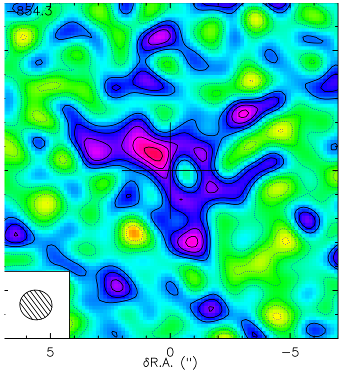
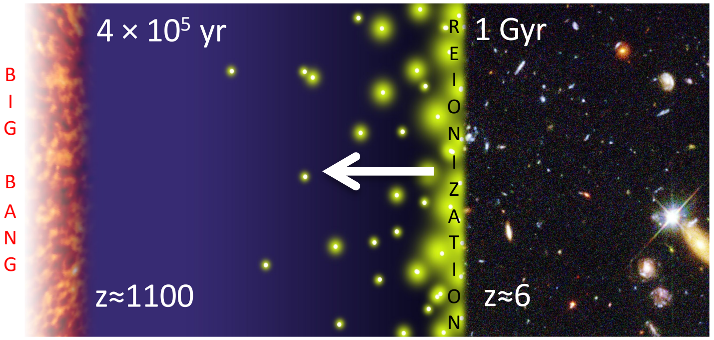
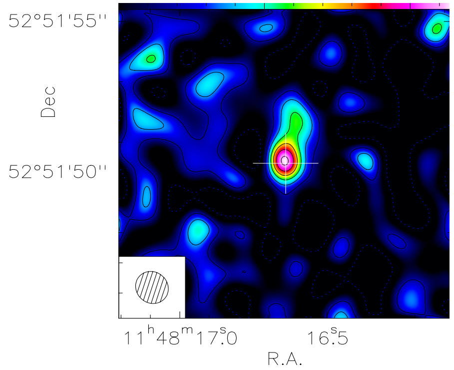
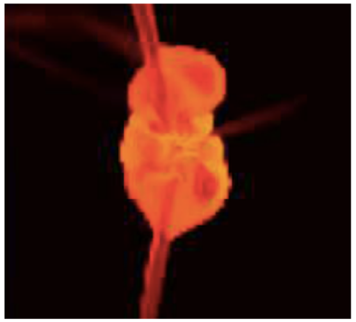
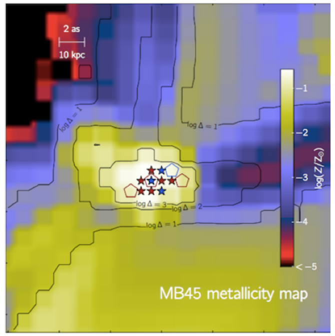






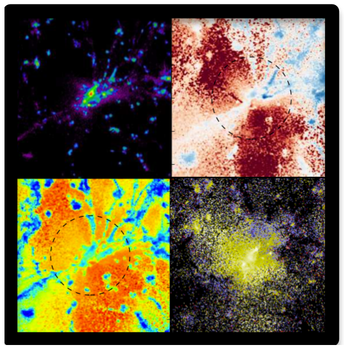
SEED BLACK HOLES

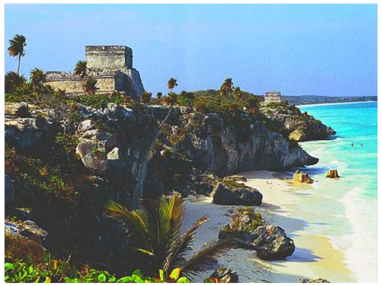


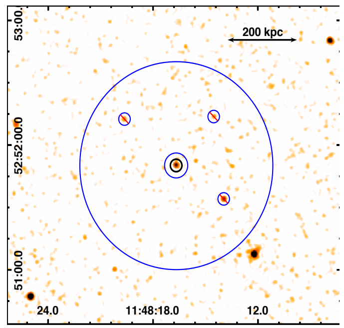


Simona Gallerani

SCUOLA NORMALE SUPERIORE



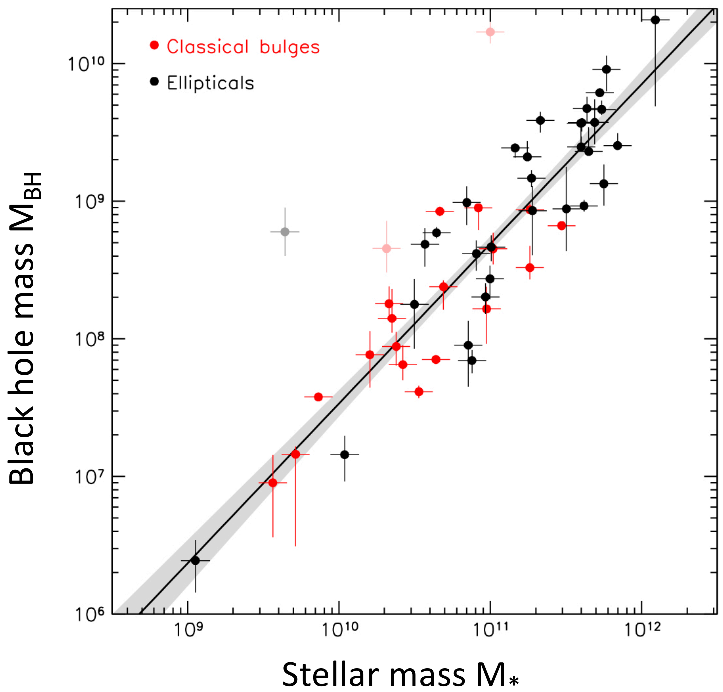




XII Mexican School on Gravitation and Mathematical Physics
"Black Holes and Gravitational Waves»
Playa del Carmen, 9th November 2018

Observations of SMBH in the local Universe

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



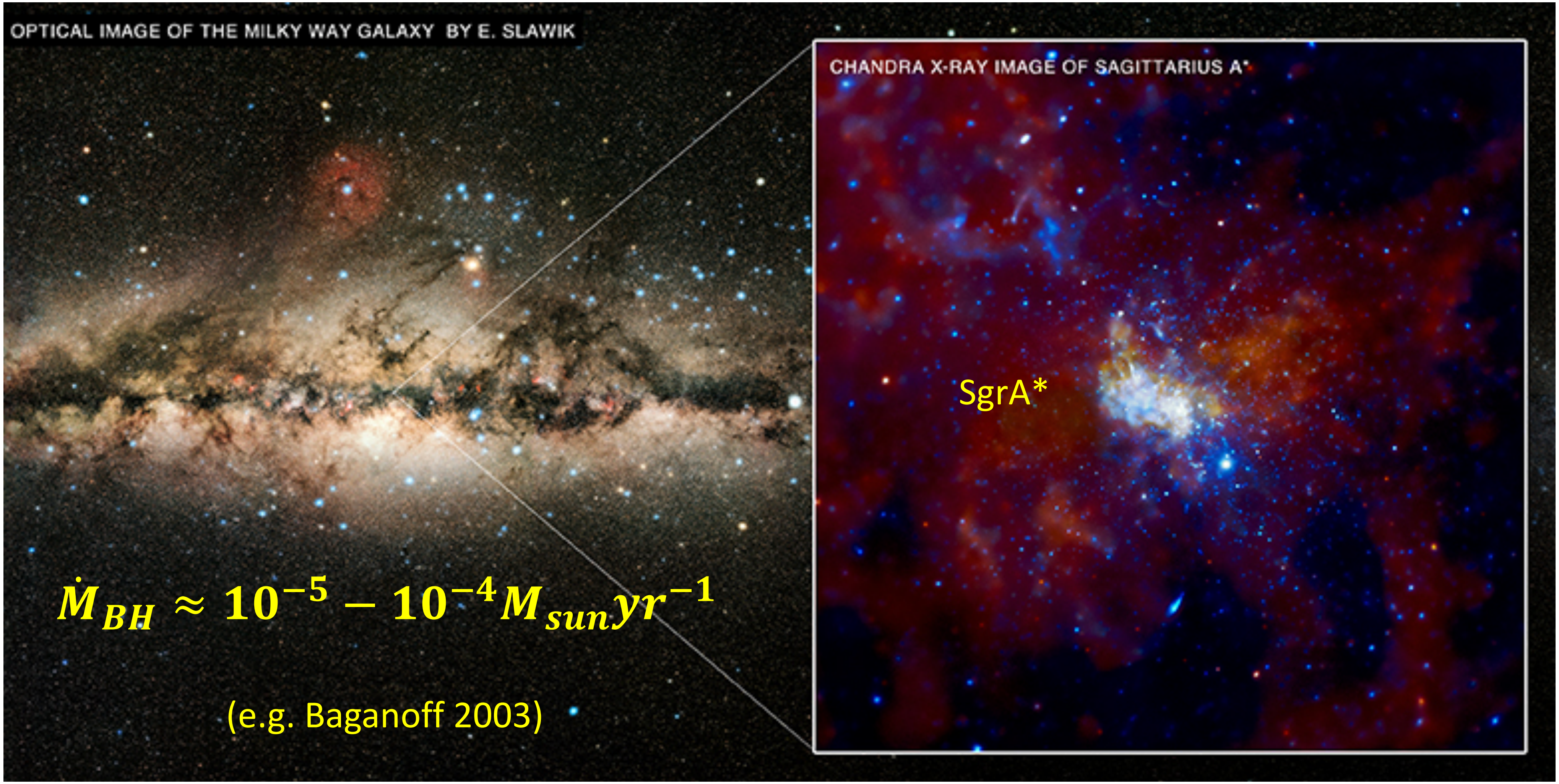
The masses of SMBHs correlate with the stellar masses of their host galaxy

Black hole – Galaxy co-evolution

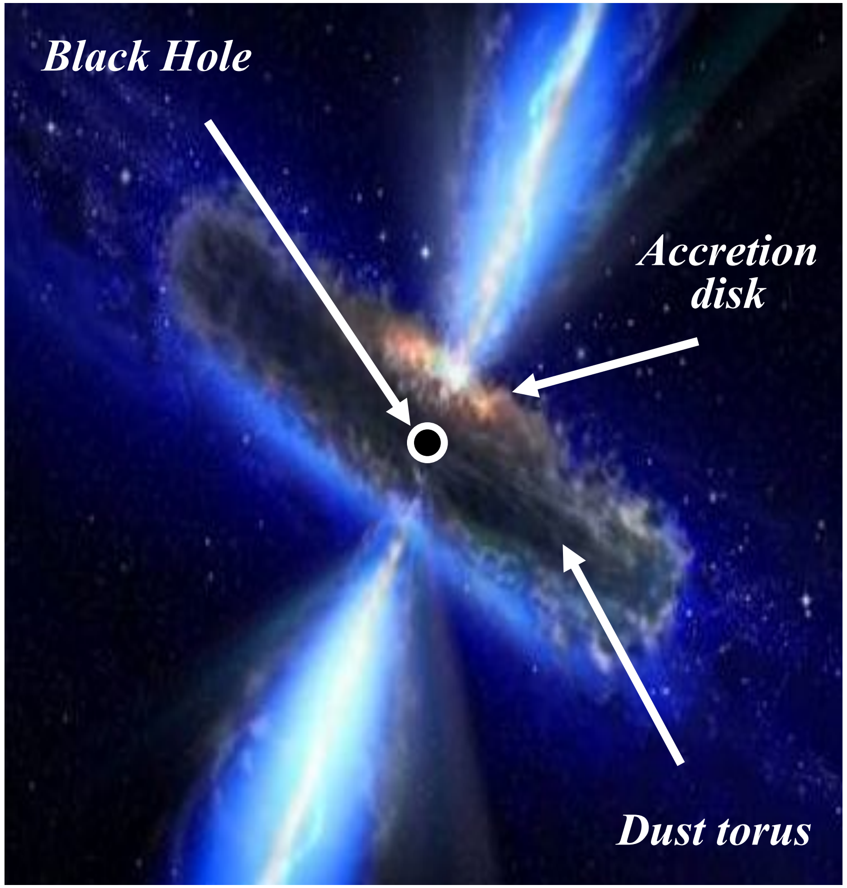
The origin of the local M_{BH} - M_* relation is still debated

Observations of Sgr A* in the Milky Way

SMBHs ($M_{BH} \approx 10^6 - 10^{10}\, M_{sun}$) are present in the center of massive galaxies,
including the Milky Way ($M_{BH} \approx 4 \times 10^6\, M_{sun}$)
(e.g. Melia & Falcke 2001, Kormendy & Ho 2013)



Active Galactic Nuclei



An **active galactic nucleus** (AGN) is defined as a galaxy containing a > $10^5\,M_{sun}$ accreting black hole with **Eddington ratio** exceeding the limit of

$$\mathbf{L_{Bol}/L_{Edd} = 10^{-5}}$$

L_{Bol} is the **Bolometric luminosity**

L_{Edd} is the **Eddington luminosity**

The Eddington luminosity, also called the «Eddington limit», is the maximum luminosity that a body can achieve such that the force exerted by radiation pressure (acting outwards) is balanced by the gravitational force (acting inwards).

(See Netzer ARA&A 2015 for a recent review)

The Eddington luminosity

The Eddington luminosity is the maximum luminosity that a body can achieve such that the force exerted by radiation pressure (F_p acting outwards) is balanced by the gravitational force (F_g acting inwards).

L	Luminosity
$\frac{L}{c}$	Momentum carried by photons per unit time
$\frac{L}{4\pi r^2 c}$	Momentum carried by photons per unit time per unit surface

The Eddington luminosity

The Eddington luminosity is the maximum luminosity that a body can achieve such that the force exerted by radiation pressure (F_p acting outwards) is balanced by the gravitational force (F_g acting inwards).

L	Luminosity
$\frac{L}{c}$	Momentum carried by photons per unit time
$\frac{L}{4\pi r^2 c}$	Momentum carried by photons per unit time per unit surface

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

Force perceived by the gas as a consequence of radiation pressure

The Eddington luminosity

The Eddington luminosity is the maximum luminosity that a body can achieve such that the force exerted by radiation pressure (F_p acting outwards) is balanced by the gravitational force (F_g acting inwards).

L	Luminosity
$\frac{L}{c}$	Momentum carried by photons per unit time
$\frac{L}{4\pi r^2 c}$	Momentum carried by photons per unit time per unit surface

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

Force perceived by the gas as a consequence of radiation pressure

$$F_g = \frac{GMm_p}{r^2}$$

Force perceived by the gas as a consequence of gravity

The Eddington luminosity

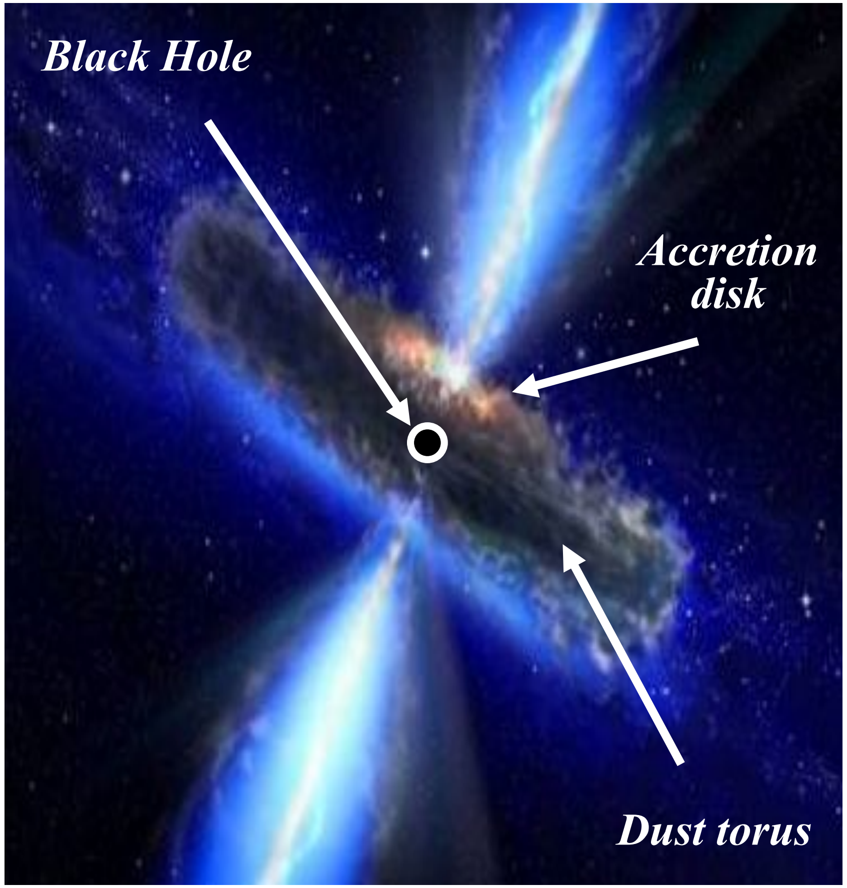
The Eddington luminosity is the maximum luminosity that a body can achieve such that the force exerted by radiation pressure (F_p acting outwards) is balanced by the gravitational force (F_g acting inwards).

$$F_p = \sigma_T \frac{L}{4\pi r^2 c} \qquad \Longleftrightarrow \qquad F_g = \frac{GMm_p}{r^2}$$

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

$$L_{EDD} = \frac{4\pi c G M m_p}{\sigma_T} \approx 1.5 \times 10^{38} \frac{M}{M_{sun}} \; erg \; s^{-1}$$

Active Galactic Nuclei



An **active galactic nucleus** (AGN) is defined as a galaxy containing a > 10^5 M_{sun} accreting black hole with **Eddington ratio** exceeding the limit of

$$\mathbf{L_{Bol}/L_{Edd} = 10^{-5}}$$

L_{Bol} is the **Bolometric luminosity**

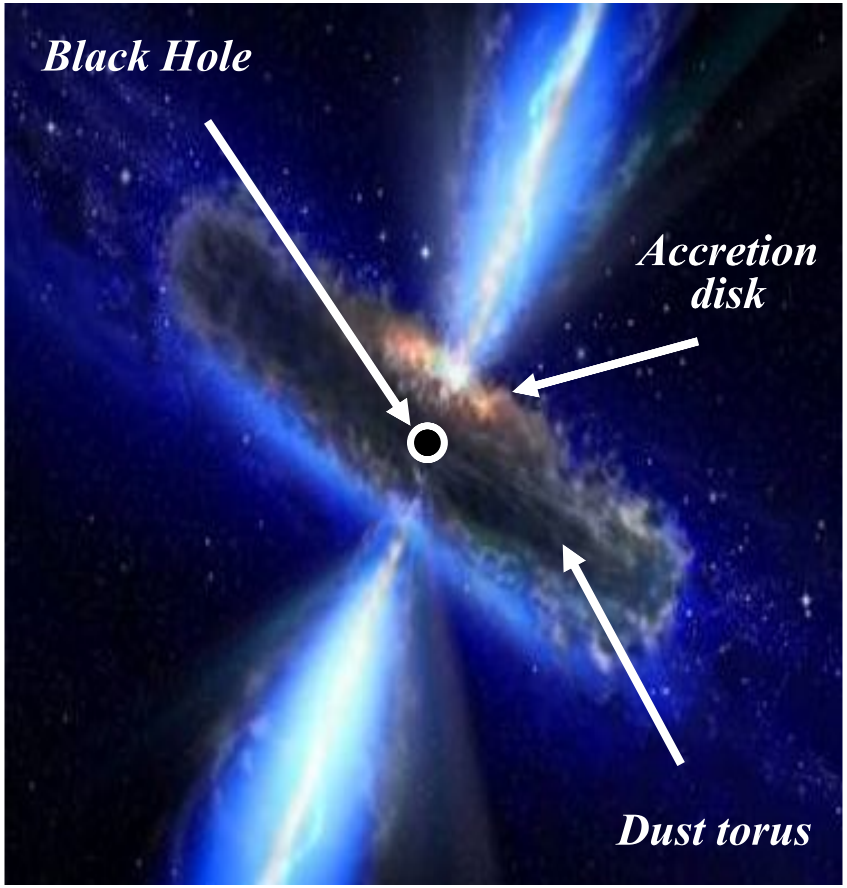
L_{Edd} is the **Eddington luminosity**

The Eddington luminosity, also called the «Eddington limit», is the maximum luminosity that a body can achieve such that the force exerted by radiation pressure (acting outwards) is balanced by the gravitational force (acting inwards).

The name AGN refers to the main feature that distinguishes these objects from ordinary (i.e. inactive) galaxies: the presence of an accreting super massive black hole (SMBH) in their center.

(See Netzer ARA&A 2015 for a recent review)

Quasars: a class of very bright Active Galactic Nuclei



An **active galactic nucleus** (AGN) is defined as a galaxy containing a > 10^5 M_{sun} accreting black hole with **Eddington ratio** exceeding the limit of

$$L_{Bol}/L_{Edd} = 10^{-5}$$

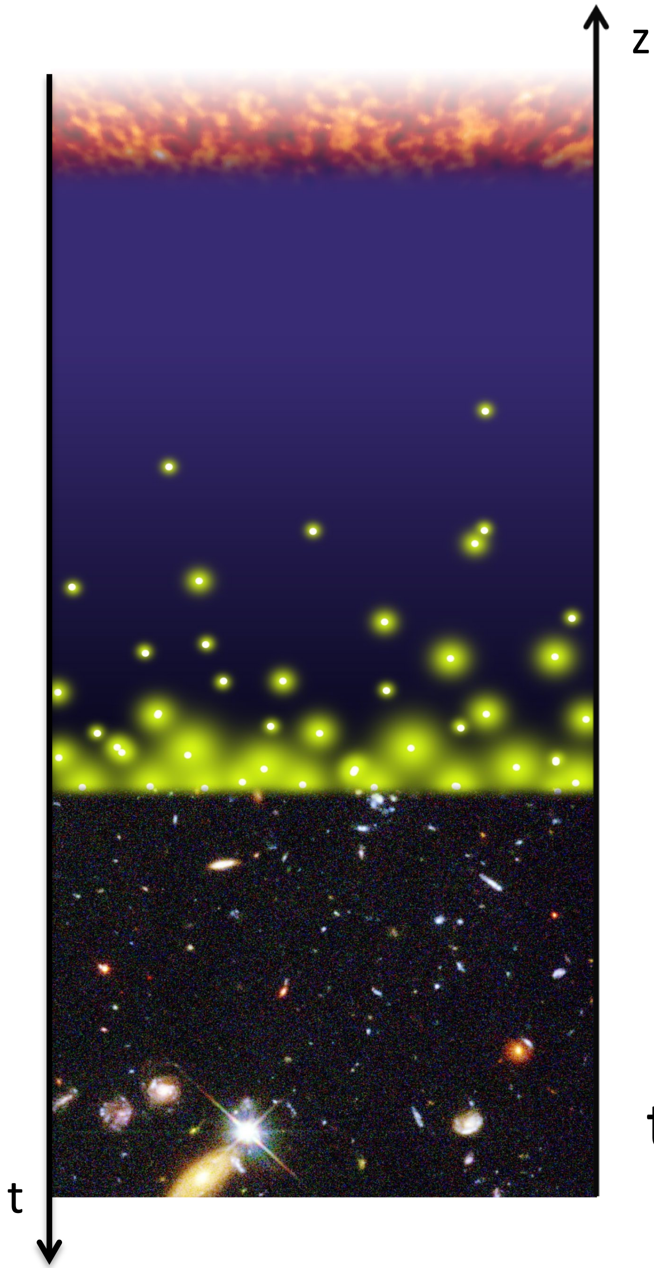
$$\boxed{L_{Bol} > 10^{46}\ \mathrm{erg\ s^{-1}}}$$

The Eddington luminosity, also called the «Eddington limit», is the maximum luminosity that a body can achieve such that the force exerted by radiation pressure (acting outwards) is balanced by the gravitational force (acting inwards).

