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Supermassive black hole formation and light up

Outline

1. Intro: SMBHs? Why? When? How?

2. When: a structure formation primer

    Dark matter: spherical collapse model

    Baryons: cooling efficiency

3. How: paths leading to MBH formation

    PopIII stars remnants

    Star/BH mergers in stellar clusters

    Direct gas collapse

Statement:

AGN are powered by black holes accreting matter

1. they are extremely luminous

2. the brightness varies on short timescales (<1 week)

3. information is carried at the speed of light from one side to the other of the source: the emitting region is <1 light week, ~10^{-3} pc

Stars cannot make it! The implication is the existence of black holes with masses > millions Msun

Stellar mass BHs

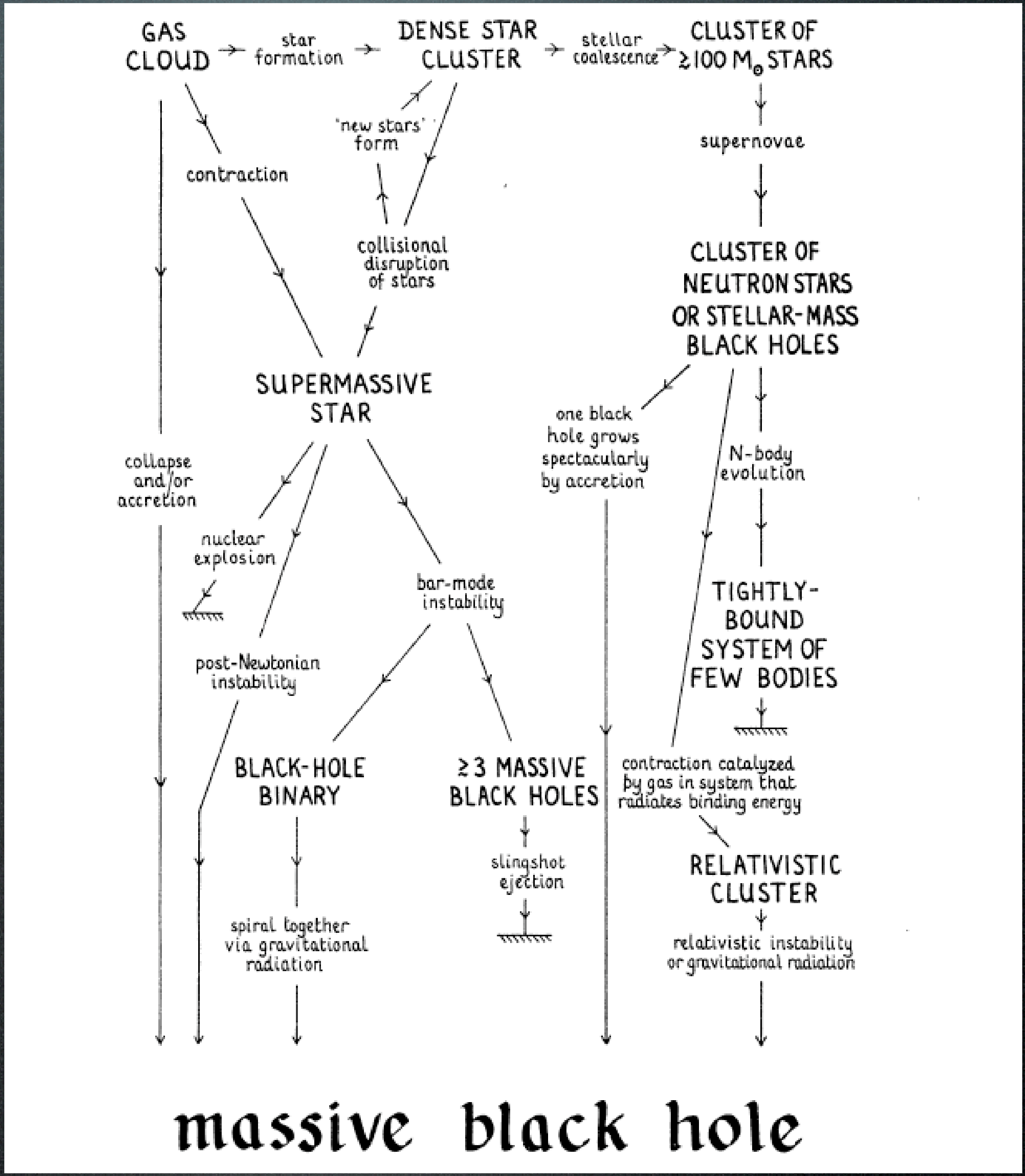
- ✔ formation through stellar evolution
- ✔ mass < few tens M_{sun}

Supermassive BHs**

- ✔ powering quasars
- ✔ dead remnants in the center of local galaxies
- ✔ mass > 10^6 M_{sun} (by convention...)

***convention: SMBH if $M>10^6 M_{sun}$*

HOW can you make a (super) massive black hole?



from Rees 1984

WHEN do you make a (super) massive black hole?

The highest redshift quasar currently known
SDSS 1148+3251 at z=6.4
has estimates of the SMBH mass
M_{BH}=2-6 x10^9 M_{sun}
(Willott et al 2003, Barth et al 2003)

AS LARGE AS THE LARGEST SMBHs

SEEN TODAY, BUT

WHEN THE UNIVERSE WAS 1 Gyr OLD!!!

Hey guys, we have to deal with cosmology...

Cosmological structure formation

The universe after the Big Bang was not completely uniform

Gravitational instability due to the non-uniform matter distribution caused matter to condense until small regions become gravitationally bound

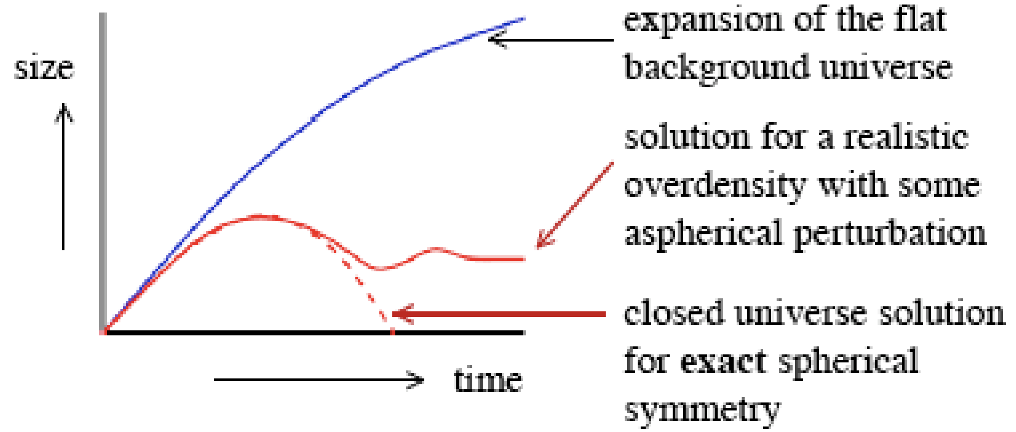
They then break away from the global expansion, collapse down on themselves, and form a galaxy at the center

Galaxies form at density peaks within large-scale structure

SPHERICAL COLLAPSE MODEL

Consider a flat, matter dominated universe (ok at early times)
Imagine a spherical volume of the universe which is slightly denser than the background

As the gravitational force inside a sphere depends only on the matter inside (Birkhoff's theorem) the overdense region behaves exactly like a small closed Universe!



Schematic evolution:

- Density contrast grows as universe expands
- Perturbation "turns around" at $R = R_{turn}$, $t = t_{turn}$
- If exactly spherical, collapses to a point at $t = 2\ t_{turn}$
- Realistically, bounces and **virializes** at radius $R = R_{virial}$

Within the spherical collapse model a halo properties are completely determined by its mass and collapse redshift: the mean density is about ~200 the background density at that redshift

VIRIAL MASS *Mvir*

Known mass and density, you can get the size (radius)

VIRIAL RADIUS

$$R_{\rm vir} = 0.784 \left(\frac{M}{10^8\ h^{-1}\ M_\odot}\right)^{1/3} \left[\frac{\Omega}{\Omega(z)}\ \frac{\Delta_c}{18\pi^2}\right]^{-1/3} \left(\frac{1+z}{10}\right)^{-1}\ h^{-1}{\rm kpc}$$

VIRIAL CIRCULAR VELOCITY $V_c=(GM_{vir}/R_{vir})^{1/2}$

$$V_c = 23.4 \left(\frac{M}{10^8\ h^{-1}\ M_\odot}\right)^{1/3} \left[\frac{\Omega}{\Omega(z)}\ \frac{\Delta_c}{18\pi^2}\right]^{1/6} \left(\frac{1+z}{10}\right)^{1/2}\ {\rm km\ s}^{-1}$$

VIRIAL TEMPERATURE $T_{vir}=\mu m_p V^2_c/2k_B$

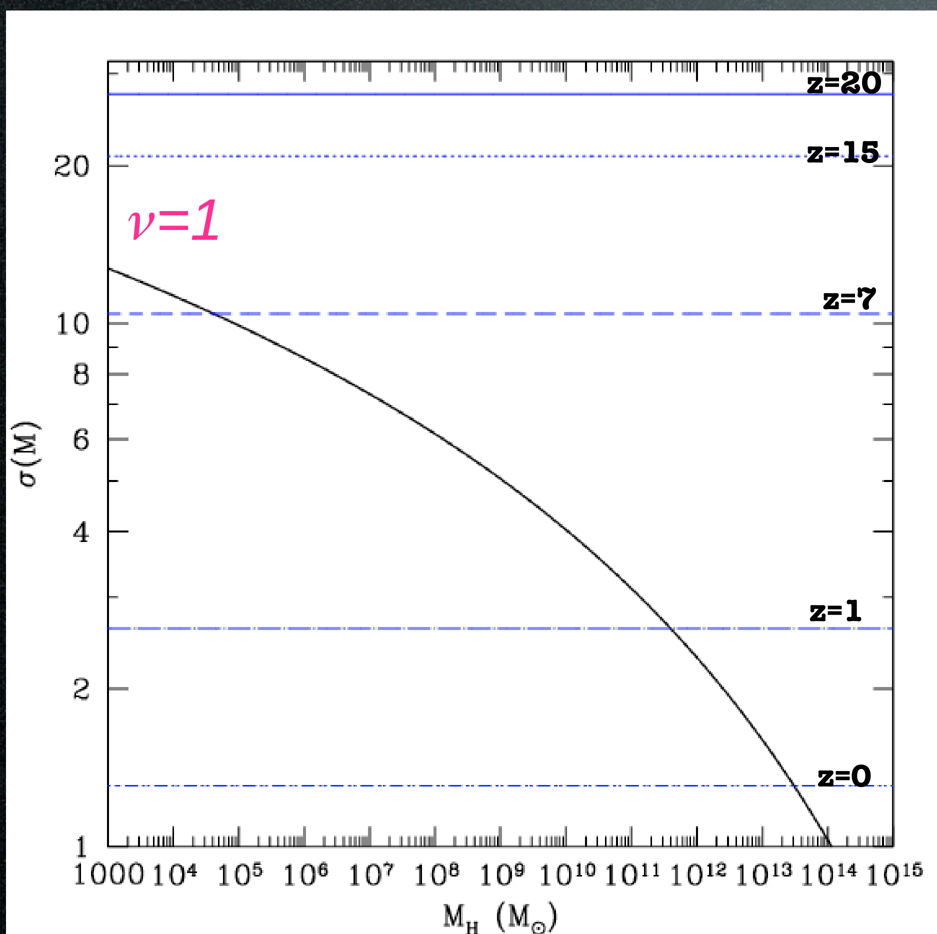
$$T_{\rm vir} = 1.98 \times 10^4 \left(\frac{\mu}{0.6}\right) \left(\frac{M}{10^8\ h^{-1}\ M_\odot}\right)^{2/3} \left[\frac{\Omega}{\Omega(z)}\ \frac{\Delta_c}{18\pi^2}\right]^{1/3} \left(\frac{1+z}{10}\right)\ {\rm K}$$

