Guillermo Haro Workshop, 2015

Current Paradigm of Direct Collapse BH formation

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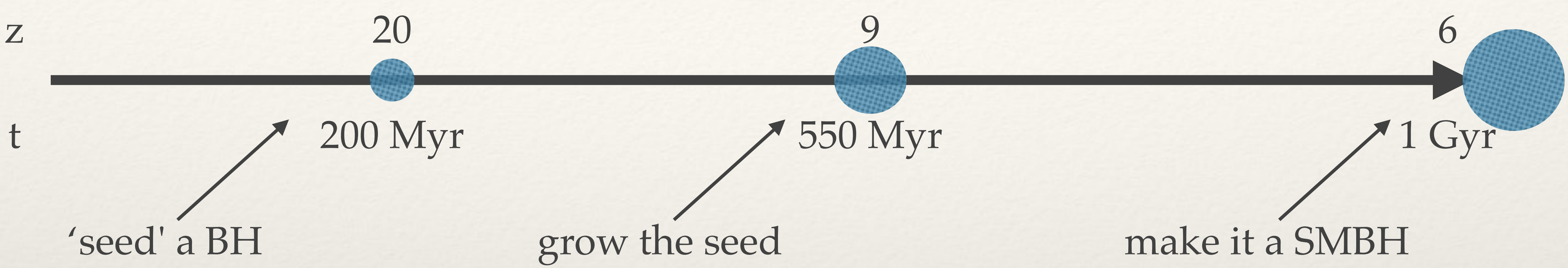
What is the Problem?

- SDSS Quasars at $z > 6$
  highest redshift: $z = 7.085$ (770 Myr) (Momjian et al. 2013)
  most massive: $z = 6.30$ (900 Myr), $M = 1.3\text{x}10^{12}$ (Wu et al. 2015)
- First Stars form at $z = 20$
  Latest Planck results push the z lower !
- How do we grow the Quasars to supermassive scales?
  time scale is $t(z_6) - t(z_{first\_star}) \sim 700$ Myr*

*Take this time with a pinch of salt

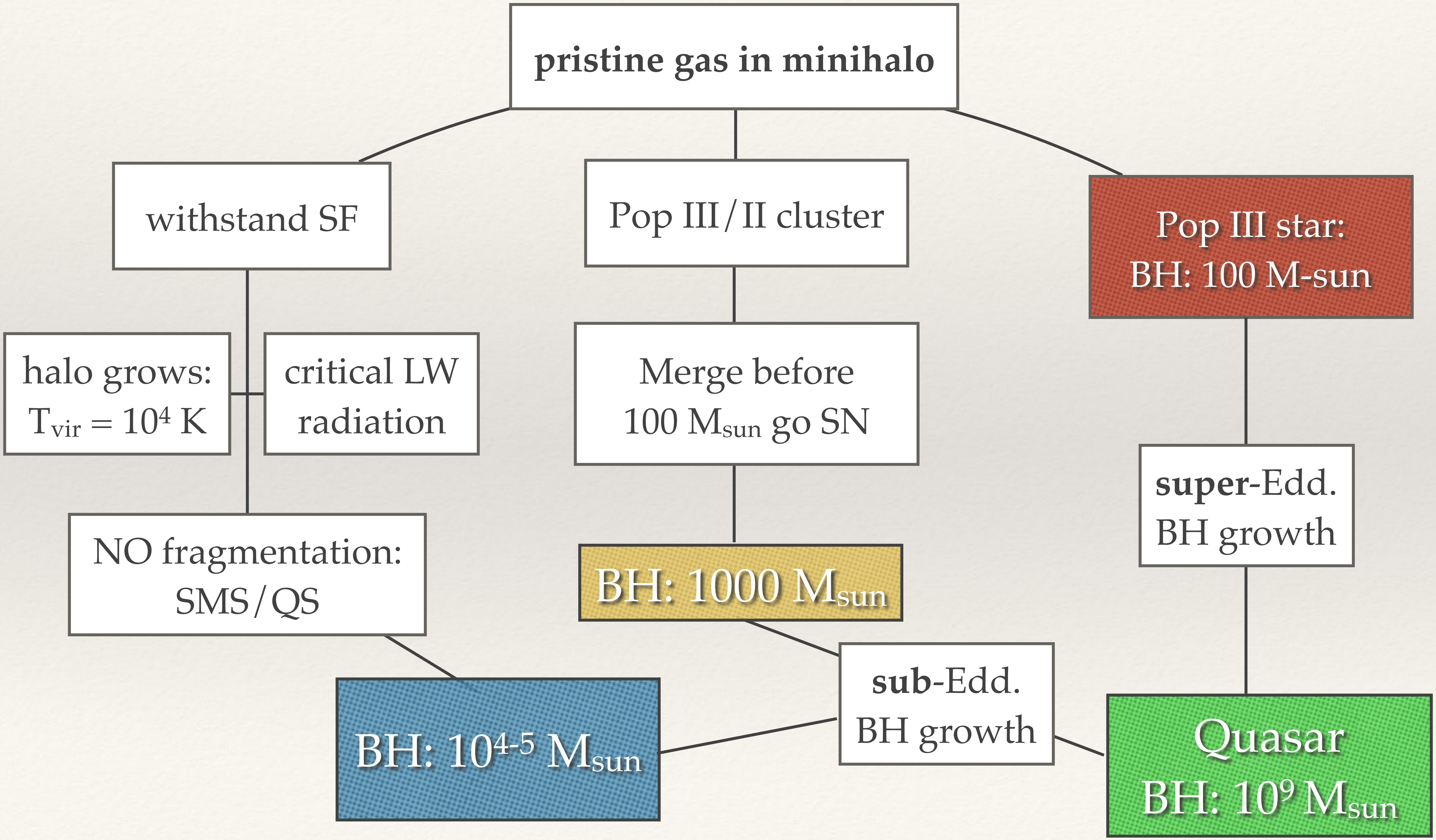
Solving the problem



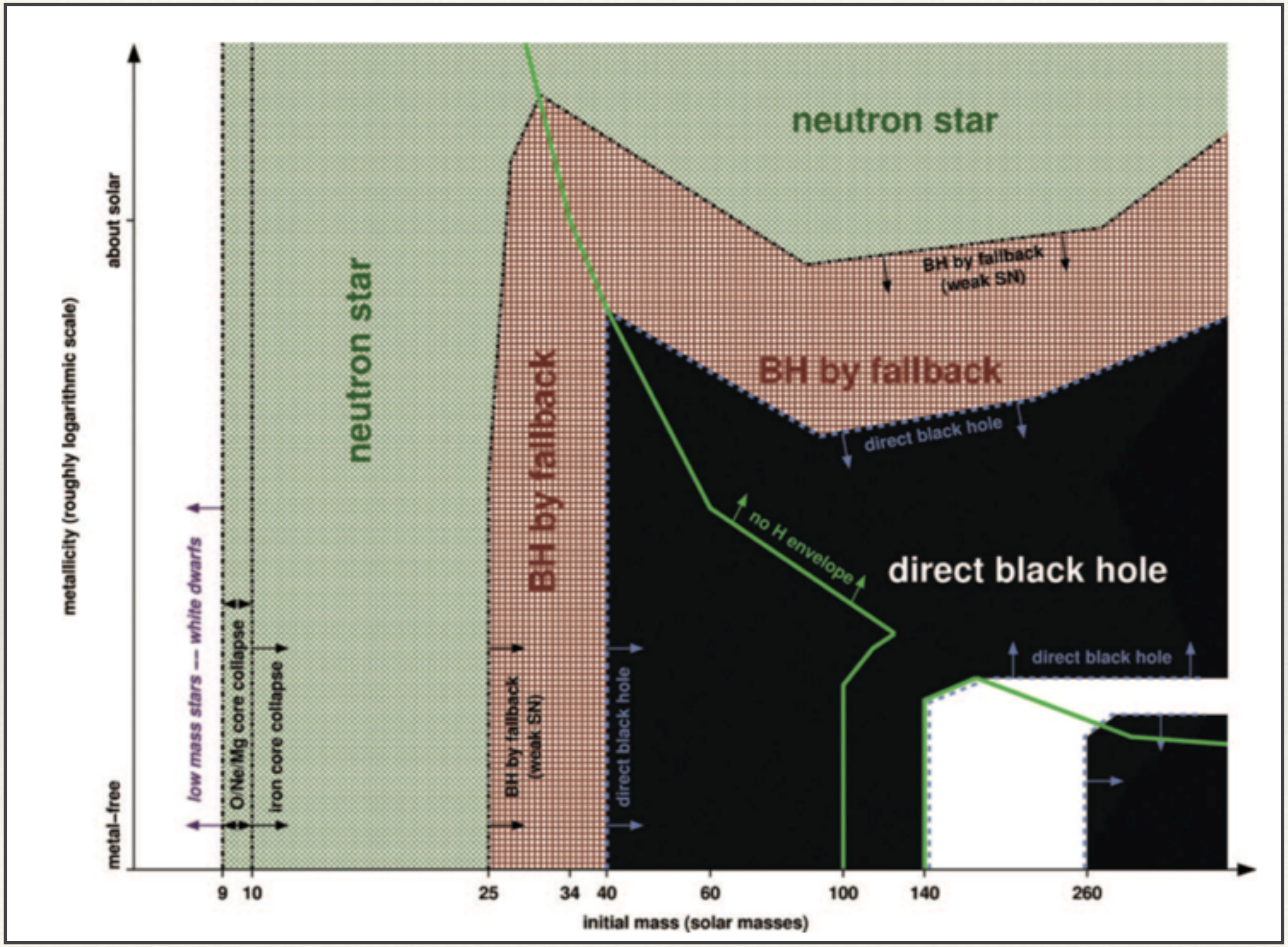
- For a given BH growth scenario: Bondi-Hoyle, Eddington etc.

- sensitive to two parameters — M_{seed}, t_{grow}

The Possible Paths



PopIII stellar BH seeds

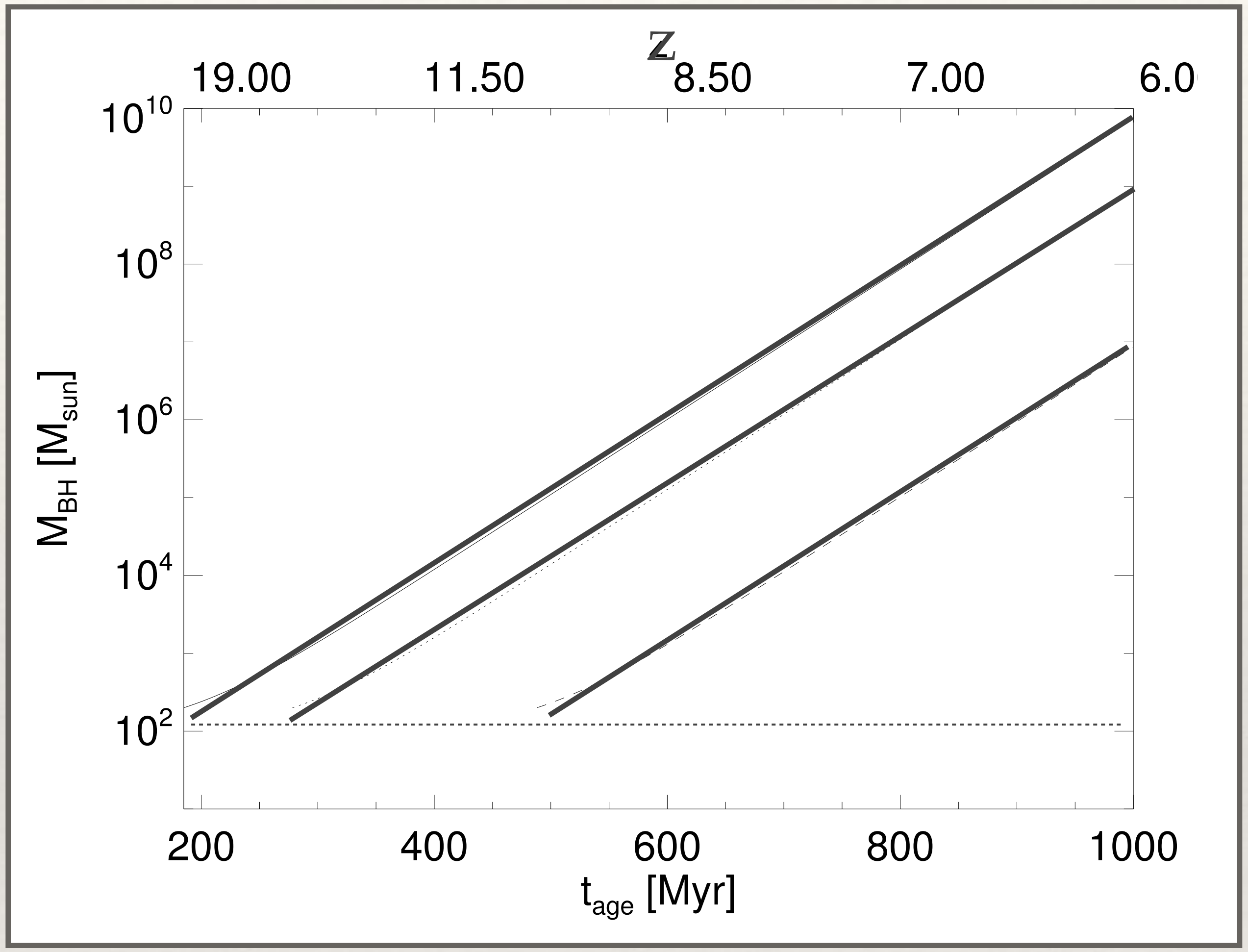


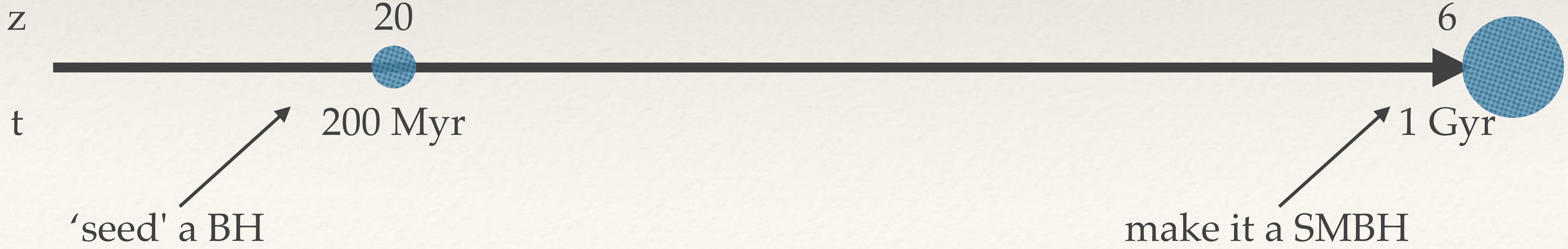
Heger et al. 2003

PopIII stellar BH seeds

Volonteri et al.
Bromm et al.
Yoshida et al.

- Assuming
  $f_{edd} = 1$
  rad. eff = 0.1
- $M_{seed} = 100\ M_{sun}$
- t_{grow} :
  $t_1\{z(20 - 6)\} = 700$ Myr
  $t_2\{z(9 - 6)\} = 200$ Myr



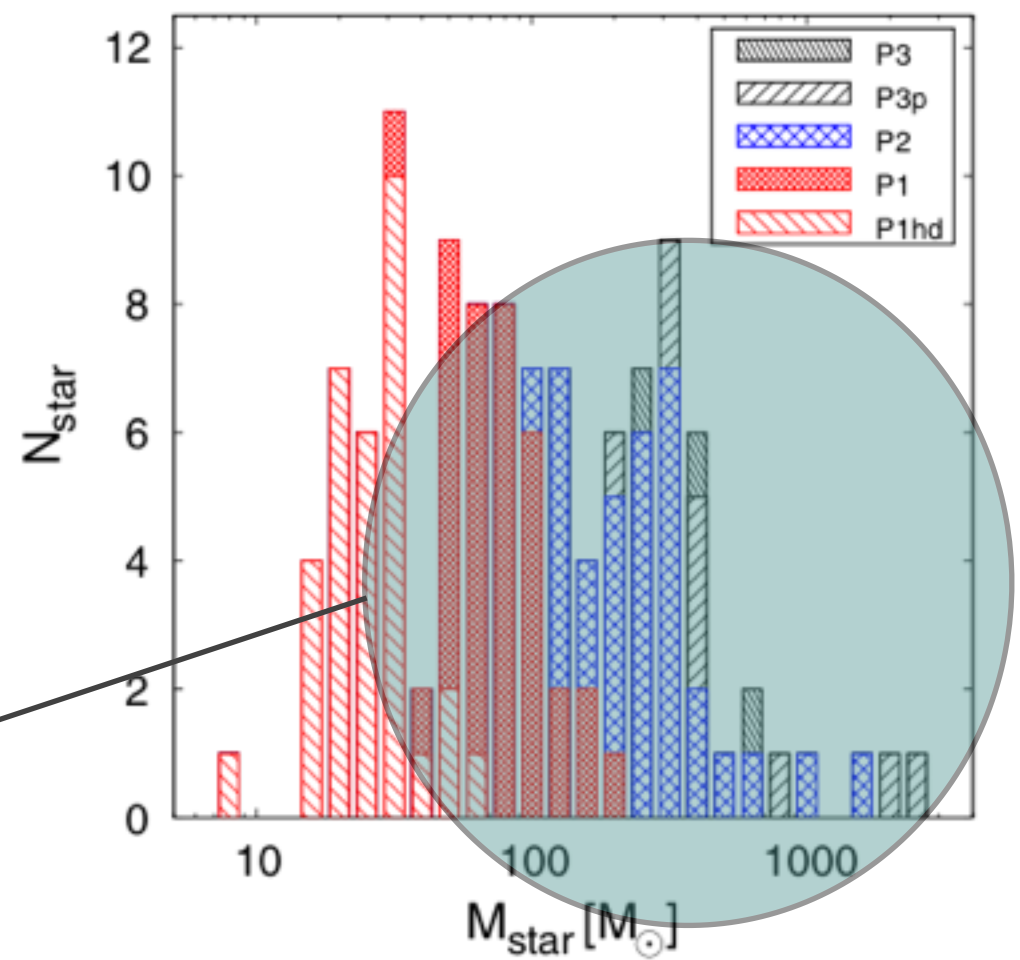


PopIII stellar BH seeds: IMF

- PopIII : IMF
- Highest mass: 1000 M_{sun}

- $M_{star} > 100\ M_{sun}$
- desirable seed mass!

