Star & galaxy formation in the early universe

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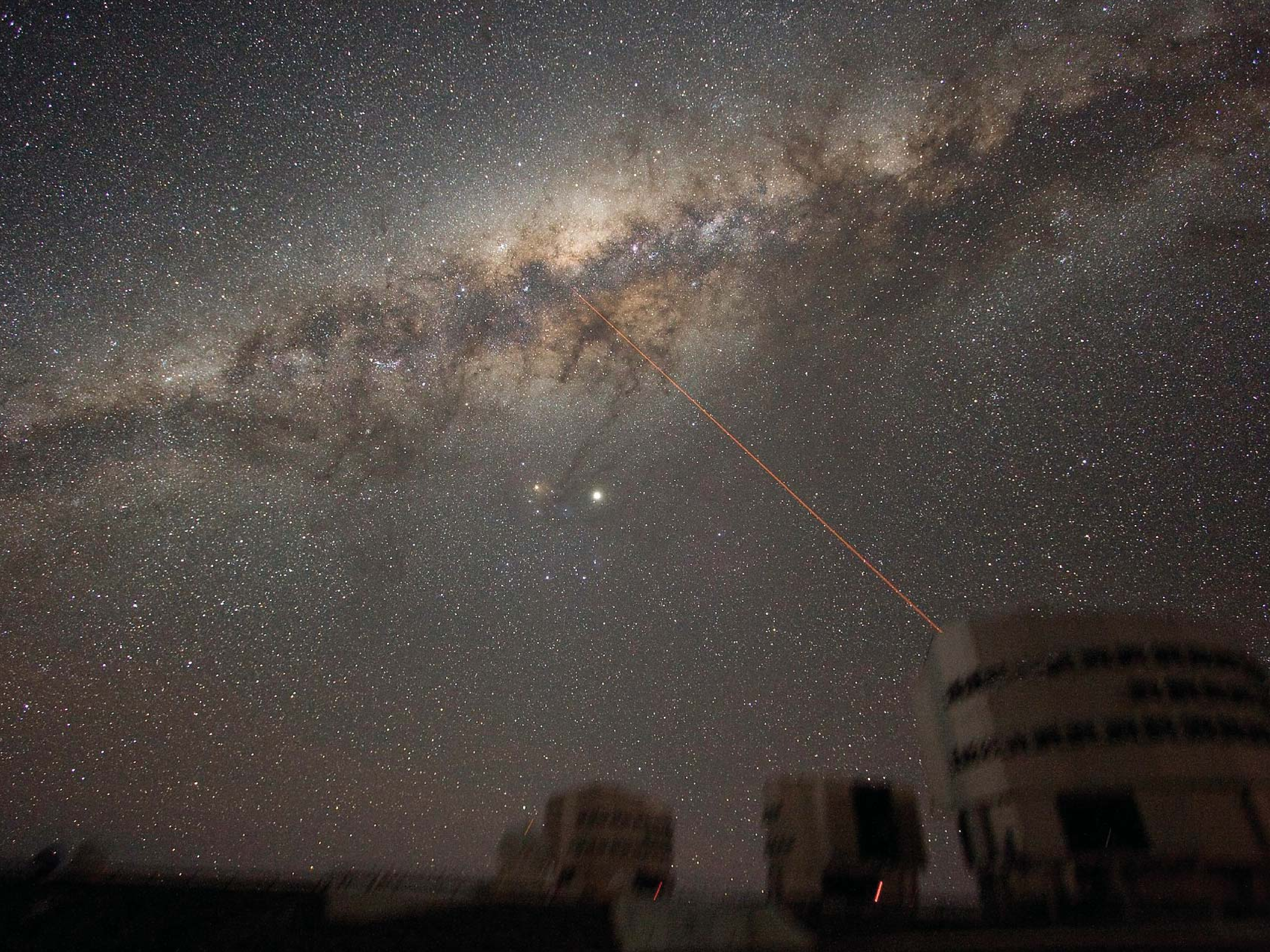
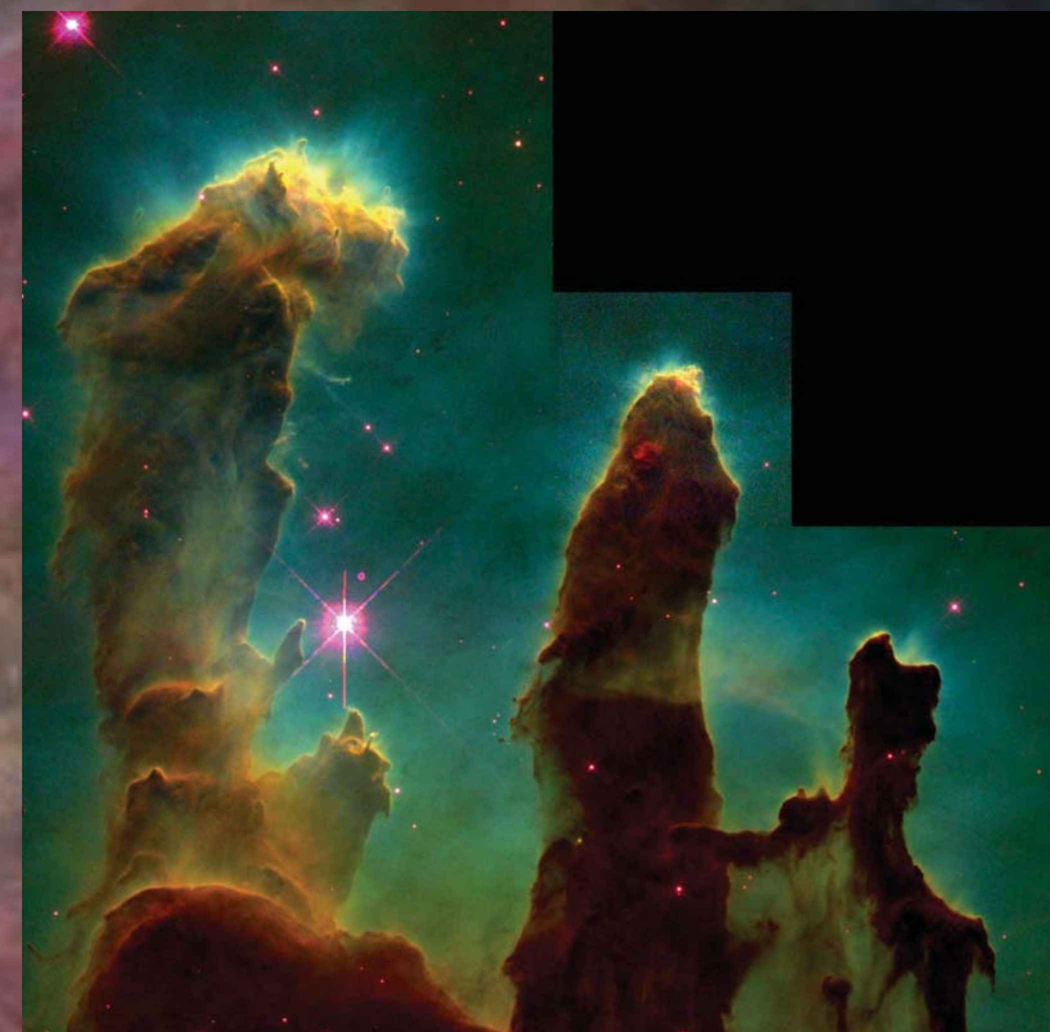
Introduction



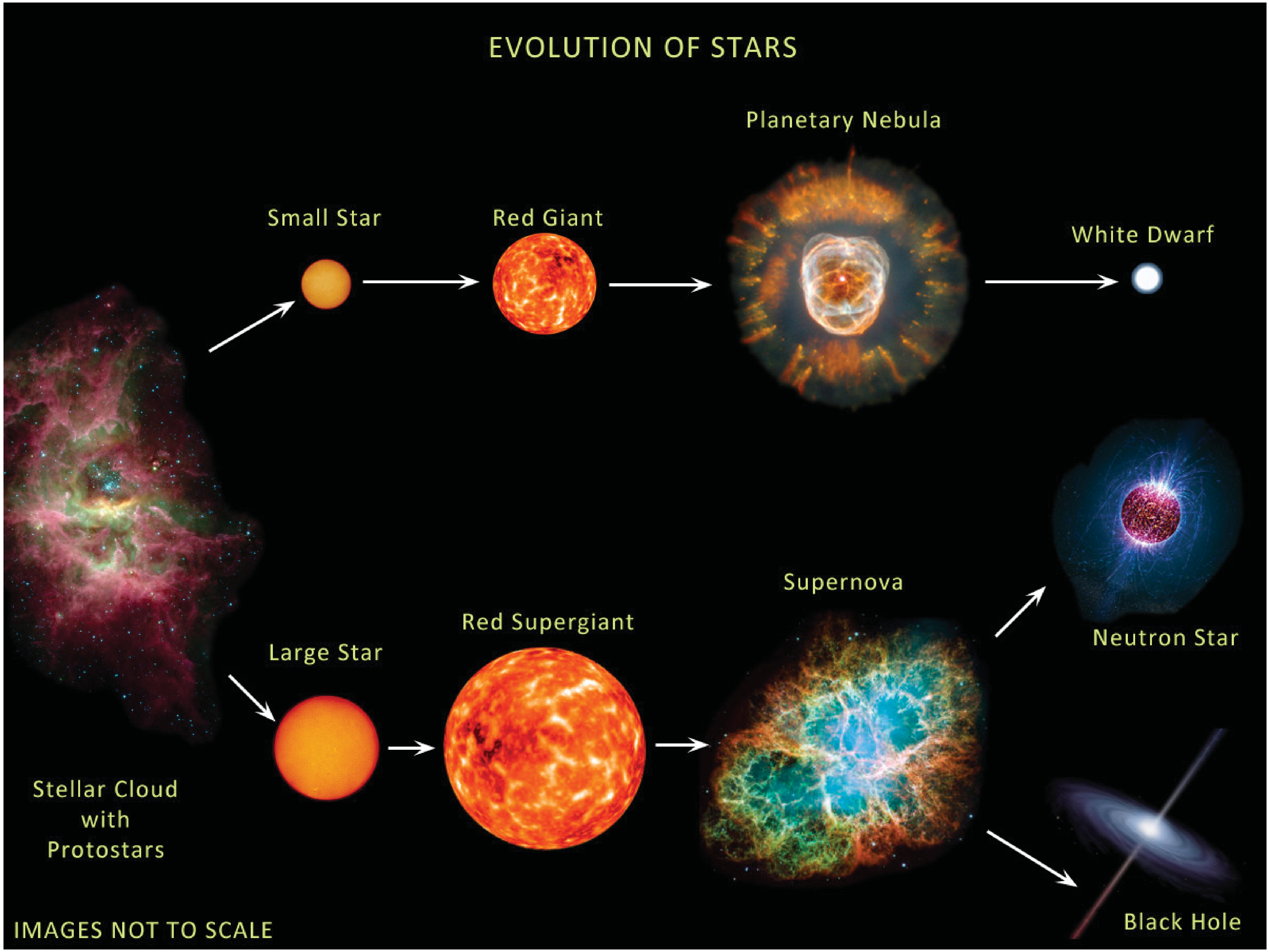
Star forming regions



http://hubblesite.org/newscenter/newsdesk/archive/releases/2006/01/

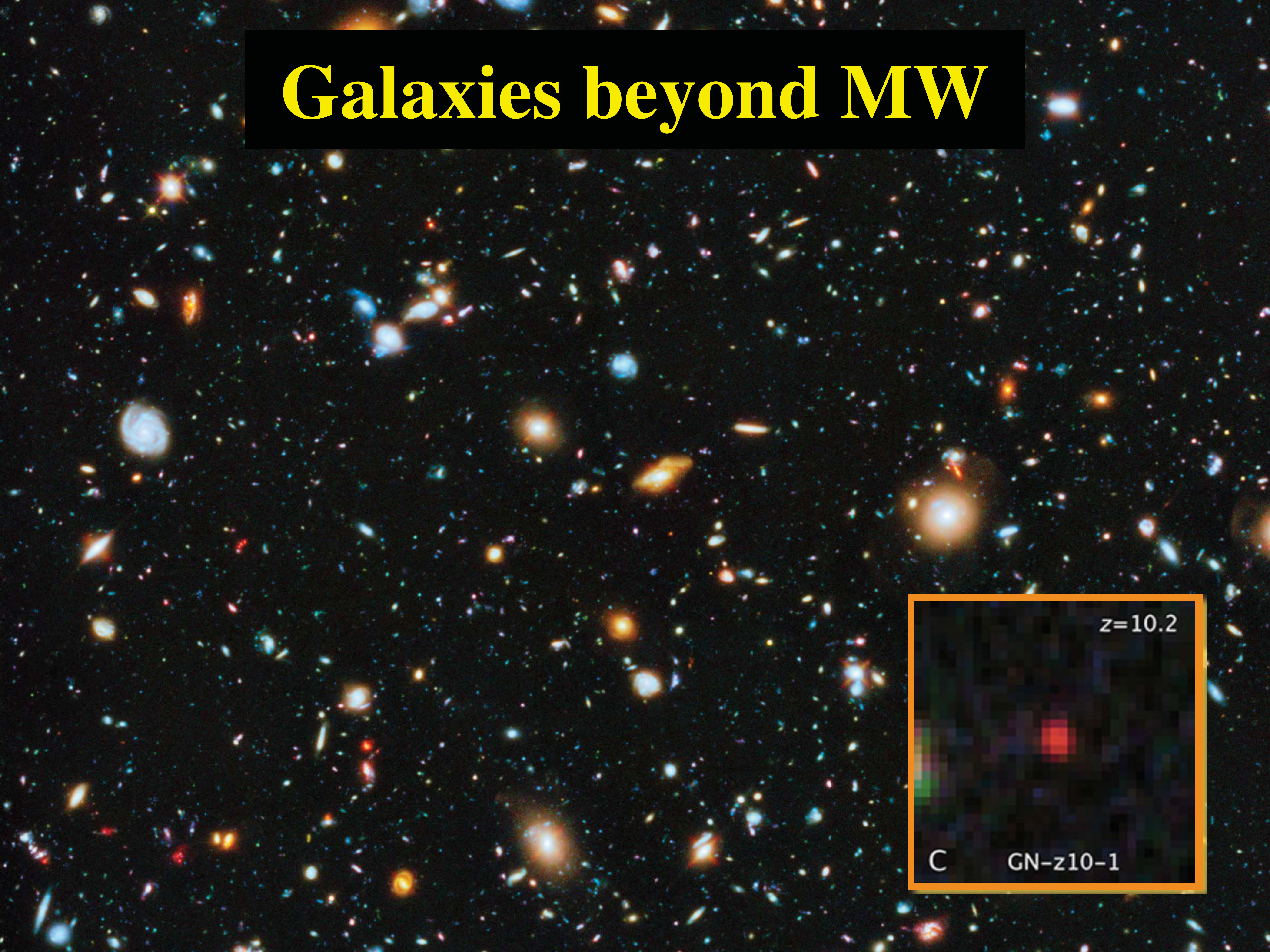
http://hubblesite.org/newscenter/newsdesk/archive/releases/2003/34/image/a

Life cycle of stars

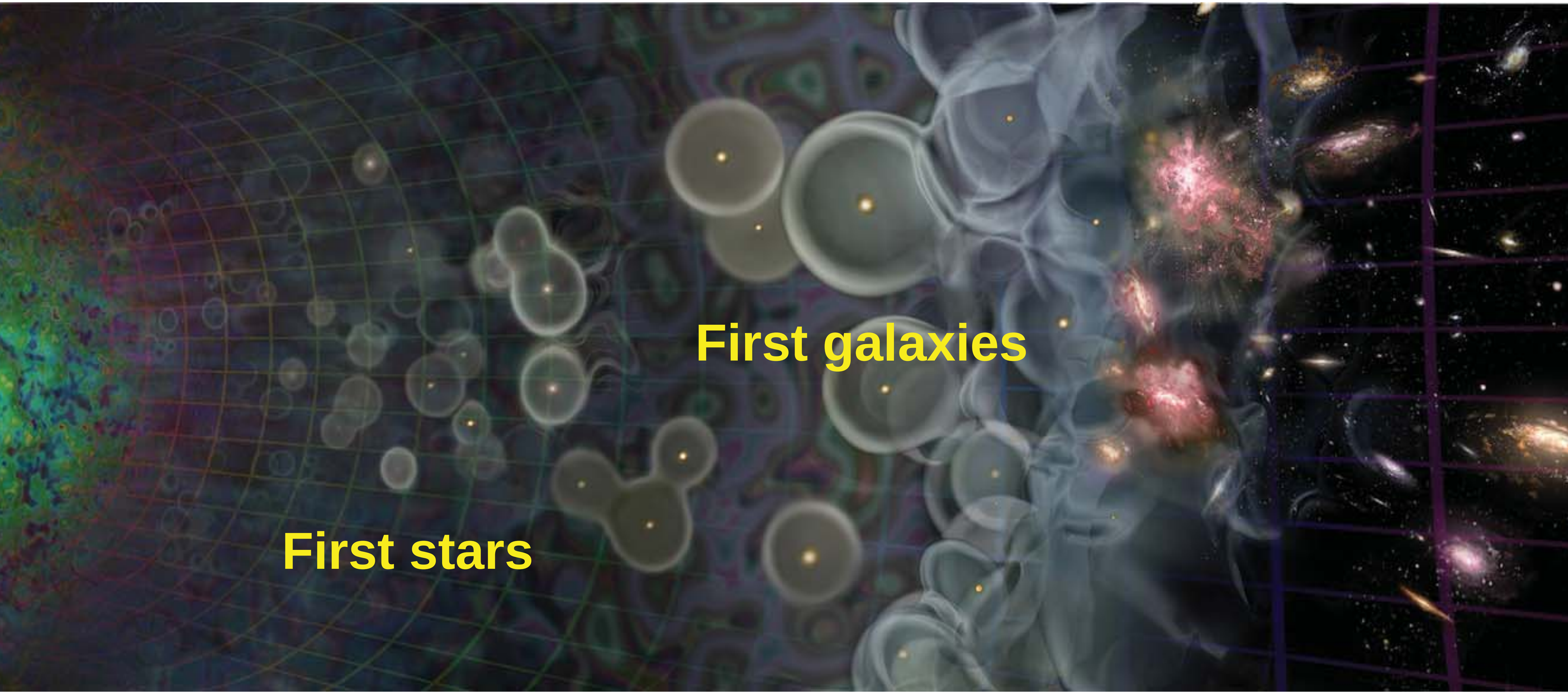


https://blackholecam.org/a-massive-star-collapsing-in-upon-itself-forms-a-black-hole/

Galaxies beyond MW

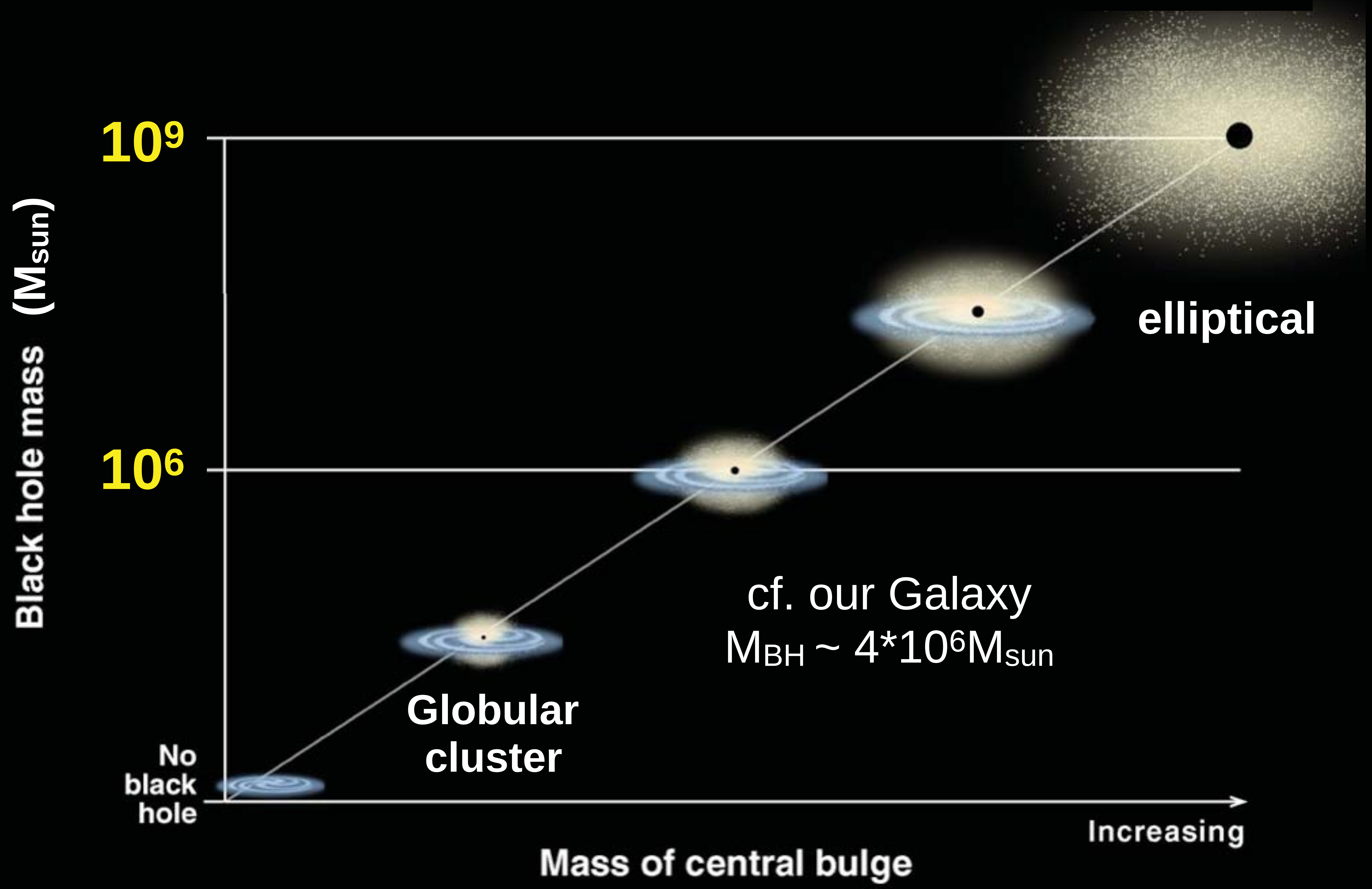


The early stage of the universe

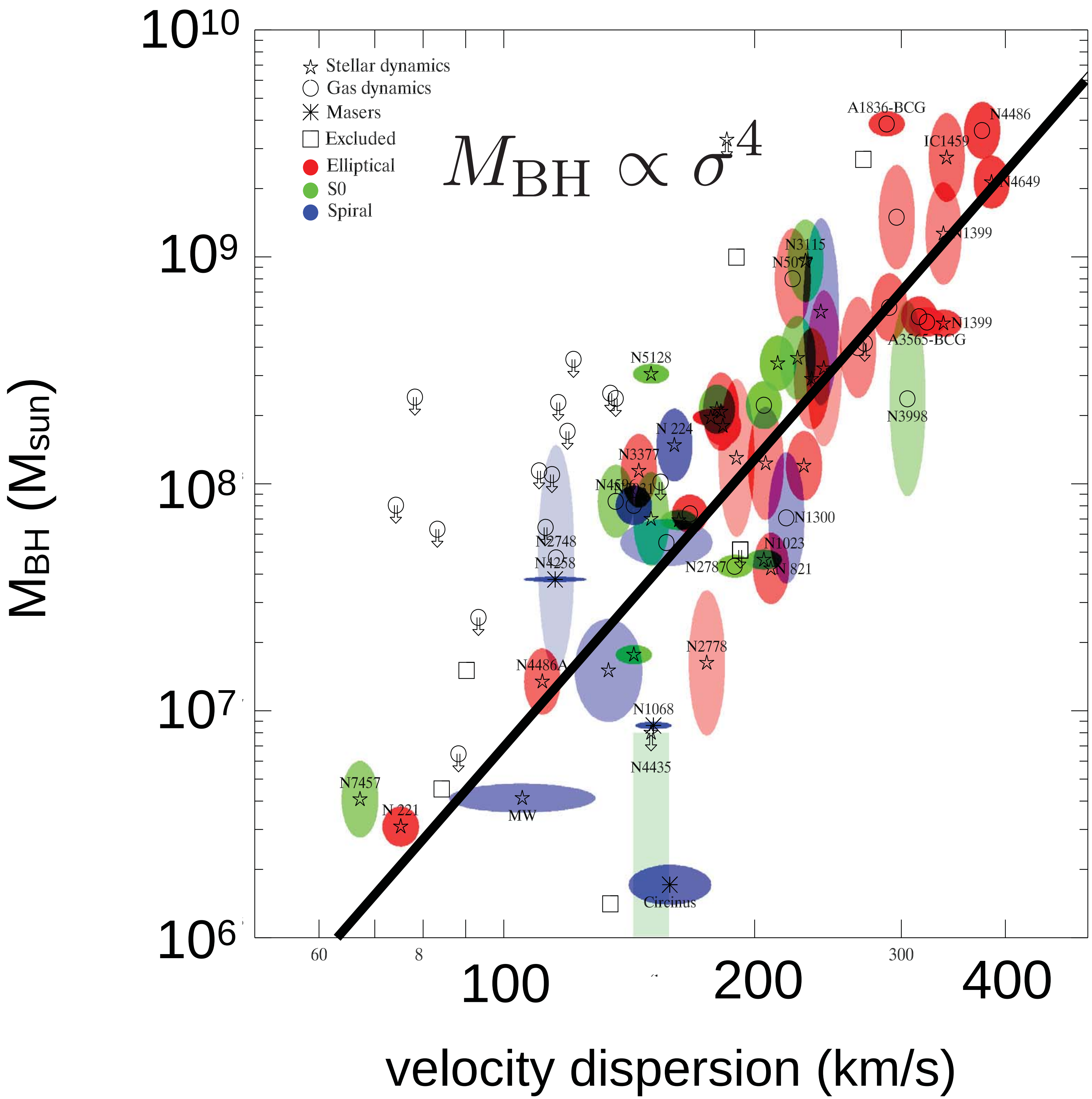


z~1100	z~20	z~6
Recombination	**Dark Ages**	**Epoch of Reionization**

Supermassive black holes (SMBHs)



