Galactic Winds in TIGRESS*

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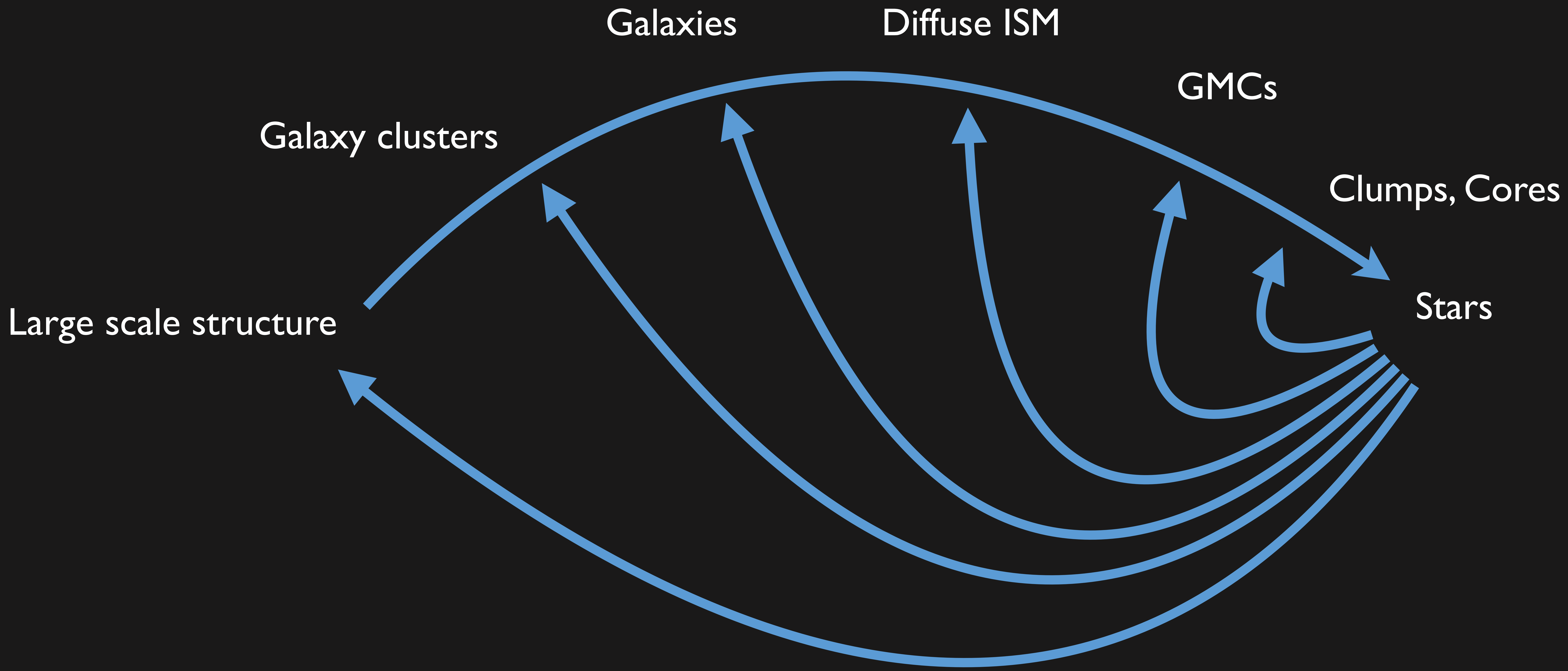
*Three-phase ISM in Galaxies Resolving Evolution with Star formation and Supernova feedback

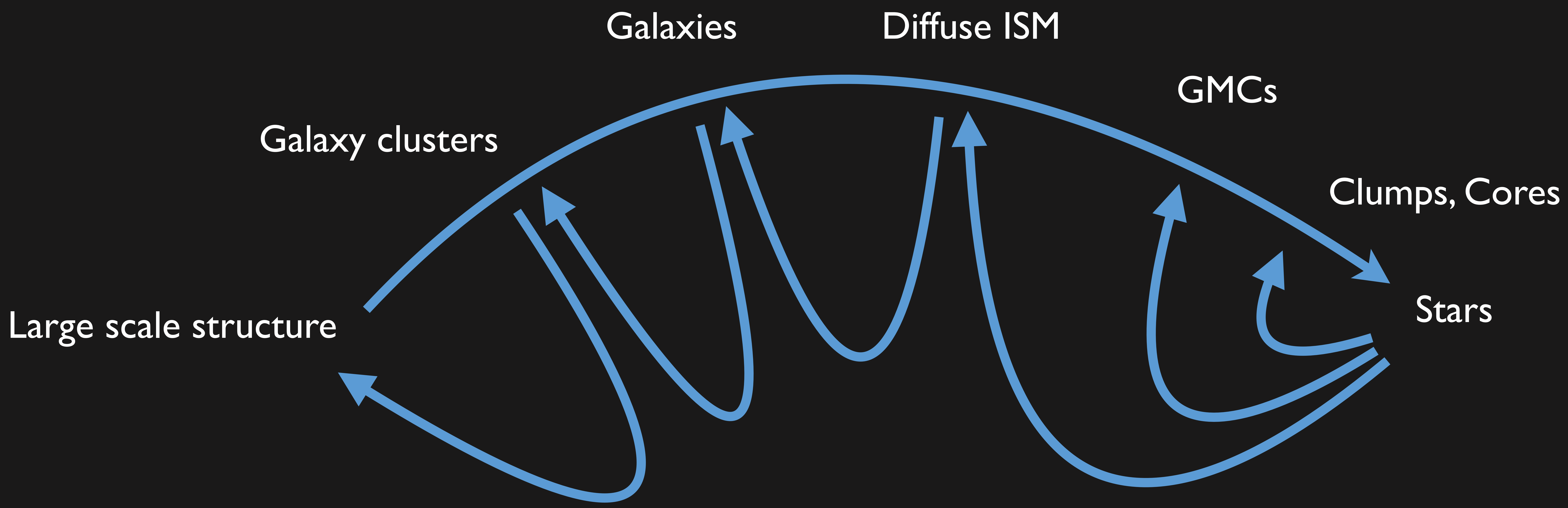
PRINCETON UNIVERSITY
FLATIRON INSTITUTE


Chanda/HST/Herchel
(G34.7-0.4)
Chanda/HST/Spitzer
GALFA-HI/J. Peek
DORADUS
CHANDRA X-RAY OBSERVATORY
HST
ESO/G. Beccari


Chanda/HST/Herchel
Chanda/HST/Spitzer
GALFA-HI/J. Peek
Stellar Feedback
(G34.7-0.4)
ISM evolution
Star Formation
HST
ESO/G. Beccari
DORADUS
CHANDRA X-RAY OBSERVATORY

To model a *feedback-loop (not an open-ended chain)*,
we need self-consistent simulations


Galaxies
Diffuse ISM
GMCs
Galaxy clusters
Clumps, Cores
Stars
Large scale structure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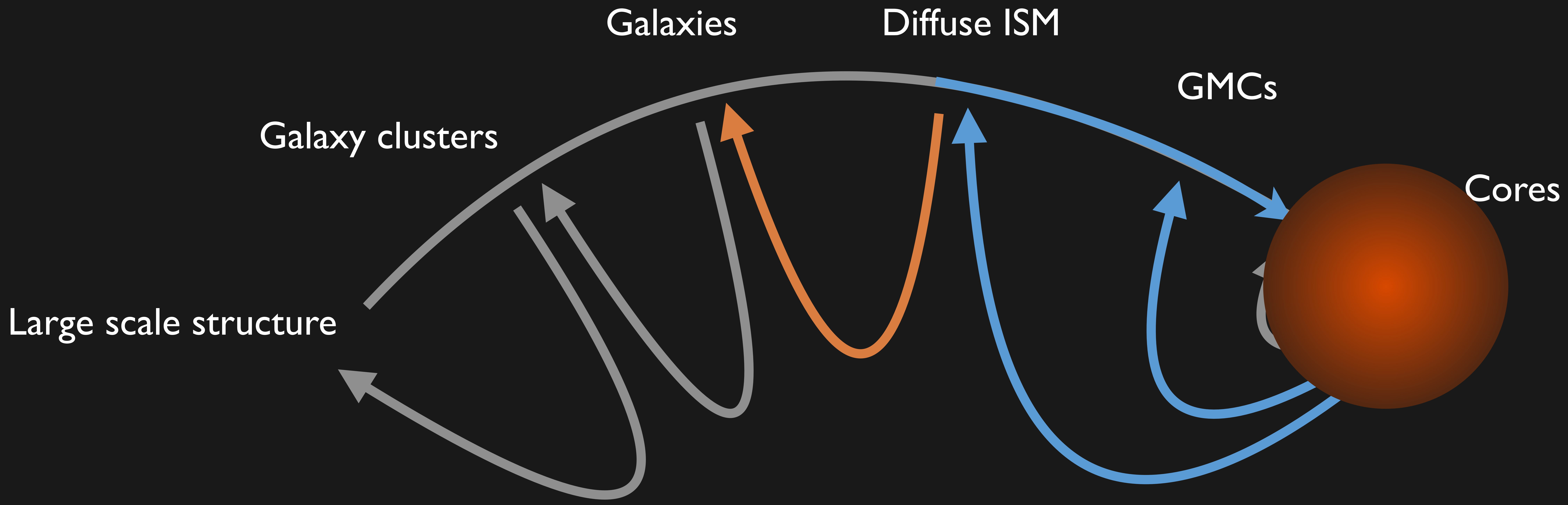
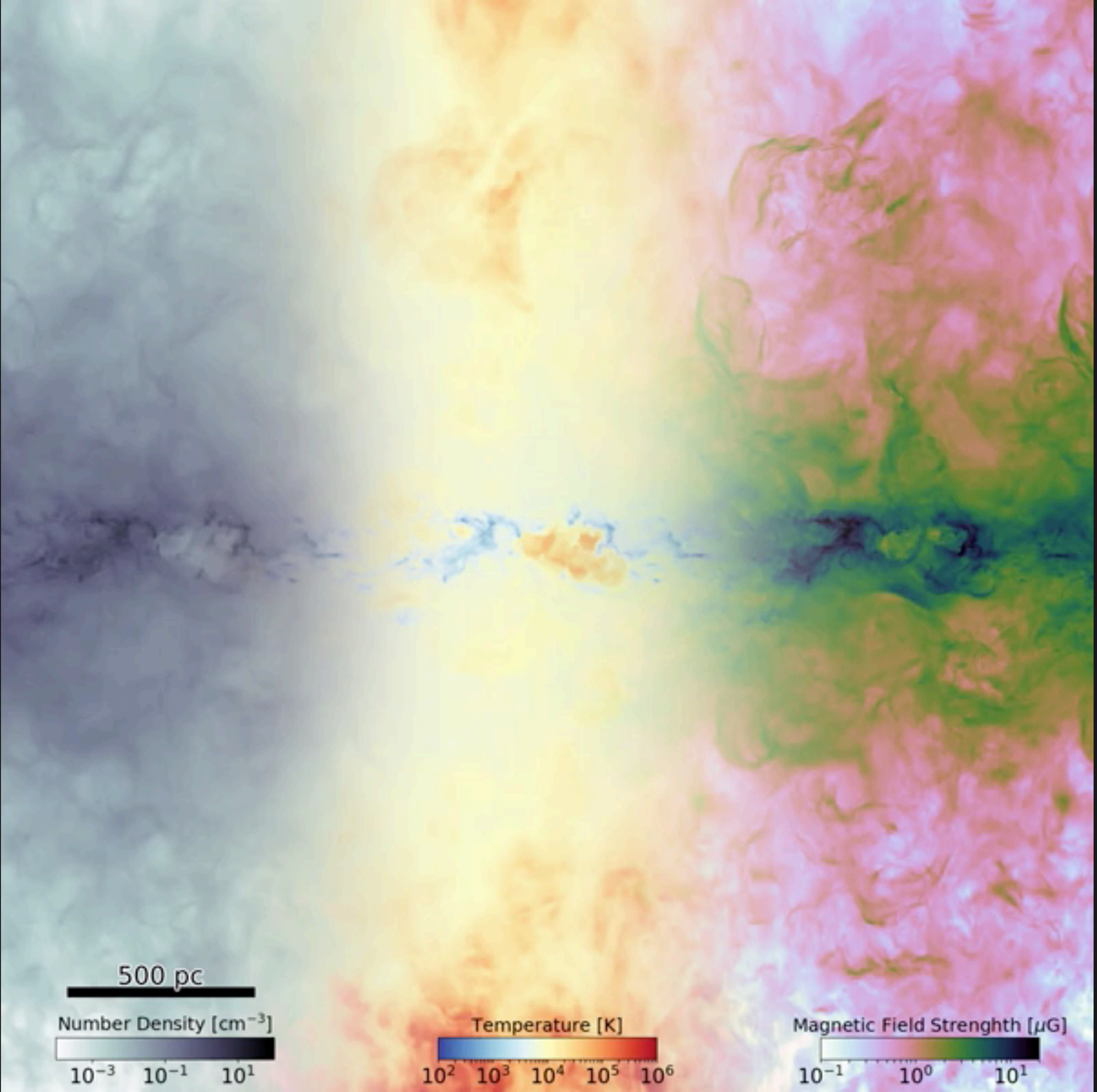

Galaxies
Diffuse ISM
GMCs
Galaxy clusters
Cores
Large scale structure


Chanda/HST/Herchel
Chanda/HST/Spitzer
GALFA-HI/J. Peek
Stellar Feedback
FUV radiation
Supernovae
Cluster/Runaway
(G34.7-0.4)
ISM evolution
MHD
Self-Gravity
Shearing-Box
Optically thin cooling
PE heating (FUV)
Star Formation
Self-Gravity
Sink Particle
HST
ESO/G. Beccari
CHANDRA X-RAY OBSERVATORY