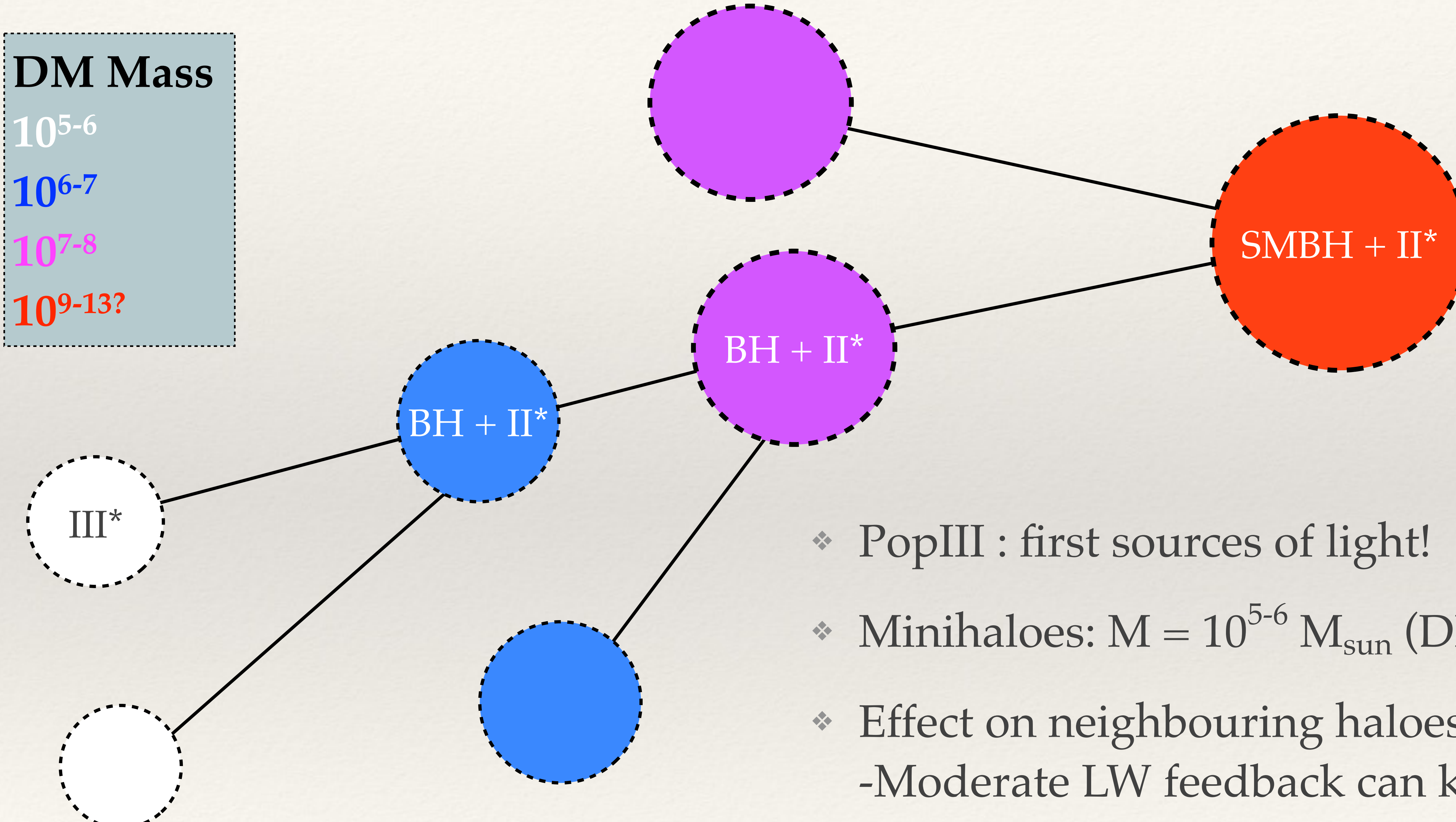
- Doesn’t have to be ‘too' common



Hirano et al. 2014

Figure 5. Final distribution of the calculated stellar masses for our 110 first stars. The red, blue, and black histograms represent the different paths of protostellar evolution: P1: KH contracting protostar (red), P2: oscillating protostar (blue), and P3: supergiant protostar (black). See the text in Section 2.2.1 for details. P1hd refers to the cases in which the gas clouds are formed by HD cooling and evolve on low-temperature tracks. P3p (predicted) indicates the same cases as P3, except that the final masses are calculated from a correlation between the properties of the cloud and the resulting stellar mass (Equation (13); see Appendix B).

PopIII stellar BH seeds: where?



- PopIII : first sources of light!
- Minihaloes: $M = 10^{5\text{-}6}\ M_{sun}$ (DM)
- Effect on neighbouring haloes:
  -Moderate LW feedback can kill SF
  -X-rays feedback
  -SN 'blow out'

PopIII stellar BH seeds: problems

- Assuming
  $f_{edd} = 1$
  rad. eff = 0.1
- $M_{seed} = 100\ M_{sun}$
- t_{grow} :
  $t_1\{z(20 - 6)\} = 700$ Myr
  $t_2\{z(9 - 6)\} = 200$ Myr

highly optimistic scenario!
ignores feedback

where is the gas?
constant availability of gas

form in mini-haloes!
merger scenario unclear

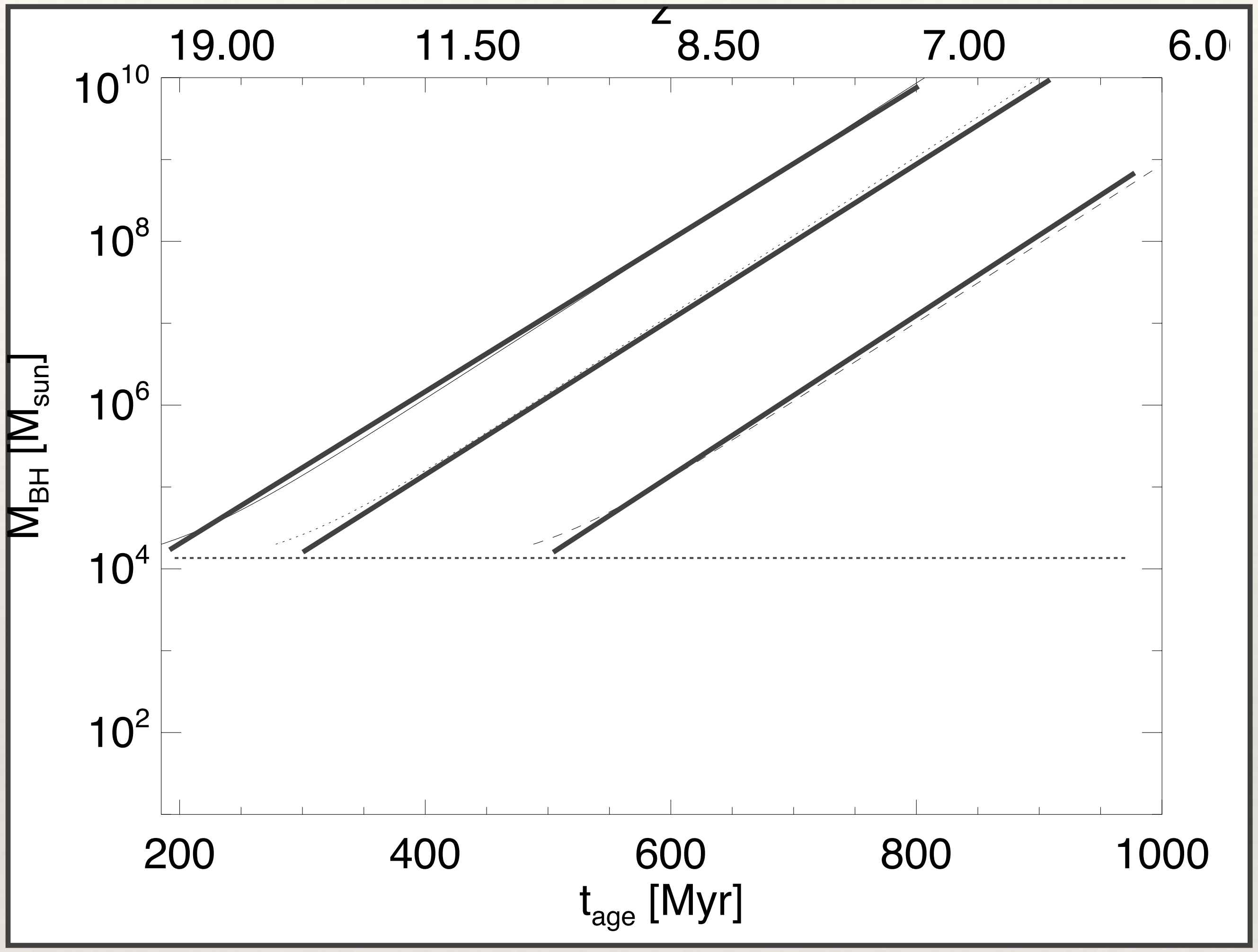
merger b/w 2 mini-haloes
- time-scale
- BH present in both

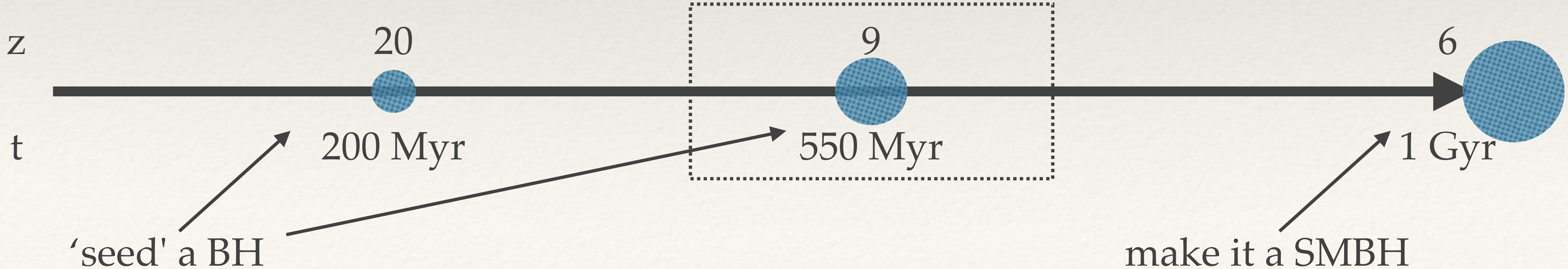
need to be super-Edd!
all the time!

Direct Collapse BH seeds

Eisenstein & Loeb
Oh & Haiman
Bromm & Loeb
Koushiappas et al.
Bullock & Dekel
Lodato & Natarajan

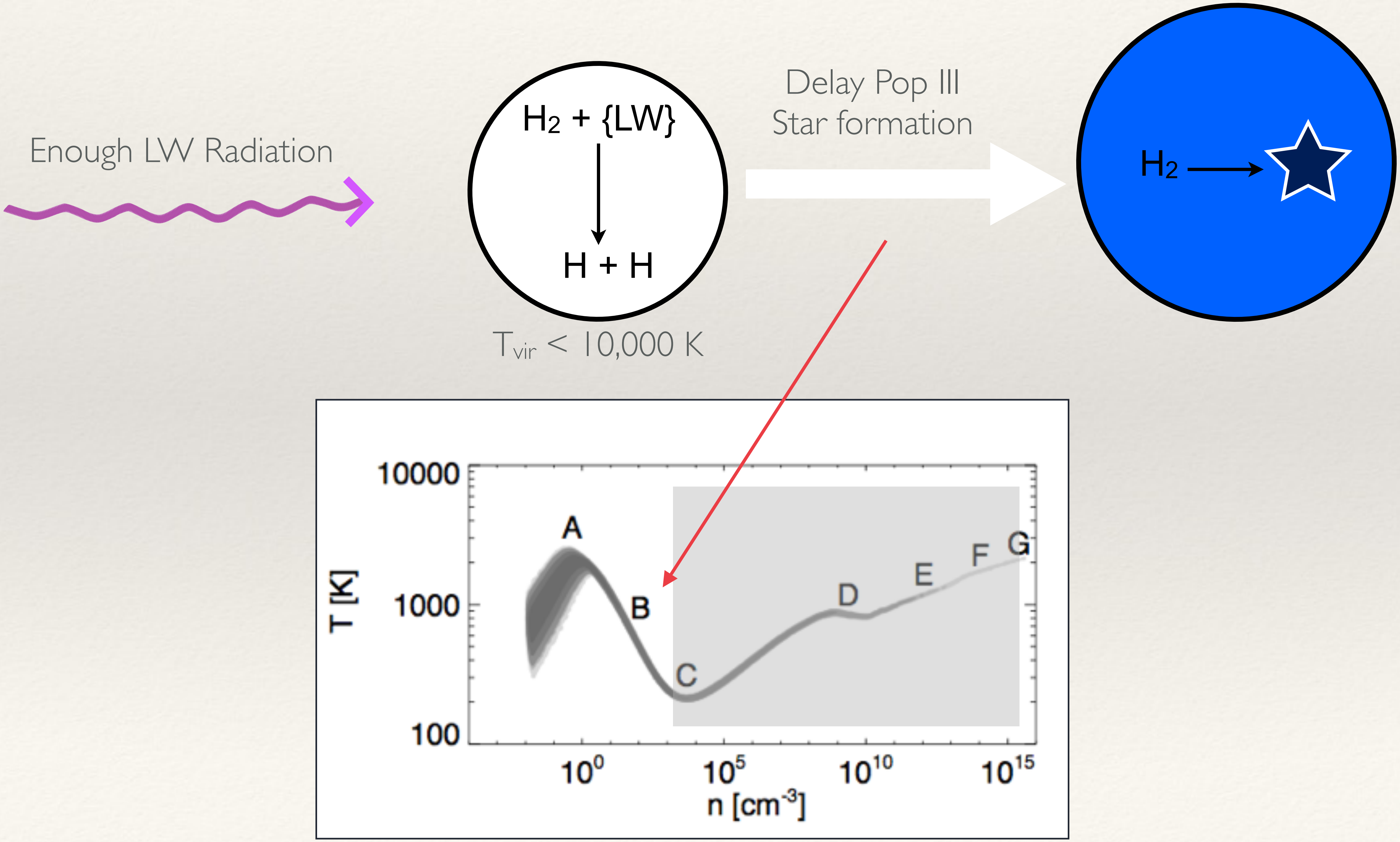
- Assuming
  $f_{edd} < 1$
  rad. eff = 0.1
- $M_{seed} = 10^{4\text{-}5}\ M_{sun}$
- t_{grow} :
  $t_1\{z(20 - 6)\} = 700$ Myr
  $t_2\{z(9 - 6)\} = 200$ Myr





