Simulating the Evolution of the Large-scale Distribution of Galaxies and Quasars

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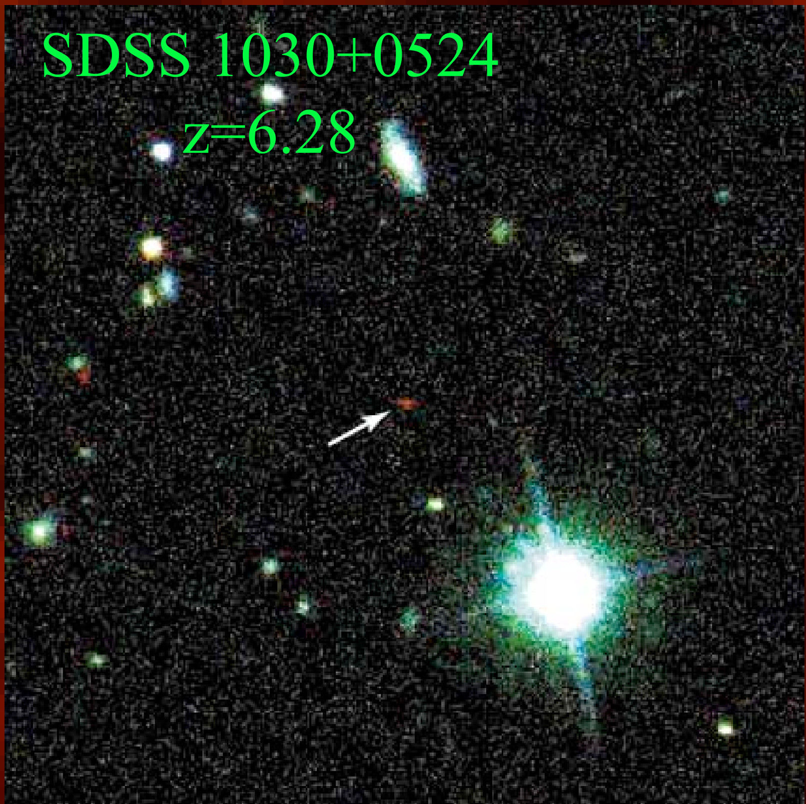
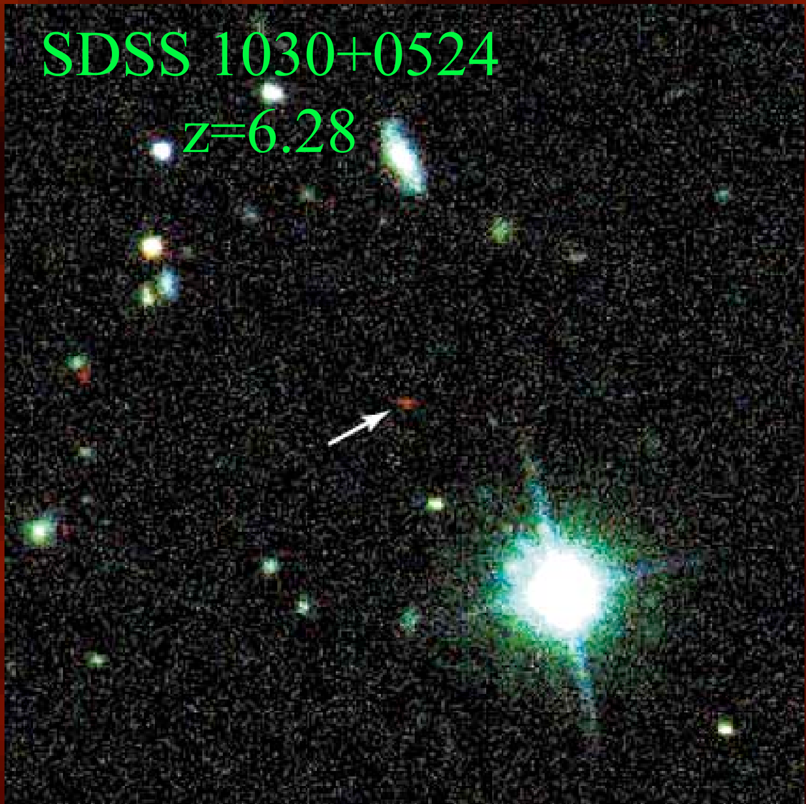
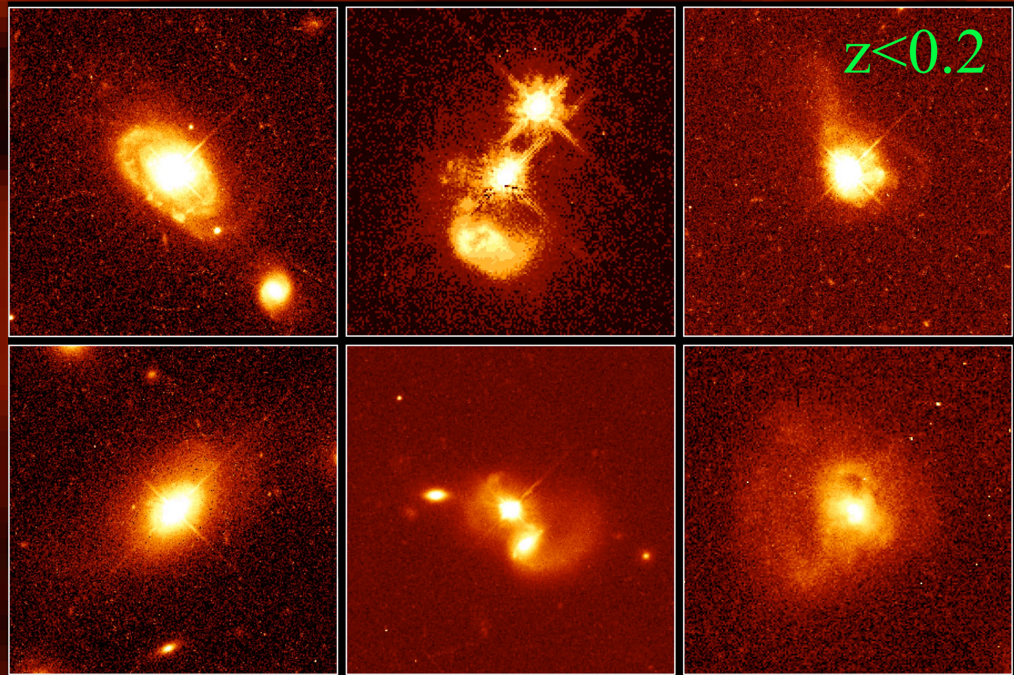
Motivation



High redshift quasars … where did they come from?

Motivation



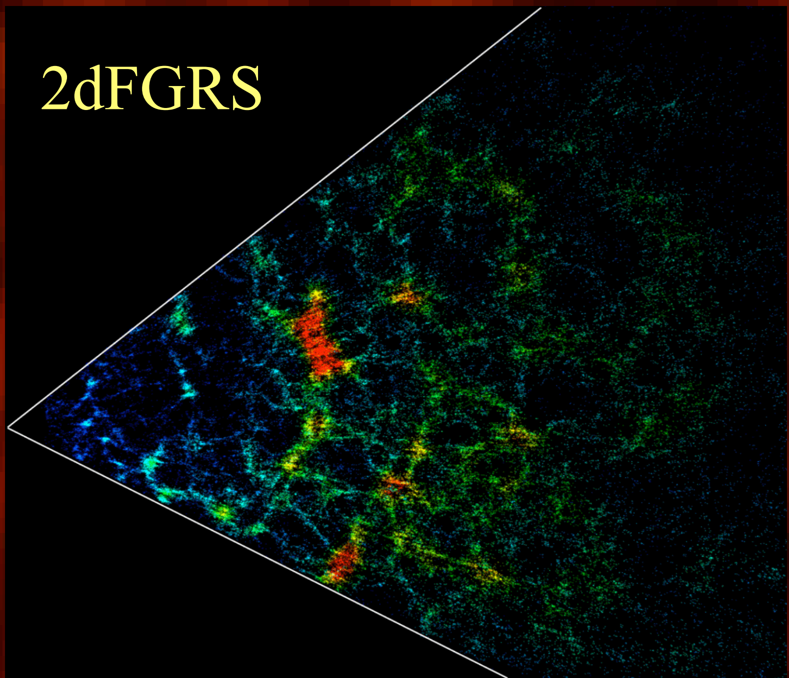


Hubble Space Telescope

High redshift quasars … where did they come from?
… and where are they today?

Motivation

… and how do they shape the properties of galaxies observed today?



e.g. the "over-cooling" problem (Fabian 1992)

Motivation

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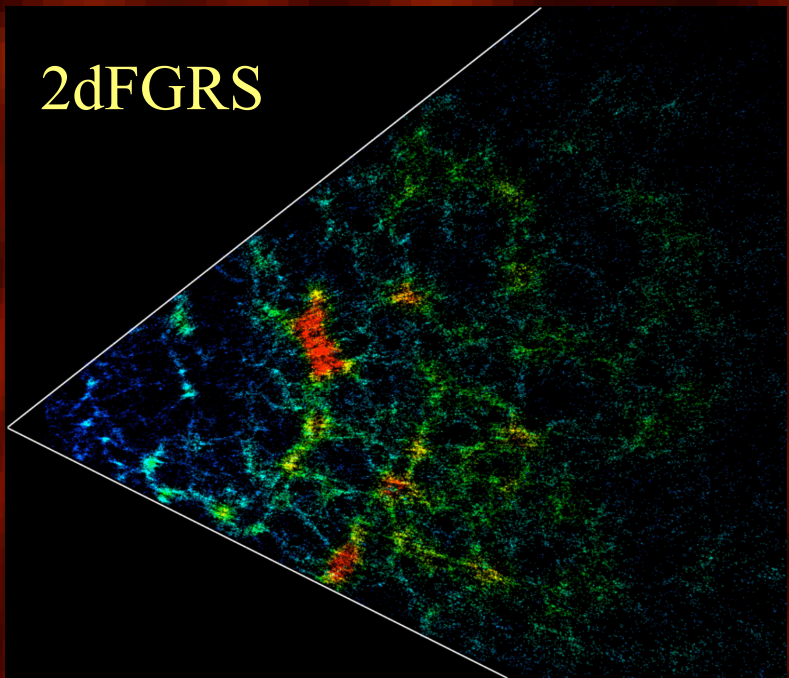

