Modelling stellar feedback

Future opportunities and challenges

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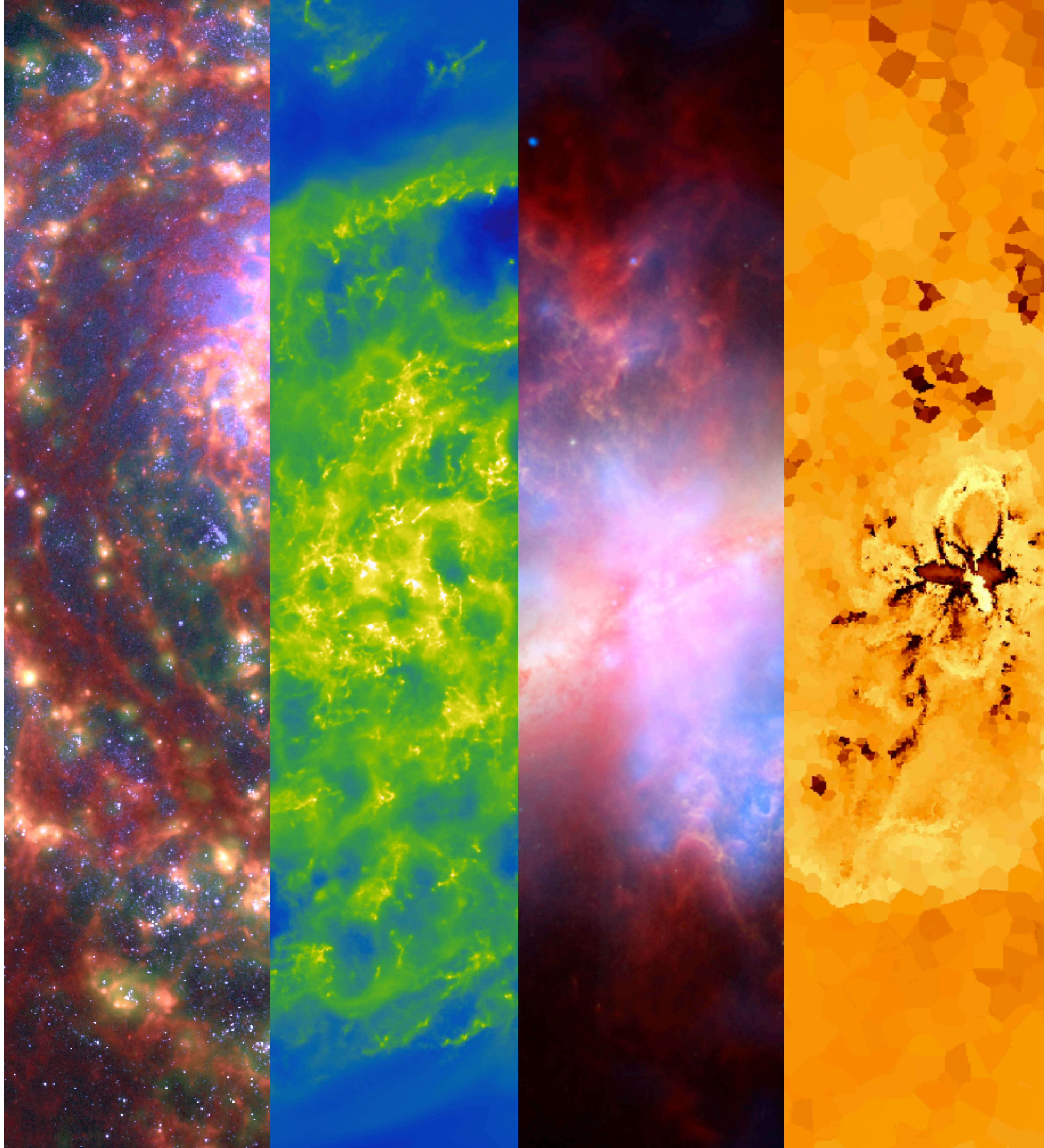

- Direct feedback/explicit models for “high resolution”
  - Individually modelled supernovae, stellar winds, radiation (photoionisation, -heating, -dissociation, pressure),…
  - + detailed ISM cooling, chemistry, star formation laws,…

- Indirect feedback/implicit/effective models for “low resolution”
  - Effective equation of state/pressure floor for ISM, hydro-decoupled winds, stochastic heating feedback, boosted supernova energy…

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  - Individually modelled supernovae, stellar winds, radiation (photoionisation, -heating, -dissociation, pressure),…
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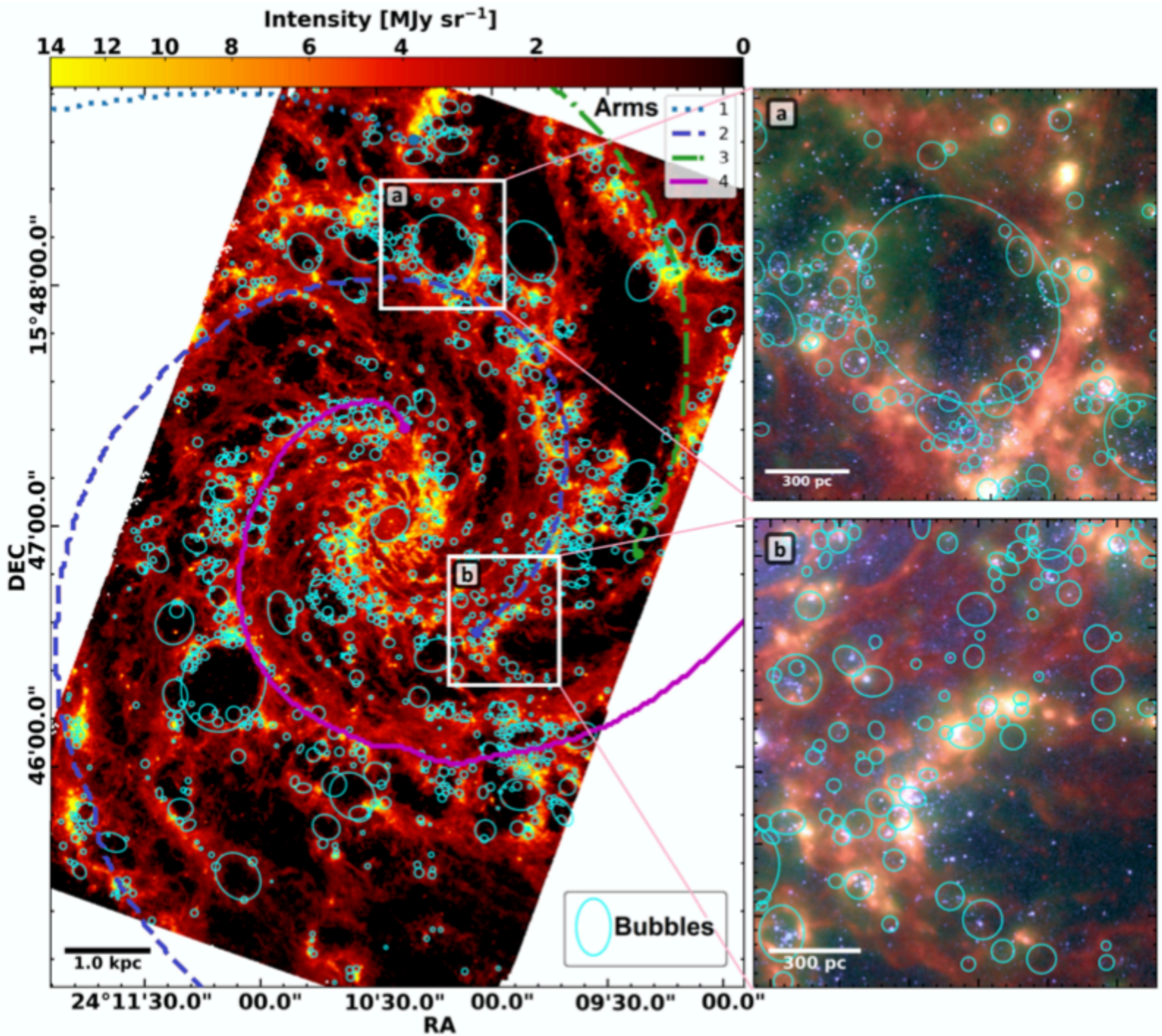
Without sufficient resolution, direct feedback models are at best effective models

- Indirect feedback/implicit/effective models for “low resolution”
  - Effective equation of state/pressure floors, hydro-decoupled winds, stochastic heating feedback, boosted supernova energy…