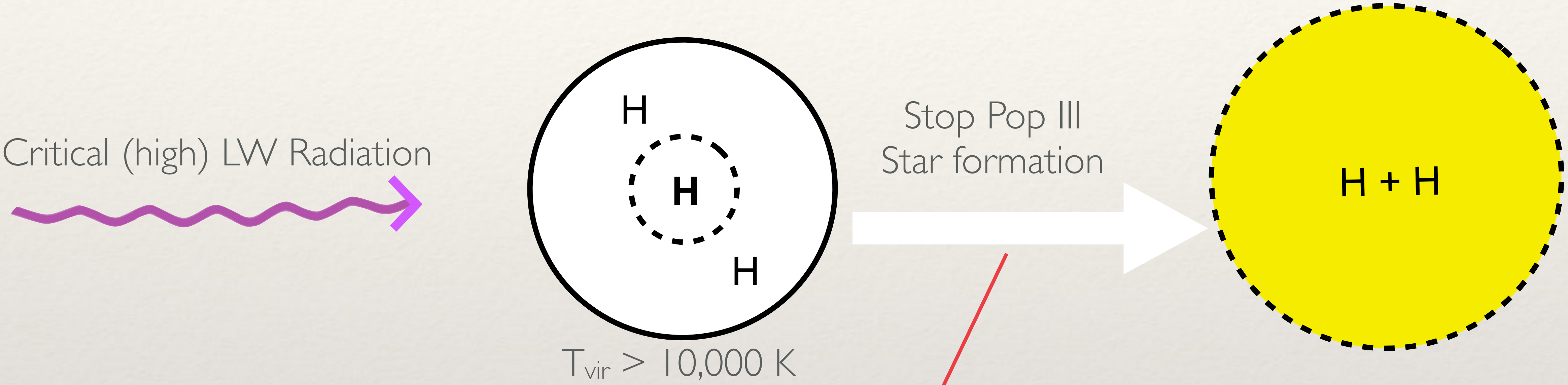
DCBH seeds: how

LW photons: 11.2 - 13.6 eV

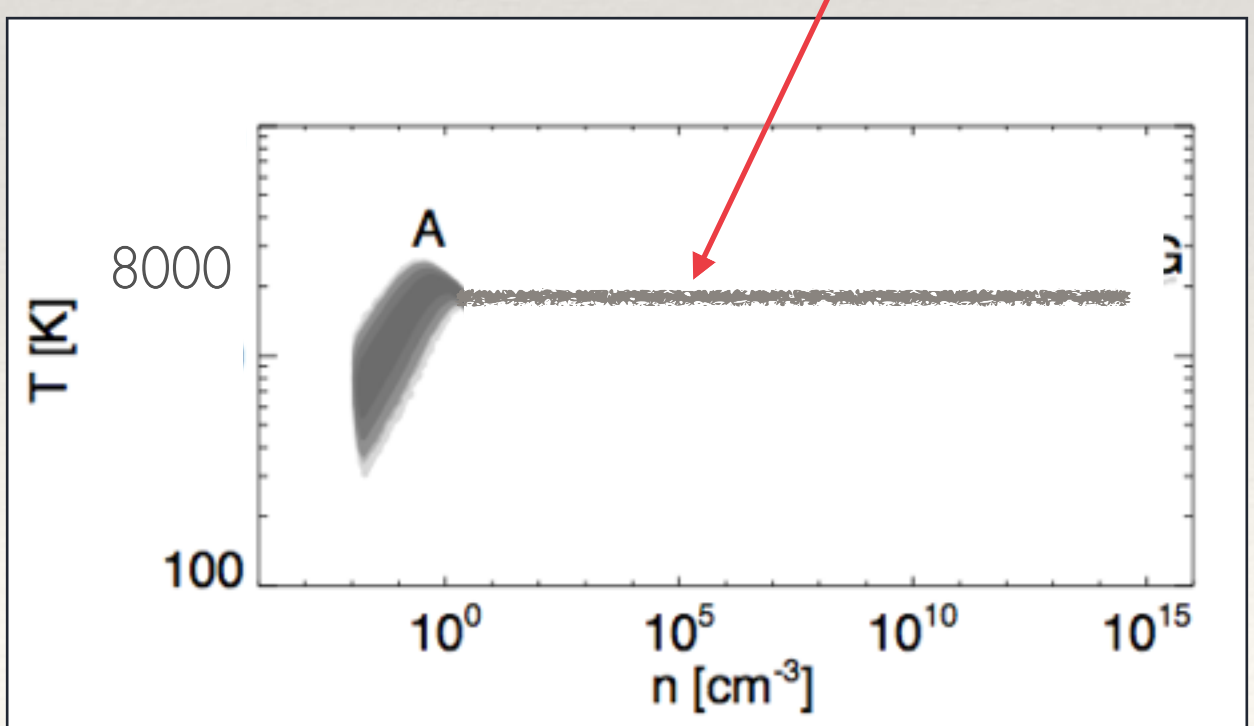


DCBH seeds: how

LW photons: 11.2 - 13.6 eV



- Pop III
  $n = 10^5\ cm^3$
  $T = 200\ K$
- $M_{BE} \sim 100\ M_{sun}$



- DCBH
  $n = 10^5\ cm^3$
  $T = 8000\ K$
- $\mathbf{M_{BE} \sim 10^5\ M_{sun}}$

DCBH seeds: problems

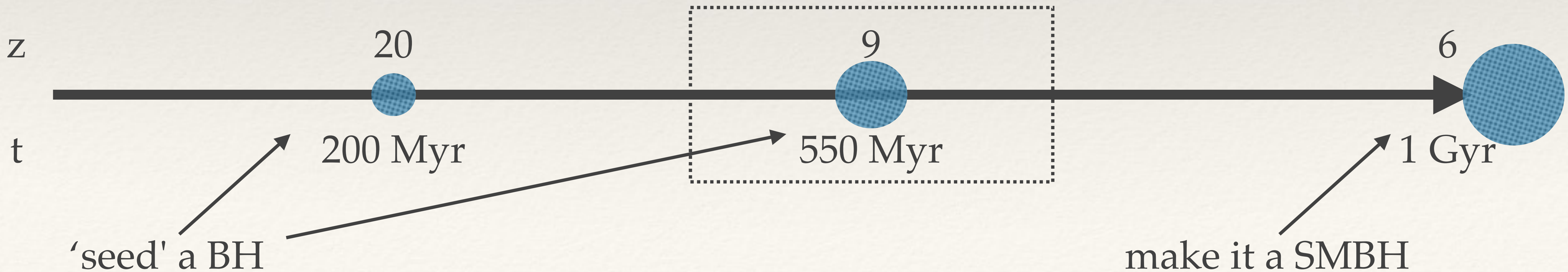
- Assuming
  $f_{edd} < 1$
  rad. eff = 0.1
- $M_{seed} = 10^{4\text{-}5}\ M_{sun}$
- t_{grow} :
  $t_1\{z(20 - 6)\} = 700$ Myr
  $t_2\{z(9 - 6)\} = 200$ Myr

What is the critical LW flux?

HOW does the gas collapse proceed?

Feedback from the DCBH once it forms

Subsequent merger:
with the LW producing galaxy



Do you like movies?

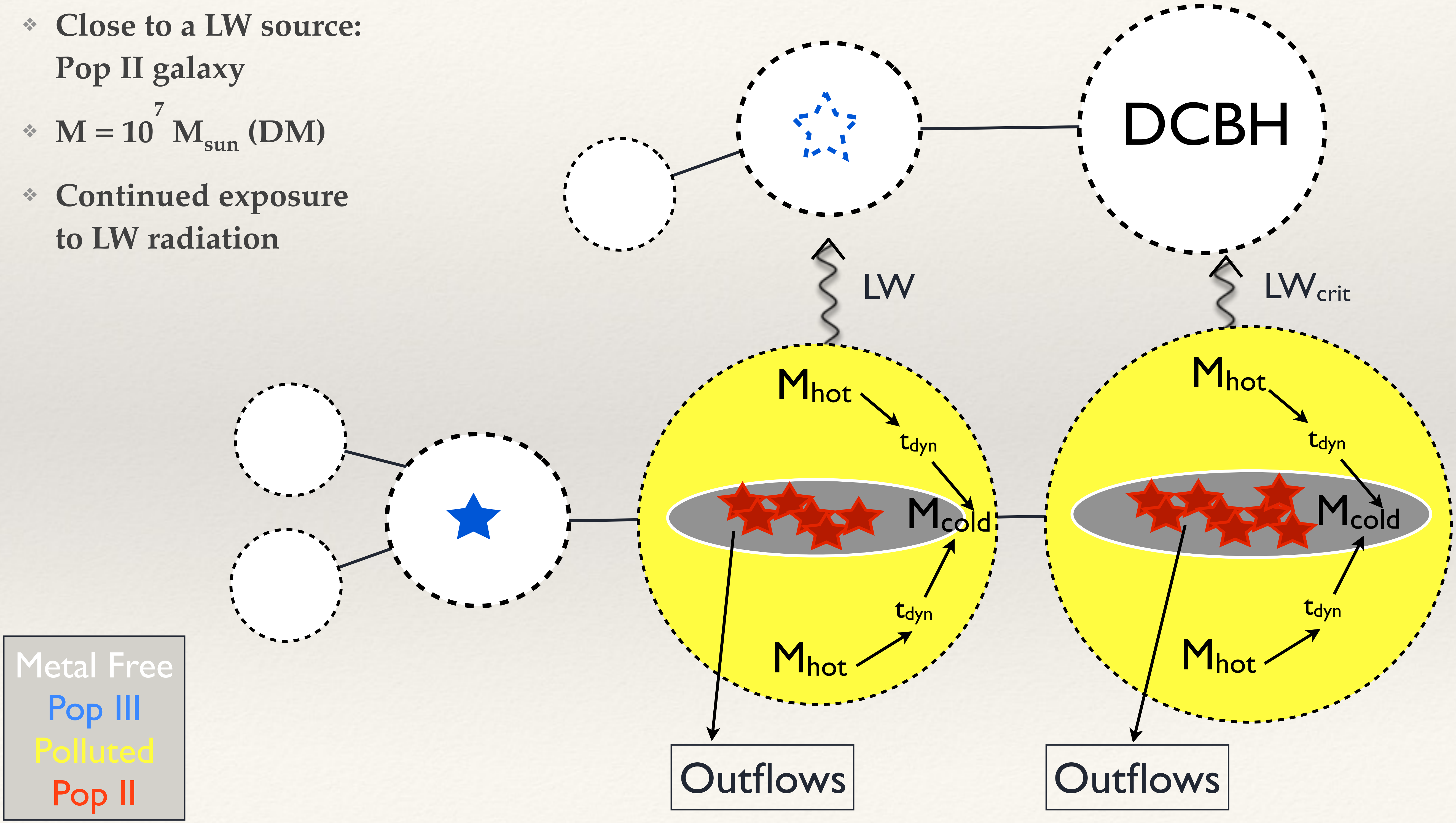
Films, cinema. NOT simulation movies…

My guilty pleasure: BOLLYWOOD!

1. Introduce the audience to your plot
2. Everything is OK, songs/dance
3. Something bad happens!
4. Oh No!
5. There is hope…

DCBH seeds: where

- Close to a LW source: Pop II galaxy
- $M = 10^7\ M_{sun}$ (DM)
- Continued exposure to LW radiation



DCBH seeds: The Hunt

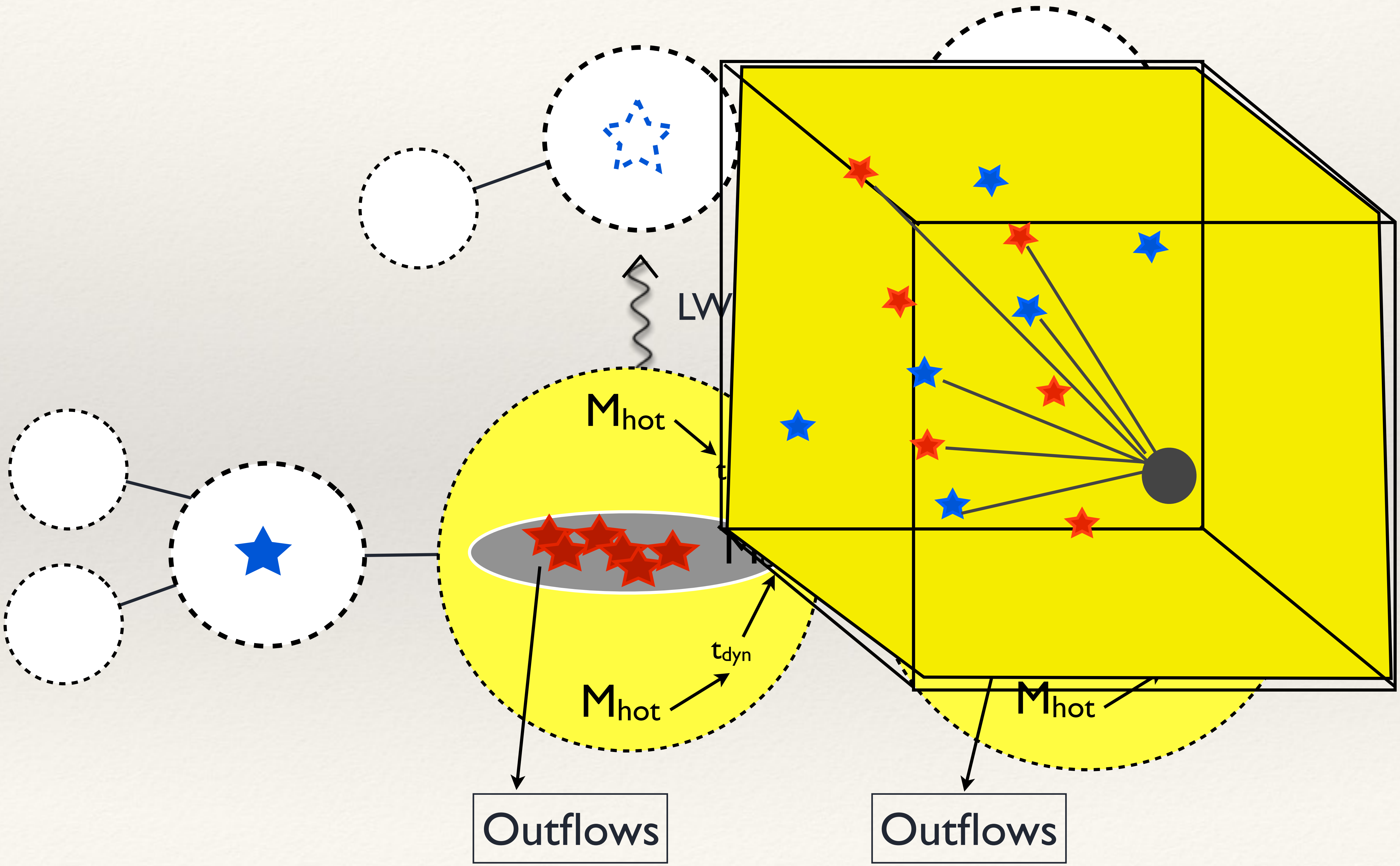
	SAM Agarwal et al. 2012	**FiBY** Dalla Vecchia et al. Agarwal et al. 2014
Cosmological Volume	Yes	Yes
Minihaloes resolved	Yes	Yes
Halo histories	Yes	Yes
Outflows	Yes	Yes
Pop III + Pop II	Yes	Yes
LW radiation: Spatial + Global	Yes	Yes
Gas	**No**	Yes
IGM Metal Dispersion	**No**	Yes

DCBH seeds: The Hunt (SAM)

- SAM
- Halo history: Merger Trees
- Subfind output: LCDM simulation
- Min halo mass required : at least 10^6 M_{solar}

Box Size	Cosmology	$N_{particles}$	Min. Halo Mass	z_{final}
4.86 Mpc	WMAP 7	768^3	10^5 M_{solar}	6

DCBH seeds: The Hunt (SAM)



DCBH seeds: The Hunt (SAM)

- **Reionisation feedback:**
  13.6 eV : photoionisation / heating of gas in haloes
  gas needs a larger potential well to re-collapse
  Vc = 20 km/s
  (Dijkstra '08)

- **LW Escape Fractions:**
  more photons = more feedback
  (Ahn et al. '09, Kitayama '04)

- **Stars:**
  Pop II stars (Starburst 99)
  sfe: 1 %

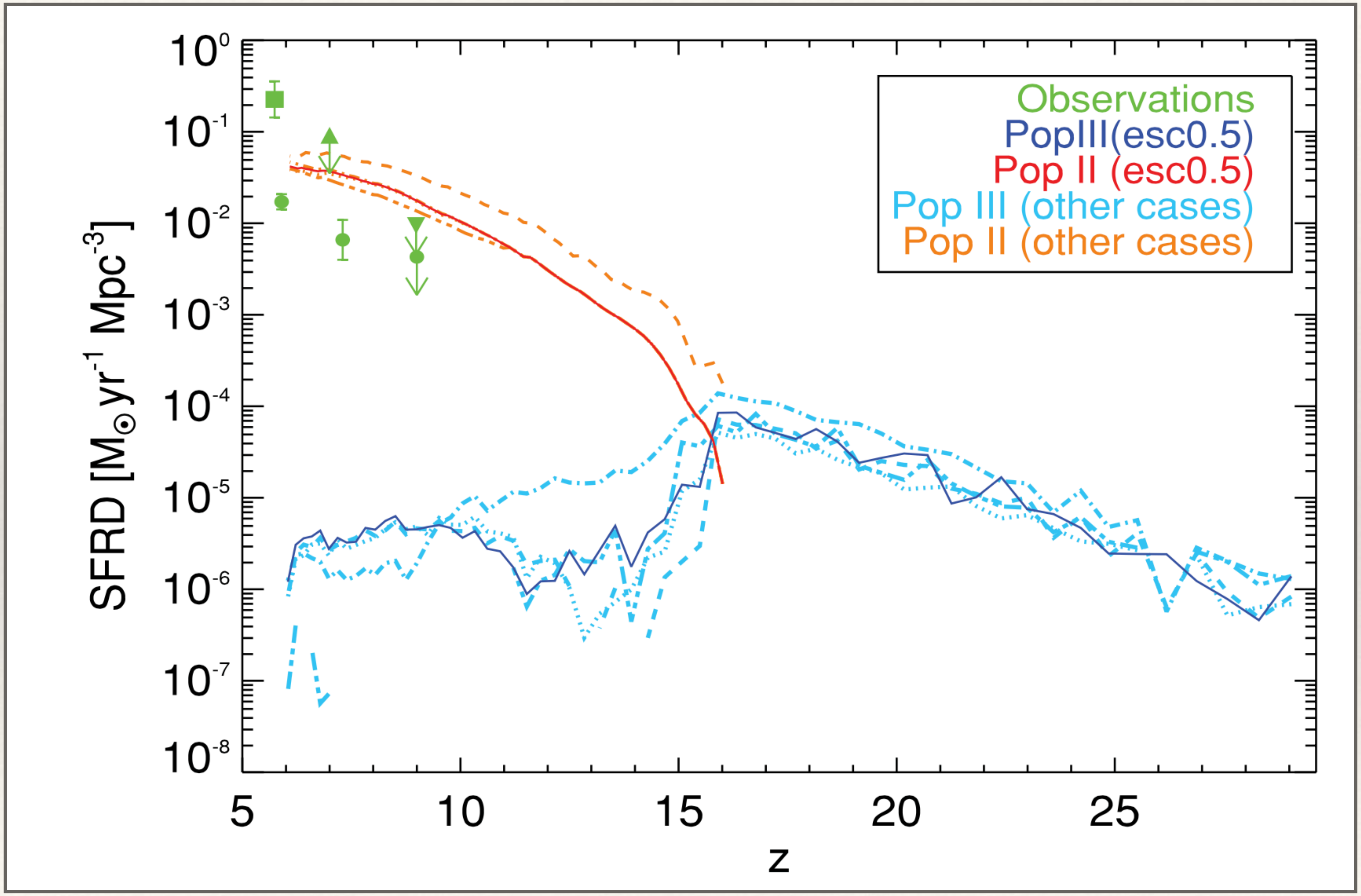
  Pop III stars (Schaerer et al.)

