

Forging Extreme Stars in Extreme Environments

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Carnegie Observatories (until Friday!)

→ SOON Flatiron Institute

Cosmic Dawn Revealed by JWST: The Physics of
the First Stars, Galaxies, and Black Holes

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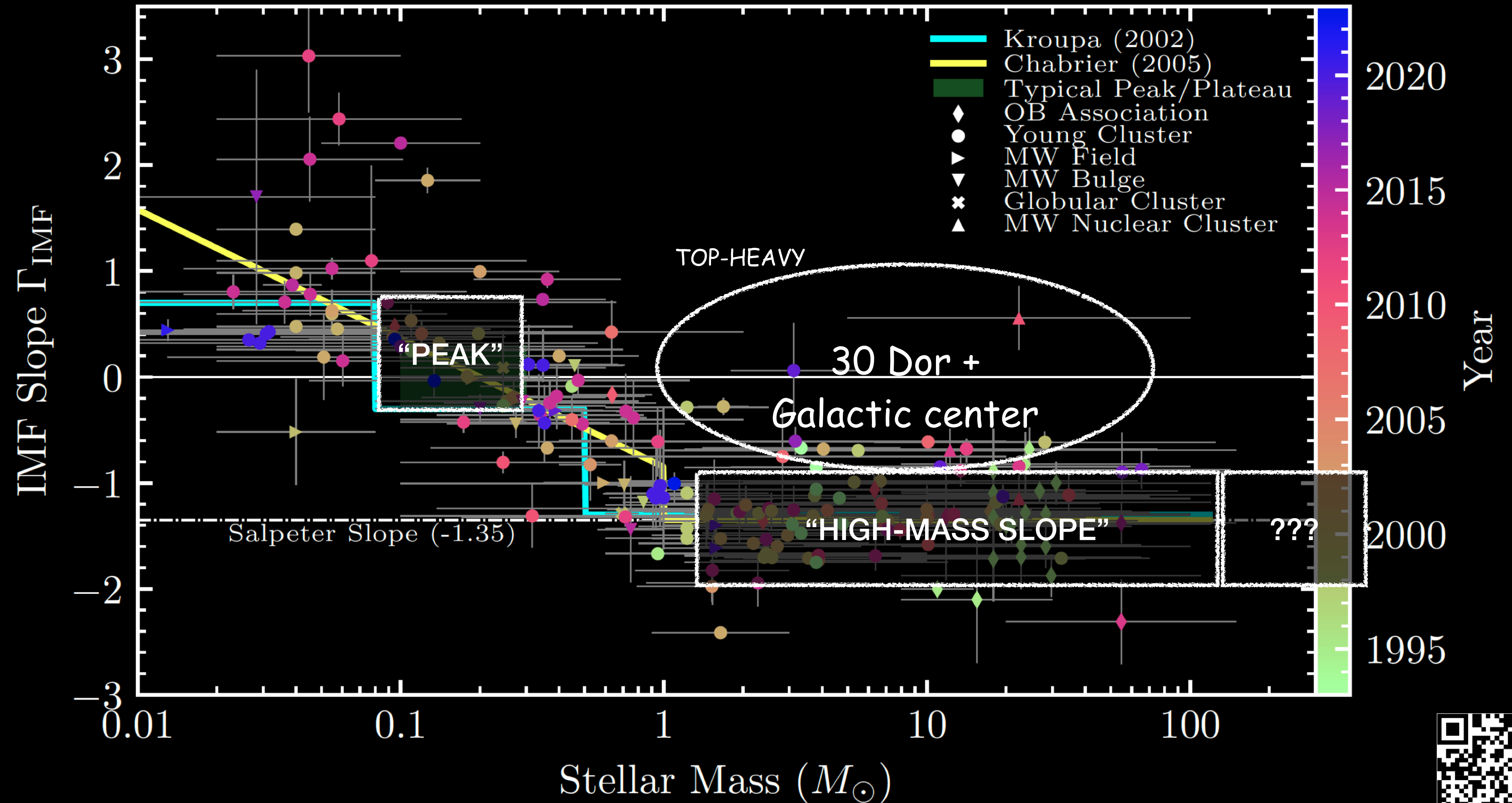
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IMF Measurements

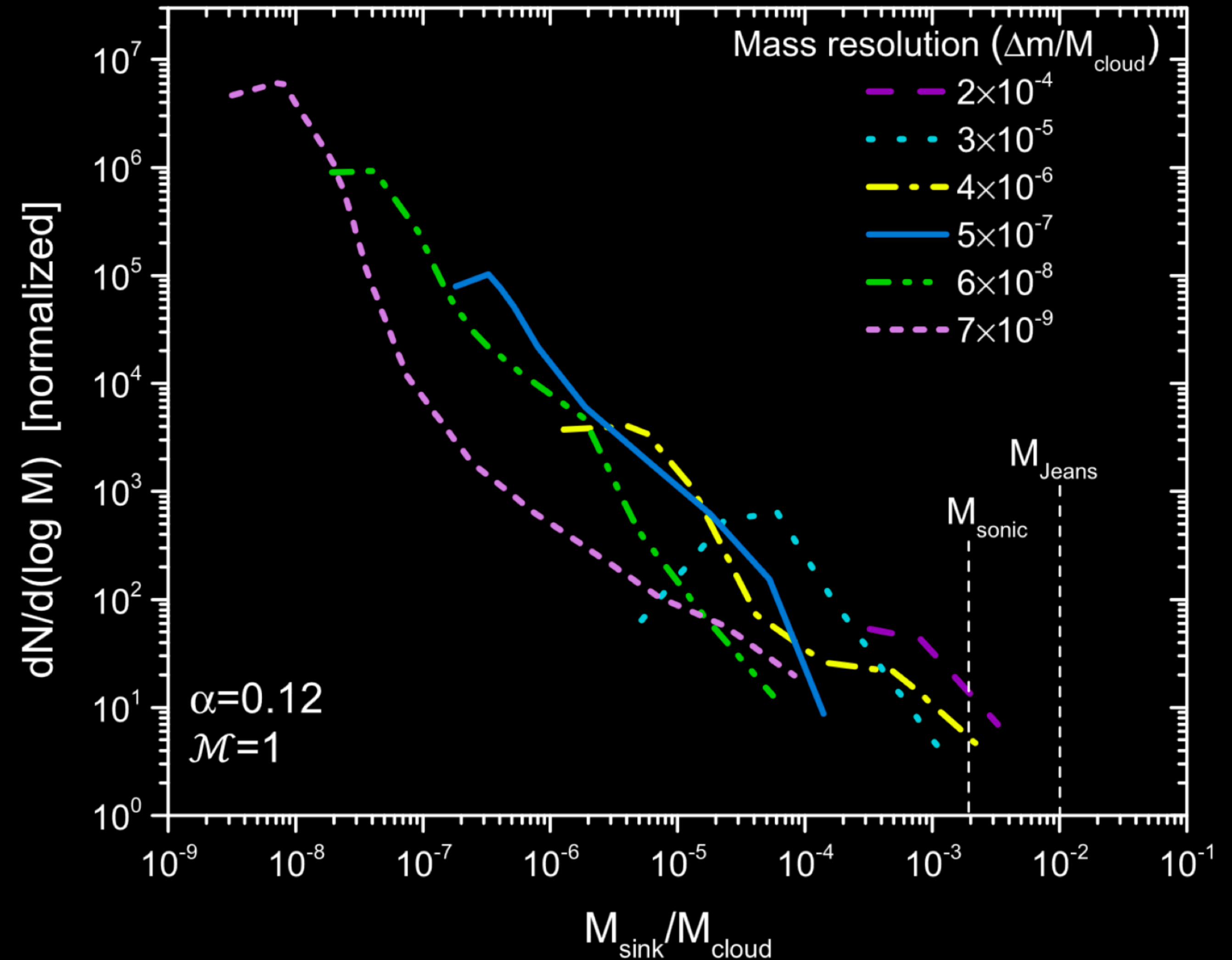
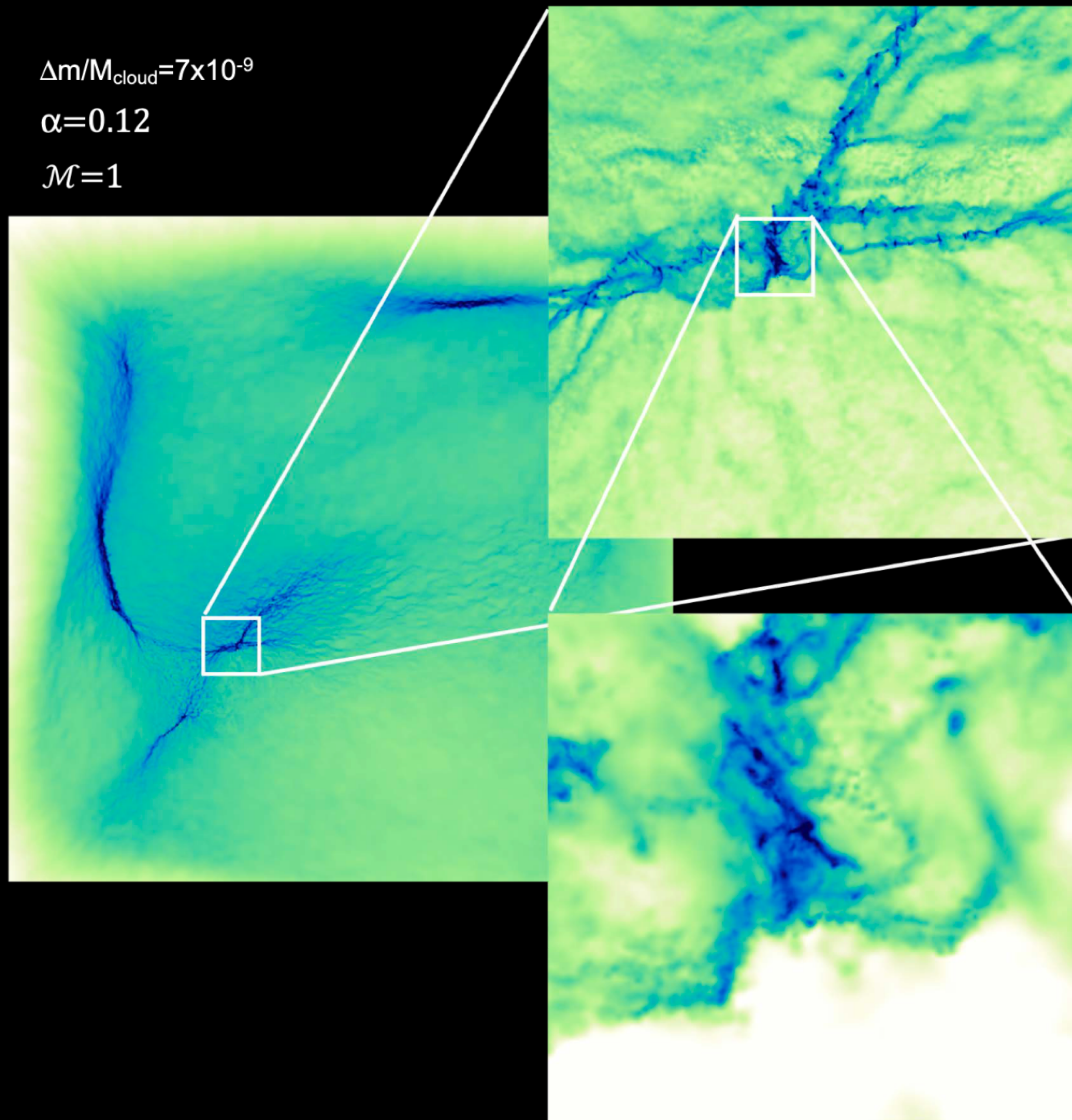