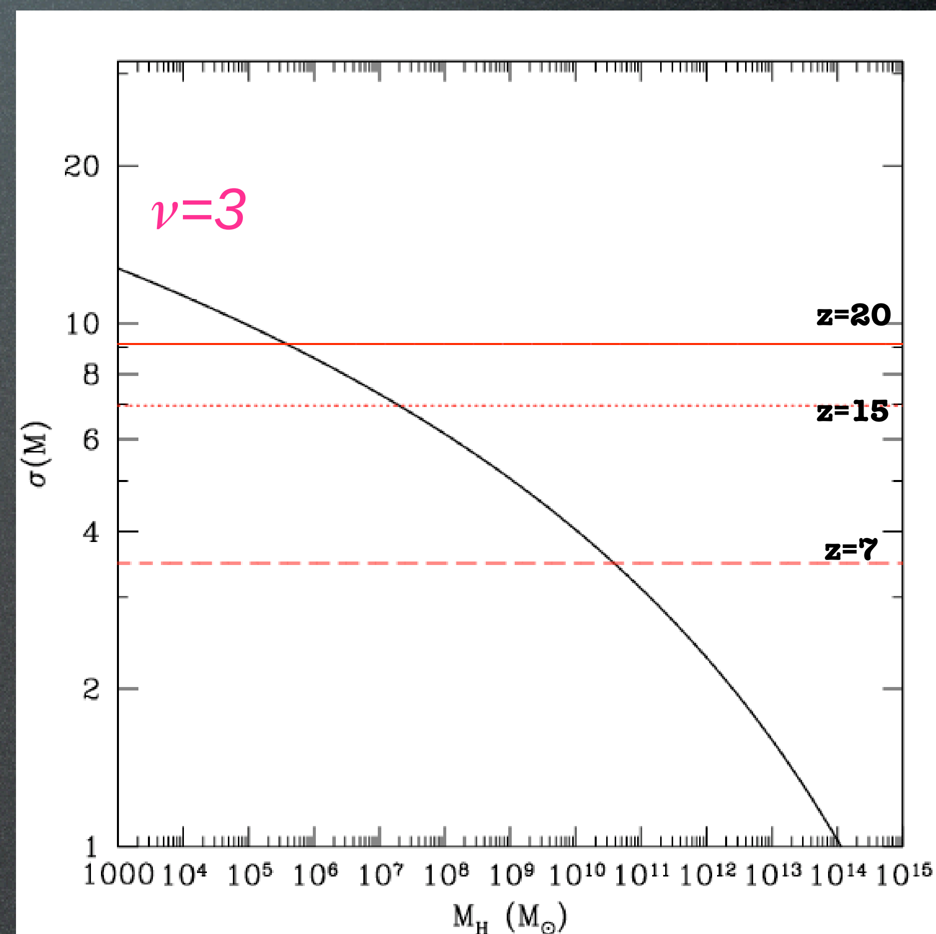
The mass function scales as

$$\frac{dN}{dM} \propto \nu e^{-\nu^2/2}$$

$$\nu = \delta_c(1+z)/\sigma(M)$$

If the fluctuation field is gaussian, the mass corresponding to ν=1 is the most common, multiples of δ define increasingly rarer - and more massive - fluctuations (2- δ, 3-δ, 4-δ...) which can collapse.

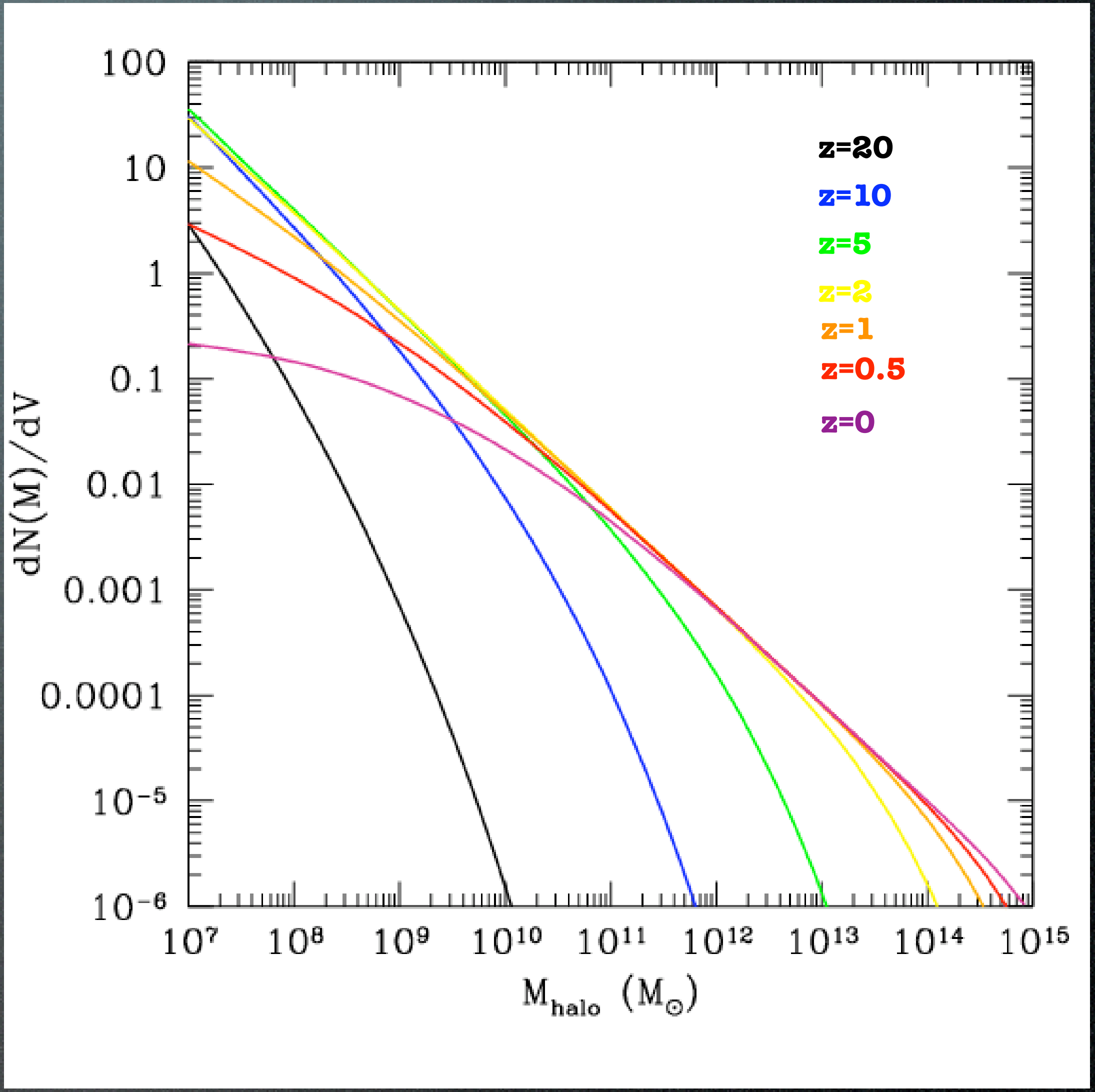


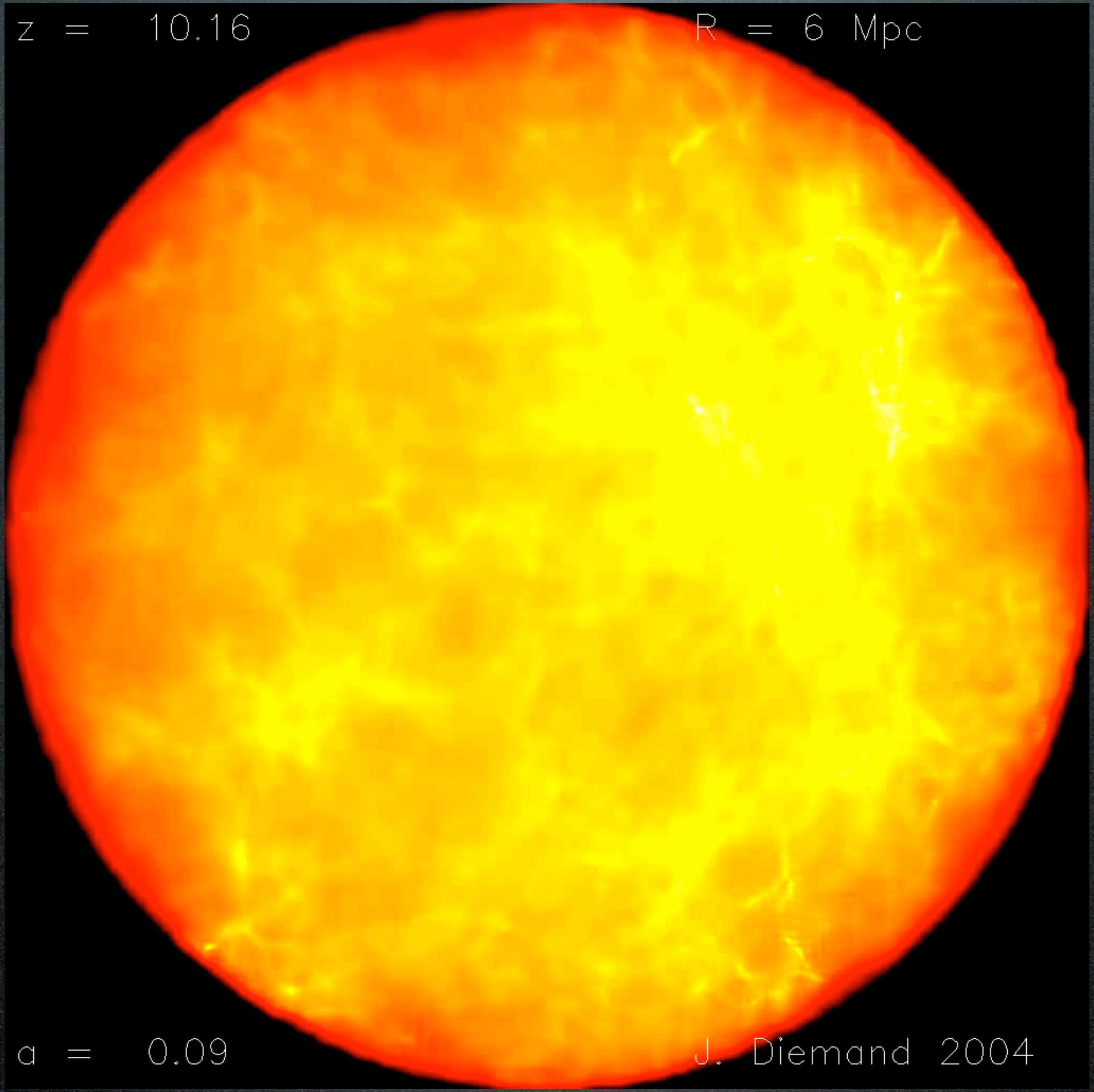


The typical halo mass is an increasing function of time: bottom-up or hierarchical structure formation

