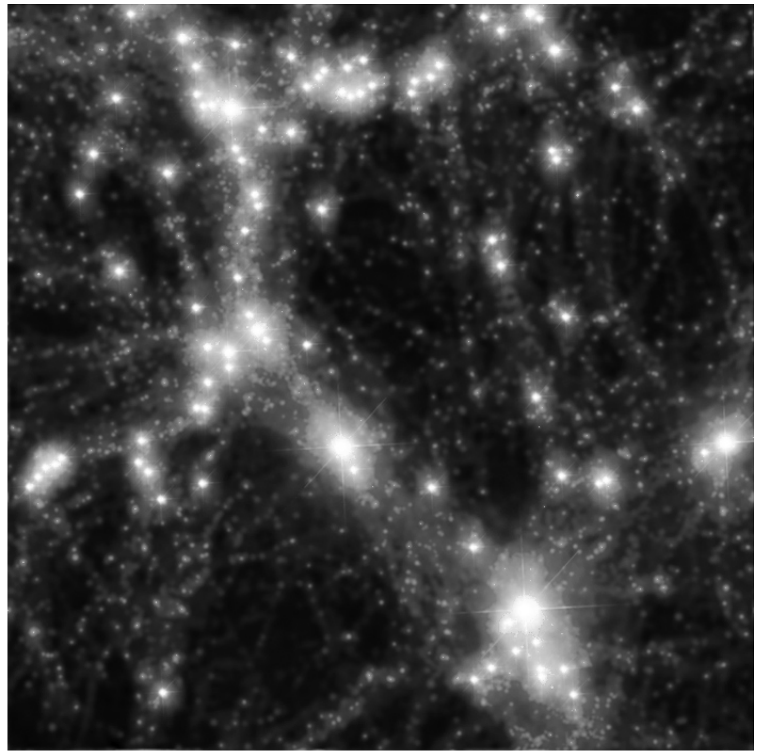
Supermassive Black Holes and Their Environments



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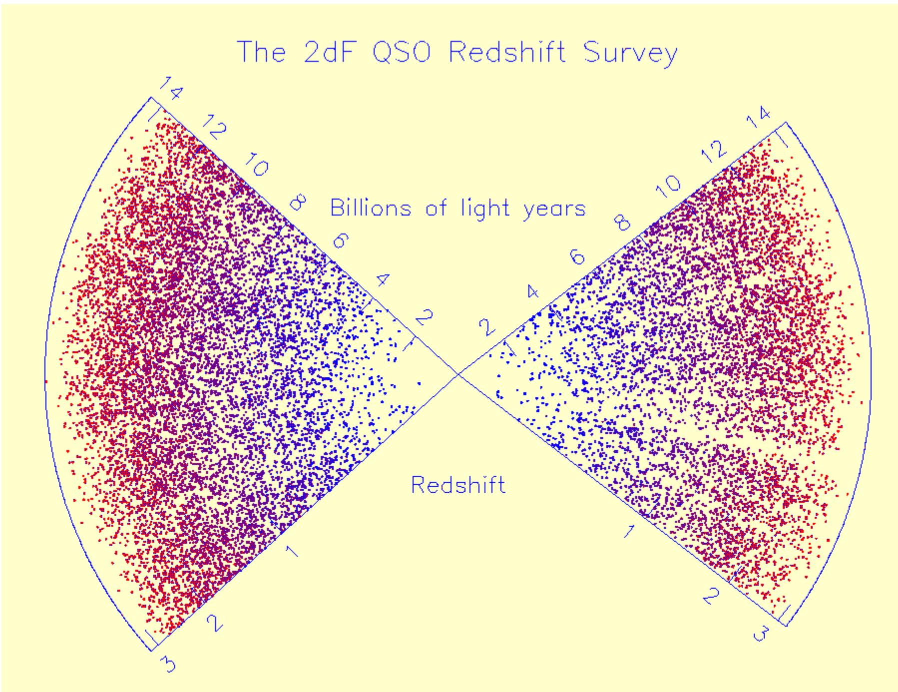
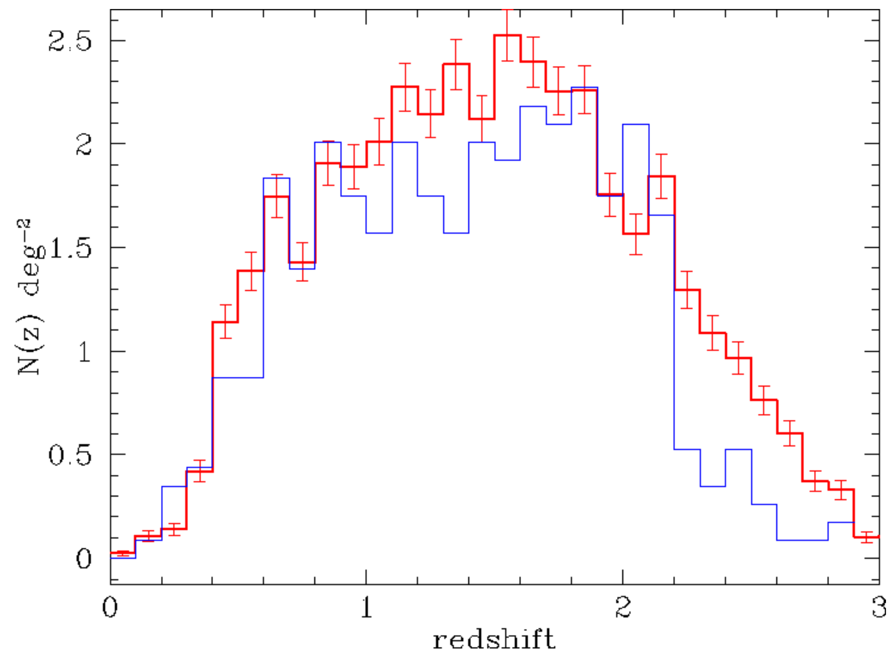
CMU, Pittsburgh

Quick overview

- Introduction
- Defining the problem/setting up the machinery
- Results/Interpreting the results
- Summary

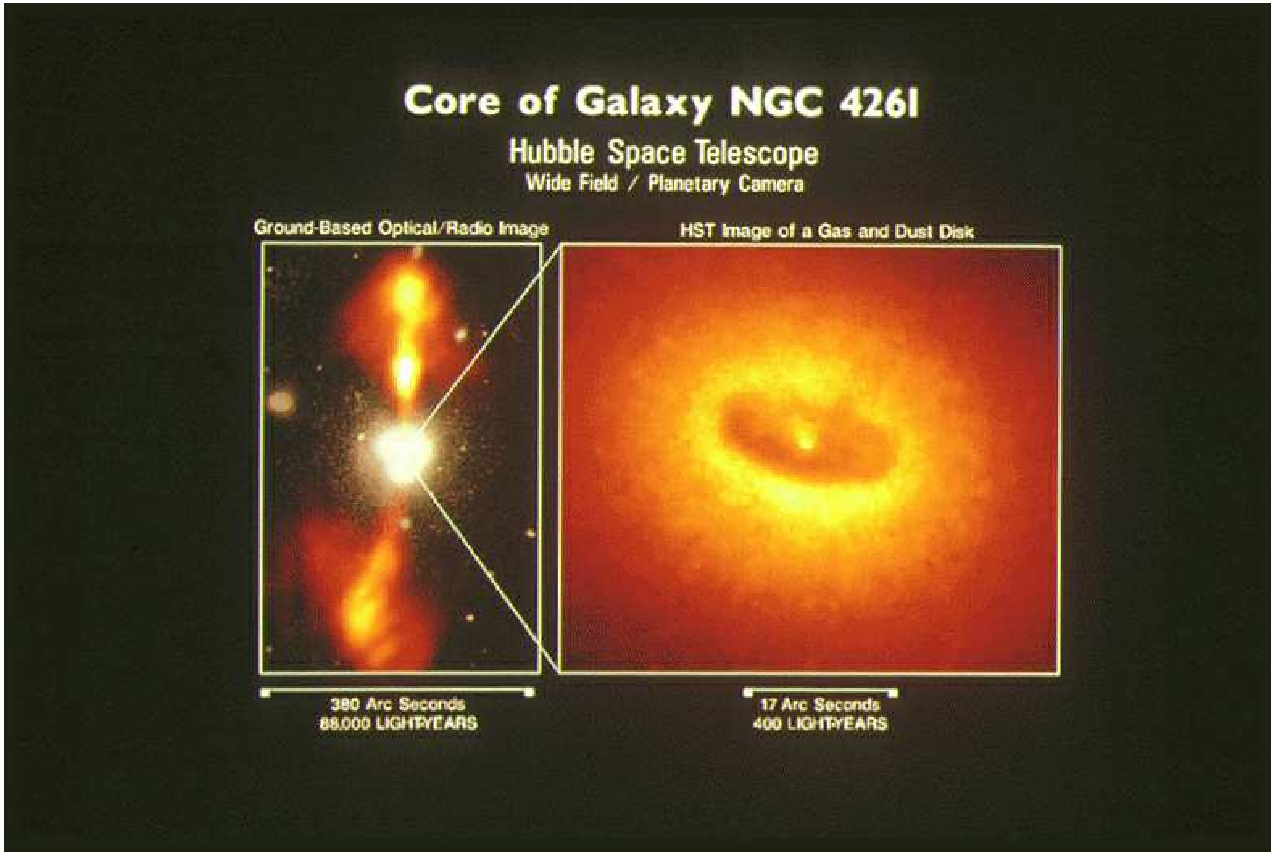
The QSO challenges





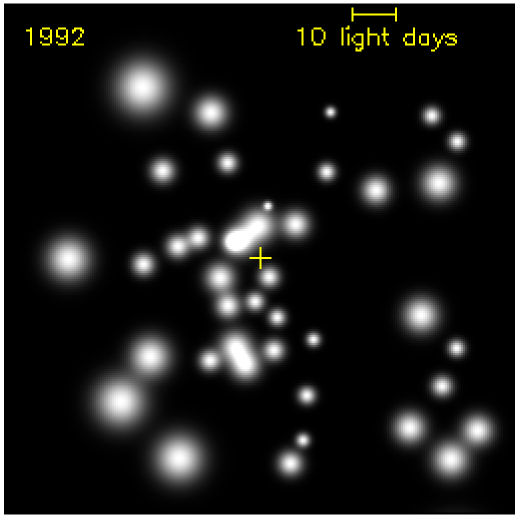
- First challenge: There are lots of them, and they have an interesting redshift distribution
- → You can't just ignore them if you want to understand galaxy formation and evolution

The QSO challenges (cont'ed)



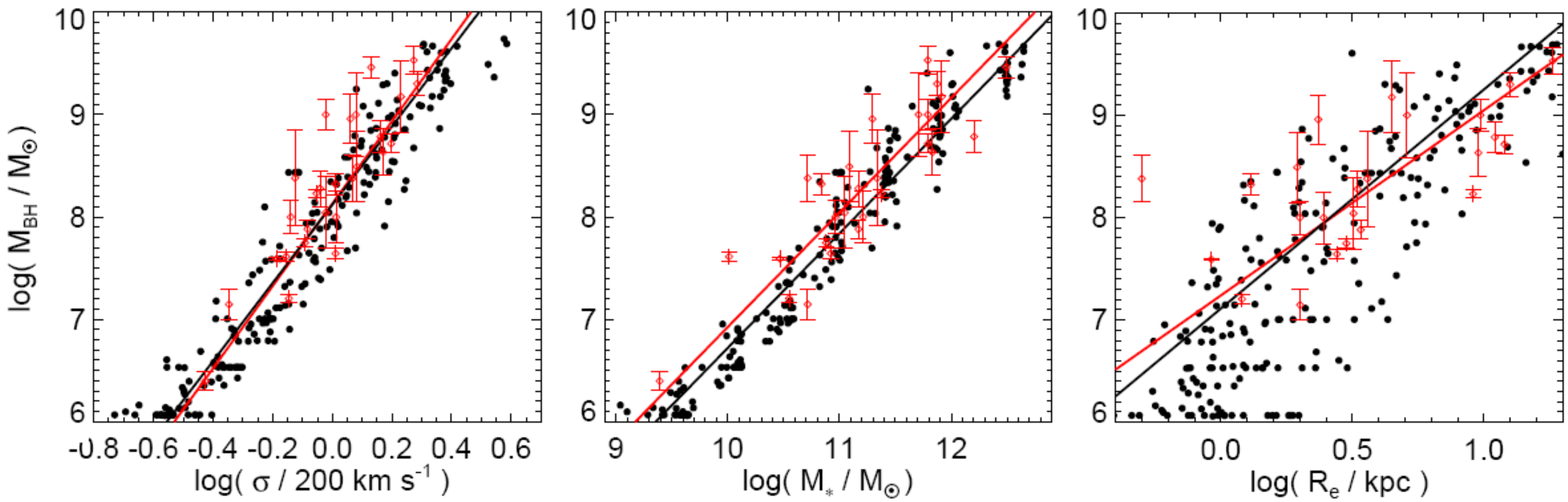
- QSOs/AGNs are powered by supermassive black holes, which sit at the centers of galaxies

The QSO challenges (cont'ed)



- Even our own Milky Way galaxy harbours a BH, albeit a "small" one ($\sim 10^6\ M_{sun}$), which we see indirectly as stars orbit around it. The BH is quite inactive.

The QSO challenges (cont'd)



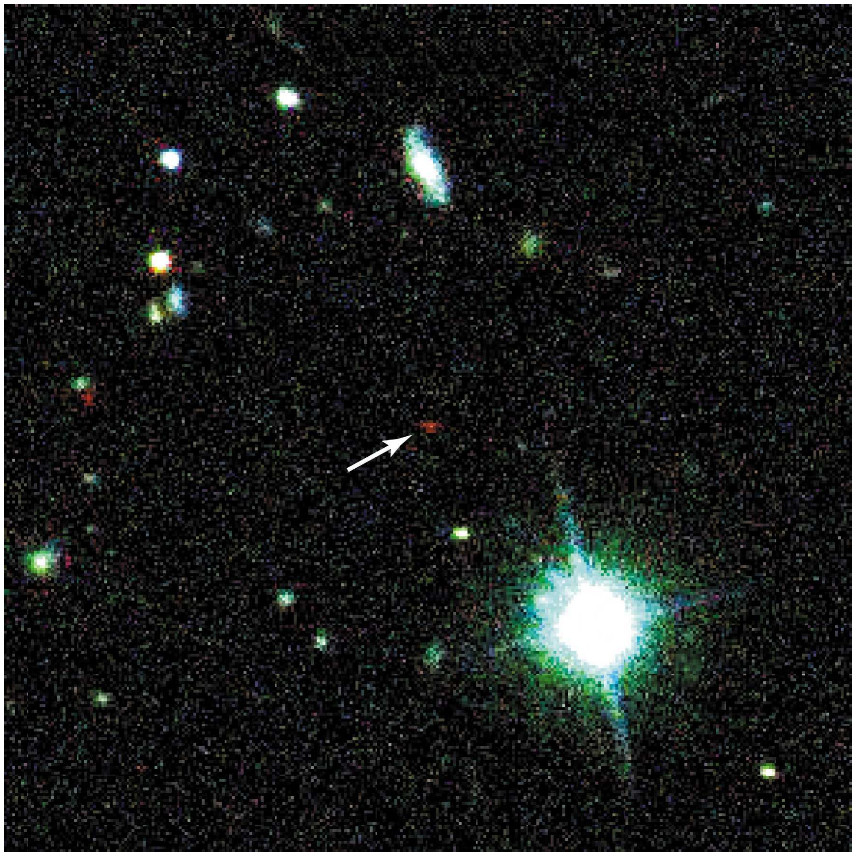
(Hopkins et al. 2007)

- Locally, we can observe AGNs and measure BH masses
- The mass of BHs is tightly coupled to properties of the hosts' bulges, with a BH fundamental plane being suggested (Hopkins et al. 2007):

$$M_{BH} \sim \sigma^{3.0} R_e^{0.43} \text{ or } M_{HB} \sim M_*^{0.54} \sigma^{2.2}$$

- Galaxy formation models have to account for this

The QSO challenges (cont'ed)



- QSOs are known out to almost z=7
- *If* local relationships are valid at high z, how is it possible these massive objects exist at such early times, in a ΛCDM cosmology that forms massive objects last?

