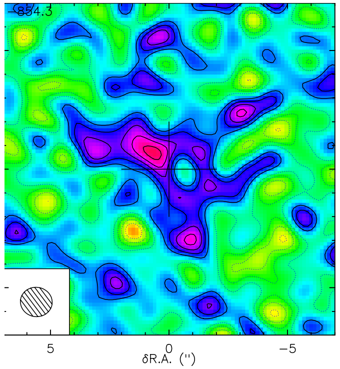
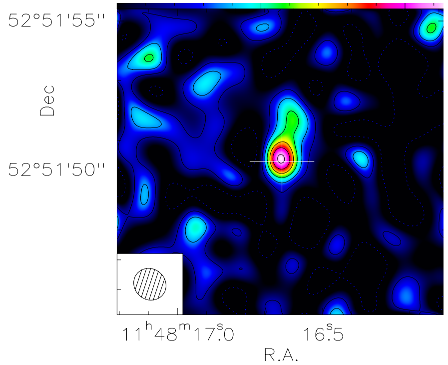




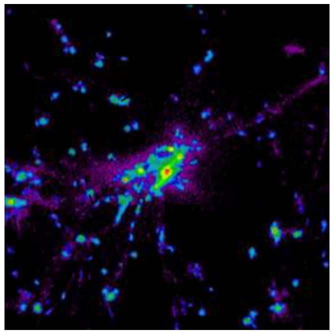
Super Massive Black Holes in the early Universe

SCUOLA NORMALE SUPERIORE

Simona Gallerani

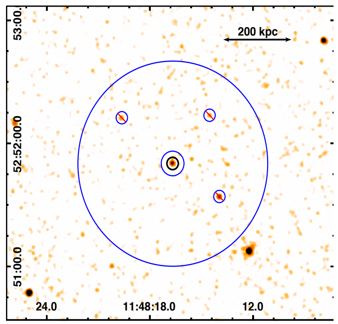
in collaboration with:

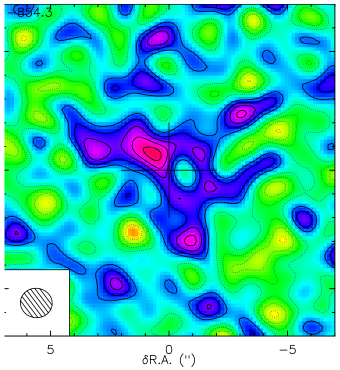
Barbara Balmaverde, Paramita Barai, Stefano Carniani, Claudia Cicone, **Andrea Ferrara**, Roberto Gilli, **Luca Graziani**, Roberto Maiolino, **Maria Carmela Orofino**, **Andrea Pallottini**, Enrico Piconcelli, Livia Vallini, Cristian Vignali, Luca Zappacosta

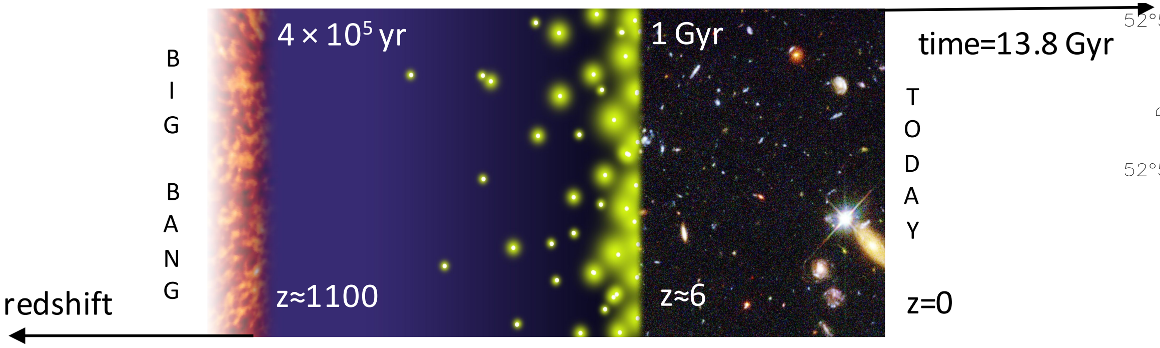


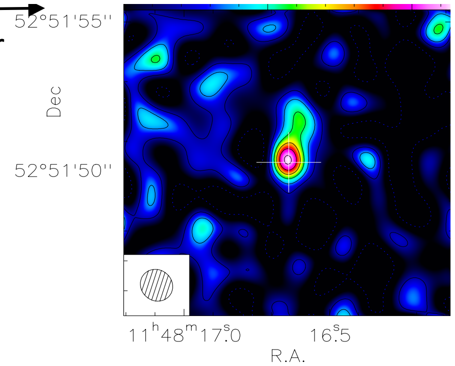
"QUANTUM GASES, FUNDAMENTAL INTERACTIONS, AND COSMOLOGY"

Pisa, 25th October 2017









Super Massive Black Holes in the early Universe

(z ≈ 6; t < 1Gyr)

SCUOLA NORMALE SUPERIORE

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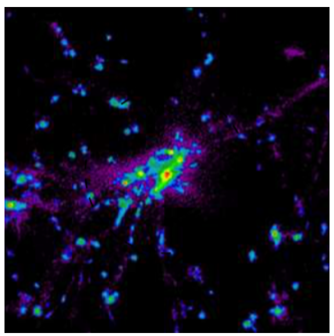

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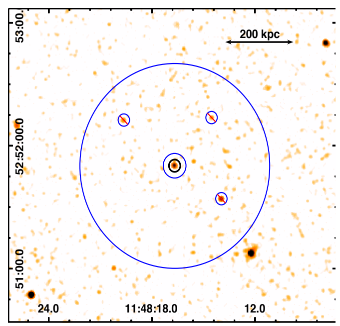
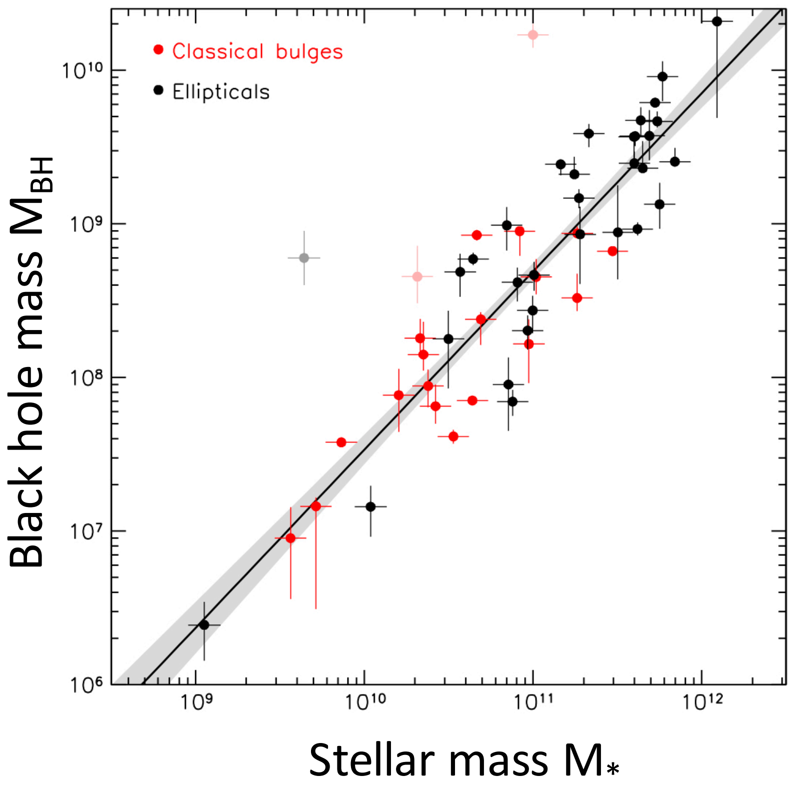


The local M_{BH} - M_* relation

SMBHs ($M_{BH} \approx 10^6 - 10^{10} M_{sun}$) are present in the center of massive galaxies, including the Milky Way.



The masses of SMBHs correlate with the stellar masses of their host galaxy

What is the origin of the local M_{BH} - M_* relation?

Active Galactic Nuclei

BLACK HOLE ACCRETION

Gas in the host galaxy is ***accreted*** onto the black hole

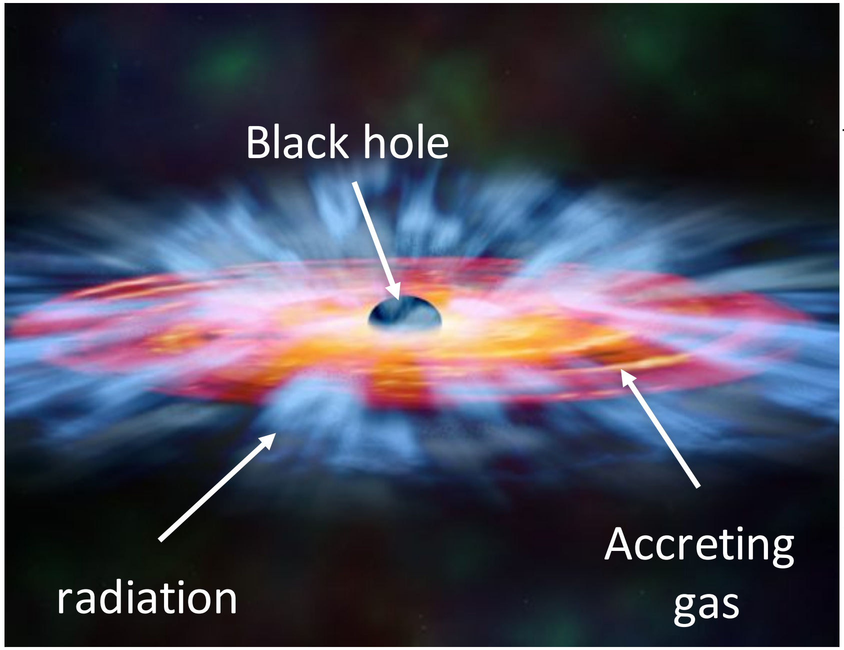
$$\dot{M}_{BH} = \alpha \frac{4\pi G^2 {M_{BH}}^2 \rho_{gas}}{(c^2 + {v_{BH-gas}}^2)^{3/2}}$$

(Bondi & Hoyle 1944; Hoyle & Lyttleton 1939)

AGN RADIATION

A fraction of the accreted rest-mass energy *is* ***radiated away***

$$L_{rad} = \varepsilon_{rad} \dot{M}_{BH} c^2 \qquad \varepsilon_{rad} \approx 10\%$$



Artistic representation of an AGN. Credit: NASA/CXC/M.Weiss

AGN FEEDBACK

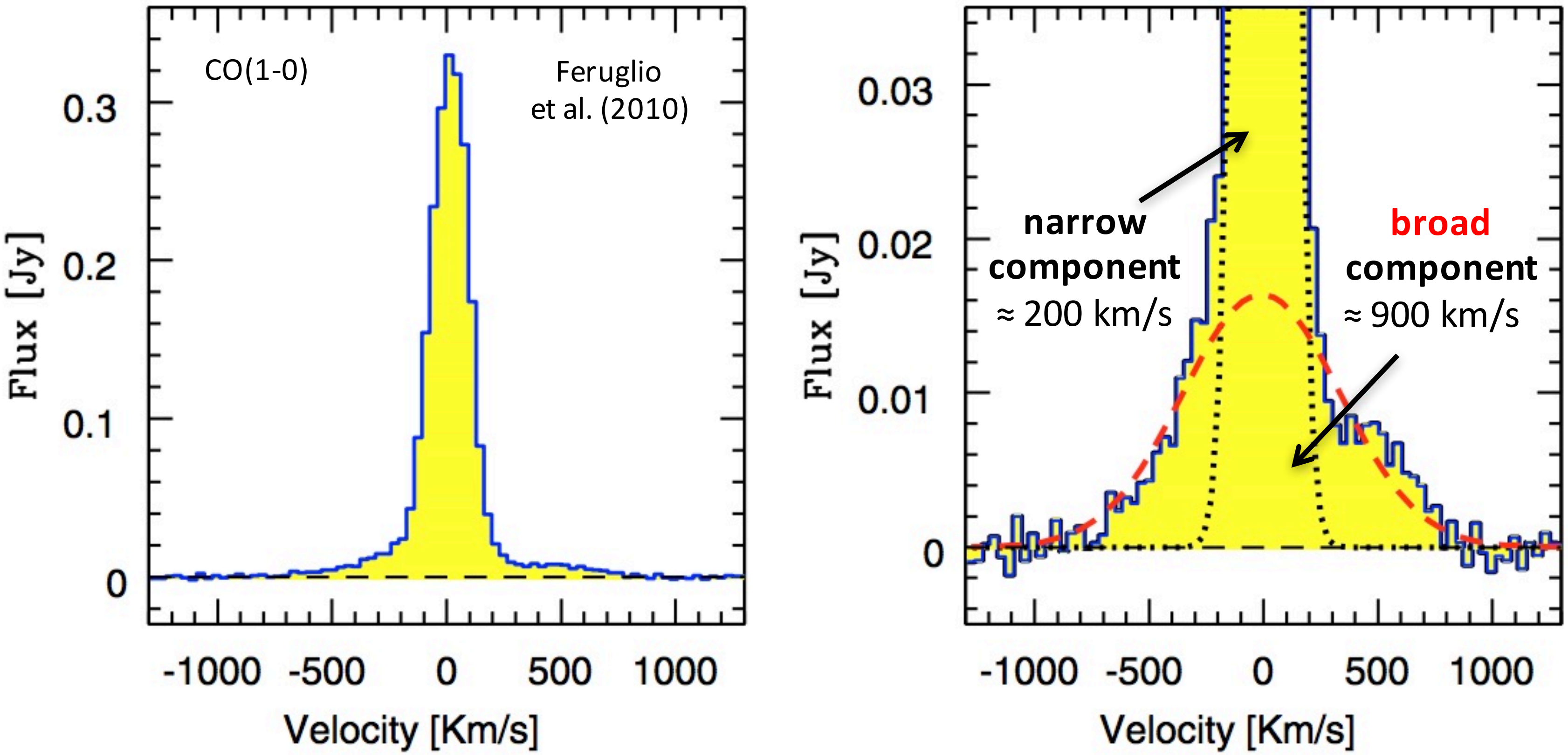
A fraction of this radiated energy is ***returned*** to the surrounding gas in terms of ***thermal/kinetic energy***