The mass functions of halos has a strong evolution with time

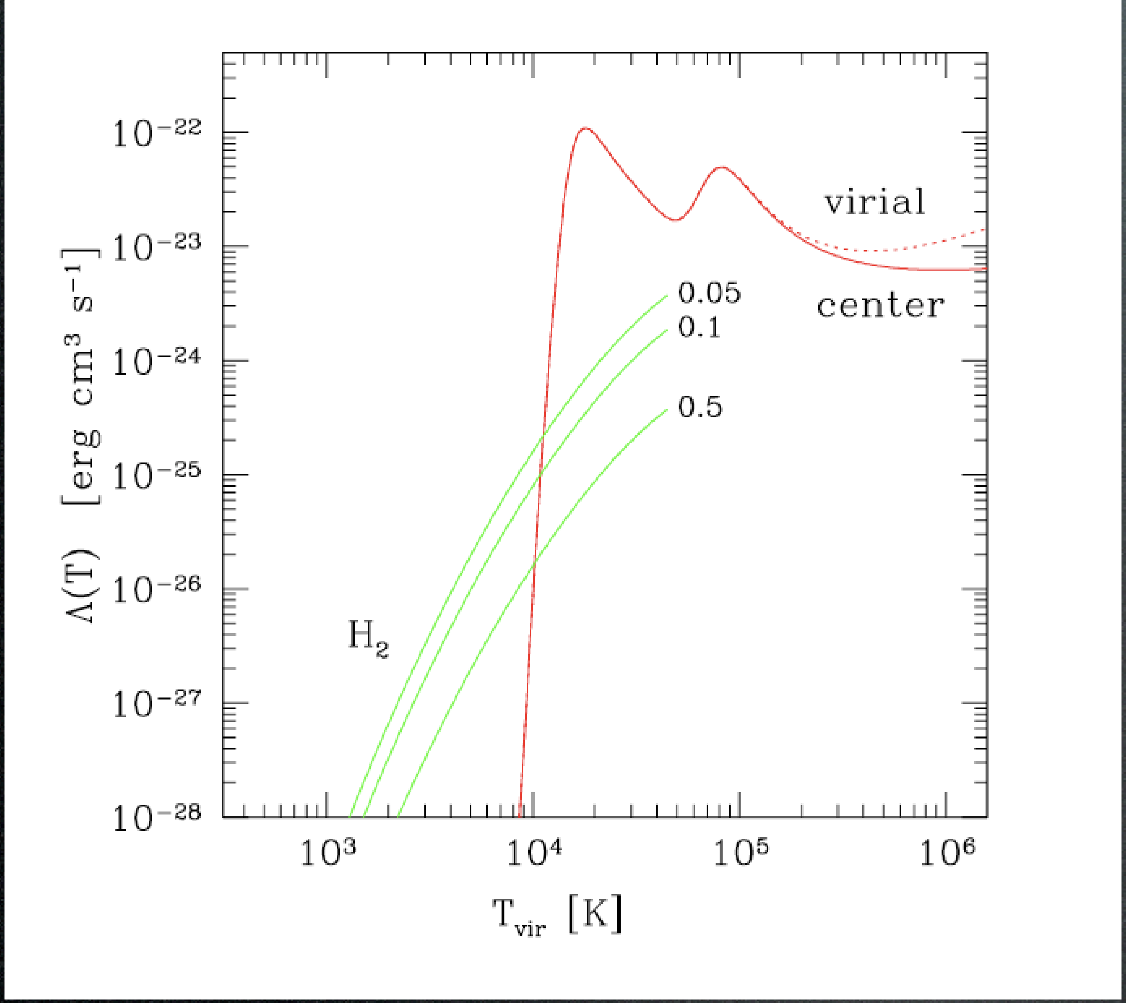
This is what we see in cosmological simulations....




z = 10.16
R = 6 Mpc
a = 0.09
J. Diemand 2004

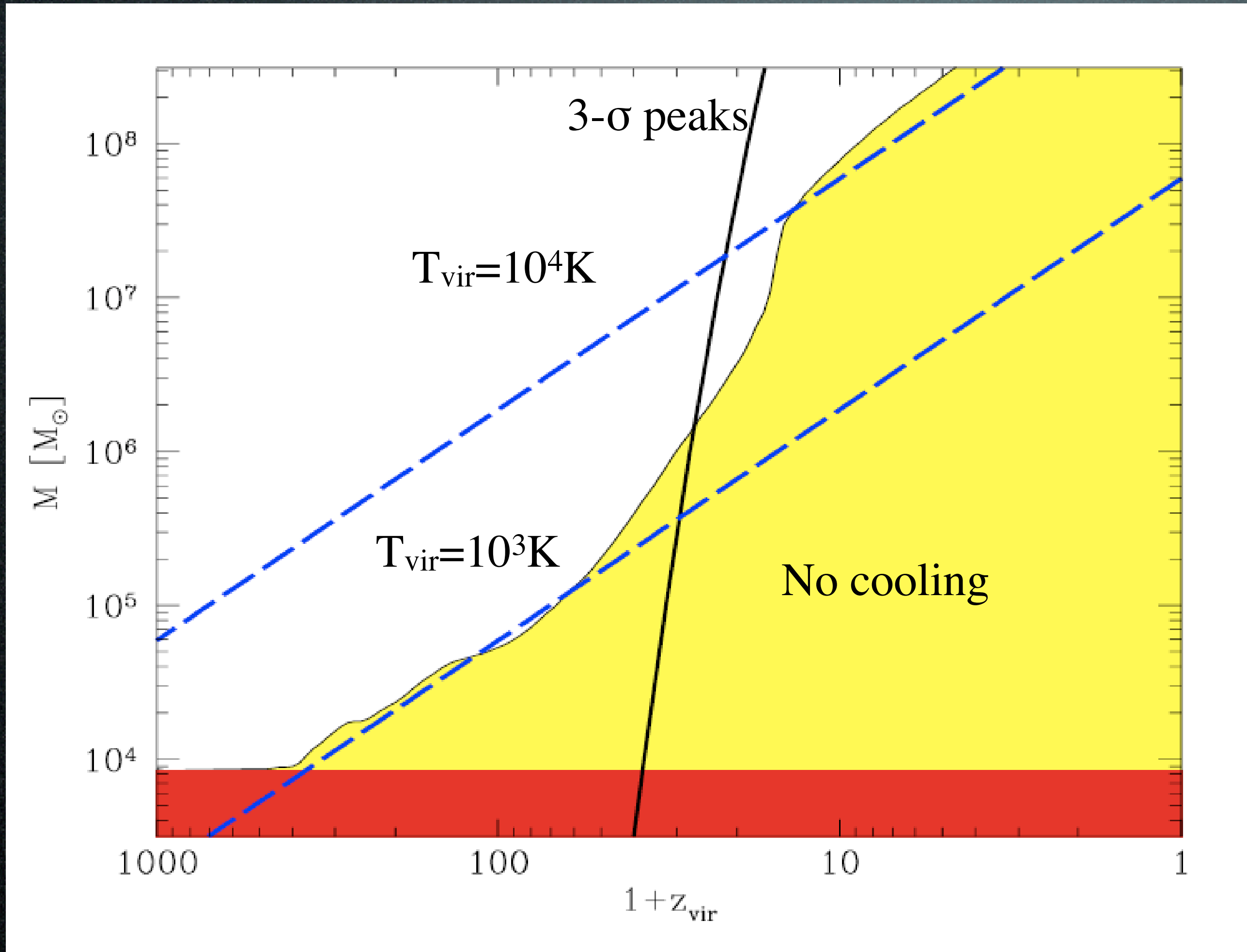
This is fine for collapsing dark matter... what about baryons

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 (tautologic...): metal line cooling does not exist!