The name AGN refers to the main feature that distinguishes these objects from ordinary (i.e. inactive) galaxies: the presence of an accreting super massive black hole (SMBH) in their center.

(See Netzer ARA&A 2015 for a recent review)

The history of the Universe in a nutshell

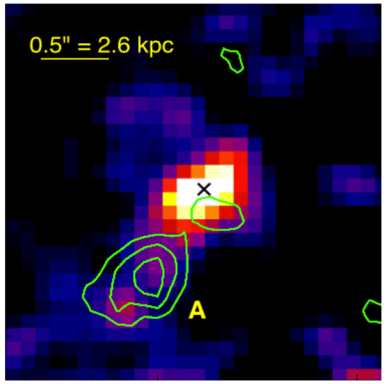


$t = 0$

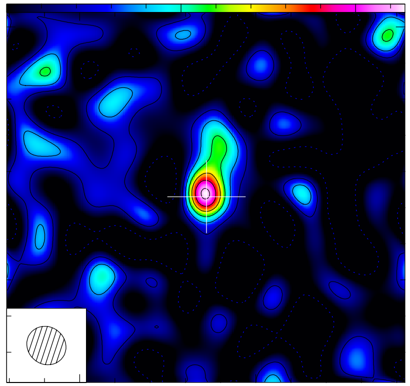
BIG BANG

$z \approx 6$
$t \lesssim 1$ Gyr

First galaxies



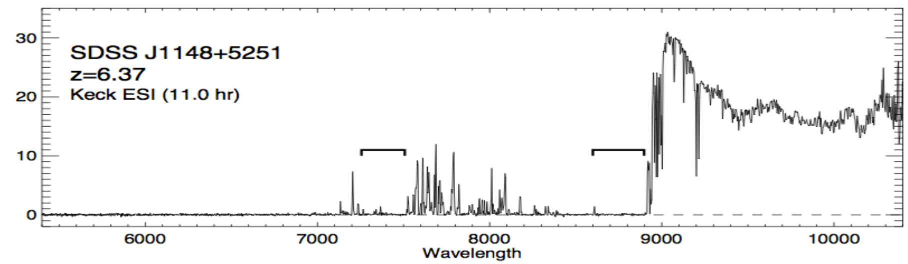
First quasars



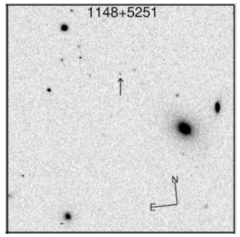
$z = 0$
$t \approx 13.8$ Gyr

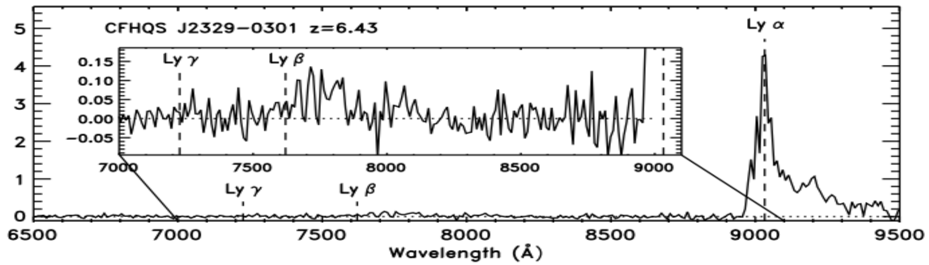
TODAY

Observations of more than 200 quasars at 5.5 < z < 7.5

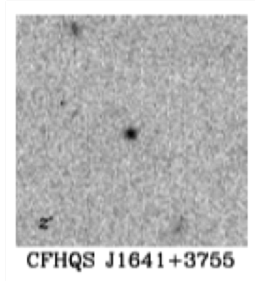


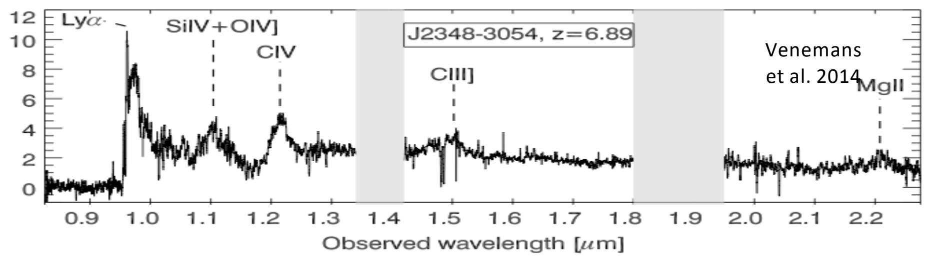
Sloan Digital Sky Survey
(SDSS, Fan et al. 2001,2003,2006)



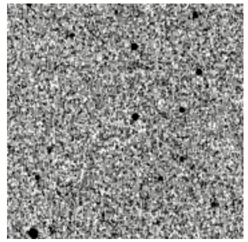


Canada-France High-z Quasar Survey
(CFHQS, Willott et al. 2005,2009,2010)

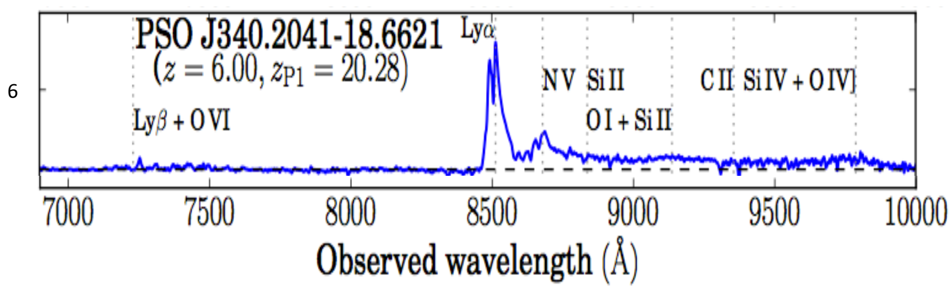




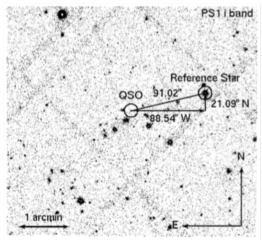
Visible and Infrared Survey Telescope
for Astronomy Kilo-degree INfrared Galaxy
(VIKING, Venemans et al. 2013, 2015)



ULAS J1120

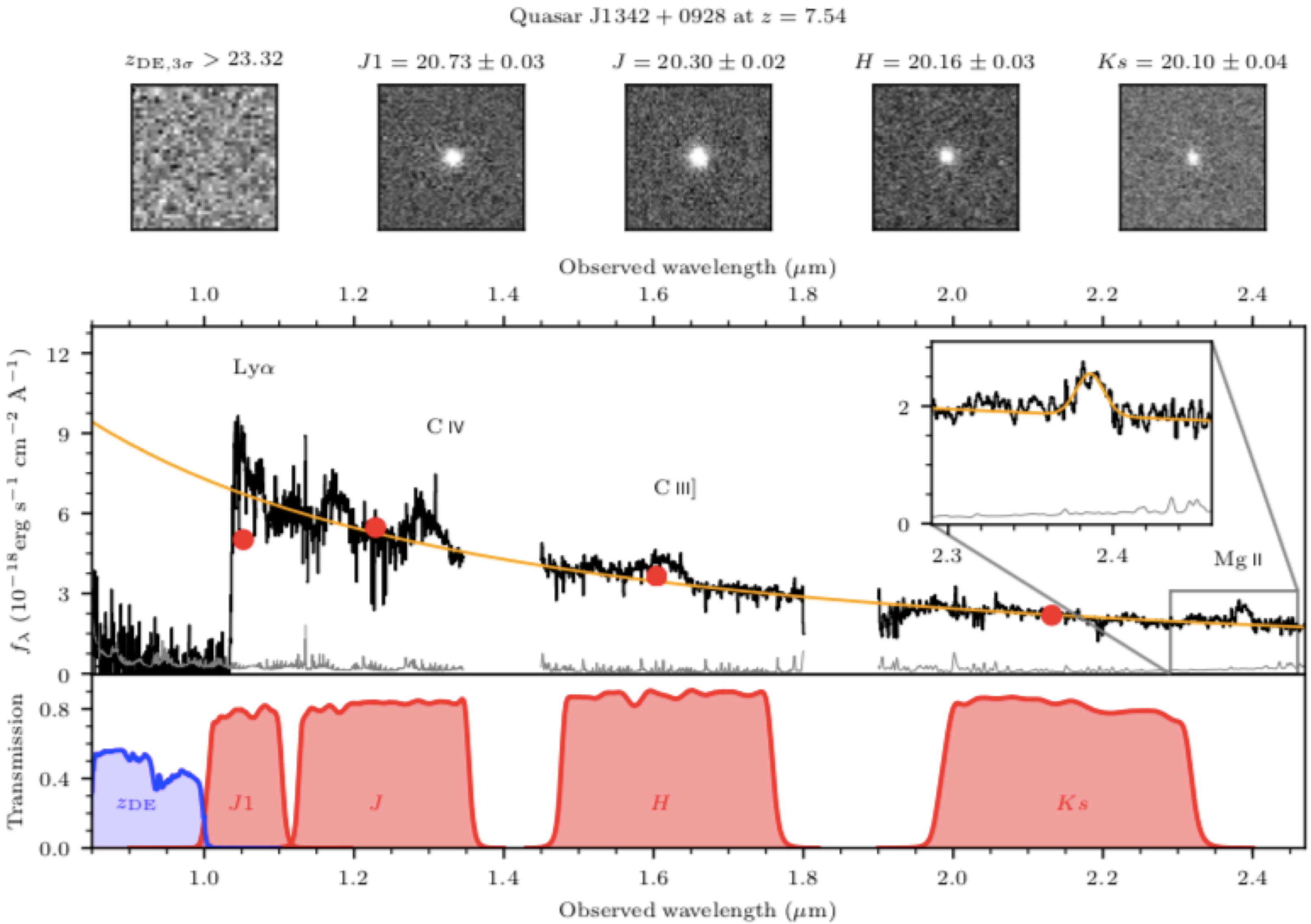


Panoramic Survey Telescope
And Rapid Response System 1
(PanSTARRS1, Banados et al. 2016)



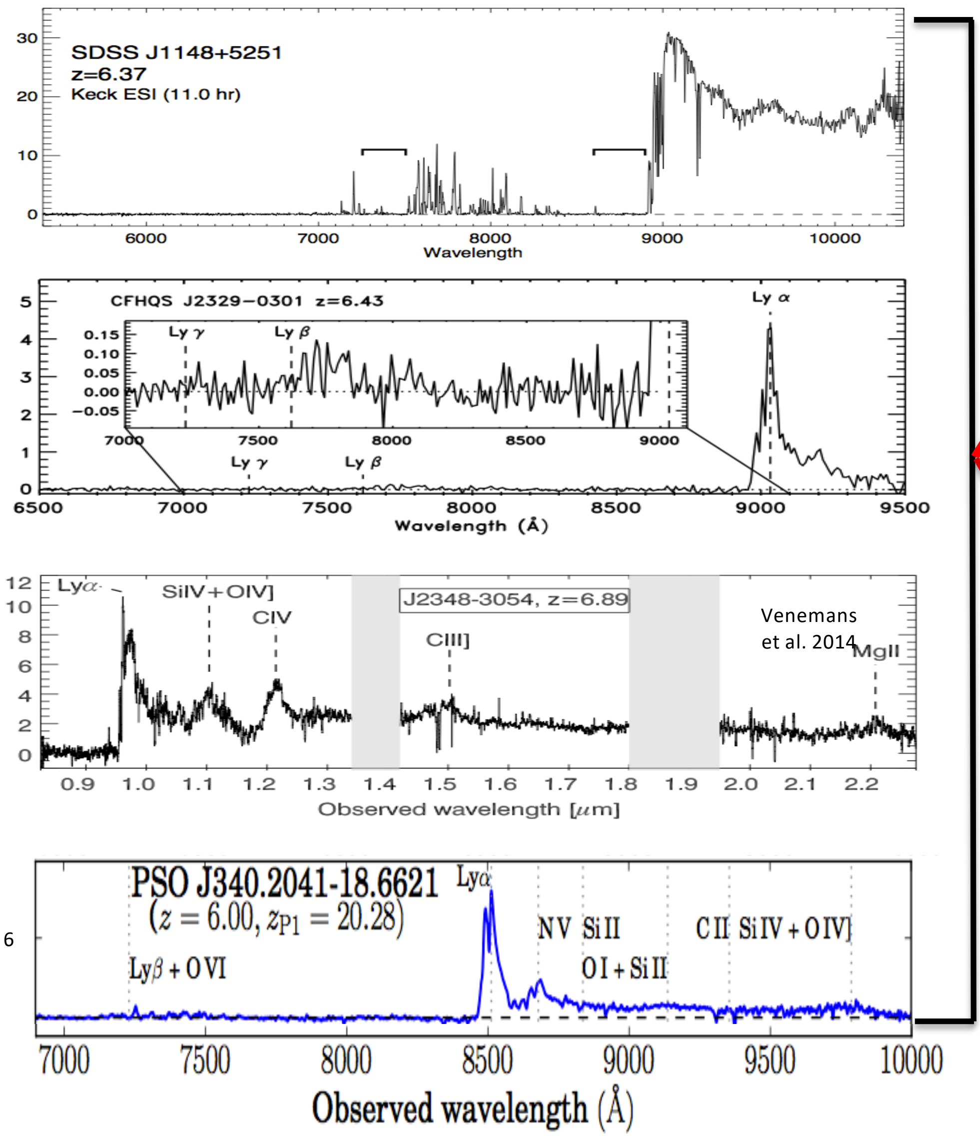
PSO J215

Current record holder



Banados et al. (2018)

Observations of more than 200 quasars at 5.5 < z < 7.5



Cosmic reionization

Fan et al. 2006, Gallerani et al. 2006, 2008a,b, Mesinger et al. 2010, Greig et al. 2017

Metal enrichment

D'Odorico et al. 2013, Pallottini et al. 2014

High-z dust properties

Maiolino et al. 2004, Gallerani et al. 2010

Host galaxy properties

Maiolino et al. 2006, Gallerani et al. 2012, Riechers et al. 2007, Gallerani et al. 2014, Venemans et al. 2017

Galaxy-BH co-evolution

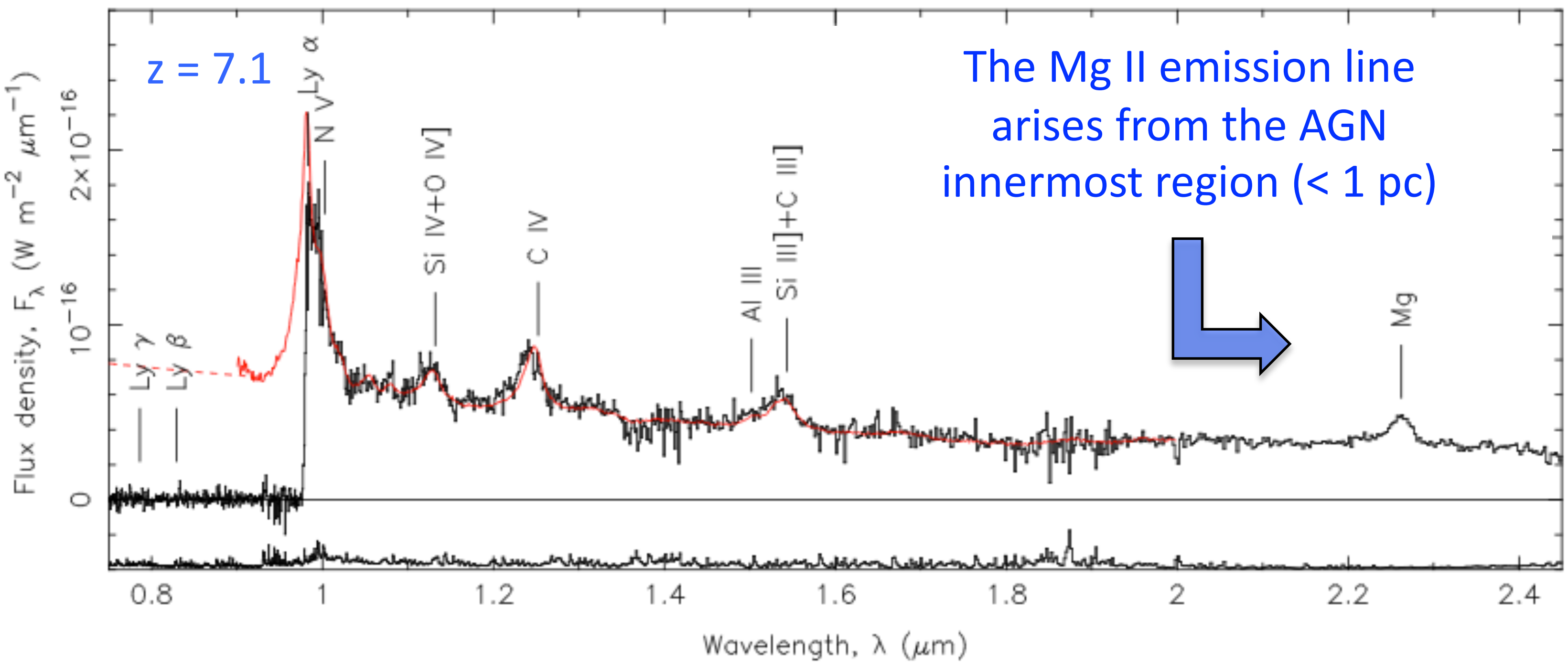
Maiolino et al. 2012, Cicone et al. 2015, Barai et al. 2017

Cosmological scales (1-100 Mpc)

Galactic scales (10 pc-10 kpc)

See Gallerani, Fan, Maiolino, Pacucci (2017) for a recent review, arXiv:1702.06123

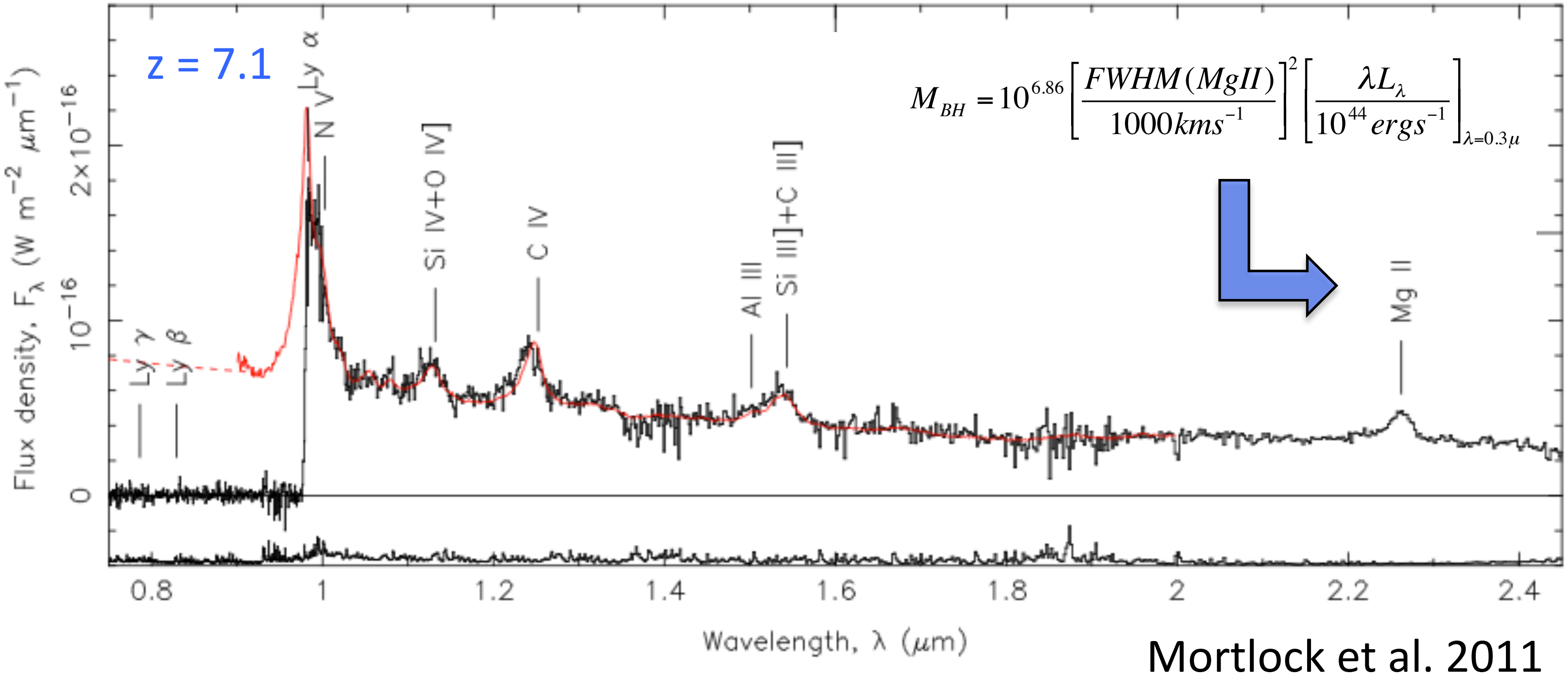
Black hole mass measurements in z ≈ 6 quasars



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



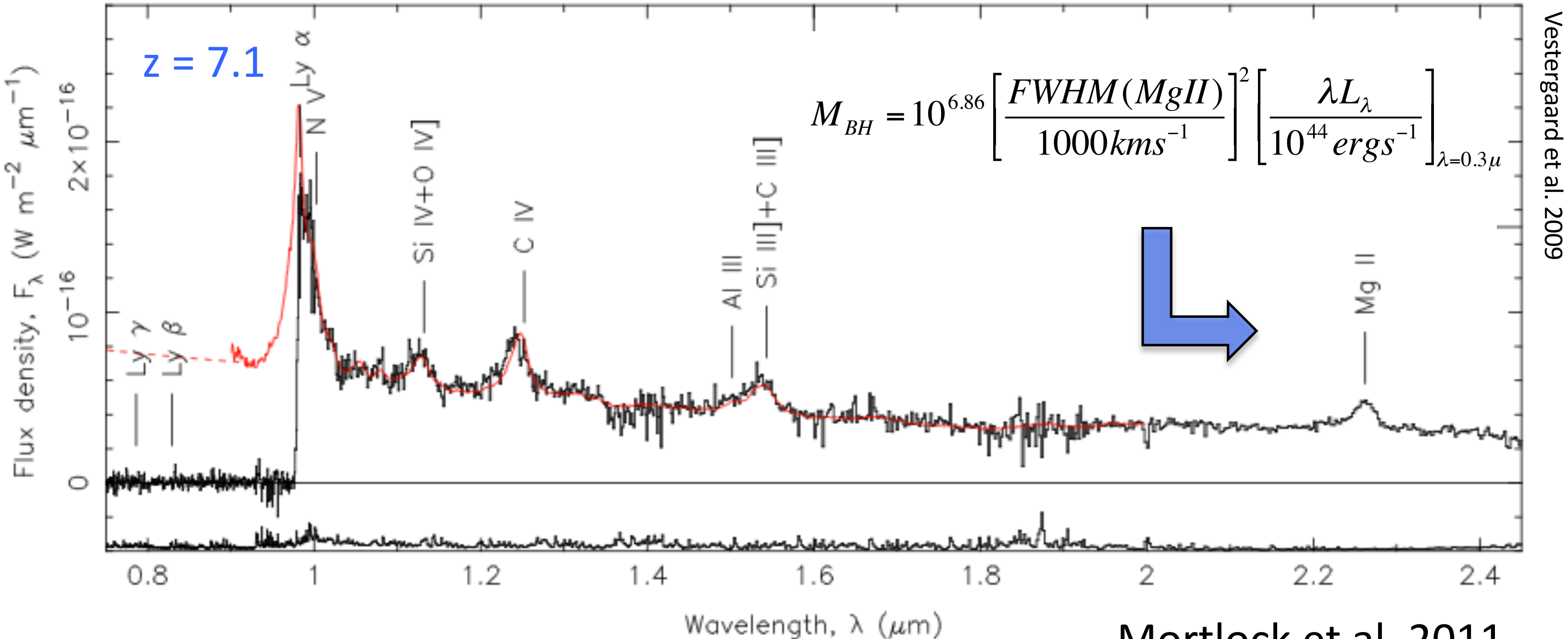
Vestergaard et al. 2009

Mortlock et al. 2011

$$\boxed{M_{BH} = 2\times10^9 M_{sun}}$$

in less than 1 Gyr!

