Galactic Winds driven by Clustered Supernovae

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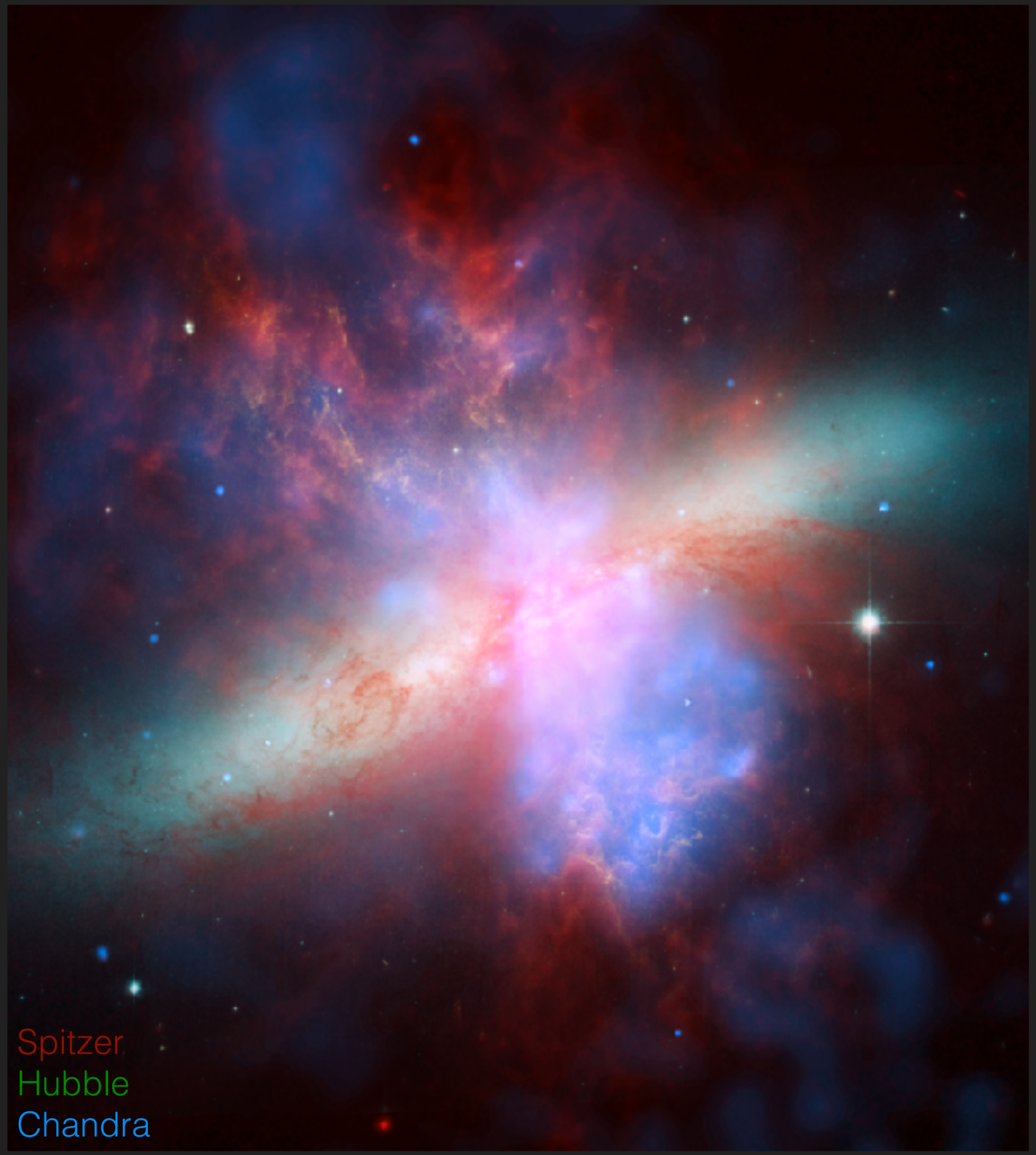
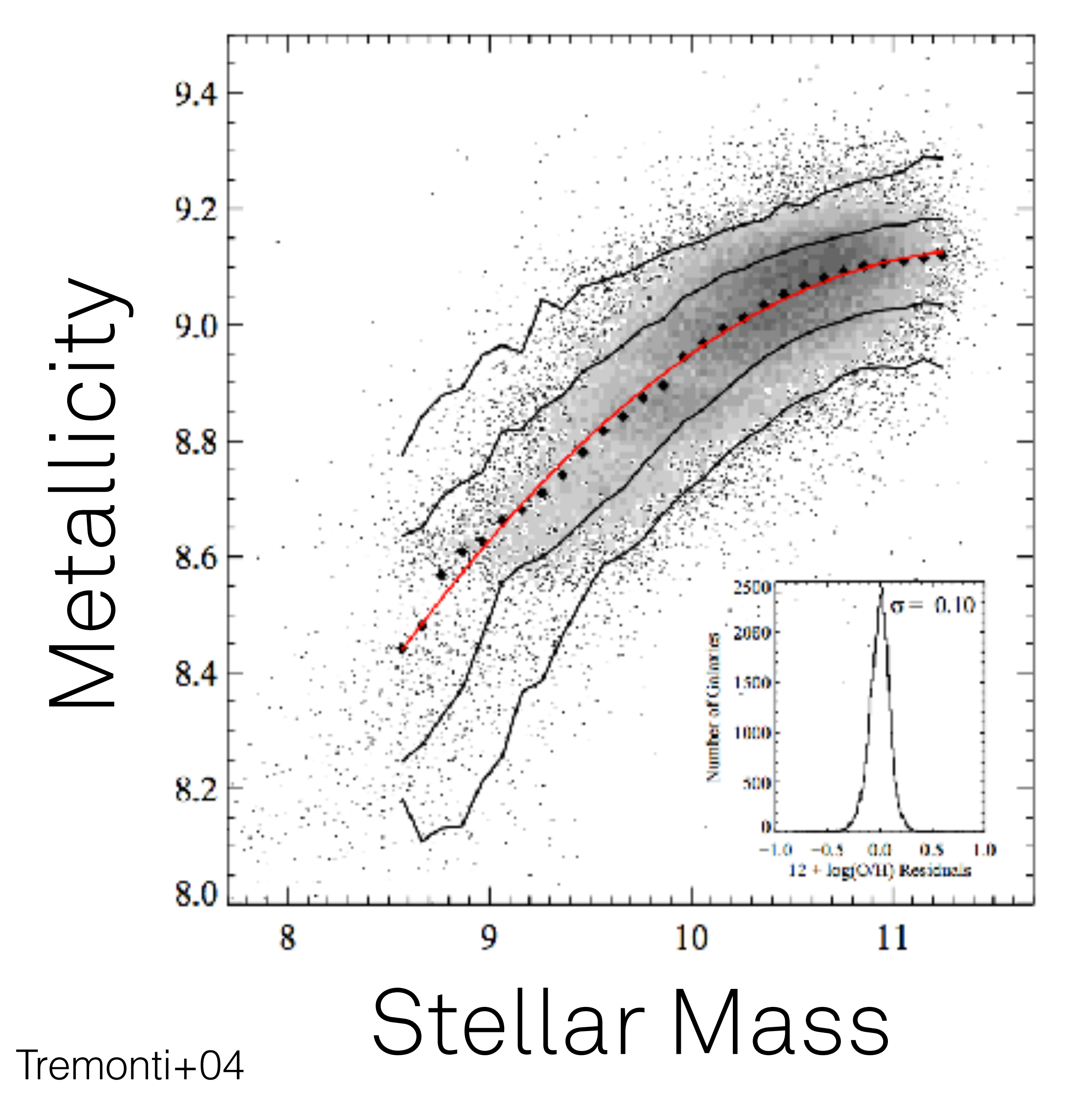
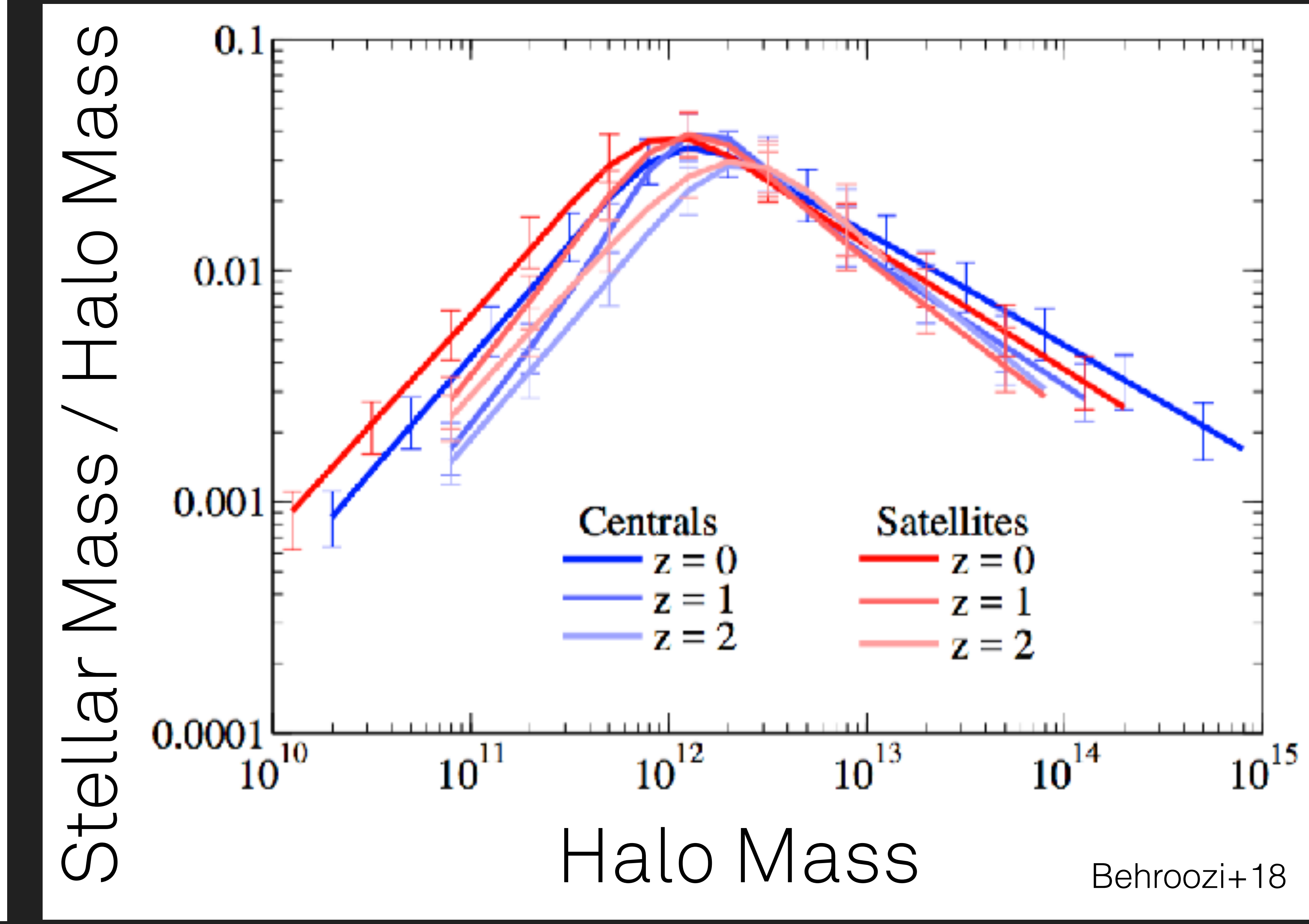
Galactic Winds Overview

