co-evolution of super-massive black holes and their host galaxies

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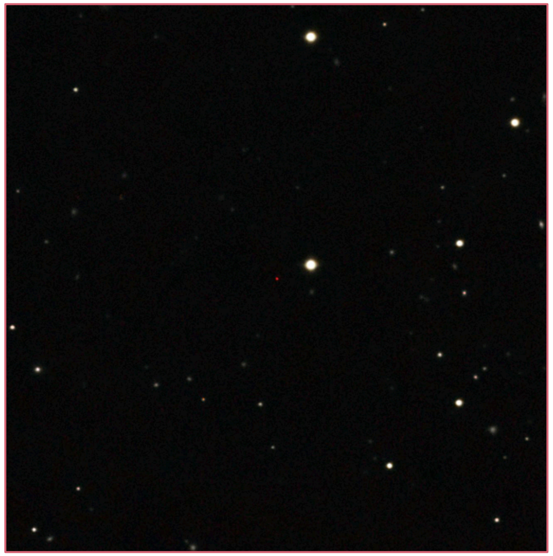
disclaimer

- *my lectures will focus on $z \geq 6$ black holes and their host galaxies*

- *my lectures will attempt to review the field from a theorist perspective*

ULAS J1120: a 2 10^9 M_{sun} black hole, 770 Myr after the Big Bang

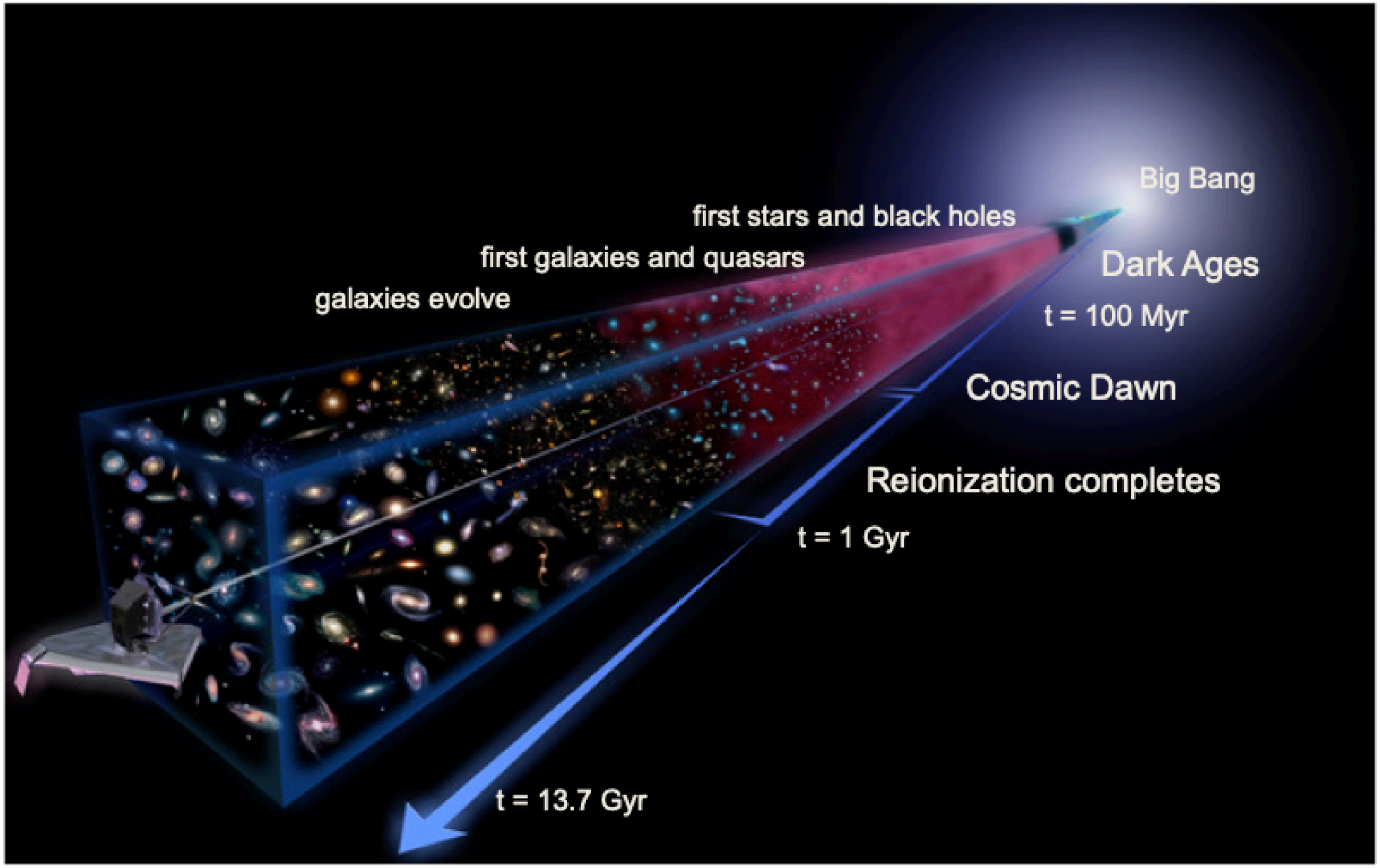


Mortlock et al. (2011)

Outline

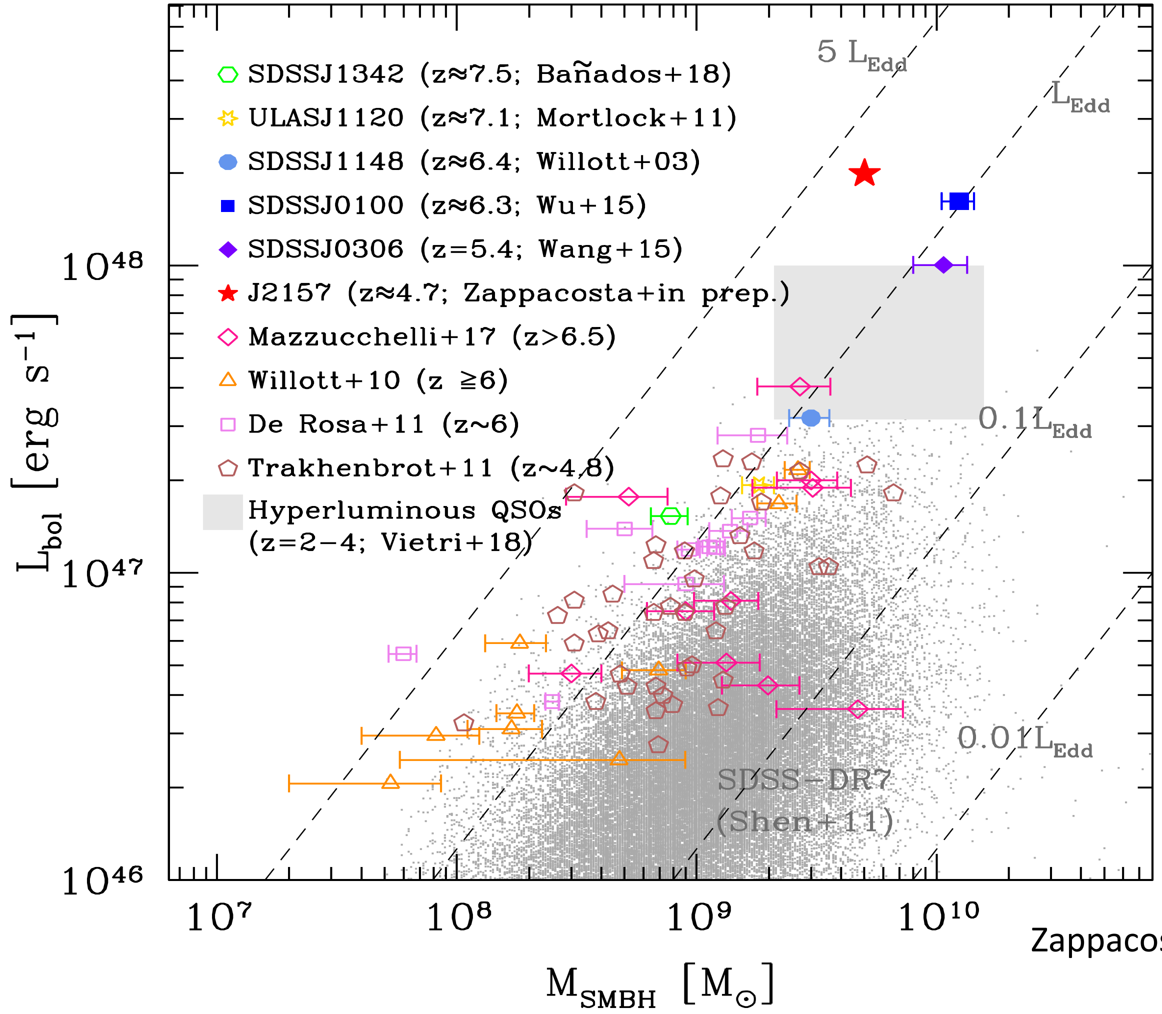
- super-massive black holes at z > 6
- a time-scale problem?
- planting black hole seeds
- growing black hole seeds
- the observability of growing and failed seeds
- what do we know about the host galaxies?
- super-massive black holes and their hosts as signposts of rapidly evolving and biased regions in the early Universe

Terra Incognita: the Universe @ cosmic dawn



the most distant supermassive BHs

a subsample of high-z SMBHs



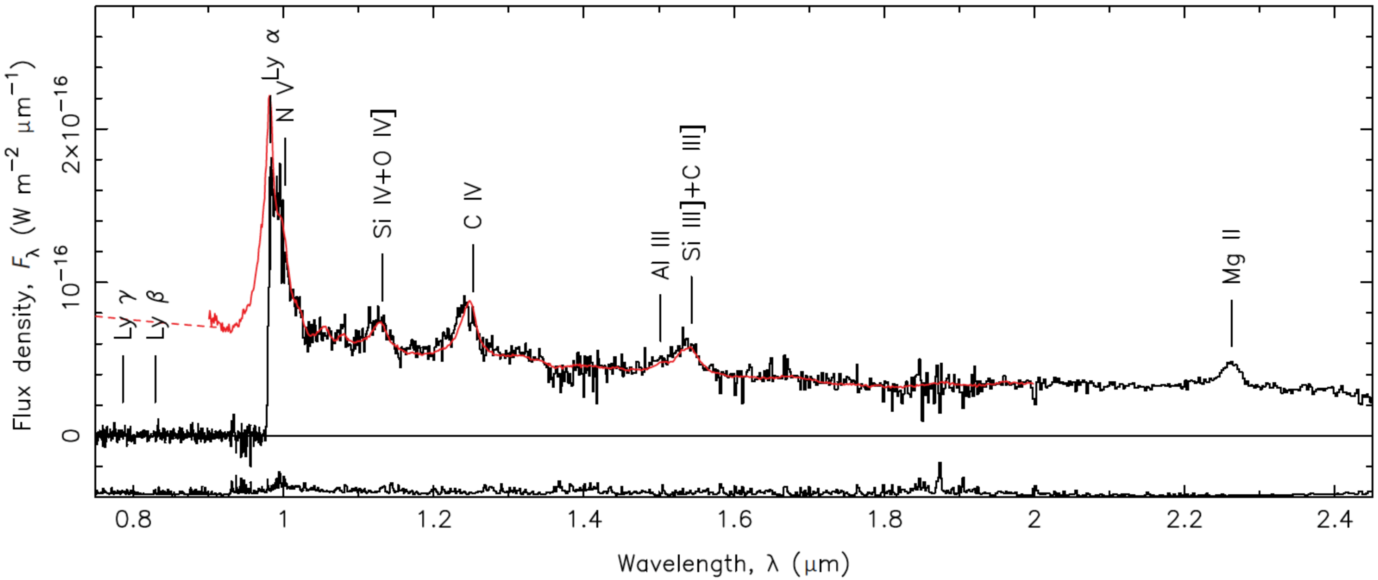
Zappacosta et al. in prep

Decarli, priv comm:

~ 340 quasars at z>5.5 ~ 190 at z > 6.0 41(+6) at z > 6.5 5(+1) at z > 7.0

quasars show very little evolution in their intrinsic properties over time

spectrum of ULAS J1120+0641 (black line) compared to a composite spectrum derived from lower-z quasars (red line)



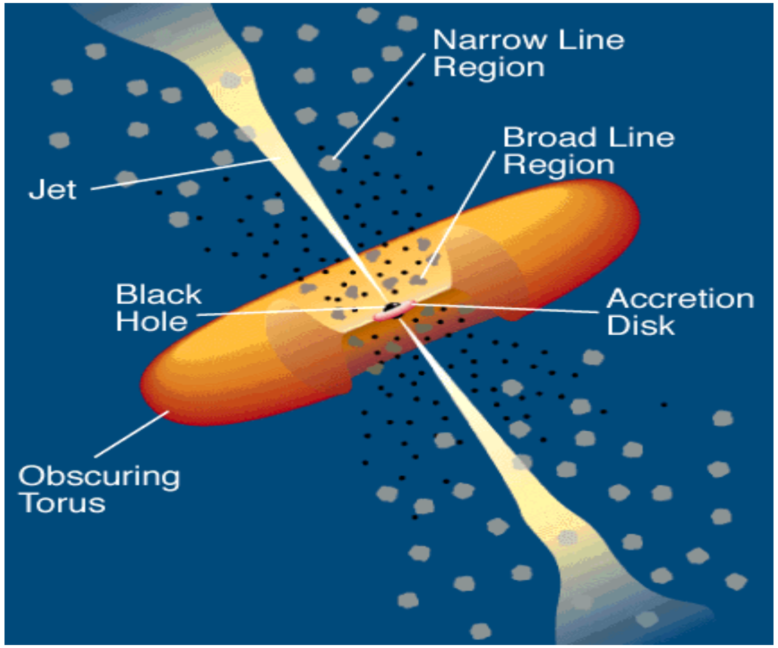
Mortlock et al. (2011)

- no flux blueward of the Lyα → neutral hydrogen absorption along the line of sight
- the spectrum of ULAS J1120+0641 is similar to those of lower redshift quasars of comparable luminosity → little evolution in the metallicity (super-solar) and physical conditions in the broad line region surrounding the nuclear black hole

how to measure supermassive black hole masses at z ≥ 6

black hole mass estimates rely on the measurement of broad emission lines (BELs) widths, and are based on the assumption that the dynamics of the Broad Line Regions (BLR)s are dominated by the gravity of the central BH

schematic representation of an AGN



(Credit: C.M. Urry and P. Padovani)

Broad Line Region: FWHM > 1000 km/s
$v^2 \sim GM/R$
R < 0.3 pc

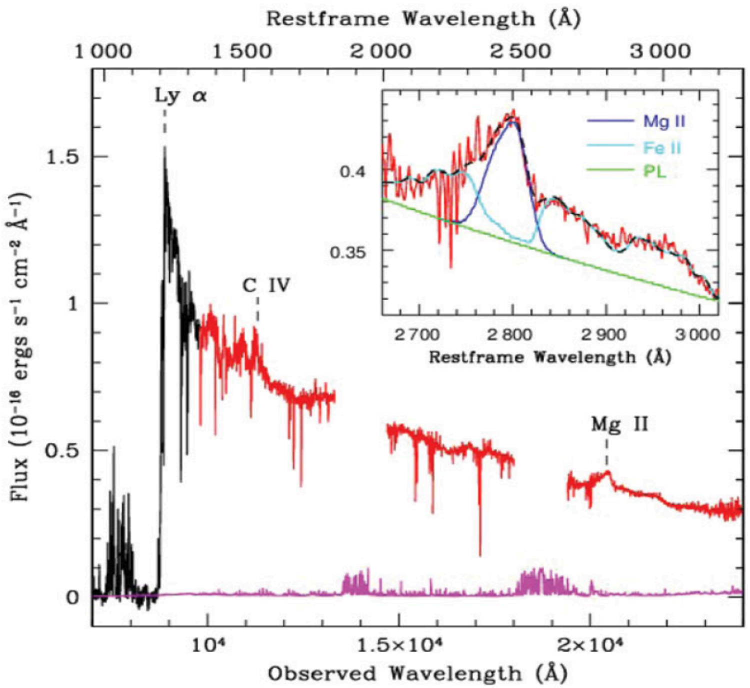
Narrow Line Region: FWHM > 100 km/s
$v^2 \sim GM/R$
10 pc < R < 100 pc

how to measure supermassive black hole masses at z ≥ 6

black hole mass estimates rely on the measurement of broad emission lines (BELs) widths, and are based on the assumption that the dynamics of the Broad Line Regions (BLR)s are dominated by the gravity of the central BH

combined optical/near-infrared spectrum of J0100+2802

Wu et al. (2015)



$M_{BH} \approx \mathbf{R_{BLR}}\, \mathbf{v^2_{BLR}}/G$

- $\mathbf{R_{BLR}}$ ←→ in local AGNs there is a relation between the optical/UV luminosity and R_{BLR}
- $\mathbf{v_{BLR}}$ ←→ from the FWHM of BLR emission lines (CIV, Mg II)

Mg II FWHM = 5 130 ±150 km s^{-1}

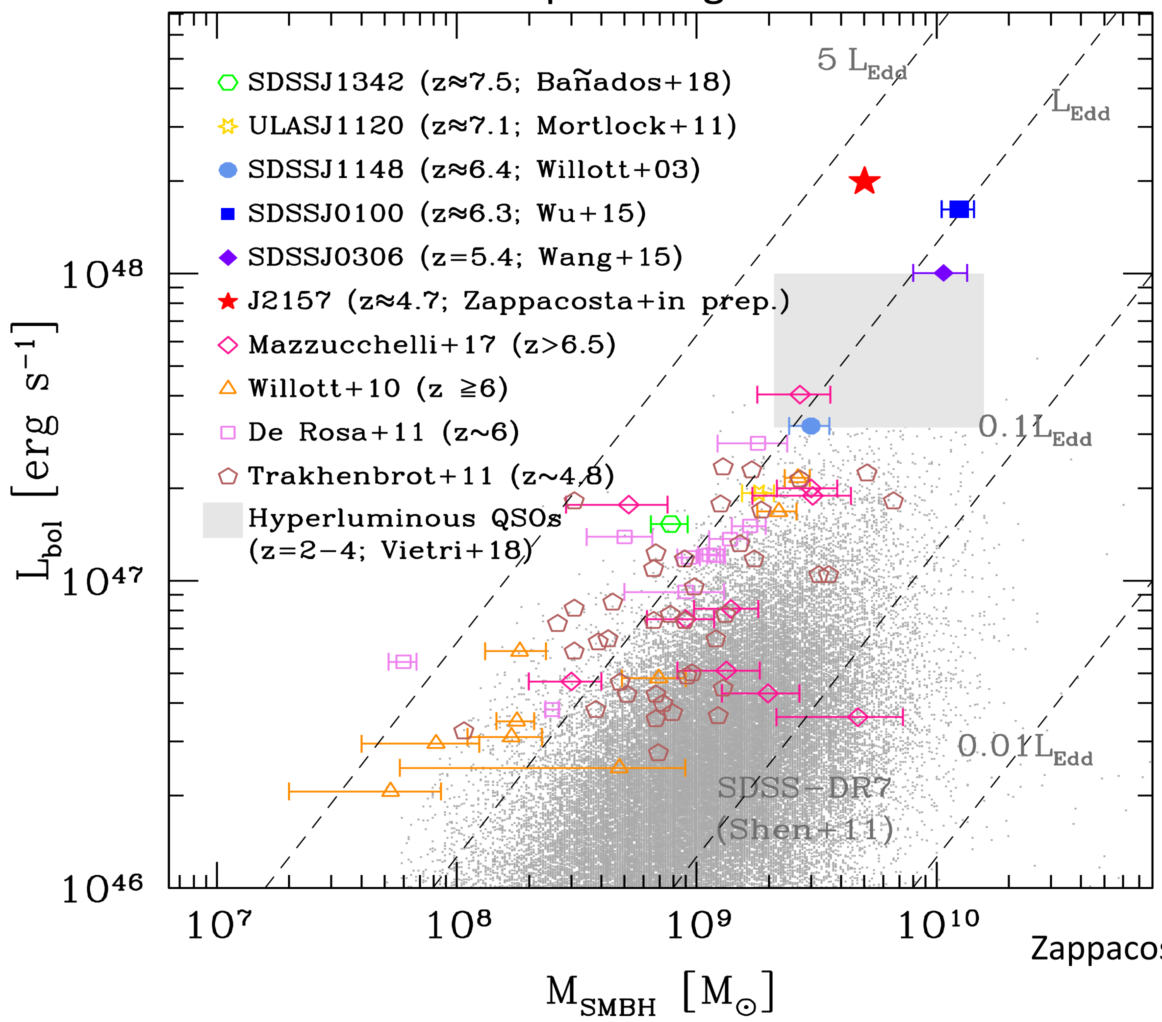
$L_{3000\ Å}$ = (3.15 ± 0.47) 10^{47}ergs s^{-1}

M_{BH} = (1.24 ±0.19) 10^{10} M_{sun}

Wu et al. (2015)

the most distant supermassive BHs

a subsample of high-z SMBHs



Zappacosta et al. in prep

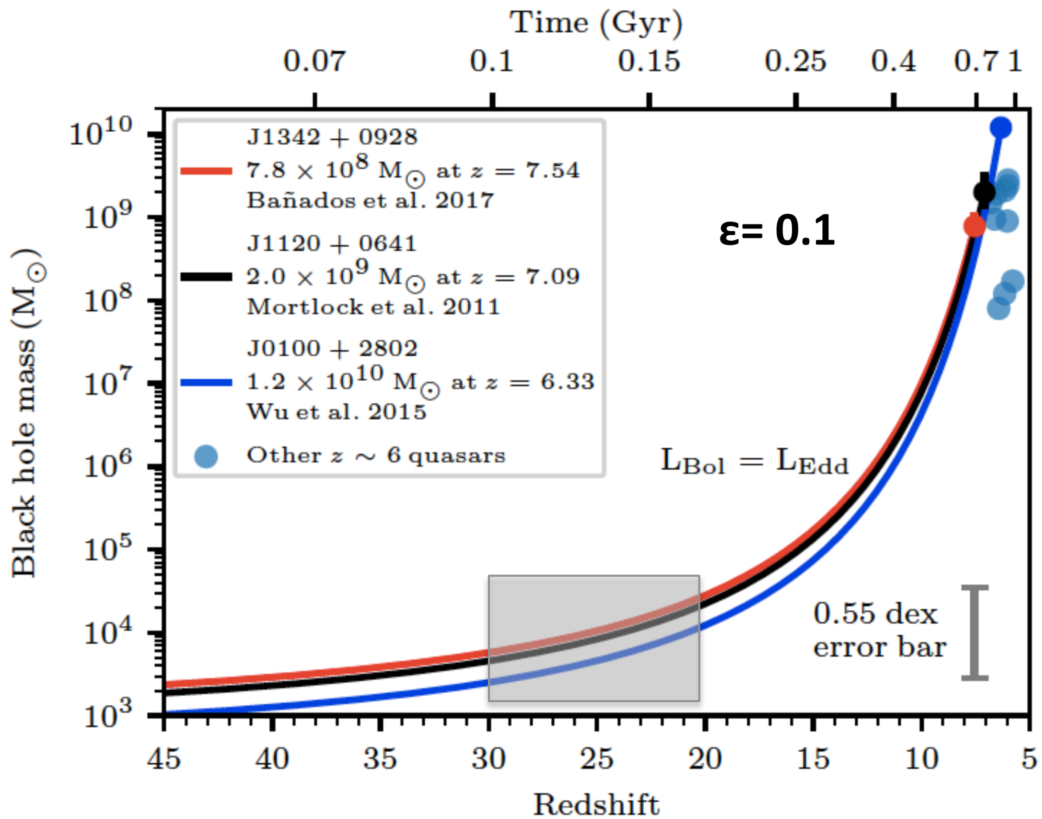
Decarli, priv comm:

~ 340 quasars at z>5.5 ~ 190 at z > 6.0 41(+6) at z > 6.5 5(+1) at z > 7.0

the first super-massive black holes

How do these SMBHs grow in less than 1 Gyr?

If $L = L_{Edd}$ then $M_{SMBH}(t) = M_{seed}(t_{form})\, e^{[(1-\varepsilon)/\varepsilon]\Delta t/tEdd}$ $t_{Edd} \approx 0.45$ Gyr



Bañados et al. (2018)

models of SMBH growth require massive seeds ($> 10^3$ - 10^5 M_{sun}) and/or episodes of super-Eddington accretion

***

the most distant quasars: theoretical challenge

How do these SMBHs grow in less than 1 Gyr?

$M_{SMBH}(t) = M_{seed}(t_{form})\, e^{[(1-\varepsilon)/\varepsilon]\Delta t/tEdd}$ $\varepsilon = 0.1$ $t_{Edd} = 0.45$ Gyr

ULAS J1342

$z = 7.45$	$t = 0.699$ Gyr	$M_{BH} = 7.8\ 10^8\ M_{sun}$
$z_{form} = 30$	$t_{form} = 0.098$ Gyr	$\rightarrow M_{seed} = 4.2\ 10^3\ M_{sun}$
$z_{form} = 20$	$t_{form} = 0.177$ Gyr	**$\rightarrow M_{seed} = 2\ 10^5\ M_{sun}$**

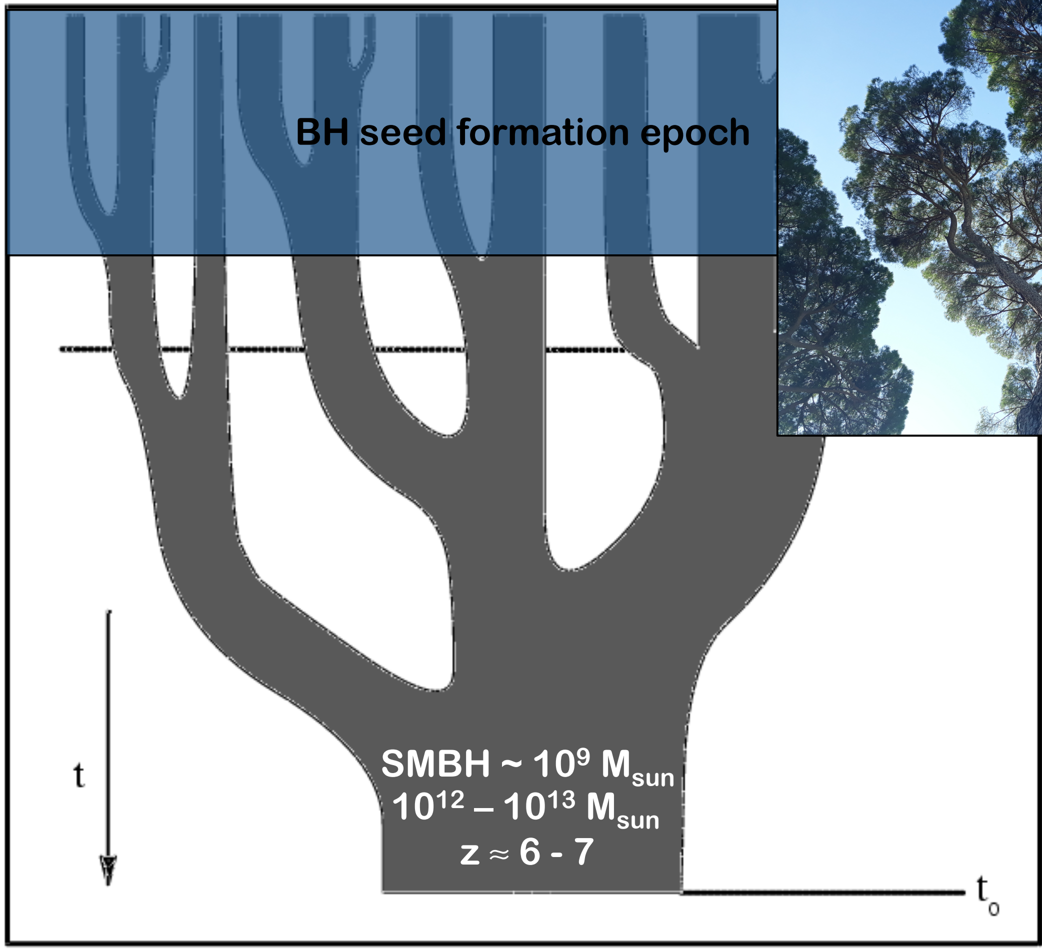
ULAS J1120

$z = 7.09$	$t = 0.745$ Gyr	$M_{BH} = 2\ 10^9\ M_{sun}$
$z_{form} = 30$	$t_{form} = 0.098$ Gyr	$\rightarrow M_{seed} = 4.8\ 10^3\ M_{sun}$
$z_{form} = 20$	$t_{form} = 0.177$ Gyr	$\rightarrow M_{seed} = 2.3\ 10^4\ M_{sun}$

ULAS J0100

$z = 6.3$	$t = 0.869$ Gyr	$M_{BH} = 10^{10}\ M_{sun}$
$z_{form} = 30$	$t_{form} = 0.098$ Gyr	**$\rightarrow M_{seed} = 2\ 10^3\ M_{sun}$**
$z_{form} = 20$	$t_{form} = 0.177$ Gyr	$\rightarrow M_{seed} = 9.7\ 10^3\ M_{sun}$

planting and growing seeds



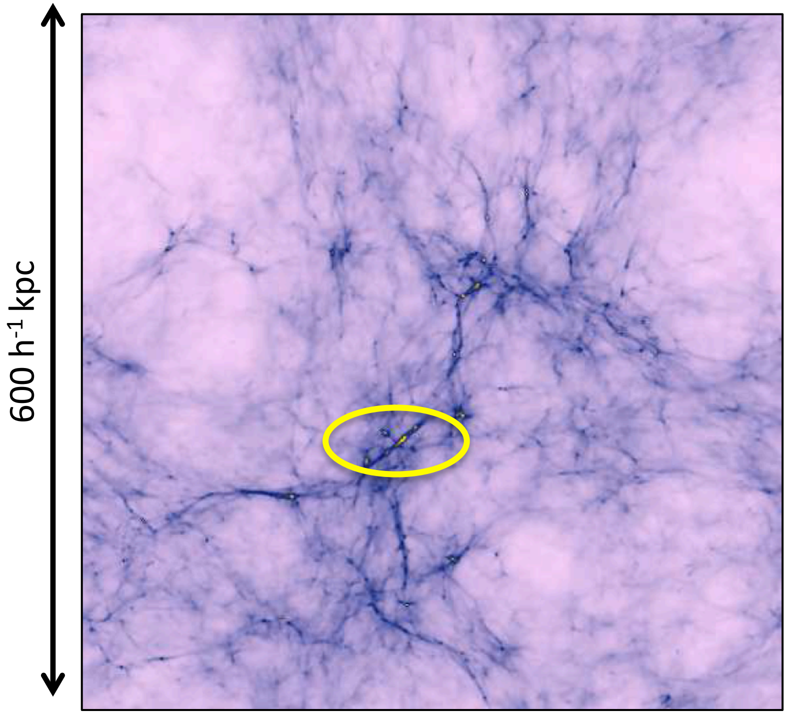
Haiman & Loeb 2001, Volonteri et al. 2003, Wyithe & Loeb 2003, Haiman 2004, Menci et al. 2004, 2008,
Shapiro 2005, Yoo & Miralda-Escude' 2004, Bromley et al. 2004, Volonteri & Rees 2005,
Li et al. 2007, Pelupessy et al. 2007, Sijacki et al. 2009, Tanaka & Haiman 2009, Lamastra et al. 2010,
Valiante et al. 2011, Petri et al. 2012; Valiante et al. 2015; 2016, 2017, 2018; Pezzulli et al. 2016, 2017; Sassano et al. 2019

main questions

- what is the mass spectrum of black hole seeds?
- when and where do they form?

first seed BH formation channel: remnants from the first stars

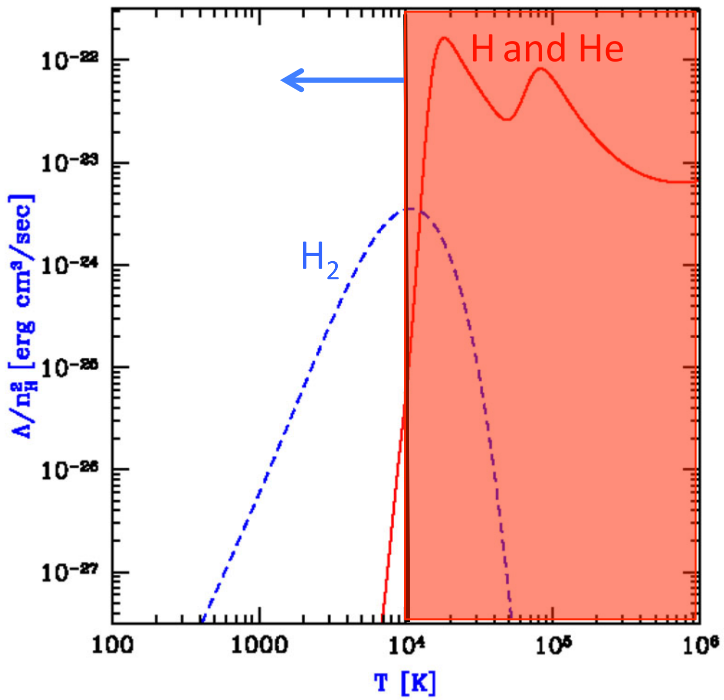
the first star forming sites in a ΛCDM cosmology