Range of SAM models

Each explores a different parameter set

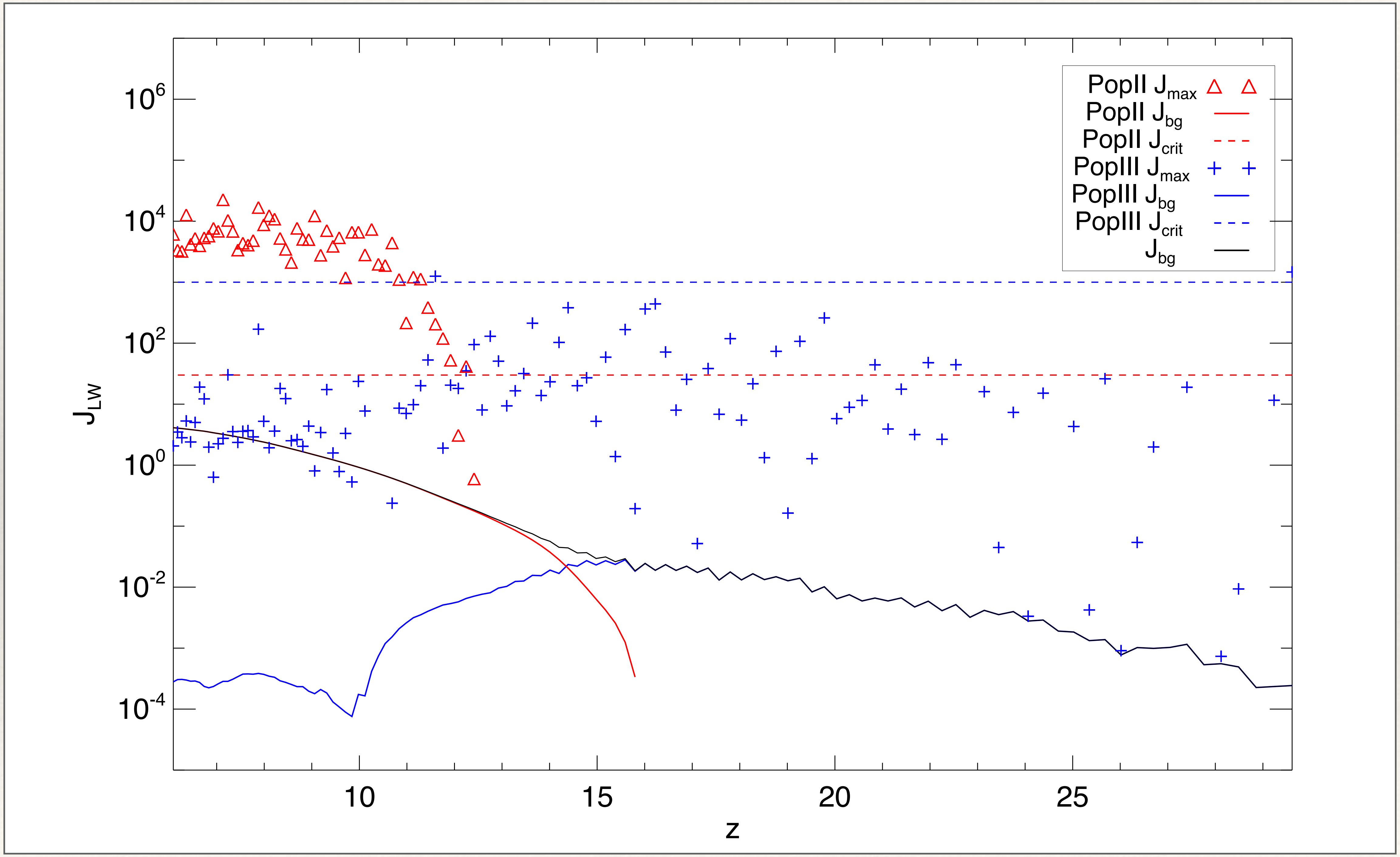
Most vs. Least optimistic scenarios

DCBH seeds: The Hunt (SAM)



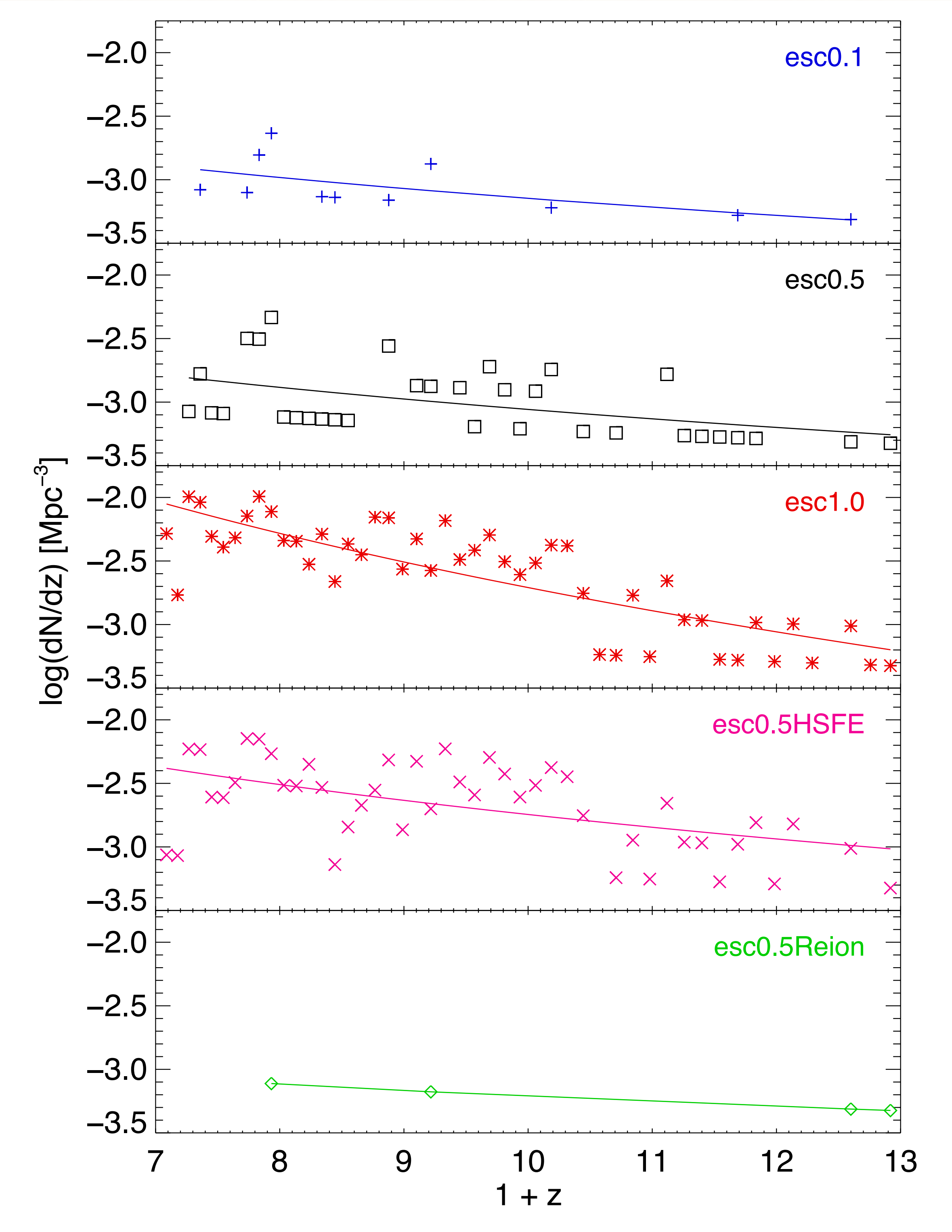
Agarwal et al. 2012

DCBH seeds: The Hunt (SAM)



Agarwal et al. 2012

DCBH seeds: The Hunt (SAM)



DC sites:

Few (<10) at z>6

in a ~100 cMpc^3 box

Quasars:

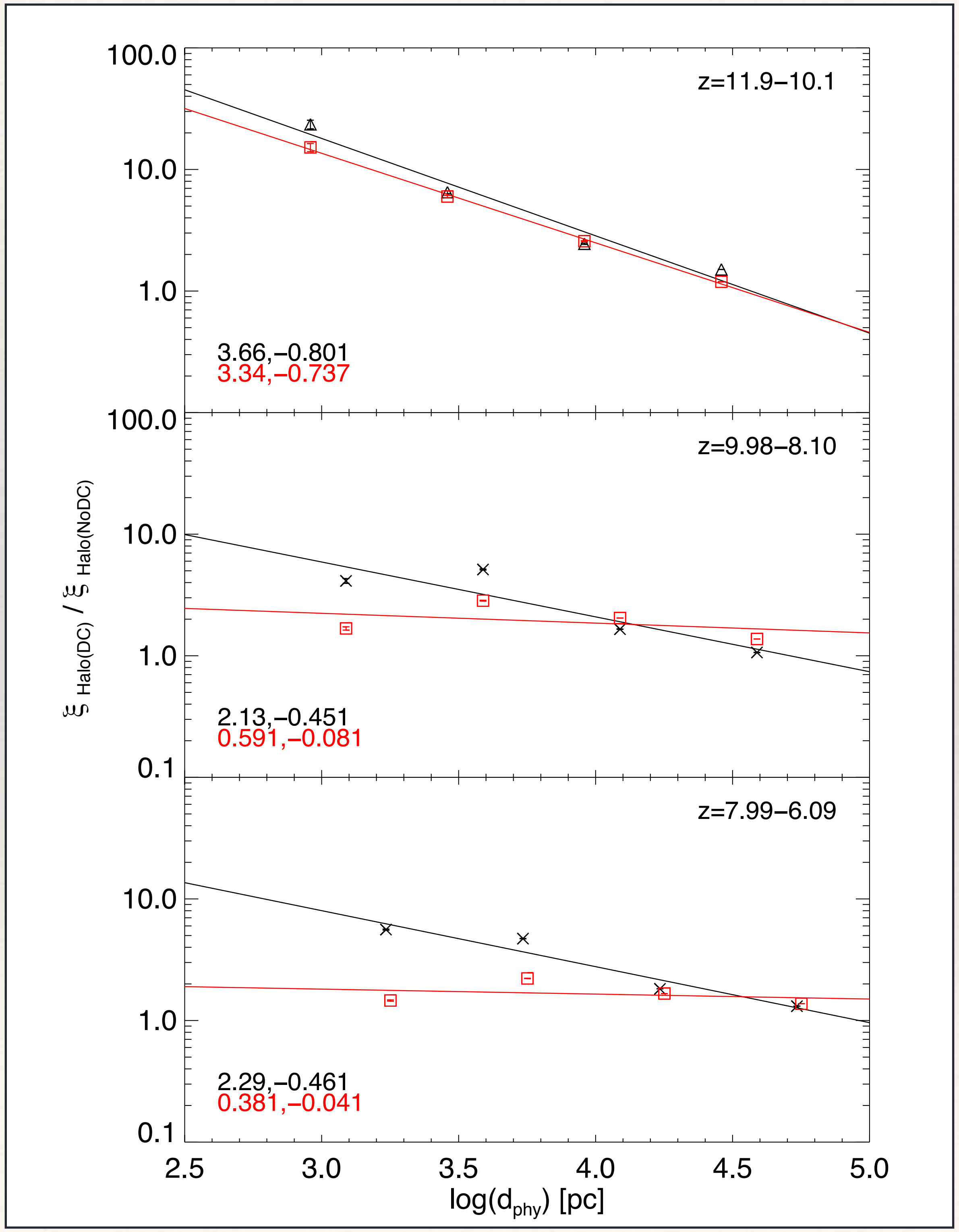
few / Gpc^3 at z>6

Discrepancy:

10^7 objects too many! (?)

Agarwal et al. 2012

DCBH seeds: The Hunt (SAM)

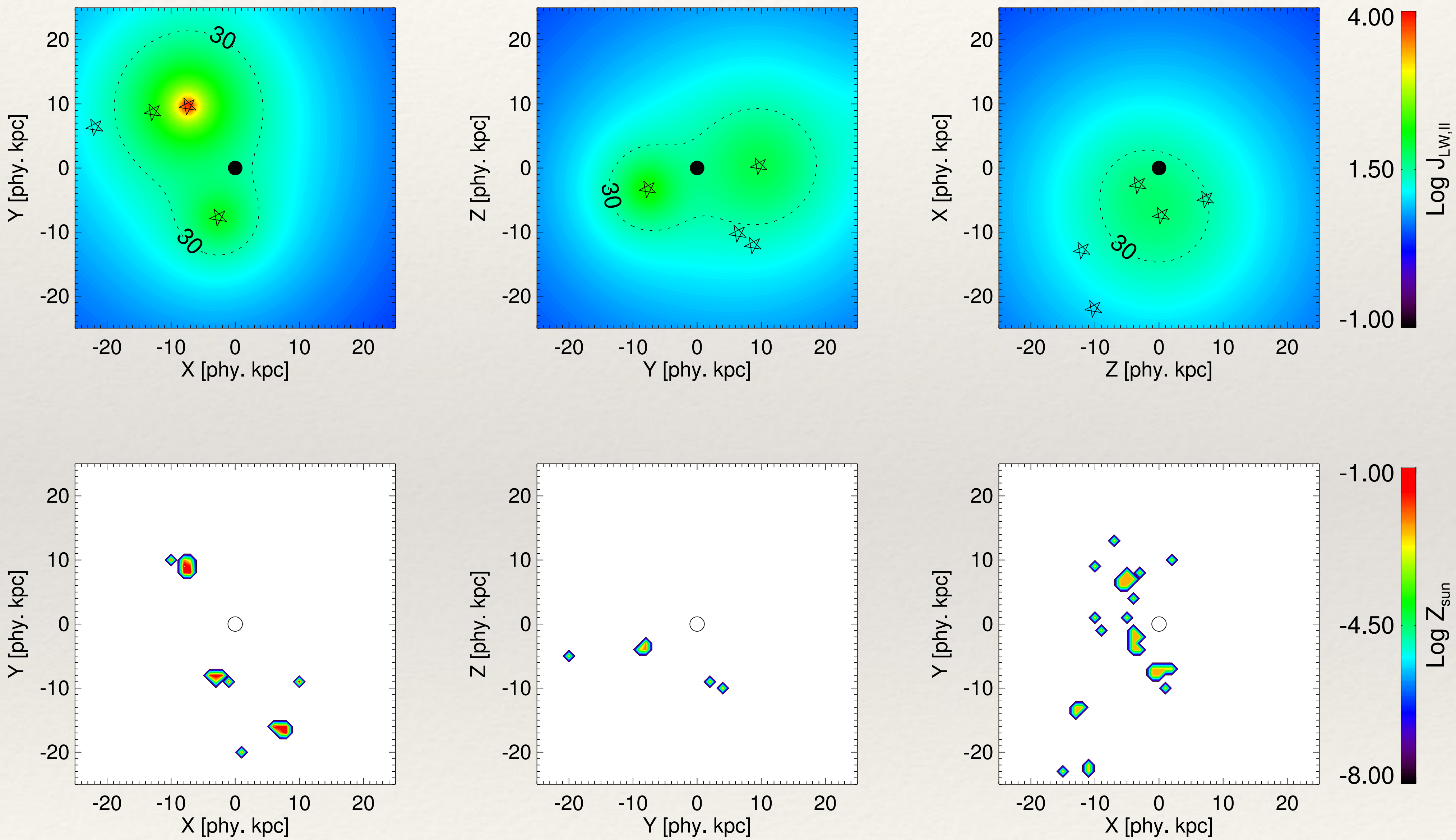


- Steeper Two point correlation
- DC sites prefer a more clustered neighbourhood
- Need to be close to a larger galaxy giving out critical LW flux

