code on NASA's *Pleiades* supercomputer and used 1.5 million cpu hours.

M_{vir}=7.9 x 10^{11} $M_{\odot}$

N_{DM}+N_{gas}+N_{star}= 7M+3M+8.6M within final r_{vir}

force resolution=120 pc

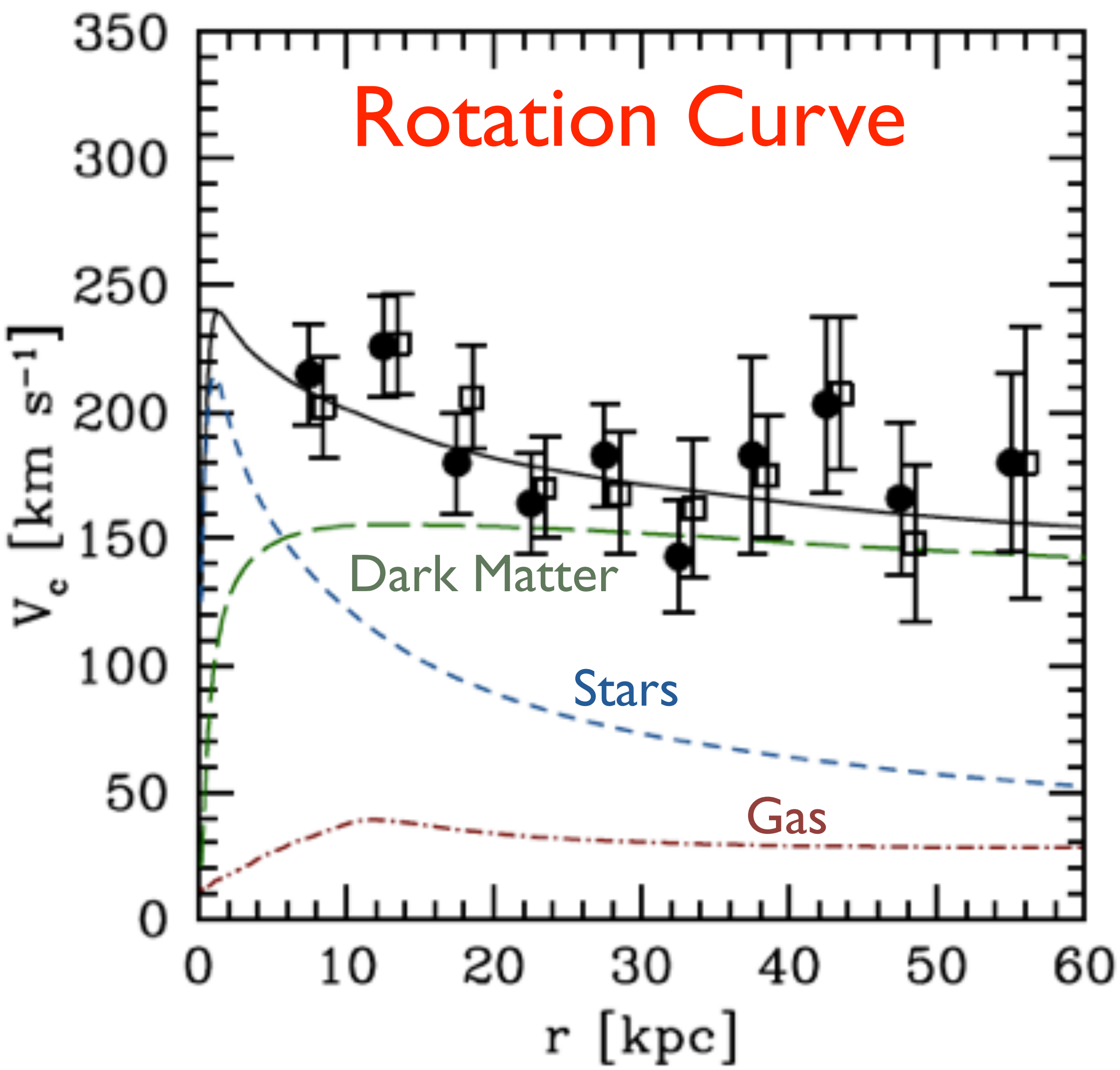
RESEARCH FUNDED BY NASA, NSF, AND SNF

Eris

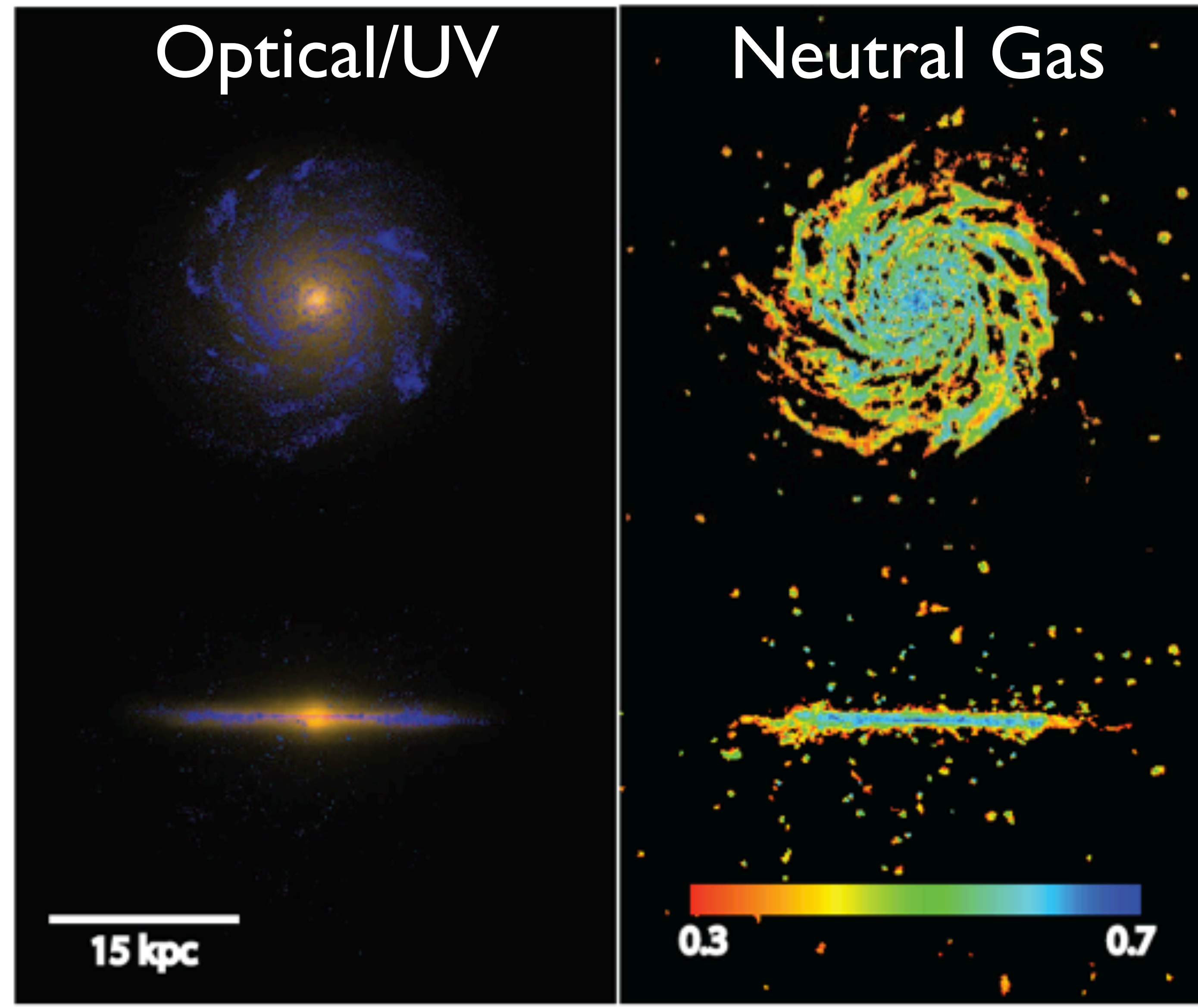
Music: To See the World in a Grain of Sand
by Nancy Abrams

FORMING REALISTIC LATE-TYPE SPIRALS IN A ΛCDM UNIVERSE: THE ERIS SIMULATION

Javiera Guedes[1], Simone Callegari[2], Piero Madau[1], & Lucio Mayer[2]



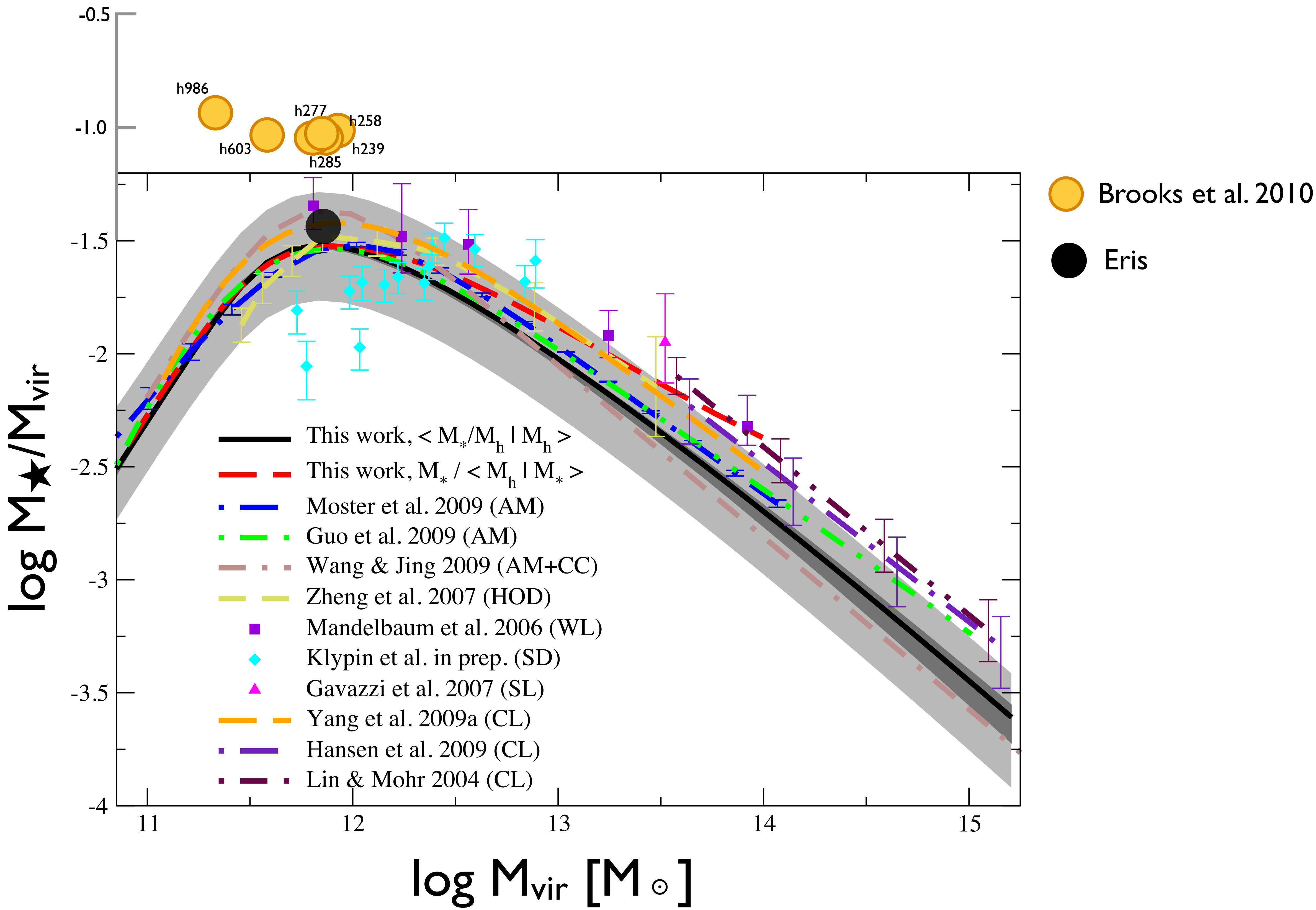
The rotation curve of the simulated Milky Way-sized galaxy (\Eris") at z = 0. The figure shows the contributions to the circular velocity of the various mass components: dark matter (long-dashed curve), stars (short-dashed curve), gas (dot-short dashed curve), and total (solid curve). The data points show two realizations of the rotation curve of the Milky Way from observations of blue horizontal-branch halo stars in the Sloan Digital Sky Survey (Xue et al. 2008), and have been set slightly from each other in radius for clarity.



Left panel: The optical/UV stellar properties of Eris at z = 0. The images, created with the radiative transfer code Sunrise (Jonsson 2006), show an i, V , and FUV stellar composite of the simulated galaxy seen face-on and edge-on. A Kroupa IMF was assumed. Right panel: Projected face-on and edge-on surface density maps of Eris's neutral gas at z = 0. The color bar shows the neutral gas fraction.

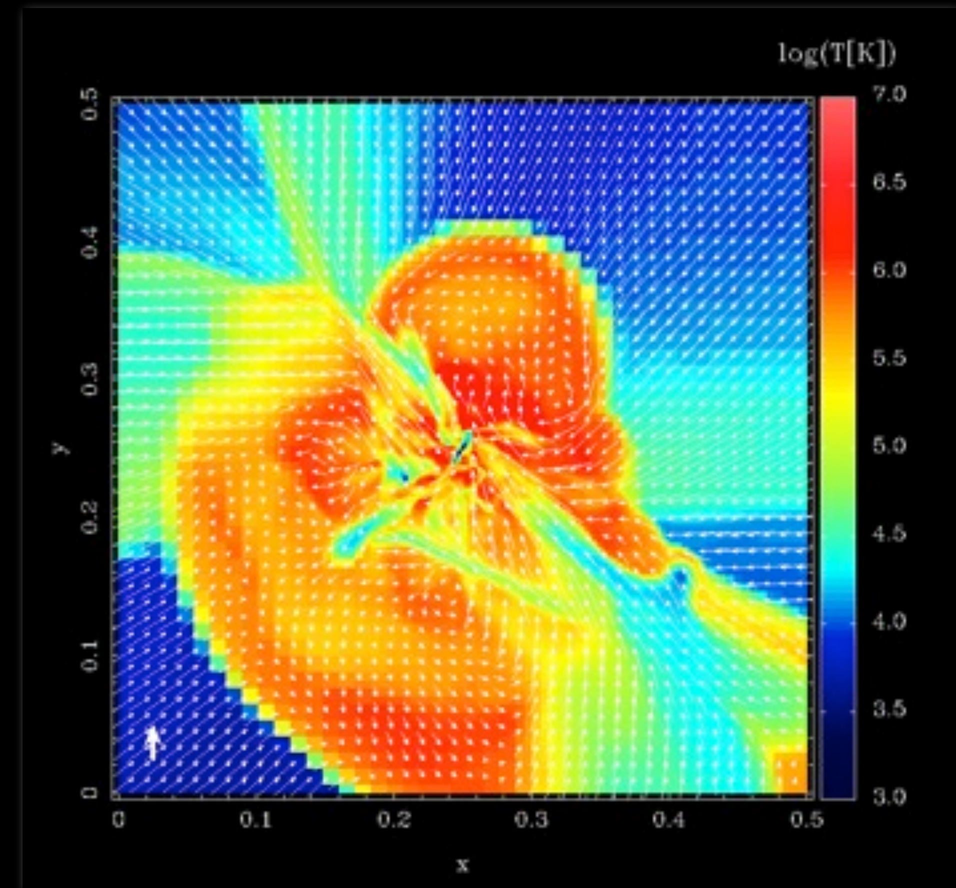
The M_{star}-M_{halo} Relation

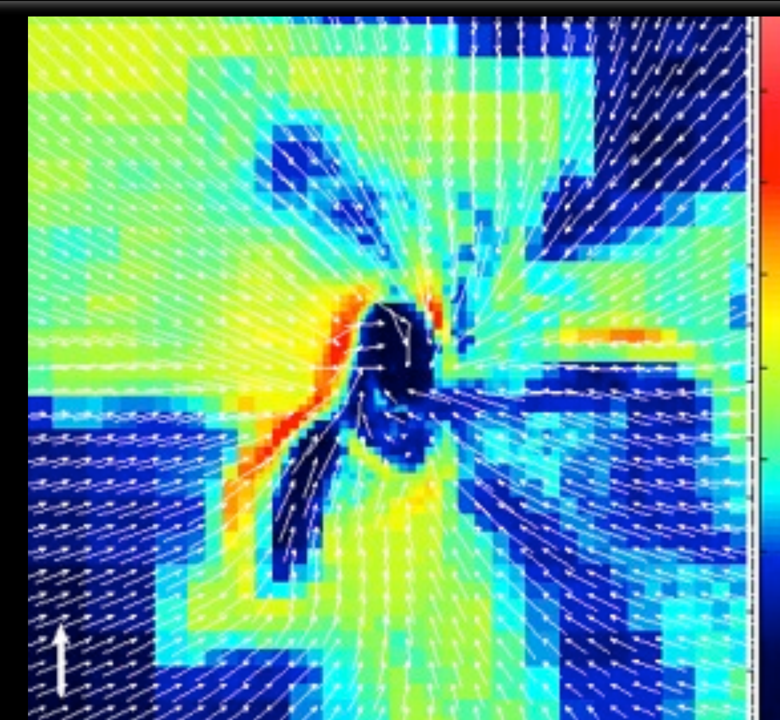
Behroozi et al 2010



hot vs. cold flows

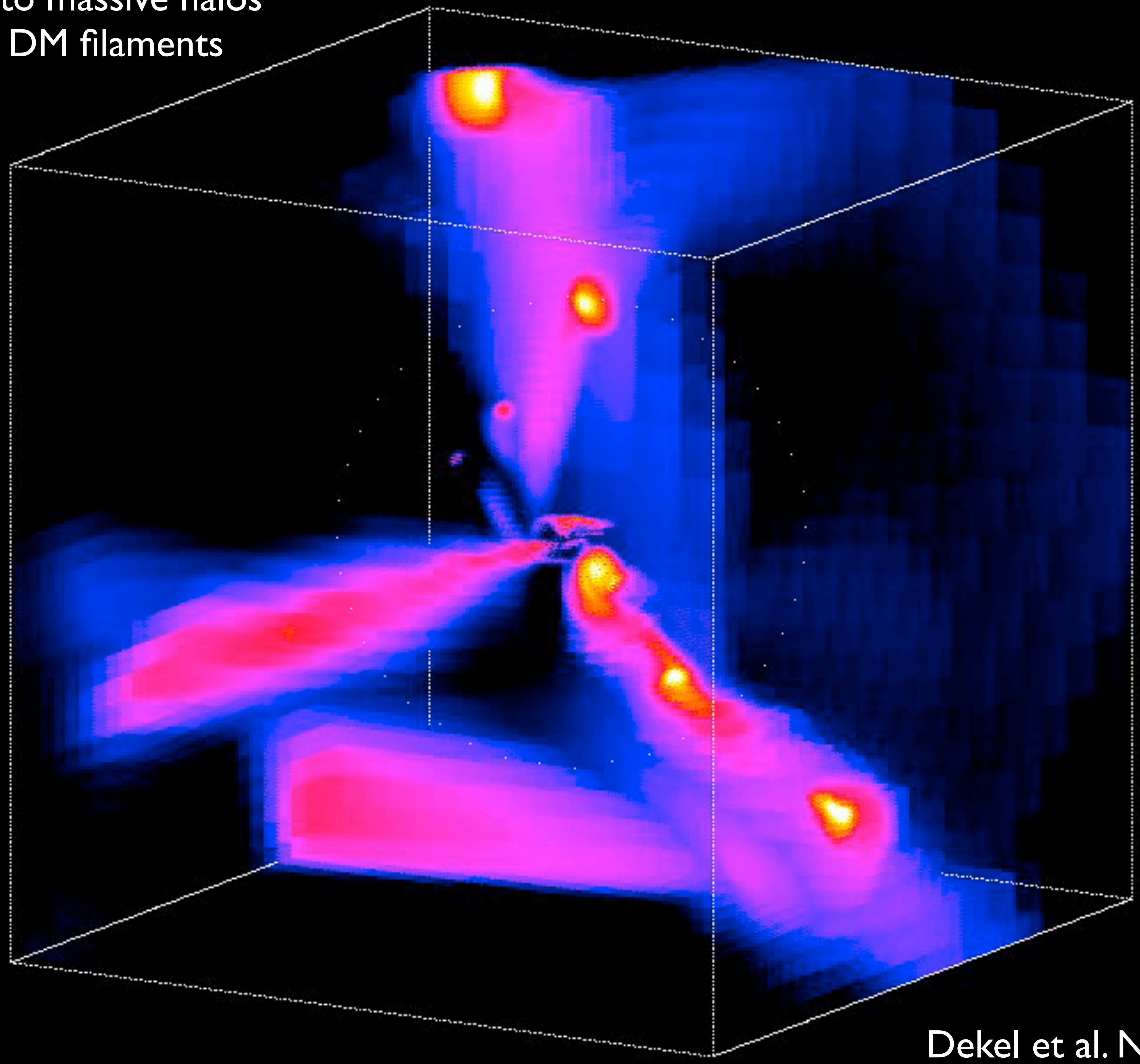
- when $r_{cool}<r_{ff}$, gas is shock heated to virial temperature then cools in a "cooling flow"
- when $r_{cool}>r_{ff}$, gas never shock heats, "falls in cold"
- halos with primarily cold vs. hot flows separated by a critical mass of few x 10^{11}-10^{12} M_{sun} (e.g. Birnboim & Dekel 2003; Keres et al. 2004)
- heating by radio jets may only be effective when a quasi-static hot gas halo is present (i.e. in large mass halos; Cattaneo et al. 2006)



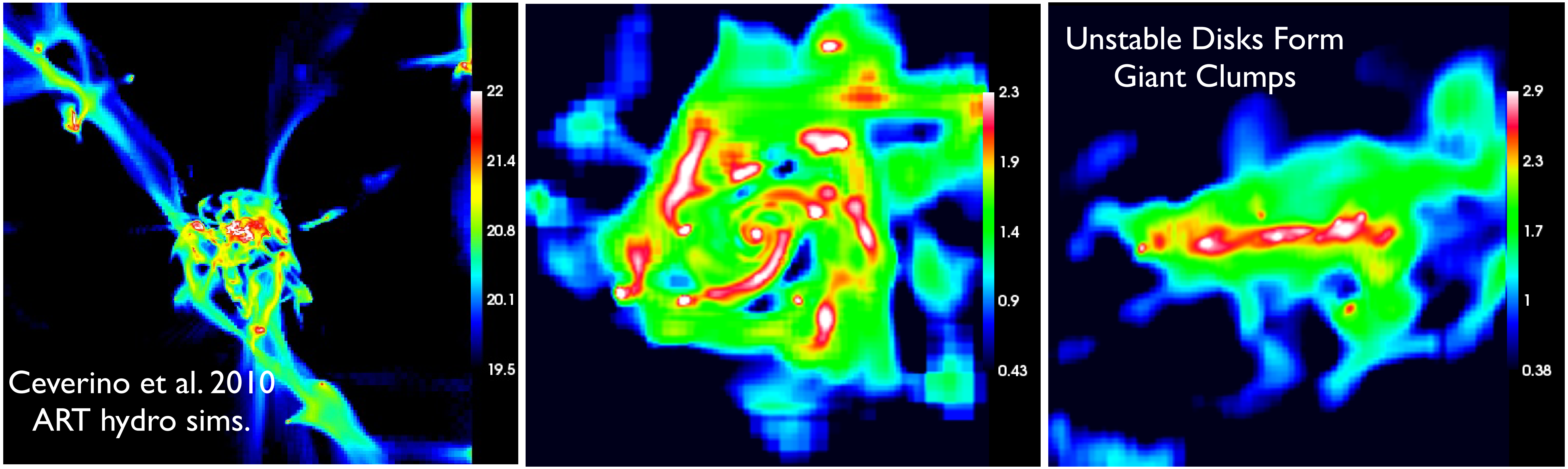


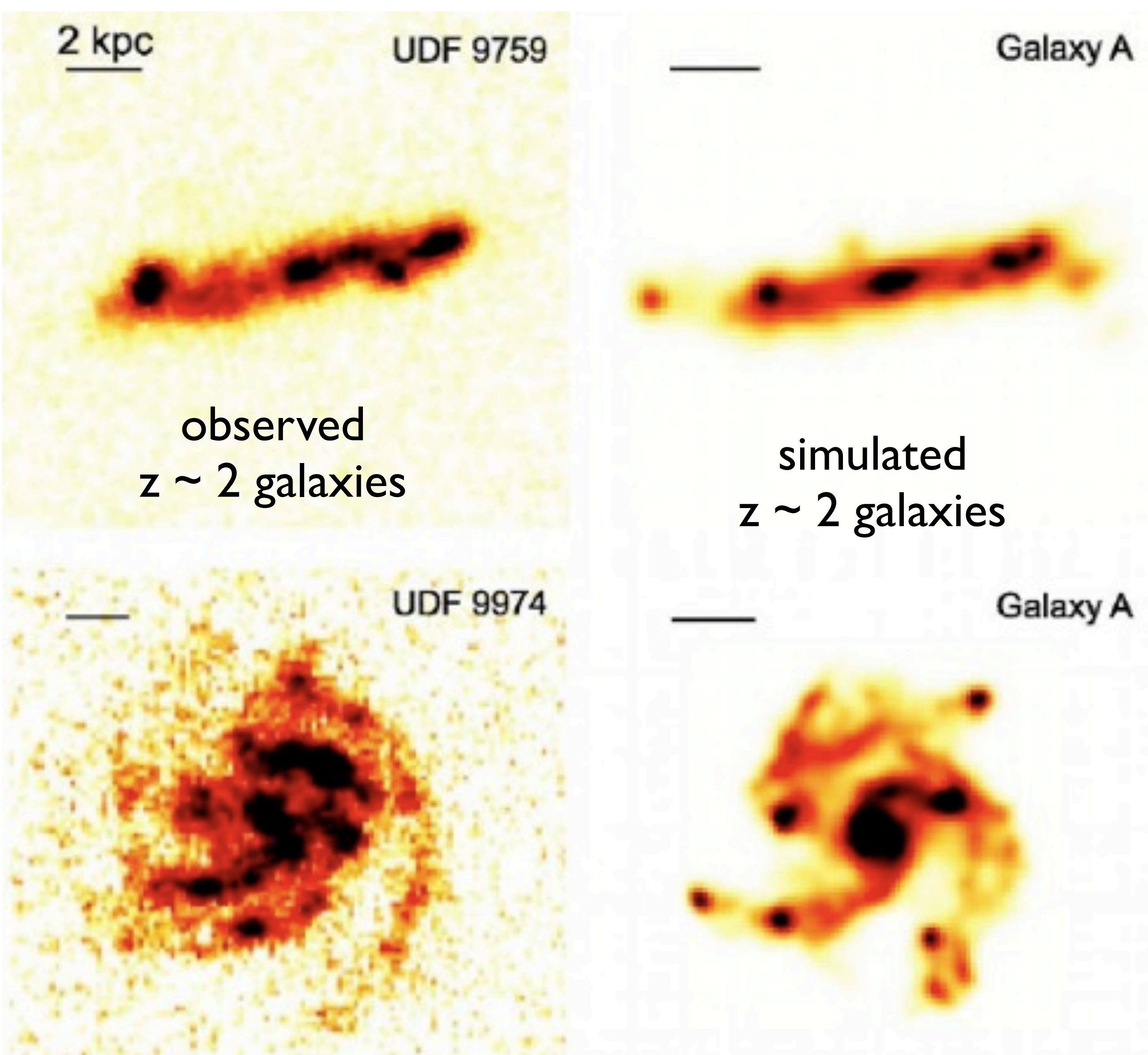
Kravtsov et al.