Yoshida et al. 2003

mini-halos with M = $10^6 - 10^7$ M_{sun} @ z = 20 − 30
$T_{vir} < 10^4$ K

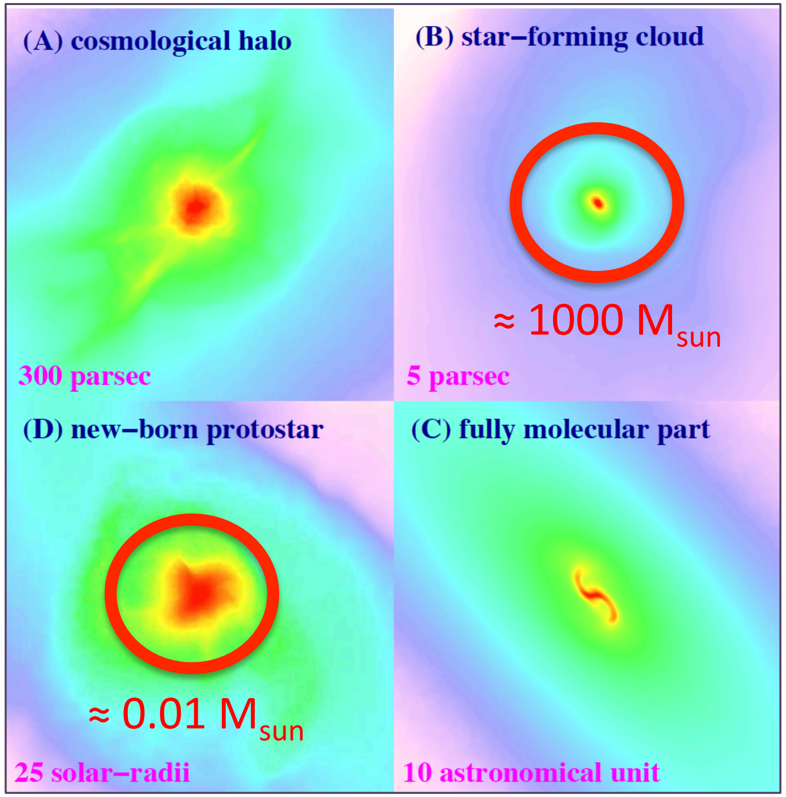
cooling rate of primordial gas



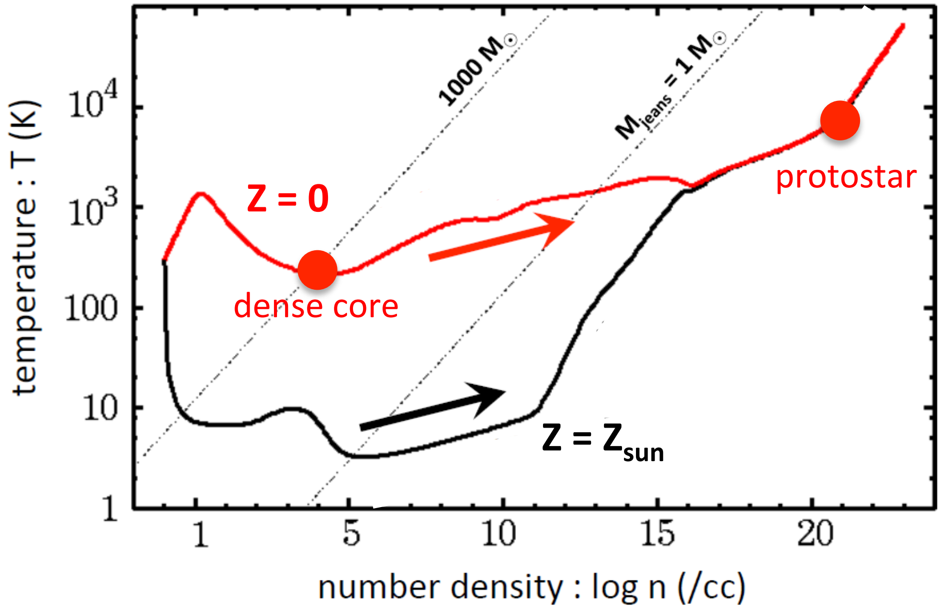
the formation of the first stars relies on H_2 cooling

protostar formation in the early Universe

projected gas distribution around the protostar



Yoshida et al. 2008

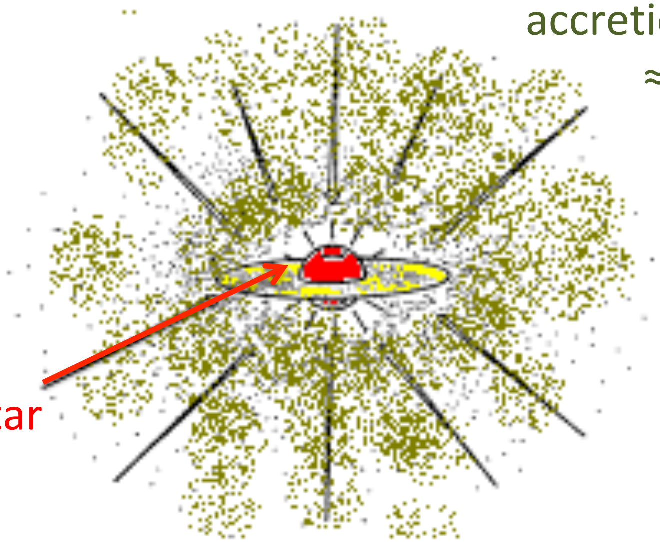


Omukai 2000

H_2 cooling leads to the formation of dense cores at $n \approx 10^4\ cm^{-3}$, $T \approx 200$ K with mass ≈ 1000 M_{sun}

*** with metal cooling ($Z = Z_{sun}$) dense cores have a mass of mass ≈ 1 M_{sun}

protostellar mass accretion



Accretion rate:

$dM/dt \approx M_j/t_{ff} \approx (c_s\ t_{ff})^3\ \rho/t_{ff} \approx c_s^3/G \approx T^{3/2}$

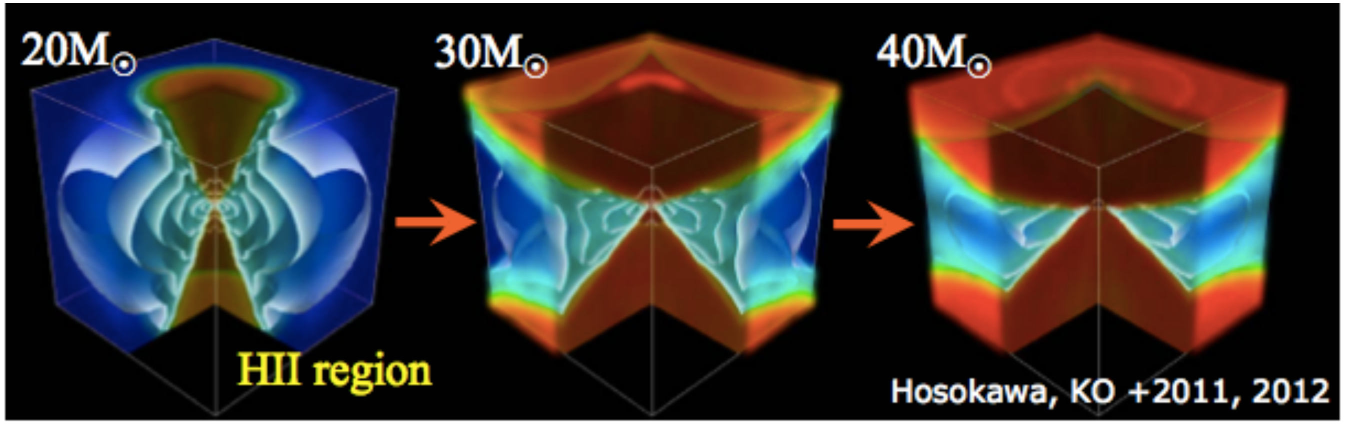
Pop I ($T \approx 10$ K): $10^{-6}\ M_{sun}/yr$

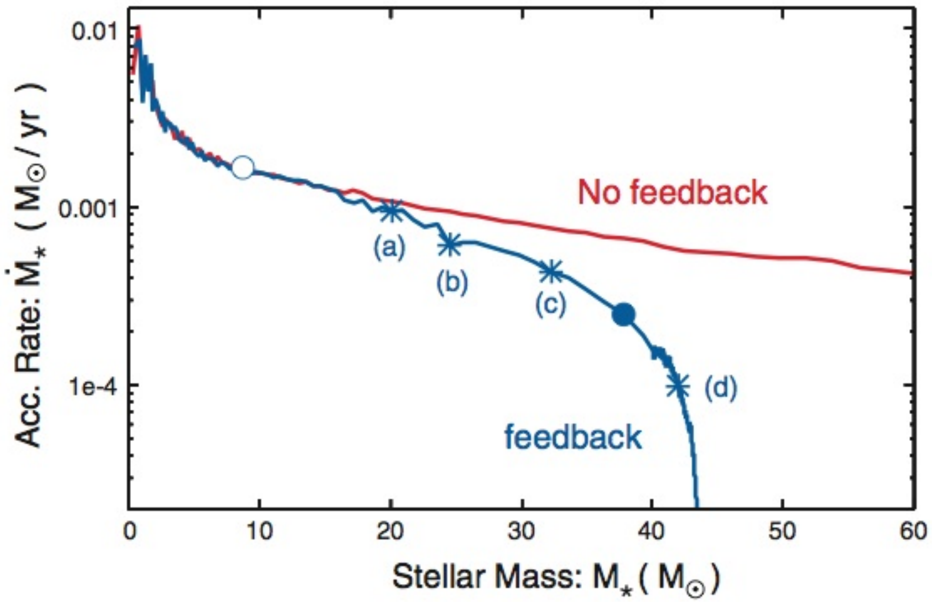
Pop III ($T \approx 200$ K): $10^{-3}\ M_{sun}/yr$

→ much higher accretion rate in Pop III star formation

the final stellar mass is set by UV feedback

2D radiation hydrodynamic simulation of the accretion phase

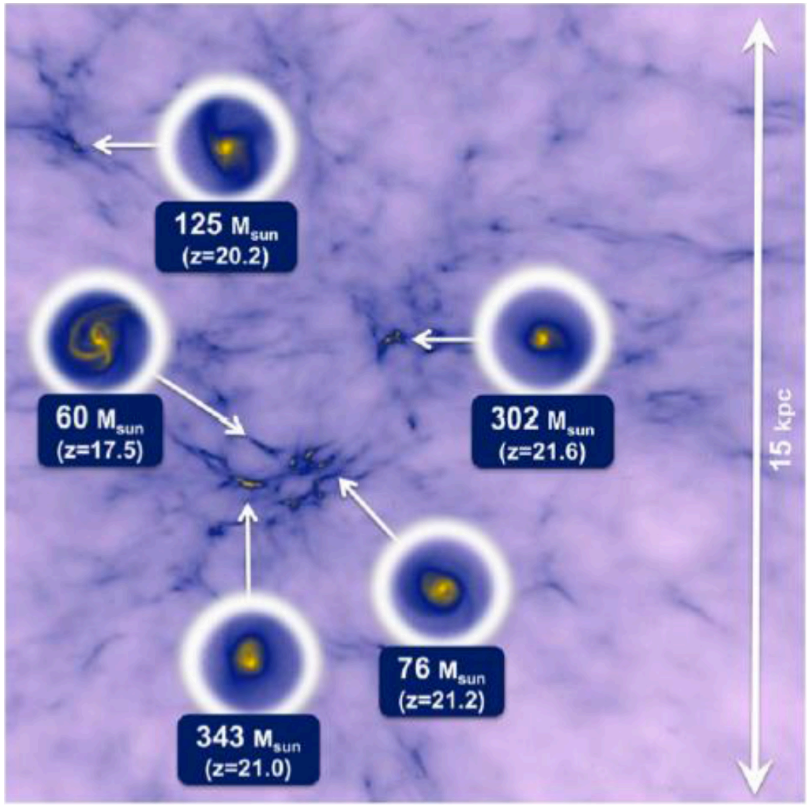


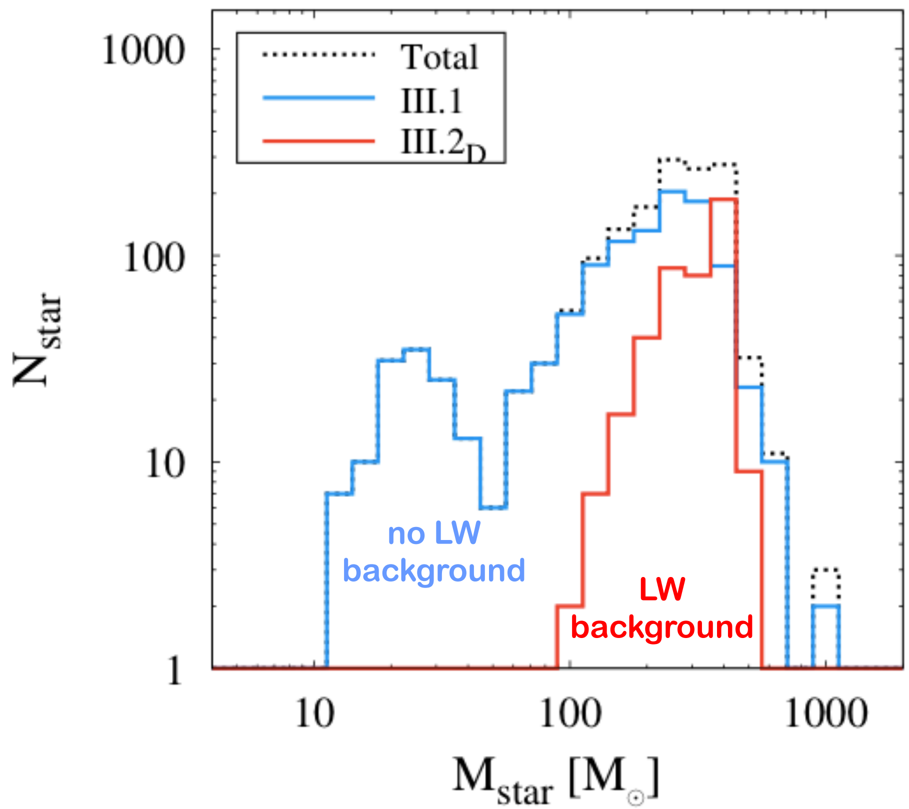


disk photo-evaporation limits
the final stellar mass to $M_* \approx 40\ M_{sun}$
but
M_* depends on the
environmental conditions
(Hirano+14, 15; Susa+14)

the mass spectrum of Pop III stars

3D cosmological simulation
+ 2D radiation hydrodynamic simulation





Hirano et al. 2014, 2015

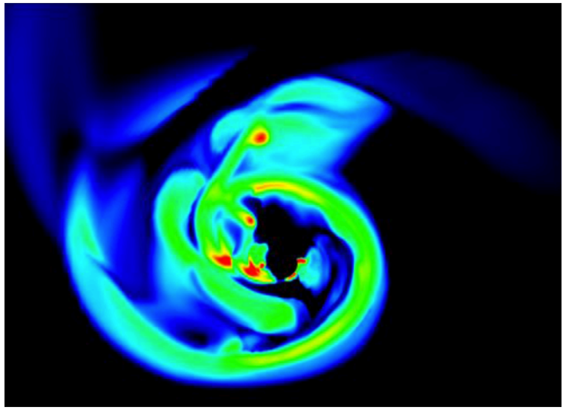
Pop III stars form within a wide mass range: few 10s - 100s up to few 1000s

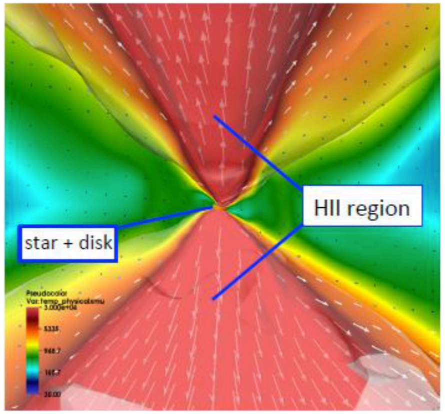
*** indirect constraints on Pop III IMF from stellar archaeology (de Bennassuti et al. 2014, 2016)

multiplicity of Pop III stars

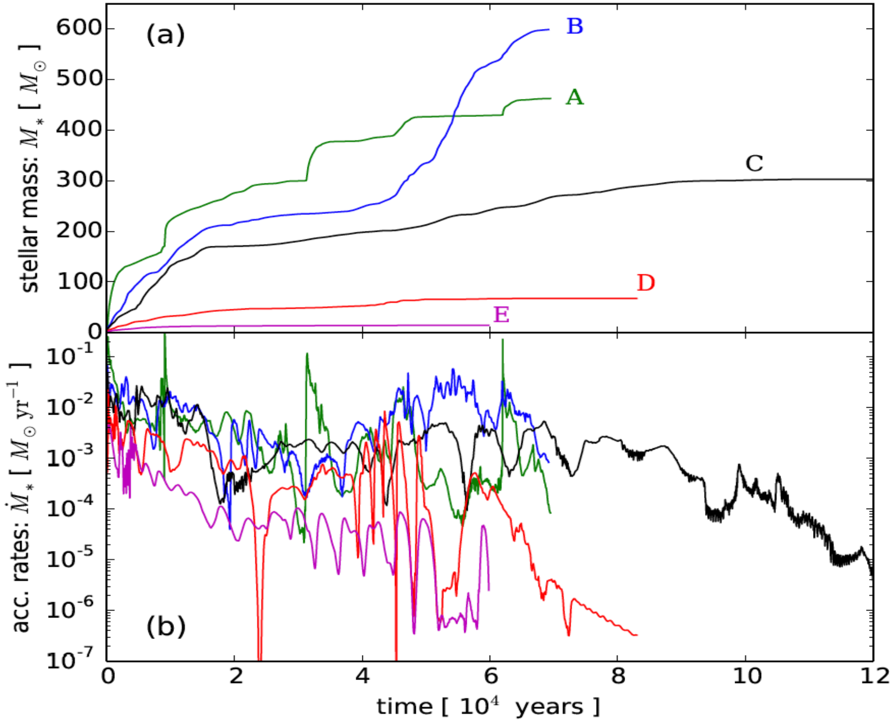
Stacy et al. (2010), Clark et al. (2011), Greif et al. (2011)

fragmentation of circumstellar disk





cosmological initial conditions (Hirano et al. 2015)
long-term (≈ 10^5 yr) evolution with 3D UV feedback
in 4 different star forming regions



Hosokawa et al. (2016)

wide diversity of natal stellar masses covering 10 M_{sun} ≤ M_* ≤ 10^3 M_{sun}

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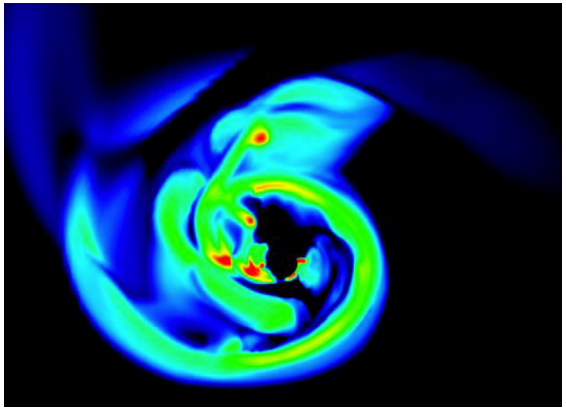
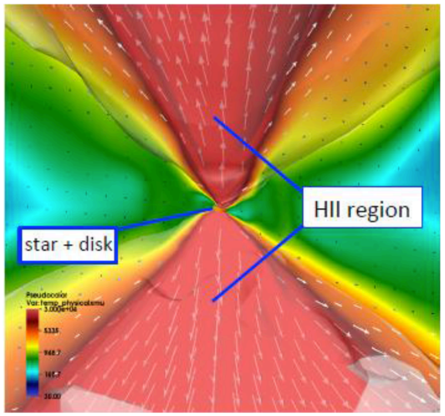
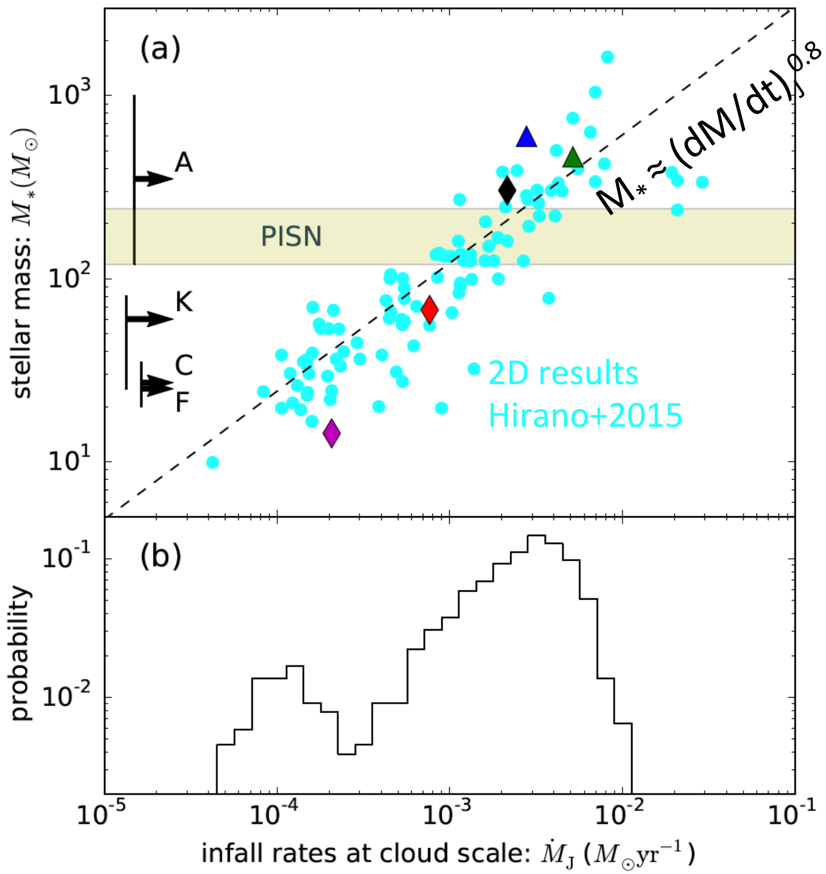




comparison between 3D and 2D simulations



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wide diversity of natal stellar masses covering 10 $M_{sun} \le M_* \le 10^3 M_{sun}$

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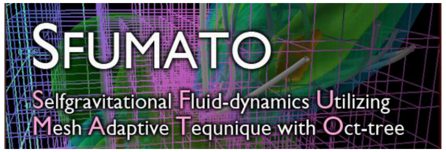
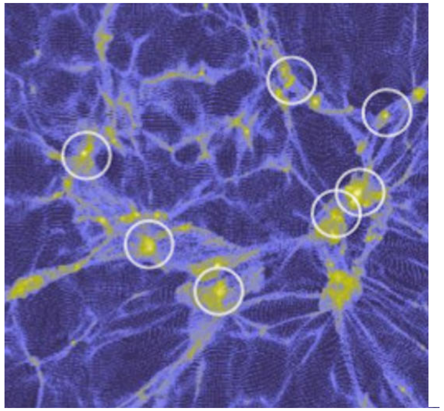
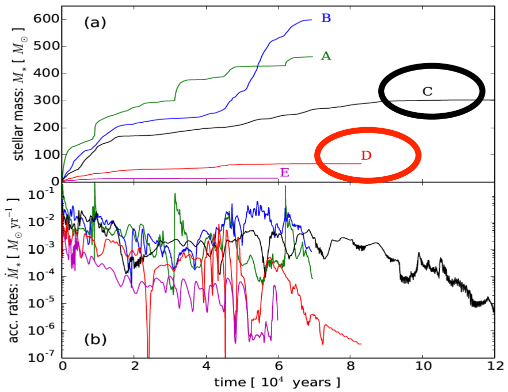


Sugimura et al. in prep

- ✓ 10 times higher resolution (AMR) especially in the outer part of the disk, where fragmentation is more active
- ✓ multiple sources of UV radiation (ART)

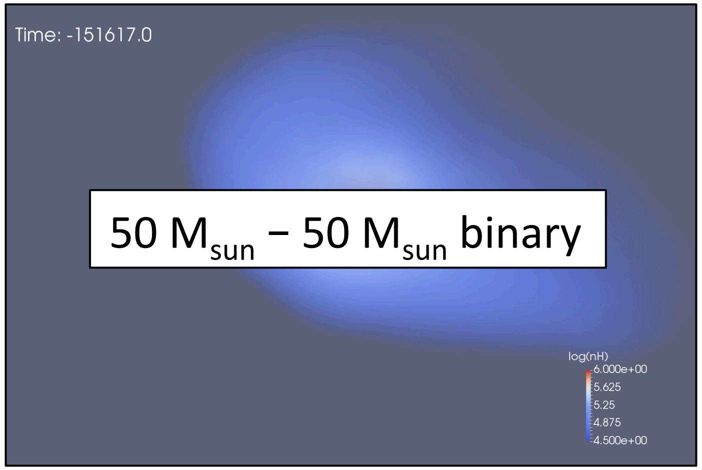


Hirano et al. (2015)

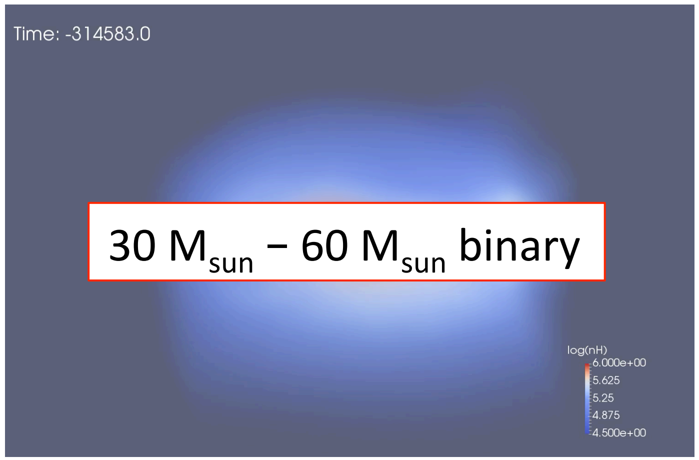


Hosokawa et al. (2016)

minihalo C

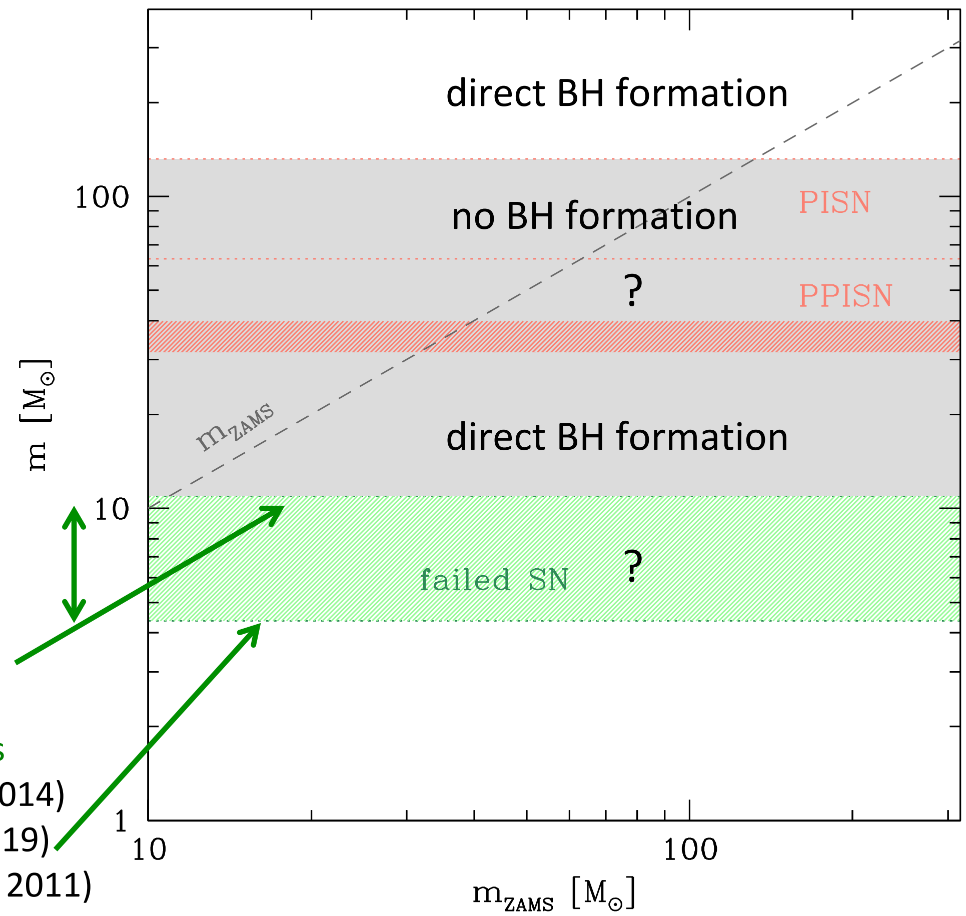


minihalo D



multiple stellar systems with massive binaries are common among Pop III stars

the mass spectrum of Pop III remnants



when do massive stars explode?

when $m_{CO} \geq 11\ M_{sun}$
(Fryer et al 2012)

when the compactness

$\xi_{2.5} > 2.5$ (Horiuchi et al. 2014)

$\xi_{2.5} > 3.0$ (Mapelli et al. 2019)

$\xi_{2.5} > 4.5$ (O'Connor & Ott 2011)

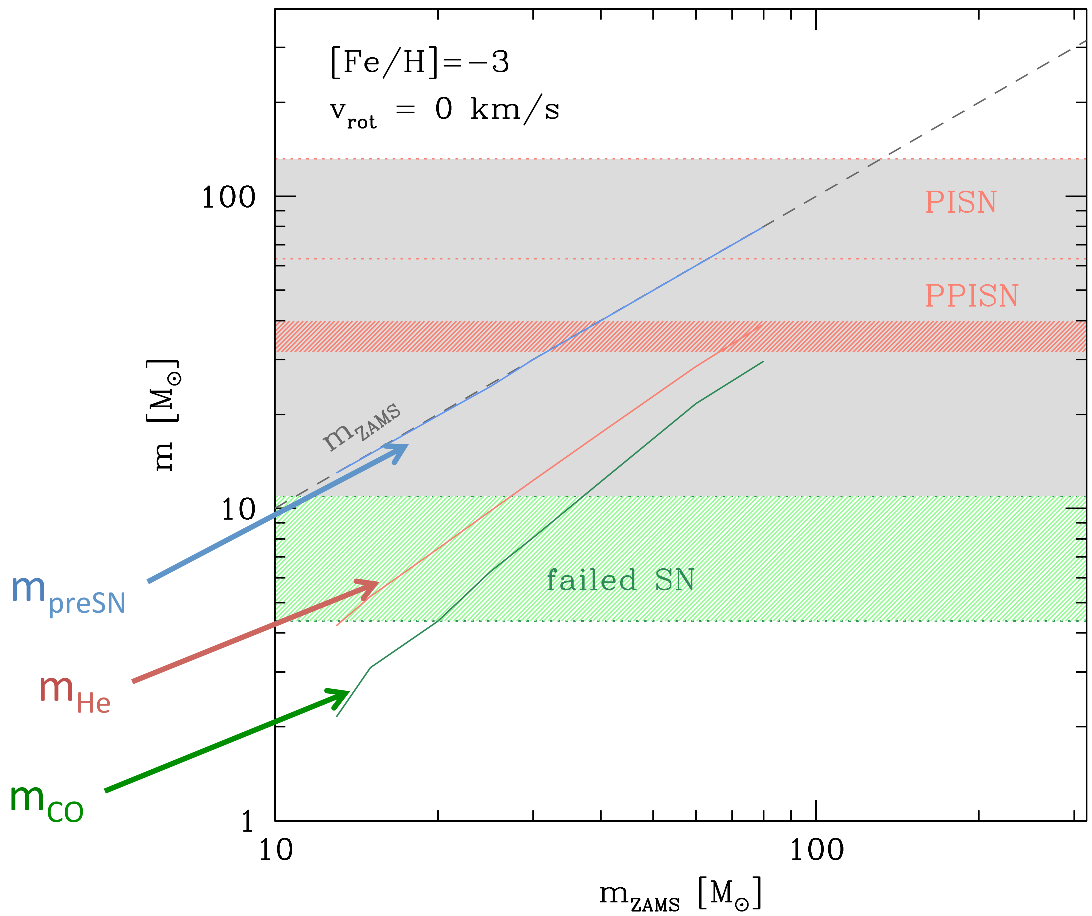
when do massive stars become pair-unstable ?

