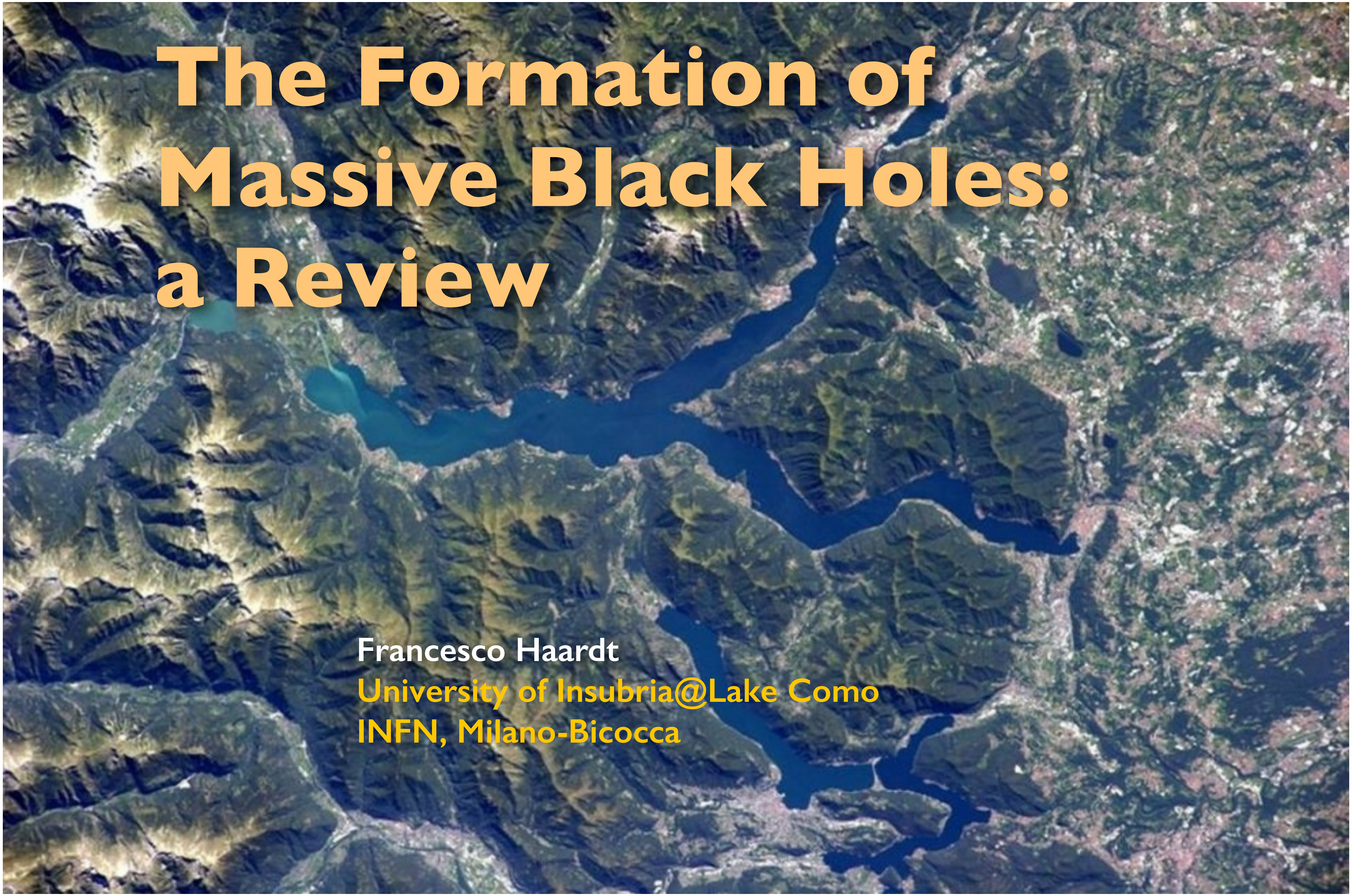


The Formation of Massive Black Holes: a Review

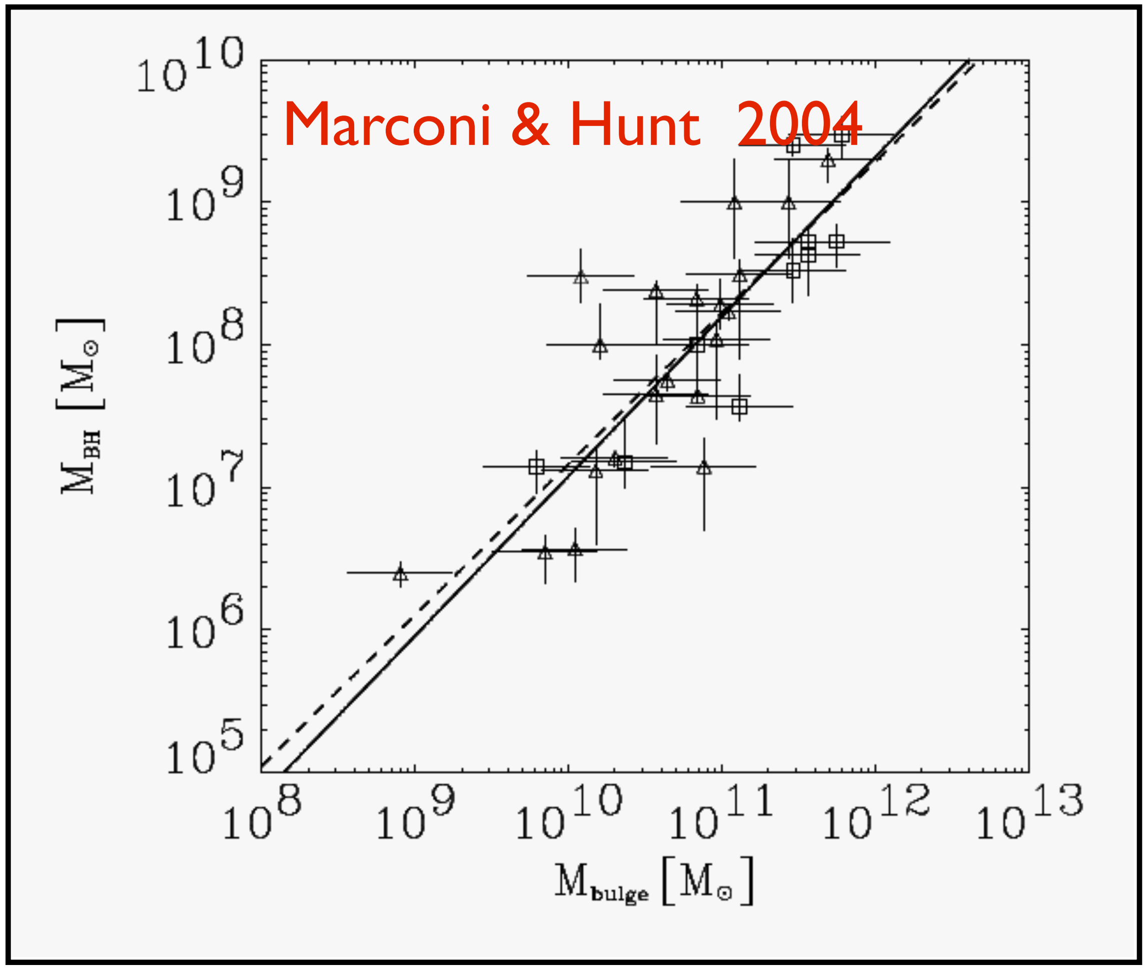
Francesco Haardt
University of Insubria@Lake Como
INFN, Milano-Bicocca

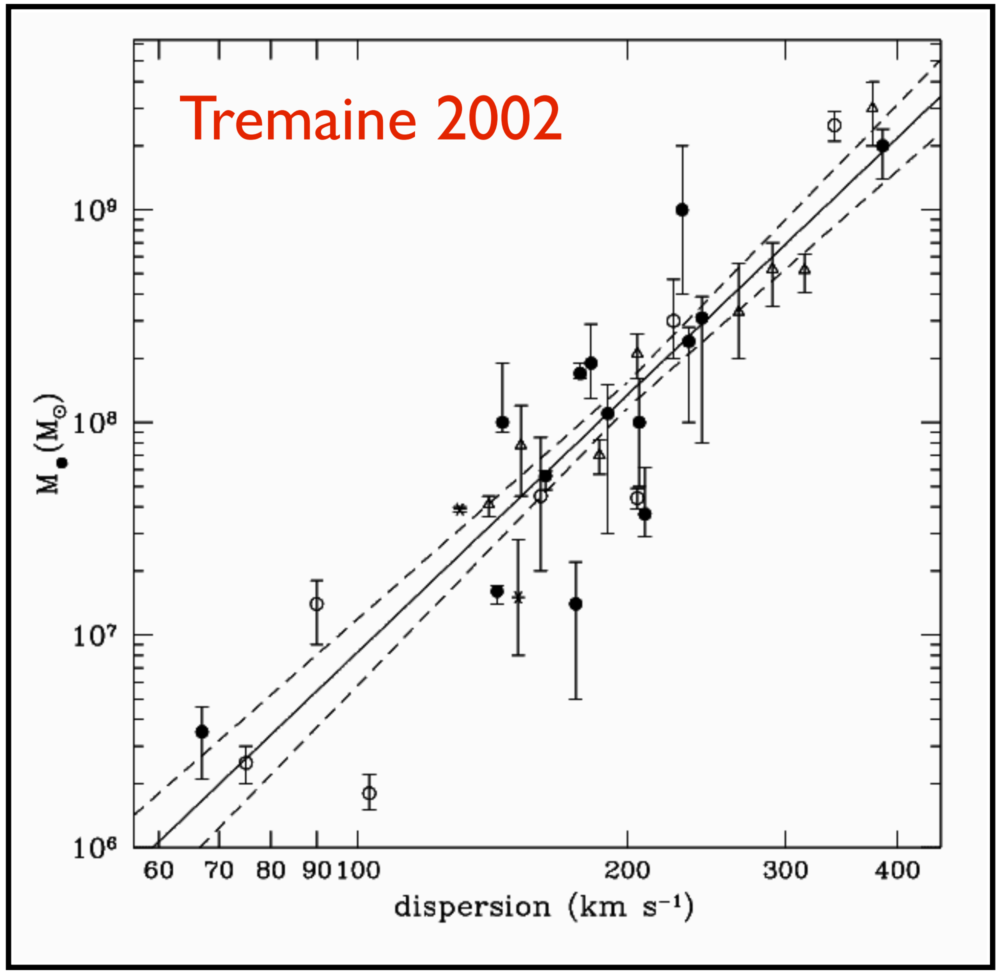
Understanding the formation and growth of MBHs along the Cosmic history.

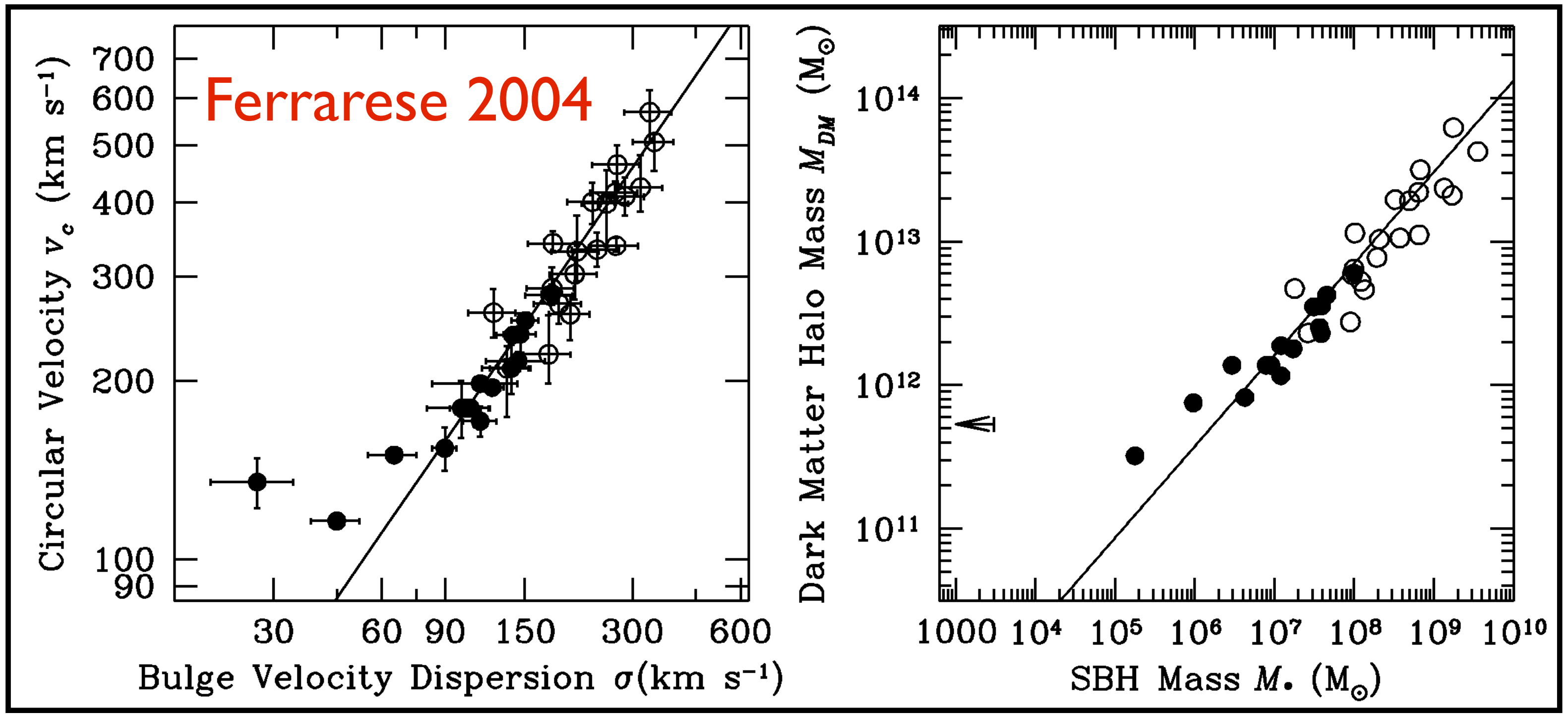
1. How fast can MBHs grow to 10^9-10^{10} $M_\odot$?
2. How many of them along the Cosmic history?

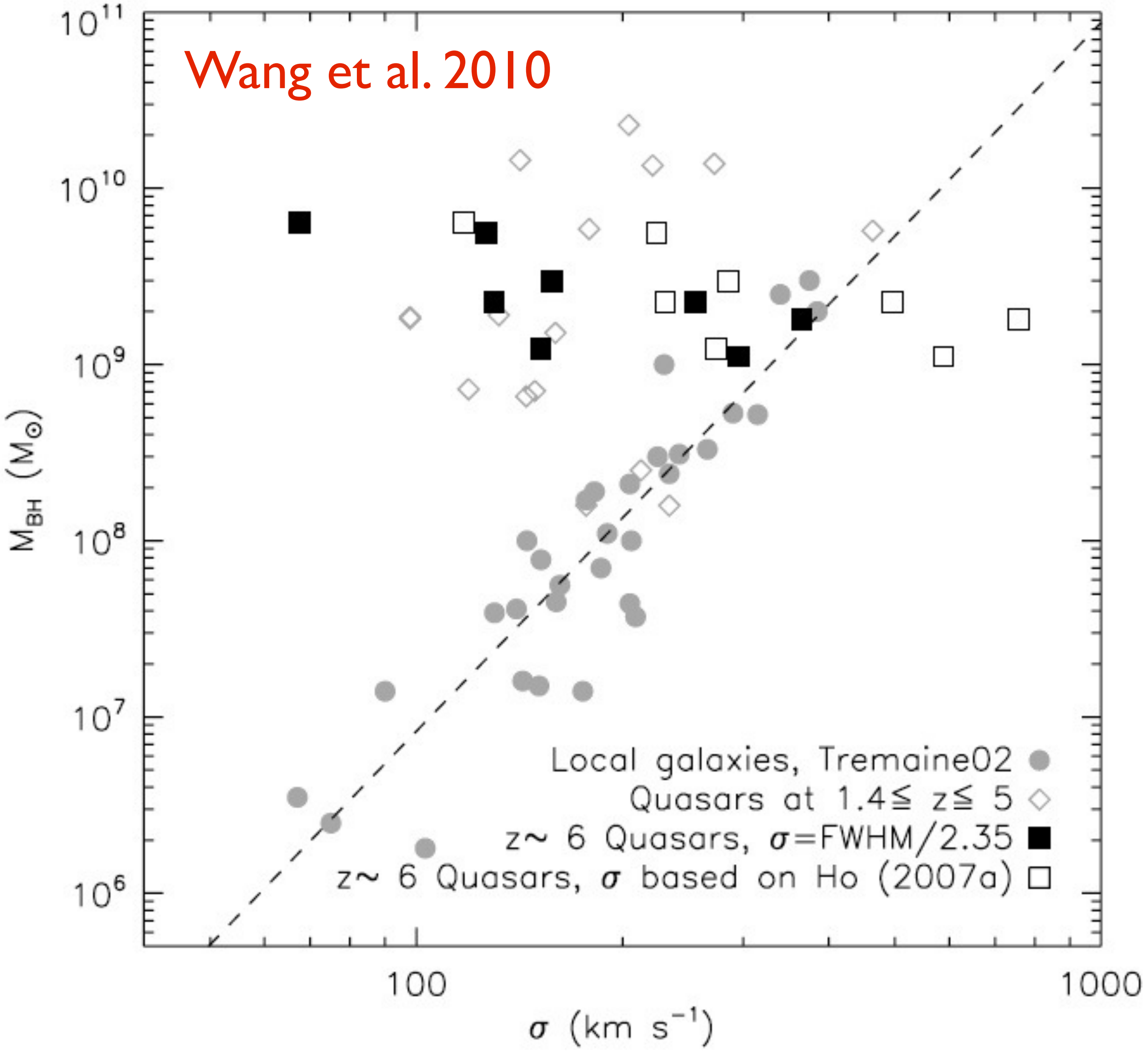
We need to understand the physics of black hole *and* galaxy mergers.

LOCAL SCALING RELATIONS


Marconi & Hunt 2004


Tremaine 2002

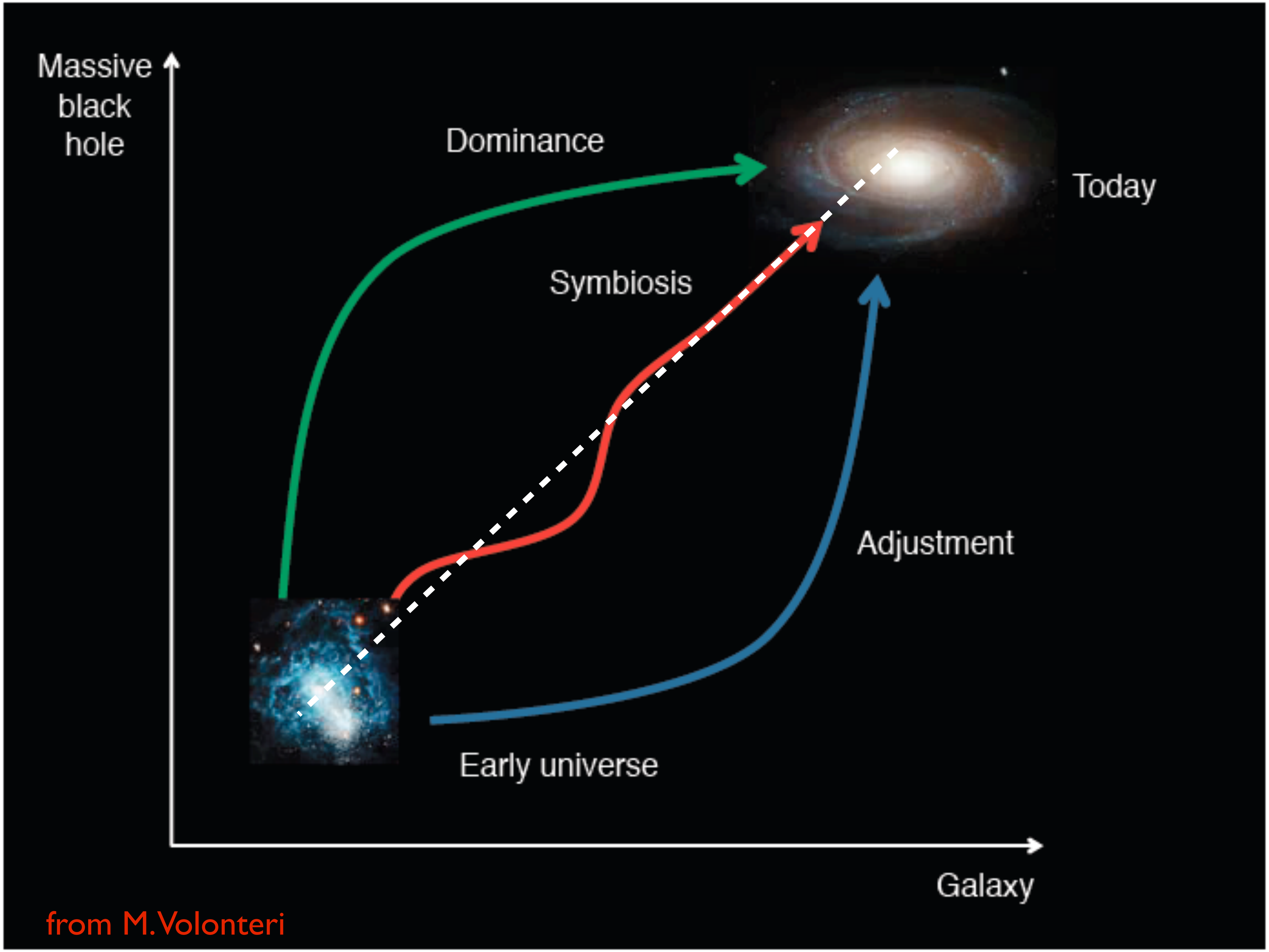

Ferrarese 2004



1. There seems to be little or no correlation between mass and velocity dispersion (Wang et al. 2010).

2. Typically black holes are ‘over massive’ at fixed mass/velocity dispersion compared to z=0 counterparts (e.g. Walter et al 2004; Decarli et al. 2010; Merloni 2010).

