Formation and cosmic evolution of supermassive black holes

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Summer school: “Black Holes at all scales”
Ioannina, Greece, Sept 16-19, 2013

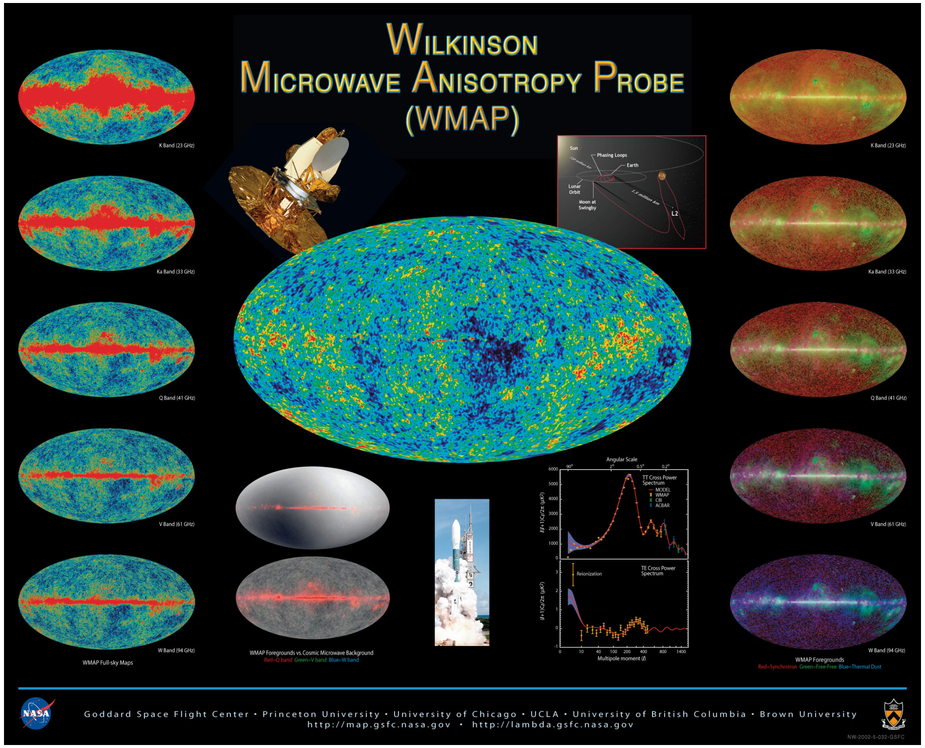
Lecture 1:

- formation of black hole seeds
- low mass versus massive seed scenarios
- growth of the black holes in the early Universe
- powering of high redshift quasars
- relative importance of gas accretion and black hole mergers with cosmic time

Lecture 2:

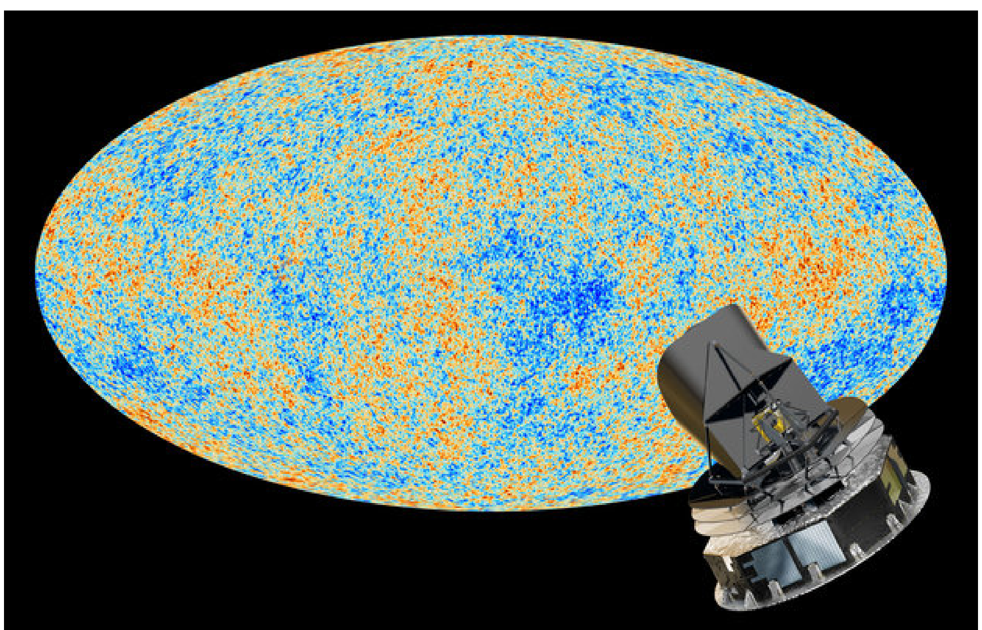
- physical conditions of accreting gas: from large scale inflows to accretion disks
- black hole binary mechanisms
- black hole spins
- gravitational recoils
- AGN feedback processes and their impact on the host galaxies across the Hubble sequence

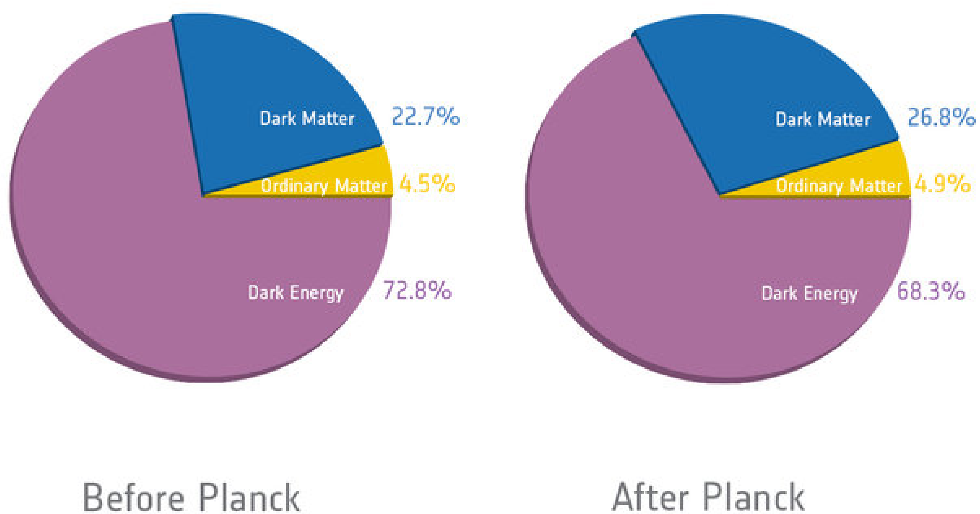
Formation of black hole seeds: the big picture



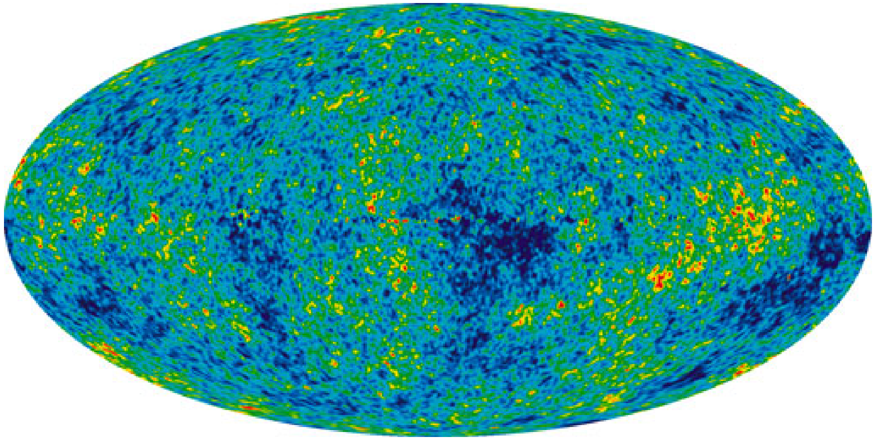
Planck data, 2013

Parameter	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031
Ω_Λ	0.6964	0.693 ± 0.019
σ_8	0.8285	0.823 ± 0.018
H_0	68.14	67.9 ± 1.5
Age/Gyr	13.784	13.796 ± 0.058





Formation of black hole seeds: the big picture

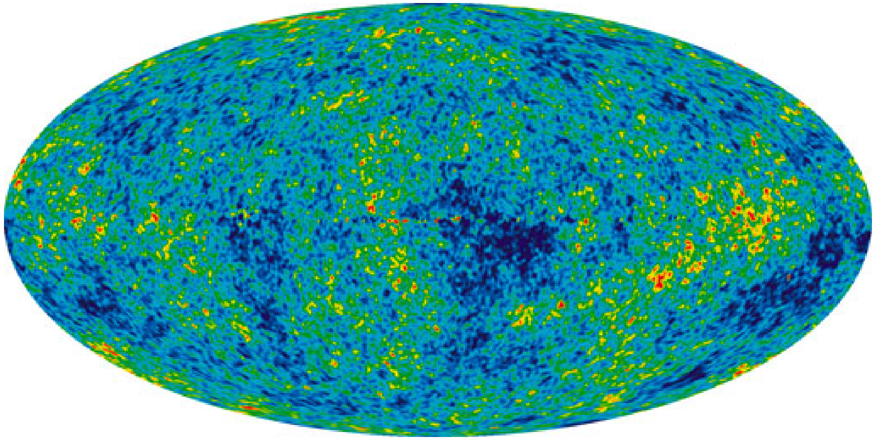


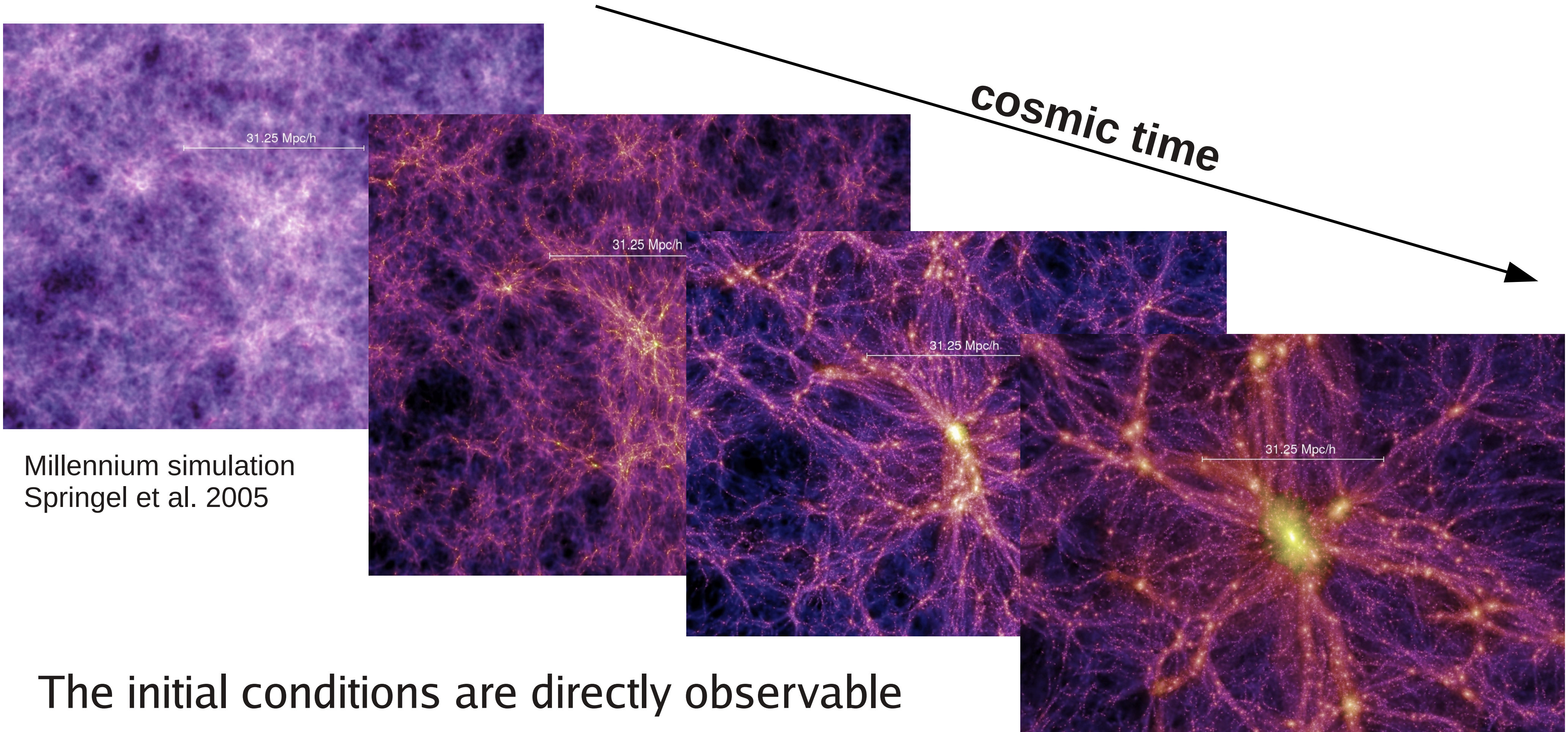
Structure formation

Density fluctuations generated by quantum fluctuations during inflation (not known from the first principles)
Gravitational collapse of small density perturbations in a quasi homogeneous Universe dominated by CDM and their subsequent growth within the hierarchical scenario

If density perturbations are very small ($\delta\rho/\rho \ll 1$) they are called linear and their evolution can be studied with a perturbative theory to the first order, e.g. with ideal fluid approximation within the Newtonian limit
Once, due to the gravitational collapse, density perturbations become large and non-linear ($\delta\rho/\rho \sim 1$) numerical integration is needed to follow accurately their evolution in time

Formation of black hole seeds: the big picture





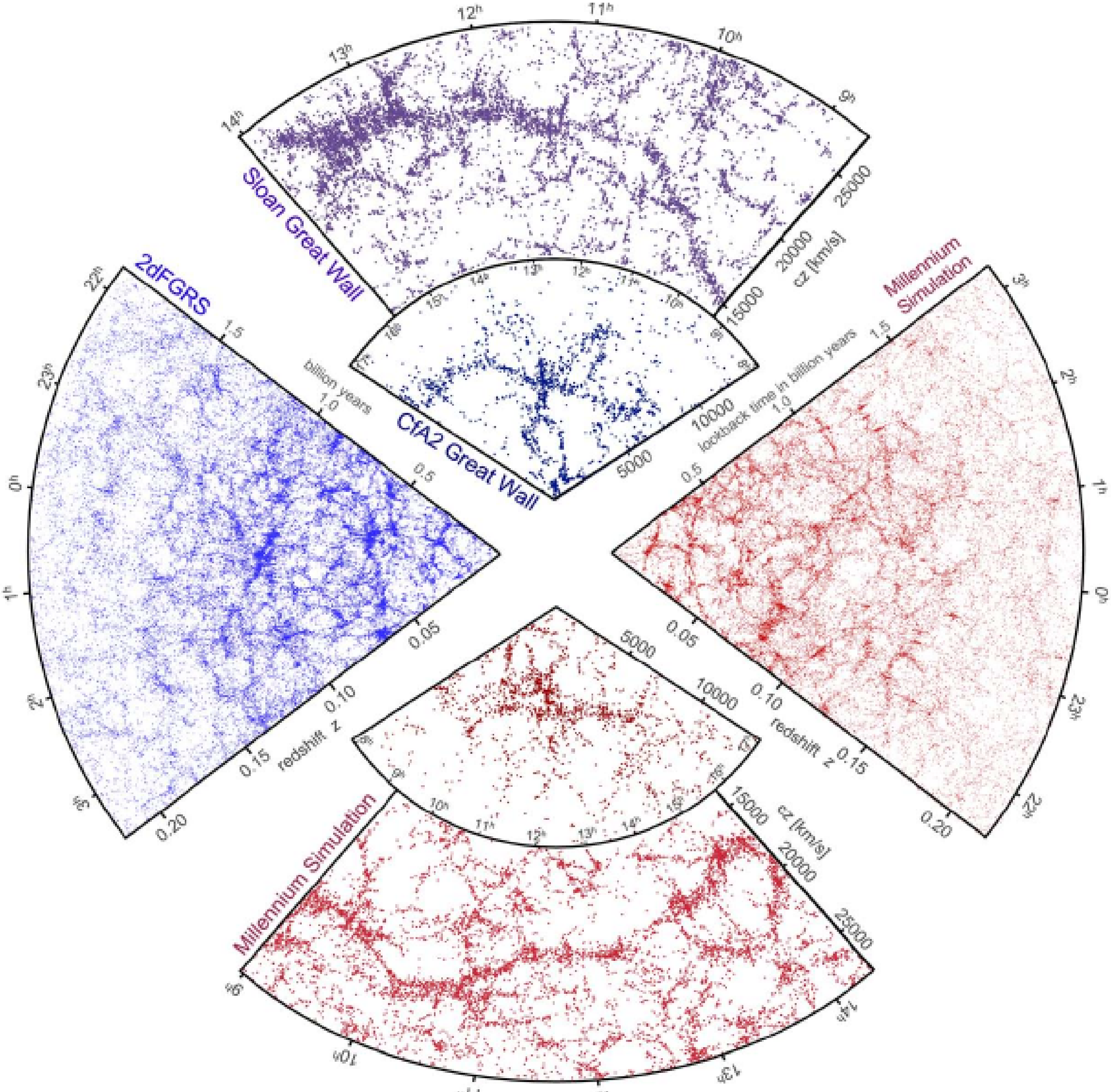
Millennium simulation
Springel et al. 2005