Hennebelle & Grudić ARAA 2024

Get the compilation and contribute to it: <https://github.com/mikegrudic/alphaplot>

Isothermal 10K Gas + Gravity = no IMF

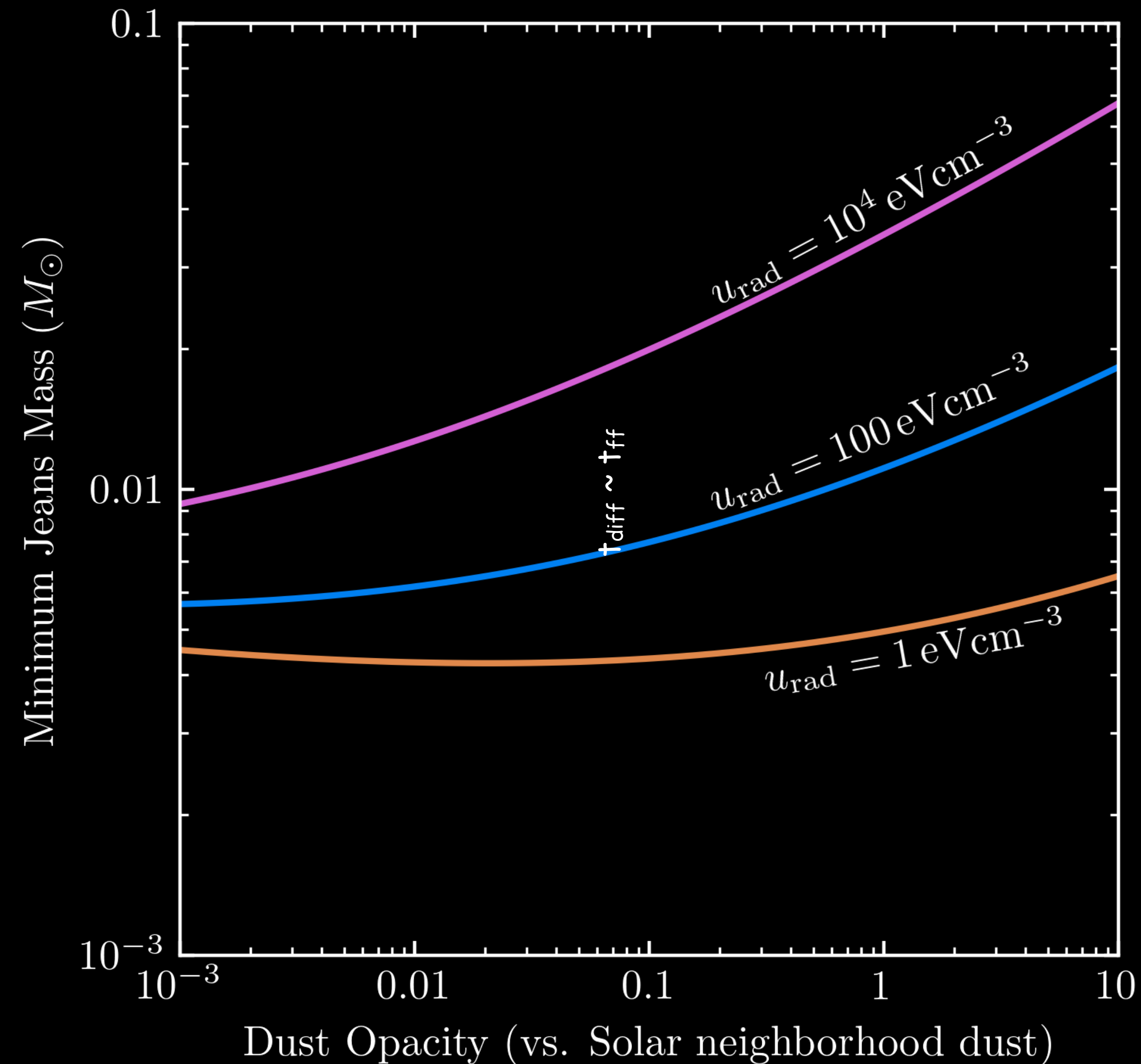
No numerically-converged mass spectrum... Martel 2006, Krumholz 2012, Guszejnov 2016,2018, Lee 2018, Smith 2023MNRAS.525.6182S



Guszejnov et al. 2018MNRAS.480..182G

The opacity limit

Minimum Jeans mass due to trapping of dust emission: Larson 1969, Low & Lynden-Bell 1976, Rees 1977, Silk 1977, Masunaga 1998, Vaytet 2017, Bhandare 2018

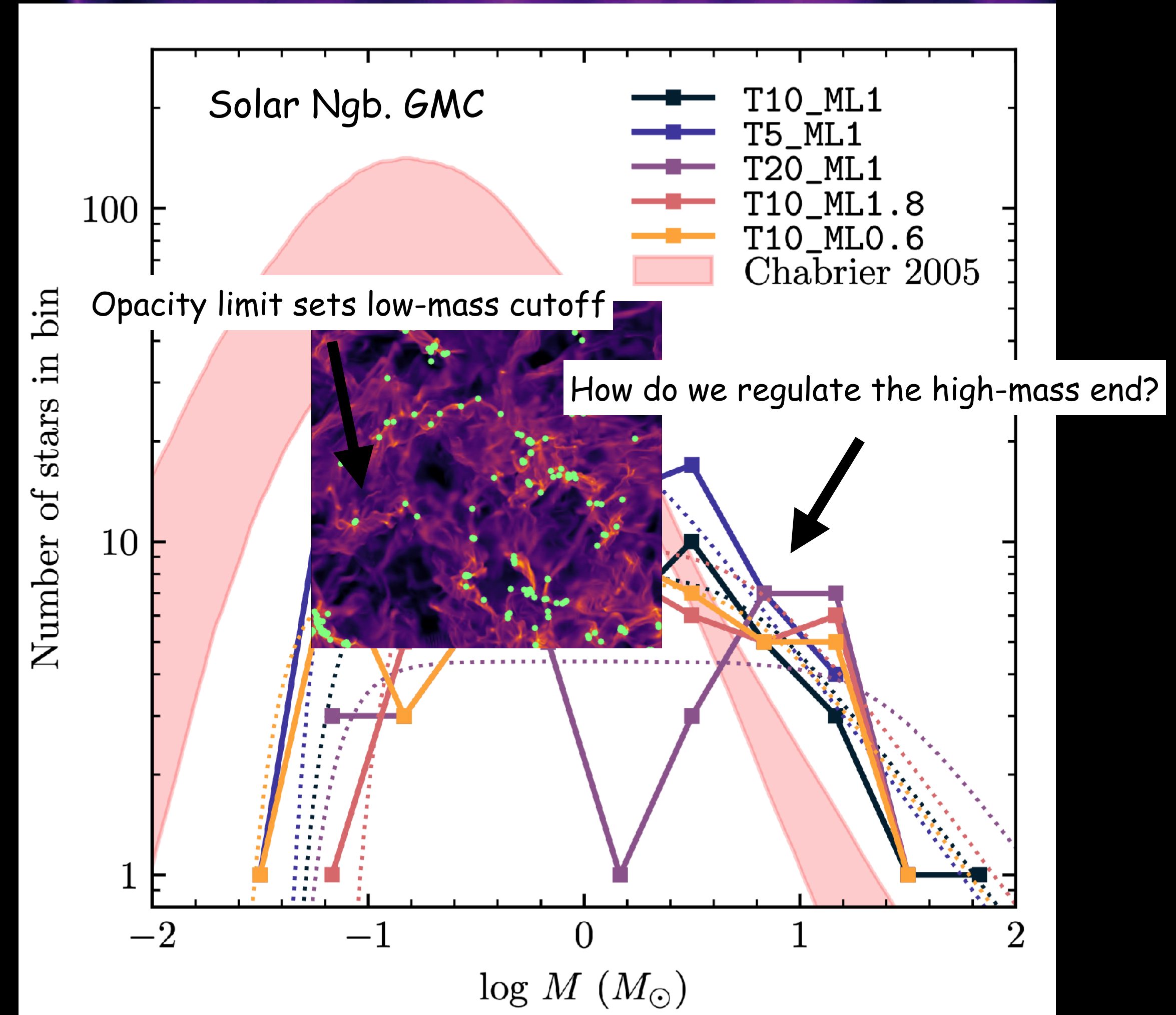
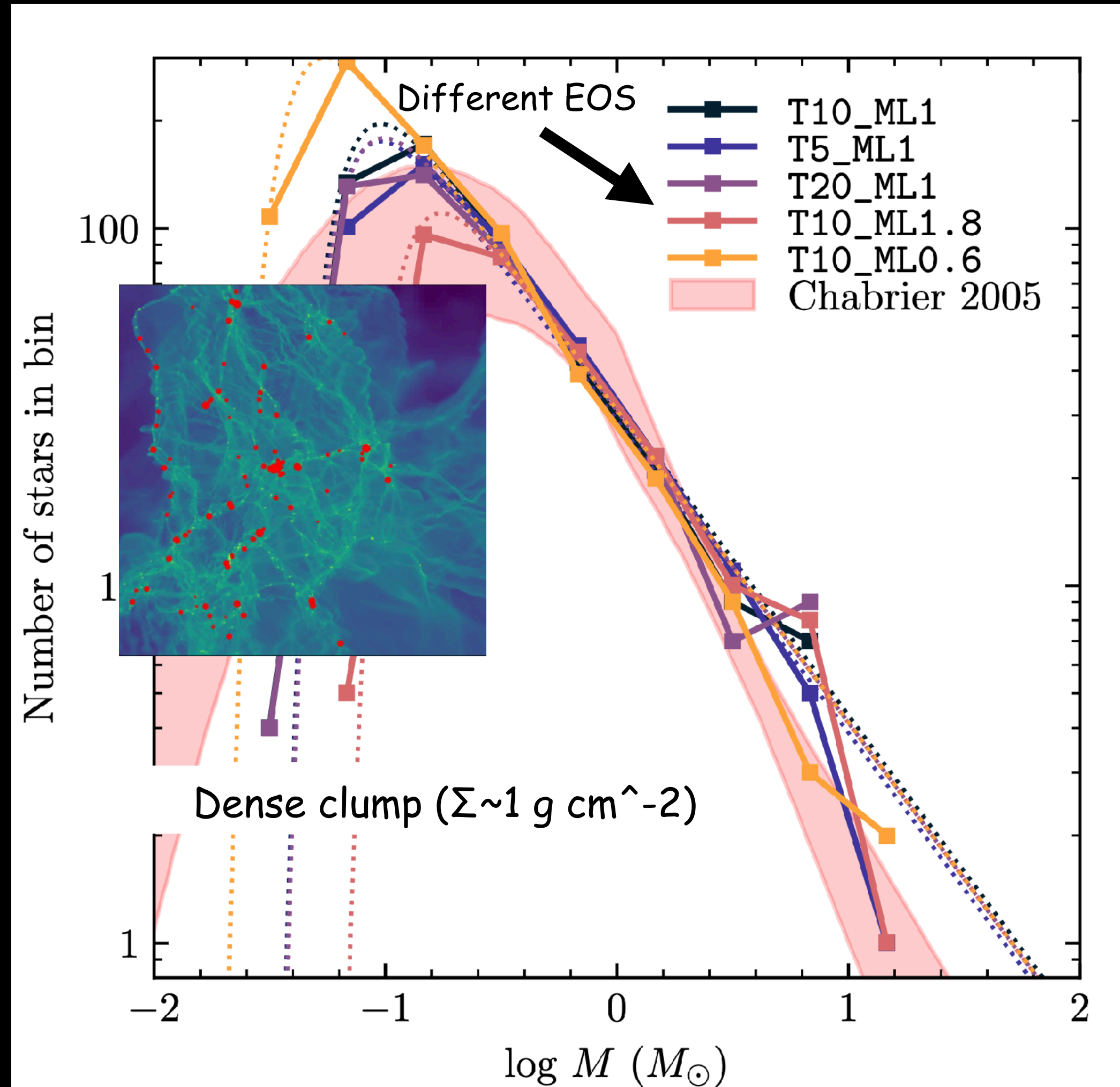


