

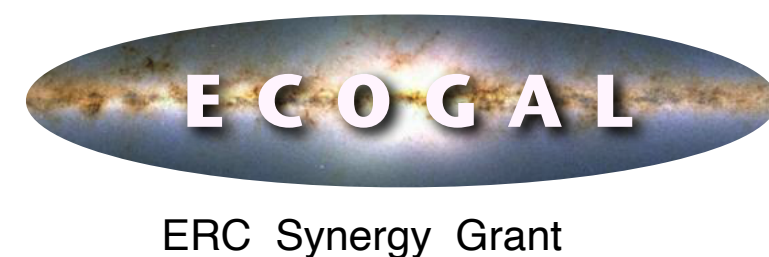
the first stars: formation, properties, impact

some theory
standard formation pathway of first stars
supermassive stars

Ralf Klessen



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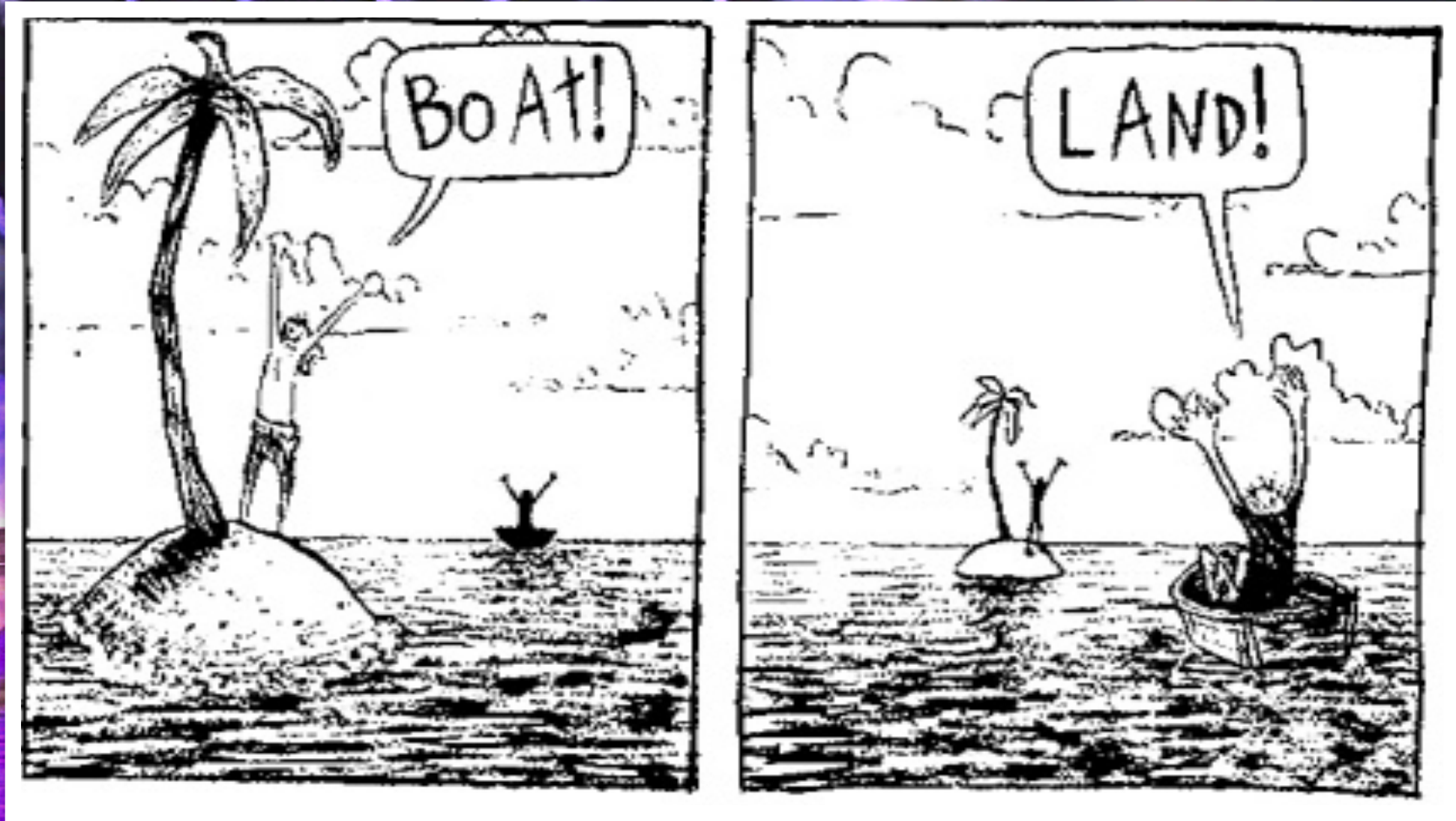
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disclaimer: this talk
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disclaimer: this talk is
largely based on ...

Annual Review of Astronomy and Astrophysics
The First Stars: Formation,
Properties, and Impact

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Keywords

cosmology, first and second stellar population, galactic archeology,
high-redshift Universe, Population III and II, star formation

Abstract

The first generation of stars, often called Population III (or Pop III), form from metal-free primordial gas at redshifts $z \sim 30$ and below. They dominate the cosmic star-formation history until $z \sim 15$ –20, at which point the formation of metal-enriched Population II stars takes over. We review current theoretical models for the formation, properties, and impact of Pop III stars and discuss existing and future observational constraints. Key takeaways from this review include the following:

- Primordial gas is highly susceptible to fragmentation and Pop III stars form as members of small clusters with a logarithmically flat mass function.
- Feedback from massive Pop III stars plays a central role in regulating subsequent star formation, but major uncertainties remain regarding its impact.

some theoretical considerations



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cosmic timeline



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cover onset of primordial star formation to early reionization

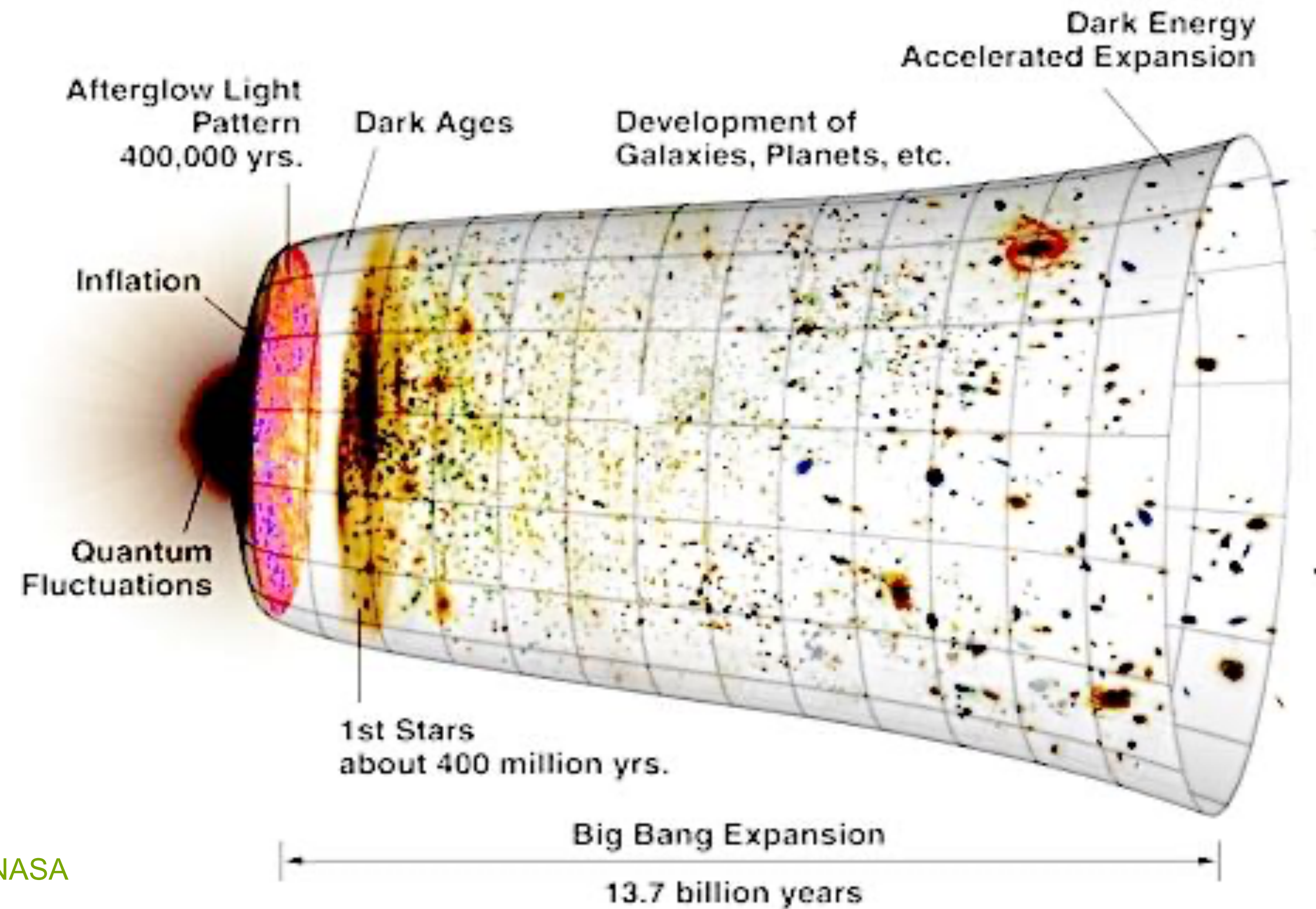


image credit: NASA

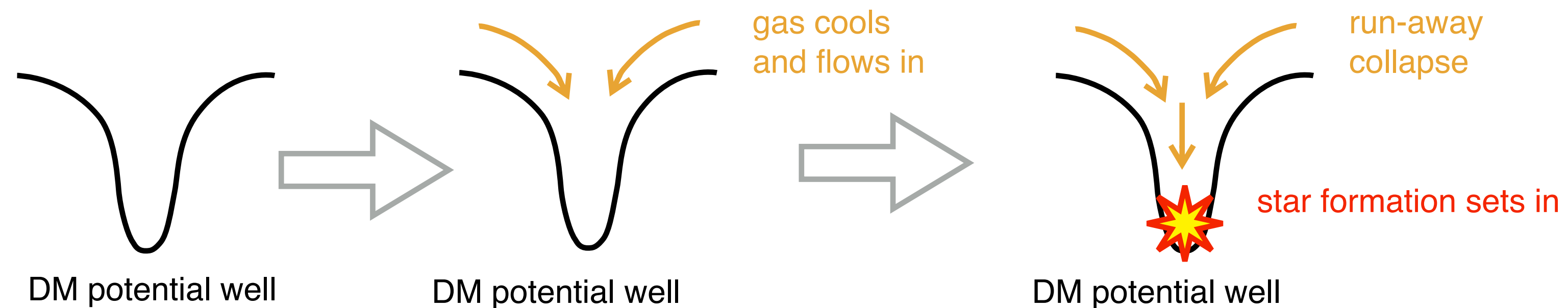
criteria for onset of star formation



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criteria for primordial star formation

- DM halos need to decouple from cosmic expansion and start to contract
- gas needs to decouple and go into run-away collapse
 - > **Jeans criterion:** $\tau_{\text{grav}} < \tau_{\text{sound}}$
- in addition, gas needs to cool away compression heat
 - > **Rees-Ostriker criterion:** $\tau_{\text{cool}} < \tau_{\text{dyn}}$
- both depend on thermodynamic response of the gas
 - > competition between heating and cooling processes
 - > importance of chemistry
- collapse needs to proceed to stellar densities



critical halo mass for star formation 1



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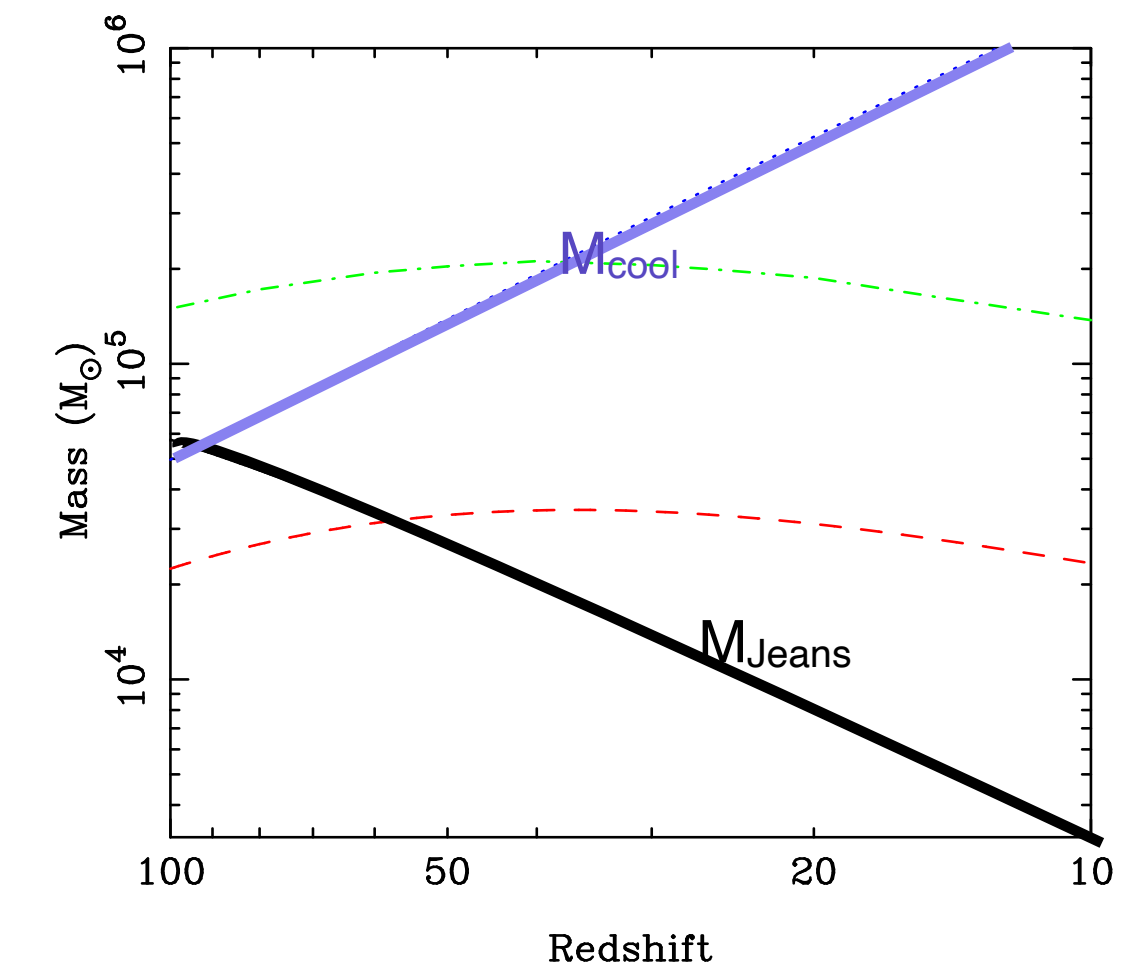
criteria for collapse and star formation

- look at competition between gravity (density ρ) and gas pressure (sound speed c_s or temperature T): ***Jeans mass***
- critical mass:

$$M_J = \frac{\pi^{5/2}}{6} \left(\frac{1}{G} \right)^{3/2} \rho^{-1/2} c_s^3 = \frac{\pi^{5/2}}{6} \left(\frac{k}{G} \right)^{3/2} \left(\frac{1}{\mu m_H} \right)^2 n^{-1/2} T^{3/2}$$

- can be extended by considering effective sound speed $c_{s,\text{eff}}^2 = c_s^2 + \sigma^2$ with $\sigma = \sigma_{\text{turb}}$ and/or $\sigma = v_{\text{Alfven}}$
- in standard LCDM a low redshift this translates to

$$M_J \approx 5 \times 10^3 M_\odot \left(\frac{\Omega_m h^2}{0.14} \right)^{-1/2} \left(\frac{\Omega_b h^2}{0.022} \right)^{-3/5} \left(\frac{z+1}{10} \right)^{3/2}$$



critical halo mass for star formation 2

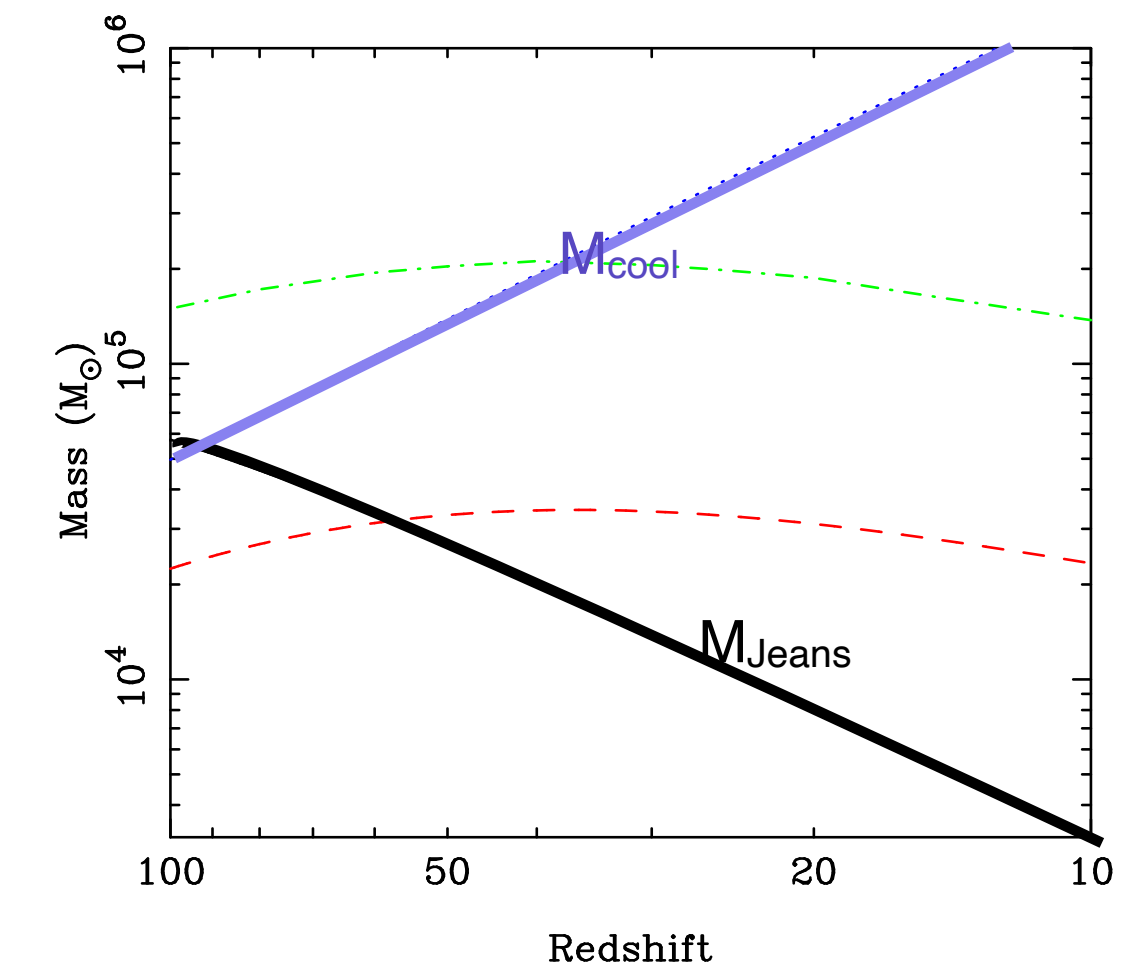


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criteria for collapse and star formation

- this is not sufficient, gas also needs to cool away excess heat: **cooling mass**
- efficient cooling often due to **molecular hydrogen**; with H_2 we reach $T \sim 500$ K and with HD down to $T \sim 100$ K (but typically not important)
- H_2 typically needs free electrons as catalyst:
 $H + e^- \rightarrow H^- + \gamma$ and $H^- + H \rightarrow H_2 + e^-$
- less important: $H + H^+ \rightarrow H_2^+ + \gamma$ and $H_2^+ + H \rightarrow H_2 + H^+$
- and at high densities ($n \lesssim 10^9 \text{ cm}^{-3}$) via the 3-body path:
 $H + H + H \rightarrow H_2 + H$
- as result:

$$M_{\text{cool}} \approx 6 \times 10^5 M_{\odot} h^{-1} \Omega_m^{-1/2} \left(\frac{\mu}{1.22} \right)^{-3/2} \left(\frac{z+1}{10} \right)^{-3/2}$$

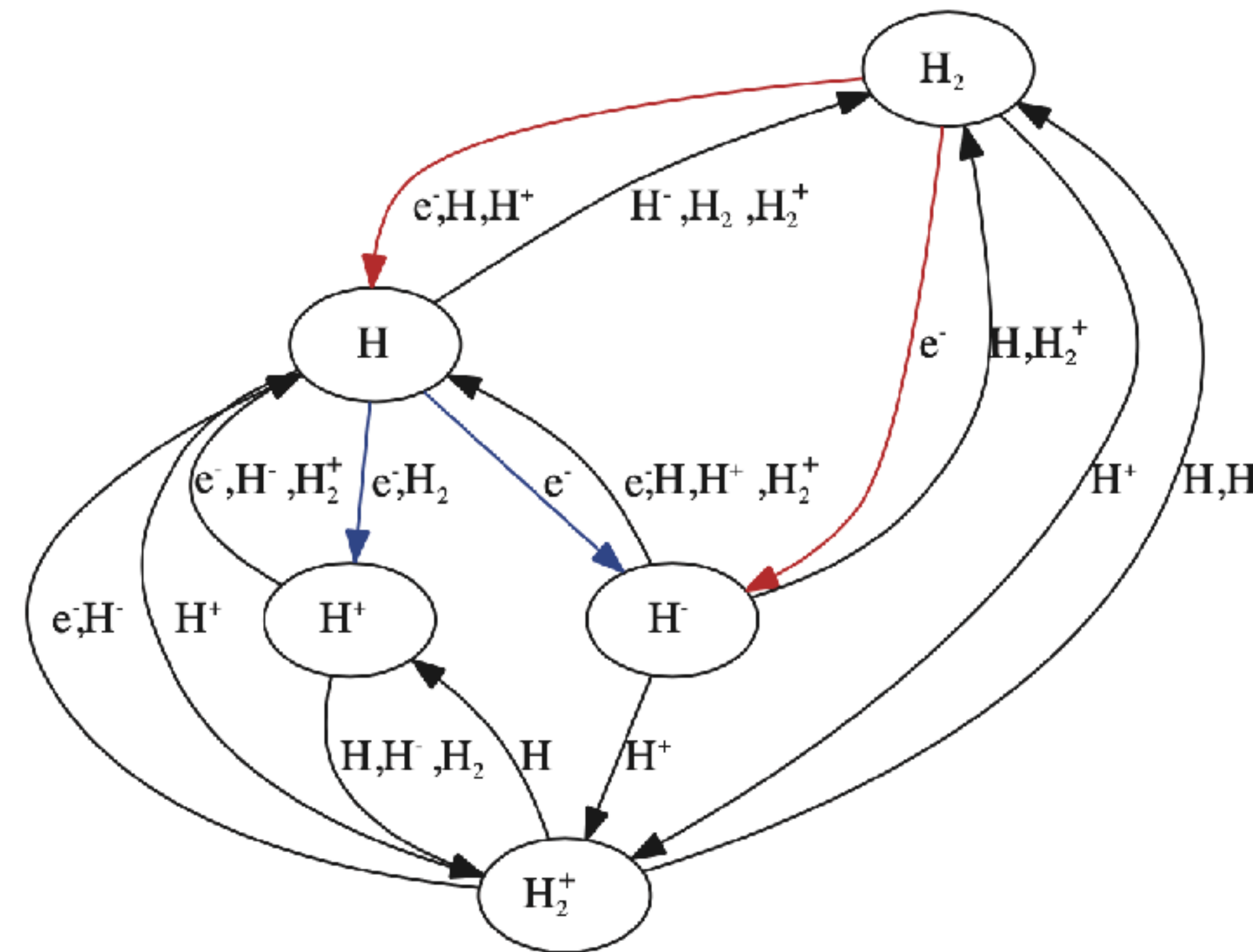


primordial chemistry



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primordial chemistry networks largely focus on H_2 as primary coolants