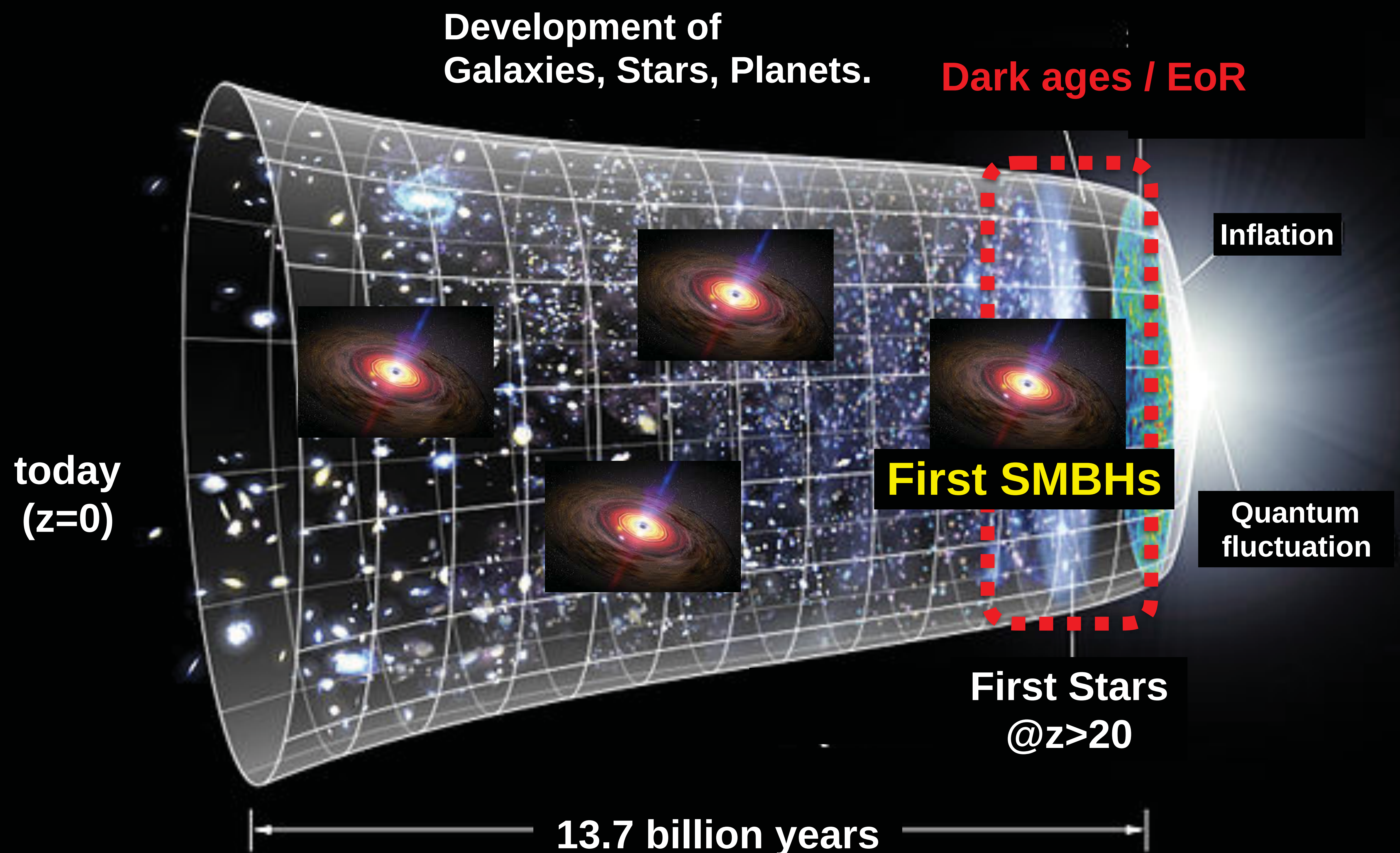
Coevolution of SMBHs with galaxies



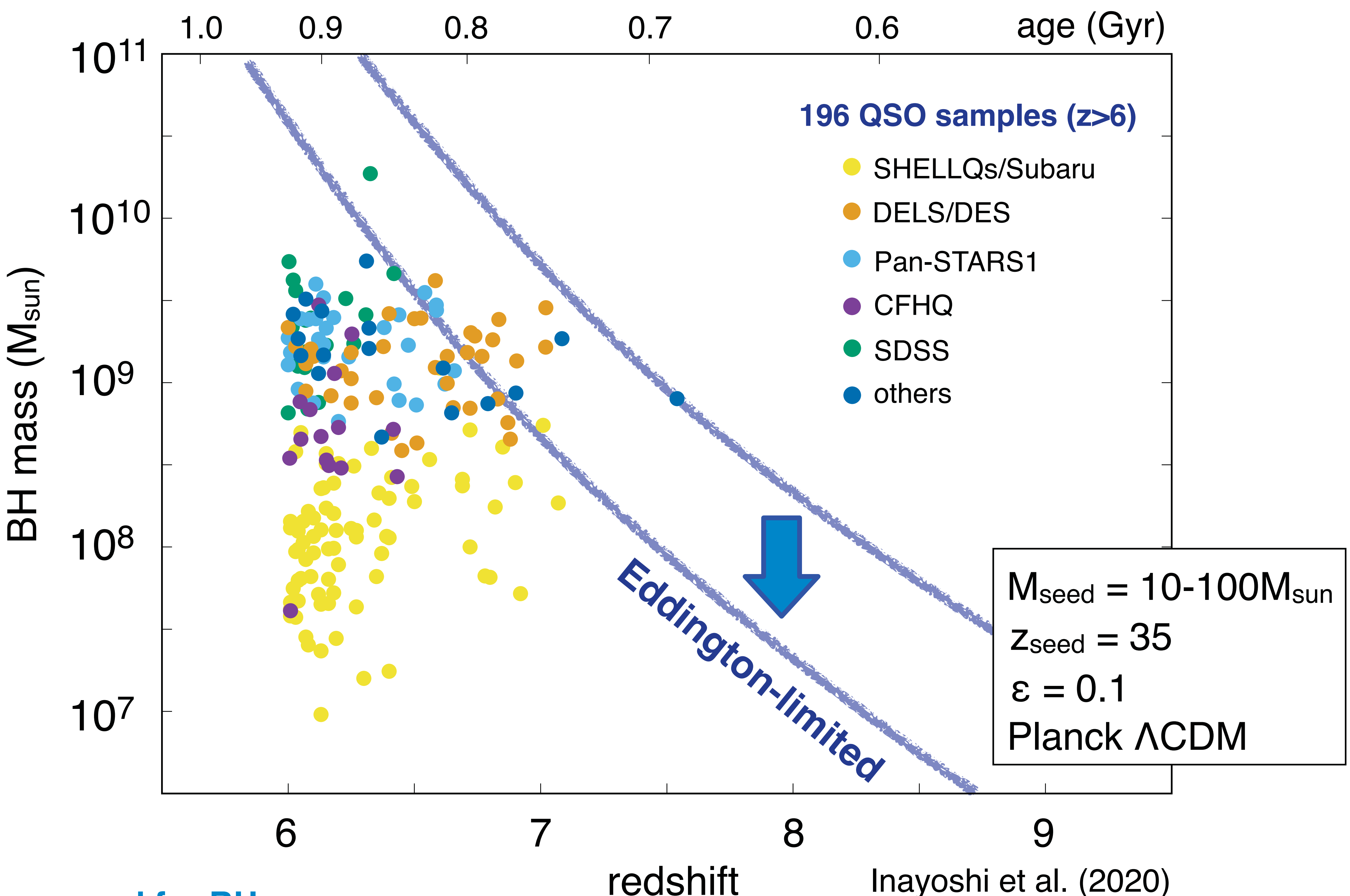
local SMBHs (z=0)

Gultekin et al. (2009)

Cosmological QSO population

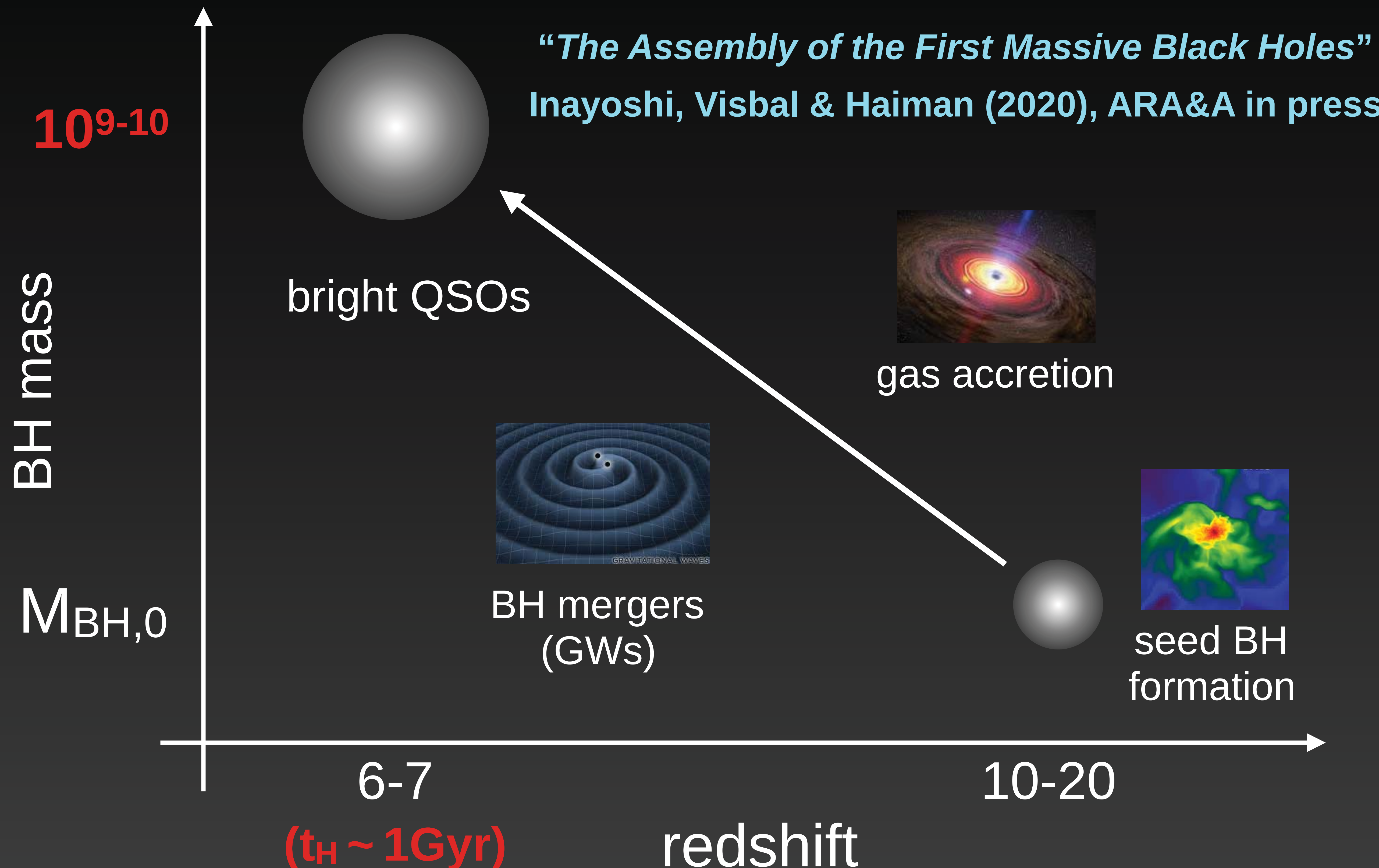


High-redshift monster BHs



$^*\lambda_{Edd}$=1 is assumed for BHs if not mass measurements

Rapid SMBH assembly

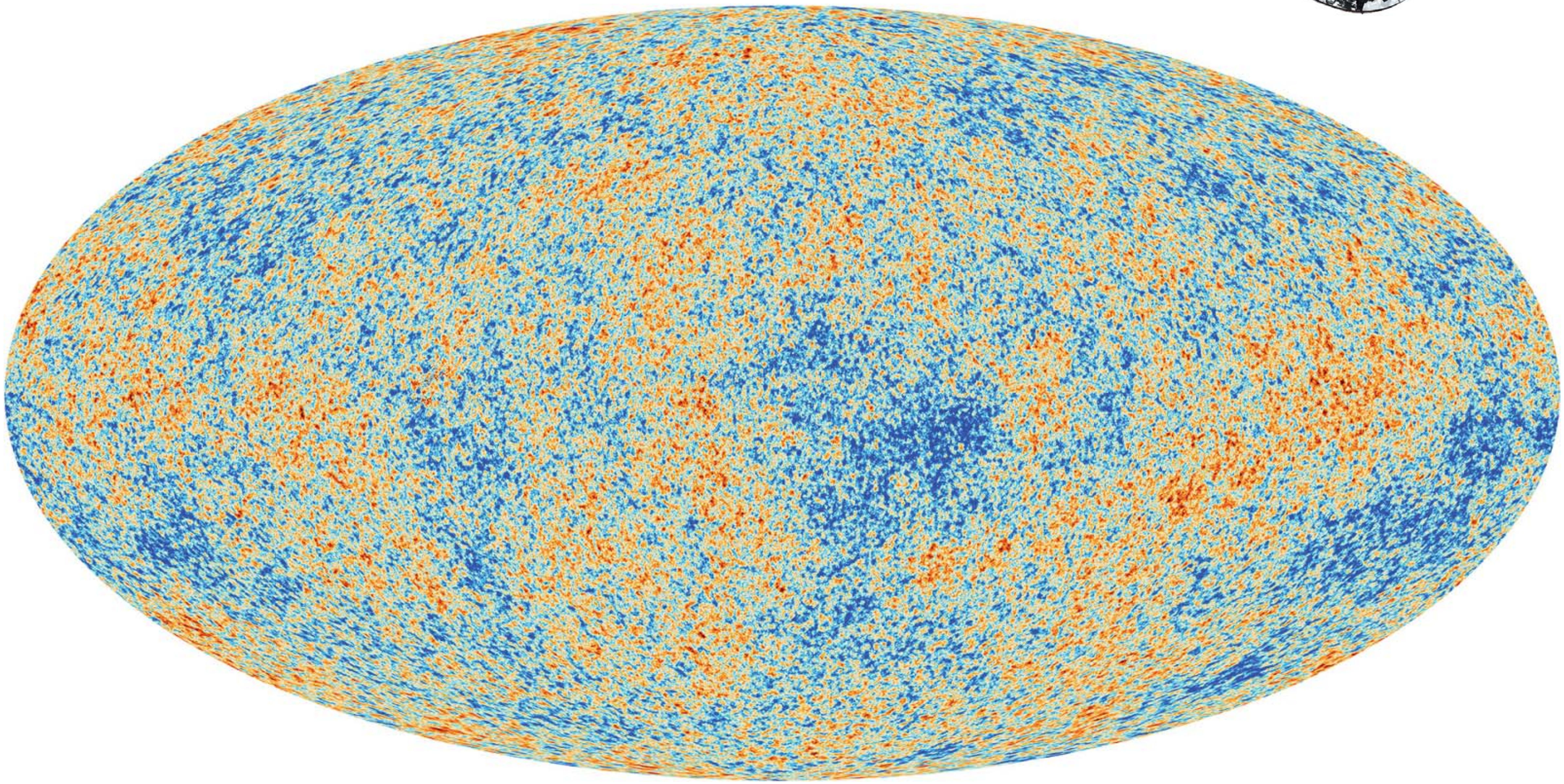


First star formation
(Pop III stars)

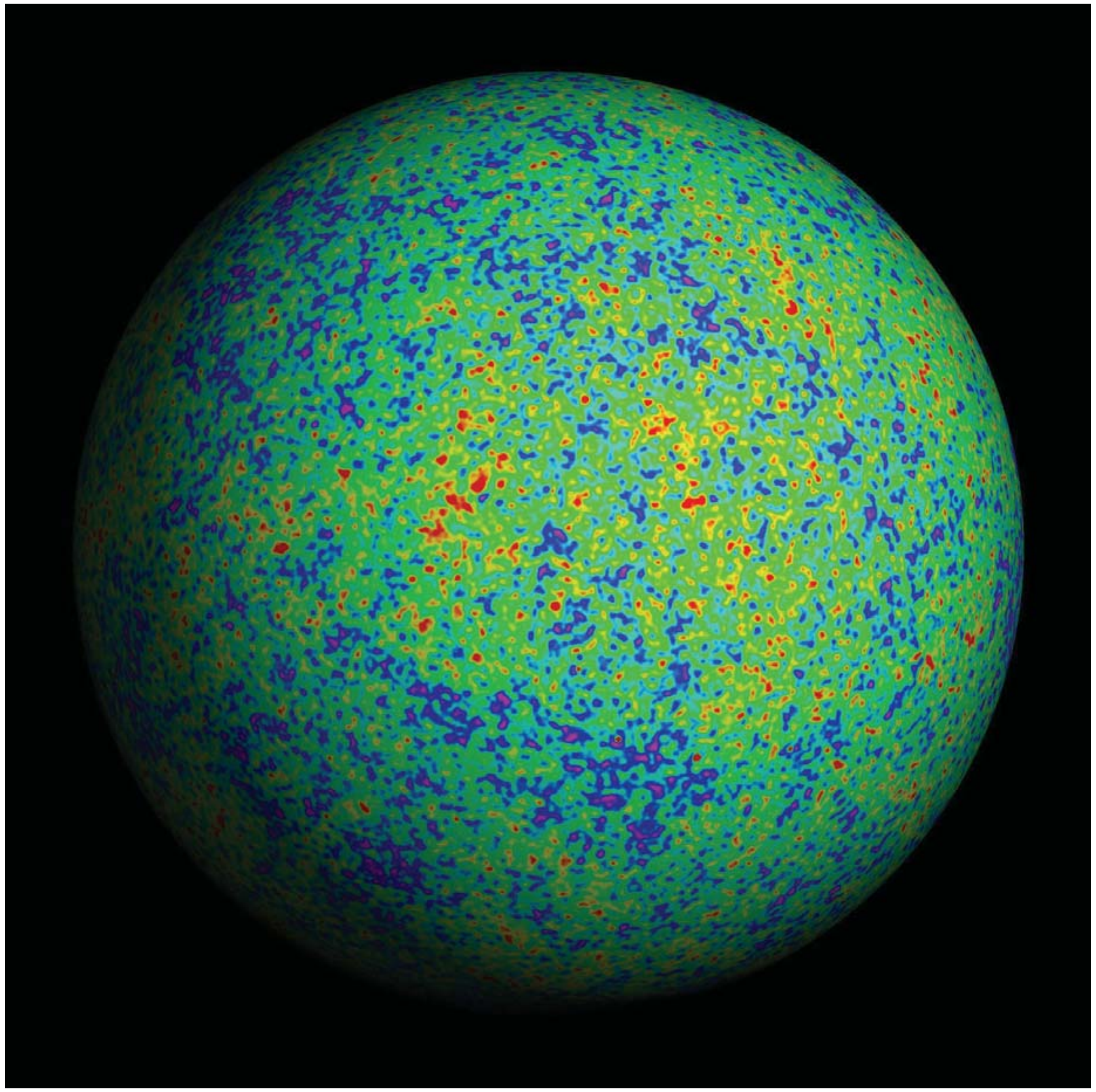
Initial conditions for our universe

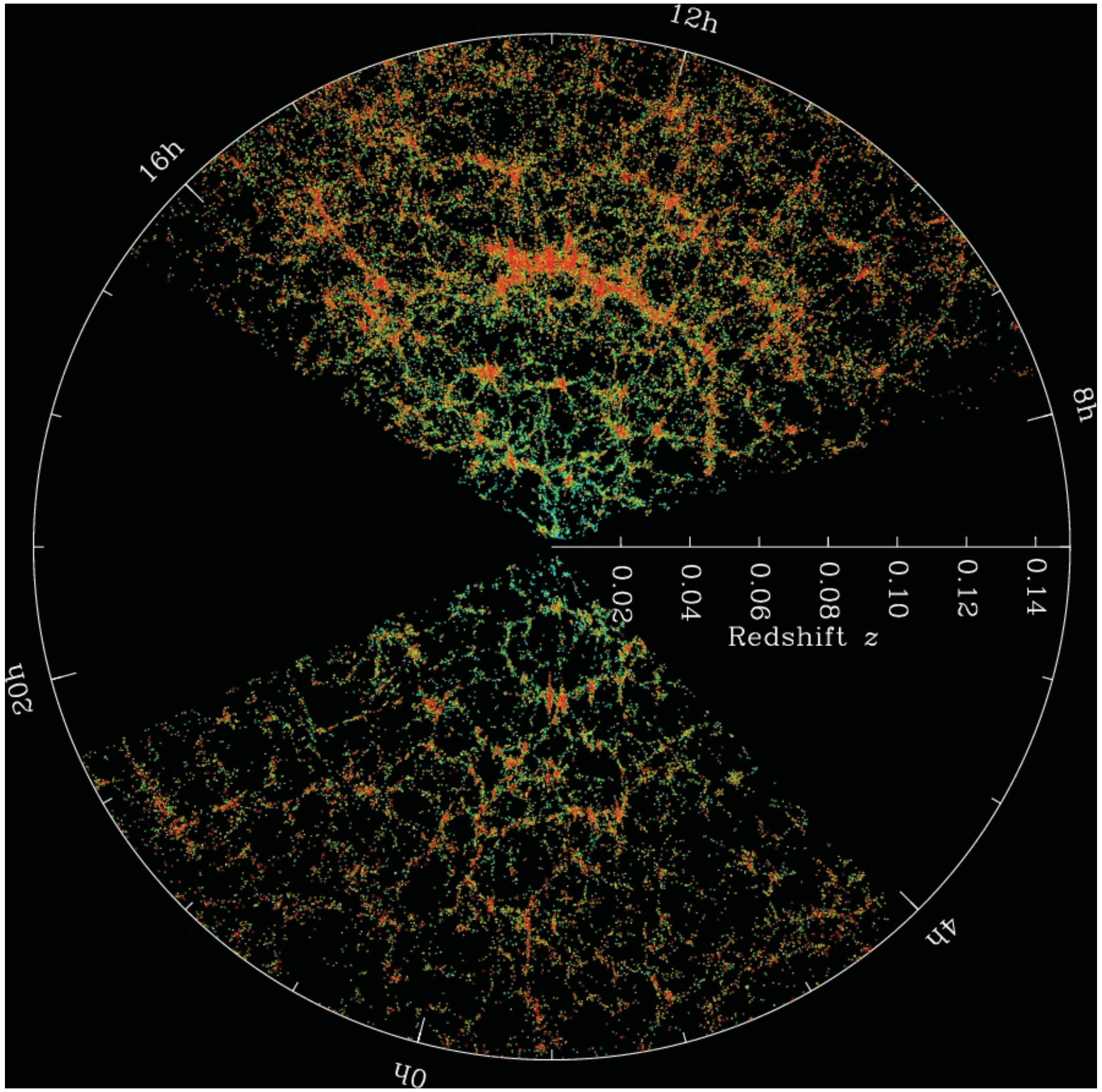
Cosmic Microwave Background (Planck Satellite)

