from the first black holes to the first quasars

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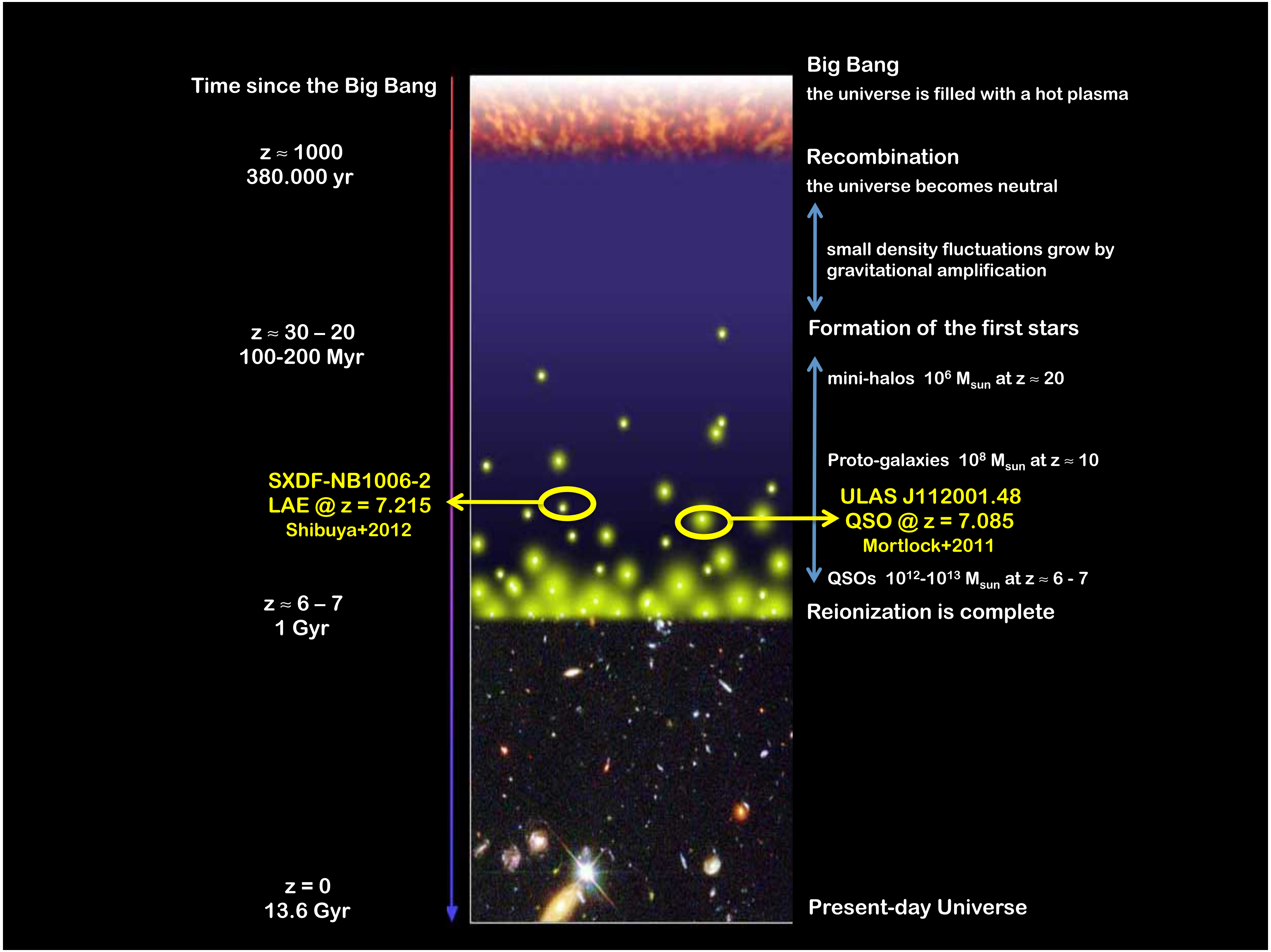
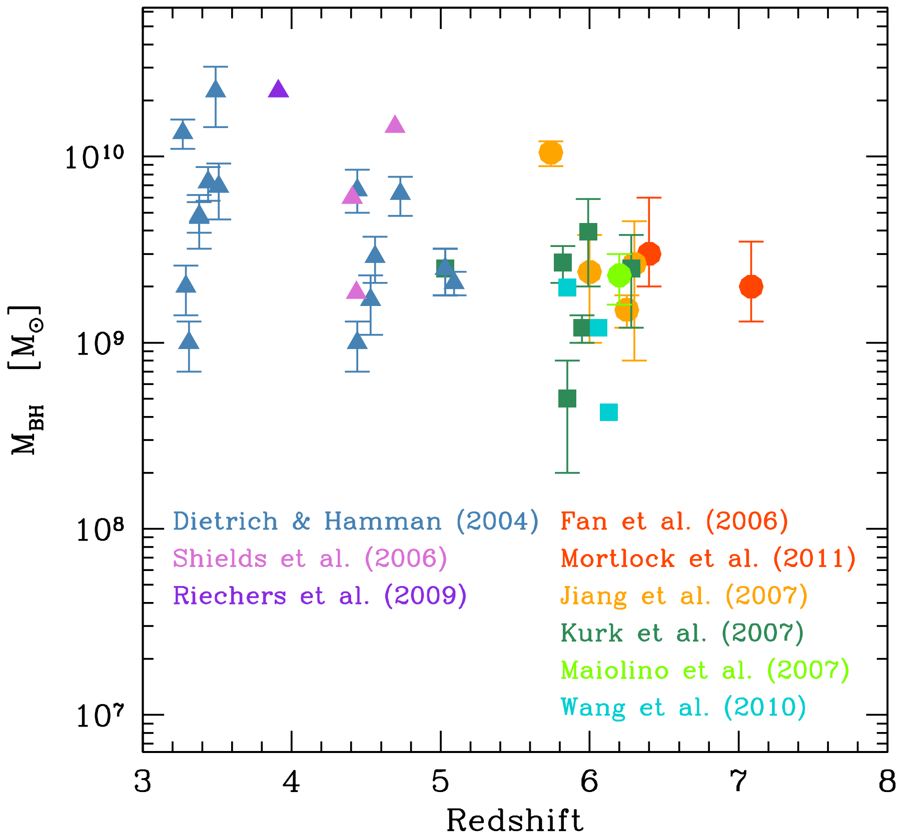
Outline

- Introduction
- The nature of BH seeds: Pop III remnants or head-on start?
- From the first BHs to the first QSOs: planting seeds along hierarchical structure formation
- Co-evolution of the first BH and galaxies: dominance, symbosis or adjustment? Clues from chemical properties of the host galaxies
- Conclusions



Time since the Big Bang
z ≈ 1000
380.000 yr
z ≈ 30 – 20
100-200 Myr
SXDF-NB1006-2
LAE @ z = 7.215
Shibuya+2012
z ≈ 6 – 7
1 Gyr
z = 0
13.6 Gyr
Big Bang
the universe is filled with a hot plasma
Recombination
the universe becomes neutral
small density fluctuations grow by gravitational amplification
Formation of the first stars
mini-halos 10^6 M_{sun} at z ≈ 20
Proto-galaxies 10^8 M_{sun} at z ≈ 10
ULAS J112001.48
QSO @ z = 7.085
Mortlock+2011
QSOs 10^{12}-10^{13} M_{sun} at z ≈ 6 - 7
Reionization is complete
Present-day Universe

growing the first quasars

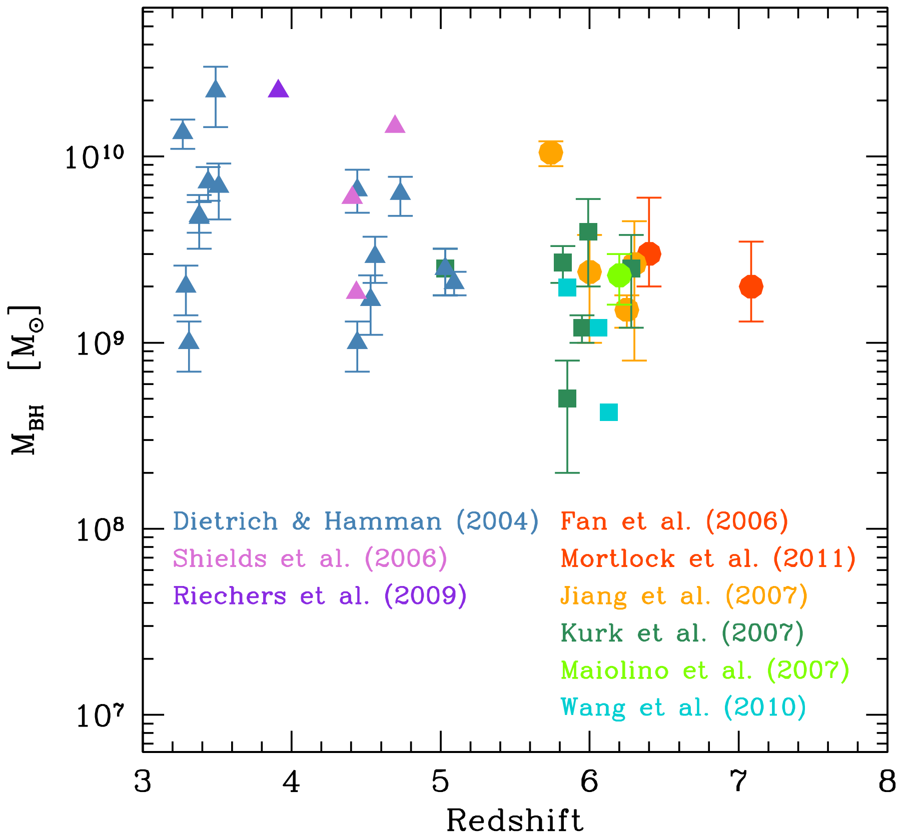


$$M(t) = M(0)\ \exp\left(\frac{1-\epsilon}{\epsilon}\frac{t}{t_{\mathrm{Edd}}}\right) \qquad t_{\mathrm{Edd}} = 0.45\,\mathrm{Gyr}, \quad \epsilon \approx 0.1$$

z = 7.085 t = 0.77 Gyr $M_{BH} = 2\ 10^9\ M_{sun}$ → $M_{seed} > 400\ M_{sun}$

z = 6.42 t = 0.87 Gyr $M_{BH} = 3\ 10^9\ M_{sun}$ → $M_{seed} > 80\ M_{sun}$

growing the first quasars



$$M(t) = M(0)\ \exp\left(\frac{1-\epsilon}{\epsilon}\frac{t}{t_{\rm Edd}}\right) \qquad t_{\rm Edd} = 0.45\,{\rm Gyr} \quad \epsilon \approx 0.1$$

z = 7.085	**Δt = 0.67 Gyr**	$M_{BH} = 2\ 10^9\ M_{sun}$	→ **$M_{seed} > 3000\ M_{sun}$**
z = 6.42	**Δt = 0.77 Gyr**	$M_{BH} = 3\ 10^9\ M_{sun}$	→ **$M_{seed} > 500\ M_{sun}$**