Bovino & Galli (2019, in Formation of the First Black Holes, eds. Latif M. and Schleicher D.R.G),
using KROME, see Grassi et al. (2014, MNRAS, 439, 2386)

effective equation of state

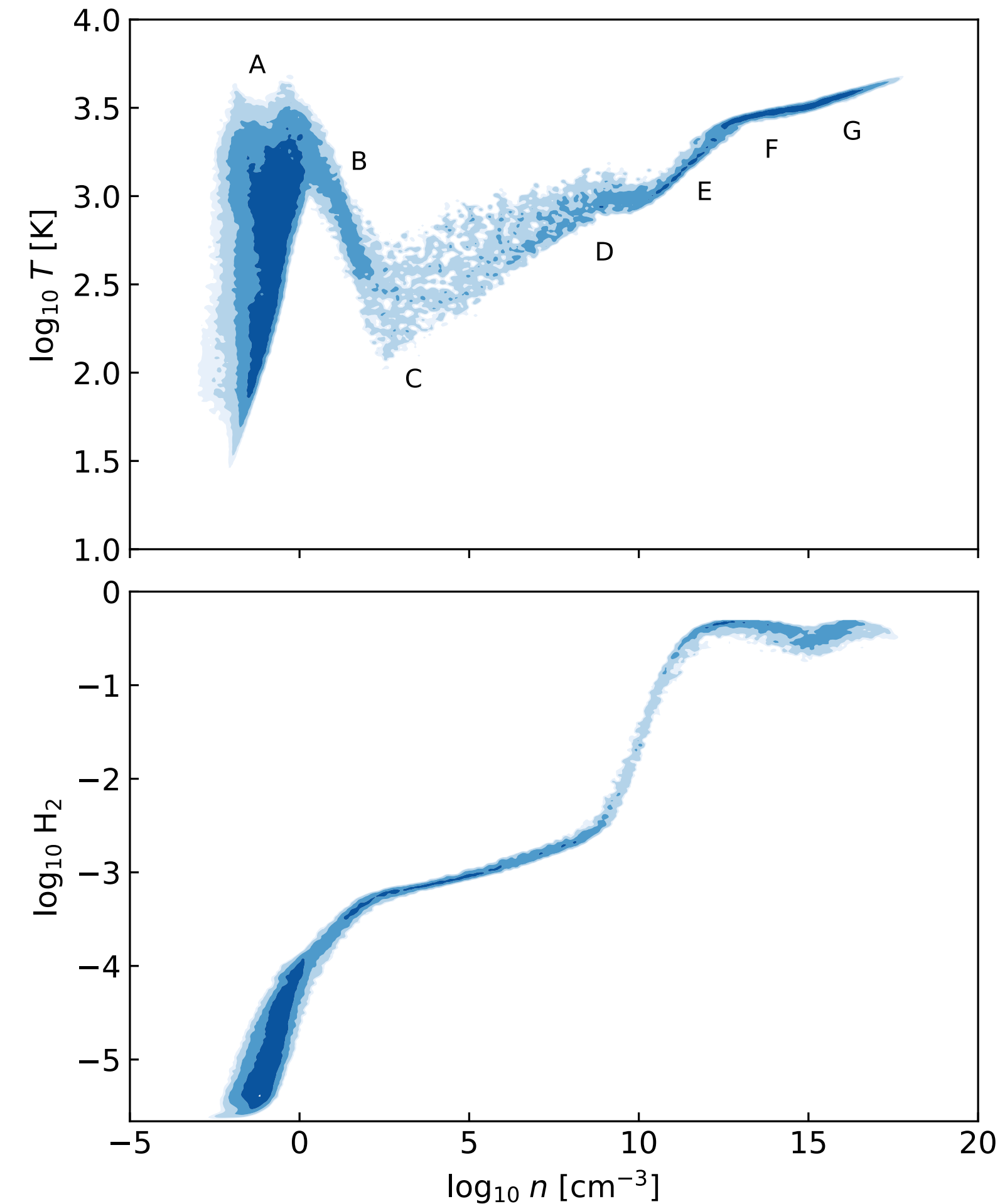
effective EOS constitutes a relation between temperature and density

- (A) gas flows into potential well and is compressionally heated
- (B) H_2 formation and run-away cooling
- (C) gas accumulates and collapse resumes
- (D) 3-body H_2 formation sets in and gas becomes fully molecular
- (E) gas becomes optically thick and temperature rises further
- (F) collision-induced emission (CIE) becomes important coolant
- (G) at $T \sim 2000$ K H_2 dissociation sets in

Klessen & Glover (2023, ARAA, 61, 65)
 inspired by Yoshida et al. (2006, ApJ, 652, 6)
 using data of Lewis Prole and Anna Schauer



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standard pathway of Pop III formation



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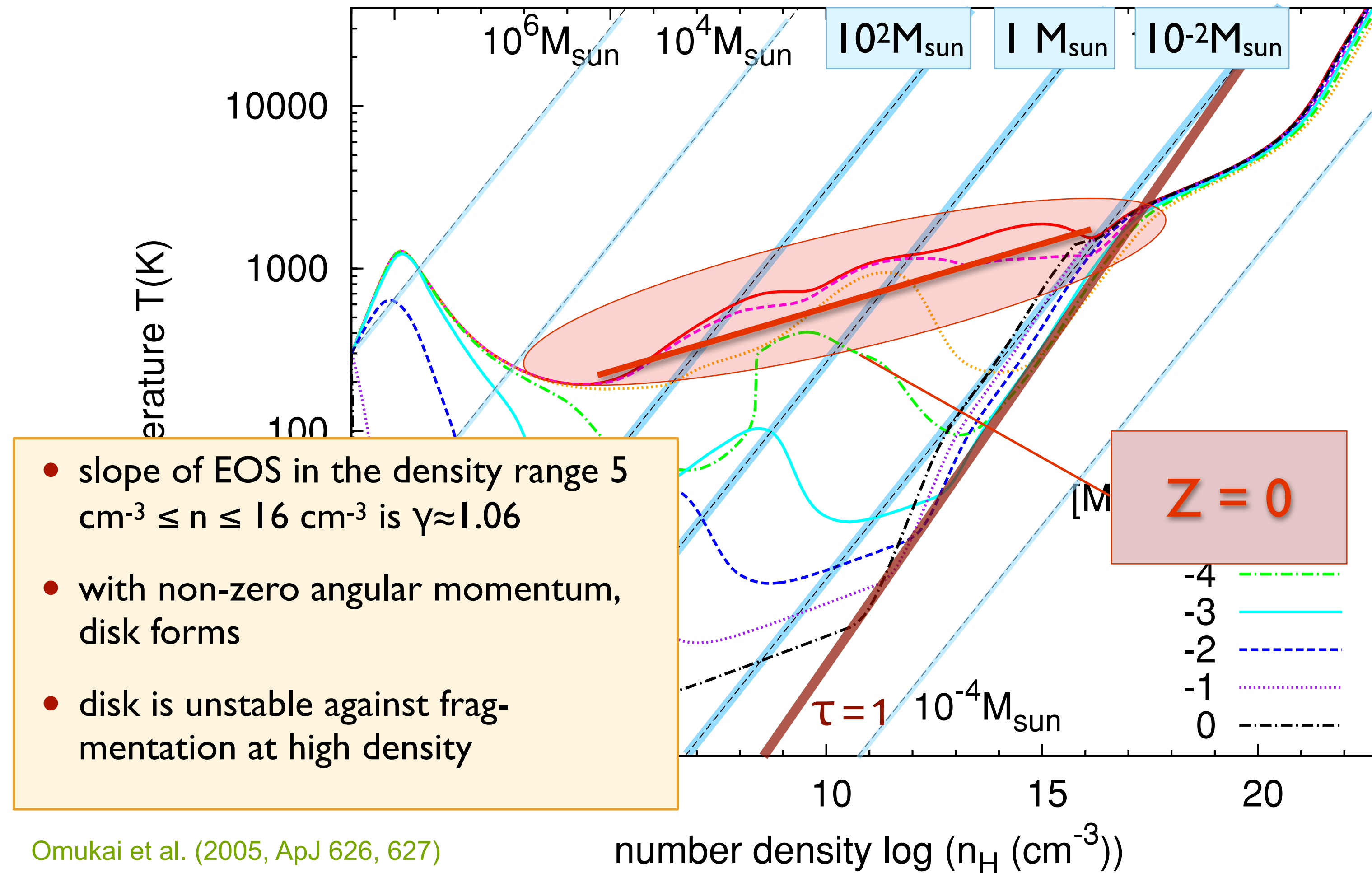


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Pop III stars



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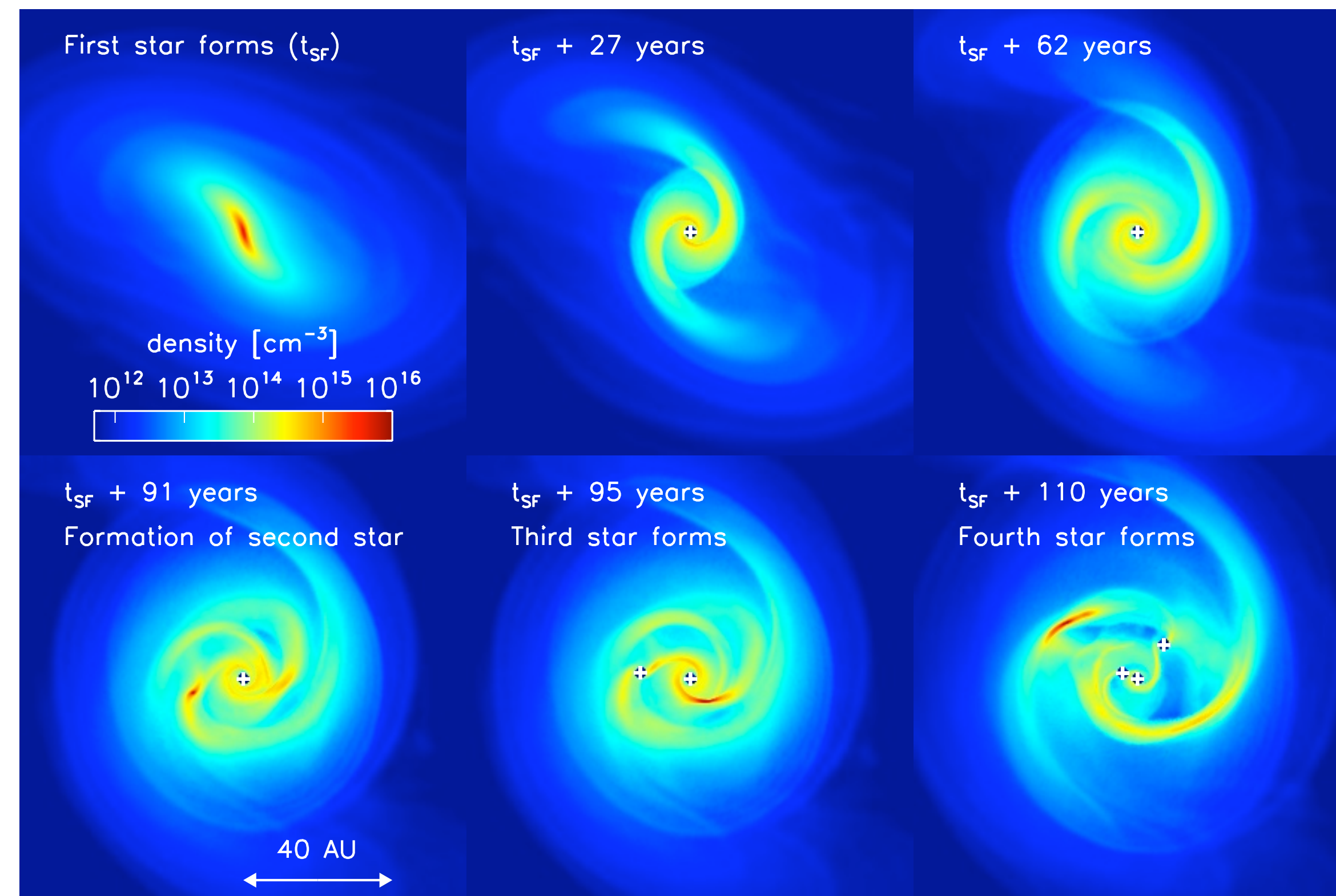


Pop III stars



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multiple Pop III stars form by disk fragmentation



Clark et al. (2011, Science, 331, 1040)

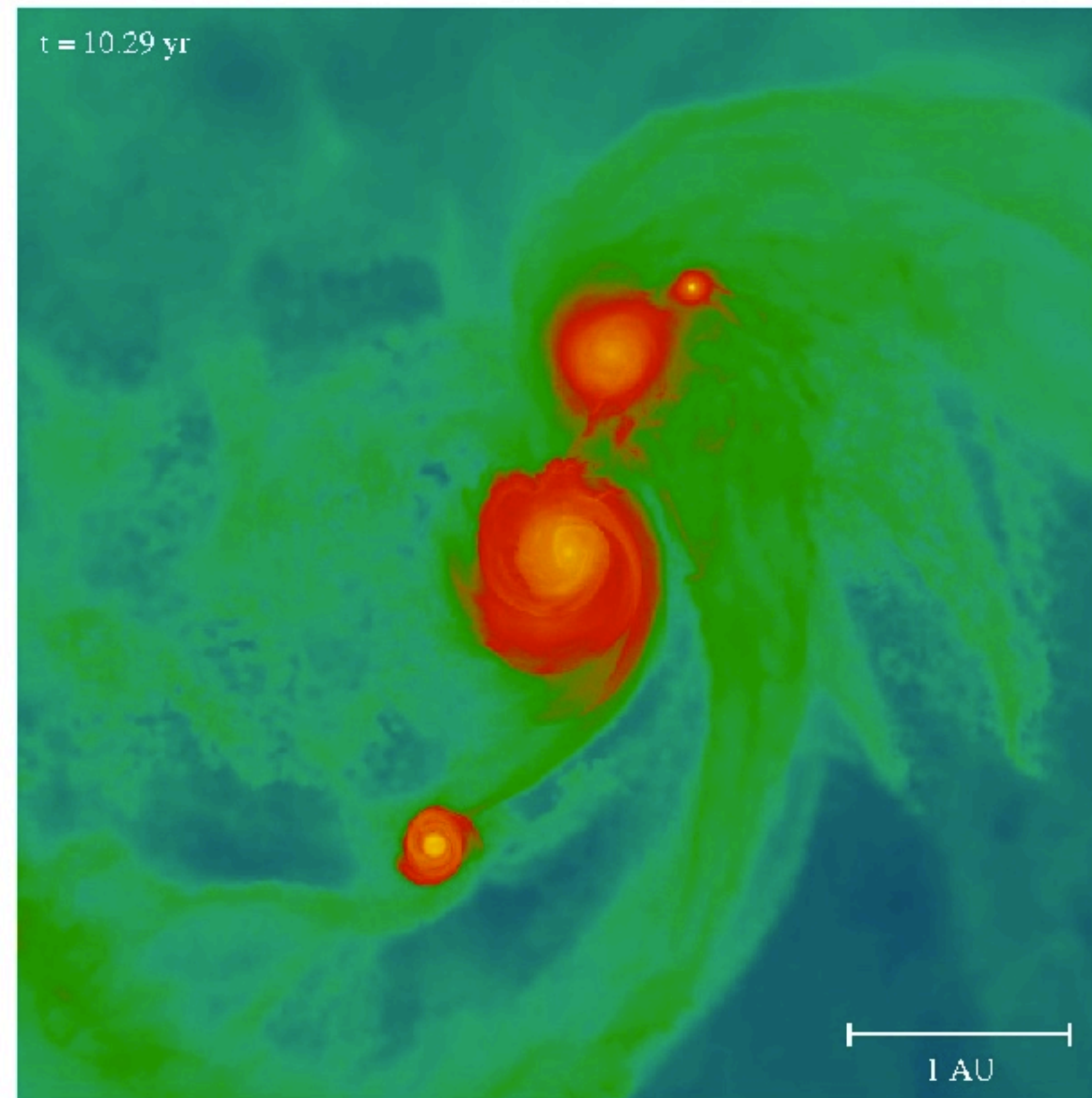
disk fragmentation

Pop III stars

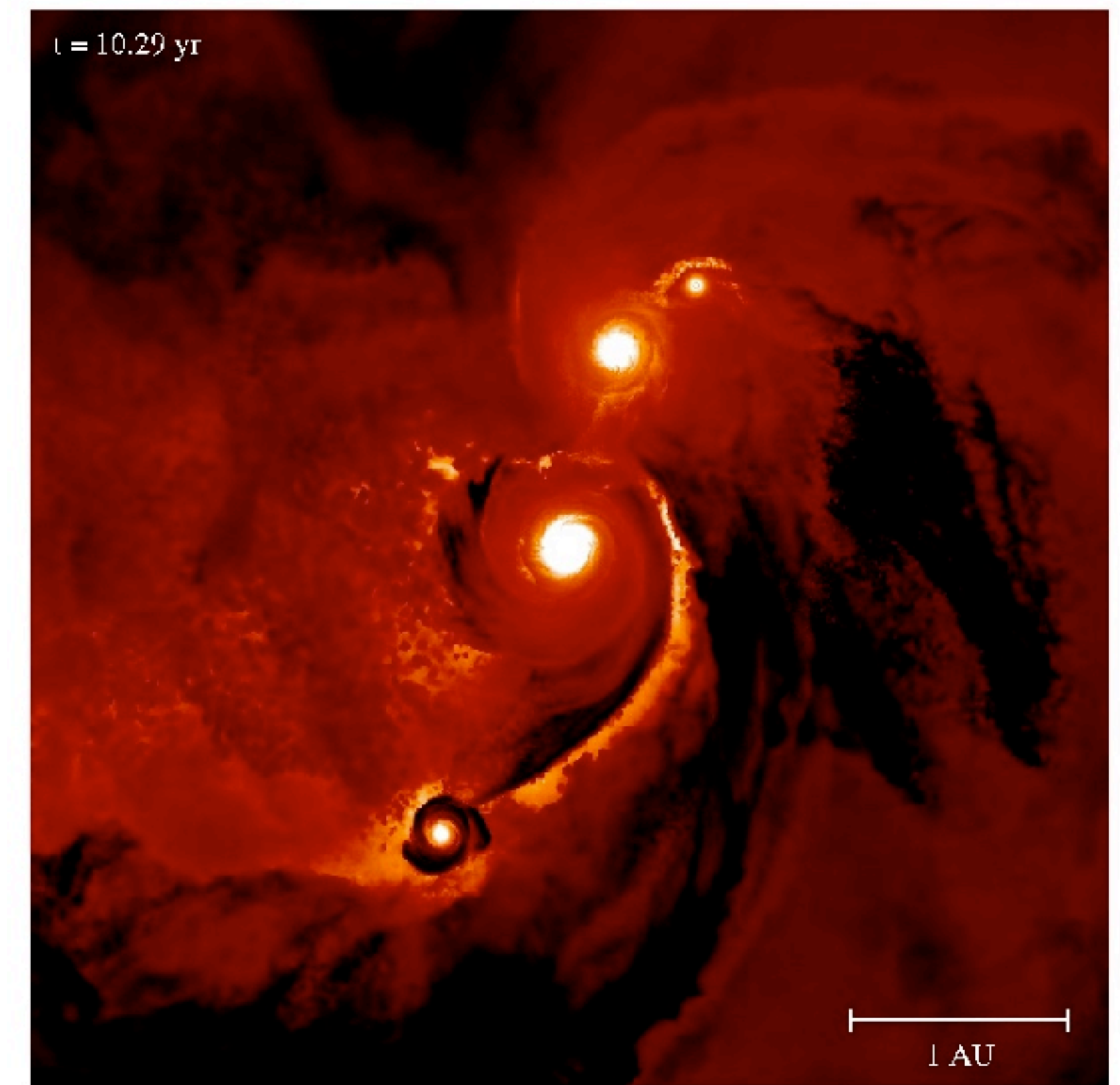


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multiple Pop III stars
form by disk fragmentation



density



temperature

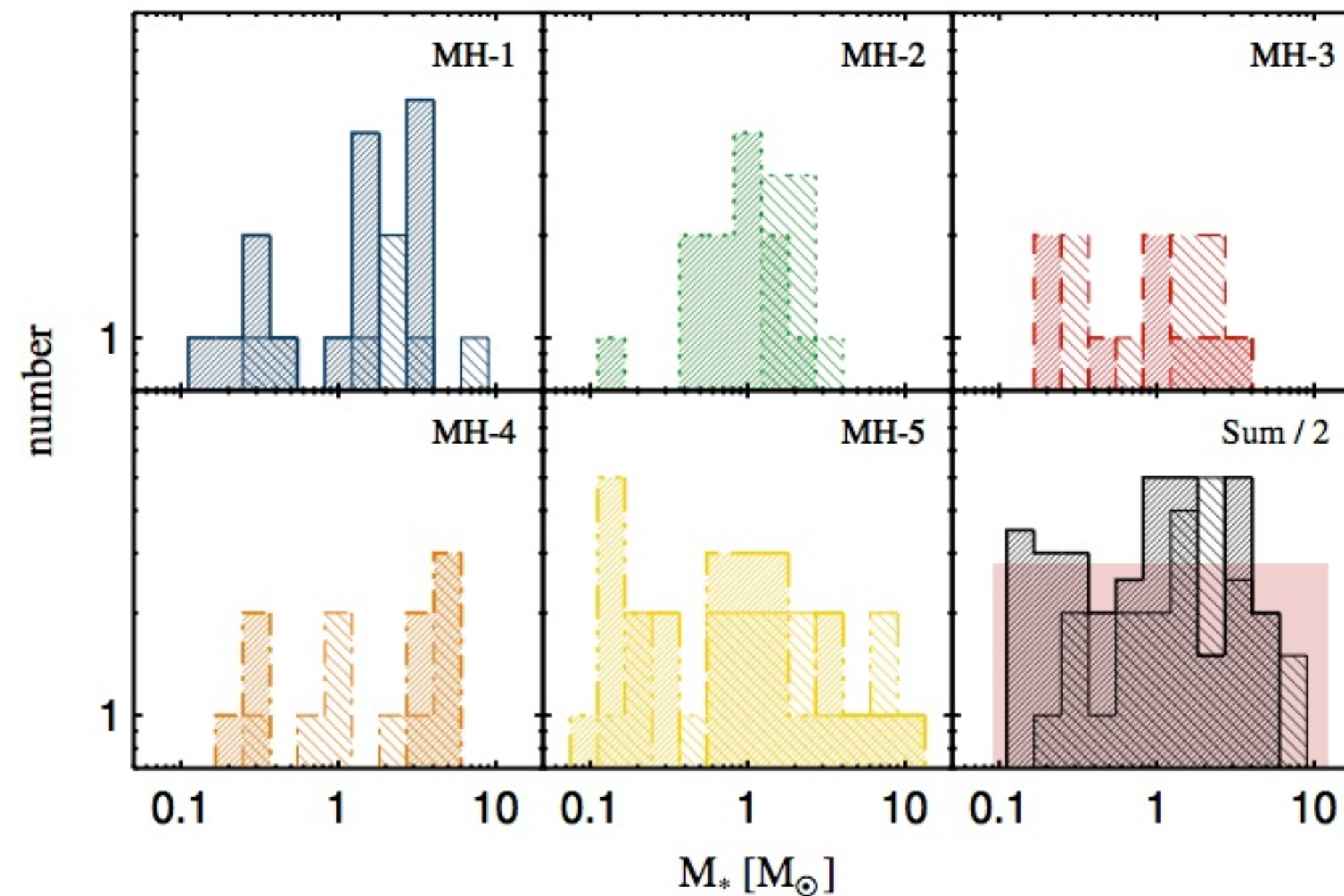
Greif et al. (2012, MNRAS, 424, 399)