Grudić & Hopkins 2023
arXiv:2308.16268



IMF from the opacity limit + hydrostatic core

Simulations with barotropic opacity-limit EOS find a pretty-good IMF... in the right conditions.



Grudić et al 2024 (in prep.) - GIZMO MFM MHD Simulations

Stellar Feedback

Protostellar Outflows



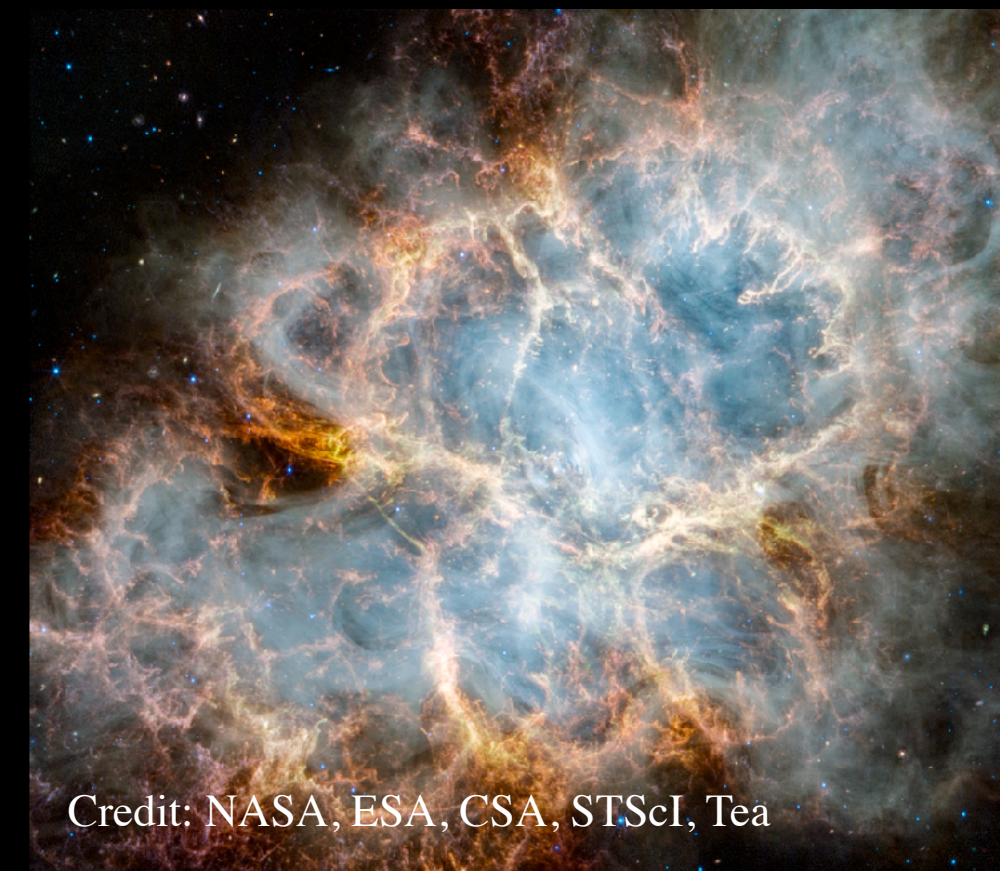
Stellar Winds



Radiation



Supernovae



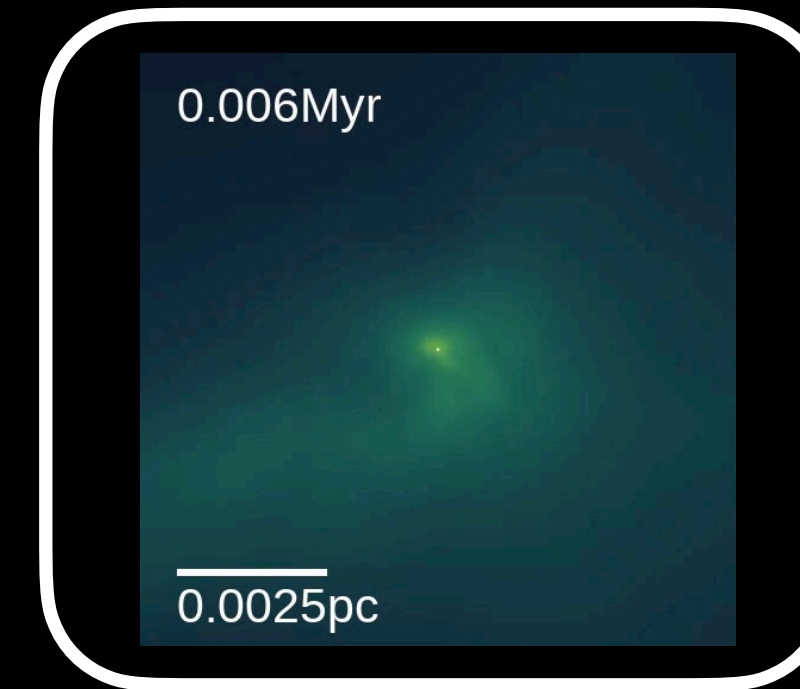
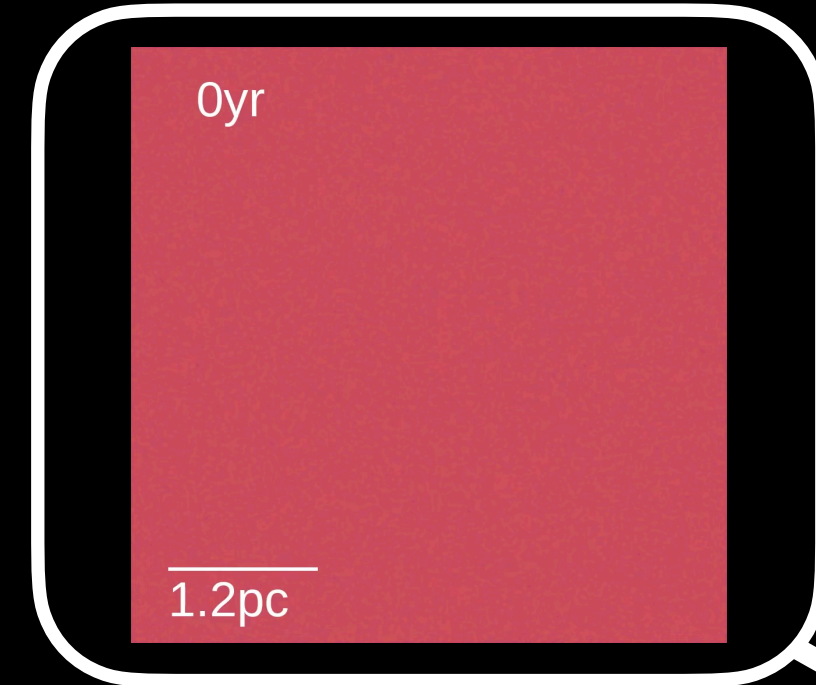
N-body dynamics (4th-order Hermite)