when $m_{He} \geq 33\ M_{sun}$
(Woosley 2017)

when $m_{He} \geq 40\ M_{sun}$
$m_{CO} \geq 32\ M_{sun}$
(Heger & Woosley 2002)
(Georgy et al. 2017)
(Limongi & Chieffi 2018)

when $m_{He} \geq 40\ M_{sun}$
(Leung et al. 2019)

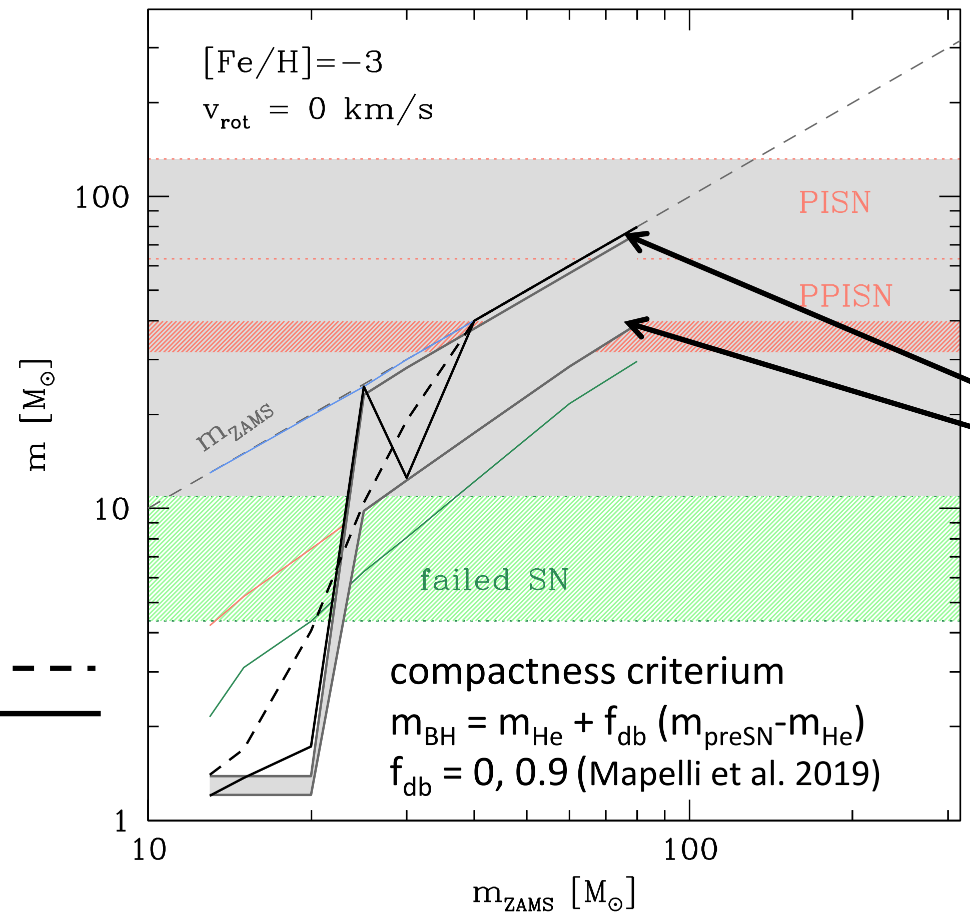
the mass spectrum of Pop III remnants



massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

$13\ M_{sun} \leq m_{zams} \leq 120\ M_{sun}$ [Fe/H] = -3 v_{rot} = 0, 150 km/s, 300 km/s

the mass spectrum of Pop III remnants



delayed SN

direct SN

(Fryer et al. 2012)

$m_{bh,max}$ = 79.90 M_{sun}

$m_{bh,max}$ = 38.90 M_{sun}

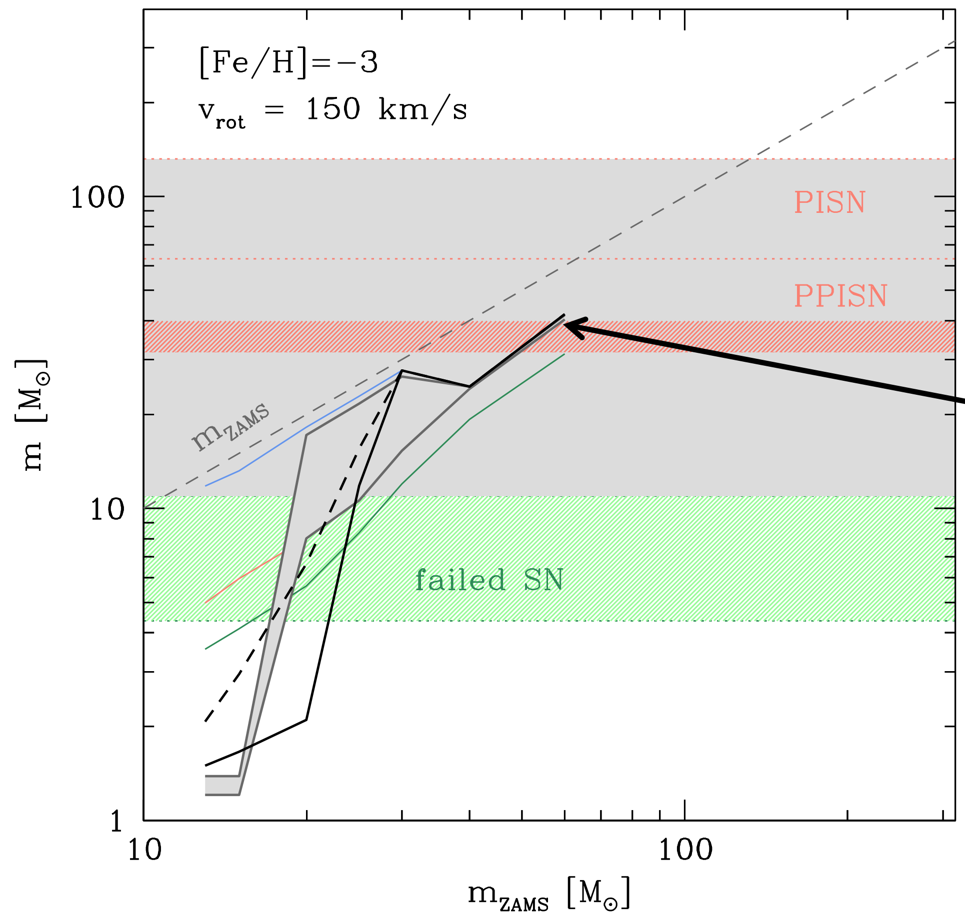
set by PPISN

and by f_{db}

massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

13 $M_{sun} \leq m_{zams} \leq$ 120 M_{sun} [Fe/H] = -3 v_{rot} = 0, 150 km/s, 300 km/s

the mass spectrum of Pop III remnants

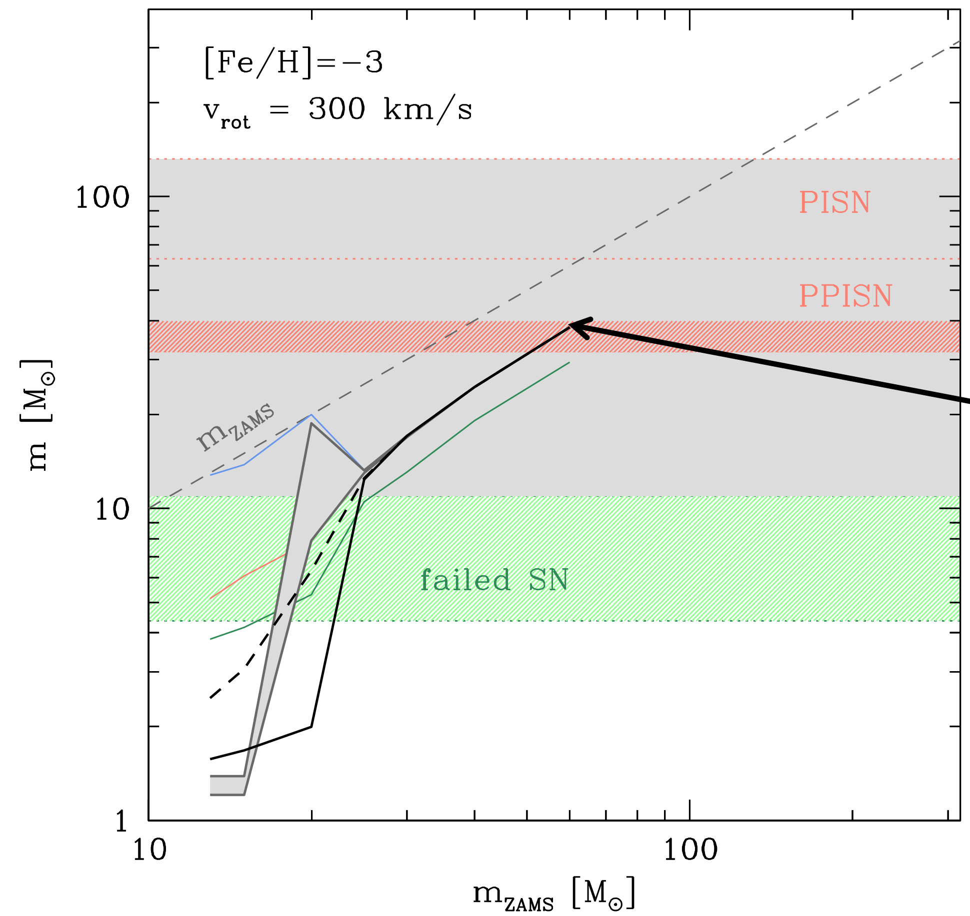


$m_{bh,max}$ = 41.9 M_{sun}
set by mass loss
and
PPISN

massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

13 $M_{sun} \leq m_{zams} \leq 120$ M_{sun} [Fe/H] = -3 v_{rot} = 0, 150 km/s, 300 km/s

the mass spectrum of Pop III remnants



$m_{bh,max}$ = 38.1 M_{sun}
set by mass loss
and
PPISN

massive stellar evolution using FRANEC (Limongi & Chieffi 2018)

13 M_{sun} ≤ m_{zams} ≤ 120 M_{sun} [Fe/H] = -3 v_{rot} = 0, 150 km/s, 300 km/s

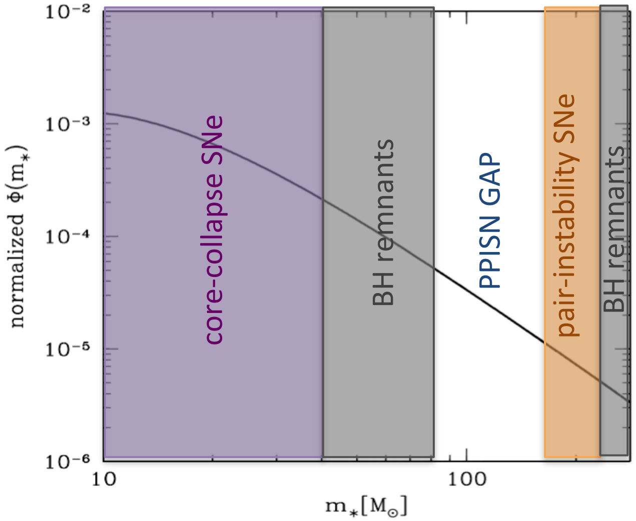
first seed BH formation channel: remnants from the first stars

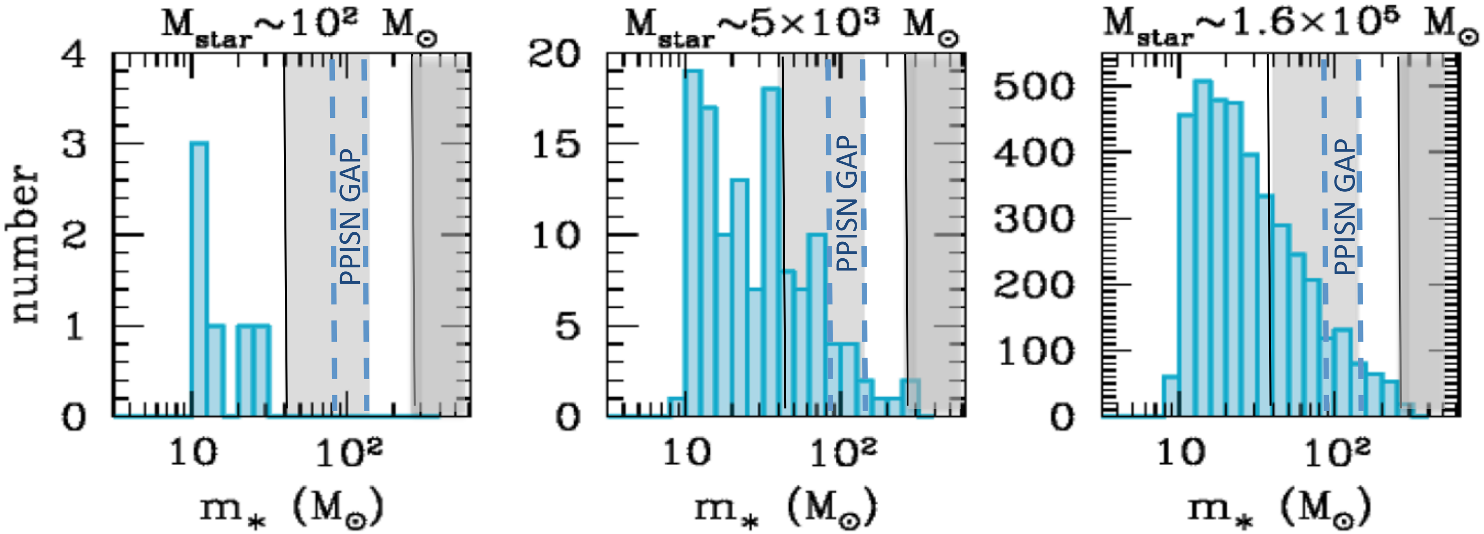
- ✓ form at $20 < z < 30$ in H_2 cooling mini-halos
- ✓ wide range of possible masses 10s − 1000s M_{sun}
- ✓ poorly constrained mass distribution
- ✓ binary/multiple massive stellar systems
- ✓ BH mass spectrum depends on the stellar mass spectrum and rotation

first seed BH formation channel: remnants from the first stars

$$\Phi(m) = \frac{dN}{dm} \propto m^{\alpha-1}\exp\left(-\frac{m_{ch}}{m}\right)$$

$m_{ch} = 20\ M_{sun}$ $\alpha = 1.35$ $m_* = [10 - 300]\ M_{sun}$

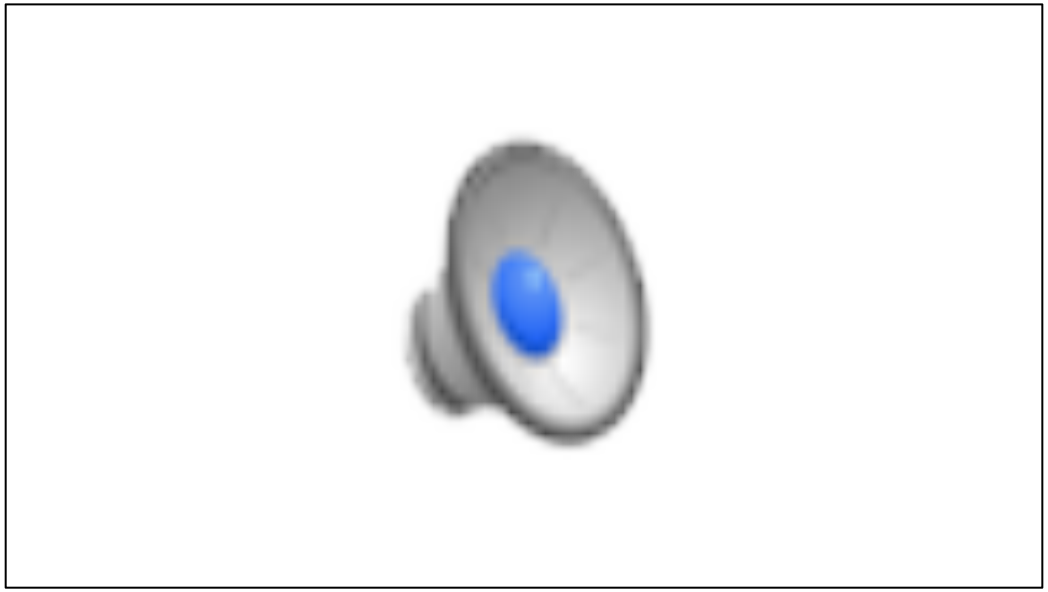




Valiante et al. 2016

second-generation black hole seeds

the renaissence simulation (Xu et al. 2016)



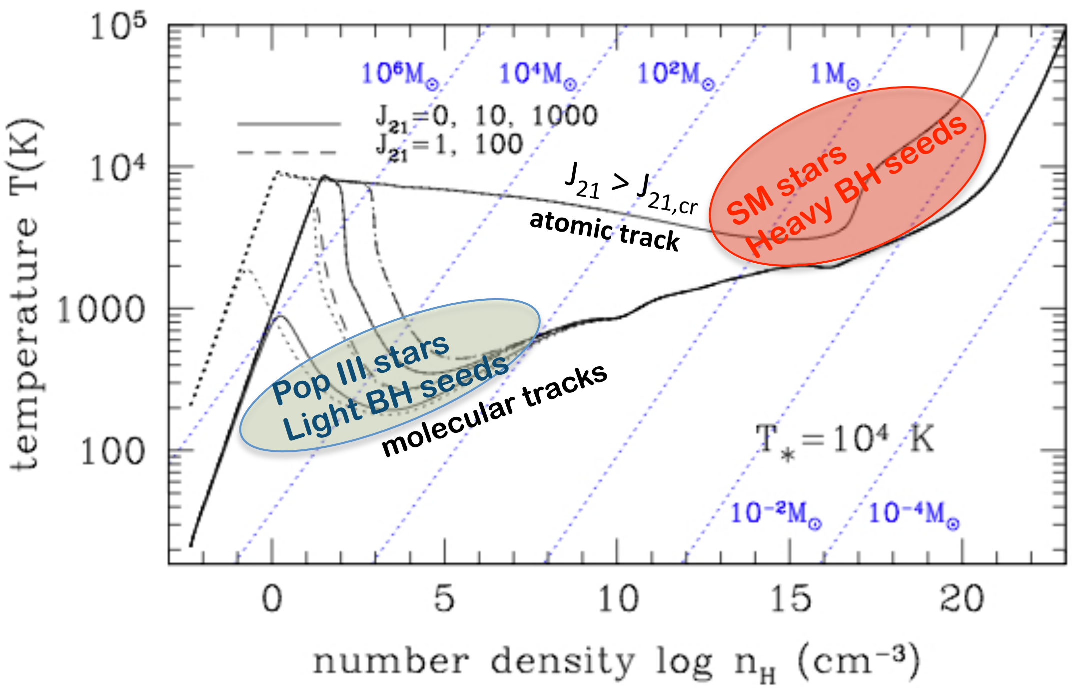
- Emission of UV photons in the Lyman Werner band [11.2 – 13.6] eV → H_2 photo-dissociation
- Supernova explosions pollute the gas with metals and dust

→ the cooling properties of the gas change → the BH mass spectrum change

second generation black hole seeds

Collapsing metal-free gas clouds under the influence of H_2 photo-dissociating UV photons in the Lyman-Werner band: (11.2 – 13.6) eV

$J_{21} = J_{LW} / 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}



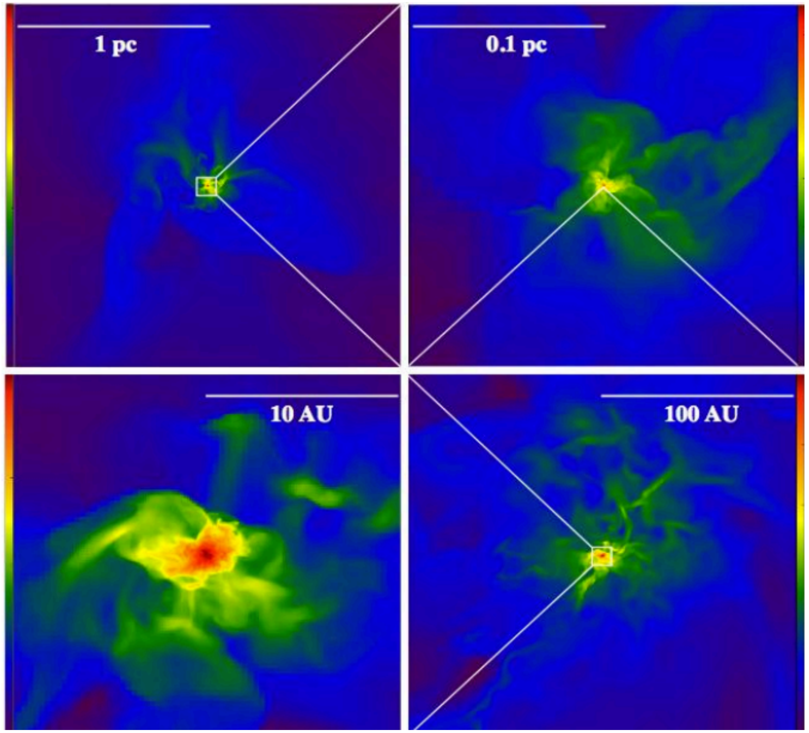
Omukai, RS, Haiman (2008)

see also Omukai 2001; Oh & Haiman 2002; Bromm & Loeb 2003; Omukai+2008; Agarwal +2012; Latif+2014; Sugimura+2014, 2015; Agarwal +2015; Latif & Volonteri 2015; ; Regan & Haehnelt 2009; Hosokawa+2012; Latif+2013,2014, 2016; Prieto+2013; Regan+2014; Inayoshi+2014;Choi +2015; Becerra +2015, 2018

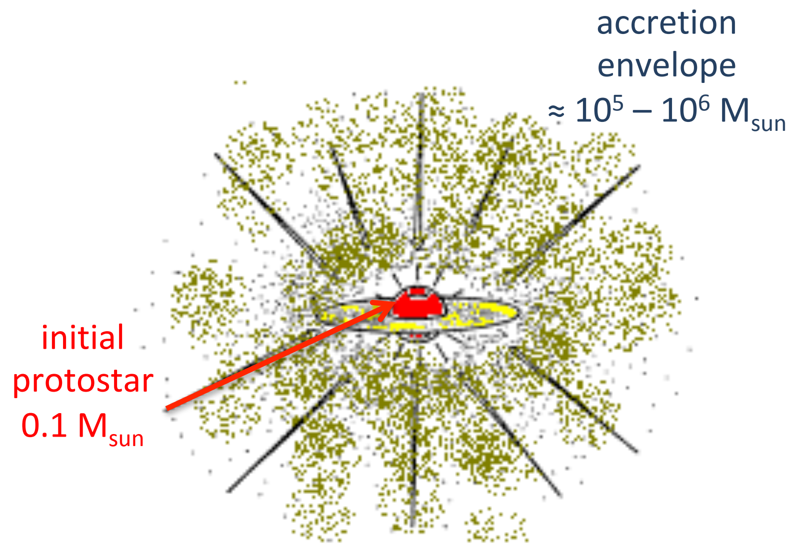
conditions for heavy black hole seeds formation

Omukai 2001; Bromm & Loeb 2003; Wise+2008; Regan & Haehnelt 2009; Hosokawa+2012;
Latif+2013,2014, 2016; Prieto+2013; Regan+2014; Inayoshi+2014;
Choi +2015; Becerra +2015, 2018; Wise et al. 2019; Ahykutalp et al. 2019

monolithic collapse in a Lyα cooling halos
with no fragmentation

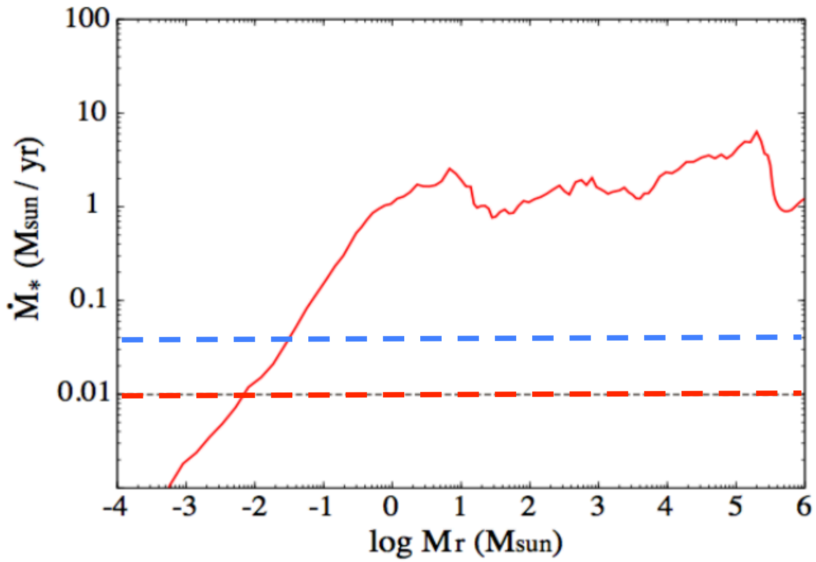


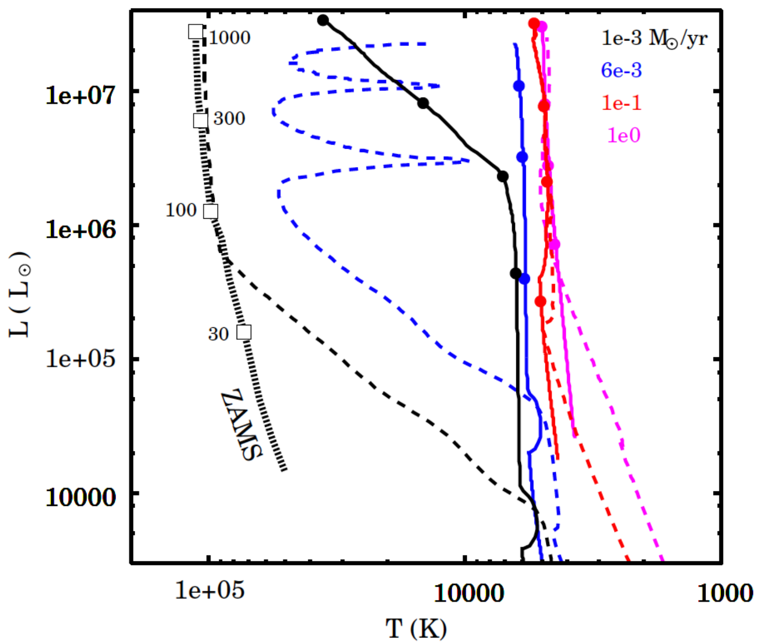
Inayoshi et al. (2014)



conditions for heavy black hole seeds formation

Omukai 2001; Bromm & Loeb 2003; Wise+2008; Regan & Haehnelt 2009; Hosokawa+2012; Latif+2013,2014, 2016; Prieto+2013; Regan+2014; Inayoshi+2014; Choi +2015; Becerra +2015, 2018; Wise et al. 2019; Ahykutalp et al. 2019





Hosokawa et al. (2012)

- formation timescale shorter than stellar lifetime (2 Myr) → high accretion rates

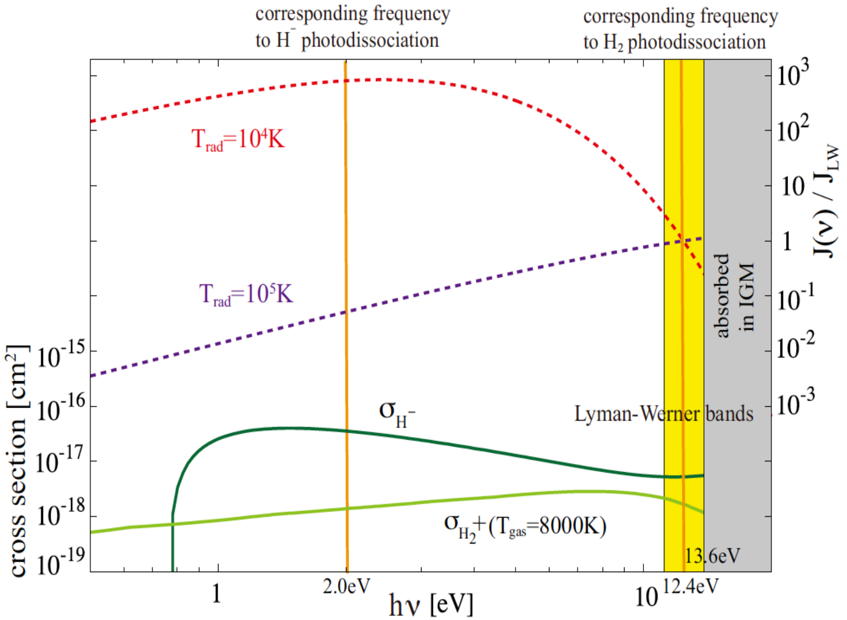
  $dM/dt > M_*/t_* \sim 10^5\ M_{sun}/2\ \mathrm{Myr} \sim 0.05\ M_{sun}/yr$

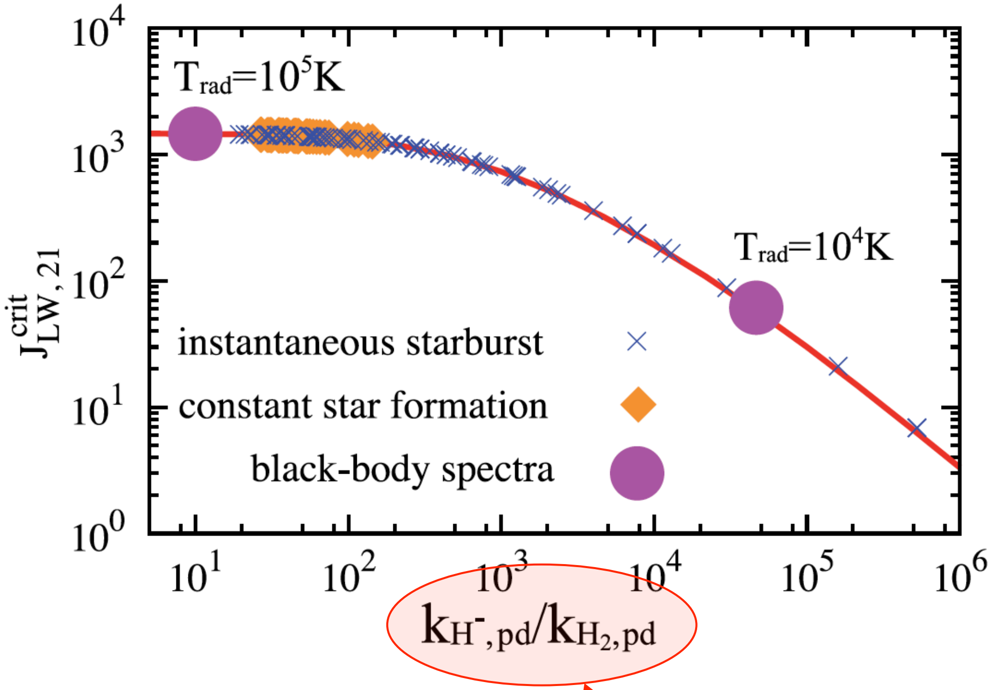
- inefficient protostellar feedback → small UV radiation from the super massive star

  if $dM/dt > 0.01\ M_{sun}/yr$, $R_{star} \sim 10$ AU and $T_{eff} \sim 10^3$ K

What is the value of J_{cr}?

the minimum value of LW flux for H_2 photo-dissociation depends on the spectral shape of the radiation field $J_{LW21,crit} = J_{LW,crit} / 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}





key parameter that determines the value of J_{cr}

H- formation reaction:

$$\mathrm{H} + e \rightarrow \mathrm{H}^- + \gamma\,,$$

H- photo-dissociation reaction:

$$\mathrm{H}^- + \gamma \rightarrow \mathrm{H} + e\,.$$

H_2 formation reaction:

