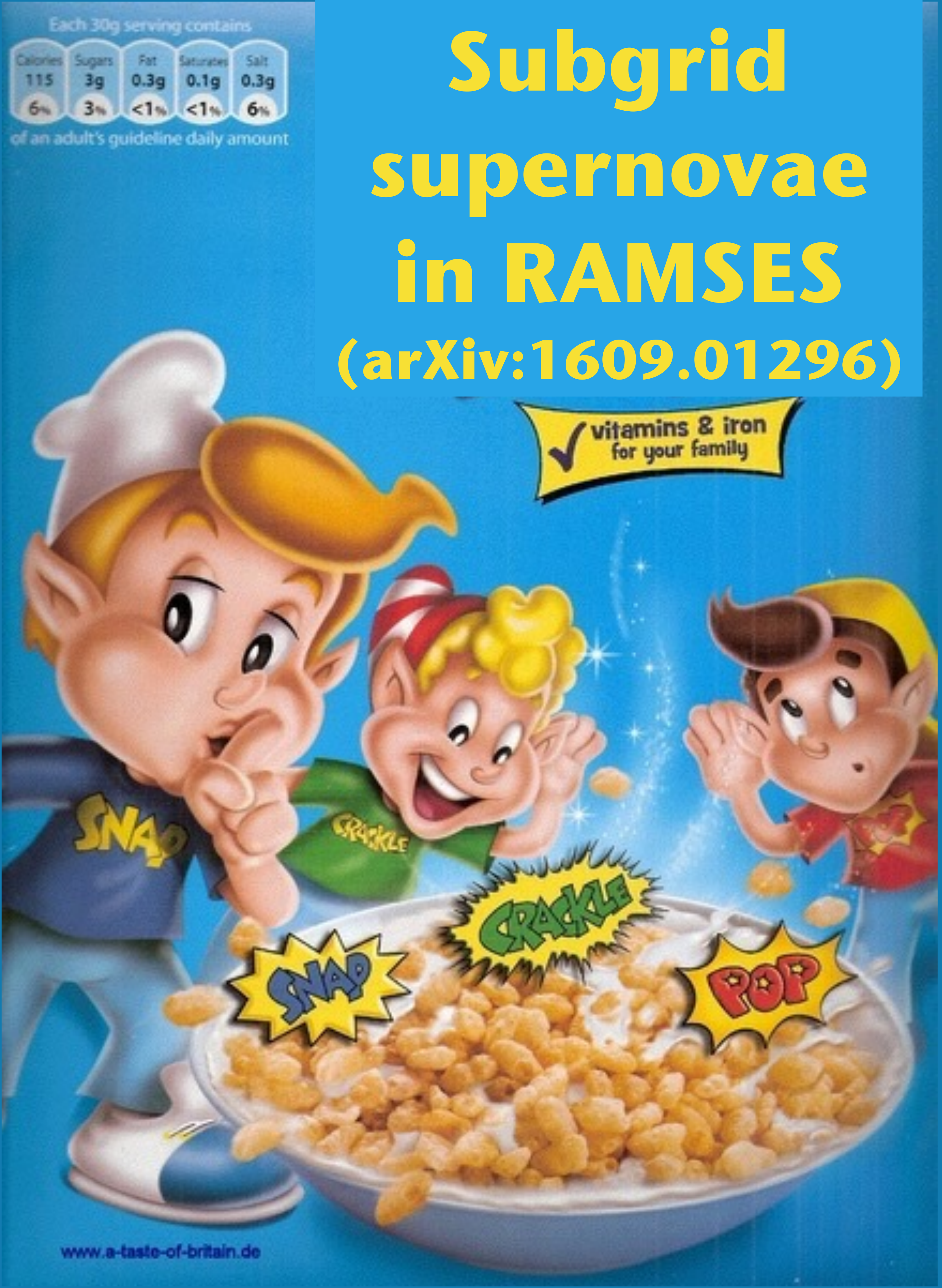
Subgrid supernovae in RAMSES

(arXiv:1609.01296)



Sterrewacht Leiden

Joki Rosdahl

with

Schaye, Dubois, Kimm, Teyssier

IAP, Oct 5th, 2016

CRAL

CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

A note on stellar radiation feedback

'Galaxies that shine: RHD simulations of disk galaxies'

Rosdahl, Schaye, Teyssier, & Agertz, MNRAS, 2015

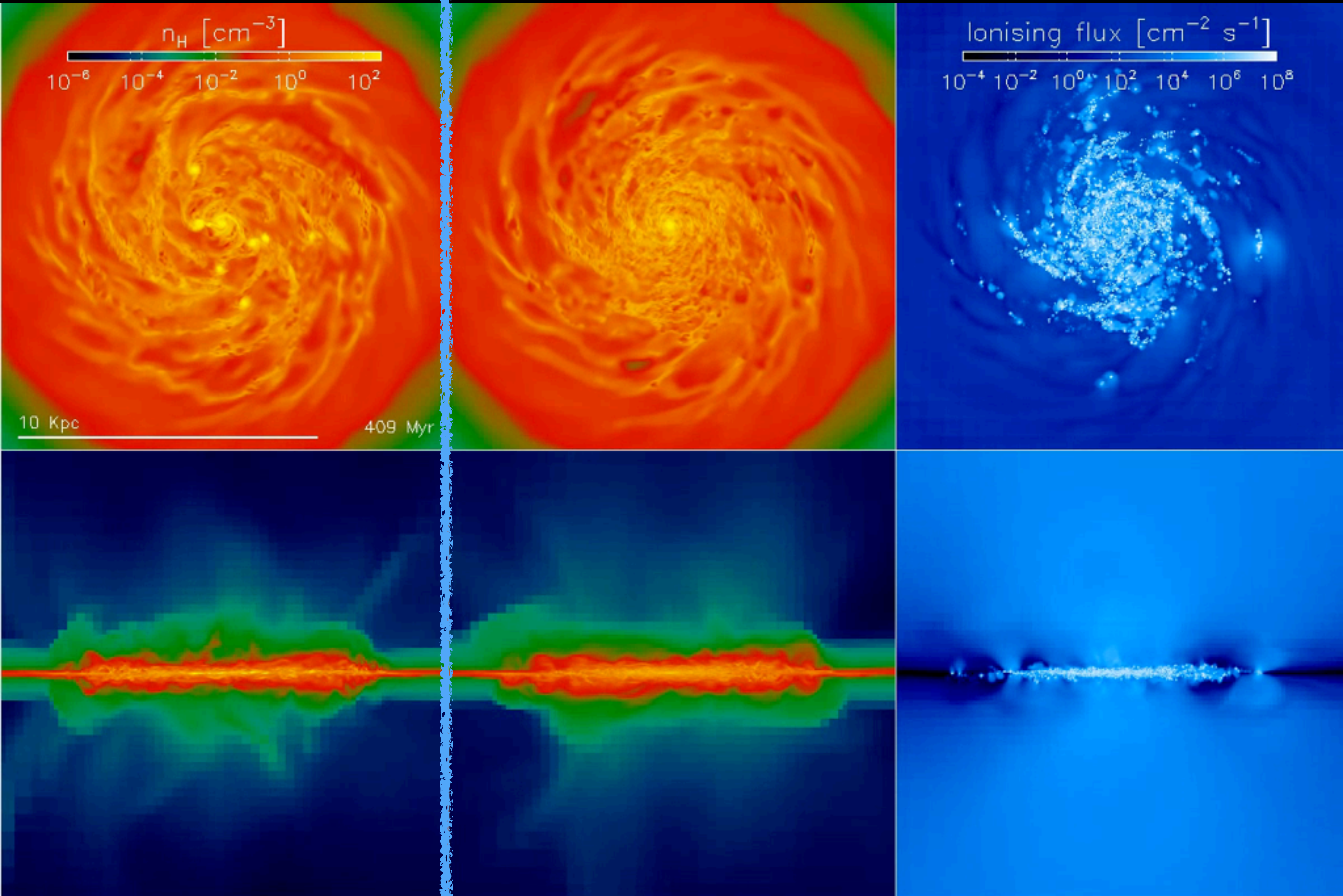
Stellar radiation feedback is a vital component in many recent cosmological simulation projects (FIRE, NIHAO, Vela)

- Photoionisation heating and multi-scattering radiation pressure suppress SFR and generate outflows
- **BUT** implemented with sub-grid recipes, making assumptions about the radiation-gas coupling

We ran (the first) radiation-hydrodynamical simulations of galaxies that directly model those radiation feedback processes, in combination with SN feedback.

Radiation feedback in an isolated galaxy, $\mathrm{M_{baryons}} = 3.5 \times 10^9\ \mathrm{M_\odot}$

SNe only | **SNe + Radiation**



Supernova feedback

So far we combined the stellar radiation with thermal dump SN feedback

Now we want more realistic SN feedback (no numerical overcooling!)

The goal is to study and compare SN recipes in RAMSES, without RT, to see what works and what doesn't.

SN feedback recipes in RAMSES

(free parameters in red)

1. Thermal dump (Katz?)

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2. Stochastic (Dalla Vecchia & Schaye)

- $\Delta T = 10^{7.5}$ K - similar to EAGLE

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3. Delayed cooling (Gerritsen, Teyssier)

- Cooling turned off in SN remnant for 10 Myr

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4. Kinetic feedback (Dubois)

- SN momentum injected into a 300 pc wide sphere
- $\Delta p = \sqrt{2\, M_{\rm swept}\, E_{\rm SN}}$, no thermal losses in the injected momentum
- $M_{\rm swept} = M_{\rm star}$

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5. Mechanical feedback (Kimm)

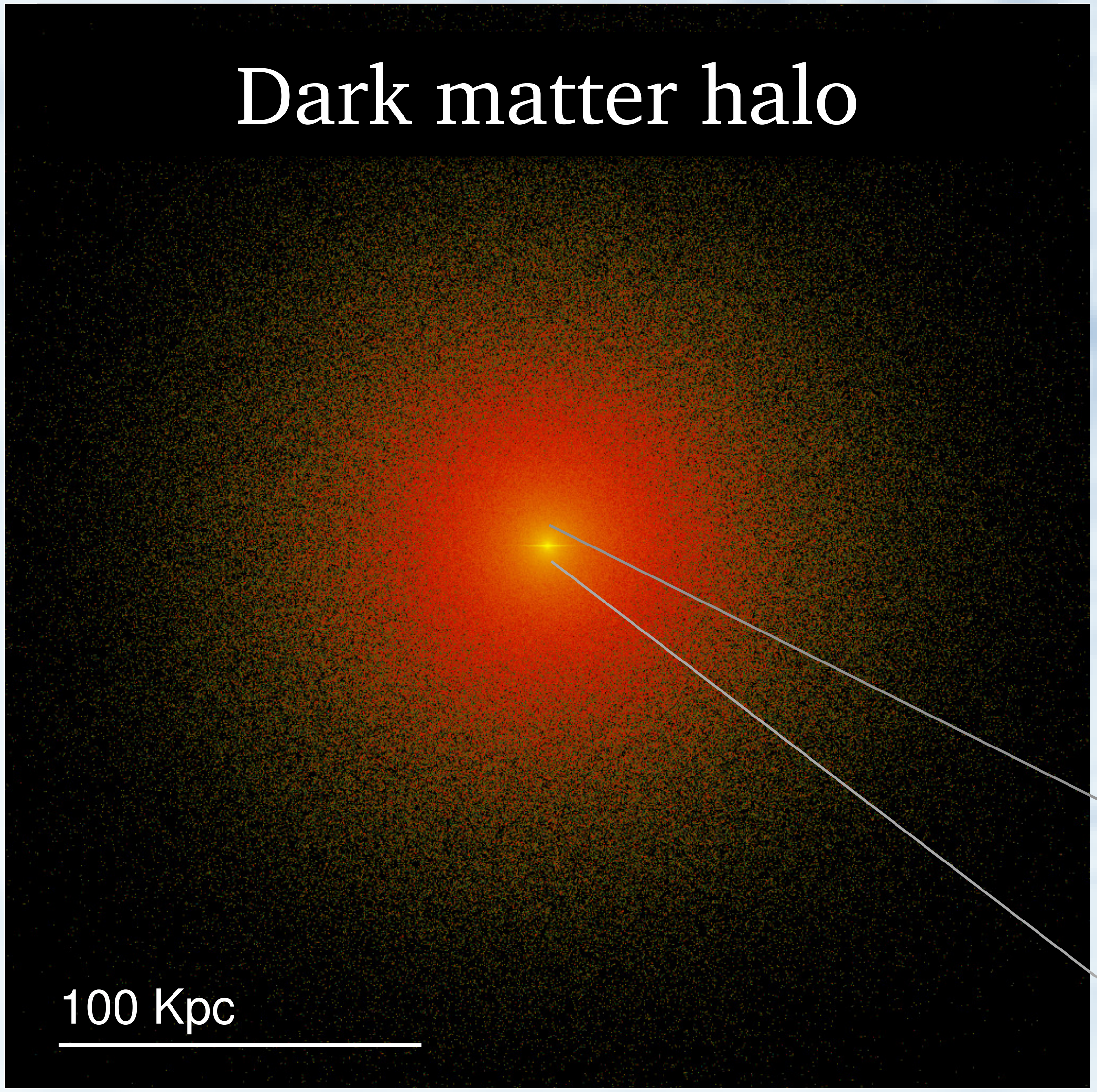
- 'Empirically' motivated momentum injection (Blondin+'98, Thornton+'98, Kim&Ostriker'15)

$$\Delta p_{\rm max} = 3 \times 10^5\ {\rm km/s\ M_\odot} \left(\frac{E_{\rm SN}}{10^{51}\ {\rm erg}} \right)^{16/17} n_{\rm H}^{-2/17} \left(\frac{Z}{Z_\odot} \right)^{-0.14}$$

