High-redshift massive black holes and AGN

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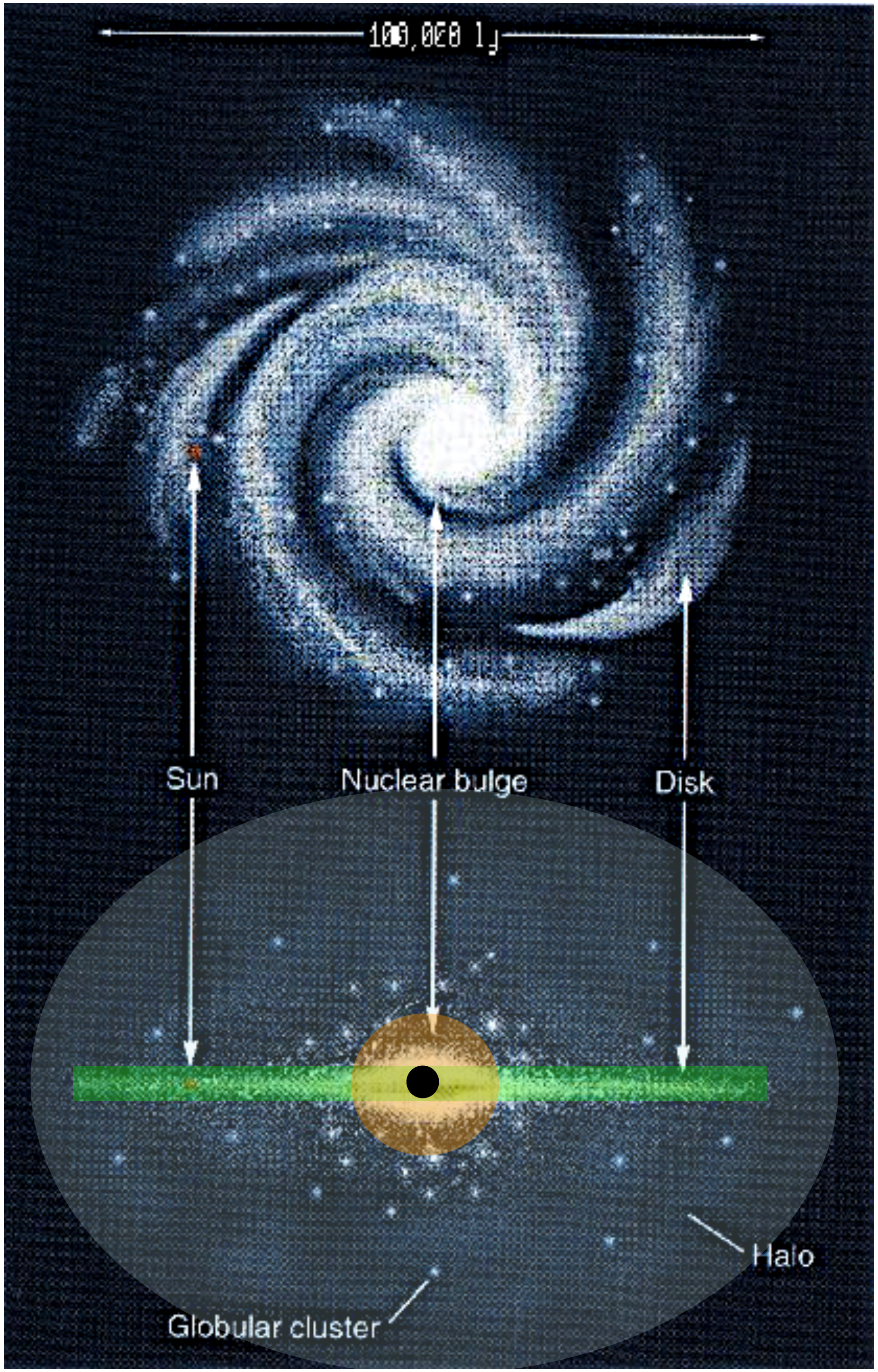


Galaxies

mass: 10^9-10^{12} solar masses

$R_{halo} \sim GM_{halo}/\sigma^2$ MEGAPARSEC

$R_{bulge} \sim GM_{bulge}/\sigma^2$ KILOPARSEC

1 parsec=3.26 light years=3×10^{18} cm
σ ~50-400 km/s for most galaxies

Massive Black Holes

mass: 10^5-10^9 solar masses

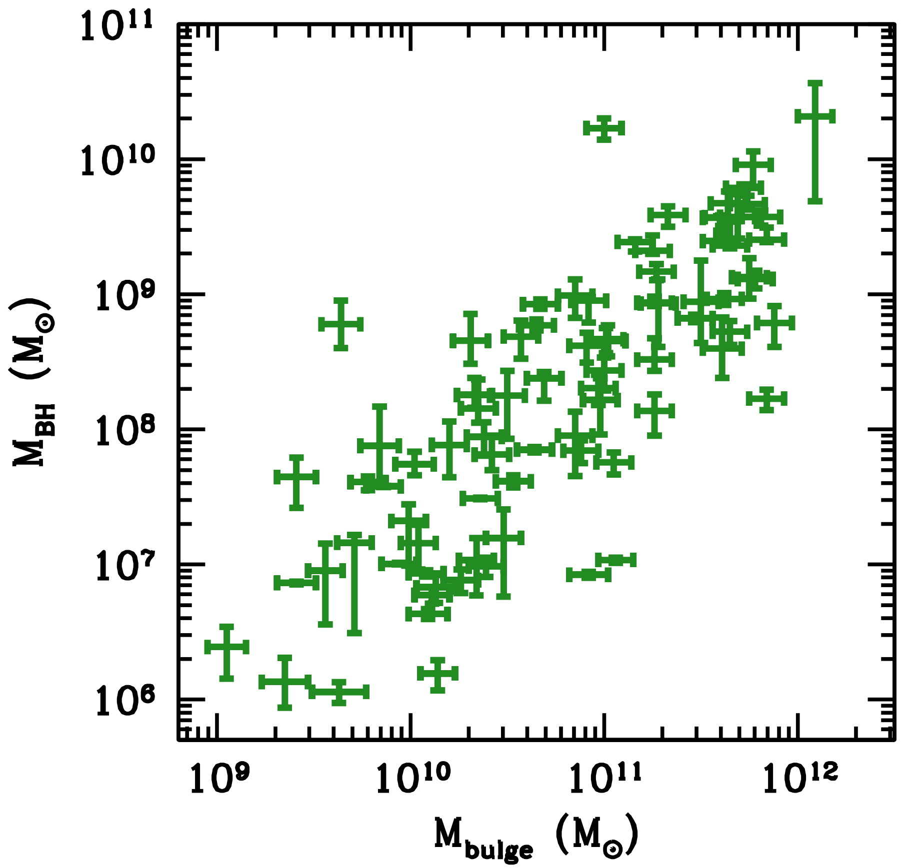
$R_{bondi} \sim GM_{BH}/c_s^2$ PARSEC

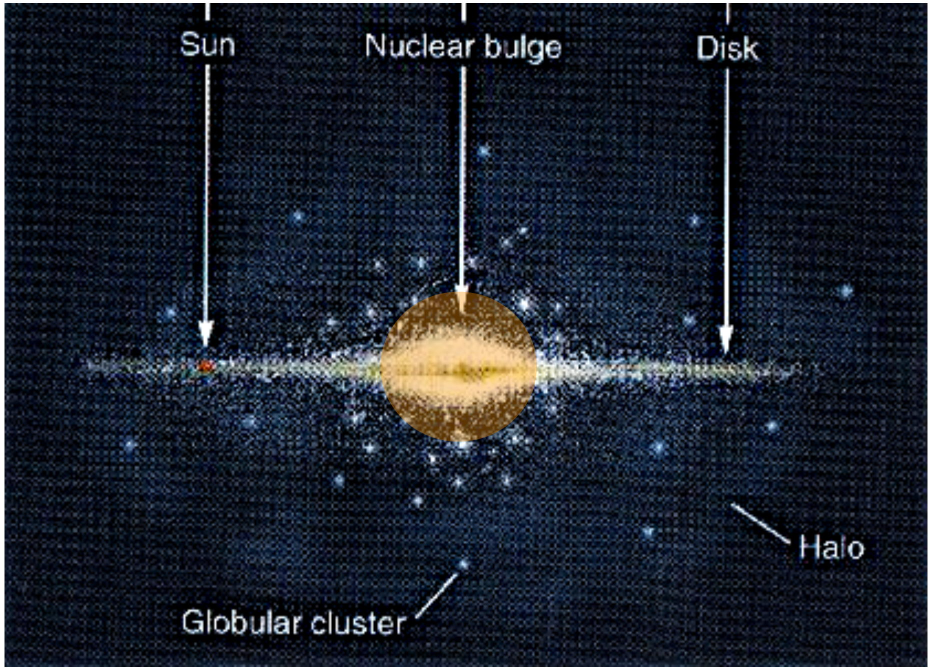
$R_{inf} \sim GM_{BH}/\sigma^2$ PARSEC

$R_{sch}=2GM_{BH}/c^2$ MICROPARSEC

c_s~10-100 km/s for most galaxies
c=3×10^5 km/s

Local samples

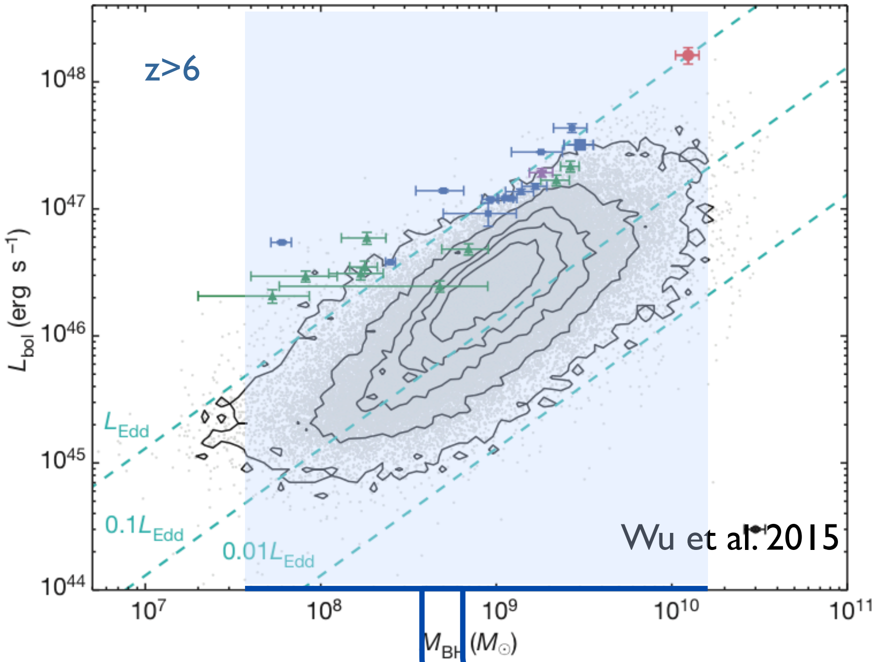




~80 MBHs detected in nearby galaxies to-date

Black hole masses correlate with galaxy properties. This may mean their growth/evolution are intimately connected.

