The first black holes

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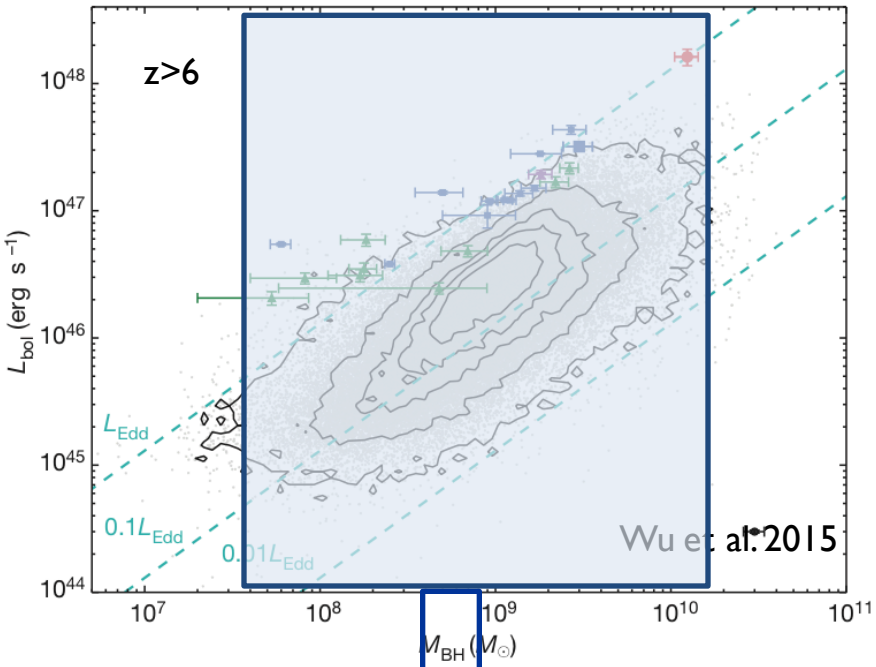
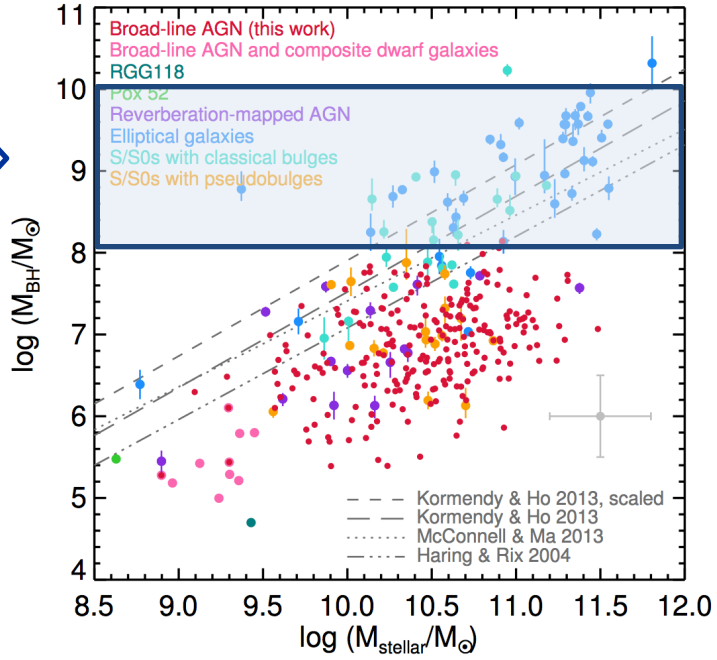
High-redshift quasars and local MBHs



As massive as the largest MBHs today, but when the Universe was ~ Gyr old



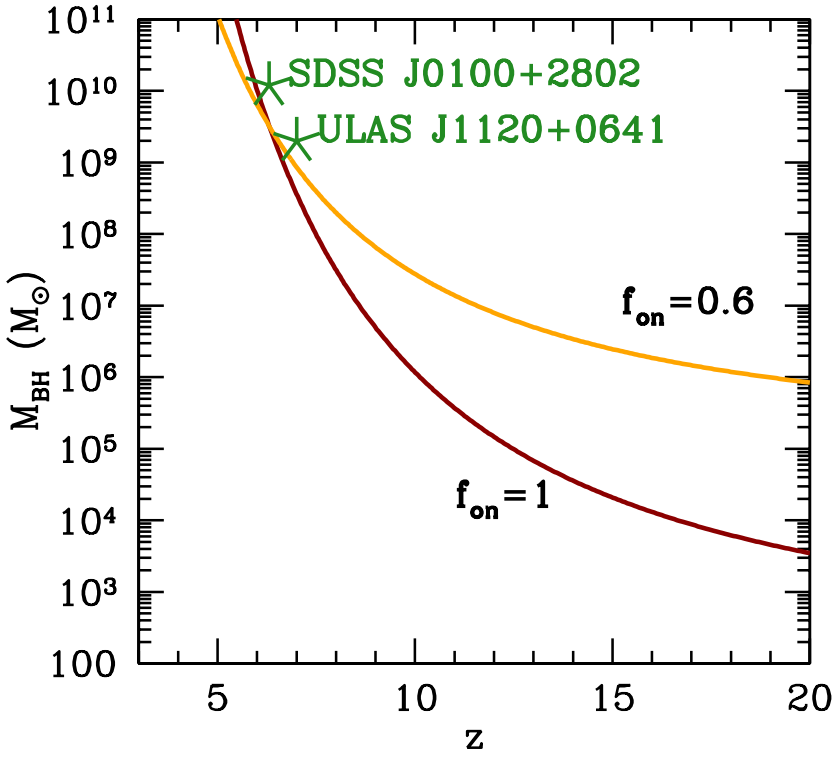
POX 52, NGC 4395: stellar mass 4×10^8 M_{sun}, MBH mass 3×10^5 M_{sun}

Galaxies without MBHs too

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 2×10^9 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)



Requirement:

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

Eddington limit?

Gas infalls from the galaxy: how does the galaxy know that it has to feed the MBH *exactly* at the Eddington limit?

Super-Eddington *accretion* does not imply highly super-Eddington *luminosity*

Trapping of radiation: photons are advected inward with the gas, rather than diffuse out

Luminosity highly suppressed $L \not\propto \dot{M}$ $L \propto \ln(\dot{M})$

Only short periods needed to ease constraints (e.g. MV & Rees 2005; MV, Silk & Dubus 2015; Pacucci, MV et al. 2015a,b; Lupi et al. 2016)

High-redshift AGN

No detection in X-ray stacking of LBGs at z>6: $L_X<10^{42}$ erg/s (Willott 2011; Fiore et al. 2012; Cowie et al. 2012; Treister et al. 2013)

Searches for point sources in deep X-ray fields has also led to inconclusive results (Giallongo et al. 2015; Weigel et al. 2015; Cappelluti et al. 2015)