Agarwal et al. 2012

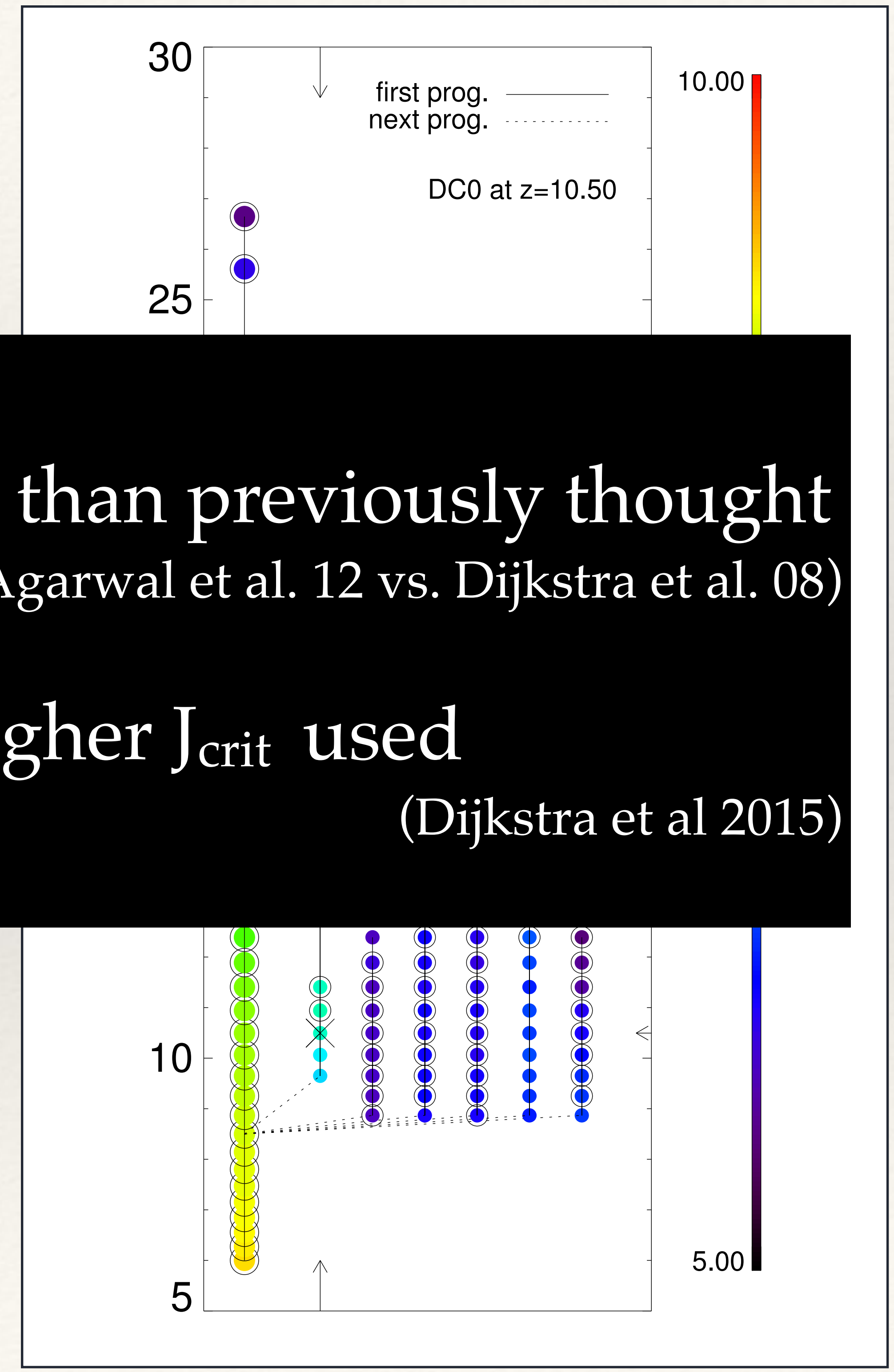
DCBH seeds: The Hunt (FiBY)

DCBH seeds: The Hunt (FiBY)



Agarwal et al. 2014a

DCBH seeds: The Hunt (FiBY)



DC (sites) seems to be more probable than previously thought

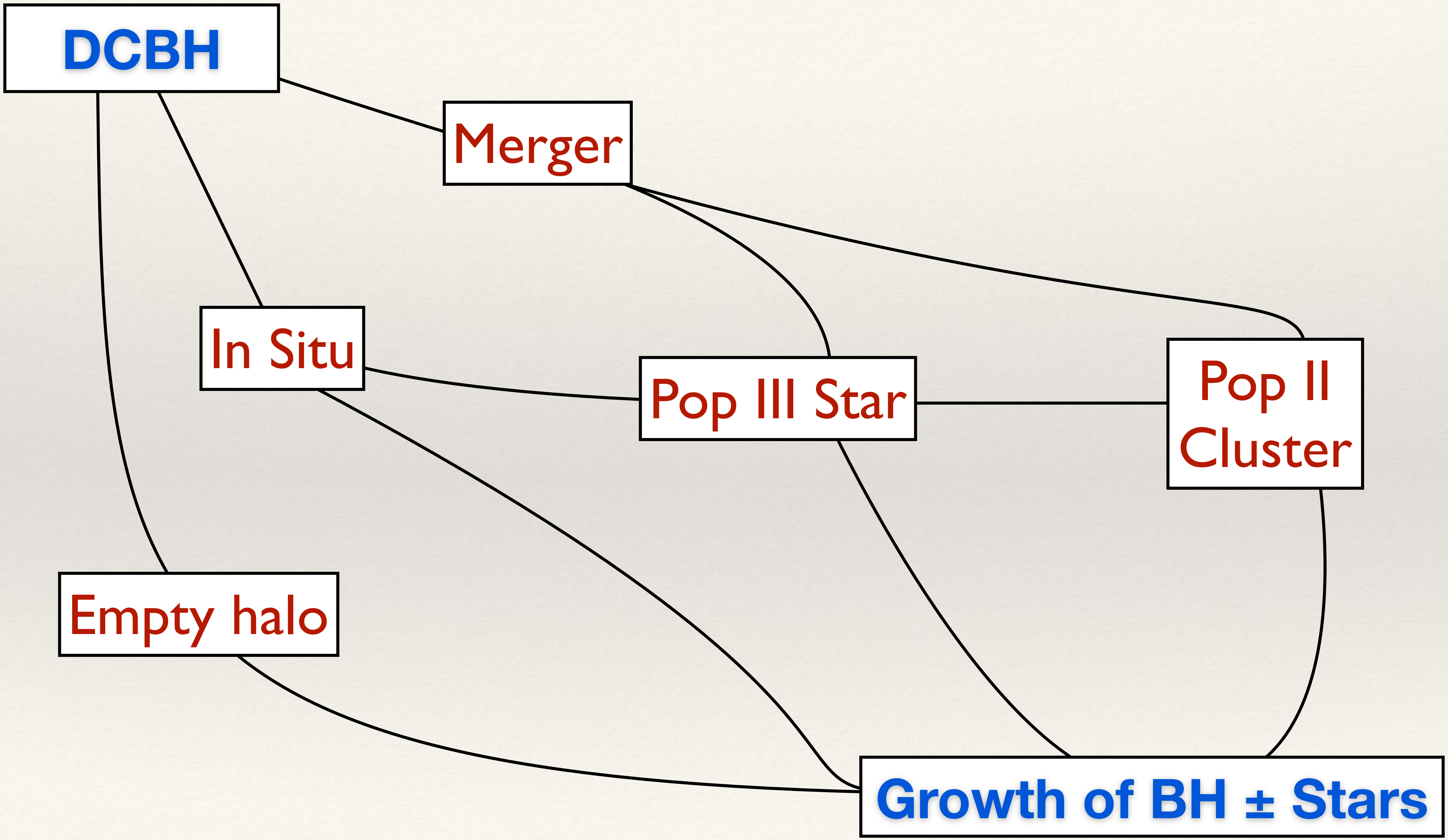
(Agarwal et al. 12 vs. Dijkstra et al. 08)

Discrepancy broken if a higher J_{crit} used

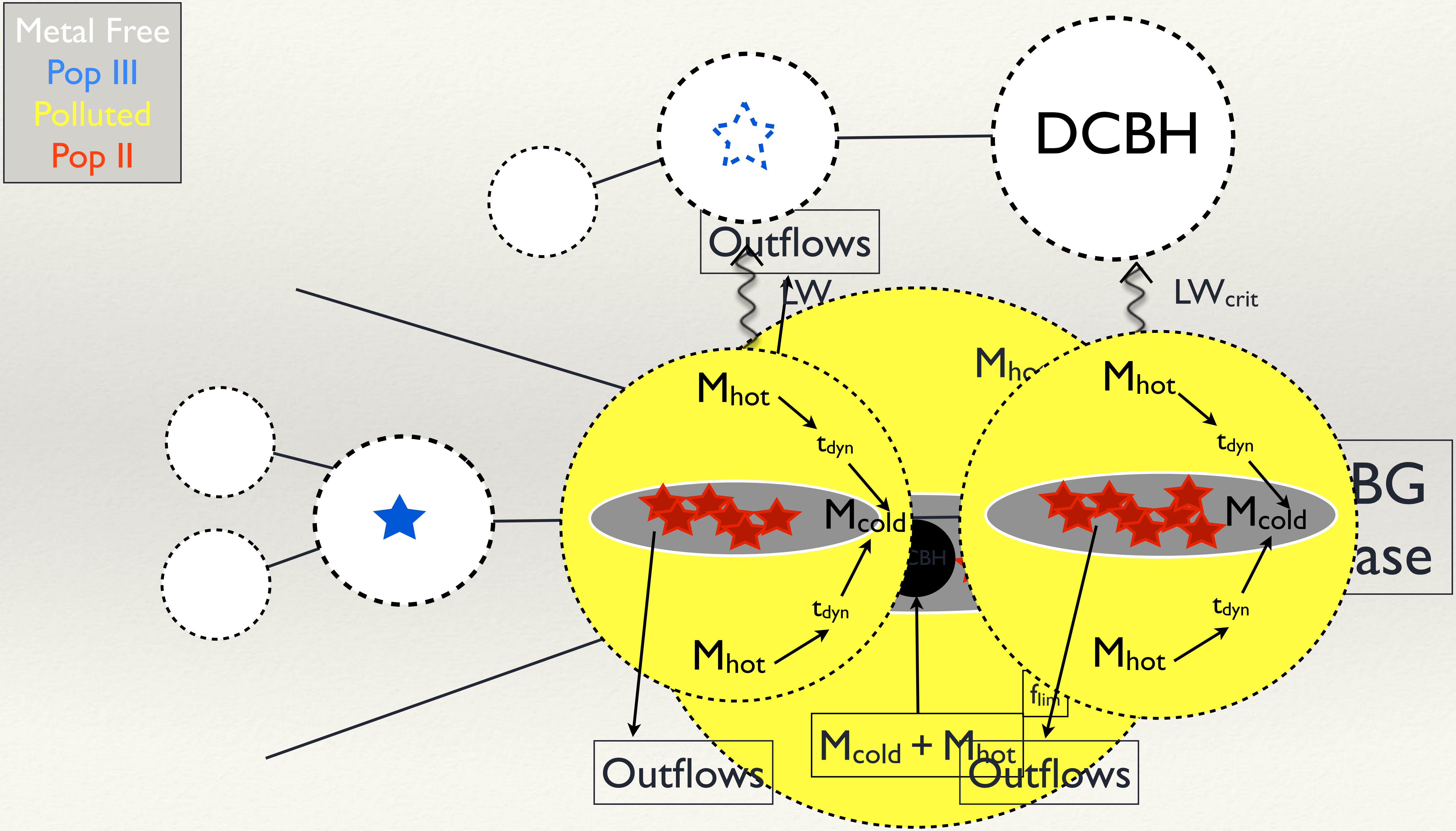
(Dijkstra et al 2015)