Defining the problem

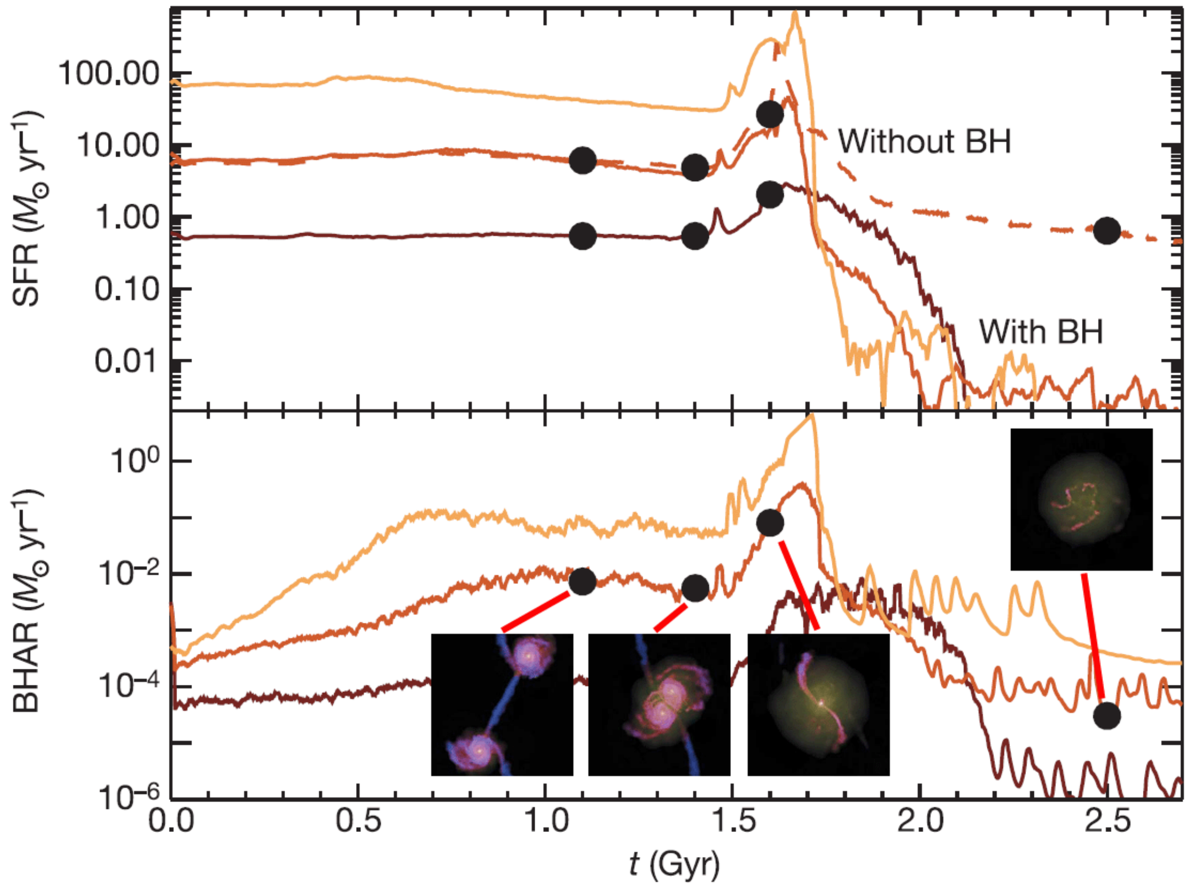
- Over the past few years, theoretical models have been developed to try to understand how SMBH are formed and how they fit into the framework of galaxy formation
- It’s a two-scale problem:
  - ~galaxy scales (and beyond): what effect has the feedback from the accretion on the host galaxy/system?
  - ~10pc or below: accretion disk, jet creation, merging of binaries…

Defining the problem (cont'ed)

- In the context of galaxy formation, small-scale problems are often "ignored"
- → assume that binaries will merge "fairly rapidly"
- → assume that some fraction of the accreted mass will be converted into feedback energy etc.
- Semi-analytical galaxy formation models have been particularly successful/useful for this problem

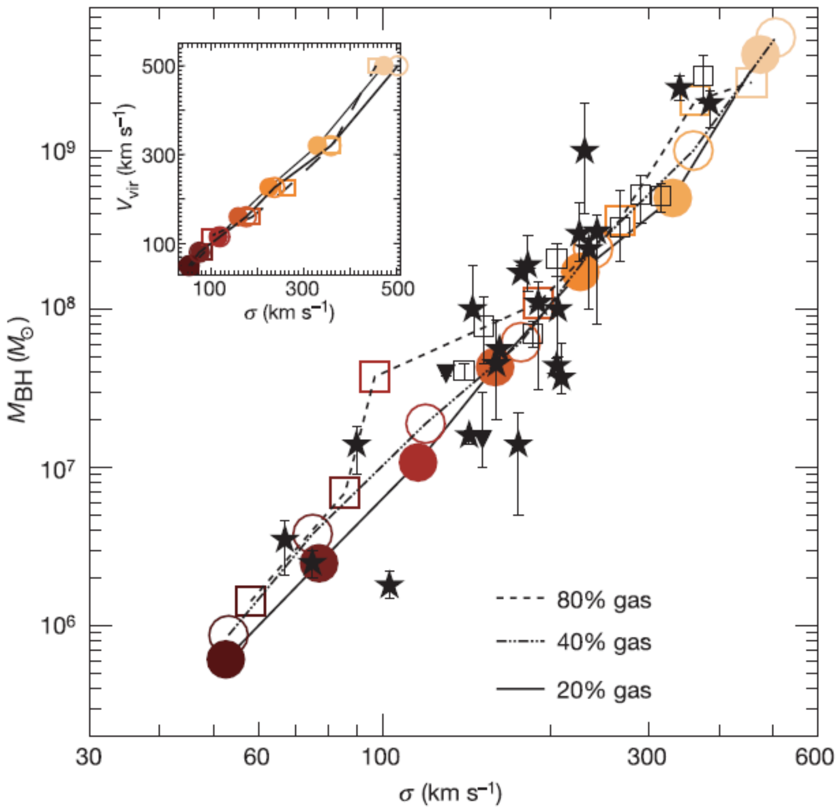
Defining the problem (cont'ed)

- But then: SPH simulations have been quite useful to study (for example) mergers of galaxies, so why not add BHs to the mix and see what happens?



(Di Matteo/ Springel/ Hernquist)

Defining the problem (cont'ed)



- Merger simulations with BHs work quite well: M_{BH}-σ relation matched (Di Matteo et al. 2005)

- But how does this actually work???

Setting up the machinery

- Take SPH code (Gadget2) that includes radiative cooling, heating, star formation/supernova feedback (Springel et al. 2003) and add black hole particles
- black hole particle = collisionless 'sink' particle that can grow in mass either via accretion of nearby gas or by merging with another BH
- Gas accretion: Bondi-Hoyle

$$\sim M_{BH}^2 \rho/(c_s^2+v^2)^{3/2}$$

ρ, c_s density, sound speed of ISM gas

M_{BH}, v mass, velocity of BH

$\rightarrow$unresolved accretion related to resolved larger-scale gas distribution

Setting up the machinery (cont'ed)

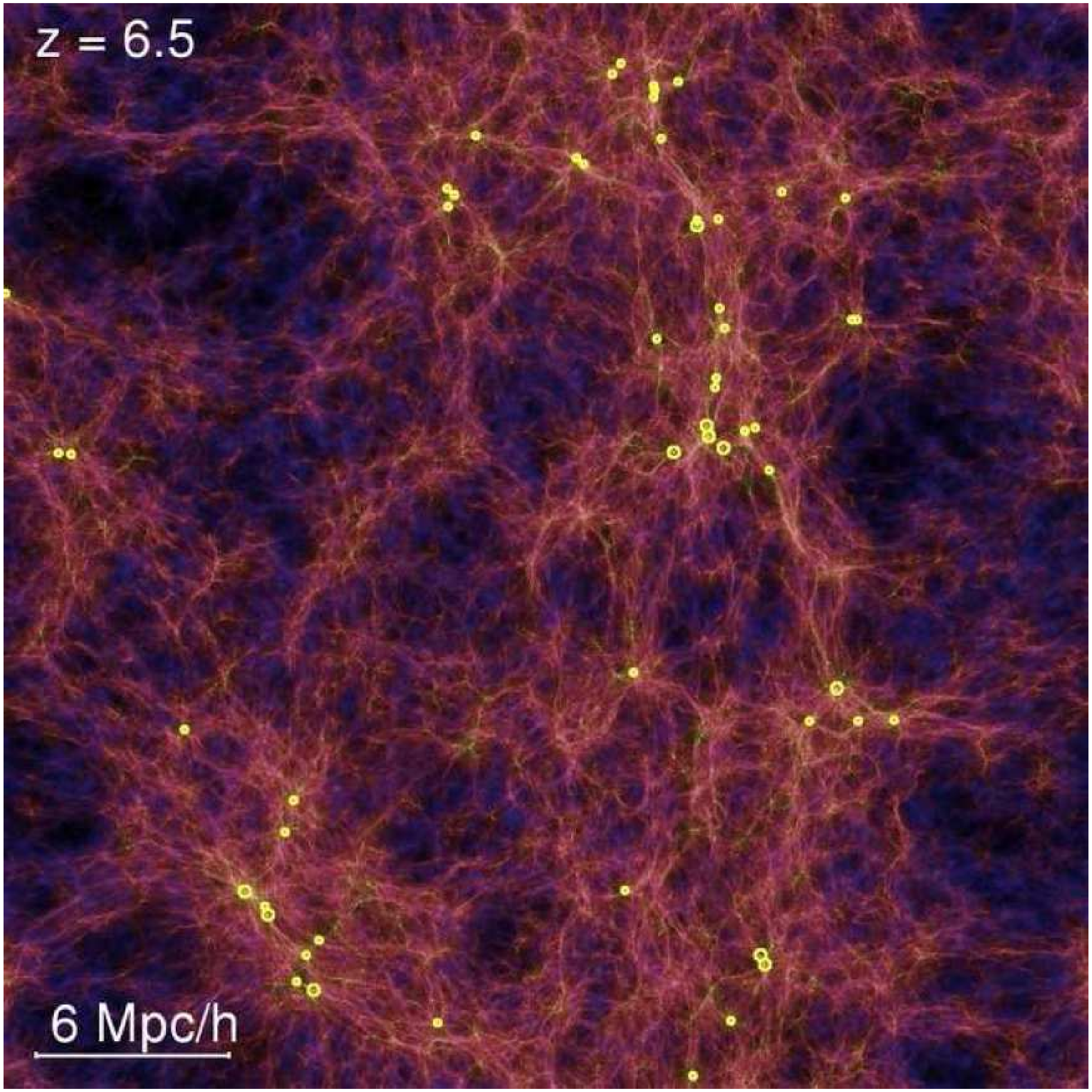
- Impose maximum for accretion: 3 times Eddington (consistent with models: Volonteri & Rees 2006)
- Set mass-to-energy conversion efficiency, i.e. relate gas accretion rate to radiated luminosity, set to standard value of 10% (for radiatively efficient accretion disk into non-rapidly spinning BH, Shakura & Sunyaev 1973)
- Set fraction of energy that can couple to surrounding gas (free parameter, determined from suites of merger sims so that M_{BH}-σ fits), 5%; note it's assumed to be isotropically
- Allow BHs to merge if they're close and if their relative velocities are low (basically at resolution limit of sim)
- → main idea: when a BH accretes material you want immediate feedback, right in the nucleus of the galaxy

Setting up the machinery (cont'ed)

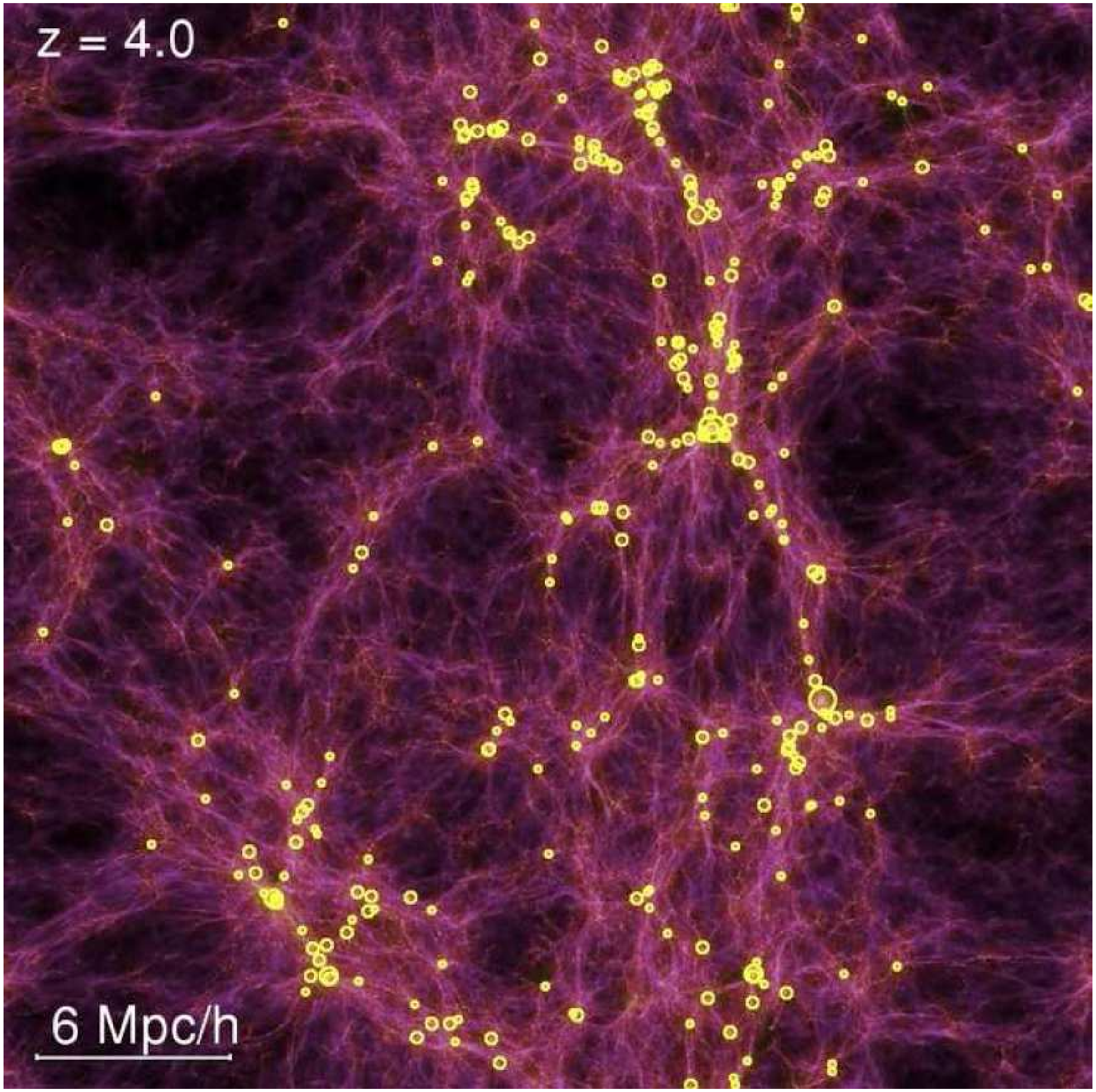
- HERE: Instead of using two merging galaxies, use cosmological volume
- Simulation suite, I'll focus on *BHCosmo*, *l = 33.75* Mpc/*h*, $N_p = 2*486^3$, $m_{DM} = 2.75*10^7$ m_{sun}/h, $m_{gas} = 4.24*10^6$ m_{sun}/h, with WMAP1 parameters
- Use FOF group finder *on the fly*, place seed BH of mass 10^5 M_{sun}/h in each halo of mass 10^{10} M_{sun}/h (which doesn't already have one)
- Run at Pittsburgh Supercomputer Center, on Cray XT3 (2k procs) over four weeks, number of floating point operations exceeding Millennium Run's (computationally ***very*** expensive when compared with semi-analytical approach!)

