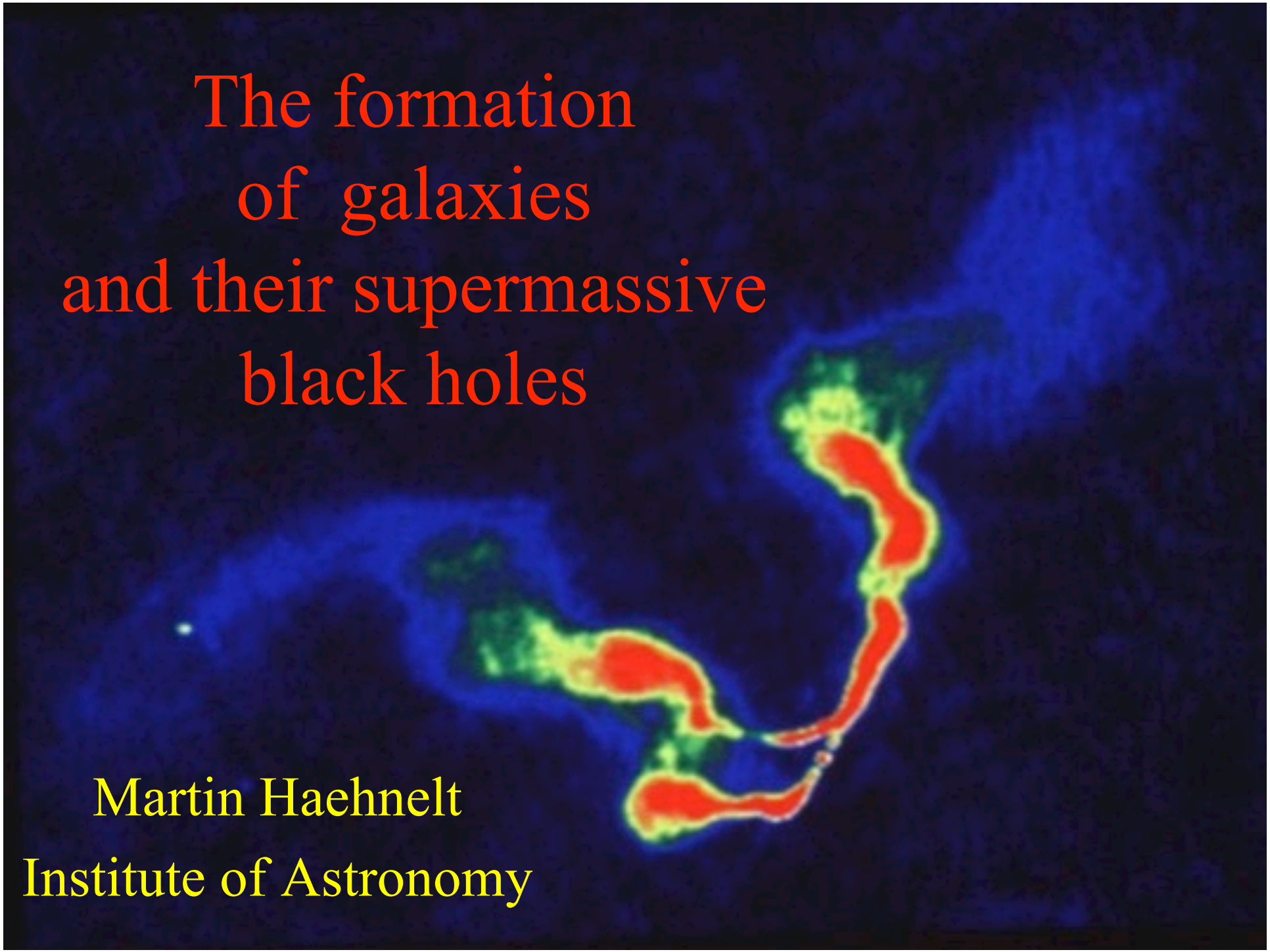
The formation of galaxies and their supermassive black holes

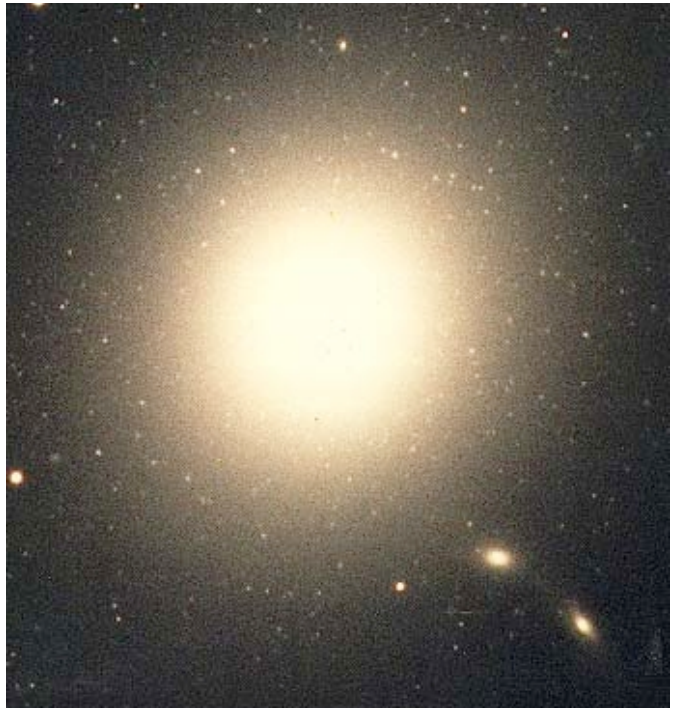


Martin Haehnelt

Institute of Astronomy

Massive black holes?