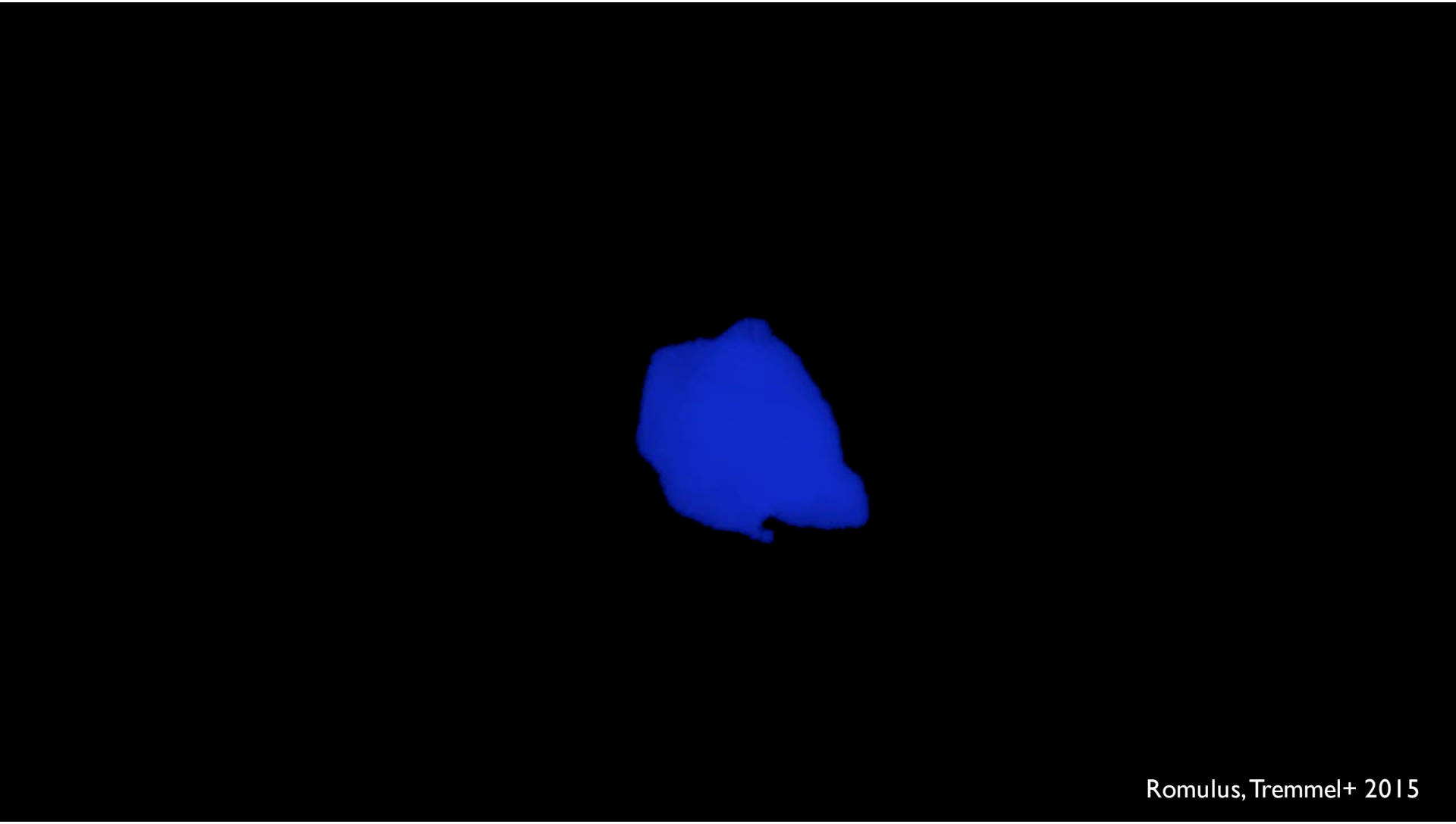
High-redshift MBHs

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

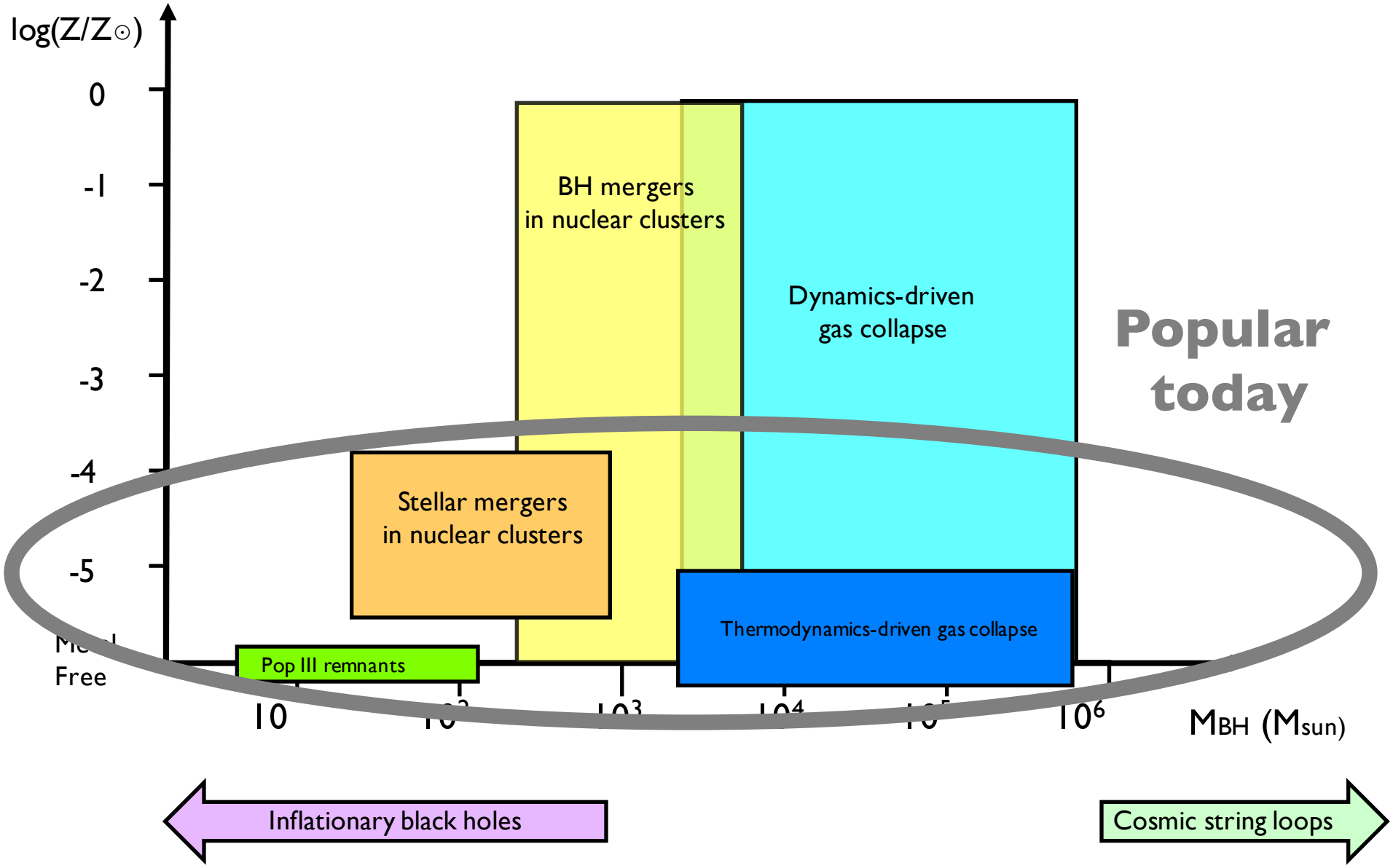
Very biased, dense halos

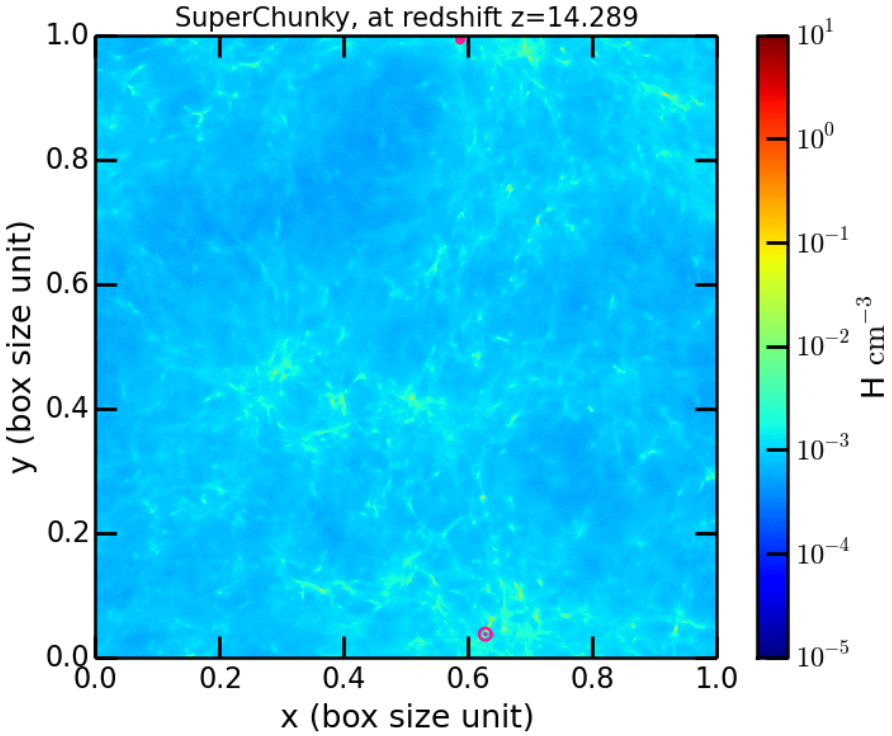
What do we expect for *normal* MBHs in *normal* galaxies?

Growing black holes in growing galaxies



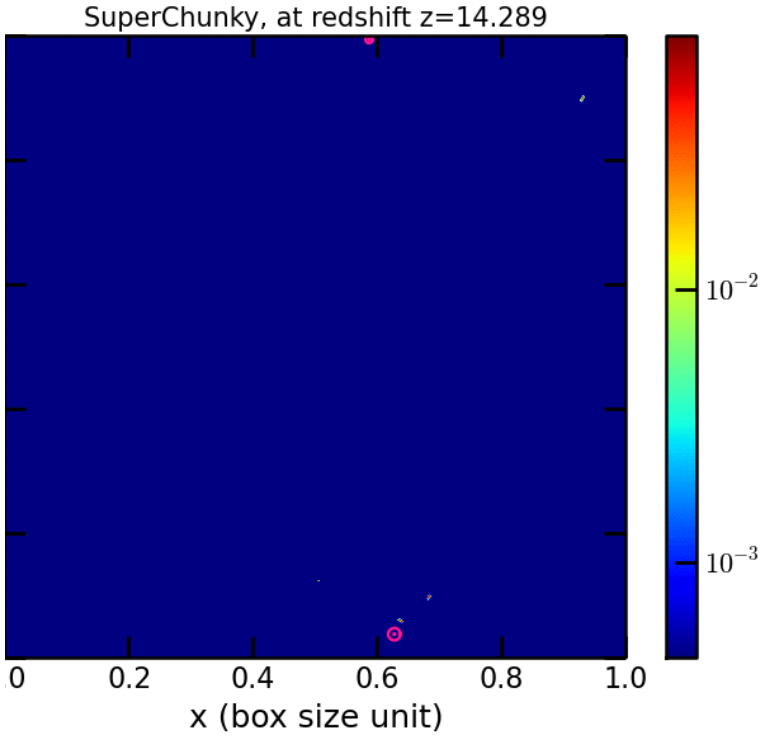
How do MBHs form?





Density map

BHs form only in high gas-density regions



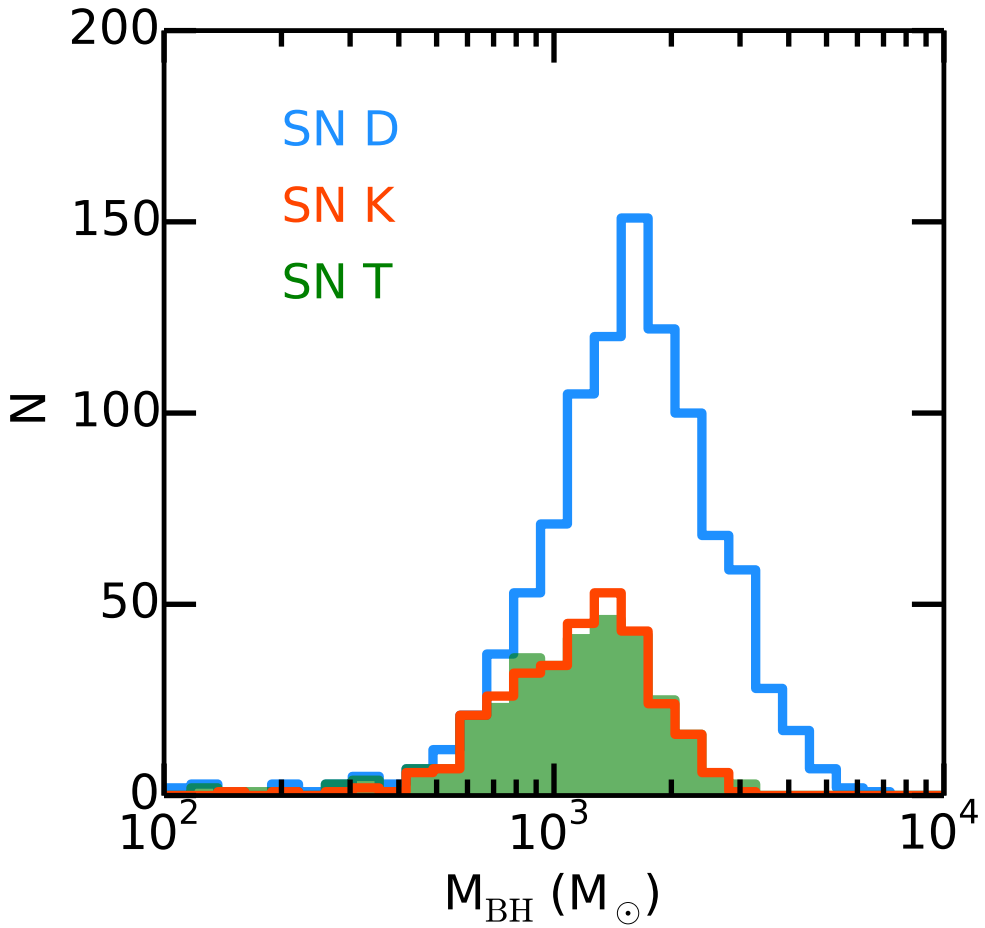
Metallicity map

BHs form in low-metallicity regions

Ramses 10 Mpc Cosmological Volume, ~80pc resolution

Habouzit, MV, Dubois 2016

How do MBHs grow in galaxies?



Initial mass function of "seed" MBHs

Ramses 10 Mpc Cosmological Volume, ~80pc resolution

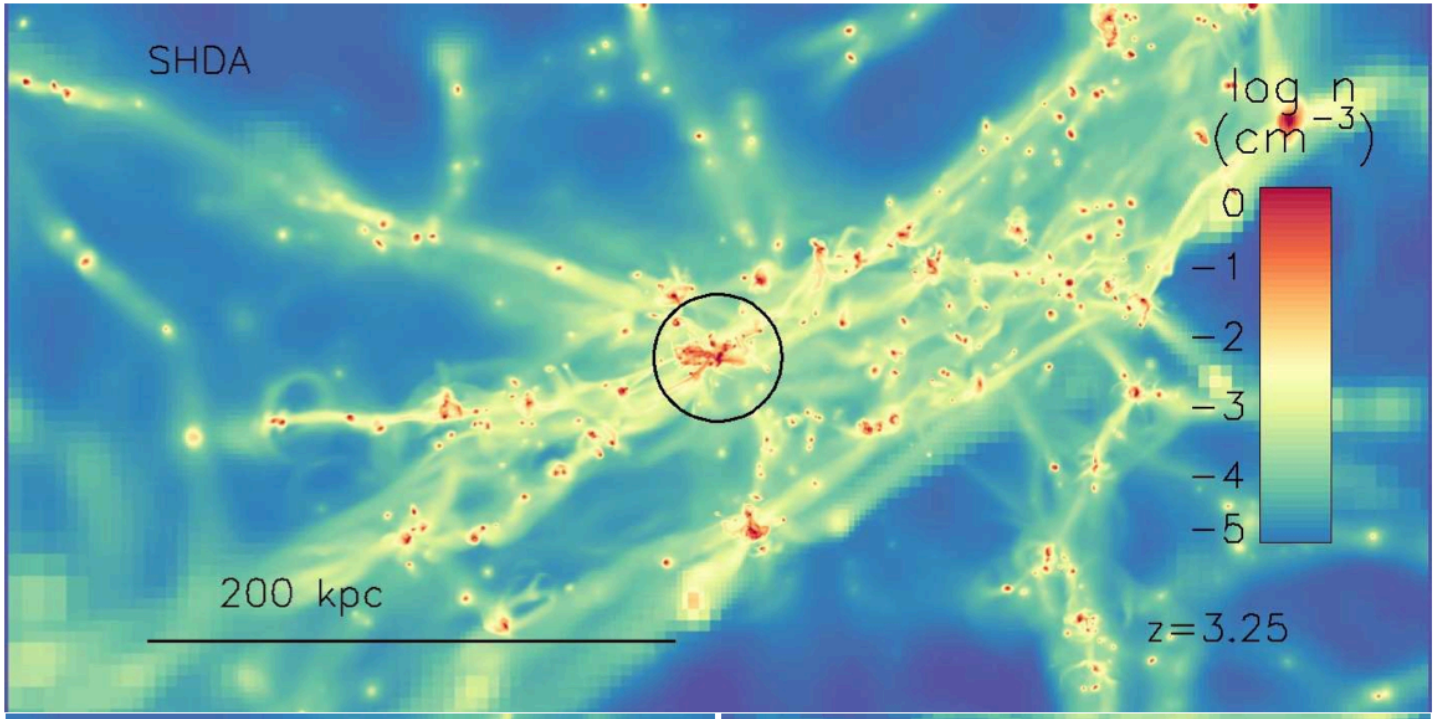
Habouzit, MV, Dubois 2016

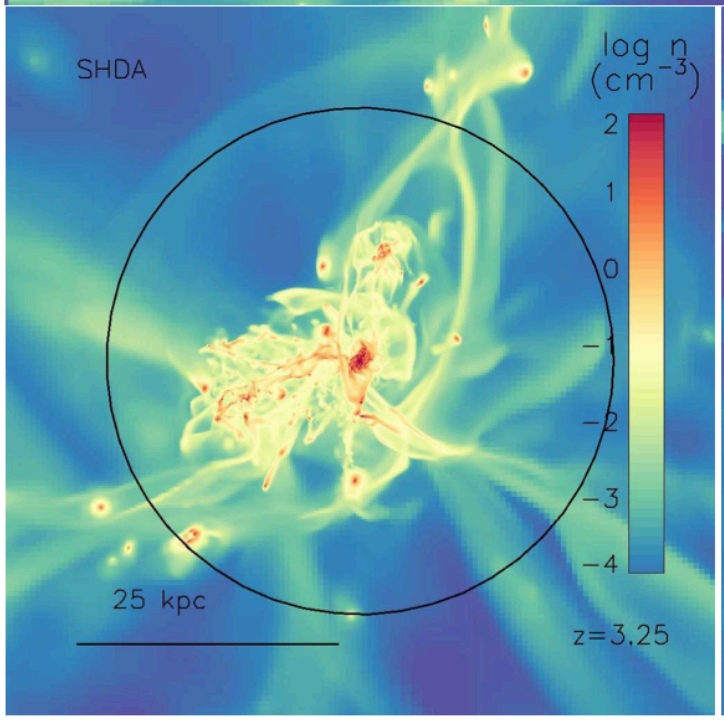
How do galaxies feed *normal* MBHs?