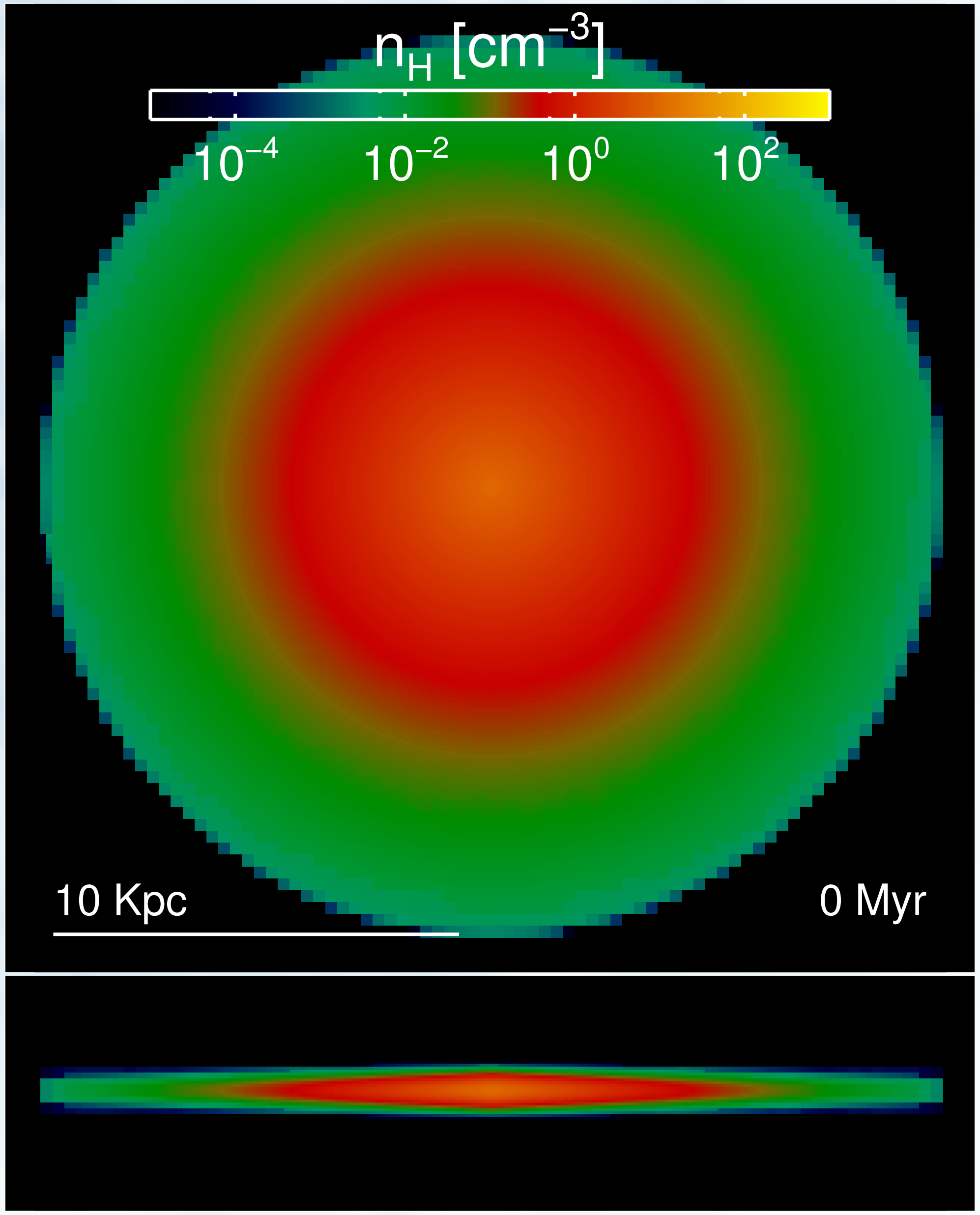
Simulation initial conditions

Galaxy acronym		v_{circ} [km s^{-1}]	R_{vir} [kpc]	L_{box} [kpc]	M_{halo} [M$_\odot$]	M_{disk} [M$_\odot$]	f_{gas}	M_{bulge} [M$_\odot$]	N_{part}	m_* [M$_\odot$]	Δx_{max} [kpc]	Δx_{min} [pc]	Z_{disk} [$Z_\odot$]
G9	Dwarf	65	89	300	10^{11}	3.5×10^9	0.5	3.5×10^8	10^6	2×10^3	2.3	18	0.1
G10	~MW	140	192	600	10^{12}	3.5×10^{10}	0.3	3.5×10^9	10^6	1.6×10^4	4.7	36	1

Isolated galaxy disks with RAMSES (AMR)



Simulation box



Galaxy

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Simulation settings and physics

-Star formation where $n_H > 10\ cm^{-3}$ and $T < 3 \times 10^3$ K

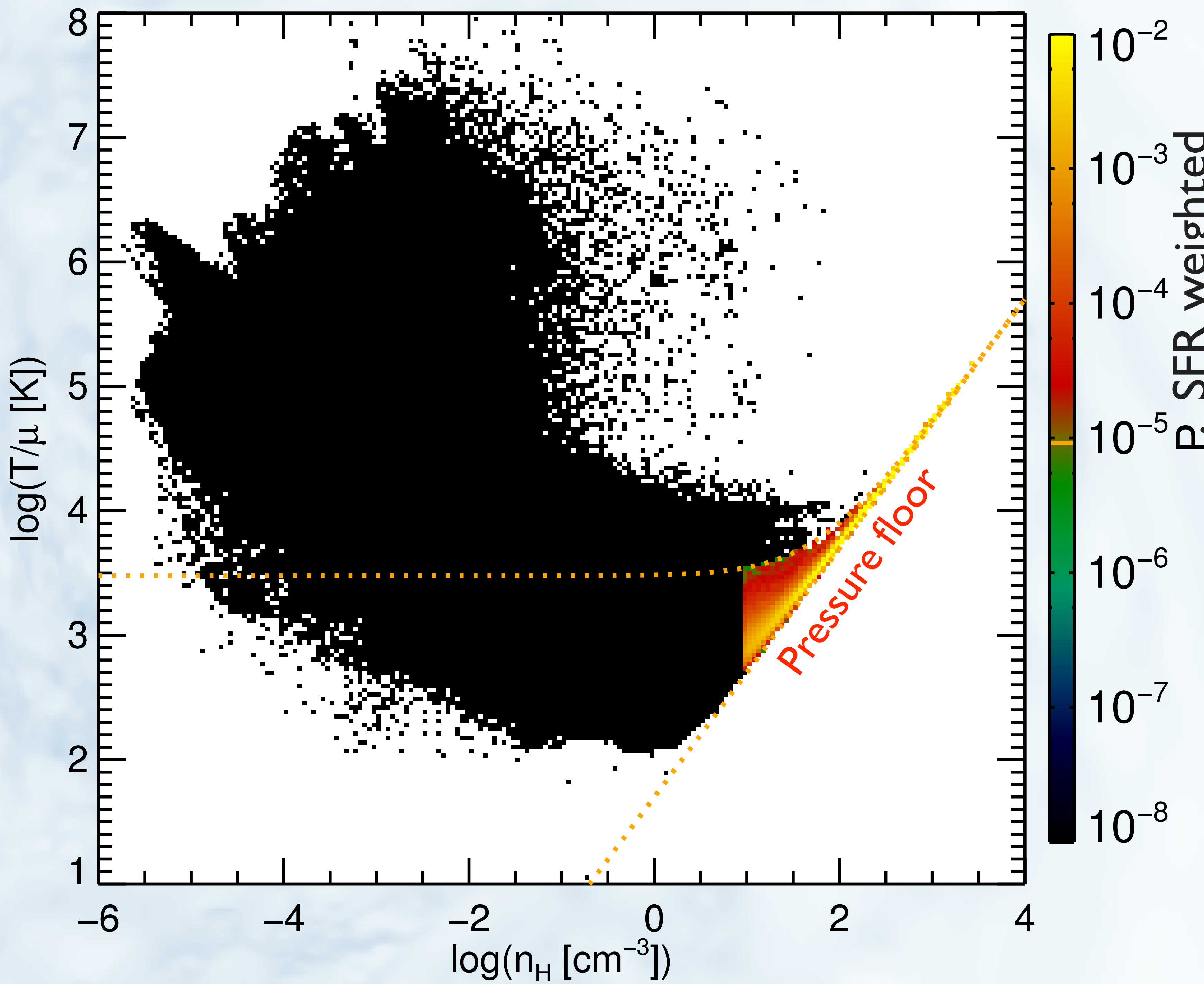
$$\dot{\rho}_* = \epsilon_{sf} \frac{\rho}{t_{ff}} \propto \rho^{3/2}$$

2% (ϵ_{sf})

-Instantaneous SN at 5 Myr

$$\epsilon_{SN} = 10^{51}\ \text{erg}\ 0.02 \frac{m_*}{M_\odot}$$

-Metal cooling to ~100 K



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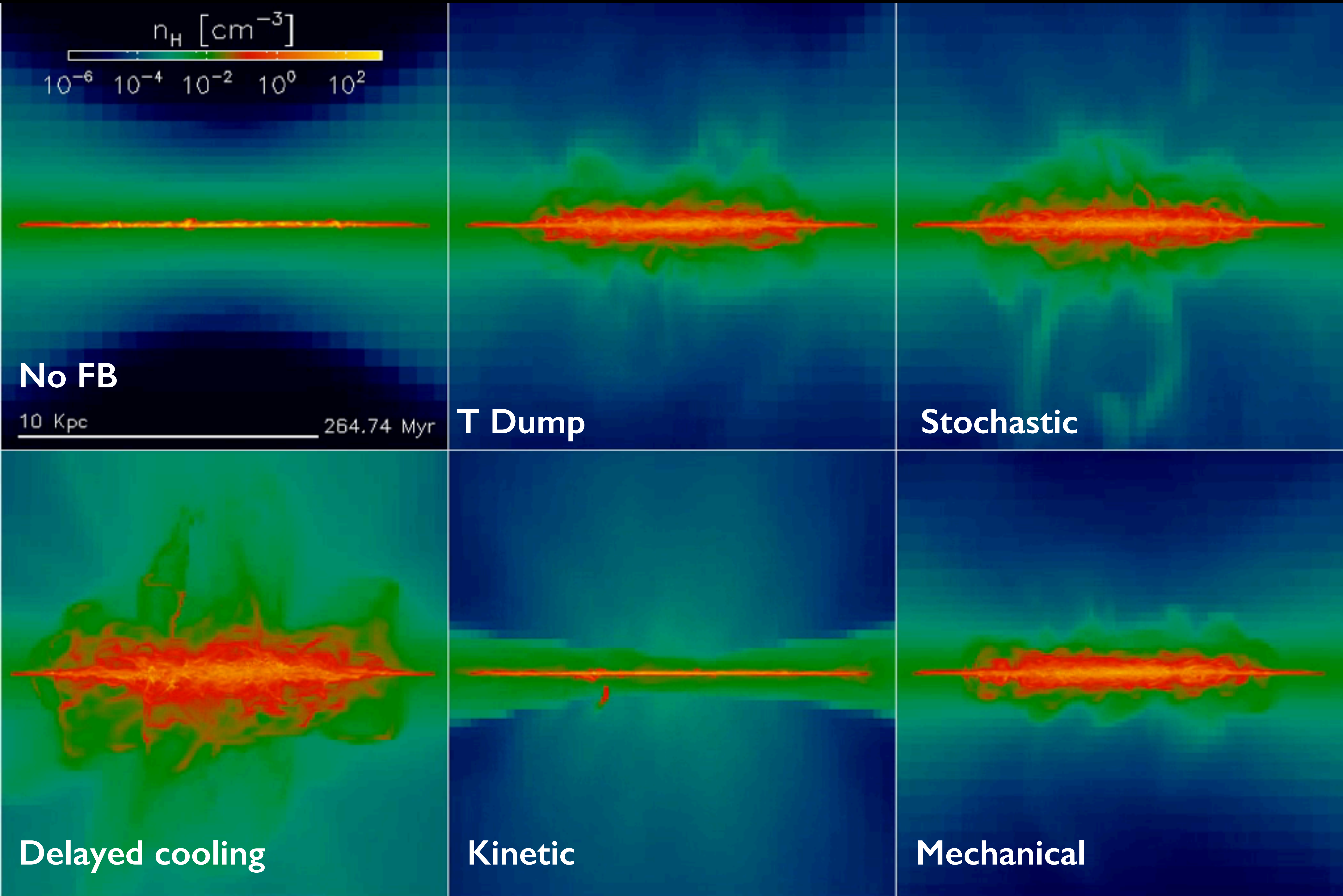
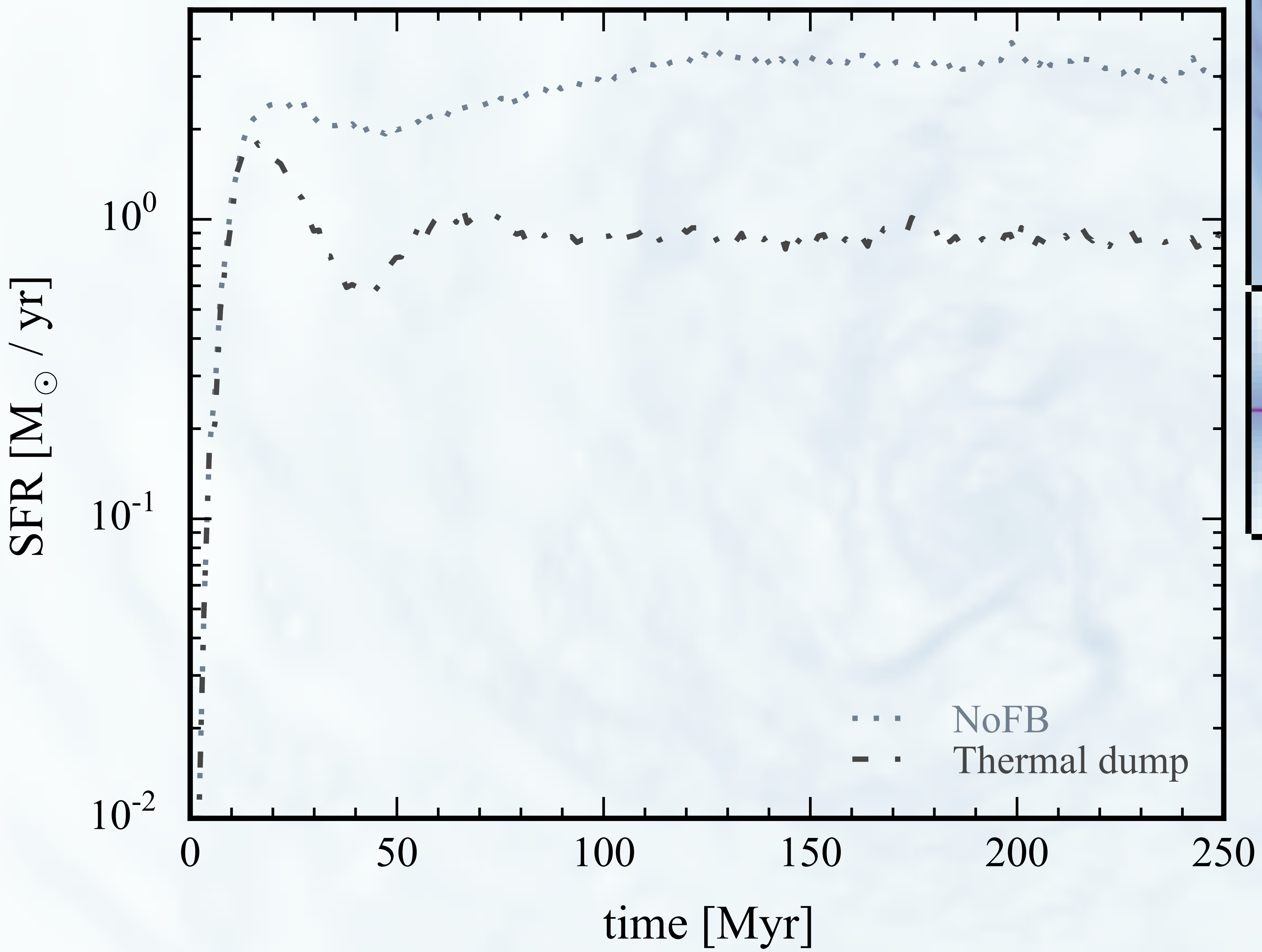
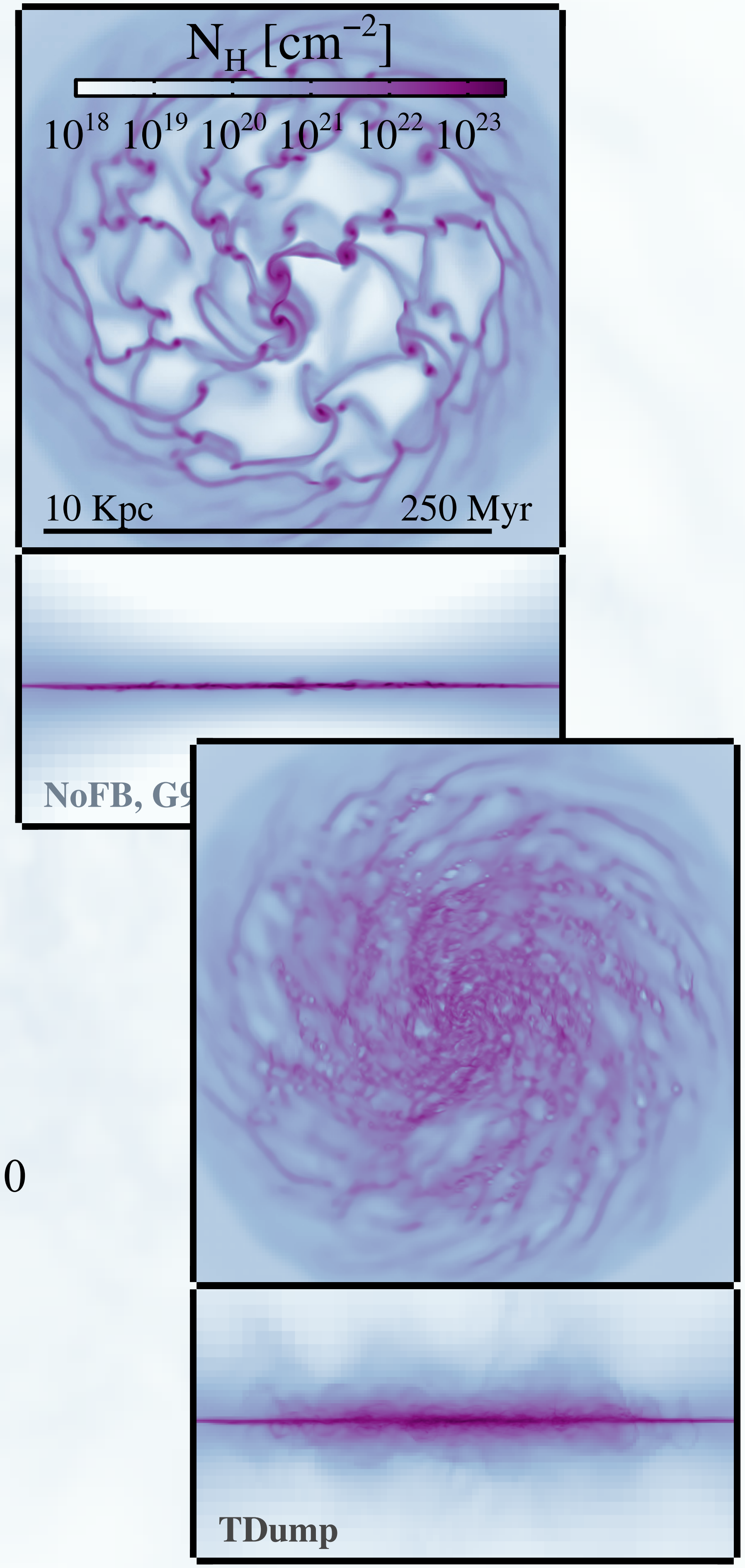
Results, dwarf galaxy