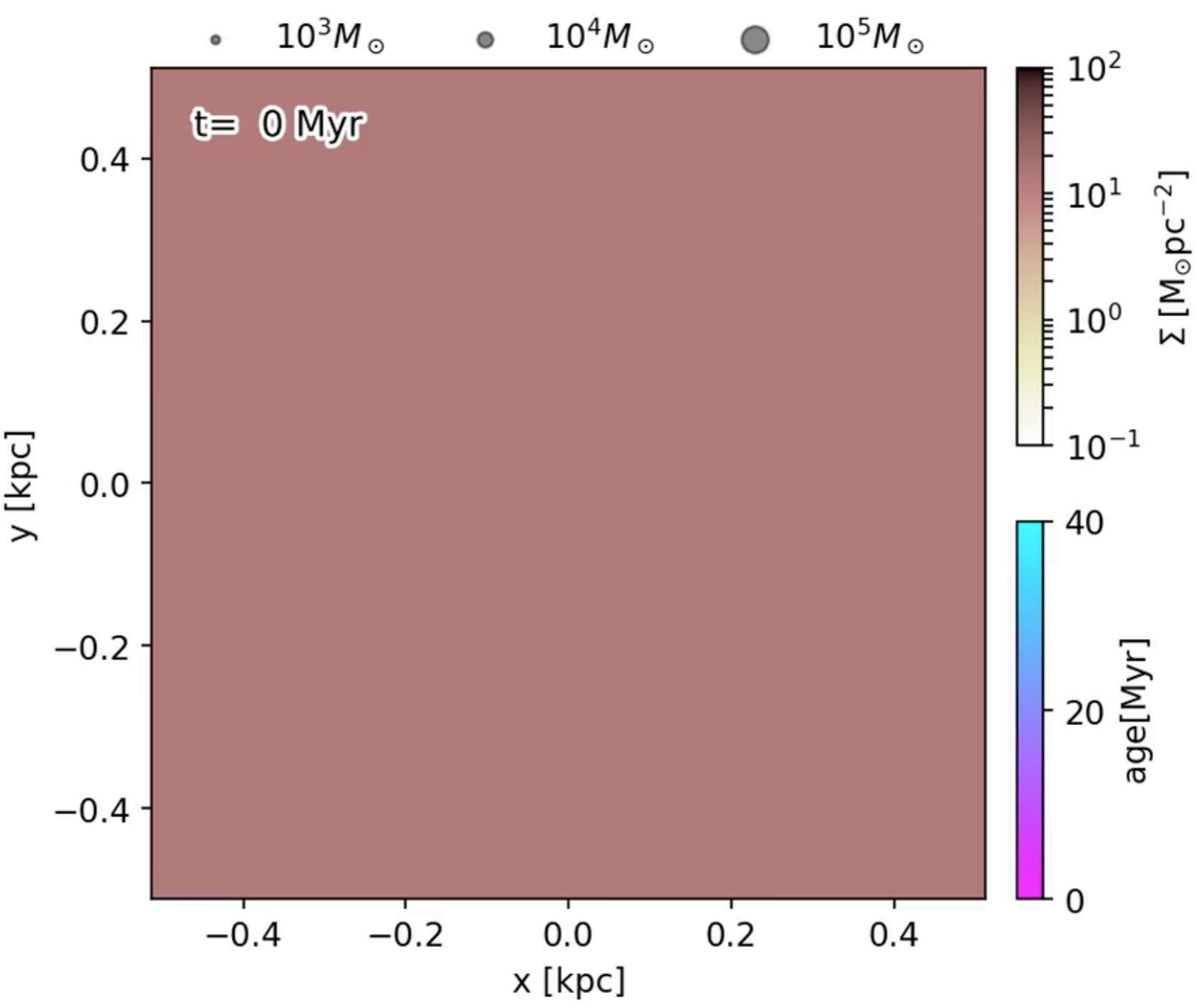


TIGRESS utilizes a local, shearing-box to ensure uniformly high-resolution (~pc) within ~kpc scale boxes

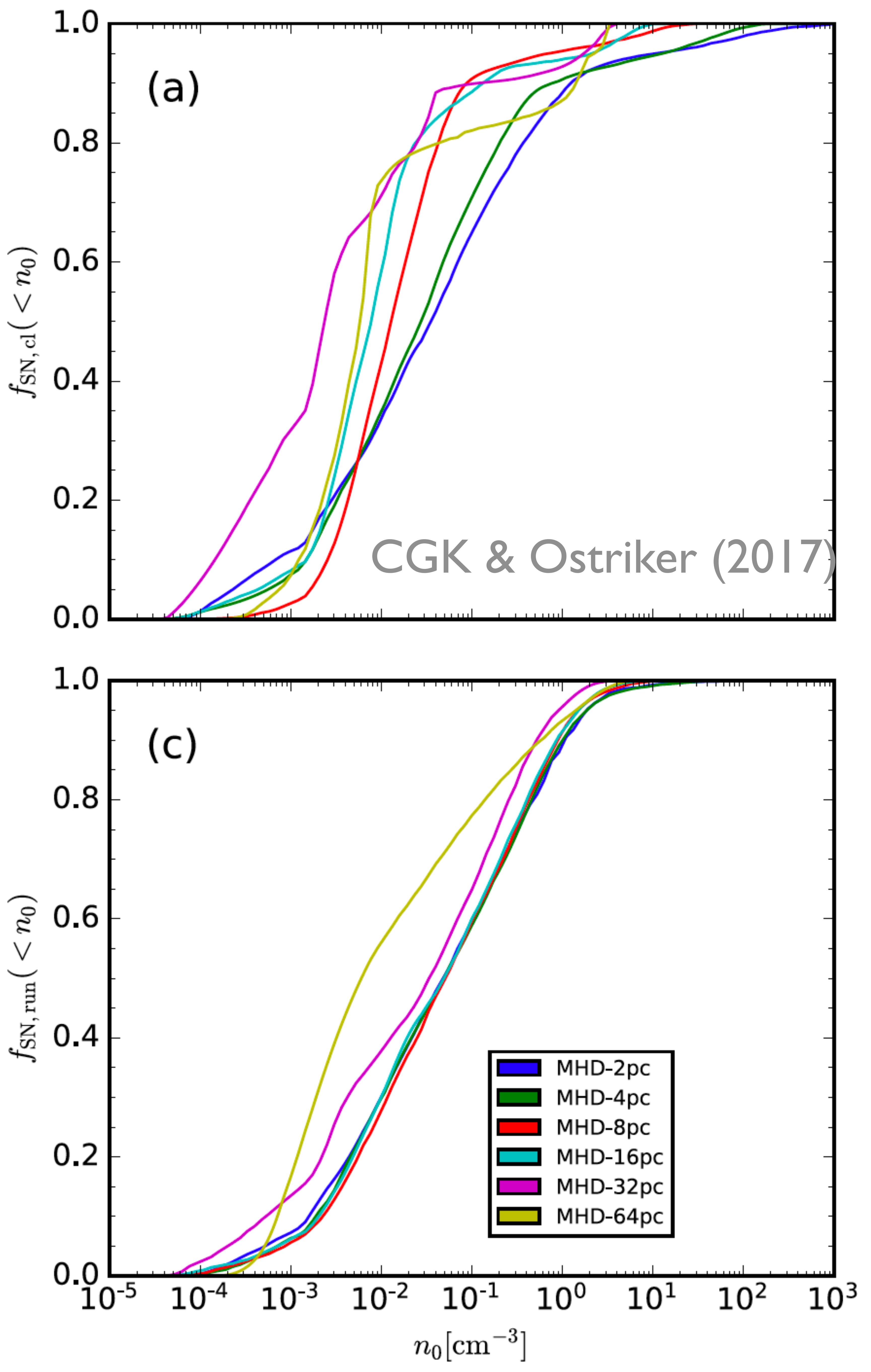
CGK & Ostriker (2017)

Self-regulation of SFRs — general principles

- Stars form when nothing can stop gravity (one-way force)…
  - (massive) stars inject energy and momentum to their surroundings — feedback
  - changes thermal (cold/warm/hot phases) and dynamical state (turbulence) of ISM
- Massive stars are short lived
  - feedback energy/momentum injection is rapid compared to system evolution
  - effects of feedback — limit further gravitational collapse and destruct collapsing clouds
- ISM is highly dissipative — short cooling, dissipation time
  - energy losses would reduce supporting forces on short timescale
  - without efficient feedback, all ISM would collapse into dense clouds and hence stars within a dynamical time



$10^3 M_\odot$
$10^4 M_\odot$
$10^5 M_\odot$
t= 0 Myr
y [kpc]
x [kpc]
Σ [$M_\odot pc^{-2}$]
age[Myr]



(a)
(c)
CGK & Ostriker (2017)
$f_{SN,cl}(< n_0)$
$f_{SN,run}(< n_0)$
$n_0[cm^{-3}]$
MHD-2pc
MHD-4pc
MHD-8pc
MHD-16pc
MHD-32pc
MHD-64pc

Feedback shapes ISM state

ISM state controls SFR

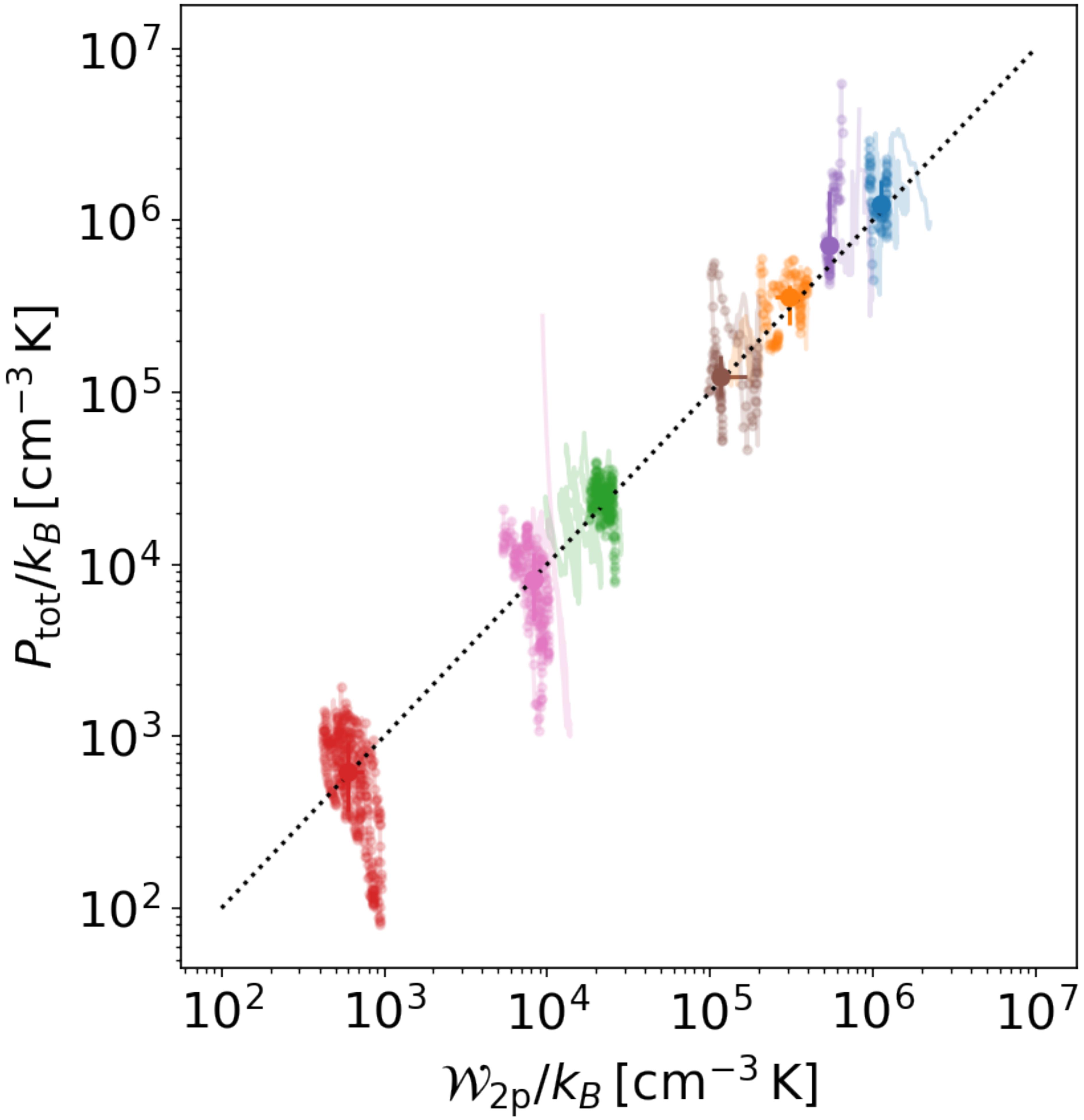
SFR changes Feedback
in a way that ISM demands

Self-regulation of SFRs

- Equilibrium model for star formation rates
    - Ostriker, Leroy, McKee (2010); Ostriker & Shetty (2011); CGK, Kim, Ostriker (2011); Shetty & Ostriker (2012); CGK, Kim, Ostriker (2013); CGK & Ostriker (2015) …
    - Stellar feedback provides pressure support — $P \sim \eta\Sigma_{SFR}$
    - pressure support should match with the ISM weight — $P \sim \Sigma\langle g_z\rangle/2$
    - On average, the ISM weight is an "attractor" for total pressure of the ISM that is determined by the level of feedback and hence SFRs — ISM conditions (both gas "fuel" and gravitational "environment") can be used to predict mean SFRs
- $\Sigma_{SFR} \sim P/\eta \sim \Sigma\langle g_z\rangle/2\eta$
    - e.g., self-gravity ($\Sigma\langle g_z\rangle/2 = \pi G\Sigma^2/2$) and turbulence ($\eta \sim (p^*/m^*)/4$) dominate in starburst
    - $\Sigma_{SFR} \sim 2\pi G\Sigma^2/(p_*/m_*)$
    - $(p_*/m_*) \sim (1\text{-}5)\times10^3$ km/s for SNe; CGK & Ostriker (2015); CGK, Ostriker, & Raileanu (2017); Martizzi+ (2015); Walch & Naab (2015); Iffrig & Hennebelle (2015)…

$$\left\langle P_{\rm th} + \rho v_z^2 + \frac{B^2}{8\pi} - \frac{B_z^2}{4\pi} \right\rangle_{z=z_{\rm max}}^{z=0} \approx \frac{\pi G \Sigma^2}{2} + \Sigma \sigma_z (2 G \rho_{\rm sd})^{1/2}$$