380,000 years after the Big Bang (z=1100)



Formation of large-scale structure

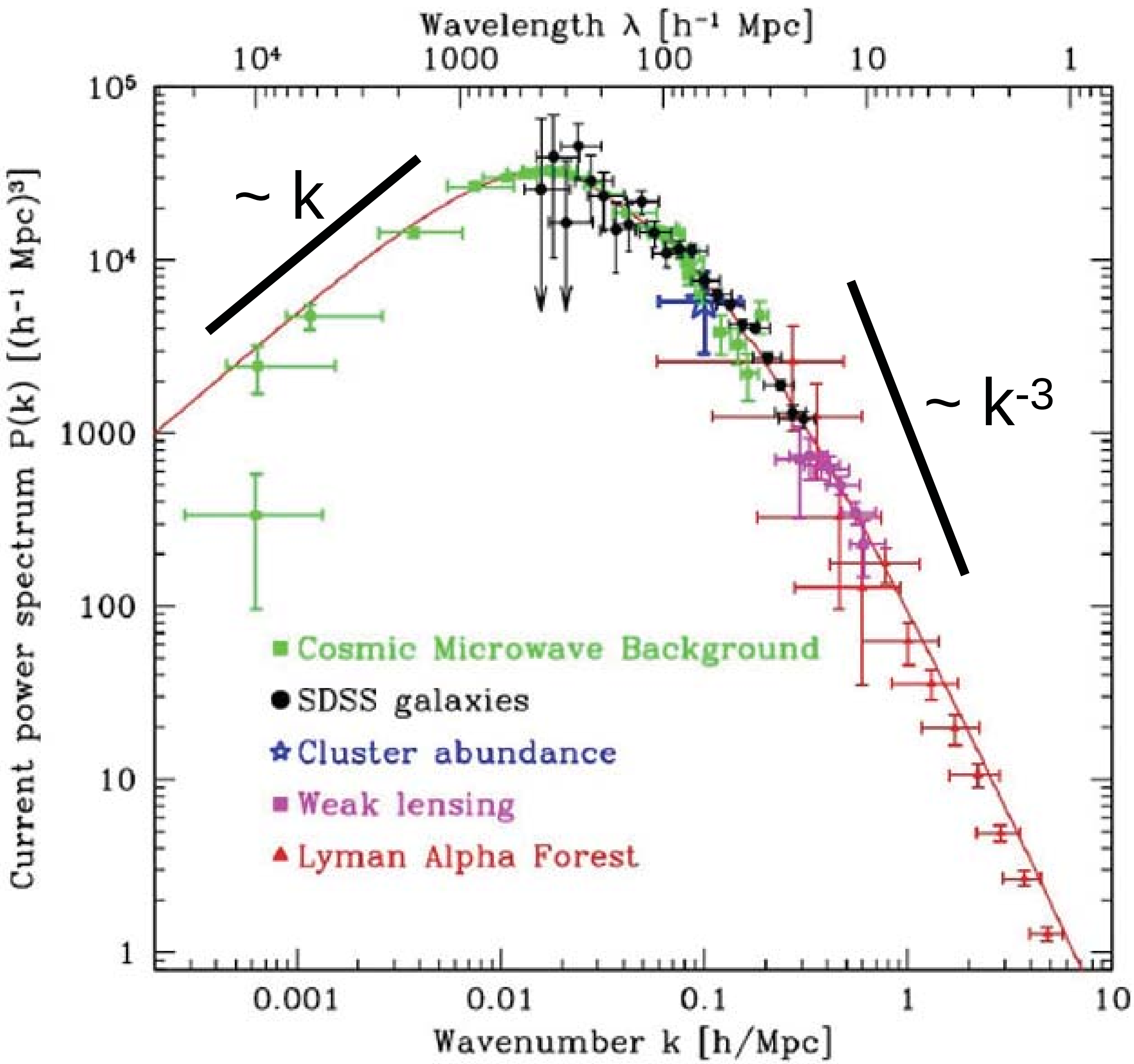


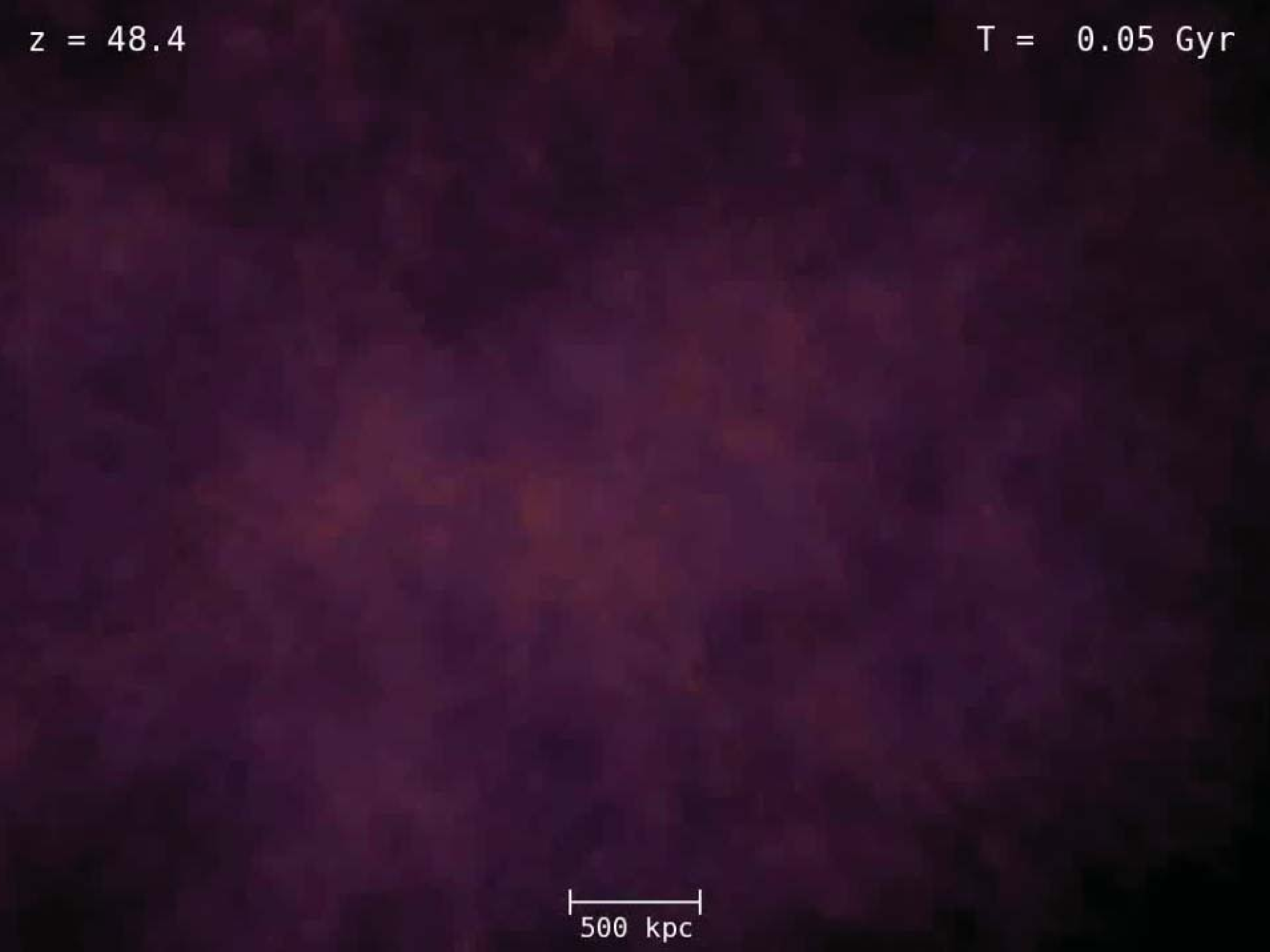


small fluctuation

highly non-linear evolution

Matter power spectrum





z = 48.4
T = 0.05 Gyr
500 kpc

Collapsed objects (DM halos)

- virial radius / temperature

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

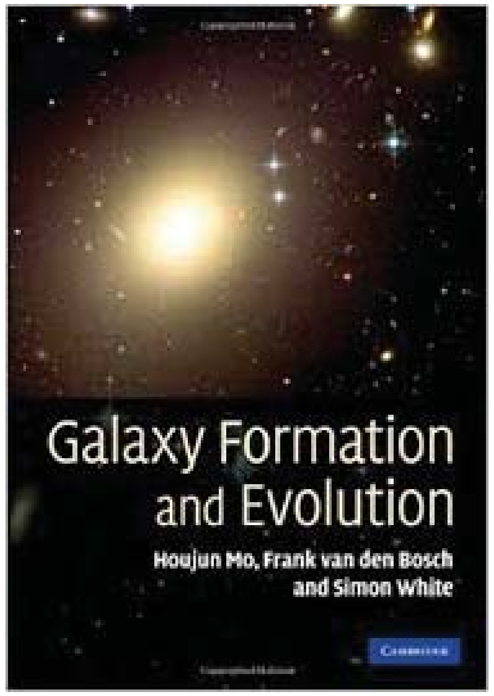
$$T_{\rm vir} = \frac{\mu m_p V_c^2}{2 k_{\rm B}} = 1.98 \times 10^4 \left(\frac{\mu}{0.6} \right) \left(\frac{M}{10^8 h^{-1} M_\odot} \right)^{2/3} \left[\frac{\Omega_m}{\Omega_m^z} \frac{\Delta_c}{18\pi^2} \right]^{1/3} \left(\frac{1+z}{10} \right) \; {\rm K}$$

- mean gas density in a collapsed object

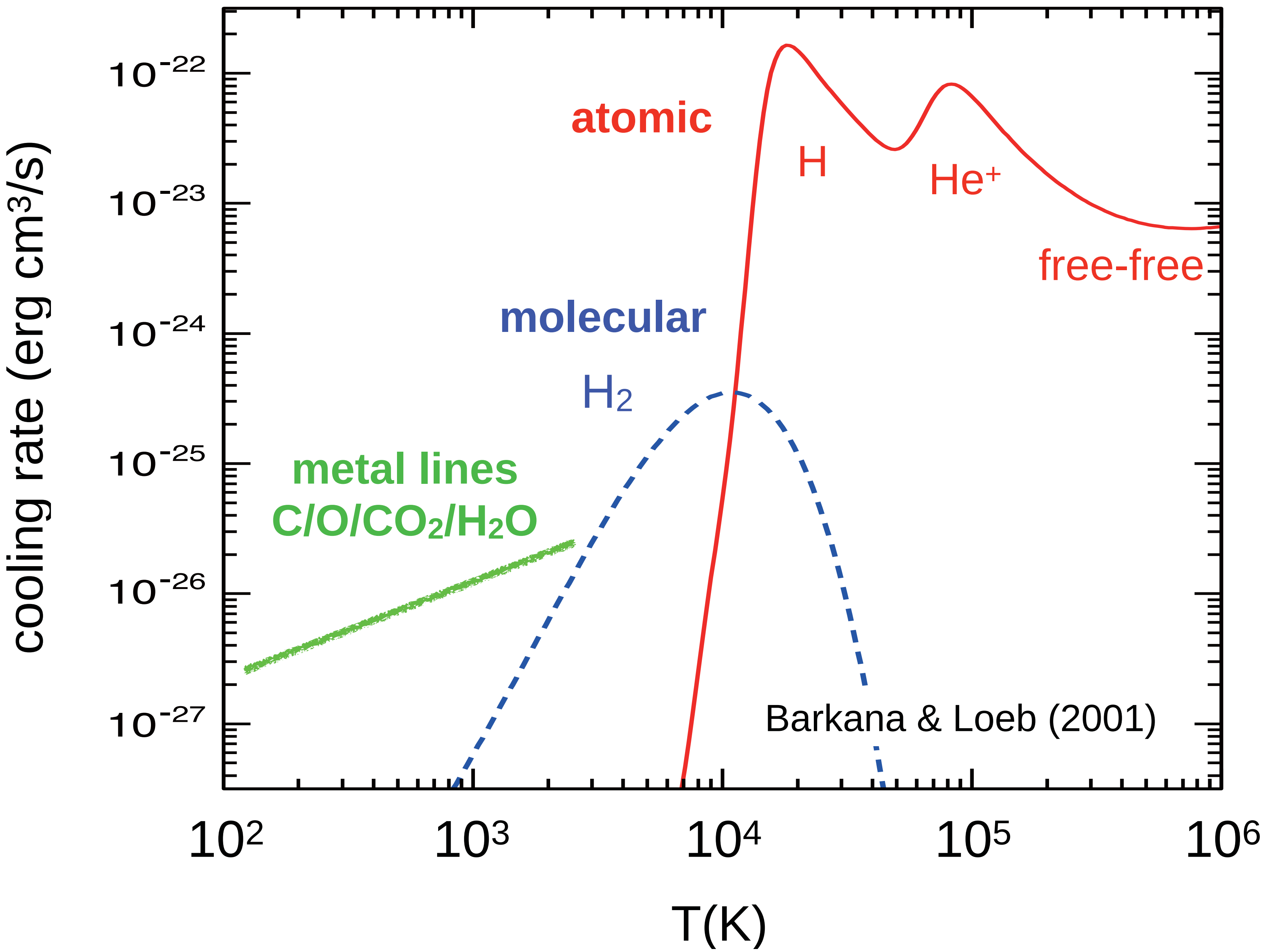
$$\bar{n}_{\rm vir} \simeq \frac{18\pi^2 \rho_{\rm crit} \Omega_{\rm b} (1+z)^3}{m_{\rm p}} \simeq 0.05 \;{\rm cm}^{-3} \left(\frac{1+z}{10} \right)^3$$

<< $10^3\ {\rm cm}^{-3}$ star formation

radiative cooling !



Radiative cooling



Galaxy / star formation: $t_{cool} < t_H$

(Rees & Ostriker 1977)

H_2 formation processes

- H_2 formation in ISM occurs on dust

- the electron-catalyzed reaction in metal-free gas

$$\left\{\begin{array}{l} \mathrm{H} + \mathrm{e}^- \rightarrow \mathrm{H}^- + \gamma \\ \mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{e}^- \end{array}\right.$$

H^- process (low density)

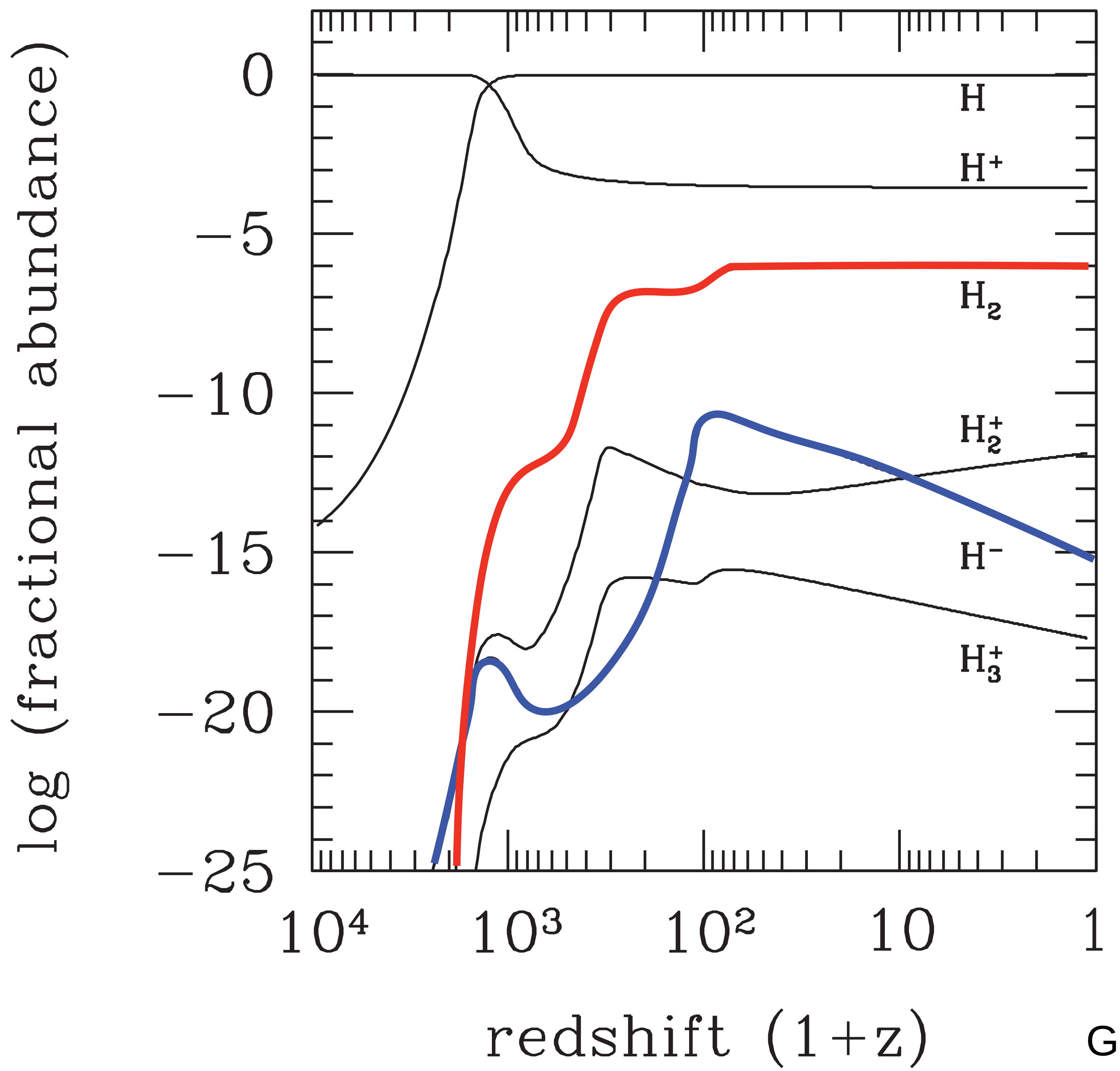
note: no dipole moment

- 3-body interaction

$$3\mathrm{H} \rightarrow \mathrm{H}_2 + \mathrm{H}$$

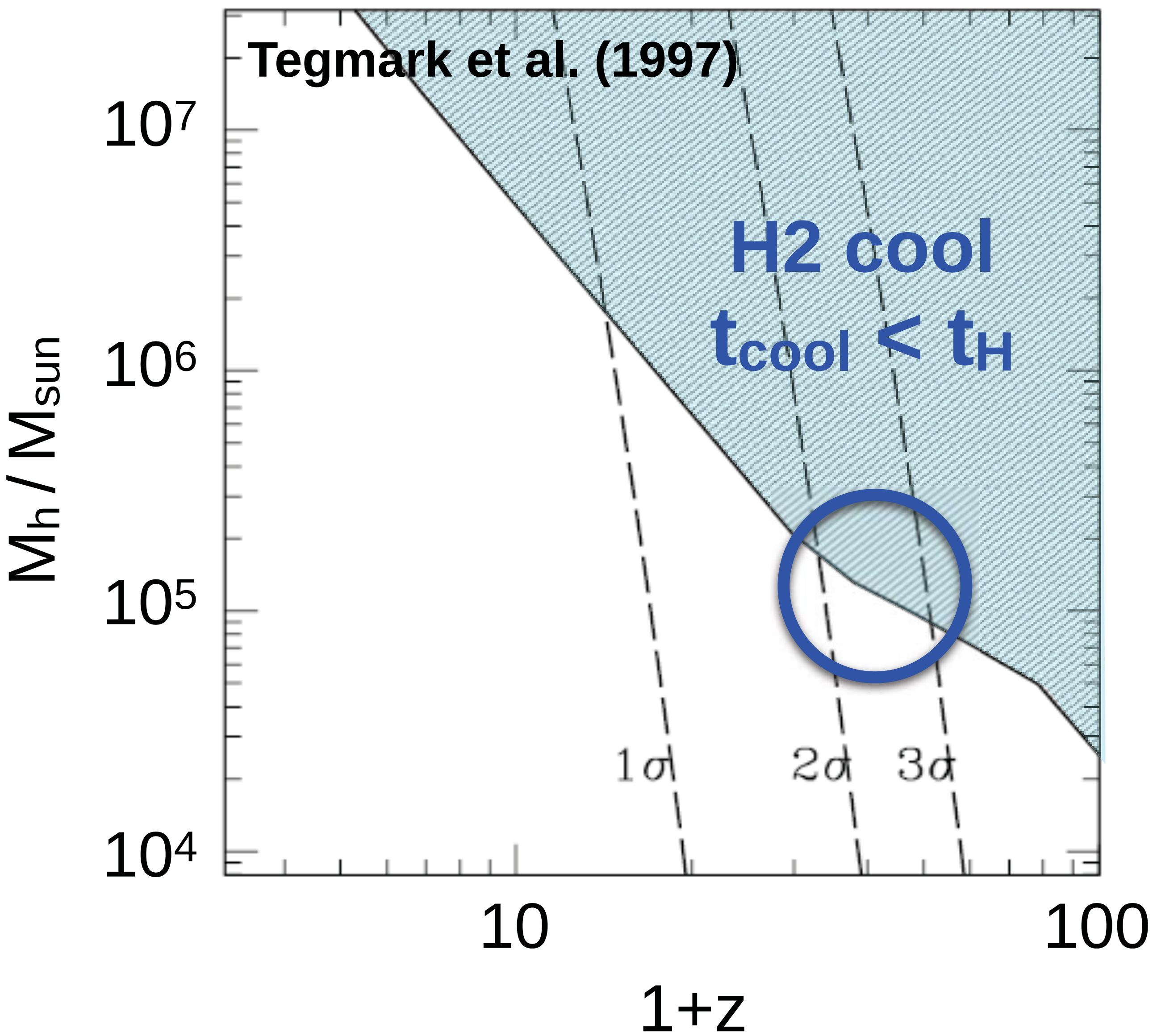
(high density; $n>10^8$ cm^{-3})

