Stellar feedback-driven galactic winds

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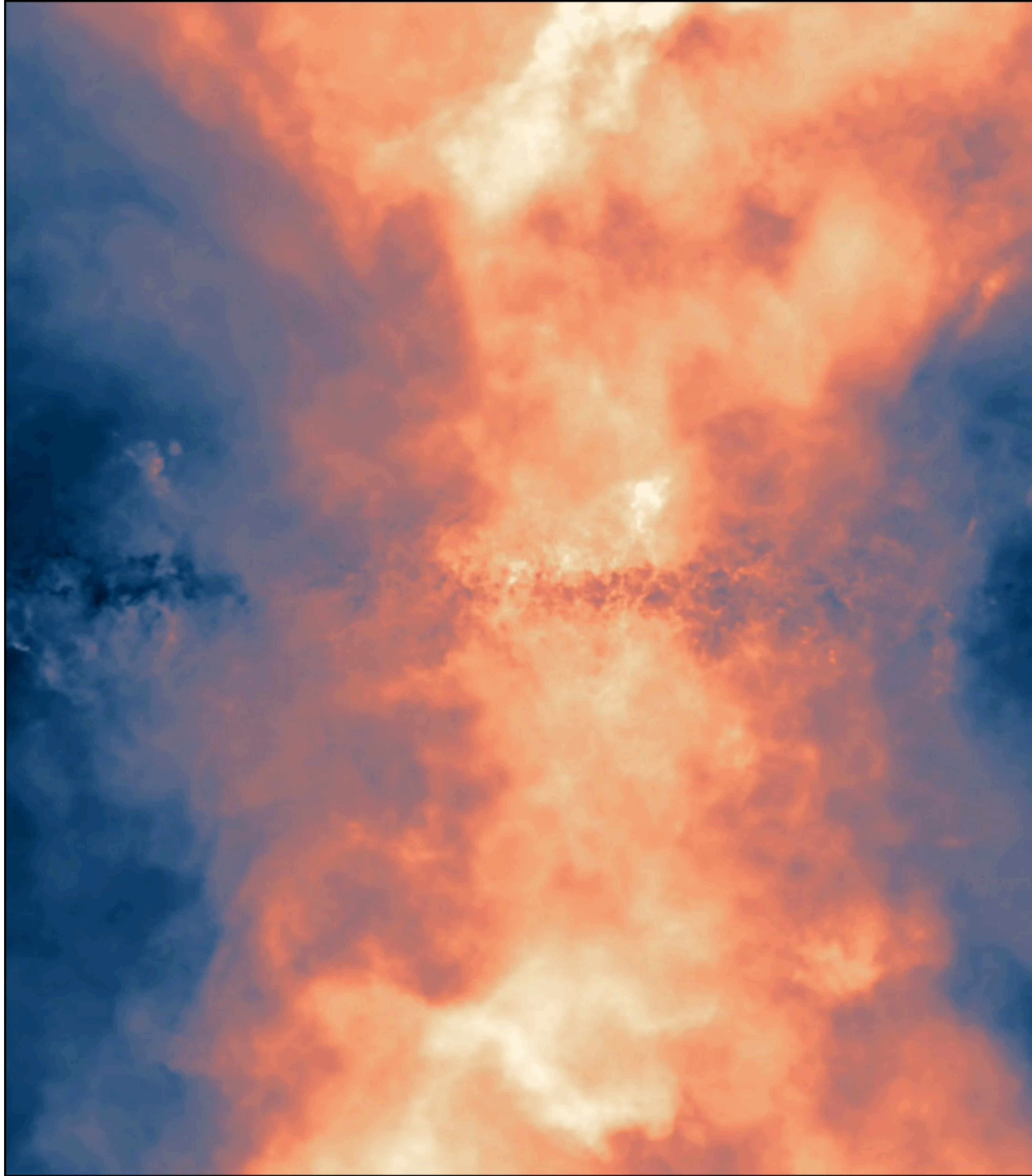
FÜR ASTROPHYSIK



GALACTIC WINDS*

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ABSTRACT

Gas ejected from stars in elliptical galaxies is heated by supernova explosions and produces outward-flowing galactic winds. Except possibly for the dust component, steady-state galactic winds are impossible to observe. However, some galactic winds have thermally unsteady cores which can be observed in optical emission lines. If the gas which is thermally unsteady remains ionized as it goes into free fall at the galactic center, objects more massive than stars tend to form. It is likely that nonthermal radio emission and optical line emission can occur only in those ellipticals with thermally unsteady galactic winds.

WHAT DO WE NEED **GALACTIC WINDS** TO DO?

We often invoke stellar feedback-driven galactic winds to:

- Regulate the stellar mass of galaxies
- Regulate gas fractions (ISM, CGM)
- Regulate enrichment (stars, ISM, CGM, IGM)
- Influence CGM phase structure
- Influence galaxy sizes via re-distribution of material
- …

Describing a wind: loading factors

Mass loading factor:

$$\eta_M = \frac{\dot{M}_{\rm out}}{\dot{M}_\star}$$

$$\tilde{v}_{\rm w} = \left(2u_\star \frac{\eta_E}{\eta_M}\right)^{\frac{1}{2}}$$

Energy loading factor:

$$\eta_E = \frac{\dot{E}_{\rm out}}{u_\star \dot{M}_\star}$$

Supernova feedback specific energy:

$$u_\star \sim \frac{10^{51}\,{\rm erg}}{100\,{\rm M}_\odot} = 5 \times 10^5\ \left({\rm km\,s^{-1}}\right)^2$$

Metal loading factor:

$$\eta_Z = \frac{\dot{M}_{Z\rm out}}{f_Z \dot{M}_\star}$$

Or enrichment factor:

$$\xi_Z = \frac{Z_{\rm out}}{Z_{\rm ISM}}$$

Describing a wind: loading factors

$$\eta_M = \frac{\dot{M}_{\rm out}}{\dot{M}_\star}$$

$$\tilde{v}_{\rm w} = \left(2u_\star \frac{\eta_E}{\eta_M}\right)^{\frac{1}{2}}$$

$$\eta_E = \frac{\dot{E}_{\rm out}}{u_\star \dot{M}_\star}$$

$$u_\star \sim \frac{10^{51}\,{\rm erg}}{100\,{\rm M}_\odot} = 5 \times 10^5\ \left({\rm km\,s^{-1}}\right)^2$$

$$\eta_Z = \frac{\dot{M}_{Z\rm out}}{f_Z \dot{M}_\star}$$

$$\xi_Z = \frac{Z_{\rm out}}{Z_{\rm ISM}}$$

Describing a wind: loading factors

Where?

What spatial scale?

From one reservoir to another? Across a surface? What geometry?

Over what timescale?

Which gas? What phase?

$$\eta_M = \frac{\dot{M}_{\rm out}}{\dot{M}_\star}$$

$$\tilde{v}_{\rm w} = \left(2u_\star \frac{\eta_E}{\eta_M}\right)^{\frac{1}{2}}$$

$$\eta_E = \frac{\dot{E}_{\rm out}}{u_\star \dot{M}_\star}$$

$$u_\star \sim \frac{10^{51}\,{\rm erg}}{100\,{\rm M_\odot}} = 5\times10^5\ \left({\rm km\,s^{-1}}\right)^2$$

$$\eta_Z = \frac{\dot{M}_{Z\rm out}}{f_Z \dot{M}_\star}$$

$$\xi_Z = \frac{Z_{\rm out}}{Z_{\rm ISM}}$$

Describing a wind: loading factors

Over what timescale?

Is this the star formation responsible for the wind?

What about wind travel time? What about burstiness?

$$\eta_M = \frac{\dot{M}_{\rm out}}{\dot{M}_\star}$$

$$\eta_E = \frac{\dot{E}_{\rm out}}{u_\star \dot{M}_\star}$$

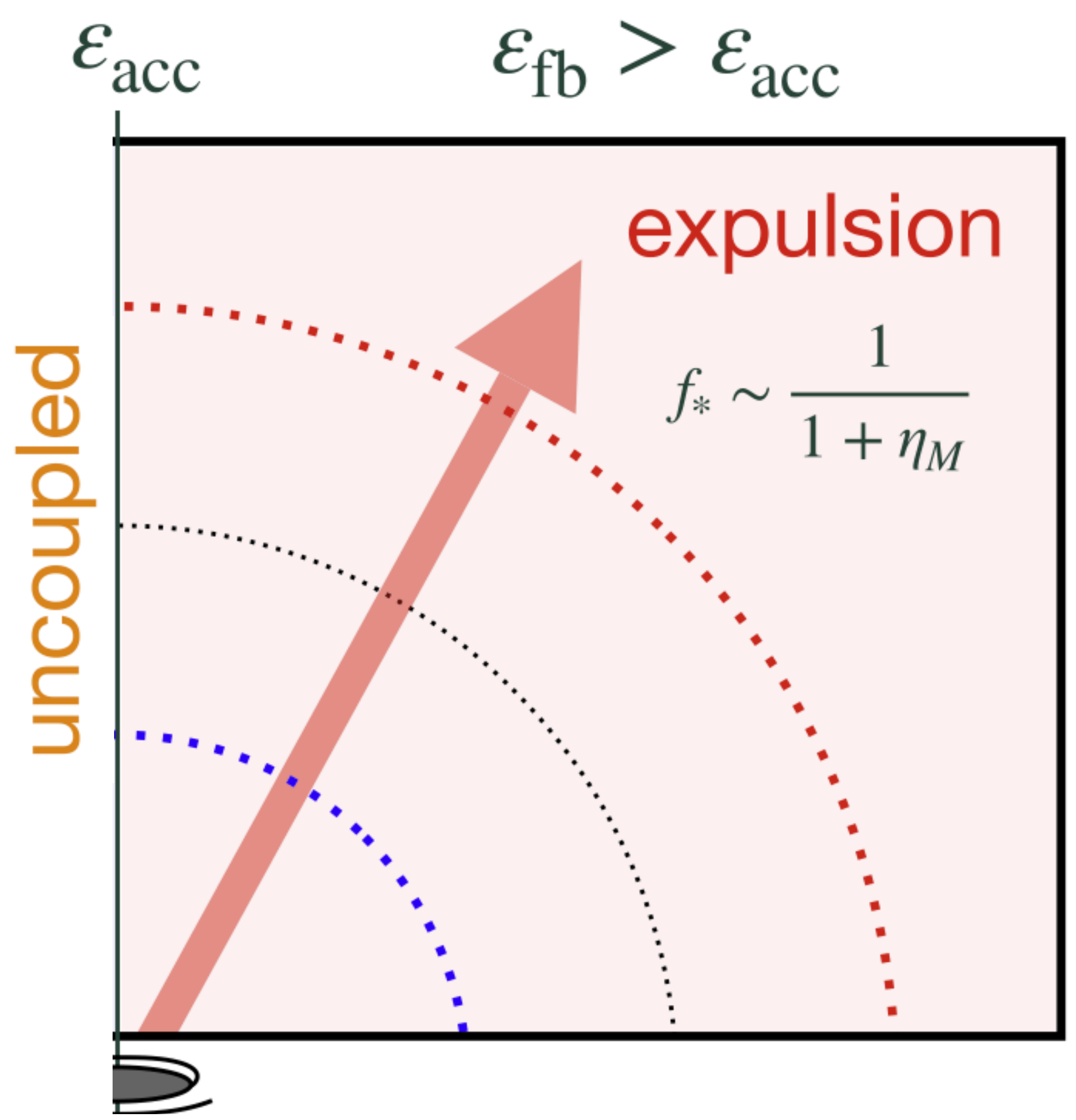
$$\tilde{v}_{\rm w} = \left(2u_\star \frac{\eta_E}{\eta_M}\right)^{\frac{1}{2}}$$

$$u_\star \sim \frac{10^{51}\,\mathrm{erg}}{100\,\mathrm{M}_\odot} = 5\times 10^5\ \left(\mathrm{km\,s^{-1}}\right)^2$$

$$\eta_Z = \frac{\dot{M}_{Z\rm out}}{f_Z \dot{M}_\star}$$

$$\xi_Z = \frac{Z_{\rm out}}{Z_{\rm ISM}}$$

The mode of galactic wind feedback

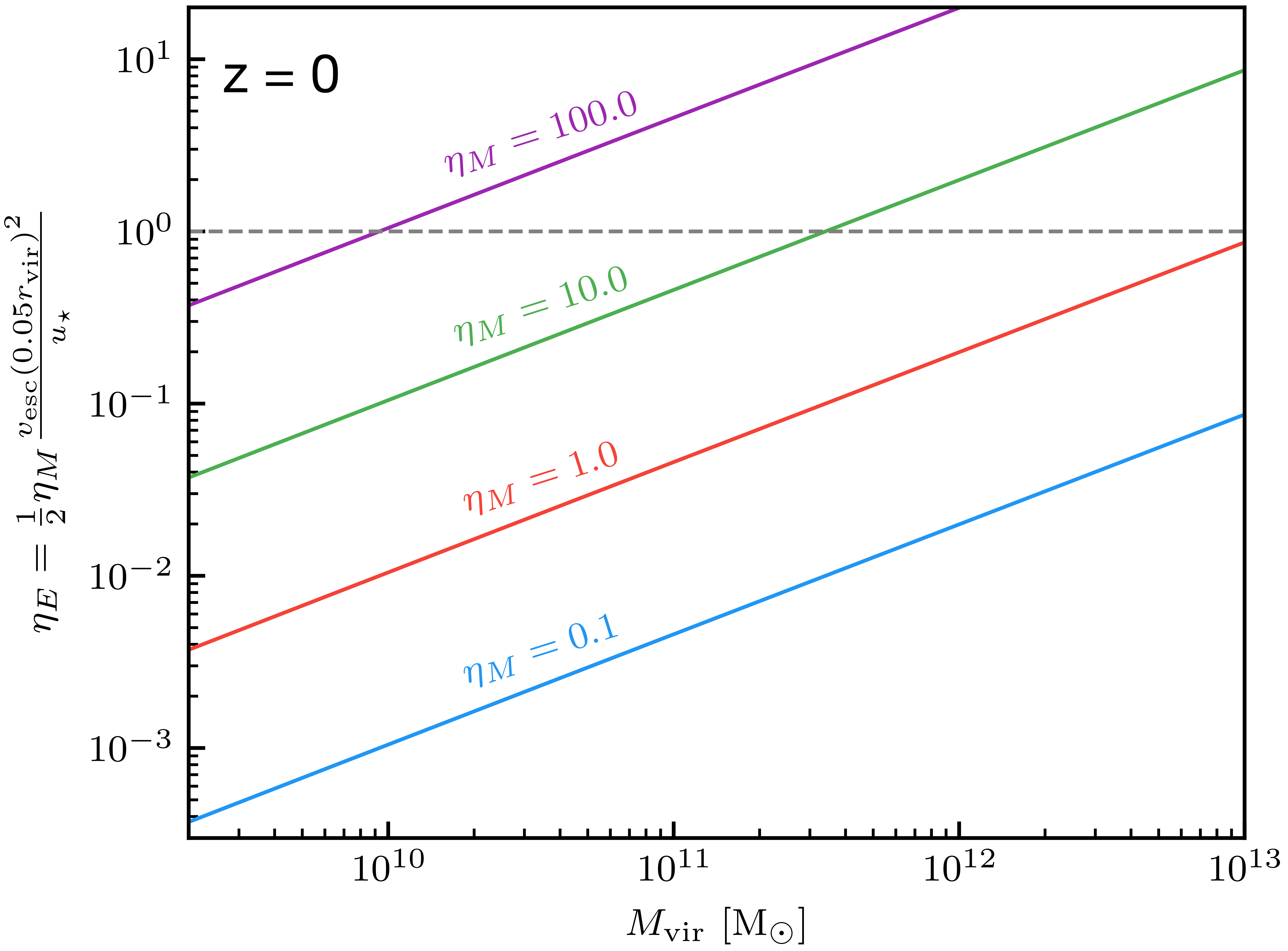


Ejective feedback

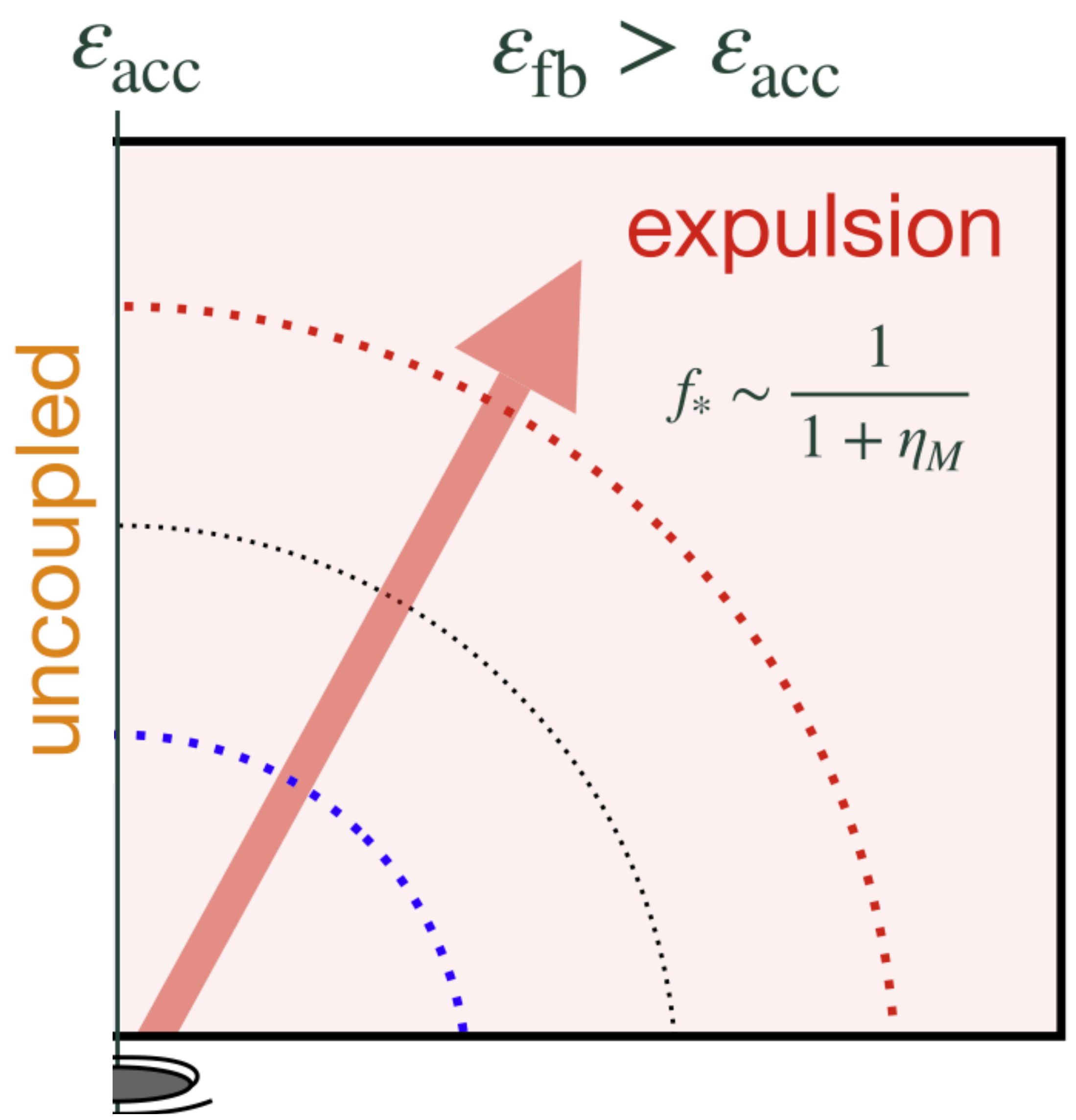
Voit+ 2024b

Energetics of Ejective feedback

If a wind has η_M at 0.05 r_{vir}, what energy loading does it need to never come back?