we see them



we need them

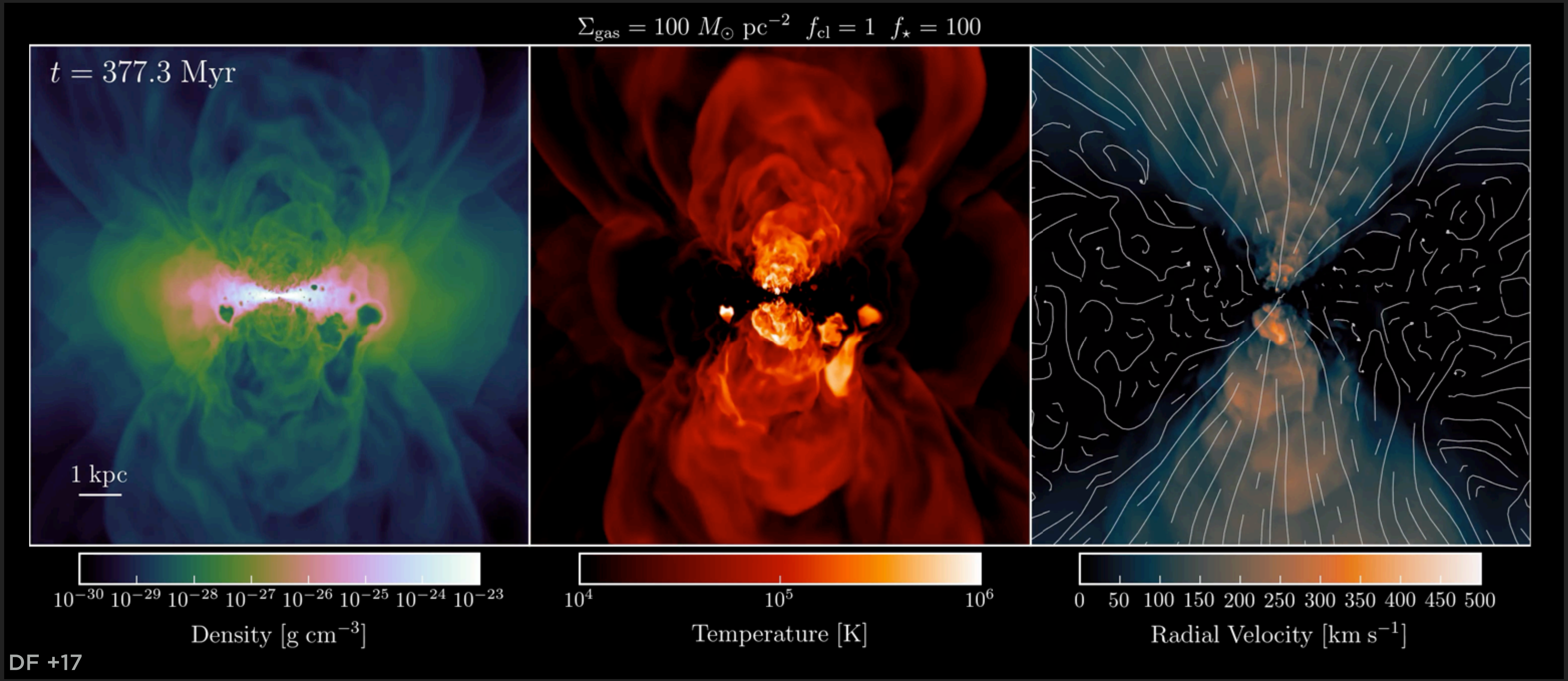




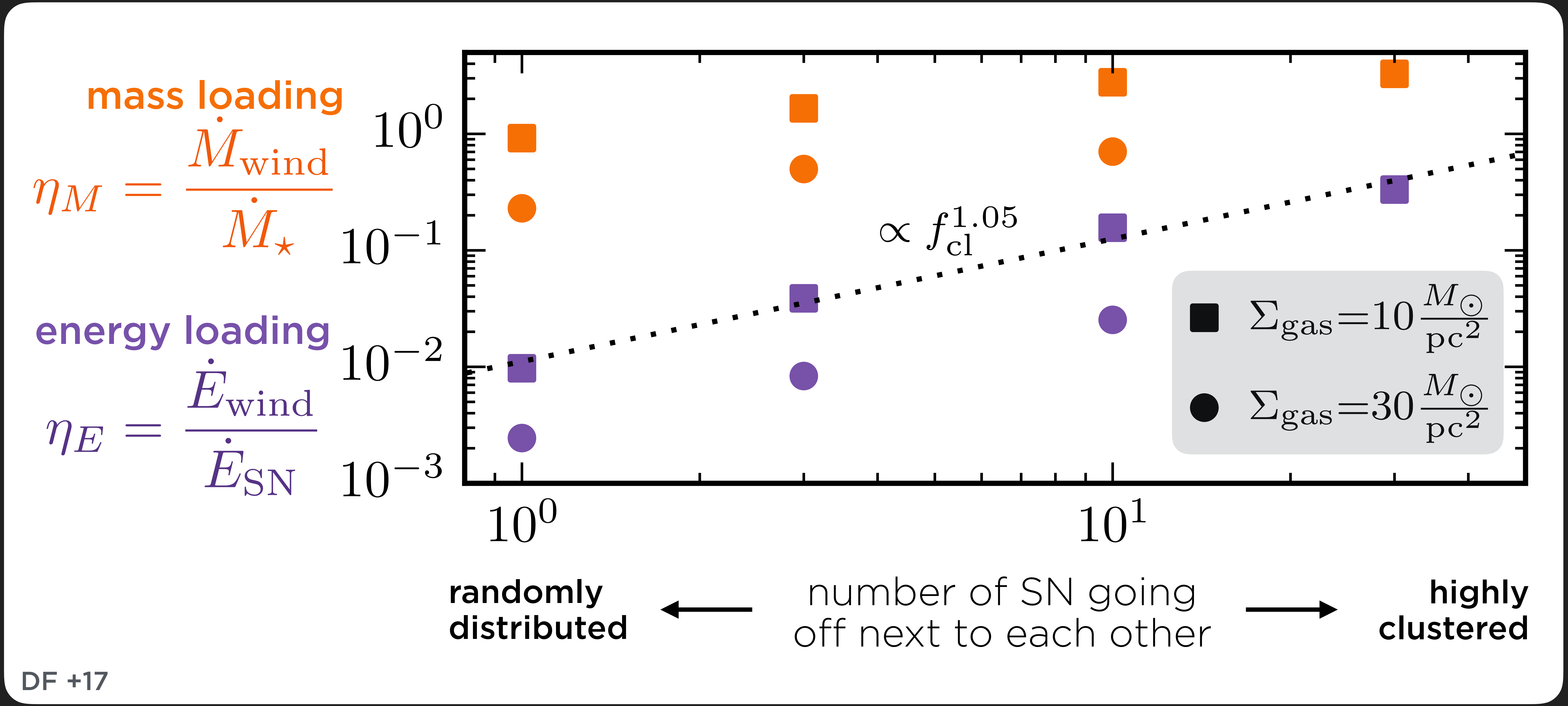
we do not understand them

How SNe launch galactic winds

Athena4.2

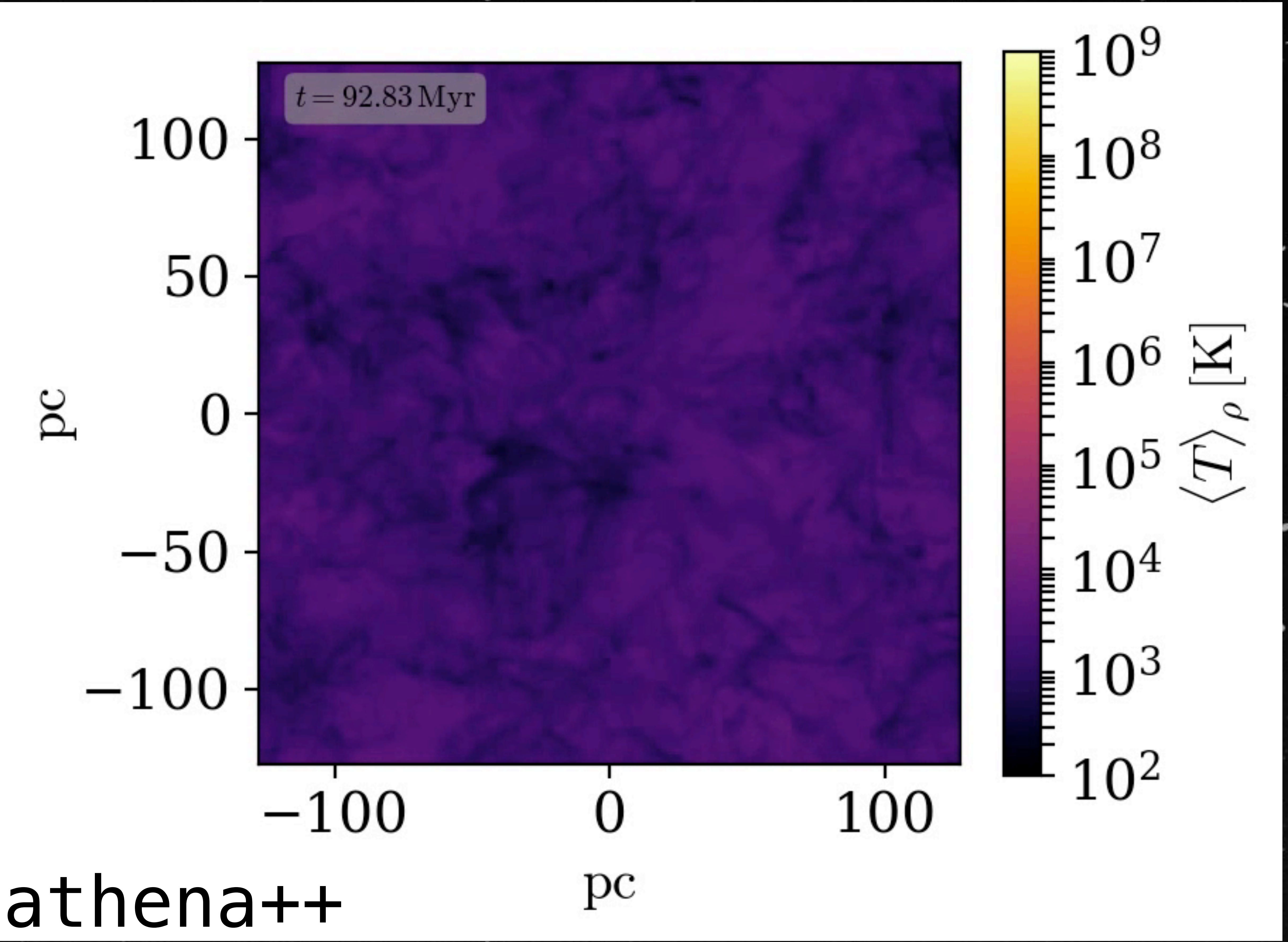


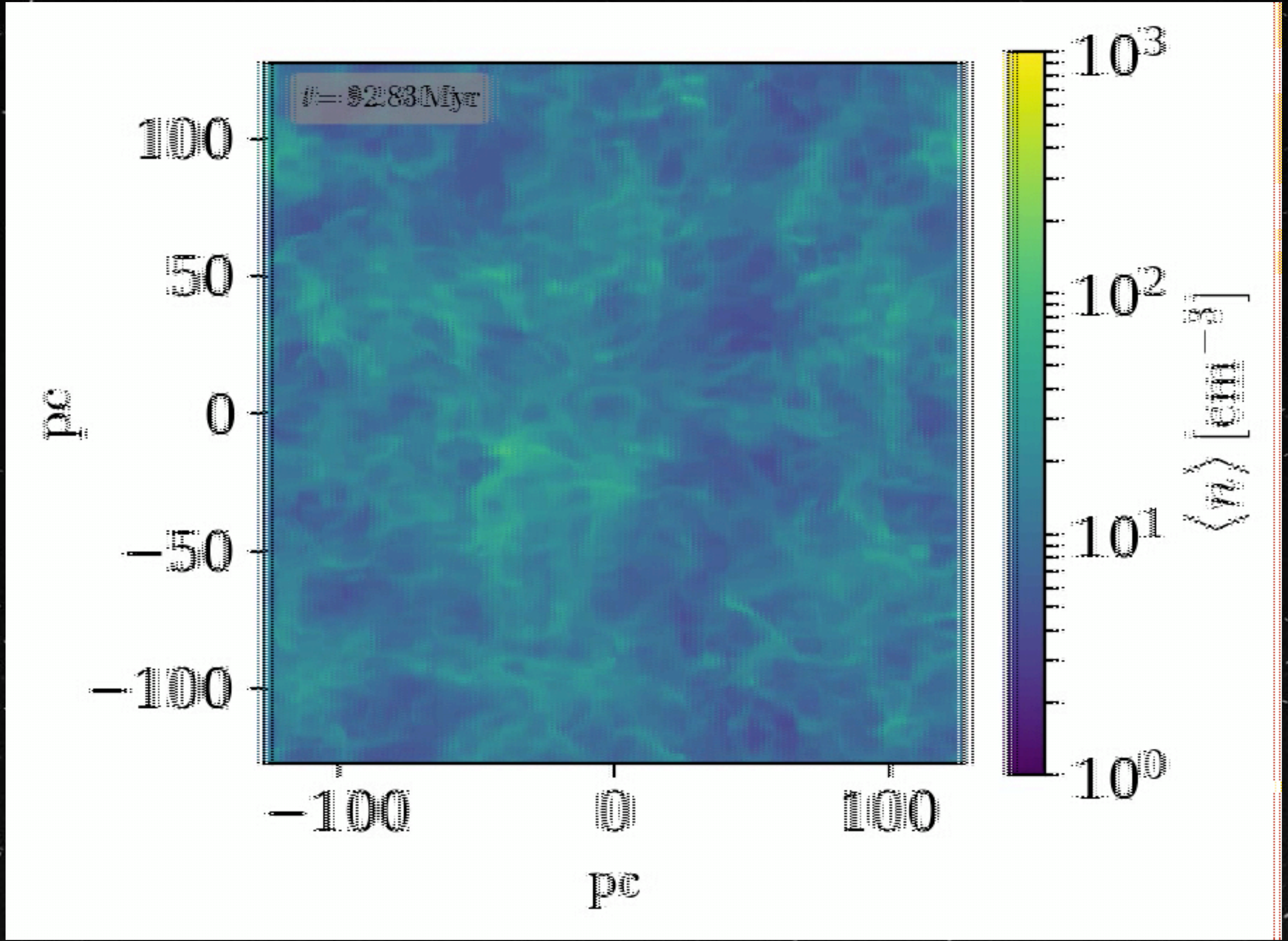
Clustering to the Rescue!



luckily stars form in clusters!