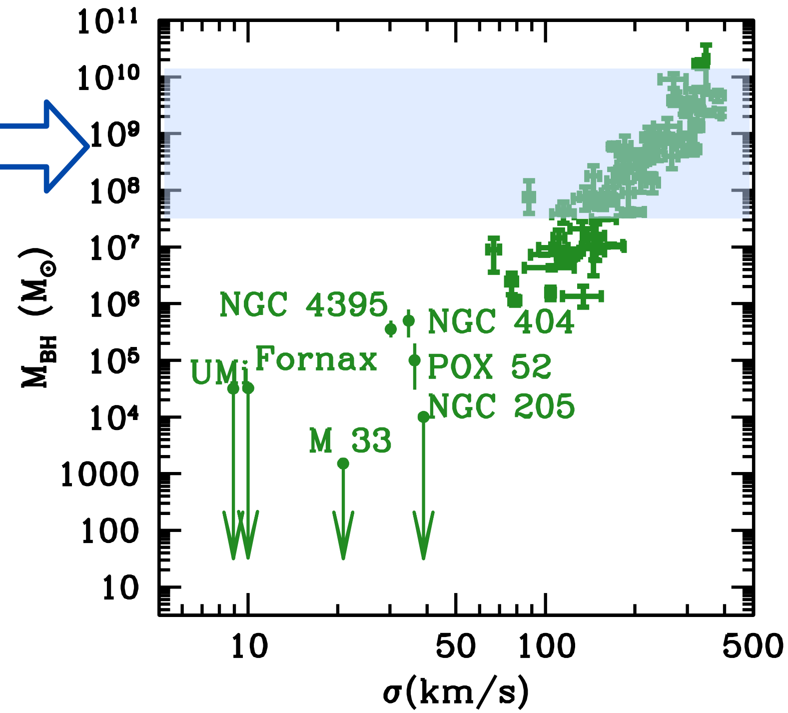
High-redshift quasars and local MBHs



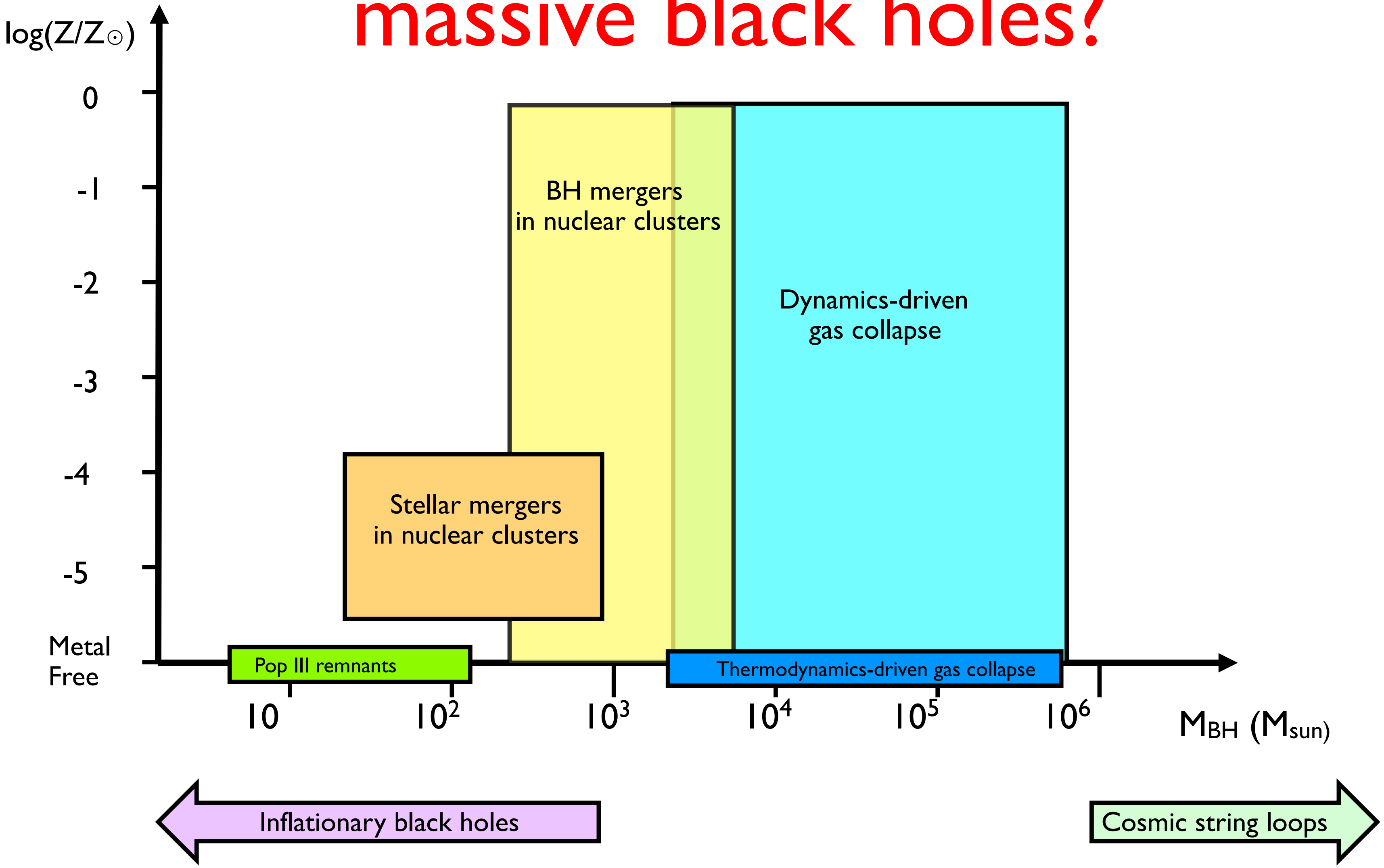
As massive as the largest MBHs today, but when the Universe was ~ Gyr old!

POX 52, NGC 4395: stellar mass 4x10^8 M$_{sun}$, MBH mass 3x10^5 M$_{sun}$

Galaxies without MBHs too

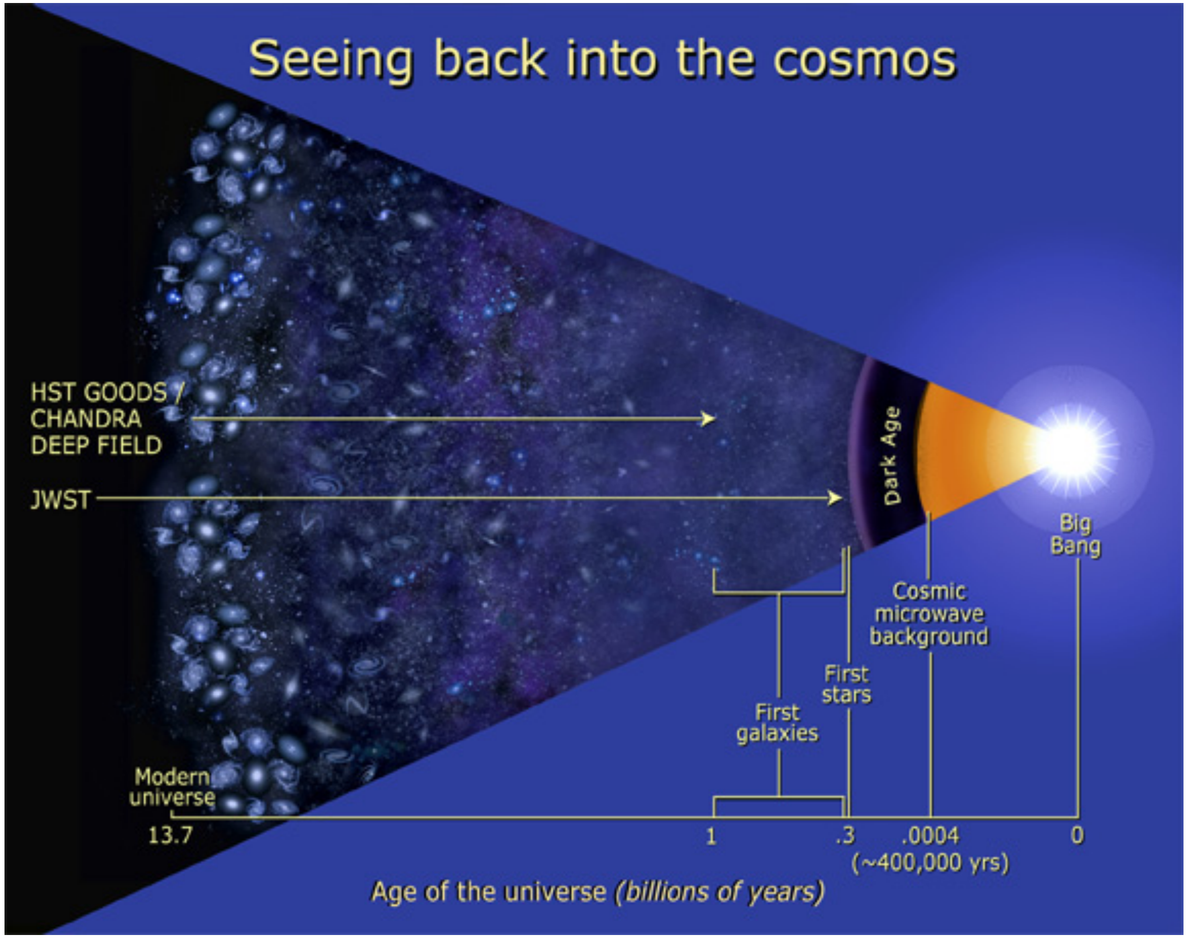


HOW can you make the first massive black holes?



Seed black holes and cosmological structure formation

How can you make the first galaxies?



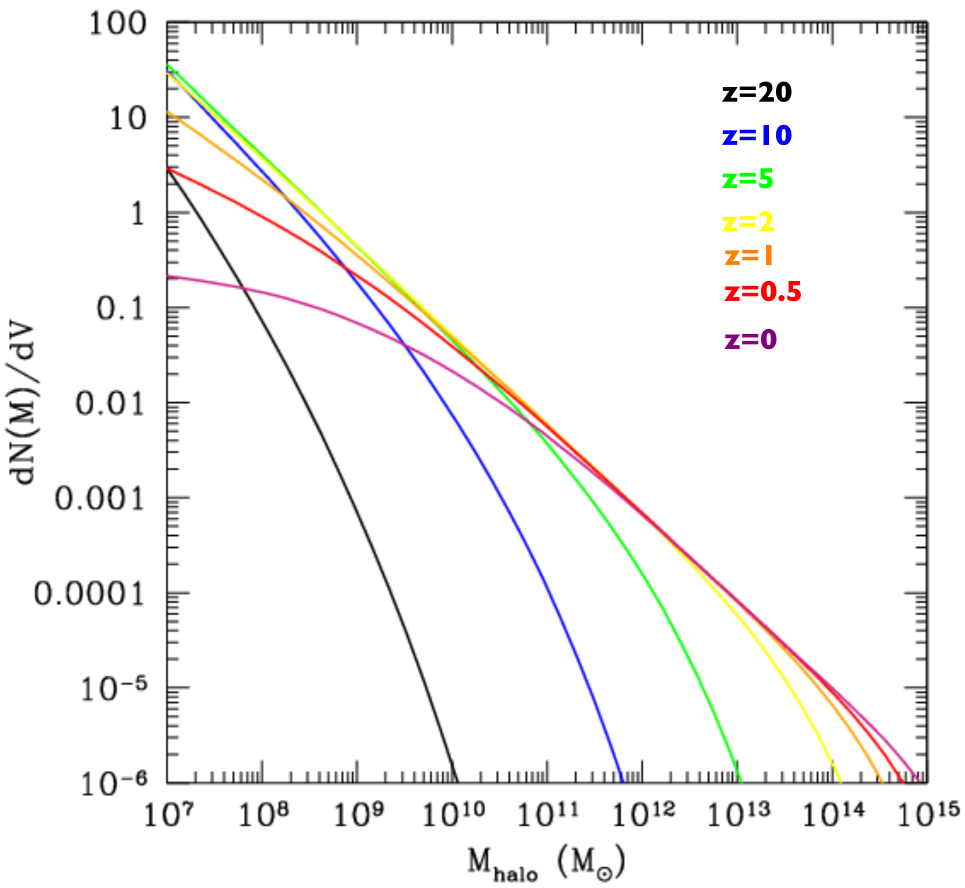
The universe after the Big Bang was not completely uniform