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?

What is the timescale for assembling a SMBH?

$$L_{Bol} = \epsilon_{rad} c^2 \dot{M}_{gas}$$

$\epsilon_{rad} \approx 0.06 - 0.3$

What is the timescale for assembling a SMBH?

$$L_{Bol} = \epsilon_{rad} c^2 \dot{M}_{gas}$$

$\epsilon_{rad} \approx 0.06 - 0.3$

$$\dot{M}_{BH} = \dot{M}_{gas}\,(1\text{-}\ \epsilon_{rad})$$

fraction of mass that is not converted in radiation is accreted by the BH

What is the timescale for assembling a SMBH?

$$L_{Bol} = \epsilon_{rad} c^2 \dot{M}_{gas}$$

$\epsilon_{rad} \approx 0.06 - 0.3$

$$\dot{M}_{BH} = \dot{M}_{gas}\,(1\text{-}\ \epsilon_{rad})$$

fraction of mass that is not converted in radiation is accreted by the BH

$$\dot{M}_{BH} = \frac{(1 -\ \epsilon_{rad})}{\epsilon_{rad}} \frac{L_{Bol}}{c^2}$$

Let us combine the two equations

What is the timescale for assembling a SMBH?

$$L_{Bol} = \epsilon_{rad} c^2 \dot{M}_{gas}$$

$\epsilon_{rad} \approx 0.06 - 0.3$

$$\dot{M}_{BH} = \dot{M}_{gas}\,(1\text{-}\ \epsilon_{rad})$$

fraction of mass that is not converted in radiation is accreted by the BH

$$\dot{M}_{BH} = \frac{(1-\epsilon_{rad})}{\epsilon_{rad}} \frac{L_{Bol}}{c^2}$$

Let us combine the two equations

$$\dot{M}_{BH} = \frac{(1-\epsilon_{rad})}{\epsilon_{rad}} \frac{4\pi G m_p}{c\sigma_T} M_{BH}$$

ASSUMPTION: *the BH is radiating at the Eddington luminosity*

What is the timescale for assembling a SMBH?

$$L_{Bol} = \epsilon_{rad} c^2 \dot{M}_{gas}$$

$\epsilon_{rad} \approx 0.06 - 0.3$

$$\dot{M}_{BH} = \dot{M}_{gas}\,(1\text{-}\ \epsilon_{rad})$$

fraction of mass that is not converted in radiation is accreted by the BH

$$\dot{M}_{BH} = \frac{(1 - \epsilon_{rad})}{\epsilon_{rad}} \frac{L_{Bol}}{c^2}$$

Let us combine the two equations

$$\dot{M}_{BH} = \frac{(1 - \epsilon_{rad})}{\epsilon_{rad}} \frac{4\pi G m_p}{c \sigma_T} M_{BH}$$

ASSUMPTION: *the BH is radiating at the Eddington luminosity*

$$\frac{dM_{BH}}{M_{BH}} = \frac{(1 - \epsilon_{rad})}{\epsilon_{rad}} \frac{dt}{t_{EDD}}$$

$t_{EDD} = Eddington\ time = \frac{4\pi G m_p}{c\sigma_T} \approx 0.45\ Gyr$

What is the timescale for assembling a SMBH?

$$L_{Bol} = \epsilon_{rad} c^2 \dot{M}_{gas}$$

$\epsilon_{rad} \approx 0.06 - 0.3$

$$\dot{M}_{BH} = \dot{M}_{gas}\,(1\text{-}\ \epsilon_{rad})$$

fraction of mass that is not converted in radiation is accreted by the BH

$$\dot{M}_{BH} = \frac{(1 - \epsilon_{rad})}{\epsilon_{rad}} \frac{L_{Bol}}{c^2}$$

Let us combine the two equations

$$\dot{M}_{BH} = \frac{(1 - \epsilon_{rad})}{\epsilon_{rad}} \frac{4\pi G m_p}{c \sigma_T} M_{BH}$$

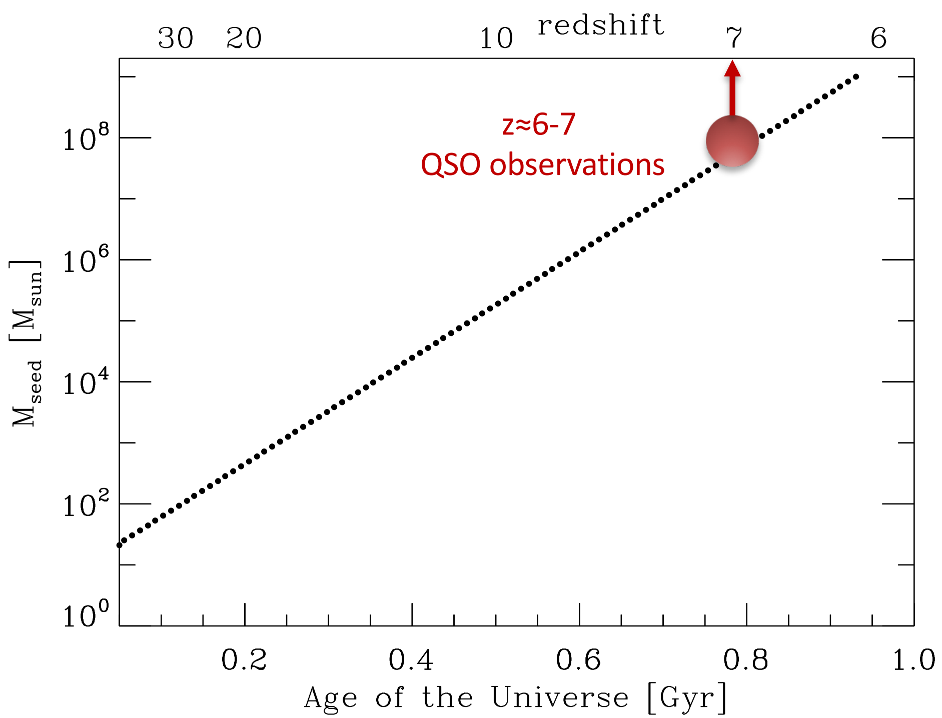
ASSUMPTION: *the BH is radiating at the Eddington luminosity*

$$\frac{dM_{BH}}{M_{BH}} = \frac{(1-\epsilon_{rad})}{\epsilon_{rad}} \frac{dt}{t_{EDD}}$$

$t_{EDD} = Eddington\ time = \frac{4\pi G m_p}{c\sigma_T} \approx 0.45\ Gyr$

$$\boxed{M_{BH}(t) = M_{BH}(t=0) \exp \frac{(1-\epsilon_{rad})}{\epsilon_{rad}} \frac{t}{t_{EDD}}}$$

What is the timescale for assembling a SMBH?



Assumptions:

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

$\varepsilon = 0.1$

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

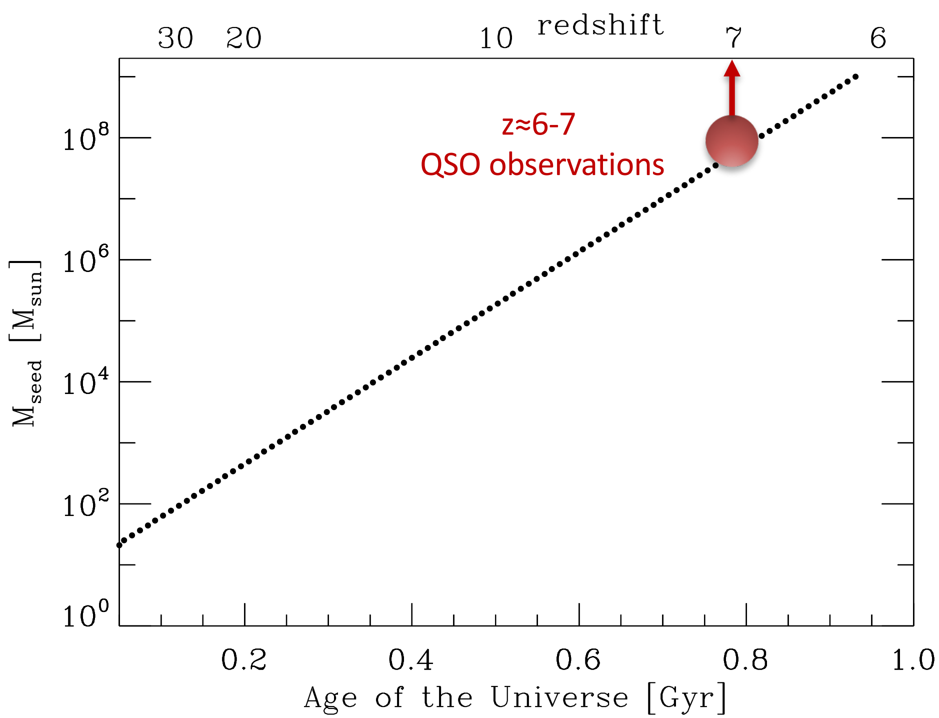
Different scenarios for the origin of SMBH seeds

1. The «PopIII» or «light seeds» scenario
2. The «dense star cluster» scenario
3. The «direct collapse» or «heavy seeds» scenario
4. The «merger-driven direct collapse» scenario
5. The «primordial black holes» scenario

Assumptions:

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

$\varepsilon = 0.1$



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

The «PopIII» or «light seeds» scenario

The first massive stars formed in the Universe after the Big Bang.

These stars are generally called «PopIII» stars, are expected to have formed hundreds million years after the Big Bang (**$z \sim 20\text{-}30$**), in dark matter mini-halos (**$M_{DM} \approx 10^6\ M_{sun}$**), and to have been massive **(>100 M_{sun}**).

The «PopIII» or «light seeds» scenario

The first massive stars formed in the Universe after the Big Bang.

These stars are generally called «PopIII» stars, are expected to have formed hundreds million years after the Big Bang (**z ~20-30**), in dark matter mini-halos (**M_{DM}≈10^6 M_{sun}**), and to have been massive **(>100 M_{sun}**).

Why first stars are massive?

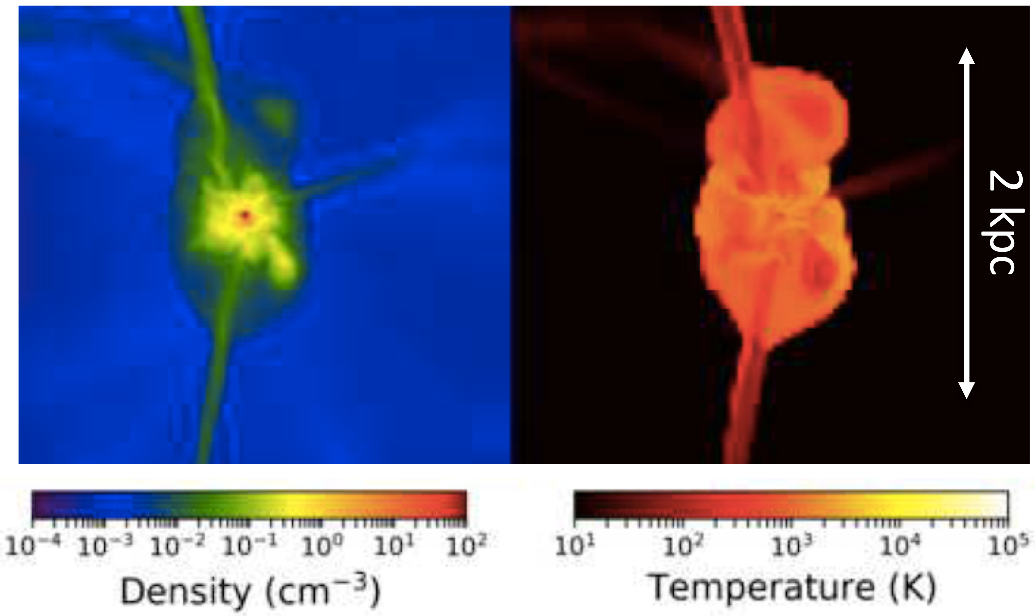
At high redshift, the gas from which stars formed was metal-free. Only hydrogen and helium are available. These elements have limited radiative transitions with respect to higher atomic number elements. Thus the gas from which PopIII stars were formed was unable to cool and fragment into small «typical stars», generally called PopII stars and characterized by 0.1 M_{sun}< M_* < 10 M_{sun} (Salpeter 1965).

The «PopIII» or «light seeds» scenario

The first massive stars formed in the Universe after the Big Bang.

These stars are generally called «PopIII» stars, are expected to have formed hundreds million years after the Big Bang (**z ~20-30**), in dark matter mini-halos (**M_{DM}≈10^6 M_{sun}**), and to have been massive **(>100 M_{sun}**).

Some simulations suggest that the first stars were as massive as **M~100-600 M_{sun}** (e.g., Abel et al. 2002; Bromm et al. 2003). PopIII stars with masses M > 260M_{sun} leave remnant BHs with **M_{seed} > 100 M_{sun}** (Fryer, Woosley & Heger 2003).



Formation of an extremely metal-poor star

In a minihalo with mass ~2 x 10^6 M_{sun}, a Pop III star with mass 13 M_{sun} is formed at redshift z = 12

Chiaki & Wise (2018)

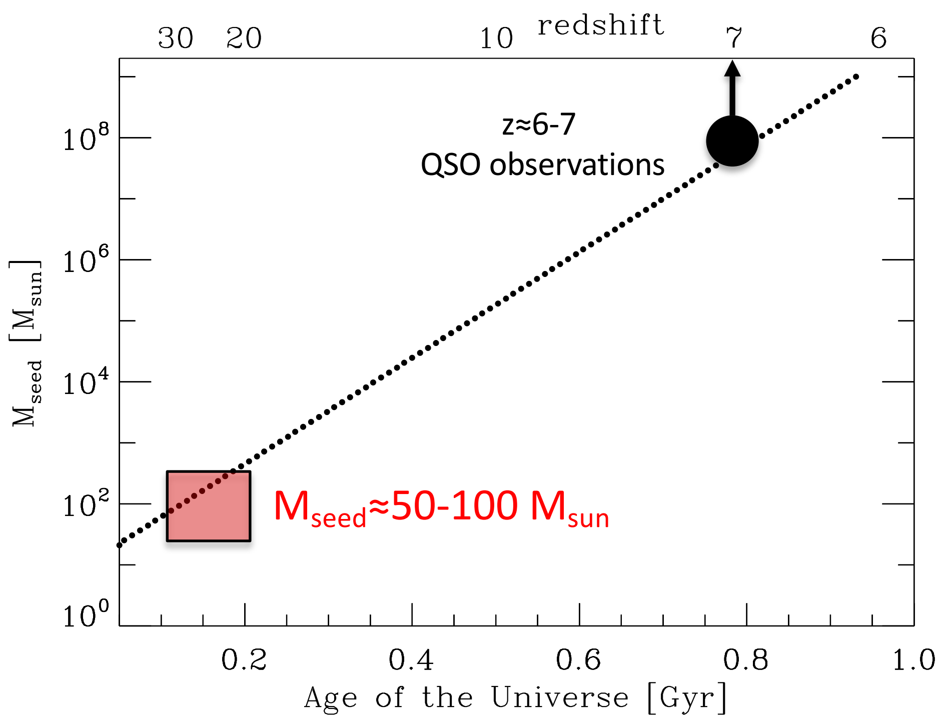
Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

$z \approx 20\text{-}30$

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

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



Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

$z \approx 20\text{-}30$

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

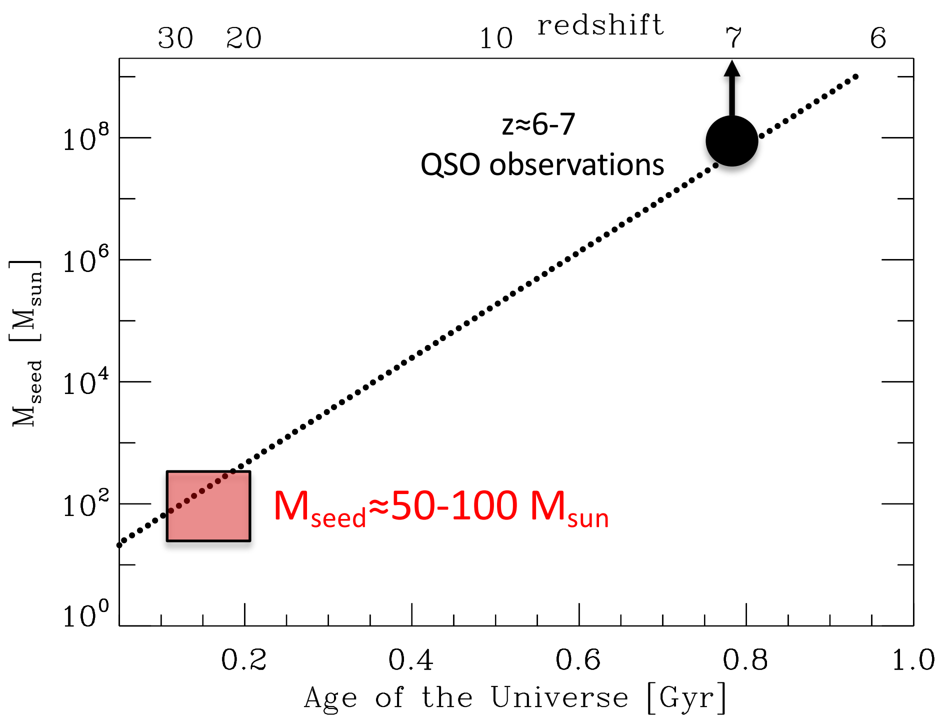
(e.g. Tegmark et al. 1997; Madau & Rees 2001; Palla et al. 2002)

…BUT

PopIII stars are expected to grow slow, at sub- Eddington rates:

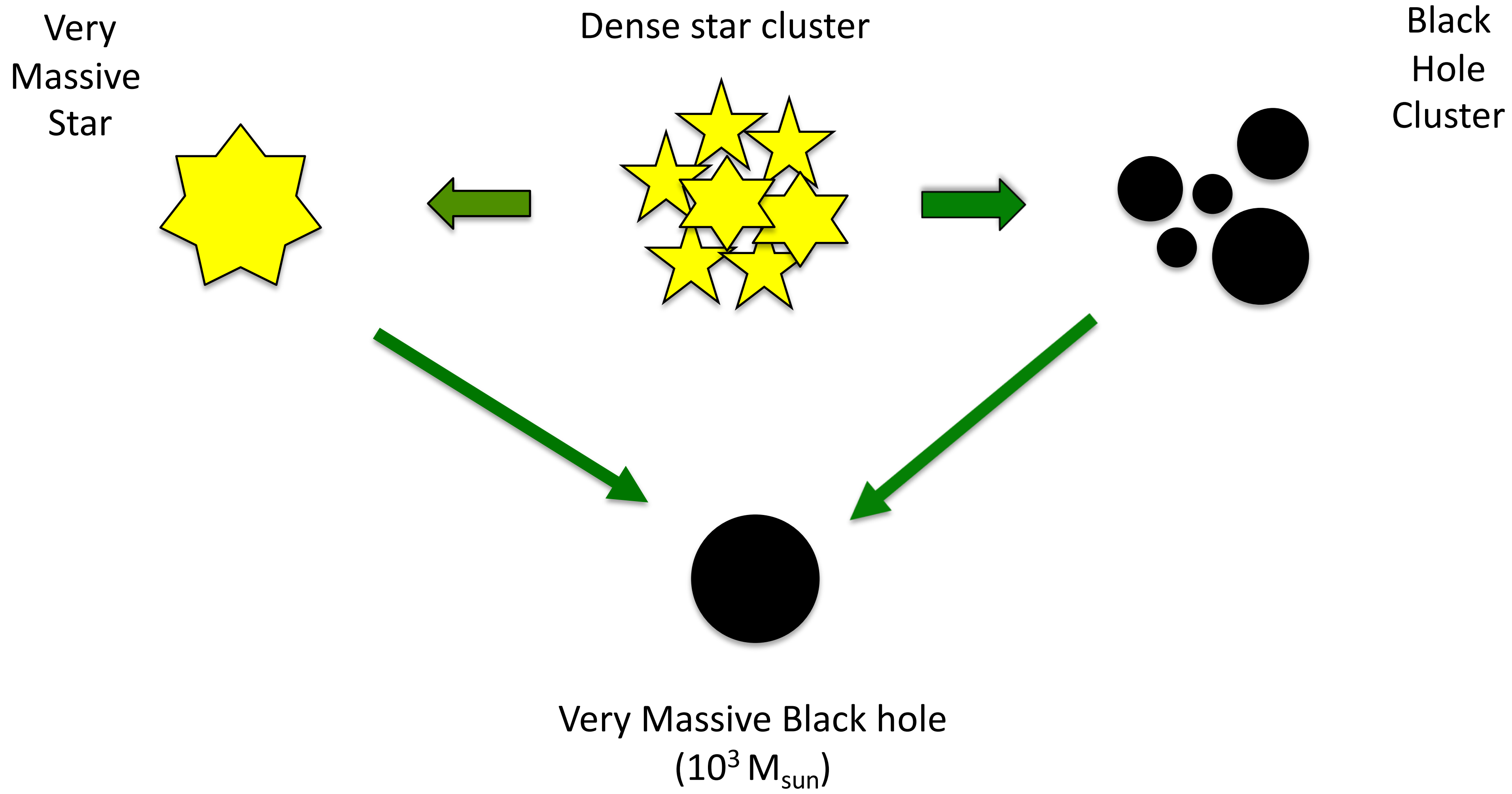
a) produce a large number of ionizing photons that photoionize the surrounding gas;

b) because of SN explosions they may expell the gas in the host mini-halo.