Giant Ellipticals/S0s



Yes

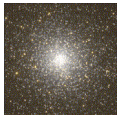
Spirals

Yes but black hole mass scales with bulge mass not total mass

Dwarfs

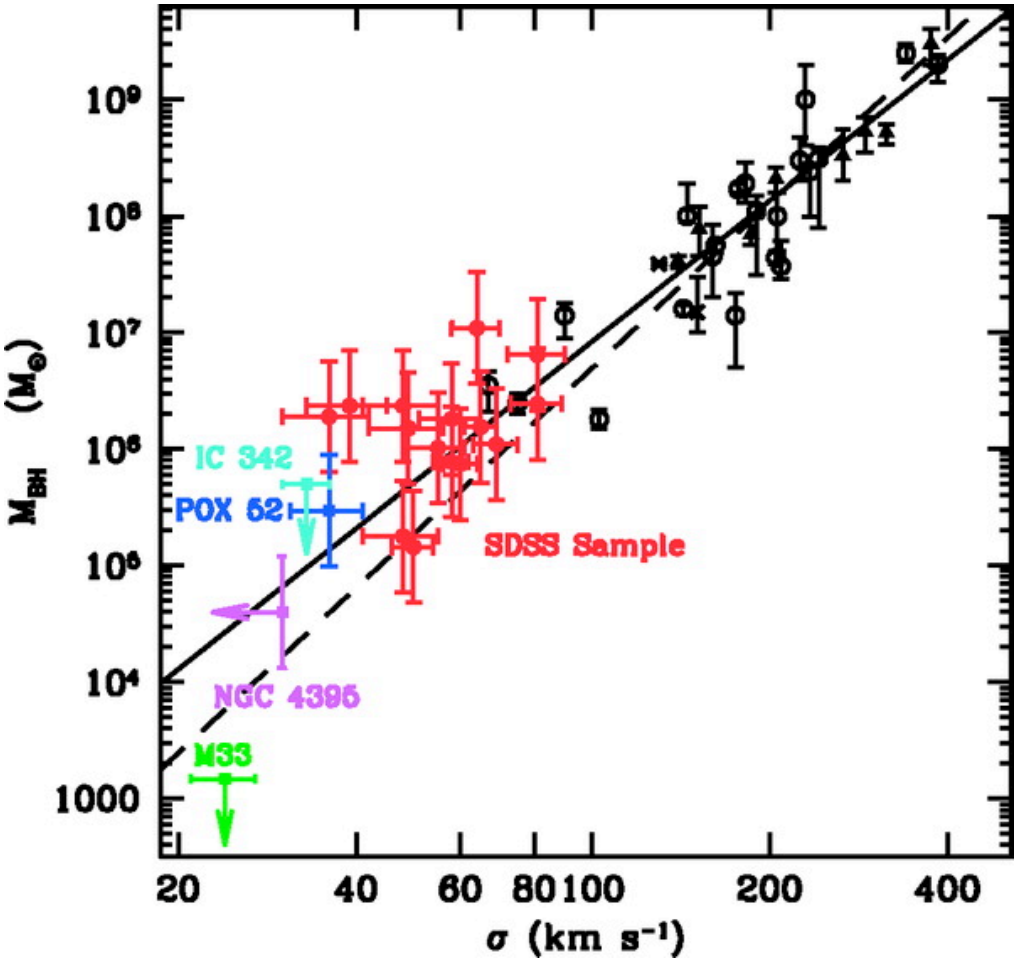
Yes,
but probably
not many

Globular Clusters



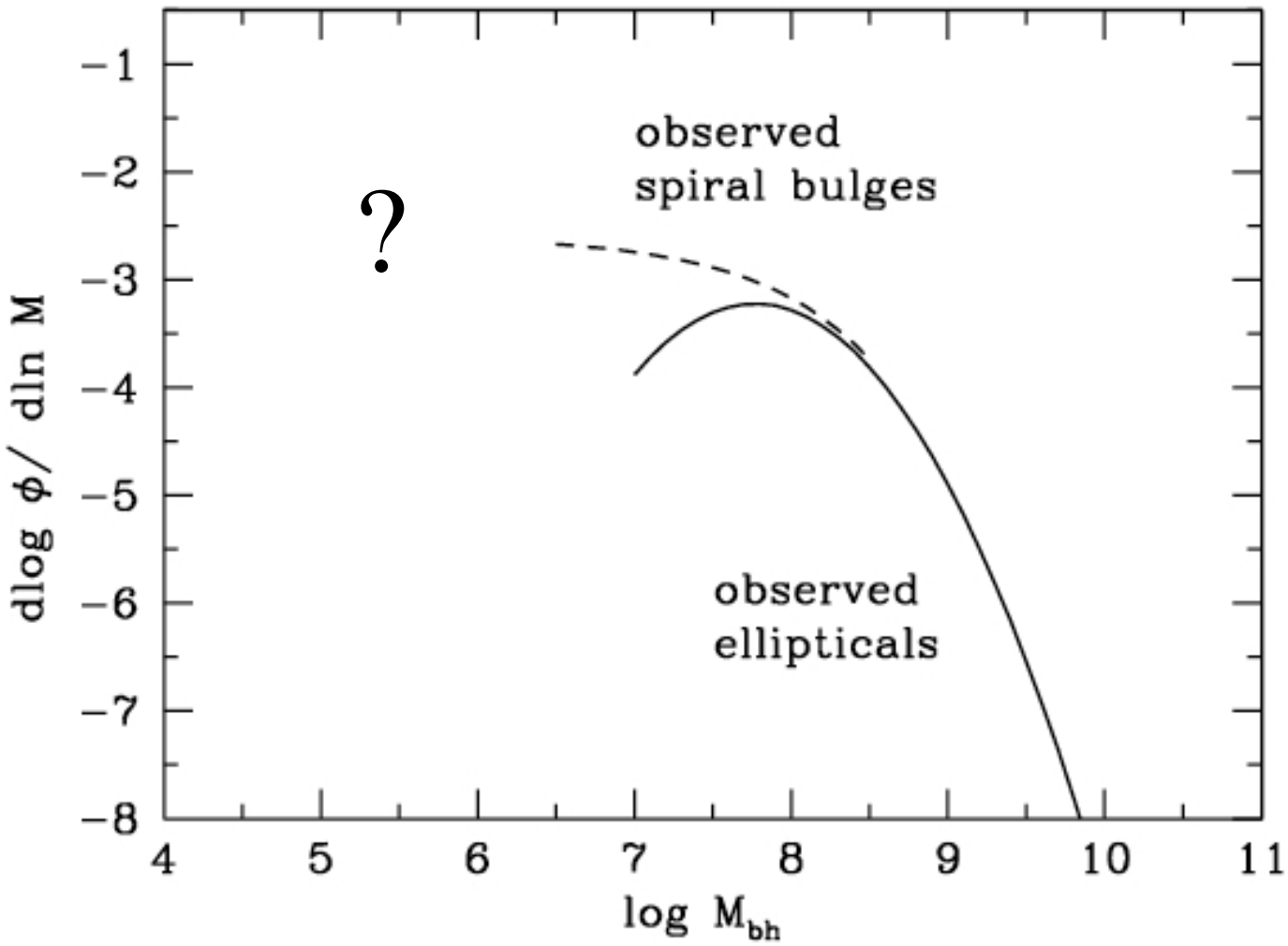
Maybe

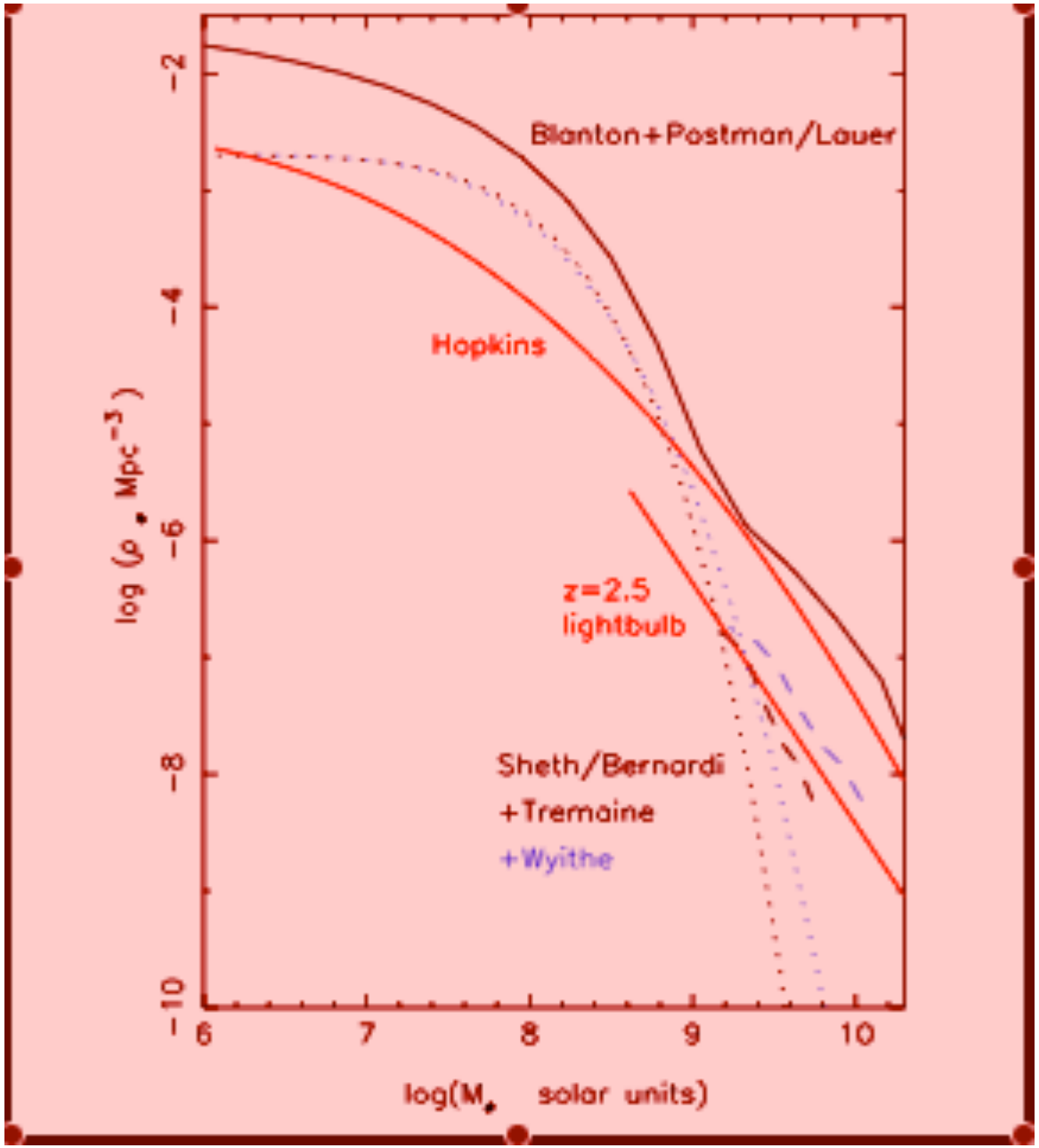
Intermediate Mass Black Holes?



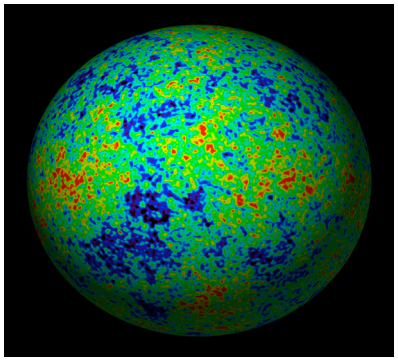
Baarth et al 2005

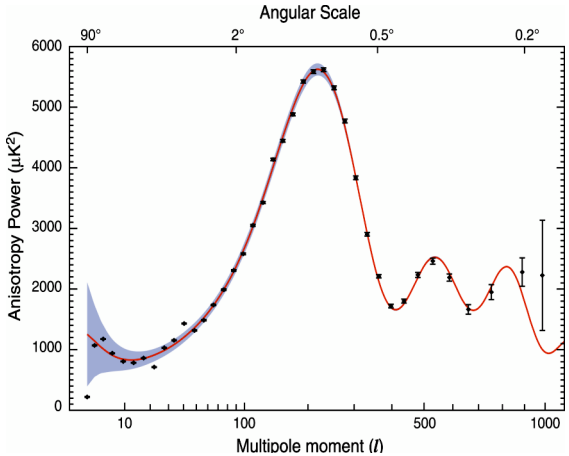
Mass function of black holes in nearby galaxies

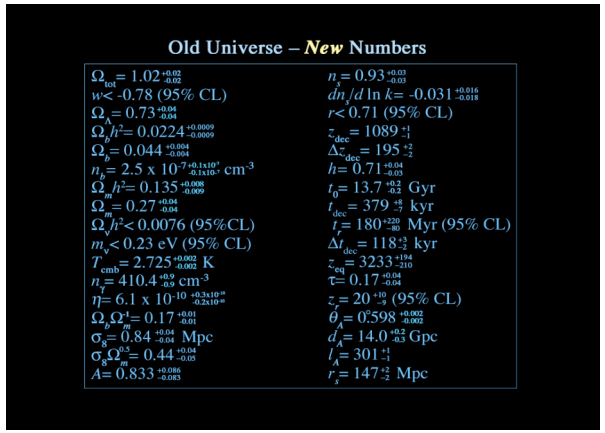


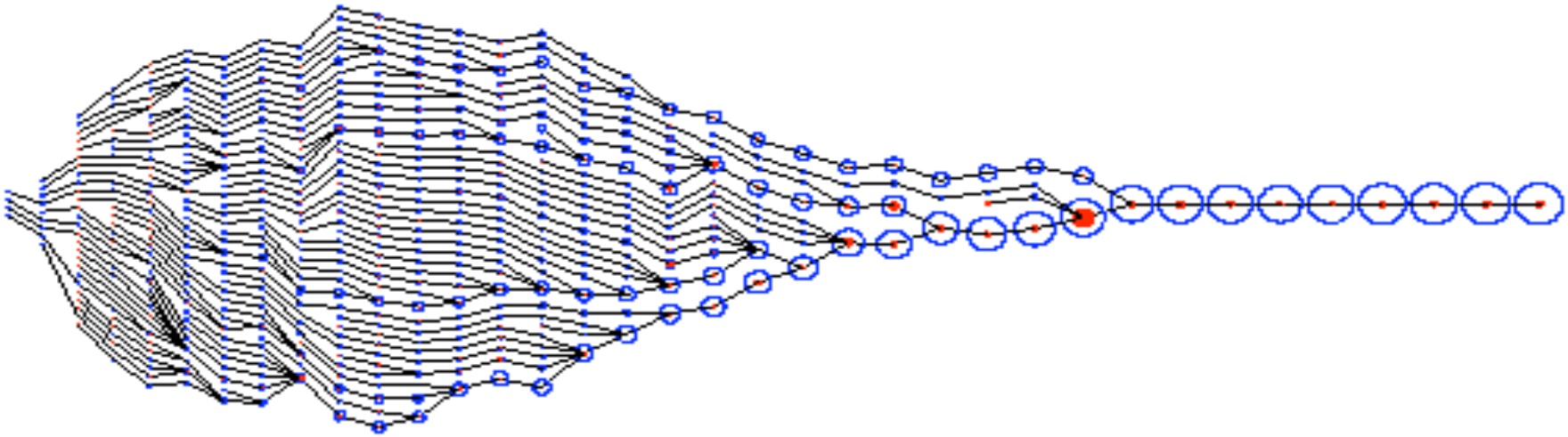

Blanton+Postman/Lauer
Hopkins
z=2.5
lightbulb
Sheth/Bernardi
+Tremaine
+Wyithe
log (ρ*, Mpc⁻³)
log(M*, solar units)
-2
-4
-6
-8
-10
6
7
8
9
10