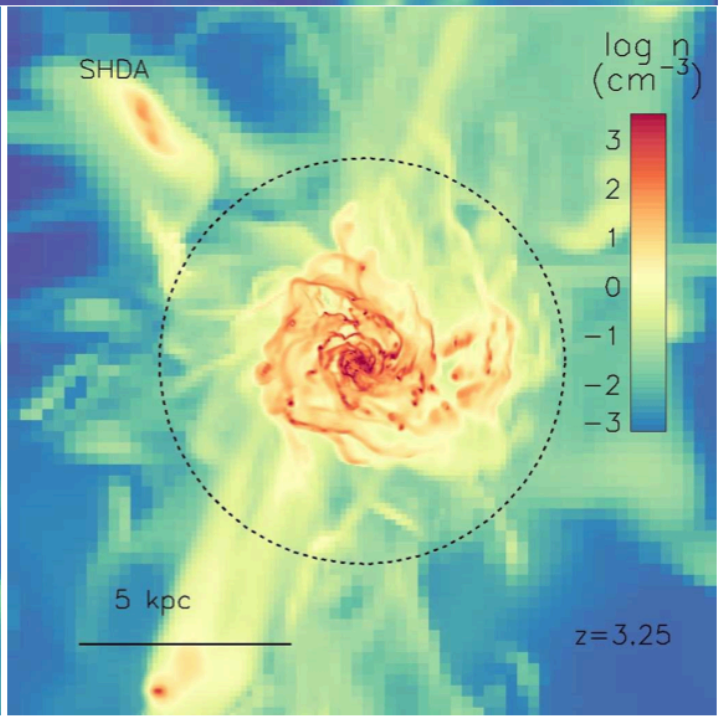
Low-mass BHs in low-mass galaxies: fragile environment

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

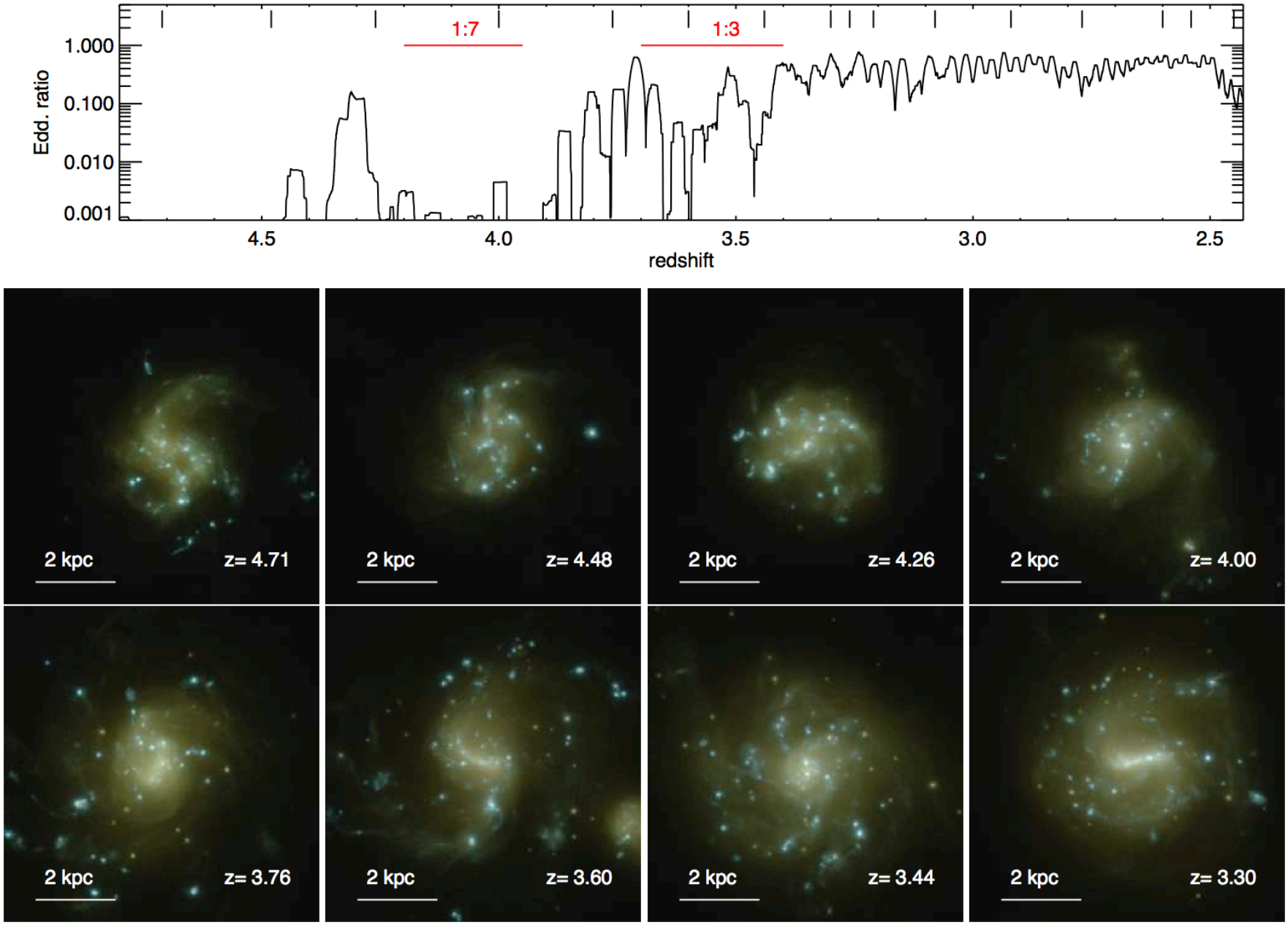
How do galaxies feed *normal* MBHs?





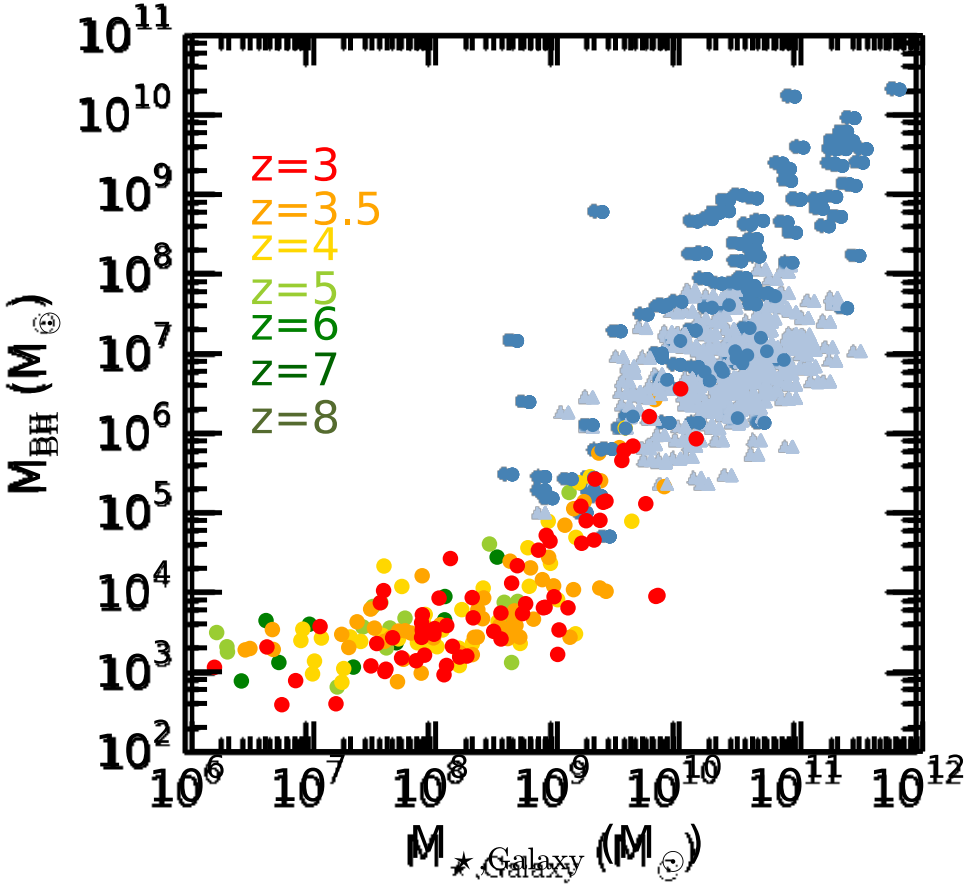


SETH
Ramses
Cosmological Zoom
~5pc resolution
Dubois+14



SETH, Ramses Cosmological Zoom, ~5pc resolution, Dubois, MV+14

How do galaxies feed *normal* MBHs?

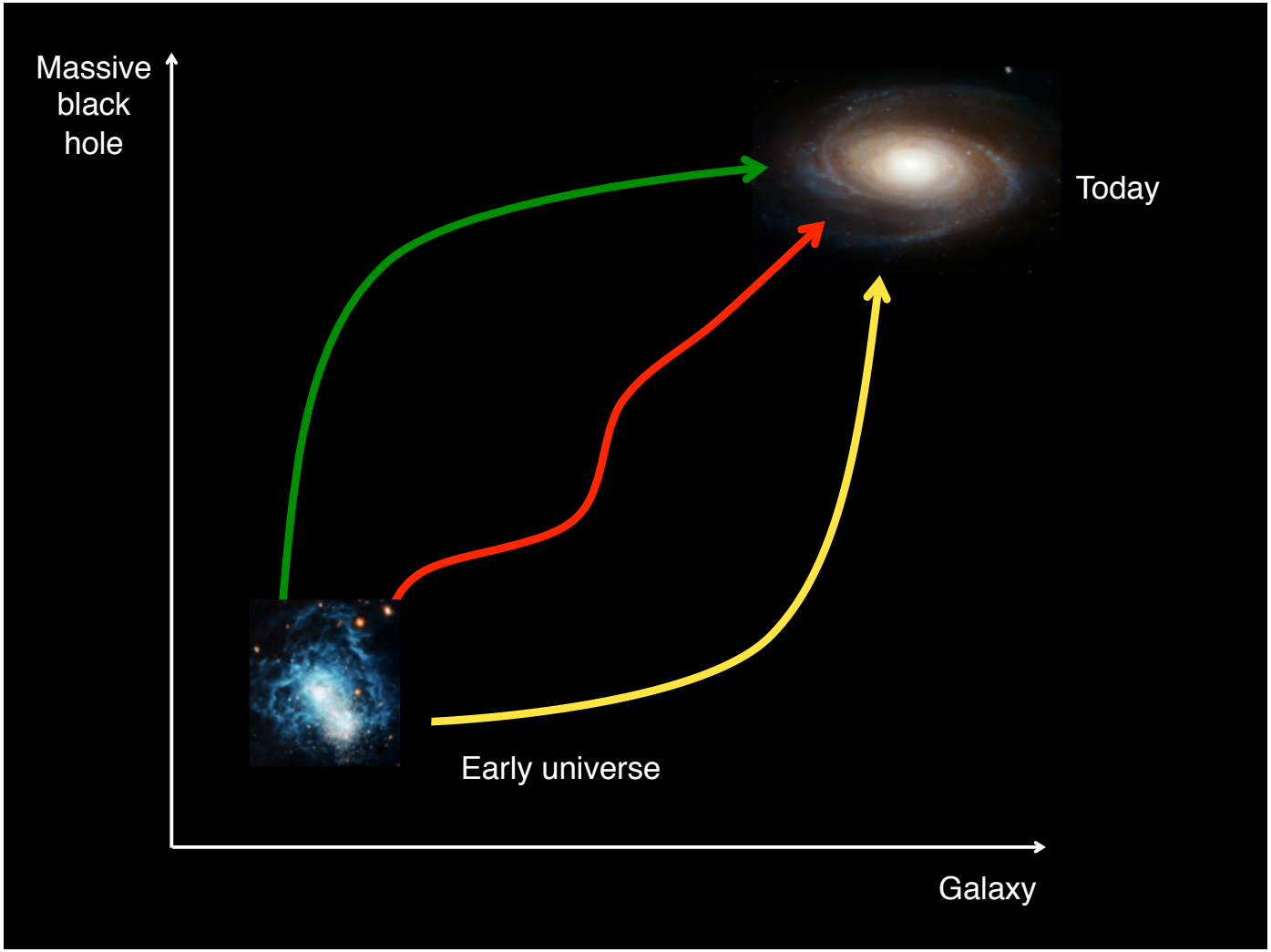


z=0 **BHs** and **AGN**
(Reines & Volonteri 2015)