The mode of galactic wind feedback

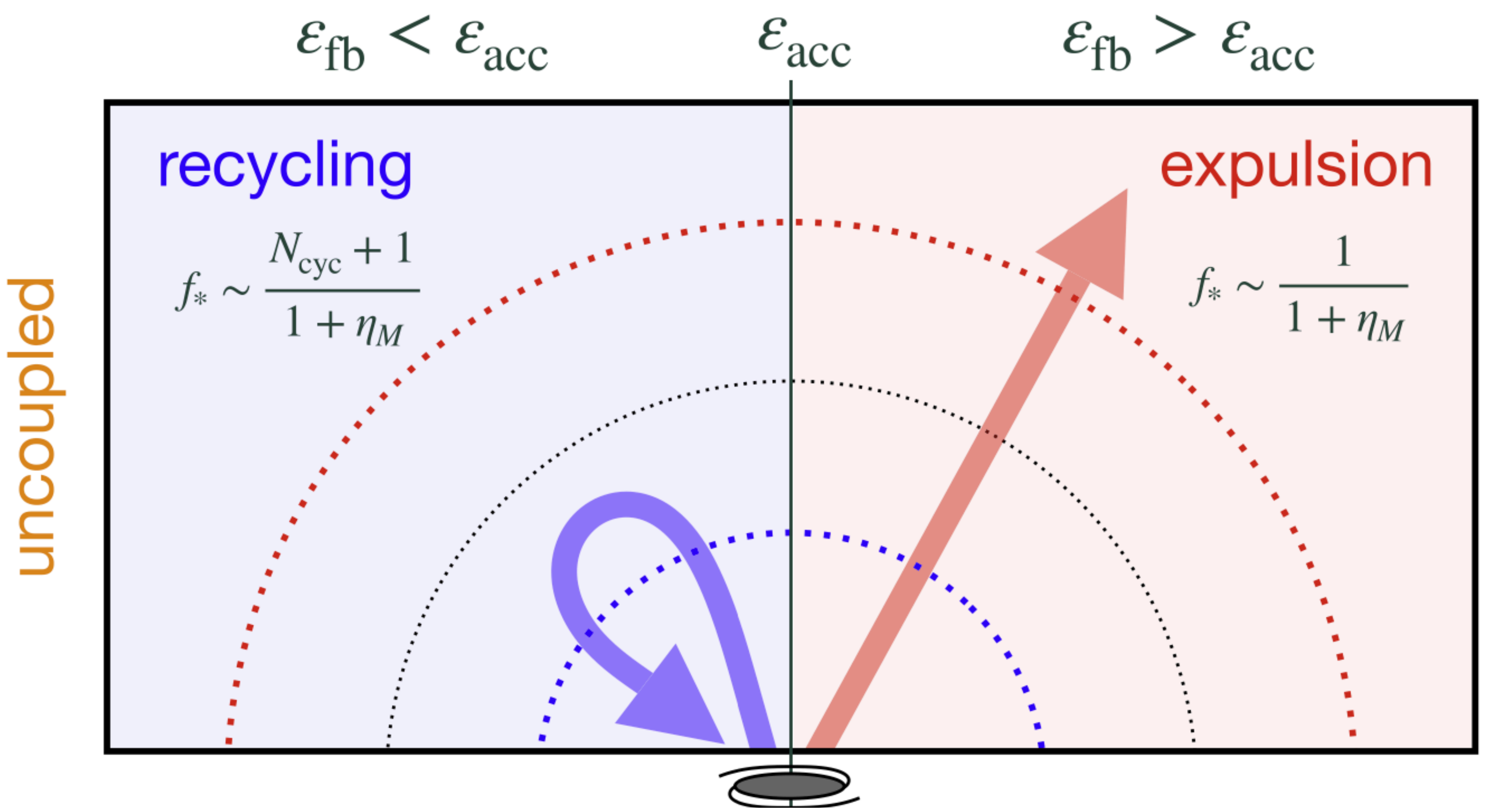


Ejective feedback

Voit+ 2024b

The mode of galactic wind feedback

Recycling crisis



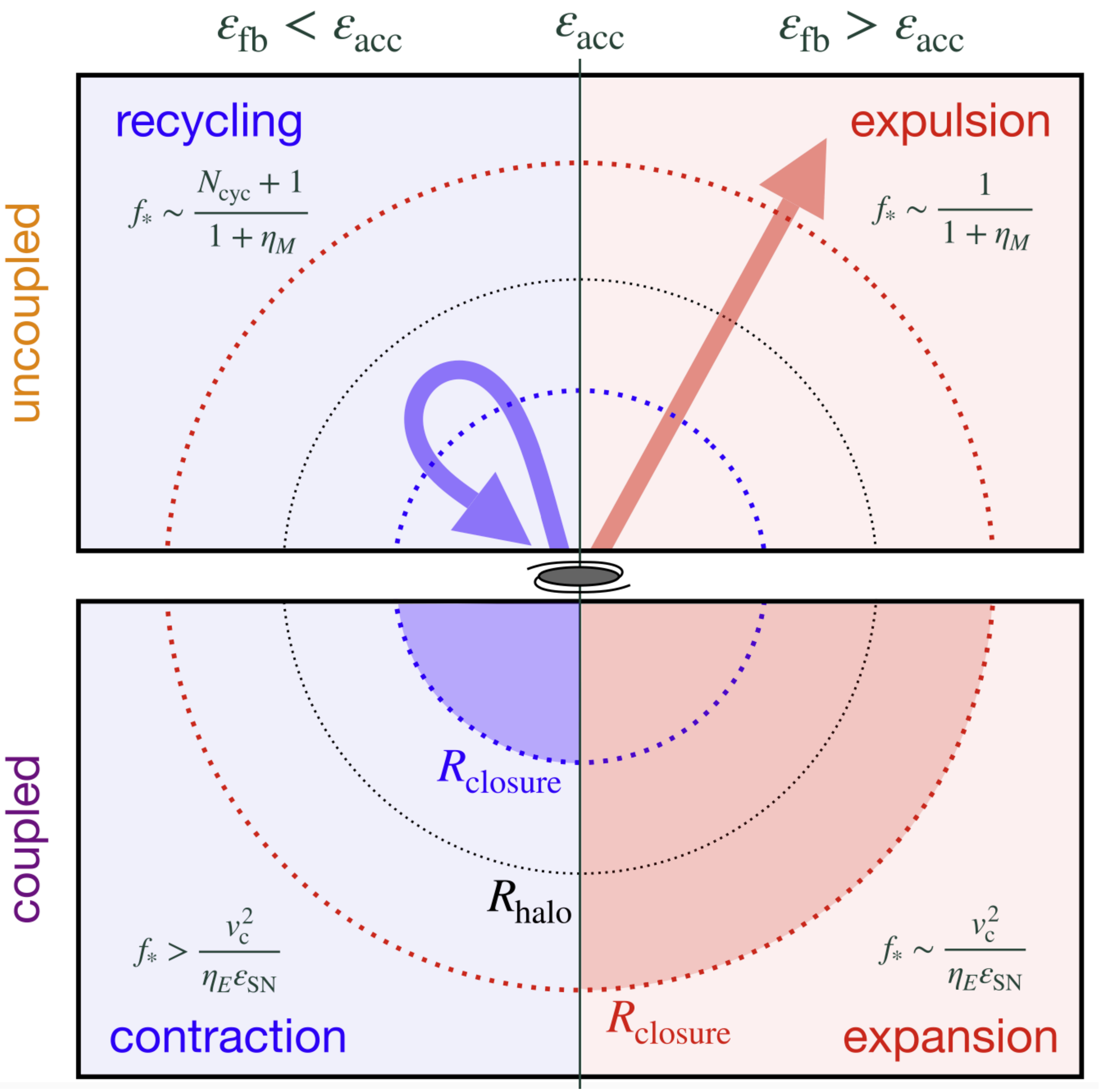
Ejective feedback

Voit+ 2024b

The mode of galactic wind feedback

Recycling crisis

Ejective feedback



Contraction crisis

Preventative feedback

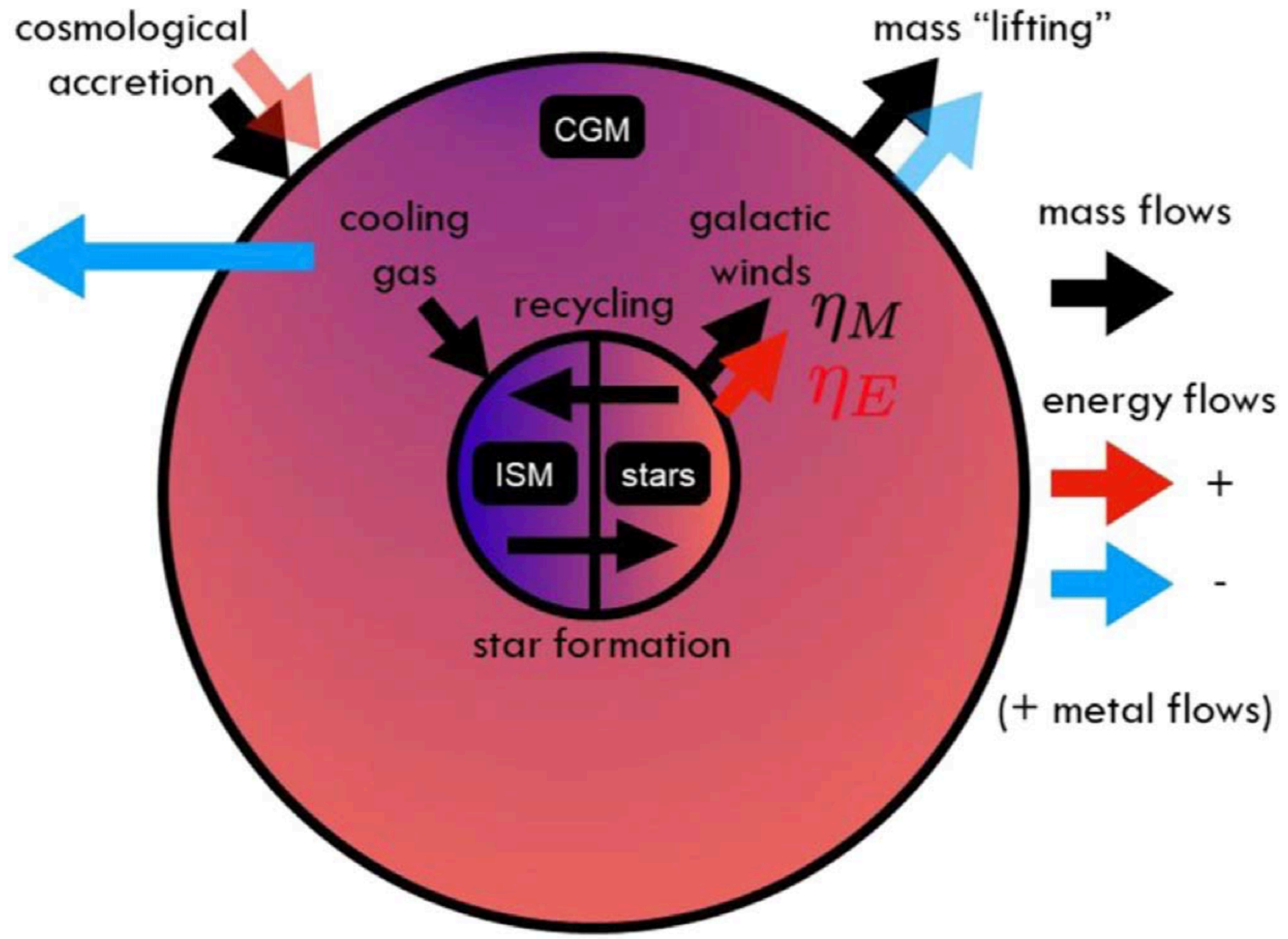
Voit+ 2024b

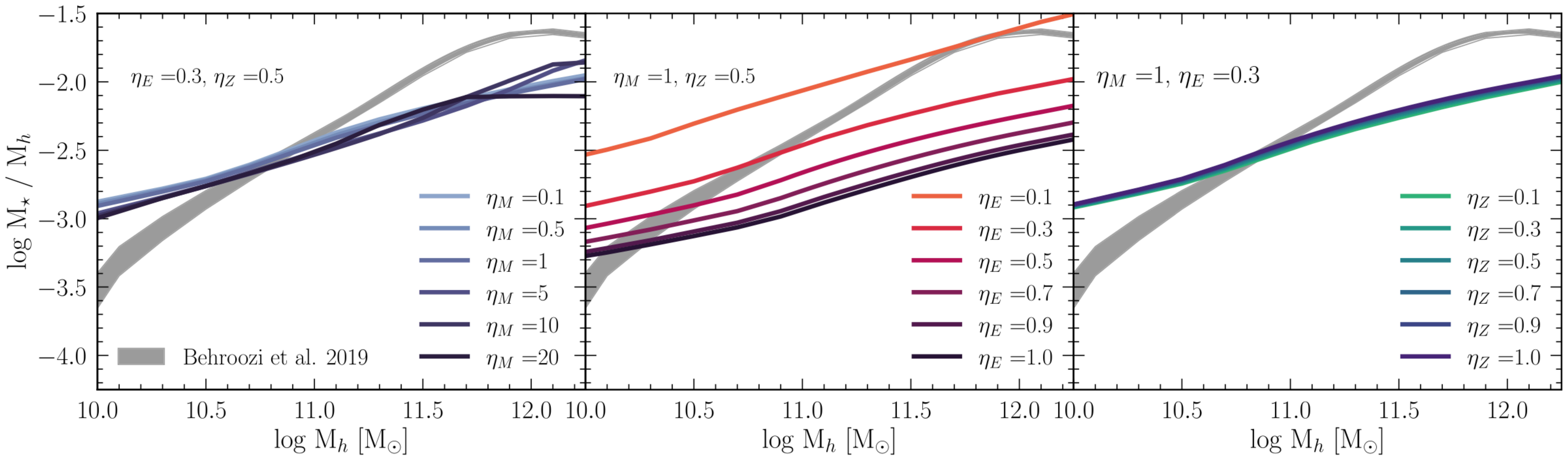
Preventative feedback in regulator models and SAMS

Carr+2023, see also e.g. Pandya+2023, Voit+2024

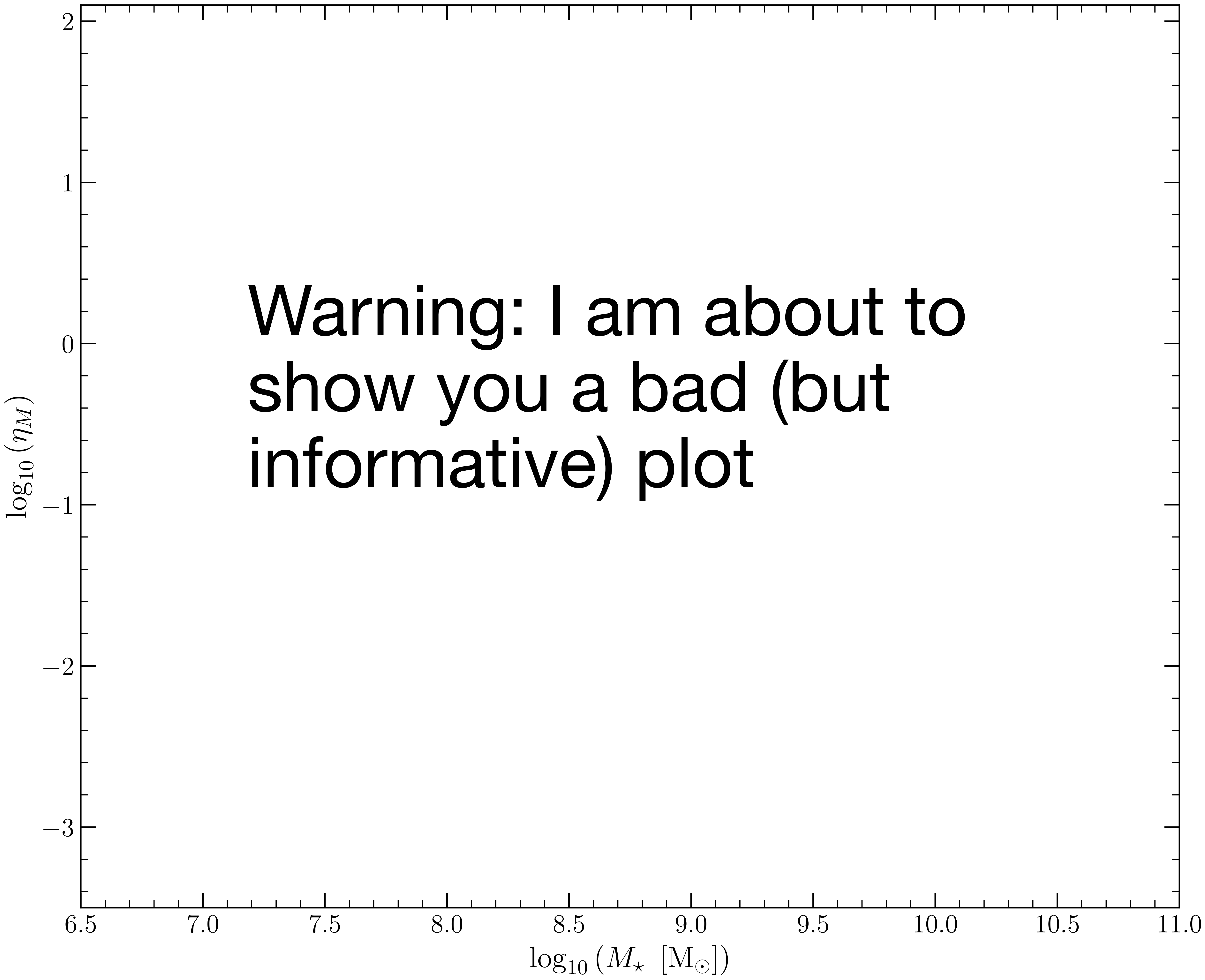
Bennett, **MCS**+ 2024 test this picture in hydro volumes