Agarwal et al. 2014a

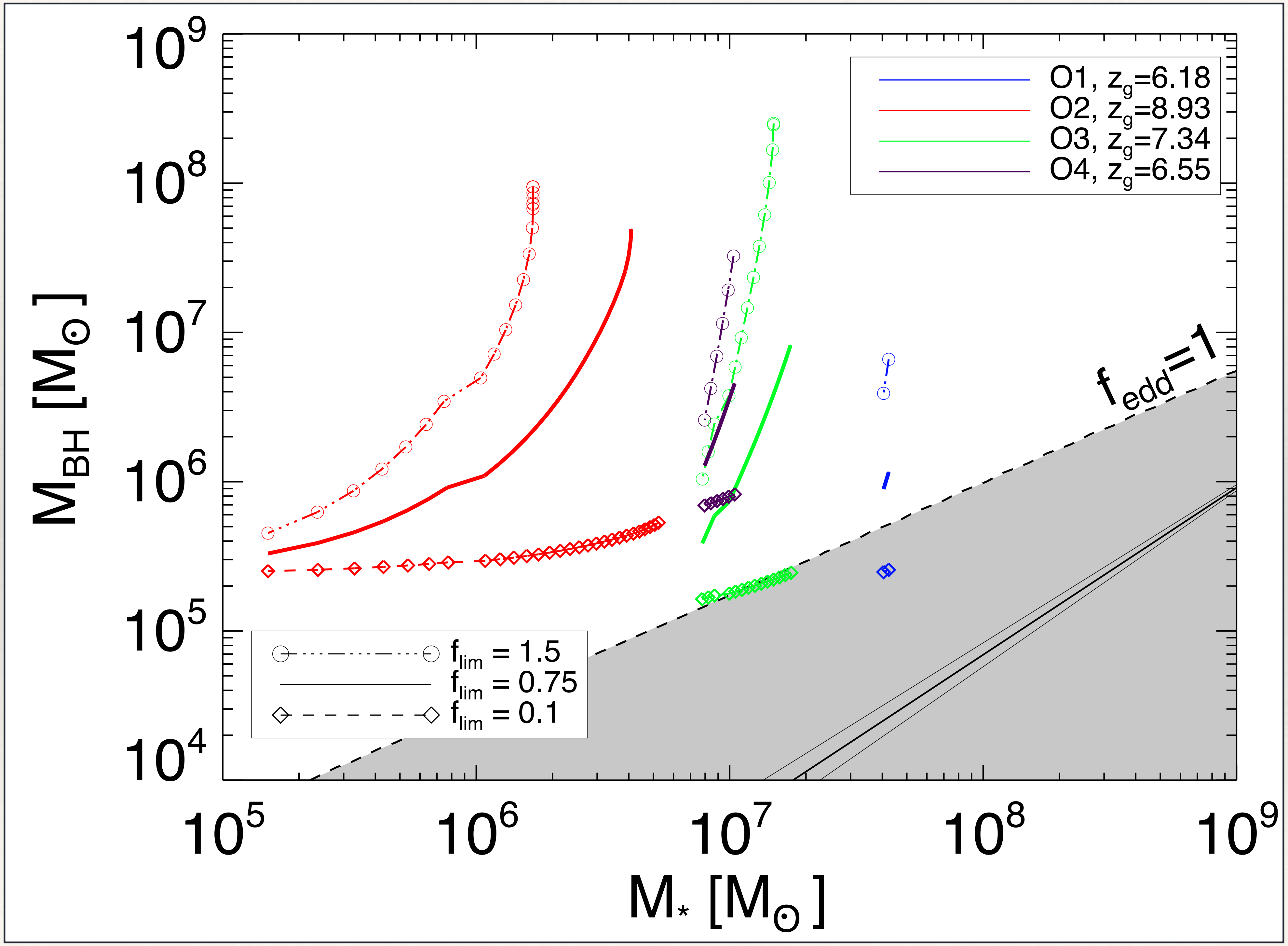
DCBH seeds: The Evolution



DCBH seeds: The Evolution

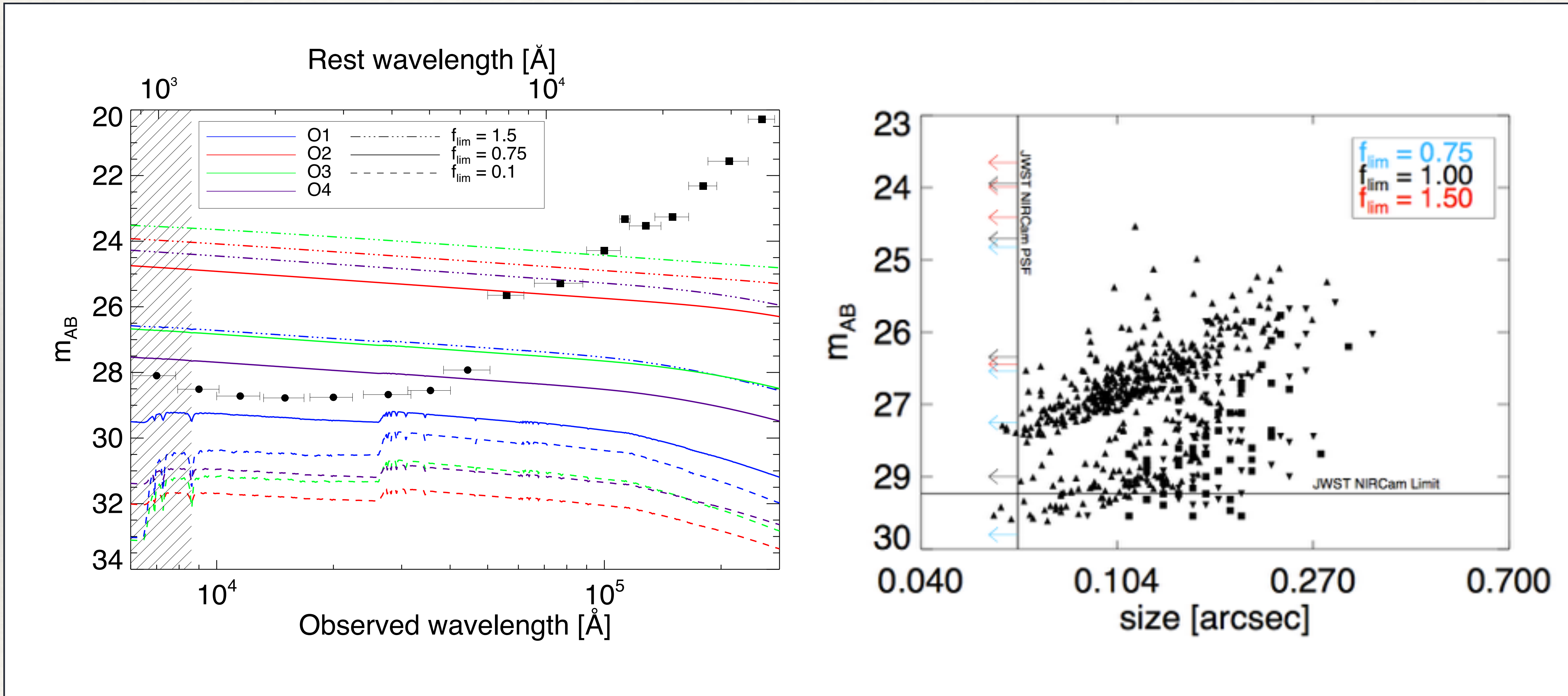


DCBH seeds: The Evolution



Agarwal et al. 2013

DCBH seeds: Observations



Agarwal et al. 2014

DCBH seeds: Revised Theory?

$$H^- + \gamma_{0.76\mathrm{eV}} \rightarrow H + e \qquad H_2 + \gamma_{LW} \rightarrow 2H$$

$$k_{H^-} = 10^{-10} \alpha J_{21} \qquad k_{H_2} = 10^{-12} \beta J_{21}$$

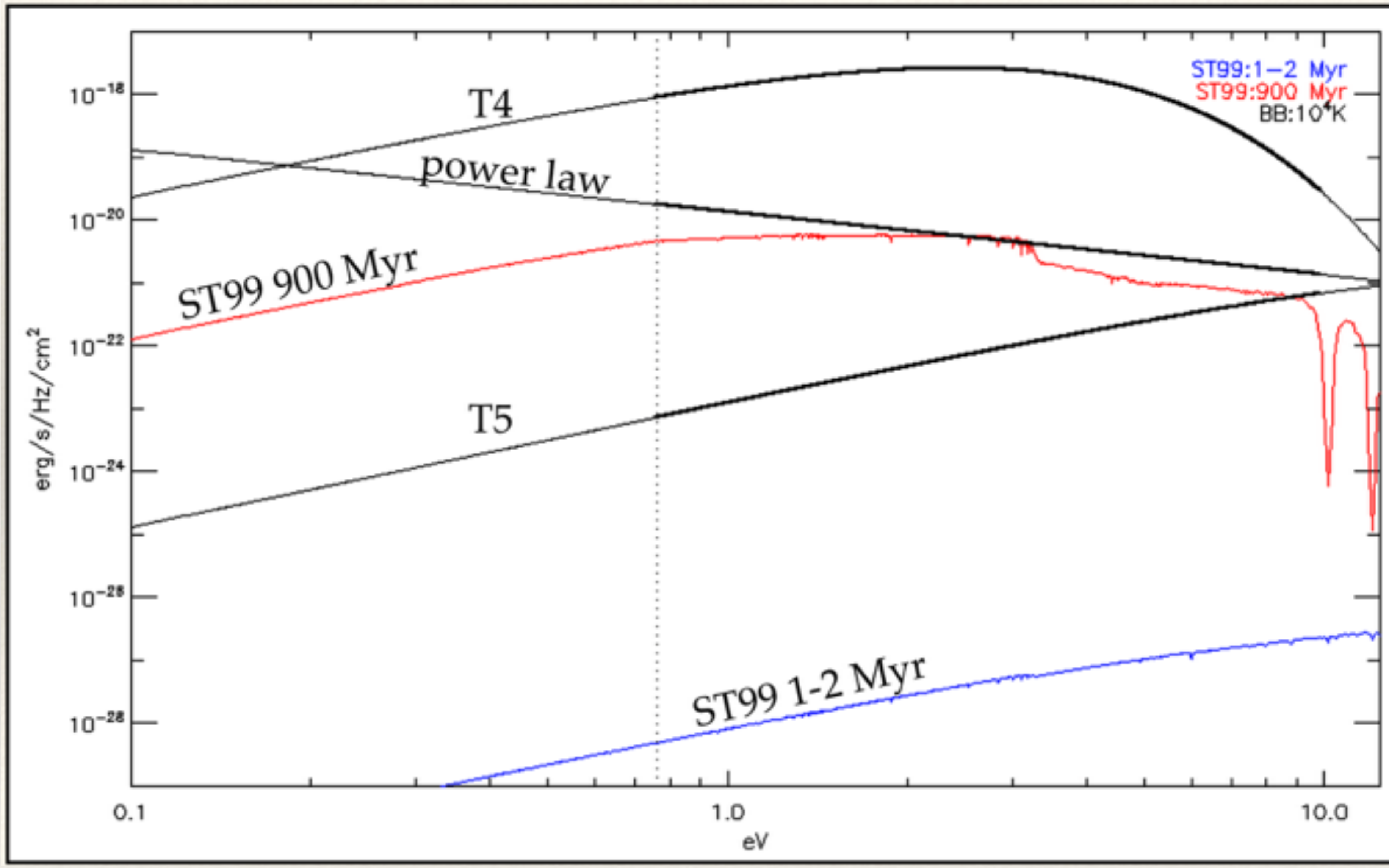
$$\alpha = \int_{0.76eV}^{13.6eV} \frac{4\pi L}{h\nu} \sigma d\nu \qquad \beta = \frac{\text{Spectrum at 12.4eV}}{\text{Spectrum at 13.6eV}}$$

- Rates depend on the shape of incident spectrum of external galaxy

- In literature the J_{crit} values have been derived by assuming
  Pop III source: black body at 10^5 K — 1000
  Pop II source : black body at 10^4 K — 30 - 100

(Omukai et al. 01, Shang et al. '10, Wolcott-Green et al. '12, Sugimura et al. '14, Dijkstra et al. '14, Agarwal et al. '15)

DCBH seeds: Revised Theory?



Rates depend on the shape of the incident spectrum from the external galaxy: relative ratios of 1eV to 12.4 eV photons

Agarwal et al. 2014b

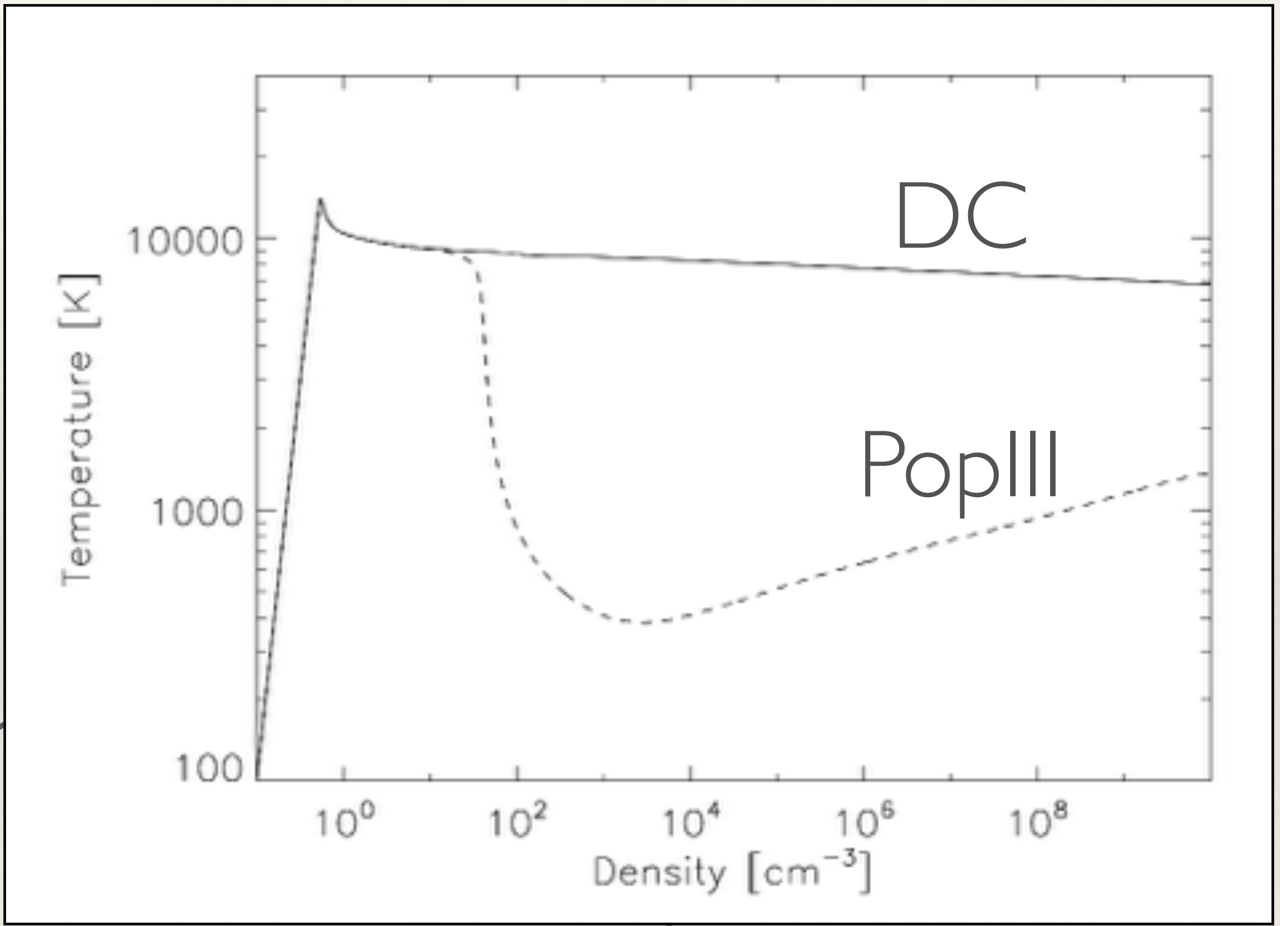
DCBH seeds: THE J_{crit}

Agarwal et al. 2015

Parameter space reaction rates: k_{H^-} , k_{H2}

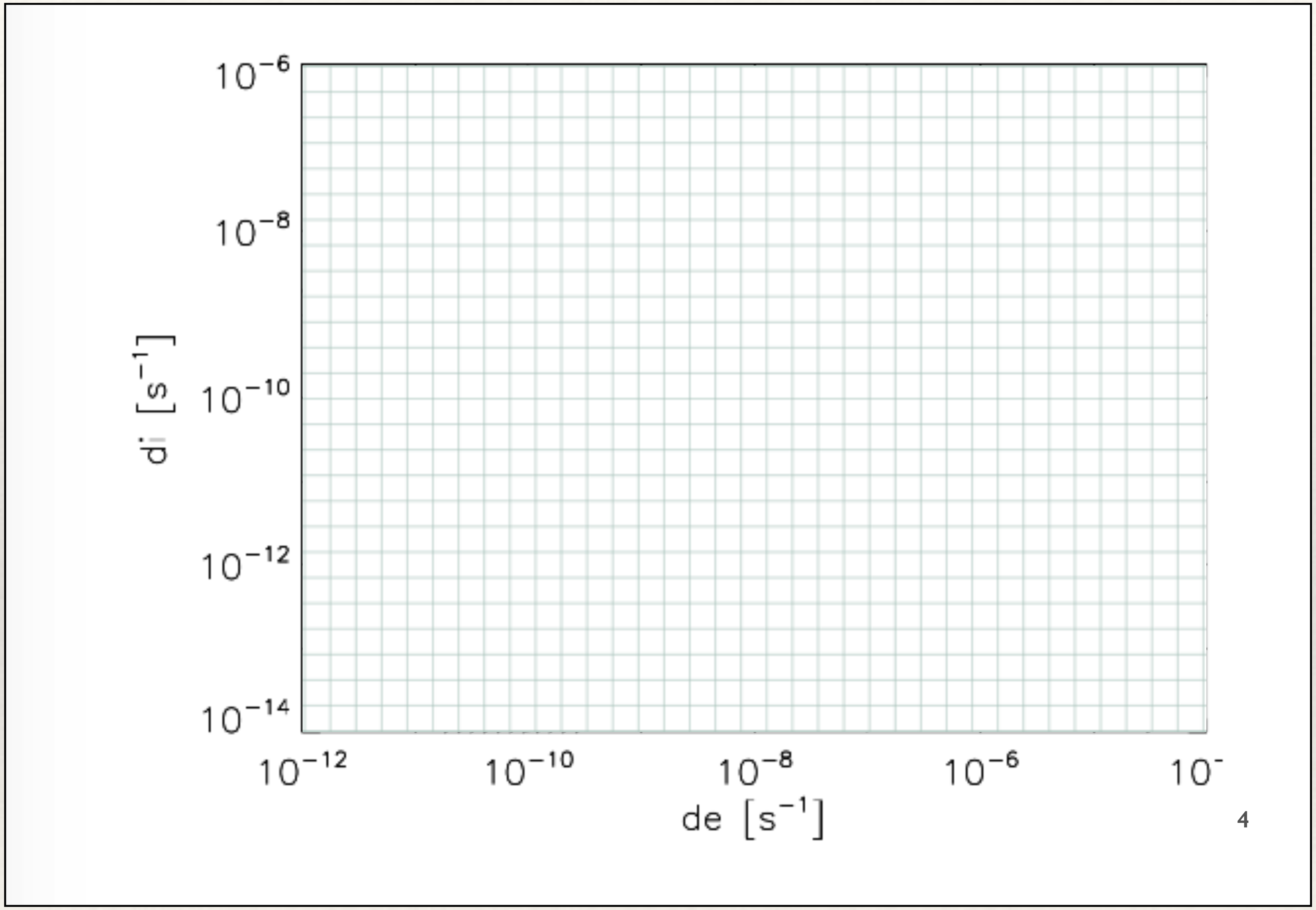
Input the rates directly into the Enzo framework with S.Glover '15 chem.

