The many lives of AGN: from super-massive black holes to host galaxy colours and luminosies

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Simon White,Volker Springel, et al.
+ the DEEP2 and AEGIS collaborations

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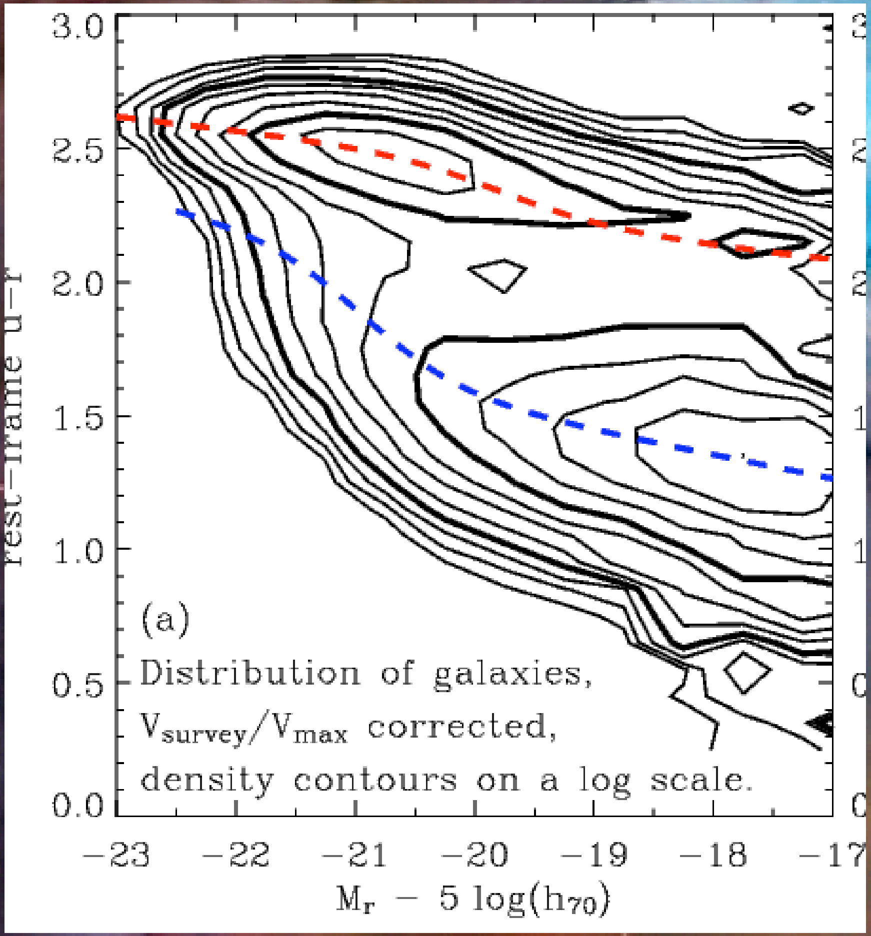
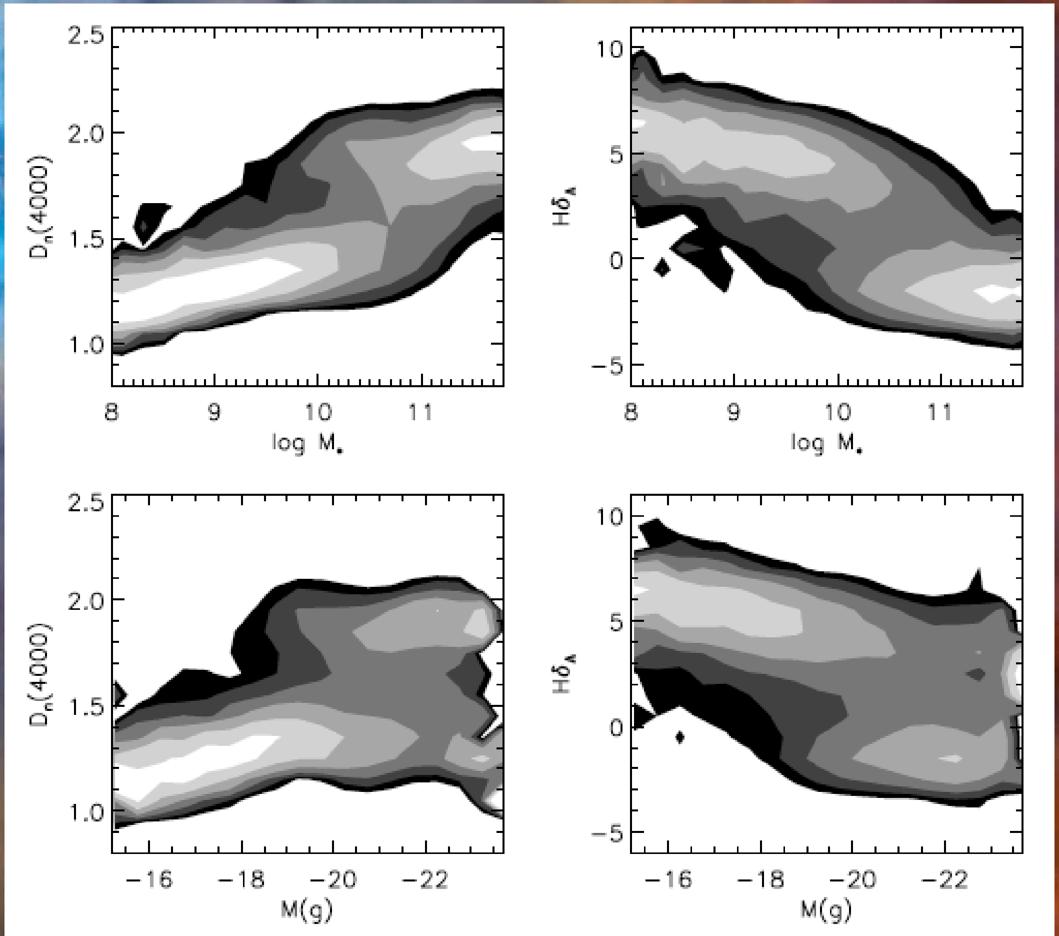
Motivation: the colour bi-modality

(Baldry et al. 2005)

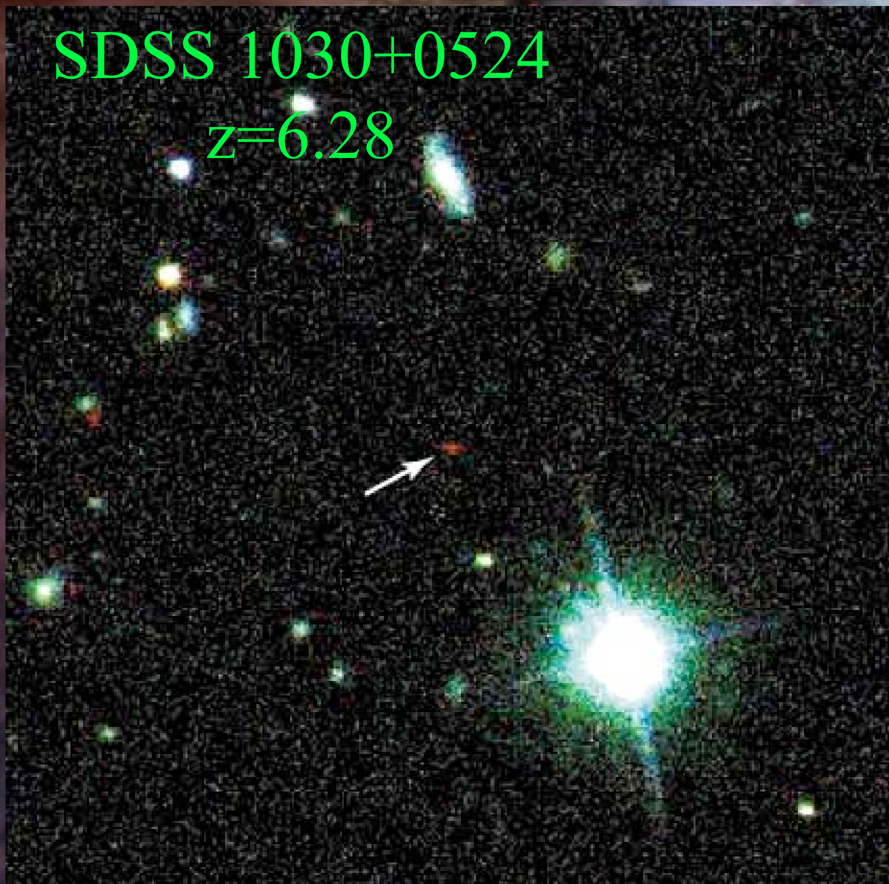


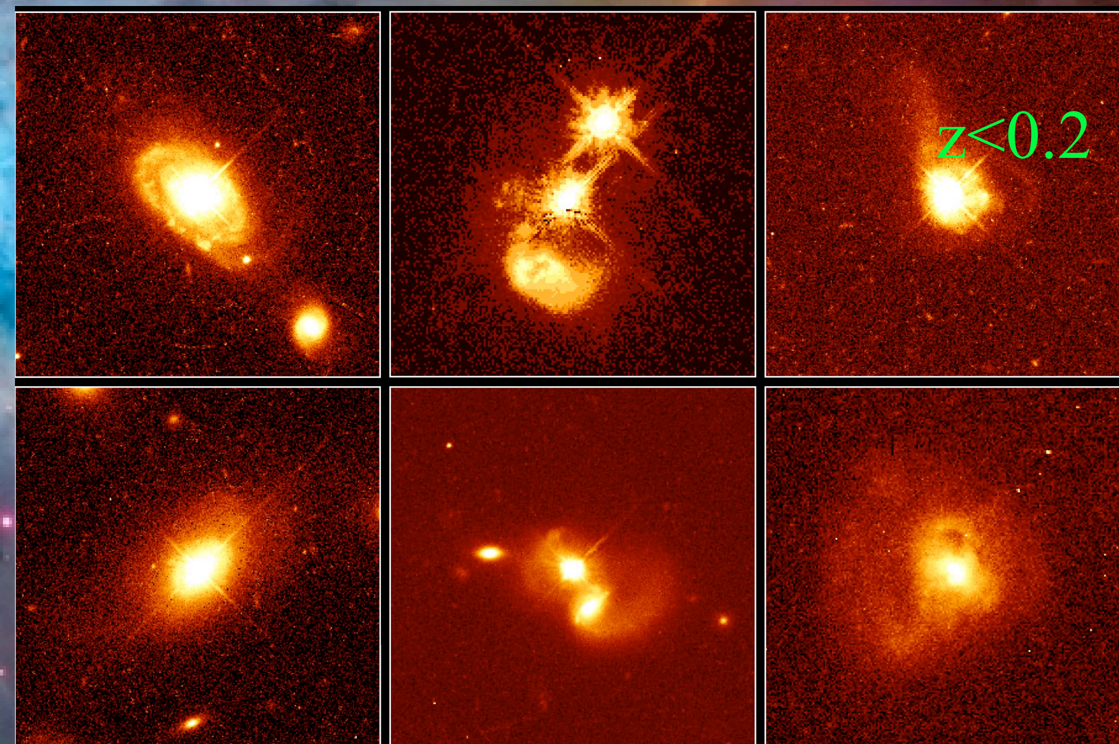
(Kauffmann et al. 2003)



Galaxies appear to live two lives ... why?

Motivation: how do you build the red sequence?



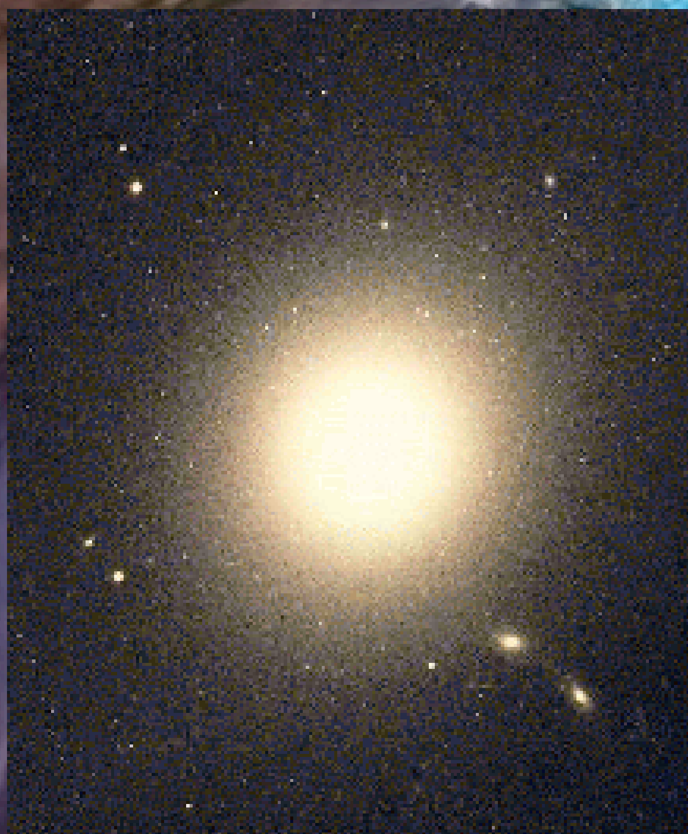


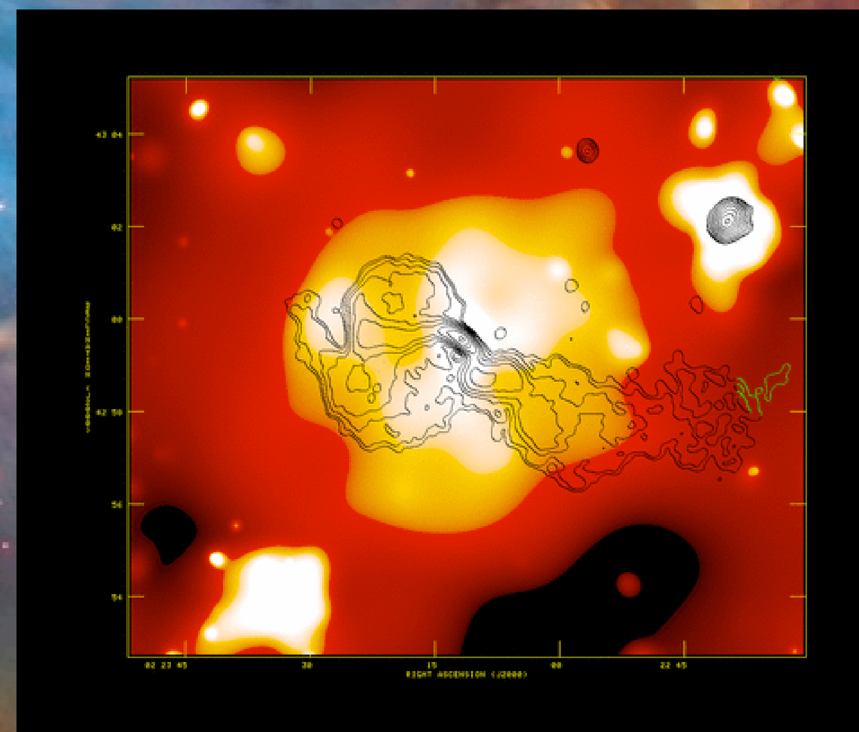
Hubble Space Telescope

High & low redshift quasars and merger induced quasar winds can make galaxies red ... e.g. Hopkins et al. 2005

Motivation: how do you build the red sequence?

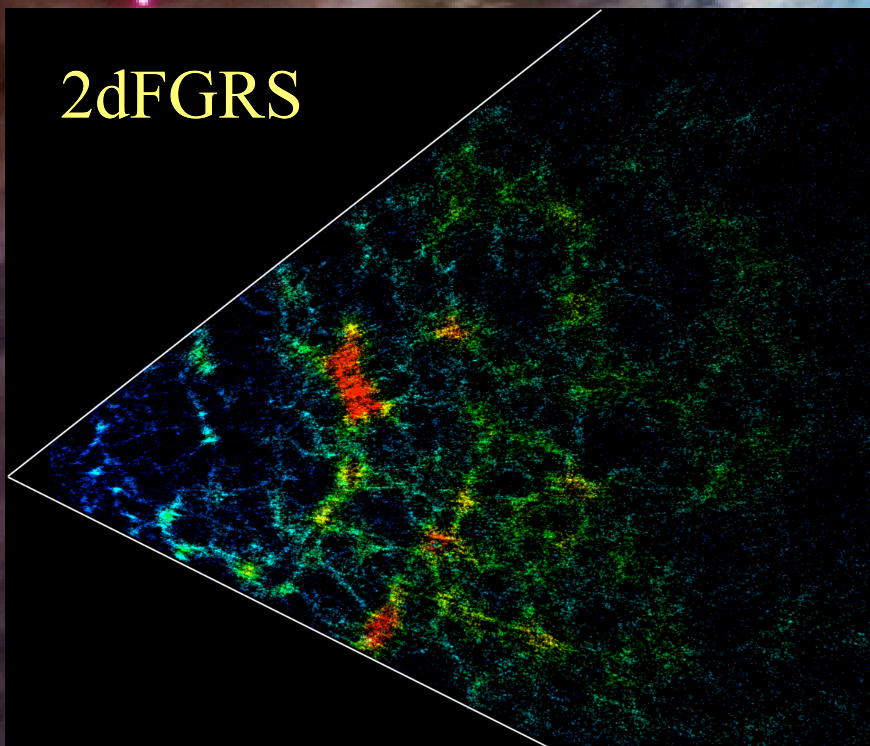
... but quasars are not seen today at the centres of galaxy clusters





Radio jets, bubbles *are* seen and can suppress cooling gas ...
(Binney et al. 1995, Best et al. 2005)

Aims



How does AGN heating influence the final properties of the galaxy population?