There is now a cosmological standard model



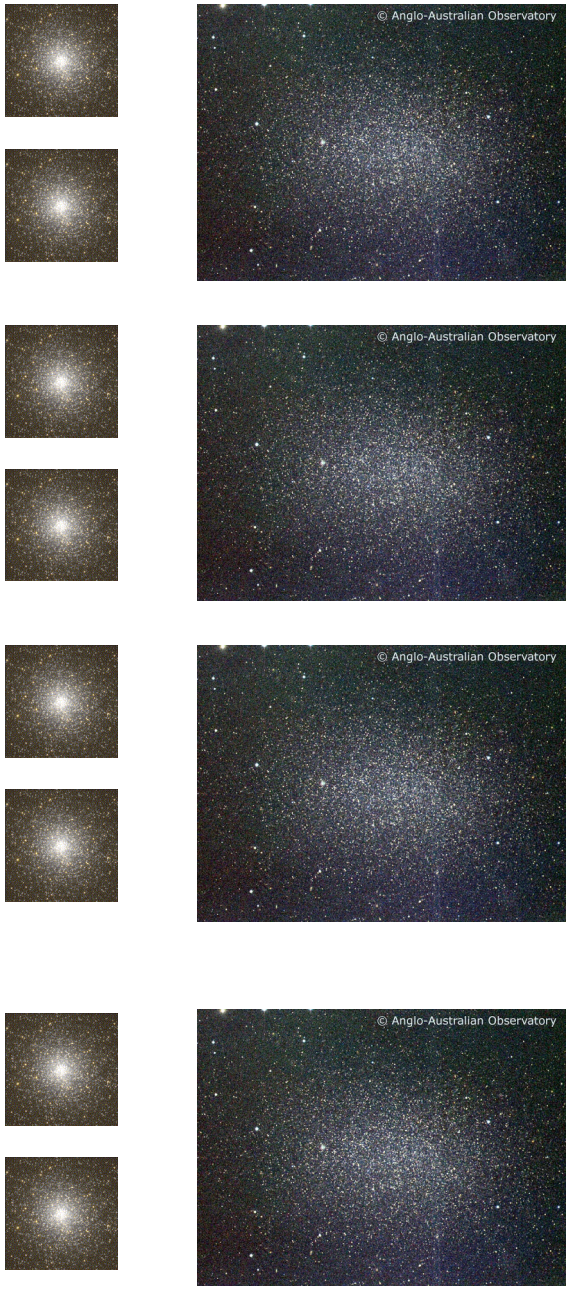






DM haloes grow hierarchically by merging.

Bullock et al.



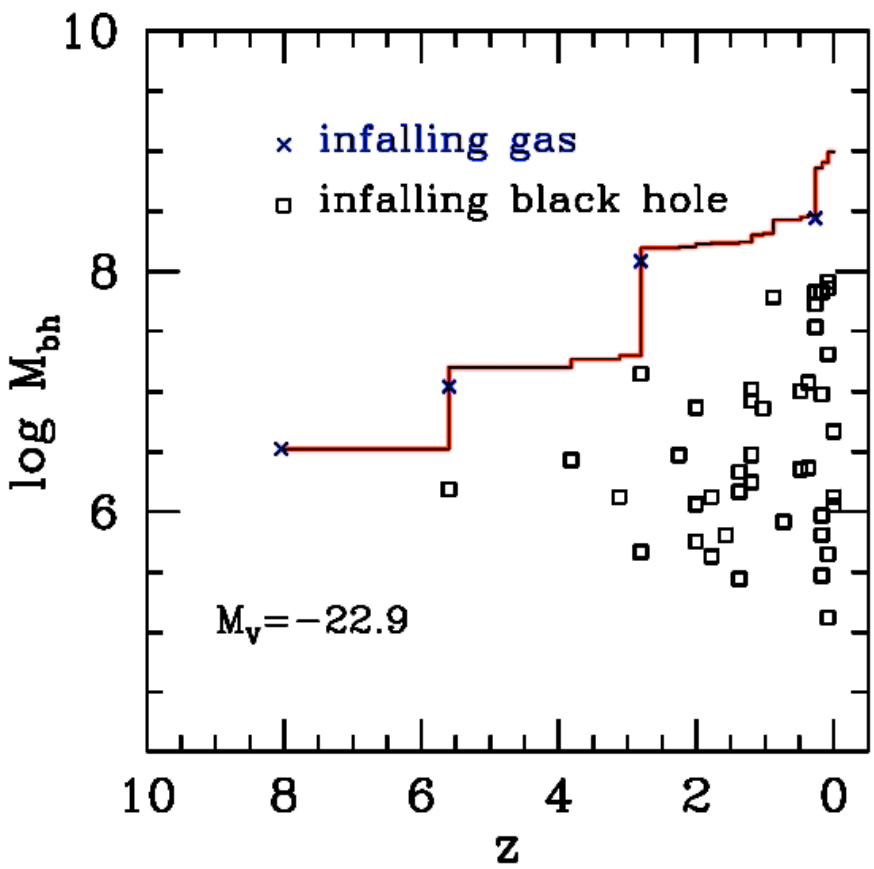
White & Rees 1978
White & Frenk 1991
Kauffmann et al. 1993
and many others

Santa Fe, 11th July 2006

The model of Kauffmann & Haehnelt

- black holes grow during major mergers
- a fixed fraction of the available cold gas is driven to the centre and accreted at arbitrarily high rates (equivalent to assuming seed black holes).
- the amount of available cold is set by the balance of gas cooling and stellar feedback.
- growth only during optically bright QSO phase.
- simplistic light curve with luminosity independent "lifetime"

Typical merging history in a bright elliptical



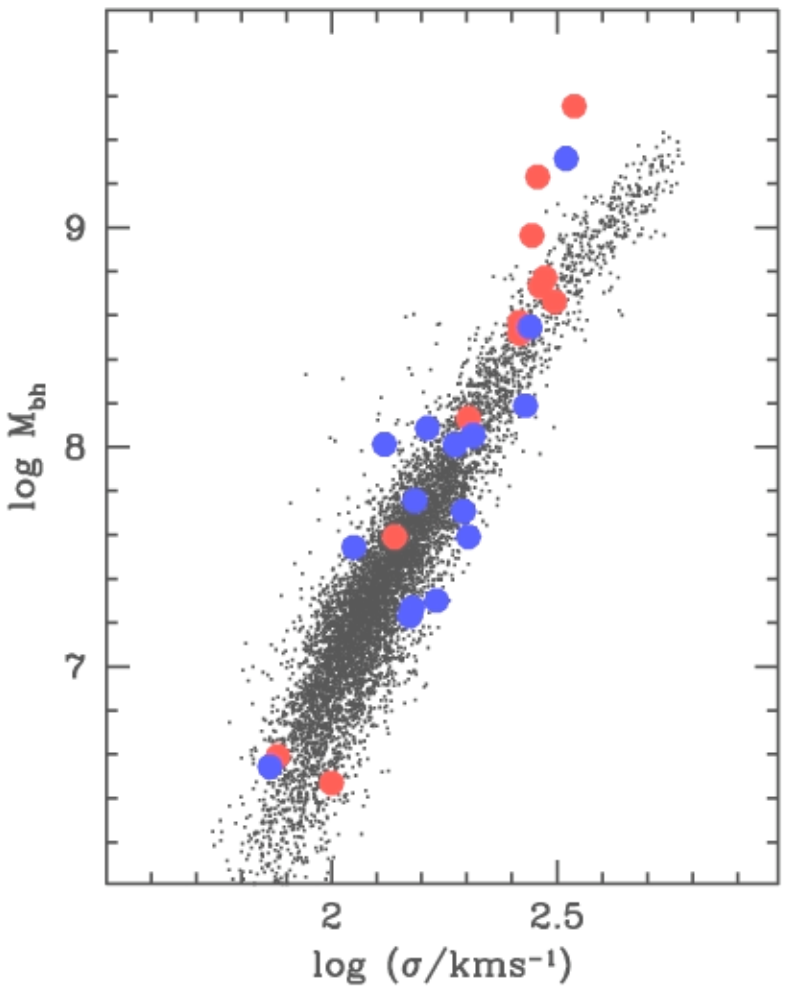
Growth of black holes dominated by accretion of gas

At late time also growth by infall and merging of black holes

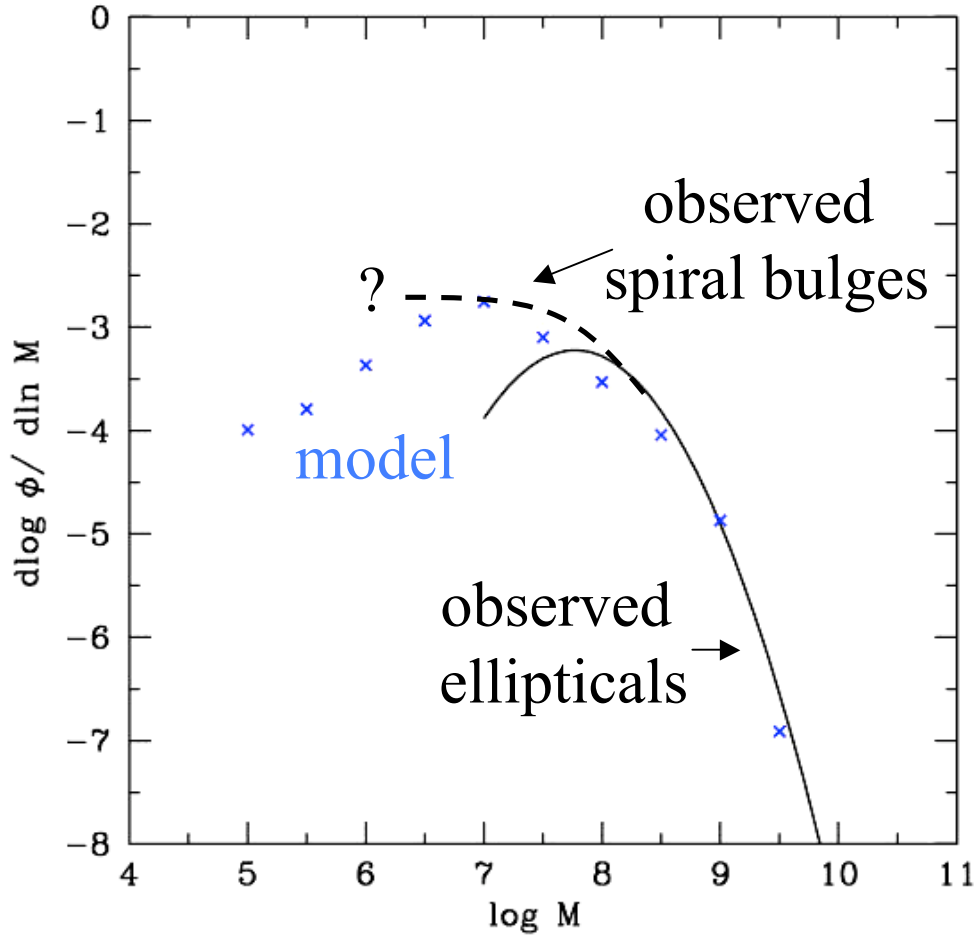
No seed black holes were assumed!

