galaxy formation theory

lecture 5

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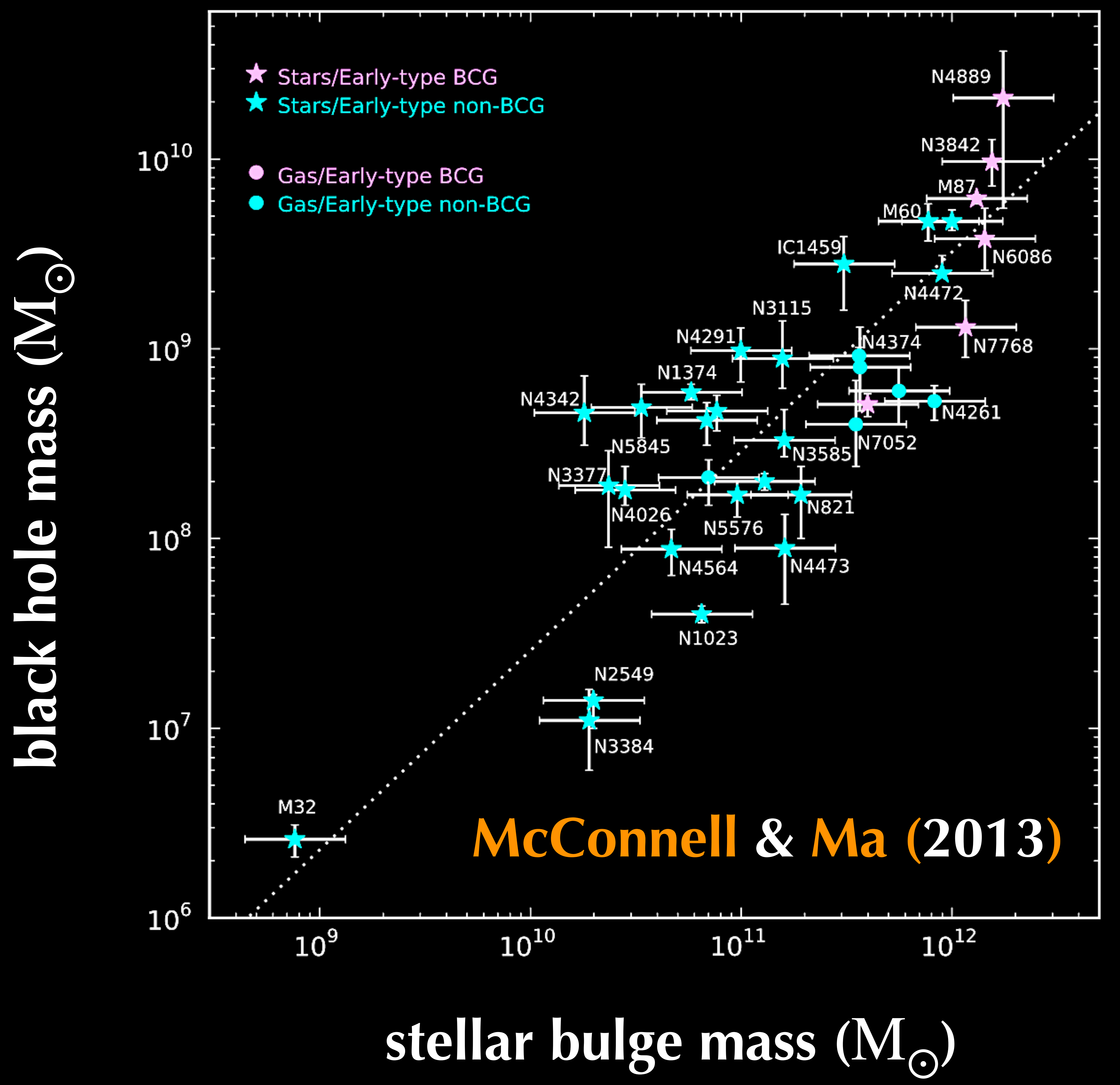
outline of the course

- 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

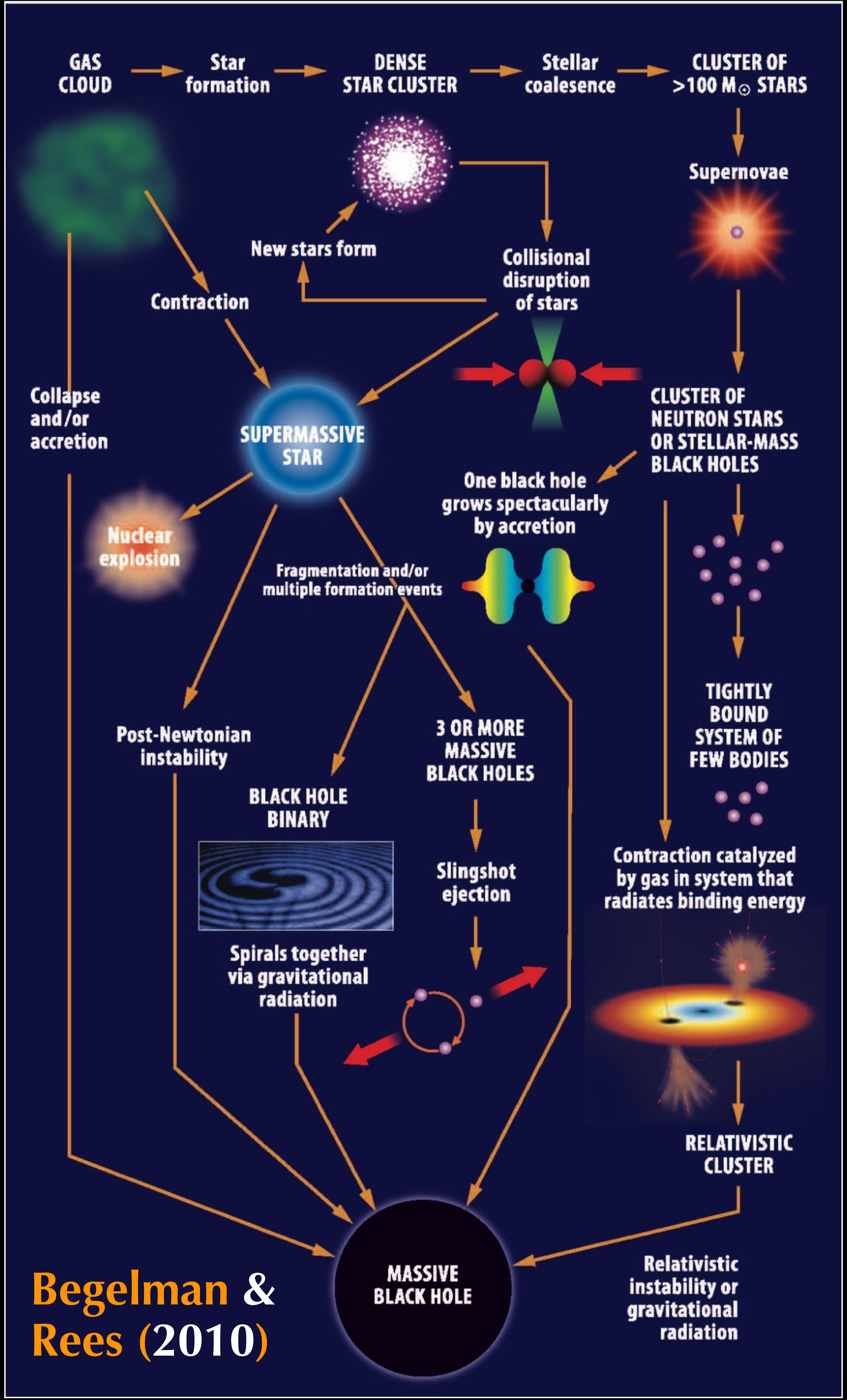


stellar spheroids in nearly all galaxies are observed central supermassive black holes (SMBHs)

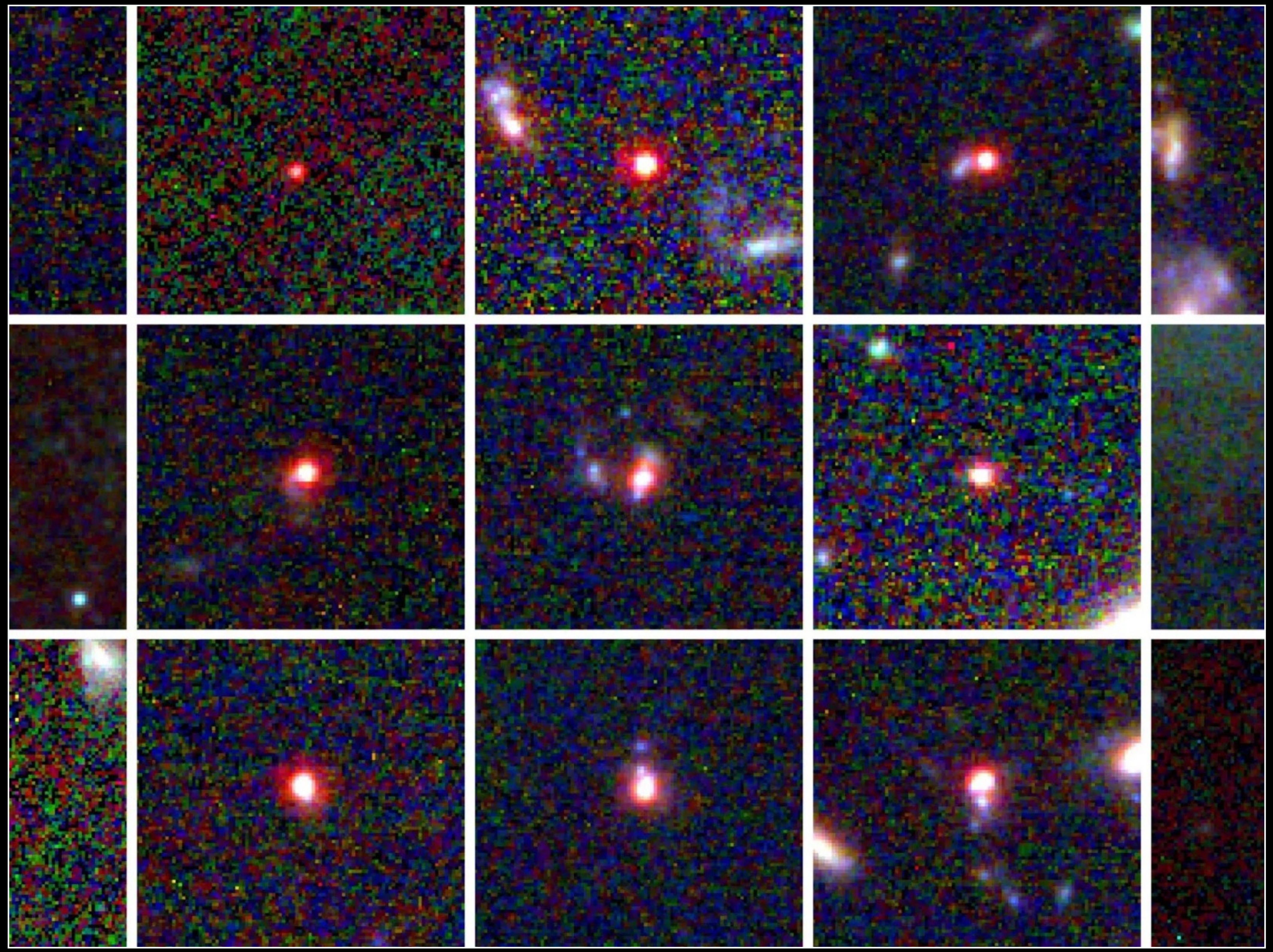
observationally, we find a correlation between the mass of the central SMBH and the stellar mass of the bulge/spheroid