$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + e\,.$$

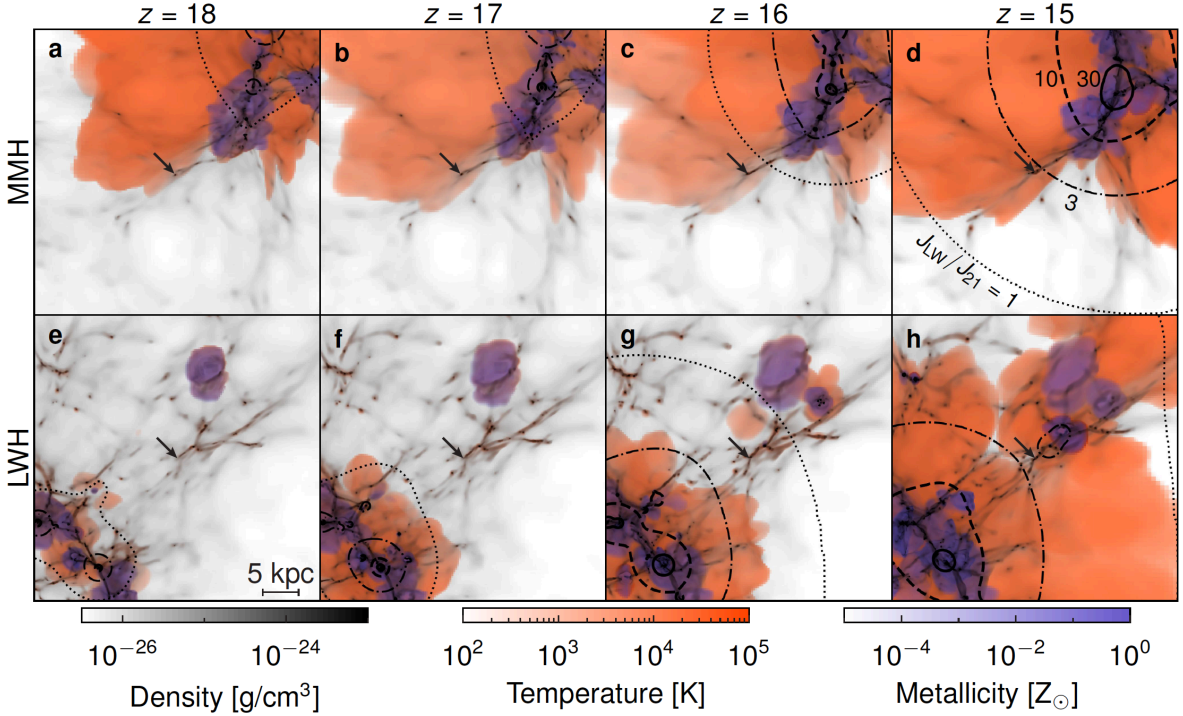
H_2 photo-dissociation reaction:

$$\mathrm{H}_2 + \gamma \rightarrow \mathrm{H}_2^* \rightarrow 2\mathrm{H}\,,$$

What is the value of J_{cr}?

structure formation dynamics, rather than a critical Lyman-Werner (LW) flux, may be the main driver of massive black hole formation in the early Universe
(Wise et al. 2019)

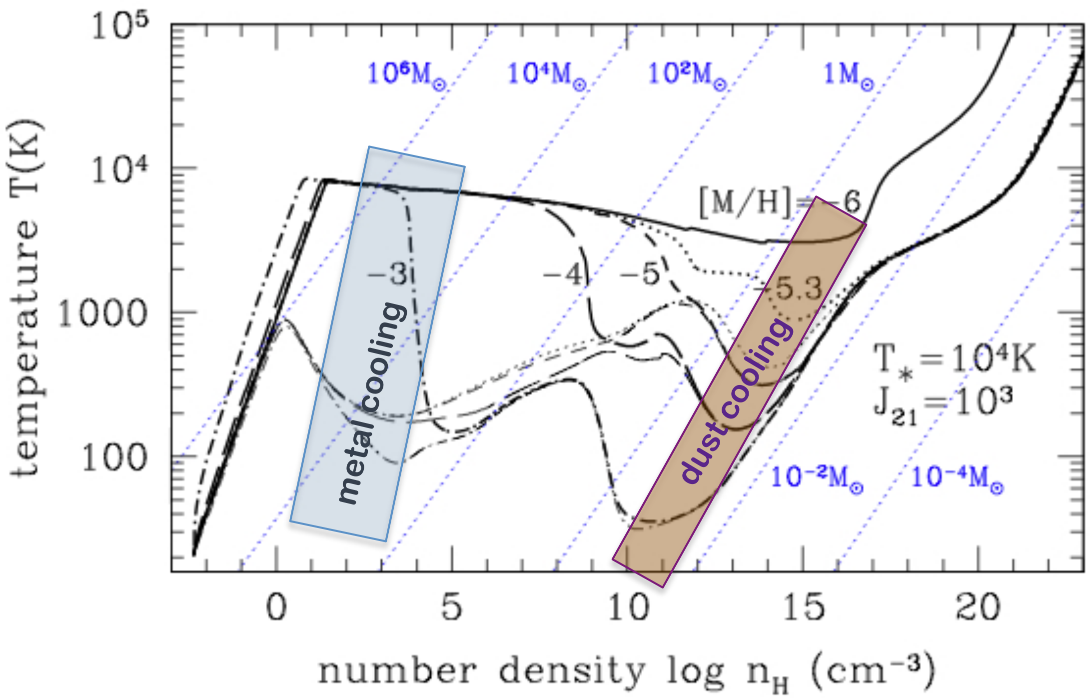
- ✓ renaissence simulation: overdense (5 Mpc)^3 region with 822 galaxies at z = 15
- ✓ 670 Lyα cooling halos
- ✓ 10 Lyα cooling halos are metal-free
- ✓ 2 have the conditions to host SMS formation despite J_{LW} = 3



second generation black hole seeds

collapsing metal/dust gas clouds under the influence of a $J_{21} > J_{cr}$ H_2 photo-dissociating flux

metal line cooling and dust cooling lead to fragmentation

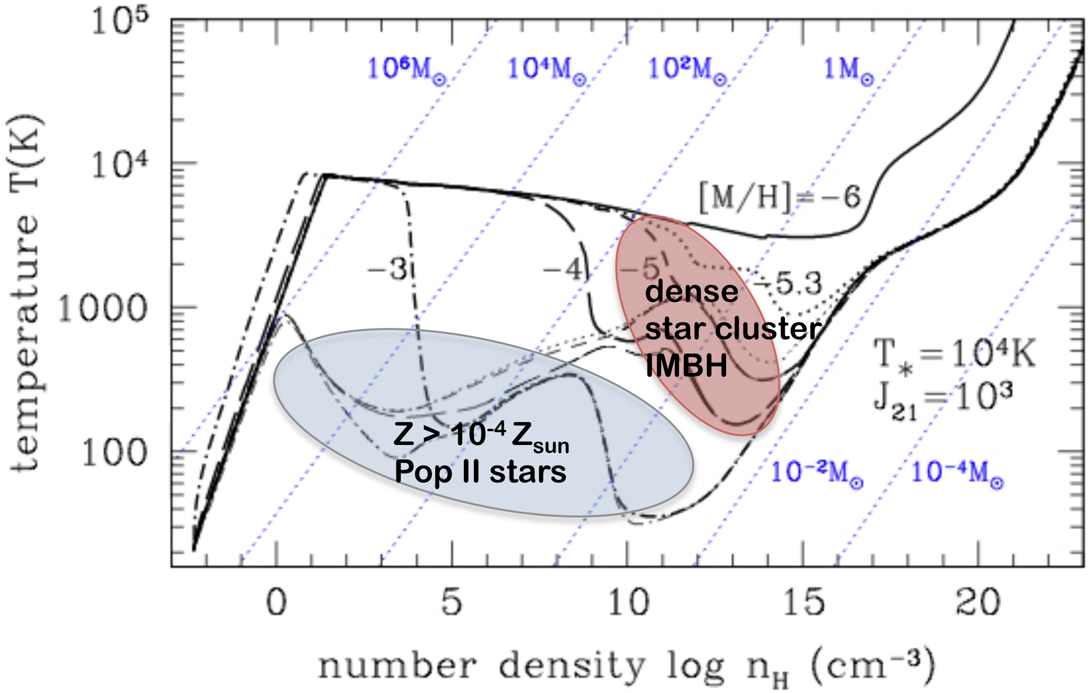


Omukai, RS, Haiman (2008)

second generation black hole seeds

collapsing metal/dust gas clouds under the influence of a $J_{21} > J_{cr}$ H_2 photo-dissociating flux

metal line cooling and dust cooling lead to fragmentation

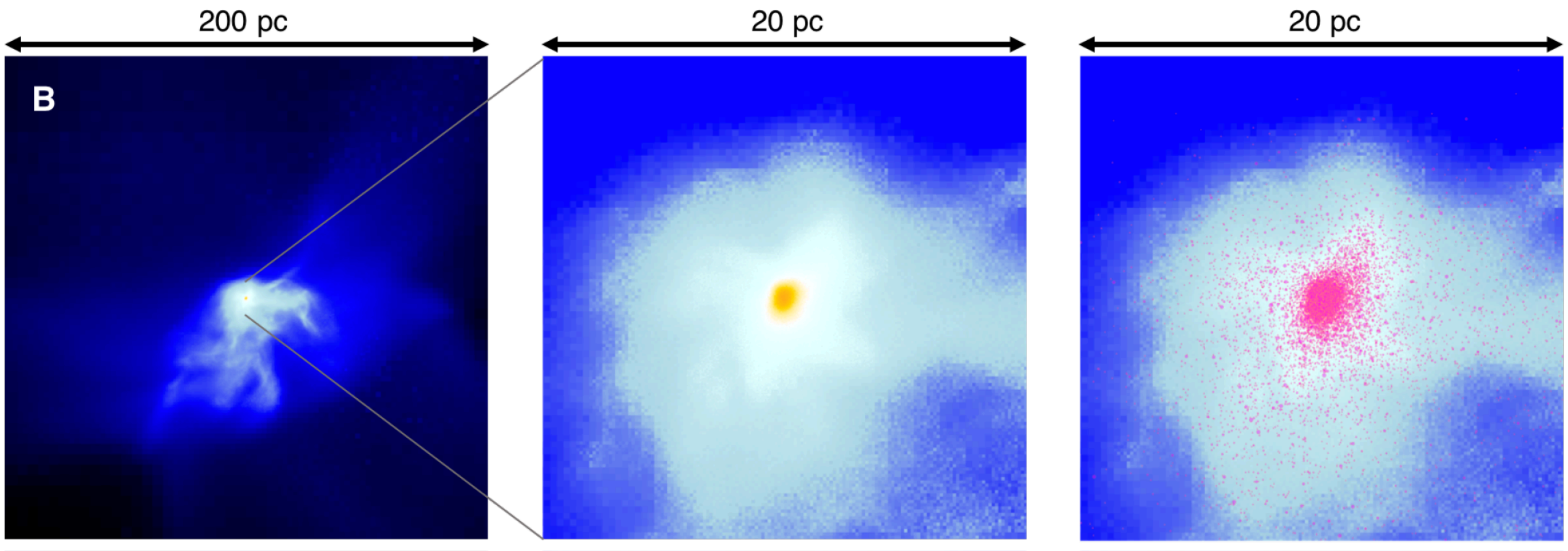


Omukai, RS, Haiman (2008)

black hole seed formation of by runaway stellar collisions

Devecchi et al. (2012), Katz et al. (2015); Sakurai et al. (2017, 2018), Reinoso et al. (2018), Schleicher et al. (2018)

using cosmological hydrodynamical simulations to set the initial conditions



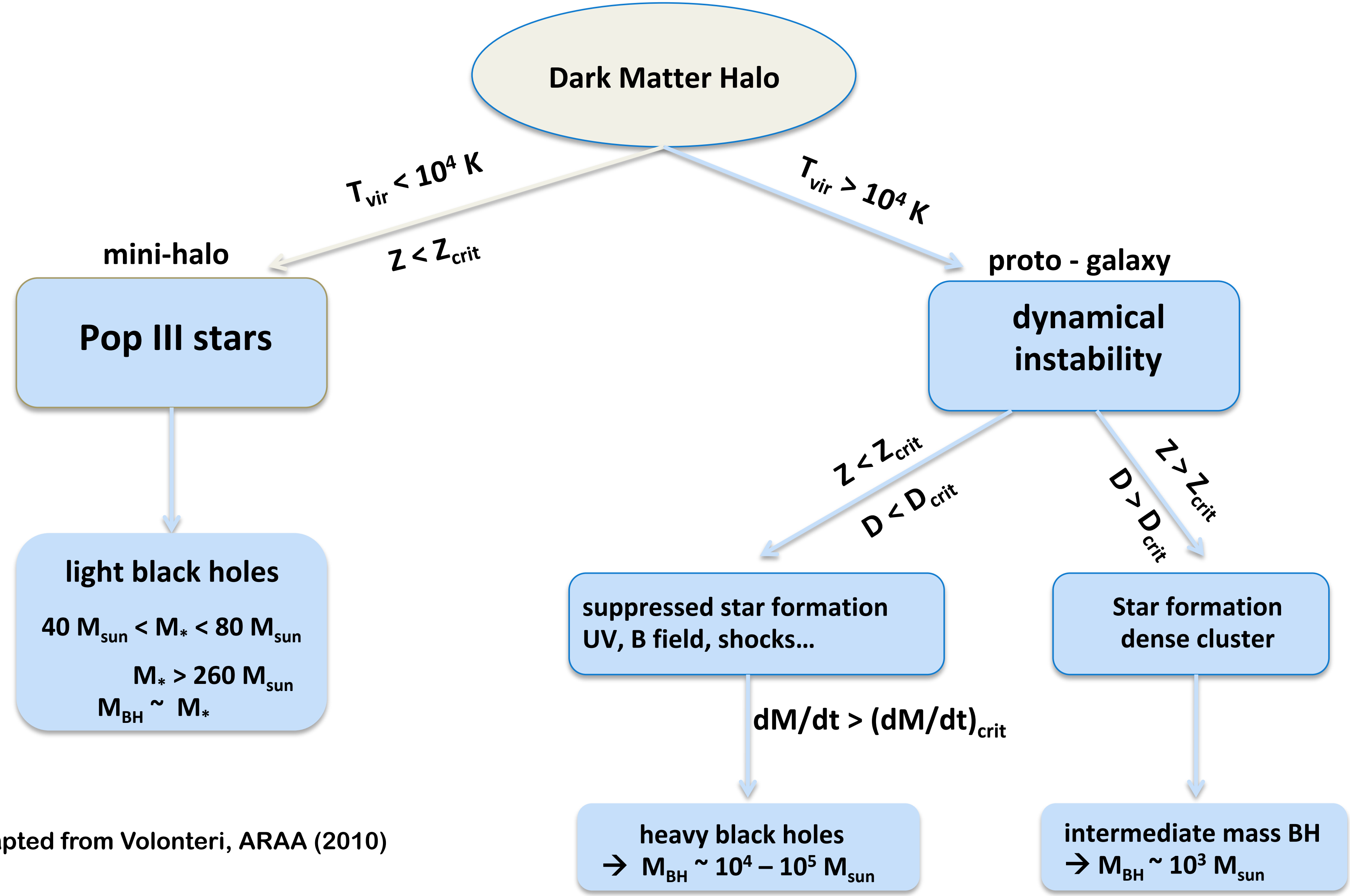
Sakurai et al. (2017, 2018)

400 – 1900 M_{sun} intermediate mass black holes

second generation BH seeds: heavy black holes from the collapse of supermassive stars and intermediate mass black holes from runaway stellar collisions in dense clusters

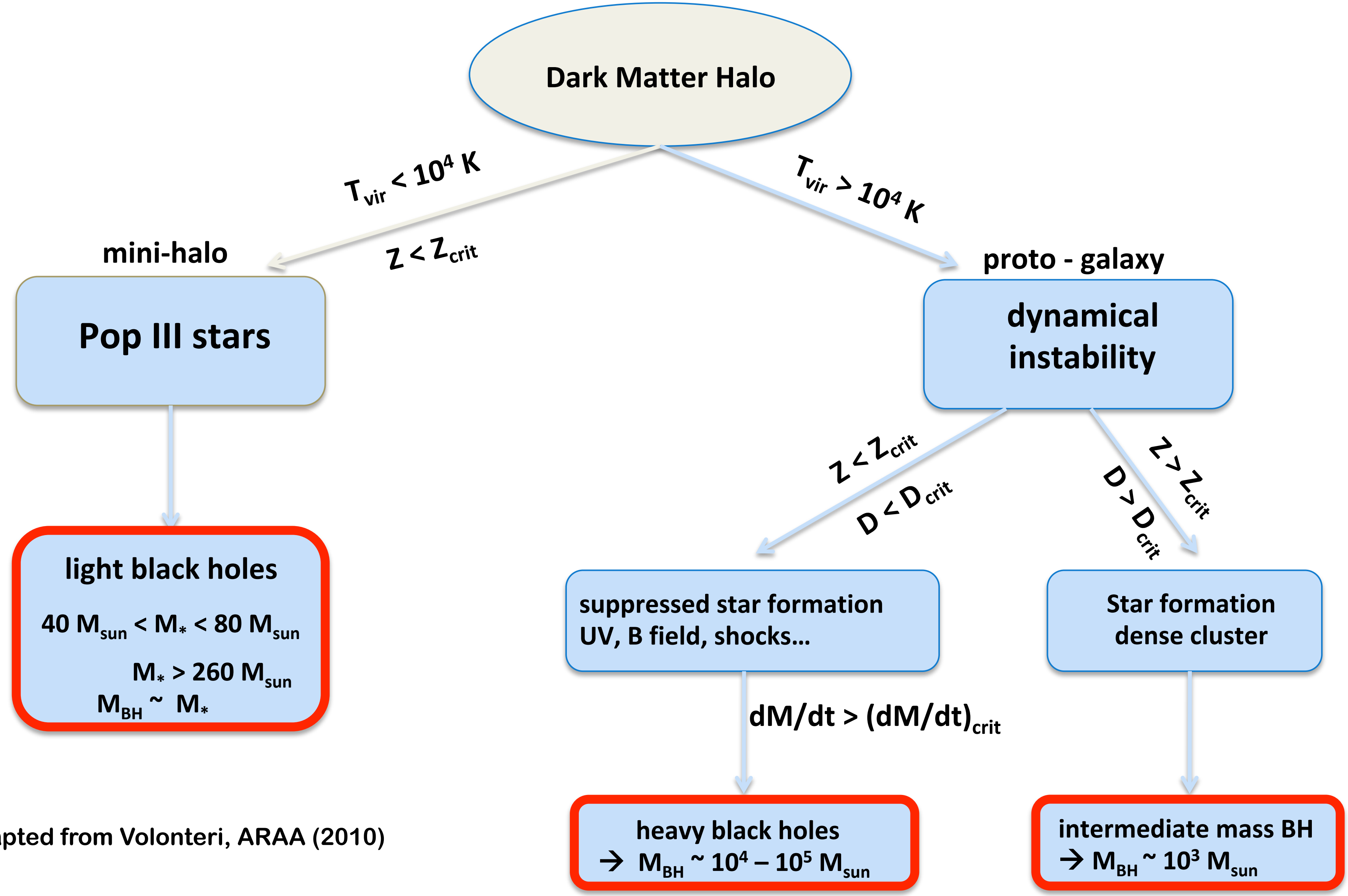
- ✓ form at $10 < z < 20$ in Lyman α cooling halos
- ✓ require suppression of H_2 cooling: $J > J_{cr}$
- ✓ if $Z < Z_{cr}$ and $D < D_{cr}$ → no metal/dust cooling → monolithic collapse
- ✓ high accretion rates → Super Massive Star formation → heavy BH
- ✓ if $Z < Z_{cr}$ and $D > D_{cr}$ → no metal but dust cooling → dense stellar cluster
- ✓ runaway collisions → intermediate mass BH

nature of BH seeds



adapted from Volonteri, ARAA (2010)

nature of BH seeds



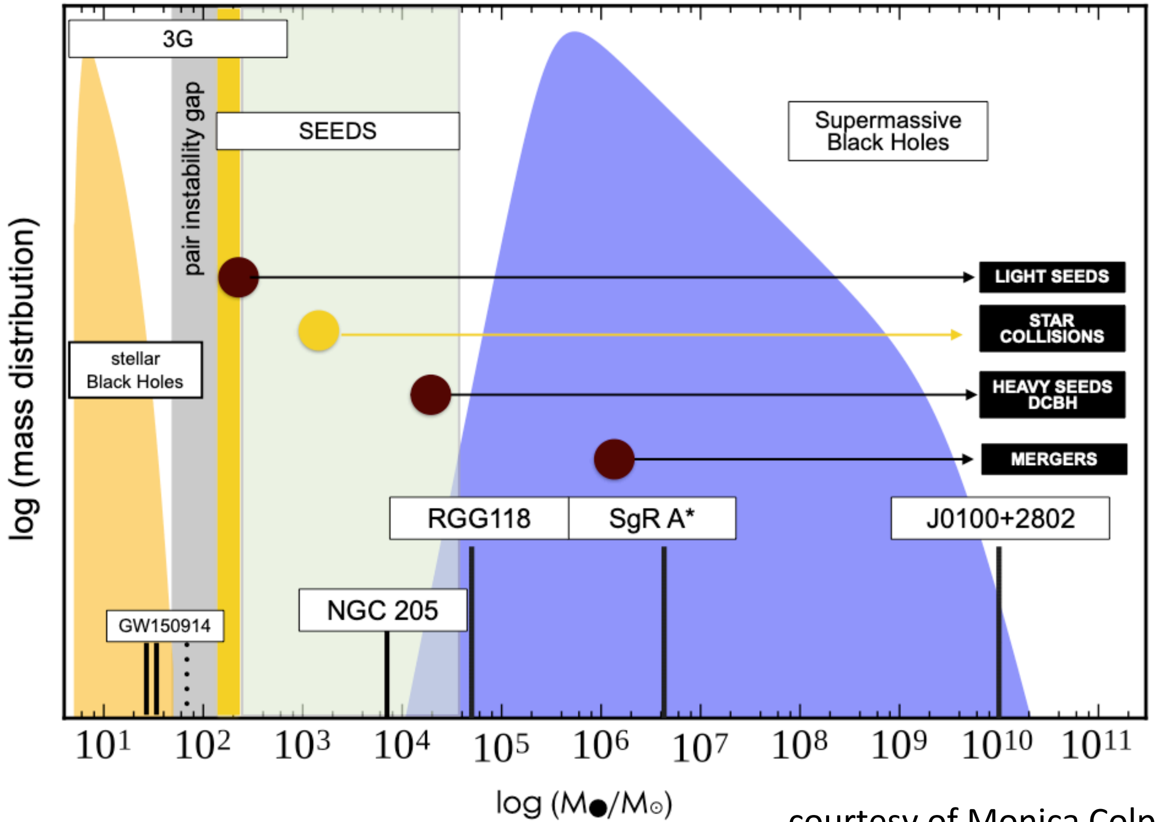
adapted from Volonteri, ARAA (2010)

Additional pathways

- ✓ merger-induced black hole formation: gas-rich mergers trigger mass inflow rates of 10^4 – 10^5 M_{sun}/yr on sub-pc scales forming a 10^5 M_{sun} BH by direct collapse or via a super-massive star (Mayer et al. 2010, 2015; Mayer & Bonoli 2019, Haemmerlé et al. 2019)

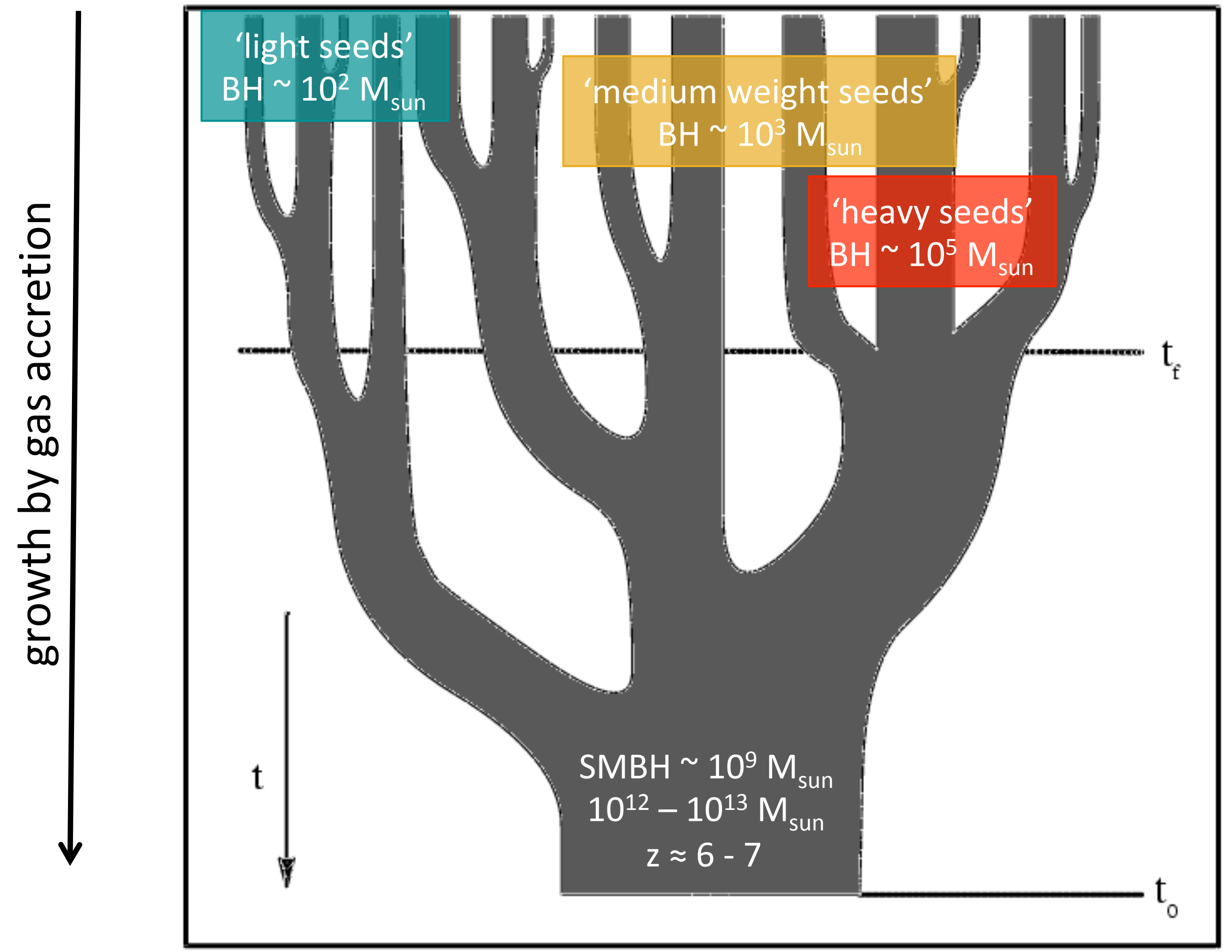
- ✓ Gas-Induced Runaway Merger model: formation of 1000 M_{sun} BHs from runaway collisions of stellar BHs in ultra-dense stellar clusters with strong gas inflows (Lupi et al. 2014)

the mass spectrum of astrophysical black holes



courtesy of Monica Colpi

the formation of the first SMBHs: planting and growing seeds



Haiman & Loeb 2001, Volonteri et al. 2003, Wyithe & Loeb 2003, Haiman 2004, Menci et al. 2004, 2008, Shapiro 2005, Yoo & Miralda-Escude' 2004, Bromley et al. 2004, Volonteri & Rees 2005, Li et al. 2007, Pelupessy et al. 2007, Sijacki et al. 2009, Tanaka & Haiman 2009, Lamastra et al. 2010, Valiante et al. 2011, Petri et al. 2012; Valiante et al. 2015; 2016, 2017, 2018; Pezzulli et al. 2016, 2017; Sassano et al. 2019

GQd: a data-constrained SAM

star formation:
PopIII/II SF via quiescent/burst mode
in mini- and Lyα-halos

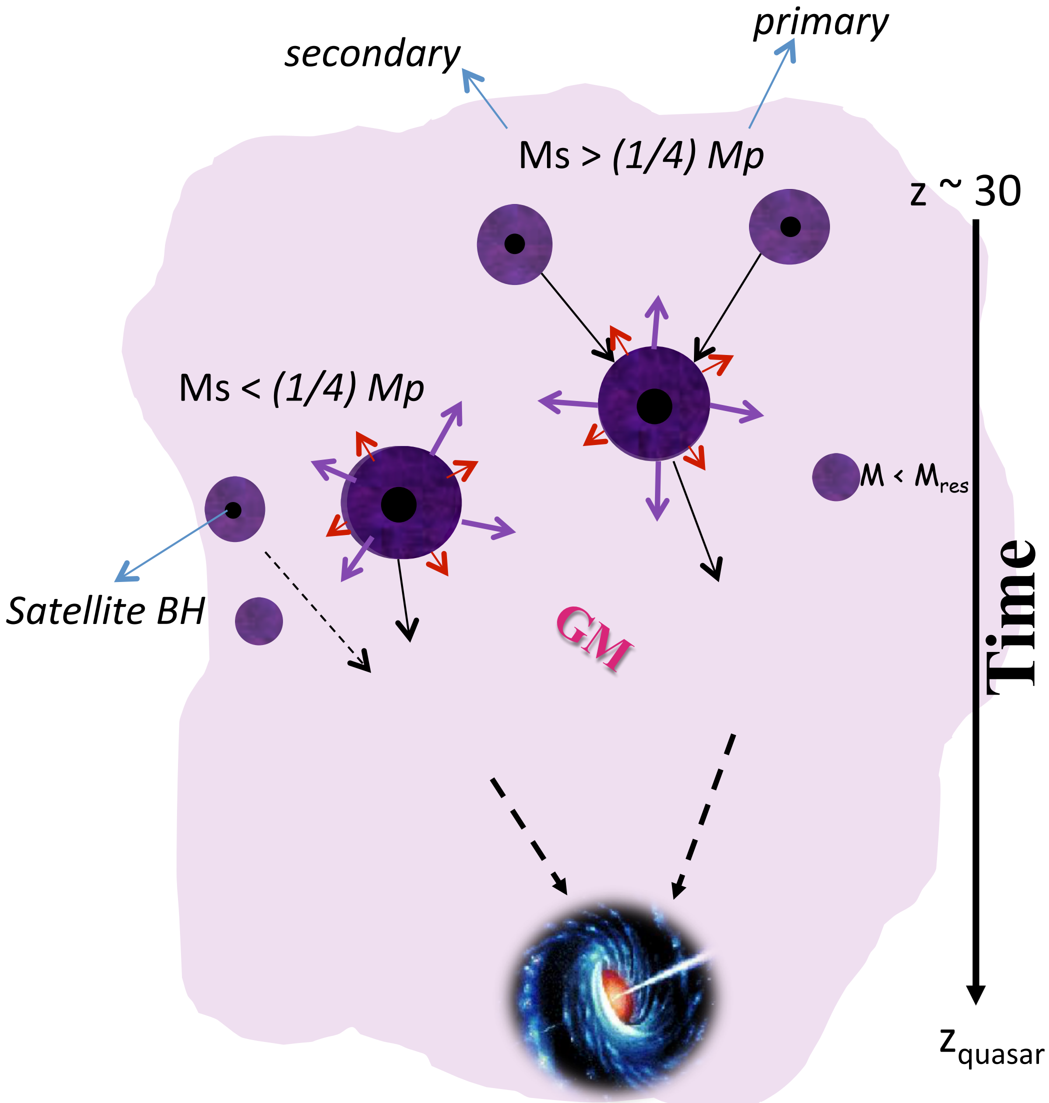
seed BHs formation
according to environmental properties

BH growth:
gas accretion and mergers

mechanical feedback:
BH/SN energy-driven winds

chemical feedback:
dust and metals enrichment

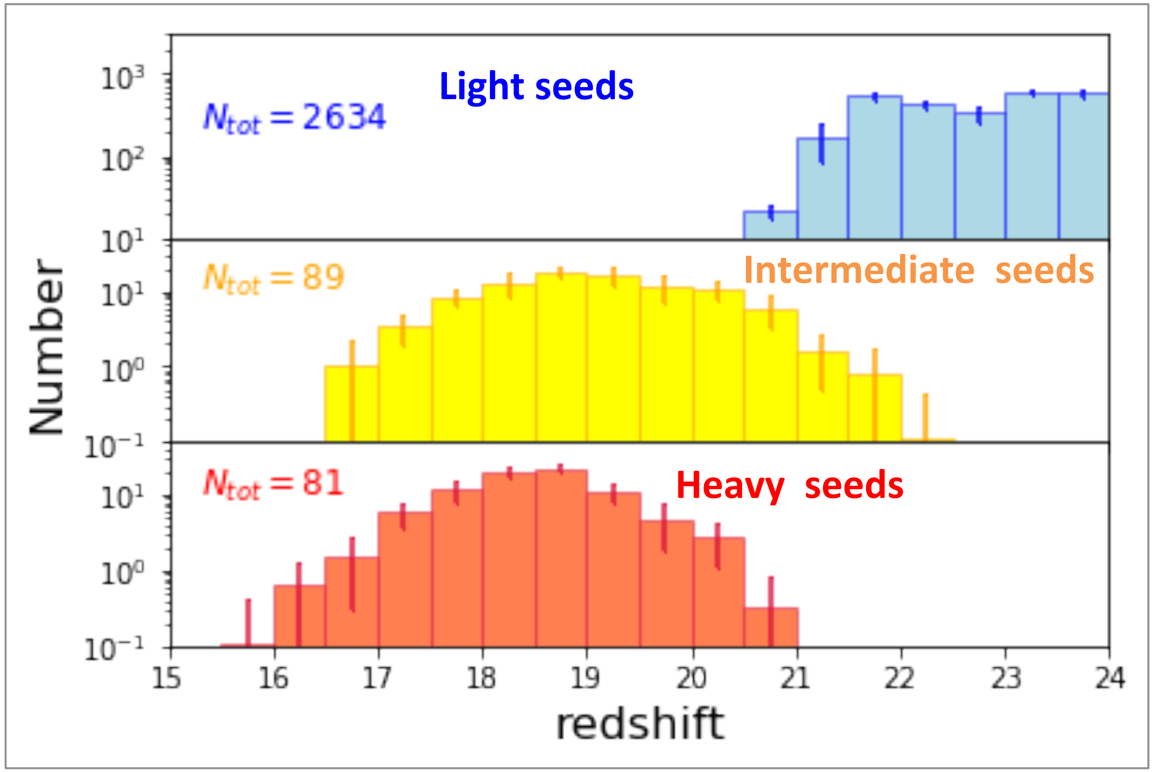
radiative feedback:
stellar and AGN UV emission