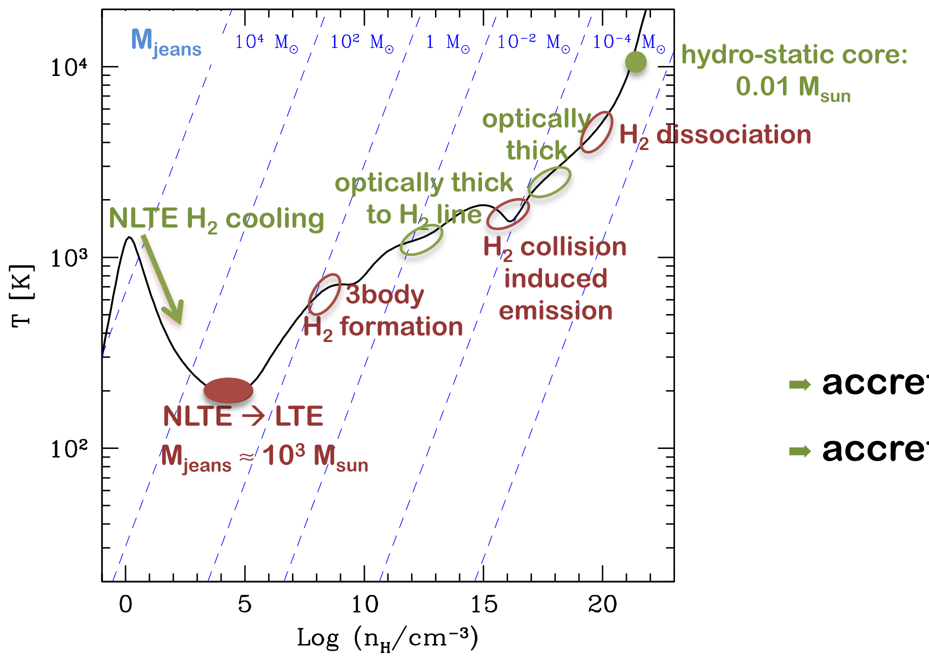
seed BHs formation scenarios

- Remnants of Population III stars forming in primordial mini-halos at $z \approx 20 - 30$
- Direct-collapse in the first proto-galaxies at $z \approx 10$
- Formation in stellar clusters at $z \approx 10$

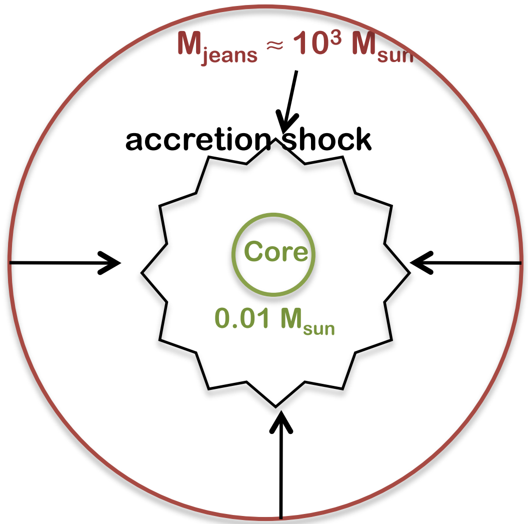
the formation of the first stars

theory for the formation of the first Pop III stars predict an IMF dominated by high-mass stars

- ✓ collapse of ≈ 10^6 M_{sun} mini-halos at $z \approx 20$ - 30
- ✓ H_2 cooling
- ✓ gas cloud becomes Jeans unstable $M_{jeans} \approx 10^3$ M_{sun}



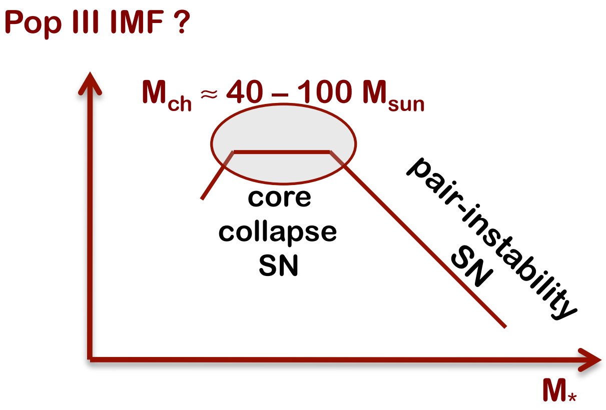
Omukai et al. 2005

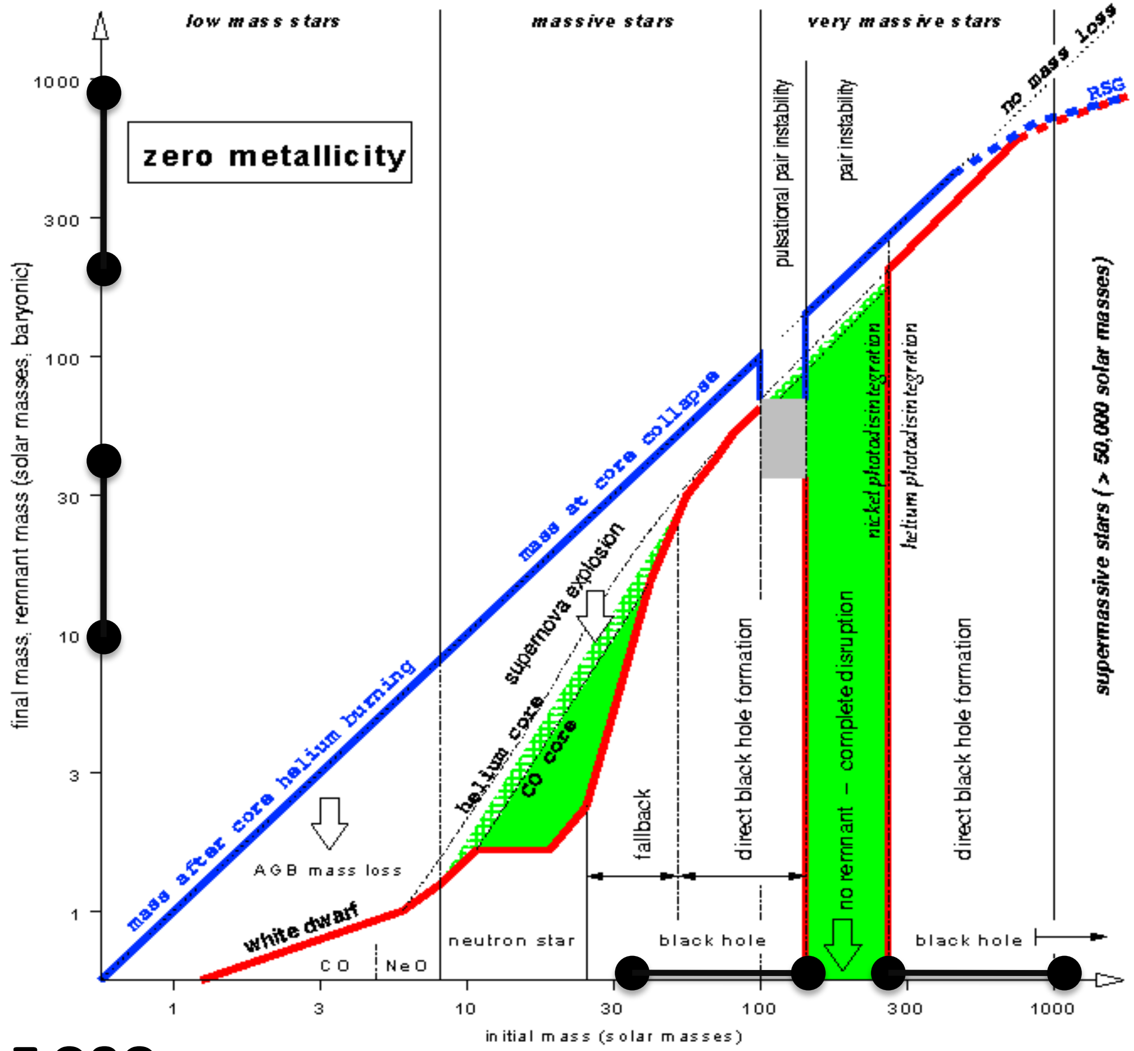


- ➡ accretion rate $dM/dt \approx M_J/t_{ff} \approx c_s^3/G \approx T^{3/2}$ (x 100 larger than Z_{sun})
- ➡ accreted gas mass $M_\star \cong$ [40 – 100] M_{sun}

Omukai & Palla 2003; Bromm et al 2004; O'Shea et al. 2007; Tan & McKee 2004; McKee & Tan 2008; Hosokawa et al. 2011

BH seeds as Pop III stellar remnants?





$40\ M_{sun} < M_* < 140\ M_{sun}$

$M_{BH} << 100\ M_{sun}$

$M_* > 260\ M_{sun}$

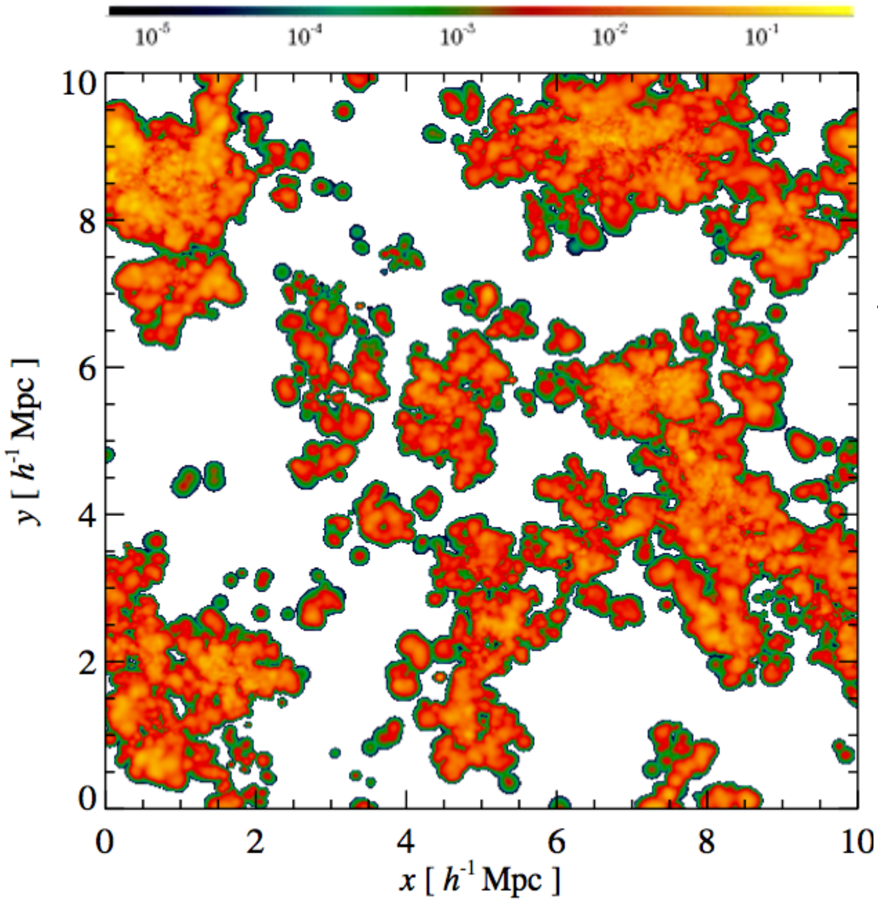
$M_{BH} > 150\ M_{sun}$

→may be too small for z ~ 6 - 7 QSOs

what happens next?