IMF of Pop III stars



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simulations suggest IMF of metal-free stars is log flat
(with hint for top-heaviness)



we see “flat”
mass spectrum

Greif et al. (2011, ApJ, 737, 75), Clark et al. (2011, Science, 331, 1040), Smith et al. (2011, MNRAS, 414, 3633), Dopcke et al. (2013, ApJ, 766, 103), Hirano et al. (2014, ApJ, 781, 60), Tanaka & Omukai (2014, MNRAS, 439, 1884), Nakauchi et al. (2014, MNRAS, 442, 2667), Wollenberg et al. (2020, MNRAS, 494, 1871), Prole et al. (2022, MNRAS, 510, 4019), Prole et al. (2022, MNRAS, 516, 2223), and many more

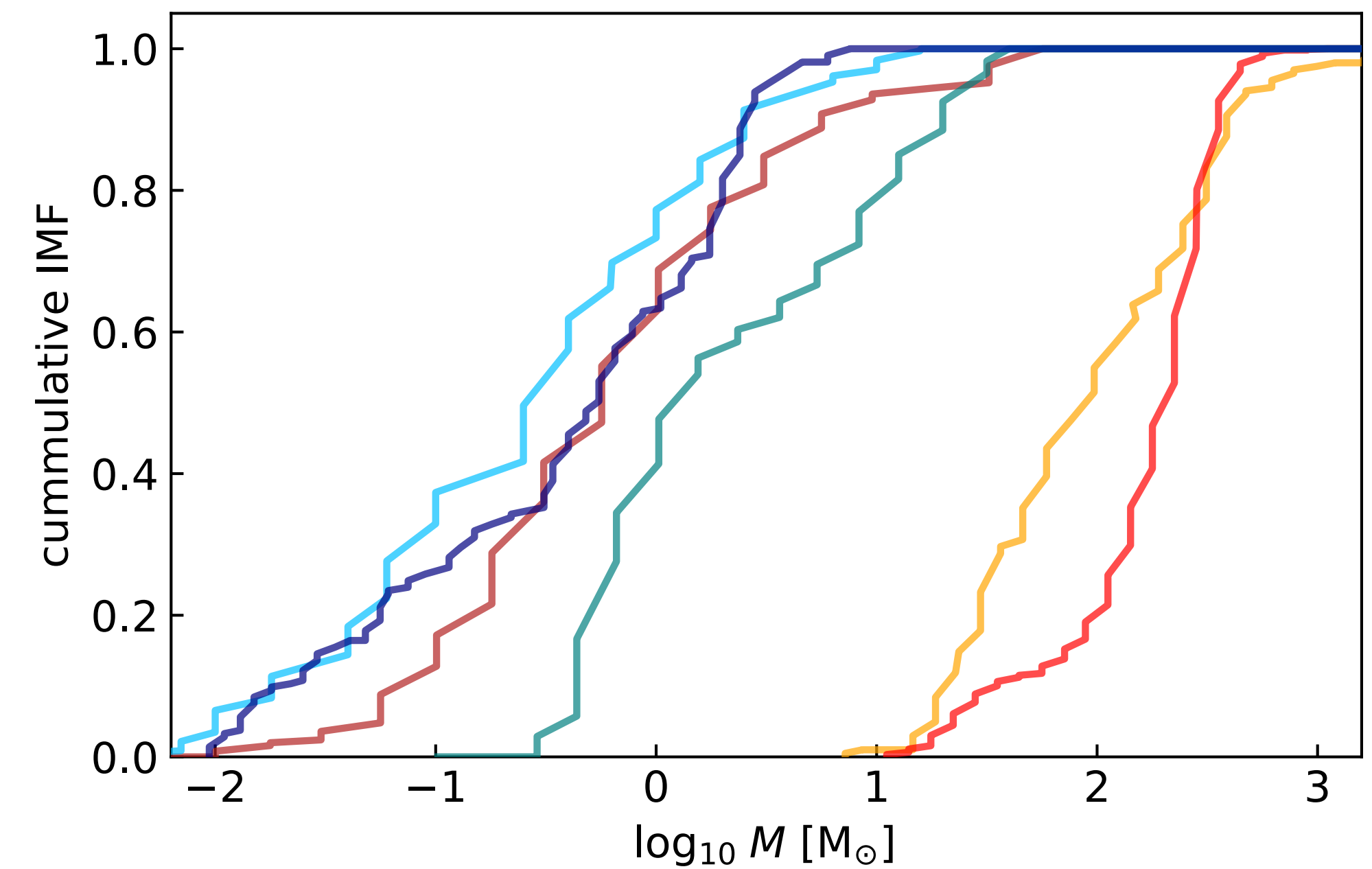
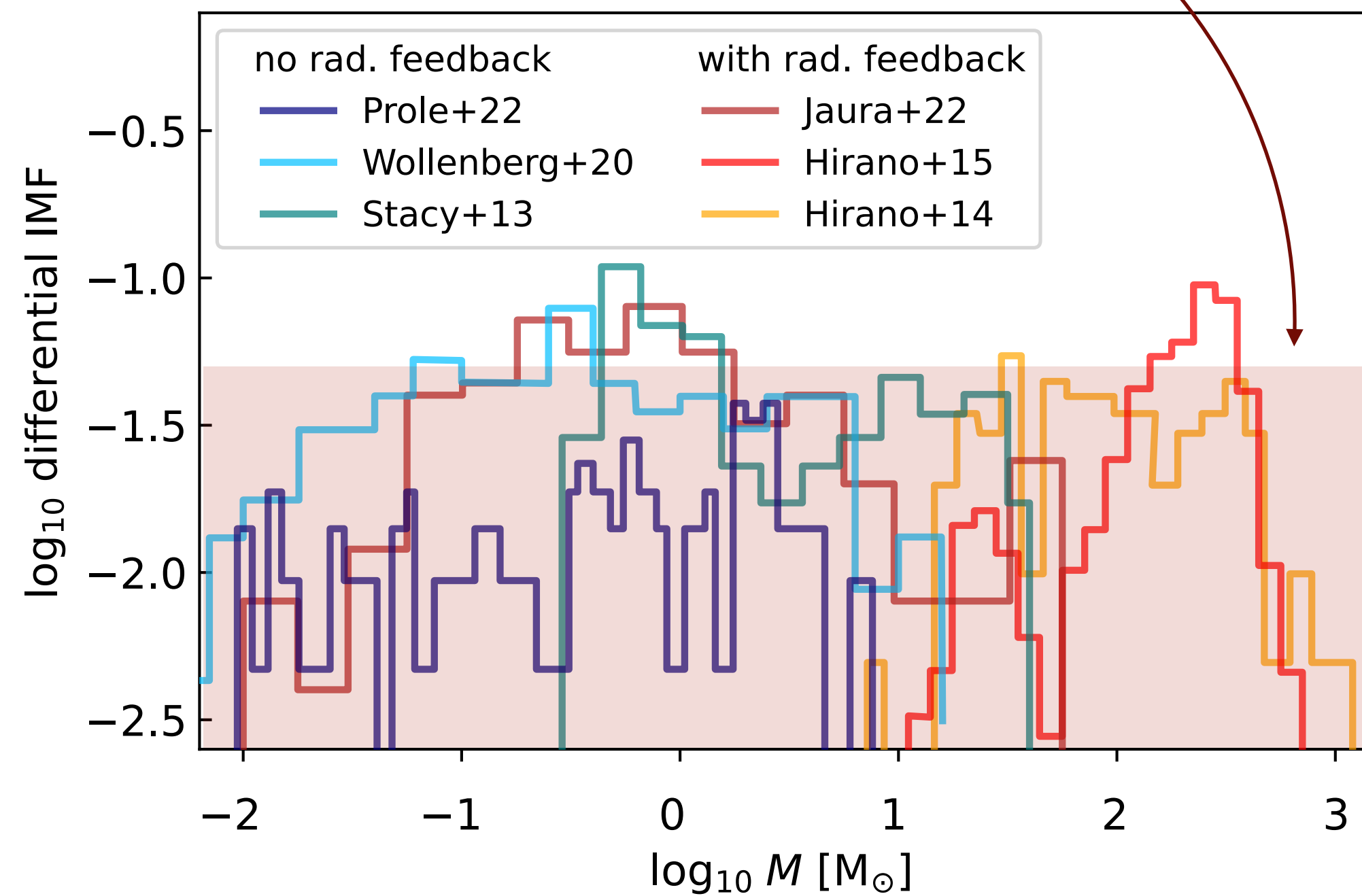
IMF of Pop III stars



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simulations suggest IMF of metal-free stars is **log flat** (meaning it is top heavy)

BUT: result depends strongly on *numerical resolution*, and on the *physics* involved, and on the way *feedback* is taken into account.



complications from more complex physics



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- our best guess for the *IMF of Pop III stars* is a **log-flat distribution** ranging from masses of **$\lesssim 1 M_{\odot}$ up few $100 M_{\odot}$**
- in the context of Pop III
 - **radiation**
 - **magnetic fields**
 - **DM annihilation**
 will **reduce degree of fragmentation**
 - relative **streaming velocity** between DM and baryons
 will increase level of turbulence and may **lead to more fragmentation**
- extreme conditions (huge mass reservoir, high density, high accretion rates) lead to formation of **supermassive stars**, which can collapse into **supermassive black holes**

IMF of primordial stars not well understood.
For time being: treat as poorly constraint parameter.

intermezzo: properties of Pop II stars



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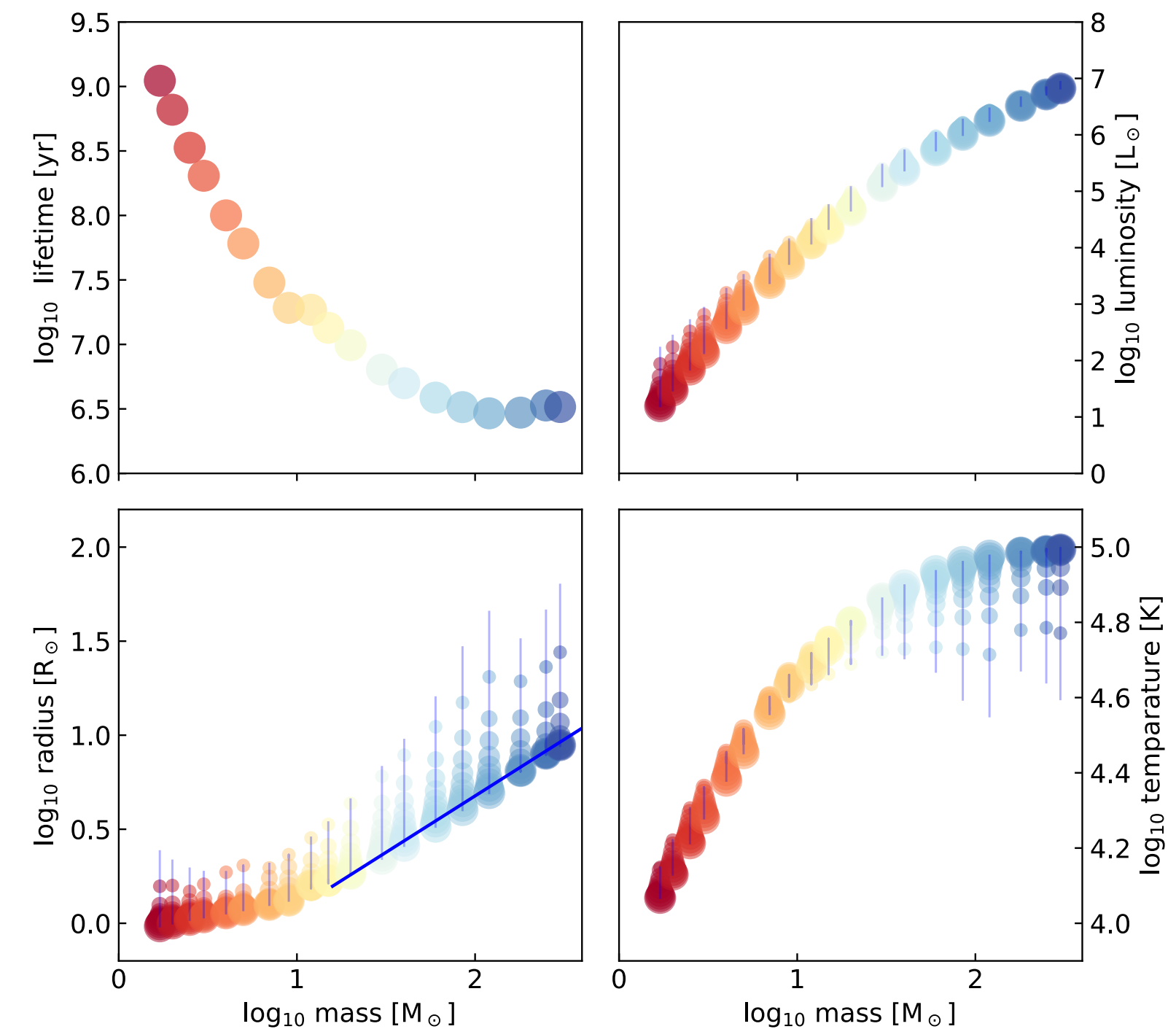
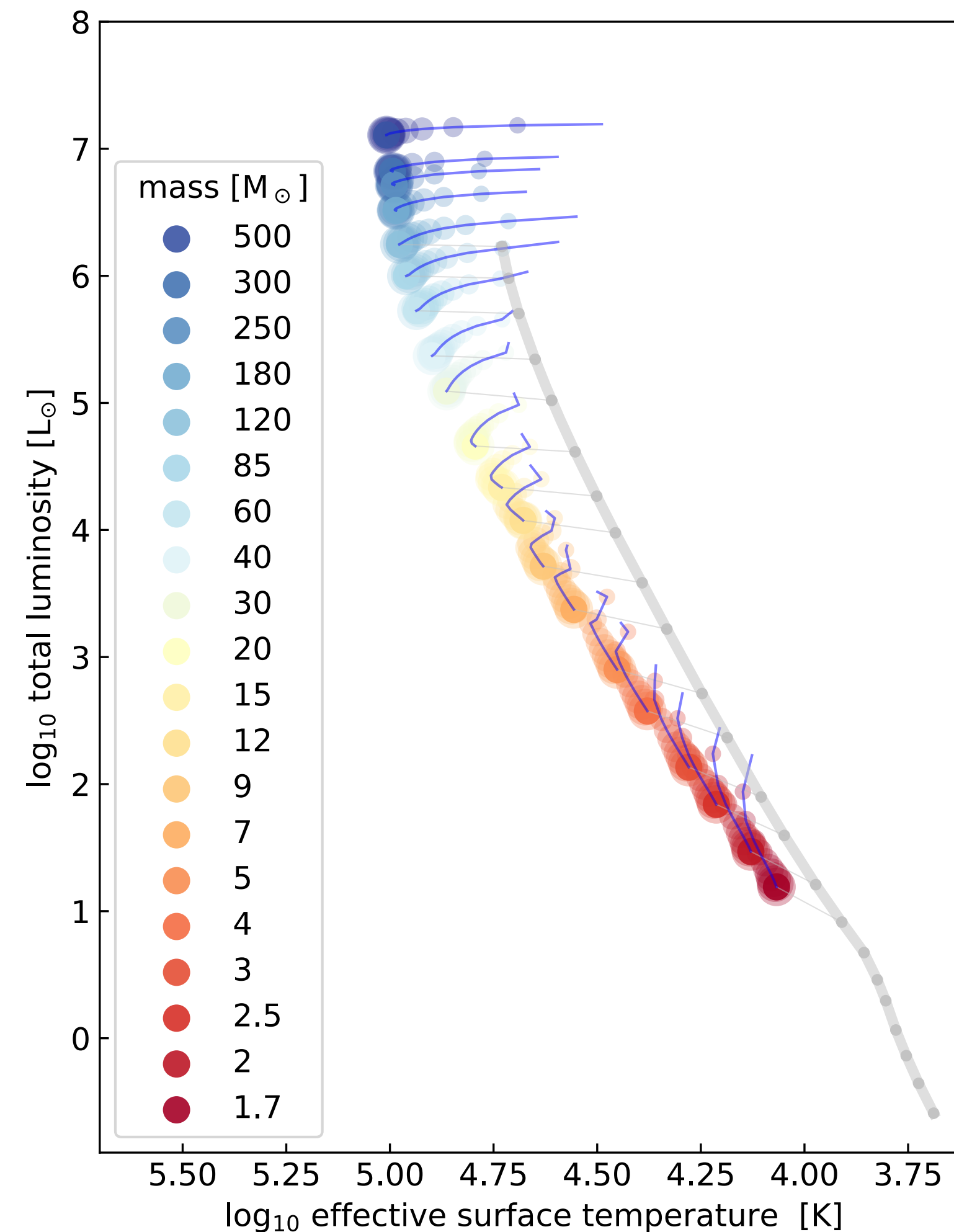


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some properties of Pop III stars



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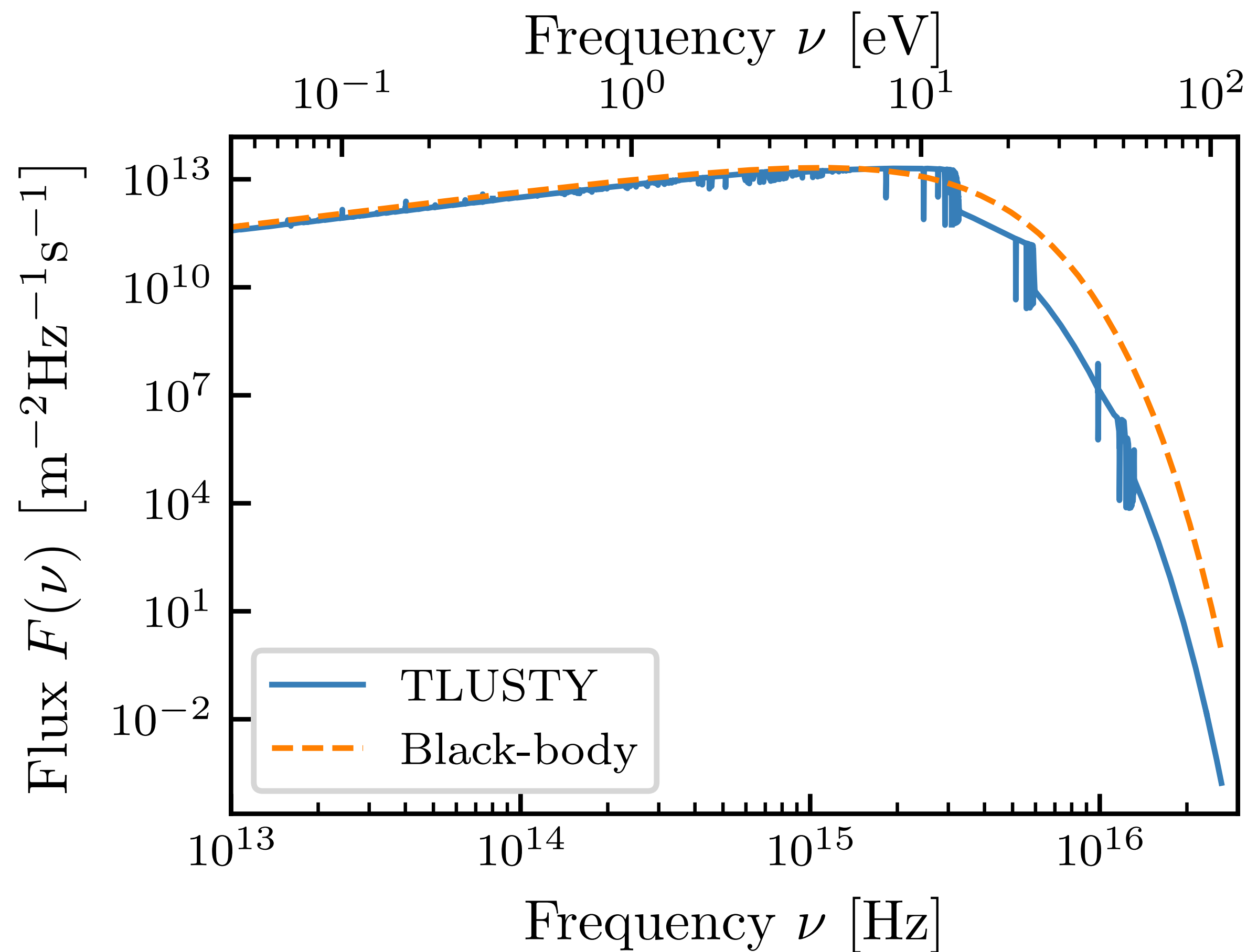
Pop III stars are typically more compact and hotter than their Pop II/I counterparts. But they have similar bolometric luminosity.

