A Critical View of ISM Modelling in Cosmological Simulations

Supernova Feedback

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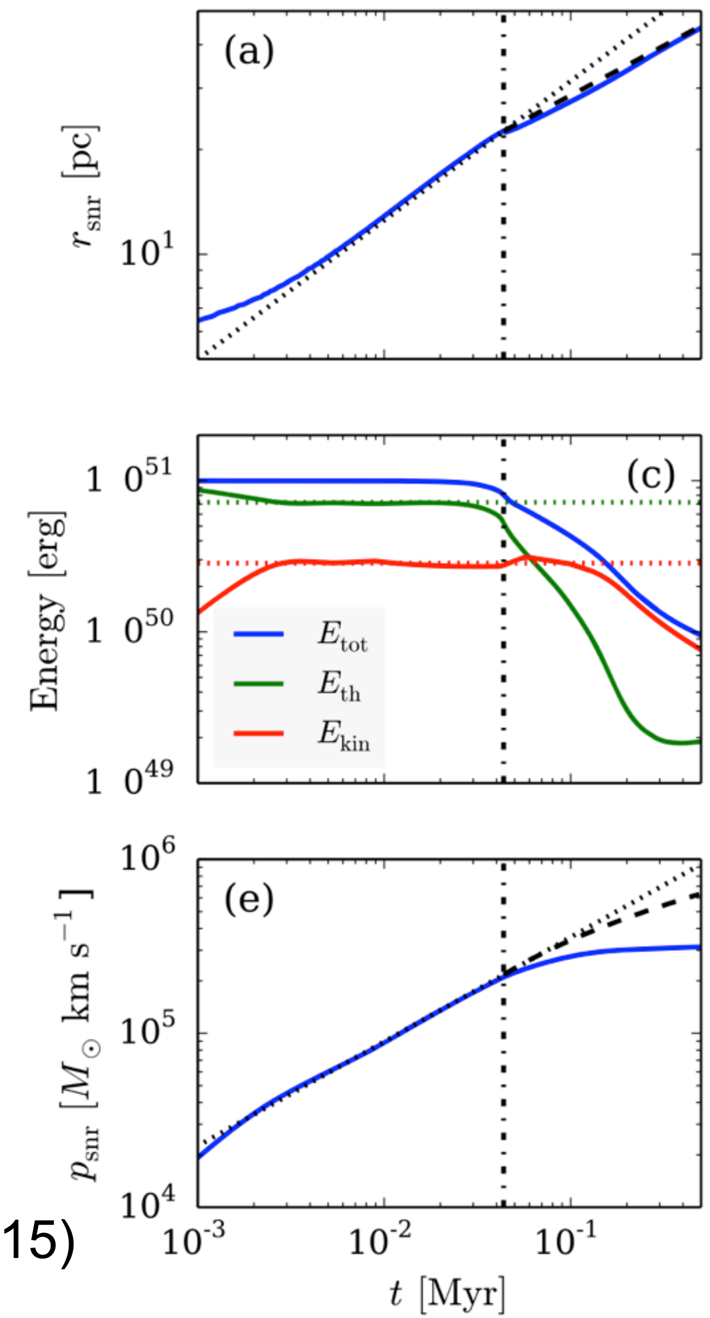
Supernova remnant evolution

- Free expansion (~10^2 yrs)
- **Sedov-Taylor** (~10^4 yrs)
- Pressure driven snowplough (~10^6 yrs)
- Momentum driven snowplough, remnant merges with ambient medium

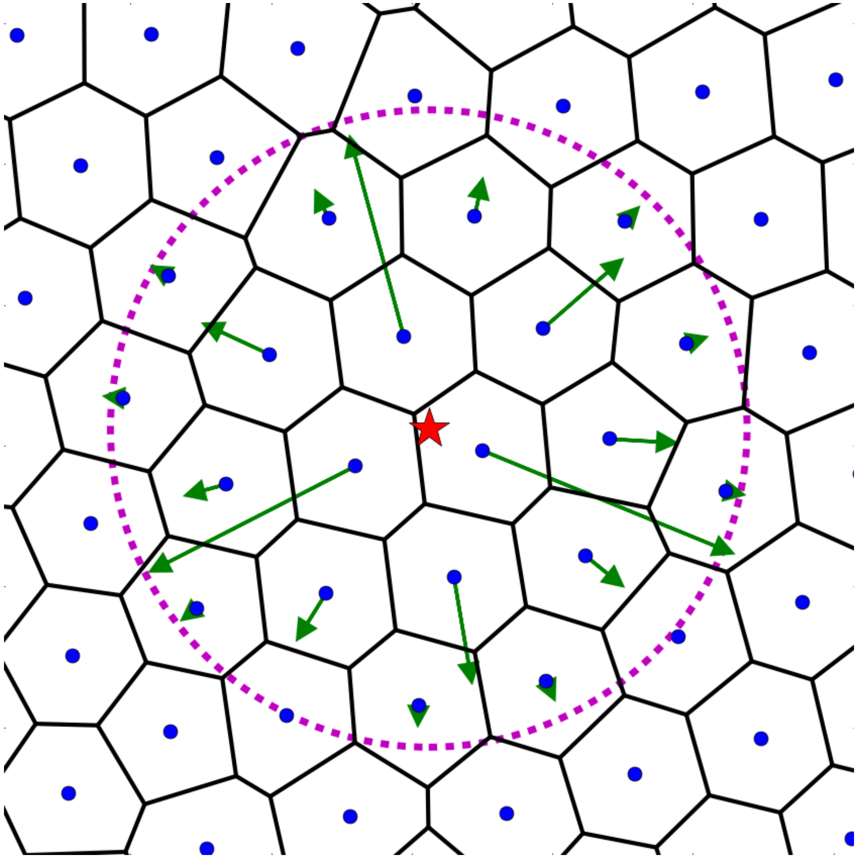


(Kim & Ostriker 2015)

Numerical Scheme

- Moving mesh code AREPO (Springel 2010)

$$\dot{\rho}_* = \frac{\varepsilon\rho}{t_{\rm ff}} \propto \rho^{3/2}, \;\; \rho > \rho_{\rm SF}$$



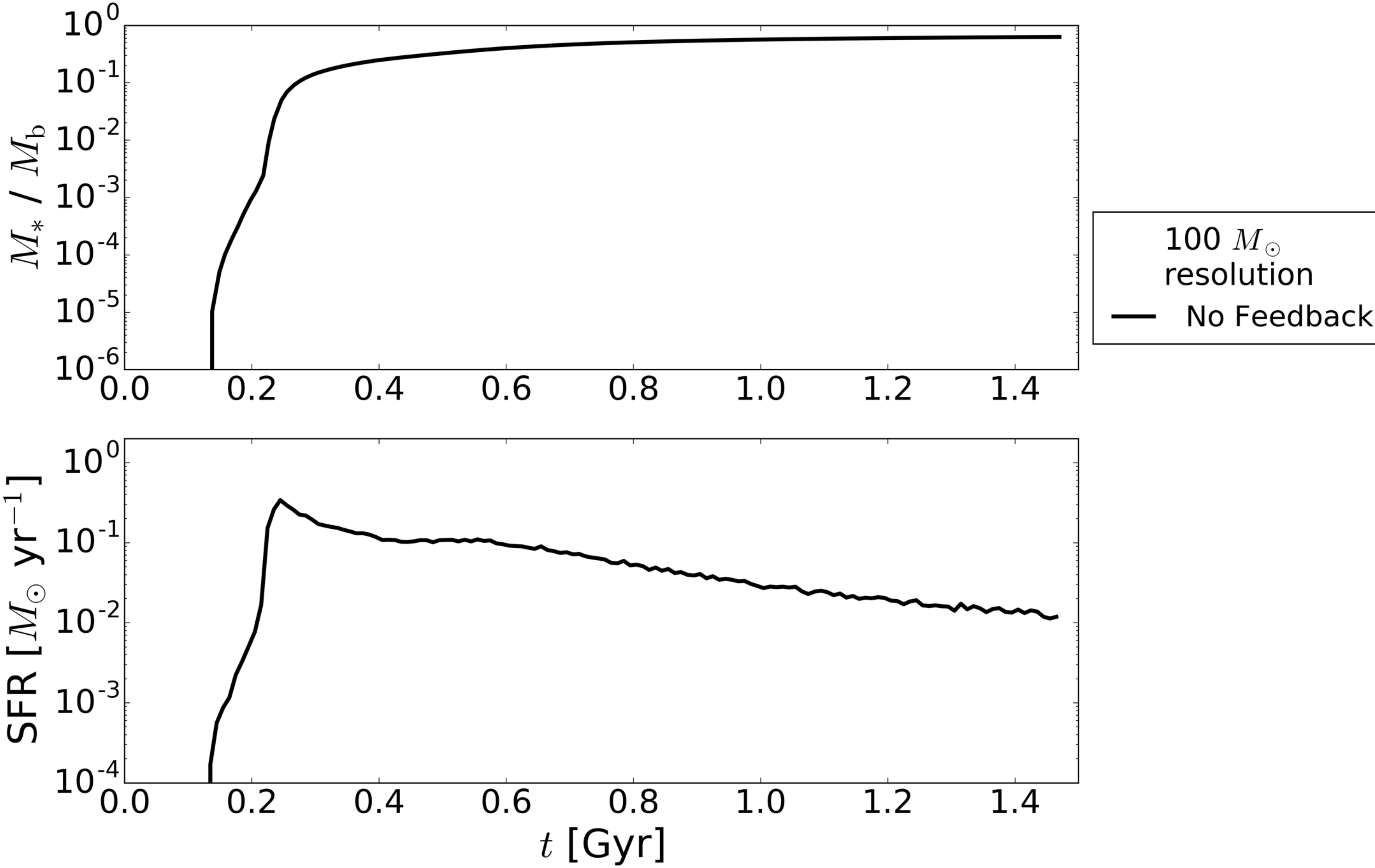
- SN rates as function of age and metallicity from STARBURST99 (Leitherer+ 1999)
- Stochastically trigger SN events
- Inject mass, energy and/or momentum to surrounding gas, weighted by kernel.