How do 10^6 Msol black holes form?

M-σ relation



Black hole mass function



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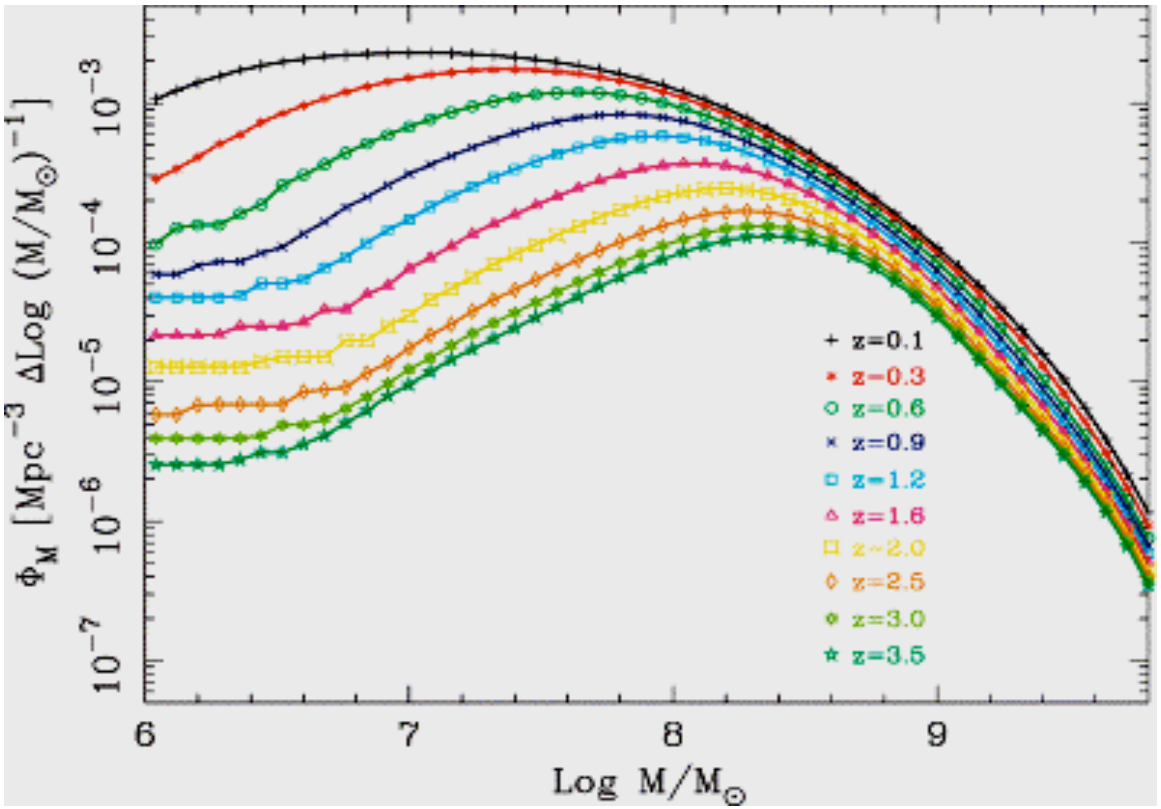
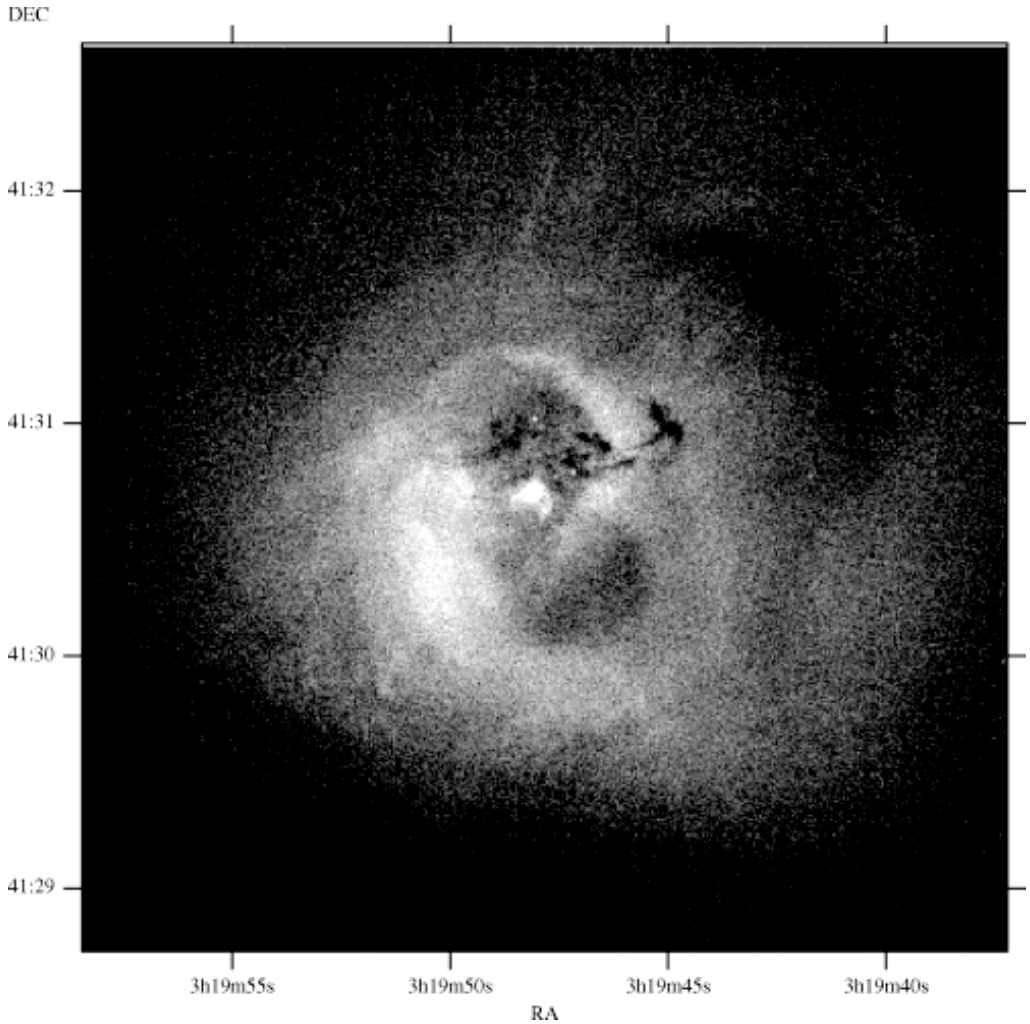
Haehnelt & Kauffmann 2000

Cosmic Downsizing



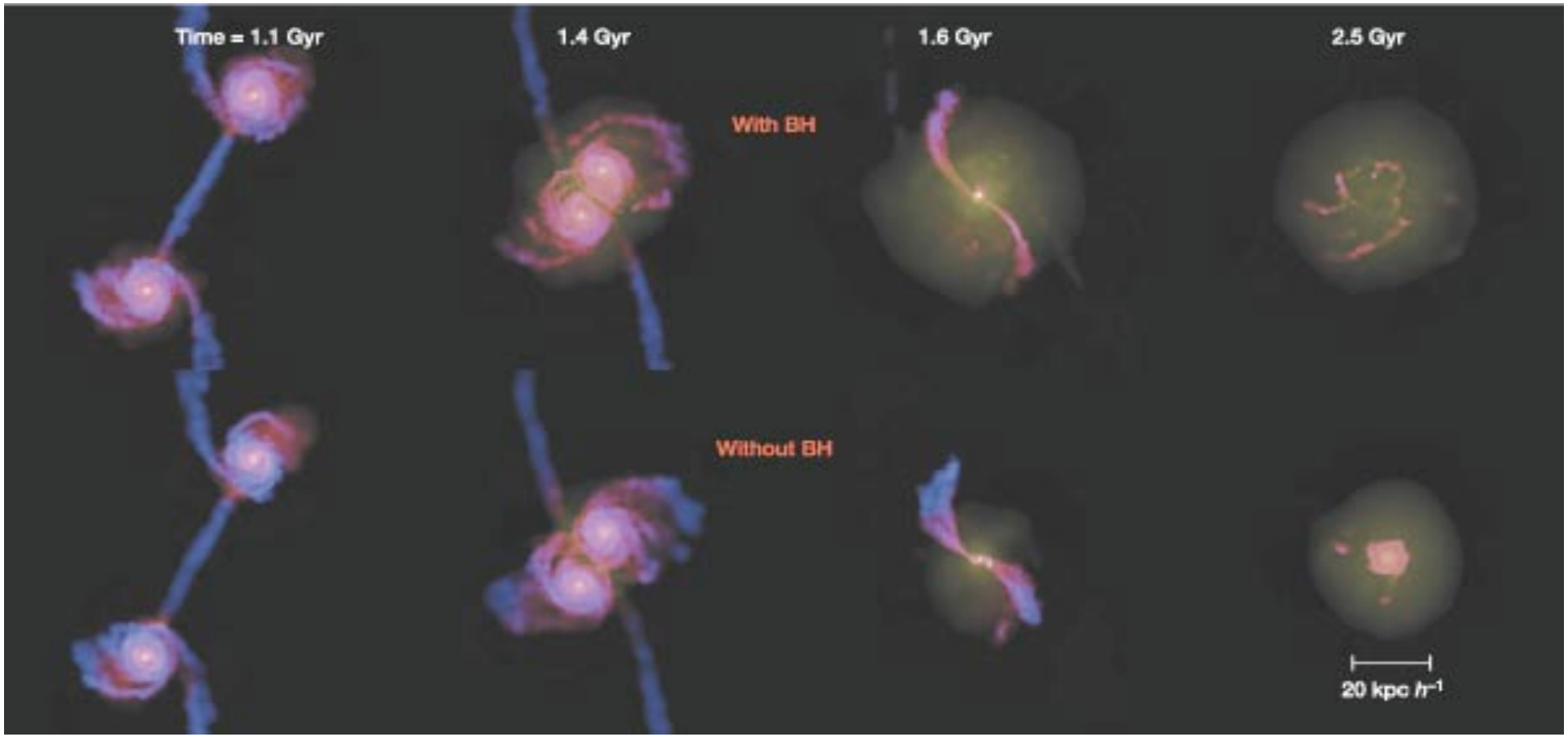
Most of the big black holes form at high redshift. Most of the black holes still growing at the present day are small. These small black holes have gained most of their mass recently.