I will present a model that illustrates how one can self-consistently explain:

- the existence of the red sequence,
- the turn-over of the luminosity function,
- the build up of stellar mass at the high mass end.

We use a dark matter simulation of cosmological scale, coupled with a model of galaxy formation with AGN, to investigate this problem.

(DC et al. 2006)

The Millennium Run Simulation

The Millennium Run N-body LCDM simulation (Springel et al. 2005):

10^{10} dark matter particles

500 Mpc/h box side length

mass resolution of 8.6 x 10^8 Msun

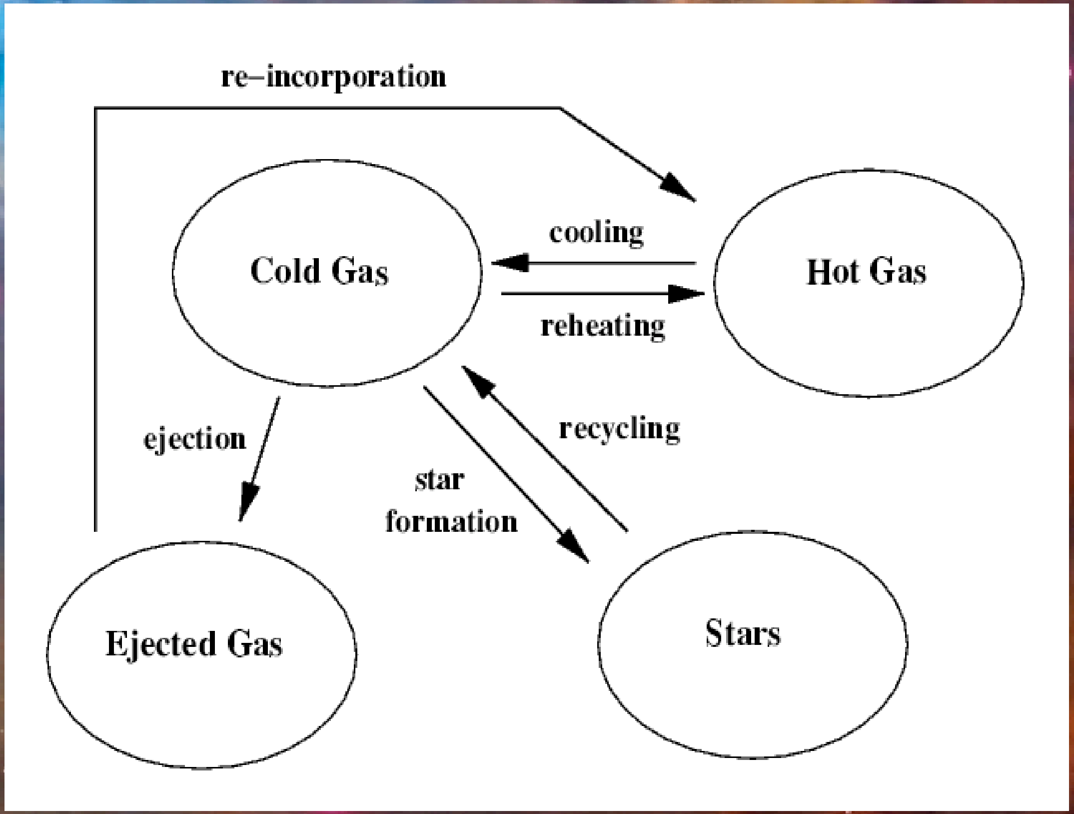
softening of 5 kpc/h

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

The Millennium Run's resolution is such that all galaxies more massive than the LMC can be resolved in a volume comparable to 2dFGRS and SDSS.

Building the Galaxy Population

The semi-analytic model of galaxy formation (White & Frenk 1992):



- gas infall and cooling
- star formation
- supernova feedback
- galaxy mergers and starbursts
- metal enrichment

- two mode AGN model

(DC et al. 2006)

Populating Galaxies with Black Holes

The AGN "quasar" mode:

In the quasar mode, super-massive black holes grow through merging events where black holes coalesce and cold disk gas is driven onto the central black hole.

$$\Delta m_{\rm BH,Q} = \frac{f'_{\rm BH}\ m_{\rm cold}}{1 + (280\,{\rm km\,s^{-1}}/{\rm V_{vir}})^2}$$

This is the primary mode of black hole growth

(Kauffmann & Haeanelt 2000)

Gas Cooling

The quasi-static x-ray emitting hot halo:

Initially 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.

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

=>

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

We assume an isothermal density profile at the virial temperature

(Bertschinger 1989, White & Frenk 1991)

Gas Heating

The AGN "radio" mode:

In the radio mode, quiescent hot gas accretes onto the central super-massive black hole. This ongoing accretion comes from the surrounding hot halo, where we capture the mean behaviour with an empirical equation.

$$\dot{m}_{\rm BH,R} = \kappa_{\rm AGN} \left(\frac{m_{\rm BH}}{10^8\, M_\odot} \right) \left(\frac{f_{\rm hot}}{0.1} \right) \left(\frac{V_{\rm vir}}{200\, {\rm km\, s^{-1}}} \right)^3$$

This accretion is typically well below the Eddington limit

(DC et al. 2006)

Gas Heating

The AGN "radio" mode:

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

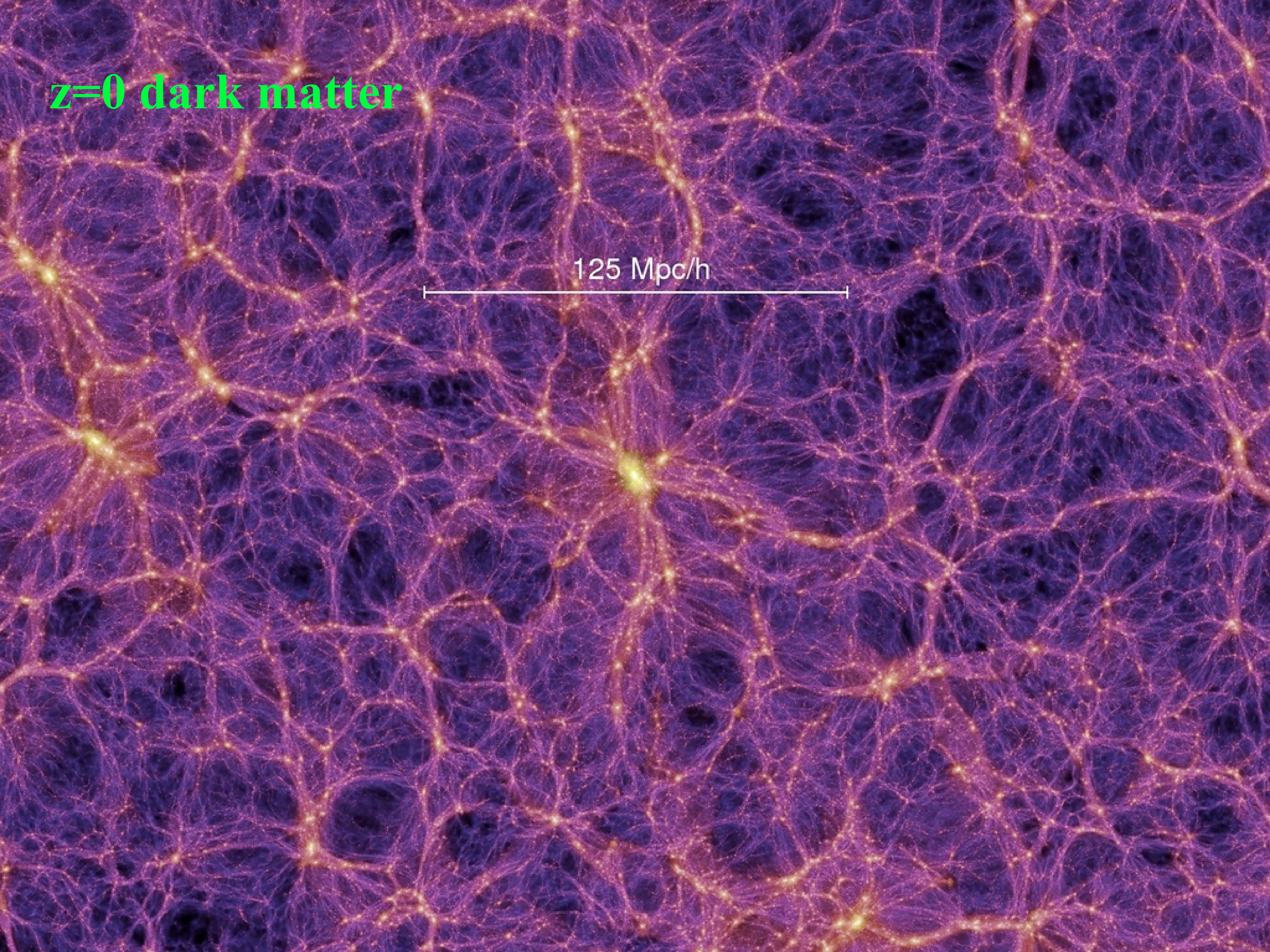
$$L_{\rm BH} = \eta \, \dot{m}_{\rm BH} \, c^2$$

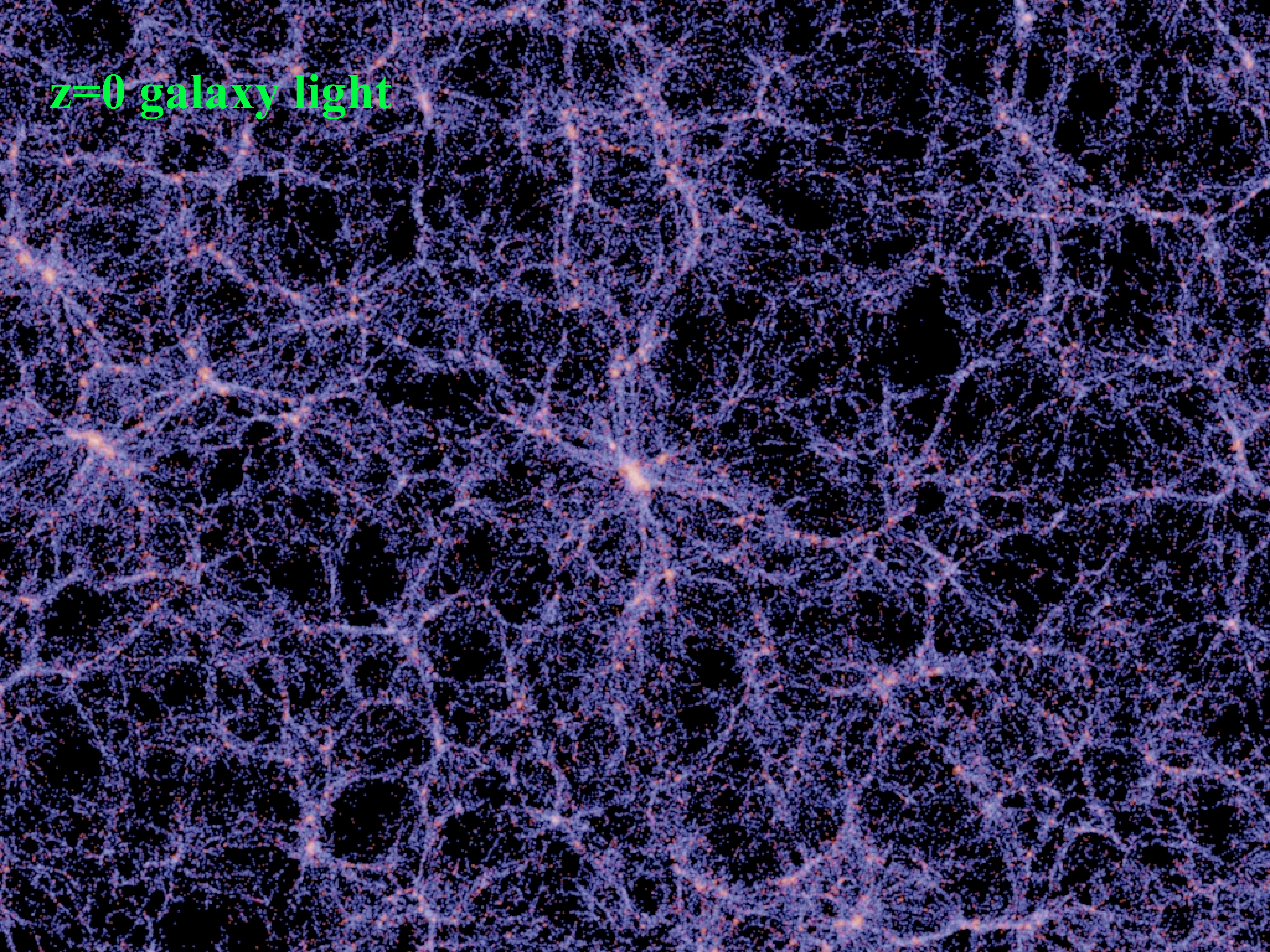
By energy conservation this outflow can suppress the inflow of cooling gas

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

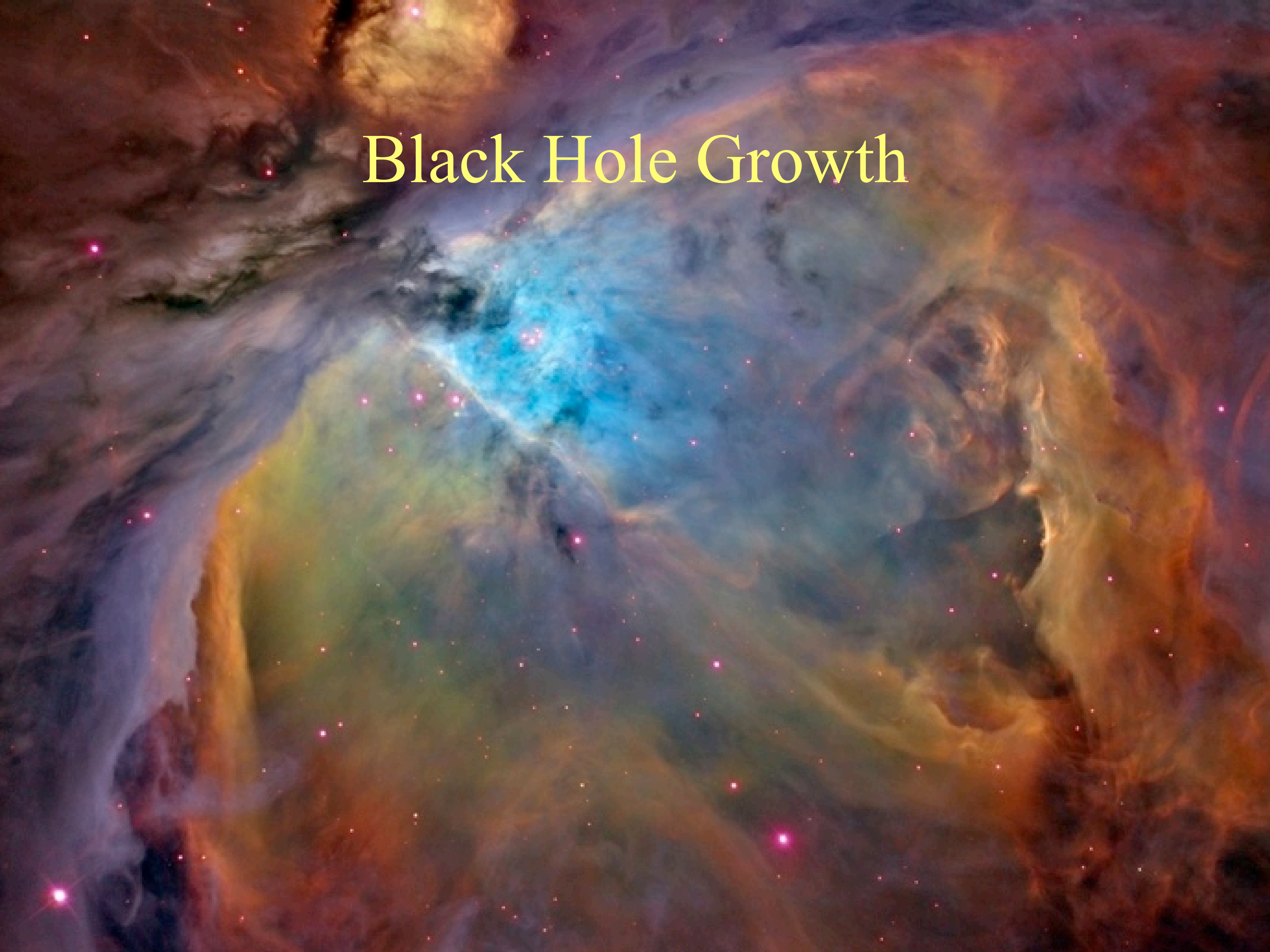
We assume that this model captures the mean behaviour of the black hole over timescales much longer then the duty cycle