Regulation of SF by increasing specific energy of CGM



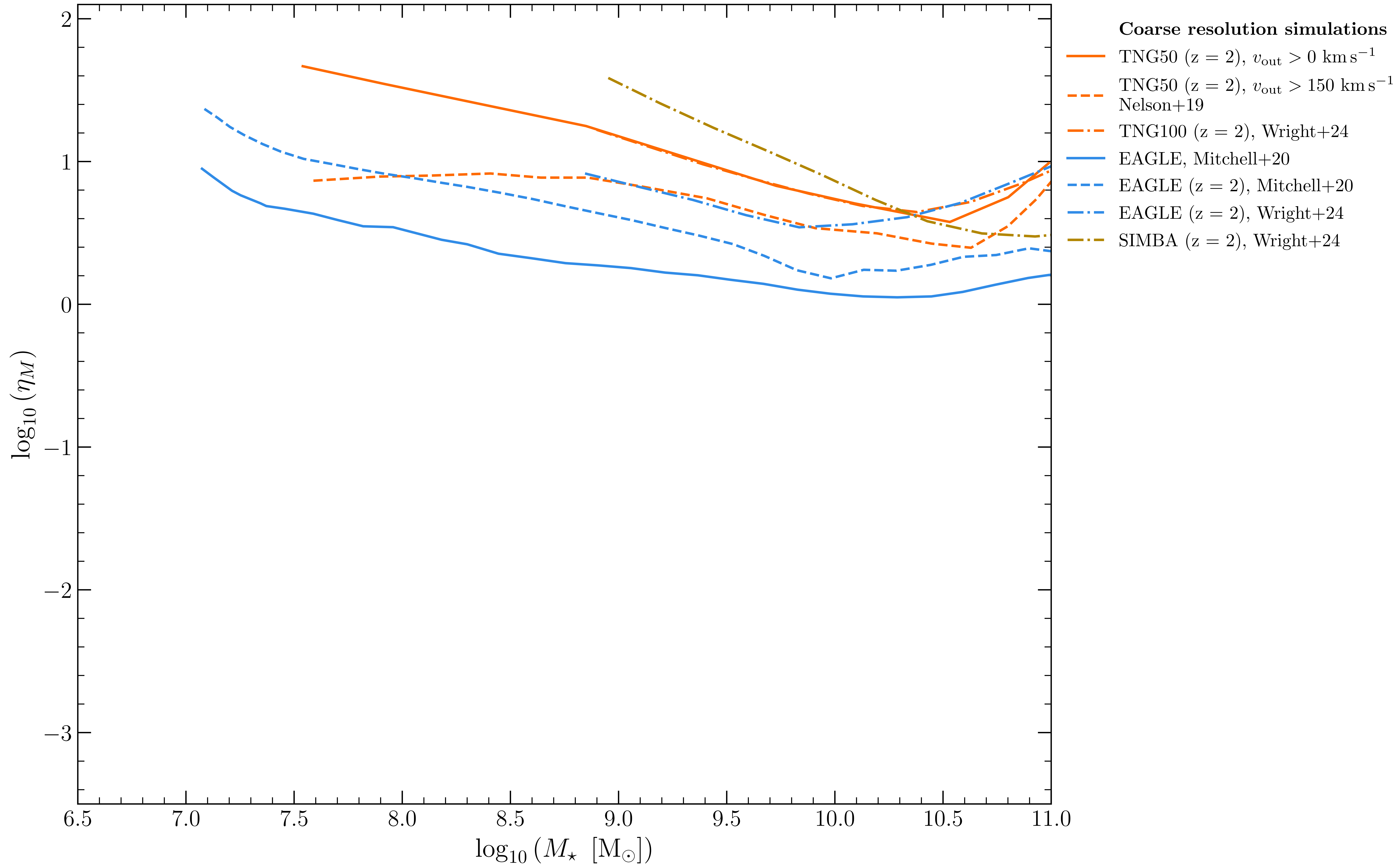


Measured mass loading factors



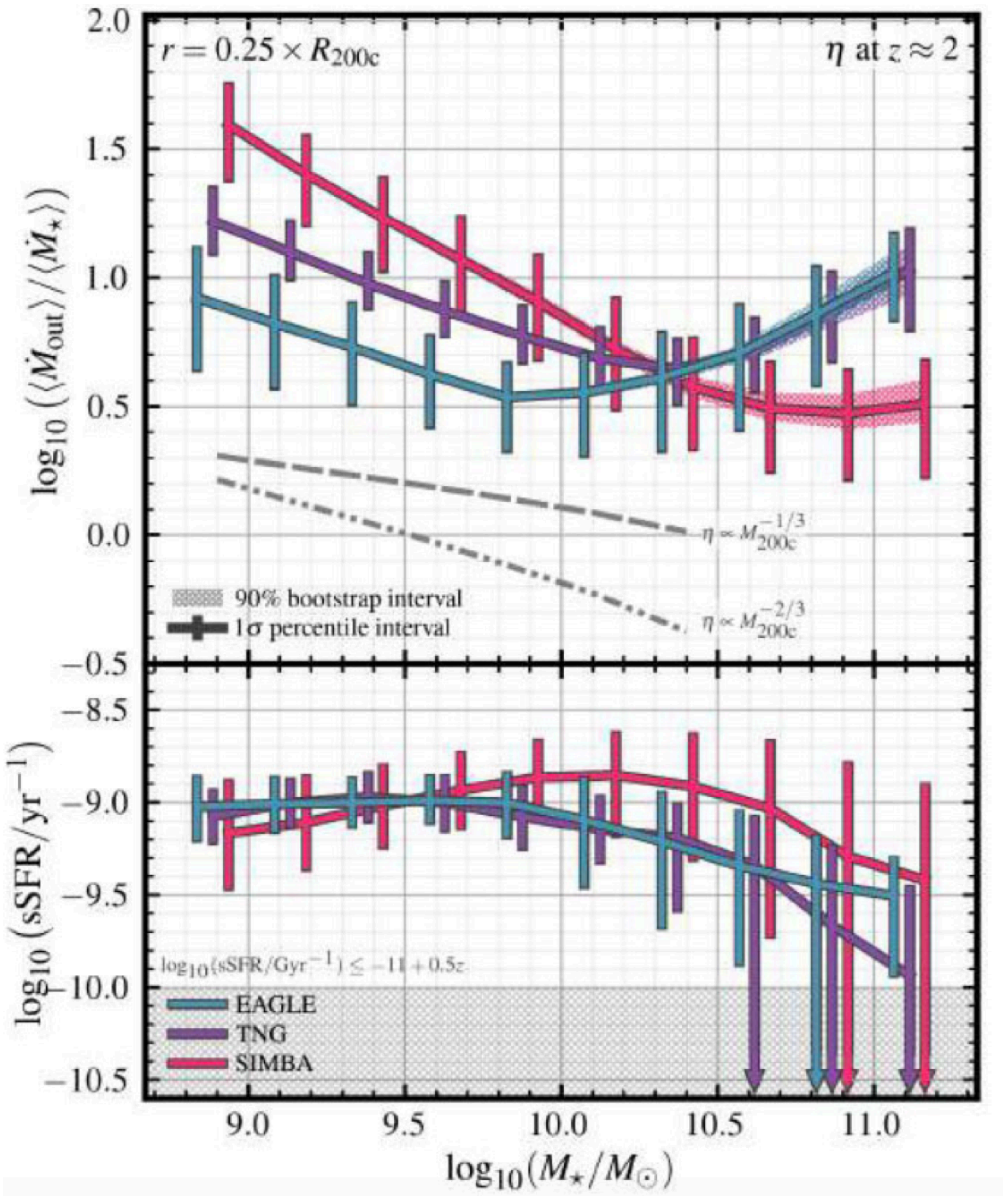
Warning: I am about to show you a bad (but informative) plot