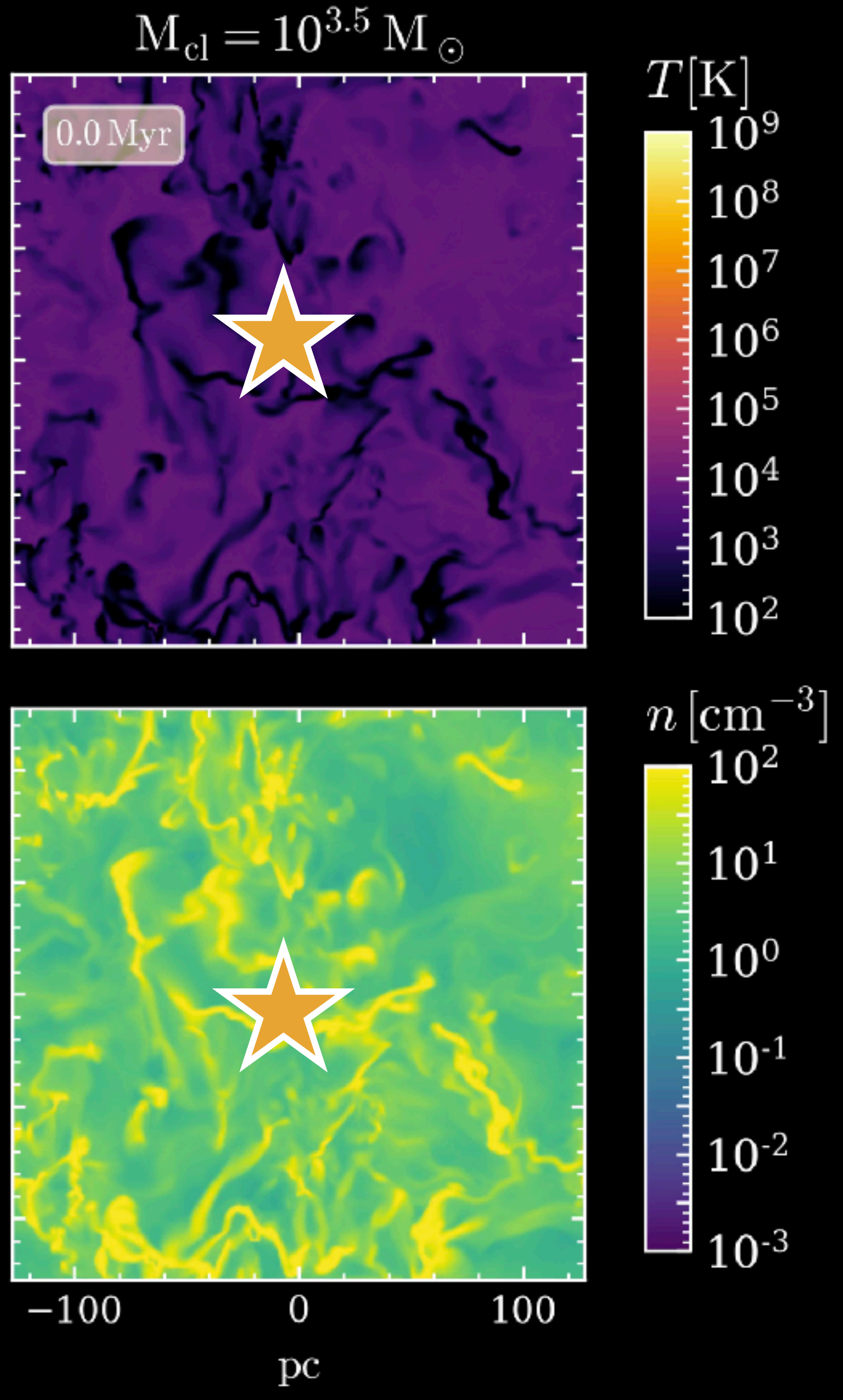
Clustered SNe in a Turbulent, Multi-Phase ISM



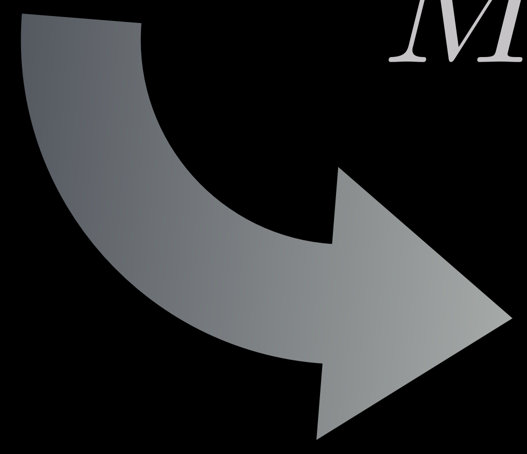


Radiative Cooling + Photo Heating + Turbulence = semi-realistic testbed ISM for SNe

Clustered SNe in a Turbulent, Multi-Phase ISM



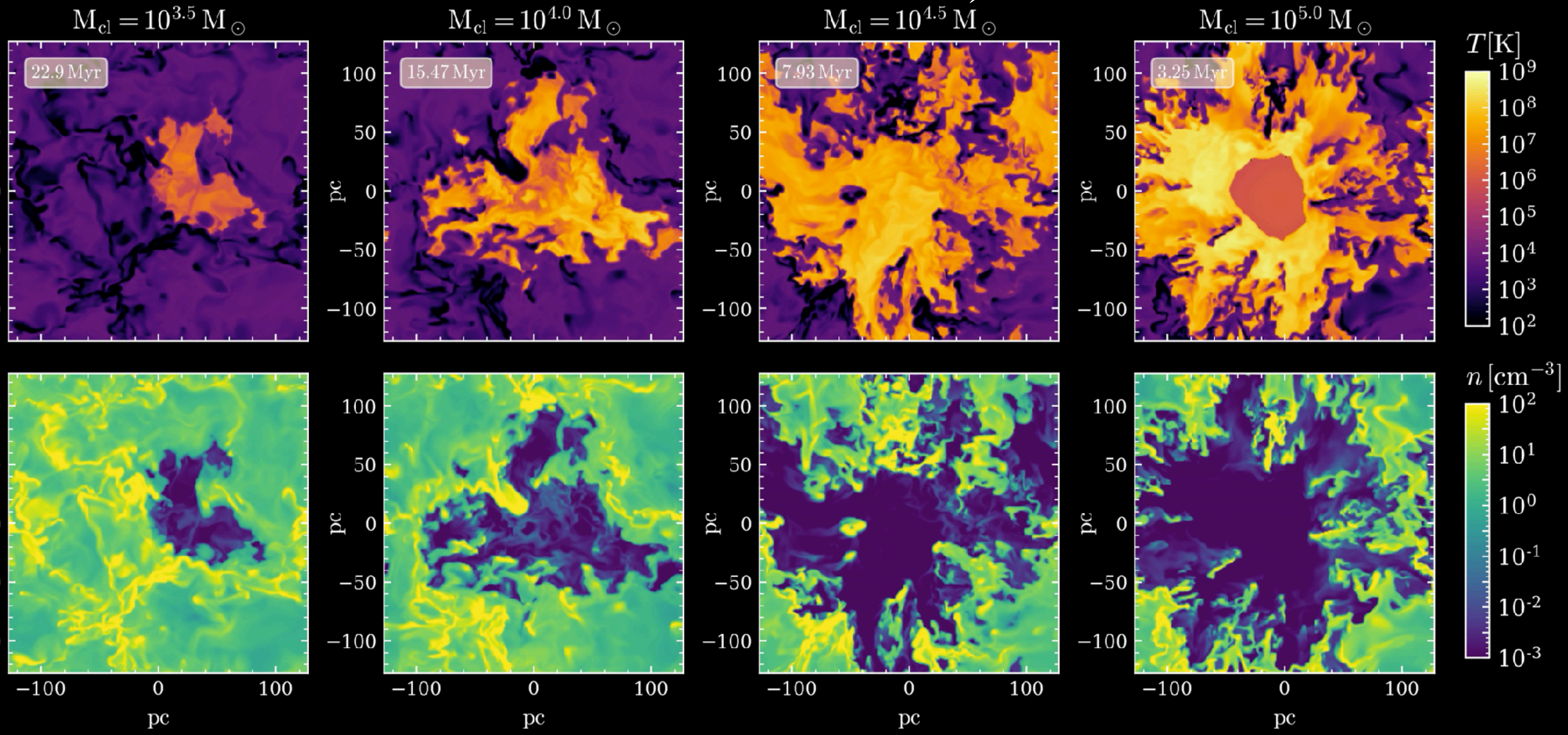
$$M_{\mathrm{GMC}} = \pi h^2 \Sigma_{\mathrm{gas}}$$



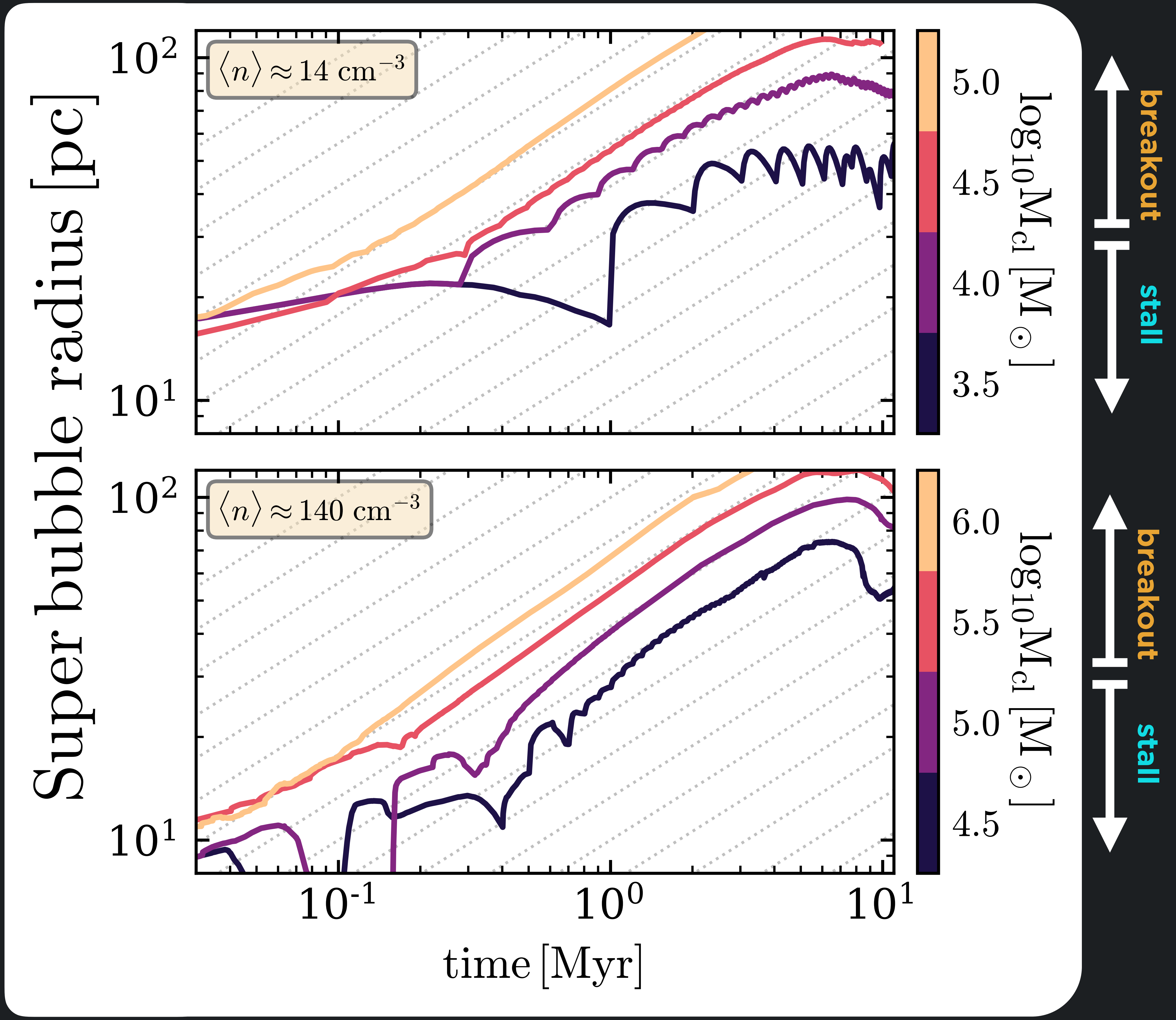
$$M_{\mathrm{Cluster}} = \epsilon_\star M_{\mathrm{GMC}}$$

$$N_{\mathrm{SN}} = M_{\mathrm{Cluster}}/100 M_\odot \qquad \Delta t_{\mathrm{SN}} = N_{\mathrm{SN}}/30\mathrm{Myr}$$

Clustered SNe in a Turbulent, Multi-Phase ISM



Super-bubble Breakout?