(DC et al. 2006)


z=0 dark matter
125 Mpc/h

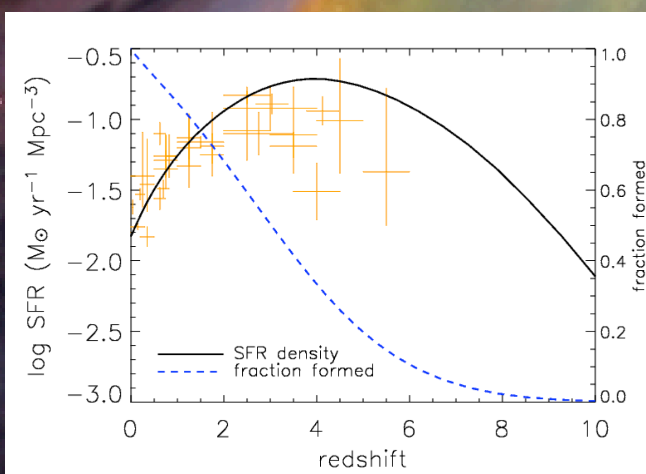

z=0 galaxy light

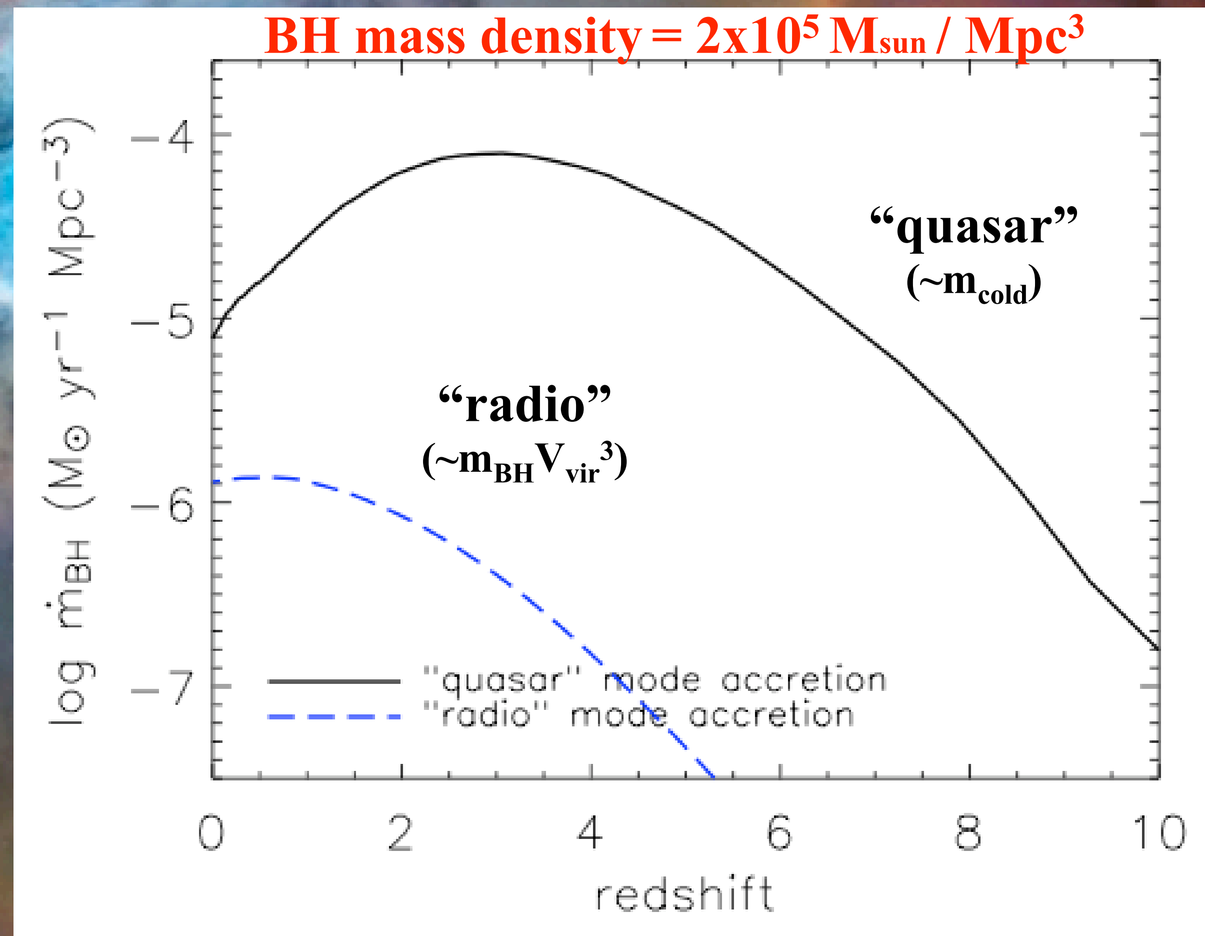
Black Hole Growth



Black Hole Growth

Black hole accretion history of the universe

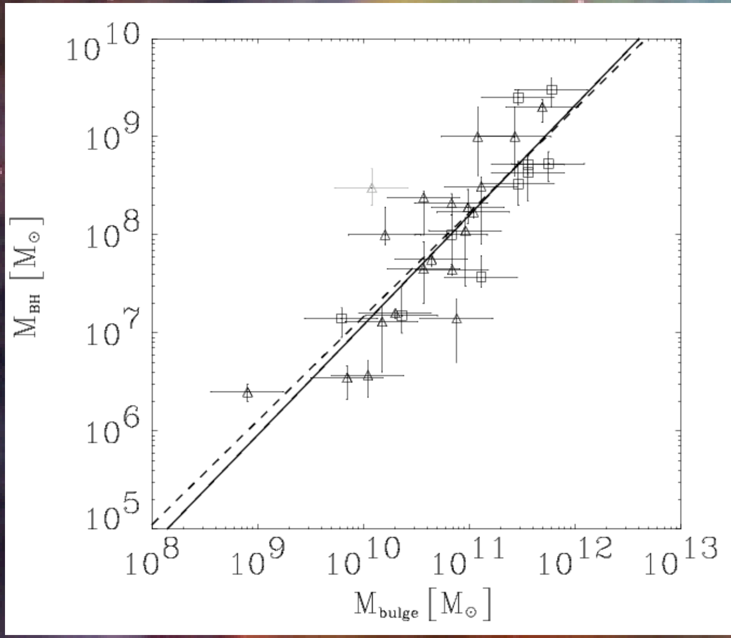




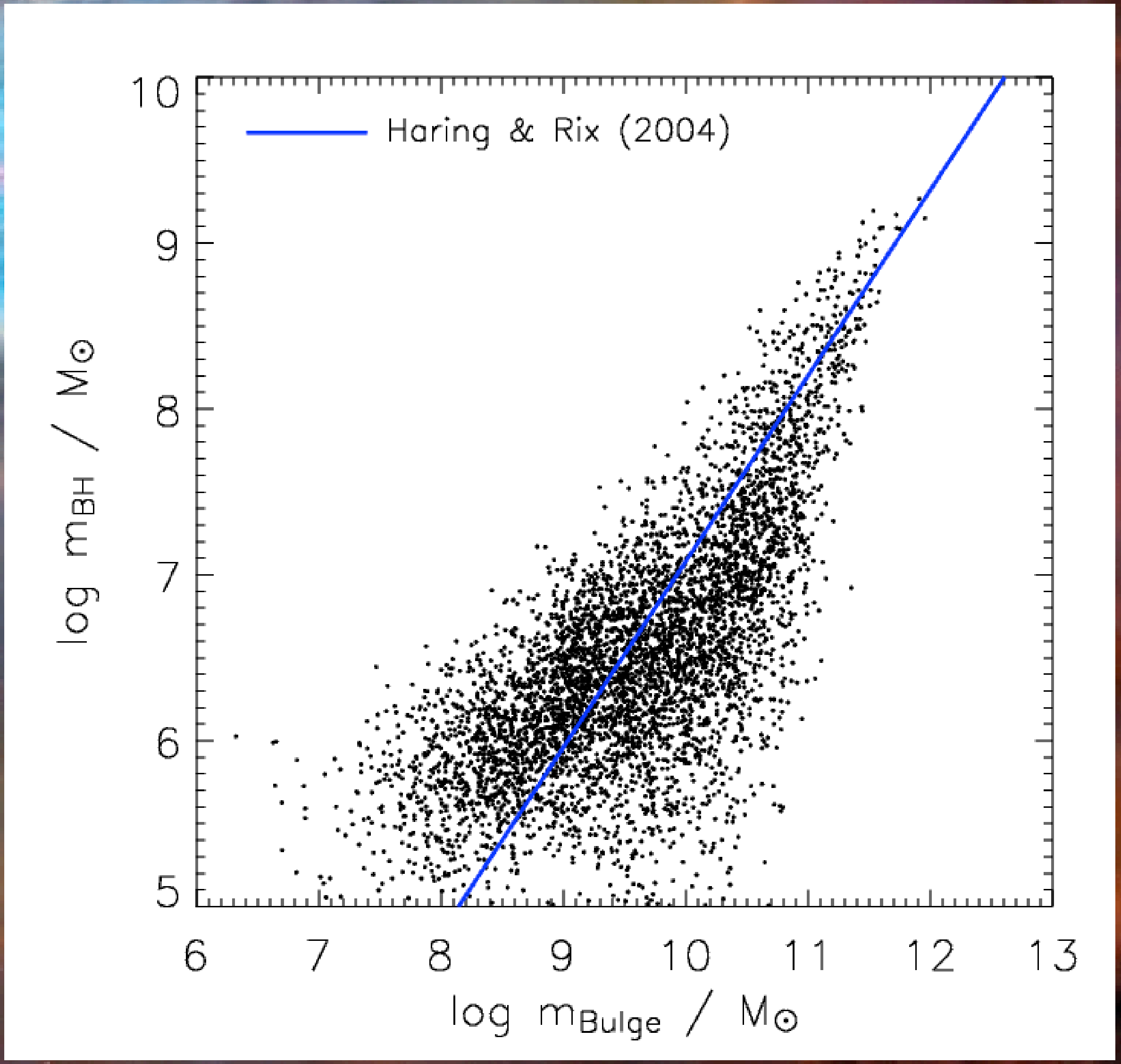
The quasar mode dominates the BH mass history

Black Hole Population

Black hole-bulge mass relation



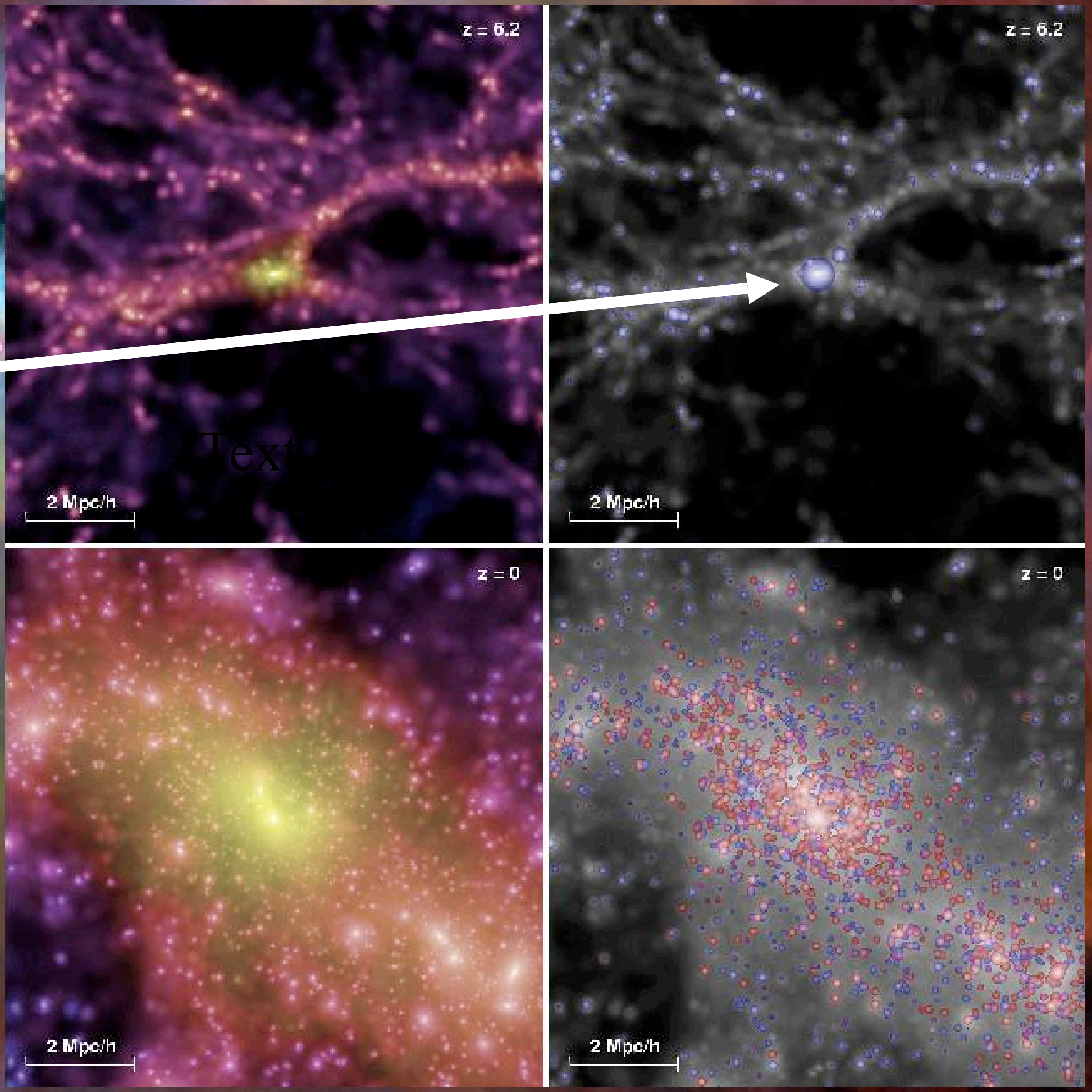
(Haring & Rix 2004)



Black Hole Growth

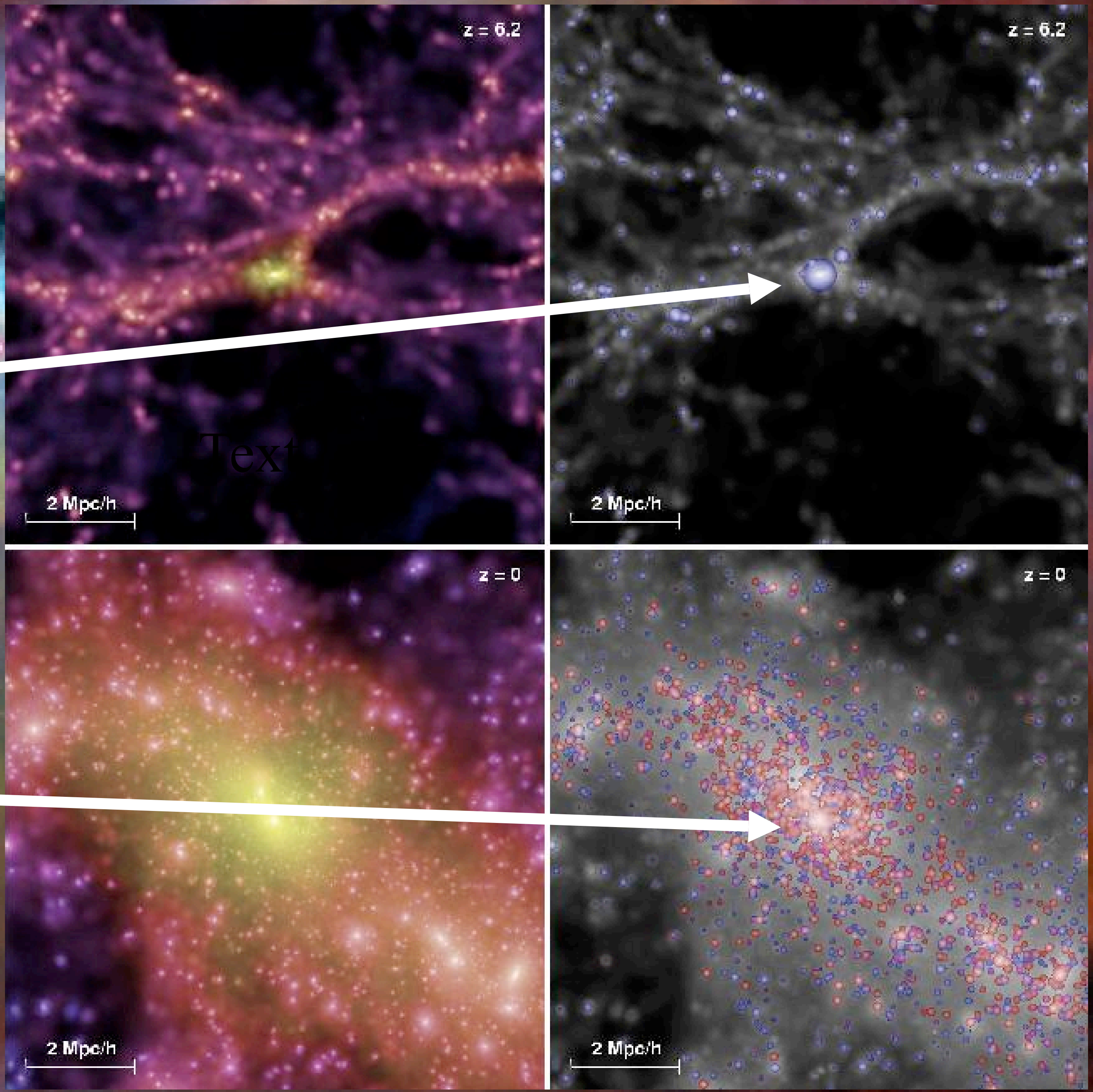
The sites of high redshift quasars (quasar mode)