NGC 628

MIRI F770W

Watkins+23

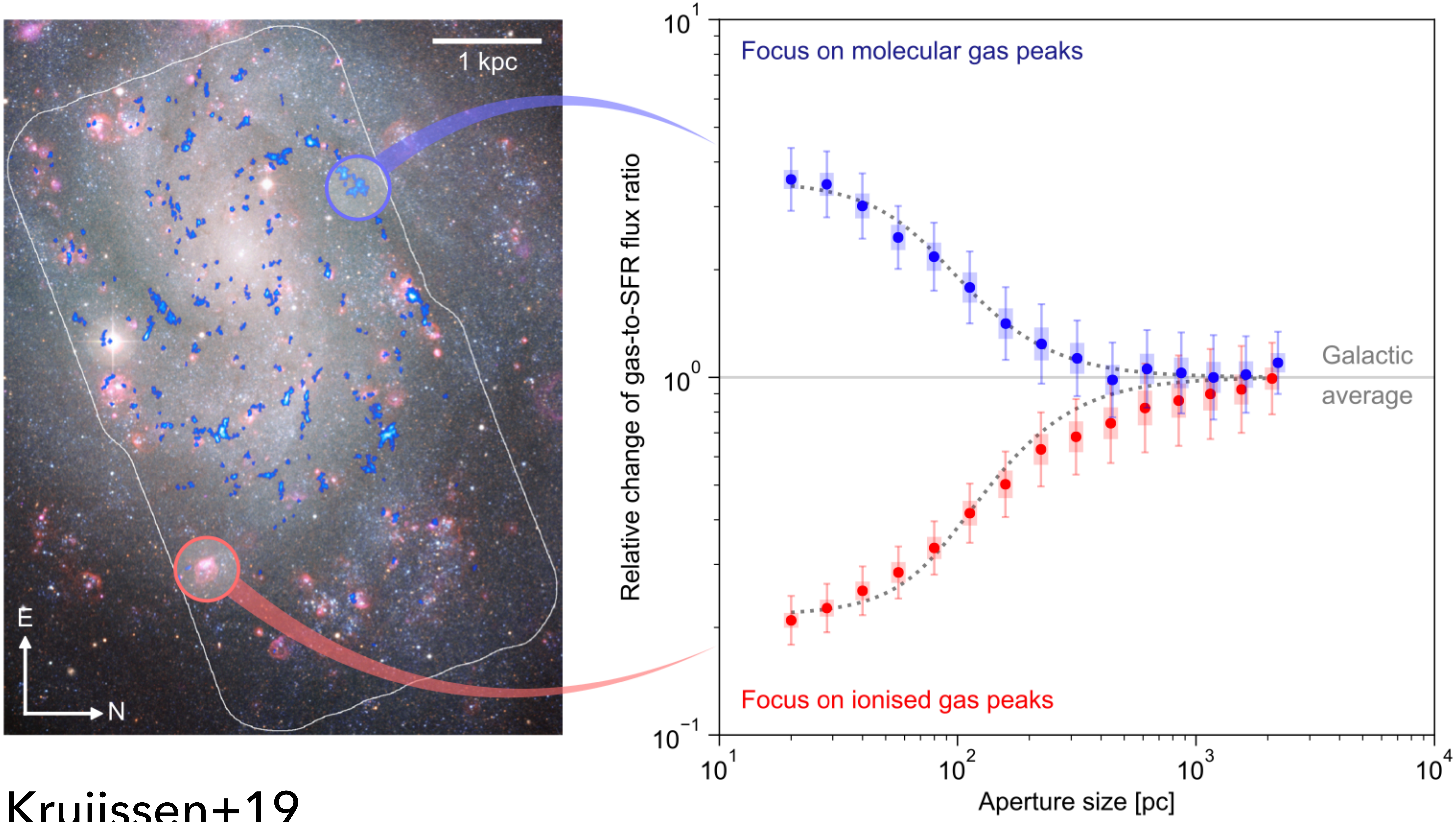


MIRI F770W

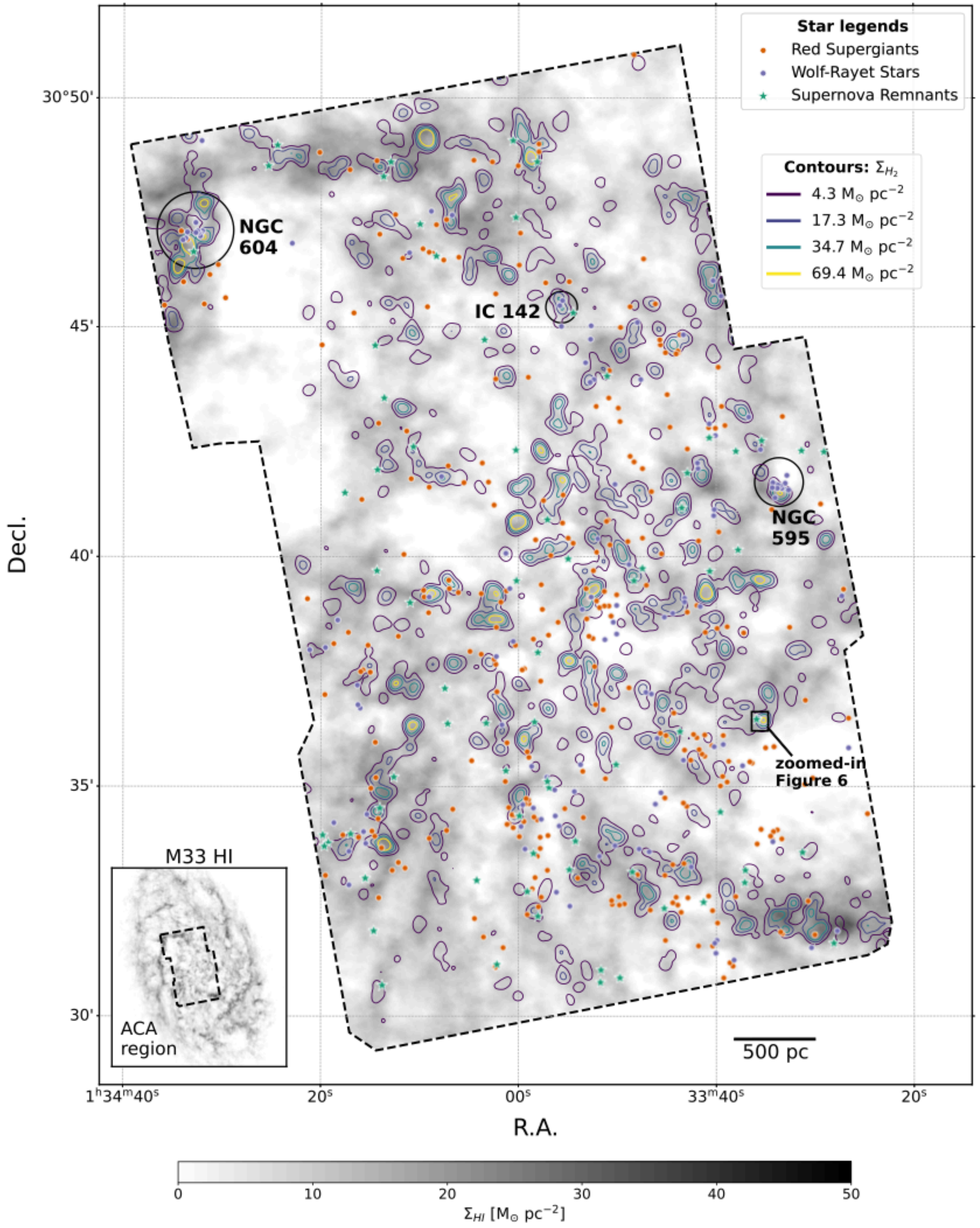
MUSE Hα

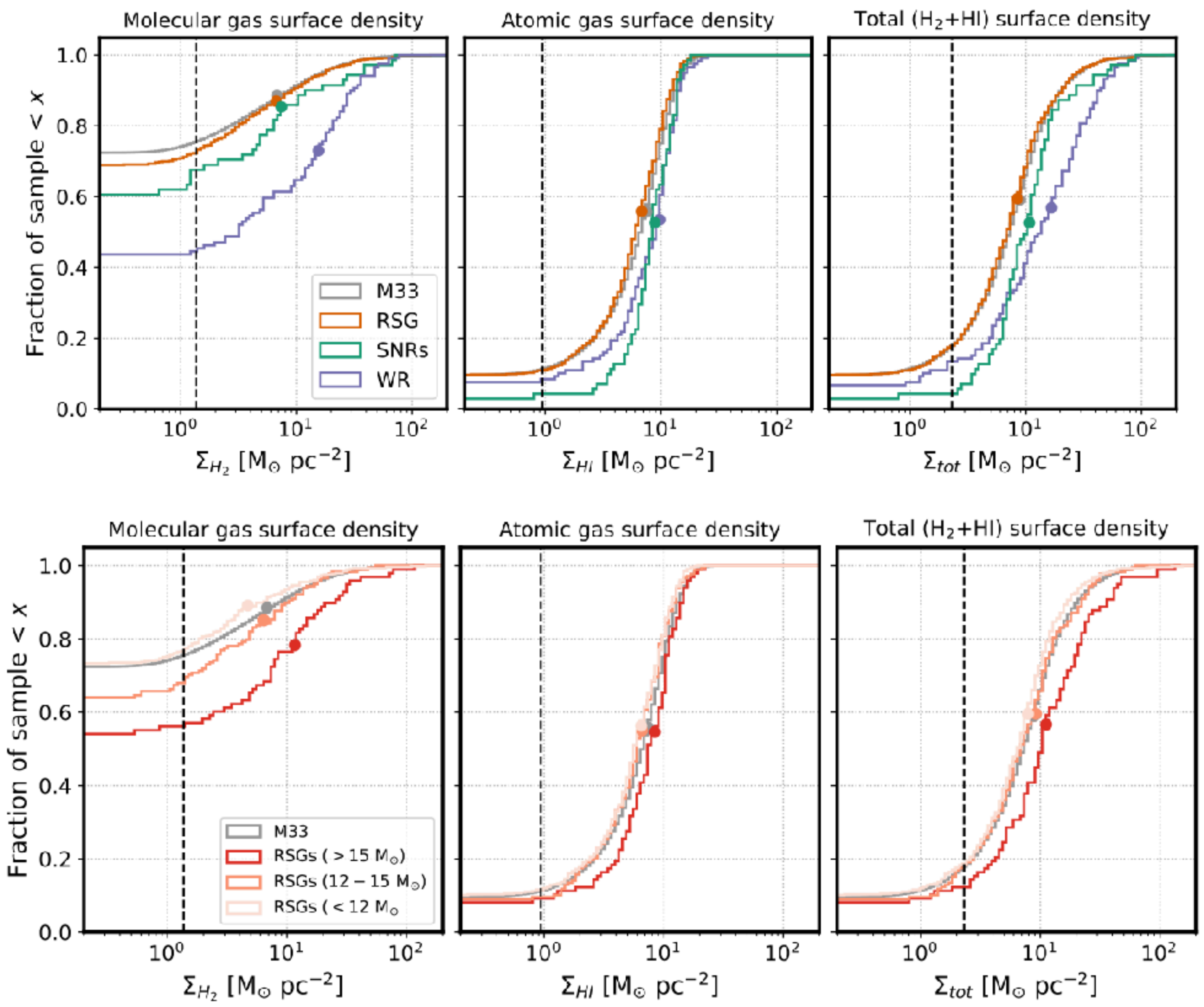
HST B-band

NGC 300

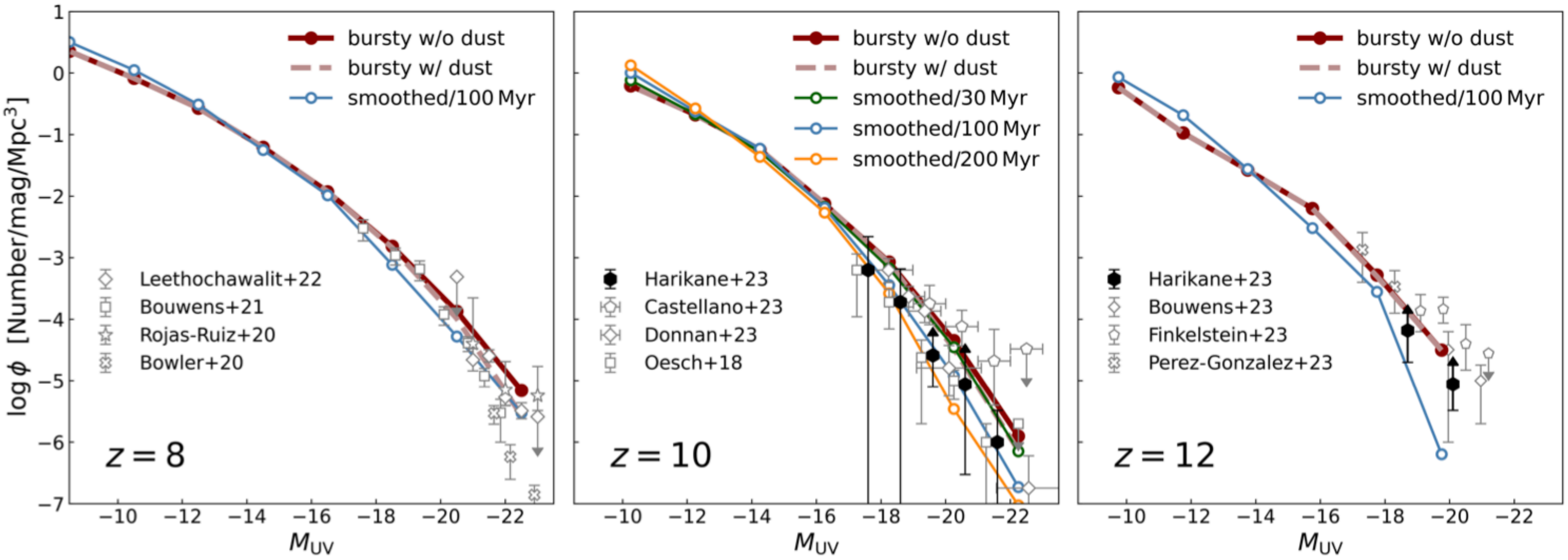


Kruijssen+19





Sarbadhicary+23



bursty w/o dust
bursty w/ dust
smoothed/100 Myr
Leethochawalit+22
Bouwens+21
Rojas-Ruiz+20
Bowler+20
$z = 8$
smoothed/30 Myr
smoothed/200 Myr
Harikane+23
Castellano+23
Donnan+23
Oesch+18
$z = 10$
Bouwens+23
Finkelstein+23
Perez-Gonzalez+23
$z = 12$
$\log \phi$ [Number/mag/Mpc^3]
$M_{\rm UV}$

Sun+23

Models for star formation and direct stellar feedback

- Arepo
- Non-equilibrium cooling (Grackle)
- Supernovae (core collapse and Ia)
- Novel model for overlapping, non-spherical H II regions
- Photoelectric heating with spatially varying FUV radiation field
- Stellar winds
- Stellar masses explicitly sampled from IMF
- Feedback linked to evolution of individual massive stars

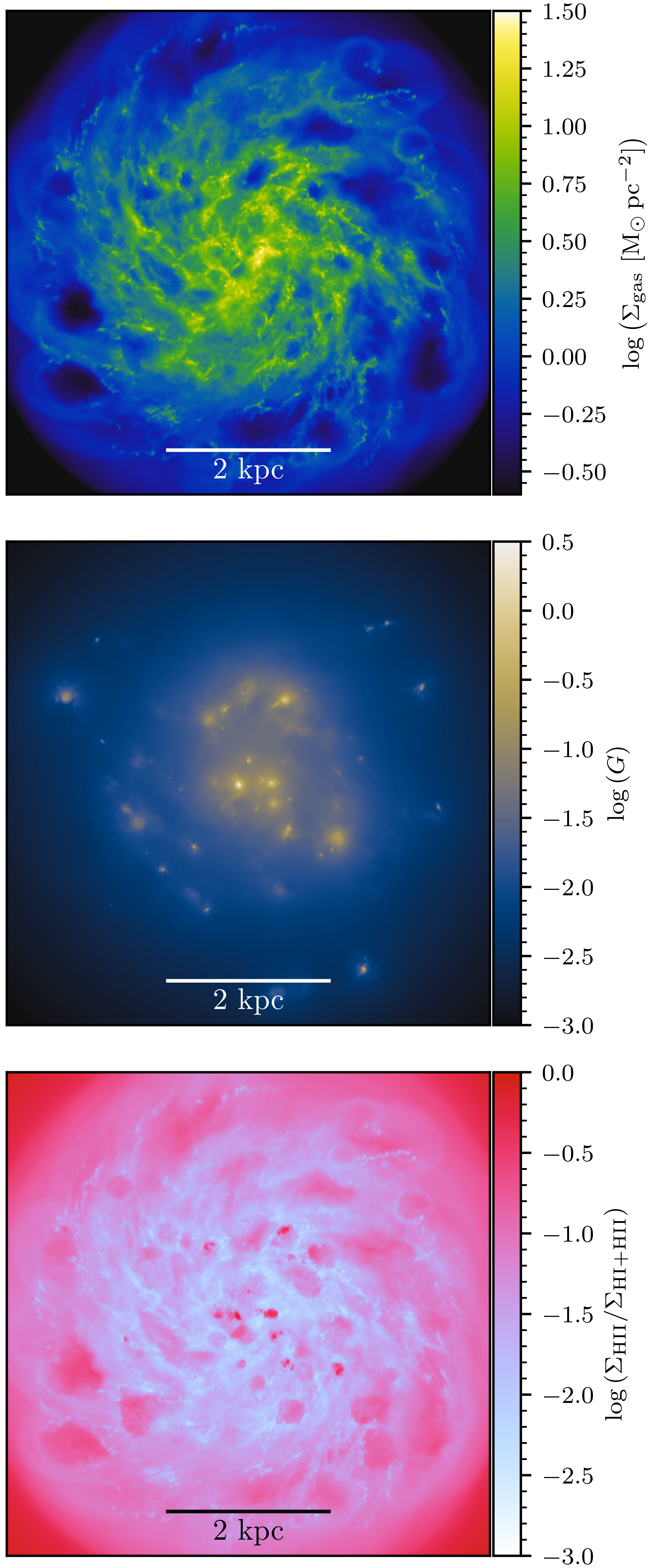
Methods described in:

Smith, Sijacki & Shen 2018

Smith, Bryan et al. 2021

Smith 2021

Smith et al. 2024 in prep.