Test Case: Radially Collapsing Gas

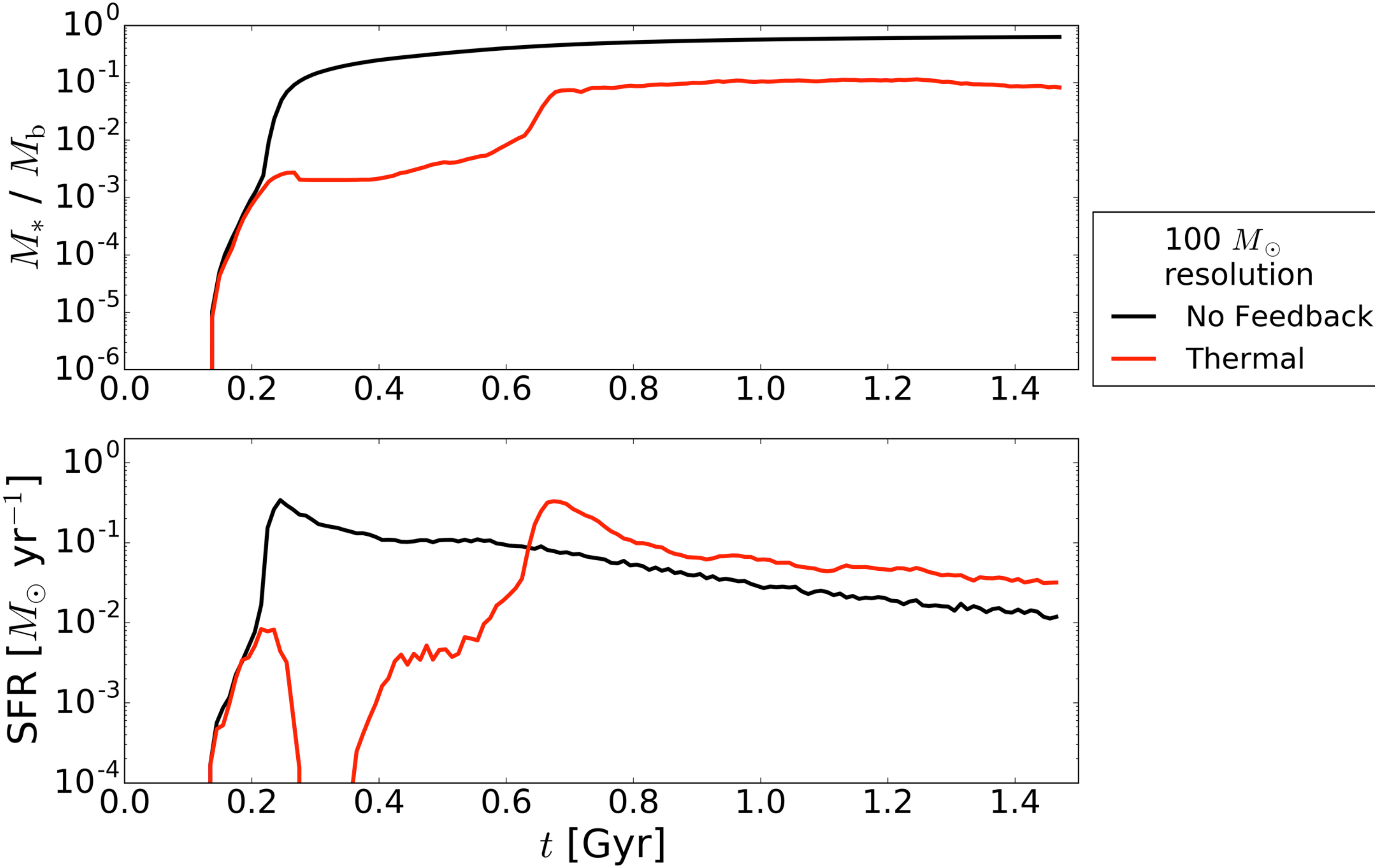
- $2.3 \times 10^9\ M_\odot$ dark matter (static potential), $1.35 \times 10^8\ M_\odot$ gas
- Cored isothermal profile with core radius $r_c = 0.5$ kpc

$$\rho(r) = \frac{\rho_0}{1 + (r/r_c)^2}$$

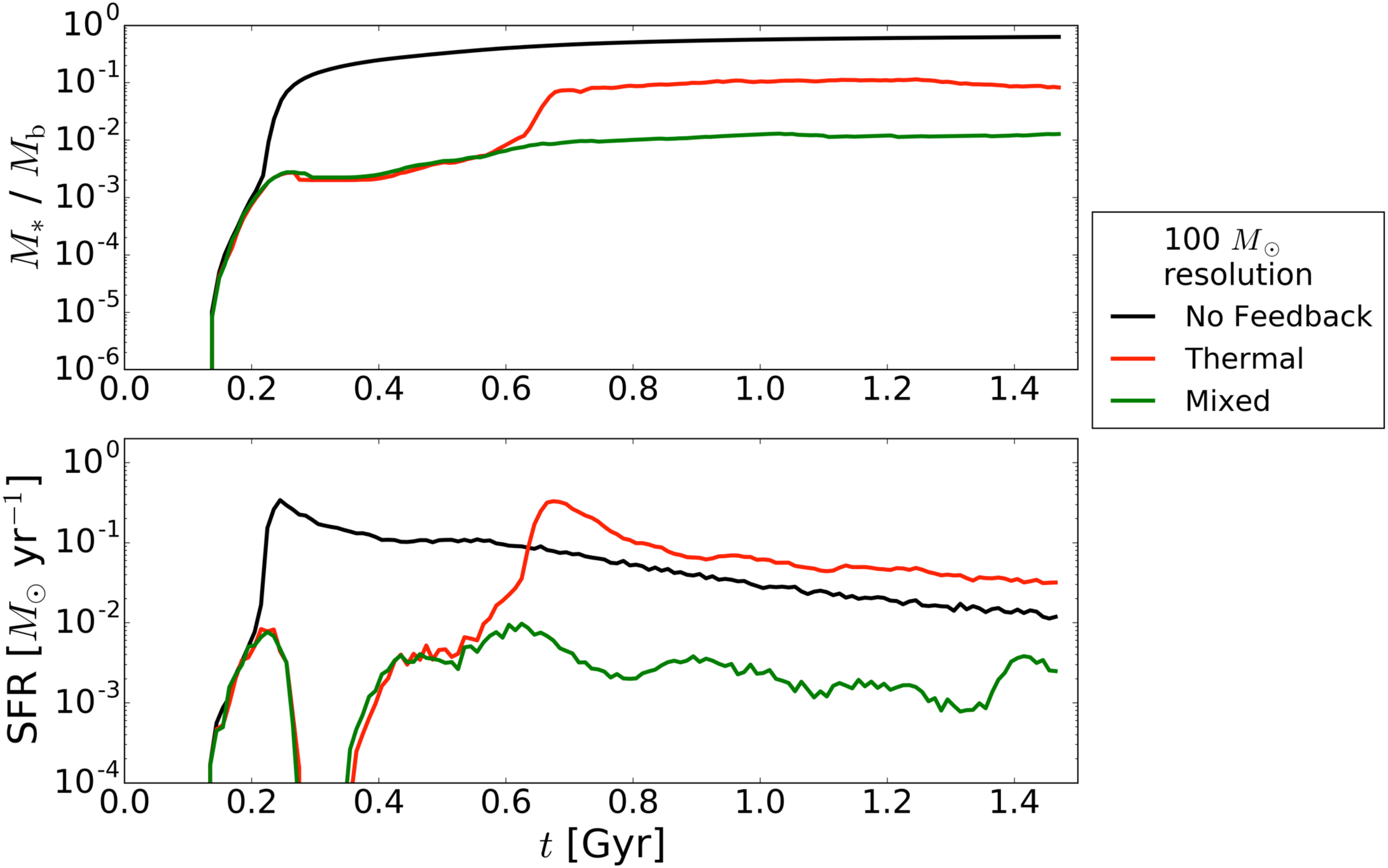
- Gas initially static, $T = 1.12 \times 10^4$ K, provides 1/3 thermal support required for equilibrium
- Primordial atomic cooling