Valiante et al. 2011, 2012, 2014,2016, 2018a,2018b
see also Pezzulli, et al. 2016, 2017a, b

Light, medium-weight or heavy?
The nature of first SMBH seeds

redshift distribution of black hole seeds



Sassano, RS, Valiante 2020

$J_{21} < J_{21,cr}$
$Z < Z_{cr}$
$D < D_{cr}$

$T_{vir} > 10^4$ K
$J_{21} > J_{21,cr}$
$Z < Z_{cr}$
$D > D_{cr}$

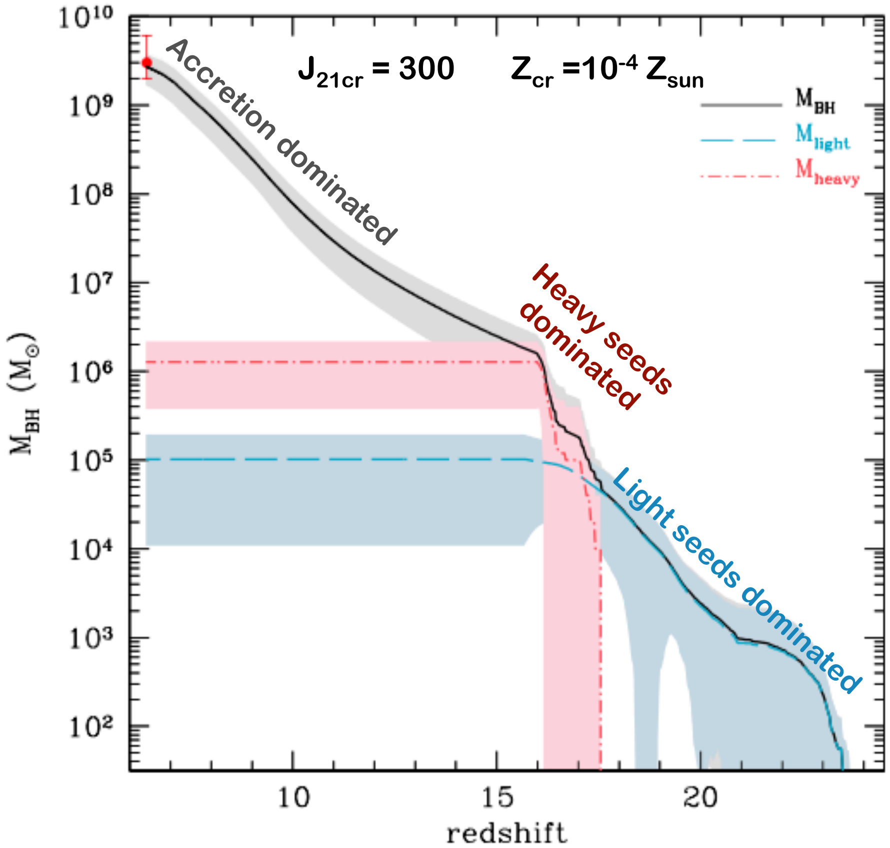
$T_{vir} > 10^4$ K
$J_{21} > J_{21,cr}$
$Z < Z_{cr}$
$D < D_{cr}$

- inhomogeneous metal enrichment
- inhomogeneous Lyman Werner radiation
- $Z_{cr} = 10^{-4} Z_{sun}$, $D_{cr} = 4.4\ 10^{-9}$, $J_{21,cr} = 300$ where $J_{21} = J_{LW} / 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}

growing the first SMBHs by Eddington-limited accretion

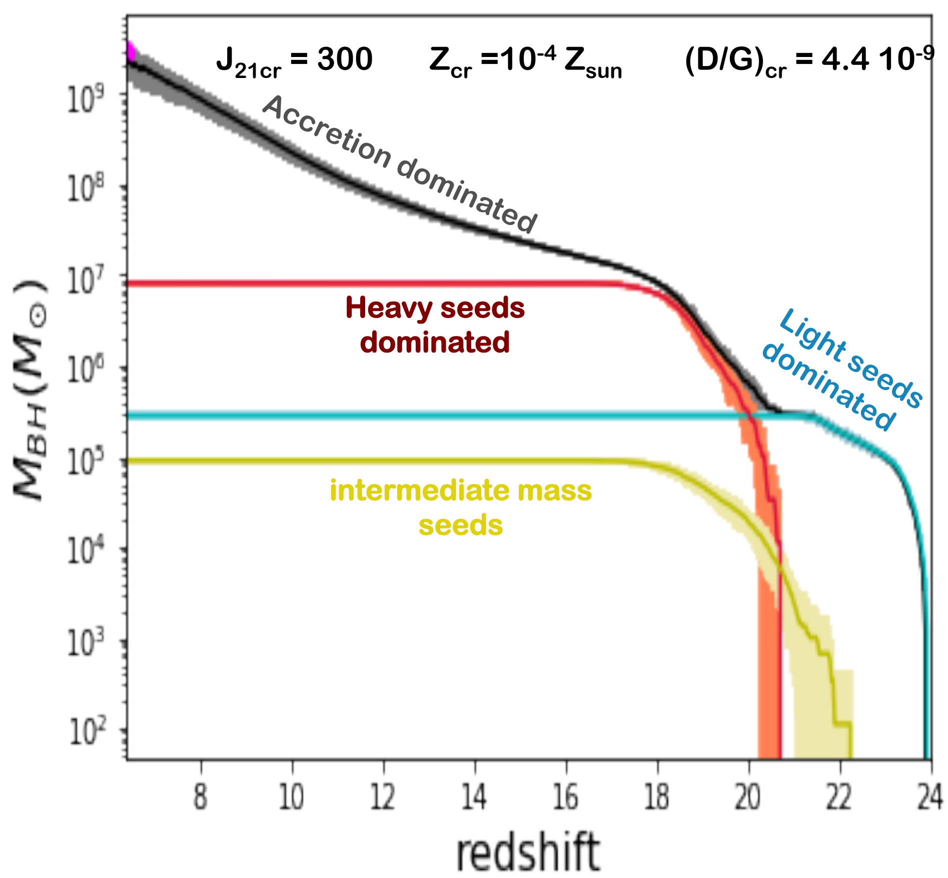
evolution of the total nuclear BH mass

Valiante et al. 2016



- homogeneous metal enrichment
- homogeneous Lyman Werner radiation
- no intermediate-mass seeds

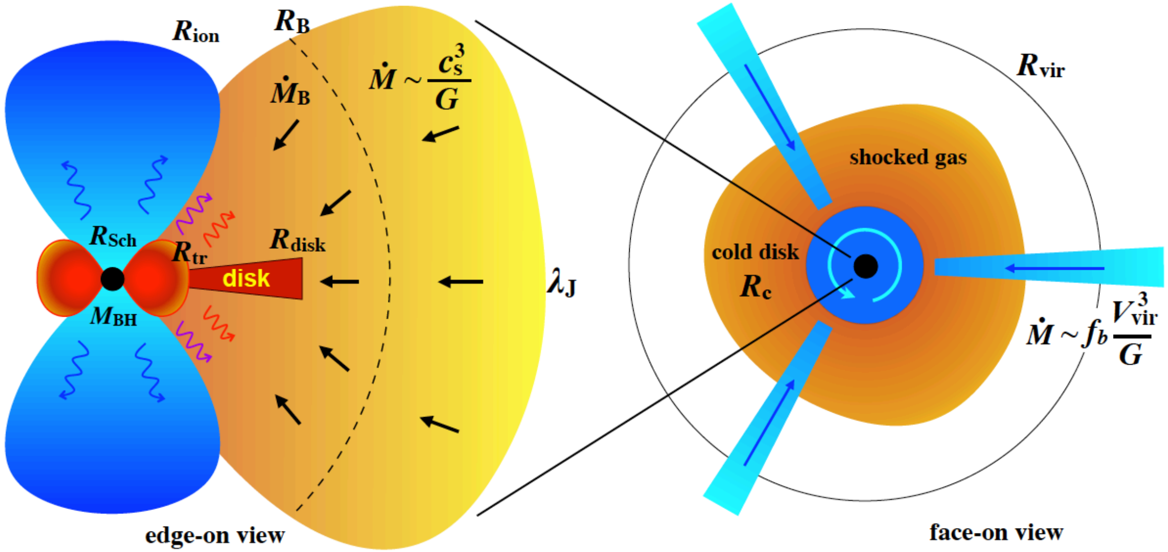
Sassano et al. 2020



- inhomogeneous metal enrichment
- inhomogeneous Lyman Werner radiation
- intermediate-mass seeds

growing black hole seeds by mass accretion

schematic illustration of the super-Eddington accretion flow on to a massive BH with mass M_{BH} (left) in a high-z galaxy (right)



Inayoshi+2020

super-Eddington accretion can occur if the photon diffusion timescale is longer than the accretion timescale → photon trapping radius > Schwarzschild radius

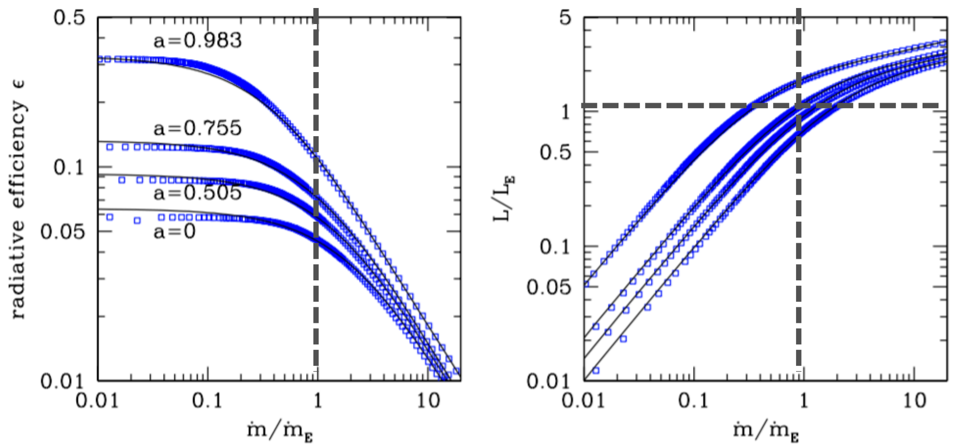
$dM_{BH}/dt > 2\ \varepsilon\ (dM/dt)_{Edd}$ $\quad\quad$ $(dM/dt)_{Edd} = L_{Edd}/(\varepsilon\ c^2)$

***

super-Eddington growth of light BH seeds

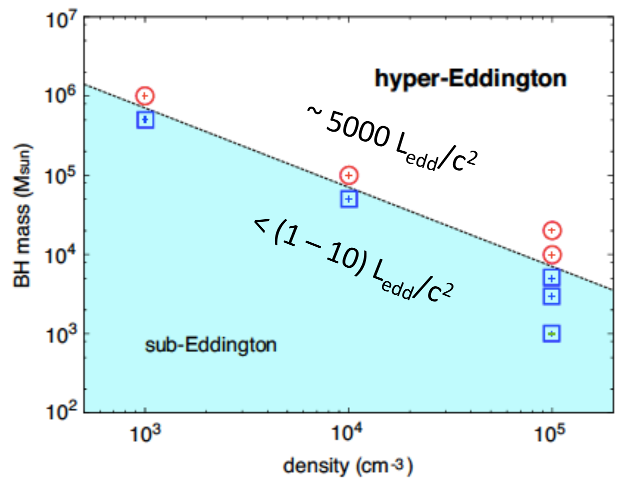
(Begelman 1979, Abramowicz et al. 1988; Ohsuga+2005; Sadowski 2011; Sadowski+2013; Sadowski and Narayan, 2016; Jiang+2017; Inayoshi & Haiman 2016; Takeo+2018)

slim disk solution



Madau+14, Sadowski+13

spherically accreting envelopes

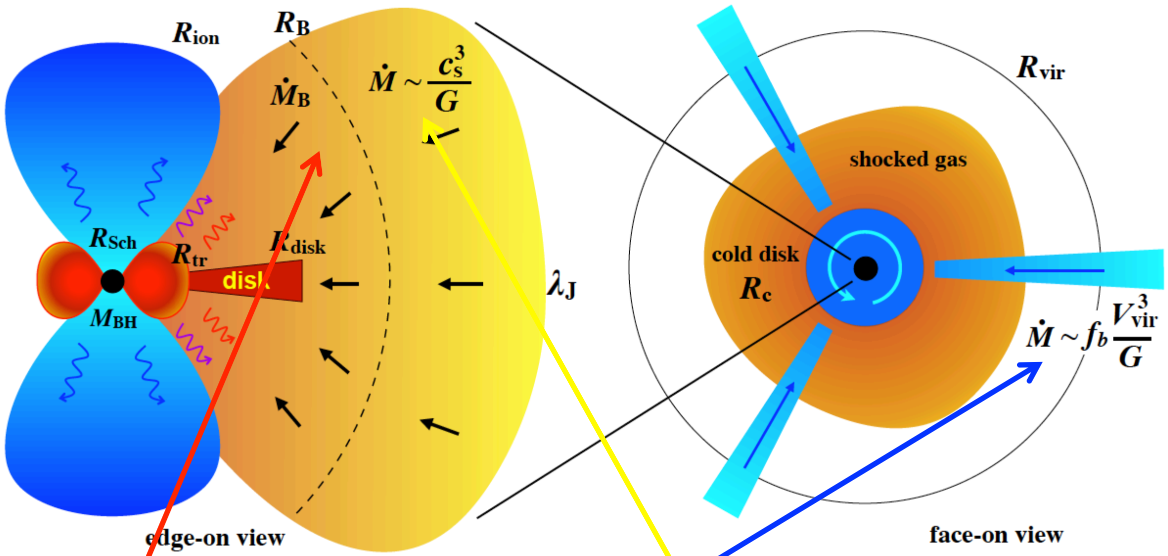


Inayoshi+2016

super-Edd accretion requires dense, highly optically thick flows:

can these conditions be met around growing BH seeds?

growing black hole seeds by mass accretion



Inayoshi+2020

Gas inflows from the large scales:

- Cold flows: baryons accrete into a DM halo along well-defined cold filamentary streams connected with the large-scale cosmic web
- the rapidly accreted gas settles into a compact circum-nuclear disk, which becomes gravitationally unstable and thus leads to fragmentation and clump formation
- on smaller scales, the dynamics of accreting gas is infuenced by gravity of the central BH. The characteristic scale is the so-called Bondi radius and it is usually much larger than the trapping radius

super-Edd growth of light BH seeds in high-z galaxies

hydro-simulations of light BH seed growth in the nuclear region of proto-galactic disks

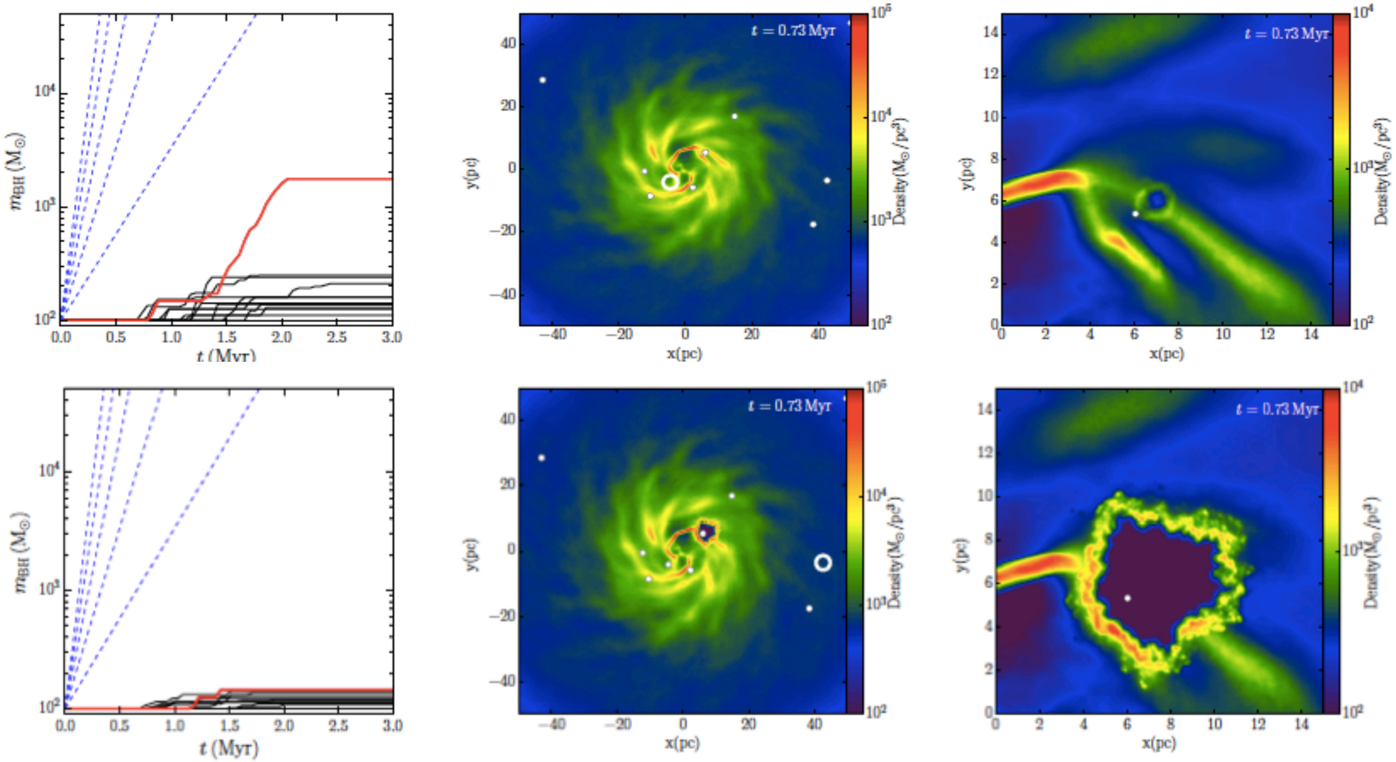
using SLIM disk sub-grid BH accretion

(Lupi+2016)

BH mass evolution | gas density maps at t = 0.73 Myr | zoom-in a region heated by the BH

slim disk model

standard ε= 0.1 model

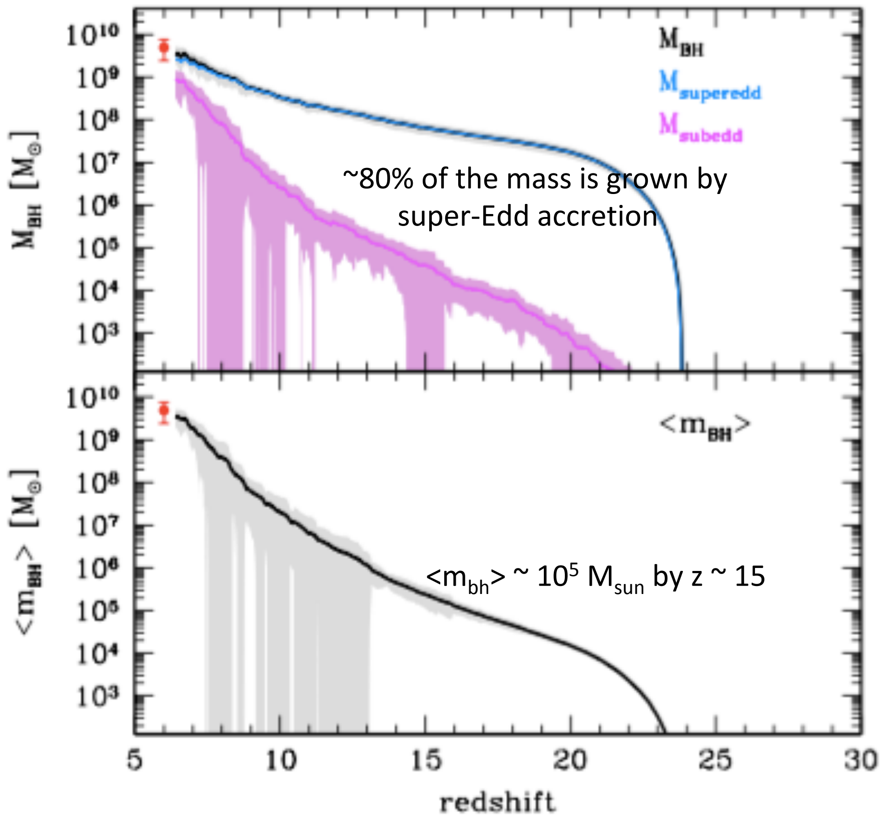


light BH seed can grow to $10^4 - 10^5$ M_{sun} in 3 Myr thanks to the low radiative efficiency of super-critical accretion

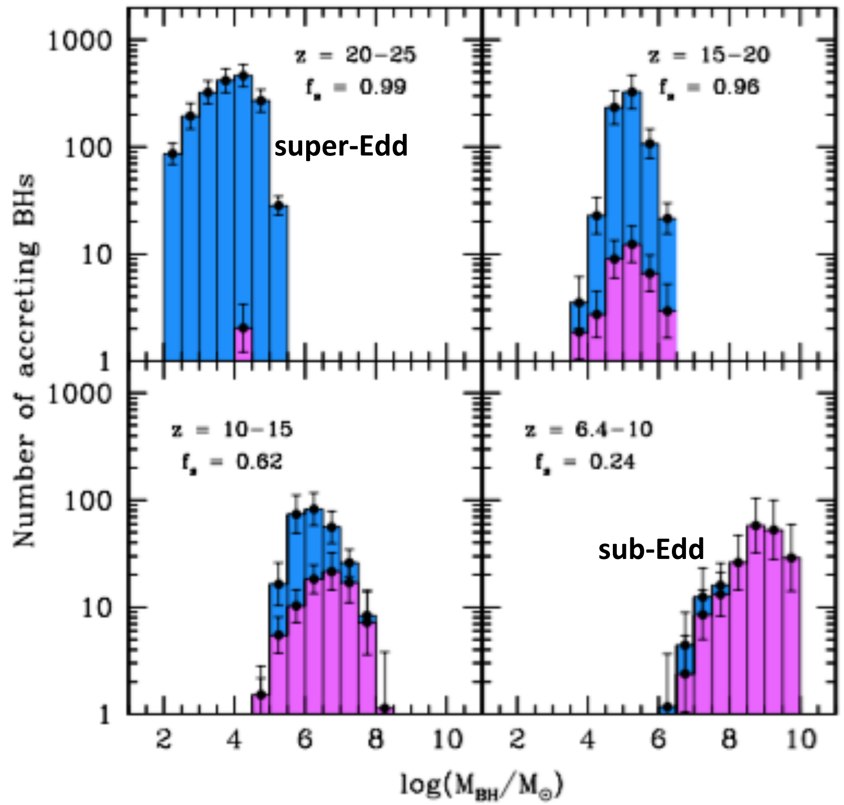
super-Eddington growth of light BH seeds

strong gas inflows facilitated during galaxy major mergers

BH mass evolution



mass/redshift distribution of accreting SMBH progenitors

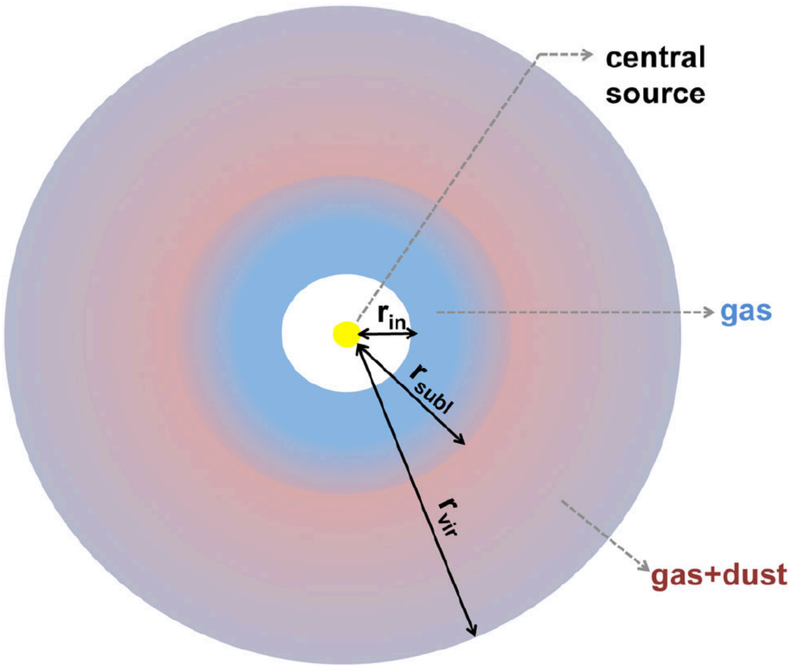


Pezzulli et al. (2016, 2017a)

first SMBHs can grow from Pop III BH remnants via short episodes of super-Edd accretion

the observability of growing and failed seeds

modeling the emission of the nuclear black hole and host galaxy



Valiante et al. 2018b

GQd

M_{bh}, dM_{bh}/dt, SFR, ISM conditions

↓

intrinsic BH emission: from optical/UV to X-ray depends on the BH mass and accretion rate

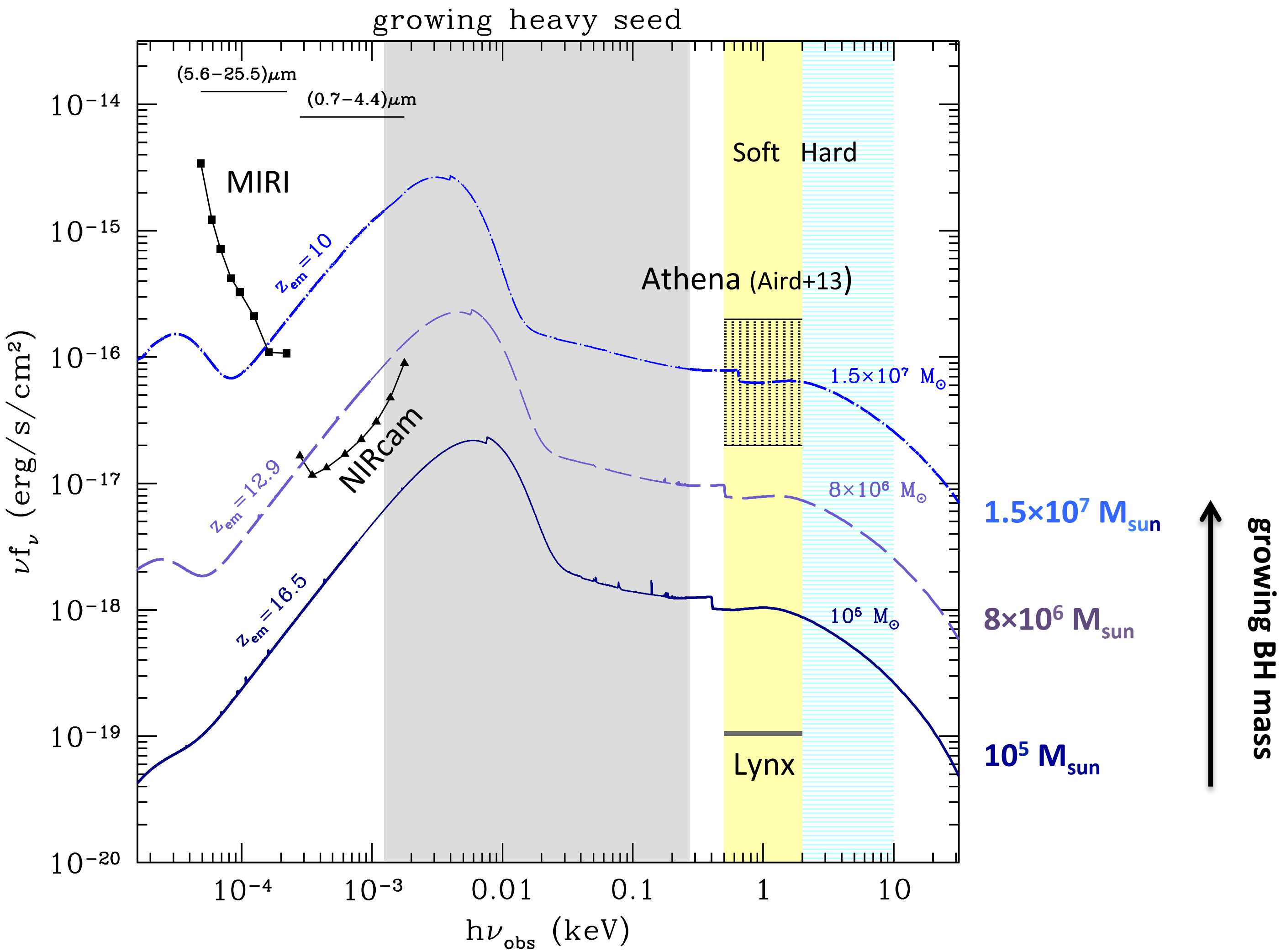
Intrinsic stellar emission: depends on the SFR, on the stellar ages and metallicity

↓

CLOUDY photo-ionization code

compute the effect of the absorbing medium (gas and dust) around the black hole and star forming regions

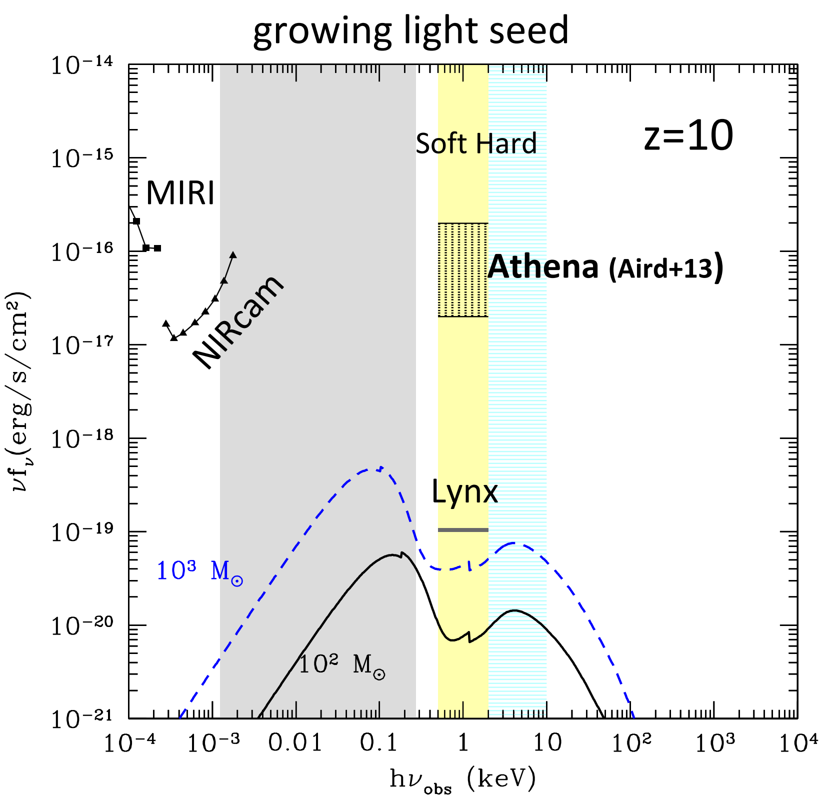
multiwavelength view of BH seeds:
the EM emission from a growing heavy seed

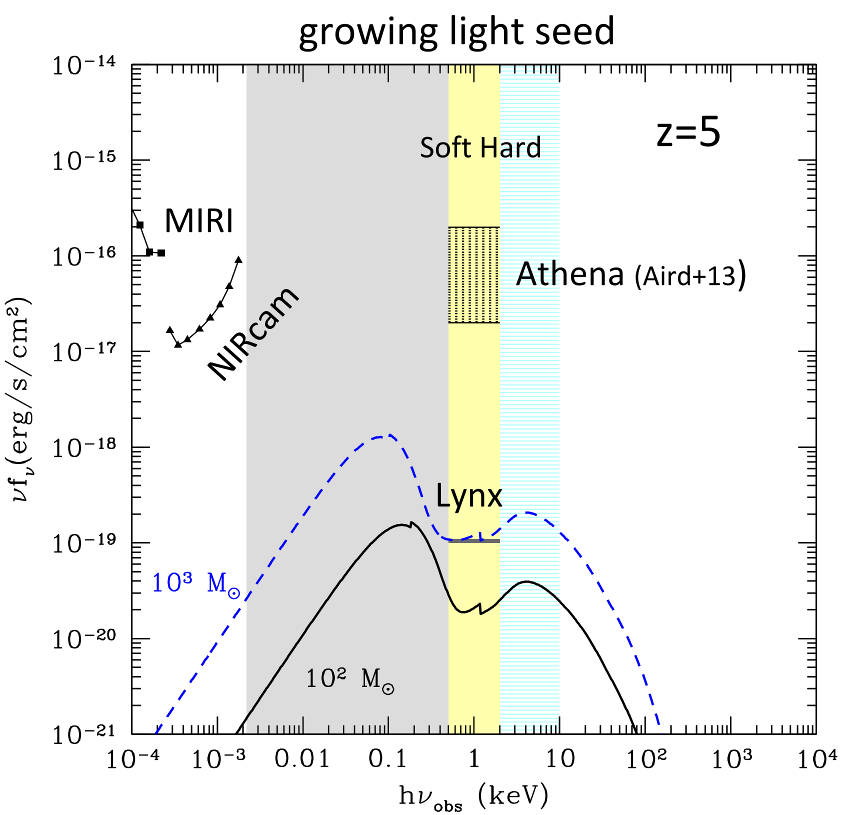


JWST and Athena (and Lynx) will be able to detect the earliest accreting (massive) black holes out to z=13 (17)

Valiante, RS et al. 2018; Valiante, Margiagli et al. 2019

multiwavelength view of BH seeds: the EM emission from a growing light seed





accreting light seeds with masses 100 Msun, 1000 Msun will not be detectable with EM facilities
3G GW detectors will be the only way to detect them!

