galaxy formation theory

lecture 5

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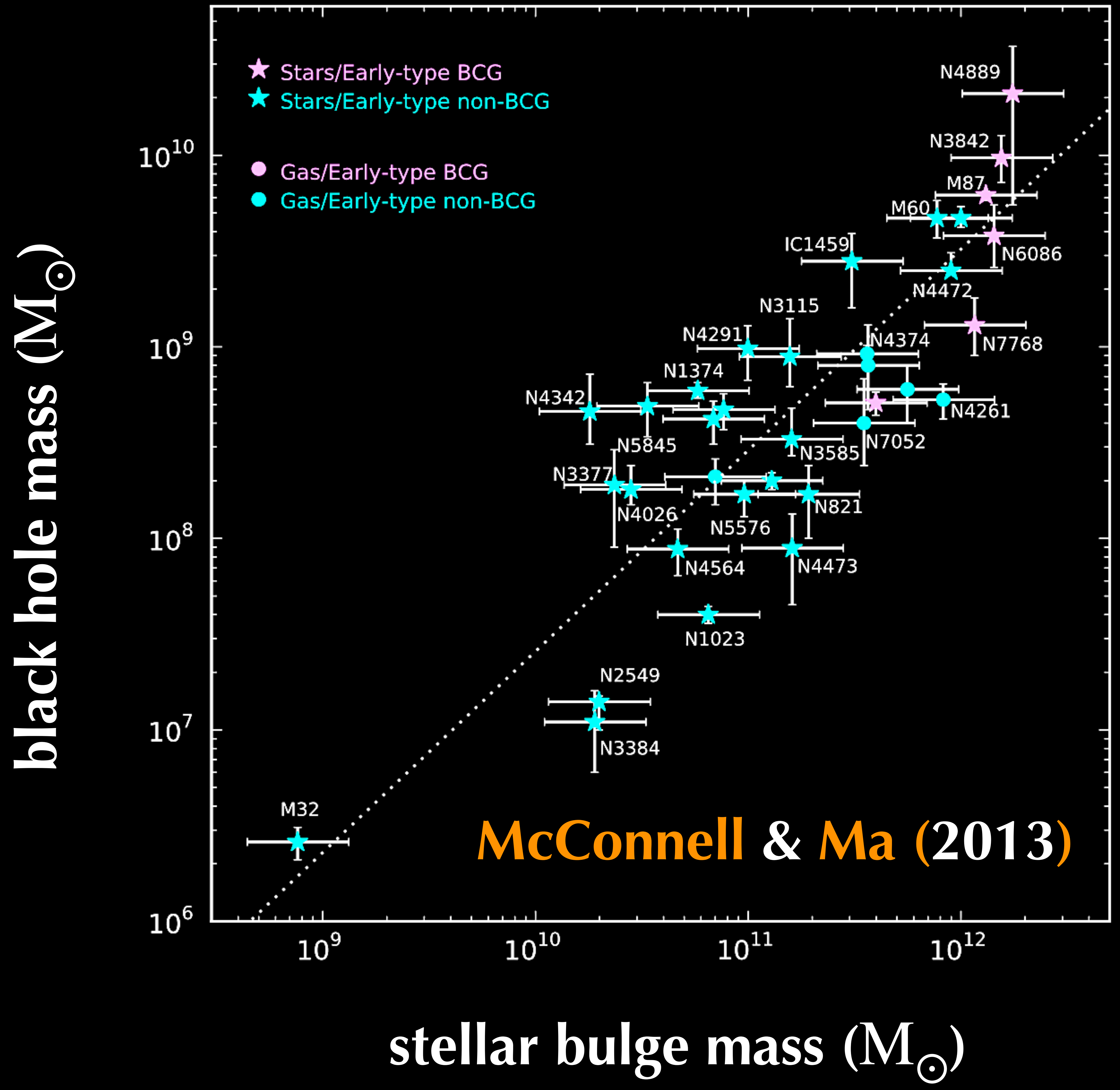
outline of the course

- a brief review of the observational background
- assembly of dark matter haloes
- gas cooling
- angular momentum
- star formation
- feedback
- galaxy mergers & morphology
- evolution of supermassive black holes