Gravitational instability caused matter to condense until small regions become gravitationally bound

They then break away from the global expansion, collapse down on themselves, and form a galaxy at the center

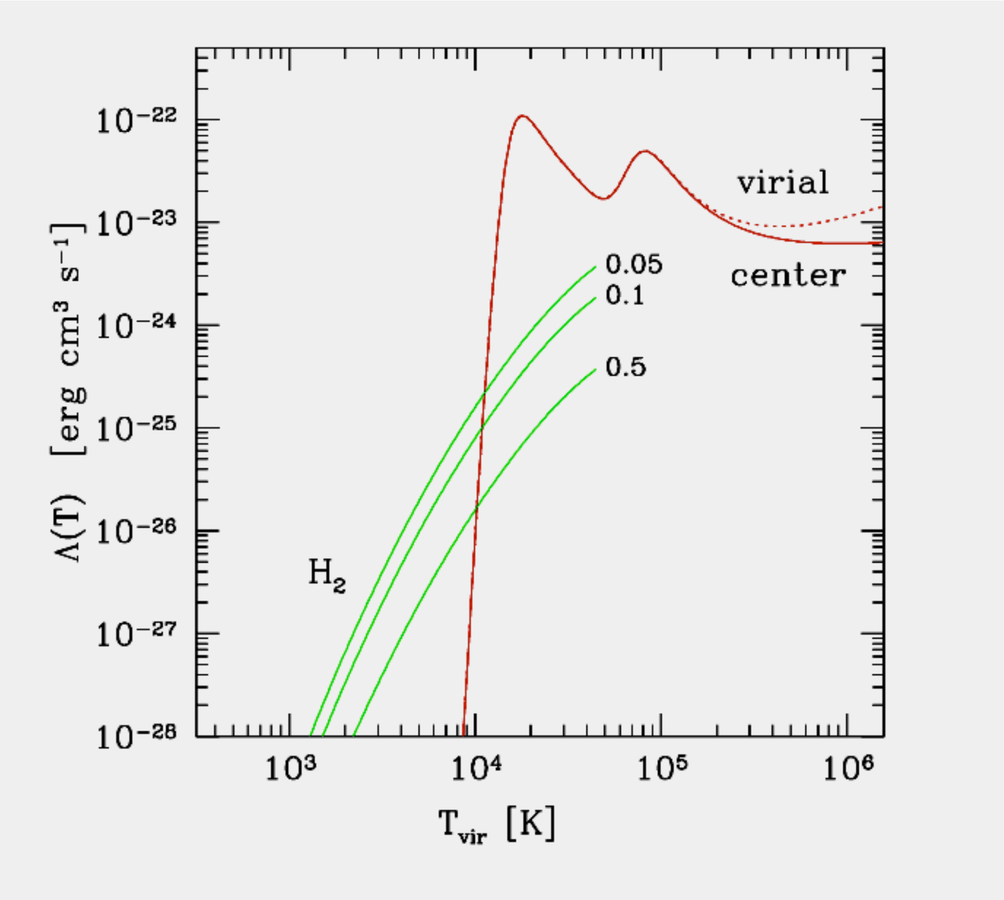
The typical halo mass is an increasing function of time: bottom-up or hierarchical structure formation

The mass functions of halos has a strong evolution with time



This is fine for collapsing dark matter... what about gas and stars?

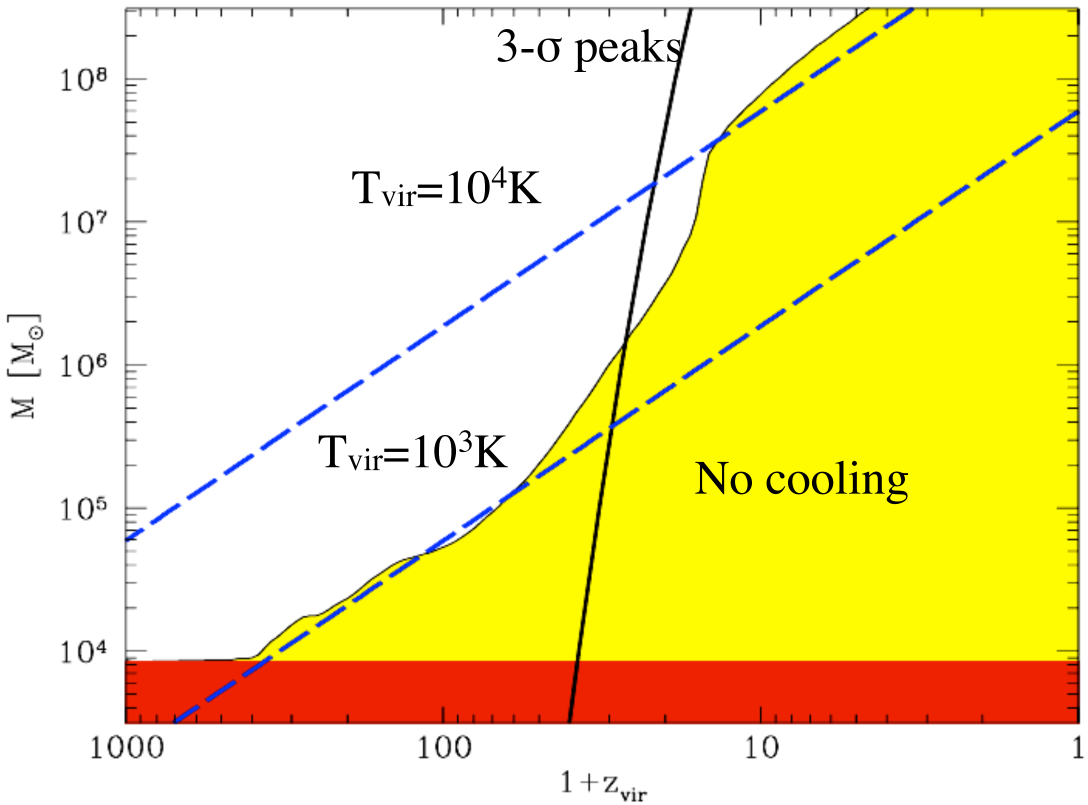
Gas needs to cool down in order to reach the density and temperatures required for star formation
BEFORE the first generation of stars, the Universe is metal free: metal line cooling does not exist!



The atomic H cooling curve drops at temperatures below 10^4K

Halos with $T_{vir} < 10^4$K have to rely on molecular hydrogen cooling

Tegmark et al.

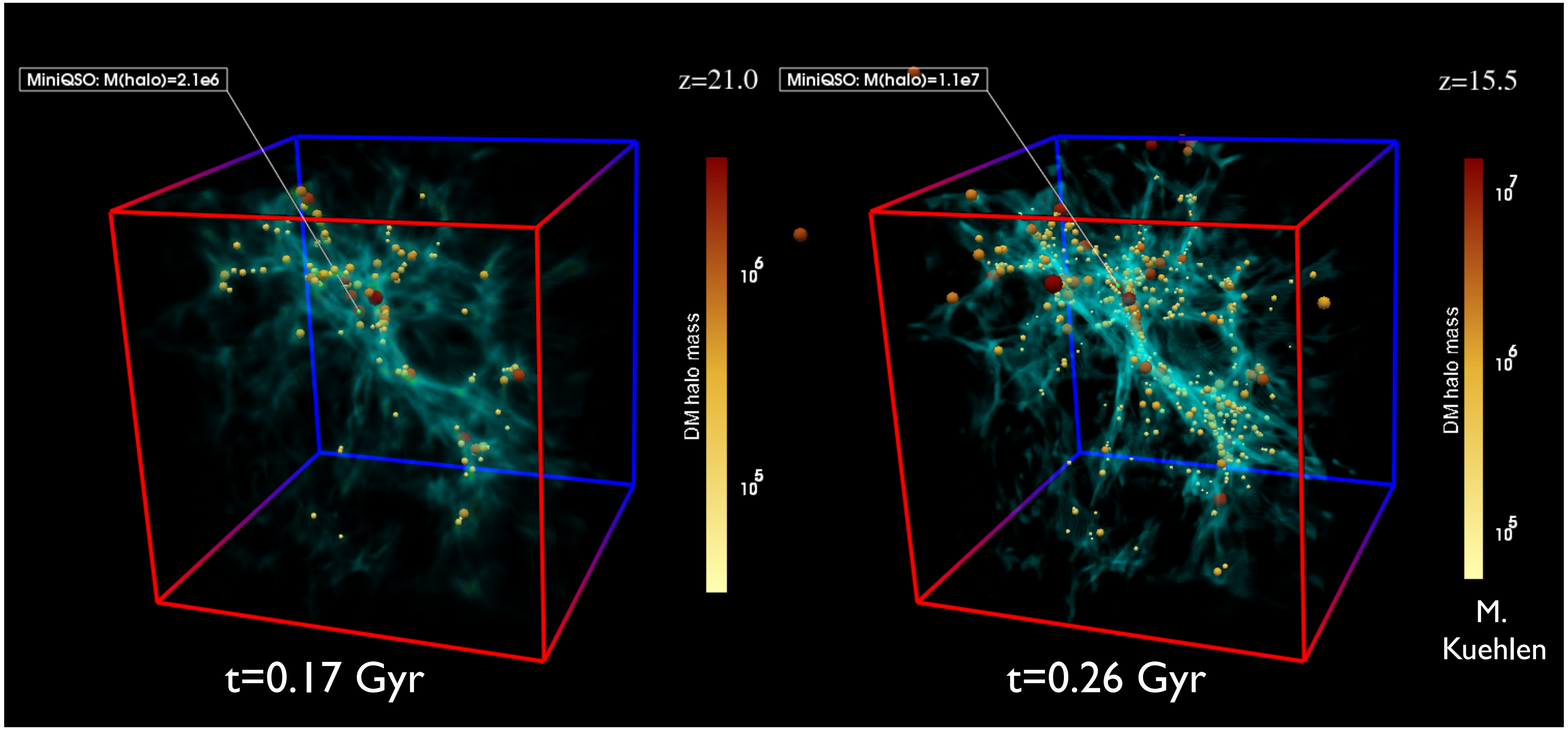


At high-z (z>20) most of the halos are small (T_{vir}< 10^4K)

But only massive enough halos can cool, even with the aid of H_2

Only a small fraction of halos at early times - the most massive ones - can host cold gas and eventually star forming clouds