The initial conditions are directly observable

Formation of black hole seeds: the big picture

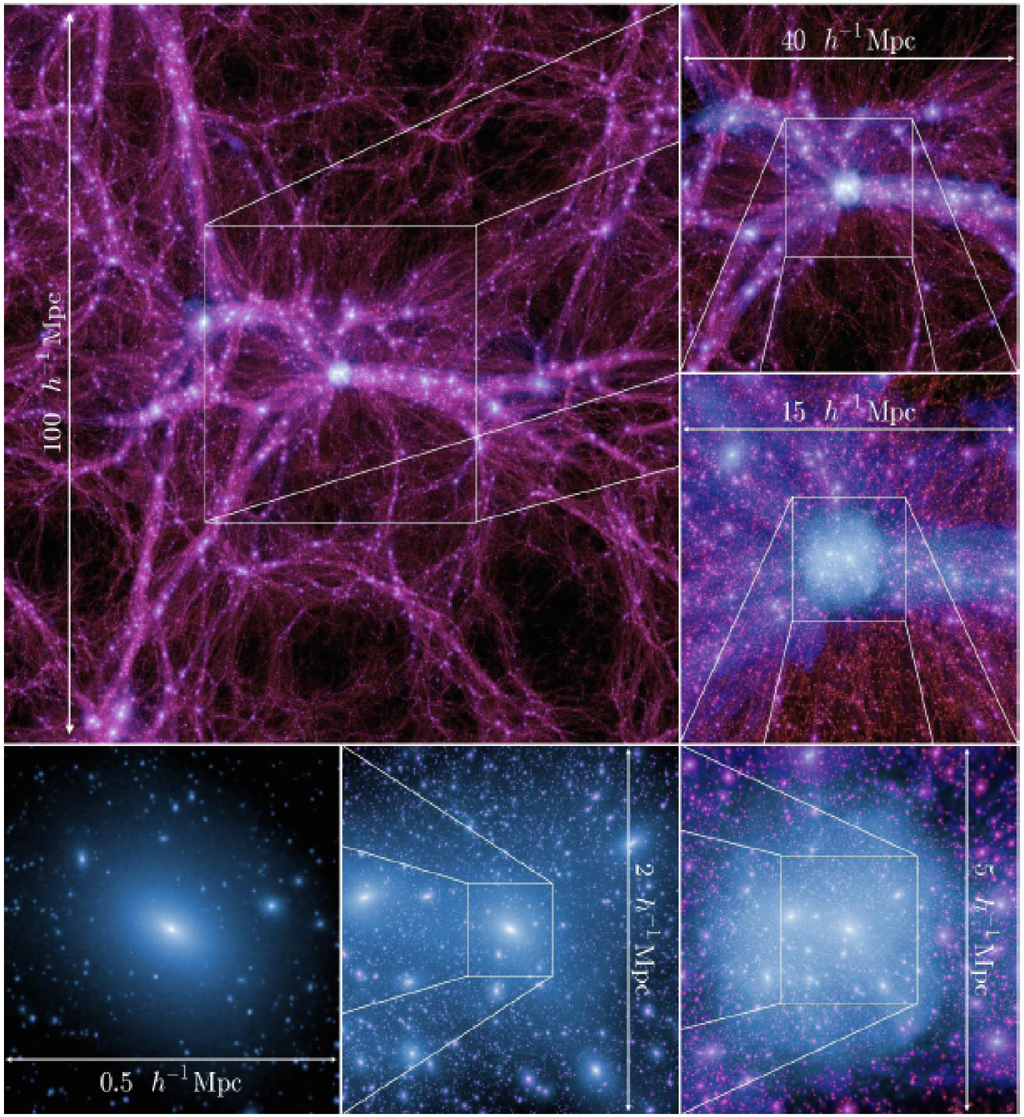
Simulated and observed large-scale structure in the galaxy distribution

MOCK PIE DIAGRAMS COMPARED TO SDSS, 2DFGRS, AND CFA-2

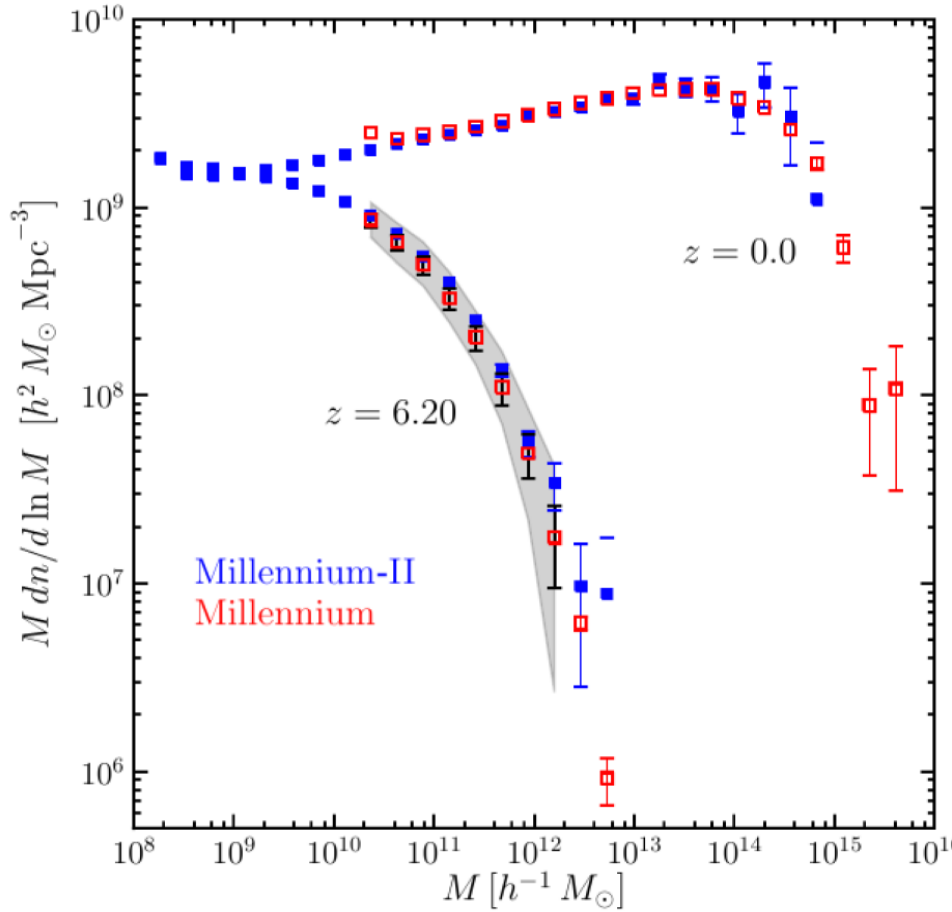


Springel et al. (2006)

Formation of black hole seeds: the big picture



halo mass function

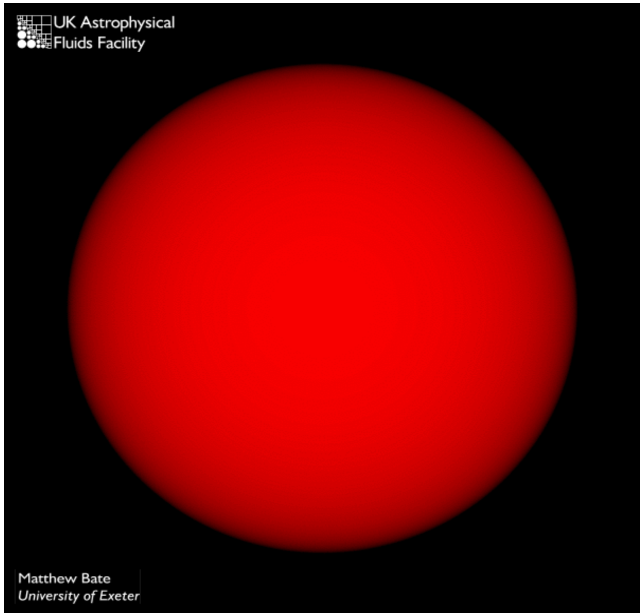


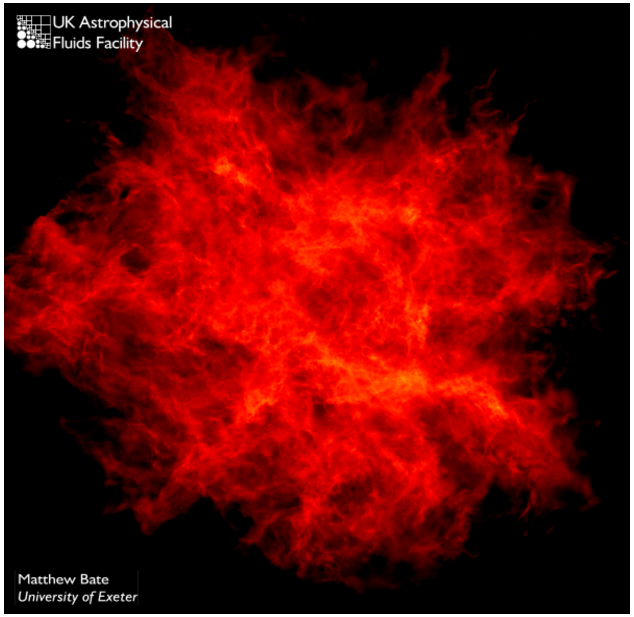
Boylan-Kolchin et al. (2009)

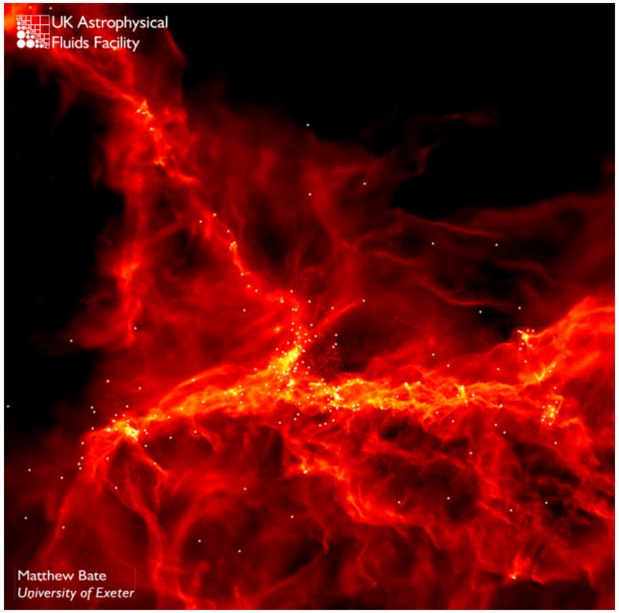
Formation of black hole seeds: baryons

Each initial density perturbation contains baryonic gas and collisionless dark matter in roughly their universal proportions. When an object collapses, the dark matter relaxes violently to form a dark matter halo, while gas shocks to the virial temperature. If gas is dense enough, gas cooling can become effective – gas loses pressure support and flows towards the centre → a protogalaxy forms

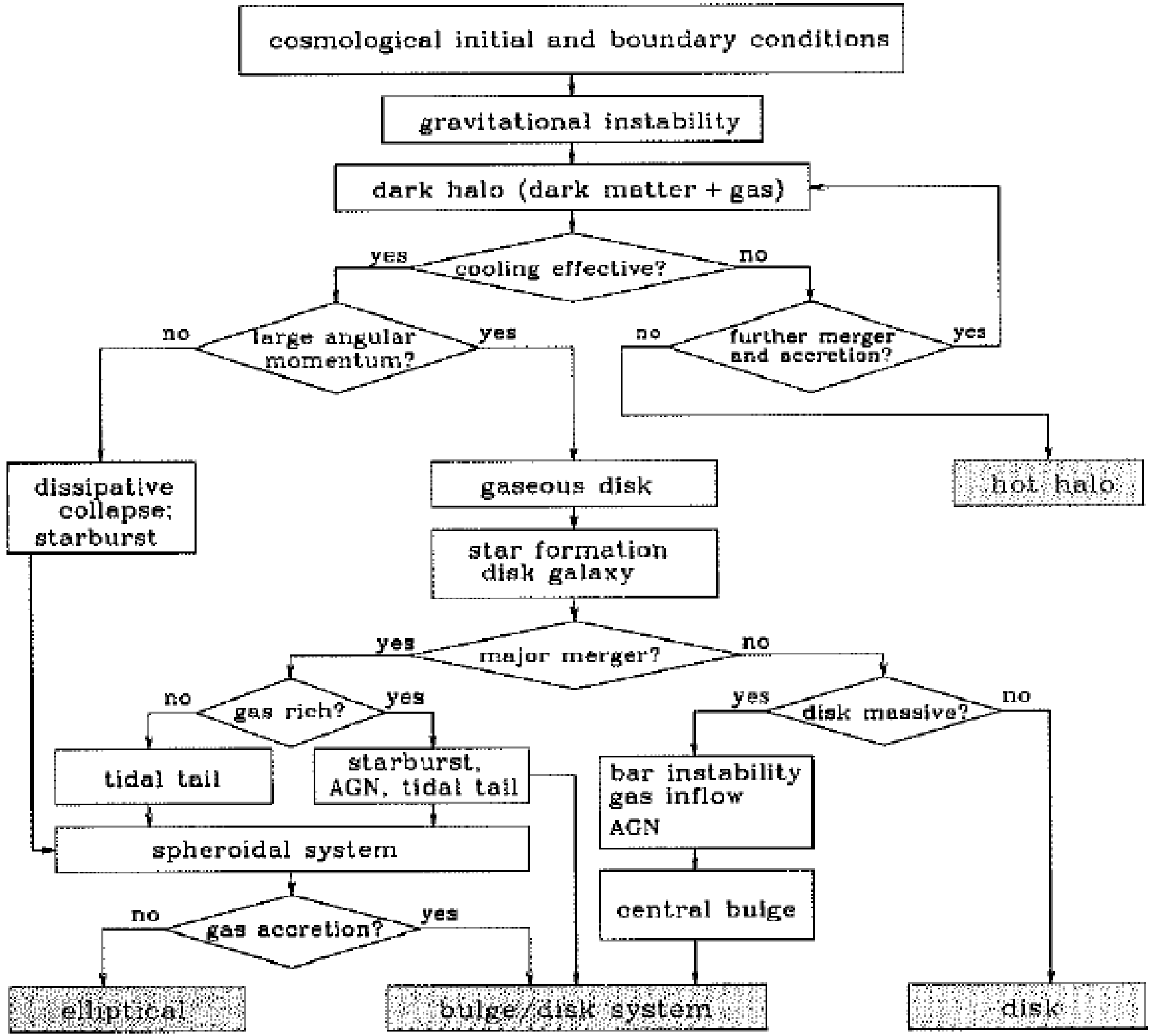
Further collapse increases the density and temperature of the gas, which can reduce the cooling time (t_cool < t_collapse). During such runaway collapse the gas becomes self-gravitating and may fragment into small, high-density cores that may form stars





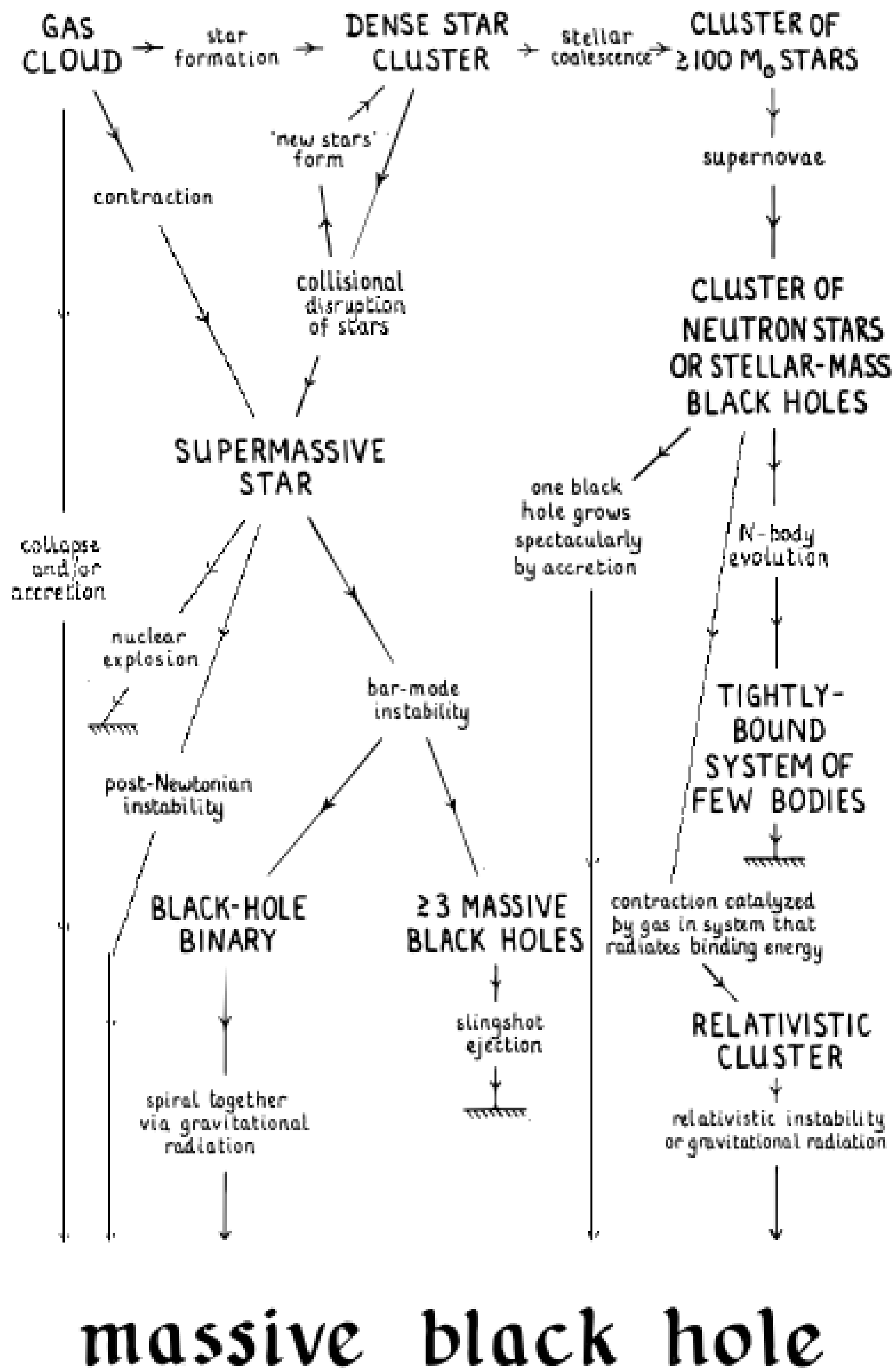


Formation of black hole seeds: baryons



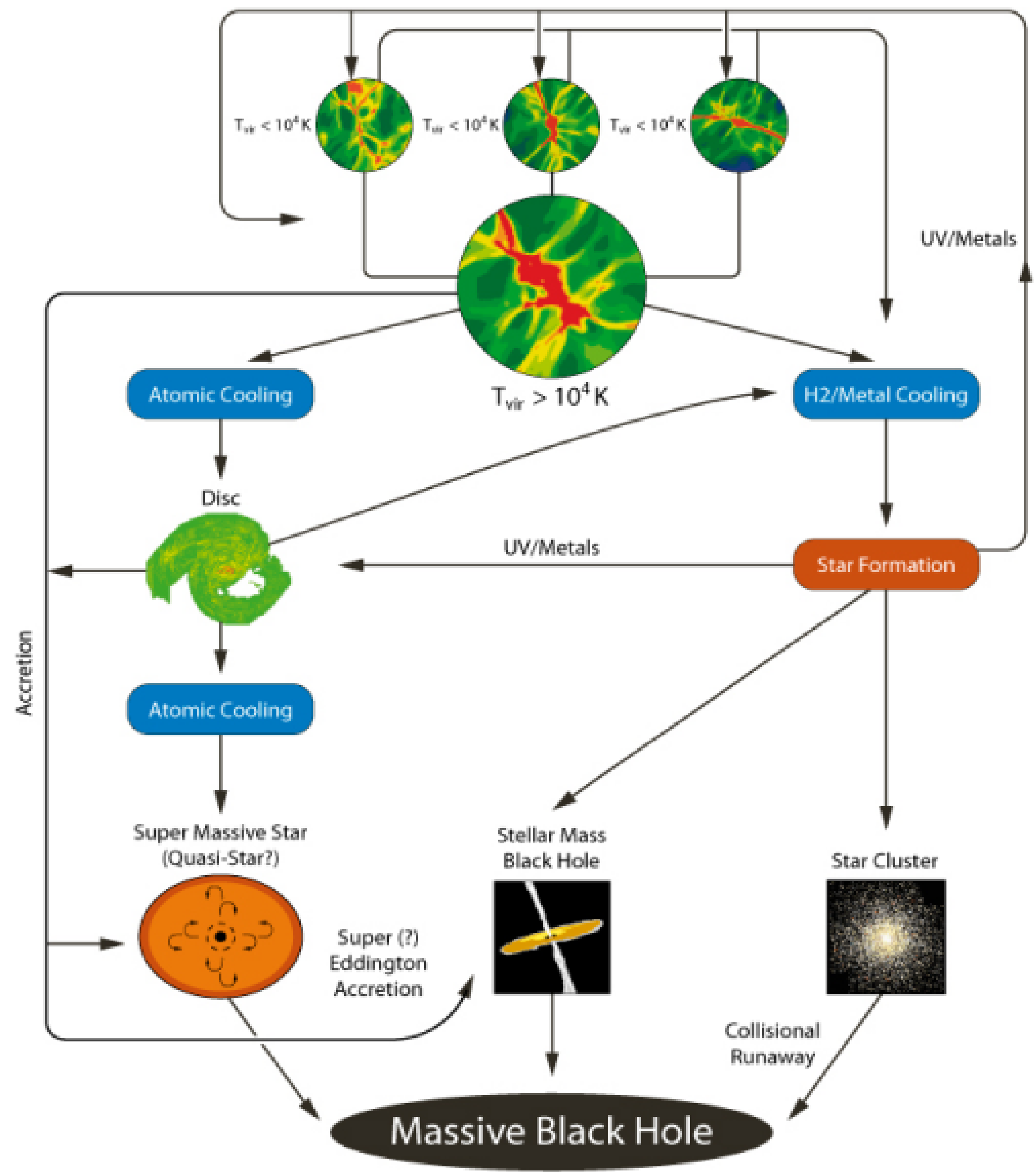
Galaxy formation and evolution
Mo, van den Bosch and White