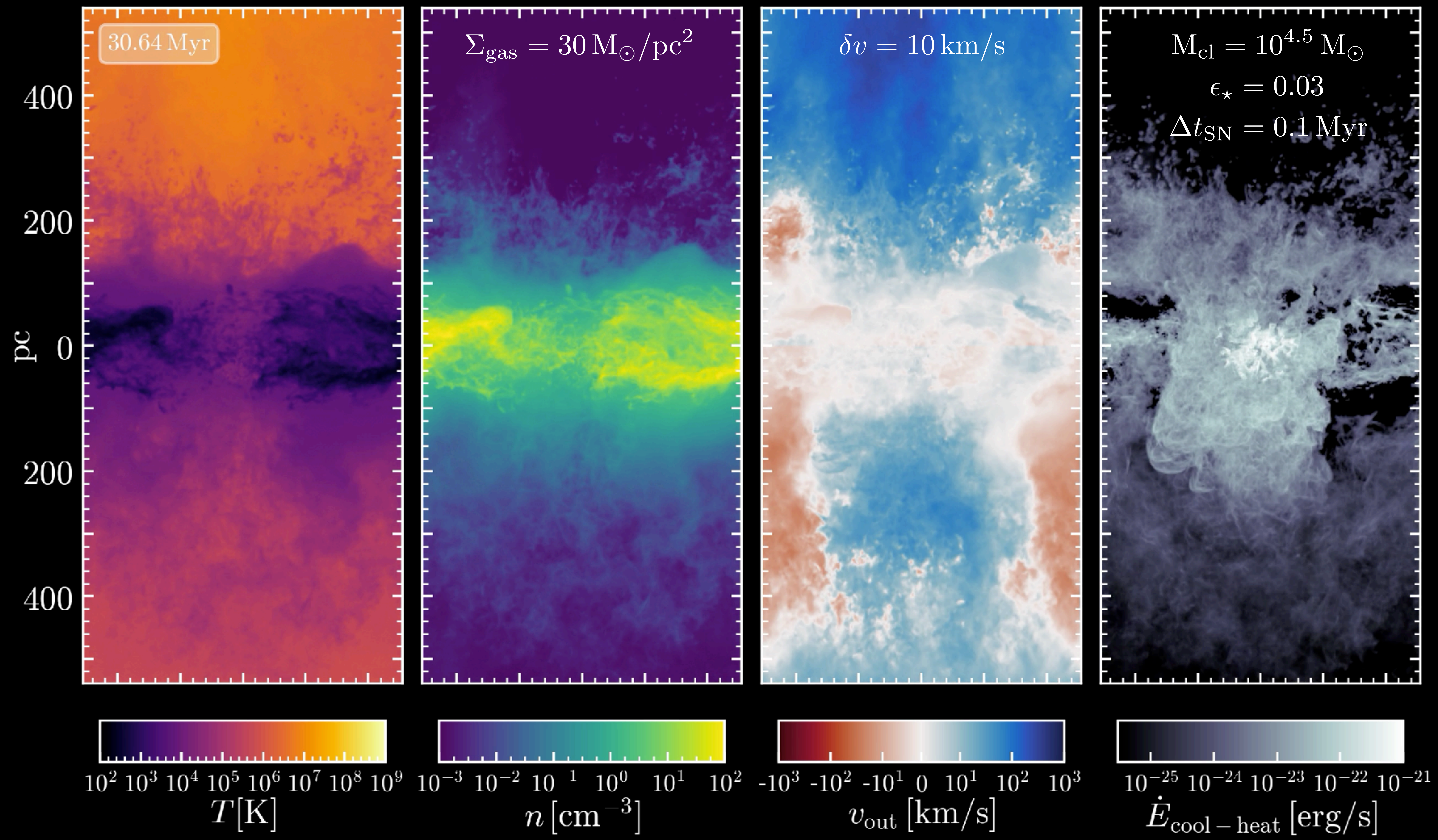
Two criteria for bubble breakout:

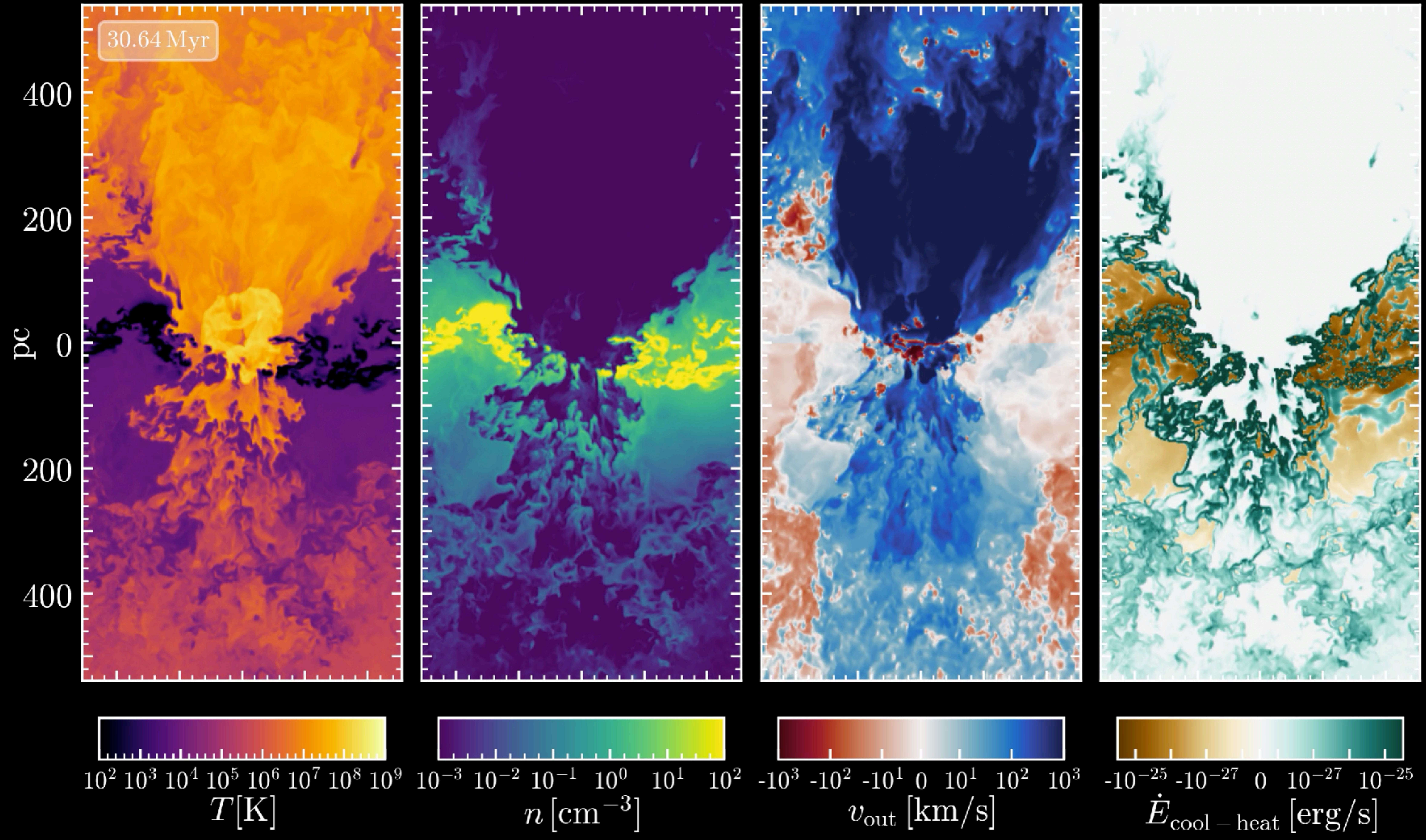
1. $r_\mathrm{bubble} \geq h$ before $t = t_\mathrm{SN}$ (easy)
2. $v_\mathrm{bubble} > \delta v$ when $r_\mathrm{bubble} = h$ (hard)

Critical SF efficiency (or cluster mass or N_SNe) to breakout prior to stalling:

$$\epsilon_{\star,\mathrm{crit}} = 0.015 \left(\frac{n_\mathrm{median}/n_\mathrm{midplane}}{0.25} \right) \left(\frac{\delta v}{10\,\mathrm{km/s}} \right)^2 \left(\frac{h}{100\,\mathrm{pc}} \right)^{-1} \left(\frac{\mathrm{P_{SN}}}{10^5\,\mathrm{M_\odot\,km/s}} \right)^{-1}$$

The Importance of Breakout


30.64 Myr
$\Sigma_{\rm gas} = 30\,{\rm M_\odot/pc^2}$
$\delta v = 10\,{\rm km/s}$
$M_{\rm cl} = 10^{4.5}\,{\rm M_\odot}$
$\epsilon_\star = 0.03$
$\Delta t_{\rm SN} = 0.1\,{\rm Myr}$
pc
400
200
0
200
400
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9
$T\,[{\rm K}]$
10^{-3} 10^{-2} 10 1 10^0 10^1 10^2
$n\,[{\rm cm}^{-3}]$
-10^3 -10^2 -10^1 0 10^1 10^2 10^3
$v_{\rm out}\,[{\rm km/s}]$
10^{-25} 10^{-24} 10^{-23} 10^{-22} 10^{-21}
$\dot{E}_{\rm cool-heat}\,[{\rm erg/s}]$

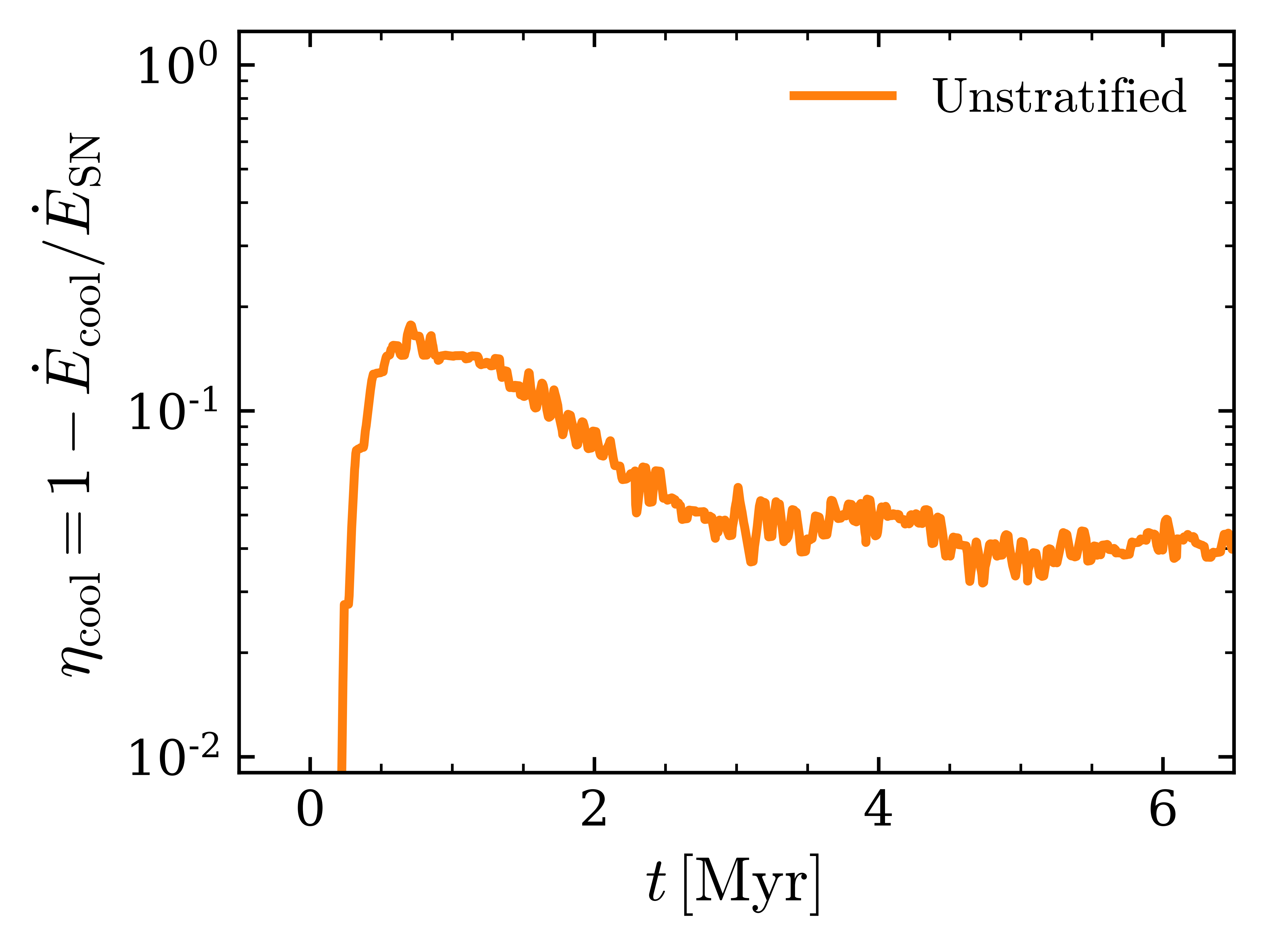


30.64 Myr
400
200
0
200
400
pc
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9
$T\,[\mathrm{K}]$
10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2
$n\,[\mathrm{cm}^{-3}]$
-10^3 -10^2 -10^1 0 10^1 10^2 10^3
v_{out} [km/s]
-10^{-25} -10^{-27} 0 10^{-27} 10^{-25}
$\dot{E}_{\mathrm{cool-heat}}$ [erg/s]