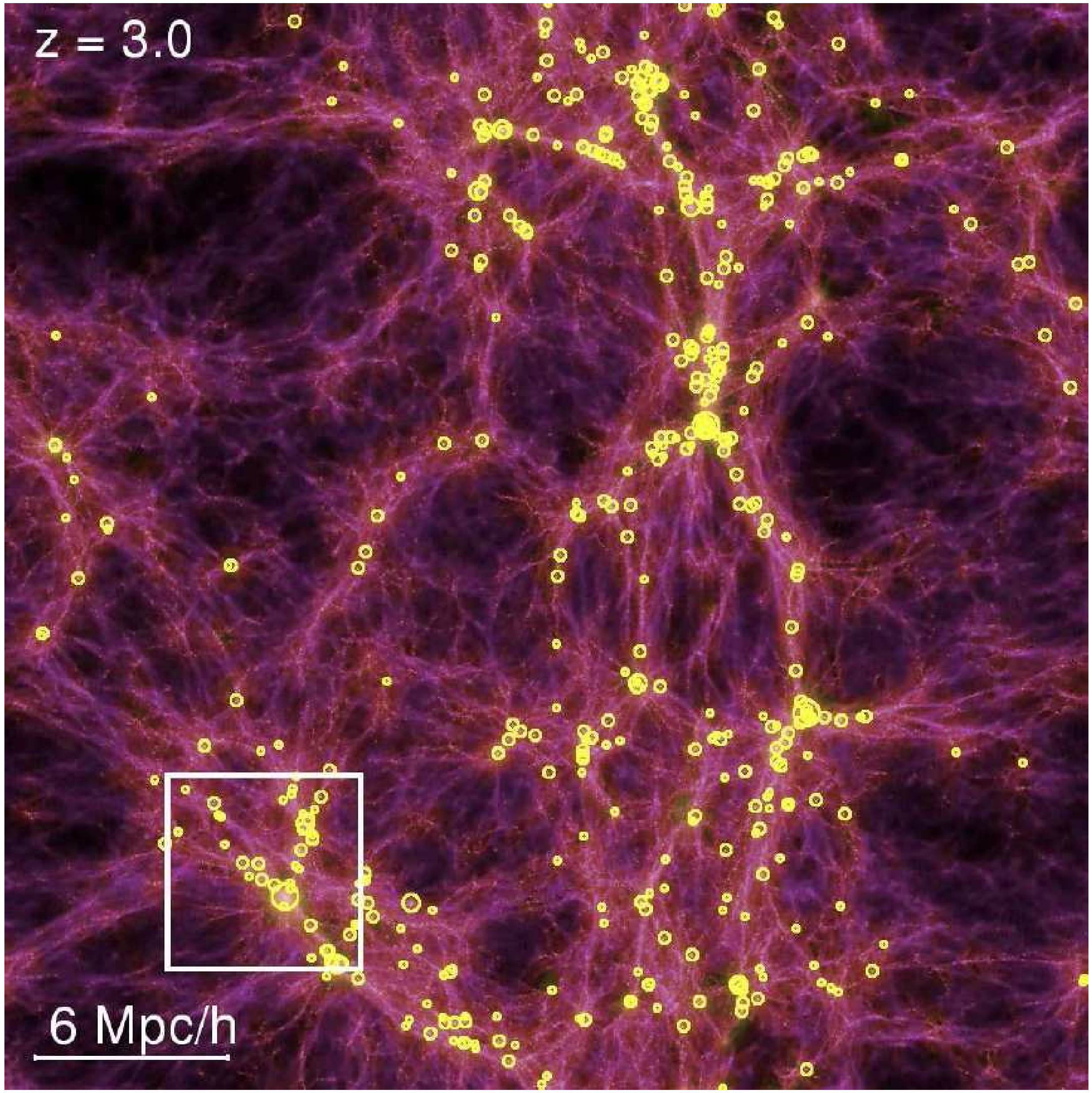
So what did we get?

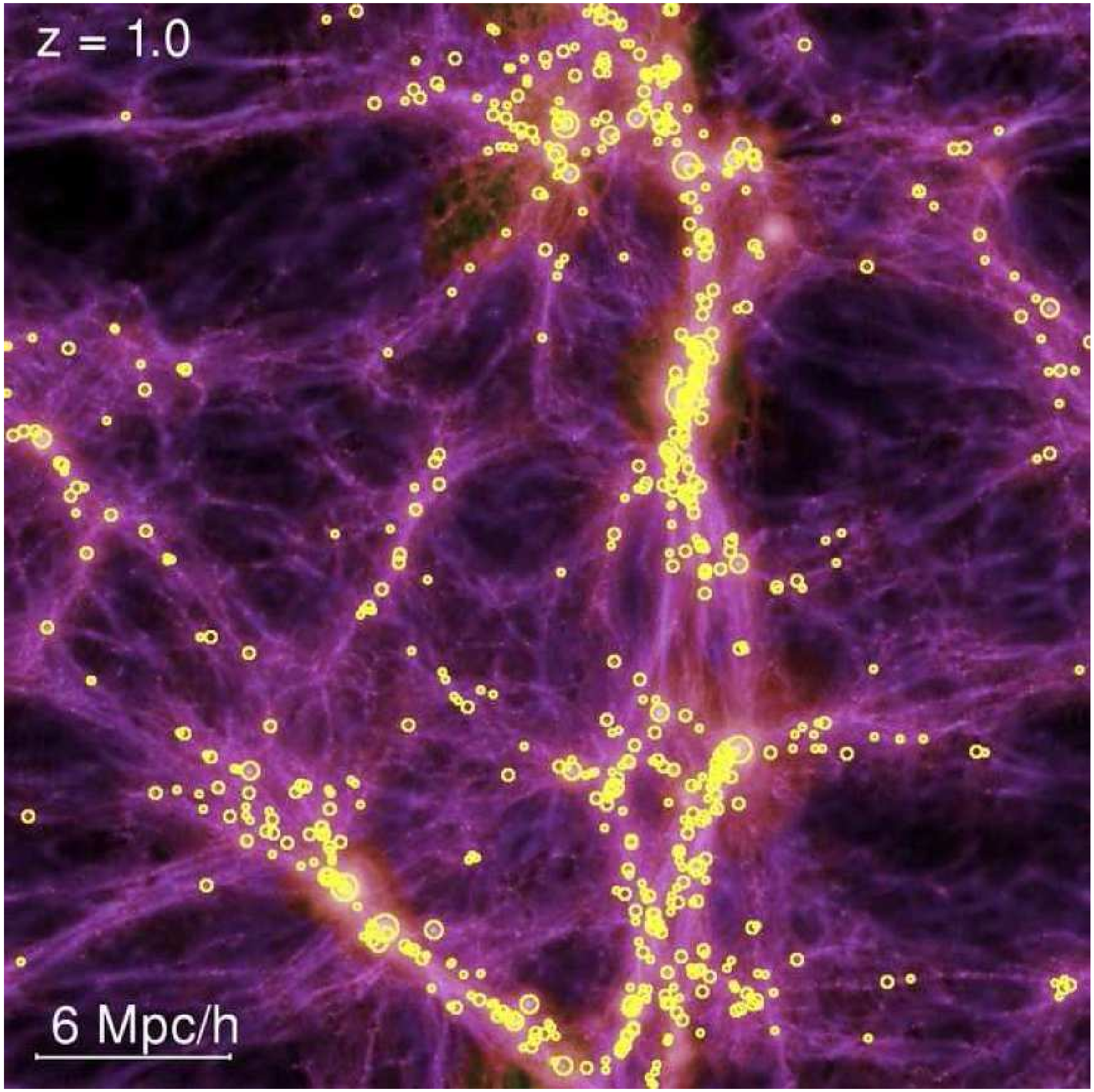
- Simulation run until *z=1*
- Each time a BH is active (accretion, merger), data output → over 3,000,000 such events
- At *z=1*, a bit more than 3,000 BHs in volume
- For each BH, we have a detailed merger tree
- But first, some pictures…



(Di Matteo et al., arXiv:0705.2269)