galaxy–SMBH co-evolution

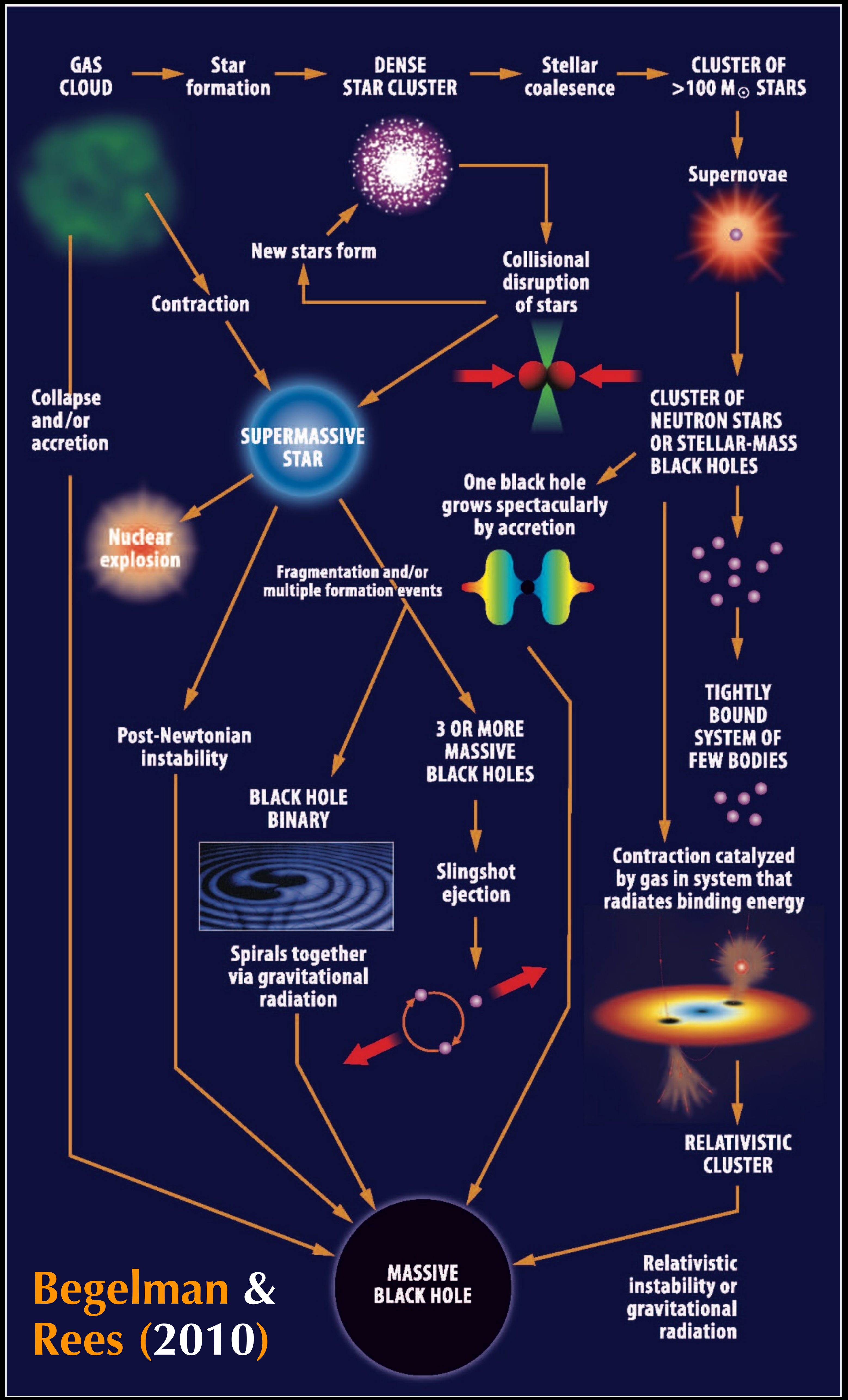


stellar spheroids in nearly all galaxies are observed central supermassive black holes (SMBHs)

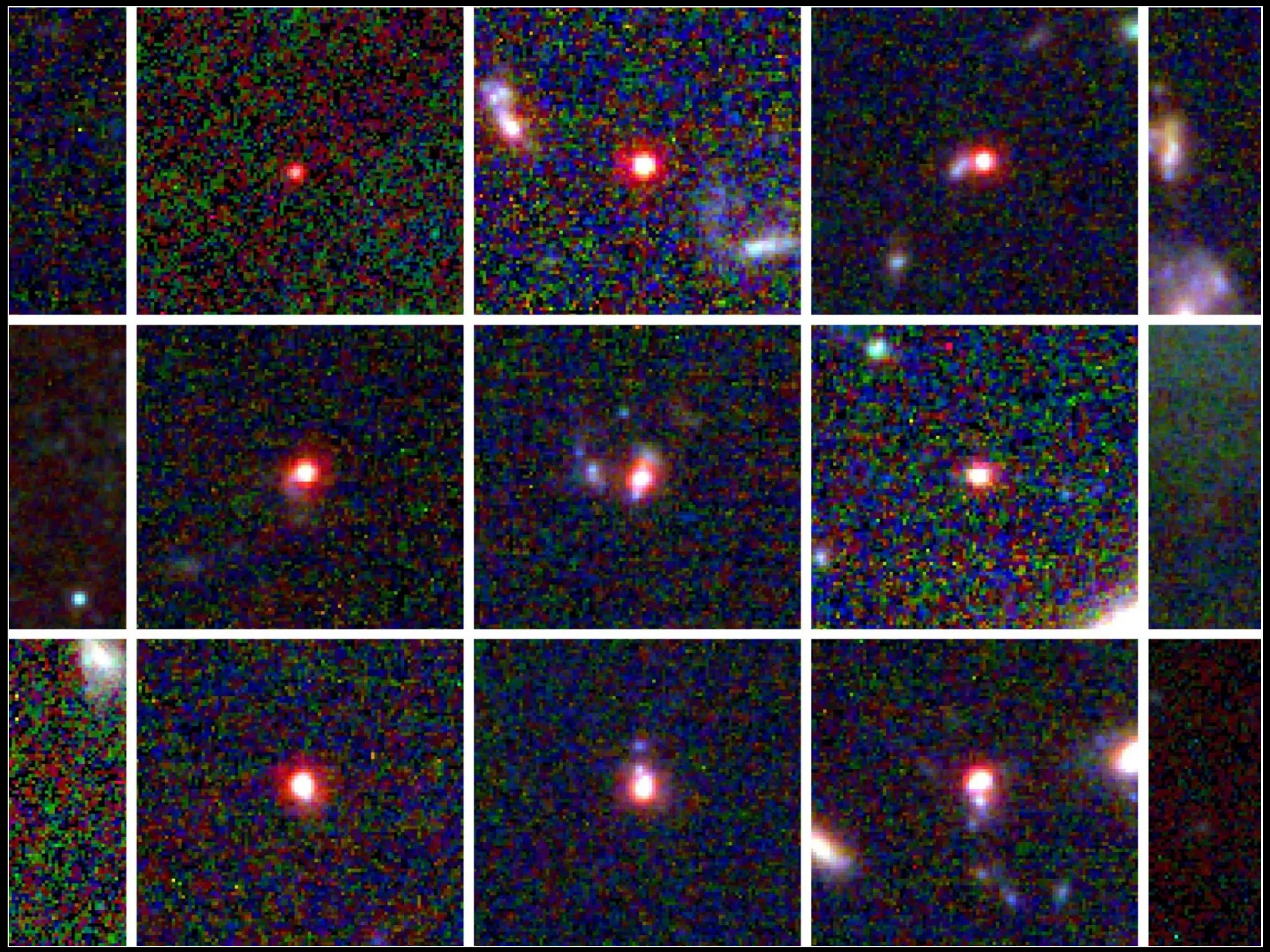
observationally, we find a correlation between the mass of the central SMBH and the stellar mass of the bulge/spheroid

