High-redshift massive black holes and AGN

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How do black holes grow to become super-massive?

Feeding BHs at high redshift

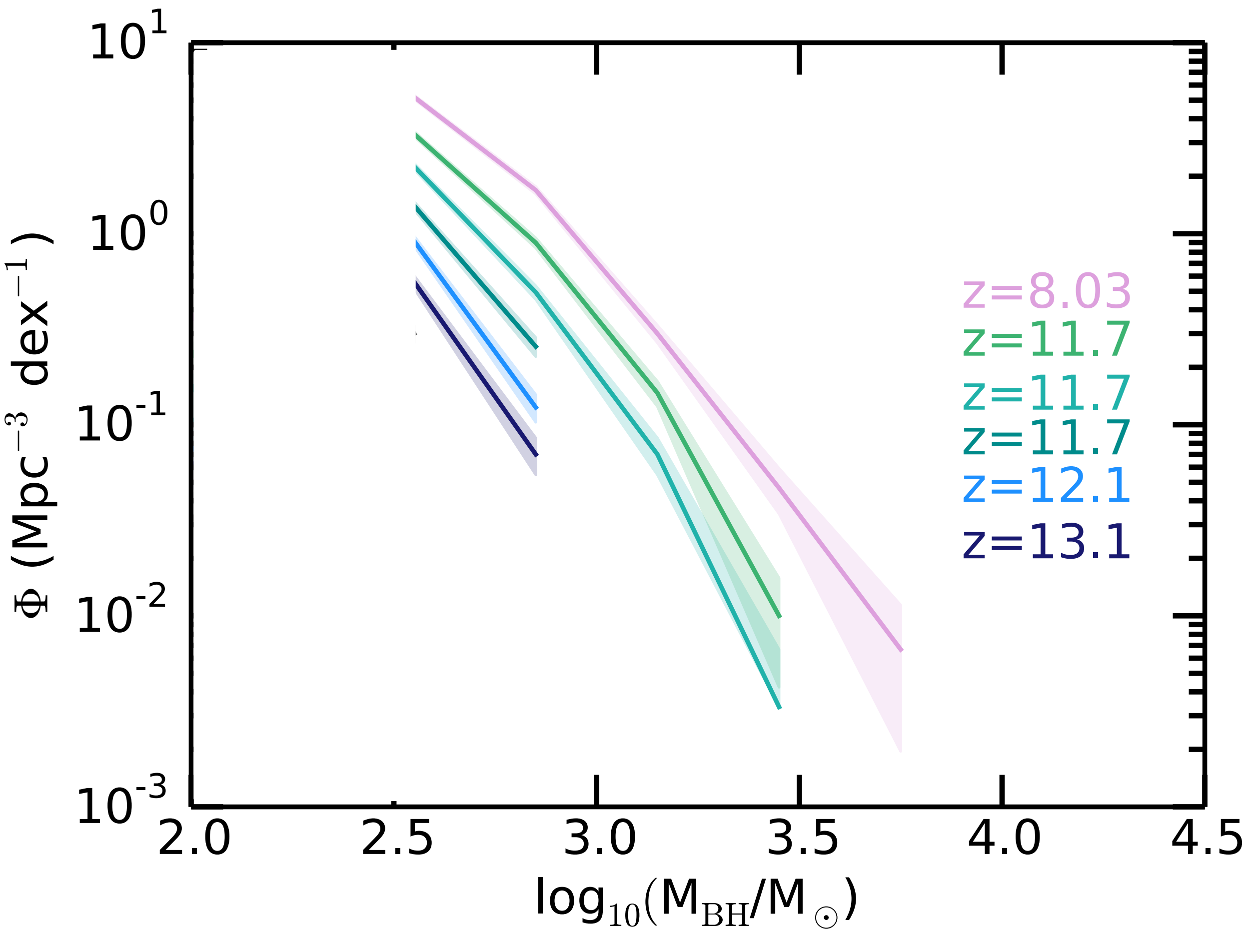
High-redshift MBHs

The billion solar mass MBHs powering the observed $z>6$ quasars are the tip of the iceberg

Very biased, dense regions

What do we expect for *normal* MBHs in *normal* galaxies?

How do galaxies feed *normal* MBHs?



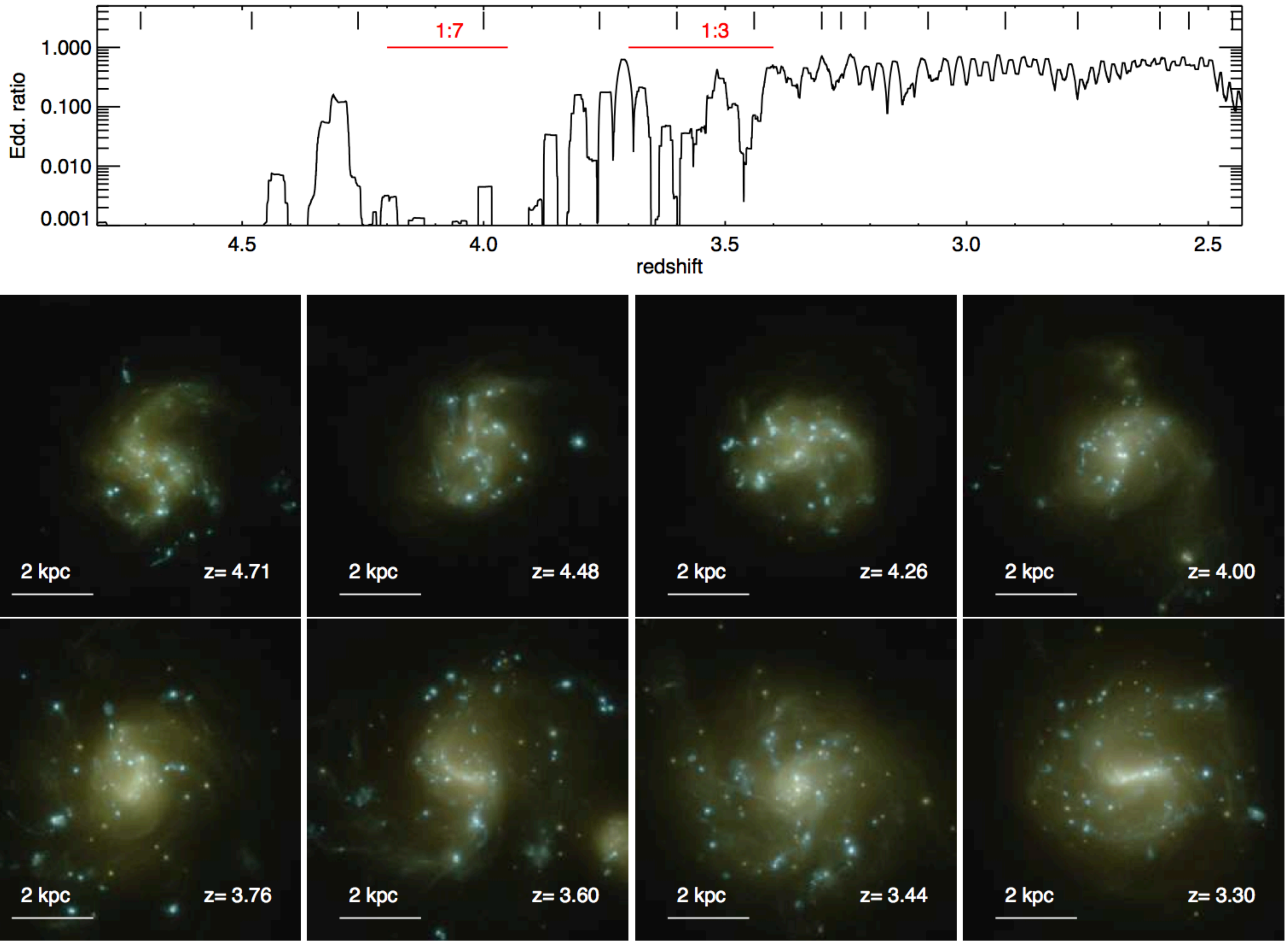
Ramses 10 Mpc Cosmological Volume, ~10pc resolution

Habouzit et al. in prep

How do galaxies feed *normal* MBHs?

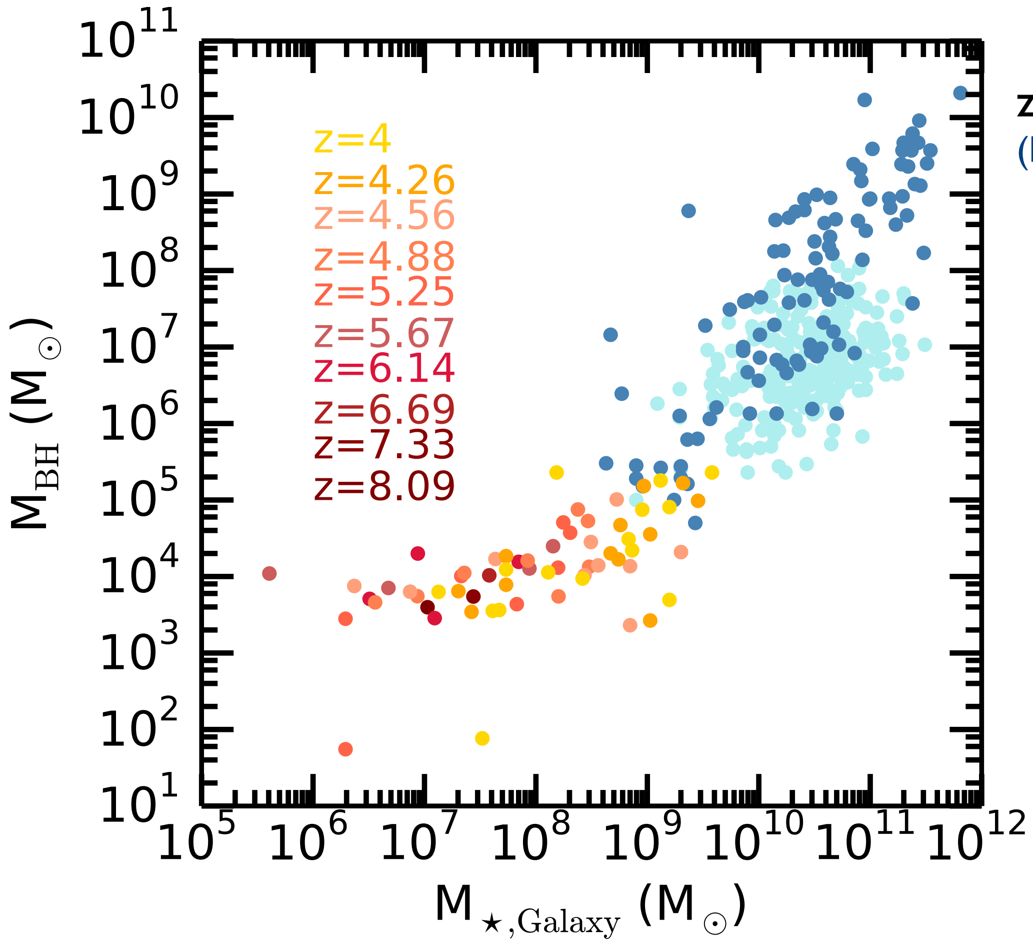
Low-mass BHs in low-mass galaxies: fragile environment

Interplay between SN feedback and MBH accretion: SN feedback is sufficient to energize the gas and suppress accretion (Dubois+14)



SETH, Ramses Cosmological Zoom, ~10 pc resolution, Dubois+14

How do galaxies feed *normal* MBHs?



z=0 **BHs** and **AGN**

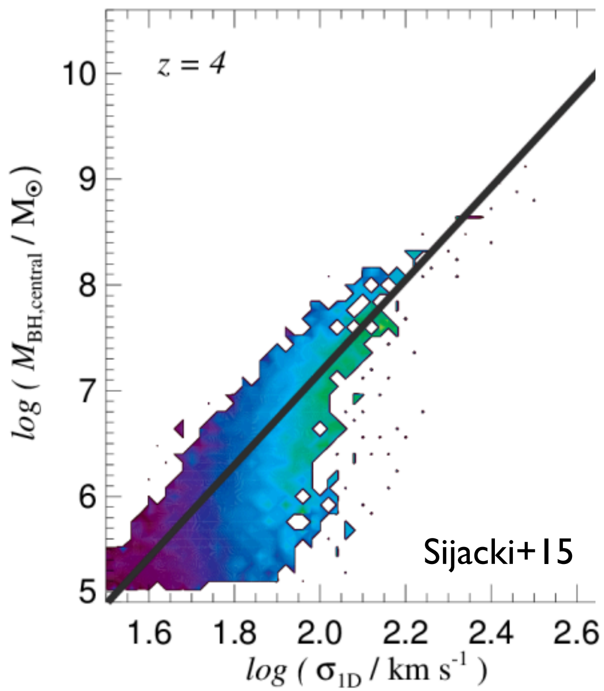
(Reines & Volonteri 2015)

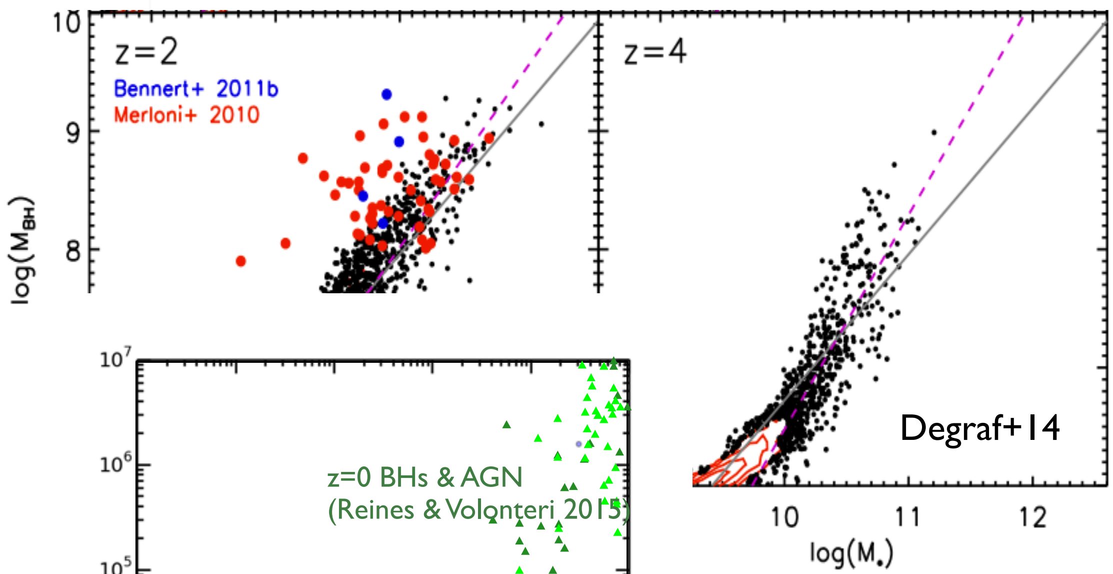
10 Mpc cosmological Volume, ~80pc resolution

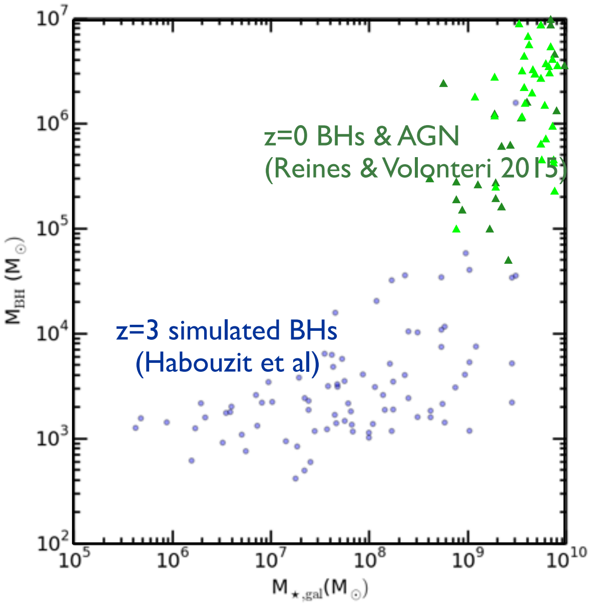
(Habouzit et al. in prep)

MBH vs M$_*$ mass function at z=6 vs z=0

Is BH-host galaxy co-evolution broken at high-z/for low mass galaxies?