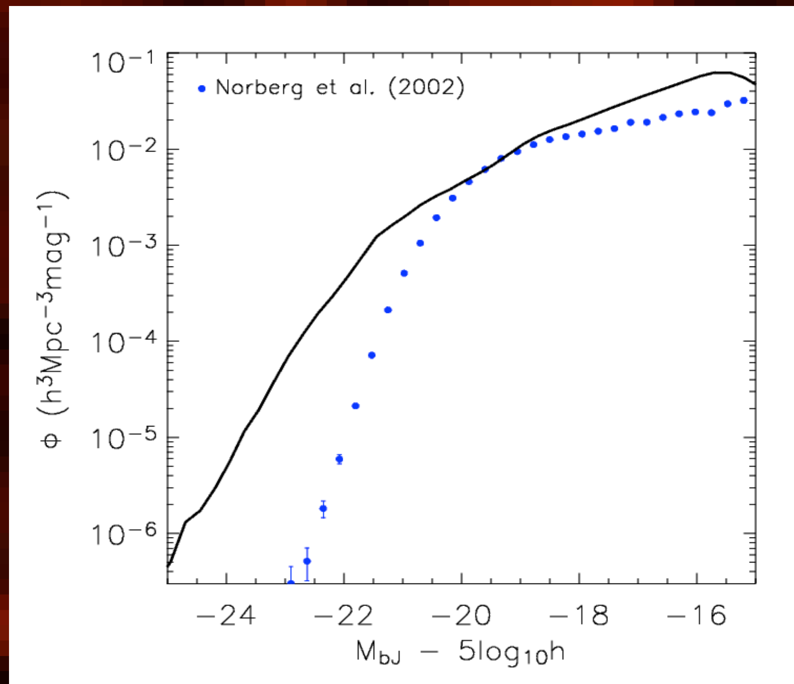

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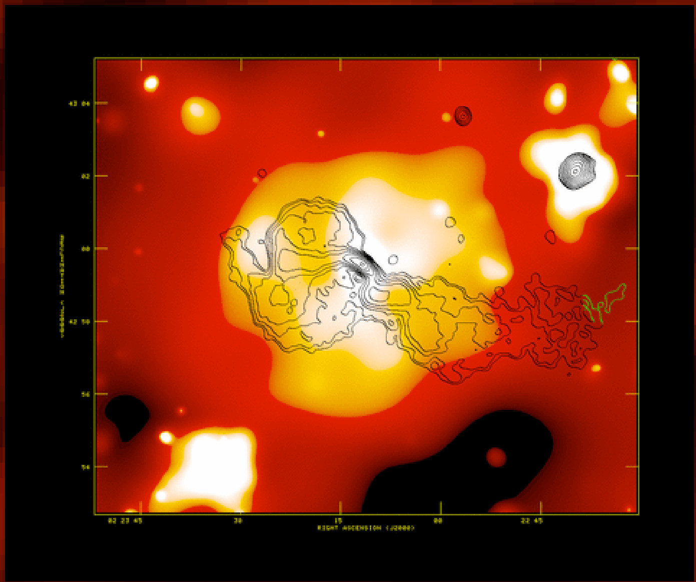
Aims



- Are massive high z quasars plausible in a simple model of black hole growth?
- Can we suppress cooling flows in an energetically feasible way?
- How does AGN feedback influence the final properties of the galaxy population?

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

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)

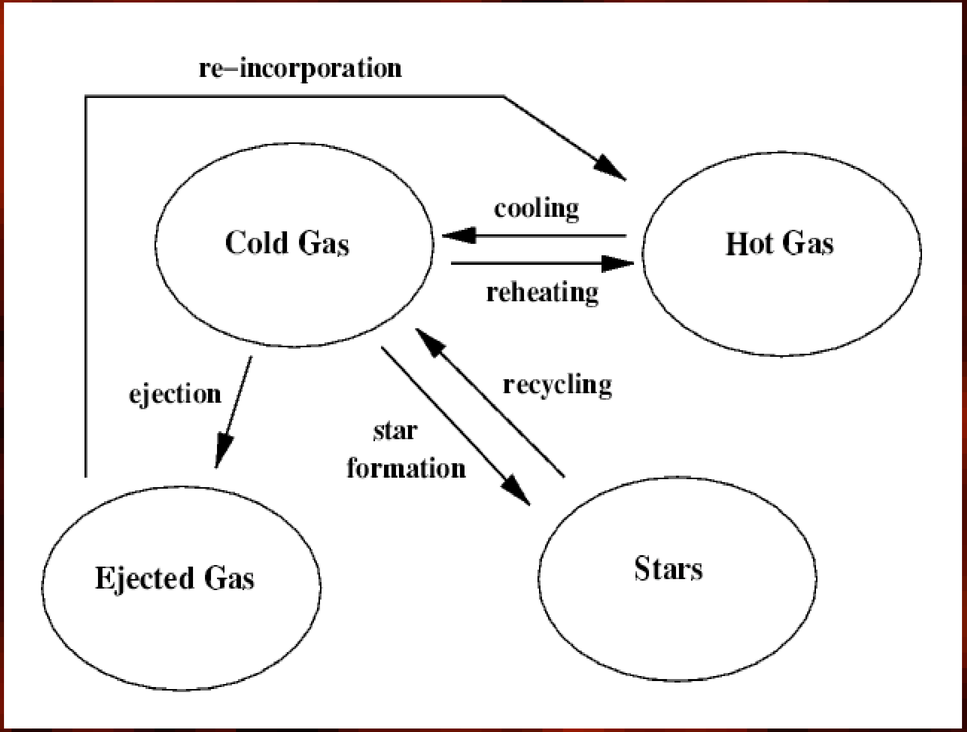
The Millennium Run's resolution is such that all galaxies more massive than the LMC can be resolved in a volume comparable to 2dFGRS and SDSS.

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



(Springel et al. 2002; De Lucia et al. 2004)

Models of Black Hole Growth

1st: the “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.

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

$$f'_{\mathrm{BH}} = f_{\mathrm{BH}}\ (m_{\mathrm{sat}}/m_{\mathrm{central}})$$

This is the primary mode of black hole growth

(Kauffmann & Haeanelt 2000)

Models of Black Hole Growth

2nd: the “radio” mode:

Models of Black Hole Growth

Bondi-Hoyle black hole accretion

(Bondi 1952)

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

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

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

** maximal cooling flow ** =>

$$\frac{r_{\rm Bondi}}{V_{\rm vir}} = \frac{2{\rm G}m_{\rm BH}}{V_{\rm vir}^3} = \frac{3}{2}\frac{\bar{\mu}m_p kT}{\rho_g(r_{\rm Bondi})\Lambda(T,Z)}$$

$$\rho_0 = \rho_g(r_{\rm Bondi}) = \frac{3\mu m_p}{4{\rm G}}\frac{kT}{\Lambda}\frac{V_{\rm vir}^3}{m_{\rm BH}}$$

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

$$\dot{m}_{\rm Bondi} = 1.9\pi {\rm G}\mu m_p \frac{kT}{\Lambda} m_{\rm BH}$$

Models of Black Hole Growth

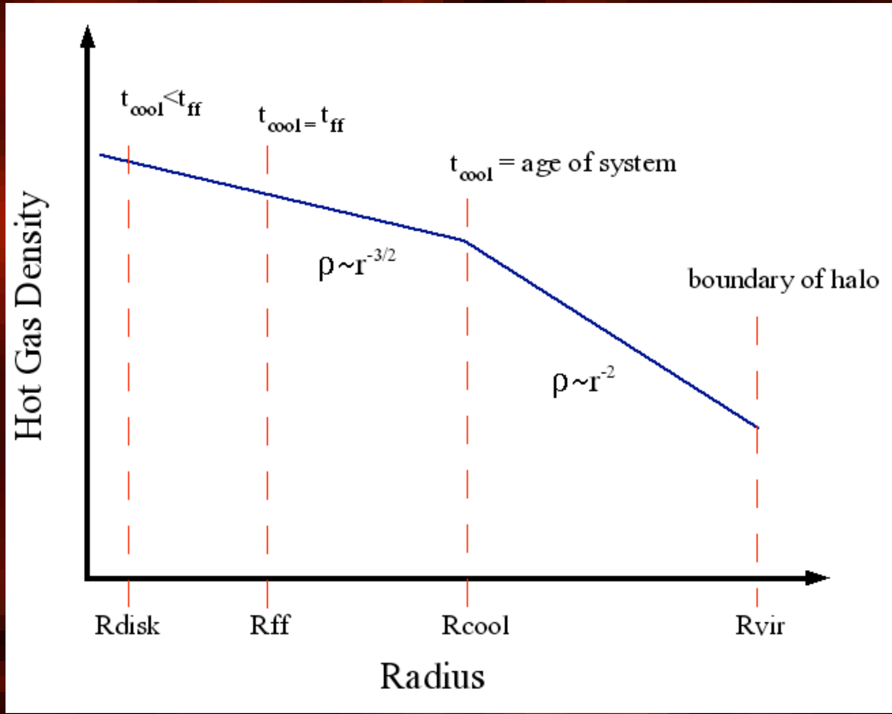
Cold clump black hole accretion

Gas flows inward at the cooling radius …

… and goes into free-fall when:

$$\frac{r_{\rm sonic}}{V_{\rm vir}} = \frac{3}{2}\frac{\bar{\mu} m_p k T}{\rho_g(r_{\rm sonic})\Lambda(T,Z)}$$

=> $$r_{\rm sonic} = \frac{1}{6\pi G \mu m_p}\frac{\Lambda}{kT}\frac{m_{\rm hot}}{M_{\rm vir}}V_{\rm vir}$$



When $r_{sonic} < 50 r_{disk}$ we accrete 0.01% (lower limit) of the cooling flow gas in cold clumps onto the BH