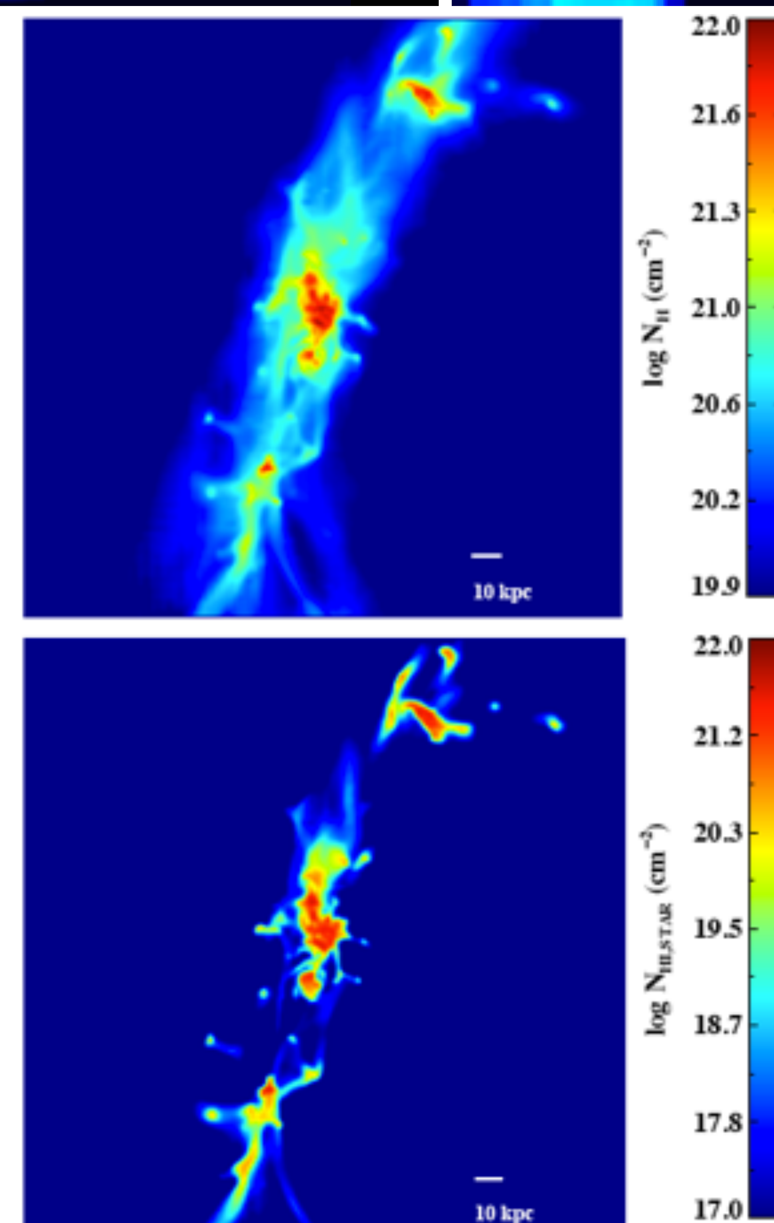
Inflows to massive halos
along DM filaments



Dekel et al. Nature 2009







Total Hydrogen

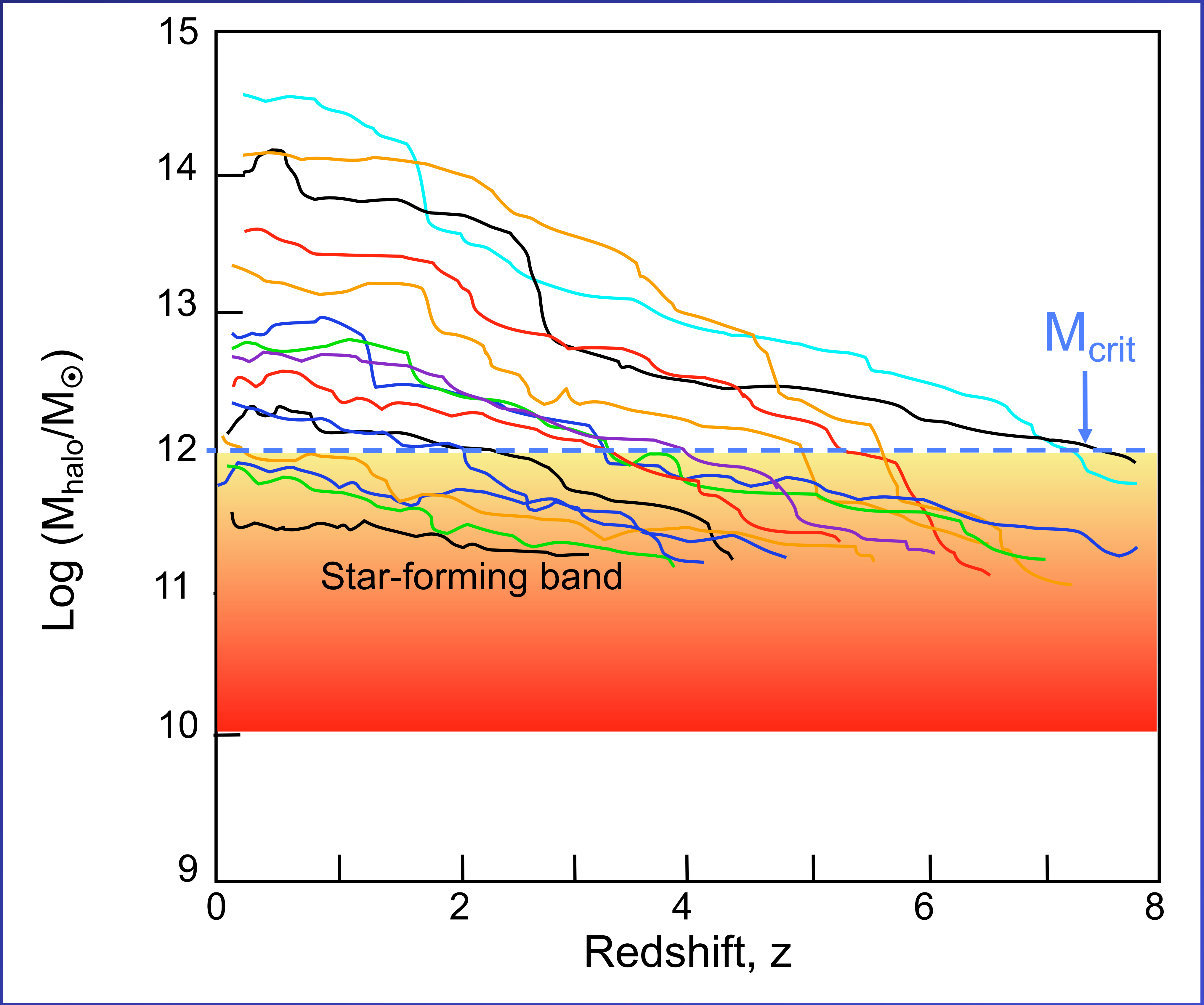
N_H

Fumagalli et al. 2011
Ly alpha absorbtion

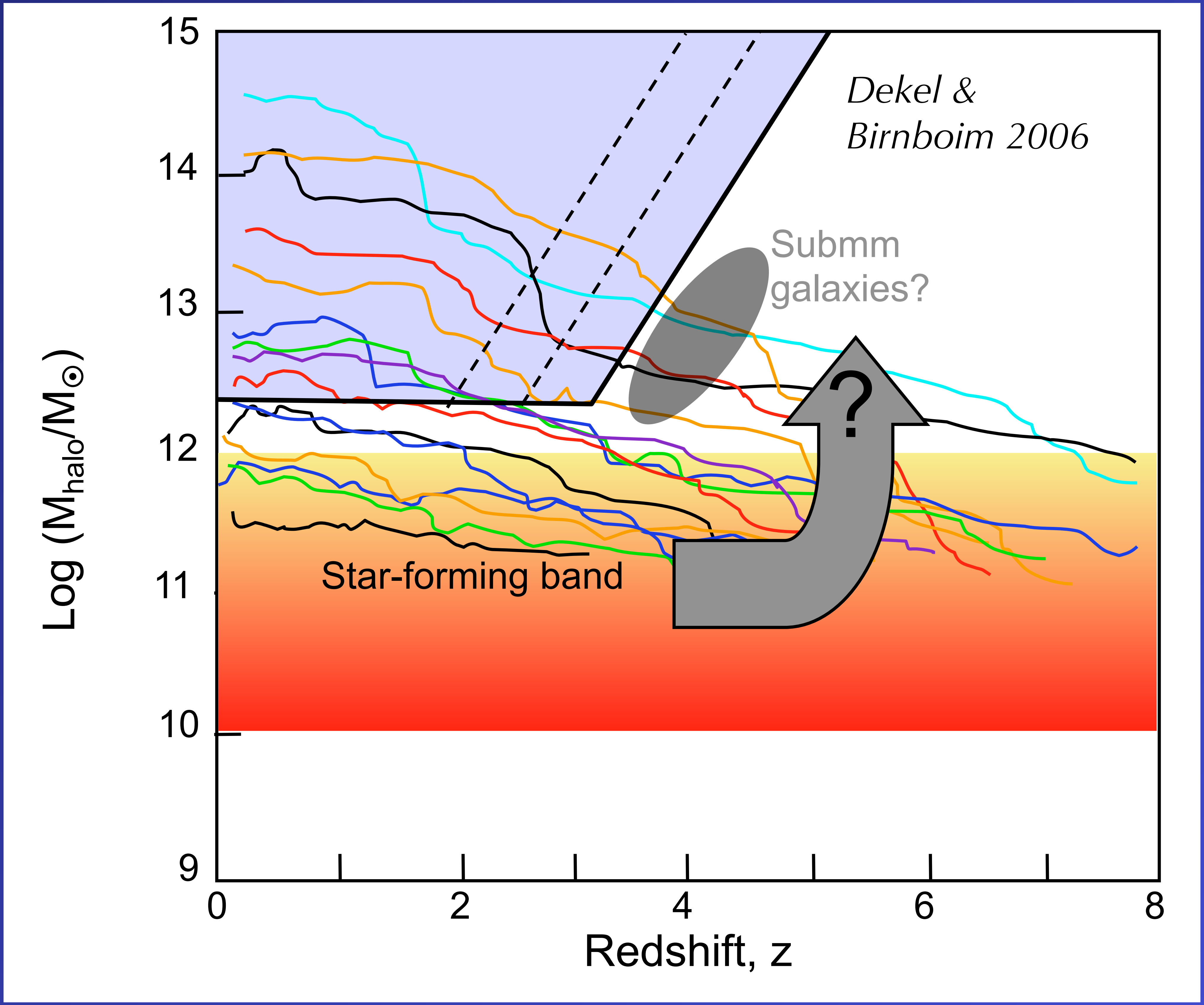
Atomic Hydrogen

N_{HI}

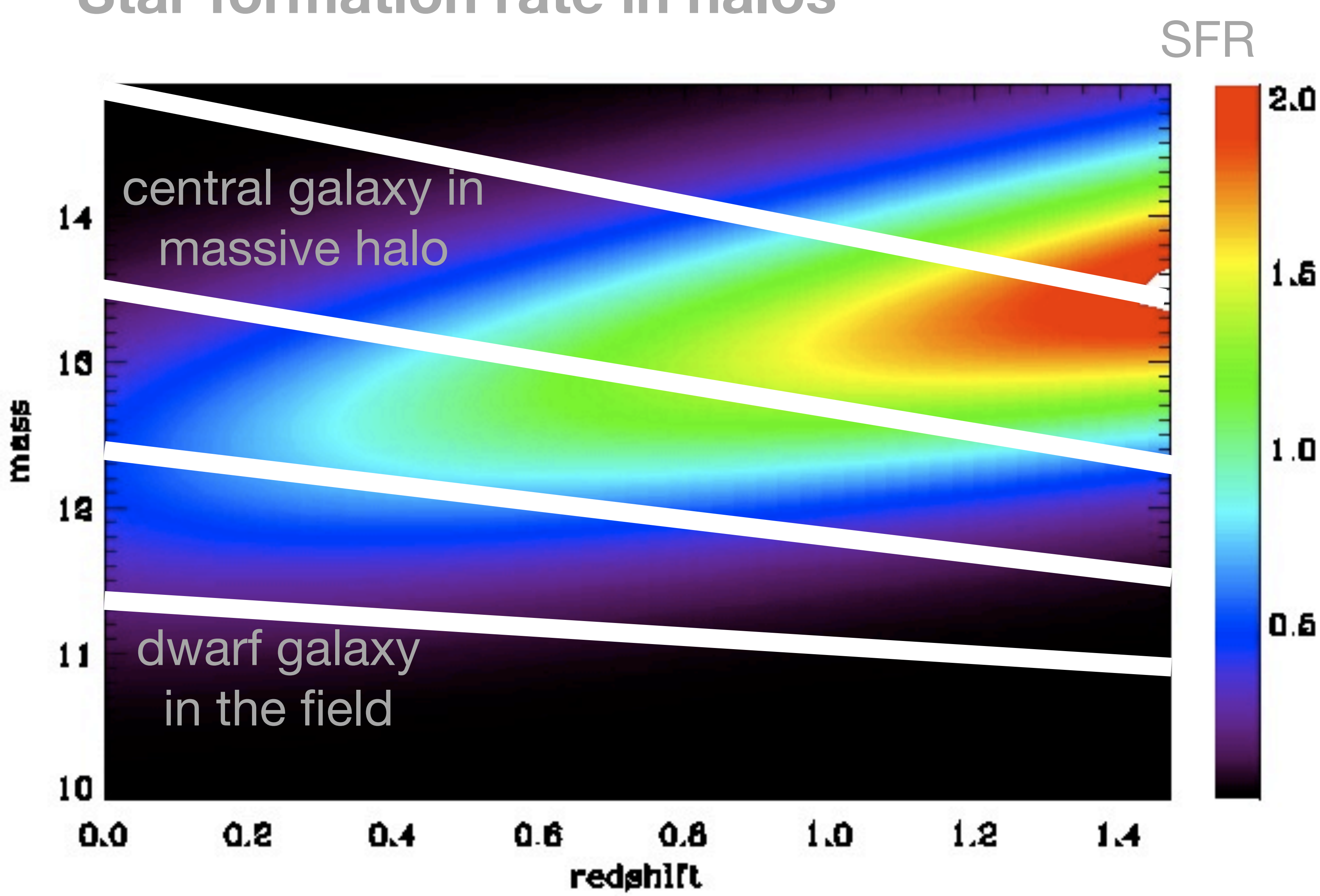
More realistic model of halo-cooling boundary



More realistic model of halo-cooling boundary



Star formation rate in halos



Typical galaxy trajectories

basic trends in galaxy formation

- massive halos host more massive galaxies (they spend more time rapidly forming stars)
- massive halos host older galaxies (they start forming stars earlier)
- massive halos host higher surface brightness galaxies (they formed more stars when the universe was denser)
- low mass galaxies always form galaxies slowly

naturally explains observed "downsizing"

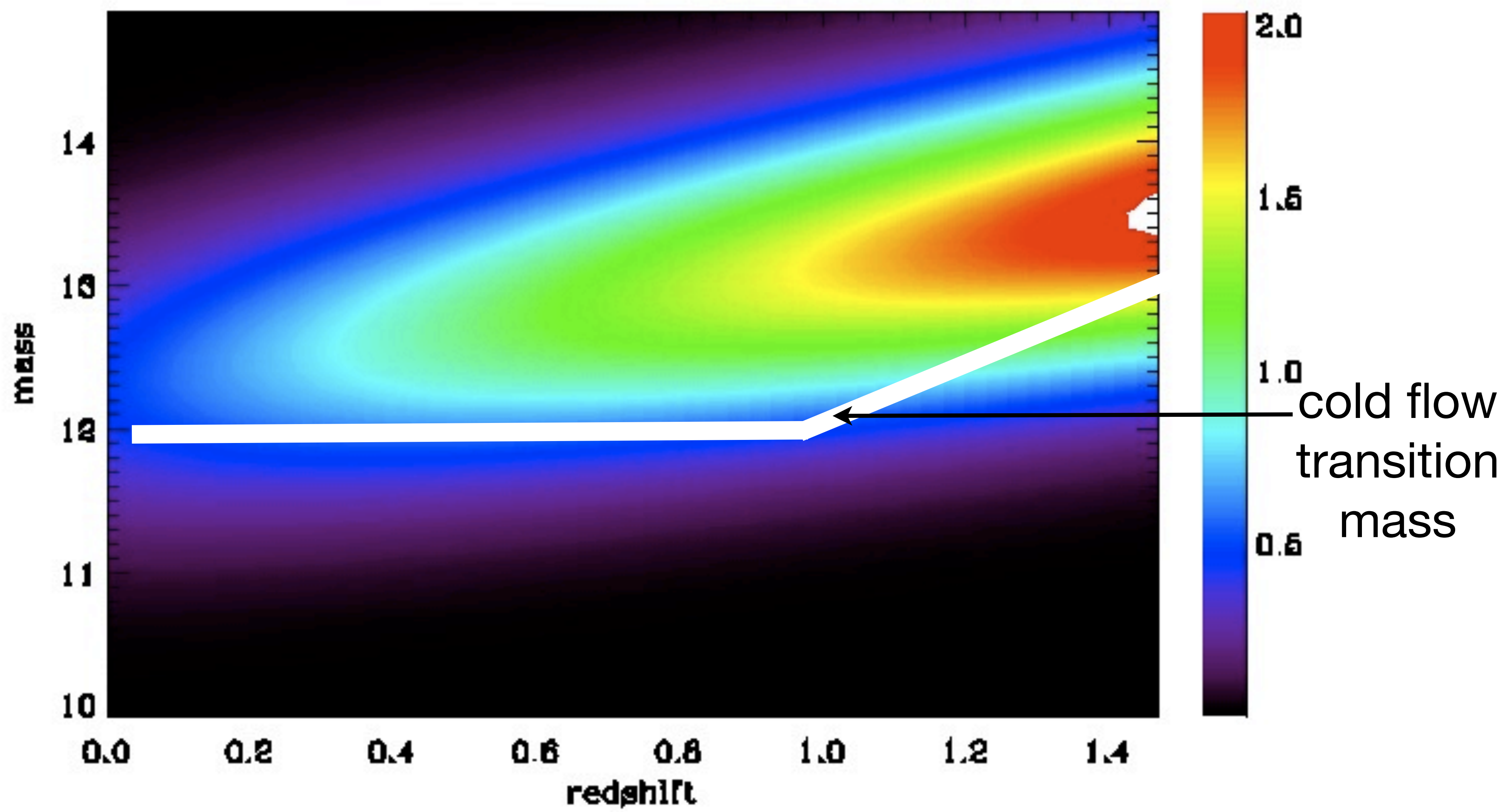
predicts "upsizing" at high redshifts

Risa Wechsler

What does this imply about the physics?

AGN feedback
shock heating
inefficient cooling

SN feedback
feedback from SF
photoionization



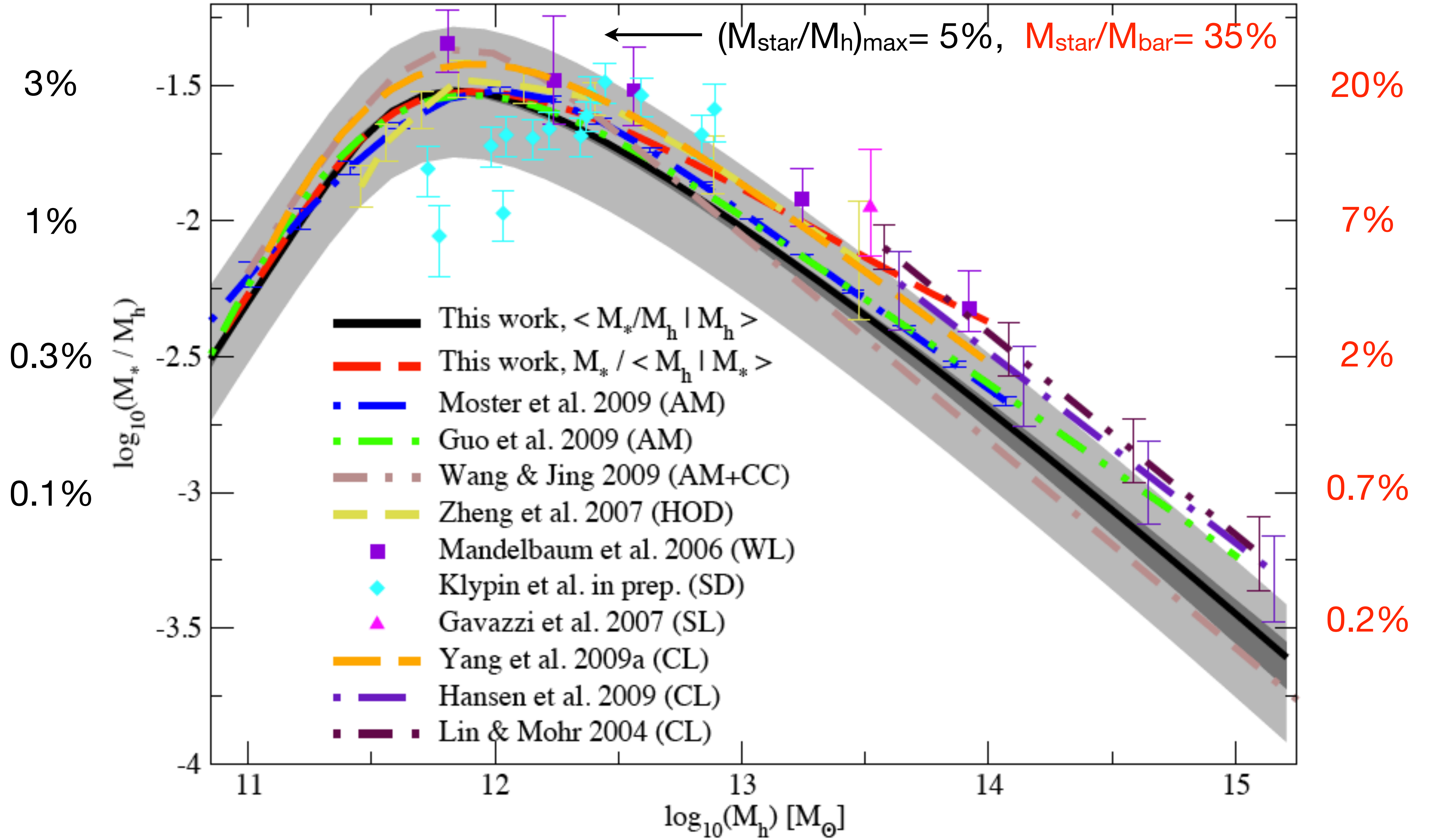
- Model implies that star formation slows for masses greater than M~1e12 halos (roughly the scale where galaxy bimodality sets in) today