Formation of black hole seeds: seed formation pathways



Martin Rees, ARA&A 1984

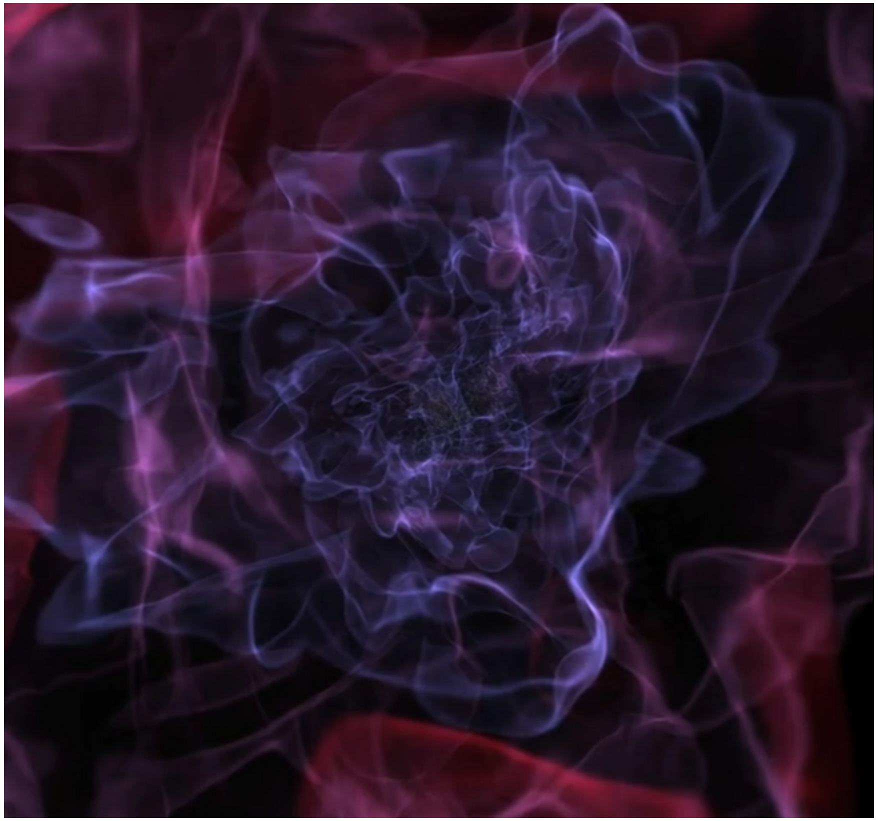
Formation of black hole seeds: seed formation pathways



Regan & Haehnelt, 2009

Formation of black hole seeds: Population III remnants

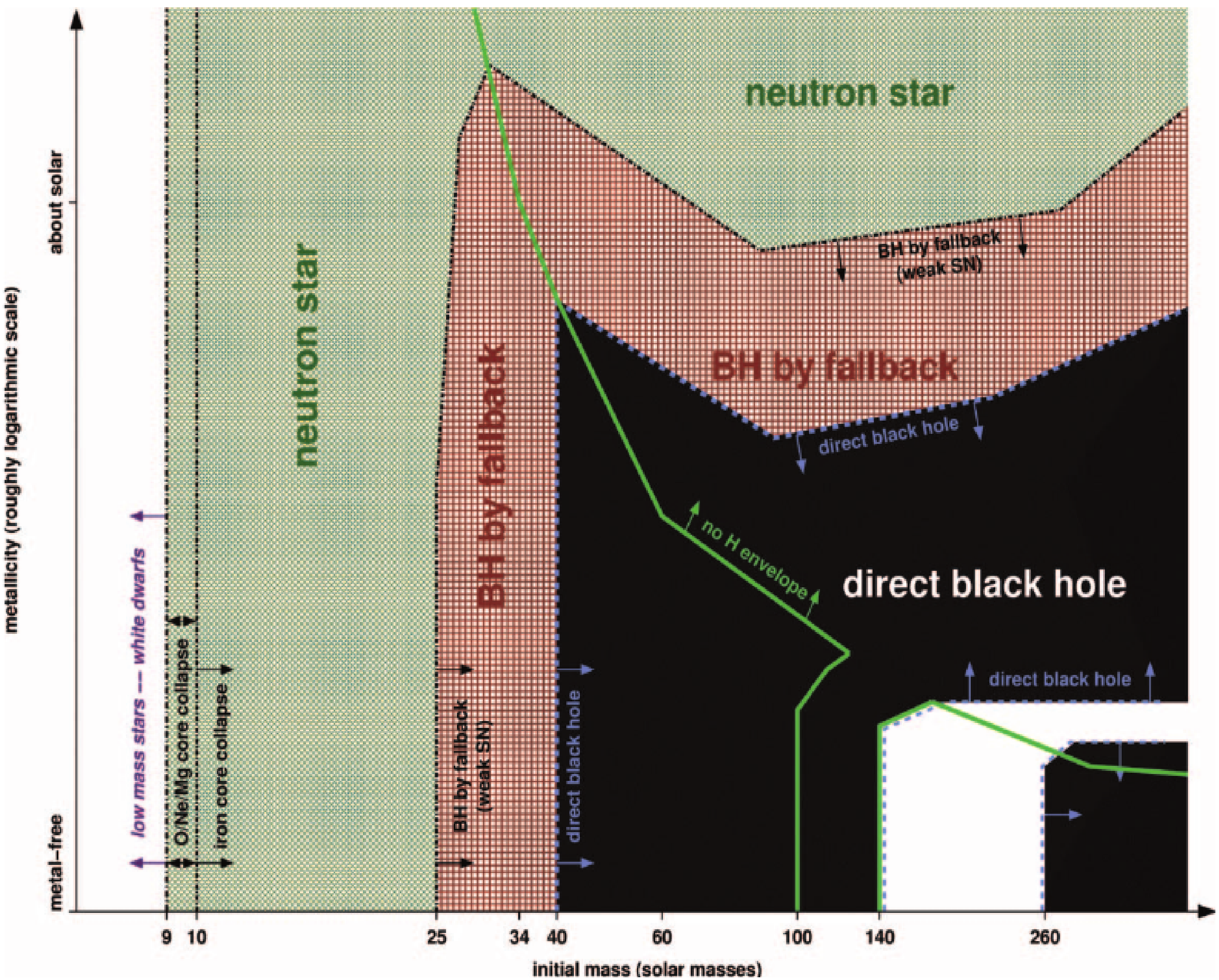
- Population III stars represent the first generation of stars formed out of zero metallicity gas
- They are expected to form in halos with virial mass ~ $10^6 M_\odot$ collapsing at z ~ 20-50 where gas cools via molecular hydrogen (no dust, no metals, no B fields)
- Numerical simulations suggest that the first generation of stars was very massive e.g ~ $100_\odot$ (Bromm et al. 1999, 2002, Abel et al. 2000, Yoshida et al. 2006) but a few newer studies suggest some fragmentation and multiple lower mass star forming (Glover et al. 2008, Stacey et al. 2009, Turk et al. 2009)



Matt Turk

Formation of black hole seeds: Population III remnants

The final fate of Population III stars depends on their mass:
1. Between 25-140 M⊙ black hole formation (mass ~ half of the stellar mass)
2. Between 140-260 M⊙ pair instability supernovae → no remnant
3. Over 260 M⊙ black hole forms (mass ~ half of the stellar mass)



Heger et al. 2003

Formation of black hole seeds: Direct collapse of gas

- Efficient gas collapse in halos with Tvir > 10^4K (essentially metal free and no H2 cooling) to avoid gas fragmentation and star formation (e.g. Haehnelt & Rees 1993, Loeb & Rasio 1994, Eisenstein & Loeb 1995, Begelman et al. 2006)
- Gas cools via atomic H to ~ 4000K, thereafter collapse proceeds adiabatically
- High local UV background is needed to prevent formation of H2 (alternatively highly turbulent medium i.e. Begelman & Shlosman 2009)
- Collapsing gas will likely settle into a rotationally supported disk, e.g. for a halo with:

$$T_{\rm vir} \gtrsim 10^4\,{\rm K} \qquad M_{\rm h} \approx 10^8\ {\rm M}_\odot \qquad r_{\rm vir} \approx 500\,{\rm pc}$$

$$\bar{\lambda}_{\rm spin} = 0.04 \qquad \lambda_{\rm spin} \equiv J|E|^{1/2}/GM_{\rm h}^{5/2}$$

$$M = f_{\rm d}\ f_{\rm gas}\ M_{\rm h}$$

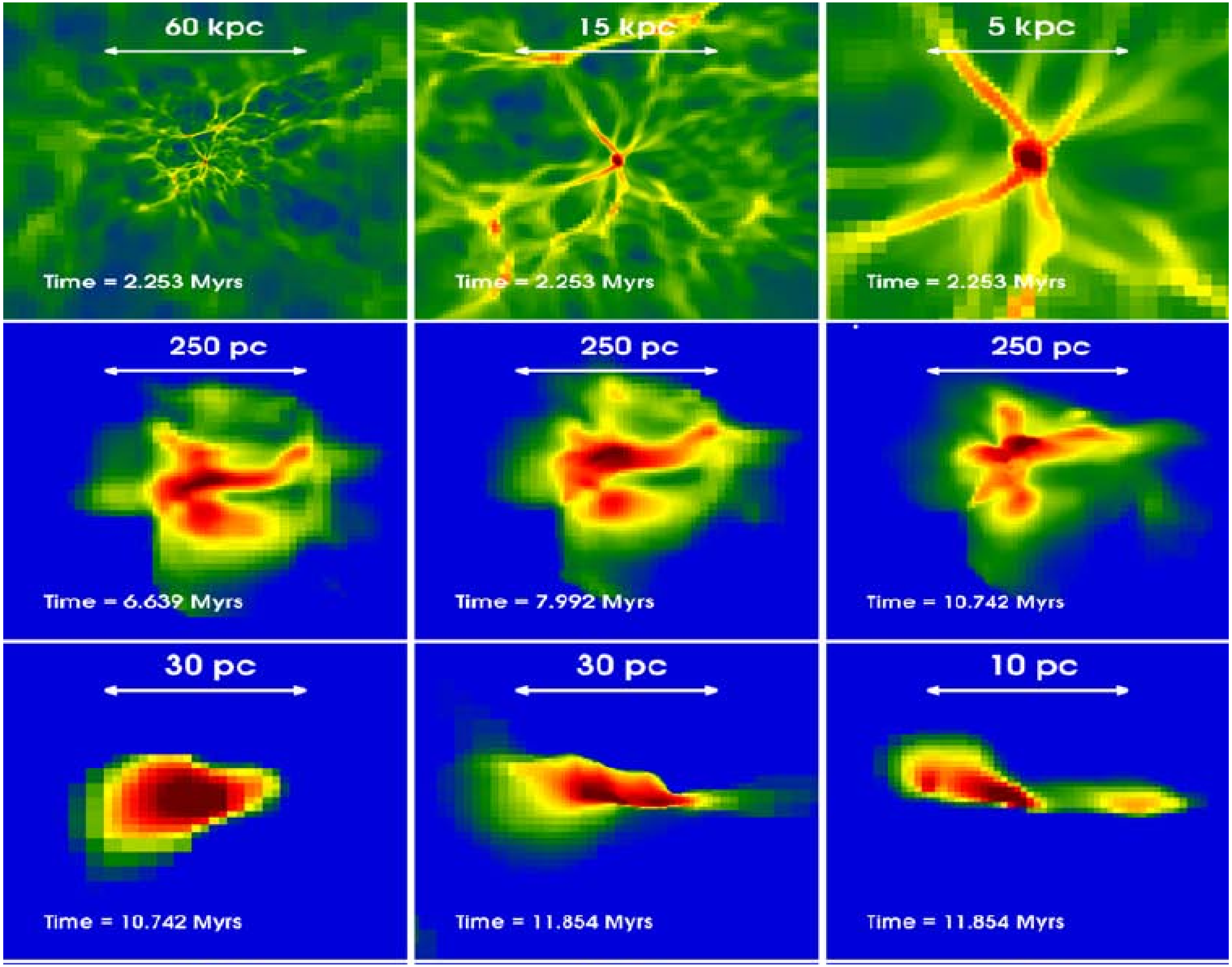
fgas ~ universal baryon fraction (0.18)
fd fraction of gas that can cool (0-1)

$$\text{scale radius} \simeq \lambda_{\rm spin} r_{\rm vir}$$

=> typical gas scale radius of a disk with mass M is ~ 20pc

Formation of black hole seeds: Direct collapse of gas

Regan & Haehnelt, 2009: "about 0.1-1% of the baryons collapse into a self-gravitating, fat, ellipsoidal, centrifugally supported disk with scale length of 0.075-0.27pc..."



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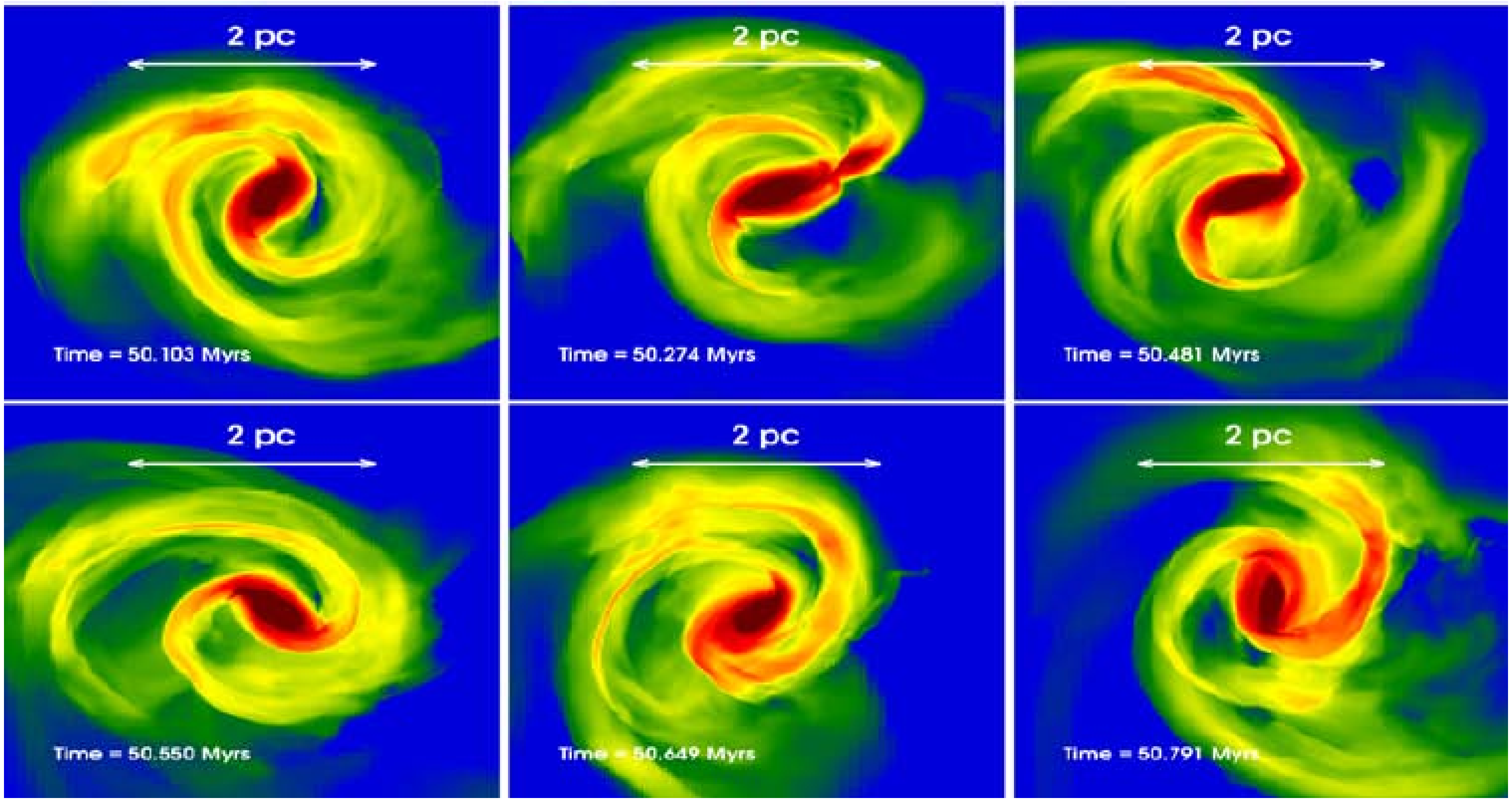
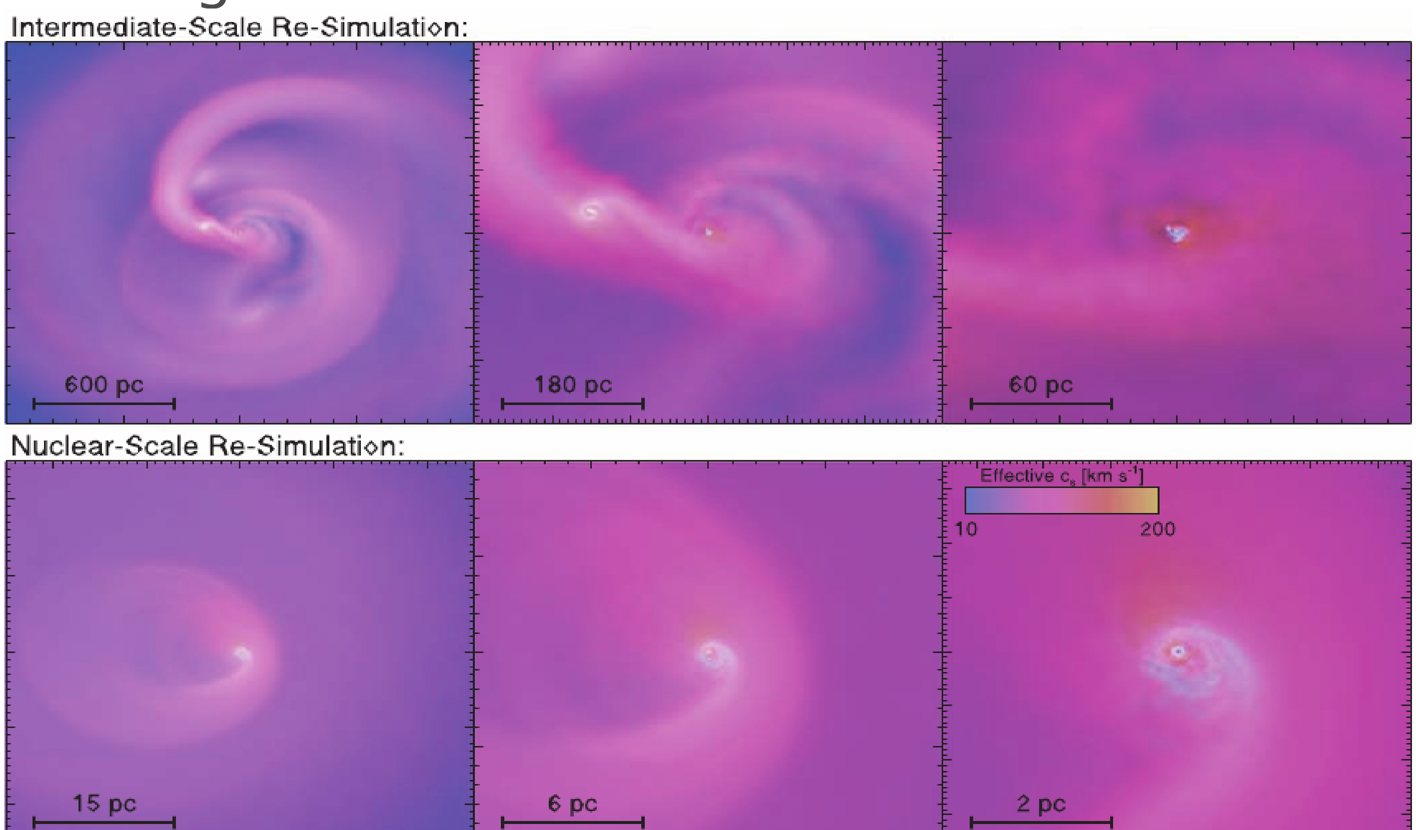
LATE TIME EVOLUTION