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

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

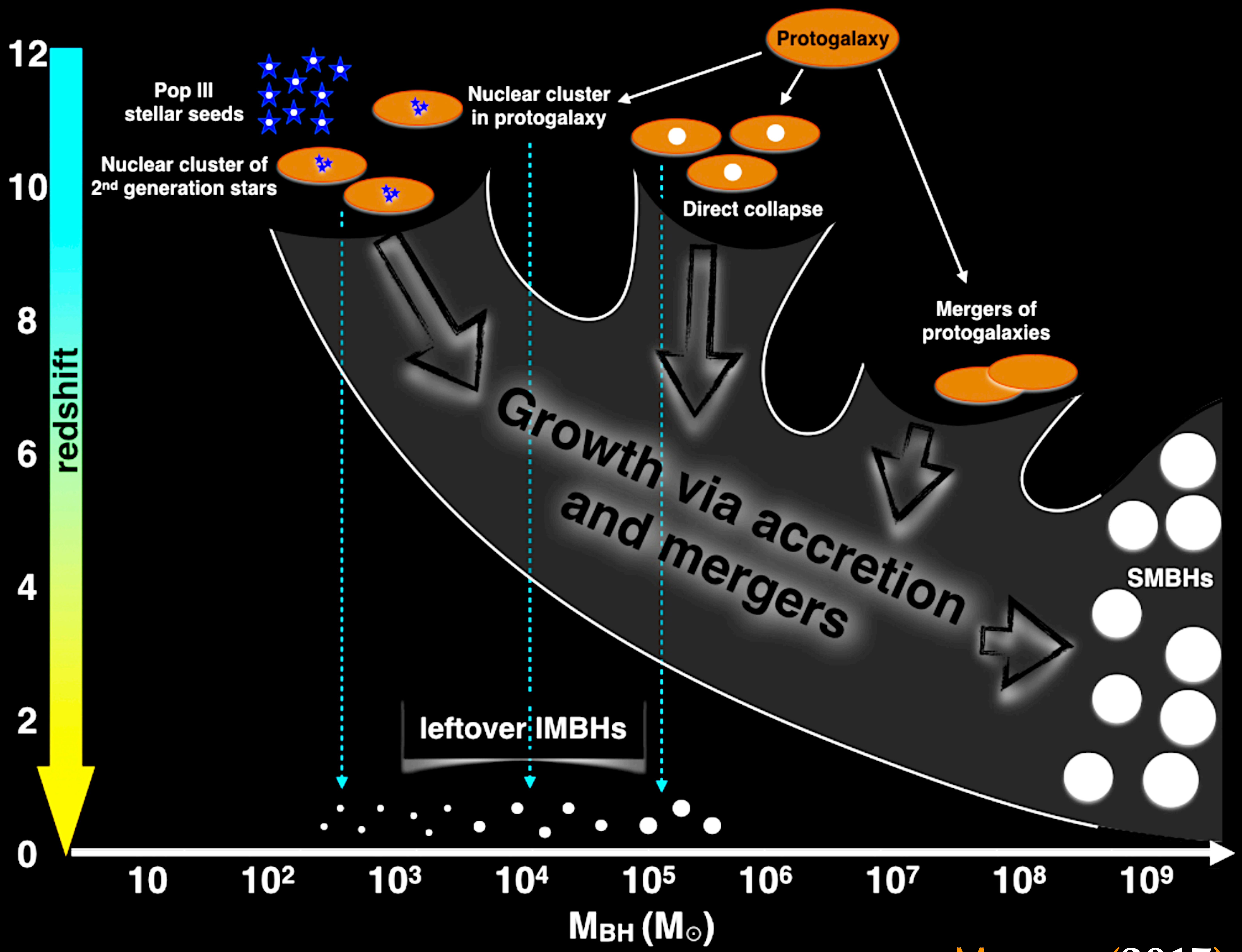


Begelman & Rees (2010)



credit: Jorryt Matthee EIGER/FRESCO survey

with JWST, we now observe black holes with masses $\sim 10^9 M_\odot$ at $z \geq 7$. at this epoch, the universe is ~750 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)

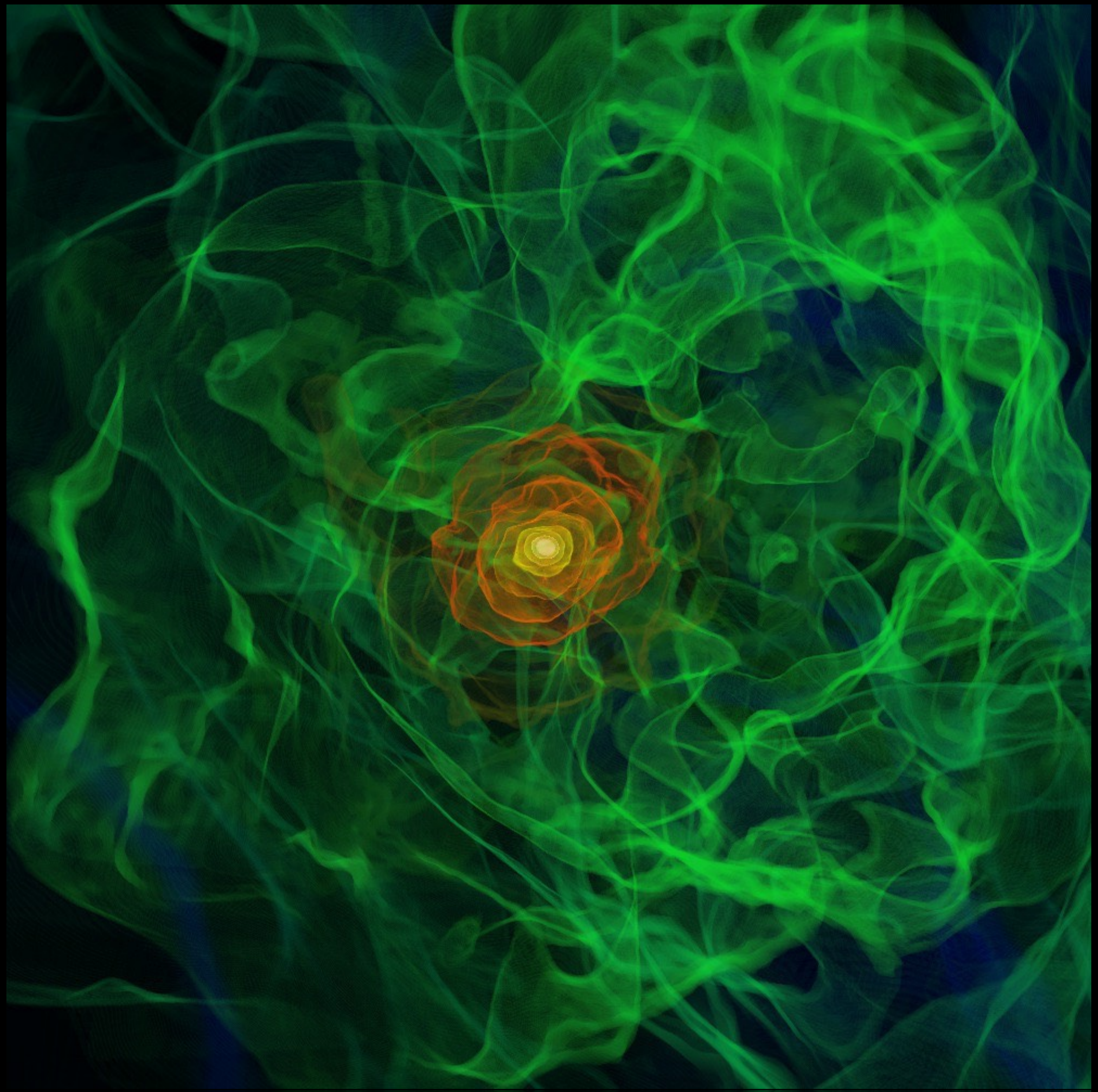
seed black holes from Pop III stars

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

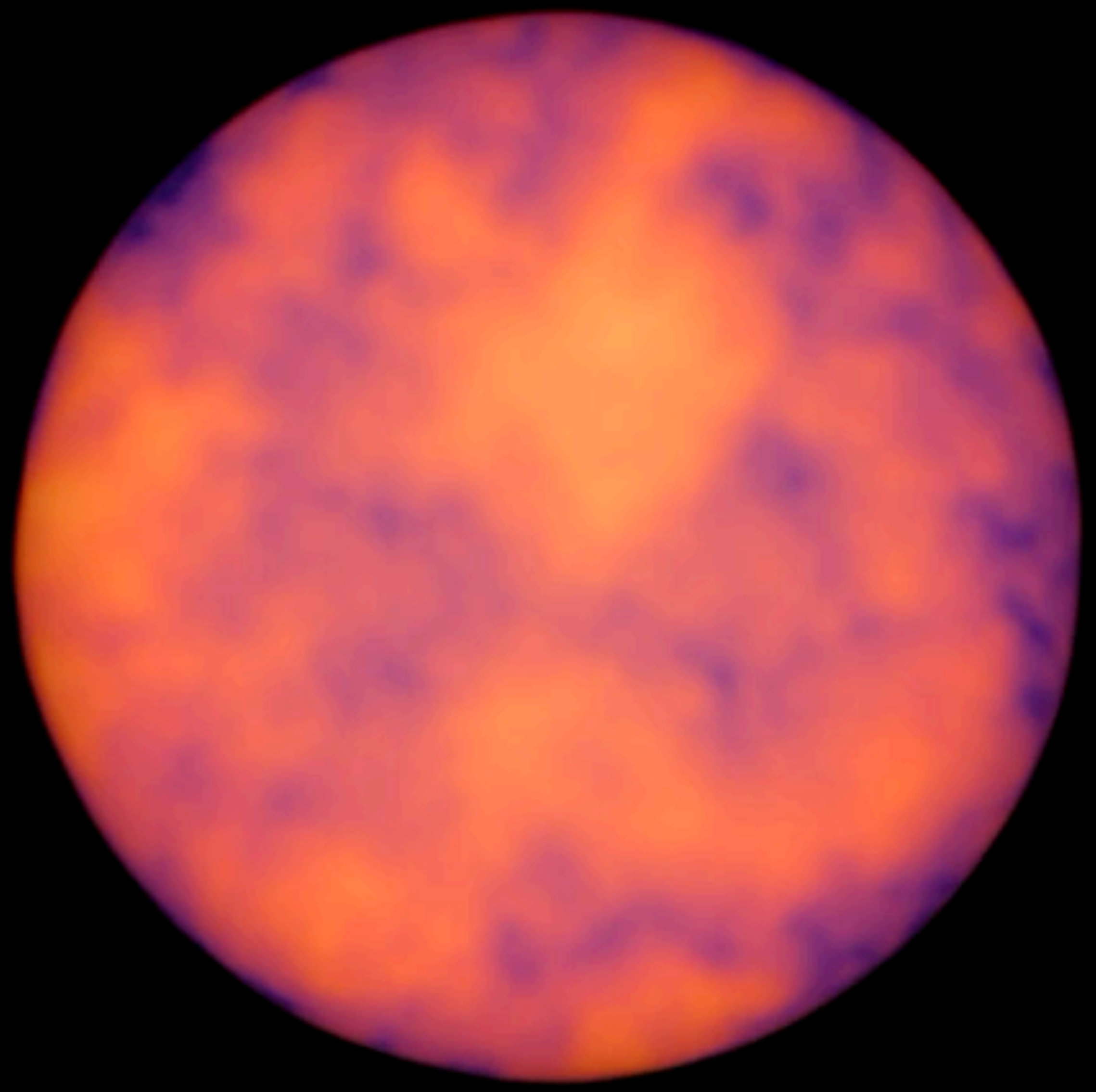
the first star-forming haloes are those in which the gas is able both to collapse into the halo, and then to cool & collapse inside the halo to become self-gravitating