$$\dot{E}_{feed} = \varepsilon_{feed} L_{rad} = \varepsilon_{feed}\, \varepsilon_{rad} \dot{M}_{BH} c^2 \qquad \varepsilon_{feed} \approx 5\%$$

AGN feedback can explain the origin of the local M_{BH} - M_* relation

AGN feedback in the local Universe

Mrk 231: the closest quasar known



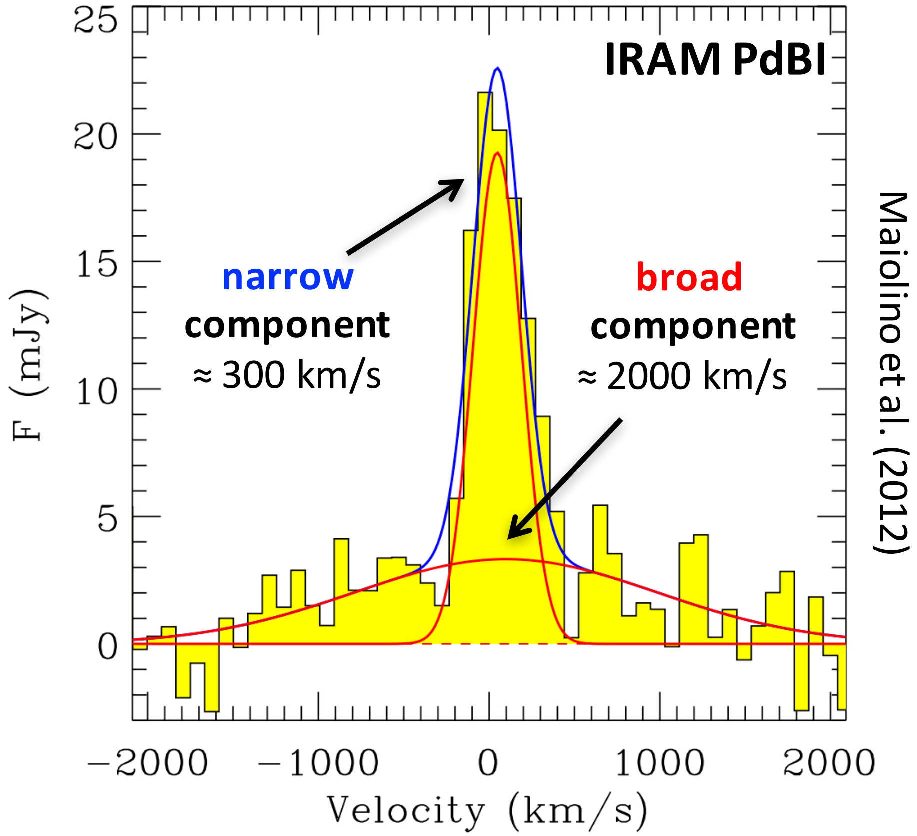
Broad wings extended up to ± 750 km/s in the CO(1-0) line

Evidence of molecular outflows in the local Universe

Quasar feedback in z ≈ 6 quasars

[CII] ($^2P_{3/2}$-$^2P_{1/2}$) @158 μm

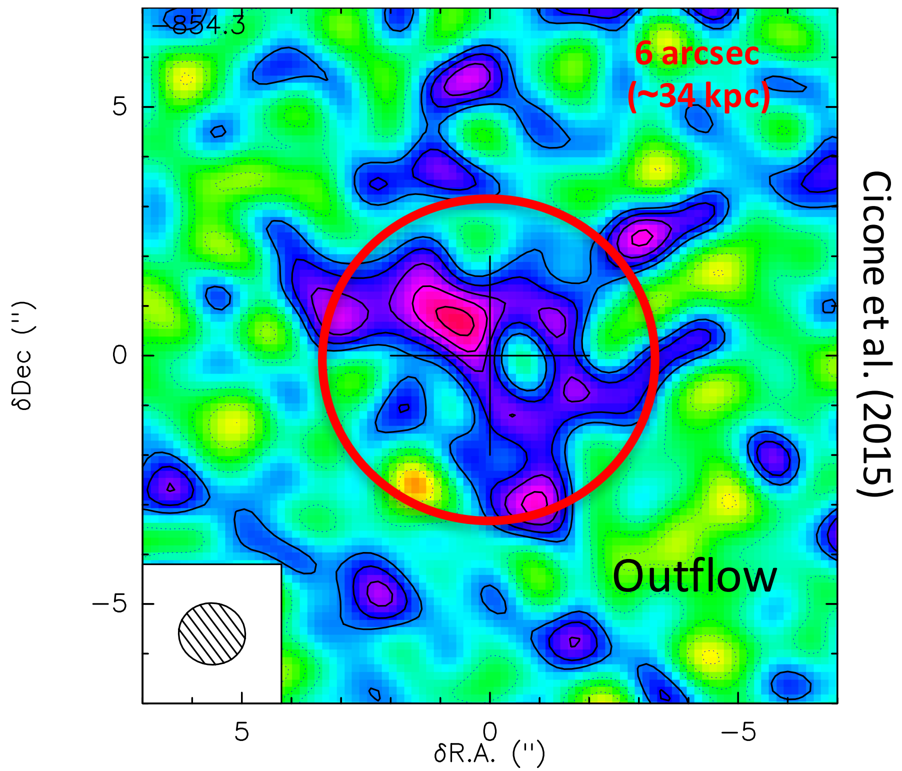
- The most important coolant of the ISM
- Detectable with sub-mm facilities at z > 4
- Detected in all z ≈ 6 quasars

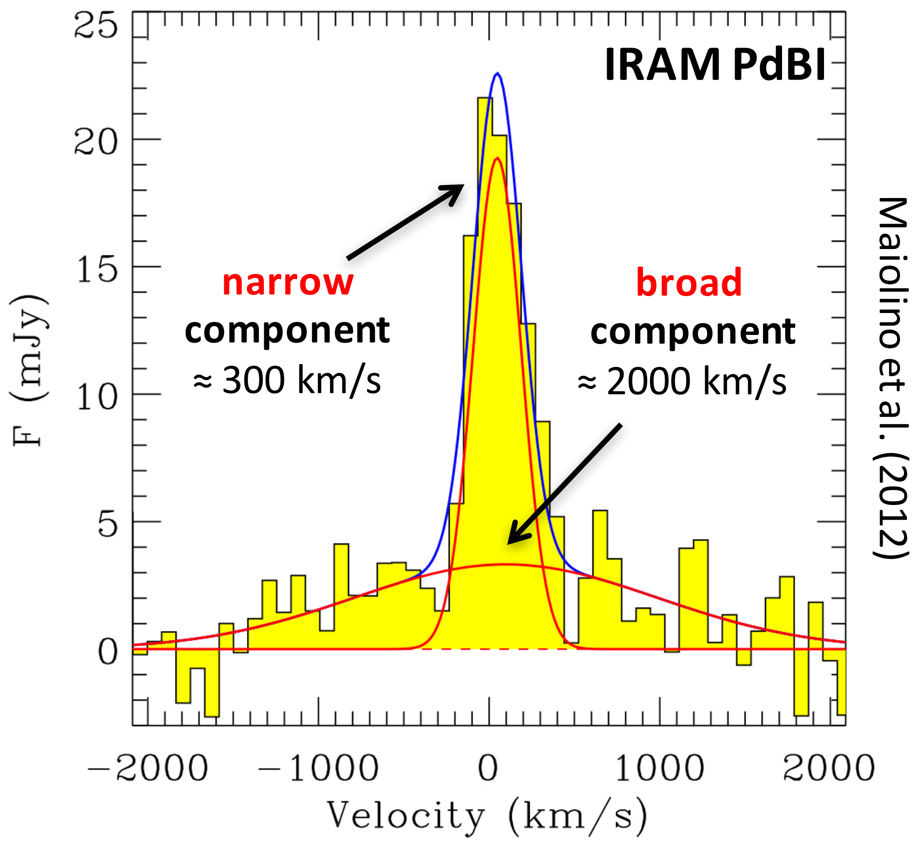


Broad wings extended up to ± 1300 km/s in the [CII] line

Evidence of fast moving gas flowing out of the host galaxy

Quasar feedback in z ≈ 6 quasars

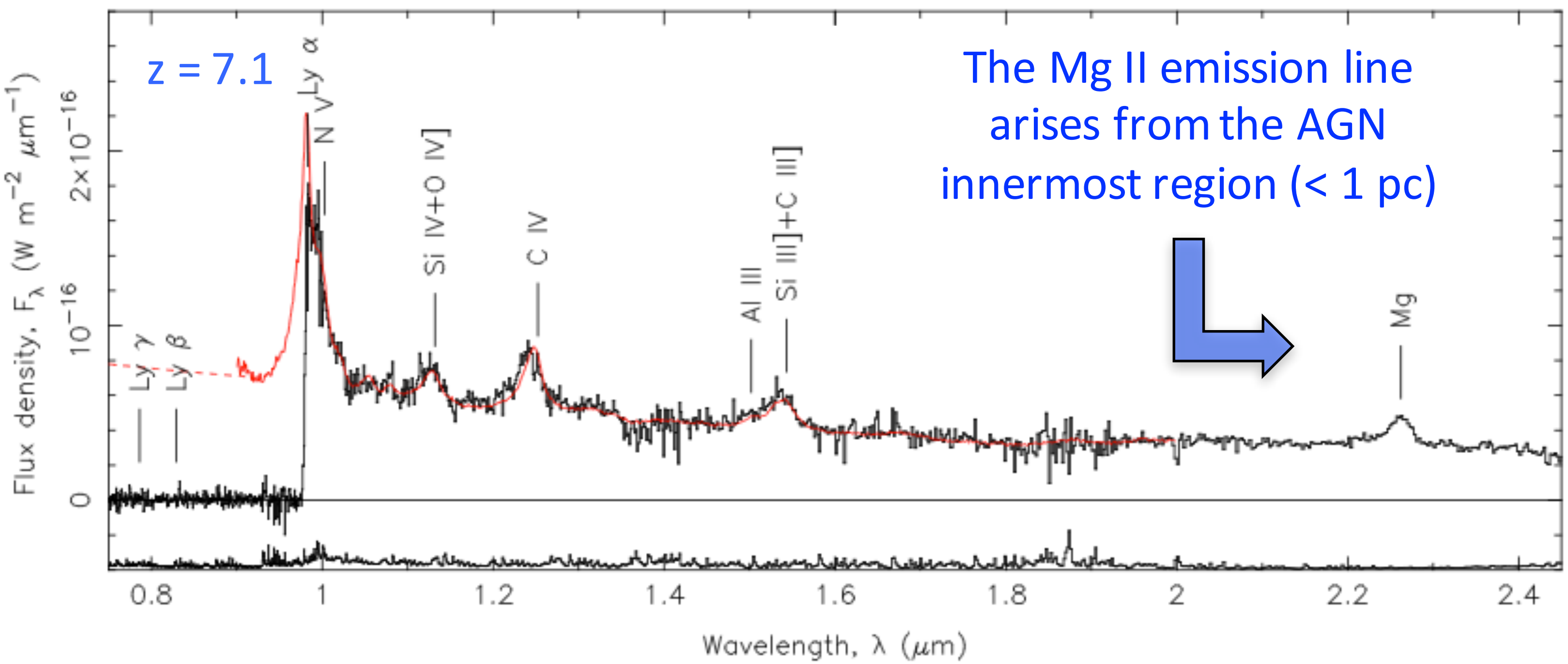




Metal-rich fast outflowing gas is distributed on ≈20 - 30 kpc

How does the M_{BH} - M_* relation evolve at high redshift?

