Galaxy Formation:

the interplay between stars, dark matter and super massive black holes

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(Simon White, Volker Springel, et al. - MPA)
(the DEEP2 & AEGIS collaborations - everywhere else)

Overview

1. Galaxy formation: the zero'th order approximation

2. Some interesting question

3. Some interesting answers?

Galaxy formation: the zero’th order approximation

The Millennium Run Simulation

QuickTime™ and a
3ivx D4 4.5.1 decompressor
are needed to see this picture.

10^{10} dark matter particles

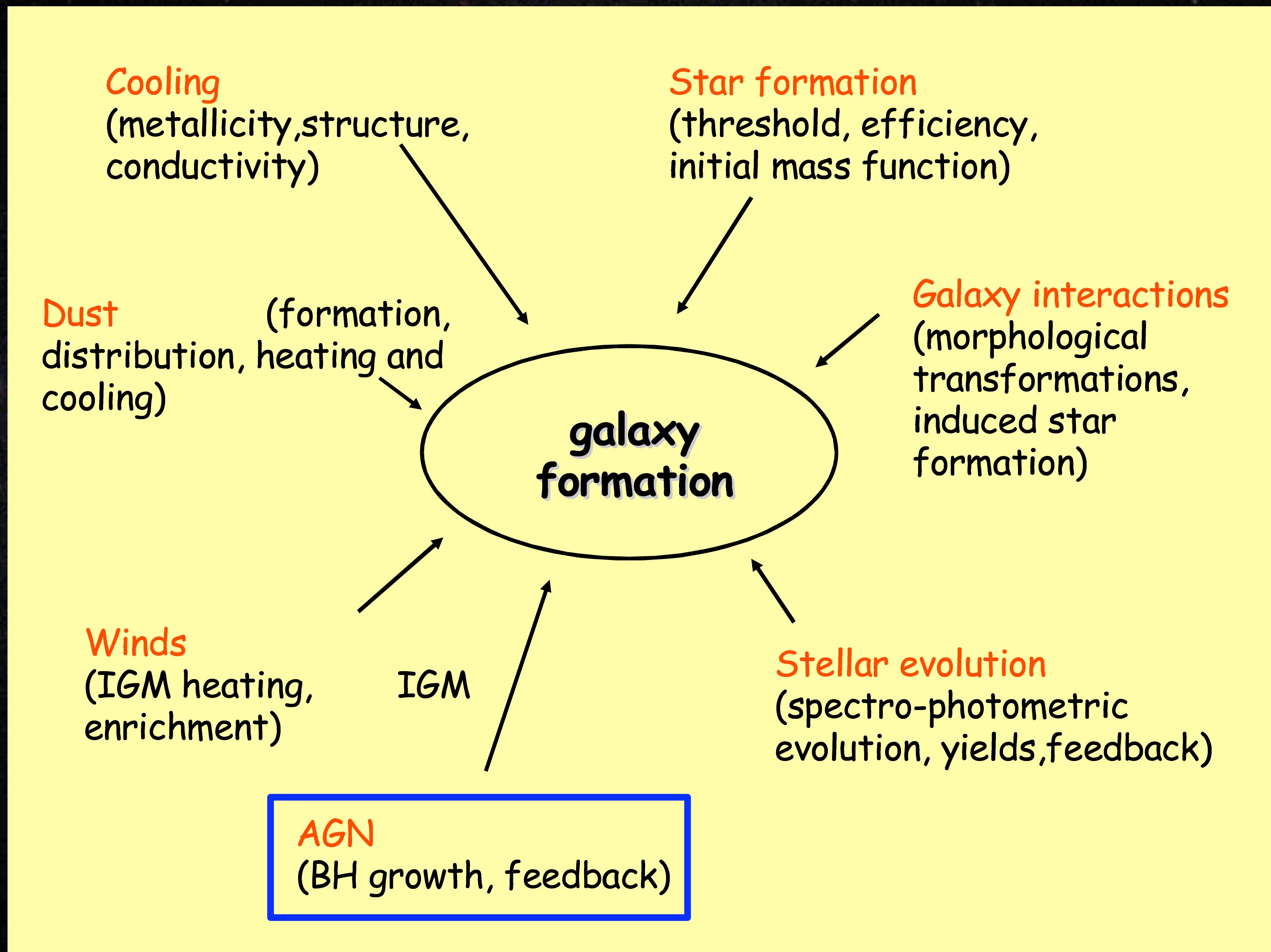
500 Mpc/h box side length

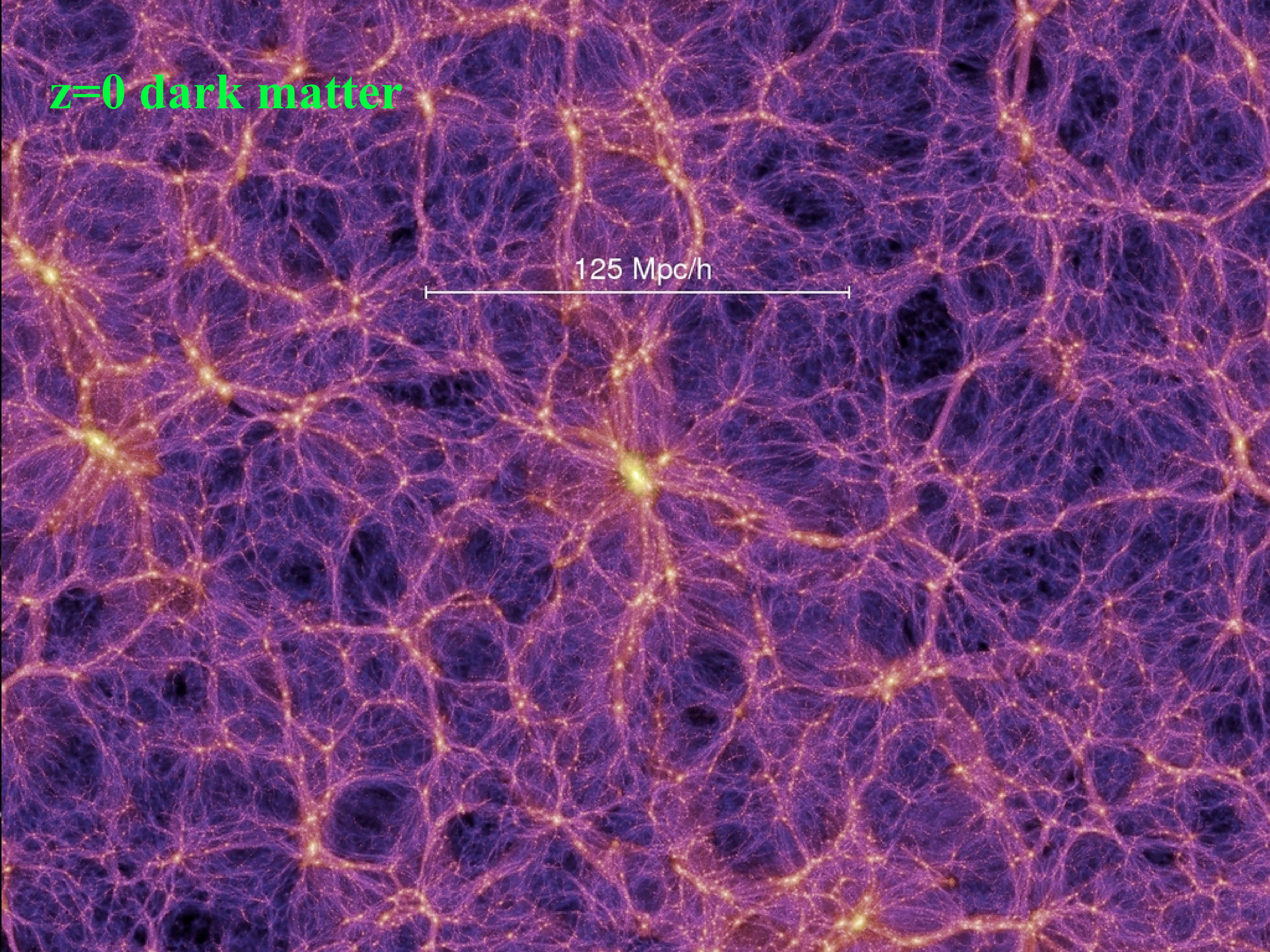
mass resolution of 8.6 x 10^8 Msun

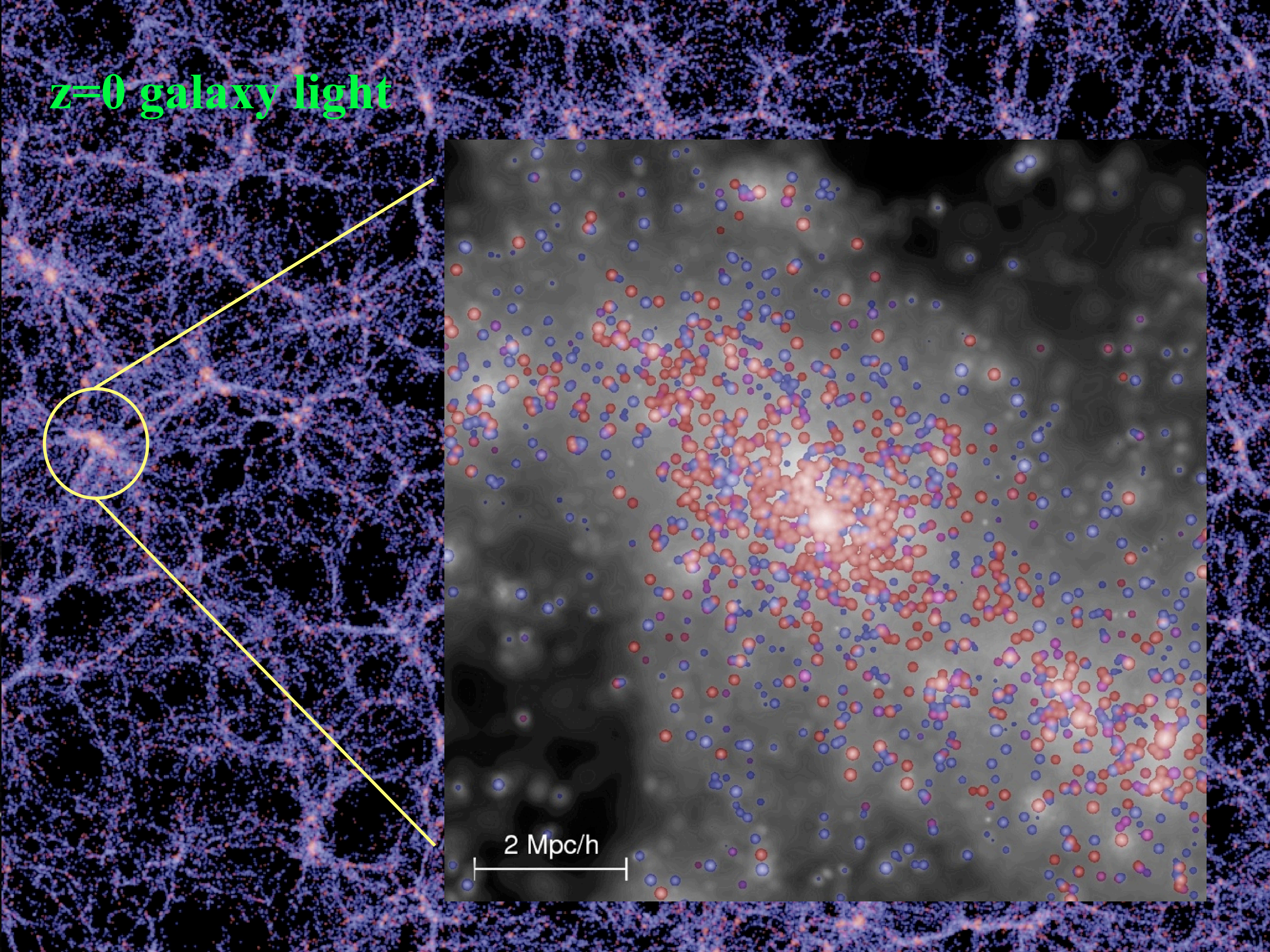
softening of 5 kpc/h

~7 million galaxies identified at z=0 (M_B<-17)

Building a Galaxy Population




z=0 dark matter
125 Mpc/h


z=0 galaxy light
2 Mpc/h

What SAMs can and can’t do

Can’t:

- necessarily produce a perfect match to your observations
- claim to be “correct”
- solve all of galaxy formation