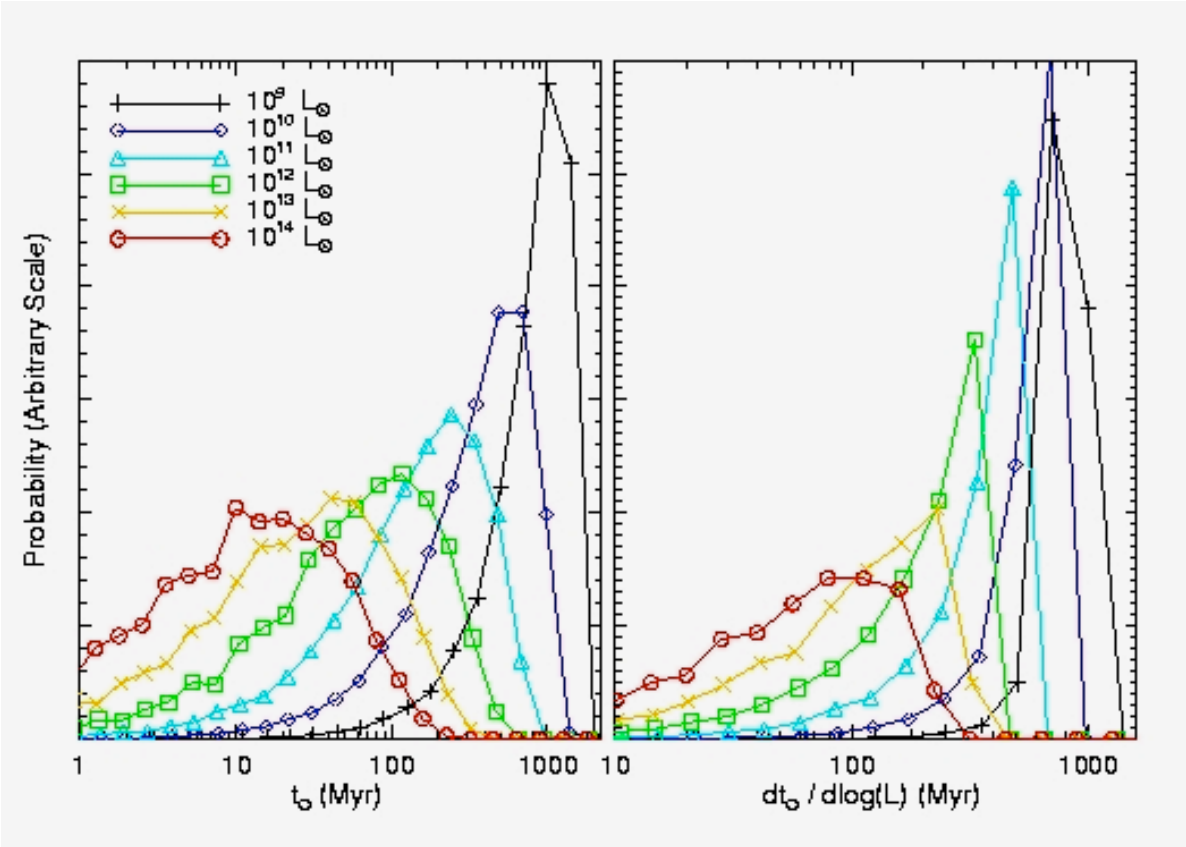
Merloni 2004



Fabian et al. 2003

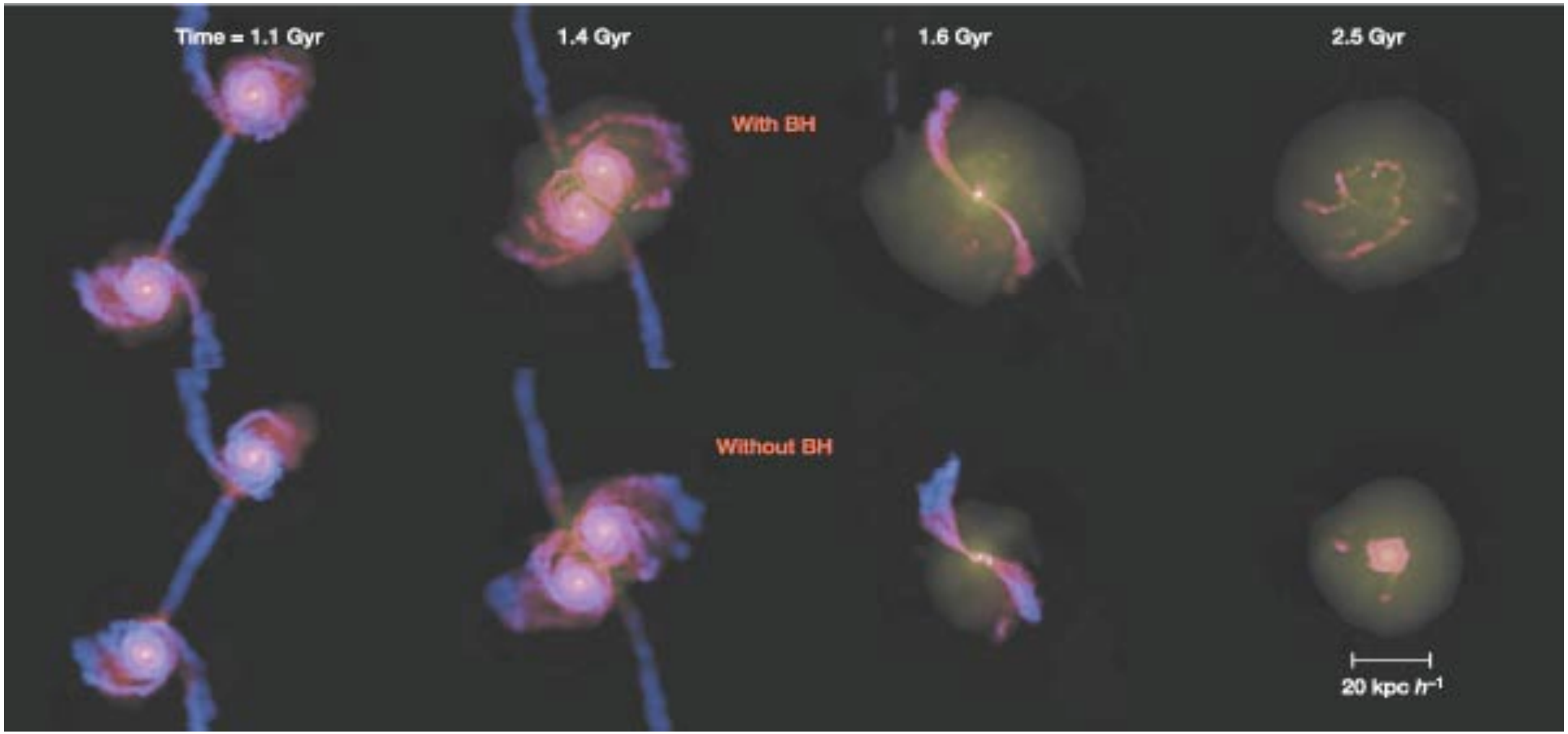
AGN heating prevents gas at centre of galaxy clusters from cooling


Time = 1.1 Gyr
1.4 Gyr
1.6 Gyr
2.5 Gyr
With BH
Without BH
20 kpc h^{-1}



Merger simulations can predict absorbing column densities, duty cycles as a function of luminosity and wavelength.

Hopkins et al 2005



Is AGN feedback really that violent?

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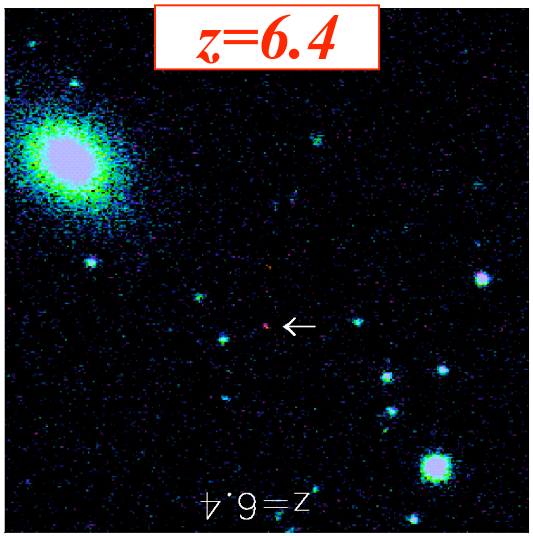
How do the very massive z=6 black holes form?



Black holes as massive as the most massive black holes today have already formed at z=6.4.

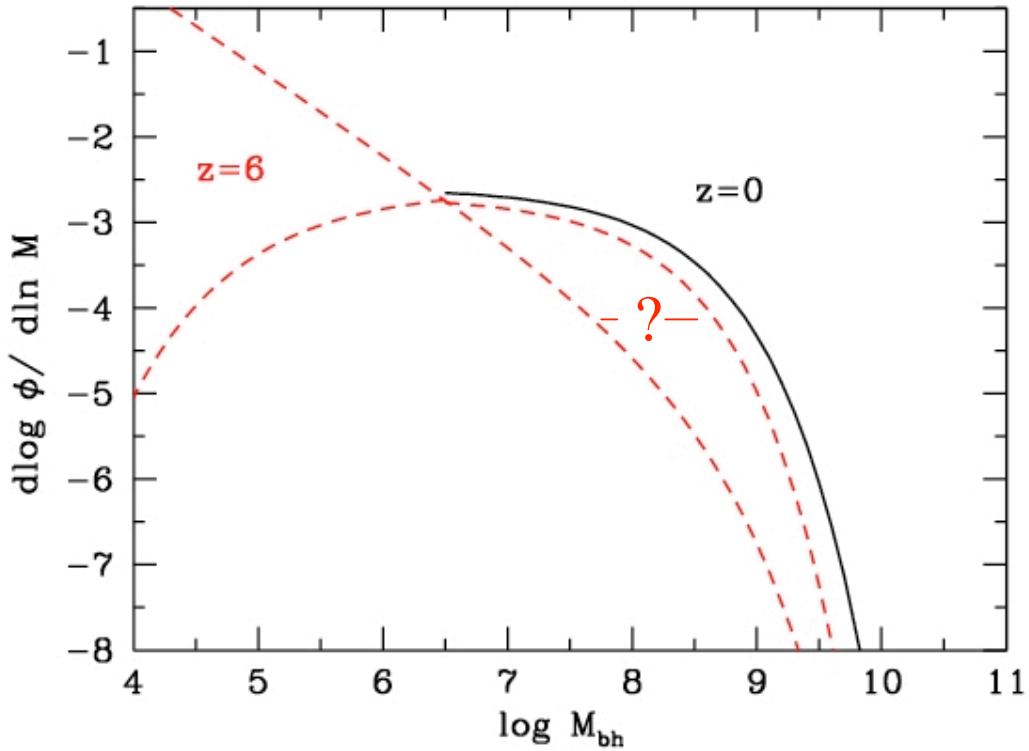
Estimated mass: 3 x 10^9 Msol

Fan et al.