Risa Wechsler

STELLAR MASS – HALO MASS RELATION

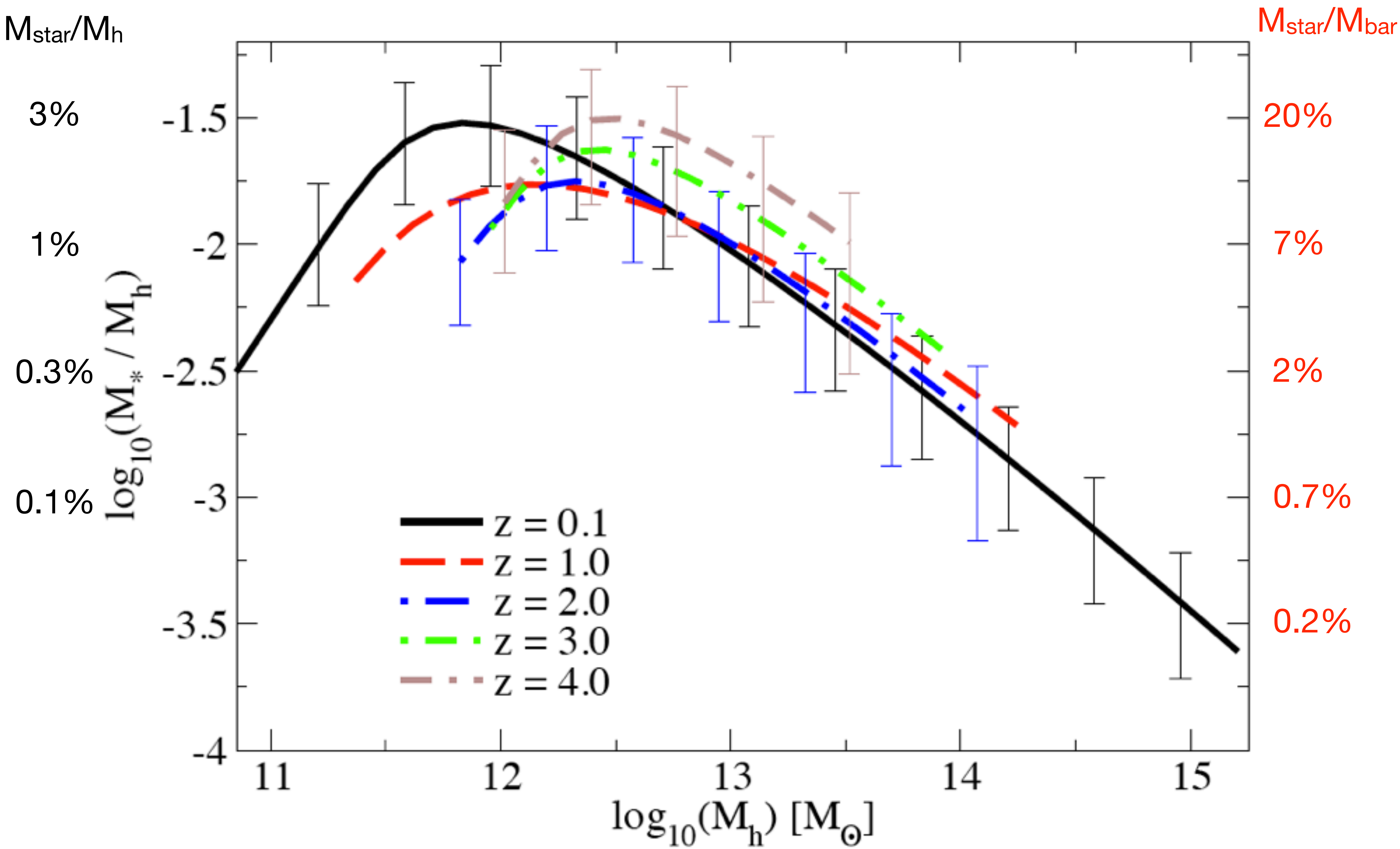
Mstar/Mh

Mstar/Mbar



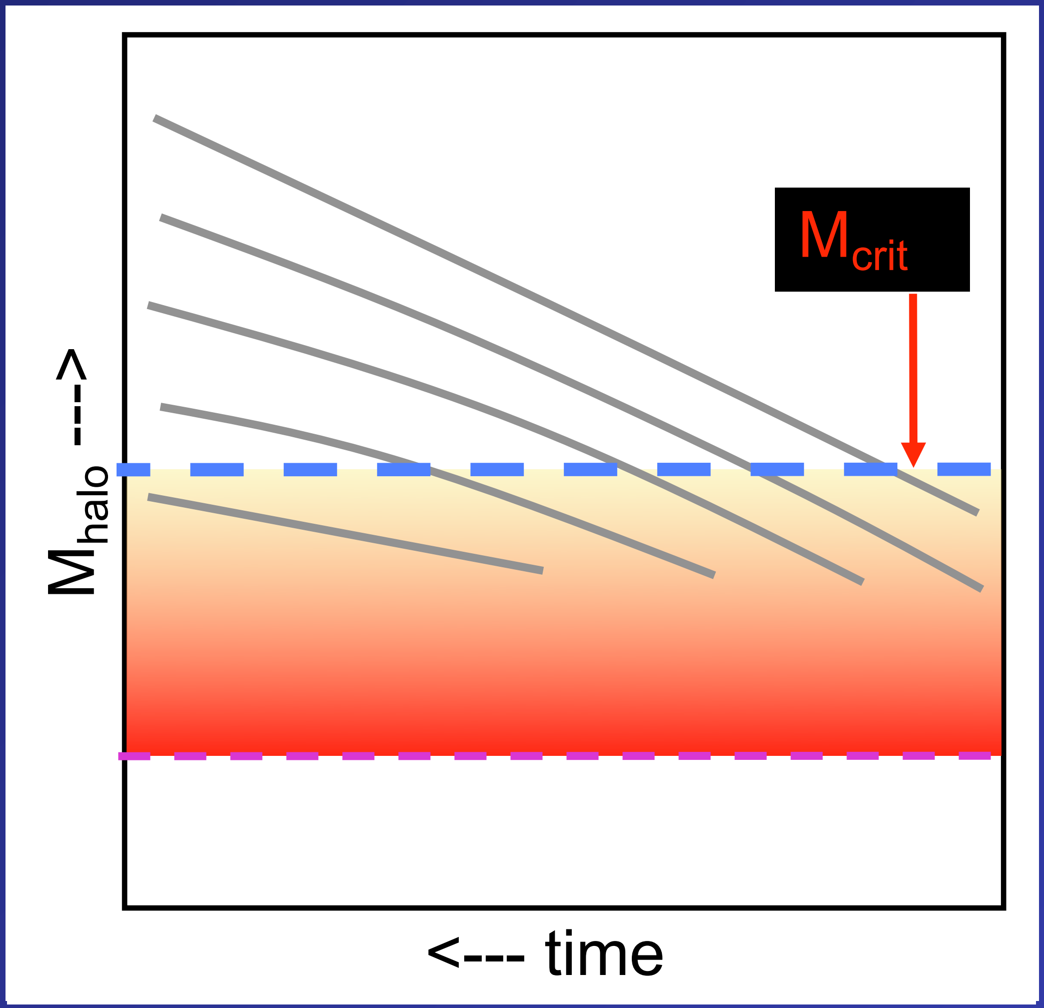
Comparison of best-fit model of Behroozi, Conroy, Wechsler (2010) at $z = 0.1$ to previously published results.

STELLAR MASS – HALO MASS RELATION EVOLUTION



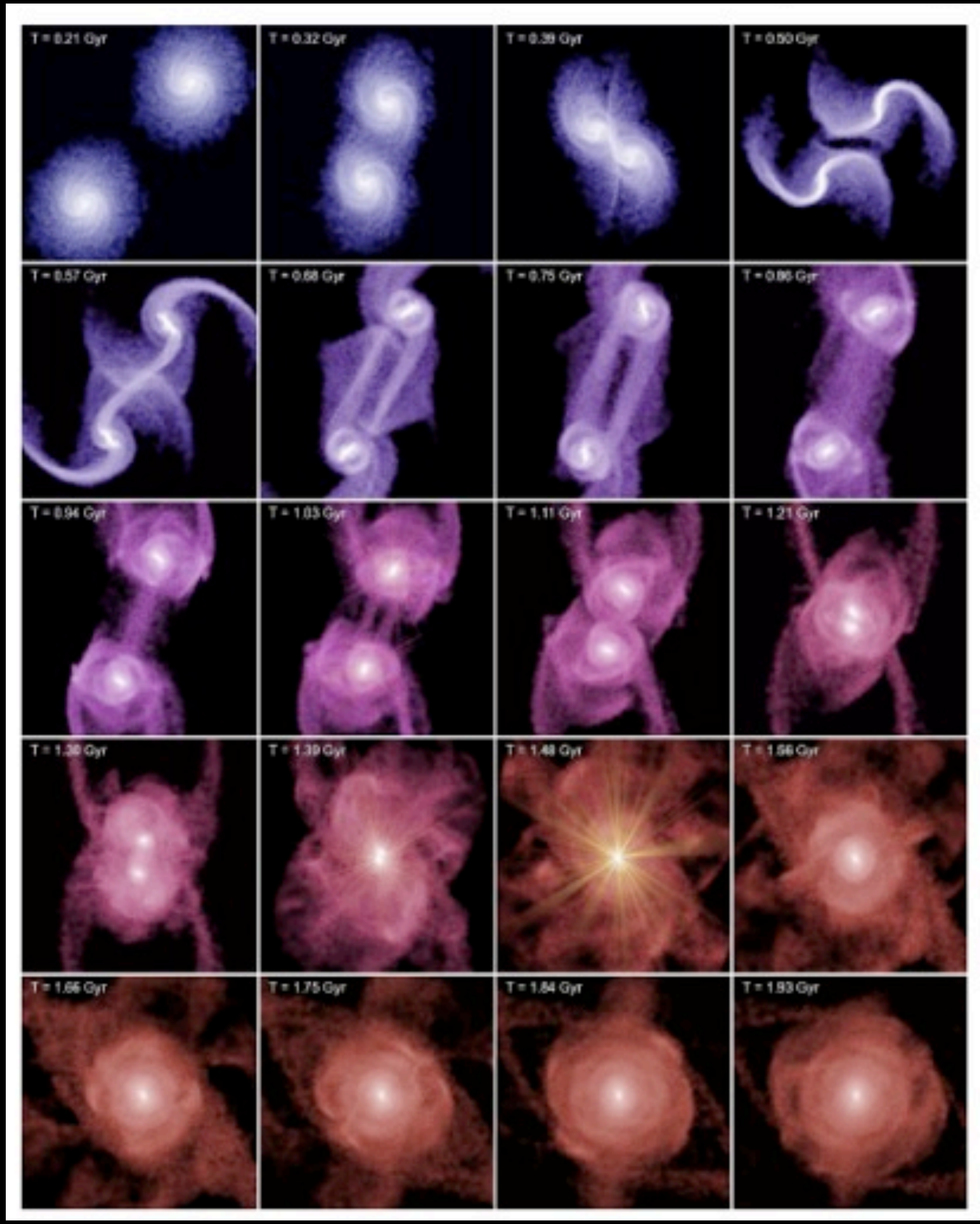
Behroozi, Conroy, Wechsler (2010)

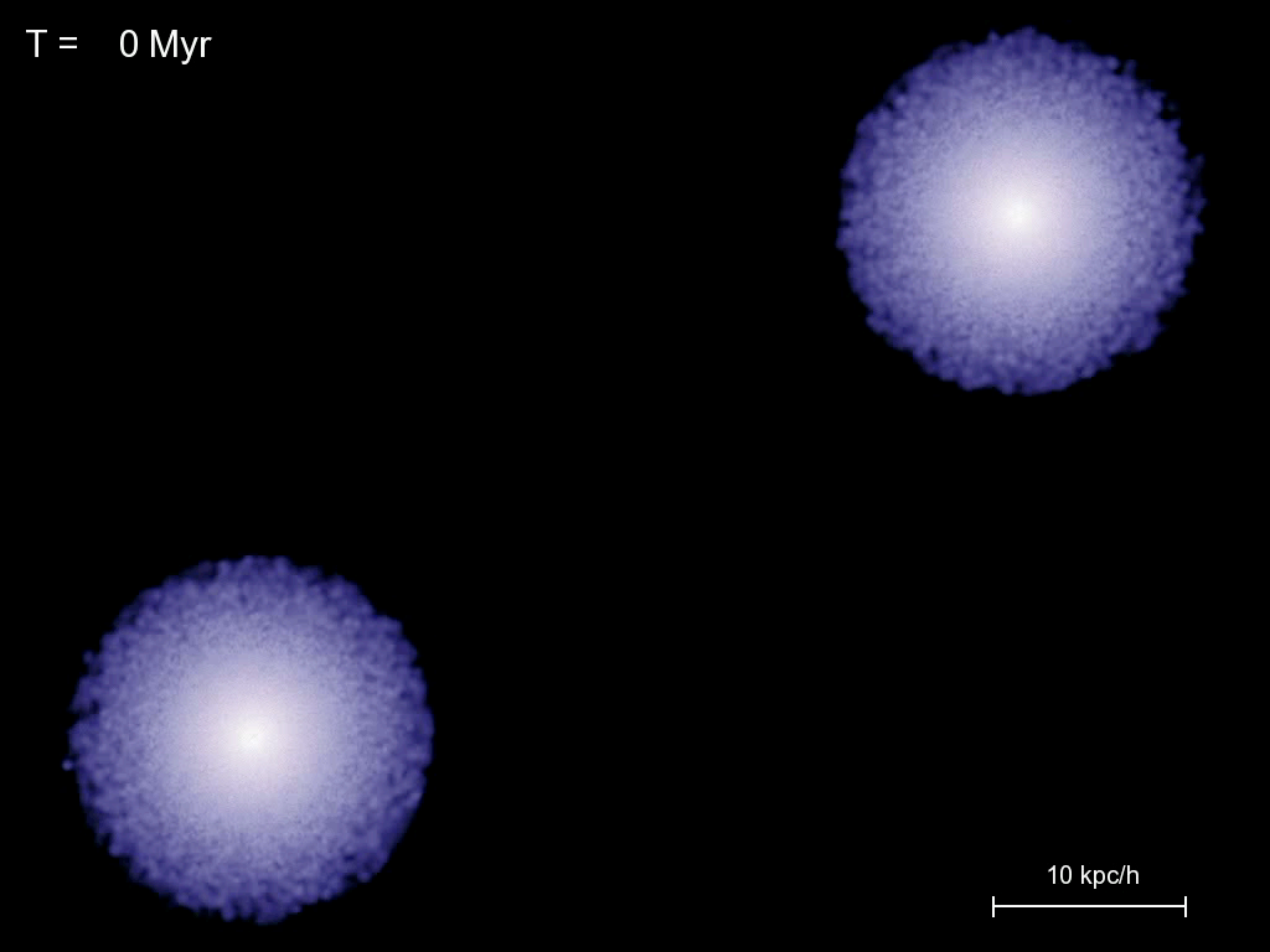
Theories for the *upper* halo star-formation boundary



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

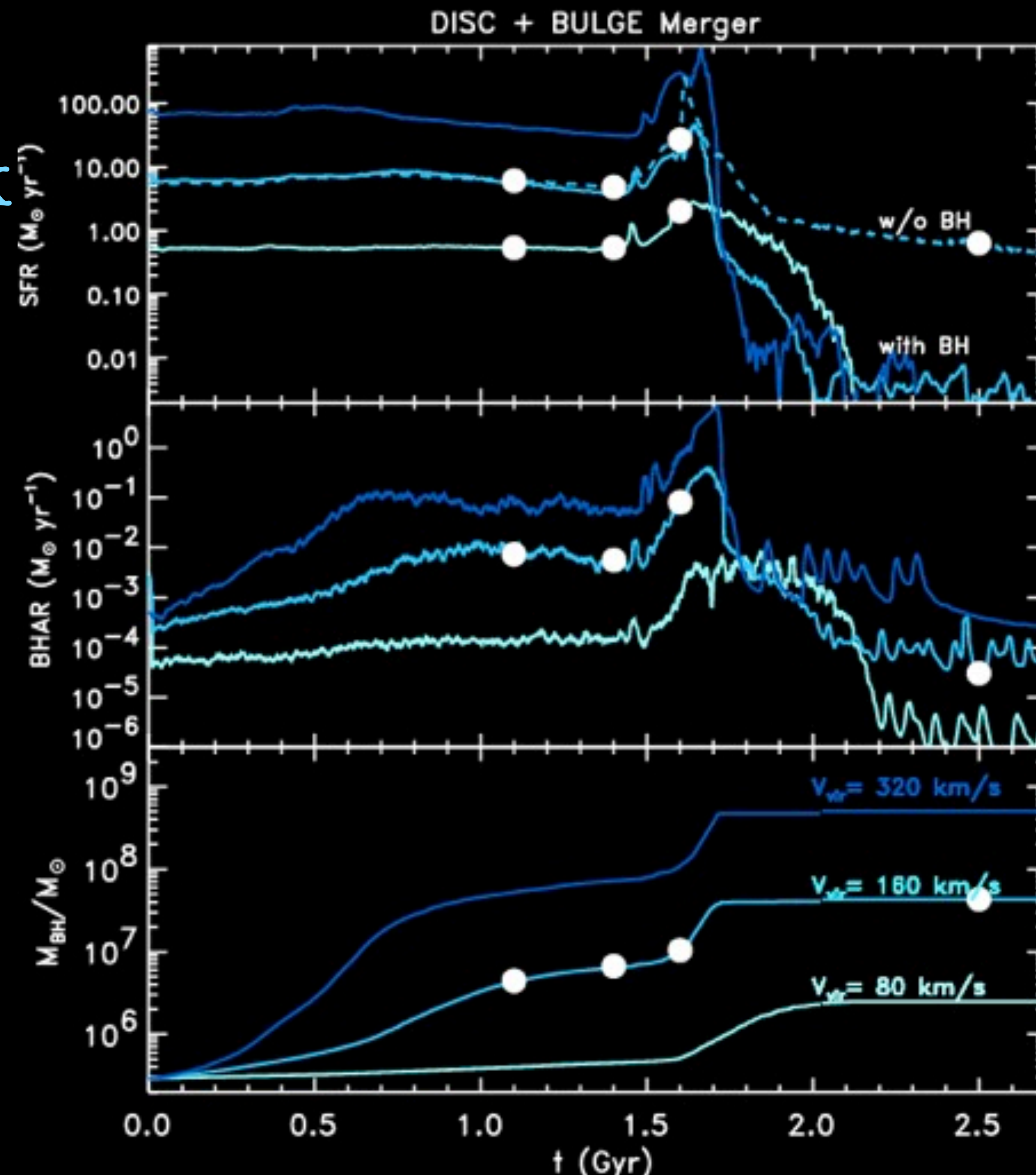
2 Merging galaxies trigger BH growth. AGN feedback drives out galaxy gas (Hopkins et al 2006).

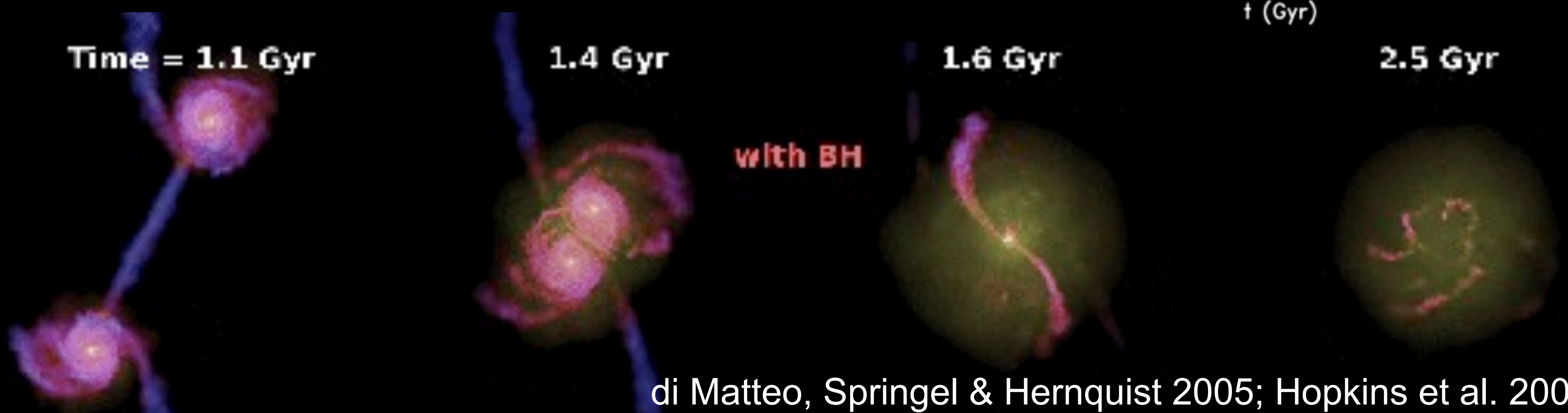



T = 0 Myr
10 kpc/h

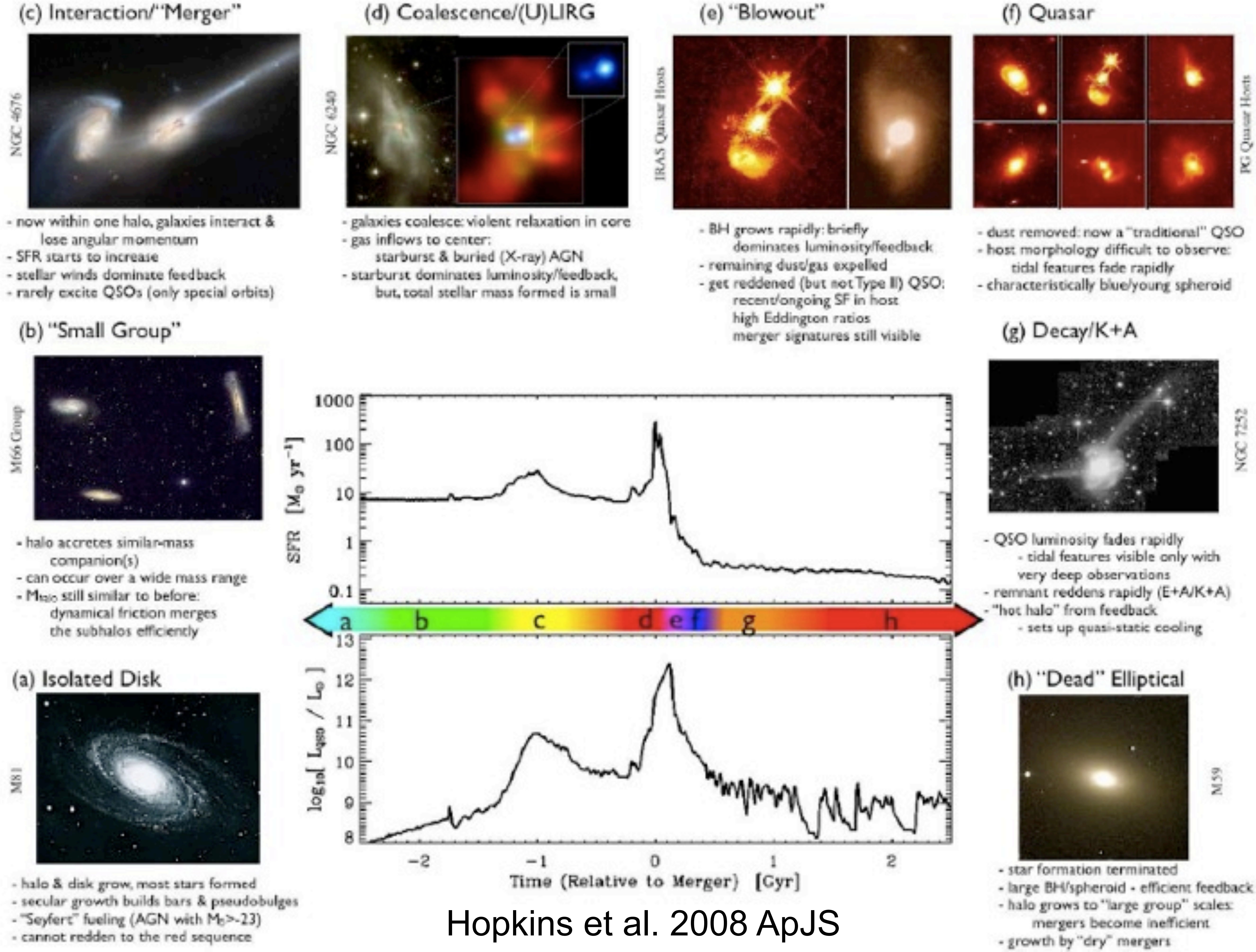
Hydrodynamic simulations of galaxy mergers including black hole growth and feedback

- 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-



Hopkins et al. 2008 ApJS

Effect of "Radio Mode" AGN heating (needed to keep red galaxies red)

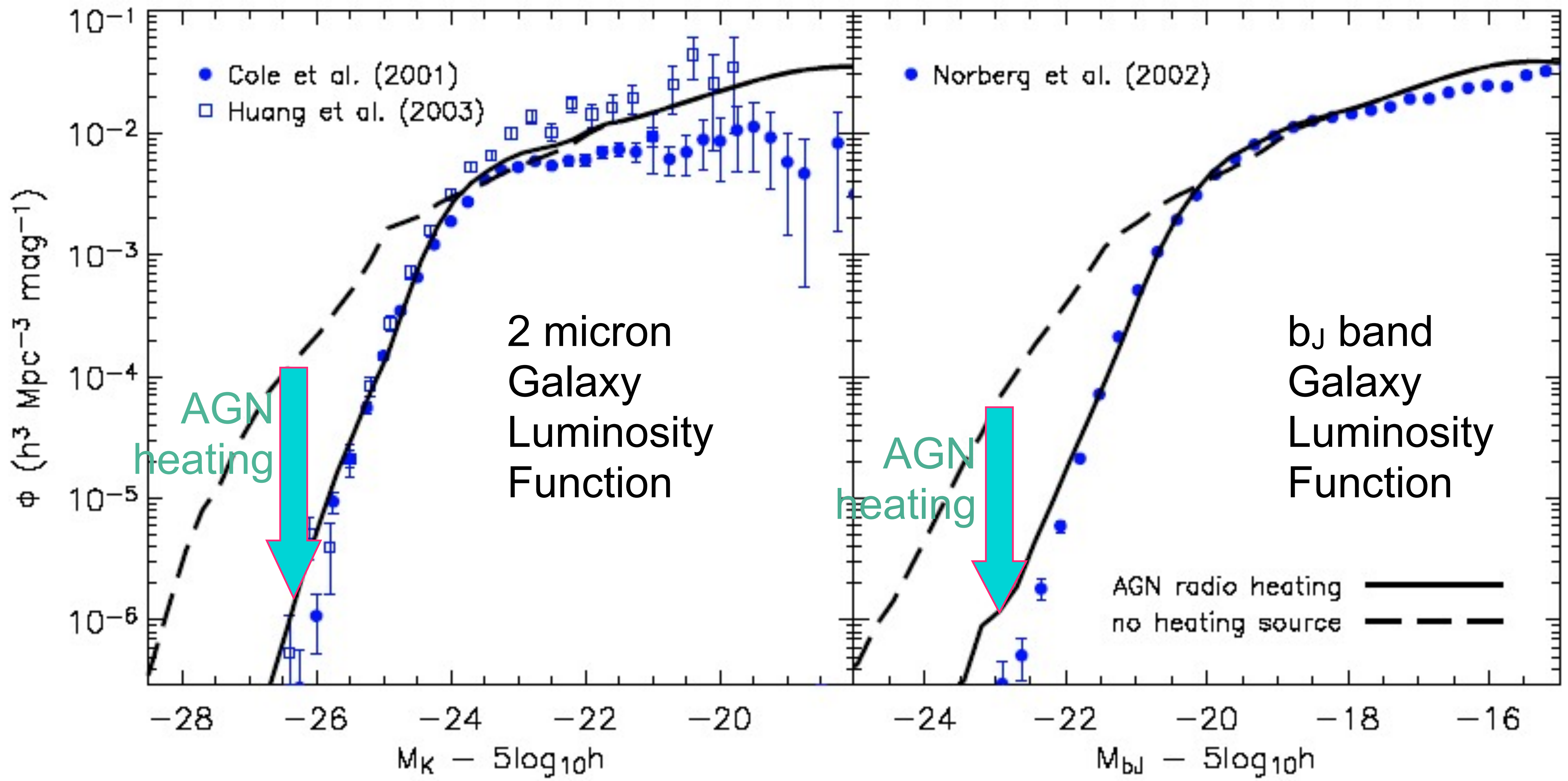
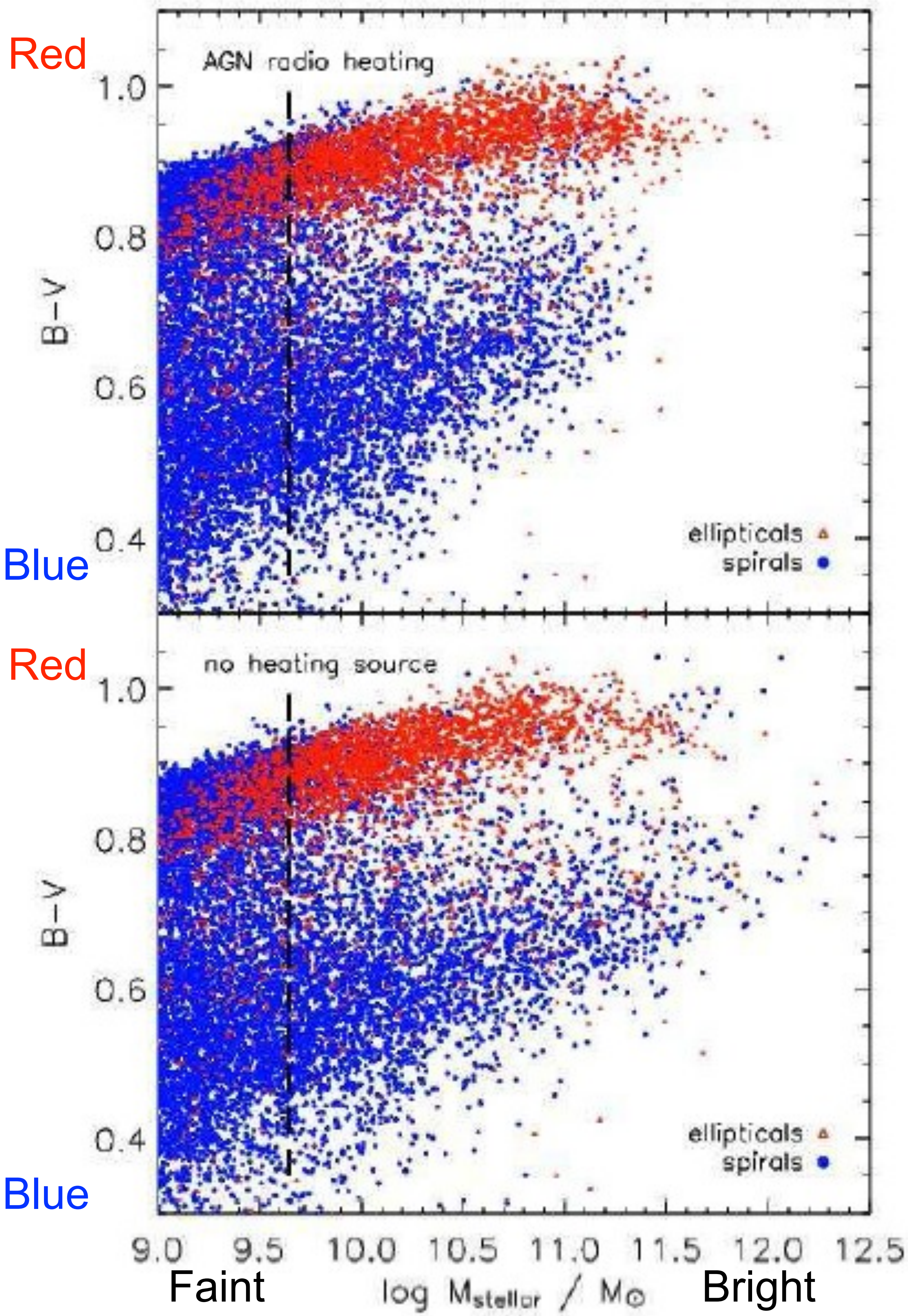


Figure 8. Galaxy luminosity functions in the K (left) and b_J (right) photometric bands, plotted with and without 'radio mode' feedback (solid and long dashed lines respectively – see Section 3.4). Symbols indicate observational results as listed in each panel. As can be seen, the inclusion of AGN heating produces a good fit to the data in both colours. Without this heating source our model overpredicts the luminosities of massive galaxies by about two magnitudes and fails to reproduce the sharp bright end cut-offs in the observed luminosity functions.