Pre-Breakout Energetics

$\Sigma_{gas} = 30\,M_\odot/pc^2 \quad M_{cl} = 10^{4.5}\,M_\odot \quad \epsilon_\star = 0.03$

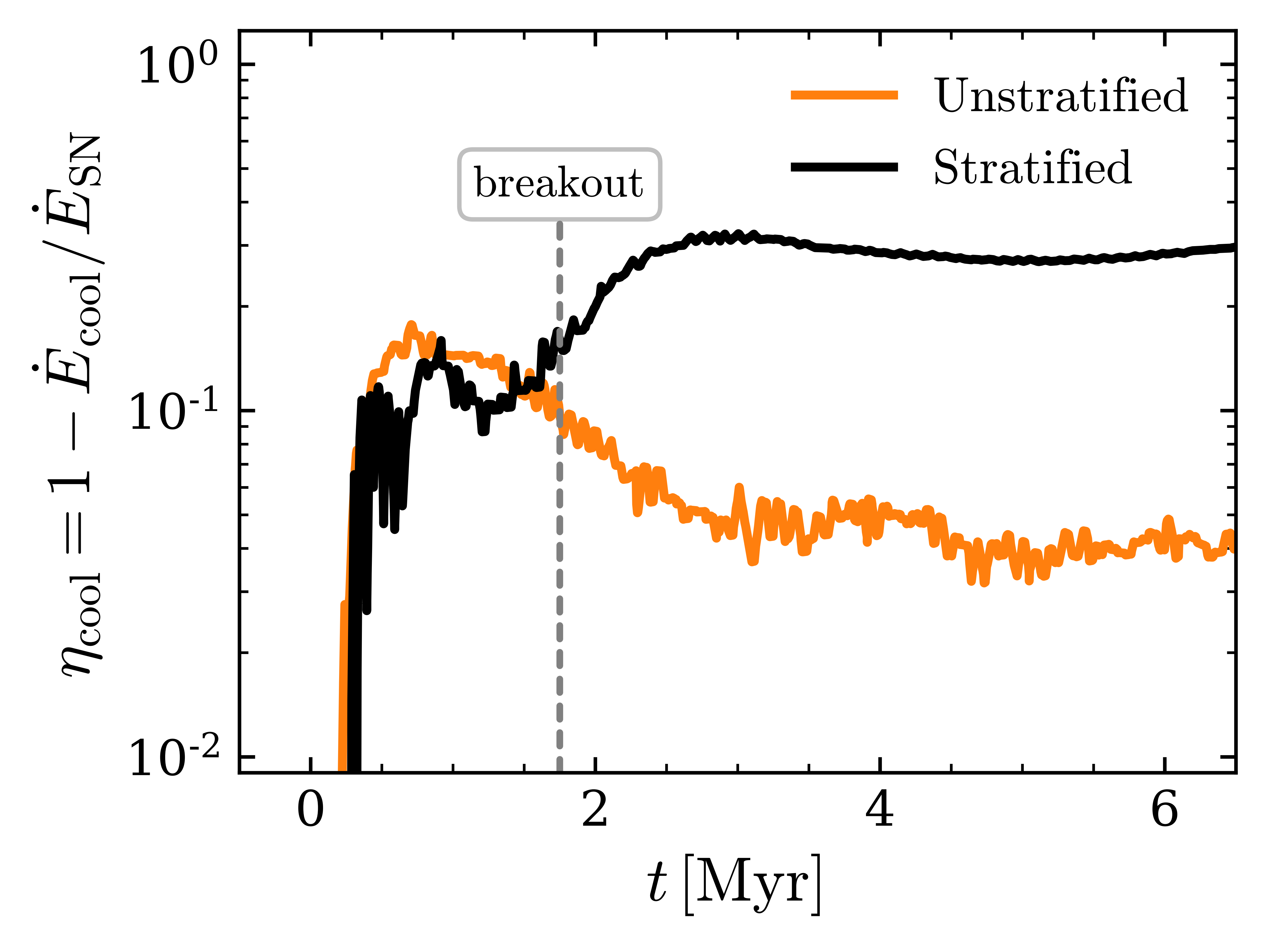
While confined within the disk >90% of the injected energy is radiated away



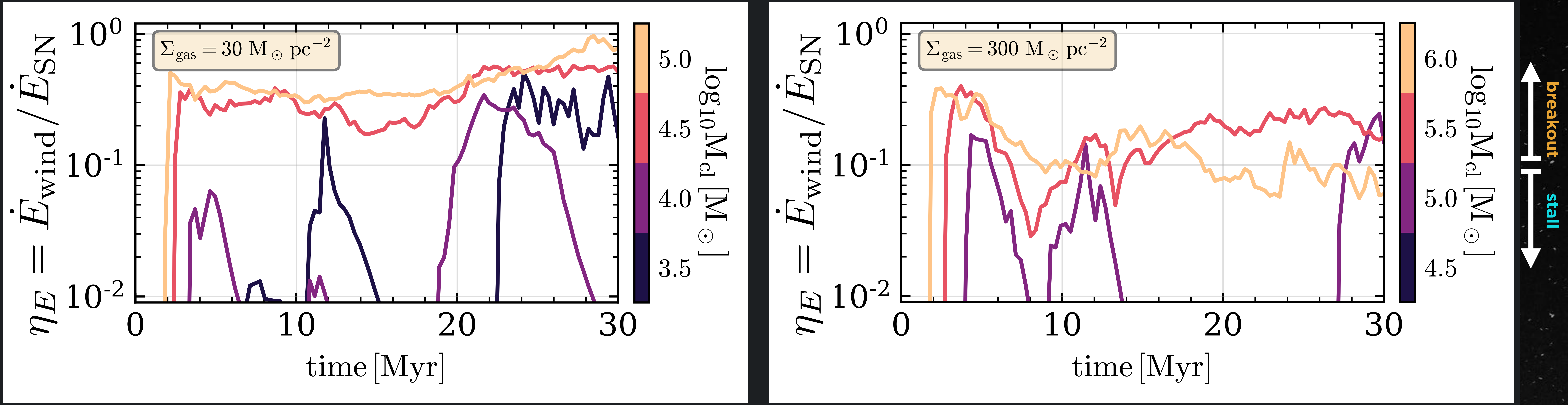
Post-Breakout Energetics

$\Sigma_{gas} = 30\,M_{\odot}/pc^2 \quad M_{cl} = 10^{4.5}\,M_{\odot} \quad \epsilon_{\star} = 0.03$

After the super-bubble breakout cooling drops by a factor of ~10 and a powerful wind is launched