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

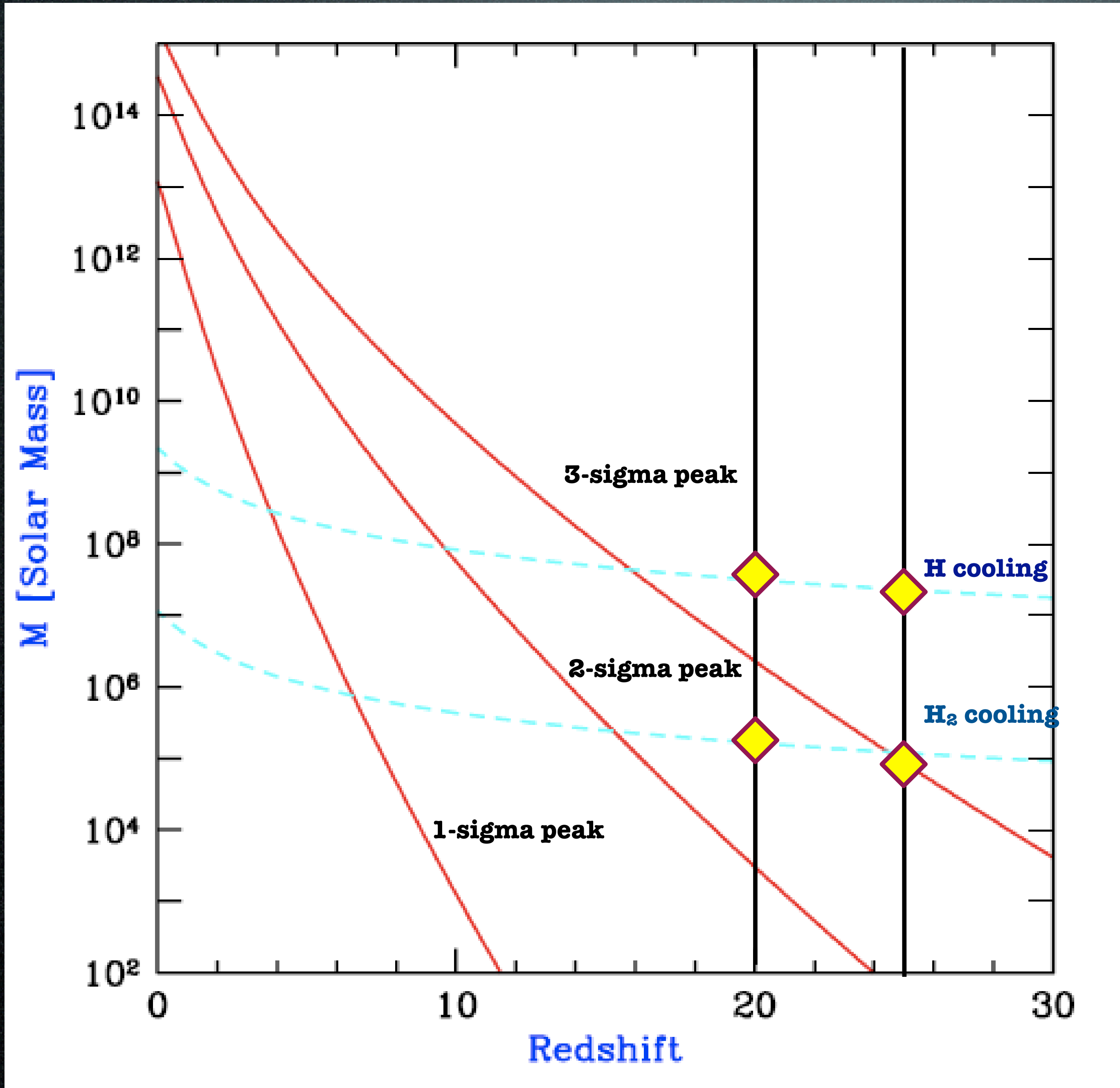
Halos with $T_{vir} < 10^4$K have to rely on molecular hydrogen cooling



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

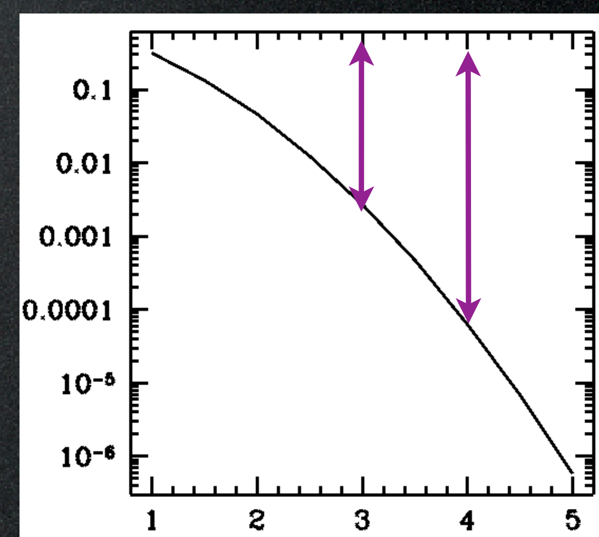
But only massive enough halos can cool, even with the aid of H_2

Only a small fraction of halos at early times can host cold gas and eventually star forming clouds

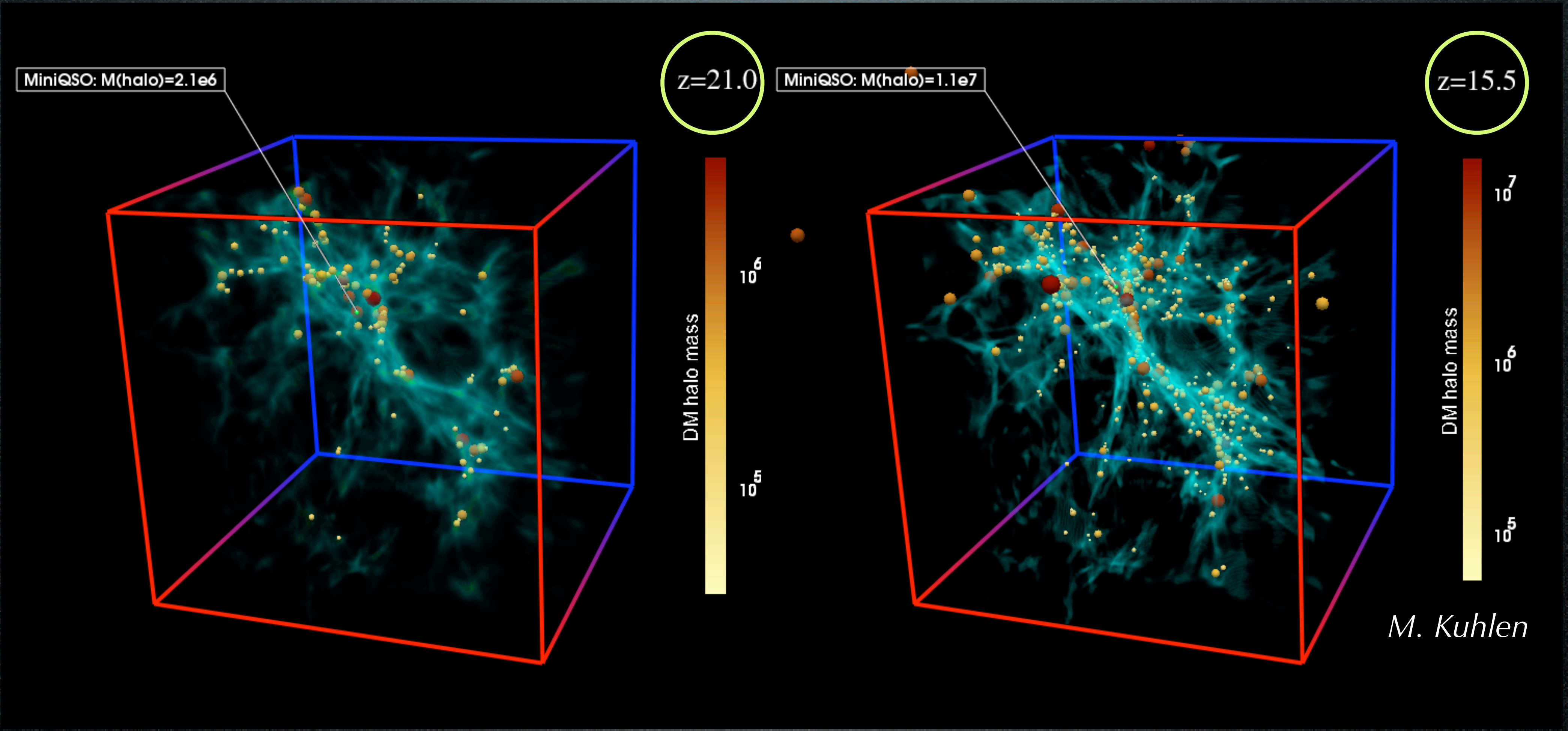


z=20-25
halos with efficient H2 cooling are peaks at 3-sigma or more from the mean: very rare