$M_{\text{baryons}} = 3.5 \times 10^9 \; M_\odot$



SFR comparison
dwarf galaxy, Δx=18 pc





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SFR comparison
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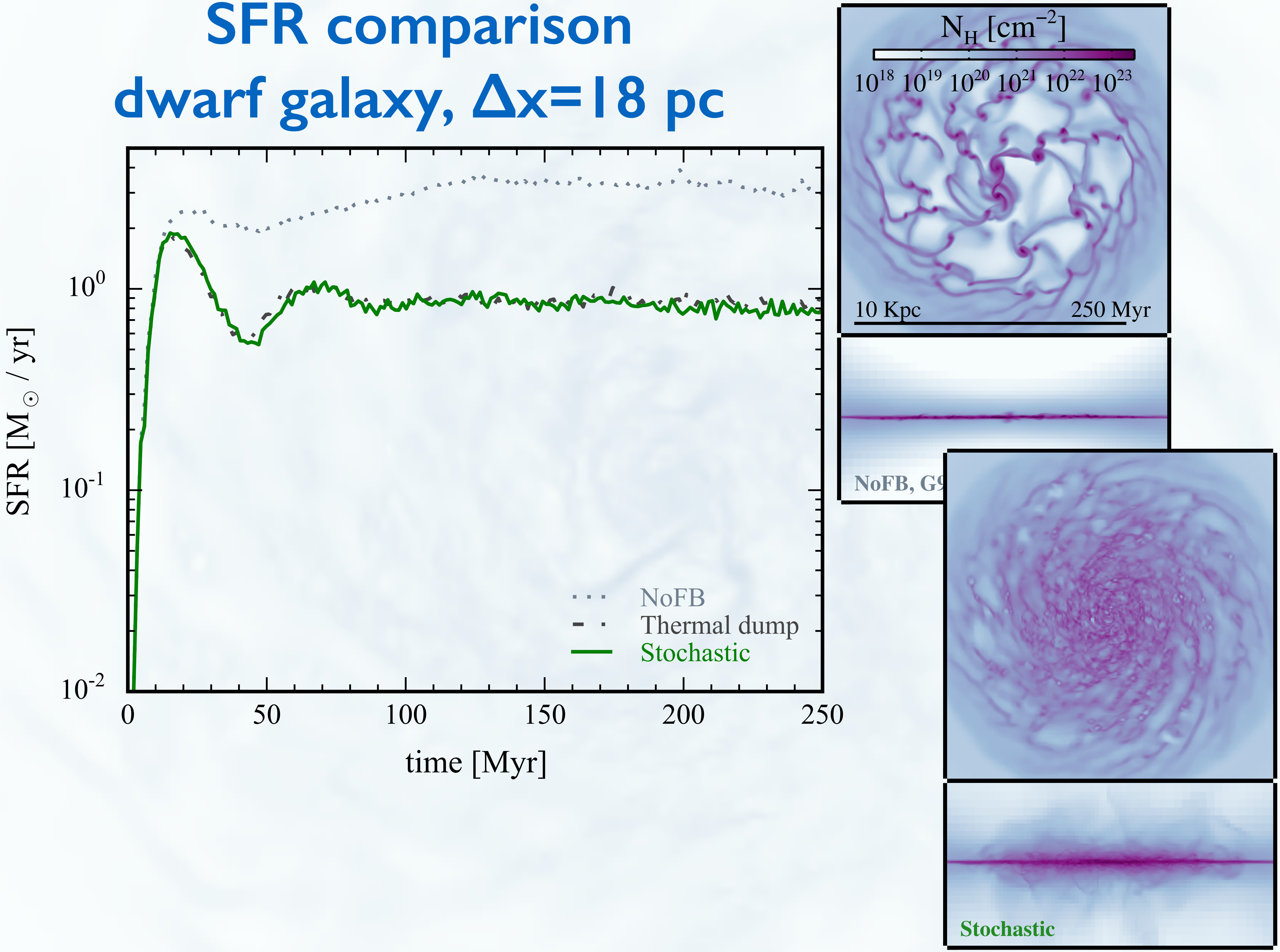

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SFR comparison
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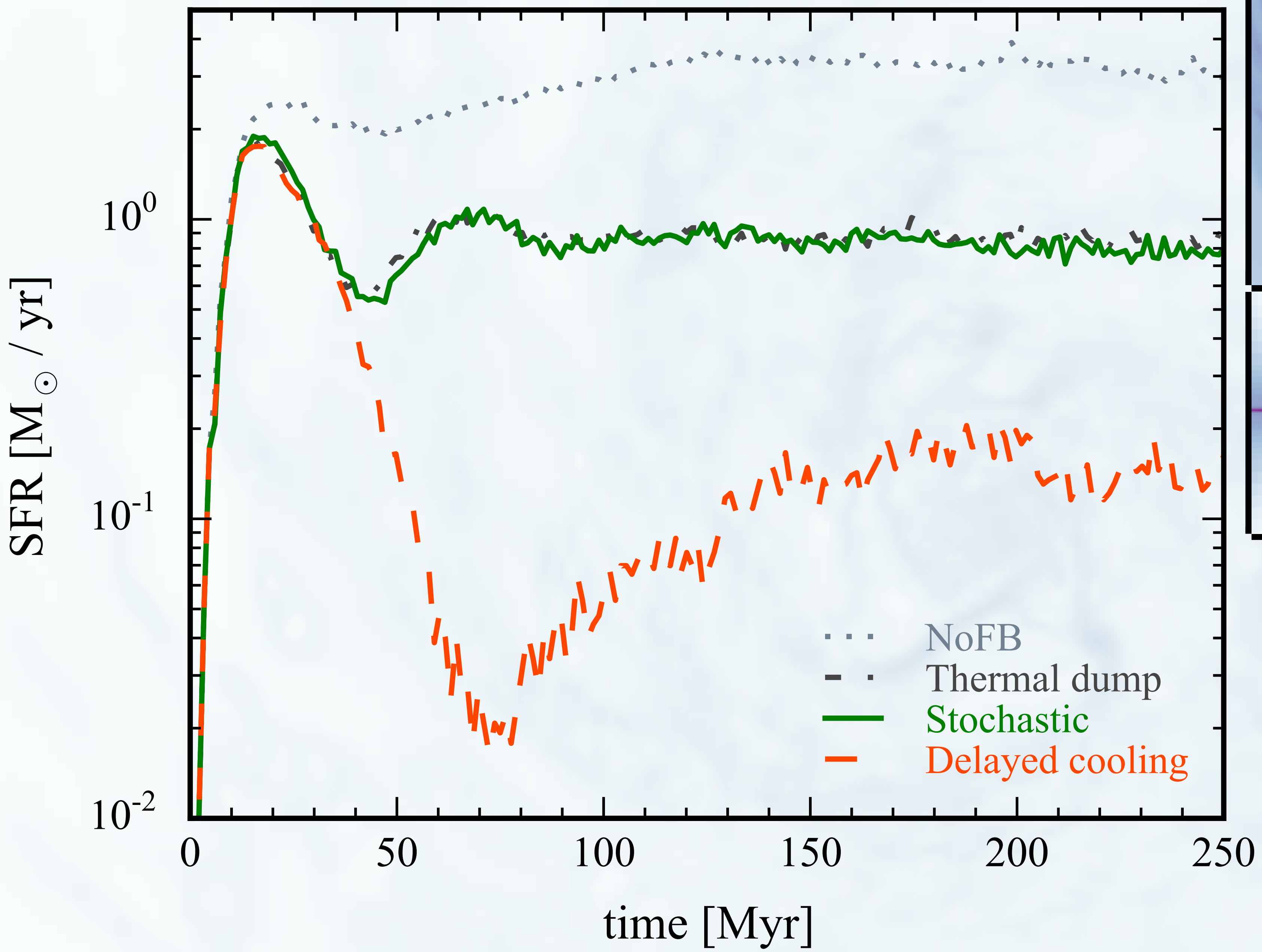

