Lectures plan

intro

- 'Classical' Cosmology and 'Modern' Cosmology and Structure in the Universe (what do we simulate?).
- The initial conditions (why cosmological simulations are unique)
- Physics and algorithms

Lecture I

(1) Multiscale simulations of black holes and galaxy formation

Lecture II

(2) Cosmological Simulations: The first massive black holes and quasars

Lecture III

(3) The IGM and Lyman-α (FEATURING: R. Croft!)

What is the history of black hole formation and evolution?

What is the formation path of MBH seeds? When/where did they form?

How MBH seeds grow? How do they impact their environments?

What are the seeds of (super) massive black holes?

Unique predictions of LCDM:

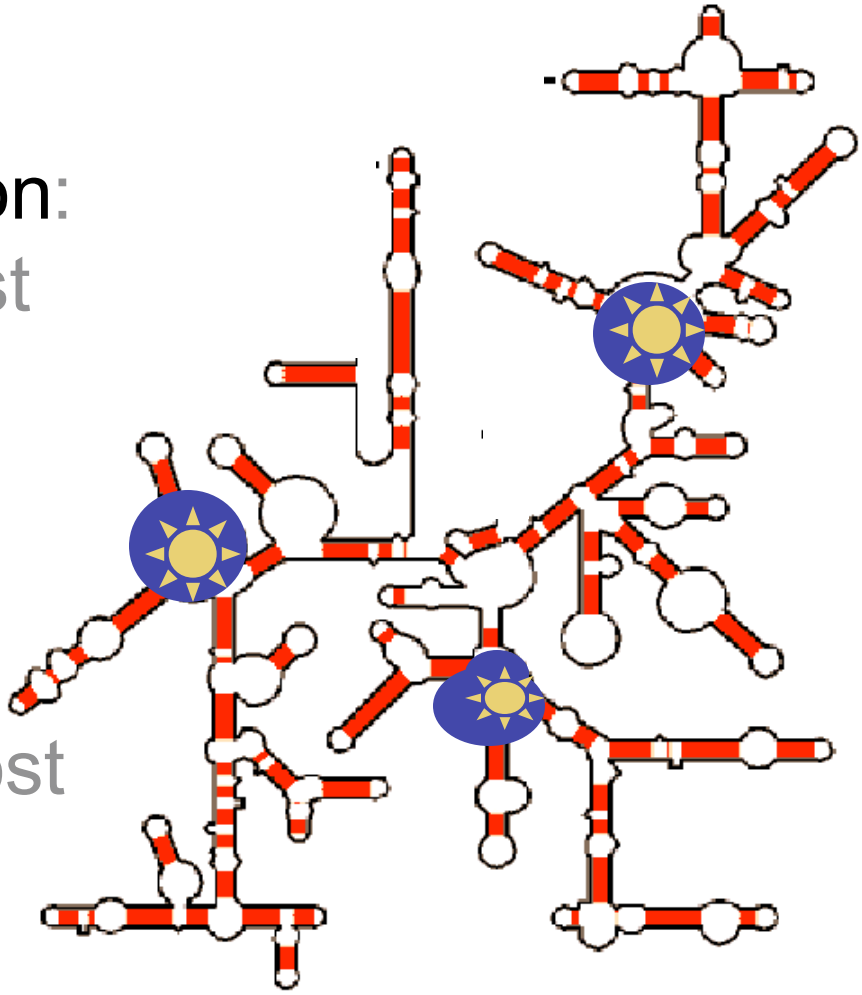
Hierarchical Structure formation:

small scales collapse first

At z=20,

$M > 10^6 M_{sun}$, gas coolant=H2

First stars (POPIII) form in most massive halos



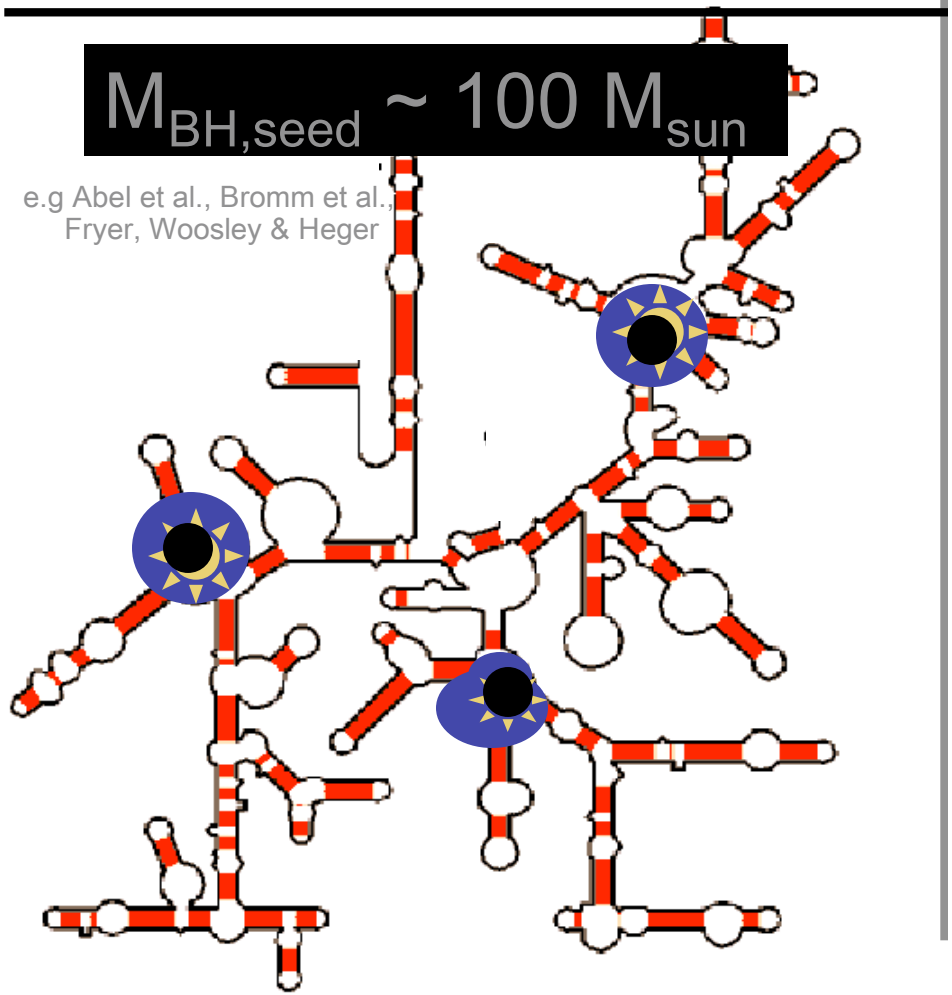
What is the formation path of MBH seeds?
When did they form? Where? Light or heavy?

PopIII stars remnants

e.g. Madau & Rees 01
Volonteri Haardt, Madau 03

$M_{BH,seed} \sim 100\ M_{sun}$

e.g Abel et al., Bromm et al.,
Fryer, Woosley & Heger



What is the formation path of MBH seeds?
When did they form? Where? Light or heavy?

PopIII stars remnants

e.g. Madau & Rees 01
Volonteri Haardt, Madau 03

$M_{BH,seed} \sim 100\ M_{sun}$

e.g Abel et al., Bromm et al.,
Fryer, Woosley & Heger

Gas dynamical processes

e.g Eisentein &Loeb 95, Bromm & Loeb 2003,
Koushiappas et al 04, Begelman et al, 06,
Lodato Natarajan 06

$M_{BH,seed} \sim 10^3\text{-}10^5\ M_{sun}$

In biased protogalaxies

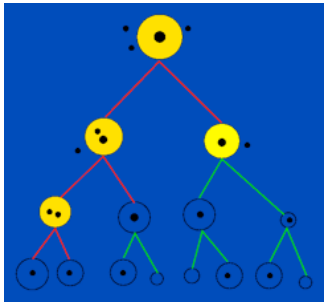
… this is all we have for the ICs for MBH in models of galaxy formation…

Key Questions:

What is the formation path of MBH seeds?
When did they form? Where? Light or heavy?

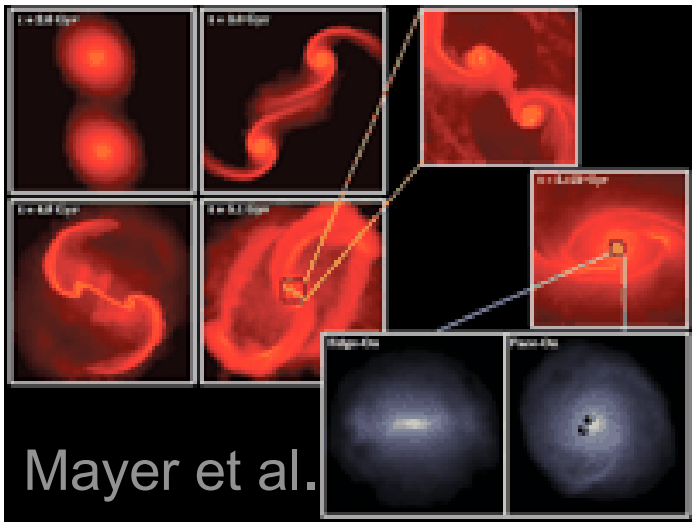
How/ where do MBH grow and shine?

How/ where do MBHs seeds grow?



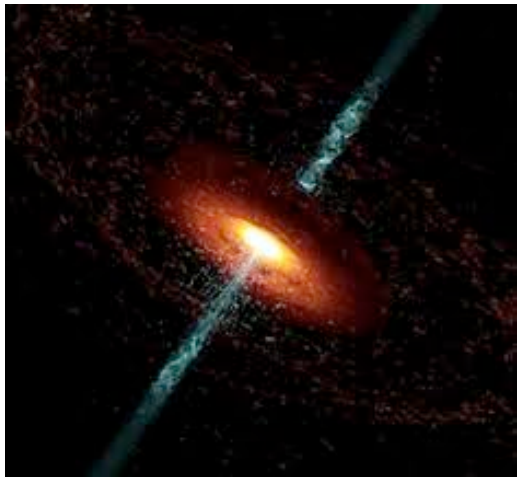
BH-BH mergers

BH mass density
almost constant with time
some reshuffle in the mass function..

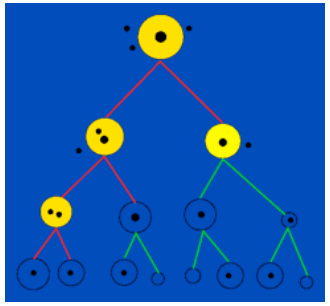


Gas Accretion

Total mass density of BHs
grows with time.

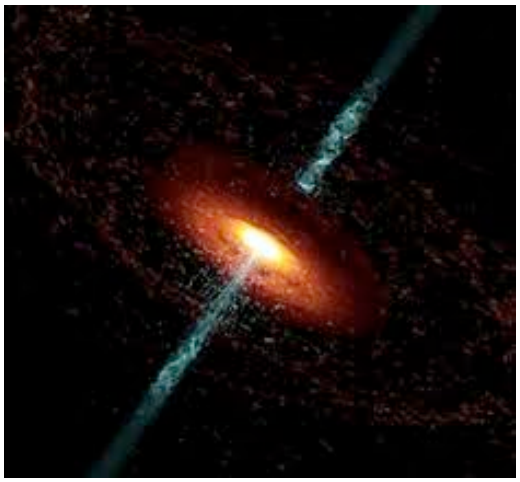


How/ where do MBHs seeds grow?



Gas Accretion

Total mass density of BHs grows with time.



$$L_{BH} = \text{efficiency } \dot{M}_{acc}\, c^2$$

Black hole Growth = Gas Supply = Activity

How/ where do MBH seeds grow at early time?

z=6 quasars imply
$M_{BH}=10^9\ M_{sun}$

First billion years requires extremely large accretion rates

$$L_{Edd} = \frac{4\pi G c m_p}{\sigma_T} M_{BH} = \varepsilon \dot{M} c^2$$

$$M_{BH} = M_{seed}\, e^{\frac{t}{t_{Edd}}}$$

$$t_{Edd} = 450\ Myr \frac{\varepsilon}{1-\varepsilon}$$

$$\ln(M_{BH}/M_{seed}) = \ln[10^9/(100-1e5)]$$
$$= 10-17 \text{ e-foldings}$$

sustained accretion at Eddington rates in early growth

Checklist for BH growth

- ✓ biased regions → Large Volumes
- ✓ Galaxy scales → High Resolution
- ✓ Gas accretion → Hydrodynamics

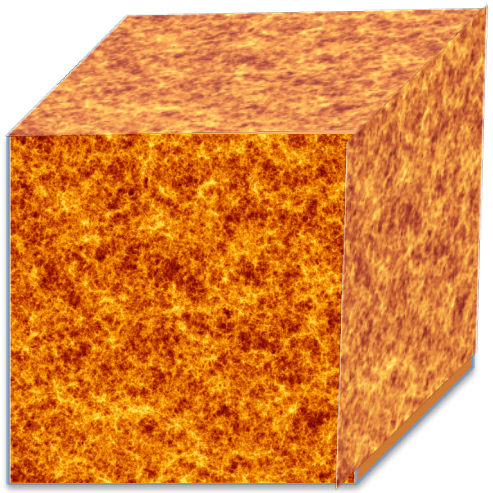
…

Journey into the growth of the first supermassive black holes

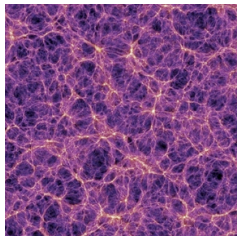
Cosmological Simulations with BH

	Zoomed halos	Uniform volumes
	Select rare peaks and re-simulate Li et al., Sijacki et al., Alvarez et al., Cattaneo et al., Bellovary et al. Teyssier et al.	whole mass function Di Matteo et al, Booth & Shaye 09, Sijacki et al.,.
CONS:	Small vol.: 1 or small samples Hand 'picked' Quasar hosts based on DM mass	Never big enough vol.! Lower res.
PROs:	highest resolution: detailed studies of host and quasar more detailed modeling	direct investigation of quasars growth as a function of environment Direct statistics: M-sigma, BH mass functions, LFs, Correlation Functions etc..

Simulation: 'Massive Black' Run



-Code used: PetaGadget (Petapps Cosmology)
-Particle number: $2x3200^3$ = 64 billion
-Box size: 533 h^{-1} Mpc
-Physics: Smoothed Particle Hydrodynamics, cooling, star formation, feedback, black holes.



- Snapshots contain 12 times more data than the Millennium simulation.
- The simulation is >30 times larger than largest published SPH run.

- Run using the whole of Kraken at NICS (99072 compute cores).

Team: N. Khandai, C.DeGraf,Y. Feng, R. Croft, V. Springel, TDM

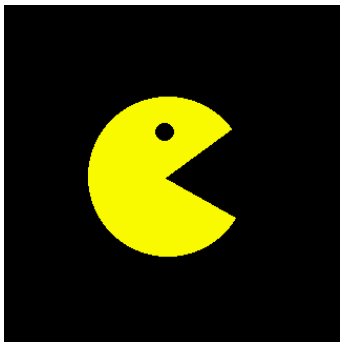
The MassiveBlack

visualization by Yu Feng

Our cosmological TimeMachine

BHs in SPH Simulations of Galaxy formation

DM, Springel, Herrnquist 05
Springel, DM, Hernquist 05



- **BH:** collisionless "sink" particle in the centre of galaxies $M_{BH(seed)}=10^5\ M_\odot$

- **ACCRETION:** relate (unresolved) accretion on BH to large scale (resolved) gas distribution