$$n(>M) \propto erfc(\nu/2)$$

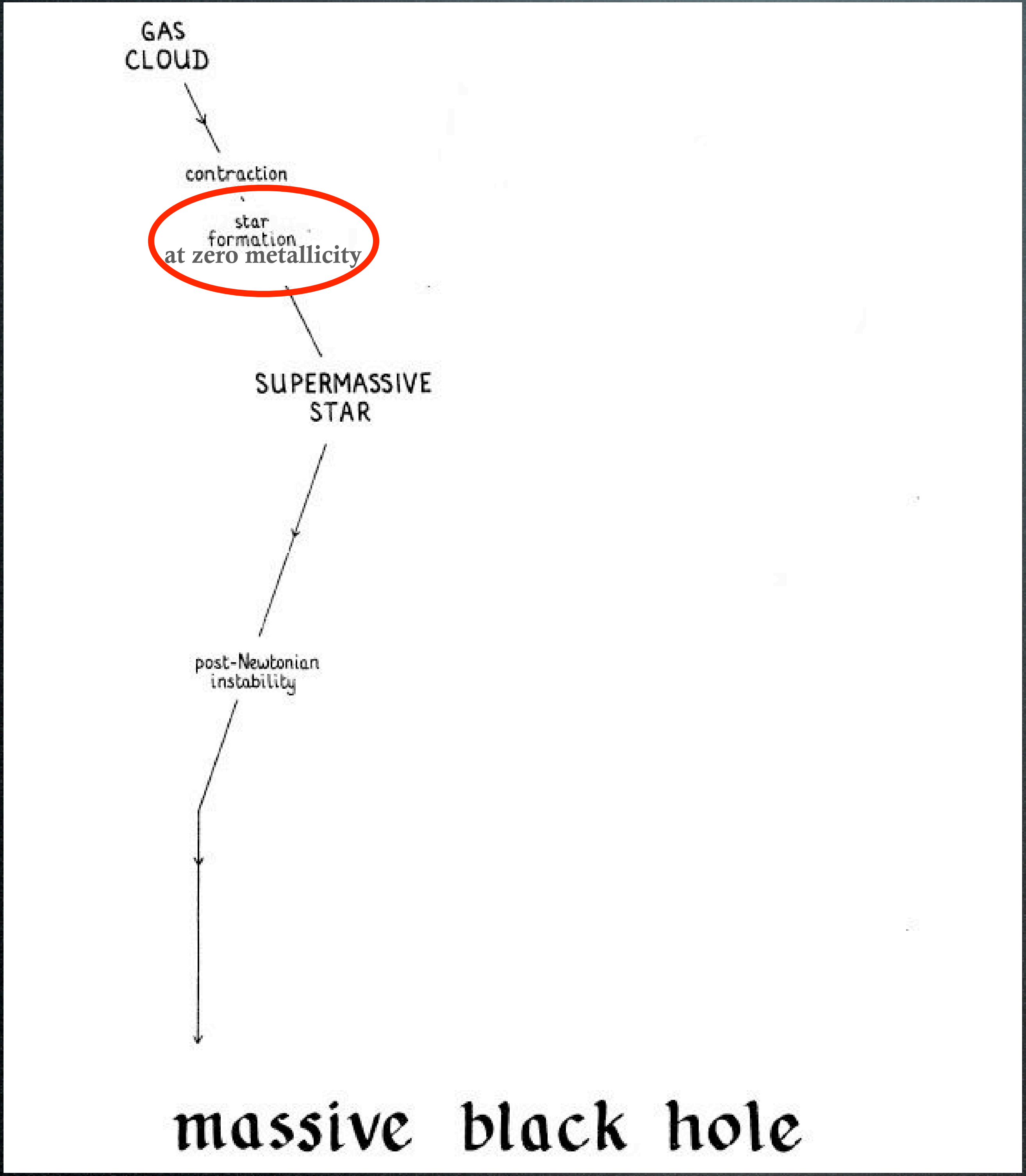


Summary



Hierarchical Galaxy Formation:
small scales collapse first

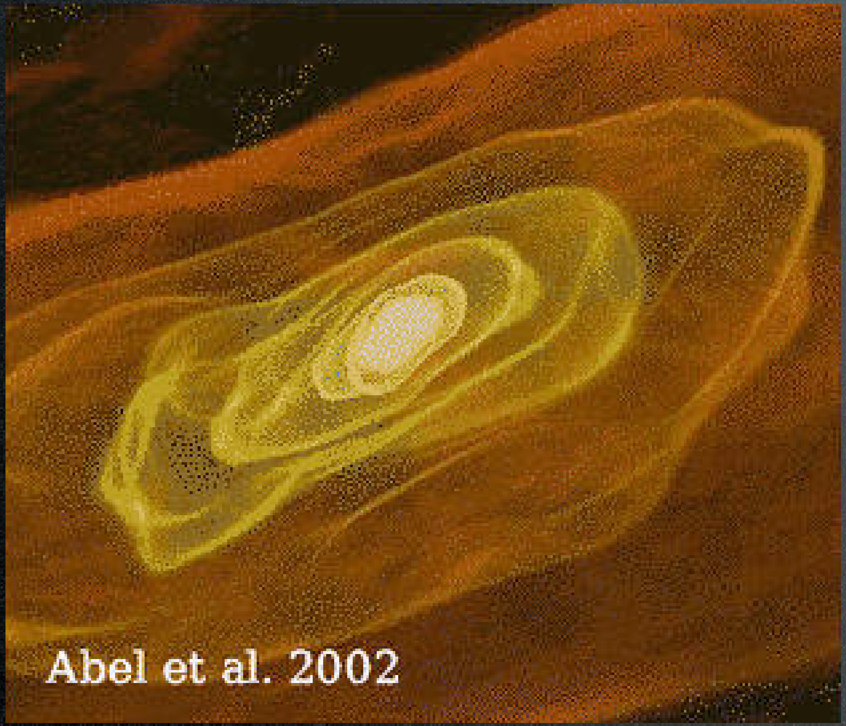
BARYONS: need to COOL only the MOST MASSIVE HALOS, i.e. the HIGHEST DENSITY FLUCTUATIONS at z~20-30



PopIII stars formation: when the Universe was metal free...

Black holes from POPIII stars

Metal free gas has to rely on inefficient H_2 cooling: slow, quasi-hydrostatic contraction



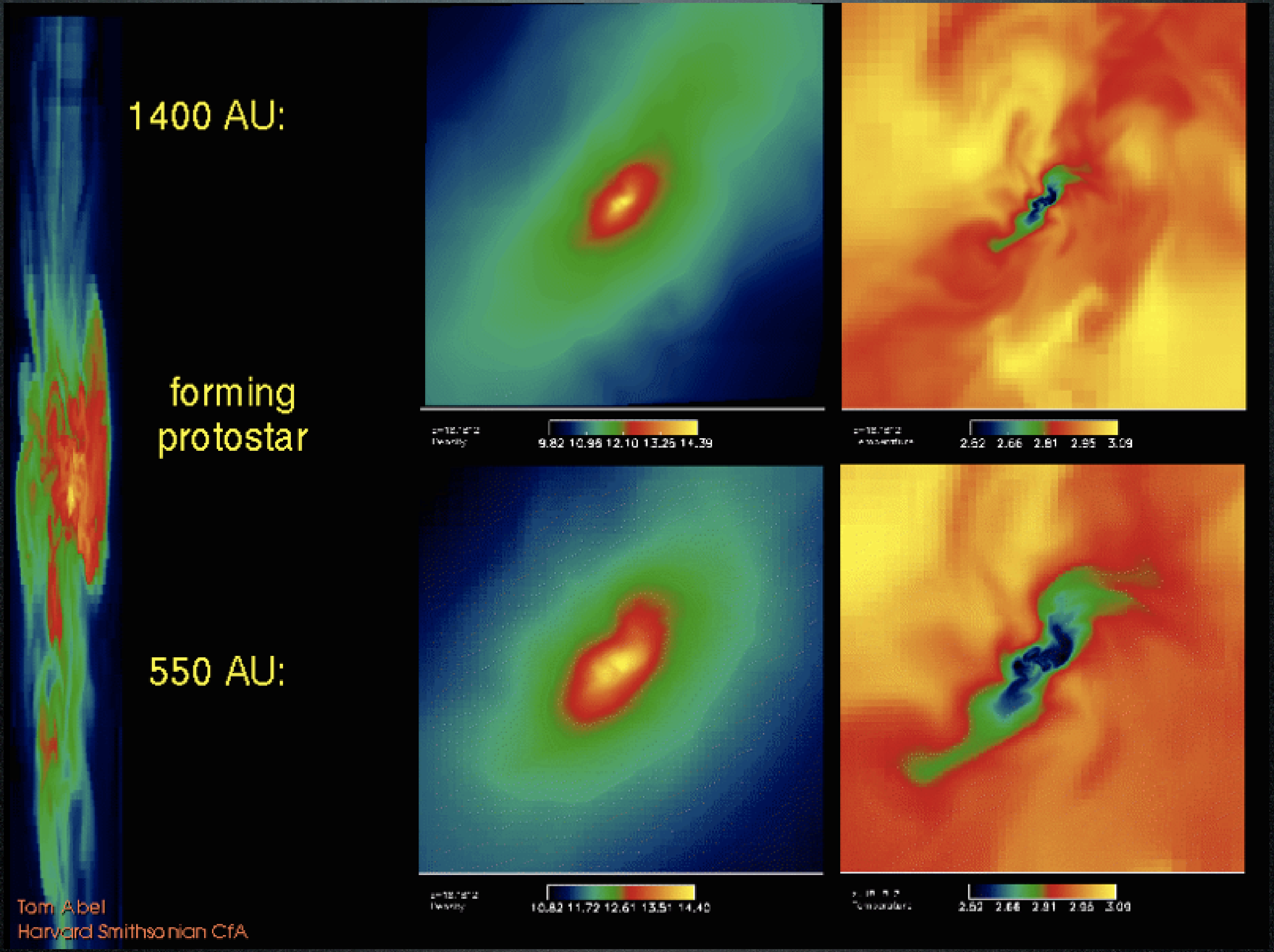
Simulations suggest that the first stars are massive

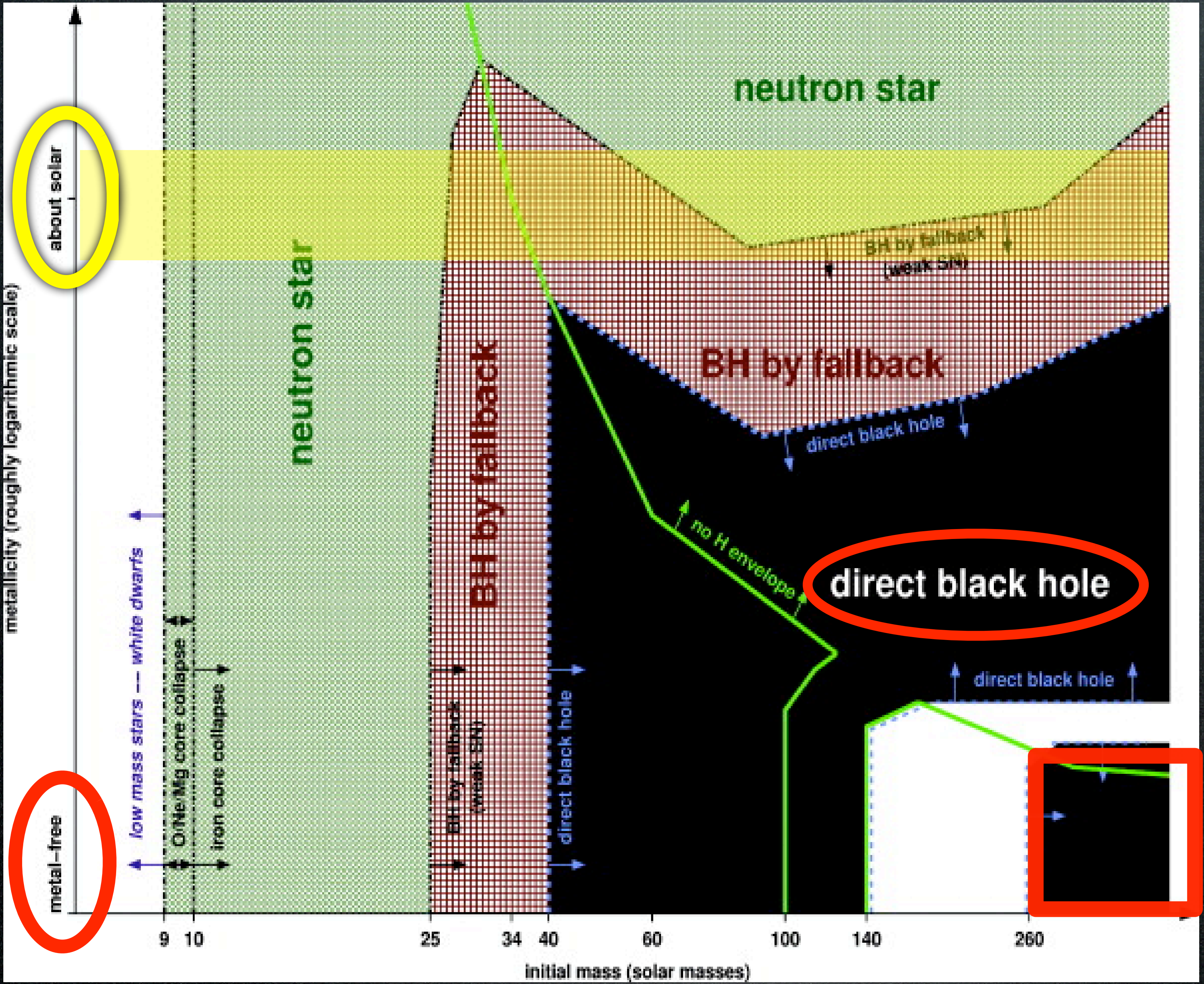
$M \sim 100\text{-}600\ M_{sun}$

(Abel et al., Bromm et al.)