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

set by cooling of primordial gas by H_2 molecules

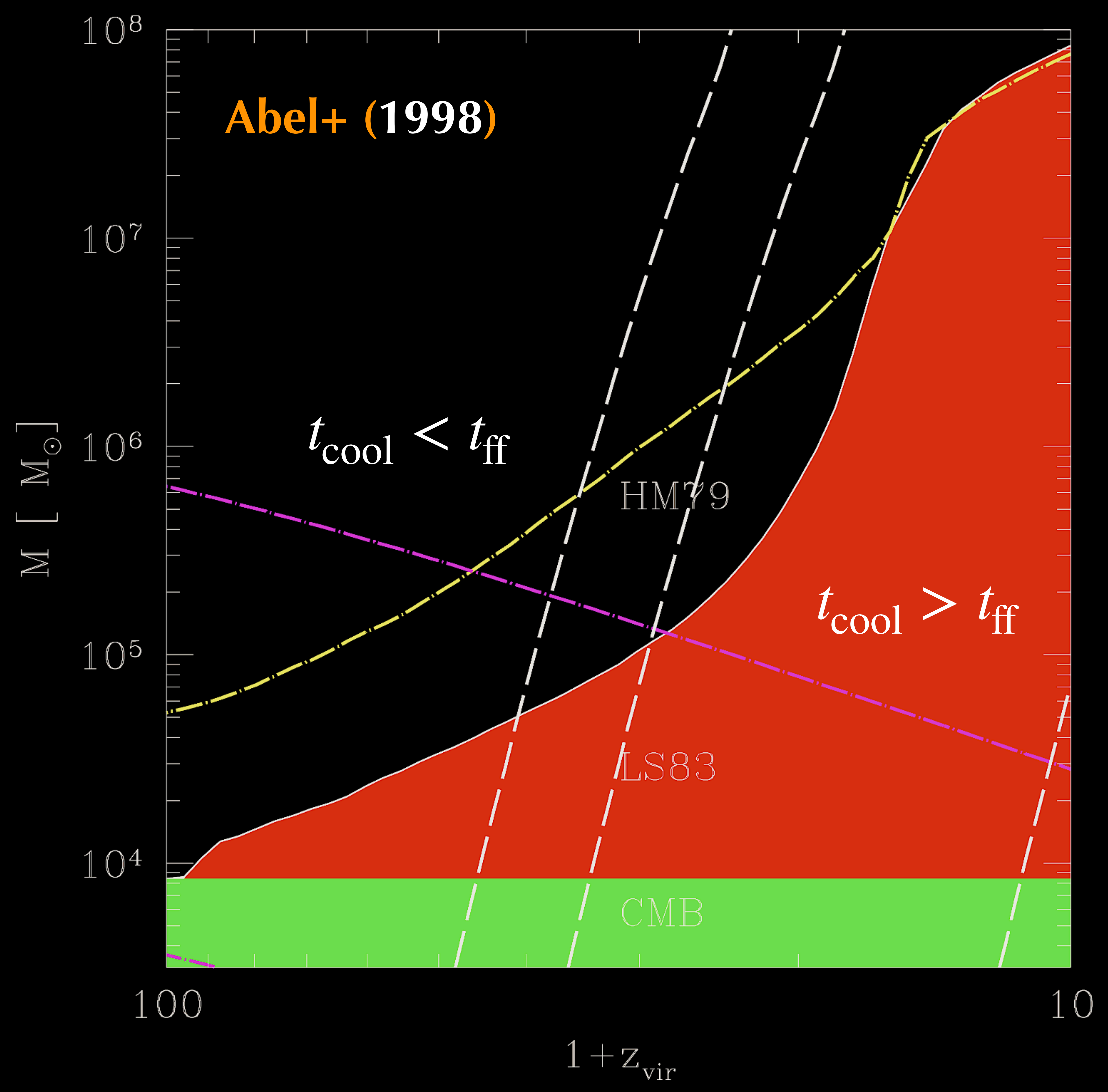


credit: Ralf Koehler & Tom Abel



credit: Mike Grudic & the STARFORGE collaboration

the **minimum halo mass** for gas cooling



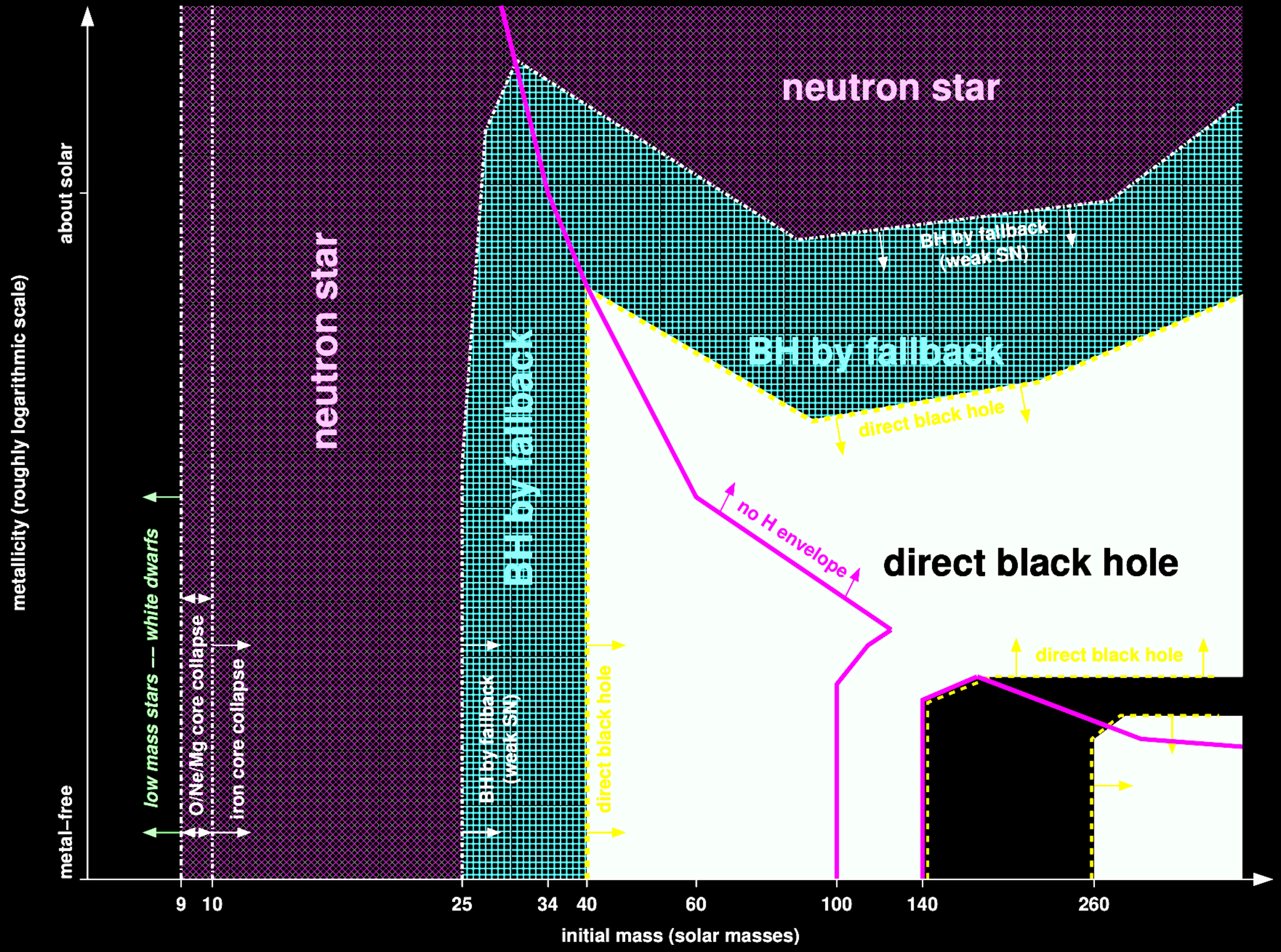
$z_{\rm vir}$ for CDM perturbations

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 $t_{\rm cool} < t_{\rm ff}$ in haloes with $T_{\rm vir} > 10^3\ K$ 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 $\Rightarrow$ neutron star remnant
- $25 < m_i < 140\,\mathrm{M}_\odot$: Type II supernovae $\Rightarrow$ BH remnant ($\sim 10 - 40\,\mathrm{M}_\odot$)
- $140 < m_i < 260\,\mathrm{M}_\odot$: pair instability supernovae $\Rightarrow$ complete disruption
- $m_i > 260\,\mathrm{M}_\odot$: photo-disintegration instability $\Rightarrow$ 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)

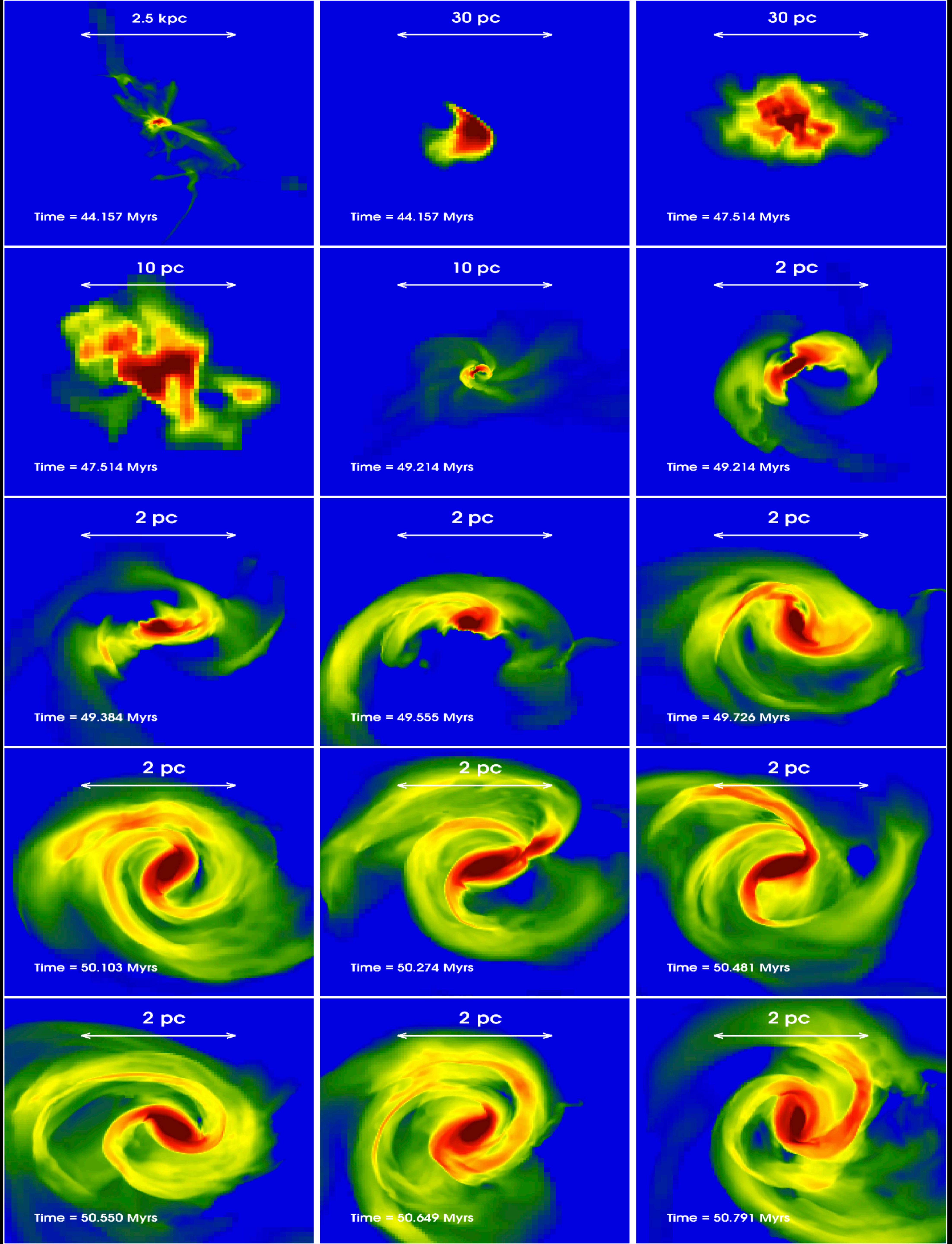
- zero or low-metallicity systems
- also need to suppress H_2 cooling $\Rightarrow$ dissociating UV background?