The first supernovae start cosmic metal enrichment

mass-averaged metallicity $Z = M_{met}/M_{gas}$

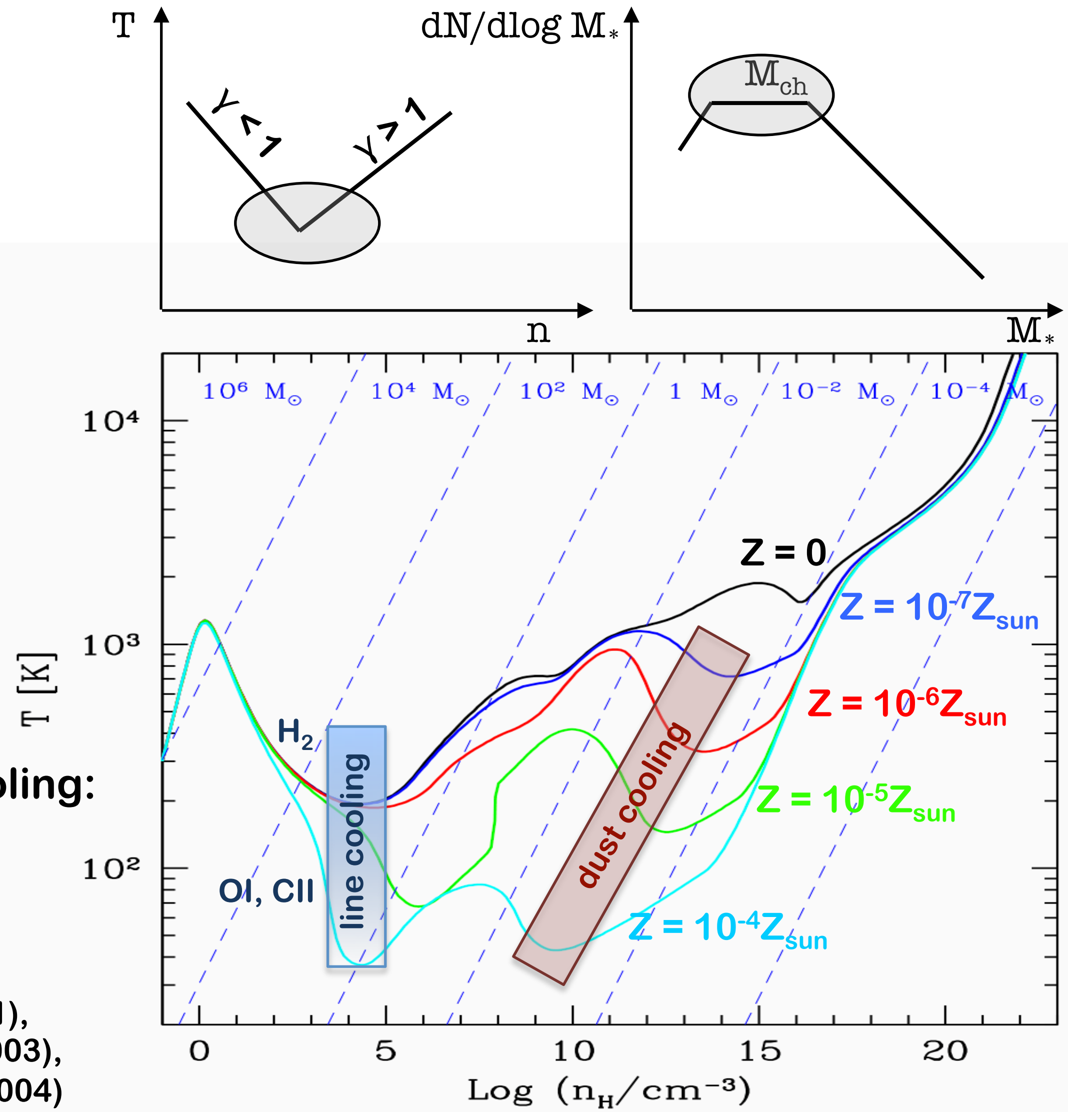


Tornatore et al 2007

→ second generation stars may form in clouds that have been polluted by metals and dust grains

→ cooling and fragmentation properties of star-forming gas change

Star formation with the first heavy elements and dust grains



metal-line cooling:

$Z > 10^{-4}\ Z_{sun}$

$M_{jeans} > 10\ M_{sun}$

Bromm et al. (2001),
Bromm & Loeb (2003),
Santoro & Shull (2004)

dust cooling:

$Z > 10^{-6}\ Z_{sun}$

$M_{jeans} < 1\ M_{sun}$

RS et al. (2002,2003,2006),
Omukai et al. (2005)

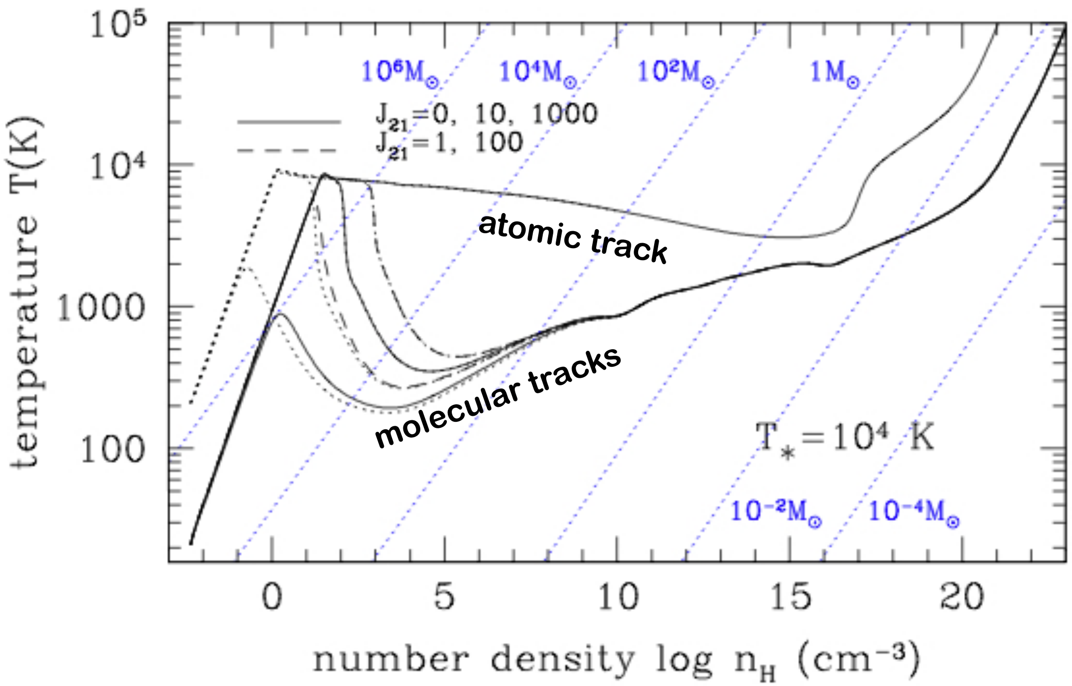
Can fragmentation be avoided?

Yes, preventing the gas to cool!

- **sub-critical metallicities $Z < Z_{cr}$**
- **inefficient H_2 cooling ←→ photo-dissociation by a strong UV flux**

$J_{21} = J/10^{-21}$ erg cm^{-2} sr^{-1} s^{-1} Hz^{-1} > $J_{21,crit} \cong 10^2 - 10^3$

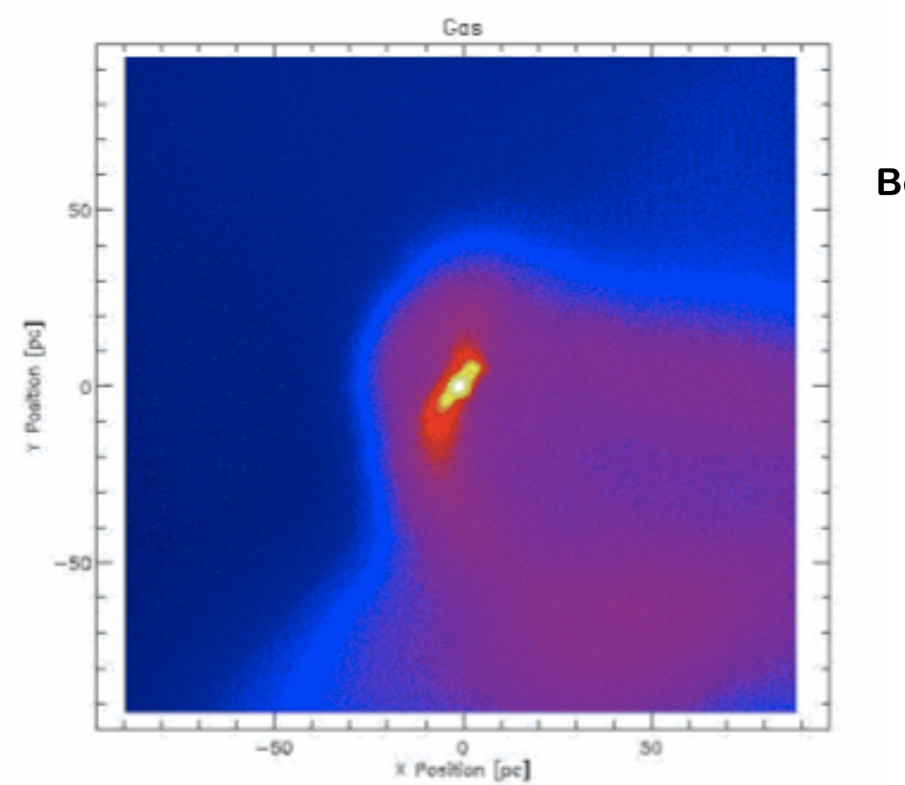
Thermal evolution of Z = 0 gas in a protogalaxy ($T_{vir} > 10^4$K)



Omukai, RS, Haiman (2007)

BH seeds: rapid direct collapse

- overcome rotational support by gravitational instabilities
- rapid collapse due to deep potential well and large accretion rates > 1 M_{sun}/yr



Loeb & Rasio (1994), Eisenstein & Loeb (1995), Oh & Haiman (2002), Bromm & Loeb (2003), Begelman et al. (2006), Lodato & Natarajan (2006), Regan & Haehnelt (2009), Shang et al. (2010)