3. Studies suggest that either many massive galaxies do not have MBHs or these BH are less massive than expected (Willott et al. 2010).

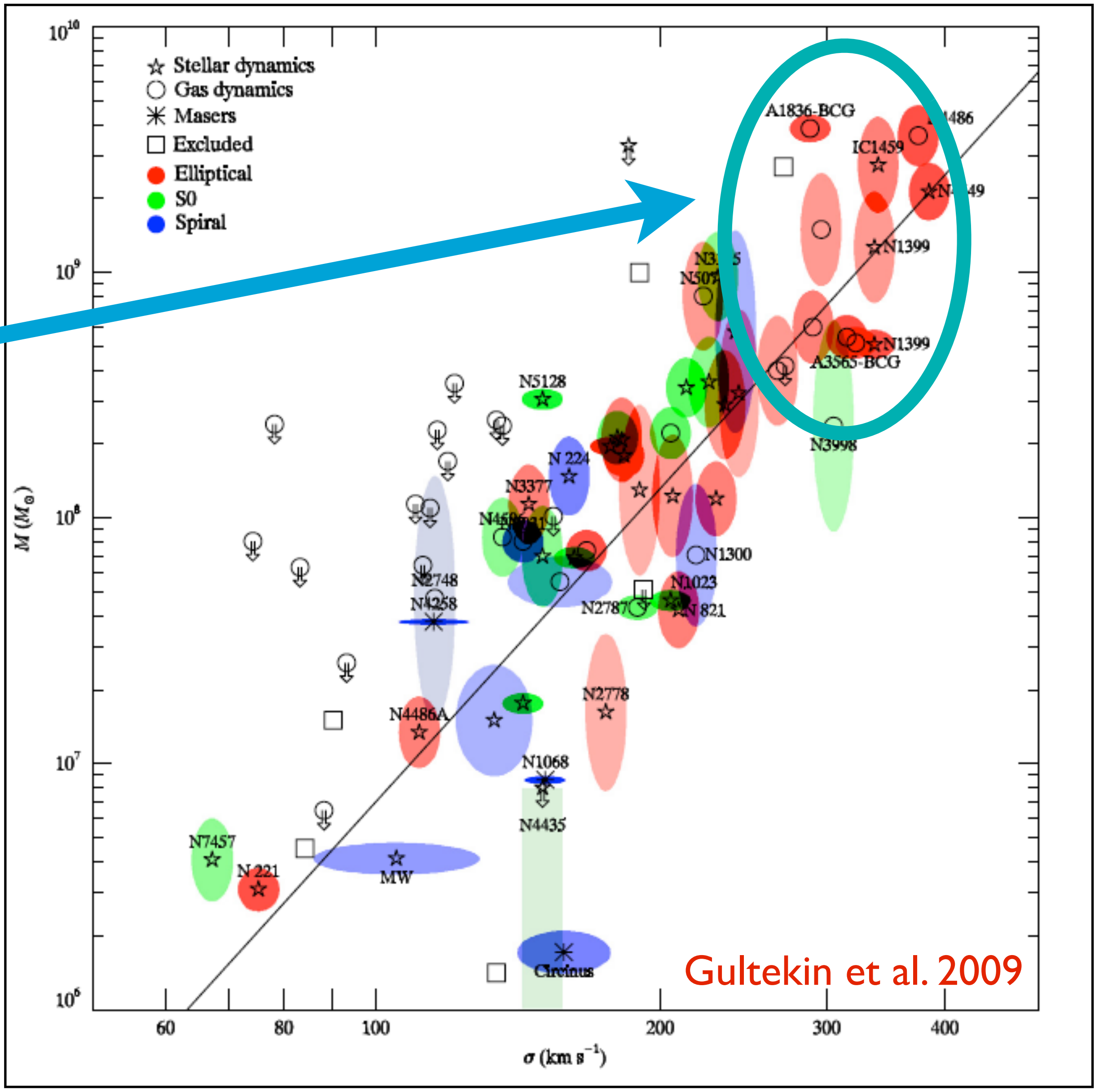


from M.Volonteri

When do you make the first SMBHs?

The QSO ULASJI 12010641
at z=7.1 has an estimated SMBH mass
$M_{BH} \sim 2 \times 10^9 \, M_\odot$ (Mortlock et al. 2011)

As massive as the largest SMBHs today, but when the Universe was only 0.75 Gyrs old



Gultekin et al. 2009

Accretion time needed by a BH to reach a given final mass:

$$M(t) = M_0 \, \mathrm{e}^{f_{\rm Edd} \frac{t}{\tau} \frac{1-\epsilon}{\epsilon}}$$

$$t_{\rm acc} = 0.45 \ {\rm Gyr} \, \frac{\epsilon}{1-\epsilon} \, f_{\rm Edd}^{-1} \, \ln(M_{\rm fin}/M_{\rm in})$$

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$M_{fin}=10^9\ M_\odot$

$M_{in}=10^2\ M_\odot$ ($10^5\ M_\odot$)

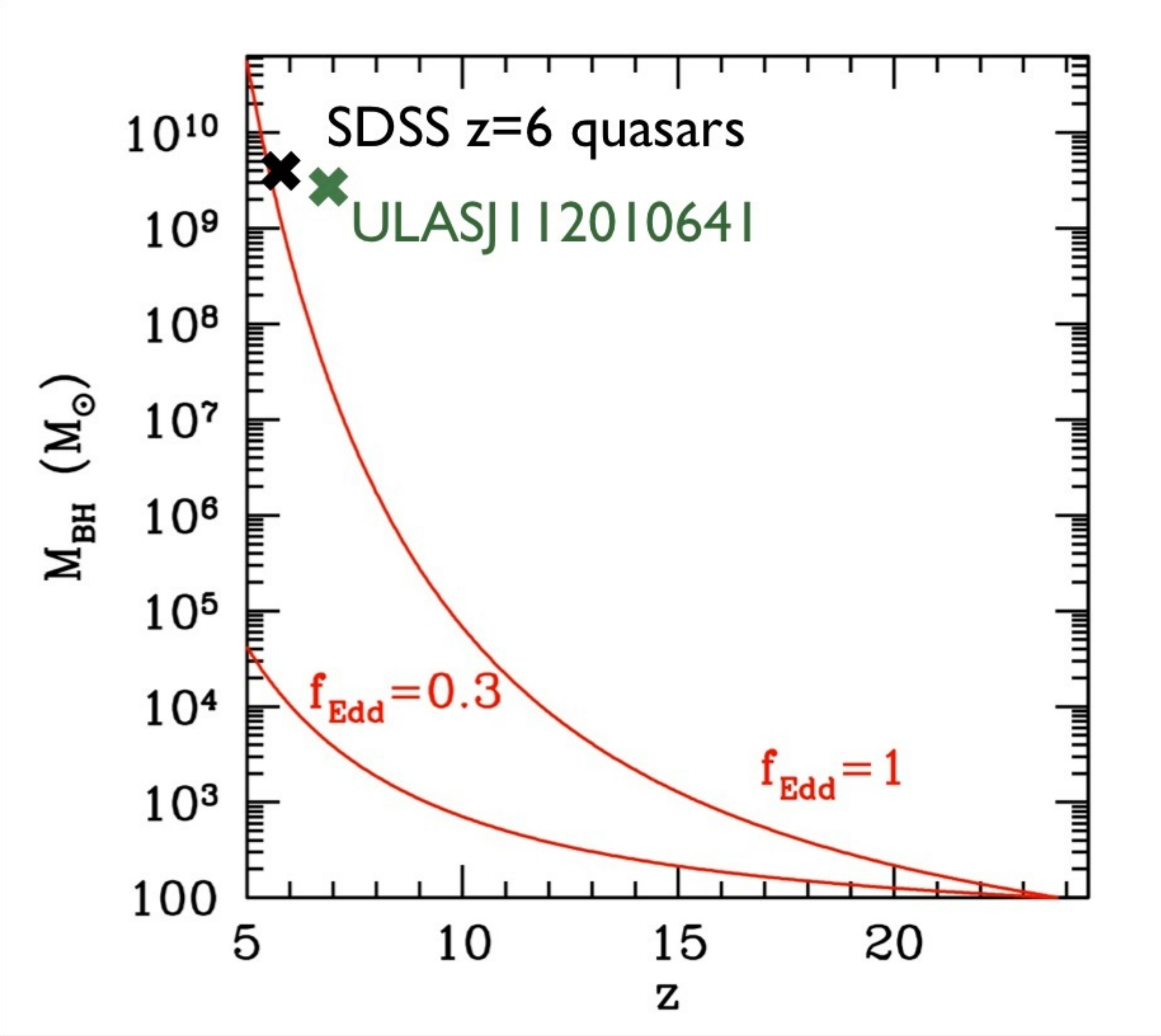
$f_{Edd}=1$

$\epsilon=0.1$

⇨ t_{acc}=0.8 Gyrs (0.45 Gyrs)

$t_H(z=7)$=0.75 Gyrs

$t_H(z=6)$=0.9 Gyrs



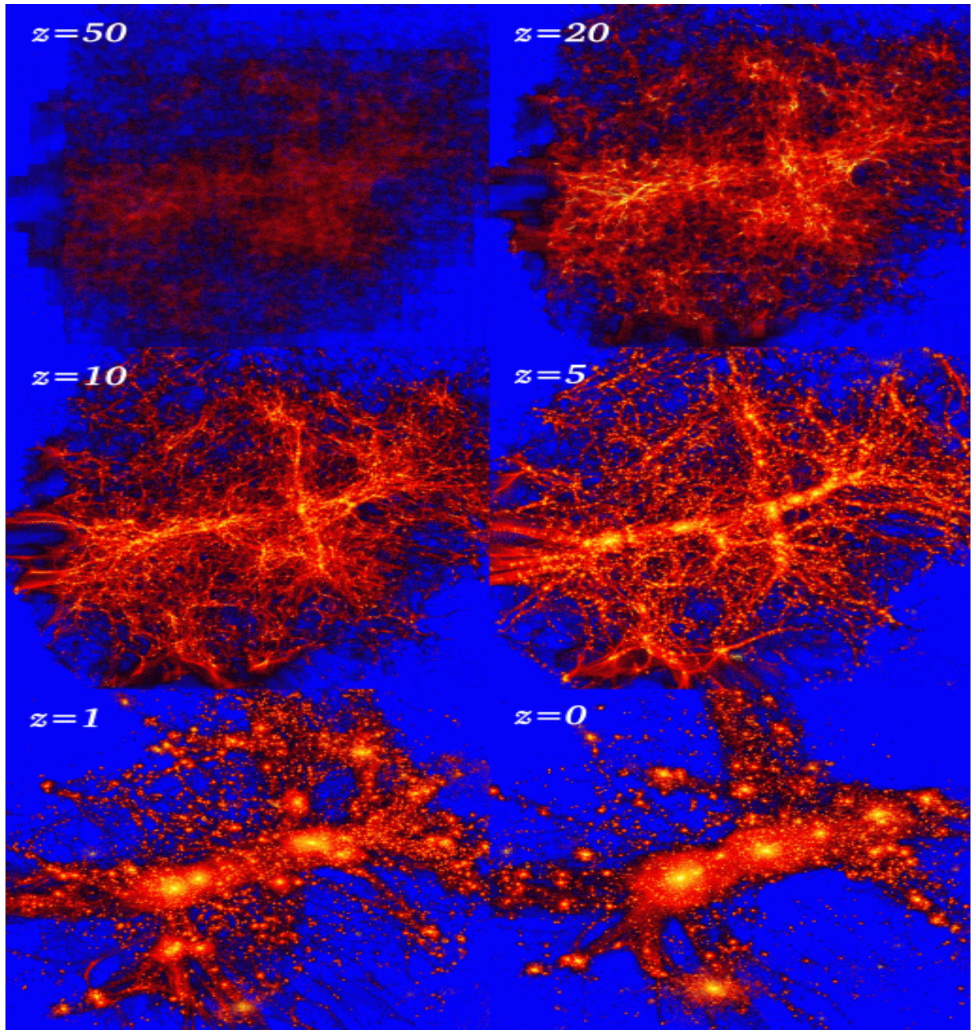
How do we make SMBH seeds?

DARK AGES

The fate of DM:

CDM: Small scales collapse first
BOTTOM-UP HIERARCHY

DM-HALOS COLLAPSE AS:
$M=10^{15}/(1+z)^{6}\ M_{\odot}$



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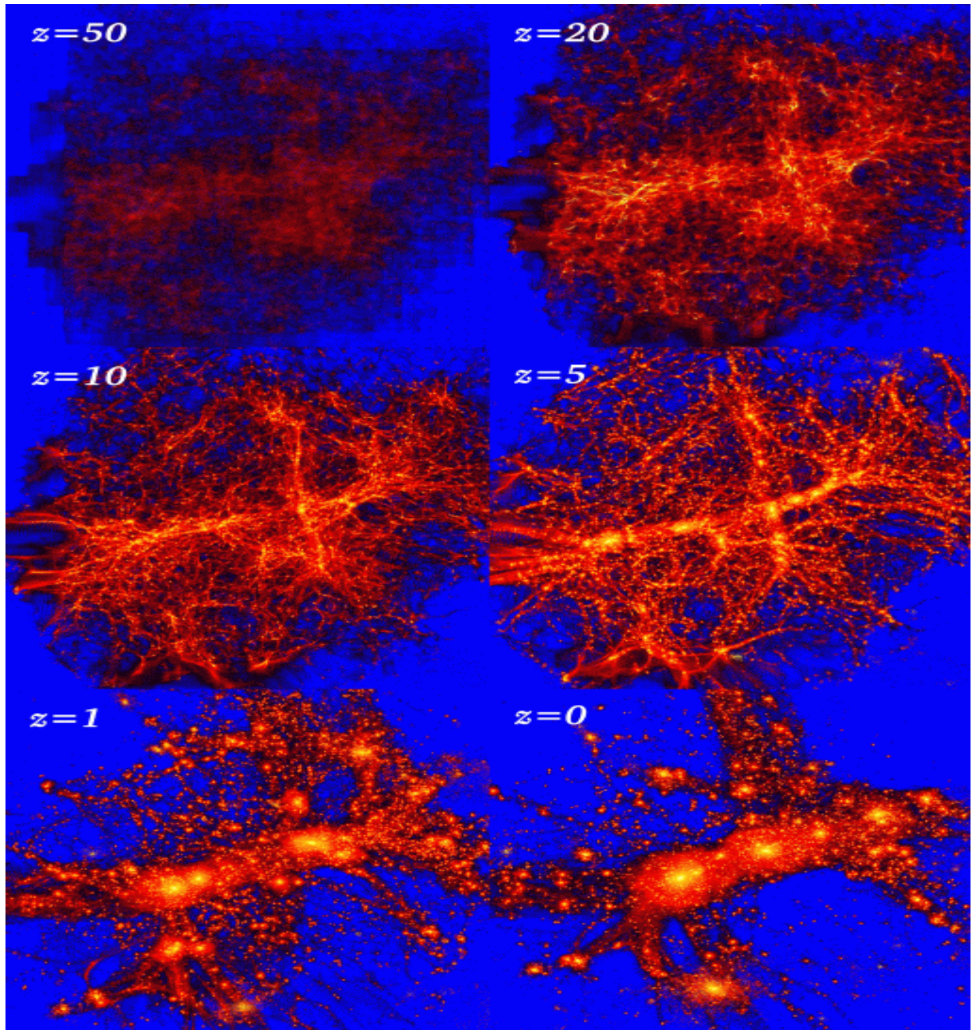


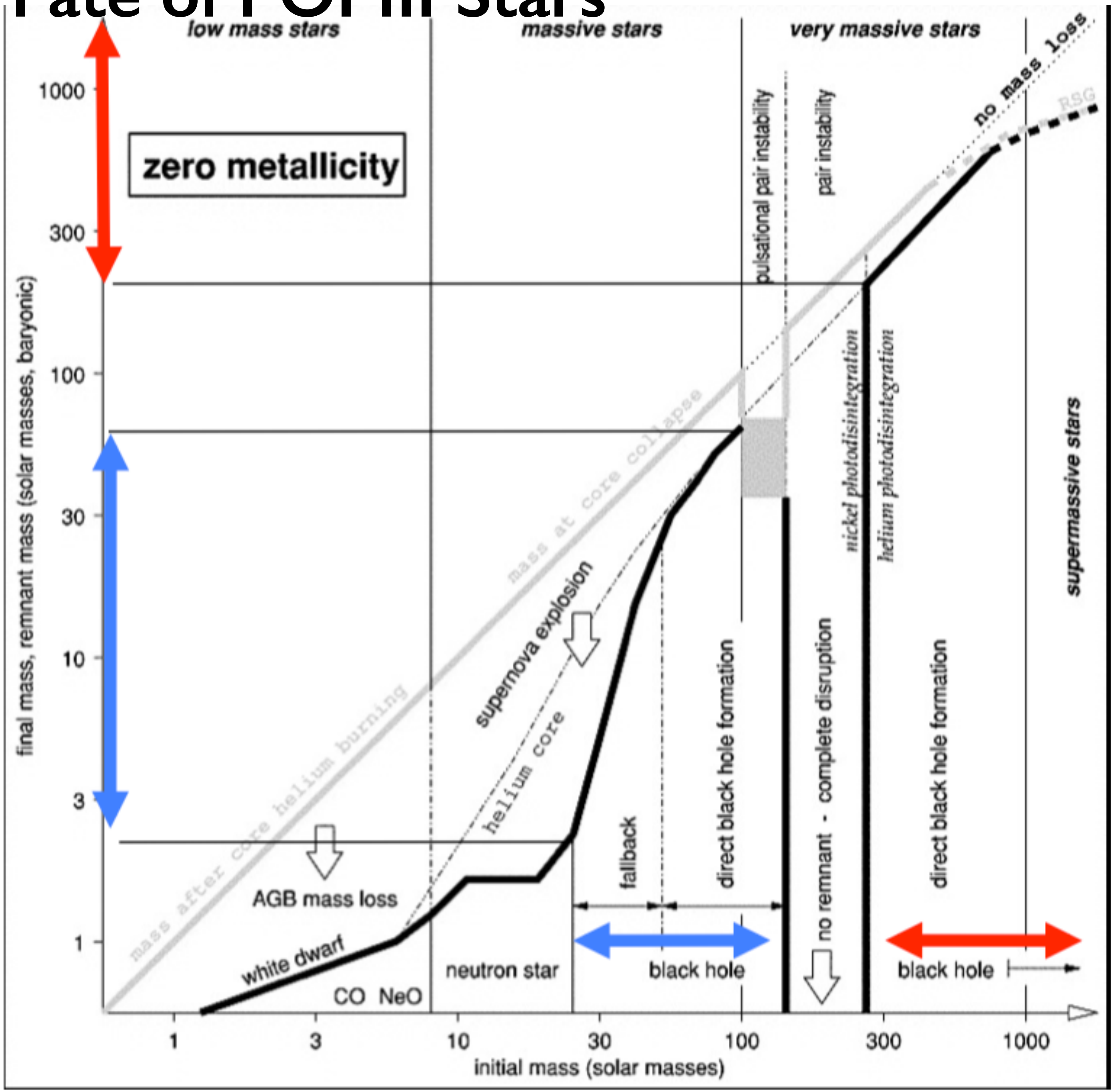
The fate of baryons:

At z≈130 baryons are free to fall into DM halos

COOLING TIME >> HUBBLE TIME ➜ ADIABATIC COLLAPSE
Baryons virialize as DM particles

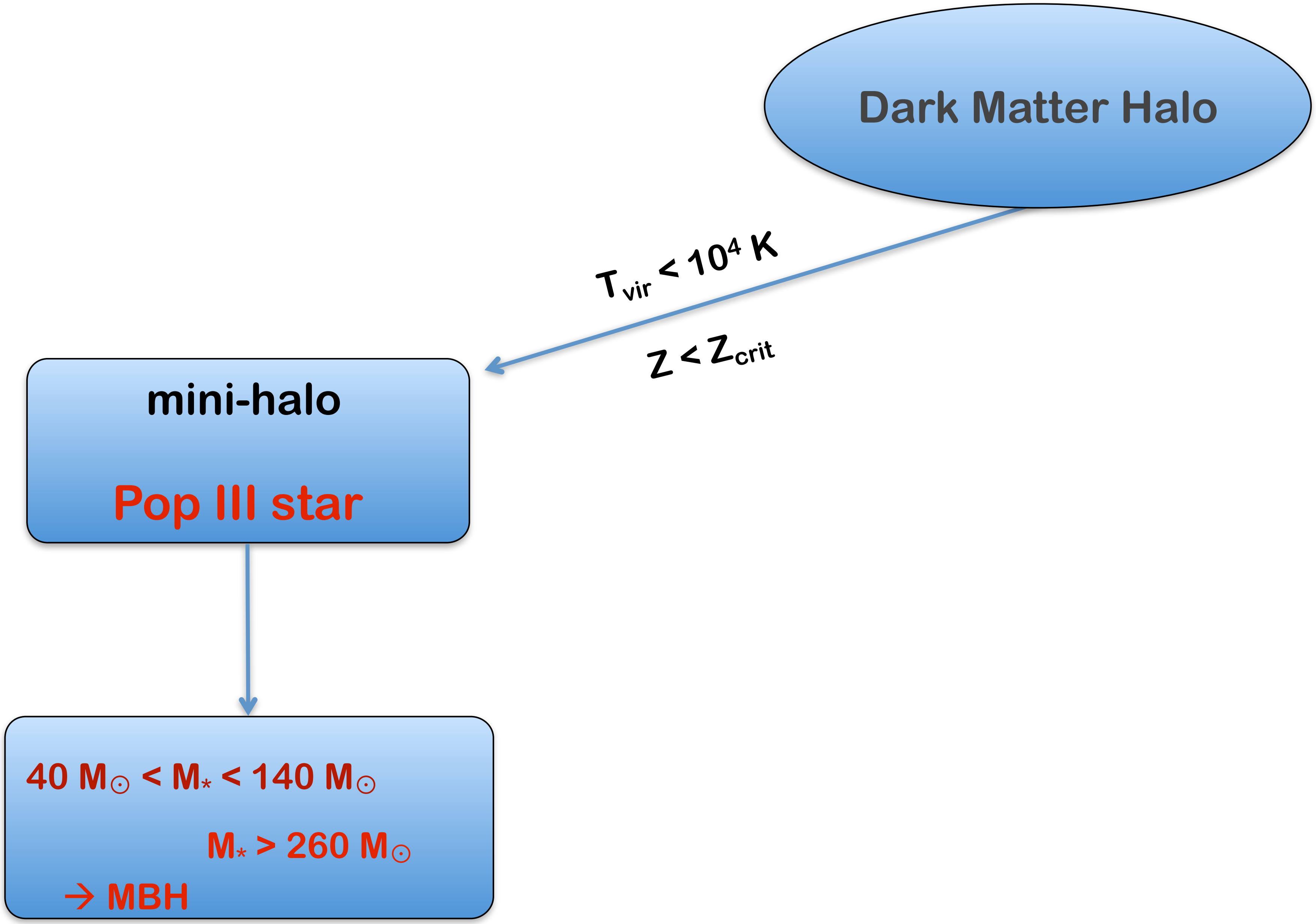
COOLING TIME << HUBBLE TIME ➜ ISOTHERMAL COLLAPSE
Baryons fall into DM potential wells ➜ Self-gravitating baryonic objects (POPIII)
➜ END OF THE DARK AGES (z≈25)