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 $M_{\rm halo} = 5 \times 10^7\,{\rm M}_\odot$ collapsing at $z = 15$ ($T_{\rm vir} = 1.4 \times 10^4\,K$)

— 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 $M_{\rm gas} \sim 10^5\,{\rm M}_\odot$ & $r \sim 1$ pc

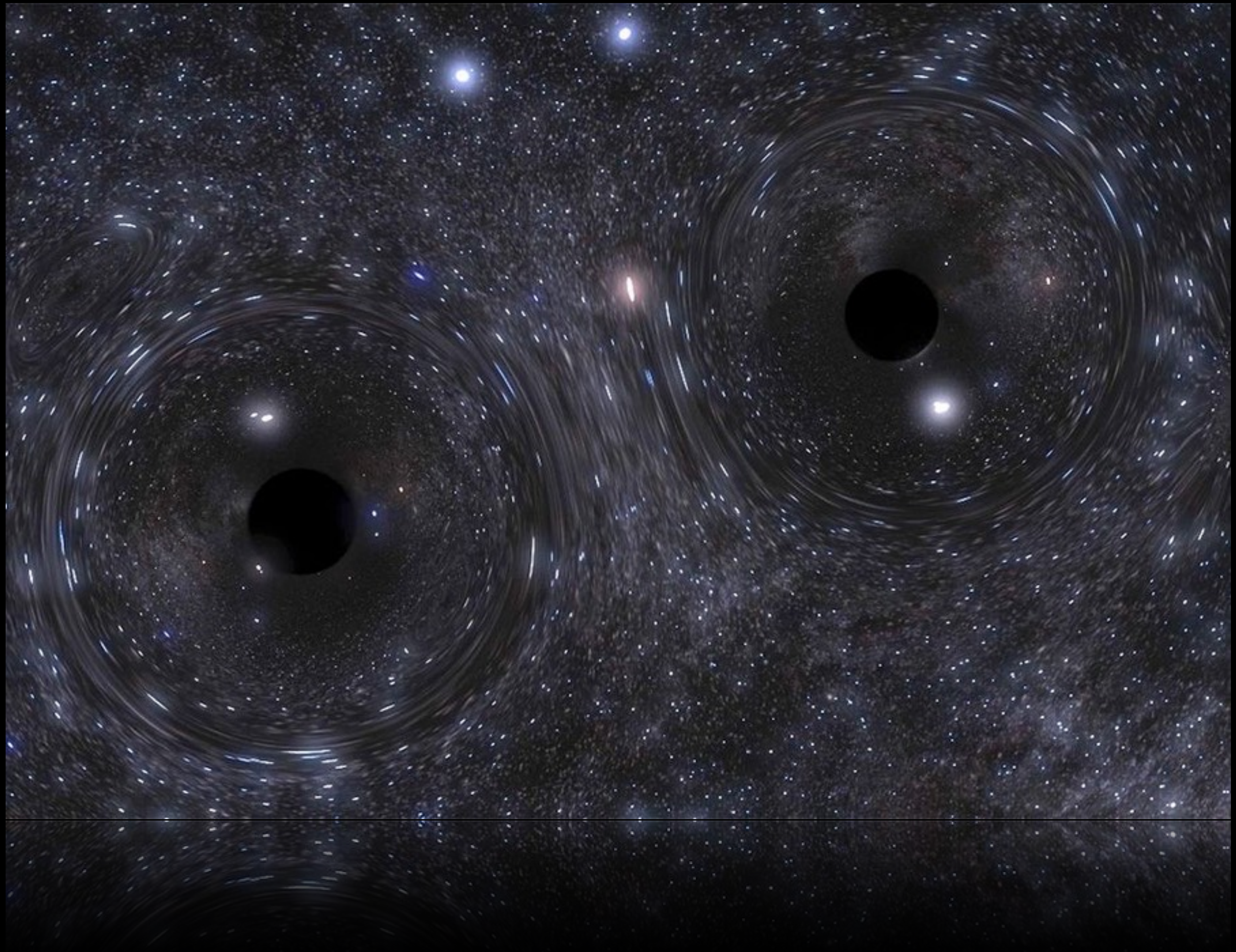
Regan & Haehnelt (2009)

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

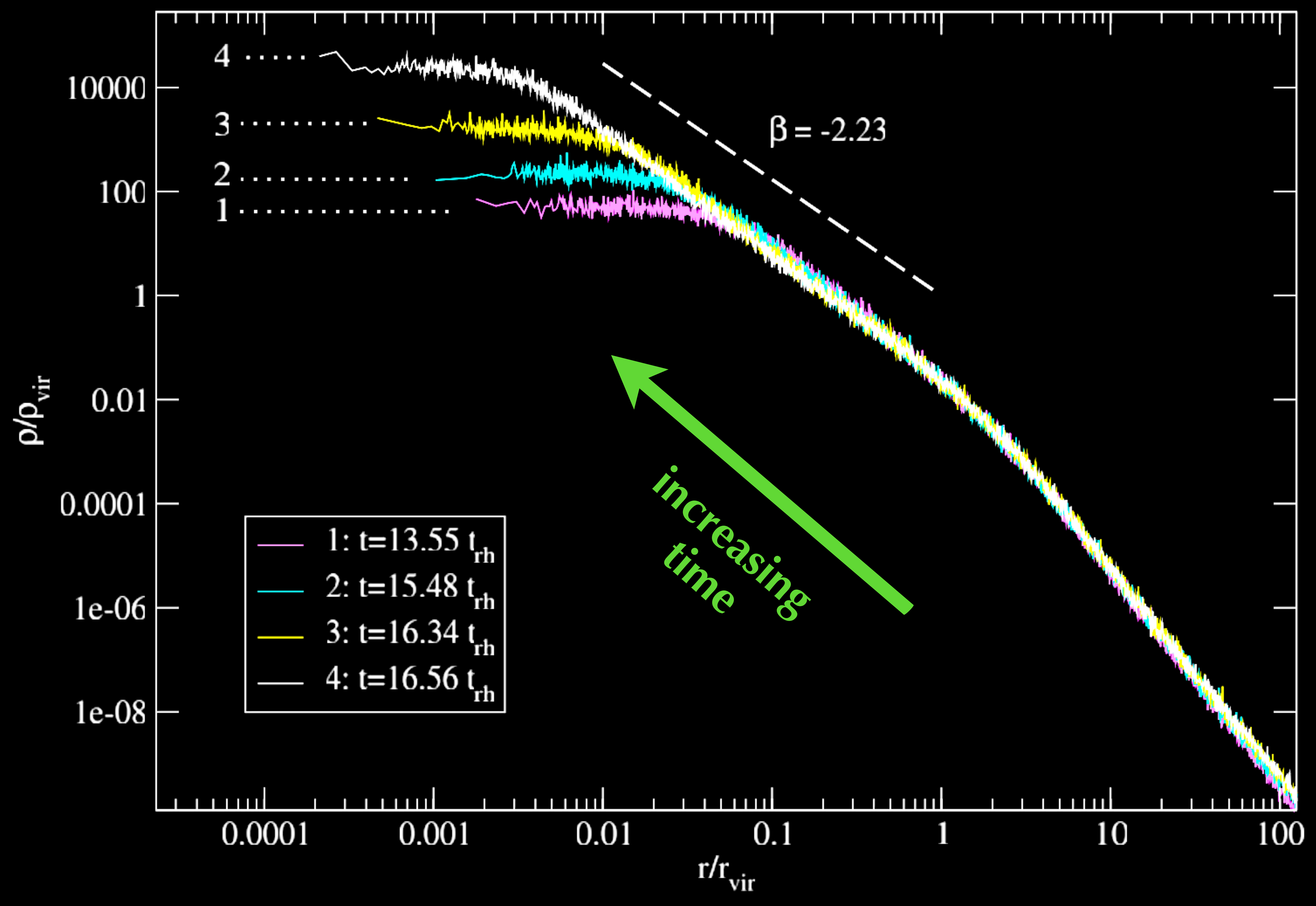
$$\boxed{t_{\rm relax} = 0.34 \frac{\sigma^3}{G^2 m \rho \ln \Lambda}}$$

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:

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



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

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

physical collisions between stars then occurs in the dense core

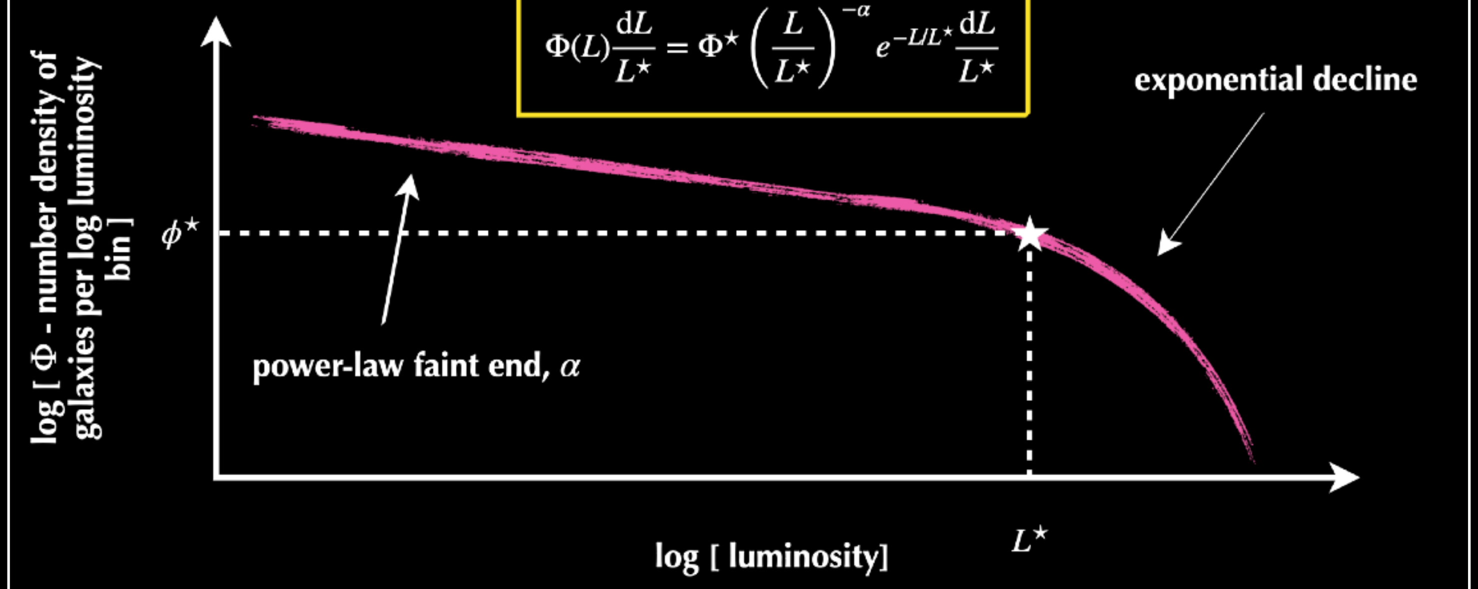
course summary

lecture 1 – the galaxy population & DM haloes

the galaxy luminosity function

Schechter (1976)

$$\Phi(L)\frac{\mathrm{d}L}{L^\star} = \Phi^\star \left(\frac{L}{L^\star}\right)^{-\alpha} e^{-L/L^\star}\frac{\mathrm{d}L}{L^\star}$$