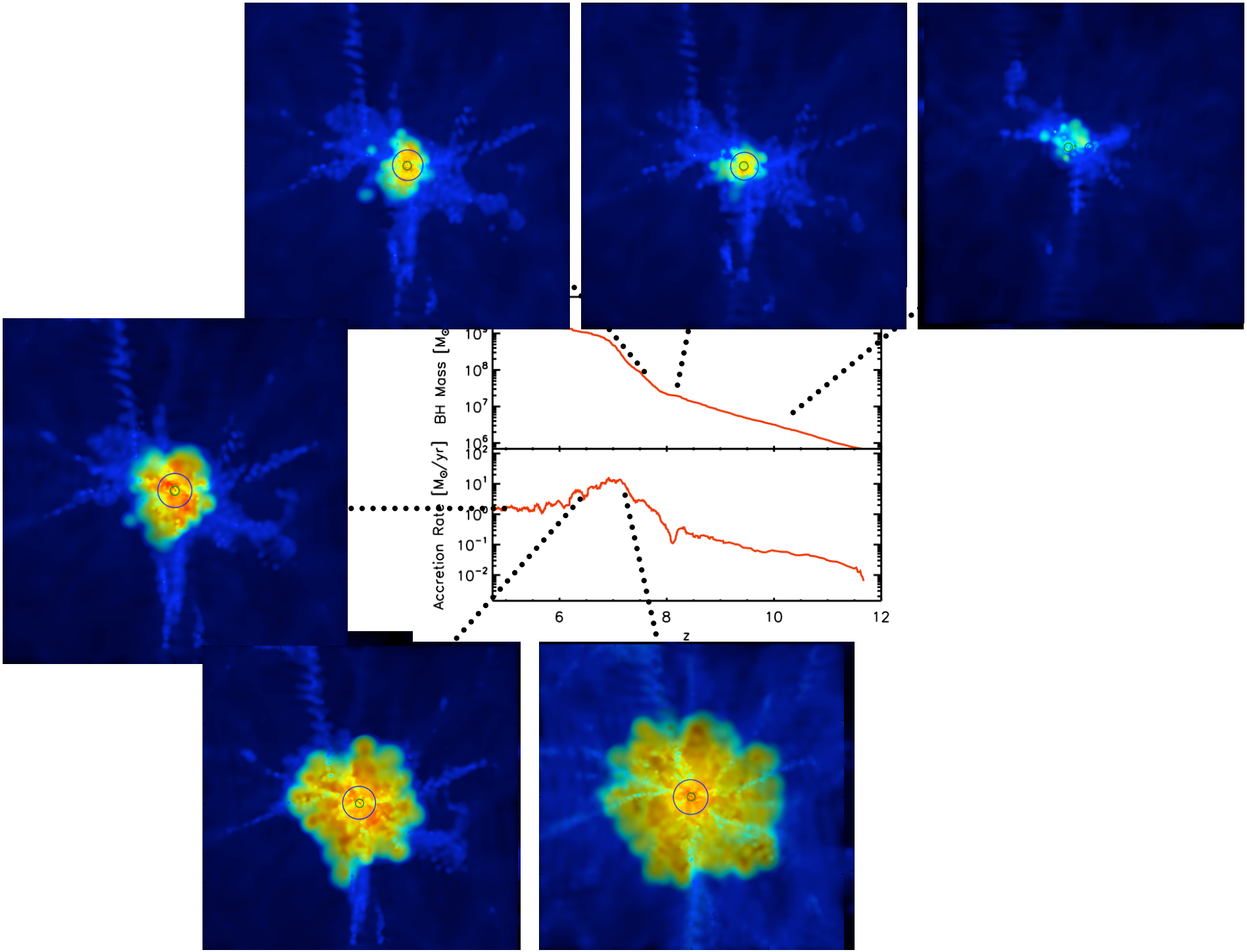
$$\dot{M}_B = 4\pi \frac{(GM_{BH})^2}{(c_s^2 + V_{rel}^2)^{3/2}} \rho$$

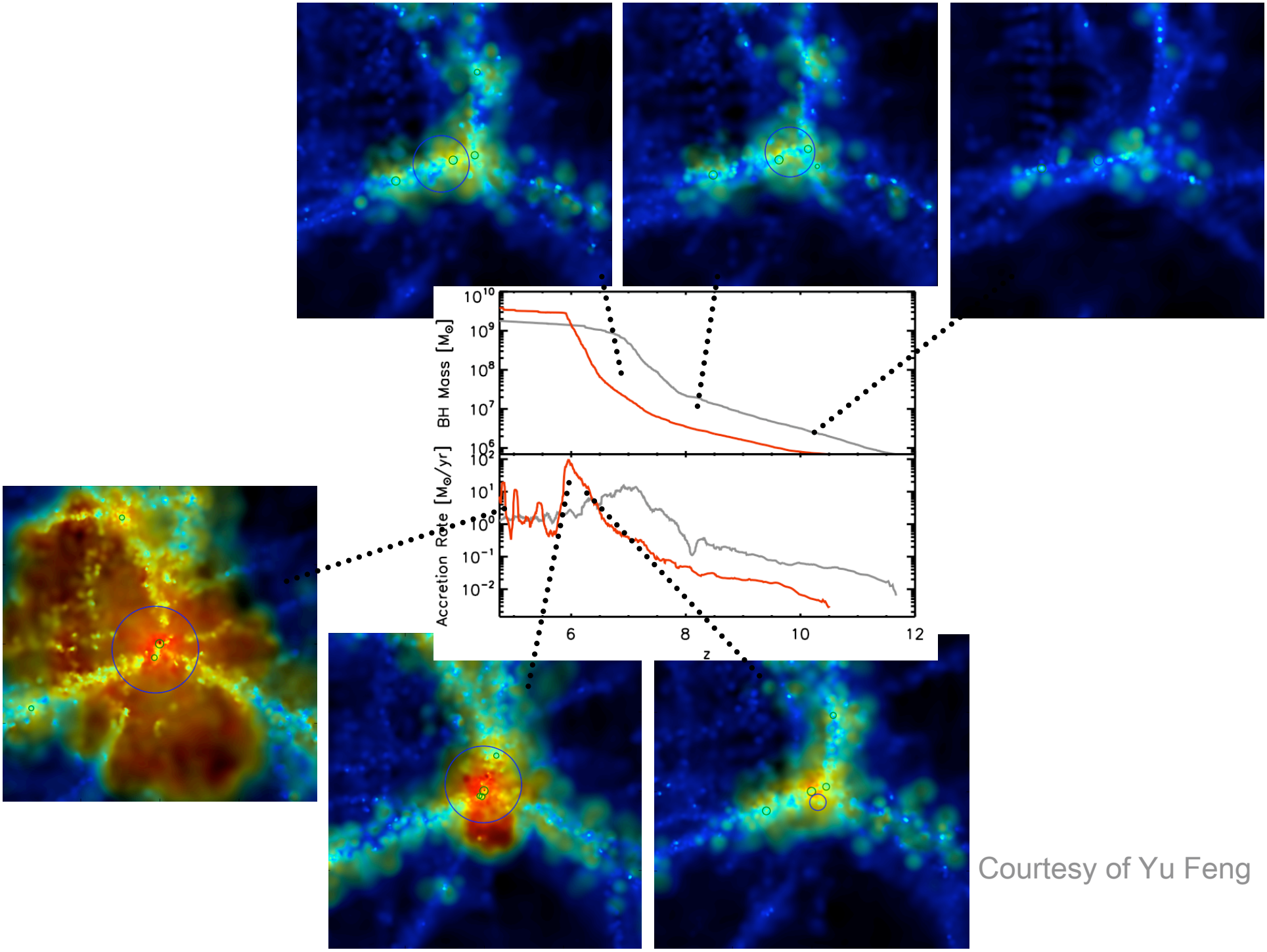
$$\dot{M}_{BH} = \min(\dot{M}_{Edd}, \dot{M}_B)$$

+ BH mergers

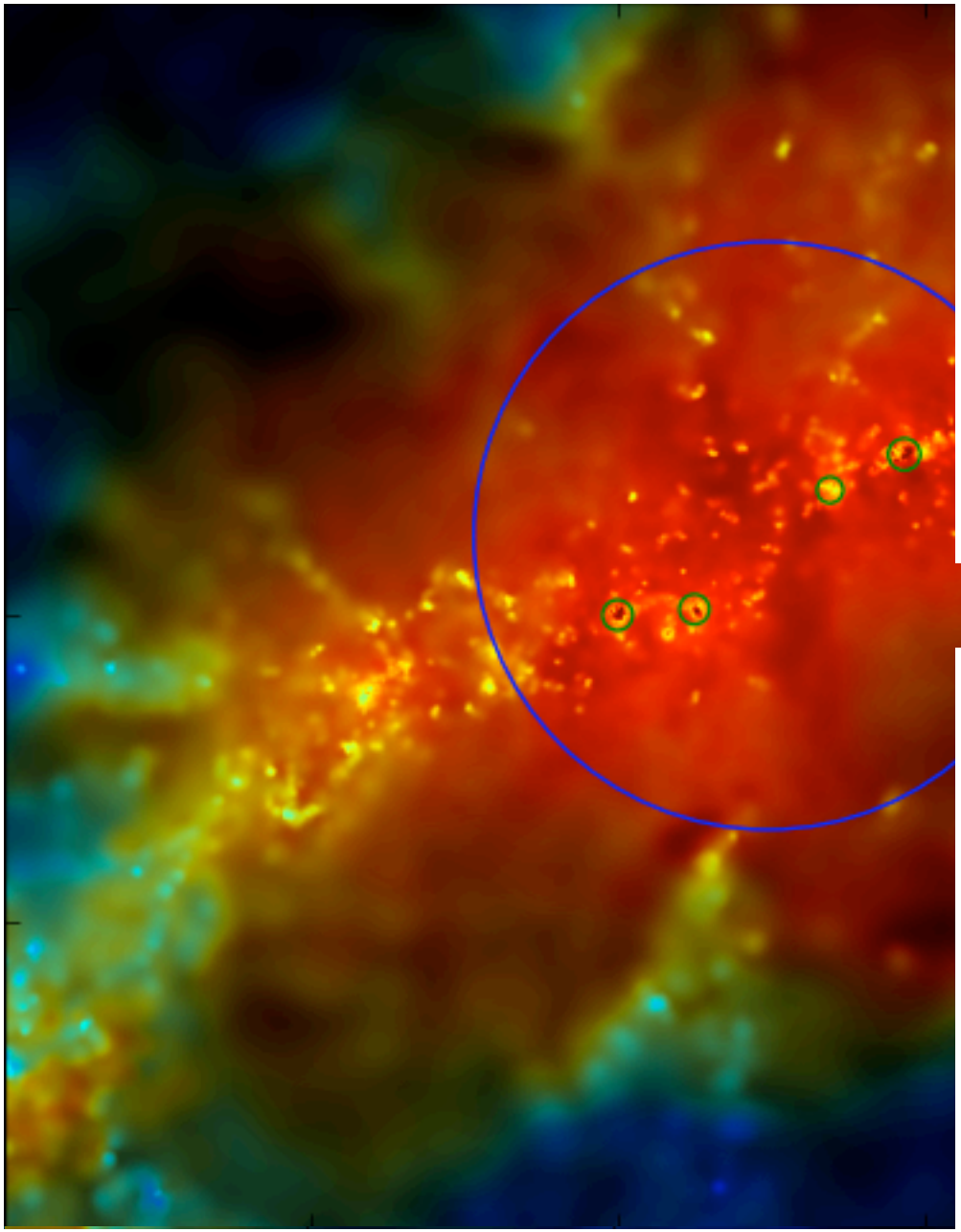
- **FEEDBACK:** energy extracted from the black hole (accretion) injected in the surrounding gas

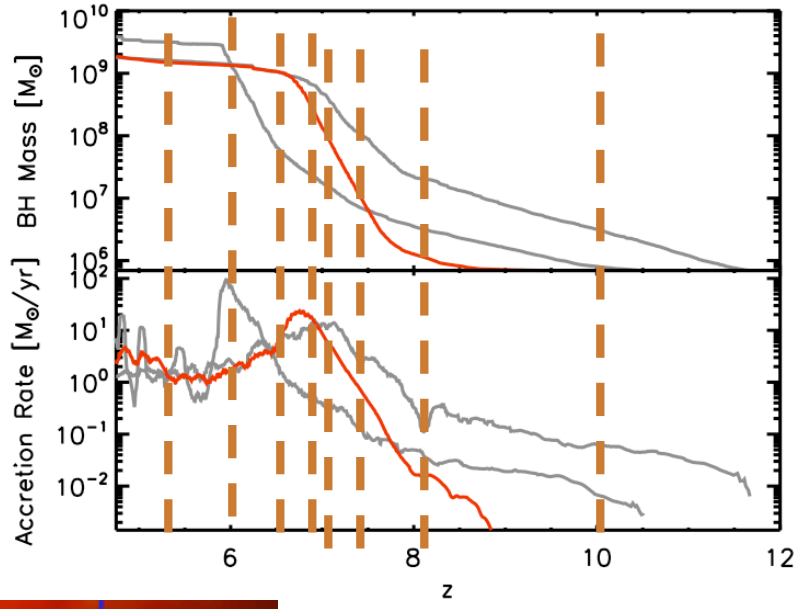
$$\dot{E}_{feed} = f(\eta \dot{M} c^2) \qquad f \approx 5\%$$