"WLM", $M_{vir} = 10^{10}\,M_\odot$, $M_{disk,star} = 7\times10^7\,M_\odot$, $M_{disk,gas} = 10^7\,M_\odot$, $m_b = 20\,M_\odot$

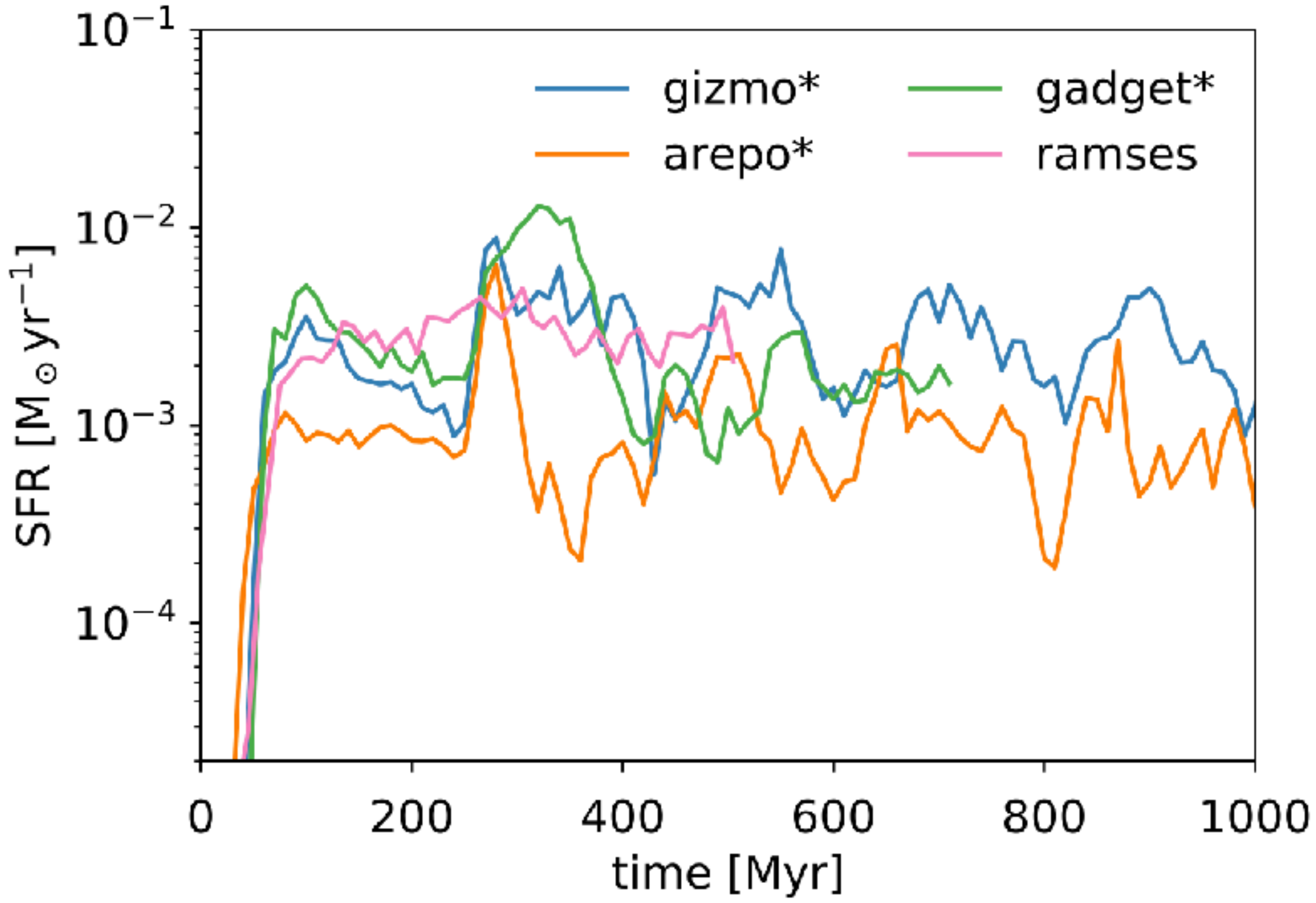
Results may depend on hydro code

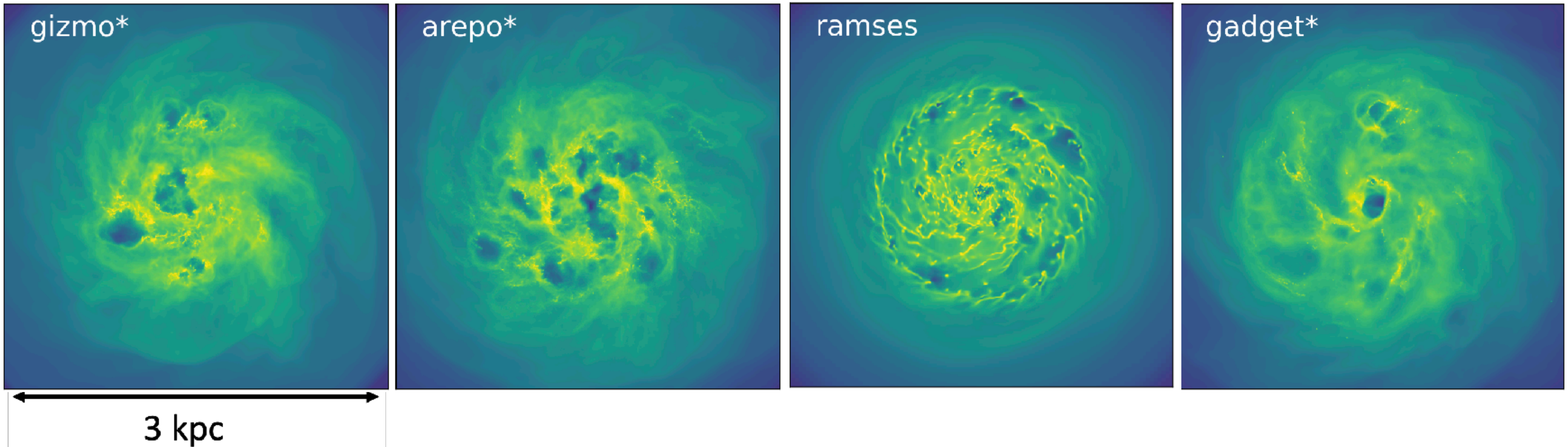
Hu, **Smith**, Teyssier, Bryan+23

High resolution ($12.5\,\mathrm{M}_{\odot}$, 3 pc) code comparison project, supernova feedback only.