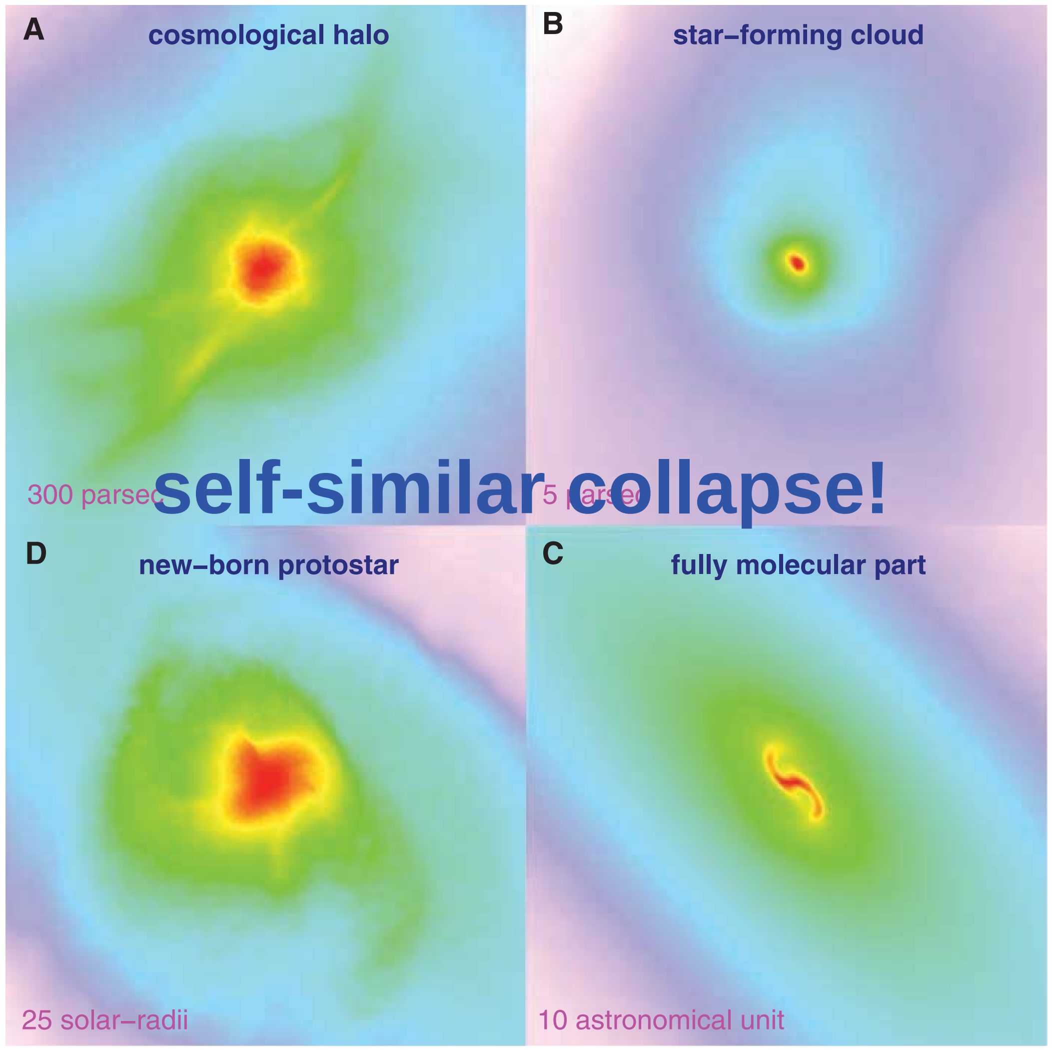
H_2 formation processes



Galli & Palla (1998)

First star formation (Z=0)



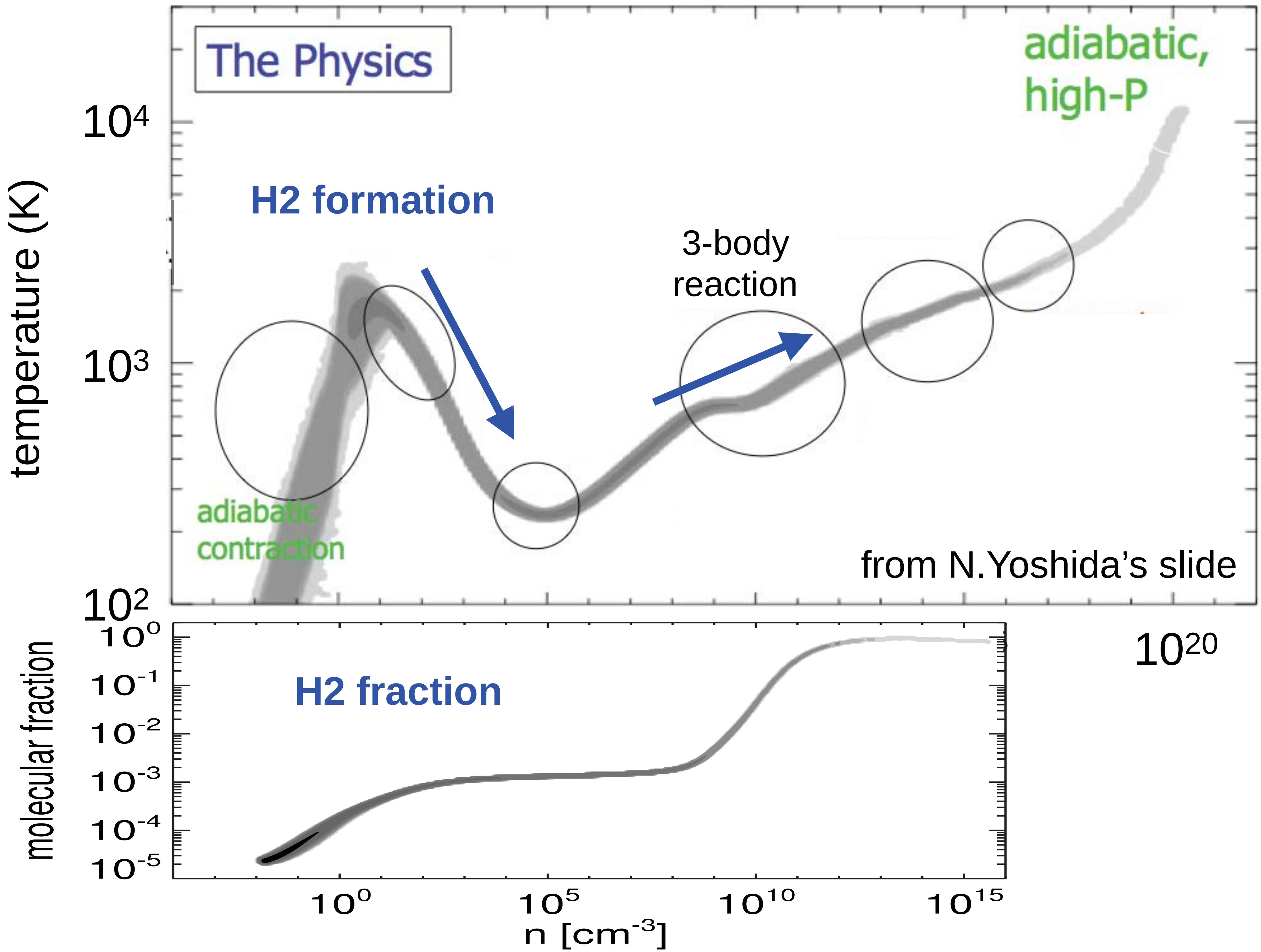


Yoshida et al. (2008)

Gravitational collapse of **metal-free** gas:

$$\mathbf{M_{cool} \sim 10^5\, M_{sun} \text{ at } z{\sim}30}$$

Star formation with H2



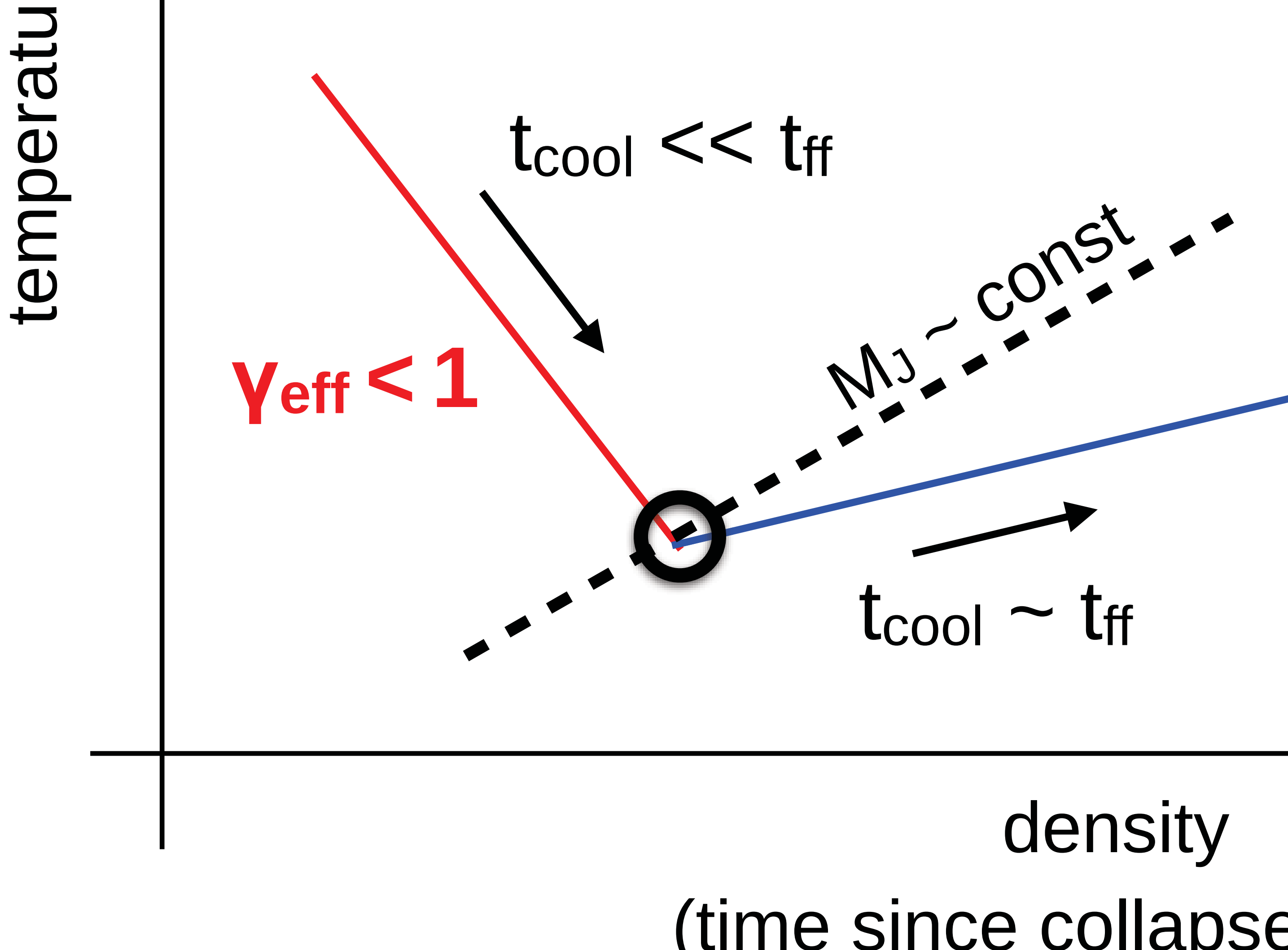
Gas fragmentation

Equation of state:

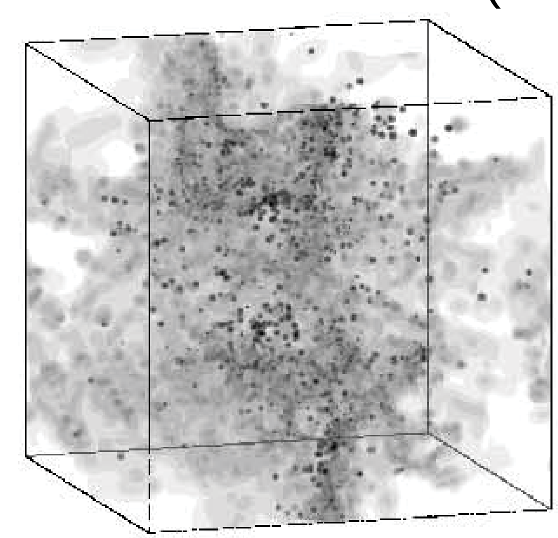
$$p \propto \rho^{\gamma_{\rm eff}} \longleftrightarrow T \propto \rho^{\gamma_{\rm eff}-1}$$

fragment's size and mass

$$\boxed{\begin{array}{c} \lambda_{\rm J} \sim c_{\rm s} t_{\rm ff} \\ M_{\rm J} \sim \rho \lambda_{\rm J}^3 \propto T^{3/2} \rho^{-1/2} \end{array}}$$

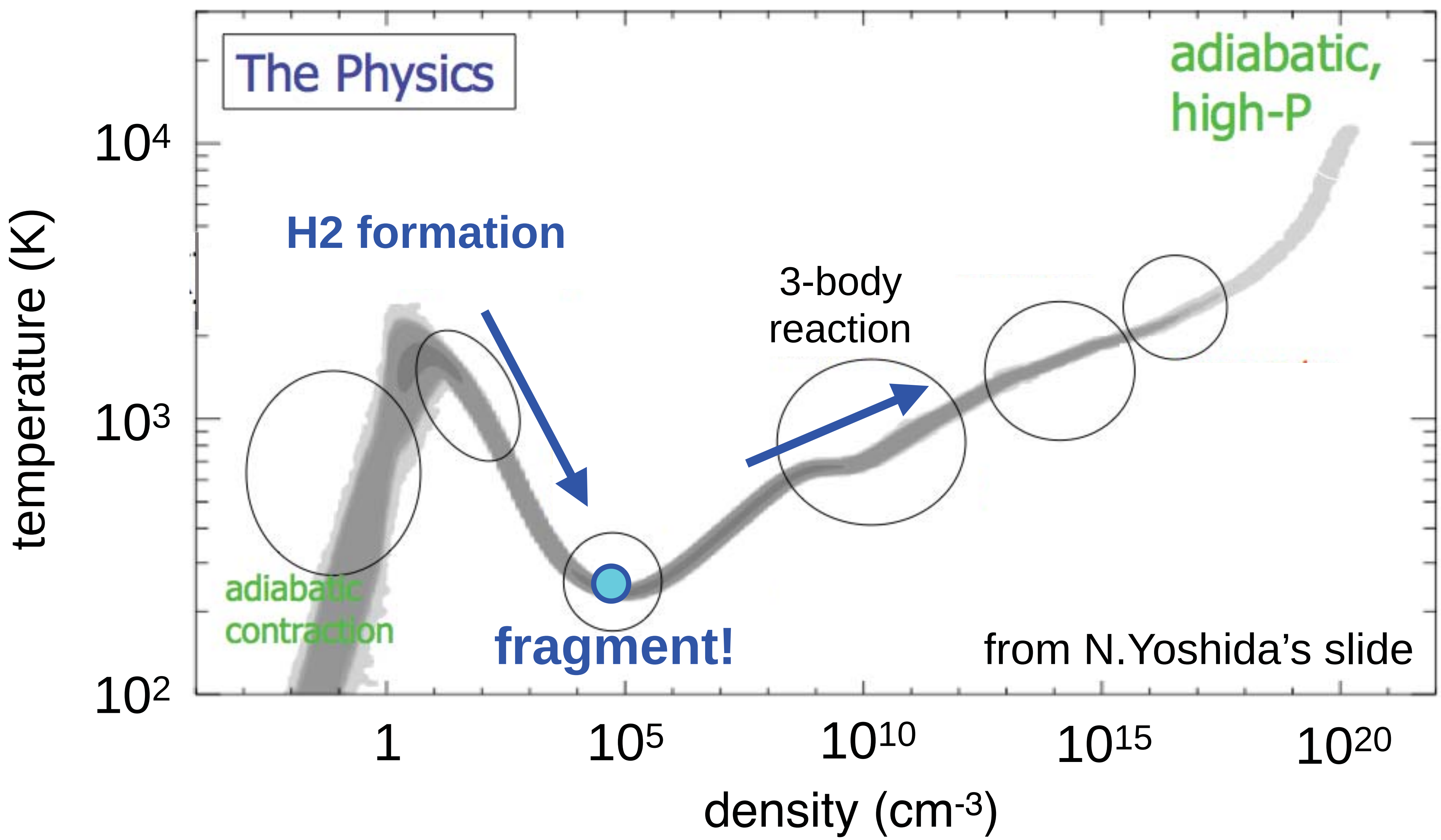


Li, Klessen & MacLow (2003)



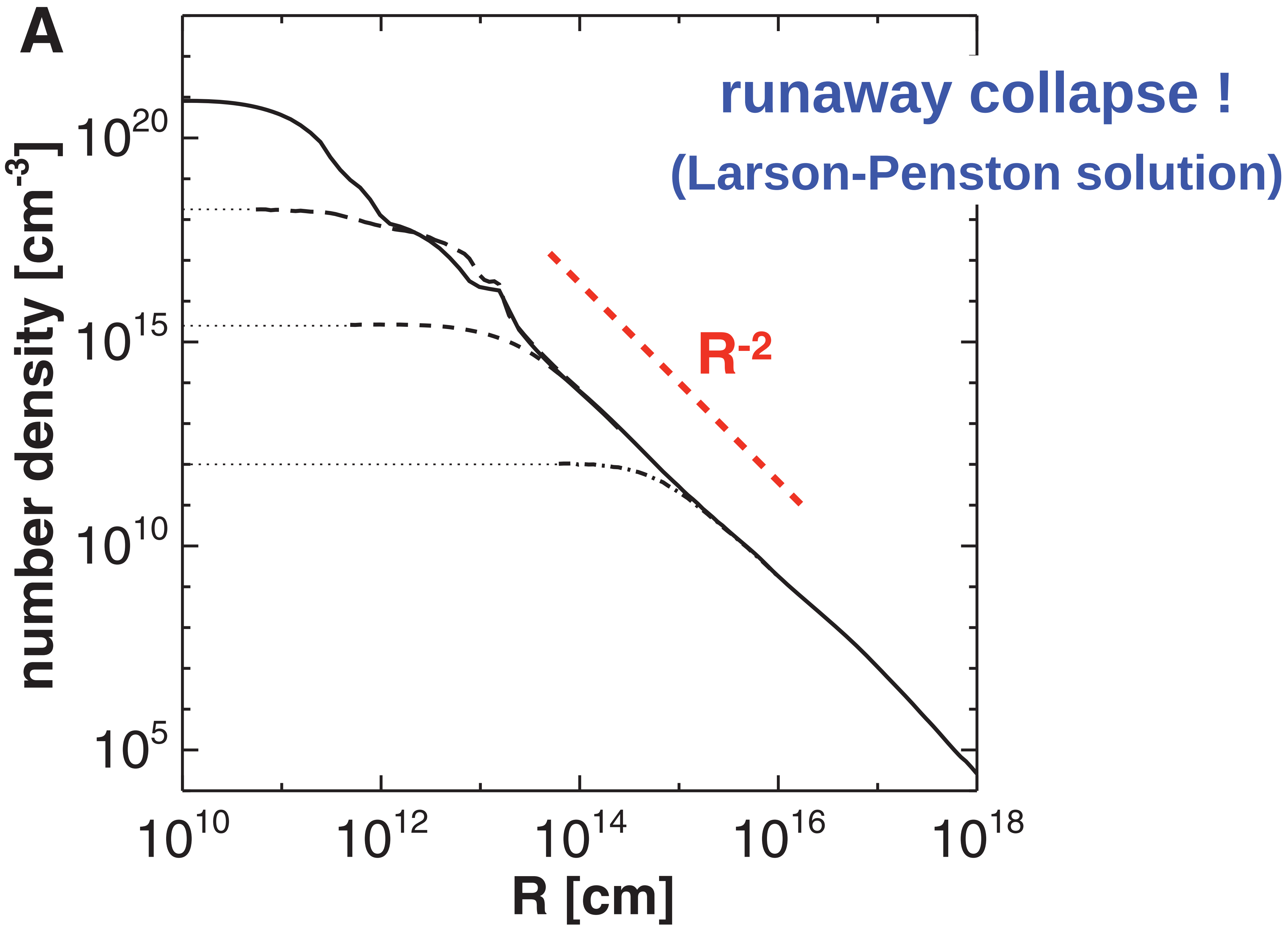
$\gamma_{\rm eff}<1$

Star formation with H2



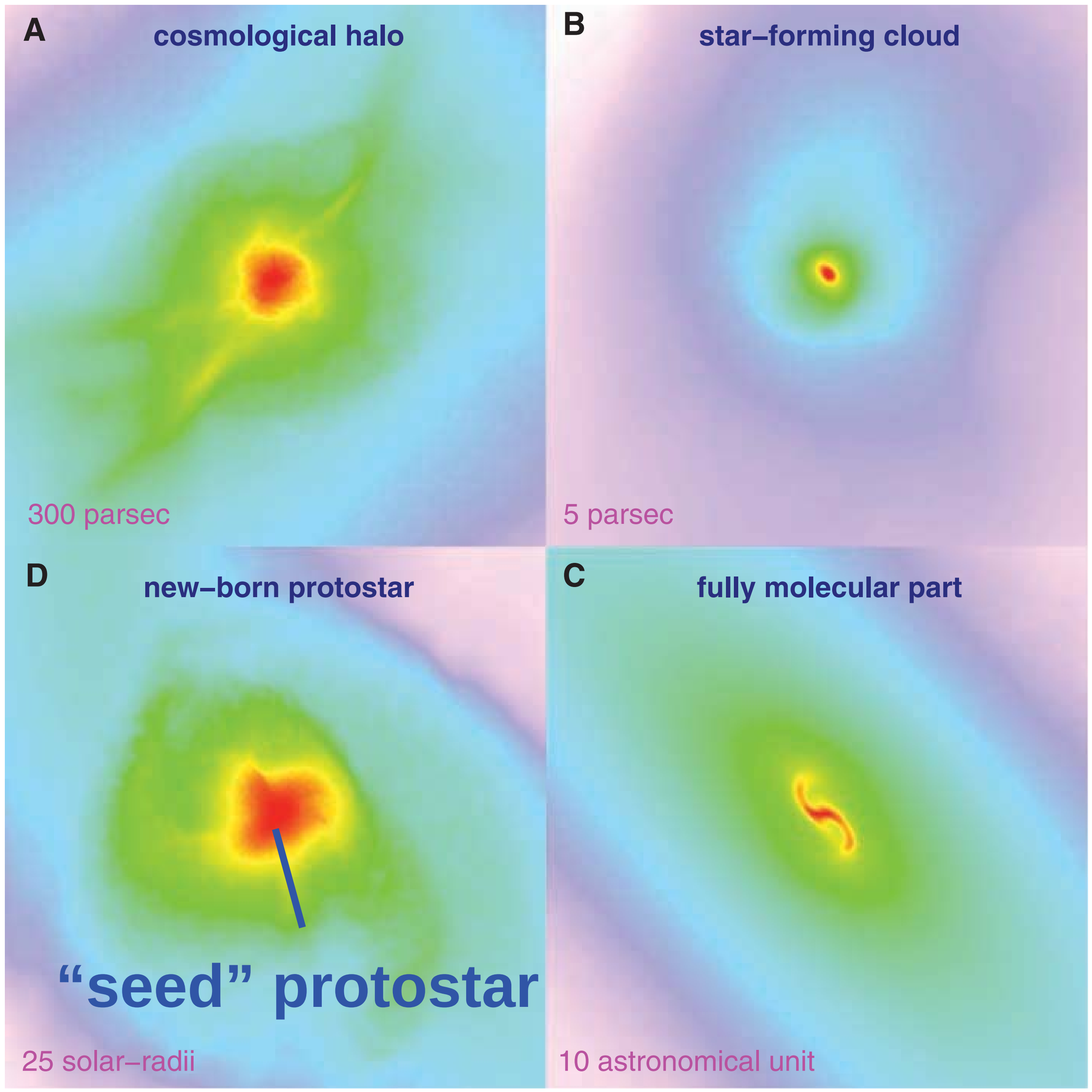
$M_{\rm J} \sim 10^3 \ M_\odot$ ⇨ massive stars!