$z = 6$:
SFR > 500 M_{sun}/yr
$M_{BH} \sim 10^{8.5\text{-}9}\ M_{sun}$
$M_{gal} \sim 10^{10}\ M_{sun}$
$M_{vir} \sim 10^{12}\ M_{sun}$



Black Hole Growth

The sites of high redshift quasars (quasar mode)

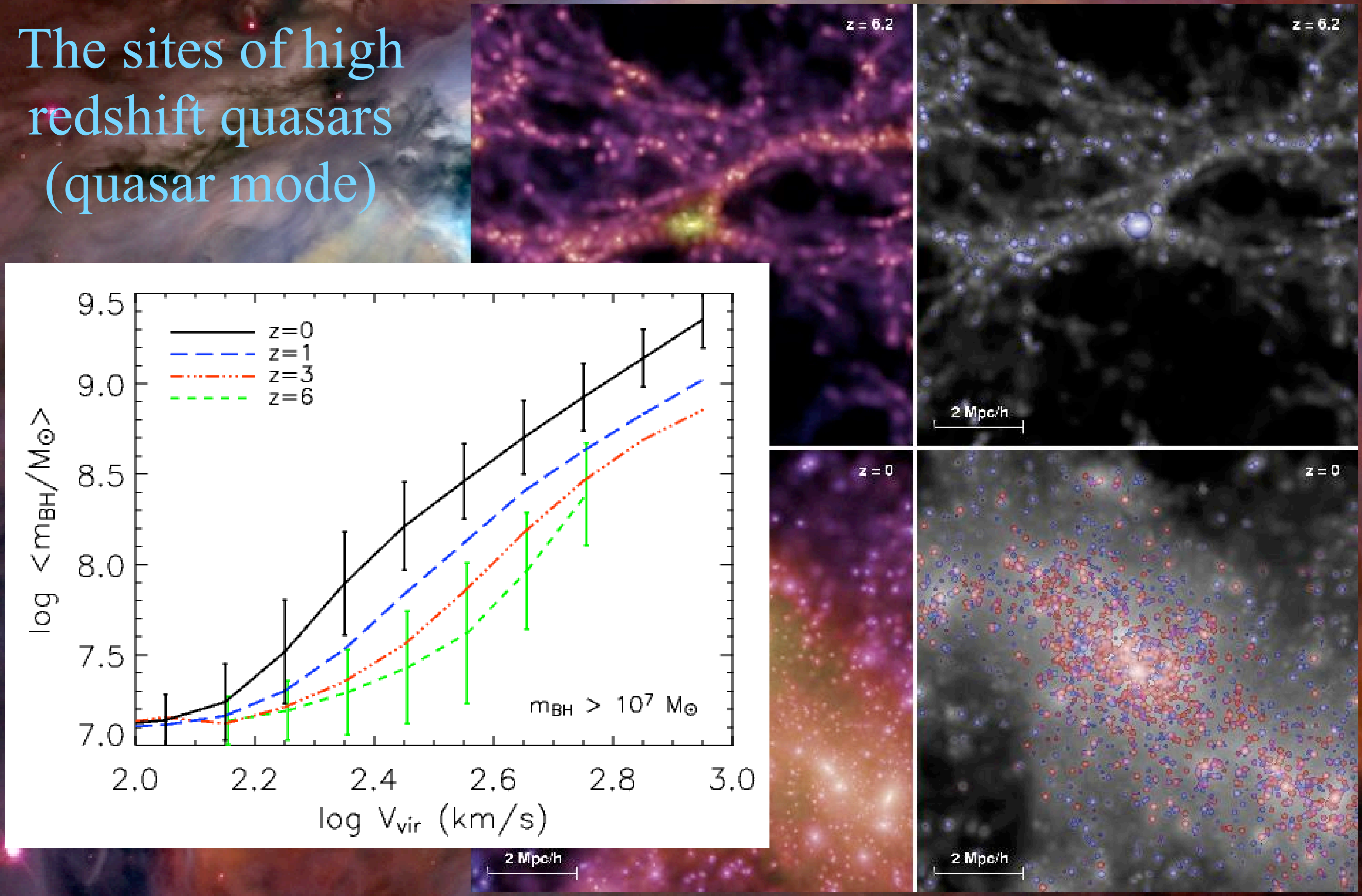


$z = 6$:
SFR > 500 M_{sun}/yr
$M_{BH} \sim 10^{8.5\text{-}9}\ M_{sun}$
$M_{gal} \sim 10^{10}\ M_{sun}$
$M_{vir} \sim 10^{12}\ M_{sun}$

$z = 0$:
SFR ~ zero
$M_{BH} \sim 5\text{x}10^{9}\ M_{sun}$
$M_{gal} \sim 10^{12}\ M_{sun}$
$M_{vir} \sim 10^{15}\ M_{sun}$

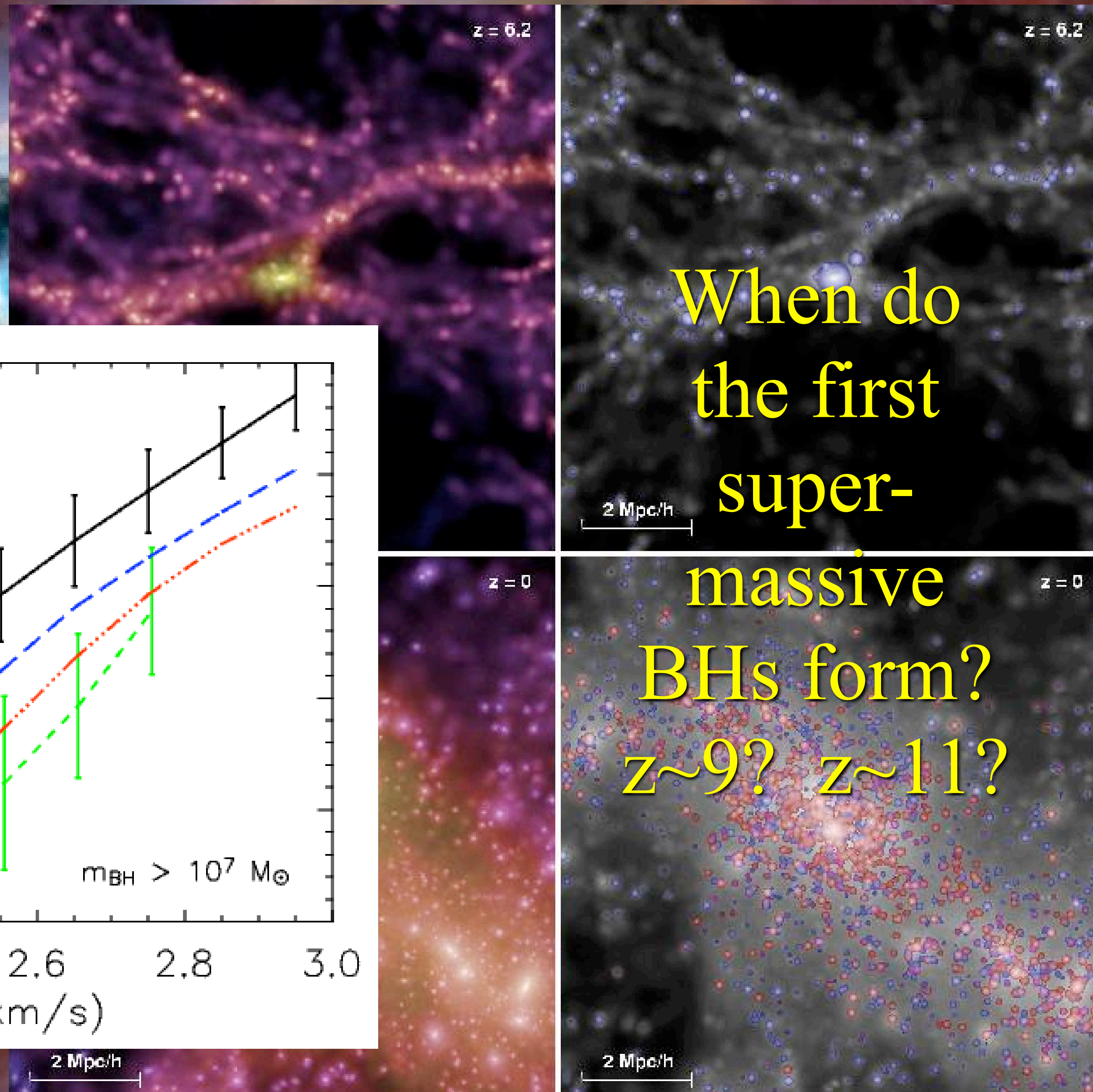
Black Hole Growth

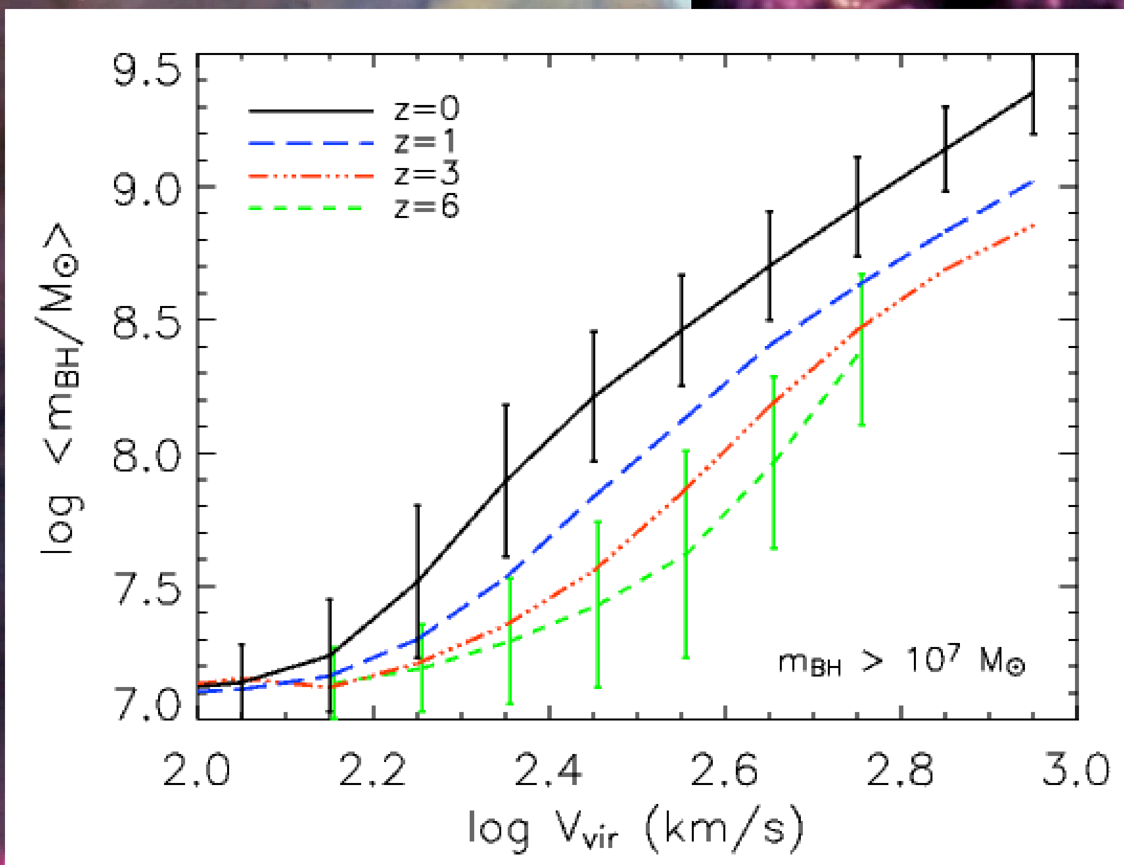
The sites of high redshift quasars (quasar mode)



Black Hole Growth

The sites of high redshift quasars (quasar mode)

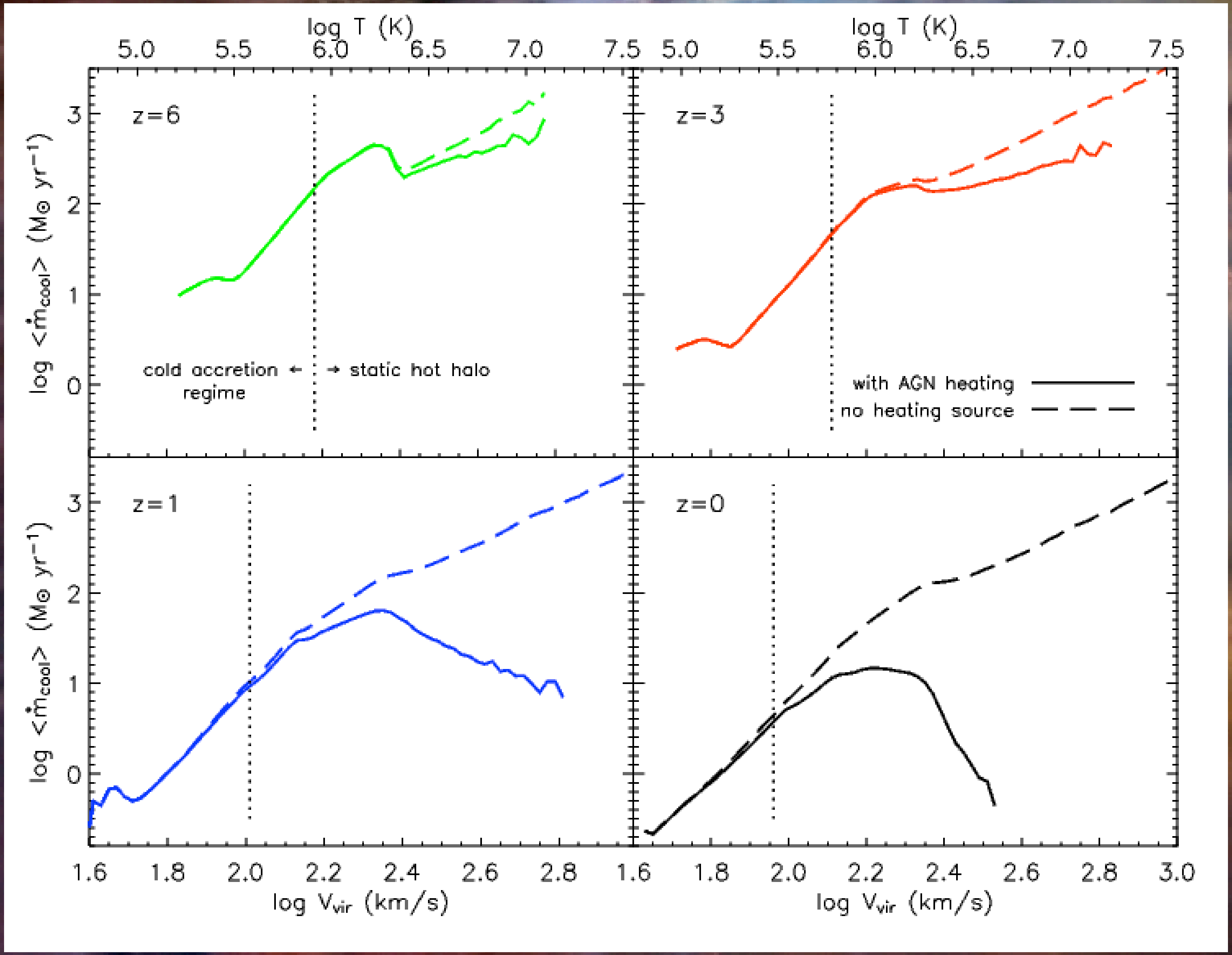




When do the first super-massive BHs form? z~9? z~11?