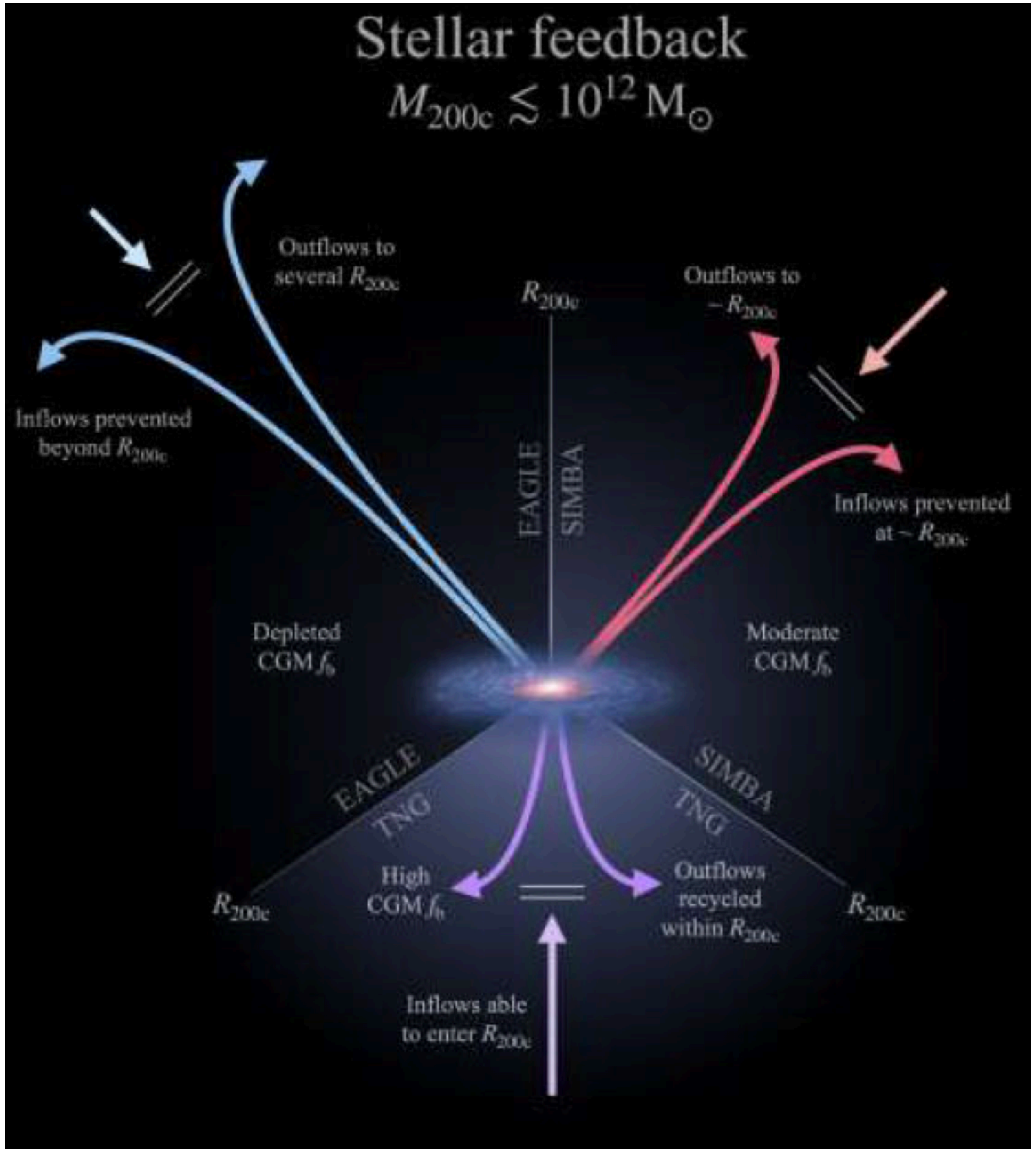
Measured mass loading factors



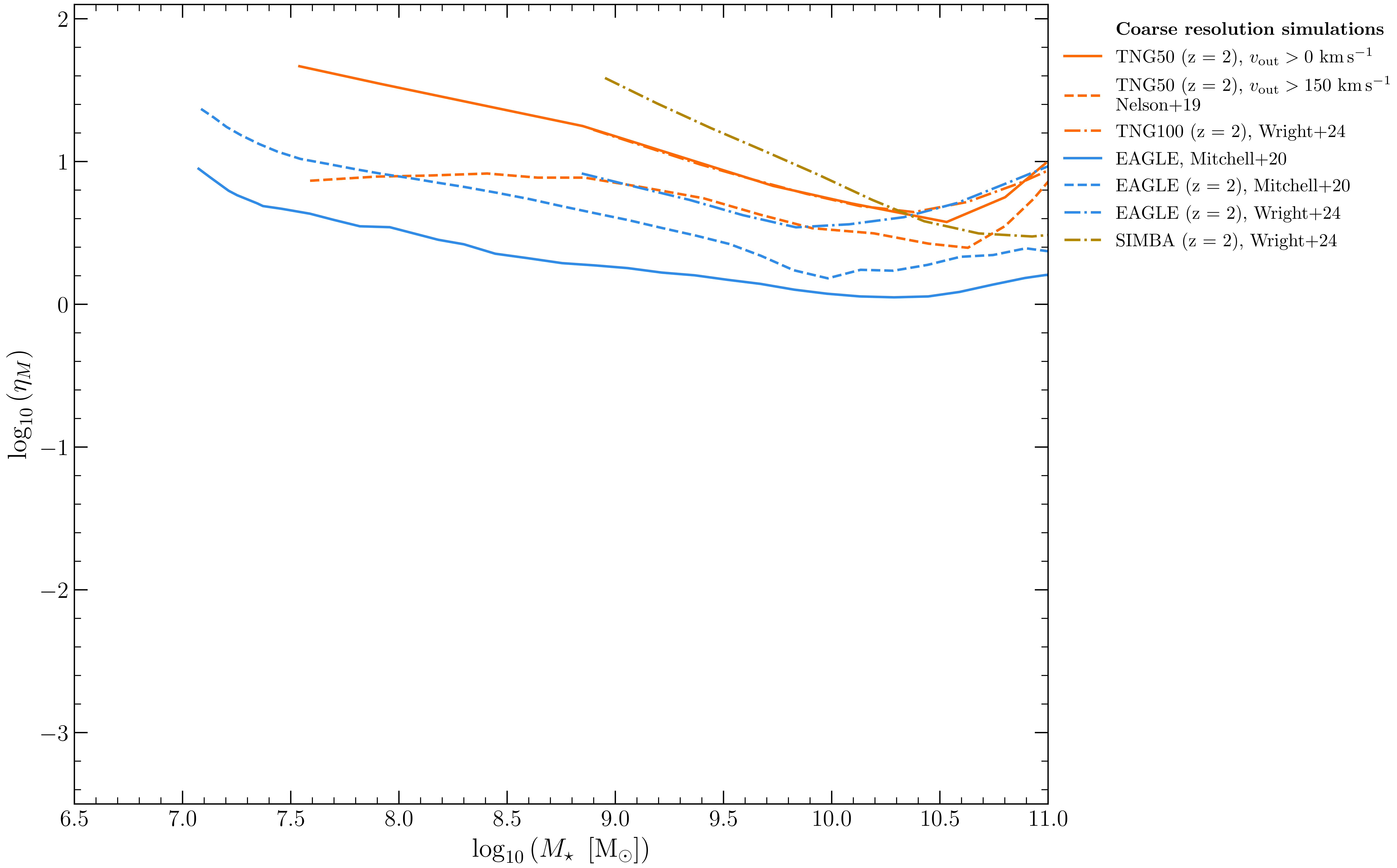
Comparing simulated baryon cycles

Wright+ 2024

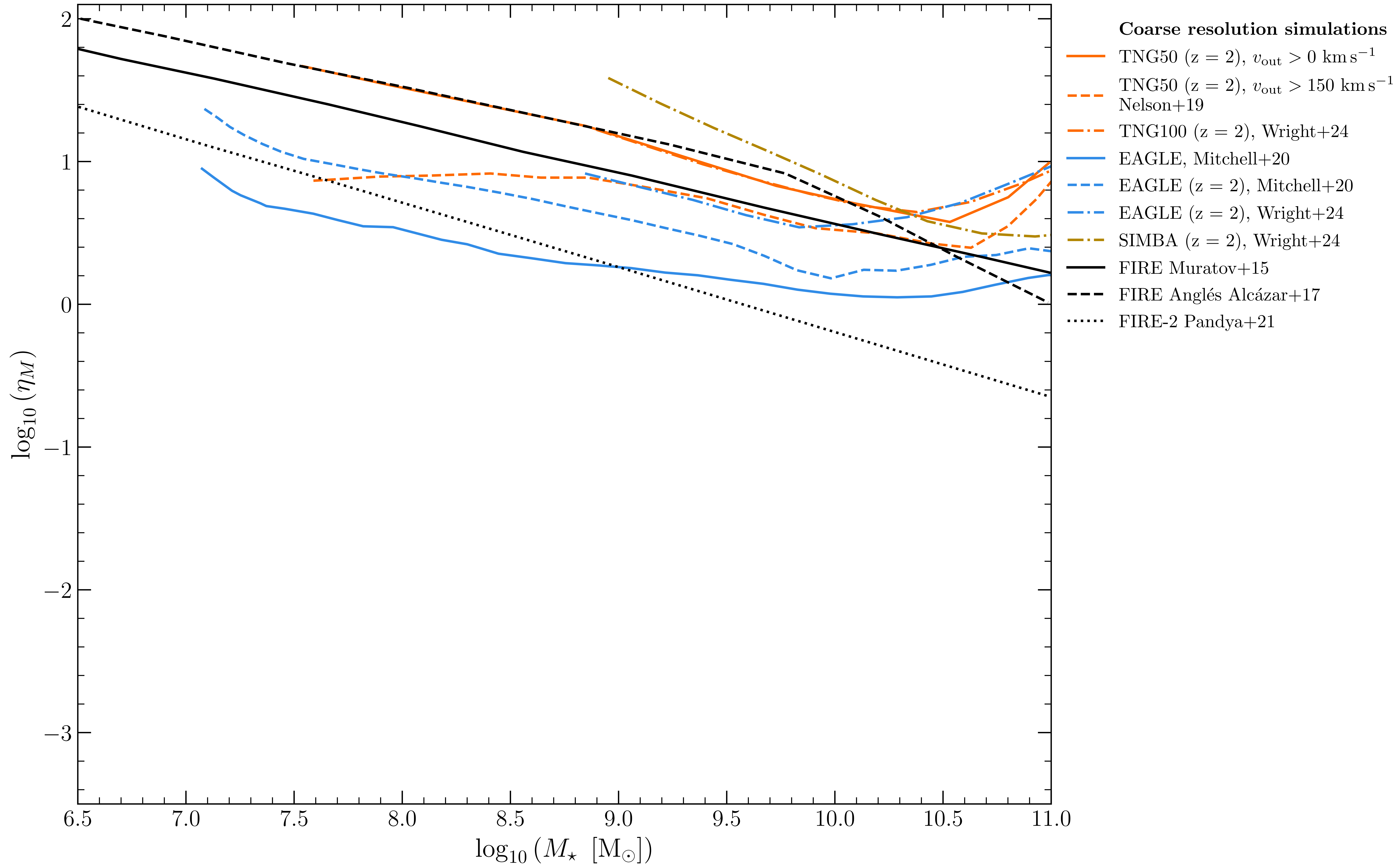




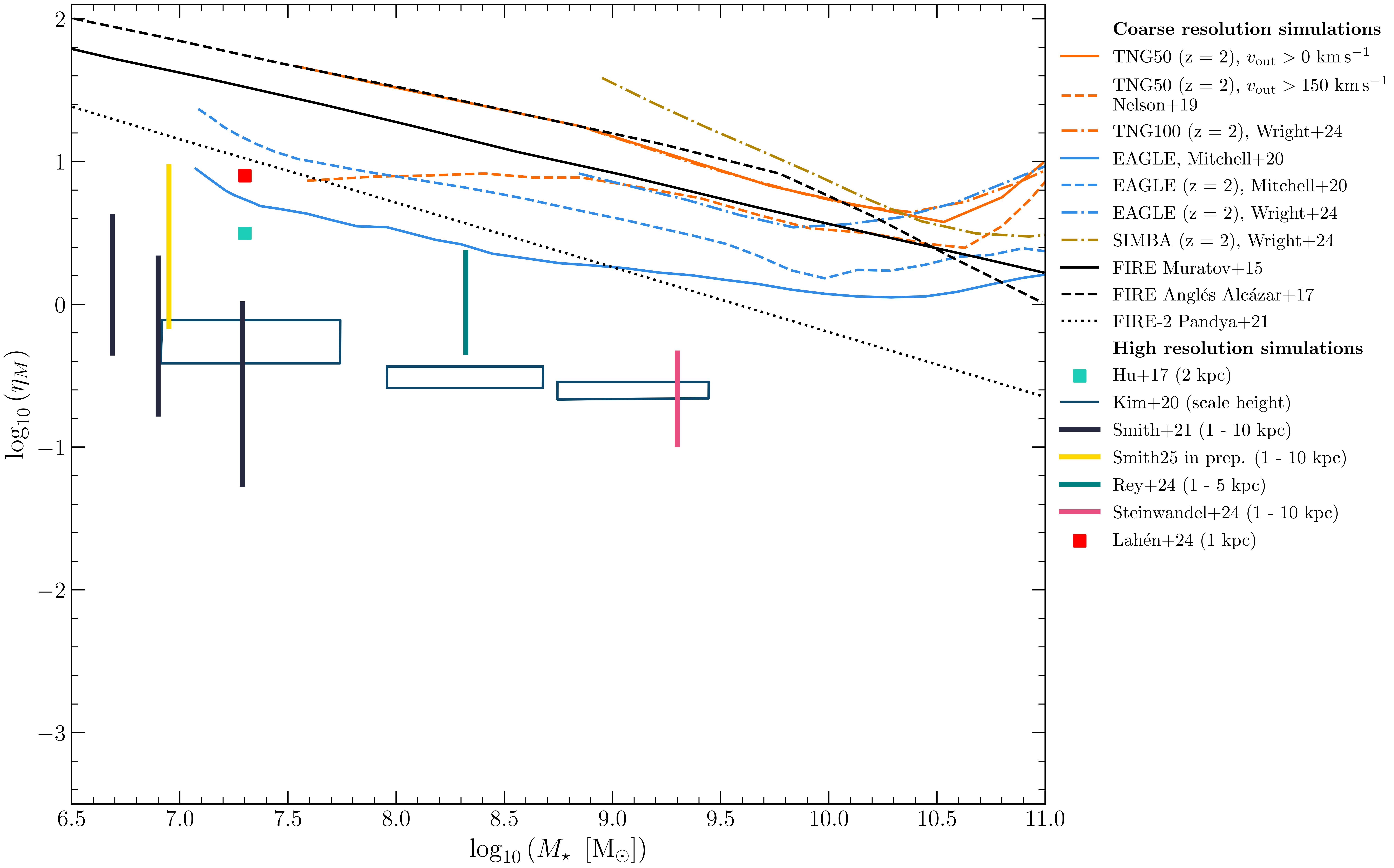
Measured mass loading factors



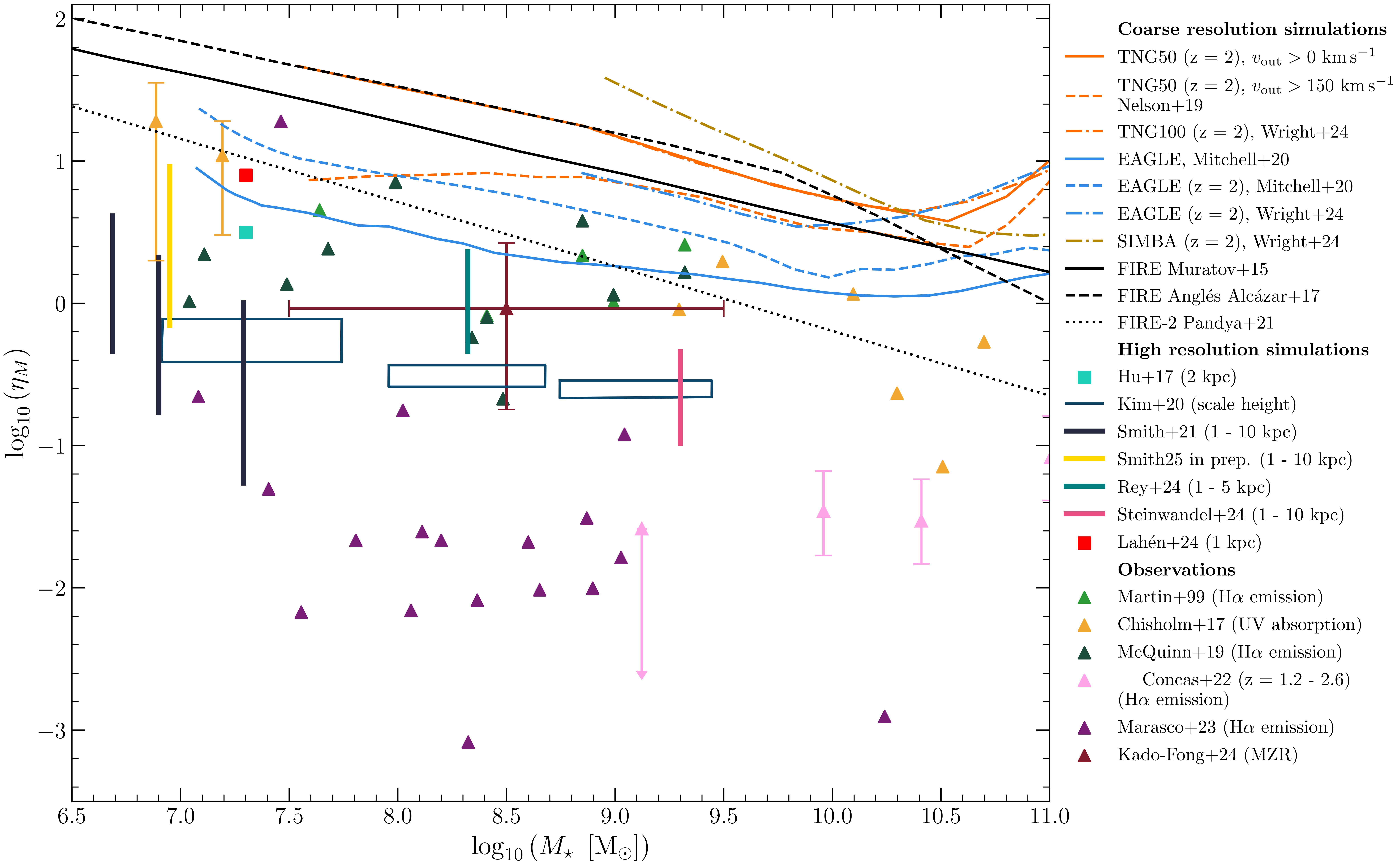
Measured mass loading factors

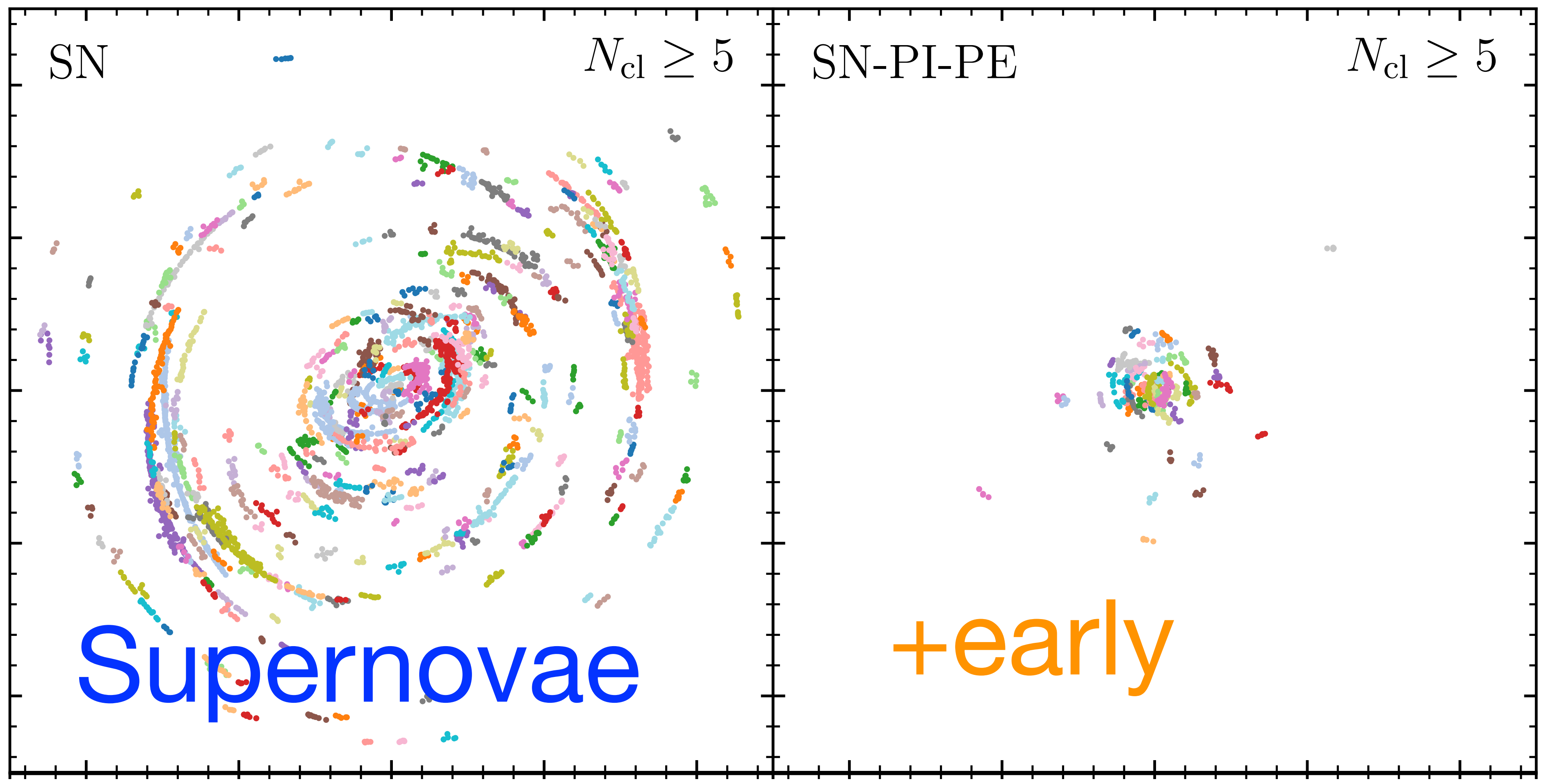


Measured mass loading factors



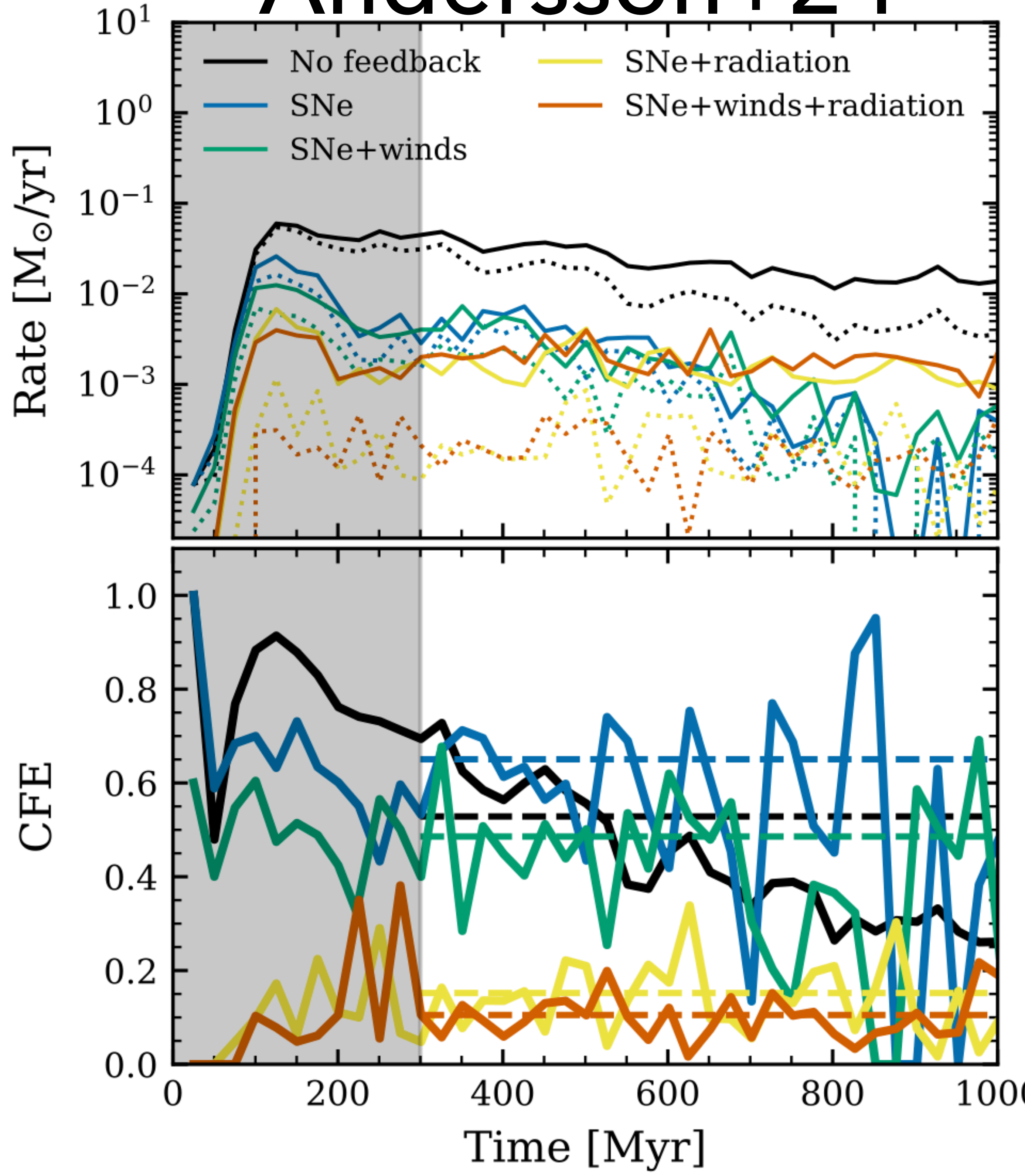
Measured mass loading factors

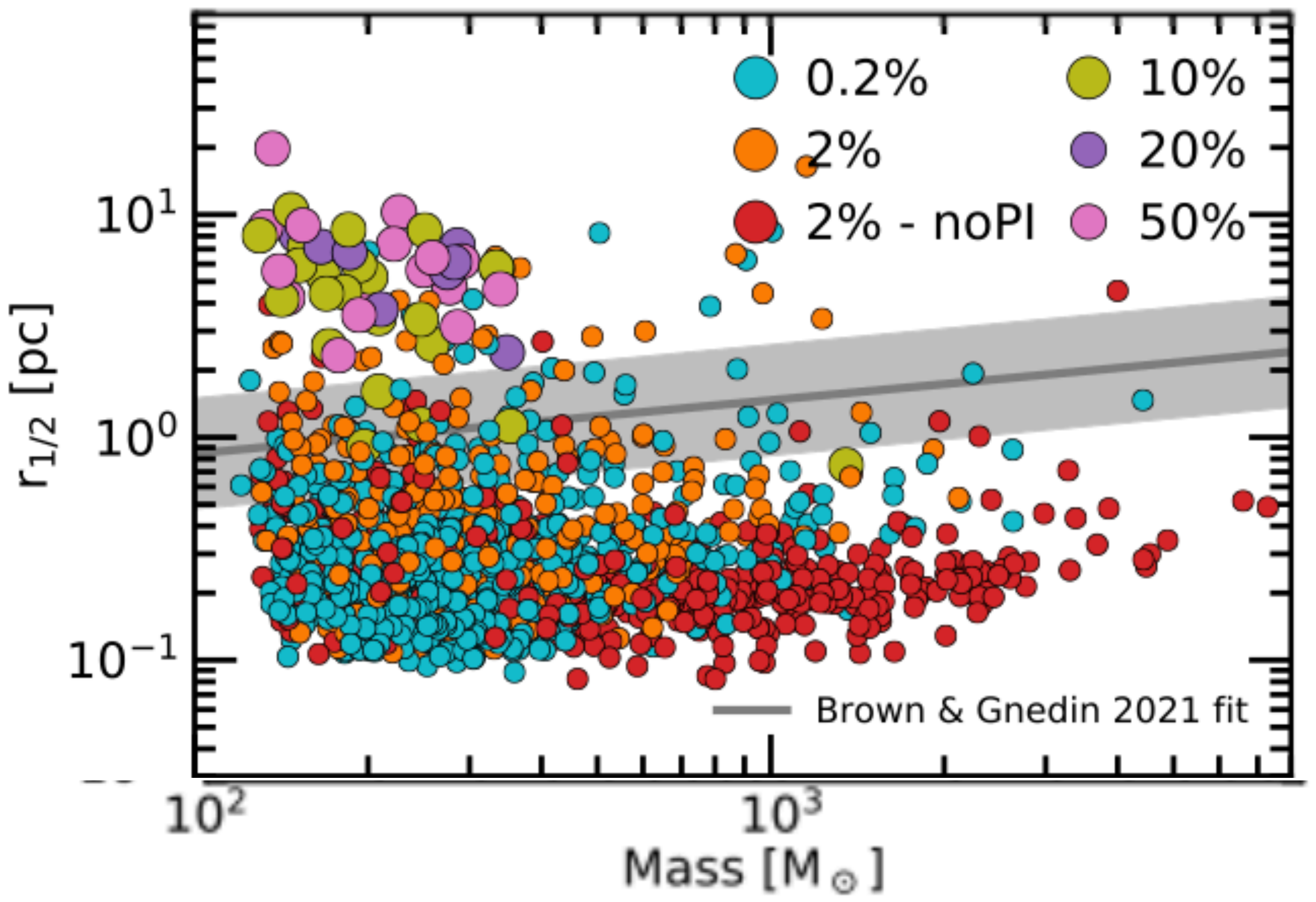




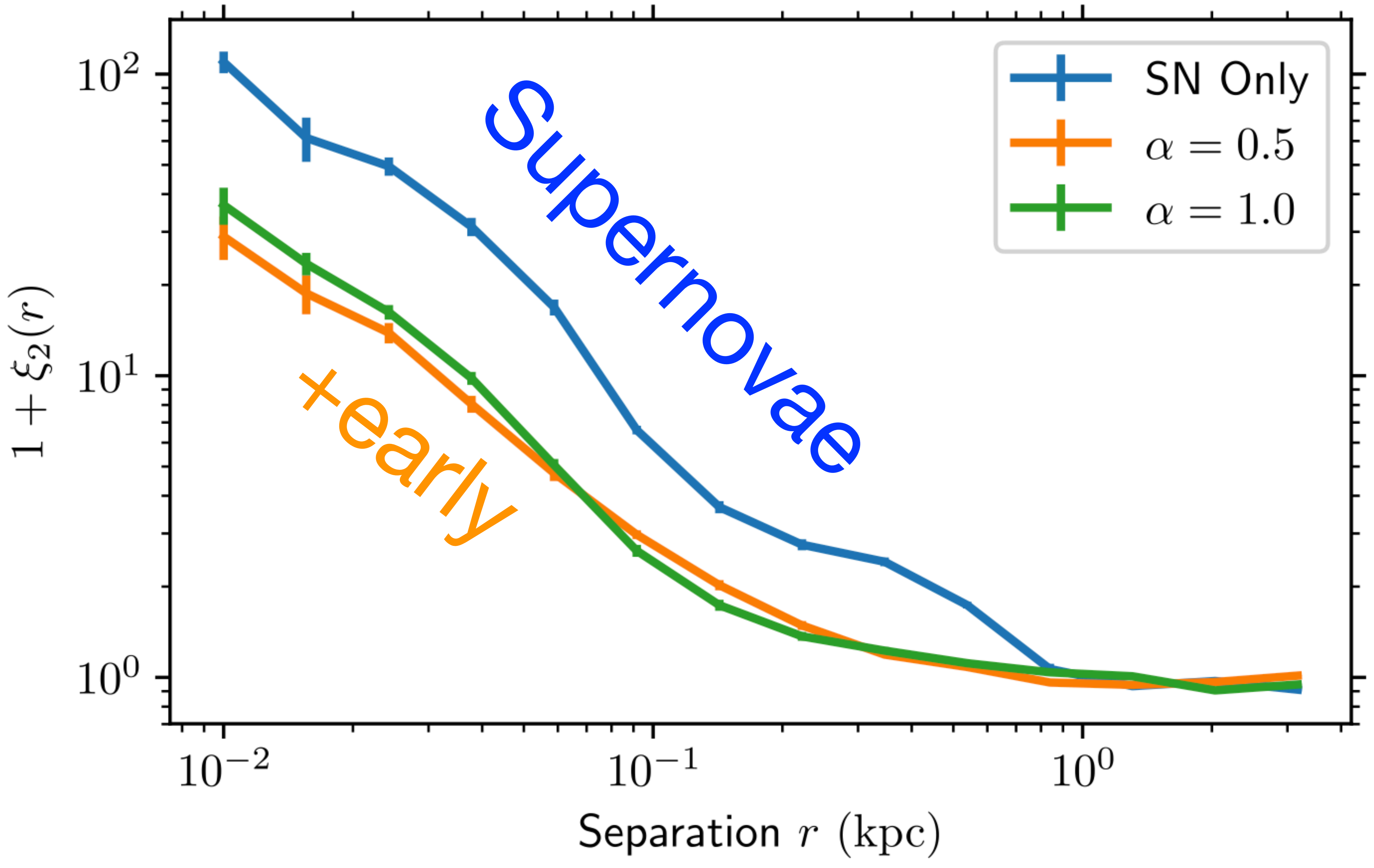
Smith+21

Andersson+24

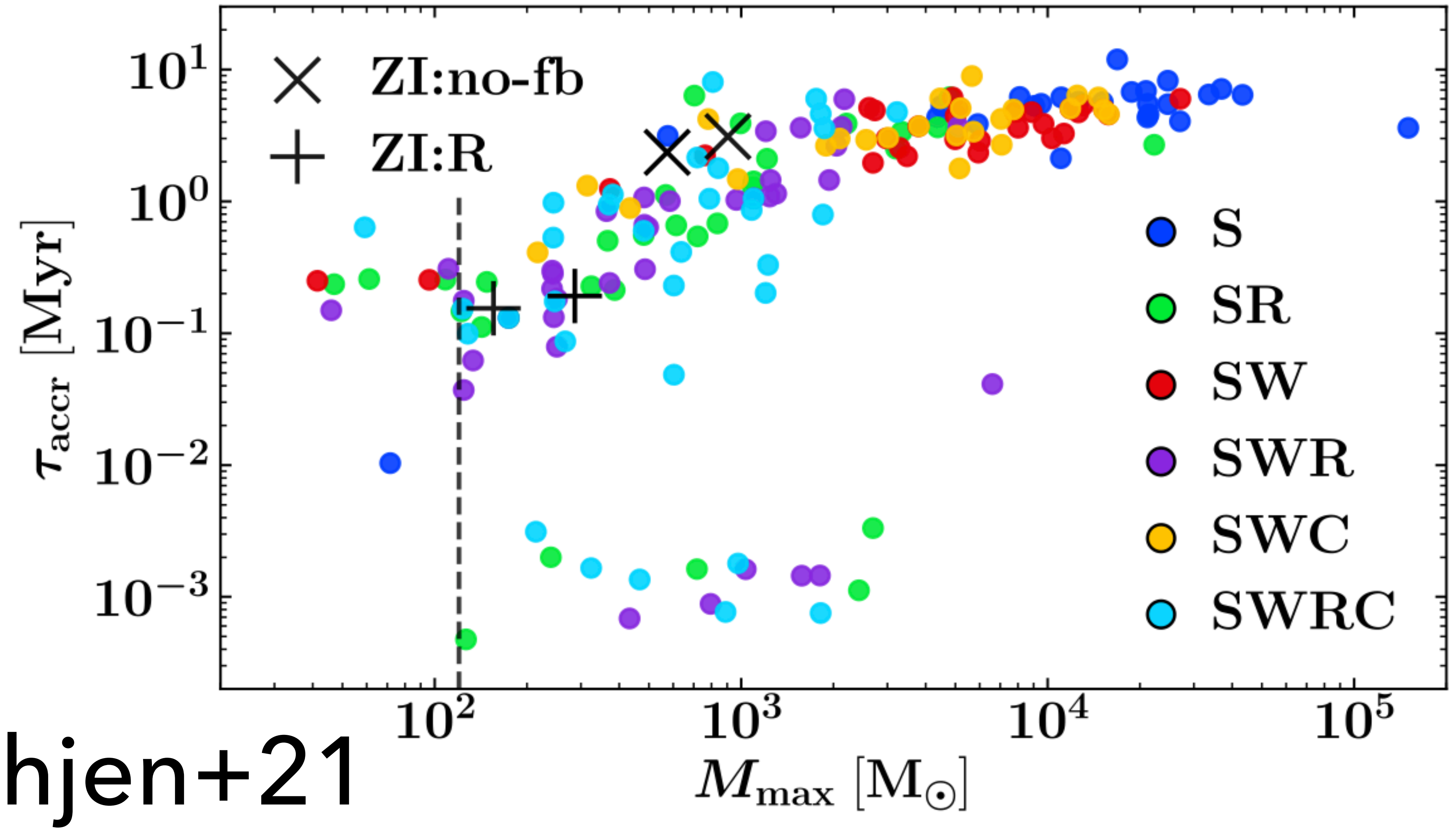




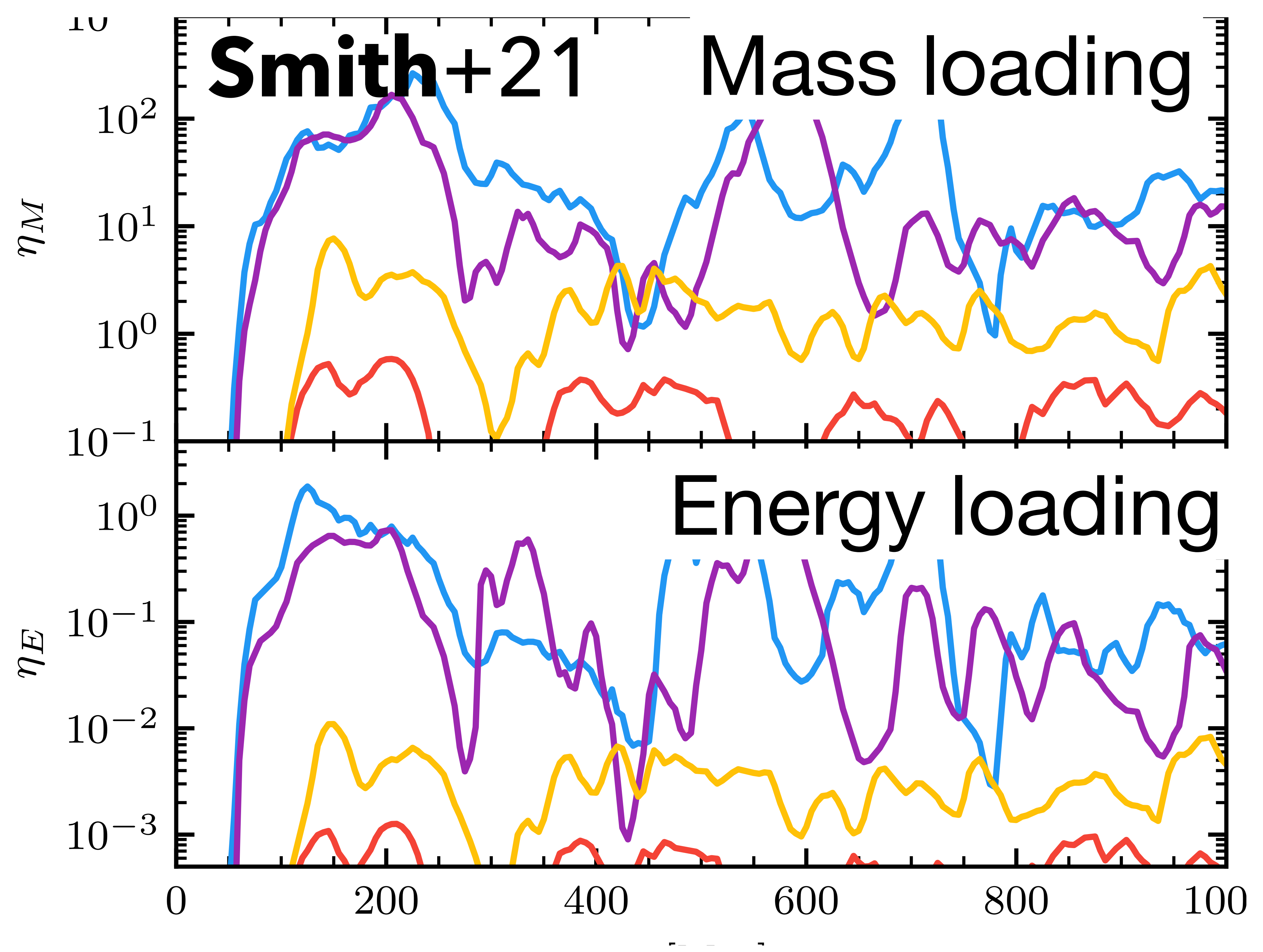