Formation of black hole seeds: Direct collapse of gas

-Mechanism for solving the angular momentum transport problem (below 20pc):
a. dark matter halos with extremely low spin values (lambda << 0.04)
b. low angular momentum tail of material
c. global dynamical instabilities i.e. "bars-within-bars" mechanism
(e.g. Shlosman et al. 1989, Begelman et al. 2006)
Self-gravitating gas clouds become bar unstable when the level of rotational support surpasses certain threshold. A bar can transport angular momentum outwards on a dynamical timescale via gravitational and hydrodynamical torques, allowing the radius to shrink.



Hopkins et al. 2010

Formation of black hole seeds: Direct collapse of gas

- Provided that gas angular momentum transfer is efficient typical gas masses within the central few parsecs can reach 10^4-$10^6 M_\odot$

- A supermassive star might form with a mass of a few $10^4 M_\odot$

- Evolution of isolated supermassive stars has been investigated numerically in full GR even in the presence of significant rotation indicating that the majority of stellar mass would collapse into a Kerr-like black hole

- If there is a fast accumulation of material onto the supermassive star, only the core of the star might collapse into a black hole with a mass of a few $M_\odot$ and thereafter black hole may growth in mass rapidly from the surrounding envelope → QUASI-STAR (Begelman et al. 2006) thus reaching 10^5-$10^6 M_\odot$

Formation of black hole seeds: Stellar cluster

- If star formation proceeds in small mini-halos with $T < 10^4$ K triggered by H2 cooling as more massive halos build up they will be metal enriched

- Fragmentation and formation of low mass stars starts as soon as gas is polluted by metals produced by the first Pop III stars

- Efficient star formation can occur in very compact nuclear star clusters

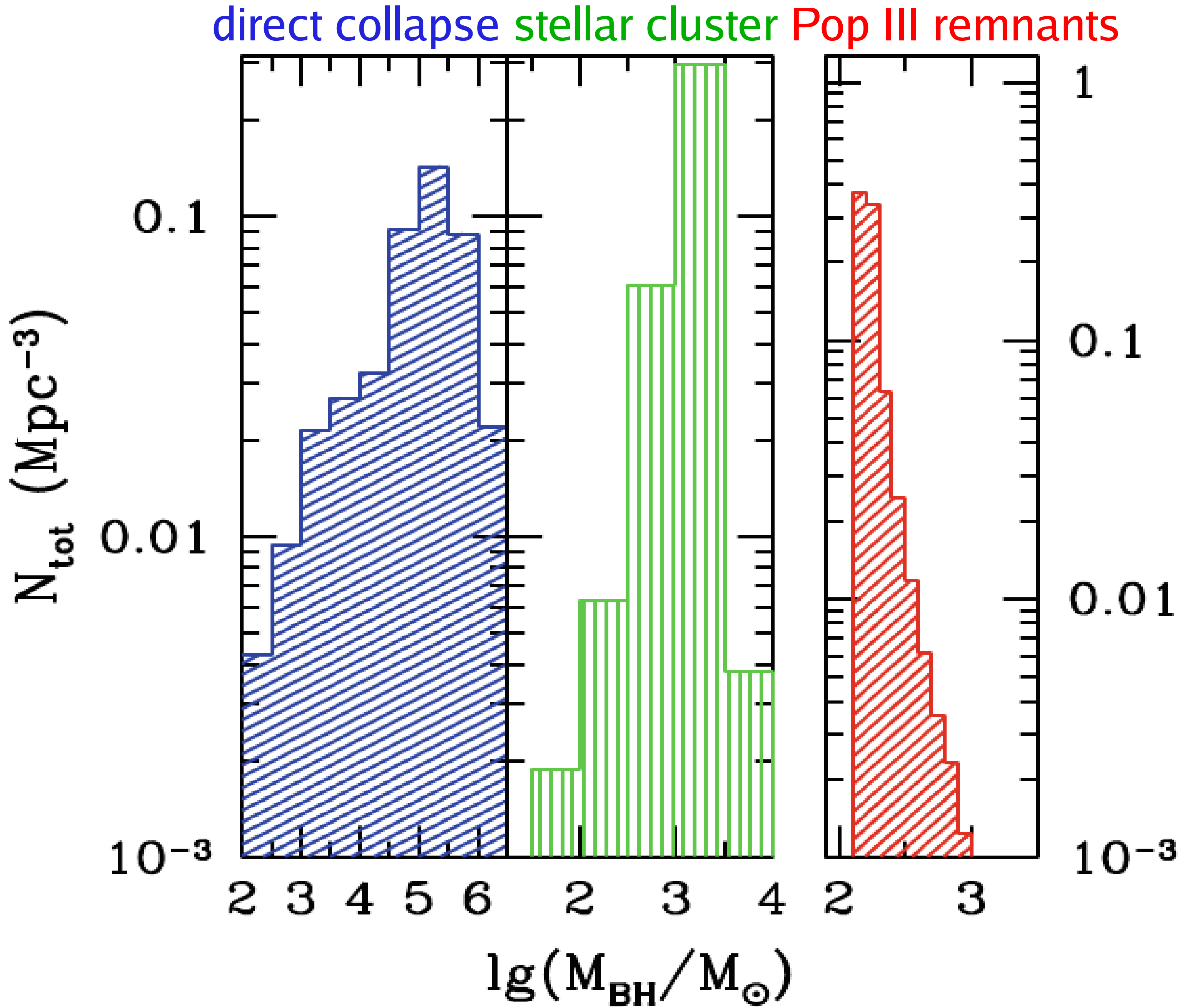
- The central core of the cluster initially contracts as the system tries to reach a state of thermal equilibrium: energy conservation leads to a decrease in the core radius as evaporation of the less bound stars proceeds → thus central density increases and the central relaxation time decreases → core collapses

- In a multi-mass system, massive stars segregate towards the centre due to the dynamical friction

- If segregation happens before the more massive stars evolve out of the main sequence (~3 Myrs), star-star runaway collision can take place leading to very massive star formation and ultimately a black hole remnant with a mass of ~ $1000 M_\odot$ → IMBH (e.g. Begelman & Rees, 1978, Portegies Zwart & McMillan, 2002, Freitag et al. 2006)

Low mass versus massive seeds scenarios

- Black hole seed mass function (Volonteri 2010)



Low mass versus massive seeds scenarios

- Soltan's argument. Similarity of the total mass in black holes today and the total mass accreted during active phases implies that most of the black hole mass is accumulated during radiatively efficient accretion

Yu & Tremaine, 2002:

We use the velocity dispersions of early-type galaxies obtained by the Sloan Digital Sky Survey and the relation between BH mass and velocity dispersion to estimate the local BH mass density to be $\rho_\bullet(z=0) \simeq (2.5 \pm 0.4) \times 10^5\, h_{0.65}^2\, \mathrm{M}_\odot\, \mathrm{Mpc}^{-3}$. We also use the quasi-stellar object (QSO) luminosity function from the 2dF Redshift Survey to estimate the BH mass density accreted during optically bright QSO phases. The local BH mass density is consistent with the density accreted during optically bright QSO phases if QSOs have a mass-to-energy conversion efficiency $\epsilon \simeq 0.1$.

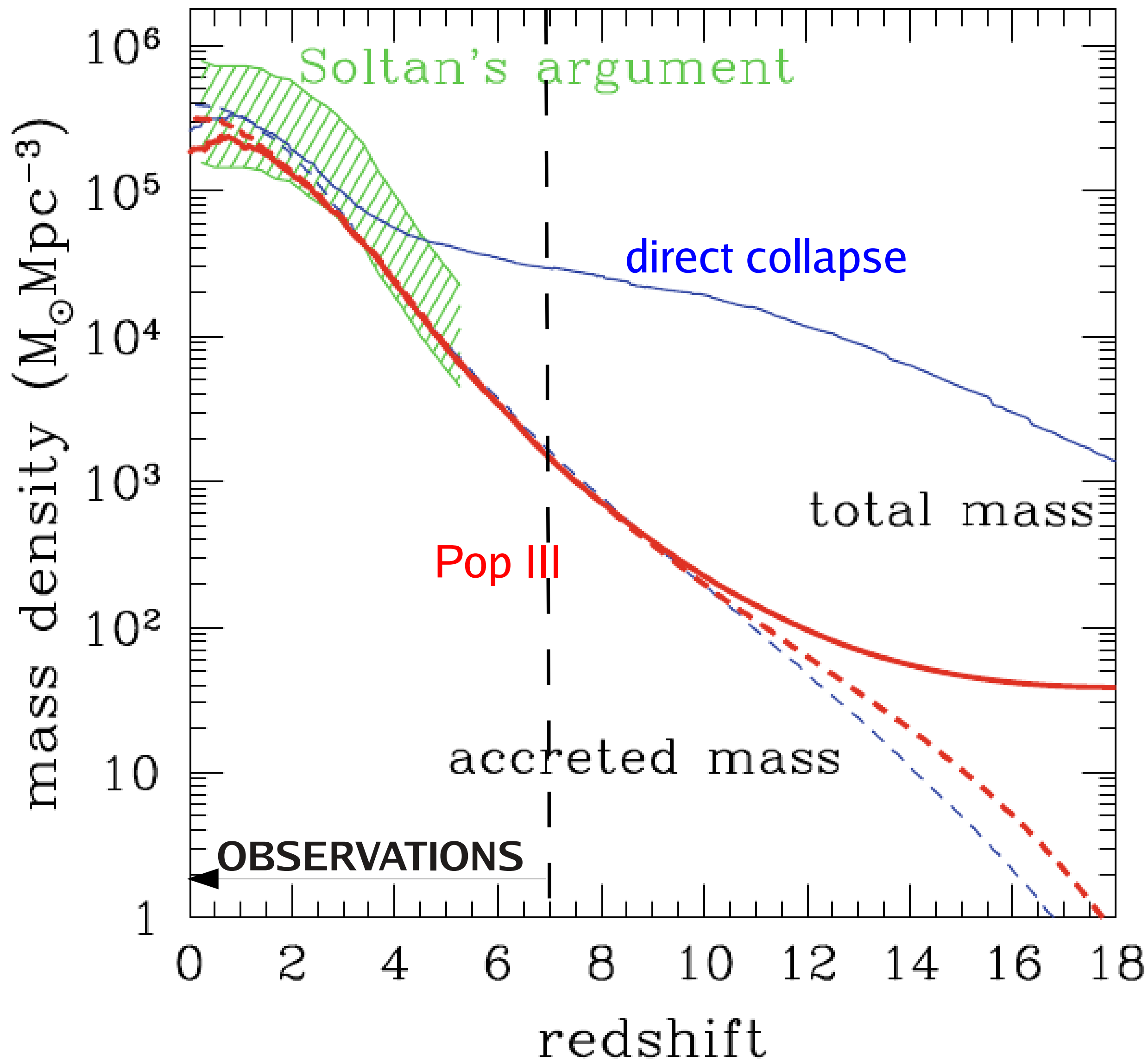
Low mass versus massive seeds scenarios

Evolution of the black hole mass density with time for different seed models (Volonteri 2010)
green shaded area: radiative efficiency 0.06-0.3

At lower redshifts efficiently accreting black holes "lose memory" of their initial seed mass

future GW detectors (eLISA?, DECIGO) could probe very high z

observation of low-mass and dwarf galaxies in the local Universe → occupation fraction sensitive to seed models



Growth of the black holes in the early Universe

Several different channels:

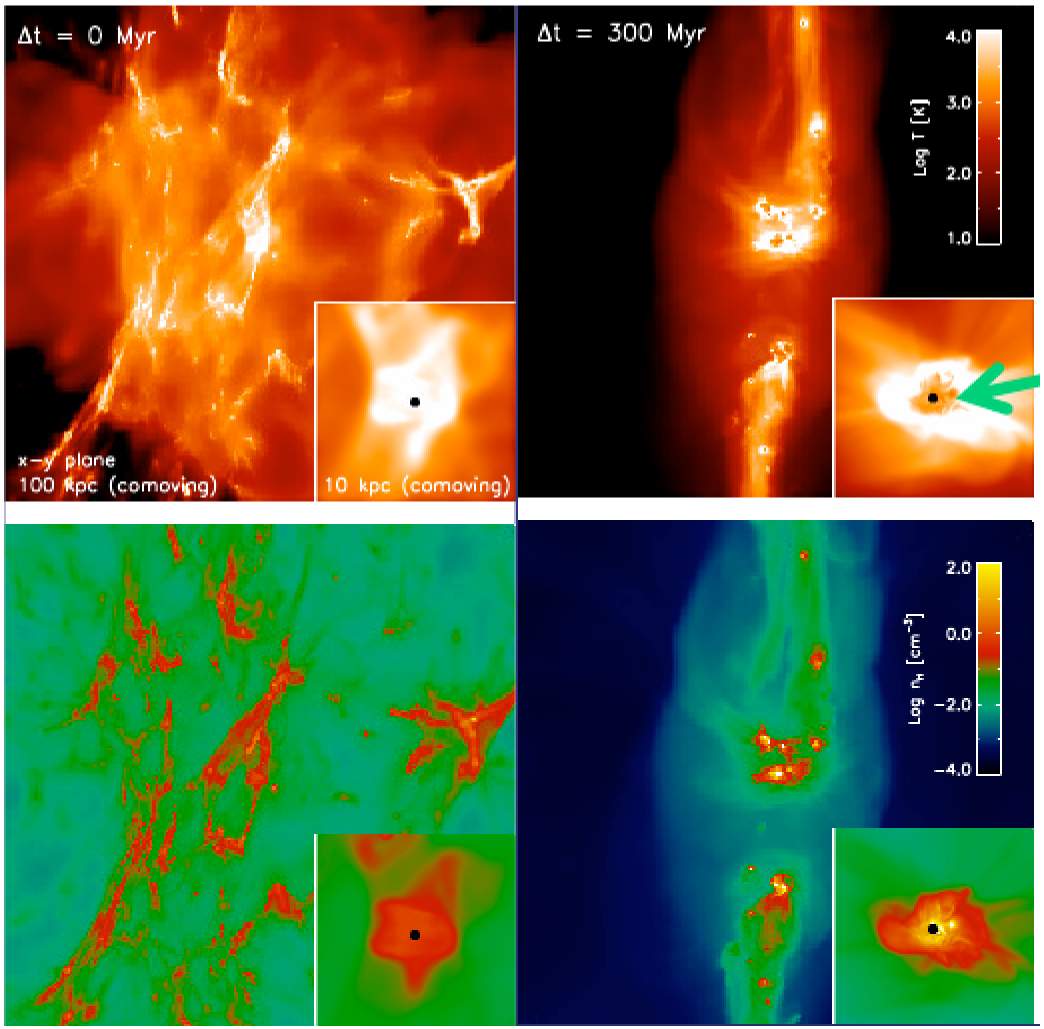
1. Gas accretion processes
2. Mergers with other black holes
3. Tidal capture of stars (e.g. in compact stellar clusters)