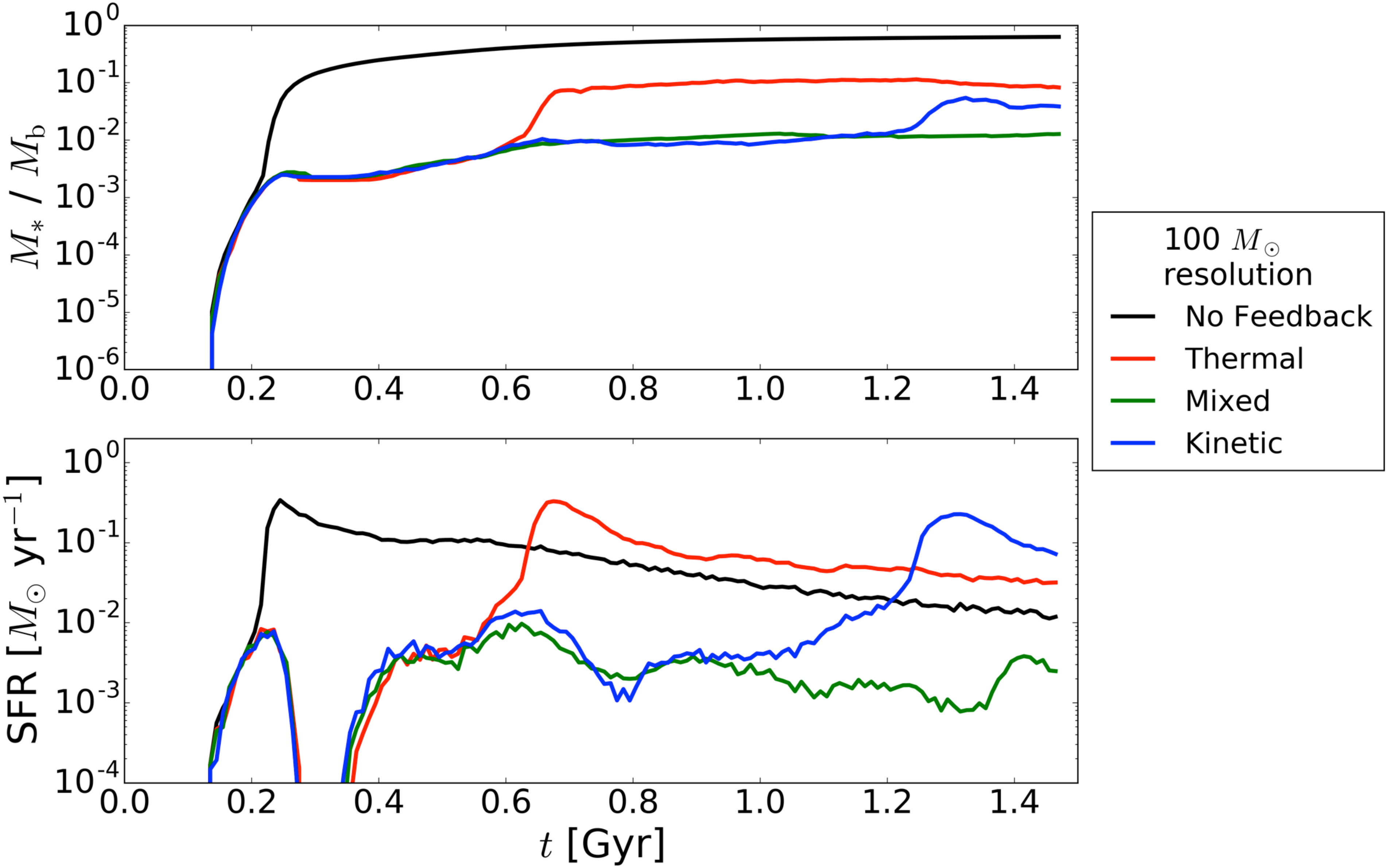
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$M_* \, / \, M_\mathrm{b}$
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
100 $M_\odot$ resolution
No Feedback
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
SFR [$M_\odot$ yr^{-1}]
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
t [Gyr]



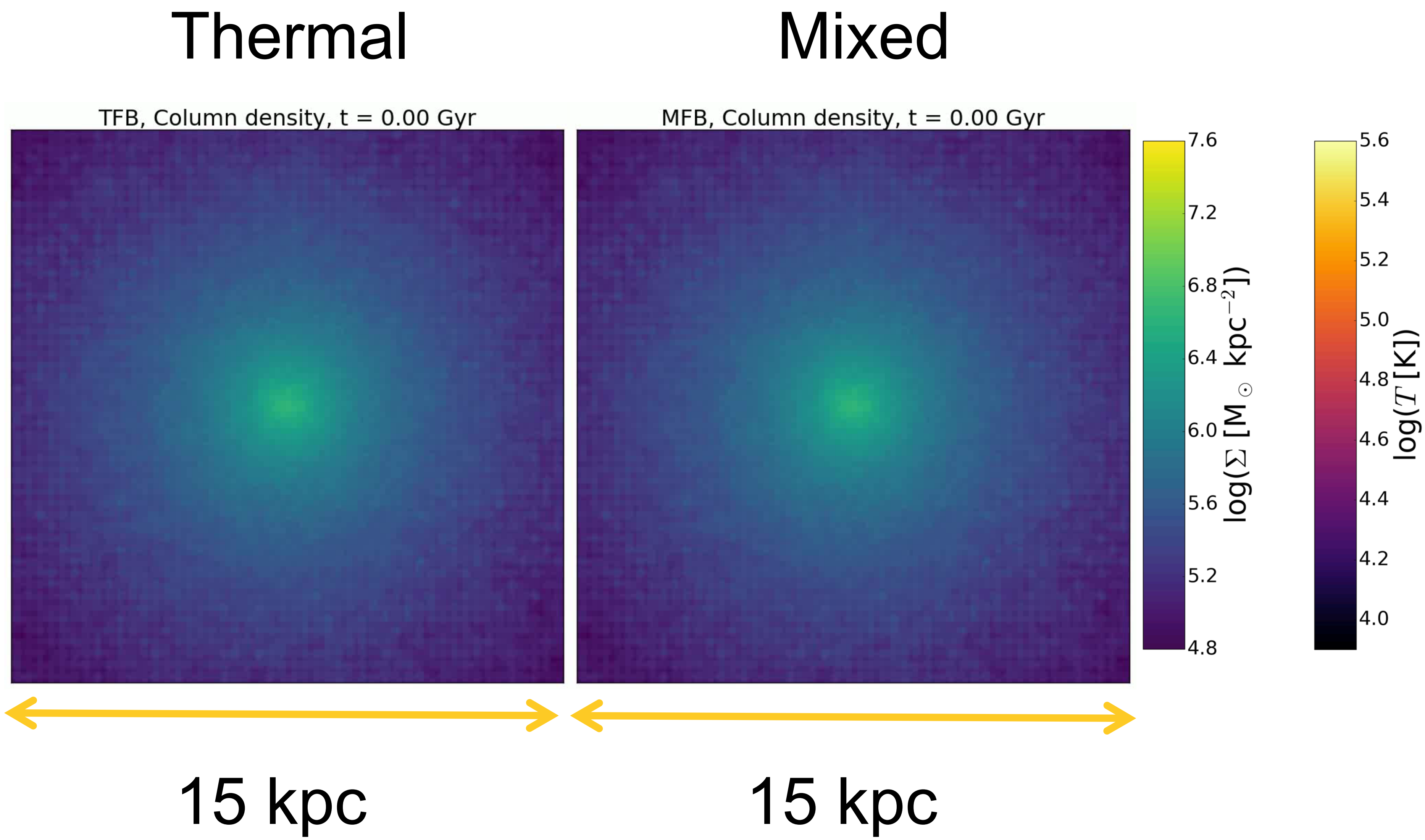
$M_* \ / \ M_\mathrm{b}$
SFR $[M_\odot \ \mathrm{yr}^{-1}]$
t [Gyr]
100 $M_\odot$ resolution
No Feedback
Thermal



$M_* \,/\, M_\mathrm{b}$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
100 $M_\odot$ resolution
No Feedback
Thermal
Mixed
SFR [$M_\odot$ yr^{-1}]
t [Gyr]



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$M_* \; / \; M_\mathrm{b}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
100 $M_\odot$ resolution
No Feedback
Thermal
Mixed
Kinetic
SFR [$M_\odot$ yr^{-1}]
t [Gyr]



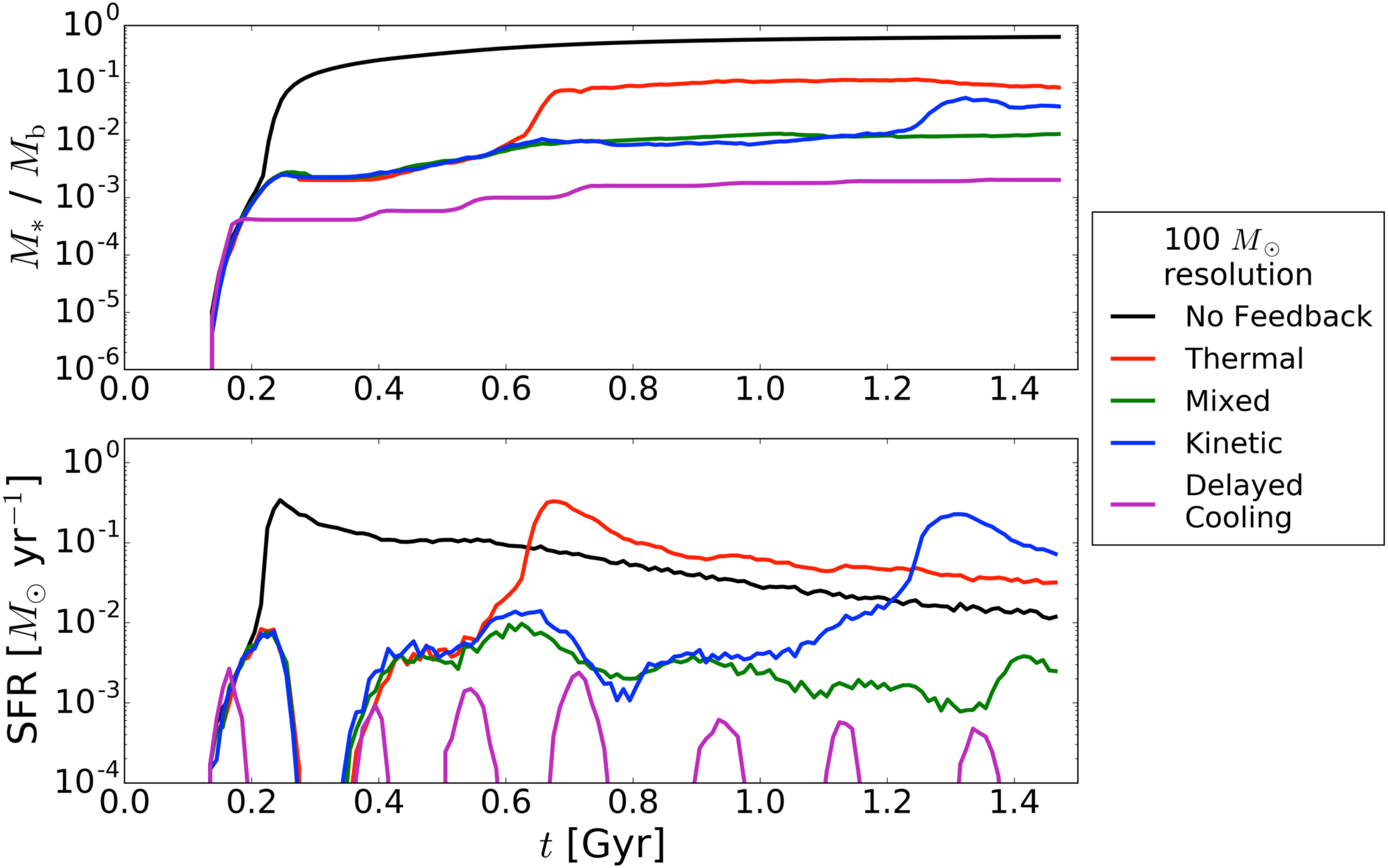
Thermal
Mixed
TFB, Column density, t = 0.00 Gyr
MFB, Column density, t = 0.00 Gyr
7.6
7.2
6.8
6.4
6.0
5.6
5.2
4.8
log(Σ [M☉ kpc⁻²])
5.6
5.4
5.2
5.0
4.8
4.6
4.4
4.2
4.0
log(T [K])
15 kpc
15 kpc