Individual star formation

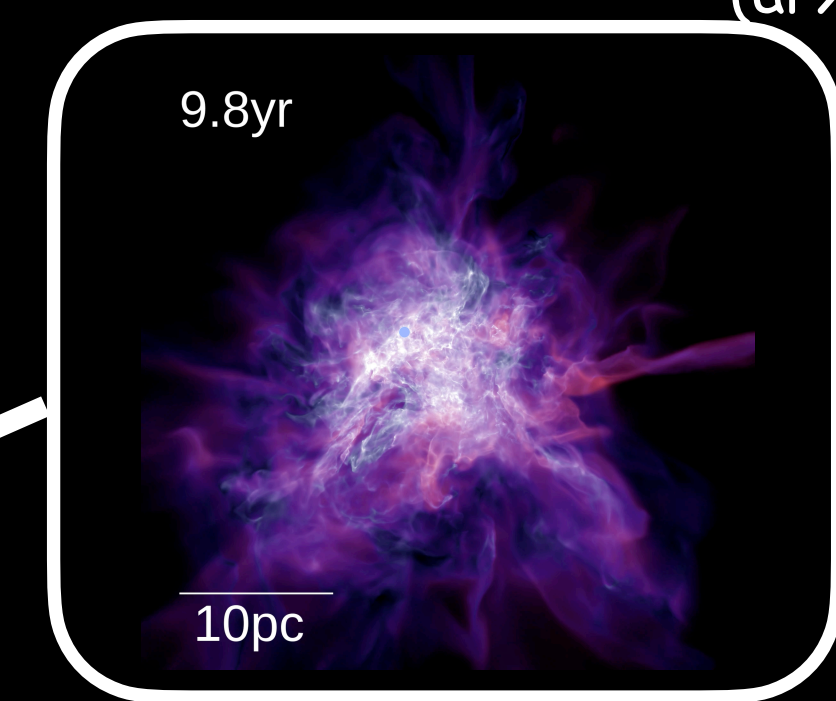


STARFORGE
methods paper
(arXiv:2010.11254)