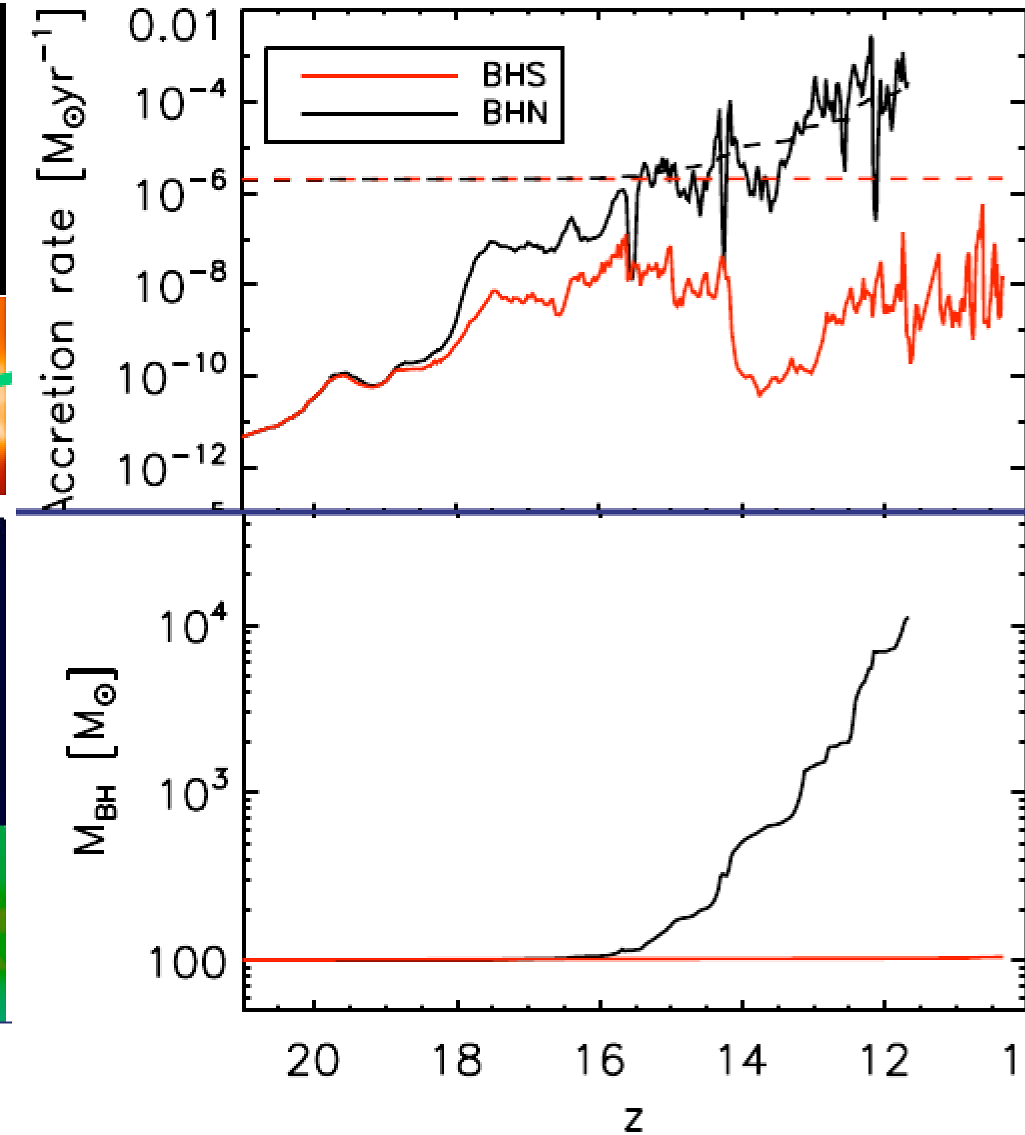
Efficiency of these channels depends on:
1. black hole seed masses and cosmic time (e.g. retention in the centre, gas accretion dependence on mass)
2. occurrence of gravitational slingshot and recoil events
3. properties of the central region and of the host galaxy (e.g. gas content and thermodynamical state)
4. larger scale environment of the host dark matter halo (e.g. merger history, gas supply)
5. stellar and black hole feedback processes

...

Growth of the black holes in the early Universe

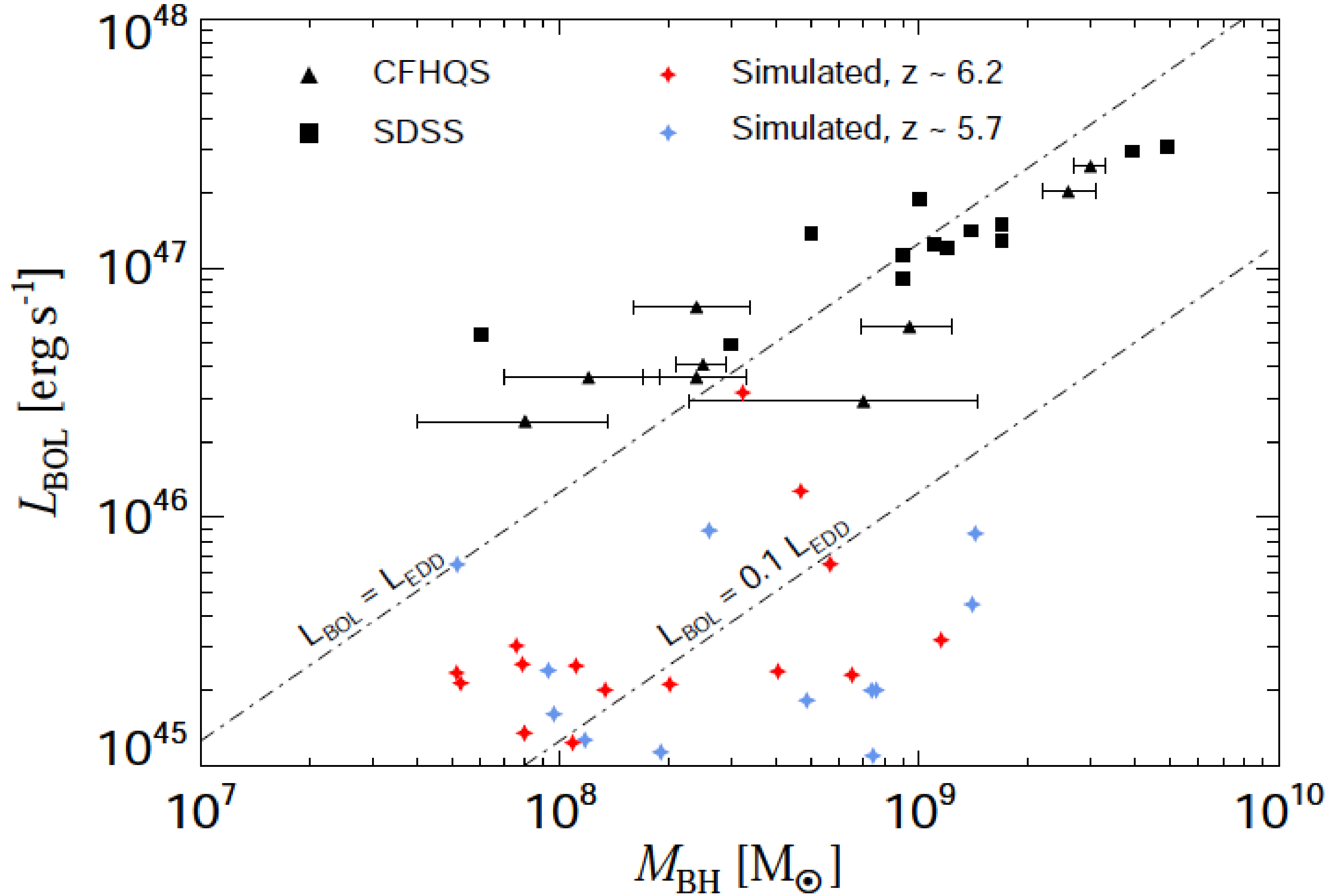
In the case of the PopIII remnants, feedback from the progenitor PopIII stars (e.g. Johnson & Bromm, 2007) and/or black holes themselves (Jeon et al. 2012) could significantly suppress black hole accretion rate





Growth of the black holes in the early Universe

While black hole seeds may form in different ways and grow in mass via different channels, observations of high redshift quasars imply very stringent time constraints on the black hole mass assembly
De Rossa et al. 2011 SDSS, Willott et al. 2010 CFHQS
Mortlock et al. 2011 QSO at z = 7.085 mass ~ 2 x $10^9 M_\odot$



Growth of the black holes in the early Universe

Light seeds might not be able to grow sufficiently in mass to power high redshift QSOs, or some more exotic processes need to be invoked (e.g. super Eddington accretion)
- In a spherically symmetric case, balance of the force imparted by the radiation of the central object with a luminosity L, and of the gravitational force exerted on the accreting material (e.g. ionized H), leads to the concept of Eddington limit

$$\frac{GMm_p}{r^2} = \frac{L\sigma_T}{4\pi r^2 c},$$

$$L_{\rm Edd} = \frac{4\pi c G M m_p}{\sigma_T}$$

$$\dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon_{\rm r}\, \sigma_{\rm T}\, c}$$

$$t_S = \frac{\sigma_T c}{4\pi G m_p} \approx 4.5 \times 10^7 yr$$

$$t_{age} \approx 8 \times 10^8 \left(\frac{\Omega_{m,0}}{0.27}\right)^{-1/2} \left(\frac{h}{0.70}\right)^{-1} \text{yr}$$ (age of universe)

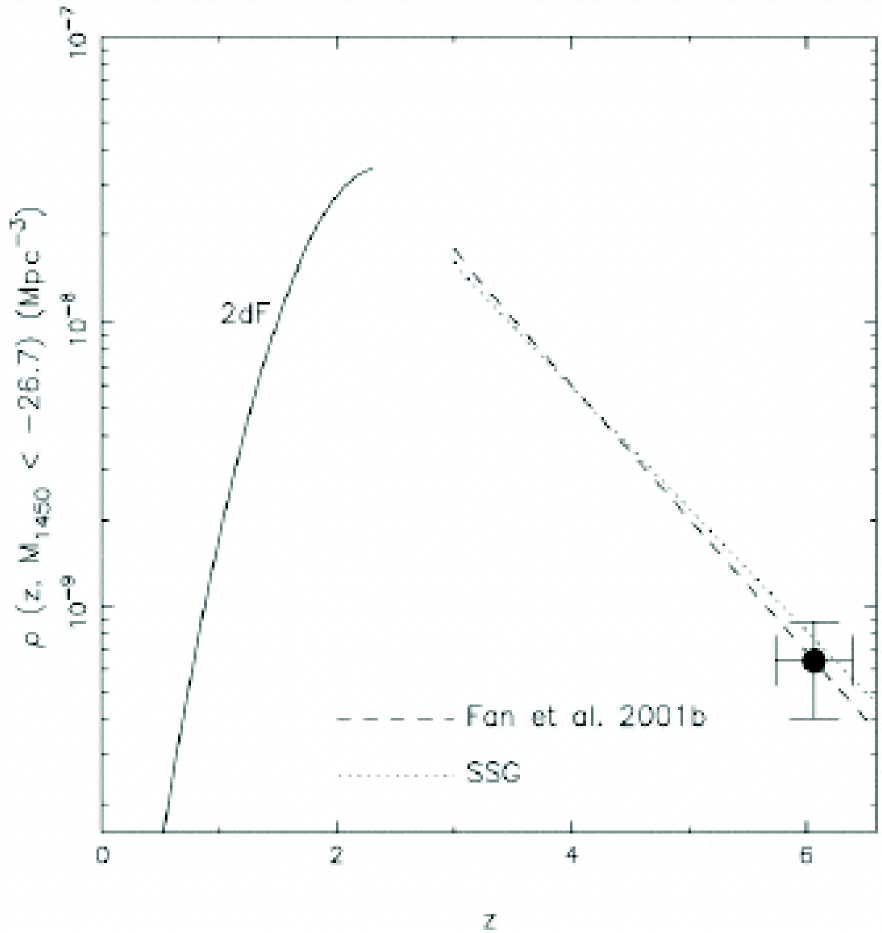
$$t_{e-fold} \approx 4.4 \times 10^7 \left(\frac{\eta}{0.1}\right) \left(\frac{\dot{M}}{\dot{M}_{Edd}}\right)^{-1} \text{yr}$$ (e-folding time)

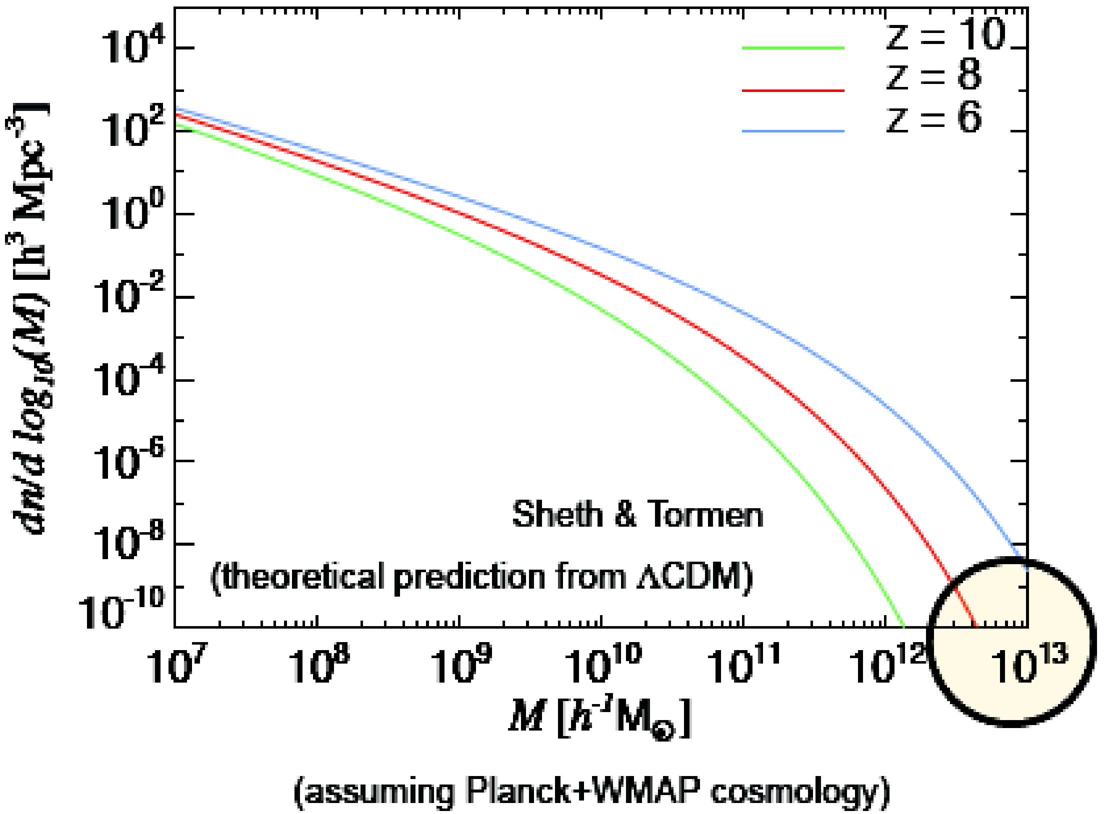
~16 e-foldings to grow a $10^9\ \mathrm{M}_\odot$ black hole by $z = 7$ from a $100\ \mathrm{M}_\odot$ seed black hole at constant rate.

$\longrightarrow$ $16 t_{e-fold} \approx t_{age}$

Powering of high redshift quasars

- Space density of luminous z ~ 6 is extremely low!





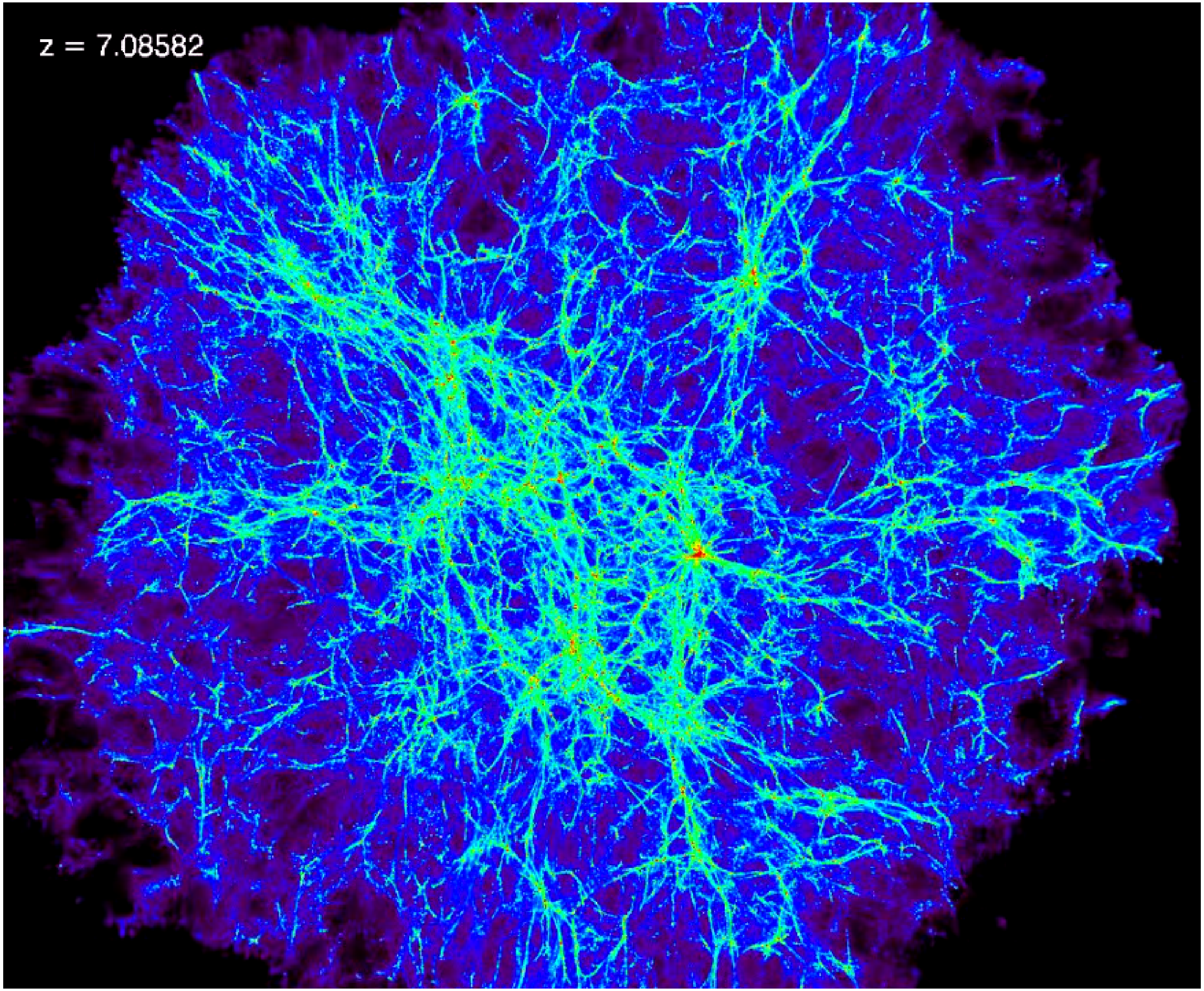
- If duty cycle is high, then quasars should inhabit halos of mass:

$$5 \times 10^{12} - 10^{13}\,\mathrm{M}_{\odot}$$

- If duty cycle is low, quasars will reside in lower mass halos.