The Fate of POPIII Stars



Heger & Woosley 2002

The Nature of BH seeds



Dark Matter Halo

$T_{vir} < 10^4$ K

$Z < Z_{crit}$

mini-halo

Pop III star

$40\ M_\odot < M_* < 140\ M_\odot$

$M_* > 260\ M_\odot$

→ MBH

z≈20-30

M_{BH}~100-600 $M_\odot$

thanks to Raffaella Schneider

POPIII Stars

Hosokawa et al. 2011

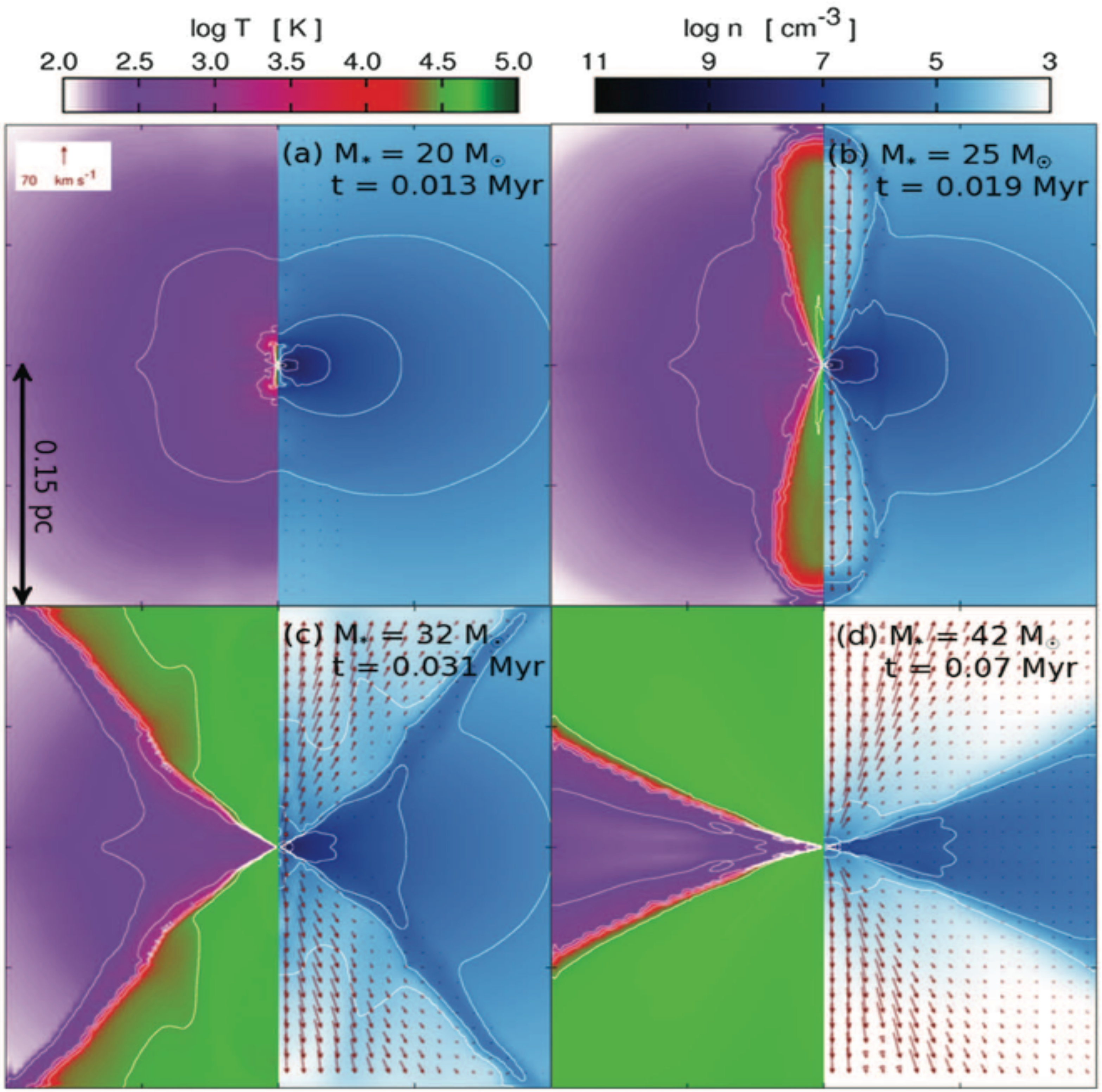


Fig. 2. UV radiative feedback from the primordial protostar. The spatial distributions of gas temperature (left), number density (right), and velocity (right, arrows) are presented in each panel for the central regions of the computational domain. The four panels show snapshots at times when the stellar mass is $M_* = 20\ M_\odot$ (**A**), $25\ M_\odot$ (**B**), $35\ M_\odot$ (**C**), and $42\ M_\odot$ (**D**). The elapsed time since the birth of the primordial protostar is labeled in each panel.

Protostar $M \sim 0.01 M_\odot$ surrounded by $1\ M_\odot$ molecular envelope.

Accretion of envelope. Further out molecular disk (~400 AU)

Accretion through the disk at $\sim 10^{-3}\ M_\odot/\mathrm{yr}$

Ionizing bipolar flux (disk self-shielded)

HII region breaks the accreting envelope

Bipolar outflows of gas

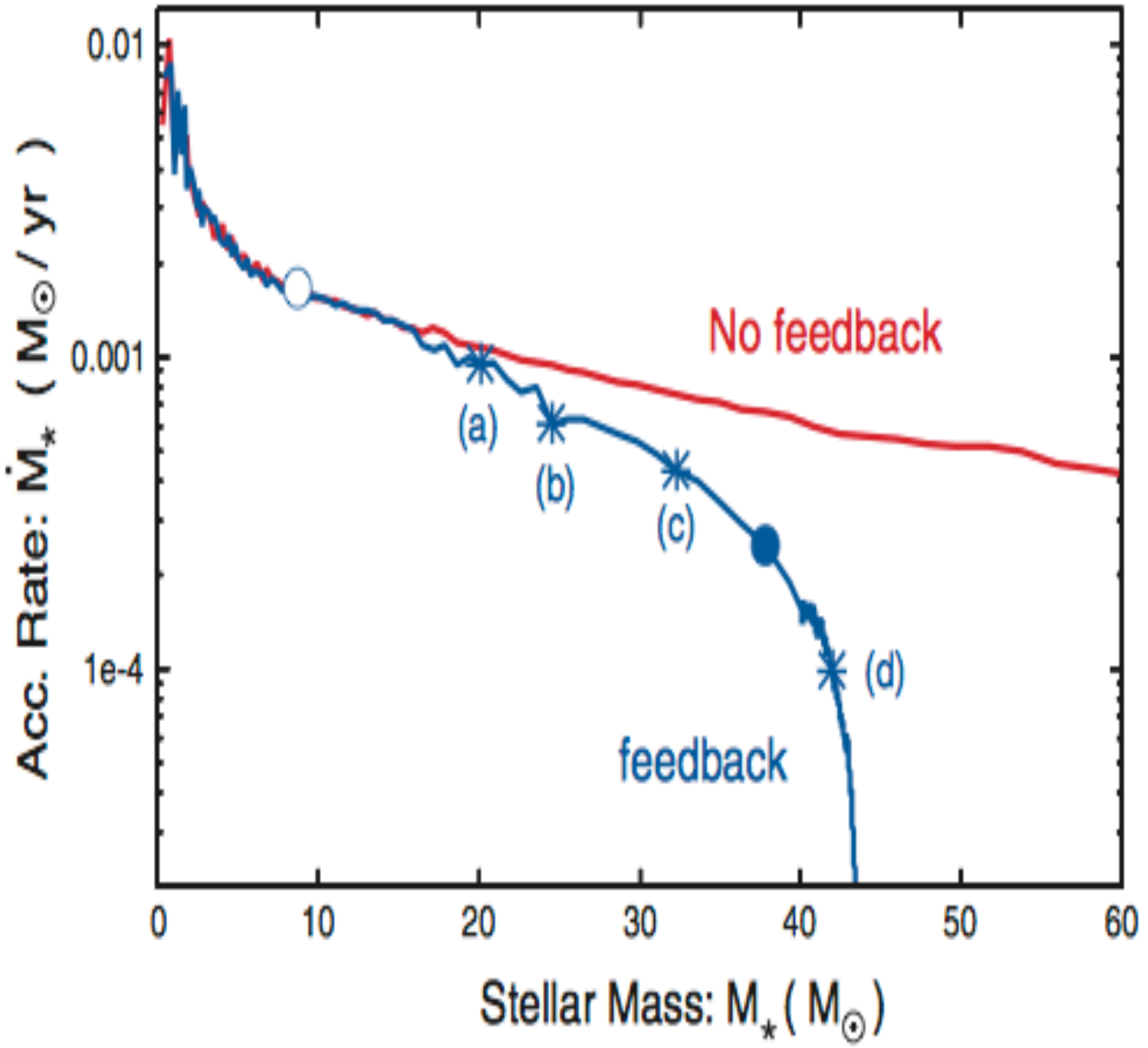
Shocks propagates into the envelope

Accretion rate falls down

Disk exposed to UV. Photoevaporation.

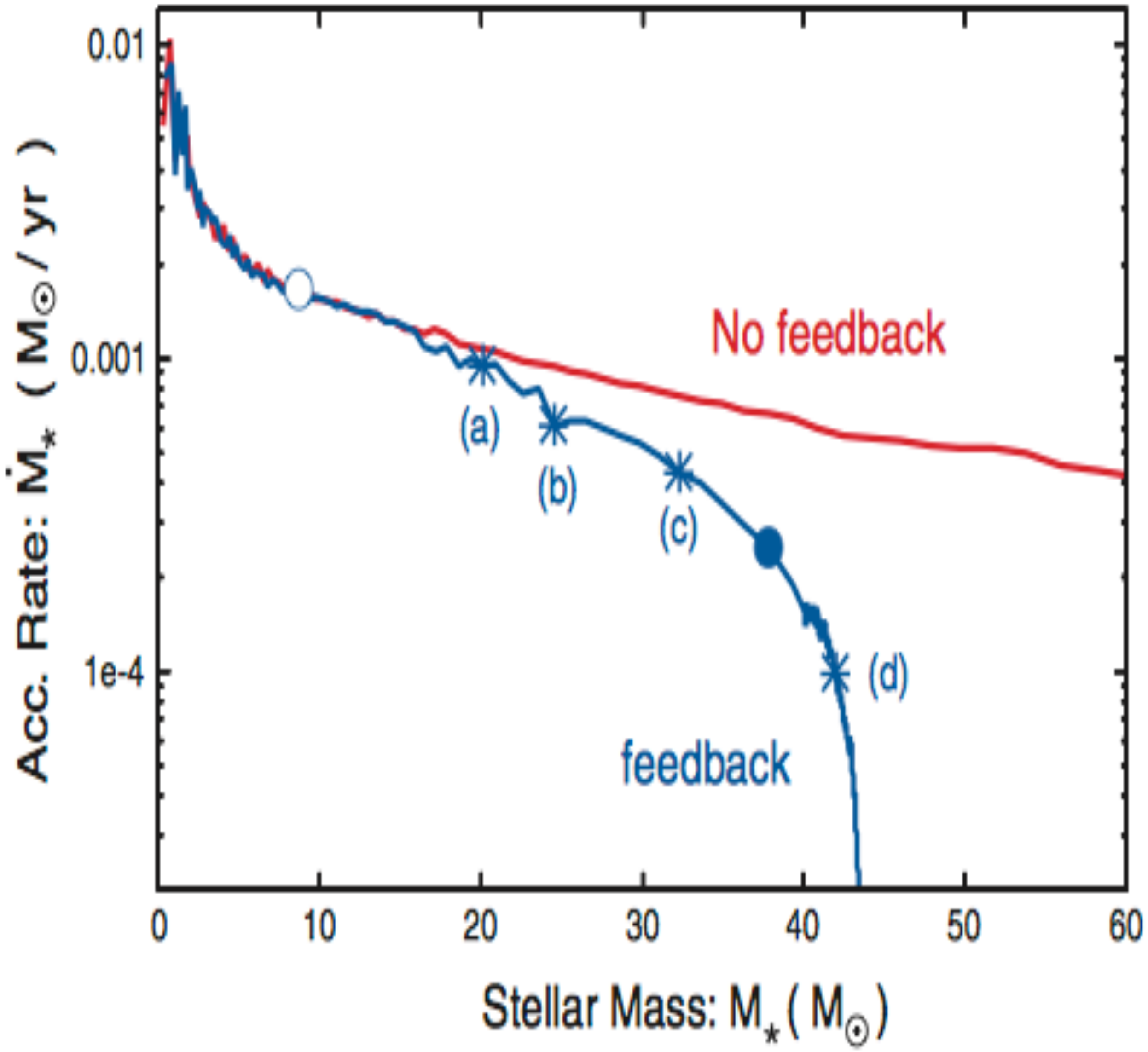
Accretion stops. $M \sim 45 M_\odot$ Limit set by self-regulating radiation feed-back

The Fate of POPIII Stars: Feedback Effects



Hosokawa et al. 2011

The Fate of POPIII Stars: Feedback Effects



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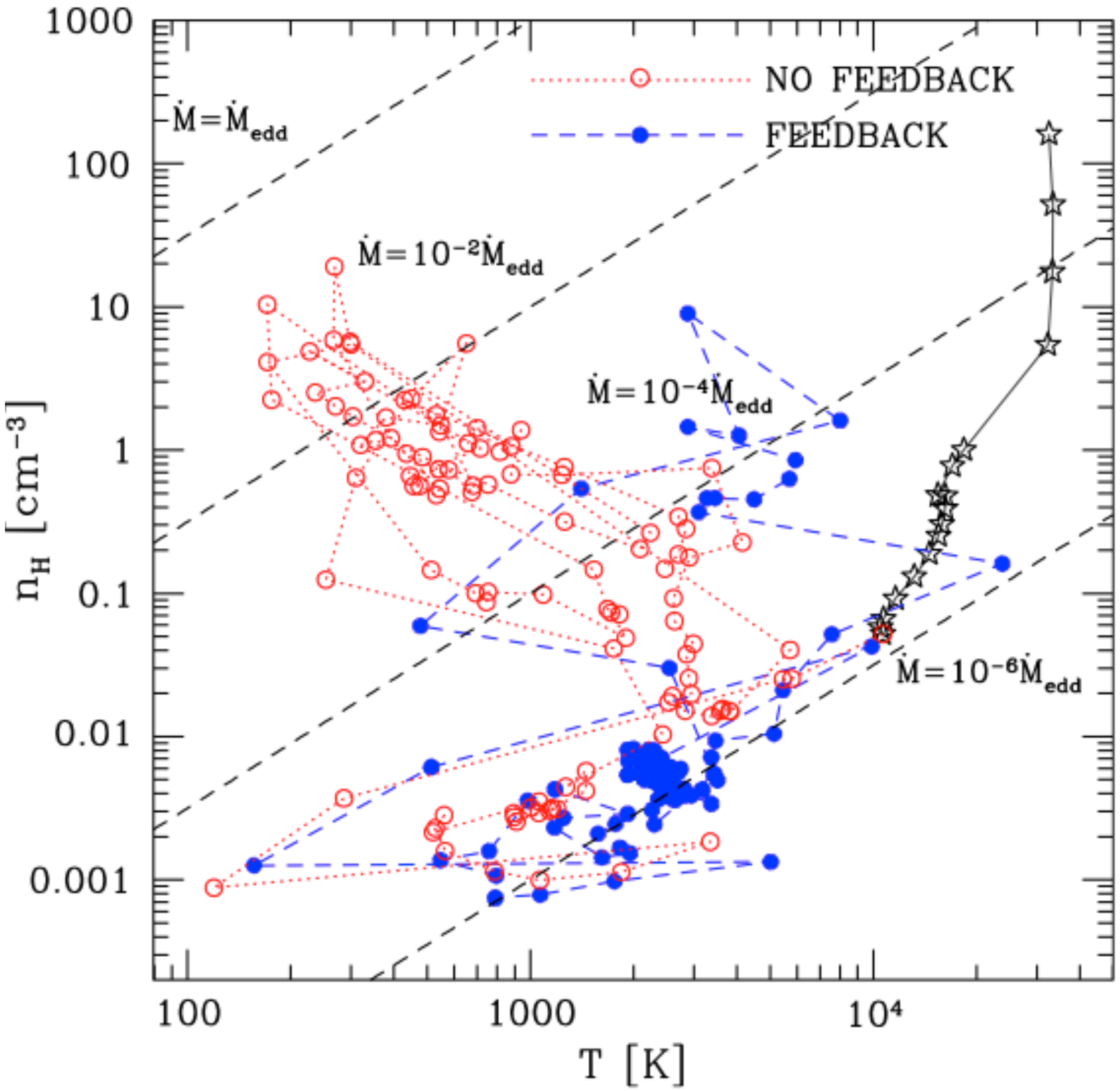

Alvarez et al. 2009

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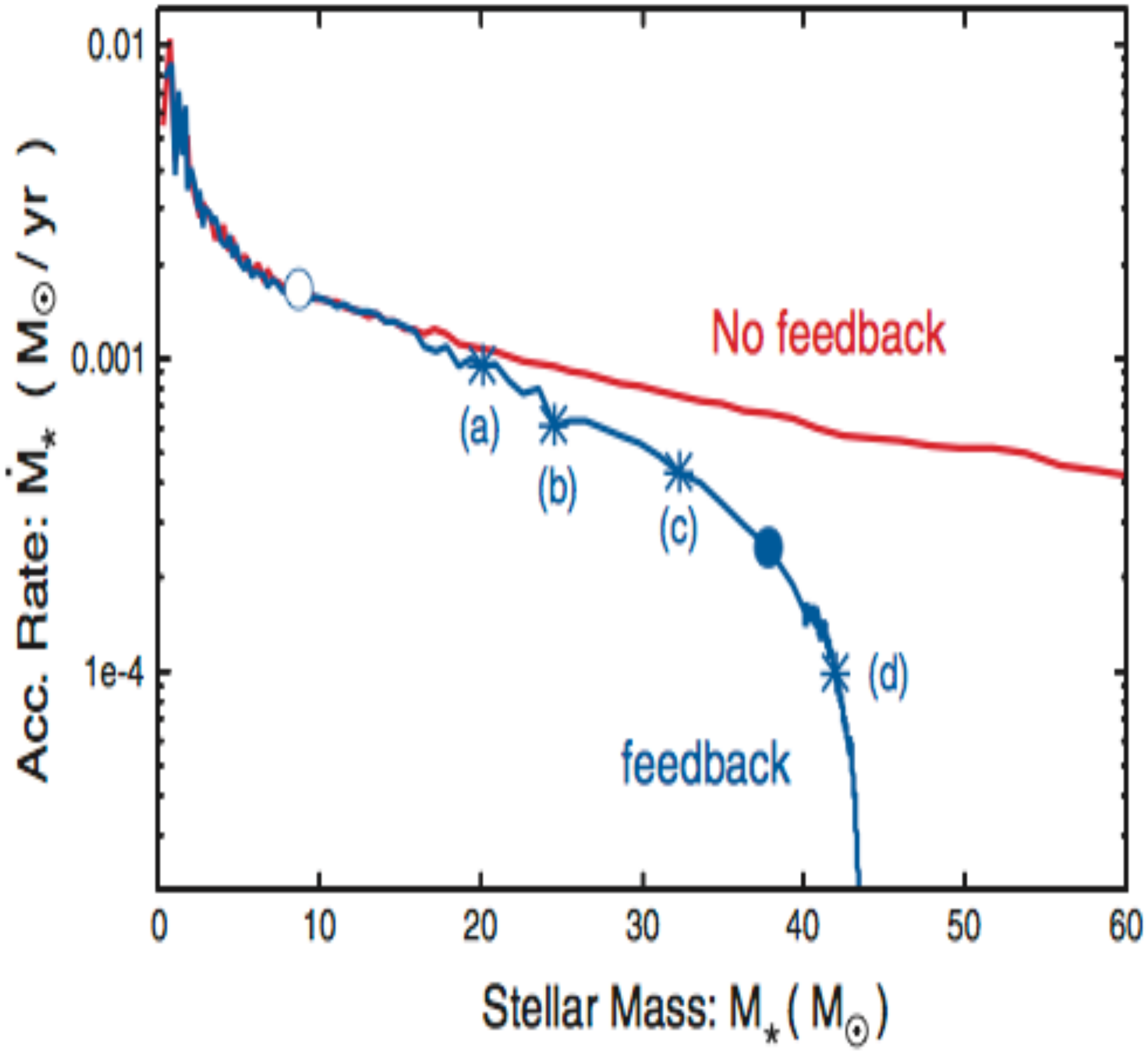