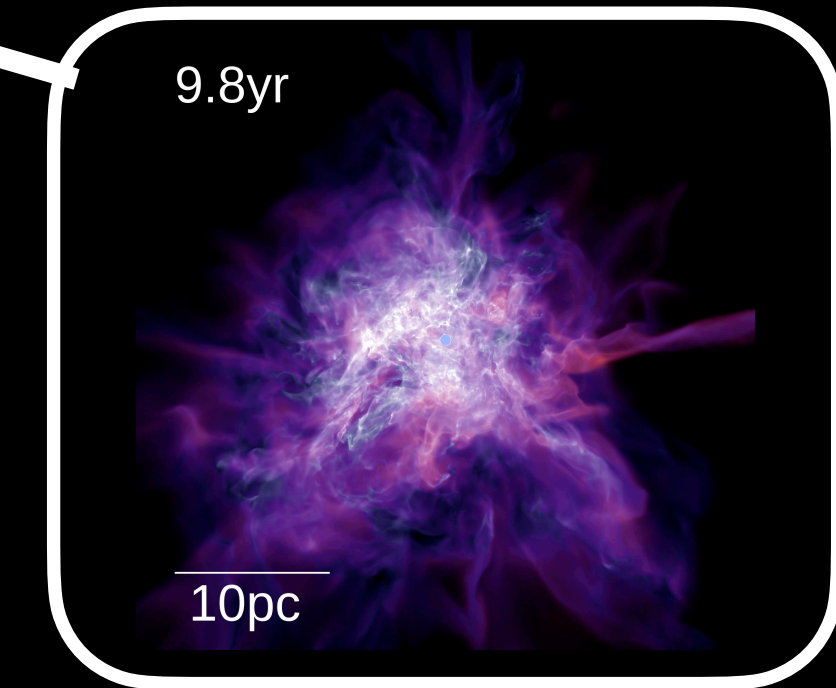
GIZMO Meshless MHD



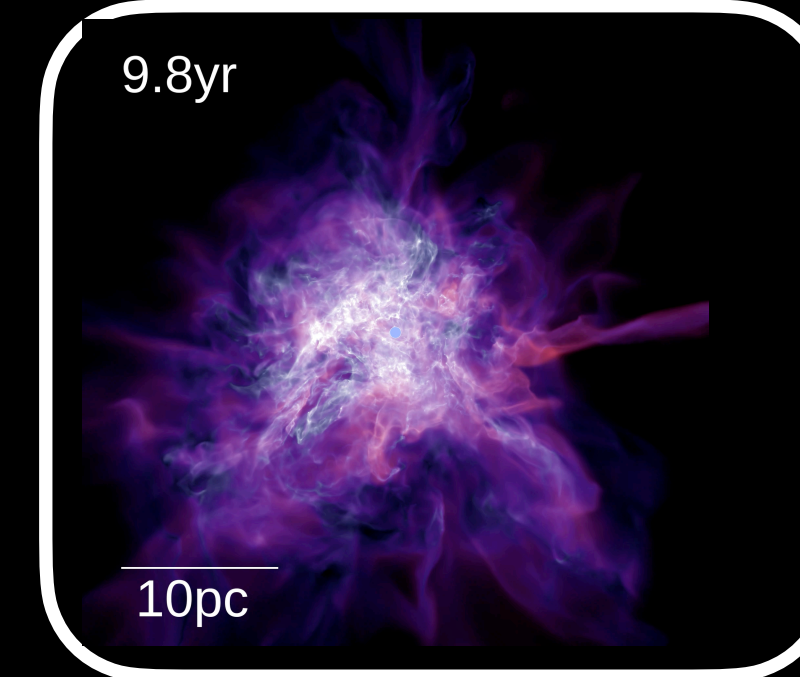
Radiation



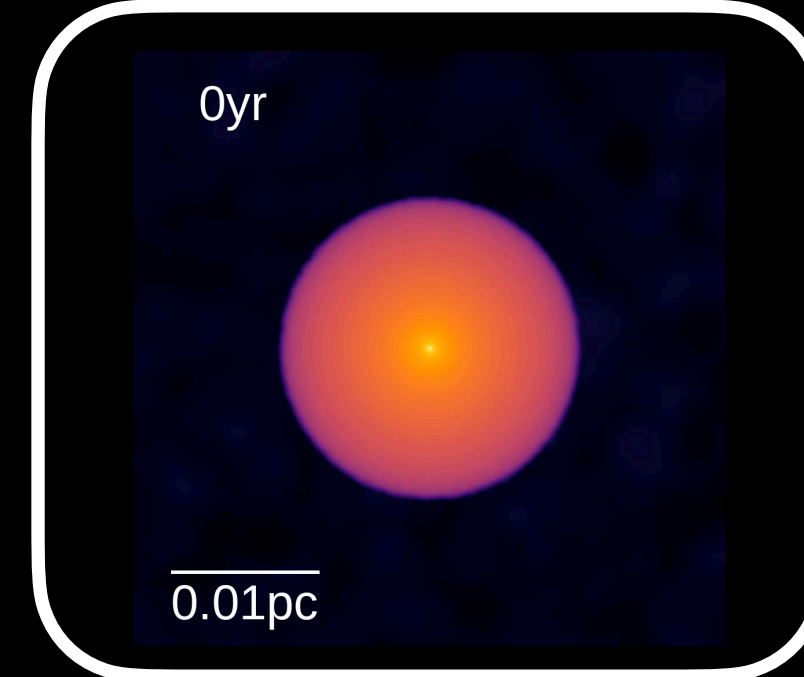
Supernovae



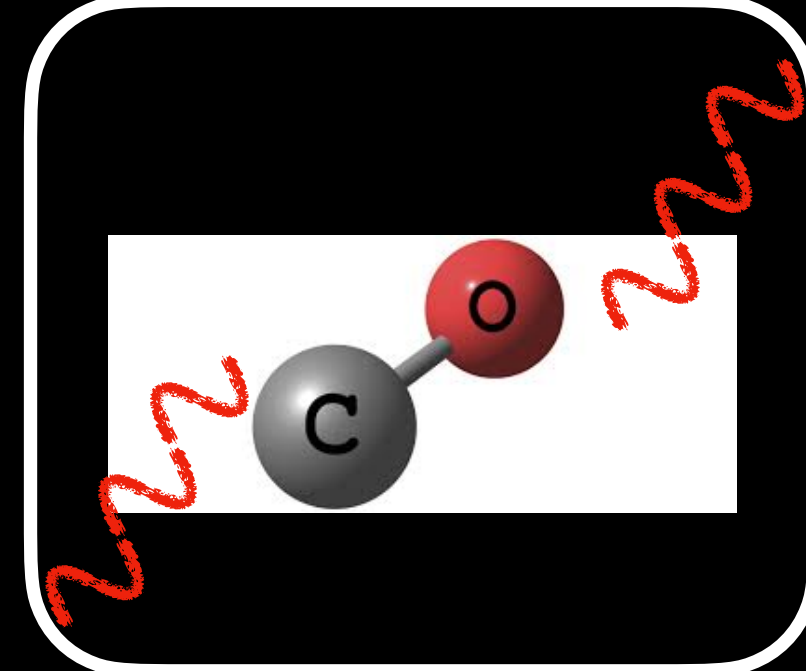
Stellar Winds



Jets



Cooling/Chemistry



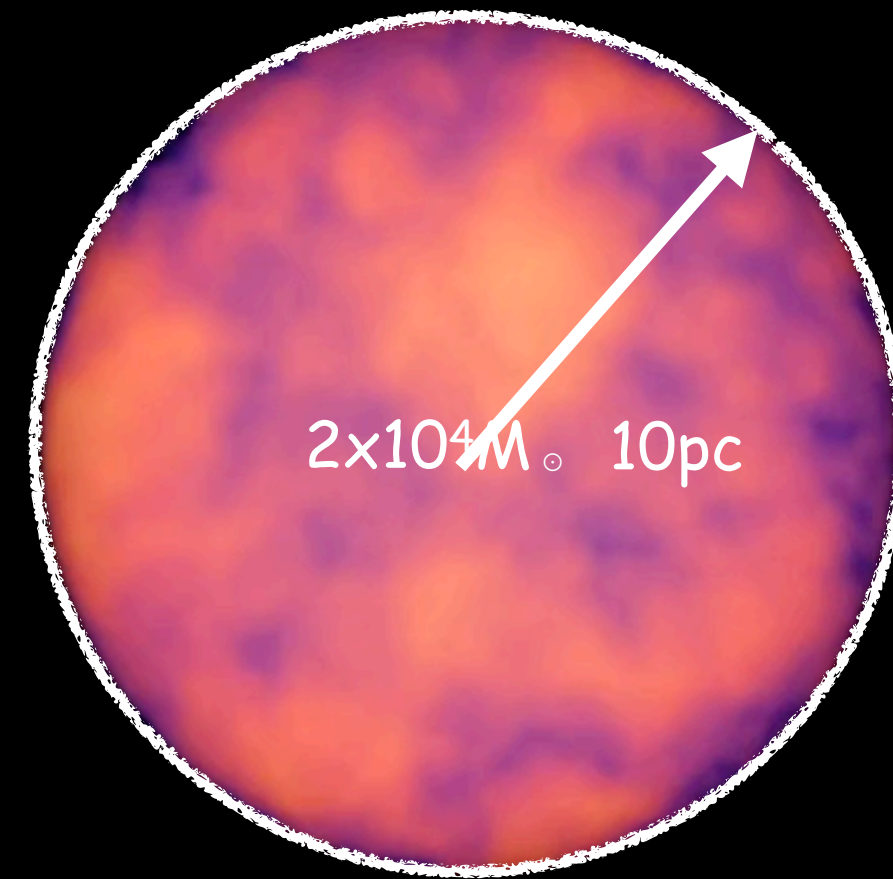
STARFORGE

Fiducial **starforge** Run - Milky Way Conditions

First simulation with all feedback physics in concert - Grudić, Guszejnov et al. 2022MNRAS.512..216G

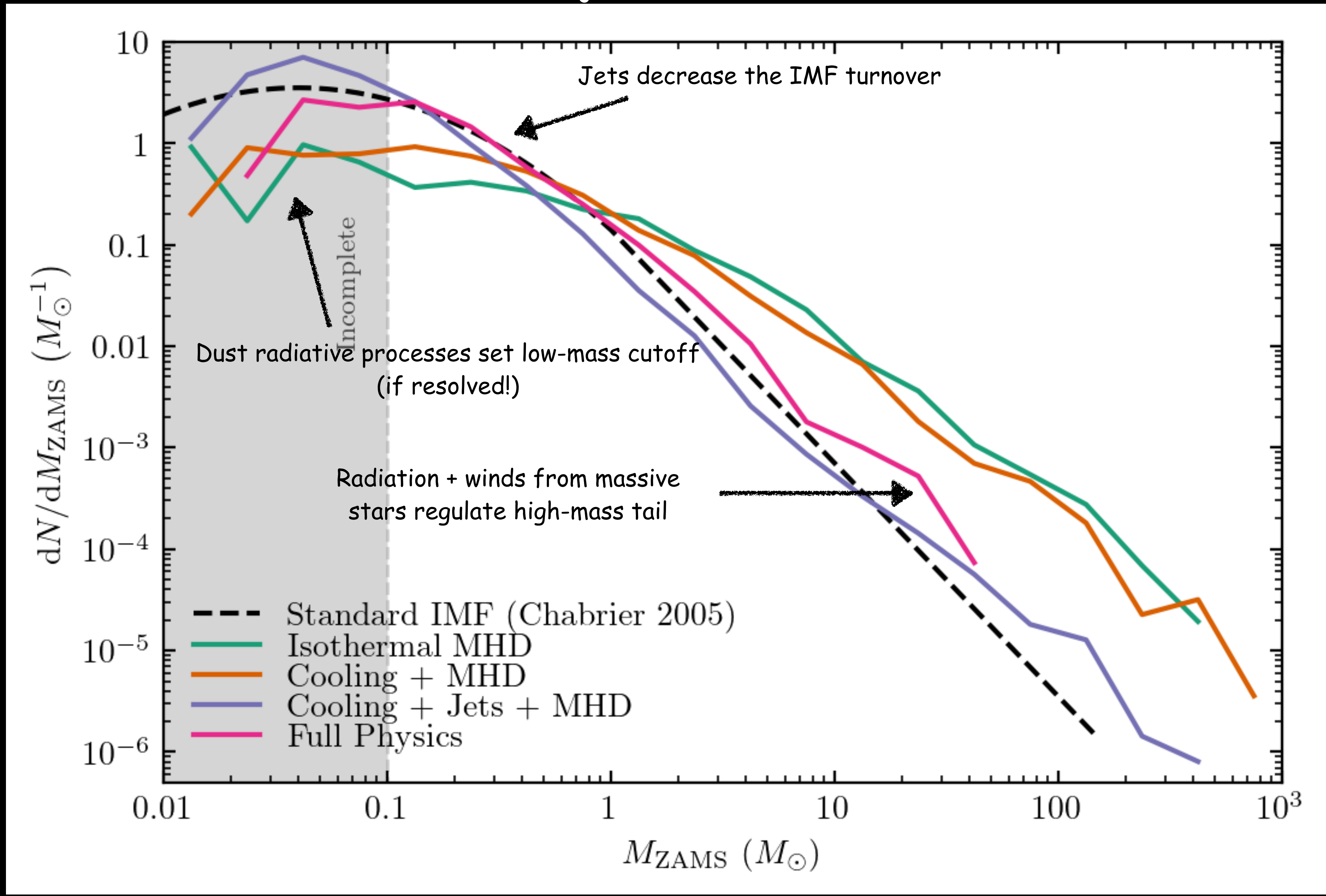


4k 60fps version



The **starforge** IMF story so far...

Guszejnov, Grudić, et al. 2022MNRAS.515.4929G
Grudić, Guszejnov et al. 2022MNRAS.512..216G
Guszejnov, Grudić et al. 2021MNRAS.502.3646G