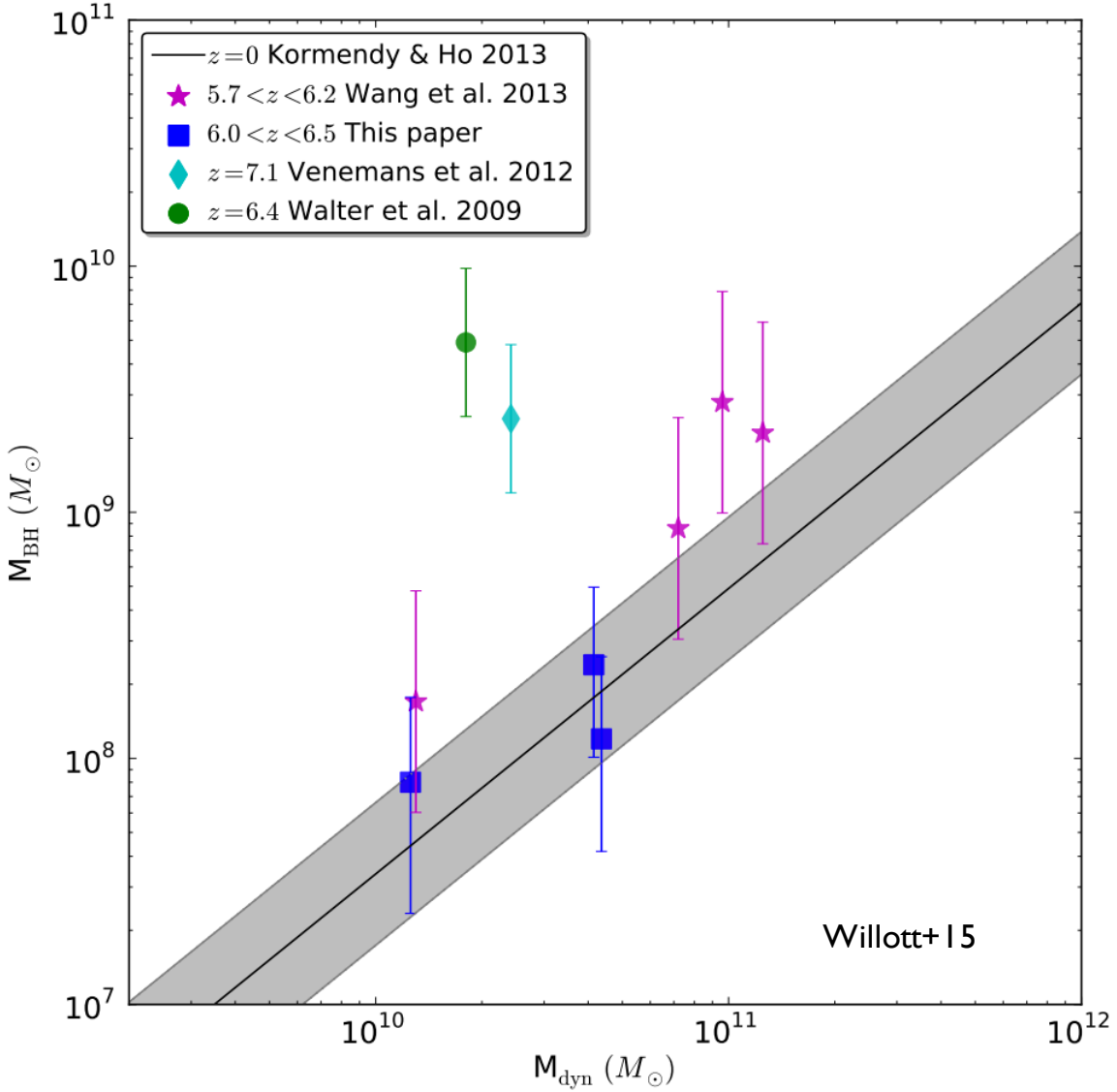
10 Mpc
cosmological volume,
~80pc resolution

Habouzit, MV, Dubois 2016

Growing black holes in growing galaxies



M_{BH} vs galaxy at high redshift



Host galaxy cannot be imaged – use radio maps of CO that traces cold gas => dynamical masses from line widths and beam size

Are MBHs over-massive at high redshift?

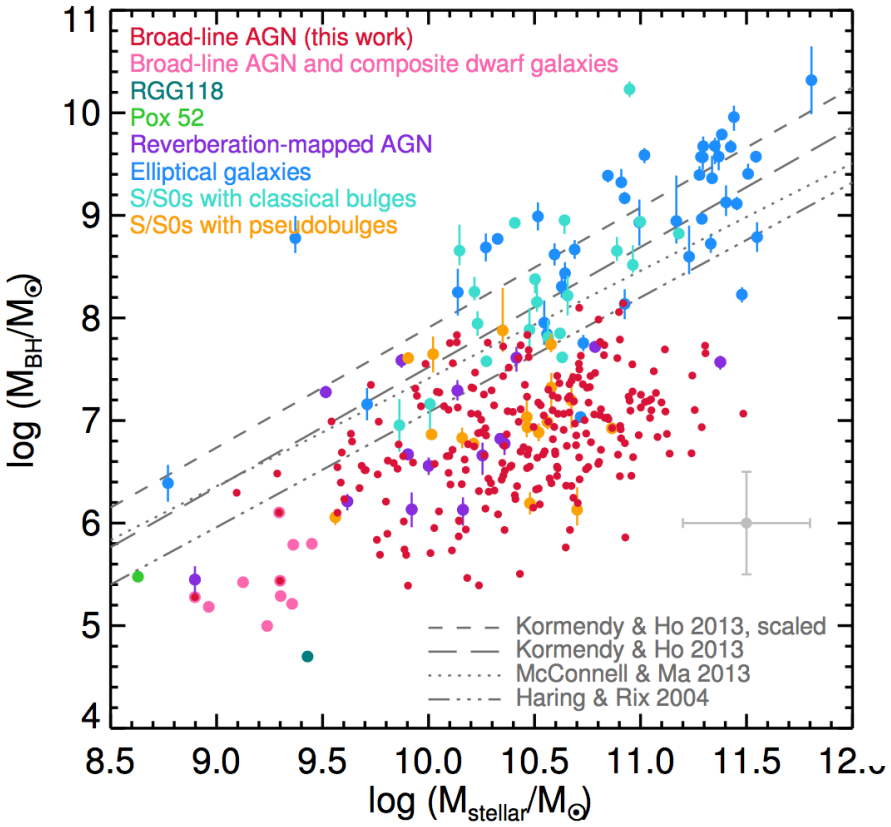
Assume an intrinsic scaling of MBH with galaxy mass

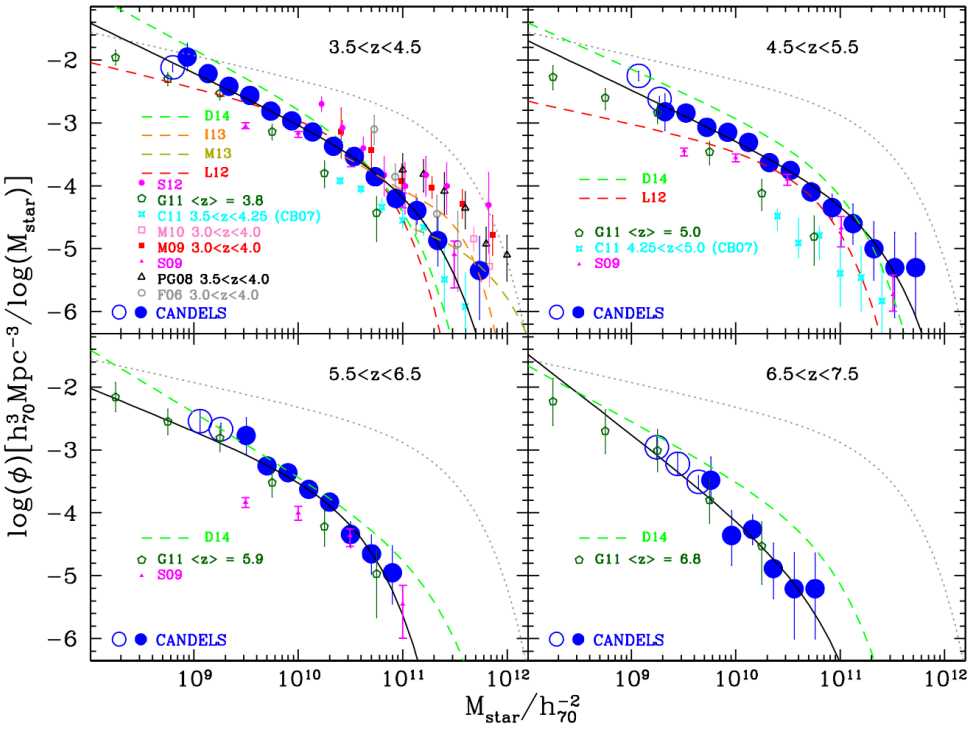
We measure galaxy mass functions out to z~7

We can estimate MBH properties from the convolution of galaxy mass functions and MBH-galaxy mass relations

$$\phi_{BH} = \phi_{gal} \frac{dM_{gal}}{dM_{BH}}$$

M_{BH} vs galaxy at high redshift





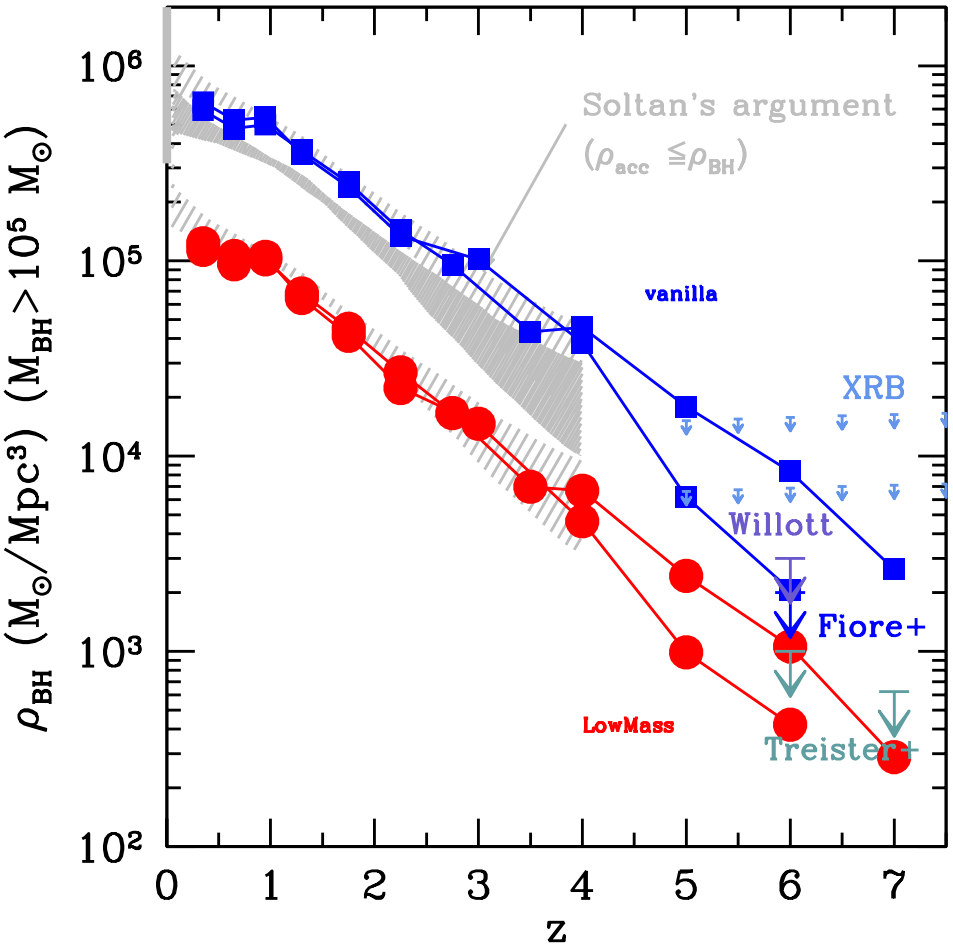
vanilla: M_{BH}~10^{-3} Mgal

low mass: M_{BH}~10^{-4} Mgal

$$\phi_{BH} = \phi_{gal} \frac{dM_{gal}}{dM_{BH}}$$

Reines & MV 2015; MV & Reines 2016

M_{BH} vs galaxy at high redshift



vanilla: $M_{BH} \sim 10^{-3}$ Mgal

low mass: $M_{BH} \sim 10^{-4}$ Mgal

$$\phi_{BH} = \phi_{gal} \frac{dM_{gal}}{dM_{BH}} \qquad \rho_{BH} = \int \phi_{BH} dM_{BH}$$