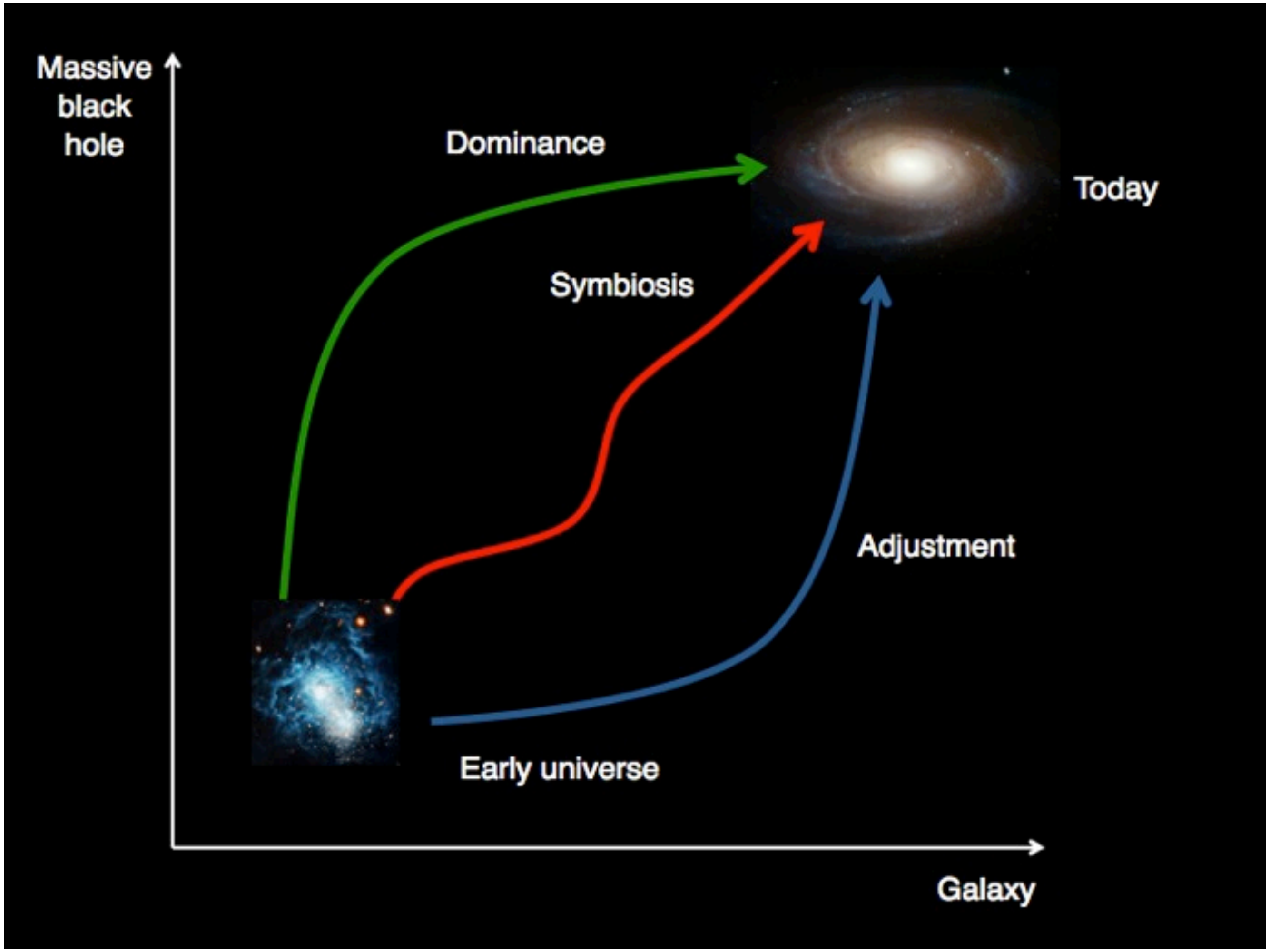




MBHs in the smallest galaxies "stuck" at low mass

How is the observed AGN vs. galaxy coevolution shaped?

M_{BH}- host relations: when are they established?



M_{BH}- host relations: redshift evolution

- At high redshift the detection of the host galaxies is very difficult especially in luminous quasars: the AGN light swamps the galaxy light

- At high redshift the estimate of the MBH mass is also more difficult as one has to rely on "virial masses" through different line widths in different redshift windows – not all lines equally good at tracing BH mass

M_{BH}- host relations: redshift evolution

- At high redshift the detection of the host galaxies is very difficult especially in luminous quasars: the AGN light swamps the galaxy light

- Also need to convert luminosity into mass – stellar population models

- Is it really bulge mass, or total stellar mass?

- At high redshift the estimate of the MBH mass is also more difficult as one has to rely on "virial masses" through different line widths in different redshift windows – not all lines equally good at tracing BH mass

M_{BH}- bulge relation: redshift evolution

- MBH- bulge luminosity: seems redshift independent (Peng et al 2006 – lensed galaxies; Decarli et al 2010; McLure et al. 2006. Note: hosts are classified as ellipticals in these samples.)

- Once bulge luminosity is converted in bulge mass assuming passive stellar evolution: MBHs are “overmassive” at fixed galaxy mass

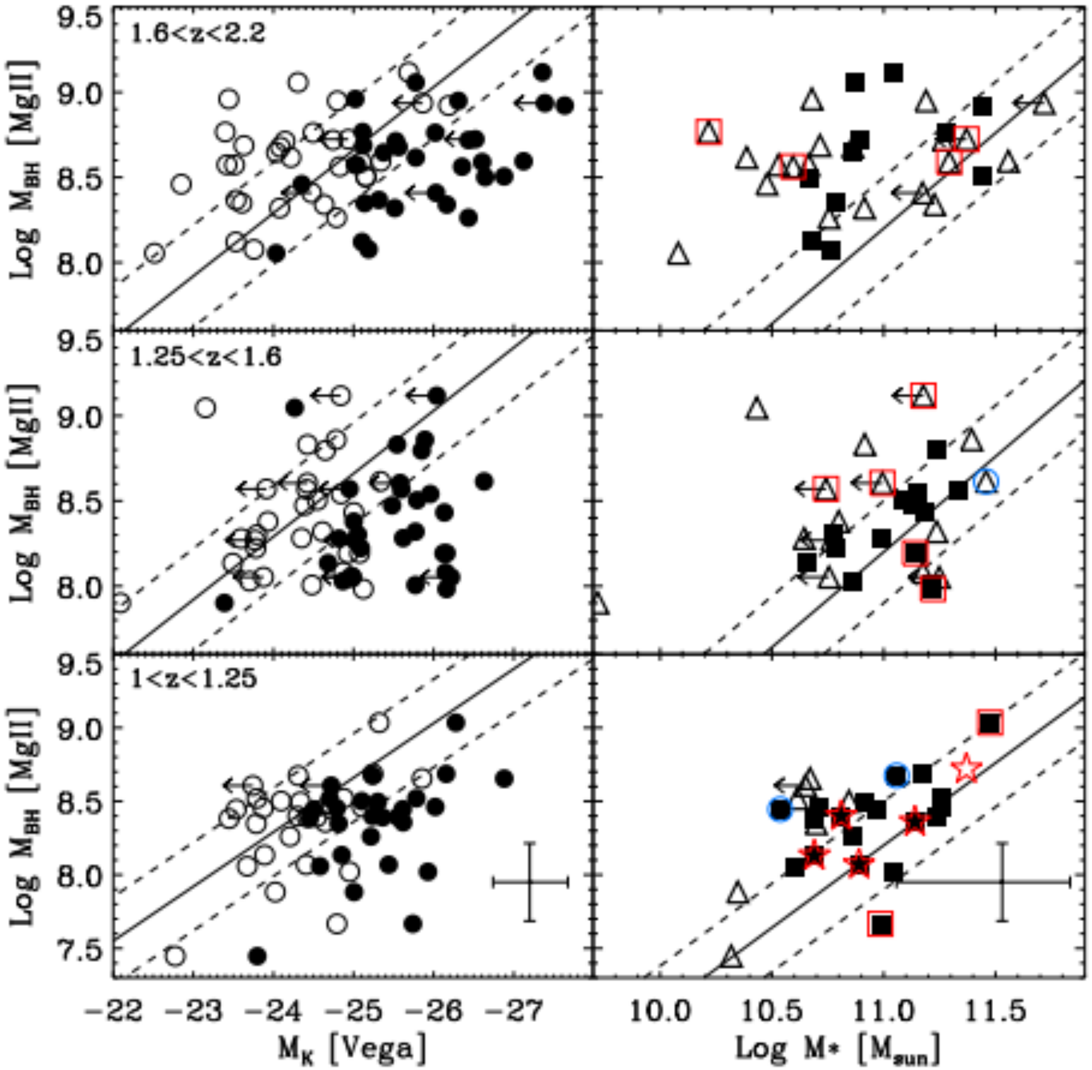
- $R=[M_{BH}(z)/Mbulge(z)]/[M_{BH}(z)/Mbulge(z)]\sim 2$ at $z<2$
- $R=\sim 3\text{-}6$ at $z\sim 2$
- $R=\sim 7$ at $z\sim 3$

M_{BH}- stellar mass relation: redshift evolution

- There is no real effe
using the same tech
sample of galaxies v

- Measure stellar mas
fitting (Merloni et al.): tl

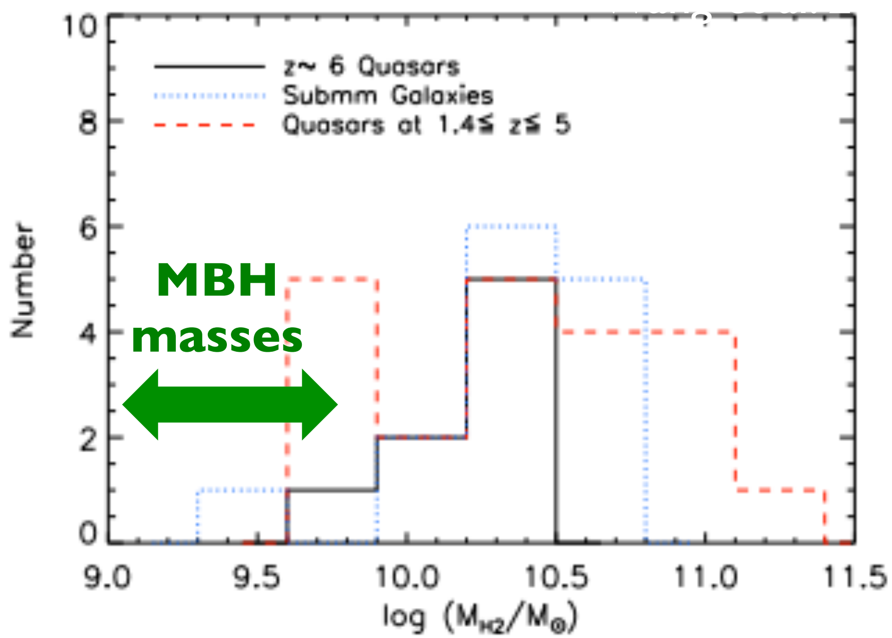
- Cisternas: R=0 at z
by z=0)
- Merloni: R ~(1+z)$^{0.6}$



M_{BH}- host relations: highest redshift

- Host galaxy cannot be imaged – use radio maps of CO that traces cold gas => gas masses and dynamical masses from line widths and beam size, plus "velocity dispersion" also from line width. Careful in comparing apples to apples!

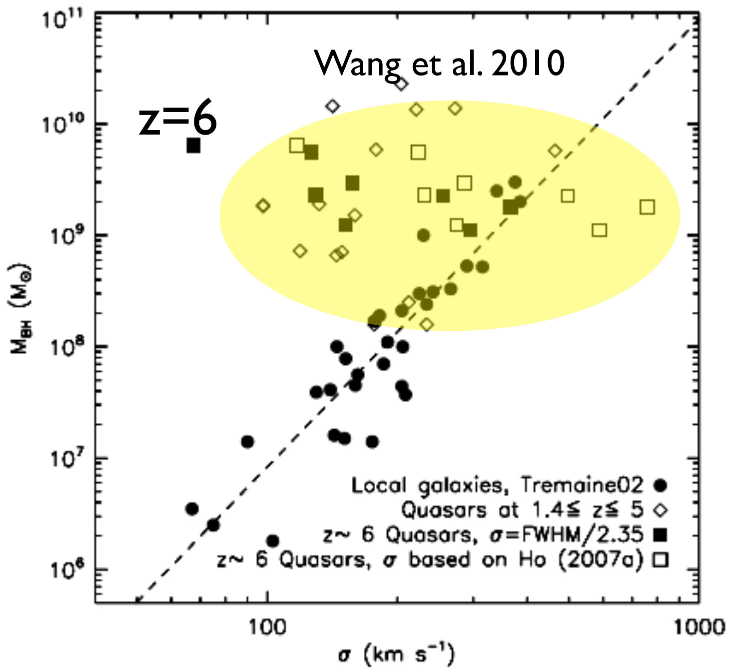
- M_{BH}~10-30% M_{gas}



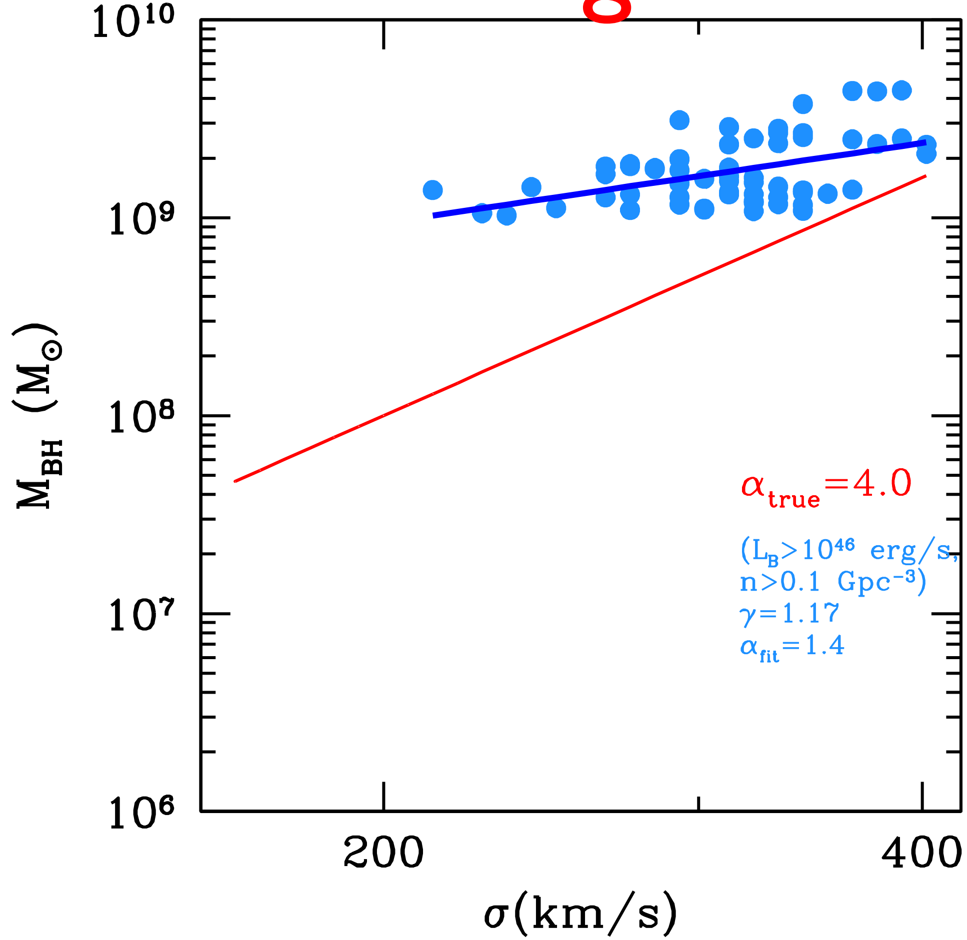
M_{BH}- host relations: highest redshift

- Host galaxy cannot be imaged – use radio maps of CO that traces cold gas => gas masses and dynamical masses from line widths and beam size, plus "velocity dispersion" also from line width. Careful in comparing apples to apples!