The «dense star cluster» scenario

Formation of a central **very massive star** from stellar mergers
and/or
Formation of a central **very massive black hole** from black hole mergers



Possible pathways for the origin of SMBH seeds

(1) <u>PopIII remnants</u>

z≈20-30

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

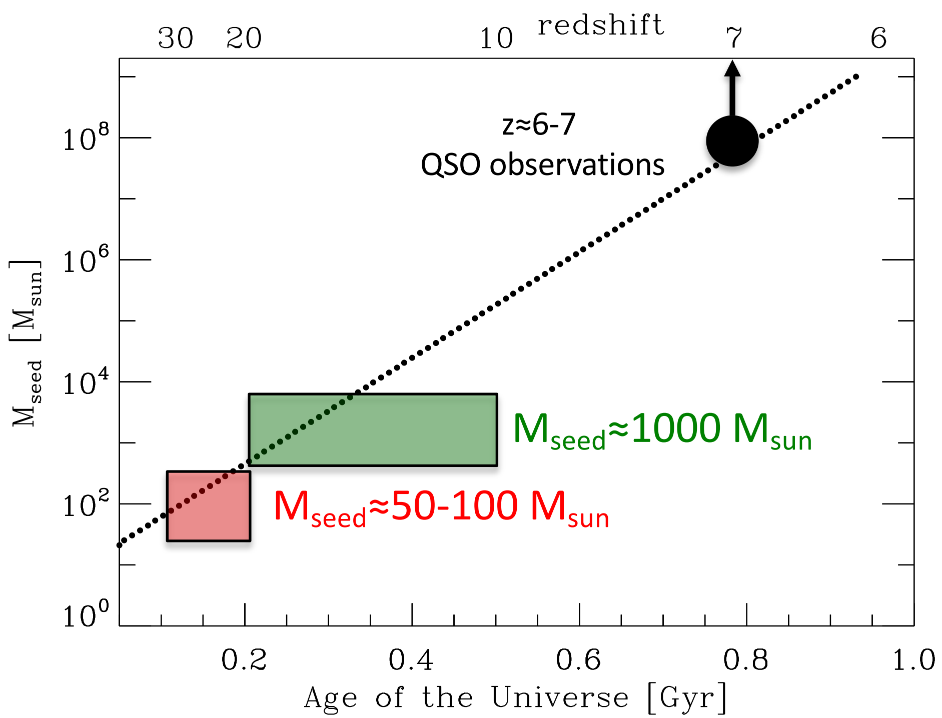
(e.g. Tegmark et al. 1997; Madau & Rees 2001; Palla et al. 2002)

(2) <u>Dense star clusters</u>

z ≈10-20

Star/black hole
collisions can lead
to the formation of
VMSs/VMBHs

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



The «direct collapse» or «heavy seeds» scenario

The idea of «direct collapse black holes» (DCBHs) was firstly proposed by Haehanel & Rees (1993) and then reconsidered by several authors (e.g. Loeb & Rasio (1994), Eisenstein & Loeb 1994; Yue et al. 2013; Ferrara et al. 2014).

Primordial gas which is contracting without fragmenting.

Contraction requires cooling. Avoiding fragmentation translates into a condition on the cooling time of the gas.

The «direct collapse» or «heavy seeds» scenario

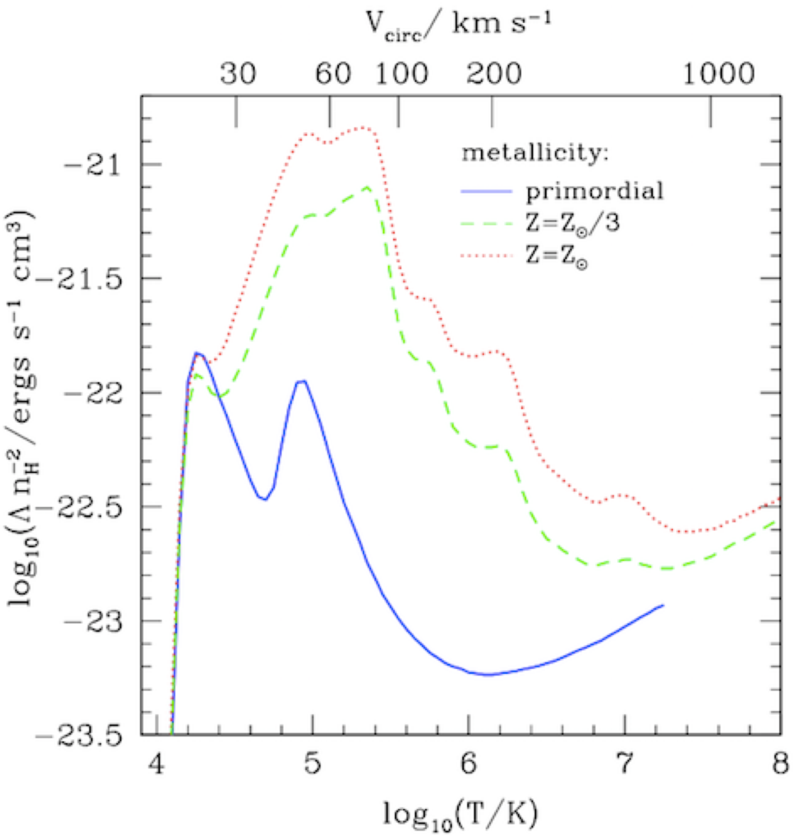
The idea of «direct collapse black holes» (DCBHs) was firstly proposed by Haehanel & Rees (1993) and then reconsidered by several authors (e.g. Loeb & Rasio (1994), Eisenstein & Loeb 1994; Yue et al. 2013; Ferrara et al. 2014).

Primordial gas which is contracting without fragmenting.

Contraction requires cooling. Avoiding fragmentation translates into a condition on the cooling time of the gas.

Let us focus on massive DM haloes ($T_{vir} > 10^4$ K). Gas of primordial composition cools down more slowly than metal enriched gas.

Dependence of the cooling function on the gas metallicity



The «direct collapse» or «heavy seeds» scenario

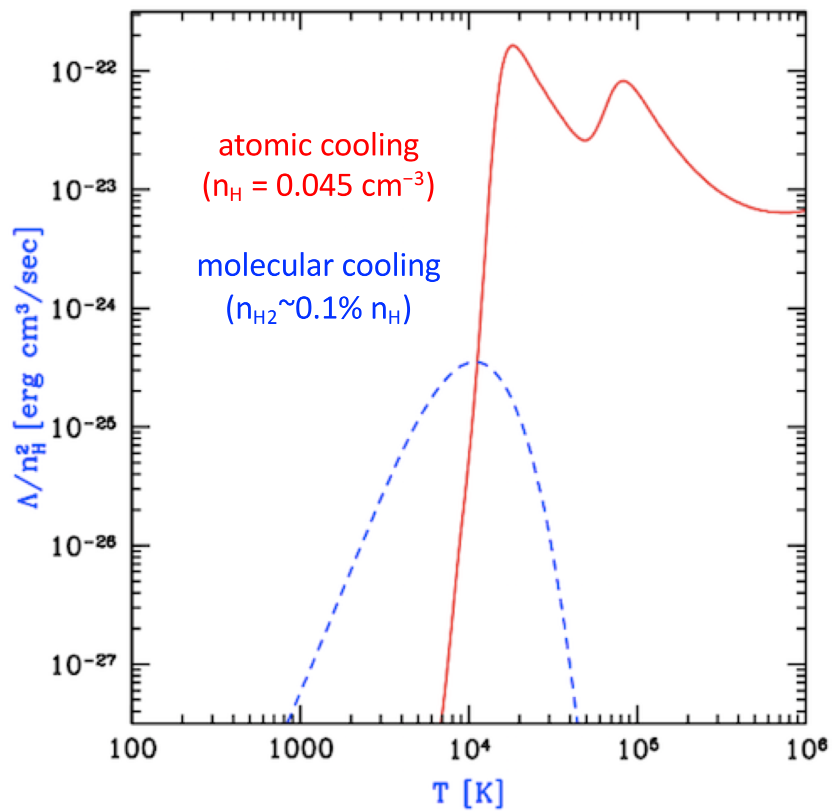
The idea of «direct collapse black holes» (DCBHs) was firstly proposed by Haehanel & Rees (1993) and then reconsidered by several authors (e.g. Loeb & Rasio (1994), Eisenstein & Loeb 1994; Yue et al. 2013; Ferrara et al. 2014).

Primordial gas which is contracting without fragmenting.

Contraction requires cooling. Avoiding fragmentation translates into a condition on the cooling time of the gas.

The optimal configuration for these conditions to be both satisfied is to have **atomic cooling halos** (T_{vir} > 10^4 K), of **primordial composition**, with **no molecular hydrogen**.

Cooling function (primordial composition)



Preventing H_2 formation

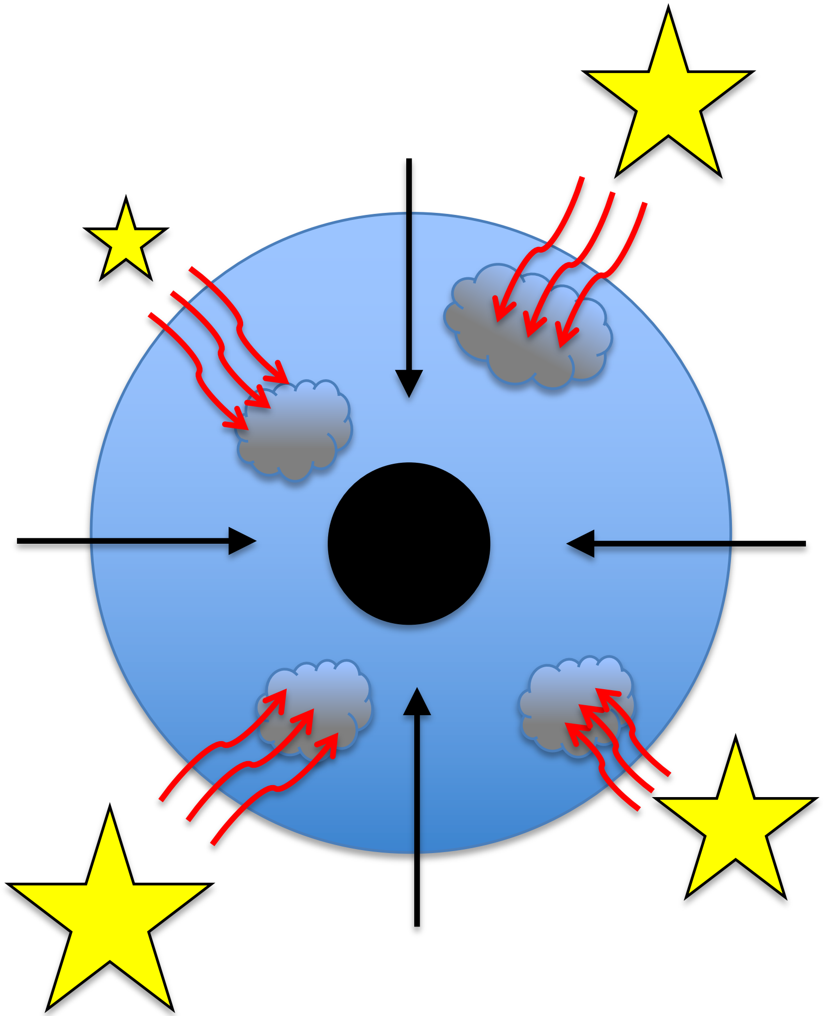
H2 can be dissociated by the presence of a large enough number of Lyman Werner UV photons, namely photons in the 11.2-13.6 eV energy band.

The critical value of the LW flux (usually referred to J_{21}) depends on the radiation spectrum (lower for hotter radiation by hotter more massive stars).

The cosmic ionizing background at z>10 is too low to meet this requirement. Local ionizing sources are required: internal vs external

The presence of internal sources requires that star formation is on-going which is what one wants to avoid to keep the gas metal-free.

More promising is the presence of external localized sources such as nearby star forming galaxy companions.



(e.g. Dijkstra et al. 2008; Agarwal et al. 2012; Dijkstra et al. 2014)

Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

$z \approx 20$-30

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

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

(2) Dense star clusters

$z \approx 10$-20

Star/black hole
collisions can lead
to the formation of
VMSs/VMBHs

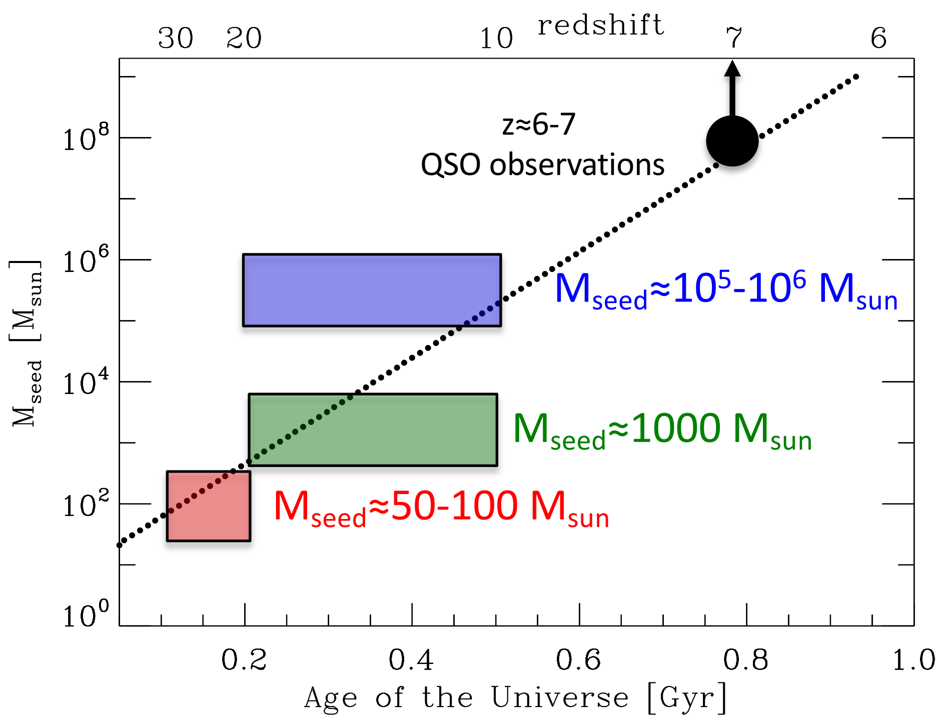
(e.g. Schneider et al. 2006; Clark et al. 2008;
Devecchi et al. 2012)

(3) Direct Collapse Black Holes

$z > 10$

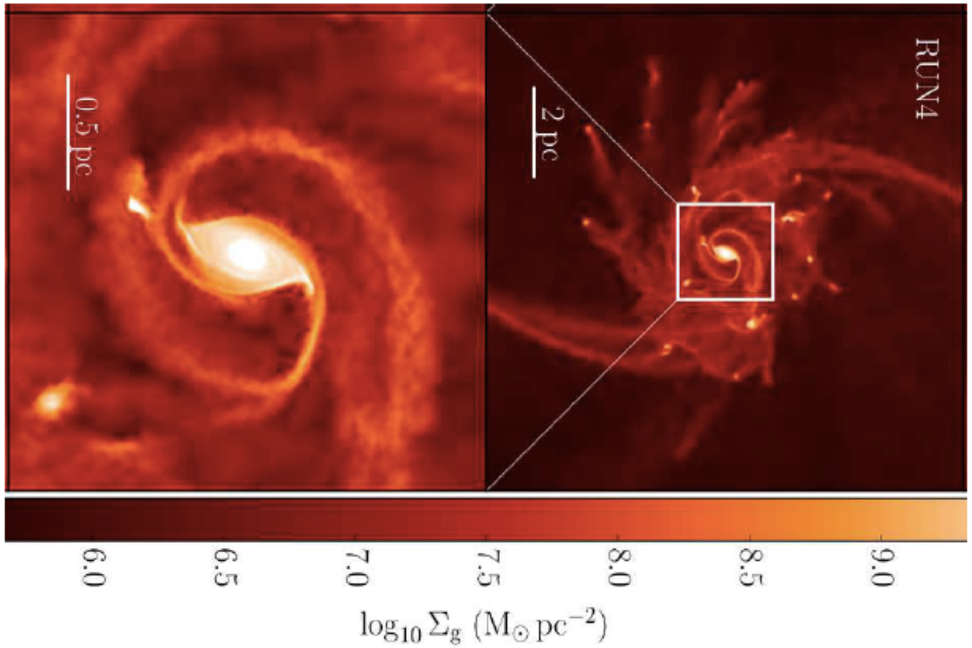
Primordial gas
irradiated by LW radiation
in atomic-cooling halos
($T_{vir} > 10^4$ K)

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



The «merger-driven direct collapse» scenario

(Mayer et al. 2010; Mayer & Bonoli 2018)



Major mergers of massive, gas-rich ($Z=Z_{sun}$) galaxies at $z > 6$ generate multi-scale gas inflows that start outside the virial radius and extends up to the galactic nucleus.

Inflowing material leads to the formation of a supermassive (10^6 M_{sun}), gravitationally bounded, compact gaseous disk, few pc in size in less than 10^5 yr.

The nuclear disk is stable against fragmentation (independently on metallicity) and may accrete at rates > 1000 $M_{sun}yr^{-1}$ thanks to an efficient angular momentum loss provided by the merger dynamics (strong torques and hydrodynamical shocks).

The next step is the formation of a supermassive star in the center of these disks.

Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

$z \approx 20$-30

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

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

(2) Dense star clusters

$z \approx 10$-20

Star/black hole
collisions can lead
to the formation of
VMSs/VMBHs

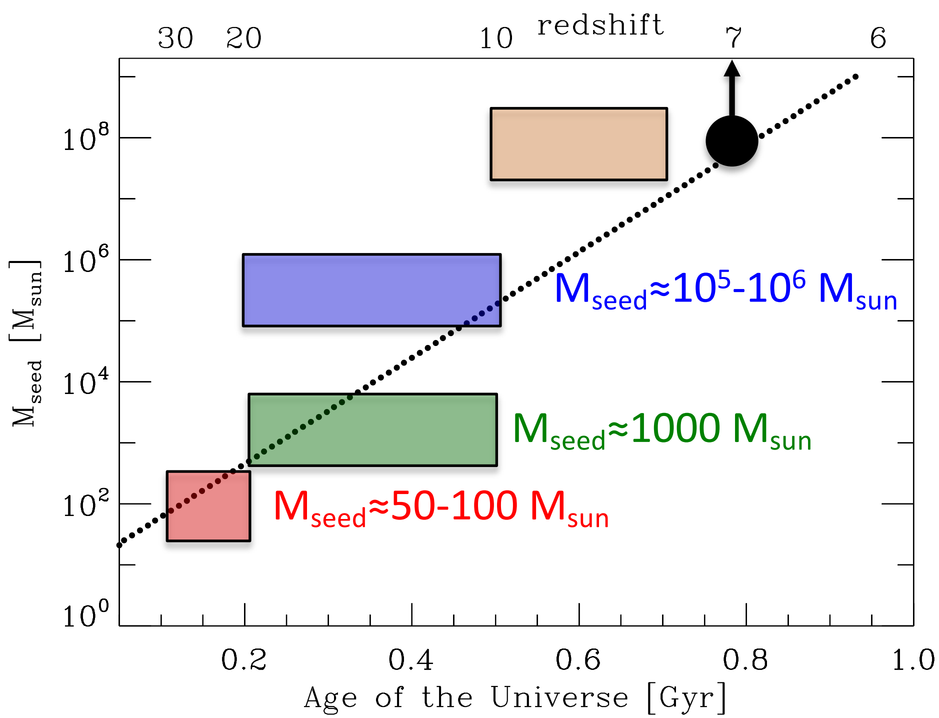
(e.g. Schneider et al. 2006; Clark et al. 2008; Devecchi et al. 2012)

(3) Direct Collapse Black Holes

$z > 10$

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

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



(4) Merger-driven DCBHs

$8 < z < 10$

Major mergers of
massive ($M_{DM} \approx 10^{12}$ M_{sun}),
metal-rich ($Z=Z_{sun}$)
galaxies

(e.g. Mayer et al. 2010; Mayer & Bonoli 2018)

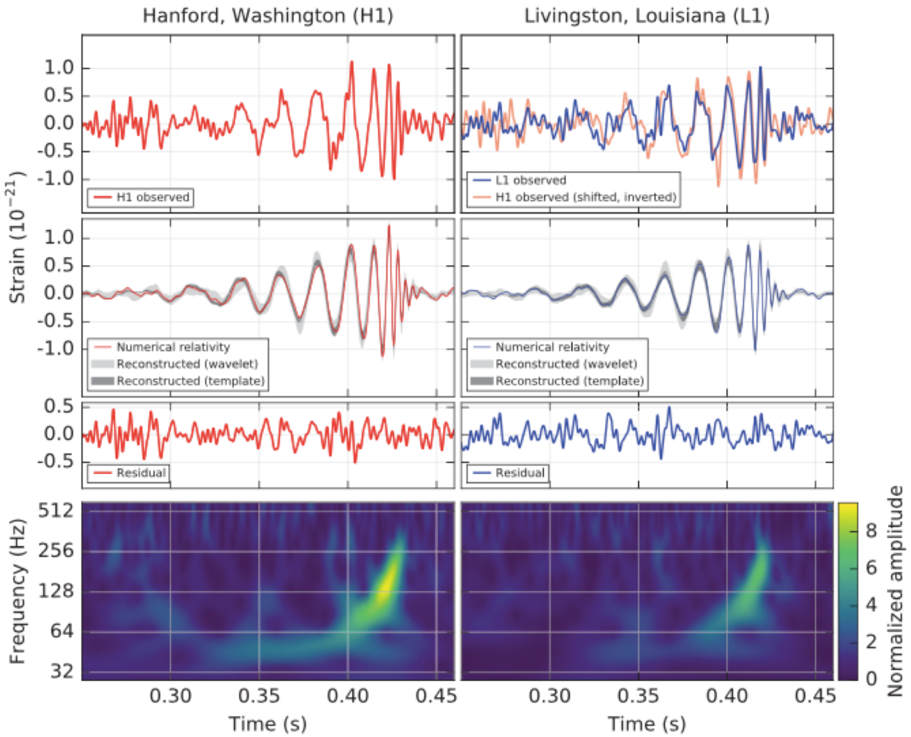
The «primordial back holes» scenario

The idea of «primordial black holes» (PBHs) was firstly proposed by Zel'dovich & Novikov (1967), and then reconsidered by Hawking (1971).

Primordial density fluctuations in the early Universe may lead to the formation of PBHs with masses down to the Planck mass (~10^{-5} g).

PBHs can be constituents of dark matter (Chapline 1975) as alternative to weakly interacting massive particles (WIMPs), the most favored DM candidates.