Klessen, & Glover (2023, ARAA, 61, 65)

BUT: spectra are more complex than simple blackbodies, and so this consideration may be wrong by a factor of a few



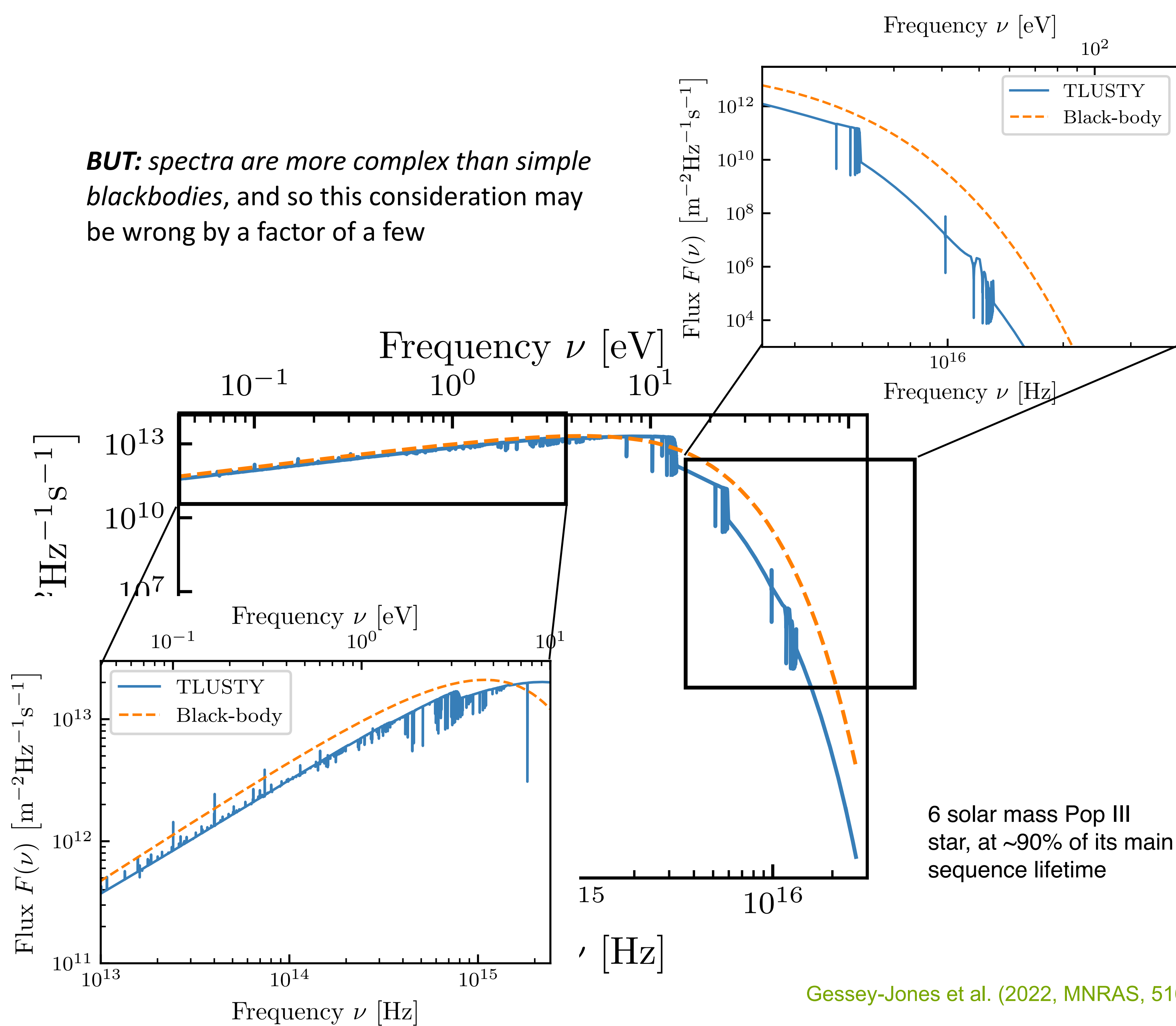
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6 solar mass Pop III
star, at ~90% of its main
sequence lifetime

star
III
OO
L

BUT: spectra are more complex than simple blackbodies, and so this consideration may be wrong by a factor of a few



Gessey-Jones et al. (2022, MNRAS, 516, 841)

pathway to supermassive stars



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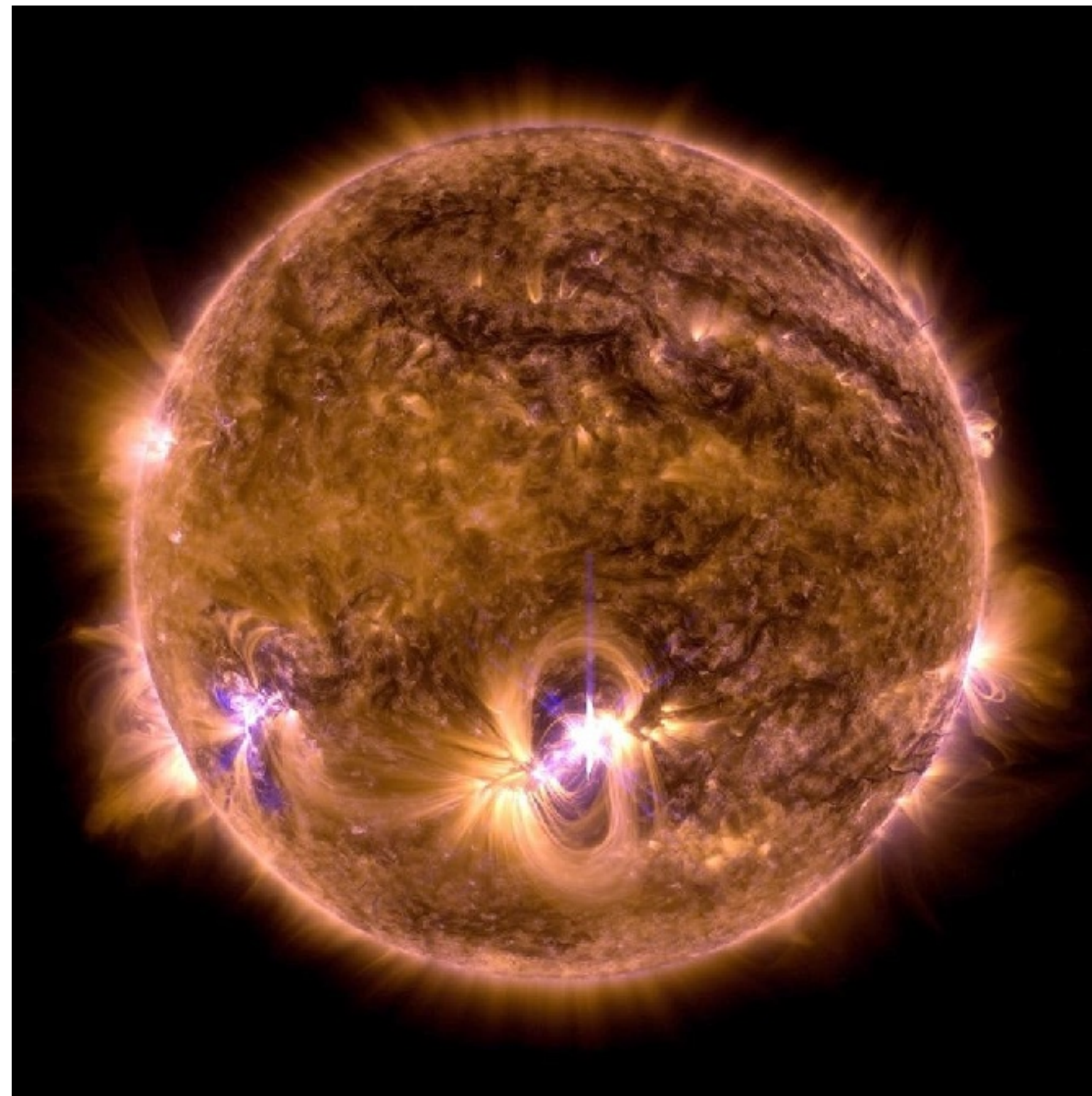


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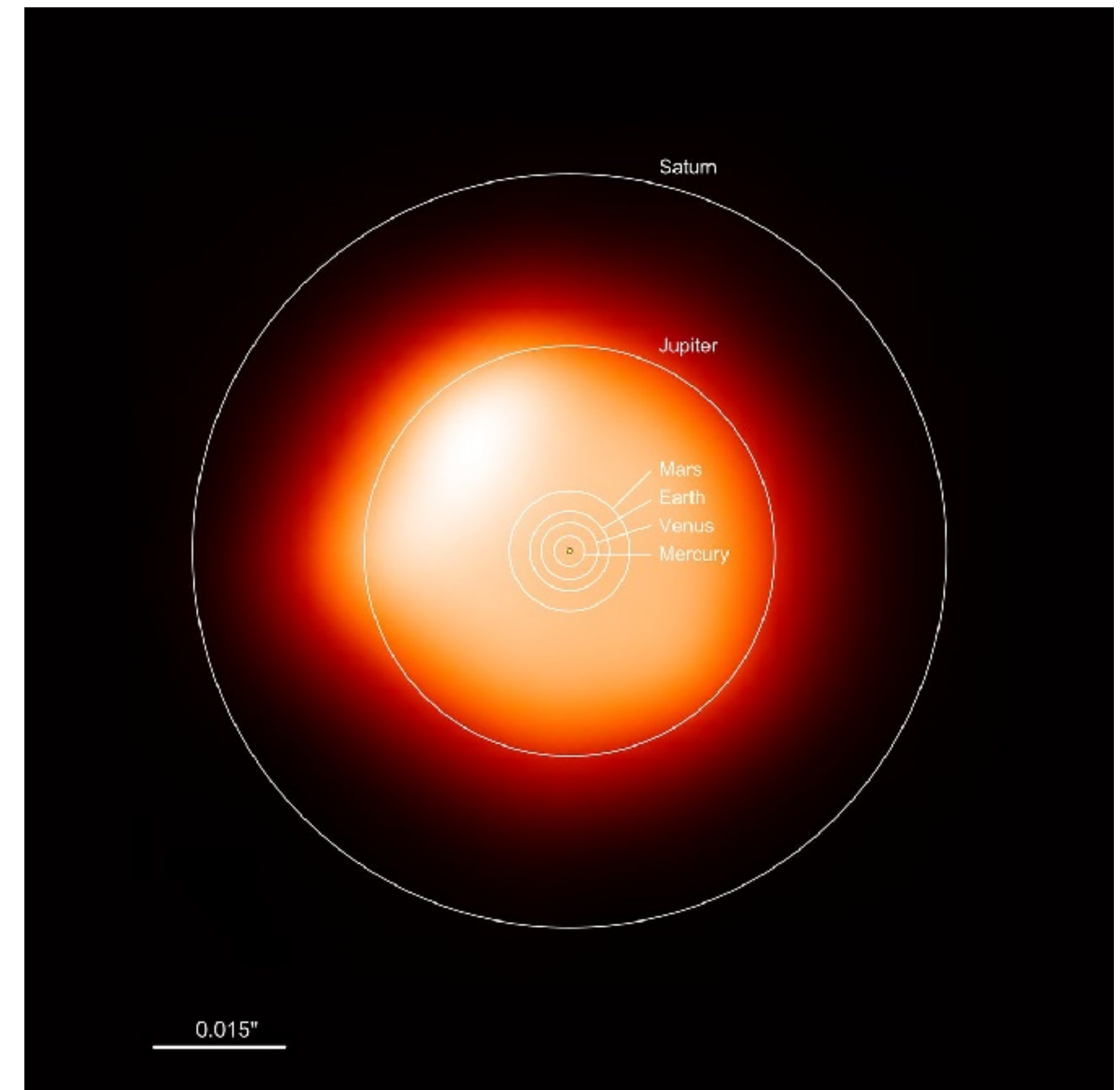
giant stars



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our Sun, a main sequence star, emits a strong solar flare flashes in this image captured by NASA's Solar Dynamics Observatory.



red supergiant Betelgeuse — one of the largest stars known. ALMA (ESO/NAOJ/NRAO)/E. O’Gorman/P. Kervella

what is needed to get higher masses?



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criteria for collapse and star formation

- look at competition between gravity (density ρ) and gas pressure (sound speed c_s or temperature T): **Jeans mass**
- critical mass:

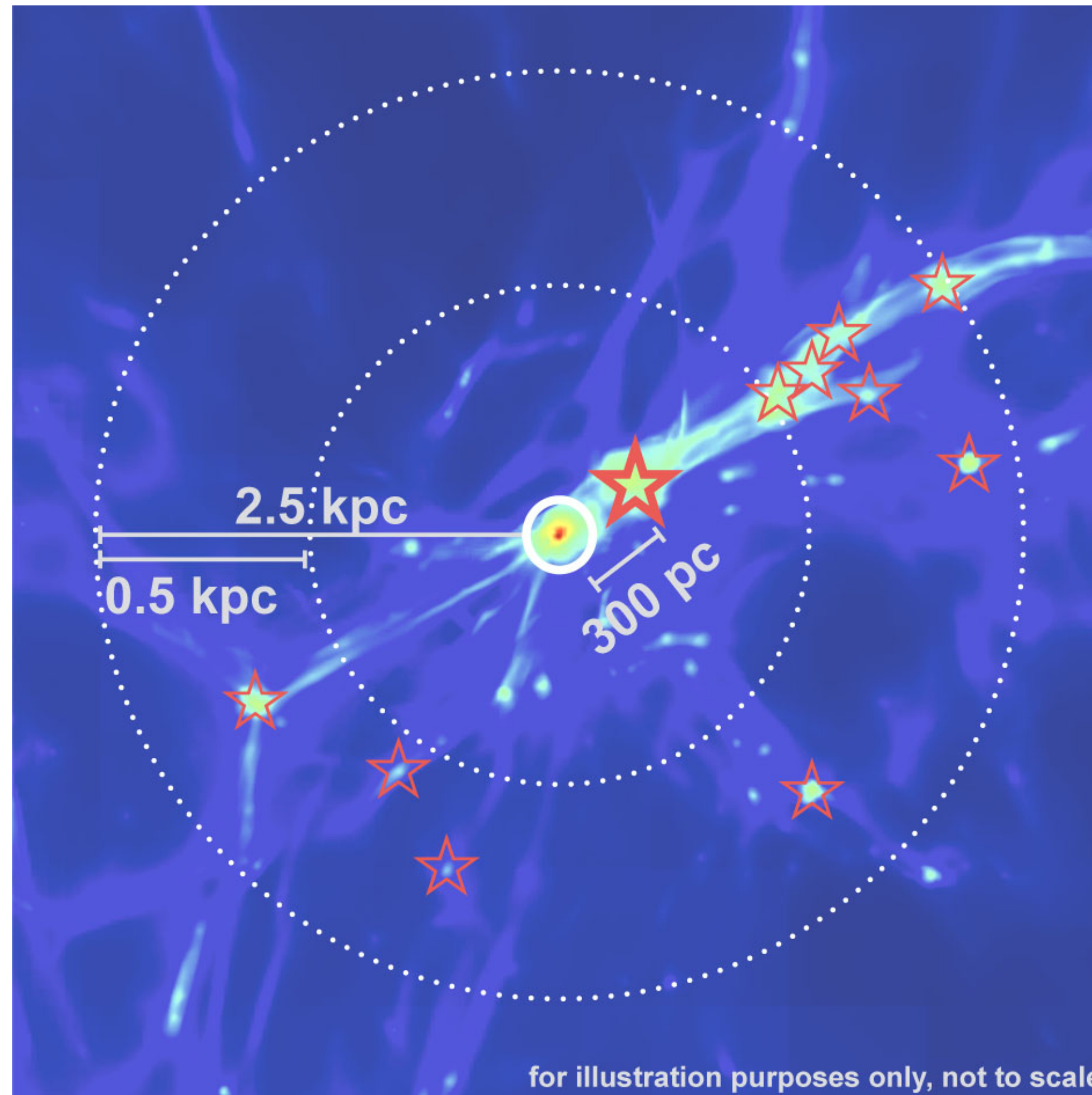
$$M_J = \frac{\pi^{5/2}}{6} \left(\frac{1}{G} \right)^{3/2} \rho^{-1/2} c_s^3 = \frac{\pi^{5/2}}{6} \left(\frac{k}{G} \right)^{3/2} \left(\frac{1}{\mu m_H} \right)^2 n^{-1/2} T^{3/2}$$

- M_J goes up if $T \nearrow$ or $\rho \searrow$
—> ***larger mass reservoir available in atomic cooling halos (as needed for SMS)***
- note: can be extended by considering effective sound speed
 $c_{s,\text{eff}}^2 = c_s^2 + \sigma^2$ with $\sigma = \sigma_{\text{turb}}$ or $\sigma = v_{\text{Alfven}}$
—> ***higher masses favored in magnetized halos and in presence of high streaming velocity***

atomic cooling halos



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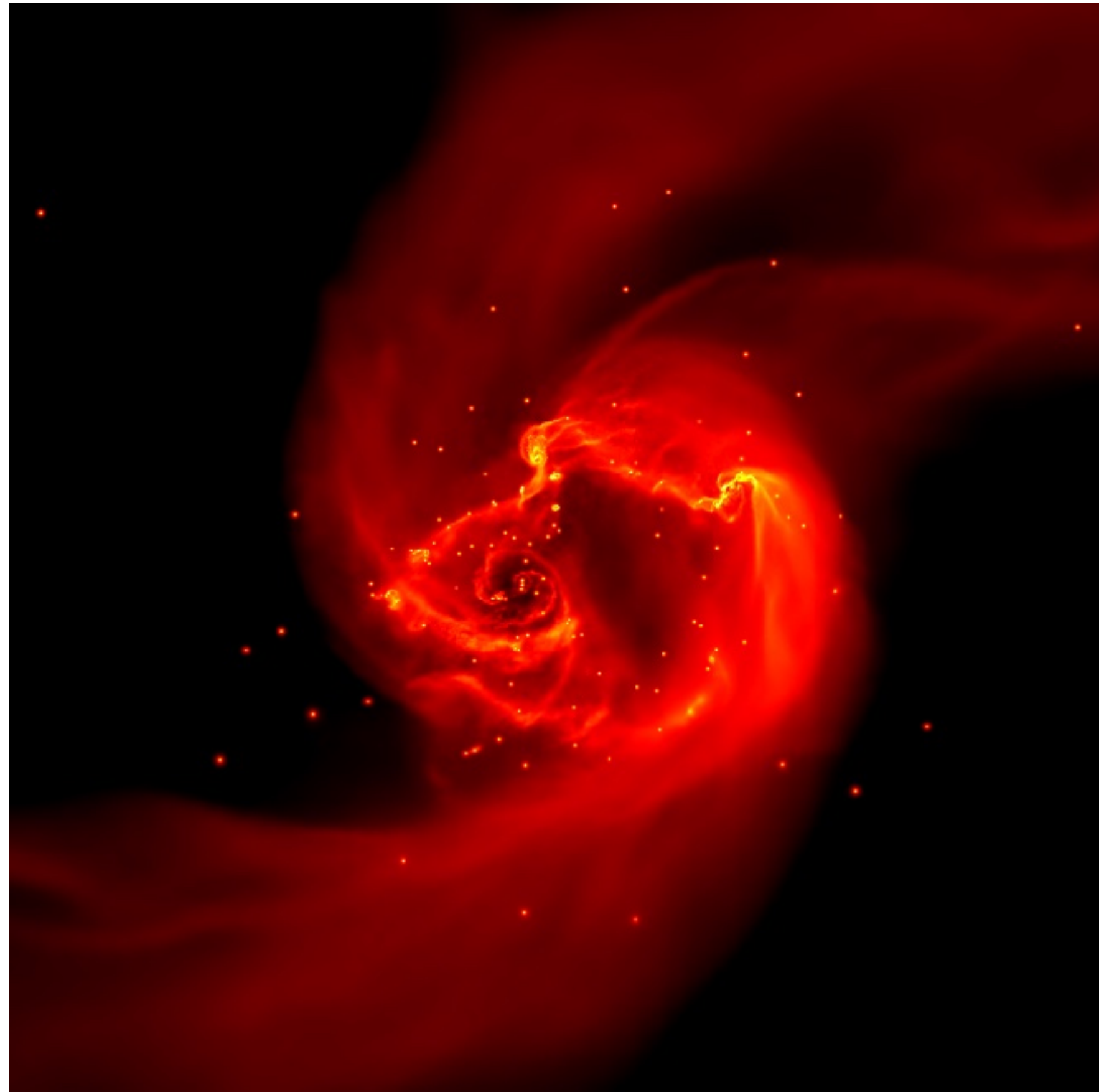


- halos come in groups
- some form Pop III stars early
- their LW/UV radiation keeps neighboring halos in atomic phase → **delayed SF**
- need well tuned conditions: “goldilock” scenario
- these sit there and accumulate mass until they collapse in atomic phase
- large gas reservoir and large inflow rates → **enhanced SF**
- remark: similar conditions are found in gas-rich high-z mergers

atomic cooling halos —> even more fragmentation!



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- halos come in groups
- some form Pop III stars early
- their LW/UV radiation keeps neighboring halos in atomic phase —> **delayed SF**
- these sit there and accumulate mass until they collapse in atomic phase —> **rapid SF**
- BUT: now rapid H₂ formation, and lots of fragmentation
—> **cluster of stars**
- again **not** a good environment for direct collapse BH

not just large mass reservoir, SMS also need dM/dt

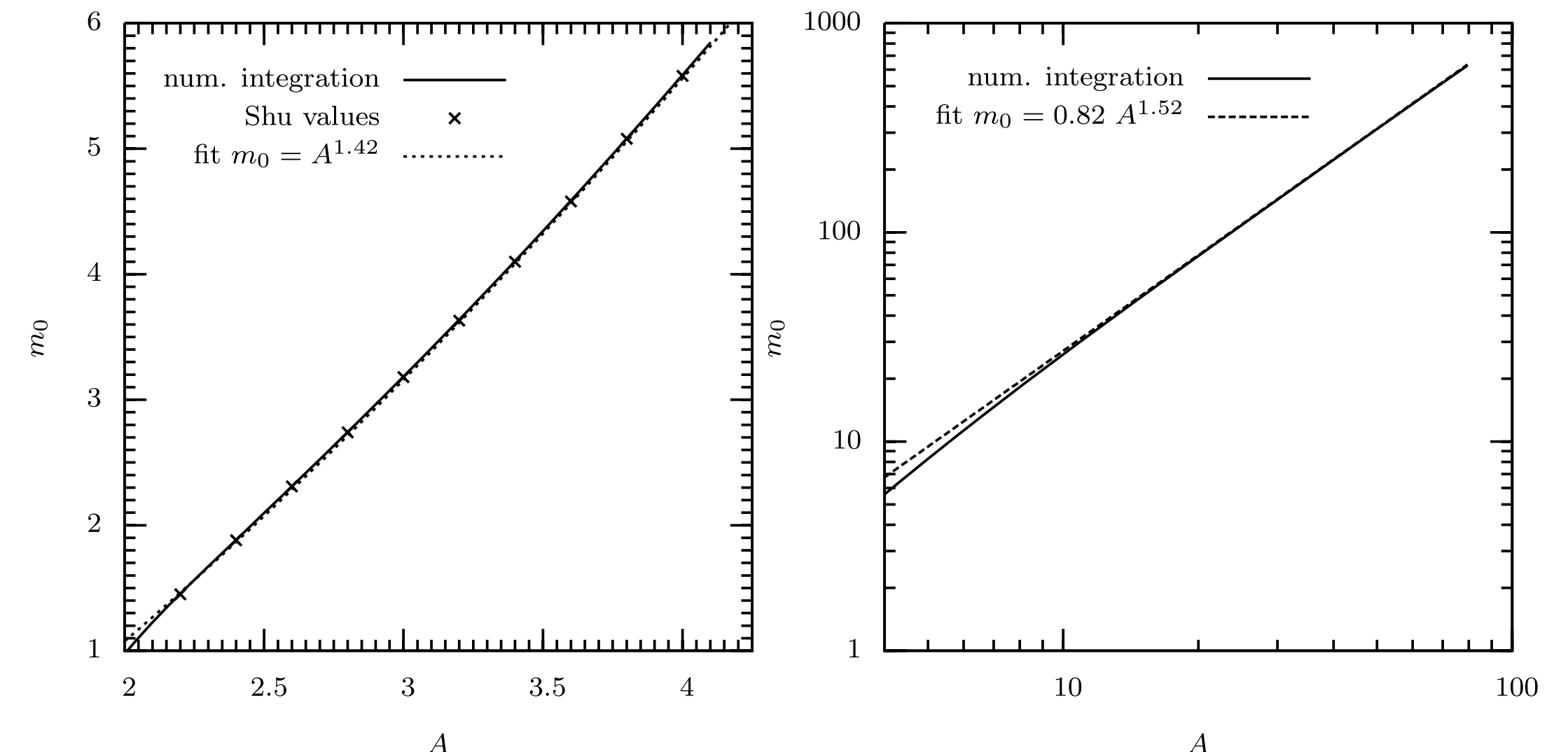


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what is the resulting accretion rate?