- M_{BH} much overmassive at fixed σ

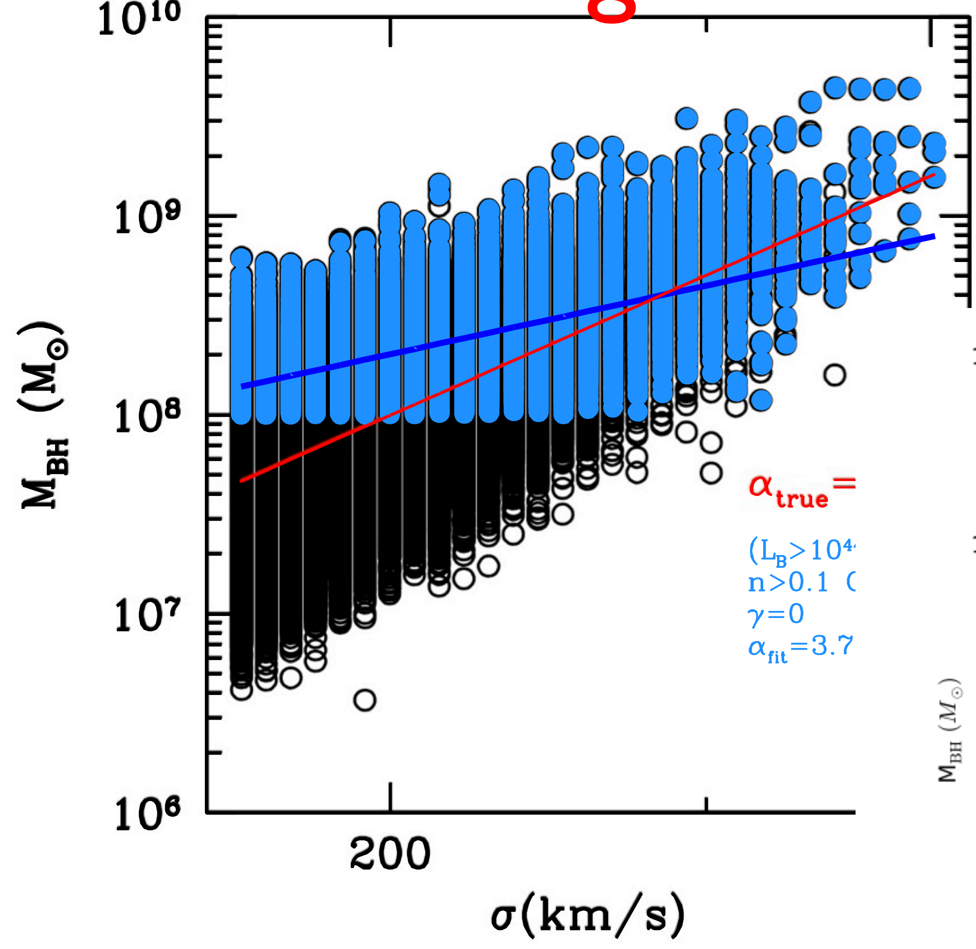


M_{BH}- host relations: highest redshift

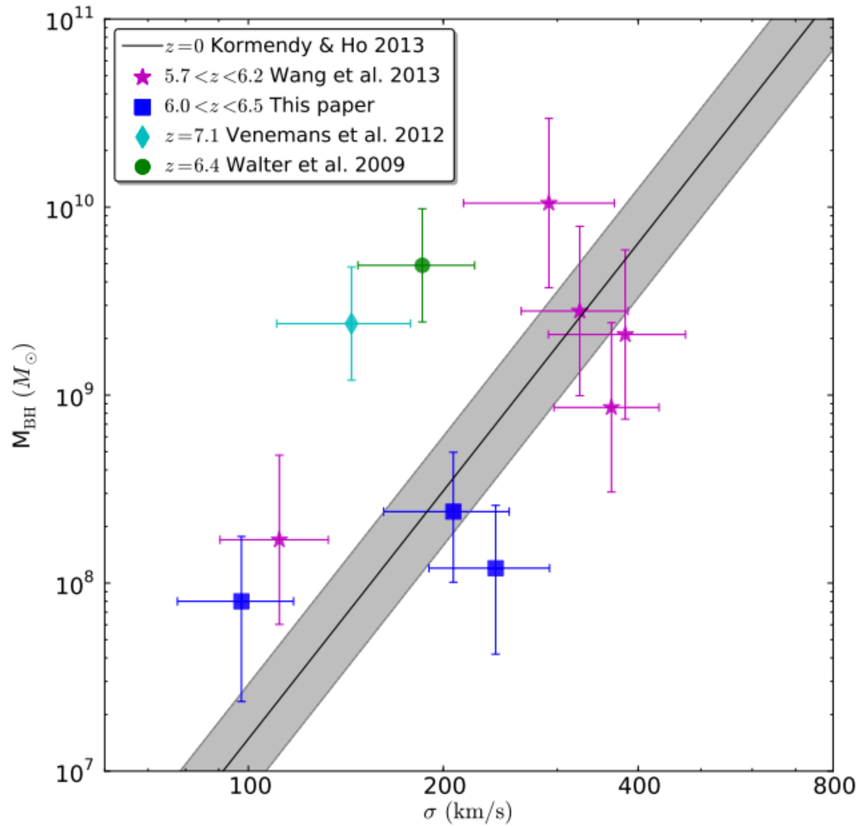


Current large-shallow surveys select only the most luminous quasars => the most massive holes at the highest redshiftt

M_{BH}- host relations: highest redshift

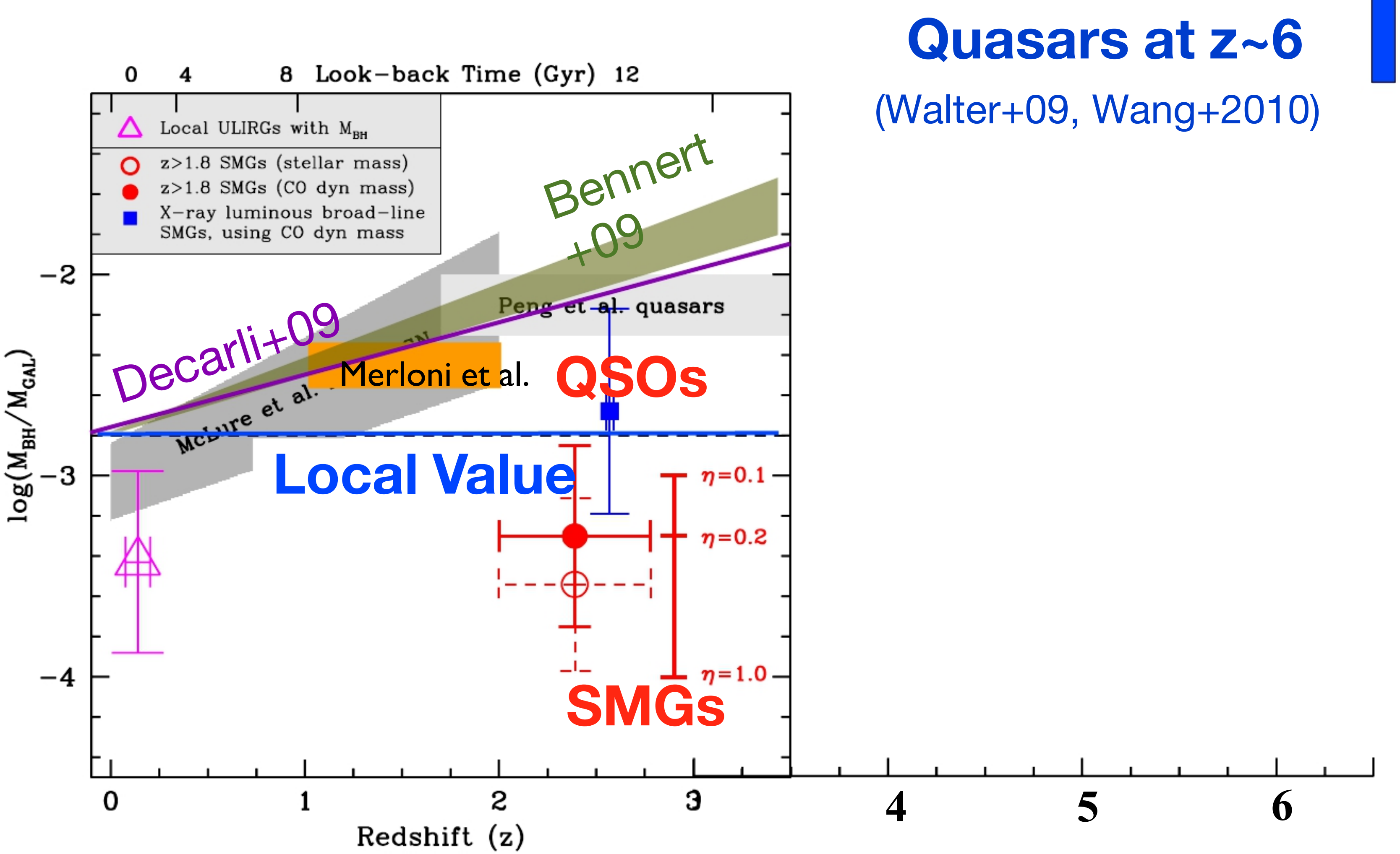


Going deeper uncovers more of the population



Large scatter!

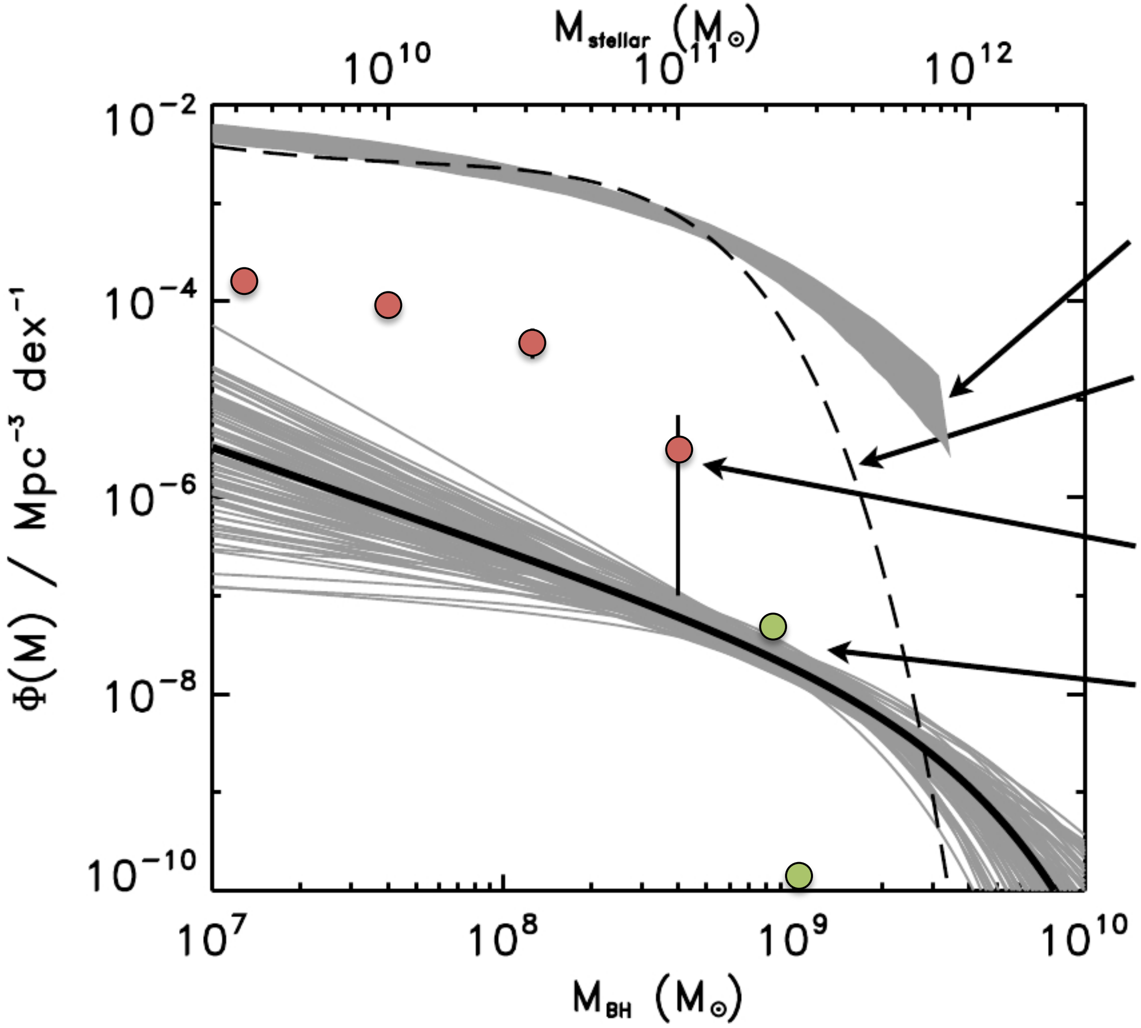
M_{BH}- host relations: summary



Courtesy of A. Marconi

MBH vs M_* mass function at z=6 vs z=0

M_* axis shifted by $4x10^{-3}$ from MBH



Local BH MF
(Shankar et al.2009)

Local stellar MF shifted by $4x10^{-3}$
(Baldry et al.2008)

z=6 stellar MF (+ Schechter fit)
shifted by $4x10^{-3}$ (Stark et al.2009)

z=6 BH MF
(Willott et al.2010b)

Willott et al.(2010)

MBH vs galaxy at z=6 vs z=0

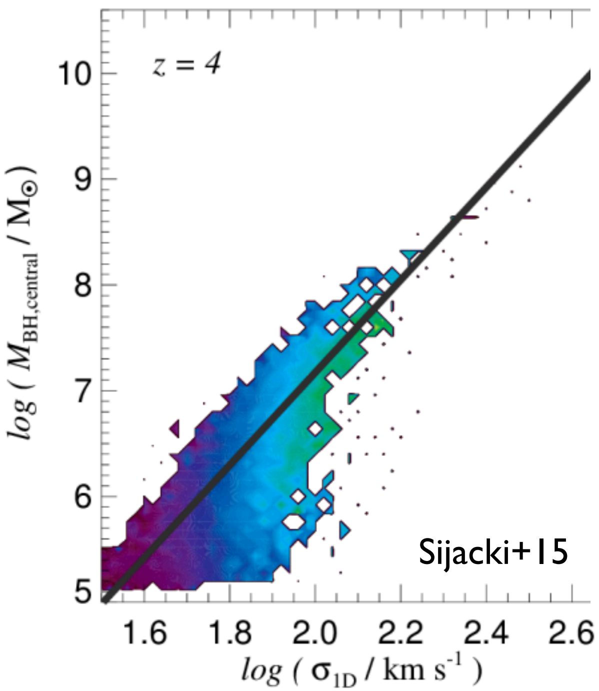
- Deficit @ low masses =>
  $M_{BH}/M_{*|z=6}$ **<<** $M_{BH}/M_{*|z=0}$

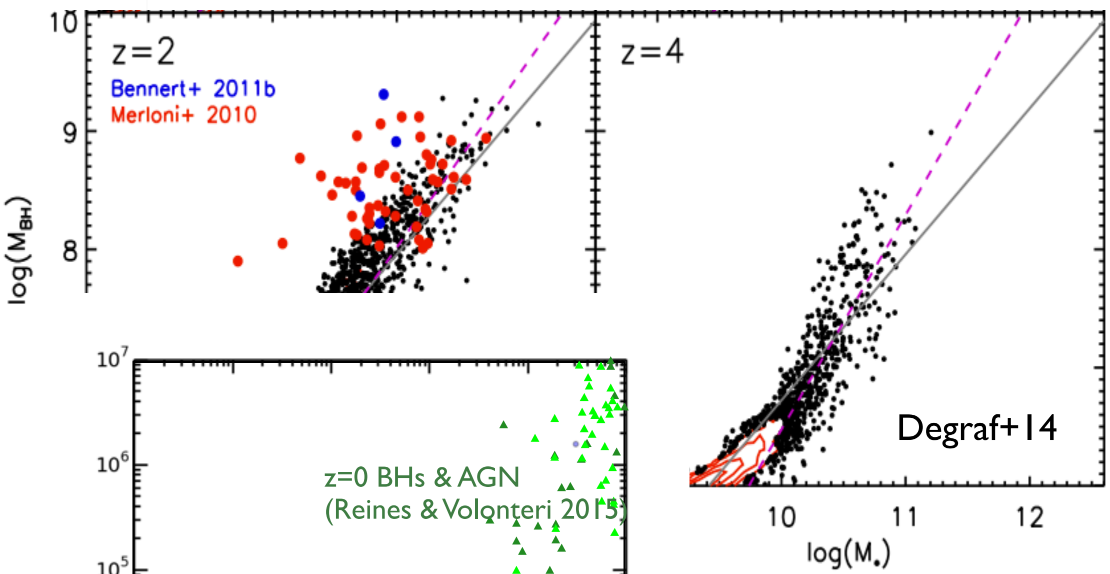
- Excess @ high masses =>
  $M_{BH}/M_{*|z=6}$ **>>** $M_{BH}/M_{*|z=0}$

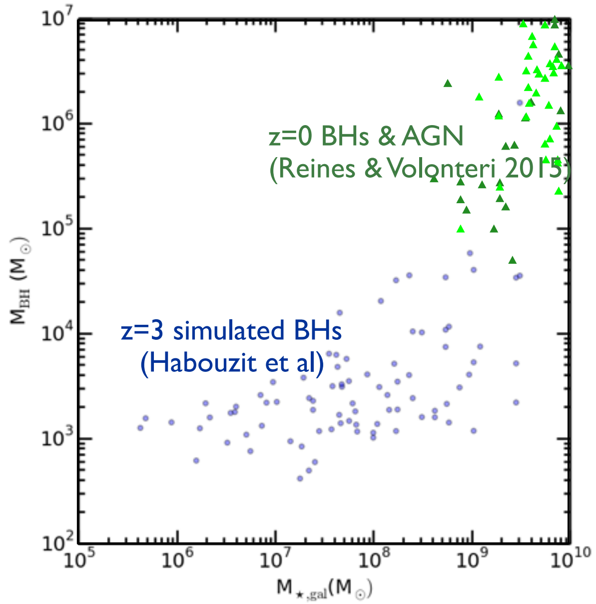
Are the BH-galaxy relations "tilted" at high-z?