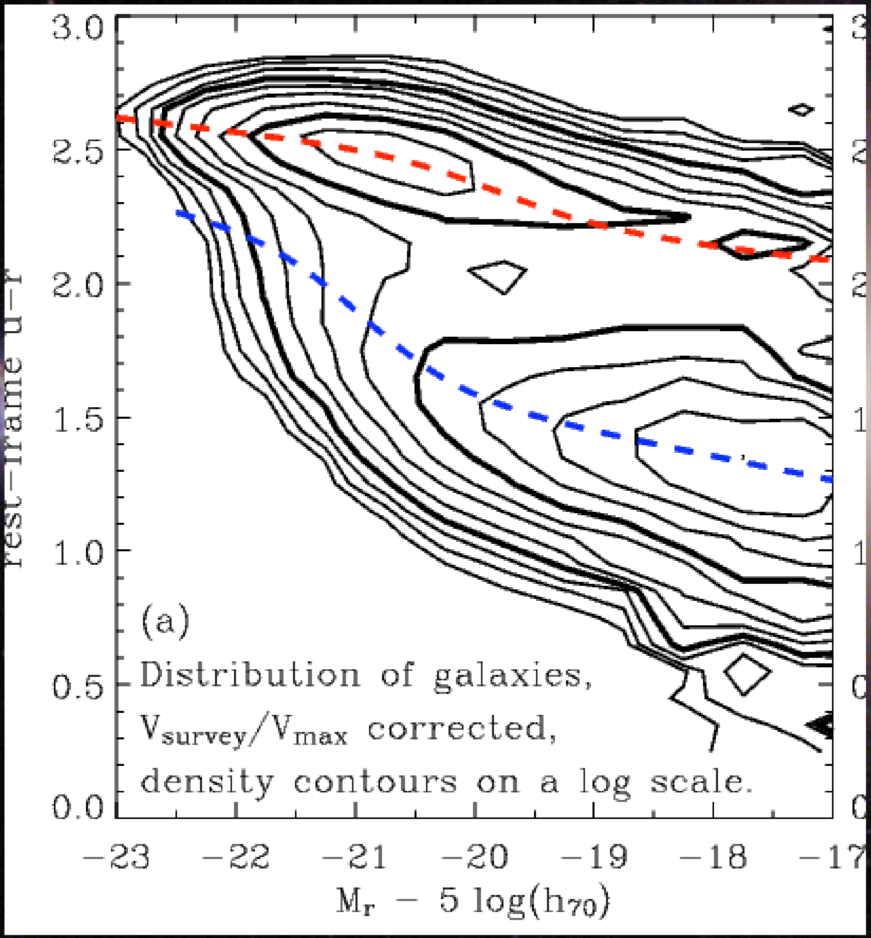
Can:

- provide a “controlled” reproduction of your analysis
- explore the physics of galaxy formation, follow the evolution of luminous structure, link galaxy populations at different epochs
- test for systematic effects, cosmic variance, etc

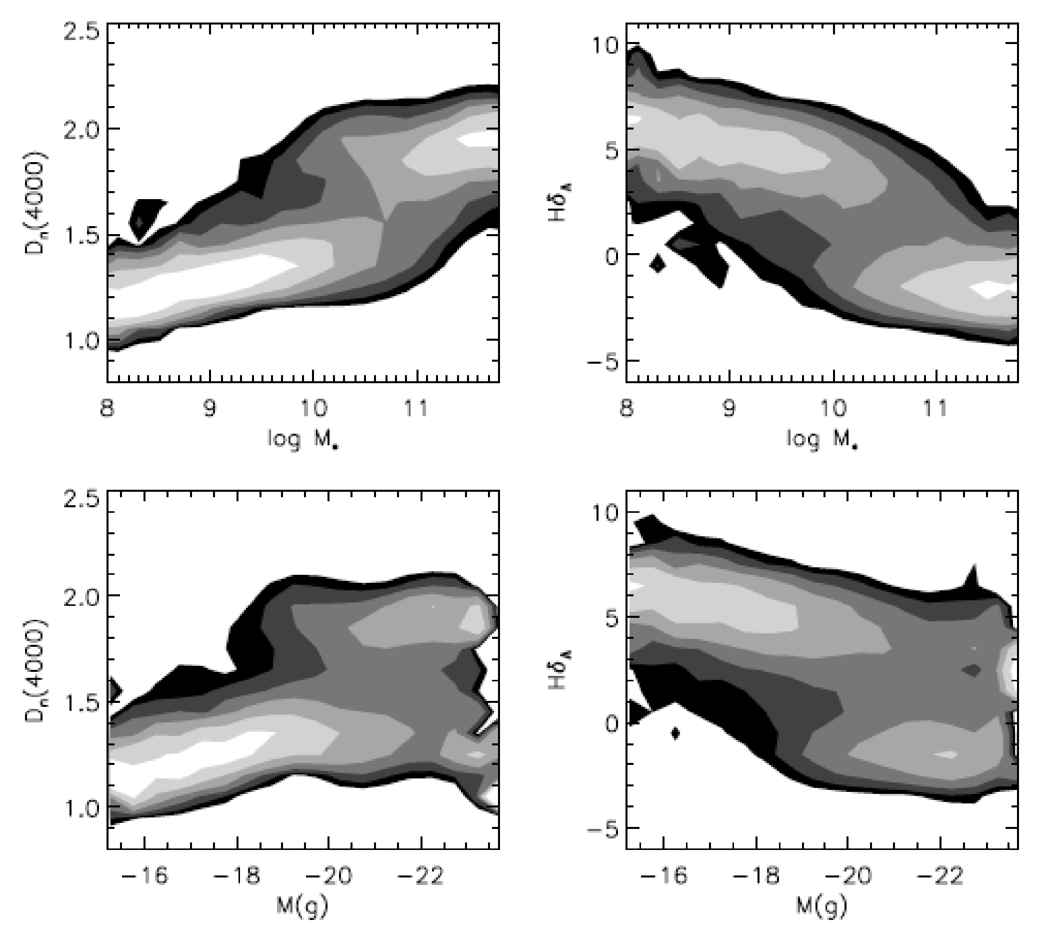
Some interesting questions

Some interesting questions

(Baldry et al. 2005)



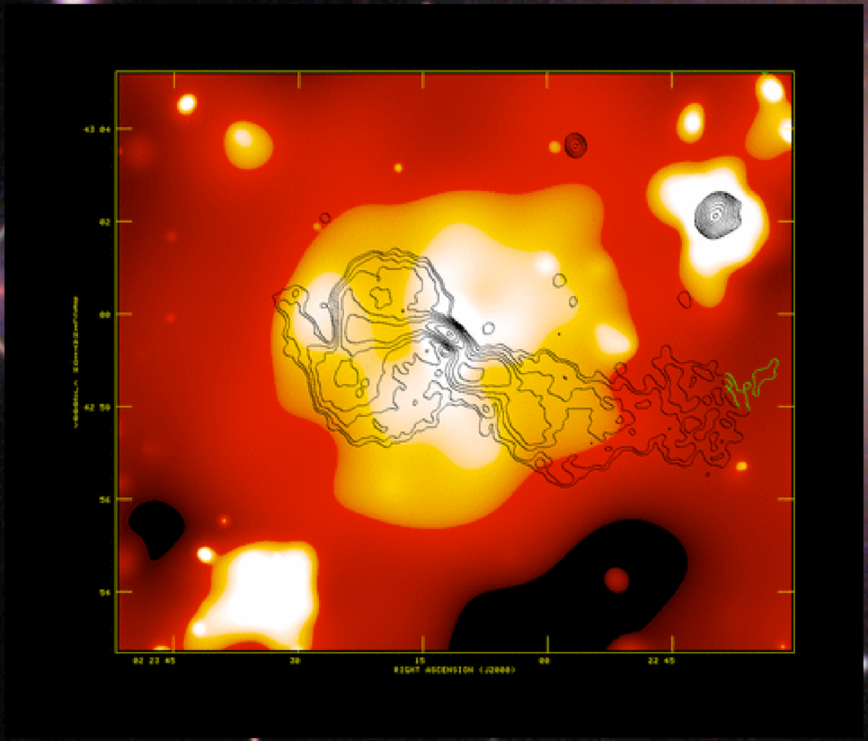
(Kauffmann et al. 2003)



Galaxies appear to live two lives … why?