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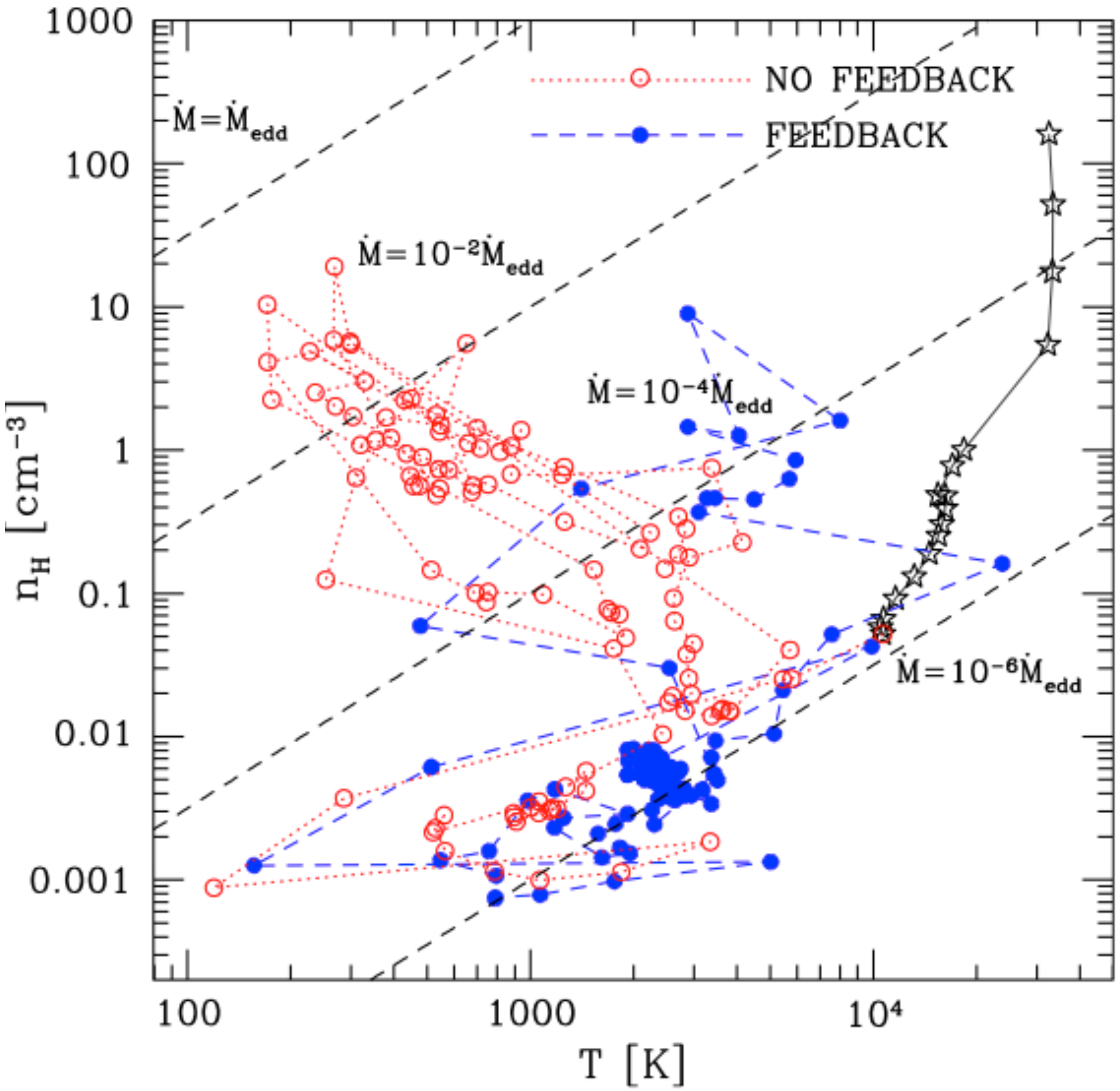
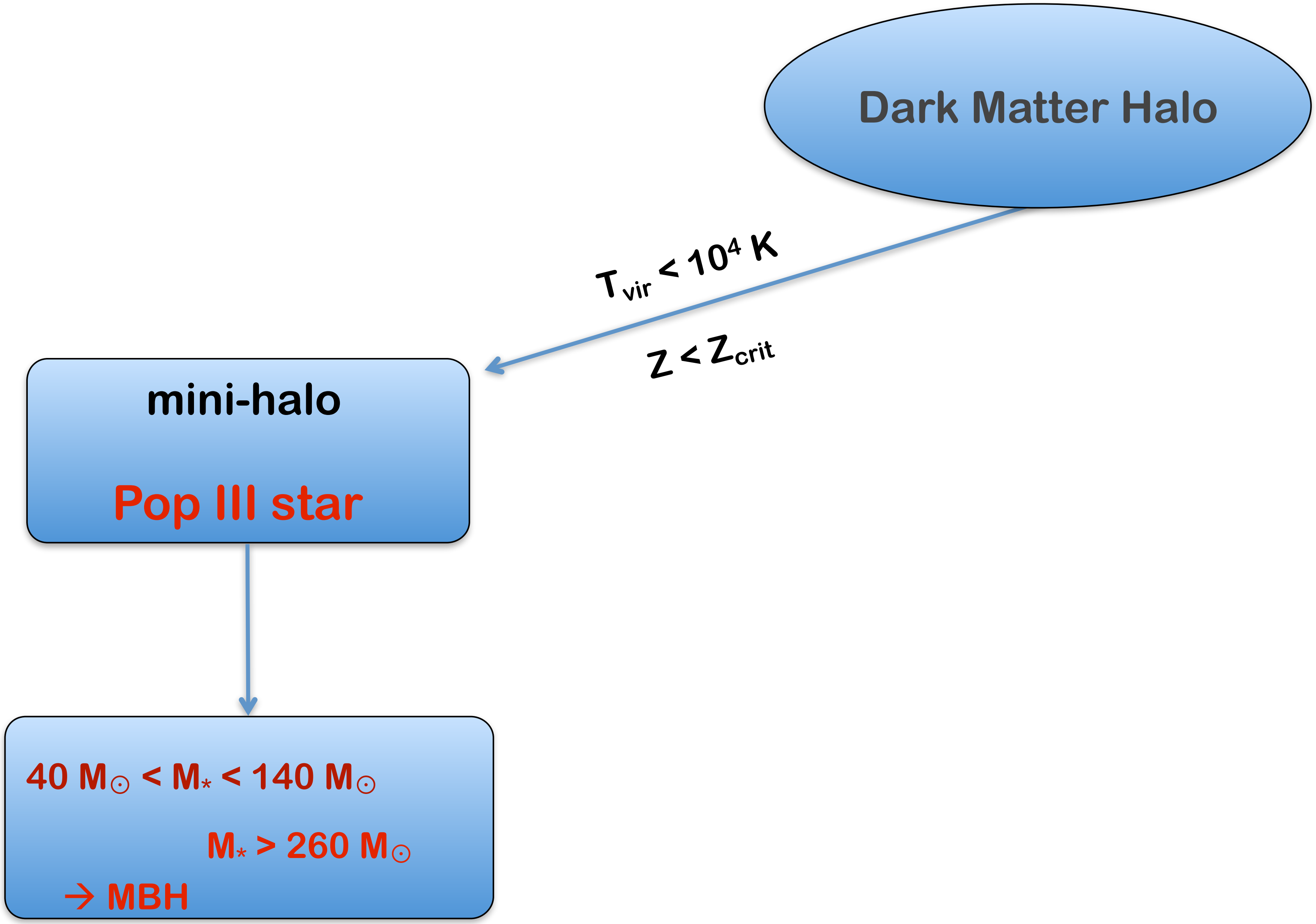


Alvarez et al. 2009

POPIIIs: massive but not very massive (~45 $M_\odot$).
Accretion rate onto the remnant: very sub-Eddington.

The Nature of BH seeds



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mini-halo

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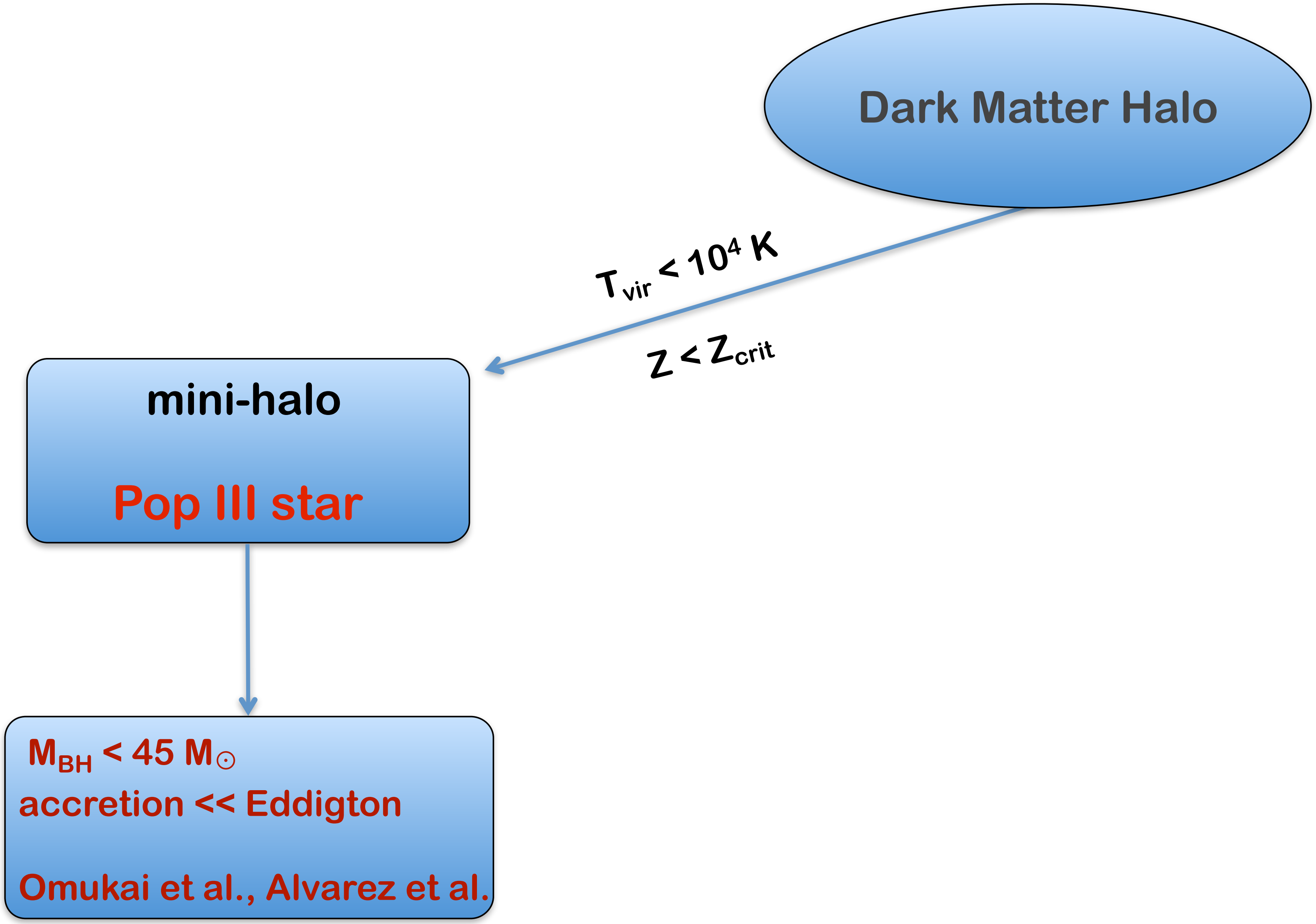

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accretion << Eddigton

Omukai et al., Alvarez et al.

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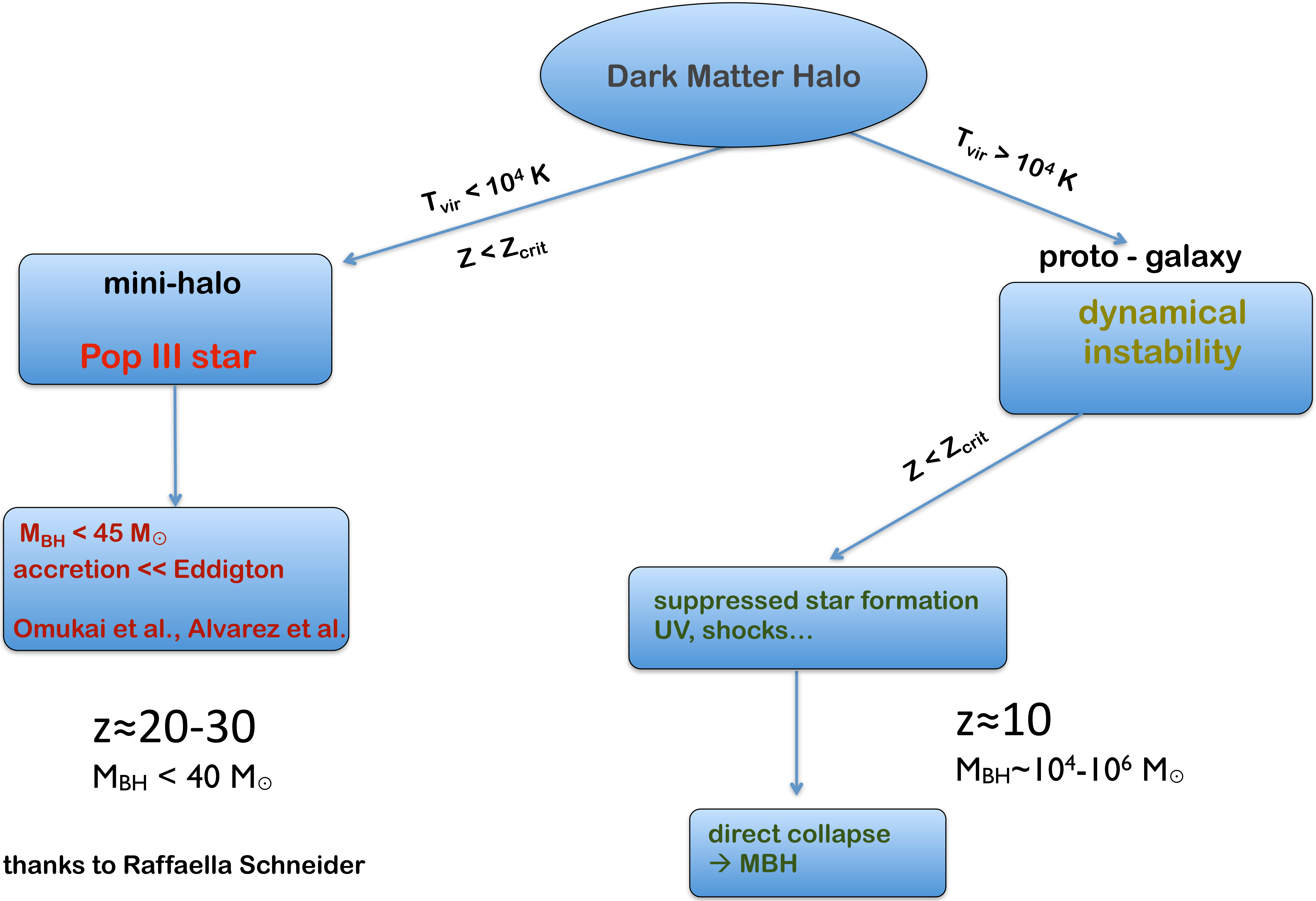
$M_{BH} < 40 M_\odot$

thanks to Raffaella Schneider

The Nature of BH seeds



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proto - galaxy

dynamical instability

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suppressed star formation
UV, shocks…

direct collapse
→ MBH

z≈20-30
$M_{BH} < 40\ M_\odot$

z≈10
$M_{BH} \sim 10^4 - 10^6\ M_\odot$

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Direct Gas Collapse

e.g., Bromm & Loeb 2003, Begelman, Volonteri & Rees 2006

☑ Deep potential well for gas infall and collapse

☑ *Global dynamical instabilities* to trigger inflow and dissipate angular momentum

☑ Inflow and formation of a super-massive star (quasistar) that collapses into a BH

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Problems

☑ Angular momentum dissipation

☑ Star Formation along the long the way down

Direct Gas Collapse

- Efficient gas collapse in halos with $T_{vir} > 10^4$ K (metal free and no H_2 cooling)
- No fragmentation and star formation (Haehnelt & Rees 1993, Begelman et al. 2006)
- Atomic cooling down to 4,000 K (collisionally excited Lyα emission), isothermal collapse, then adiabatic
- Local Lyman-Werner UV to prevent H_2 formation (o.w. turbulent medium)
- Collapsing gas settles into a rotationally supported disk.
- Scale radius: ~ 20 pc (for $M_{halo} = 10^8\ M_\odot$)

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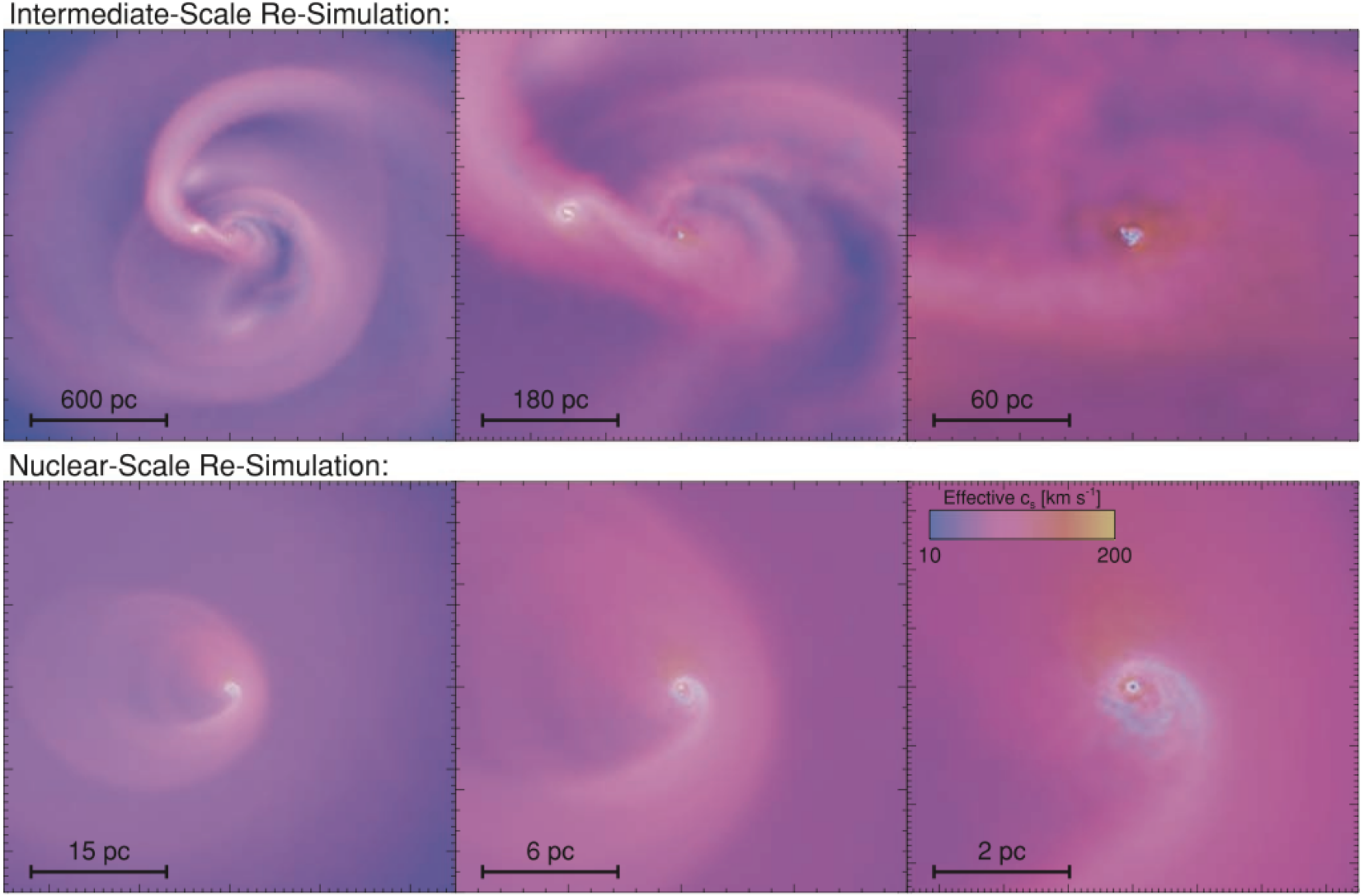
- Angular momentum problem solved if: a) DM halo with very low spin ($\lambda_{spin}<<0.04$); b) presence of low angular momentum gas; c) onset of global dynamical instabilities, bars-within-bars (Shlosman et al. 1989 Begelman et al. 2006).
- A bar can transport angular momentum outwards on a dynamical timescale via gravitational and hydrodynamical torques, allowing the radius to shrink.
- If gas can cool, this shrinkage leads to even greater instability on shorter timescale, and the process cascades

Hopkins & Quataert 2010



- If this all works, typical gas masses within the central few pc can reach 10^4-10^5 $M_\odot$
- A Very Massive Star forms with M_{star}~10^4 $M_\odot$. Numerical full-GR calculations predict the core of the VMS collapses into a few $M_\odot$ Kerr BH (via neutrino cooling). A ***Quasistar*** is formed: a stellar-size BH embedded into a very massive stellar envelope
- Ultrafast accretion at Eddington rate (where mass is the Quasistar mass)
- The 10 $M_\odot$ BH can swallow 1-10% of the Quasistar envelope: MBH reaches 10^4-10^5 $M_\odot$