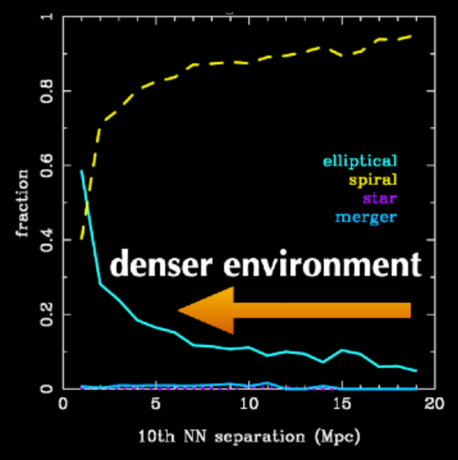
morphological correlations

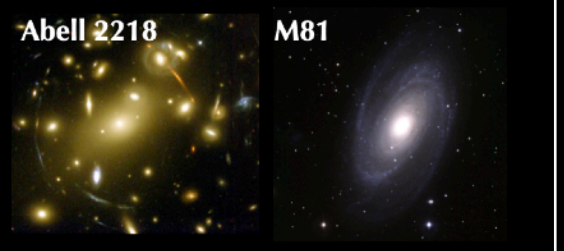
morphology varies most strongly with:

- luminosity/mass: most massive/ luminous galaxies are ellipticals
- environment: high-density regions are dominated by E/S0 while low-density "field" is where we find spirals and irregulars.

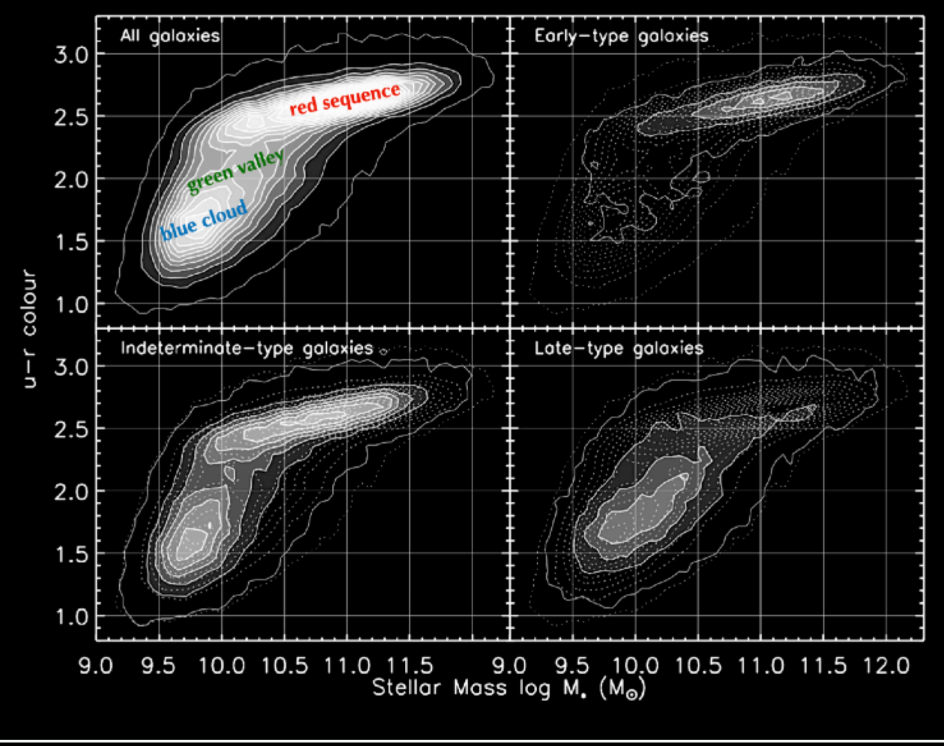
and correlates with:

- colour: most E/S0 galaxies are red, while most spirals/Irr are blue
- spectral type: most spiral/Irr have strong emission lines, while most E/S0 are absorption line systems





the distribution of galaxy colours at present day



galaxy colours roughly delineate star-forming vs passive/quenched galaxies

SDSS data [credit: https://pages.astronomy.ua.edu/keel/galaxies/systematics.html]

galaxy properties, correlations & scaling relations

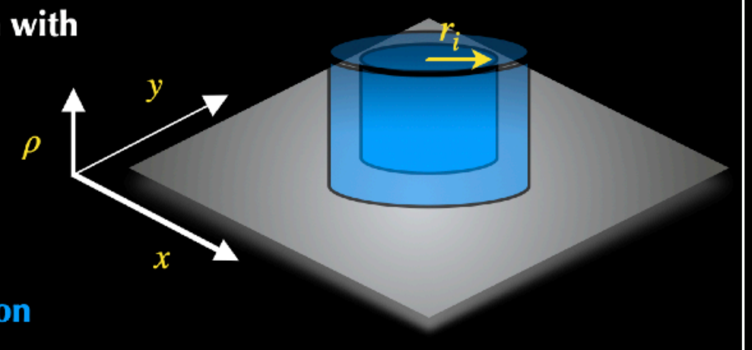
spherical collapse model

at some initial time, t_i, let r_i denote the (physical) radius of a mass shell contained within a spherical perturbation with overdensity δ_i

the mass enclosed within the shell is:

$$M(<r) = \frac{4}{3}\pi r_i^3 \bar{\rho}_i \left[1+\delta_i\right] = \frac{4}{3}\pi r^3(t)\,\bar{\rho}(t)\left[1+\delta(t)\right]$$

mass conservation



the equation of motion of this mass shell under gravity can de derived using Newton's shell theorem:

$$\frac{\mathrm{d}^2 r}{\mathrm{d}t^2} = -\frac{GM}{r^2}$$

"a spherically symmetric mass distribution outside a sphere exerts no force on it"

[also known as Birkhoff's theorem]

integrating this equation yields:

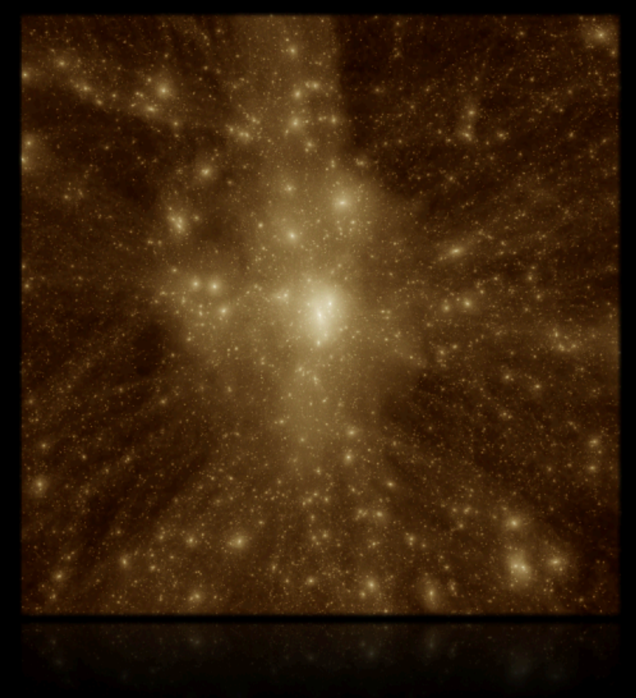
$$\boxed{\frac{1}{2}\left(\frac{\mathrm{d}r}{\mathrm{d}t}\right)^2 - \frac{GM}{r} = E}$$

energy per unit mass of the shell

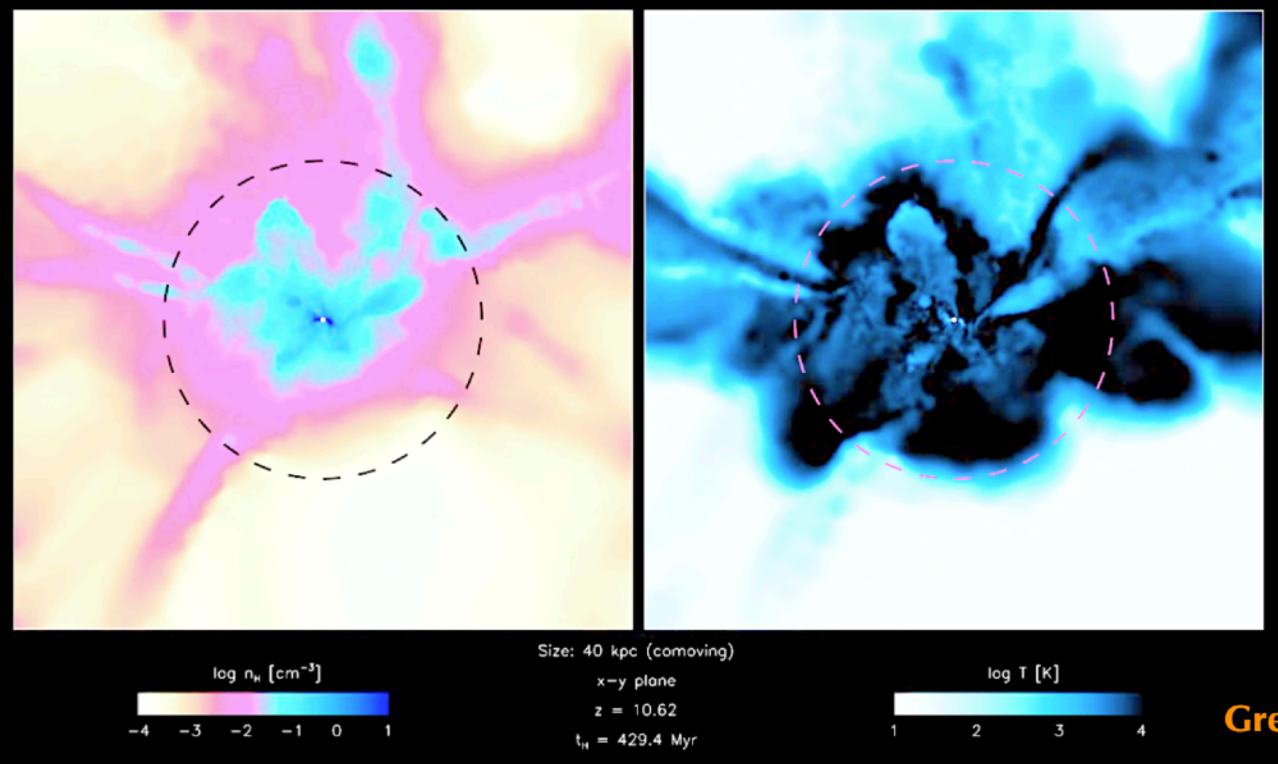
virialised dark matter haloes

characteristic quantities in DM haloes

- haloes in simulations are roughly in dynamical equilibrium at mean interior densities: $M(<r_{\rm vir})/(4\pi/3 r_{\rm vir}^3) = \rho_{\rm vir}(z)$
- $\rho_{\rm vir}$ is given by spherical collapse model: $\rho_{\rm vir}(z) = \Delta_{\rm vir}\,\rho_m(z) \sim 200\,\rho_m(z) \propto (1+z)^3$
- which also defines a characteristic radius for each halo: $r_{\rm vir} \propto M^{1/3}/(1+z)$
- characteristic circular velocity for halo: $V_{\rm vir} = \left(GM(<r_{\rm vir})/r_{\rm vir}\right)^{1/2} \propto M^{1/3}(1+z)^{1/2}$



lecture 2 – gas cooling & angular momentum



Greif+ (2008)

some important timescales in gas cooling

- the age of the Universe, which is roughly the Hubble time, is given by:

$$t_H = \frac{1}{H(z)} \propto \frac{1}{\sqrt{G\rho_m}} \qquad \rho_m = \Omega_m \rho_{\rm crit}$$