- simple isothermal models give $\dot{M} = m_0 c_s^3 / G$ (see e.g. Shu 1977)
- **so again $\dot{M} \nearrow$ if $T \nearrow$**
- BUT: recall there is also the *multiplication factor* $m_0 \propto A^{3/2}$ with $A \propto N_J^{2/3}$ so that $m_0 \propto N_J$ with N_J number of Jeans masses (Girichidis et al. 2011)
- **also: $\dot{M} \nearrow$ in collisions of two halos or two proto galaxies**
(e.g. Zwick 2023, MNRAS, 518, 2076)
- again high degree of turbulence will lead to **fragmentation**

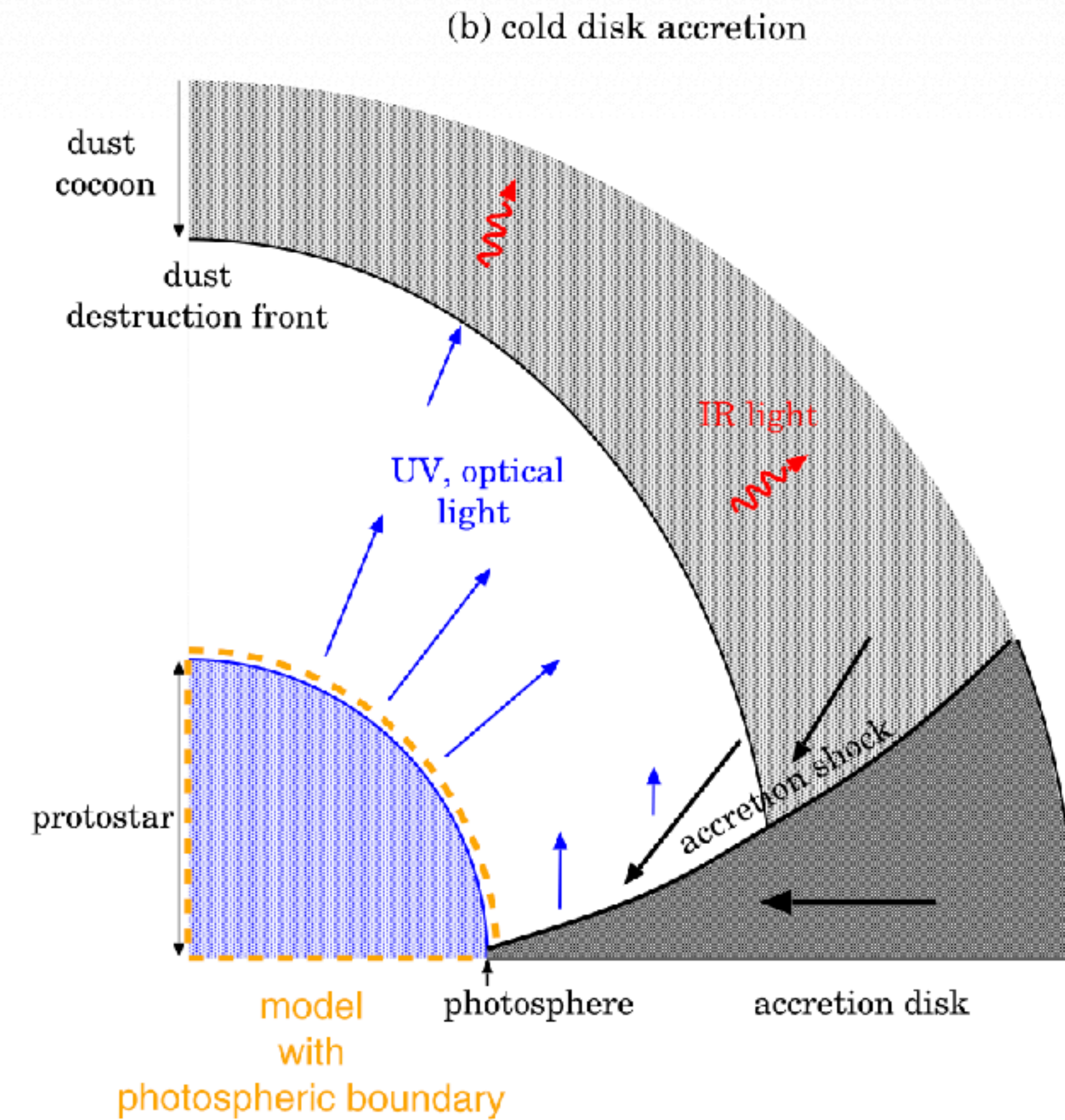
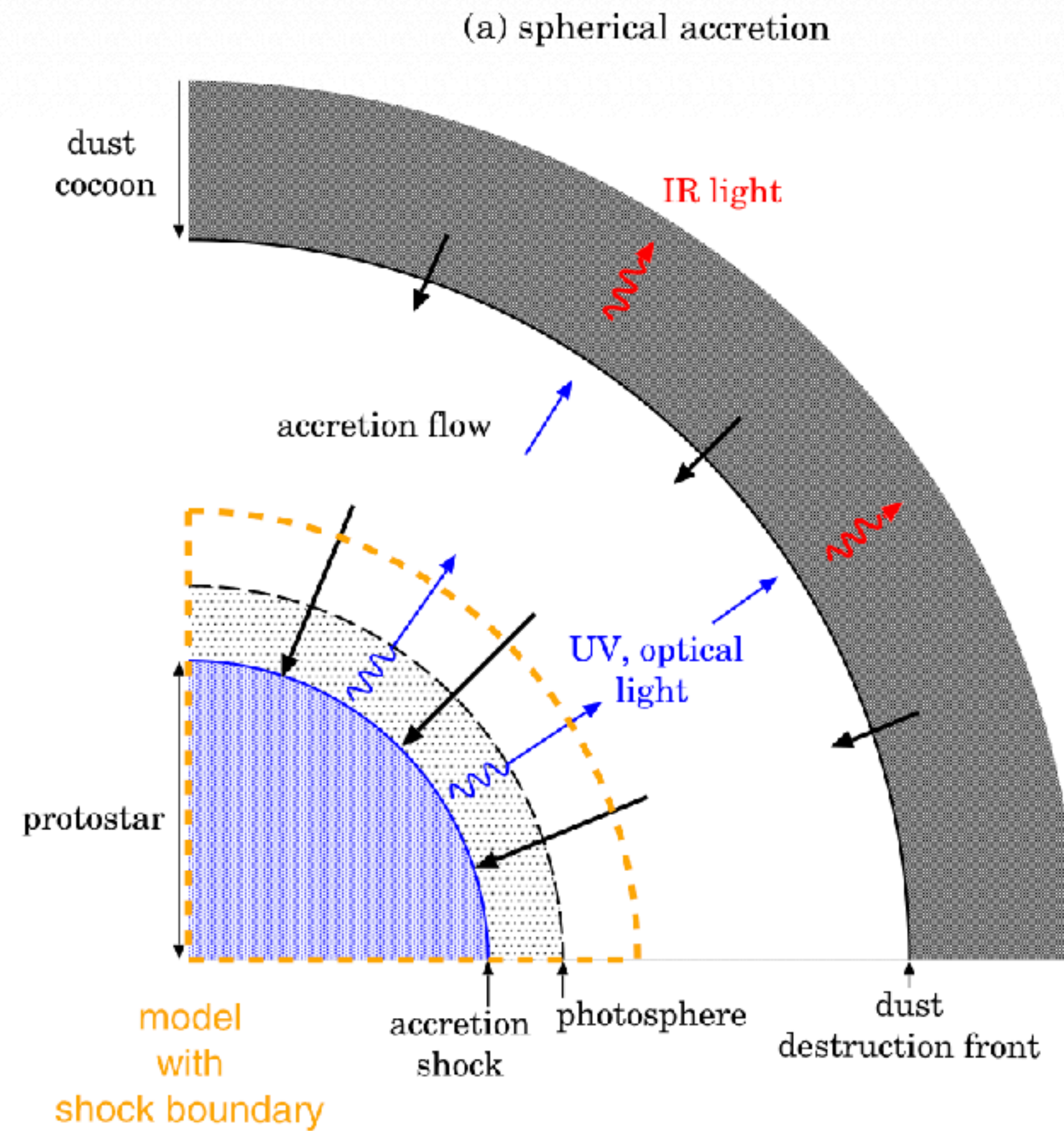
Shu (1977, ApJ, 214, 488),
Girichidis et al. (2011, MNRAS, 413, 2741),
Mayer et al. (2010, Nature, 466, 108)



role of accretion and mass growth



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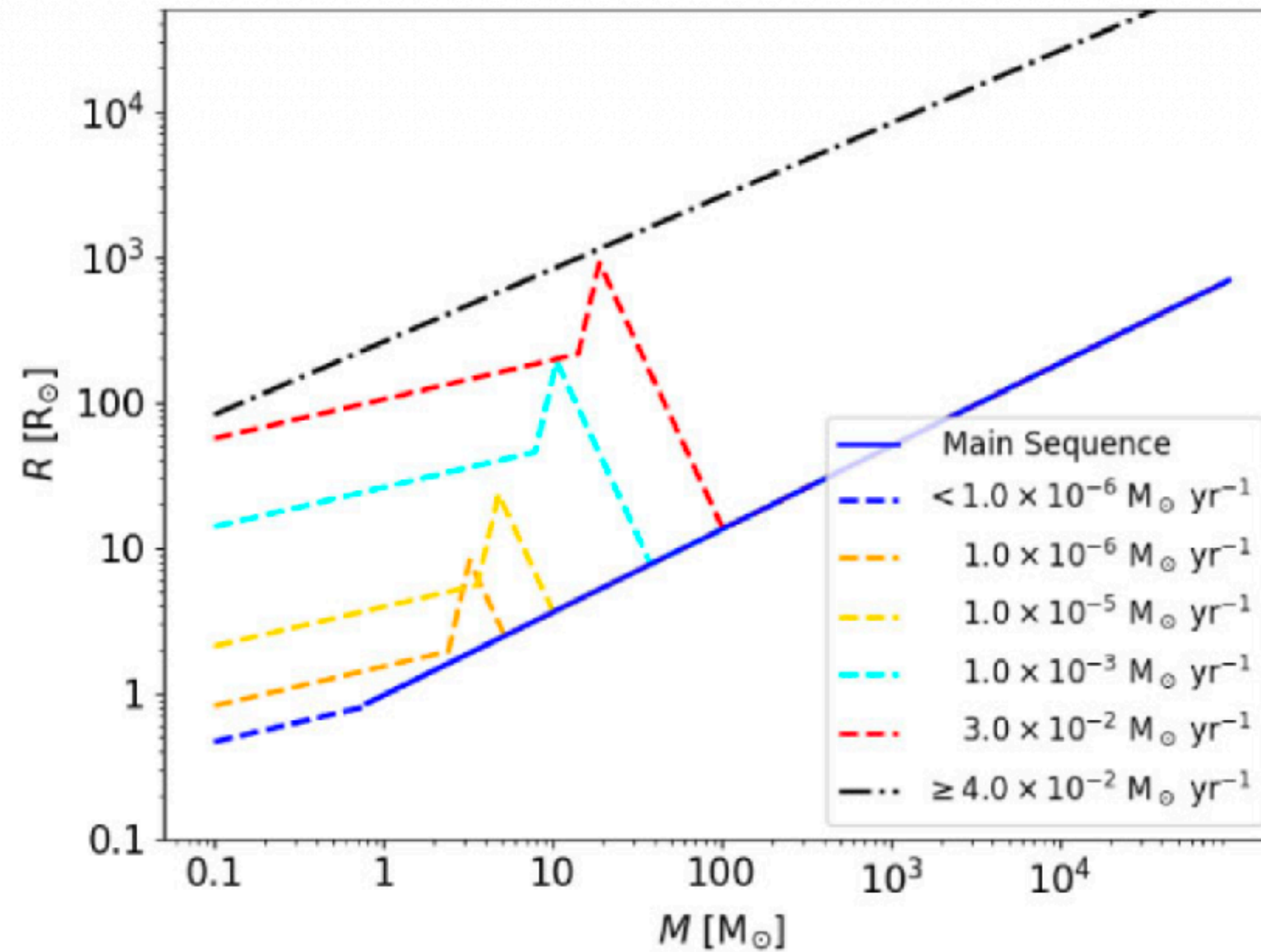


Hosokawa et al. (2010, ApJ, 721, 478)

role of accretion and mass growth



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- depending on accretion rate, the star may never go through Kelvin-Helmholtz contraction phase!
- star remains puffy and red as long as the accretion flow is maintained.
- surface temperatures remain low, even for high-mass stars:
 $T \sim 3000 - 4000 \text{ K}$

important consequences
for early star formation
and cosmic reionization!

stellar evolution with different dM/dt



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How do stars evolve for different accretion rates?

- for $\dot{M} \geq 0.1 M_{\odot}/\text{yr}$ stars evolve with bloated radii

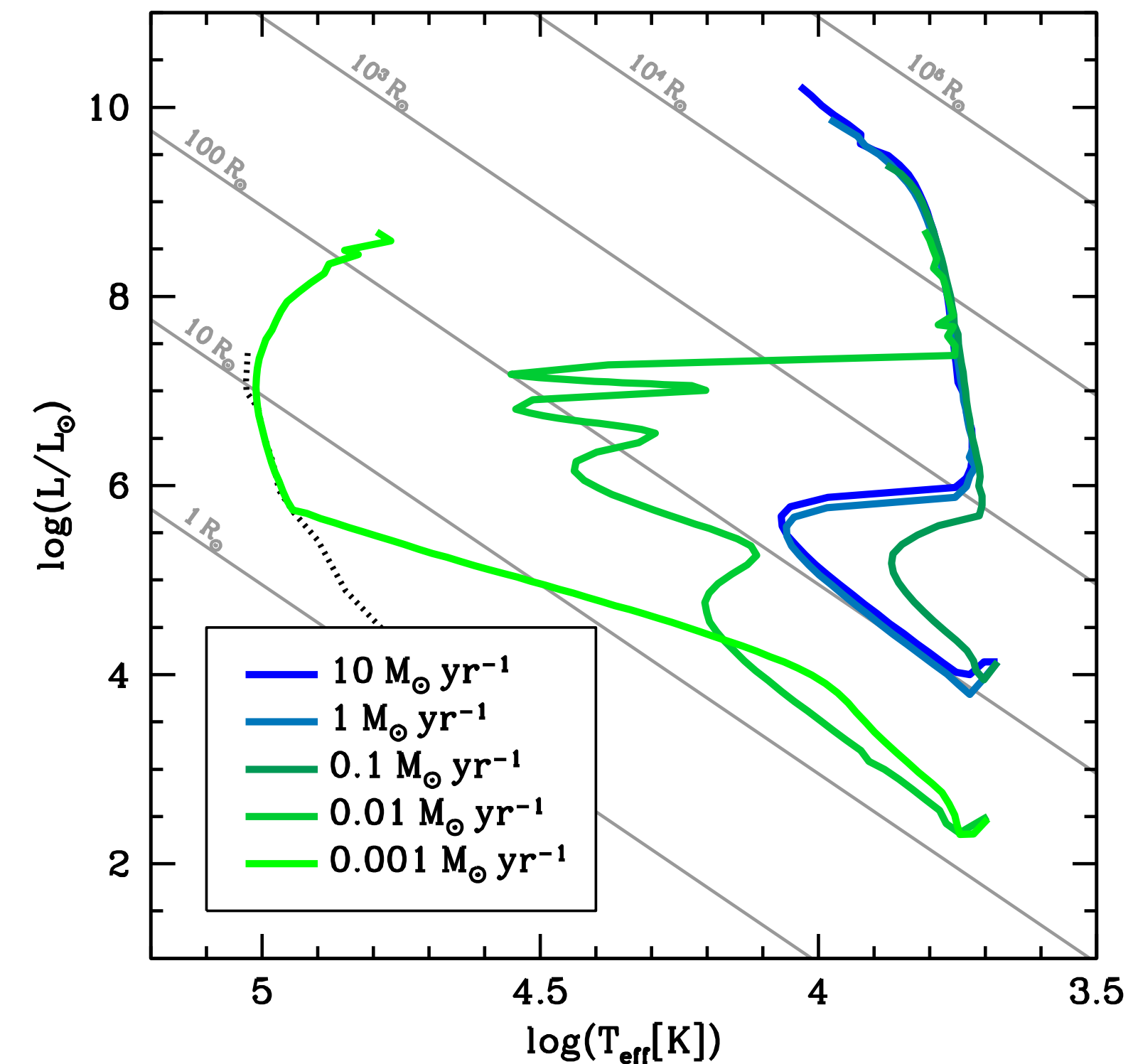


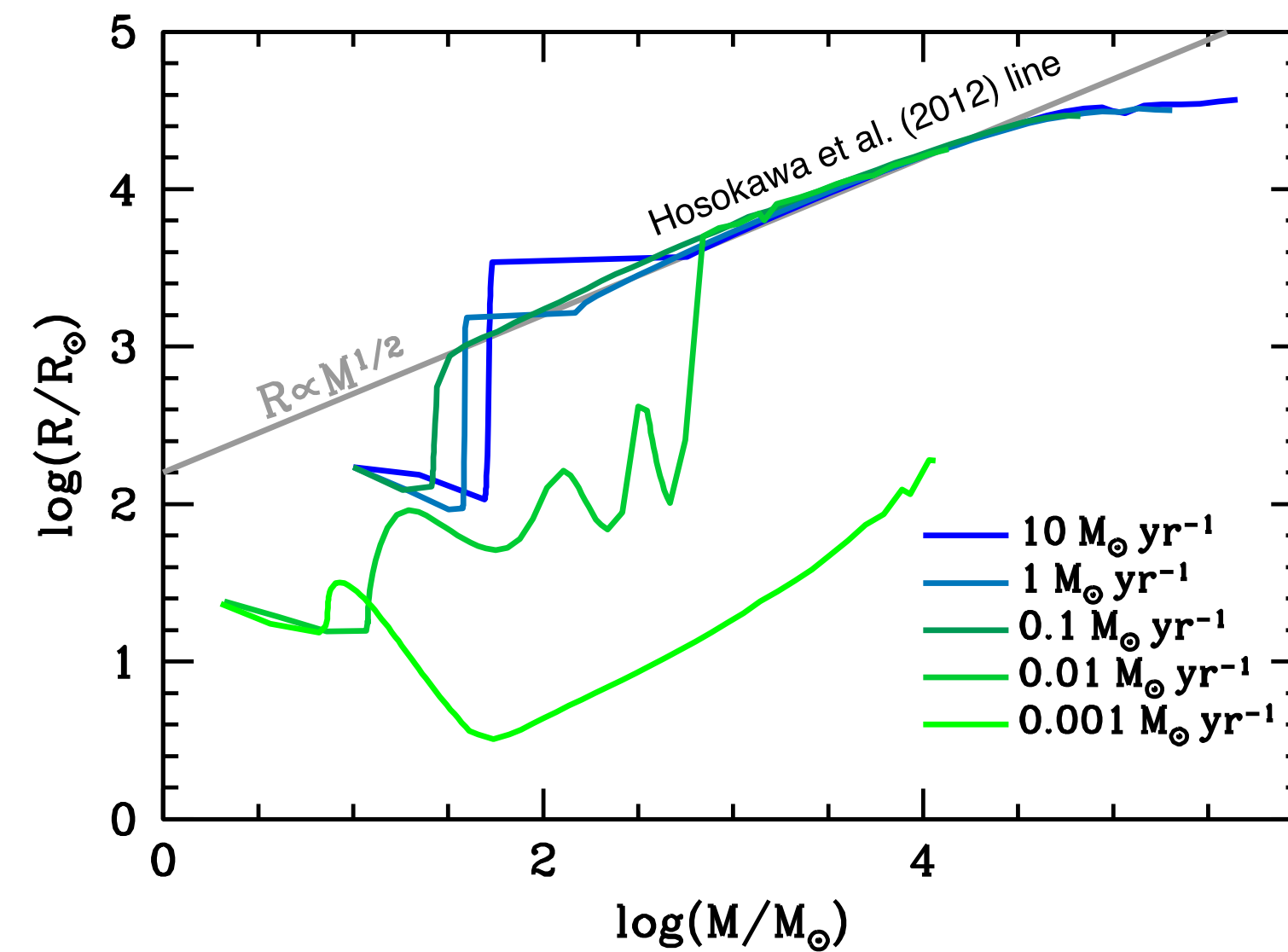
Figure 1. Evolutionary tracks on the HR diagram for the models at the indicated accretion rates. The grey straight lines indicate the stellar radius, and the black dotted curve is the ZAMS of Schaerer (2002).

Haemmerlé et al. (2018, MNRAS 474, 2757)
see also Hosokawa et al. (2012, ApJ, 756, 93),

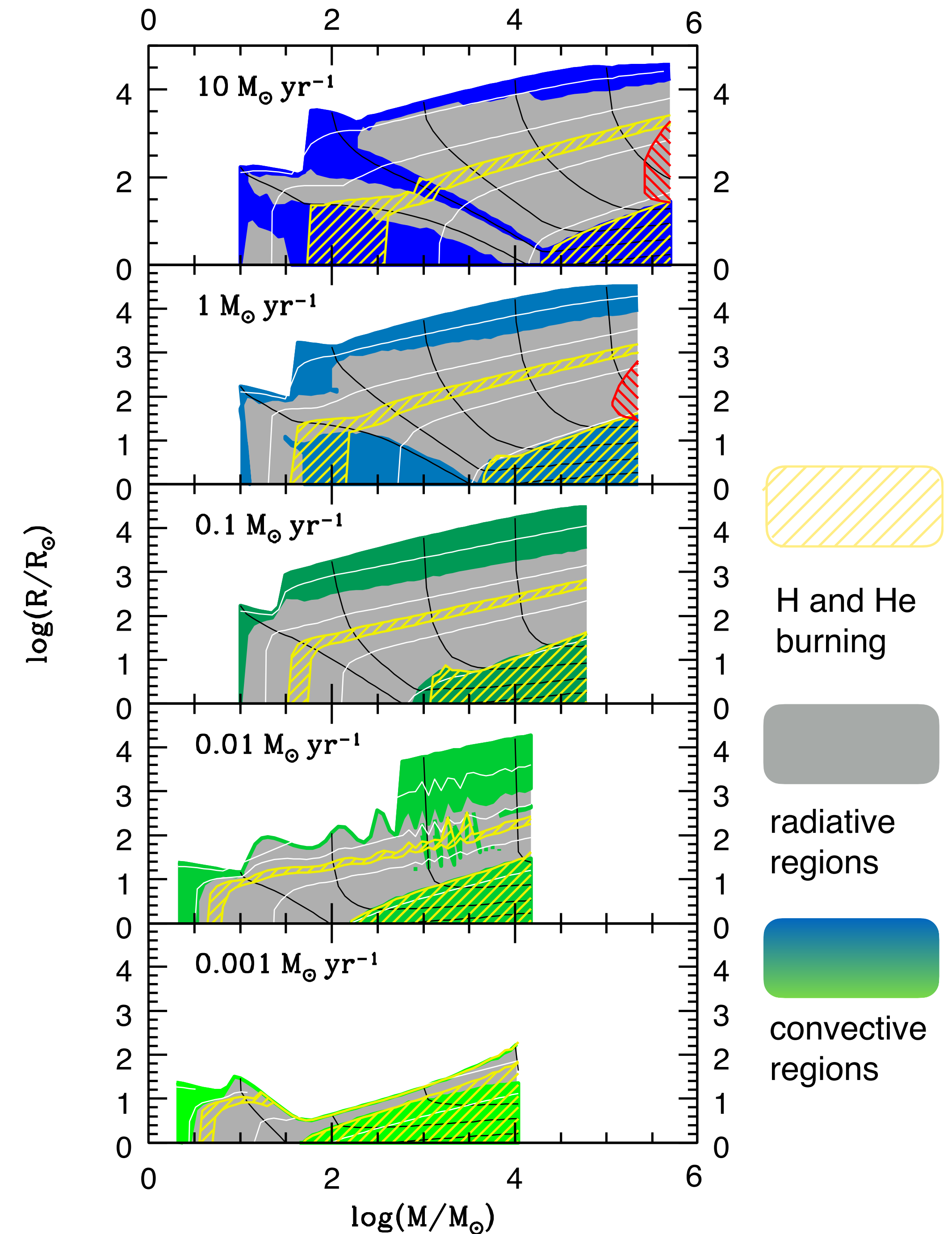
stellar evolution with different dM/dt

How do stars evolve for different accretion rates?