Begelman et al. 2006

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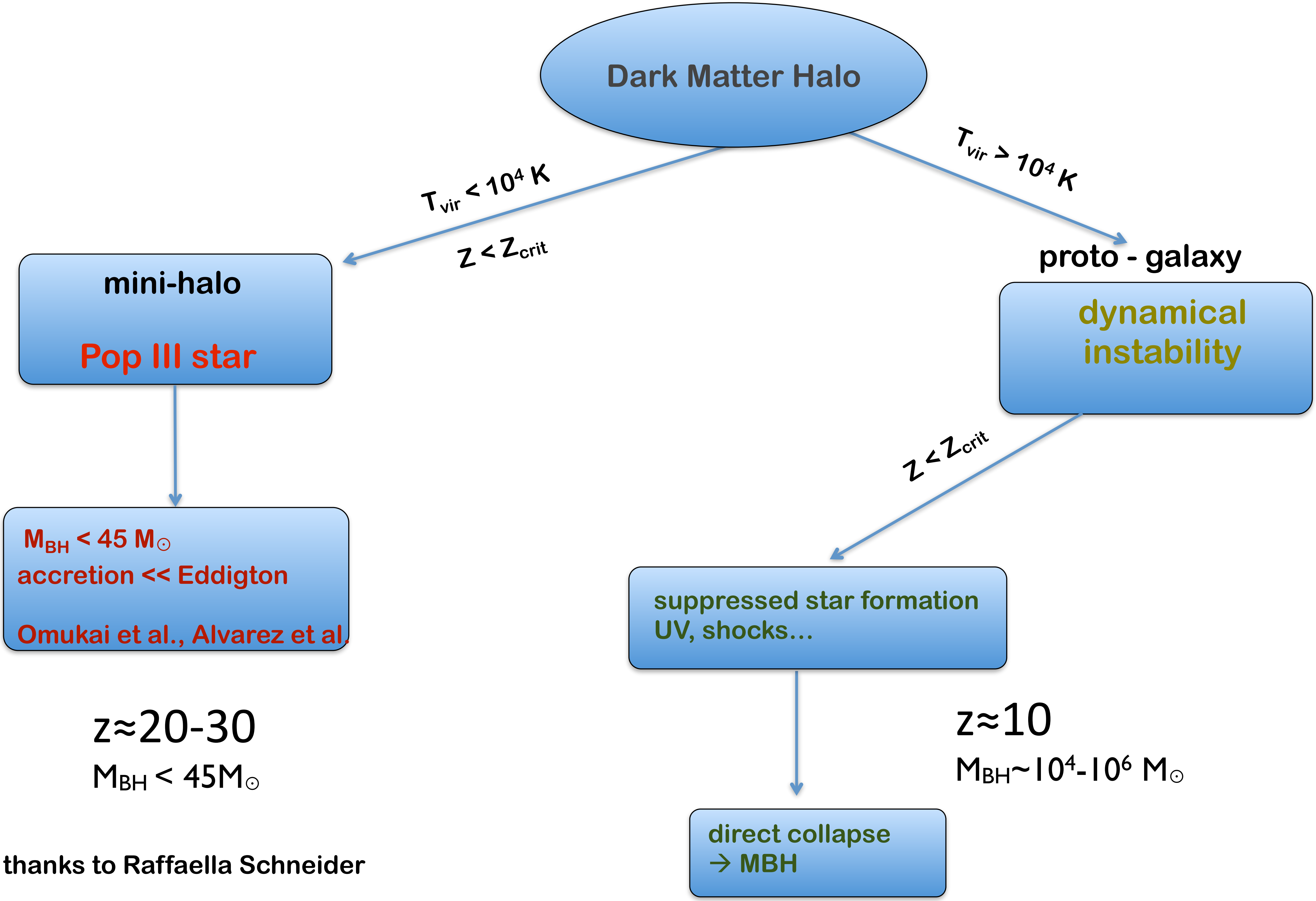
Begelman et al. 2006

Instead of going into BH formation, collapsing gas can fragment and form stars

The Nature of BH seeds



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mini-halo

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Omukai et al., Alvarez et al.

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UV, shocks…

direct collapse
→ MBH

z≈20-30

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$M_{BH} \sim 10^4 - 10^6\ M_\odot$

thanks to Raffaella Schneider

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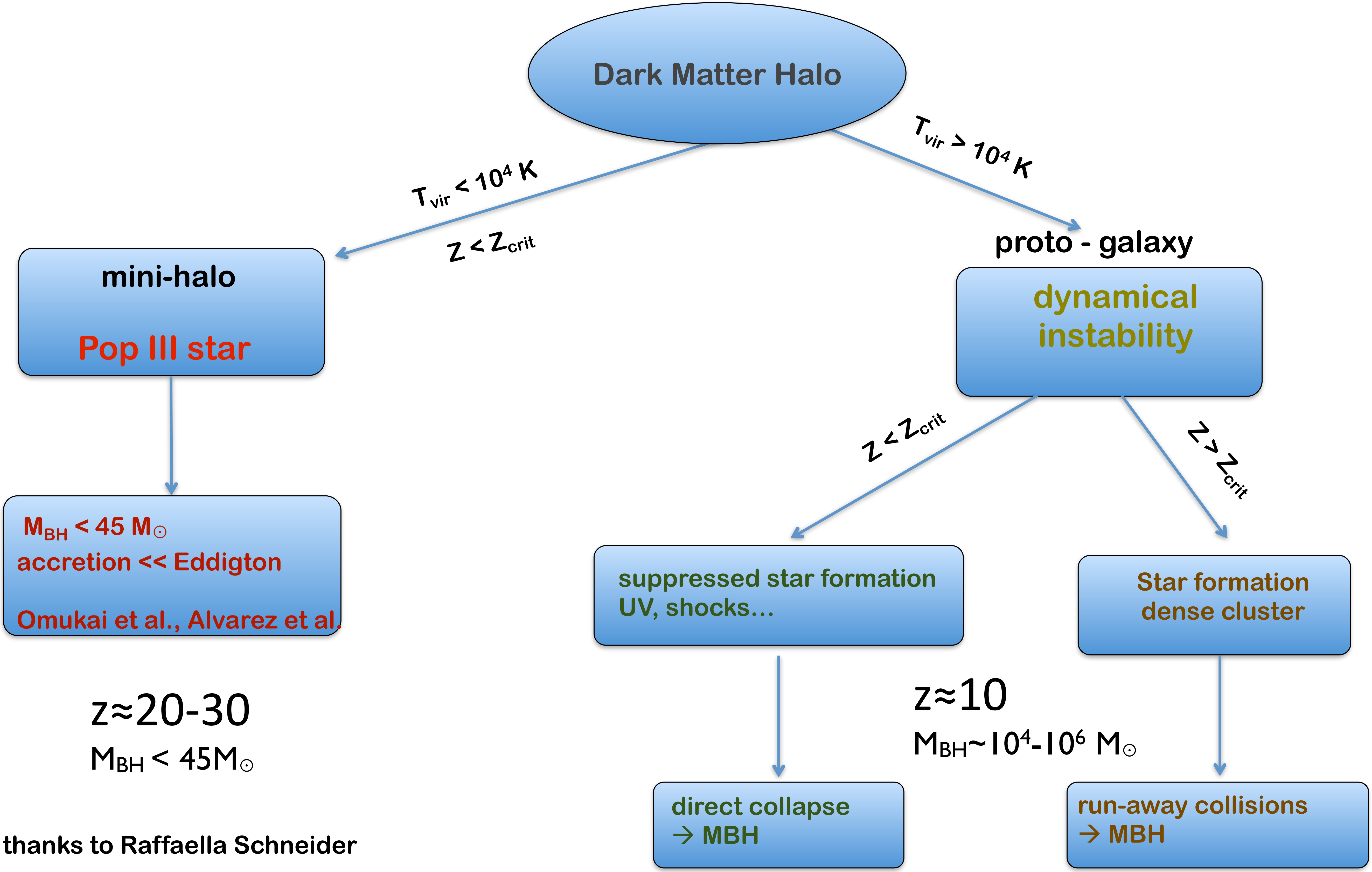

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Star formation
dense cluster

run-away collisions
→ MBH

thanks to Raffaella Schneider

Star Formation and Run-Away Collapse

e.g., Devecchi & Volonteri 2009

- If gas is metal enriched by first POPIII stars can not avoid fragmentation
- *Local dynamical instabilities* lead to mass infall
- The inflow produces an inner, compact, very dense star cluster
- Mass segregation: more massive stars sink to the centre of the cluster
- Stellar collisions form a VMS
- The VMS accretes gas. BH remnant of 10^3 $M_\odot$ (Begelman & Rees 1978, Freitag et al. 2006)

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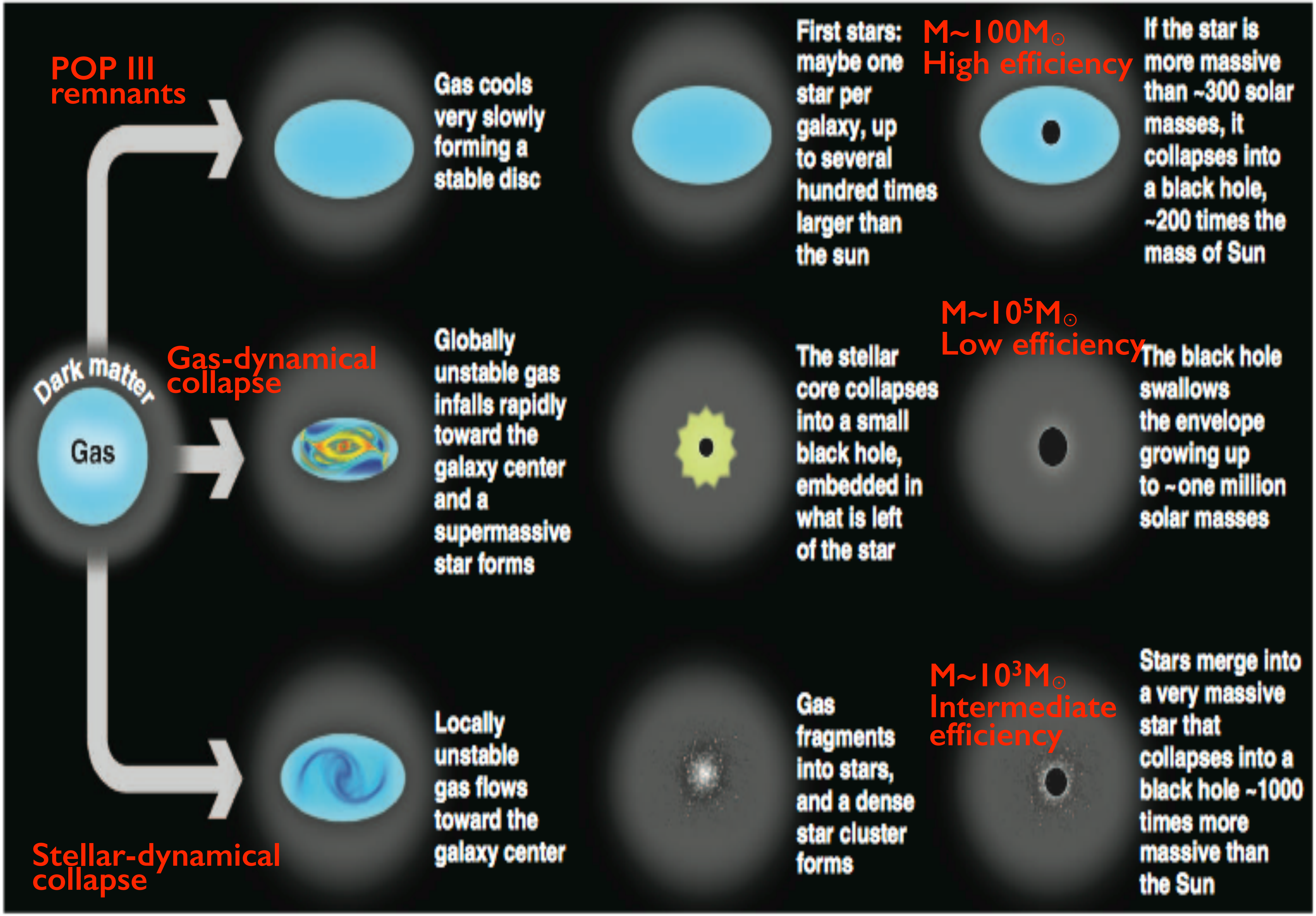
- This route happens above a critical metallicity: $Z>10^{-5}$ $Z_\odot$. But Z needs not to be too high to avoid excessive gas consumption by star formation
- Time for mass segregation must be << main-sequence timescale (3 Myrs) to avoid SN driven mass-loss, and formation of compact objects (small cross section)

The Nature of BH seeds

from Volonteri 2010



POP III remnants

Gas cools very slowly forming a stable disc

First stars: maybe one star per galaxy, up to several hundred times larger than the sun

$M\sim100M_\odot$
High efficiency

If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun

Gas-dynamical collapse

Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms

The stellar core collapses into a small black hole, embedded in what is left of the star

$M\sim10^5M_\odot$
Low efficiency

The black hole swallows the envelope growing up to ~one million solar masses

Stellar-dynamical collapse

Locally unstable gas flows toward the galaxy center

Gas fragments into stars, and a dense star cluster forms

$M\sim10^3M_\odot$
Intermediate efficiency

Stars merge into a very massive star that collapses into a black hole ~1000 times more massive than the Sun

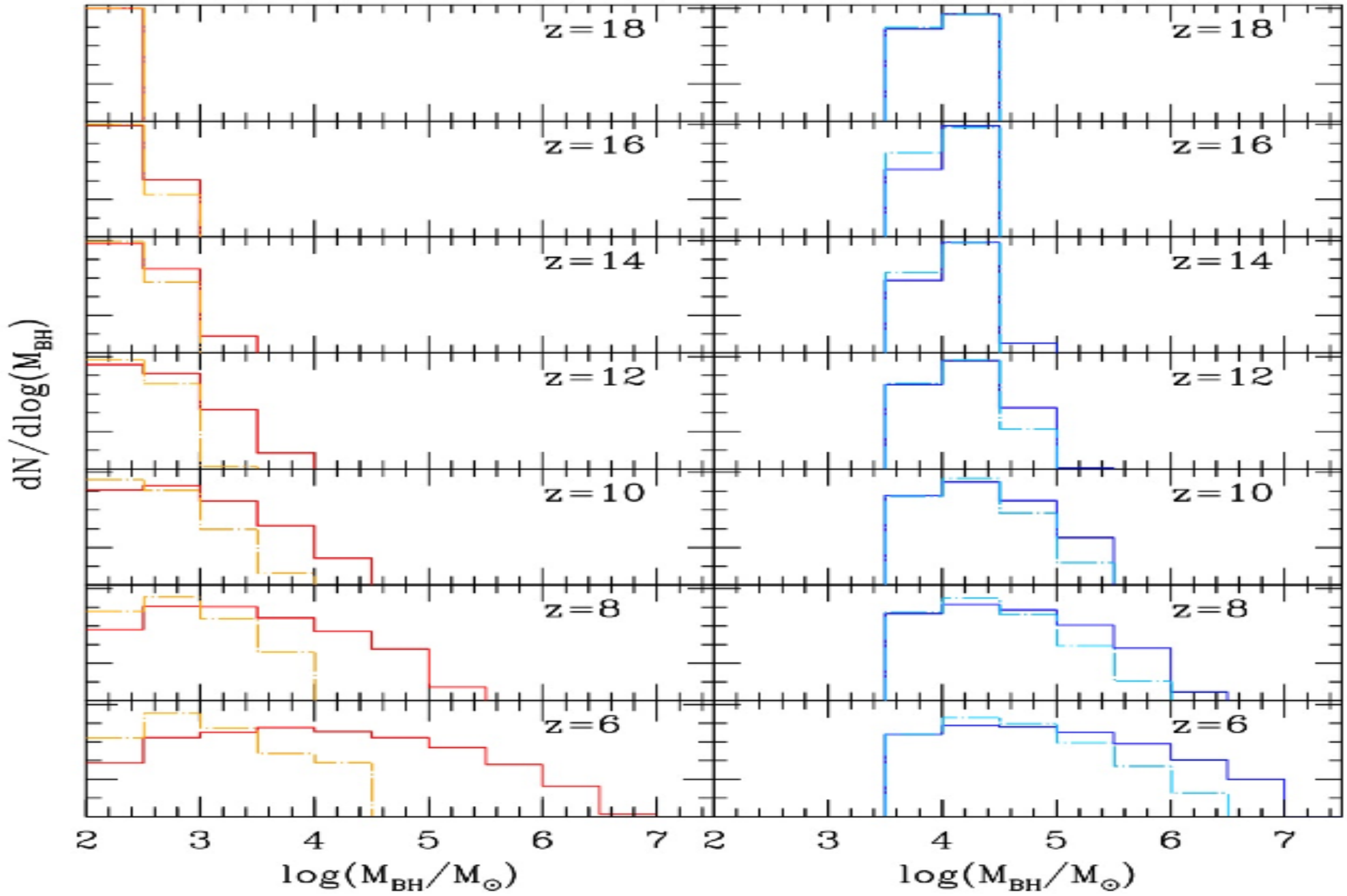
Low Mass Seeds vs High Mass Seeds

Volonteri & Gnedin 2009

Light Seeds

solid: Eddigton limited
dashed: a la “Merloni Heinz”

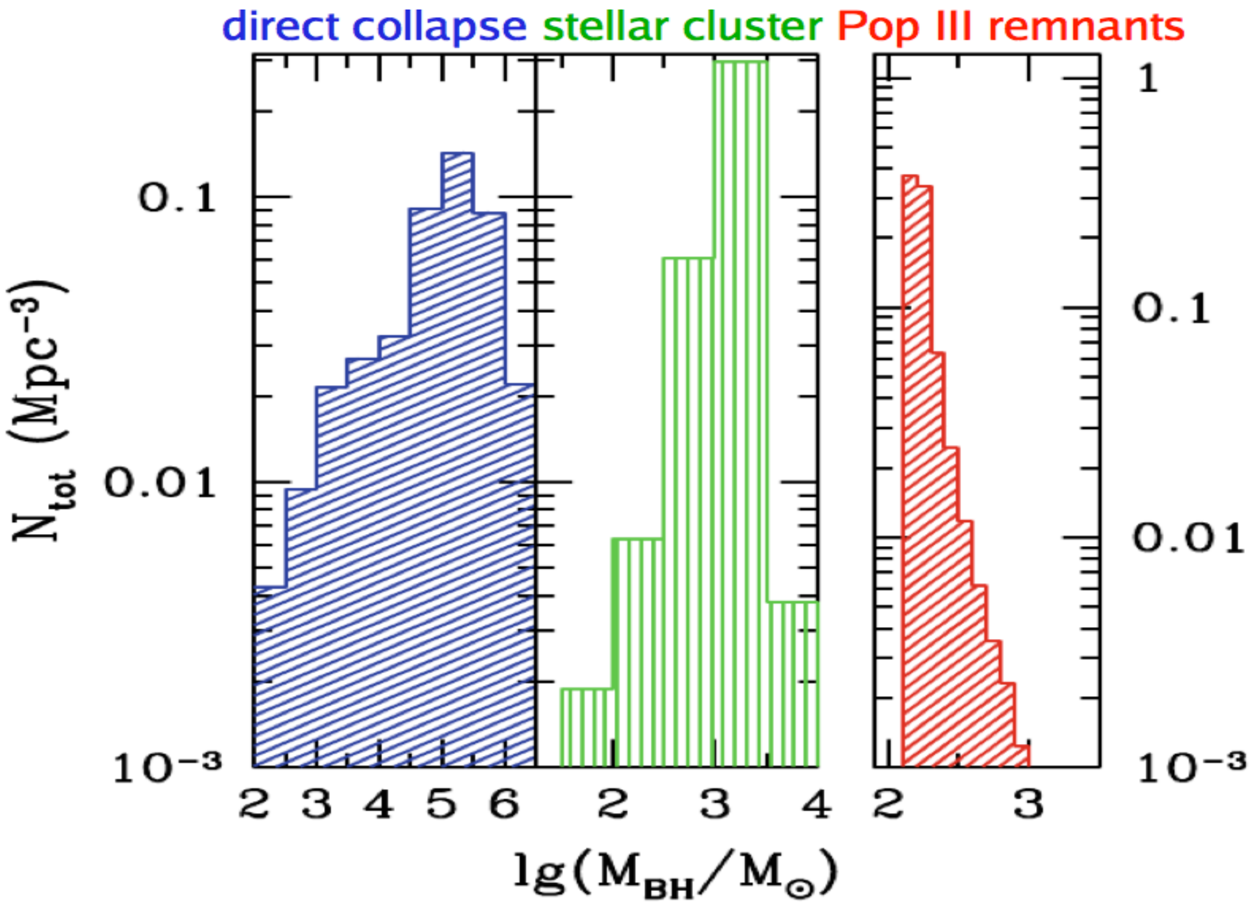
Heavy Seeds



Low Mass Seeds vs High Mass Seeds

Volonteri 2010

Madau & Rees 2001



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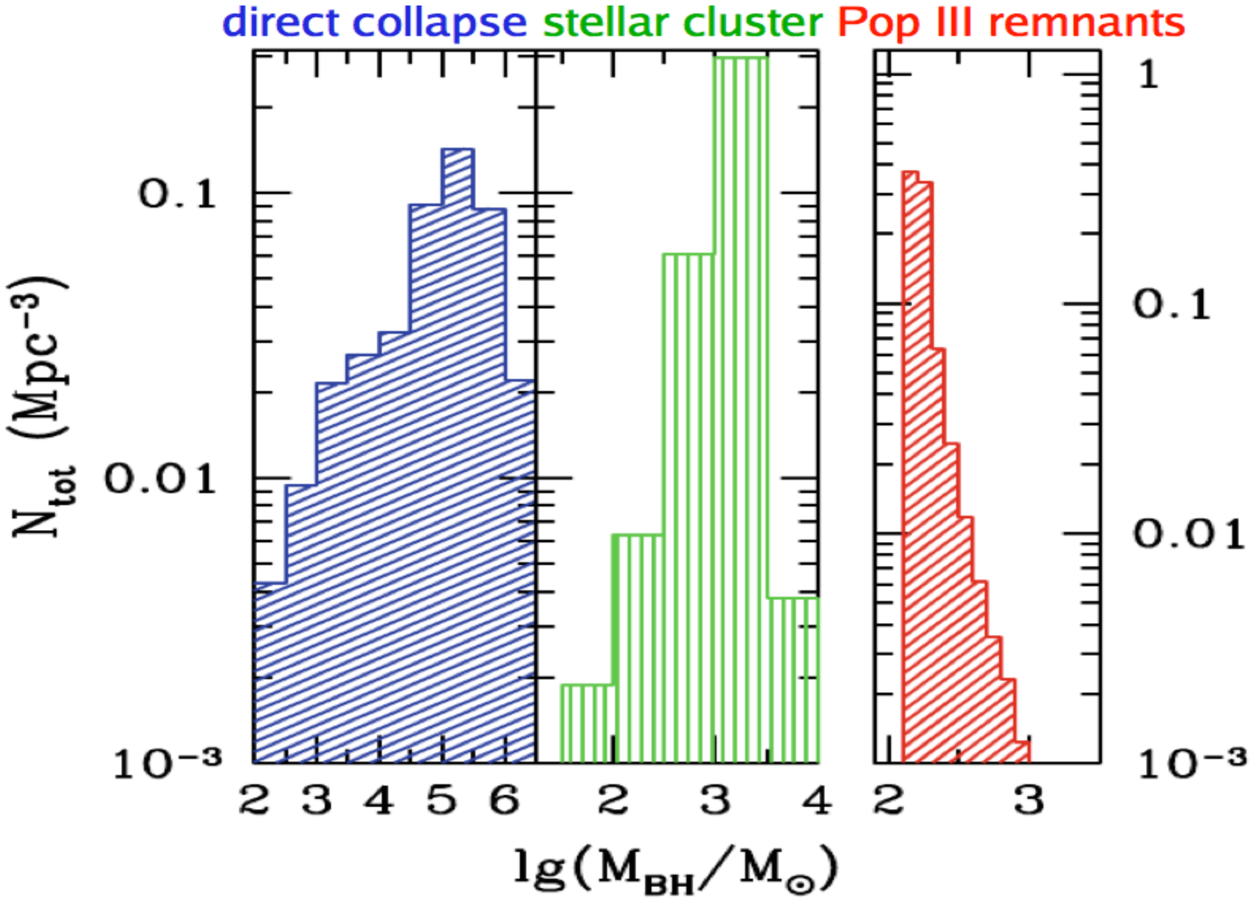