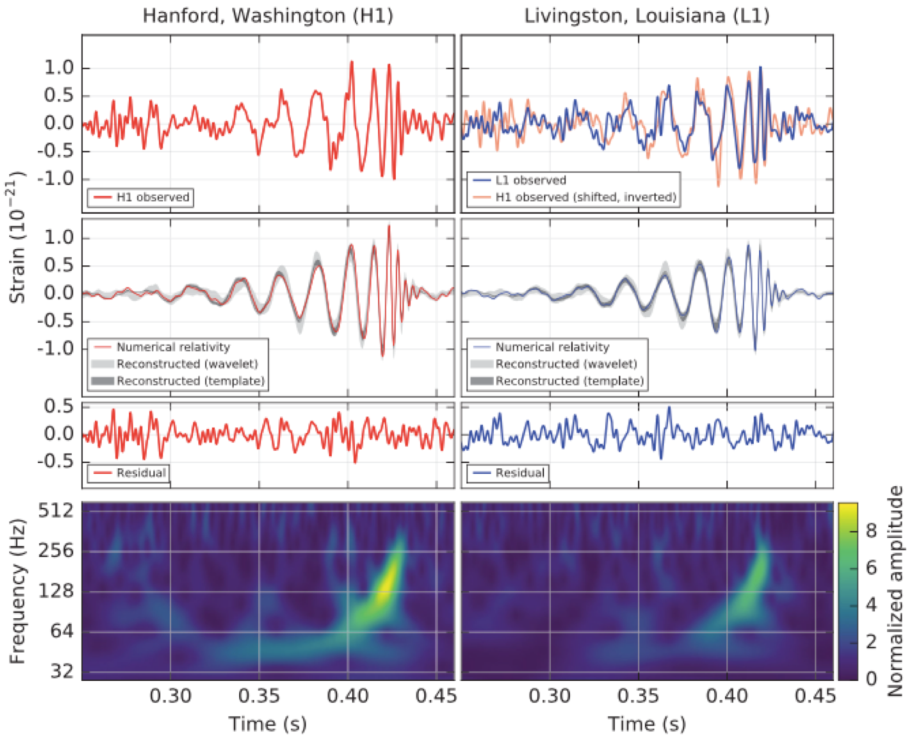
Gravitational wave detection from merging BHs

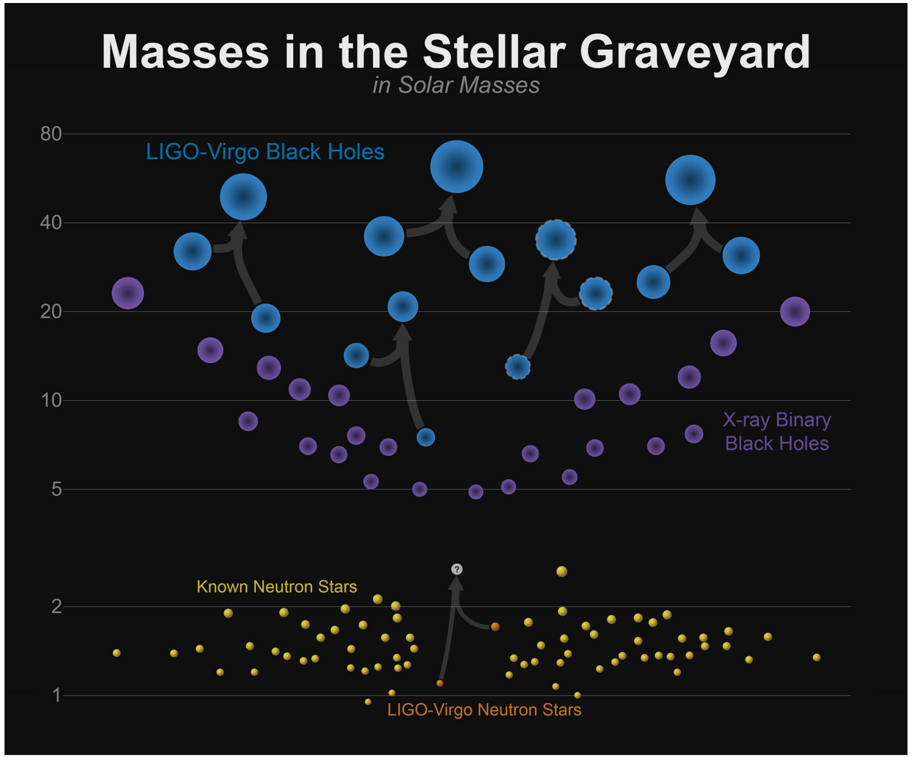


First detection of gravitational waves from the merging of two 20-30 M_{sun} black holes

(February 11, 2016, LIGO and VIRGO collaboration, Abbott et al. 2016)

Observations of «stellar» black holes by GW





First detection of gravitational waves from the merging of two 20-30 M_{sun} black holes

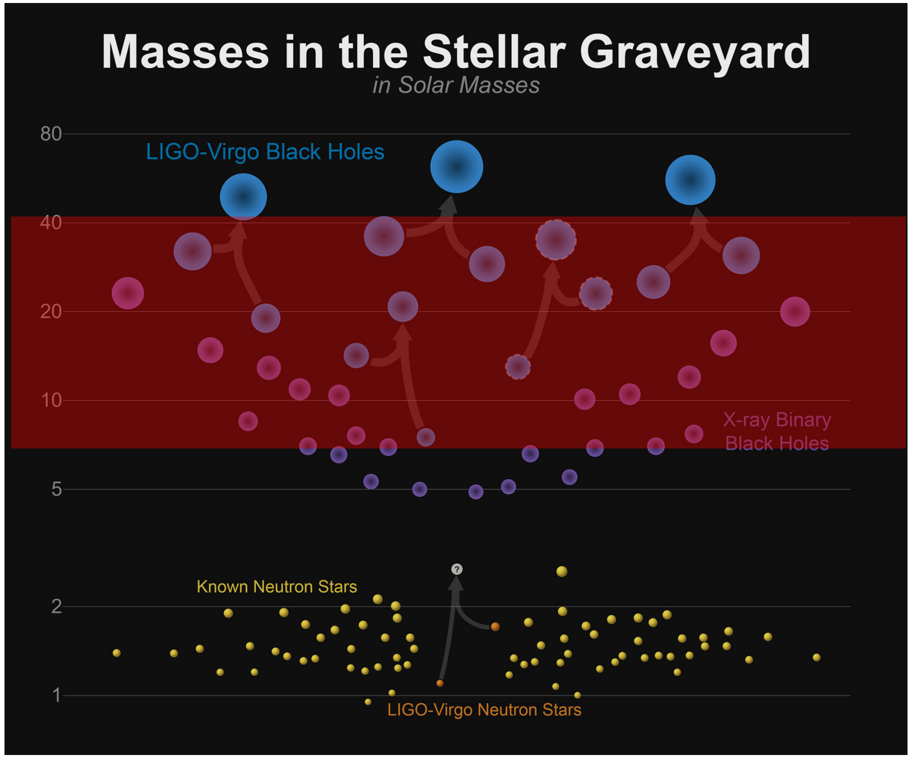
(February 11, 2016, LIGO and VIRGO collaboration, Abbott et al. 2016)

A total of six (one potential) GW signals have been confirmed so far:

- 5 BH binary mergers
- 1 double neutron star merger

The BH-NS binary is still missing

Black hole masses measured by GW experiments



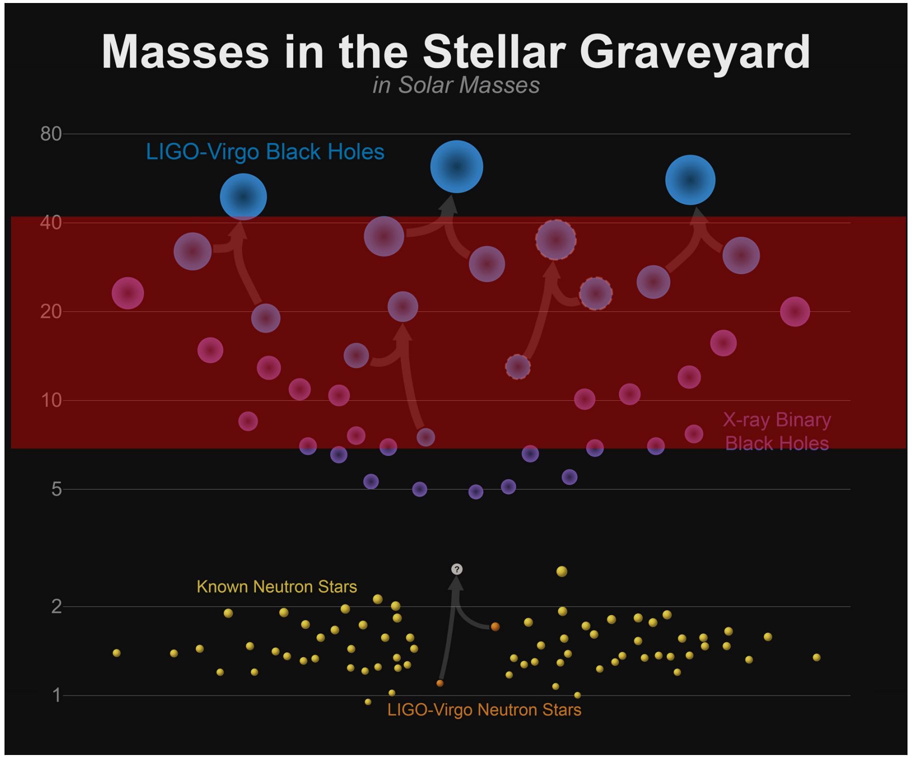
$10\ M_{sun} < M_{BH} < 40\ M_{sun}$

Black hole masses measured by GW experiments

1) Larger than BH masses measured by X-ray binary experiments

$M_{BH} \lesssim 20\ M_{sun}$

https://stellarcollapse.org/sites/default/files/table.pdf



$10\ M_{sun} < M_{BH} < 40\ M_{sun}$

Black hole masses measured by GW experiments

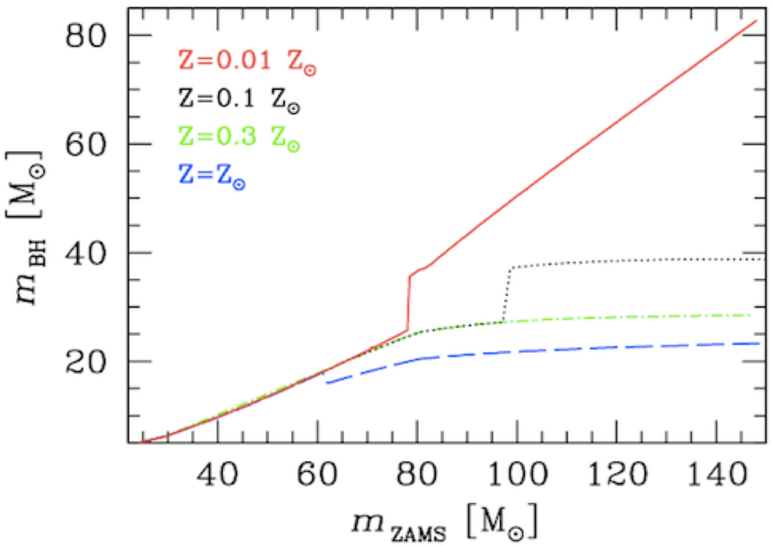
1) Larger than BH masses measured by X-ray binary experiments

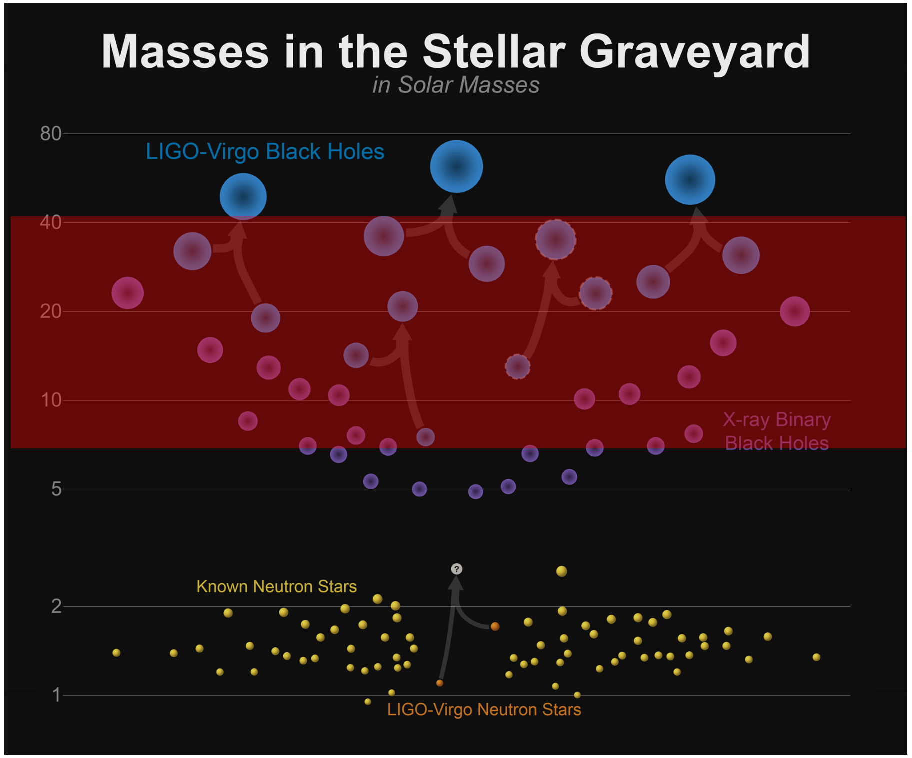
$M_{BH} \lesssim 20\ M_{sun}$

https://stellarcollapse.org/sites/default/files/table.pdf

2) Larger than BH masses expected from stellar evolution models

$M_{BH} \lesssim 20\ M_{sun}$ (for $Z=Z_{sun}$, e.g. Mapelli 2013)





$10\ M_{sun} < M_{BH} < 40\ M_{sun}$

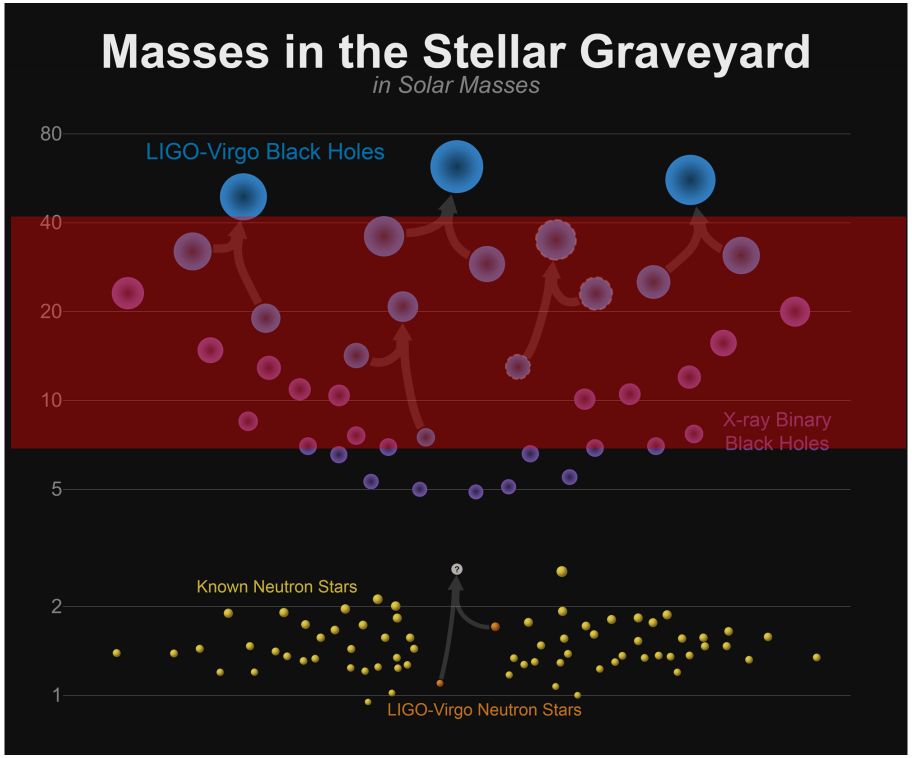
Black hole masses measured by GW experiments

1) Larger than BH masses measured by X-ray binary experiments
$M_{BH} \lesssim 20\ M_{sun}$
https://stellarcollapse.org/sites/default/files/table.pdf

2) Larger than BH masses expected from stellar evolution models
$M_{BH} \lesssim 20\ M_{sun}$ (for $Z=Z_{sun}$, e.g. Mapelli 2013)

3) Consistent with PBH mass constraints from CMB studies
$10\ M_{sun} < M_{PBH} < 100\ M_{sun}$

PBHs accrete primordial gas in the early Universe and convert a fraction of it into radiation. The resulting injection of energy into the primordial plasma affects its thermal and ionization history possibly leaving signatures in the CMB frequency spectrum and its temperature/polarization power spectra (e.g. Ali-Haimoud & Kamionkowski 2017).



$10\ M_{sun} < M_{BH} < 40\ M_{sun}$

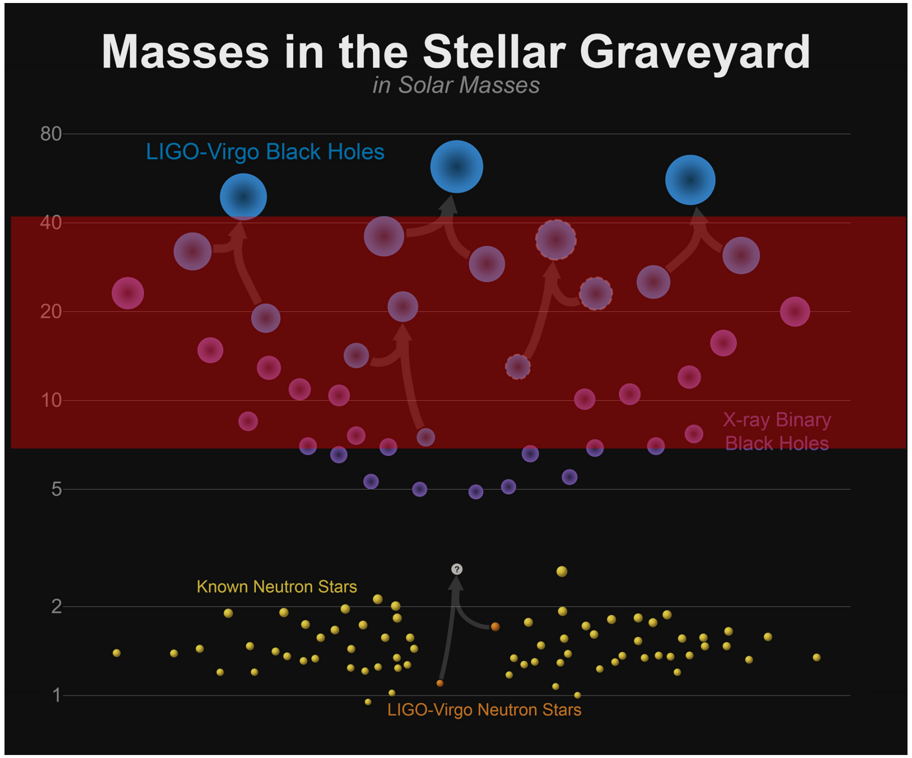
Black hole masses measured by GW experiments

1) Larger than BH masses measured by X-ray binary experiments
$M_{BH} \lesssim 20\ M_{sun}$
https://stellarcollapse.org/sites/default/files/table.pdf

2) Larger than BH masses expected from stellar evolution models
$M_{BH} \lesssim 20\ M_{sun}$ (for $Z=Z_{sun}$, e.g. Mapelli 2013)

3) Consistent with PBH mass constraints from CMB studies
$10\ M_{sun} < M_{PBH} < 100\ M_{sun}$

PBHs accrete primordial gas in the early Universe and convert a fraction of it into radiation. The resulting injection of energy into the primordial plasma affects its thermal and ionization history possibly leaving signatures in the CMB frequency spectrum and its temperature/polarization power spectra (e.g. Ali-Haimoud & Kamionkowski 2017).

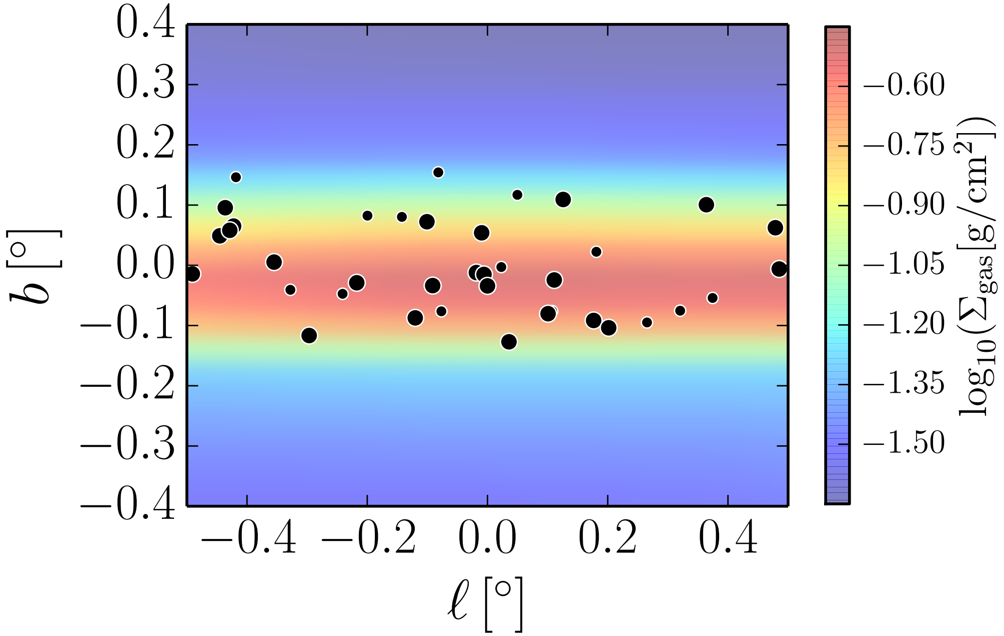


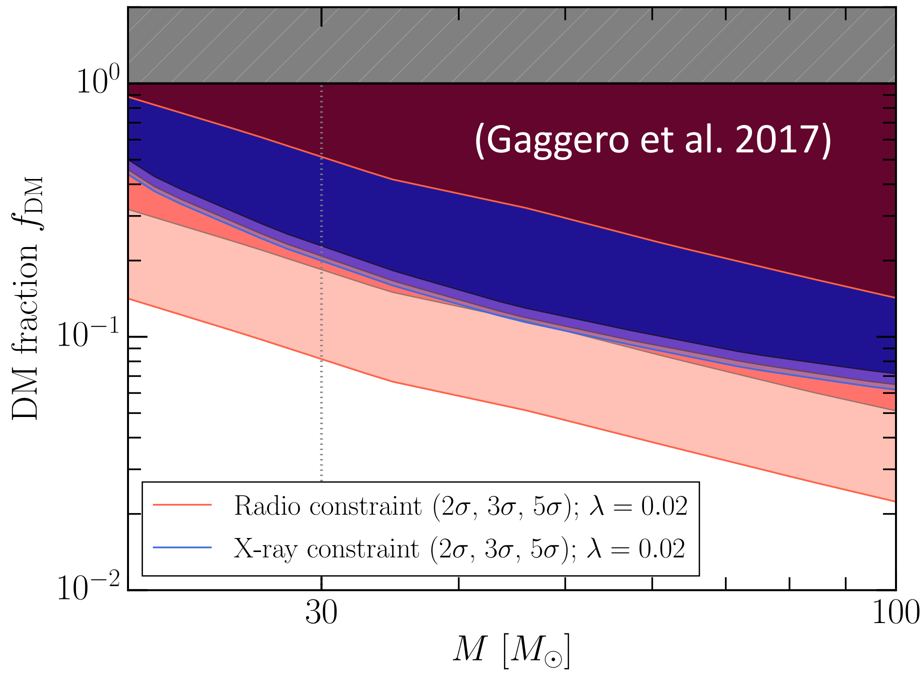
$10\ M_{sun} < M_{BH} < 40\ M_{sun}$

Primordial black holes are possible candidates for SMBH seeds

What about Dark Matter?