Delayed Cooling

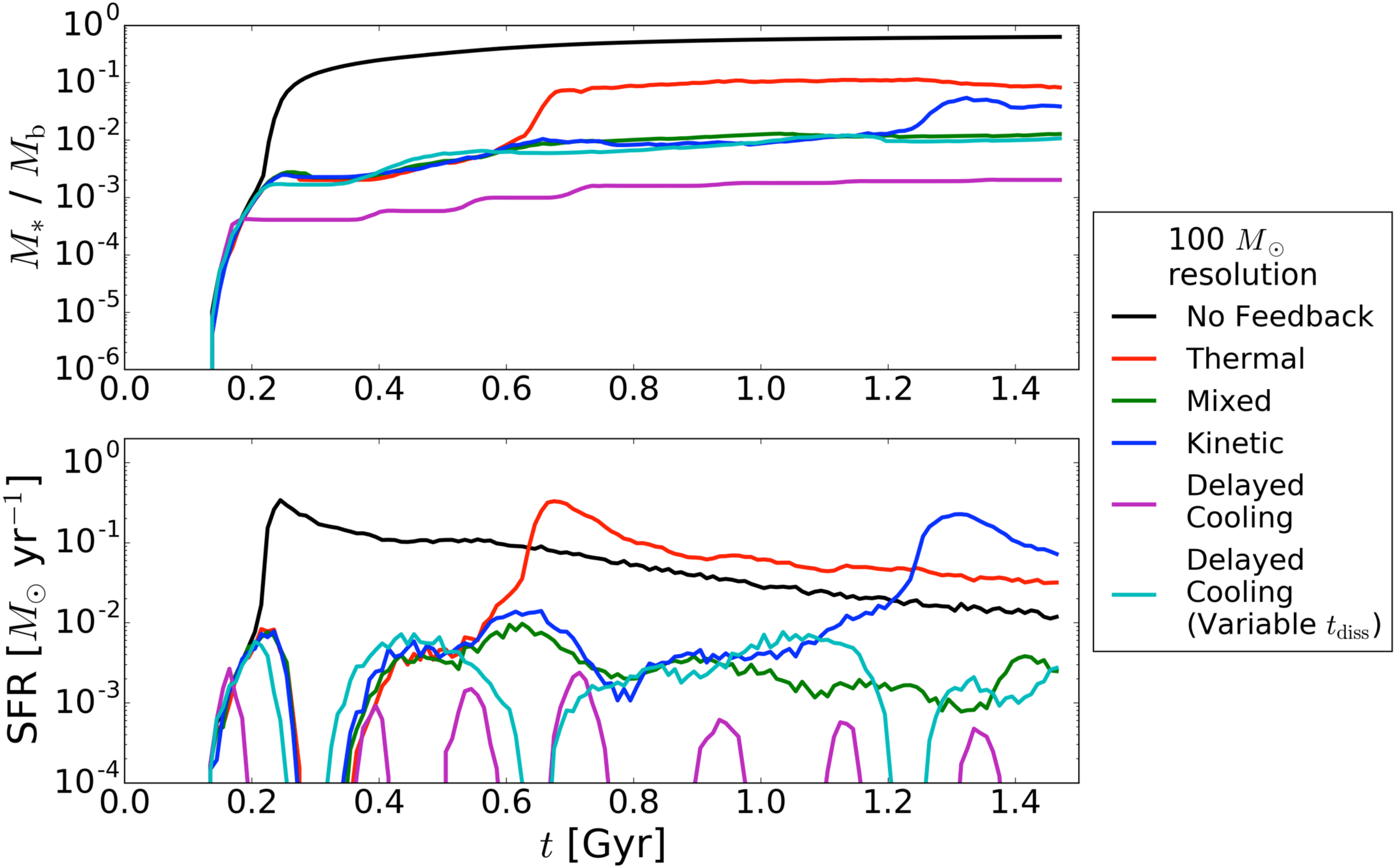
- Delayed Cooling Feedback (based on Teyssier+ 2013)
- Assume E_{SN} locked up in non-thermal processes with much longer dissipation time than cooling time.
- Inject thermal energy but track injected SN energy in passive scalar ε_{SN}
- Advect with gas and dissipate as $\dot{\varepsilon}_{SN} = \varepsilon_{SN} / t_{\mathrm{diss}}$
- Turn off radiative cooling when:

$$\sigma_{\mathrm{SN}} = \sqrt{2\varepsilon_{\mathrm{SN}}} > 10 \text{ km s}^{-1}$$

- $t_{\mathrm{diss}} = 10 \text{ Myr}$ or $t_{\mathrm{diss}} = \dfrac{\Delta x}{\sigma_{\mathrm{SN}}}$