Croton et al. 2006

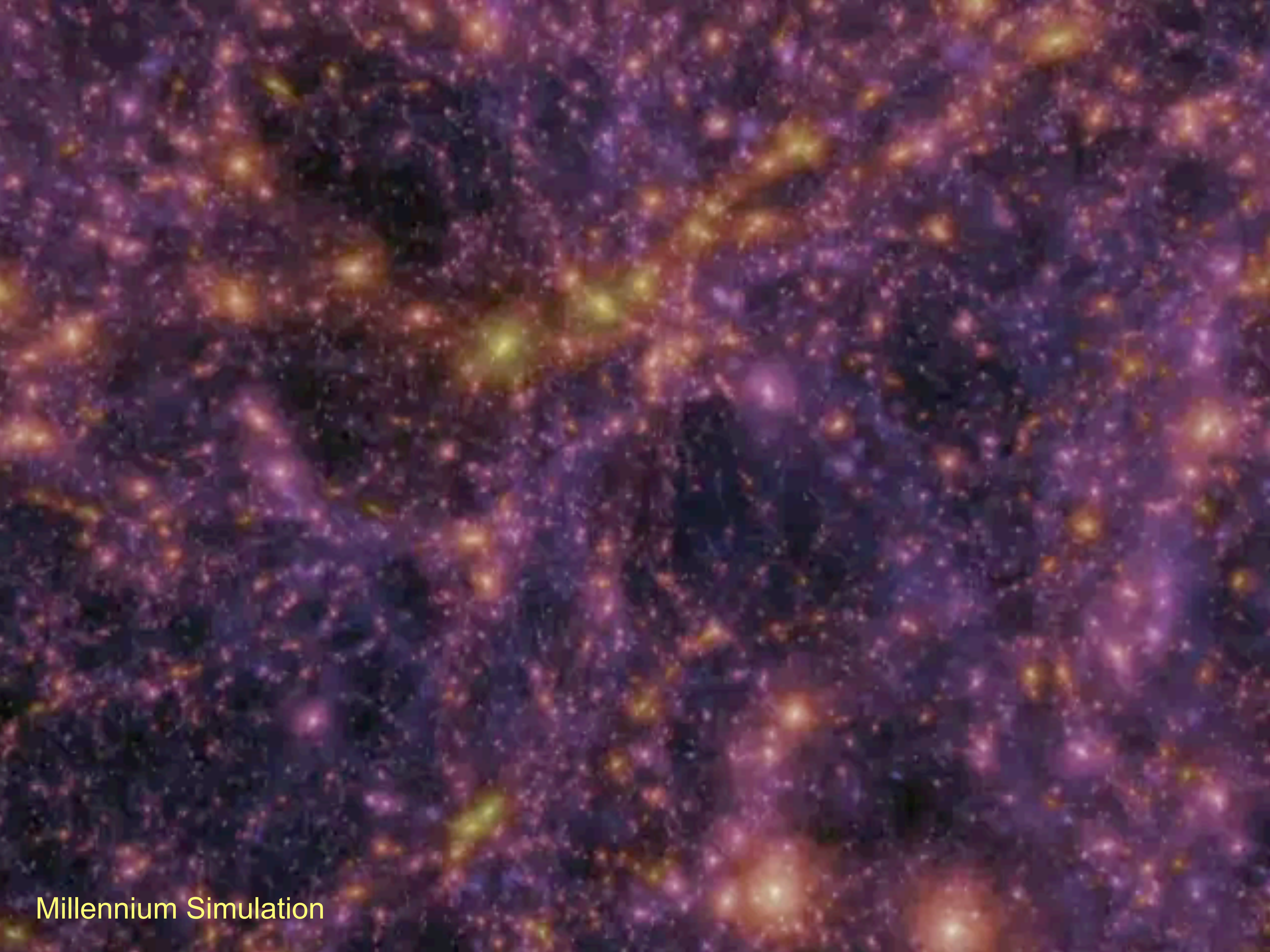


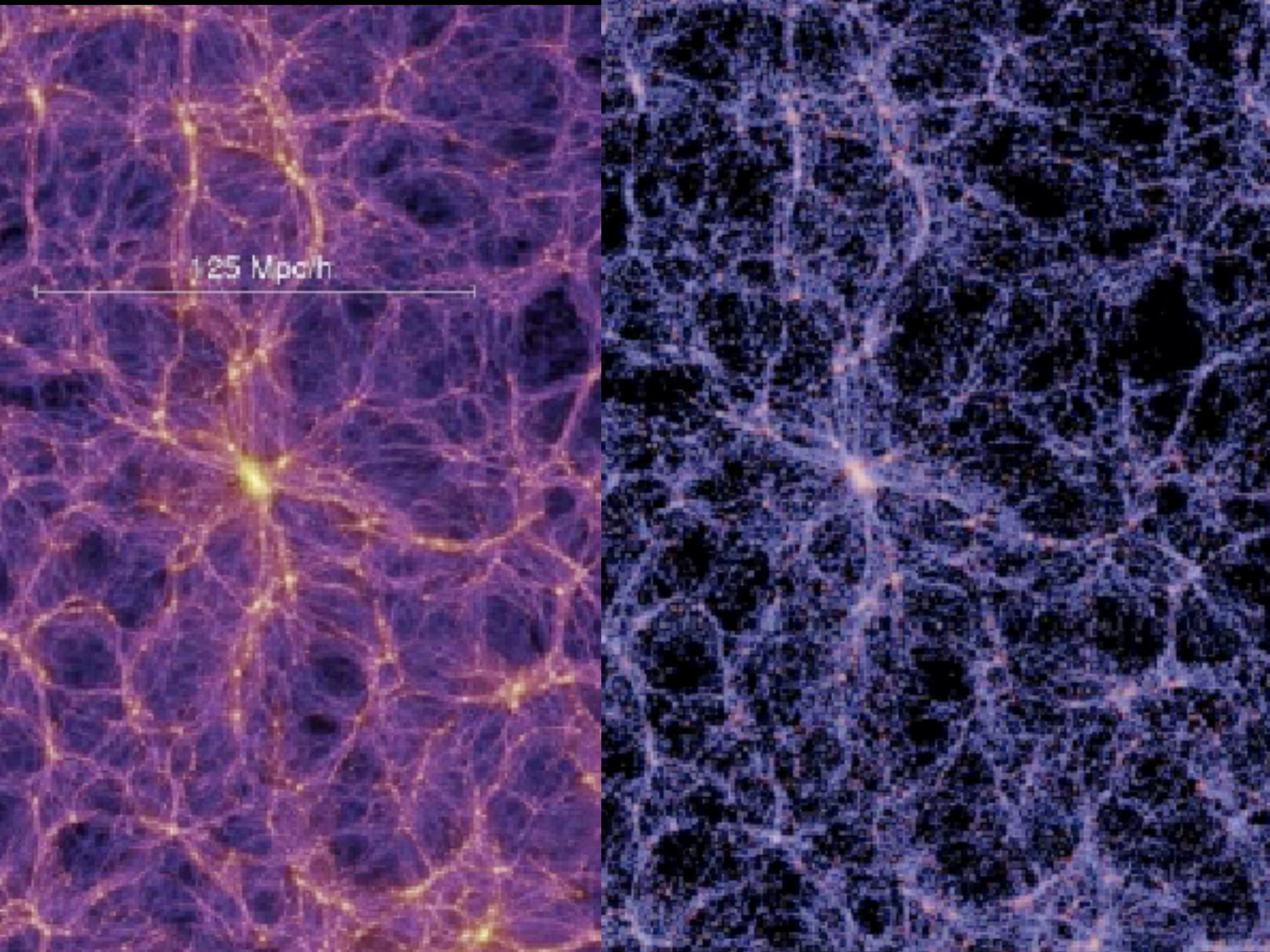
Color Magnitude Diagram

With AGN “radio mode” heating – brightest galaxies are red, as observed

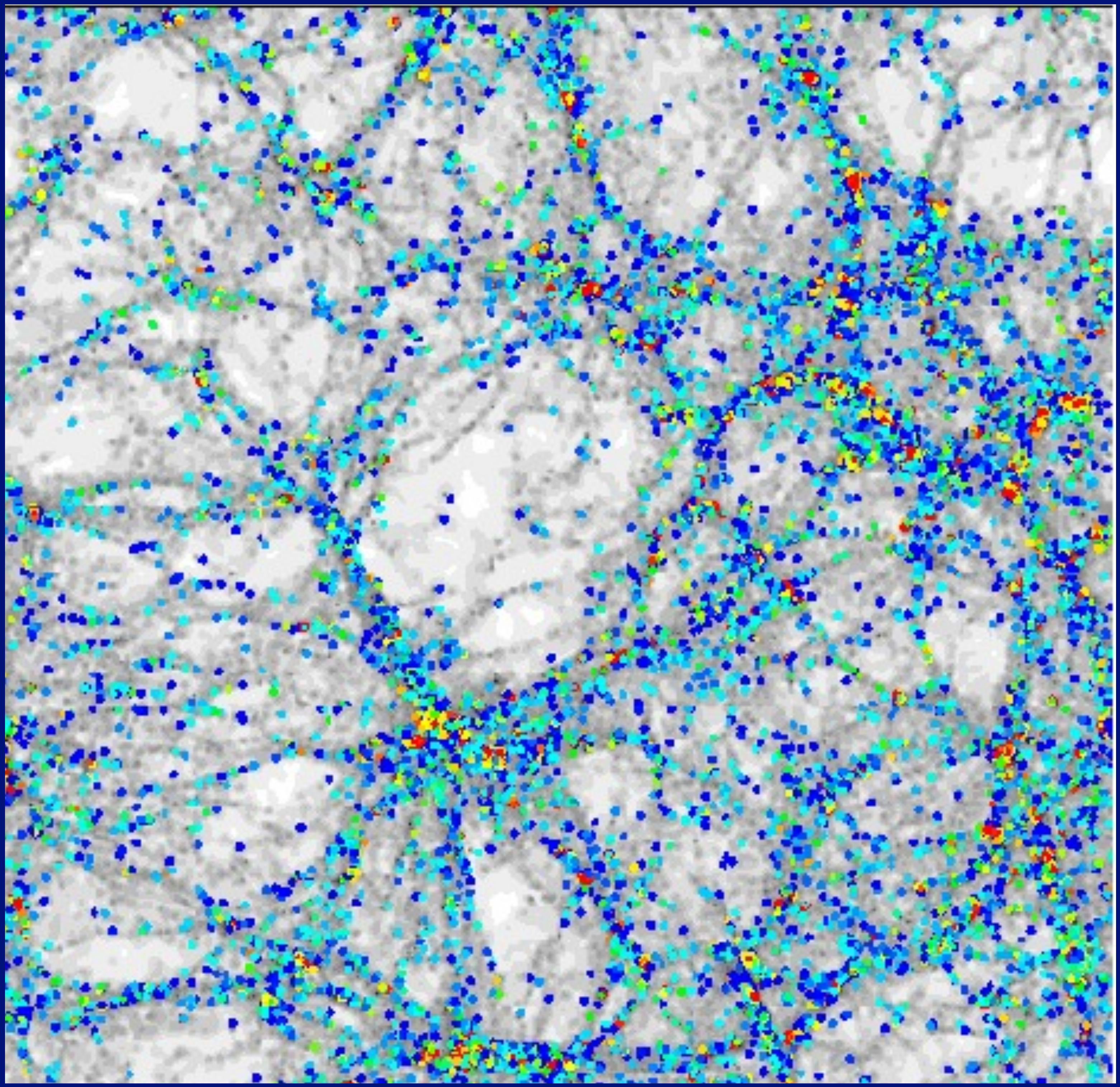
Without heating – brightest galaxies are blue

Croton et al. 2006


Millennium Simulation


125 Mpc/h

Galaxy type correlated with large scale structure



elliptical

elliptical

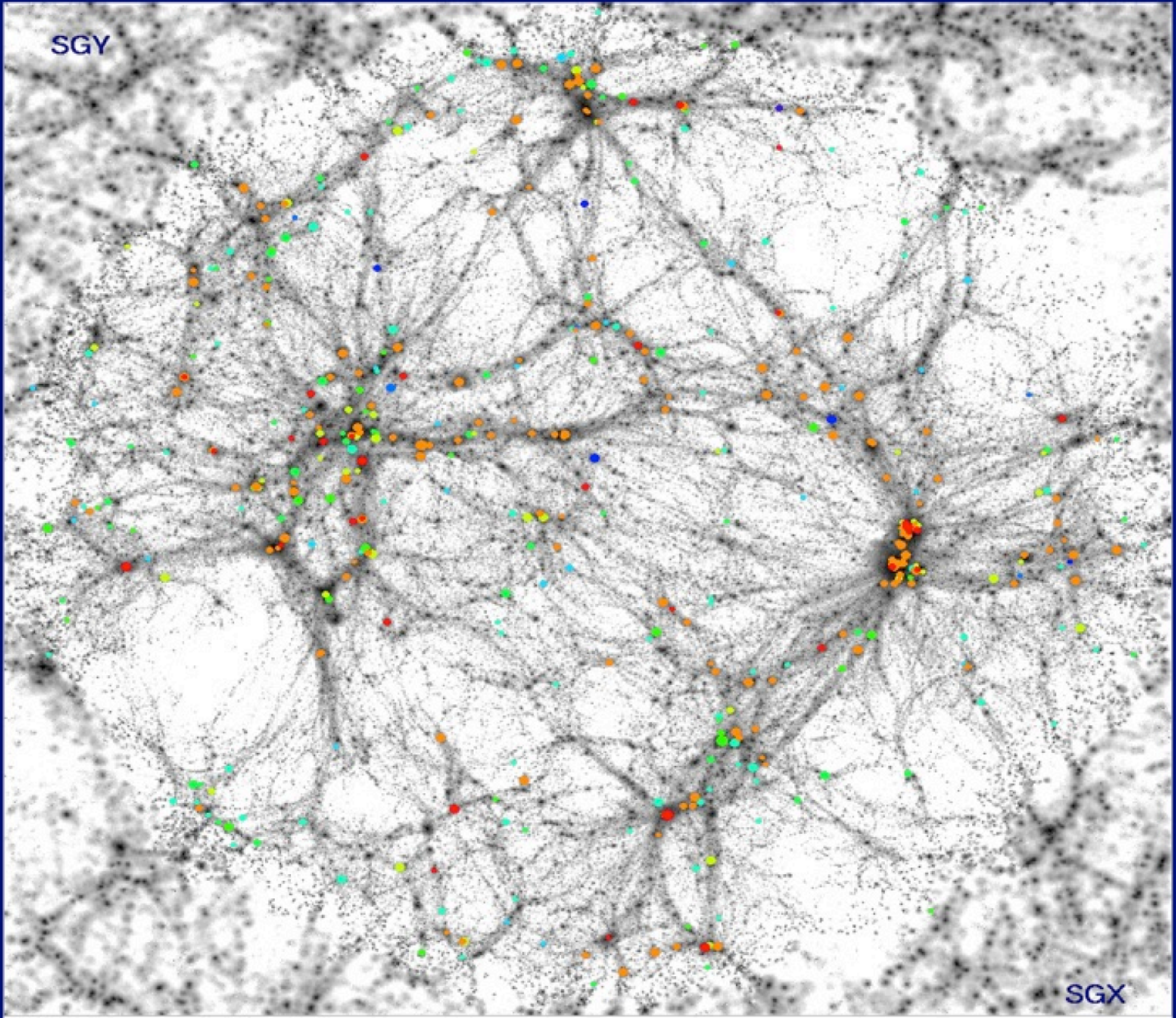
bulge+disk

disk

Semi-Analytic Modeling

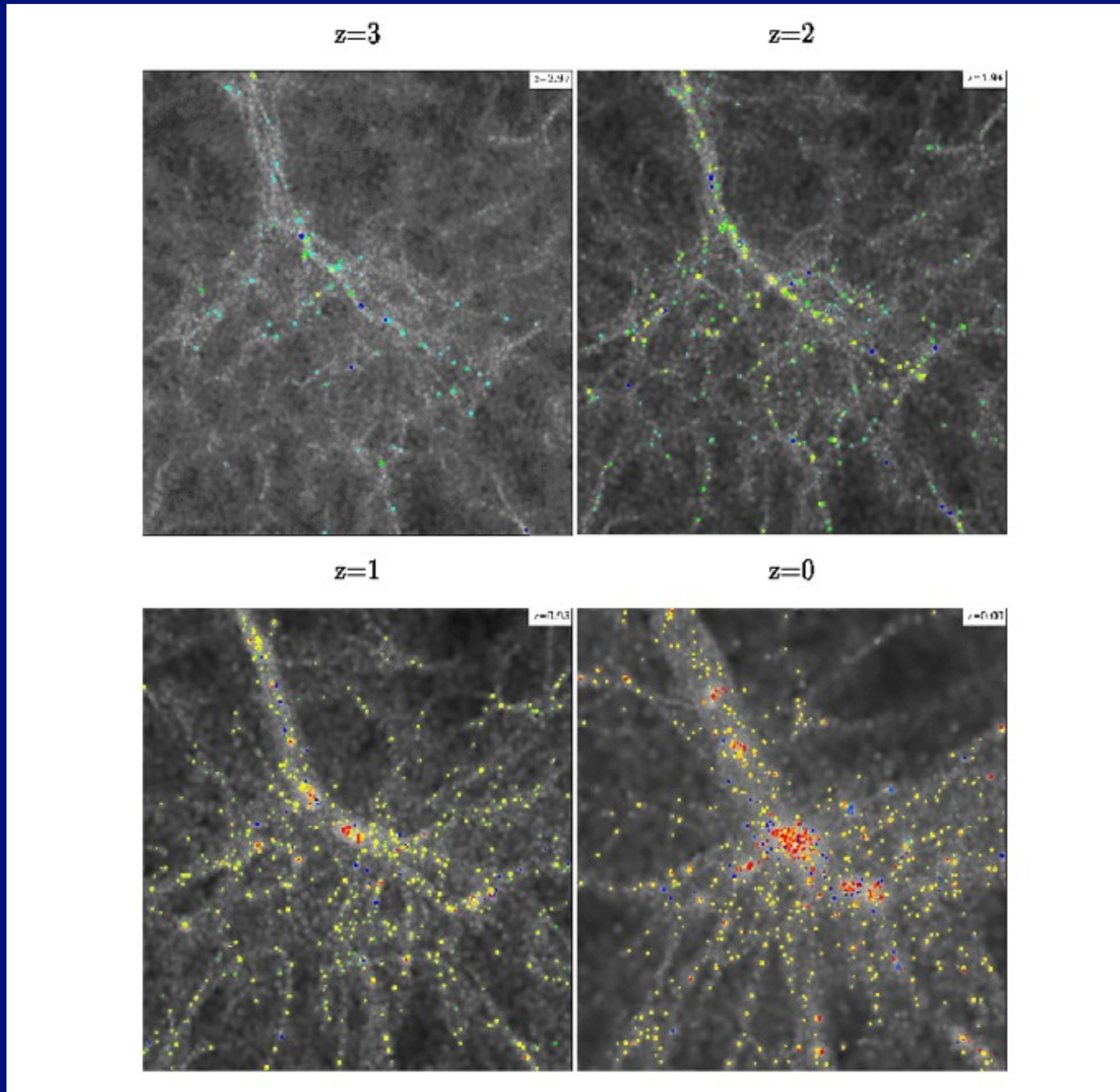
Kauffmann et al.

Elliptical galaxies in clusters in the local universe



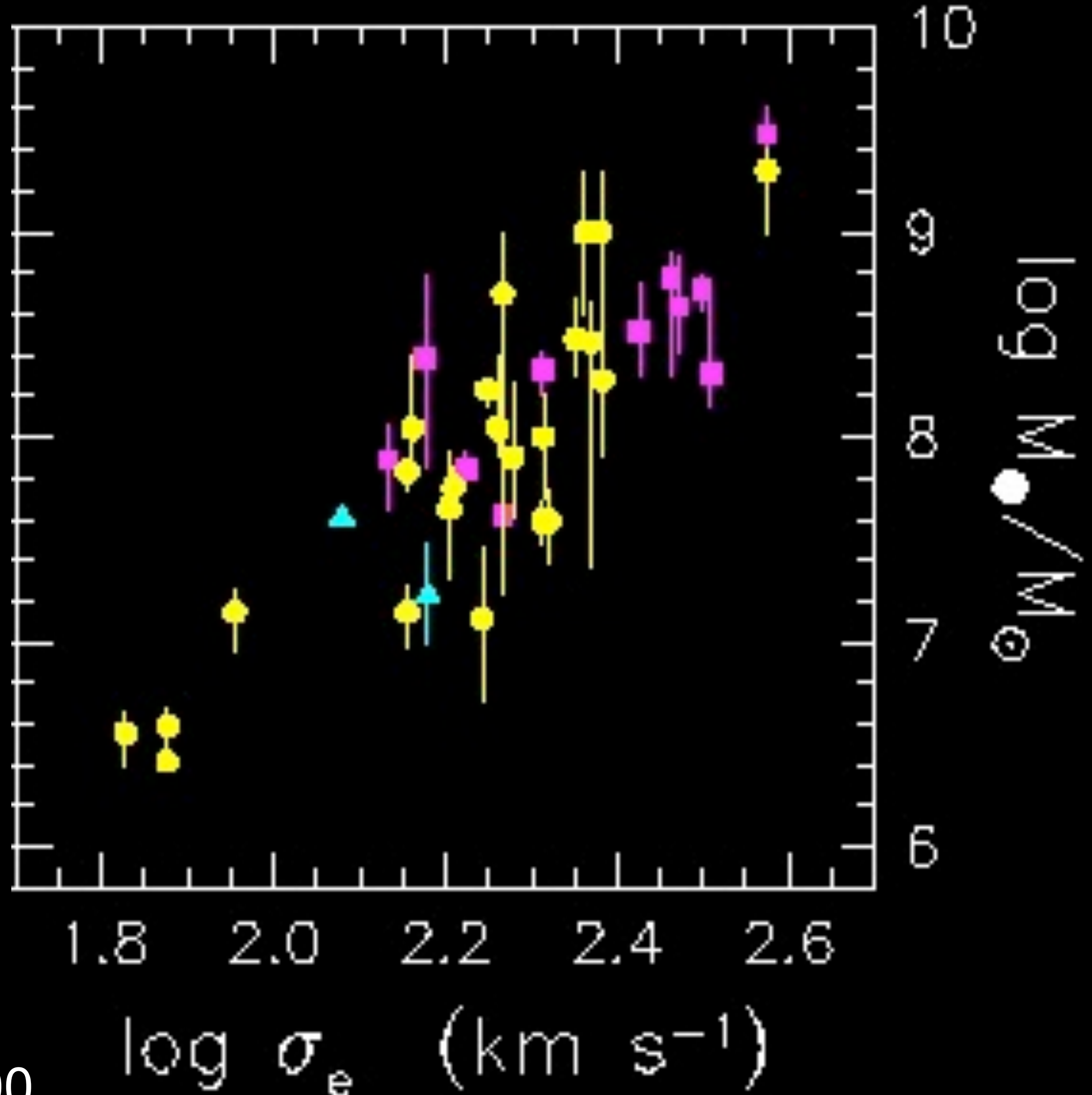
ΛCDM CR : E and S0 galaxies
Credits : Mathis, Lemson, Springel, Kauffmann, White and Dekel.