- the dynamical time (or the so-called "free-fall" time) of the system is set by:

$$t_{\rm ff} = \left(\frac{3\pi}{32 G \bar{\rho}_{\rm tot}}\right)^{1/2} \qquad \bar{\rho}_{\rm tot} = \bar{\rho}_{\rm DM} + \bar{\rho}_{\rm gas}$$

in the absence of pressure, sets the timescale on which a gas cloud collapses under gravity & the timescale on which the system is restored to equilibrium after being disturbed

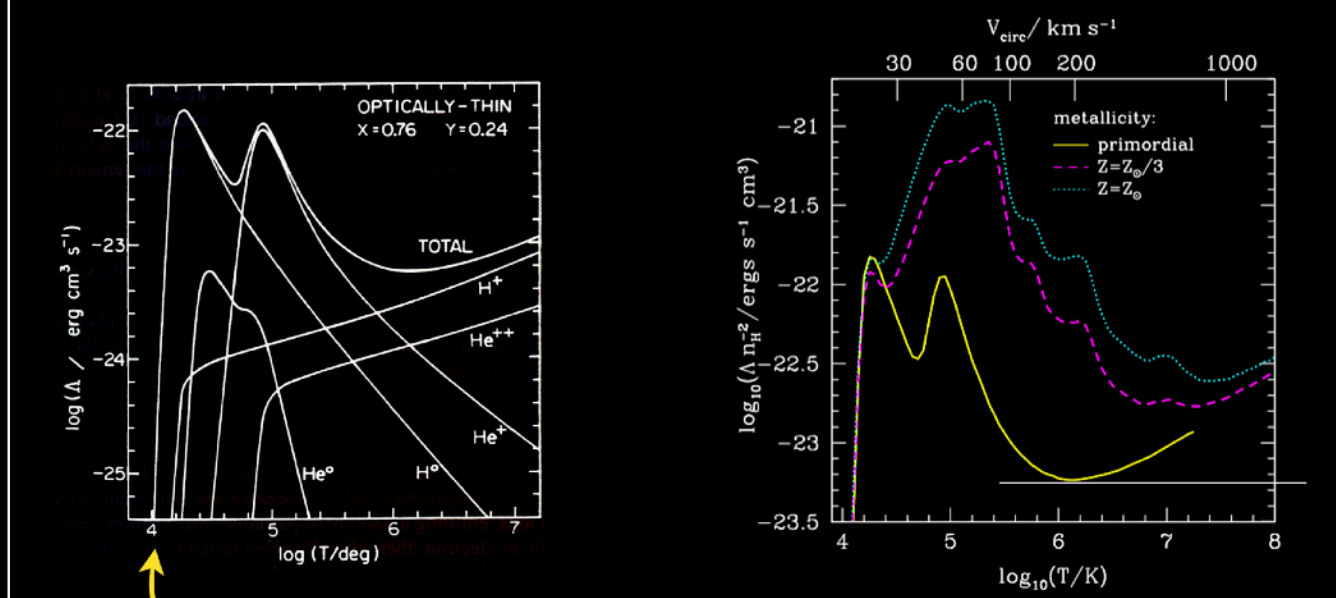
$t_{\rm cool} > t_H$ cooling is unimportant & gas is in hydrostatic equilibrium

$t_{\rm ff} < t_{\rm cool} < t_H$ system in quasi-hydrostatic equilibrium. gas contracts as system cools but it has enough time to restore hydrostatic equilibrium.

$t_{\rm cool} < t_{\rm ff}$ gas unable to respond in time to loss of pressure: as $t_{\rm cool} \propto \rho^{-1}$, cooling proceeds faster and faster — it is a "catastrophic" process

primordial gas (H + He)

metal-enriched gas



atomic cooling cuts off for T < 10⁴K

cooling most rapid here

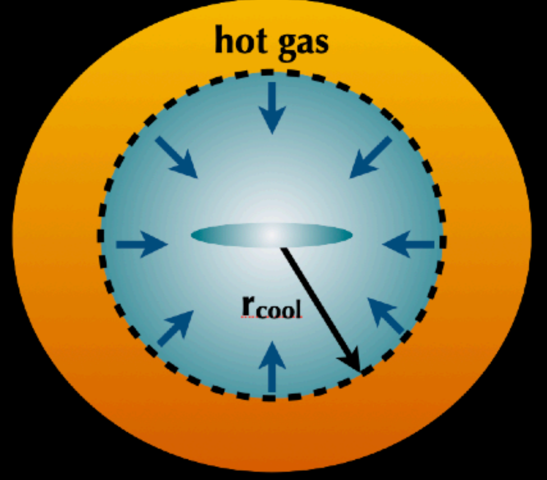
bremsstrahlung dominates; cooling is inefficient

shock heating, radiative cooling, cooling timescales

halo ⇔ gas angular momentum

the importance of angular momentum in galaxy formation

- if the gas contained in a halo can radiate away all of its energy, then what halts its gravitational collapse is angular momentum (assuming it cannot transfer all of this to the DM halo)
- stars & gas in galactic discs are on nearly circular orbits — centrifugally supported against gravity, $V_{\rm rot} = (GM(<r)/r)^{1/2}$
- so, the sizes of galaxy discs are controlled by how much angular momentum they have



(i) assume that gas cools out to some radius, $r_{\rm cool}$

(ii) gas in halo initially has same specific angular momentum as the DM halo itself

(iii) gas conserves J as it collapses

(iv) collapse eventually stops when the gas becomes rotationally supported

gas angular momentum ⇔ disc sizes

a simple model for the radii of galaxy discs

this model therefore predicts that:

$r_{\rm disc} \sim \lambda_H r_{\rm cool}$ if gas cools only within the radius $r_{\rm cool}$

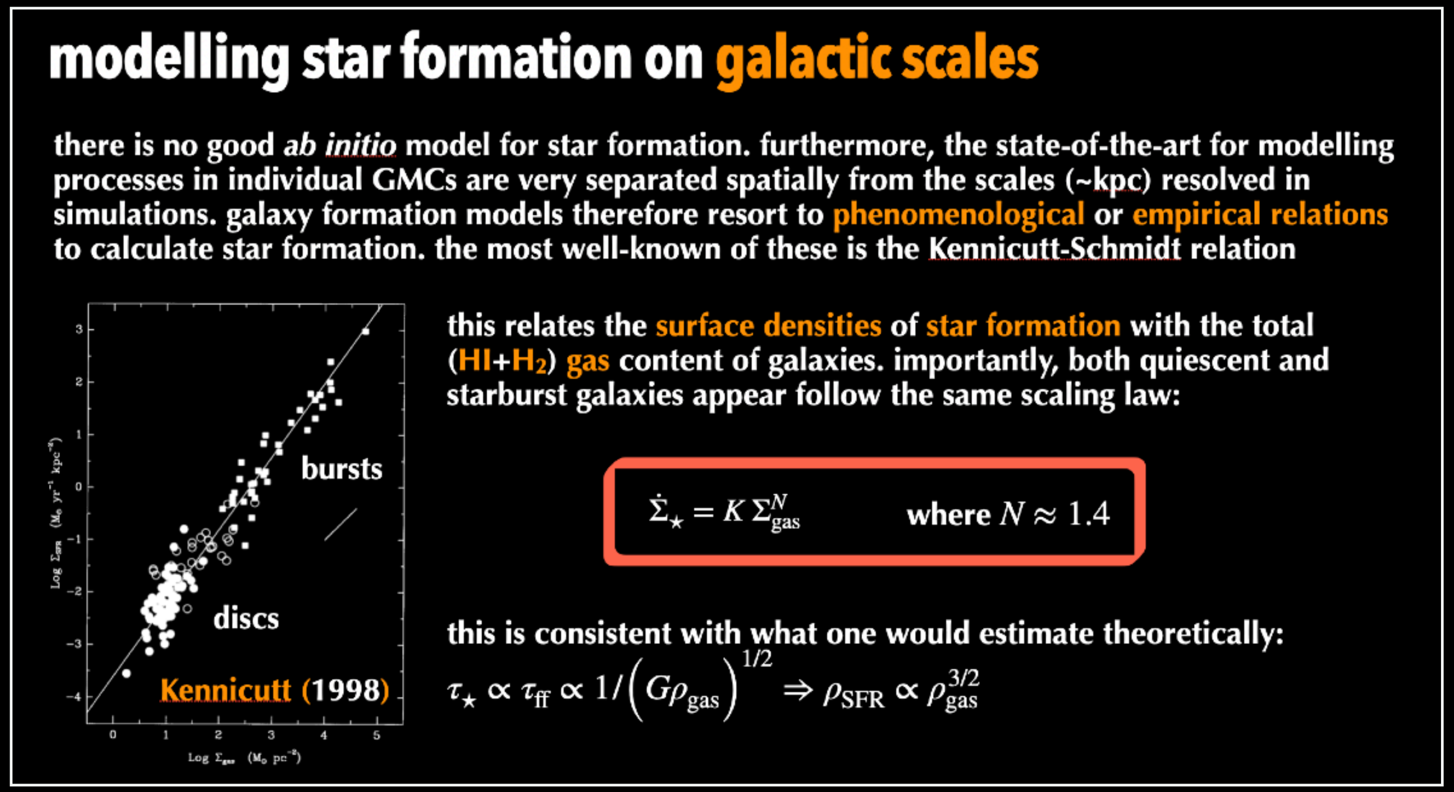
$r_{\rm disc} \sim \lambda_H r_{\rm vir}$ if all the gas within the halo cools to form a disc

when combined with the predicted values of λ_H from cosmological simulations, it turns out that this is in ~rough~ agreement with the observed sizes of galaxy discs at z~0. but there have been several updates to the model inc. Mo, Mao & White (1998), Dutton & van den Bosch (2012) etc.