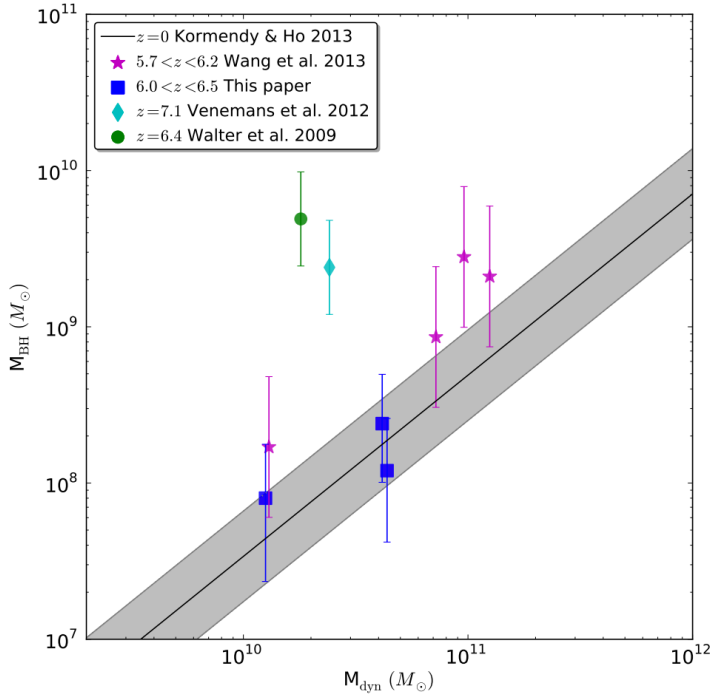
Caveat: uncertainties on the stellar mass function => MBH density dominated by MBHs in galaxies below the knee

Reines & MV 2015; MV & Reines 2016

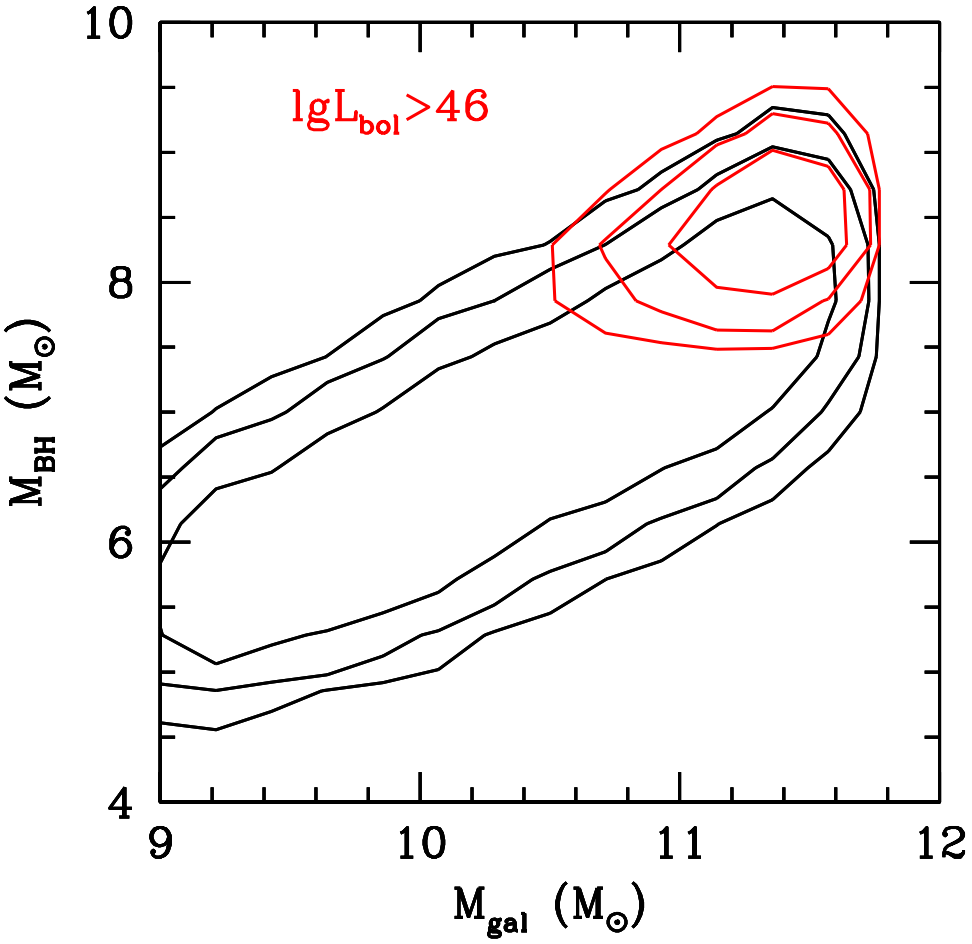
High-redshift MBHs

Current limits/candidates high-z AGN compatible with a population of MBHs similar to low-z counterpart in galaxies of similar mass

How about the high-z quasars?

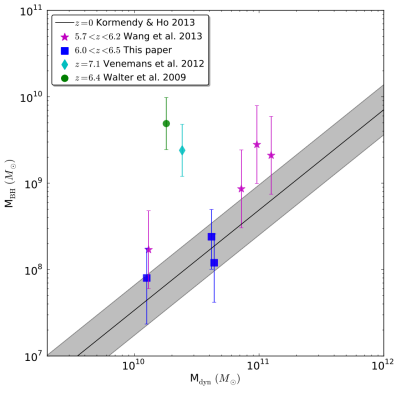


M_{BH} vs galaxy at high redshift



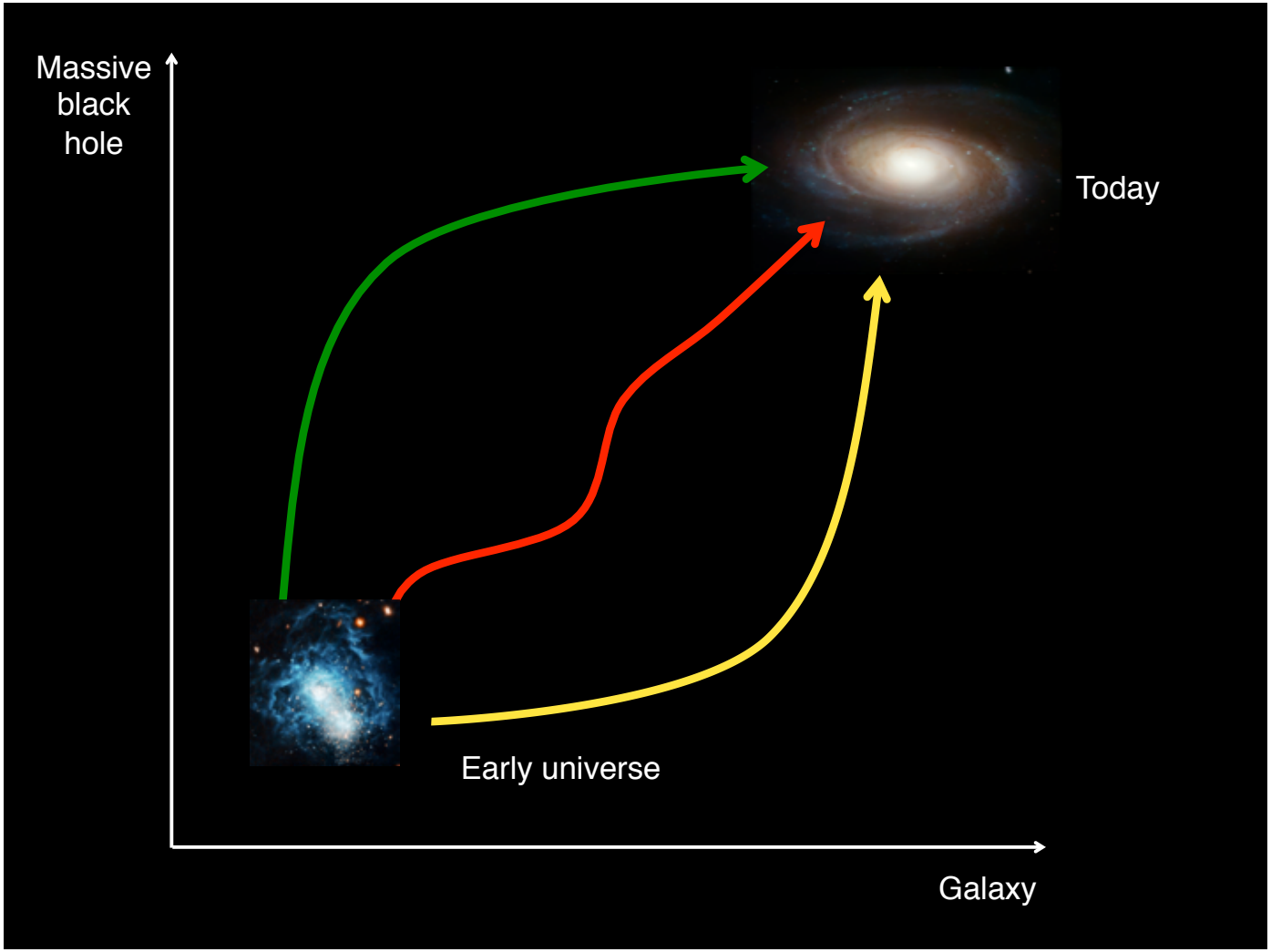
Current large-shallow surveys select only the most luminous quasars, $L_{bol}>10^{46}$ erg/s

$\Rightarrow$ the most massive holes at a given stellar mass



Lauer et al. 2007; MV & Stark 2011; MV & Reines 2016

Growing black holes in growing galaxies



Growing black holes in growing galaxies: contribution to reionization

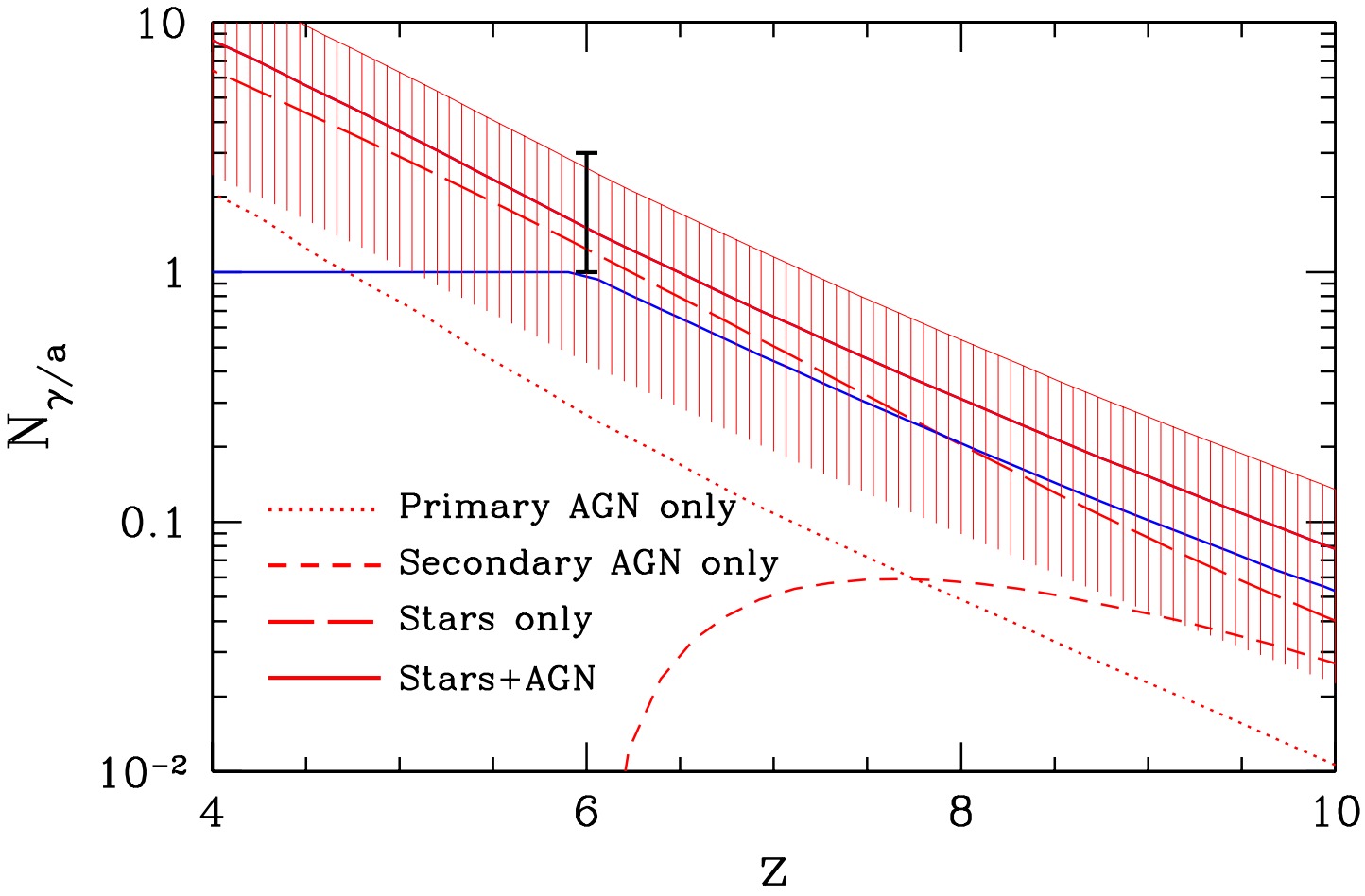
Galaxies form stars and emit ionizing photons

MBHs accrete and emit ionizing photons

Relative Role of Stars and Quasars in Cosmic Reionization

MBHs predicted to contribute 20-50% of ionizing photons (MV & Gnedin 2009)