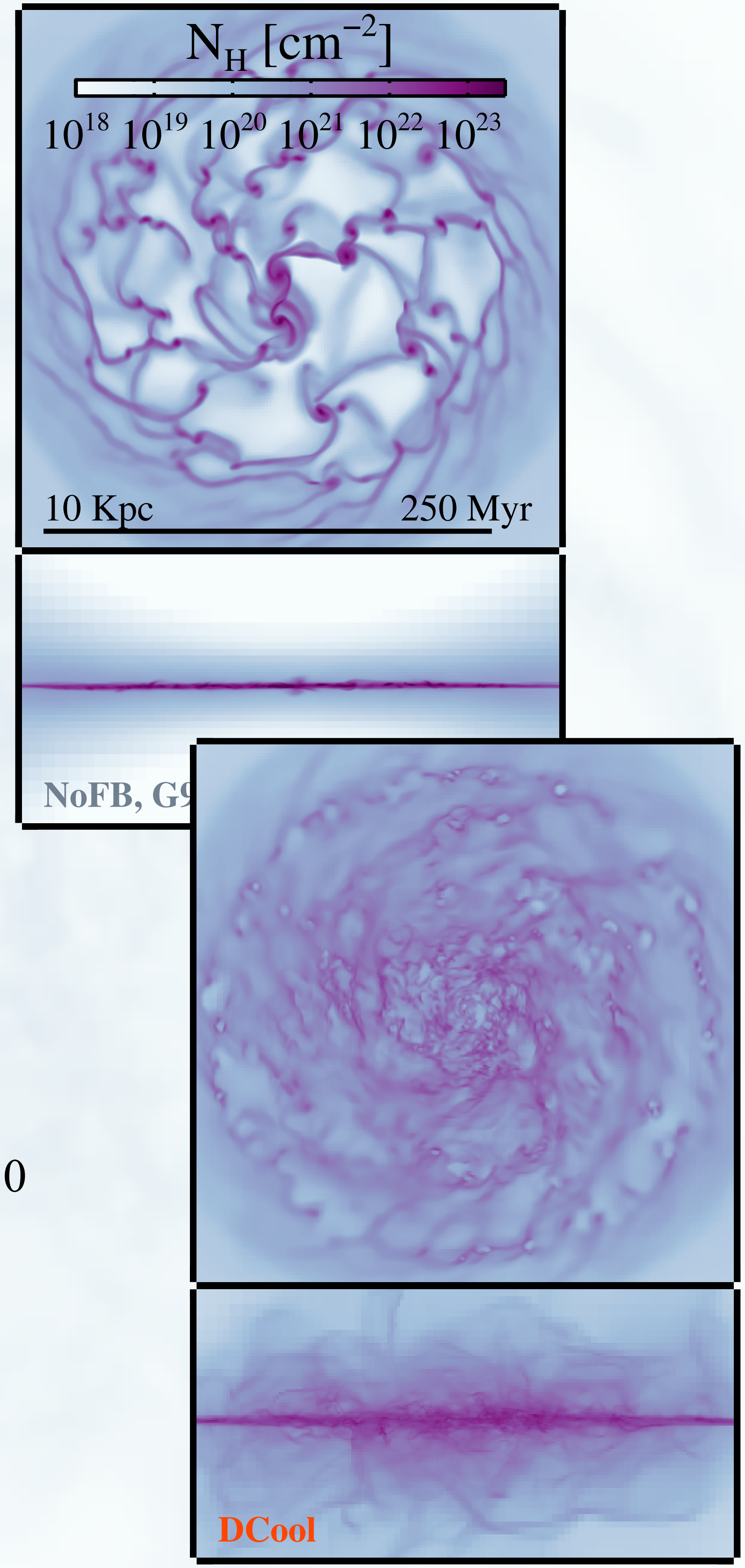

SFR comparison
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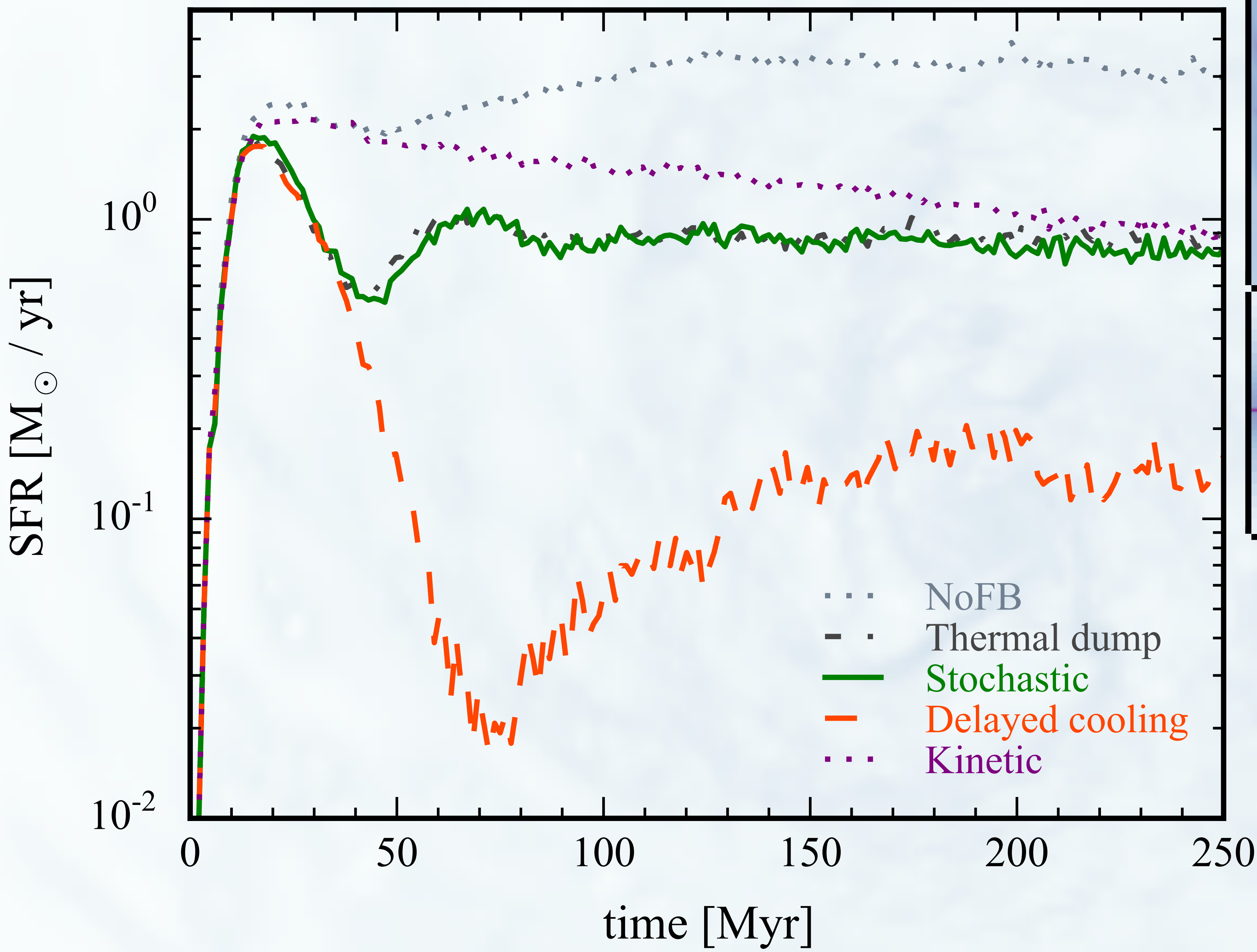
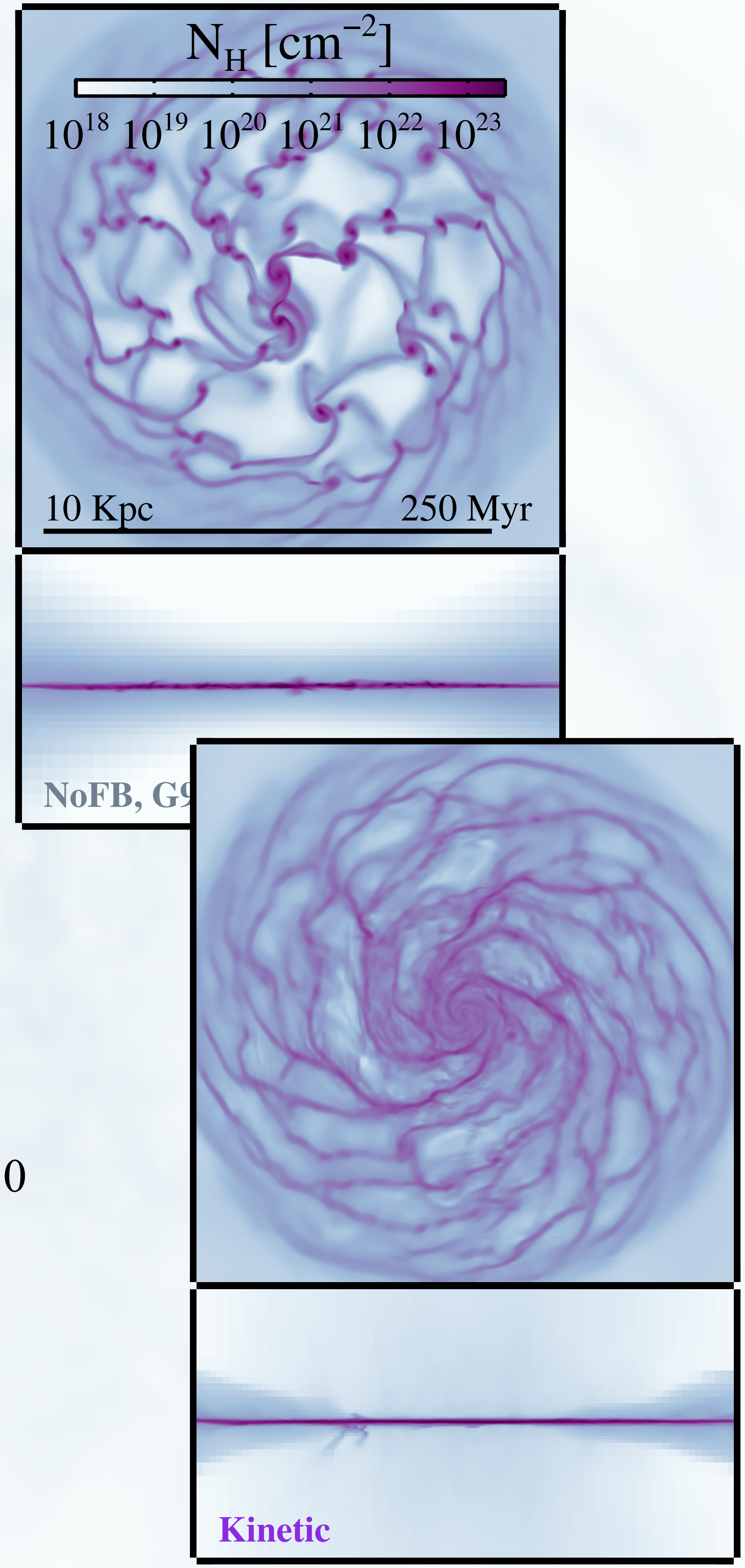
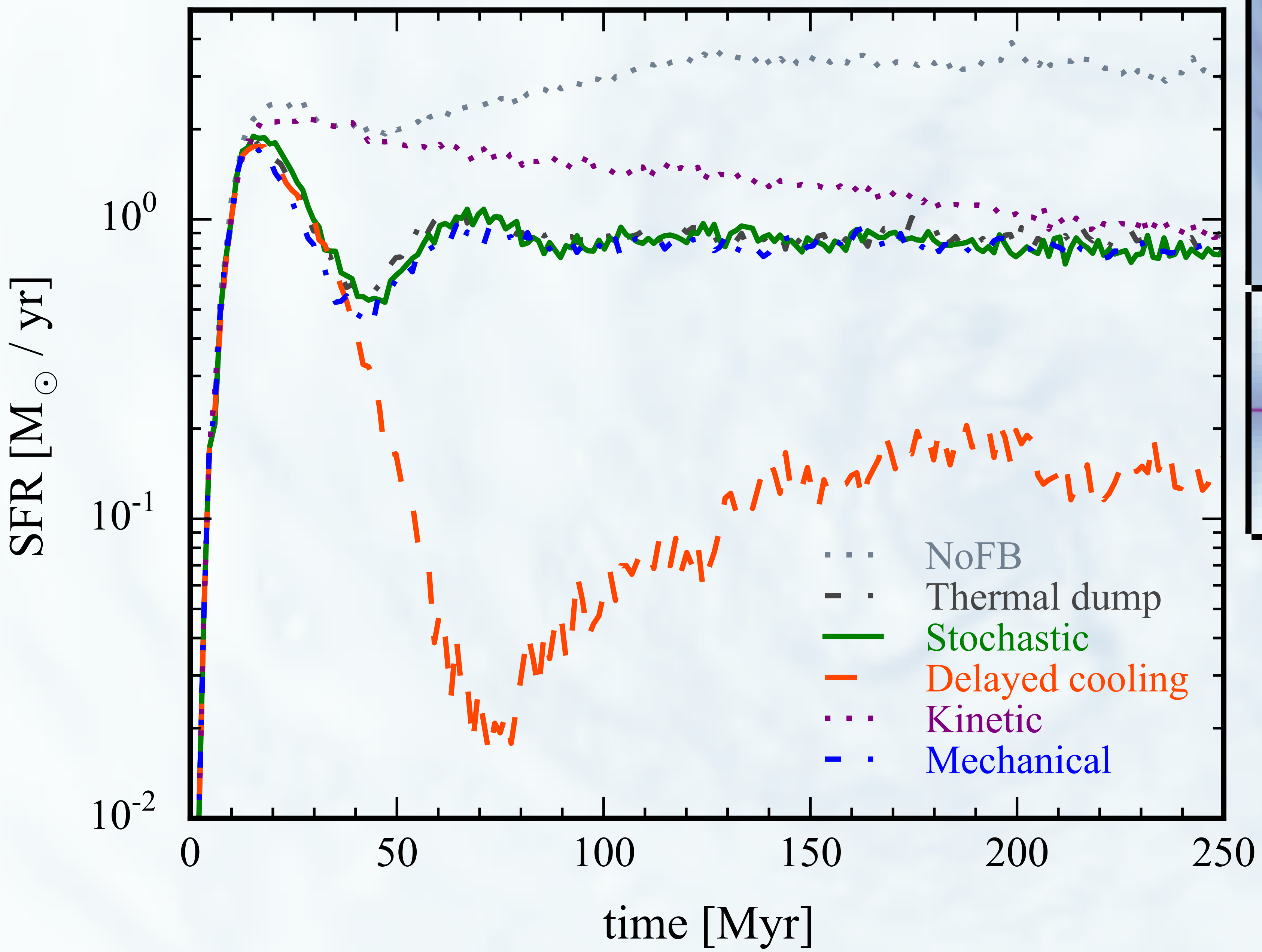
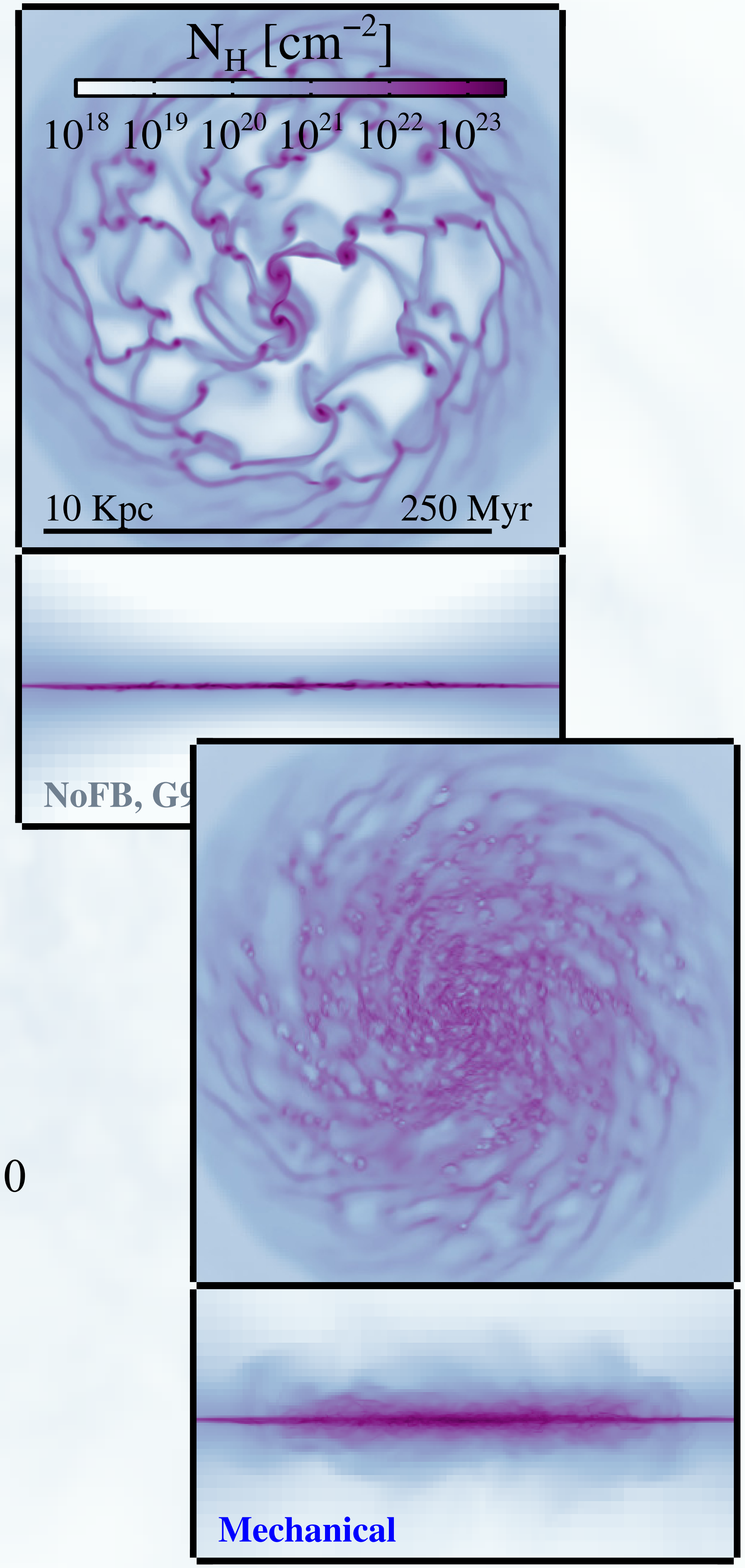




SFR comparison
dwarf galaxy, Δx=18 pc





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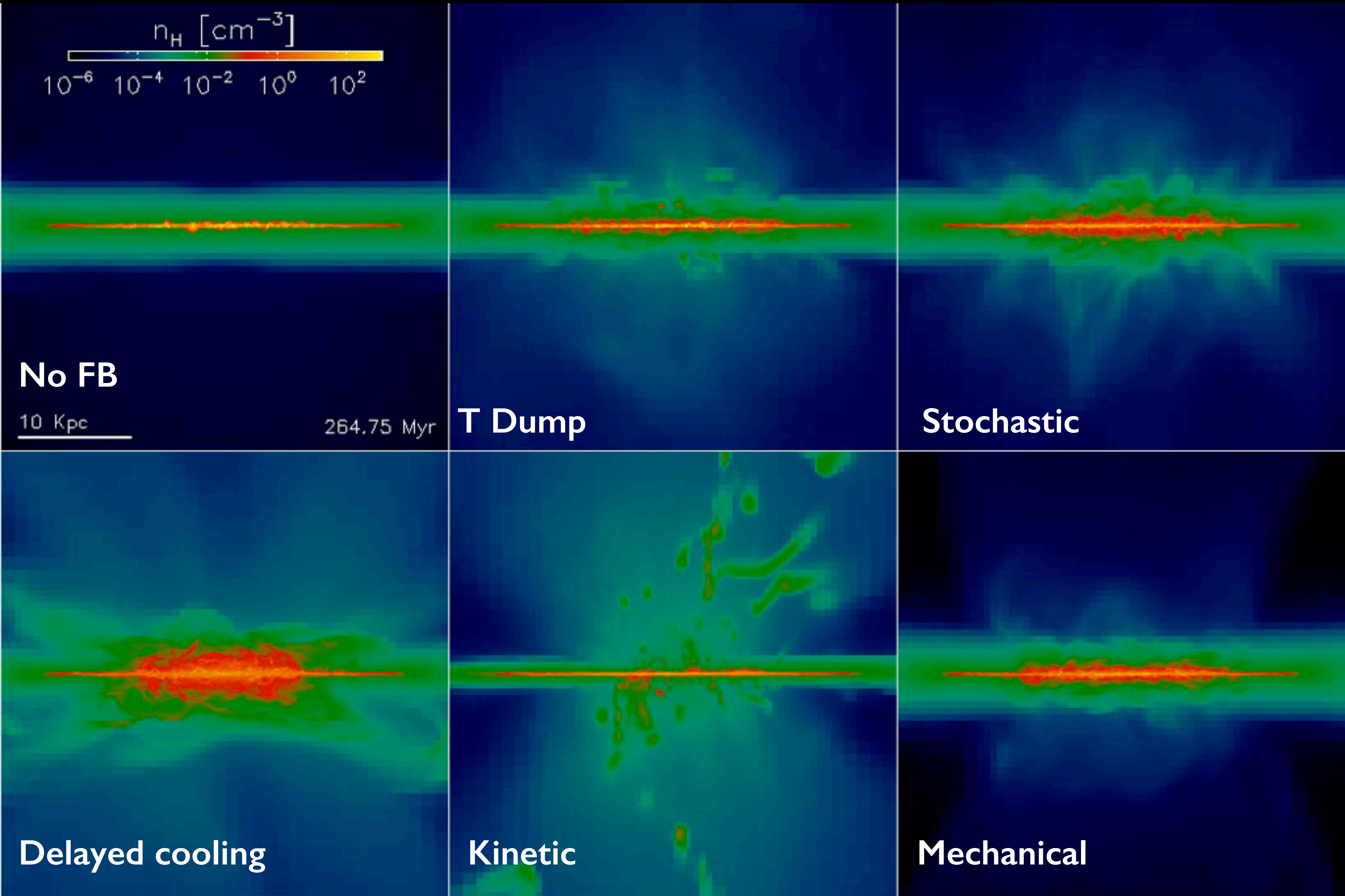
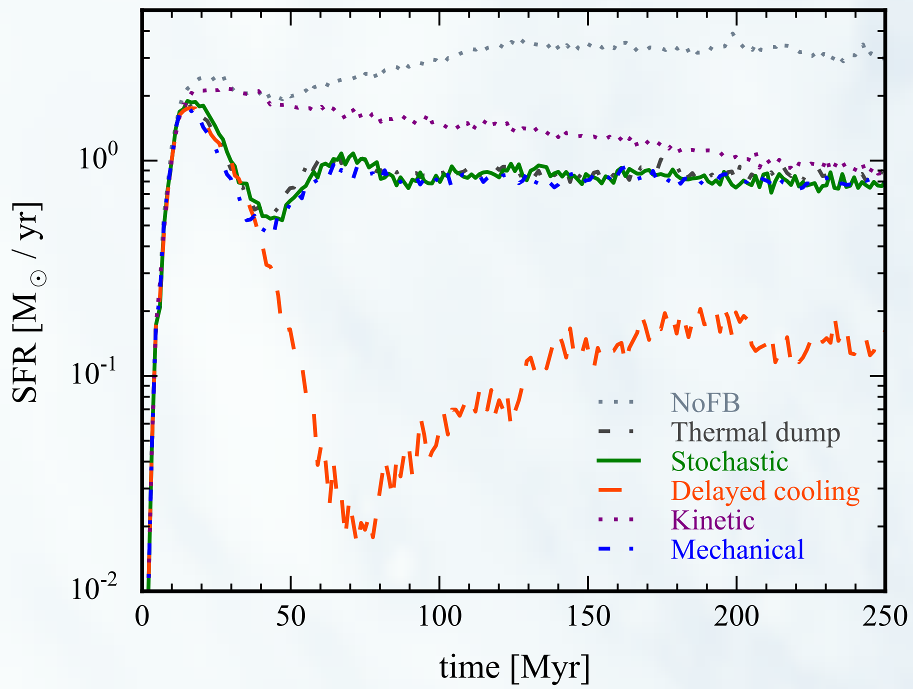
Massive (MW) galaxy