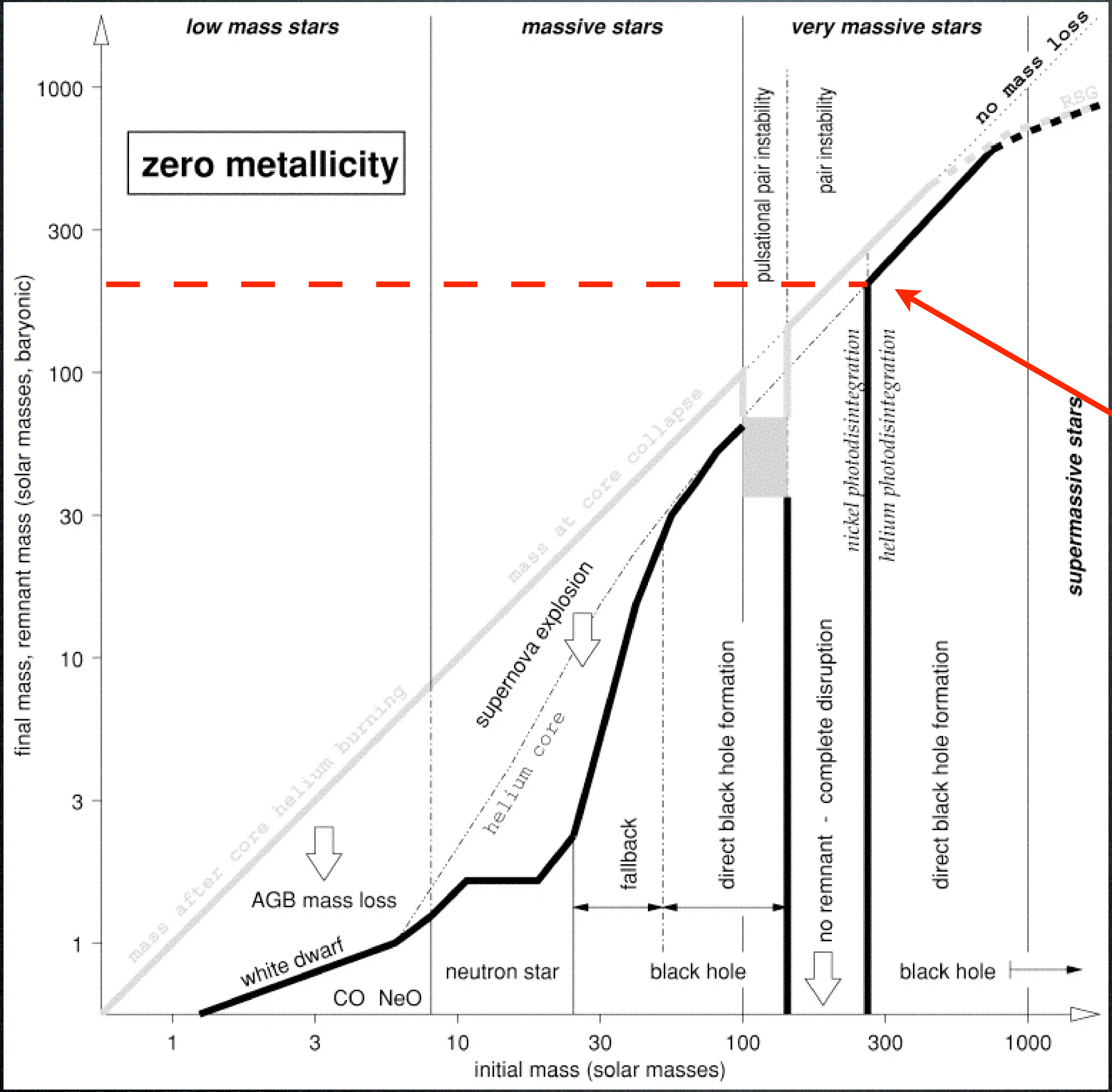
and come in small batches (1 to ~a few per halo)

Black holes from POPIII stars



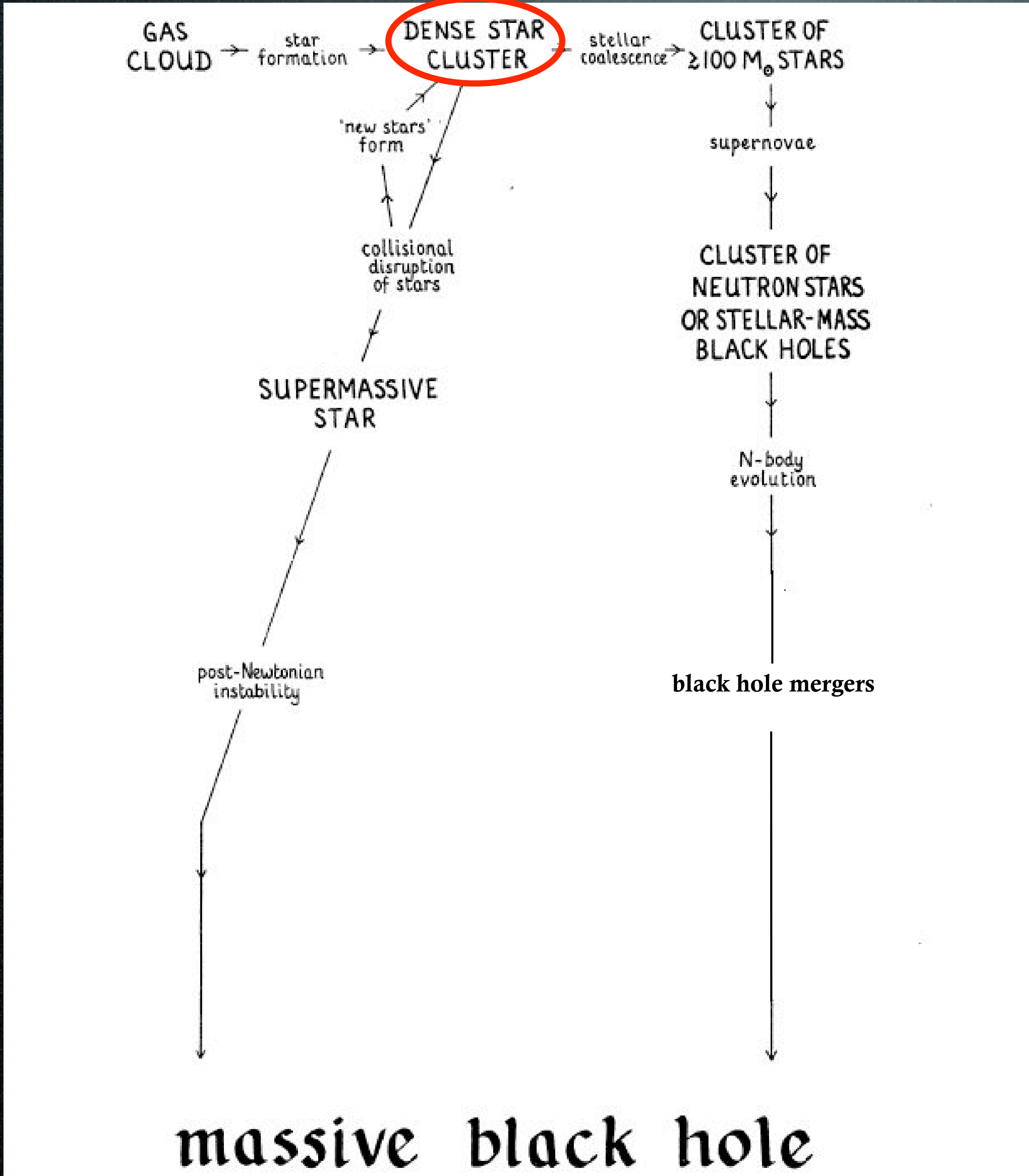


Heger et al. 2002



Metal free dying stars with $M > 260 M_{sun}$ leave **remnant BHs** with $M_{seed} \approx 100 M_{sun}$

(Fryer, Woosley & Heger)



Need to form a cluster of stars: much later than standard PopIII stars formation

1. Runaway merger of massive stars

Core collapse due to Spitzer's mass-segregation instability: merge massive stars and build up a large mass

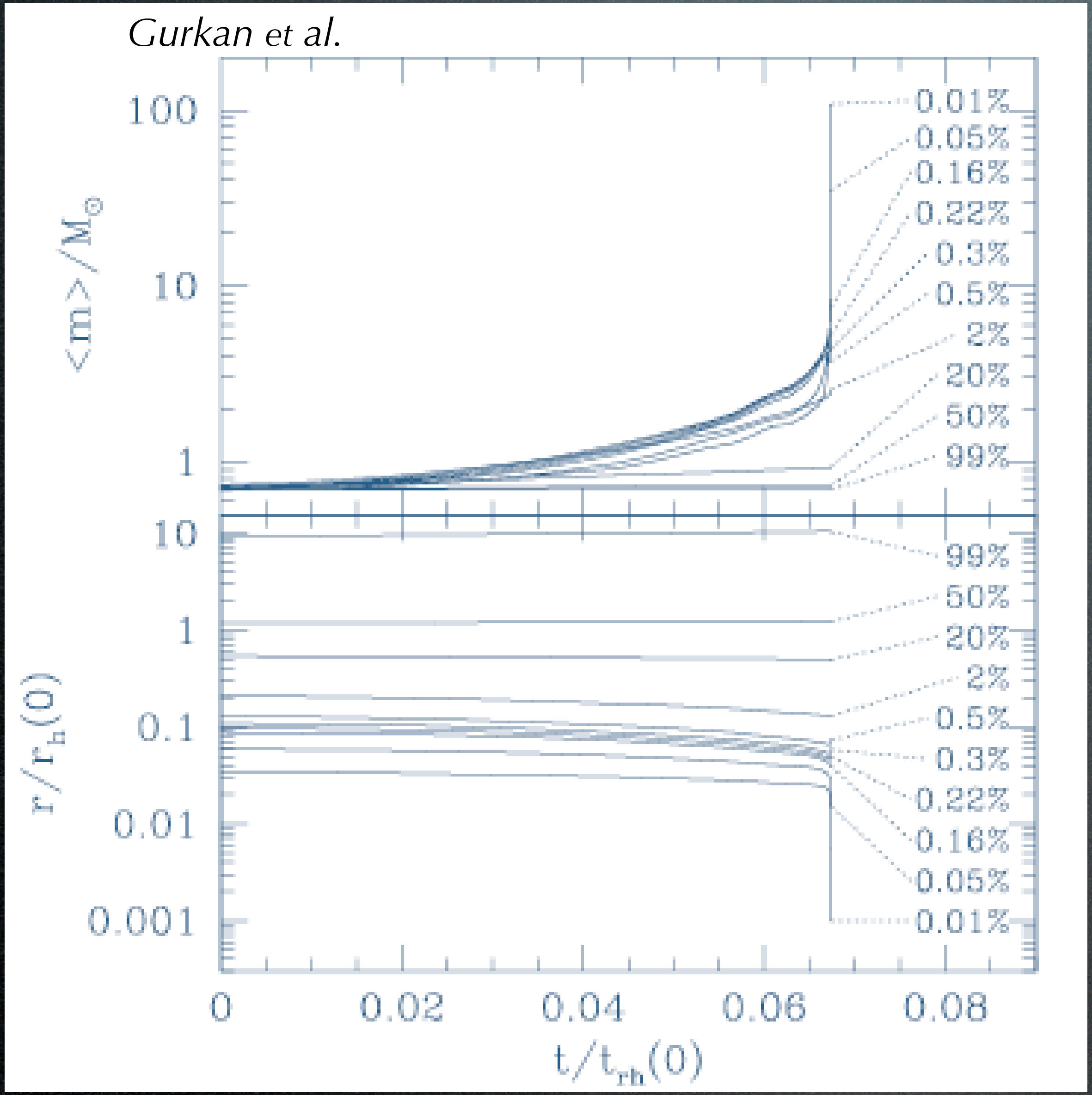
→ supermassive star collapsing into an IMBH