Growing black holes in growing galaxies: contribution to reionization



MV & Gnedin 2009

High-redshift MBHs

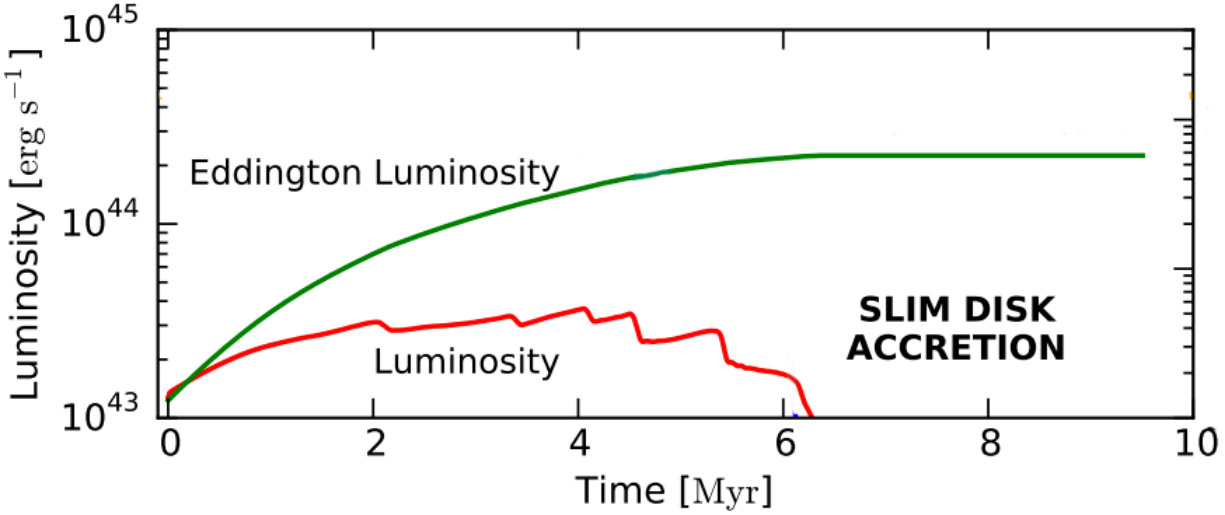
"Ab-normal" MBHs in "normal" galaxies are those that grow fast and can be detected as luminous quasars

"Normal" MBHs in "normal" galaxies may grow slowly

Current limits/candidates high-z AGN compatible with a population of MBHs similar to low-z counterpart in galaxies of similar mass

Relative role of stars and MBHs in cosmic reionization

Super-critical accretion



High-z halo feeding a 10^5Msun MBH

1D simulation with RT

Slim disc accretion: L \propto ln(Mdot)

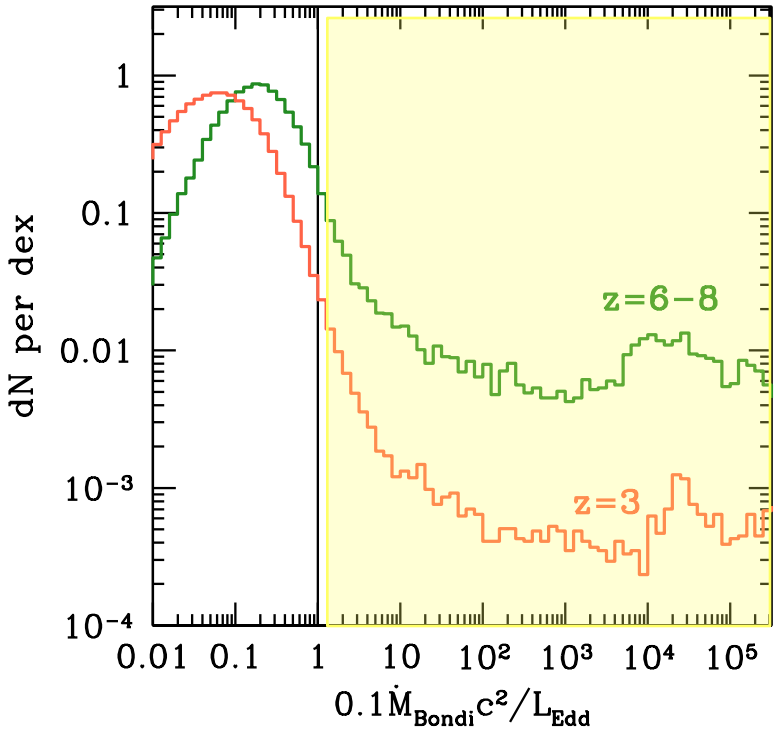
BH accretes all available gas in 10 Myr (compared to 100 Myr for "standard" accretion)

Luminosity sub-Eddington, while accretion super-critical

Pacucci et al. 2015a,b

Eddington limit?

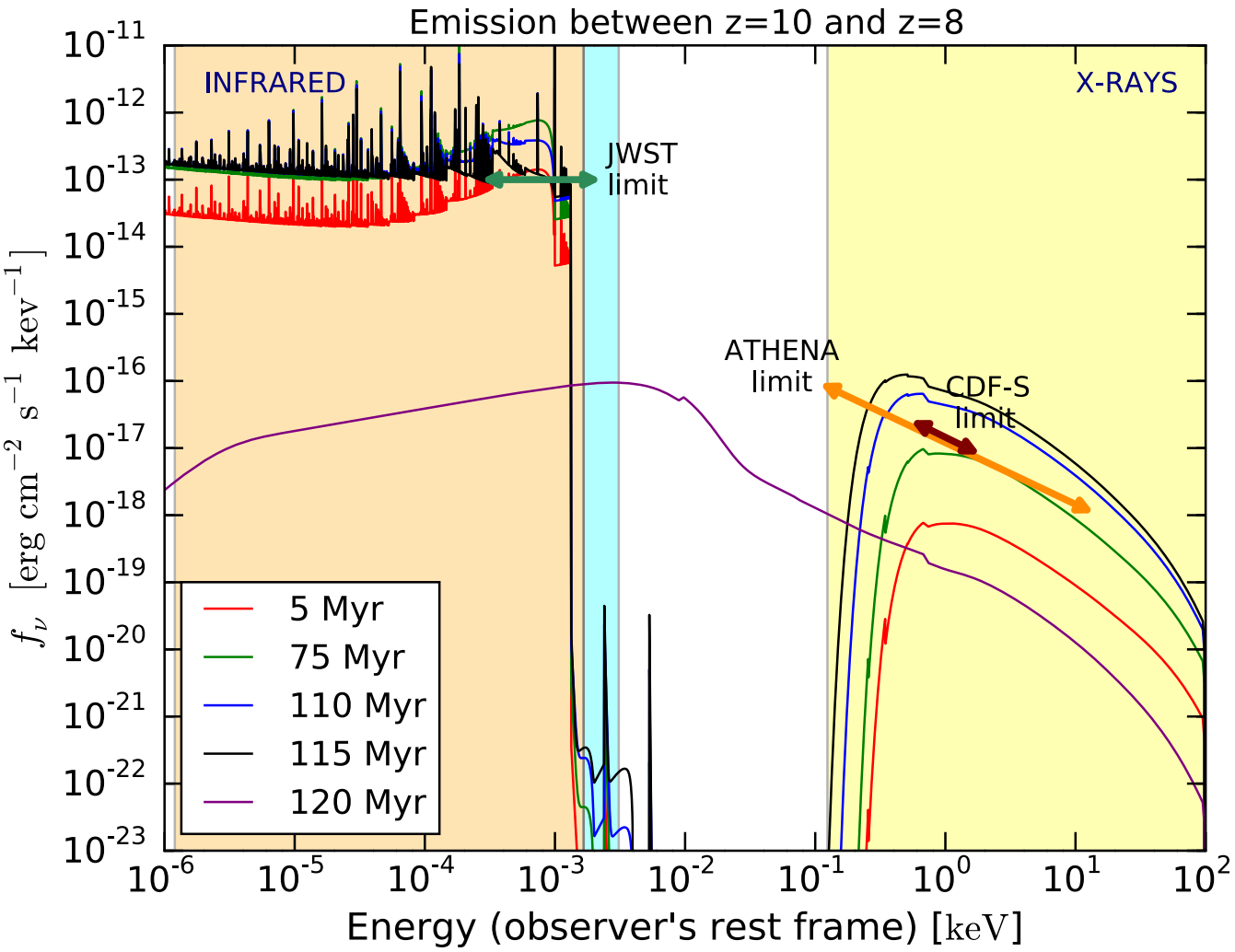
Gas infalls from the galaxy: how does the galaxy know that it has to feed the MBH *exactly* at the Eddington limit?



- Estimate Eddington rate for BHs in Horizon-AGN -- 3×10^6 Mpc^3 (Dubois+14)
- Supercritical inflows possible, ~10% at z>6
- What happens when they reach the MBH?

Volonteri, Silk & Dubus 2015

How do the first black holes shine?



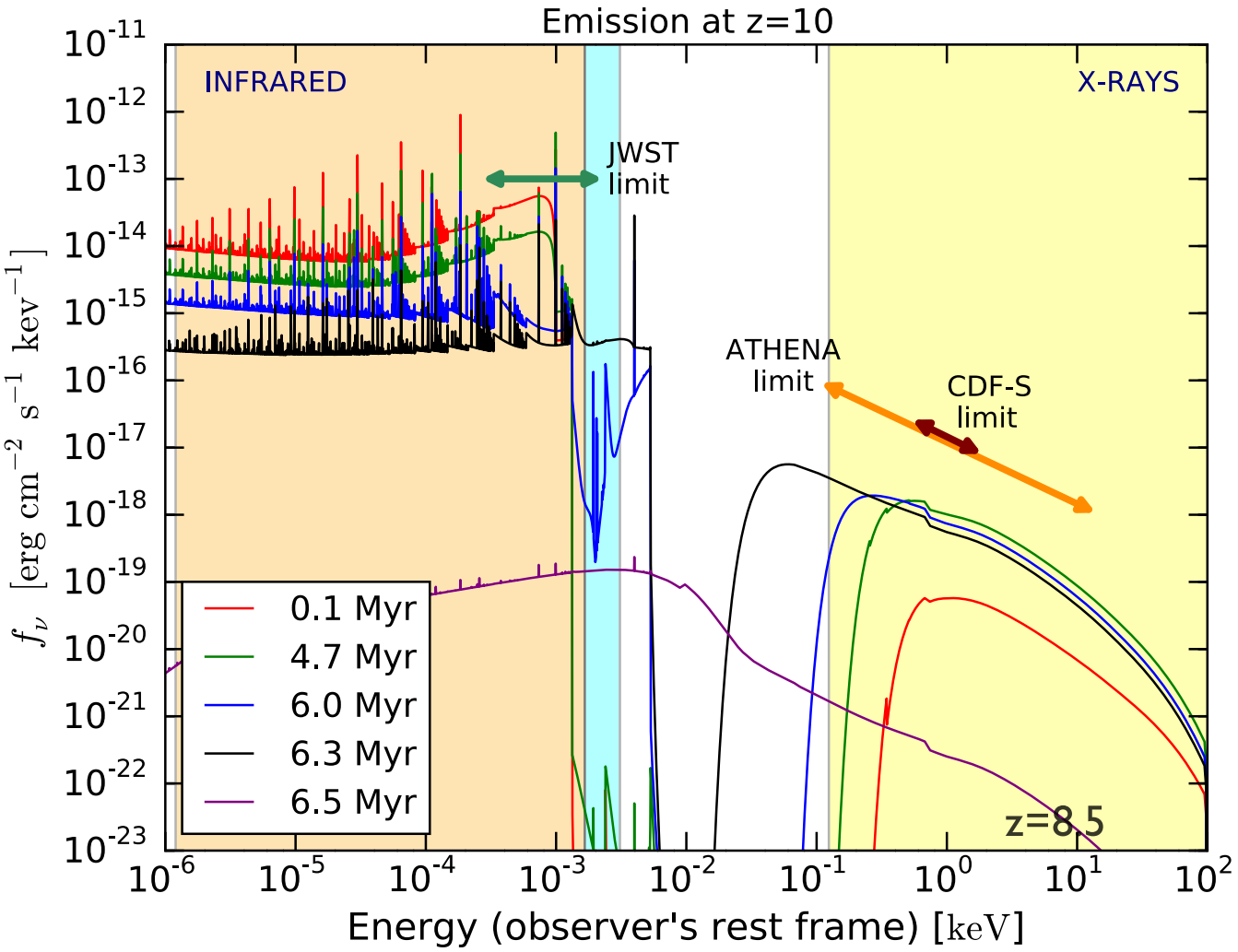
10^5 Msun MBH at z=8-10

CDF-S already gives constraints on the number density of these accreting BHs!

JWST and ATHENA will have "easy" life

Pacucci et al. 2015

Caveat: super-critical MBHs are fainter!