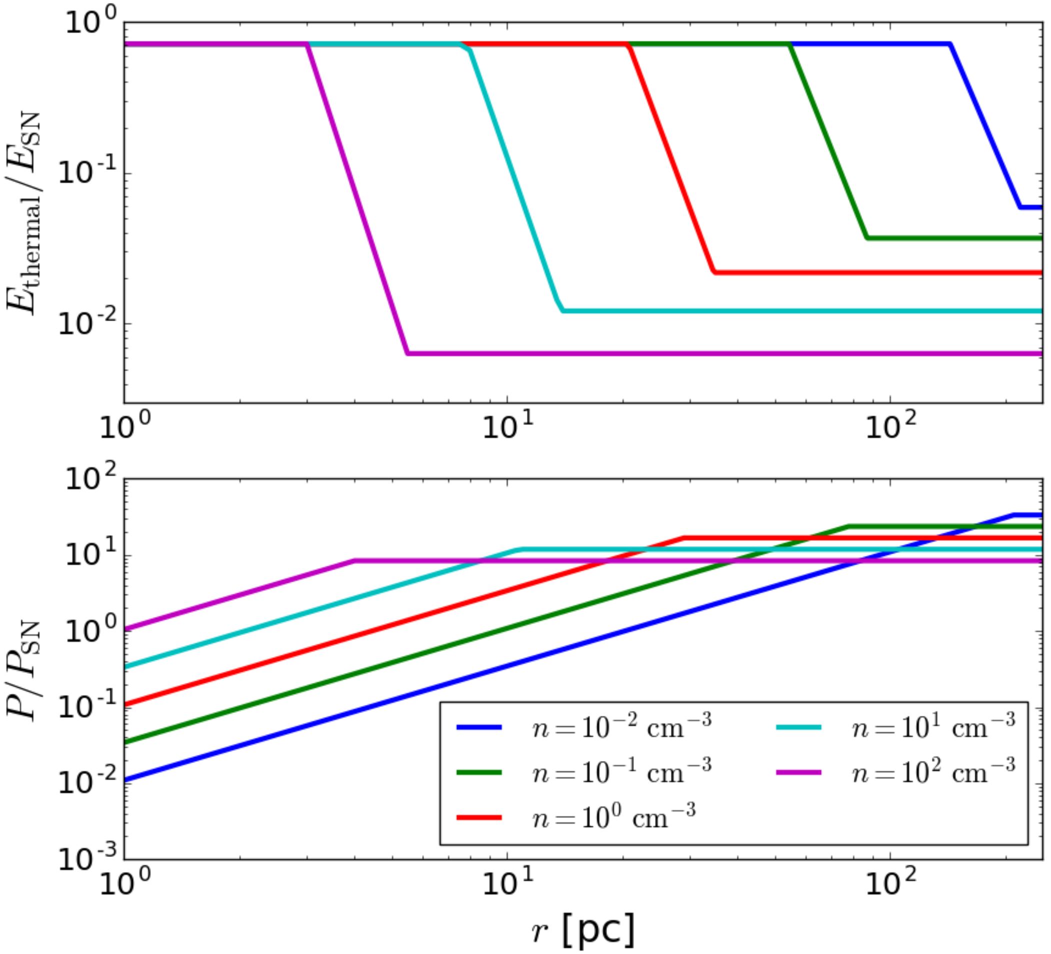


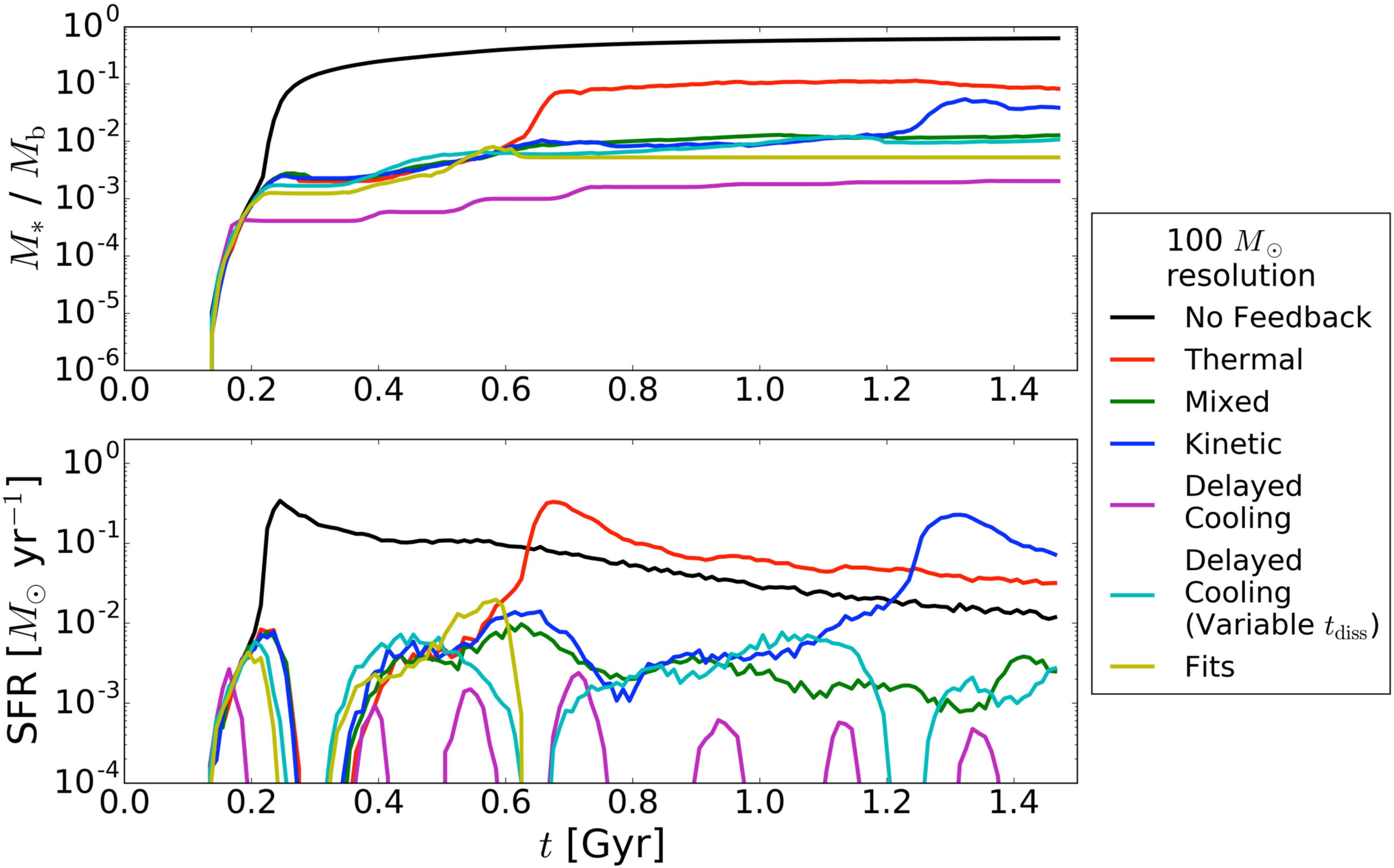
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$M_* \;/\; M_\mathrm{b}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
SFR [$M_\odot$ yr^{-1}]
t [Gyr]
100 $M_\odot$ resolution
No Feedback
Thermal
Mixed
Kinetic
Delayed Cooling


$M_* \ / \ M_\mathrm{b}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
SFR [$M_\odot$ yr^{-1}]
t [Gyr]
100 $M_\odot$ resolution
No Feedback
Thermal
Mixed
Kinetic
Delayed Cooling
Delayed Cooling (Variable t_diss)

Fits to high resolution simulations

- Use fits from Martizzi+ 2015
- Fits to high resolution simulations of individual blastwaves
- Obtain thermal energy and momentum as a function of blastwave radius, background density and metallicity

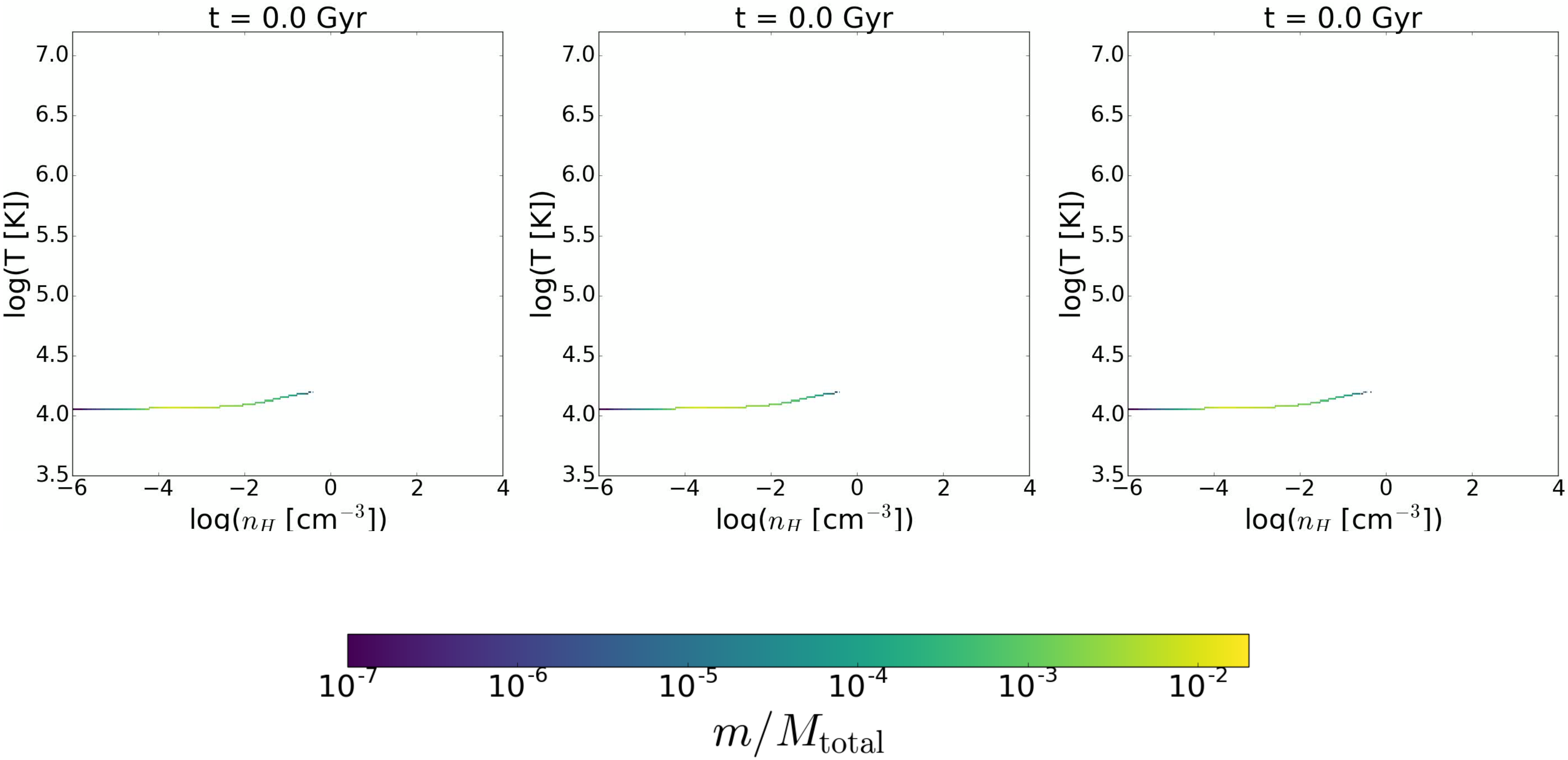


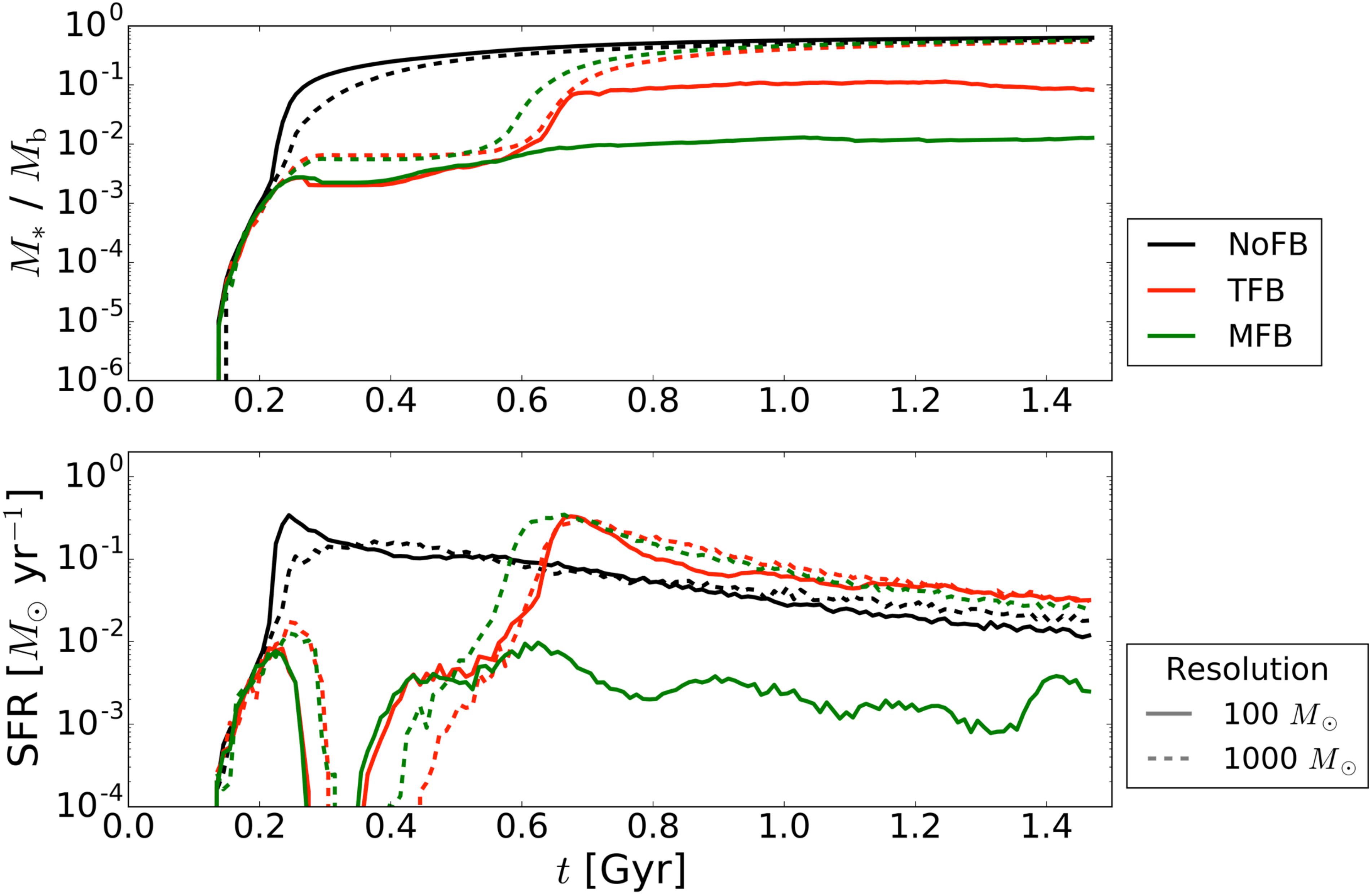


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
M_* / $M_{\rm b}$
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
SFR [$M_\odot$ yr^{-1}]
t [Gyr]
100 $M_\odot$ resolution
No Feedback
Thermal
Mixed
Kinetic
Delayed Cooling
Delayed Cooling (Variable $t_{\rm diss}$)
Fits