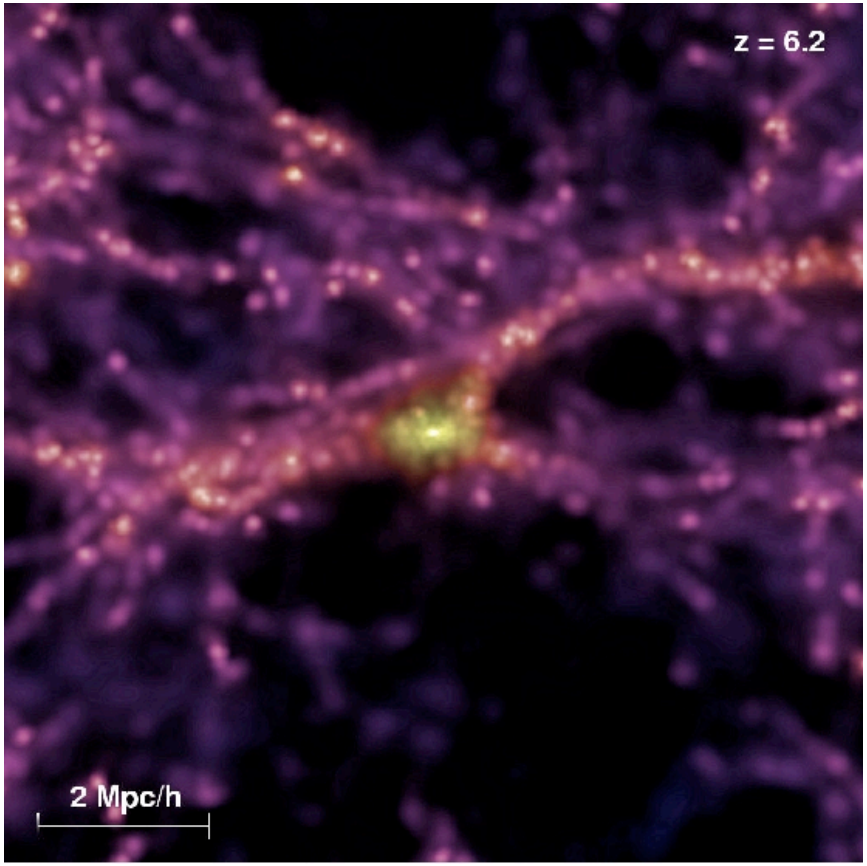
Age of Universe at z=6.4: 0.8-0.9 Gyr

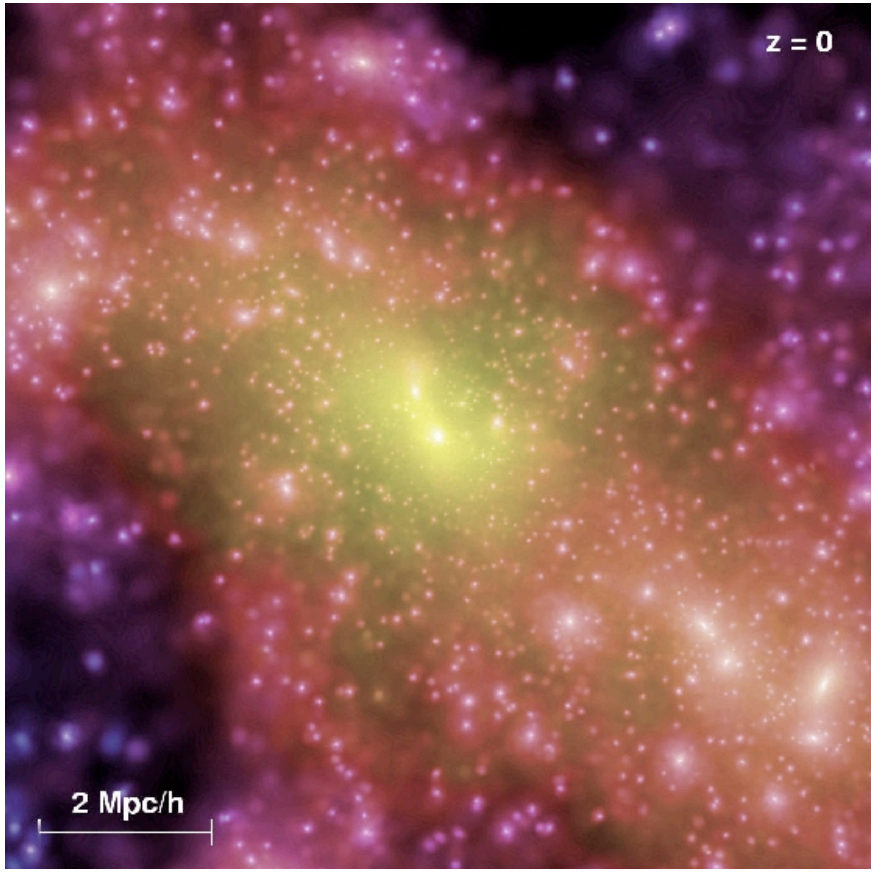
→ For Eddington limited accretion only 20 $\varepsilon_{0.1}^{-1}$ e-foldings possible!

But



We have little idea what the mass function at high redshift looks like



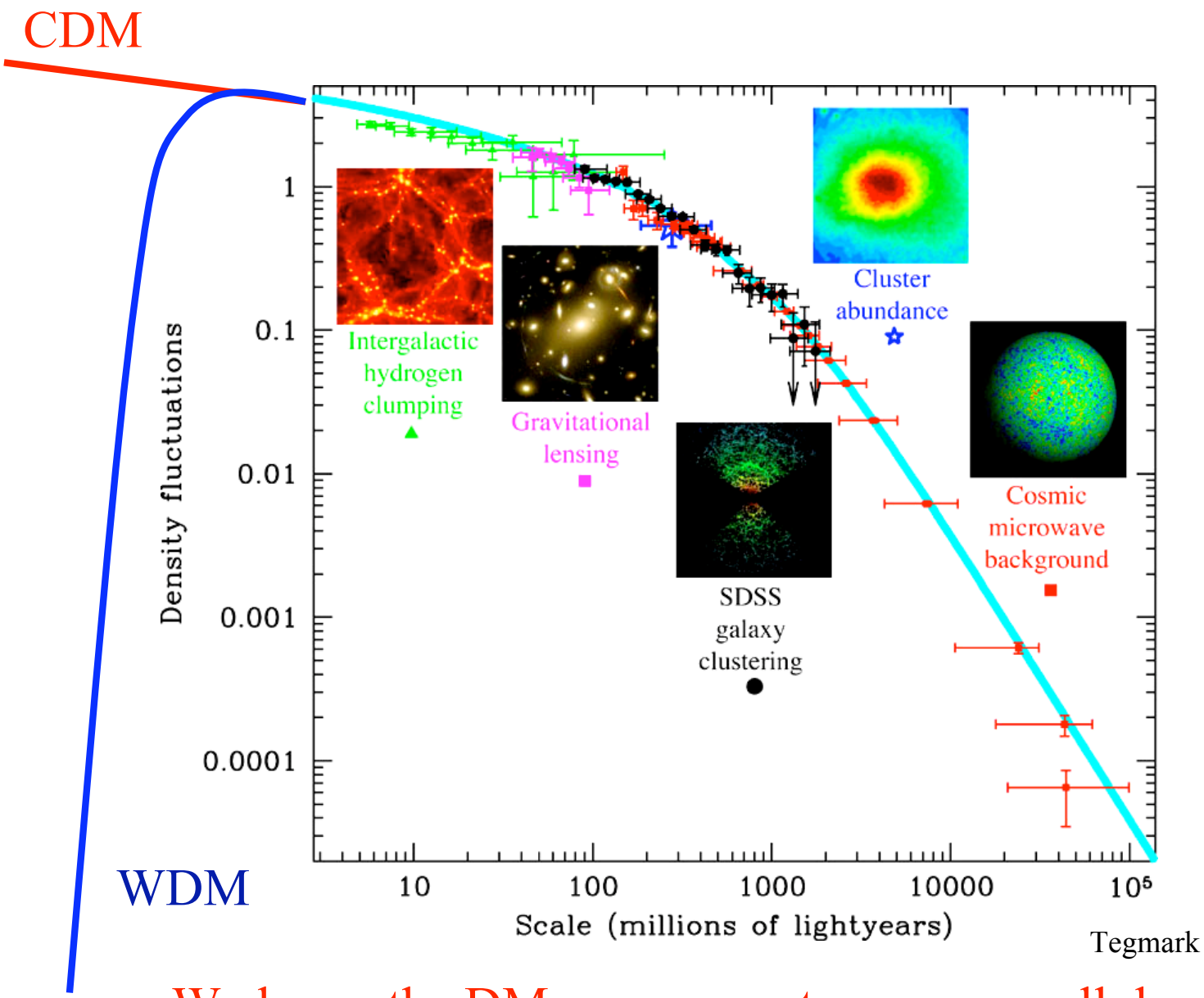


Stellar mass: 7 x 10^{10} Msol?

Springel et al 2005

Is that massive enough to host a 3 x 10^{9} Msol black hole?

When does the hierarchical growth start?