Gravitational Waves constraints on PBHs as DM





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

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.

Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

$z \approx 20$-30

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

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

(2) Dense star clusters

$z \approx 10$-20

Star/black hole
collisions can lead
to the formation of
VMSs/VMBHs

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

(3) Direct Collapse Black Holes

$z > 10$

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

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

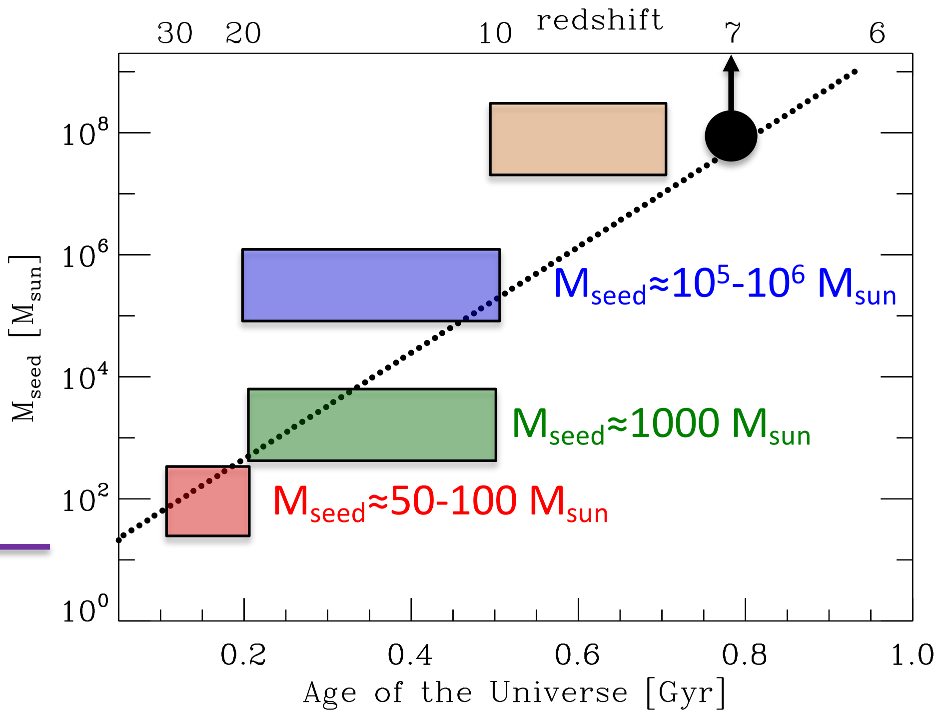
(5) Primordial Black Holes

$z > 2.3 \times 10^4 h^2 \Omega_m \approx 3300$

Direct collapse of
primordial density
inhomogeneities

$M_{seed} \approx 10$-100 M_{sun}

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



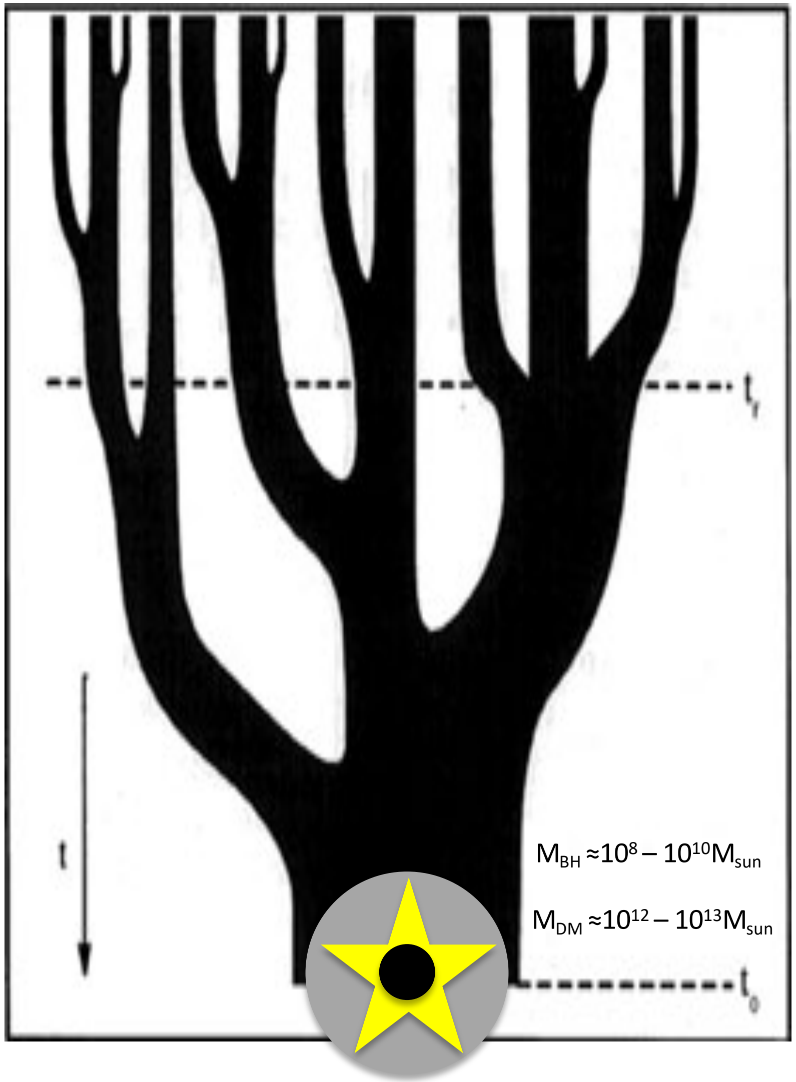
(4) Merger-driven DCBHs

$8 < z < 10$

Major mergers of
massive ($M_{DM} \approx 10^{12}$ M_{sun}),
metal-rich ($Z=Z_{sun}$)
galaxies

(e.g. Mayer et al. 2010; Mayer & Bonoli 2018)

A possible strategy to discover SMBH progenitors

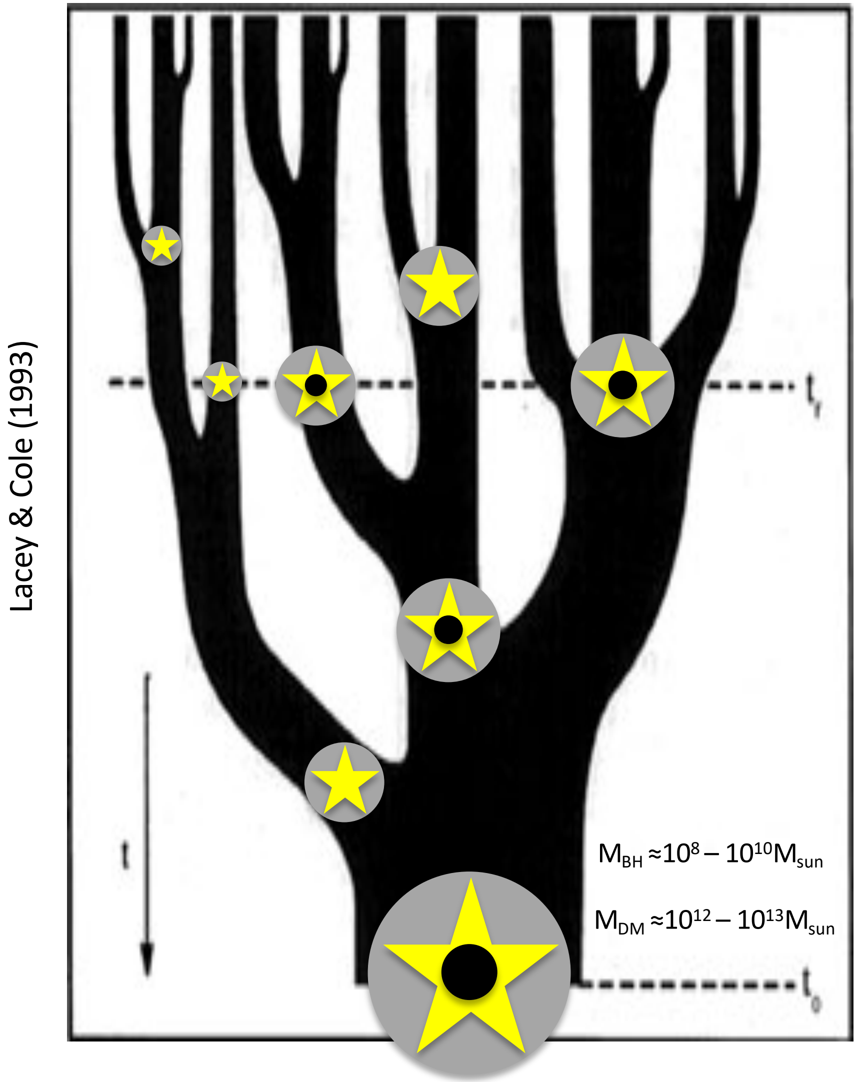


Lacey & Cole (1993)

According to the hierarchical model of structure formation, massive DM halos are formed as a consequence of the merging of smaller systems.

At high redshift, with current observational facilities we are detecting SMBHs that are likely hosted in 10^{12}-10^{13} M_{sun} DM haloes.

A possible strategy to discover SMBH progenitors



According to the hierarchical model of structure formation, massive DM halos are formed as a consequence of the merging of smaller systems.

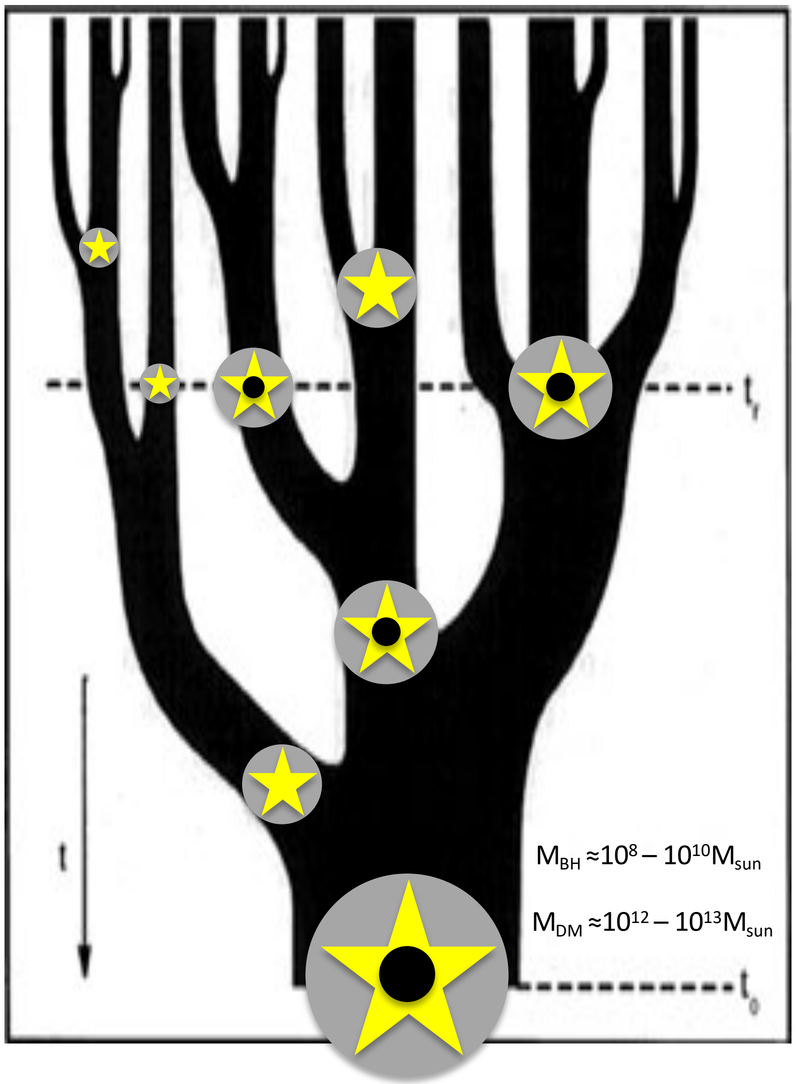
At high redshift, with current observational facilities we are detecting SMBHs that are likely hosted in 10^{12}-10^{13} M_{sun} DM haloes.

These must be the result of the merging of smaller halos that at a given point in the past have harbored BH seeds that have grown up to 10^8-10^{10} M_{sun} at redshift 6.

How can we detect them?

A possible strategy to discover SMBH progenitors

Lacey & Cole (1993)



According to the hierarchical model of structure formation, massive DM halos are formed as a consequence of the merging of smaller systems.

At high redshift, with current observational facilities we are detecting SMBHs that are likely hosted in 10^{12}-10^{13} M_{sun} DM haloes.

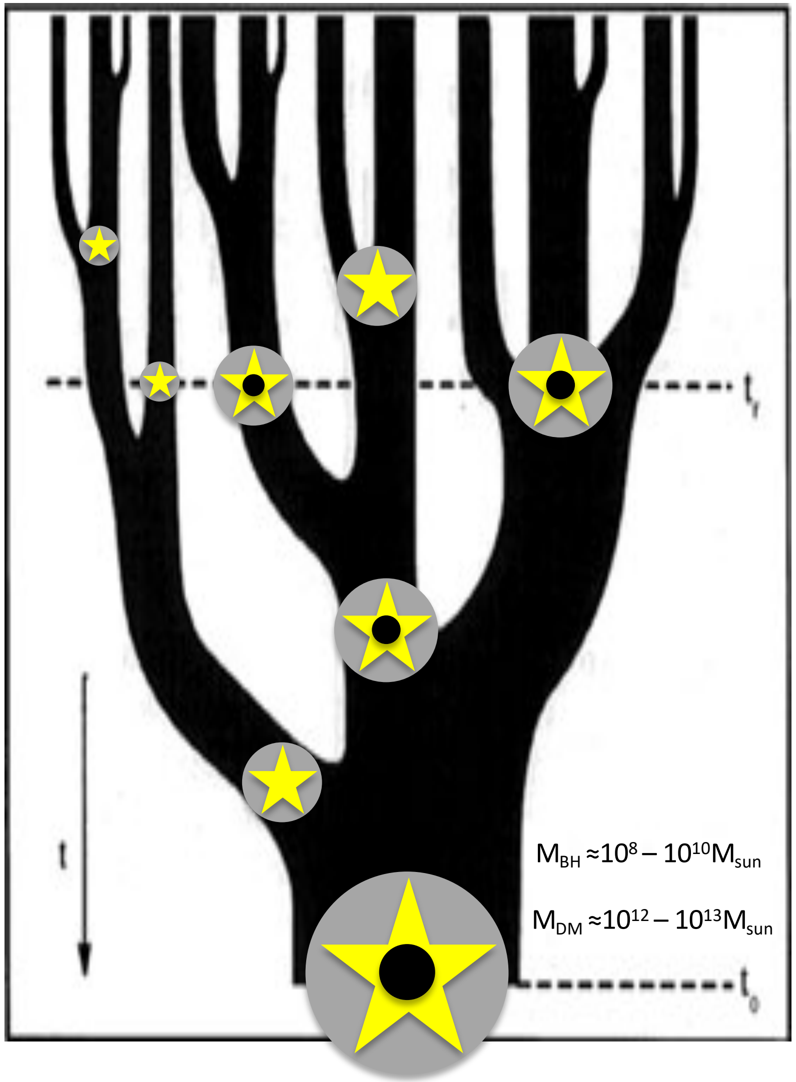
These must be the result of the merging of smaller halos that at a given point in the past have harbored BH seeds that have grown up to 10^8-10^{10} M_{sun} at redshift 6.

How can we detect them?

Sinergy between multi-wavelength data & cosmological simulations

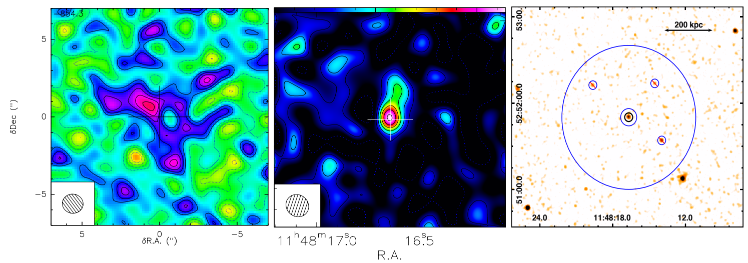
A possible strategy to discover SMBH progenitors

Lacey & Cole (1993)



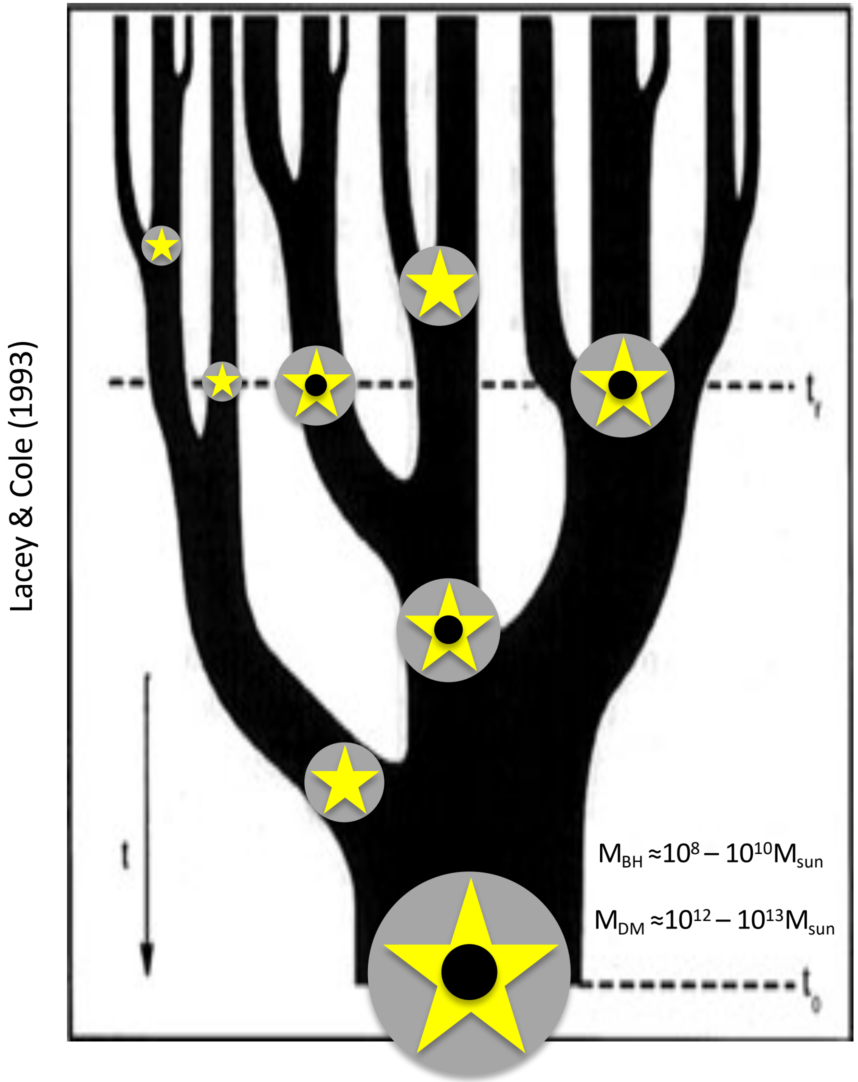
STEP 1

Multi-wavelength observations of z≈6 quasars



Sinergy between multi-wavelength data & cosmological simulations

A possible strategy to discover SMBH progenitors

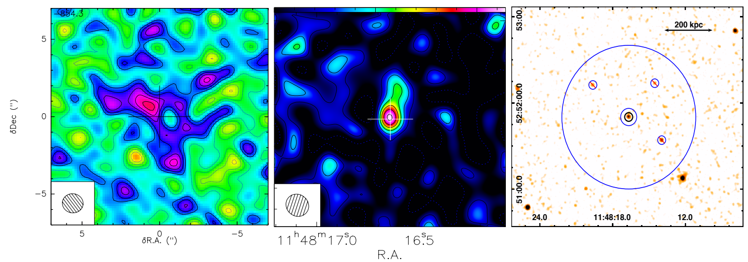


STEP 2

Numerical simulations of quasars (100 < z < 6) constrained by means of z≈6 observations

STEP 1

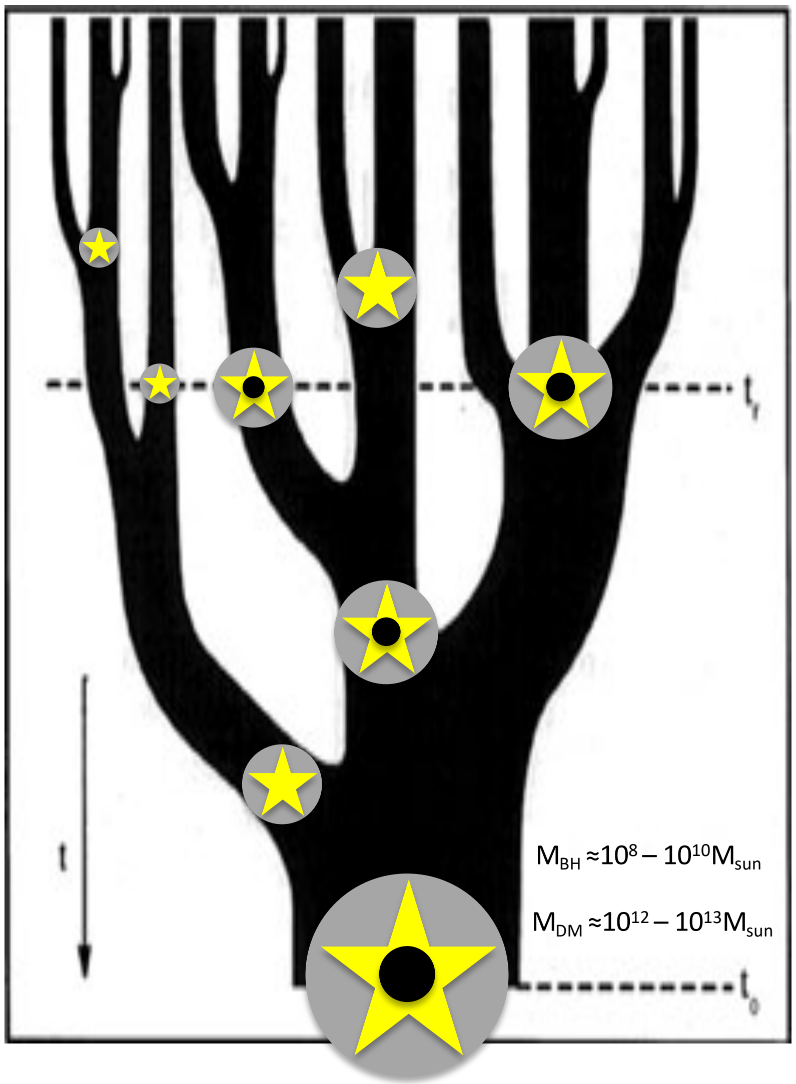
Multi-wavelength observations of z≈6 quasars