Hislop+22

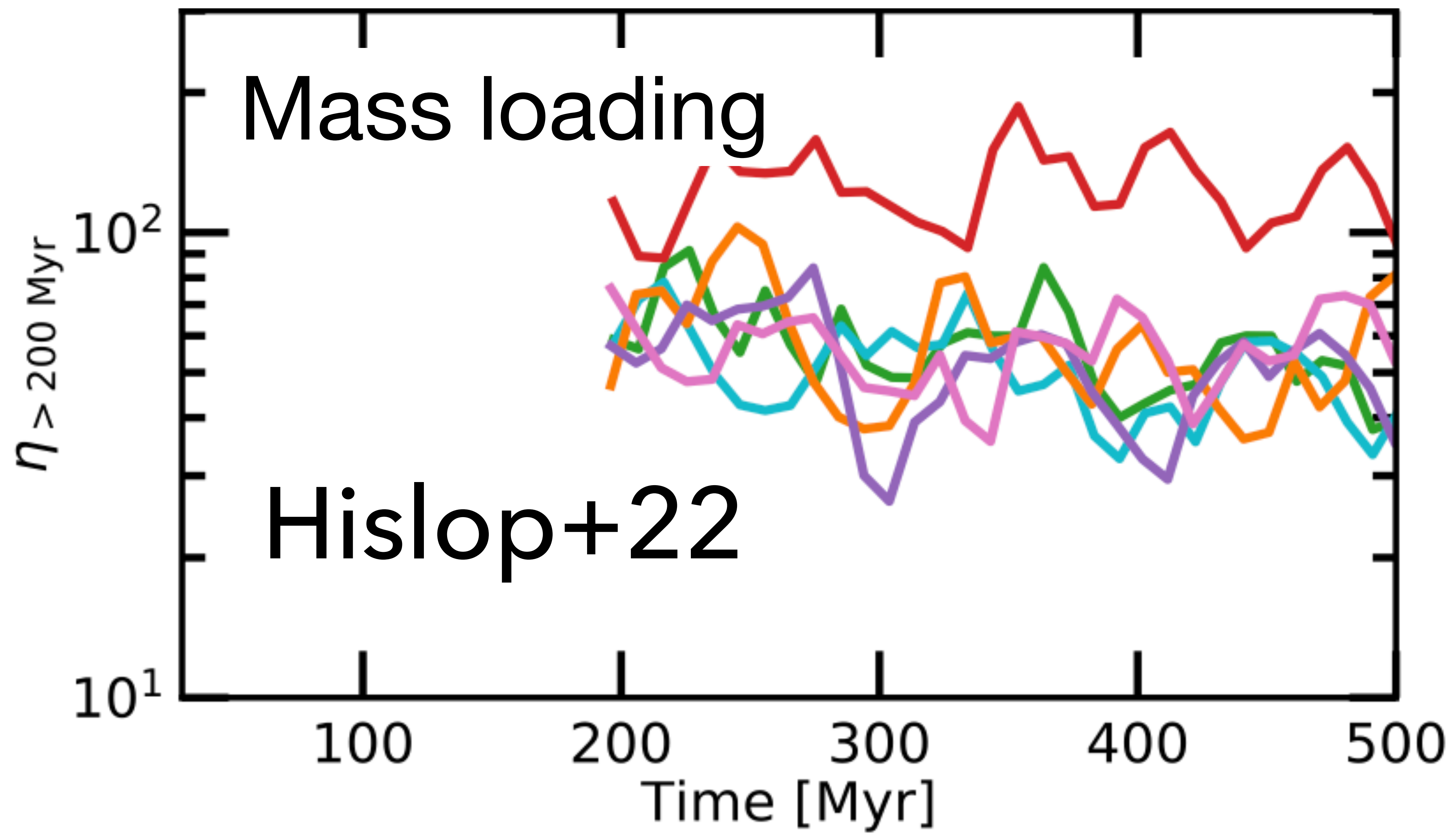


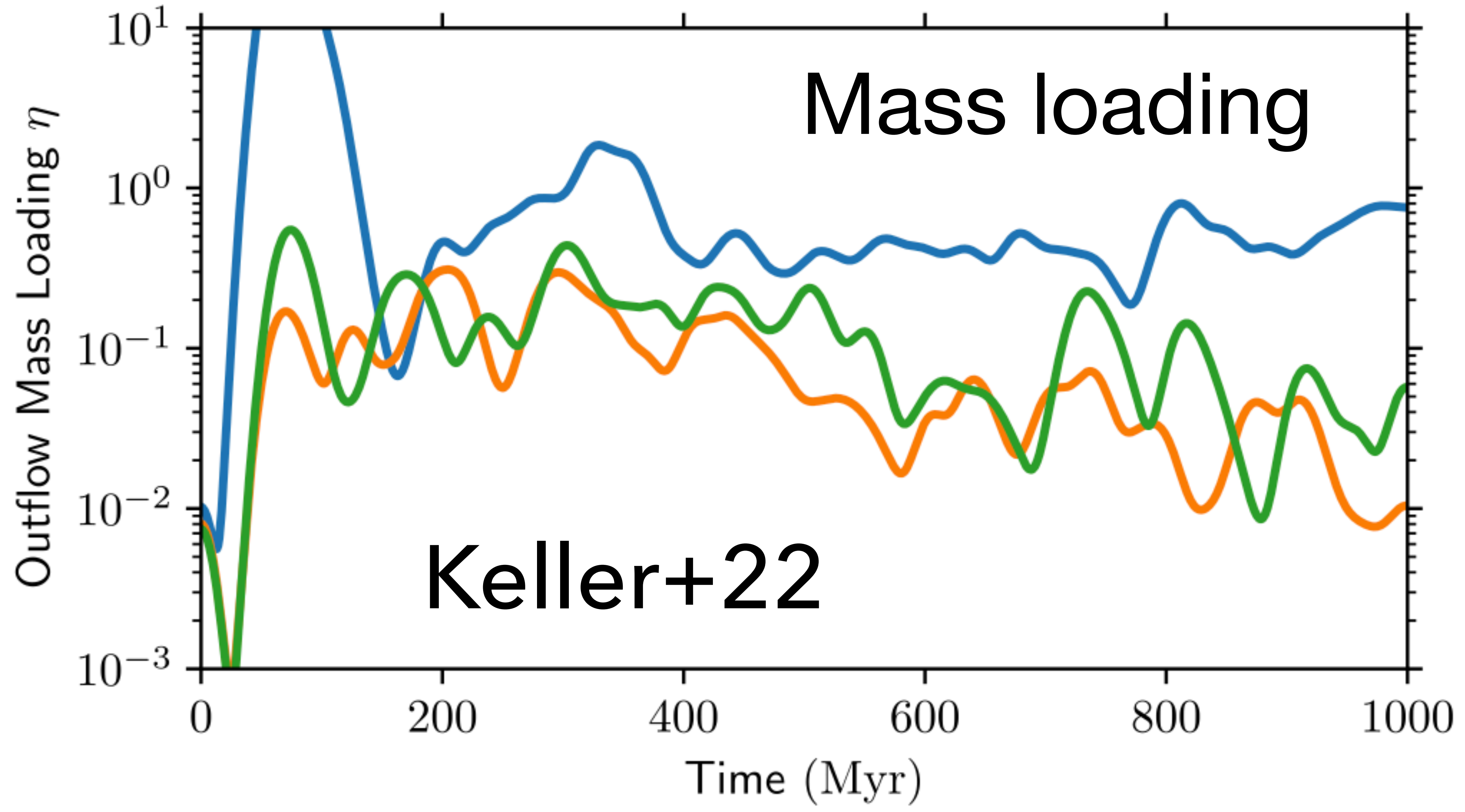
Keller+22

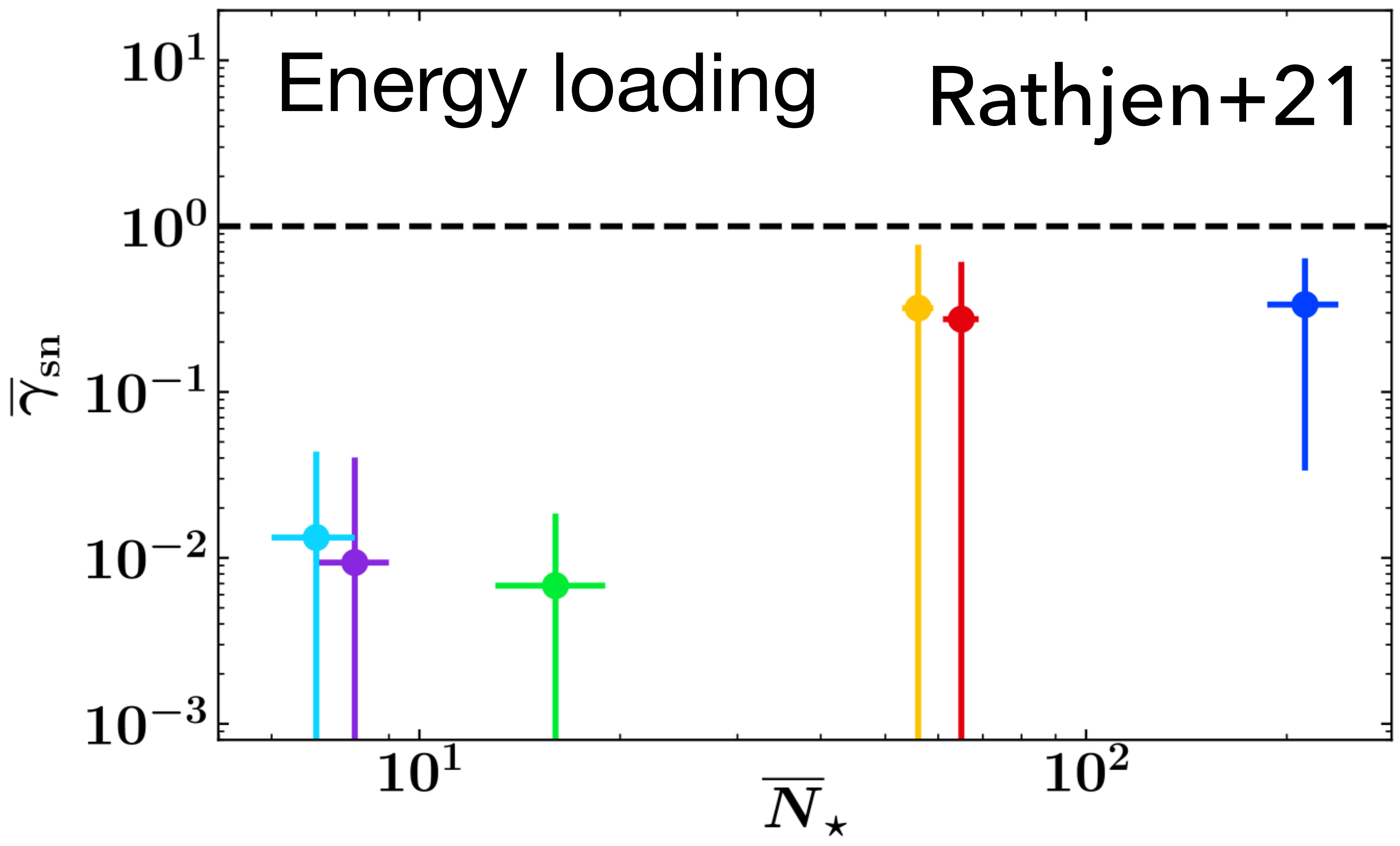


Rathjen+21

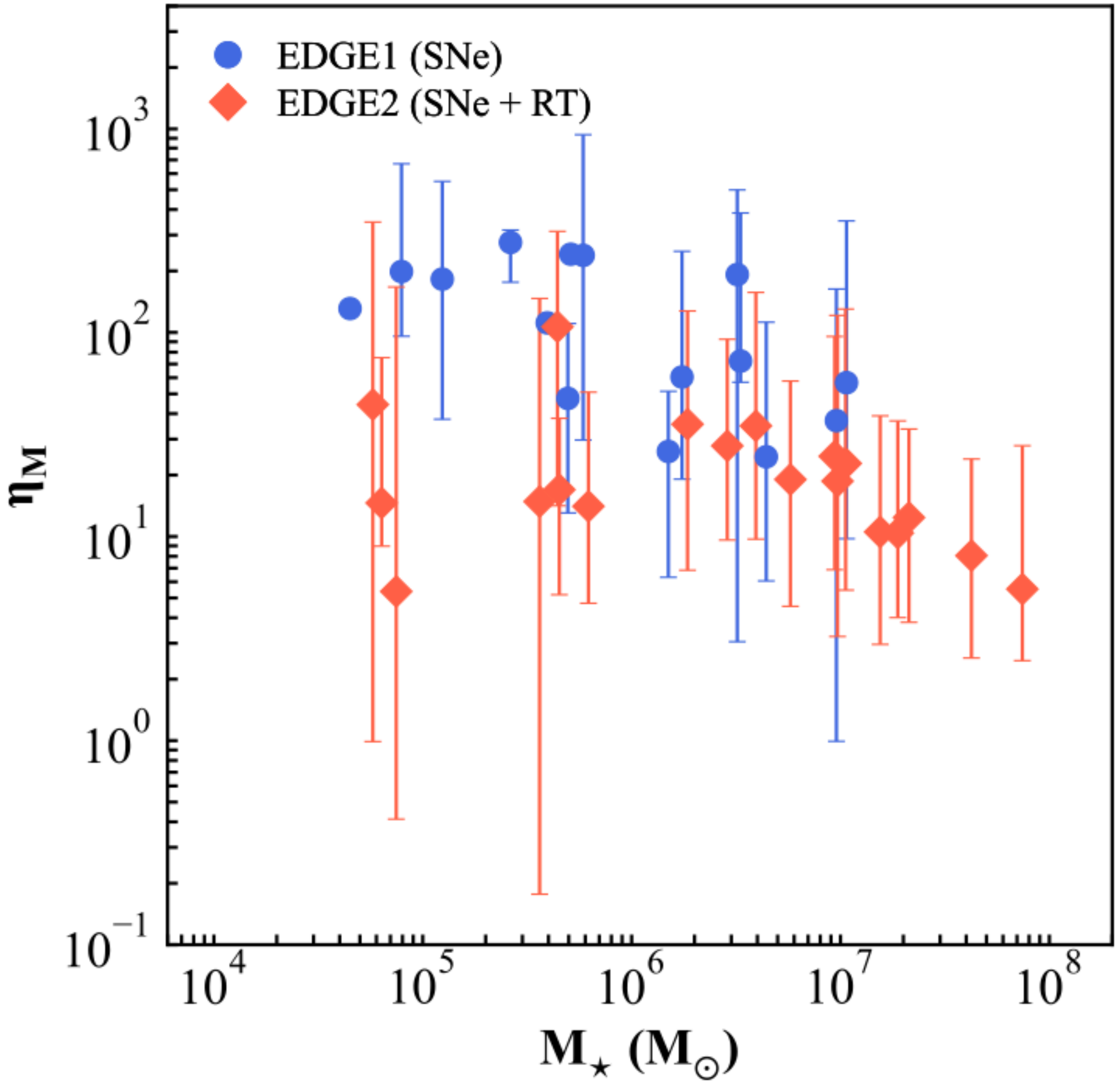

Smith+21
Mass loading
Energy loading
η_M
η_E
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
200
400
600
800
100


Mass loading
Hislop+22
$\eta_{>200\ \mathrm{Myr}}$
10^2
10^1
100
200
300
400
500
Time [Myr]


Mass loading
Keller+22
Outflow Mass Loading η
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
200
400
600
800
1000
Time (Myr)


Energy loading
Rathjen+21
$\overline{\gamma}_{\mathrm{sn}}$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
$\overline{N}_\star$