$$\Rightarrow M_{\mathrm{BH}} \propto M_{\mathrm{bulge}}$$

this suggests a co-evolution between SMBHs and their host galaxies

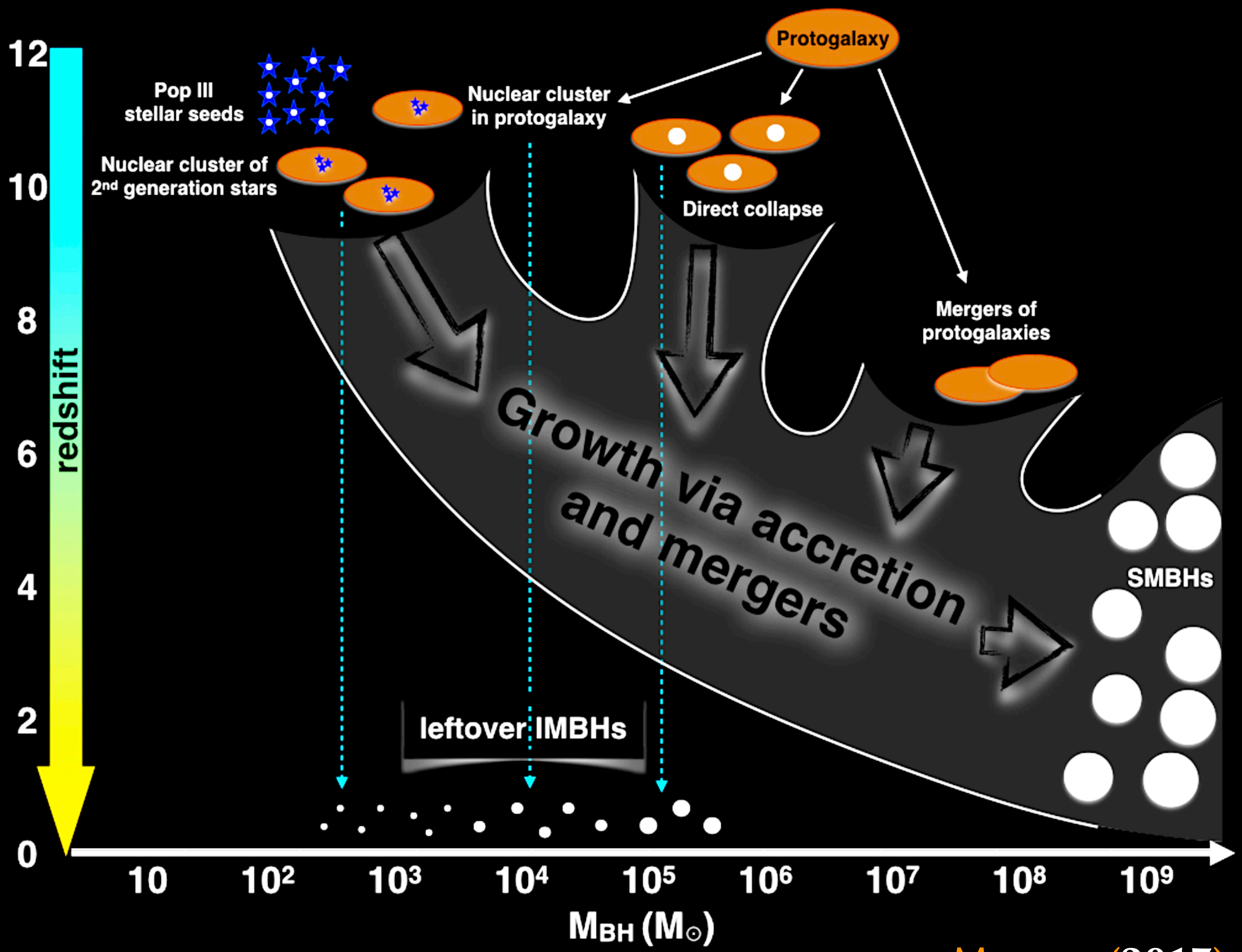


Begelman & Rees (2010)



credit: Jorryt Matthee EIGER/FRESCO survey

with JWST, we now observe black holes with masses $\sim 10^9 M_\odot$ at $z \geq 8$. at this epoch, the universe is ~500 Myr old. how is there enough time for SMBHs to get this big so early on?



different formation mechanisms leads to different BH seed masses at high-z

Mezcua (2017)