- for $\dot{M} \geq 0.1 M_{\odot}/\text{yr}$ stars evolve with bloated radii
- different stellar structure for different $\dot{M}$



Haemmerlé et al. (2018, MNRAS 474, 2757)
see also Hosokawa et al. (2012, ApJ, 756, 93),



stellar evolution with different dM/dt

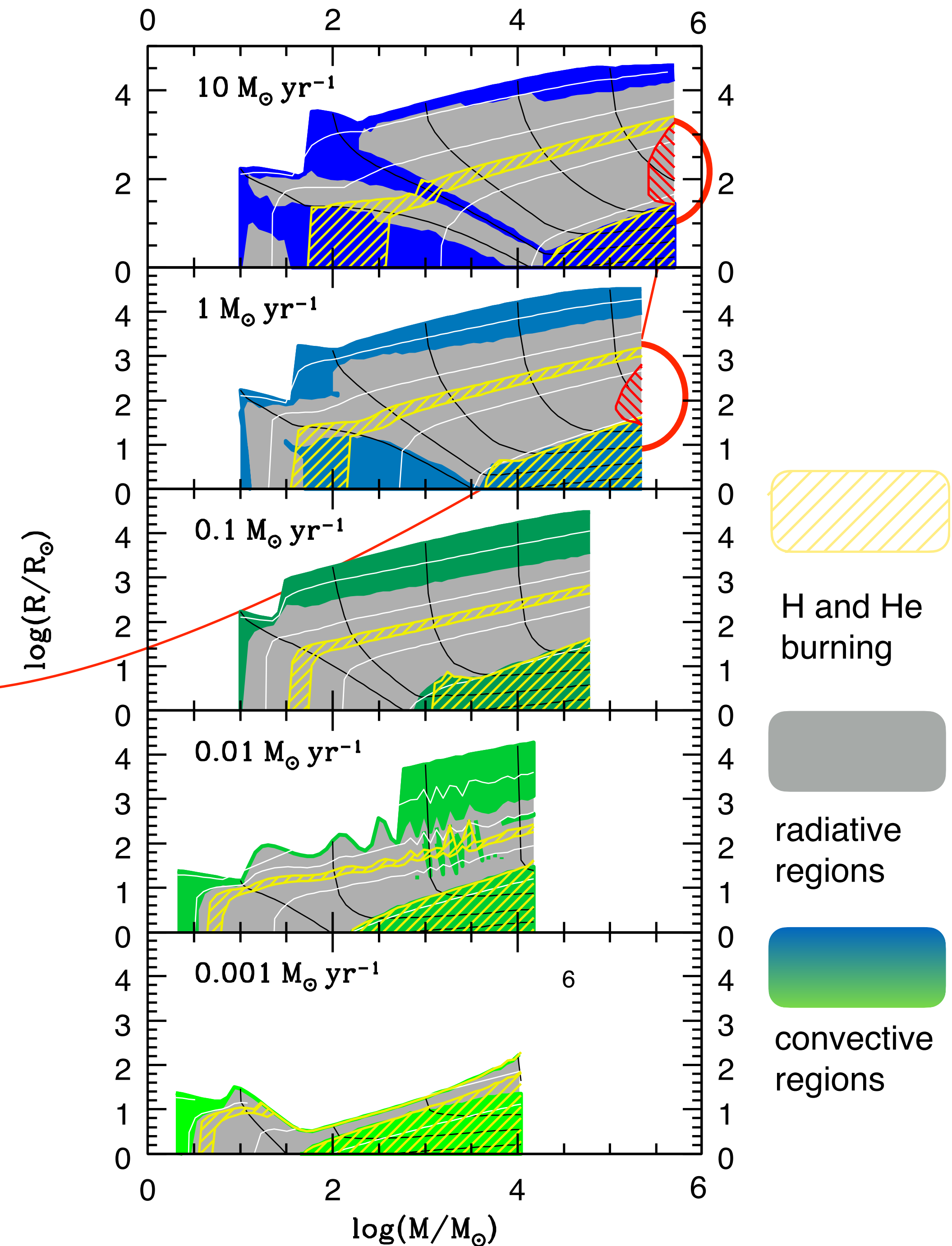
How do stars evolve for different accretion rates?

- for $\dot{M} \geq 0.1 M_{\odot}/\text{yr}$ stars evolve with bloated radii
- different stellar structure for different $\dot{M}$
- for large $\dot{M}$ stars evolve until GR instability sets in

Chandrasekhar (1964, ApJ, 140, 417),
Haemmerlé (2021a, A&A, 647, A83),
Haemmerlé (2021b, A&A 650, A204)

pathway to supermassive stars,
easily reaching several $10^5 M_{\odot}$!

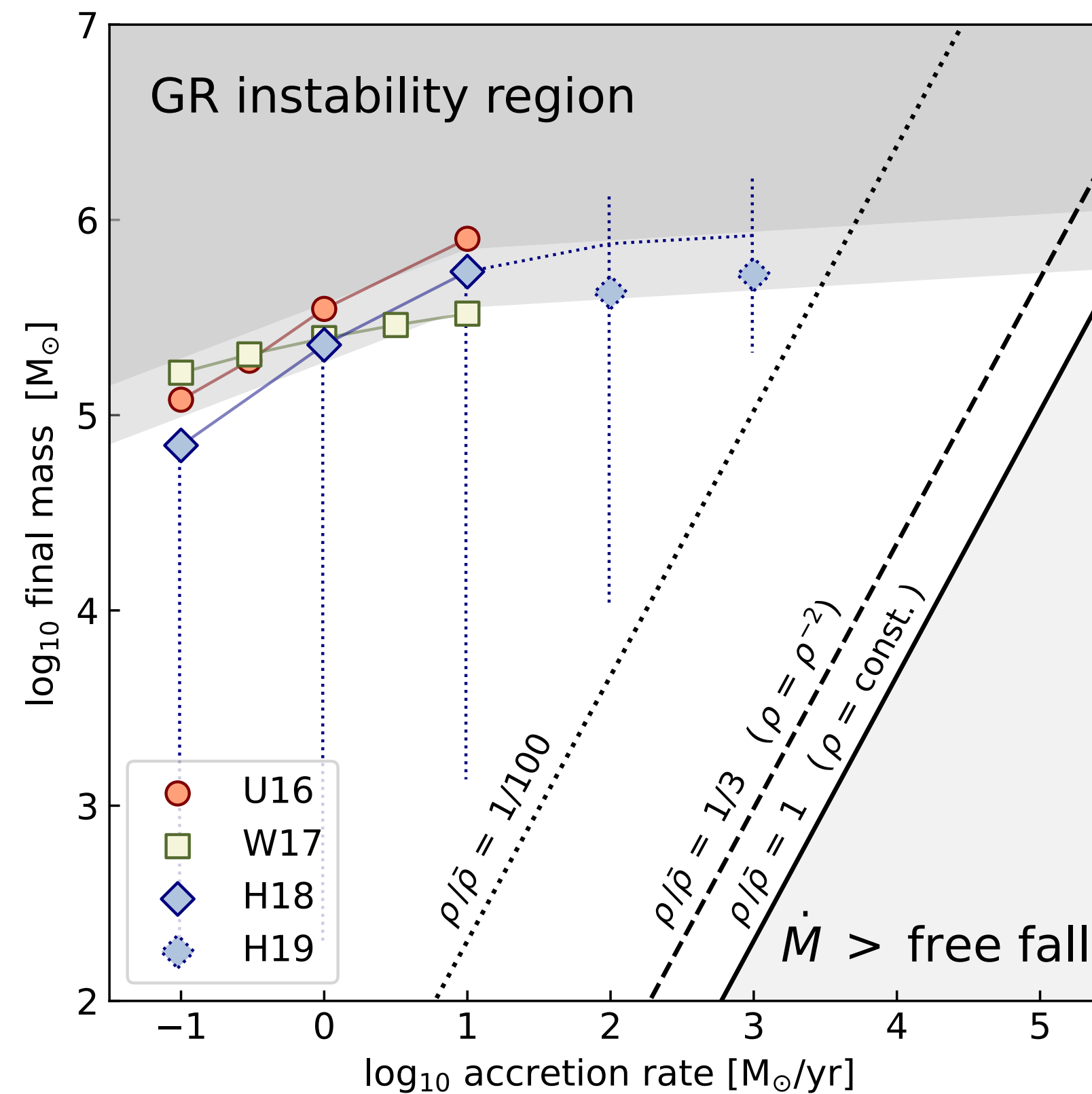
Haemmerlé et al. (2018, MNRAS 474, 2757)
see also Hosokawa et al. (2012, ApJ, 756, 93),



what is the maximum stellar mass possible?



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Umeda et al. (2016, ApJ, 830, L34),
Woods et al. (2017, ApJ, 842, L6),
Haemmerlé et al. (2018, MNRAS, 474, 2757)

- for accretion rate above $0.1 M_{\odot}/\text{yr}$, stars can easily reach several $10^5 M_{\odot}$ before GR instability kicks in
- then they collapse directly into a black hole of the same mass
- while accreting the stars are extremely puffed up and cold (3000 - 4000 K)
- no ionizing radiation: hard to see, little impact

Haemmerlé (2020, A&A 644, A154)
Haemmerlé (2021a, A&A 647, A83)
Haemmerlé (2021b, A&A 650, A204)

image from Klessen, & Glover (2023, ARAA, 61, 65)

we face a dilemma!



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to form SMS, we need

- (1) a sufficiently large mass reservoir ($M_{\text{gas}} \sim 10^6 M_{\odot}$)
- (2) maintain $\dot{M} \geq 0.1 M_{\odot}/\text{yr}$ for a sufficiently long time

then can reach masses above $10^5 M_{\odot}$ before the GR instability kicks in and they collapse into a BH...

BUT:

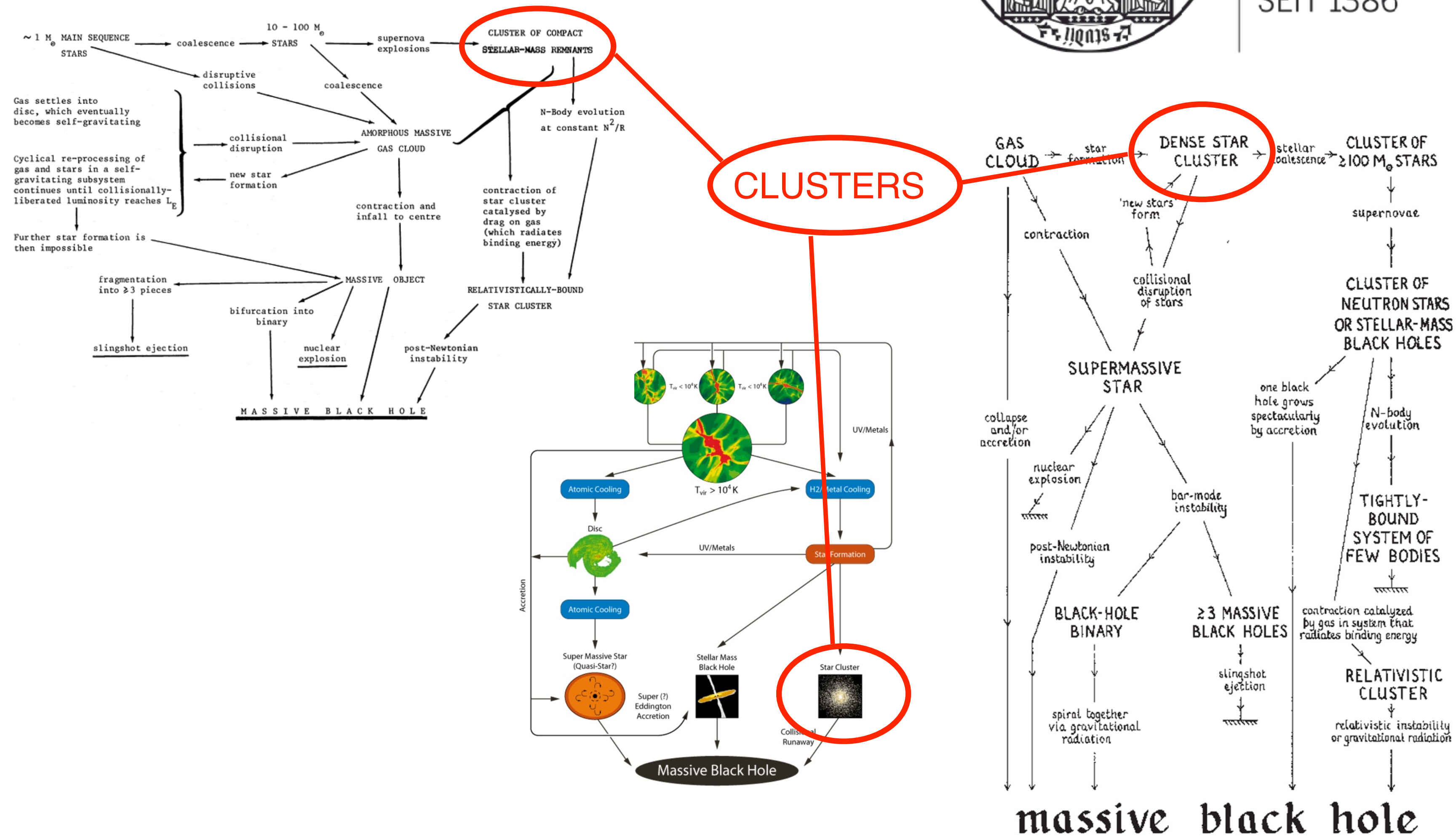
- (3) gas under these conditions will fragment!

WHAT IS THE WAY OUT?

(proto)stellar clusters !!



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Begelman & Rees (1978, MNRAS, 185, 847), Rees (1984, ARA&A, 22, 471),
Regan & Haehnelt (2009, MNRAS, 396, 343), Woods et al. (2019, PASA, 36, e027)

how to form seeds of supermassive BHs?



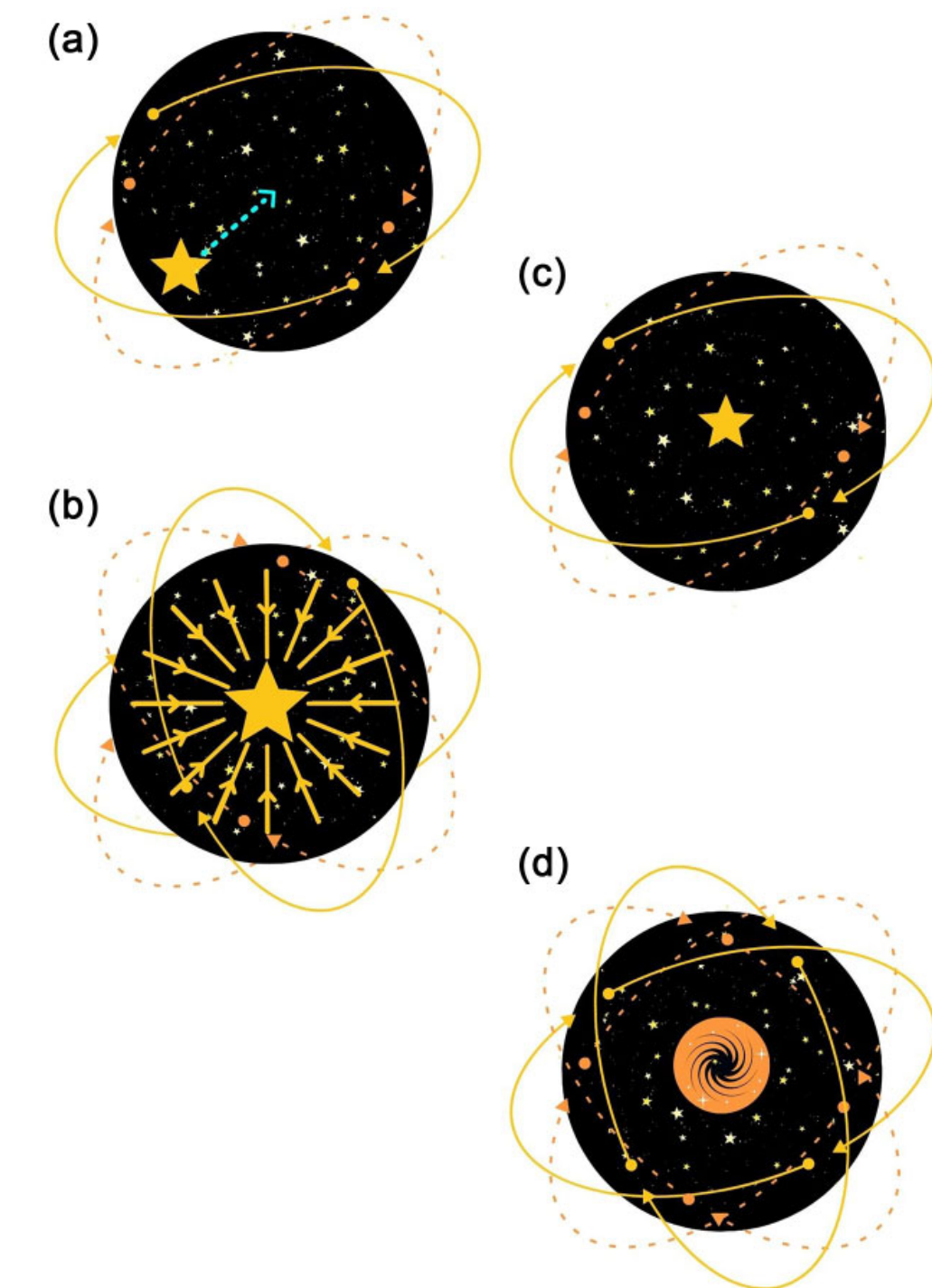
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clusters that form in massive and very dense gas clouds have

- (1) a sufficiently large mass reservoir ($M_{\text{gas}} \sim 10^6 M_{\odot}$)
- (2) individual stars have high accretion rates and evolve along large-R tracks

result is

- (3) combination of high stellar density and large stellar radii results in large collision rates
- (4) together this results in **run-away mass growth** of 1 or 2 objects to build SMS



Schleicher et al. (2022, MNRAS, 512, 6192)