The cooling flow problem

Gas should be condensing out of the hot component in cluster systems, but BCG’s are red and dead.



Are cooling flows heated by low luminosity AGN?
(Binney et al. 1995, Best et al. 2005)

Gas Cooling

The quasi-static x-ray emitting hot halo:

- Assume the baryon fraction inside the virial radius.
- Cooling Radius: the radius out to which the gas in the hot halo has had time to cool given the age of the system.
- We assume an isothermal density profile at the virial temperature

$$t_{\rm cool} = \frac{3}{2} \frac{\bar{\mu} m_{\rm p} k T}{\rho_{\rm g}(r) \Lambda(T, Z)}.$$

=>

$$\dot{m}_{\rm cool} = 0.5 m_{\rm hot} \frac{r_{\rm cool} V_{\rm vir}}{R_{\rm vir}^2}.$$

(Bertschinger 1989, White & Frenk 1991)

Gas Heating

Bondi-Hoyle black hole accretion (Bondi 1952)

Assumption: the hot gas around the central black hole is static and has uniform density:

$$\dot{m}_{\rm Bondi} = 2.5\pi \mathrm{G}^2 \frac{m_{\rm BH}^2 \rho_0}{c_{\rm s}^3}$$

Assumption: maximal cooling flow. Thus, at the Bondi radius, the gas density is determined by equating the cooling time to the free fall time:

$$\frac{2 r_{\rm Bondi}}{c_{\rm s}} \approx \frac{4 \mathrm{G} m_{\rm BH}}{V_{\rm vir}^3} = \frac{3}{2}\frac{\bar{\mu} m_{\rm p} kT}{\rho_{\rm g}(r_{\rm Bondi})\Lambda(T, Z)}$$

=> $$\rho_0 = \rho_{\rm g}(r_{\rm Bondi}) = \frac{3\mu m_{\rm p}}{8\mathrm{G}}\frac{kT}{\Lambda}\frac{V_{\rm vir}^3}{m_{\rm BH}}$$

Using this local BH gas density gives a Bondi accretion rate of:

$$\dot{m}_{\rm Bondi} \approx \mathrm{G}\mu m_{\rm p}\frac{kT}{\Lambda} m_{\rm BH}$$

Gas Heating

(Croton et al 2006)

The quiescent AGN "radio" mode:

Such accretion leads to a low energy outflow from the black hole

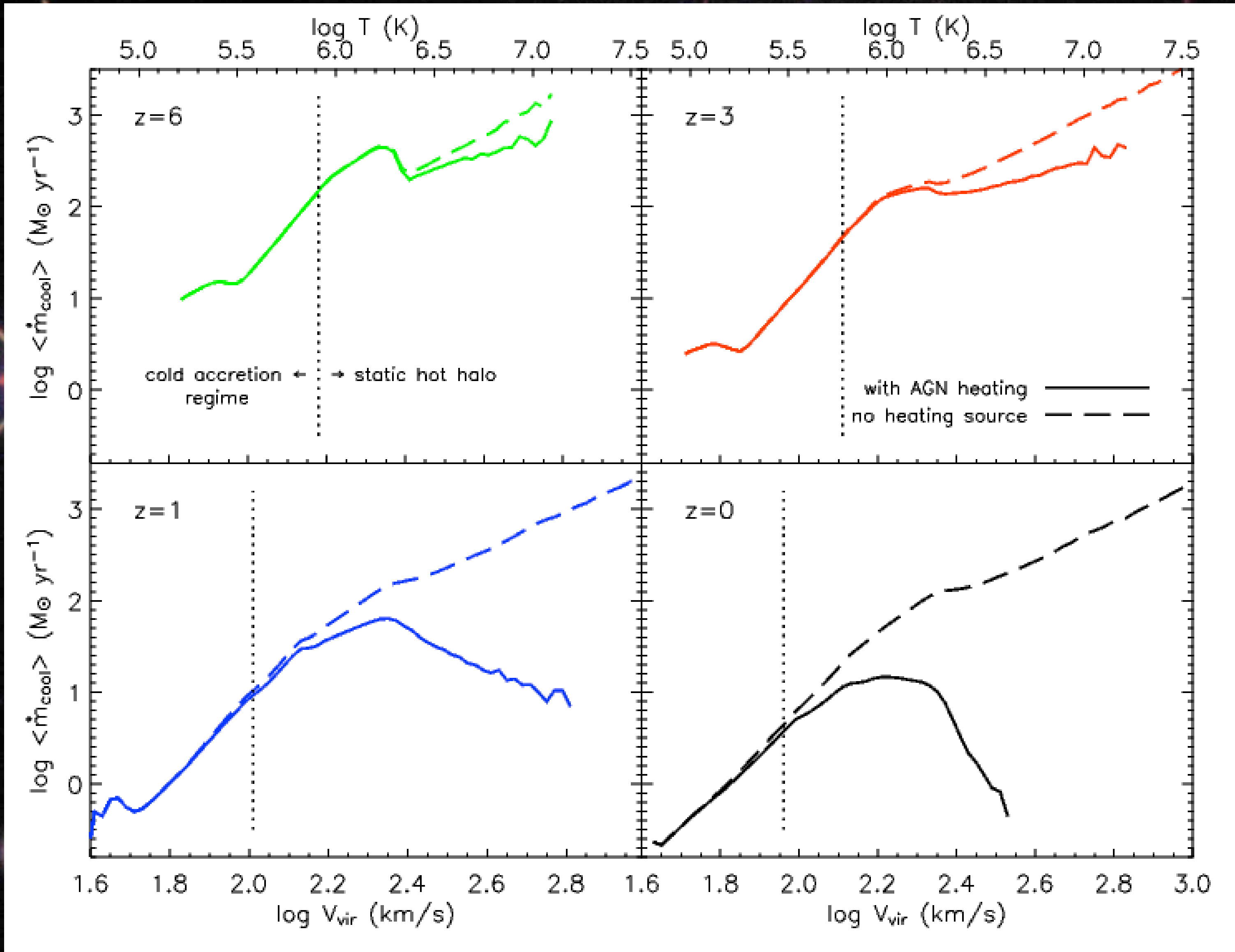
$$L_{\rm BH} = \eta \, \dot{m}_{\rm BH} \, c^2$$