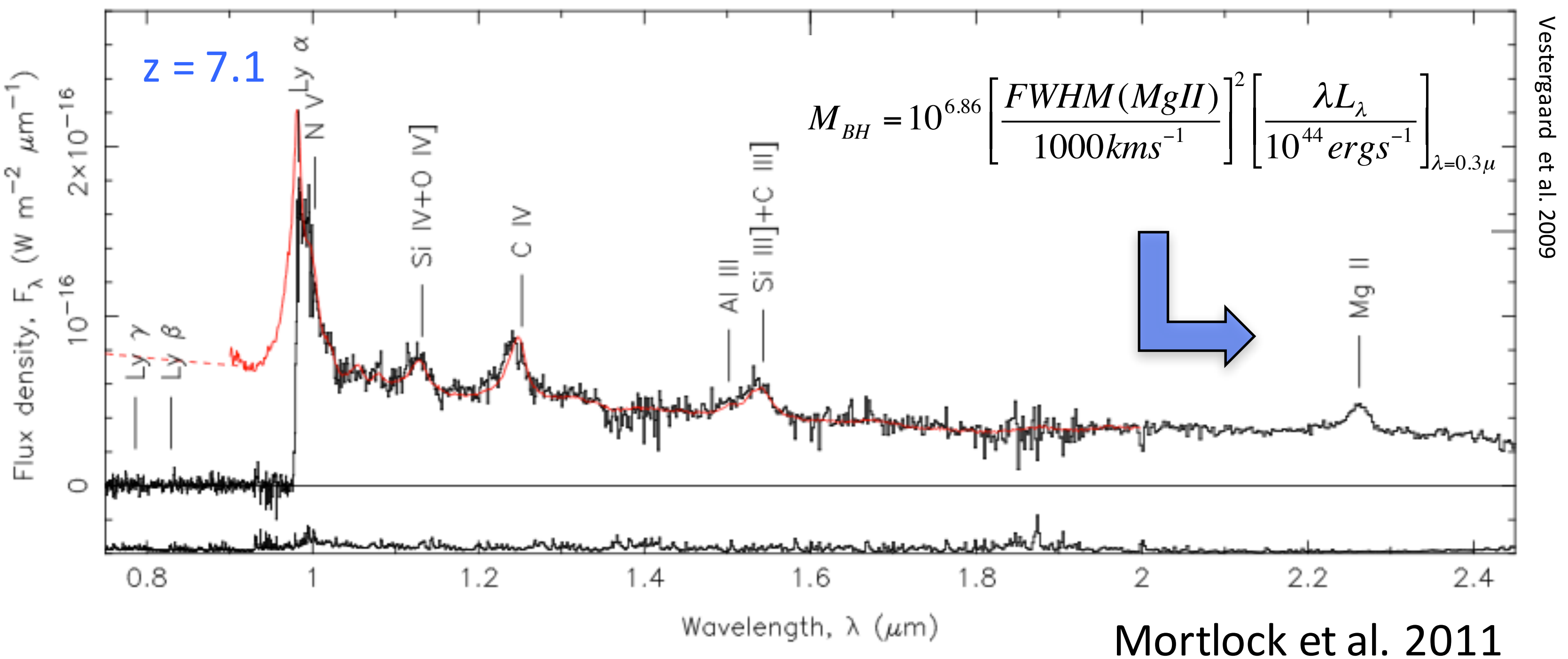
Black hole mass measurements in z ≈ 6 quasars



Vestergaard et al. 2009

$$M_{BH} = 10^{6.86}\left[\frac{FWHM(MgII)}{1000kms^{-1}}\right]^2\left[\frac{\lambda L_\lambda}{10^{44}ergs^{-1}}\right]_{\lambda=0.3\mu}$$

Black hole mass measurements in z ≈ 6 quasars



Mortlock et al. 2011

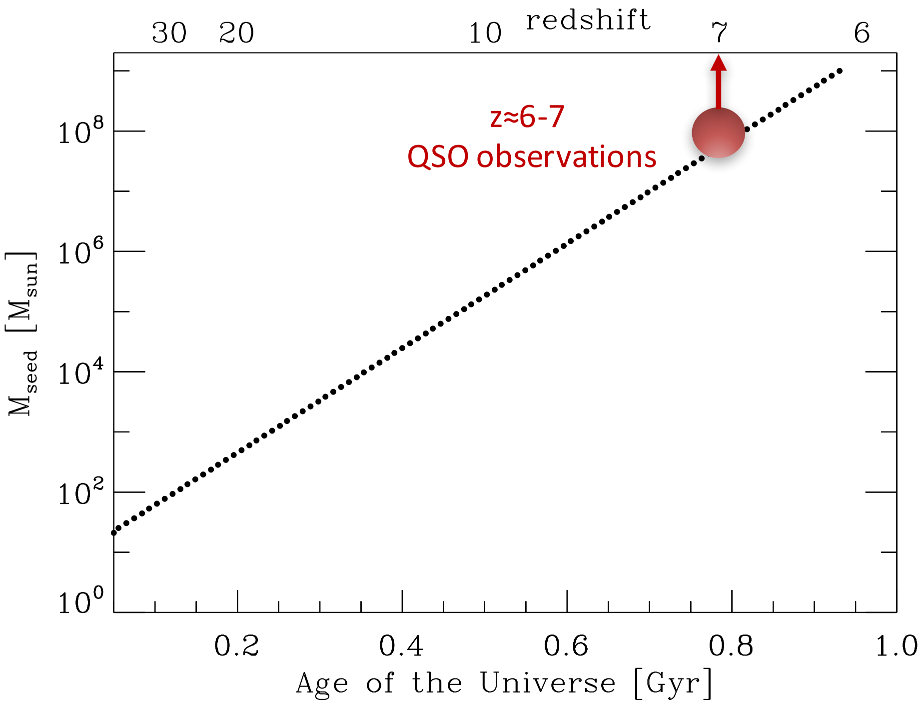
Tens of z ≈ 6 quasars

(e.g. Barth et al. 2003; Jiang et al. 2007; Wang et al. 2010; Wu et al. 2015)

$$M_{BH} = (0.02 - 1.10) \times 10^{10} M_{sun}$$

How SMBHs have formed in less than 1 Gyr?

Possible pathways for the origin of SMBH seeds



Assumptions:

The BH is radiating at L_{EDD} for all the time spent accreting

$\varepsilon = 0.1$

$$\dot{M}_{BH} = \frac{(1-\varepsilon)L_{EDD}}{\varepsilon c^2}$$

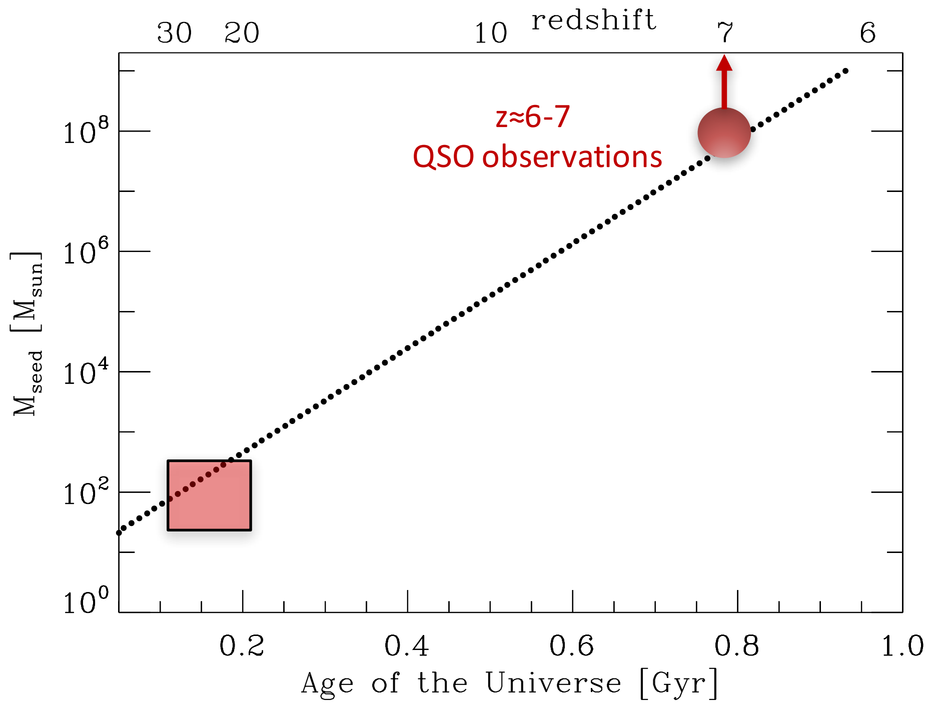
Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

collapse of primordial stars
(M_{PopIII}>100 M_{sun})
in DM minihalos
(M_{DM}≈10^6 M_{sun})

z≈20-30

M_{seed}≈50-100 M_{sun}



(e.g. Tegmark et al. 1997;
Madau & Rees 2001;
Bromm et al. 2002)

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(M_{DM}≈10^6 M_{sun})

z≈20-30

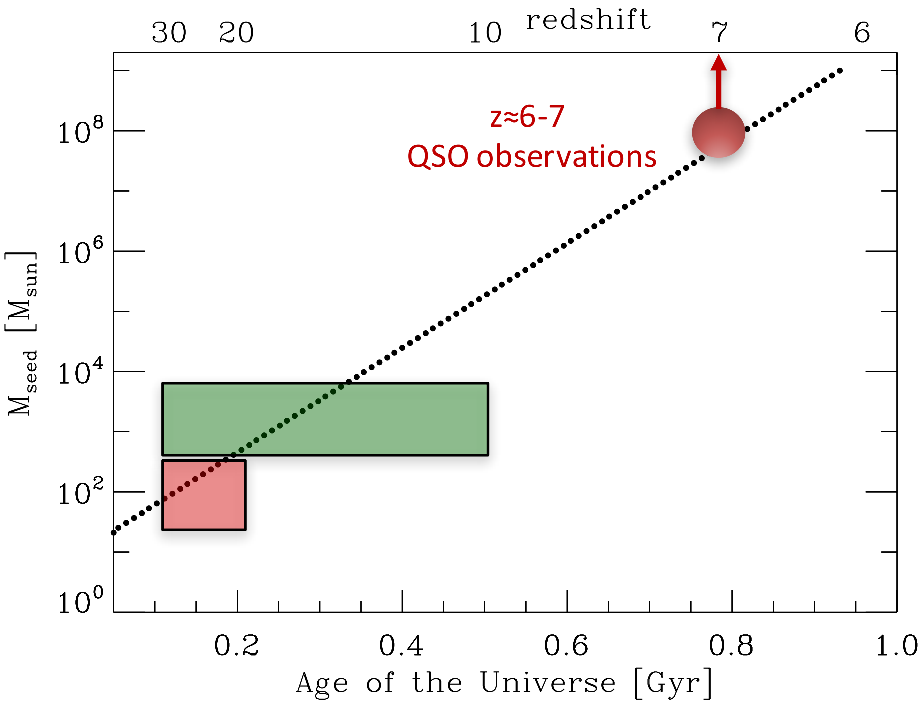
(2) Compact nuclear star clusters

Star collisions
can lead
to the formation of VMSs

z ≈10-20

M_{seed}≈1000 M_{sun}

M_{seed}≈50-100 M_{sun}



(e.g. Schneider et al. 2006;
Clark et al. 2008;
Devecchi et al. 2012)