Valiante, RS et al. 2018; Valiante, Margiagli et al. 2019

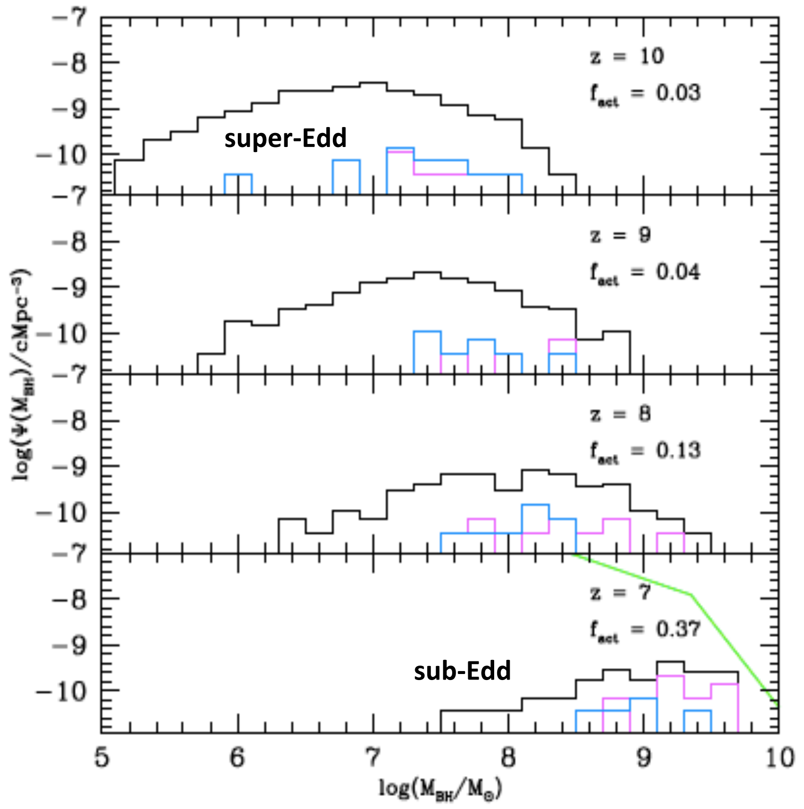
the observability of episodic super-Eddington accretion

the main factor limiting the observability of SMBH seed accreting at super-Eddington rates may be their low active fraction

f_{act} = fraction of active BHs

$\lambda_{Edd} > 5\ 10^{-3}$

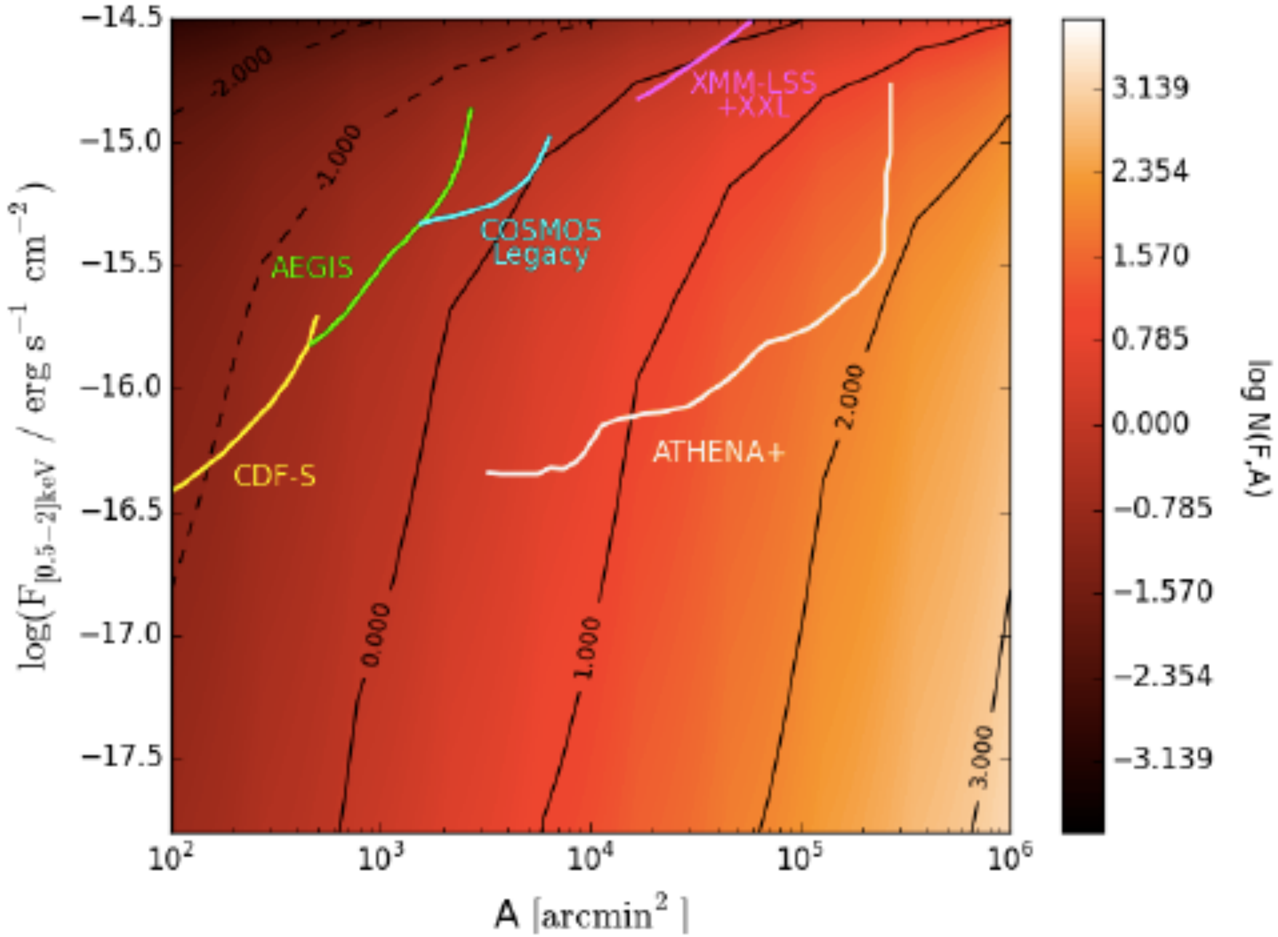
$<f_{act}> \sim 1\%$



Pezzulli et al. 2017b

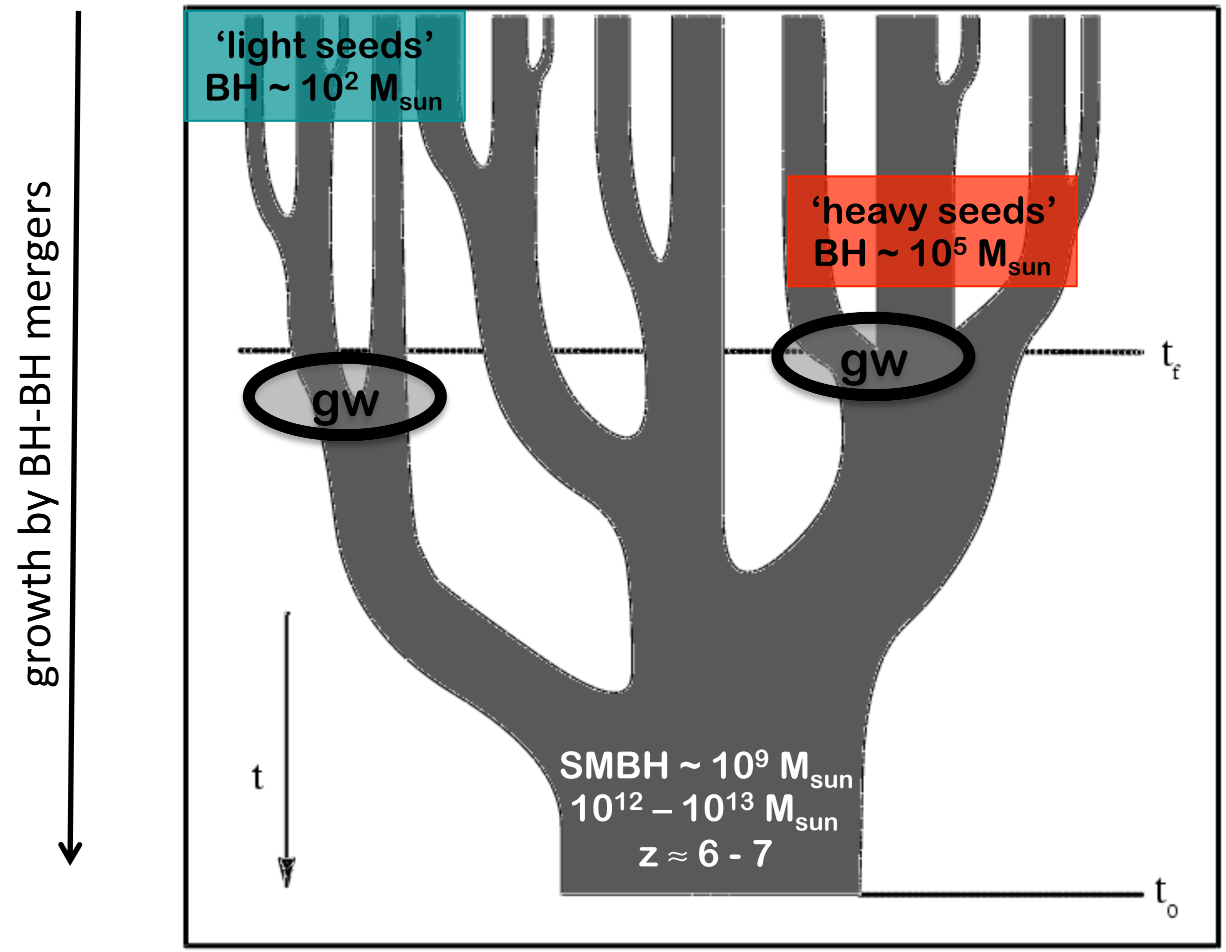
the observability of episodic super-Edd accretion

surveys with larger fields at shallower sensitivities
maximize the probability of detection



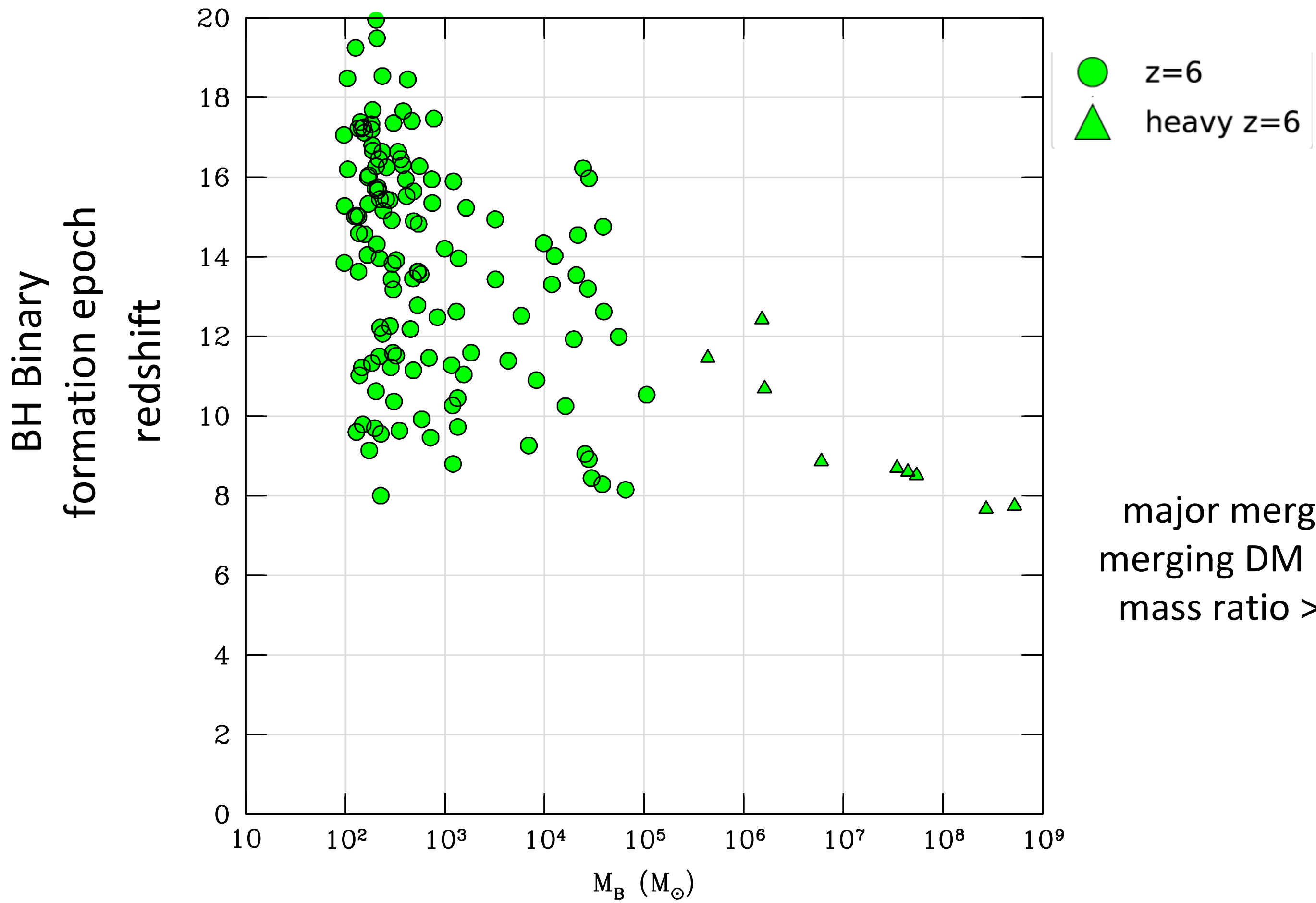
Pezzulli et al. 2017b

emission of gravitational waves during galaxy mergers



Haiman & Loeb 2001, Volonteri et al. 2003, Wyithe & Loeb 2003, Haiman 2004, Menci et al. 2004, 2008, Shapiro 2005, Yoo & Miralda-Escude' 2004, Bromley et al. 2004, Volonteri & Rees 2005, Li et al. 2007, Pelupessy et al. 2007, Sijacki et al. 2009, Tanaka & Haiman 2009, Lamastra et al. 2010, Valiante et al. 2011, Petri et al. 2012; Valiante et al. 2015; 2016, 2017, 2018; Pezzulli et al. 2016, 2017; Sassano et al. 2019

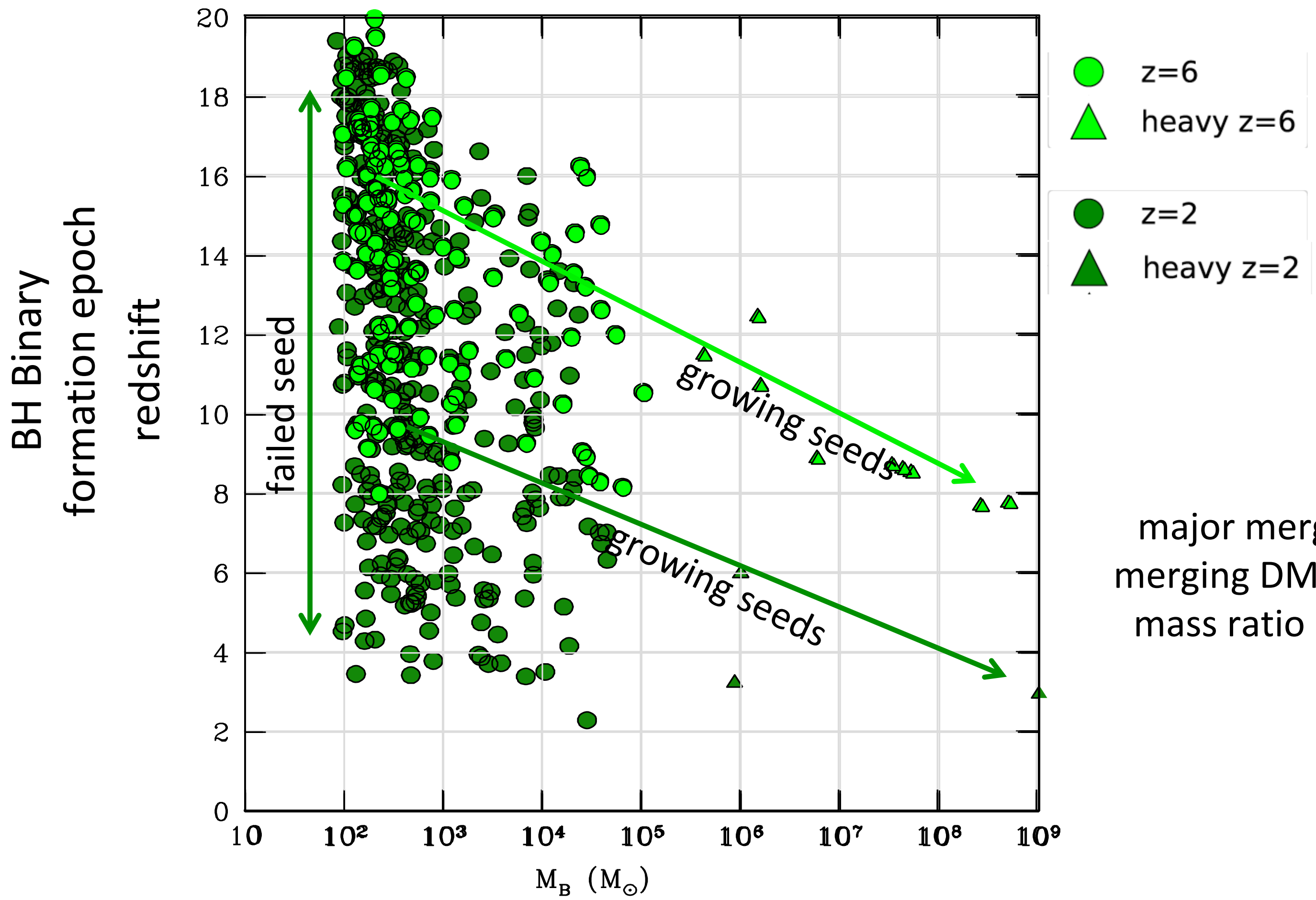
cosmological binary black hole mergers



major mergers:
merging DM halos
mass ratio > 1:4

the black holes are assumed to merge with the hosts galaxies

cosmological binary black hole mergers

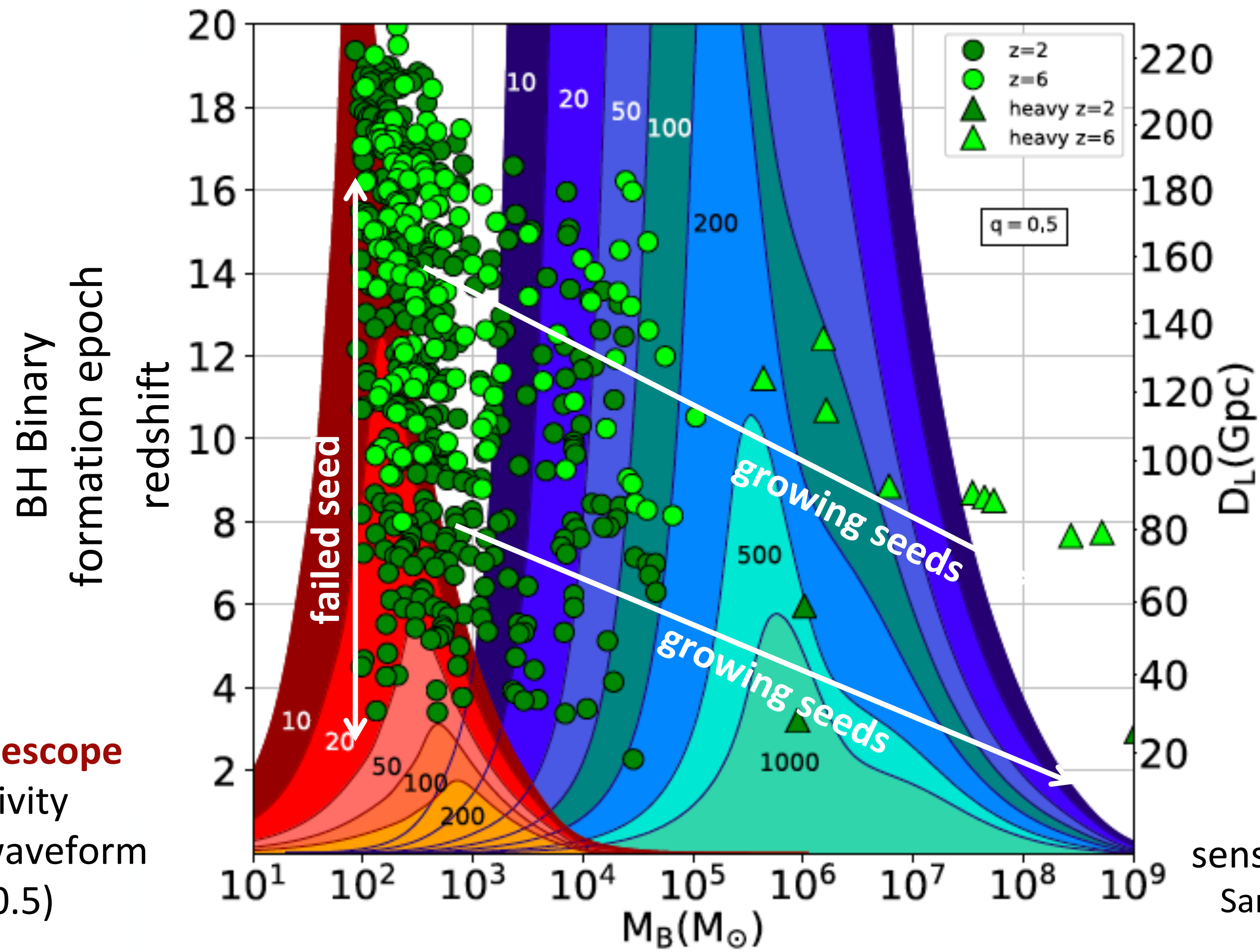


major mergers:
merging DM halos
mass ratio > 1:4

the black holes are assumed to merge with the hosts galaxies

cosmological binary black hole mergers

data-constrained models (GQd): >10^9 M_{sun} BH @ z=2 or 6 in 10^{13} M_{sun} DM halos



major mergers:
merging DM halos
mass ratio > 1:4

Einstein Telescope
ET_D sensitivity
PhenomC waveform
(spin=0, q=0.5)

LISA
sensitivity curve (q=0.5)
Santamaria et al (2010)

the black holes are assumed to merge with the hosts galaxies

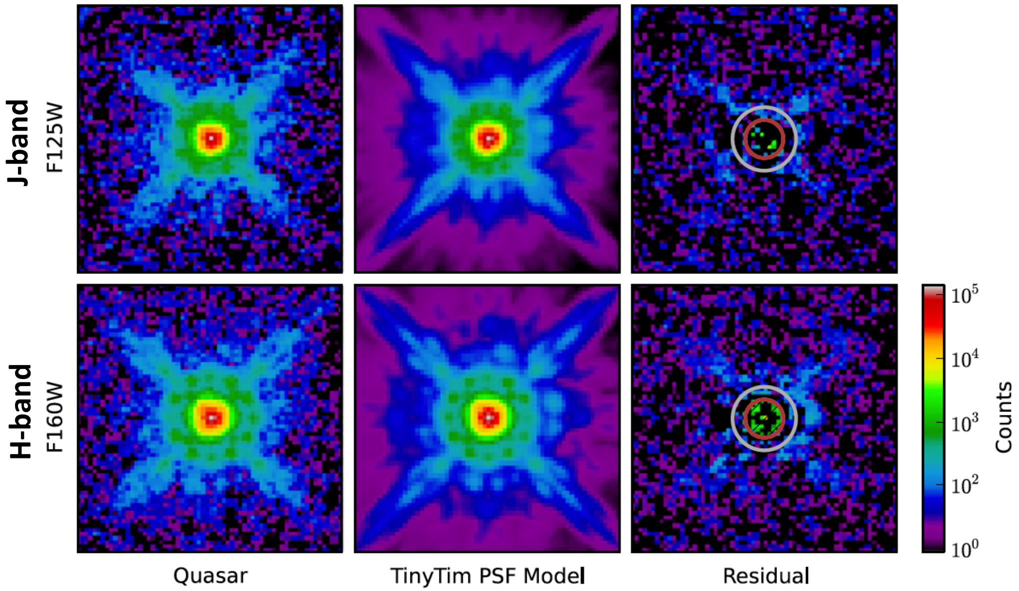
Valiante, Mangiagli et al. 2020

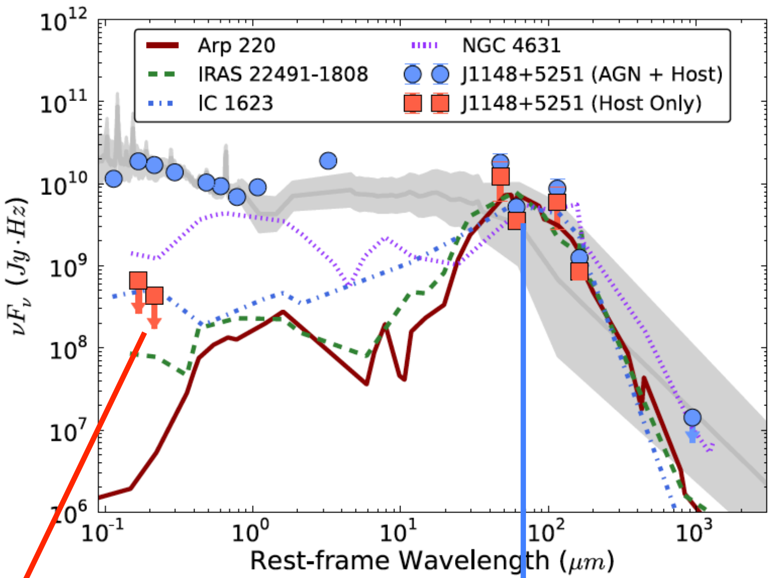
what do we know about the host galaxy?

can we see the host galaxy?

bright quasars at z = 6 over-shine the galaxy and it is very hard to see the stellar component, although several attempts have been made (Matchley+12, Decarli+12, McGreer+14)

HST observations with WFC-3 of the z = 6.42 quasar J1148+5251 (Matchley et al. 2012)





assuming a Salpeter IMF [0.1 – 100] M_{sun}
and a continuous SFR in the past 100 Myr
and no dust attenuation

$$\text{SFR}\ (M_\odot\ yr^{-1}) = 1.4 \times 10^{-28}\ L_\nu\ (\text{ergs s}^{-1}\ \text{Hz}^{-1})$$

SFR < 210 – 250 M_{sun}/yr → M_{star} < [2.10 – 2.50] 10^{10} M_{sun}

assuming a Salpeter IMF [0.1 – 100] M_{sun}
and a starburst of age 10 - 100 Myr

$$\text{SFR}\ (M_\odot\ yr^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\text{ergs s}^{-1})$$

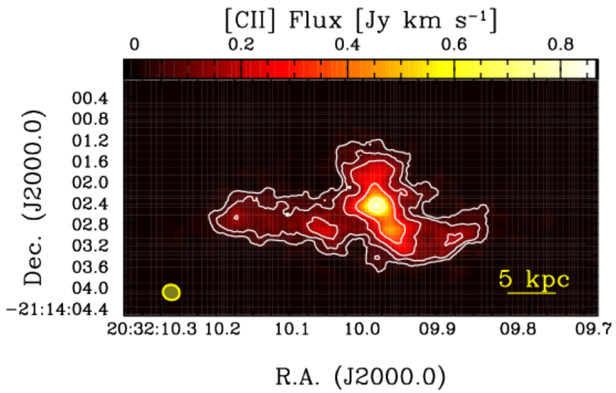
SFR = 2380 M_{sun}/yr → M_{star} = 2.4 [10^{10} – 10^{11}] M_{sun}

more extended emission is associated to galaxy mergers

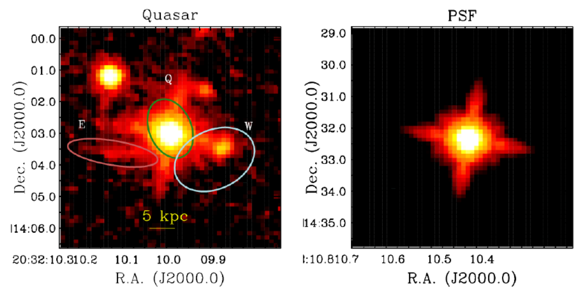
high-resolution ALMA and HST imaging of a z = 6.23 quasar reveal an ongoing merger

Decarli et al. (2019)