By energy conservation this outflow can suppress the inflow of cooling gas

$$\dot{m}'_{\rm cool} = \dot{m}_{\rm cool} - \frac{L_{\rm BH}}{\frac{1}{2} V_{\rm vir}^2}$$

We assume that this model captures the mean behaviour of the black hole over timescales much longer then the duty cycle

Radio Mode “Quenching”

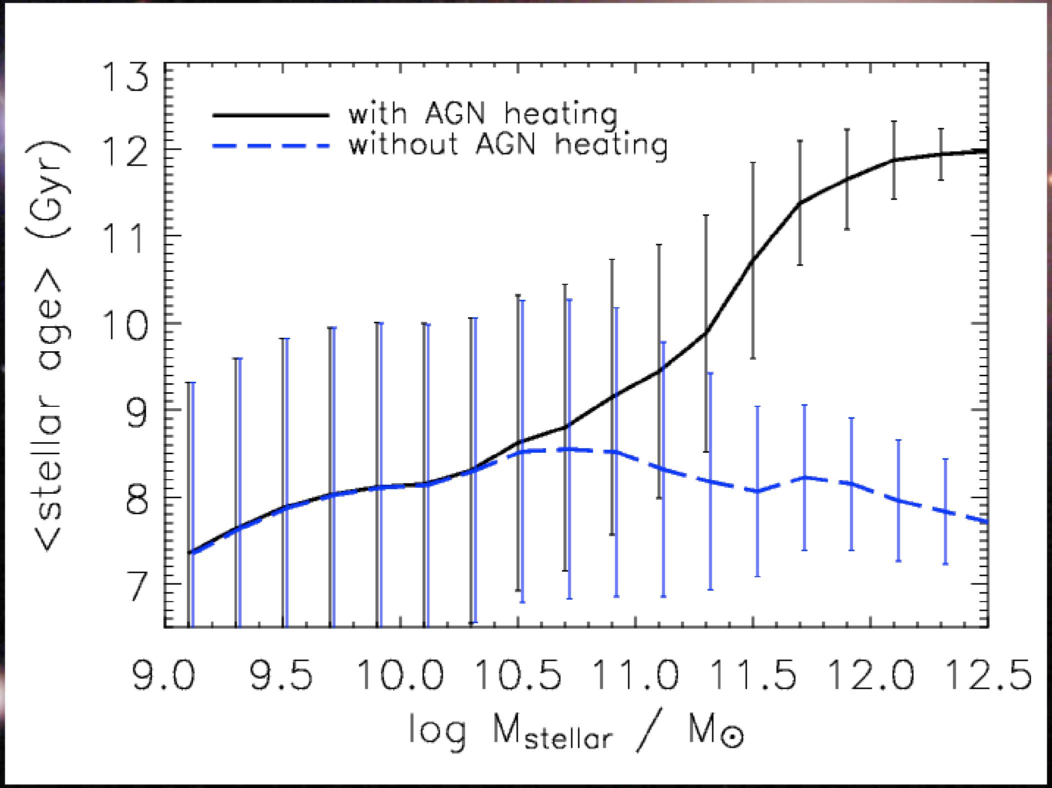


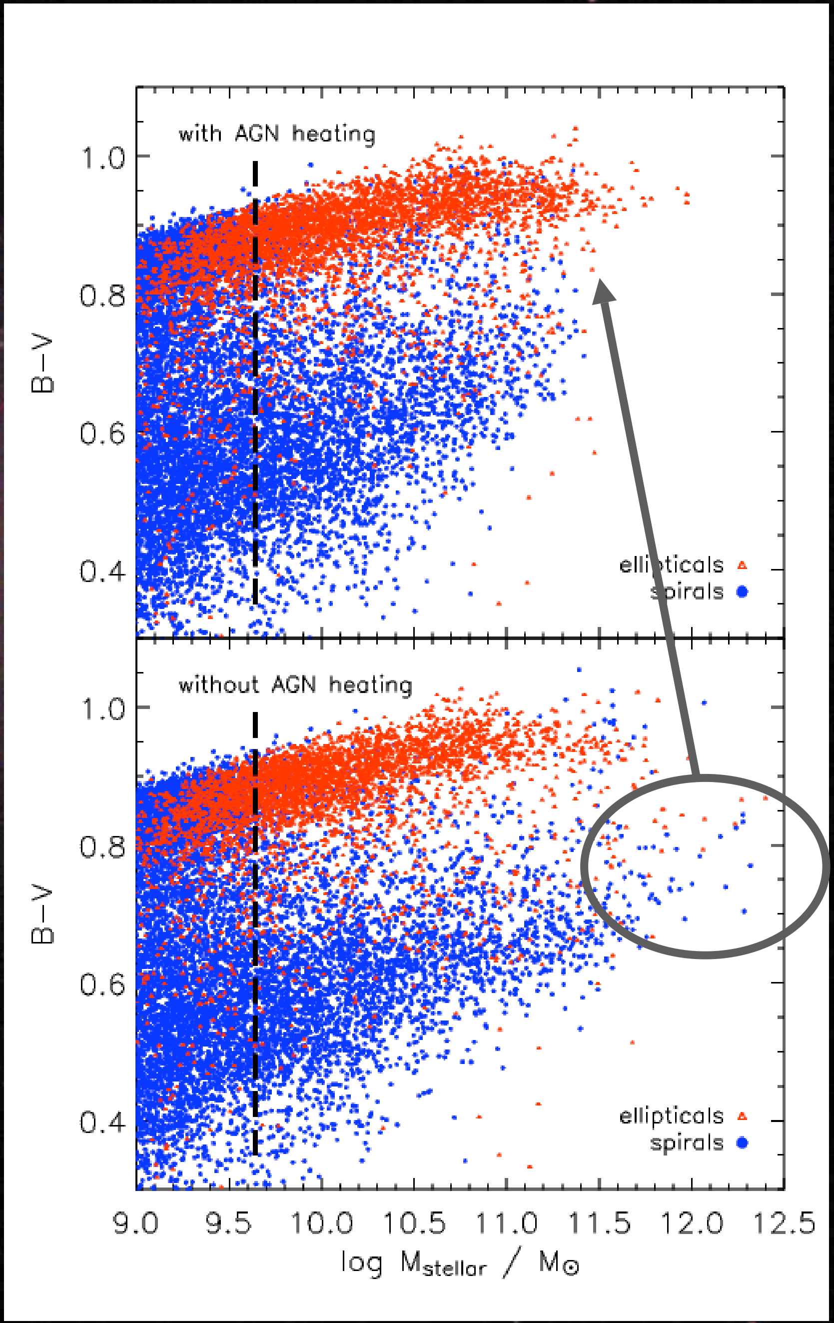
Suppression of cooling gas