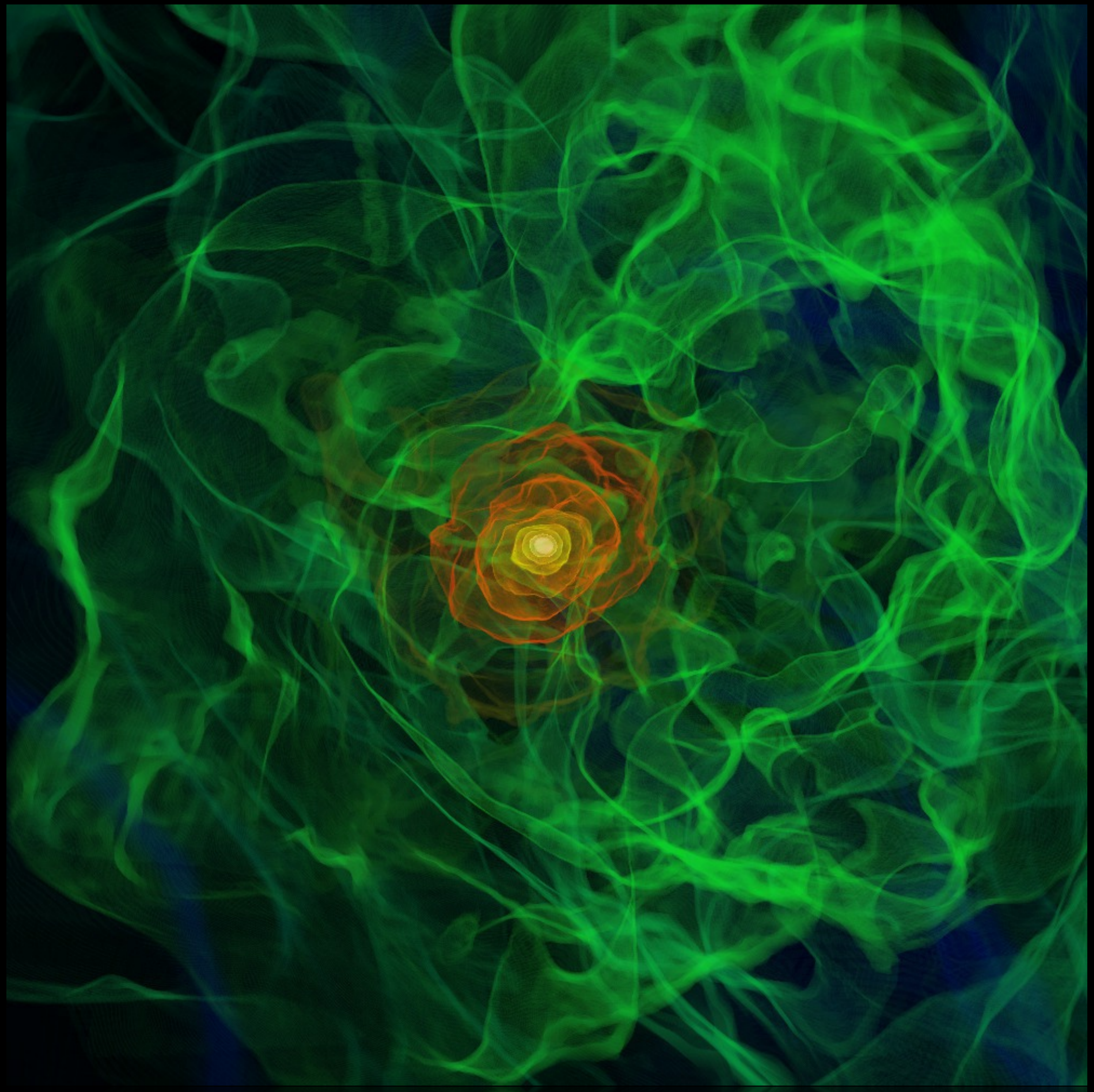
seed black holes from Pop III stars

in a CDM universe, the first dark matter haloes should form very early and with very low mass

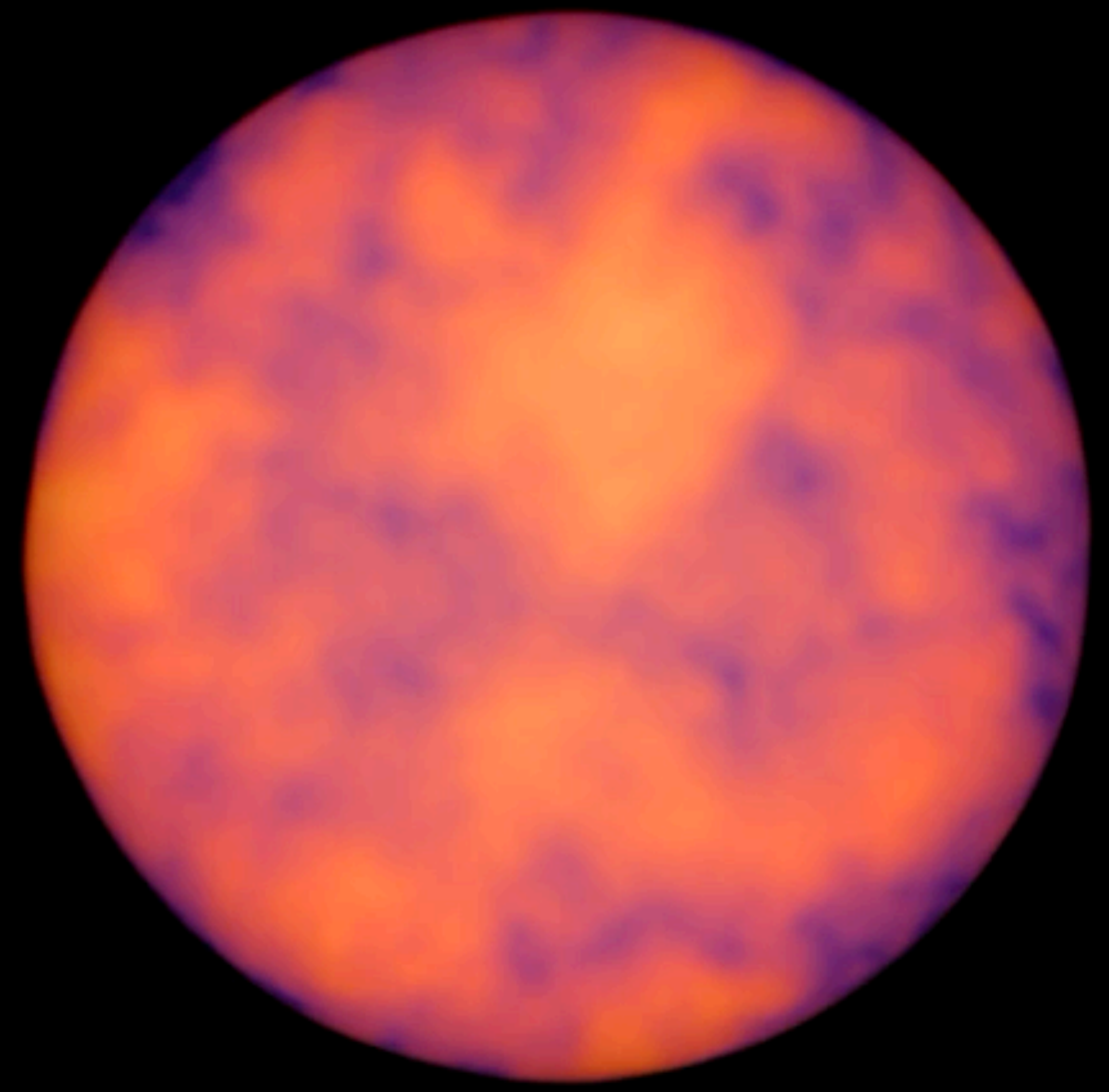
the first star-forming haloes are those in which the gas is able both to collapse into the halo, and then to cool & collapse inside the halo to become self-gravitating

the first, so-called Pop III stars, formed from zero metallicity gas, and are thought to form in sub-galactic haloes with masses $\underline{\sim 10^5 - 10^6\,\mathrm{M}_\odot}$ at $z \sim 30 - 50$.