Collapsing gas profile



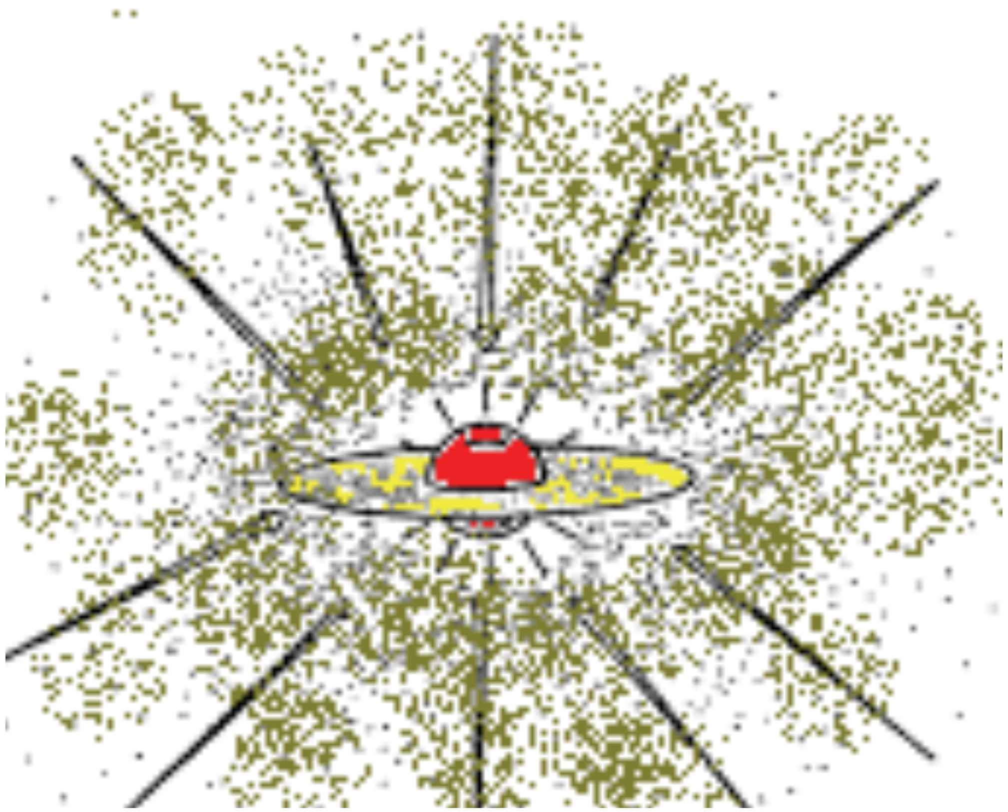
Dynamics of collapsing/accreting gas

early collapse stage



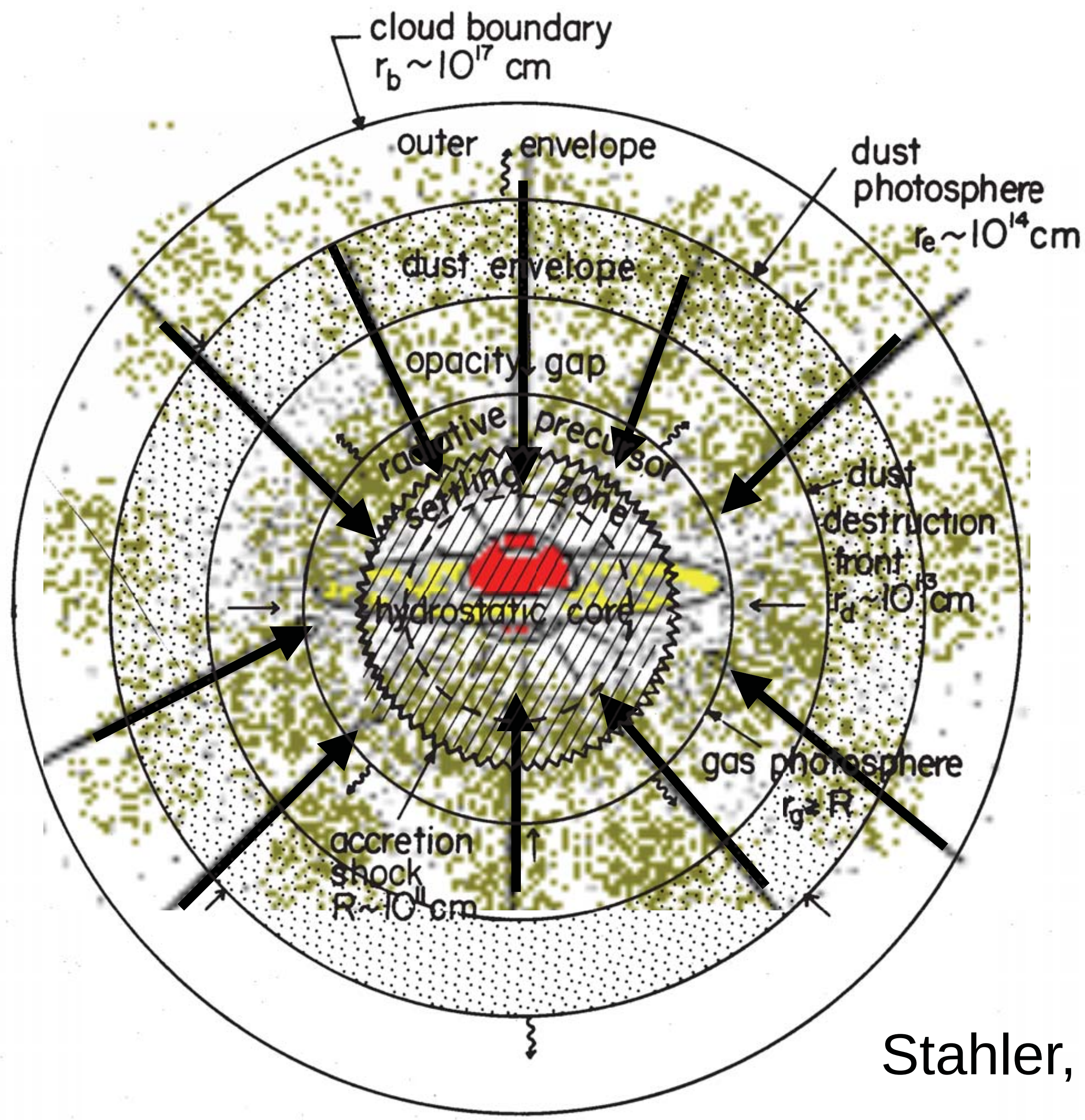
Yoshida et al. (2008)

late accretion stage



final stellar mass will be determined in the phase

Protostellar accretion (PopIII)

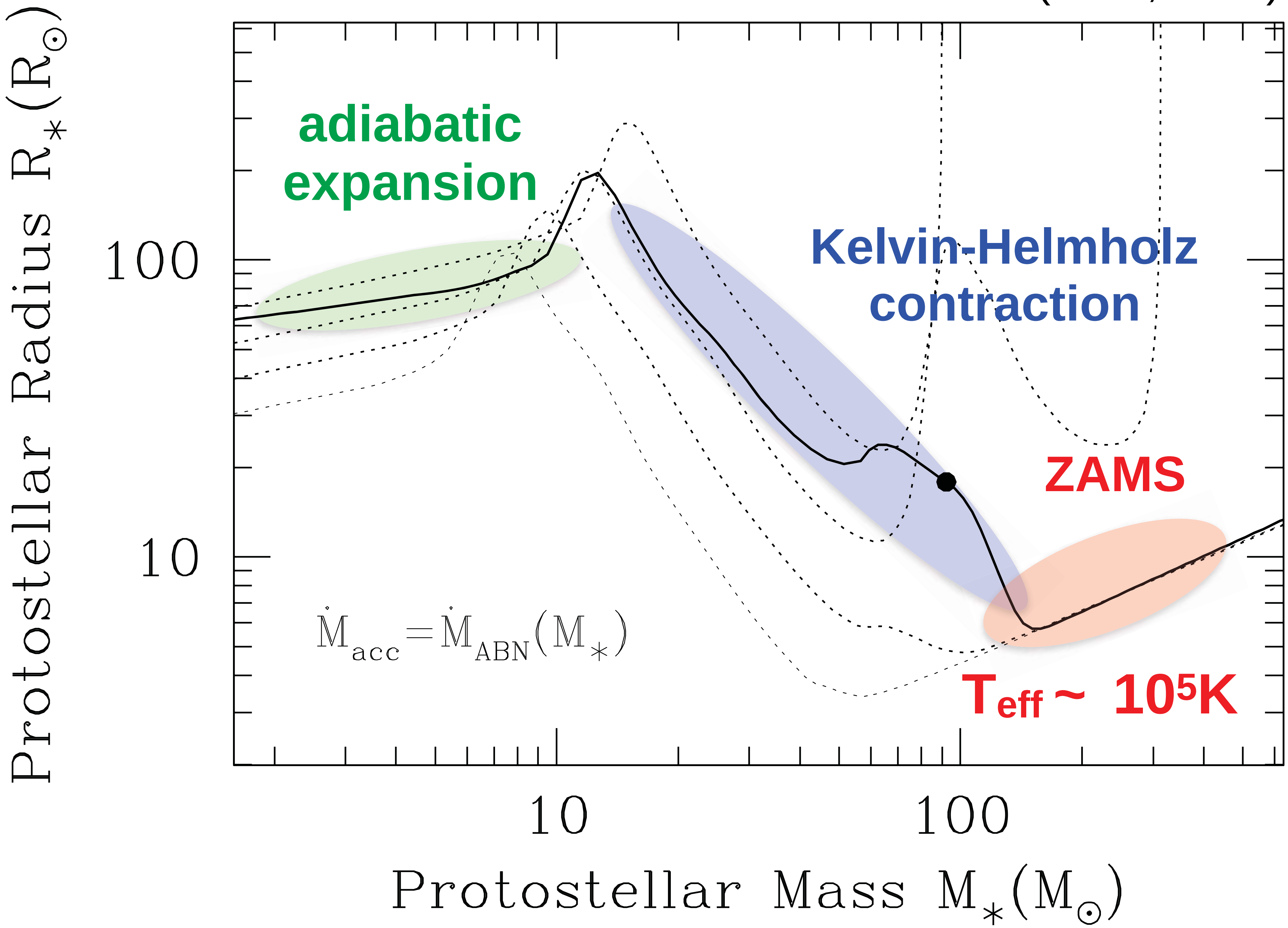


Stahler, Shu & Taam (1980)

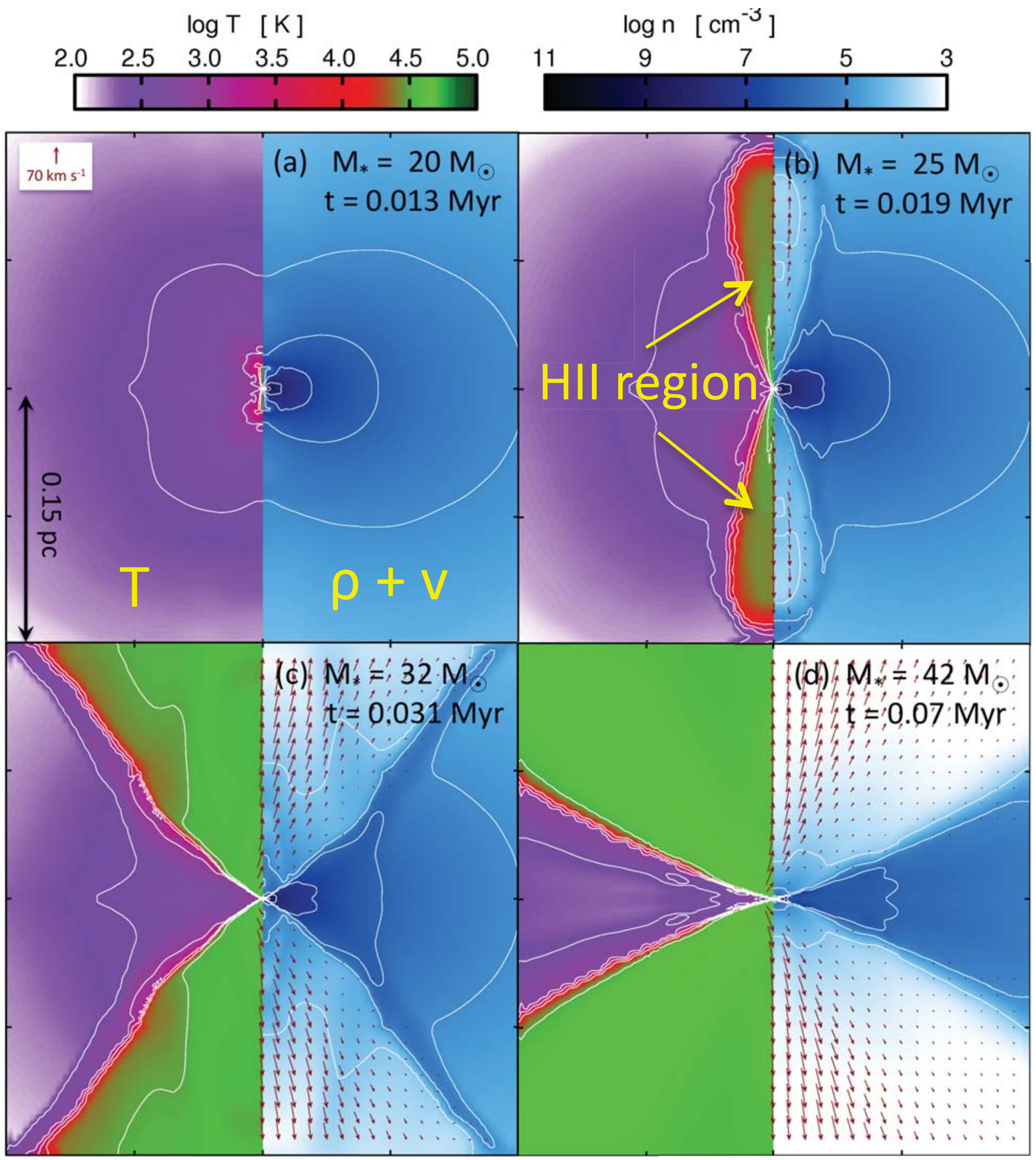
$$\dot{M}_\star \sim \frac{M_\mathrm{J}}{t_\mathrm{ff}} \sim \frac{c_\mathrm{s}^3}{G} \propto T^{3/2} \sim \mathbf{10^{-3}}\ M_\odot \mathrm{yr}^{-1}$$

Protostellar accretion (PopIII)

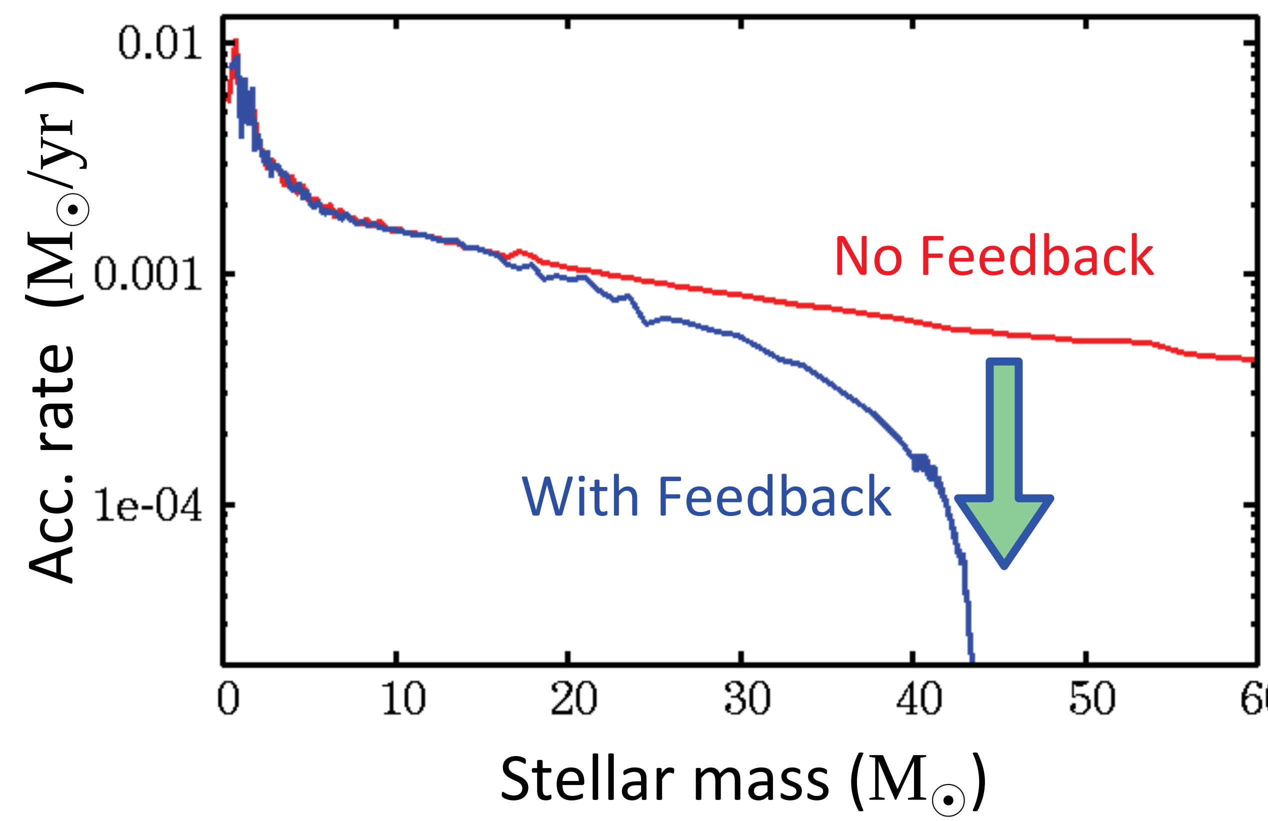
Omukai & Palla (2001, 2003)



Stellar evolution + RHD

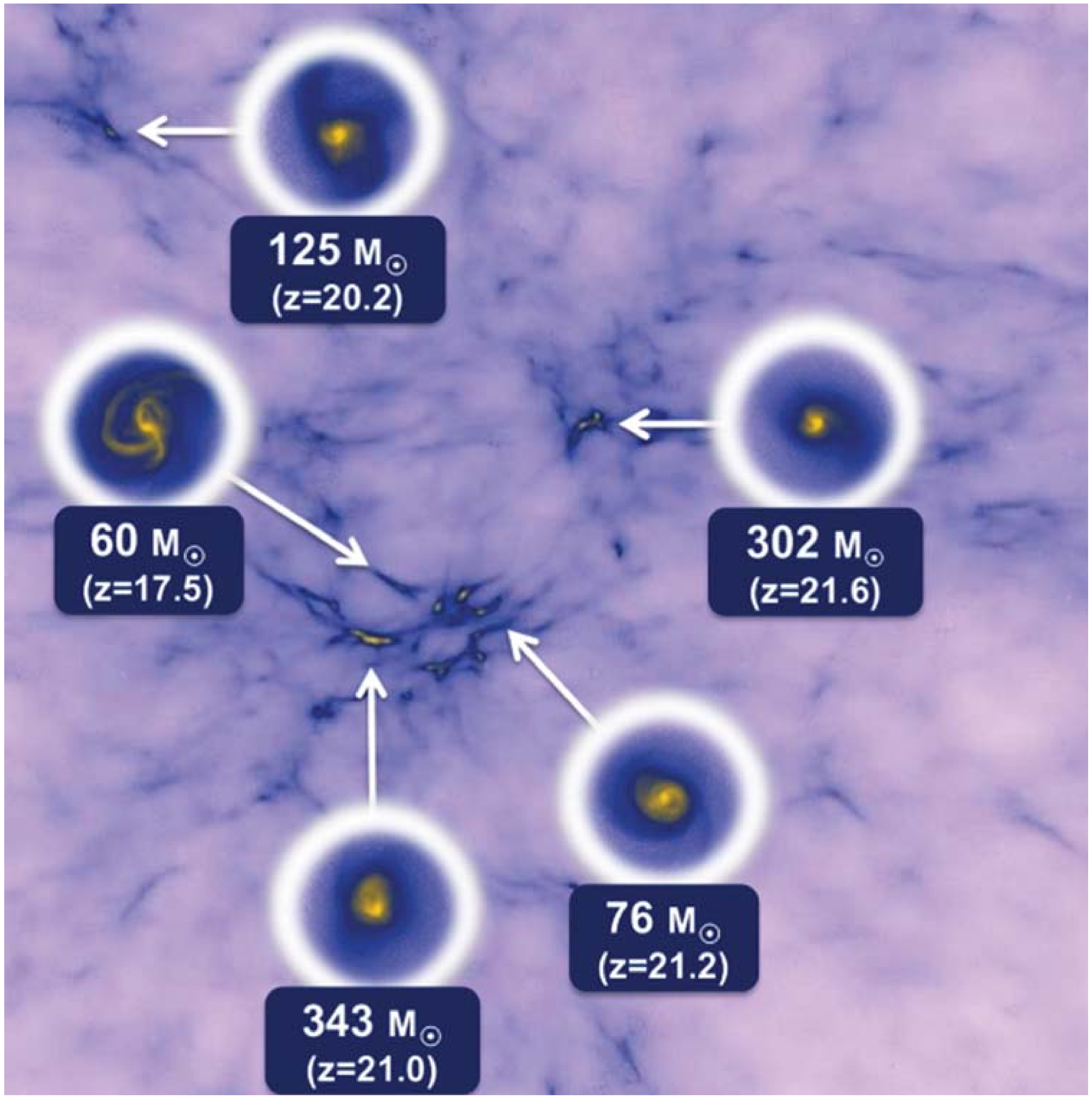


Hosokawa et al. (2011), see also
Stacy et al. (2012), McKee & Tan (2008)