Problems:

1. $t_{merge} << t_{MS}$: to avoid mass loss in SN, and formation of compact objects (smaller cross section)

2. binaries: competing effects

- hard binaries become harder: shrink giving energy to the cluster → heat + expansion → halt core collapse
- larger collisional cross section: enhanced merging



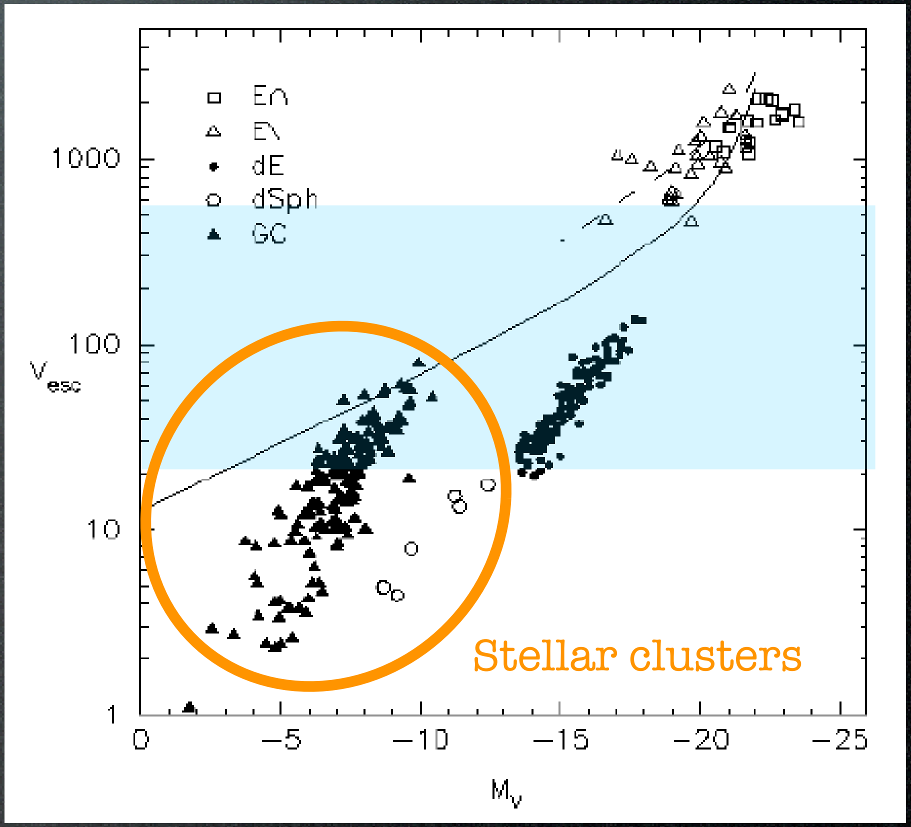
Mass segregation: the most massive stars end up in the center of the stellar cluster

2. Merger of stellar mass BHs

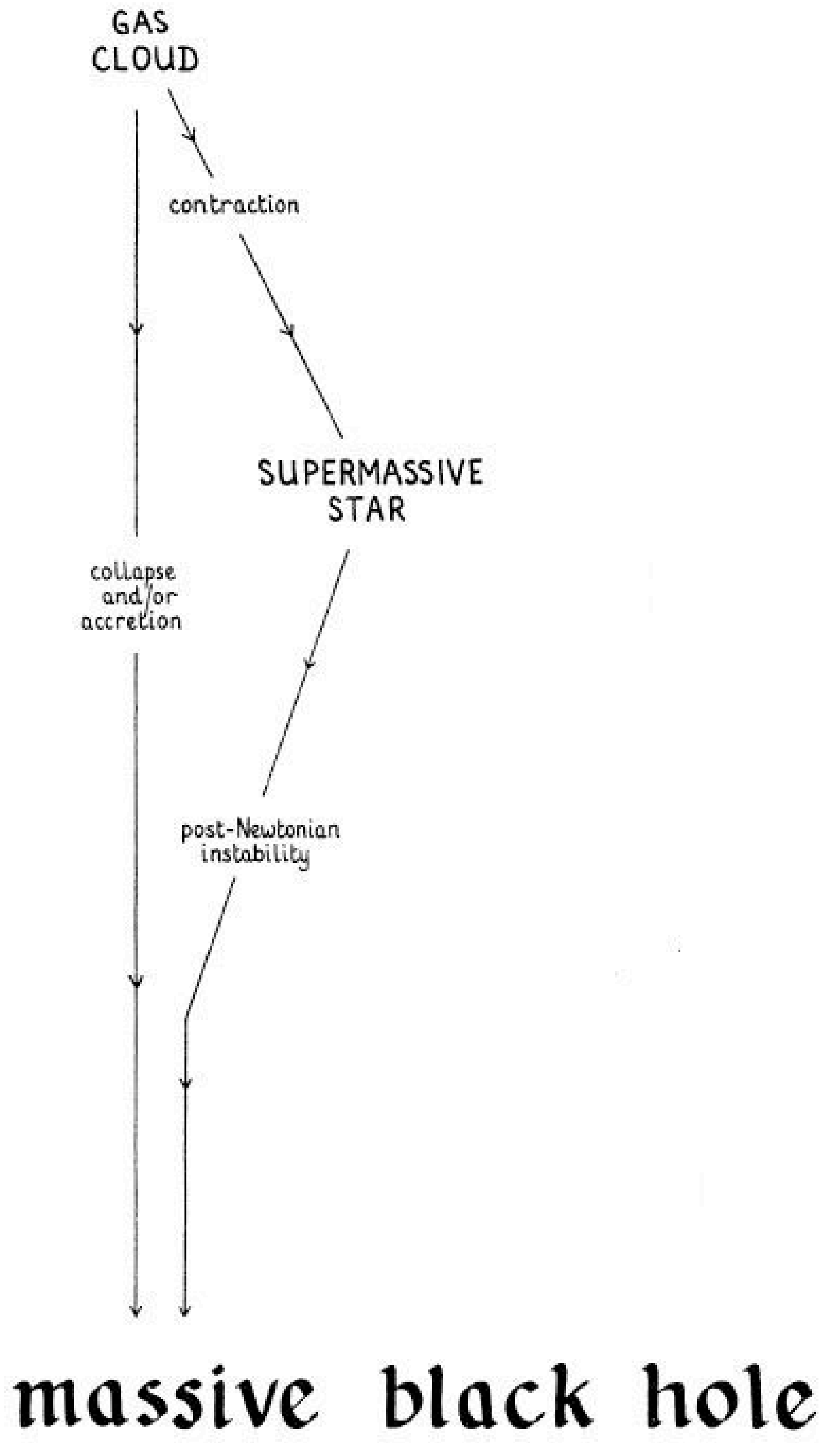
BHs in binaries: harden scattering single stars and merge by emission of GW

Problem: gravitational rocket can eject the merging binary from the cluster

Solution: start with a BH with M>50 M_{sun} → need for an IMBH to form a larger one



from Merritt et al 2004



Direct contraction of a gas cloud into a BH encounters a couple of problems:

1. ANGULAR MOMENTUM TRANSPORT
Because of its angular momentum, collapsing gas clouds become rotationally supported at 10^{6-8} Schwarzschild radii.

2. STAR FORMATION
Instead of going into BH formation, the gas can fragment and form stars

1. ANGULAR MOMENTUM TRANSPORT

BH formation: gravitational binding energy ~ total energy

$$\frac{GM^2}{R} \simeq Mc^2 \rightarrow R \simeq \frac{GM}{c^2} \qquad R_{\rm Sch} = 2\frac{GM}{c^2}$$

Angular momentum can halt collapse when the rotational support equals the gravitational binding energy

$$\frac{J^2}{MR^2} \approx \frac{GM^2}{R} \rightarrow R \approx \frac{J^2}{GM^3} \approx \frac{GM}{v^2} \rightarrow \boxed{R_J \approx \left(\frac{c}{v}\right) R_{\rm Sch}}$$

There must be VERY efficient outward transport of J

2. STAR FORMATION

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

BAD^3:

- ✔ competition in gas consumption (i.e. part of the gas goes into stars instead of into BH formation
- ✔ collisionless stars do not dissipate angular momentum efficiently
- ✔ SNe can blow away the gas reservoir

1. Consider only halos with EXTREMELY low angular momentum

Eisenstein & Loeb 1995

2. Consider only the material, in a given halo, with EXTREMELY low angular momentum

Koushiappas, Bullock & Dekel 2004

3. Consider gravitationally unstable systems

Begelman, Volonteri & Rees 2006

1. BH formation in low angular momentum halos

DM halos acquire angular momentum by tidal torques

SPIN PARAMETER: $\lambda = \frac{J|E|^{1/2}}{GM_H^{5/2}}$ lognormal distr $\langle\lambda\rangle$=0.04