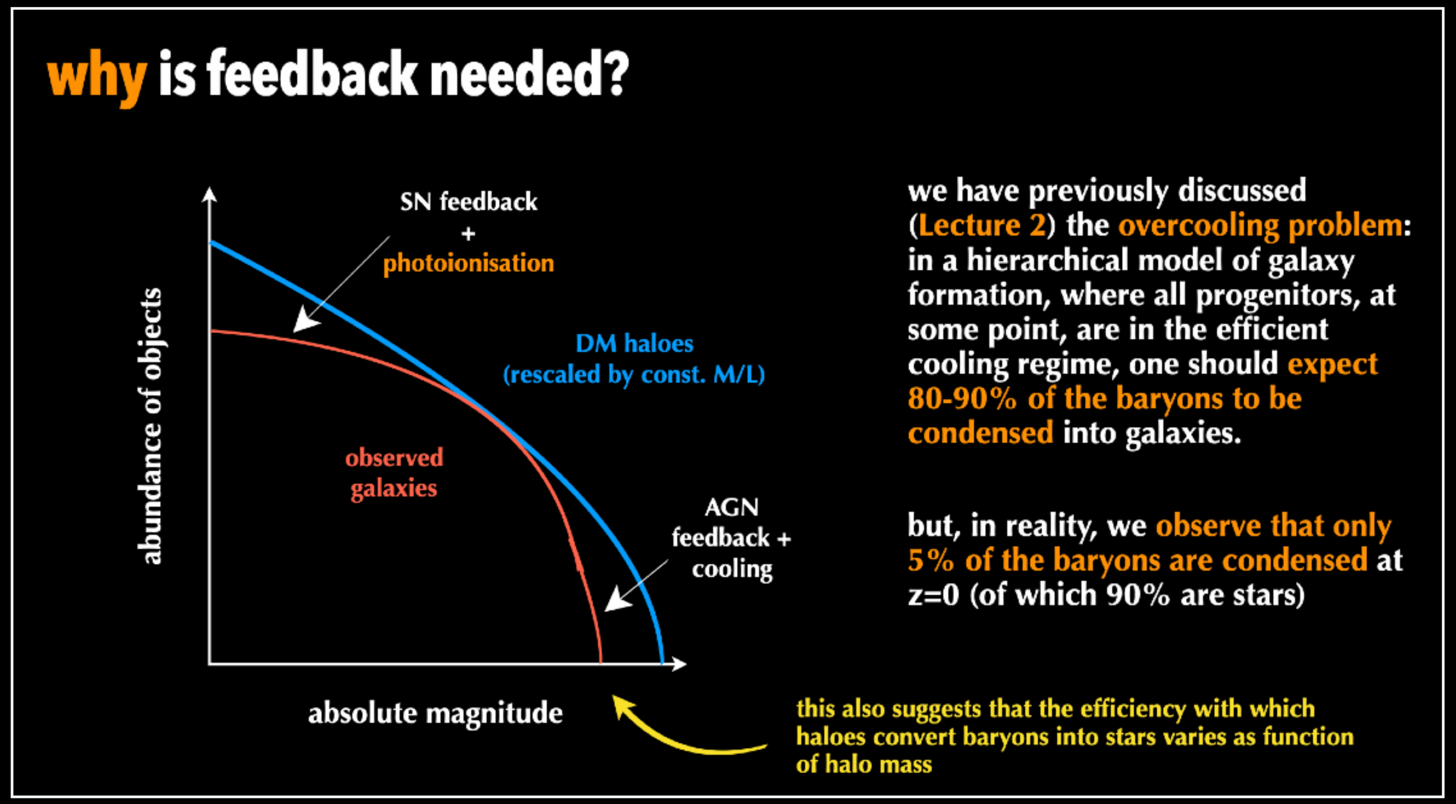
what about the sizes of spheroids? if the spheroid galaxies are formed by merging galaxy discs, then their sizes are determined by the sizes of their progenitor discs — and, therefore, also determined (indirectly) by disc angular momentum