Hierarchical Galaxy Formation



Milky Way's dark matter halo mass ~10^{12} solar masses

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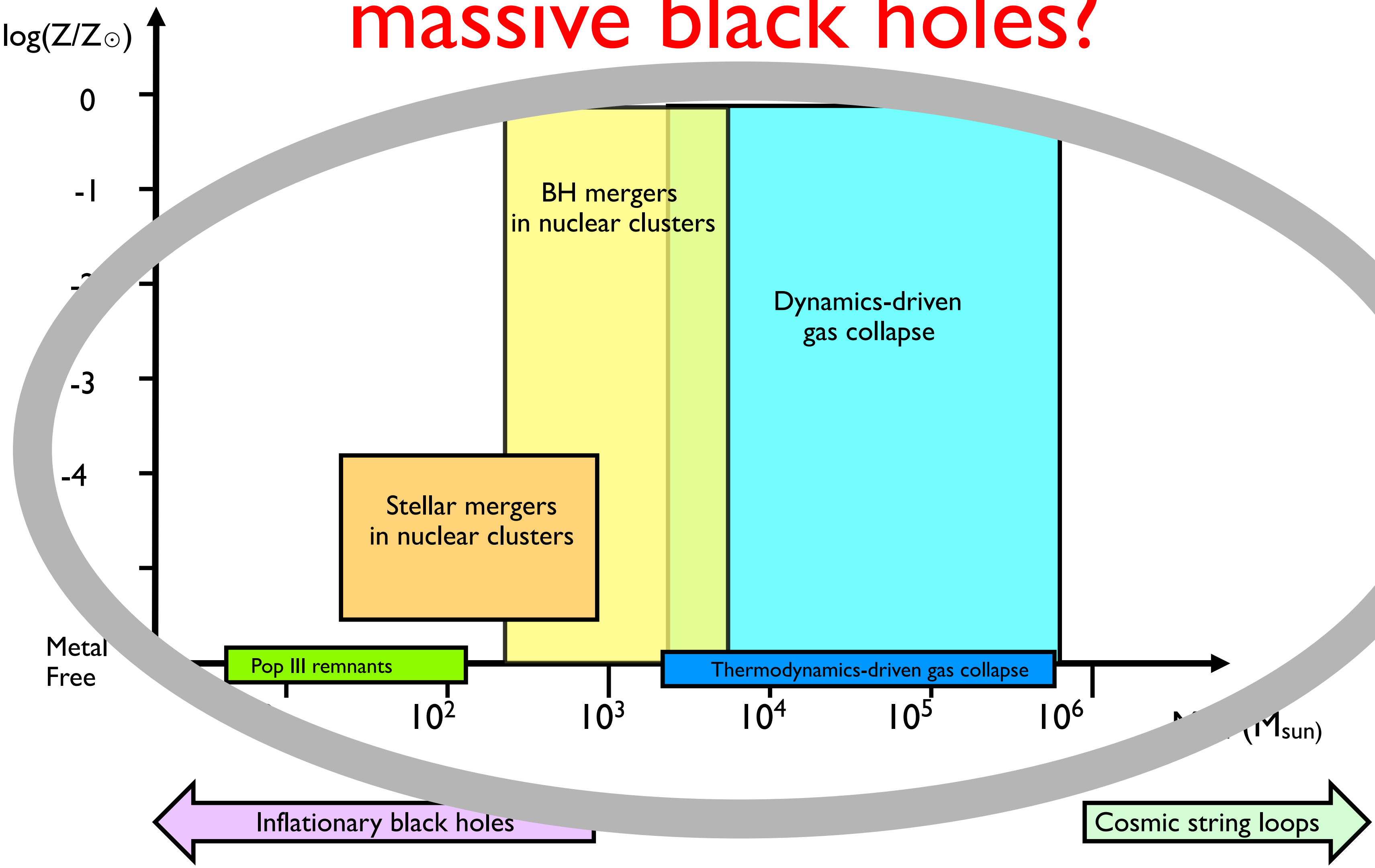
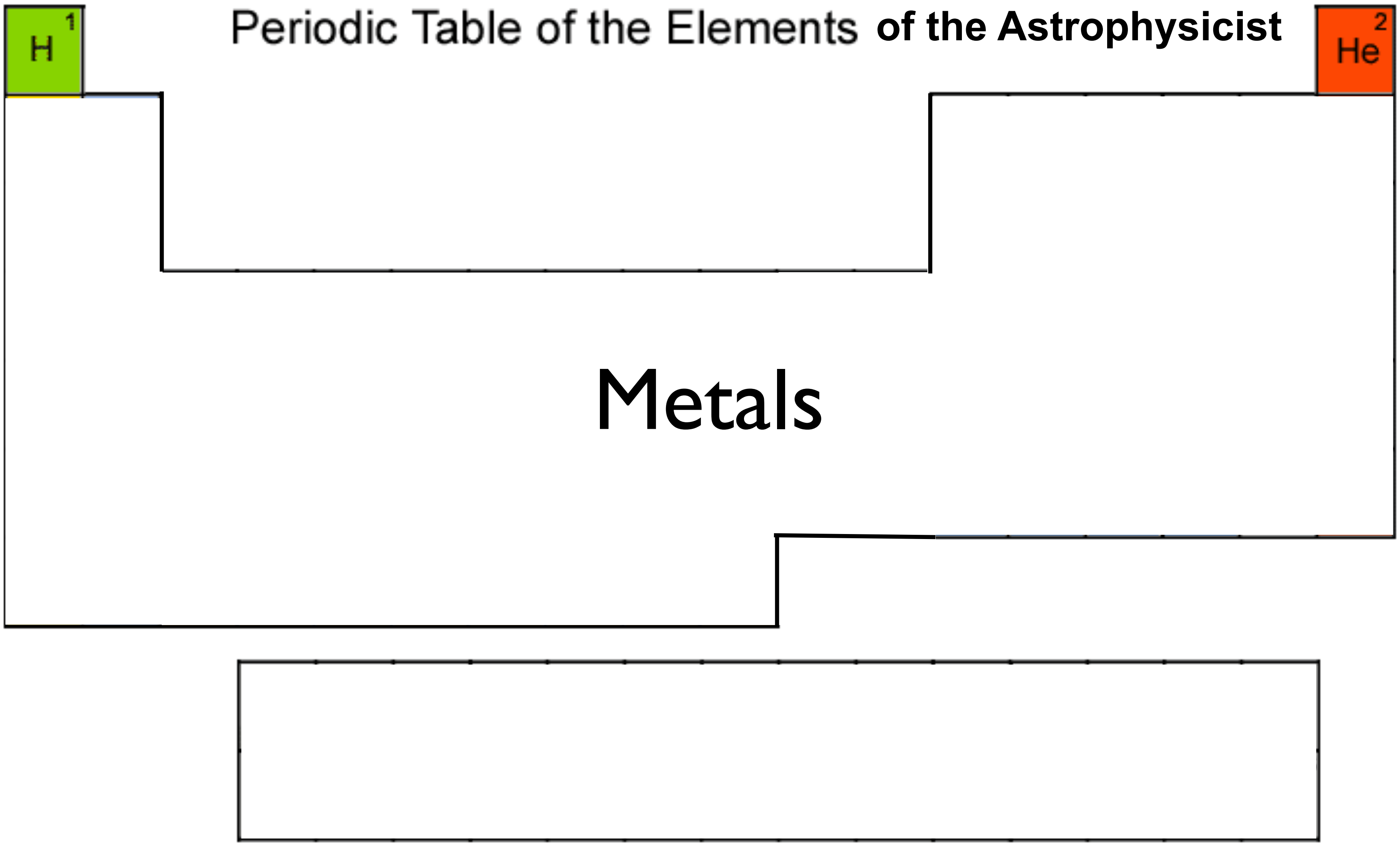


Periodic Table of the Elements

- hydrogen
- alkali metals
- alkali earth metals
- transition metals
- poor metals
- nonmetals
- noble gases
- rare earth metals

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr


Periodic Table of the Elements of the Astrophysicist
H 1
He 2
Metals

Why low metallicity?

(e.g. Bromm & Loeb 2003, Spaans & Silk 2006, Begelman, MV & Rees 2006, Shang et al. 2010, Latif et al. 2013)

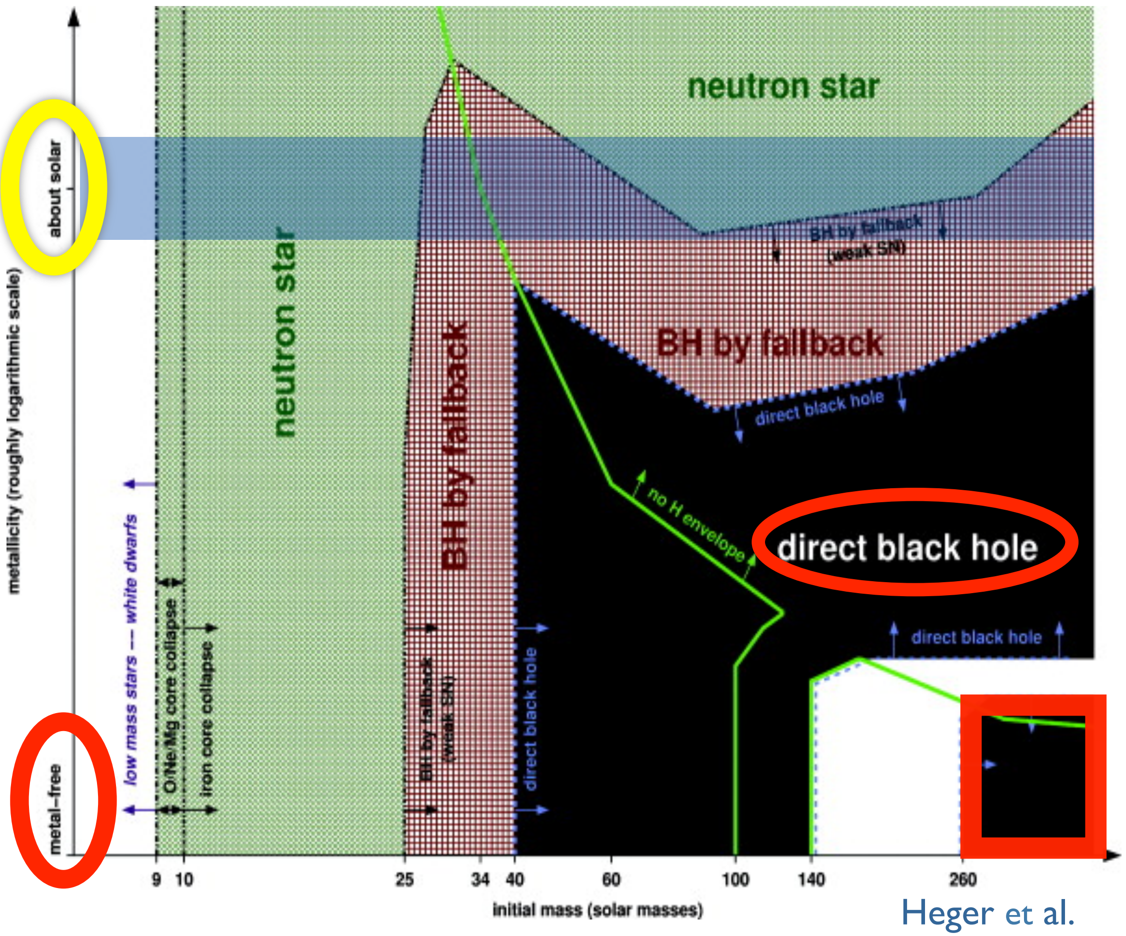
✔Forming a single very massive star makes is easier to form a single very massive BH

✔ Key parameter is the inflow rate on the central object: Mdot>0.01-0.1 Msun/yr

✔ Primordial gas composition and suppression of H_2 formation by dissociating UV flux help

✔ But they are *not* necessary conditions

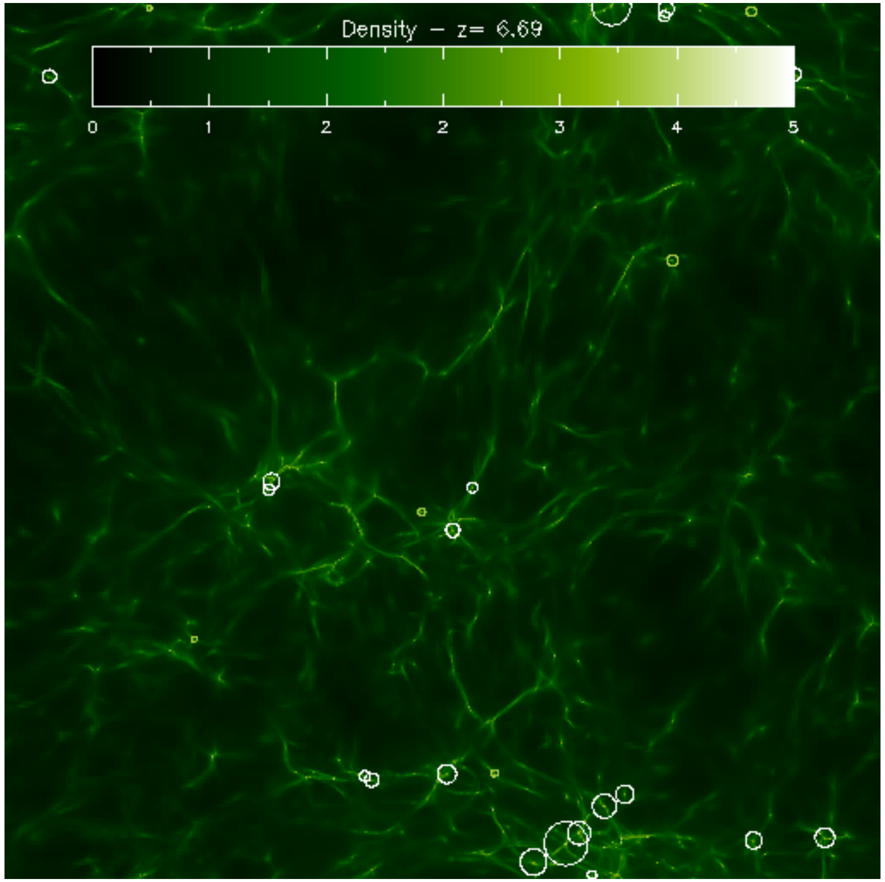
Why low metallicity?