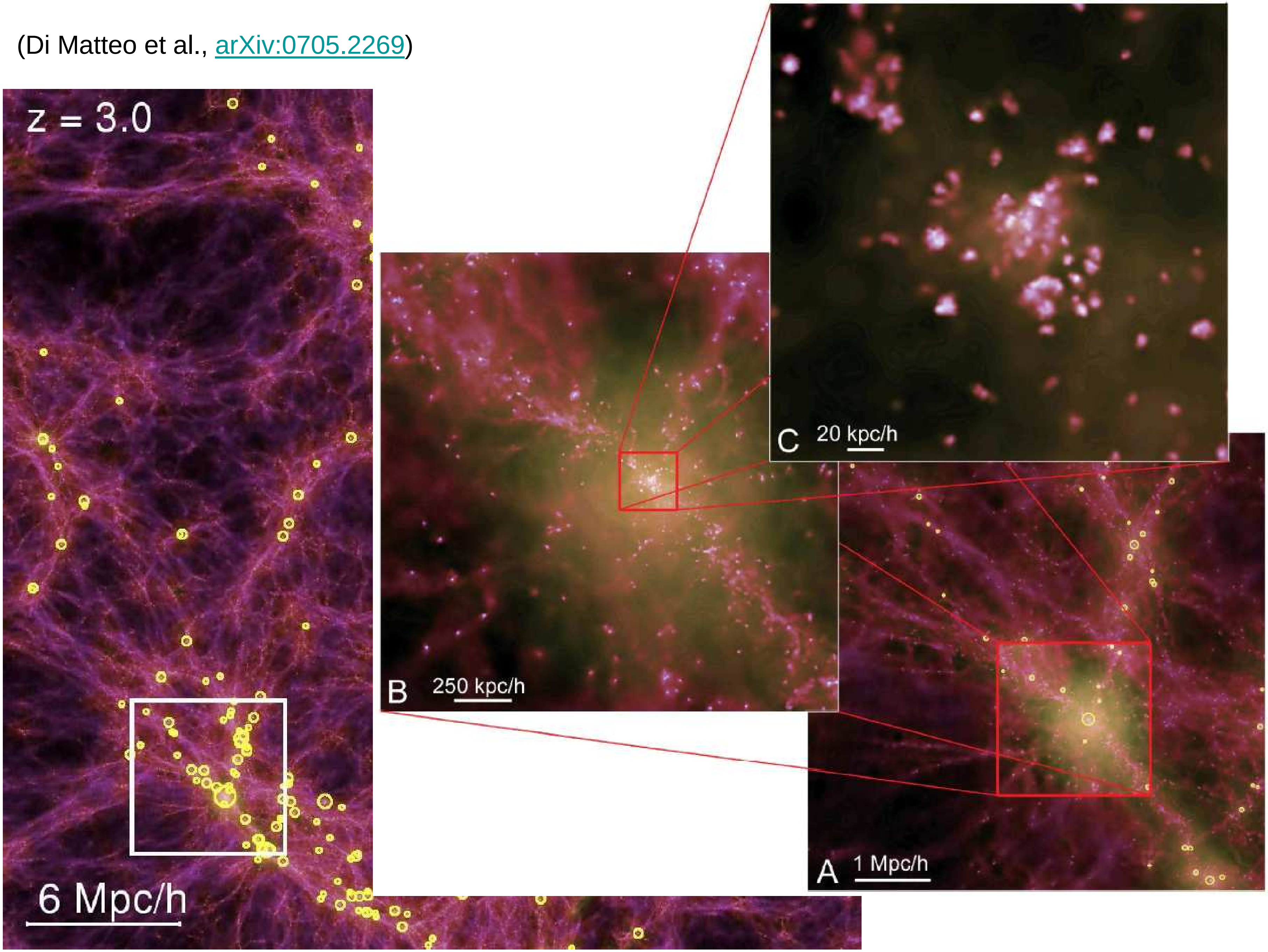

z = 4.0
6 Mpc/h

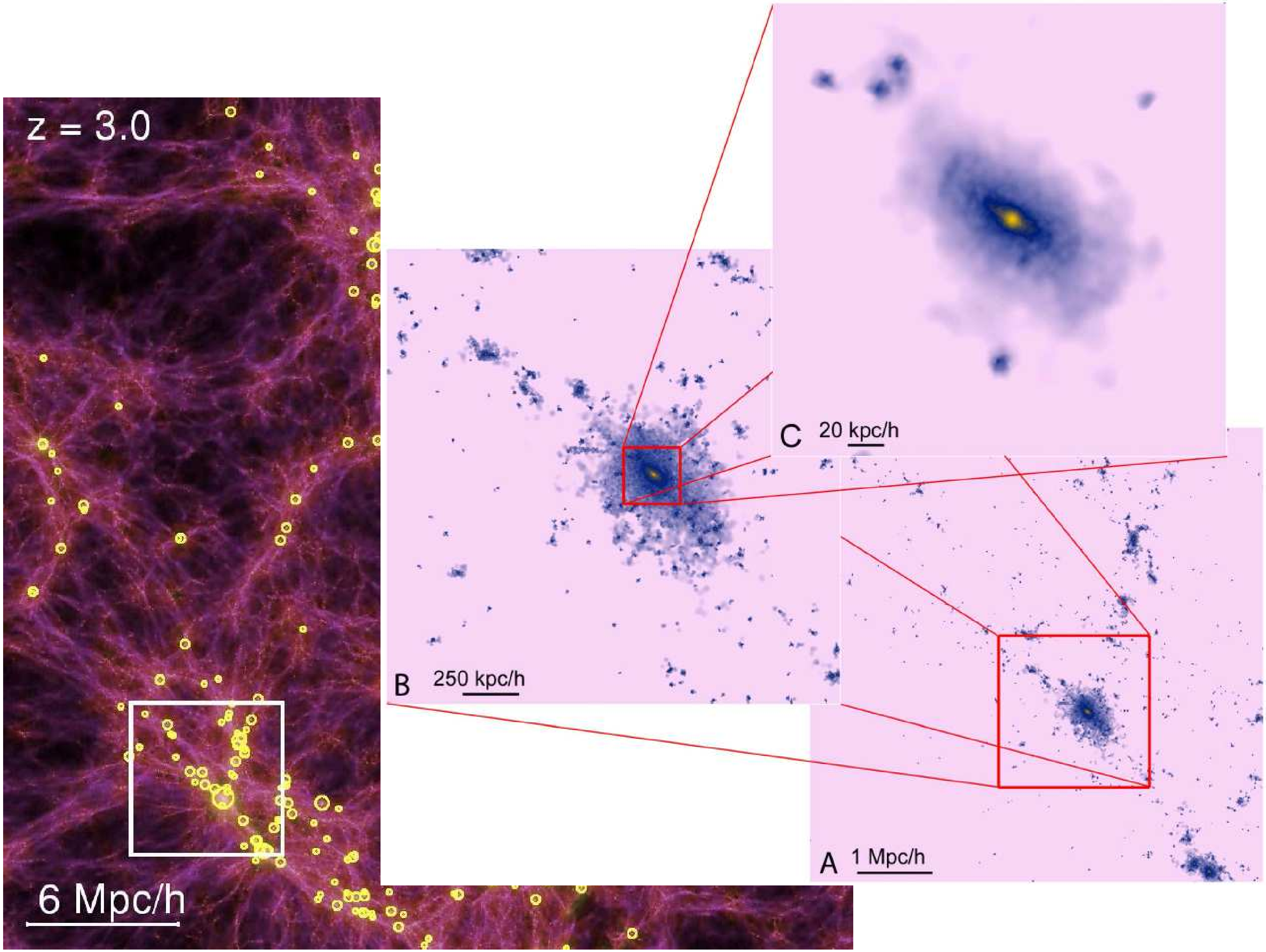

z = 3.0
6 Mpc/h

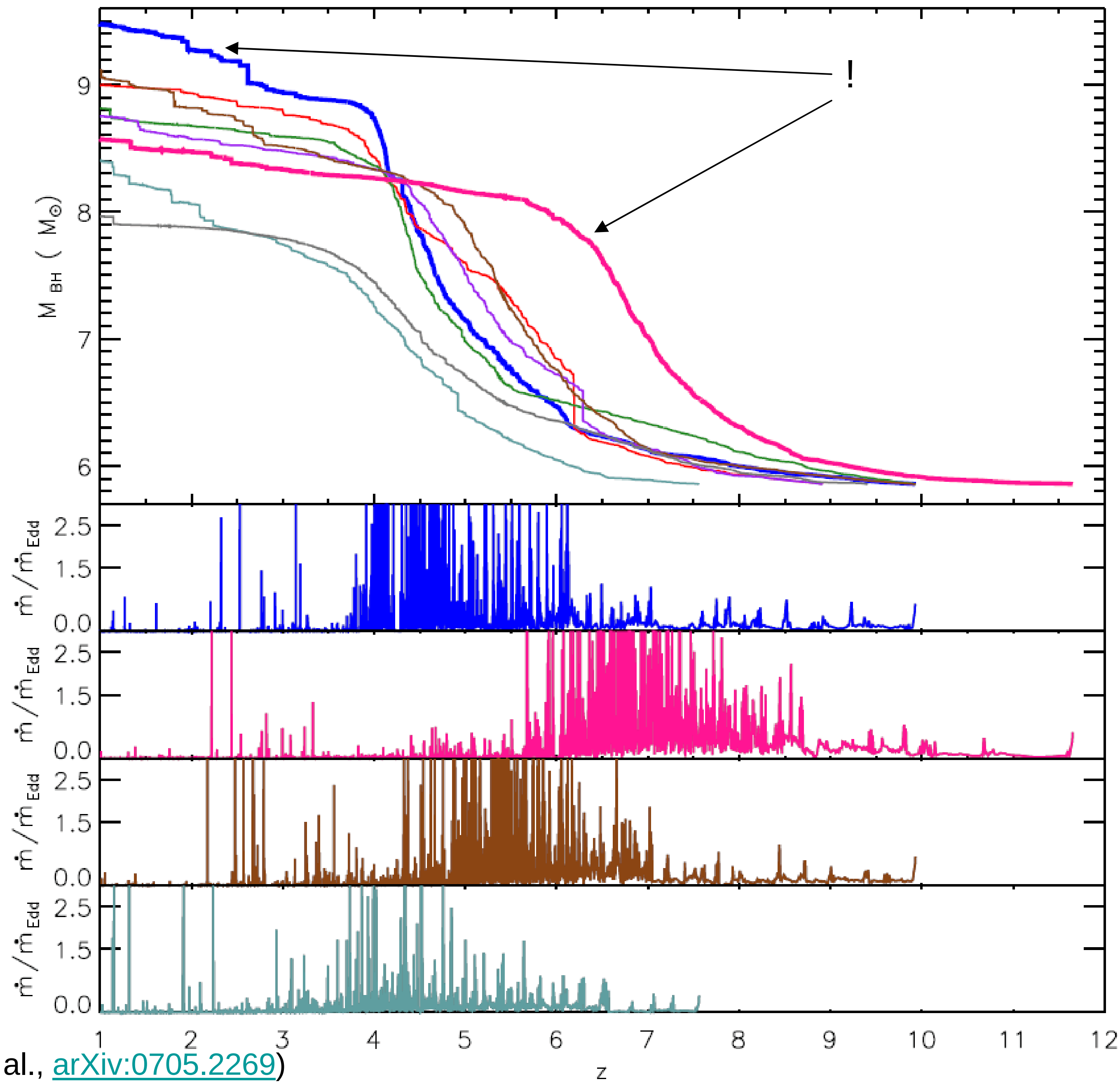


z = 1.0
6 Mpc/h

(Di Matteo et al., arXiv:0705.2269)




z = 3.0
6 Mpc/h
B
250 kpc/h
C
20 kpc/h
A
1 Mpc/h



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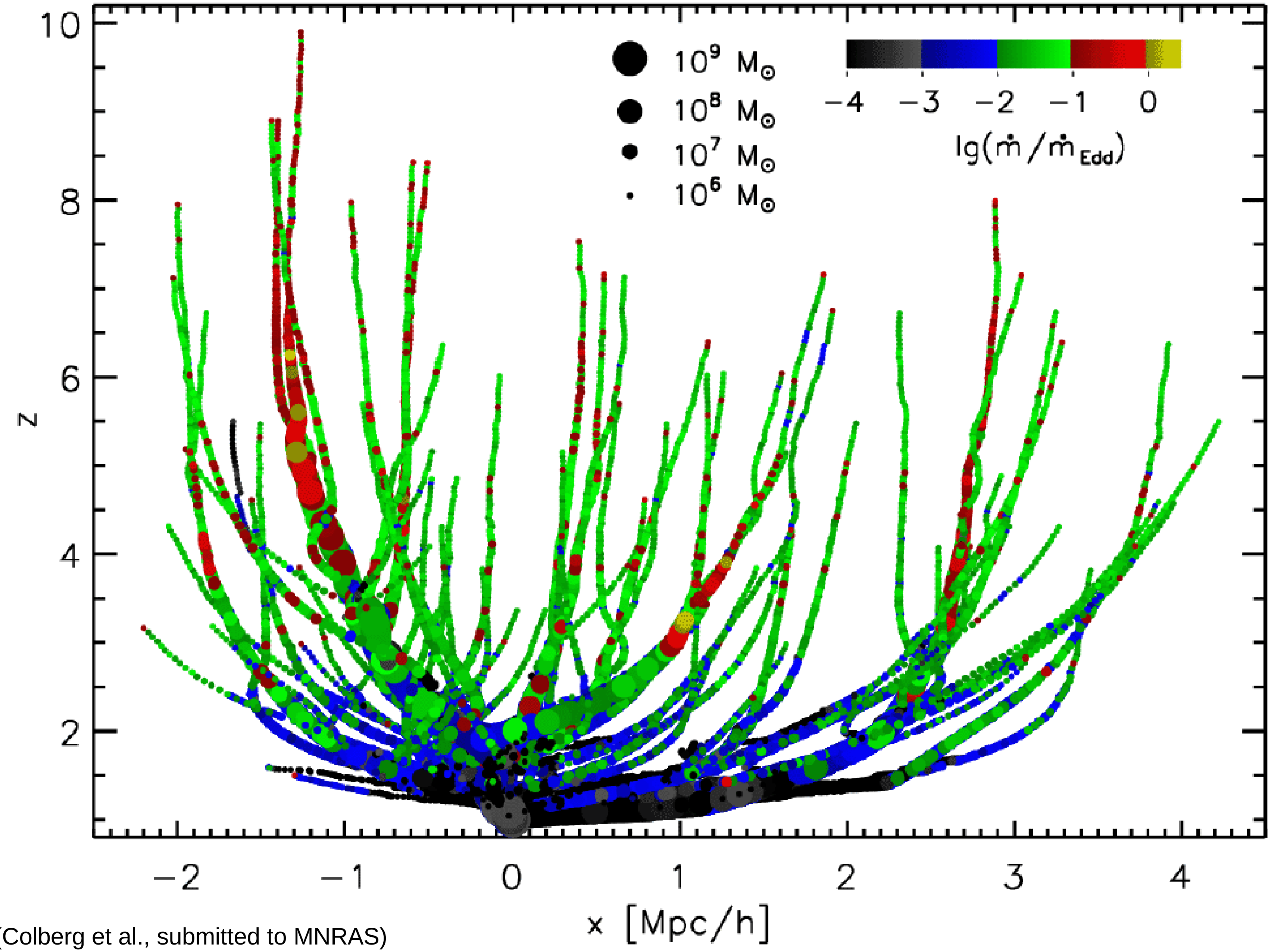
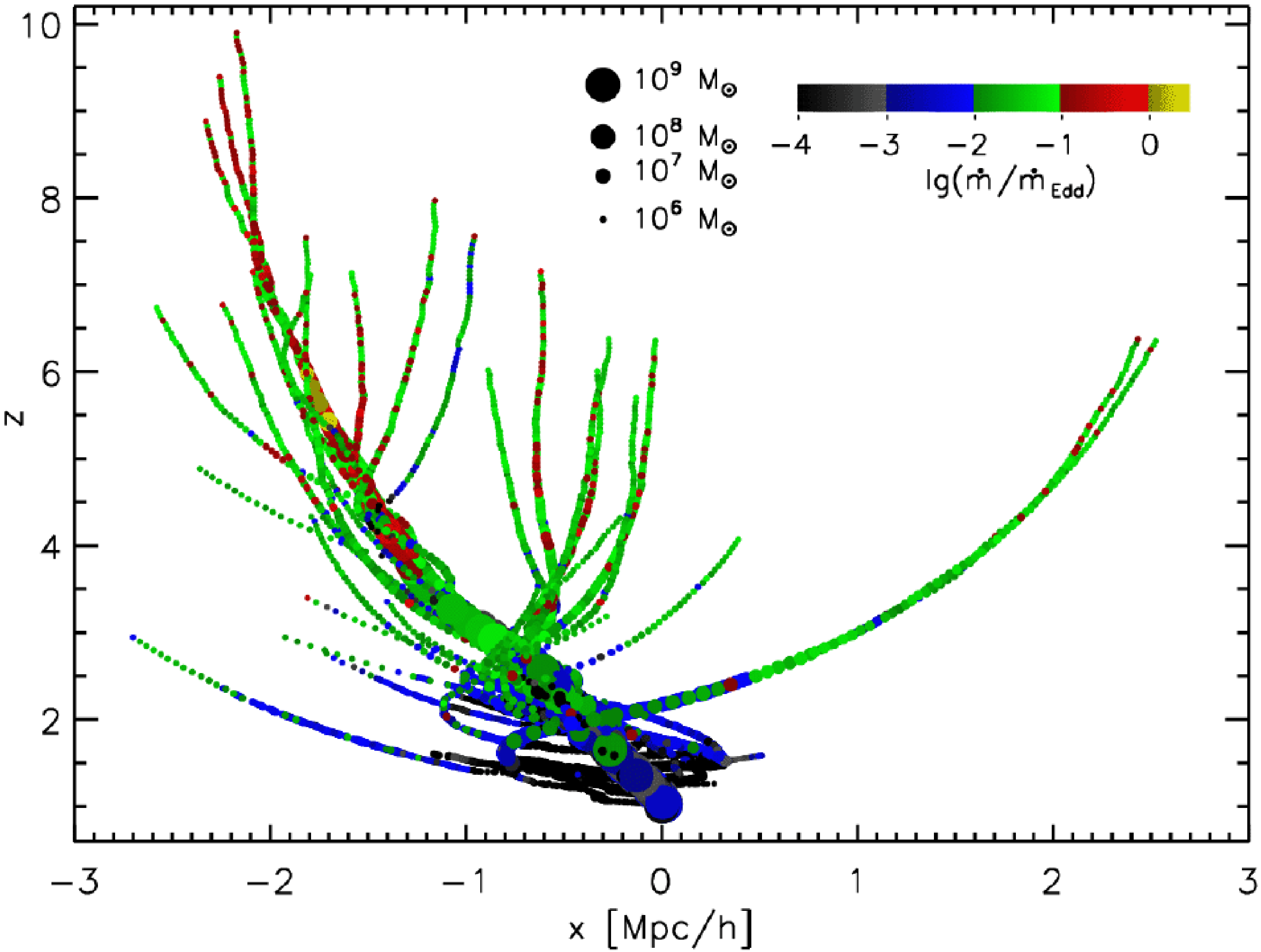
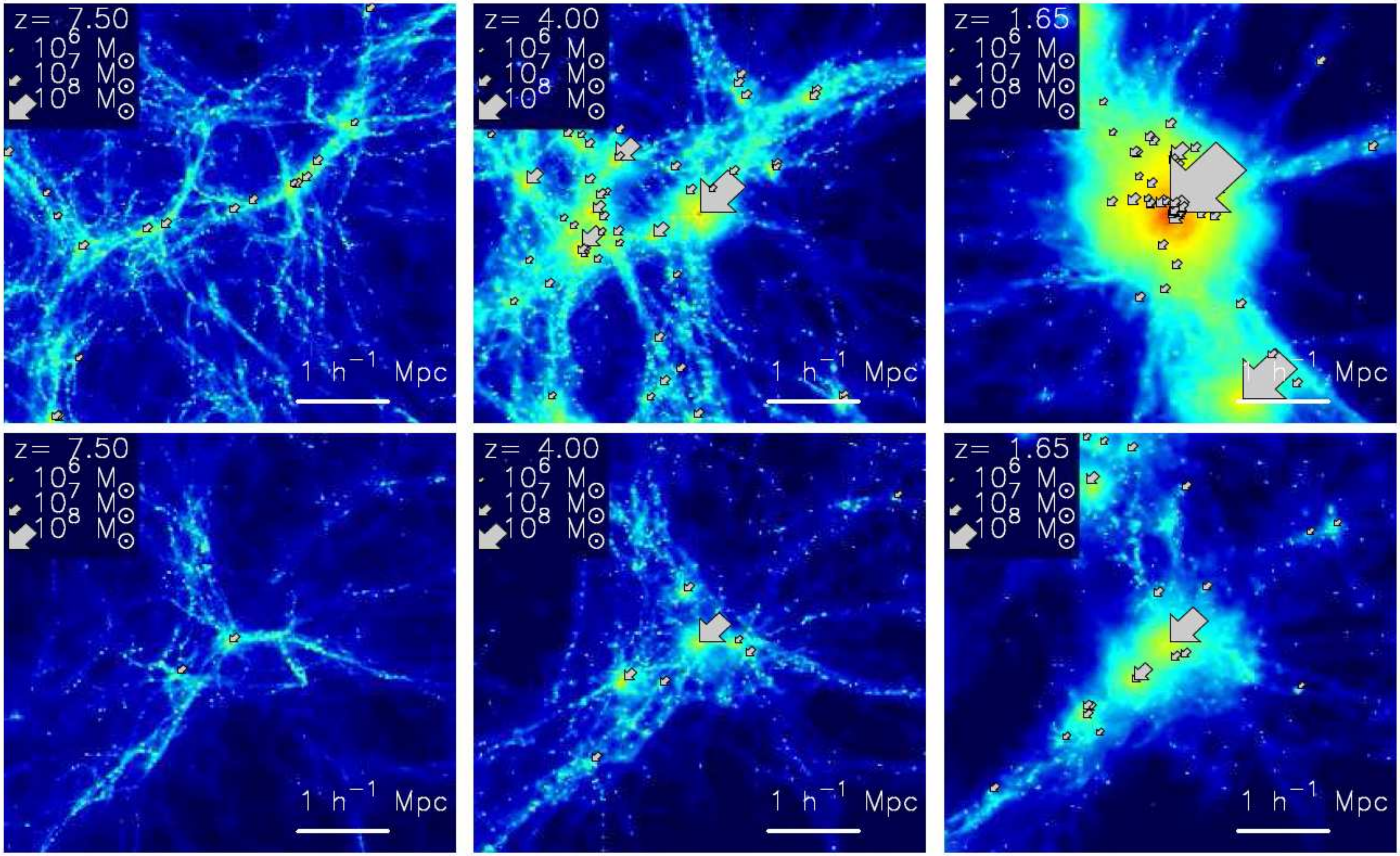