Cooling flow suppression is most efficient in massive halos and at late times

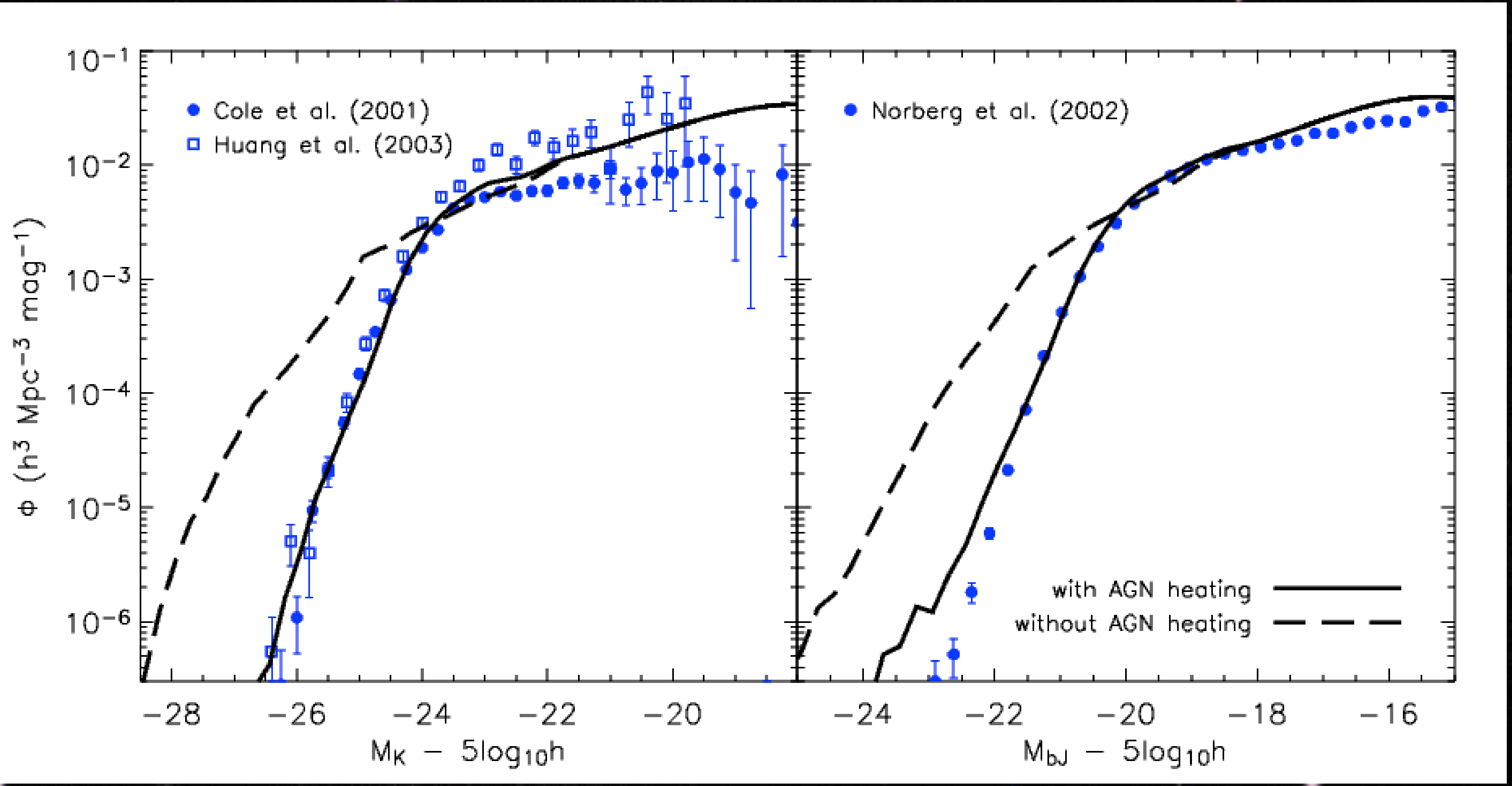
Galaxy Colours and Ages

B-V colour bi-modality
and mean stellar age





Luminosity Functions



The K and bJ-band luminosity functions with and without AGN

Energy Considerations

Total cooling energy
vs.
Total heating energy
by z=0

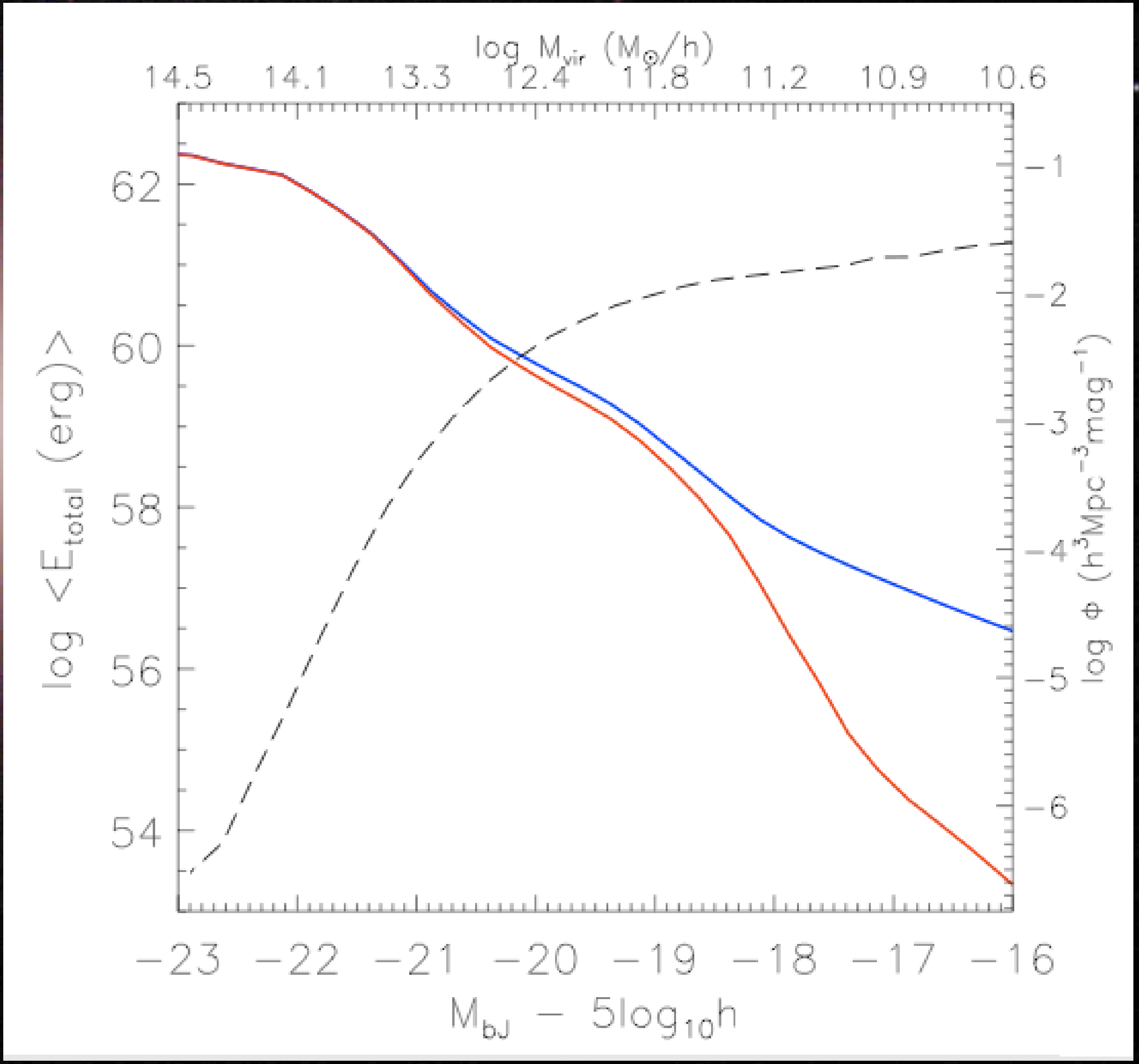
LF knee corresponds to:

$E_{cool} \sim E_{heat}$

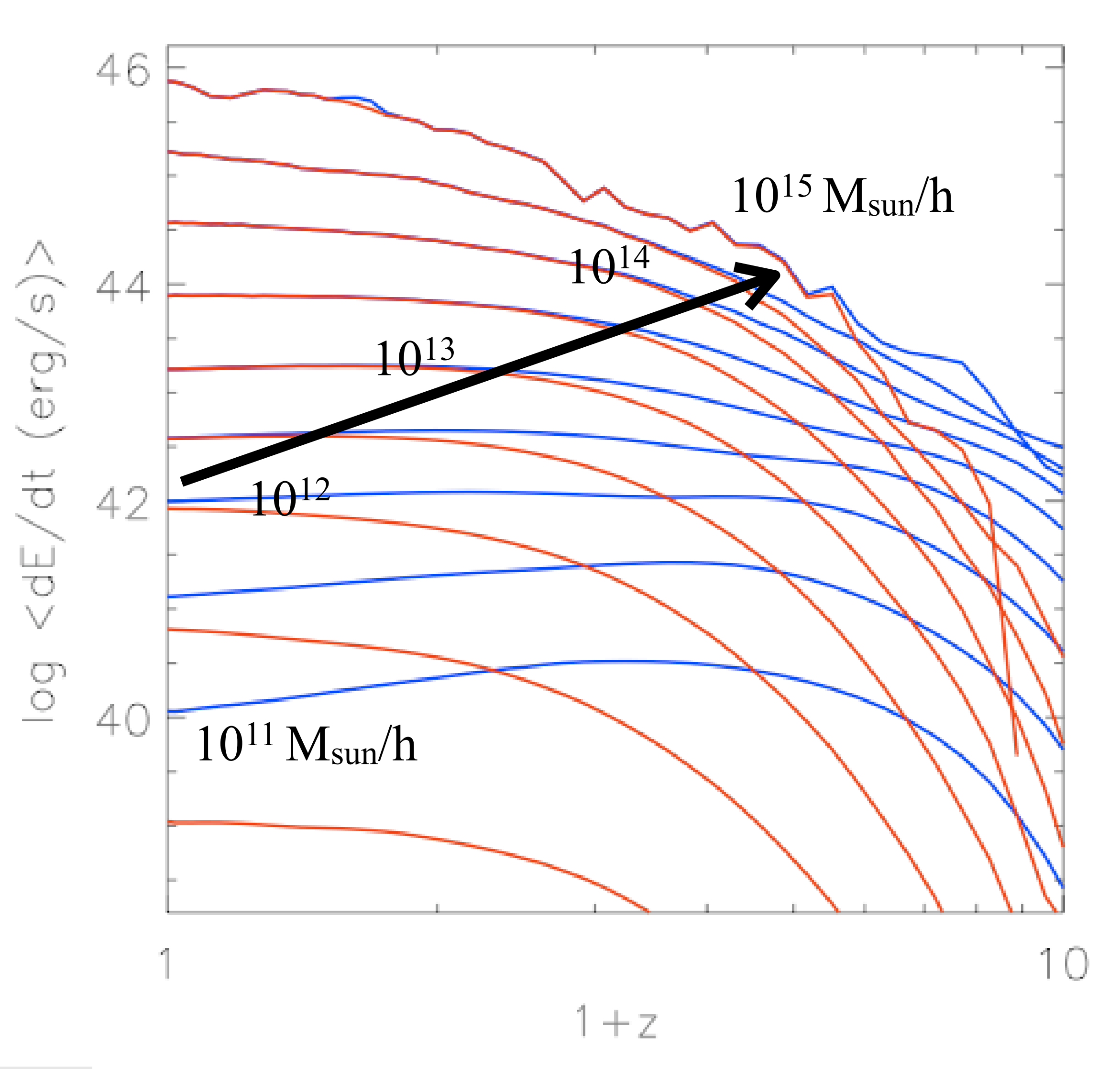
$M_{bJ} \sim -19 .. -20$

$M_{vir} \sim 10^{11.5-12.5} M_{sun}/h$

(Croton et al in prep.)