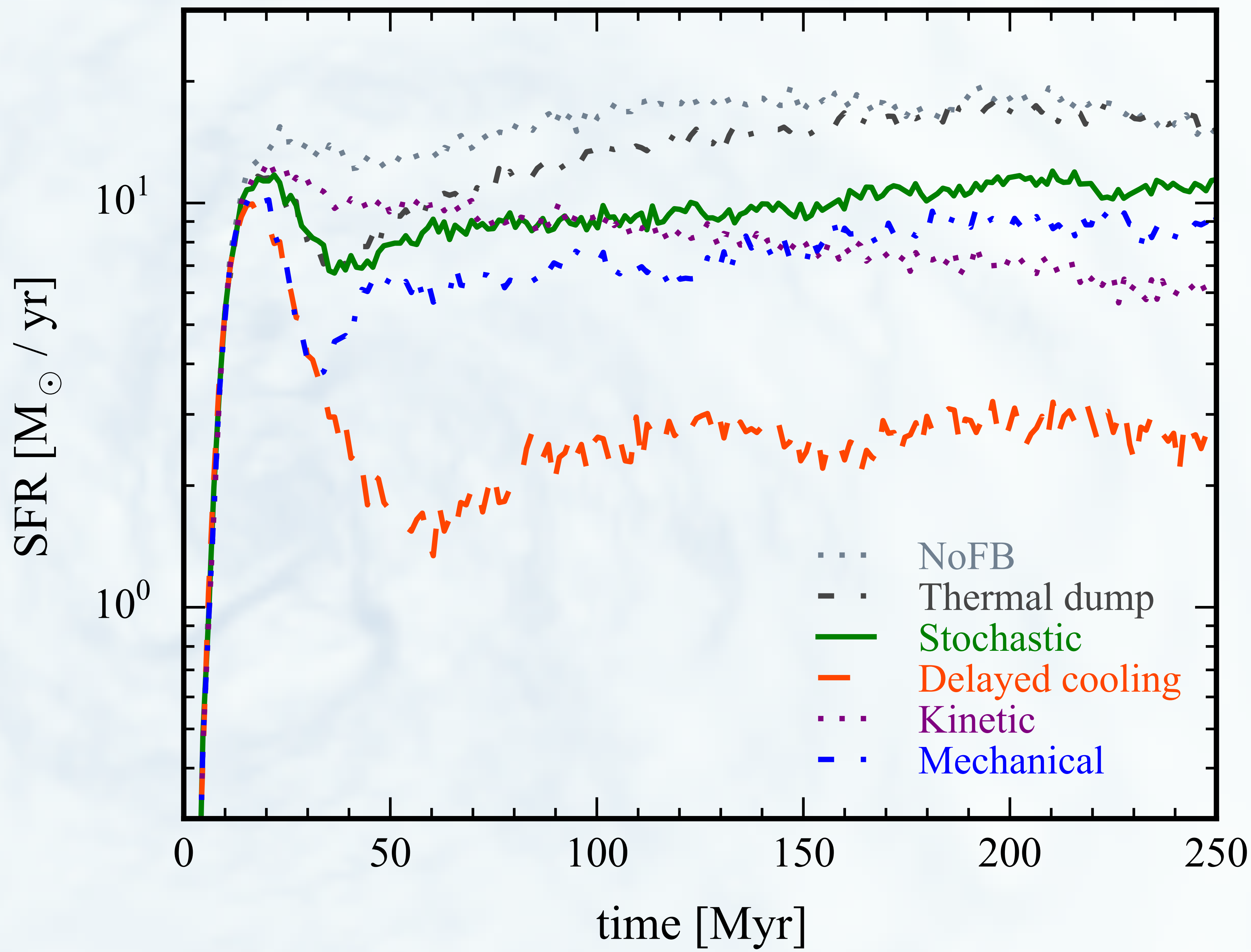


SFR comparison, massive galaxy

Dwarf



MW



Galaxy acronym		$v_{\rm circ}$ [km s^{-1}]	$R_{\rm vir}$ [kpc]	$L_{\rm box}$ [kpc]	$M_{\rm halo}$ [M$_\odot$]	$M_{\rm disk}$ [M$_\odot$]	$f_{\rm gas}$	$M_{\rm bulge}$ [M$_\odot$]	$N_{\rm part}$	m_* [M$_\odot$]	$\Delta x_{\rm max}$ [kpc]	$\Delta x_{\rm min}$ [pc]	$Z_{\rm disk}$ [$Z_\odot$]
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SFR comparison

Why are TDump, Stochastic, and Mechanical feedback so similar in the low mass galaxy?

…Because stochastic feedback = thermal dump at low density

Stochastic SN probability in dwarf:

$$p_{\rm SN} = \frac{E_{\rm SN}}{\Delta\epsilon \; m_{\rm cell}}$$
$$= 1.6 \left(\frac{\eta_{\rm SN}}{0.2}\right) \left(\frac{m_*}{2 \times 10^3 \ {\rm M}_\odot}\right) \left(\frac{\Delta x}{18 \ {\rm pc}}\right)^{-3} \left(\frac{n_{\rm H}}{10 \ {\rm cm}^{-3}}\right)^{-1} \left(\frac{\Delta T_{\rm stoch}}{10^{7.5} \ {\rm K}}\right)^{-1}$$

…same in MW,
but higher SN densities

SFR comparison

Why are TDump, Stochastic, and Mechanical feedback so similar in the low mass galaxy?

…Because stochastic feedback = thermal dump at low density

…and because mechanical feedback is 'resolved' at low density

Mechanical feedback:

momentum injection depends on the local mass-loading factor:

$$\Delta p = \frac{w_c}{N_{\rm inj}} \begin{cases} \sqrt{2\chi\, m_{\rm ej}\, f_e\, E_{\rm SN}} & \text{if } \chi < \chi_{\rm tr}, \\ 3\times10^5\, {\rm M_\odot}\, \frac{\rm km}{\rm s}\, {\rm E}_{51}^{\frac{16}{17}}\, {\rm n}_0^{-\frac{2}{17}}\, {\rm Z}'^{-0.14} & \text{otherwise.} \end{cases}$$

$$\chi \equiv \frac{\Delta m_{\rm W}}{\Delta m_{\rm ej}} = 0.63\, \chi_{\rm tr} \left(\frac{w_c}{4}\right)^{-1} \left(\frac{n_{\rm H}}{10\,{\rm cm^{-3}}}\right)^{\frac{21}{17}} \left(\frac{\Delta x}{18\,{\rm pc}}\right)^{3} \left(\frac{\eta_{\rm SN}}{0.2}\right)^{-\frac{15}{17}} \left(\frac{m_*}{2\times10^3\,{\rm M_\odot}}\right)^{-\frac{15}{17}} \left(\frac{m_{\rm SN}}{10\,{\rm M_\odot}}\right)^{\frac{15}{17}} \left(\frac{Z}{0.1\,Z_\odot}\right)^{0.28}.$$

χ is ~factor two higher in MW, mostly due to higher metallicity

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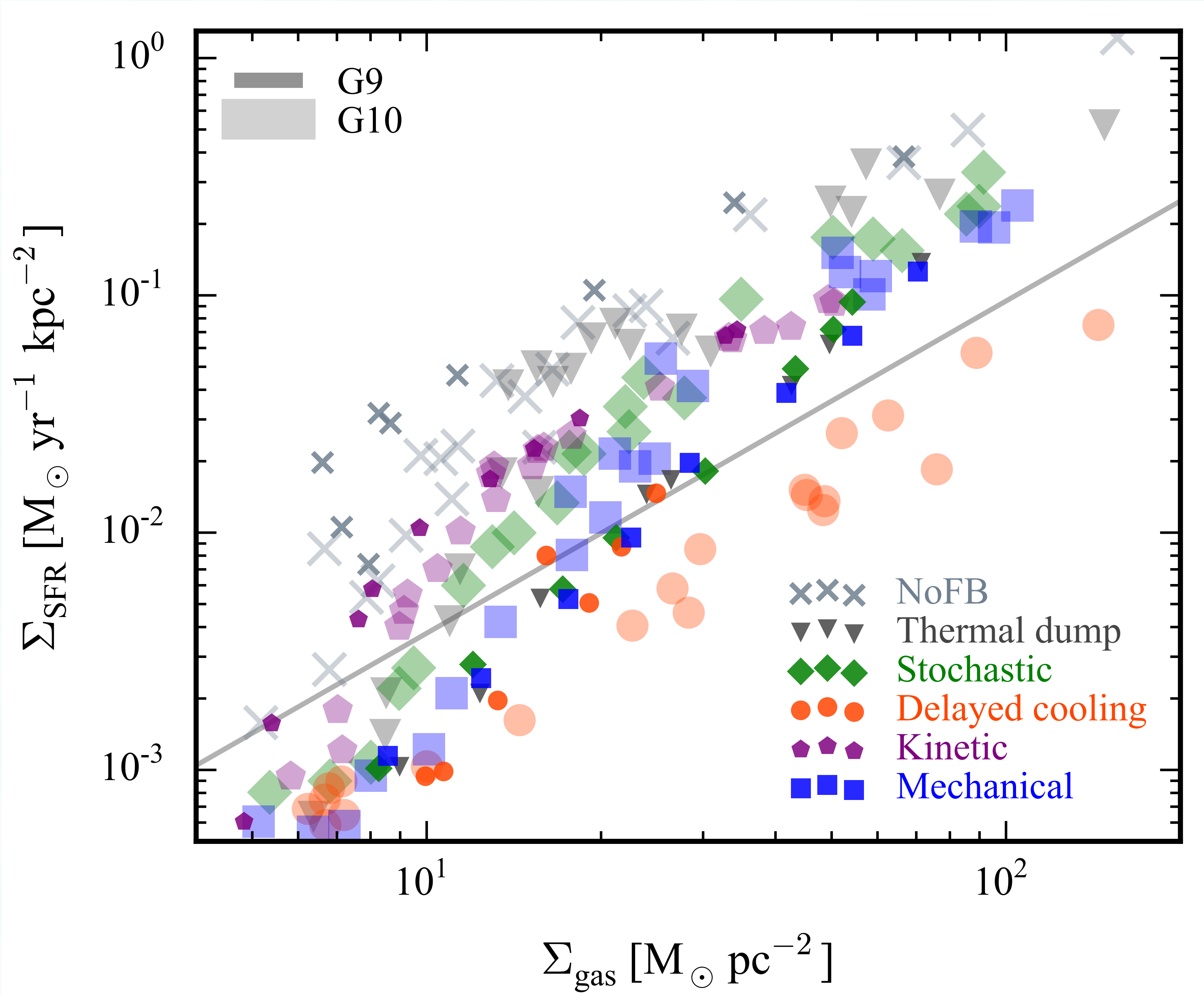
Kennicutt-Schmidt relation

