Stellar feedback in a galactic disk with HD and RHD

Joki Rosdahl

Romain Teyssier, Joop Schaye, Oscar Agertz

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Sterrewacht Leiden

The 'general' overcooling problem

(Navarro & Benz, 1991)

Realistic galaxies require *efficient supernova feedback*

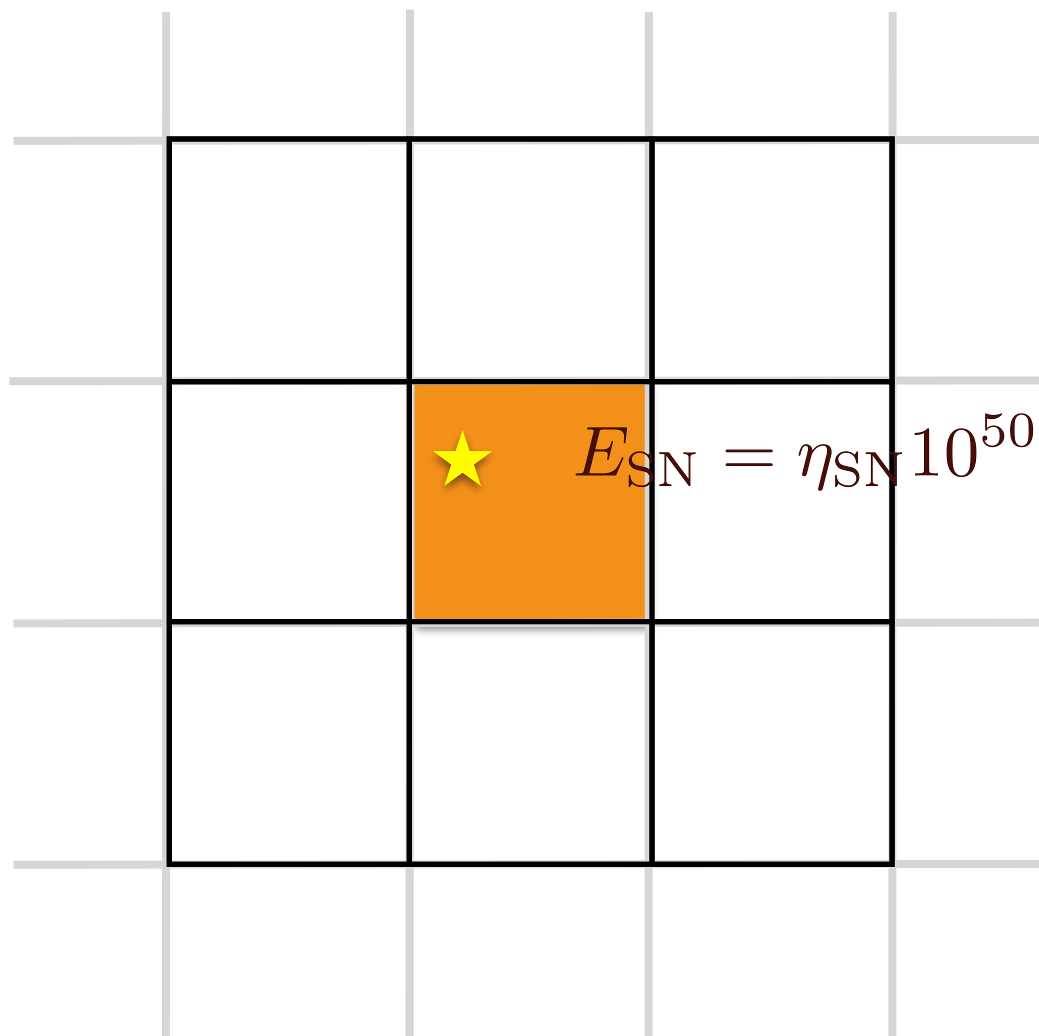
Without it, they are:

- **too compact, star forming**
- **no outflows or fountains**

But: modelling SNe by first principles does not work

The ‘special’ overcooling problem

- SN feedback: instantaneous thermal energy injection
  - Good resolution: Sedov blast ➜ momentum conserving shell
  - Practical resolution: blast not resolved ➜ energy radiates away



$E_{\rm SN} = \eta_{\rm SN} 10^{50}\ {\rm erg/M_\odot} \times m_*$

The ‘special’ overcooling problem

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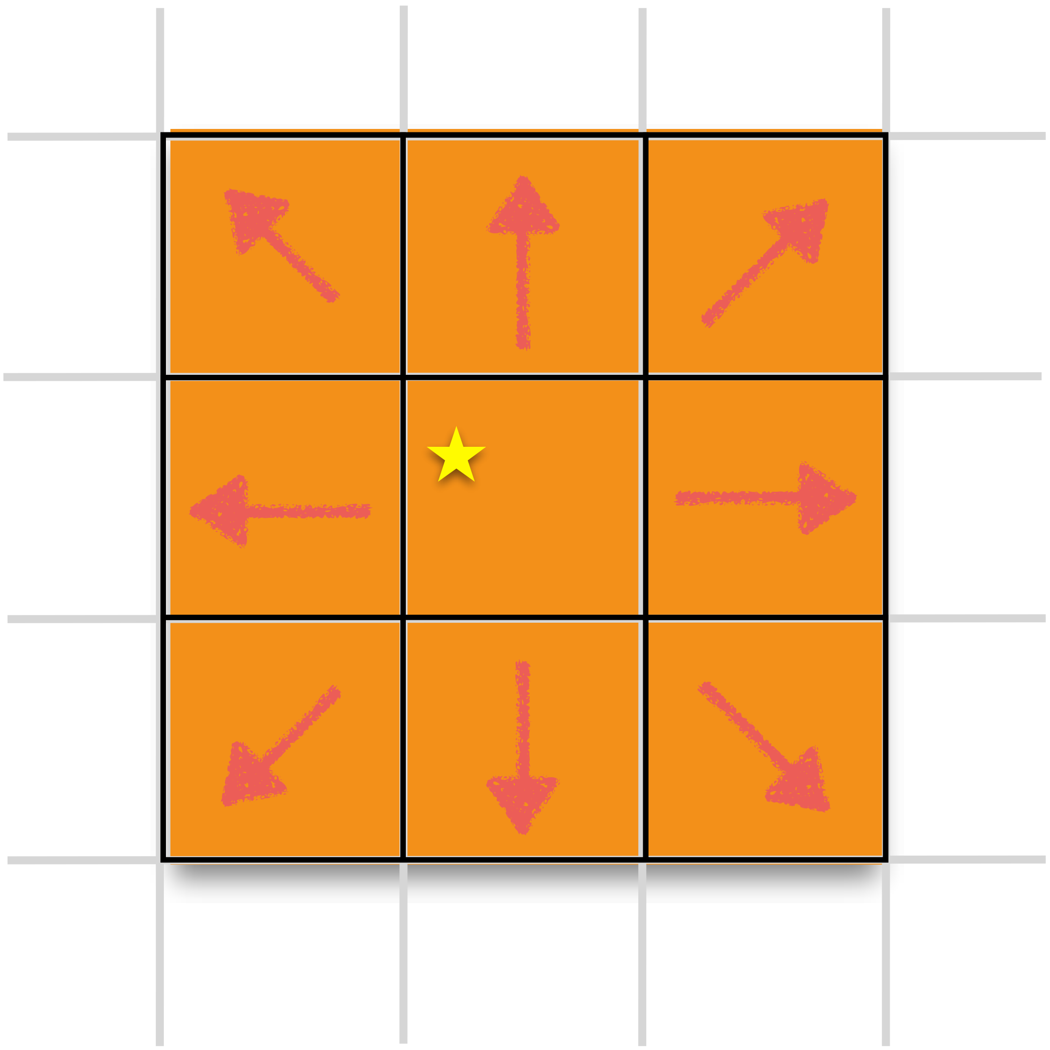