$M_{BH} \sim 10^5 - 10^6\ M_{sun}$ @ z =10

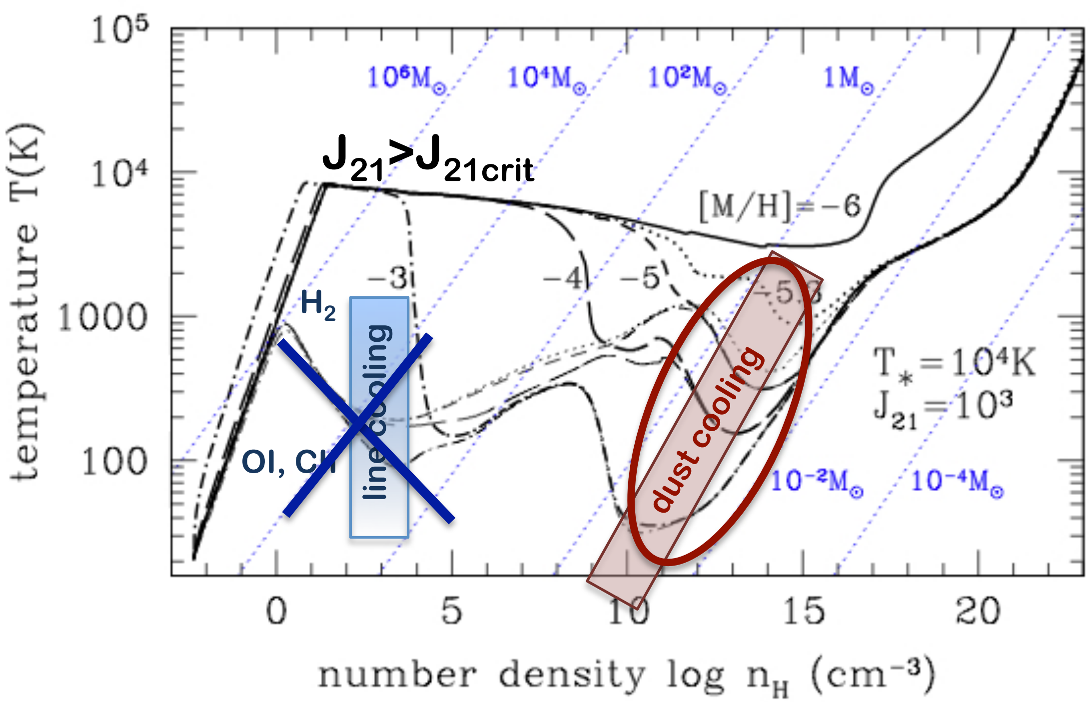
Can fragmentation be avoided?

No, if progenitors of the first galaxies have experienced SF

- super-critical metallicities $Z \geq Z_{cr}$
- inefficient H_2 cooling ←→ photo-dissociation by a strong UV flux

$J_{21} = J/10^{-21}$ erg cm^{-2} sr^{-1} s^{-1} Hz^{-1} > $J_{21,crit} \cong 10^2 - 10^3$

Thermal evolution of $Z \geq 10^{-6} Z_{sun}$ gas in a protogalaxy ($T_{vir} > 10^4$K)



Omukai, RS, Haiman (2007)

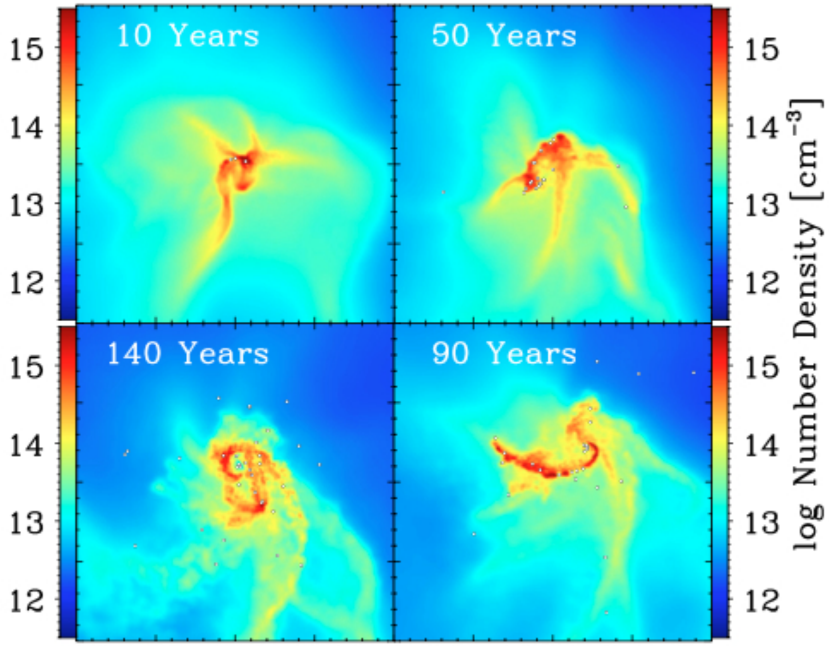
BH seeds: formation in a dense stellar cluster

- dust-induced fragmentation leads to the formation of a dense stellar cluster:

~ 1000 fragments with mass M_{frag} ~ 0.1 M_{sun} in a 0.01 pc region with free-fall time ~300 yr

- dynamical friction timescale: $t_{fric} \sim 1.6 \times 10^3$ yr $(M_R/10^2 M_{sun})$

Very Massive Star forms by stellar mergers if t_{fric} < 4 Myr (Portegies-Zwart et al. 2004)



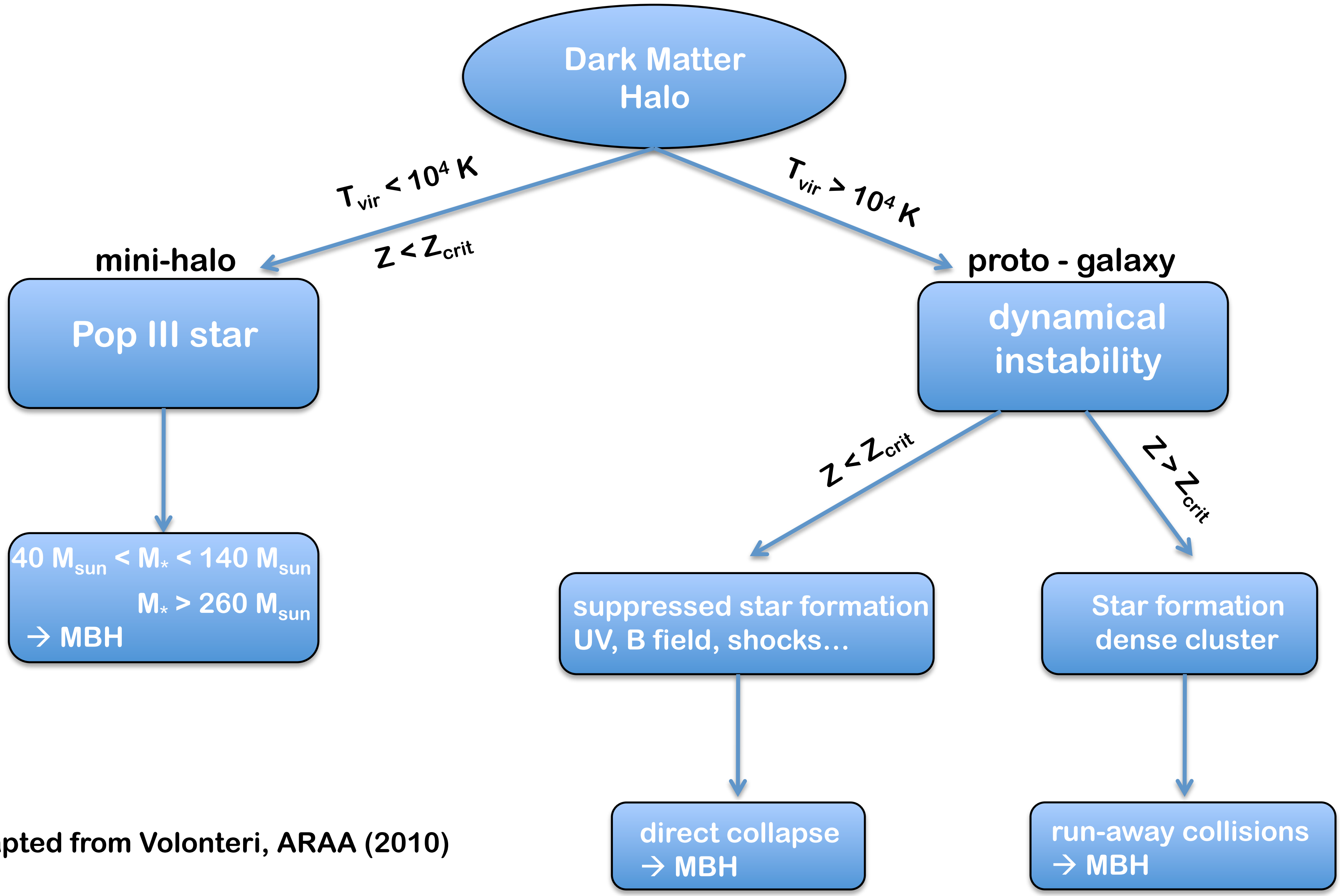
Dopcke et al. (2011)

Tsuribe & Omukai (2006), Clark et al. (2008), Omukai et al. (2010)

$M_{BH} \sim 10^2 - 10^3\ M_{sun}$ @ z =10

Omukai, RS, Haiman (2008),
Devecchi & Volonteri (2009),
Devecchi et al. (2010), Devecchi et al. (2012)
Oh & Haiman (2002), Bromm & Loeb (2003),

nature of BH seeds

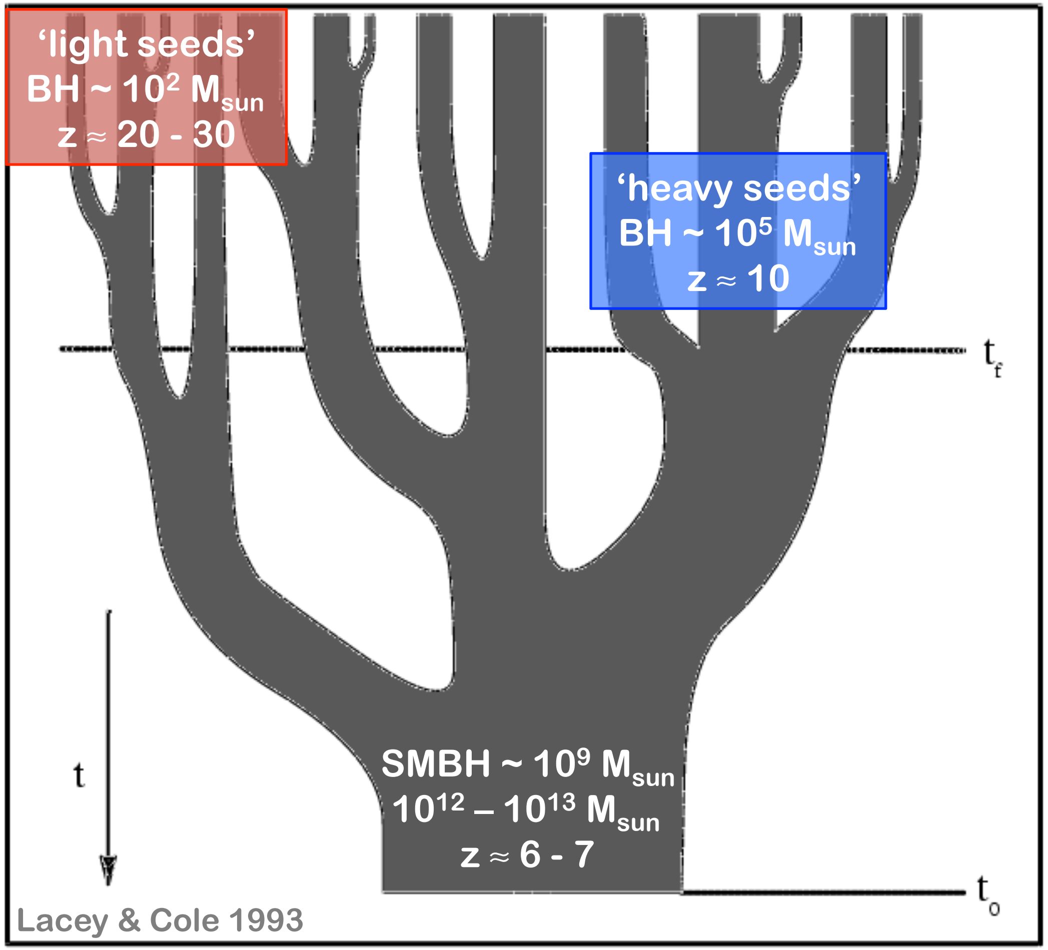


adapted from Volonteri, ARAA (2010)