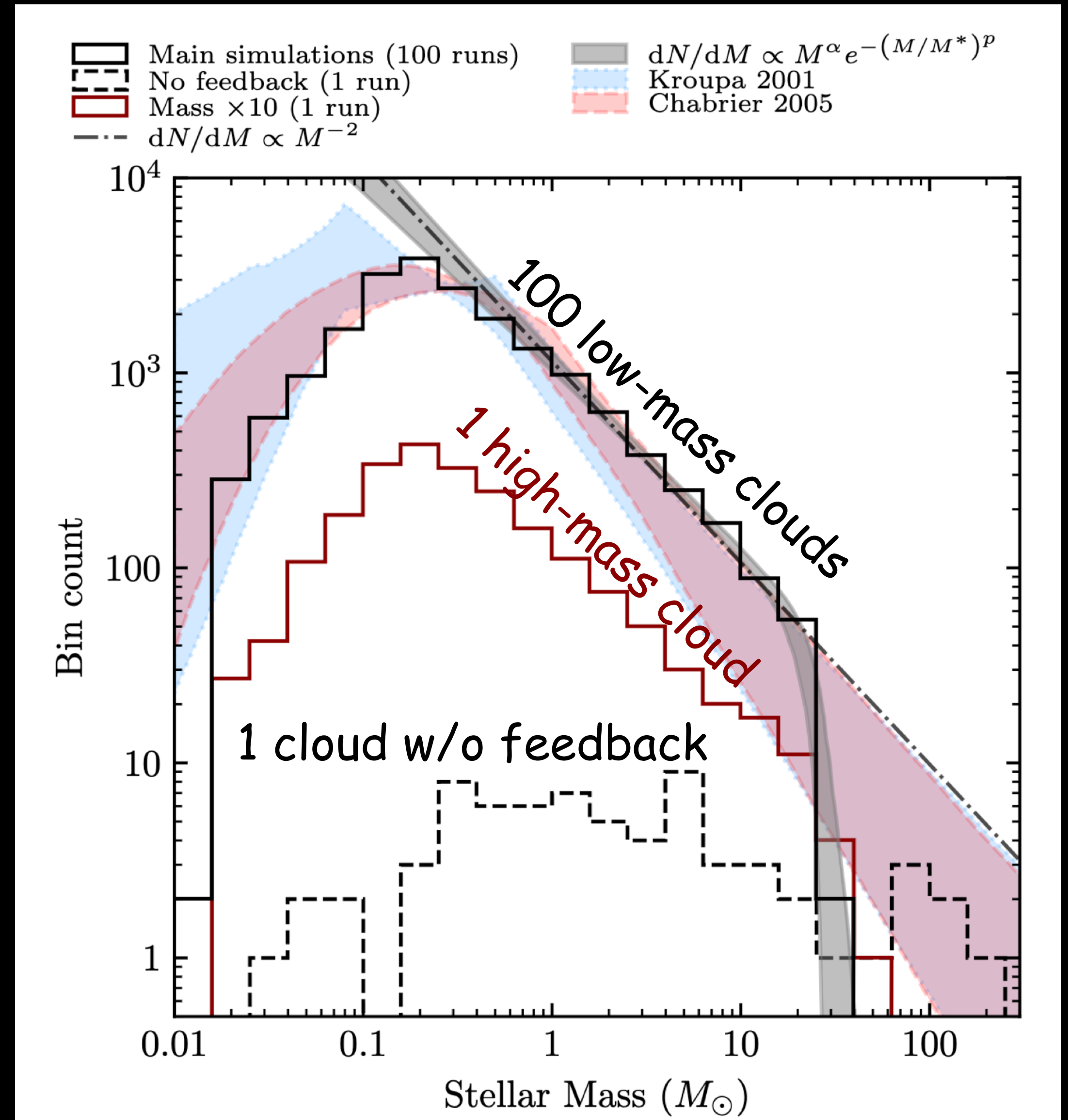


Upper IMF cutoff in **starforge**

Grudić et al 2023 OJAp...6E..48G

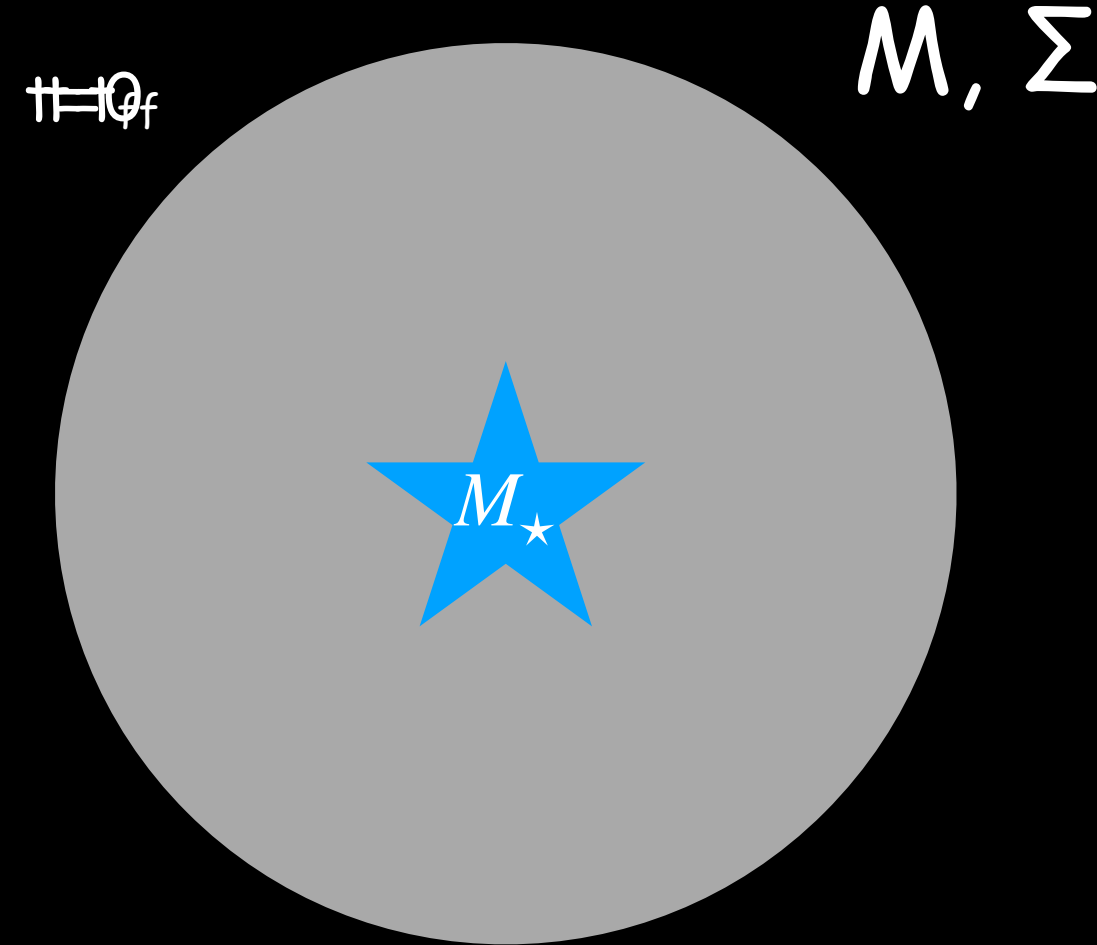
The upper IMF cutoff in STARFORGE simulations is:

- Not just a size-of-sample effect
- Set by feedback physics
- Depends on cloud properties: M , Σ , Z , etc.



M_{up} from feedback physics: back-of-the-envelope

e.g. Grudić et al 2023 OJAp...6E..48G



How much feedback do you need to disrupt a cloud within $\sim 1 t_{\text{ff}}$?

Momentum feedback (e.g. Steigman 1975, radiatively efficient winds, radiation pressure): $\dot{P} \propto L \propto M\Sigma$ (Radiation)
 $\propto \dot{M}_{\text{wind}} v_{\text{wind}} \propto M\Sigma$ (Winds)

Energy feedback (e.g. Weaver 1977, radiatively inefficient winds): $L_{\text{wind}} = \frac{1}{2} \dot{M}_{\text{wind}} v_{\text{wind}}^2 \propto M^{5/4} \Sigma^{5/4}$

Photoionization (e.g. Spitzer 1978, Hosokawa 2006): $\mathcal{Q}(H^0) \propto M^{3/2} \Sigma^{5/2}$

Denser, more-massive clouds can tolerate more-massive stars without being disrupted.

Dust Radiation Pressure

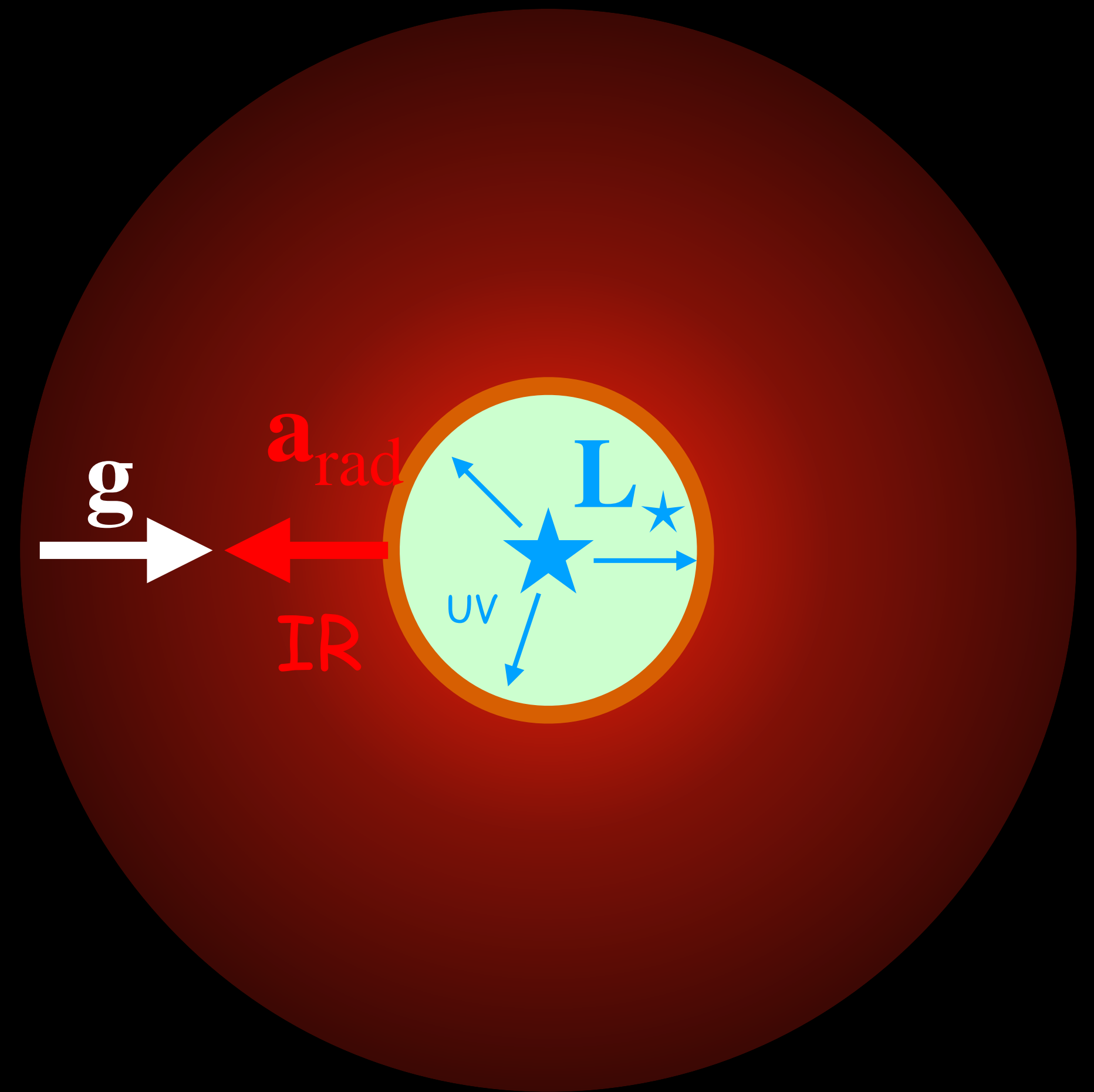
$$L_{\star} \approx L_{\text{edd}}(\sigma_T) = \frac{4\pi GMm_p c}{\sigma_T} = 3 \times 10^6 L_{\odot} \left(\frac{M}{100 M_{\odot}} \right)$$

$$\kappa_{\text{d,IR}} \lesssim 5Z_d \text{ cm}^2 \text{ g}^{-1}$$

$$\frac{a_{\text{rad}}}{g} = \frac{L_{\star}}{L_{\text{edd}}(\kappa_{\text{d,IR}})} = \frac{\kappa_{\text{d,IR}} m_p}{\sigma_T} \lesssim 20Z_d$$