(e.g. Tegmark et al. 1997;
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Star collisions
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to the formation of VMSs

z ≈10-20

(3) Direct Collapse Black Holes

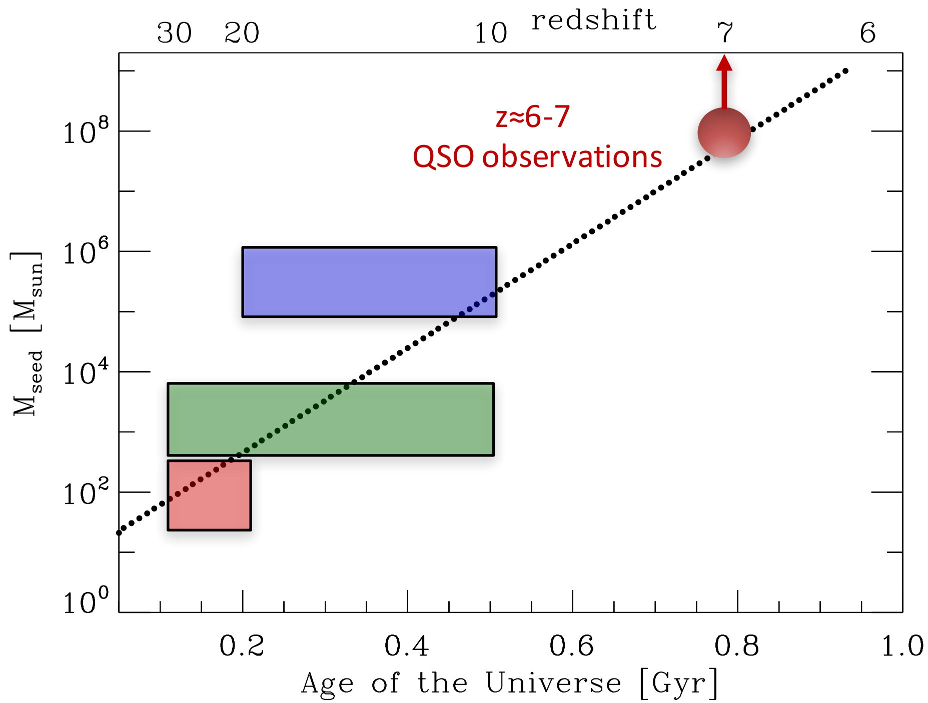
Primordial gas
irradiated by LW radiation
in atomic-cooling halos

z > 10

M_{seed}≈10^5-10^6 M_{sun}

M_{seed}≈1000 M_{sun}

M_{seed}≈50-100 M_{sun}



(e.g. Haehnelt & Rees 1993;
Yue et al. 2013; Pallottini et al. 2017;
Pacucci et al. 2017)

(e.g. Schneider et al. 2006;
Clark et al. 2008;
Devecchi et al. 2012)

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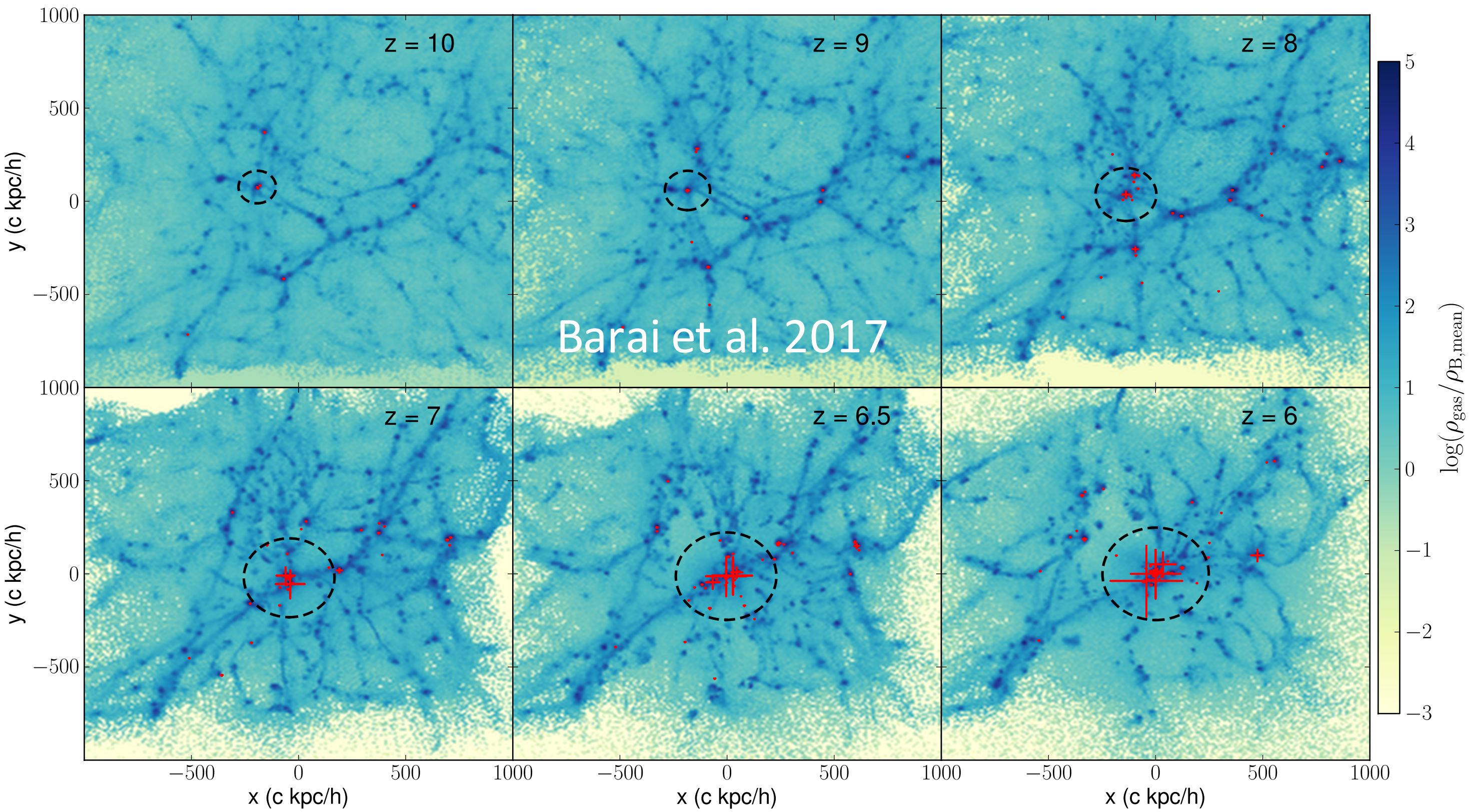
Cosmological simulations of a z ≈ 6 quasar



GADGET-3 (Springel 2005)

$100 > z > 6$

$L_{box} \approx 2\ h^{-1}$ c Mpc

$m_{DM}^{res} = 4 \times 10^{6}\ M_{sun}$

$\lambda_{smooth} = 1\ h^{-1}$ c kpc

$M_{DM}^{tot} \approx 4 \times 10^{12}\ M_{sun}$

Star formation ($n > 0.1\ cm^{-3}$)

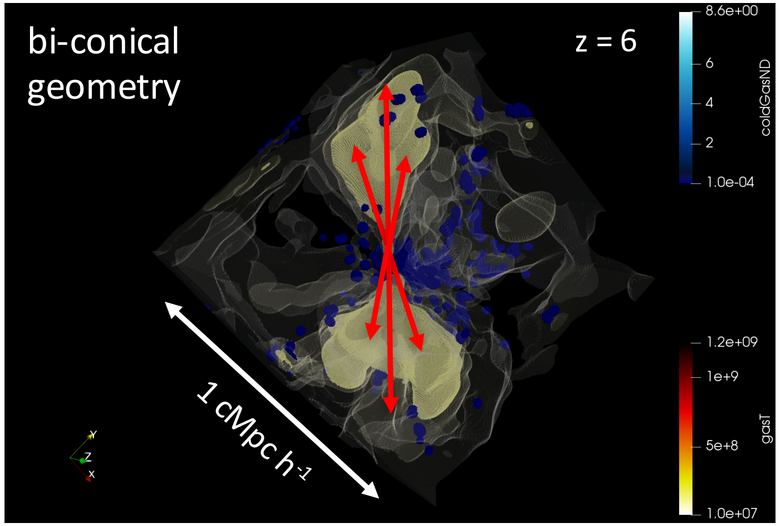
BLACK HOLE SEEDING: $10^5\ M_{sun}$ BH in $M_{DM} > 10^9 M_{sun}$

BLACK HOLE GROWTH: Gas accretion and galaxy merging

QUASAR FEEDBACK: Kinetic energy deposition

Cosmological simulations of a z ≈ 6 quasar

Graziani et al. in prep.



QUASAR FEEDBACK

Quasar feedback energy is distributed as kinetic energy

We have assumed a bi-conical and spherical geometry

Surrounding ***gas is driven outward***

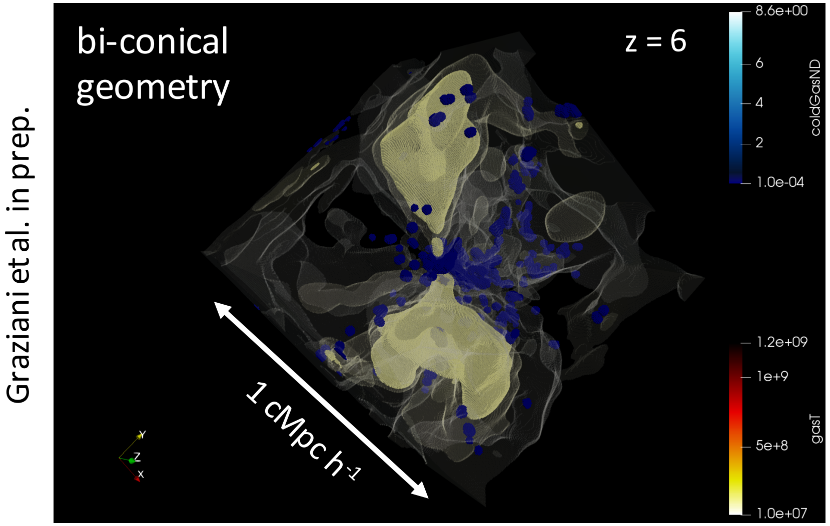
$$(v_{outflow}, \dot{M}_{outflow}) \qquad v_{outflow} = 10^4\, km/s$$

$$\frac{1}{2}\dot{M}_{ouflow}{v_{outflow}}^2 = \dot{E}_{feed}$$

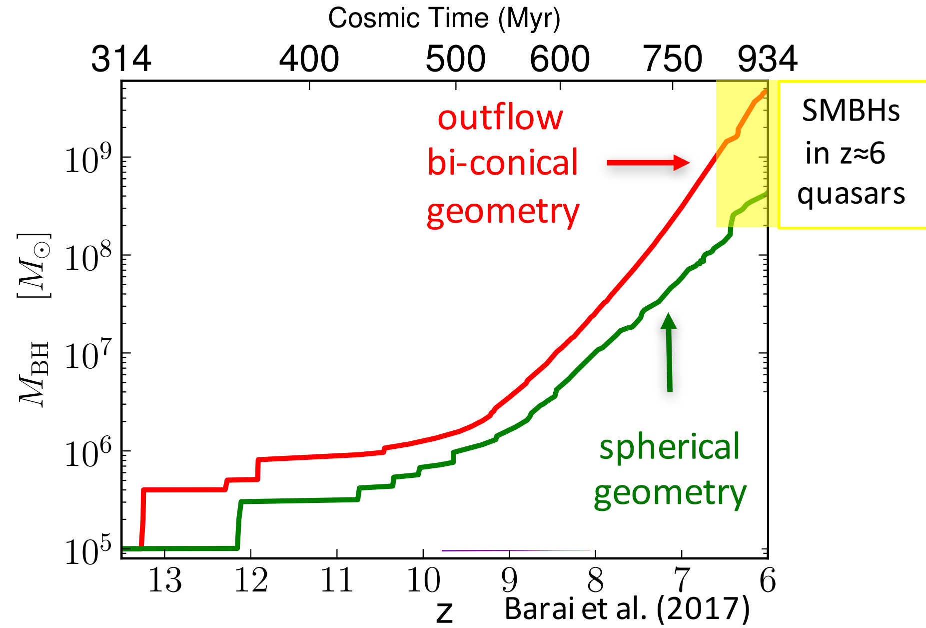
↓

$$\dot{M}_{outflow} = 2\ \varepsilon_{feed}\ \varepsilon_{rad}\ \dot{M}_{BH}\left(\frac{c}{v_{outflow}}\right)^2$$