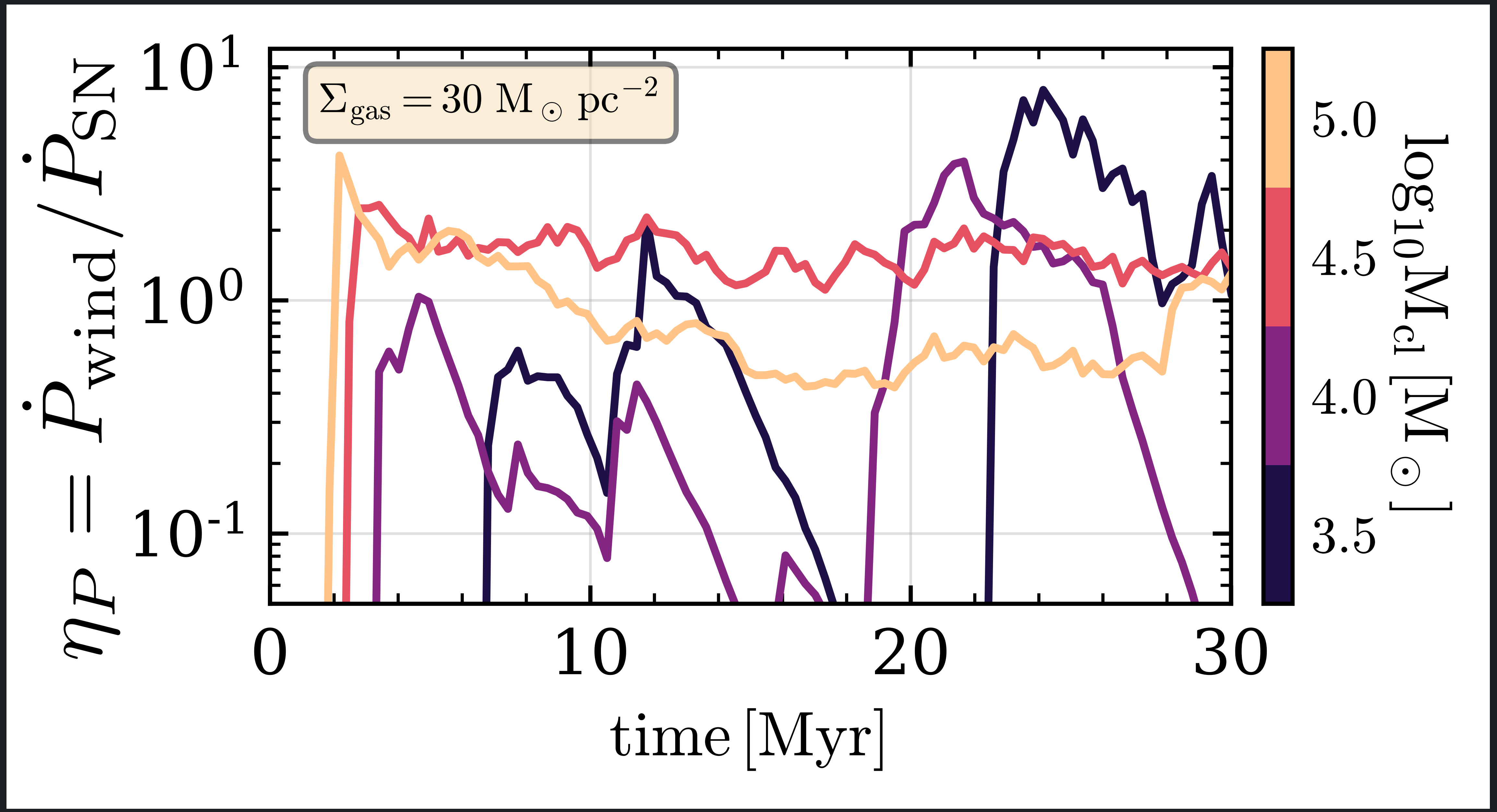
Galactic Wind Energy Loading

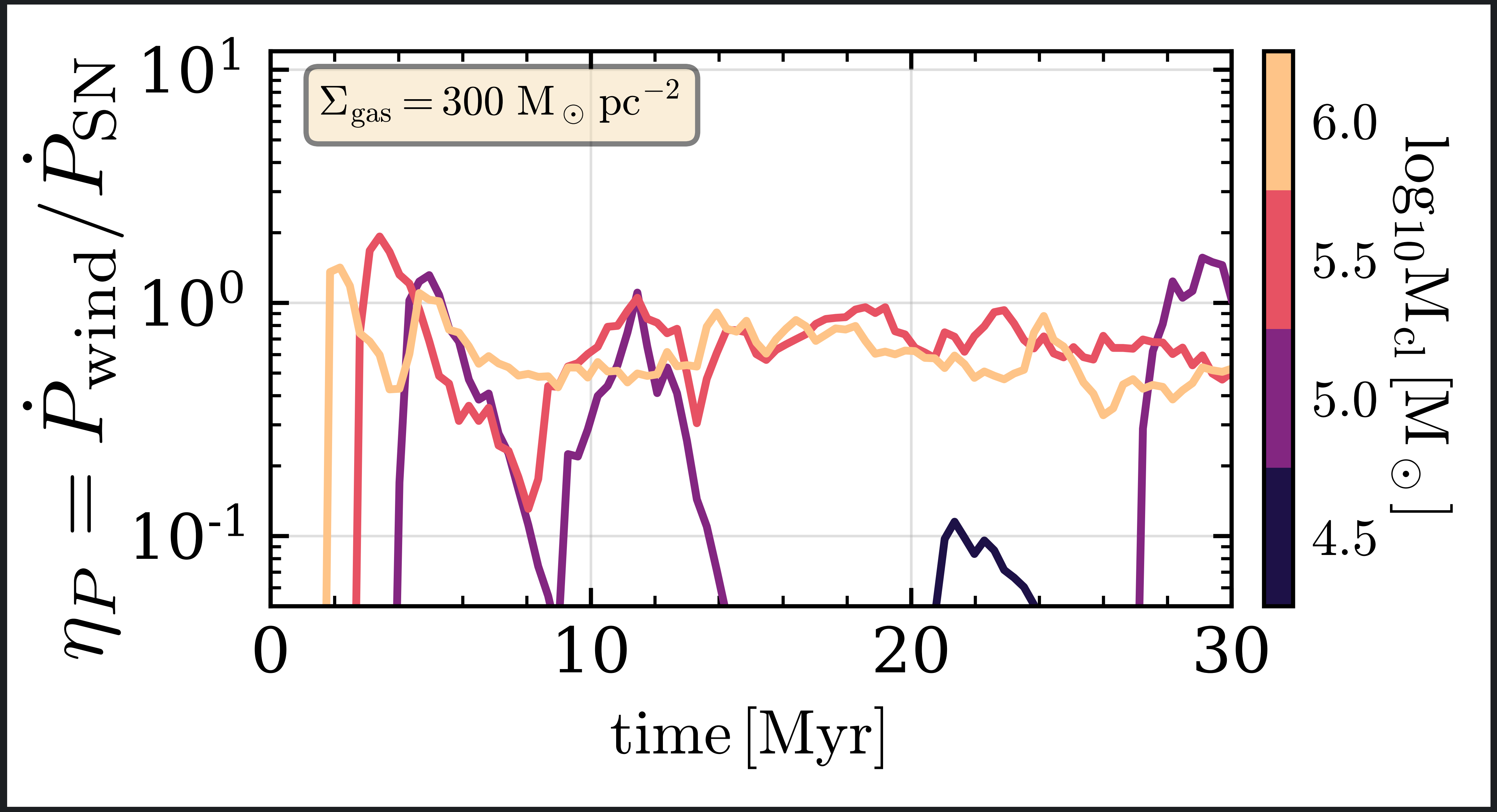


Clusters with $\epsilon_\star \gtrsim \epsilon_{\star,crit} \approx 0.015$ breakout

Drive winds with $\eta_E \sim 0.1 - 0.8$

Galactic Wind Momentum Loading

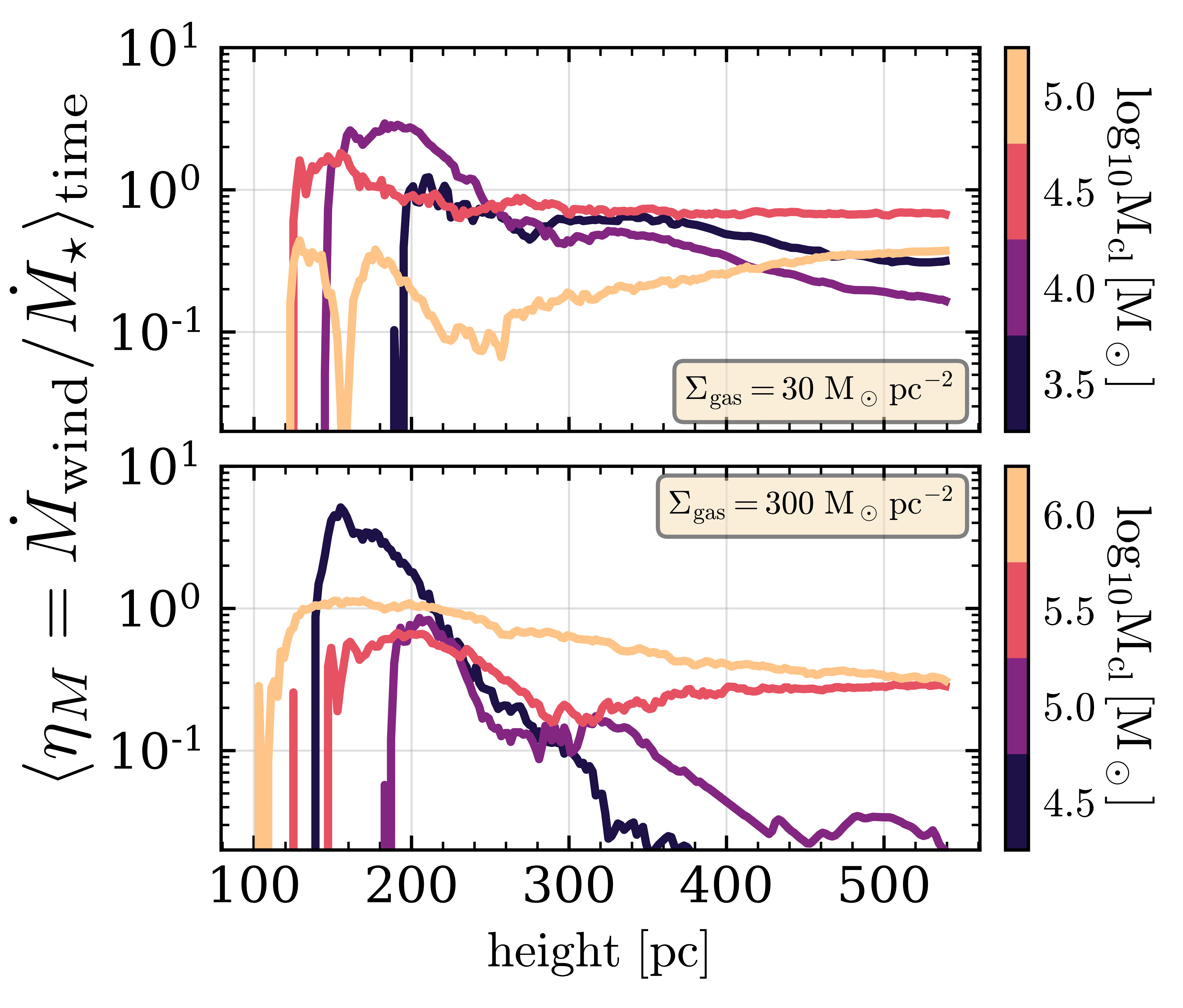


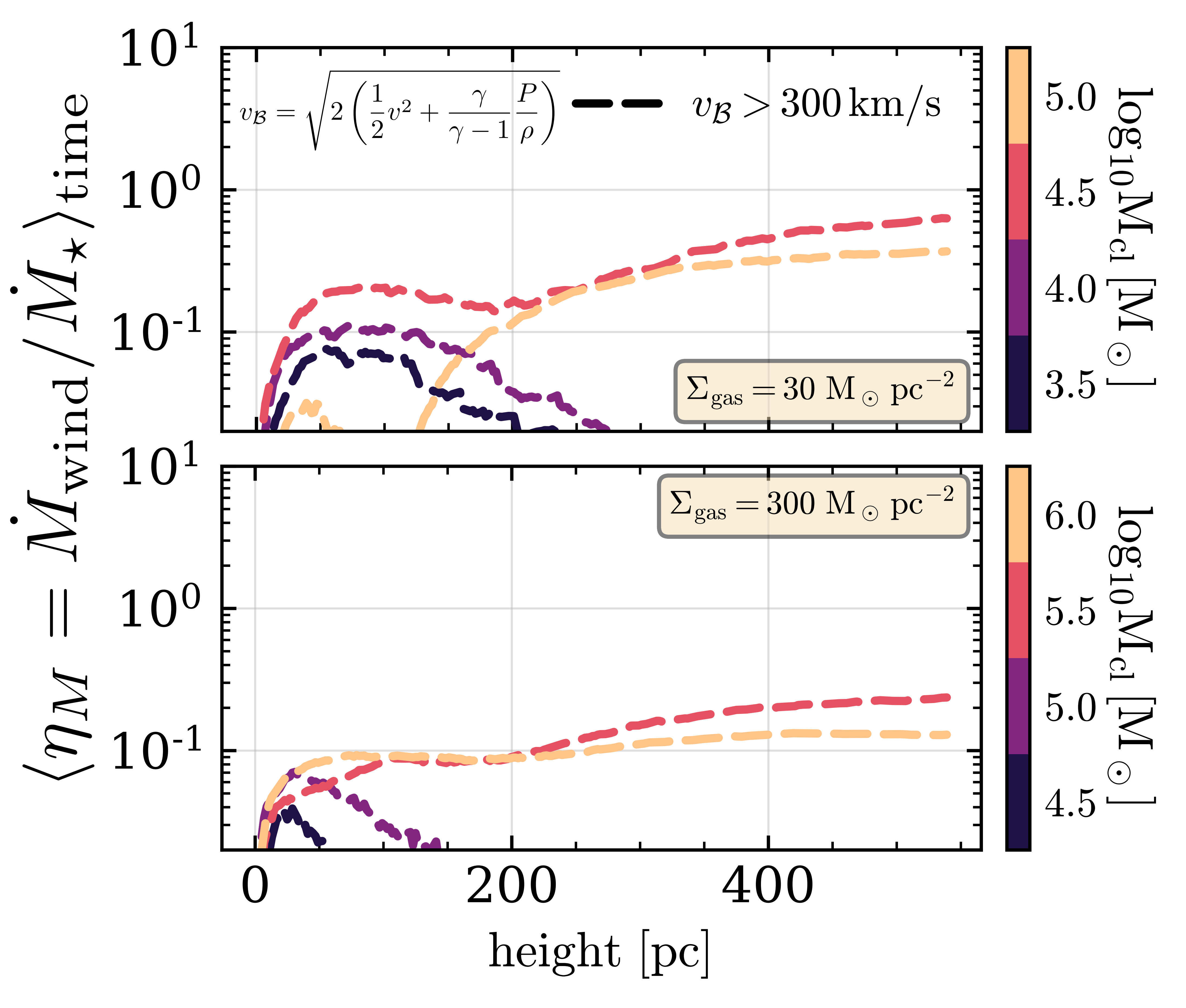


Momentum flux = injected momentum b.c.