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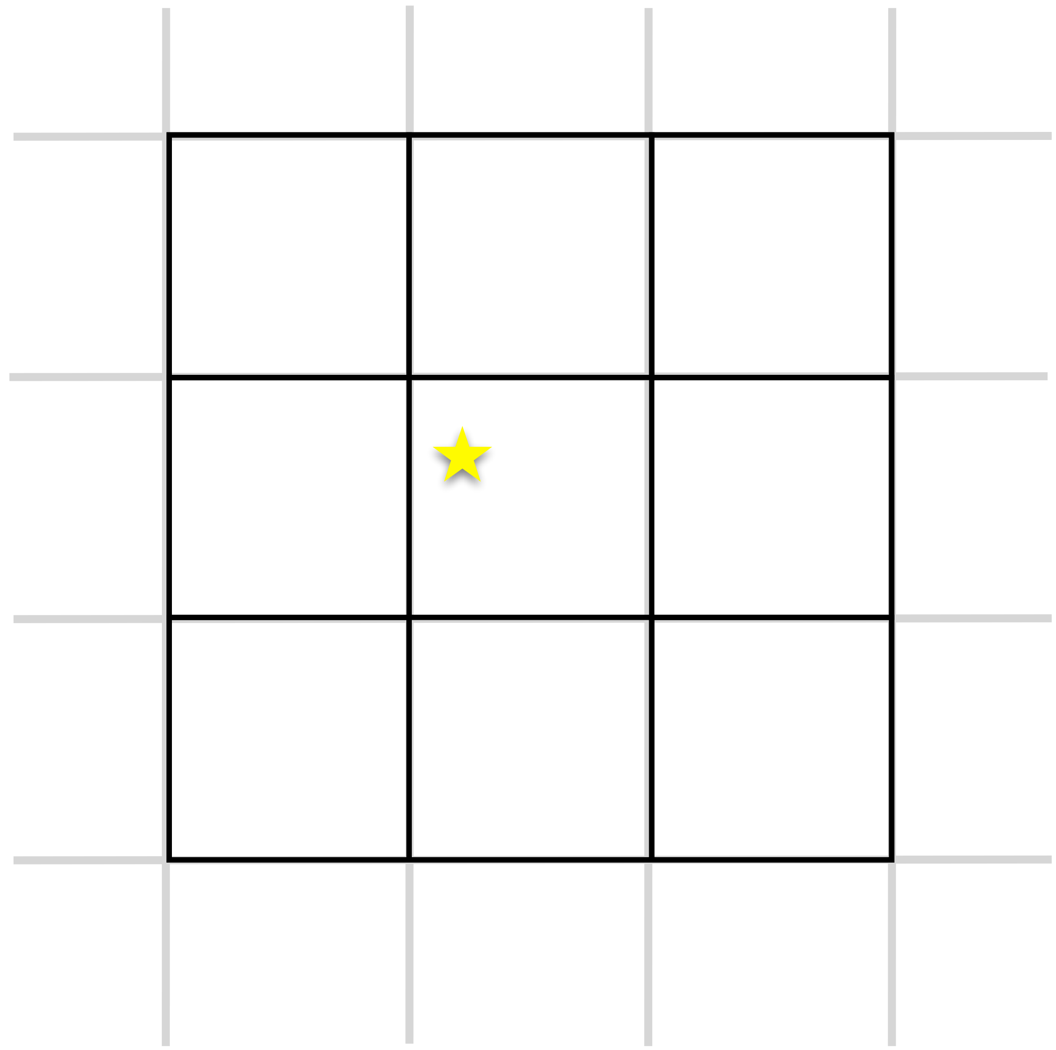