Volonteri & Stark 2011

MBH vs galaxy at z=0 vs z=6

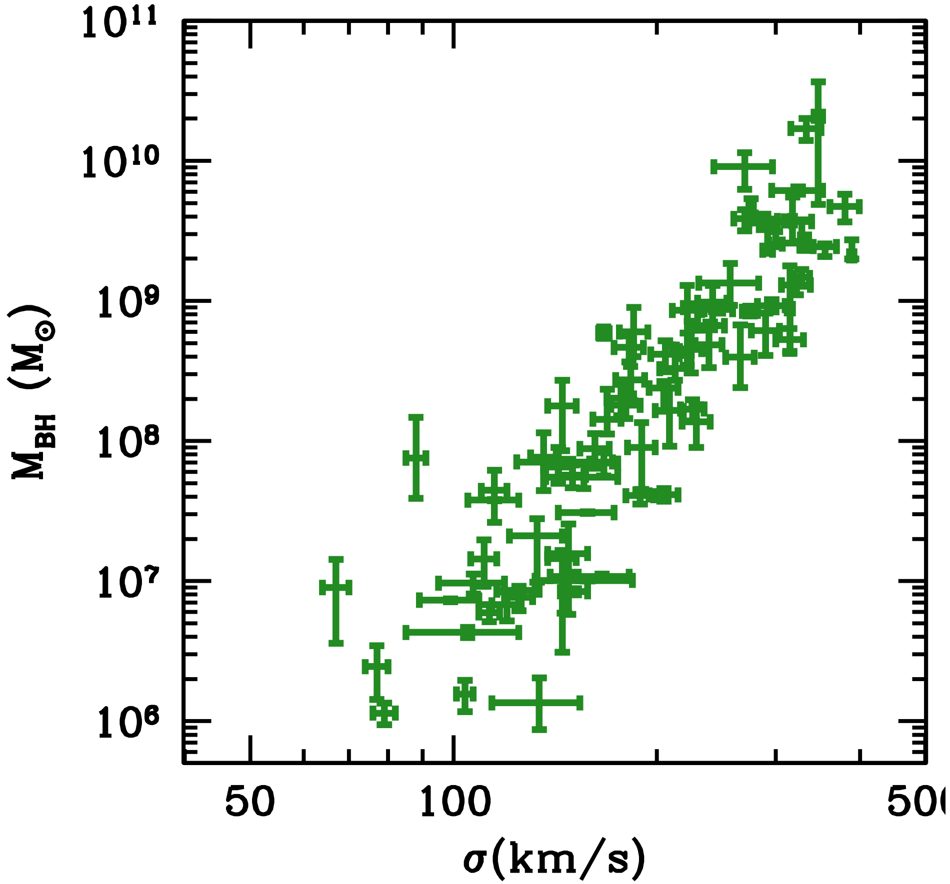


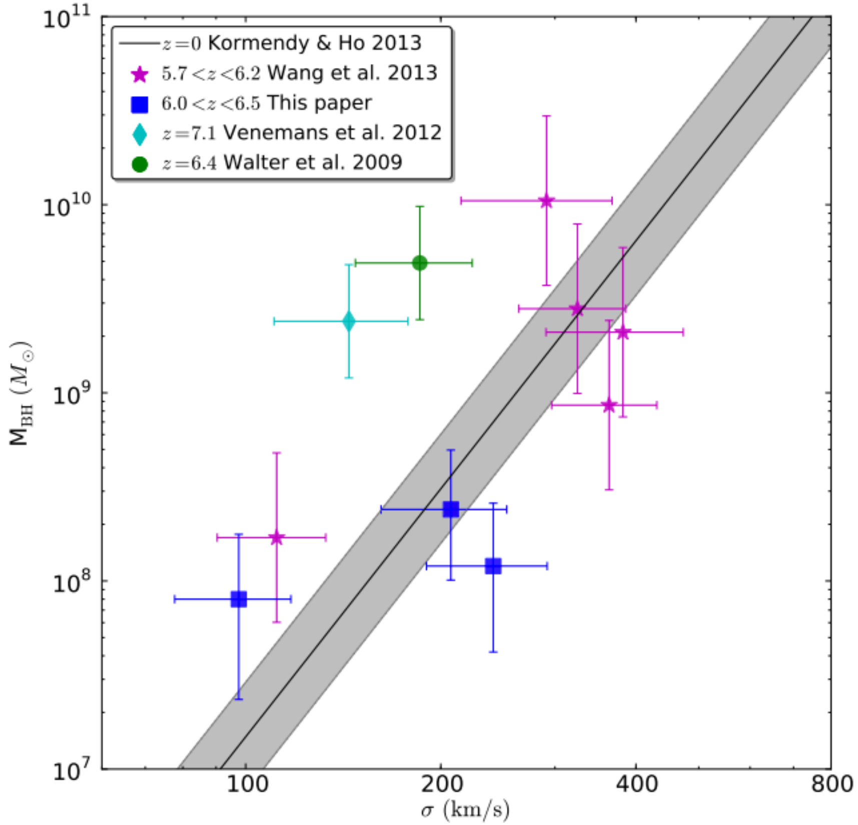




MBHs in the smallest galaxies "stuck" at low mass

MBH vs galaxy at z=0 vs z=6

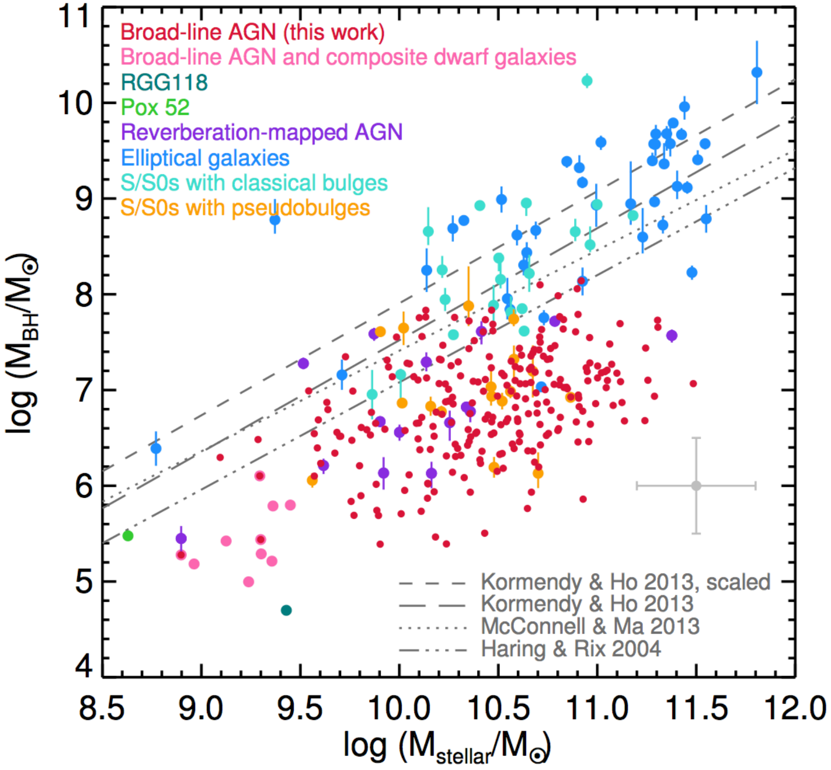


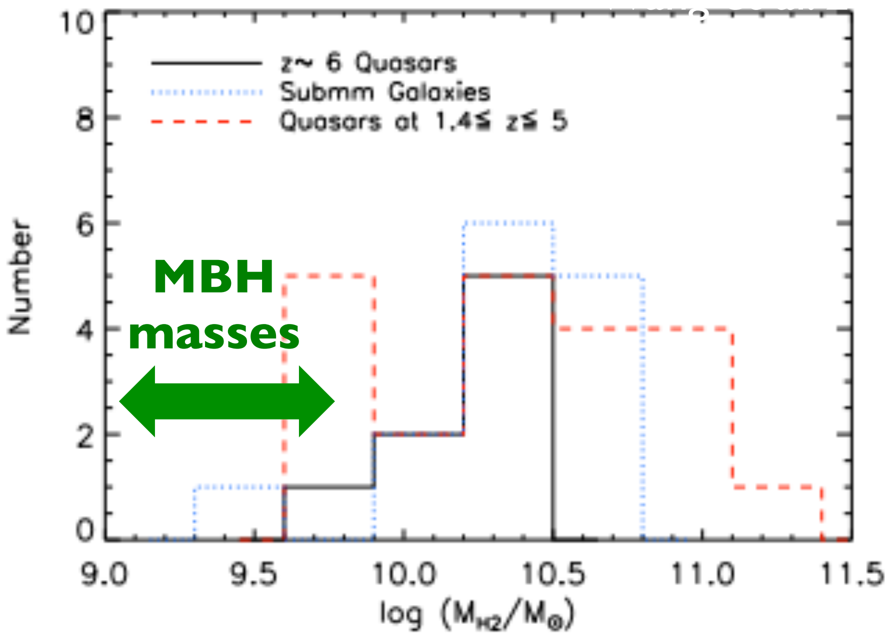


- stellar velocity dispersion
- dynamical BH mass

- gas dispersion
- “virial” BH mass

MBH vs galaxy at z=0 vs z=6

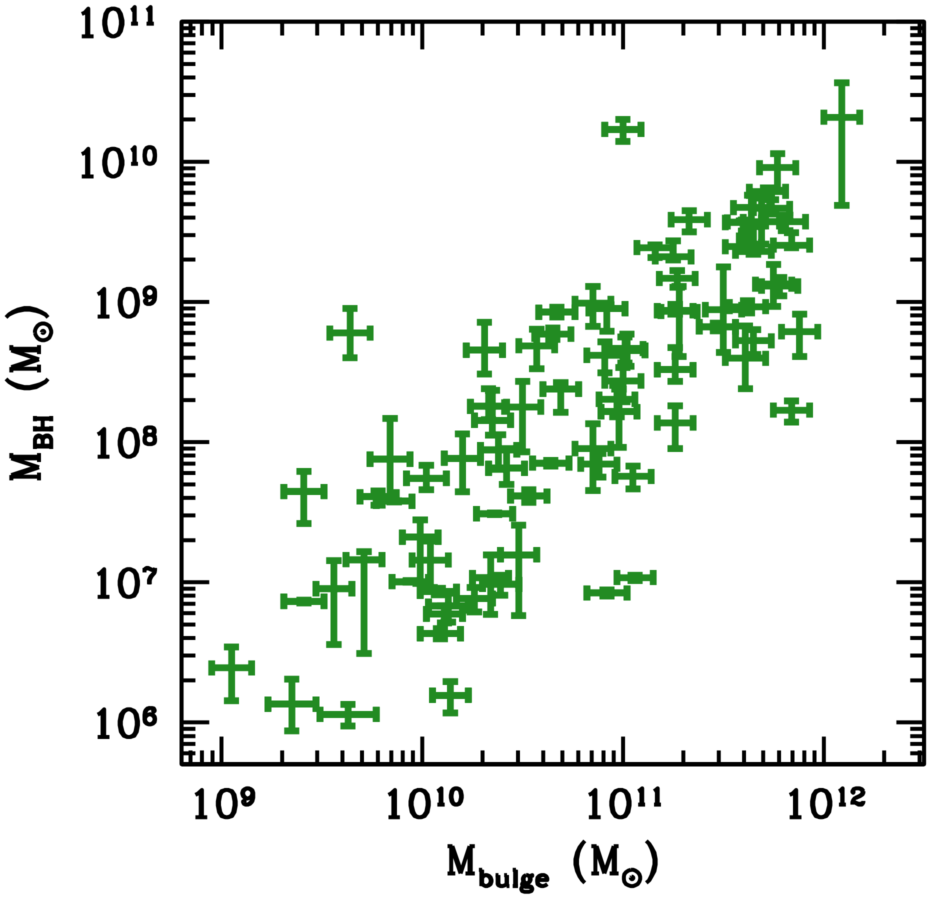


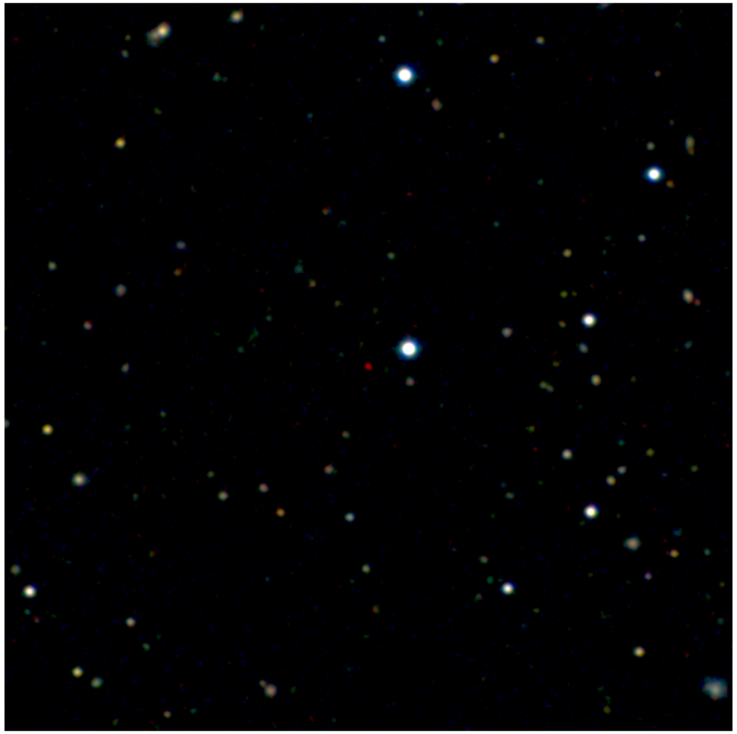


- galaxy stellar mass
- dynamical/virial BH mass

- gas "dynamical mass"
- "virial" BH mass

MBH vs galaxy at z=0 vs z=6





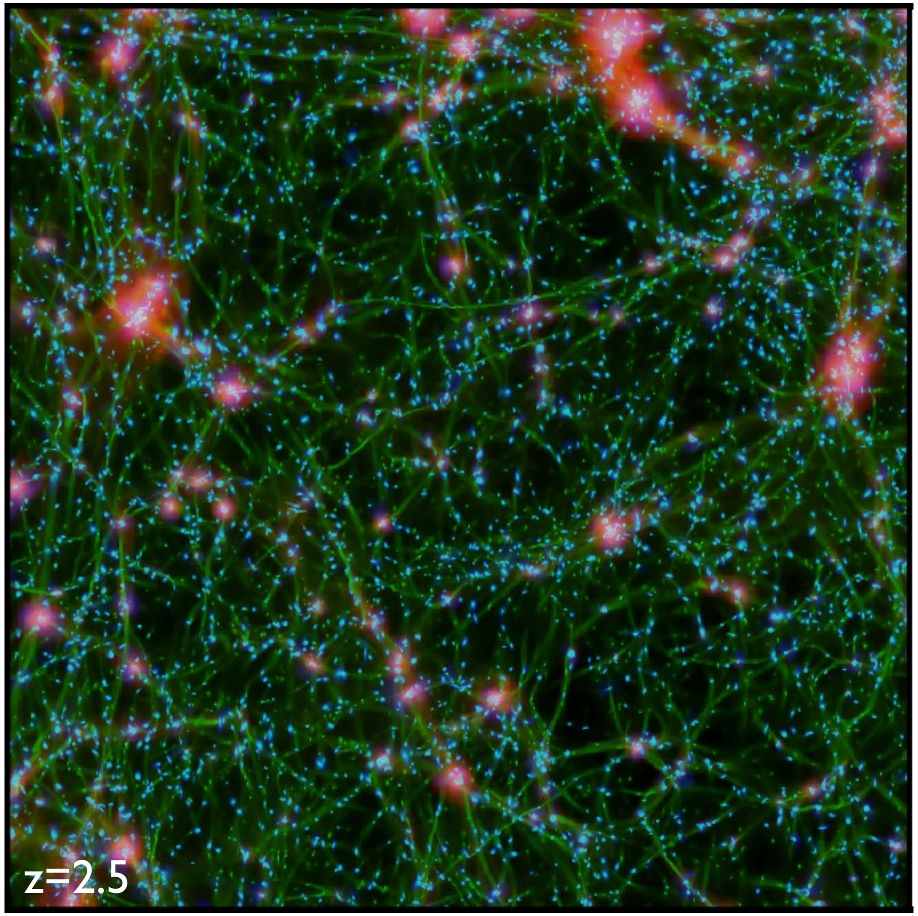
- galaxy stellar mass
- dynamical BH mass

- bulge/disc decomposition?
- do bulges exist?

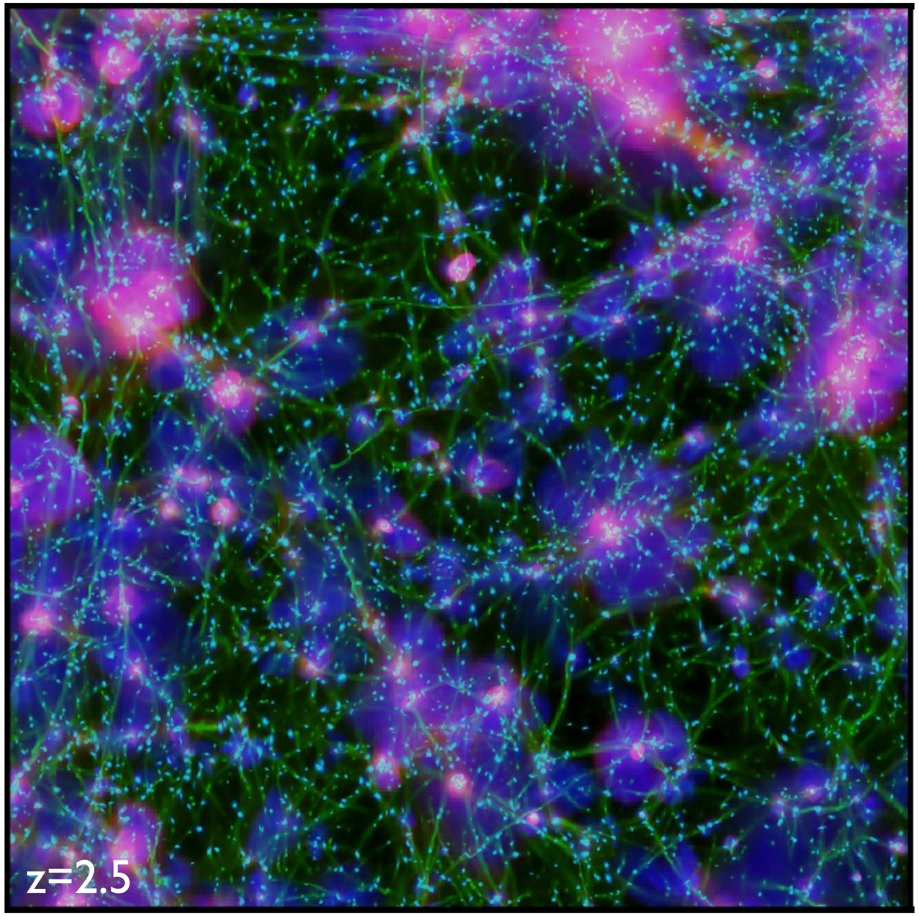
The role of feedback at high redshift

How do MBHs affect galaxies?