Cosmological simulations of a z ≈ 6 quasar



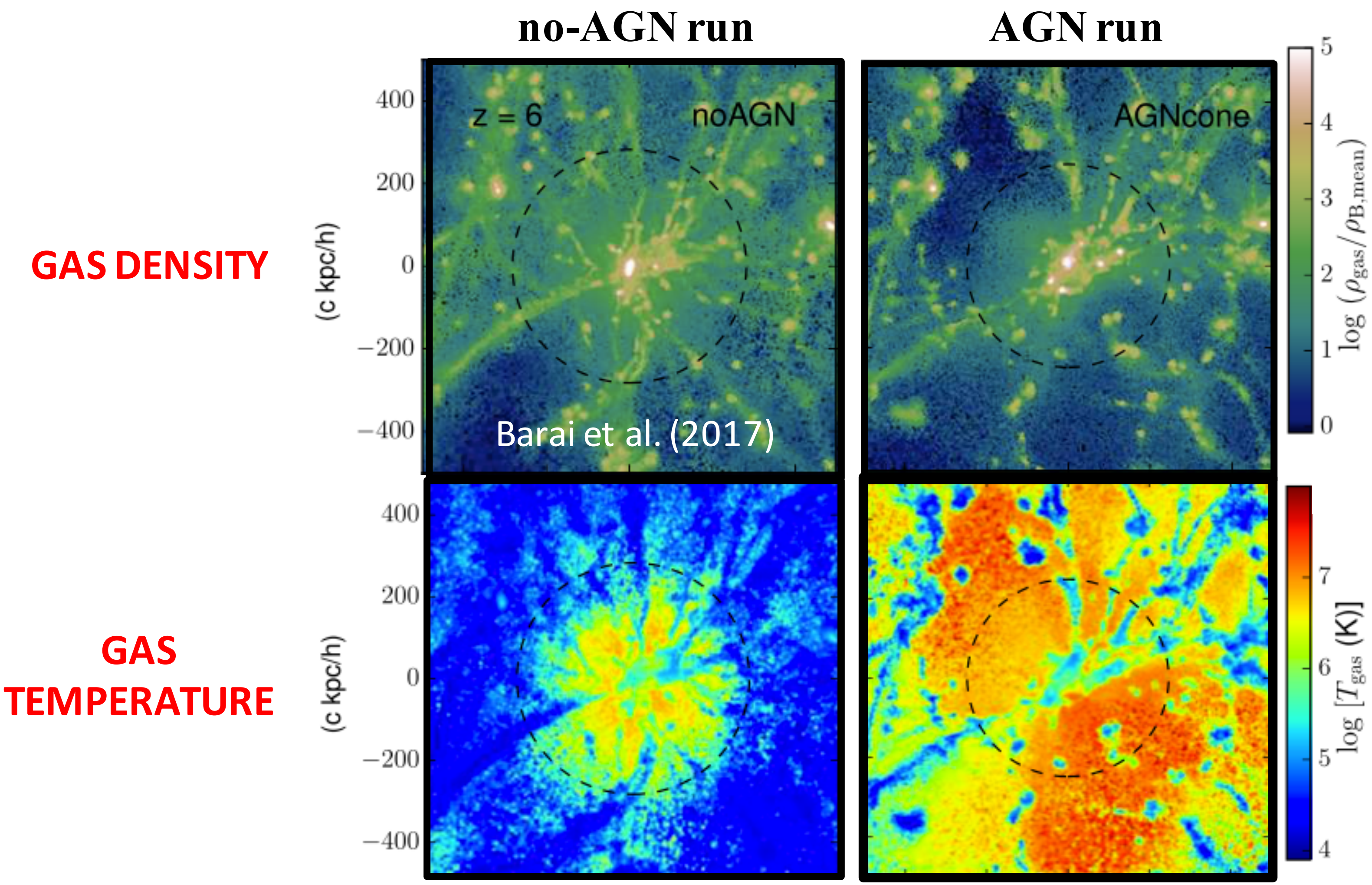
QUASAR FEEDBACK



BLACK HOLE MASS EVOLUTION

At z ≈ 6 a SMBH with $M_{BH} \approx 10^8$-10^9 M_{sun} is formed, in agreement with BH mass measurements obtained from the Mg II emission line.

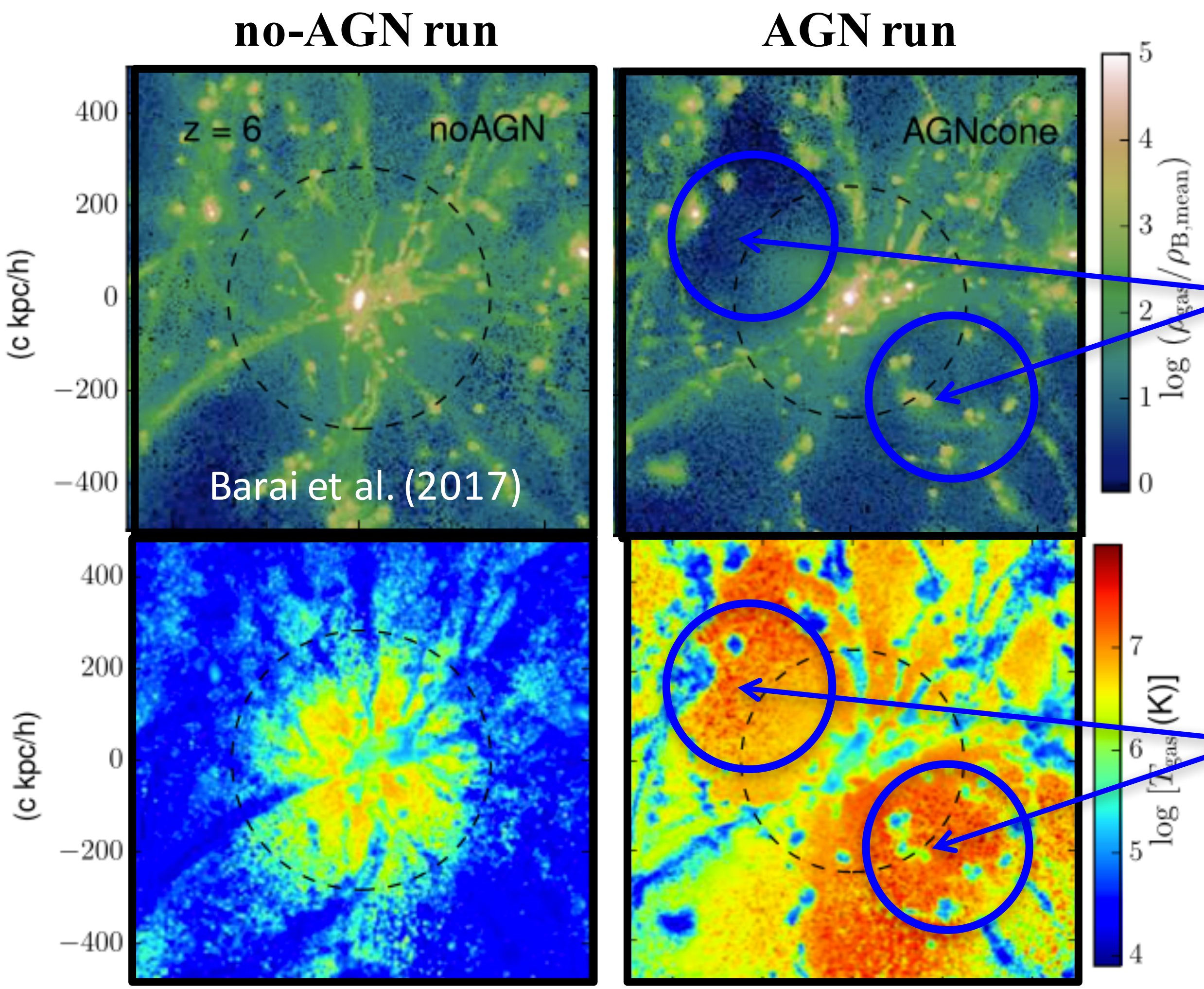
Quasar feedback effects on the host galaxy