Models of Black Hole Growth

The "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

Models of Black Hole Growth

The "radio" mode:

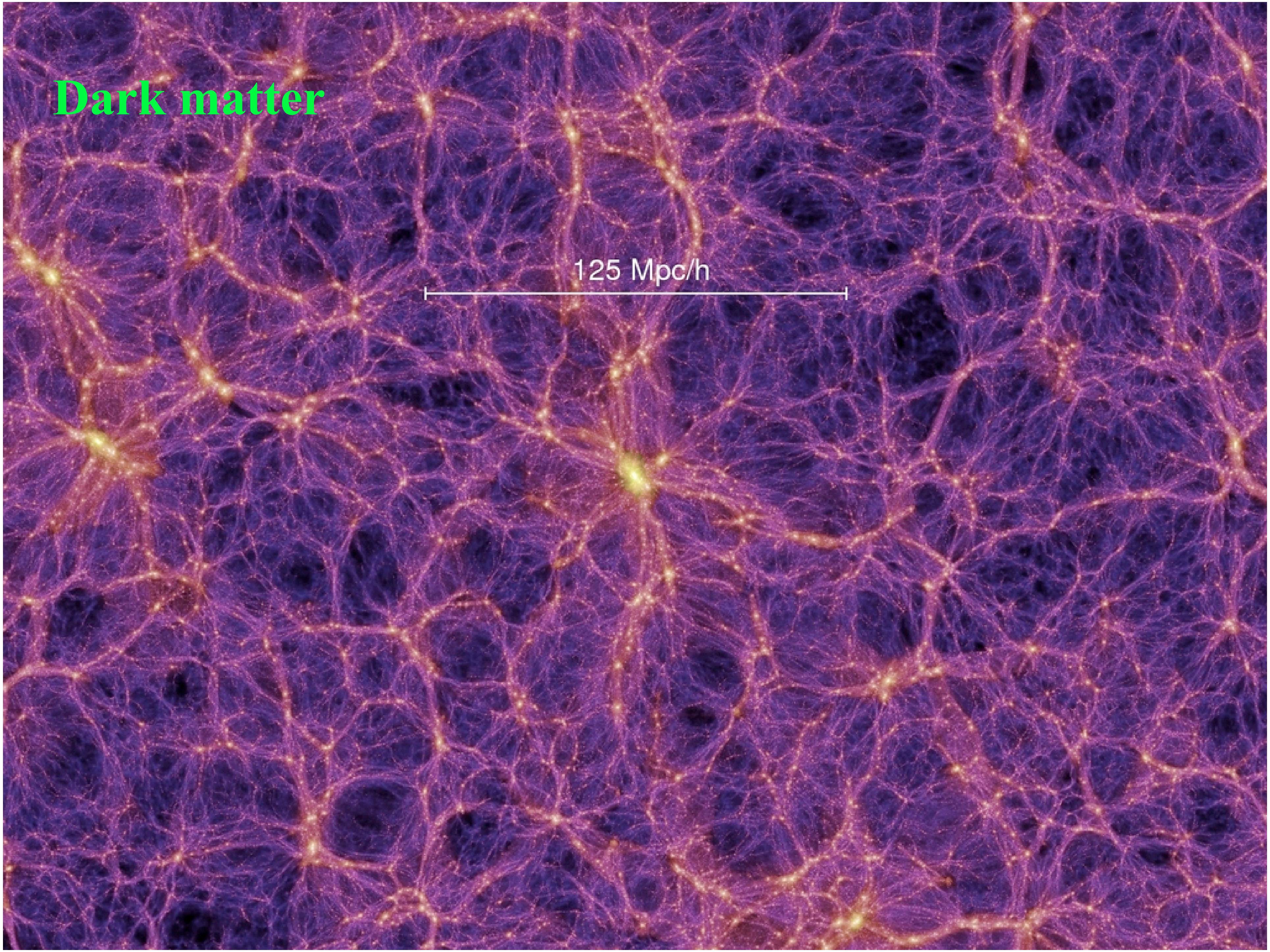
Such accretion leads to a low energy outflow from the black hole

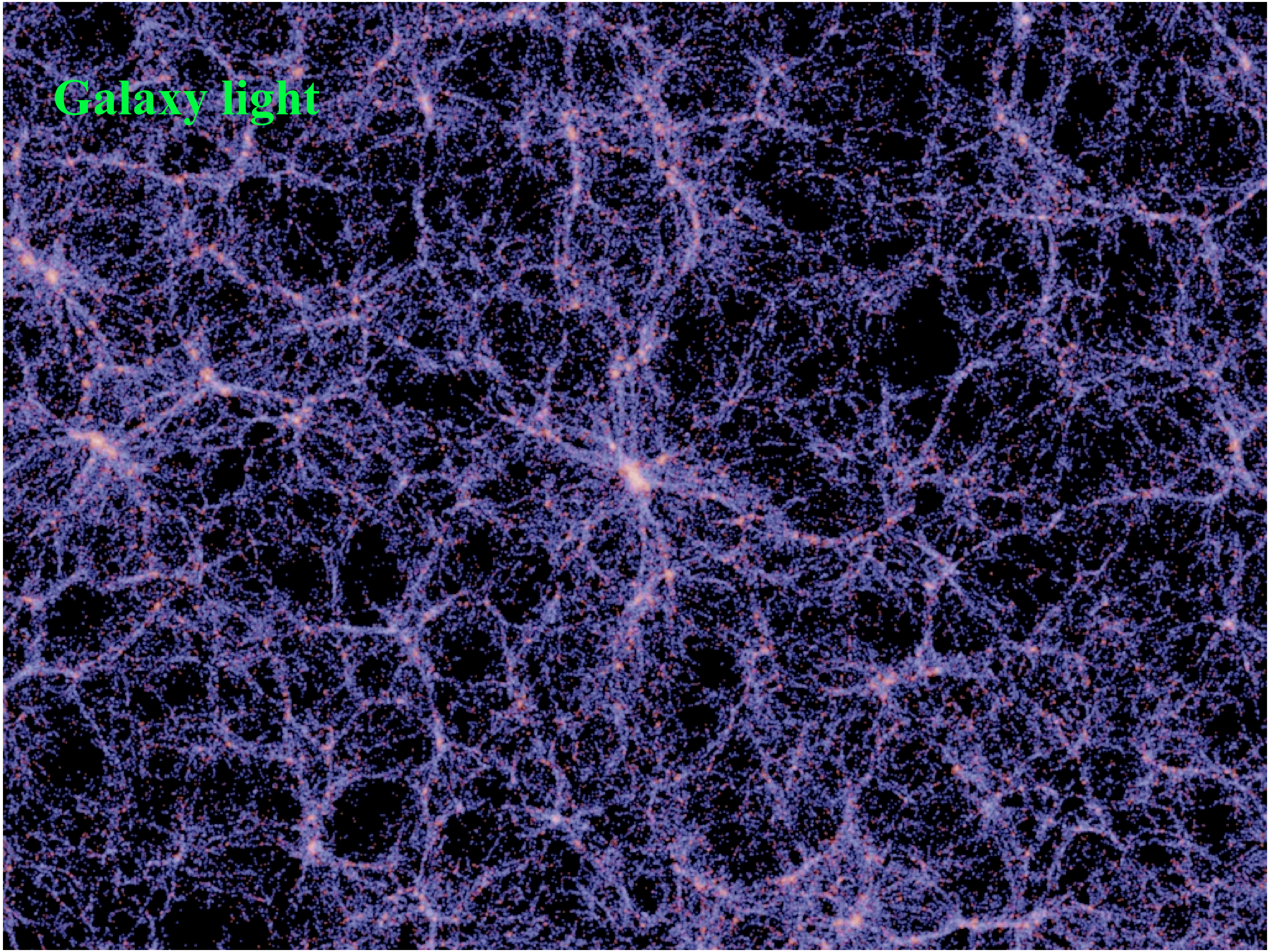
$$L_{\rm BH} = \eta\, \dot{m}_{\rm BH}\, c^2$$