Horizon-noAGN



Horizon-AGN



Horizon-AGN (Dubois+14): L_{box}=140 Mpc, 7×10^9 gas cells, dx~1 kpc, AMR (Ramses)
Green: gas density / Red: temperature / Blue: metallicity

AGN feedback

Feedback: the positive or negative effect of AGN radiation and kinetic energy on the galaxy

Different types of feedback at play:

- How feedback affects the galaxy

- How feedback affects the MBH

AGN feedback

"If the velocity dispersion of the galaxy is σ then the binding energy of the galaxy bulge, which is of mass Mgal, is Egal ≈ Mgal σ^2

The mass of the MBH is $\sim M_{BH} \sim 10^{-3}$Mgal. Assuming a radiative efficiency of 10%, then the energy released by the growth of the black hole is given by $E_{BH} = 0.1 M_{BH} c^2$

Therefore E_{BH}/Egal$\sim 10^{-4}(c/\sigma)^2$. Most galaxies have $\sigma <$ 400 kms−1 , so E_{BH}/Egal > 80.

The energy produced by the growth of the black hole therefore exceeds the binding energy by a large factor

If even a small fraction of the energy can be transferred to the gas, then an AGN can have a profound effect on the evolution of its host galaxy"

Fabian 2012

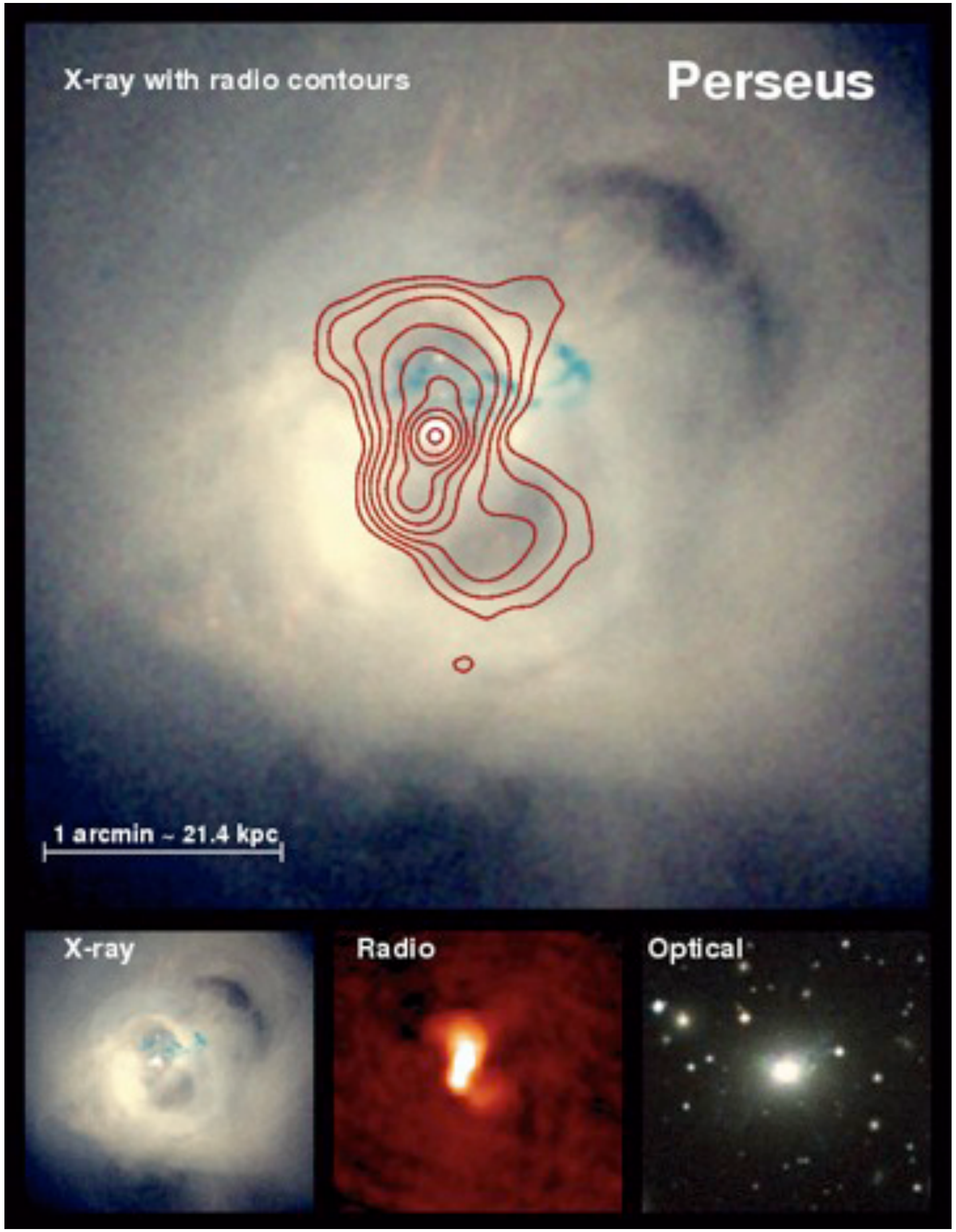
AGN energy output: feedback flavors

- Radiative:
  - Winds/outflows from accretion discs [QSOs/Seyfert]
    - BAL QSOs
    - UV absorbers
    - Warm absorbers
    - UFO (X-ray Ultra-Fast Outflows)

- Kinetic
  - Powerful radio galaxies [RLQ, FRII]
  - Low –luminoisty jetted-dominated sources

Courtesy of A. Merloni

AGN feedback at work



“Chandra image shows concentric ripples interpreted as sound waves generated by the expansion of the central pressure peaks associated with the repetitive blowing of bubbles”

Feedback in galaxies: radiation not jets

If accretion rate close to Eddington radiation pressure ~ balances gravity => either stops gas from infalling, or energizes it or even unbinds it from galaxy

Equilibrium between infall and outflow established when either energy or momentum balance

Fabian 2012

Feedback in galaxies: radiation not jets

Energy balance:

- The galaxy is assumed to be isothermal with radius r , so that its mass is Mgal = $2\sigma^2 r/G$.
- The maximum gas collapse rate ~$2 f\sigma^3/G$, is equivalent to the gas content, fMgal , collapsing on a freefall time, r/σ => A power of ~$f\sigma^5/G$ needed for balance
- Equate this power to $L_{Edd} = 4\pi G M_{BH} m_p c/\sigma_T$
- Obtain maximum mass of MBH before gas swept away:

$$M_{\rm BH} \sim \frac{f\sigma^5\sigma_{\rm T}}{4\pi G^2 m_{\rm p} c},$$

Fabian 2012

Feedback in galaxies: radiation not jets

Momentum balance:

- Balance the outward radiation force with the inward one due to gravity

$$\frac{4\pi G M_{\rm BH} m_{\rm p}}{\sigma_{\rm T}} = \frac{L_{\rm Edd}}{c} = \frac{G M_{\rm gal} M_{\rm gas}}{r^2} = \frac{f G M_{\rm gal}^2}{r^2} = \frac{f G}{r^2}\left(\frac{2\sigma^2 r}{G}\right)^2$$

- Obtain maximum mass of MBH before gas swept away

$$\frac{4\pi G M_{\rm BH} m_{\rm p}}{\sigma_{\rm T}} = \frac{f 4\sigma^4}{G},$$

Fabian 2012

An example from simulations

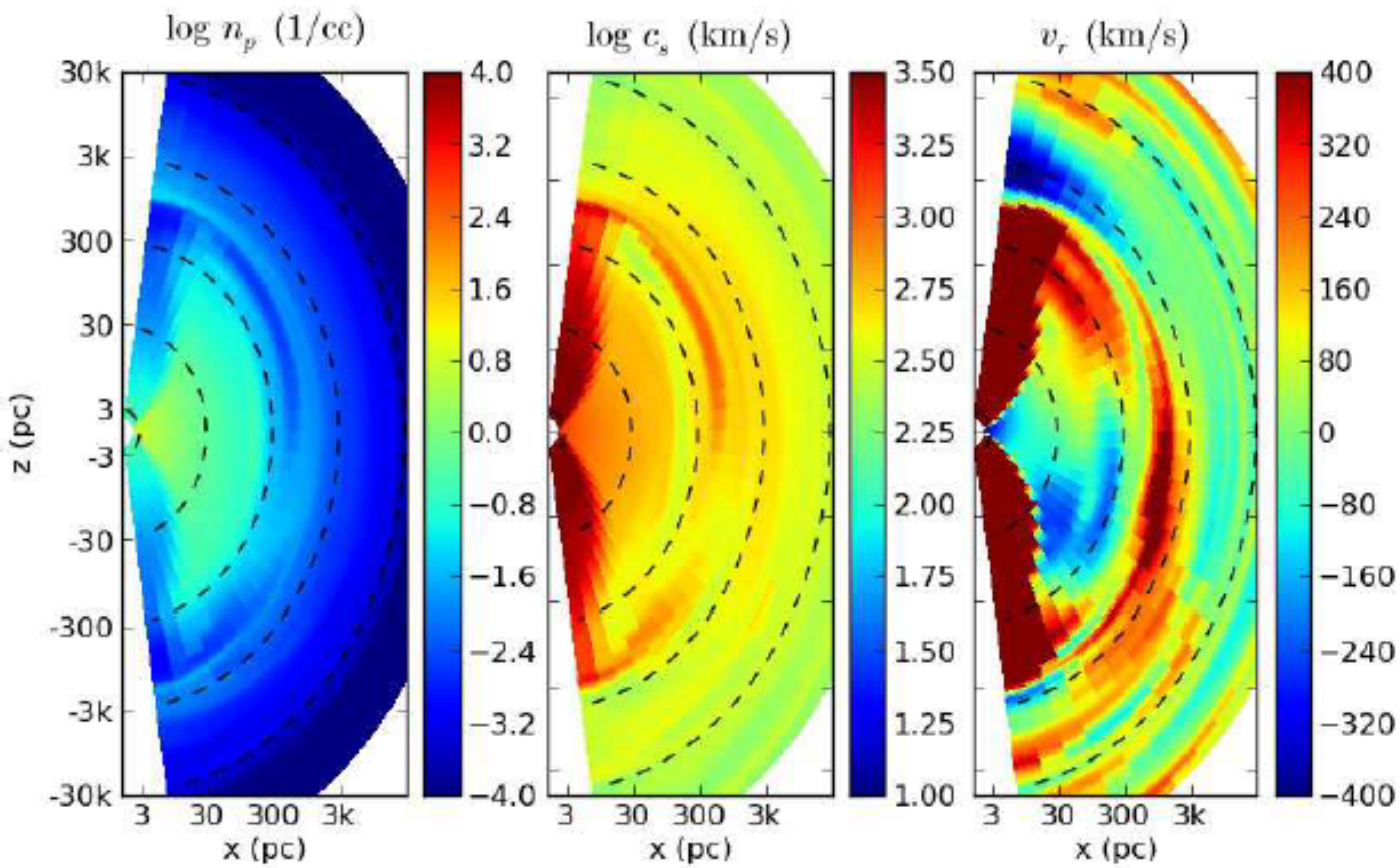


FIG. 3.— Simulation snapshot during an accretion event. A significant quantity of hot, outflowing gas injects energy and momentum into the interstellar medium at $r \simeq 1$ kpc.

Novak et al 2012

An example from simulations

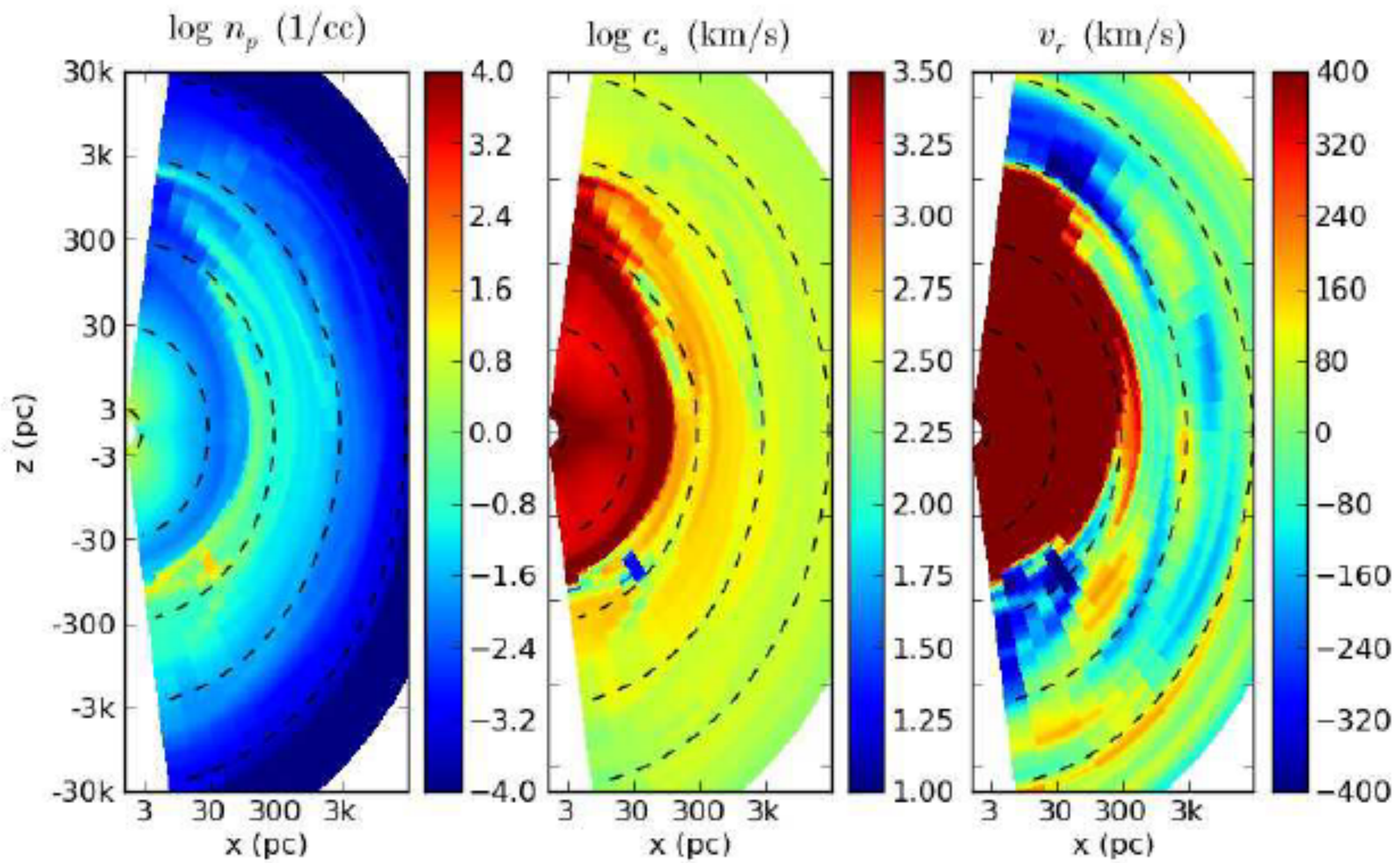
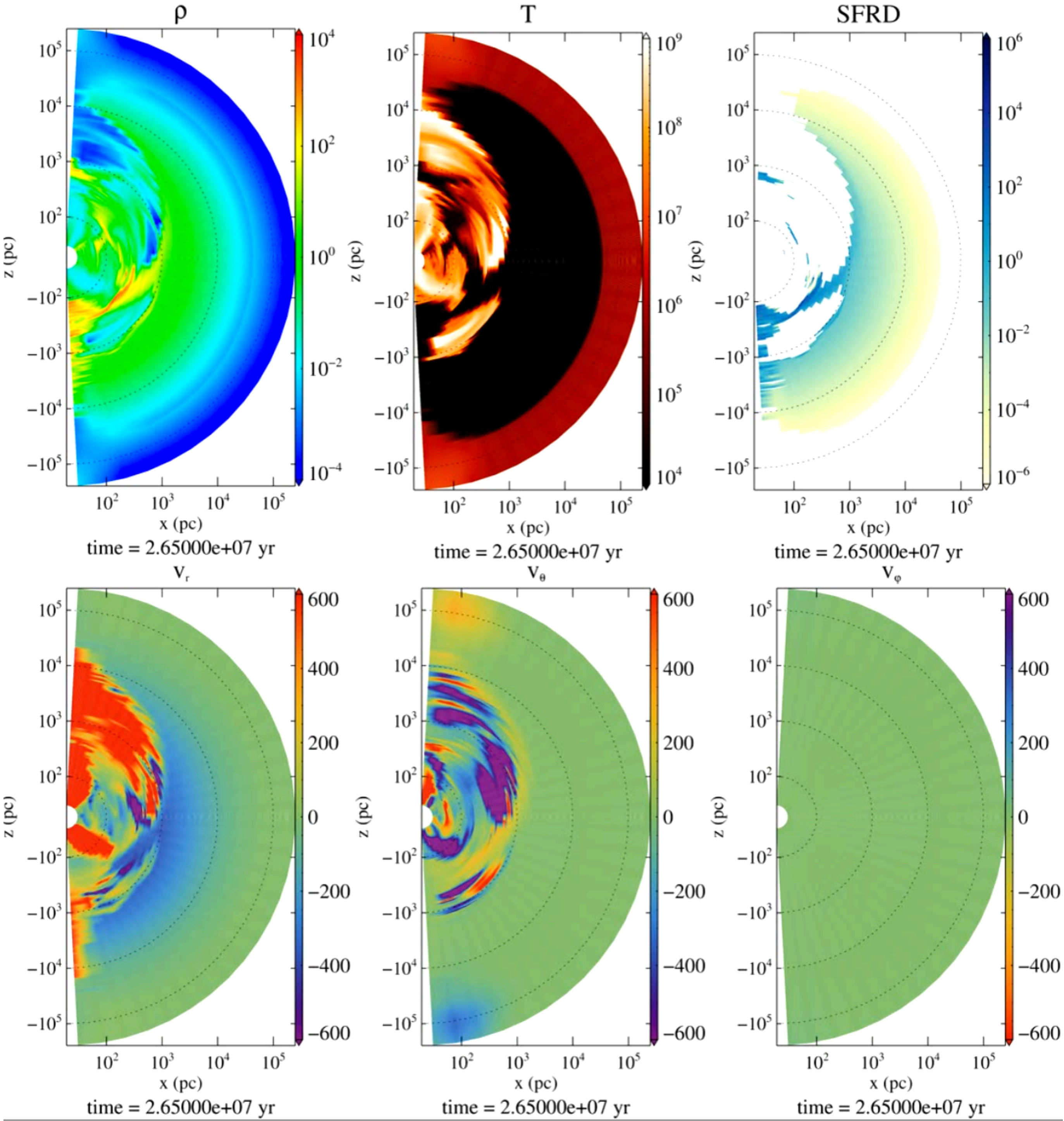


FIG. 4.— Simulation snapshot showing the final stages of a major accretion event. A hot, expanding bubble of gas extends to 100 pc, shutting down further SMBH accretion. Dense, overlying gas has caused the initially bipolar BAL wind to become quasi-spherical. The hot bubble is breaking through the overlying gas in at the north pole, which will lead to a unipolar wind.