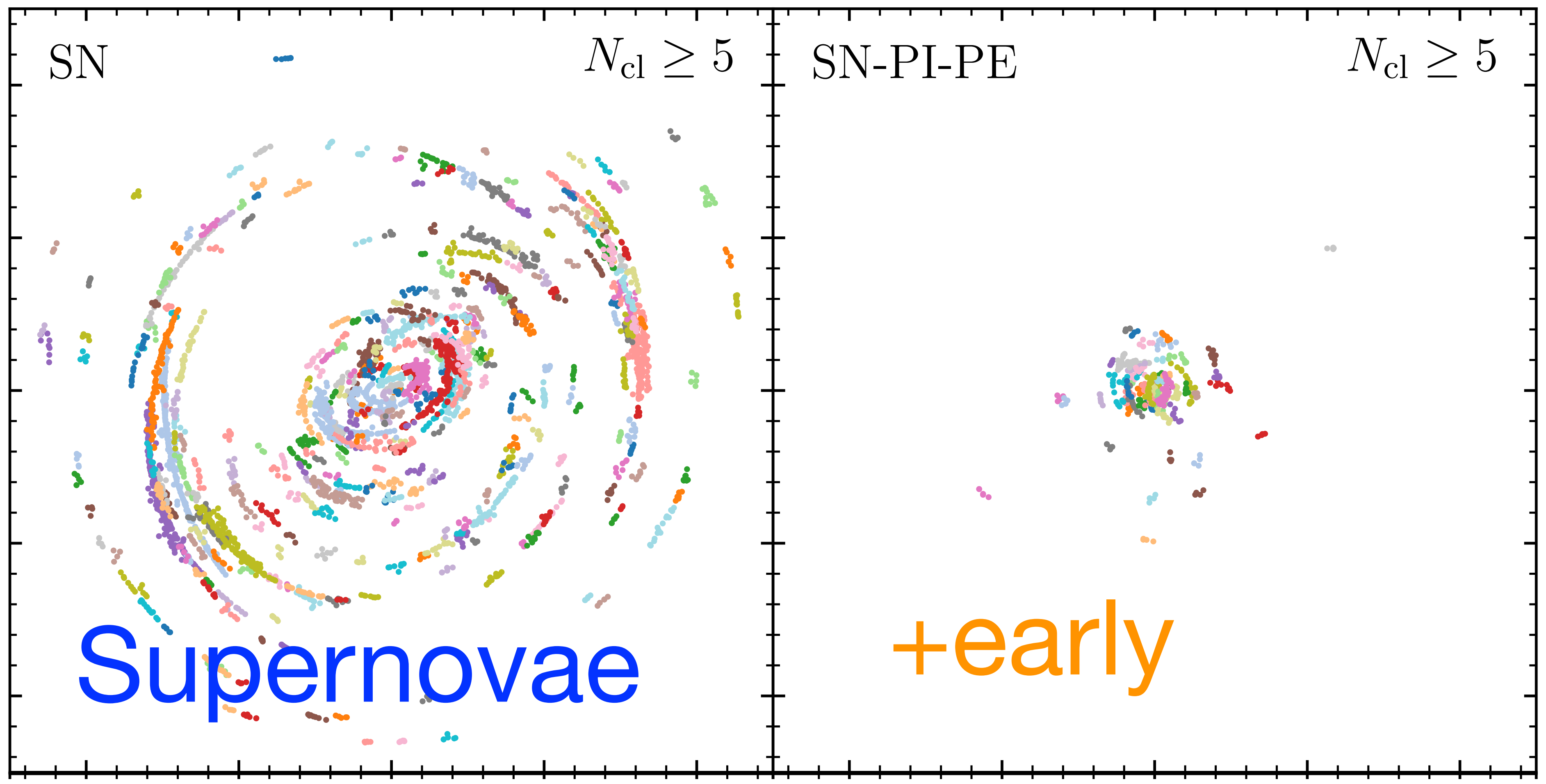
Gizmo, Gadget, Arepo, Ramses

Lagrangian codes may give burstier SFRs



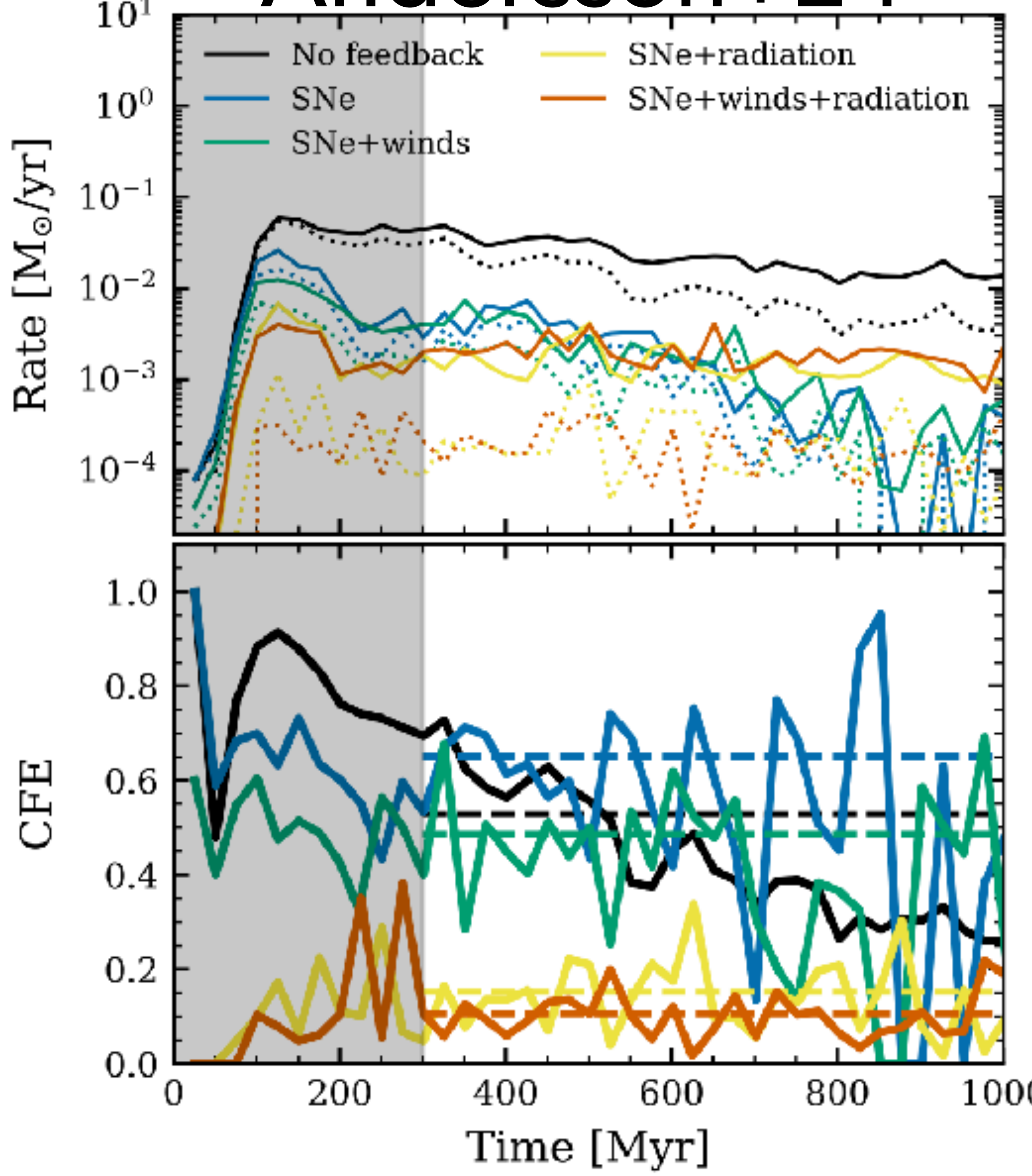


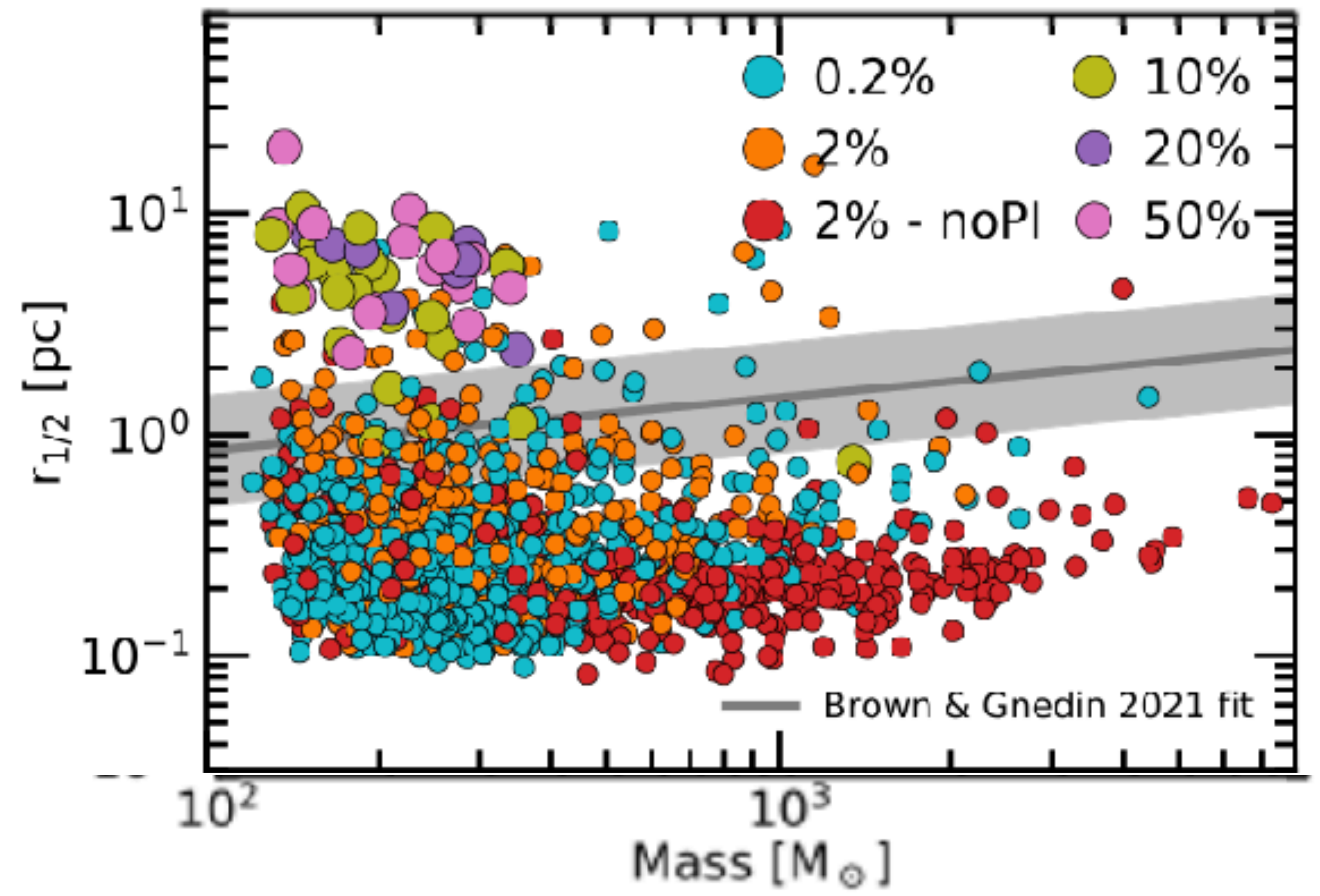

t = 0.50 Gyr
1 kpc
Gas surface density
Temperature
(New) stellar surface density
Mid-plane FUV ISRF
Gas surface density (edge)
Metallicity (edge)
HII regions
Massive stars
CC SNe
Type Ia SNe
Massive stars and SNe