ISM response to feedback

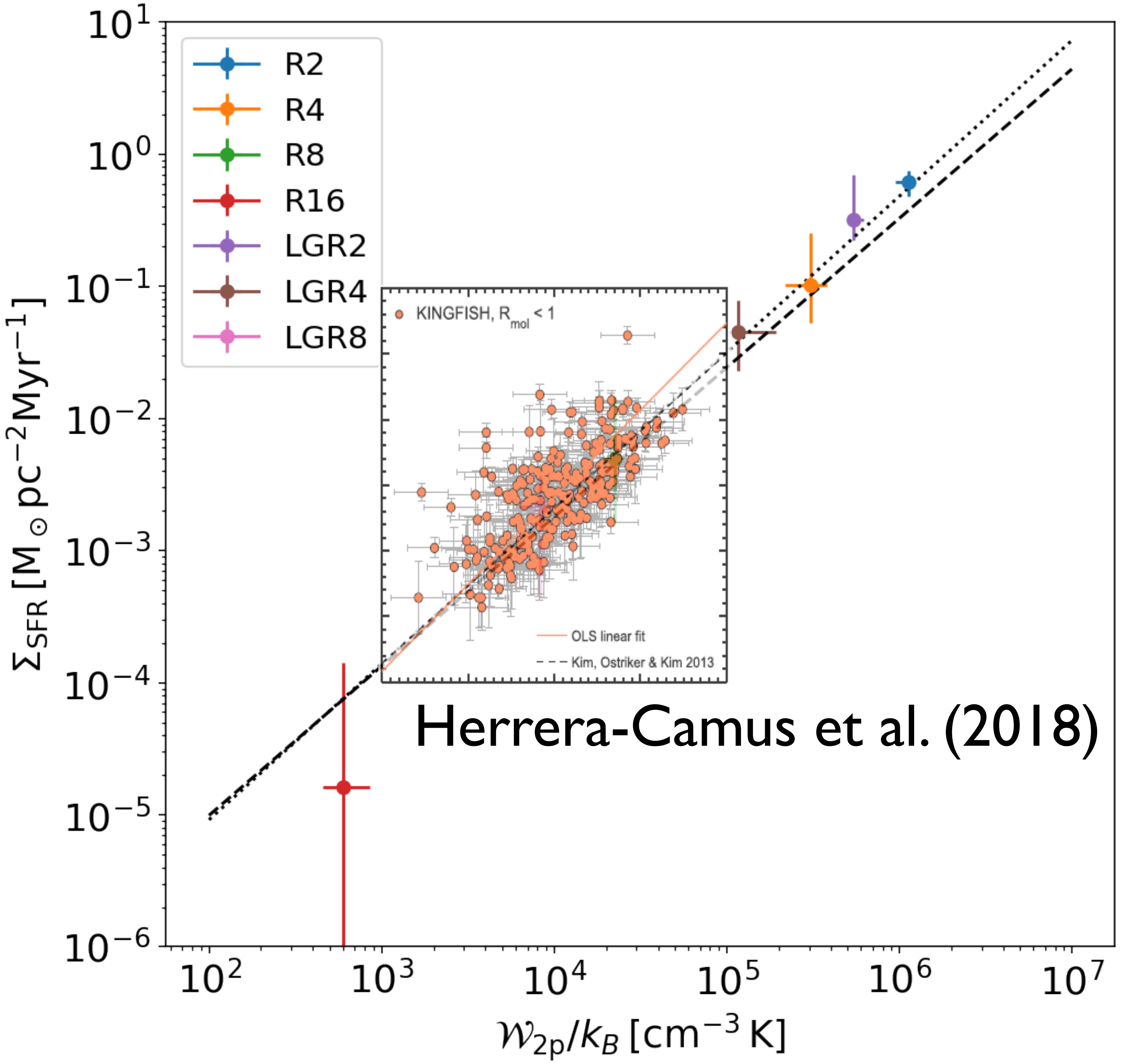


ISM response to gravity

P=ηΣ$_{SFR}$

$P_{\rm th} \sim \eta_{\rm th}\Sigma_{\rm SFR}$ $P_{\rm turb} \sim \eta_{\rm turb}\Sigma_{\rm SFR}$ $P_{\rm mag} \sim \eta_{\rm mag}\Sigma_{\rm SFR}$