Powering of high redshift quasars

- If z~ 6 QSO are residing in very massive dark matter halos, they are living in very rare, overdense and gas-rich environments – ideal for rapid black hole growth

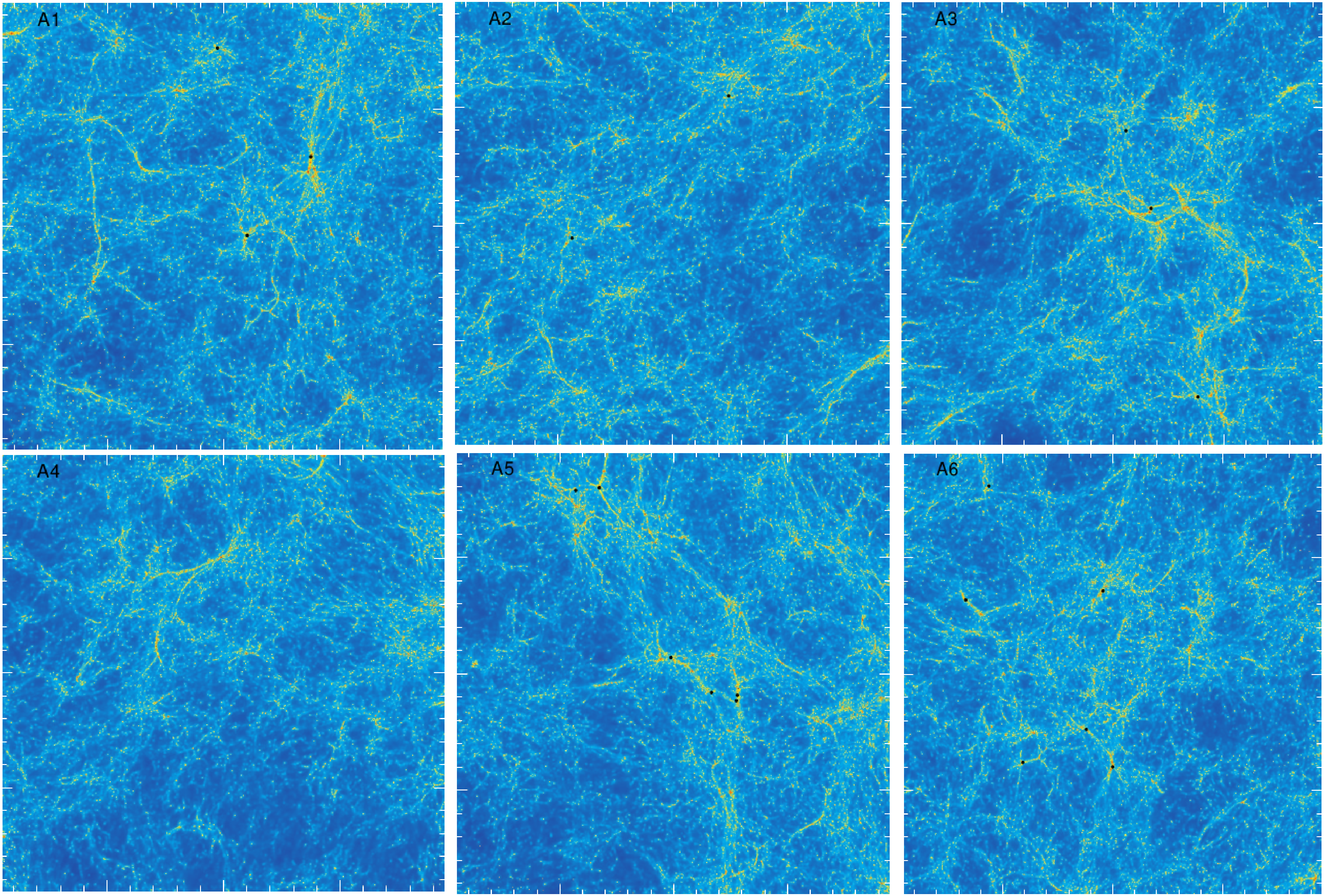


Sijacki et al. 2009

Powering of high redshift quasars

Costa, Sijacki et al. 2013

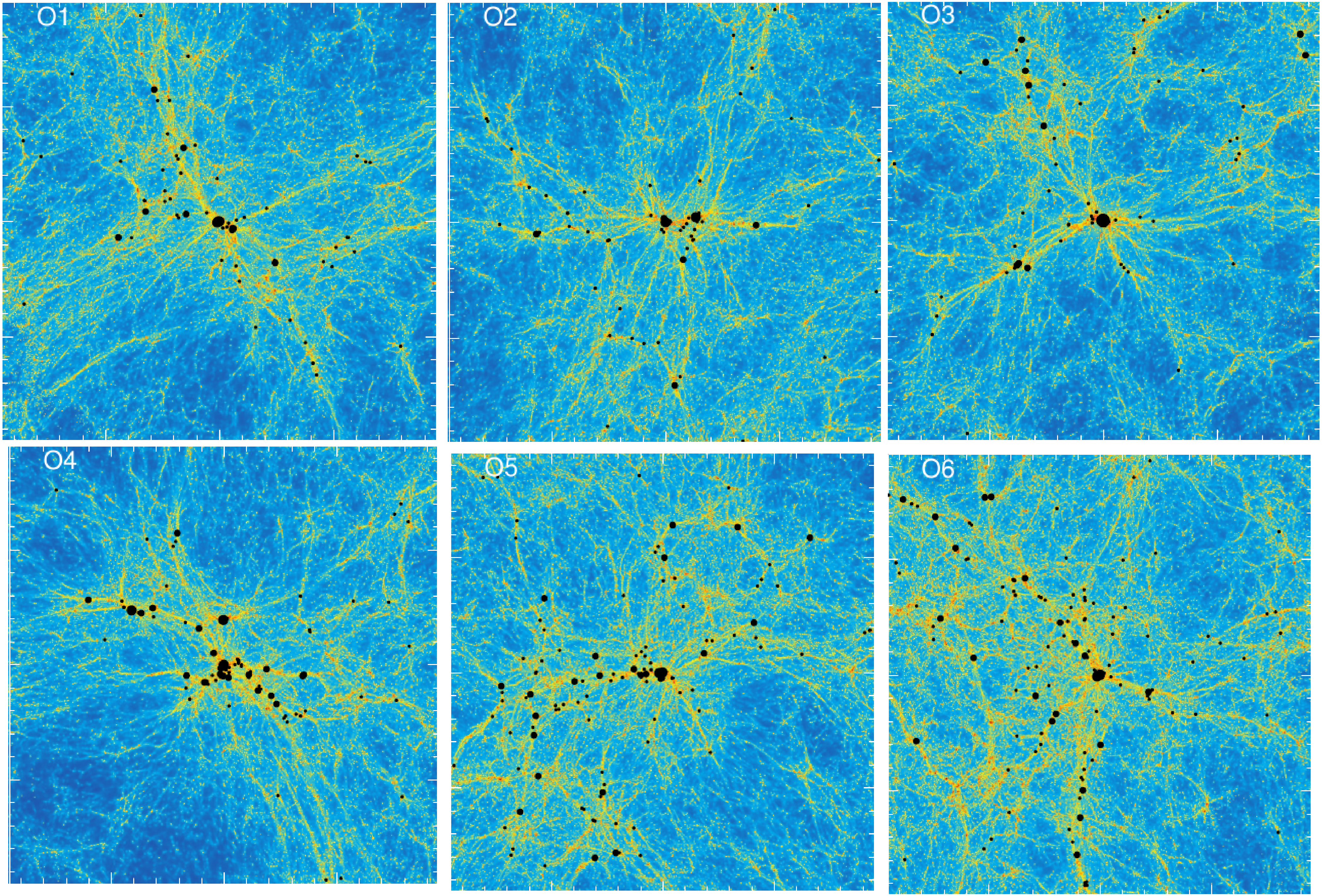
AVERAGE REGIONS OF UNIVERSE AT z ~ 6



Powering of high redshift quasars

Costa, Sijacki et al. 2013

OVERDENSE REGIONS OF UNIVERSE AT z ~ 6

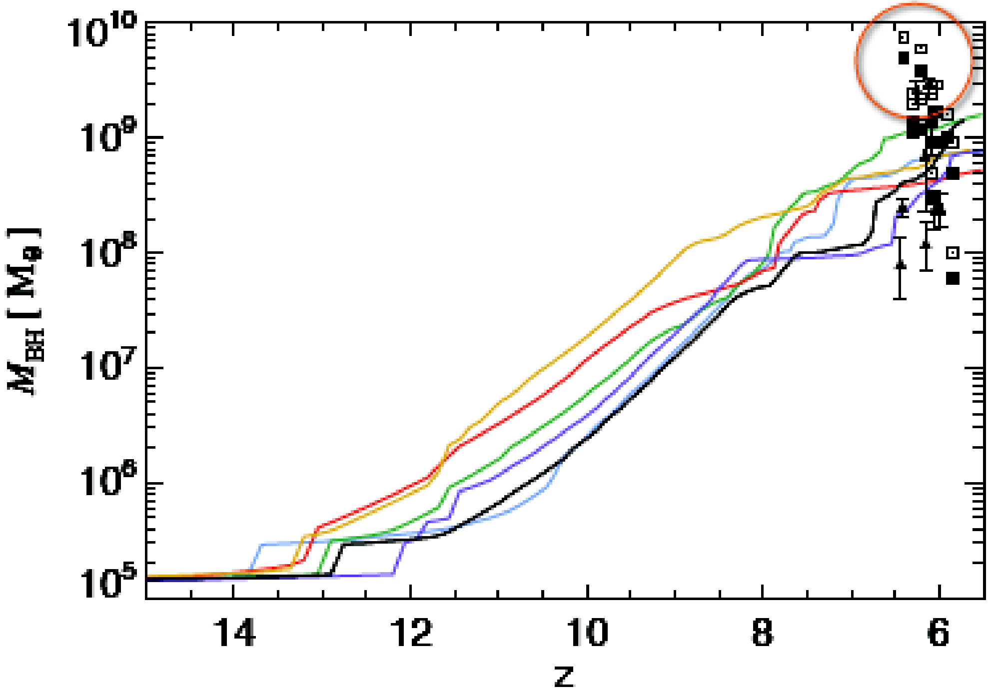


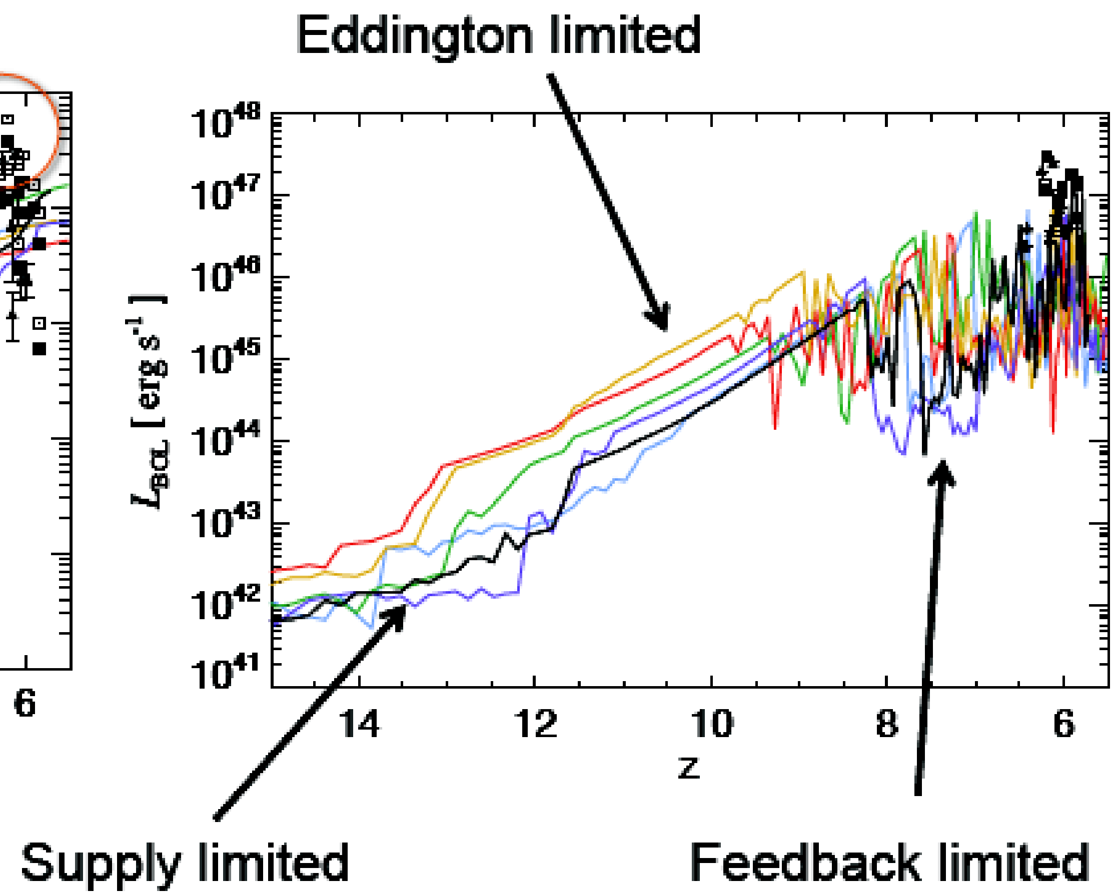
Powering of high redshift quasars

Costa, Sijacki et al. 2013

- Growth of the bright QSOs

(even Millennium box appears too small)



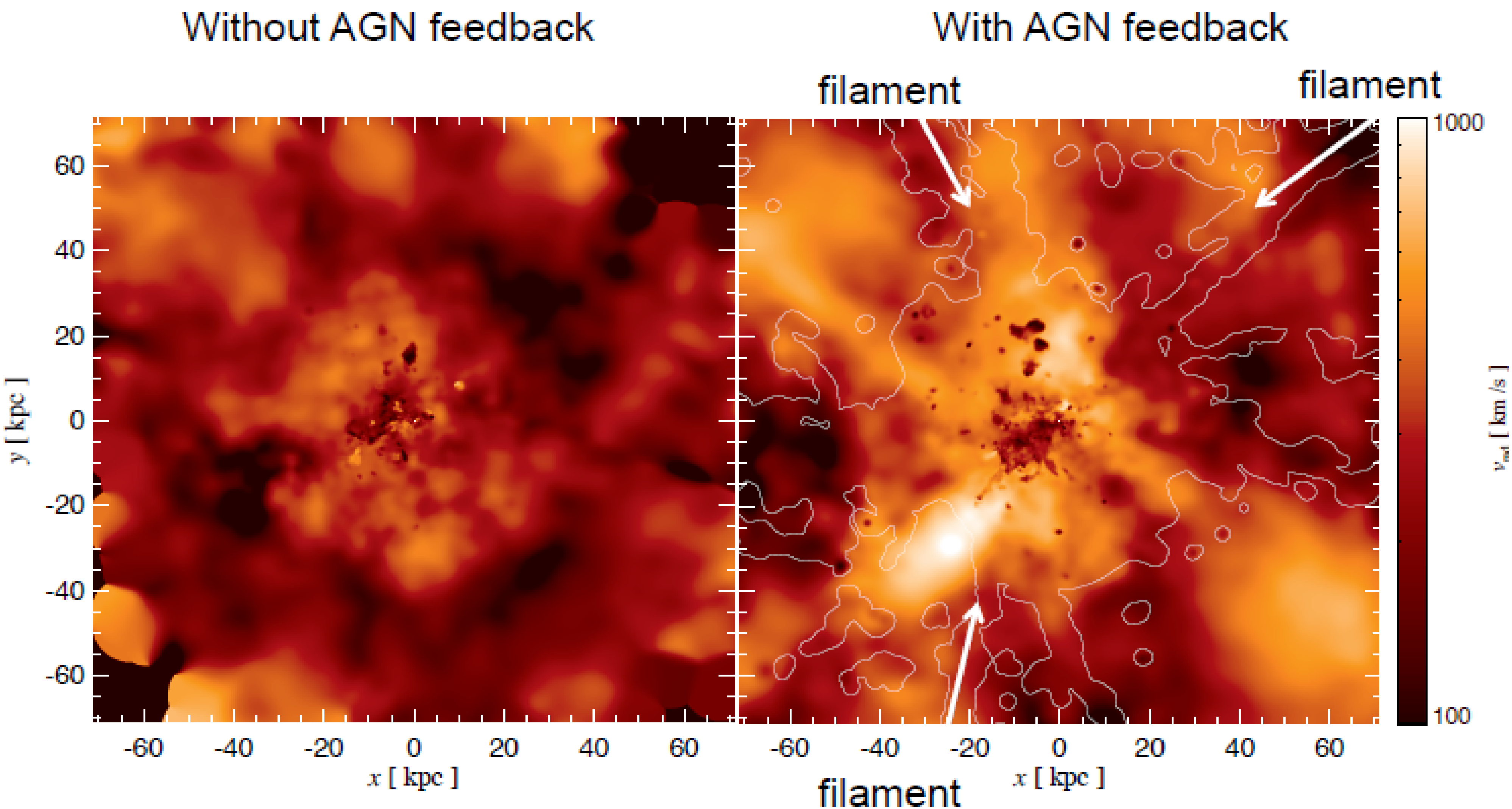


Strong selection effect:
Quasars only detected during high accretion episodes.