Gas mass: $M_g = f_g M_H$ and becomes rotationally supported at the radius

$$R_J = \frac{J}{GM_g} = \frac{GM_H^2 \lambda^2}{|E|^{1/2} f_g}$$

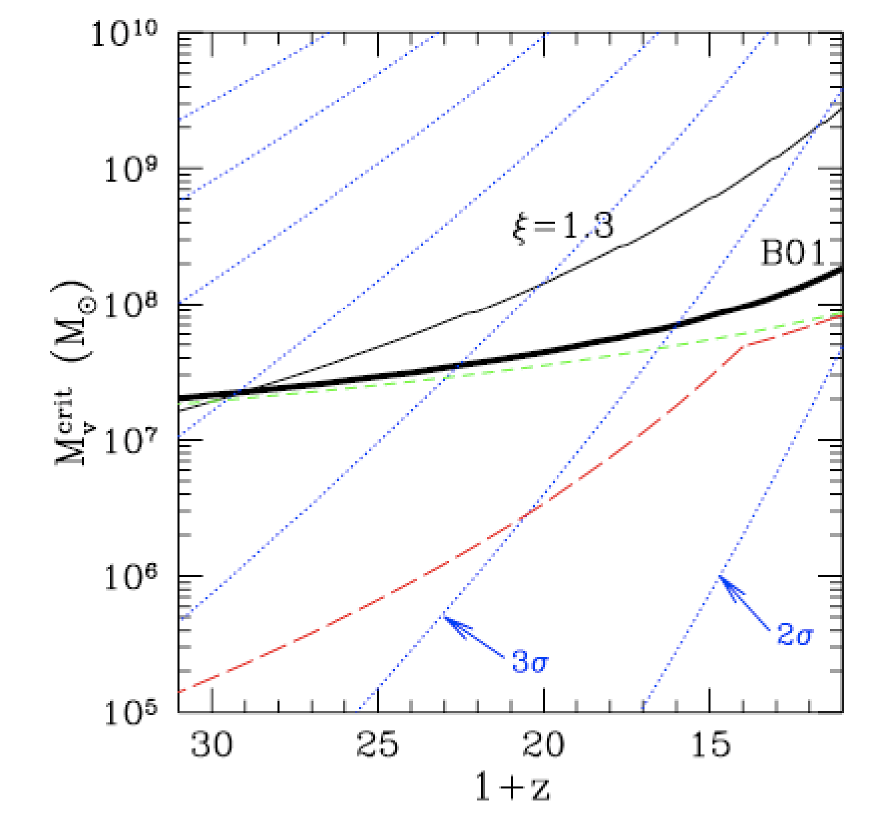
need: low spin, high gas fraction

Viscous timescale (to transport ang. mom.) $\nu \propto c_s H$ $\frac{H}{R} = \frac{c_s}{v_K} \propto \frac{c_s R^{1/2}}{M^{1/2}}$

$$t_{\rm vis} = \frac{R_J^2}{\nu} (\propto R_J^{1/2} \sqrt{f_g M_H} c_s^{-2}) \approx 10^6 {\rm yr} \frac{\lambda}{0.001} \left(\frac{M_H}{10^8 M_\odot} \right)^{3/2}$$

2. BH formation from low angular momentum material in a given halo

- ✔ The specific angular momentum is not constant: mixing up
- ✔ Still need a short enough viscous timescale and "on the verge of instability" discs
- ✔ Setting the Toomre parameter for the discs Q=1 and requiring efficient gas cooling sets a minimum mass for efficient ang. mom. transport



The mass of the seed BH scales 10^{-3}-10^{-4} M_H

Too much mass in BH seeds?

Can be more than enough to make

all today SMBH without need of

quasar and accretion?

3. BH formation in bar-unstable discs

Systems with runaway global dynamical instability:

BARS-WITHIN-BARS

Self-gravitating gas clouds become bar-unstable when the level of rotational support surpasses a certain threshold

A bar can transport angular momentum outward on a dynamical timescale via gravitational and hydrodynamical torques, allowing the gas to shrink.

Provided that the gas is able to cool, this shrinkage leads to even greater instability, on shorter timescales, and the process cascades

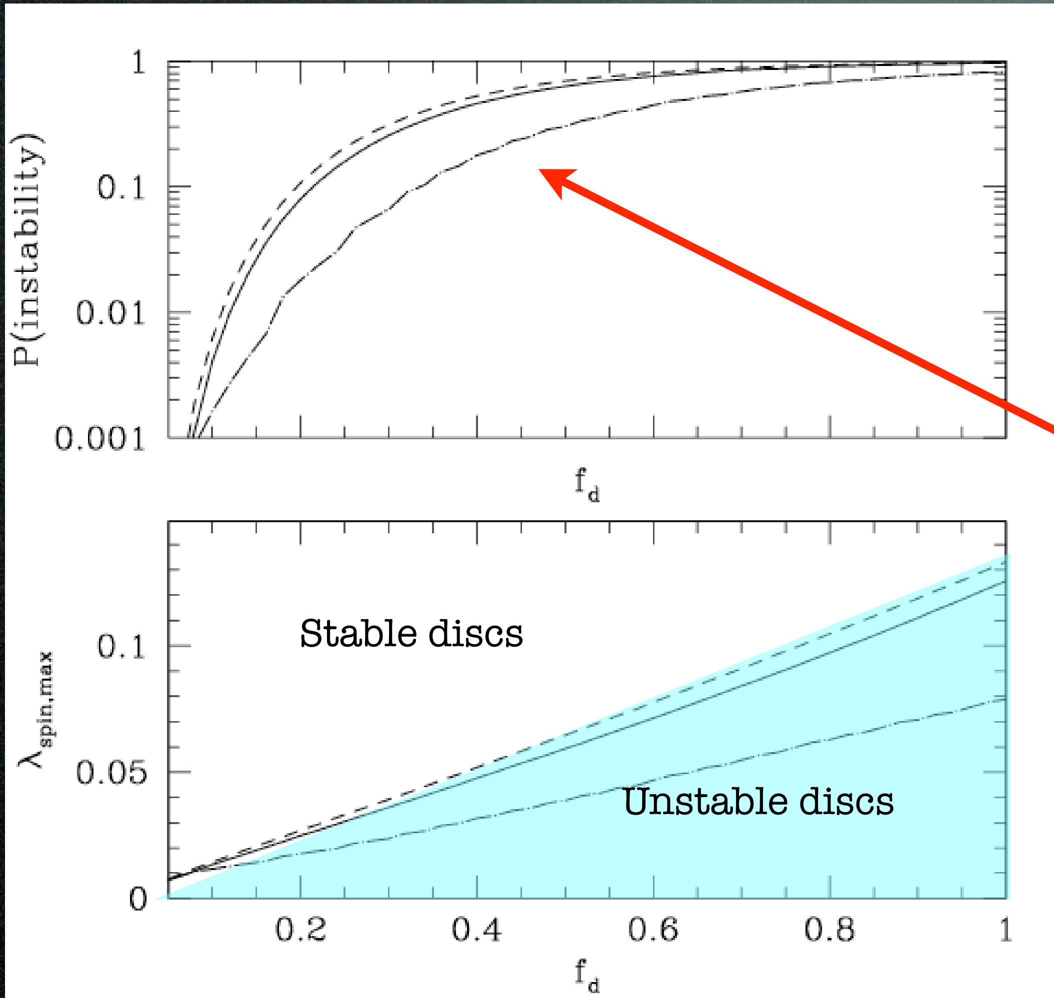
REQUIREMENTS: high gas-to-stars fraction + cold gas

That's fine in high-z systems before SF picks up, and with efficient cooling (e.g. halos with $T_{vir}>10^4K$)

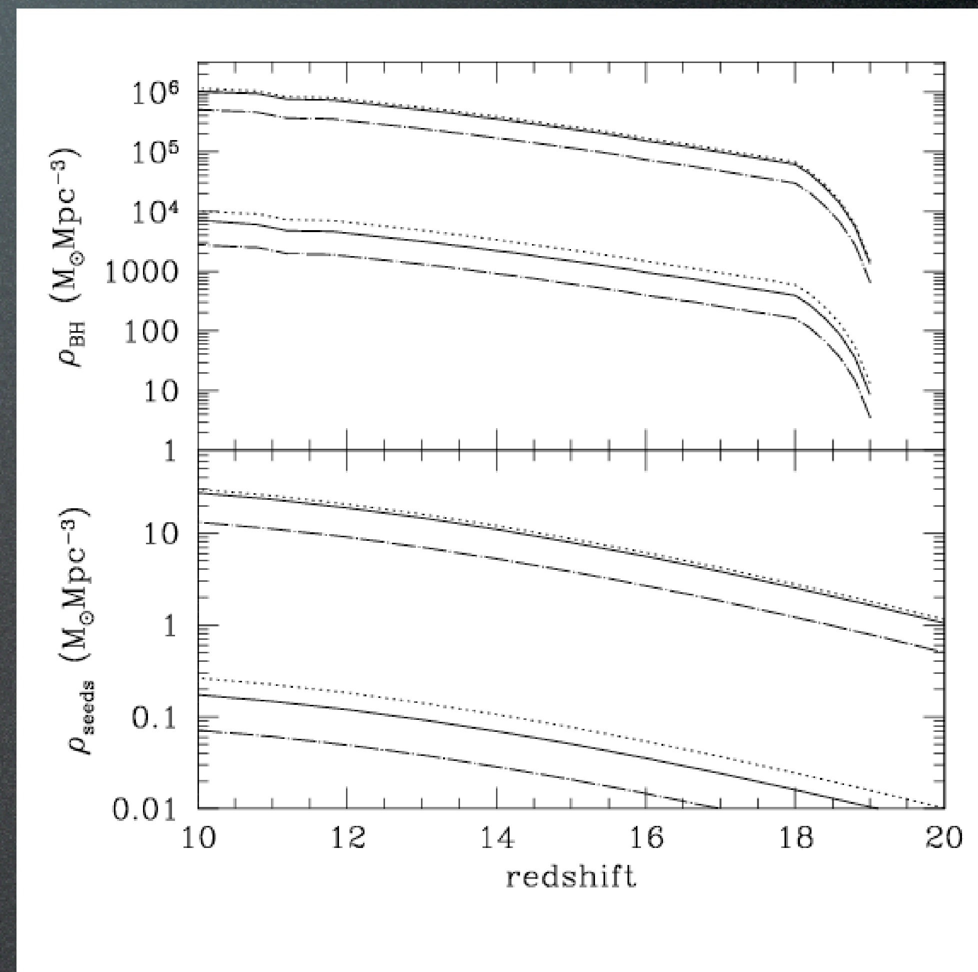
SPIN PARAMETER:

lognormal distr <λ>=*0.04*

Once we know the maximum spin parameter for which discs are unstable, we can find the fraction of halos hosting a disc prone to bar-in-bar instability



Gas fraction collapsing in the disc



Supercritical accretion onto pregalactic BHs in UNSTABLE discs

what happens to the material which accumulates at the center anyway?
Does a MBH pop up out of the blue?

runaway infall and accumulation of matter in the center

formation of a “quasistar” ~ 10^5 M_{sun} and a seed BH~20 M_{sun}

the seed BH can grow at the
Eddington rate of the star >> Eddington rate of the BH

That’s how you go from a teeny tiny seed to a MBH!