(Colberg et al., submitted to MNRAS)

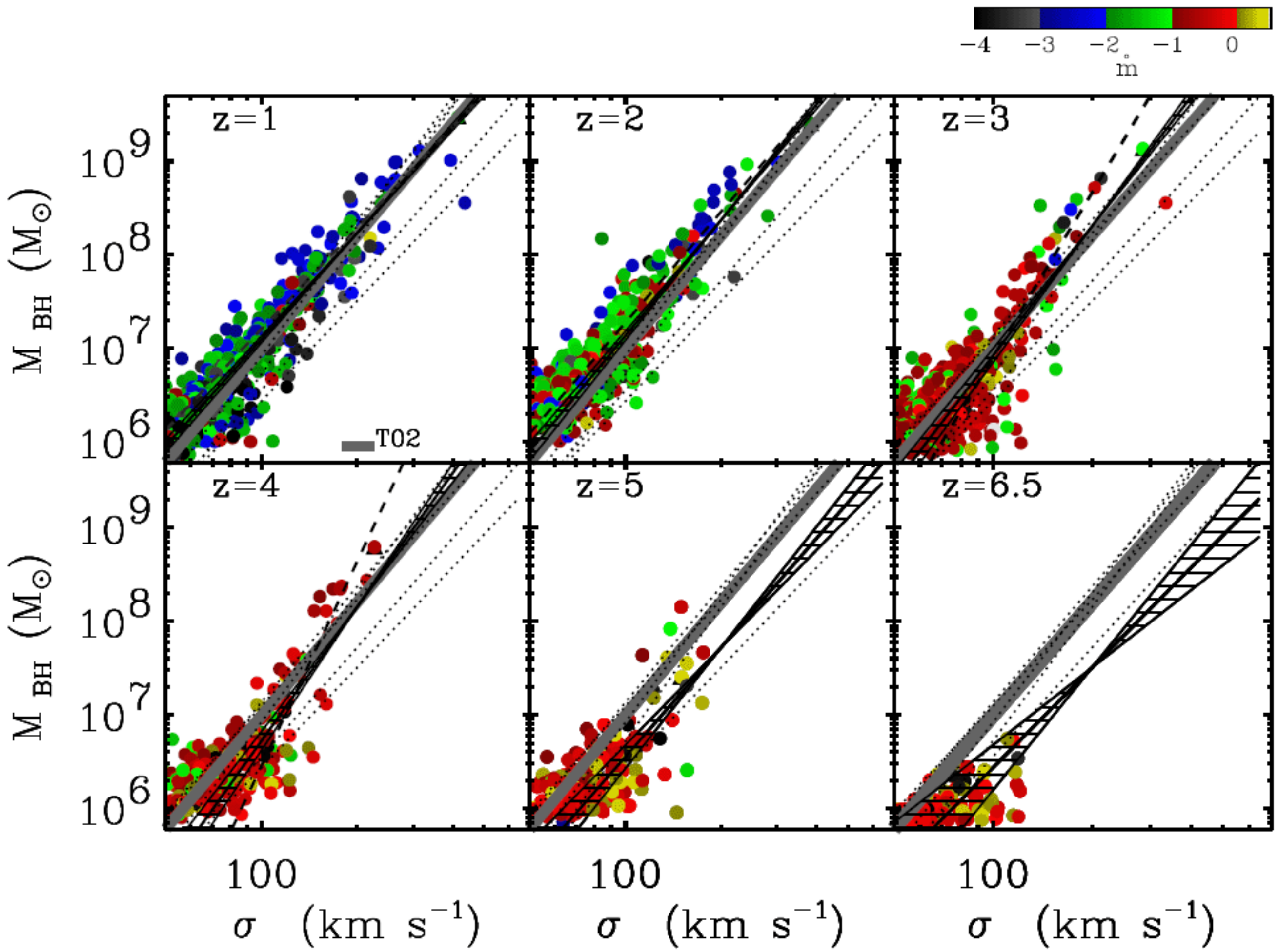


$10^9\ M_\odot$
$10^8\ M_\odot$
$10^7\ M_\odot$
$10^6\ M_\odot$
−4 −3 −2 −1 0
$\lg(\dot{m}/\dot{m}_{Edd})$
z
x [Mpc/h]

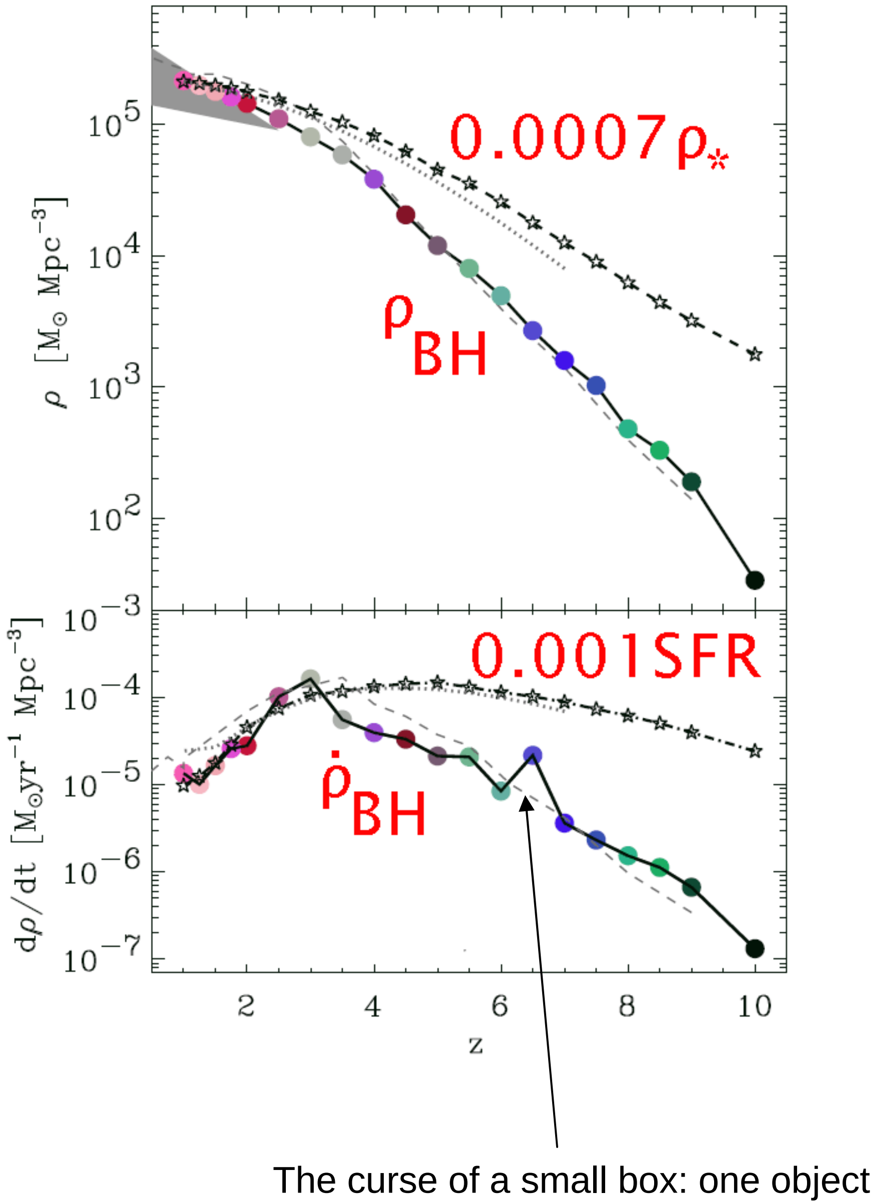


(Di Matteo et al., arXiv:0705.2269)

This all *looks* cool, but does it make sense?

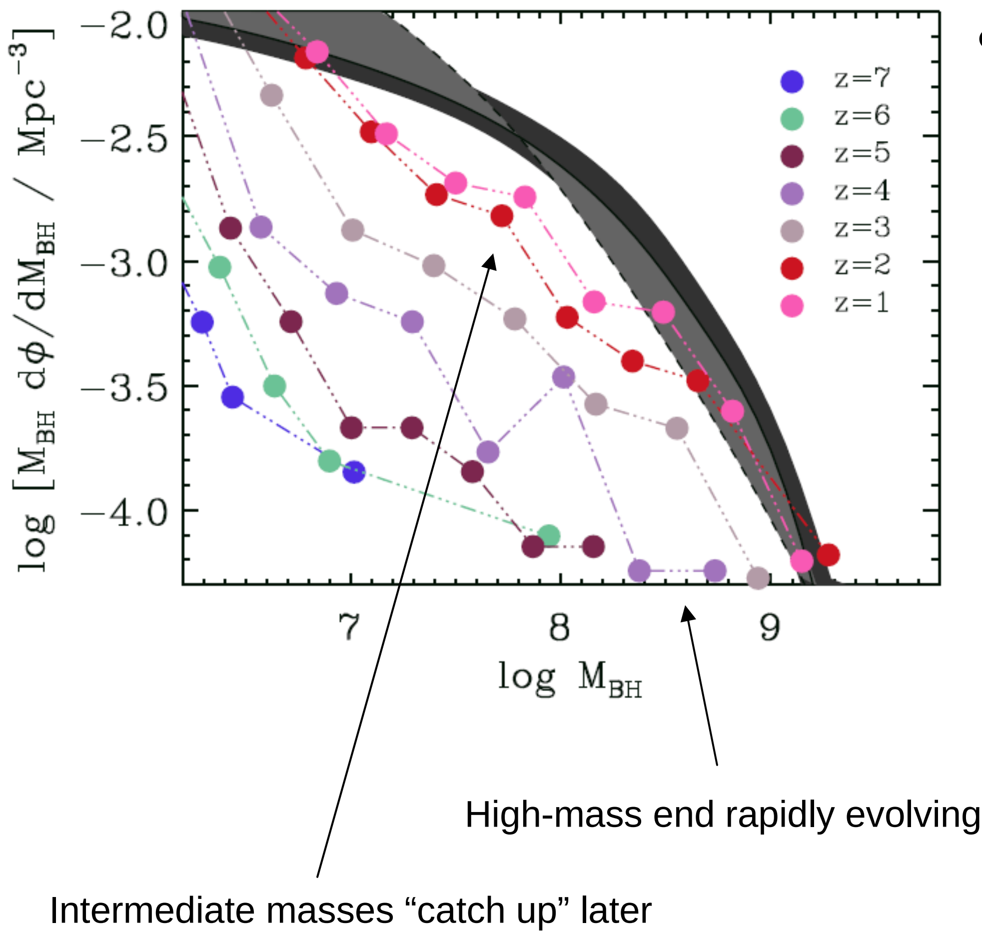


- Di Matteo et al.: M_{BH}-σ relations at different *z* (thick grey line: local observations); weak evolution $M_{BH}/\sigma \sim (1+z)^{-0.2}$; consistent with Hopkins' fundamental plane; but note: it's quite a small sample of BHs



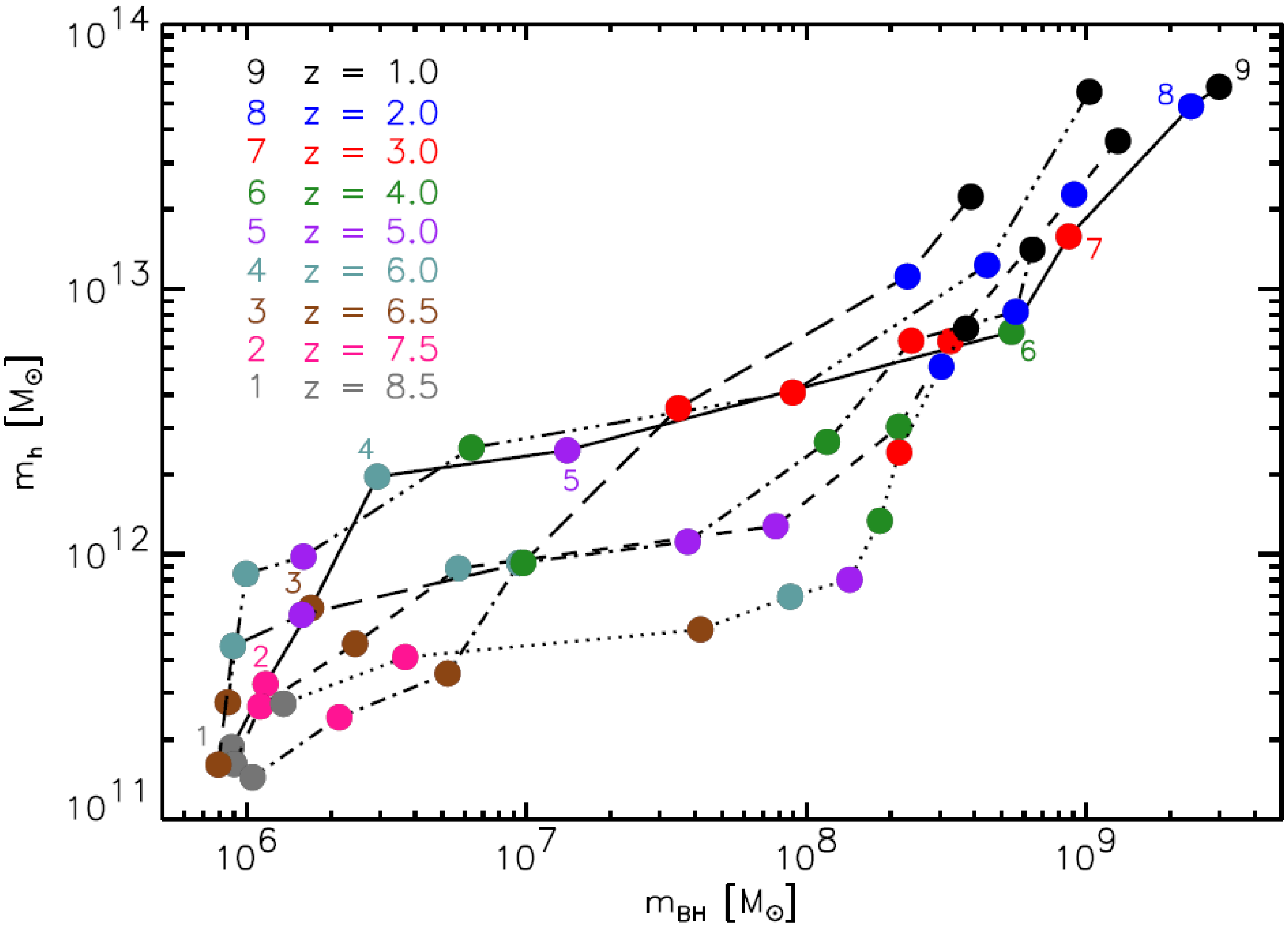
- Di Matteo et al.: Evolution of cosmological BH density consistent with observations
- Global BH accretion more narrowly peaked than SFR, around *z=3*