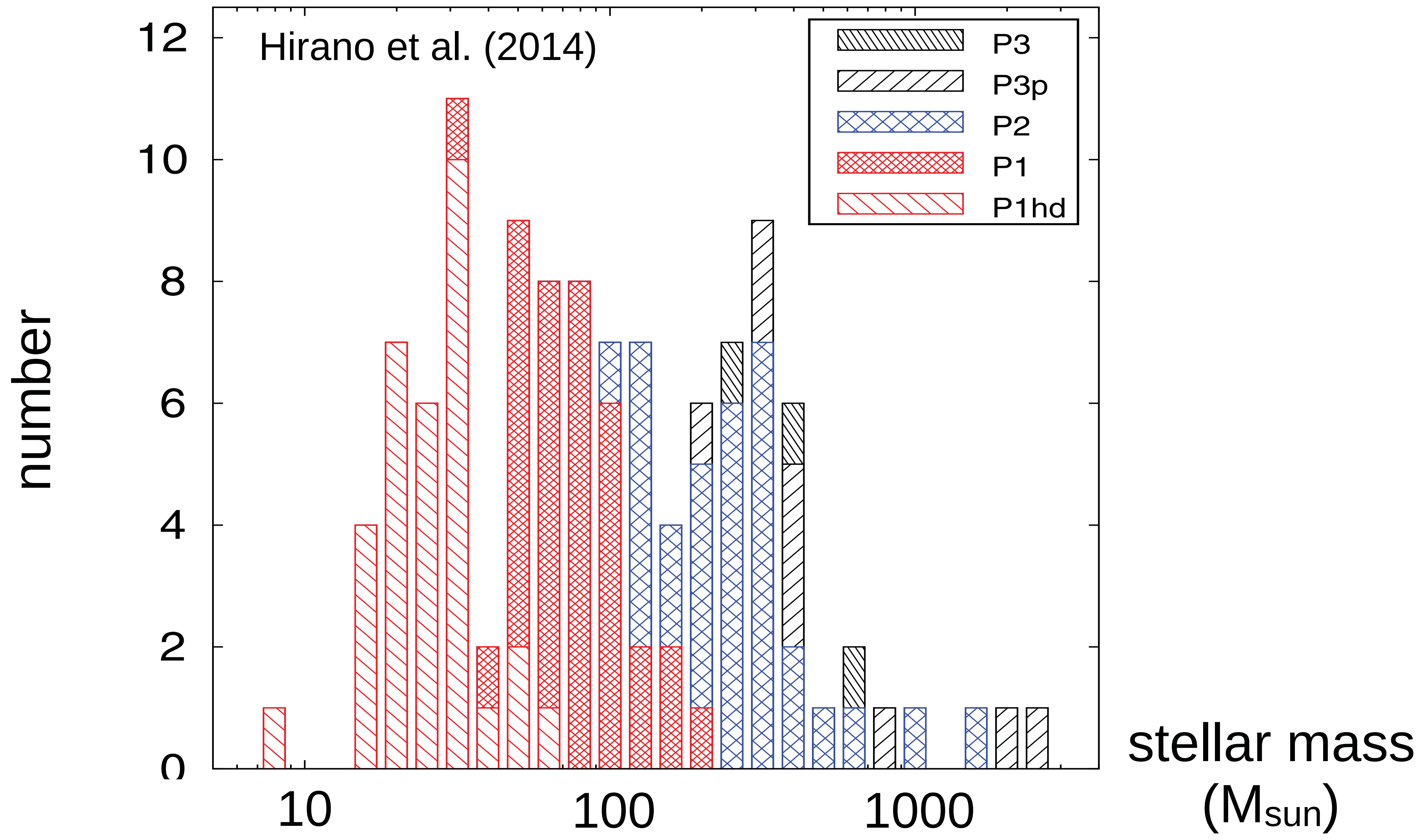


Radiative heating (UV rad.) shuts off stellar growth

100 PopIII calculations…



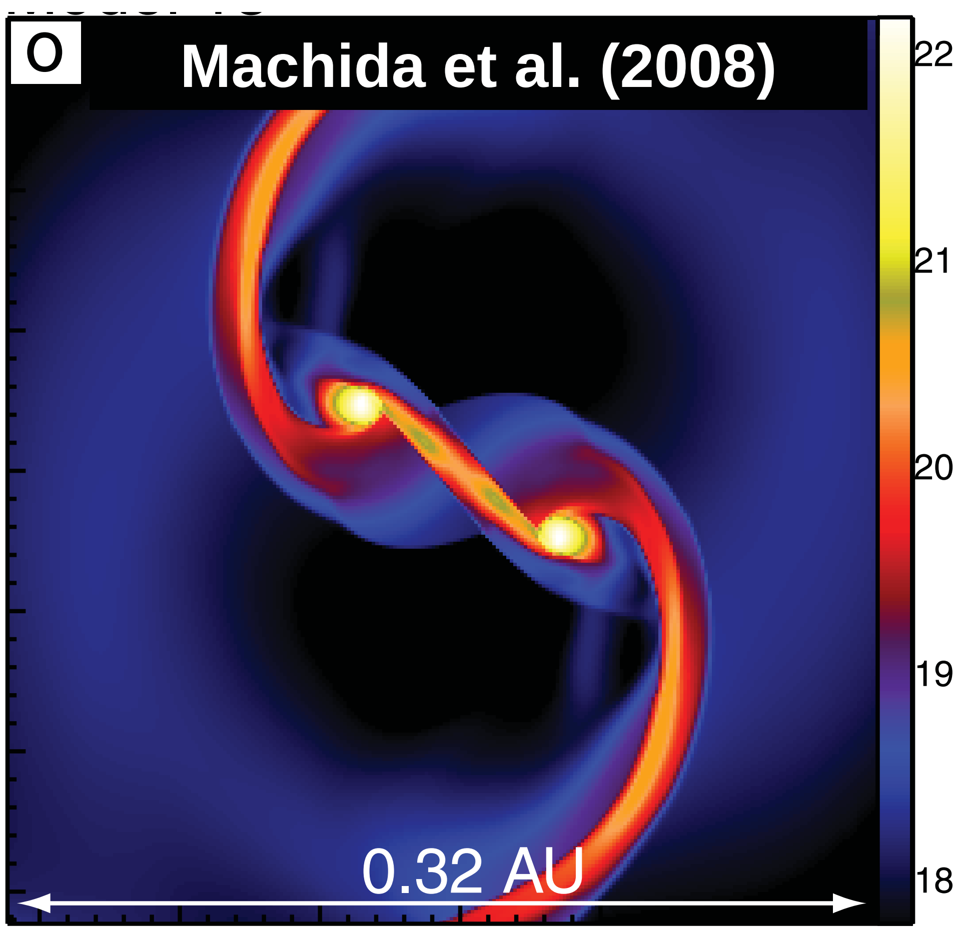
PopIII stellar IMF

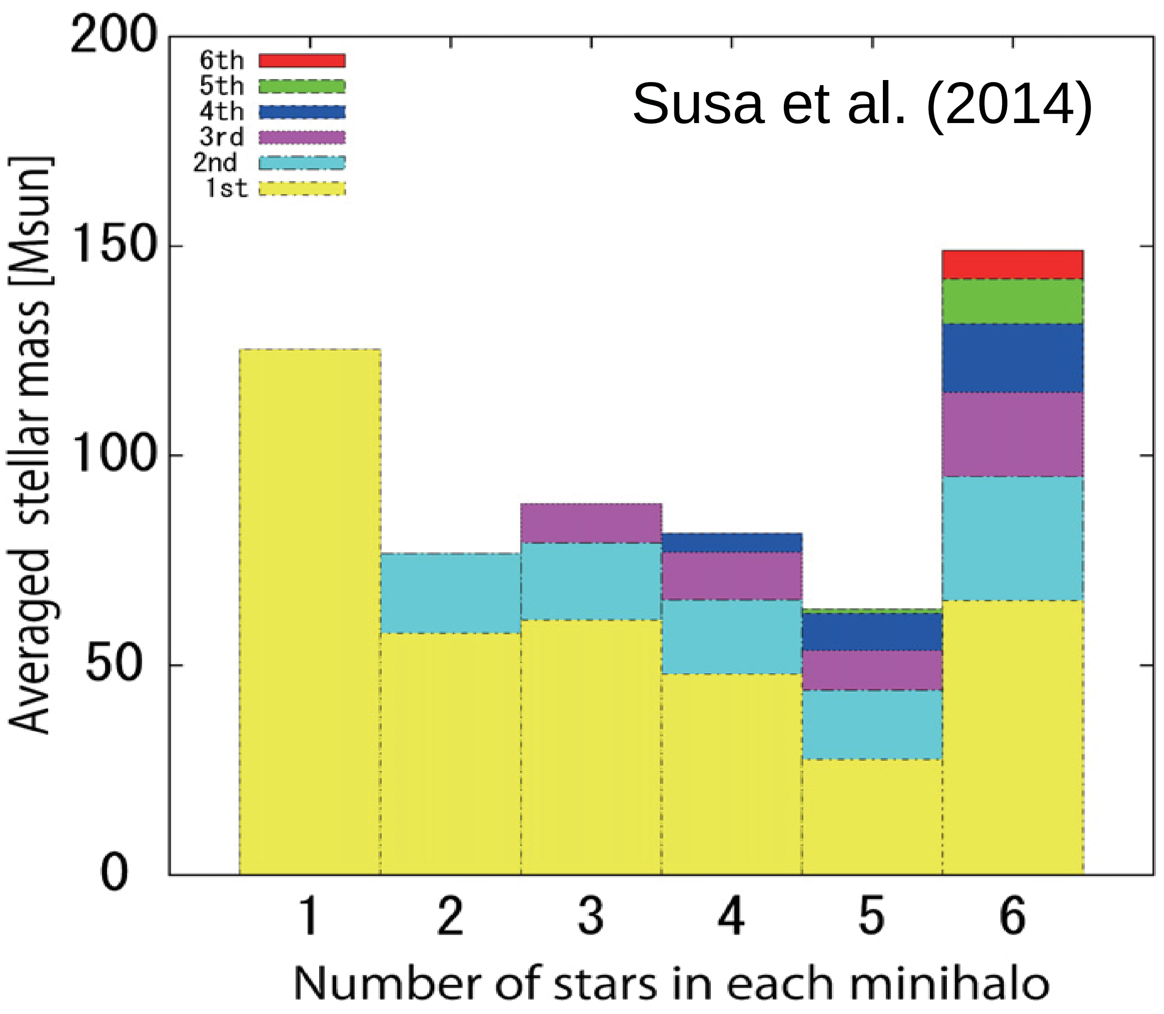


PopIII IMF : **top-heavy** (~100M_{sun})

PopIII binary formation

Turk et al. (2009); Stacy et al. (2013,2016), Susa et al. (2013), Hosokawa et al. (2016)



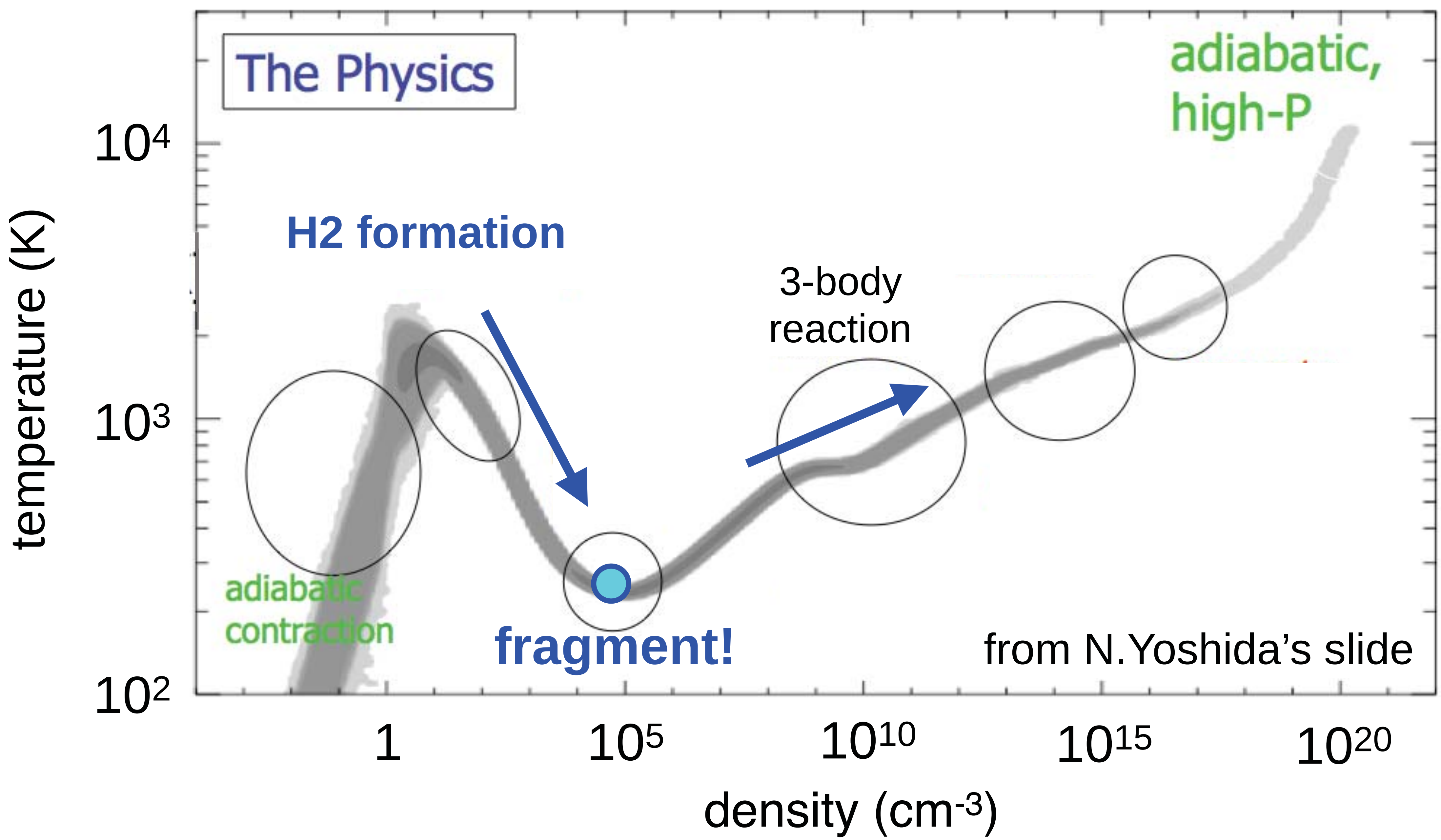


- Binary formation due to disk fragmentation
- high binary fraction (f_{bin}~60% @MW)

Formation of massive BH seeds

(special situations of Pop III formation)

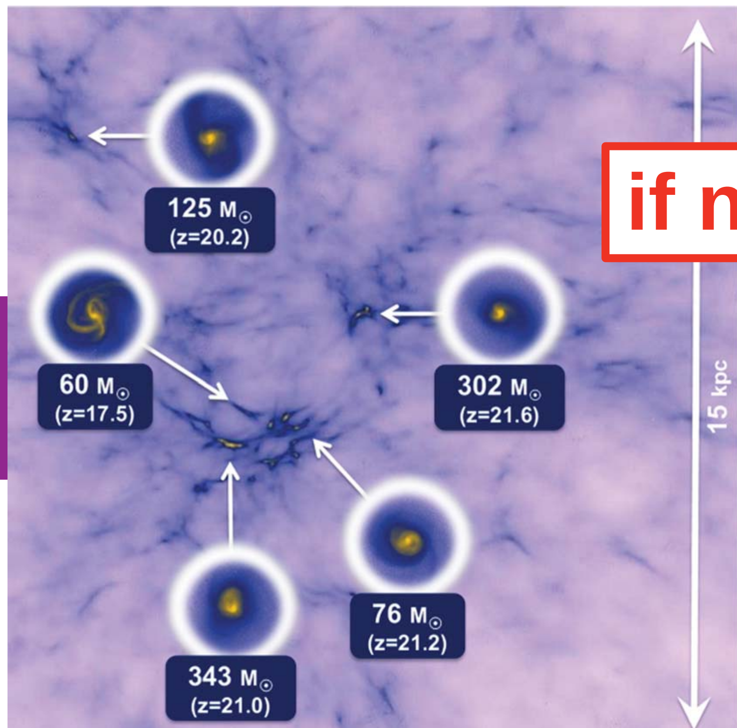
Star formation with H2



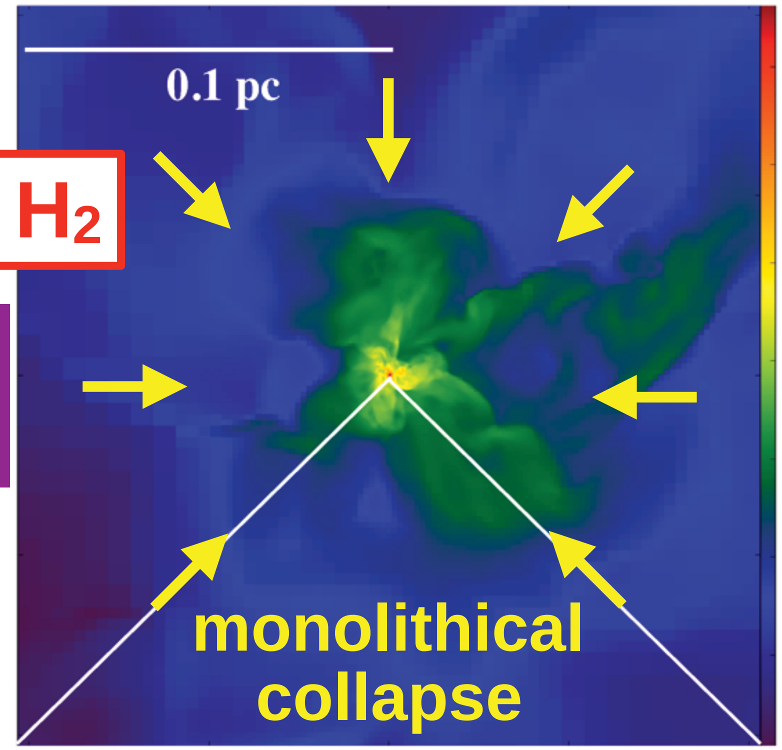
PopIII stars: massive but $\mathbf{M_{*}<10^{3}\,M_{sun}}$

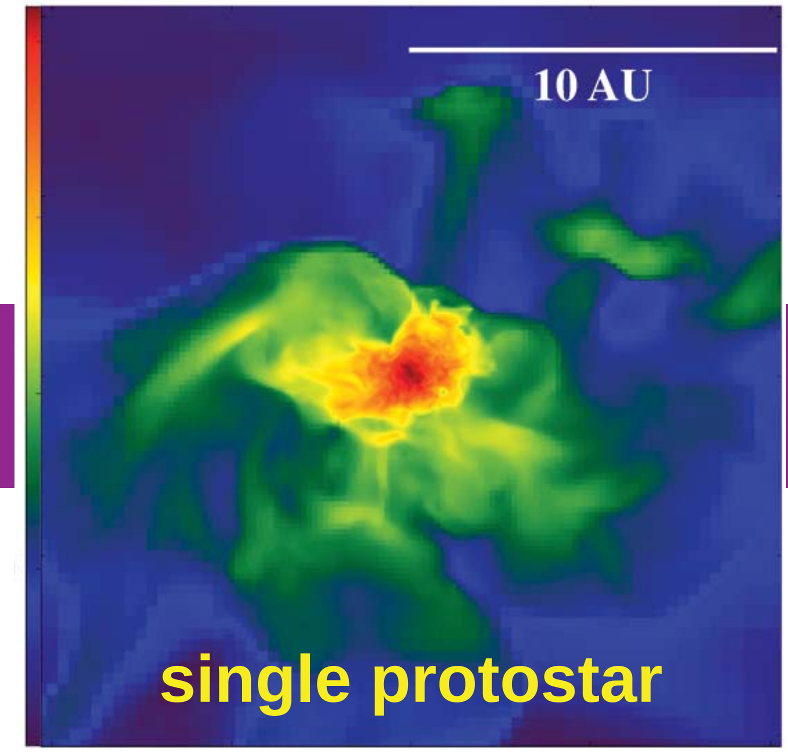
High-z star formation

cosmological scales



if no H_2





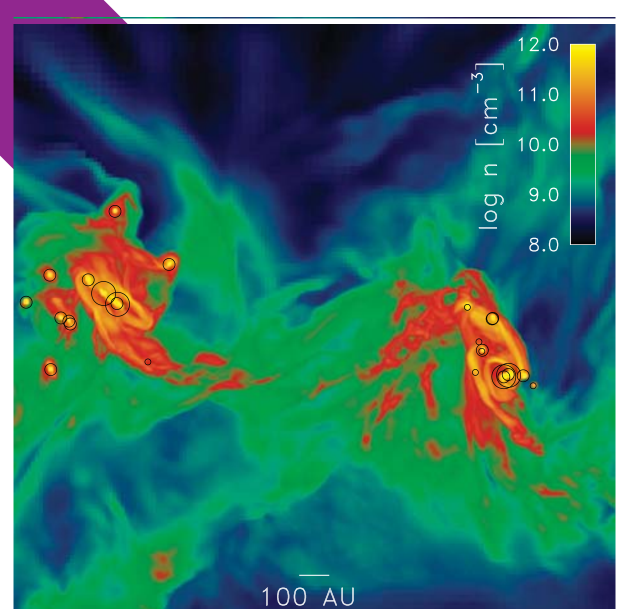
H cooling
~10^4K

no fragment

normally…

H_2 cooling
~$10^{2\text{-}3}$ K

fragment



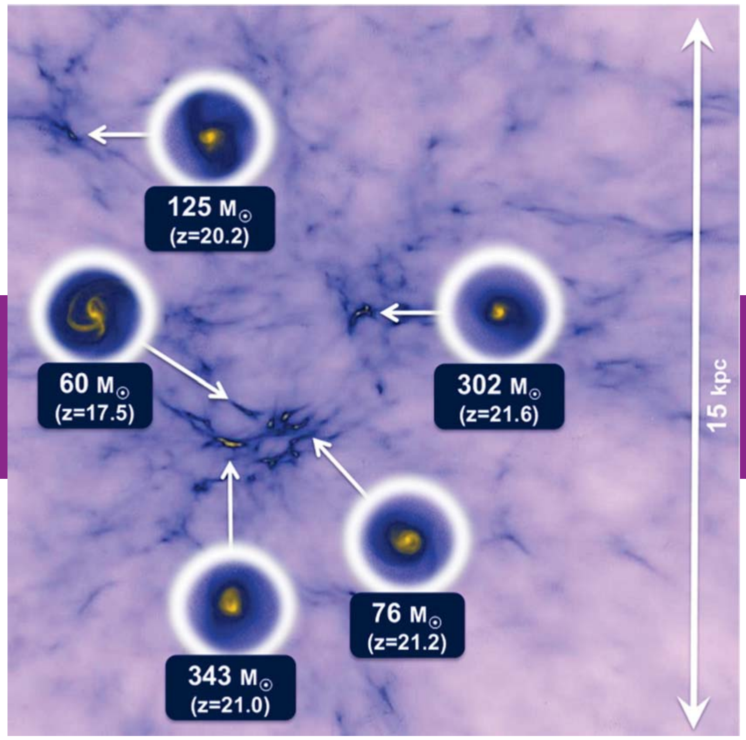
Safranek-Shrader et al. (2016)

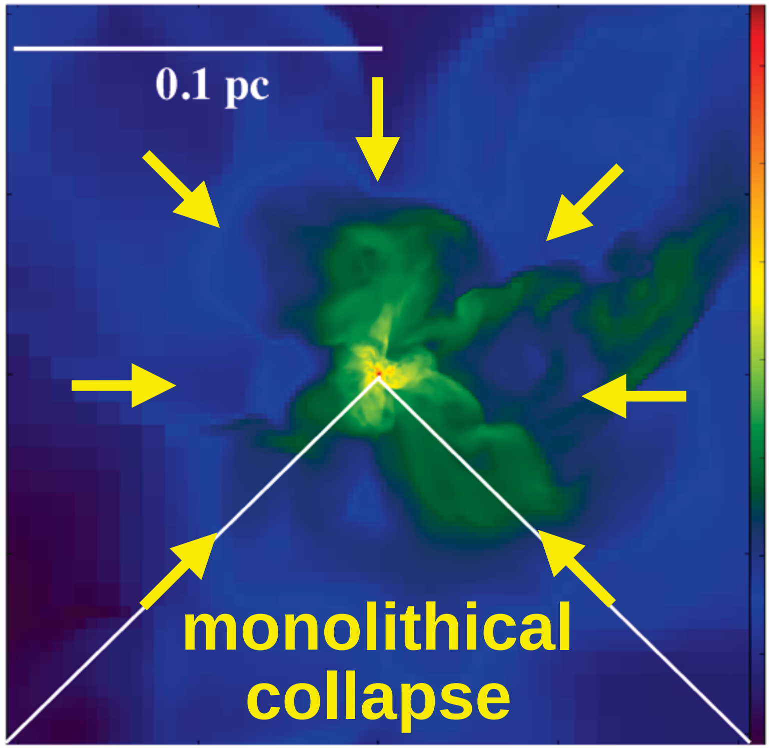
Pop III stars

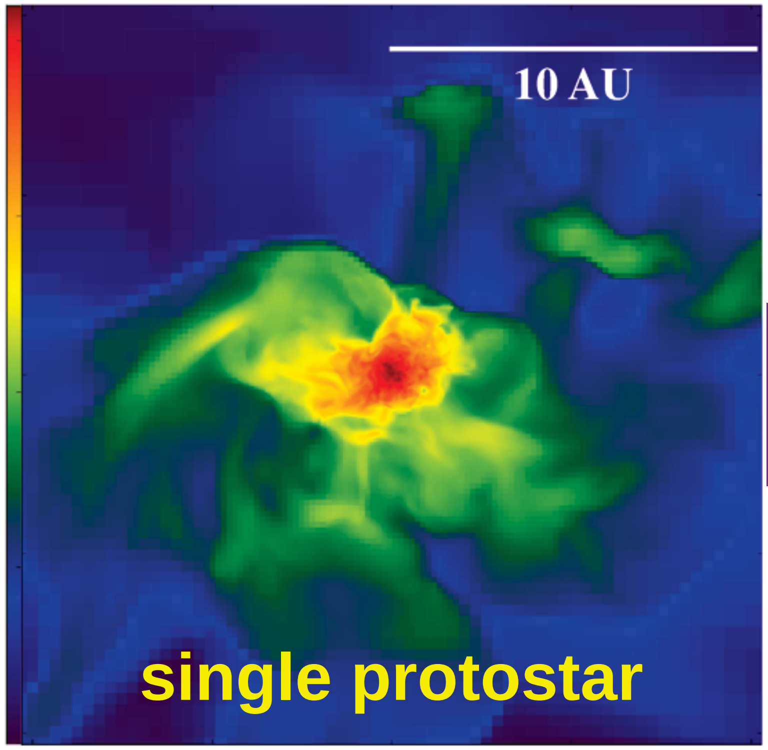
$$M_* \sim 100\ M_\odot$$

High-z star formation

cosmological scales







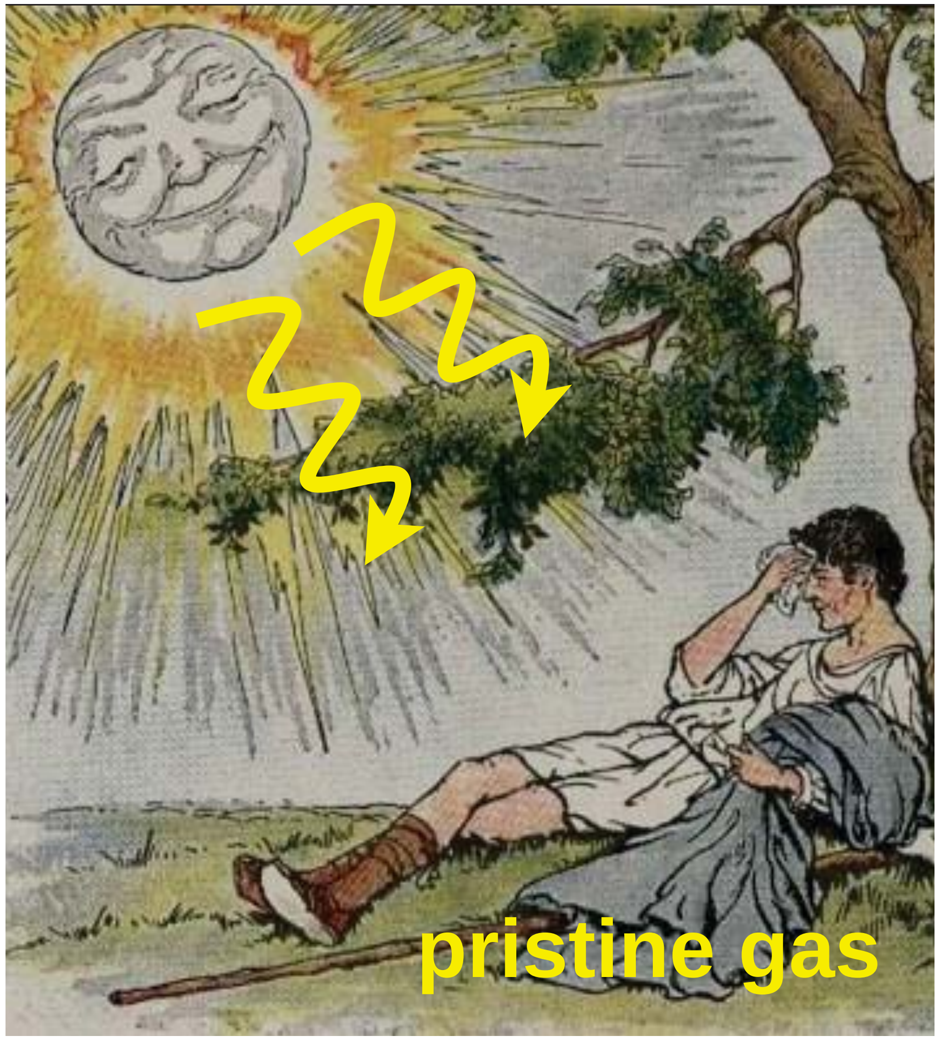
- high mass / no fragments: $M_{\rm J} \sim \rho \lambda_{\rm J}^3 \propto \dfrac{c_{\rm s}^3}{\sqrt{\rho}}$
- very high accretion rate: $\dot{M}_{\rm acc} \sim \dfrac{M_{\rm J}}{t_{\rm ff}} \sim \dfrac{c_{\rm s}^3}{G}$