Formation of galaxies in a cluster



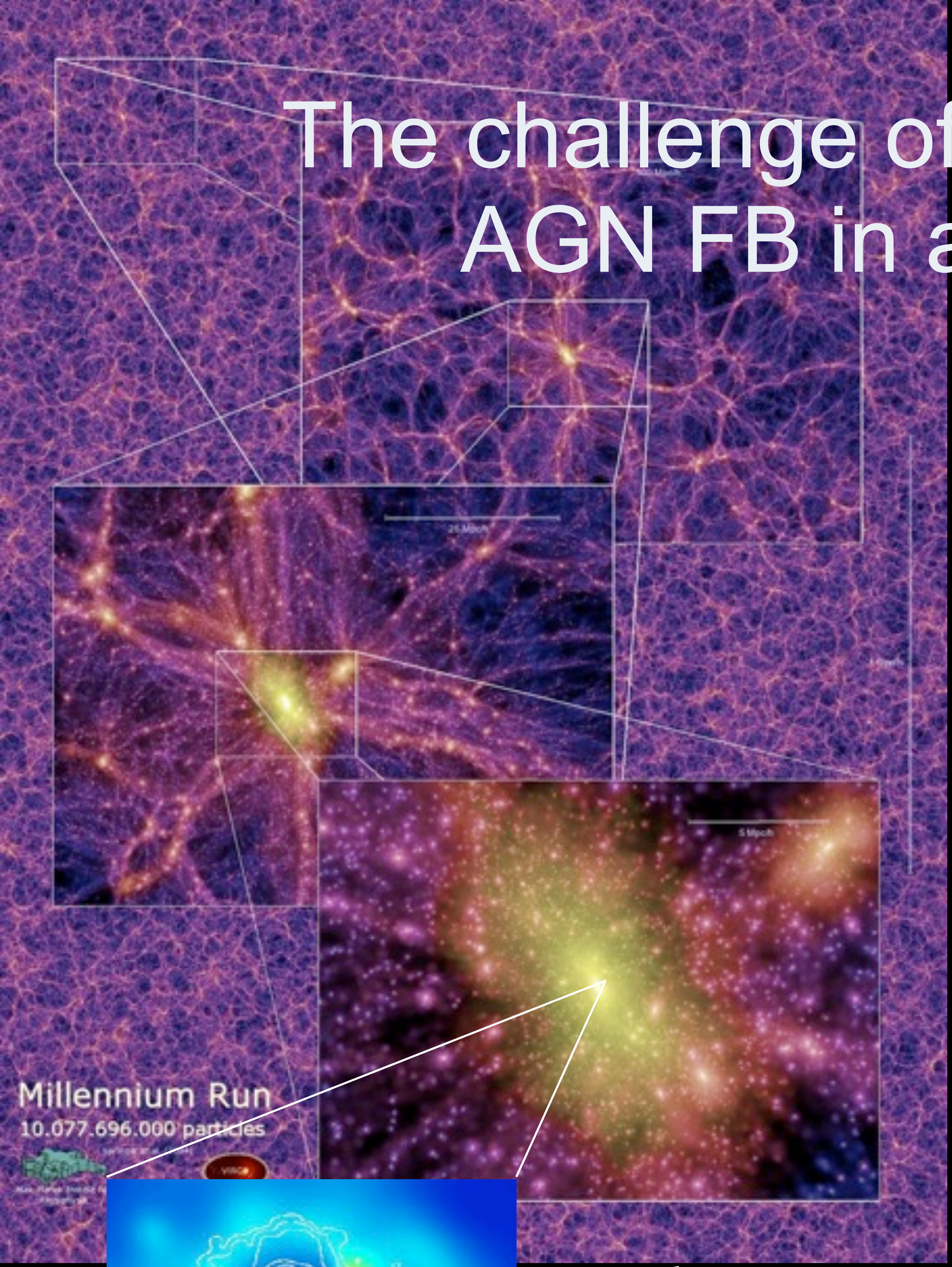
Why AGN Feedback Can Make Massive Galaxies Red/Dead

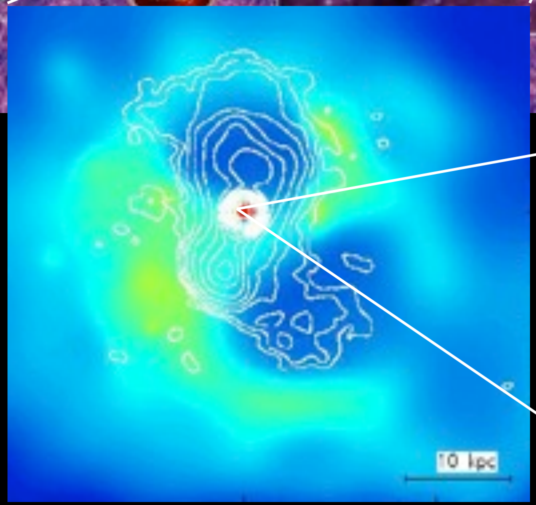
- Need mechanism to
  - quench star formation in massive galaxies
  - stop cooling in clusters
- SN feedback inadequate: not enough energy, little star formation in red galaxies
- BH mass closely connected with host galaxy's spheroid mass: $M_{BH} \sim 10^{-3} M_{stellar\ spheroid}$
- Bigger BH ⇒ more energy ($L_{max} \sim L_{Edd} \sim M_{BH}$)

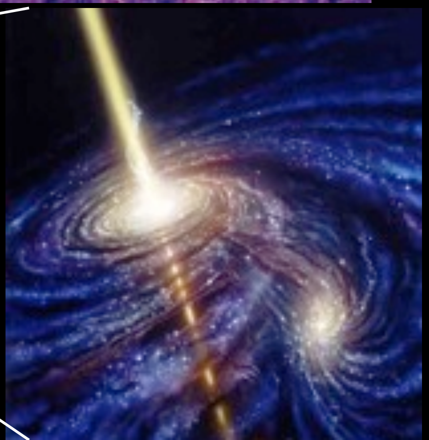


Magorrian et al. 1998;
Gebhardt et al. 2000,
Ferrarese & Merritt 2000

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







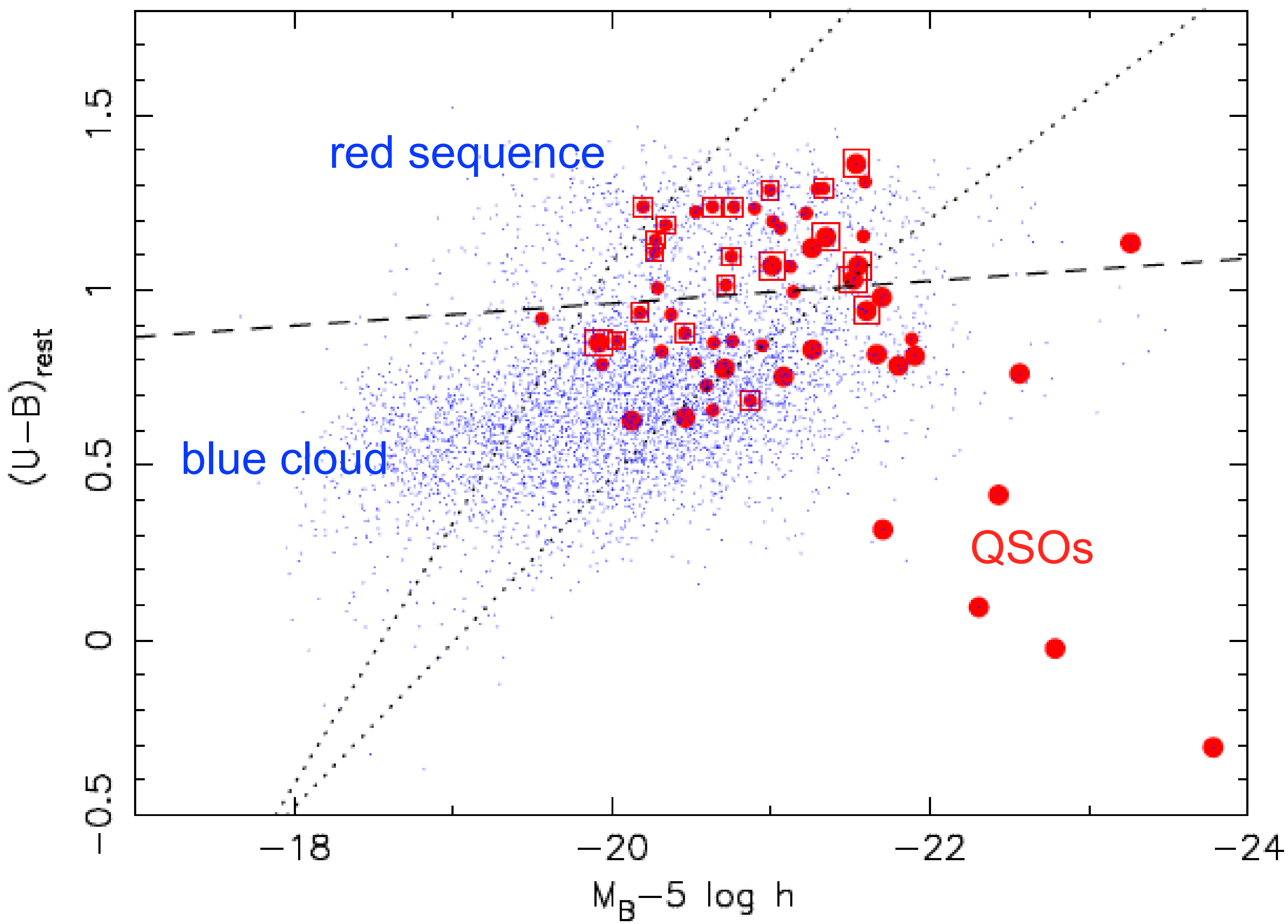
- dynamic range:
  - Gpc (luminous QSO)
  - few 100 Mpc (LSS)
  - 10's of kpc (ICM, jets)
  - sub-kpc (star formation, stellar FB)
  - few 100 pc (nuclear gas inflows, starbursts, AGN feeding, winds)
  - pc & sub-pc (accretion disk, BH mergers, etc)
- poorly understood physics (B-fields, conduction,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

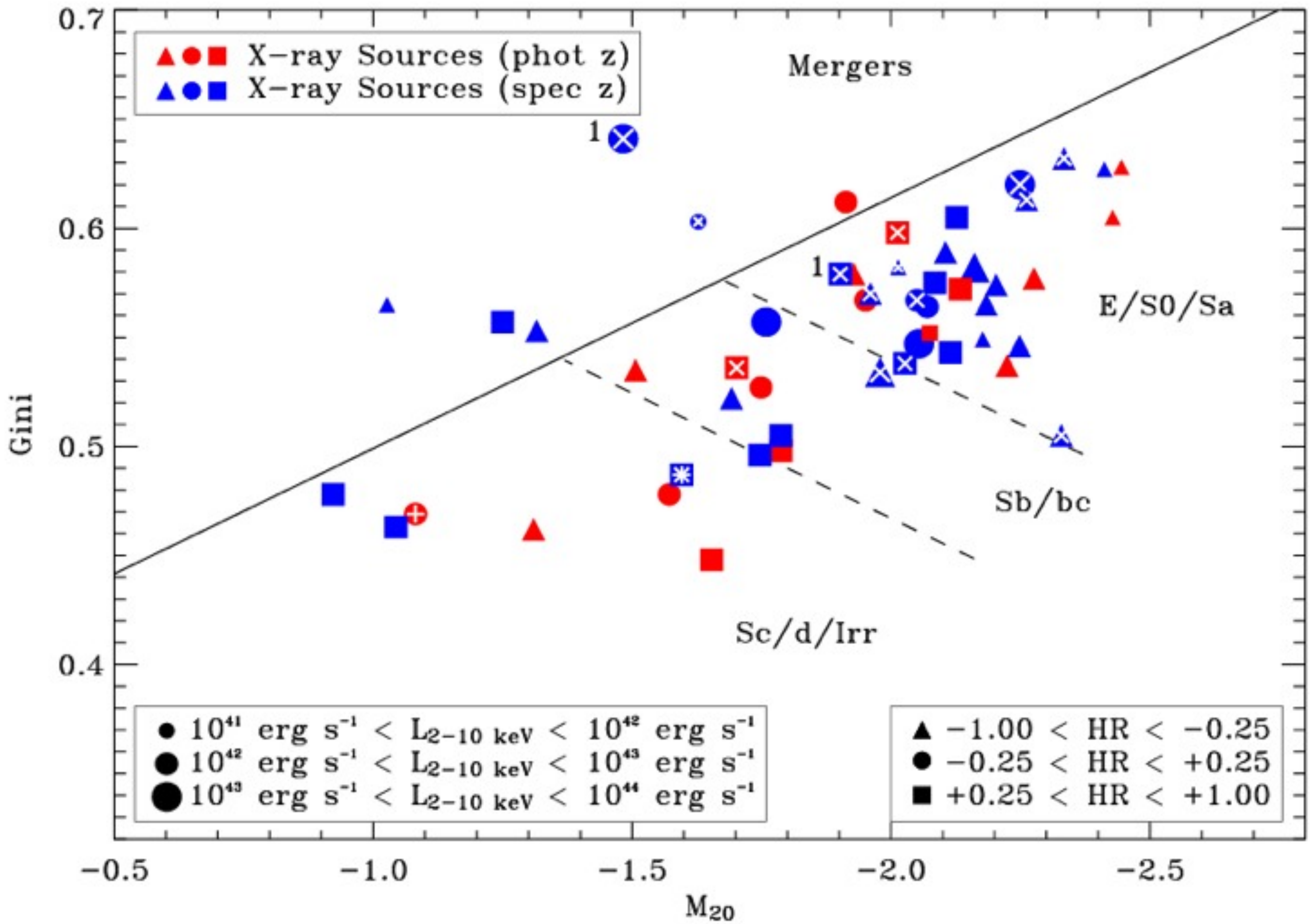
Di Matteo, Springel & Hernquist 2005

Color-Magnitude Diagram of EGS X-ray selected AGN

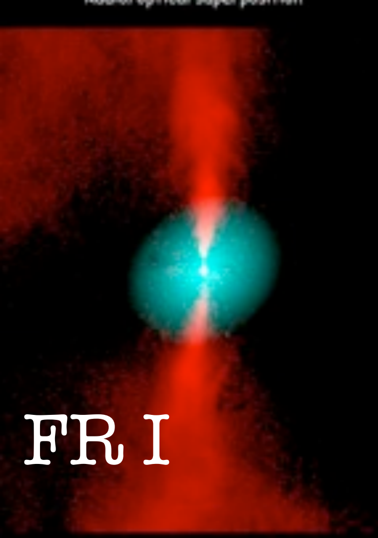


Rest-frame U-B colour is plotted against the B-band absolute magnitude for DEEP2 comparison galaxies (small blue dots) and X-ray sources (filled red circles) in the EGS in the range $0.7 < z < 1.4$. Squares around the symbols indicate hard X-ray sources, and more luminous systems ($L_X > 10^{43}$ erg 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.)

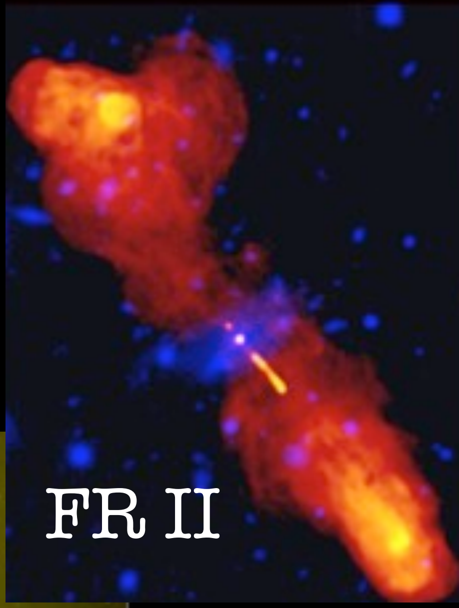
Morphological distribution of EGS X-ray selected AGN



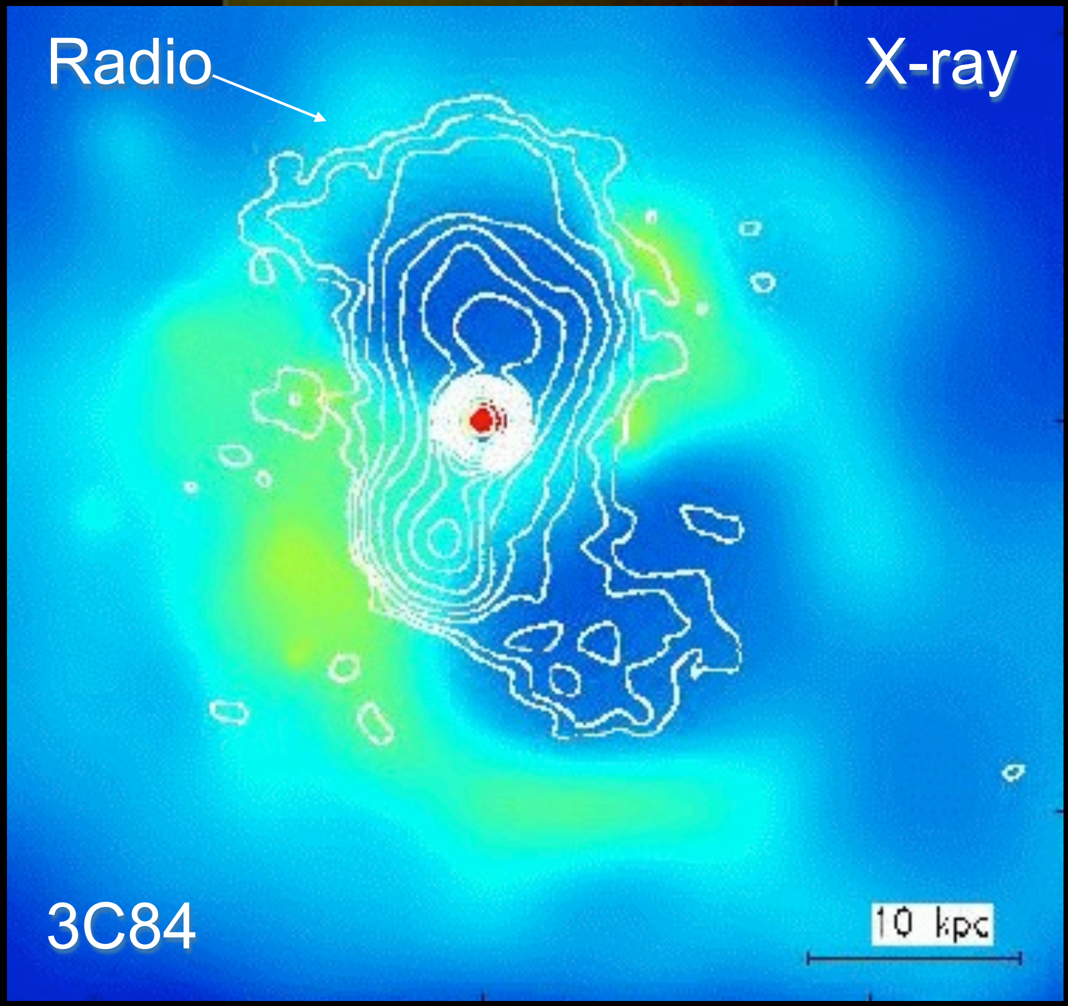
The highest fraction of EGS galaxies hosting AGN are early-types, not mergers. This suggests that the AGN activity is delayed, rather than occurring mainly during and immediately following mergers as the Hopkins et al. simulations predicted. (Christy Pierce et al., ApJ Letters, May 2007).



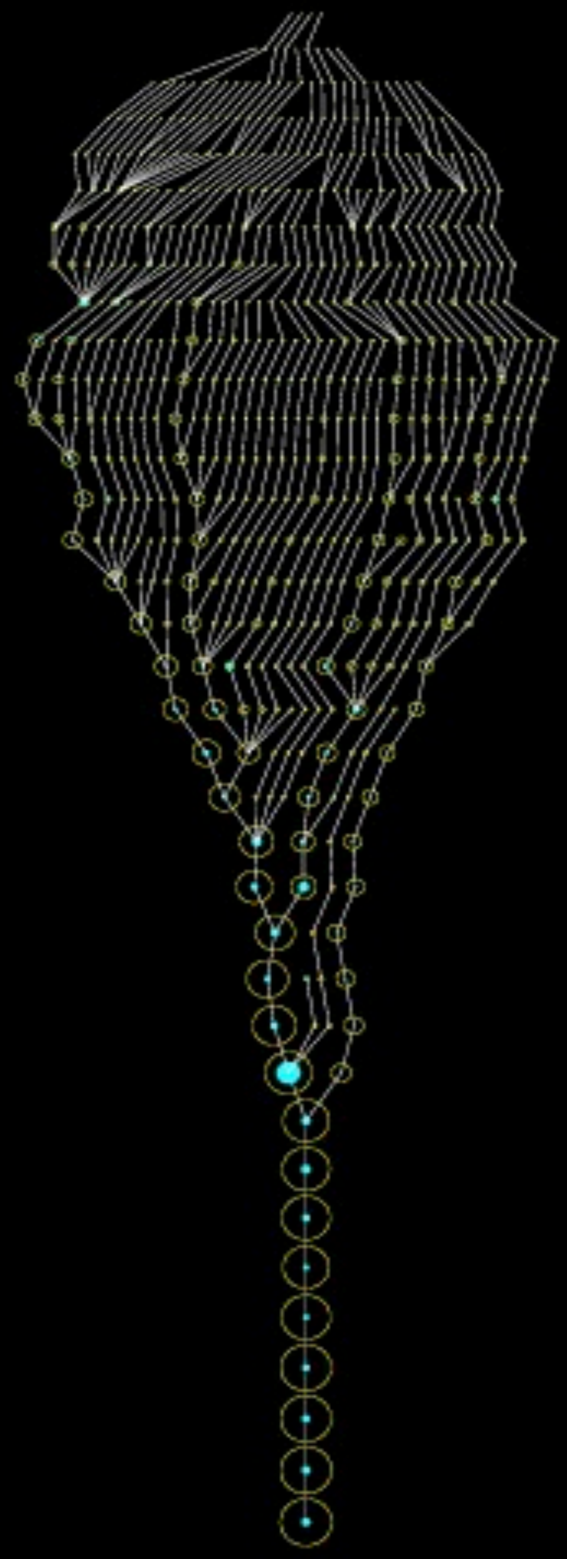
AGN feedback 2: Radio Mode



- **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

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

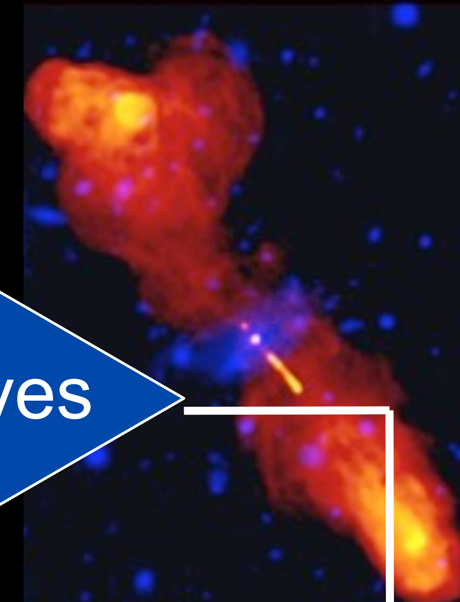
- Energy released by accretion drives a wind
- BH merge when their galaxies merge; mass is conserved

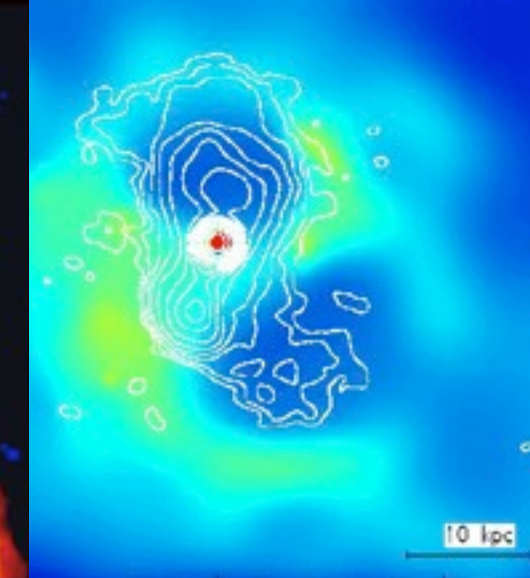
Somerville, Hopkins, Cox, et al. 2008 MN
Somerville, Gilmore, Primack, & Dominguez 2011 MN

no

quasi-hydrostatic hot gas halo?