AGN and Galaxy Properties

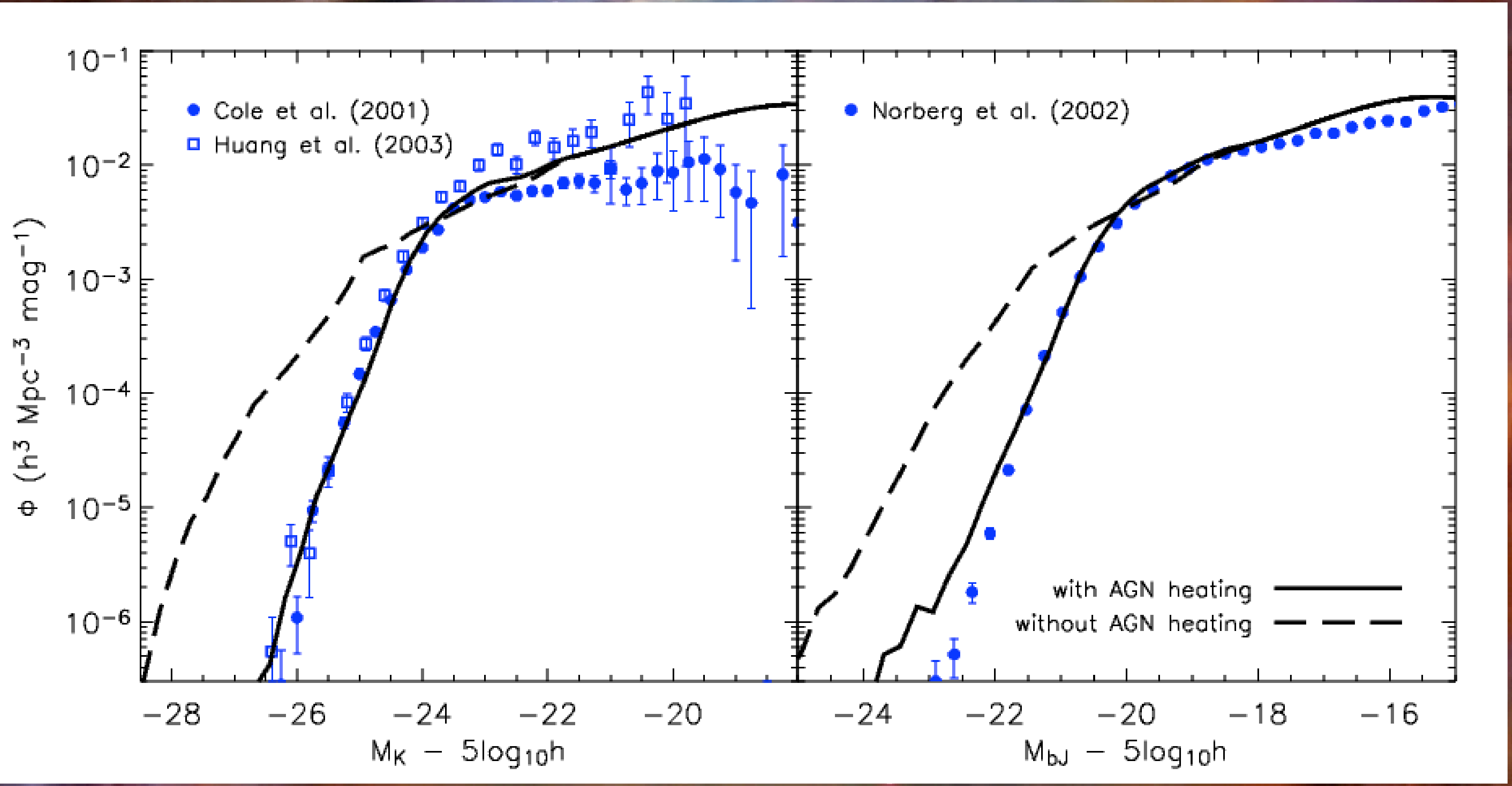
Radio Mode "Quenching"



Suppression of cooling gas

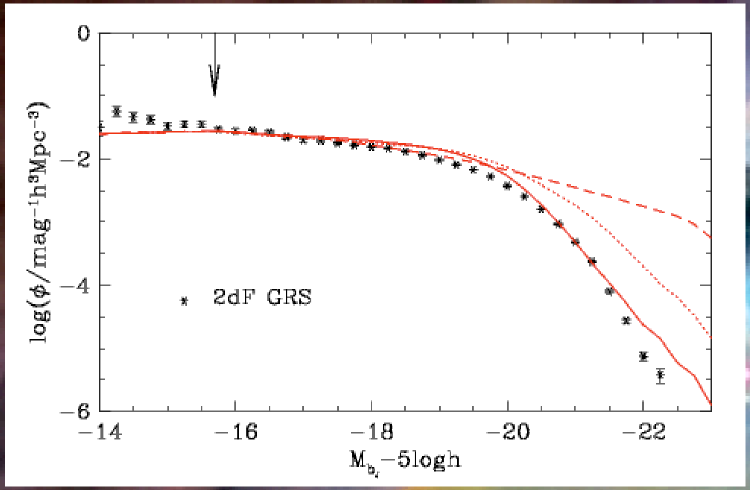
Cooling flow suppression is most efficient in massive halos and at late times

Luminosity Functions



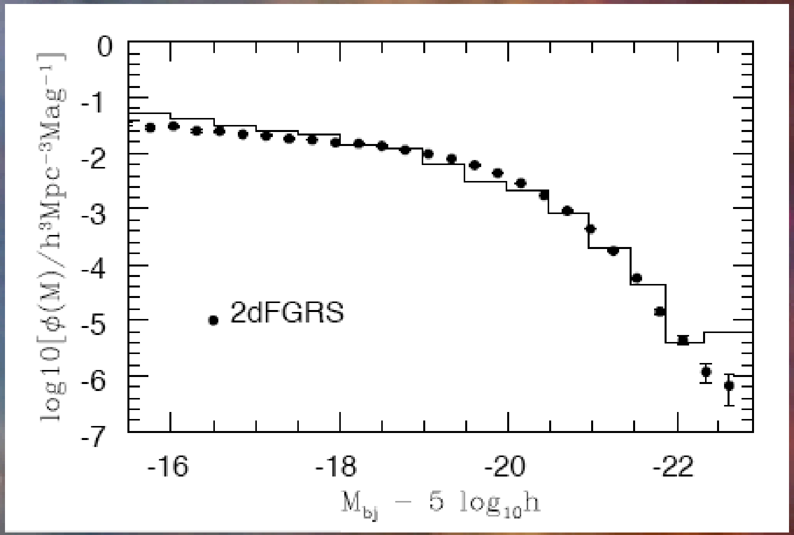
The K and bJ-band luminosity functions with and without AGN

Luminosity Functions

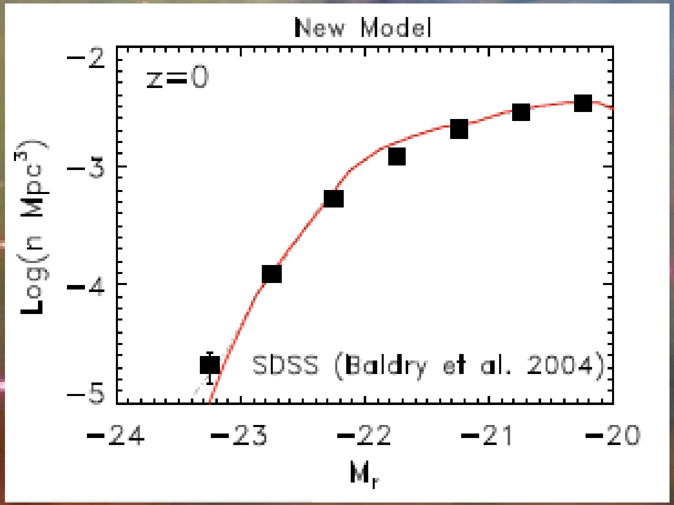


Bower et al. 2005
(astro-ph/0511338)

Kang et al. 2006
(astro-ph/0601685)



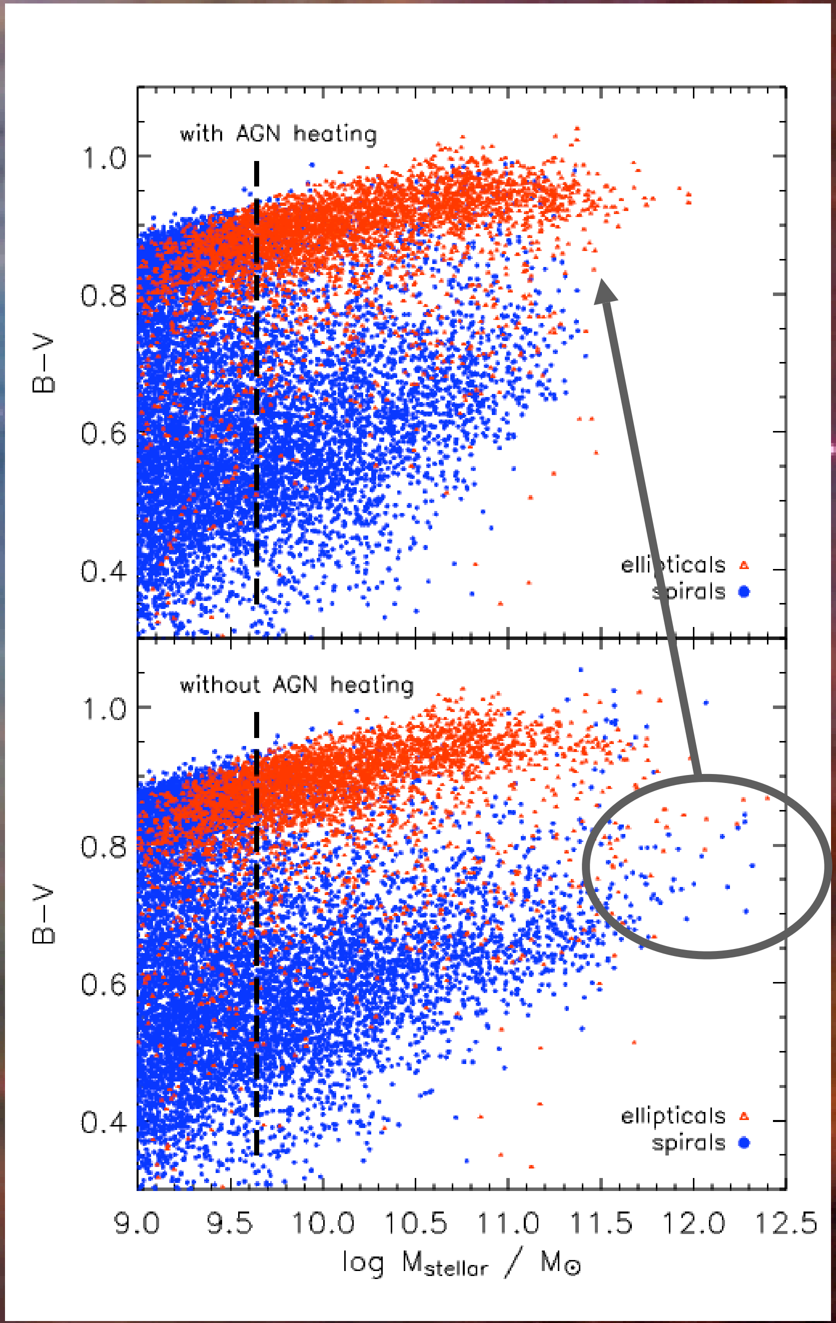
Cattaneo et al. 2006
(astro-ph/0601295)