Black Hole Mass Function



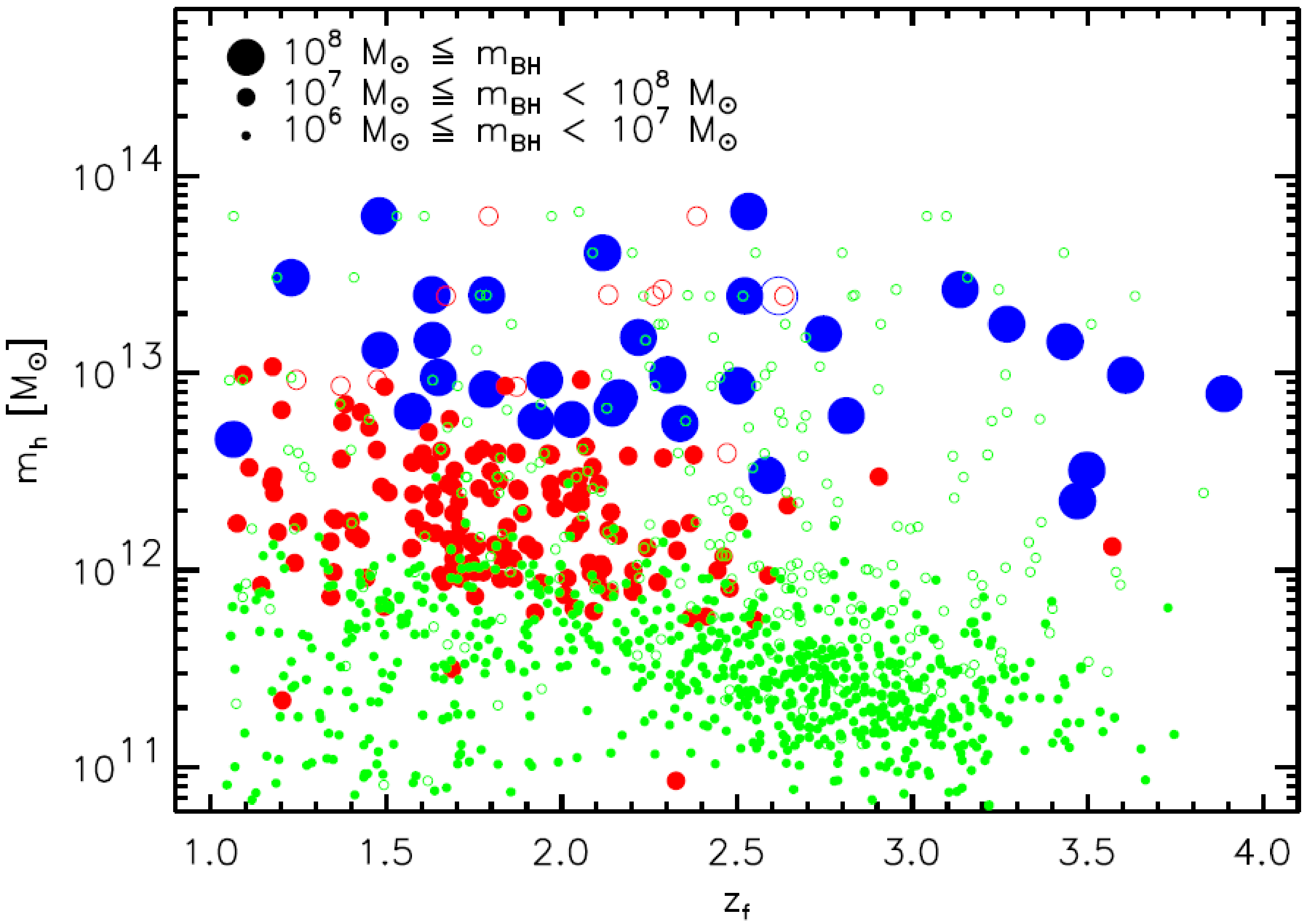
- Di Matteo et al.: Black hole mass function in good agreement with observations (grey bands; dark: local [Marconi et al. 2004]; bright: from hard Xray [Shankar et al. 2004])

SMBH and their Environments



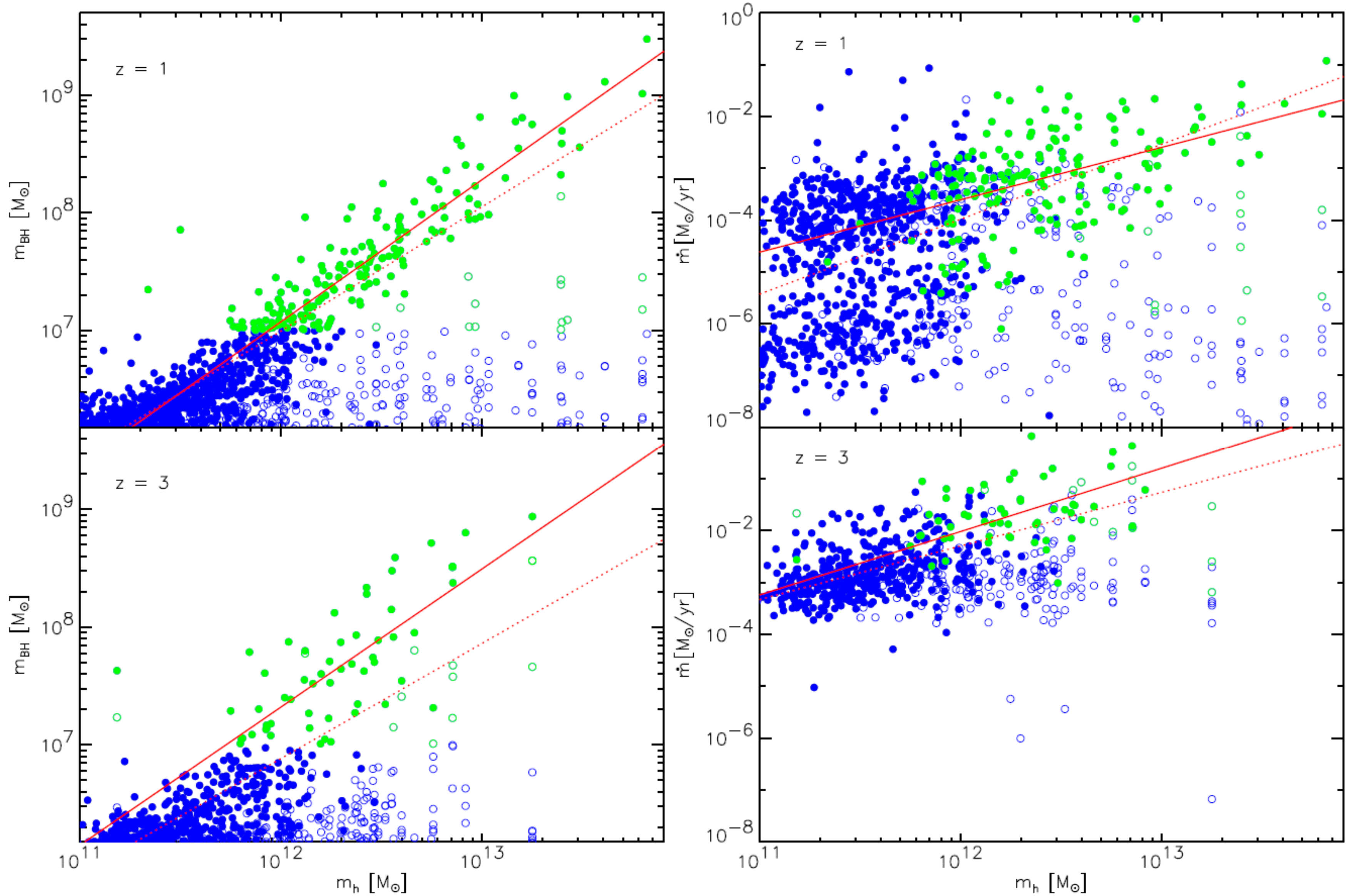
- For the largest masses, BHs and their host haloes evolve in a somewhat decoupled way

SMBH and their Environments (cont'ed)

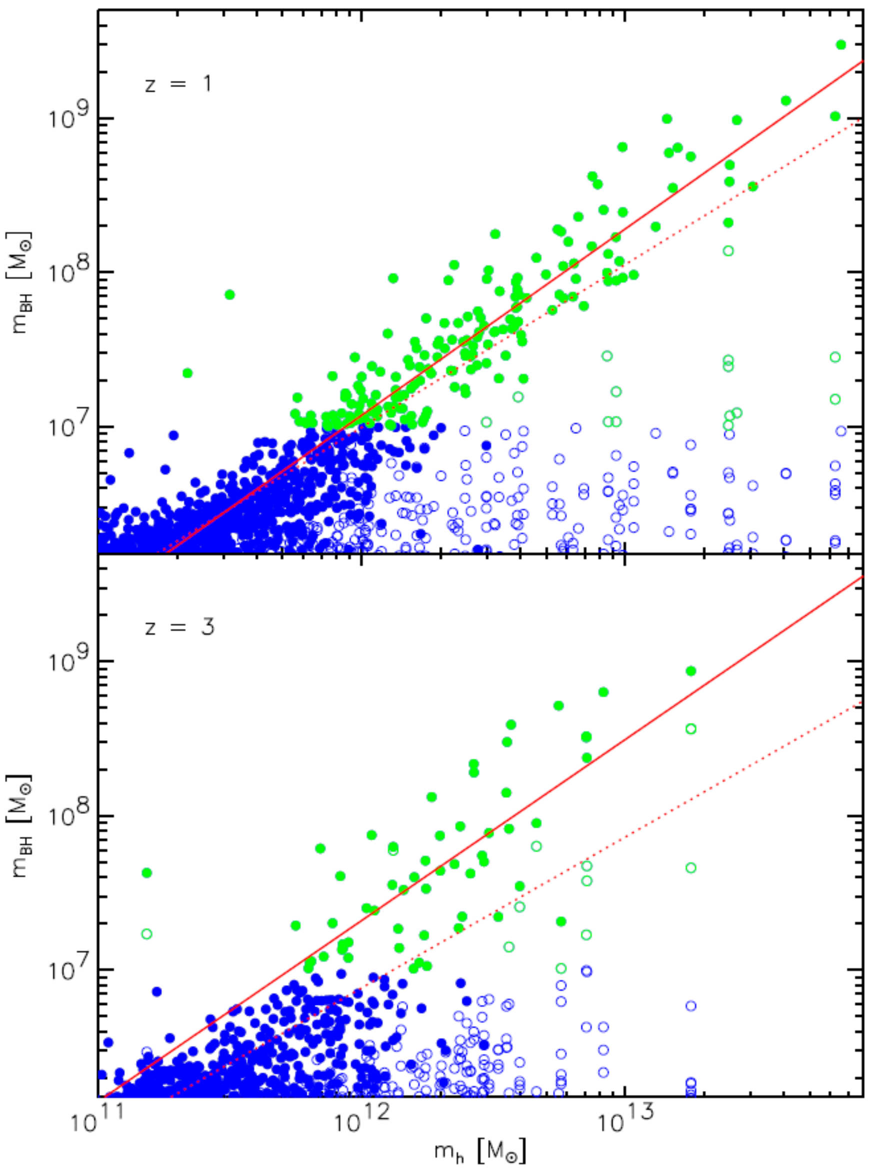


- → formation redshifts of largest BHs *not* following hierarchical build-up of structure
- → formation of massive BHs at high z generic feature of the model

SMBH and their Environments (cont'ed)



SMBH and their Environments (cont'ed)



α=1.21±0.05; c=0.1±0.01

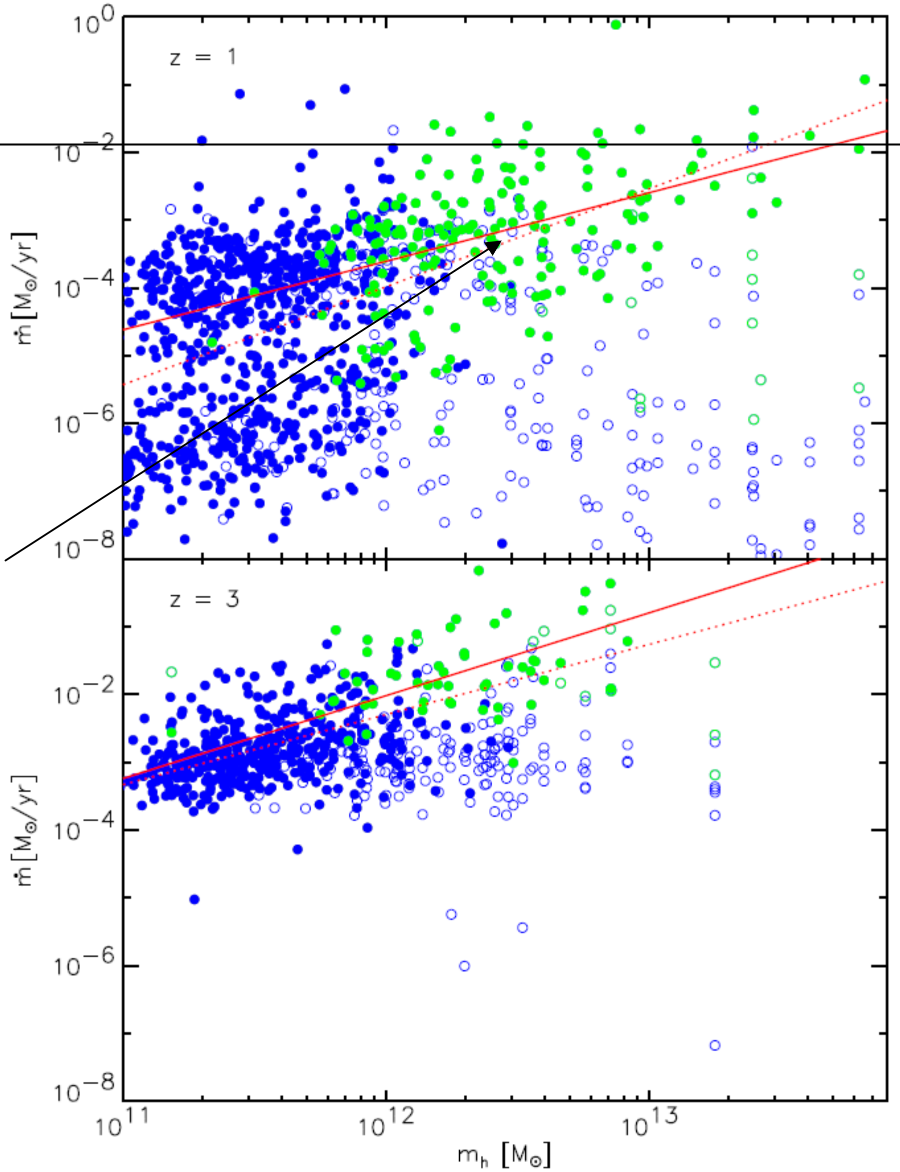
Relation typically expressed as $m_{BH}/10^8M_{sun} = c\ (m_h/10^{12}M_{sun})^{\alpha}$ (Ferrarese 2002)