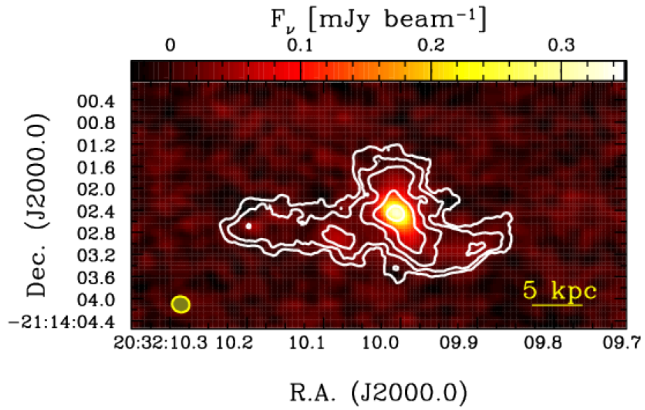
emission from interstellar gas

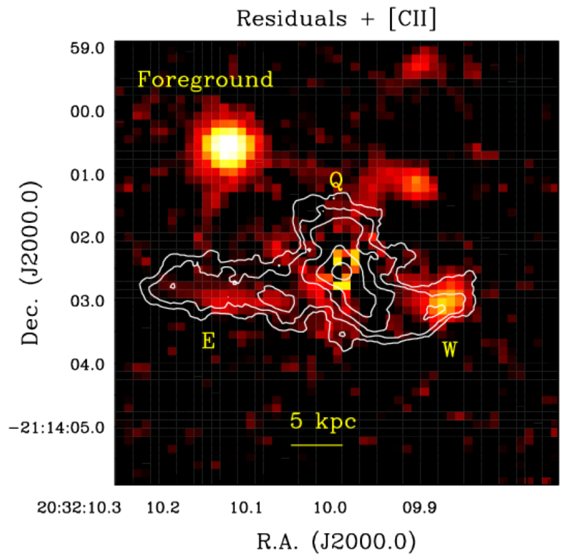


emission from young stars



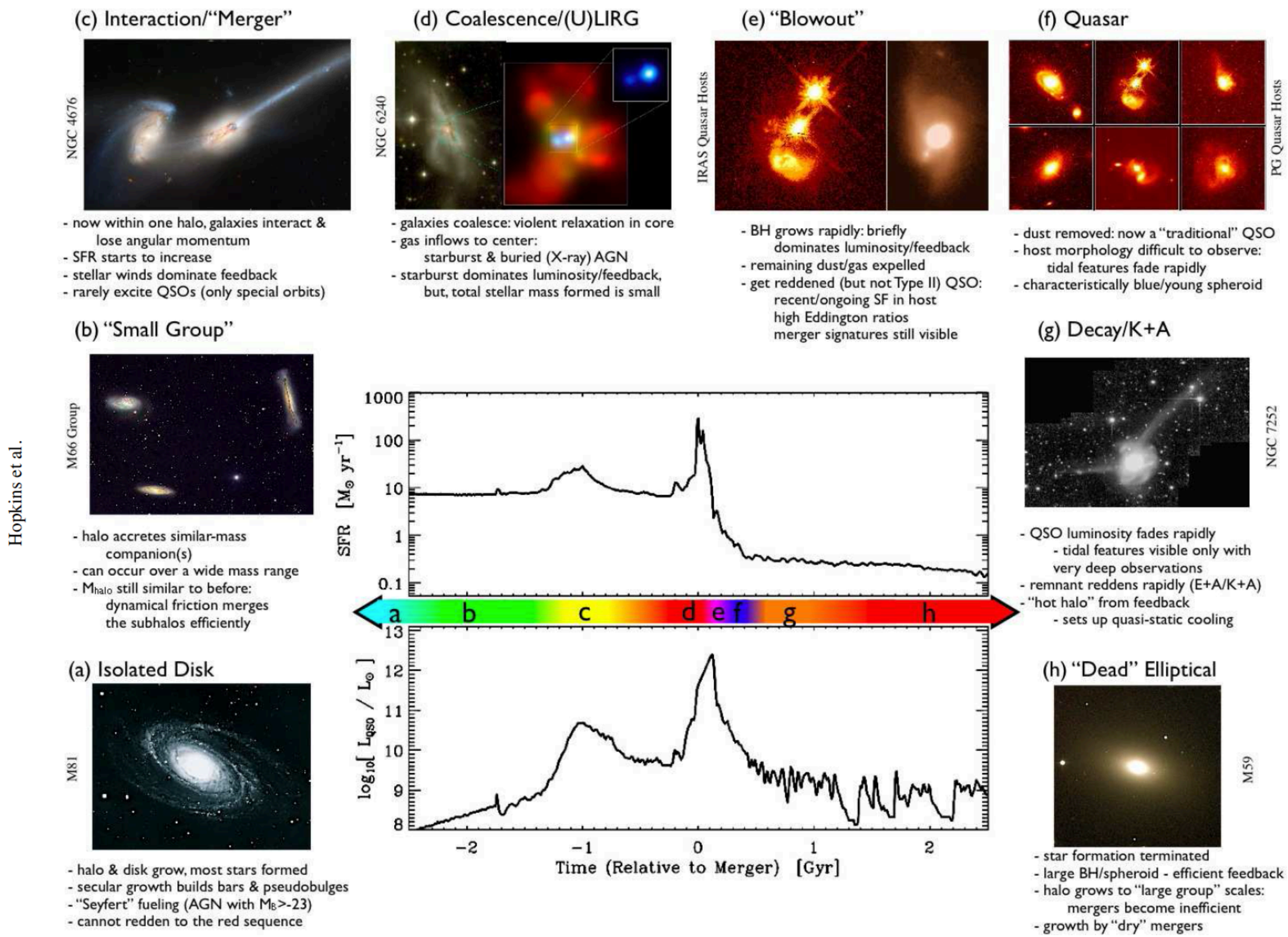
emission from interstellar dust





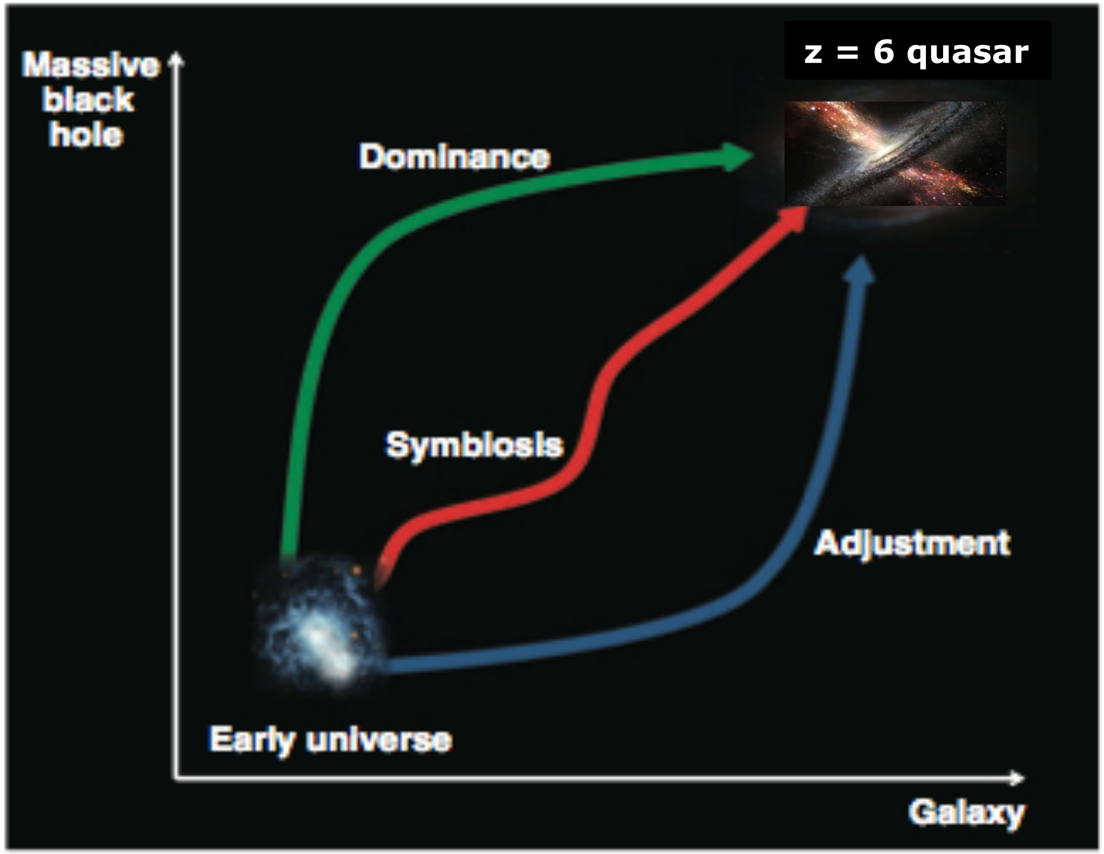
a single galaxy that is tidally stripped by the interaction with the quasar

co-evolution driven by mergers?



Hopkins et al. 2007

Co-evolution of the first BH and galaxies: dominance, symbiosis or adjustment?



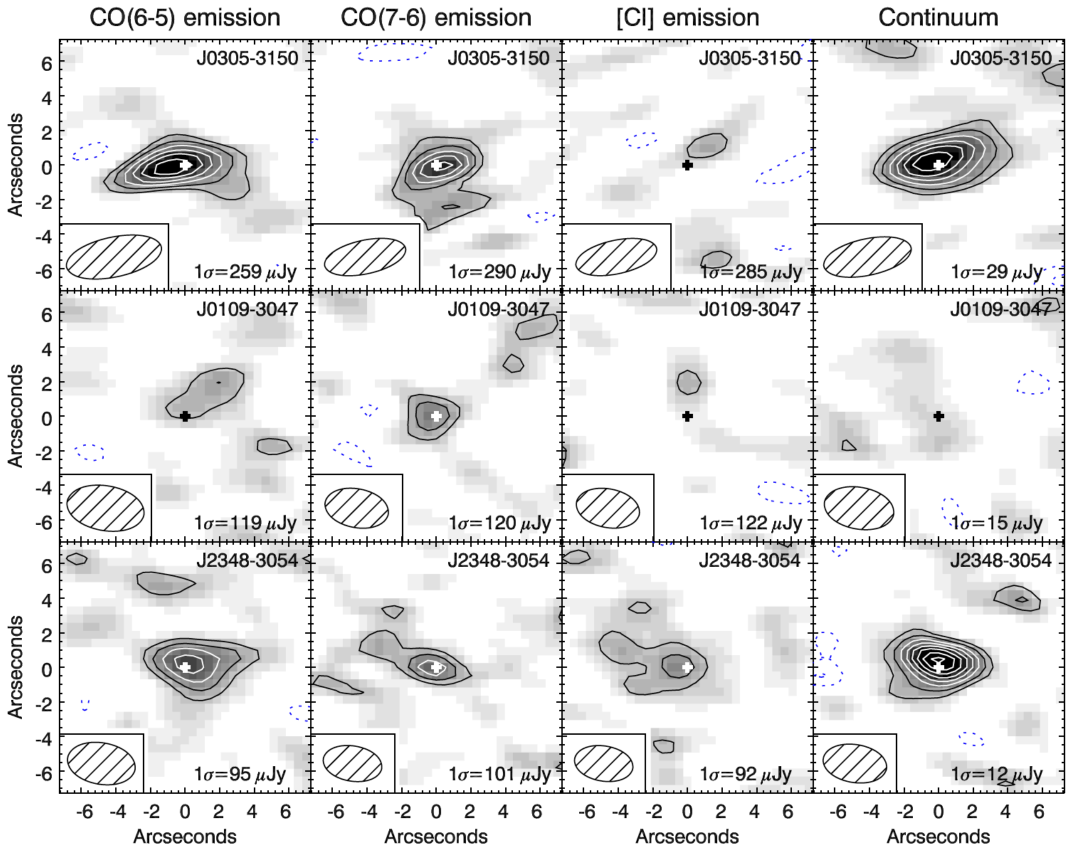
adapted from Volonteri 2012

different pathways reflect BH seeds birth and growth conditions

dust and gas emission from quasars hosts

observations in the (sub) millimeter regime have the potential to trace the rest-frame far-infrared (FIR) emission in the quasar host, as well as key diagnostic lines of their interstellar medium (see review by Carilli & Walter 2013)

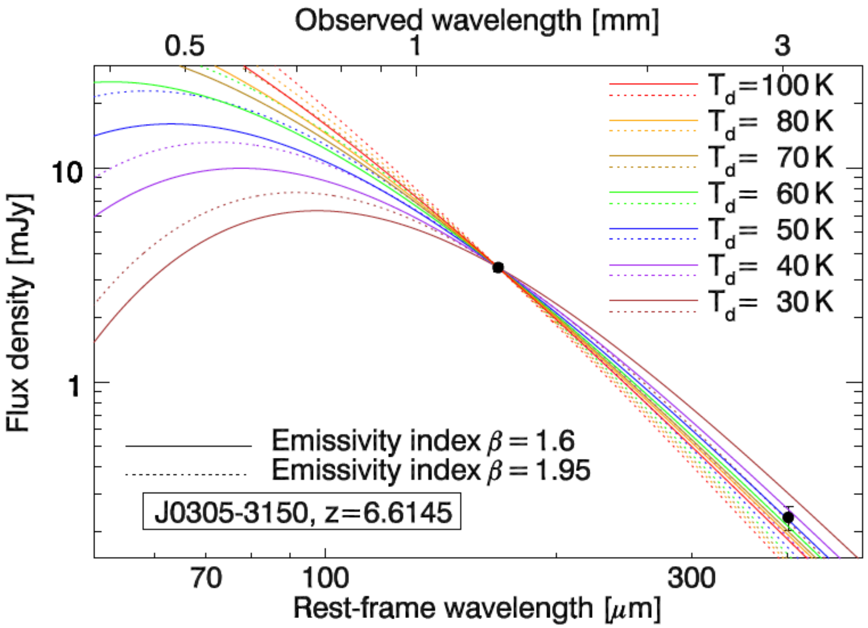
deep ALMA observations of three z ≈ 7 quasar hosts

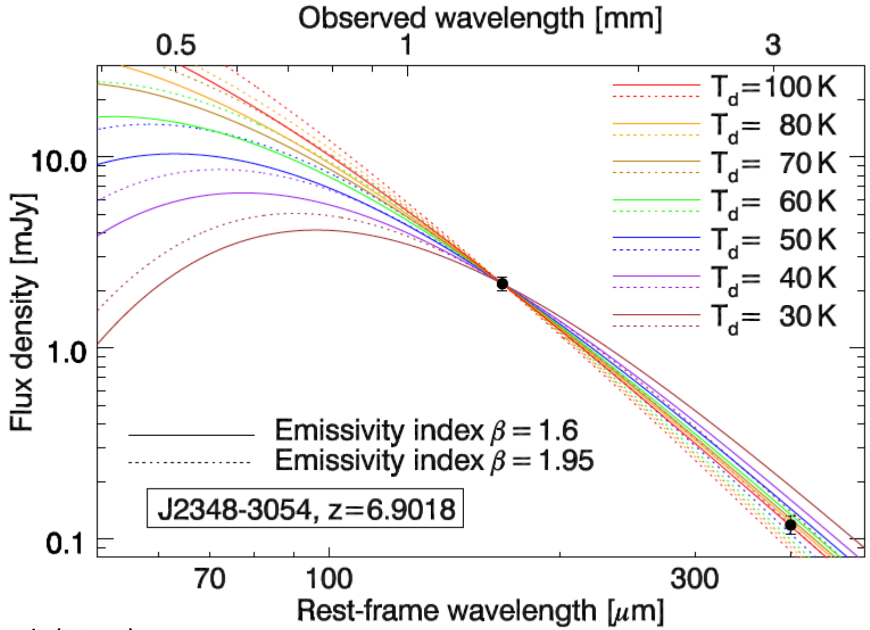


Venemans et al. 2017

FIR emission from quasars hosts

continuum emission in the rest-frame FIR allows to infer the dust mass and total FIR luminosity (SFR)





Venemans et al. (2017)

with only two data points there is a strong degeneracy between dust temperature and emissivity

$$M_{\rm dust} = \frac{S_{\nu_0}\, d_{\rm L}^2(z)}{(1+z)\,\kappa_{\rm d}(\nu)\, B(\nu,\, T_{\rm d})},$$

$$L_{\rm FIR} = 4\pi M_{\rm dust} \int \kappa_{\rm d}(\nu)\, B(\nu,\, T_{\rm d})\, {\rm d}\nu.$$

$$\kappa_{\rm d}(\nu) \;=\; \kappa_0(\nu/\nu_0)^{\beta}$$

$$\mathrm{SFR}\ (M_\odot\ yr^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s^{-1}})$$

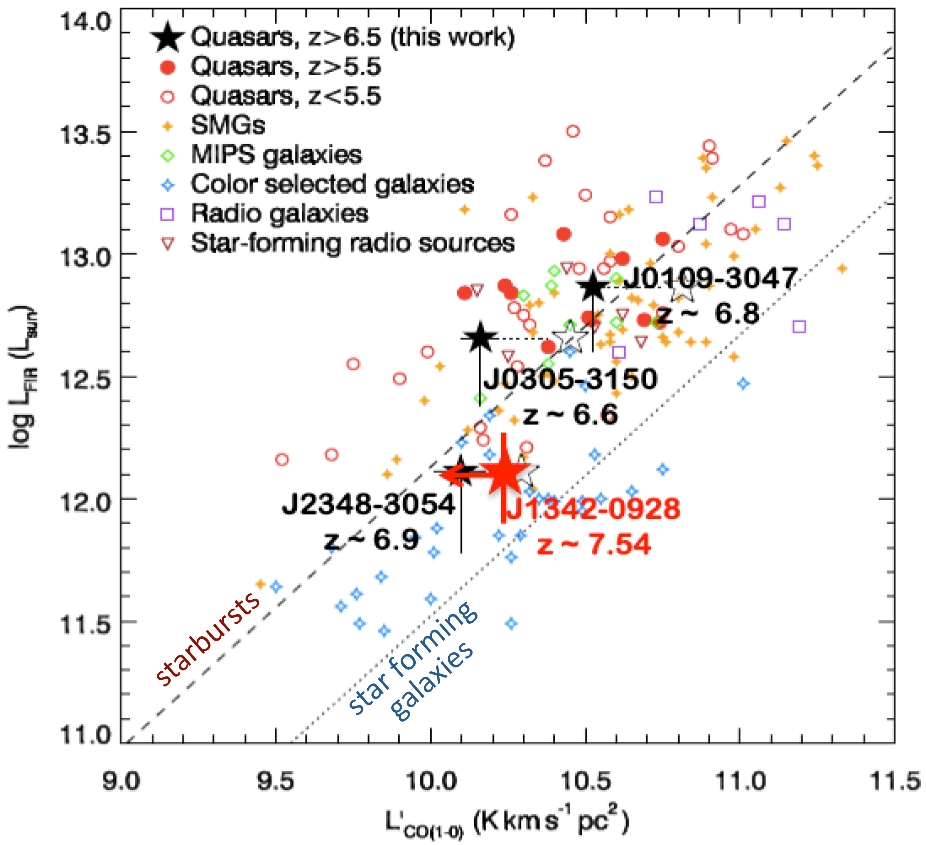
M_{dust} ~ [0.7 – 24] x 10^8 M_{sun}

SFR ~ [200 - 2000] M_{sun}/yr

FIR and CO emission from quasars hosts

the CO luminosity allows to estimate the molecular gas mass in the interstellar medium

adapted from Venemans et al. (2017)



proxy for the molecular gas mass

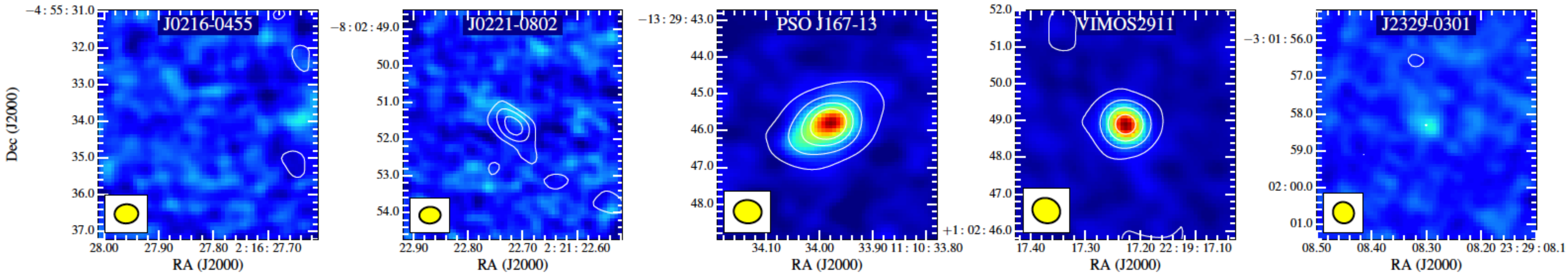
$M_{H2} = \alpha\, L'_{CO(1-0)}$ with $\alpha = 0.8\ M_{sun}/(\mathrm{K\ km\ s^{-1}\ pc^2})$

$M_{H2} = [0.7 - 3] \times 10^{10}\ M_{sun}$

FIR emission lines from quasars hosts

emission lines (CI, CII, CO) allow to study the dynamics of the gas and its physical properties (T, n)

ALMA [C II] line (color scaling) and continuum (white contours) maps of five z > 6 quasars



Willott et al. (2017)

Assuming that line emission comes from a thin disk where the velocity structure is entirely due to rotation:

$M_{dyn} \sim 2.3 \times 10^5 v_{circ}^2 \; R \; M_{sun}$

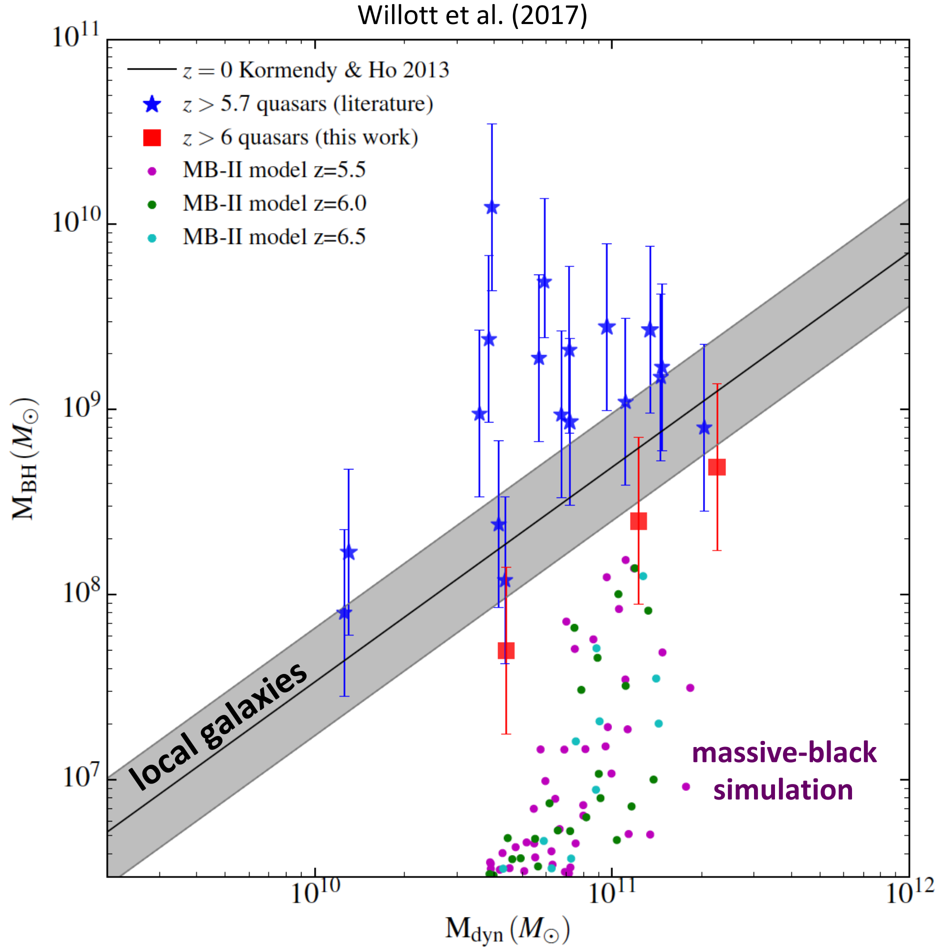
$V_{circ} = 3/4 \; FWHM/\sin i$

$I = \cos^{-1} amin/amax$

$M_{dyn} = [4.4 \times 10^{10} - 2.3 \times 10^{11}] \; M_{sun}$

when this is possible, then: $M_{star} = M_{dyn} - M_{gas}$

black hole – dynamical mass relation

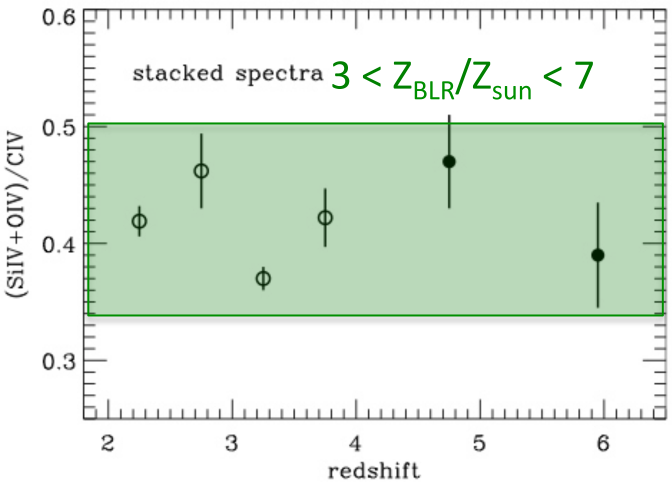


- quasars powered by lower BH masses show dynamical masses consistent with the local relation
- the full sample shows a very wide scatter compared to the local relationship and to simulations

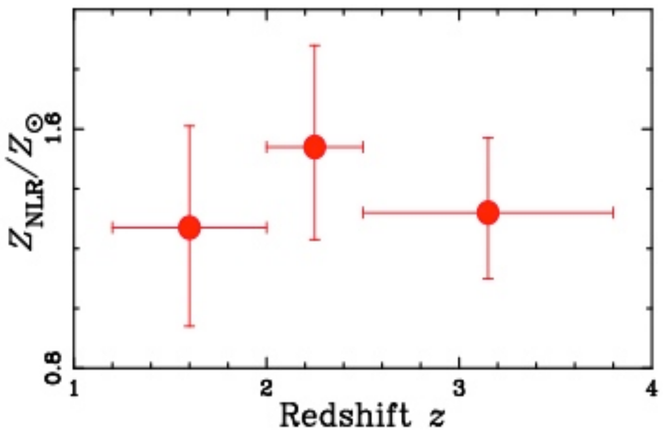
clues from the chemical properties of the host galaxies

high-z QSOs host galaxies are chemically mature systems: super solar metallicities in BLR/NLRs and no (or little) evolution in the abundance ratios

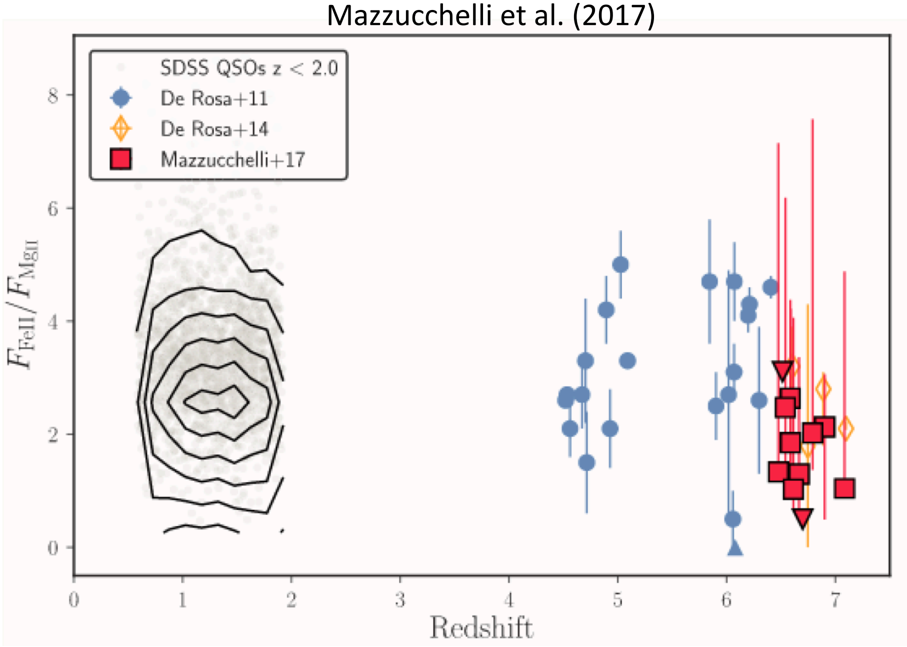
metallicity of the BLRs Nagao+2006, Juarez+2009



metallicity of the NLRs Matsuoka+2009

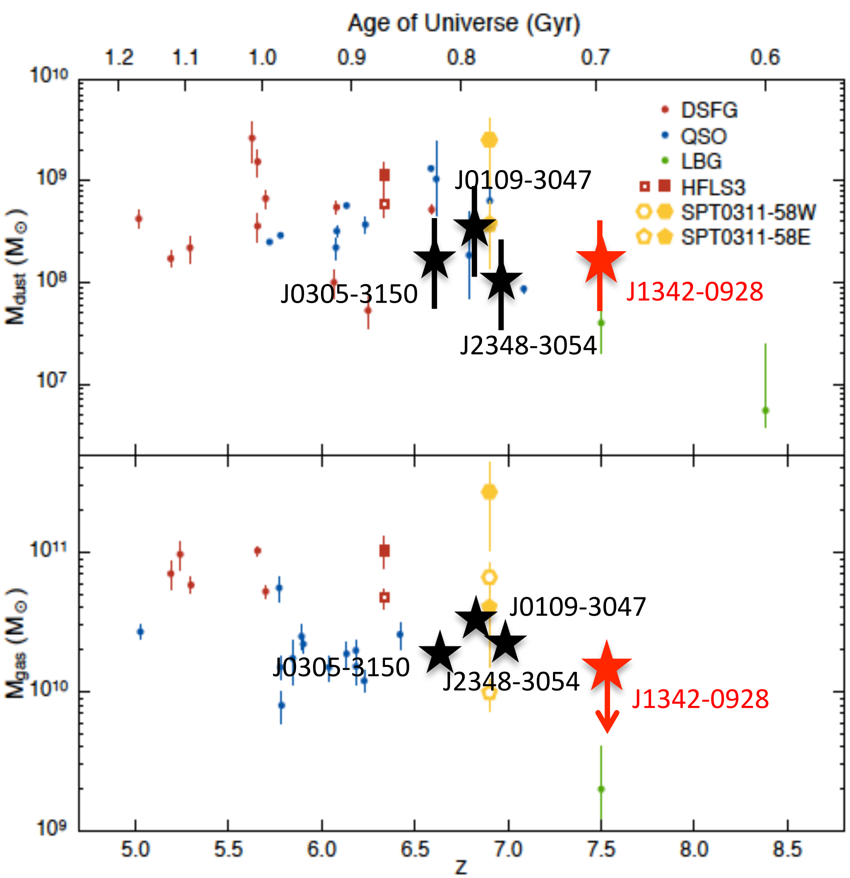


relative abundance of Mg and Fe in the BLR
Mazzucchelli et al. (2017)

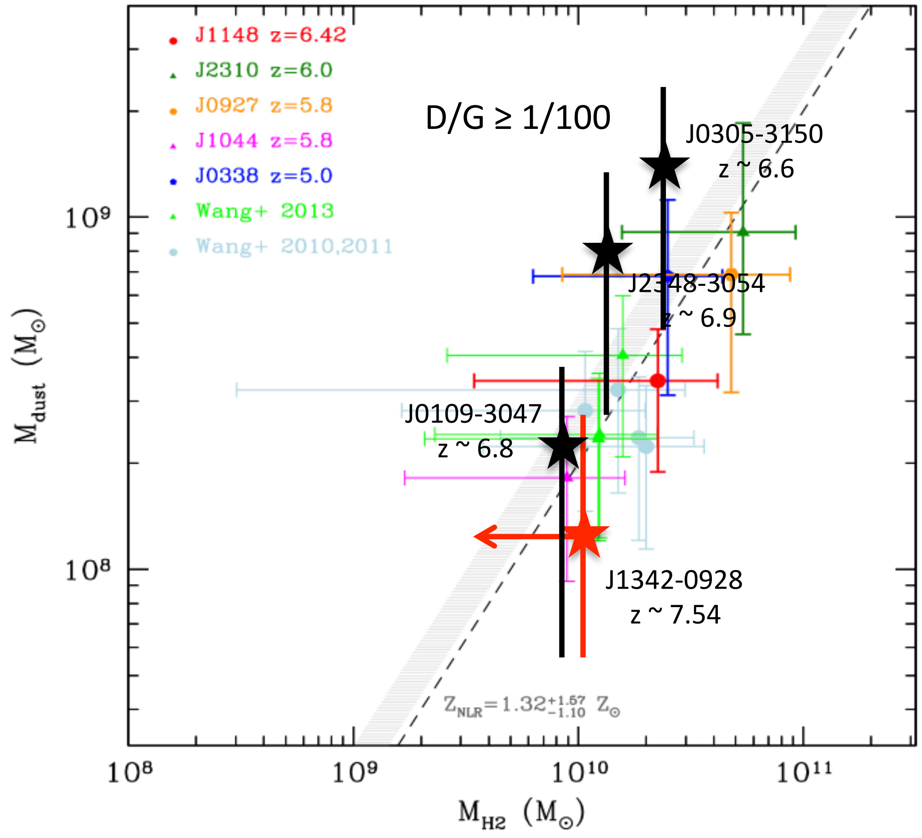


clues from the chemical properties of the host galaxies

high-z QSOs host galaxies are chemically mature systems: large dust masses and dust-to-gas ratios (D/G) comparable to or larger than the MW value