From the first BHs to the first QSOs: planting and growing seeds

growth by
gas accretion

limited by feedback

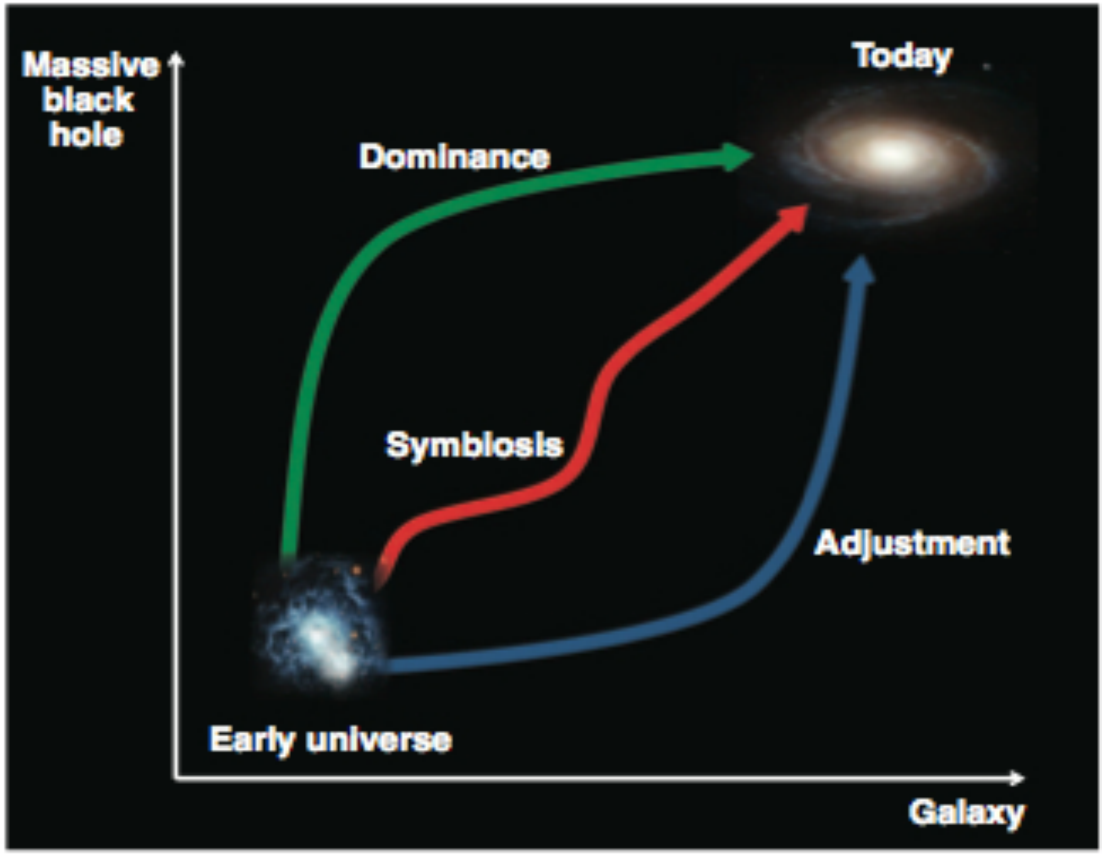


growth by
BH-BH mergers

limited by gravitatioal recoil

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

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



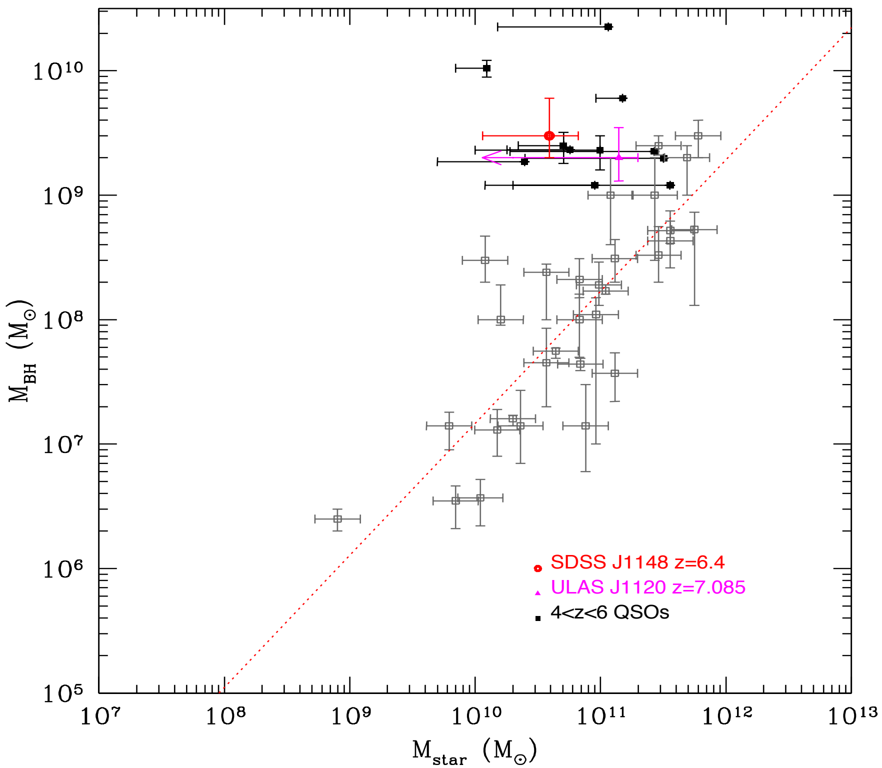
Volonteri 2012

different pathways reflect BH seeds birth and growth conditions

Co-evolution of the first BH and galaxies: footprints in the M_{bh} – M_{bulge} relation at early times ?

in AGN-selected samples M_{bh}/M_{bulge} evolves to larger values at higher z

Walter et al. 2004; Peng et al. 2006; McLure et al. 2006; Riechers et al. 2008; Merloni et al. 2010; Wang et al. 2010



Valiante et al. in prep

$M_{bulge} = M_{dyn} – M_{gas}$

$M_{dyn} = 2.3 \times 10^5 \, v_{circ}^2 \, R$

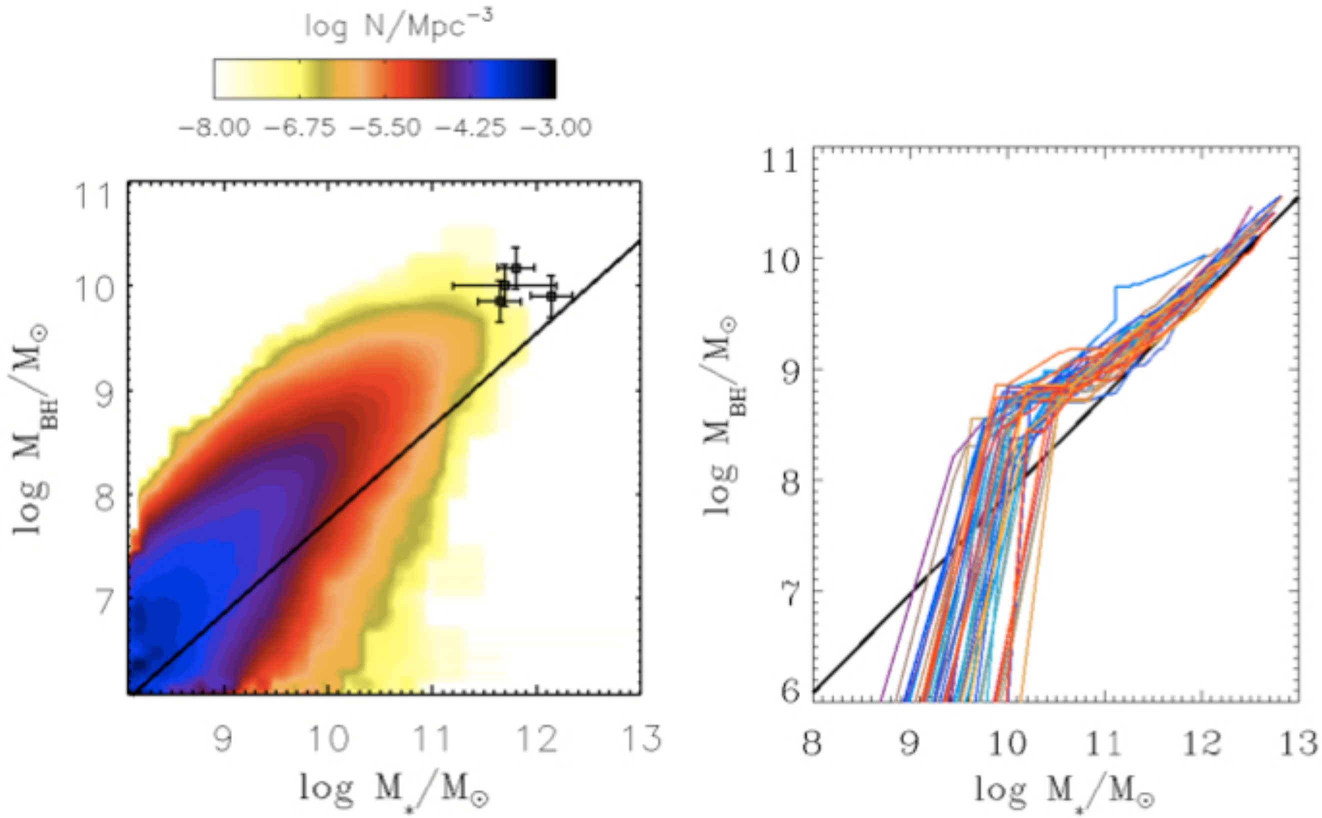
$M_{gas} = M_{H2} \leftarrow L_{CO}$

$v_{circ} = ¾$ CO FWHM / sin i

$<i> = 40°$ $<R> = 2.5$ kpc

Co-evolution of the first BH and galaxies: footprints in the $M_{bh} – M_{bulge}$ relation at early times ?