Sinergy between multi-wavelength data & cosmological simulations

A possible strategy to discover SMBH progenitors

Lacey & Cole (1993)



STEP 3

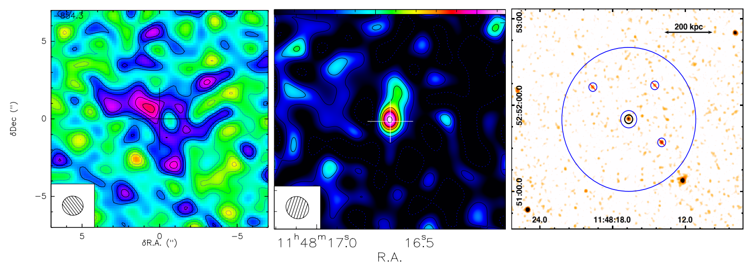
Predictions for observational signatures of SMBH progenitors (ALMA, JWST, Lynx, eLISA)

STEP 2

Numerical simulations of quasars (100 < z < 6) constrained by means of z≈6 observations

STEP 1

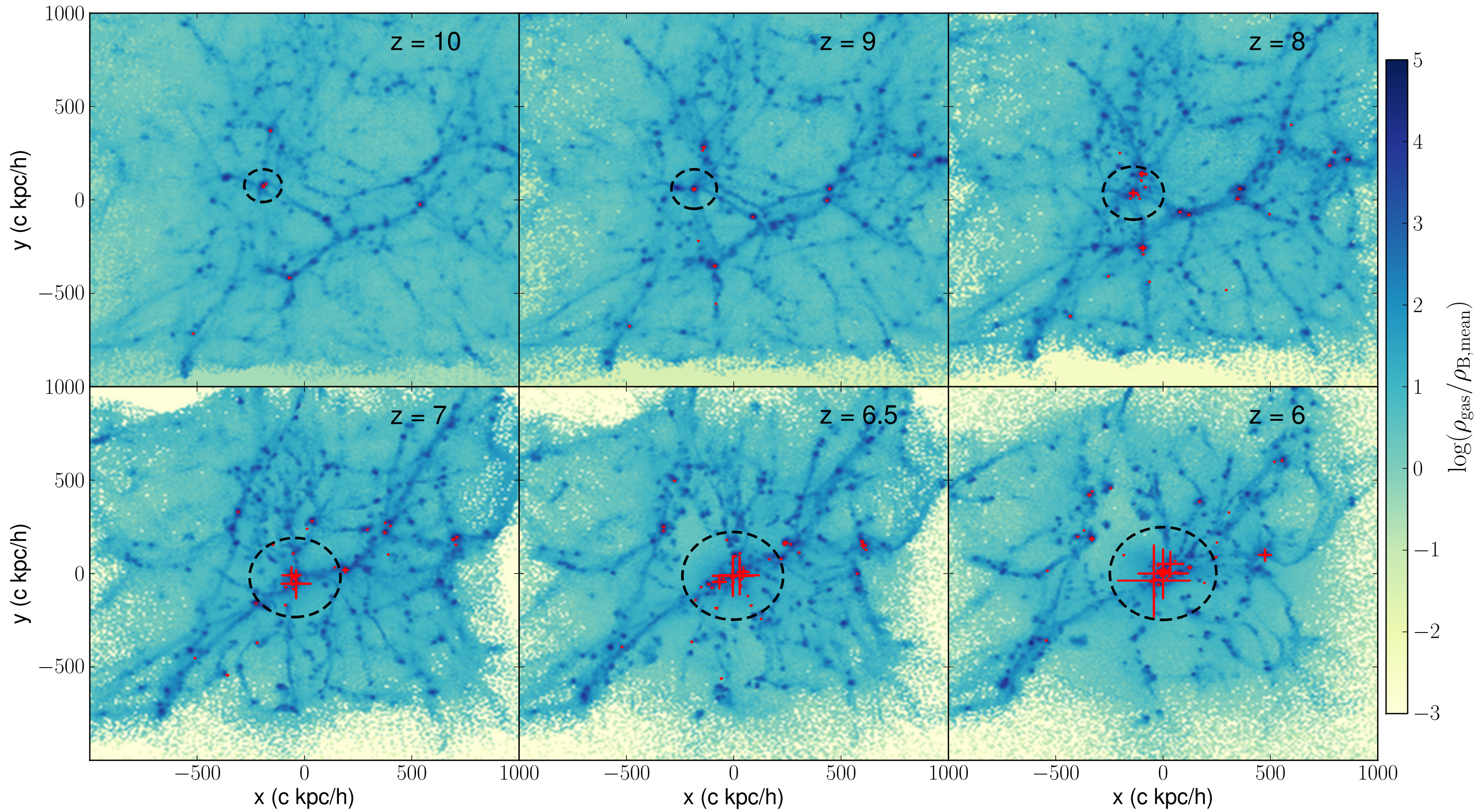
Multi-wavelength observations of z≈6 quasars



Sinergy between multi-wavelength data & cosmological simulations

Cosmological simulations of a z ≈ 6 quasar

Barai, SG, et al. 2017



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: ($n > 0.1\ cm^{-3}$) - **SN FEEDBACK**

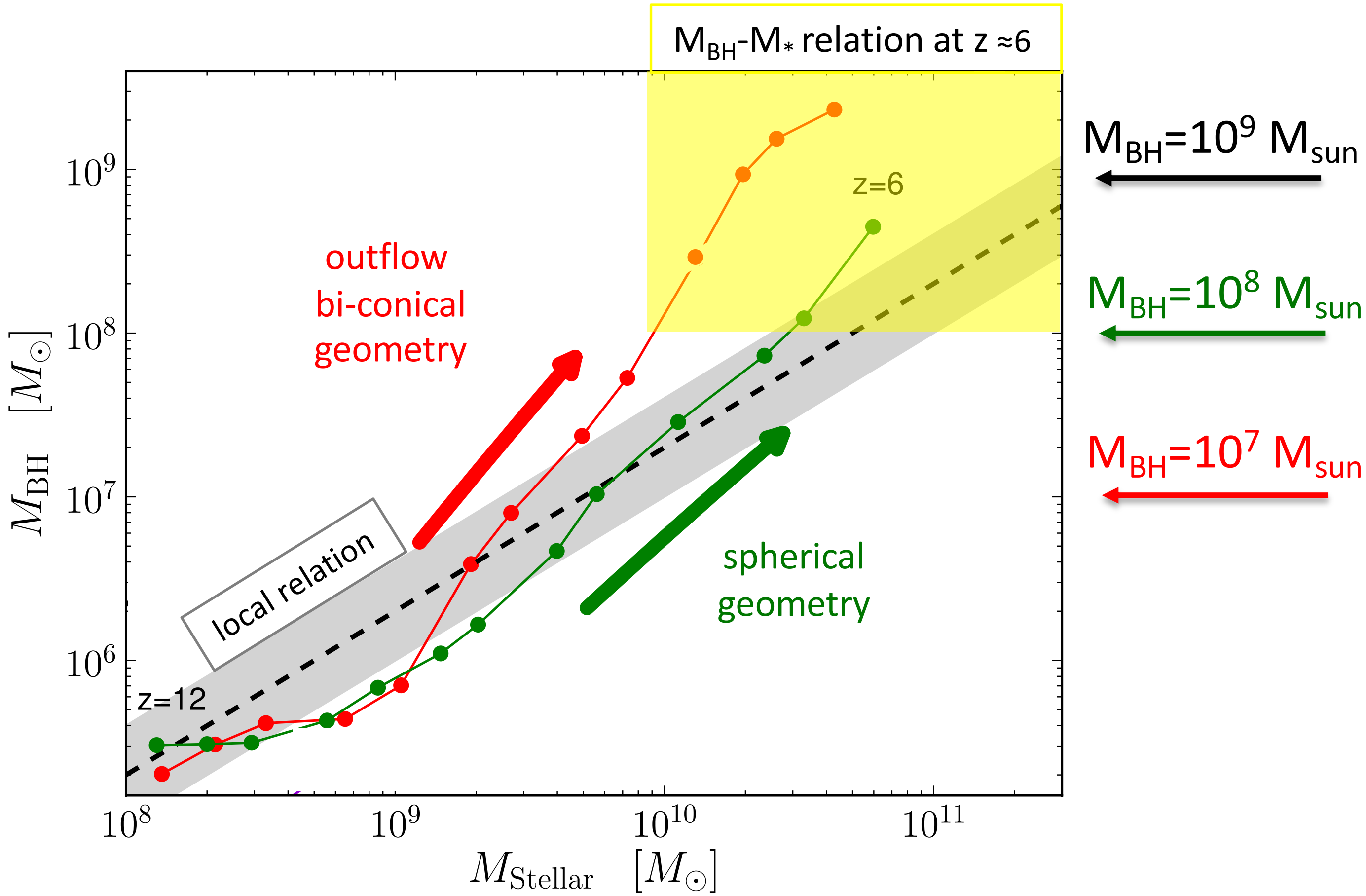
BLACK HOLE SEEDING: $10^5\ M_{sun}$ BH in $M_{DM} > 10^9 M_{sun}$

BLACK HOLE GROWTH: Gas accretion and galaxy merging

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

(Bondi & Hoyle 1944; Hoyle & Lyttleton 1939)

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



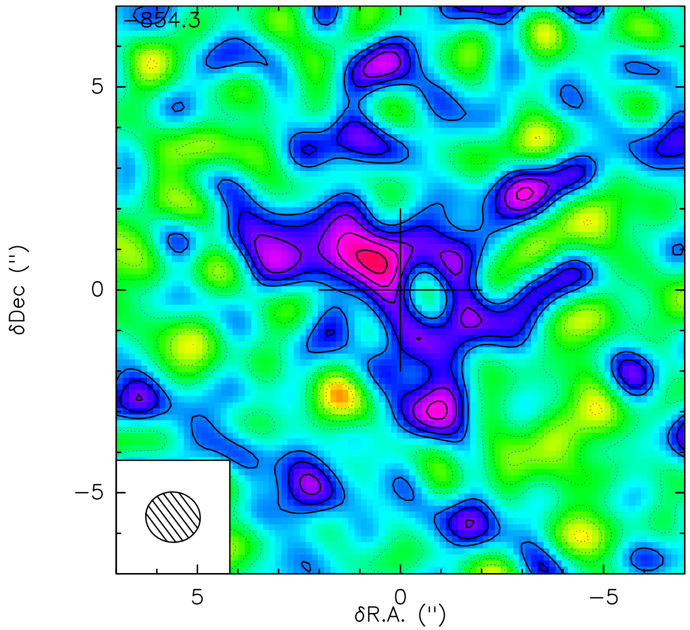
Deviation from the local M_{BH}-M_* relation

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

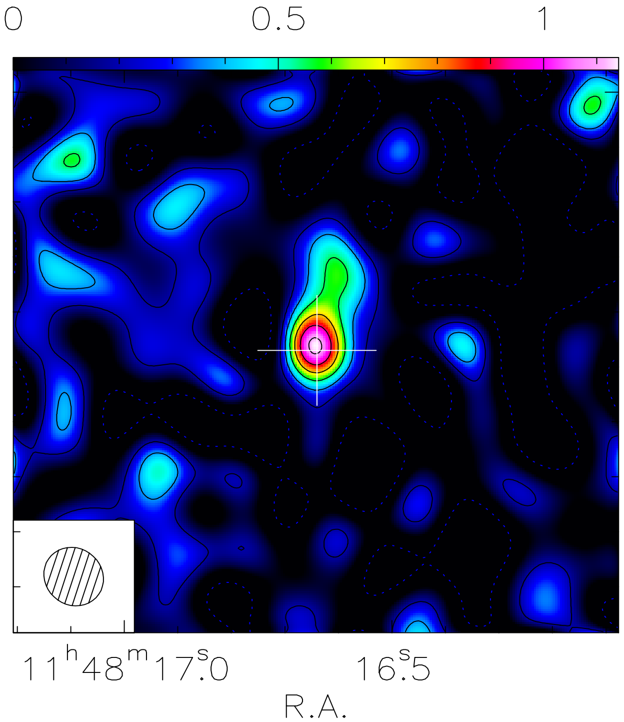
COMPARISON WITH OBSERVATIONS

[CII] emission line
@158 μm



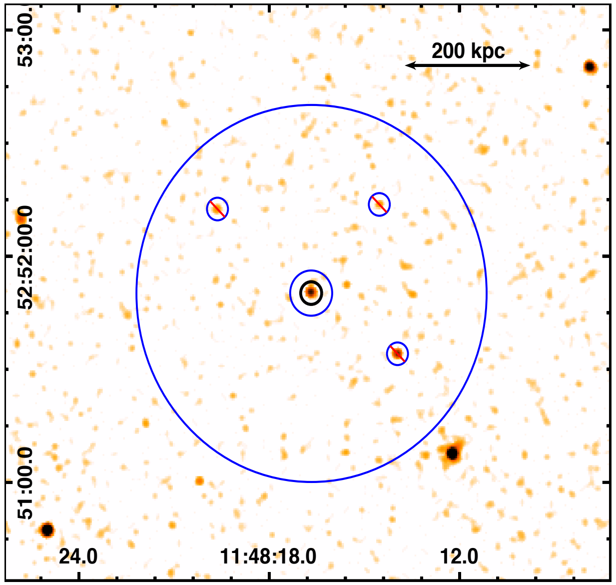
Maiolino, SG, et al. (2012)
Cicone, Maiolino, SG, et al. (2015)

CO(17-16) emission line
@264 GHz



Gallerani et al. (2014)

X-ray continuum
emission

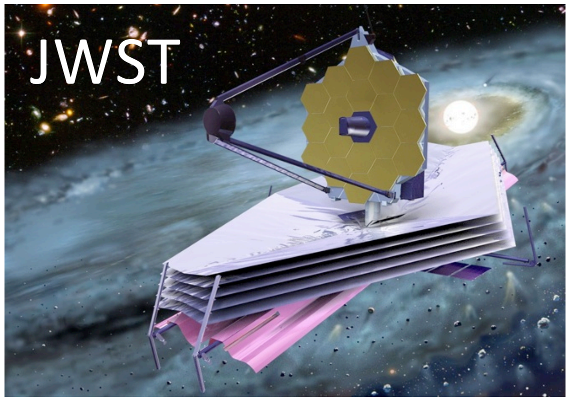


Gallerani et al. (2017)

WORK IN PROGRESS

WHAT IS NEXT?

Sub mm and mm wavelength range

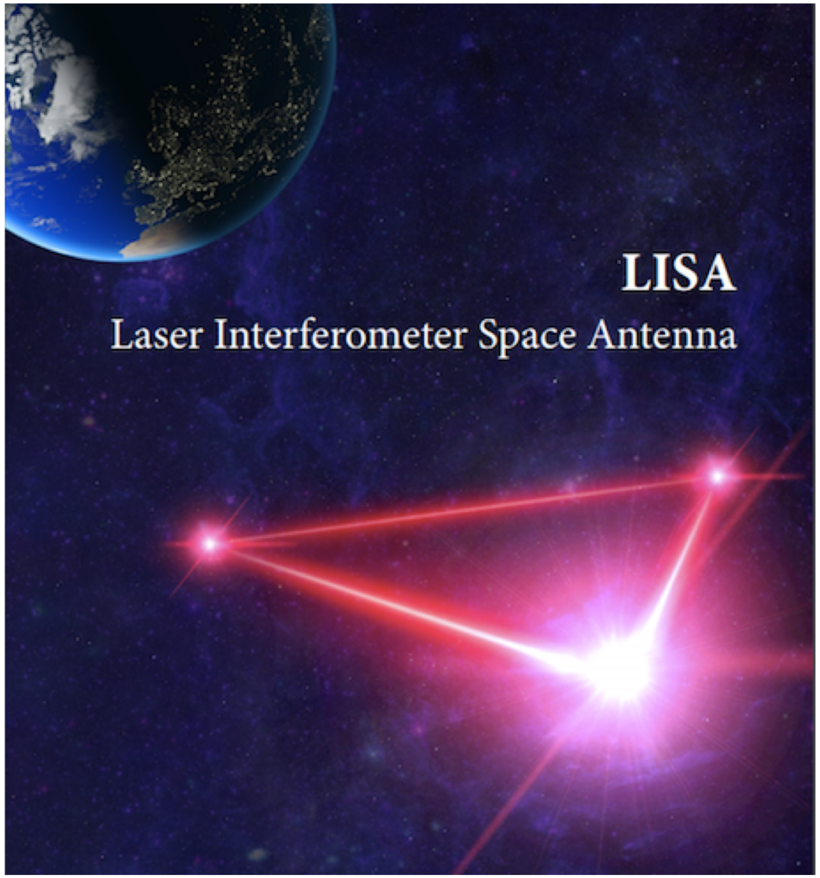


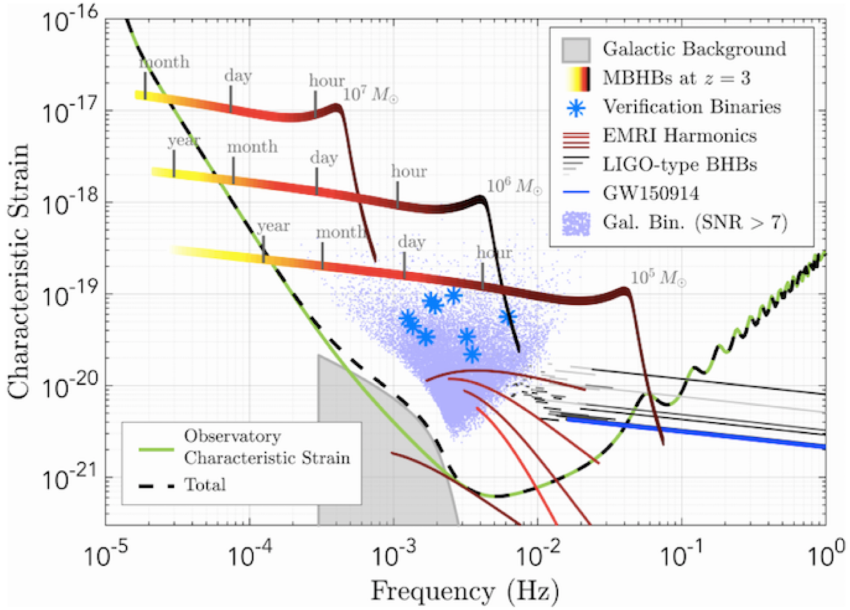
Near Infra Red

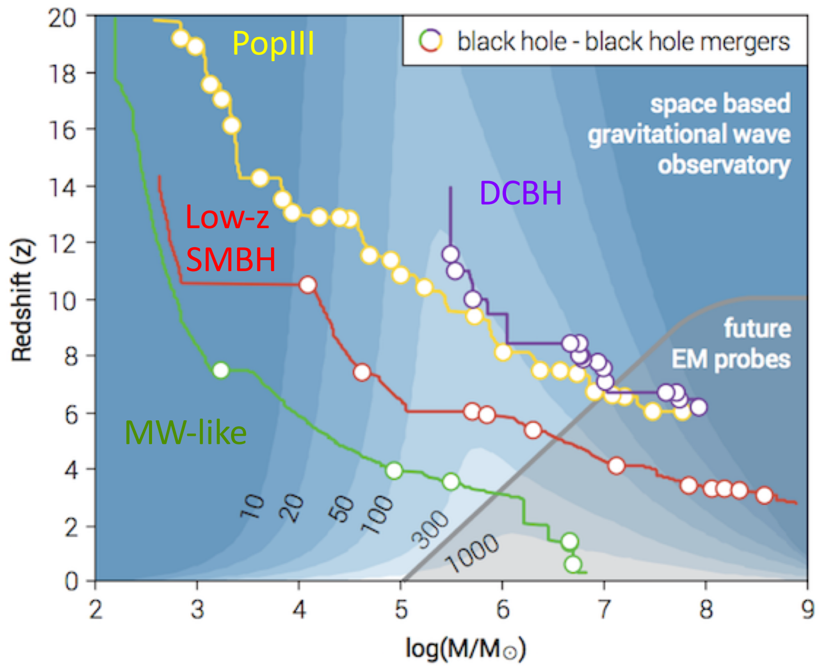
X-ray

WHAT IS NEXT?

Gravitational waves detection from space

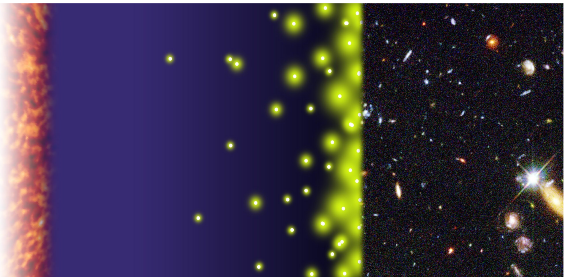






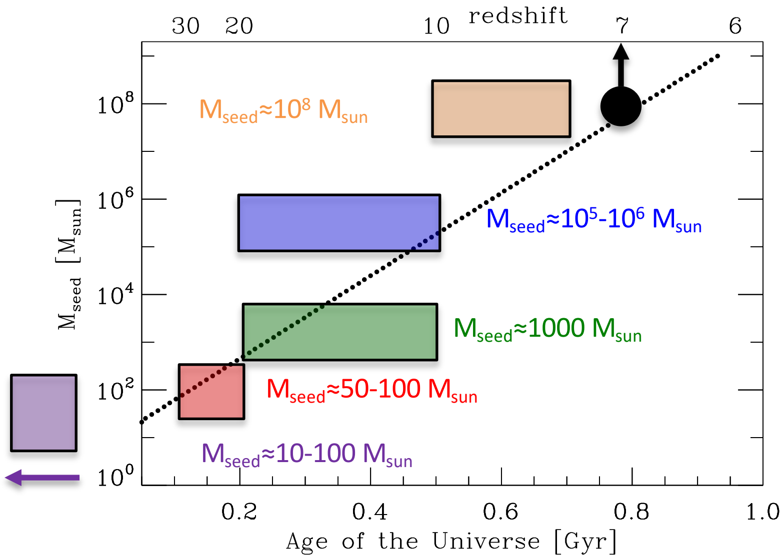
Compared to the Earth-based gravitational wave observatories like LIGO and VIRGO, eLISA addresses the much richer frequency range between 0.1mHz and 1Hz, inaccessible on Earth due to arm length limitations and terrestrial gravity gradient noise.