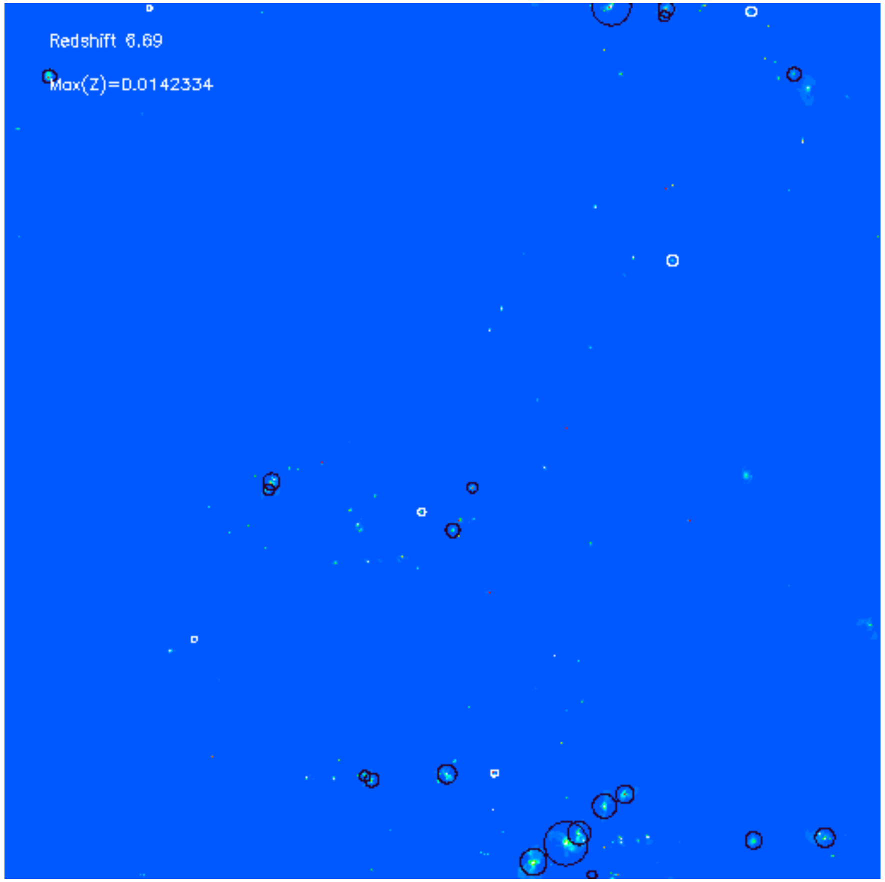


Heger et al.

Low metallicity is important if going through a supermassive star phase: models with quasistars* or stellar mass BH mergers *do not care* about metallicity

*powered by accretion on an embedded BH created by core collapse





Density map
BHs form only in high gas-density regions

Metallicity map
BHs form in low-metallicity regions just before they get enriched

Circles: galaxies with BHs

Habouzit, MV+ in prep

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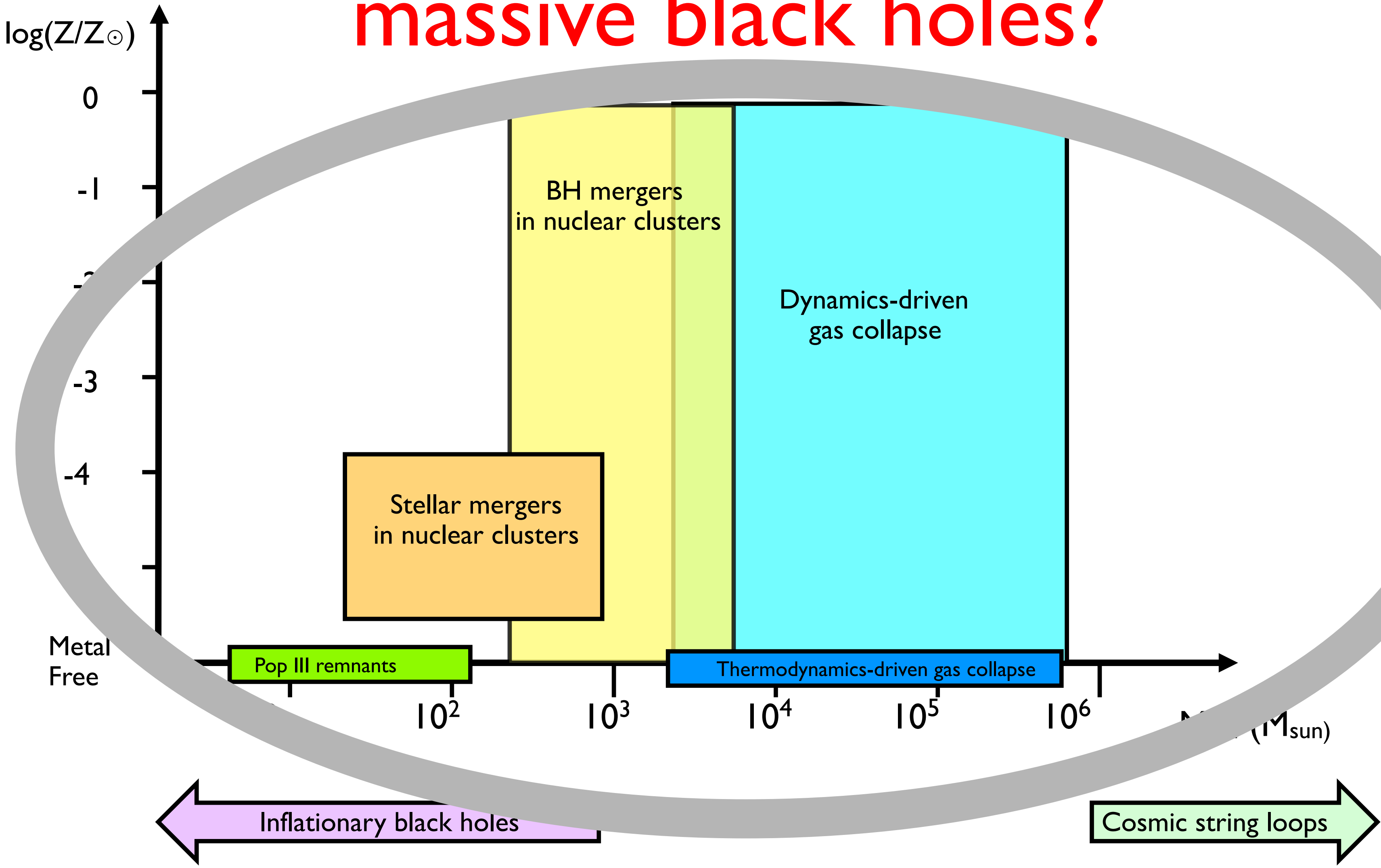
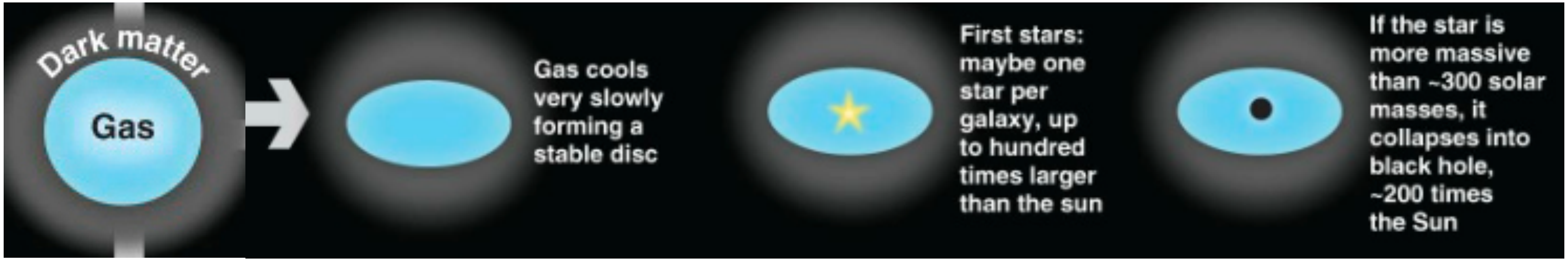


PopIII stars remnants

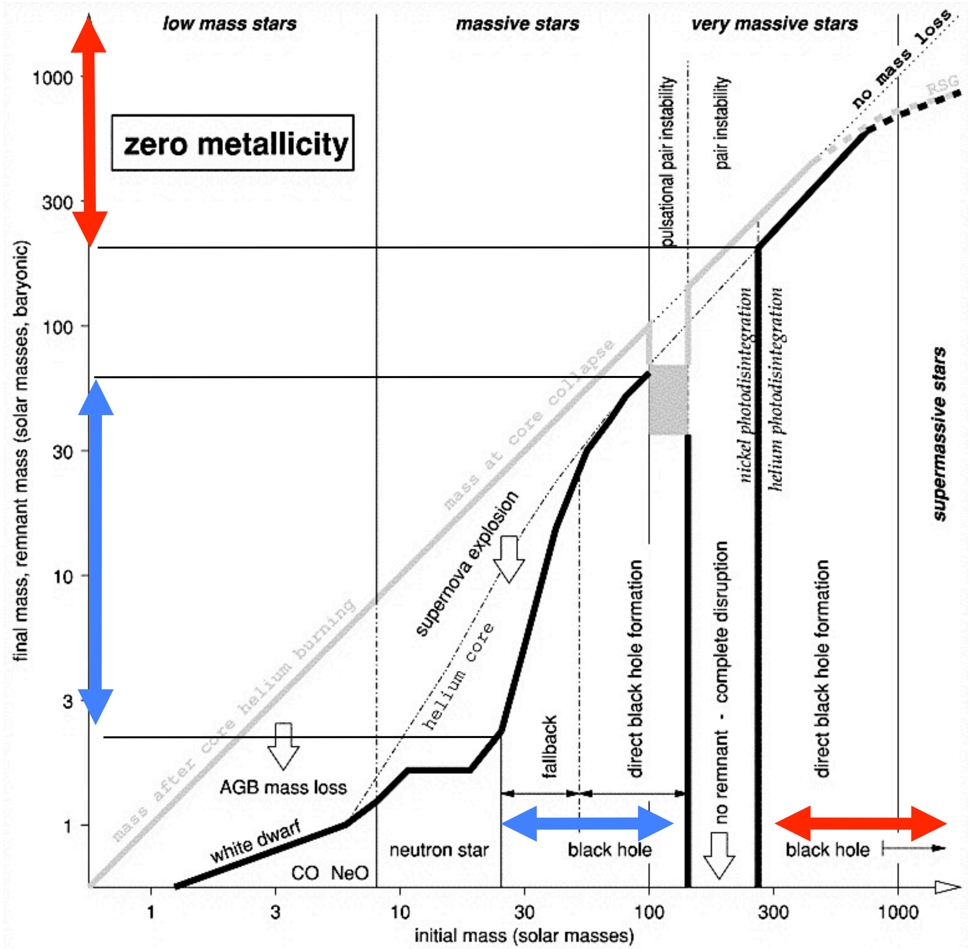
(e.g., Madau & Rees 2001; MV, Haardt & Madau 2003)



✔Some simulations suggest that the first stars are massive M~100-600 Msun (e.g., Abel et al. 2002; Bromm et al. 2003)

✔ Metal free dying stars with M>260Msun leave remnant BHs with Mseed≥100Msun (Fryer, Woosley & Heger 2003)

Problem: are the first stars massive enough?