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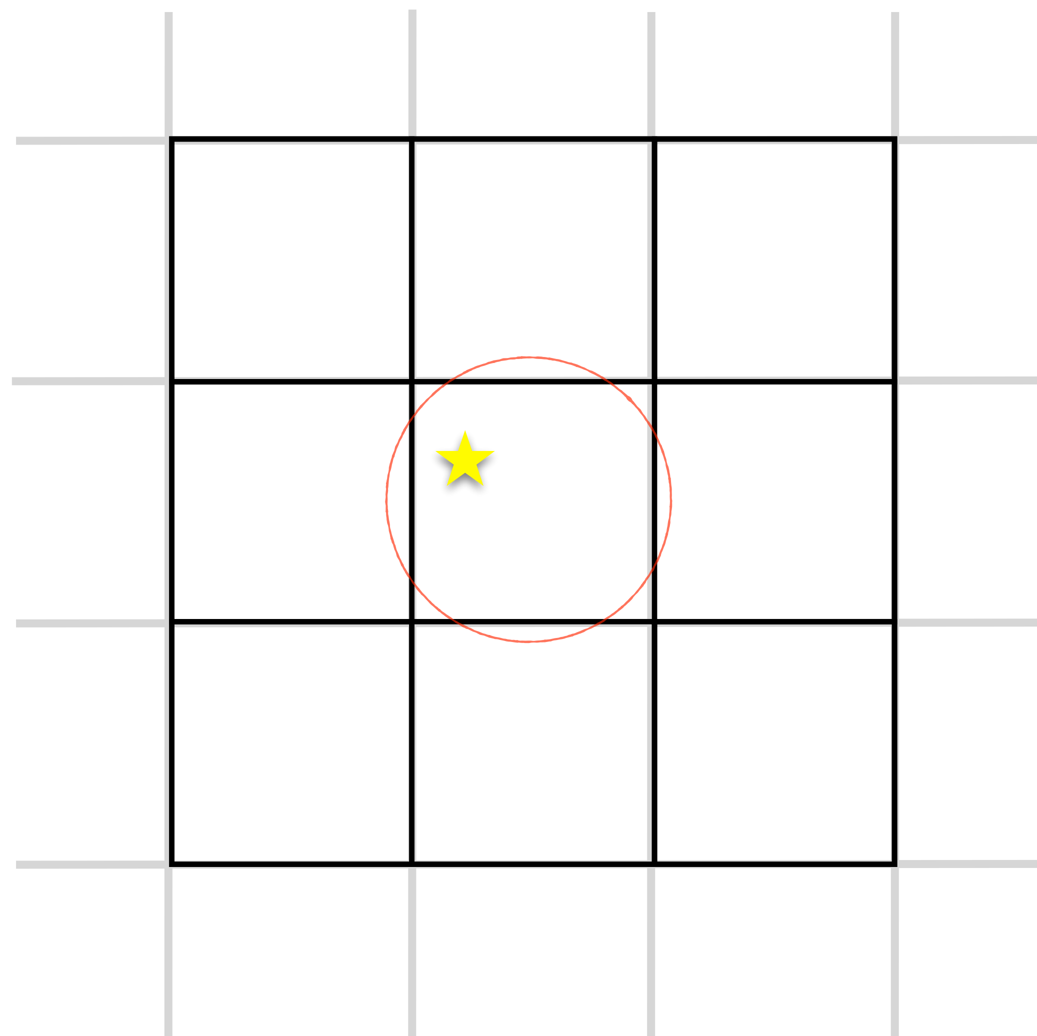