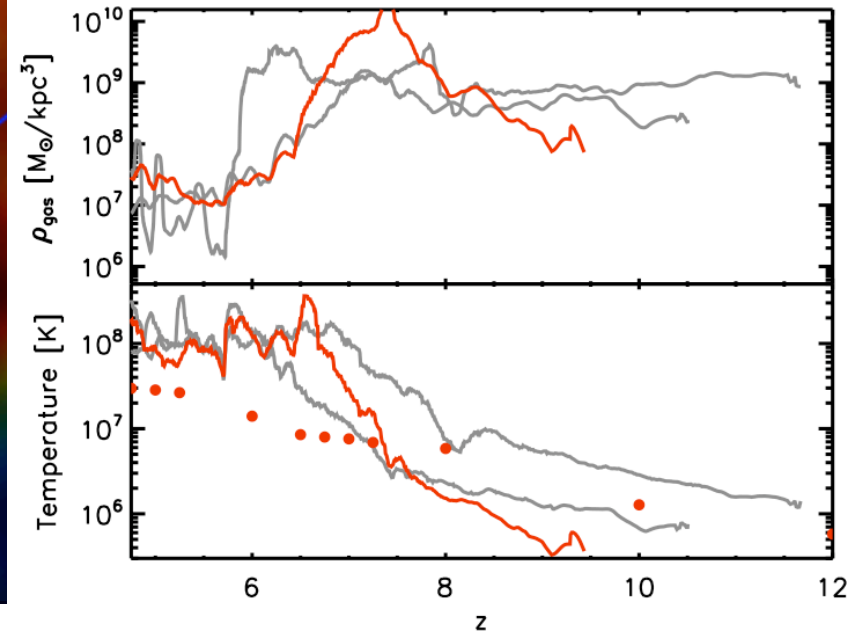

BH Mass [M⊙]
Accretion Rate [M⊙/yr]
z
6
8
10
12



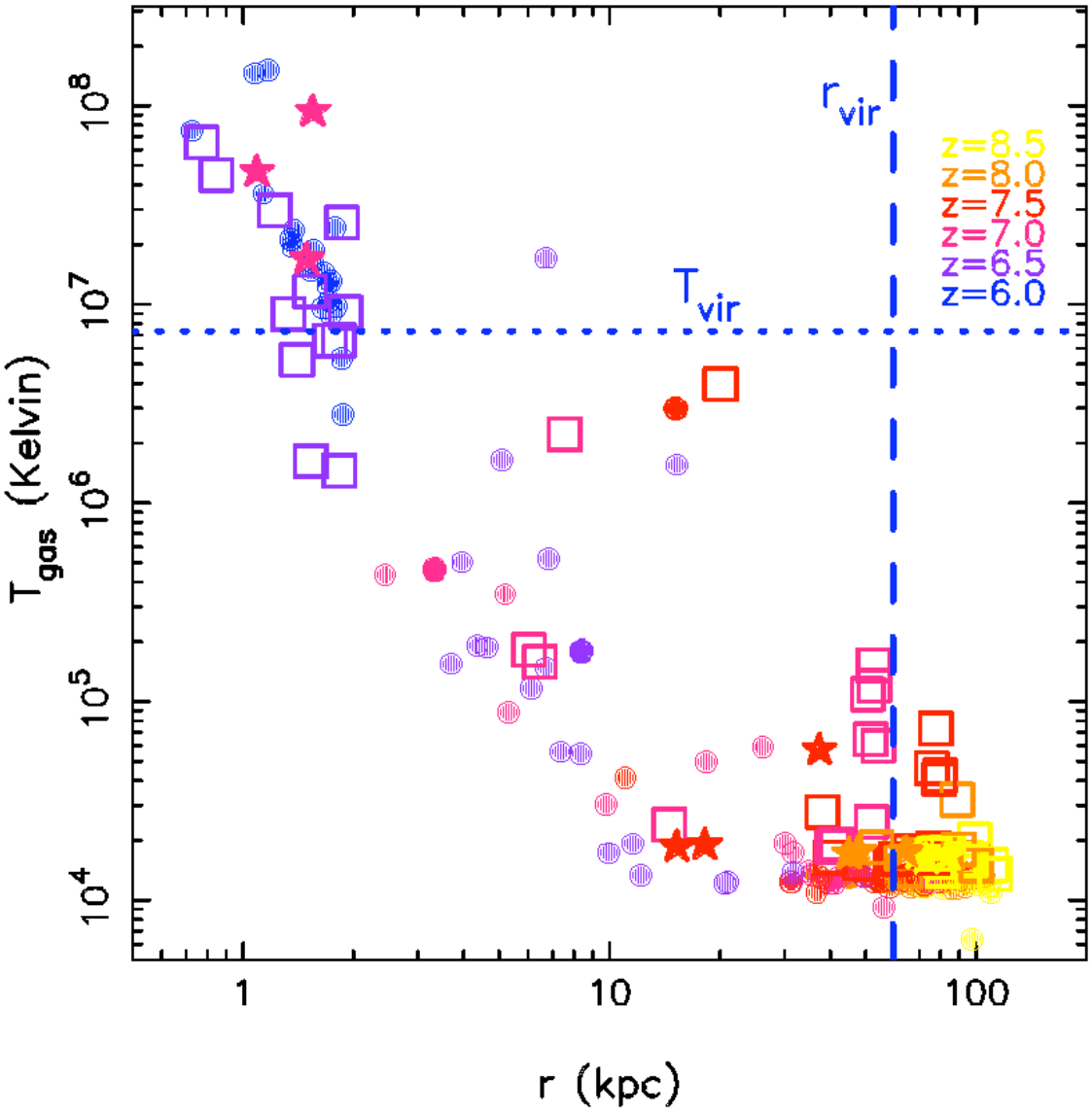
Courtesy of Yu Feng




BH Mass [M⊙]
Accretion Rate [M⊙/yr]
z


ρgas [M⊙/kpc³]
Temperature [K]
z

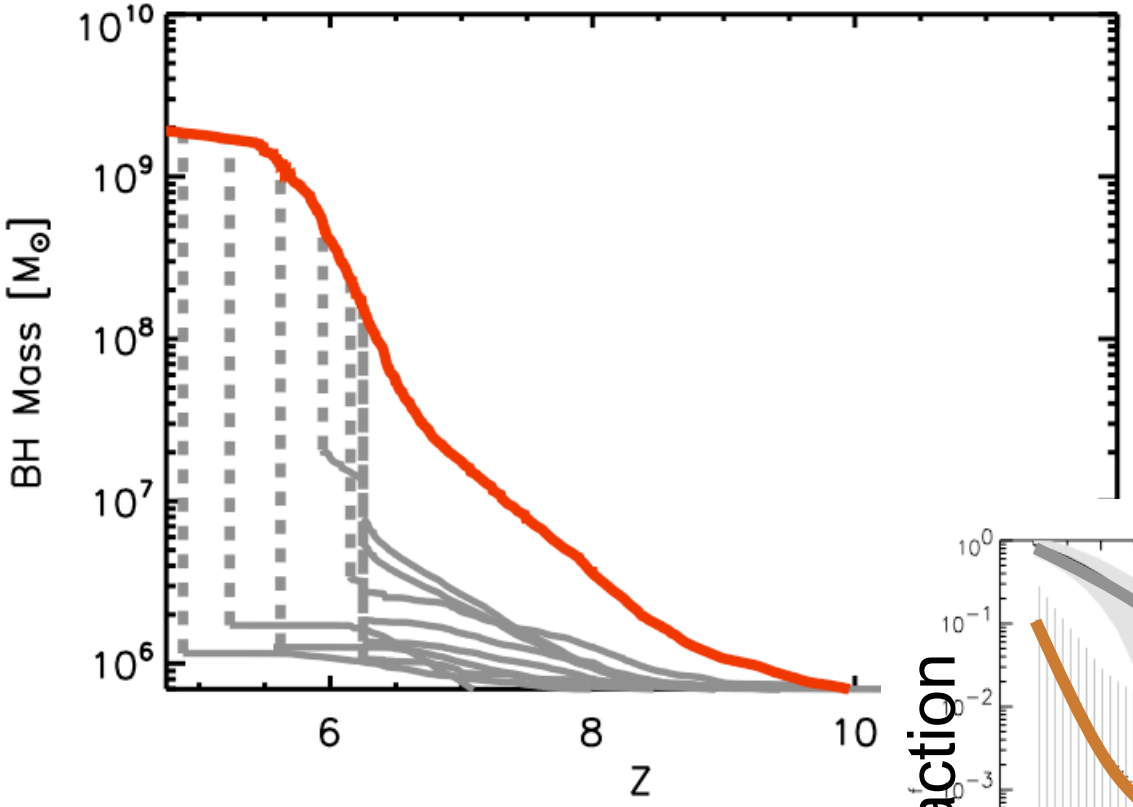
Cold flows and BH fuelling



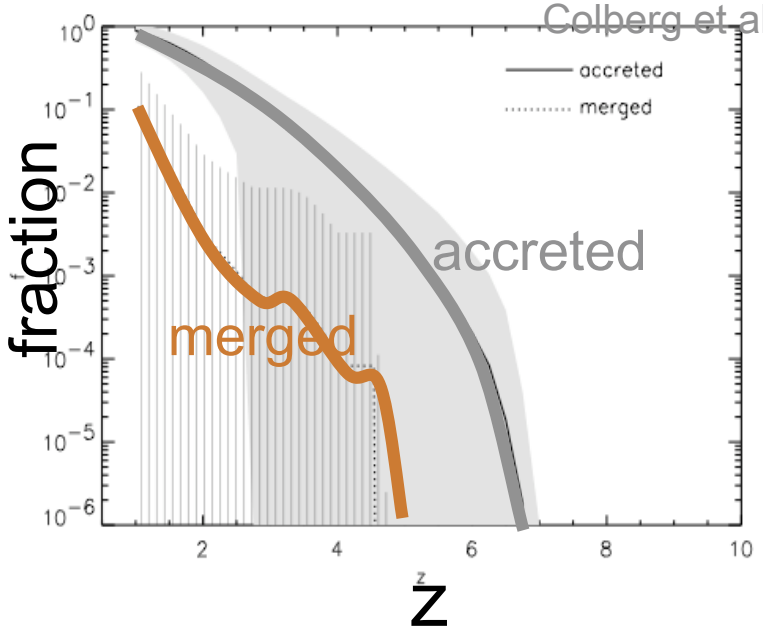
How/ where do MBHs grow?

MBH mergers are rare events

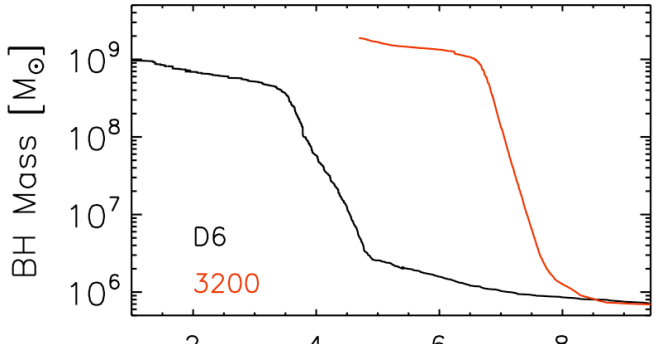
Mass growth dominated by gas accretion (cf. Soltan's argument)

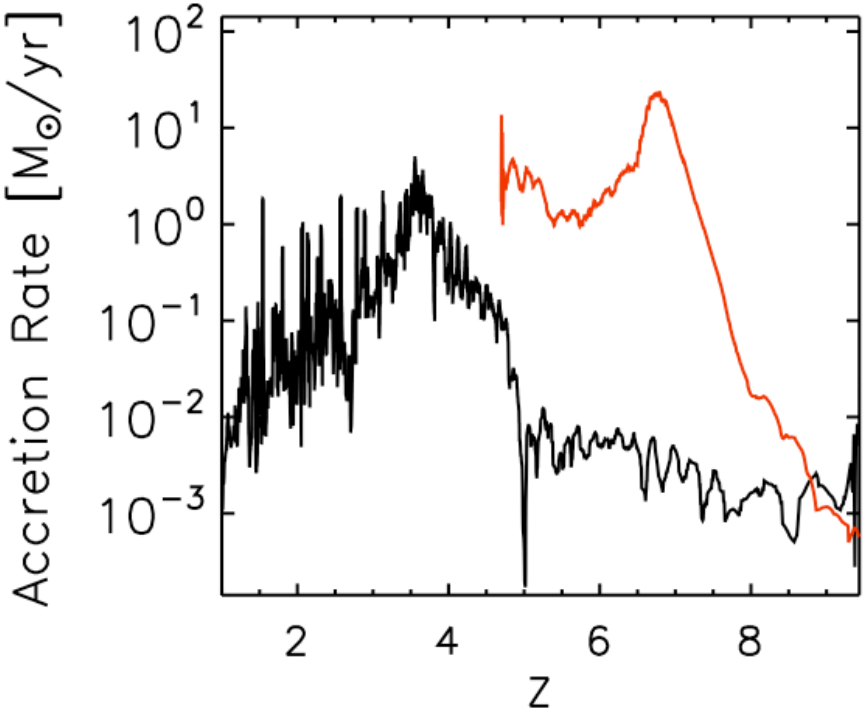


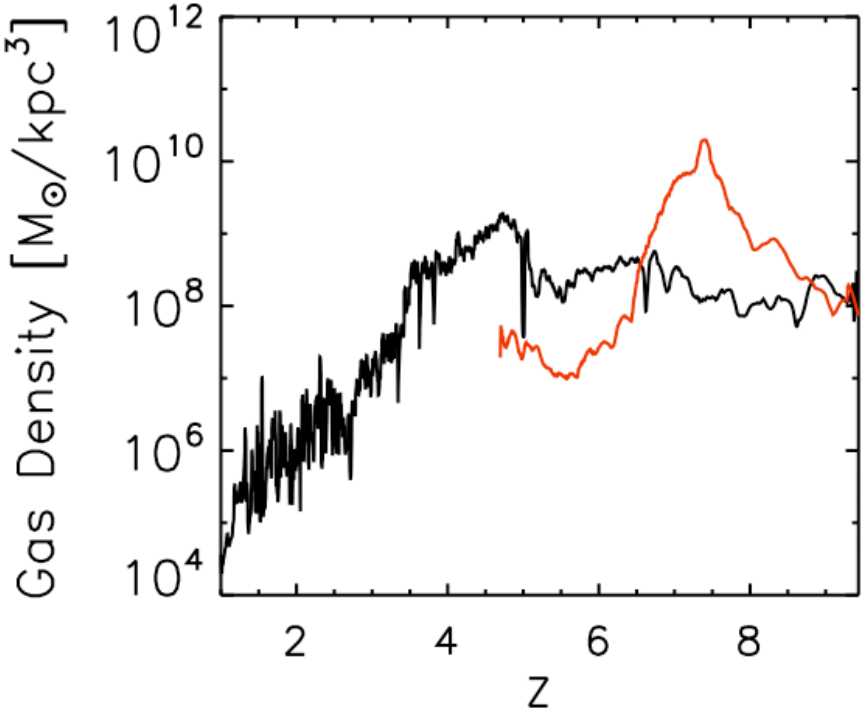
Colberg et al. 08



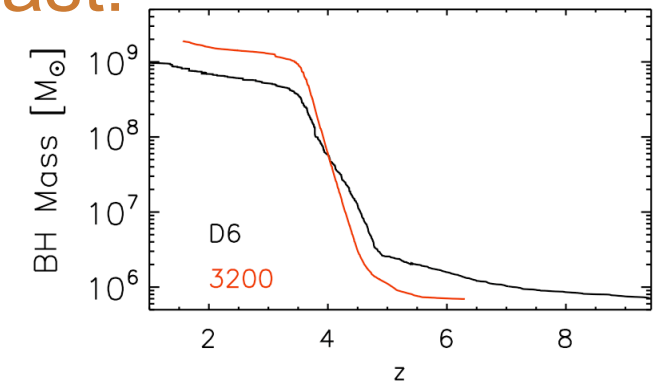
First Quasars, MBHs assemble fast!

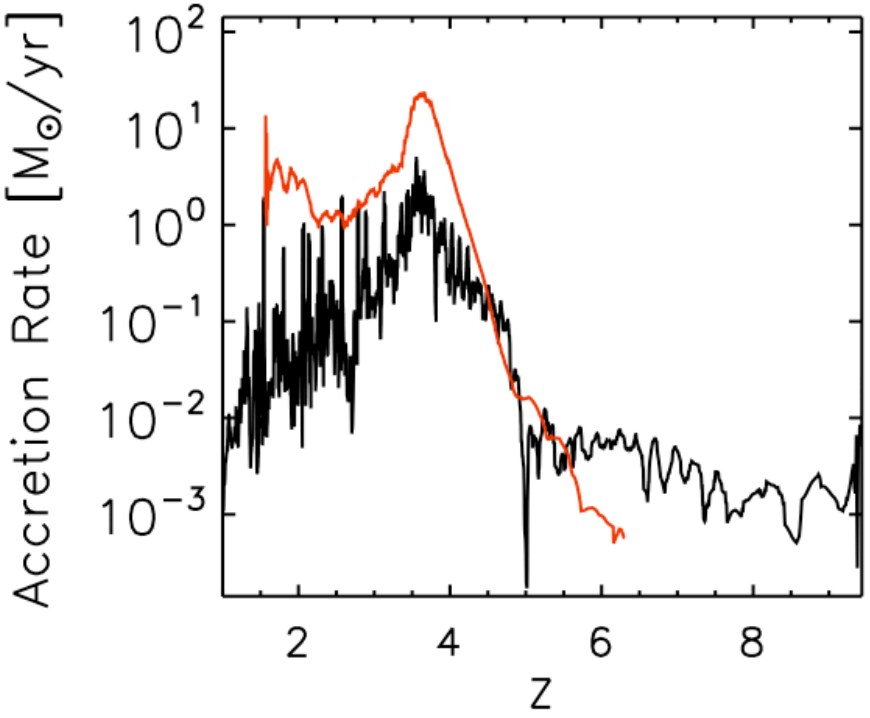


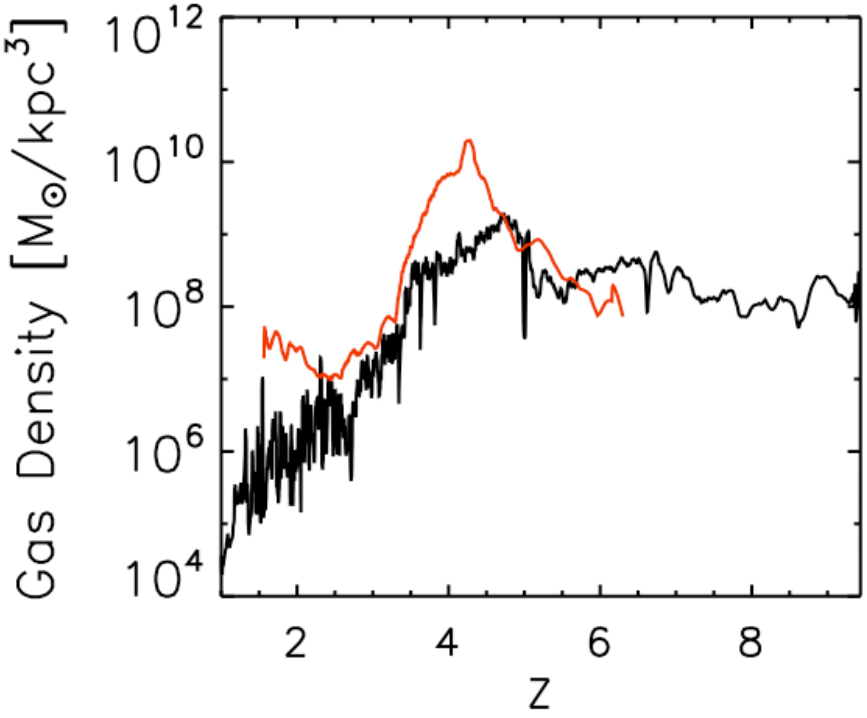




First Quasars, MBHs assemble fast!



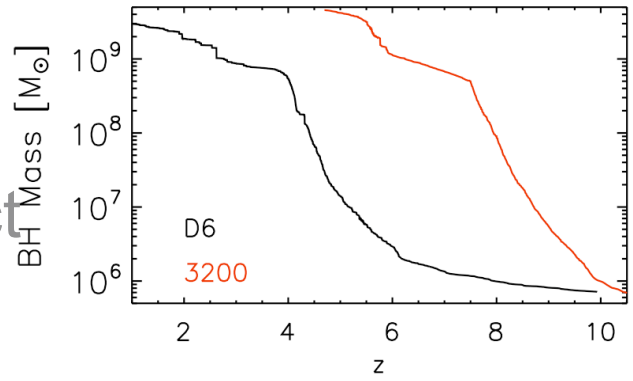


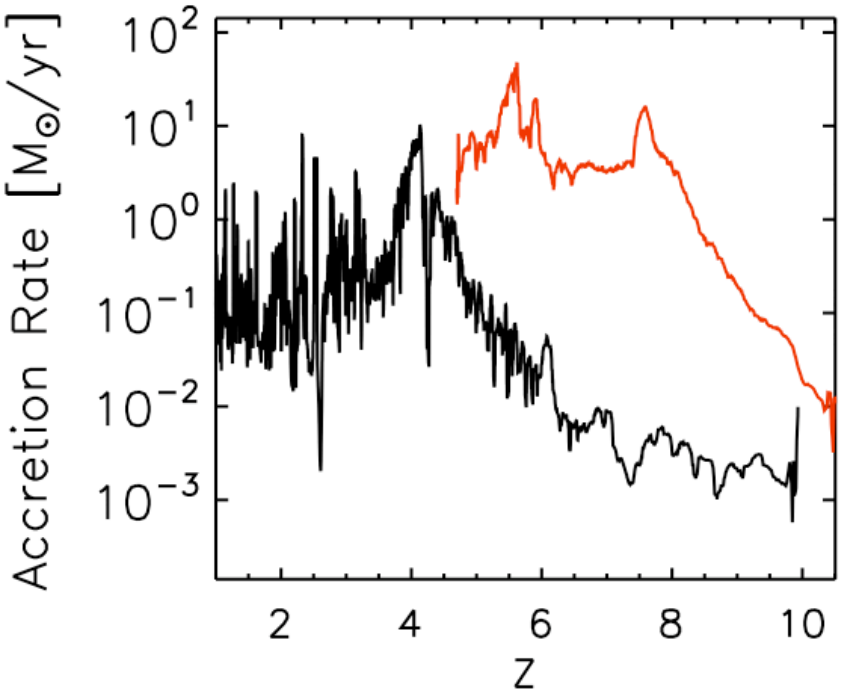


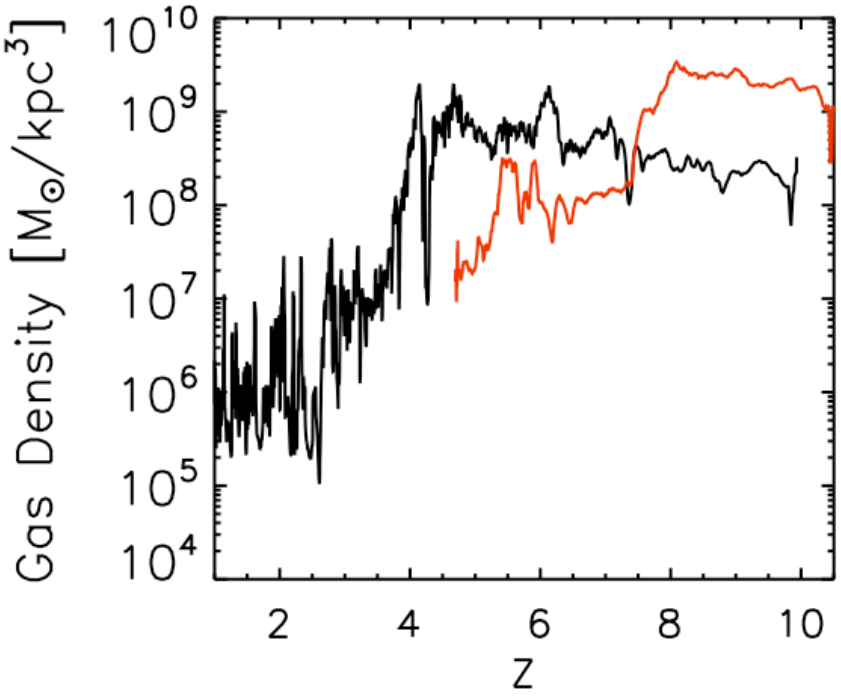
First Quasars, MBHs assemble fast!