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

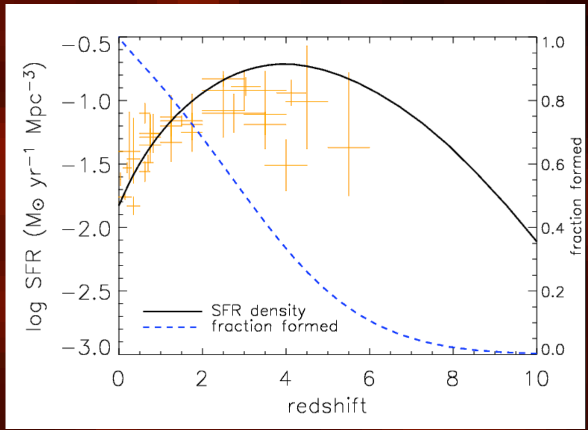

Dark matter
125 Mpc/h

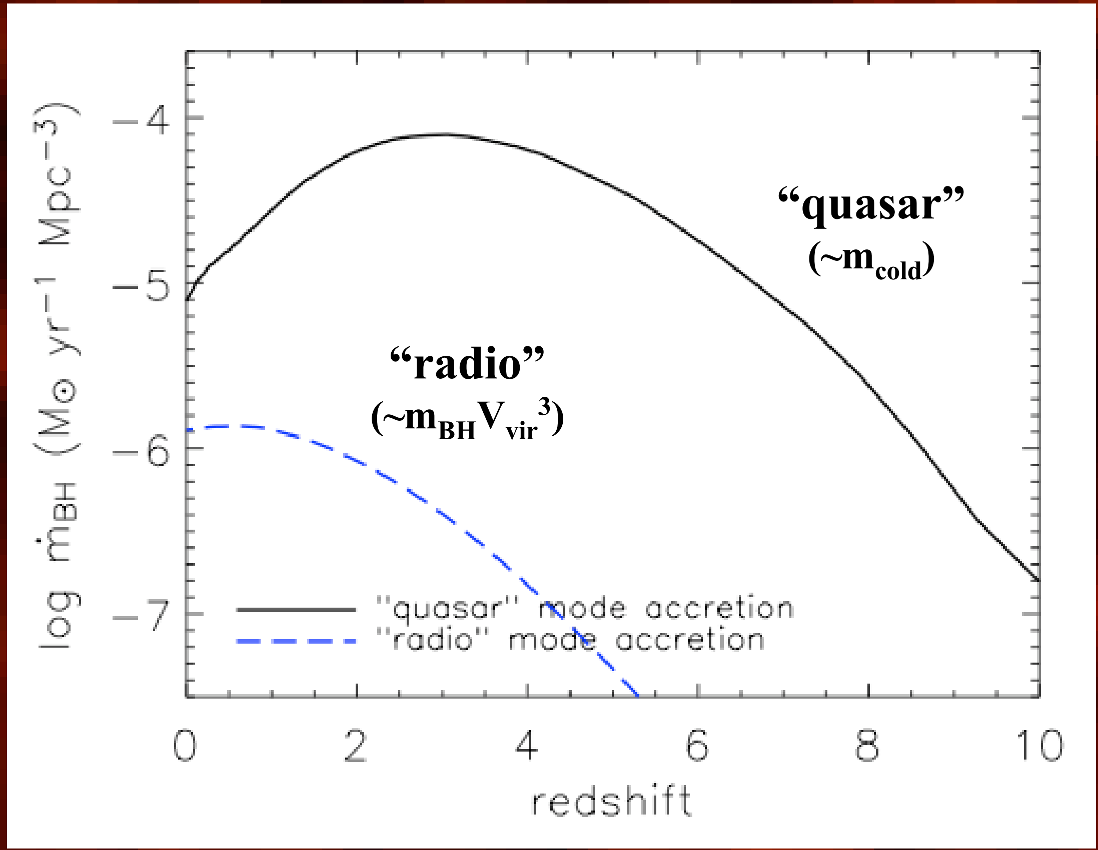

Galaxy light

Black Hole Growth

Black Hole Growth

Black hole accretion history of the universe

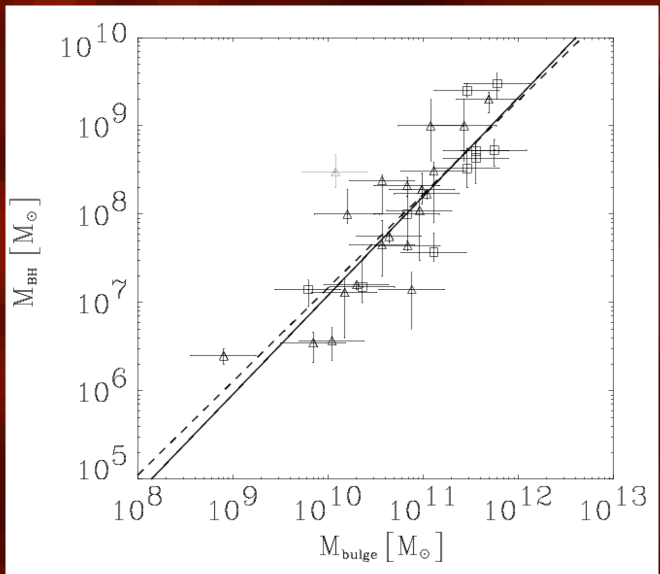




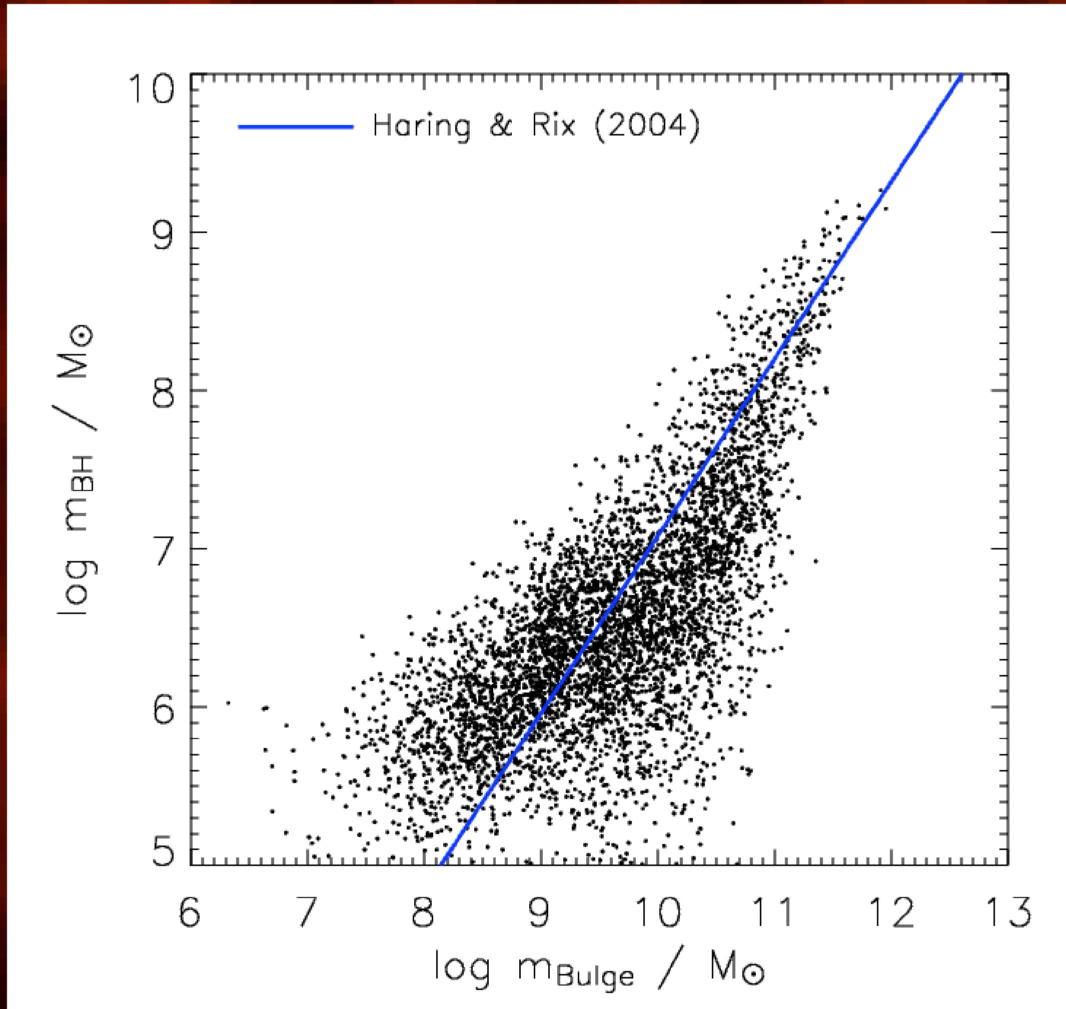
The quasar mode dominates the BH mass history

Black Hole Growth

Black hole-bulge
mass relation

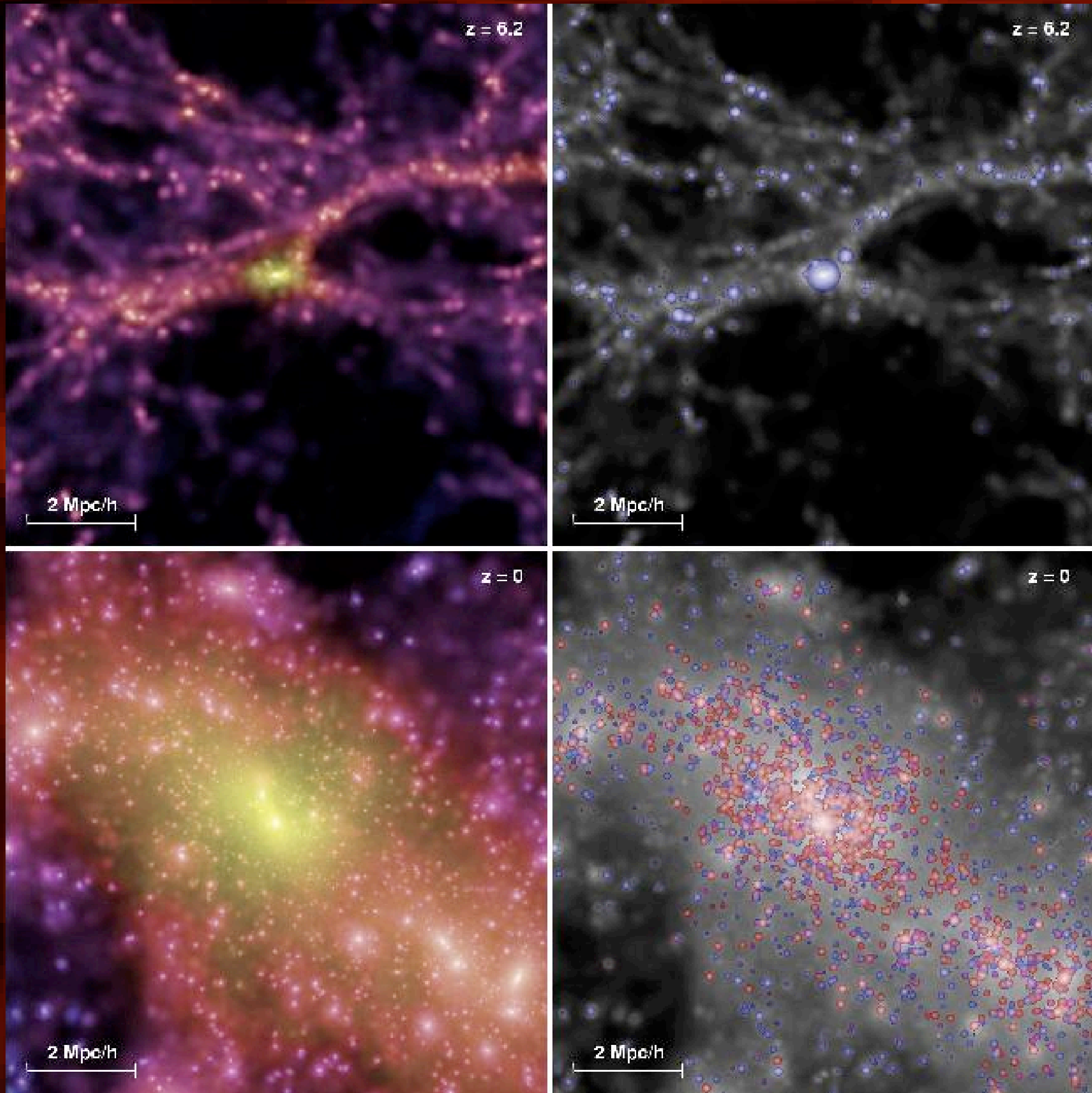


(Haring & Rix 2004)