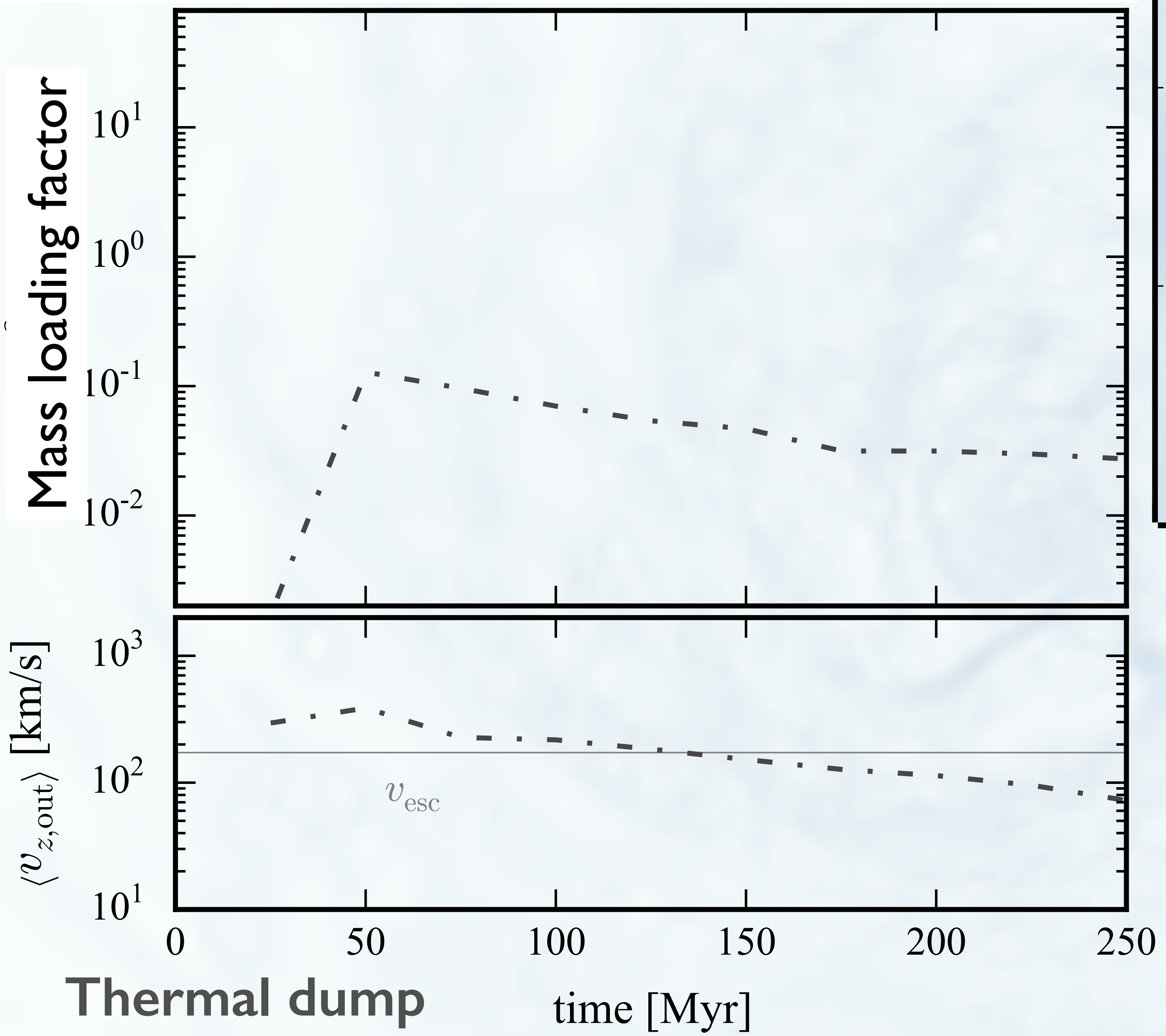


2%

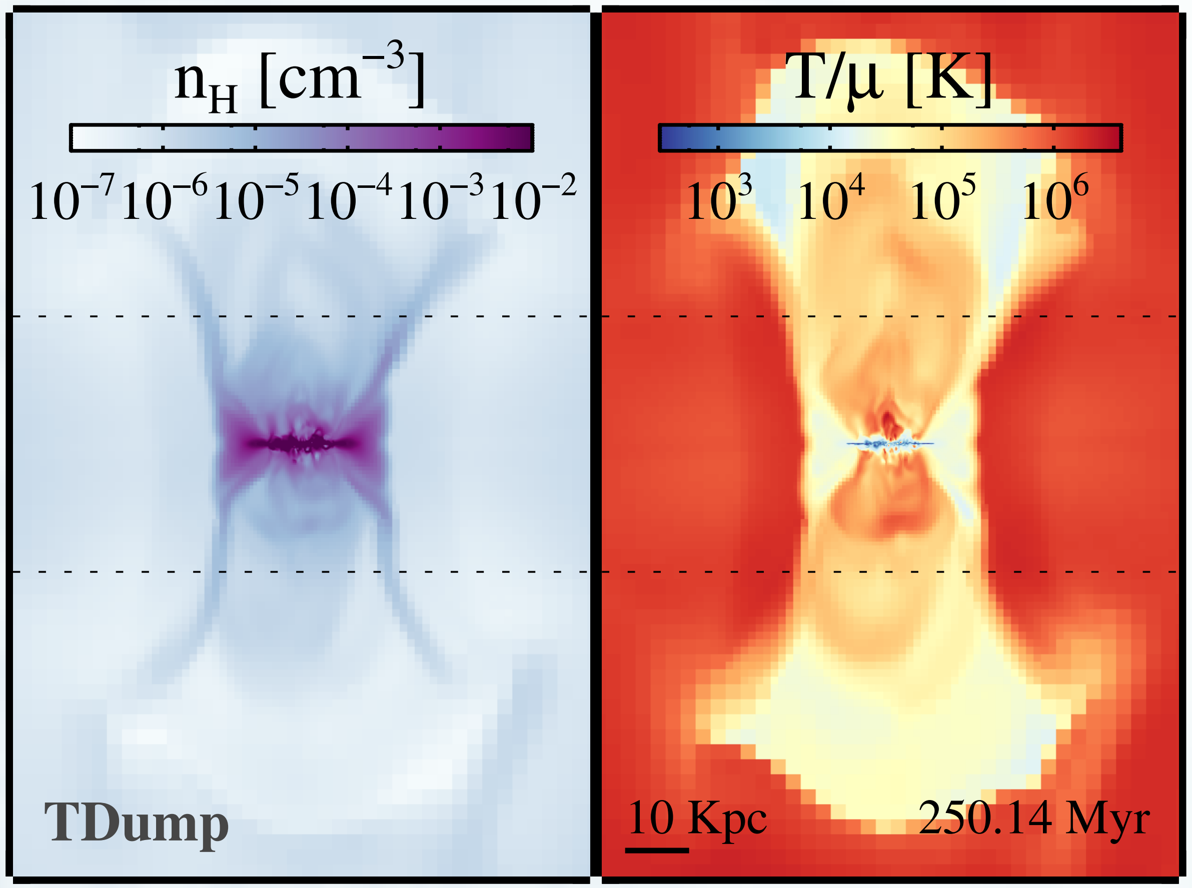
$$\dot{\rho}_* = \epsilon_{sf} \frac{\rho}{t_{ff}} \propto \rho^{3/2}$$

Only delayed cooling can reproduce observed SF inefficiency.
With other recipes, only lower ϵ_{sf} helps in getting more realistic KS relation
…but the cost is that feedback then does nothing.