Quenching vs. Halo Mass

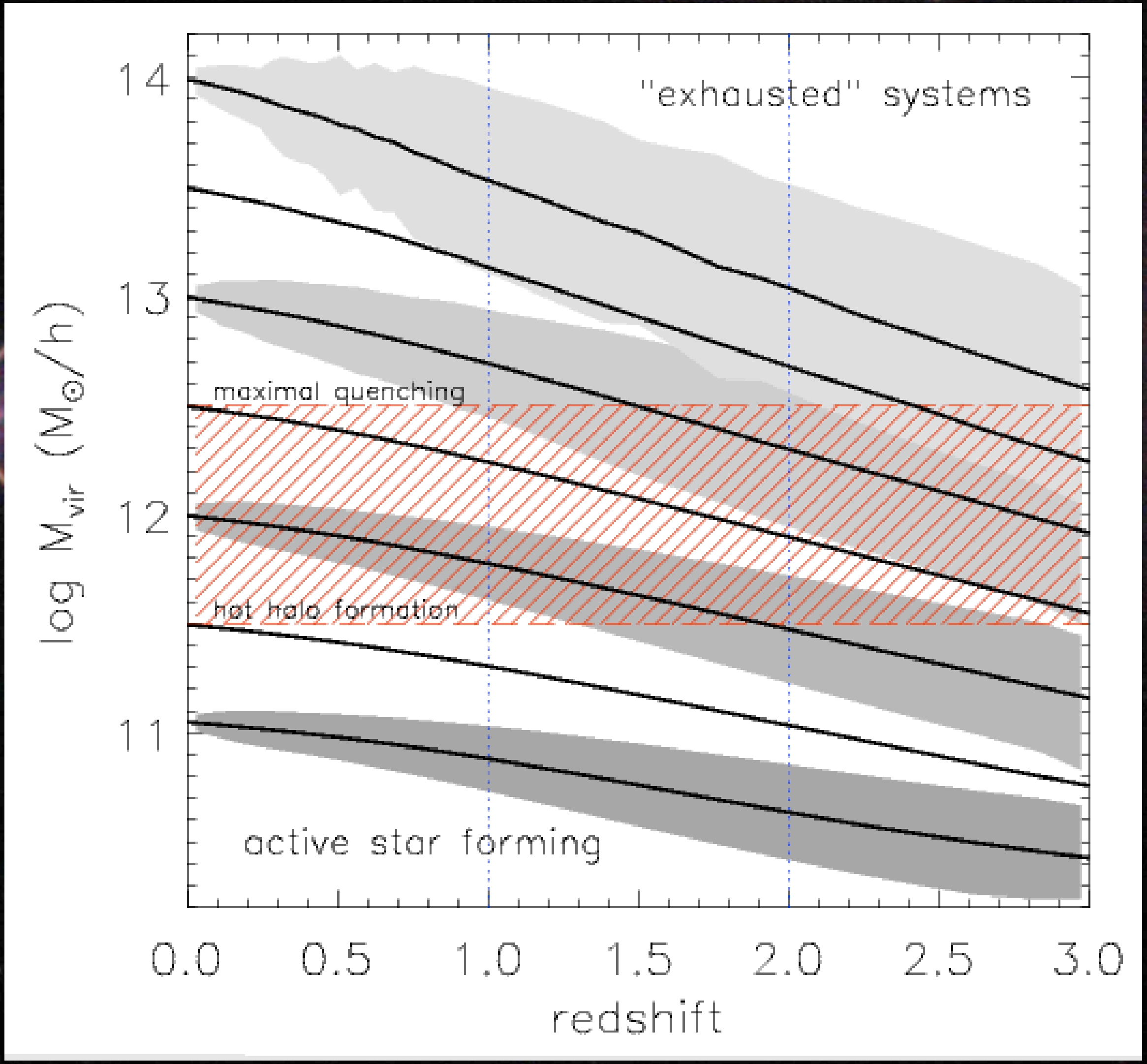


Cooling Rates
vs.
Heating Rates

currently $M_{vir} \sim 10^{12} M_{sun}/h$ halos are initiating quenching

(Croton et al in prep.)

Quenching vs. Halo Mass



Critical halo mass thresholds

currently $M_{vir} \sim 10^{12} M_{sun}/h$ halos are initiating quenching

(Croton et al in prep.)

Why Does Such Heating Work?

- Unlike other heating mechanisms (e.g. super-winds, starbursts, ...), AGN heating suppresses star formation without itself requiring star formation to efficiently operate.

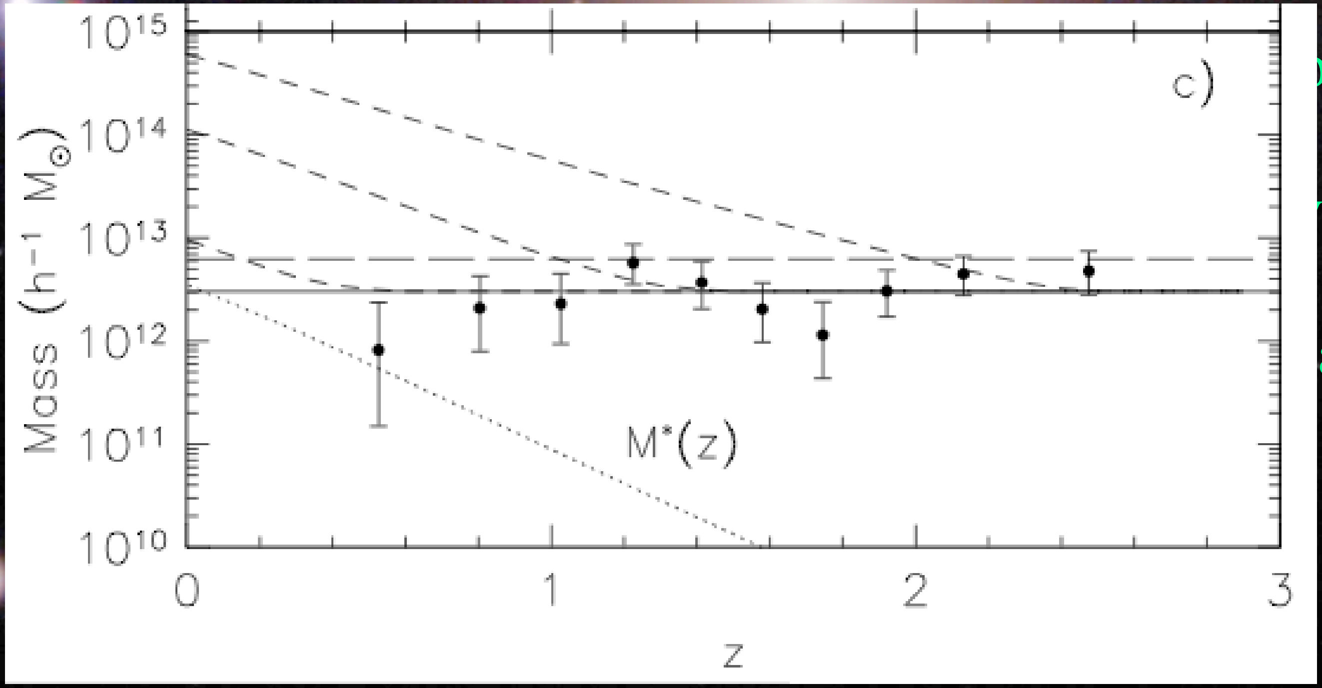
- Unlike "event" mechanisms (e.g. merger driven quasar winds), whatever quenches star formation needs to be an ongoing process (local massive ellipticals are not quasars!). However see Scannapico et al. 2006.

An AGN-like low energy heating source, fed from the hot x-ray halo, is an energetically feasible candidate

How we can test this picture ...

Work in progress:

evolution of the quasar luminosity function



olometric heating rates

AGN and vs. redshift

and their environment

Croom et al. 2005

Conclusions

1. Low luminosity AGN can keep red galaxies on the red sequence in spite of the hierarchical growth of cosmic structure.

2. A model where the heating rate is independent of star formation appears to work best for the global properties, but targeted observational tests are needed to understand this in detail.

3. We really need accurate stellar and halo masses of quenching systems to better understand the global processes operating

The full Millennium Run galaxy + halo catalogues
(~25 million galaxies/halos, $0<z<127$)
are now available through the GAVO SQL interface for use by the community
http://www.mpa-garching.mpg.de/Millennium/ see astro-ph/0608019