$\propto T^{3/2}$

higher temperature is required

Ways to suppress H_2 formation

Lyman-Werner irradiation



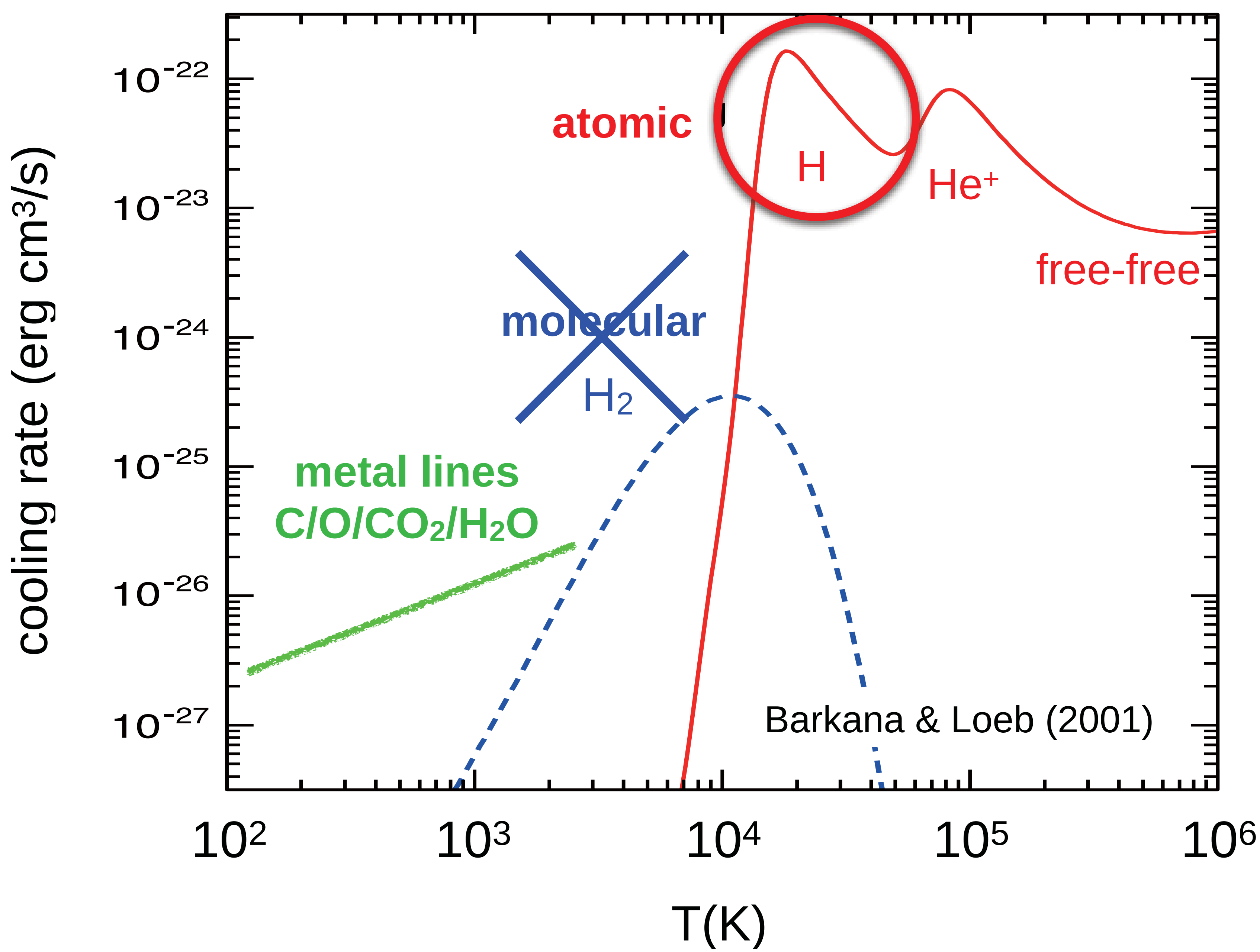
$$H_2 + \gamma_{\rm LW} \rightarrow 2\ \rm H$$

baryonic streaming motion

$$v_{\rm eff}^2 \equiv c_s^2 + \boxed{v_{\rm bsm}^2}$$

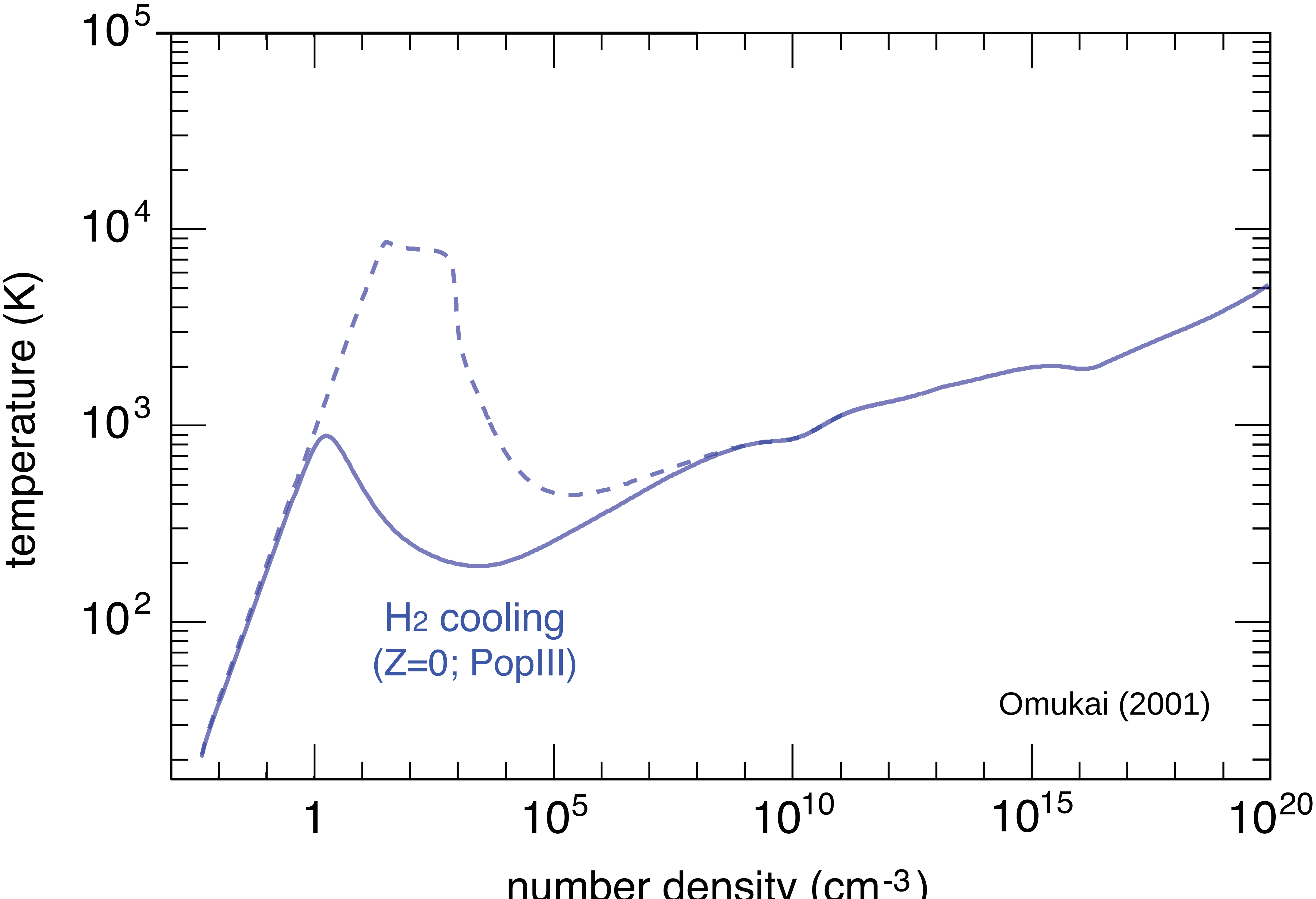
Bromm & Loeb 2003; Shang +2010; Latif +2013; Johnson +(2013); Regan +2014; Inayoshi +2014; Sugimura + 2014; Visbal +2015; Latif +2016; Chon+2016; Hirano+2018; Inayoshi+2018; Wise +2019; Luo+2019 etc…

Radiative cooling w/o H_2

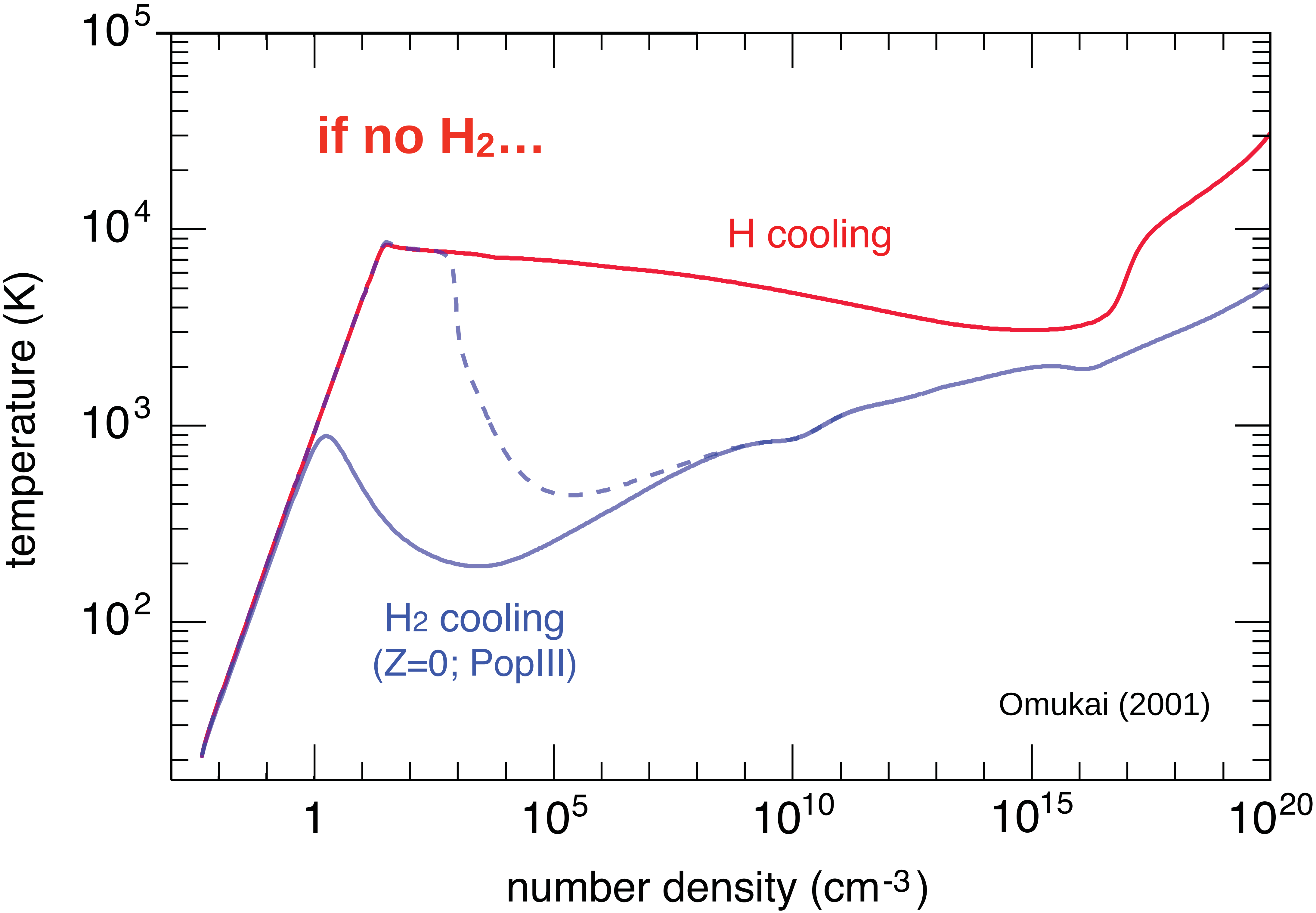


H atomic cooling is important (**higher T**)

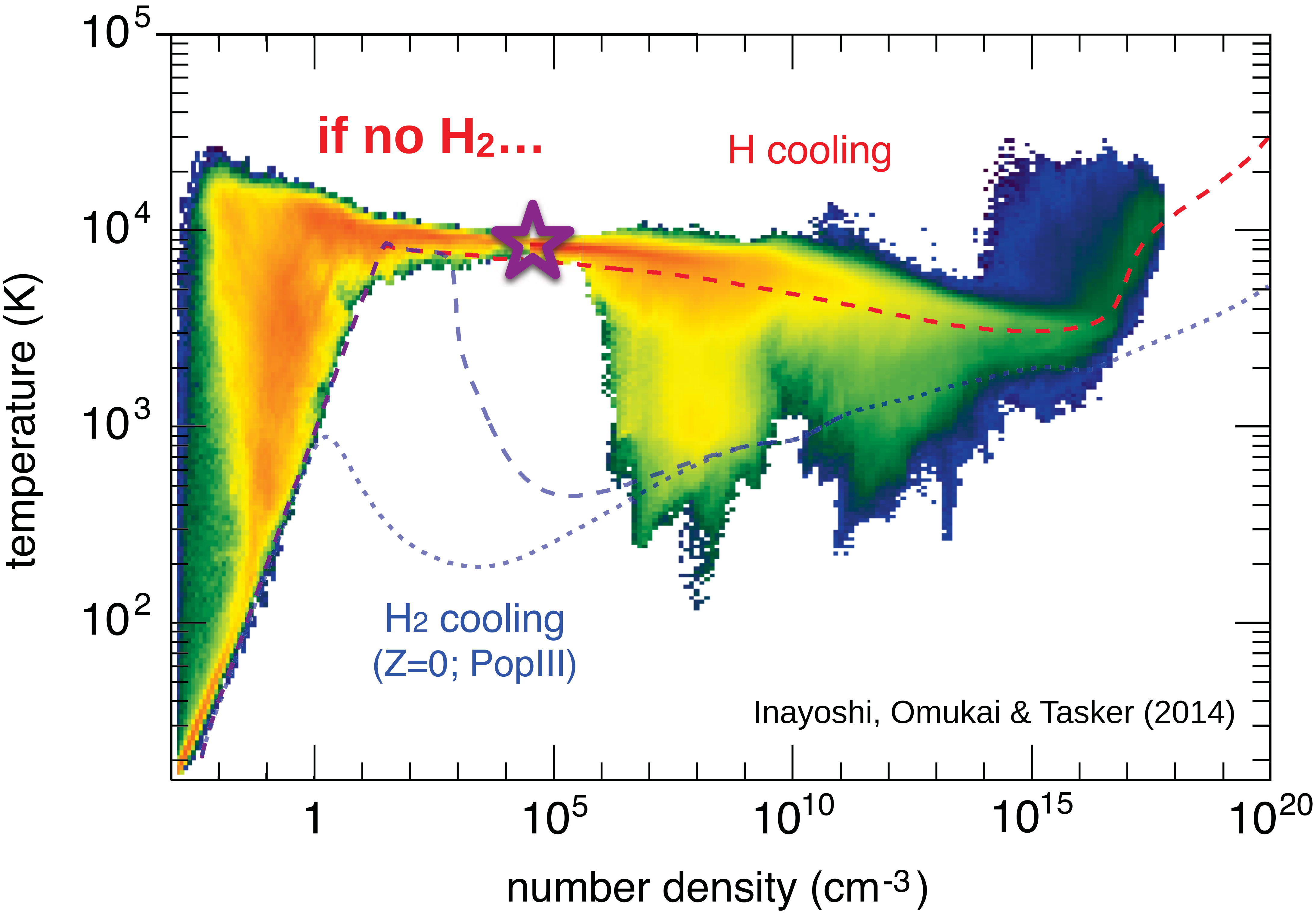
Star formation w/o H2



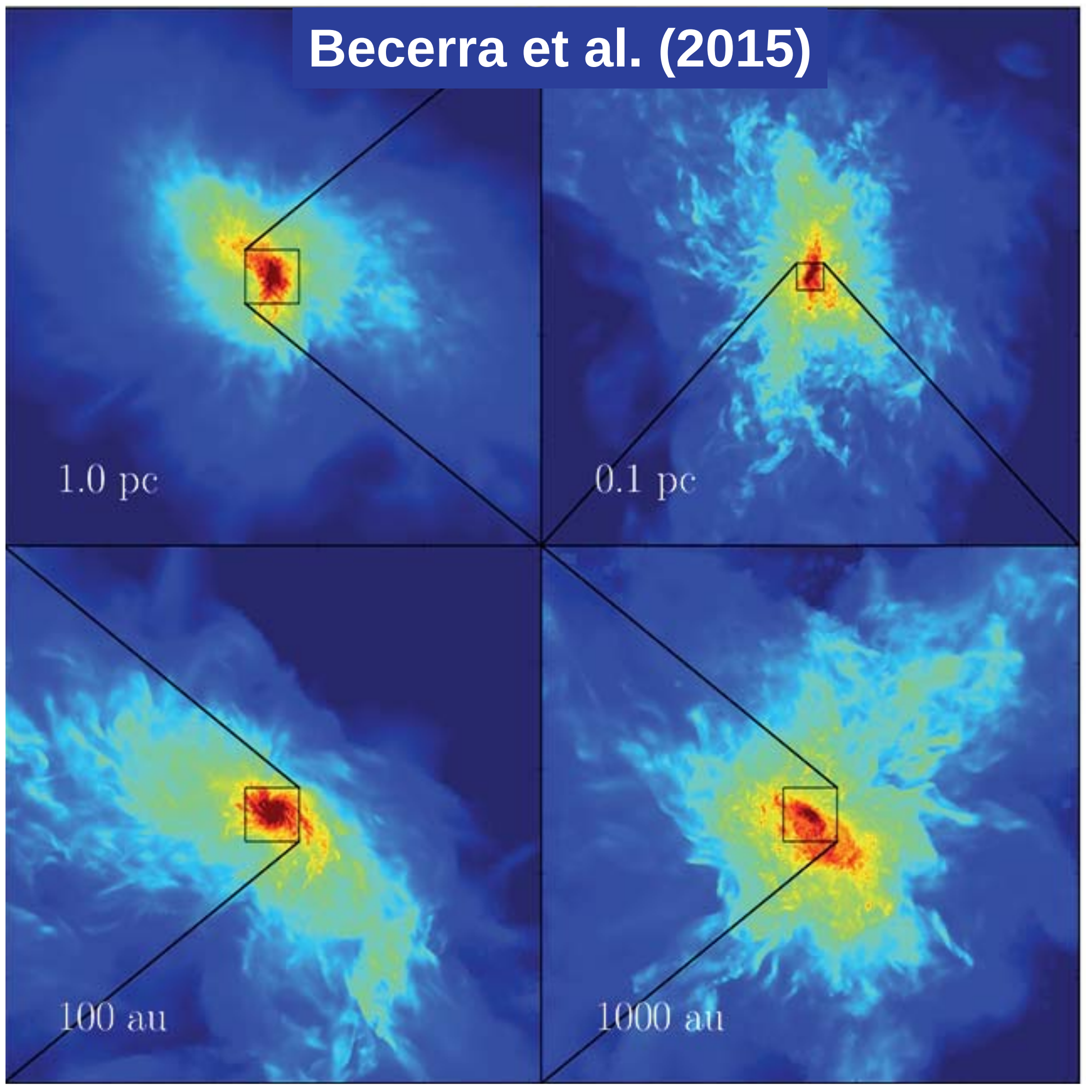
Star formation w/o H2



Star formation w/o H2

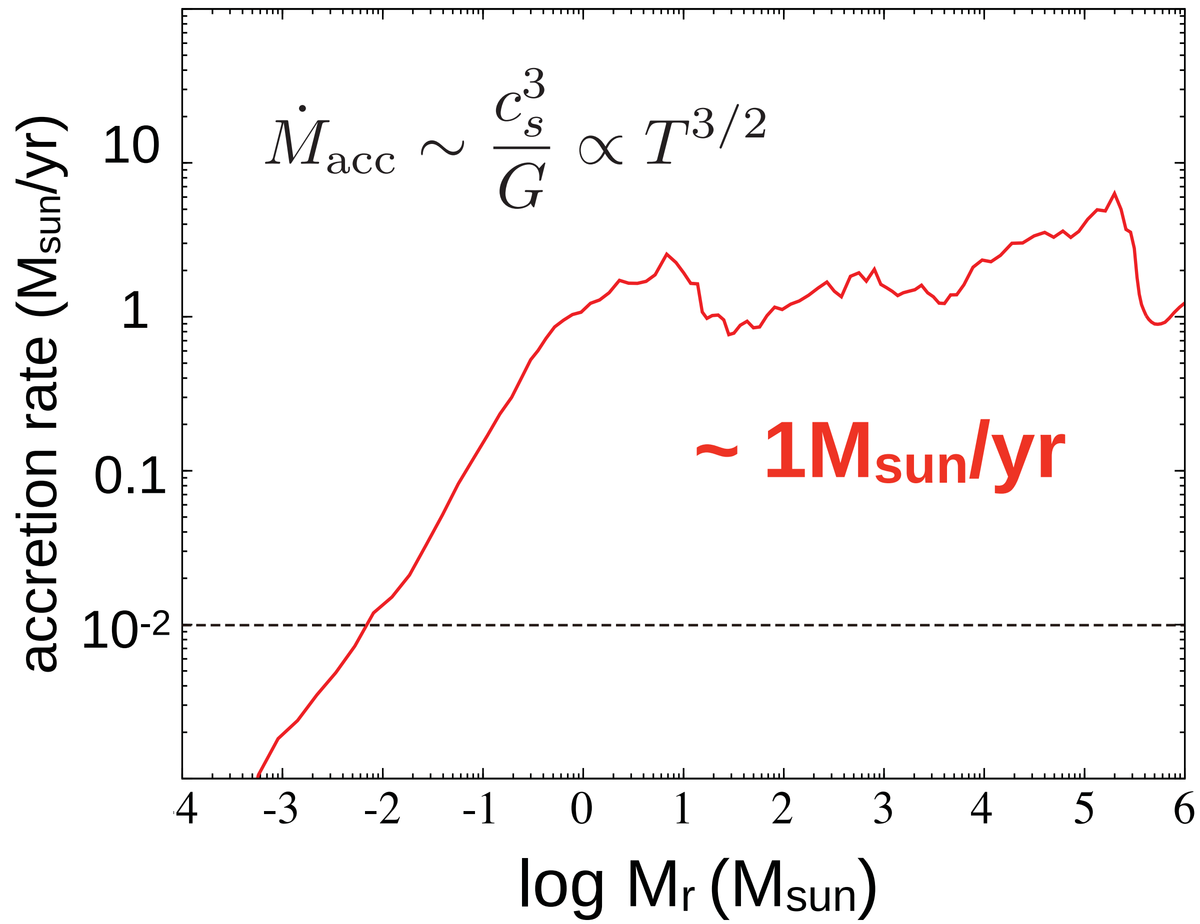


No fragments / high Mdot!