set by cooling of primordial gas by H_2 molecules

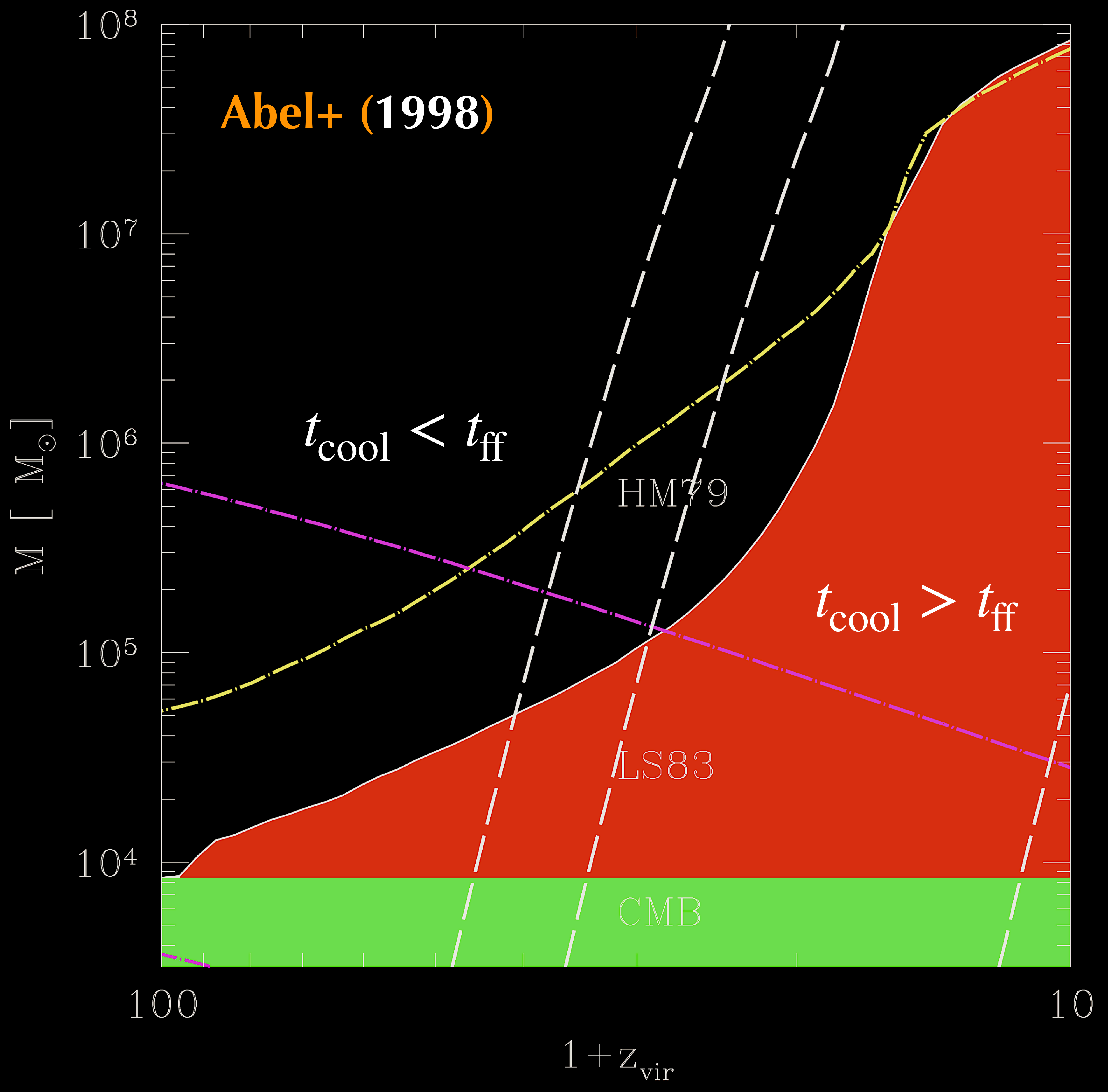


credit: Ralf Koehler & Tom Abel



credit: Mike Grudic & the STARFORGE collaboration

the **minimum halo mass** for gas cooling



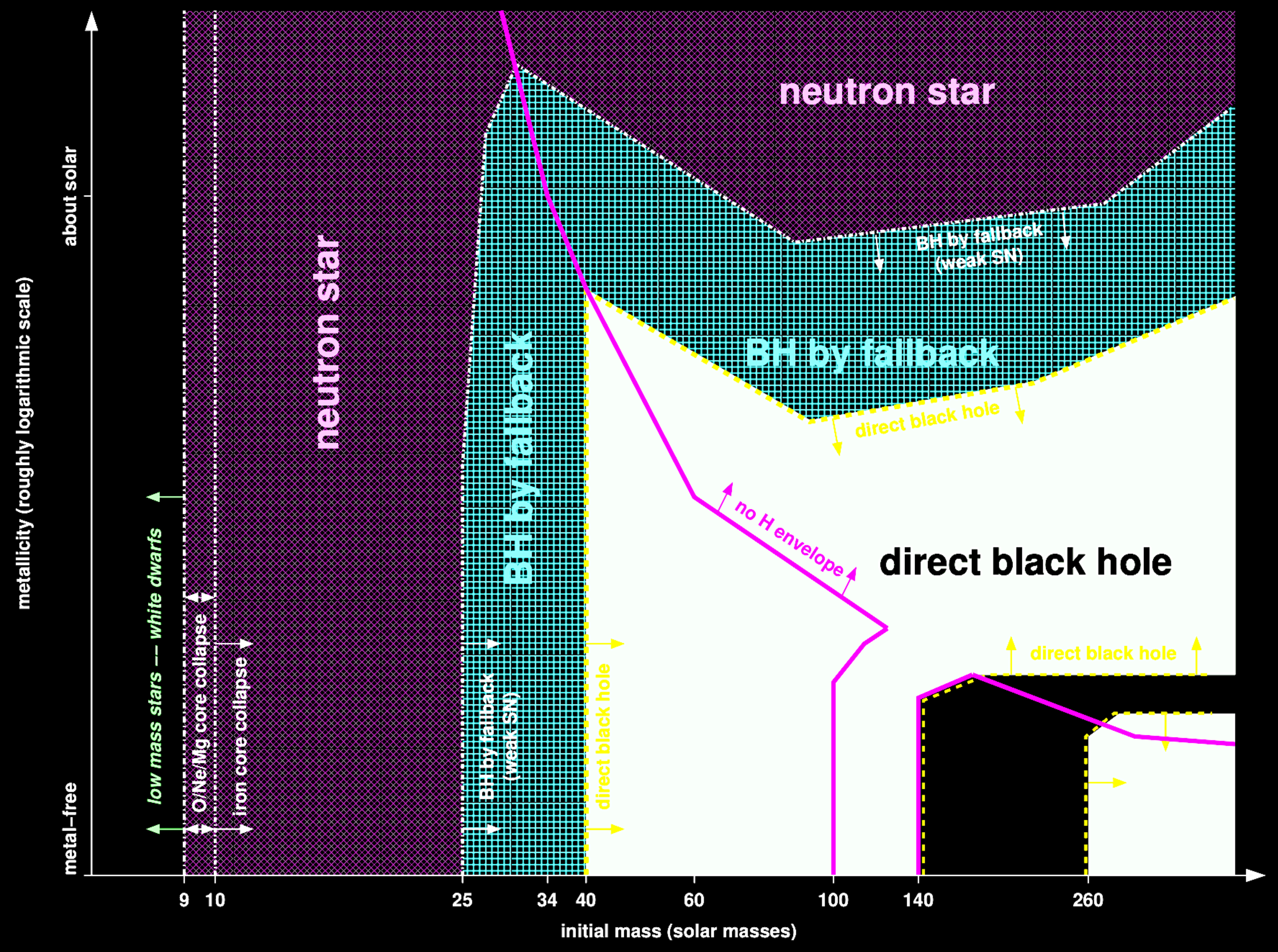
z_{vir} for CDM perturbations

the formation of H_2 in dust-free gas is catalysed by the electrons left over from recombination

rotational and **vibrational** transitions in H_2 molecules allow cooling for $T < 10^4 K$

a detailed calculation of formation and cooling by H_2 $\Rightarrow f_{H_2} \sim 10^{-3}$ allows $t_{cool} < t_{ff}$ in haloes with $T_{vir} > 10^3\,K$ at $z \sim 20 - 50$

remnants of Pop III stars



Heger+ (2003)

Pop III stars form with initial masses $m_i \sim 10^2\,\mathrm{M}_\odot$. they live a few Myr, then explode or collapse:

- $m_i < 25\,\mathrm{M}_\odot$: Type II supernovae ⇒ neutron star remnant
- $25 < m_i < 140\,\mathrm{M}_\odot$: Type II supernovae ⇒ BH remnant ($\sim 10 - 40\,\mathrm{M}_\odot$)
- $140 < m_i < 260\,\mathrm{M}_\odot$: pair instability supernovae ⇒ complete disruption
- $m_i > 260\,\mathrm{M}_\odot$: photo-disintegration instability ⇒ core-collapse to massive BH ($\sim 0.5\,m_i > 100\,\mathrm{M}_\odot$)

Pop III stars therefore yield BH remnants with $m \sim 10 - 100\,\mathrm{M}_{\odot}$, depending on the IMF for Pop III stars (uncertain)

they subsequently grow through

gas accretion

BH-BH mergers

(but these are susceptible to ejection from low-mass haloes by gravitational wave recoil (binaries) or slingshots (in multiple BH systems))

how fast do BH seeds grow through gas accretion?

one would imagine that the growth of the BH is regulated by the amount of gas available.
in addition to this, there is also a radiation pressure on the gas from the accreting BH