Black Hole Growth

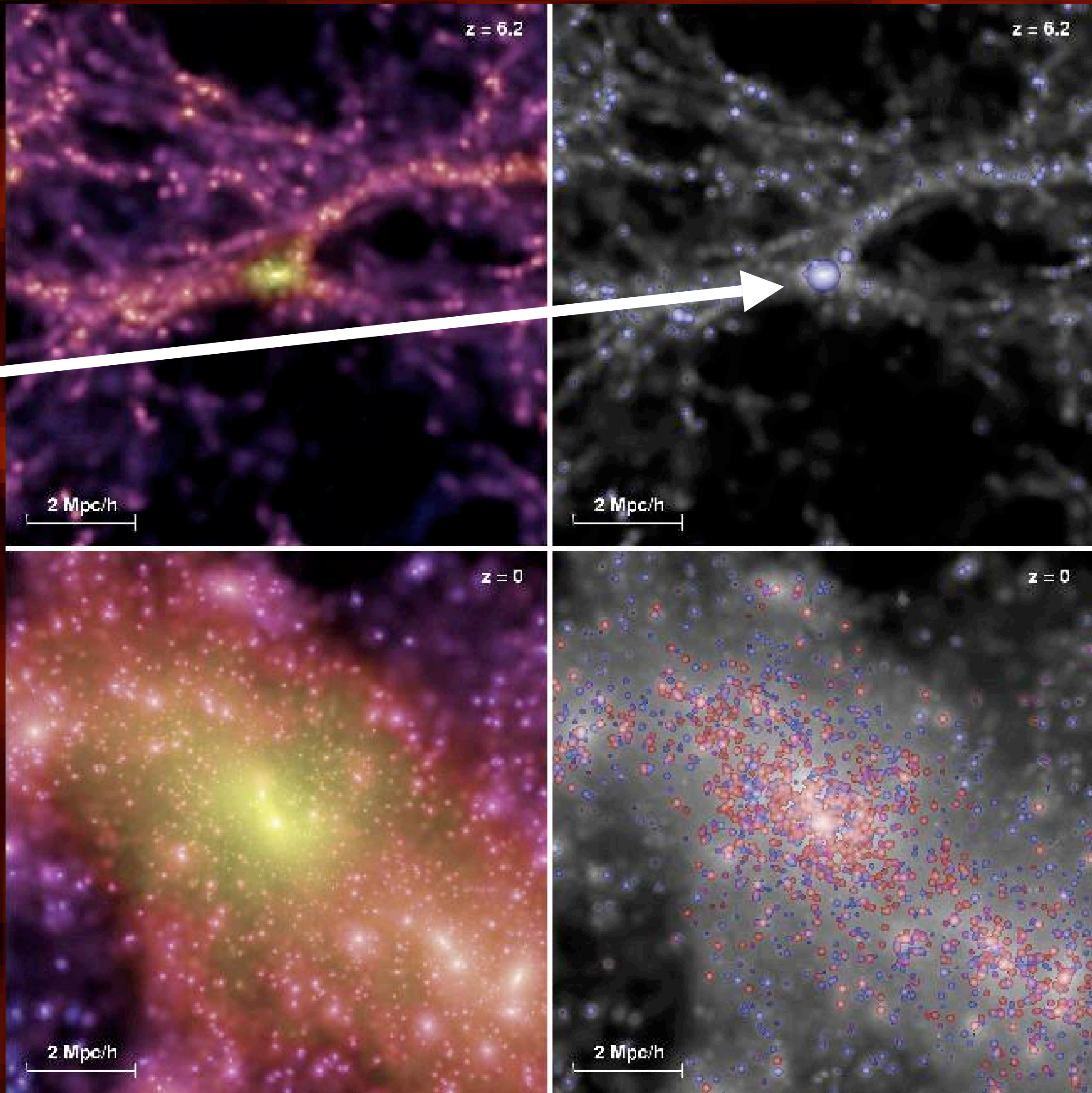
The sites of high redshift quasars (quasar mode)



Black Hole Growth

The sites of high redshift quasars (quasar mode)

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



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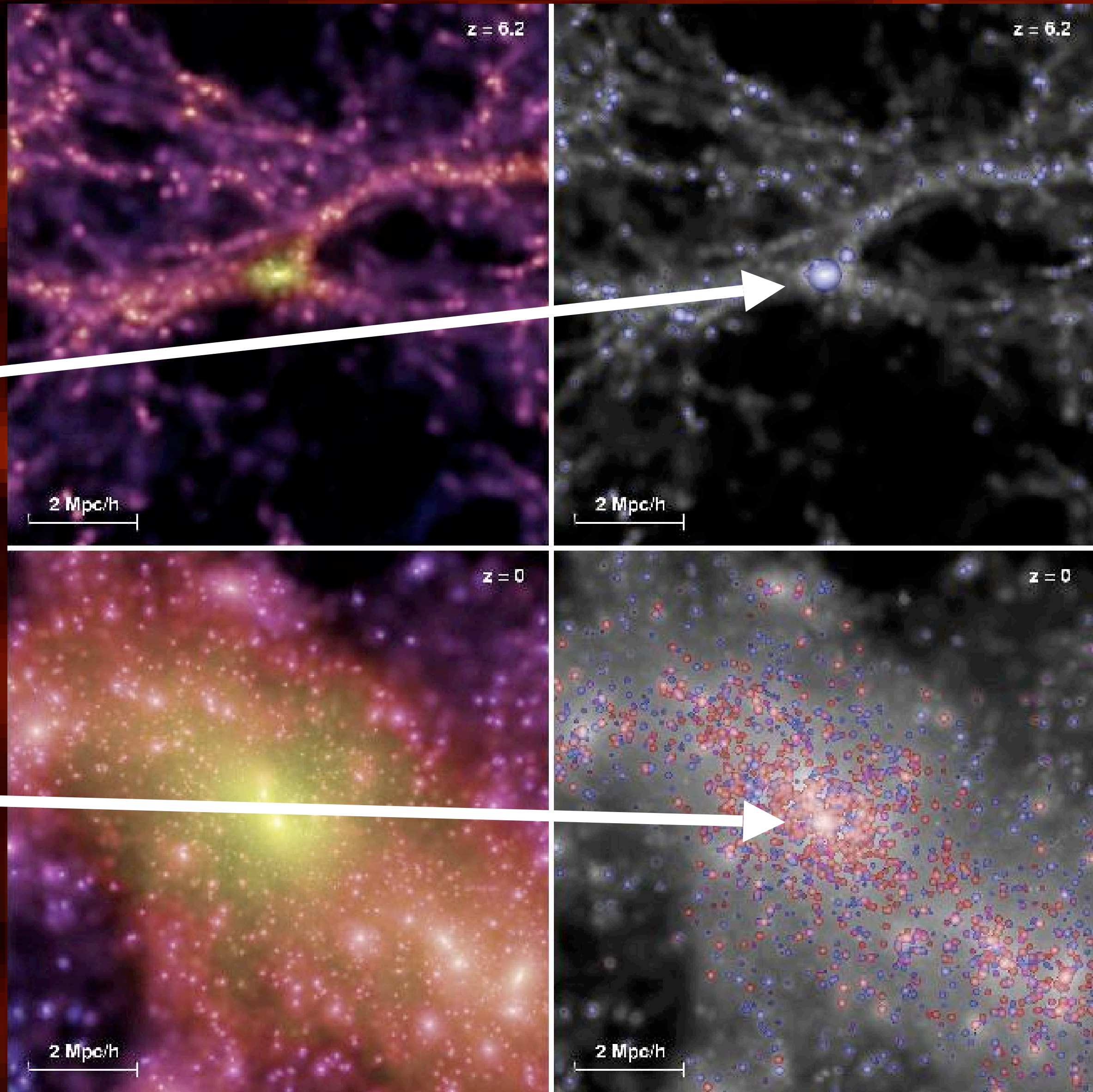
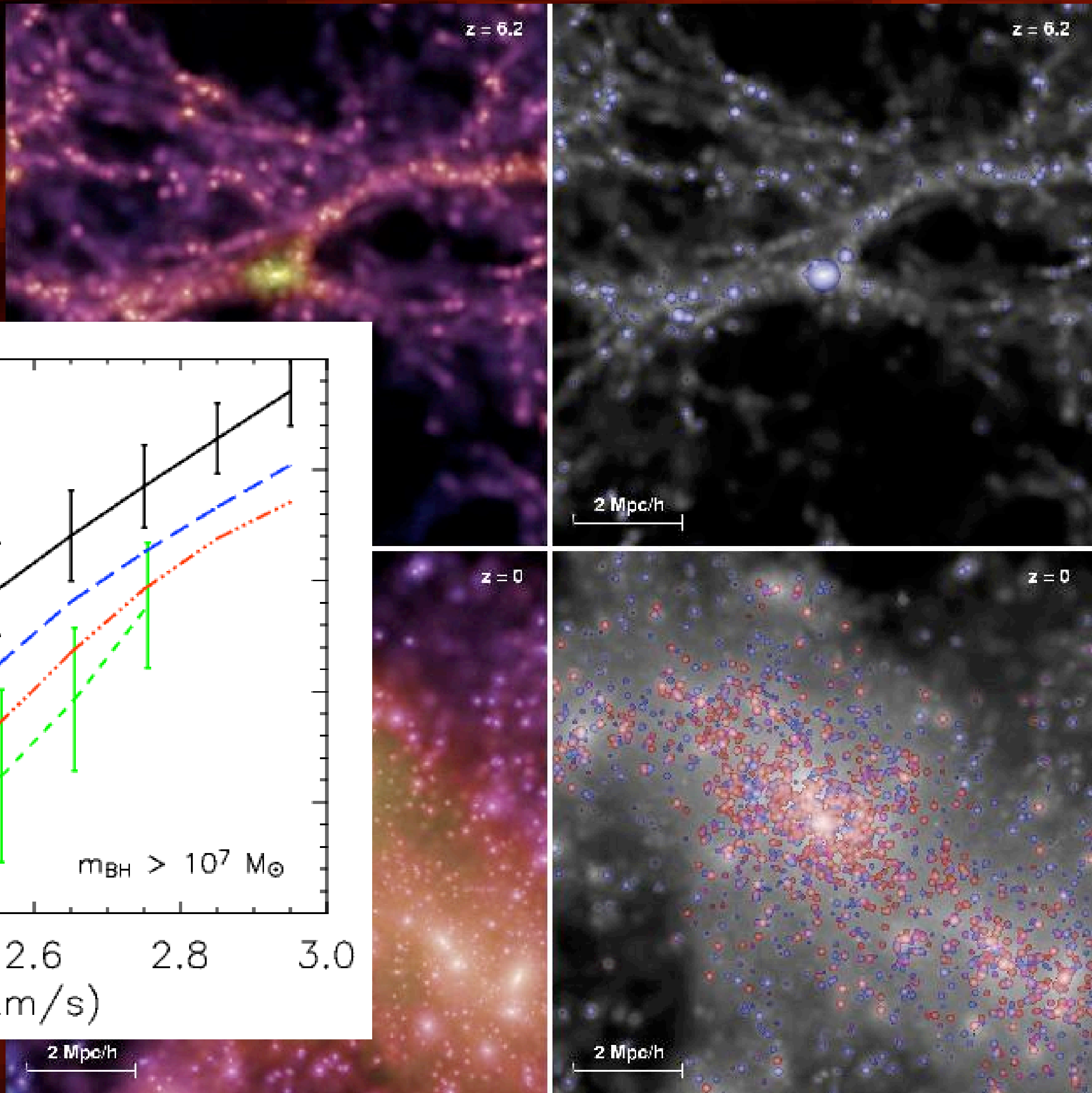