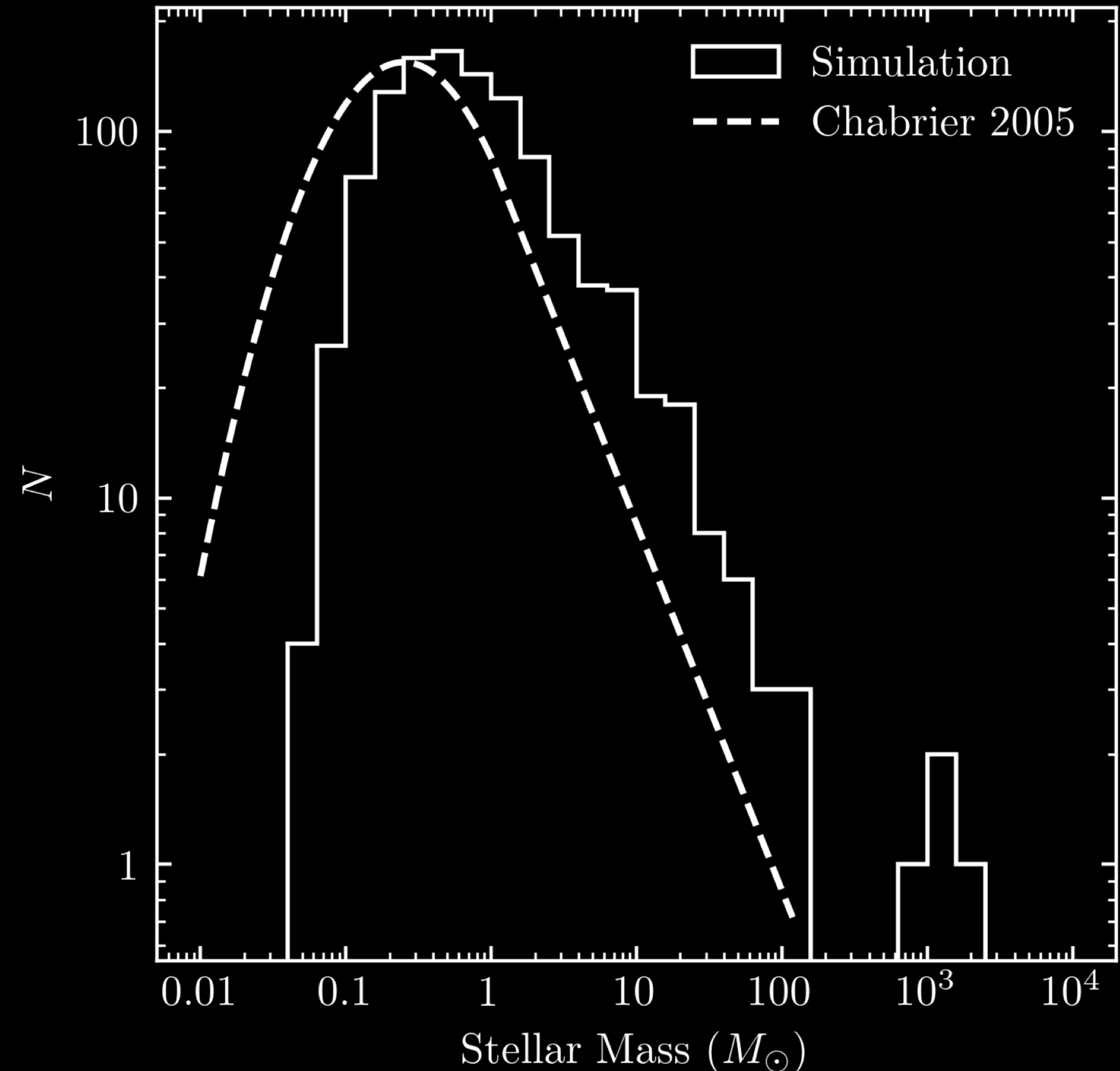
$Z_d = 1$: Radiation pressure important; dust+gas have to do fancy things to reach the star
(Krumholz 2009, Kuiper 2010)

$Z_d \lesssim 0.05$: Radiation pressure on dusty neutral gas doesn't work



High-density, $0.01Z_{\odot}$ cloud simulation

- $M = 2 \times 10^4 M_{\odot}$; $\Sigma \sim 10^4 M_{\odot} \text{pc}^{-2}$; $Z = 0.01Z_{\odot}$
- Results:
 - Maximum stellar mass: $1778 M_{\odot}$, + 3 other $> 1000 M_{\odot}$ stars in a quadruple
 - Powerful $\sim 100 \text{km/s}$ stellar wind-driven outflow
 - Rest-frame-UV light-to-mass ratio: $\sim 10\times$ more than standard zero-age SSP
 - High- z UVLF? N enrichment? SMBH seeds?



Mass Reservoirs Feeding Very Massive Stars

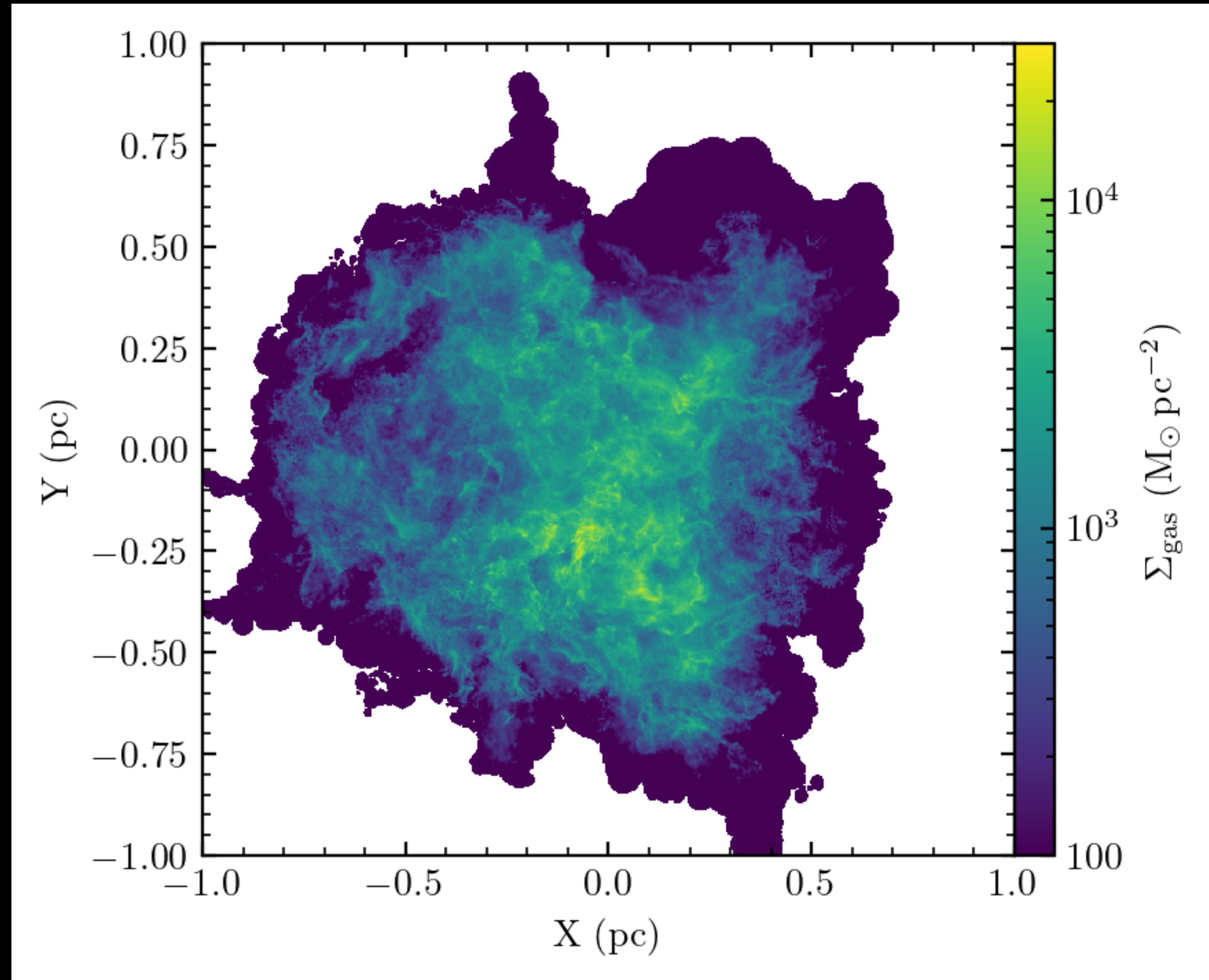
All Gas

Paul ($1778M_{\odot}$)

John ($1288M_{\odot}$)

George ($1212M_{\odot}$)

Ringo ($981M_{\odot}$)