Quasar feedback effects on the host galaxy

GAS DENSITY

GAS TEMPERATURE



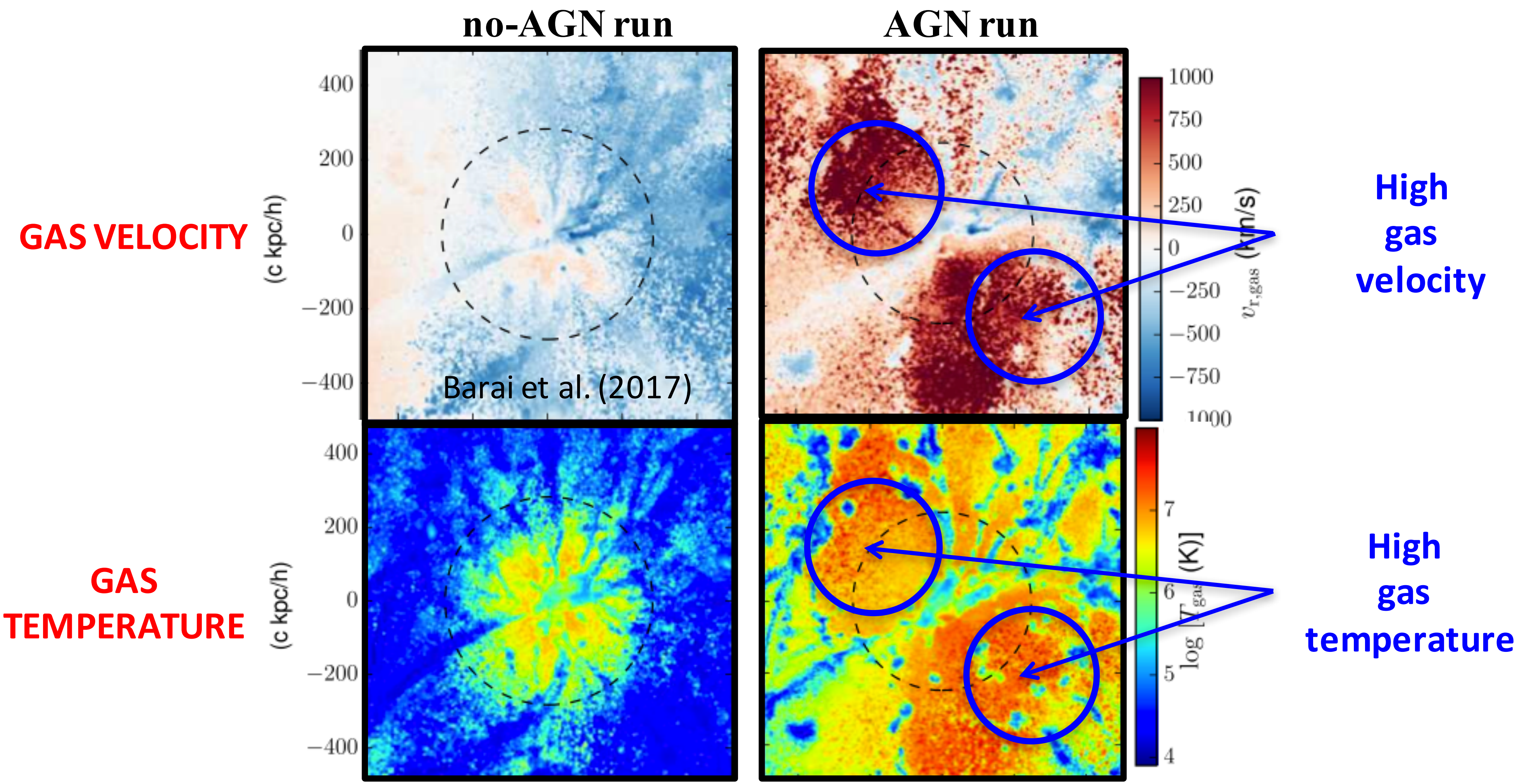
Low gas density

location and extension of the outflow

High gas temperature

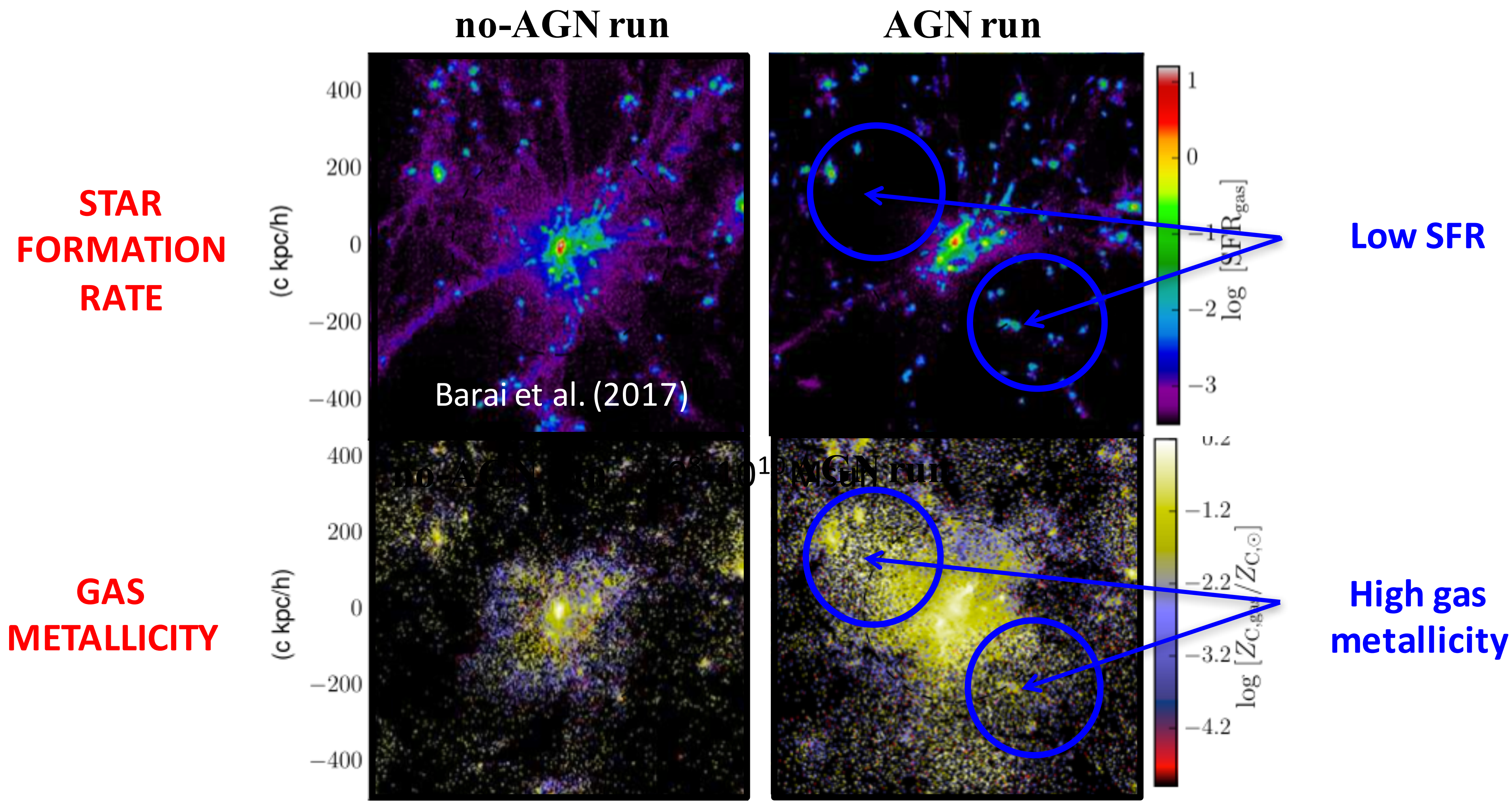
The gas density and temperature maps shows the location and extension of the outflowing gas

Quasar feedback effects on the host galaxy



In the AGN run, particles reach very large velocities (up to 1000 km s^{-1})

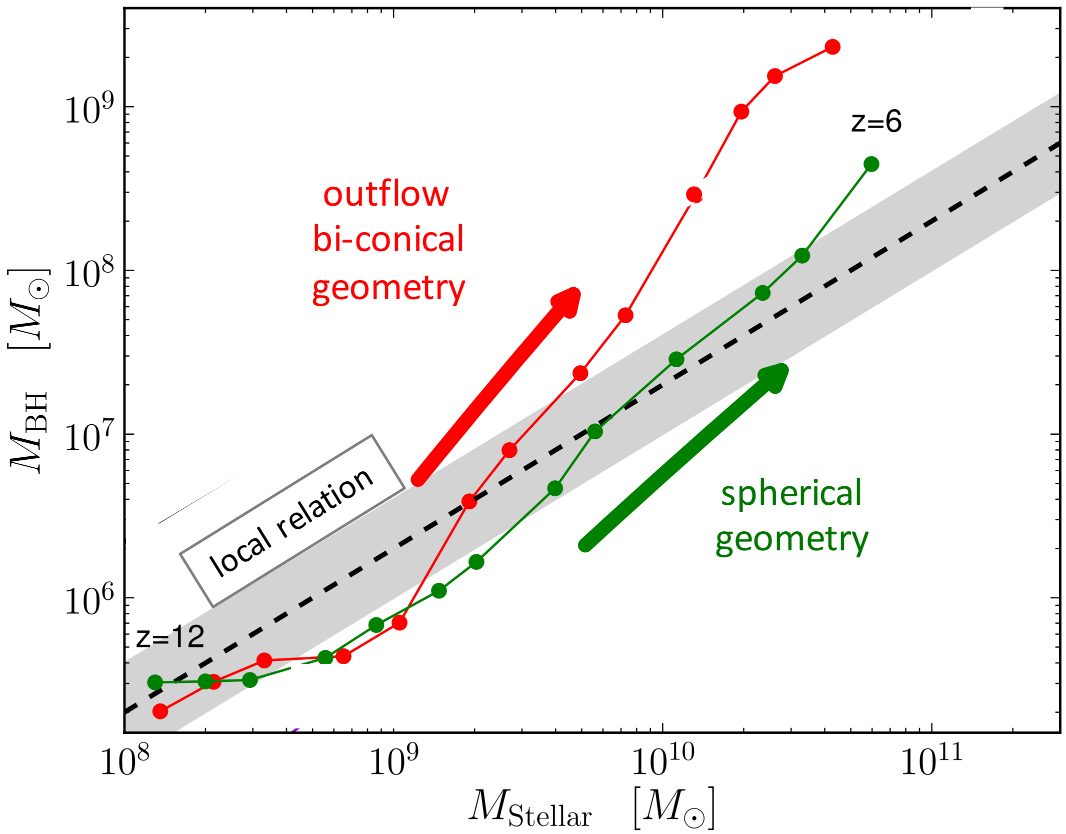
Quasar feedback effects on the host galaxy



Star formation is quenched due to the shock-heated low density gas

Fast outflowing metals are distributed on >10 kpc scales in agreement with [CII] observations of high-z quasars.

The M_{BH}-M_* relation at high redshift



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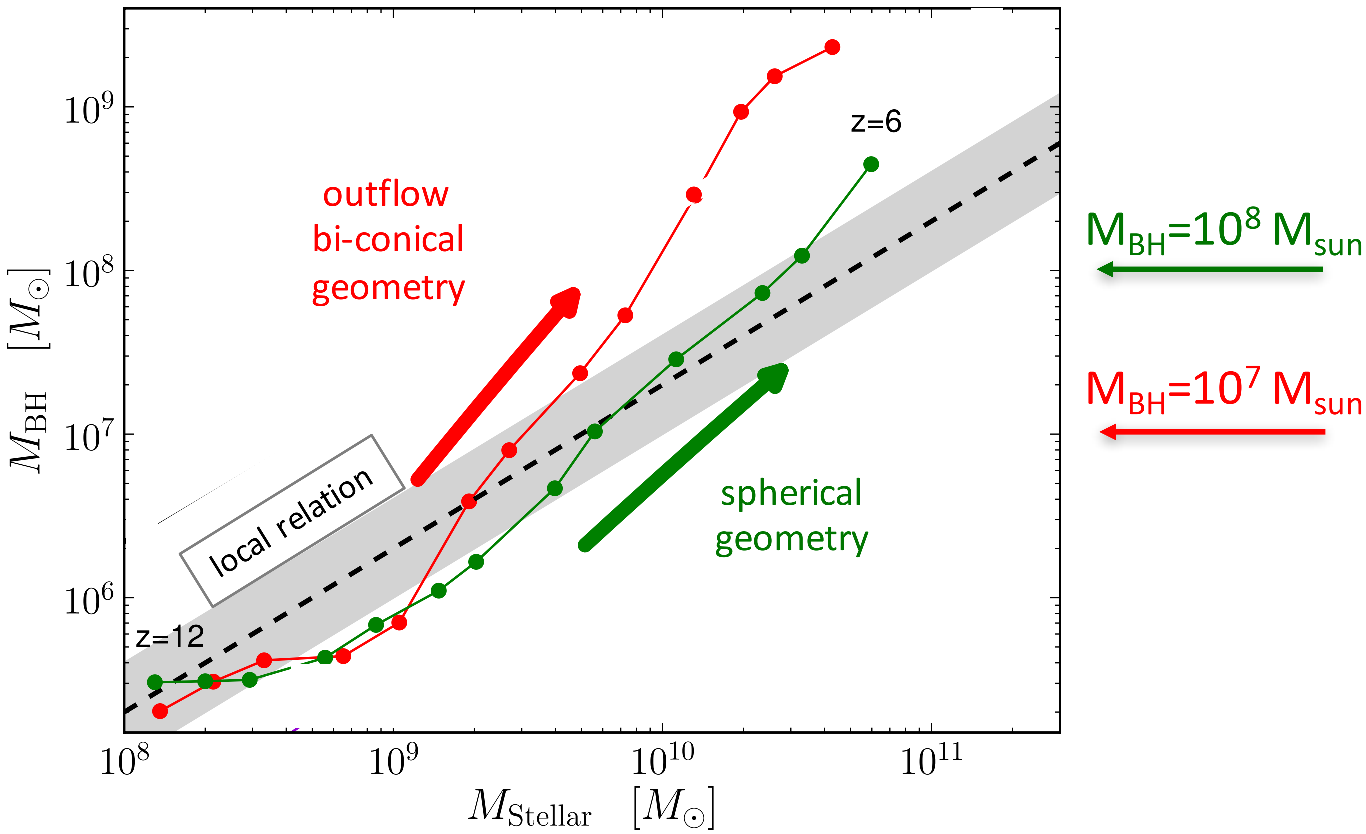
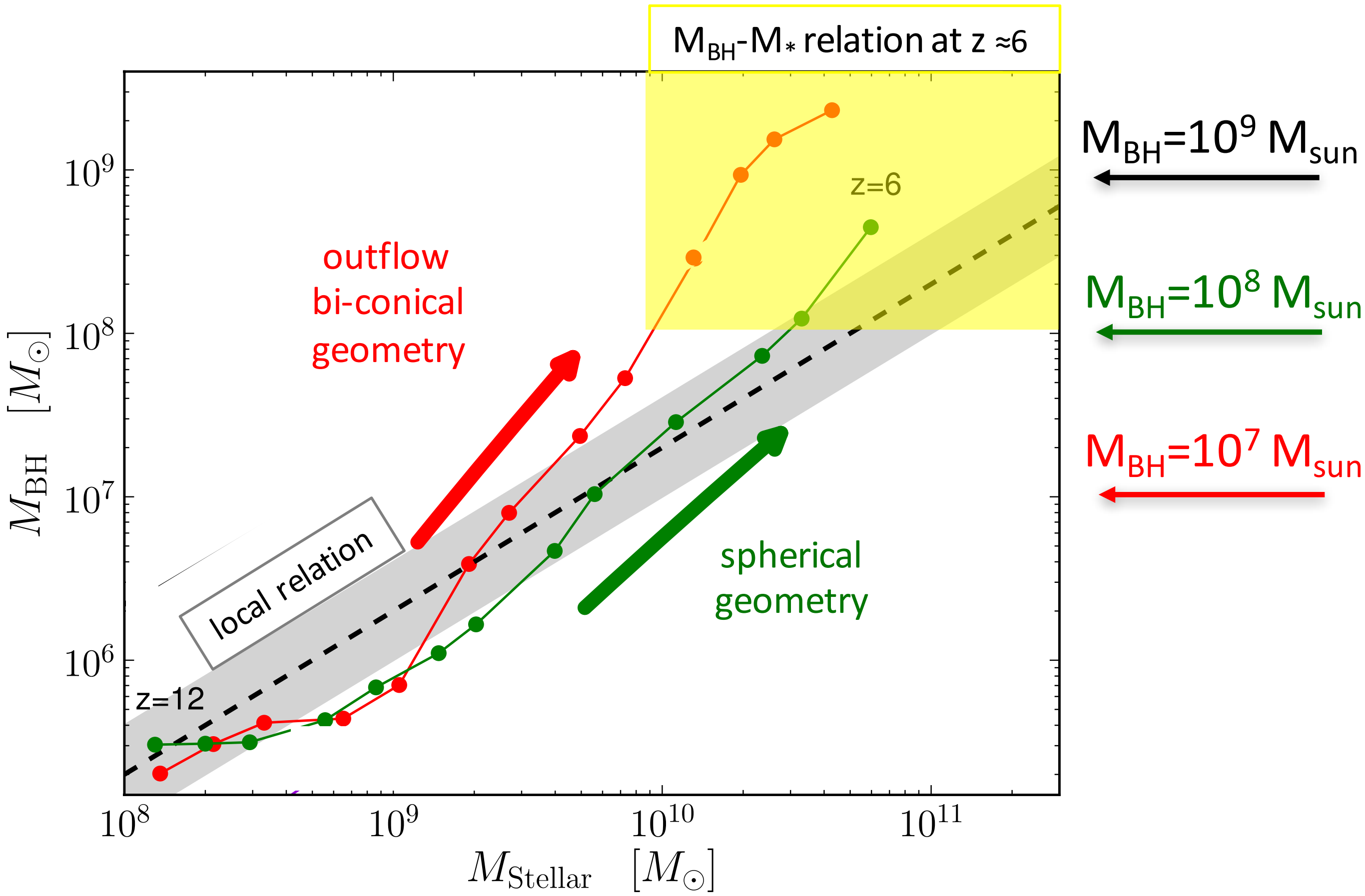