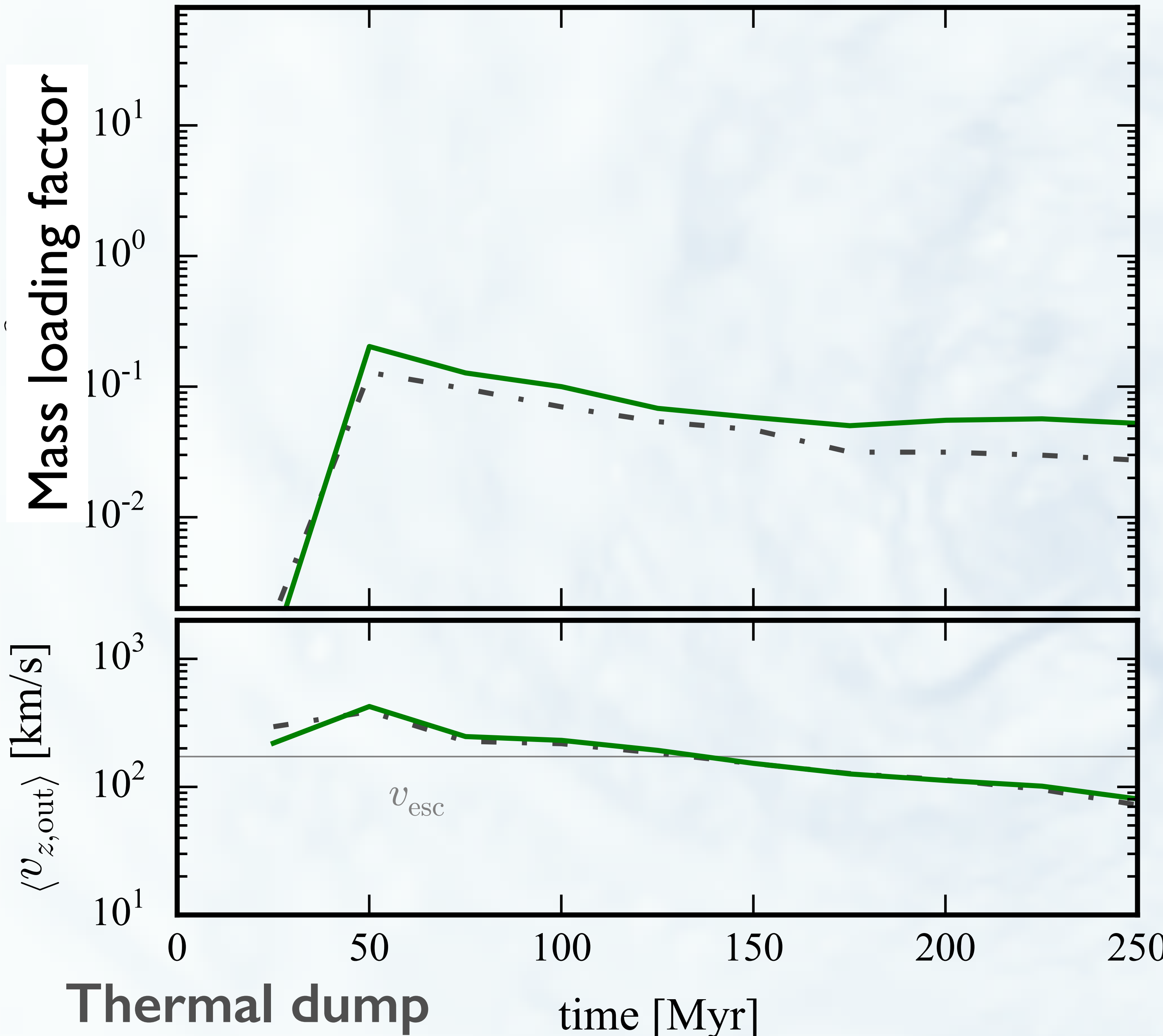
Outflows 20 kpc from dwarf



Thermal dump

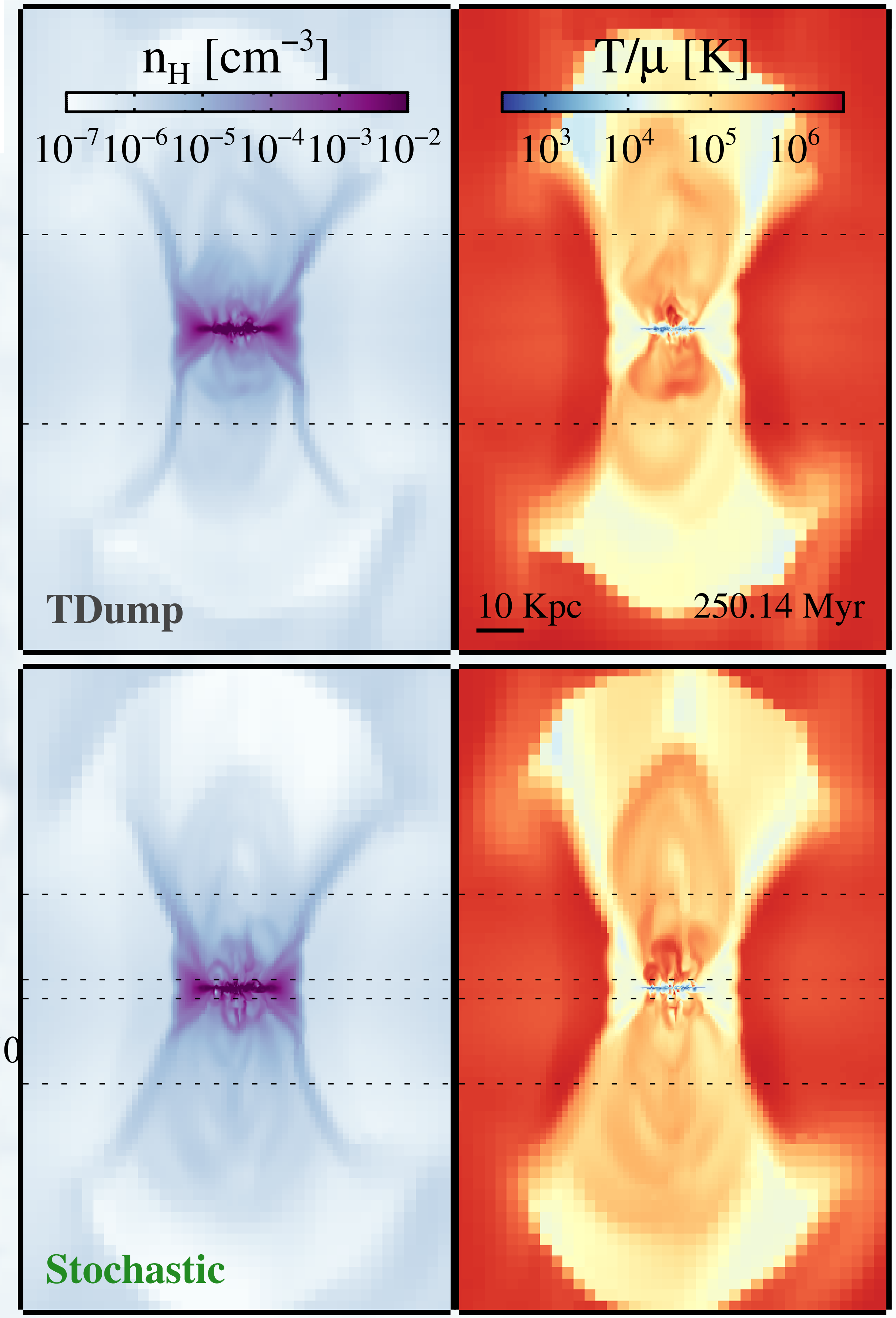


Outflows 20 kpc from dwarf



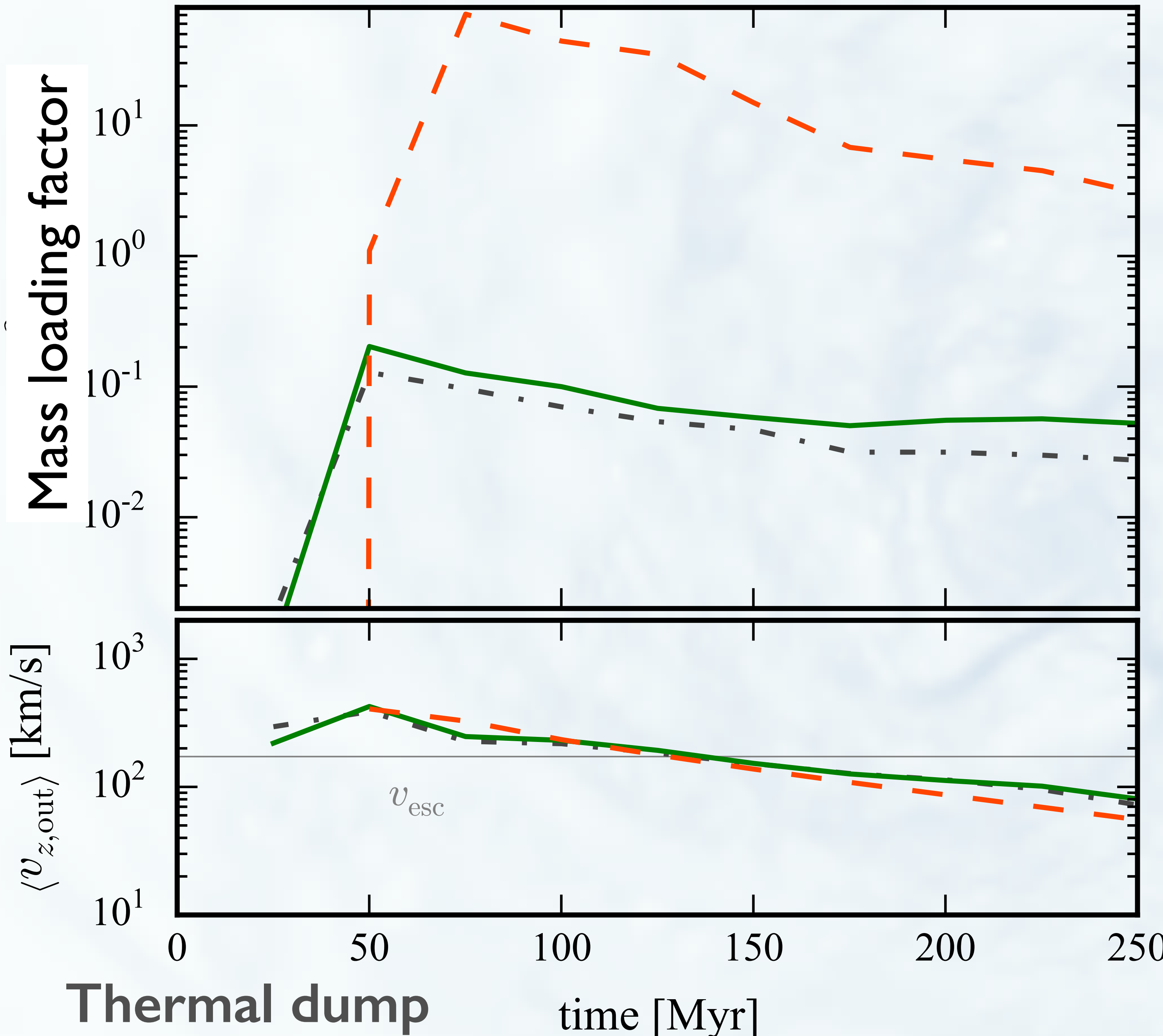
Thermal dump
Stochastic

Outflows

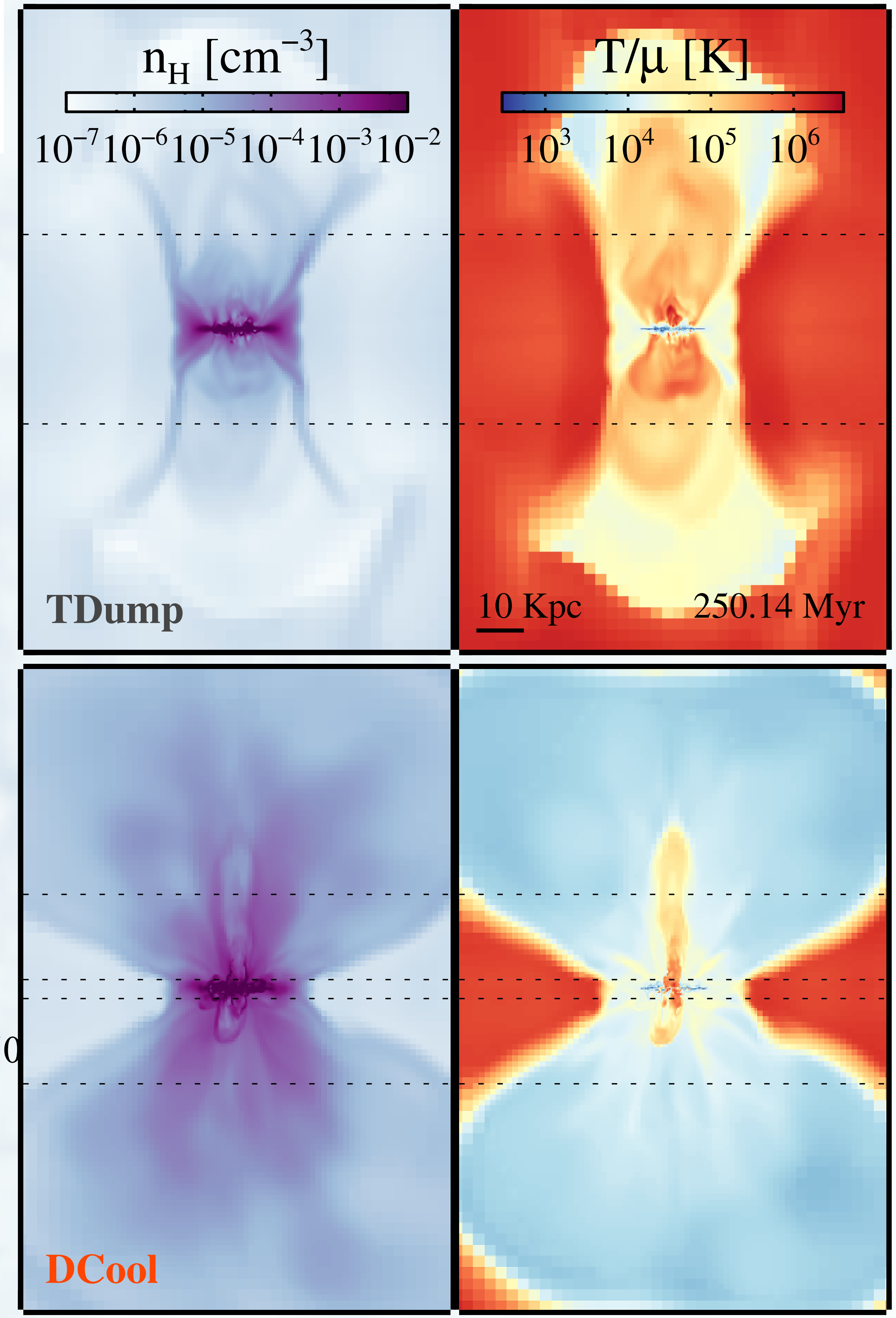


Outflows 20 kpc from dwarf

Outflows

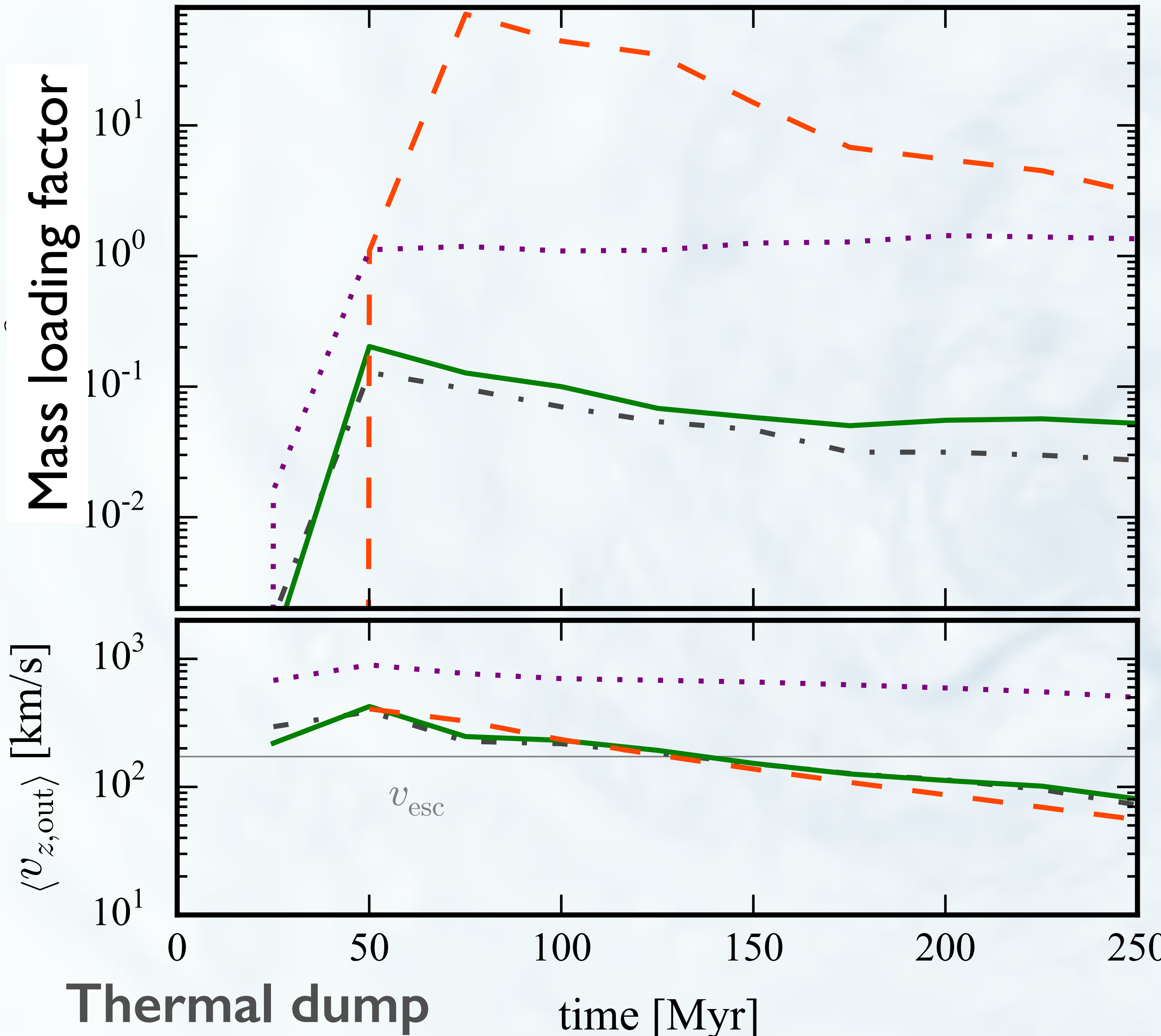


Thermal dump
Stochastic
Delayed Cooling

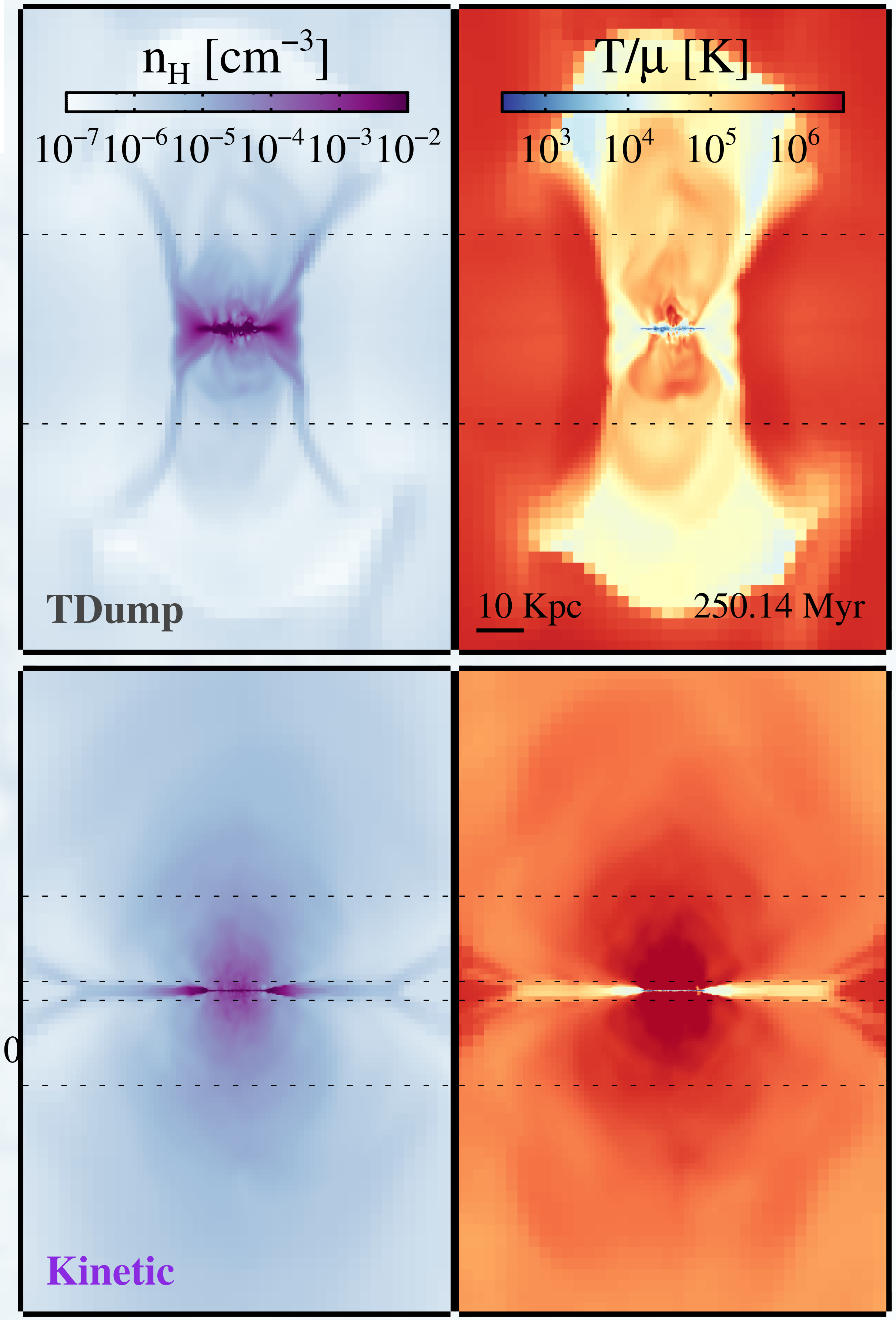


Outflows

Outflows 20 kpc from dwarf

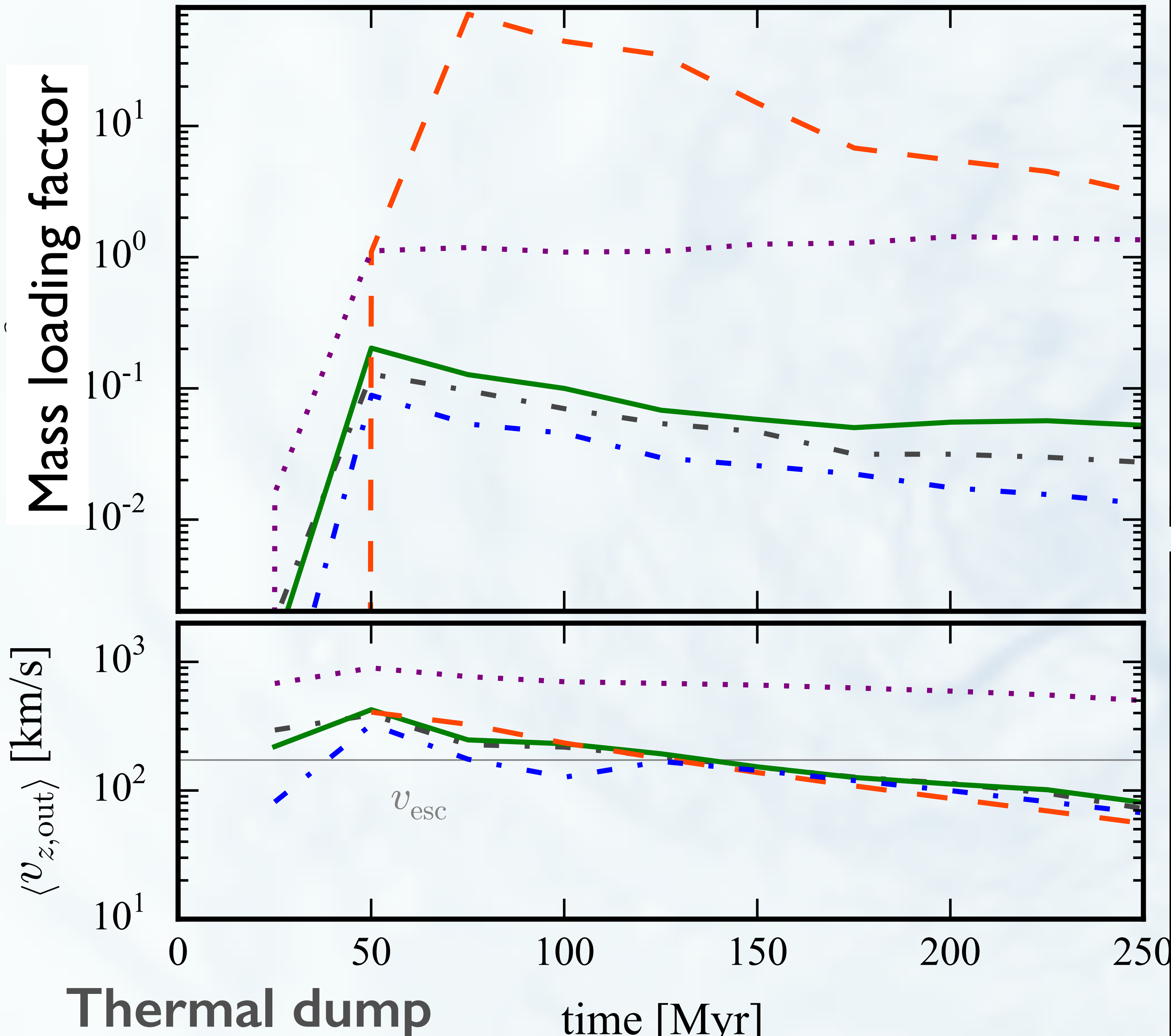


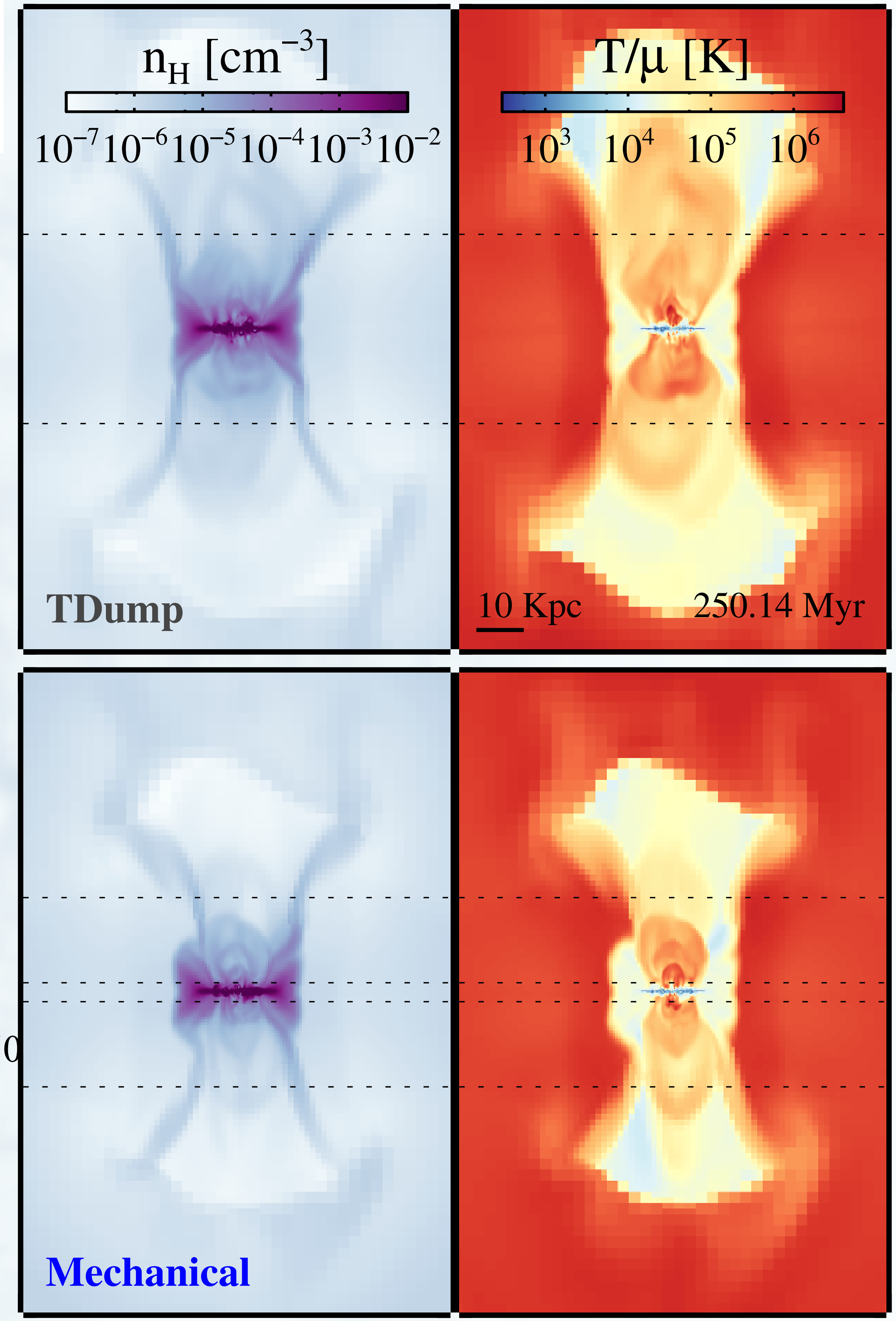
Thermal dump
Stochastic
Delayed Cooling
Kinetic



Outflows 20 kpc from dwarf

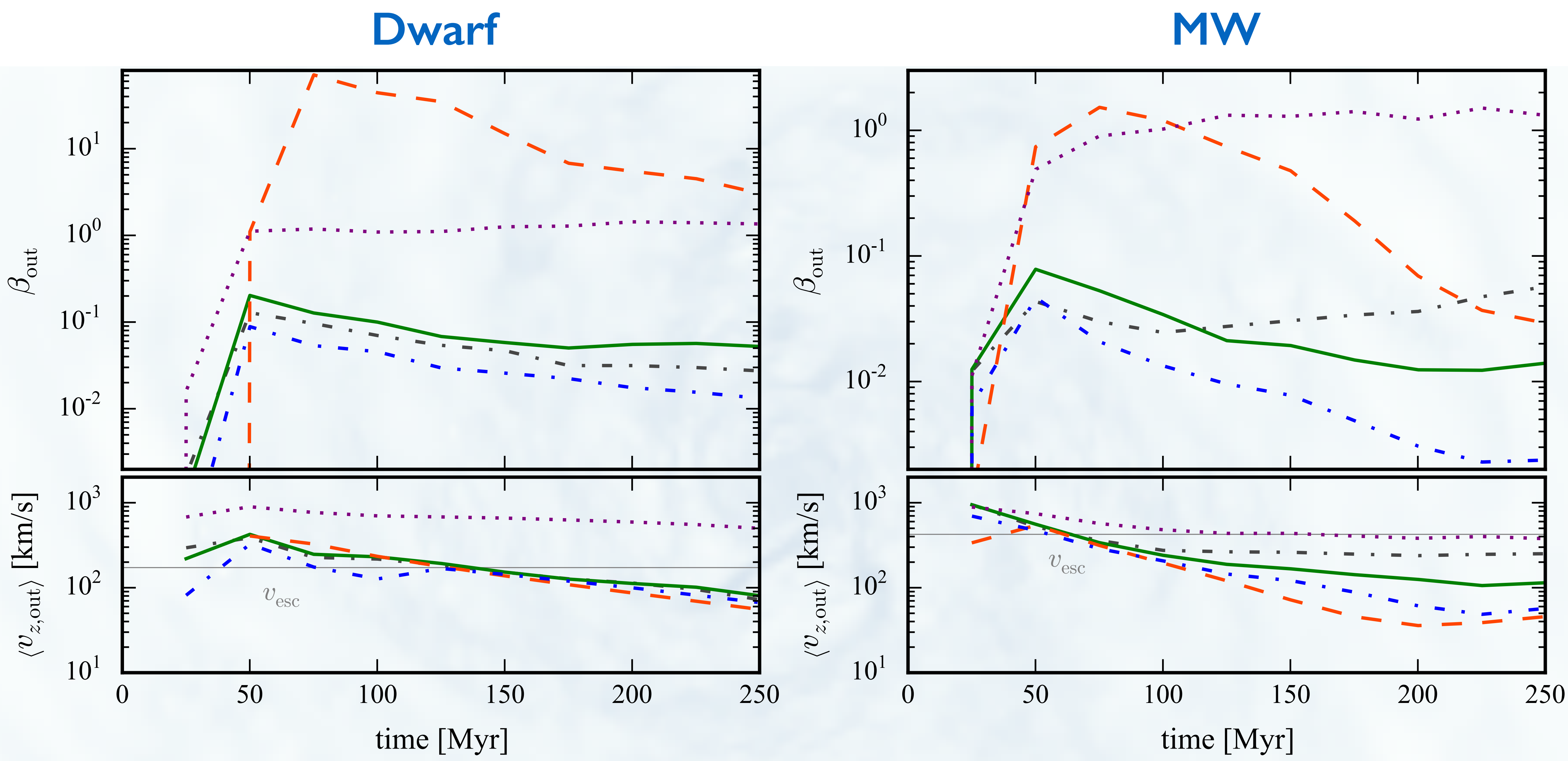
Outflows





Thermal dump
Stochastic
Delayed Cooling
Kinetic
Mechanical

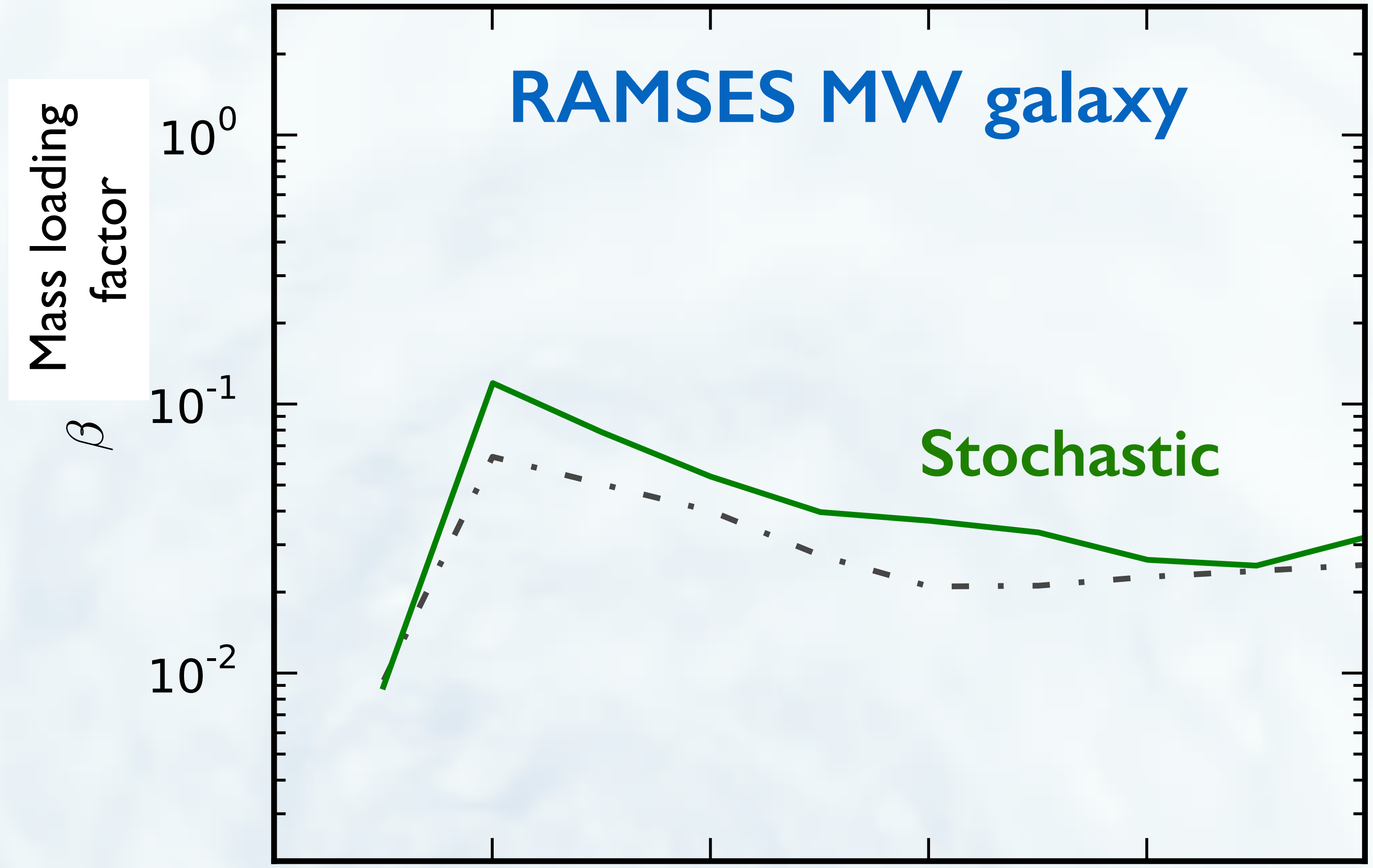
Outflows at 20 kpc for different galaxy masses



Thermal dump
Stochastic
Delayed Cooling
Kinetic
Mechanical