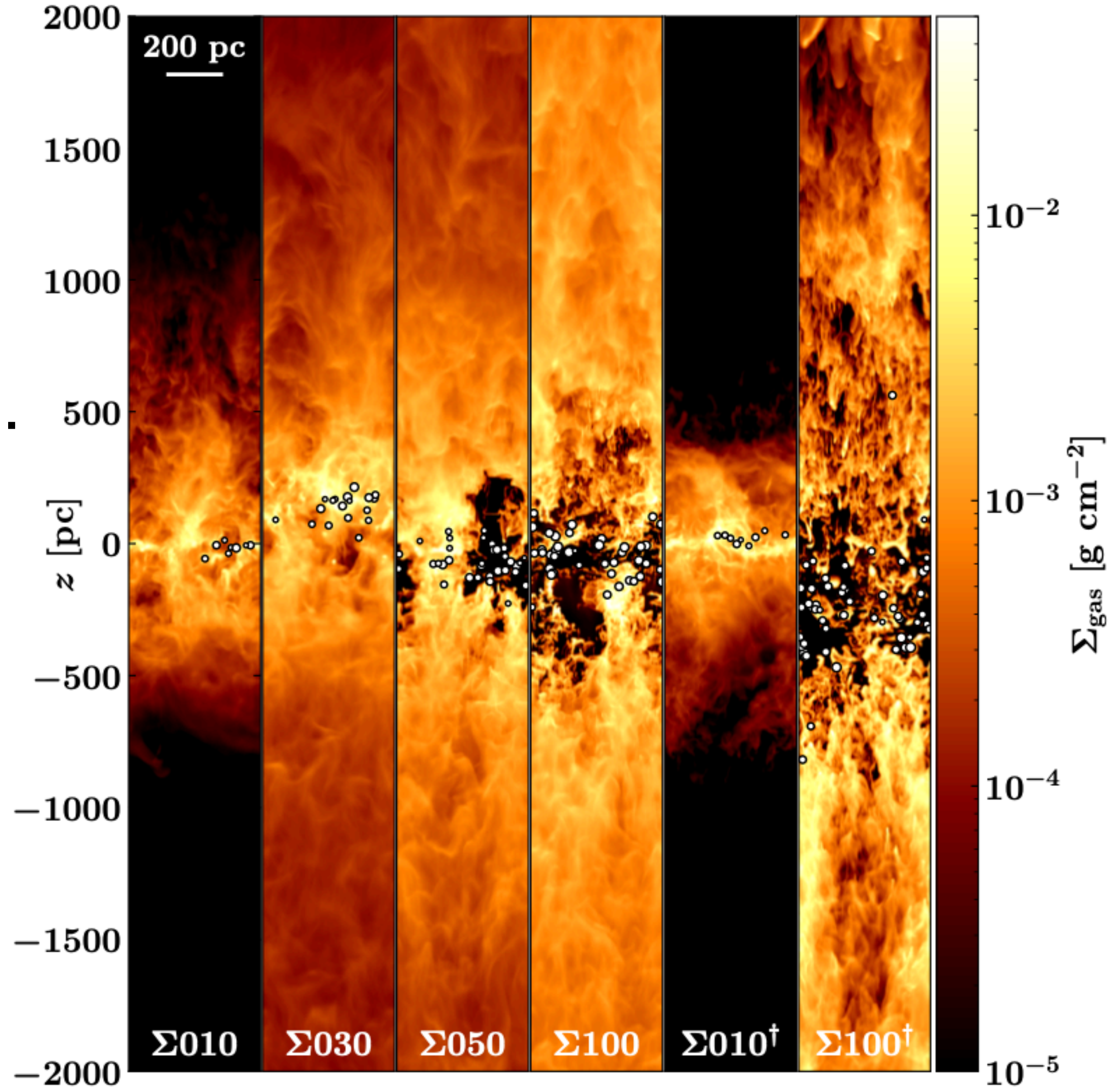
Suppression of mass loading in cosmological dwarfs by early feedback



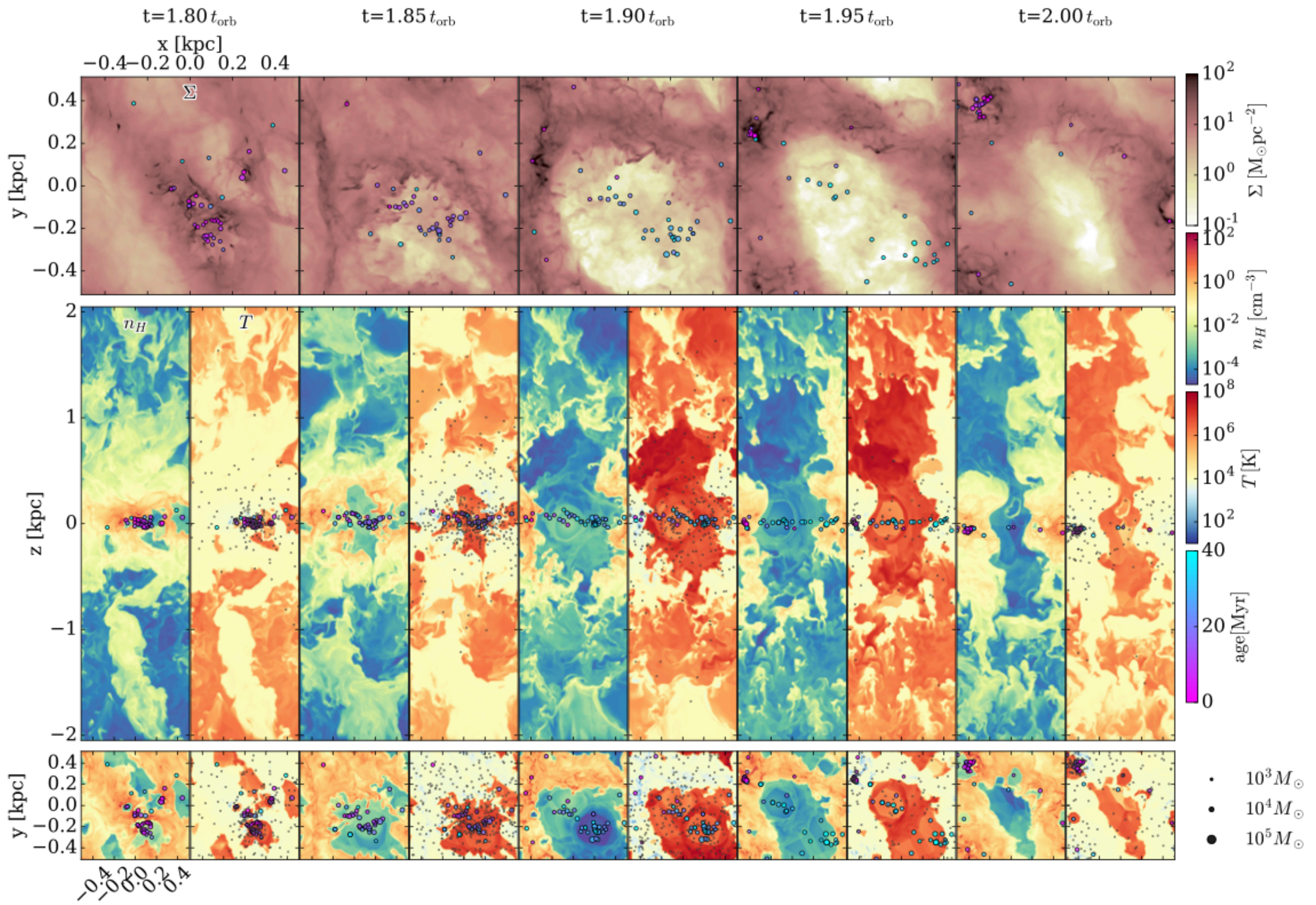
Rey+ 2025, measured at 0.25 r_{200}, averaged over history

Keep everything the same, except vary discretisation of formed stellar mass

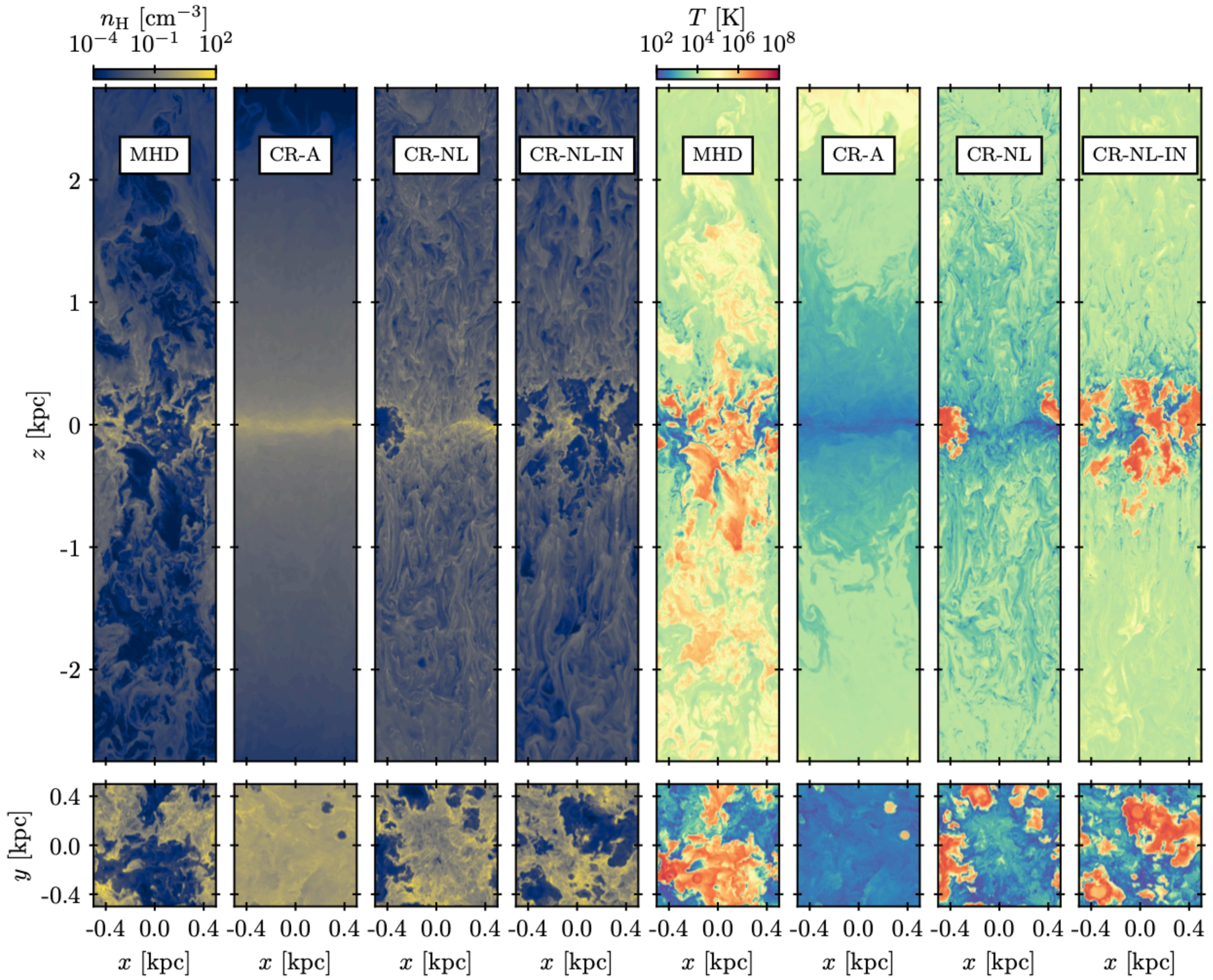
SILCC: Walch+15, Girichidis+16,18, Gatto+16, Peters+17, Rathjen+21,23,24,…