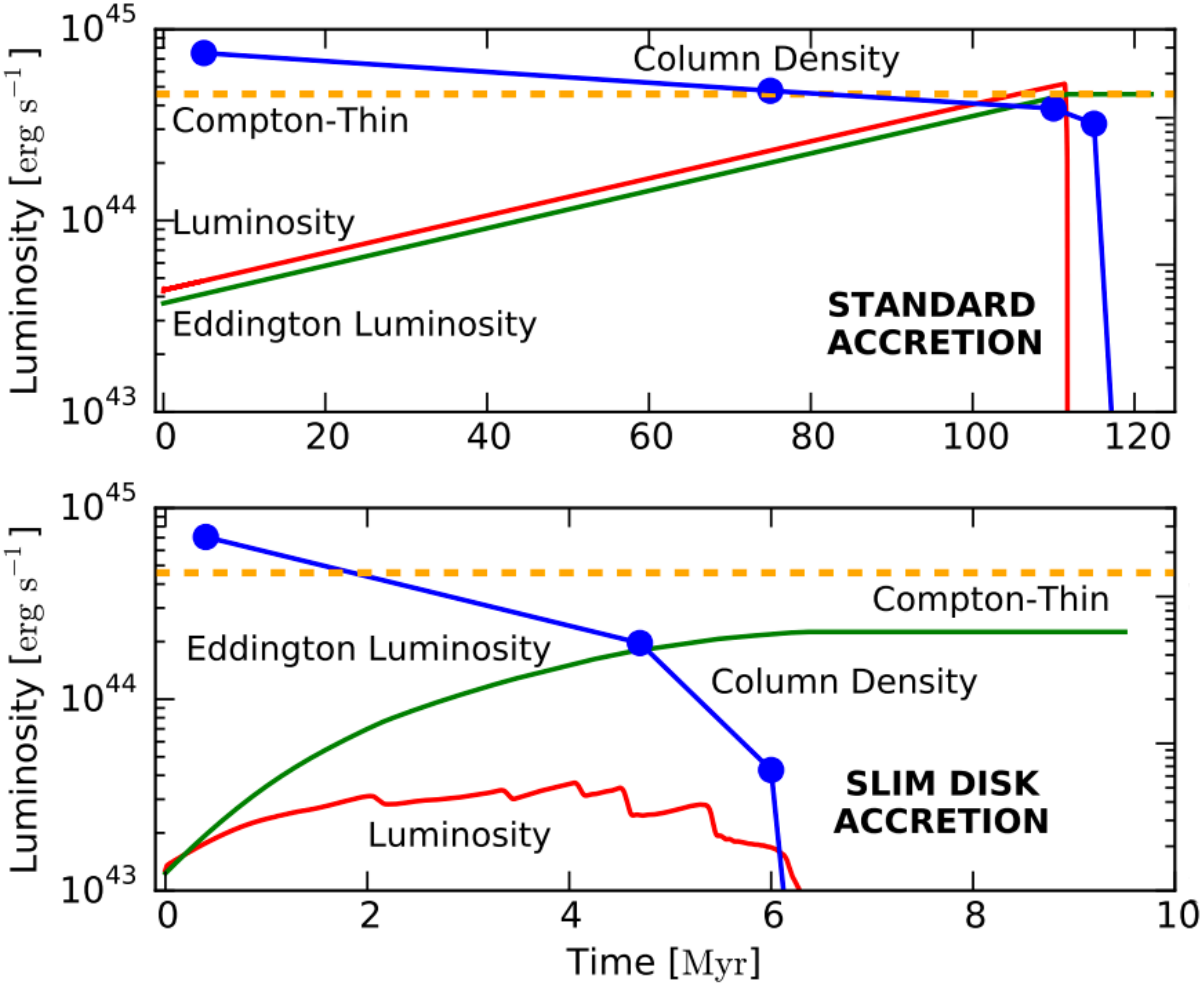


Slim disc accretion:
L \propto ln(Mdot)

Super-critical BHs are short-lived and fainter than Eddington-limited ones

Pacucci et al. 2015

How do the first black holes grow?



Standard accretion:
L \propto Mdot

Luminosity mildly super-Eddington

Slim disc accretion:
L \propto ln(Mdot)

Luminosity sub-Eddington, while accretion super-critical

Pacucci, MV & Ferrara 2015

Is low metallicity necessary?

(e.g. Bromm & Loeb 2003, Spaans & Silk 2006, Begelman, MV & Rees 2006, Shang et al. 2010, Latif et al. 2013)

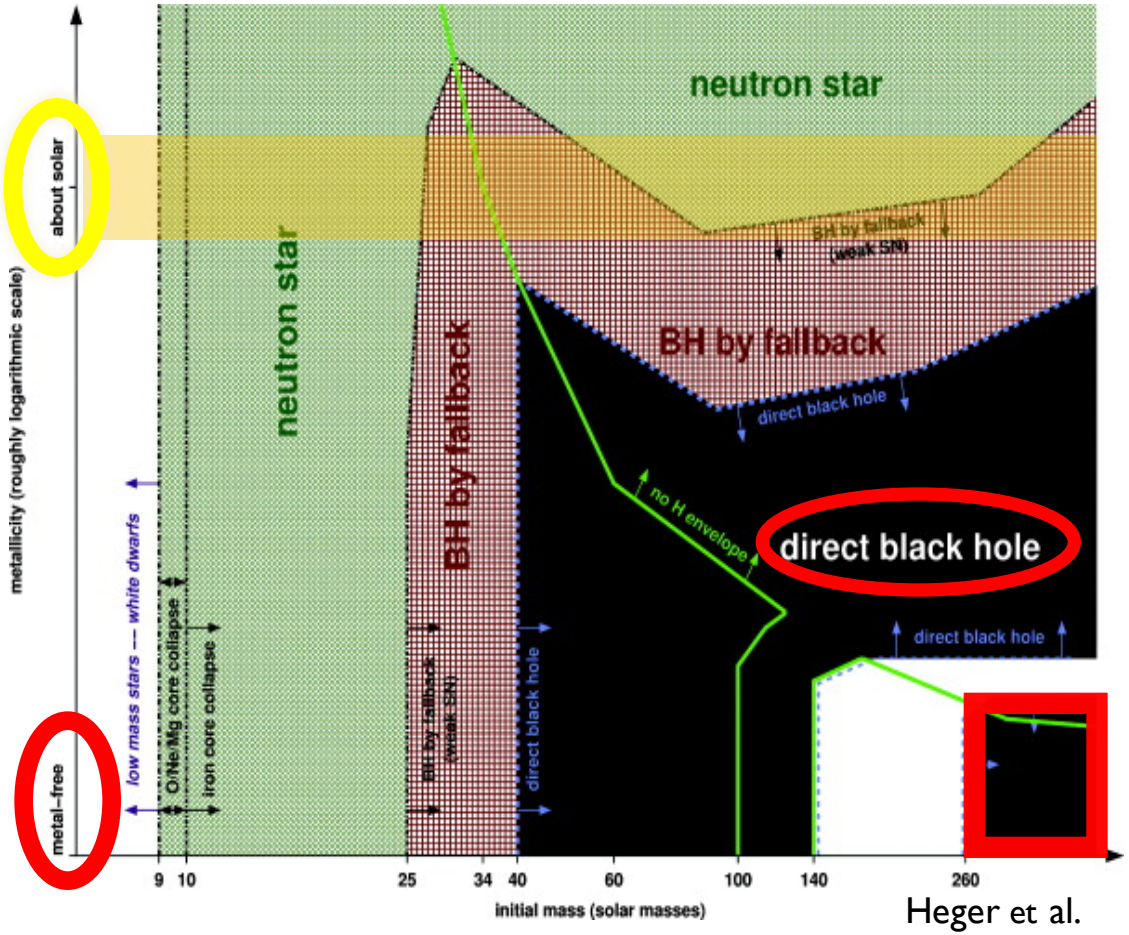
✔ Forming a single very massive star makes is easier to form a single very massive BH

✔ Key parameter is the inflow rate on the central object: Mdot>0.01-0.1 Msun/yr

✔ Primordial gas composition and suppression of H_2 formation by dissociating UV flux help

✔ <u>But they are *not* necessary conditions</u>

Is low metallicity necessary?



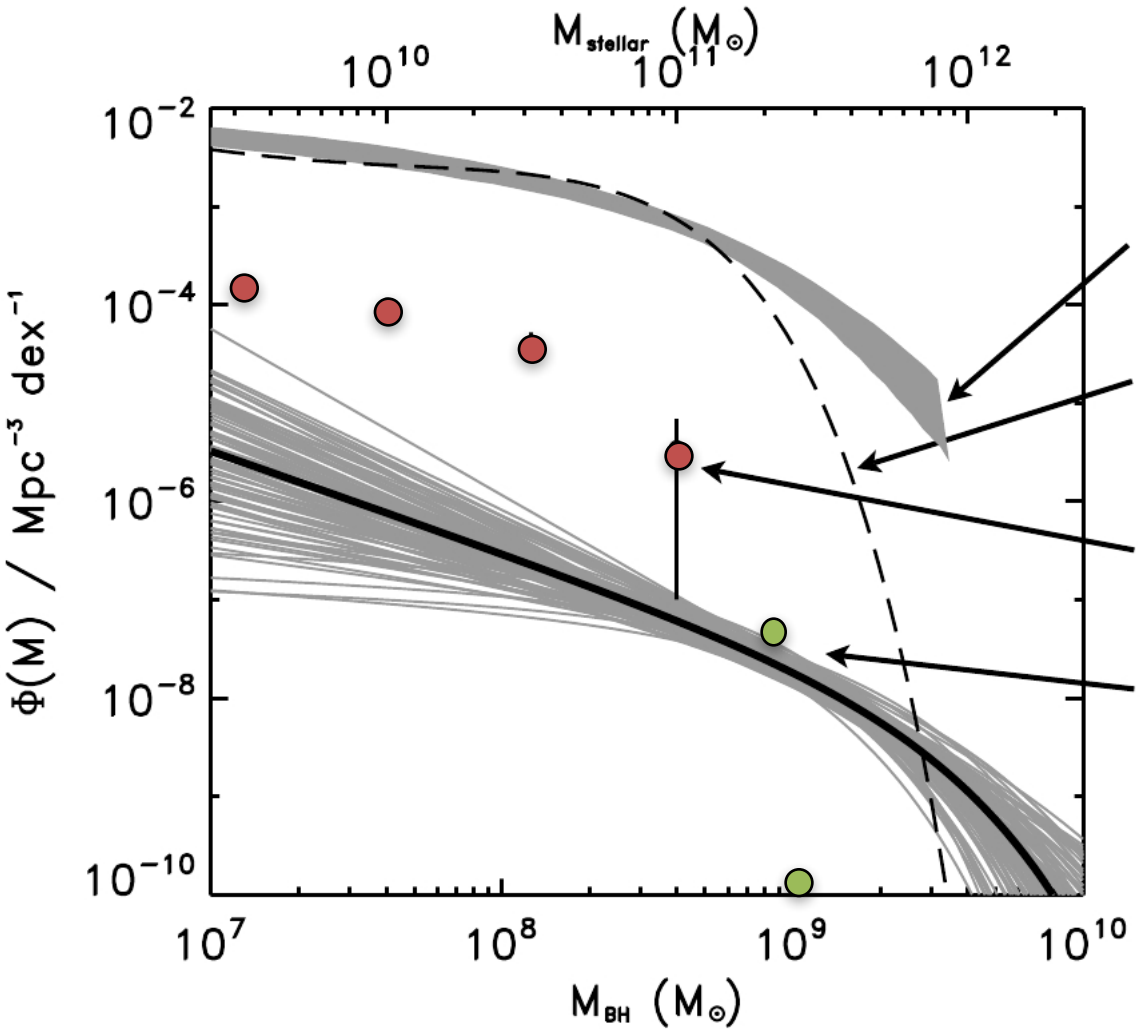
Heger et al.

Low metallicity is important if going through a supermassive star phase: models with quasistars* or stellar mass BH mergers *do not care* about metallicity

*powered by accretion on an embedded BH created by core collapse

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

M_* axis shifted by 4×10^{-3} from MBH



Local BH MF
(Shankar et al.2009)

Local stellar MF shifted by 4×10^{-3}
(Baldry et al.2008)

z=6 stellar MF (+ Schechter fit)
shifted by 4×10^{-3} (Stark et al.2009)

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

Willott et al.(2010)

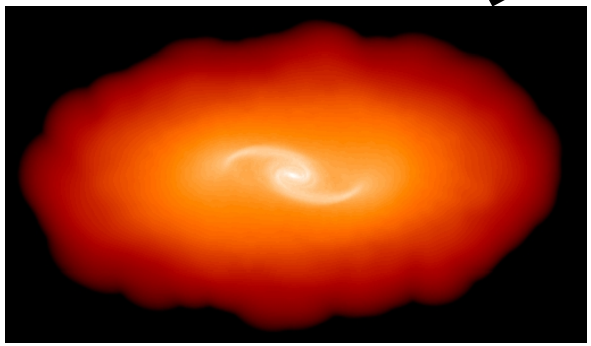
Key open questions on the cosmic evolution of MBHs

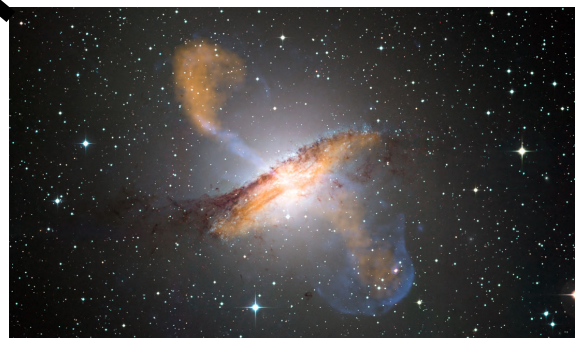
how do MBHs form?

how do galaxies feed MBHs?