Most model agree - the effect of AGN appears to be a generic result

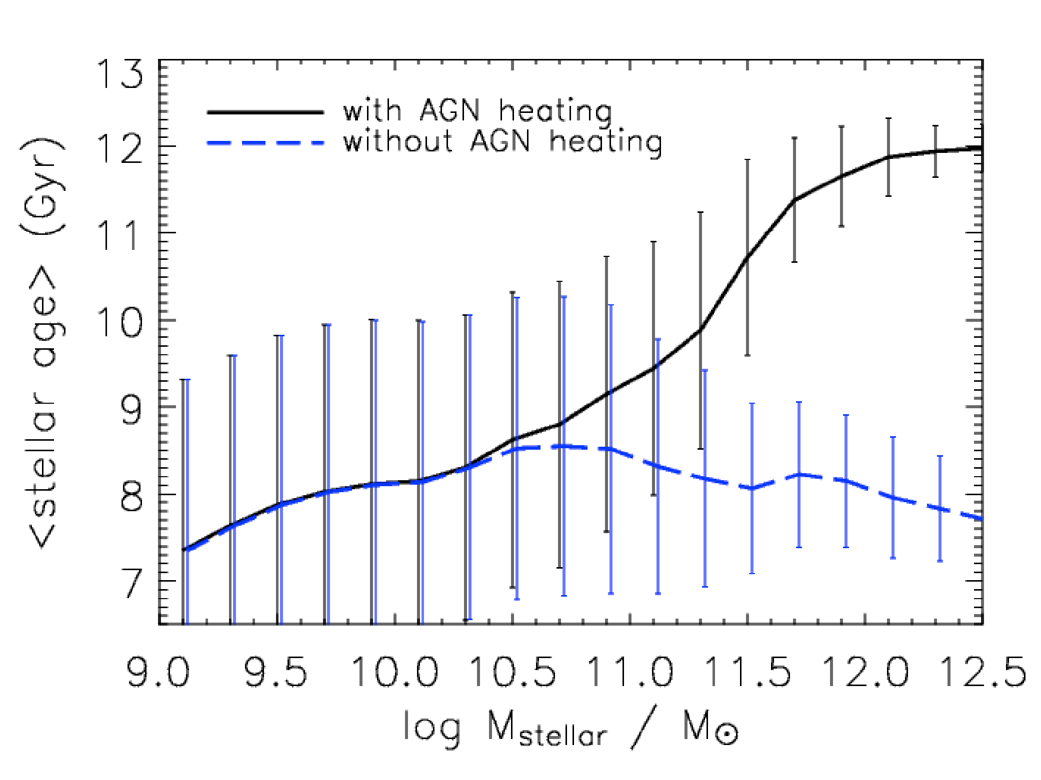
Galaxy Colours and Ages

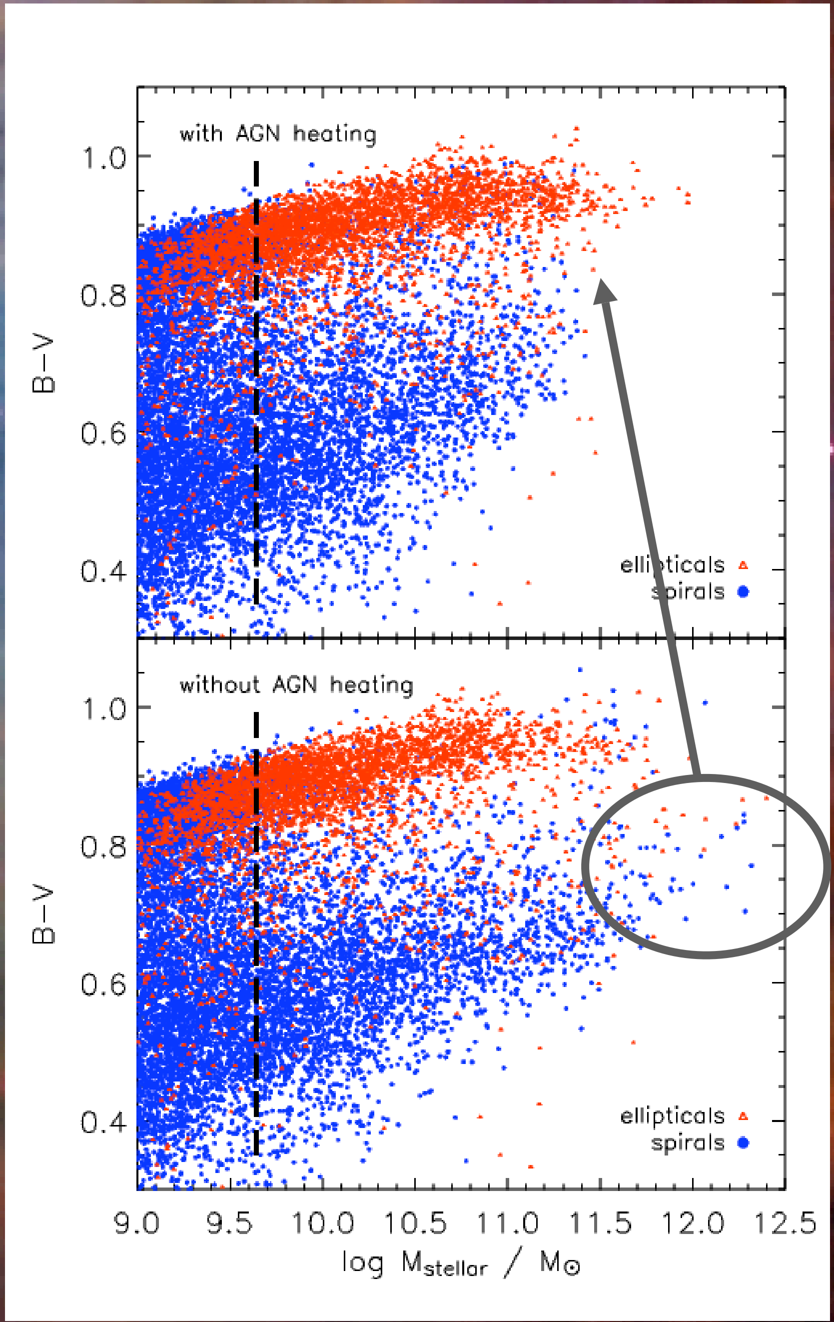
B-V colour bi-modality



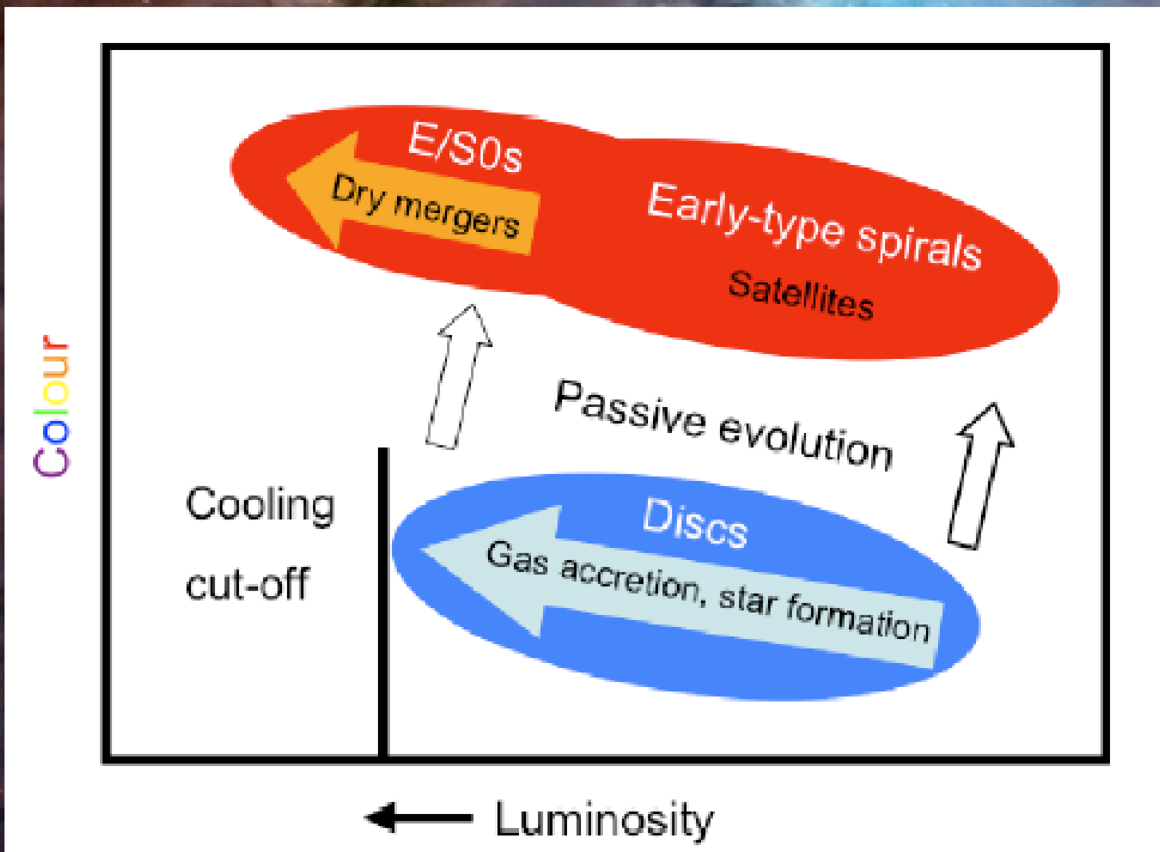
Galaxy Colours and Ages

B-V colour bi-modality and mean stellar age

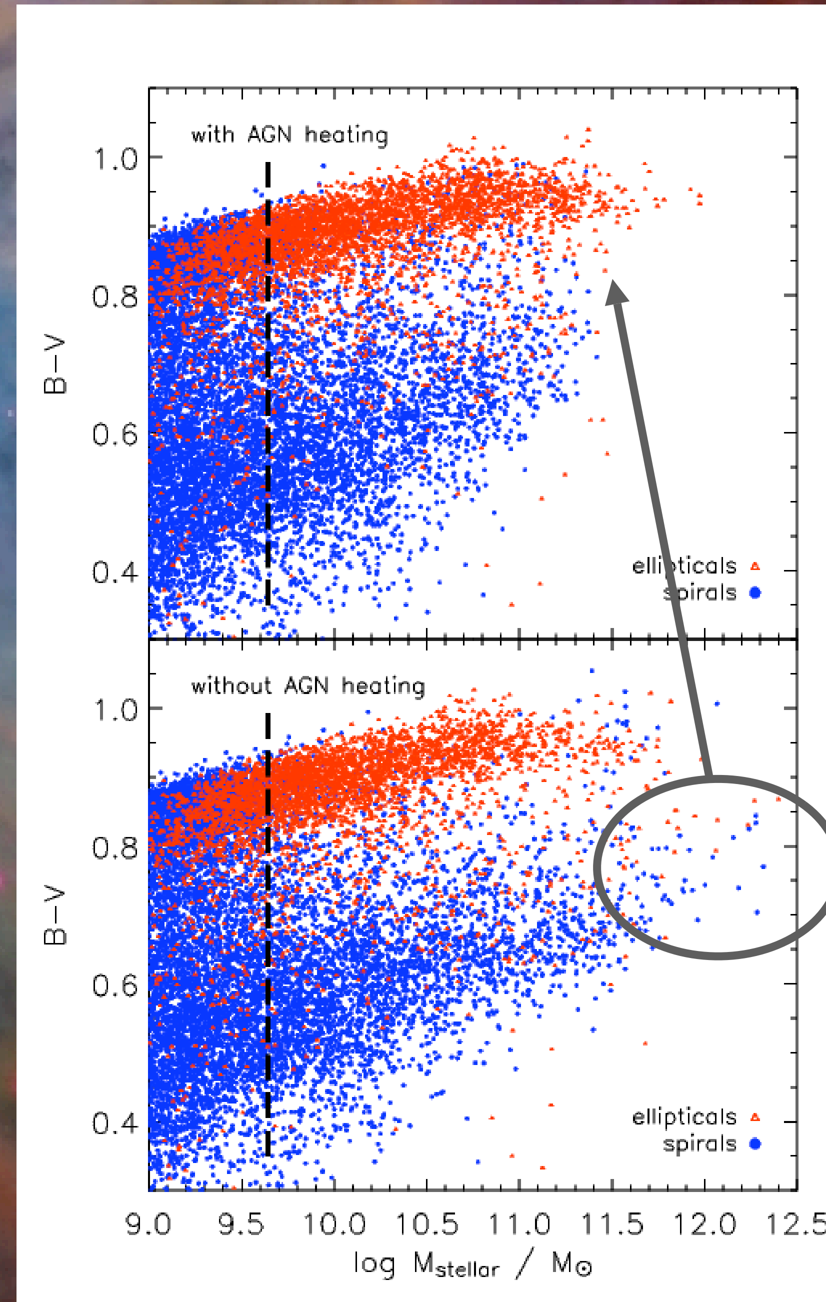




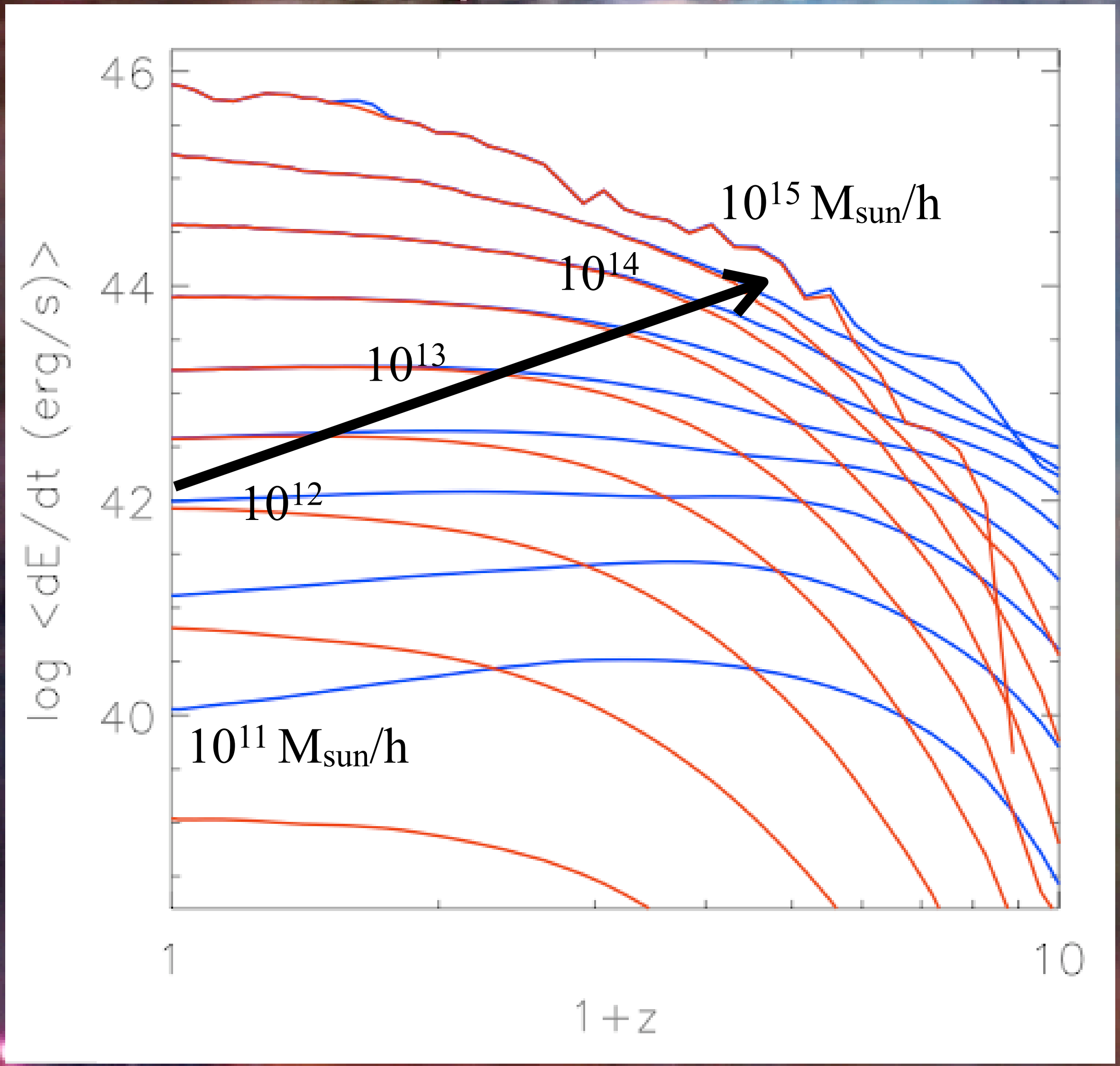
Galaxy Colours and Ages



Cattaneo et al. 2006



Quenching vs. Halo Mass



Cooling Rates
vs.
Heating Rates

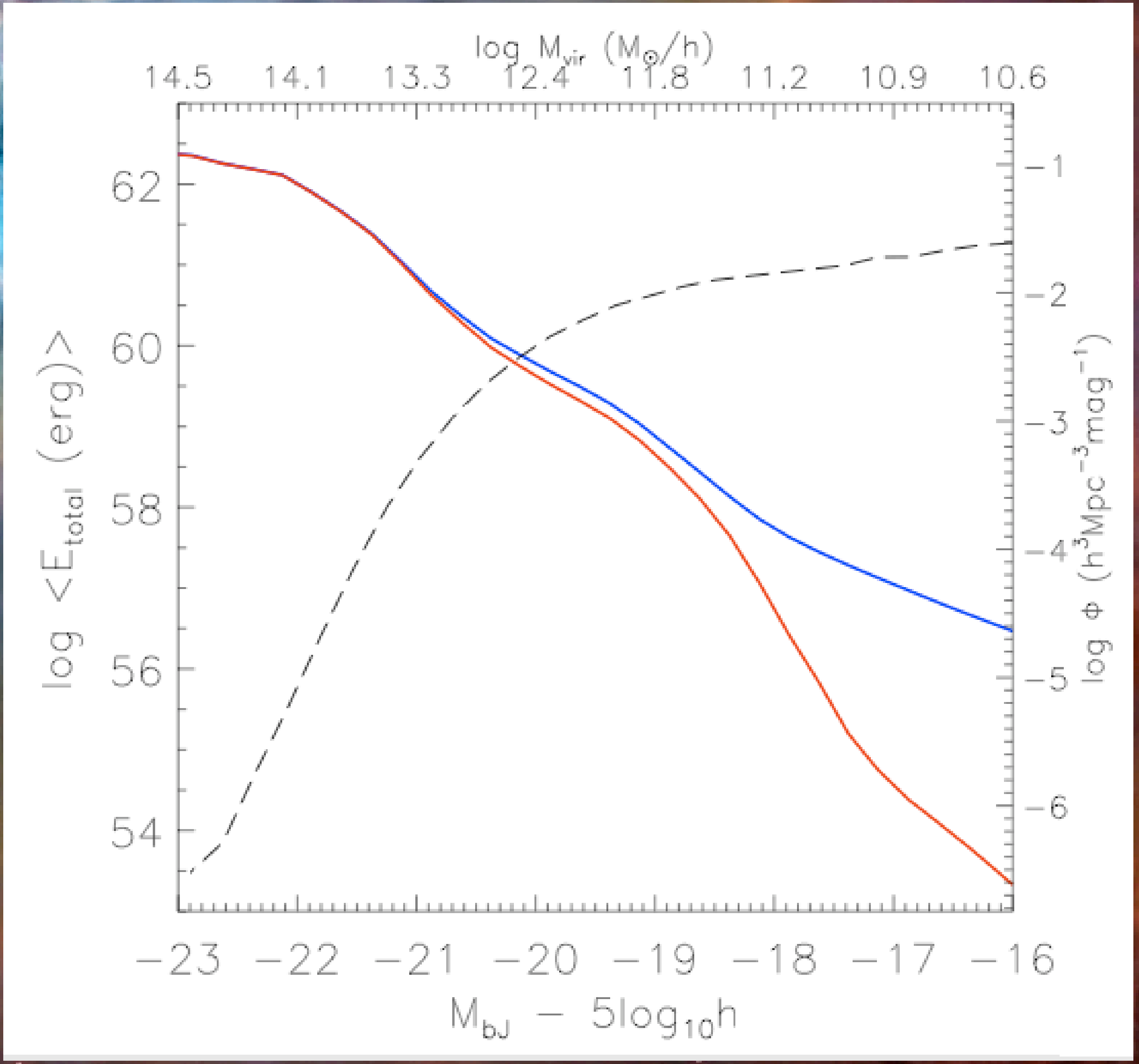
currently $M_{vir} \sim 10^{12} M_{sun}/h$ halos are initiating quenching

Energy Considerations

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

LF knee corresponds to:

$E_{cool} \sim E_{heat}$
$M_{bJ} \sim -19 .. -20$
$M_{vir} \sim 10^{11.5\text{-}12.5} M_{sun}/h$



Why Does Such Heating Work?

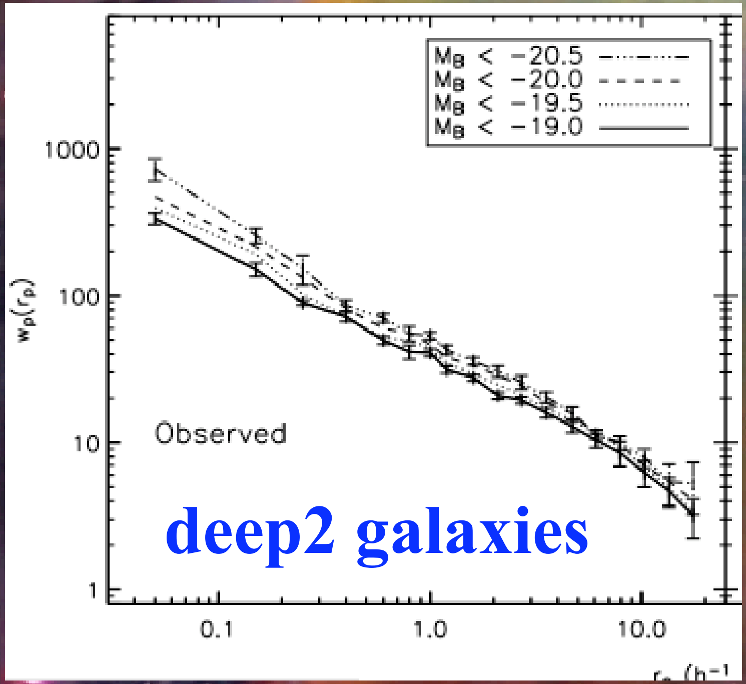
- Unlike other heating mechanisms (e.g. super-winds, starbursts, ...), AGN heating suppresses star formation without itself requiring star formation to efficiently operate.