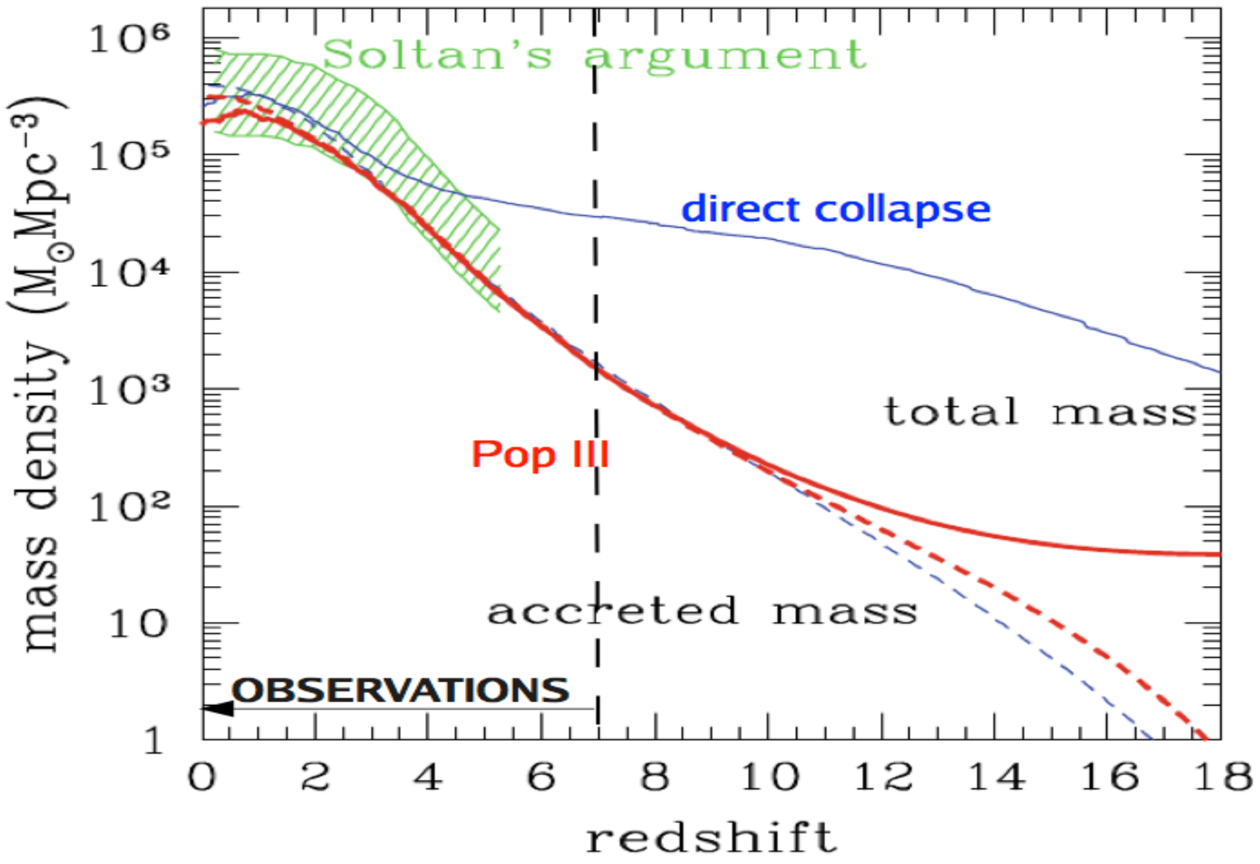

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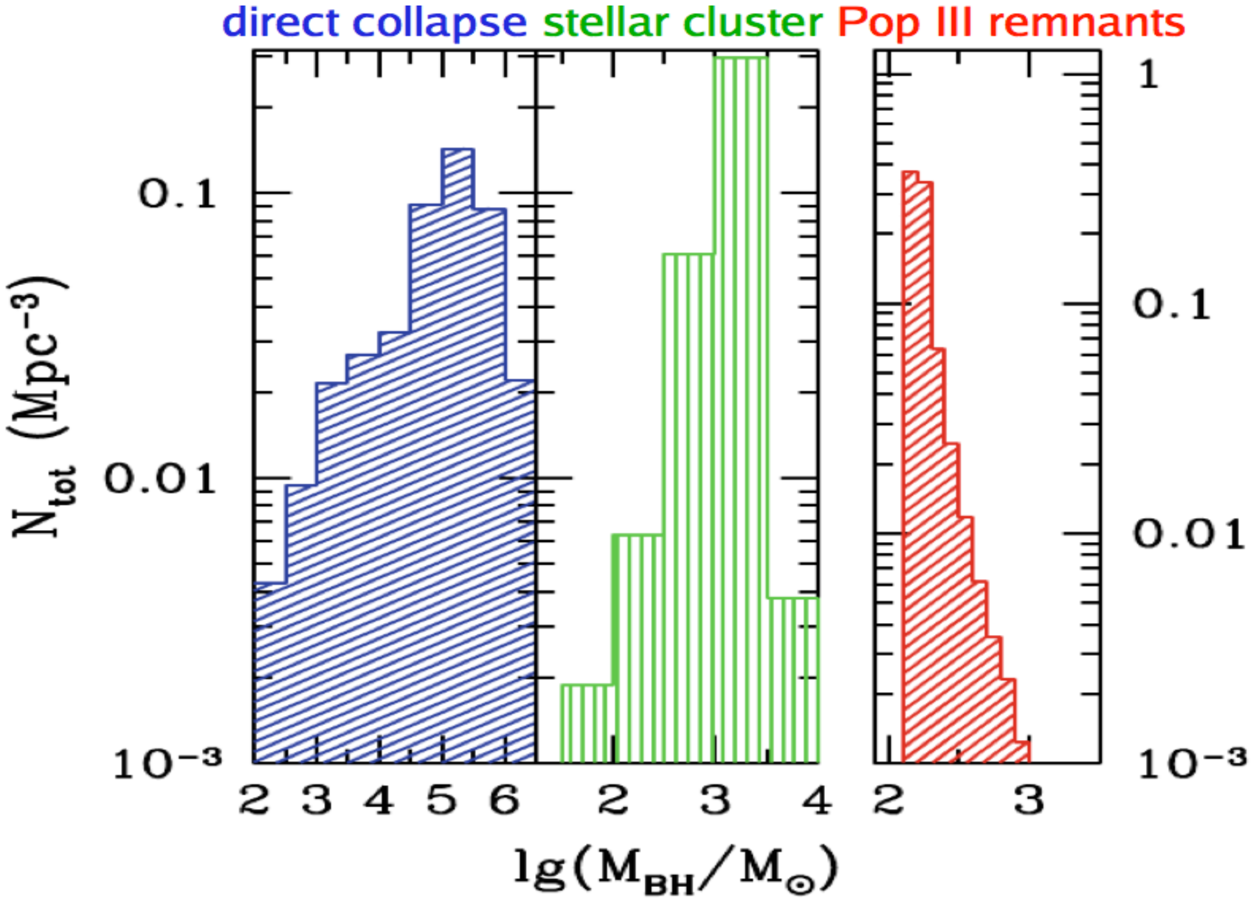
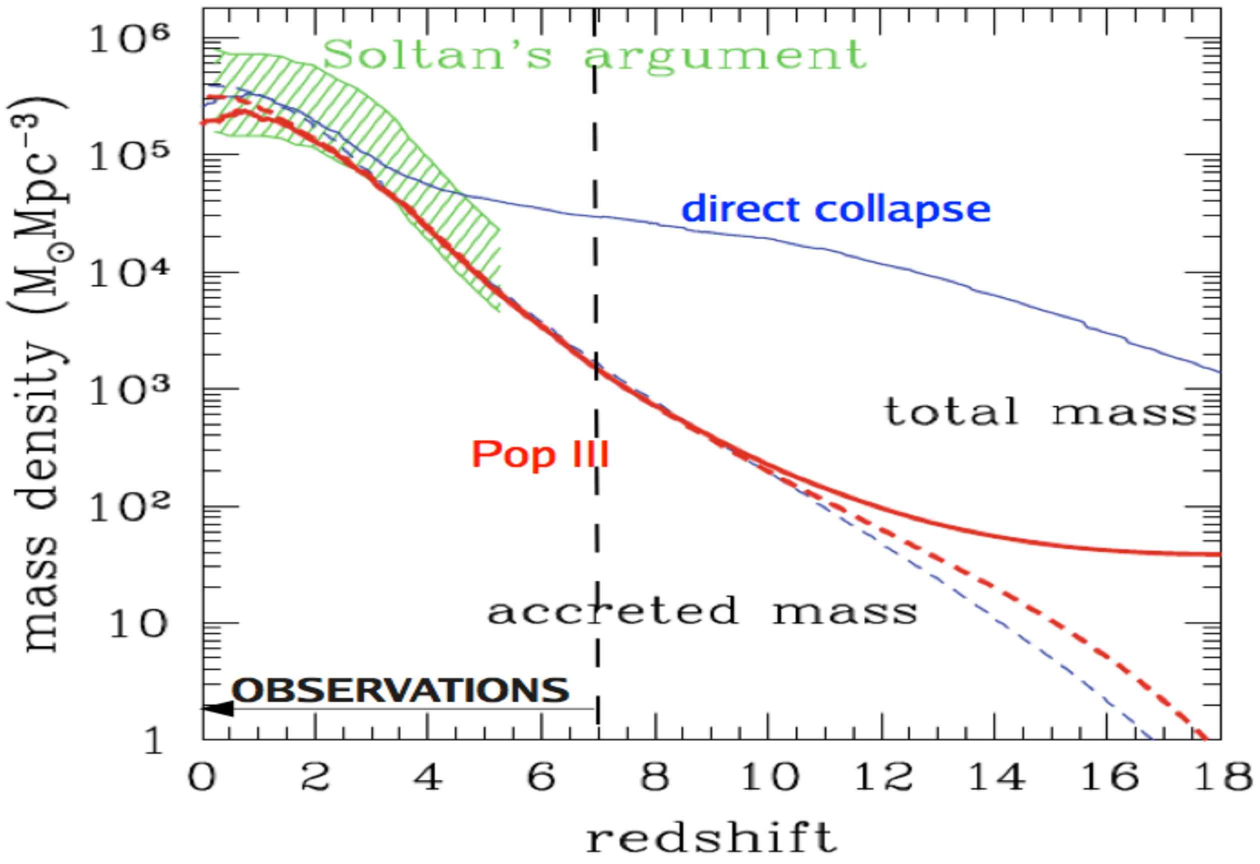
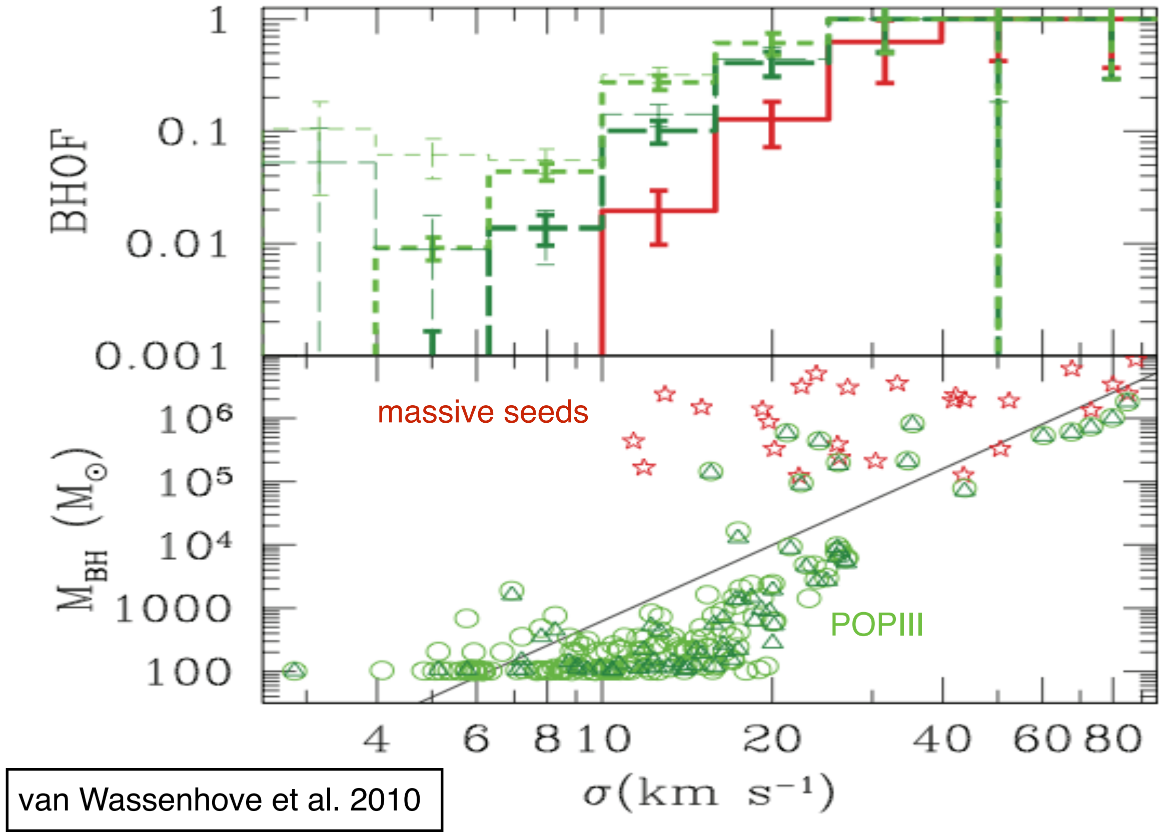
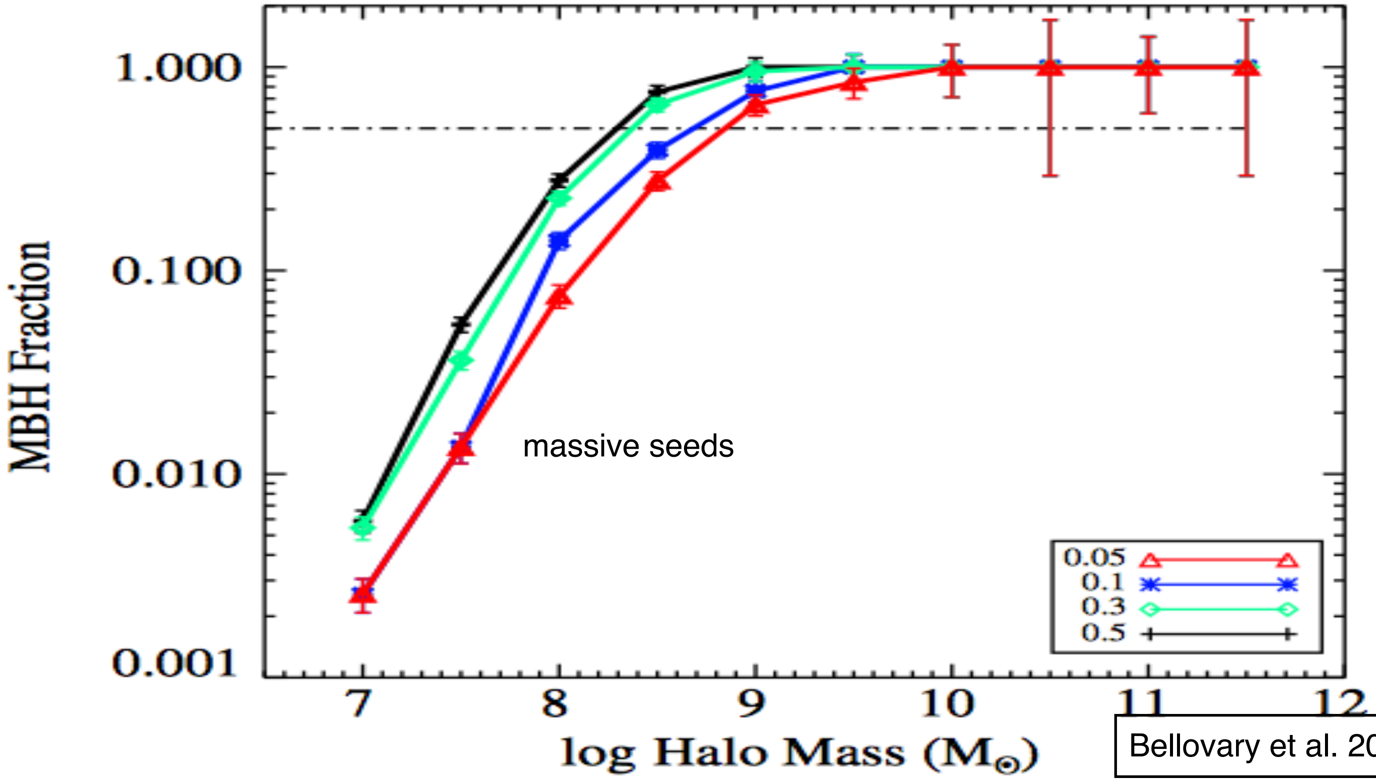