Agreement with the local M_{BH}-M_* relation

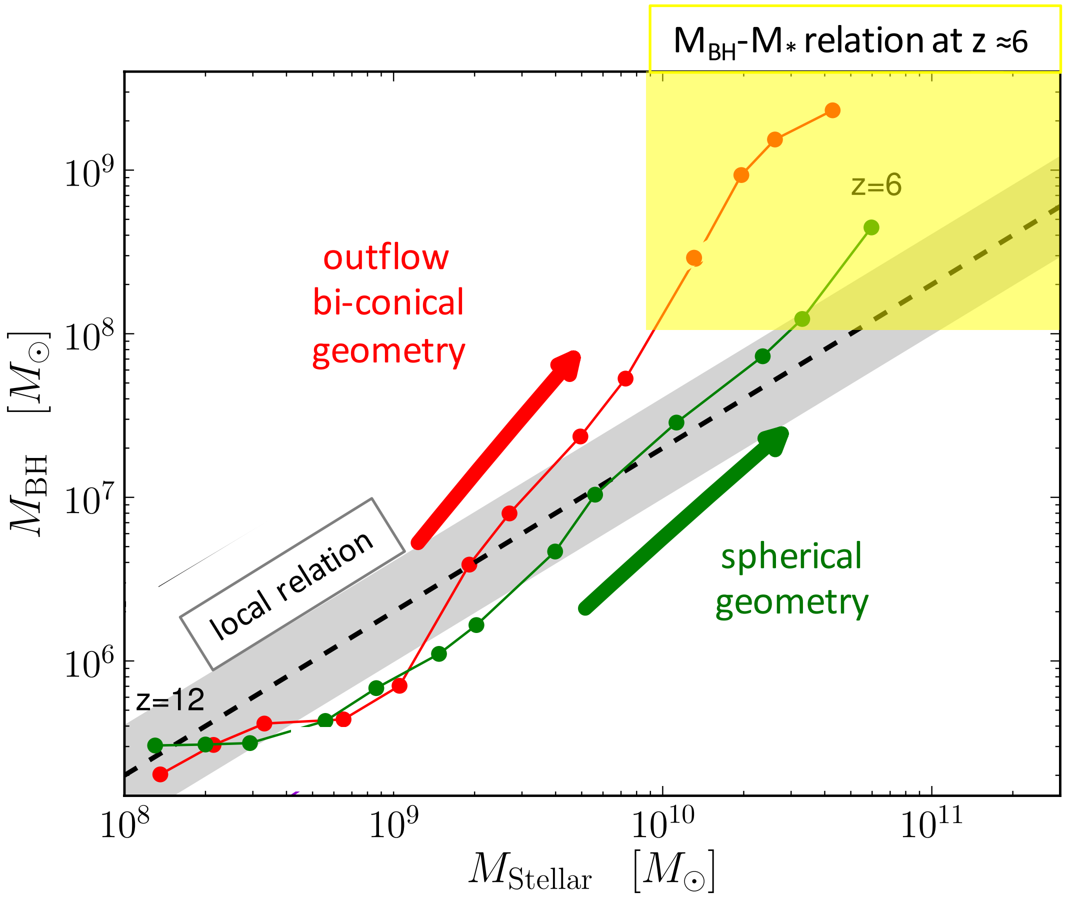
The M_{BH}-M_* relation at high redshift



Deviation from the local M_{BH}-M_* relation

Agreement with the local M_{BH}-M_* relation

The M_{BH}-M_* relation at high redshift



$M_{BH}=10^9\ M_{sun}$

$M_{BH}=10^8\ M_{sun}$

$M_{BH}=10^7\ M_{sun}$

Deviation from the local M_{BH}-M_* relation

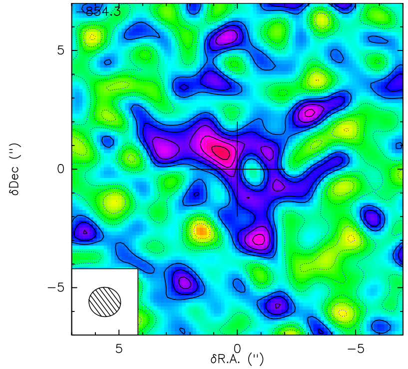
Agreement with the local M_{BH}-M_* relation

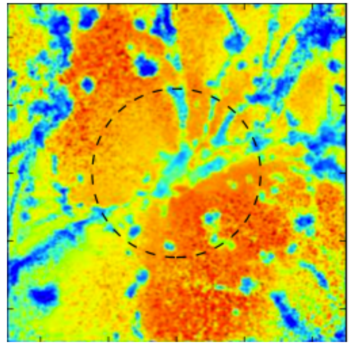
More observations of z ≈ 6 quasars are required to put tighter constraints on the M_{BH}-M_* relation at high redshift

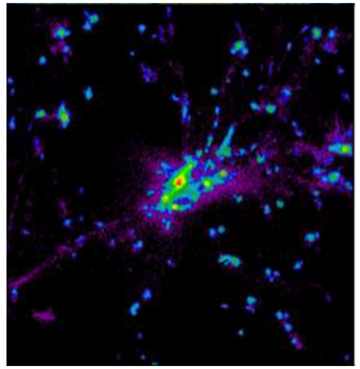
Are quasar feedback in z ≈ 6 quasars more efficient than in local Universe counterparts?

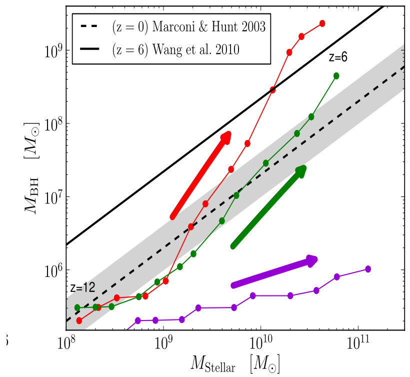
Super Massive Black Holes in the early Universe

- $z \approx 6$ quasars are powered by 10^8-10^{10} Msun BH
- Quasar feedback are in place at high-z
- Cosmological simulations can reproduce the BH observed masses starting from massive seeds (M_{seed}= 10^5 Msun)
- Quasar feedback quenches star formation expelling the surrounding gas out of the host galaxy
- The M_{BH}-M_* does not evolve with z for M_{BH}=10^7 -10^8 M_{sun}
- Above this mass range the BH grows faster than M_*









Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

collapse of primordial stars
(M_{PopIII}>100 M_{sun})
in DM minihalos
(M_{DM}≈10^6 M_{sun})

z≈20-30

(2) Compact nuclear star clusters

Star collisions can lead
to the formation of VMSs
in H_2-cooling halos
(T_{vir}<10^4 K)

z ≈10-20

(3) Direct Collapse Black Holes

Primordial gas
irradiated by LW radiation
in atomic-cooling halos
(T_{vir}>10^4 K)

z > 10

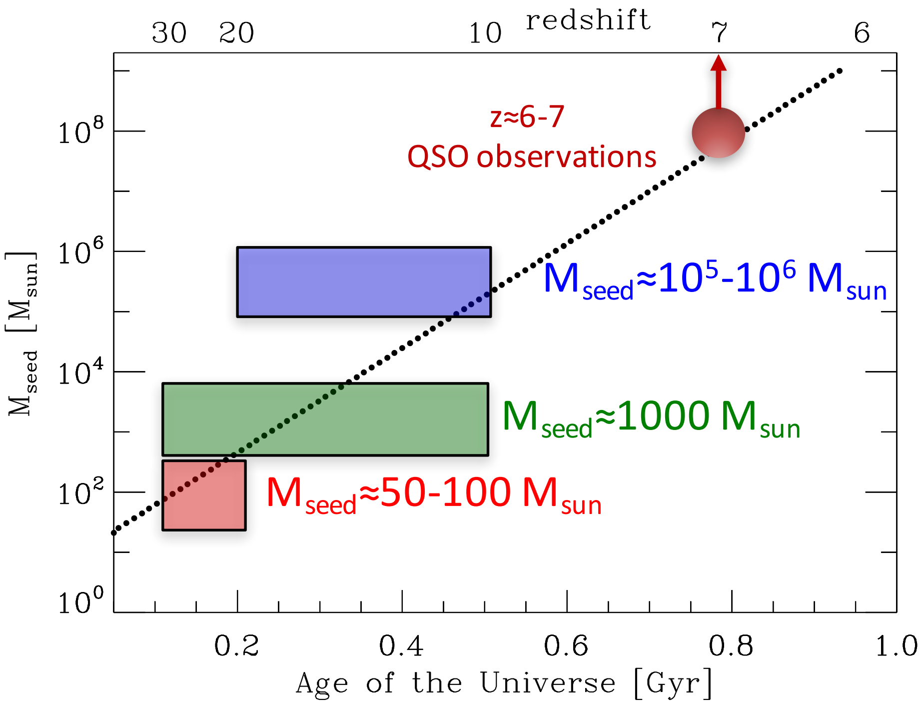
z ≈ 3300 ⟵ …

(4) Primordial Black Holes

Direct collapse of
primordial density
inhomogeneities

z > 2.3 x $10^4 h^2 \Omega_m$
(radiation-dominated era)

DM candidates



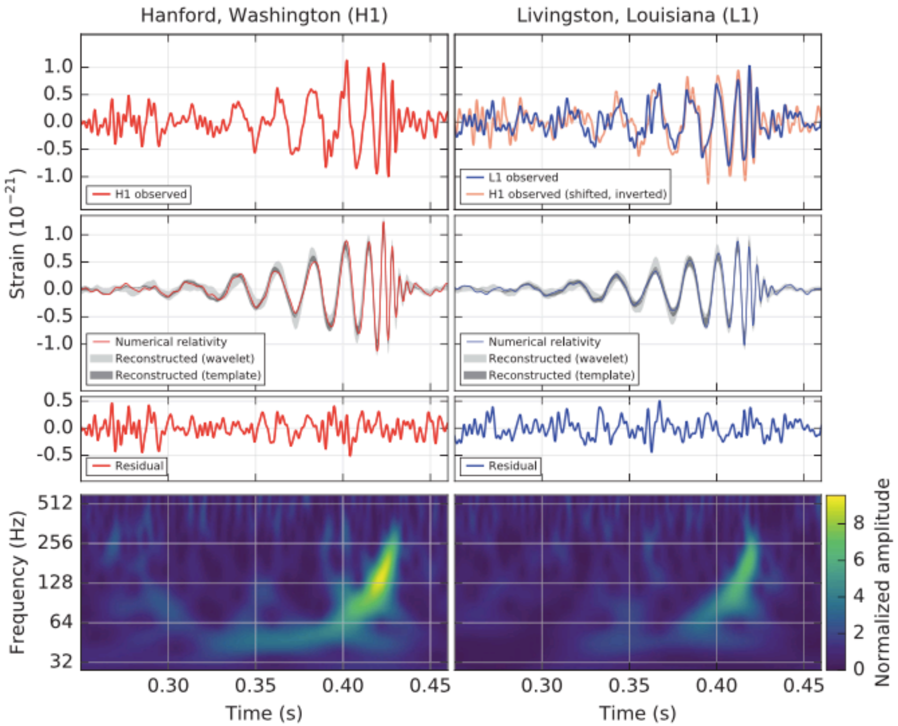
(e.g. Zel'dovich & Novikov 1967; Hawking 1971; Chapline et al. 1975; Bernal et al. 2017)