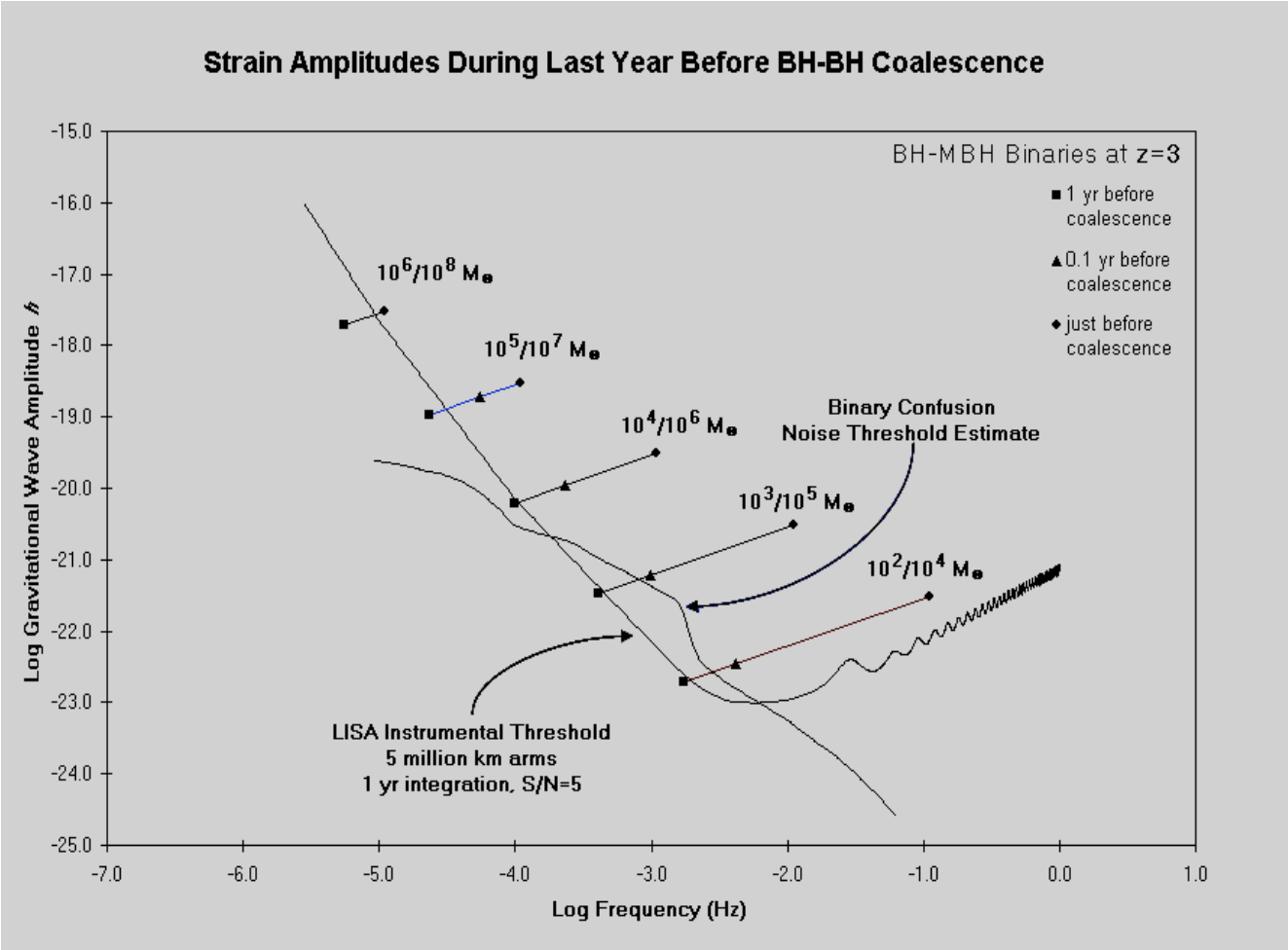


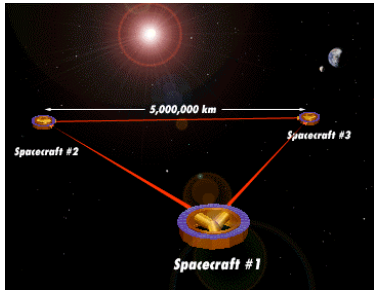
Tegmark

We know the DM power spectrum very well down to dwarf galaxy scale!

Major uncertainties for build-up of supermassive black holes

- Dark matter power spectrum on small scales
- Do intermediate mass black holes form in stellar clusters?
- Effect of stellar feedback on growth of black holes in shallow potential wells
- Kick velocities due to gravitational recoil
- The final parsec problem





LISA can see merger of supermassive black holes with high S/N

but: sensitivity at low frequency and armlength are important

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Predicted merger rates

$$\frac{dN_{\mathrm{merg}}}{dz\,dt} = 4\pi\, R^2(z)\, c\, \frac{dn_{\mathrm{ev}}}{\mathrm{dz}}$$

Comoving density of events per unit redshift

$$R(z) = \frac{c}{H_0} r(z) = \frac{c}{H_0} \int_0^z \frac{1}{\left(\Omega_{\mathrm{mat}}(1+z)^3 + \lambda\right)^{1/2}} dz$$

$$\frac{dN_{\mathrm{merg}}}{dz\,dt} \approx 0.08 \left(\frac{dn_{\mathrm{ev}}/\mathrm{dz}}{10^{-3}\,\mathrm{Mpc}^{-3}} \right) r^2(z)\,\mathrm{yr}^{-1}$$

A rough estimate

$$\rho_{\rm bh} \approx 2.5\cdot 10^5\, M_{\rm sun}\ {\rm Mpc}^{-3}$$
$$\langle M_{\rm bh}\rangle \approx 10^8\, M_{\rm sun}$$
$$\Phi_{\rm bh} \approx 2.5\cdot 10^{-3}\ {\rm Mpc}^{-3}$$

"minimum" rate:

merger rate per galaxy: $\dfrac{dN_{\rm merg}}{dz\ {\rm gal}} = 1.3\ (1+z)^{\gamma}$

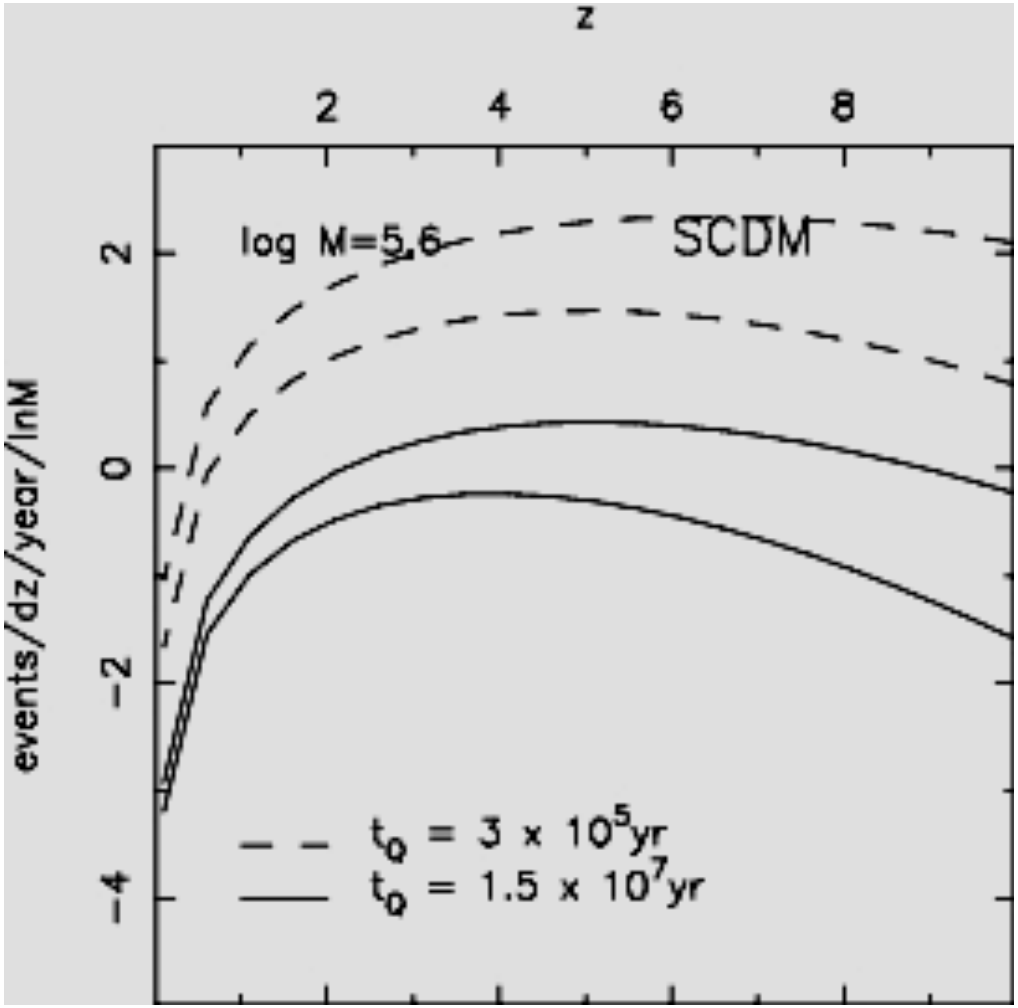
$$\frac{dN_{\rm merg}}{dz\,dt} = 0.26\ r^2(z)(1+z)^{\gamma}\ \ {\rm yr}^{-1}$$

"maximum" rate:

Assume equal mass splitting

$$\frac{dN_{\rm merg}}{dt} \approx 200\left(\frac{M_{\rm min}}{10^5\, M_{\rm sun}}\right)^{-1}\ {\rm yr}^{-1}$$

Predictions based on QSO as tracers of SMBH mergers



Haehnelt 1998

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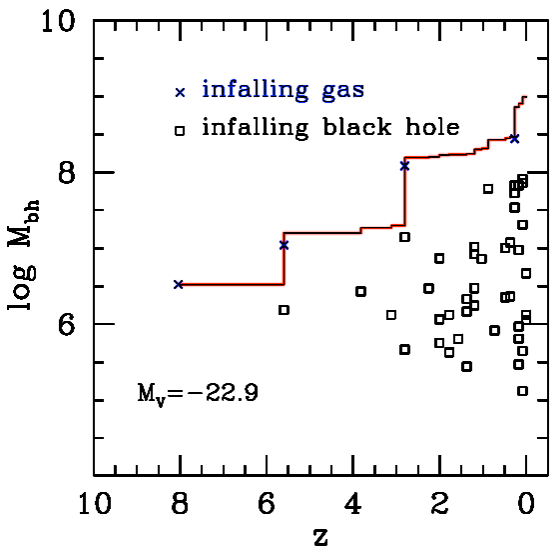
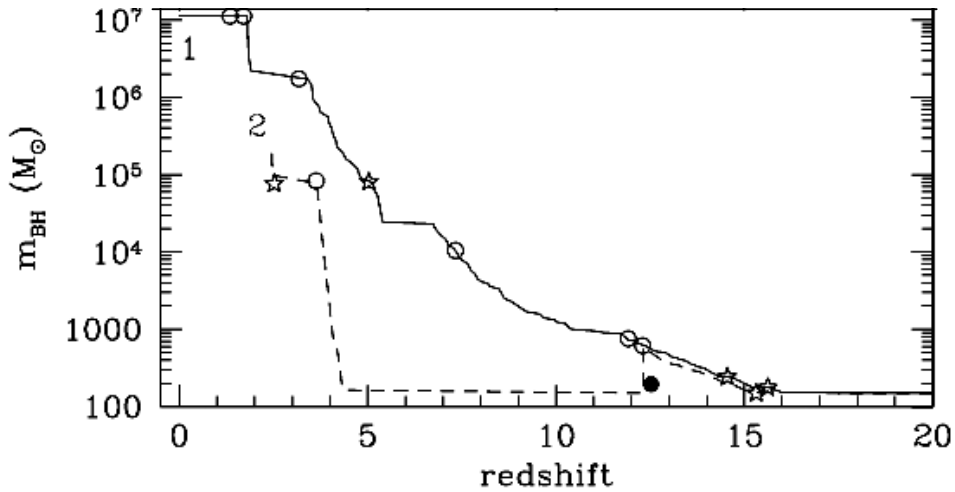