the radiation pressure exceeds the force due to gravity when:

$$\boxed{L > L_{\rm Edd} = \frac{4\pi G M m_p}{c\sigma_{\rm T}}}$$

so, if $L = \epsilon \dot{M} c^2 < L_{\rm Edd}$, the fastest a BH can grow is:

$$M(t) = M(0)\ \exp\left(\frac{1-\epsilon}{\epsilon}\frac{t}{t_{\rm Edd}}\right)$$

where $t_{\rm Edd} = c\sigma_{\rm T}/4\pi G m_p = 0.45\,{\rm Gyr}$

how fast do BH seeds grow through gas accretion?

$$\boxed{M(t) = M(0)\,\exp\left(\frac{1-\epsilon}{\epsilon}\frac{t}{t_{\rm Edd}}\right)}$$

based on this, we can estimate how much a seed BH could feasibly grow under reasonable assumptions for ϵ.

for $\epsilon = 0.1$ (thin accretion disc), need $\Delta t = 0.3\,\mathrm{Gyr}$ to grow a $10^9\,\mathrm{M}_\odot$ SMBH from a $10^6\,\mathrm{M}_\odot$ seed, but $\Delta t = 0.9\,\mathrm{Gyr}$ from a $10\,\mathrm{M}_\odot$ seed.

since $10^9\,\mathrm{M}_\odot$ BHs seems to exist already at $z > 6$ when the age of the Universe $< 1\,\mathrm{Gyr}$, growth from small seeds by gas accretion appears to be challenging

BUT this limit on BH growth may be relaxed for (1) non-spherical flow (2) lower radiative efficiency (e.g. slim accretion disc) (3) super-Eddington accretion

seed black holes from direct collapse

if a $10^5 - 10^6\,\mathrm{M}_\odot$ gas cloud can cool and collapse without fragmenting, it may form a supermassive star (SMS)

the SMS may then produce a $10^4 - 10^6\,\mathrm{M}_\odot$ BH (1) by general relativistic instability in SMS supported by radiation pressure or (2) core-collapse followed by accretion of envelope. this is feasible in early-forming, low-metallicity objects with $M_{\rm vir} > 10^8\,\mathrm{M}_\odot$

for this to happen:

need to avoid fragmentation

(inefficient cooling)