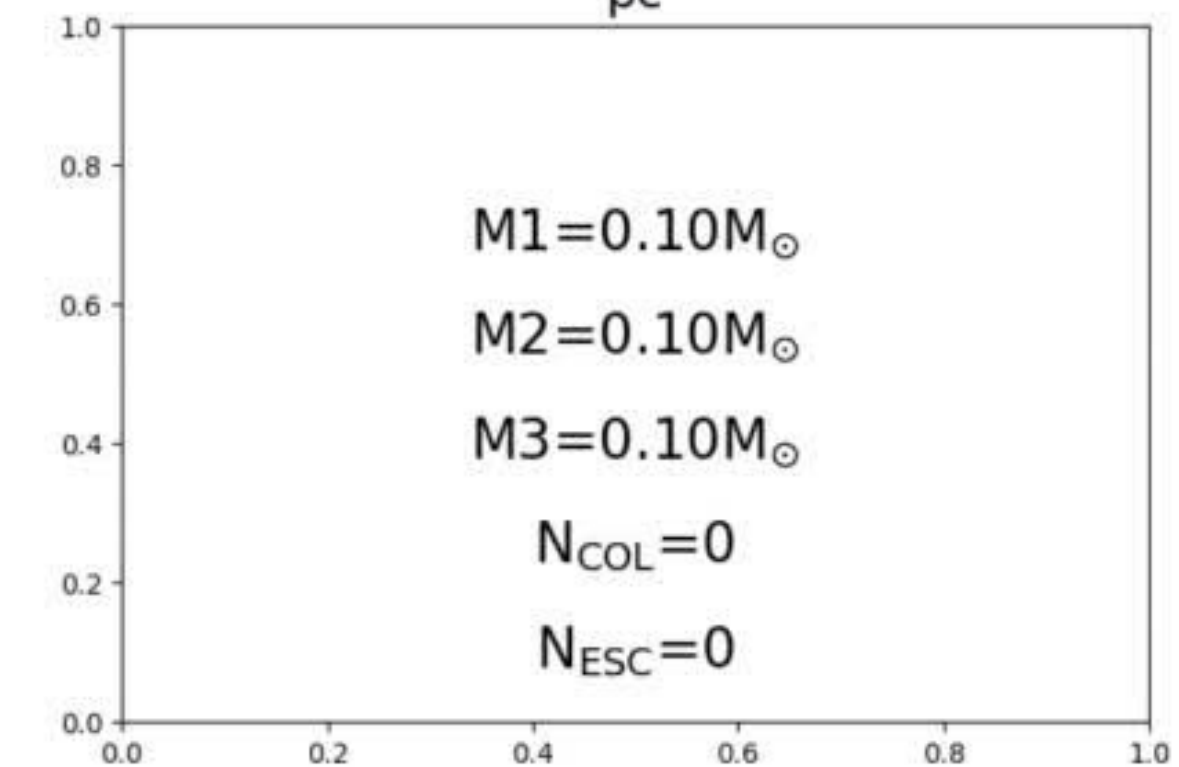
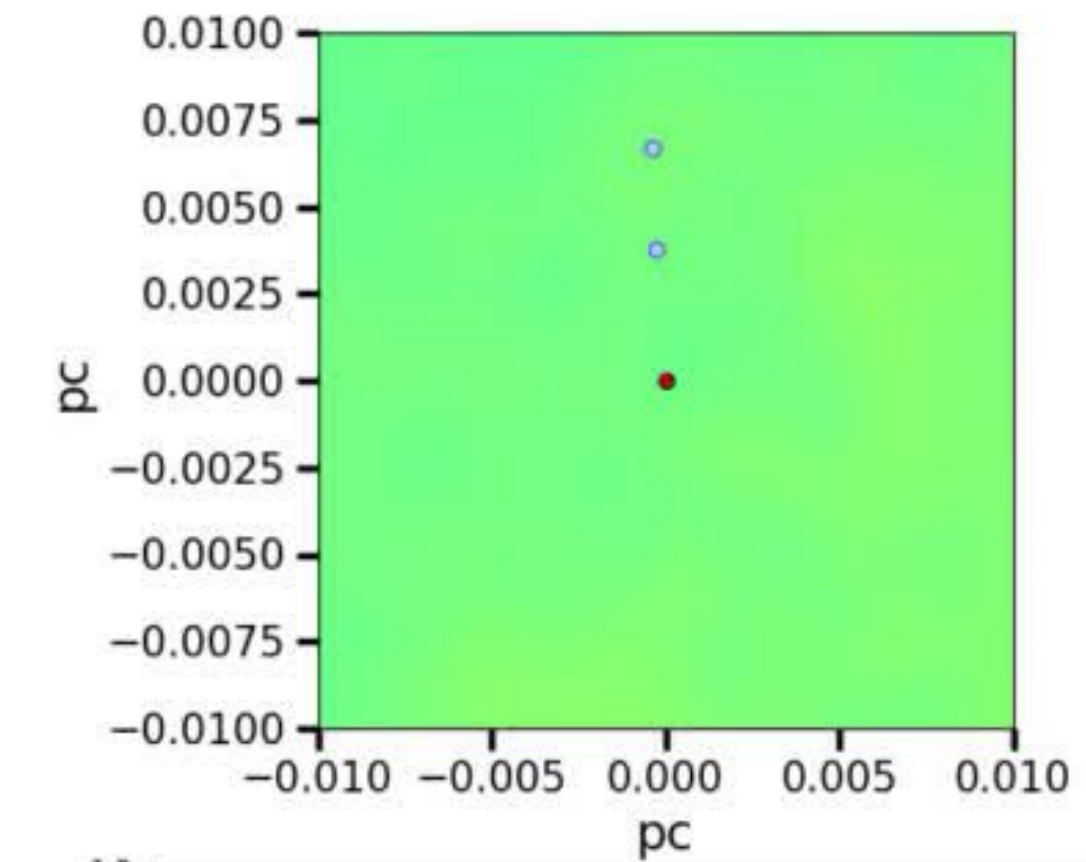
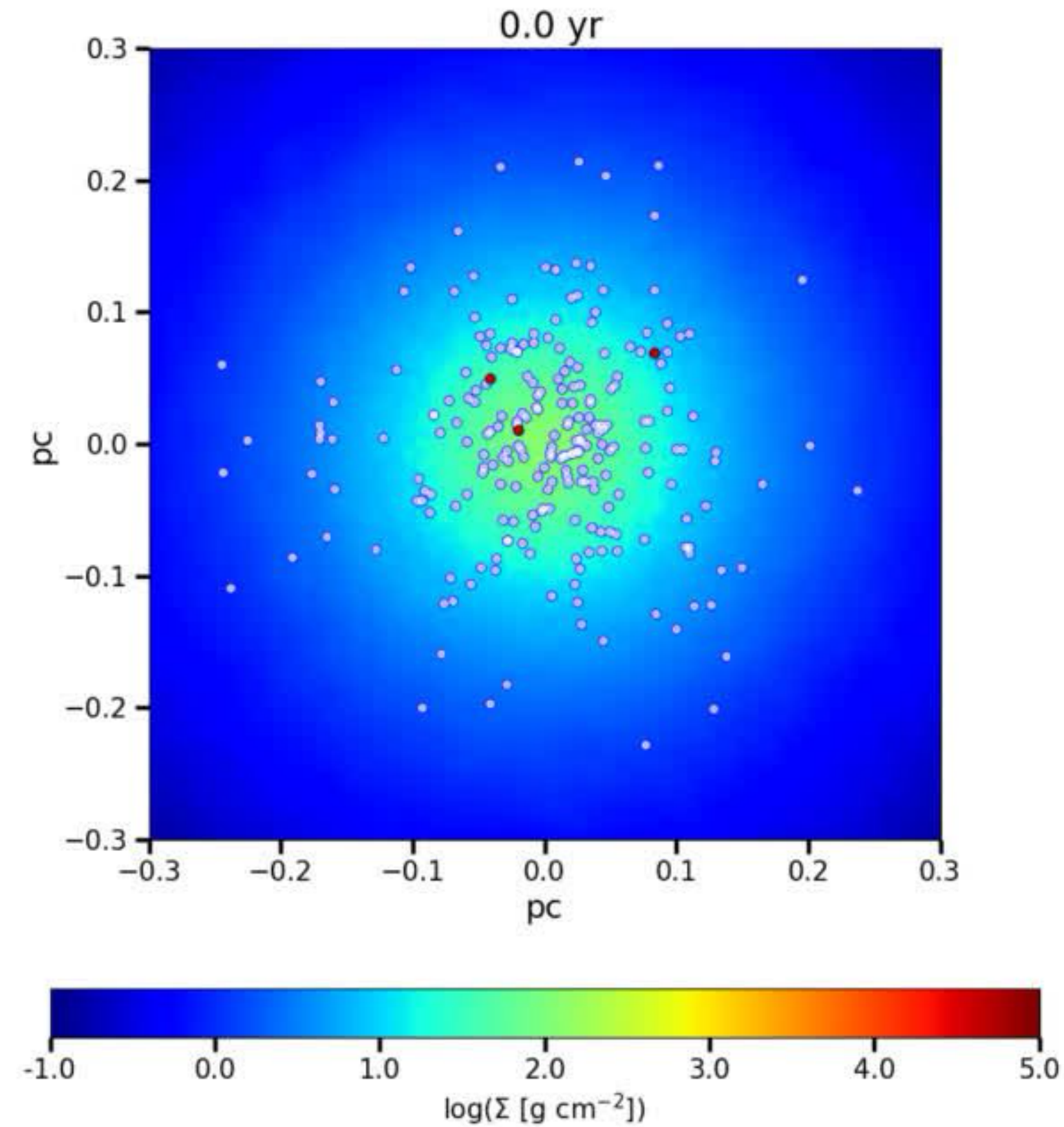
Reinoso et al. (2018, A&A, 614, A14), Boekhold et al. (2018, MNRAS, 476, 366), Alister Seguel et al. (2020, MNRAS, 493, 2352), Reinoso et al. (2020, A&A, 639, A92), Vergara et al. (2021, A&A, 649, A160), Schleicher et al. (2022, MNRAS, 512, 6192), Reinoso et al. (2023, MNRAS, 521, 3553), Schleicher et al. (2023, MNRAS, 521, 3972), Nandal & Cho (2026, ApJ, 999, 100)

how to form seeds of supermassive BHs?

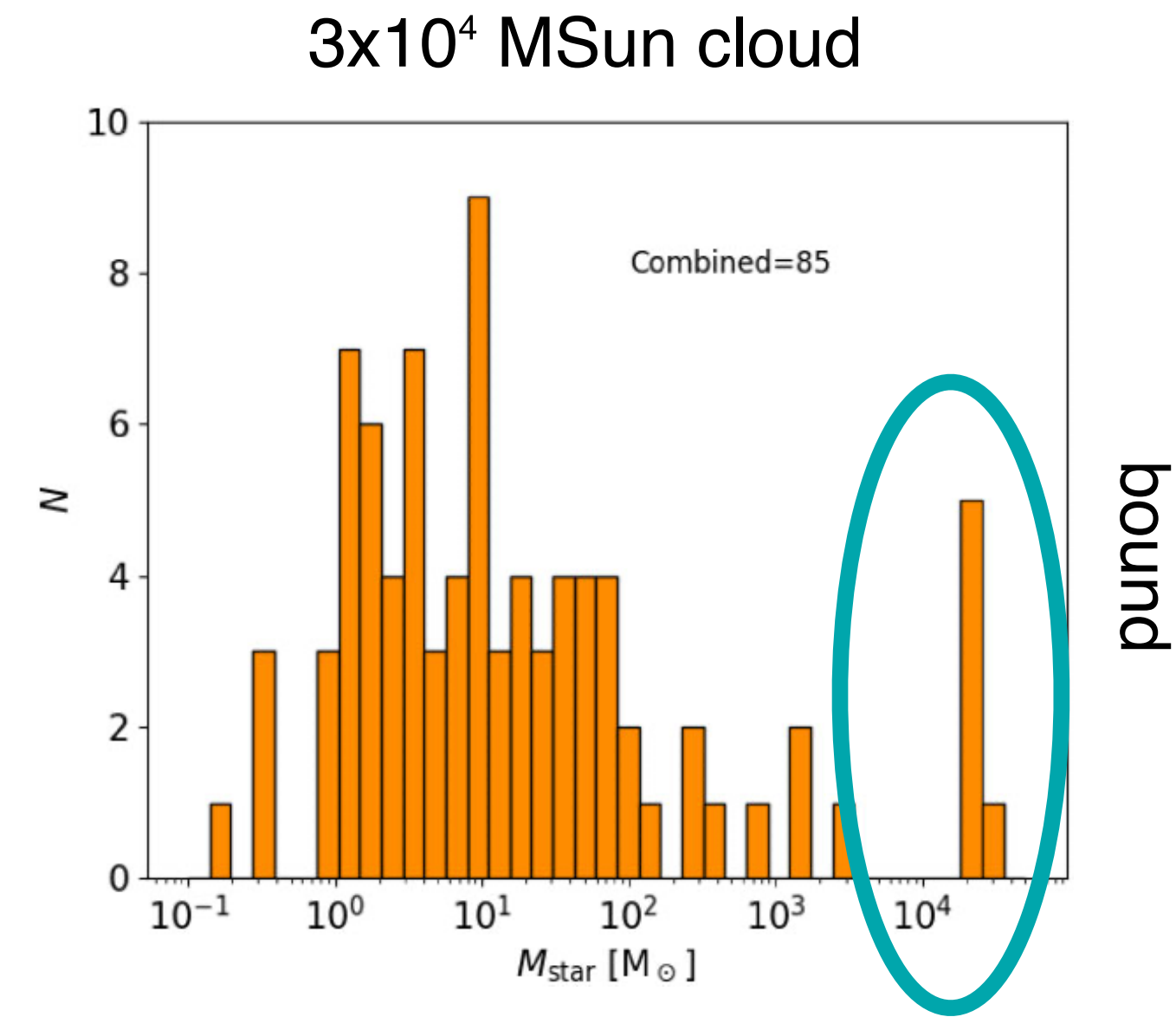
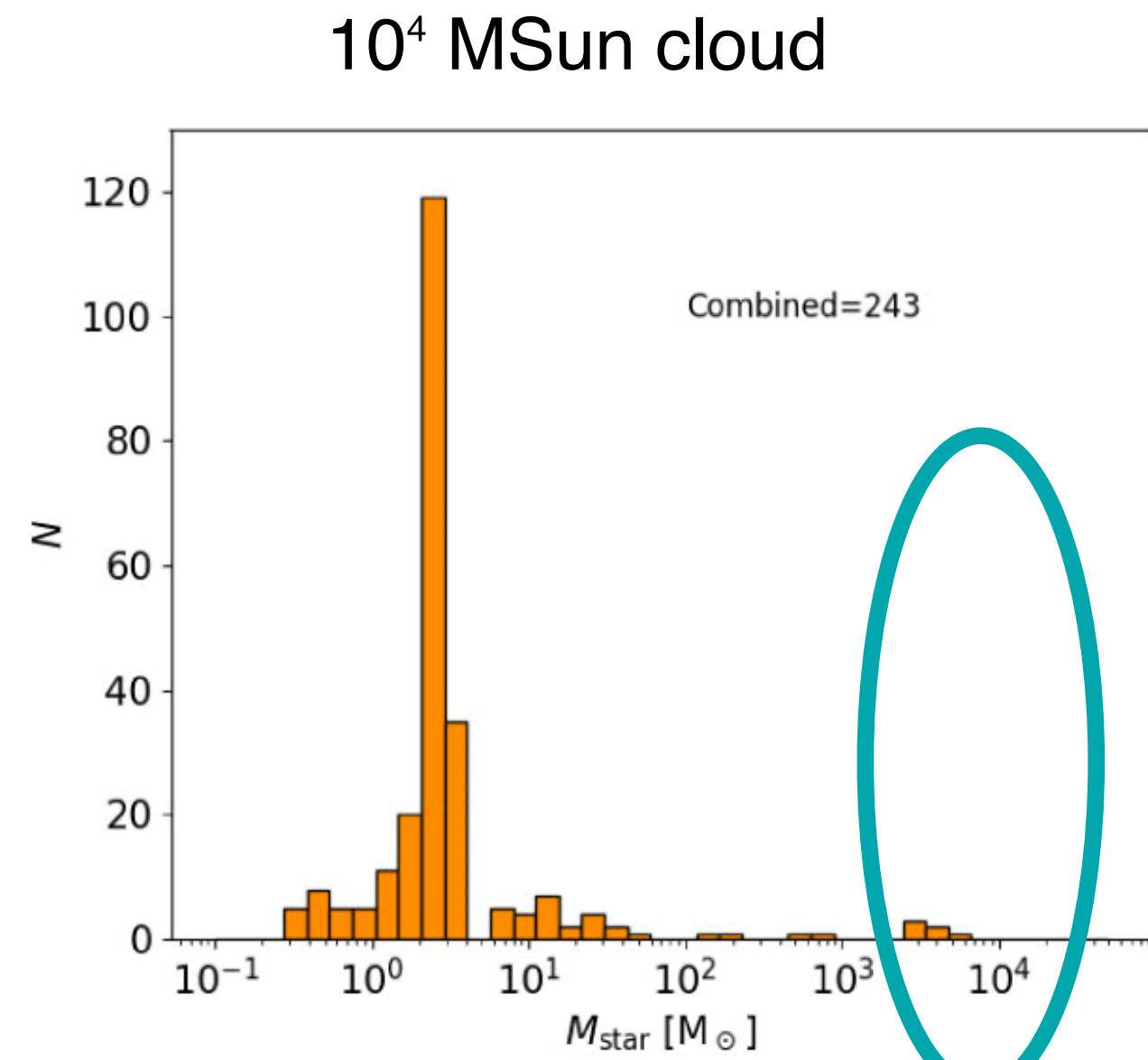


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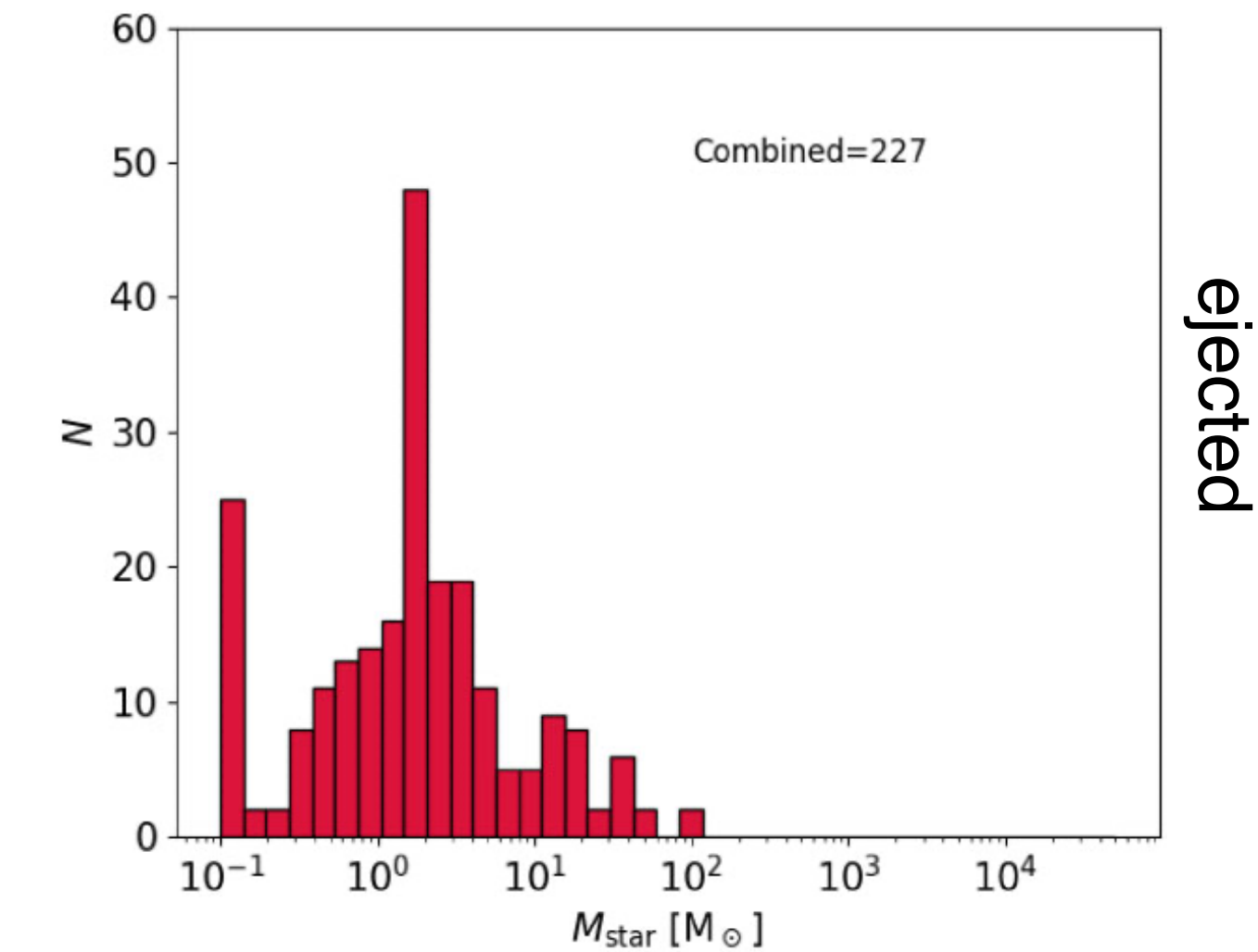
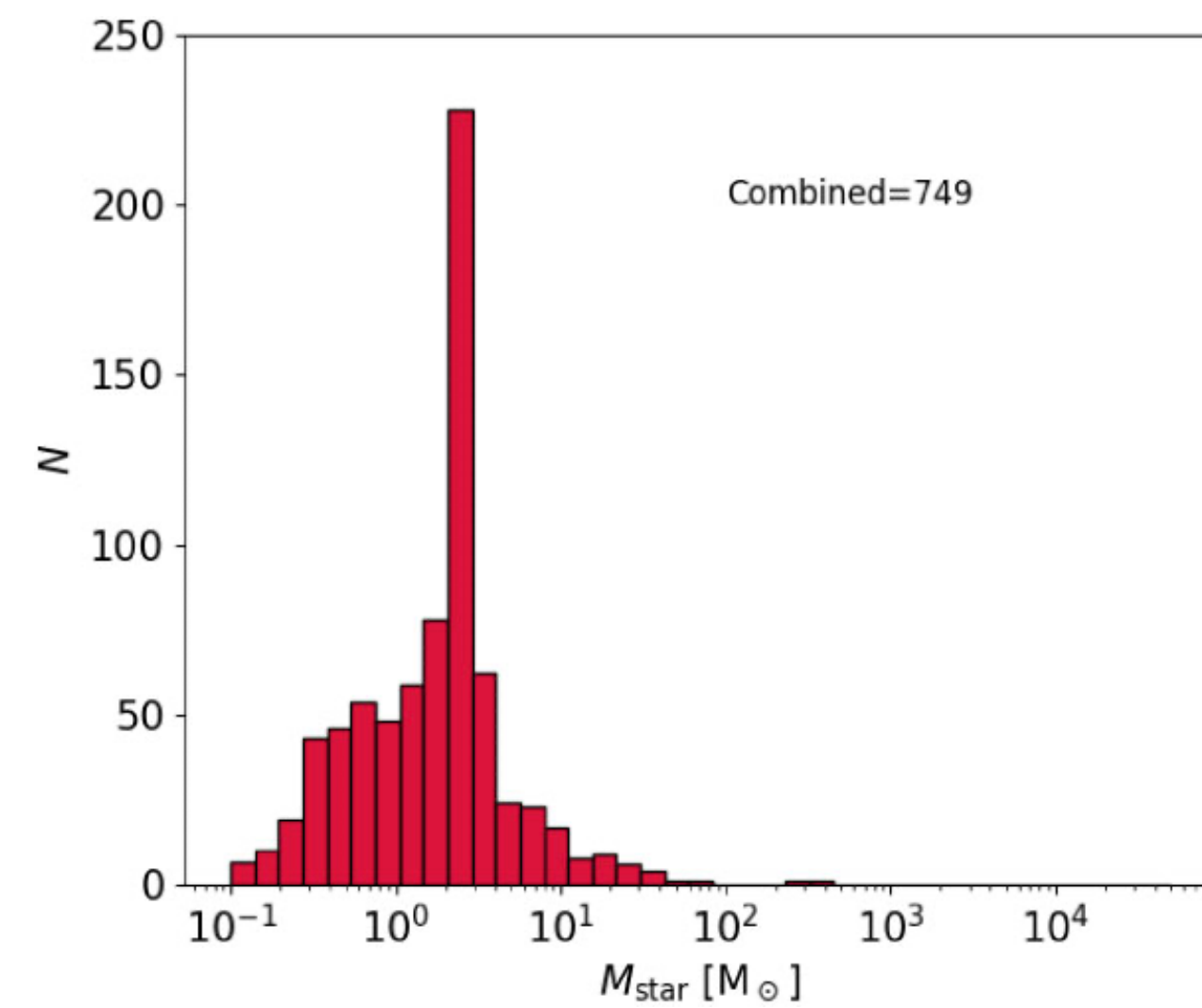
example of $10^4 M_{\odot}$ cloud



Reinoso et al. (2018, A&A, 614, A14), Boekhold et al. (2018, MNRAS, 476, 366), Alister Seguel et al. (2020, MNRAS, 493, 2352), Reinoso et al. (2020, A&A, 639, A92), Vergara et al. (2021, A&A, 649, A160), Schleicher et al. (2022, MNRAS, 512, 6192), Reinoso et al. (2023, MNRAS, 521, 3553), Schleicher et al. (2023, MNRAS, 521, 3972)



bound



ejected

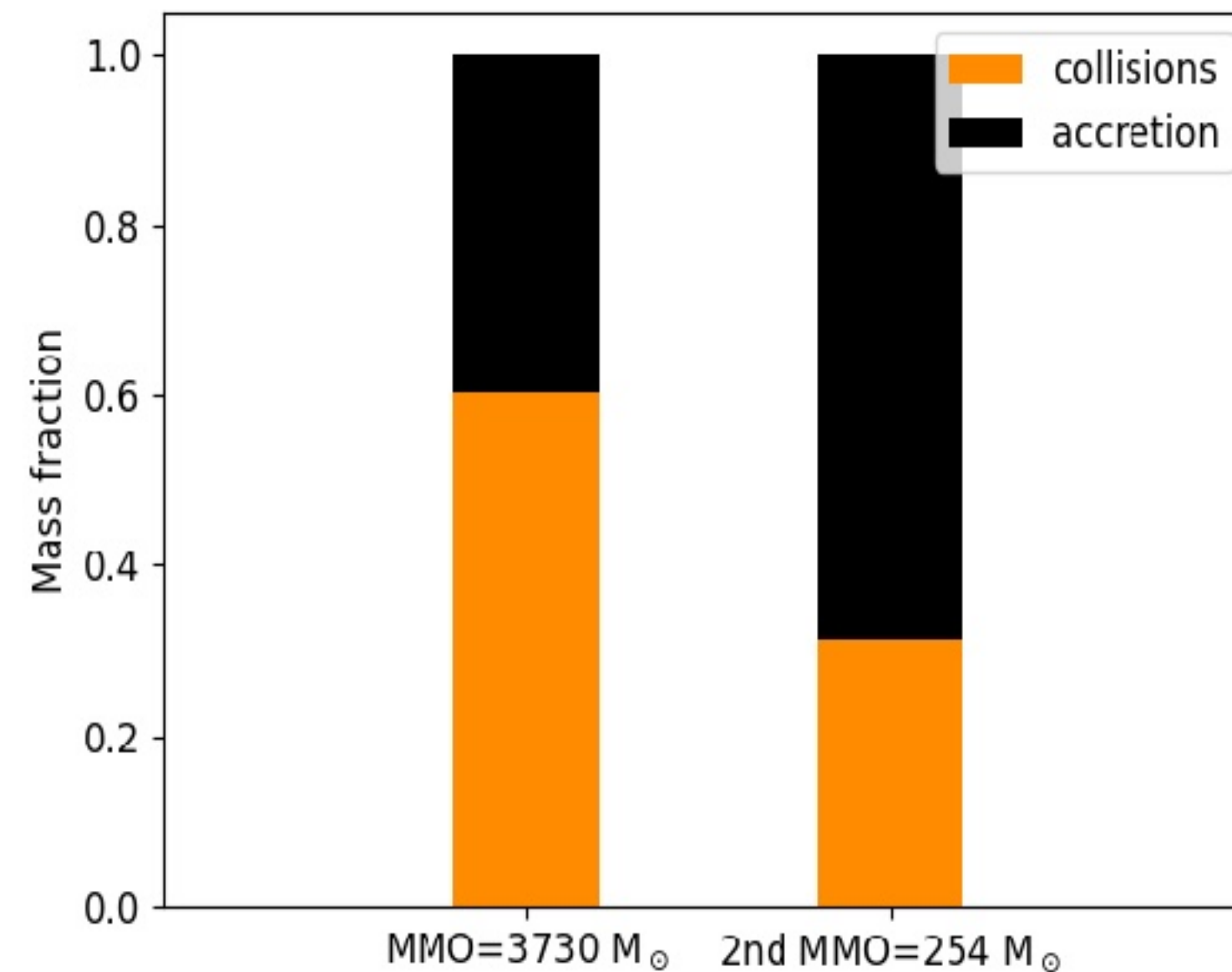
all simulations combined

Reinoso et al. (2018, A&A, 614, A14), Boekhold et al. (2018, MNRAS, 476, 366), Alister Seguel et al. (2020, MNRAS, 493, 2352), Reinoso et al. (2020, A&A, 639, A92), Vergara et al. (2021, A&A, 649, A160), Schleicher et al. (2022, MNRAS, 512, 6192), Reinoso et al. (2023, MNRAS, 521, 3553), Schleicher et al. (2023, MNRAS, 521, 3972)

combination of collisions and accretion



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- in this specific case, 60% of the mass comes from collisions
- *run-away collisions* occur, as long as stars remain in *puffed-up configuration*
- requires *collision cadence shorter than Kelvin-Helmholtz time*, otherwise stars contract & collision cross section drops
- puffy stars are like *super luminous red giants*, with $T_{\text{eff}} \sim 3500 \dots 4000 \text{ K}$
- model for ***Little Red Dots*** ???