- 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!).

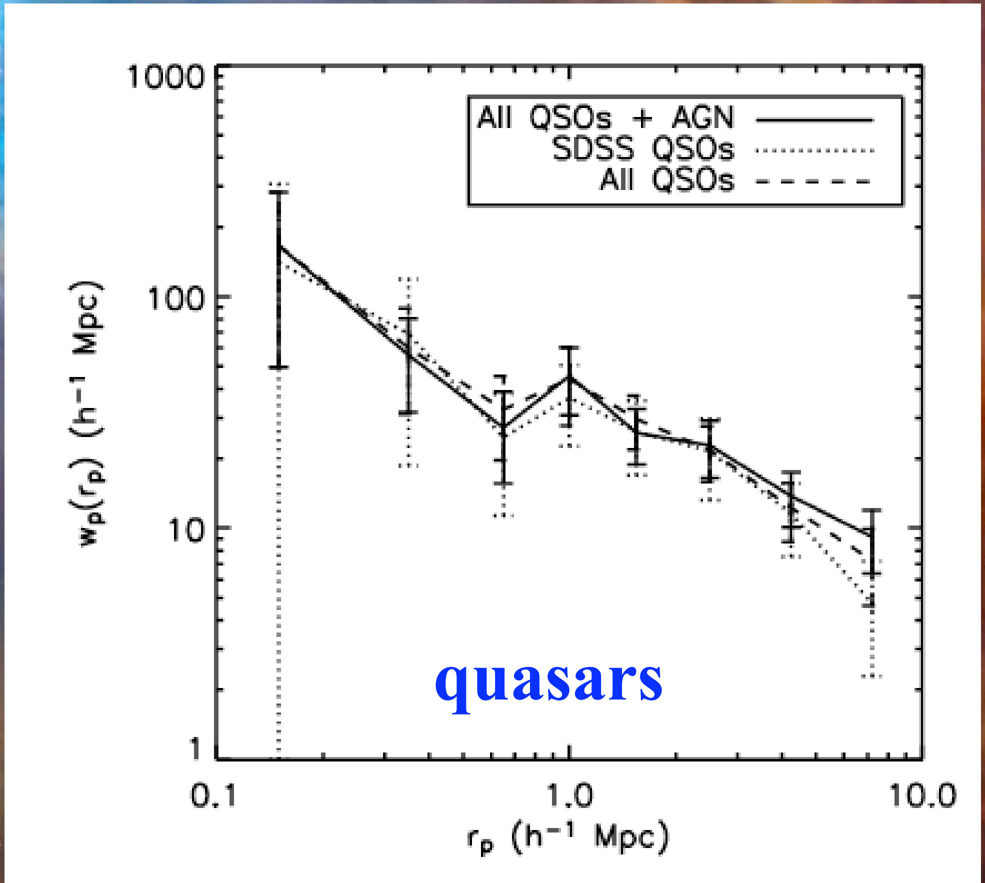
An AGN-like low energy heating source, fed from the hot x-ray halo, is an energetically feasible candidate

AGN in the EGS at z~1

Clustering of DEEP2 galaxies around SDSS QSOs at z=0.7-1.4.



36 SDSS + 16 DEEP2 spectroscopic QSOs



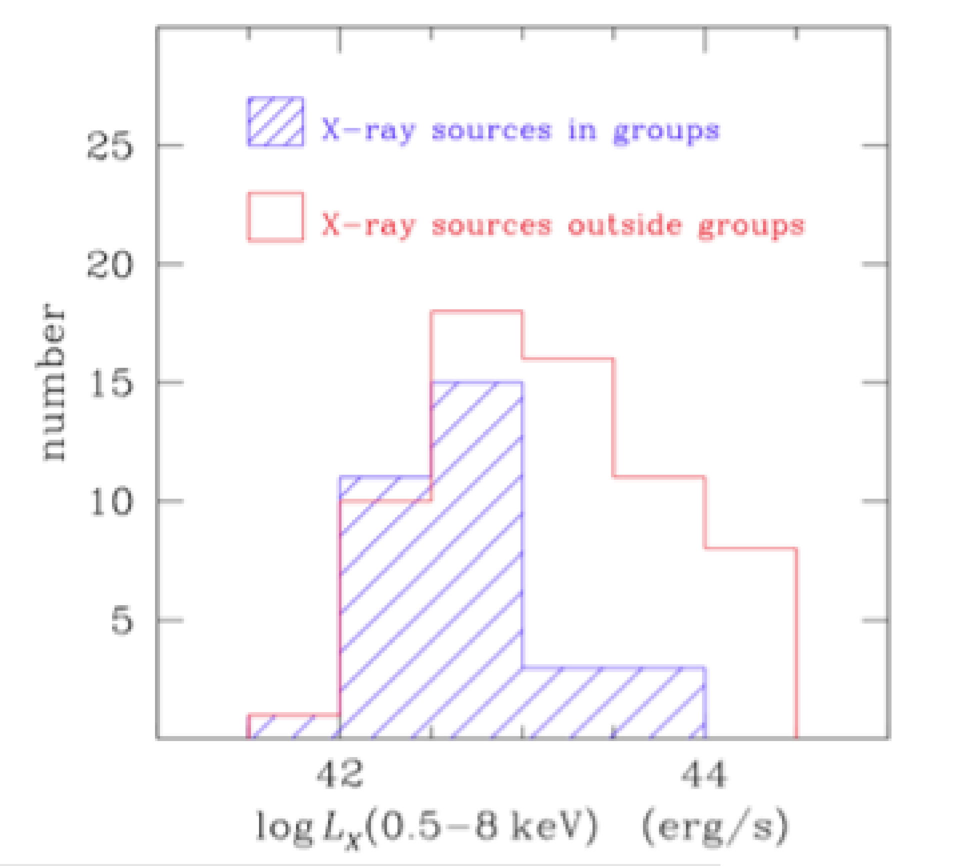
Coil et al. 2006 (AJ submitted)

AGN in the EGS at z~1

Field AGN are more luminous

Denser environments host quieter AGN

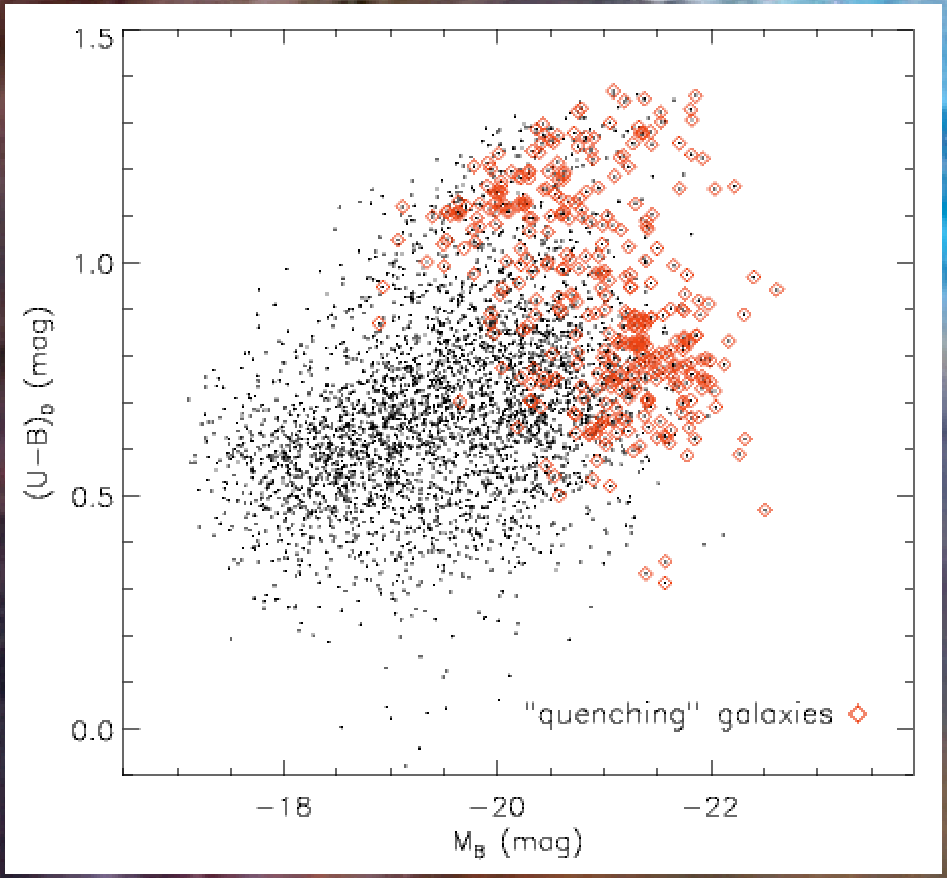
NANDRA ET AL. (IN PREP.)

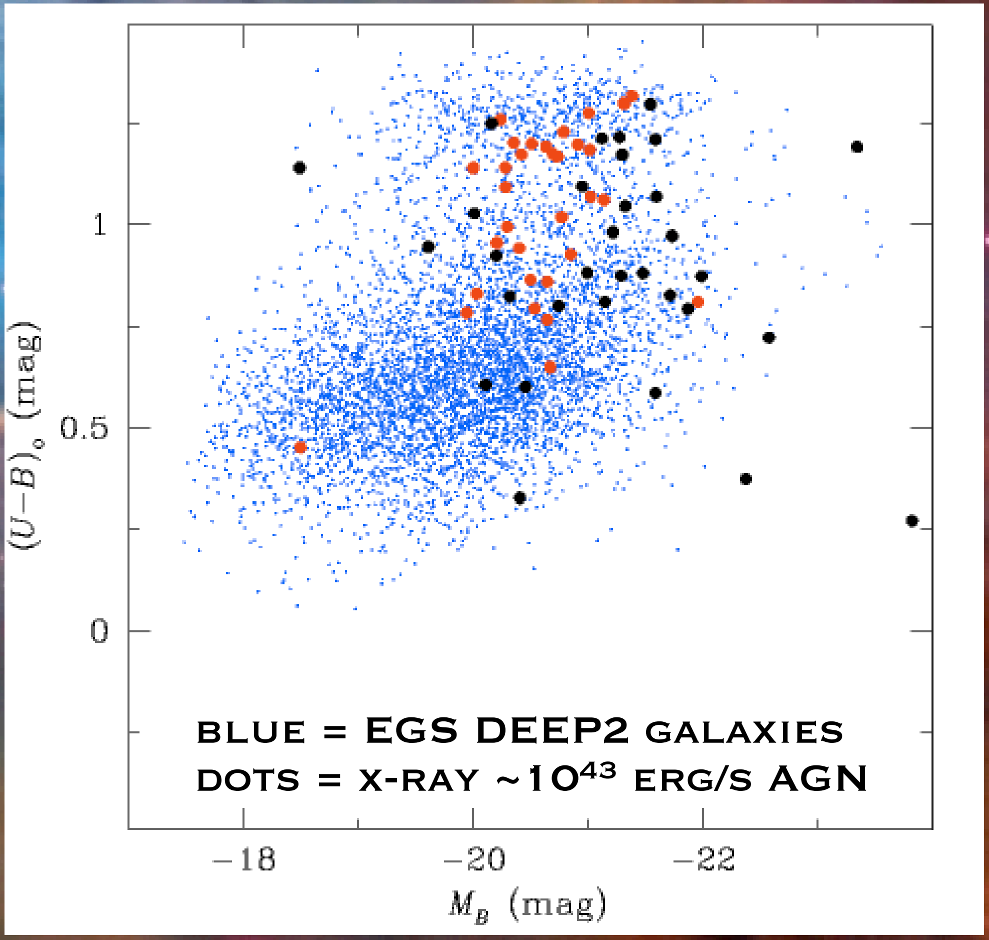


Chandra x-ray AGN in the EGS

AGN in the EGS at z~1

NANDRA ET AL. (IN PREP.)





DEEP2 semi-analytic mock

Chandra x-ray AGN in the EGS

A Consistent Picture?

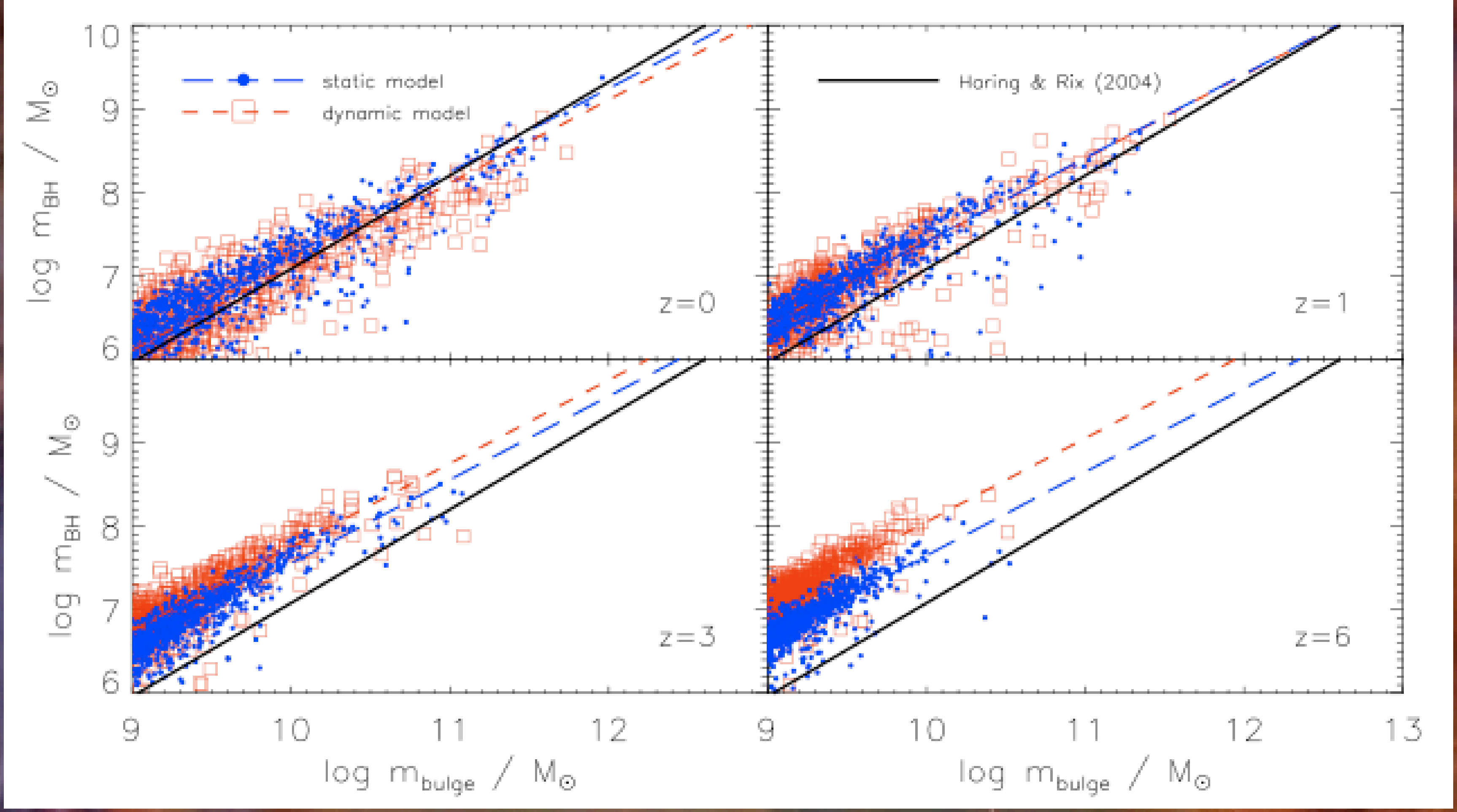
Star formation "quenching" occurs from lower energy heating in group and cluster systems

For quasars to shine they need mergers + cold gas

This is what we're starting to see at z~1

BH-bulge Mass Evolution

BH-bulge Mass Evolution



Can we isolate the source of this evolution?

DC astro-ph/0512375

BH-bulge Mass Evolution

$$\frac{\textbf{BLACK HOLE MASS}}{\textbf{BULGE MASS}}$$

BH-bulge Mass Evolution

Progenitor BHs

BLACK HOLE MASS

BULGE MASS

Progenitor bulges

BH-bulge Mass Evolution

Cold gas accretion (~m_{cold})

Progenitor BHs

BLACK HOLE MASS

BULGE MASS

Starburst (~m_{cold})

Progenitor bulges

BH-bulge Mass Evolution

?