BH dominance: rapid growth at early times due to efficient accretion triggered by galaxy mergers

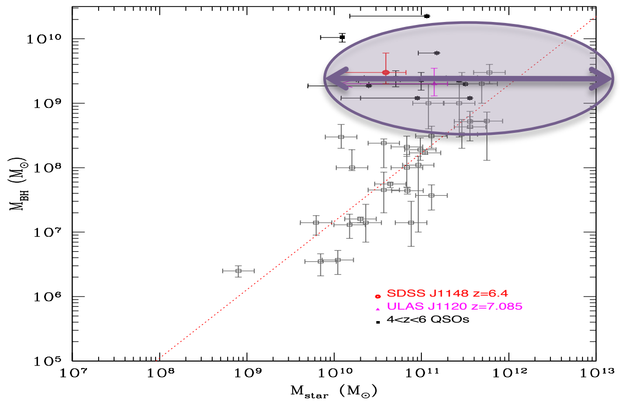


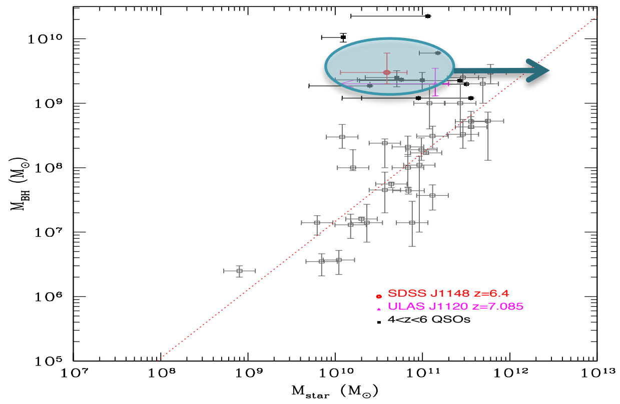
Lamastra et al. 2010

Is the observed off-set of z ~ 6 QSOs in the M_{bh} – M_{bulge} relation real?

Selection effects may be very important:

- scatter in the M_{bh} – M_{bulge} relation + steep mass function → z ~ 6 QSOs preferentially selected in low-mass hosts than what would be in a volume-limited sample (Lauer et al. 2007, Volonteri & Stark 2011)
- galaxy samples selecting starbursts without luminous AGN show a negative M_{bh}/M_{bulge} evolution (Alexander et al. 2008)
- high-z QSOs are preferentially viewed face-on (Ho et al. 2007)
- high-z QSOs observations probe only a smaller (inner) fraction of the host mass (Haiman 2012)



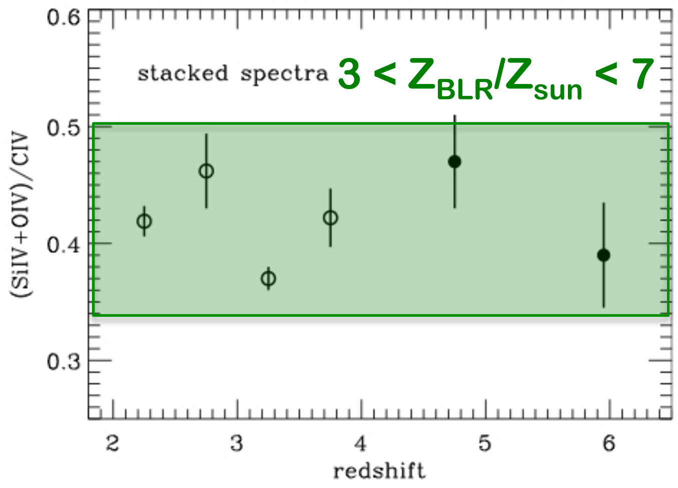


Clues from the chemical properties of the host galaxies

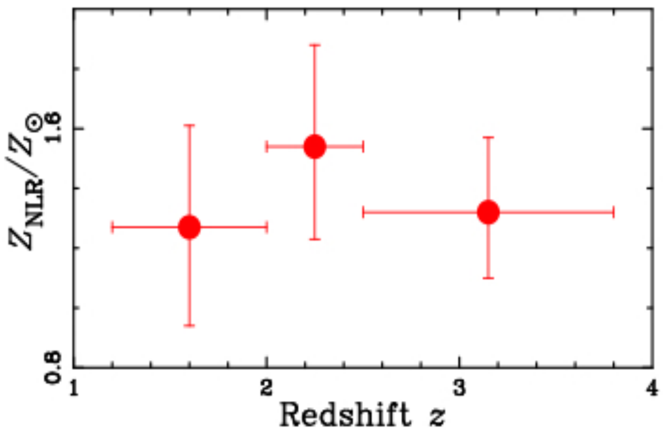
high-z QSOs host galaxies are chemically mature systems:

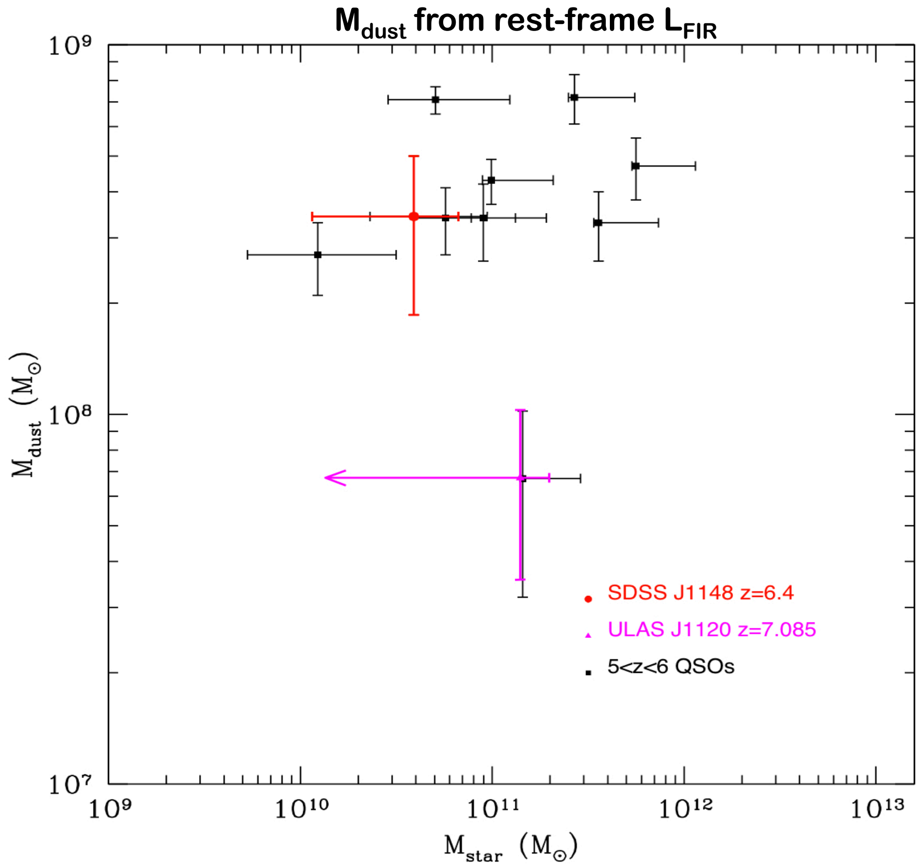
super solar metallicities in BLR/NLRs and $M_{dust} \sim 10^8\ M_{sun}$

BLRs Nagao+2006, Juarez+2009



NLRs Matsuoka+2009





Valiante et al. in prep

GAlaxyMErgerTree&Evolution

Salvadori, RS, Ferrara (2007)

with BH evolution/feedback and dust formation/processing in the ISM

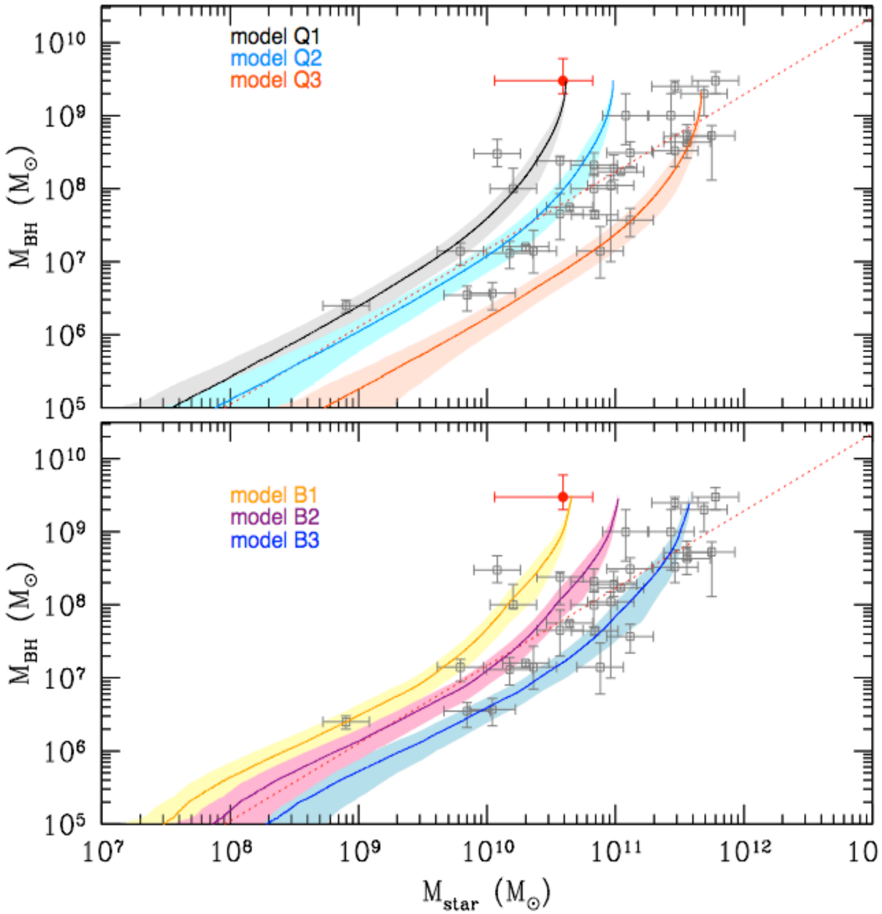
Valiante, RS, Salvadori & Bianchi (2011, 2012)

- 50 merger histories of a 10^{13} M_{sun} halo @ z =6.4 → SDSS J1148
- star formation in quiescent and/or merger-driven bursts
- BH growth via gas accretion and mergers
- BH feedback
- chemical enrichment (metals and dust) on the stellar characteristic timescales