Simulations in good agreement with observations (e.g. Shankar & Mathur 2007)

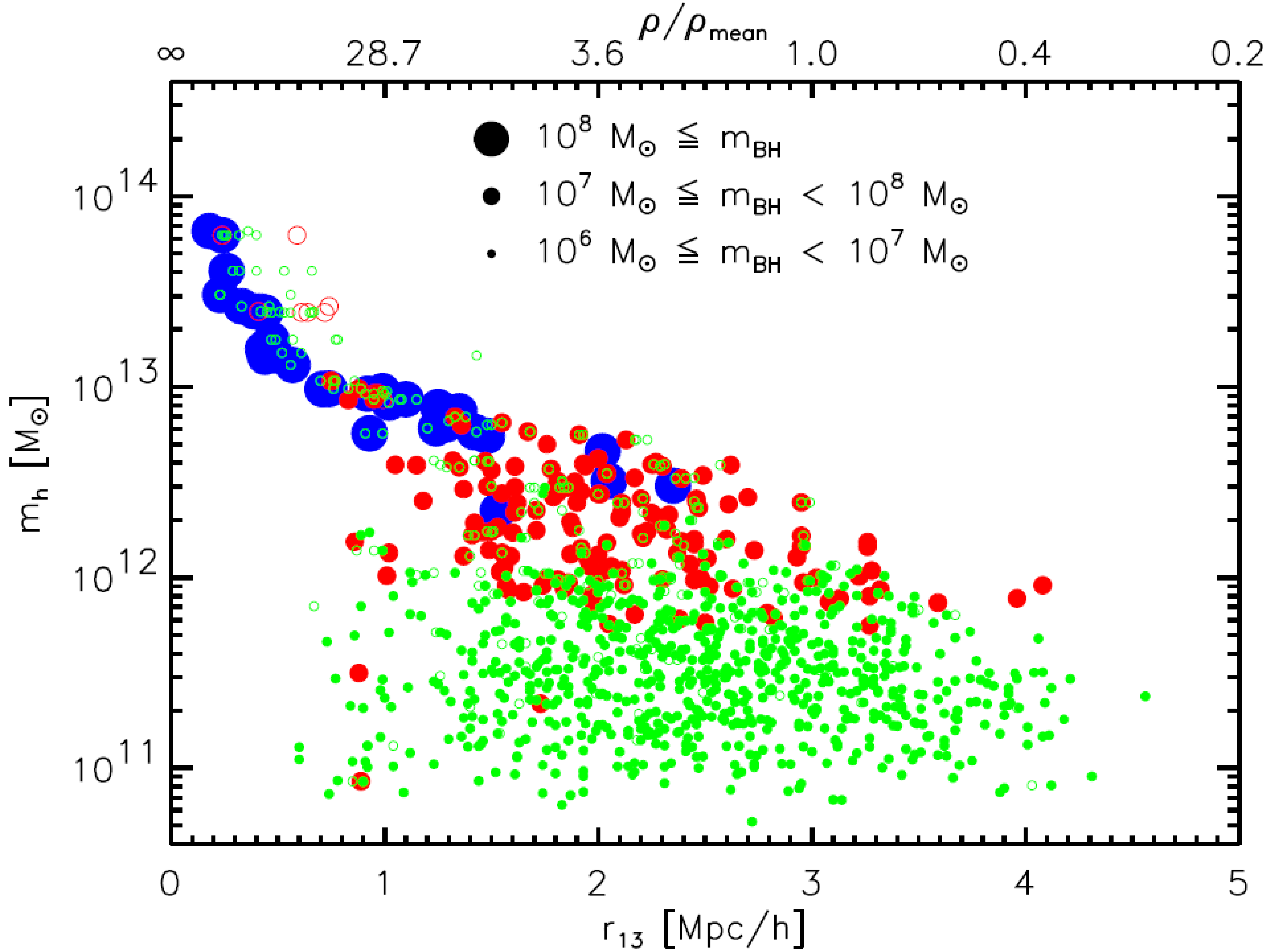
SMBH and their Environments (cont'd)

Most active BHs distributed quite evenly across halo mass range
→ if sim is correct, the clustering of AGN should be luminosity independent – indeed seen in DEEP2 (Coil et al. 2007)

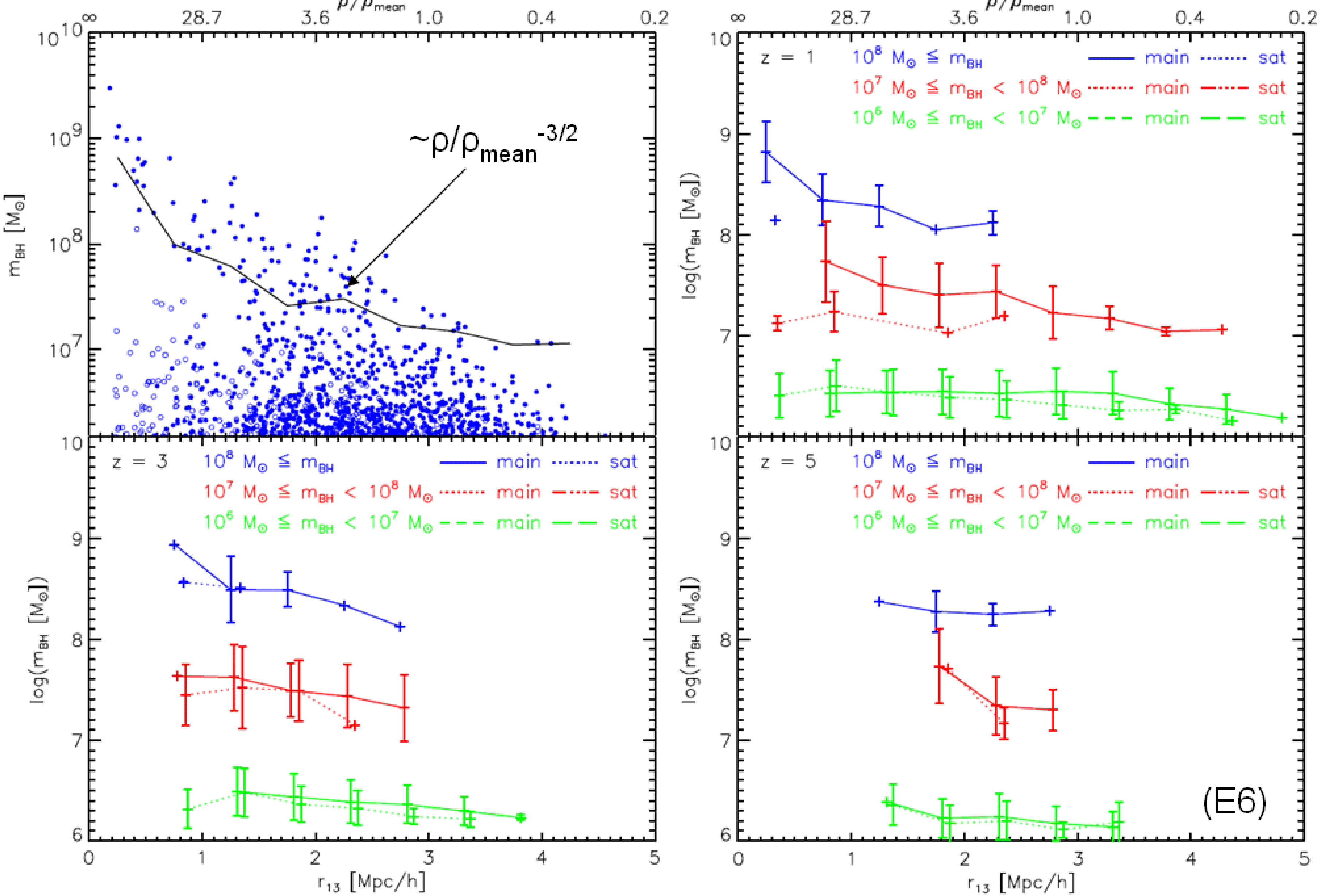
Slopes for relation similar to what is found for mass r'ship



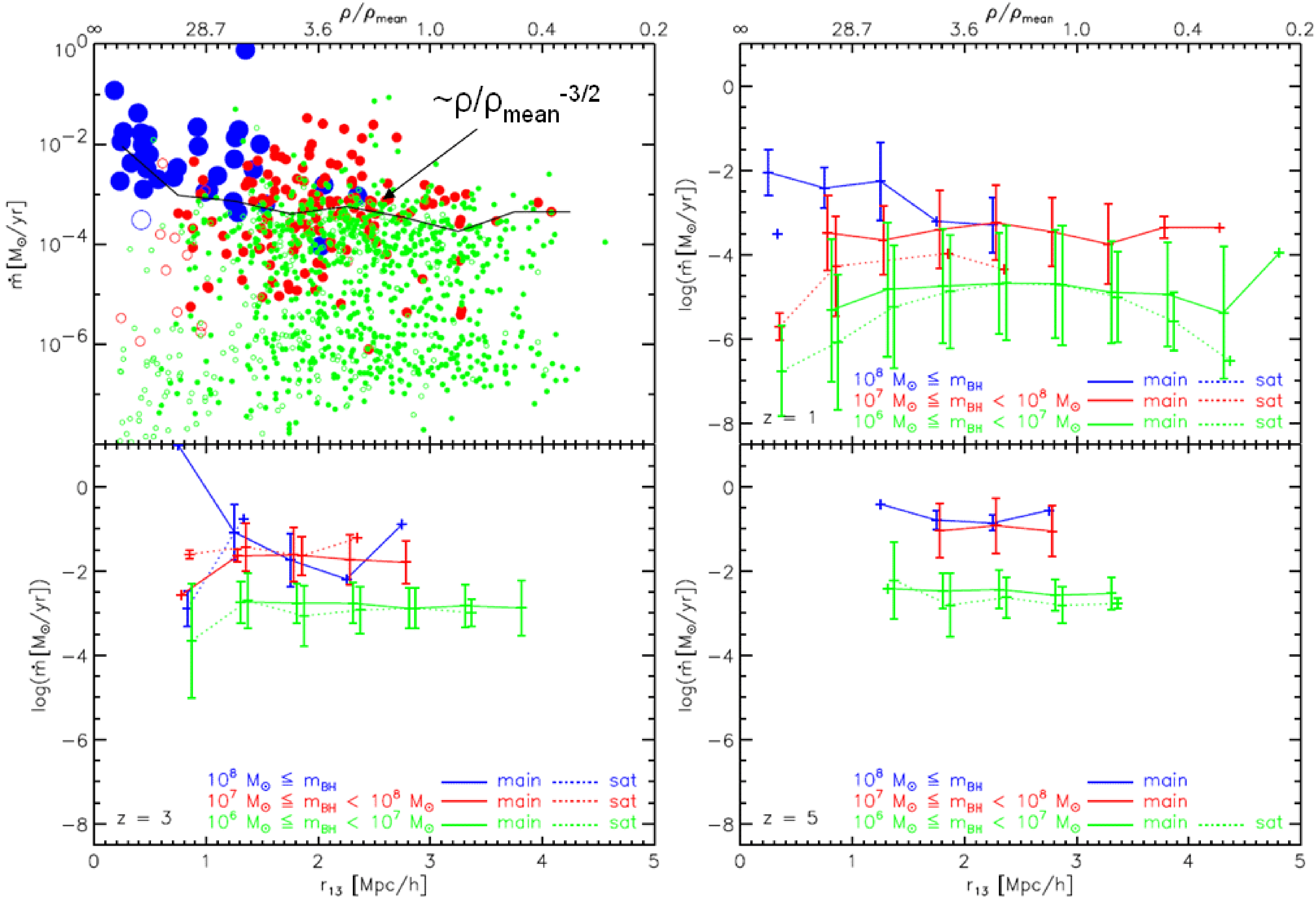
SMBH and their Environments (cont'ed)



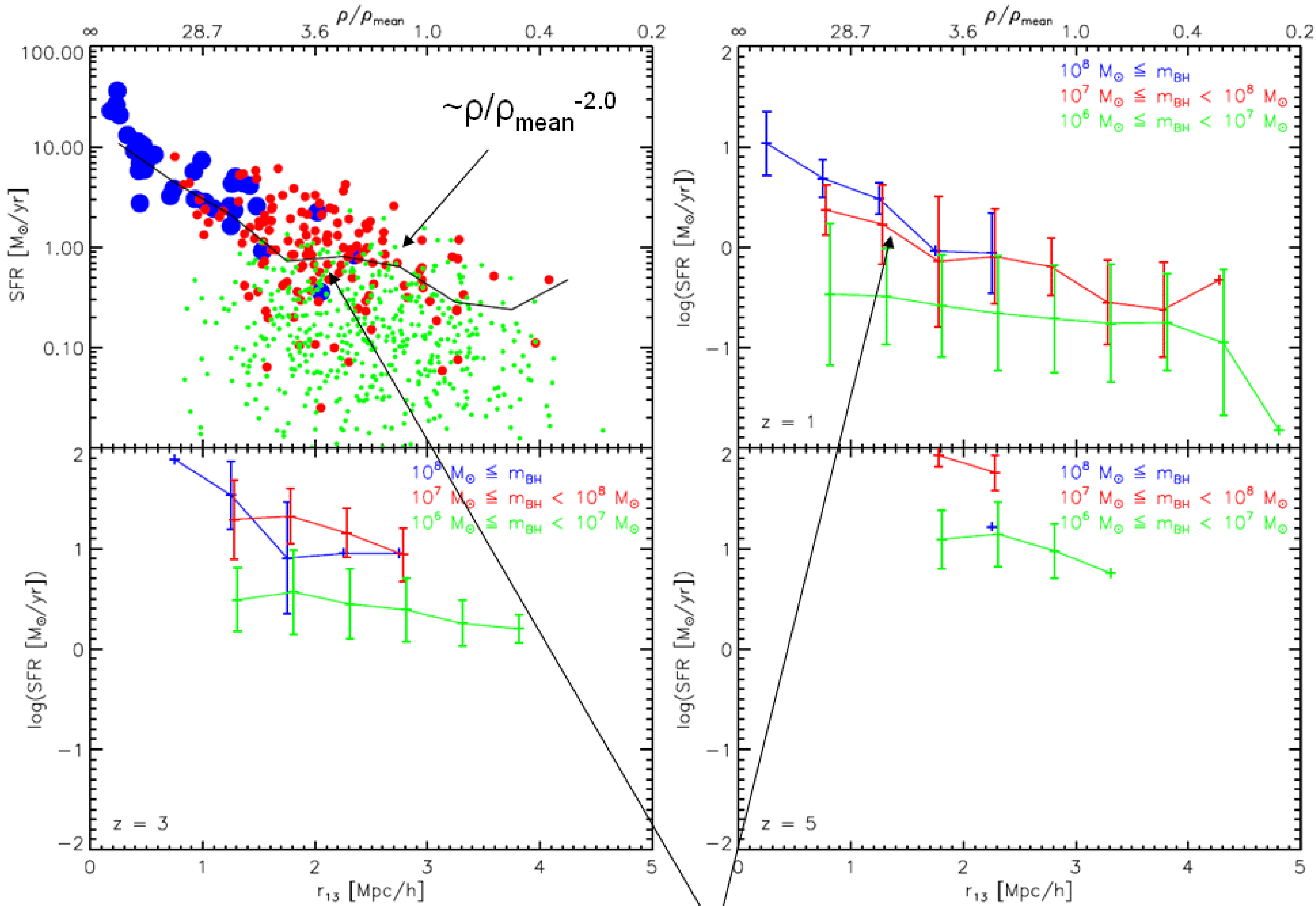
- Using adaptive measure of (large-scale) environment