- ✓Higher gas densities / cold flows
- ✓Steeper potentials for feeback to act

  - ➢ Z=6 quasars easy !

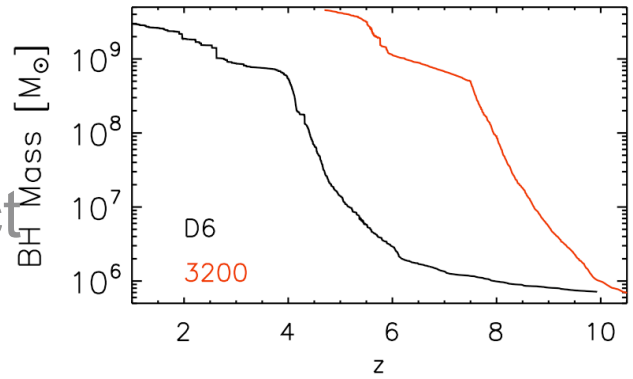


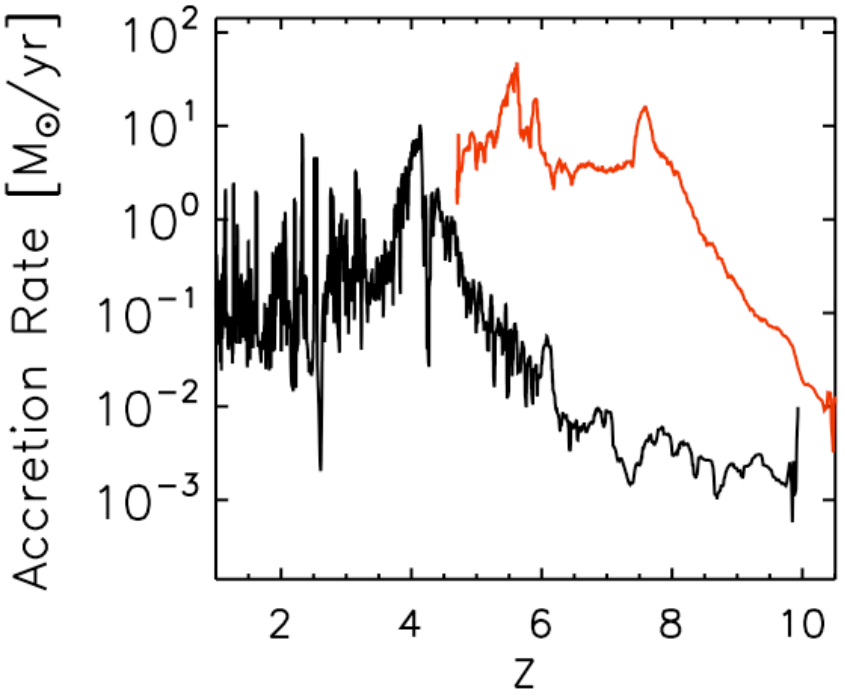


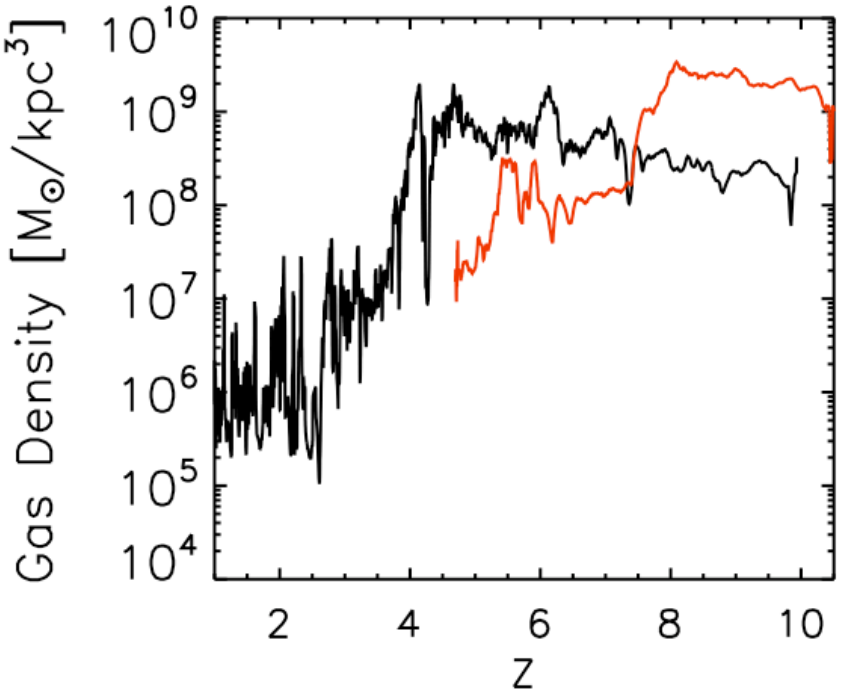


First Quasars, MBHs assemble fast!

- ✓Higher gas densities / cold flows
- ✓Steeper potentials for feeback to act
  - ➢ Z=6 quasars!

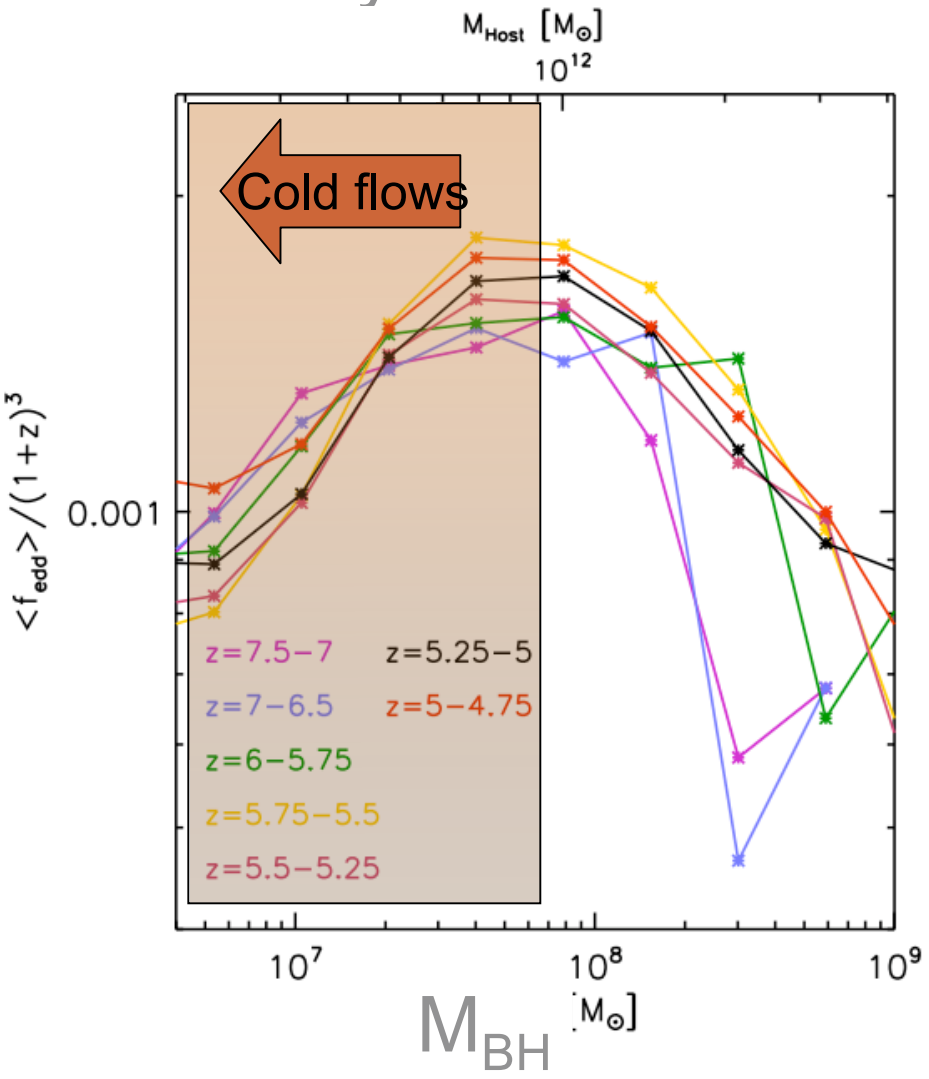






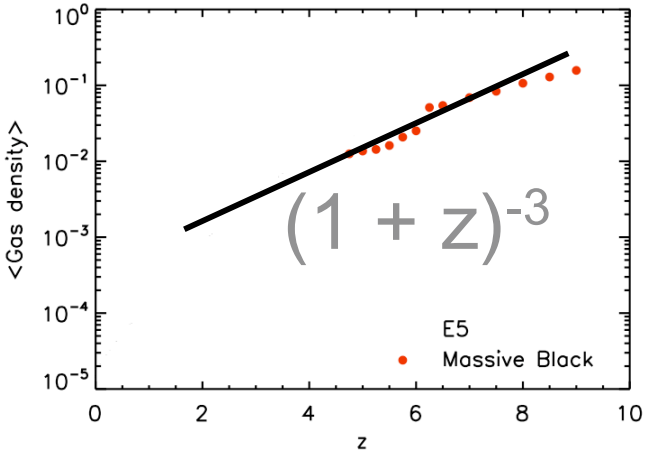
How/ where do MBHs grow?

Set by:



DeGraf et al, 2011a

★ cold gas inflow into galaxies (cold flows)



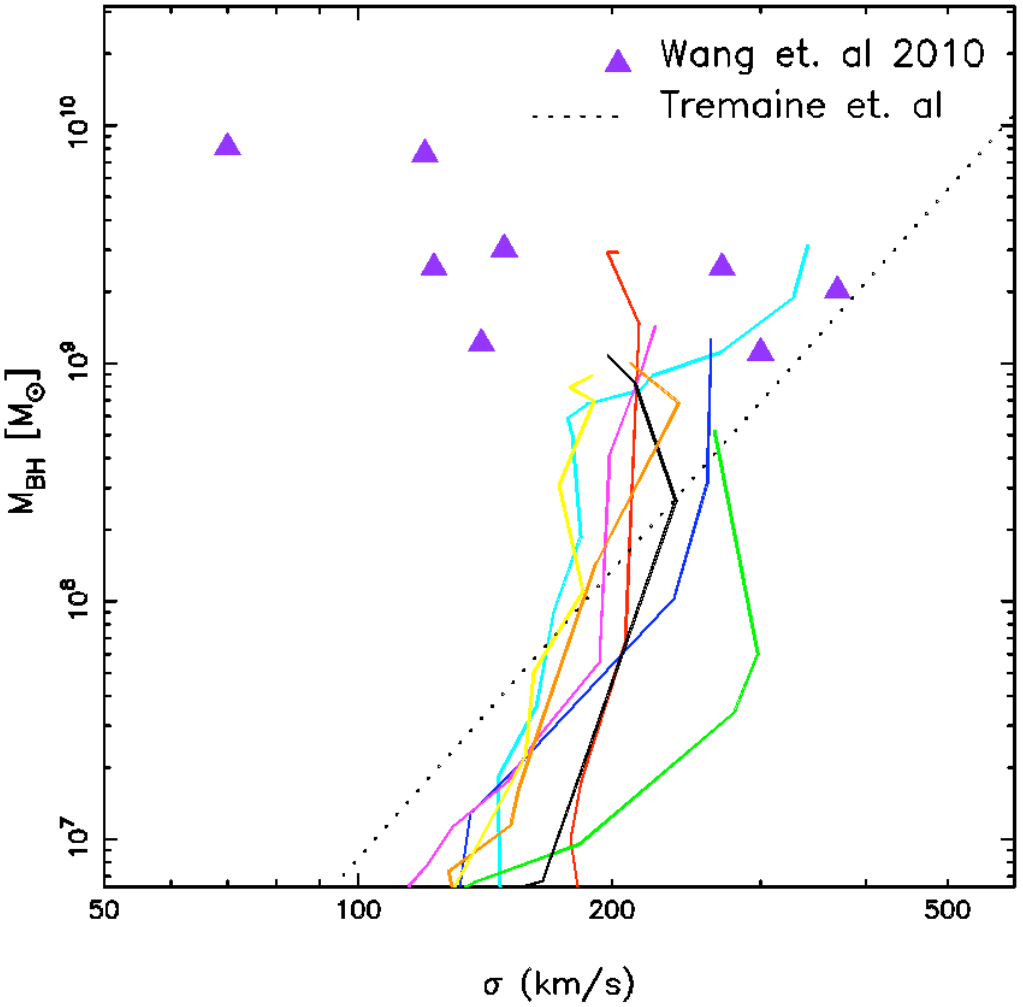
density…

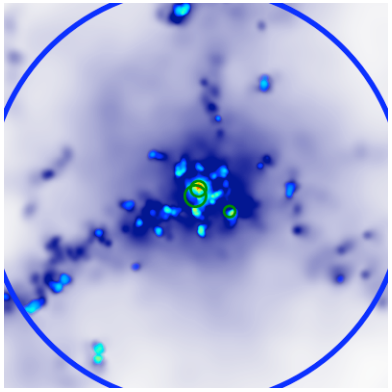
★ Gas outflow due to AGN feedback -(Mbh-sigma)!

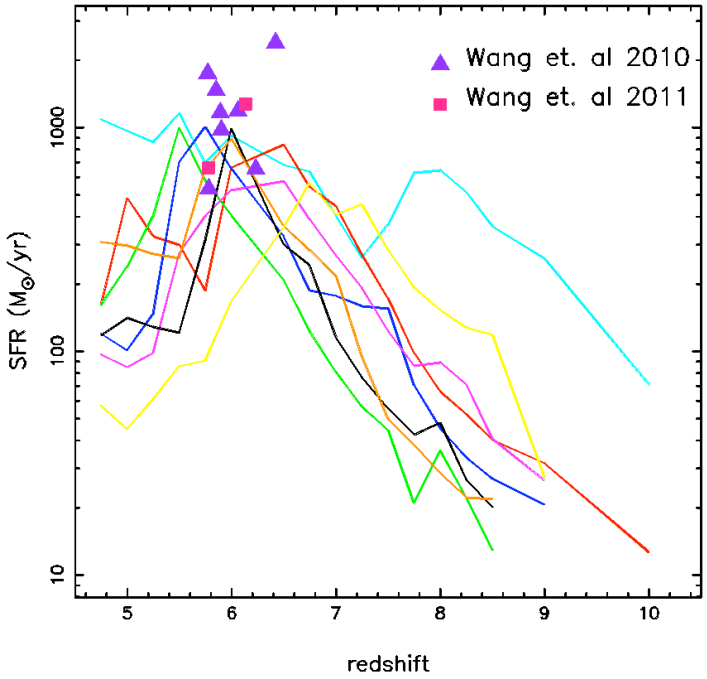
….At least for the bulk of the growth

Z=6 Quasar Hosts: The M_{BH}-sigma relation

Khandai et al. 2011





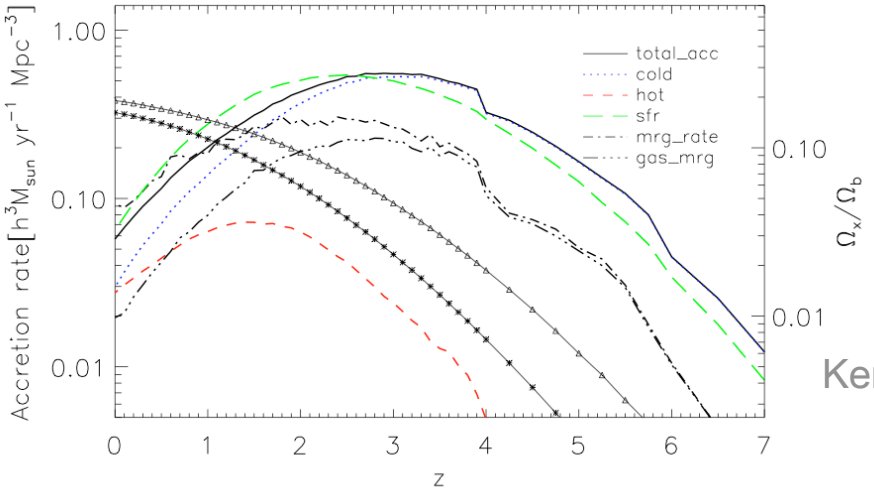


Black Holes grow first!