$M_* > 260\ M_{sun} \rightarrow M_{BH} > 150\ M_{sun}$

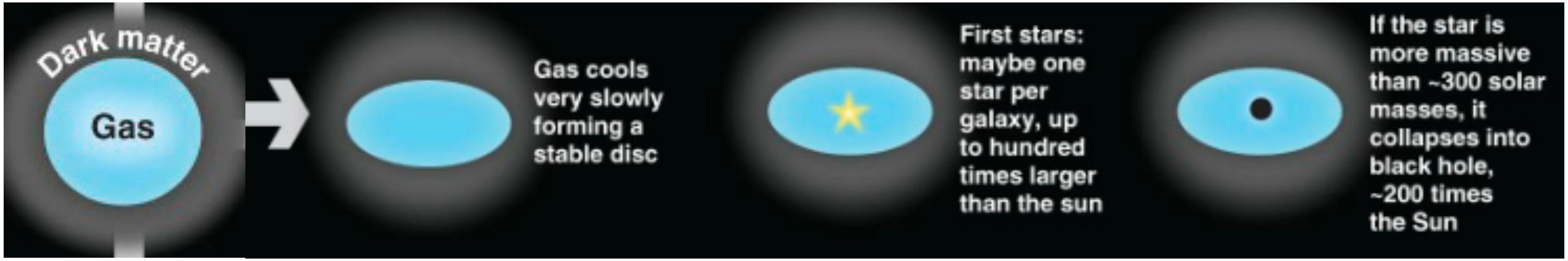
Recent simulations revise the initial estimates of the stellar masses to possibly much lower values, just a few tens Msun

$M_* \sim 30\text{-}150\ M_{sun} \rightarrow M_{BH} << 100\ M_{sun}$

If BH mass too small difficult to settle down into galaxy center => dynamics suppresses accretion/growth opportunities

PopIII stars remnants

(e.g., Madau & Rees 2001; MV, Haardt & Madau 2003)

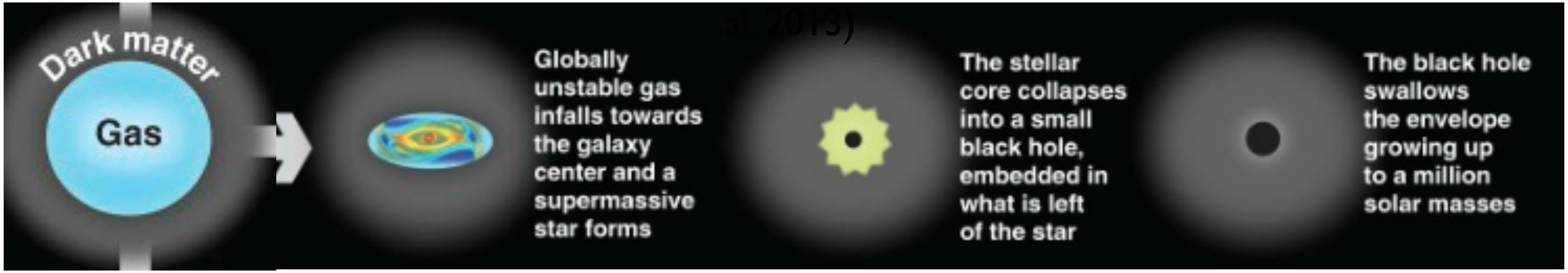


✔Recent estimates suggest lower star masses. If BH mass too small may be difficult to grow (but see Alexander & Natarajan 2014)

✔A few sufficiently massive stars would do (Hosokawa+15)

Gas-driven collapse

(e.g. Bromm & Loeb 2003, Begelman, MV & Rees 2006, Lodato & Natarajan 2006, Latif et al. 2013)



✔Formation of supermassive star collapsing into a MBH of $\sim 10^4$-10^6 M_{sun}

✔ Feasible if star formation is suppressed, and most of the gas is accreted onto the central protostar

✔Key parameter: inflow rate on the central object. If Mdot>0.1 Msun/yr => supermassive star or quasi star*

*powered by accretion on an embedded BH created by core collapse

Star formation: enemy of direct collapse

✔ competition in gas consumption (i.e. part of the gas goes into stars instead of BH formation

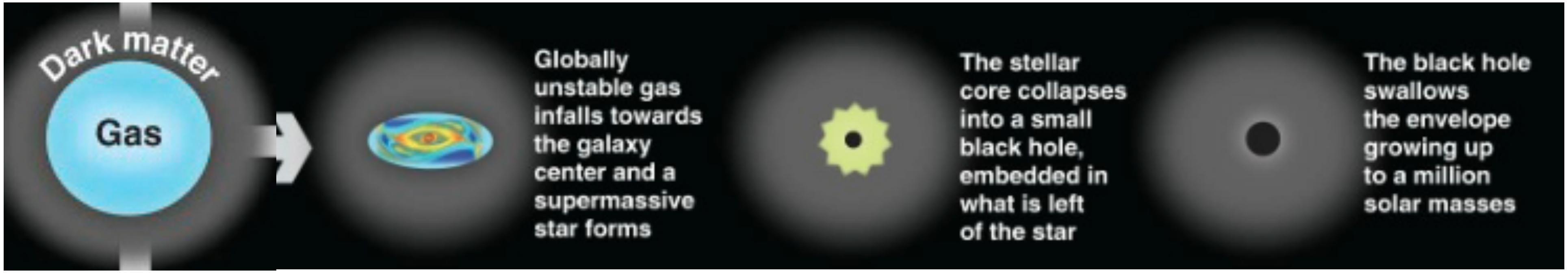
✔ collisionless stars do not dissipate angular momentum efficiently

✔ SNe can blow away the gas reservoir

Gas-driven collapse: dynamics

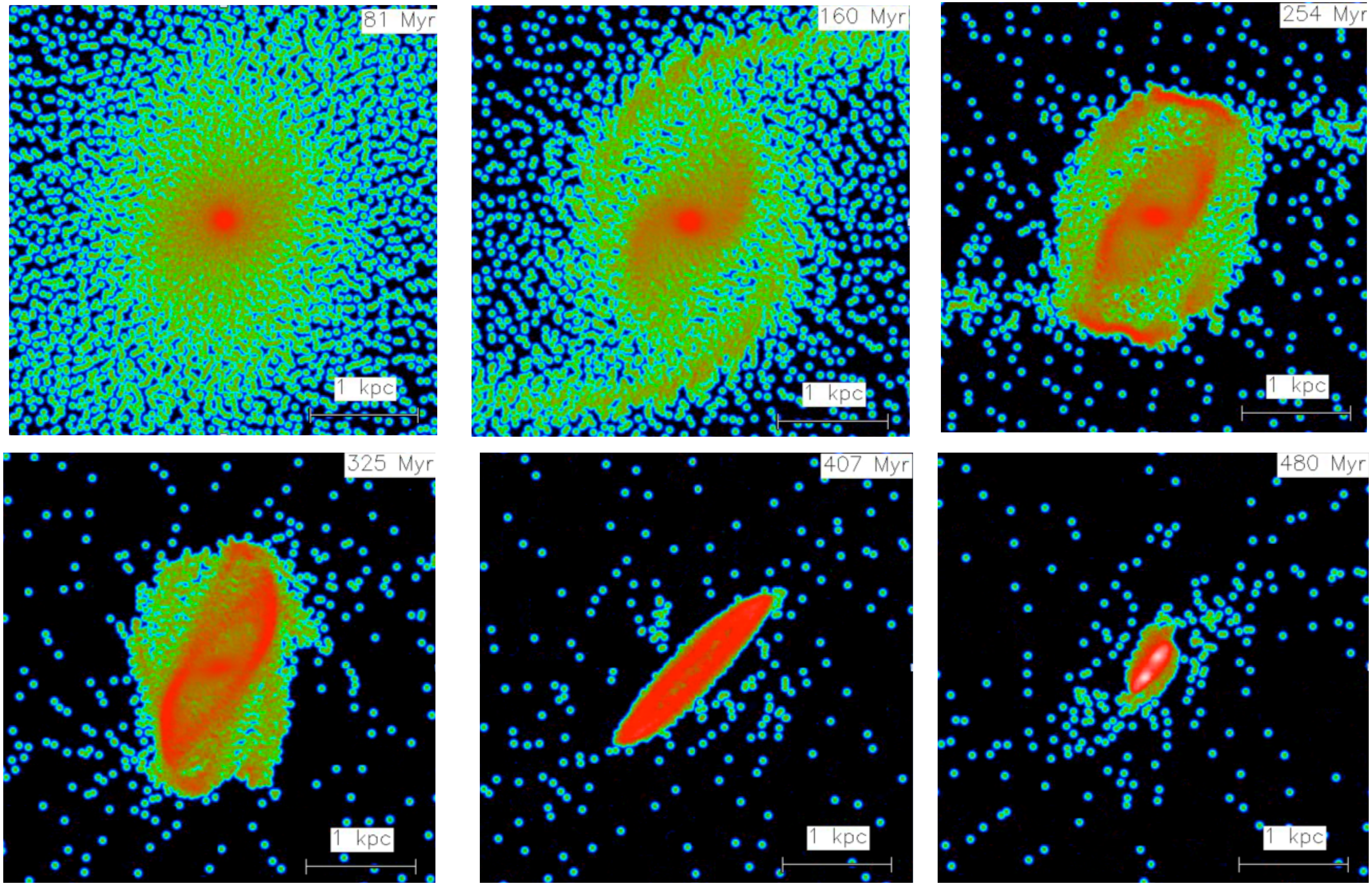
Gas-driven collapse: dynamics

(e.g. Begelman, MV & Rees 2006, Lodato & Natarajan 2006, Mayer et al. 2010)



✔Mdot is high: if *global dynamical instabilities* trigger inflow and dissipate angular momentum on timescales shorter than star formation (Begelman, MV & Rees 2006)

✔ No metallicity threshold



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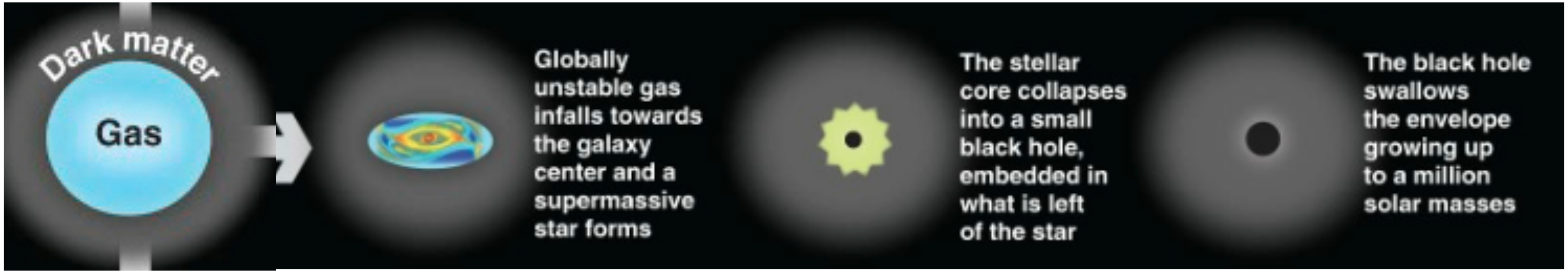
Gas-dynamical collapse: thermodynamics