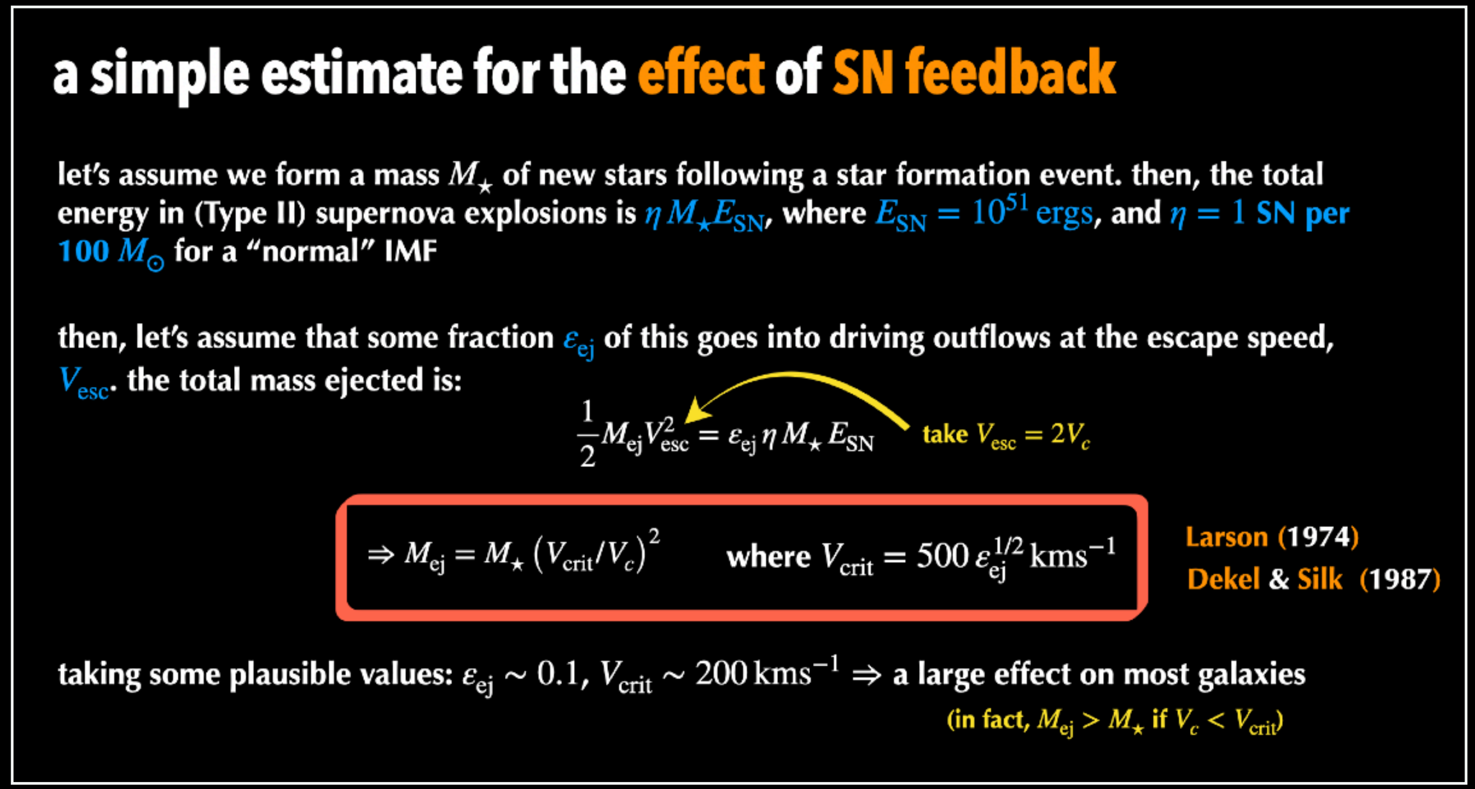
lecture 3 – star formation & feedback

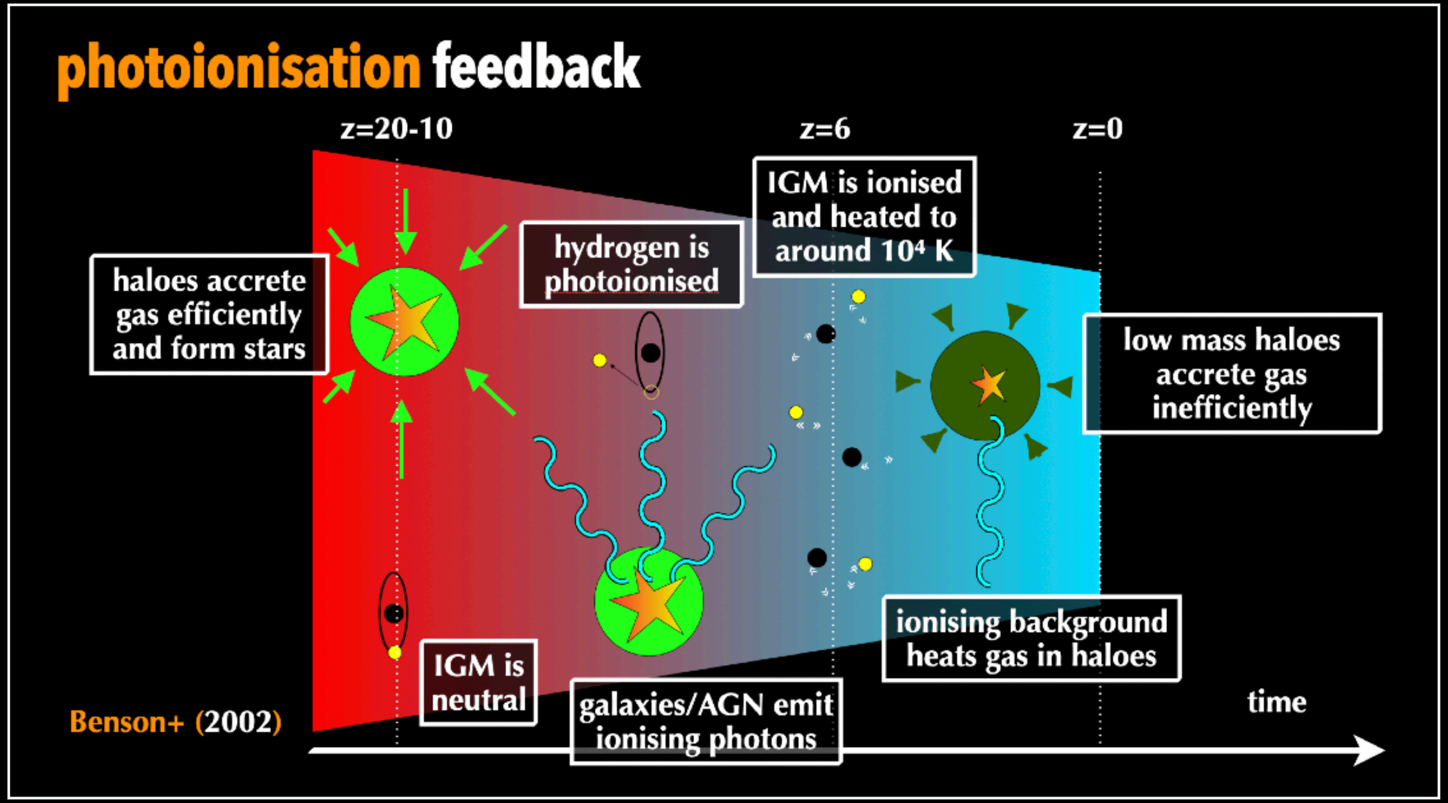
the Kennicutt-Schmidt law

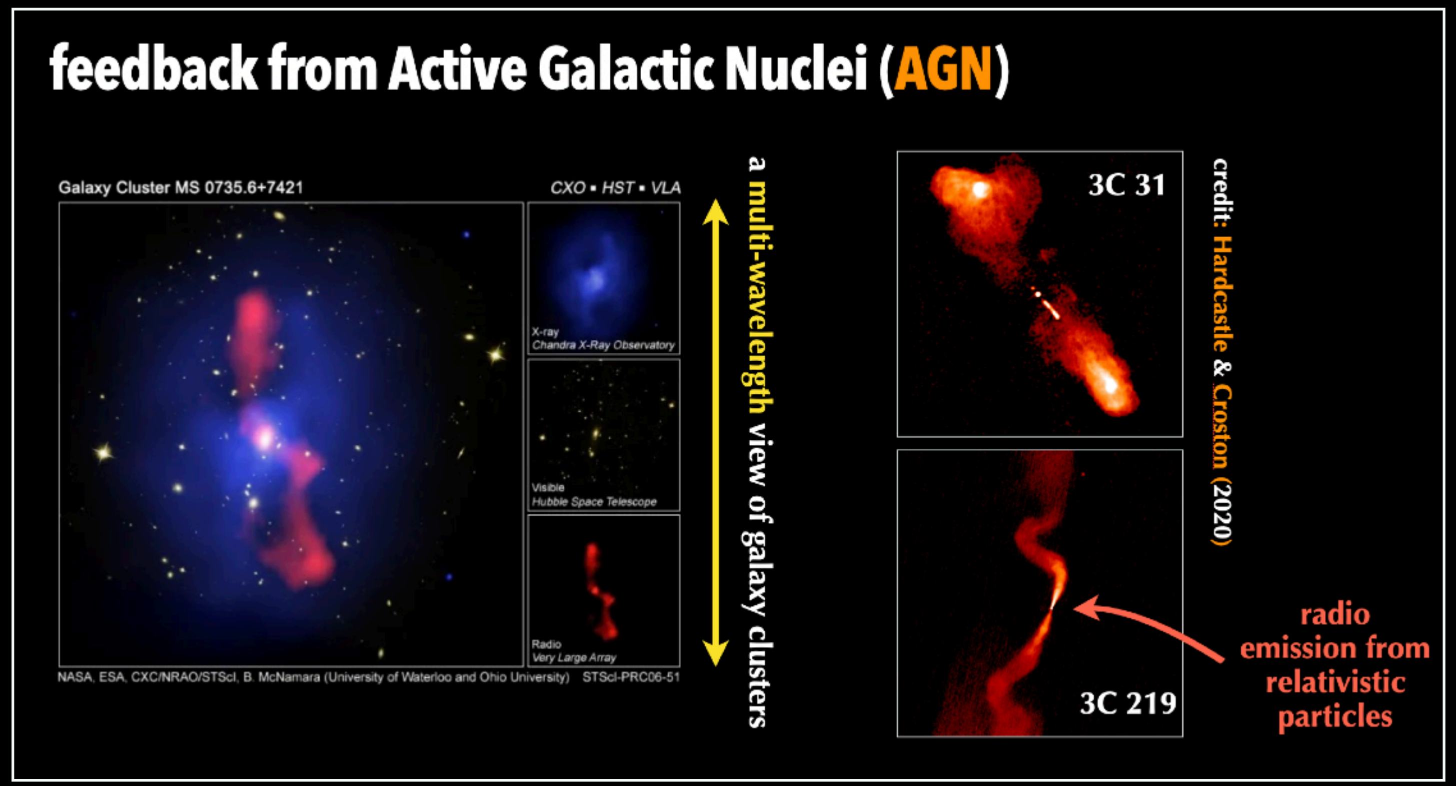


feedback shapes the galaxy distribution









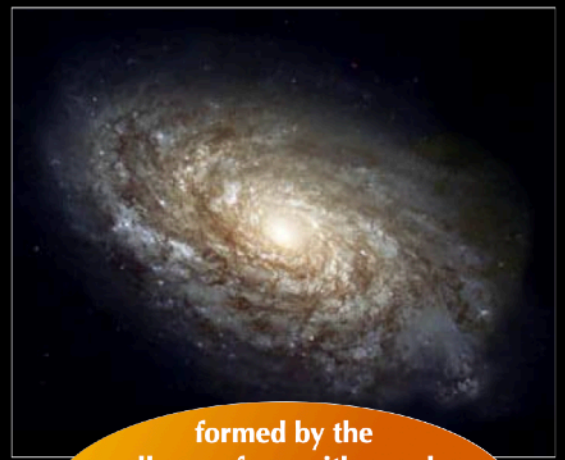
different modes of feedback: from stars and SMBHs

lecture 4 – galaxy mergers & morphology

galaxy mergers create spheroids

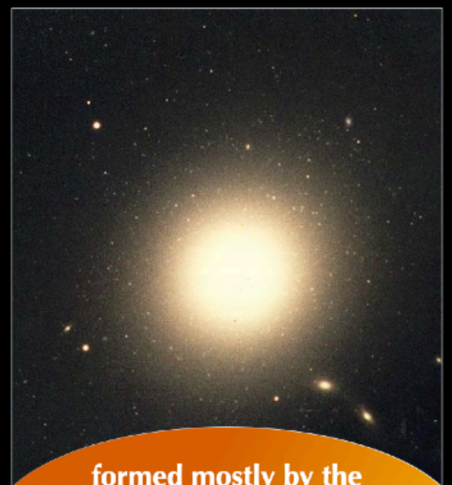
a broad classification of galaxy morphologies

discs



formed by the collapse of gas with angular momentum in DM haloes, following radiative cooling (lecture 2)

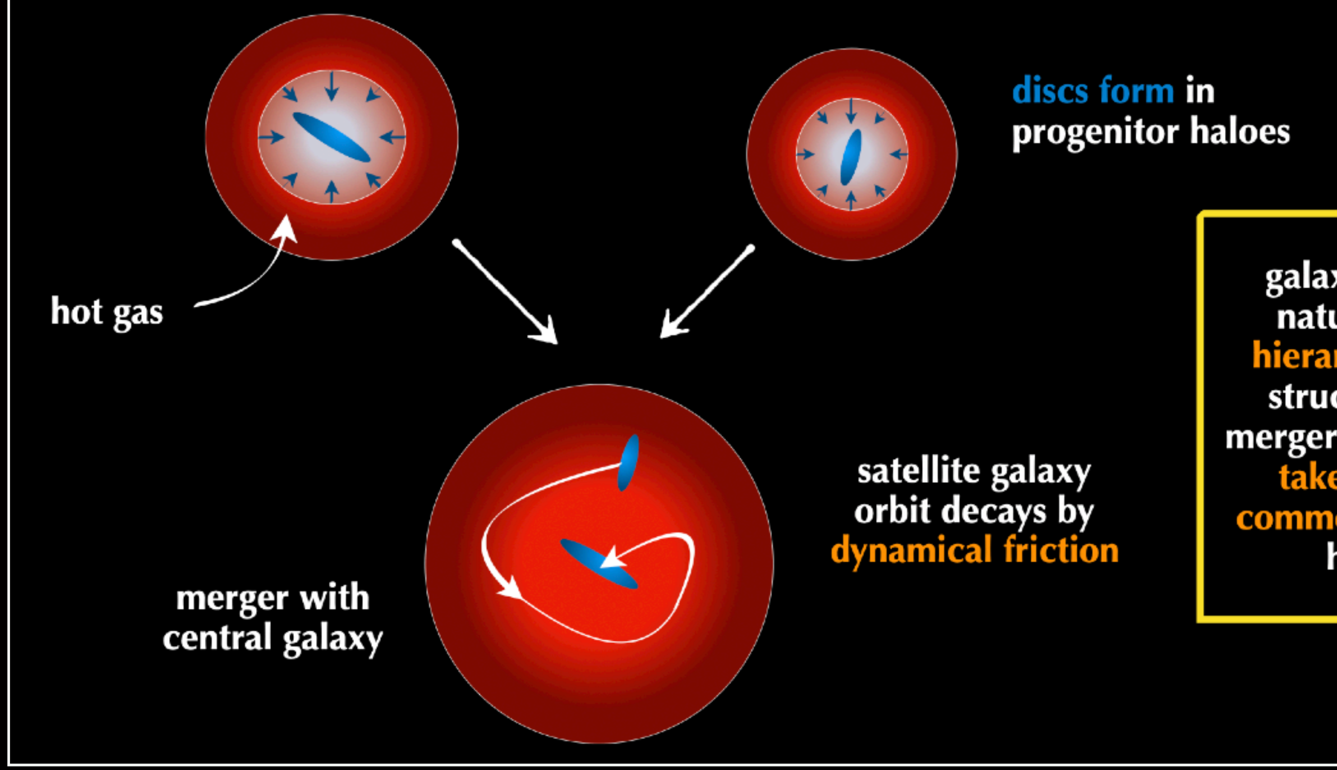
spheroids



formed mostly by the mergers of galaxy discs; some form by dynamical instabilities in galaxy discs

mergers caused by dynamical friction

how do galaxy mergers happen?



galaxy mergers are a natural outcome of hierarchical models of structure formation. mergers between galaxies take place within a common halo, following halo mergers

merger timescale depends on the ratio $M_{\rm sat}/M_{\rm halo}$

galaxy merger timescale in a DM halo

a galaxy orbiting in a dark matter halo feels dynamical friction against the halo, which causes its orbit to shrink. over time, the satellite shrinks to the centre

for an object on a circular orbit with radius r, orbiting inside a halo with an isothermal density profile $\rho = \dfrac{V_c^2}{4\pi G r^2}$

$$\frac{dr}{dt} = -\frac{0.43\ln\Lambda}{r}\frac{GM_{\rm sat}}{V_c}$$

so, a satellite galaxy sinks from $r = r_i$ to $r = 0$ over a timescale:

$t_{\rm orb} = r_i/V_c$

$$\boxed{t_{\rm fric} = \frac{1.17}{\ln\Lambda}\frac{r_i^2 V_c}{GM_{\rm sat}} = \frac{1.17}{\ln\Lambda}\frac{M_{\rm halo}(<r_i)}{M_{\rm sat}}t_{\rm orb}}$$

$t_{\rm fric}/t_{\rm orb} \sim 1$ for $M_{\rm sat}/M_{\rm halo} \sim 1$

$t_{\rm fric}/t_{\rm orb} \gg 1$ for $M_{\rm sat}/M_{\rm halo} \ll 1$

$\ln\Lambda \sim \ln\left(1 + M_{\rm halo}/M_{\rm sat}\right)$

i.e. merger timescales long/short for small/large satellites

the Toomre parameter sets the stability of rotating discs

gravitational stability of a rotating disc

the local stability of a thin, rotating gas disc with surface density, $\Sigma_{\rm gas}$, and velocity dispersion, $\sigma_{\rm gas}$, depends on the following ratio (Toomre 1964):

essentially balancing the competing effects of gravity, gas pressure, and rotation

$$\boxed{Q = \frac{\kappa\,\sigma_{\rm gas}}{\pi G \Sigma_{\rm gas}}}$$

$$\kappa = \left(R\frac{d\Omega^2}{dR} + 4\Omega^2\right)^{1/2}$$

"epicyclic" frequency

$Q < 1 \Rightarrow$ locally unstable

$Q > 1 \Rightarrow$ locally stable for axisymmetric perturbations

similar result for stellar discs:

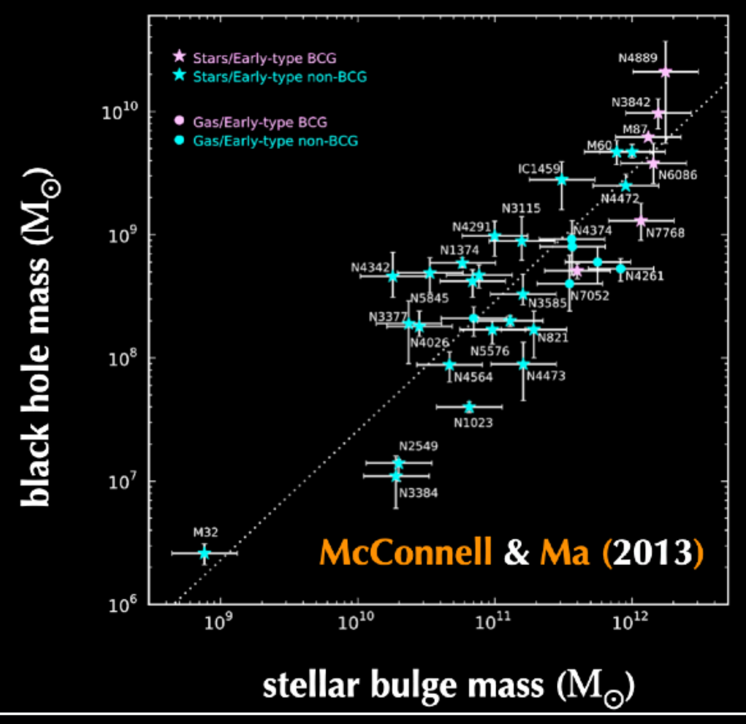
$$\boxed{Q = \frac{\kappa\,\sigma_\star}{3.36\,G\Sigma_\star}}$$

in practice, $Q > 2-3$ seems to be needed in order to be stable against the formation of spiral structure and bars

lecture 5 – supermassive black holes

the BH mass-bulge mass relation in galaxies

galaxy–SMBH co-evolution



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for this to happen:

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- 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?
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the radiation pressure exceeds the force due to gravity when:

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

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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:

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

the many pathways for SMBH formation