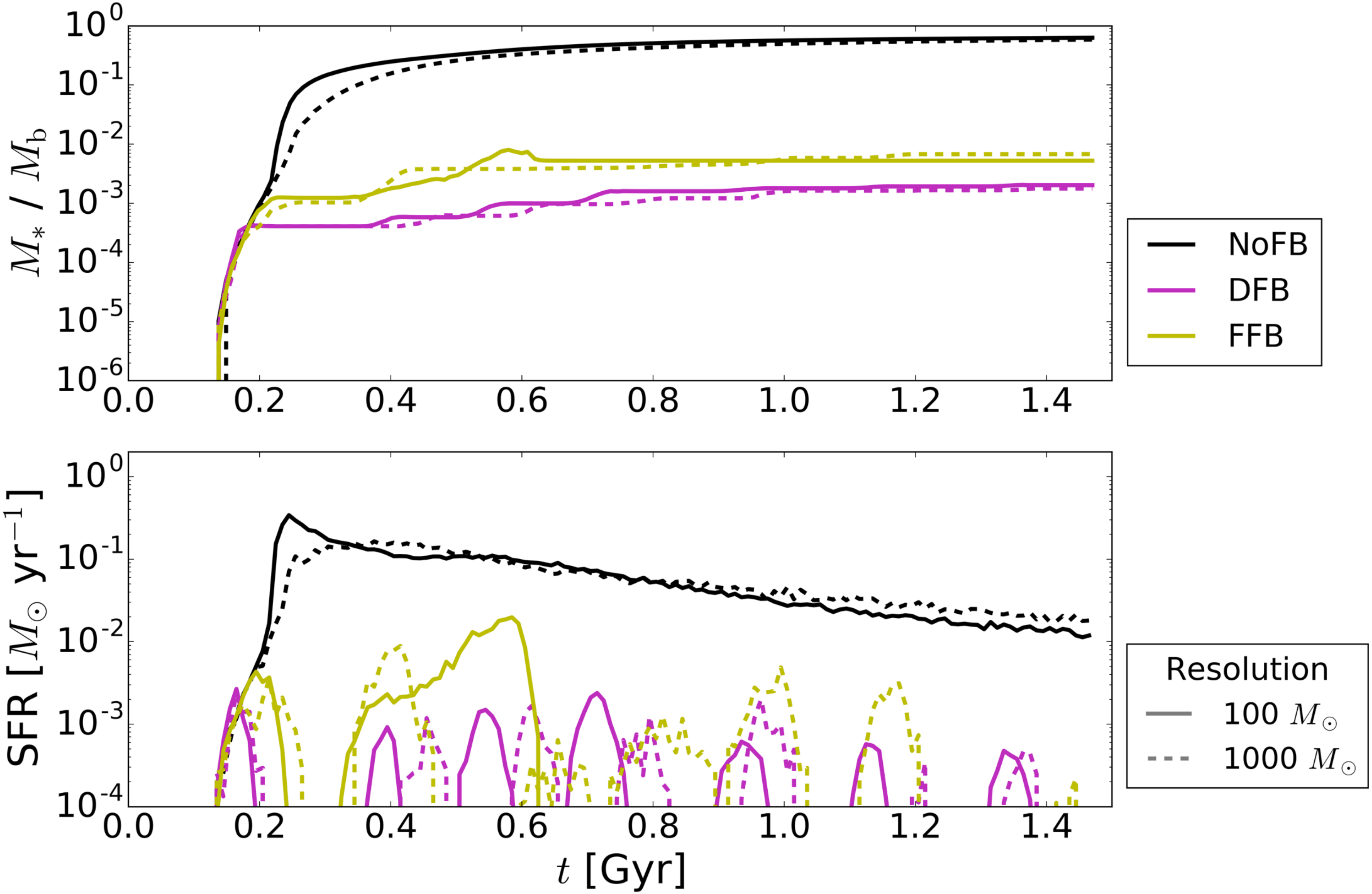
Phase Diagrams

Thermal | Delayed Cooling | Fits





10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
M_* / M_b
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
NoFB
TFB
MFB
SFR [$M_\odot$ yr^{-1}]
t [Gyr]
Resolution
100 $M_\odot$
1000 $M_\odot$

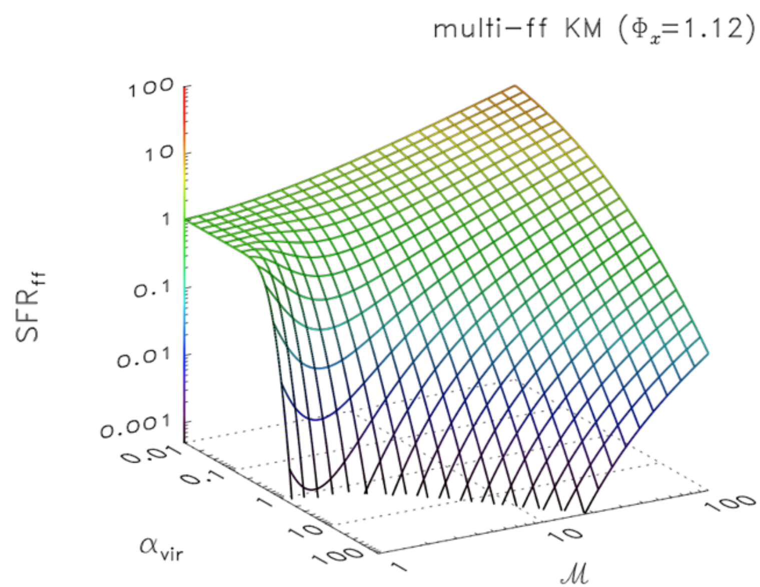


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$M_* \ / \ M_{\rm b}$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
NoFB
DFB
FFB
10^{-1}
10^{-2}
10^{-3}
10^{-4}
SFR $[M_\odot \ {\rm yr}^{-1}]$
t [Gyr]
Resolution
100 $M_\odot$
1000 $M_\odot$

Non-SN processes

- 'Pretreatment' of ISM by other feedback processes will enhance SN effectiveness e.g.
  - Stellar winds
  - Radiation pressure
  - Photoionisation
- More realistic 'clustered' star formation criteria e.g. Krumholz & McKee (2005), Federrath & Klessen (2012)

$$\varepsilon \rightarrow \mathrm{SFR}_{\mathrm{ff}}\left(\alpha_{\mathrm{vir}}, \mathcal{M}, b, \beta\right)$$



Federrath & Klessen (2012)

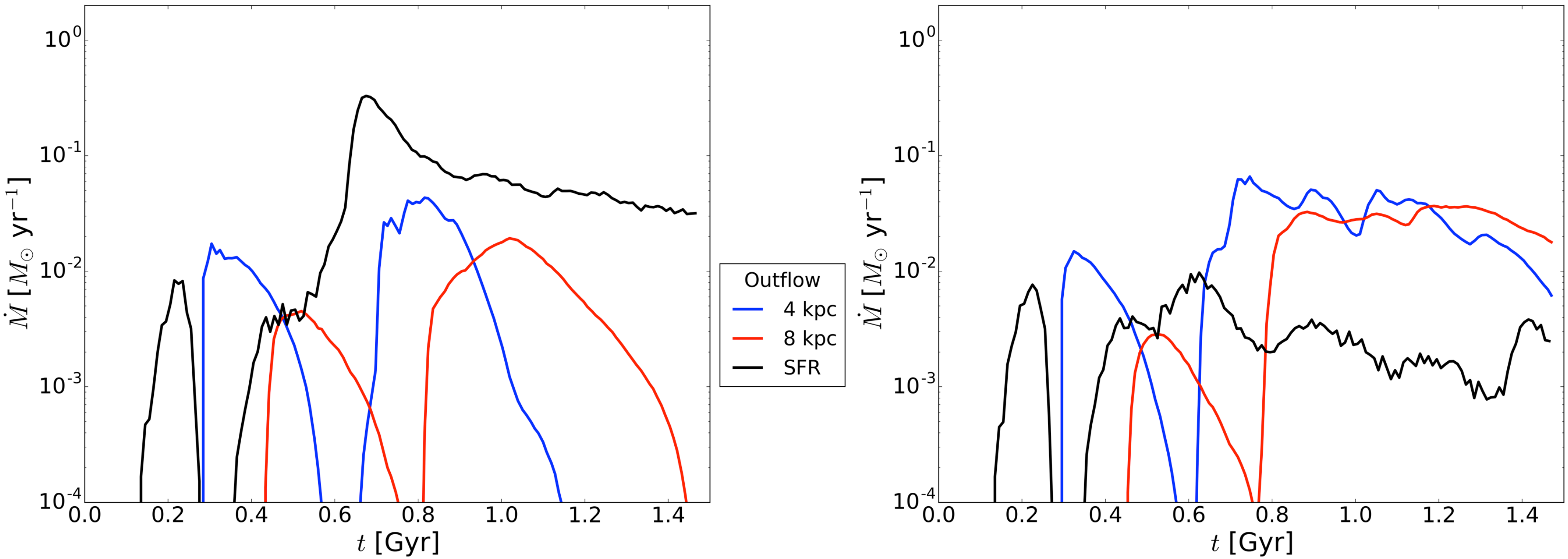
Summary

- Supernova feedback is a key ISM process that must be included in cosmological simulations.
- Resolution issues make accurate modelling of SN feedback challenging.
- Results can be strongly dependent on choice of feedback implementation. Consequences of choice are non-trivial and must be understood in order to produce physically relevant simulations.
- SN feedback alone is not the whole picture; other processes and more physical star formation criteria will interact with SN feedback in a complex manner.