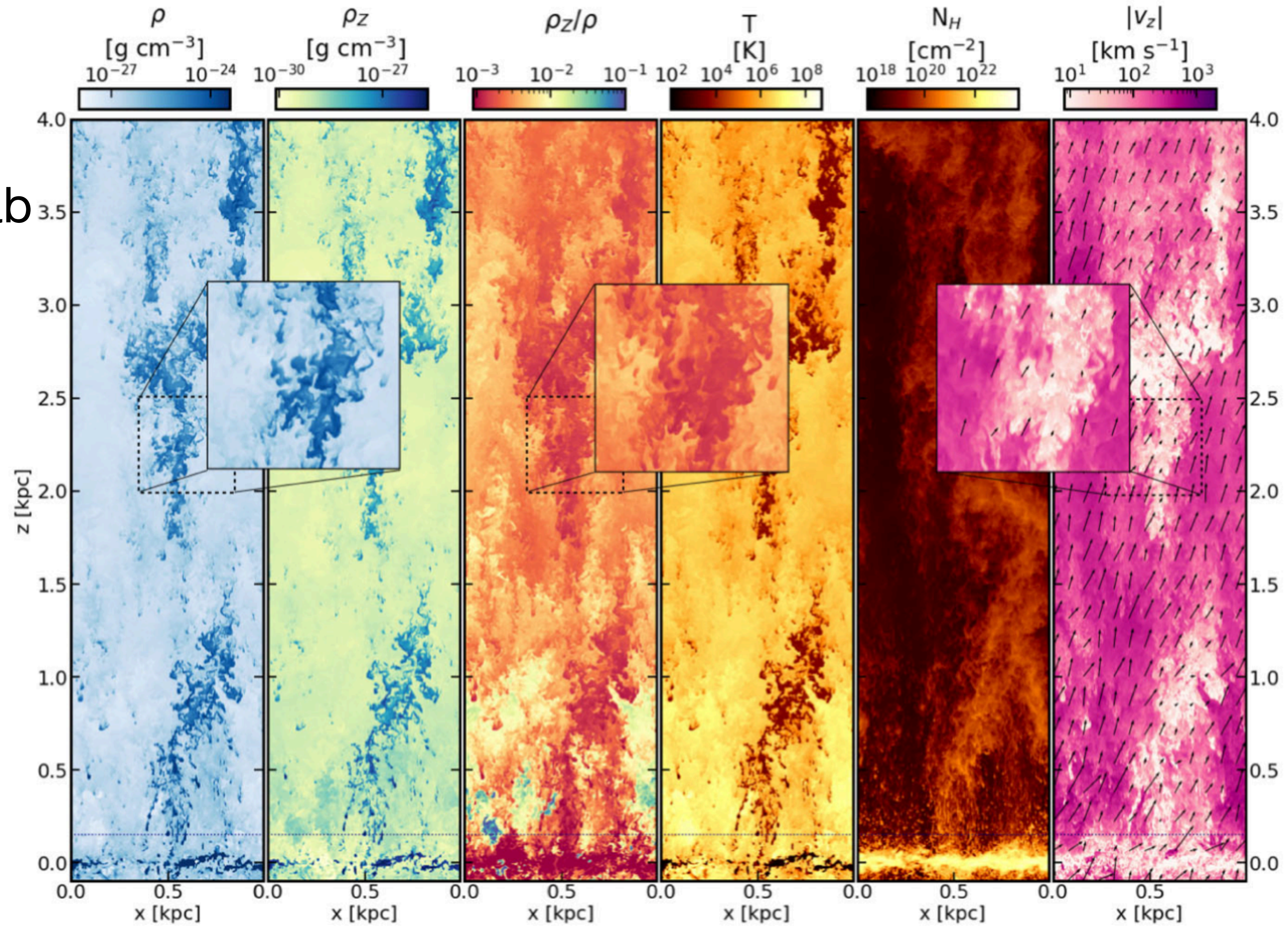
TIGRESS: Kim+17,18, 20,23,…



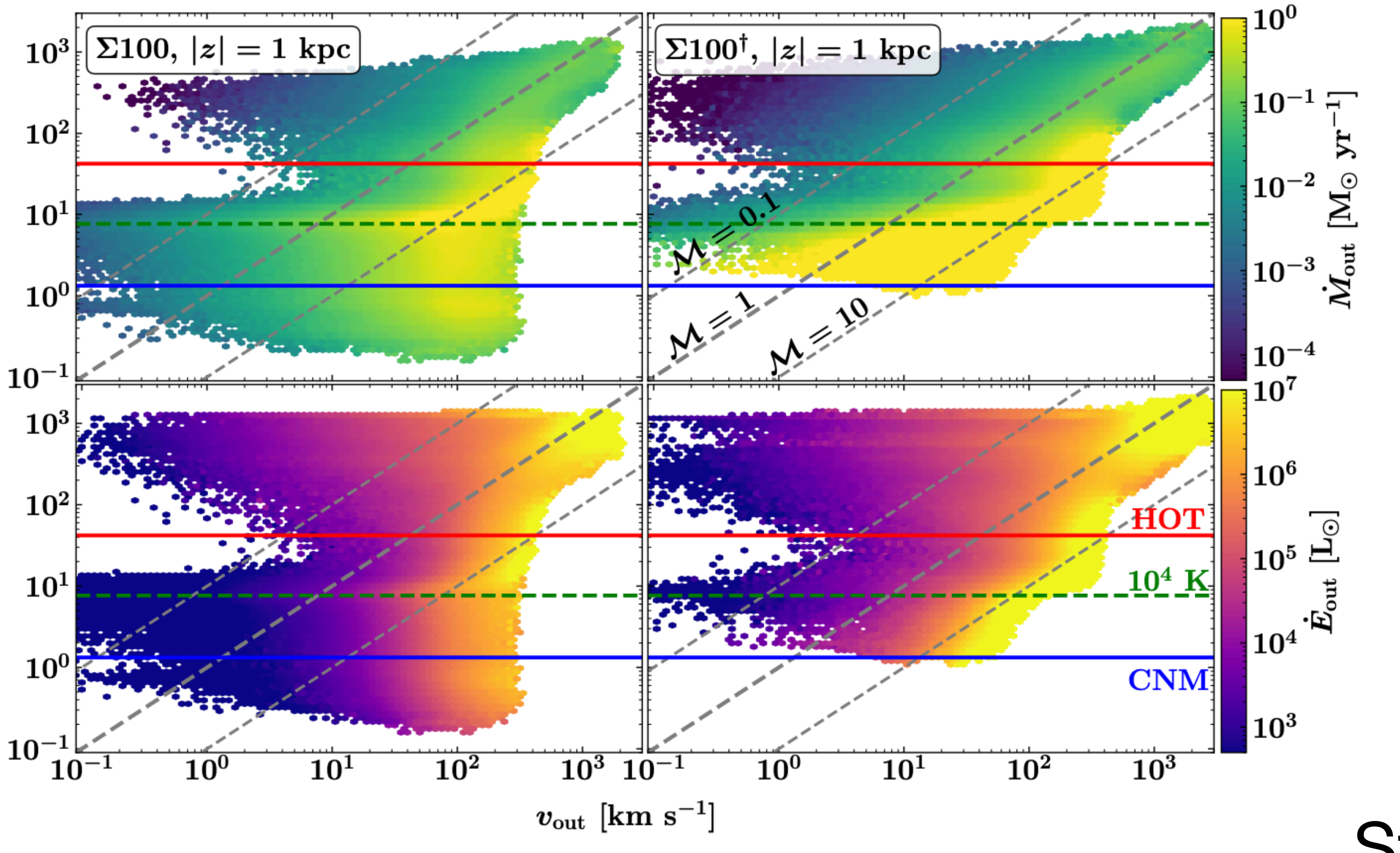
Sike+25



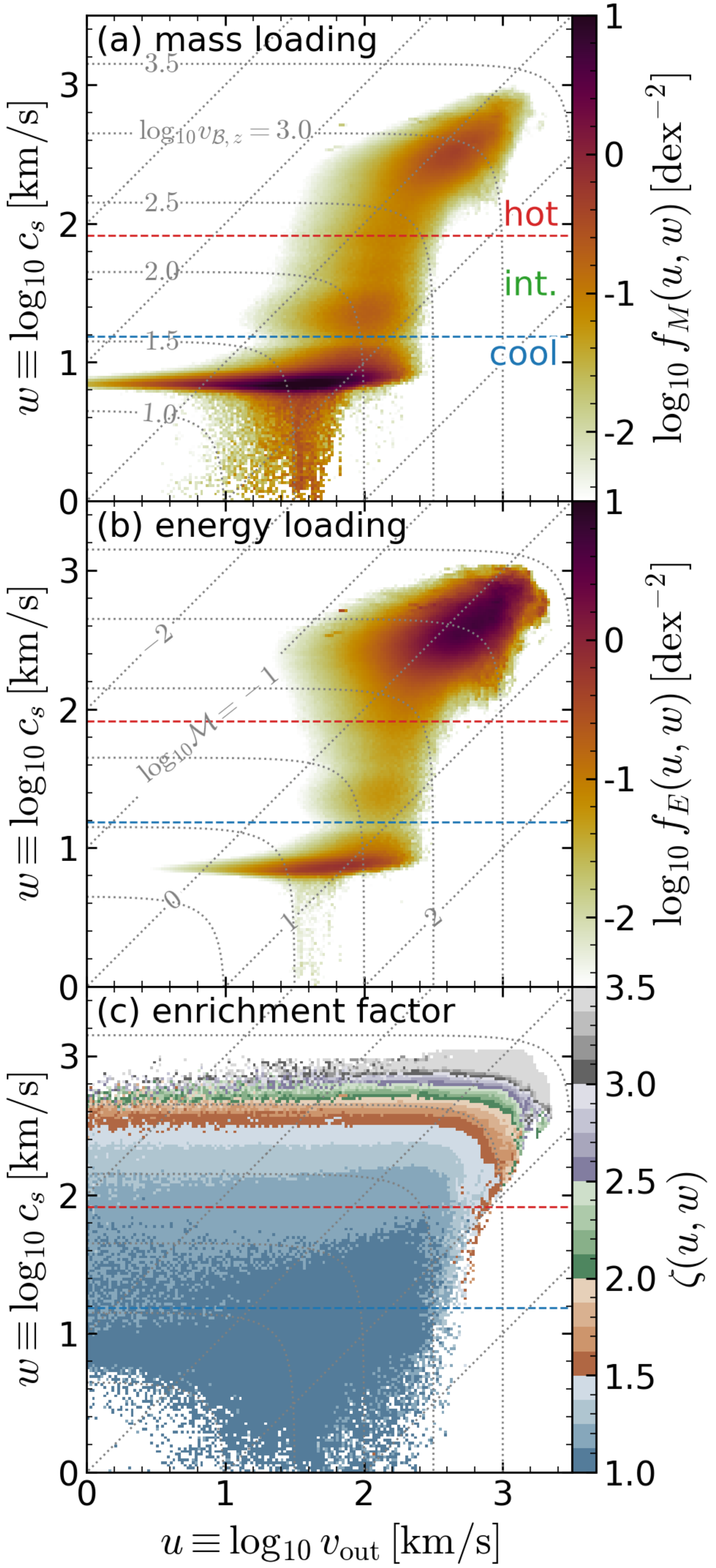
QED: Vijayan+24,25ab



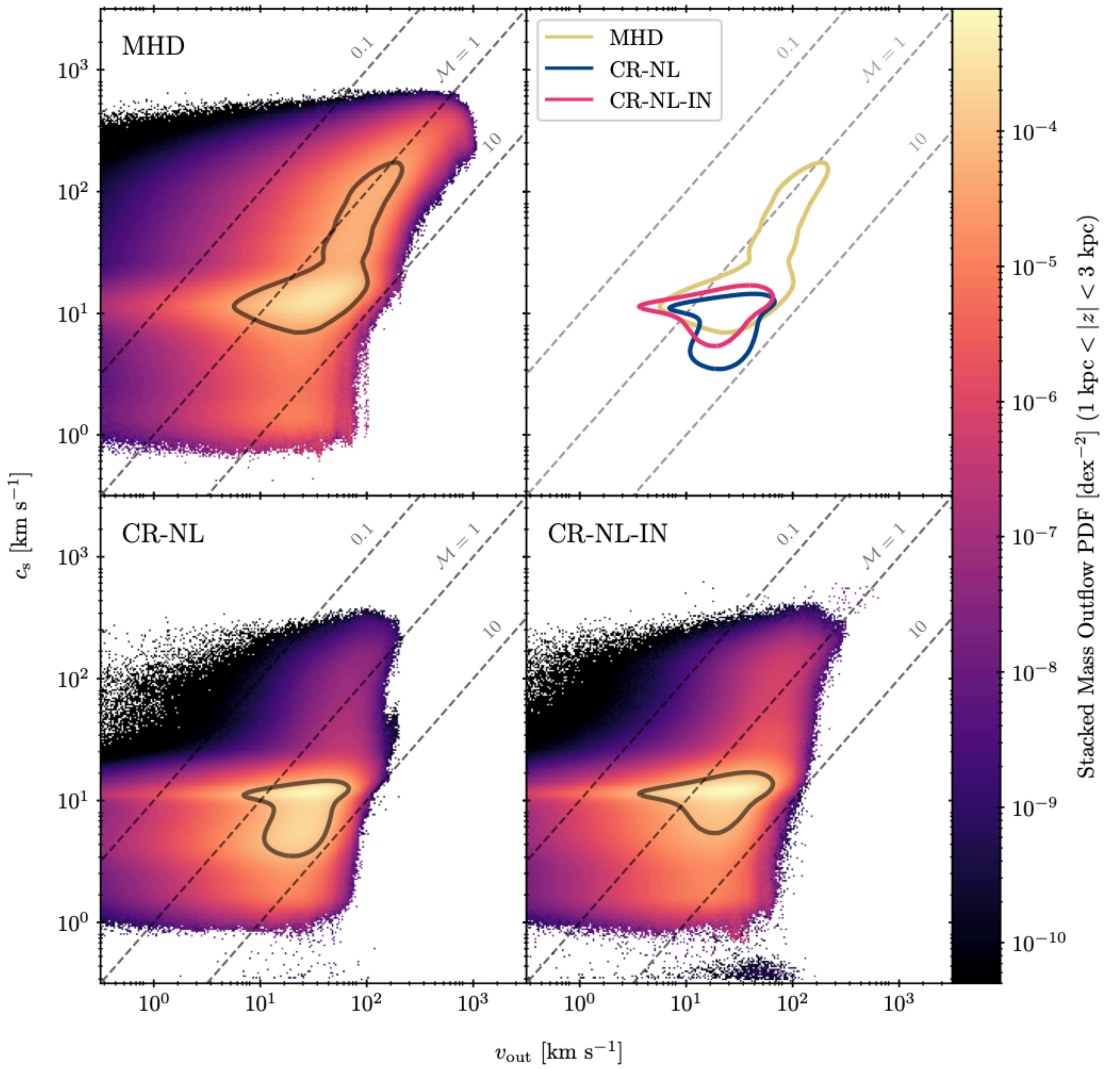
Rathjen+23



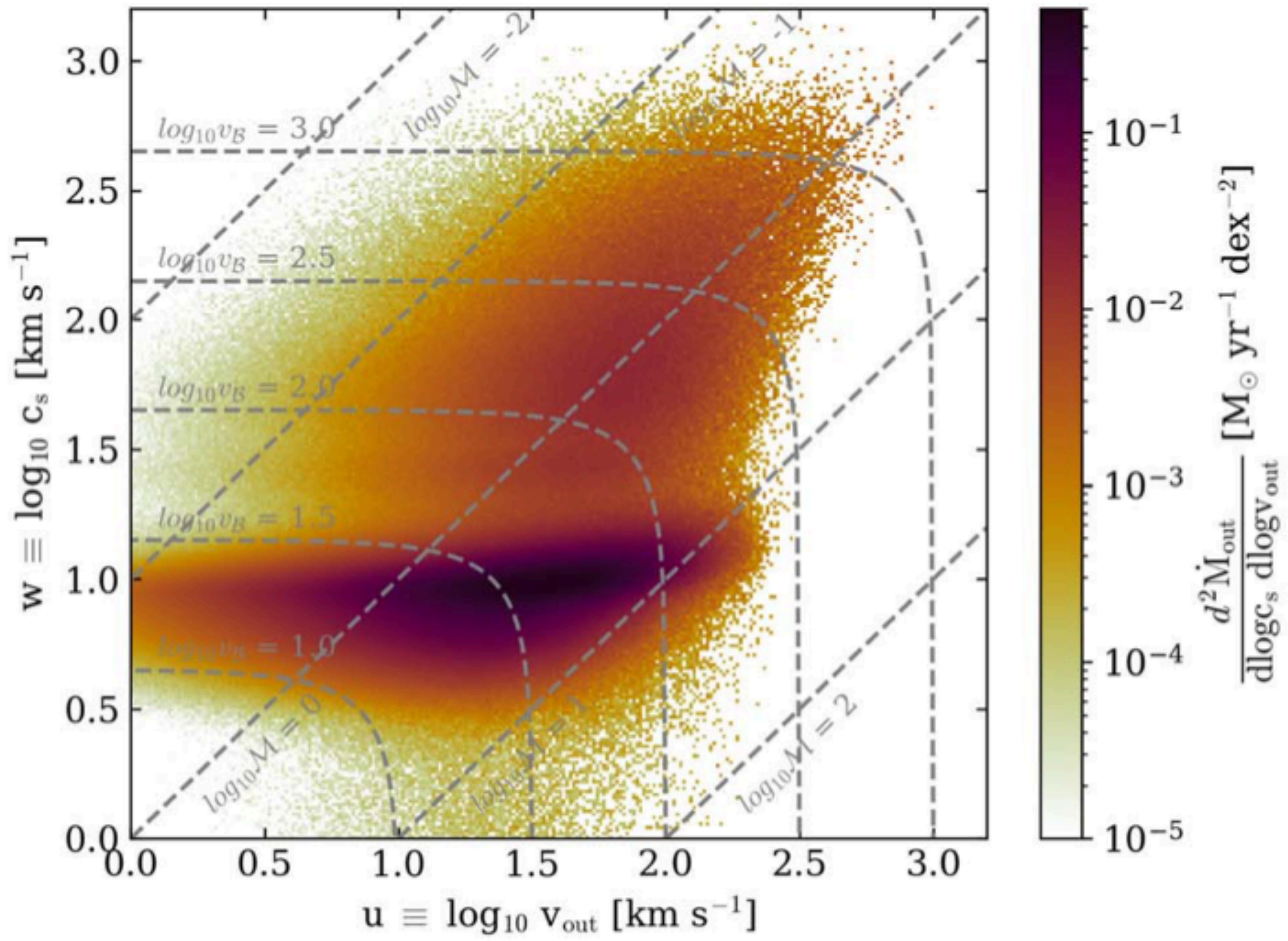
Kim+2020



Sike+25



Steinwandel+24

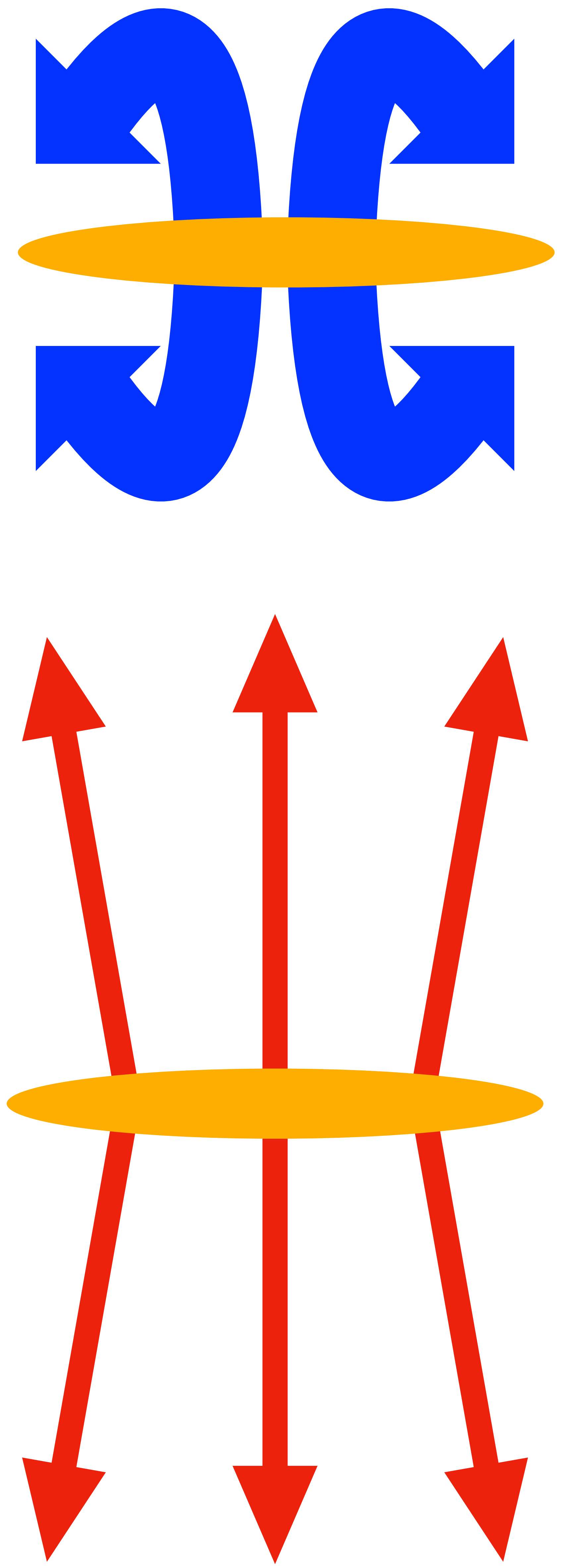


Multiphase outflows

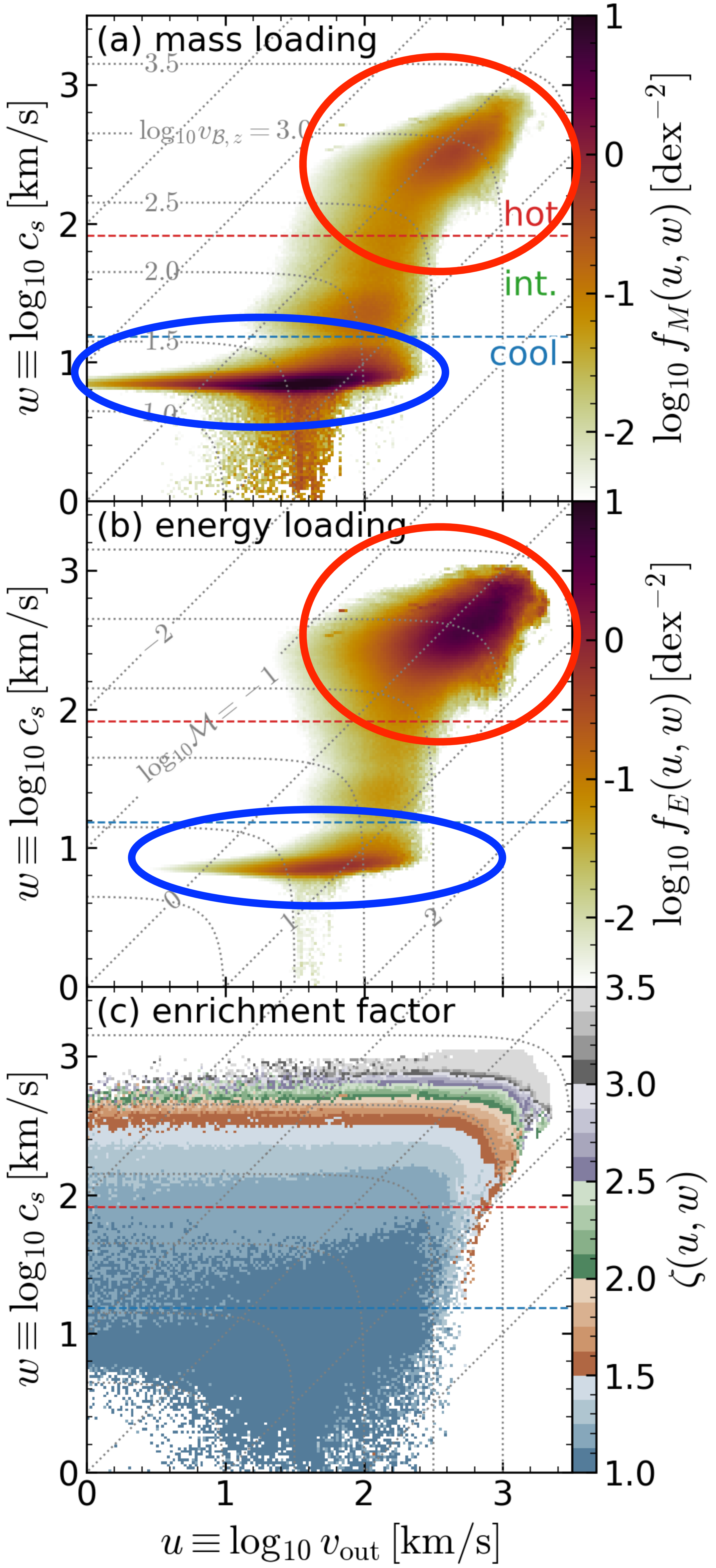
Resolved ISM simulations produce highly multiphase outflows

Mass loading dominated by cold/warm slow moving material (ejective feedback)

Energy loading dominated by hot, fast, metal enriched outflow (preventative feedback)