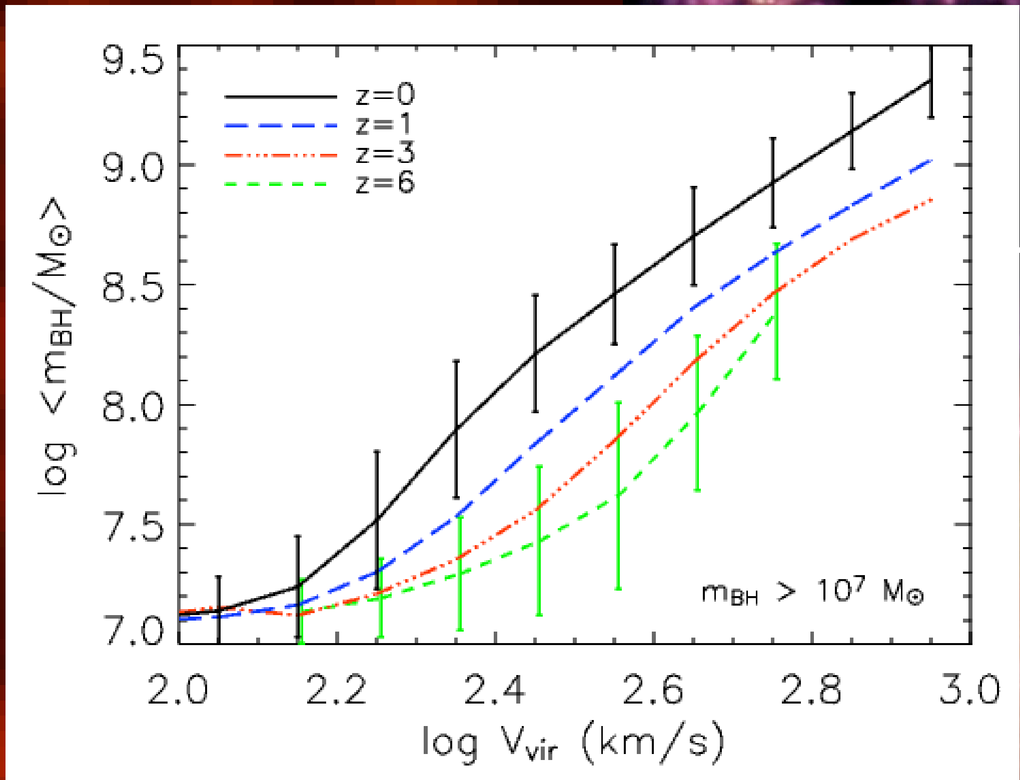
z = 6:
SFR > 500 M_{sun}/yr
$M_{BH} \sim 10^{8.5\text{-}9} M_{sun}$
$M_{gal} \sim 10^{10} M_{sun}$
$M_{vir} \sim 10^{12} M_{sun}$

z = 0:
SFR ~ zero
$M_{BH} \sim 5x10^{9} M_{sun}$
$M_{gal} \sim 10^{12} M_{sun}$
$M_{vir} \sim 10^{15} M_{sun}$

Black Hole Growth

The sites of high redshift quasars (quasar mode)





AGN and Galaxies

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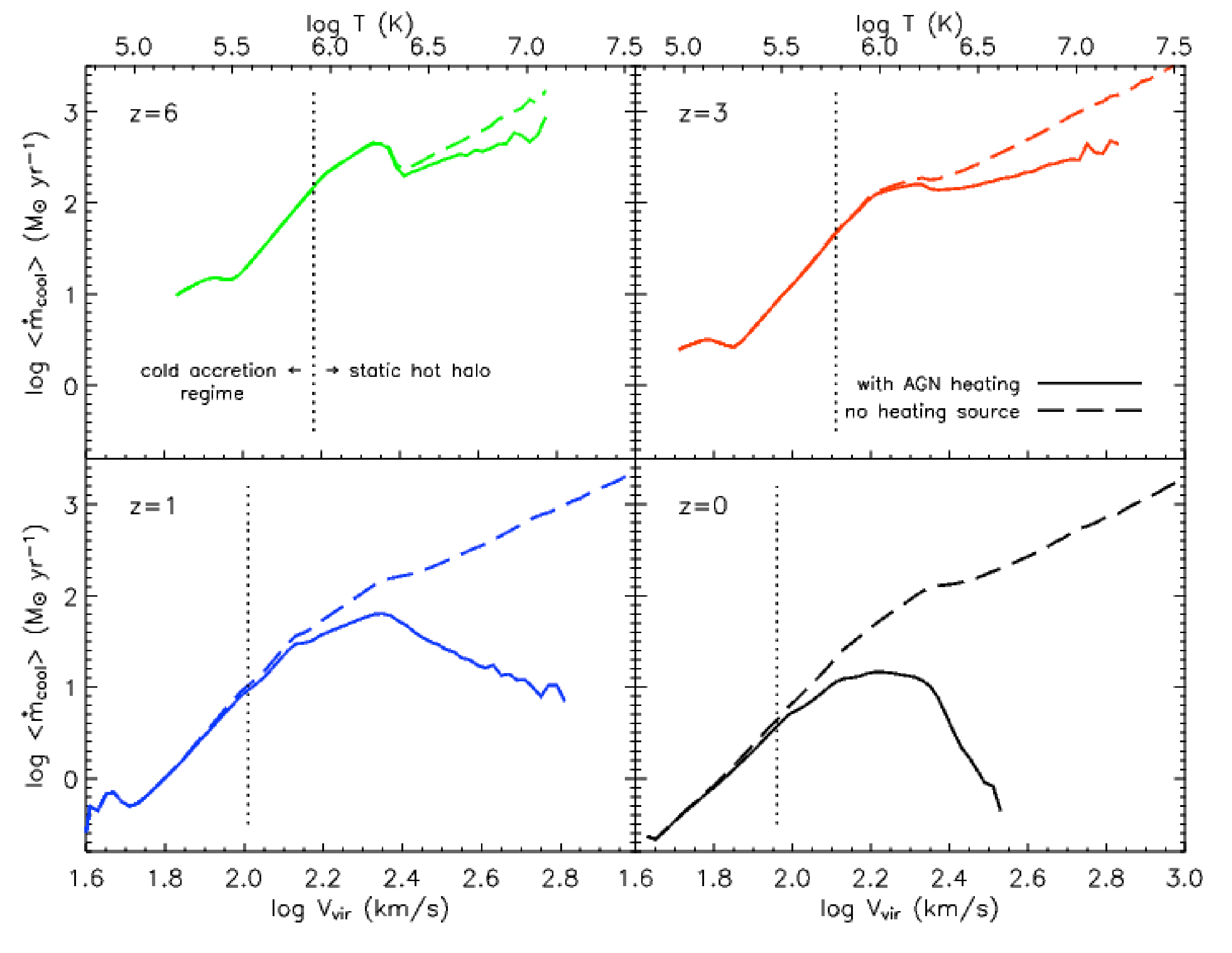
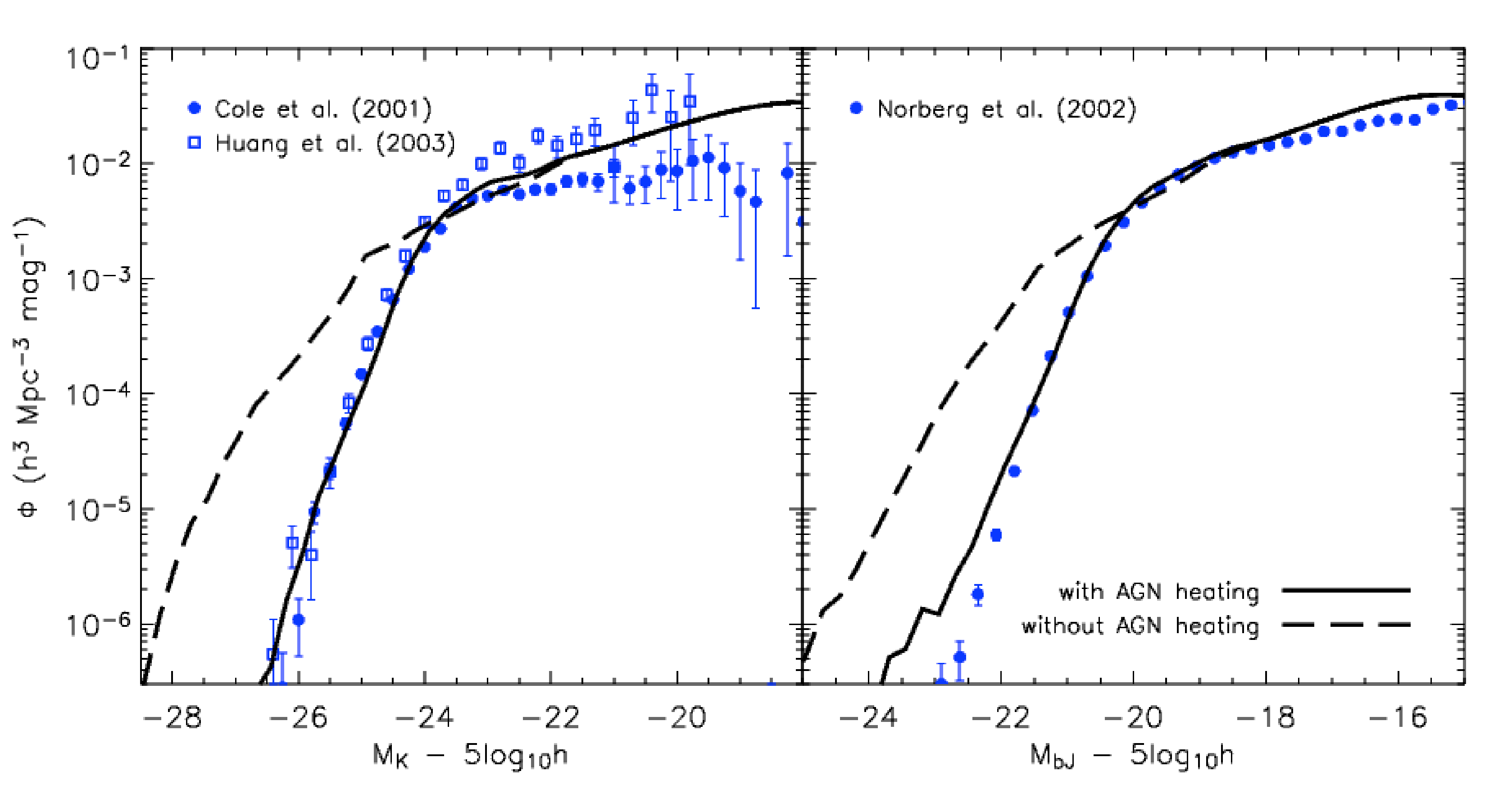