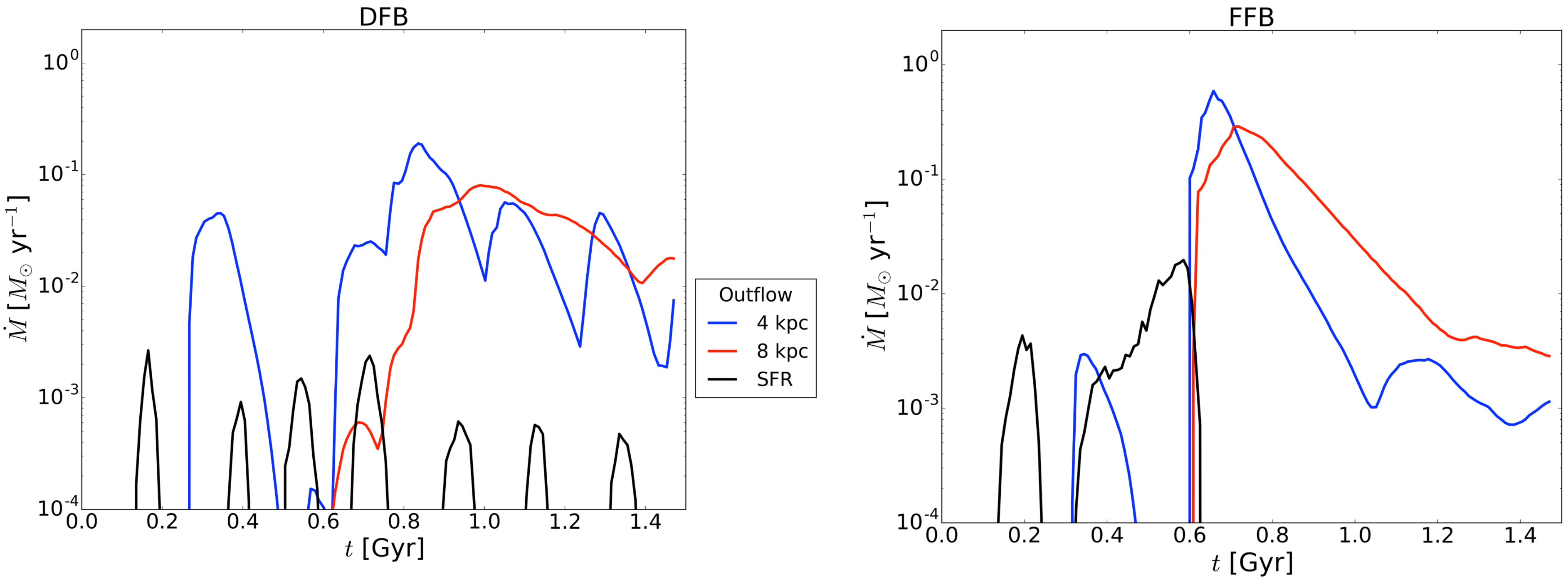
Outflows

Thermal

Mixed



Outflows

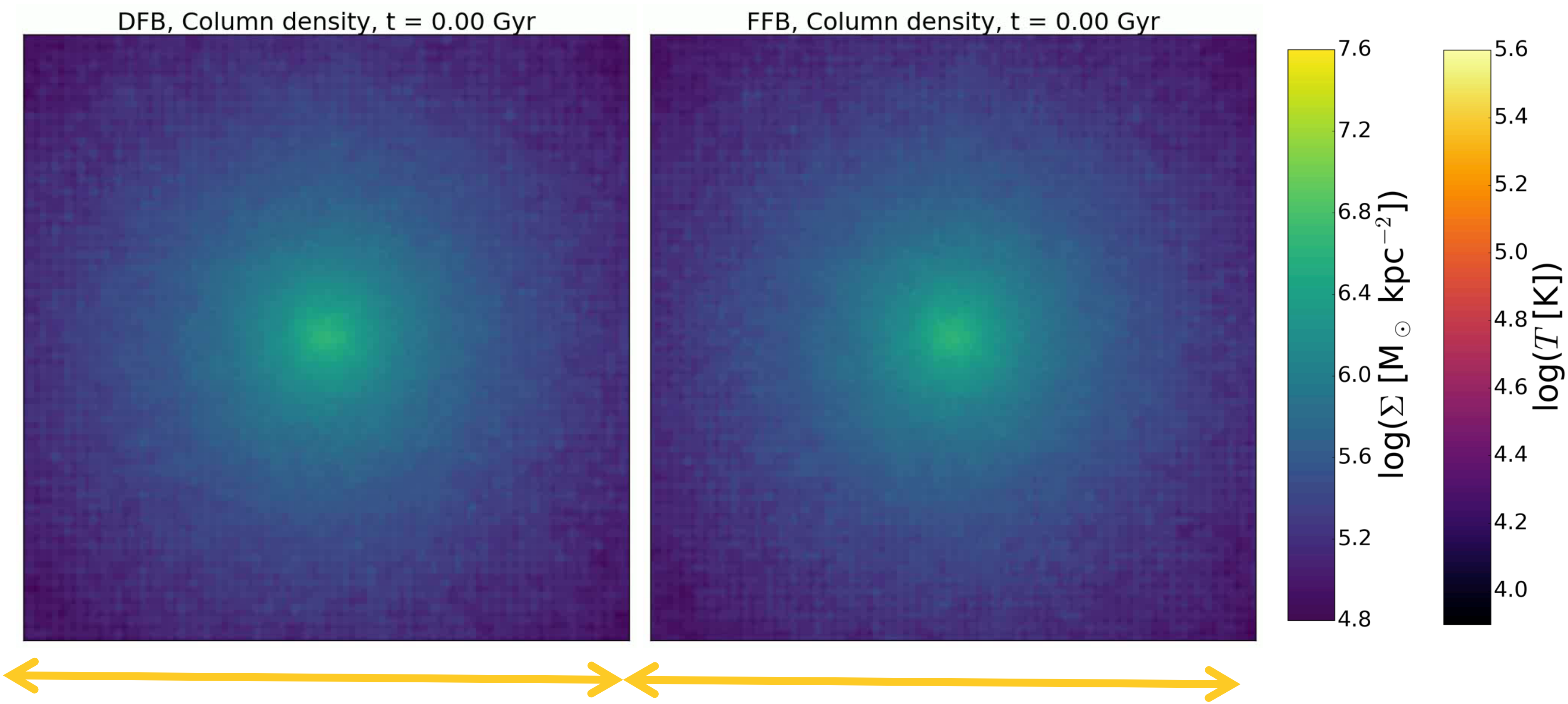

DFB
FFB
Outflow
4 kpc
8 kpc
SFR
$\dot{M}$ [$M_\odot$ yr^{-1}]
t [Gyr]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

Test 2: Cosmological 'zoom-ins'

- Run dark matter only 40 cMpc/h cosmological box to $z = 6$
- Select 1.12×10^{10} $M_\odot$ halo and trace back to initial conditions.
- $m_{dm} = 6.7\times10^4$ $M_\odot$, 8.3×10^3 $M_\odot$, 1.0×10^3 $M_\odot$
- $m_{gas} = 1.2\times10^4$ $M_\odot$, 1.6×10^3 $M_\odot$, 1.9×10^2 $M_\odot$
- Primordial cooling
- UV background (Haardt & Madau 2012)
- Self-shielding (Rahmati+ 2013)