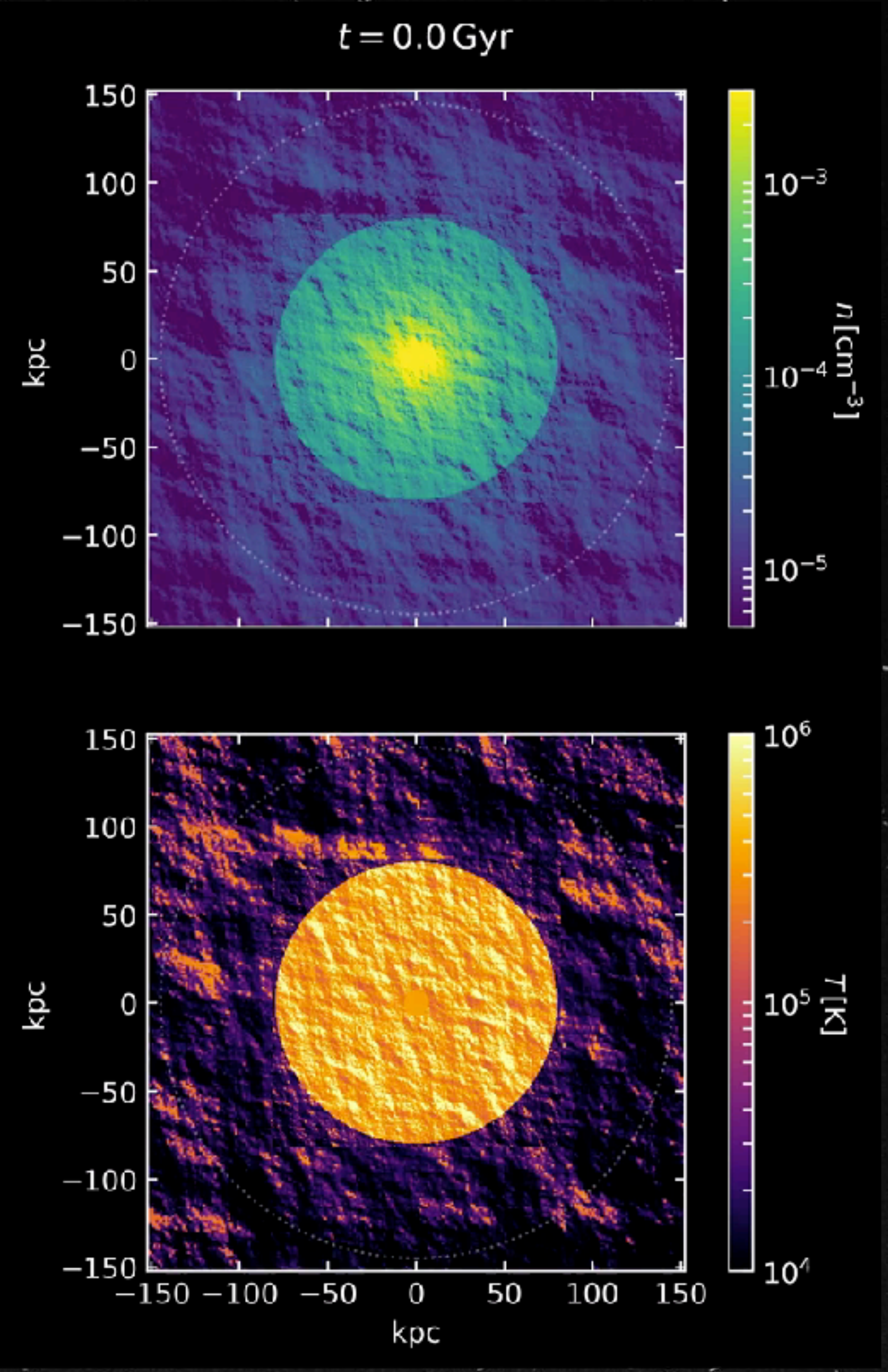
hot gas vents before doing work on ISM

Galactic Wind Mass Loading





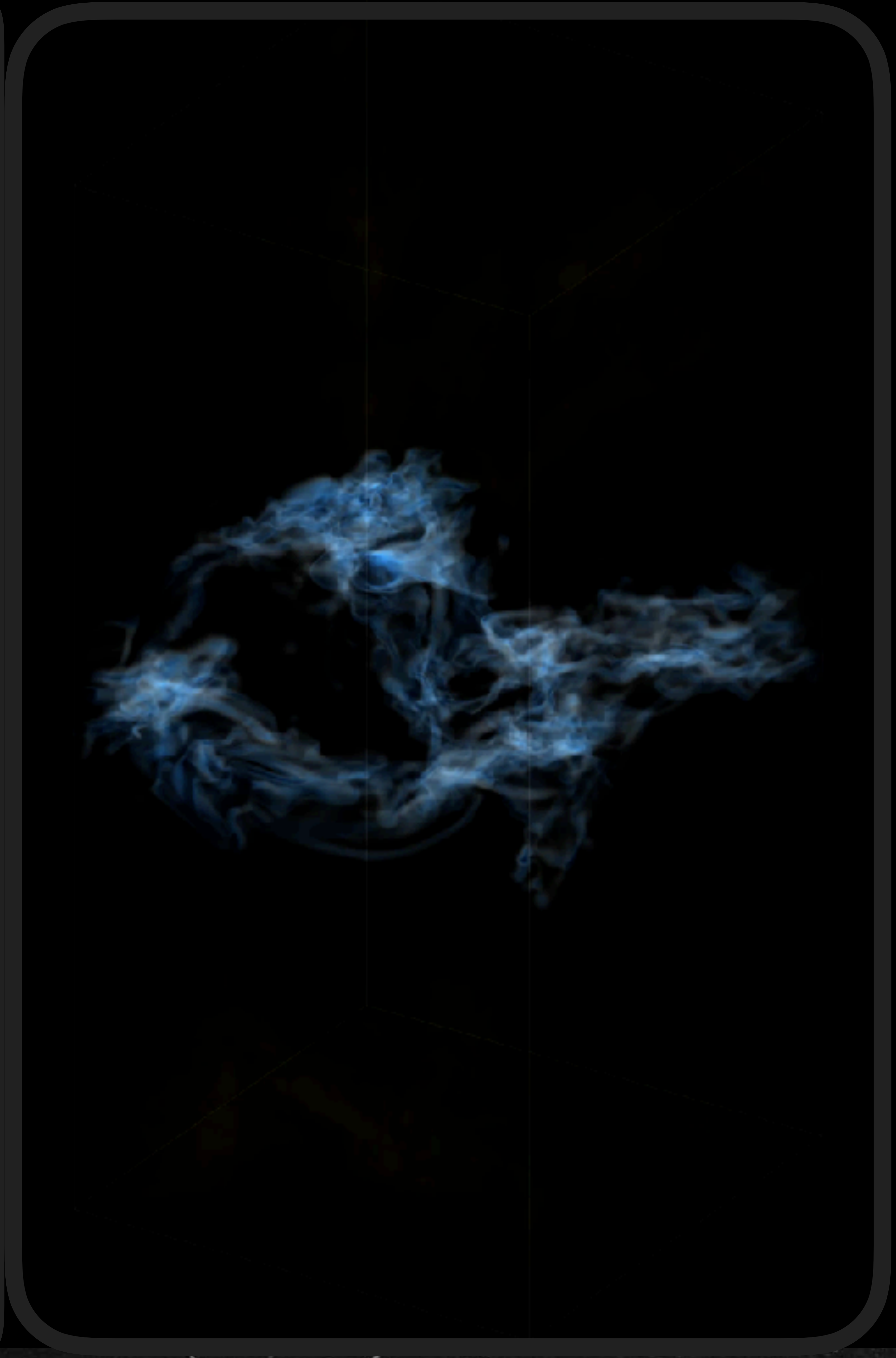
Clustered SNe can drive powerful galactic winds



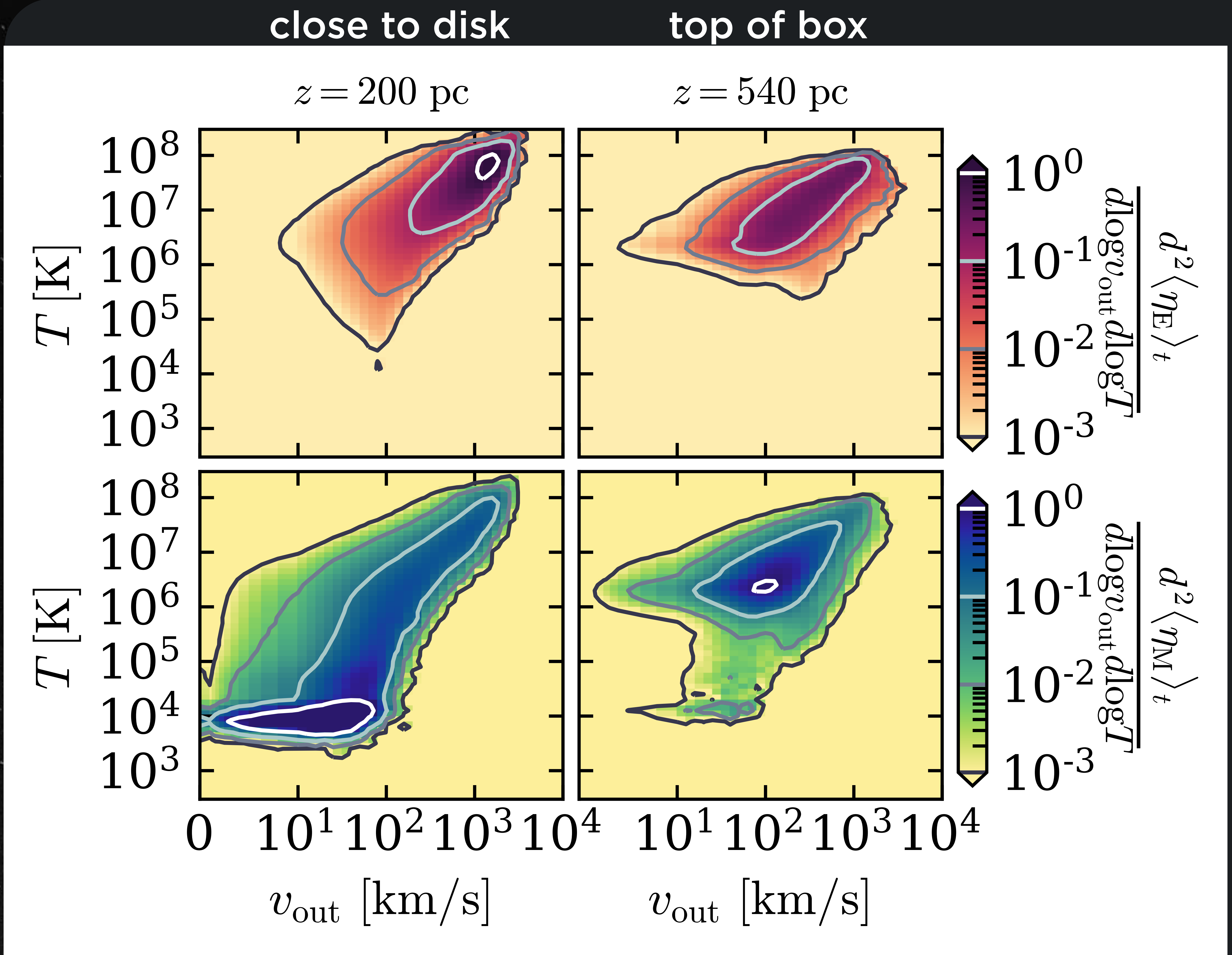
Spatio-temporal clustered SNe can breakout of galactic disk under a wide range of conditions

Create "chimney" and vent efficiently into the CGM. The energy, mass, and momentum flux is a significant fraction of amount injected by SNe

$$\eta_E \sim 0.1 - 0.8 \;\; \eta_M \sim 0.1 - 1 \;\; \eta_P \sim 1$$

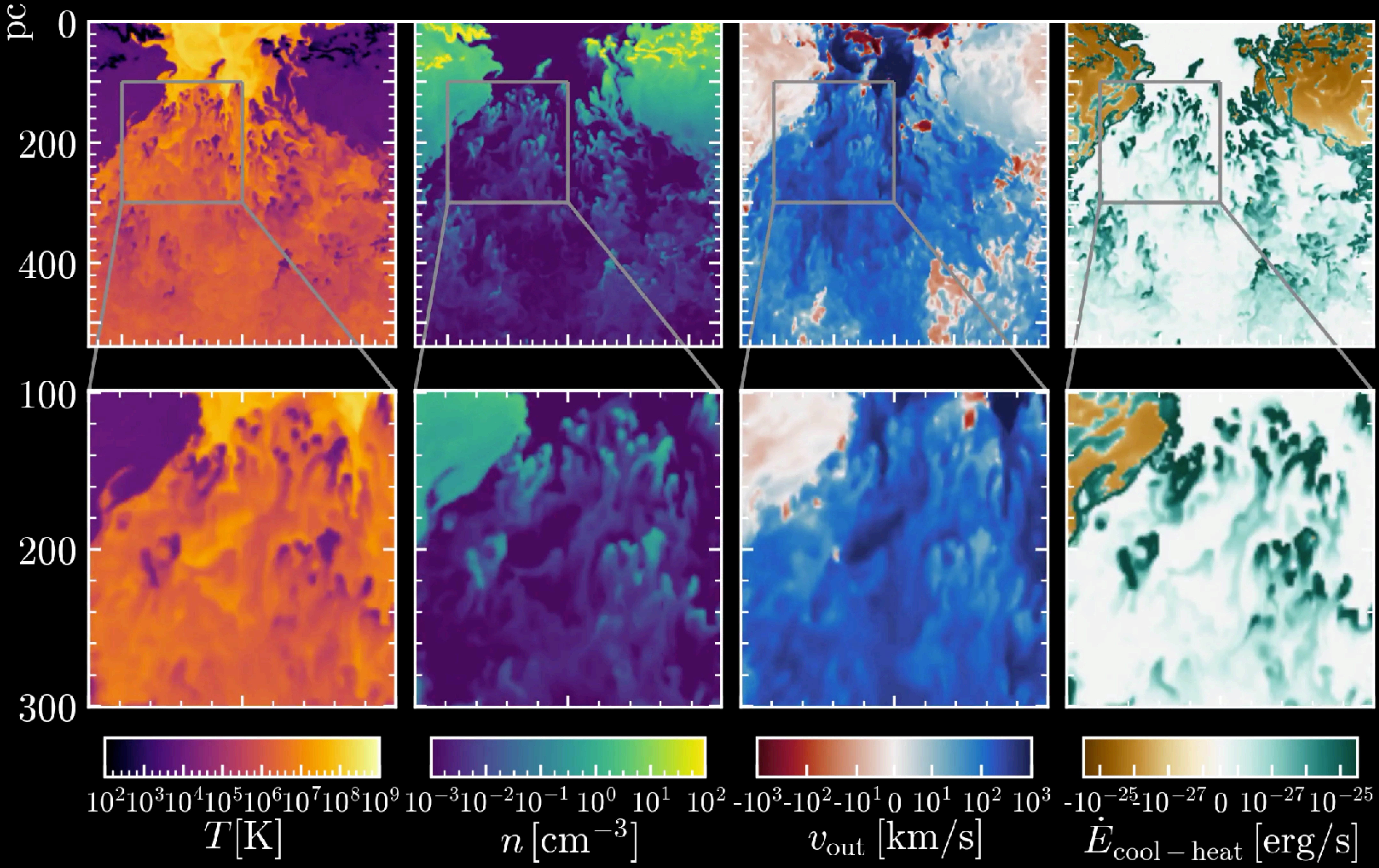


Galactic Wind Phase Structure



Wind is mostly hot ($T>10^6$ K) & fast (v>100 km/s)