Suppression of cooling gas (radio mode)

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

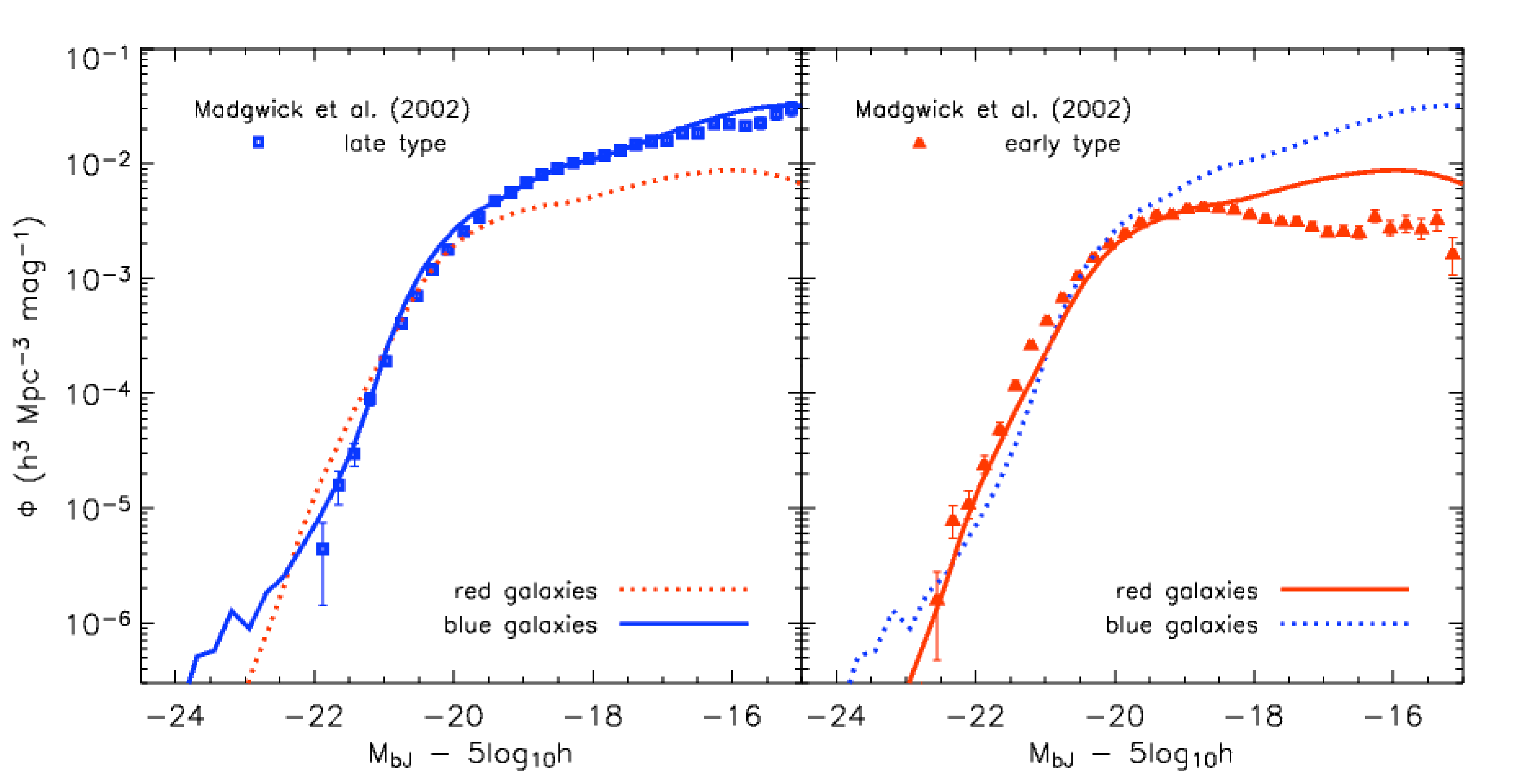
AGN and Galaxies



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

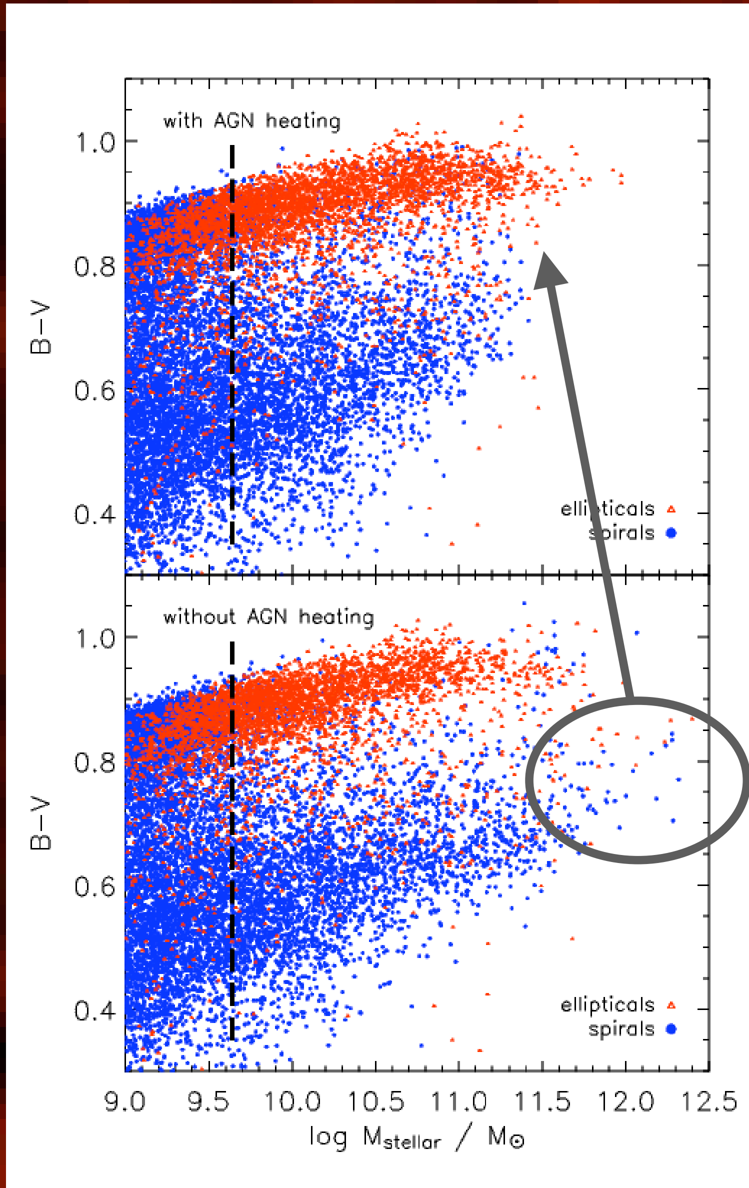
AGN and Galaxies

Split by colour, the blue and red LFs do well to reproduce the type dependent 2dFGRS LF (Madgwick et al. 2002)