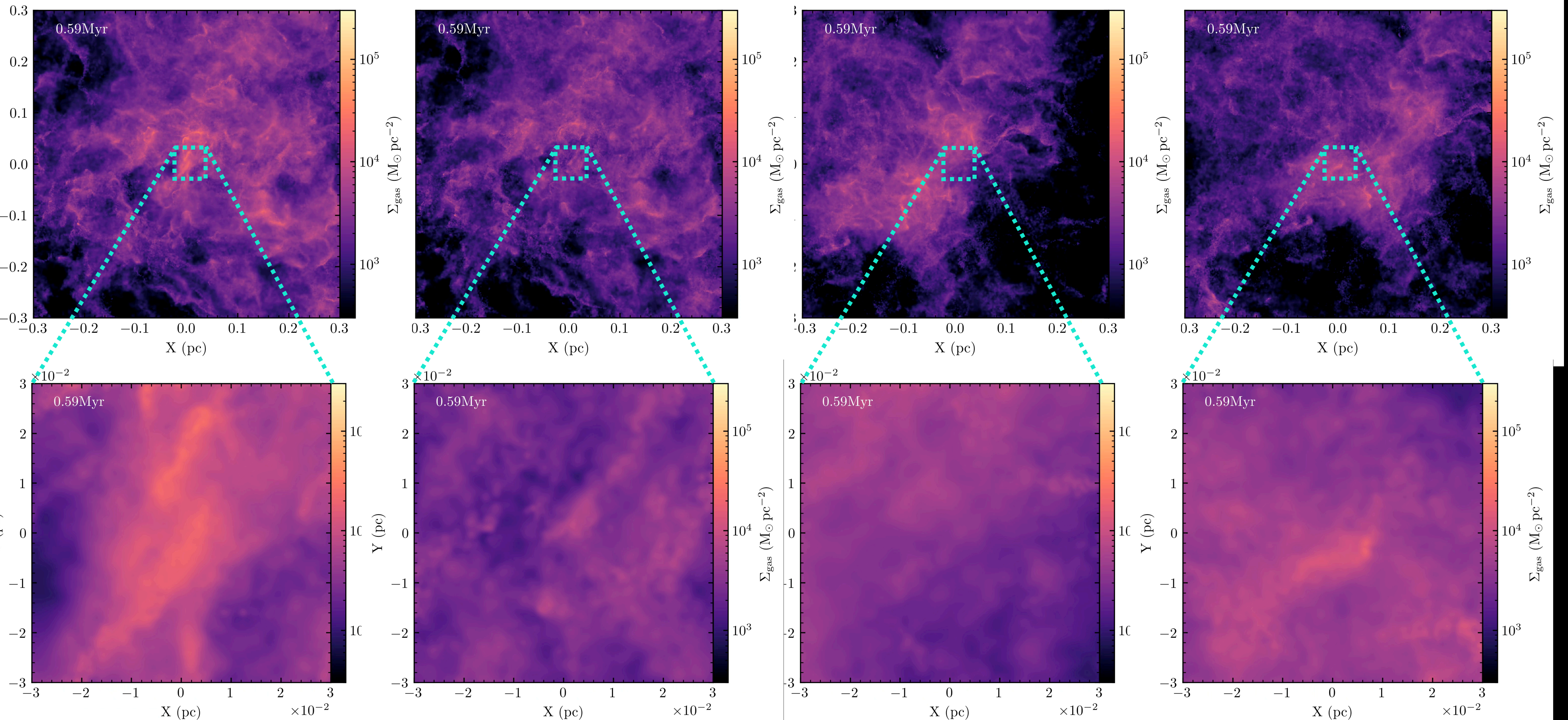
Accretion Reservoirs

Paul

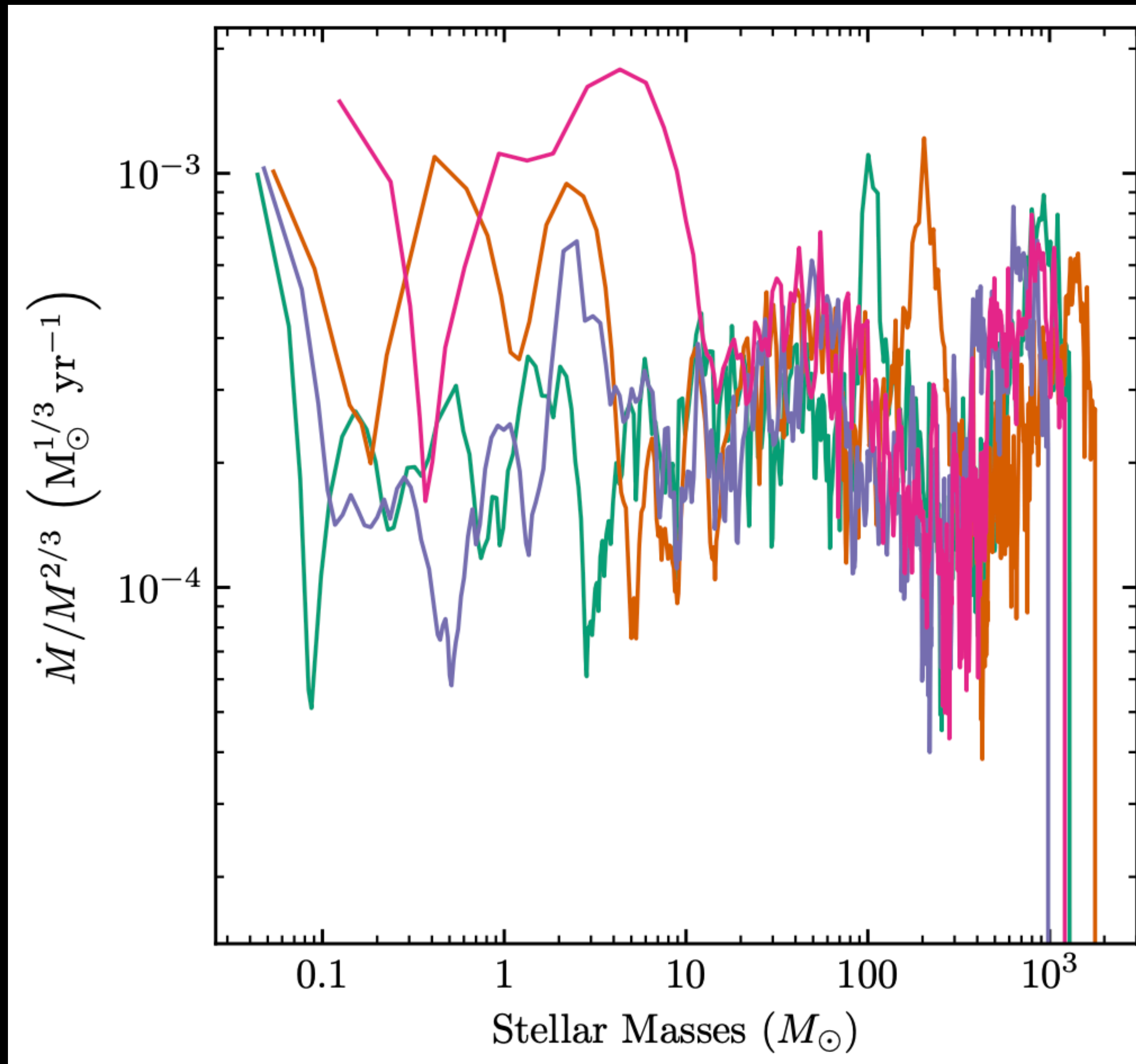
John

George

Ringo



Accretion Histories of Very Massive Stars



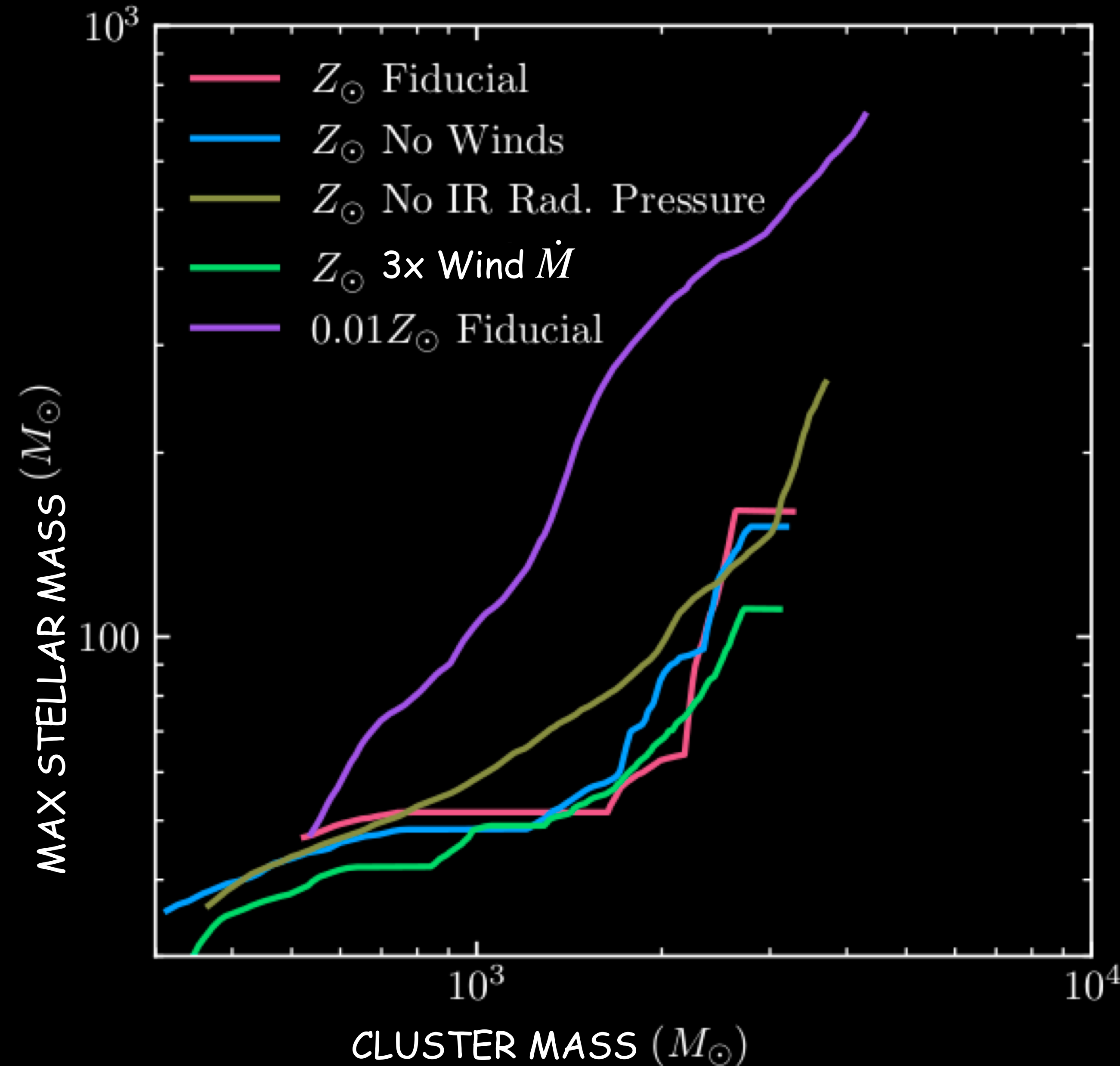
Tidal-lobe-limited competitive accretion
(Bonnell 2001):

$$\dot{M}_* = \pi \rho v_{\text{inf}} \left(\frac{M_*^{2/3}}{\sum_{i=1}^{N_{\text{comp}}} M_i^{2/3}} \right) R_{\text{tidal}}^2,$$

Stars accrete from a common
inflow with cross-section
determined by their Hill sphere.

VMS at low Z due to
runaway accretion, not
higher Jeans mass.

Effect of Feedback and Z on M_{max} (High Σ clouds)



Anatomy of the IMF

*for pop I and II