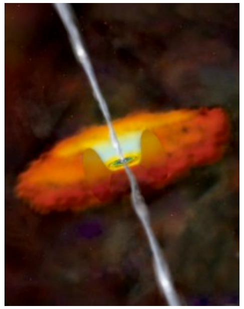
Novak et al 2012

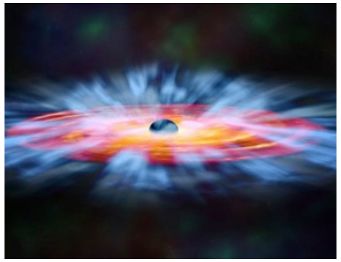


Complex interaction between feeding, feedback, star formation

Courtesy of A. Negri

Another example from simulations





Kinetic energy with bipolar outflow
Mass ejected with velocity 10 000 km/s (not really relativistic jet)

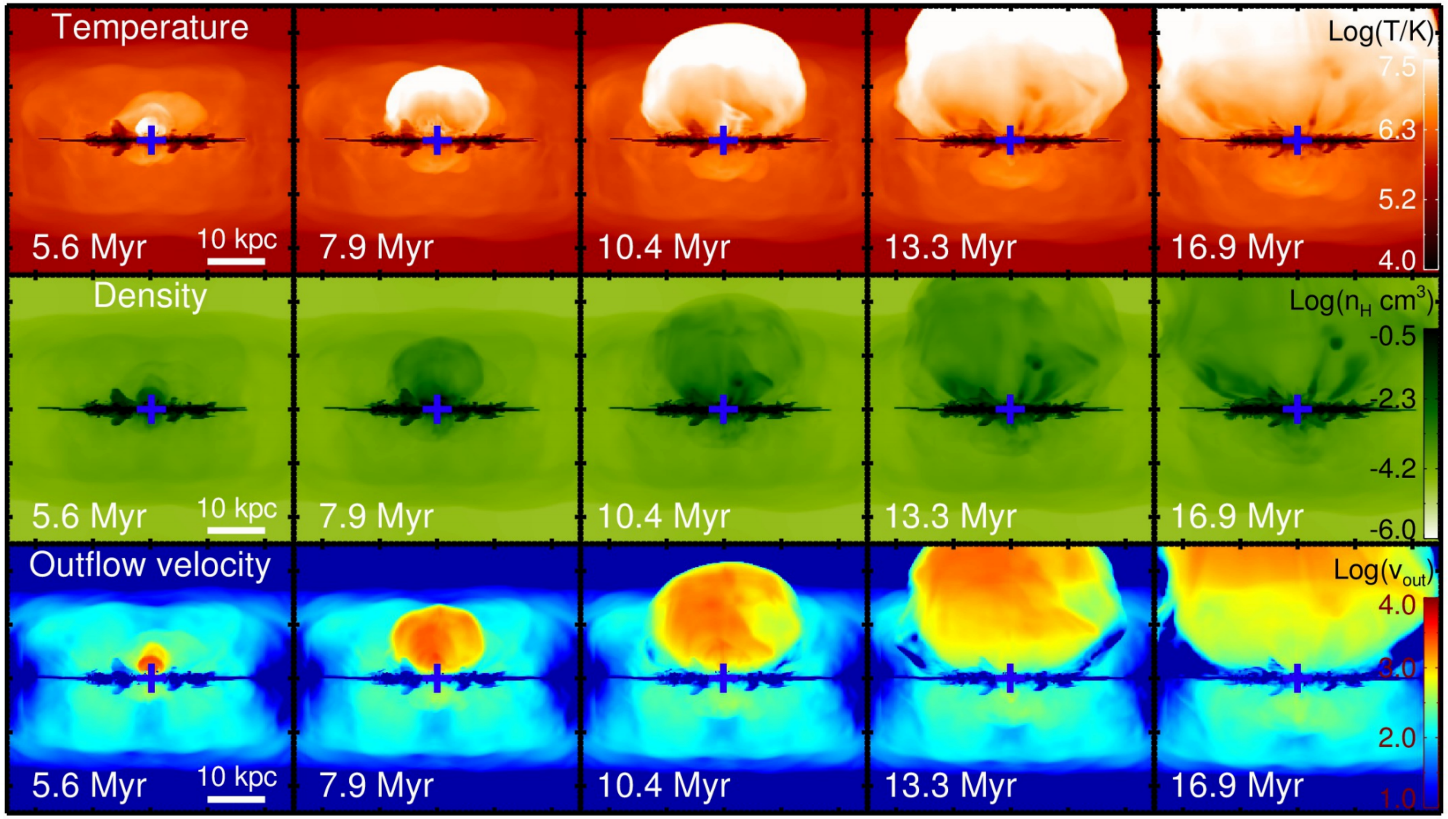
=> kinetic feedback

Modification of the internal energy

=> increase the gas temperature

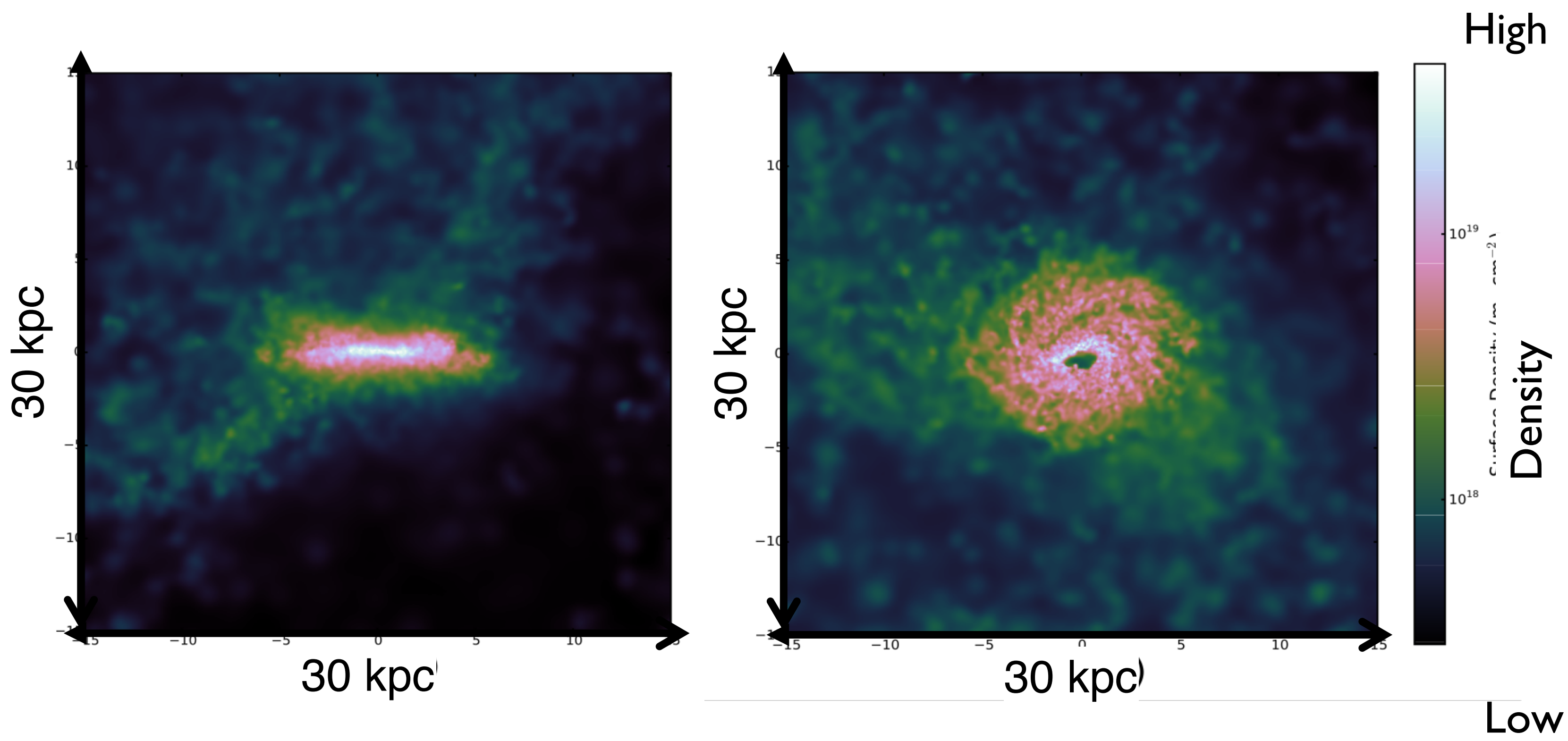
=> decreases star formation

AGN feedback does not destroy galaxies



Winds find the easiest path through low-density gas – avoid dense parts of the galaxy disc, leaving it unscathed (Gabor & Bournaud 2014, Roos+15)

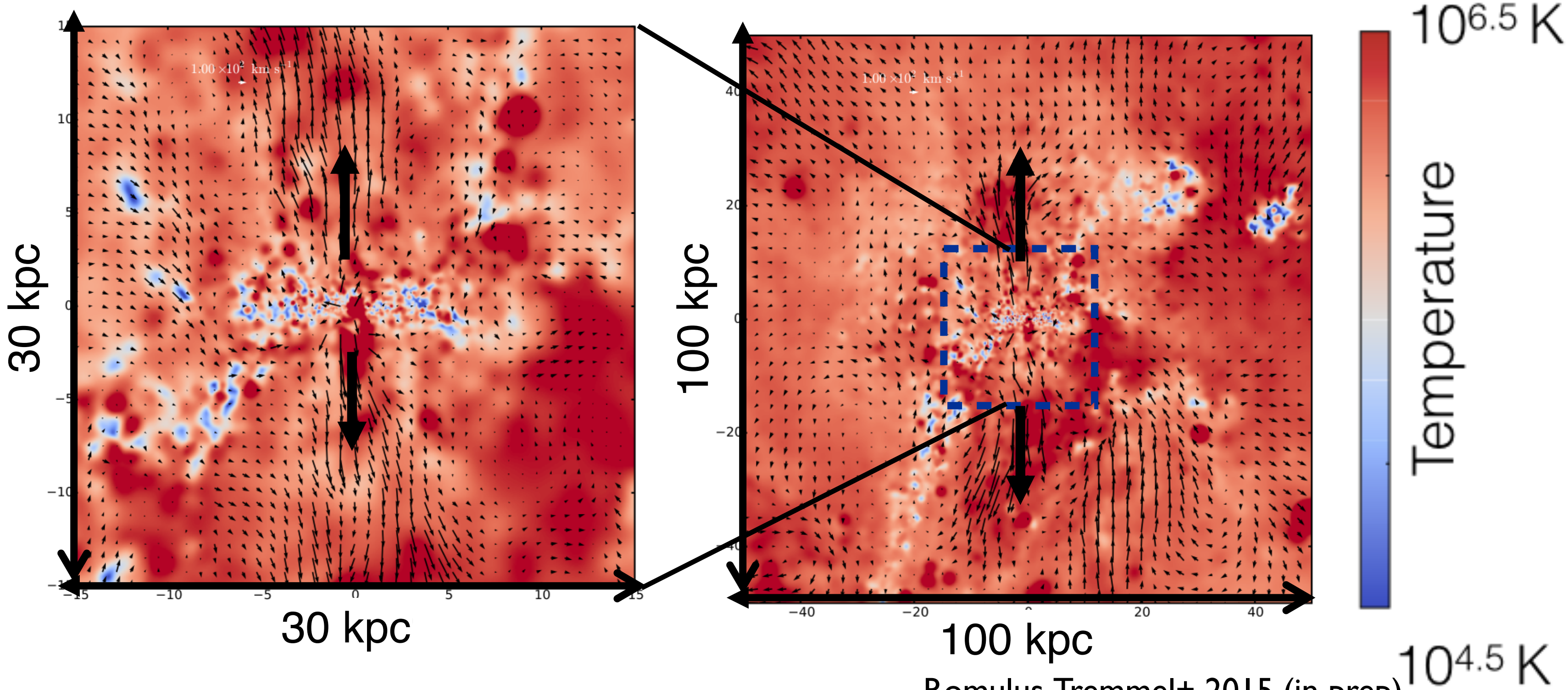
How do MBHs affect galaxies?



Romulus, Tremmel+ 2015 (in prep)

AGN feedback does not “blast away” galaxies, but prevents gas inflows (Dubois+2013, Costa+14, Tremmel+ in prep)

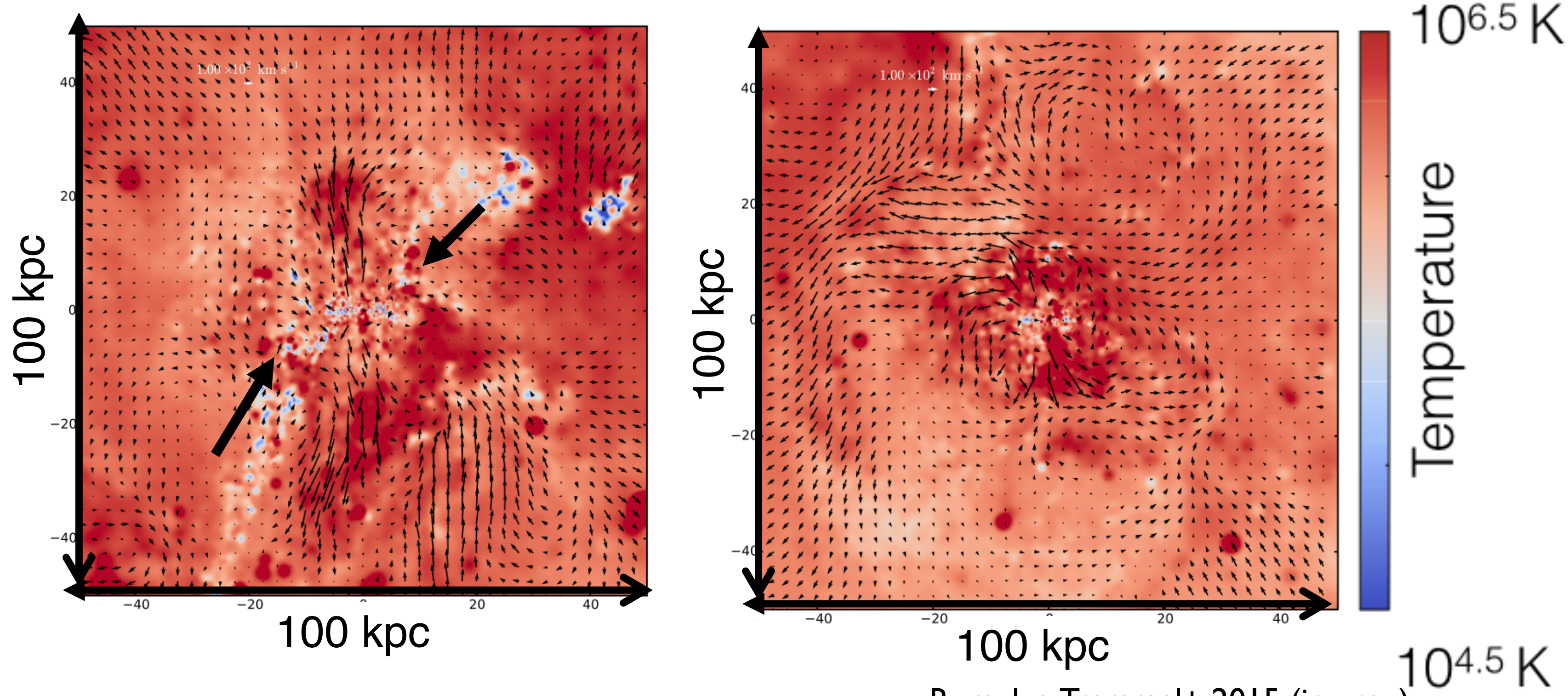
How do MBHs affect galaxies?