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

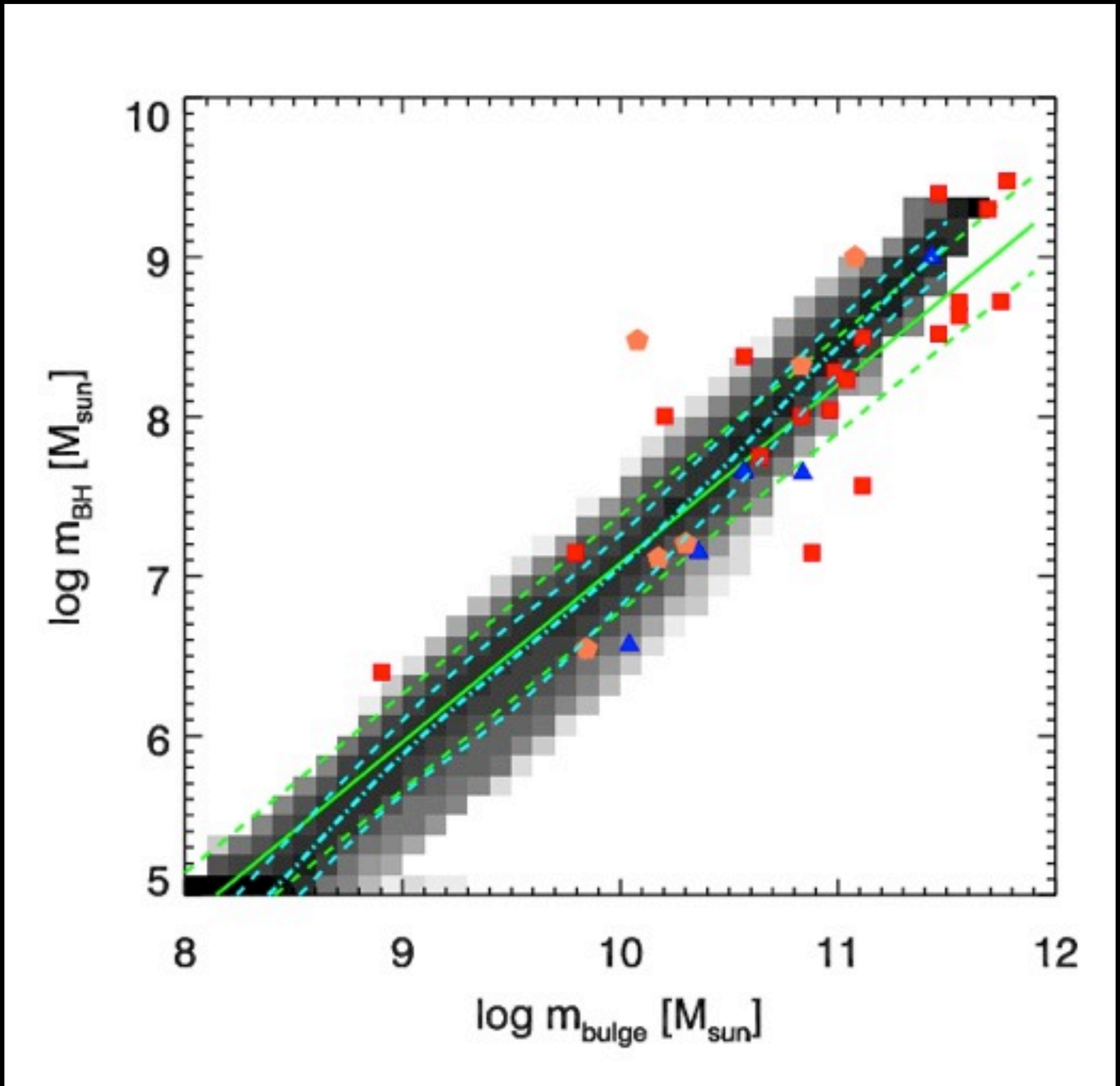
in the absence of new fuel, stars evolve passively...

cooling and accretion resumes

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



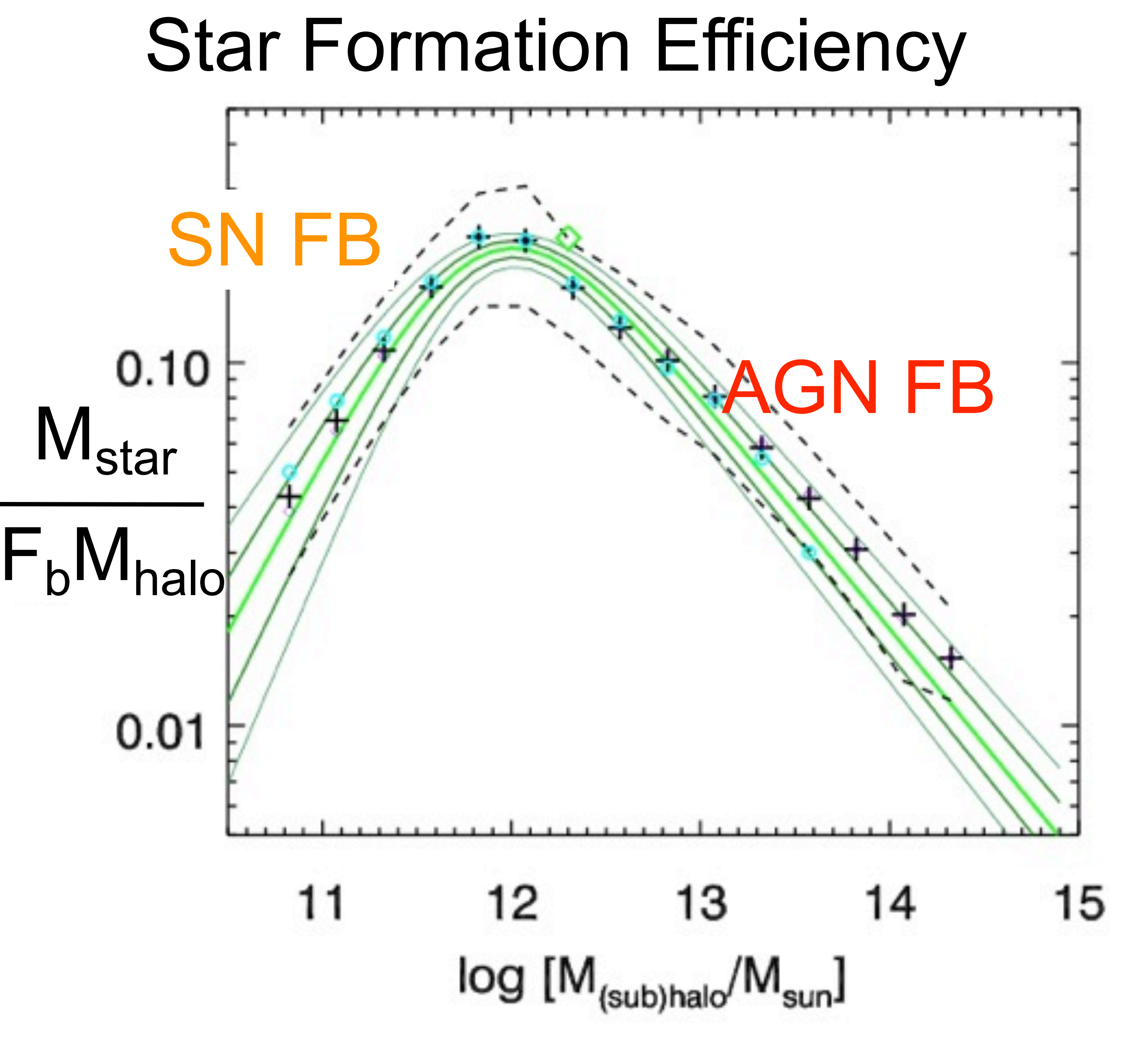
matches slope & scatter of observed relation

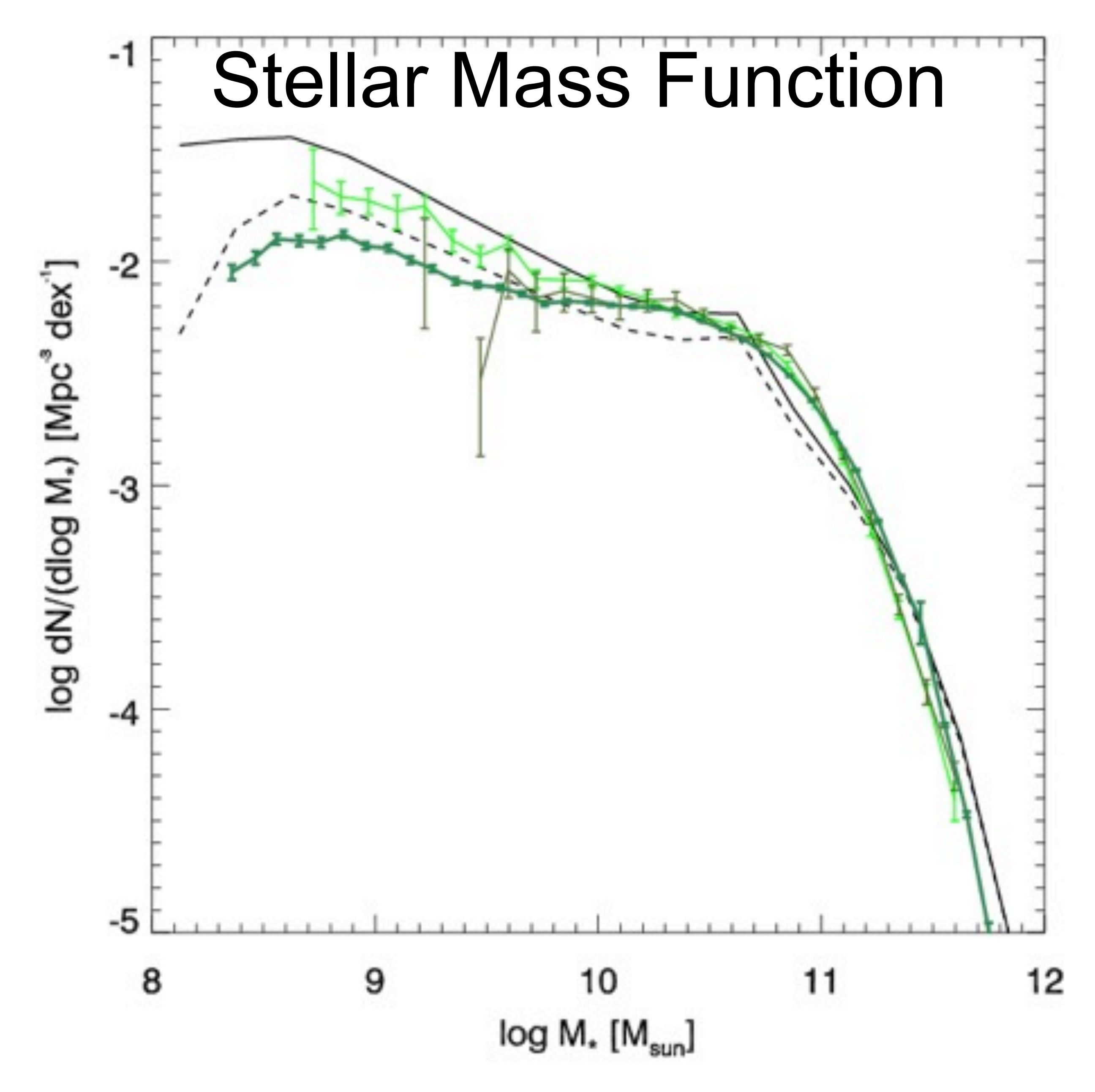
large symbols:
Haering & Rix data
green: H&R fit + scatter
intrinsic scatter: 0.3 dex

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

Somerville et al. 2008

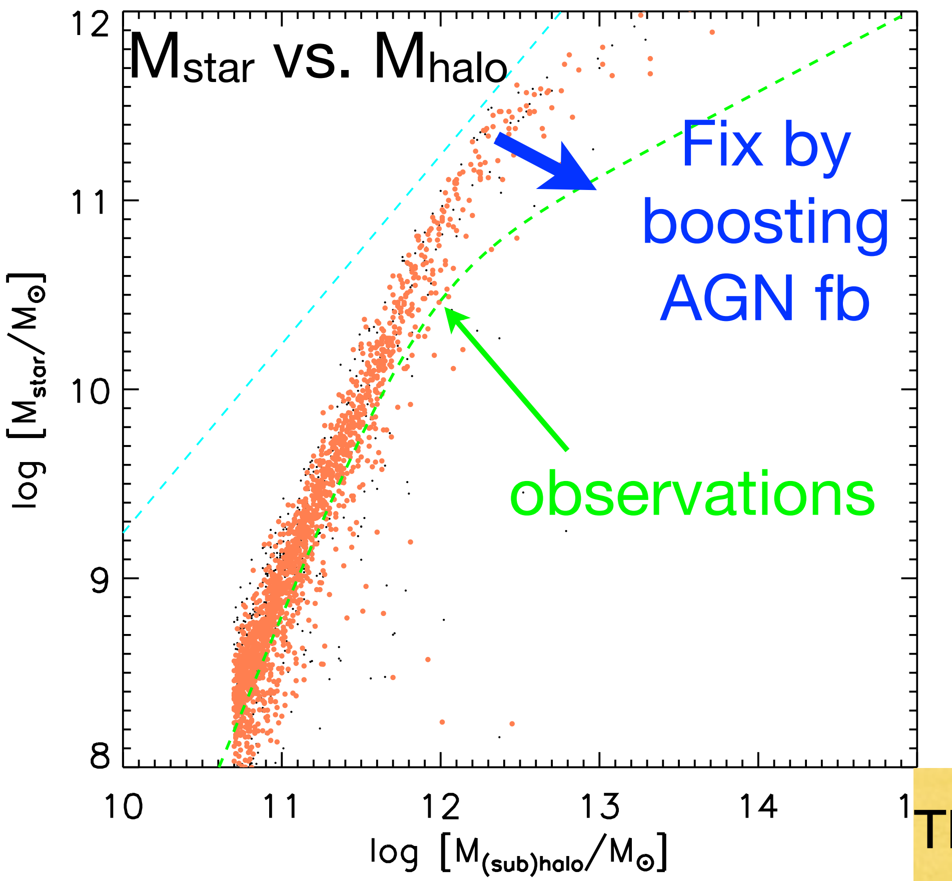
AGN Heating Leads to Galaxy Mass Functions at z~0 in Agreement with Observations

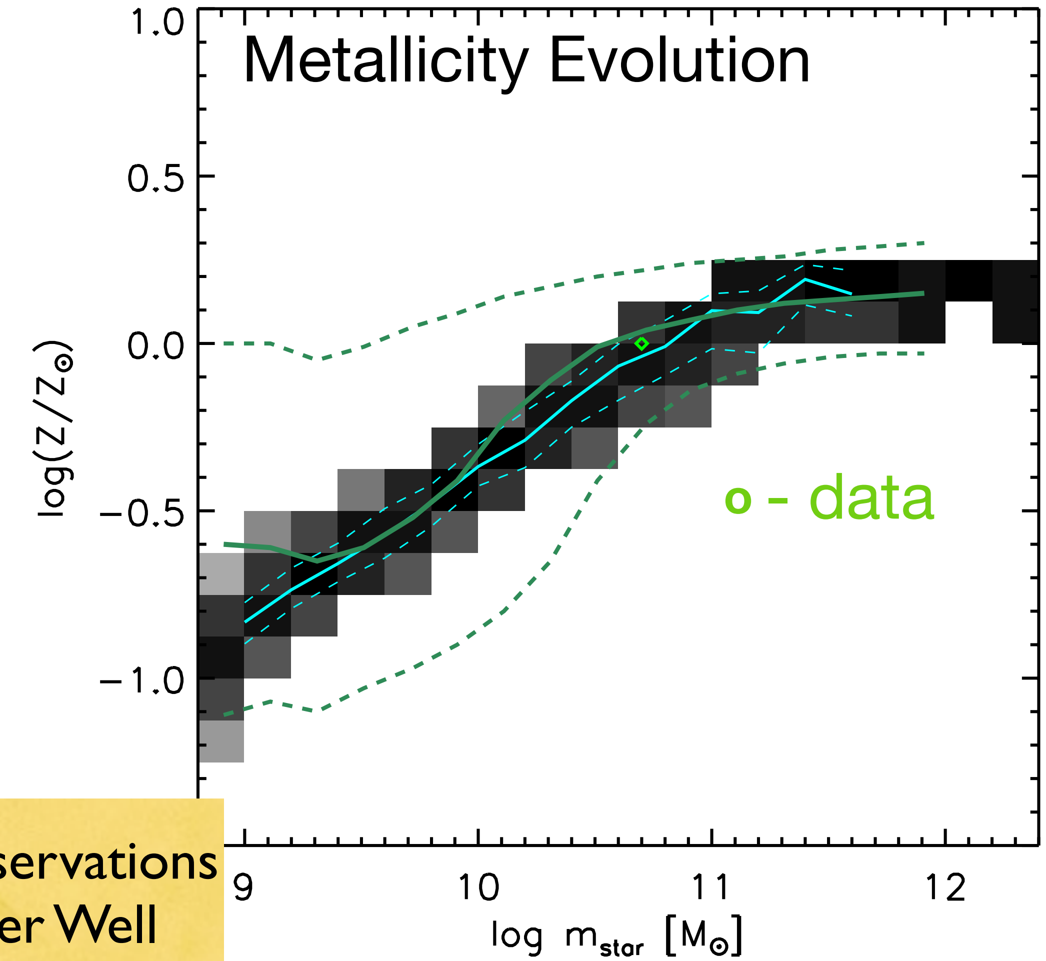




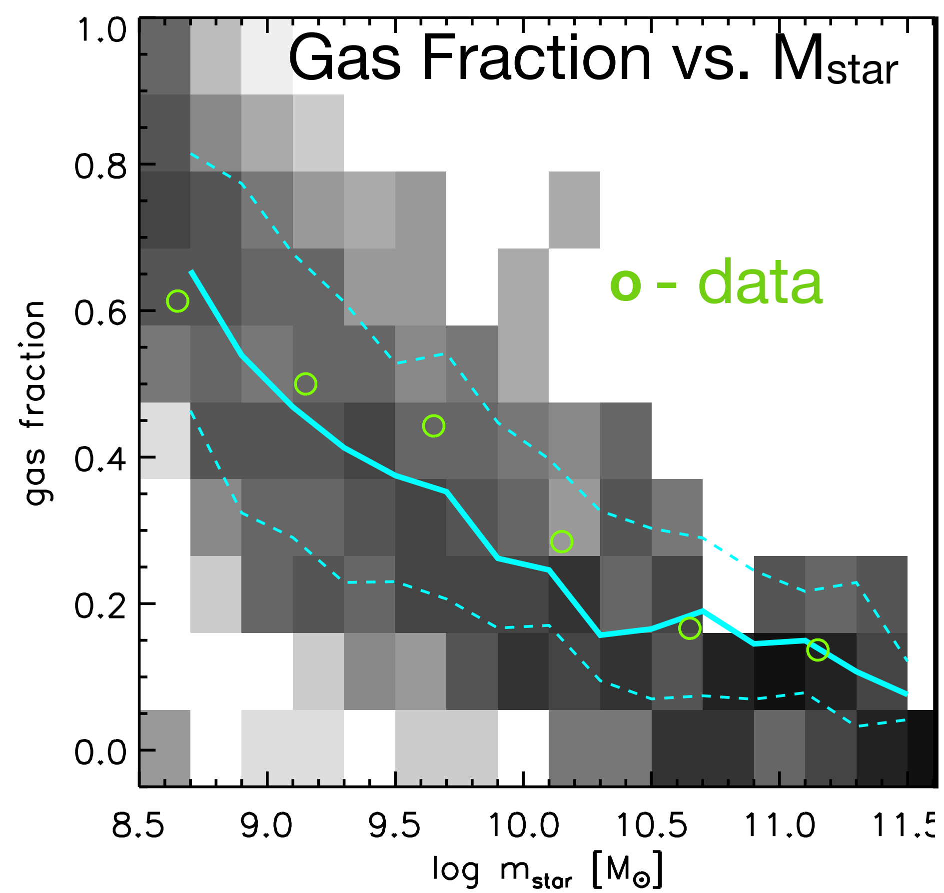
Somerville et al. 2008

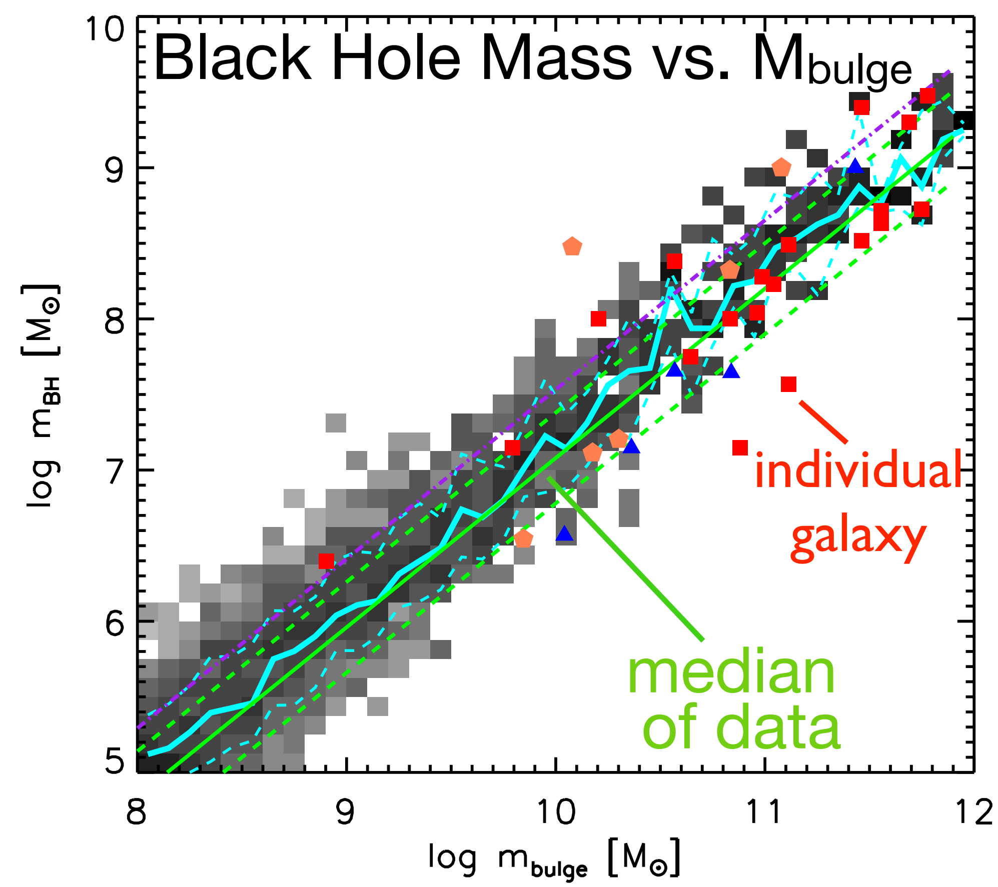
First SAM galaxy results with Bolshoi - Rachel Somerville