AGN and Galaxies

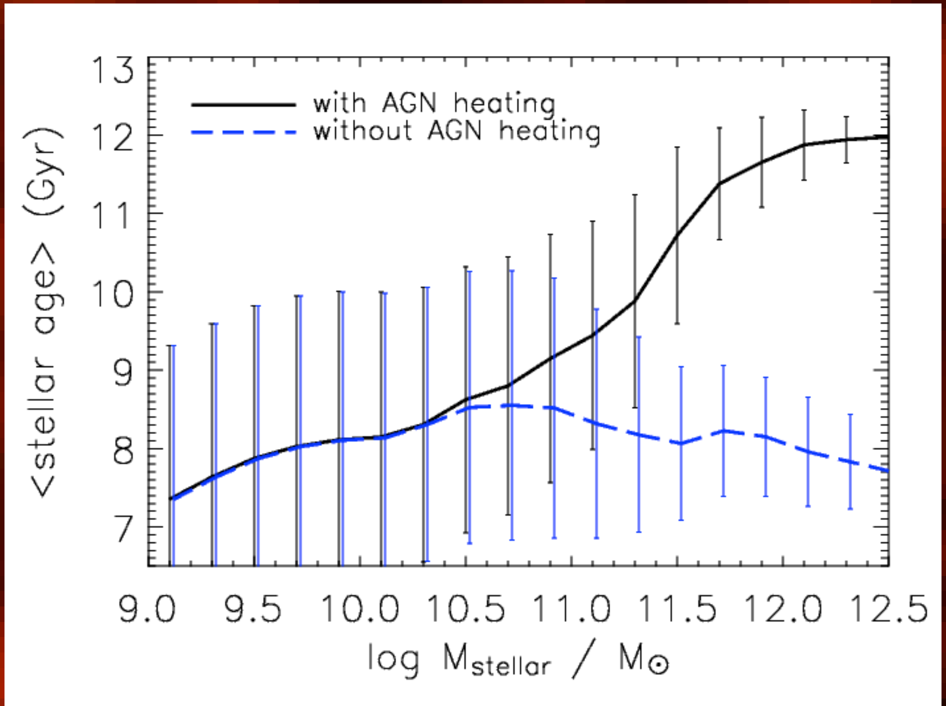
B-V colour bi-modality

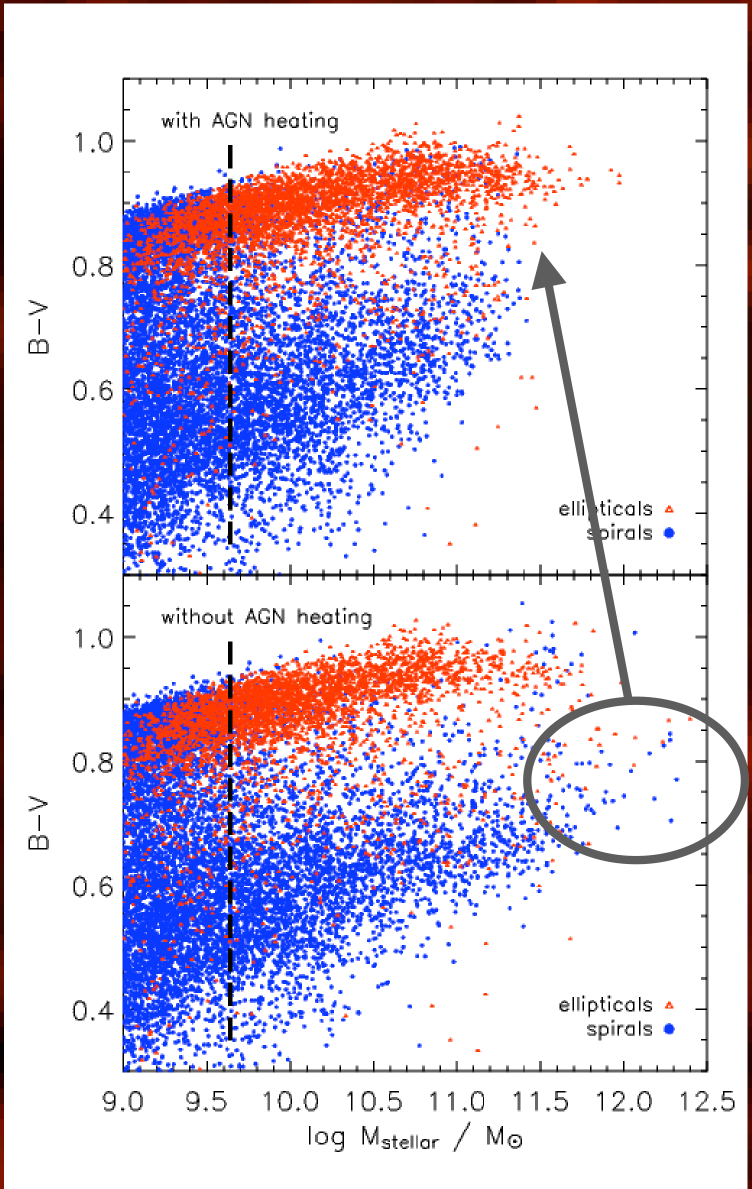


AGN and Galaxies

B-V colour bi-modality

and mean stellar age

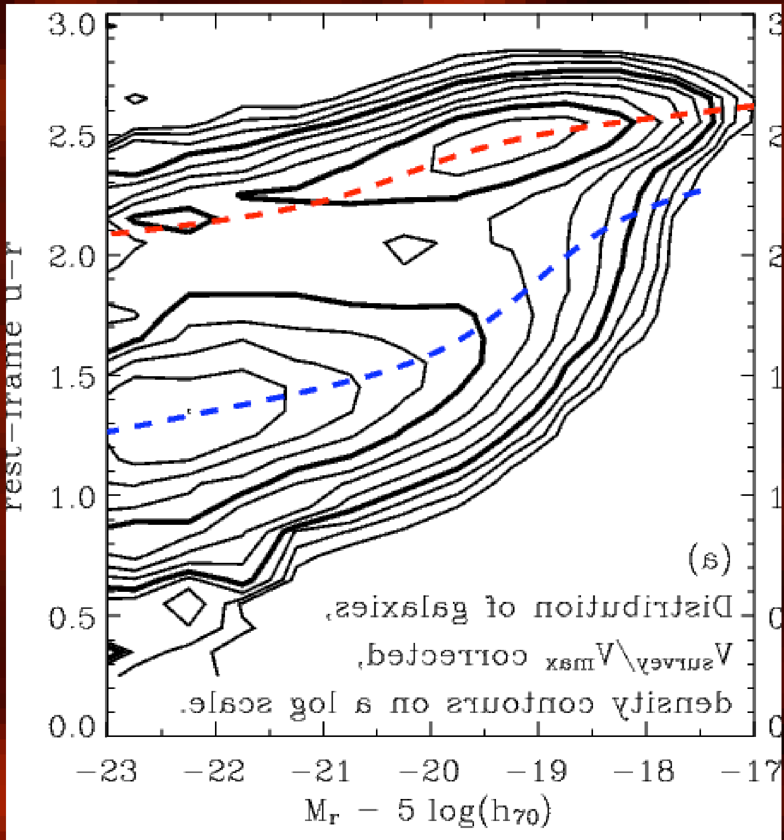


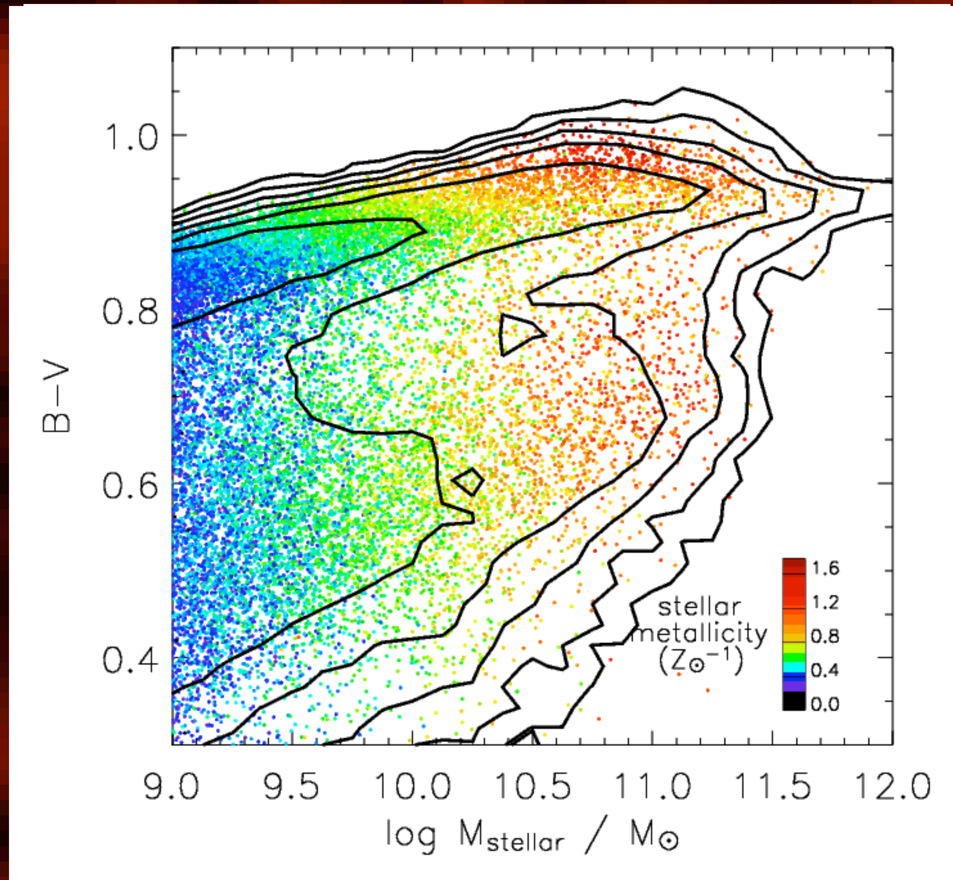


AGN and Galaxies

B-V colour bi-modality and metallicity

Baldry et al. astro-ph/0410603





Conclusions

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

- Energetically feasible
- Identification of high z quasars
- Significantly changes massive galaxy evolution:
  - bright-end luminosity function cut off and shape
  - bright-end colours and mean stellar ages

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

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