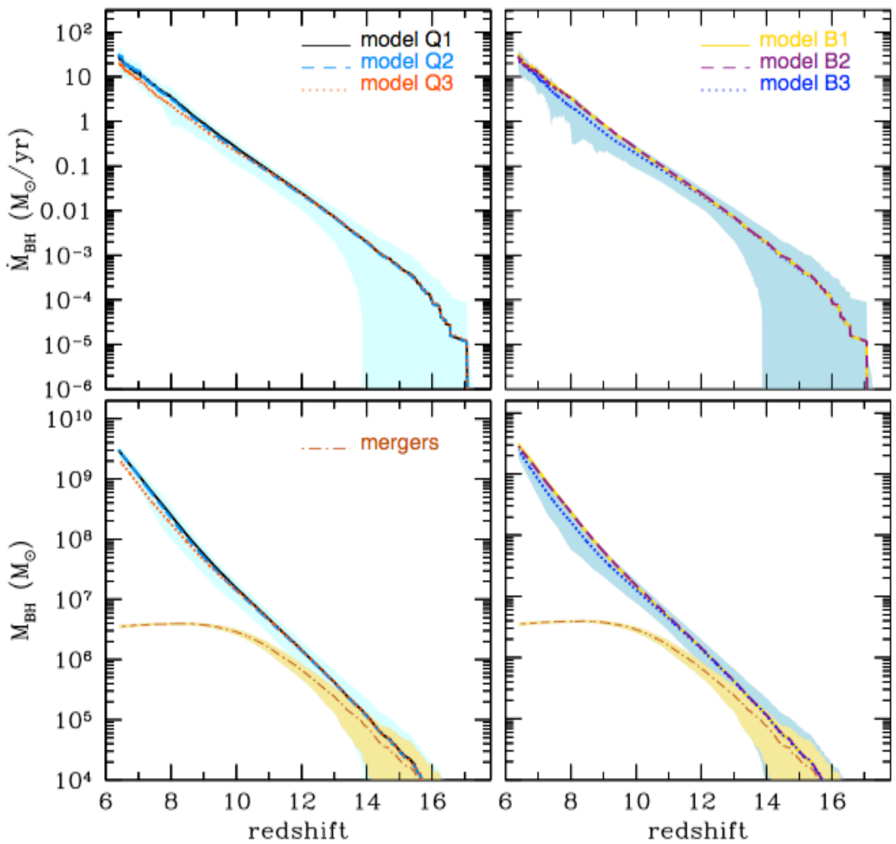
Evolution of high-z QSOs: SDSS J1148

Valiante et al (2011, 2012)

SDSS J1148: testing different evolutionary paths



Evolution of the nuclear black hole mass & accretion rate

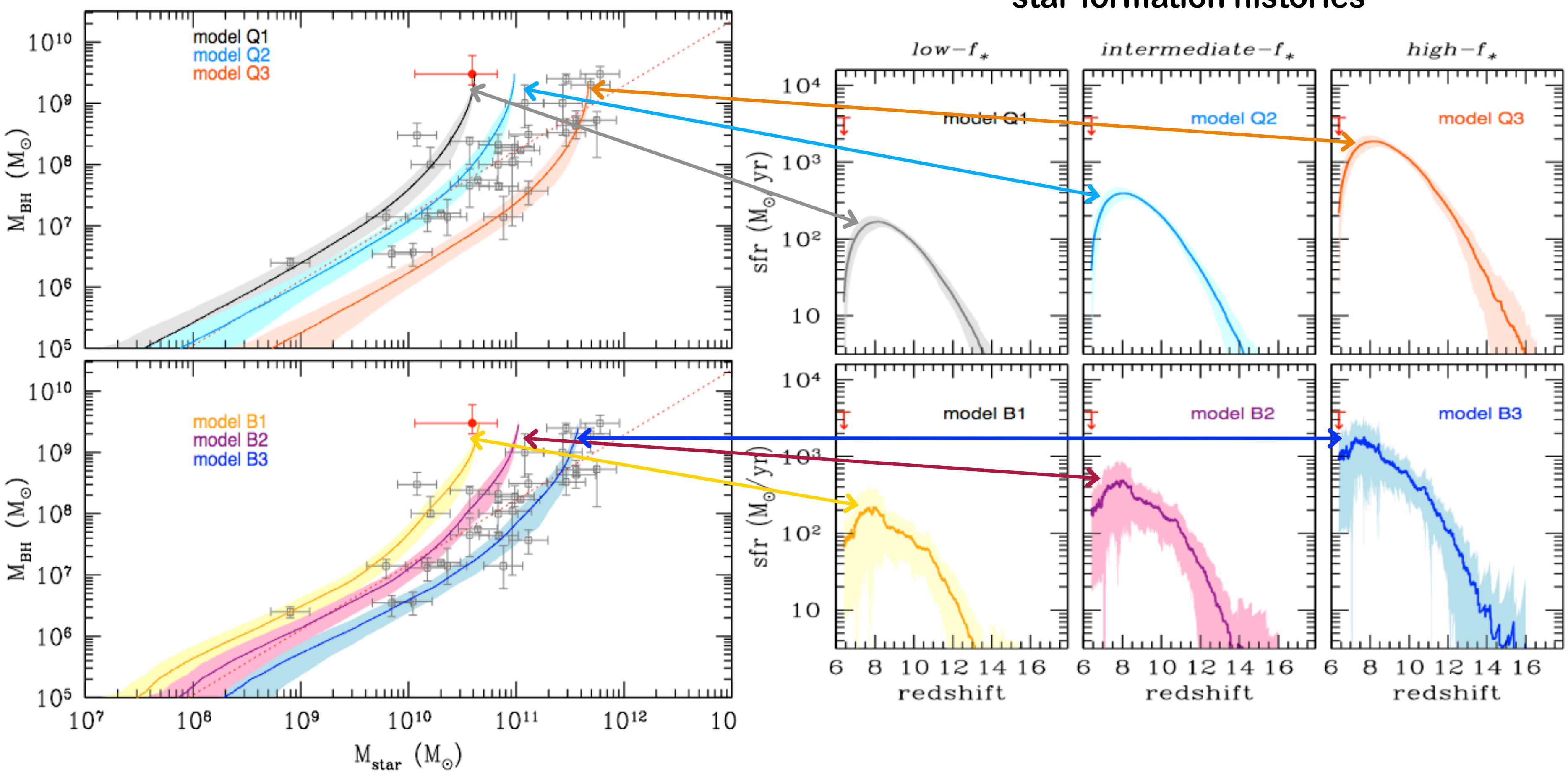


Evolution of high-z QSOs: SDSS J1148

Valiante et al (2011, 2012)

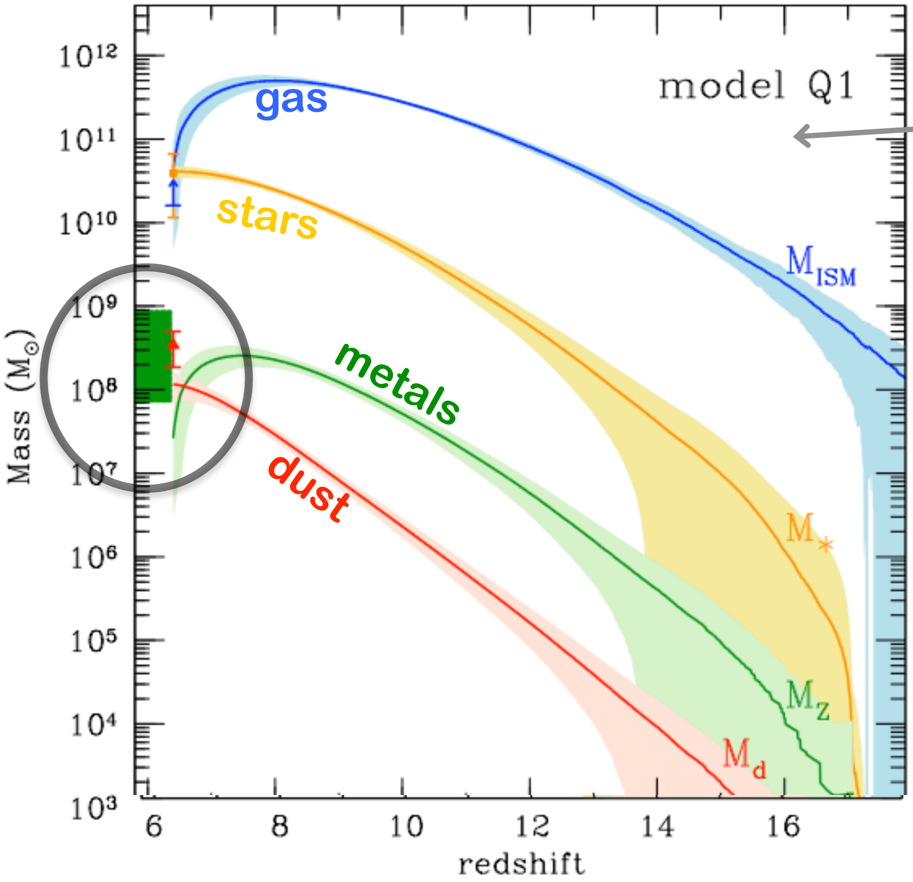
SDSS J1148: testing different evolutionary paths

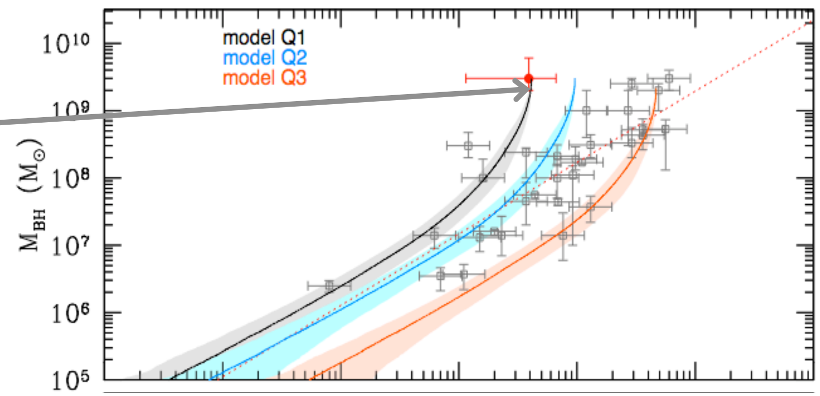
star formation histories



chemical evolution of SDSS J1148 host

Valiante et al. (2011, 2012)