van Wassenhove et al. 2010



Bellovary et al. 2011

Low Mass Seeds vs High Mass Seeds

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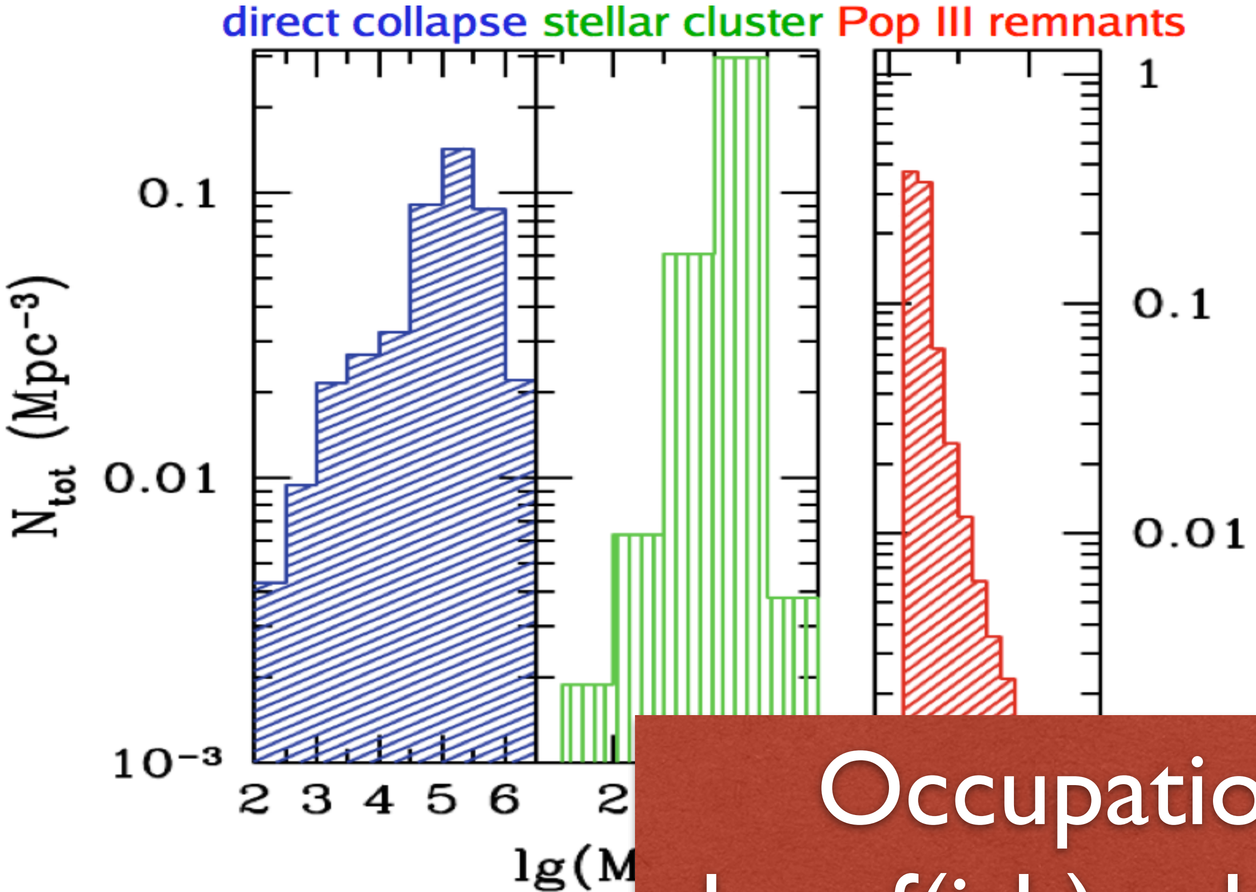
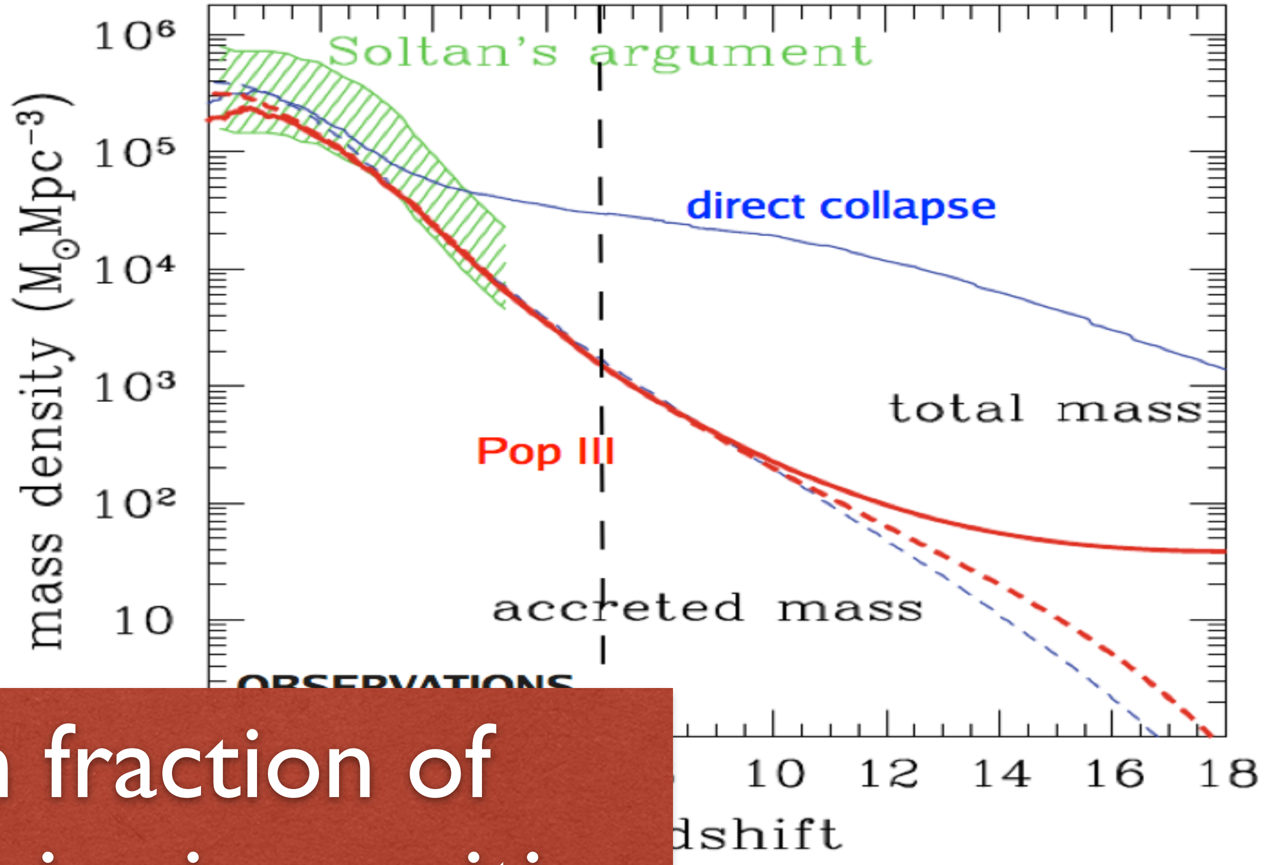
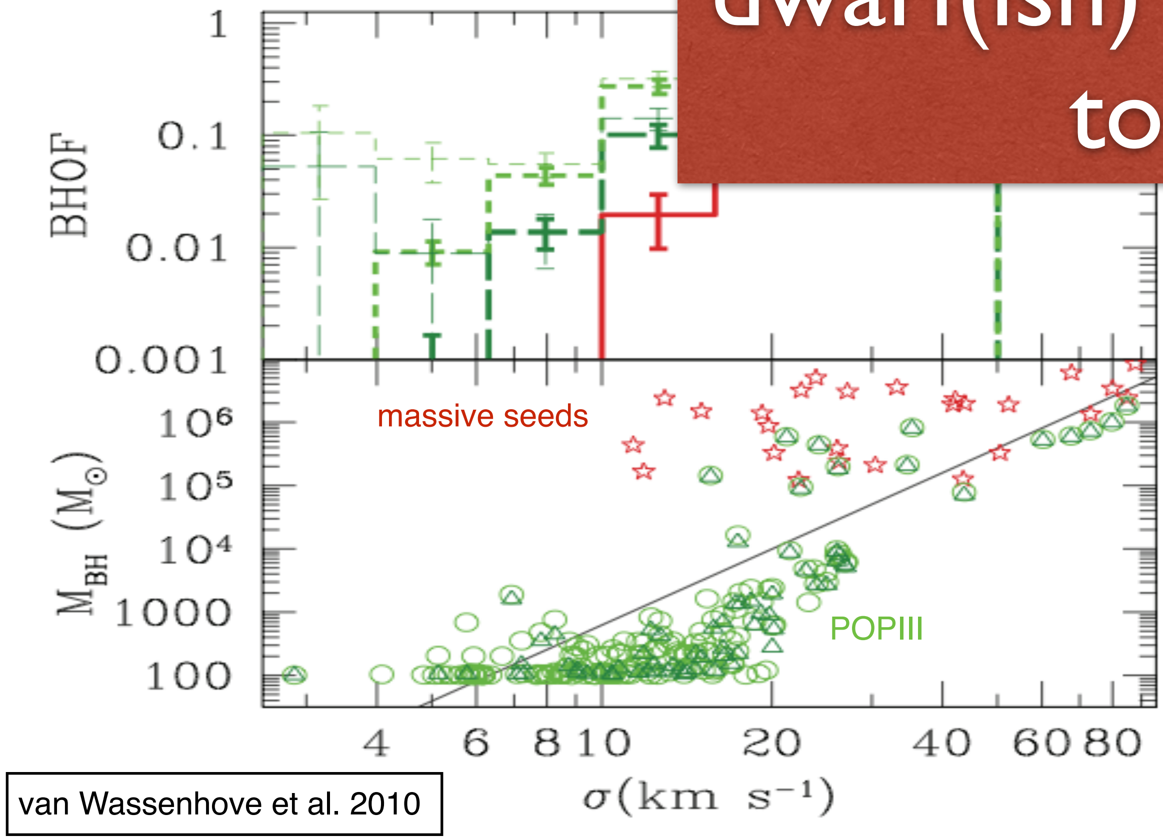




Occupation fraction of dwarf(ish) galaxies is sensitive to seed mass



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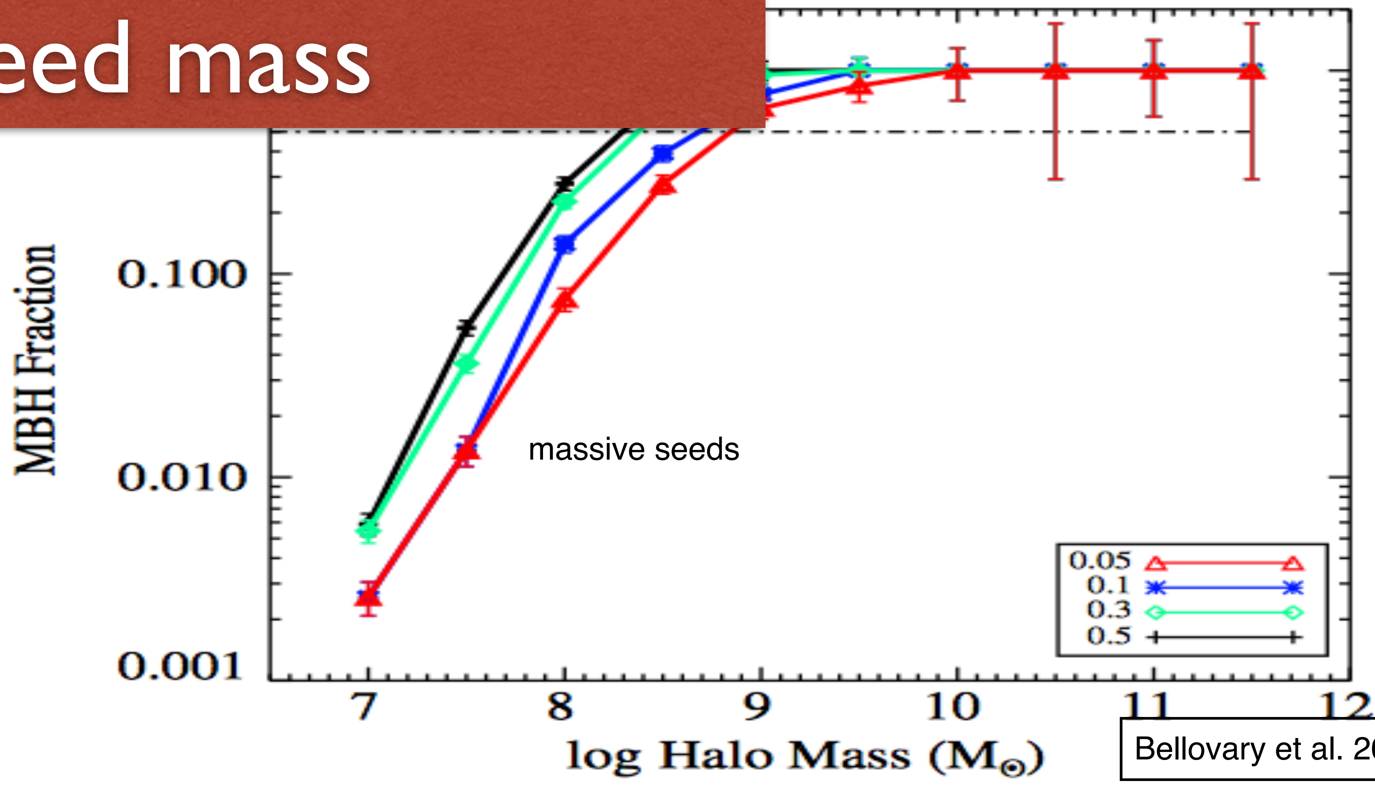
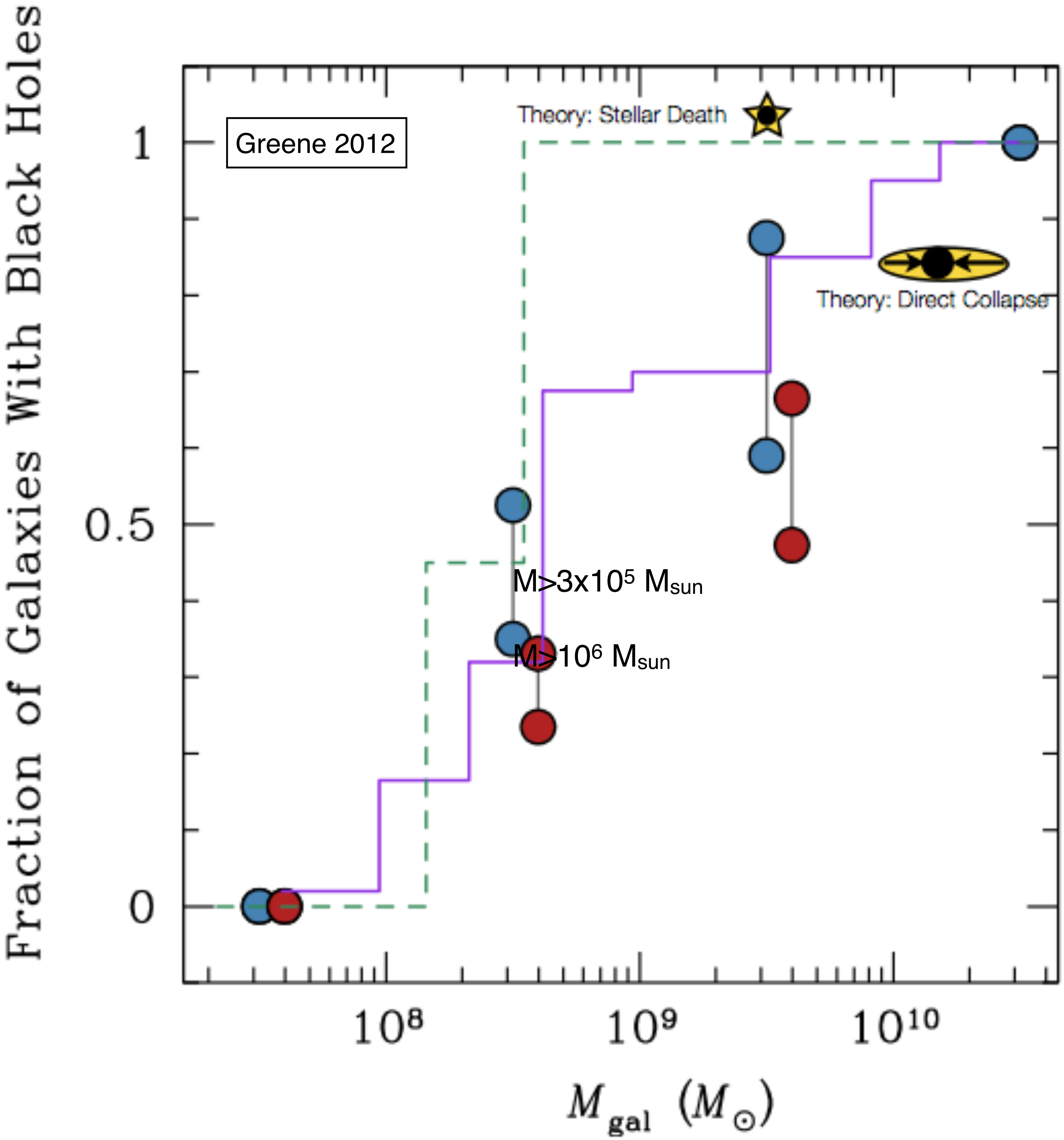


Bellovary et al. 2011

Low Mass Seeds vs High Mass Seeds (observations)



POPIII seeds (green) and massive seeds (purple) from Volonteri et al. (2008).

Estimates from Desroches et al. (2009, blue) and Gallo et al. (2010, red).

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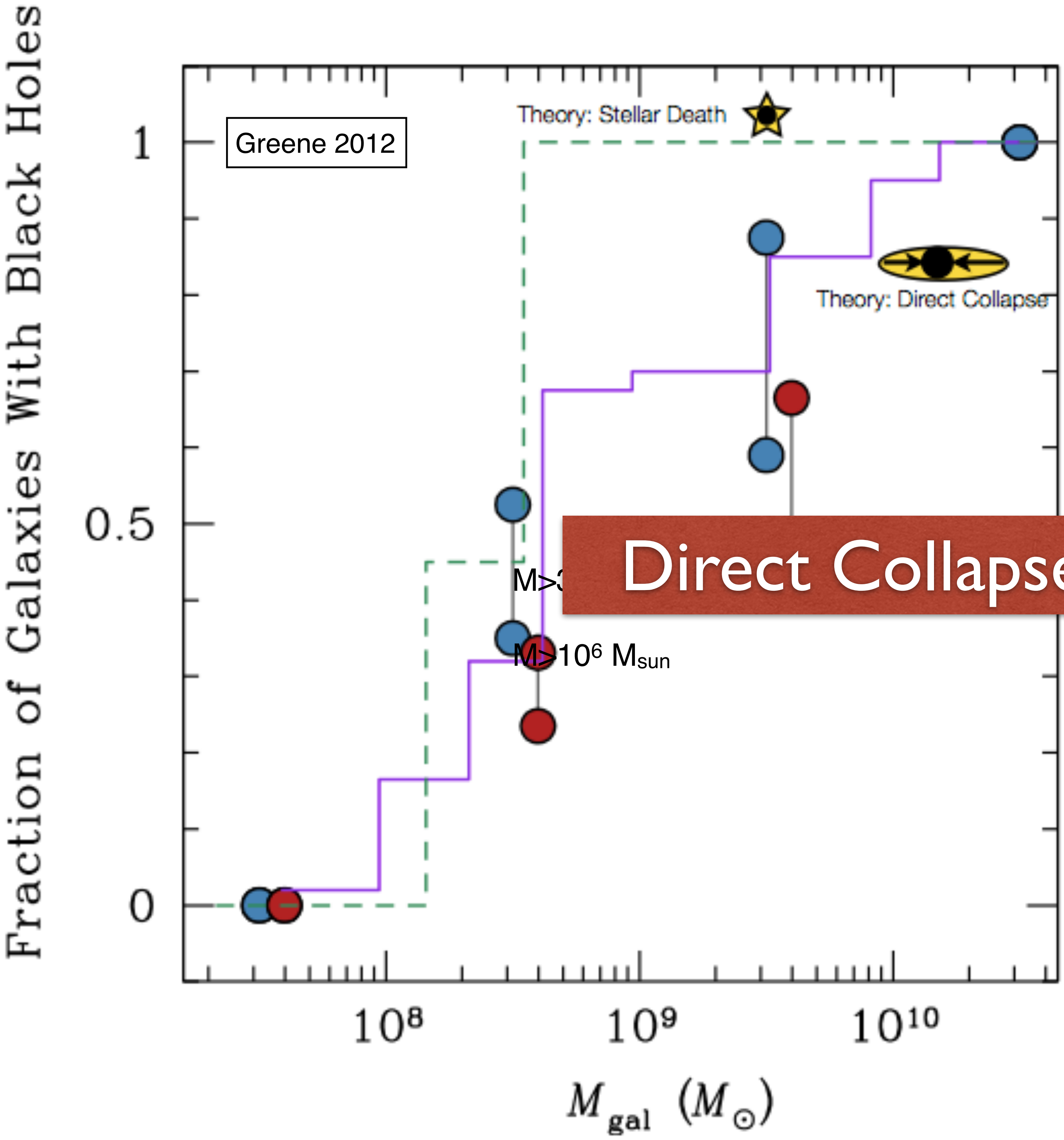

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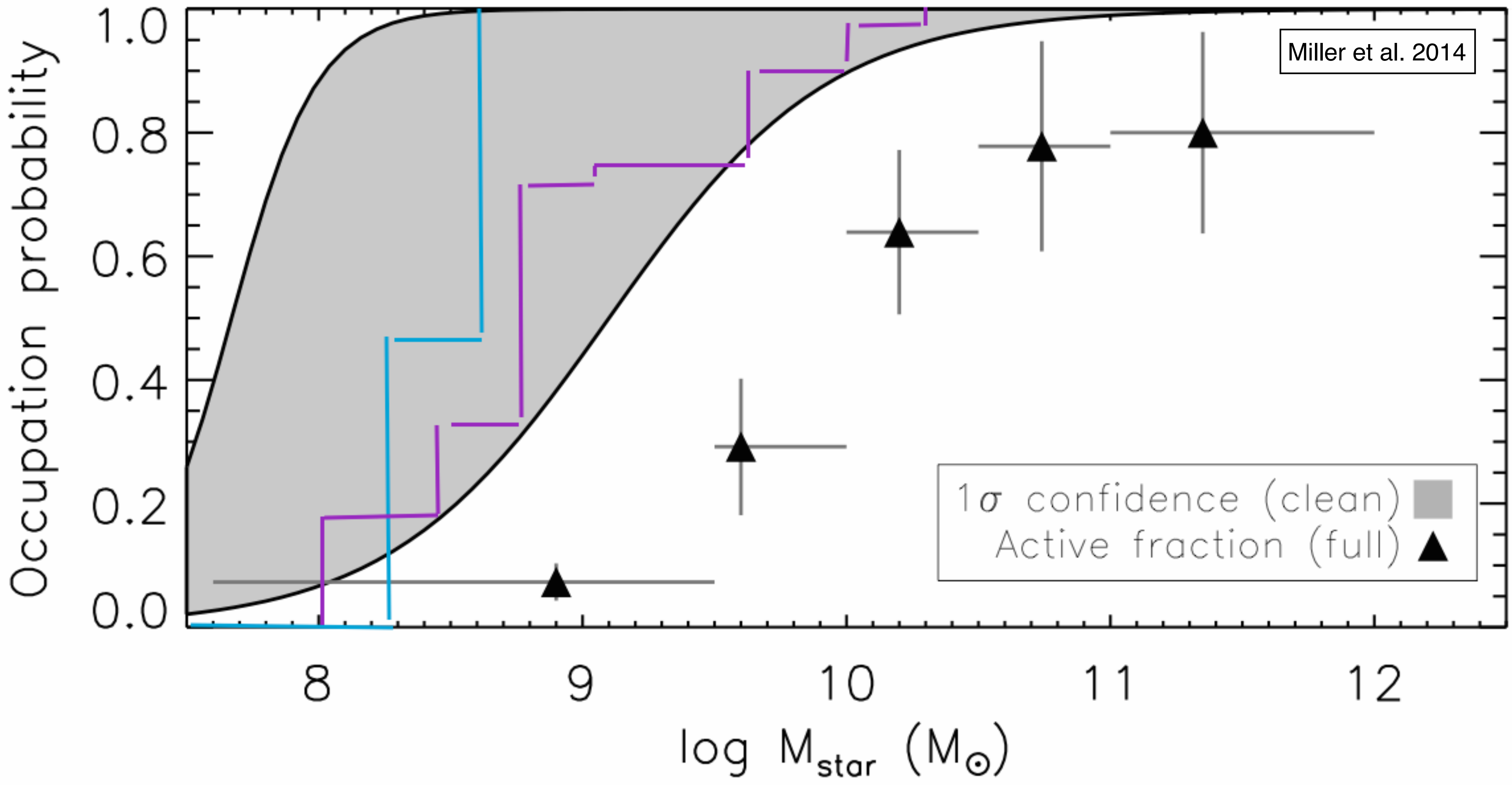