gravitational collapse

Inayoshi, Omukai & Tasker (2014)

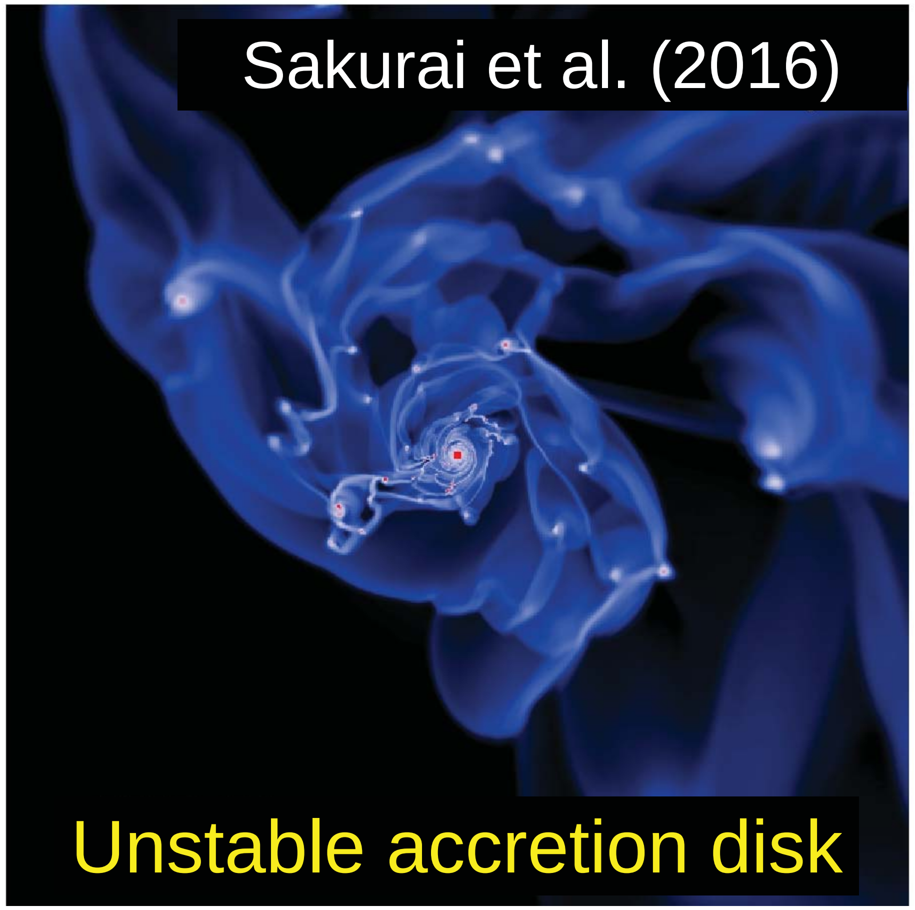


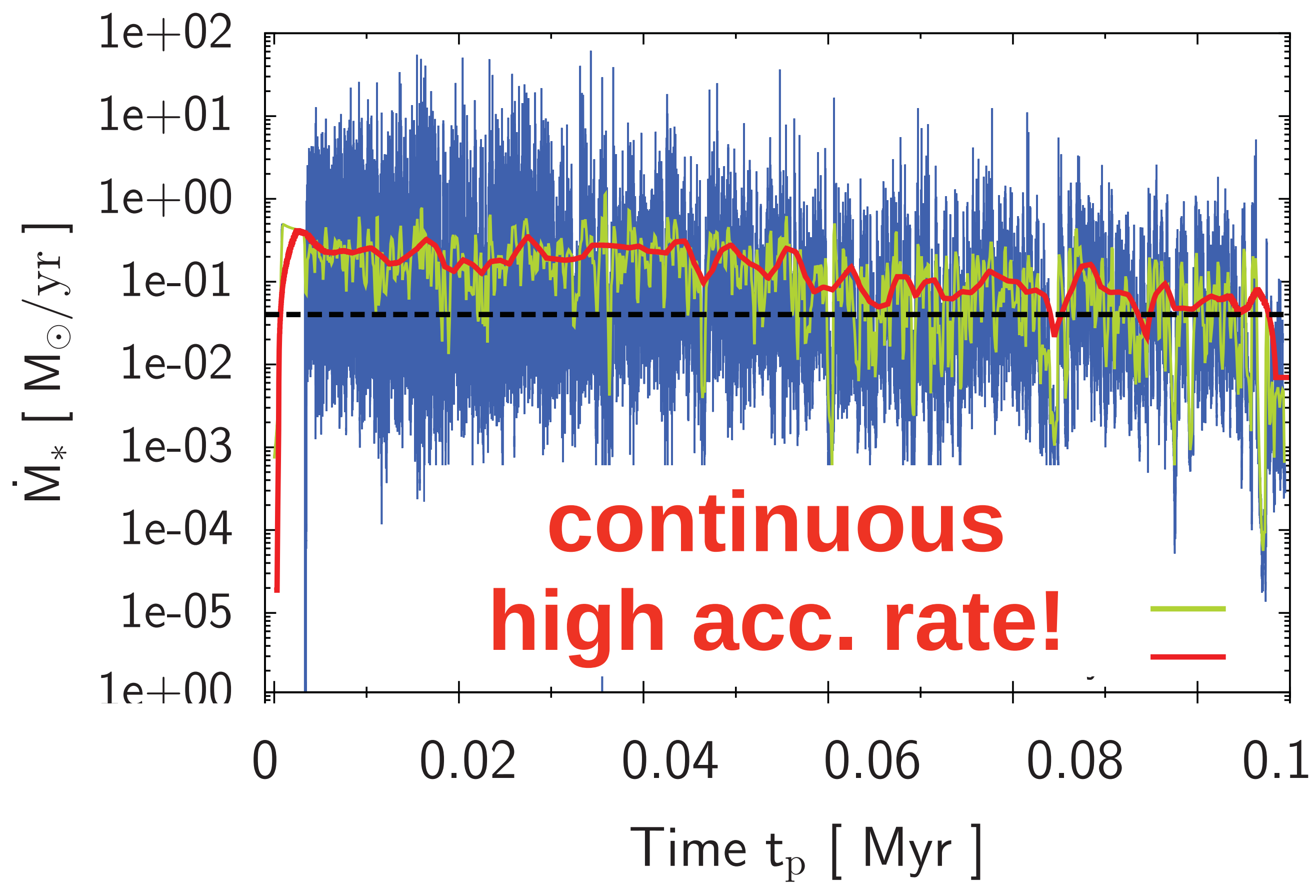
$$M_\star \approx \dot{M}_{\rm acc} \times t_{\rm life} \sim O(10^5)\ M_\odot$$

pristine & H_2 free gas ➡

- **no/weak fragmentation**
- **high accretion rate**

Massive accretion disk





KI & Haiman (2014)

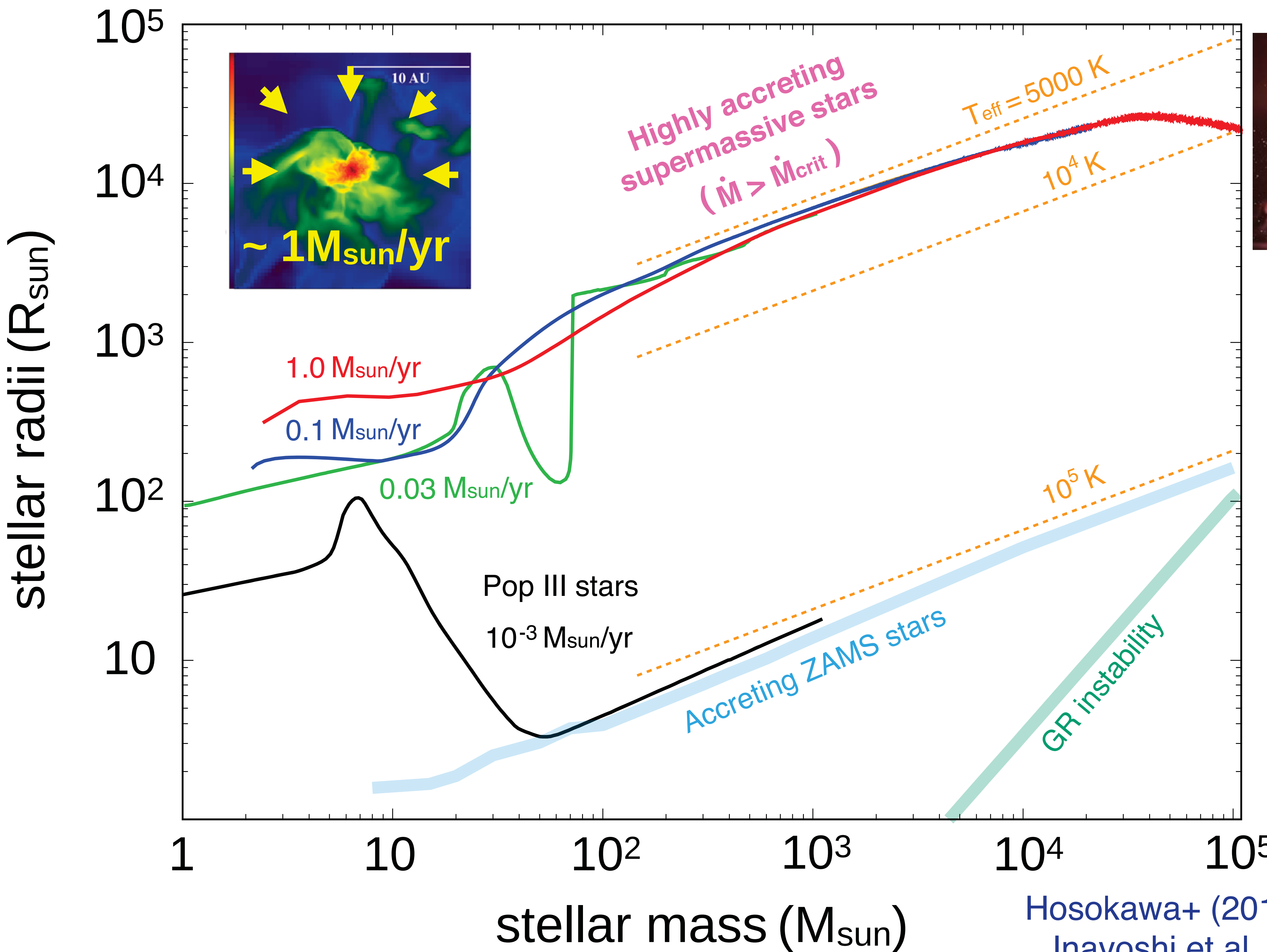
Toomre's instability:

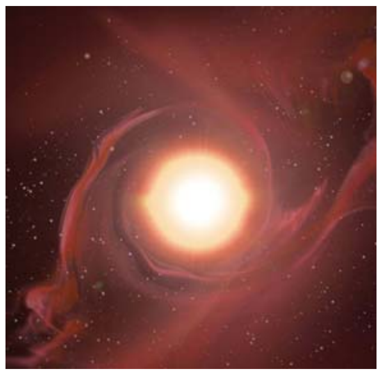
$$Q \sim \frac{c_s \Omega}{\pi G \Sigma} \sim \frac{\alpha c_s^3}{G \dot{M}_{\rm ext}} \sim 1$$

$$t_{\rm mig} \sim \frac{1}{\alpha} \frac{2\pi}{\Omega} \sim t_{\rm orb} < t_{\rm KH}$$

clumps migrate inward
before forming stars

Rapidly accreting protostar





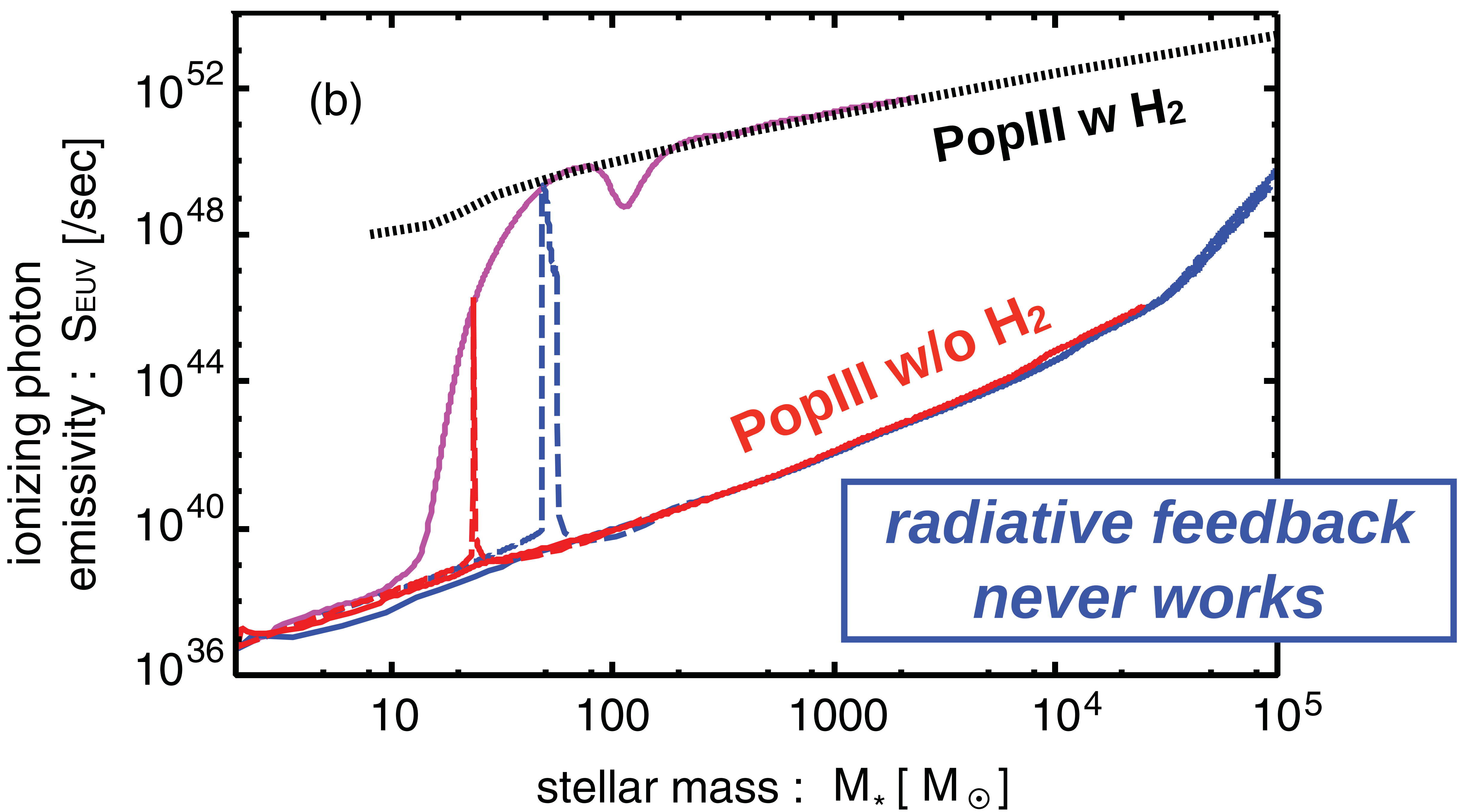
growth to

~$10^5 M_{sun}$

Hosokawa+ (2012,2013)
Inayoshi et al. (2020)

Rapidly accreting protostar

Hosokawa, KI et al. (2013)



Direct-collapse!

- Newton gravity + GR correction

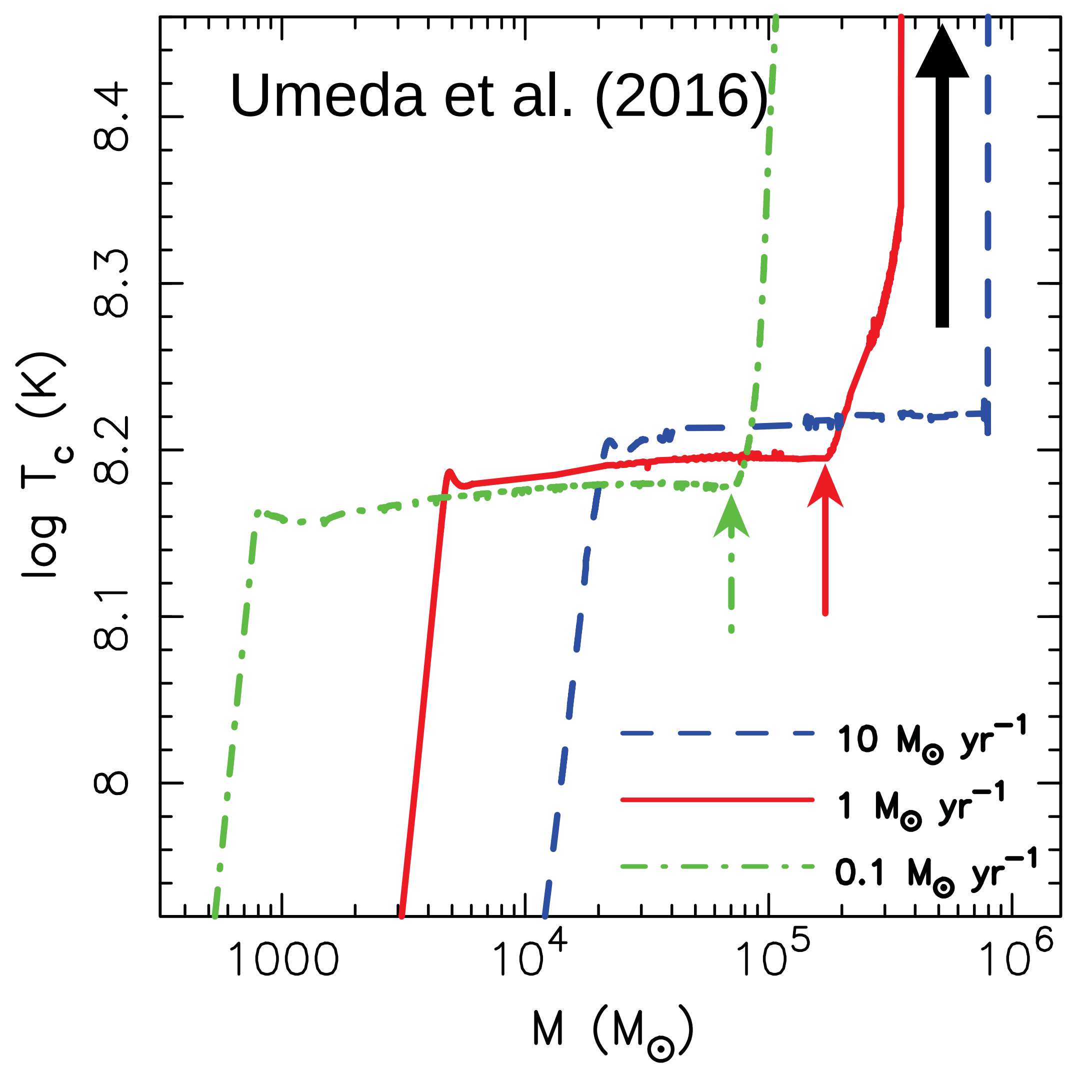
$$\frac{dp}{dr} = -\frac{G\epsilon(r)\mathcal{M}(r)}{c^2r^2}\left[1+\frac{p(r)}{\epsilon(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{\mathcal{M}(r)c^2}\right]\left[1-\frac{2G\mathcal{M}(r)}{c^2 r}\right]^{-1}$$

pressure -> energy -> mass…

no stable stellar structure if

$M_* >$ a few $\times 10^5 M_{sun}$

(see textbook by Shapiro & Tuekolsky)

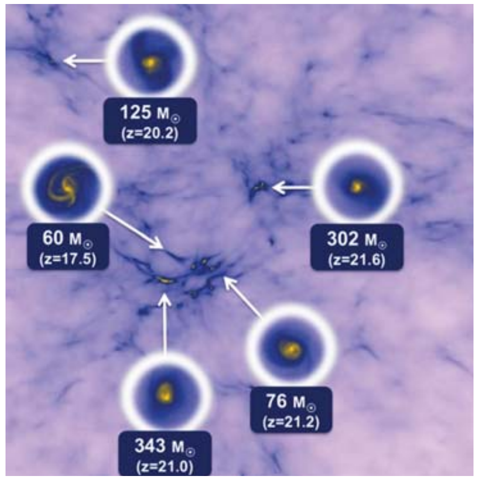


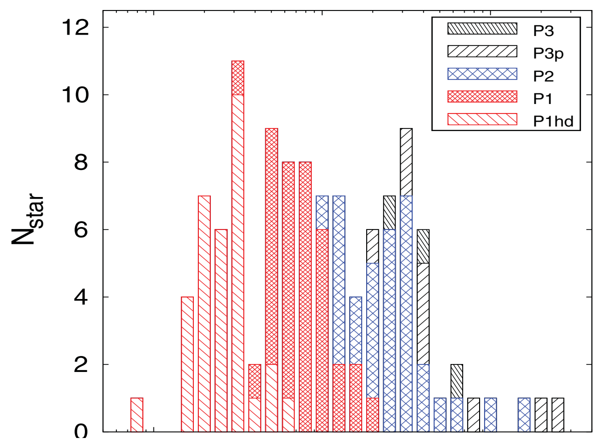
Summary

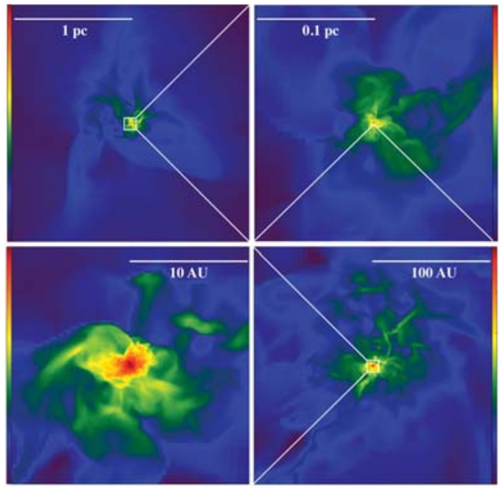
- Pop III stars form at z~20 in mini-halos via H_2 cooling

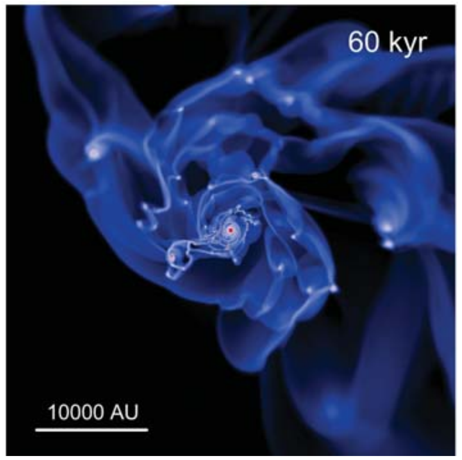
- Pop III stars are typically massive (10-1000 M_{sun})

- Metal-free star formation w/o H2 provides seeds of high-z SMBHs (DCBHs)









Thank you!