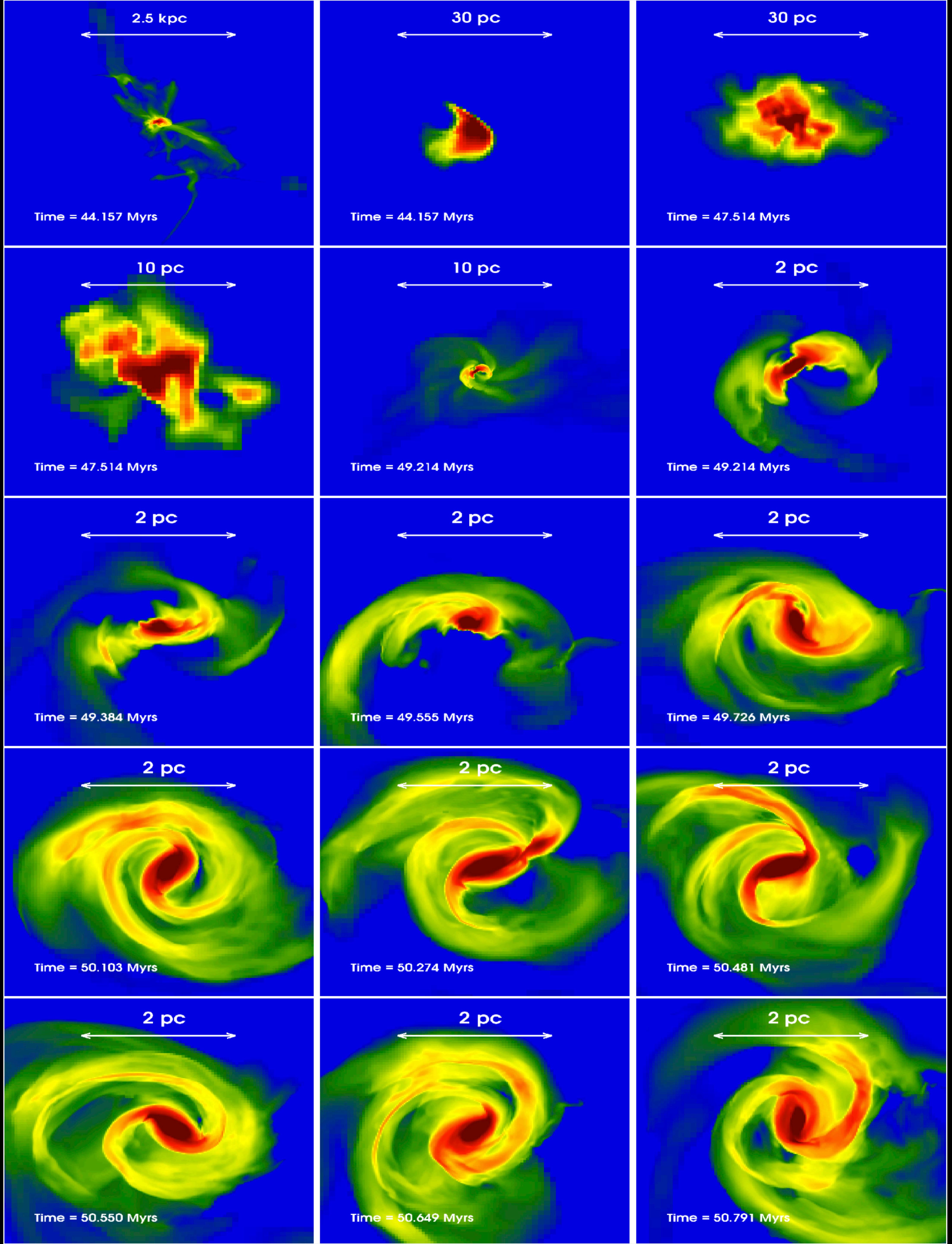
- zero or low-metallicity systems
- also need to suppress H_2 cooling ⇒ dissociating UV background?

need angular momentum

(or rotational support will halt collapse)

- turbulence?
- gravitational torques due to instabilities in self-gravitating gas discs?

credit: John Regan



simulation of gas collapse in a halo of mass $M_{\text{halo}} = 5 \times 10^7\,\mathrm{M}_\odot$ collapsing at $z = 15$
($T_{\text{vir}} = 1.4 \times 10^4\,K$)

— assumes no metals & no H_2
(i.e. cooling by H & He only)

angular momentum transport in disc by gravitational torques forms a compact object at centre with $M_{\text{gas}} \sim 10^5\,\mathrm{M}_\odot$ & $r \sim 1$ pc

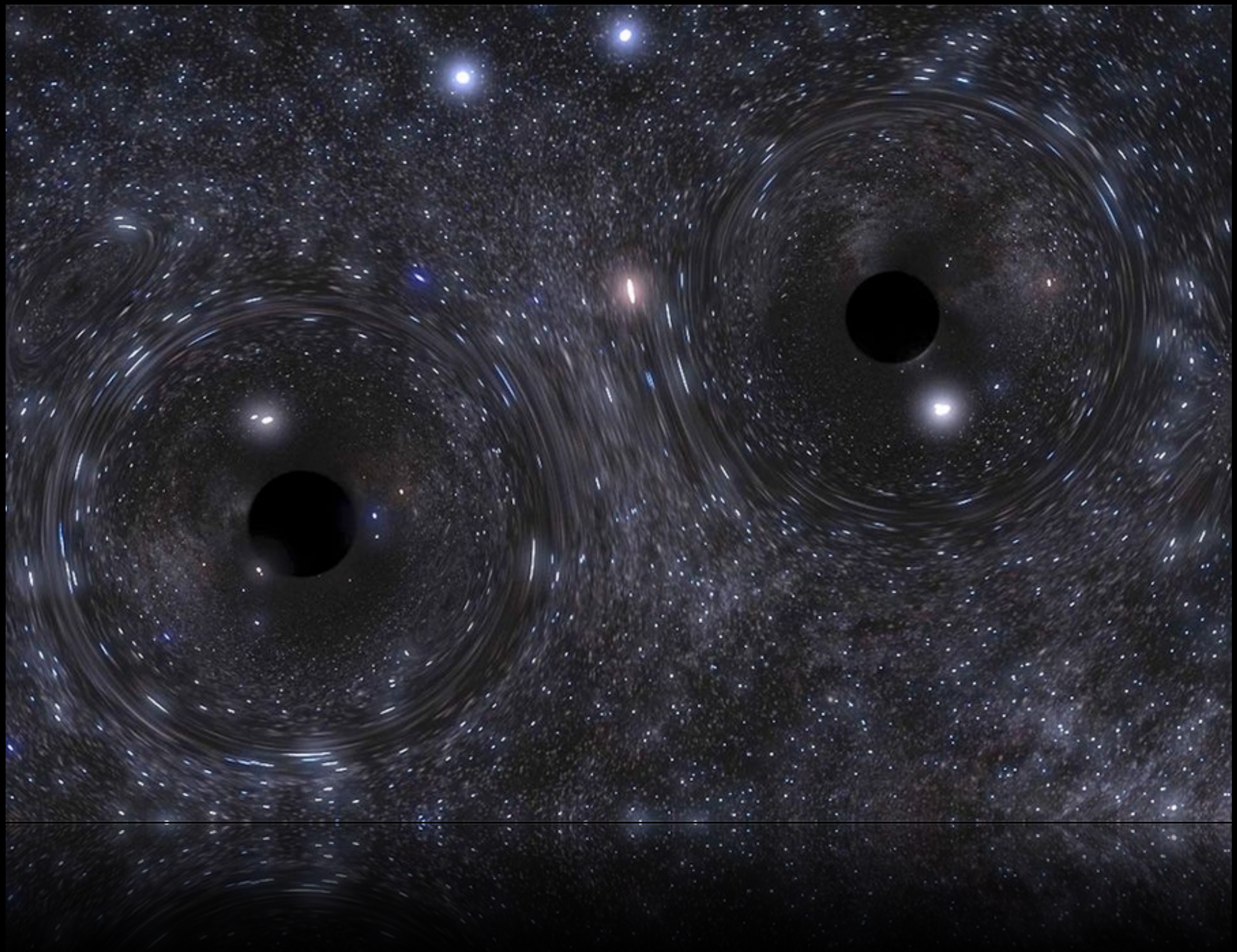
Regan & Haehnelt (2009)