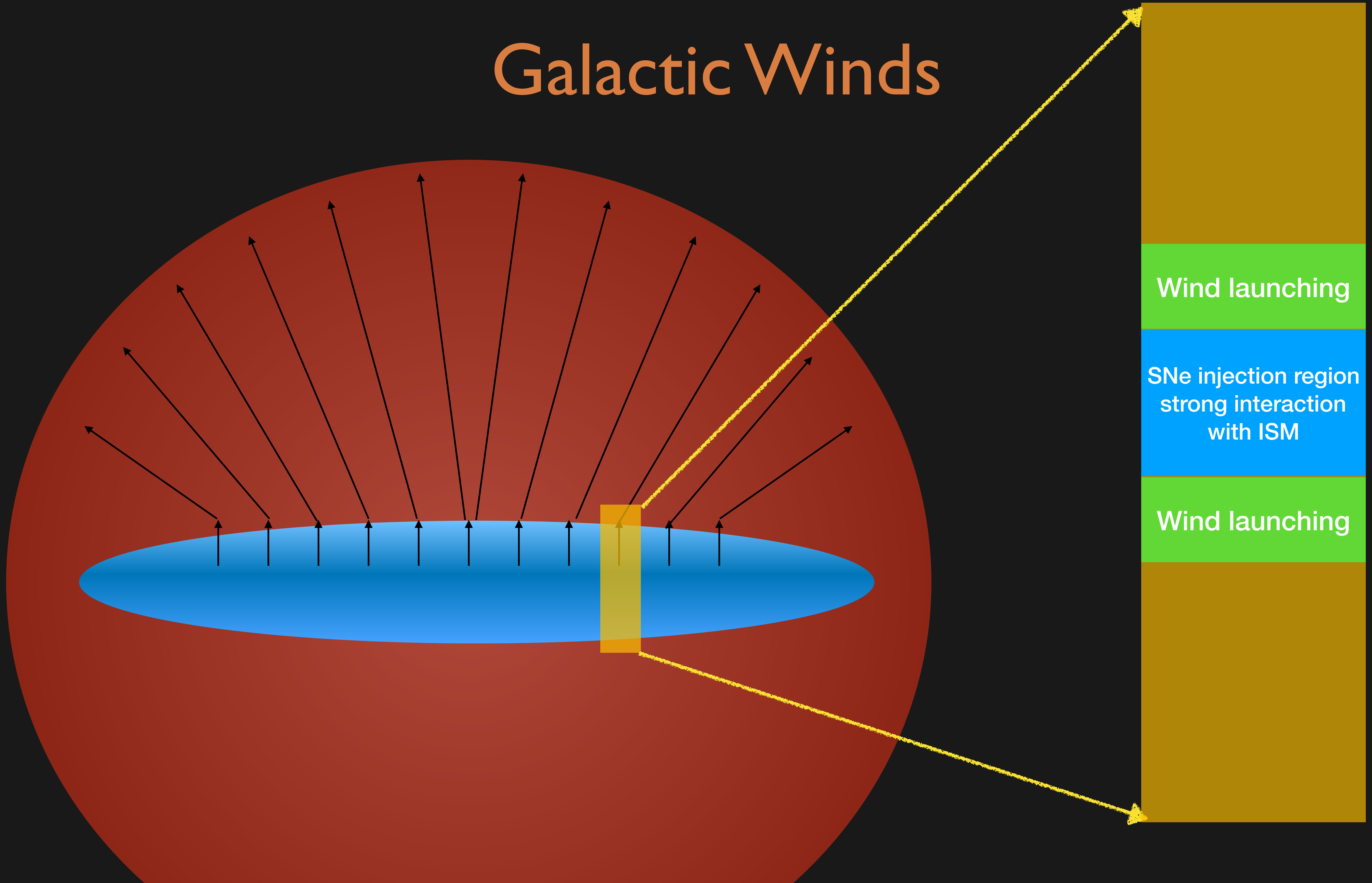
Supply

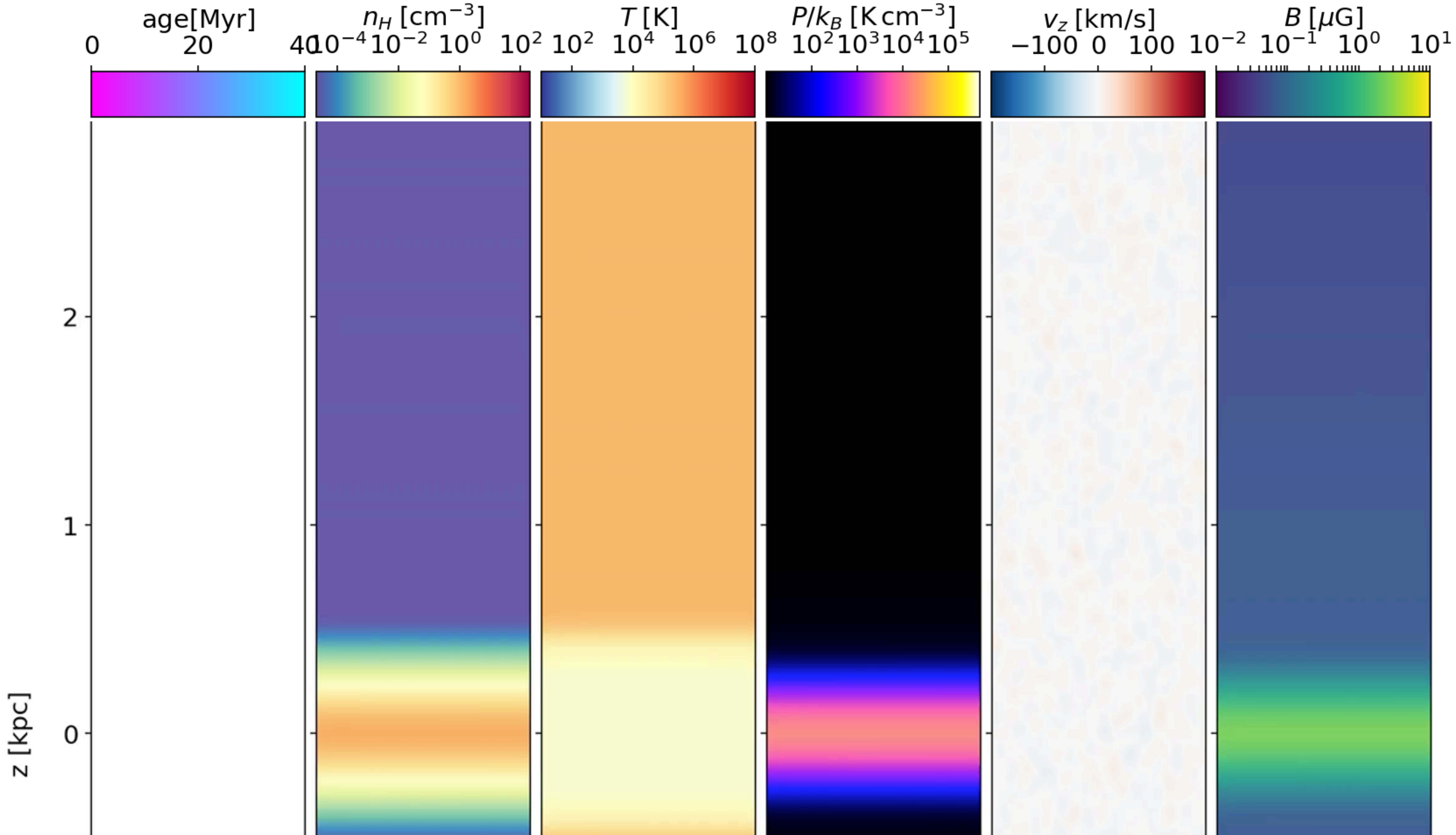


Demand

$$\approx \frac{\pi G \Sigma^2}{2} + \Sigma \sigma_z (2 G \rho_{\rm sd})^{1/2}$$

Galactic Winds



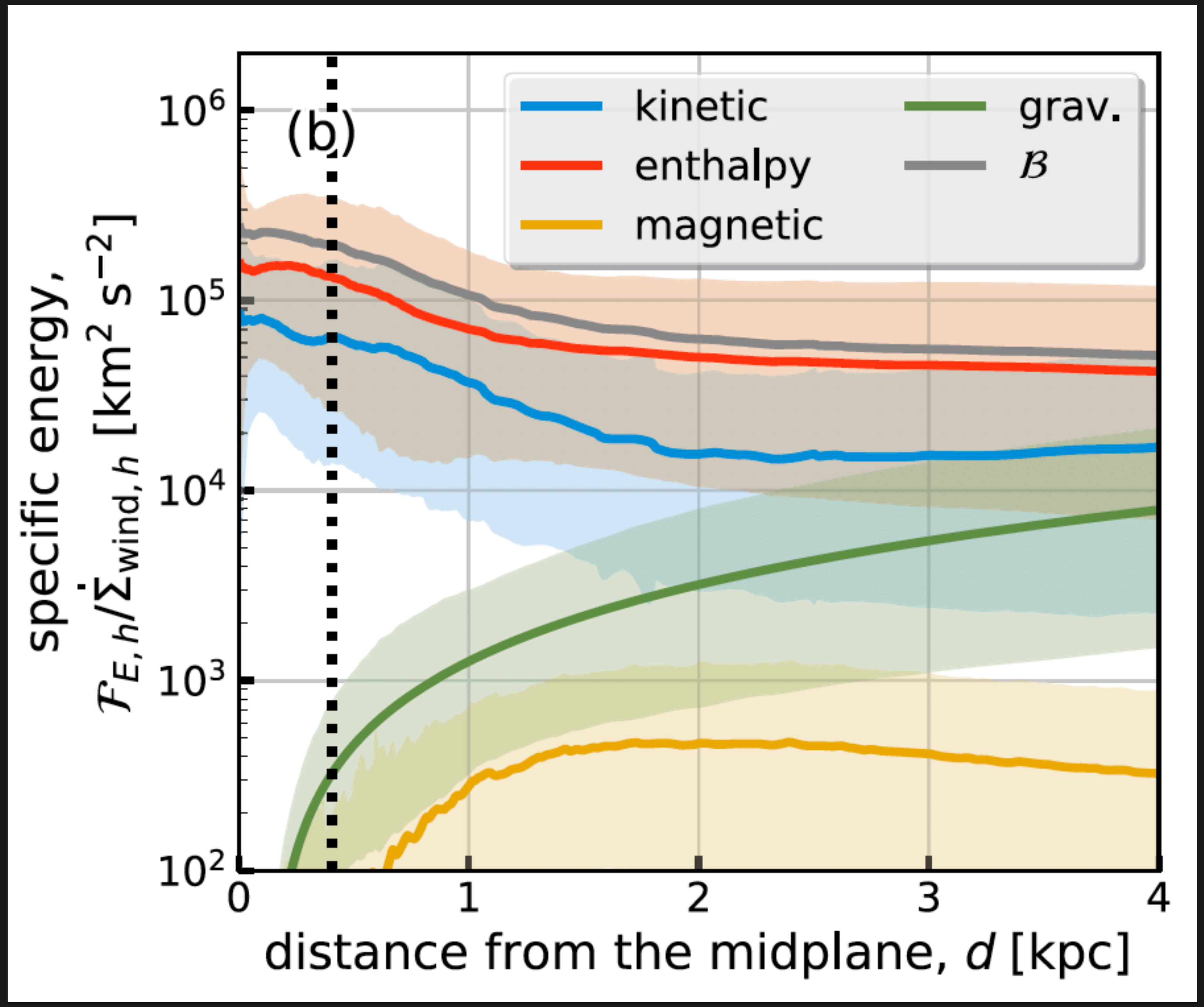


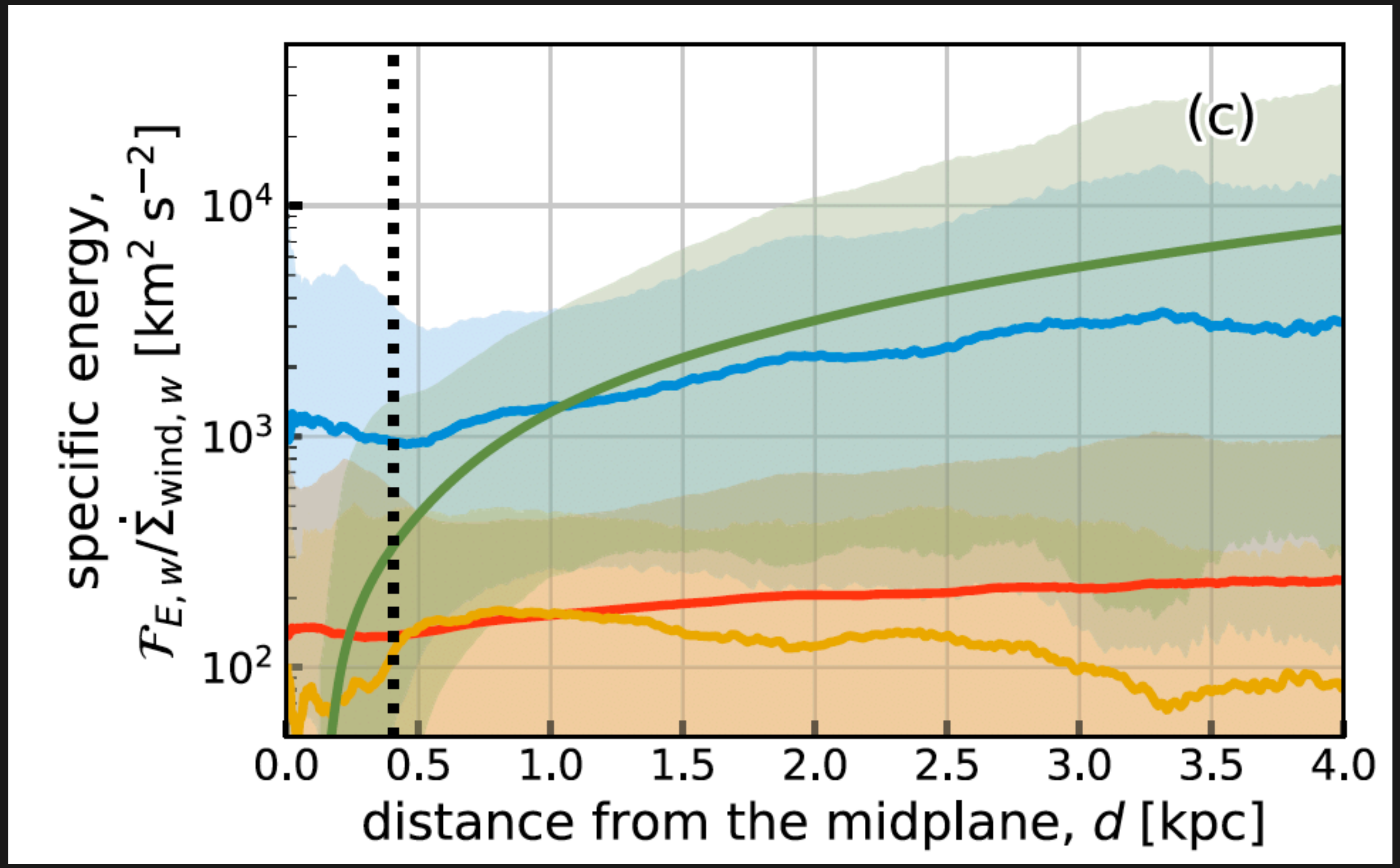
age[Myr]
0
20
40
n_H [cm^{-3}]
10^{-4} 10^{-2} 10^{0} 10^{2}
T [K]
10^{2} 10^{4} 10^{6} 10^{8}
P/k_B [K cm^{-3}]
10^{2} 10^{3} 10^{4} 10^{5}
v_z [km/s]
−100 0 100
B [μG]
10^{-2} 10^{-1} 10^{0} 10^{1}
z [kpc]
2
1
0

Multiphase Outflows

- Outflows are multiphase
  - volume filling hot gas — constant mass and energy fluxes — winds
  - clumpy warm gas — not enough energy to escape — fountains

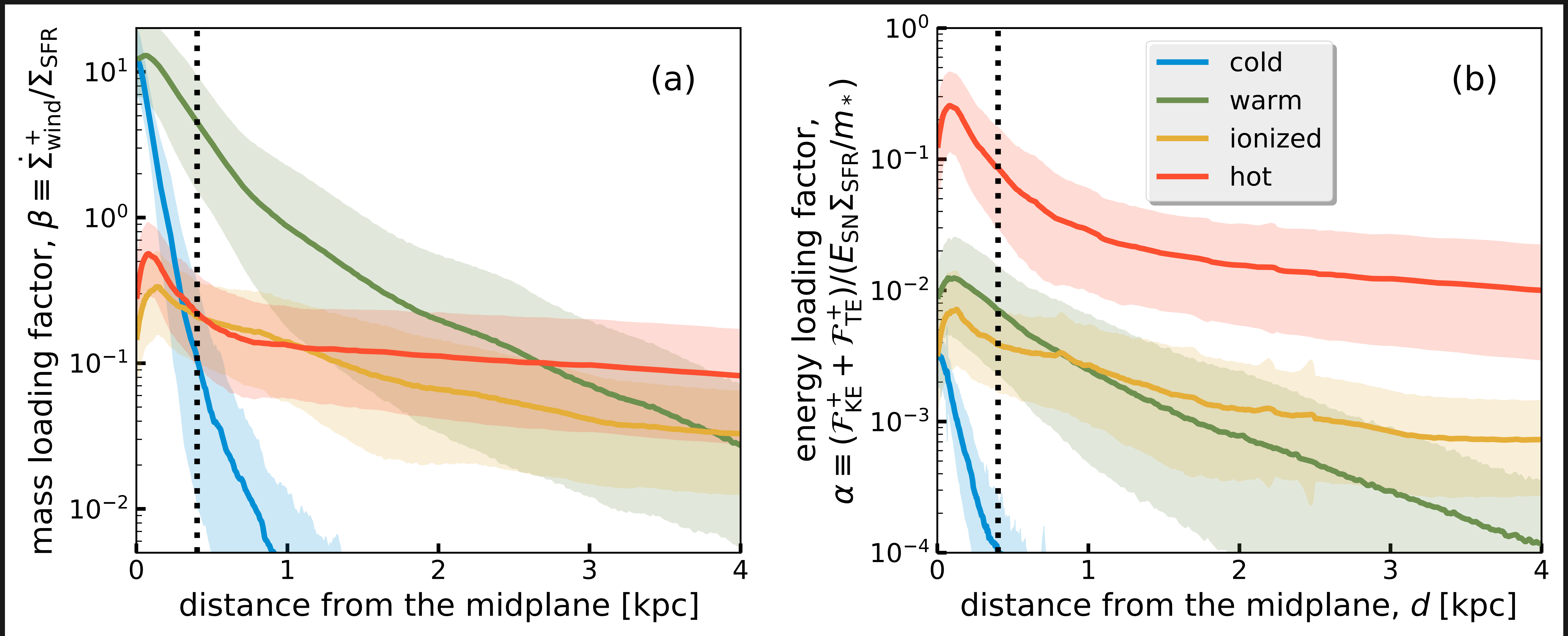
CGK & Ostriker (2018)