How/ where do MBHs grow?

Set by:

✓ cold gas inflow into galaxies (cold flows/mergers)



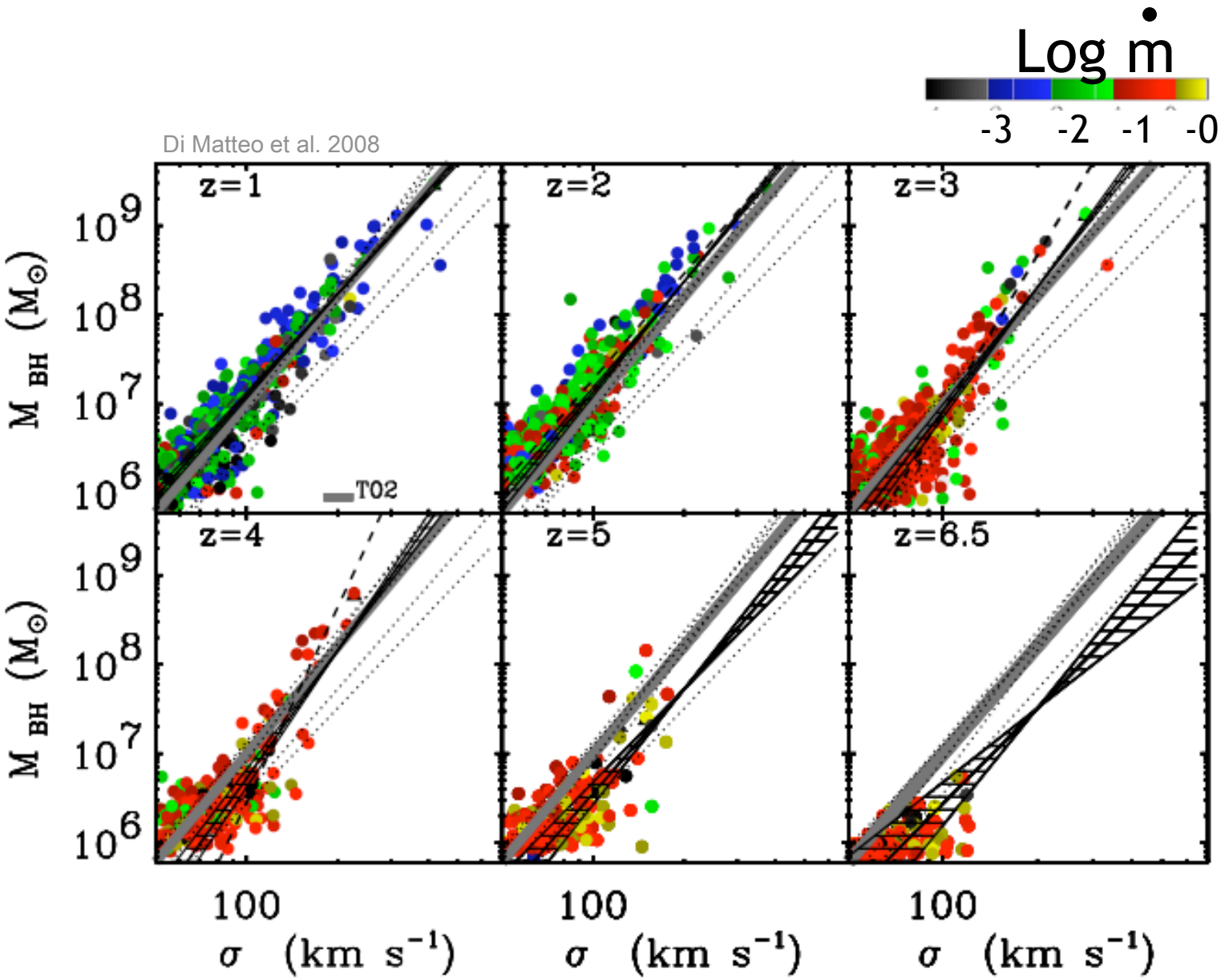
Keres et al. 09

✓ Gas outflow due to AGN feedback - (Mbh-sigma)!

The history of massive black holes
Assembly evolution, statistical properties..

do we get it right?

The cosmological evolution of the M_{BH}-sigma relation

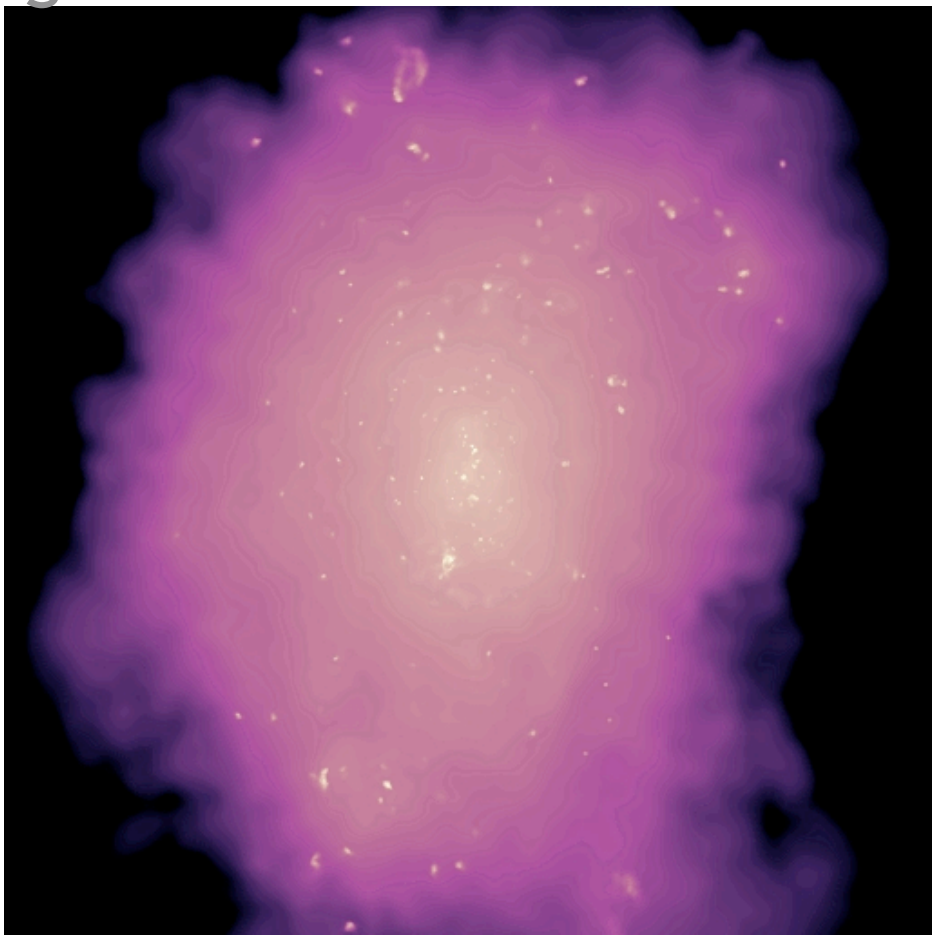


Di Matteo et al. 2008

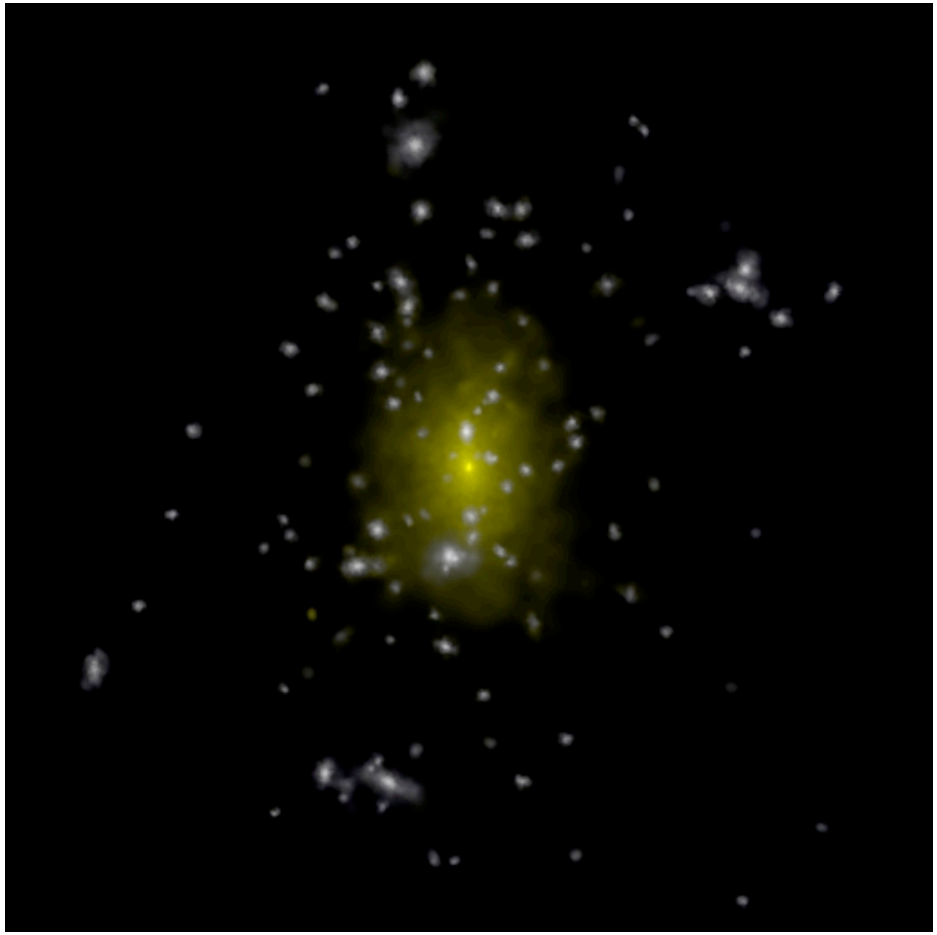
See also Robertson et al. 2006

The cosmological evolution of the M_{BH}-sigma relation

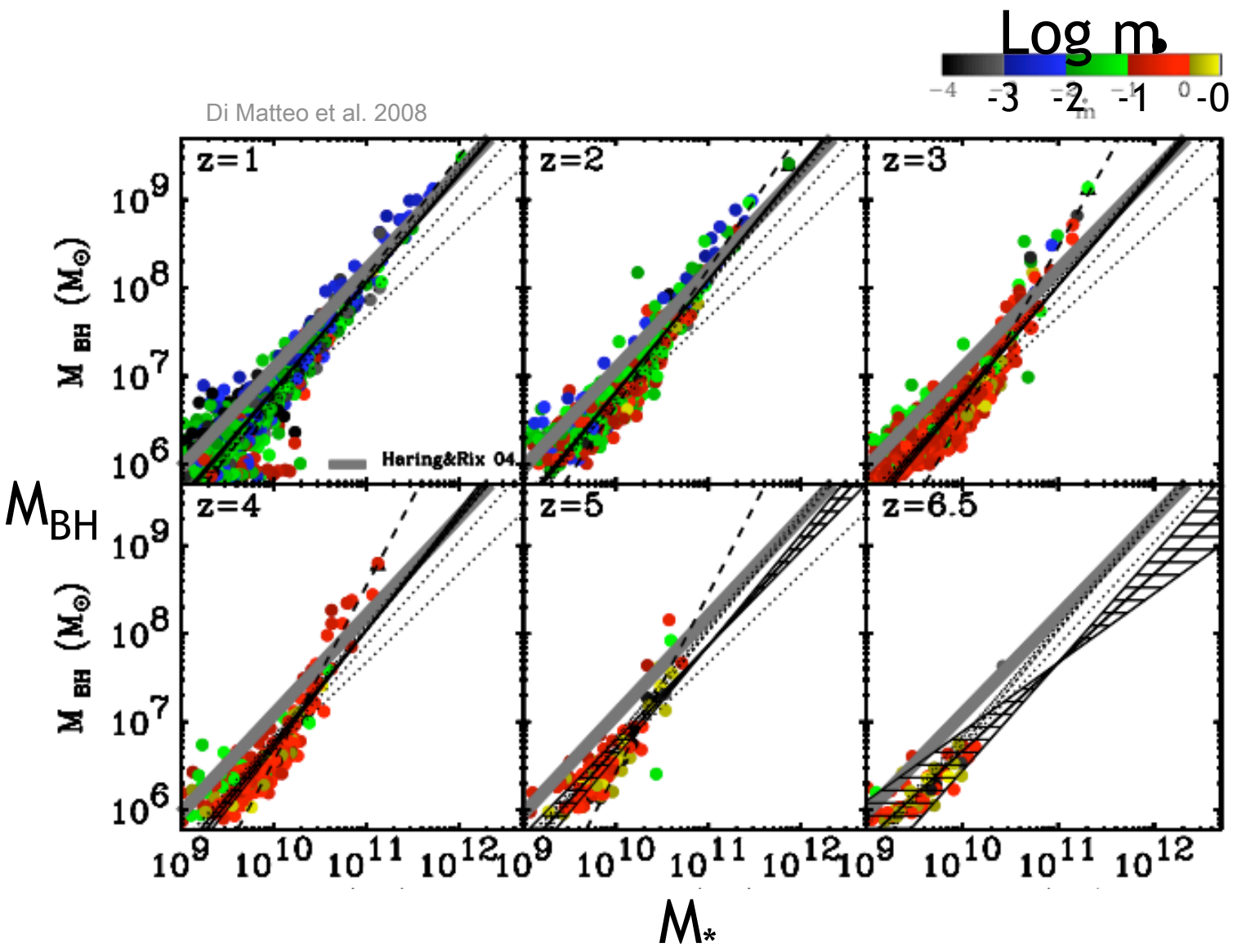
gas



stars

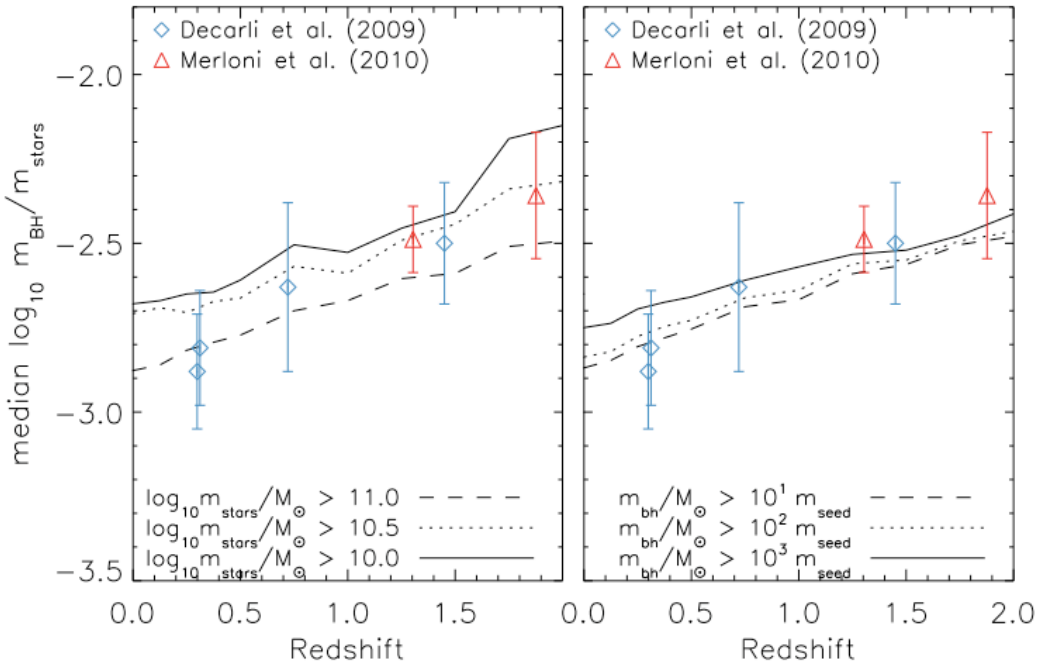


The cosmological evolution of the M_{BH}-M_* relation

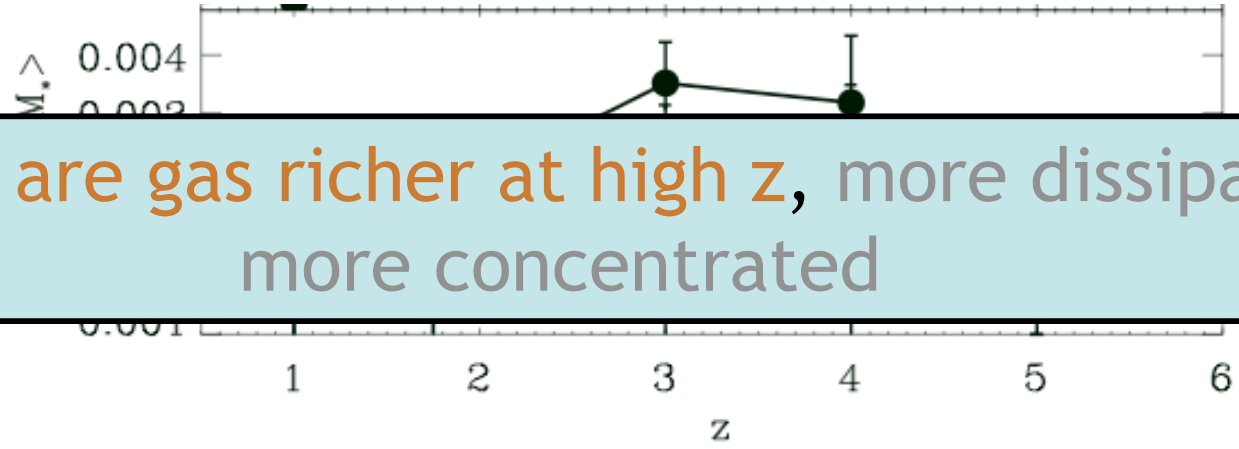


What drives the evolution in the M_{BH} - Mstar relation?