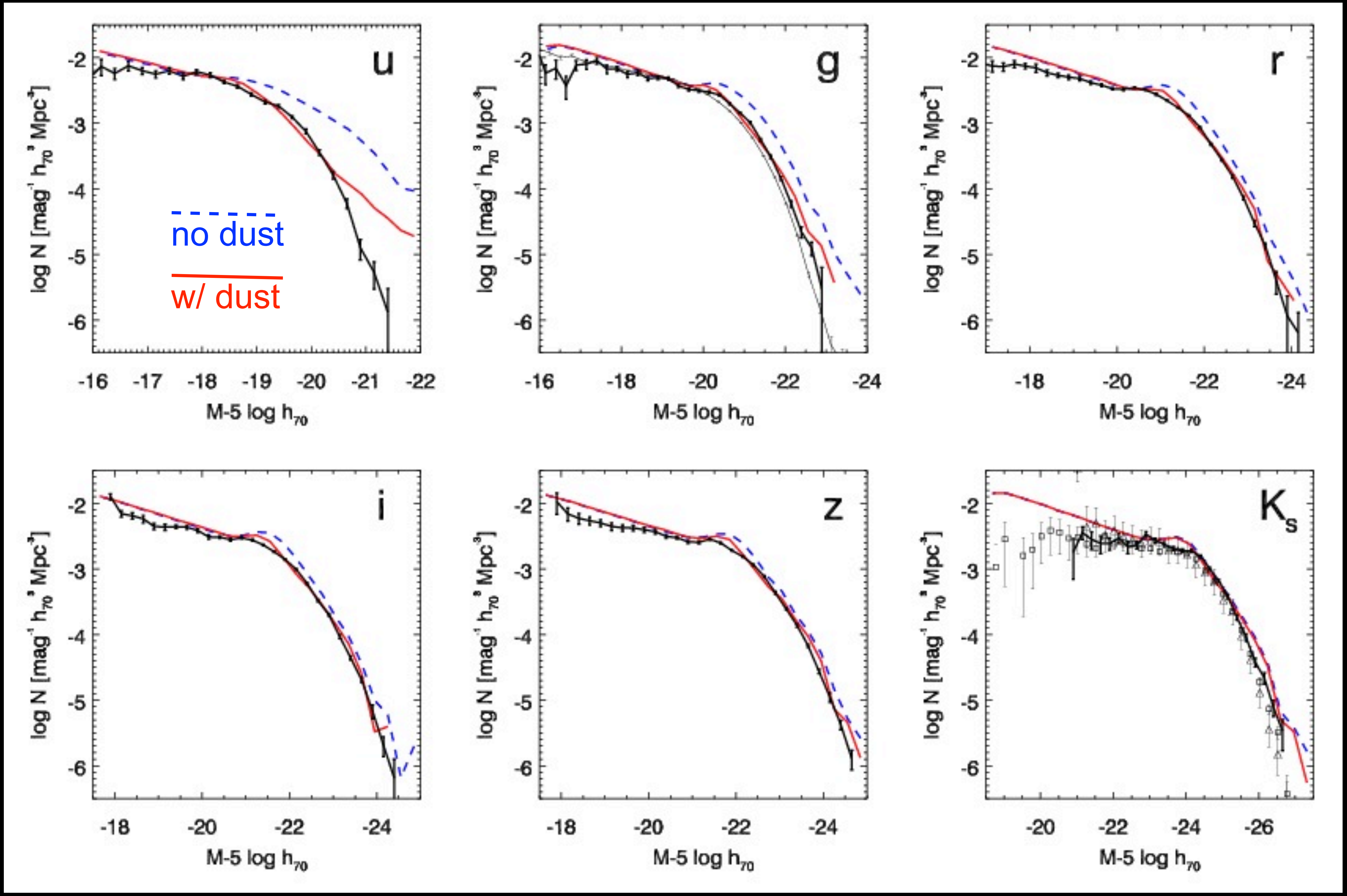


Theory & Observations Agree Rather Well





Local Luminosity Functions

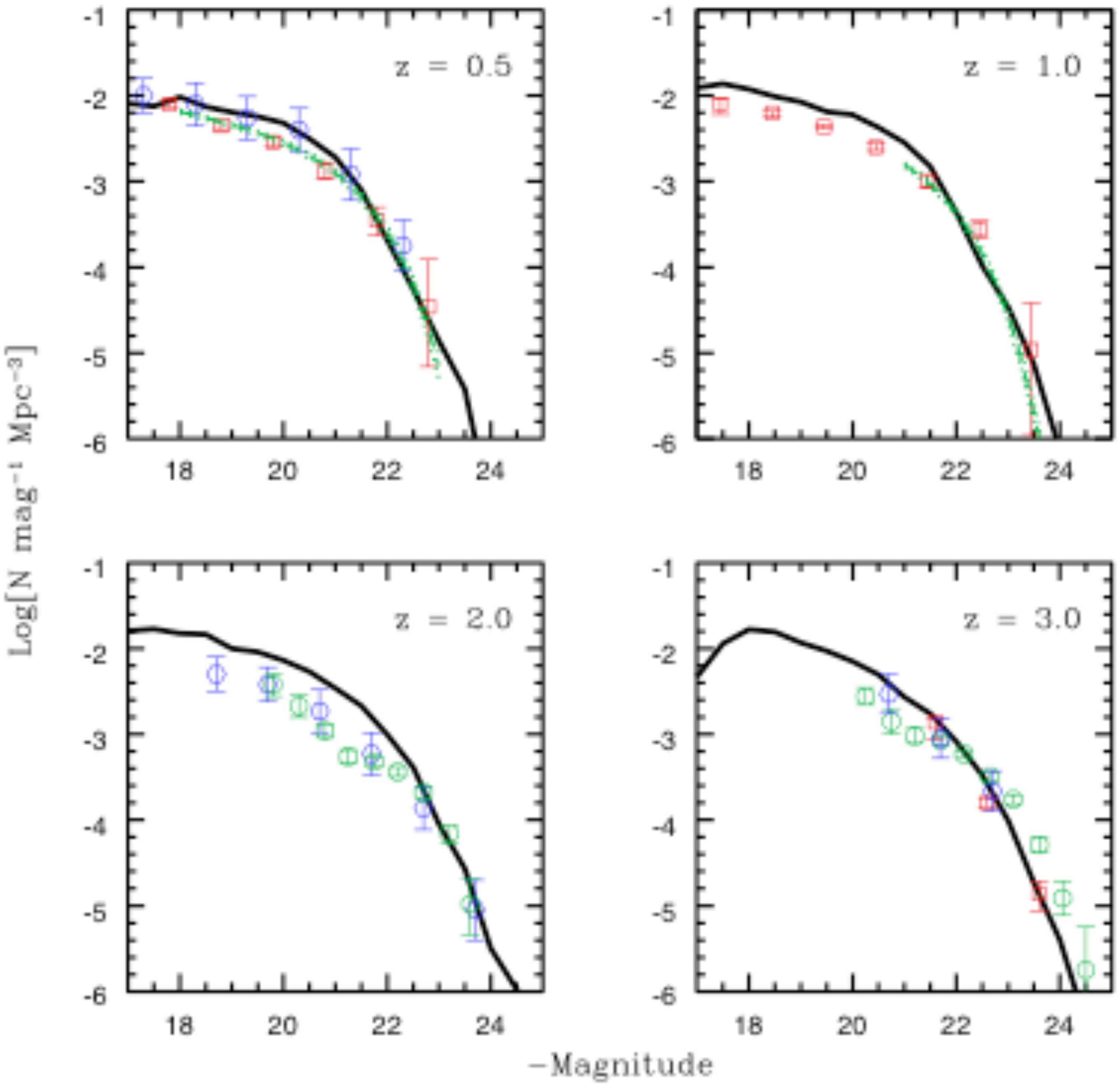


Somerville et al. 2008

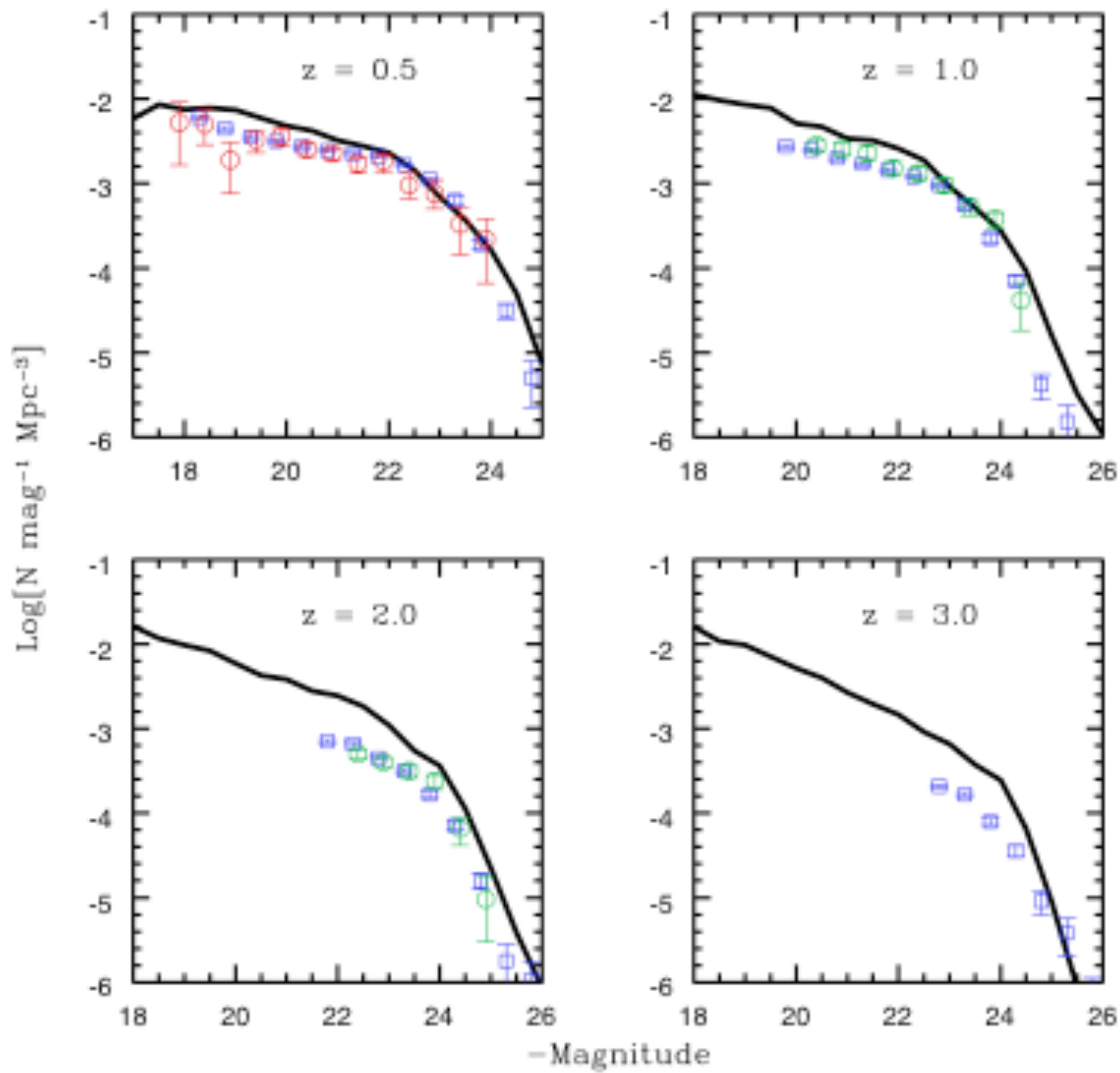
Some Results from our Semi-Analytic Models

Evolving Luminosity Functions

B-band



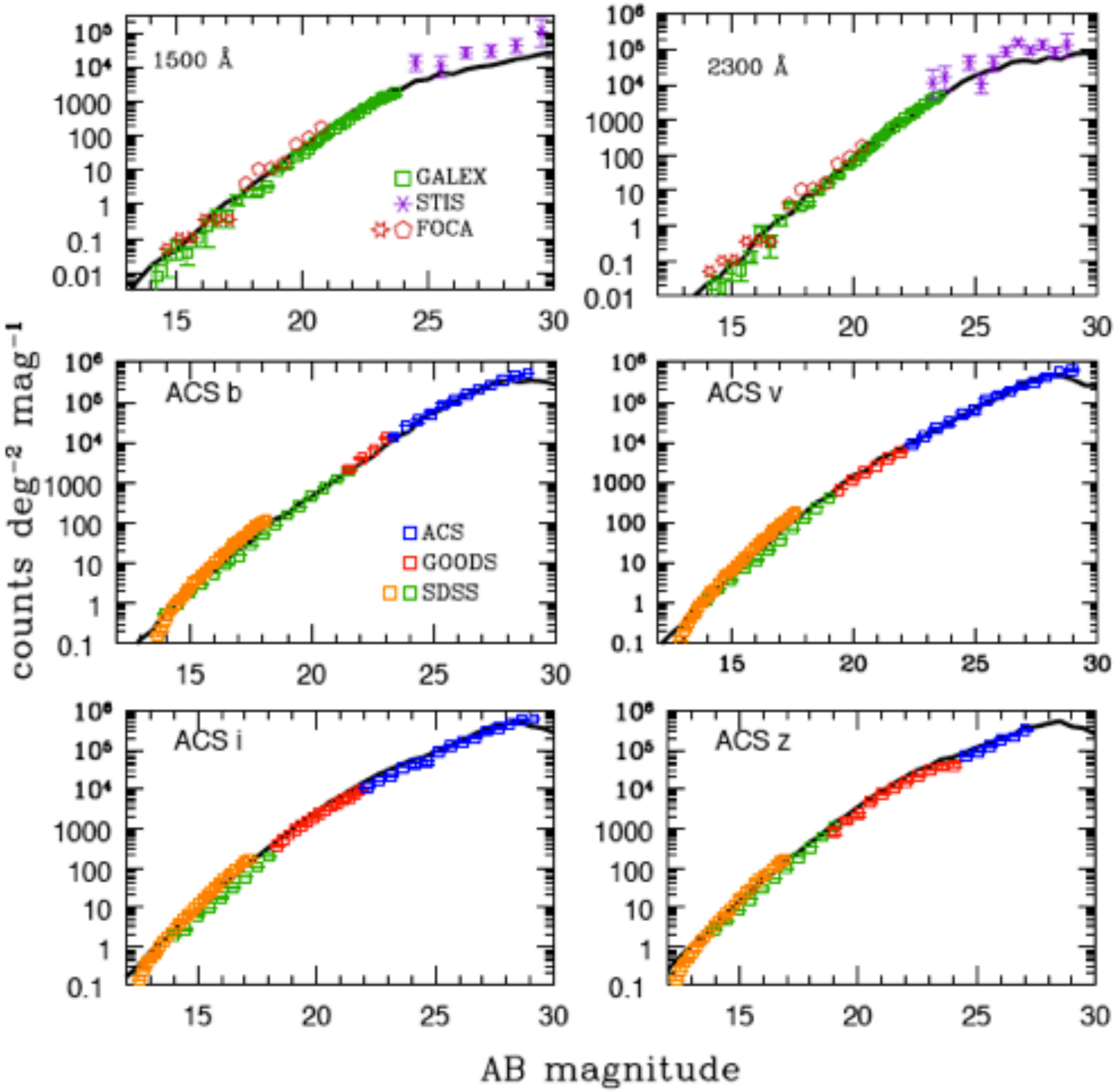
K-band



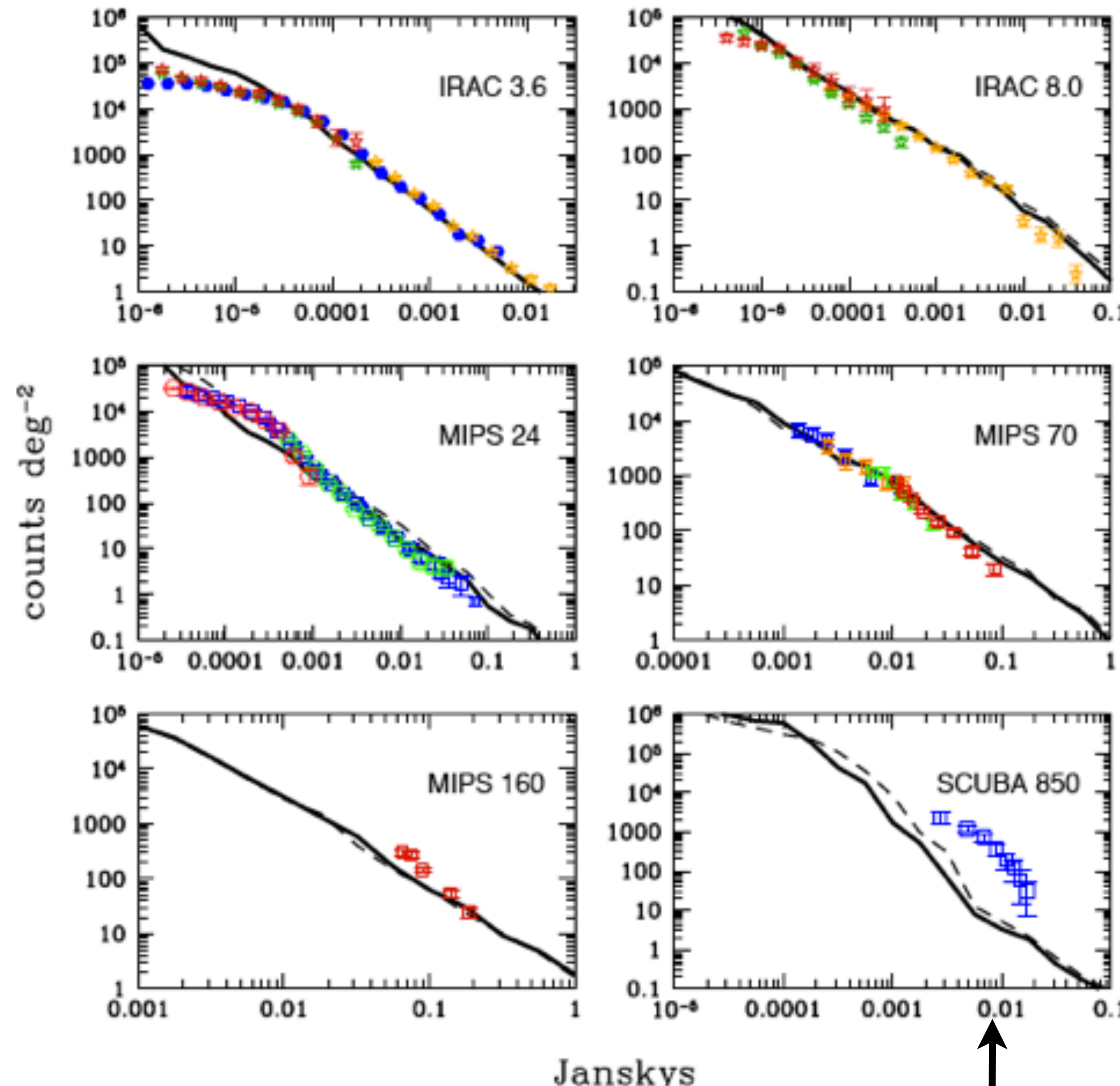
Somerville, Gilmore, Primack, & Dominguez (2011)

Some Results from our Semi-Analytic Models

Number Counts in UV, b, v, i, and z Bands



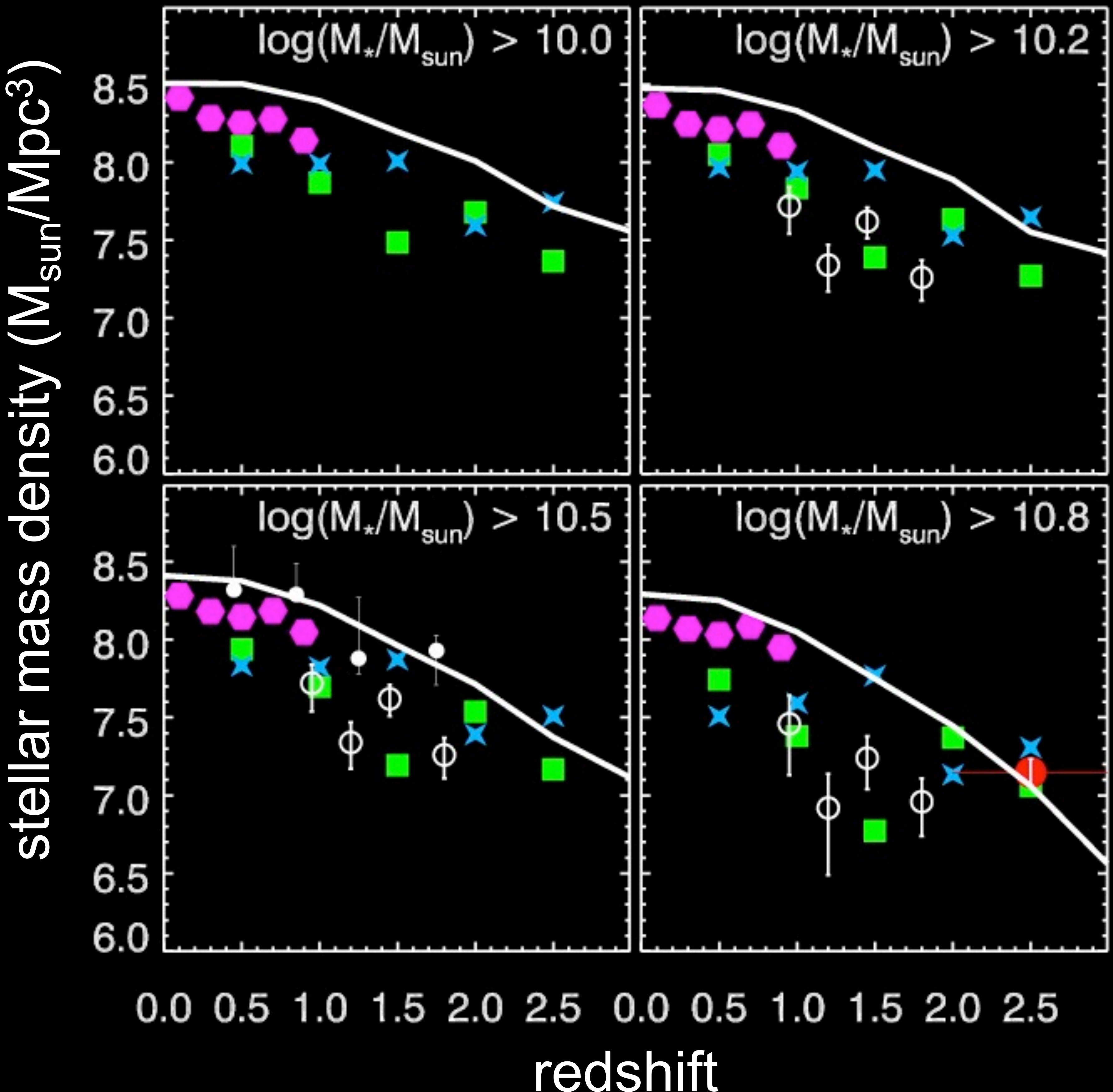
3.6, 8, 24 and 24, 70, 160, & 850 μm Bands



Somerville, Gilmore, Primack, & Dominguez (2011)

The one failure is at 850 μm

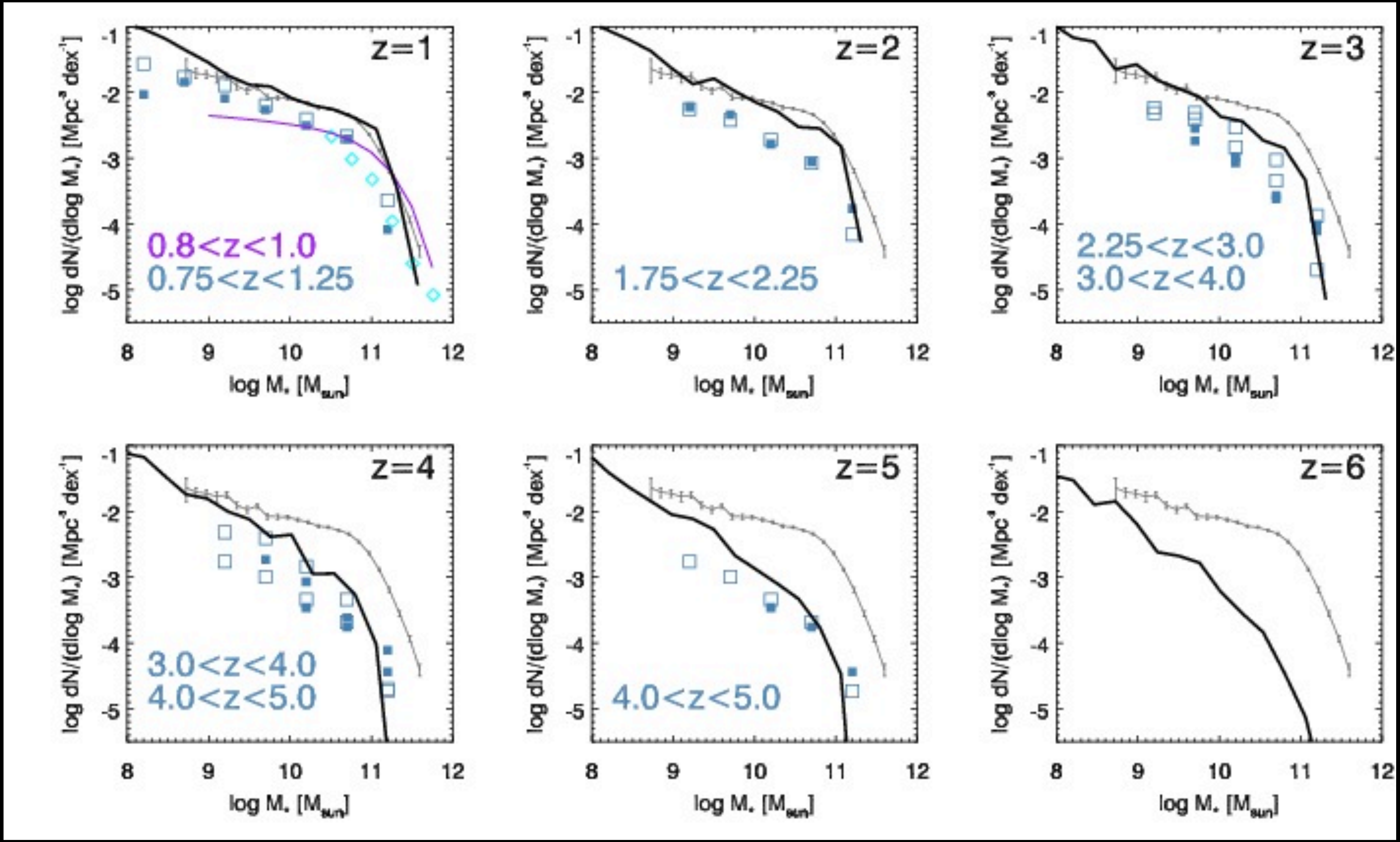
Model produces enough massive galaxies at high redshift



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

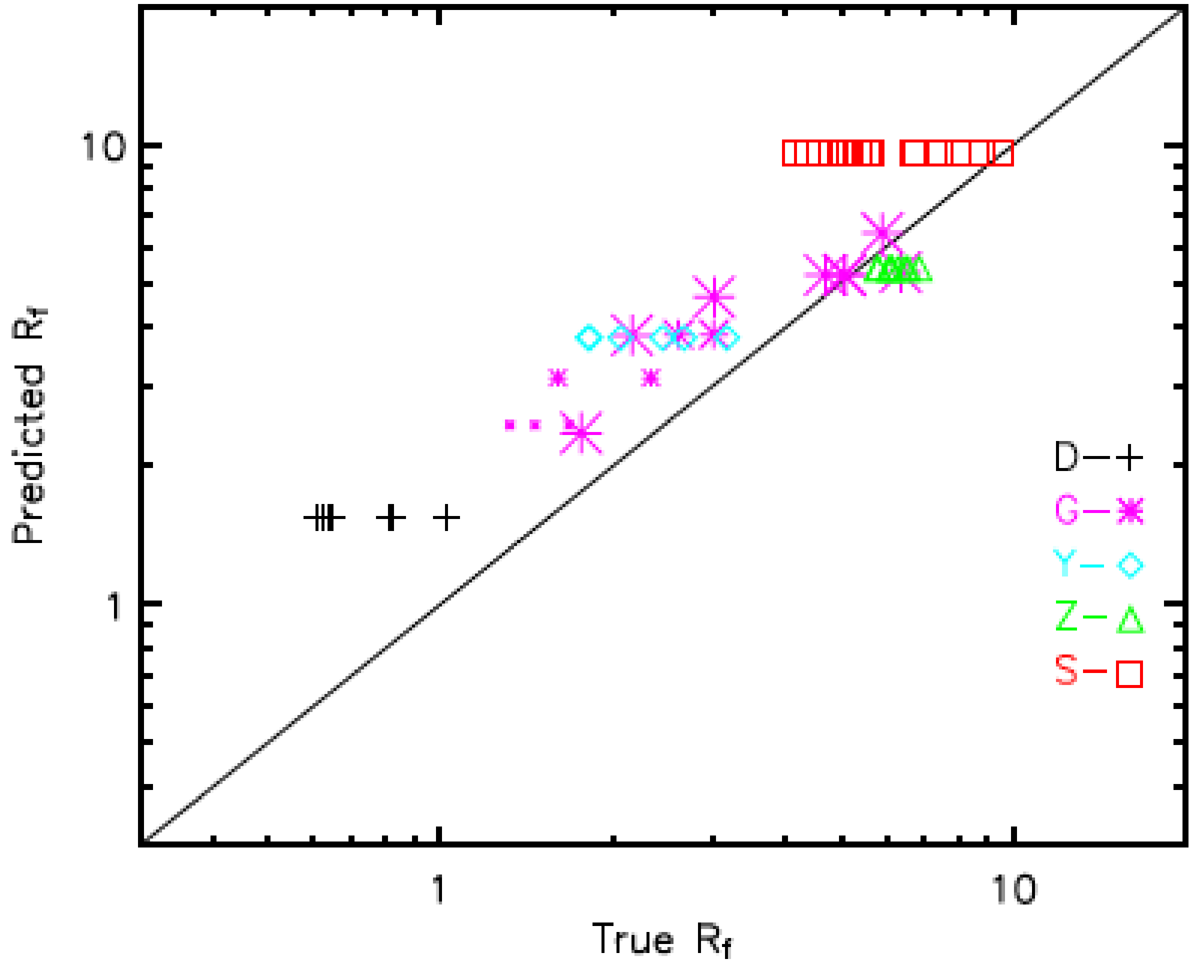
We might expect that a more energetic encounter will cause increased tidal stripping and puff up the remnant.