Cold gas accretion (~m_{cold})

Progenitor BHs

BLACK HOLE MASS

BULGE MASS

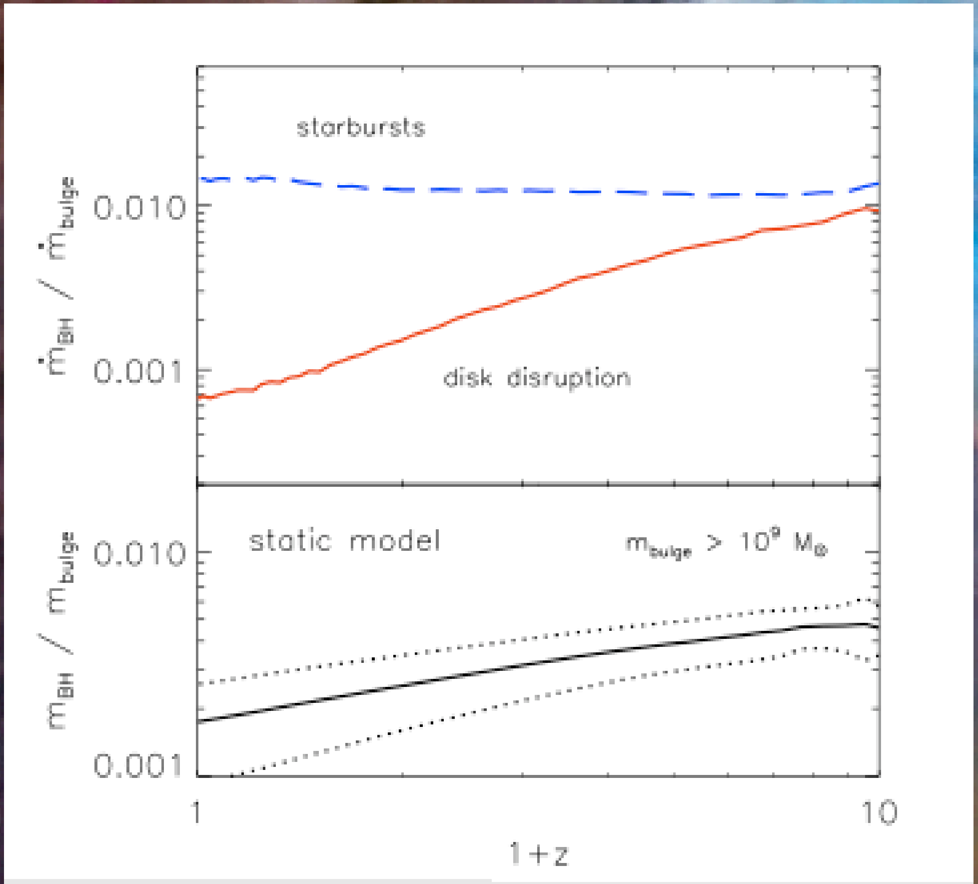
Starburst (~m_{cold})

Progenitor bulges

Disrupted disks

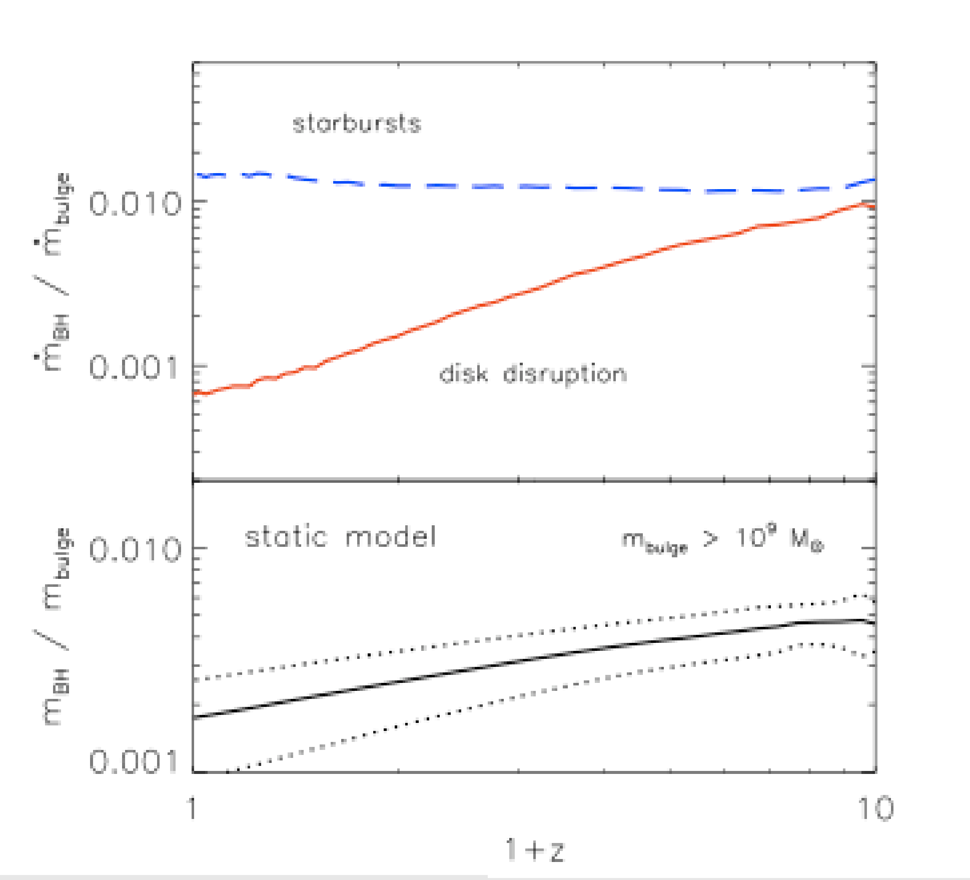
BH-bulge Mass Evolution

Considering the ratio of the growth rates:



BH-bulge Mass Evolution

Considering the ratio of the growth rates:



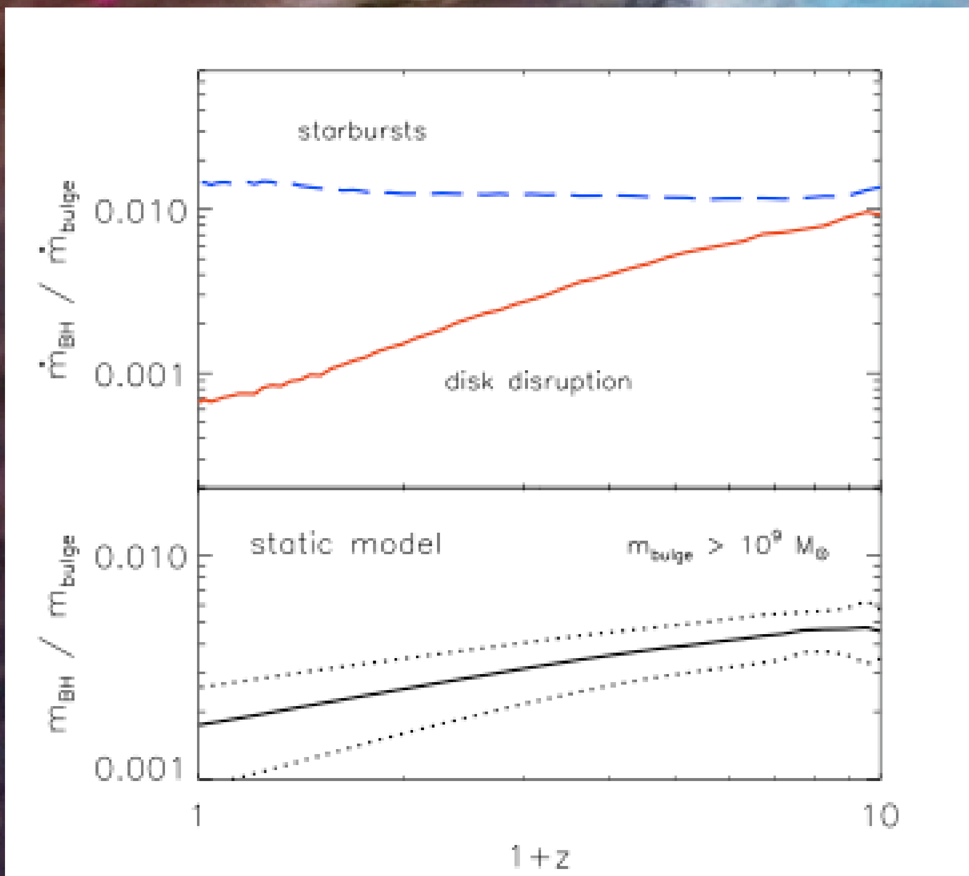
Why?

Madau plot: star formation increases until z~1 -> galaxy disks

LCDM: merger rate increases until low redshift … disks -> bulges

BH-bulge Mass Evolution

Considering the ratio of the growth rates:



Why?

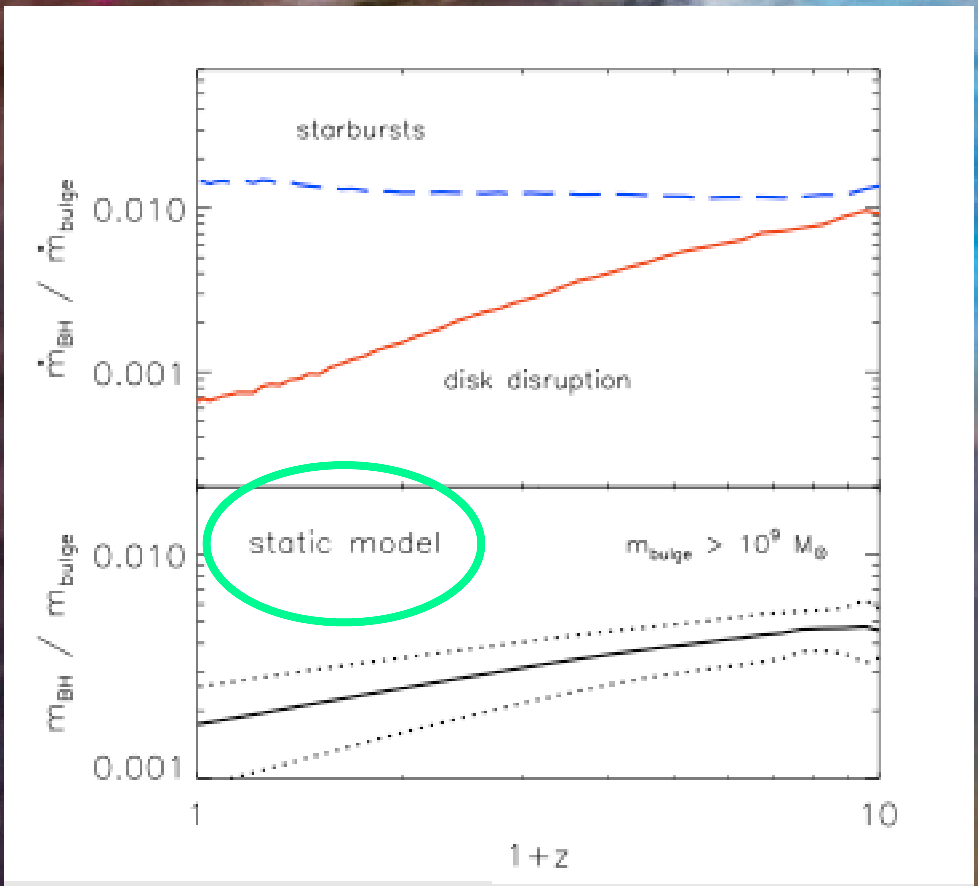
Madau plot: star formation increases until z~1 -> galaxy disks

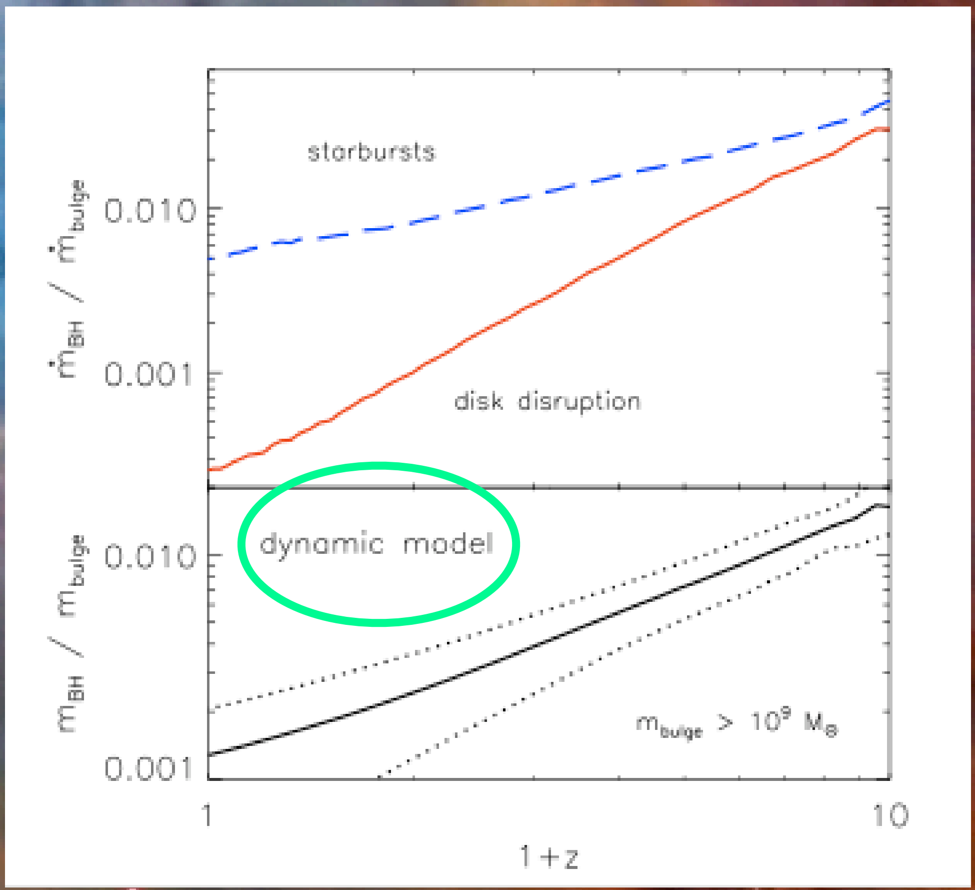
LCDM: merger rate increases until low redshift … disks -> bulges

If mergers are the primary triggers of BH and bulge growth, then disrupted disks can drive evolution in the BH-bulge mass relation

BH-bulge Mass Evolution

Considering the ratio of the growth rates:





A dynamic model, where BH accretion evolves as (1+z), displays much stronger evolution.

Conclusions

Addition of simple black hole accretion to the semi-analytic model:

- Energetically feasible, very sub-Eddington accretion
- Significantly changes massive galaxy evolution:
  - bright-end luminosity function cut off and shape
  - bright-end colours and mean stellar ages
  - *keeps galaxies on the red sequence*
- Predicts z~1 suppression of star formation in group and cluster sized systems.
- Evolution in bulge growth from disrupted disks can drive evolution in the black hole mass-bulge mass relation.

Such modelling is now allowing us to study galaxy assembly, and quasar and radio populations, from low to high redshift

A lot being done, a lot to be done ....

Ongoing projects:

Brainerd et al: dynamics masses of satellites
Brown et al: clustering of high z red sequence galaxies
Conroy et al: high z satellite galaxies
Crawford & Peacock: far-IR at z~2
Dominguez & Lambas: identifying galaxy groups
Eisenstein et al: colour-magnitude relation of LRGs
Peacock: baryon wiggles
Pearce et al: fossil groups
Prada et al: z=0 satellite galaxies and subhalo dynamics
Rudnick et al: stellar mass density evolution
Sales & Lambas: distribution and properties of satellite galaxies
Springel et al: the MR and high z quasars
Skibba & Sheth: HOD models and marked correlation functions
Weinmann & van den Bosch: HOD models and the SDSS
Zwaan et al: HI selected galaxy samples

DeLucia et al: elliptical galaxies
Kitzbichler et al: galaxies on the light cone
Lemson et al: the virtual observatory
Hayashi et al: arc statistics of strong lensing
Springel et al: RS and ISW effects
De Lucia et al: NGST high z predictions
Thacker et al: structure function of galaxies
Evrard et al: cluster resimulations + semianalytics
Moeller et al: galaxy envoronments & strong lensing
Bertone et al: chemical enrichment of ISM, IGM
Tissera et al: galaxy pairs and SDSS
Croton et al: AGN and cooling flows
Croton: BH-bulge evolution
Croton et al: the galaxy "Gao" effect
Croton et al: void galaxies at z~1 with DEEP2

~9 million galaxies, $1.25\times10^{8}\,Mpc^{3}/h^{-3}$, ugriz (SDSS) or BVRIK, $M_B<-16.4$

http://www.mpa-garching.mpg.de/galform/agnpaper

The many lives of AGN:
from super-massive black holes to host galaxy colours and luminosies

Darren Croton

Simon White,Volker Springel, et al.
+ the DEEP2 and AEGIS collaborations

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Max Planck Institute for Astrophysics, Garching

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