Gas-driven collapse: thermodynamics

(e.g. Bromm & Loeb 2003, Spaans & Silk 2006, Begelman, MV & Rees 2006, Shang et al. 2010, Latif et al. 2013)

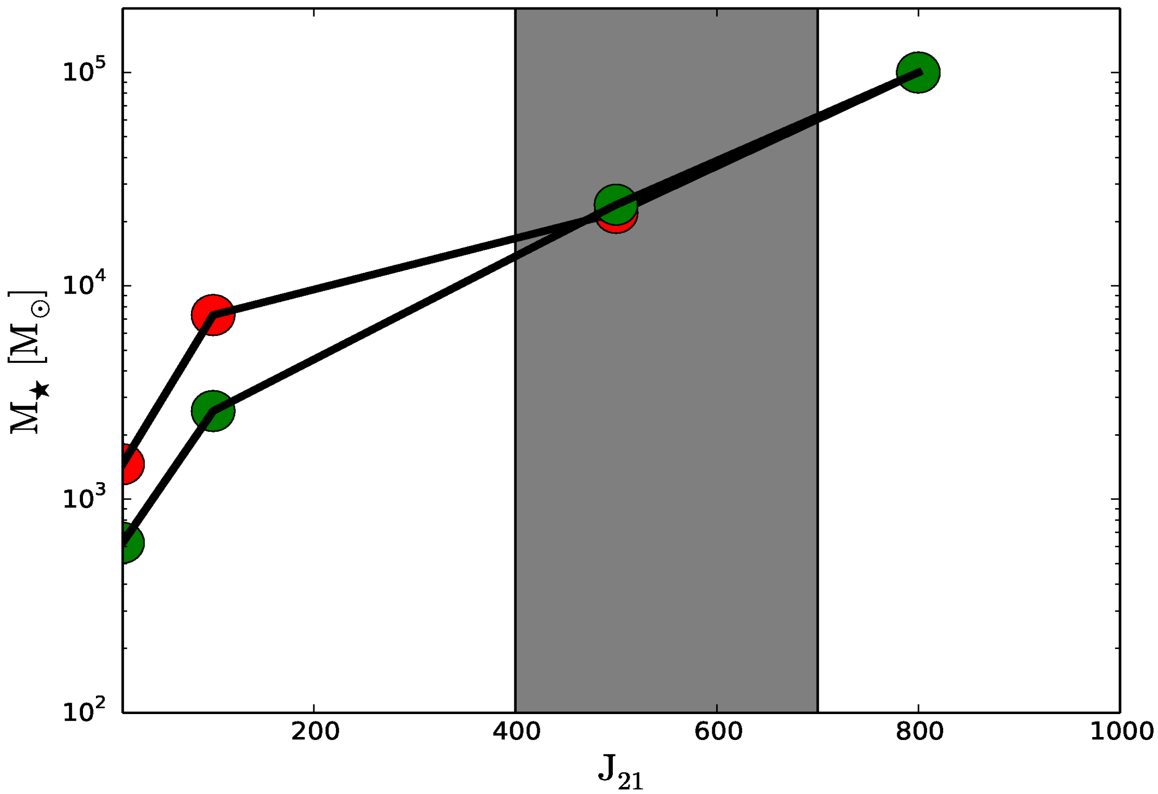


✔Mdot is high: if star formation delayed, e.g.,

-primordial gas composition => radiative cooling inefficient

-H_2 formation suppressed by strong dissociating UV flux => UV background flux (J_{21})

UV background vs stellar mass



Average background J21<10!!! Need strong local sources

$$J_{21,bg} = 0.3 \left(\frac{1+z}{16}\right)^3 \left(\frac{\dot{\rho}_{\star,II}}{10^{-3} M_\odot \, yr^{-1} Mpc^{-3}}\right)$$

$$J_{21,local} = 3 \sum_{i,stars<5Myr} \left(\frac{r_i}{1kpc}\right)^{-2} \left(\frac{m_i}{10^3 M_\odot}\right)$$

Latif et al. 2014

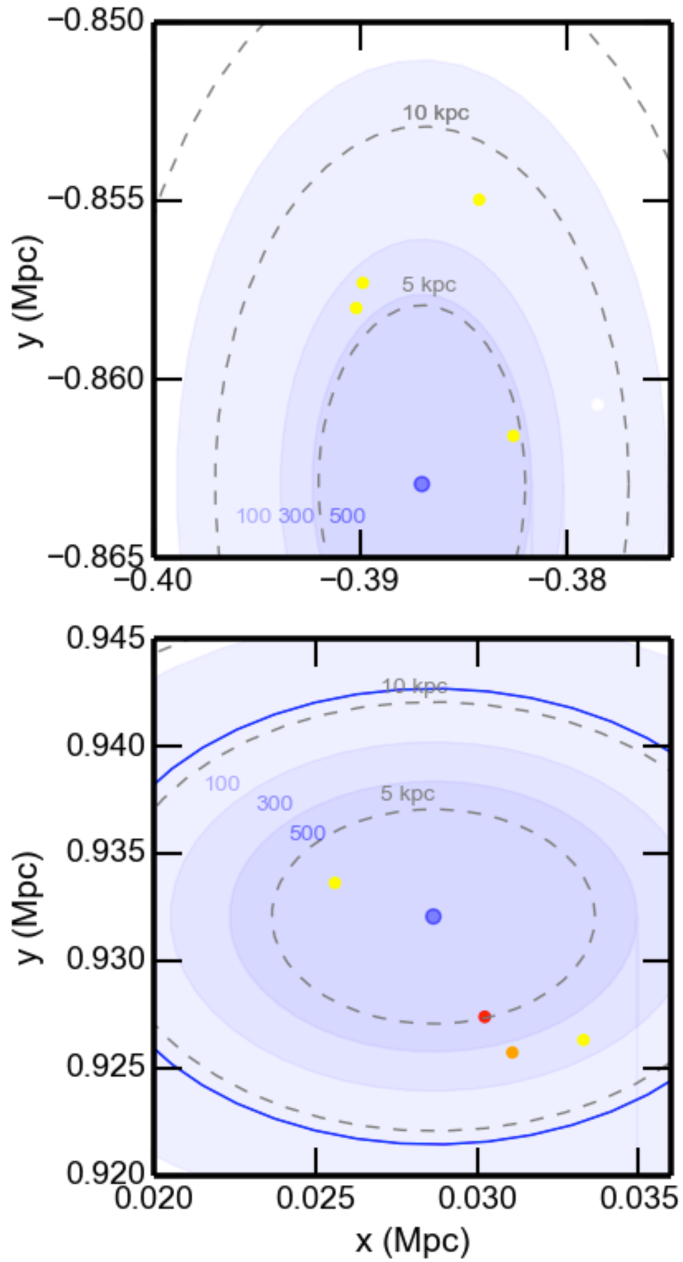
UV background vs metal enrichment

Need strong local stellar sources to provide dissociating radiation throughout collapse~10-100 Myr

BUT

Stars explode in ~10 Myr and pollute the environment

Z=0 direct collapse: tough conditions



Contours: strength of the dissociating field:
yellow J21 ⩾ 100
orange J21 ⩾ 300
red J21 ⩾ 500

Blue ellipse: expansion of the metal bubble

Timesteps: 1 Myr

Within 10 Myr no galaxy meets the metal/H_2 requirements

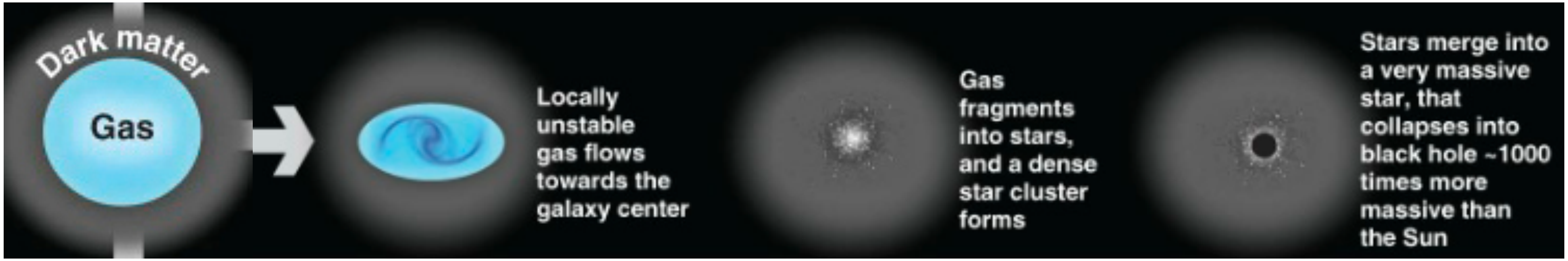
Collapse, free-fall time ~10-100 Myr

Dijkstra+14, Habouzit, MV et al. 2015

Stellar-dynamical processes:
stellar mergers

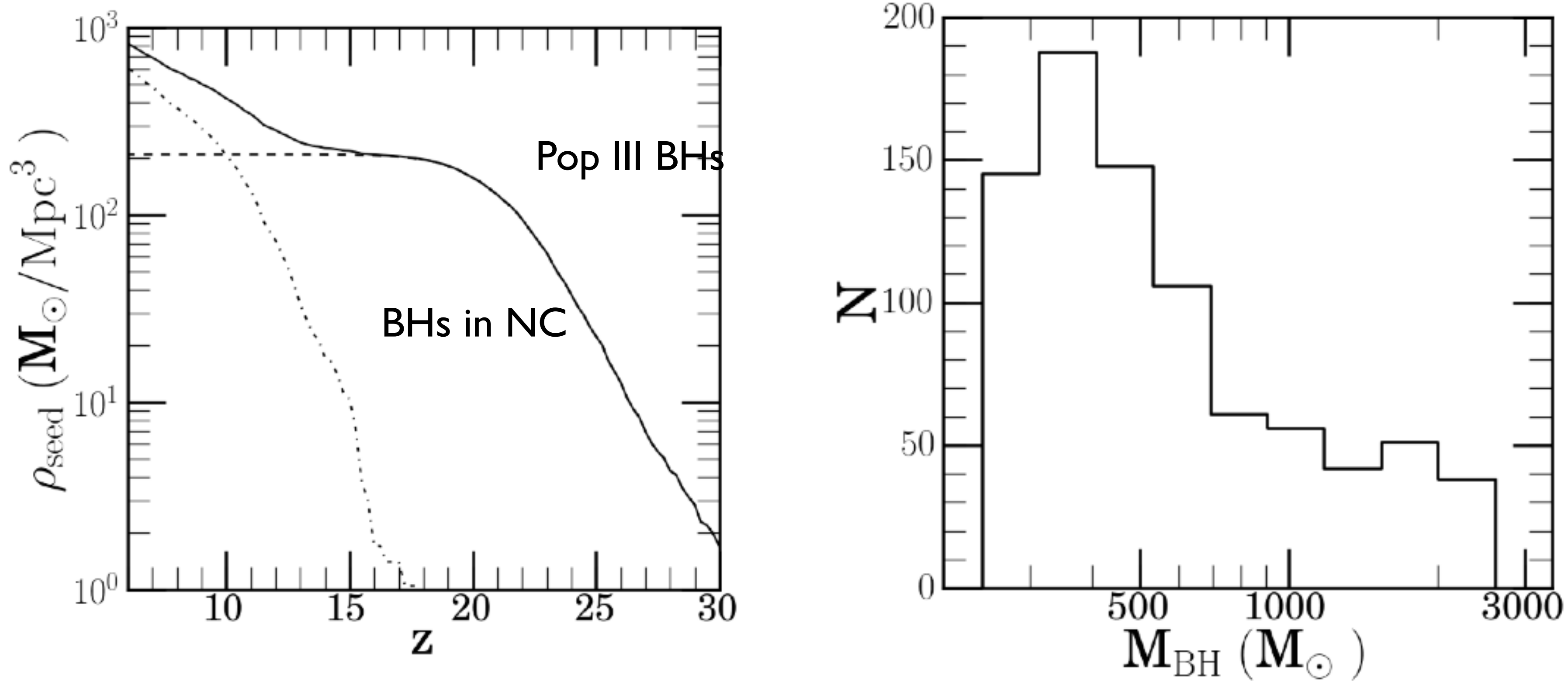
Stellar-dynamical processes: stellar mergers