Delayed Cooling

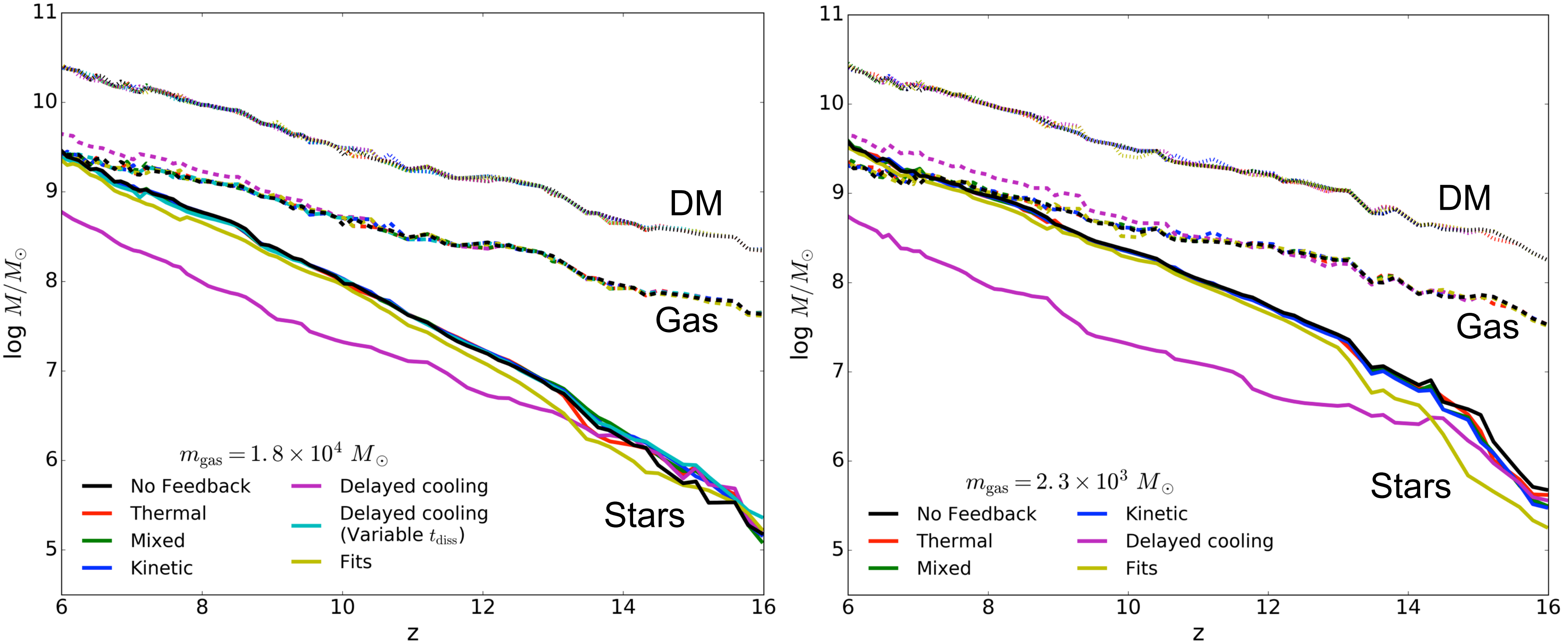
Fits



15 kpc

15 kpc

Cosmological zoom-ins



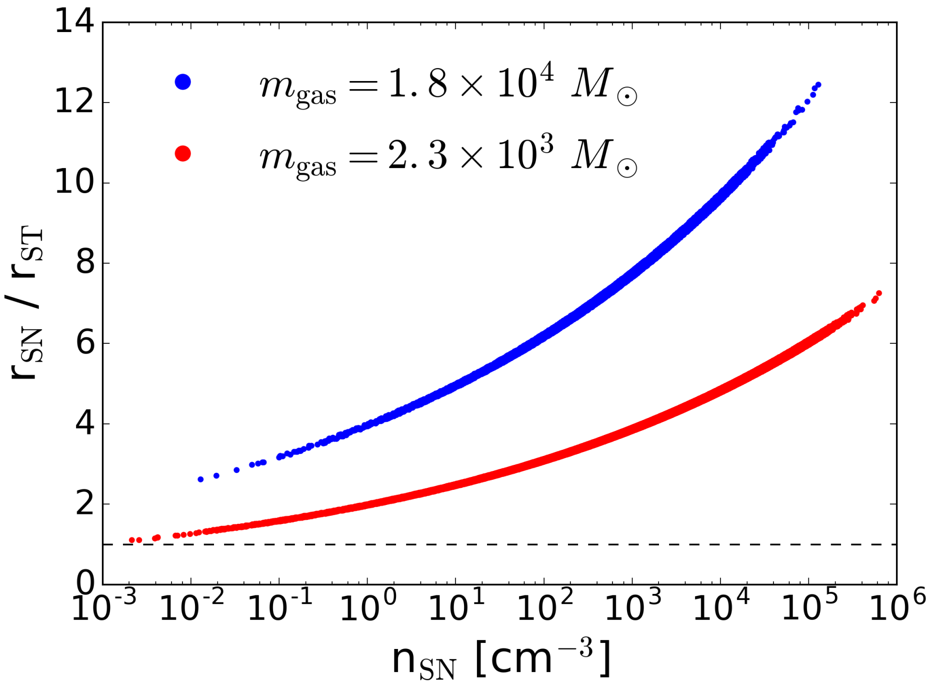
$m_{gas} = 1.8\times10^4\ M_\odot$
$m_{DM} = 6.7\times10^4\ M_\odot$

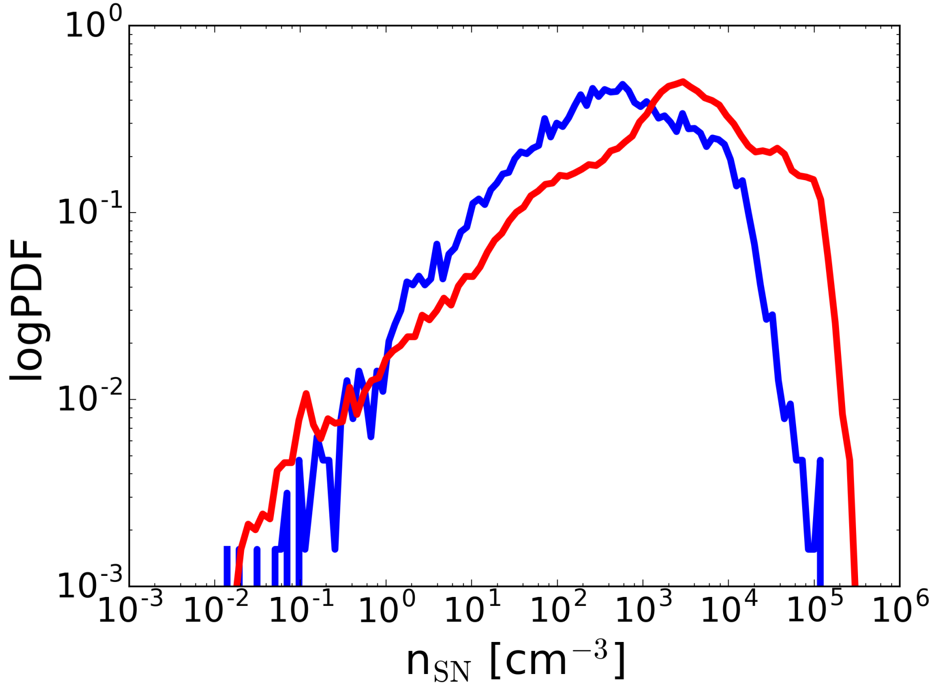
$m_{gas} = 2.3\times10^3\ M_\odot$
$m_{DM} = 8.3\times10^3\ M_\odot$

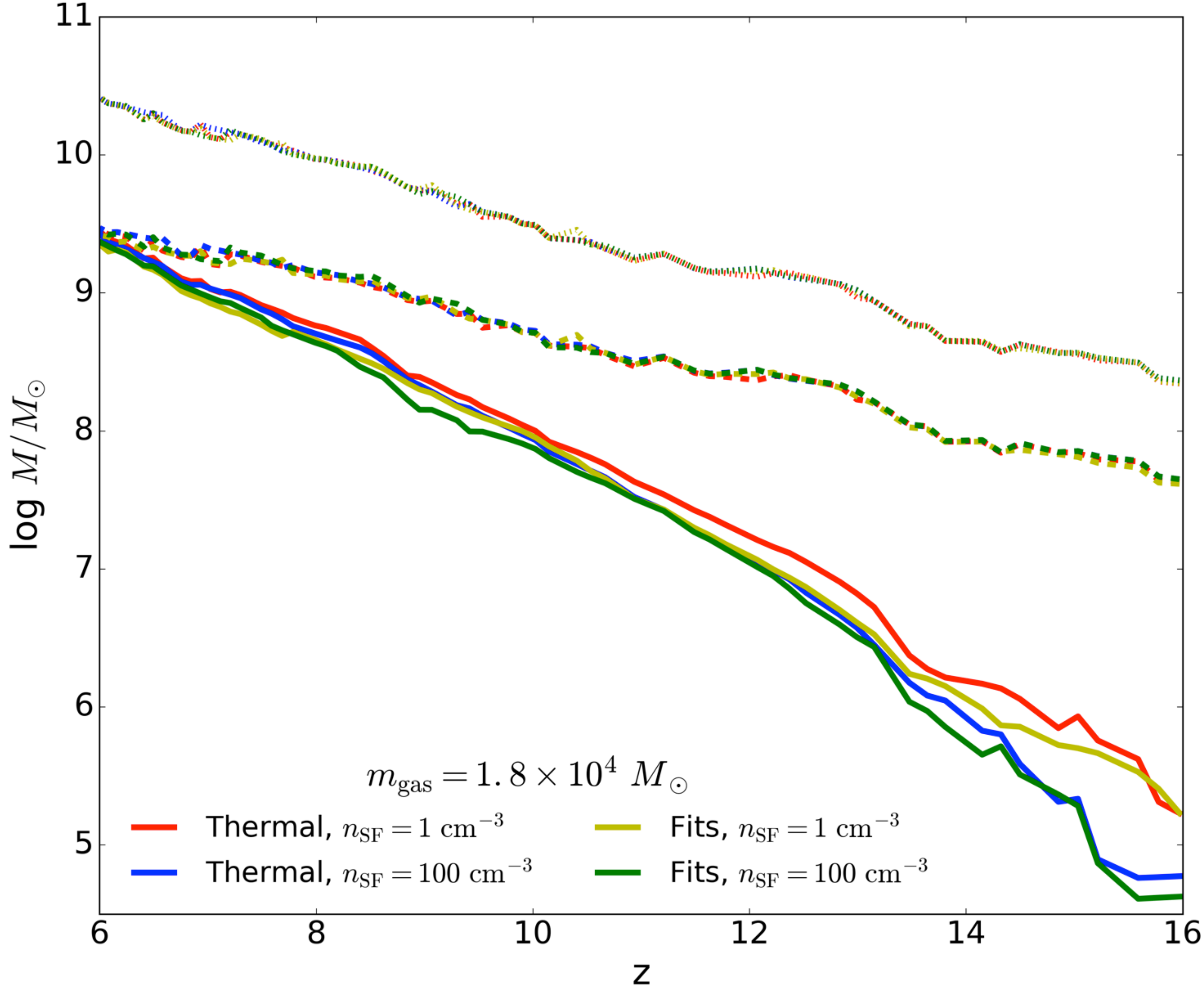
UV background (Haardt & Madau 2012)
Self-shielding (Rahmati+ 2013)

Supernovae sites

Thermal feedback







11
10
9
8
7
6
5
log $M/M_\odot$
6
8
10
12
14
16
z
$m_{\rm gas} = 1.8 \times 10^4\ M_\odot$
Thermal, $n_{\rm SF} = 1\ {\rm cm}^{-3}$
Thermal, $n_{\rm SF} = 100\ {\rm cm}^{-3}$
Fits, $n_{\rm SF} = 1\ {\rm cm}^{-3}$
Fits, $n_{\rm SF} = 100\ {\rm cm}^{-3}$