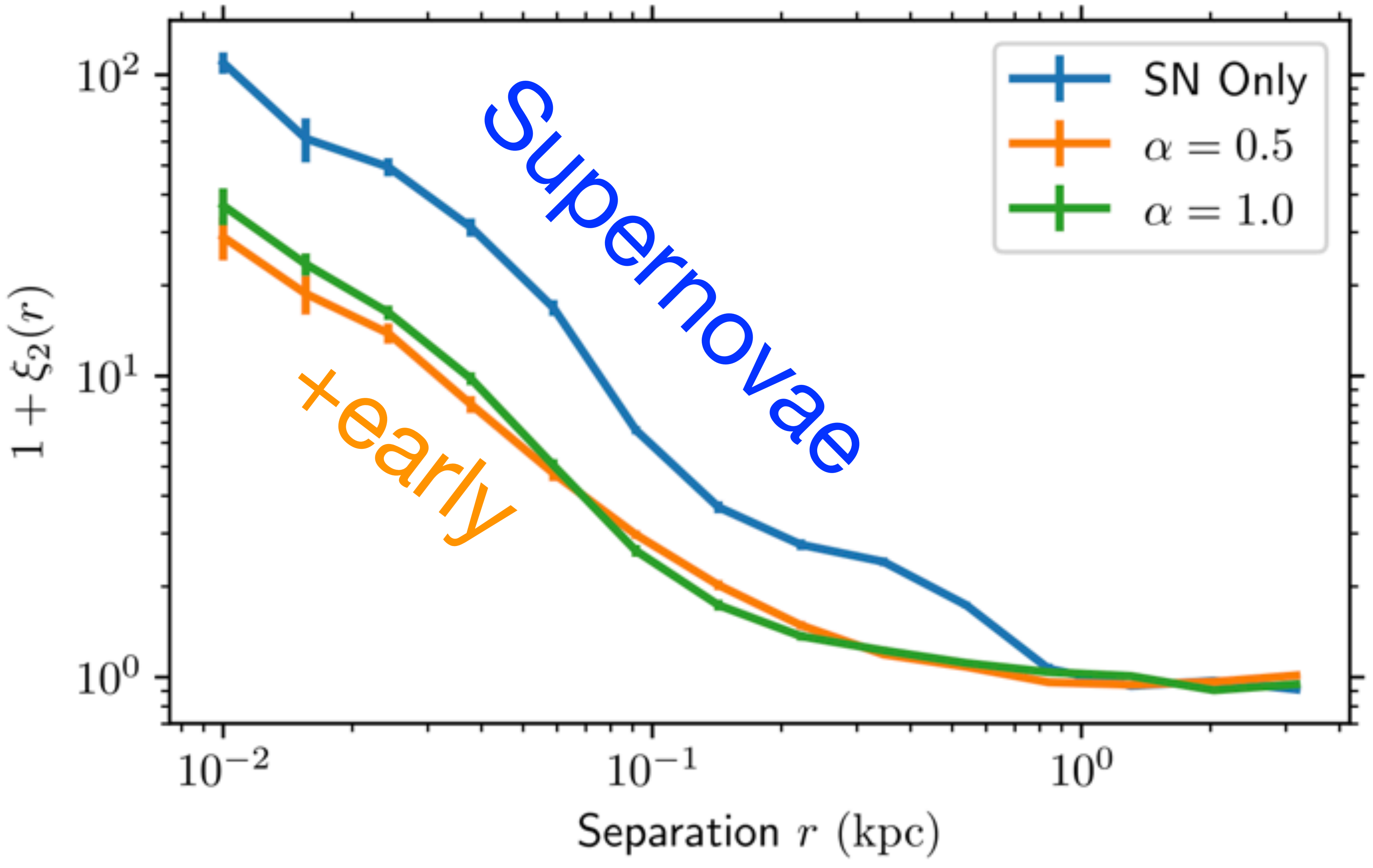
Smith+21

Andersson+24

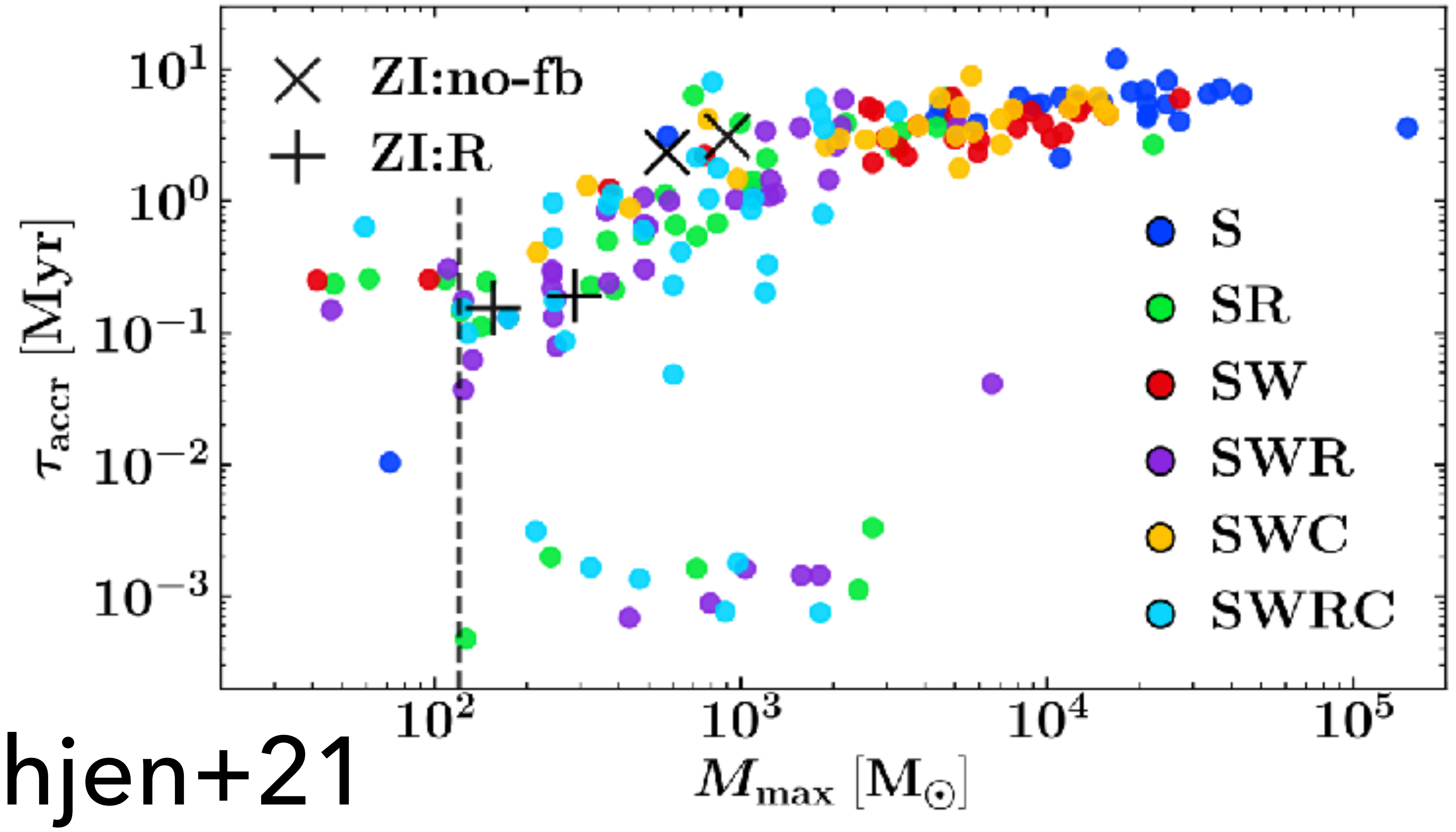




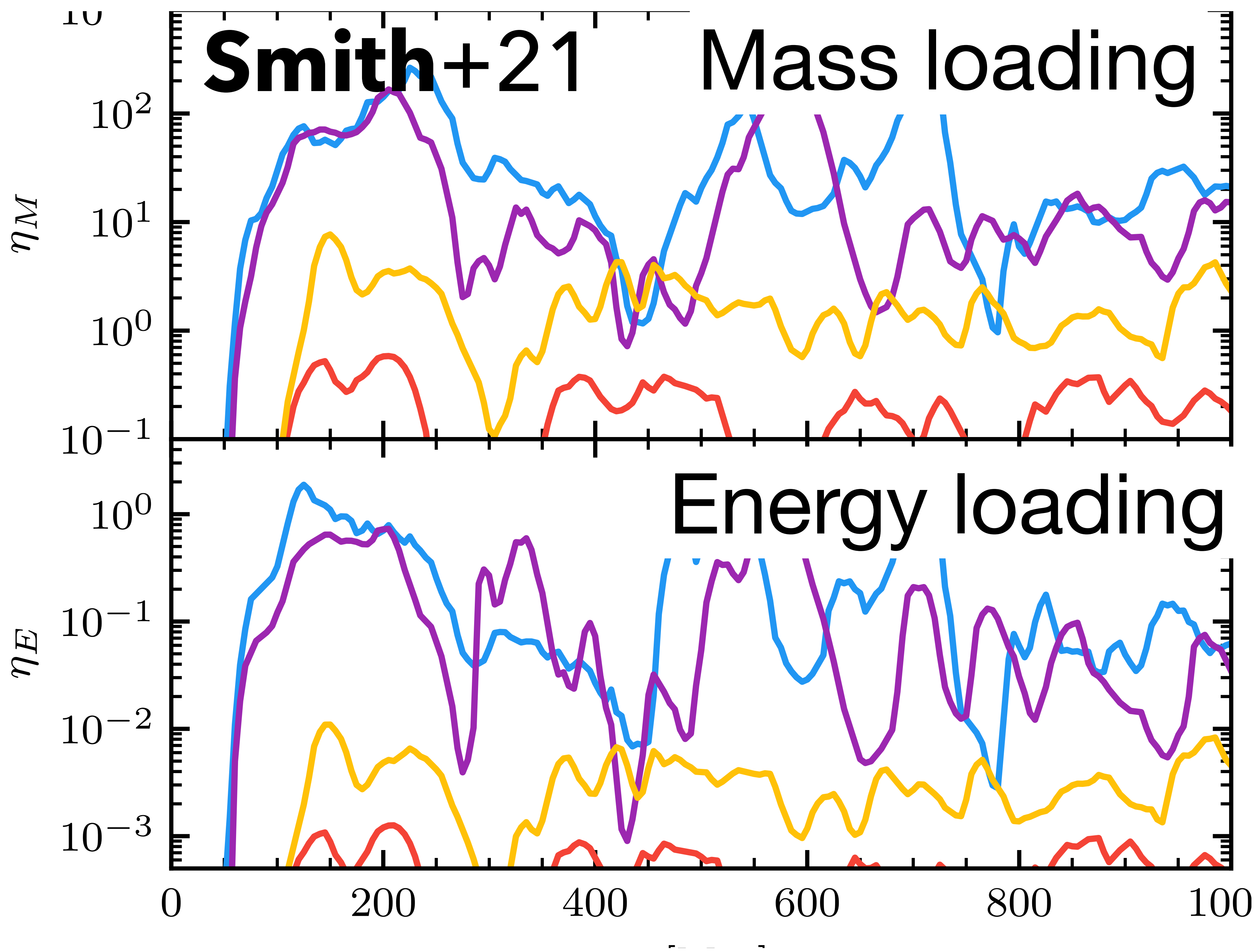
Hislop+22

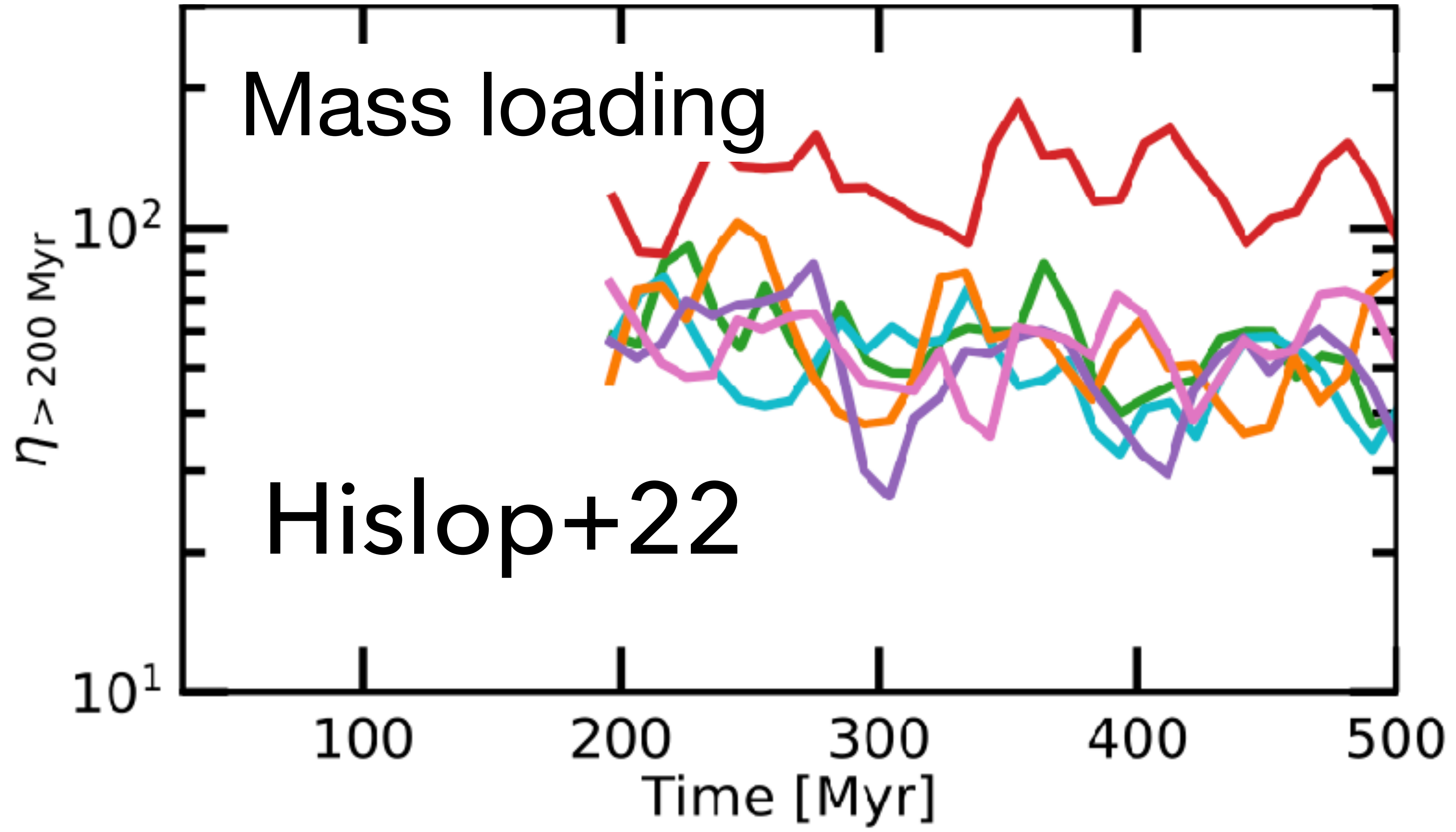


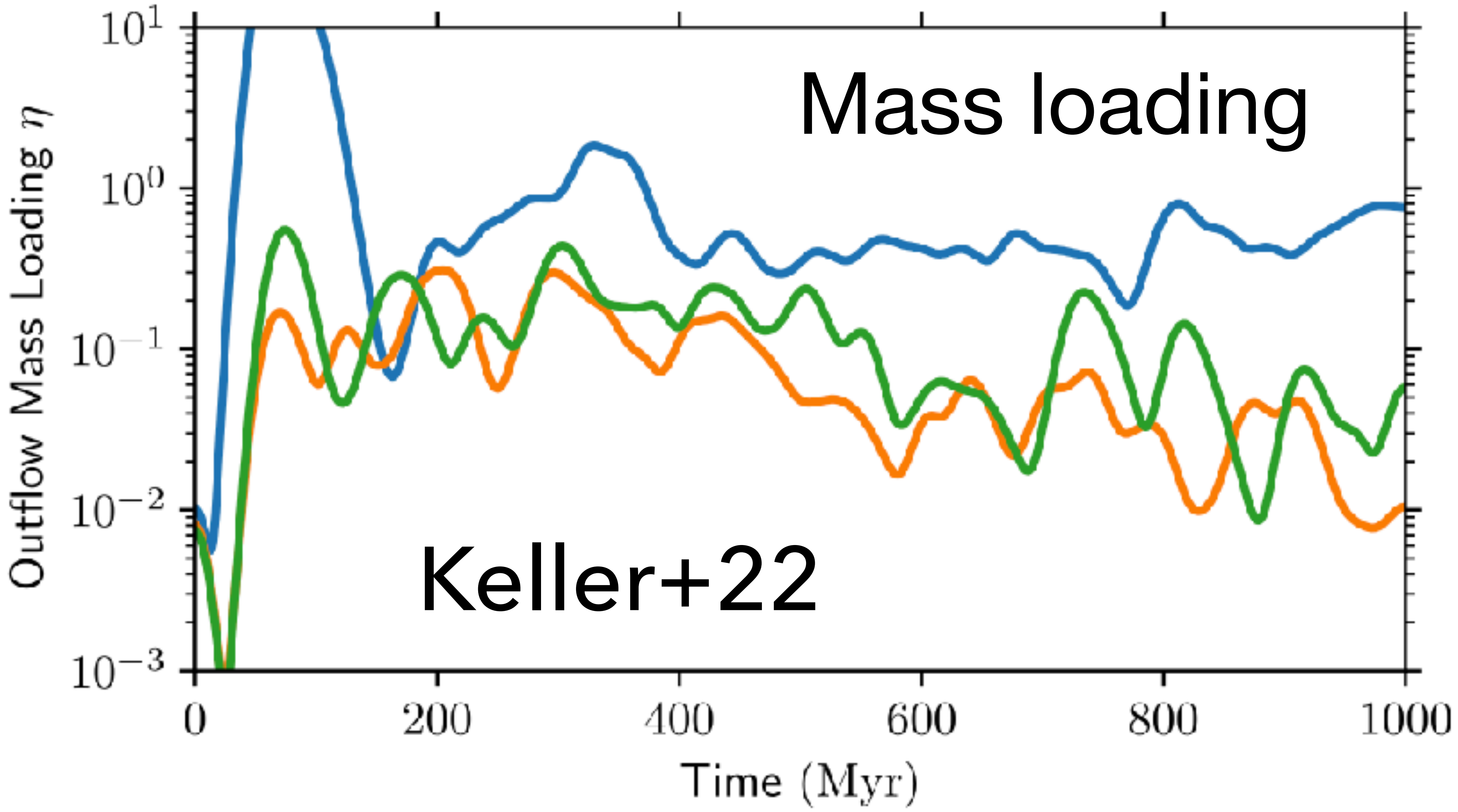
Keller+22

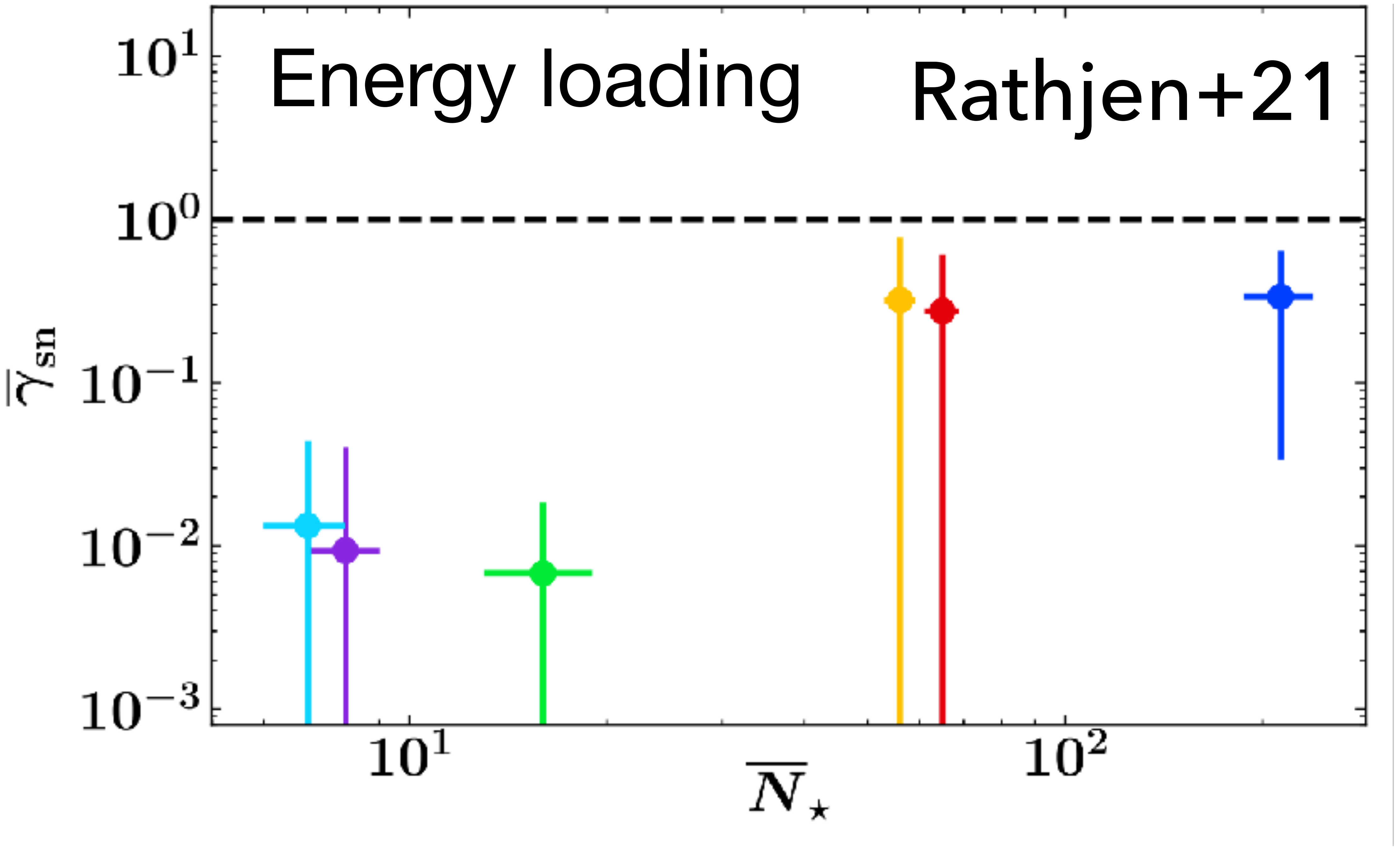


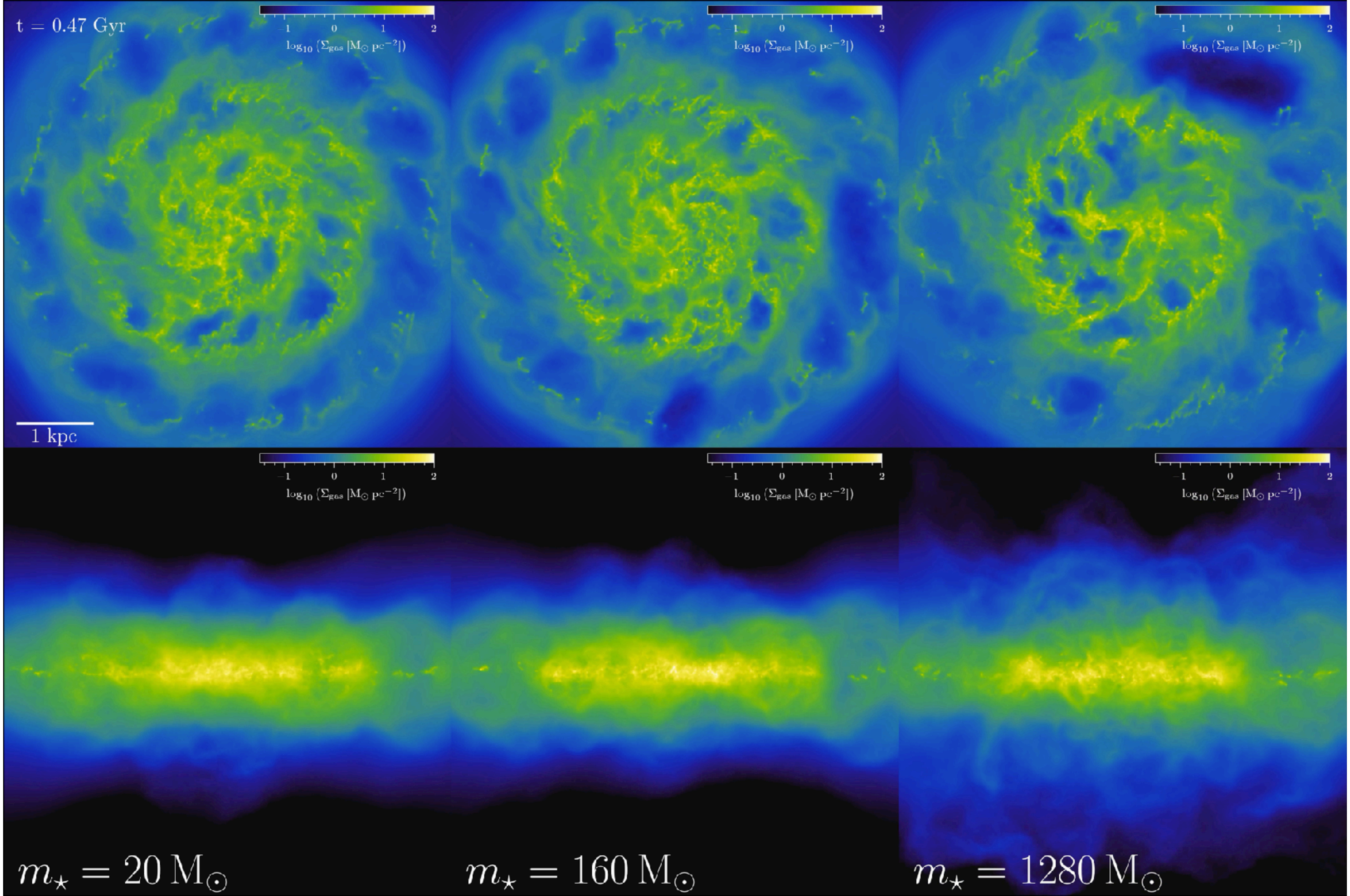
Rathjen+21


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)