Booth and Schaye 2010



$M_{BH}/M_* = (1+z)^{0.5}$



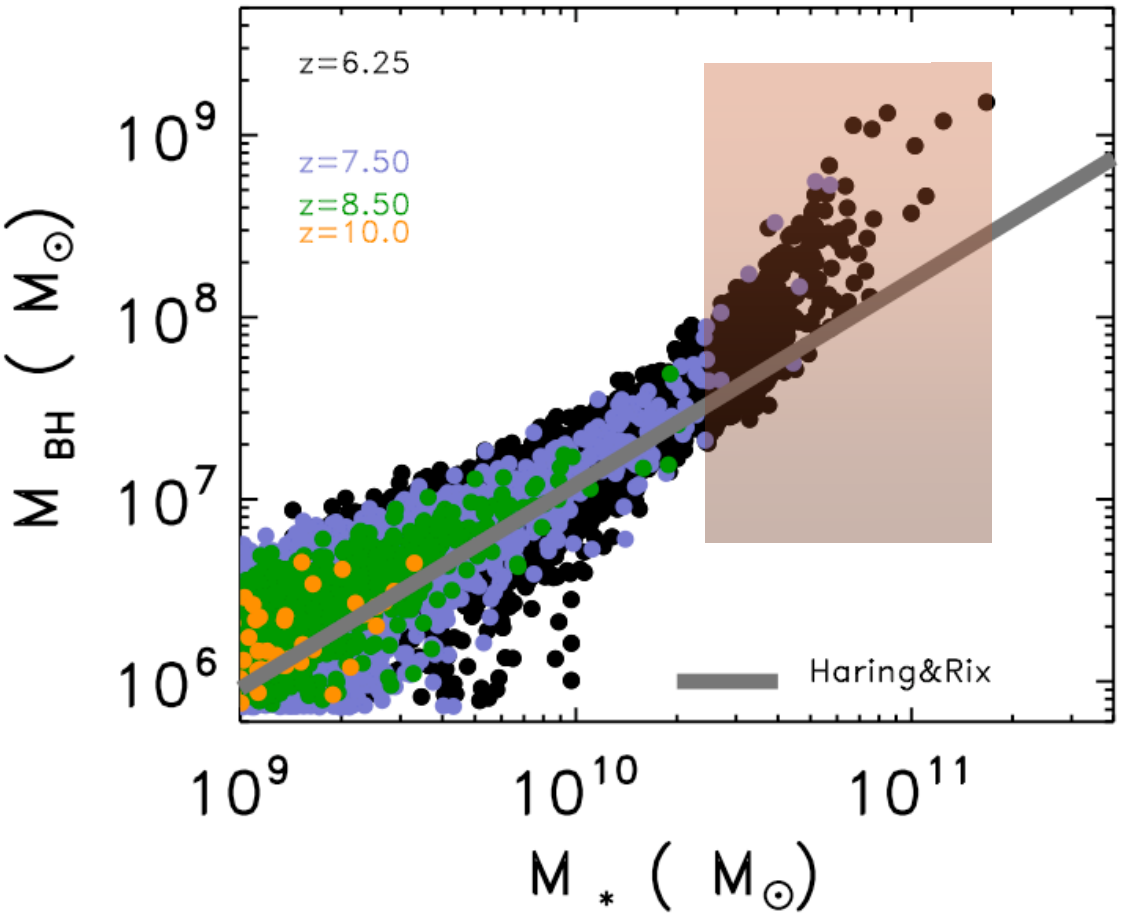
Halos are gas richer at high z, more dissipational, more concentrated

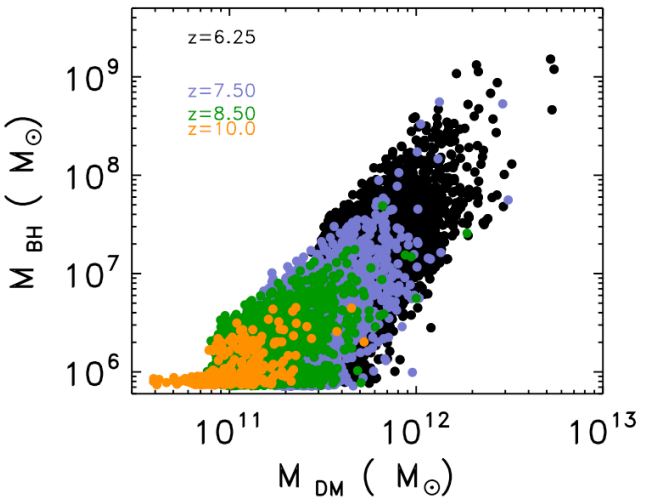
2010
2010
2010

Di Matteo et al. 2008

MBH vs M*

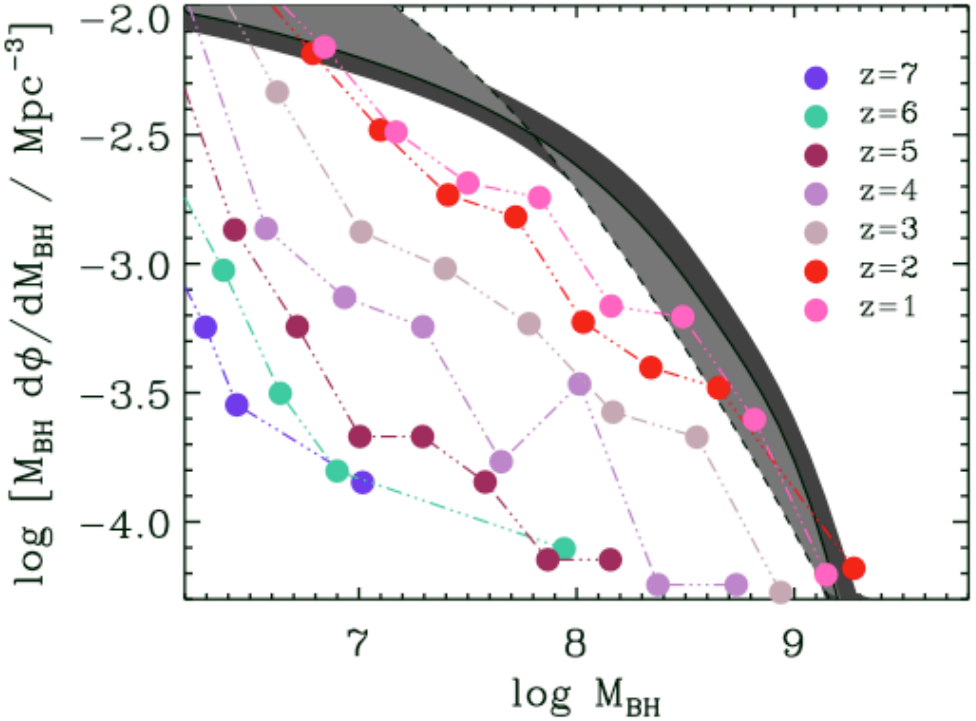
Black holes grow first



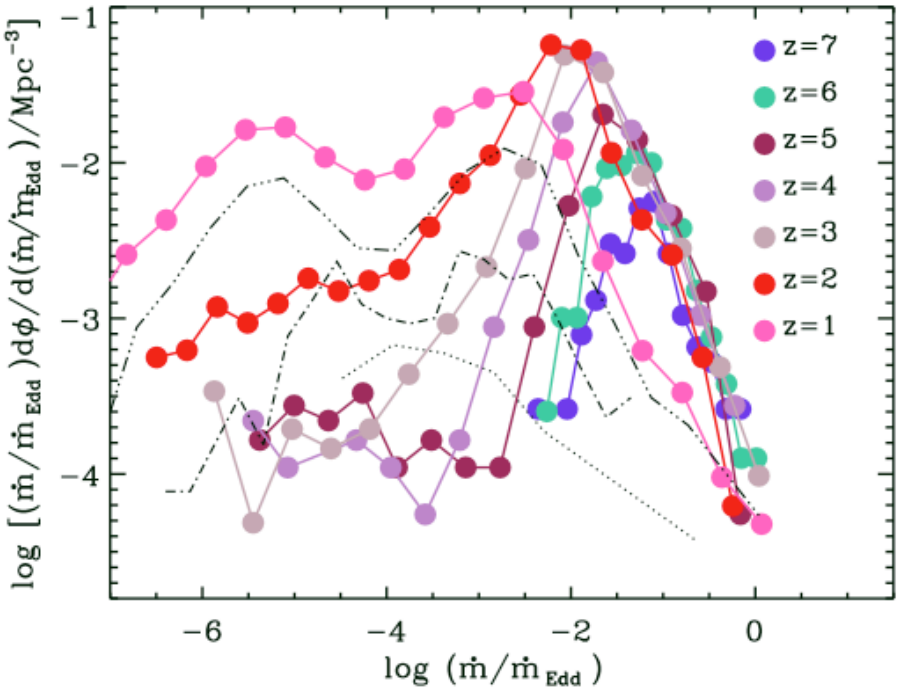


‘BH downsizing’