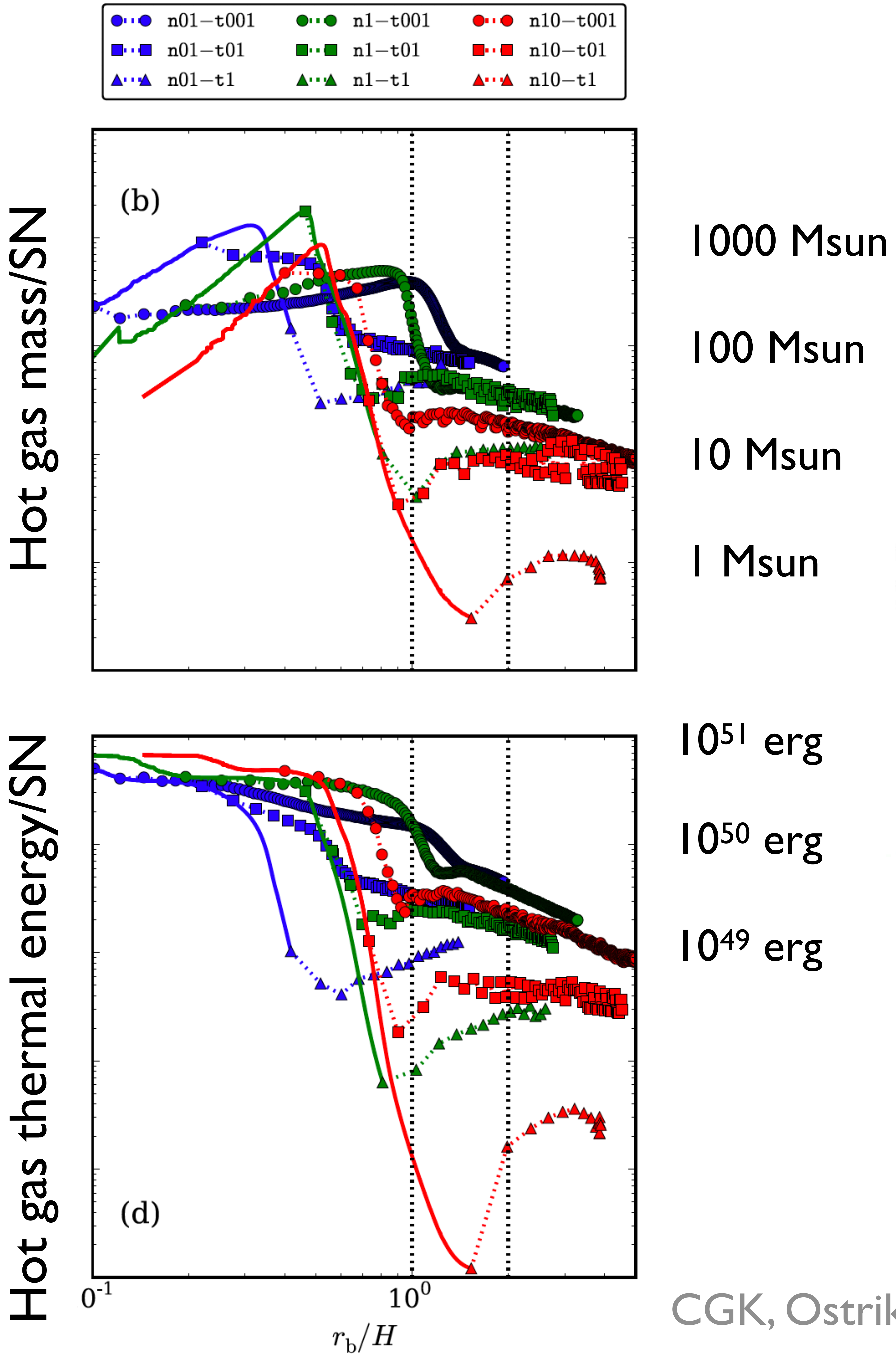


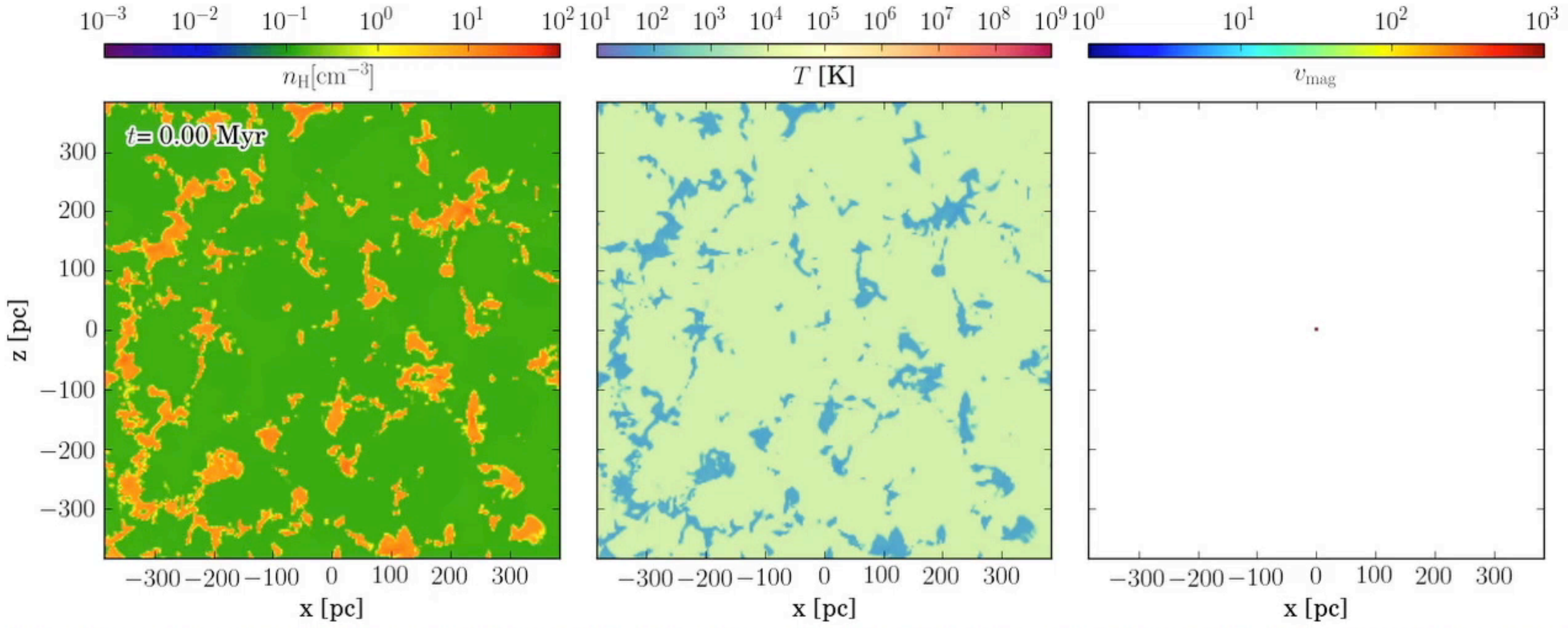
Hot Winds

- Mean properties of hot winds in solar neighborhood (Milky Way)
  - mass loading ~ 0.1
  - energy loading ~ 0.01



CGK & Ostriker (2018)



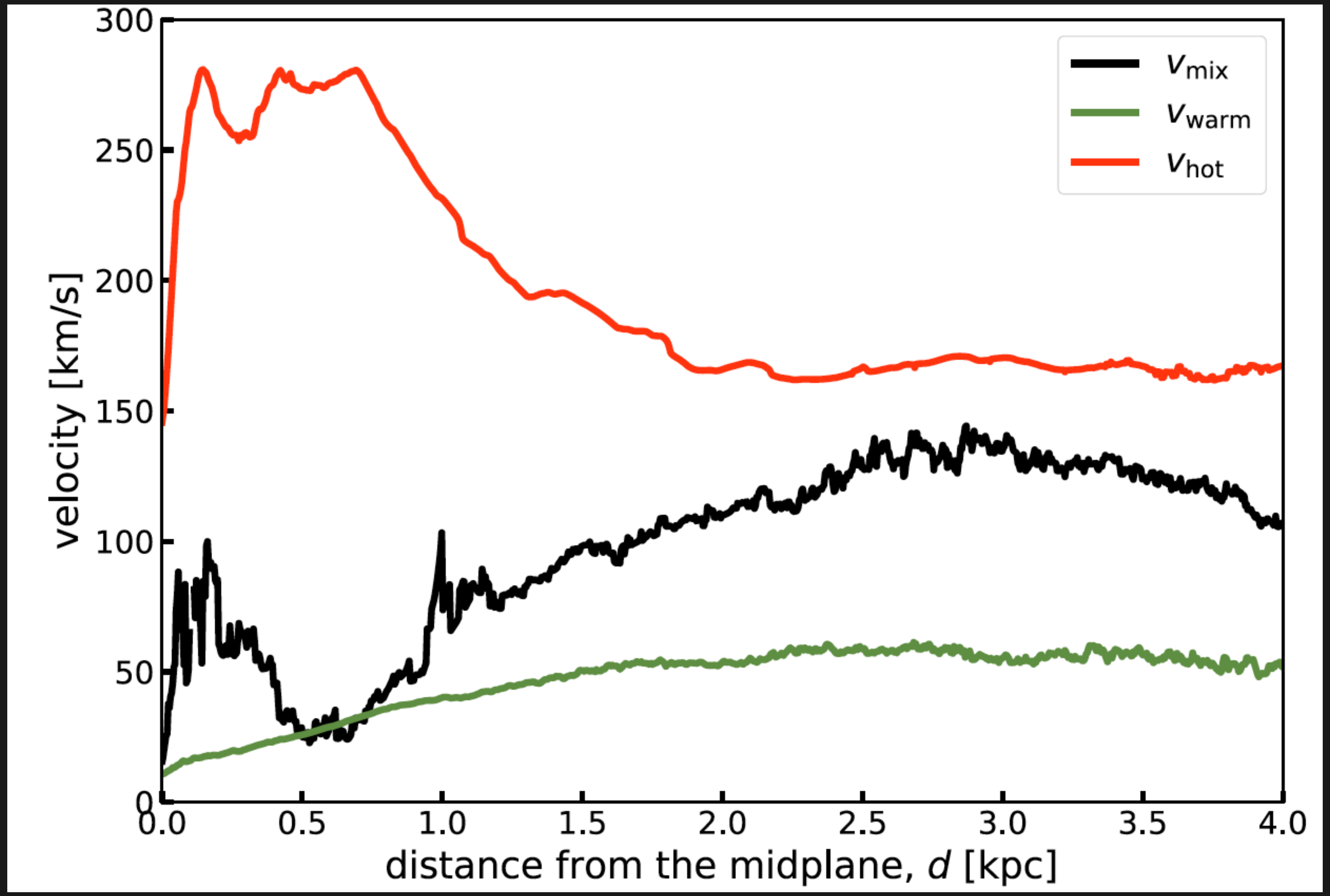


- Remaining hot gas mass/SN after the shell formation ~ 1-100M_{sun}
- Remaining thermal energy/SN after the shell formation ~ 0.001-0.1E_{SN}

CGK, Ostriker, & Raileanu (2017)

Hot Winds

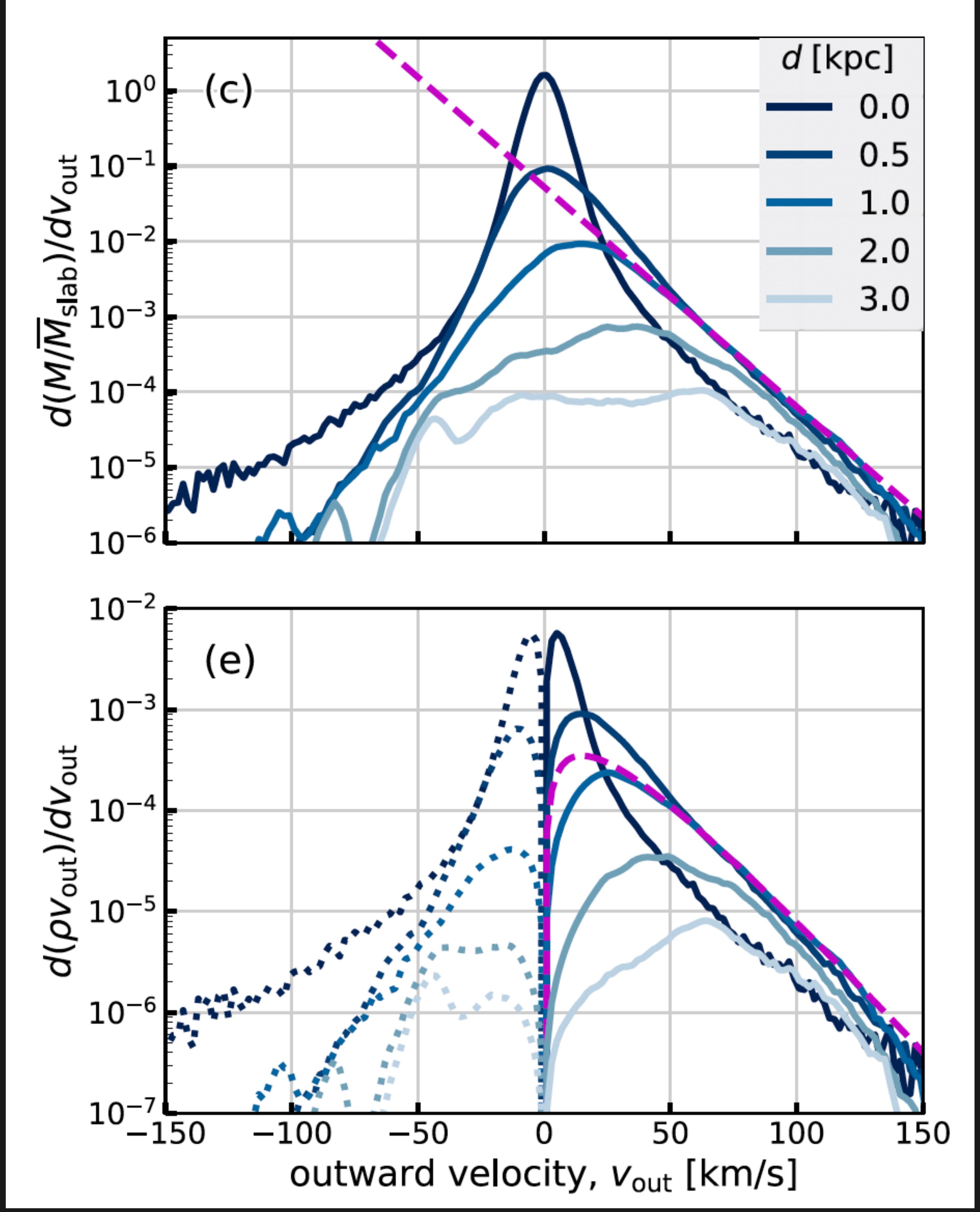
- Mean properties of hot winds in solar neighborhood (Milky Way)
  - mass loading ~ 0.1
  - energy loading ~ 0.01



- Be cautious about numerical mixing
  - mixed single-phase outflow can either escape or fall back entirely

Warm Fountains

- SNe accelerate significant warm gas to v_{out}~50-100km/s
  - exponential distribution of dM/dv_{out}
- This can escape from dwarf galaxies with shallower gravitational potential ($v_{out}>v_{esc}$)
- Warm fountains can be further accelerated by
  - interaction with hot winds
  - cosmic ray pressure gradients



CGK & Ostriker (2018)

Warm Fountains

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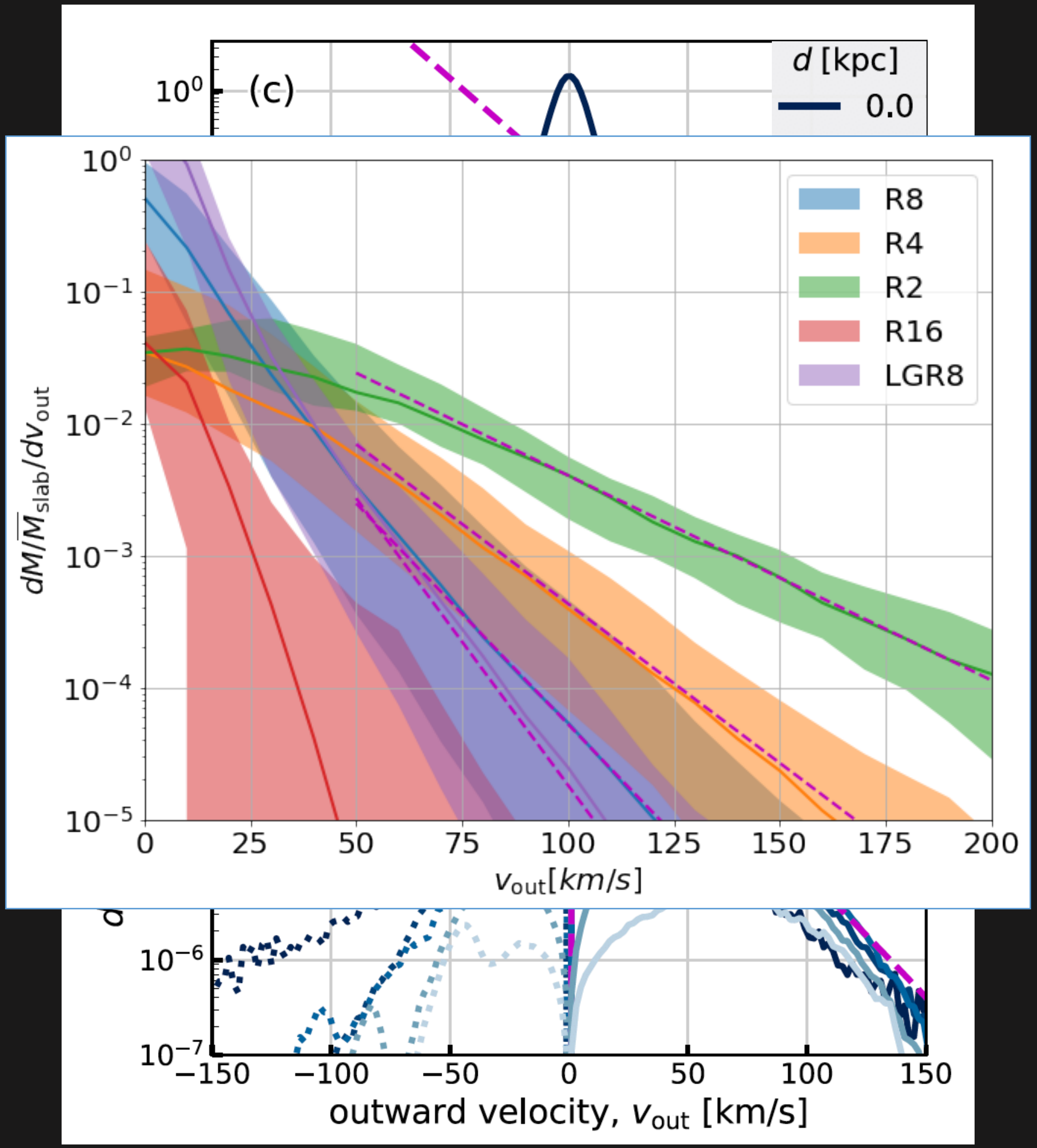
- Warm fountains can be further accelerated by
  - interaction with hot winds
  - cosmic ray pressure gradients
- More high-velocity warm gas with higher SFRs