Find the rate parameter space where you find DC



Compare it to rate parameter space from realistic SEDs: Starburst 99

DCBH seeds: THE J_{crit}

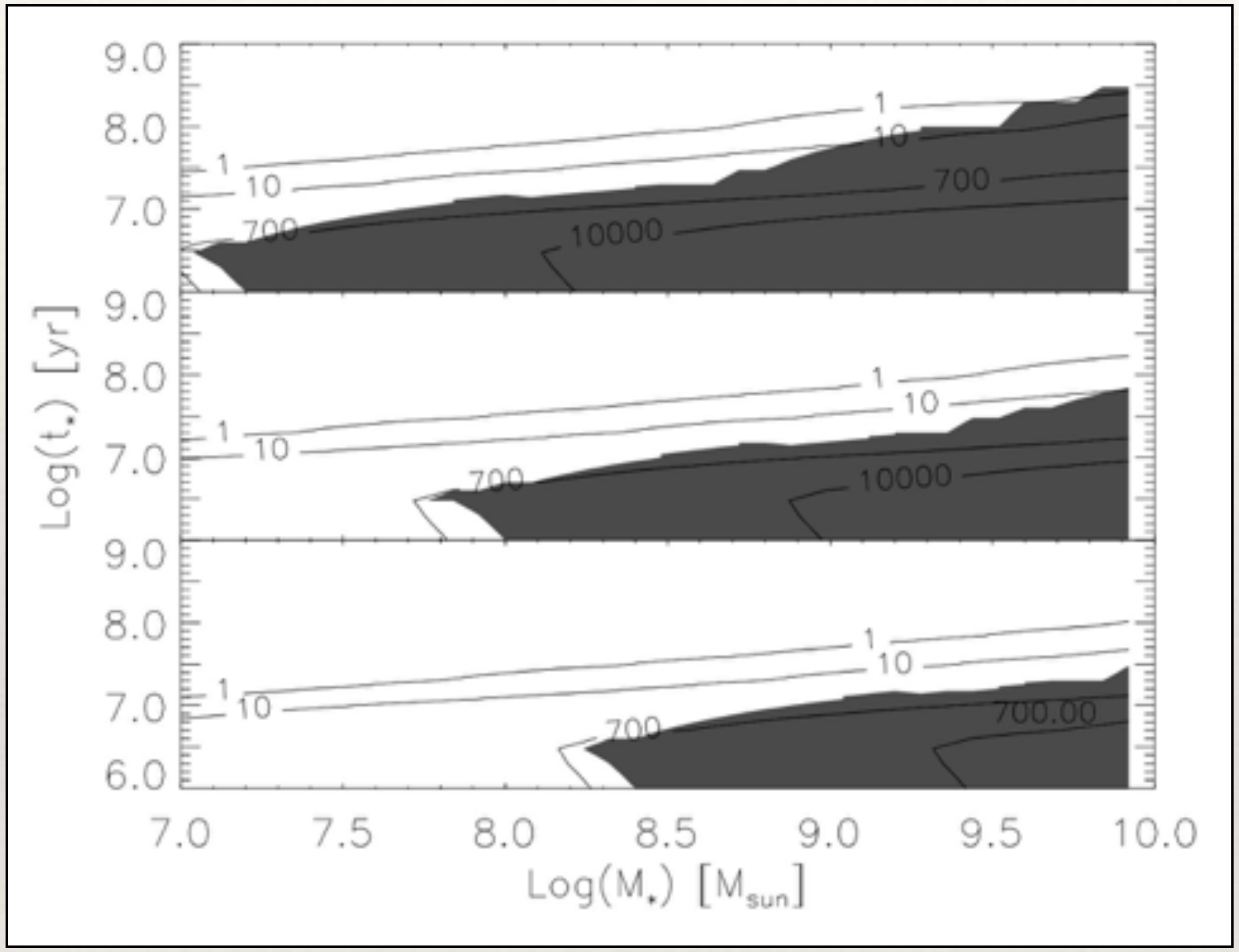


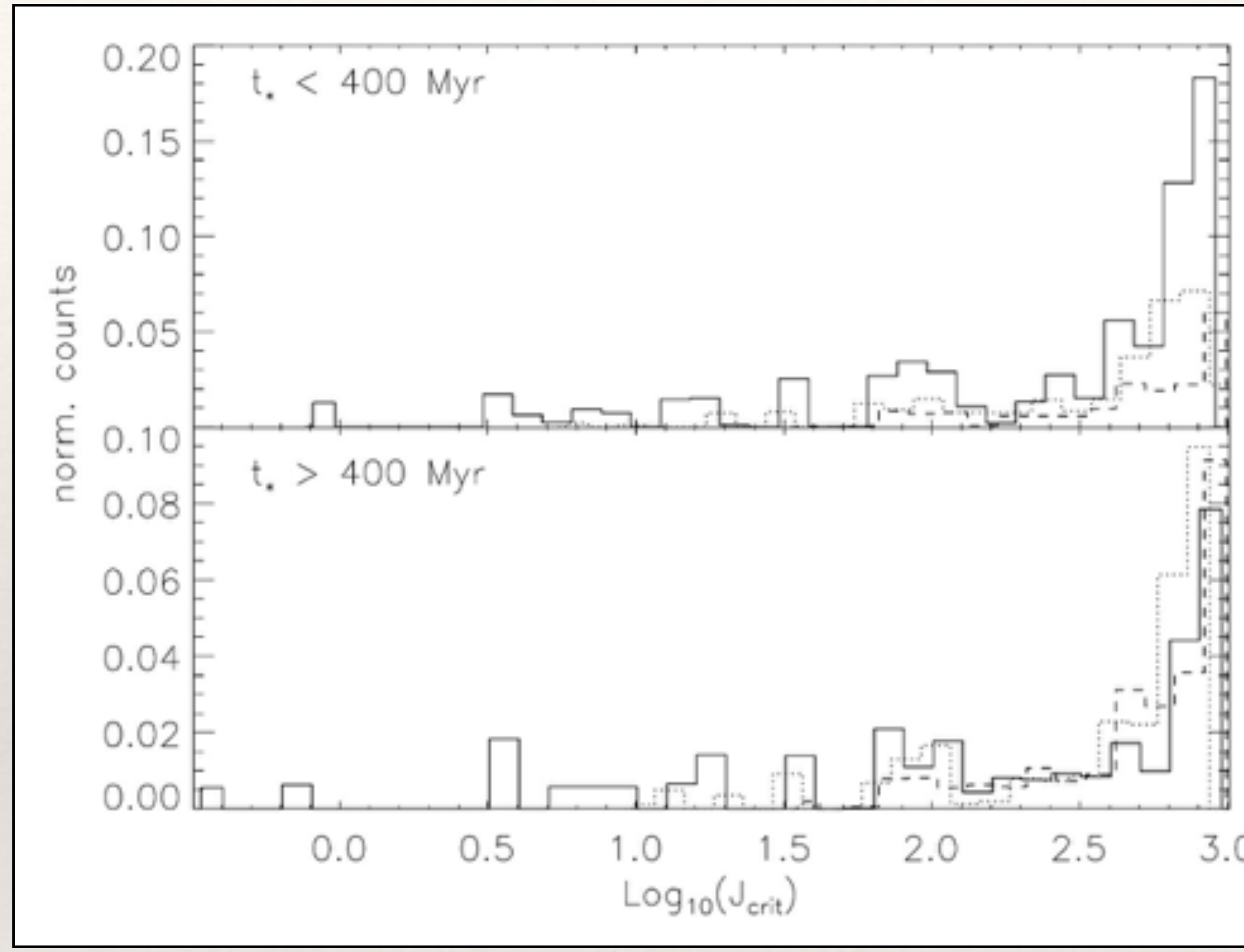
Agarwal et al. 2015

ST99: galaxy is placed 5 kpc from the atomic cooling halo

de: photo-detachment of H^-
di: photo-dissociation of H_2

DCBH seeds: THE J_{crit}





ST99: ISF, Z = 0.004 IMF: Salpeter [1-100]

No "unique" value of J_{crit} : depends on the age, SFH of the galaxy

Agarwal et al. 2015

DCBH seed: Found?

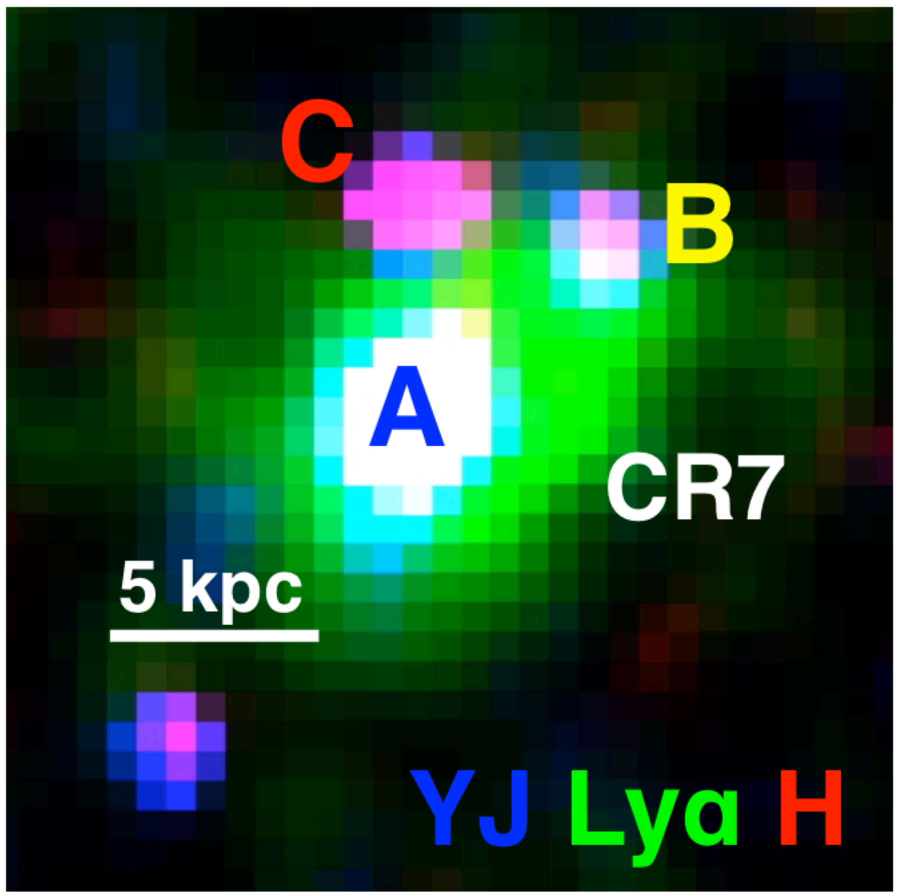
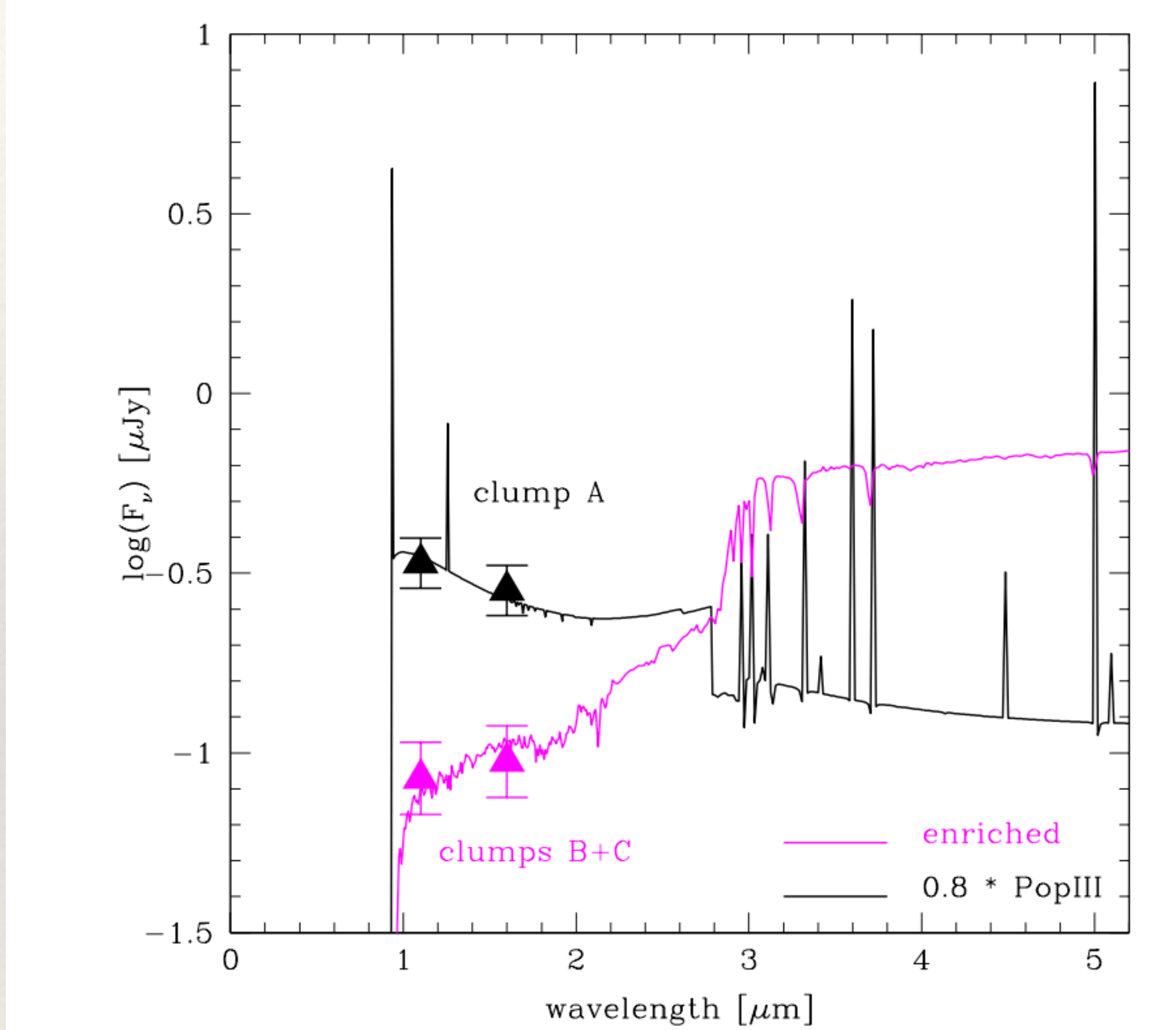


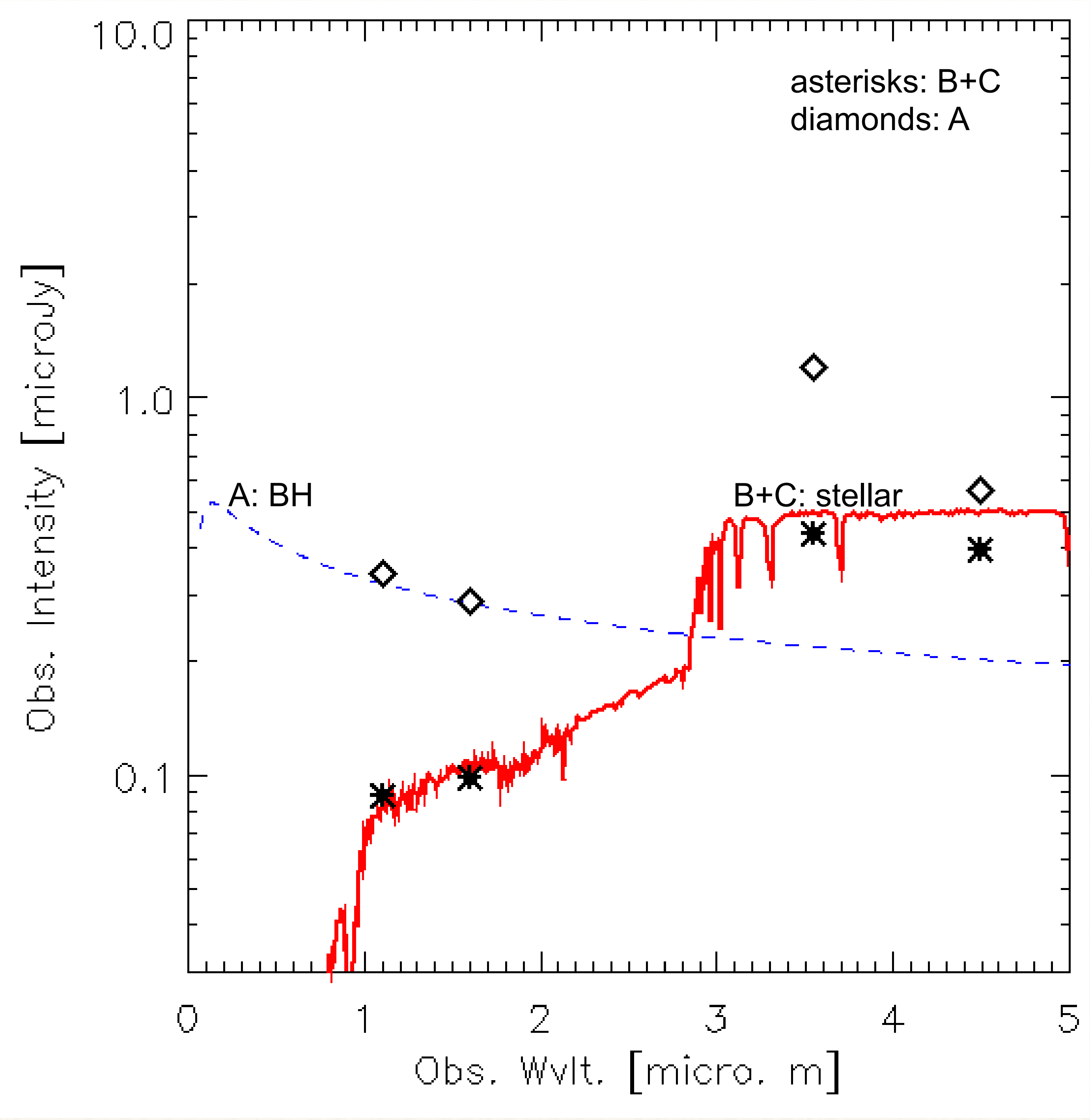
FIG. 7.— A false colour composite of CR7 by using NB921/Suprime-cam imaging (Lyα) and two *HST*/WFC3 filters: F110W (YJ) and F160W (H). This shows that while component A is the one that dominates the Lyα emission and the rest-frame UV light, the (likely) scattered Lyα emission seems to extend all the way to B and part of C, likely indicating a significant amount of gas in the system. Note that the reddest (in rest-frame UV) clump is C, with B having a more intermediate colour and with A being very blue in the rest-frame UV.