Cold component may be larger with
- B-fields & cosmic rays
- higher resolution
- time to cool/condense


pc
0
200
400
100
200
300
$10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9$
$T\,[\mathrm{K}]$
$10^{-3} 10^{-2} 10^{-1}\ 10^0\ 10^1\ 10^2$
$n\,[\mathrm{cm}^{-3}]$
$-10^3\ -10^2\ -10^1\ 0\ 10^1\ 10^2\ 10^3$
$v_{\mathrm{out}}\ [\mathrm{km/s}]$
$-10^{-25}\ -10^{-27}\ 0\ 10^{-27}\ 10^{-25}$
$\dot{E}_{\mathrm{cool-heat}}\ [\mathrm{erg/s}]$

Critical Surface Density for Galactic Wind Launching

A simple model for star formation and galactic wind driving

$$\mathrm{M_{cl}} = \epsilon_\star \pi h^2 \Sigma_{\rm gas} \qquad \epsilon_\star = \epsilon_\circ \Sigma_{\rm gas}/\Sigma_{\rm max}$$

For bubble to breakout:

$$v_{\rm bubble}(h) \geq \delta v$$

Critical Gas Surface density:

$$\Sigma_{\rm gas} \gg \Sigma_{\rm crit} \approx 30\,\mathrm{M_\odot/pc^2} \;\Rightarrow\; \dot{\Sigma}_\star \gg 0.03\mathrm{M_\odot/kpc^2/yr}$$

Critical Surface Density for Galactic Wind Launching

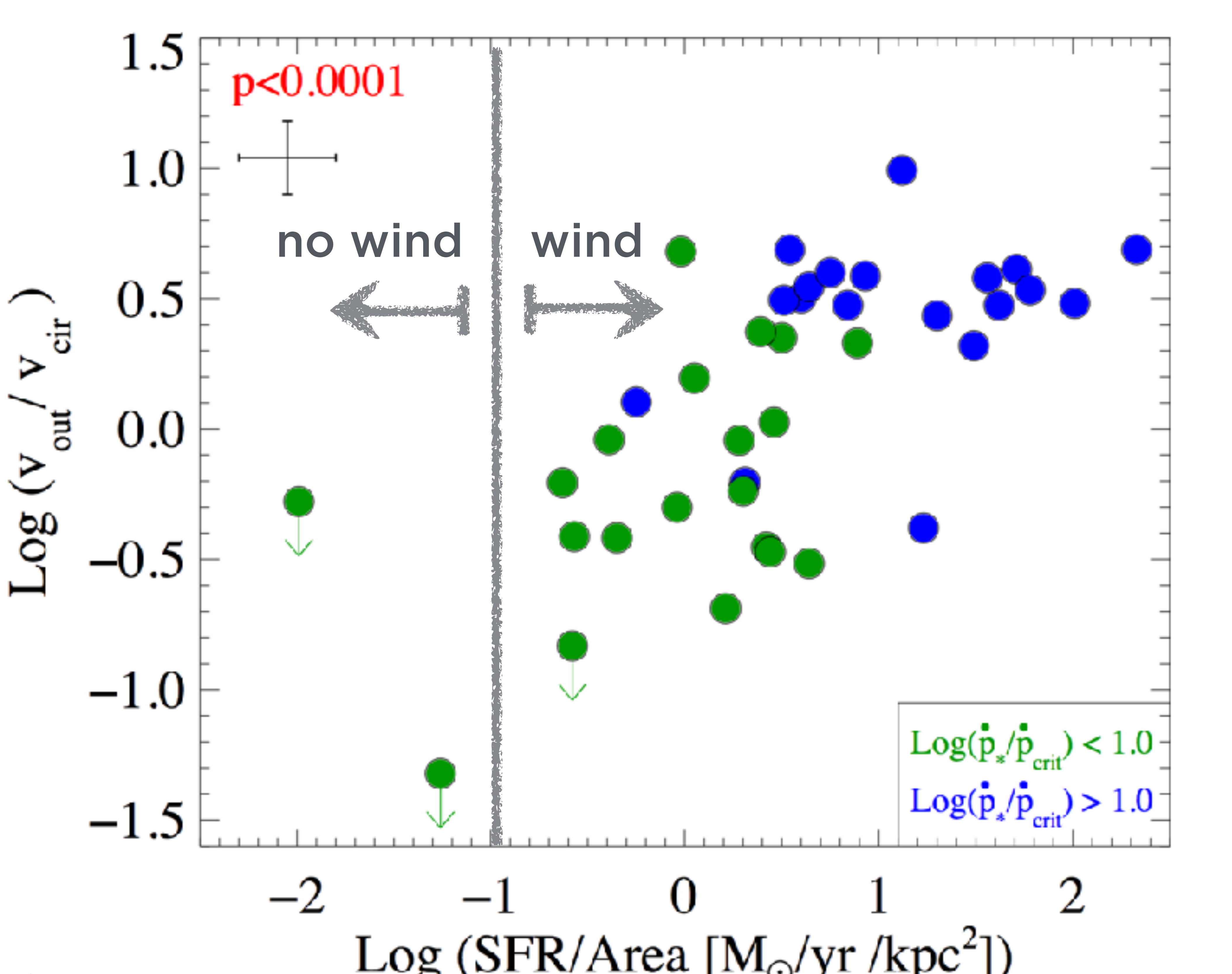
Critical Gas Surface density for galactic wind launching:

$$\Sigma_{\rm gas} \gg \Sigma_{\rm crit} \approx 30\,{\rm M_\odot/pc^2}$$

$$\dot{\Sigma}_\star \gg 0.03\,{\rm M_\odot/kpc^2/yr}$$

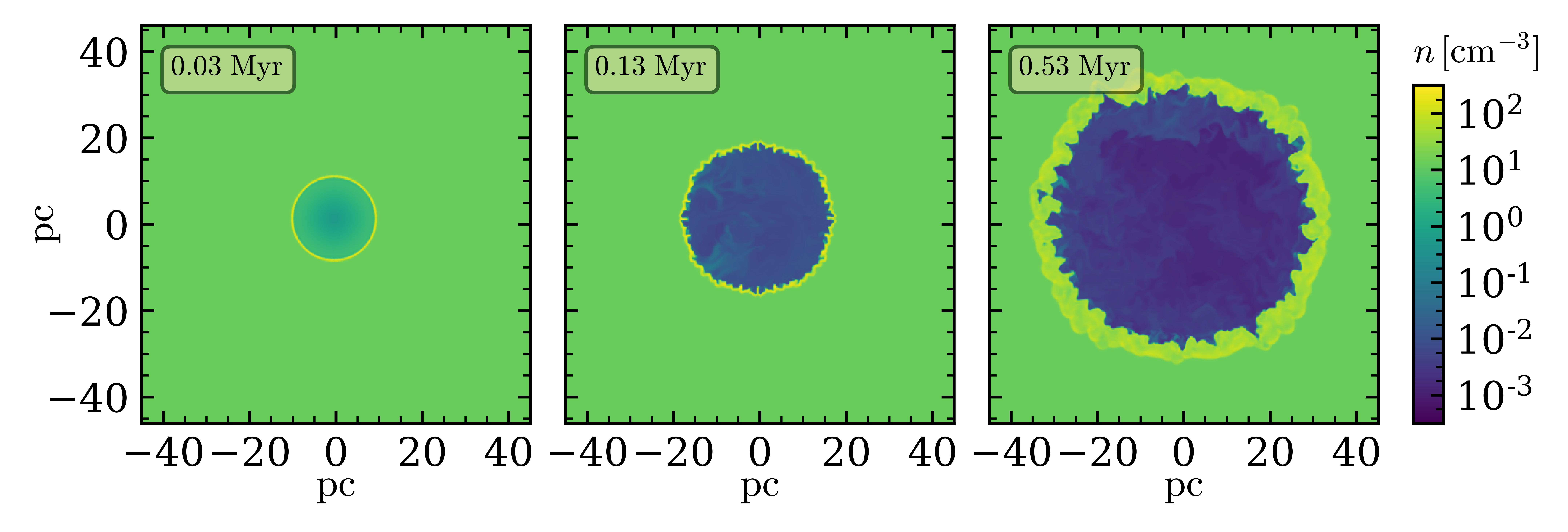
Similar to the observed threshold $\sim 0.1\,{\rm M_\odot/kpc^2/yr}$

e.g. Heckman (2002)

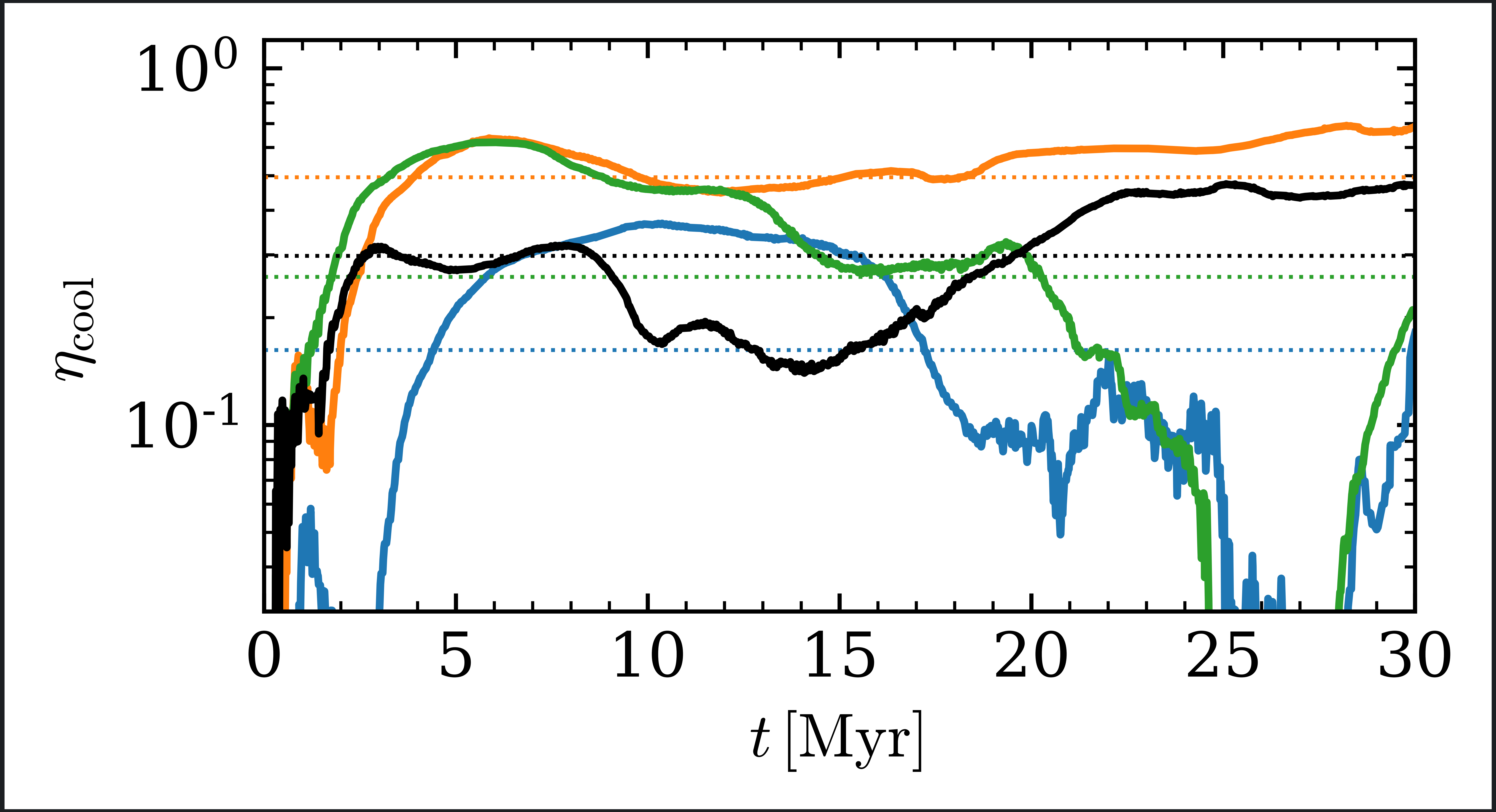


Heckman+15

ISM-Bubble Mixing — Importance of 3D



Sensitivity to ISM Turbulence



Numerical Convergence