Kauffmann & Haehnelt

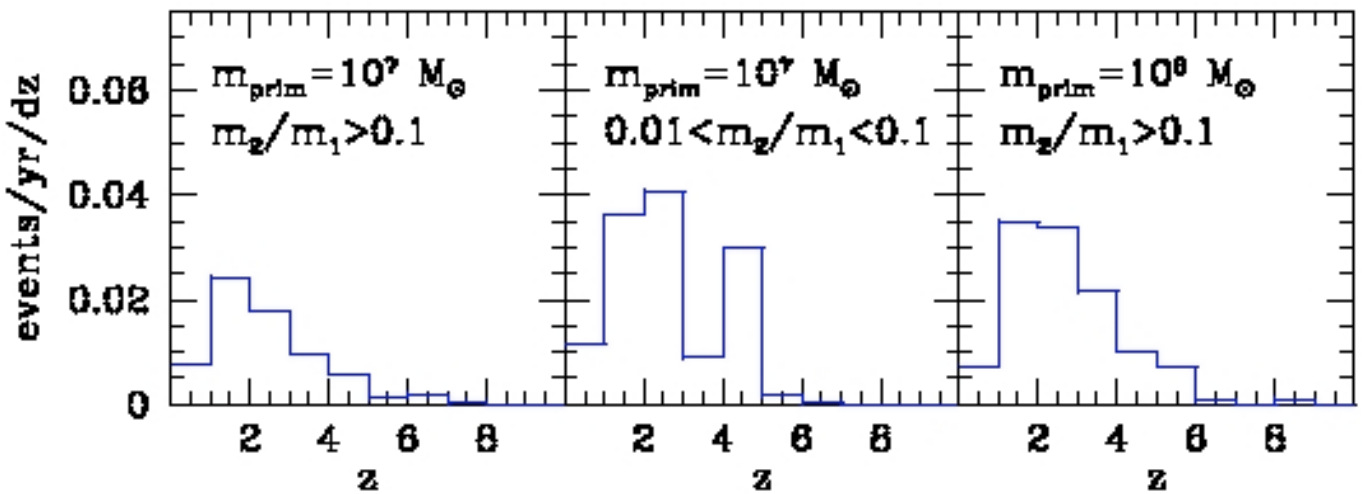


Volonteri et al.

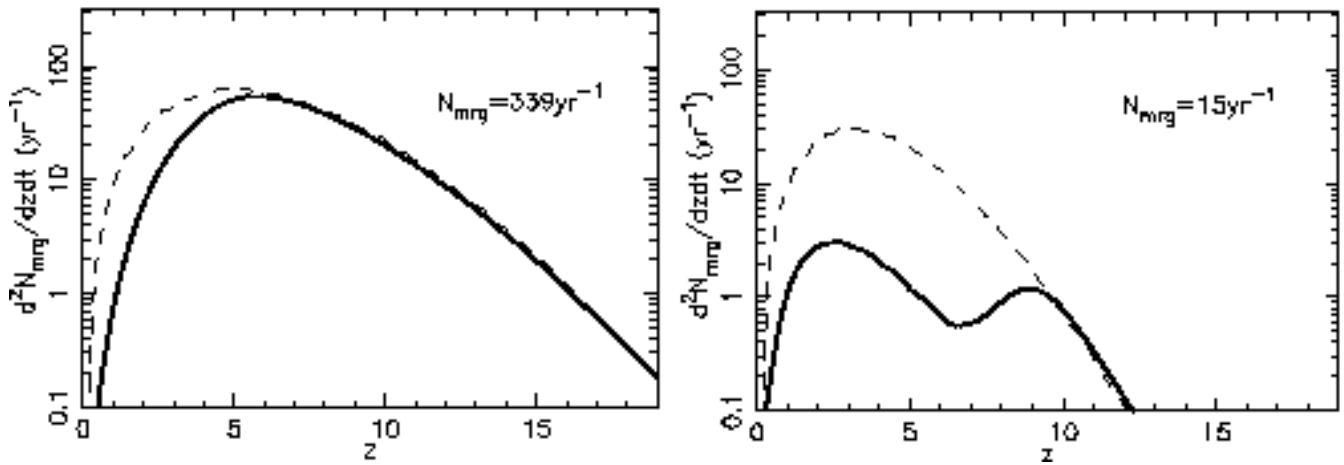
Does the hierarchical growth start with a minimum seed mass?

or

Does the hierarchical assembly extend all the way to stellar mass black holes?

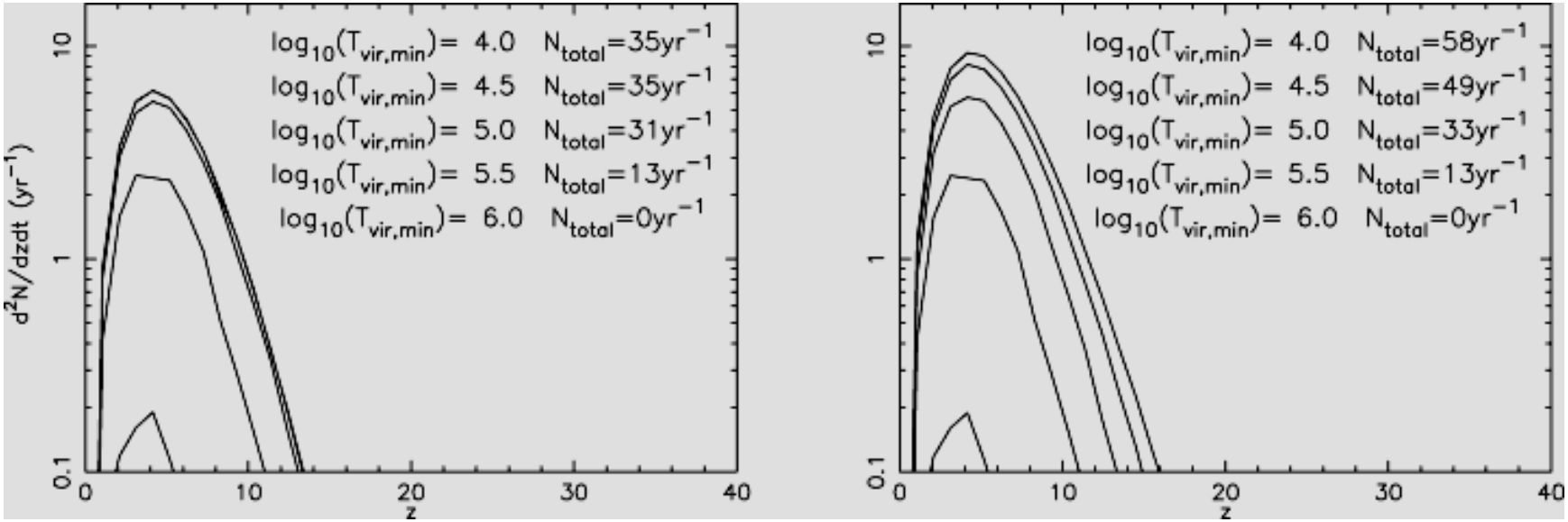


Haehnelt 2003



Wyithe & Loeb 2002

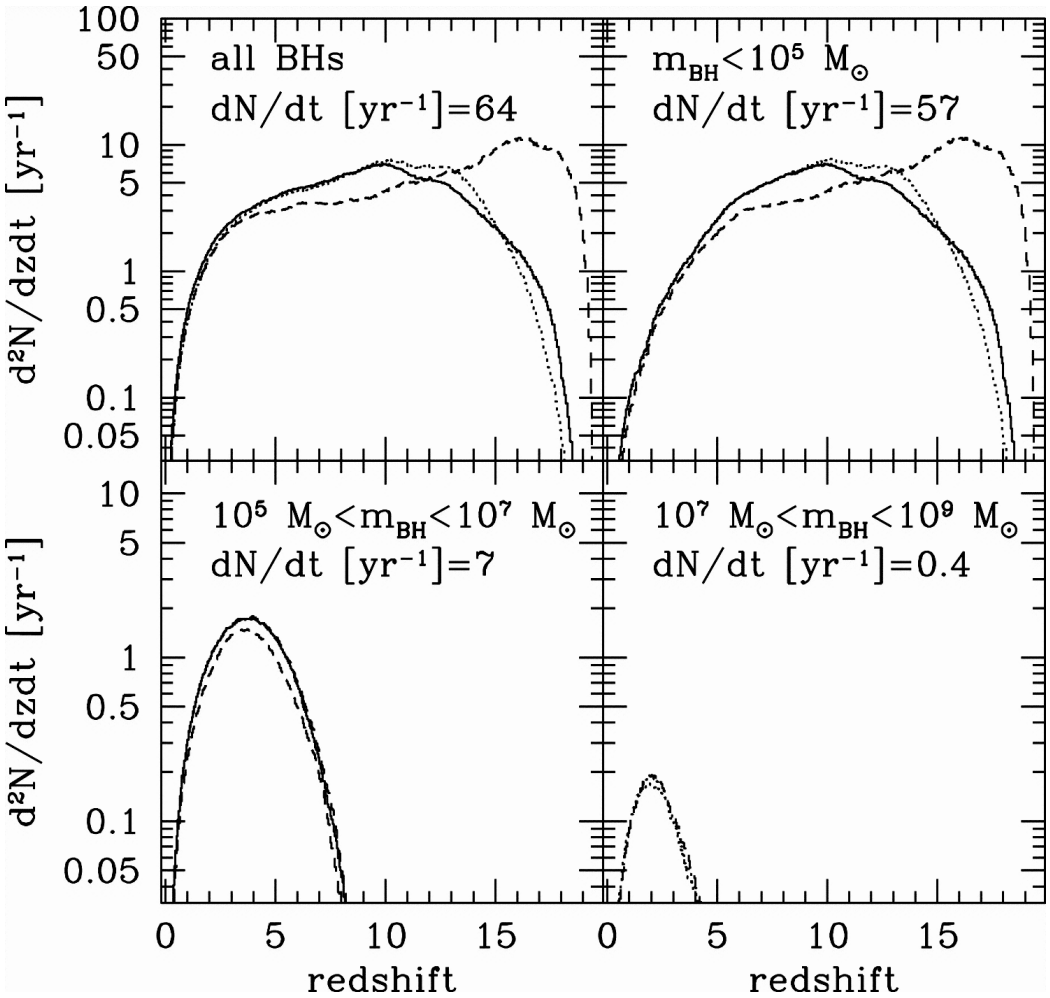
LISA will tell if massive black holes build up hierarchically all the way from stellar mass black holes



Rhook & White 2005

Rates are dominated by shallow potential wells

Predictions of Volonteri et al model



Sesana et al. 2004

Summary

The growth history of massive black holes at z<6 is observationally reasonably well characterized.

Models were black holes grow in short episods during major mergers from the cold gas available for star formation in short episods and in a more continuous accretion mode from hot gas fit the bill reasonable well. AGN feedback is an essential requirement but in which form?

The early stages of supermassive black holes are still very speculative, but future X-ray missions and LISA should help.