Romulus, Tremmel+ 2015 (in prep)

Active MBH creates large scale, polar outflow

How do MBHs affect galaxies?

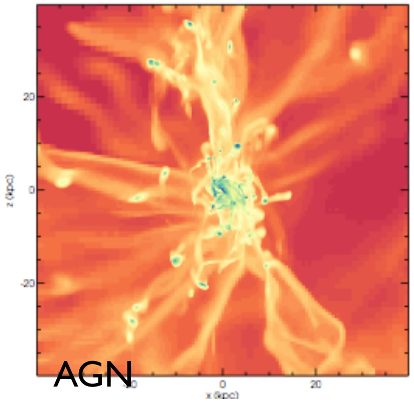


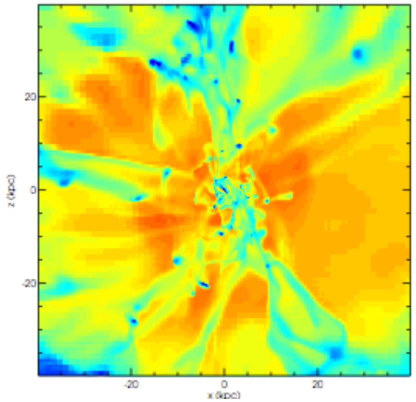
Romulus, Tremmel+ 2015 (in prep)

Cold CGM eventually destroyed, leaving a hot halo

How do MBHs affect galaxies?

no AGN

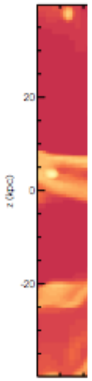


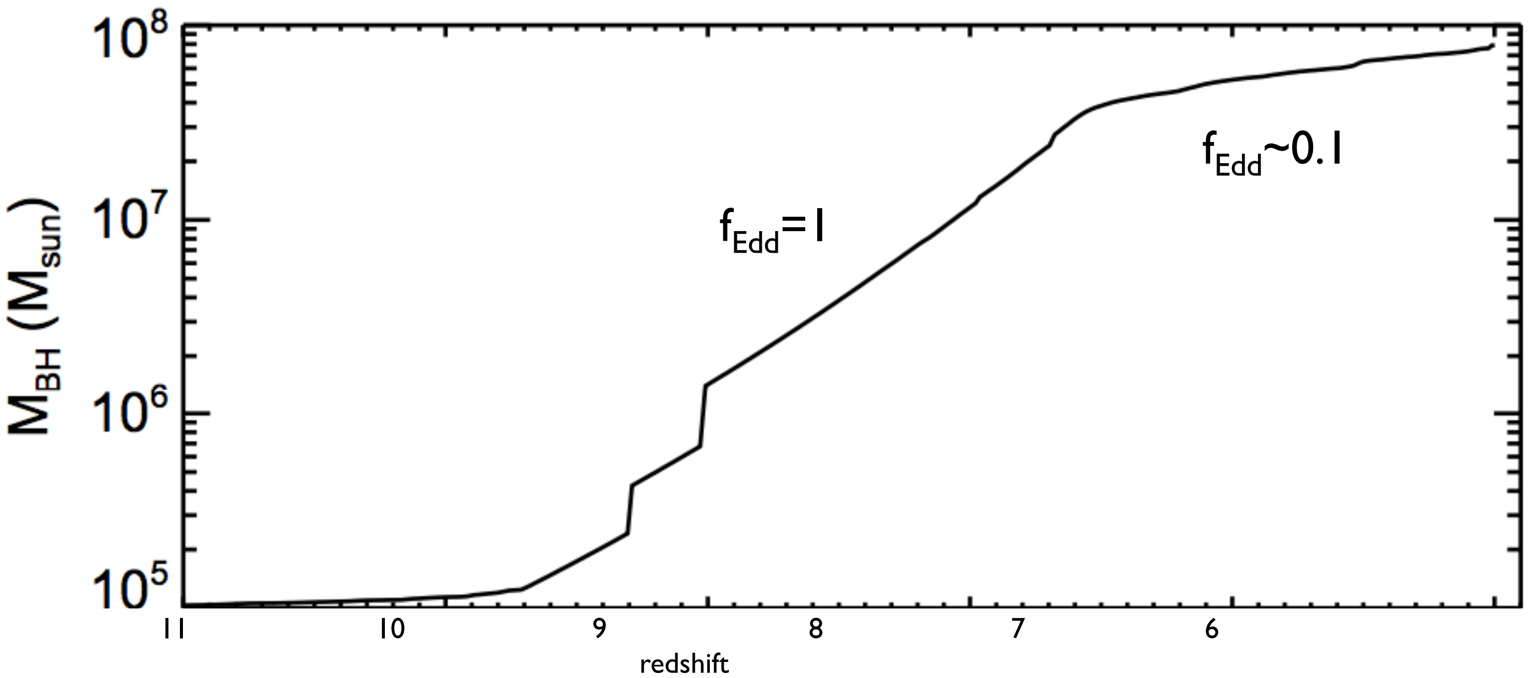


Cold filaments are strongly perturbed due to AGN energy injection

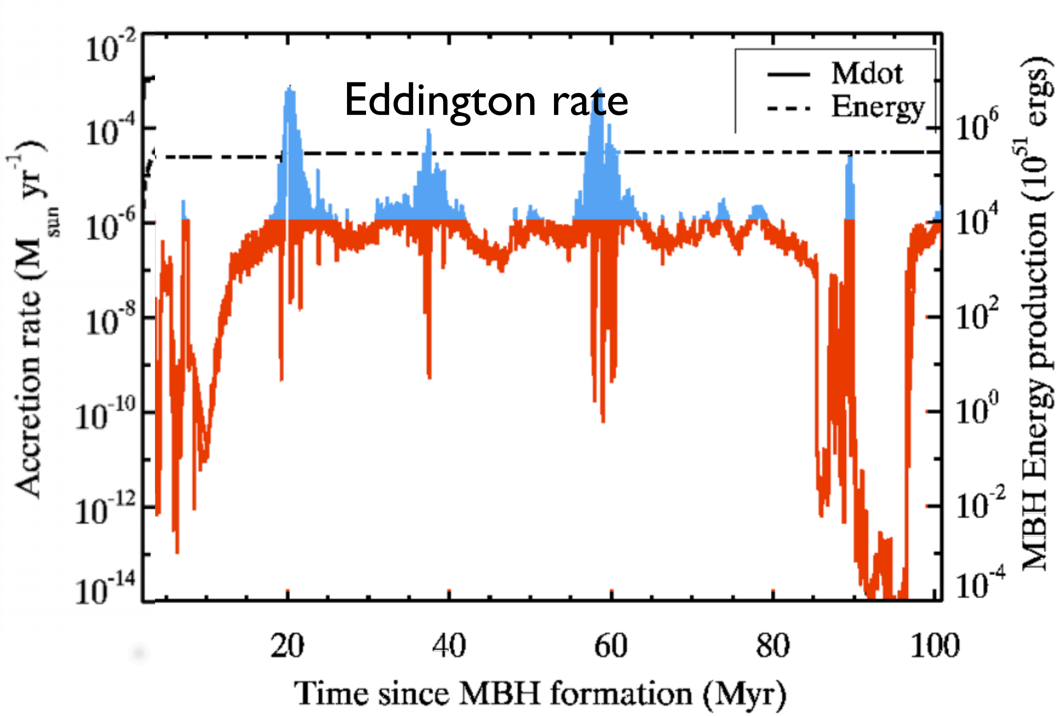
The growth of the MBH slows down as the galaxy does not receive fresh

AGN





How do MBHs affect MBHs ?



ENZO cosmological zoom, Δx=3.6 pc
$M_{vir}=2.2\times10^8 M_\odot$,
$M_{BH}=5\times10^4 M_\odot$ at z=15

Include X-ray feedback

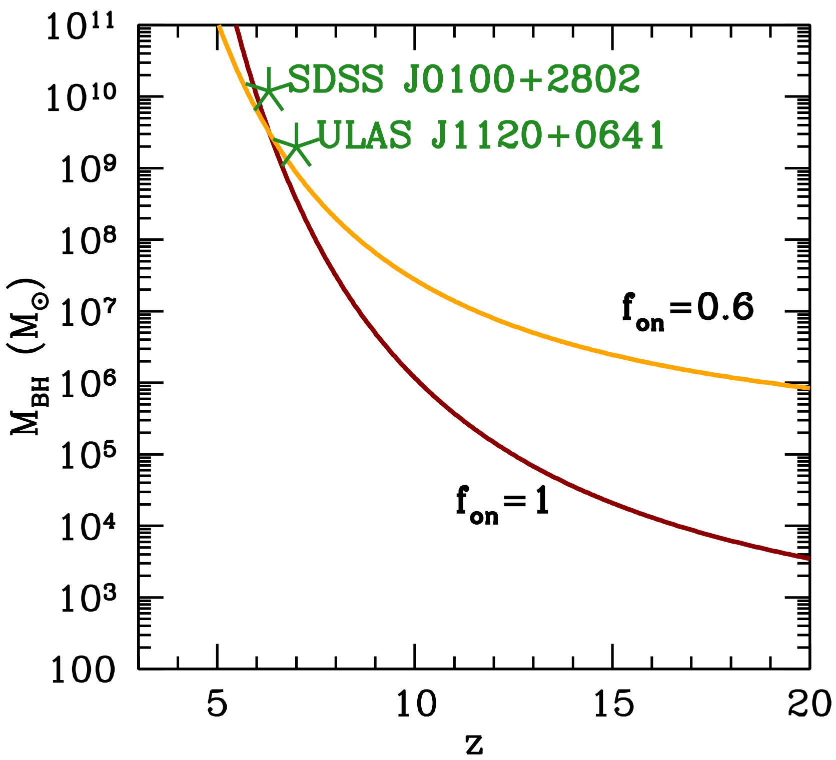
~10-20% of Eddington rate

AGN feedback from seed MBHs may stunt their early growth (Alvarez+2009; Aykutalp+14)

High-redshift quasars

Very bright quasars in the SDSS with z>6 (Willott et al., 2003; Fan et al., 2006; Jiang et al., 2009)

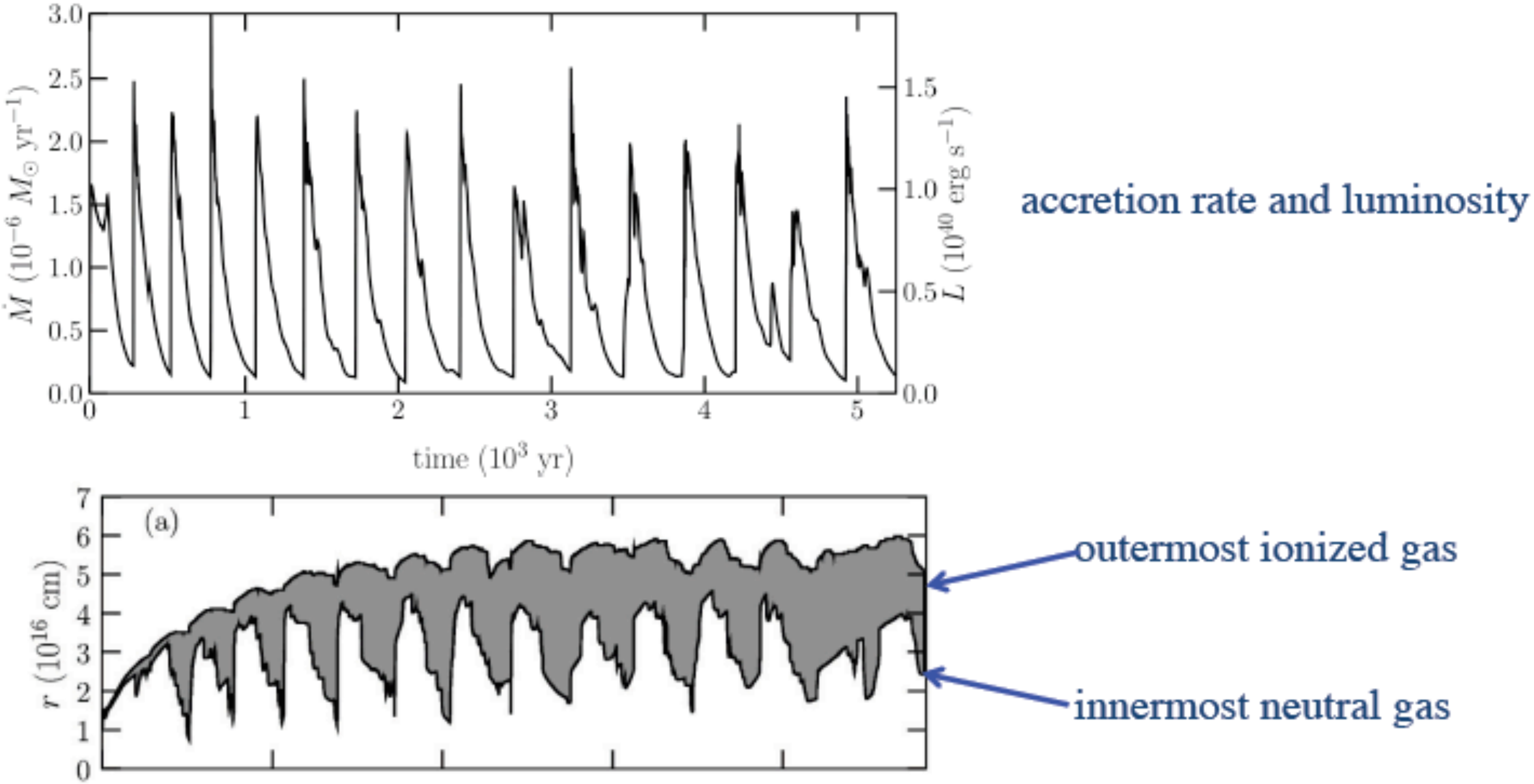
Detection of a $2x10^9$ M_{sun} BH at z=7 and a 10^{10} M_{sun} BH at z=6.3 (Mortlock et al., 2011, Wu et al. 2015)



<u>Requirement</u>:

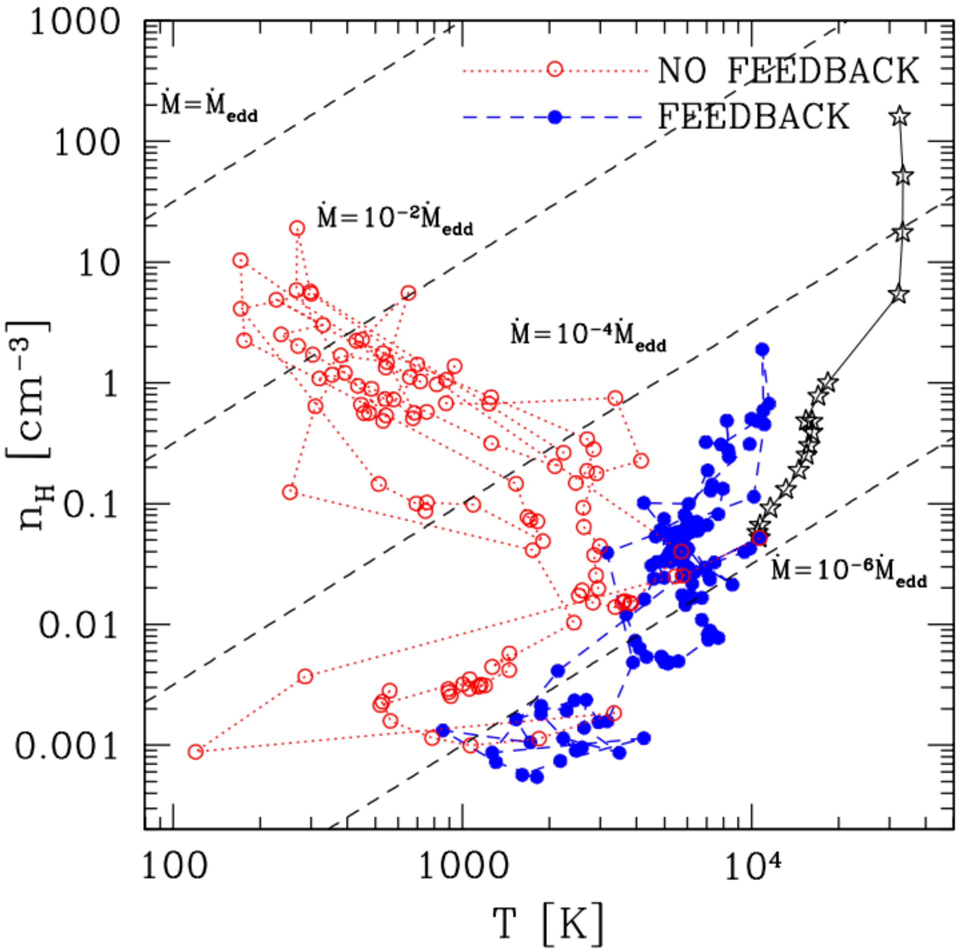
- Need to grow at the Eddington limit for the whole time (M_0~300 M_{sun}) or 60% of the time (M_0~$10^5 M_{sun}$)