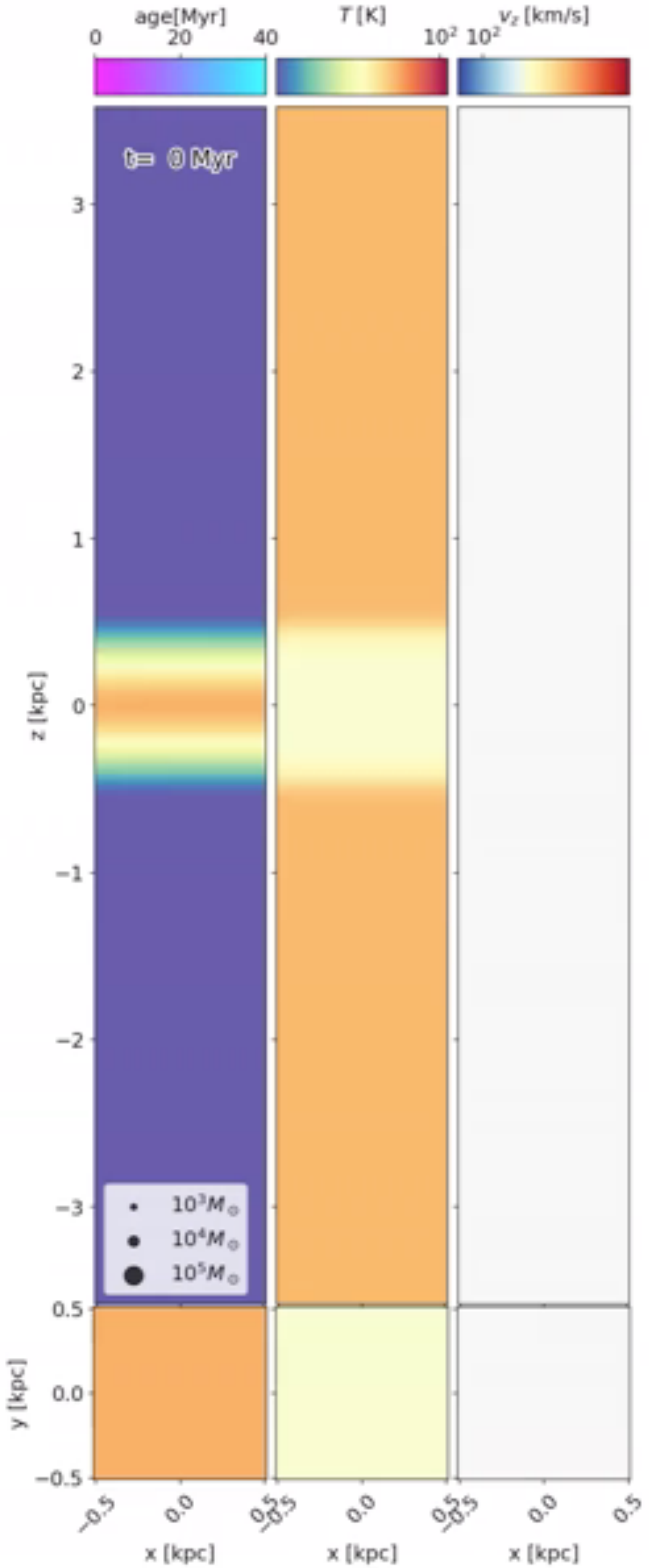


CGK & Ostriker (2018)

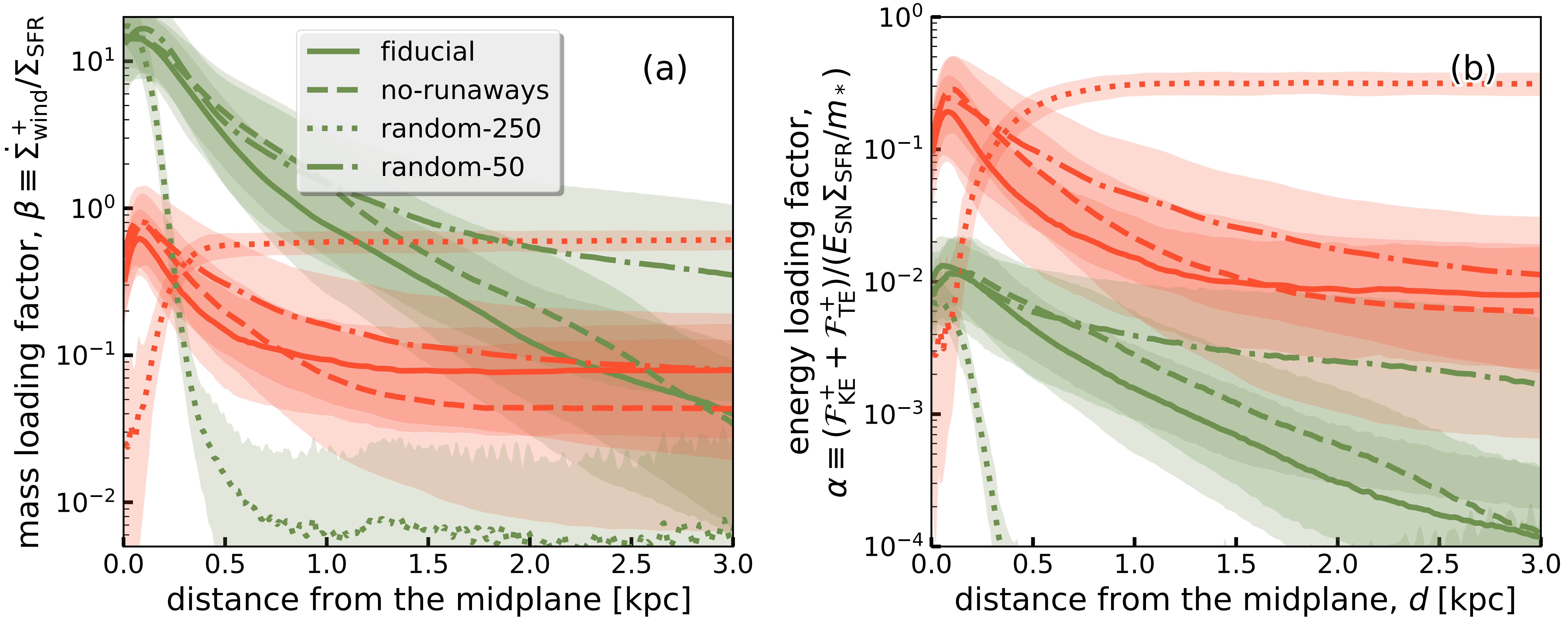
Pitfalls — the devil is in the details

- Outflow properties are time-dependent!
  - SFRs and hence SN rates are fluctuating in time
  - Clustering of SNe — one massive cluster can drive significant outflows
  - SNe positions are correlated with the ISM — H_{gas} vs H_{SN}
- Stochasticity — substantial evolution driven by rare events — one simulation cannot tell us everything

Vertically-extended SNe

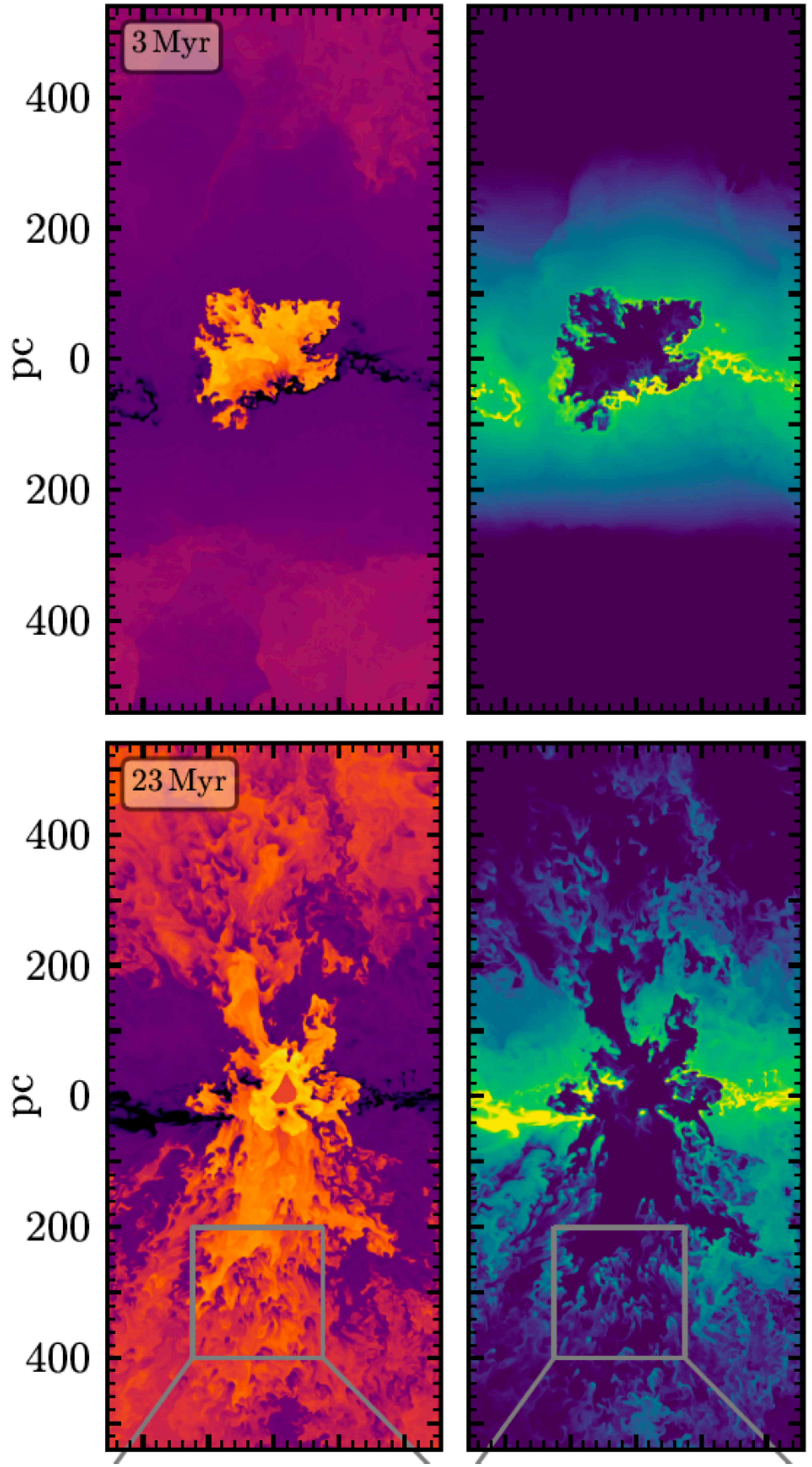


- If SN distribution is vertically extended (H_{SN}>H_{gas}; e.g., Li et al. 2017), mass and energy loading factors can be
  - higher for hot gas (red-dotted)
  - lower for warm (green-dotted)



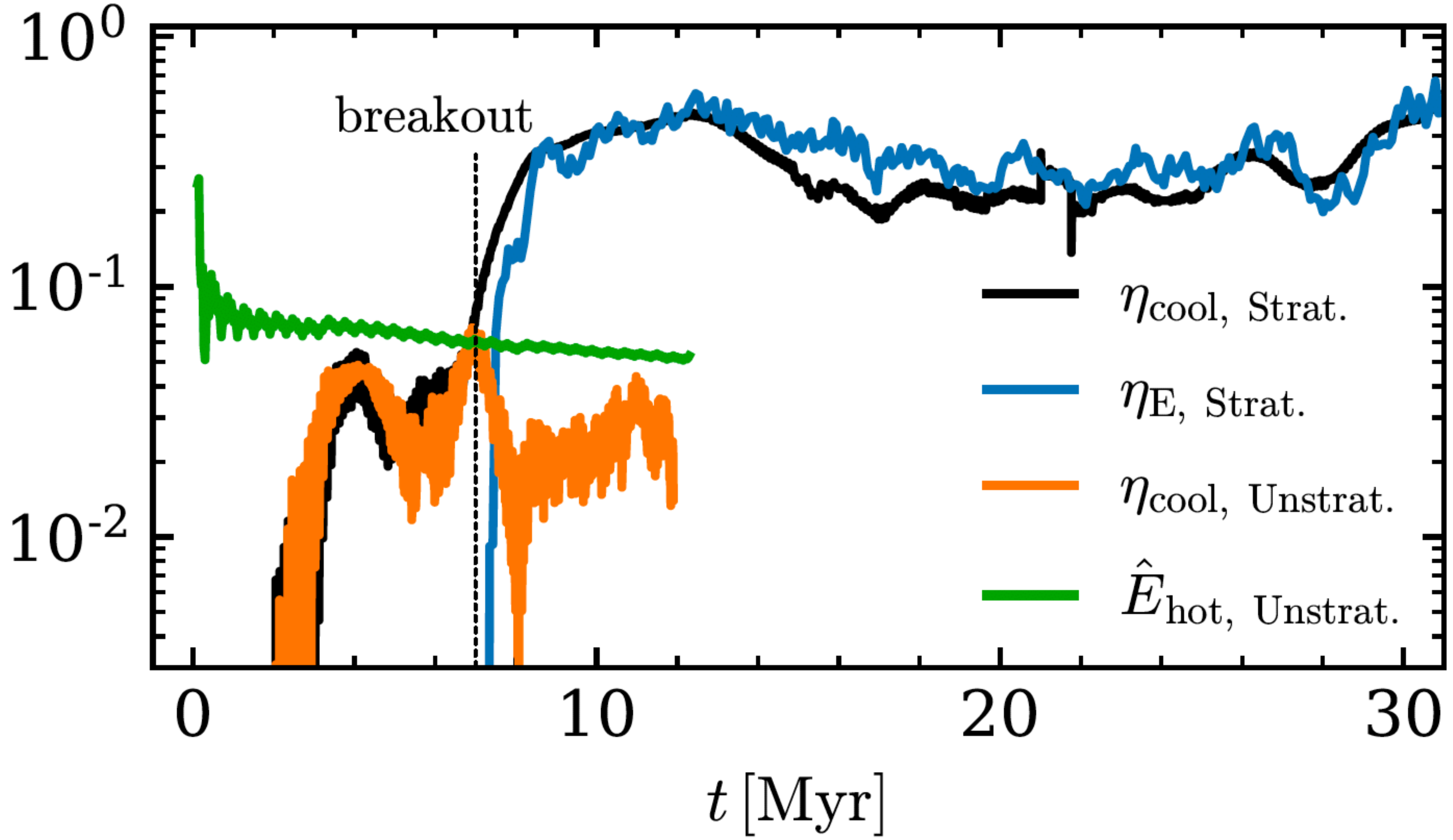
CGK & Ostriker (2018)