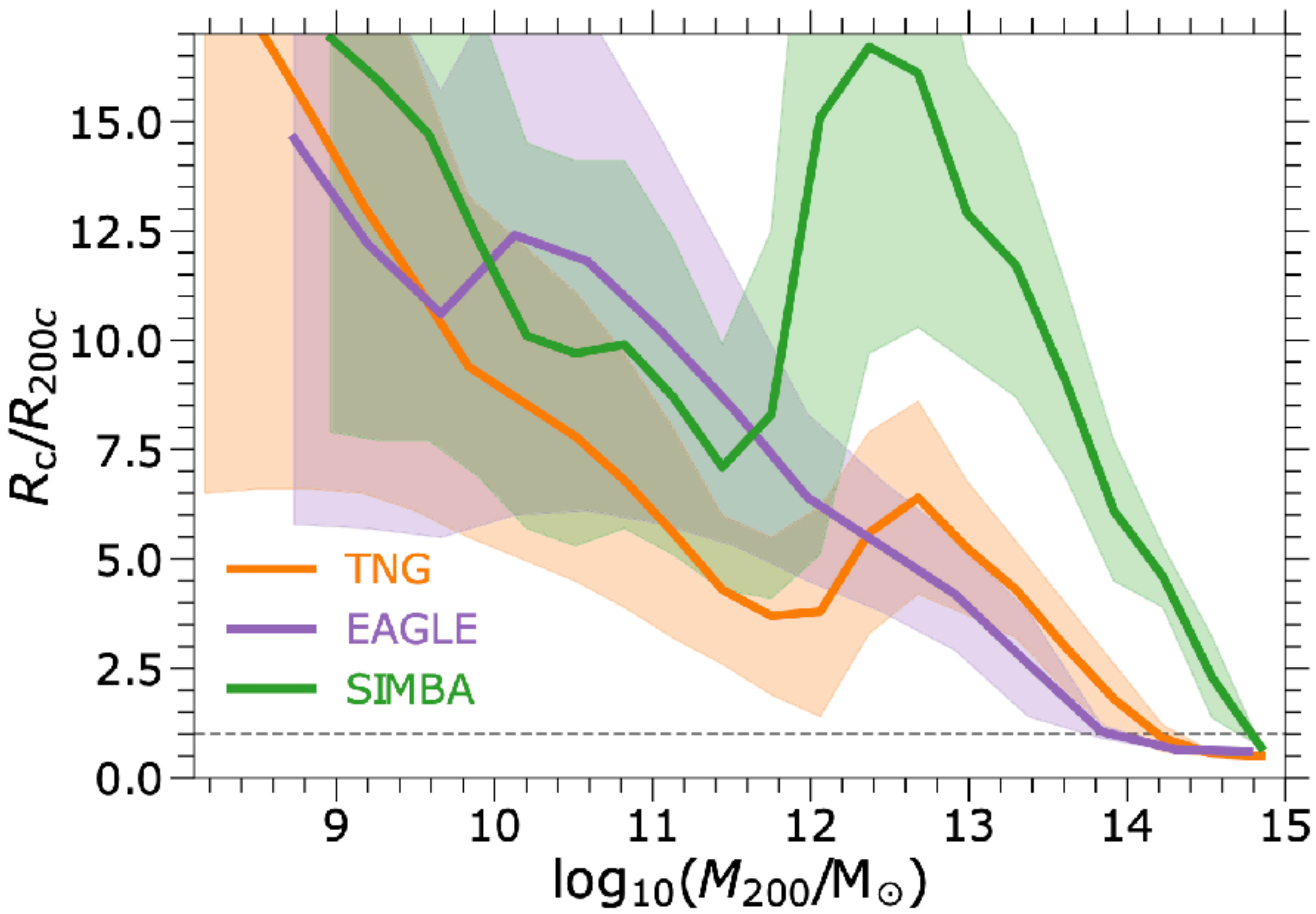

Energy loading
Rathjen+21
$\overline{\gamma}_{\mathrm{sn}}$
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
$\overline{N}_\star$



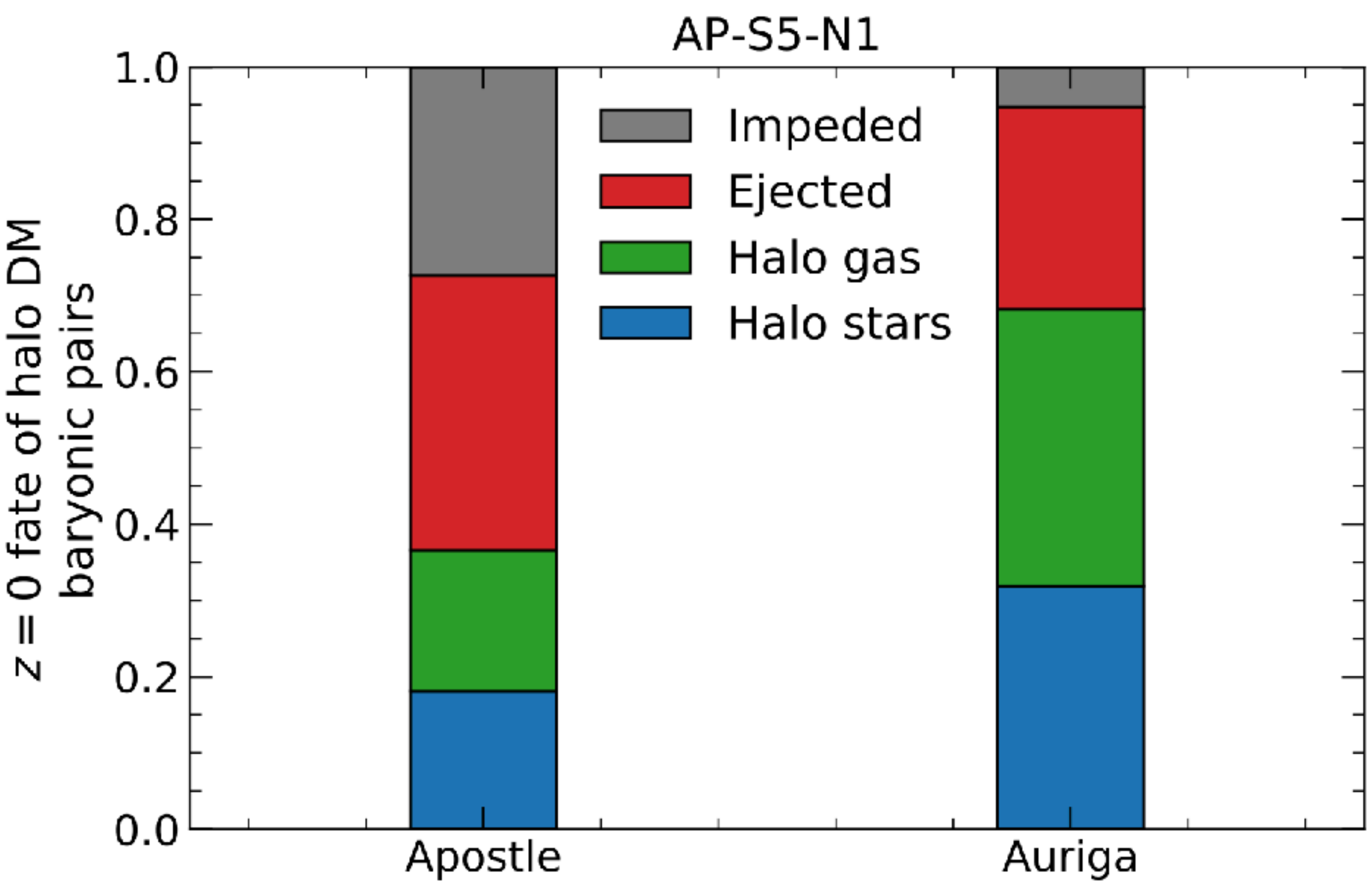
t = 0.47 Gyr
1 kpc
$\log_{10}(\Sigma_{\rm gas}\,[{\rm M_\odot\,pc^{-2}}])$
−1 0 1 2
$m_\star = 20\,{\rm M_\odot}$
$m_\star = 160\,{\rm M_\odot}$
$m_\star = 1280\,{\rm M_\odot}$

Stellar mass resolution requirements

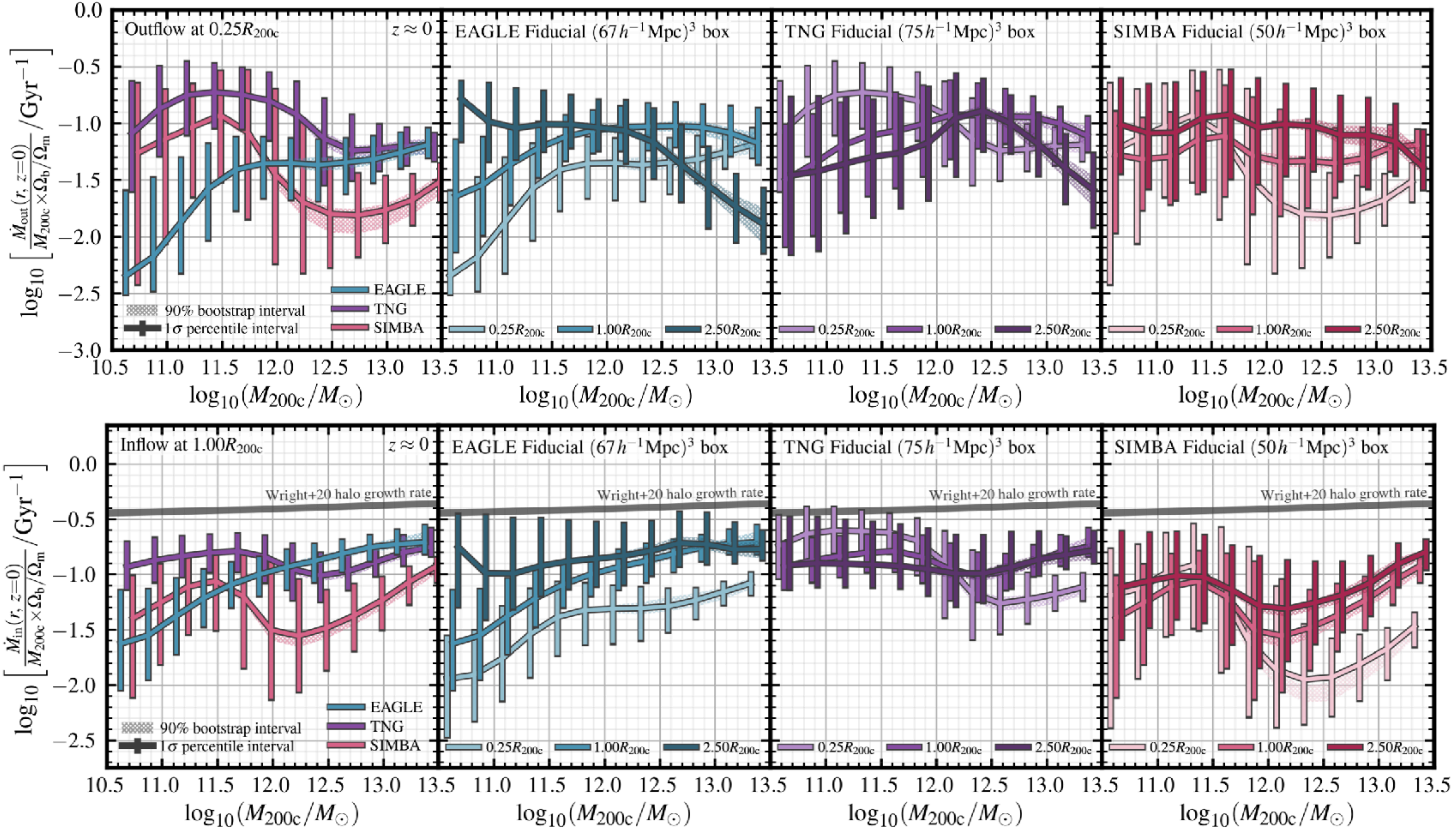
- From IMF, 1 supernova progenitor per $\sim 100\,\mathrm{M}_\odot$ of stars formed.
- Need $100\,\mathrm{M}_\odot$ resolution to a resolve “cluster” of 1 supernova
- The worse the stellar mass resolution, the more numerically overclustered the SNe in space and time
- Outflow mass and energy loadings overestimated, SFR is too bursty.
- Triggering individual SNe from a star particle does not help
    - The SNe progenitors are already safely locked up inside
    - Concentrated pre-SN feedback increases SNe efficiency without penalising clustering



Ayromlou+23



Kelly+22


Outflow at $0.25R_{200c}$
$z \approx 0$
EAGLE Fiducial $(67h^{-1}\mathrm{Mpc})^3$ box
TNG Fiducial $(75h^{-1}\mathrm{Mpc})^3$ box
SIMBA Fiducial $(50h^{-1}\mathrm{Mpc})^3$ box
$\log_{10}\left[\frac{\dot{M}_{\rm out}(r,z=0)}{M_{200c}\times\Omega_b/\Omega_m}/\mathrm{Gyr}^{-1}\right]$
$\log_{10}(M_{200c}/M_\odot)$
EAGLE
TNG
SIMBA
90% bootstrap interval
1σ percentile interval
$0.25R_{200c}$
$1.00R_{200c}$
$2.50R_{200c}$
Inflow at $1.00R_{200c}$
Wright+20 halo growth rate
$\log_{10}\left[\frac{\dot{M}_{\rm in}(r,z=0)}{M_{200c}\times\Omega_b/\Omega_m}/\mathrm{Gyr}^{-1}\right]$