Observed by: Sobral et al. 2015

Claimed as DCBH: Pallotini et al. 2015

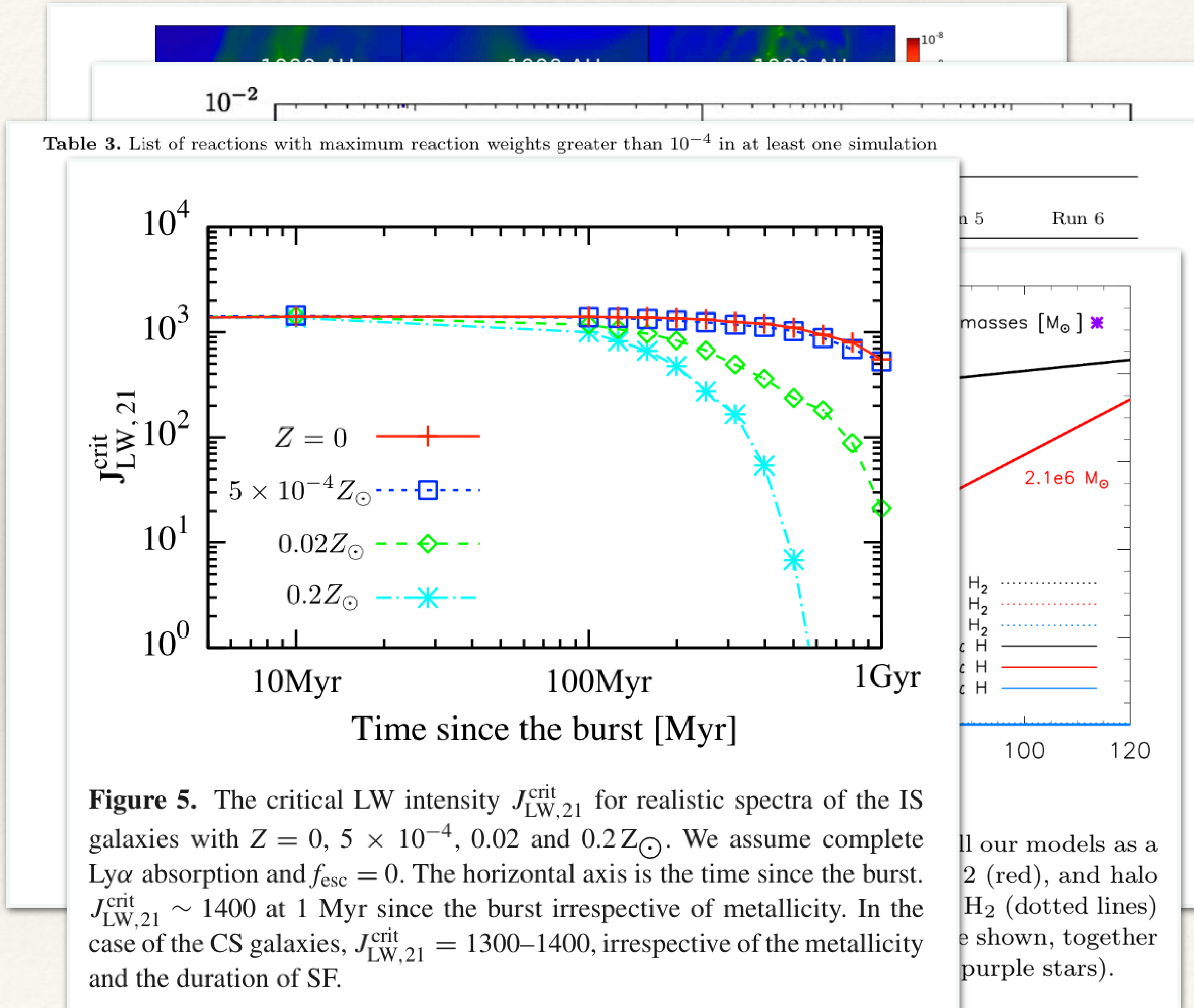
DCBH seed: found?



Agarwal et al. 2015b in prep

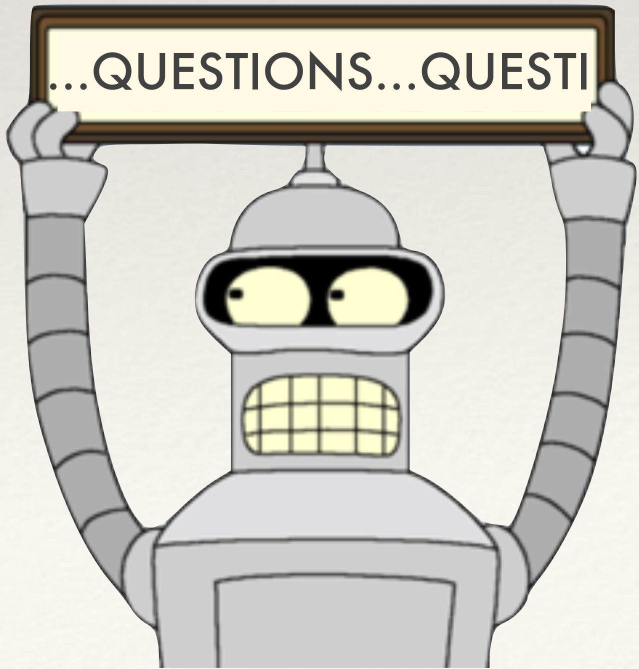
DCBH seeds: Recently…

- Latif et al.
  NO fragmentation
- Aykutalp et al.
  X-ray feedback
- Glover et al.
  relevant chemistry
- Scahuer et al.
  f_{esc} of LW
- Sugimura et al.
  J_{crit}



DCBH: Take Away Message

- DCBH works — maybe too well — still << frequent as Pop III seeds
- Local LW flux — essential for z>6 galaxy formation models
- DCBH form in satellites of LW producing galaxies
- DCBH prefer clustered environments
- DCBH can merge with the galaxies later on: OBG
- Need to account for realistic SEDs : BB not enough
- All DCBH are not 'future' SMBH

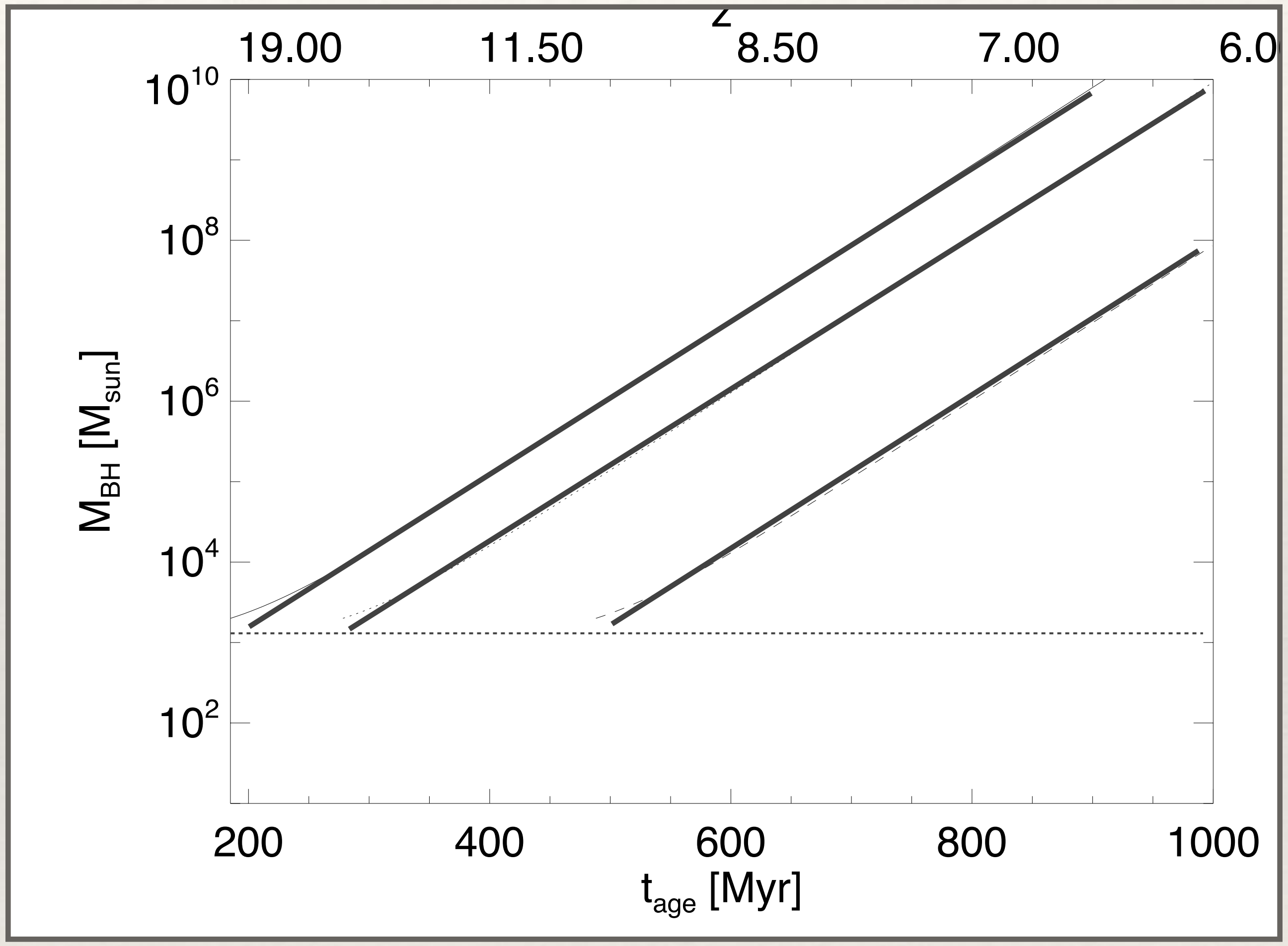


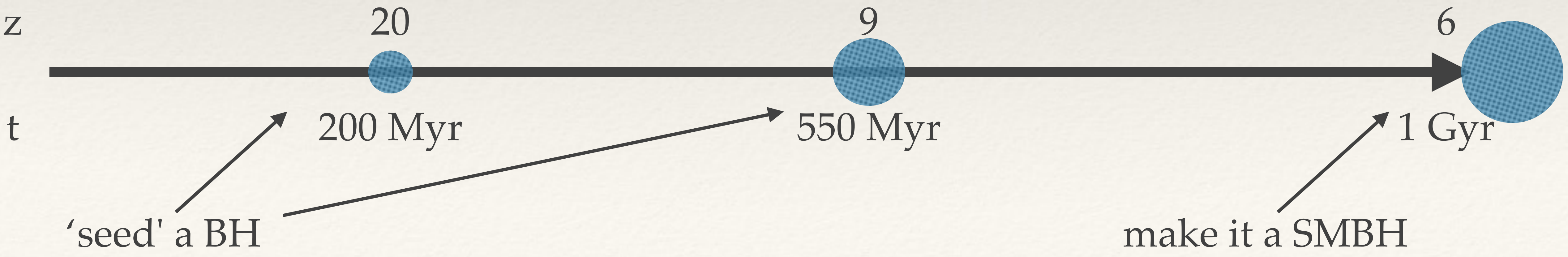
Stellar cluster BH seeds

Zwart et al.
Volonteri et al.
Katz et al.

Cluster $M = 10^{4\text{-}6}\ M_{sun}$ — Merge within few Myr — $M_{BH} = 10^{4\text{-}5}\ M_{sun}$

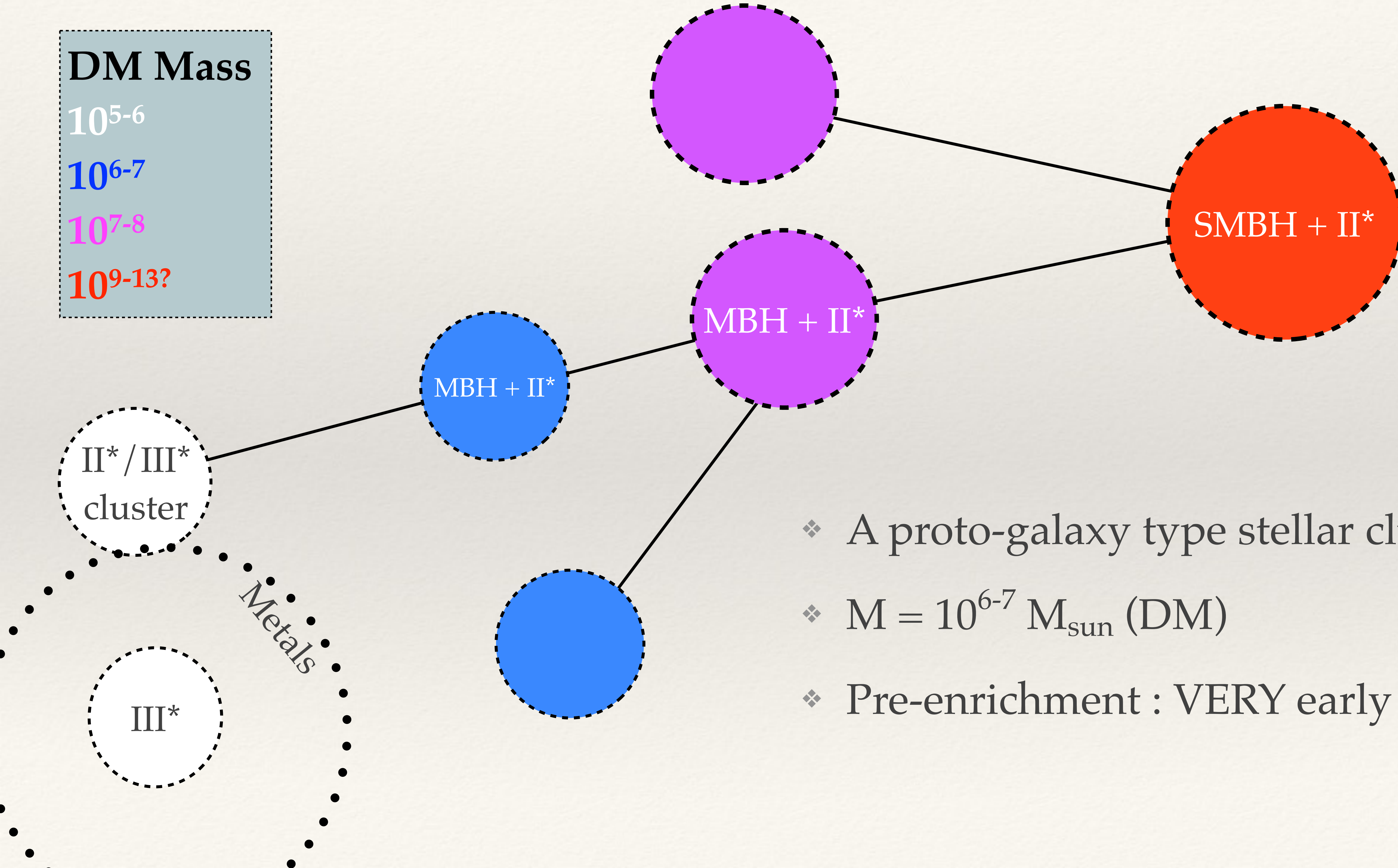
- Assuming
  $f_{edd} < 1$
  rad. eff = 0.1
- $M_{seed} = 1000\ M_{sun}$
- t_{grow} :
  $t_1\{z(20 - 6)\} = 700$ Myr
  $t_2\{z(9 - 6)\} = 200$ Myr





Stellar cluster BH seeds: where?

DM Mass
10^{5-6}
10^{6-7}
10^{7-8}
$10^{9-13?}$



- A proto-galaxy type stellar cluster
- $M = 10^{6-7}\ M_{sun}$ (DM)
- Pre-enrichment : VERY early on

Stellar cluster BH seeds: problems

Cluster M = $10^{4\text{-}6}$ M_{sun} — Merge within few Myr — $M_{BH} = 10^{4\text{-}5}$ M_{sun}

- Assuming
  $f_{edd} < 1$
  rad. eff = 0.1
- $M_{seed} = 1000\ M_{sun}$
- t_{grow} :
  $t_1\{z(20 - 6)\} = 700$ Myr
  $t_2\{z(9 - 6)\} = 200$ Myr

formation epoch:
Pop II cluster- VERY early on

N-body problem

mergers:
all stars must merge
timescale < 3 Myr