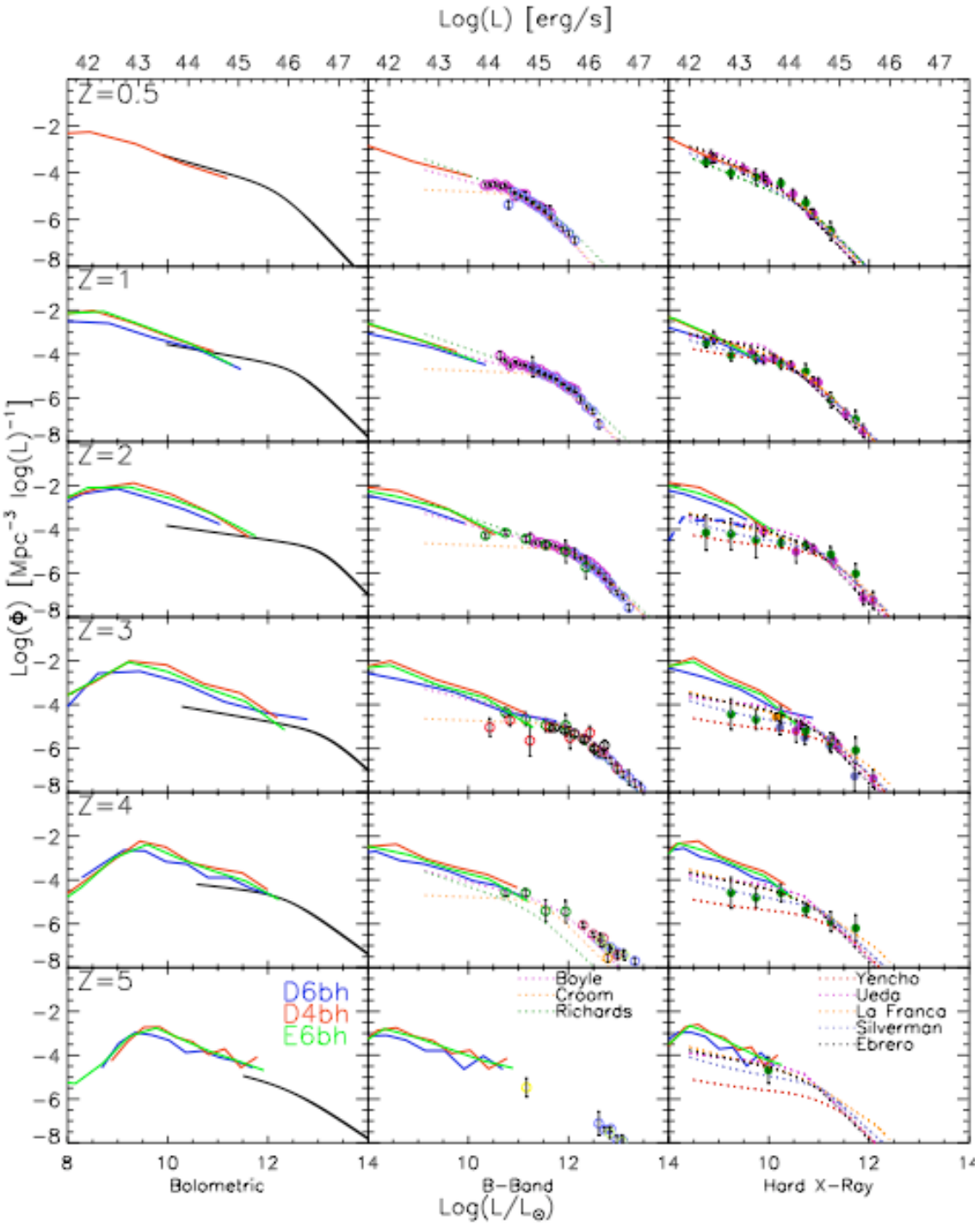
BH mass function



BH accretion function



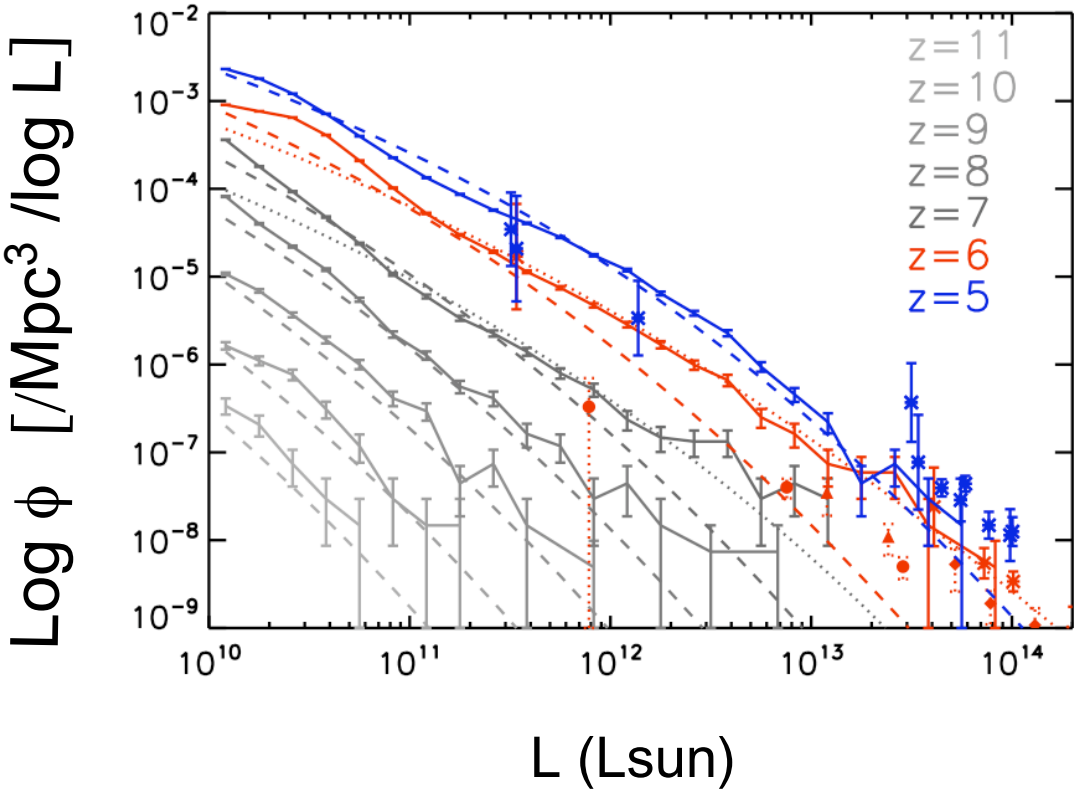
AGN luminosity function



DeGraf, DM, Springel 2010

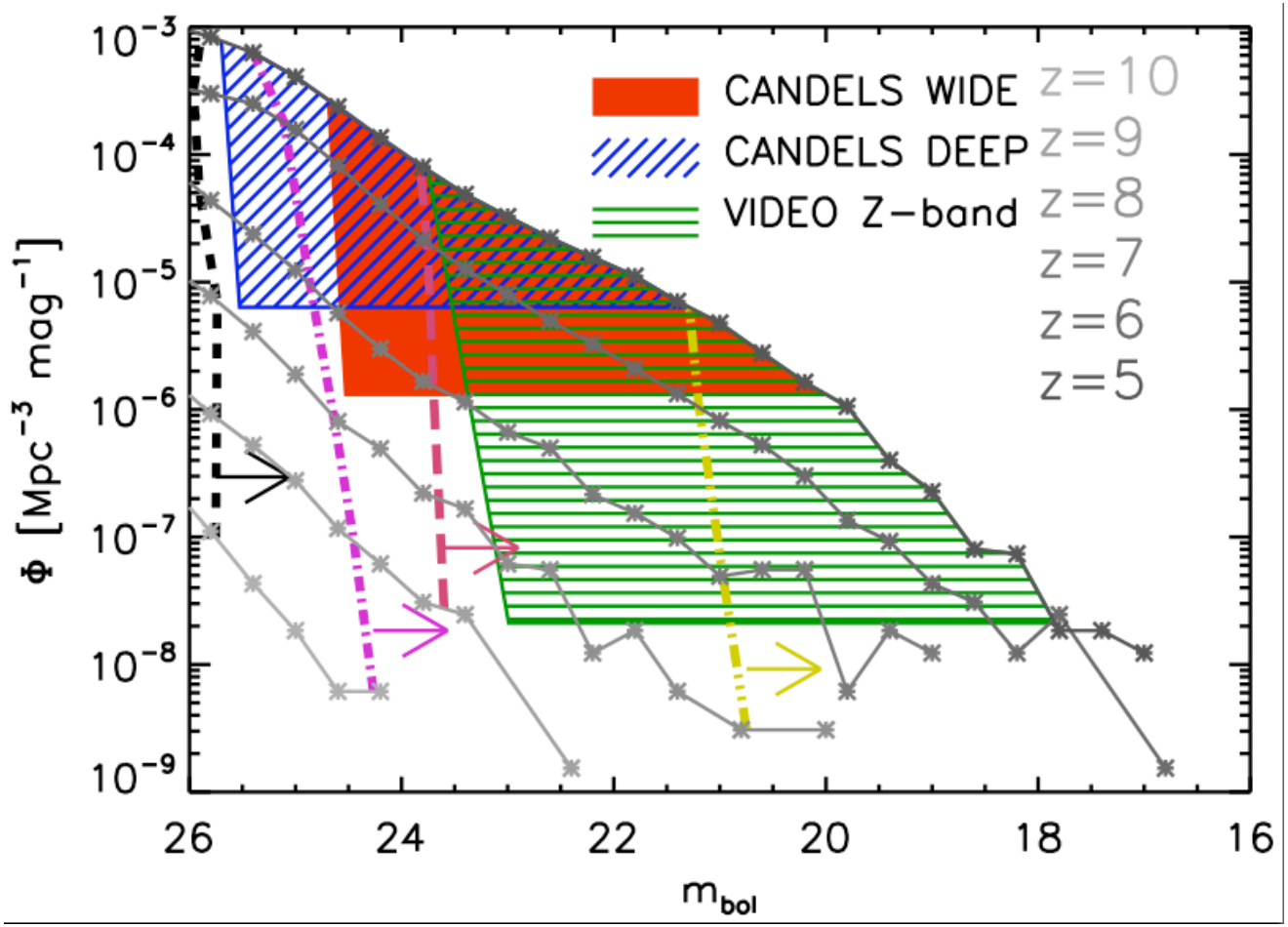
Luminosity Functions z=6 and beyond…

DeGraf et al. 2011

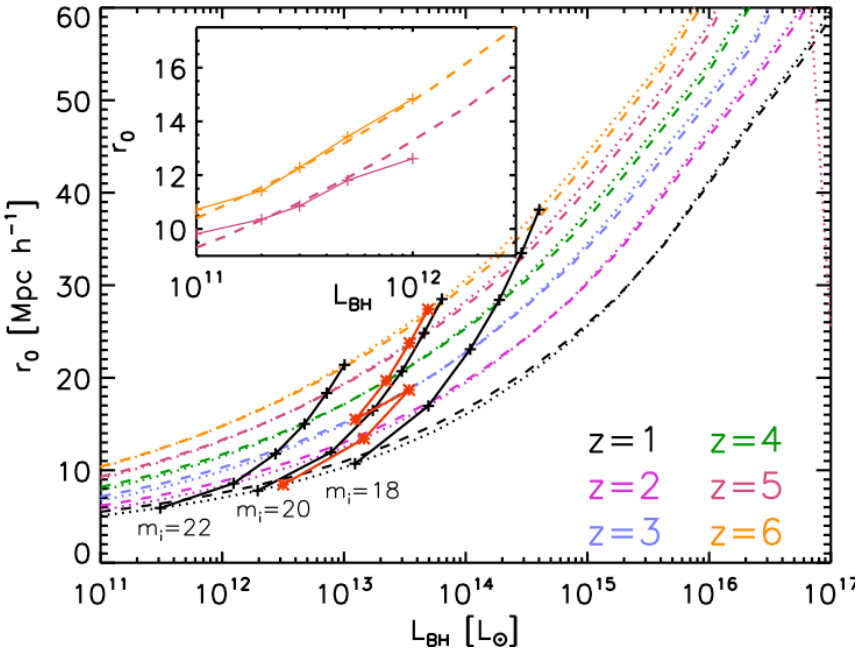


Luminosity Functions z=6 and beyond…

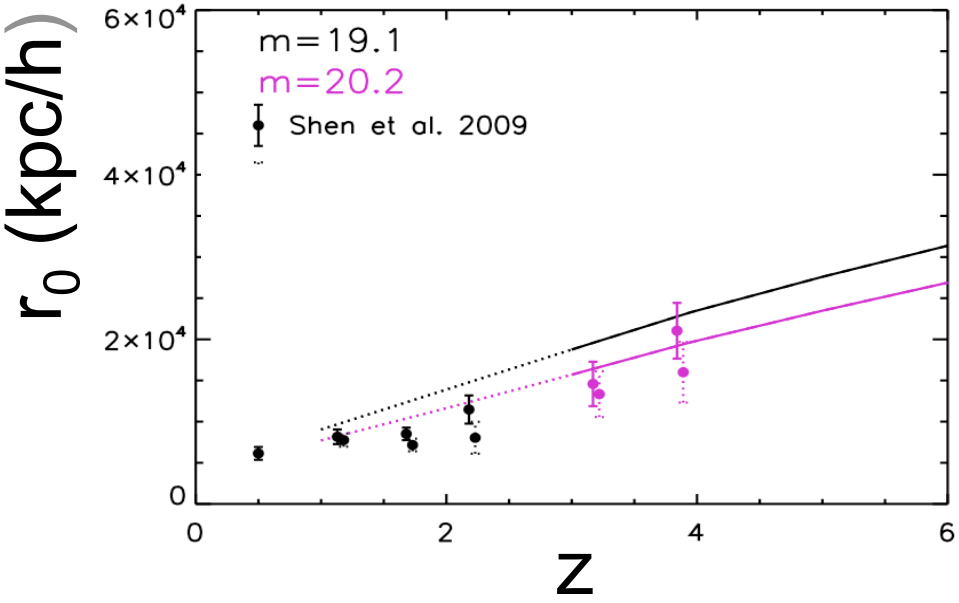
DeGraf et al. 2011



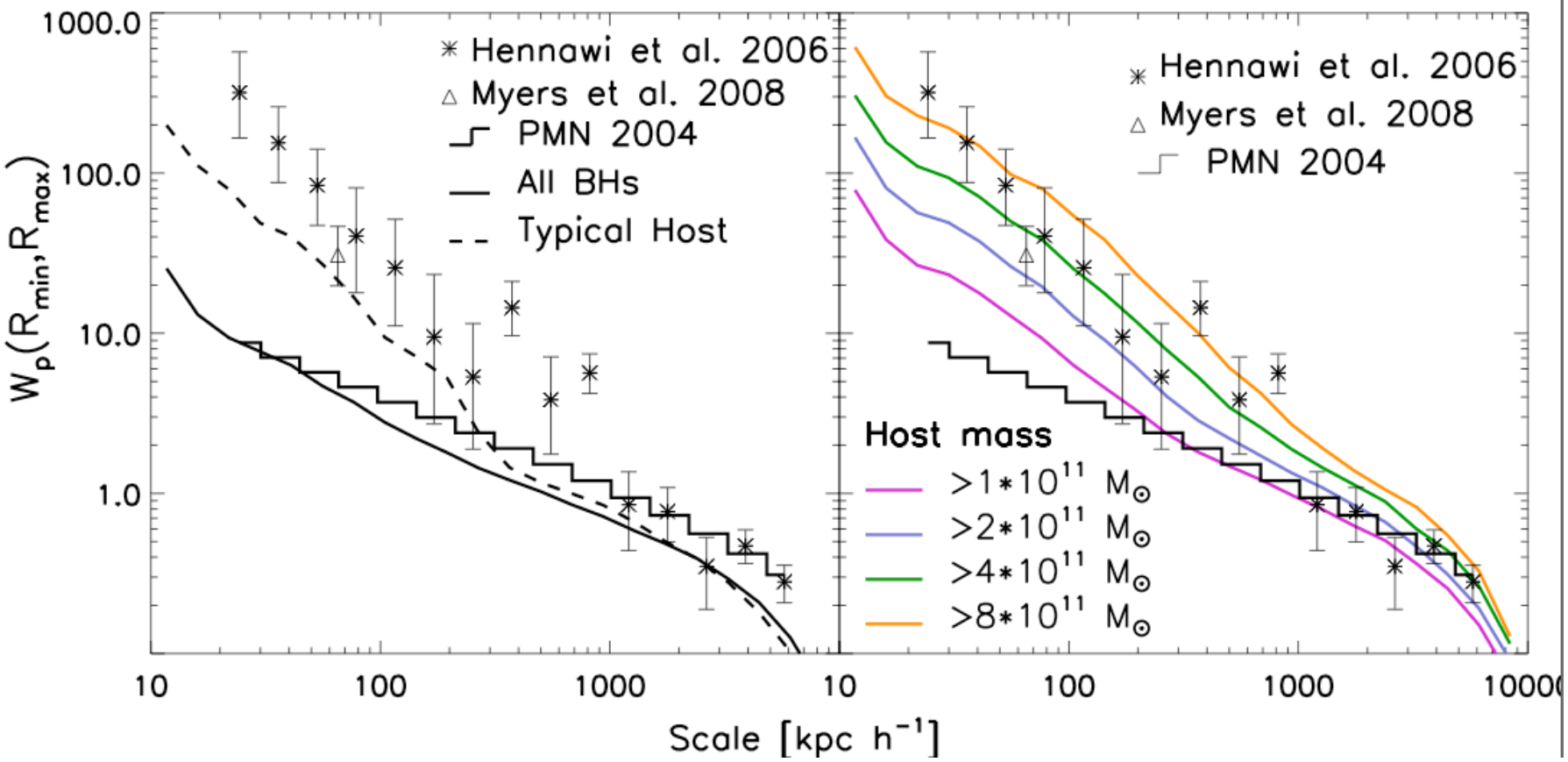
Quasar clustering: Large scales



DeGraf et al. 2011



Quasar clustering: small scales

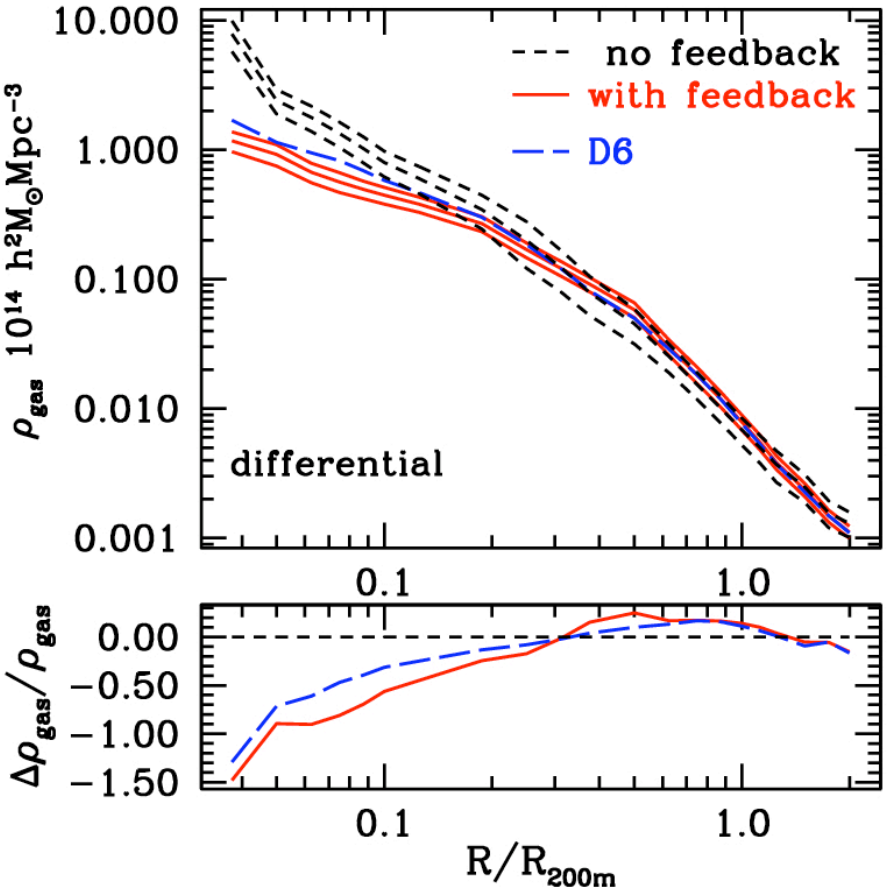


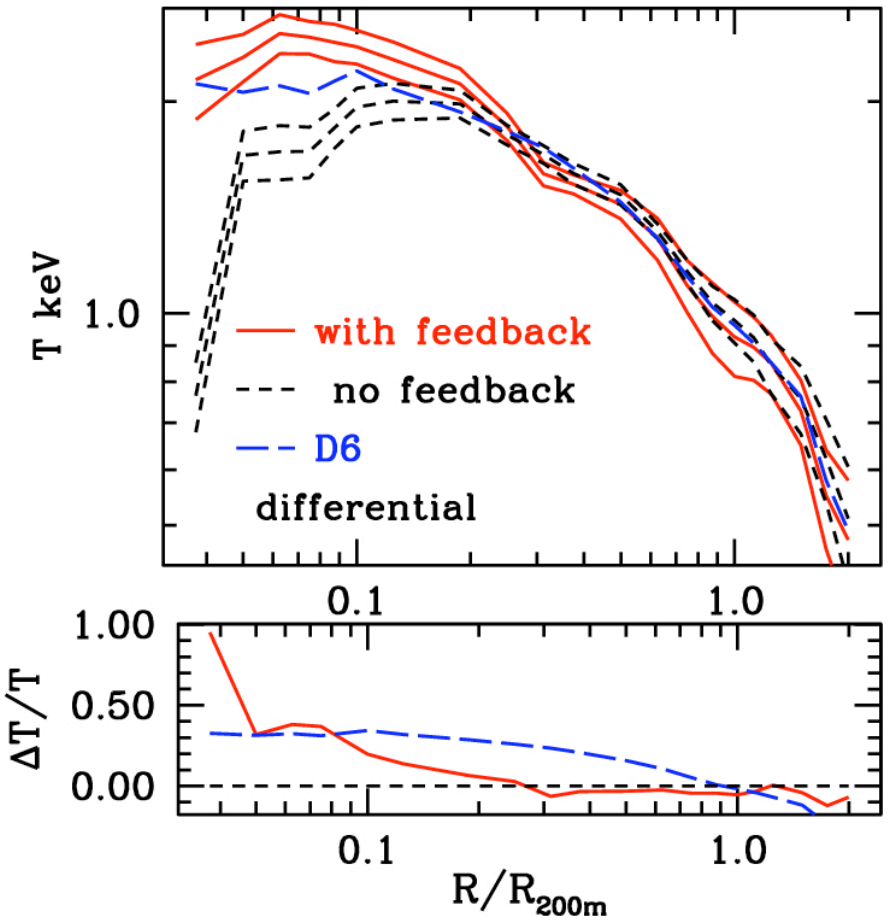
Small scale excess: evidence for multiple BHs within halos, e.g. mergers

Galaxy Clusters and AGN feedback

AGN feedback and its effects on groups/clusters

Bhattacharya, DM, Kosowsky, 2008





Entropy enhanced in the inner regions!