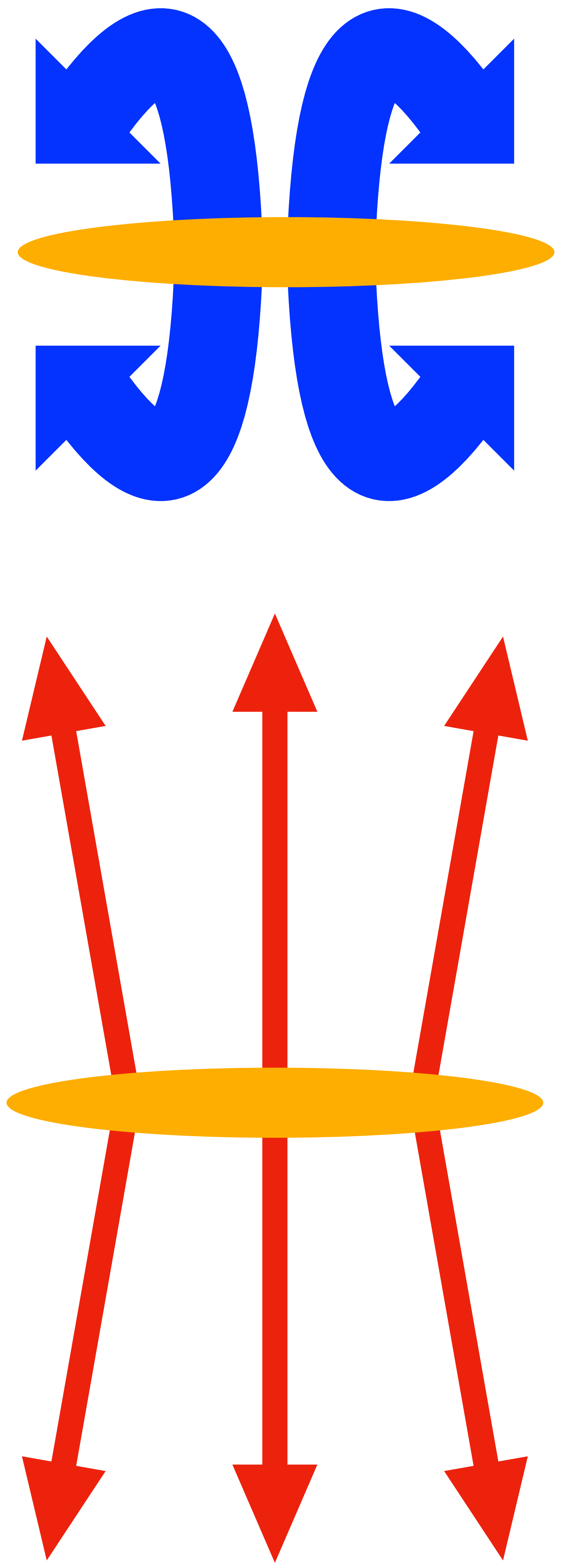
Wright+24

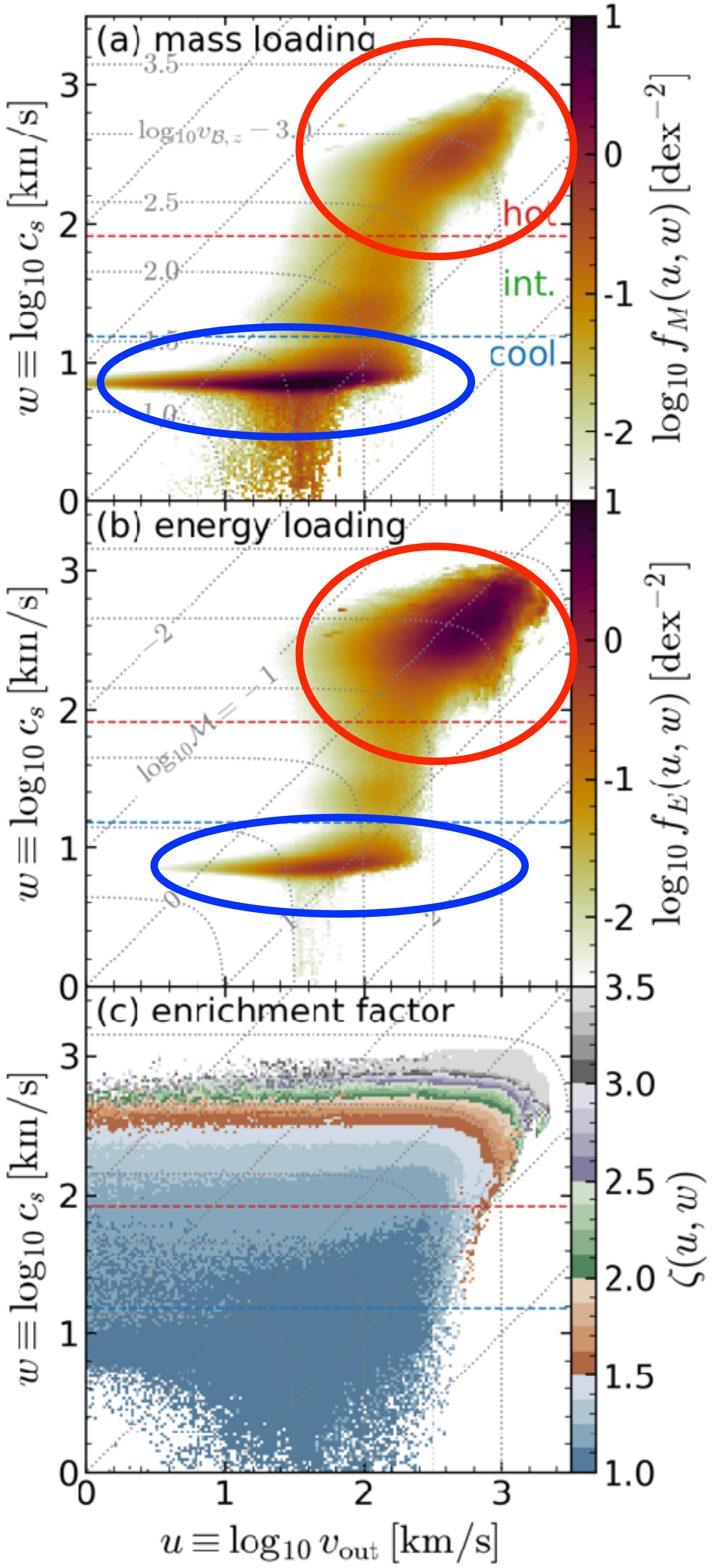
Multiphase outflows

Resolved ISM simulations produce highly multiphase outflows

Mass loading dominated by cold/warm slow moving material

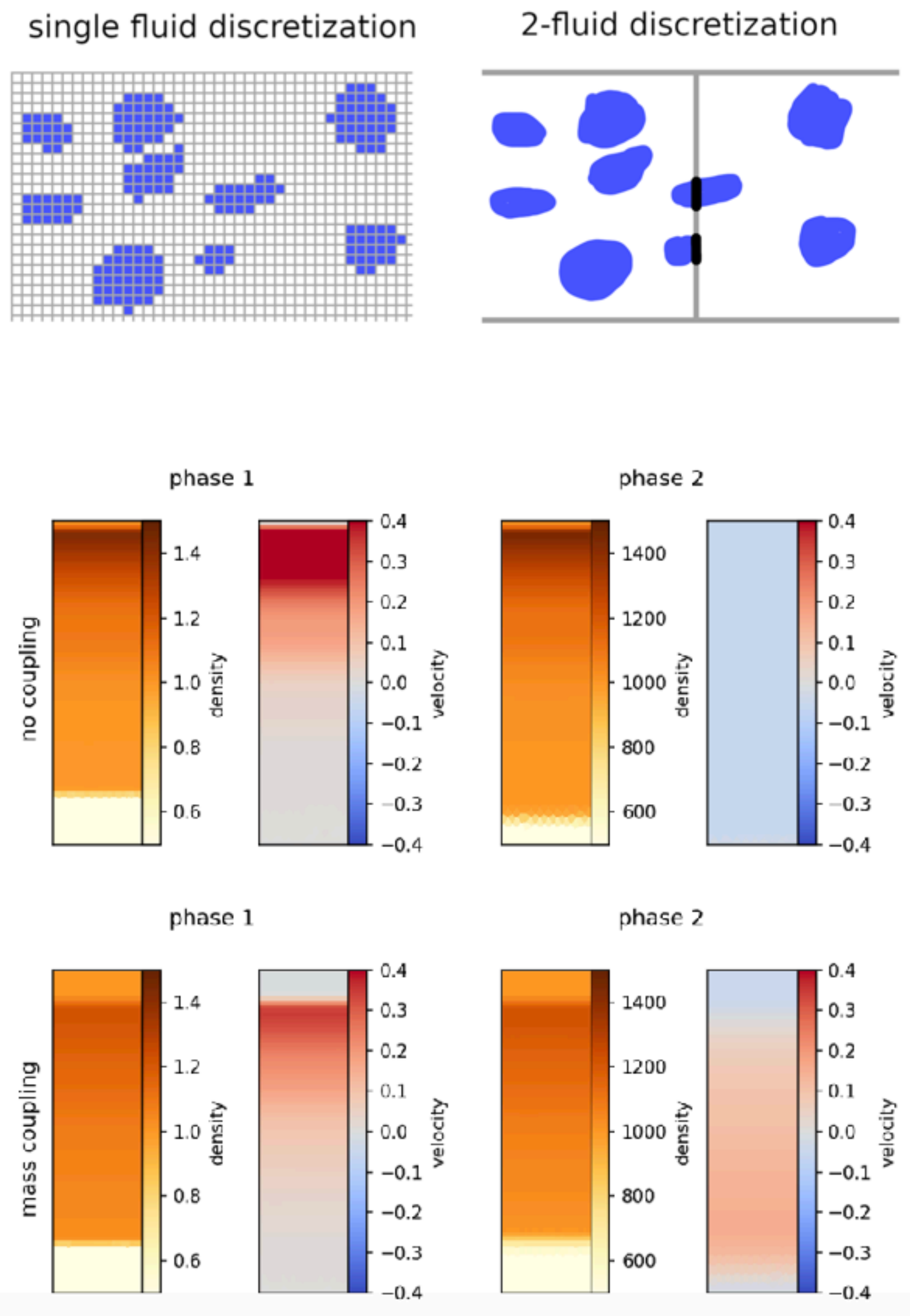
Energy loading dominated by hot, fast, metal enriched outflow