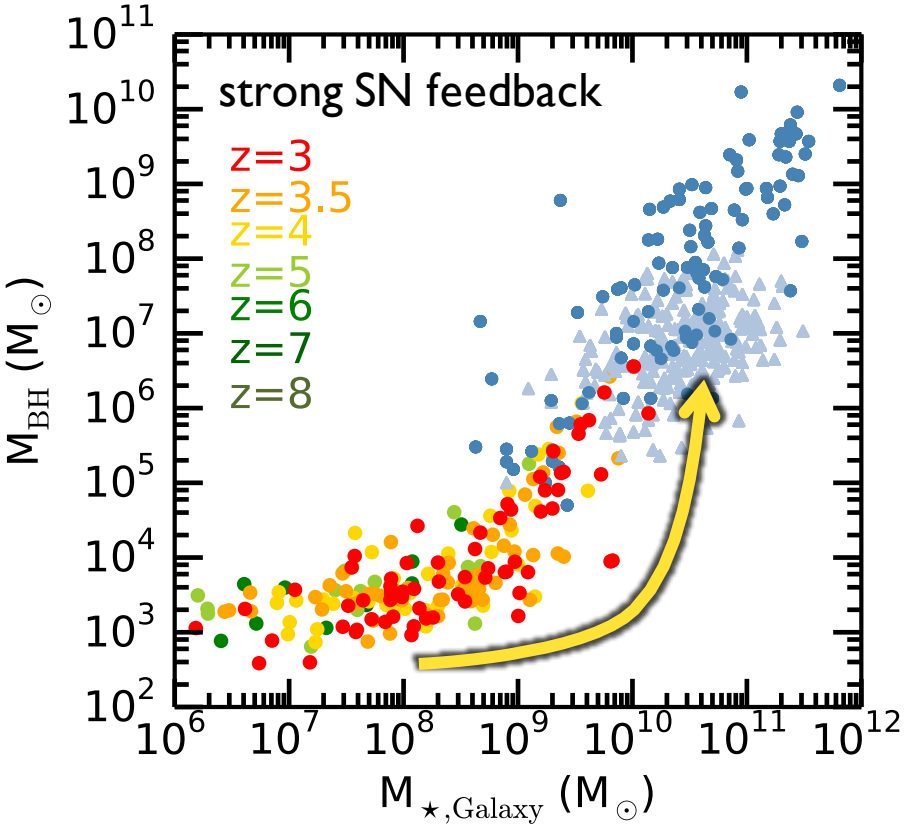
Connecting the dots

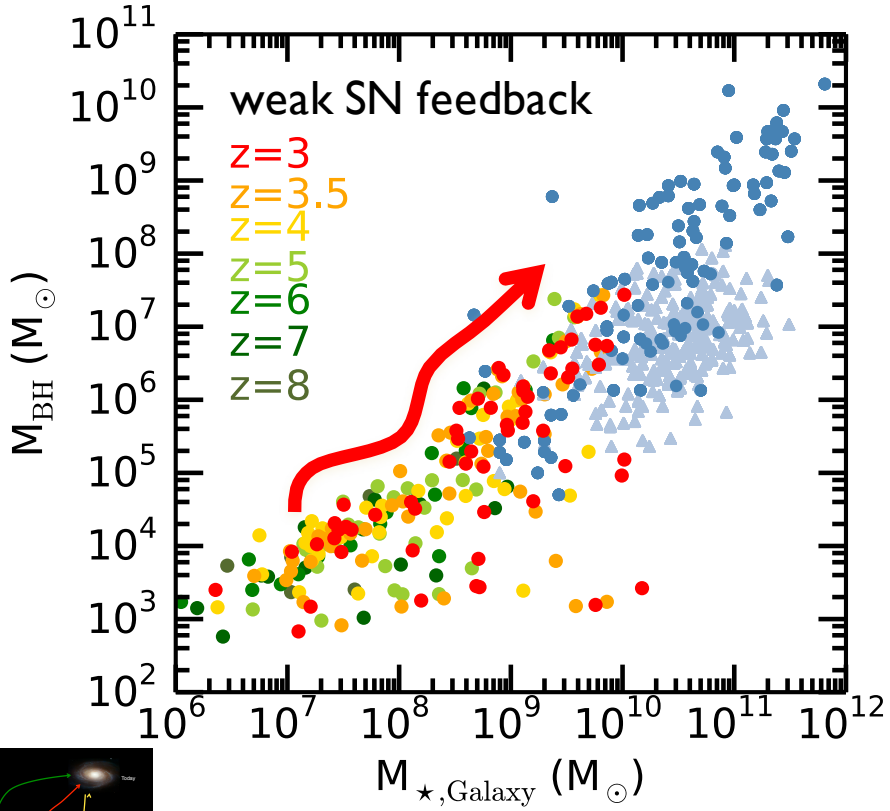
how do MBHs affect galaxies?

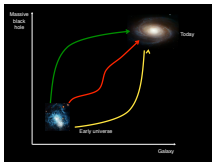




How do galaxies feed *normal* MBHs?



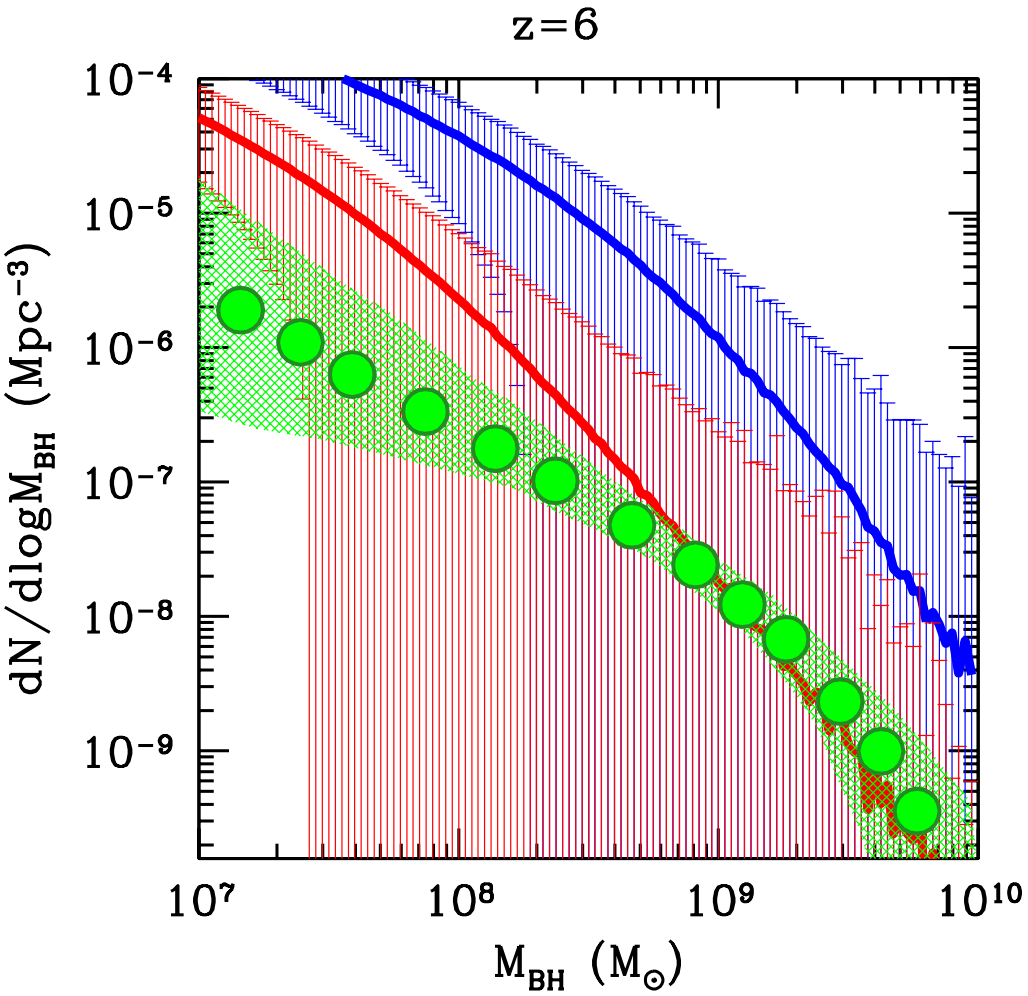




SN feedback is sufficient to slow MBH growth

Habouzit, MV, Dubois 2016

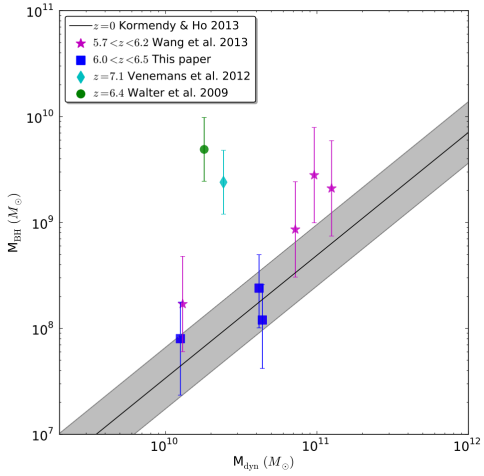
M_{BH} vs galaxy at high redshift



Green: MF from AGN luminosity function, assuming $<f_{Edd}>$=0.6, 75% active fraction (Willott+10)

vanilla: M_{BH}~10^{-3} Mgal

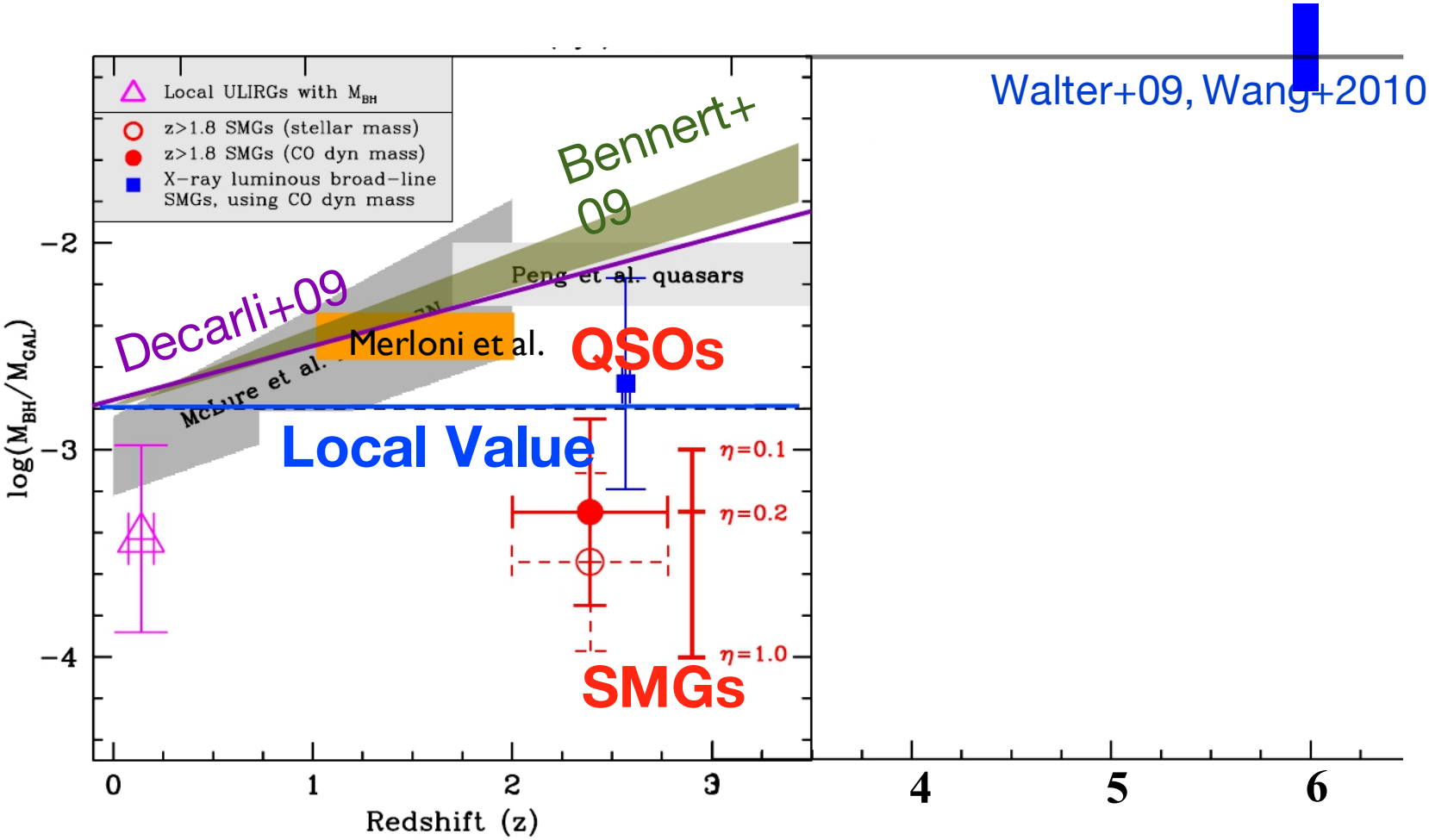
low mass: M_{BH}~10^{-4} Mgal



Adapted from MV & Reines 2016

M_{BH} vs galaxy at high redshift

At z=0 M_{BH}~1-4x10^{-3} M_*



Courtesy of A. Marconi

Alexander et al. 2007 + Marconi's additions