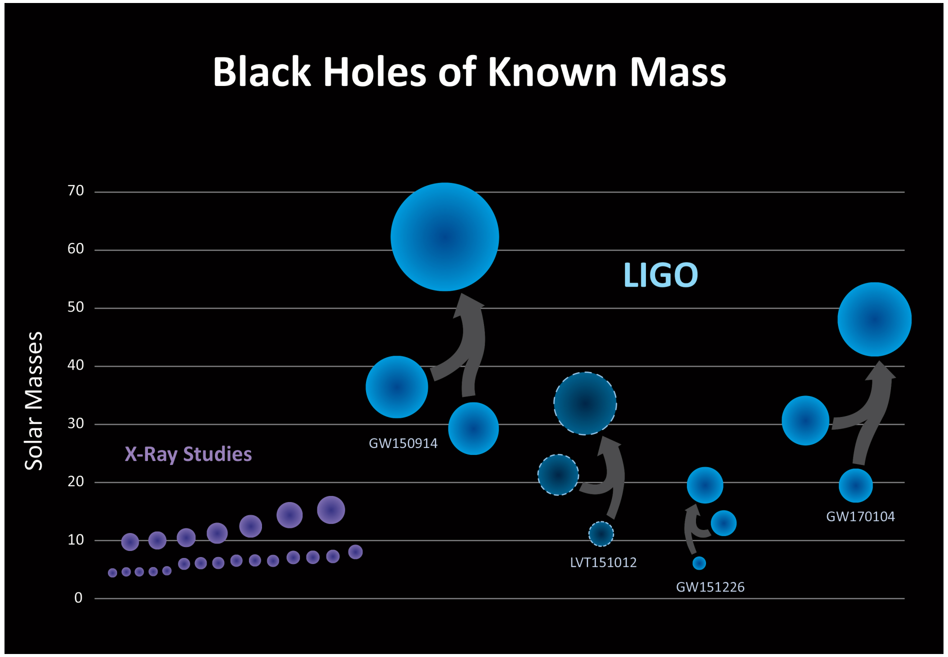
(e.g. Haehnelt & Rees 1993; Yue et al. 2013; Pallottini et al. 2017; Pacucci et al. 2017)

(e.g. Schneider et al. 2006; Clark et al. 2008; Devecchi et al. 2012)

(e.g. Tegmark et al. 1997; Madau & Rees 2001; Palla et al. 2002)

Gravitational wave detection from merging BHs



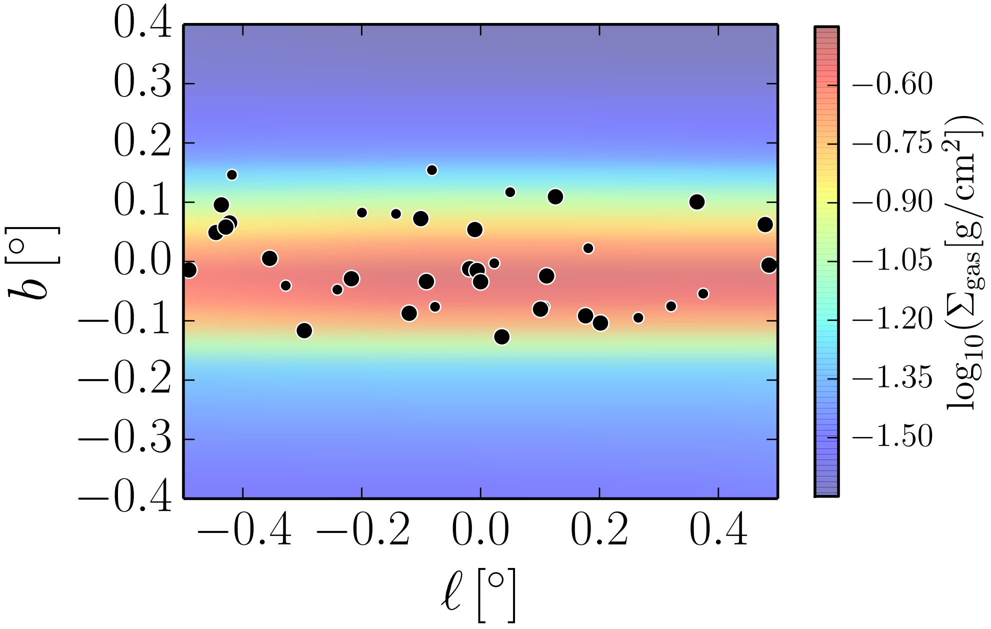


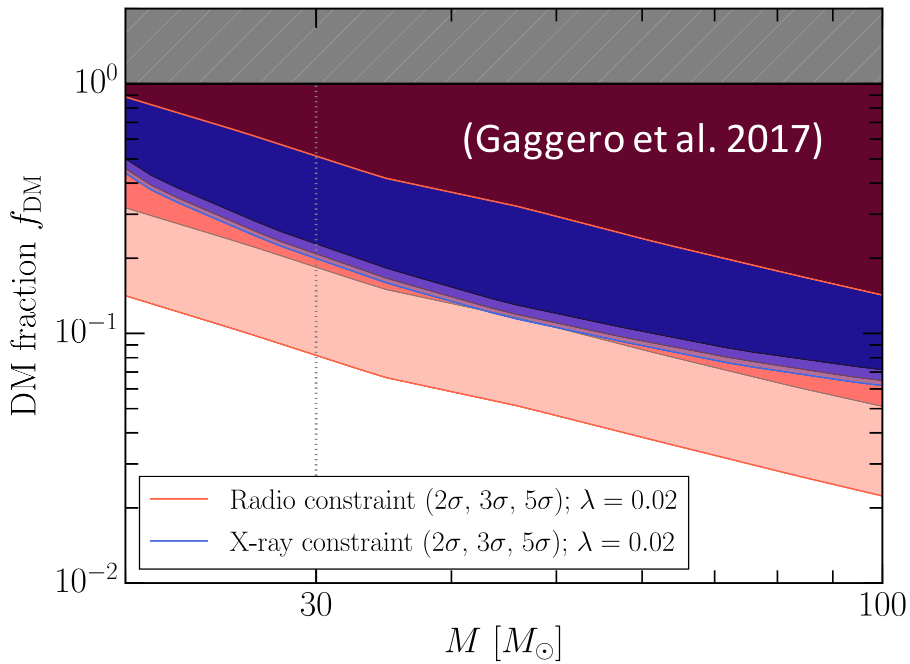
The measured BH masses (10-40 M_{sun}) and event rate (2-53 $Gpc^{-3}yr^{-1}$)

provide important constraints on the hypothesis

that PBHs can be constituents of DM

Gravitational Waves constraints on PBHs as DM





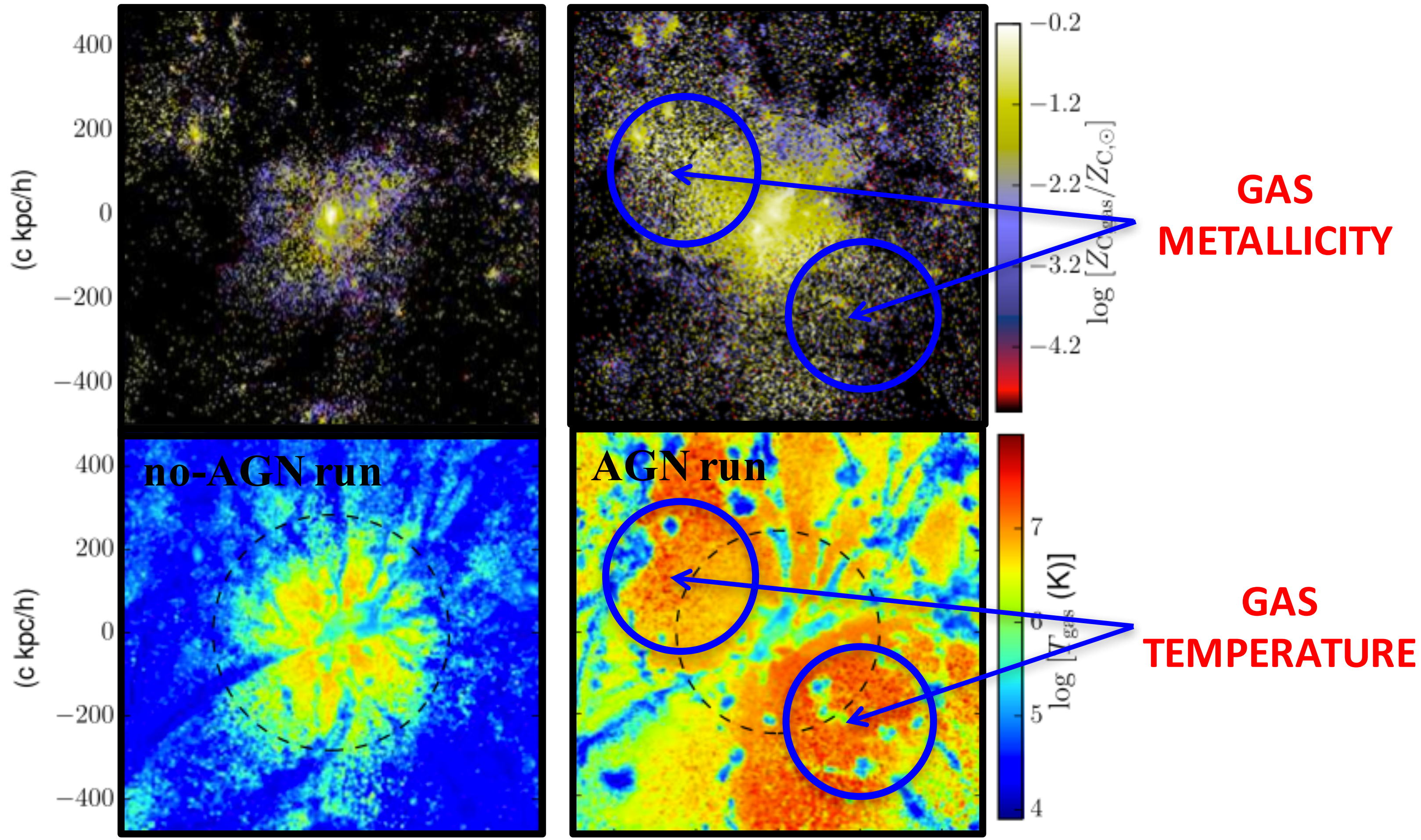
Assumption: a fraction f_{DM} of Dark Matter in the Galactic Ridge is constituted by PBHs

Method: Model of gas accretion onto PBHs; predictions of X-ray and radio emission

Result: 30 M_{sun} PBHs cannot constitute more than 10% of DM in our galaxy.

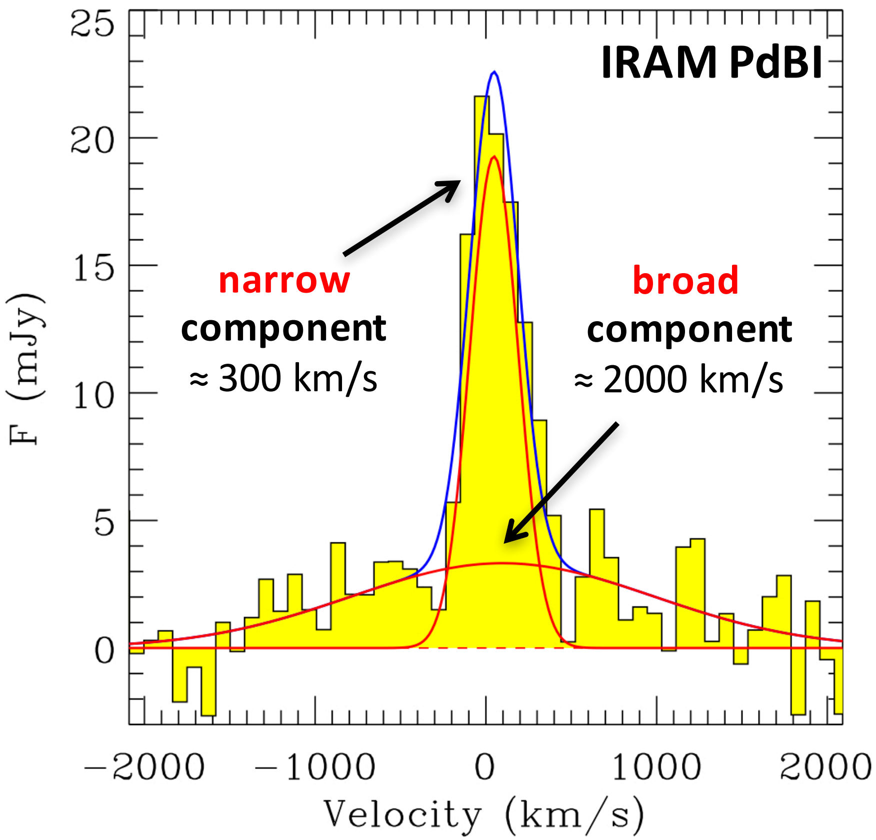
Quasar-driven feedback: Gas metallicity

Barai et al. (2017)



Metals are distributed on very large scale (≥ virial radius) possibly being ejected in the inter-galactic medium

[CII] emission in J1148 at z ≈ 6.4



Broad wings
extended up to
± 1300 km/s

indication of a
powerful outflow

Maiolino et al. (2012)

Evidence of strong quasar feedback at z≈6