Omukai et al. 2009; Devecchi & MV 2009, Devecchi et al. 10, 12; Katz et al. 2015



- ✔ Mass segregation in nuclear star cluster: massive stars sink to the center
- ✔ Stellar collisions form a very massive star
- ✔ At low metallicity ⇒ massive black hole $\sim 10^3$ M_{sun}

Stellar-dynamical processes: stellar mergers



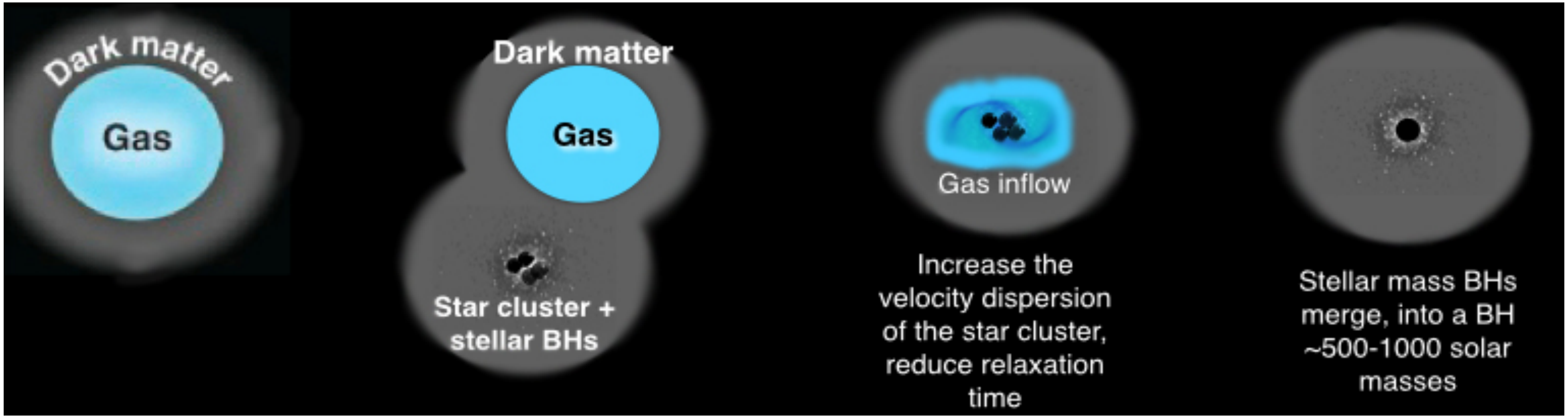
$$10^{-5}\,Z_\odot < Z < 10^{-3}\,Z_\odot$$

Devecchi & MV 2009, Devecchi, MV et al. 10, 12

Stellar-dynamical processes:
stellar BH mergers

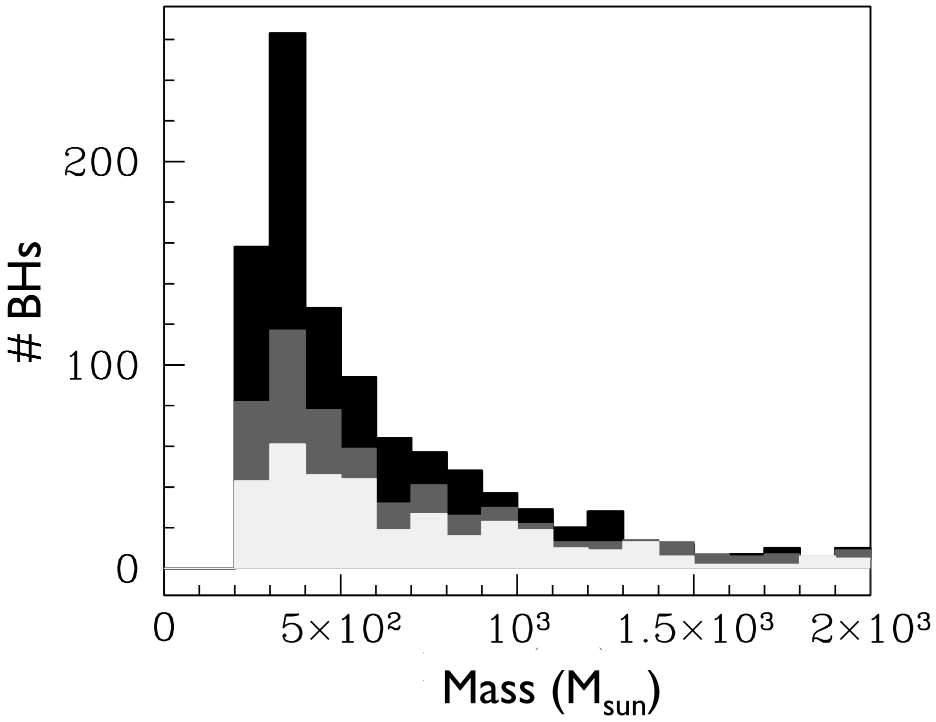
Stellar-dynamical processes: stellar BH mergers

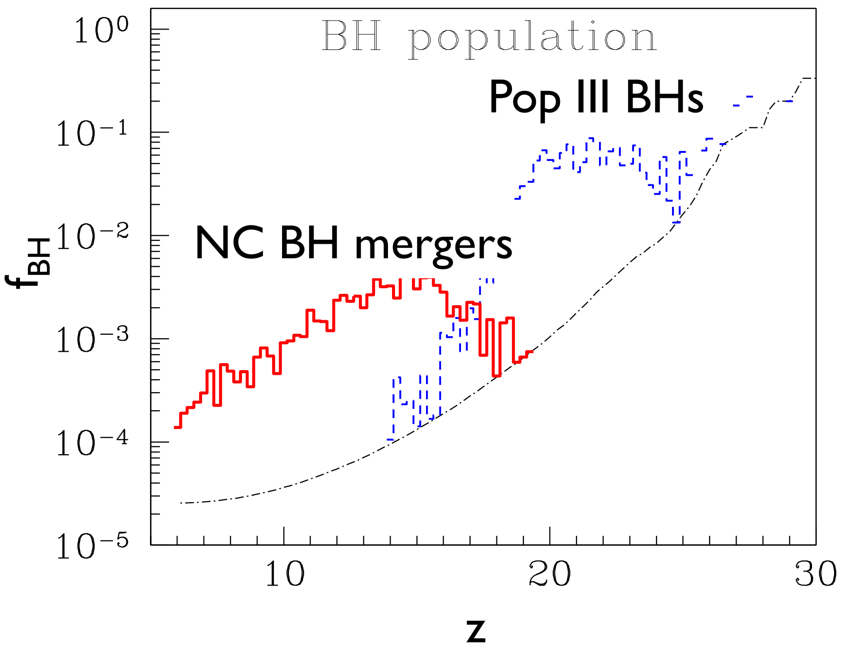
Davies, Miller & Bellovary 2011, Miller & Davies 2012; Lupi et al. 2014



- ✔ Merging stellar BHs normally ejected (3-body, GW)
- ✔ Merger-driven gas inflow increases velocity dispersion
- ✔ BHs merge ⇒ massive black hole $\sim 10^3$ M_{sun}
- ✔ No metallicity threshold

Stellar-dynamical processes: stellar BH mergers





Lupi et al. 2014

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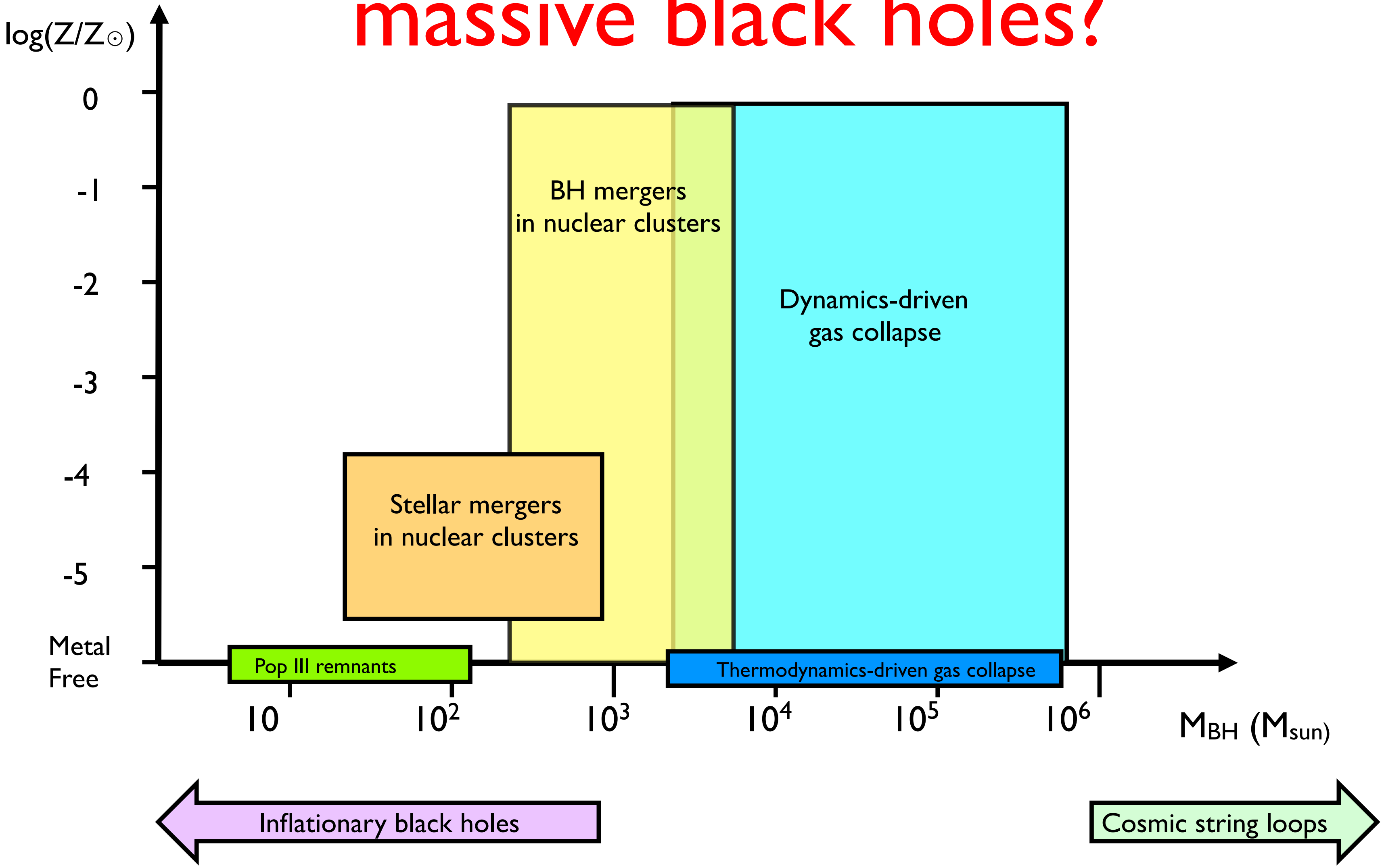

How do the seeds grow?