Powering of high redshift quasars

Costa, Sijacki et al. 2013

- Powerful AGN feedback at z ~ 6

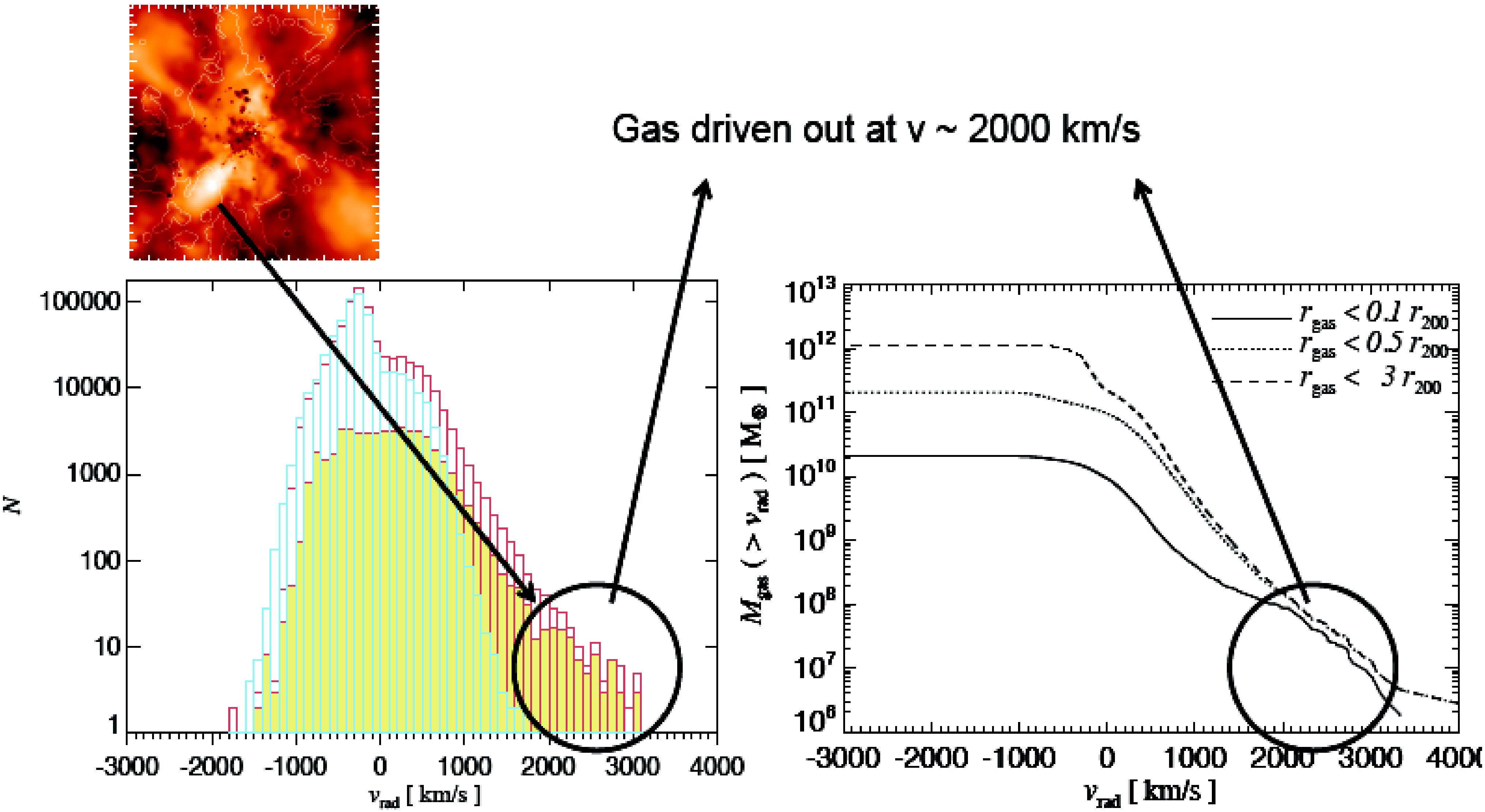


Outflow very anisotropic

Powering of high redshift quasars

Costa, Sijacki et al. 2013

- Powerful AGN feedback at z ~ 6

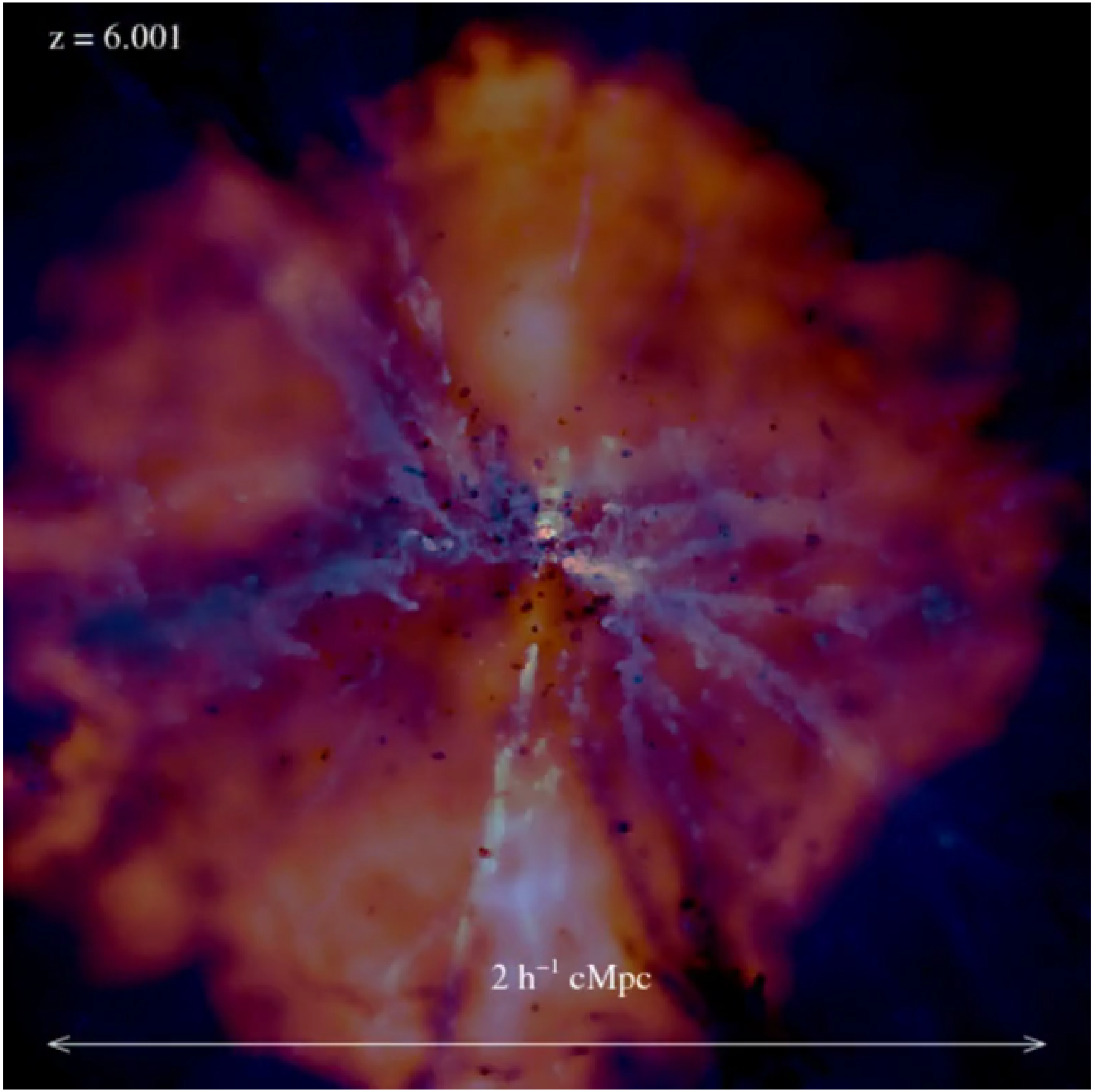


AGN drives an outflow that fills outer regions with hot gas and metals.

Powering of high redshift quasars

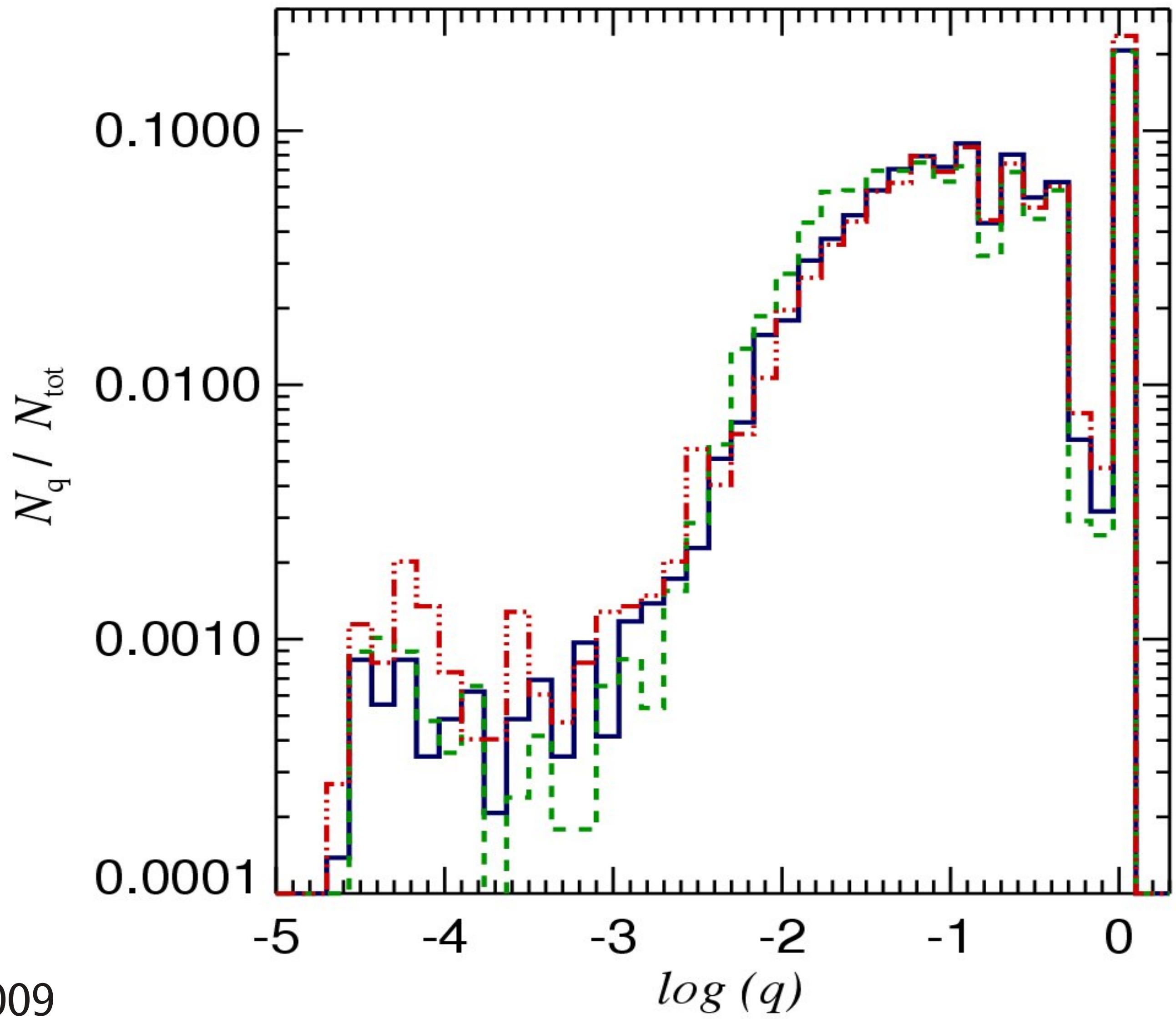
Costa, Sijacki et al. 2013

- Powerful AGN feedback at z ~ 6



Relative importance of gas accretion and BH mergers with cosmic time

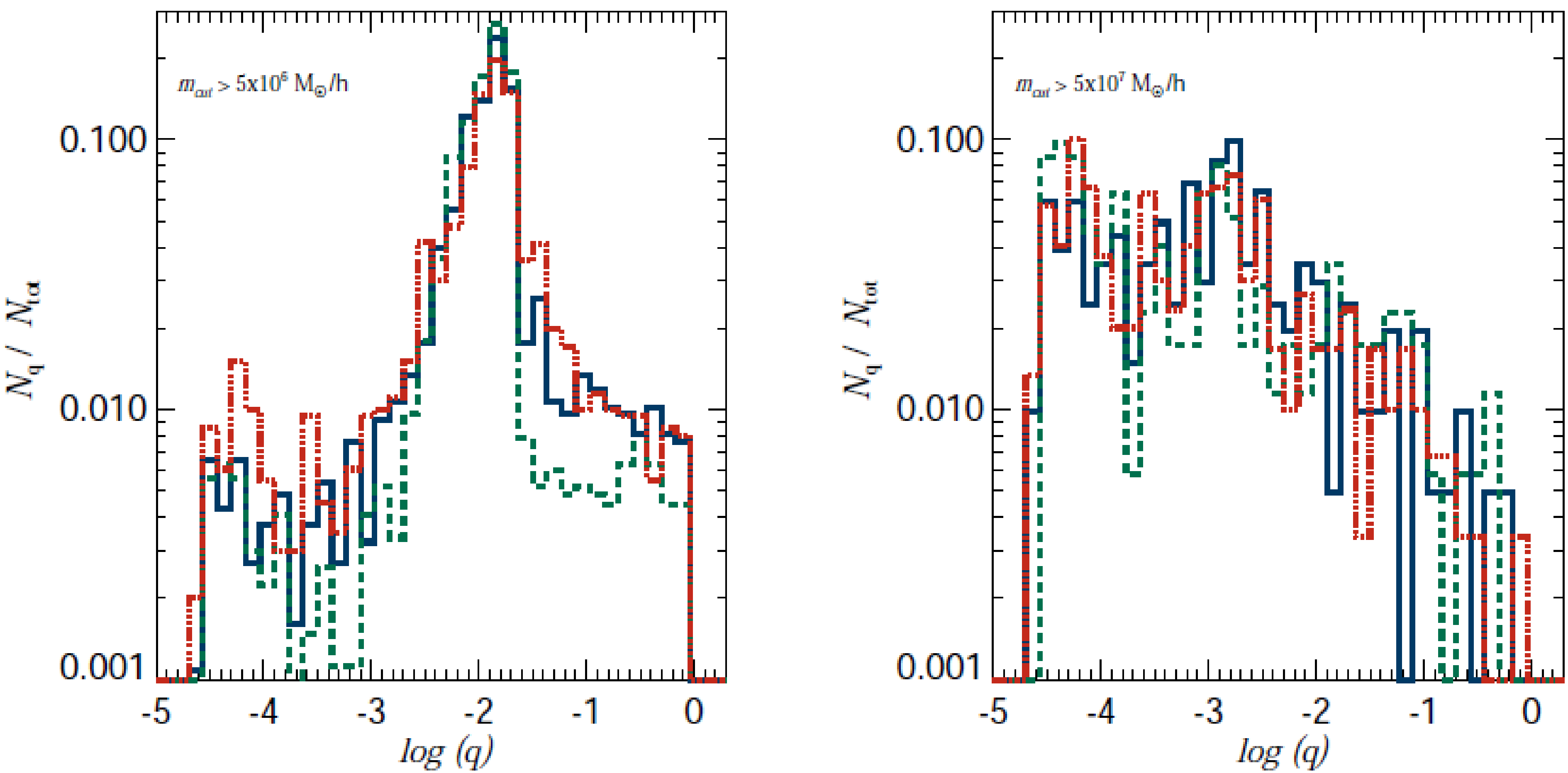
- assuming very efficient black hole merging occurs, distribution of mass ratios for all BH mergers at z > 6 from a cosmological simulation



Sijacki et al. 2009

Relative importance of gas accretion and BH mergers with cosmic time

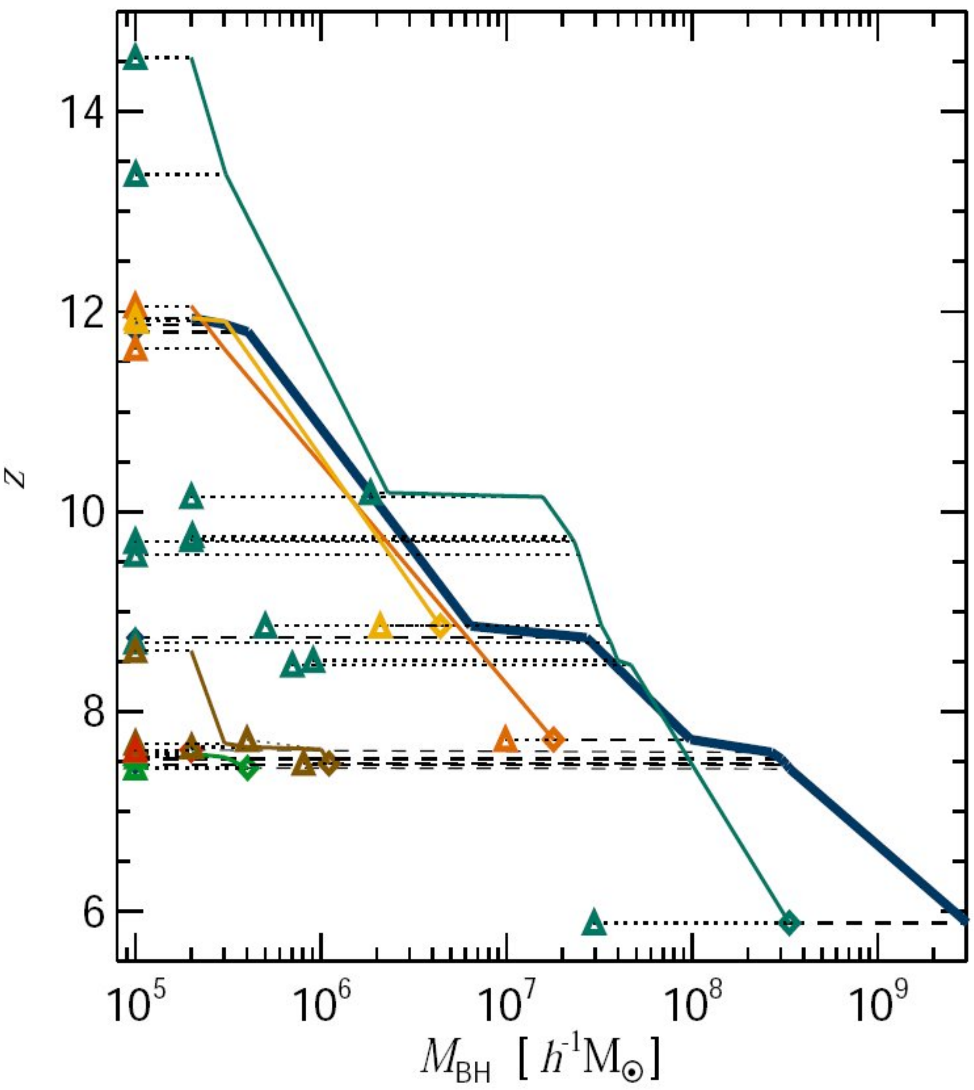
- distribution of mass ratios for all BH mergers at z > 6 for BH pairs where at least one BH has mass larger than a threshold value