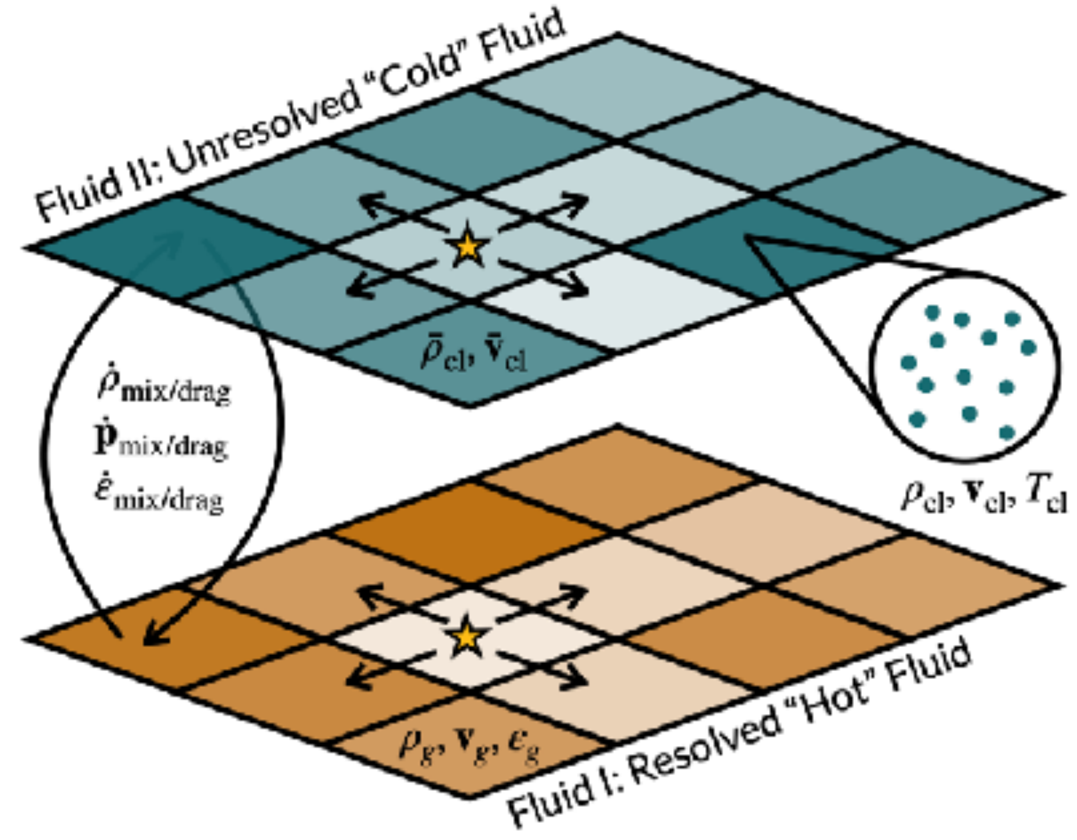


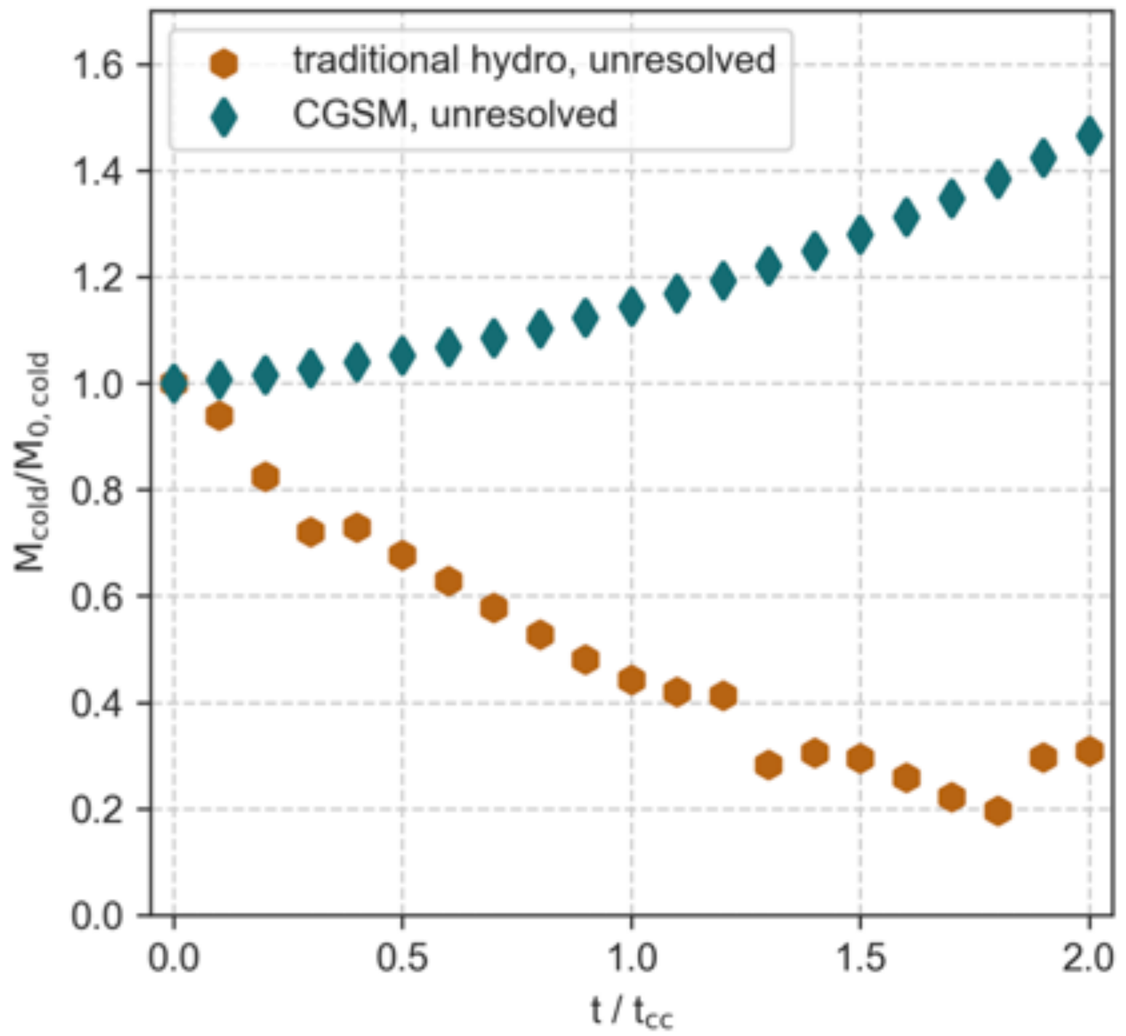
Kim+2020

Weinberger & Hernquist 23

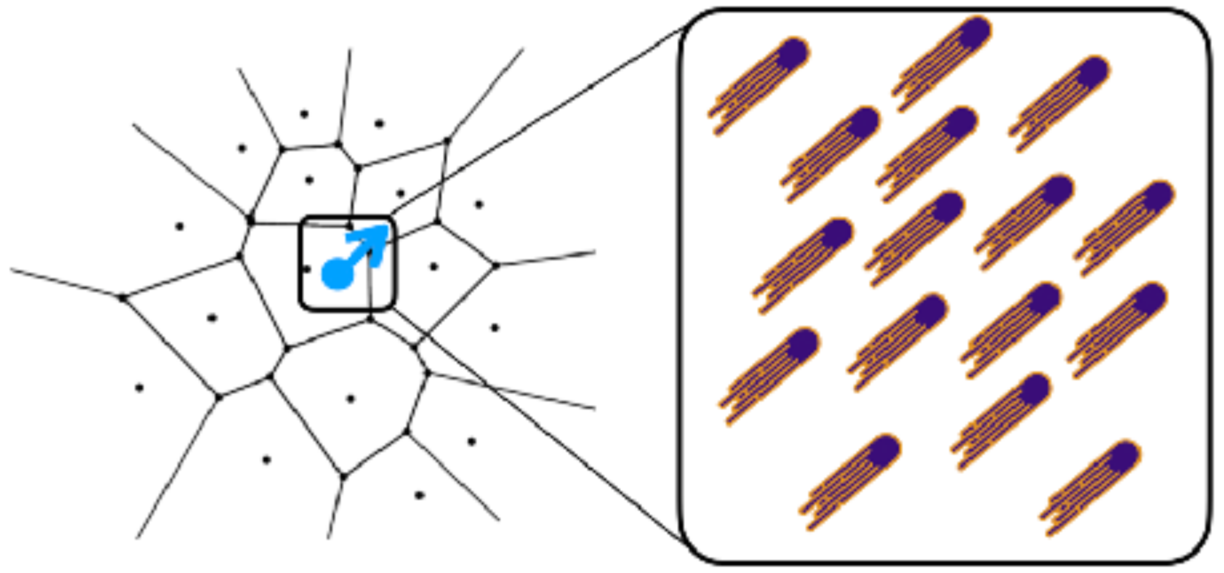


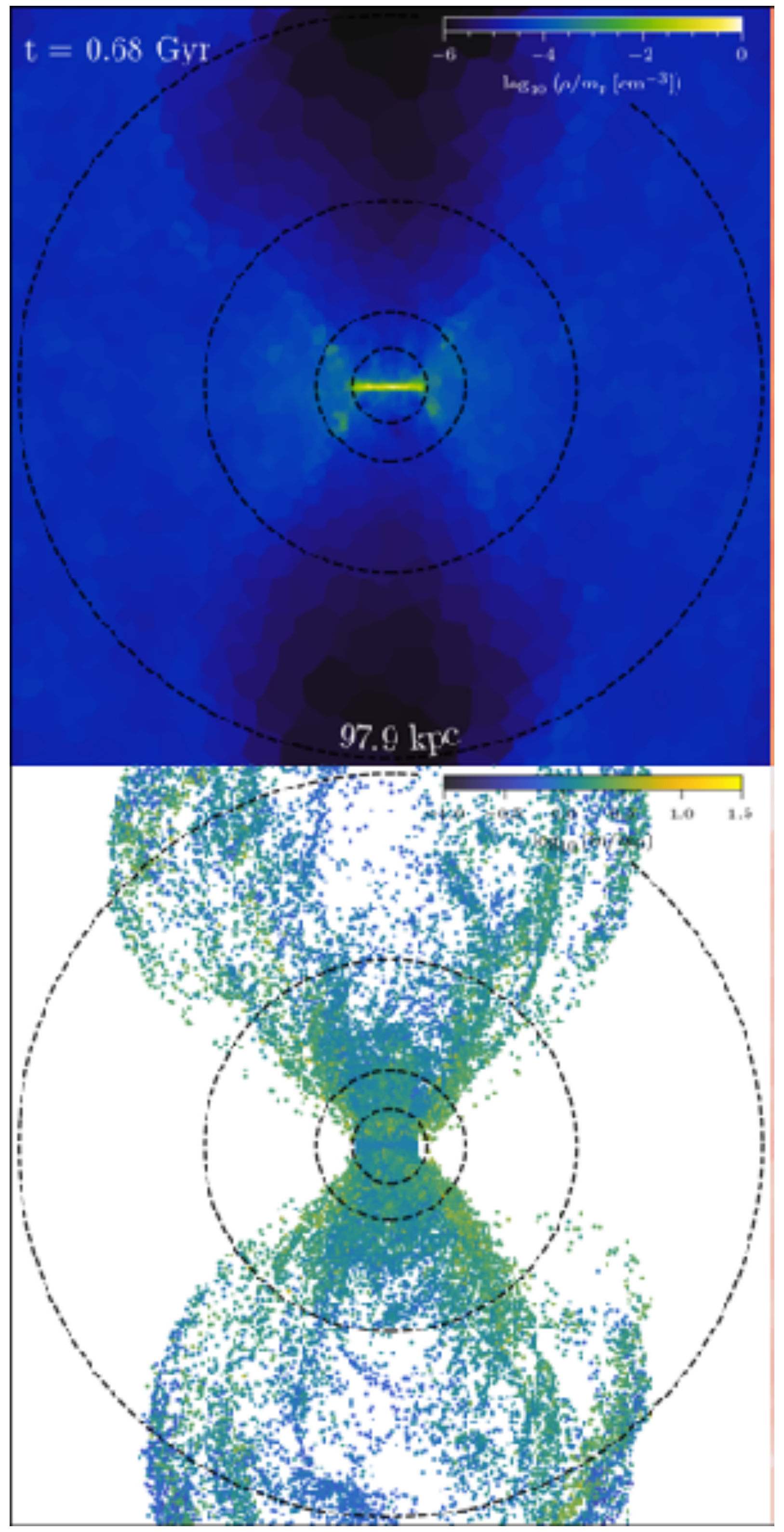
Butsky+24

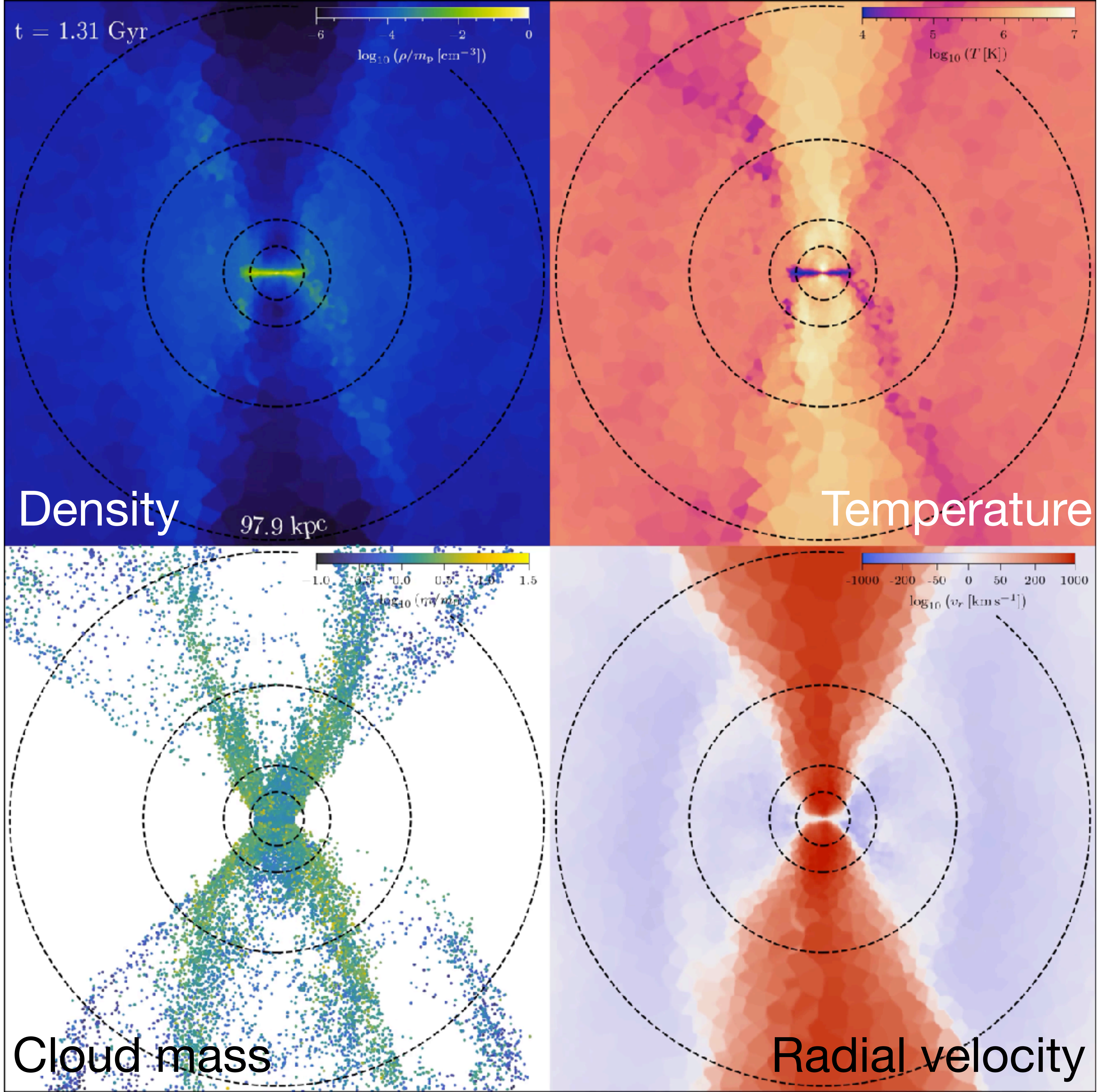




Smith, Fielding, Bryan+24a
Smith, Fielding, Bryan+24b in prep.







Arkenstone

Smith, Fielding, Bryan+24b in prep.

Hot wind component:

$\eta_M = 0.32, \eta_E = 0.9$

Cold wind component:

$\eta_M = 1, \eta_E = 0.01$

$m_{\mathrm{cl0}} = 10^3\,\mathrm{M}_\odot$

Summary

- With simulations with "resolved" direct stellar feedback, we can interpret observational results for feedback clustering and SFR burstiness
  - Caveat: Very high resolution needed to natively capture clustering (~1 massive star per star particle -> 100 $M_\odot$). Resolution requirements to capture interaction with ISM equally (or more) strenuous.
  - Can't afford "star by star" in most galaxies, how do we compensate for this?
- Producing "sensible" galaxies at poor resolution is now achievable with indirect/effective feedback models. But how do we learn?
  - CGM properties and outflow/inflow analysis are useful discriminants. But resolution limitations on how we can inject feedback might be biasing our view of the baryon cycle?
  - A focus on multiphase physics might provide a path.