~100 Msun MBH seed



Milosavljevic et al 07

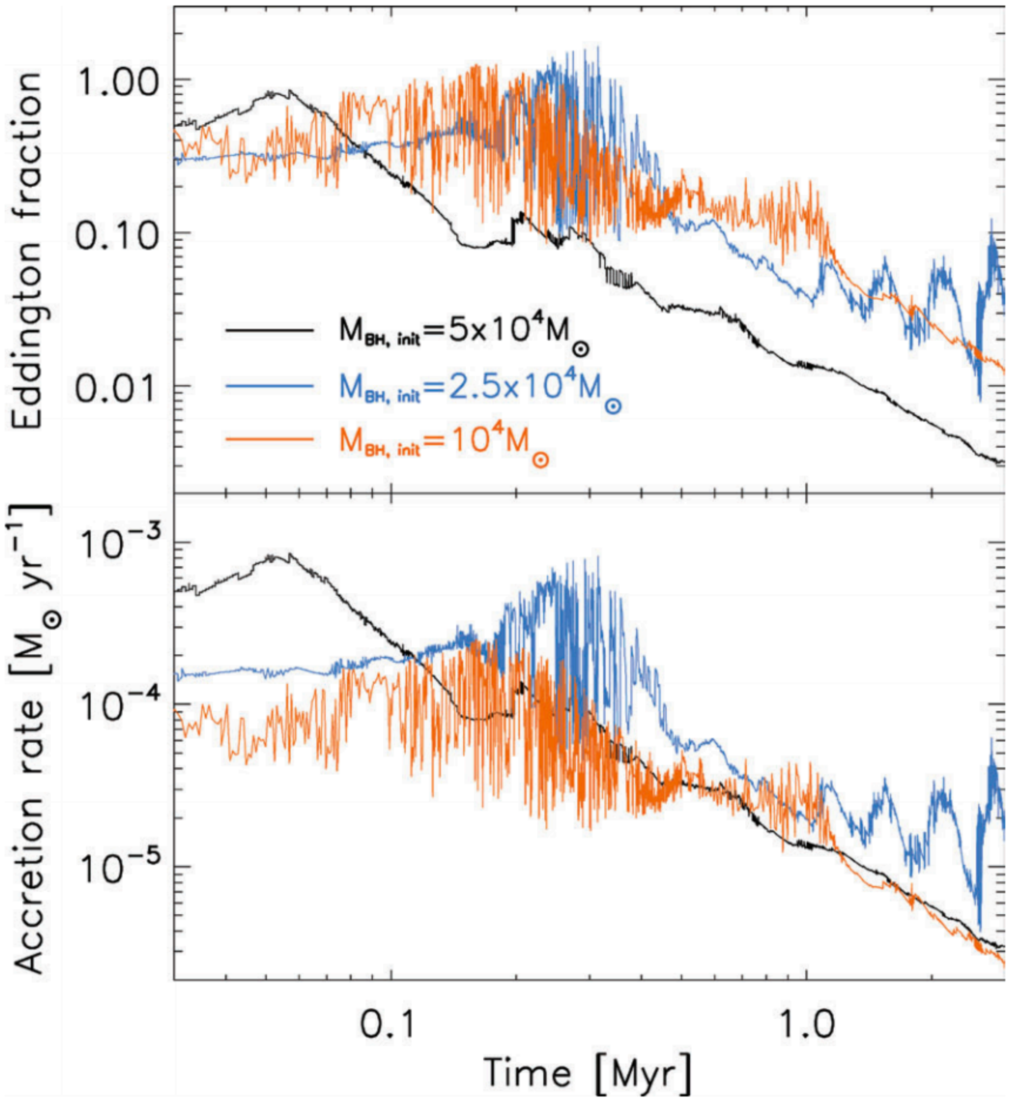
~100 Msun MBH in a ~10^5 Msun halo



~0.1 pc resolution

Alvarez et al. 2009

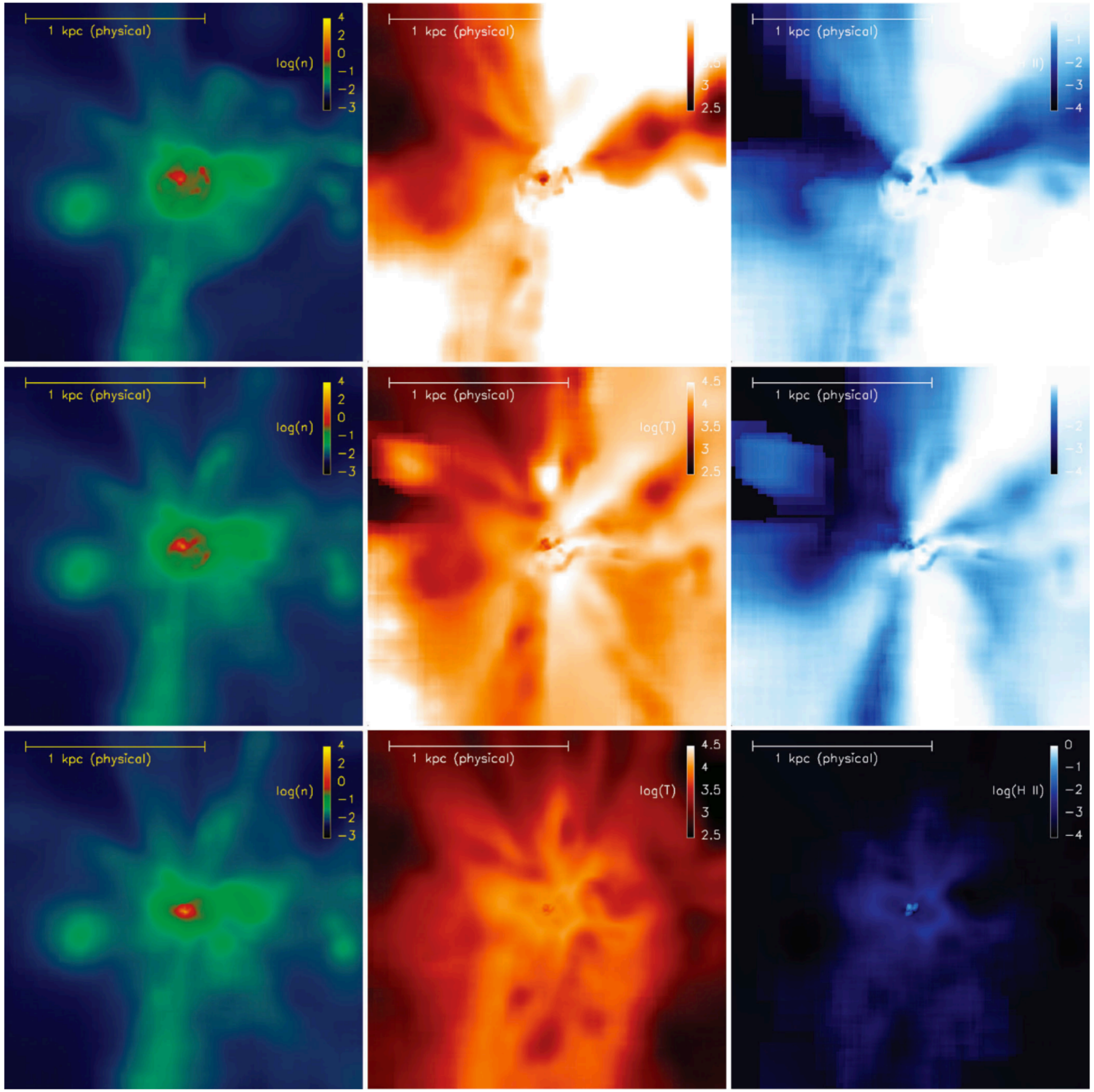
~10^4 Msun MBH in a ~10^7 Msun halo



~0.1 pc resolution

Johnson et al. 2011

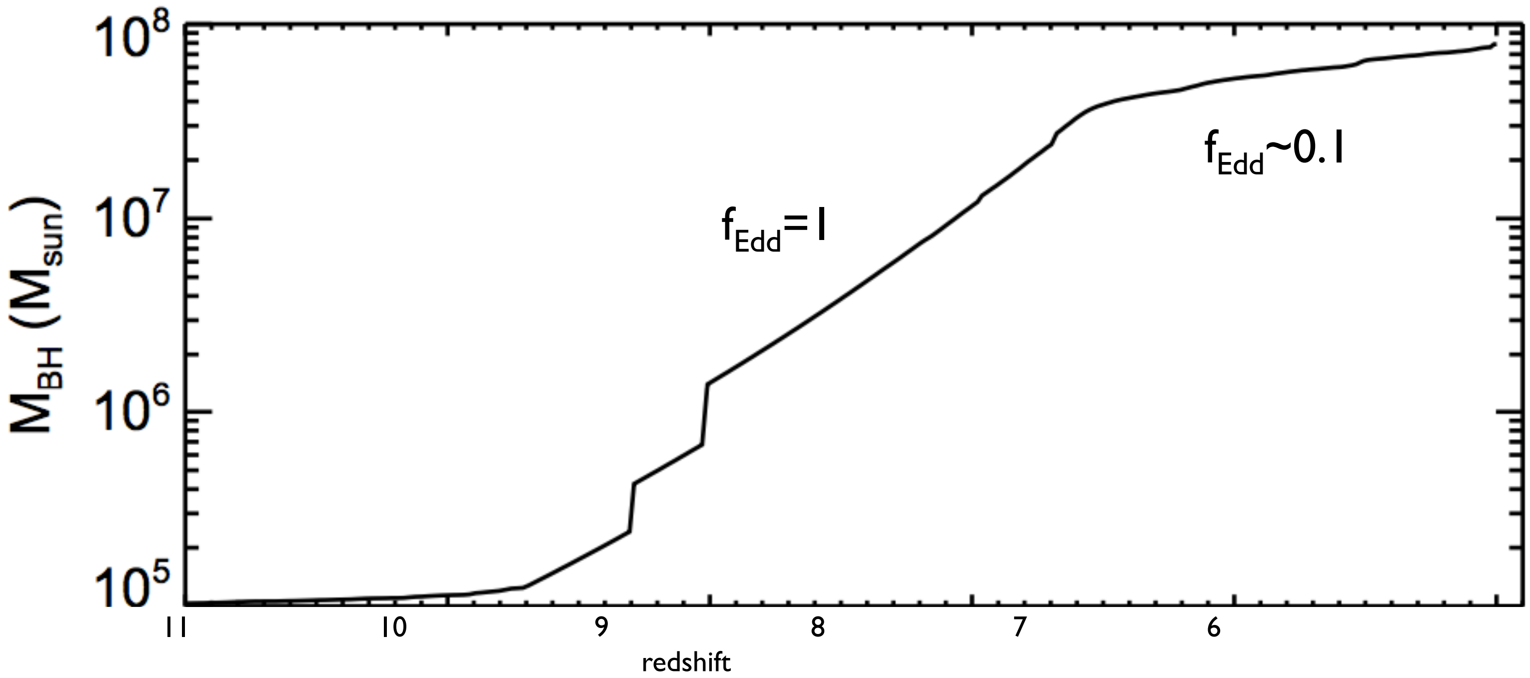
~10^4 Msun MBH in a ~10^7 Msun halo



Projected number density (left), density-weighted temperature (middle) density-weighted H II fraction (right)

Johnson et al. 2011

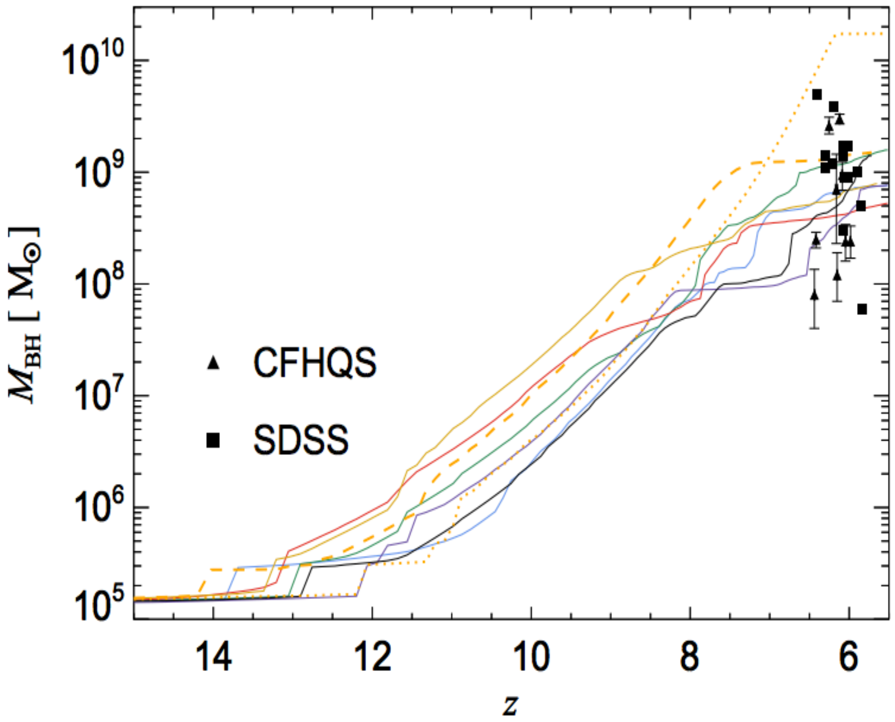
~10^5 Msun MBH in a ~10^{10} Msun halo



~10 pc resolution

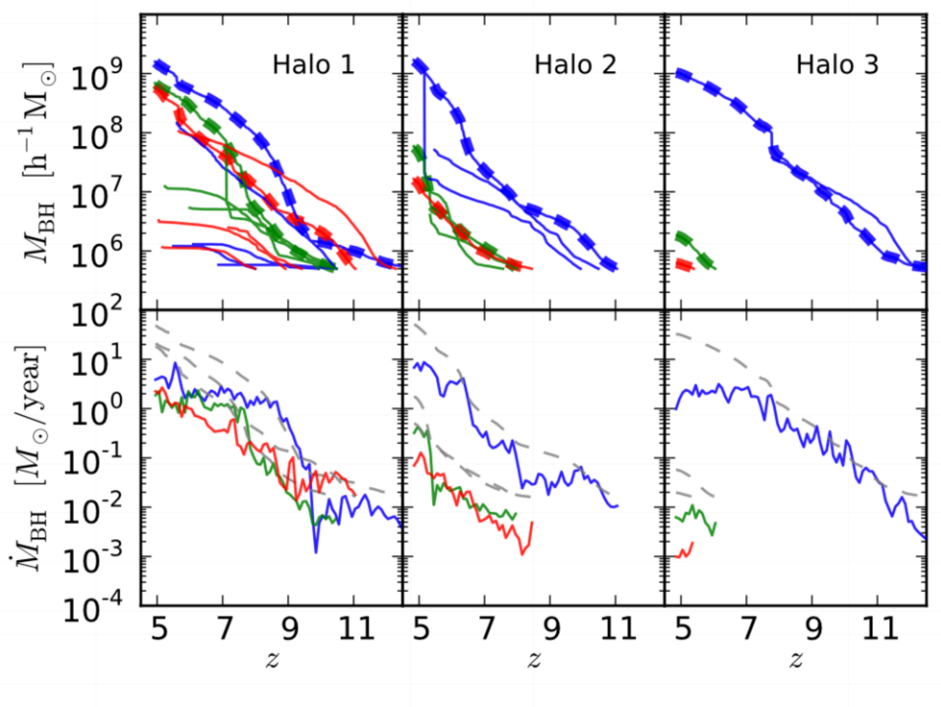
Dubois et al. 2013

~10^5 Msun MBH in a ~10^{10} Msun halo



~550 pc resolution

Costa et al. 2013



~300 pc resolution

Feng et al. 2014

How do MBHs affect MBHs ?

I am still confused, but:

- MBHs seem to grow only once the halo/galaxy is sufficiently massive

- Before that AGN (and SN) feedback thwart the growth of the MBH

Summary

1. High-z quasars and MBHs
    - currently limited to the brightest quasars, most massive BHs
    - need to find lower luminosity/mass MBHs to understand formation and early growth
    - JWST/ATHENA/SKA will help!

2. How do MBHs form?
    - Still unclear
    - Seed masses between 100-10^5 Msun

Summary

3. The high-z largest MBHs grow by (from high- to low- redshift):
   - Cold flows
   - Clumpy discs
   - Galaxy mergers
   - Secular instabilities

4. High-z MBHs and galaxies
   - MBH-galaxy relationships: change?
   - Bulge/galaxy mass, gas/stellar velocity dispersion?
   - Need to compare apples to apples

Summary

5. AGN feedback
   - How do energy/momentum/radiation from the MBH couple to the gas?
   - How does AGN feeding/feedback work on sub-parsec scales?