- Small mass loading factor in dwarf galaxy, except with 'strong' feedback recipes
- …and even lower in more massive galaxy

Comparison to stochastic SNe in Gadget



Mass-loading factor

$\beta \approx 0.03$

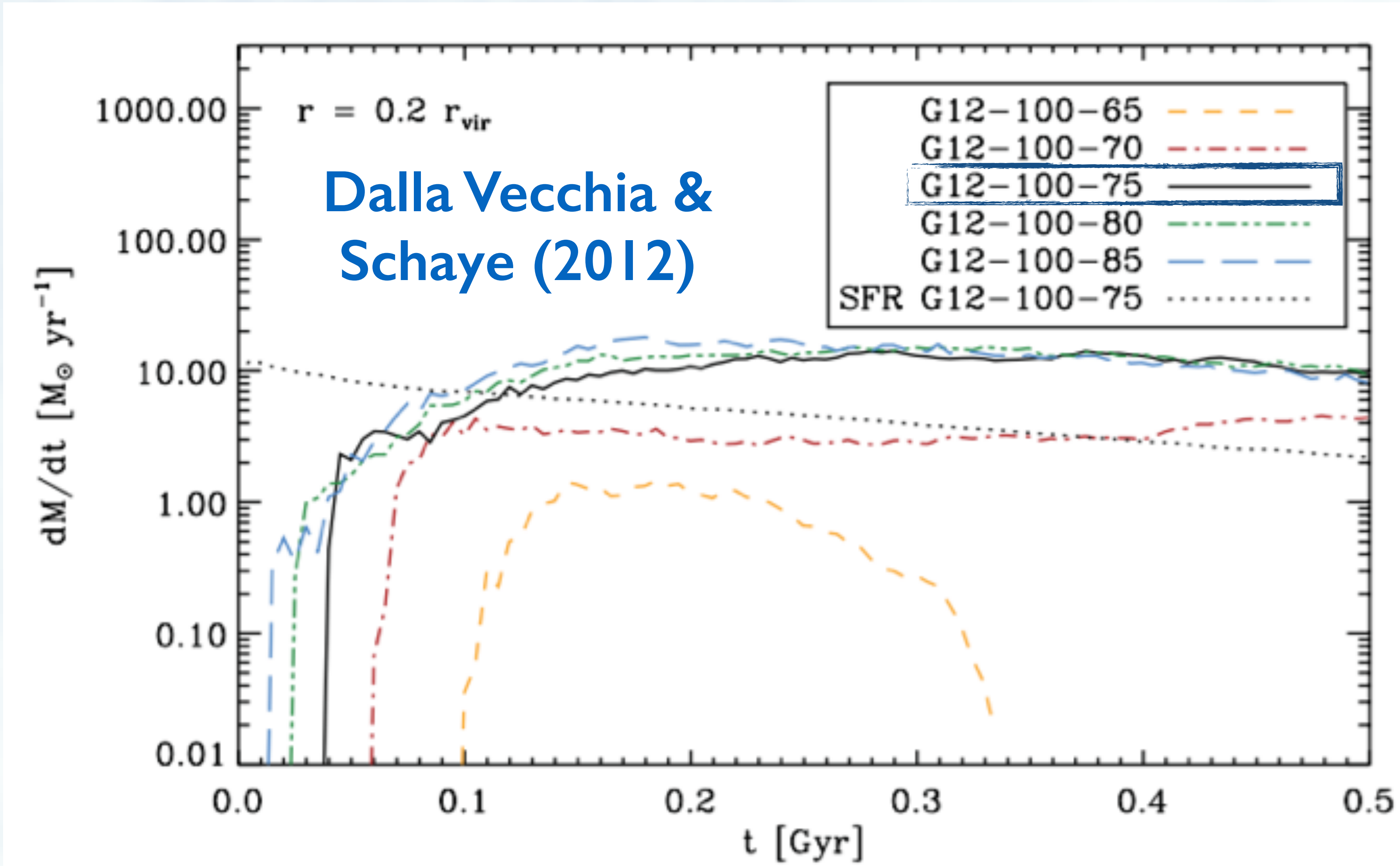
$\beta \approx 5$

- Dalla Vecchian & Schaye (2012) ran isolated disks with stochastic feedback in Gadget

- They got 100 times higher mass-loading than us!!

- Similar differences found by Nigel Mitchell with FLASH

- But of course there are setup differences



Summary

SN feedback recipes show a range of behaviours

Delayed cooling: 'best' at suppressing SF but cold and dense outflows

Kinetic: strong winds but a very thin and over-starforming disk

Mechanical: most realistic, but too many stars and weak outflows

All but delayed cooling overproduce stars

Overcooling, or missing physics (e.g. feedback/SF)?

Outflows appear much weaker than in similar SPH simulations with a similar SN recipe