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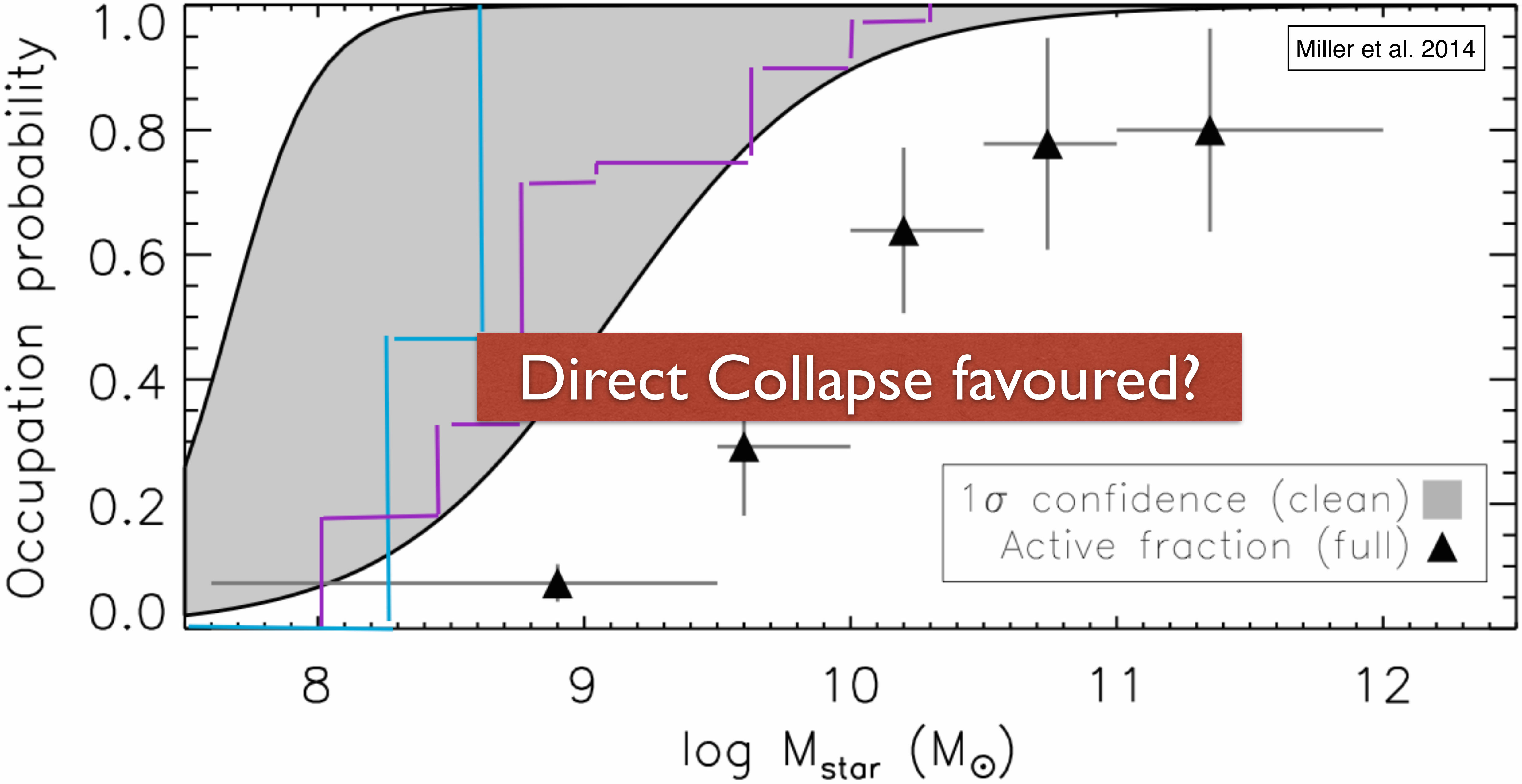

Direct Collapse favoured?

SMBHs at "Low" Redshifts by Gas Collapse

- Simulation of two well-formed hi-z MW-like galaxies merger

Mayer et al. 2010

- Self-gravitating turbulent nuclear disk (r~40 pc, M~2x10^9 M$_\odot$) forms
- Gravo-turbulent instabilities drive the gas toward the centre at very high rate, 10^4 M$_\odot$/yr
- A ~1pc size spherical structure grows by 13% of the disk mass (>10^8 M$_\odot$) in 0.1 Myr. T~10^7K prevents fragmentation.
- The core collapse into a BH + envelope = Quasistar
- The key point:

$$\dot{M} \approx M_J/t_{ff} = \frac{\pi^2}{8G} c_s^3 \simeq 5 \times 10^3 \left(\frac{T}{10^7 K}\right)^{3/2} \quad \mathrm{M_\odot yr^{-1}}$$

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- Would T be so high with a realistic thermodynamics? (the simulation uses a polytropic EoS)

Ferrara, FH & Salvaterra 2013

- On which timescale is turbulence (the source of energy) dissipated?

Conclusions

Light Seeds

- POPIII stars form copiously in the high-z Universe (z~20).
- $M_{star} \sim 45\ M_\odot$ —> $M_{BH} < 45 M_\odot$
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- Direct gas collapse at high-z (z~10) needs low angular momentum haloes and high UV-H_2 dissociating flux. J_{crit}? (see Latif et al. 2014)
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Observations

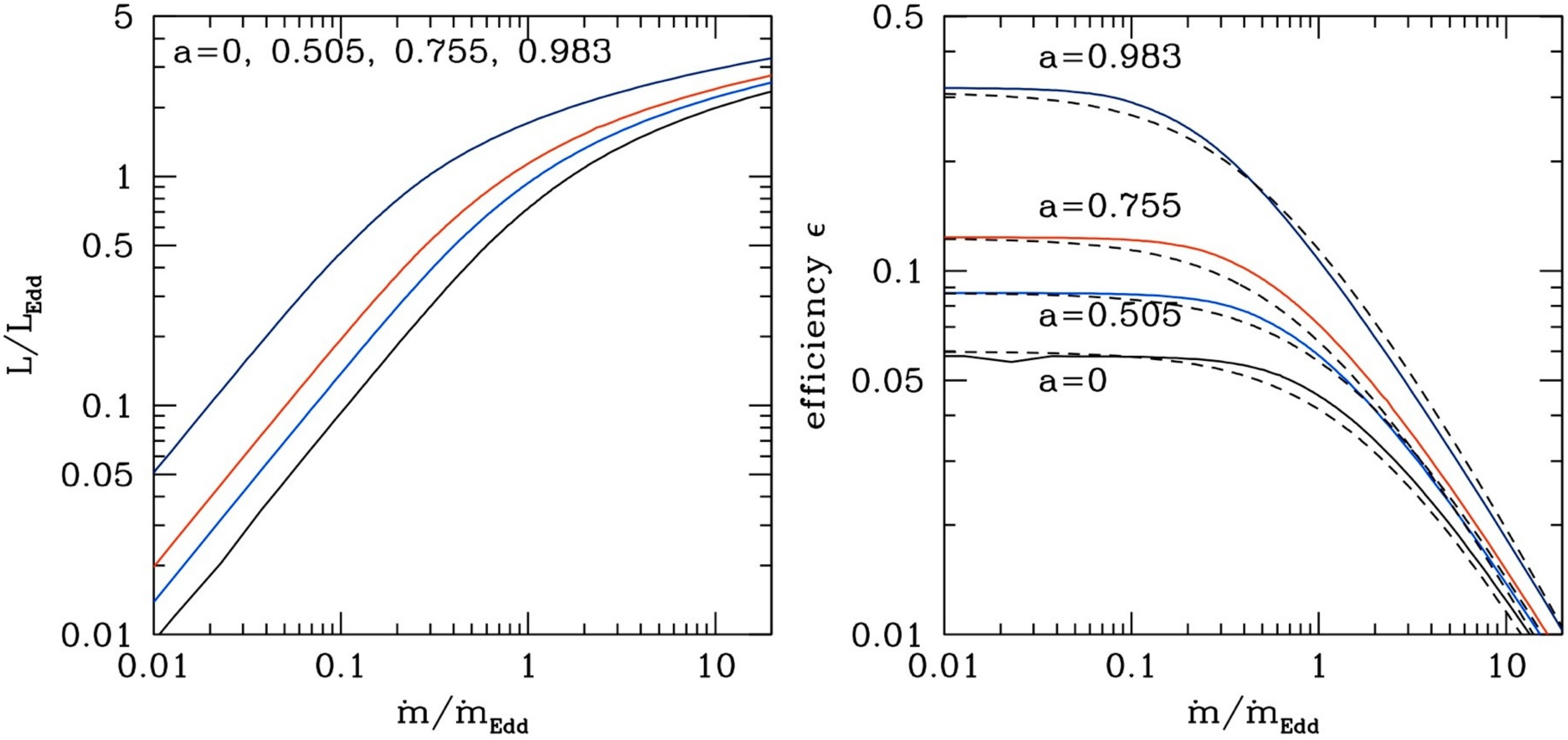
- Imprint of seeds on occupation fraction.
- Observations tell nothing so far.
- Future GW observations (eLISA) of the MBH merger rate at very-high redshifts.

SuperEddington accretion (slim disks)

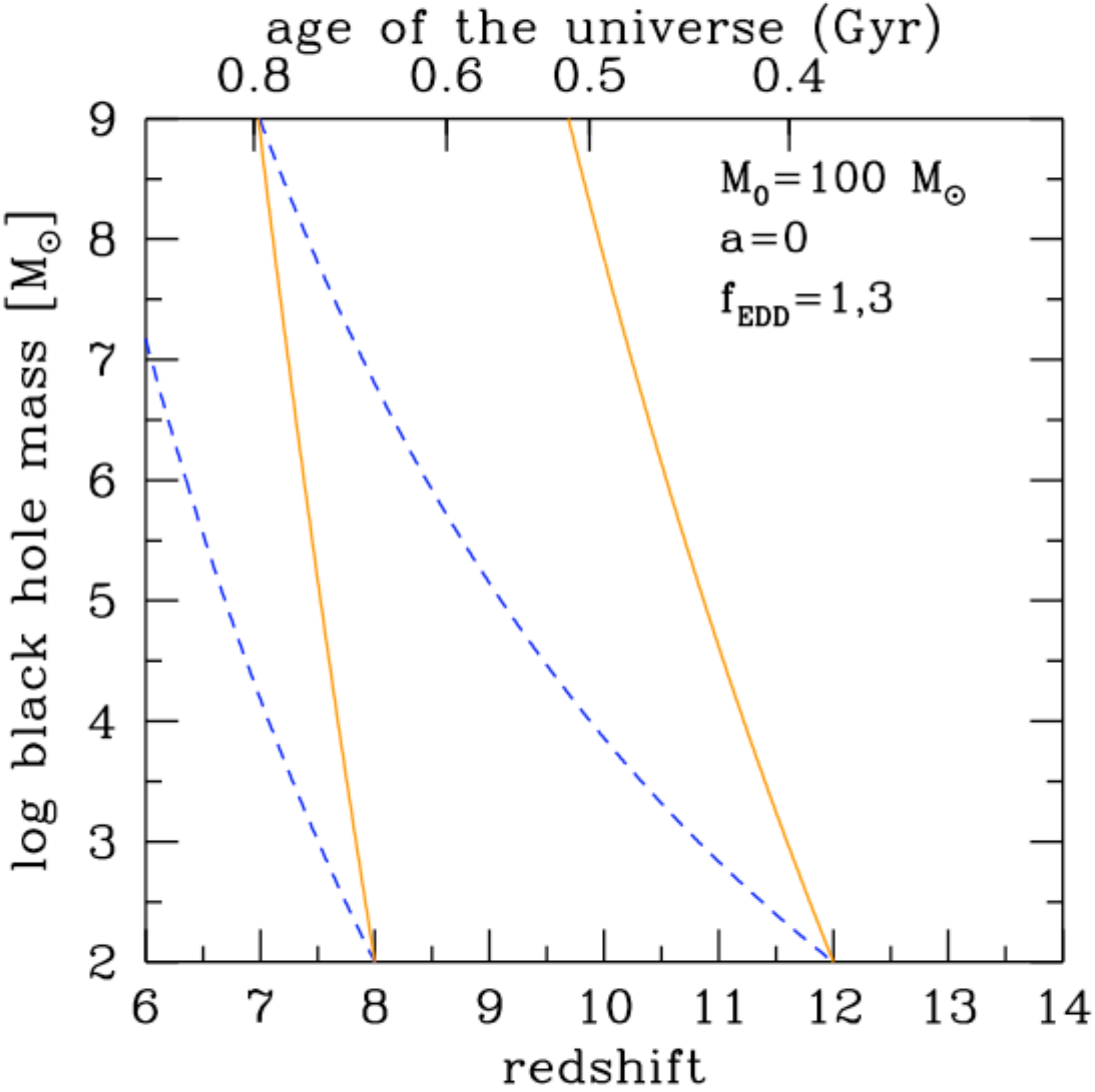
Madau, FH & Dotti 2014

$$M(t) = M_0 \, e^{f_{\rm Edd} \frac{t}{\tau} \frac{1-\epsilon}{\epsilon}}$$

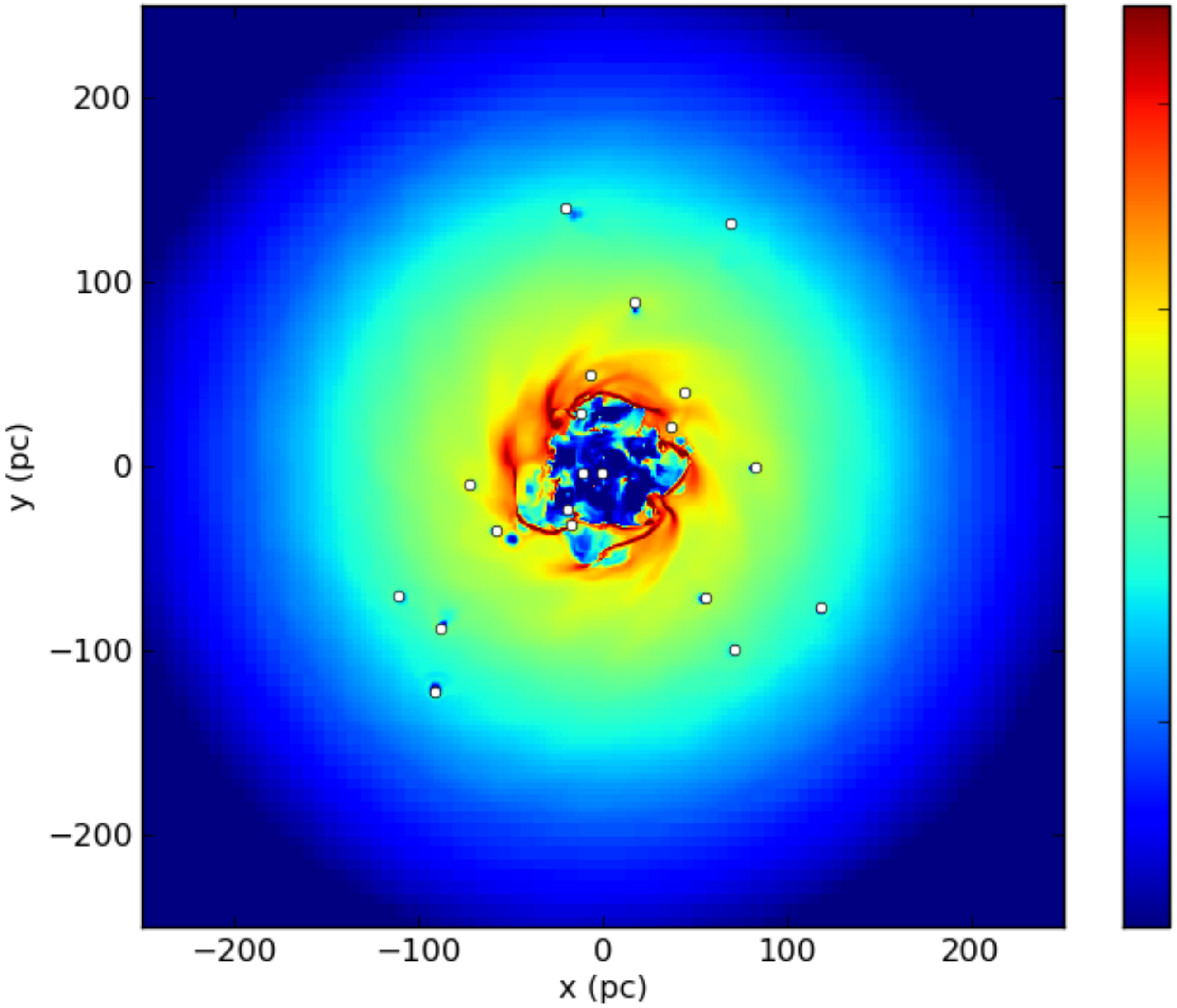
τ≅0.44 Gyrs

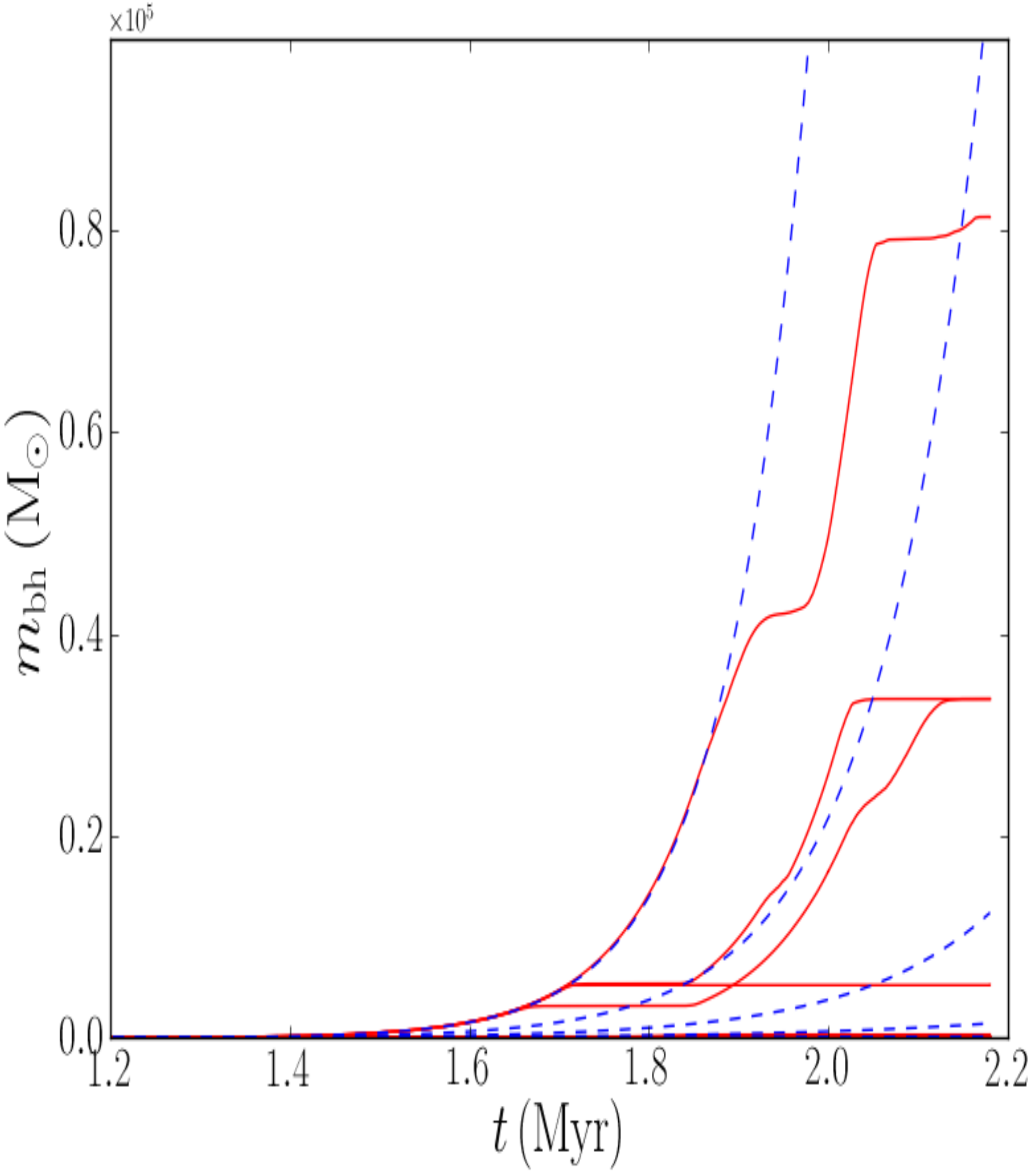


Madau, FH & Dotti 2014



SuperEddington accretion at not-so high z





Lupi et al., in prep