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

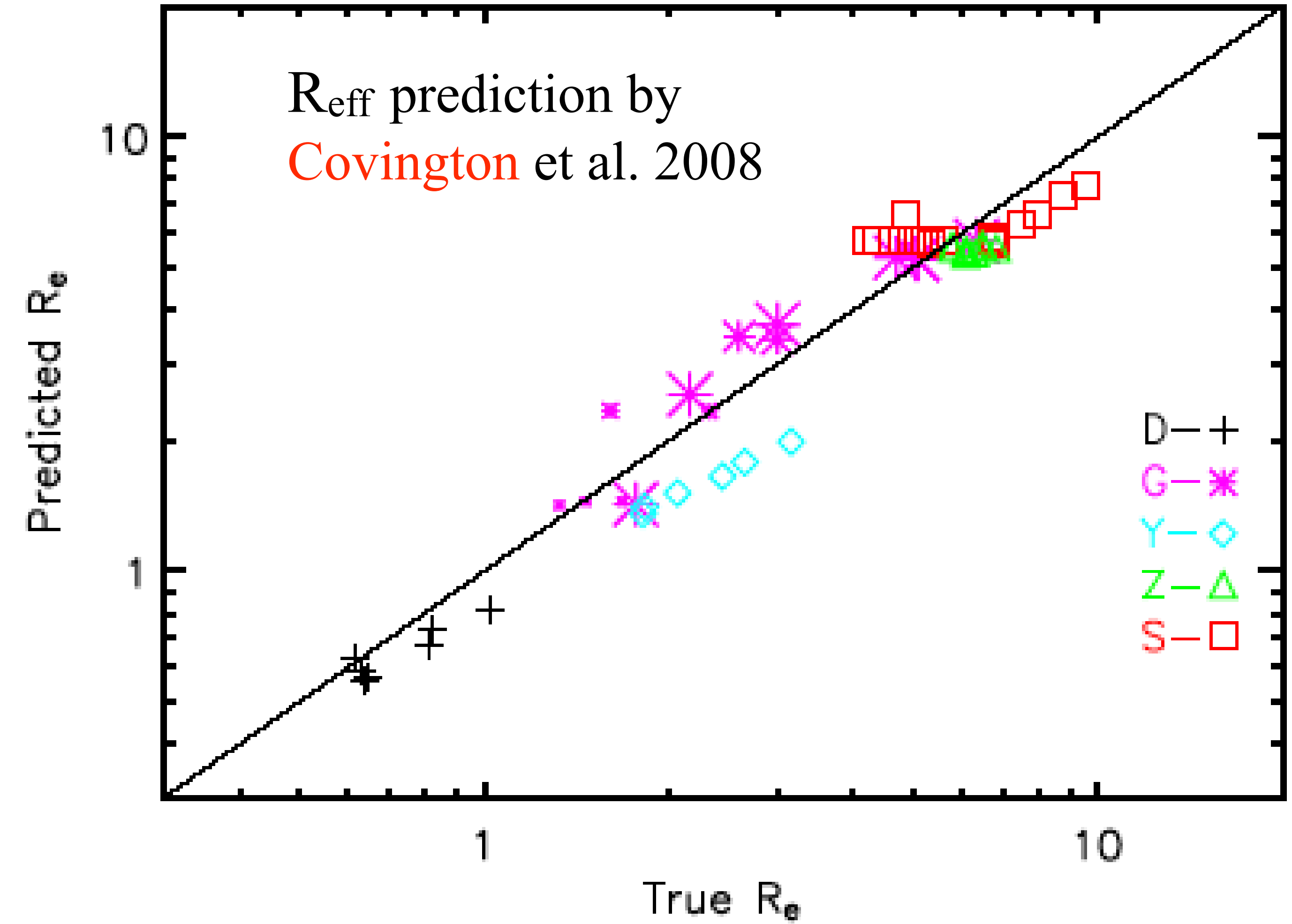
Why? Dissipative effects cause more energetic encounters to result in smaller remnants. The greater the impulse, the more the gas is disturbed, therefore the more it can radiate and form stars.

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

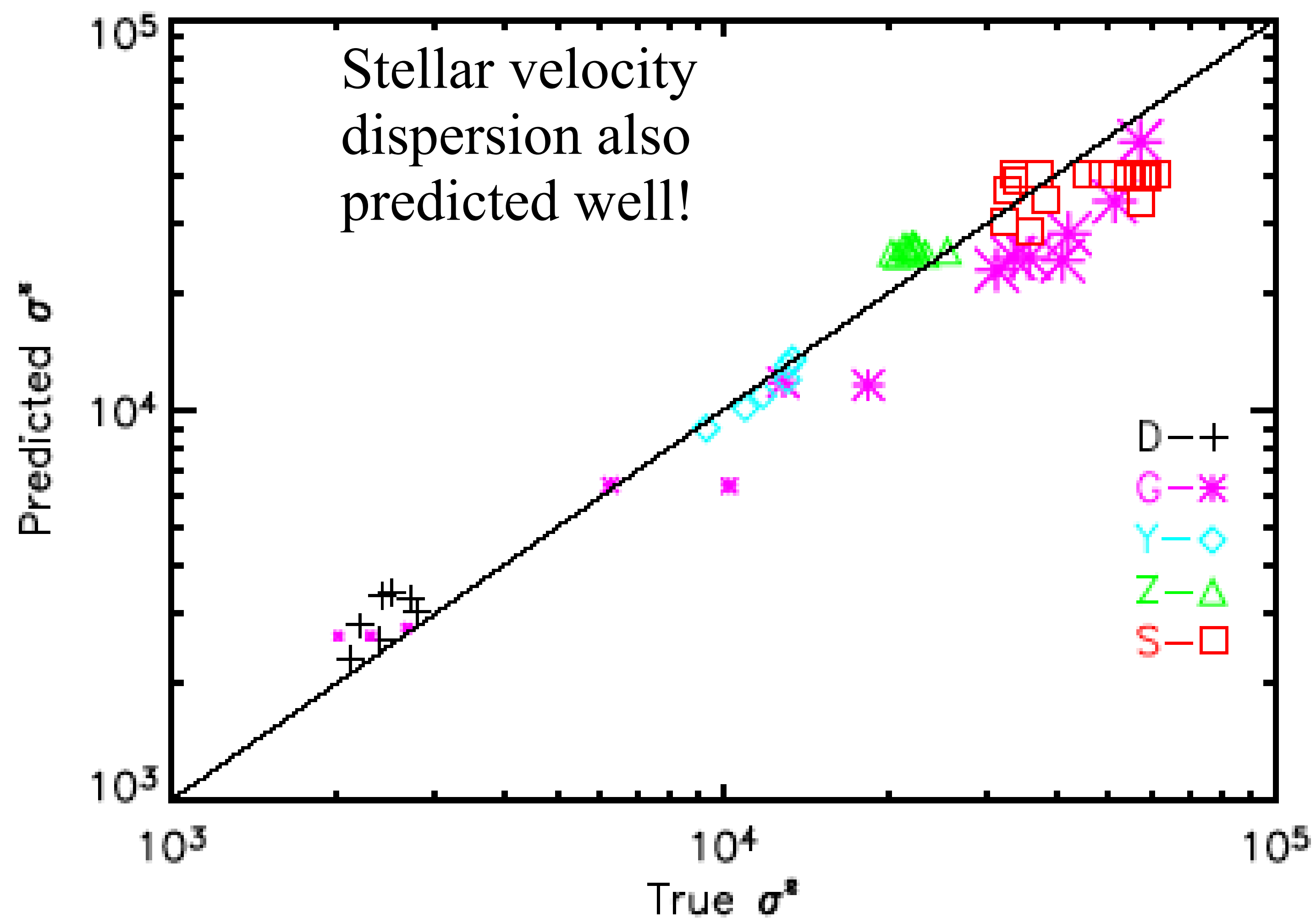
Matt Covington, Cox, Dekel, & Primack MNRAS 2008



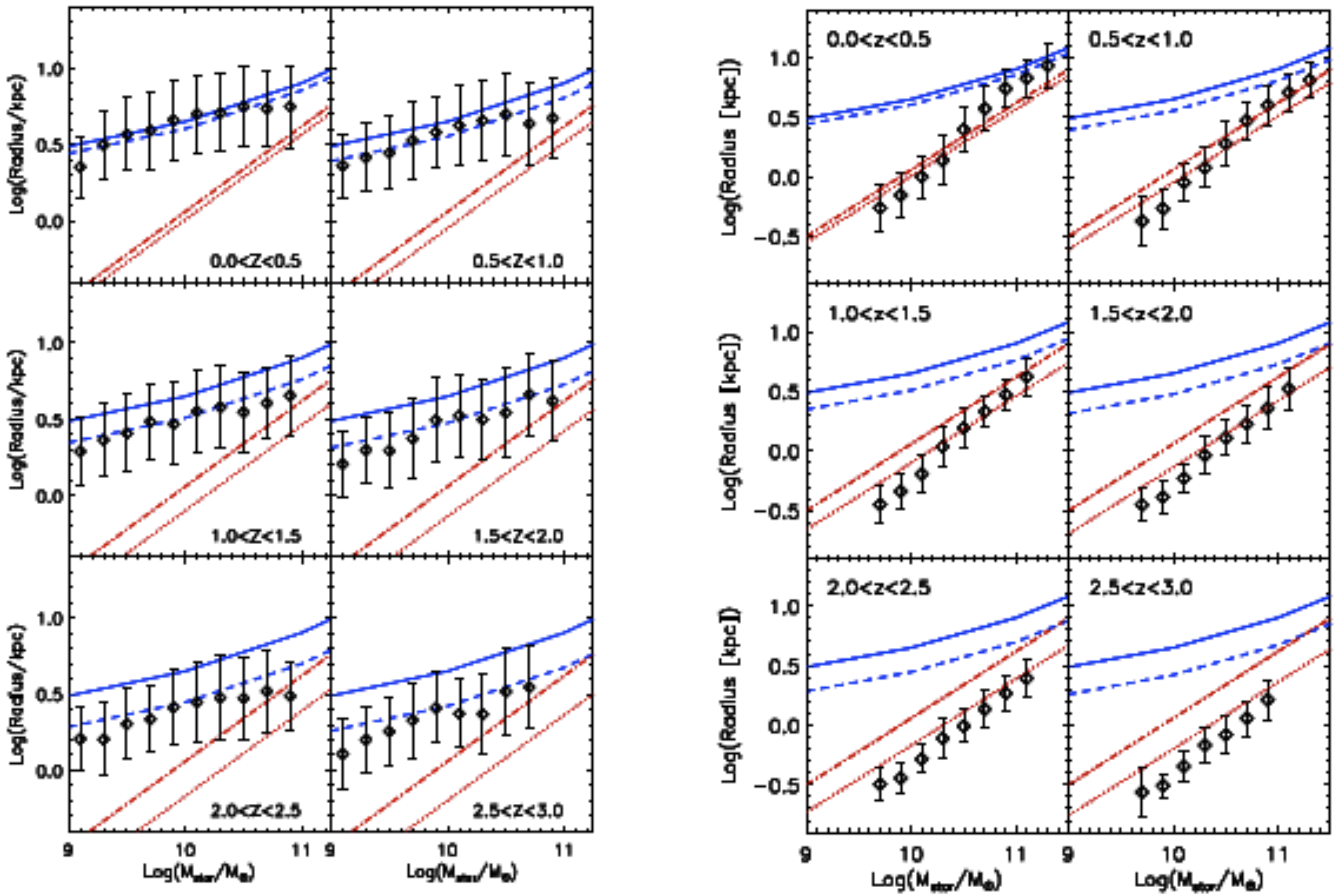
R_{eff} prediction by Cole et al. 2000 dissipationless model, best for dry merging



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

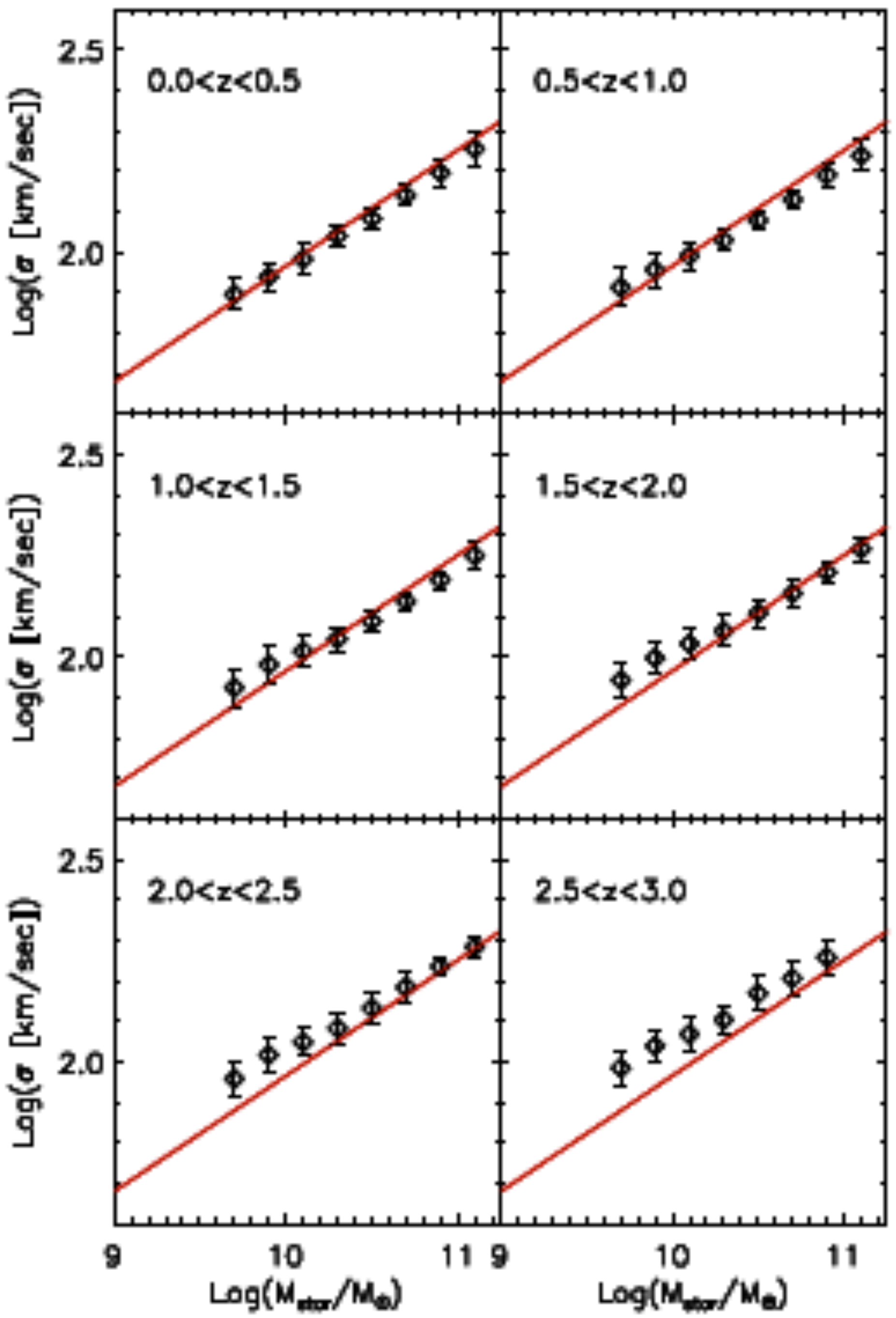
higher z data Trujillo+06

SPHEROIDS

z ~ 0 observations SDSS

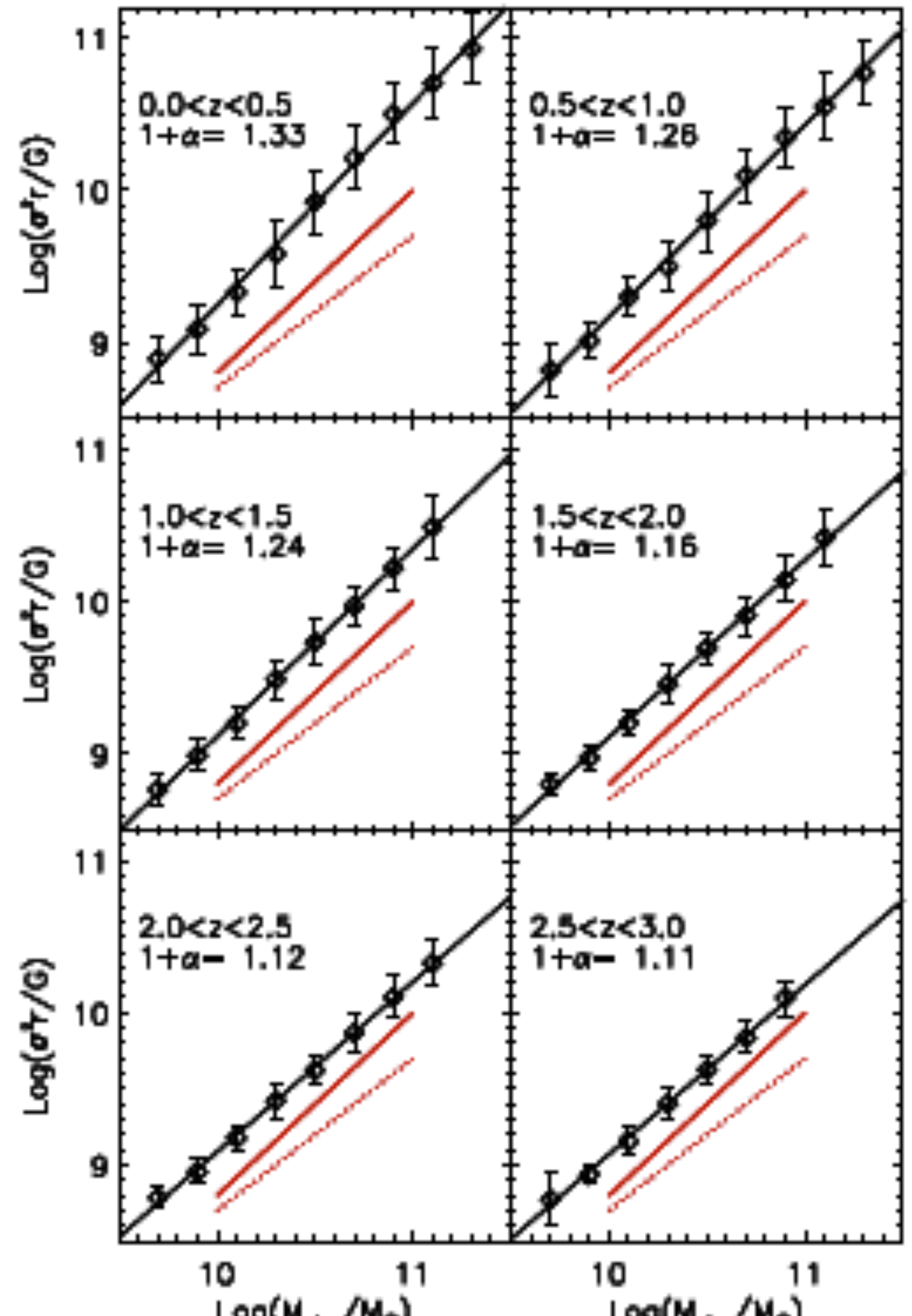
higher z data Trujillo+06

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.**



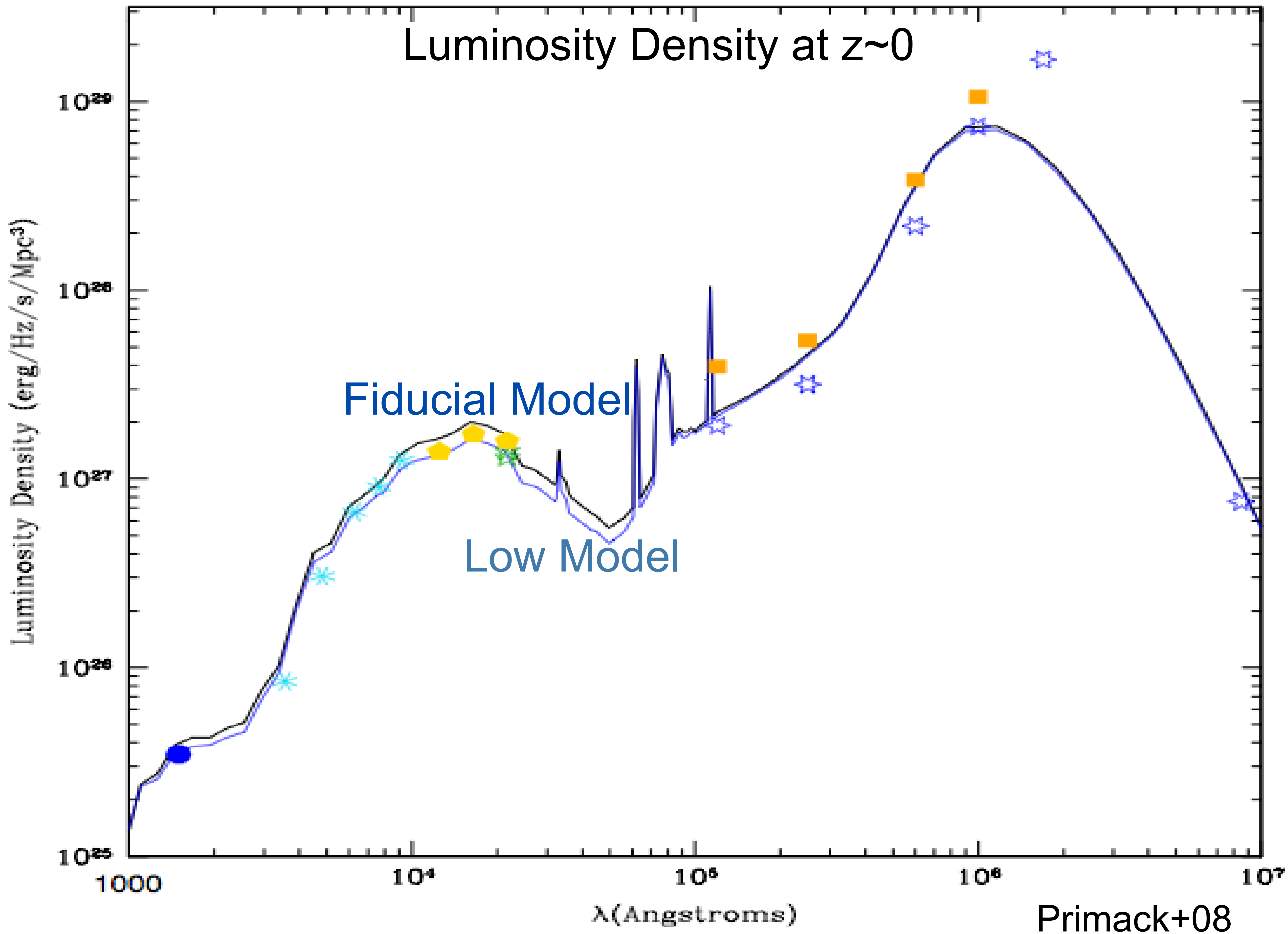
observed scaling
$M_{dyn} \propto M_*^{1.2}$

virial scaling

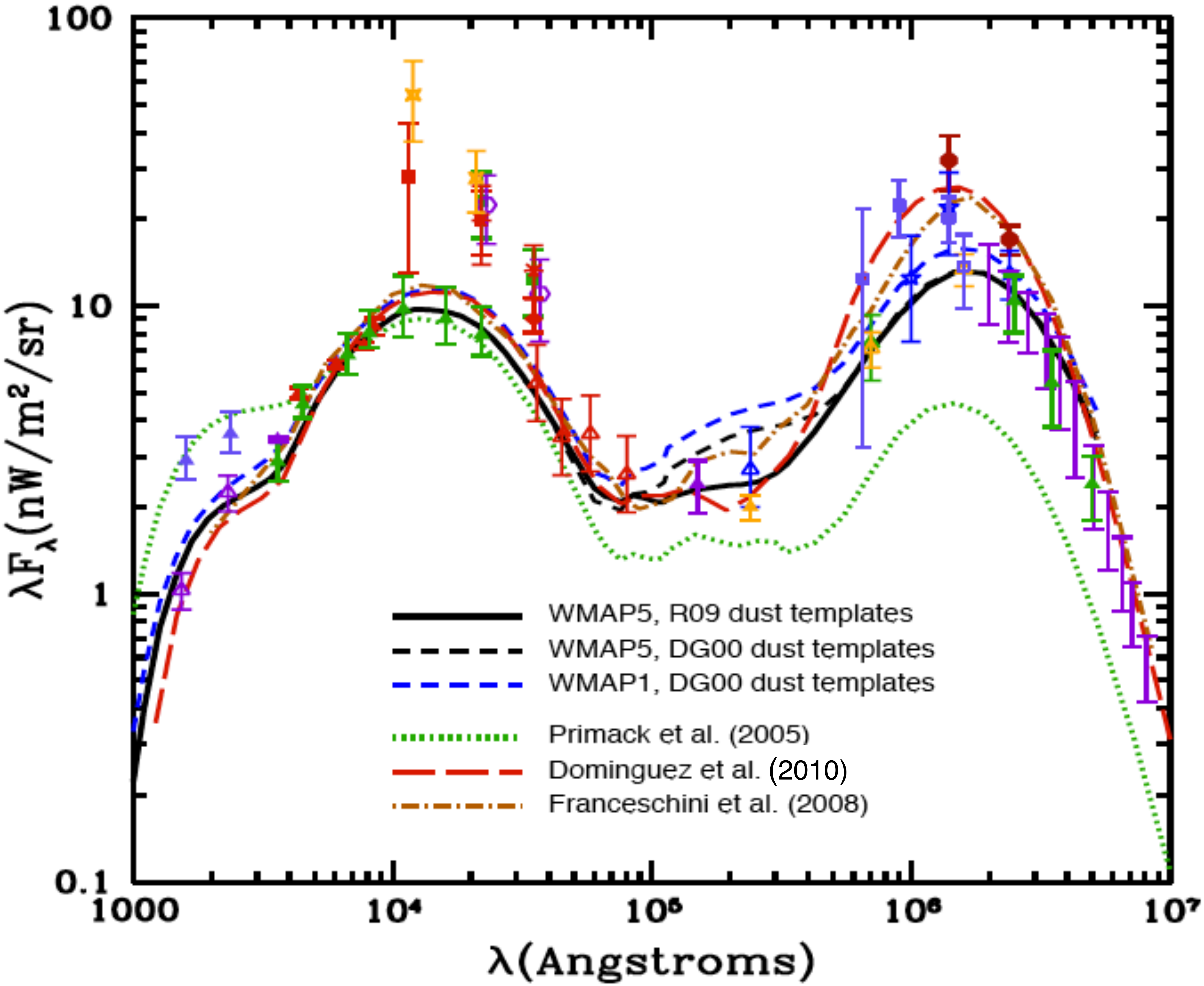
Matt Covington
dissertation 08

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.


Luminosity Density at z~0
Fiducial Model
Low Model
Luminosity Density (erg/Hz/s/Mpc^3)
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
1000
10^4
10^5
10^6
10^7
λ(Angstroms)
Primack+08

EBL from our Semi-Analytic Models



Gilmore, Somerville, Primack, & Dominguez (2011)

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.

COSMOLOGY: Ripe Questions Now

Lots of great research still to be done!

Nature of Dark Matter - ΛCDM $n_{halos}(V_{max},z)$, clustering vs. observations

Nature of Dark Energy - by SN1a, BAO, structure formation by grlensing, ...

How Galaxies Form and Evolve

- Early galaxies and reionization: pop III?, escape fraction, upsizing
- Mechanisms of early SF and AGN: gas-rich mergers *vs.* cold inflows
- What quenches SF: AGN, shock heating for $M_{halo} > 10^{12}\, M_{sun}$, morphology
- Evolution of galaxy morphology: need new morphology measures
- Evolution of galaxy kinematics and metallicity (need spectra)
- Extragalactic Background Light (EBL): measure, constrain with γ-rays

Theoretical Approaches

- Simulations: dissipationless, hydrodynamic
- Mock catalogs, Sub-Halo Abundance Matching (“SHAM”)
- Semi-Analytic Models (SAMs) constrained by simulations & observations
- Toy Models to clarify key astrophysical processes