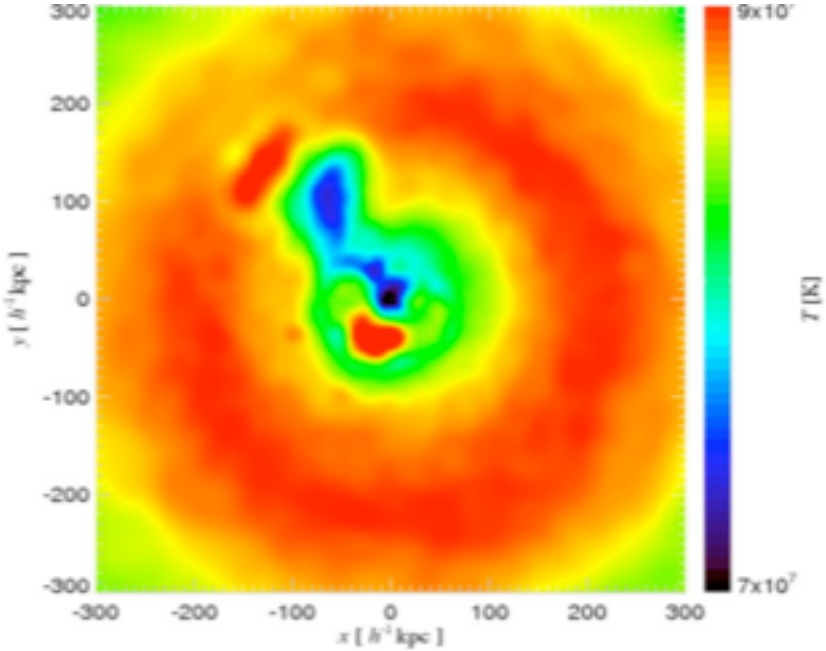
Cosmological Simulations of AGN heated clusters

Sijacki+07

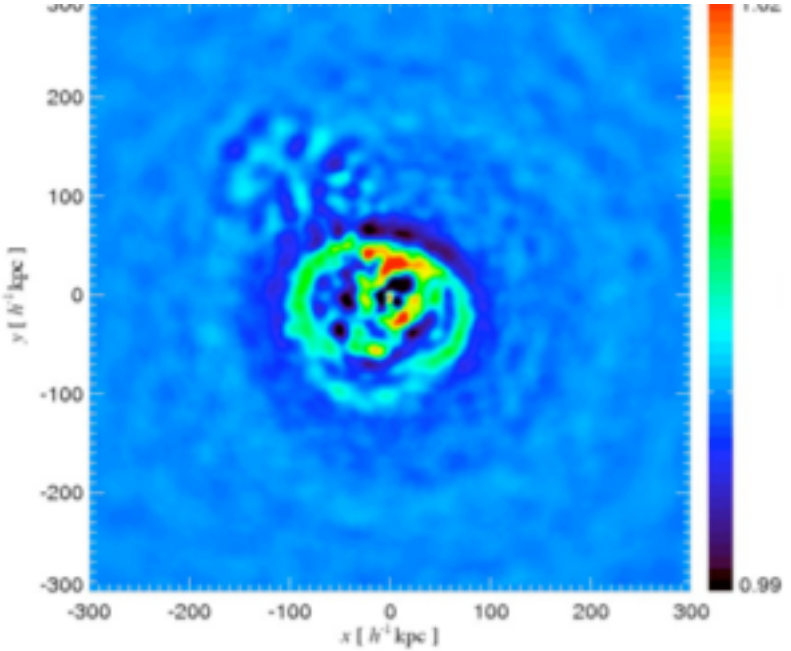
"Radio" feedback:

- below $BHAR_{radio}$ = 0.01, AGN feedback is mechanical =>

recurrent, hot bubble episodes

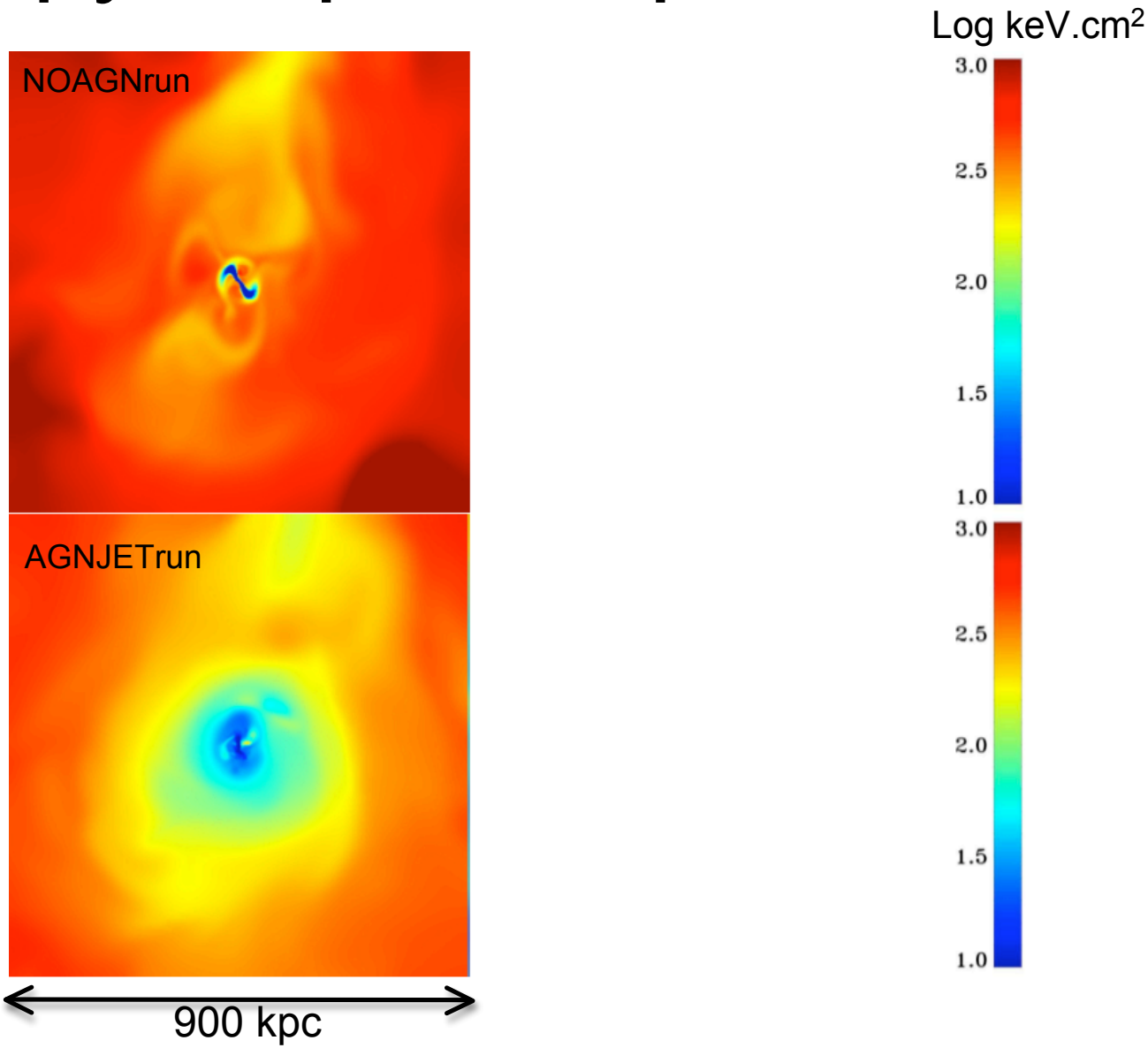


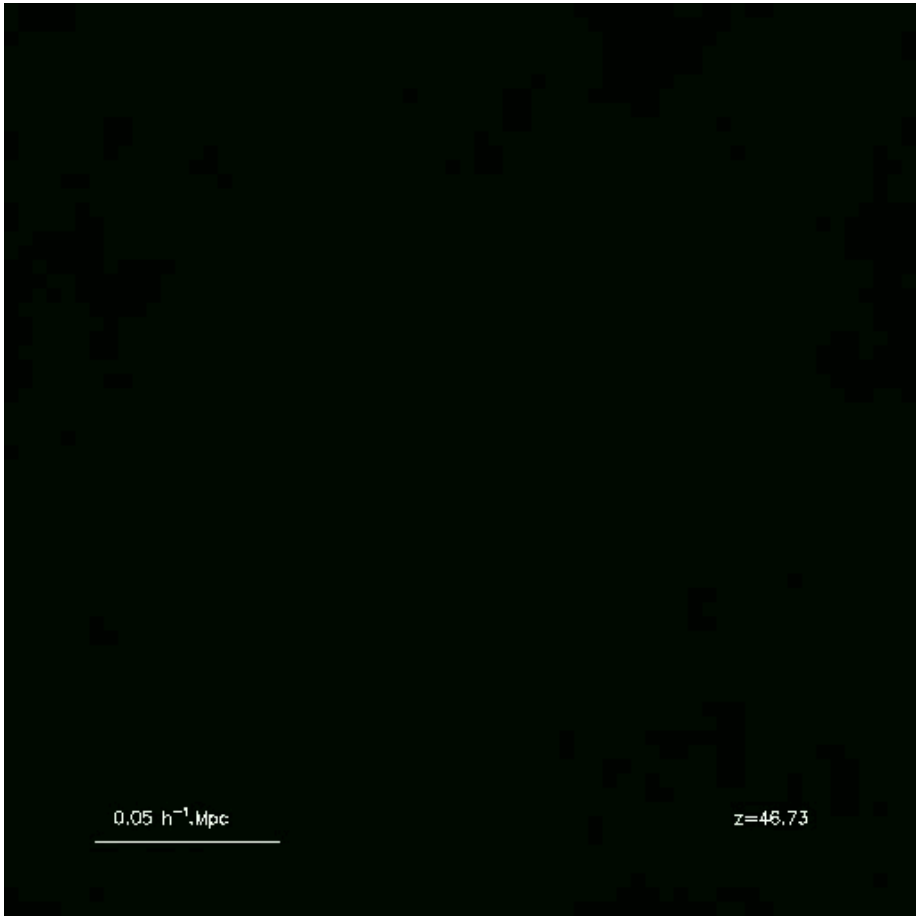
TEMPERATURE MAPS

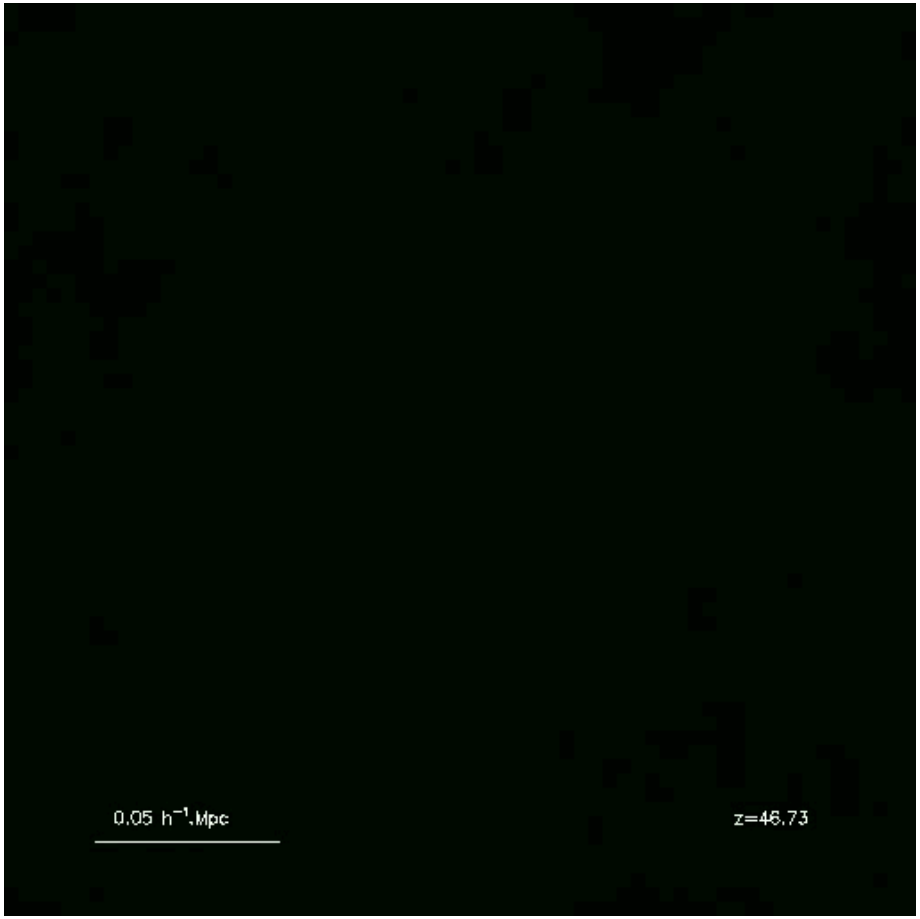


PRESSURE MAPS

Entropy maps comparison



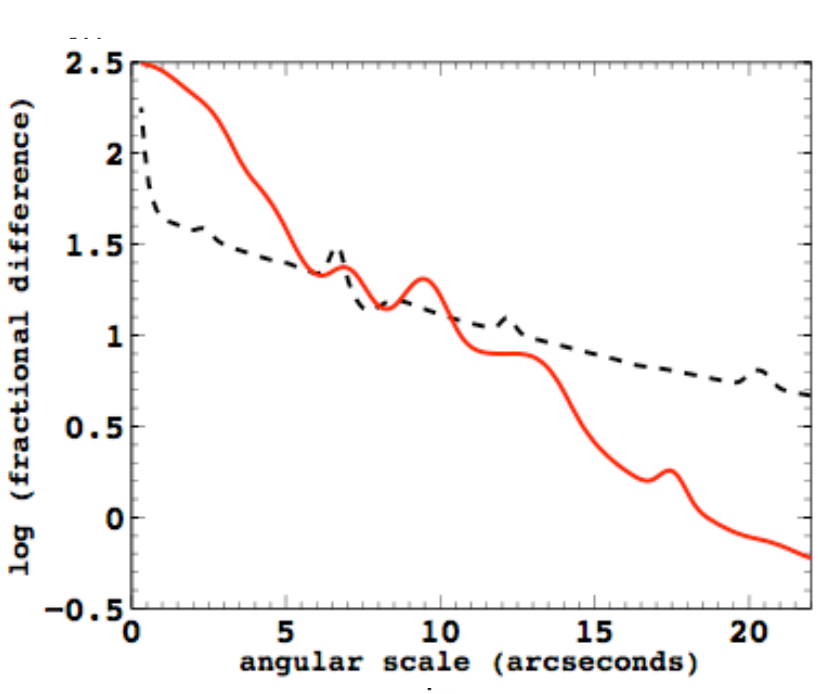


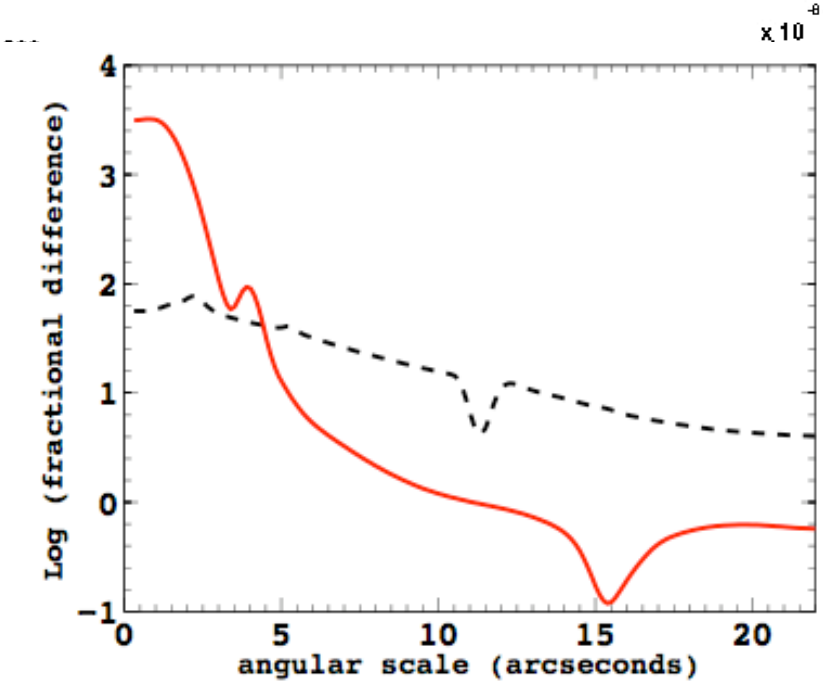


Teyssier, Dubois,
Slyz, Devrient

The AGN feedback and its SZ effect: Direct detection?

Chatterjee, DM, Kosowsky, '08.





ΔY

Quasar feedback heats the gas around the BHs
Leading to SZ directly detectable by ALMA and CCAT

Summary & Conclusions:

1. We have included BHs in simulations of LCDM - in a sub-resolution model

2. First quasars, the BH population LFs, clustering and M-sigma relation

   Large scale /environments gas inflows regulate Growth/AGN triggering

   AGN Feedback M-sigma - sets gas outflow - BH mass 'normalized' energy unbinds gas

3. BH feedback affects clusters and galaxy colors

First Massive black holes, z=6 quasars

- where: first MBH grow in biased regions
- how: Critical accretion can be sustained due to cold gas accretion during first large halo formation
- MBHs grows ‘first’

Need full hydro cosmological simulation to attempt this