SUMMARY

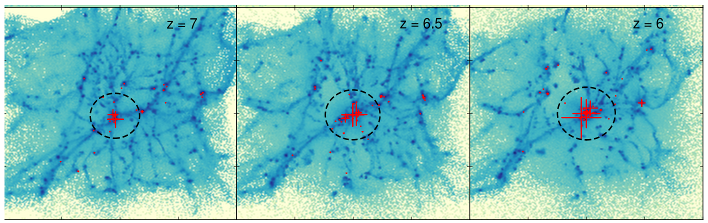


Super massive black holes (M_{BH} ≈10^8-10^{10} M_{sun}) are present both in the **local Universe** and in the most distant epochs **(t≲1 Gyr after the Big Bang; z ≳ 6)** reachable so far with currently available telescopes.

Theoretical model are facing **problems** to explain their **existence at high redshift.** Different scenarios are available for their seeds formation: PopIII, DCBH, Dense star clusters, Merger-driven DCBH, PBHs. **The origin of SMBH seeds is still unclear.**

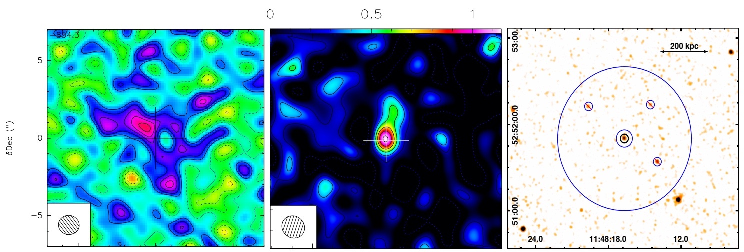


Sinergy between cosmological simulations and multi-wavelength data to exploit at best the potential of future facilities:



e.g.

JWST, Lynx, eLISA



RADIATIVE EFFICIENCY ε_{rad}

From GR it results that the **inner stable orbit** in an accretion disk surrounding a BH is

$$\boldsymbol{R_0 = 3\, R_{SCH}},$$

where R_{SCH} is the Schwarzschild radius $\boldsymbol{R_{SCH} = \frac{2GM}{c^2}}$. For $R < R_0$ matter falls into the BH.

Being $\boldsymbol{\Omega = -\frac{GMm}{R}}$, the gravitational potential energy of a mass m at a distance R from the BH of mass M, the variation of the gravitational potential energy when it passes from $R = \infty$ to $R = R_0$ is given by:

$$\Delta\boldsymbol{\Omega} = \Omega(\infty) - \Omega(R_0) = 0 - \left(-\frac{GMm}{R_0}\right) = \frac{GMm}{R_0} = \boldsymbol{\frac{GMm}{3R_{SCH}}}.$$

RADIATIVE EFFICIENCY ε_{rad}

From the virial theorem it results that ½ of this energy is radiated away

$$E = \frac{\Delta\Omega}{2} = \frac{GMm}{6R_{SCH}} = \frac{GMm}{6}\frac{c^2}{2GM} = \frac{1}{12}mc^2.$$

Being $\mathrm{e} = mc^2$ the rest energy of the mass, it results that a fraction

$$\boldsymbol{\varepsilon_{rad}} = \frac{e}{E} = \frac{1}{12} = \mathbf{0.083}$$

of it is radiated away during the accretion process.

Consider that in stellar nuclear reaction this efficiency is $\varepsilon^*_{rad} \approx 0.7\% = 0.007$.

The process of matter accretion around a BH is the most powerful way of converting gravitational potential energy in radiation.

The first Gyr of the Universe in a nutshell

Understaning the origin of SMBH seeds is fundamental

to unswer fundamental questions related

to the properties of the early Universe

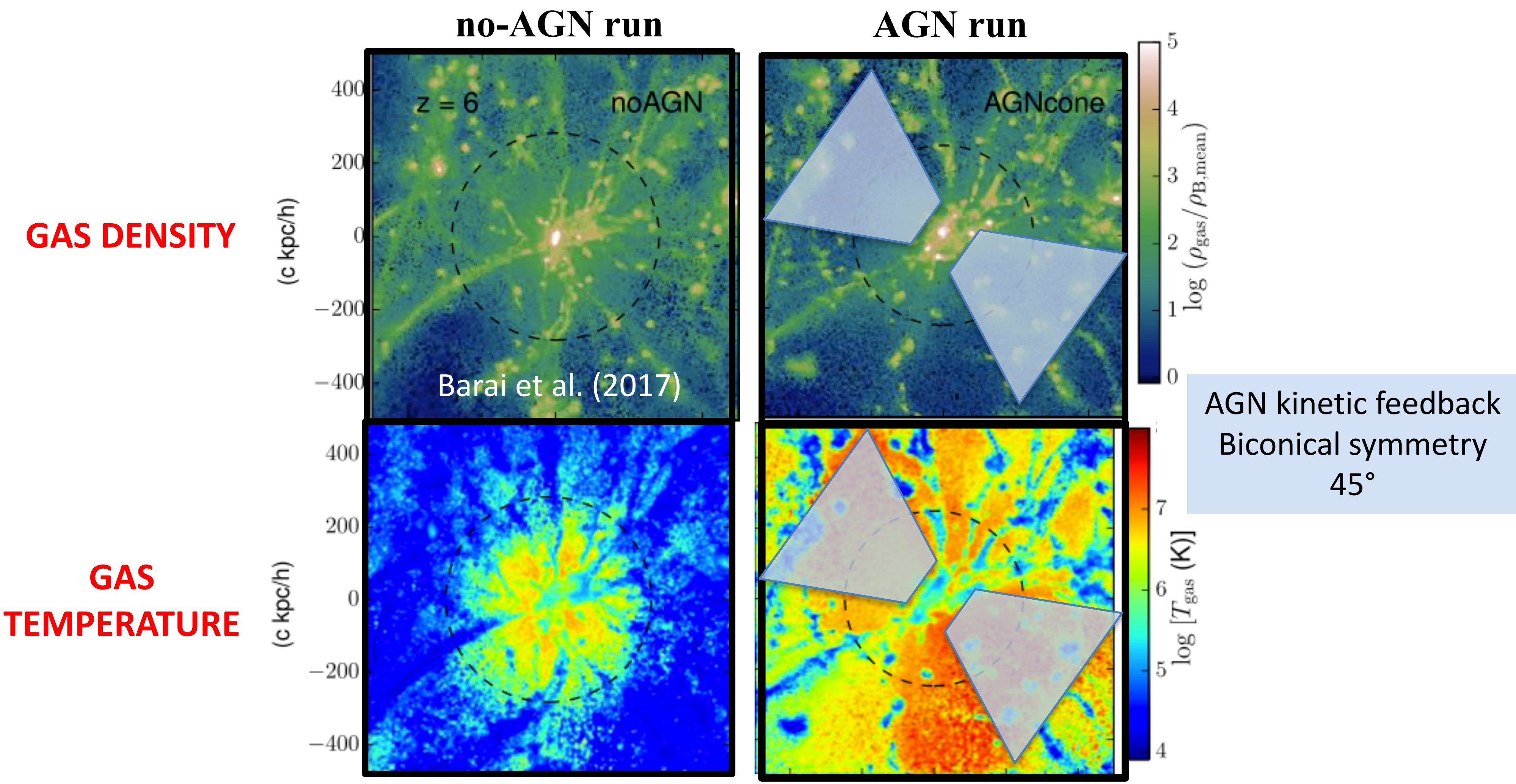
1) How do high redshift quasars form and evolve?

2) What are the properties of their host galaxies?

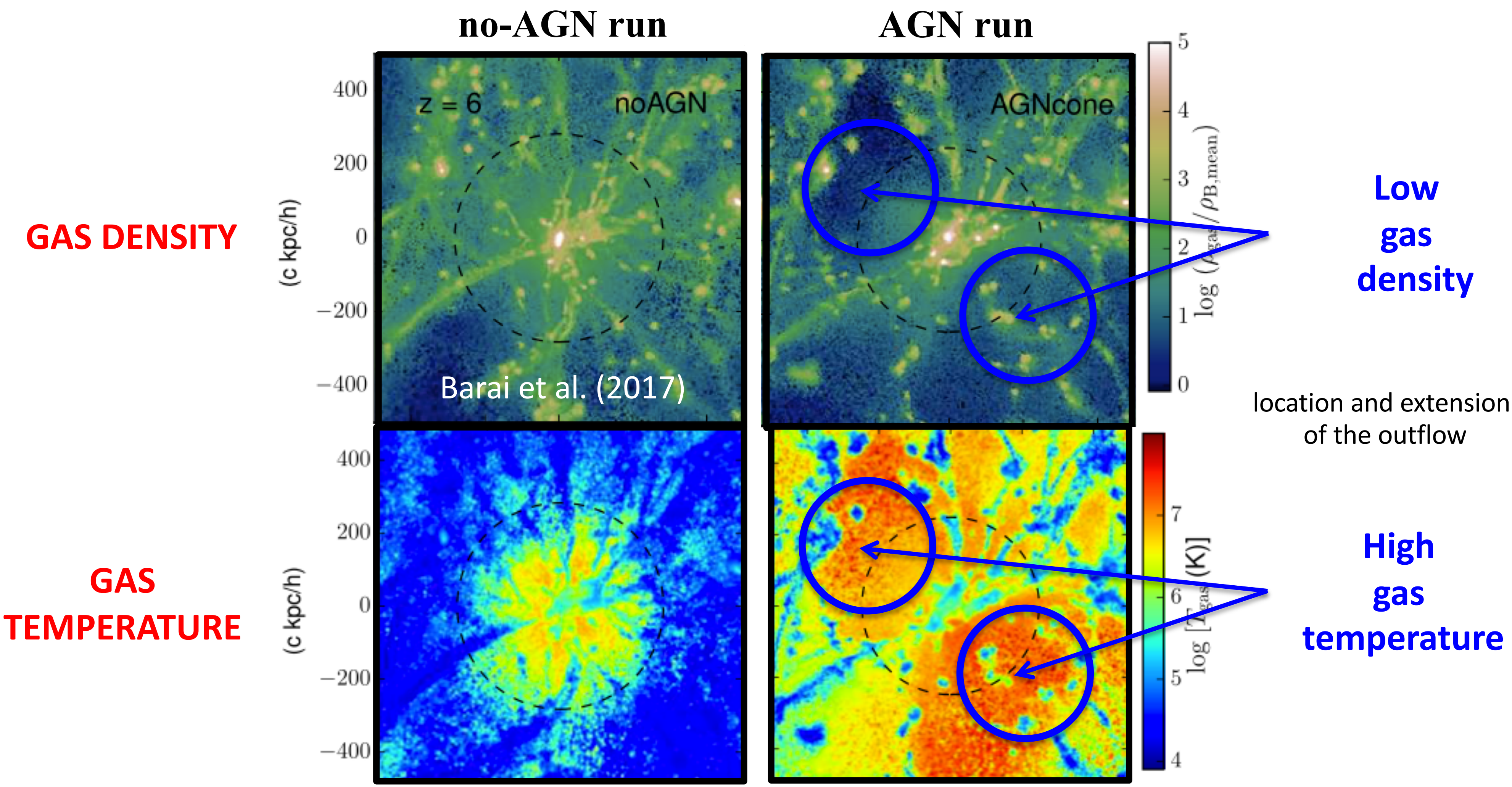
3) What are the sources of cosmic reionization?

(Massive or dwarf) galaxies? (Faint or bright) quasars?

Quasar feedback effects on the host galaxy

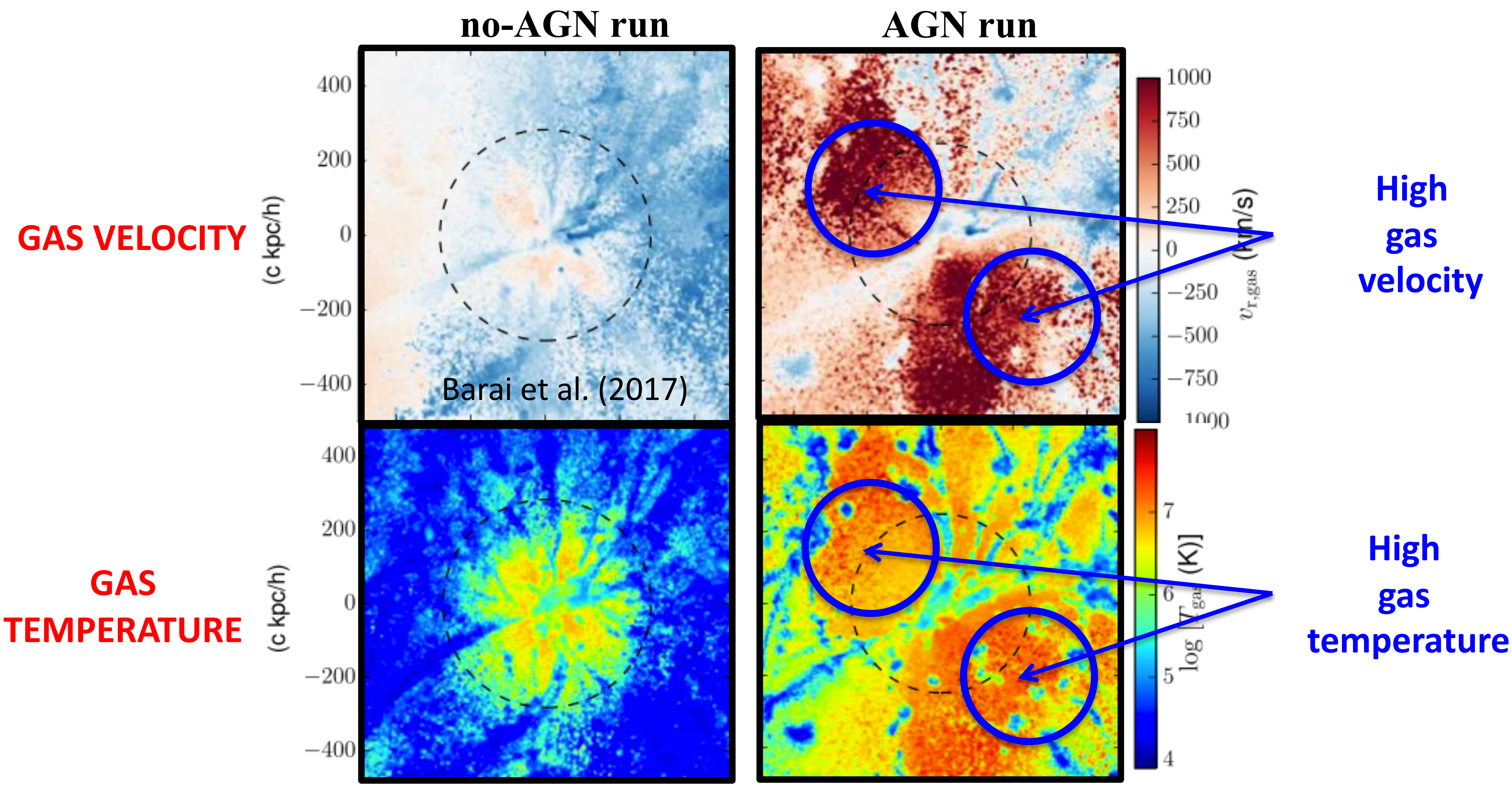


Quasar feedback effects on the host galaxy



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

Quasar feedback effects on the host galaxy

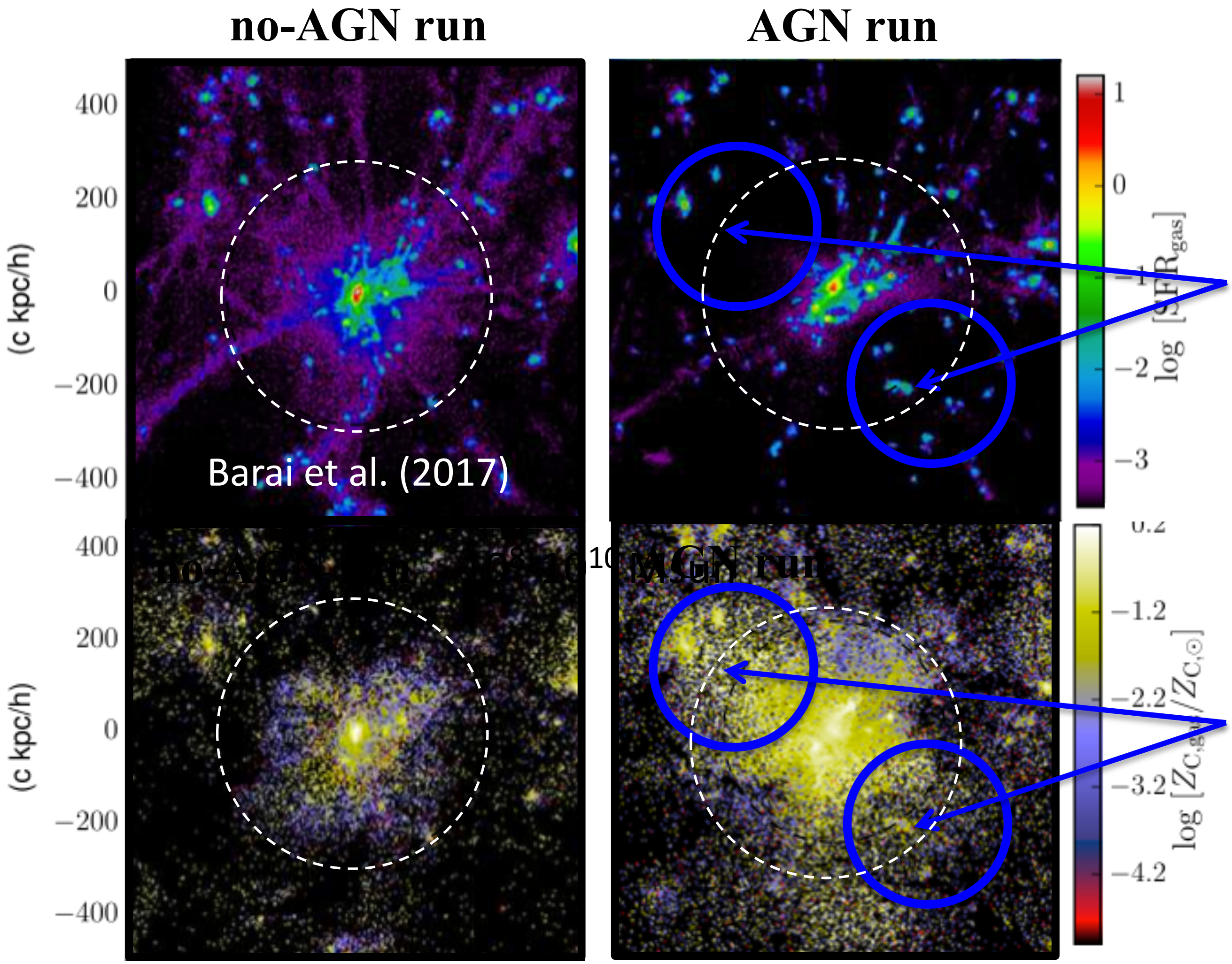


In the AGN run, particles reach very large velocities (up to 1000 km s^{-1}) in agreement with the outflow velocities as inferred from the broad wings of the [CII] line observations

Quasar feedback effects on the host galaxy

STAR FORMATION RATE

GAS METALLICITY



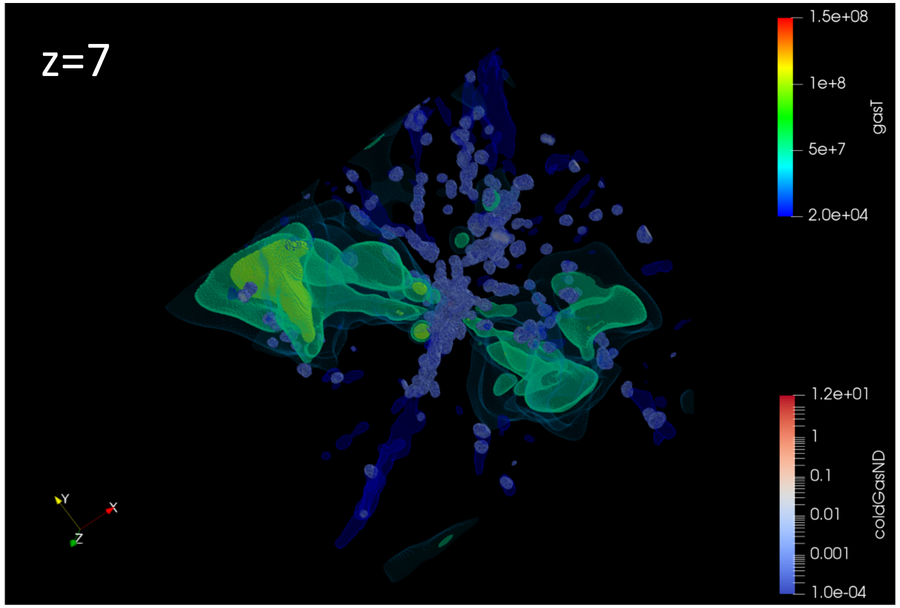
Low SFR

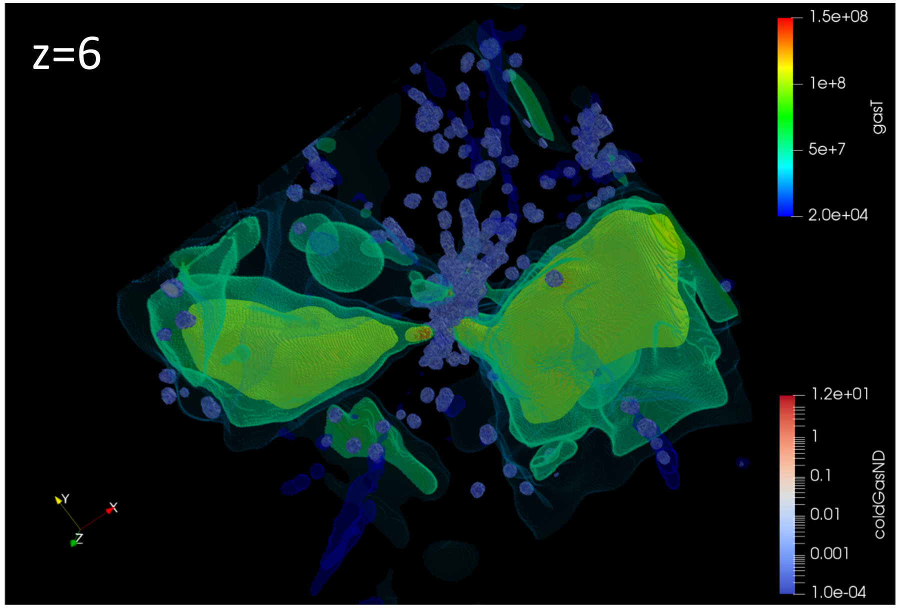
High gas metallicity

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

Fast outflowing metals are distributed on large scales (≥ virial radius) possibly being ejected in the surrounding intergalactic medium.

Orientation effects on the detection of outflows





Although a powerful outflow is in place,
fast-moving gas would be detectable only along directions
intercepting the outflow orientation.