formation of black holes in primordial star clusters

finally, massive black holes might form by mergers of stars and/or stellar mass BHs in dense, early-formed star clusters

these stars/BHs could be high mass (if 1st generation, zero metals — Pop III) or normal stellar mass (if 2nd generation, metal-enriched — Pop II)

stellar collisions could become frequent if cluster undergoes core collapse driven by 2-body relaxation



credit: https://news.mit.edu/2018/dense-stellar-clusters-may-foster-black-hole-megamergers-0410

2-body relaxation in star clusters

encounters (gravitational scattering) between pairs of objects in a compact system results in energy exchange, which is dominated by distant, weak encounters. this results in a relaxation timescale (i.e., the time for a star to change velocity):

stellar mass

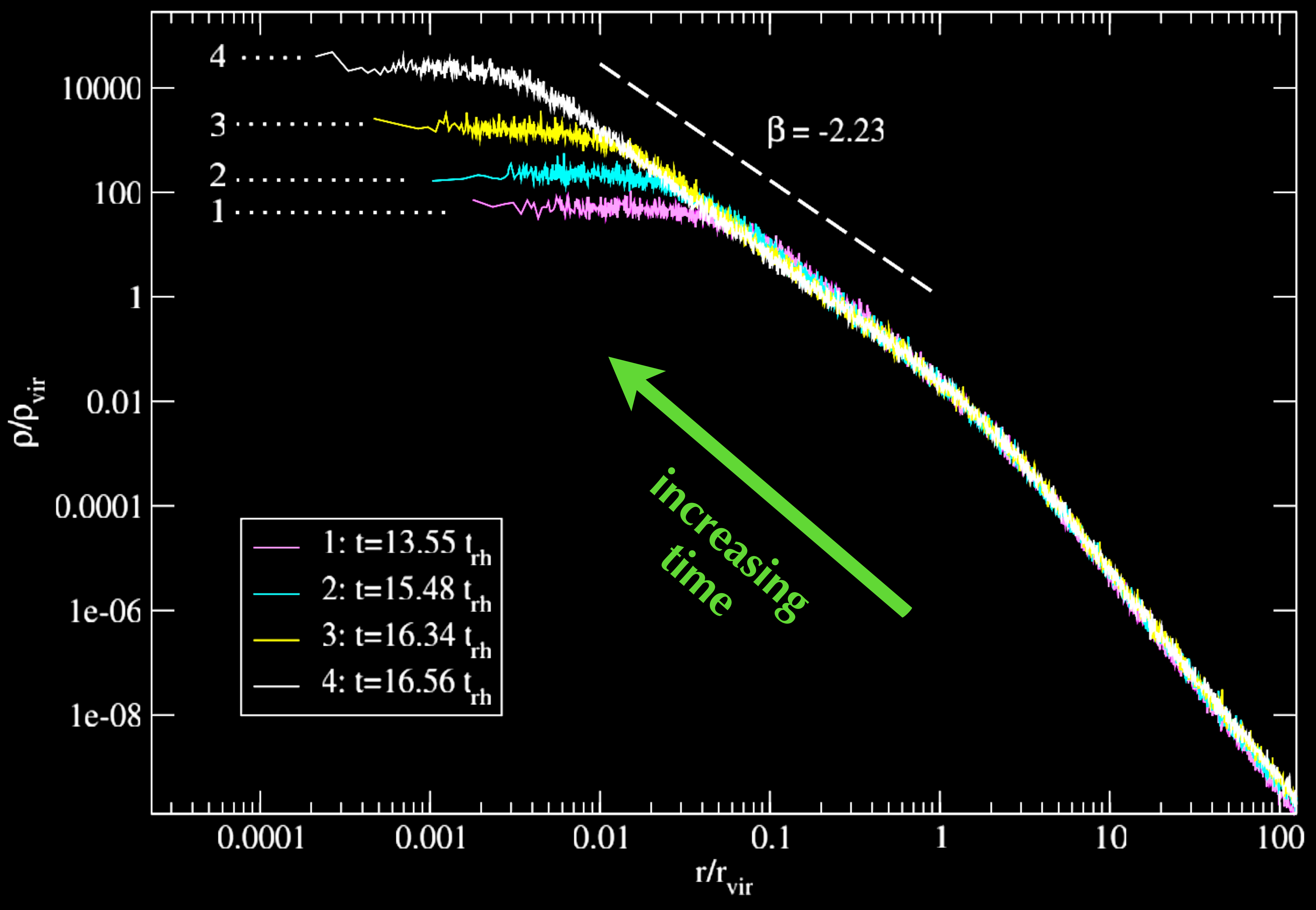
$$\boxed{t_{\mathrm{relax}} = 0.34 \frac{\sigma^3}{G^2 m \rho \ln \Lambda}}$$

velocity dispersion

Coulomb logarithm, which allows for long-range interactions

for a spherical star cluster, the relaxation time at the half-mass radius (a measure of the characteristic size of the system) is:

$$t_{\mathrm{relax},h} \approx \frac{0.8\,\mathrm{Gyr}}{\ln(0.1N)} \left(\frac{M_{\mathrm{cluster}}}{10^5\,\mathrm{M}_\odot}\right)^{1/2} \left(\frac{R_h}{1\,\mathrm{pc}}\right)^{3/2} \left(\frac{1\,\mathrm{M}_\odot}{m}\right)$$



Pattabiraman+ (2013)

energy exchange by 2-body scattering leads to core collapse

this results in a transfer of energy from inner to outer regions ⇒ runaway collapse of central regions

$$t_{cc} \sim 10\, t_{\mathrm{relax},h}$$

physical collisions between stars then occurs in the dense core