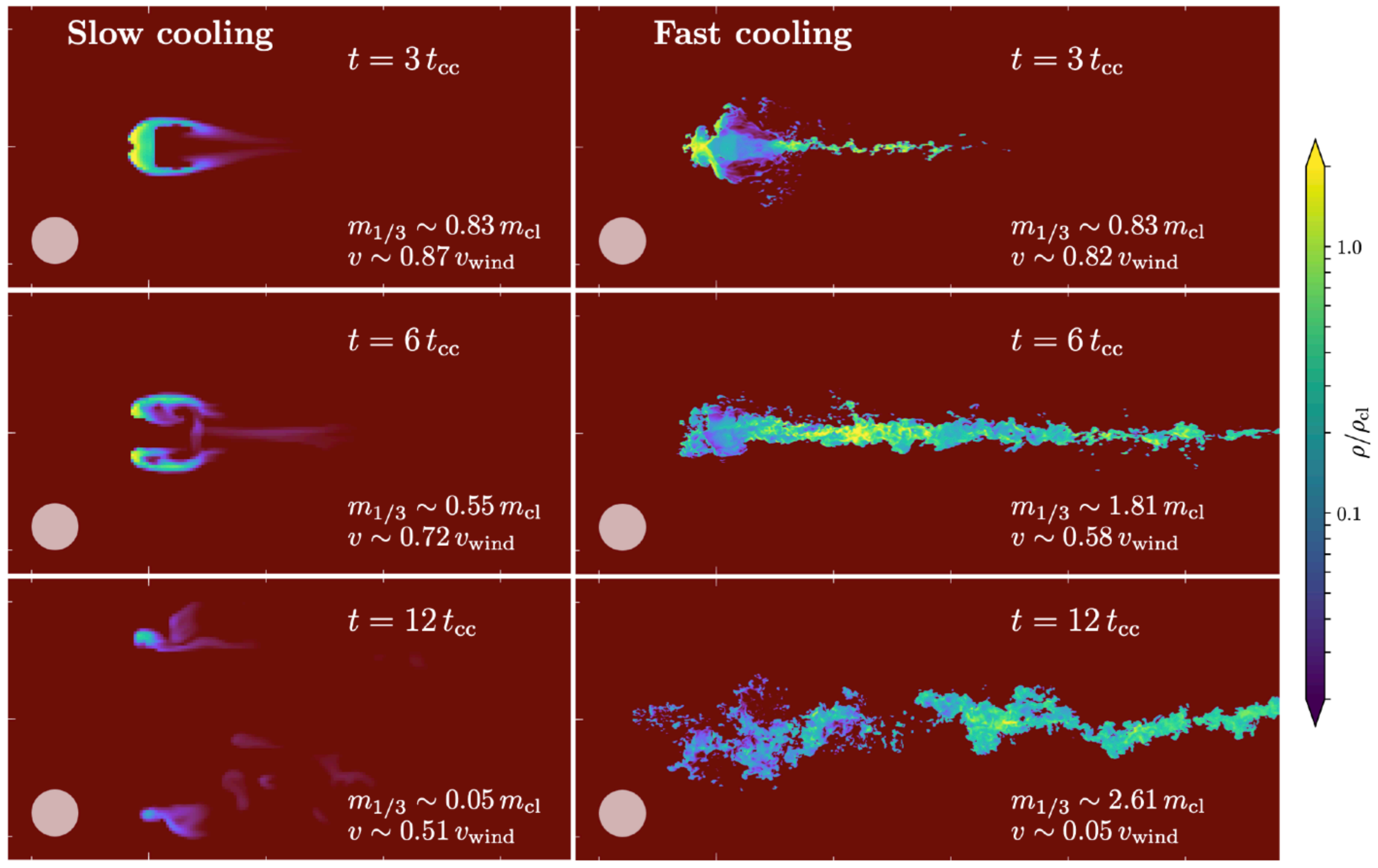
Kim+2020



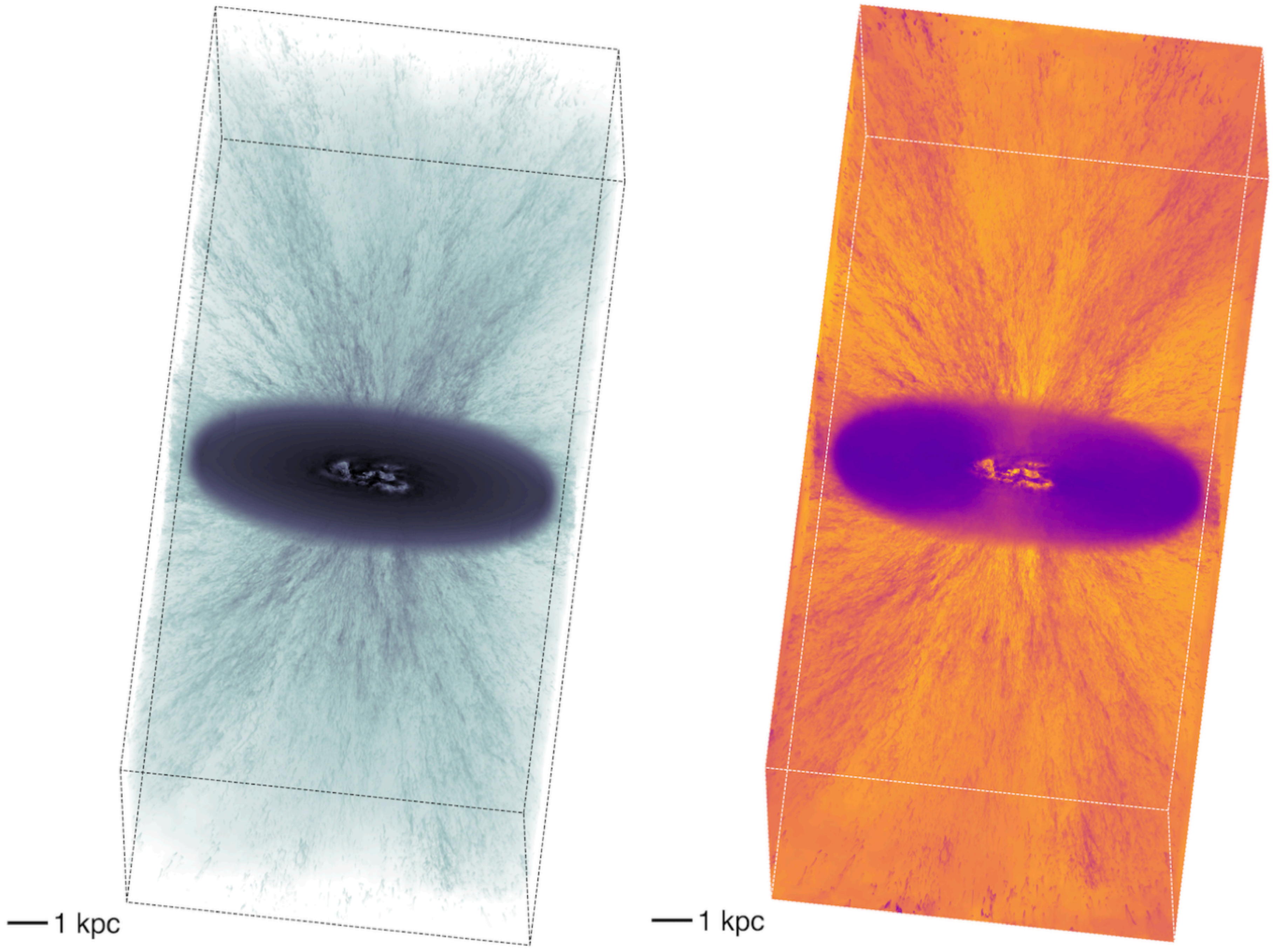
Phase interactions

Highly complex co-evolution of gas phases, relevant physics is very small-scale

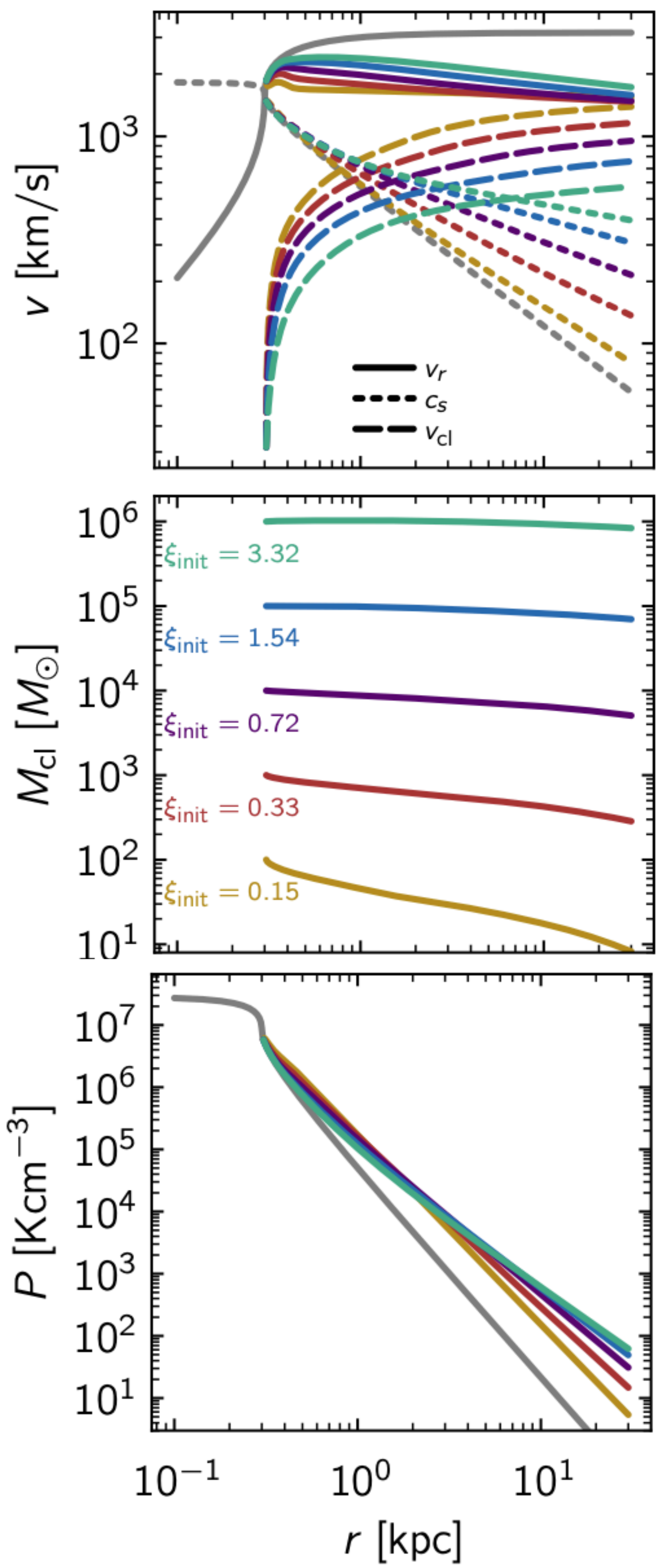
But can have large scale impact on evolution of the wind



Gronke & Oh 2018

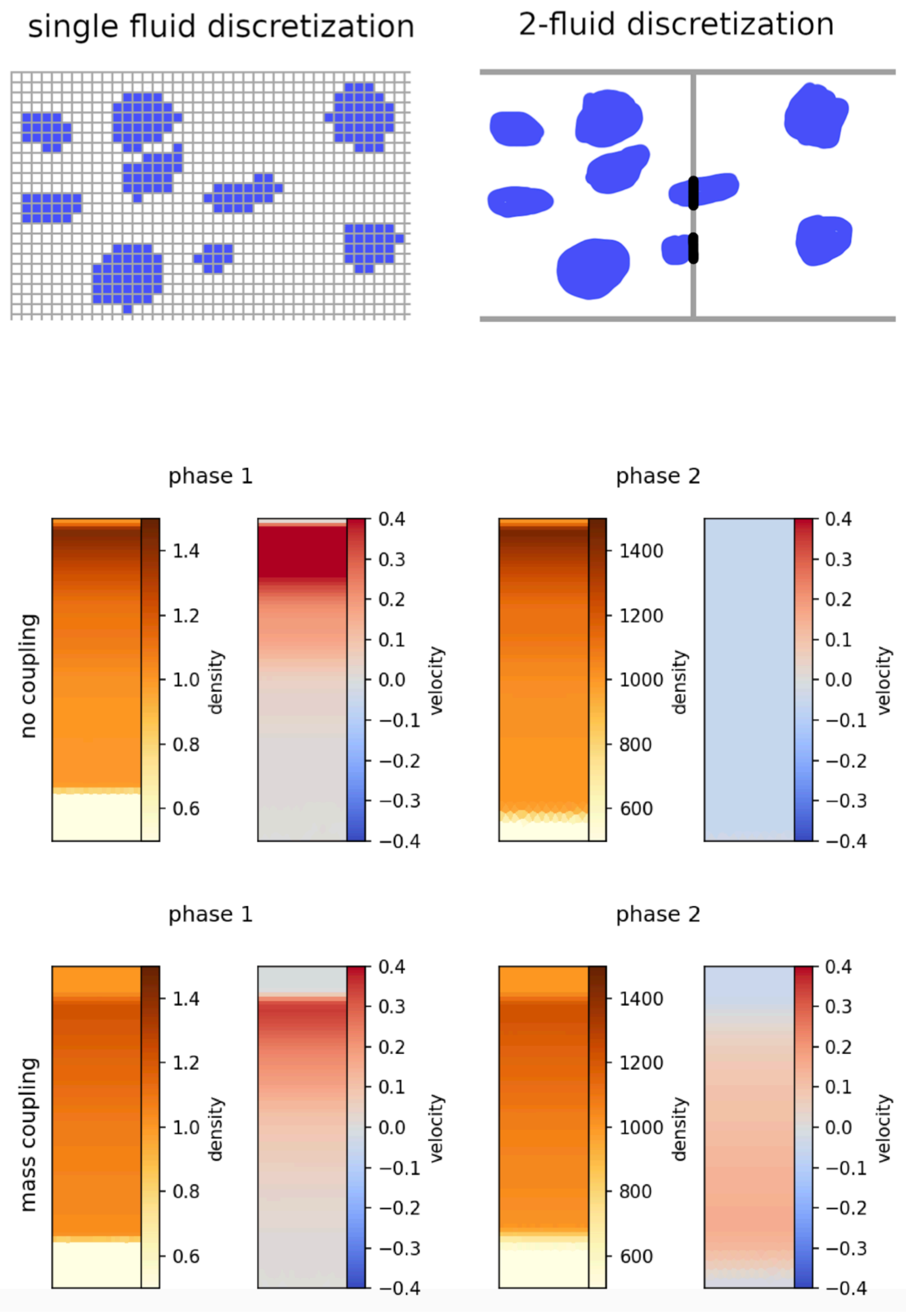


Schneider+2020

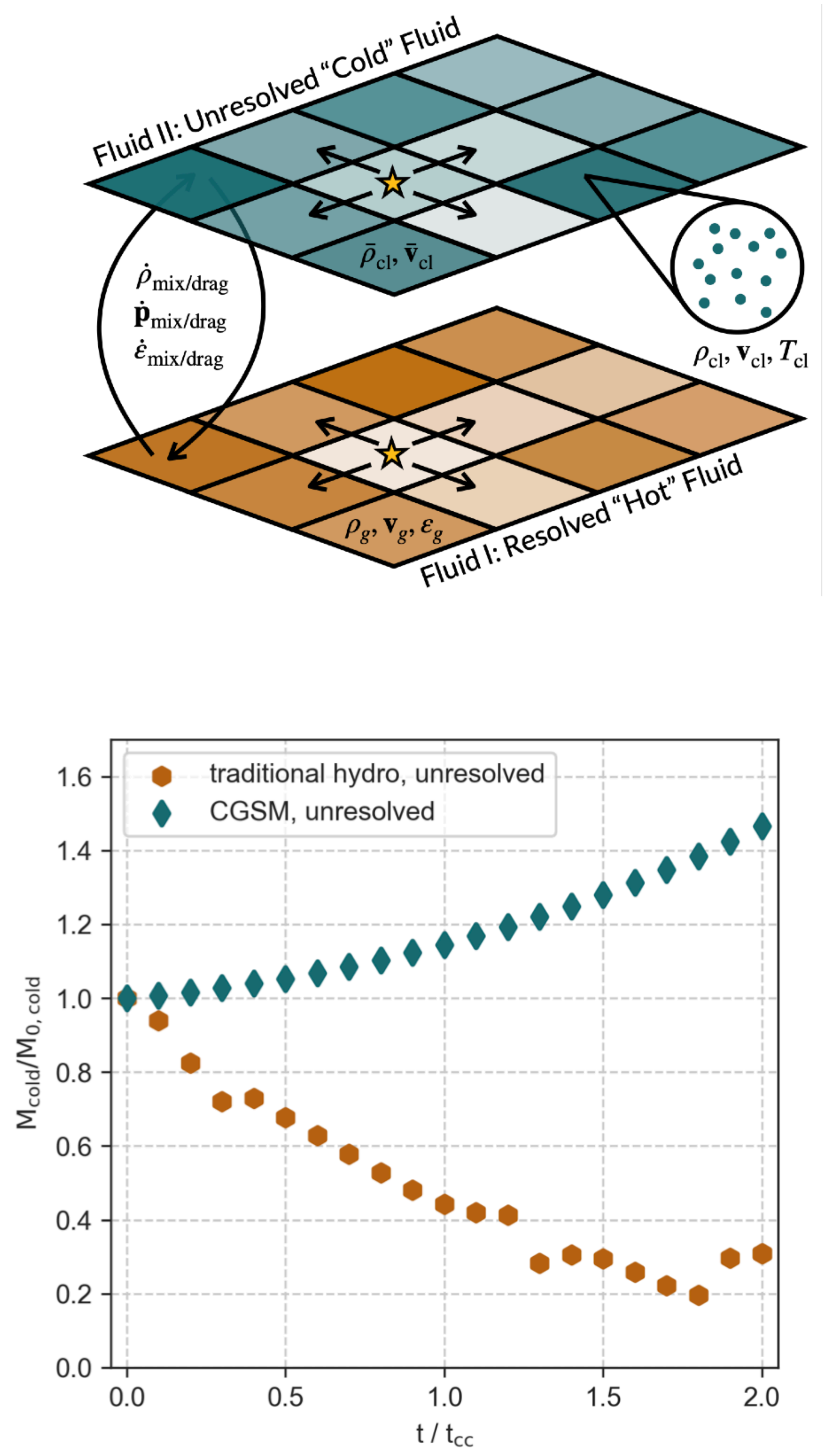


Fielding & Bryan 2022

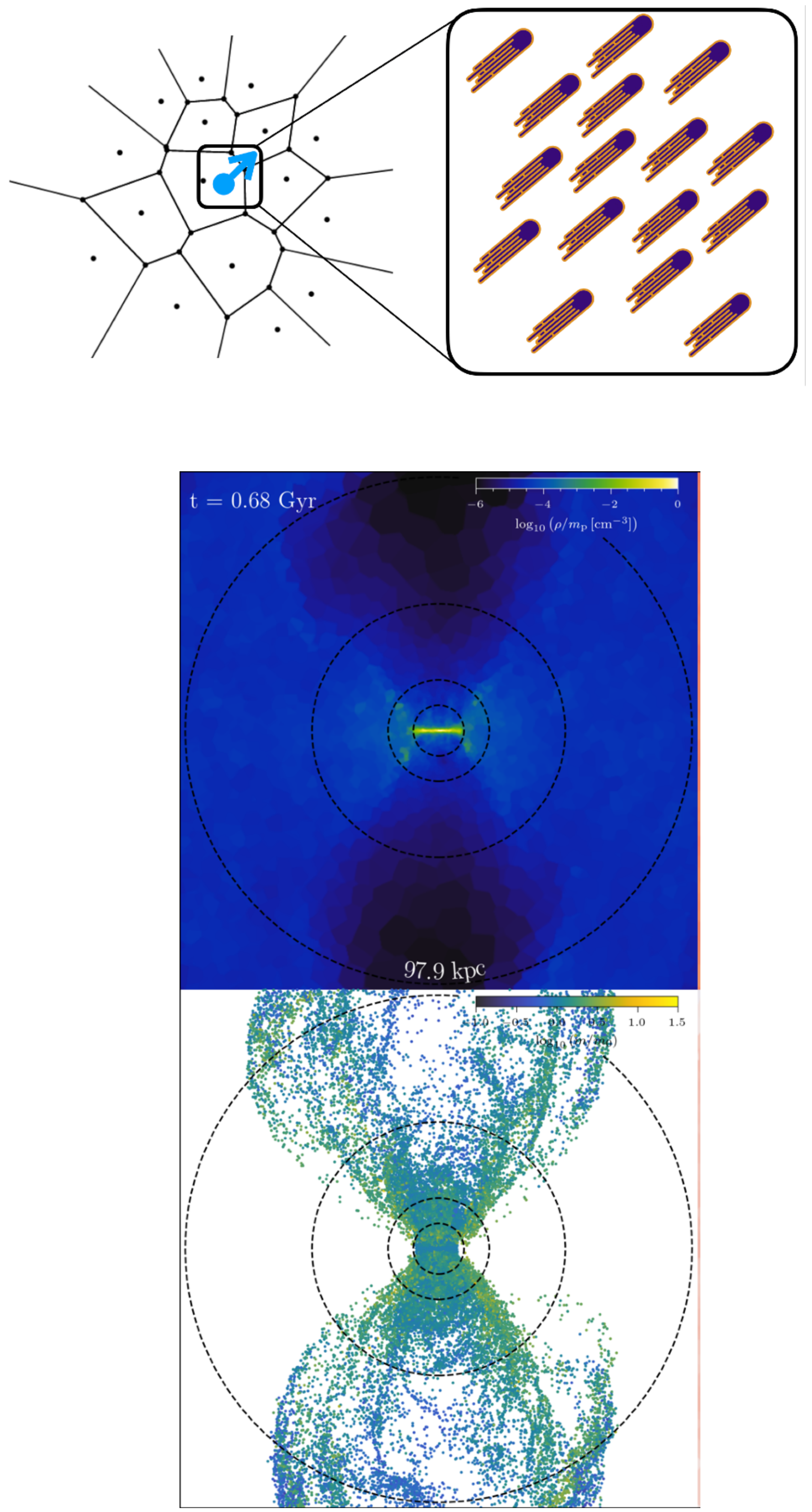
Weinberger & Hernquist 23
Das+23

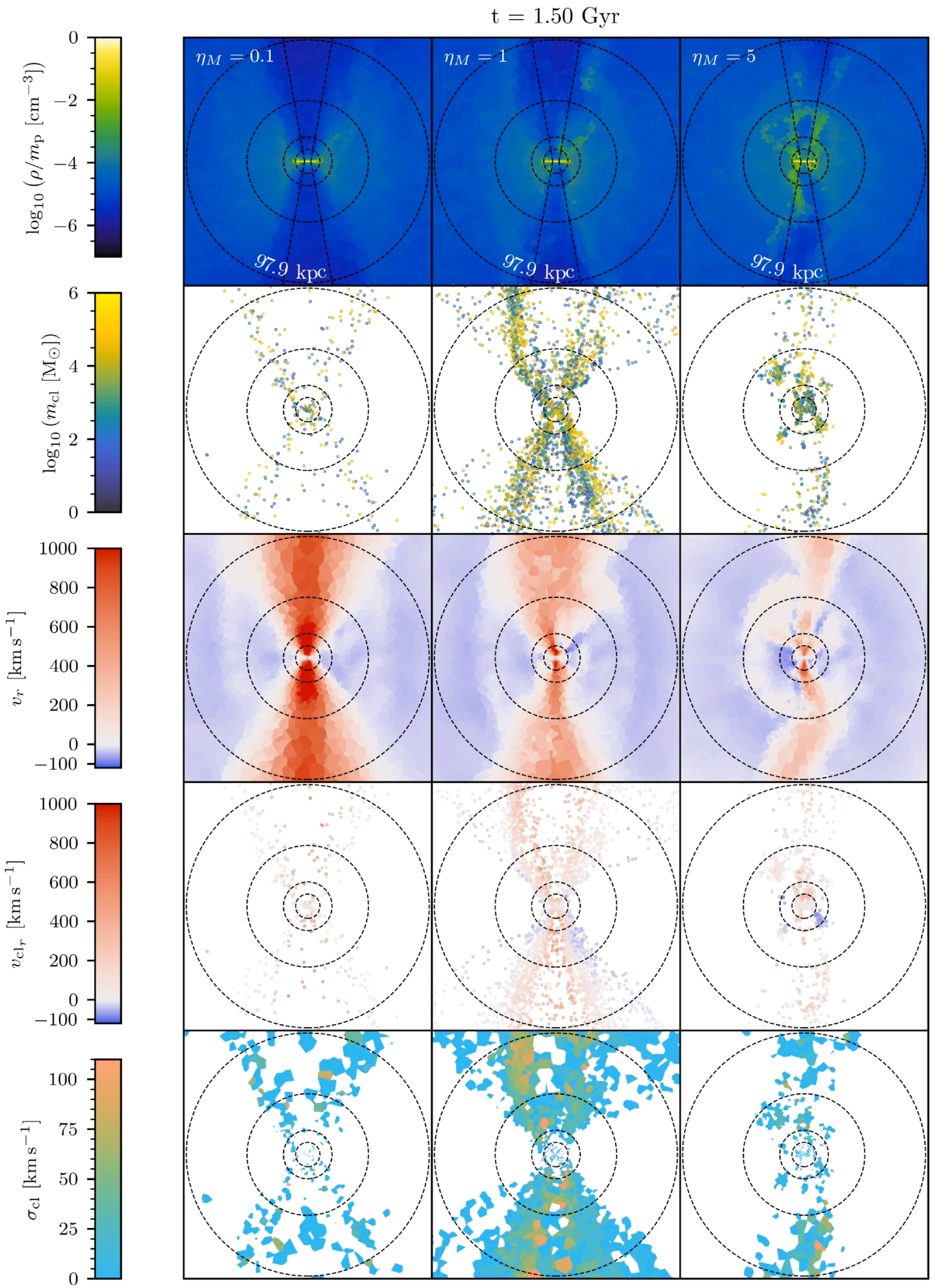


Butsky+24



Smith+24a,b "Arkenstone"





Resolved gas density

Cloud particles, cloud masses

Resolved gas radial velocity

Cloud particles radial velocity

Velocity dispersion of clouds within each cell

Smith+2024b

Summary

1. There are multiple modes in which stellar feedback driven galactic winds can participate in the baryon cycle
    - Ejective vs. preventative (and combinations of both)
    - $\frac{\eta_E}{\eta_M}$ is as important as η_M
    - CGM properties may provide constraints
2. Tensions between high resolution idealised and coarse resolution cosmological simulations?
    - Possibly, but we could be comparing apples with oranges
    - Need very high resolution, ideally “star-by-star” simulations to capture “a priori” wind generation
    - Observational comparison on even footing more important than ever
3. Multiphase nature of winds significantly complicates the picture
    - Combination of idealised experiments with novel numerical methods (e.g. multi-fluid approaches) will help

I didn’t talk about:

- Chemical enrichment. What constraints can the MZR and abundance patterns place on winds?
- How does any of this work at high redshift? Does it still make sense to talk about “winds”?
- How do we forward model the simulations? What are the most robust ways to obtain constraints? How do we account for selection effects e.g. are we simulating the right things?

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