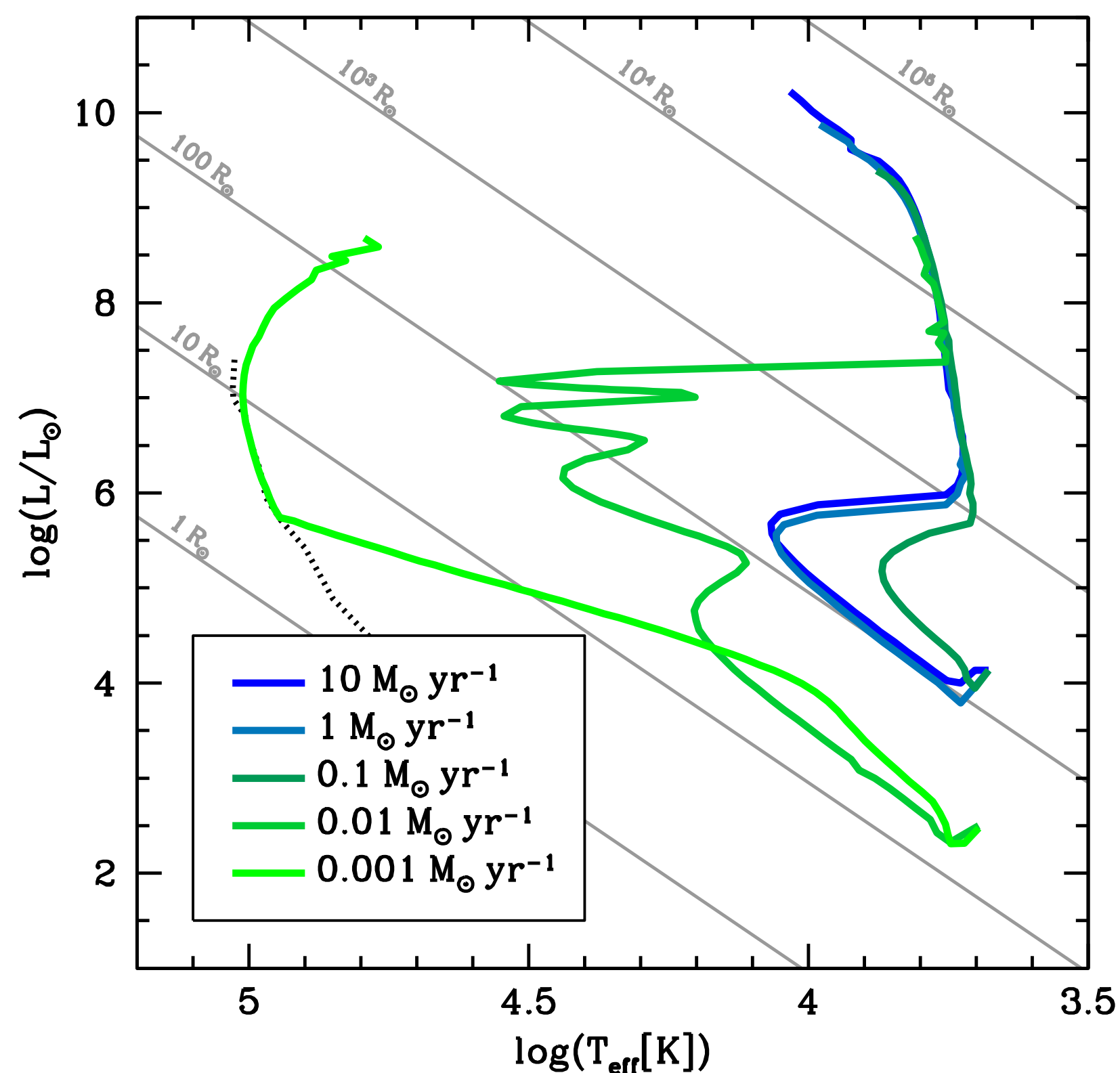
Nandal & Loeb (2026, ApJ, 998, 124),
also Roman-Garza et al. (in prep.)

Reinoso et al. (2018, A&A, 614, A14), Boekhold et al. (2018, MNRAS, 476, 366), Alister Seguel et al. (2020, MNRAS, 493, 2352), Reinoso et al. (2020, A&A, 639, A92), Vergara et al. (2021, A&A, 649, A160), Schleicher et al. (2022, MNRAS, 512, 6192), Reinoso et al. (2023, MNRAS, 521, 3553), Schleicher et al. (2023, MNRAS, 521, 3972)

SMSs as model for LRDs?



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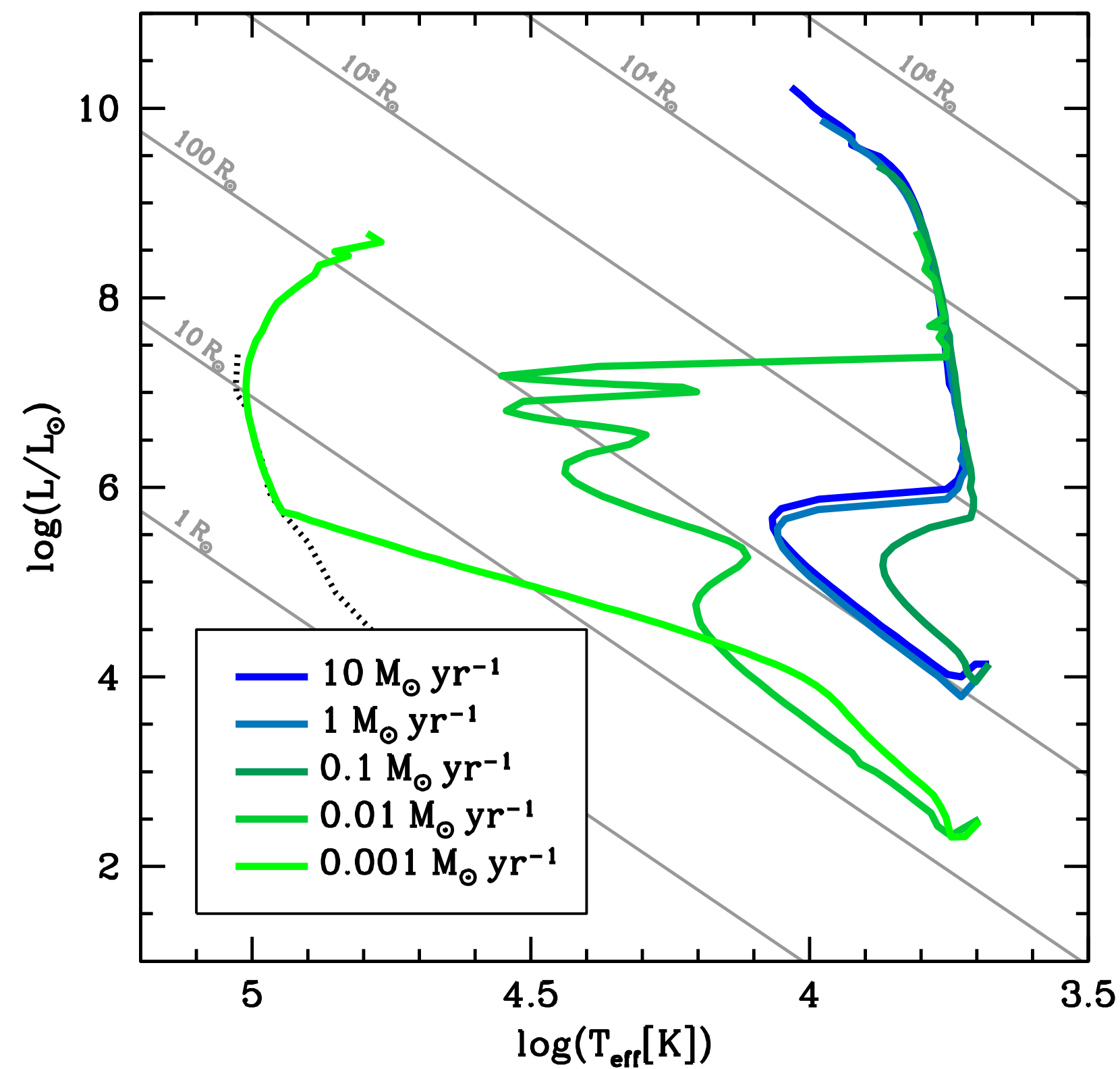


- heavily accreting SMSs are *very luminous*:
 $L \sim 10^8 \dots 10^{11} L_{\odot}$
- due to large radii they have *low* surface temperatures: $T \sim 4000$ K
- no ionizing photons, spectra similar to *red supergiants*
- this may be a model for ***Little Red Dots ...***
Nandal & Loeb (2026, ApJ, 998, 124)

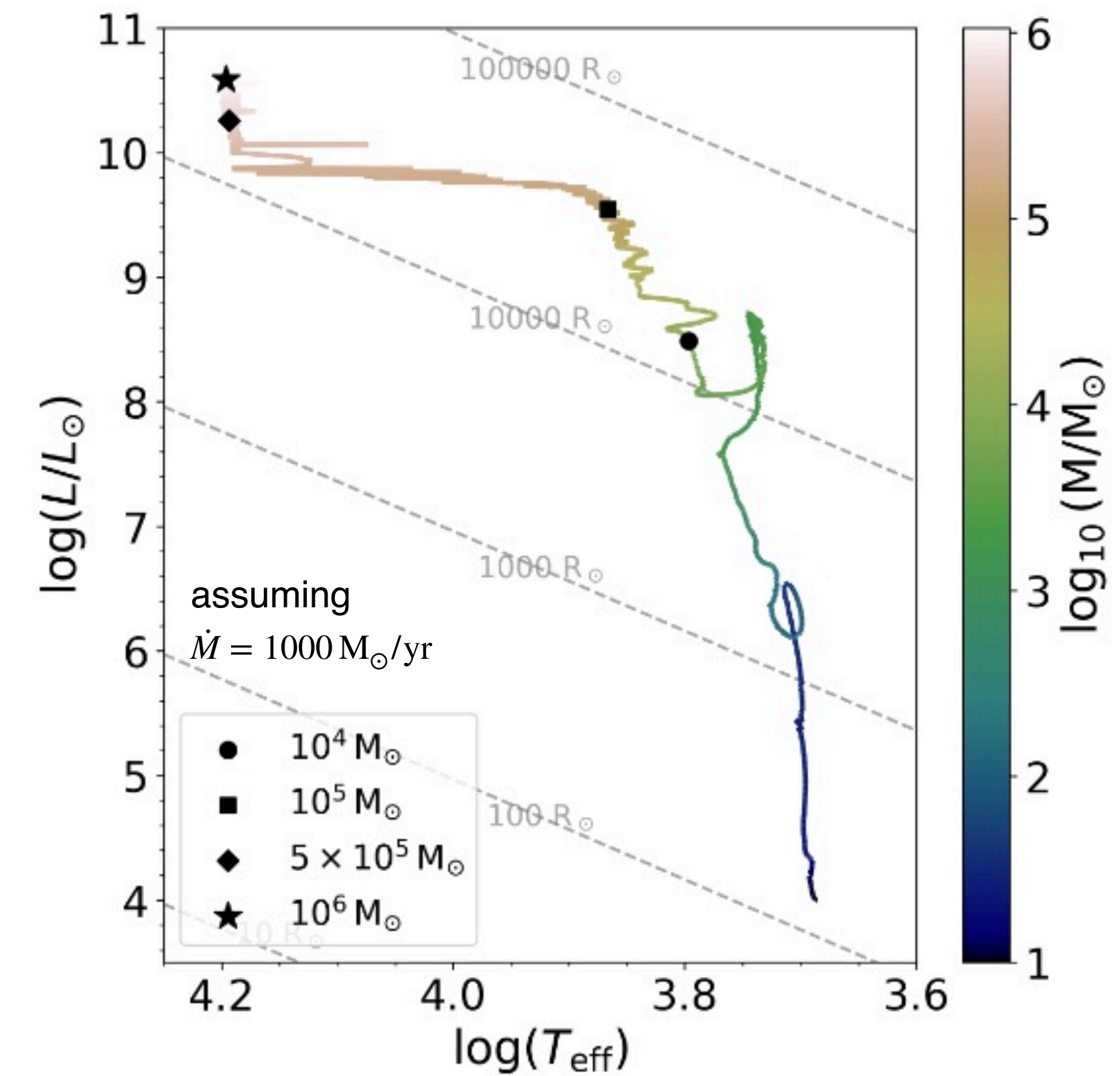
SMSs as model for LRDs?



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Haemmerlé et al. (2018, MNRAS 474, 2757)



Nandal & Loeb (2026, ApJ, 998, 124)

SMSs as model for LRDs"



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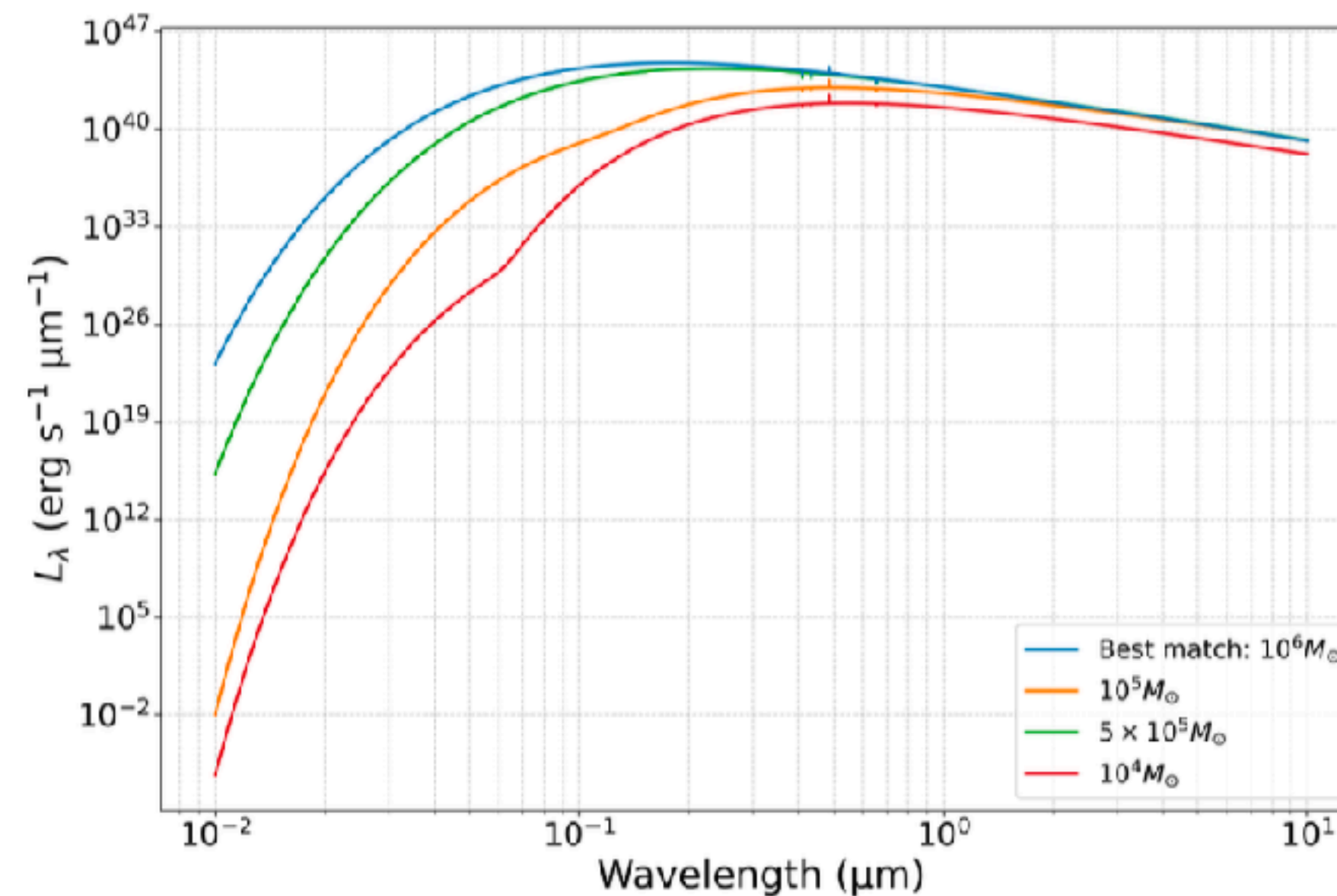
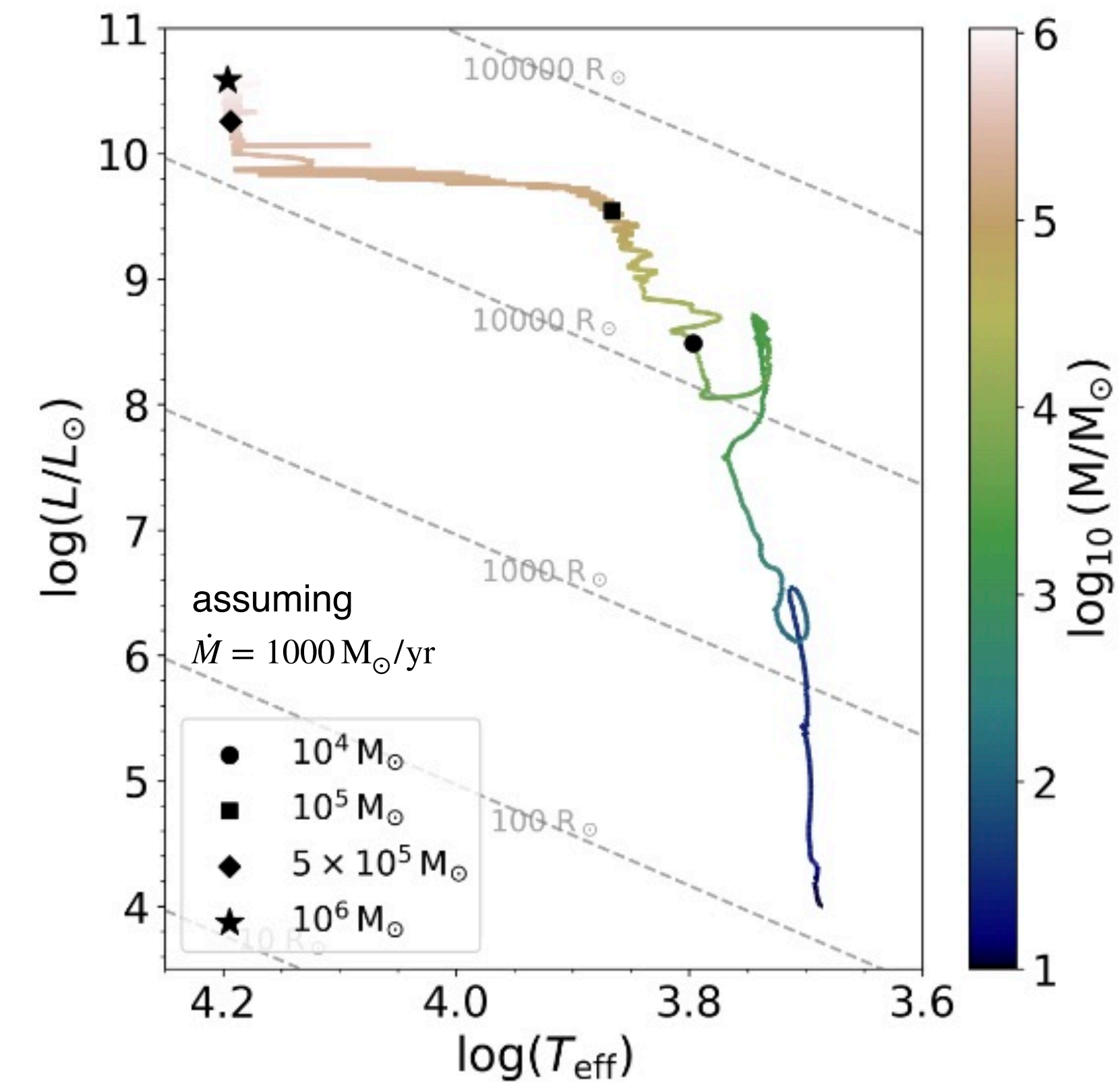


Figure 2. The intrinsic luminosity spectrum (L_λ) of Population III SMSs as a function of stellar mass. The overall luminosity increases steeply with mass, as expected for stars shining near their Eddington limit. While lower-mass models ($10^4 M_\odot$, $10^5 M_\odot$, and $5 \times 10^5 M_\odot$) are orders of magnitude too faint to match the observed brightness of luminous LRDs, the $10^6 M_\odot$ model (blue curve) produces a luminosity that closely matches the observational requirements for both “The Cliff” and “MoM-BH*-1.”



take home points

early star formation is equally complex than present-day star formation

typical Pop III stars probably had masses 20 - 40 $M_{\odot}$

supermassive stars can easily reach $10^5 M_{\odot}$ if subject to high accretion rates (link to 'little red dots'?)



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