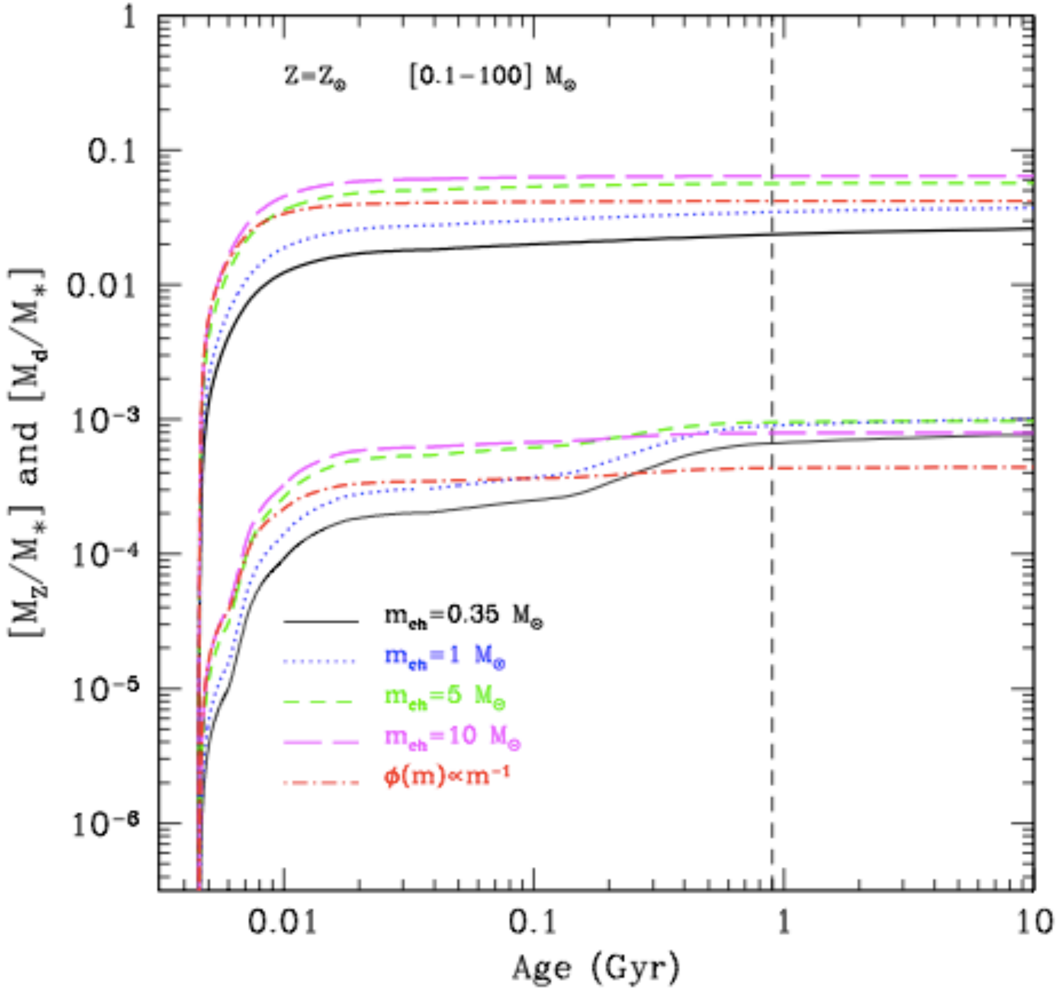
adapted from Marrone et al. 2017



adapted from Valiante et al. 2014,

stars produce heavy elements and dust

metallicity dependent metal and dust yields from SN and AGB stars

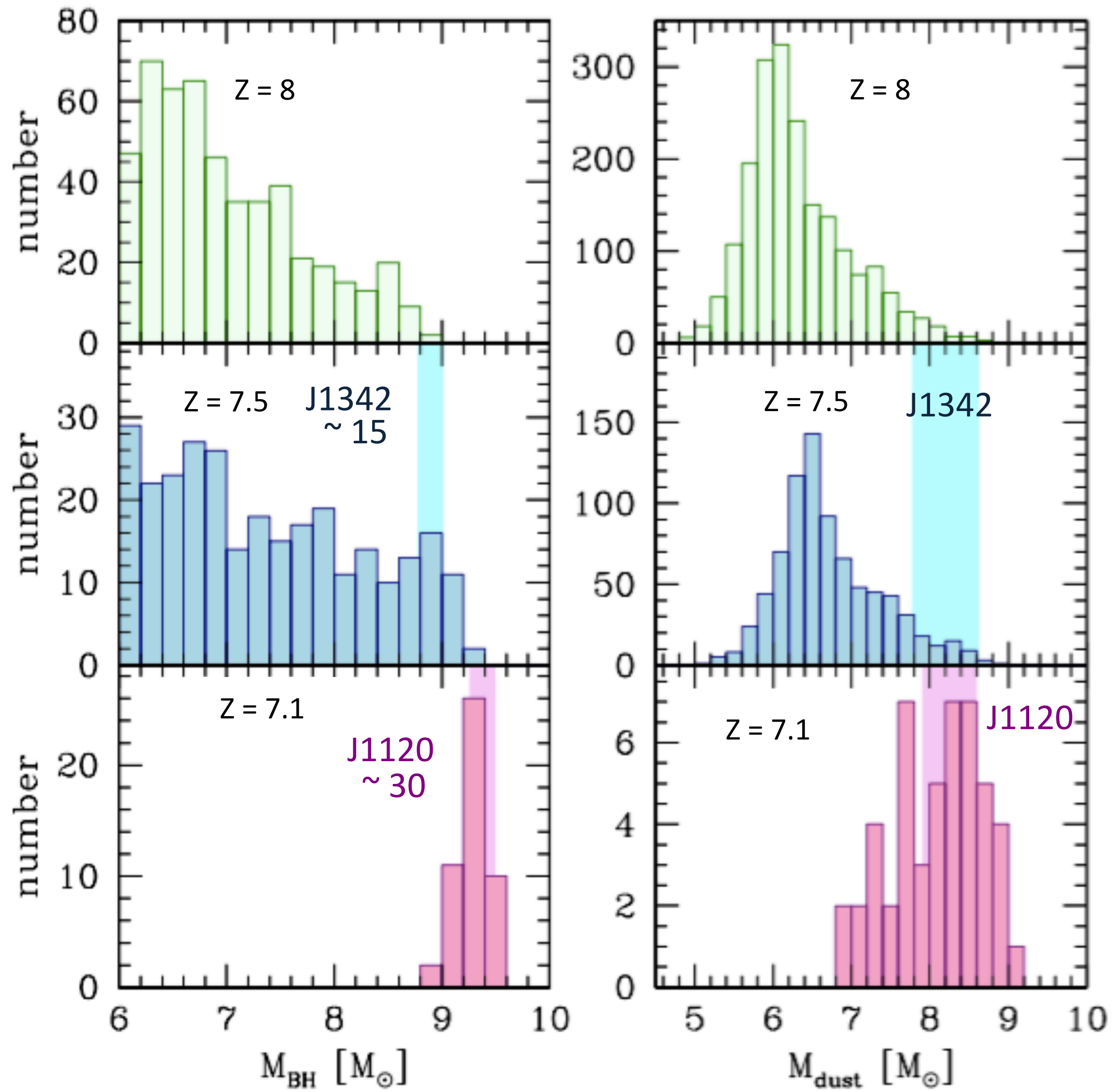


relative importance of SN and AGB stars depends on IMF

Valiante et al. 2009, 2011

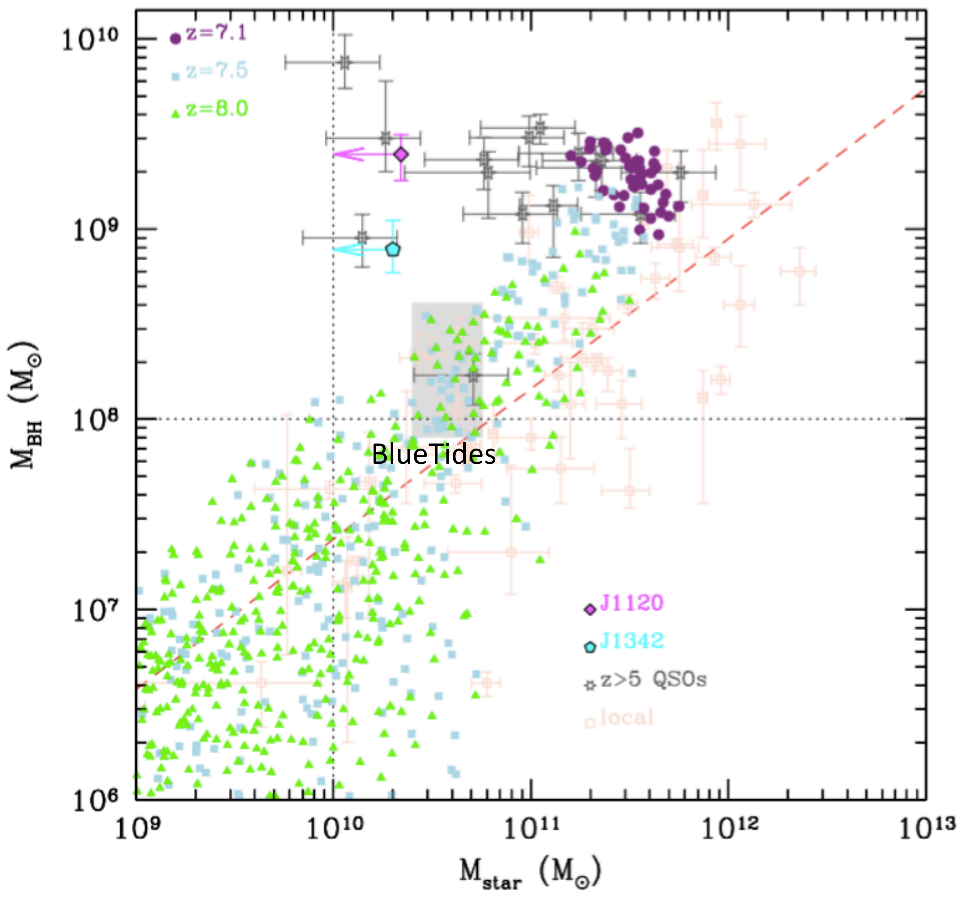
the assembly of the host galaxy: from J1342 @ z = 7.5 to J1120 @ z = 7.1

black hole and dust mass distributions for 50 simulations

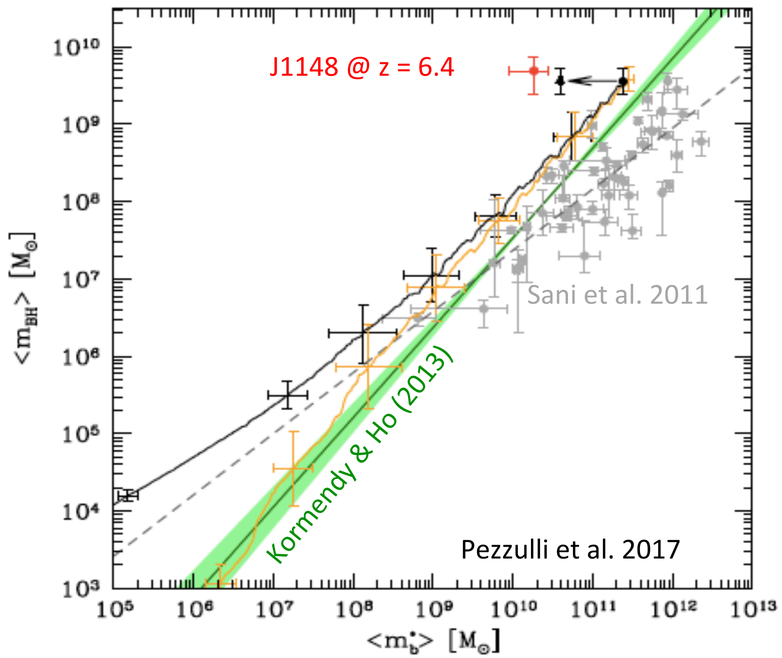


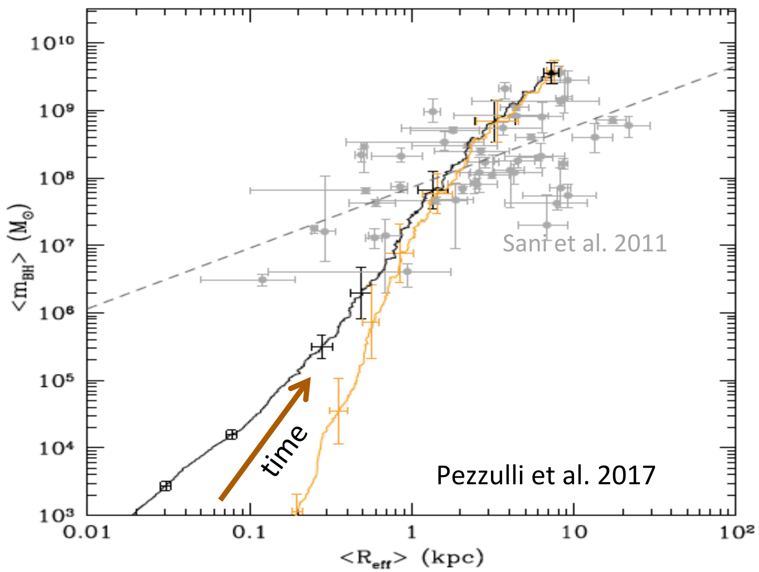
Valiante et al. in prep

co-evolution at cosmic dawn



Valiante et al. in prep

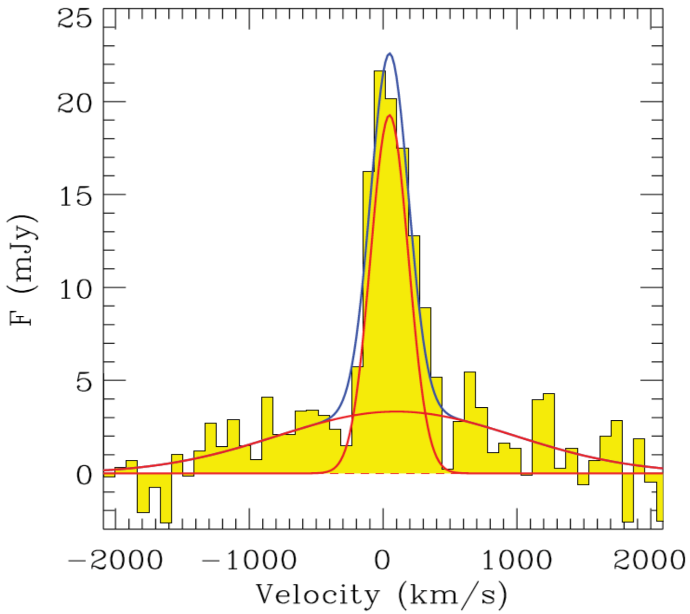




the nuclear black hole and its host appear to grow hand-in-hand

evidence of strong quasar feedback in the early Universe

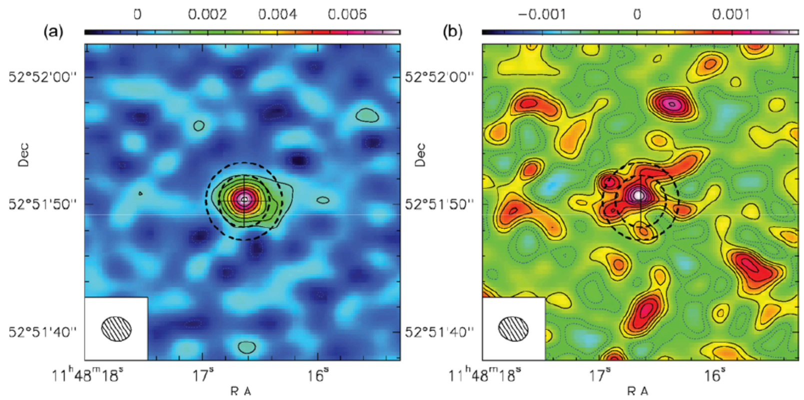
IRAM PdB observation of the CII (158 micron) line in the z = 6.4 quasar J1148 (Maiolino et al. 2012)



double Gaussian fit:

- Narrow component FWHM = 345 km/s tracing gas within the host
- Broad component FWHM = 2030 km/s tracing strong outflows

map of the narrrow CII   map of the broad CII



$$M_{\rm out}/{\rm M}_\odot = 0.77\left(\frac{0.7L_{\rm [CII]}}{{\rm L}_\odot}\right)\left(\frac{1.4\times10^{-4}}{X_{\rm C^+}}\right)\times\frac{1+2e^{-91K/T}+n_{\rm crit}/n}{2e^{-91K/T}}$$

$$\dot{M}_{\rm out} = \frac{v_{\rm out}\times M_{\rm out}}{R_{\rm out}}$$

$M_{out} > 7\ 10^9\ M_{sun}$ $R_{out} = 8$ kpc

$v_{out} = 1300$ km/s
(maximum velocity observed in the wings)

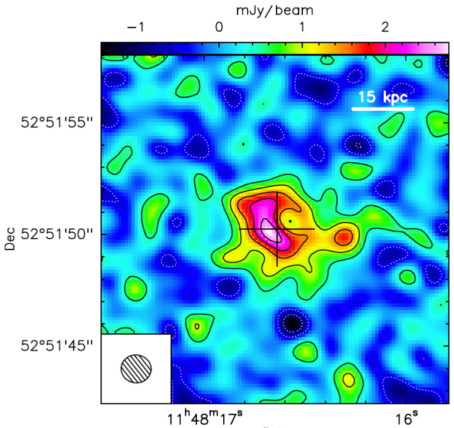
$dM_{out}/dt > 3500\ M_{sun}/yr$

this outflow rate is larger than the SFR (3000 M_{sun}/yr) and must be powered by the AGN
the gas content in the host galaxy will be cleaned, and star formation quenched, in less than 6 Myr

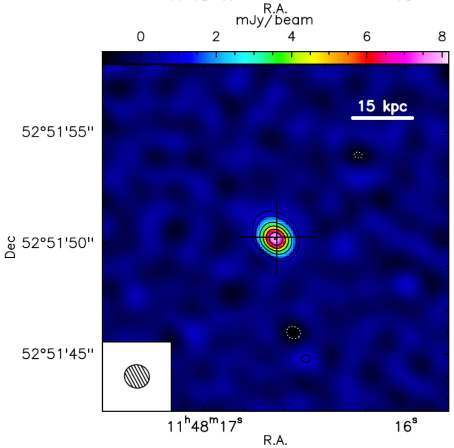
spatially resolved quasar driven outflow

IRAM PdB observation of the CII (158 micron) line in the z = 6.4 quasar J1148 (Cicone et al. 2015)

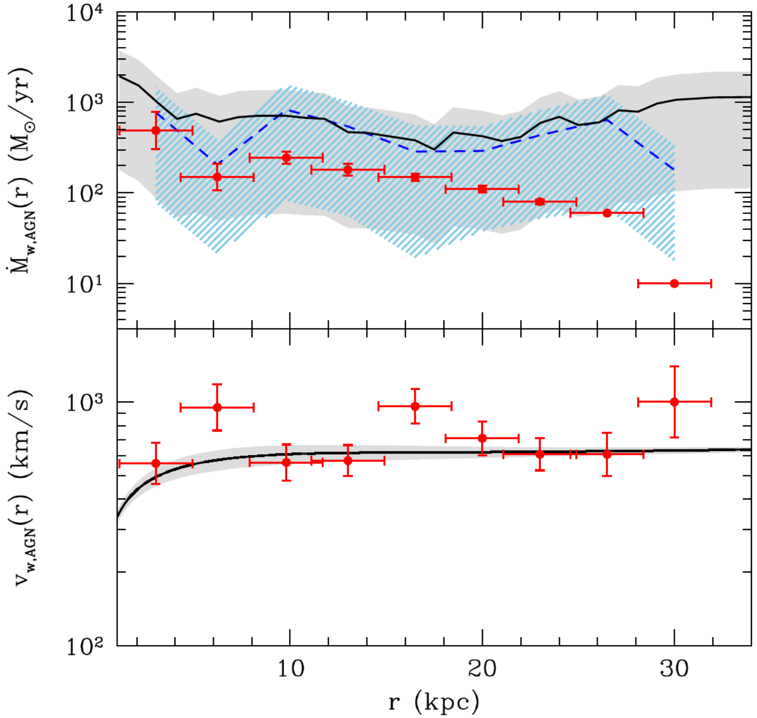
map of the broad CII



map of the narrow CII



observations (red) compared to model predictions

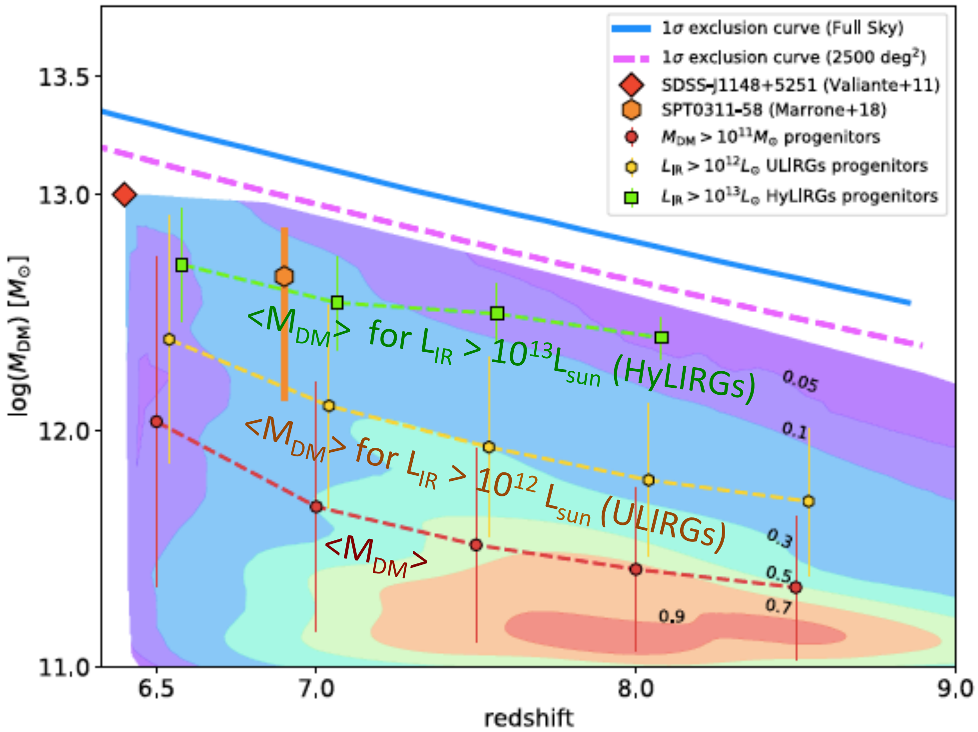


Pezzulli et al. (2016)

a very extended outflow out to a distance of 30 kpc from the nucleus

the IR luminous progenitors of z = 6 quasars

density plot of DM halos hosting progenitors of z = 6 quasars



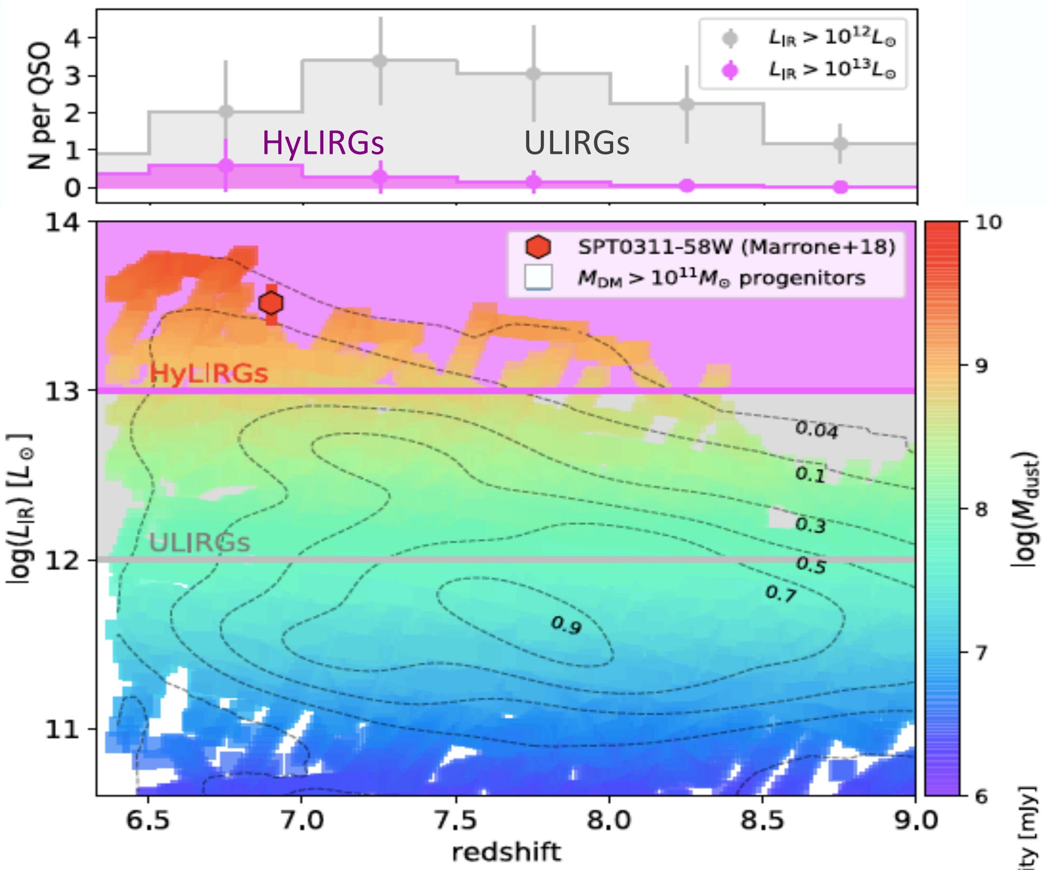
Ginolfi et al. (2018)

HyLIRGs similar to z = 6.9 SPT0311-58 (Marrone+2018) are hosted in $M_{DM} \sim 10^{12.5} - 10^{13}\ M_{sun}$

these systems can be found in the family tree of z ~ 6 quasars

the IR luminous progenitors of z = 6 quasars

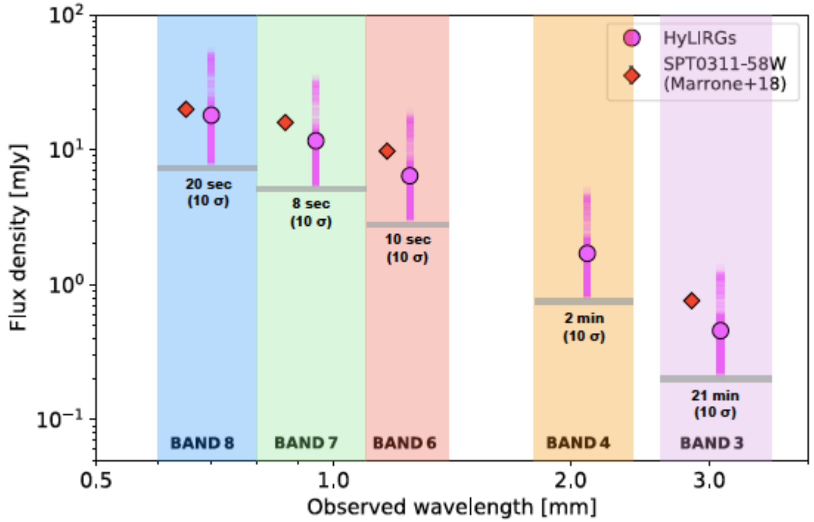
Ginolfi et al. (2018)



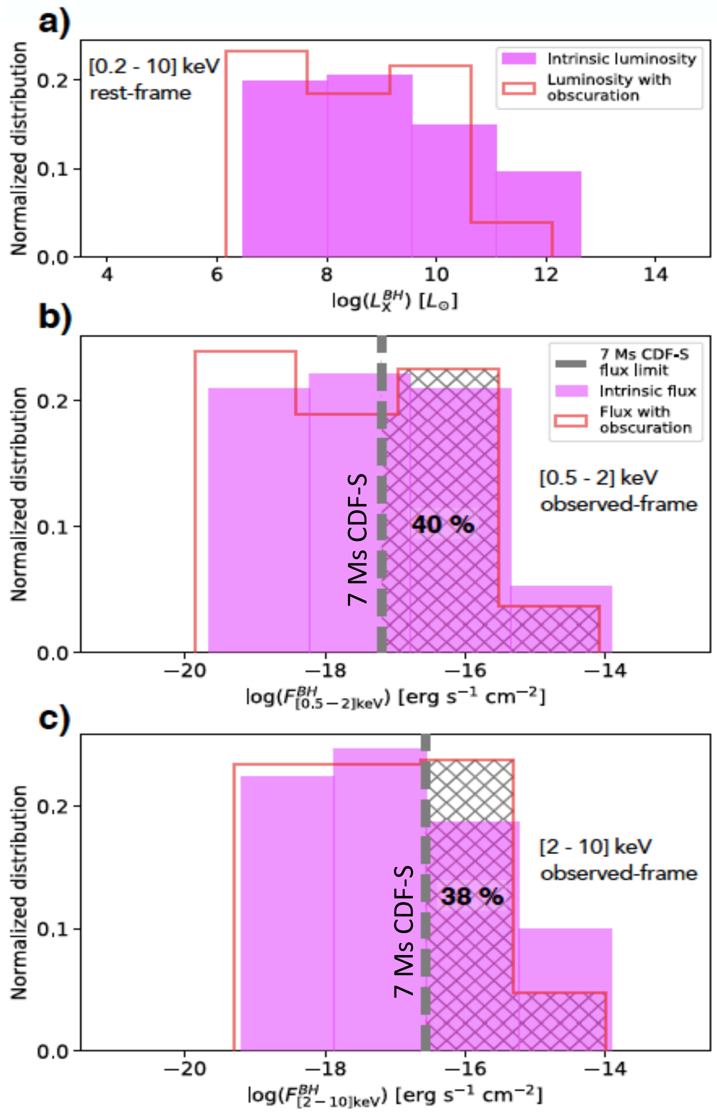
each z = 6 quasar has, on average, ~ 2.8 ULIRGs and ~ 0.4 HyLIRGs progenitors at 6.5 < z < 8

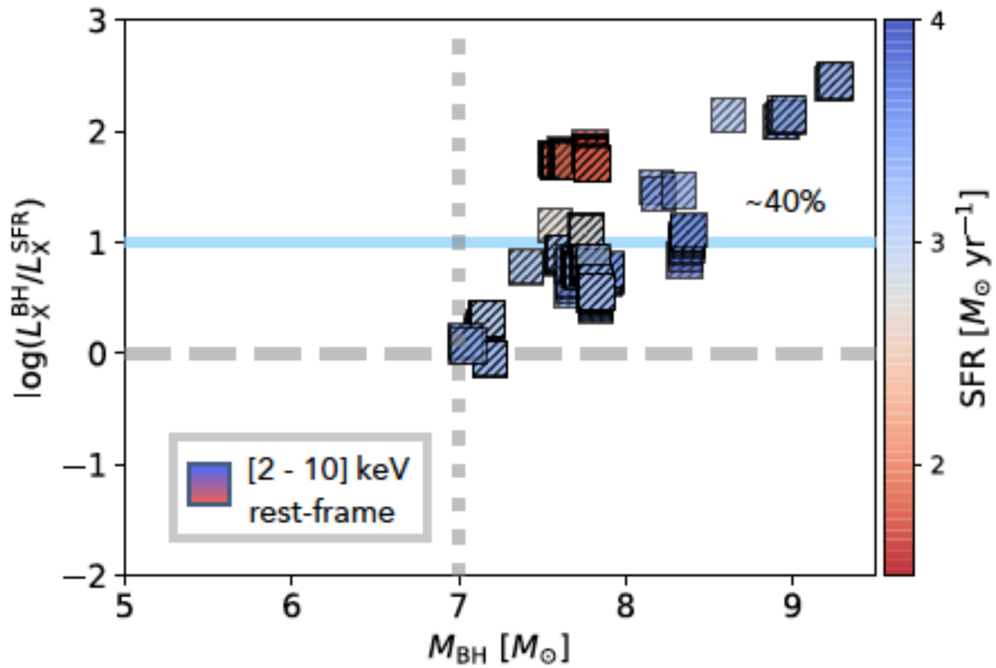
~ 180 quasars @ z > 6 → ~ 70 HyLIRGs

all these systems can be observed with ALMA



X-ray properties of HyLIRGs at z > 6





Ginolfi et al. (2018)

summary

- $z = 6$ quasars are extremely interesting systems: they mark rapidly growing overdensities and provide valuable constraints on the early evolution of galaxies and their nuclear black holes

- $z = 6$ SMBHs grow from BH seeds trough gas accretion and mergers. The BH seeds mass distribution depend on their birth conditions and is sensitive to early galaxy evolution

- Gas accretion (Eddington limited or super-Eddington) is also very sensitive to the physical properties of the gas flow around the black hole and how this is fed at galaxy-scale

- The properties of the host galaxies are hard to constrain, but mm/submm observations have been able to probe the morphology, dynamical mass, gas dynamics, SFRs and ISM conditions in these "extreme" systems

- Future observational facilities (multi-band EM and GW observations) might be able constrain the assembly history of the first quasar

some additional bibliographic suggestions

- Inayoshi, Visbal, Haiman, *The assembly of the first massive black holes*
2020 Annual Review of Astronomy & Astrophysics
https://ui.adsabs.harvard.edu/abs/2019arXiv191105791I/abstract

- Special Publications of the Astronomical Society of Australia issue following a Symposium organized in July 2015 during the European Week of Astronomy and Space Science (EWASS) by R. Schneider, R. Valiante, M. Volonteri

- Gallerani et al. *Physical properties of the first quasars*
https://ui.adsabs.harvard.edu/abs/2017PASA...34...22G/abstract
- Valiante et al. *On the formation of the first quasars*
https://ui.adsabs.harvard.edu/abs/2017PASA...34...31V/abstract

- Volonteri, *Formation of supermassive black holes*
2010, The Astronomy and Astrophysics Review
https://ui.adsabs.harvard.edu/abs/2010A%26ARv..18..279V/abstract

- Carilli, Walter *Cool gas in high-redshift galaxies*
2013, The Astronomy and Astrophysics Review
https://ui.adsabs.harvard.edu/abs/2013ARA%26A..51..105C/abstract