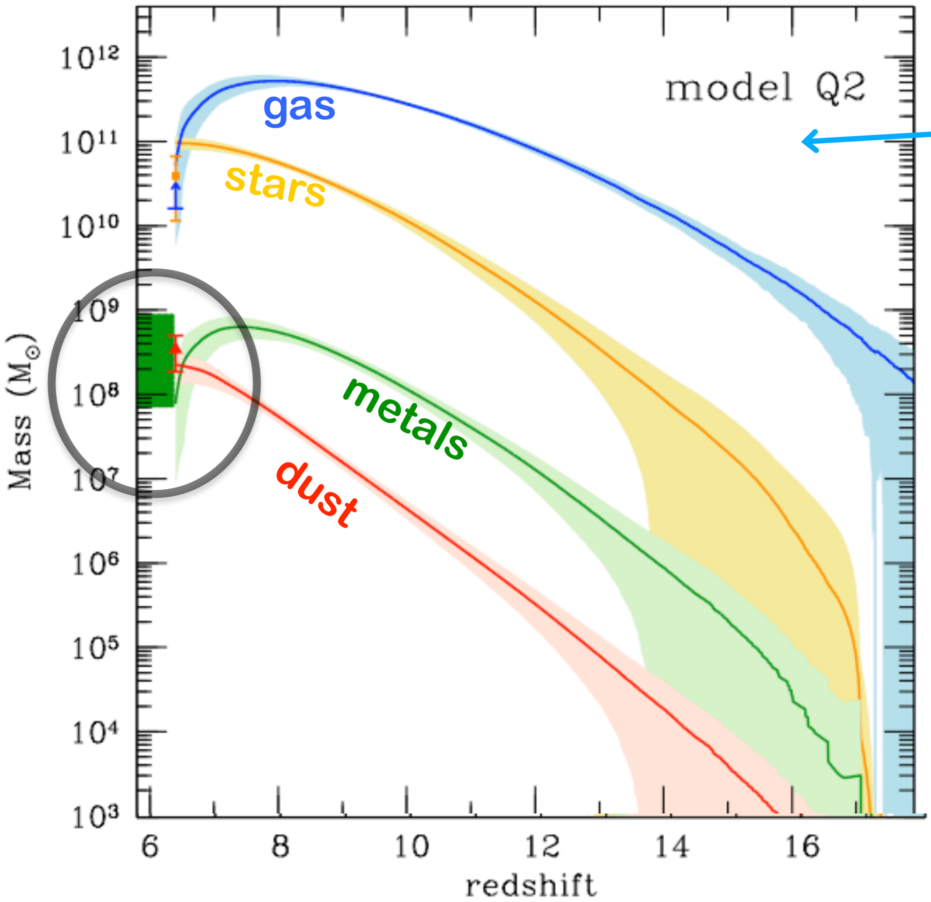


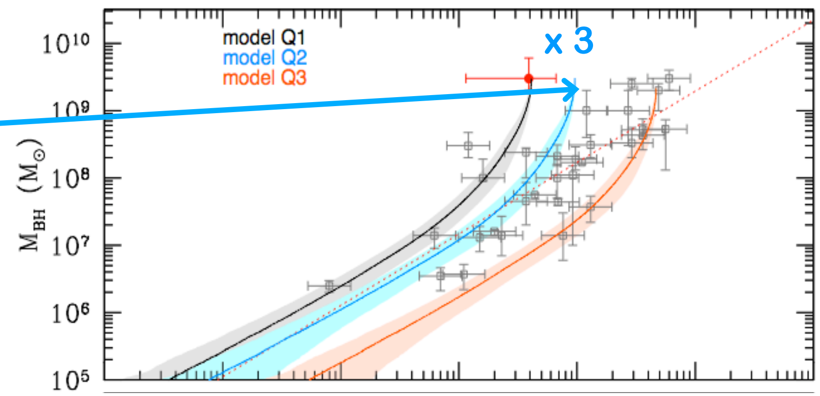


metals and dust are <u>underpredicted</u> by models which reproduce z ~ 6 M_{bh}-M_{star}

chemical evolution of SDSS J1148 host

Valiante et al. (2011, 2012)



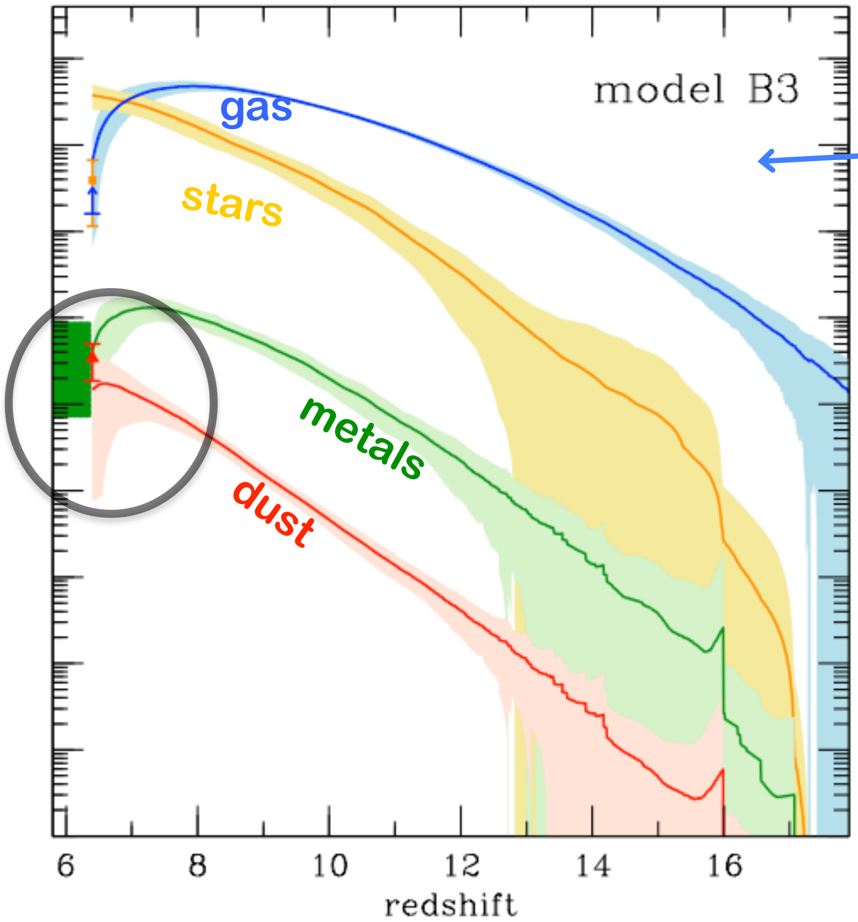


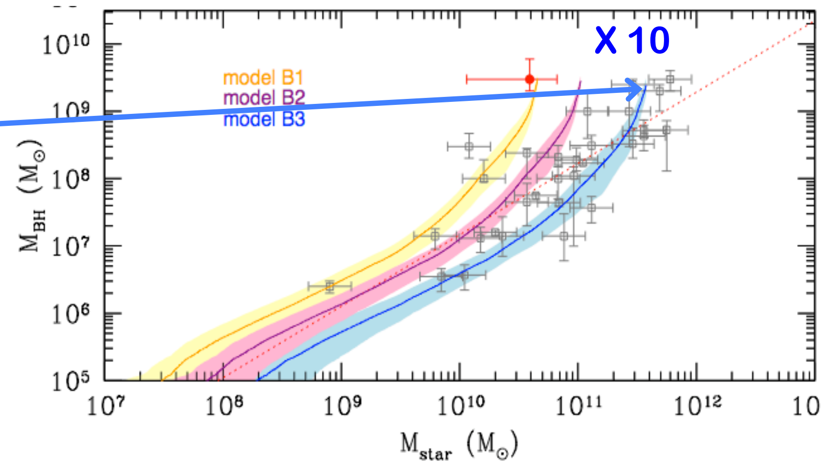
metals and dust are reproduced if M_{star} is a factor 3 – 10 larger:

→ M_{bh}-M_{star} consistent with the local correlation

chemical evolution of SDSS J1148 host

Valiante et al. (2011, 2012)





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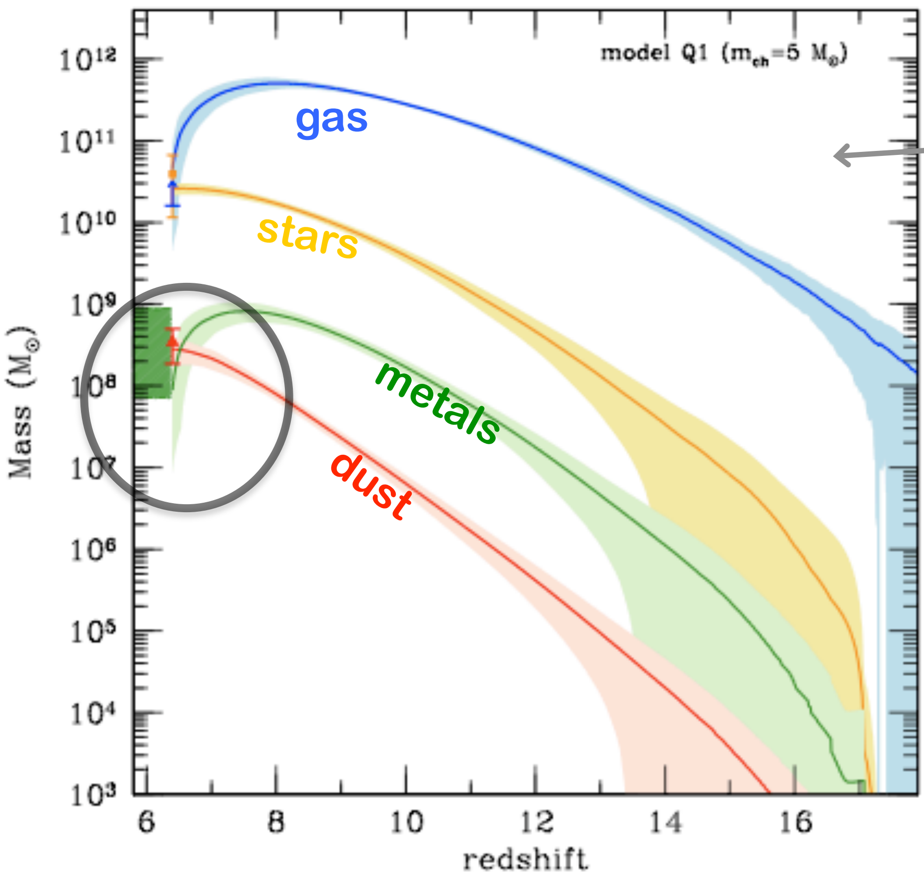

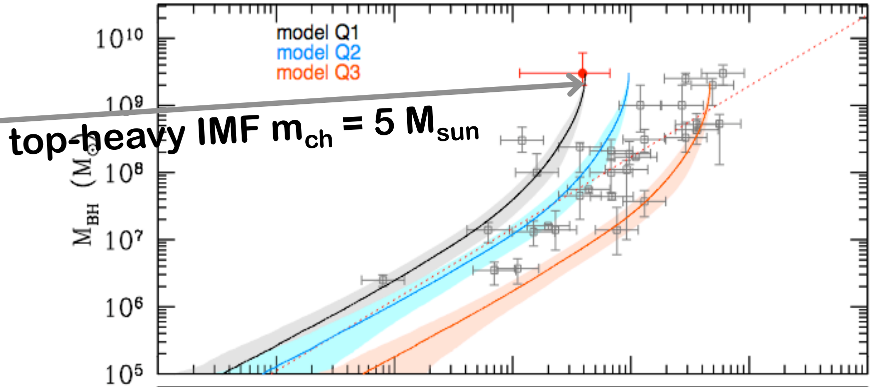

chemical properties can be reconciled with z ~ 6 M_{bh}-M_{star} for a top-heavy IMF

Summary

- The nature of BH seeds: Pop III remnants are likely to be too “light”…
  direct collapse scenarios lead to “heavy” seeds but require peculiar environmental conditions

- From the first BHs to the first QSOs: still hard to model accounting for BH dynamics and various radiative and chemical feedback effects

- Tension between the observed mass function of SMBHs @ $z = 6$ and upper limits on the accreted mass density at $z > 5$ from the unresolved CXRB?
  Tension between the observed mass density @ $z = 6$ and the positive evolution of the locally observed $M_{bh} – M_{star}$ correlation?

- Co-evolution of the first BH and galaxies: dominance, symbosis or adjustment?
  Still hard to answer. Selection effects might influence the inferred correlation at $z = 6$

- Chemical properties of $z \sim 6$ QSOs host galaxies can give important constraints on evolutionary scenarios and on the nature and properties of the stars that dominate the evolution