Fielding et al. 2018

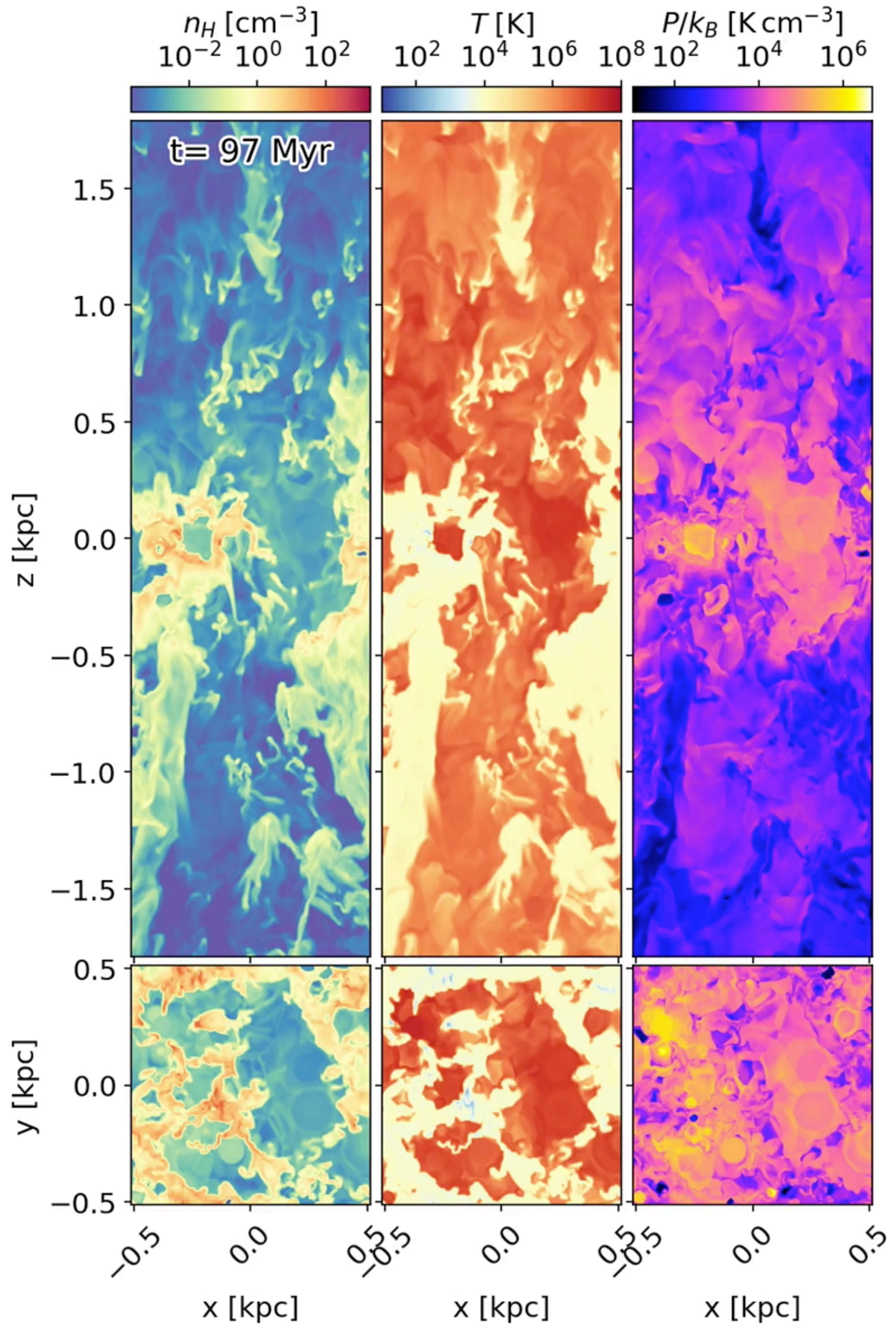


Clustered SNe

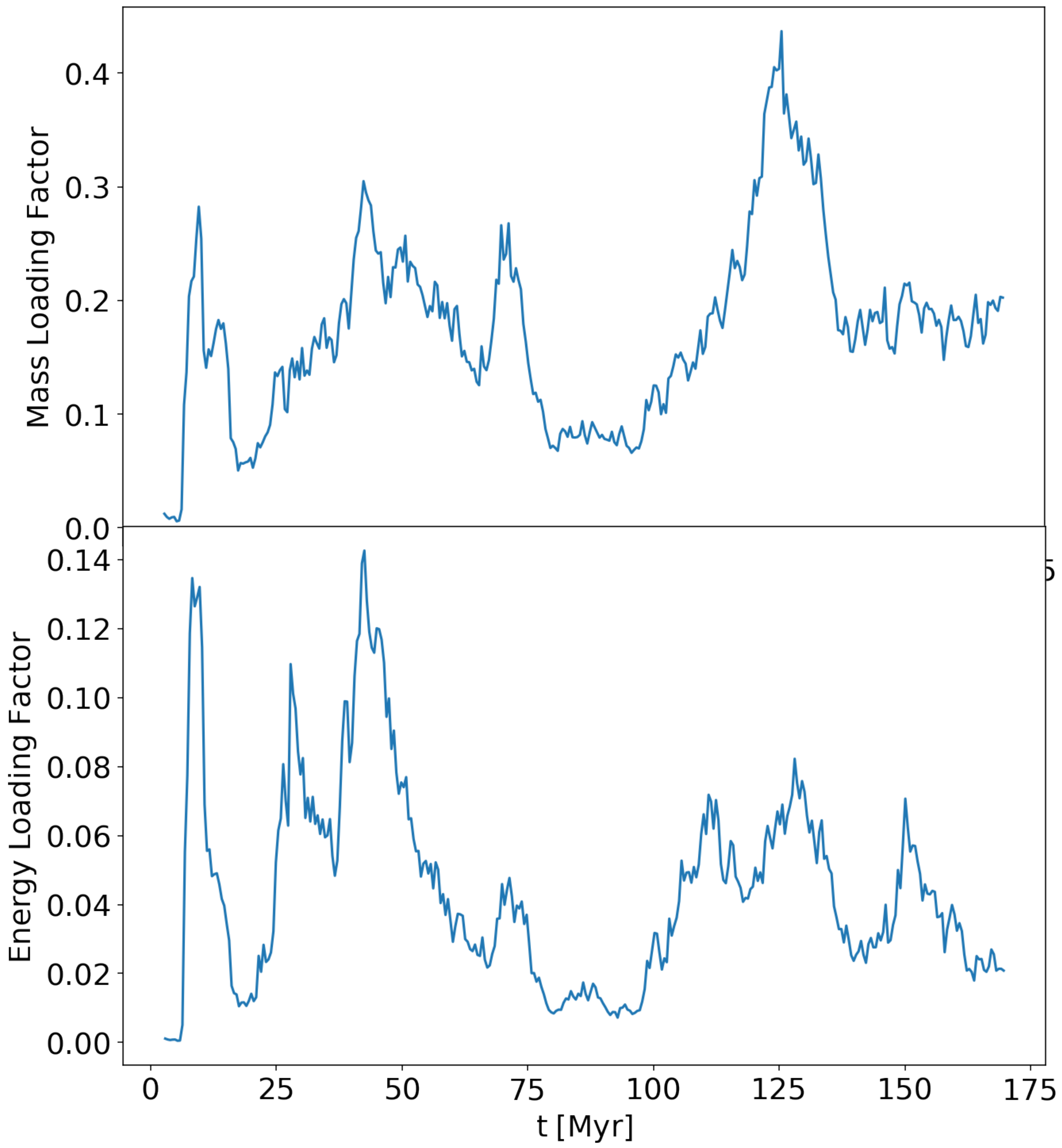
- One massive cluster can drive winds with higher mass and energy loading factors
  - earlier SNe open up a cavity and help subsequent SN energy to vent out