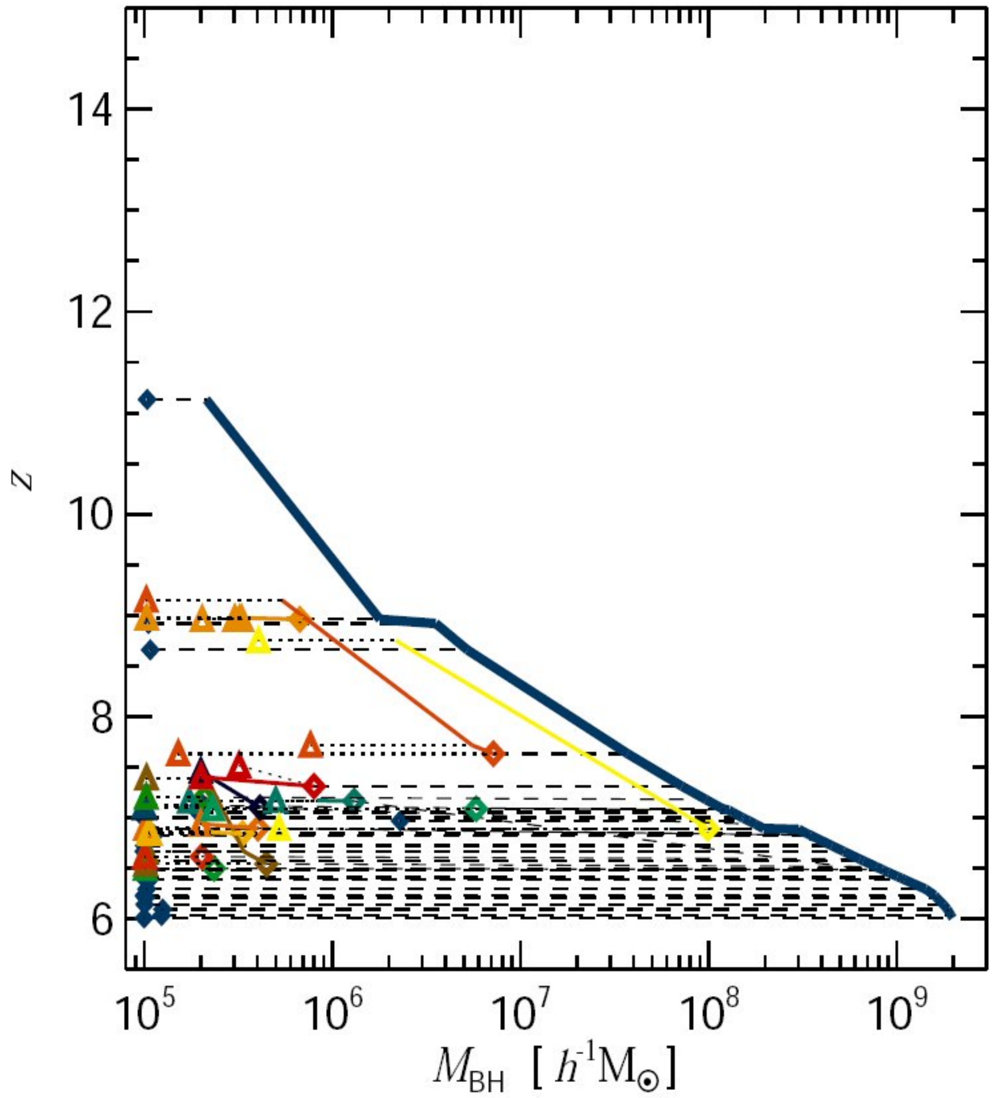


Sijacki et al. 2009

Relative importance of gas accretion and BH mergers with cosmic time

- BH mergers more important when BH seeded earlier, but final BH mass mostly due to the Eddington limited accretion





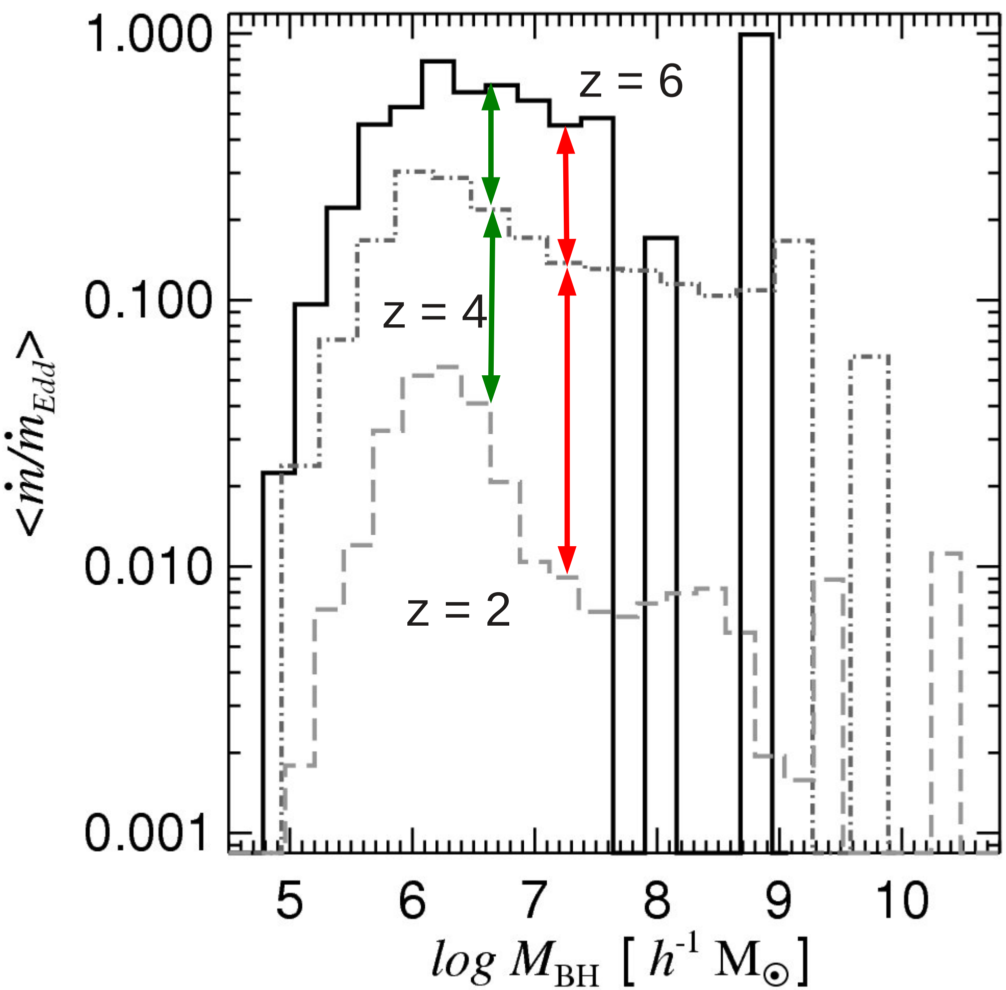
total mass of BHs that merge onto the main progenitor < 20% / 10%
(Sijacki et al. 2009)

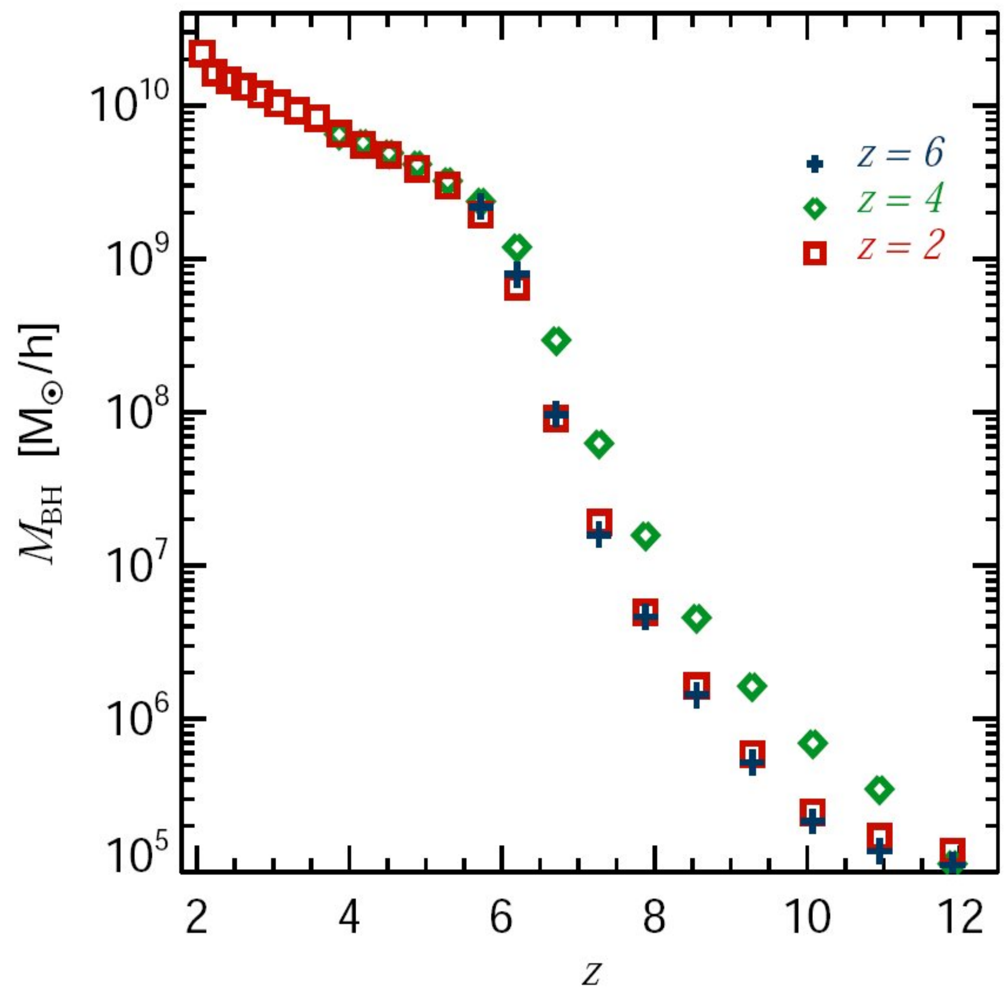
Relative importance of gas accretion and BH mergers with cosmic time

- Tracking z ~ 6 QSO descendants to lower redshifts

DESCENDENTS OF Z=6 QSOs LIKELY MOST MASSIVE BHs TODAY with M_{BH} above M_{BH}-σ relation

(e.g. Lauer et al. 2007, Kormendy & Ho, 2013)



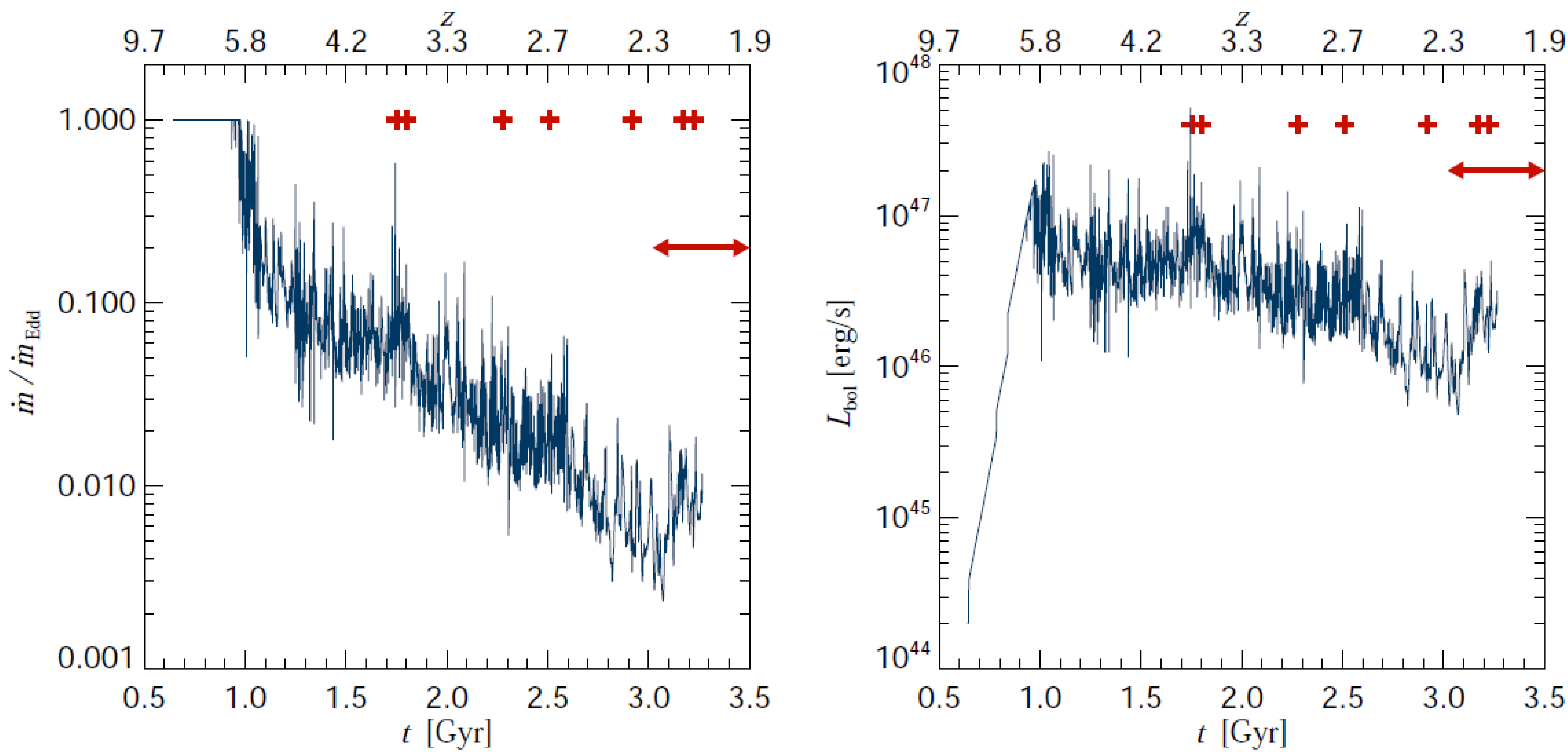


CLEAR SIGNITURE OF BH DOWNSIZING

Sijacki et al. 2009

Relative importance of gas accretion and BH mergers with cosmic time

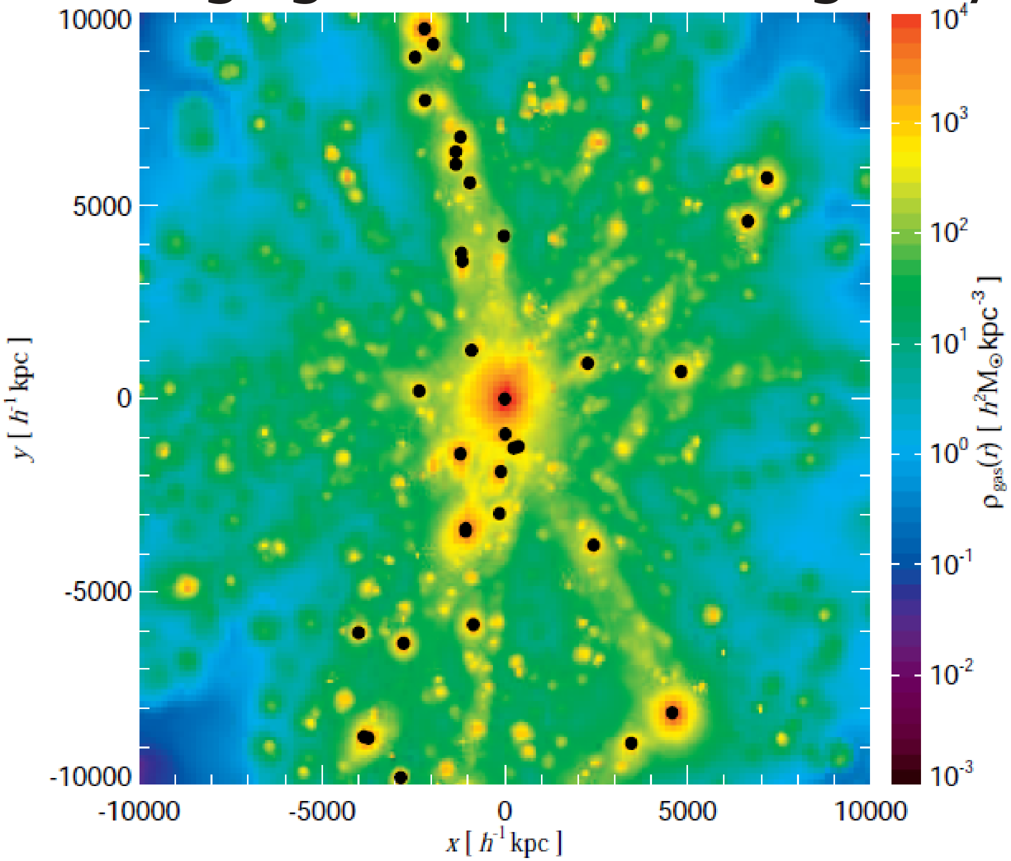
- Relation between the mergers and enhanced BH growth



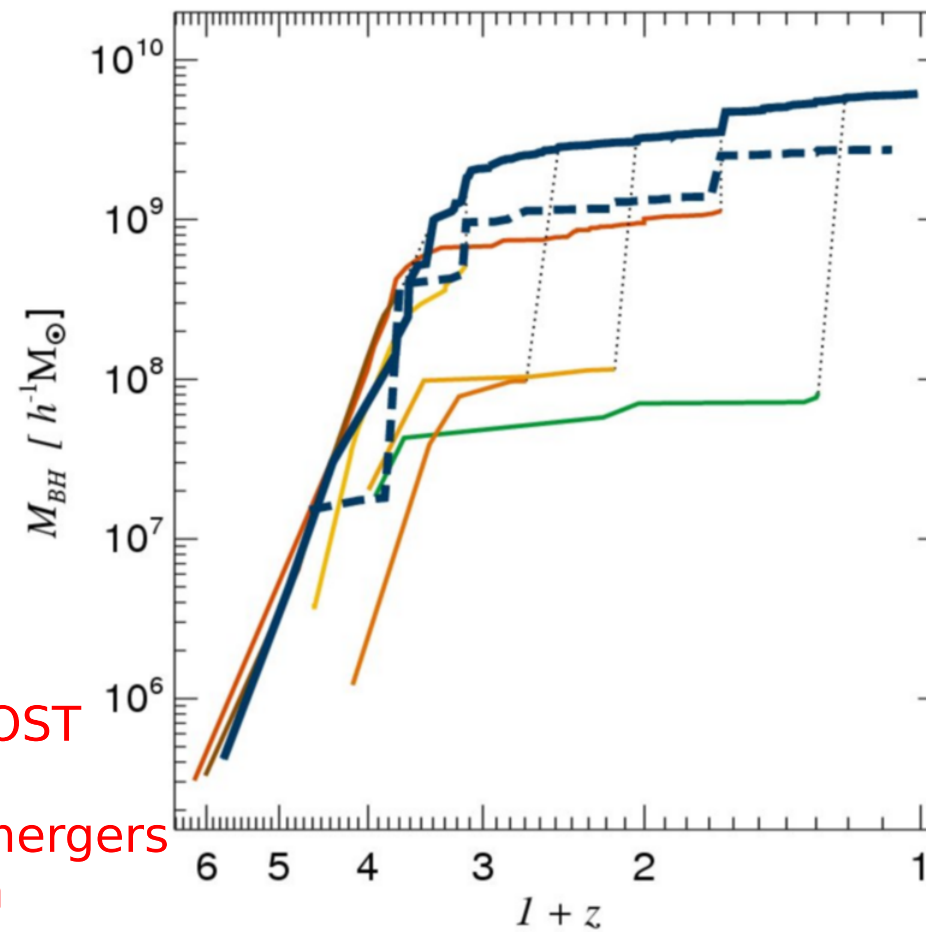
Sijacki et al. 2009

Relative importance of gas accretion and BH mergers with cosmic time

- BH merging and accretion in galaxy clusters at z ~ 0



Sijacki et al. 2007



MERGER TREE OF THE MOST MASSIVE BH AT Z = 0:
45% of mass due to BH mergers
55% due to gas accretion