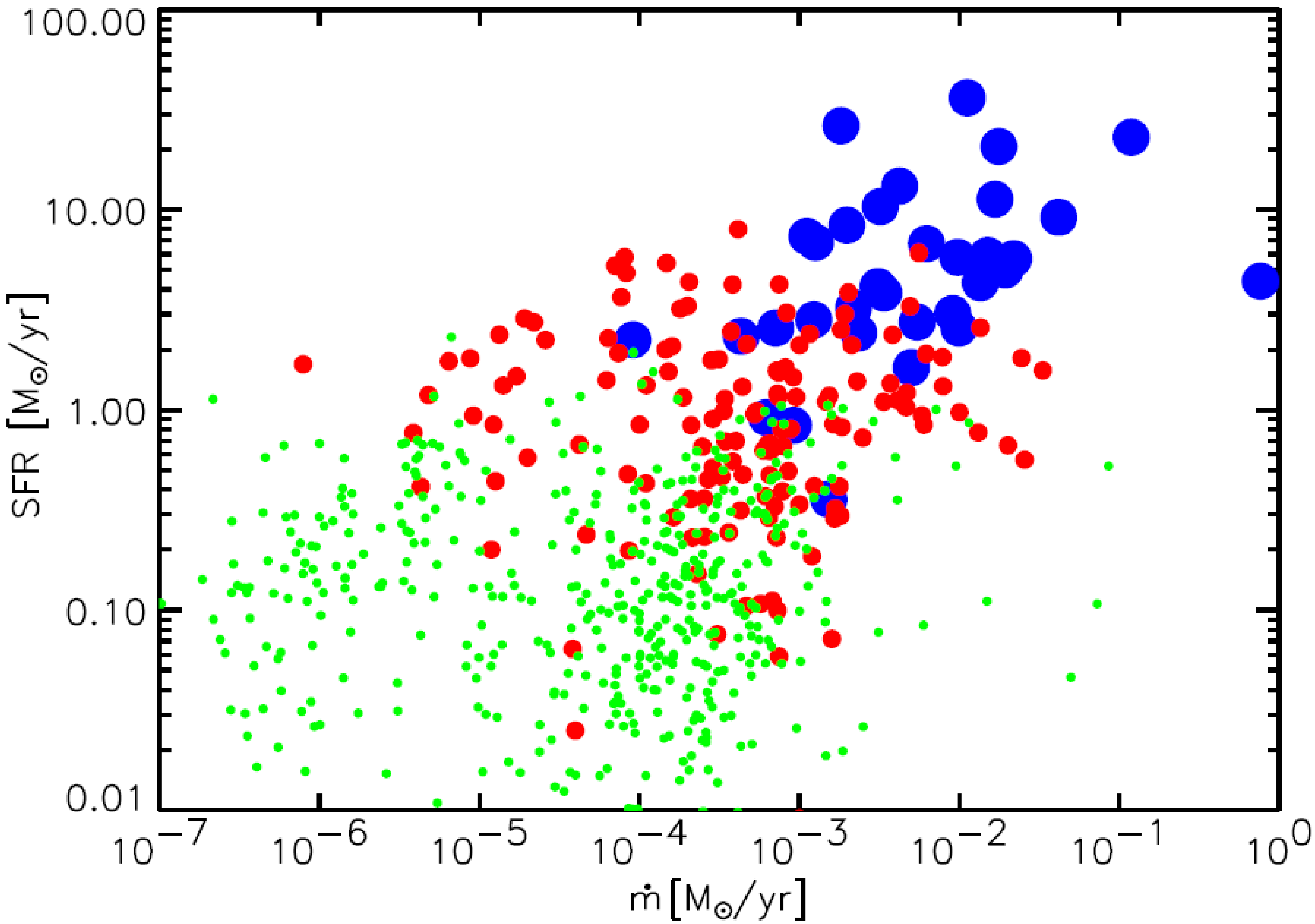
ρ/ρmean
∞
28.7
3.6
1.0
0.4
0.2
~ρ/ρmean^-3/2
mBH [M⊙]
log(mBH [M⊙])
z = 1
z = 3
z = 5
10^8 M⊙ ≦ mBH
10^7 M⊙ ≦ mBH < 10^8 M⊙
10^6 M⊙ ≦ mBH < 10^7 M⊙
main
sat
r13 [Mpc/h]
(E6)



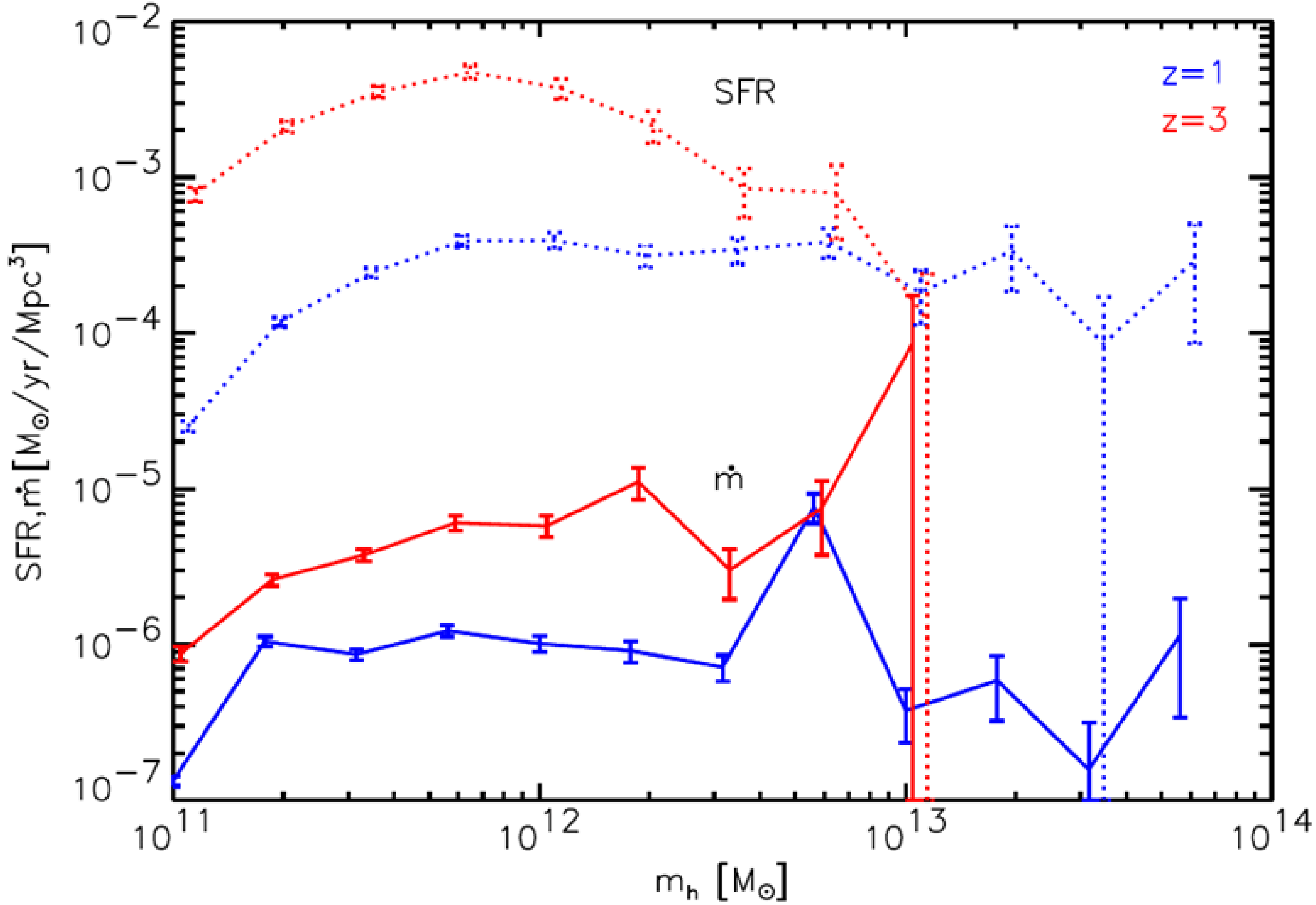
Enhanced accretion in higher density regions consistent with picture that gas rich mergers are main trigger of quasar phase (c.f. Di Matteo et al. 2007); more accretion at higher *z*



consistent with *z=1* observations
(GOODS – Elbaz et al. 2007, DEEP2 – Cooper et al. 2007)

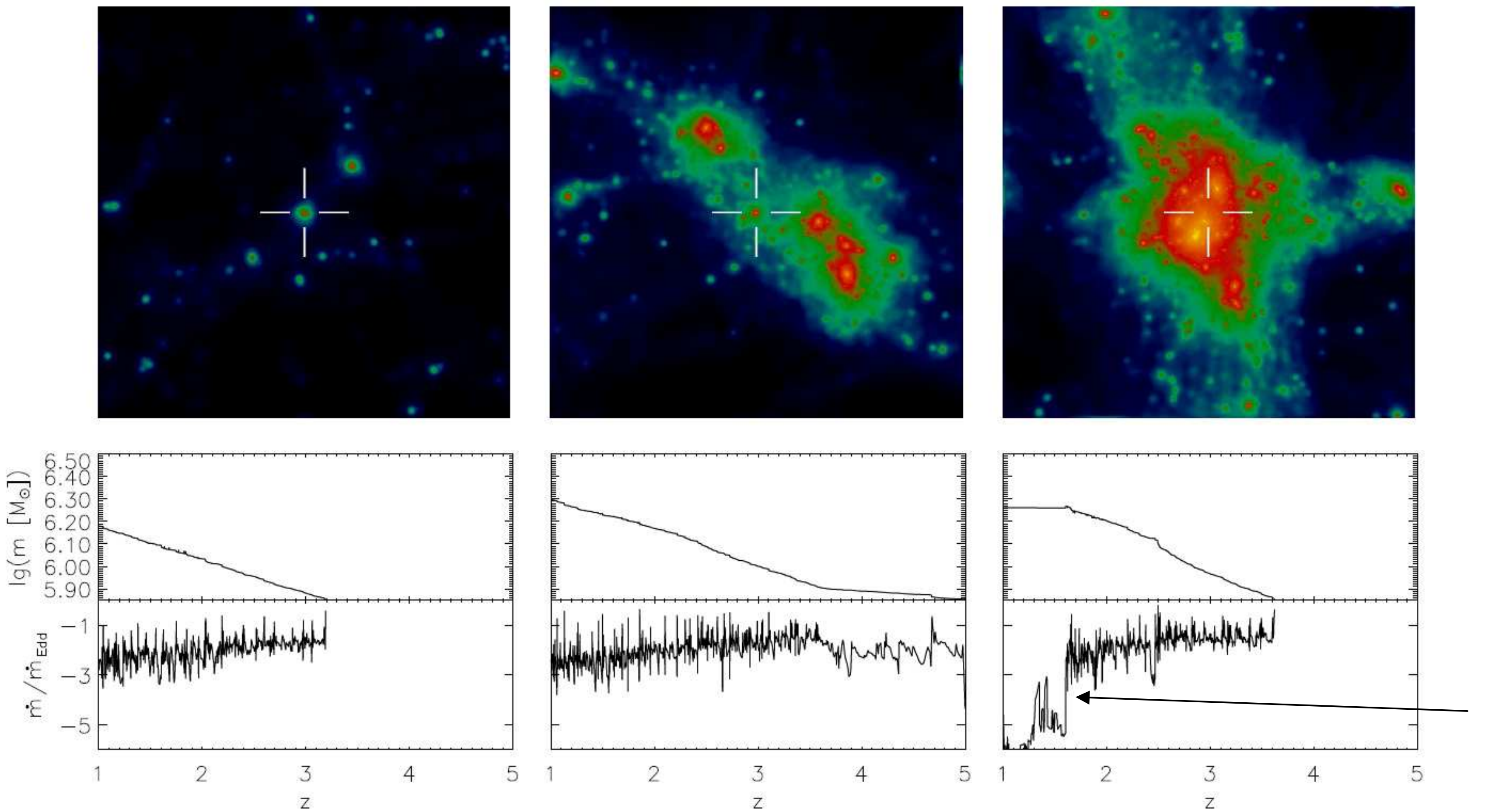


- No simple one-to-one relationship between SFR and BH accretion



- SFR density peaks at slightly lower halo masses than accretion rate density (the high-mass end is very noisy b/c of the small volume!)
- "Peak" in accretion rate density about at position of observed QSO halo masses (somewhat above $10^{12} M_{sun}$); also agrees with Hopkins et al. (2007)'s semi-analytical modeling

SMBH and their Environments (cont'ed)



- Lowest mass BHs show no density dependencies, in fact they all evolve very slowly, even in voids (void AGN – Constantin et al. 2007); only 20% of these have ever experienced a merger

Summary

- Cosmological SPH simulations that include BHs have become a valuable tool to study the formation of SMBHs – they are computationally expensive, but they don't rely on too many assumptions
- They show that
  1. The formation history of the most massive BHs is very complex, with many of them forming *anti-hierarchically*
  2. Massive BHs at high z are a generic feature
  3. The most massive BH at high z need not be the most massive BH at low z

Summary (cont'ed)

4. The simulation reproduces the M_{BH}-σ relation, indictating some evolution with *z*
5. The m_{BH}-m_{halo} relation also matches observations well
6. Most active BHs distributed evenly across haloes at *z=1* → luminosity independent clustering of AGN as seen in DEEP2
7. BH masses, accretion rates, and their hosts SFR scale as $\rho/\rho_{mean}^{-3/2}$, $\rho/\rho_{mean}^{-3/2}$, and ρ/ρ_{mean}^{-2}, respectively
8. Peak in BH accretion density as function of halo mass consistent with observed values
9. At *z=1*, there exists a large population of $\sim 10^6\ M_{sun}$ BHs across a very wide range of environments, all accreting very slowly (accounting for void AGN)