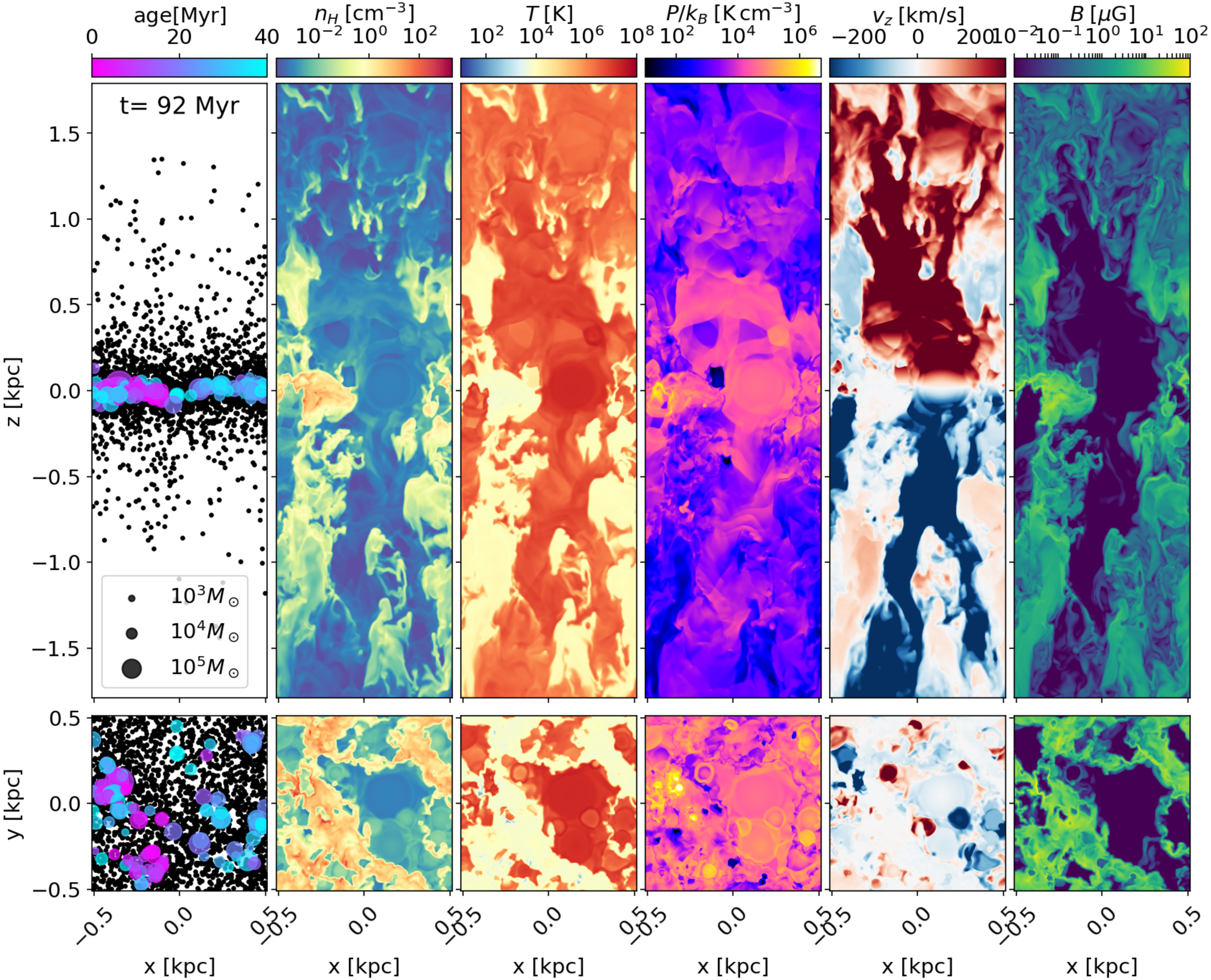


Clustered SNe

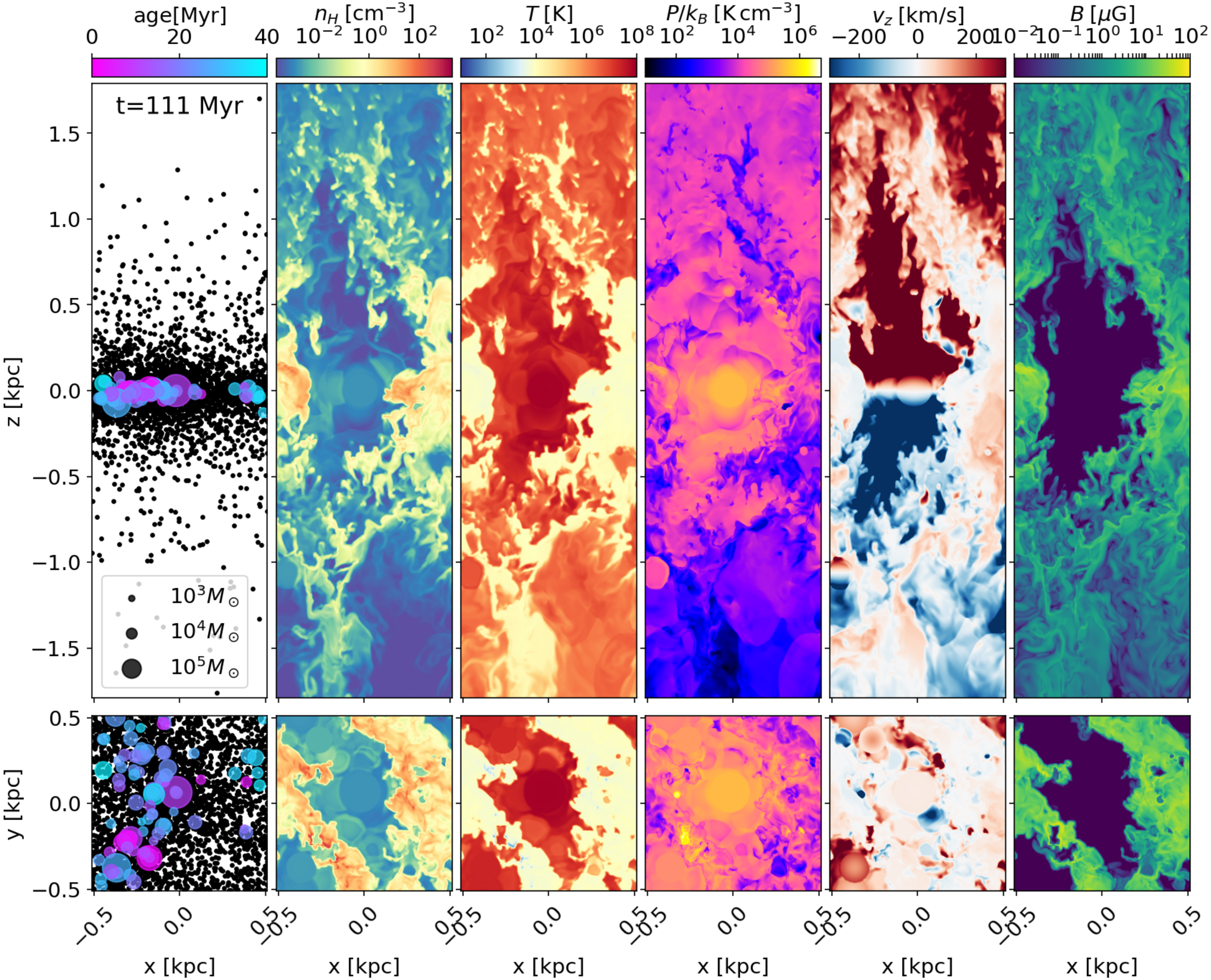


- How long does the cavity last?
- How does the massive cluster form?
  - Is sink particle approach good enough?
  - Early feedback?

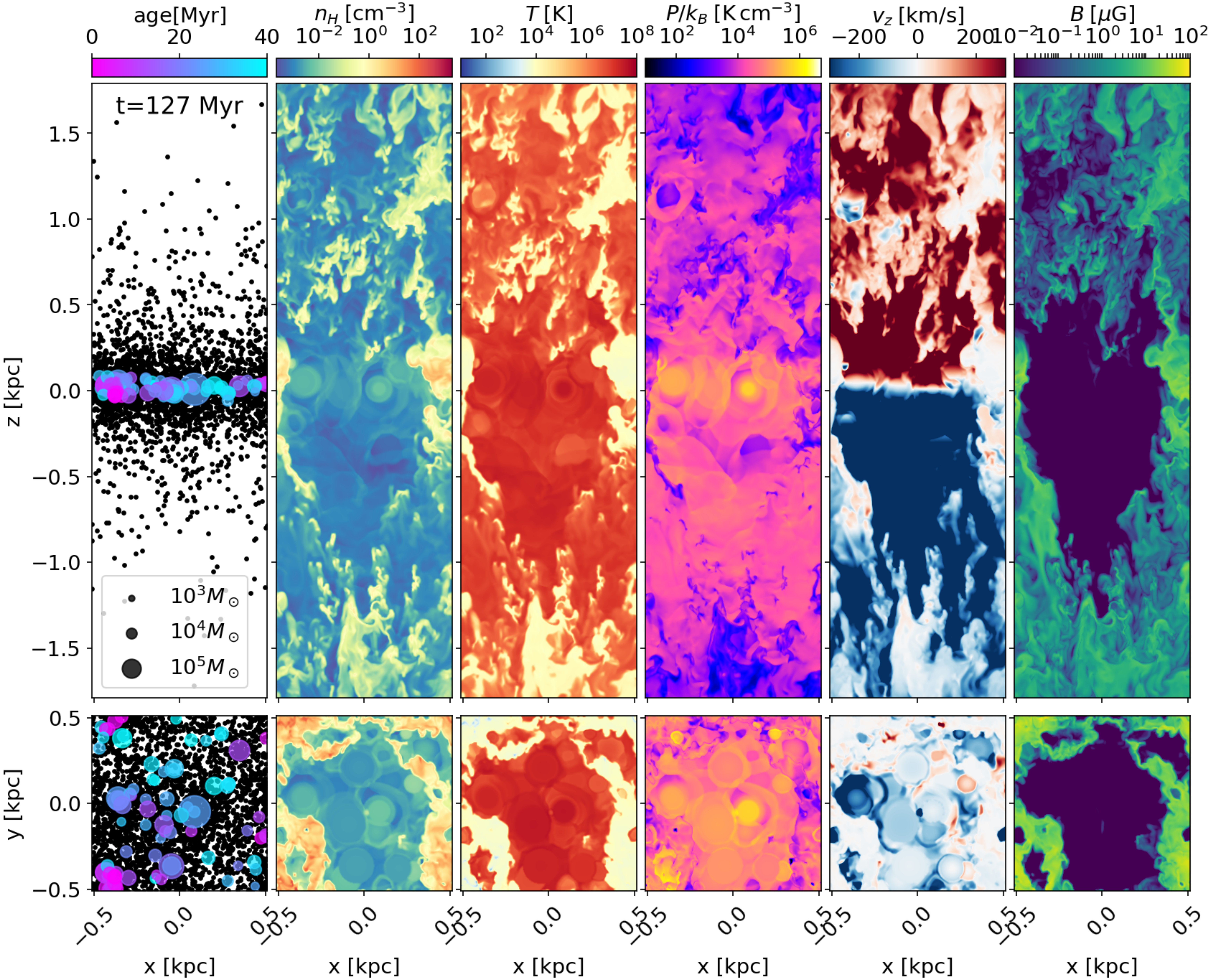




age[Myr]
0 20 40
n_H [cm^{-3}]
10^{-2} 10^{0} 10^{2}
T [K]
10^2 10^4 10^6 10^8
P/k_B [K cm^{-3}]
10^2 10^4 10^6
v_z [km/s]
−200 0 200
B [μG]
10^{-2} 10^{-1} 10^0 10^1 10^2
t= 92 Myr
$10^3 M_\odot$
$10^4 M_\odot$
$10^5 M_\odot$
z [kpc]
y [kpc]
x [kpc]

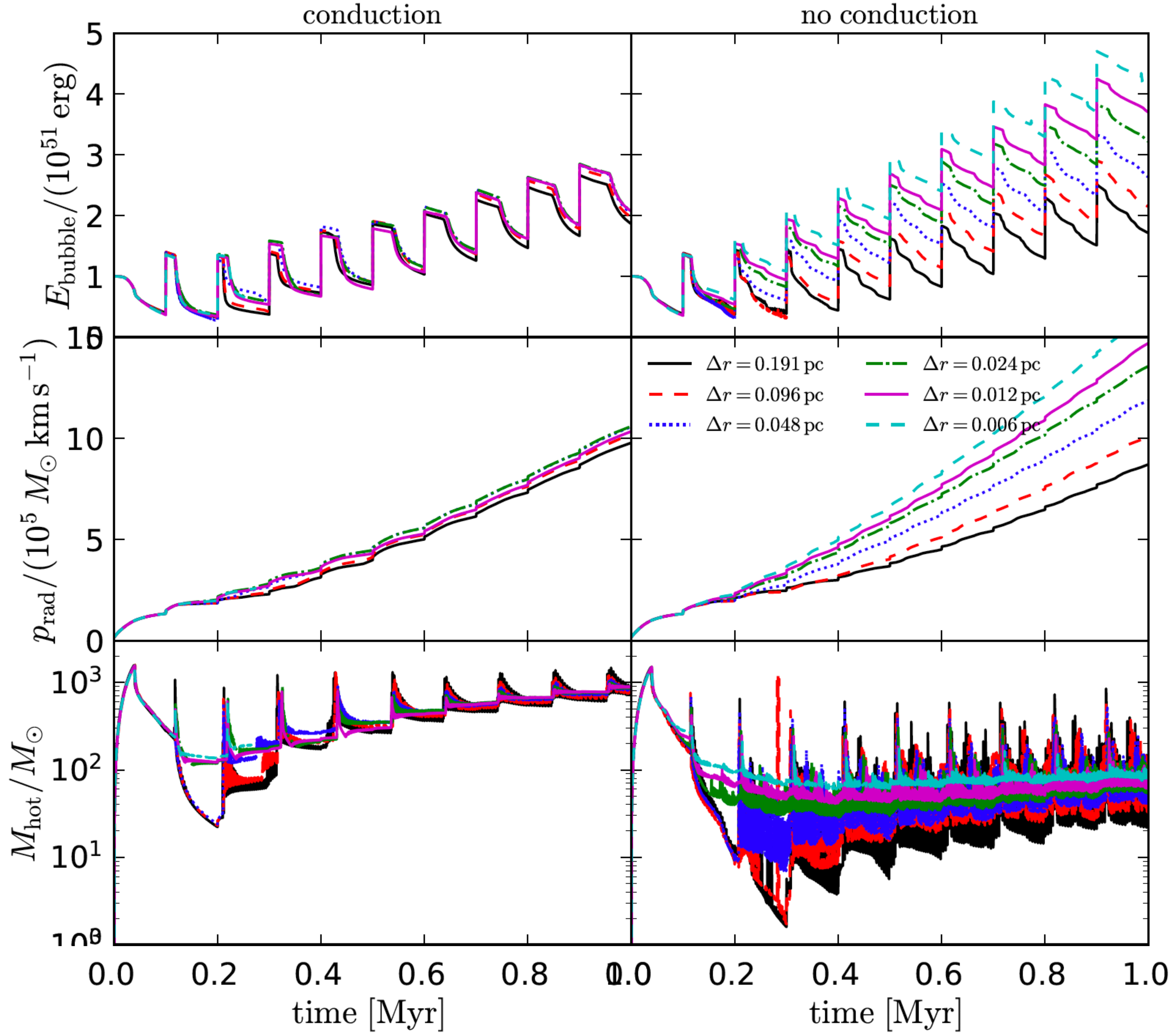


age[Myr]
0 20 40
n_H [cm^{-3}]
10^{-2} 10^0 10^2
T [K]
10^2 10^4 10^6 10^8
P/k_B [K cm^{-3}]
10^2 10^4 10^6
v_z [km/s]
−200 0 200
B [μG]
10^{-2} 10^{-1} 10^0 10^1 10^2
t=111 Myr
z [kpc]
1.5 1.0 0.5 0.0 −0.5 −1.0 −1.5
$10^3 M_\odot$
$10^4 M_\odot$
$10^5 M_\odot$
y [kpc]
0.5 0.0 −0.5
x [kpc]
−0.5 0.0 0.5



age[Myr]
0 20 40
n_H [cm^{-3}]
10^{-2} 10^0 10^2
T [K]
10^2 10^4 10^6 10^8
P/k_B [K cm^{-3}]
10^2 10^4 10^6
v_z [km/s]
−200 0 200
B [μG]
10^{-2} 10^{-1} 10^0 10^1 10^2
t=127 Myr
$10^3 M_\odot$
$10^4 M_\odot$
$10^5 M_\odot$
z [kpc]
1.5 1.0 0.5 0.0 −0.5 −1.0 −1.5
y [kpc]
0.5 0.0 −0.5
−0.5 0.0 0.5
x [kpc]

El-Badly, Ostriker, CGK in prep.



Thermal conduction

- Hot gas mass/SN ~ 100M_{sun}
  - Thermal conduction can evaporate shell gas (or enclosed clouds) into the hot interior
    - e.g., Castor et al. 1975; Weaver et al. 1977; Cowie & McKee 1977; Mac Low & McCray 1988
  - The conductive mass flux is reduced compared to classical theory by cooling, saturation of thermal conduction, and discreteness of events
- Be cautious that without conduction (or “physical” interface driven by 3D instabilities), energy/momentum injection per SN event can be boosted by an order of magnitude
    - e.g., Gentry et al. 2017

Concluding Remarks

- mass/momentum/energy cycles in star-forming ISM due to gravity and feedback
- Feedback shapes ISM, and resulting SFR adjusts feedback in a way that ISM demands
- Multiphase galactic outflows are outcome of collective effects of SN feedback and interaction with the ISM
- In our Milky Way-like models,
  - Escaping hot gas mass is about 10 times smaller than that locked into stars
  - Escaping hot gas energy is about 10-100 times smaller than that injected by SNe
  - SNe accelerate warm gas to high-velocity (50-100km/s), which can or cannot escape depending on gravitational potential and presence of additional feedback; high-velocity warm outflow rate comparable to SFR
- Spatio-temporal correlations of SNe themselves and with the ISM are crucial

mean number density [cm^{-3}]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
−3000 −2000 −1000 0 1000 2000 3000
z [pc]
1.0
0.8
0.6
0.4
0.2
0.0
−3000 −2000 −1000 0 1000 2000 3000