- Missing physics: Cosmic rays, stellar winds, radiation

Layout: Feedback experiments with RAMSES

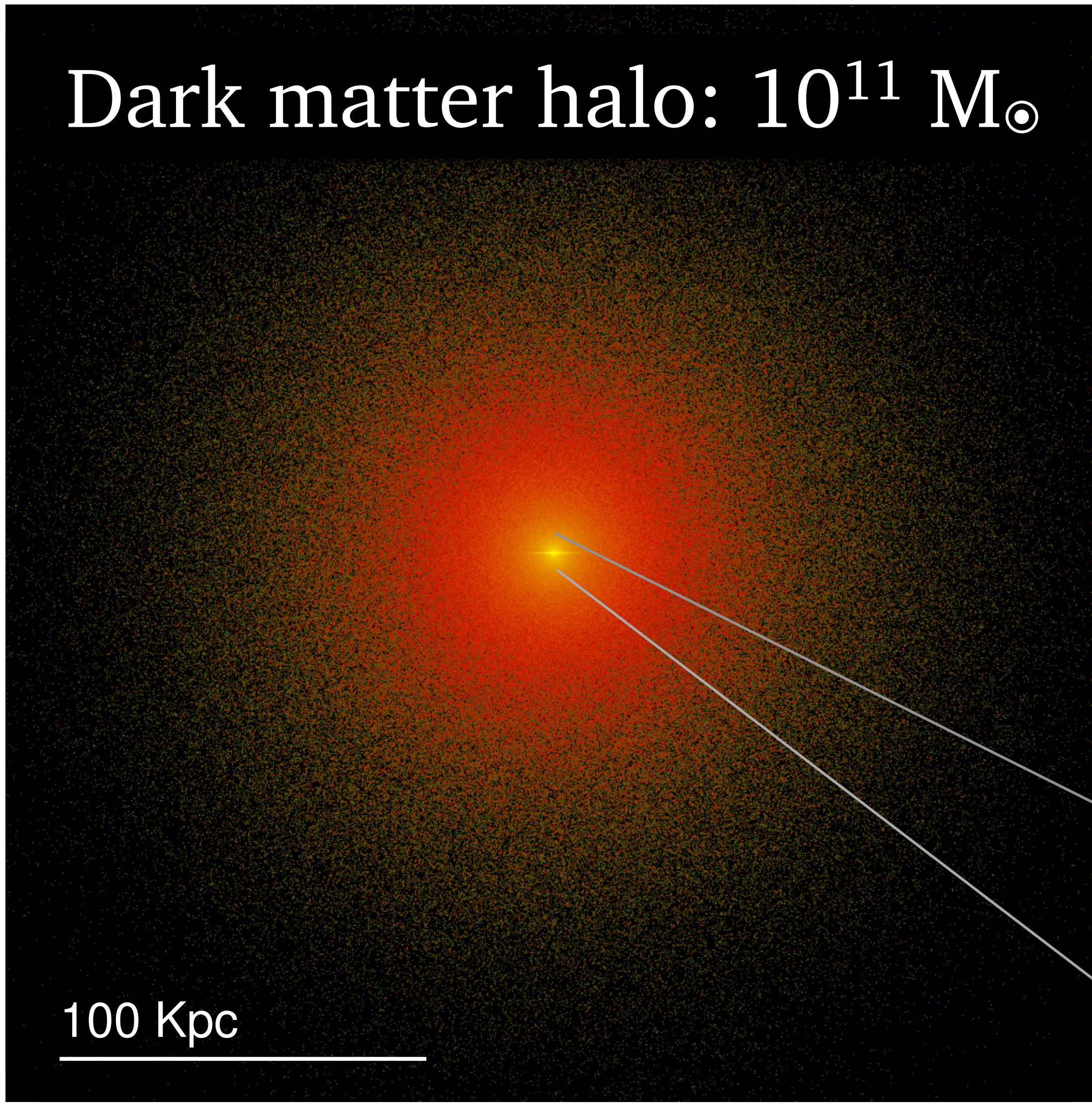
1. Simulation setup

2. Subgrid recipes
   - Stochastic
   - Kinetic
   - Delayed cooling

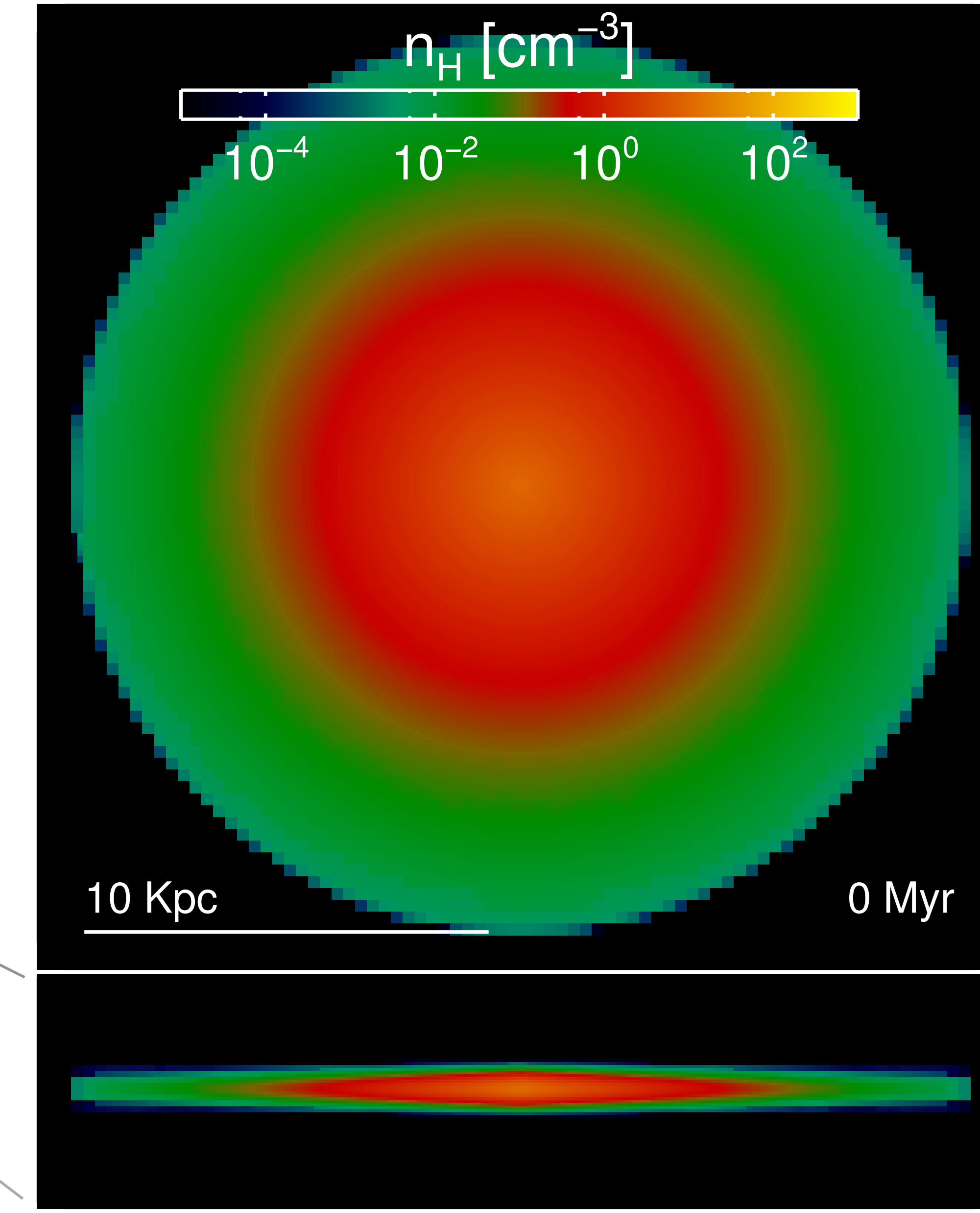
3. Radiation feedback with radiation-hydrodynamics

Simulation initial conditions

Isolated galaxy disc with RAMSES (AMR)



Simulation box



Galaxy

-4×10^9 $M_\odot$ baryonic disc, 50% stars, 50% gas
-3 10^6 DM/stellar particles
-CGM: $n_H \sim 10^{-6}$ cm^{-3} gas at 10^6 K

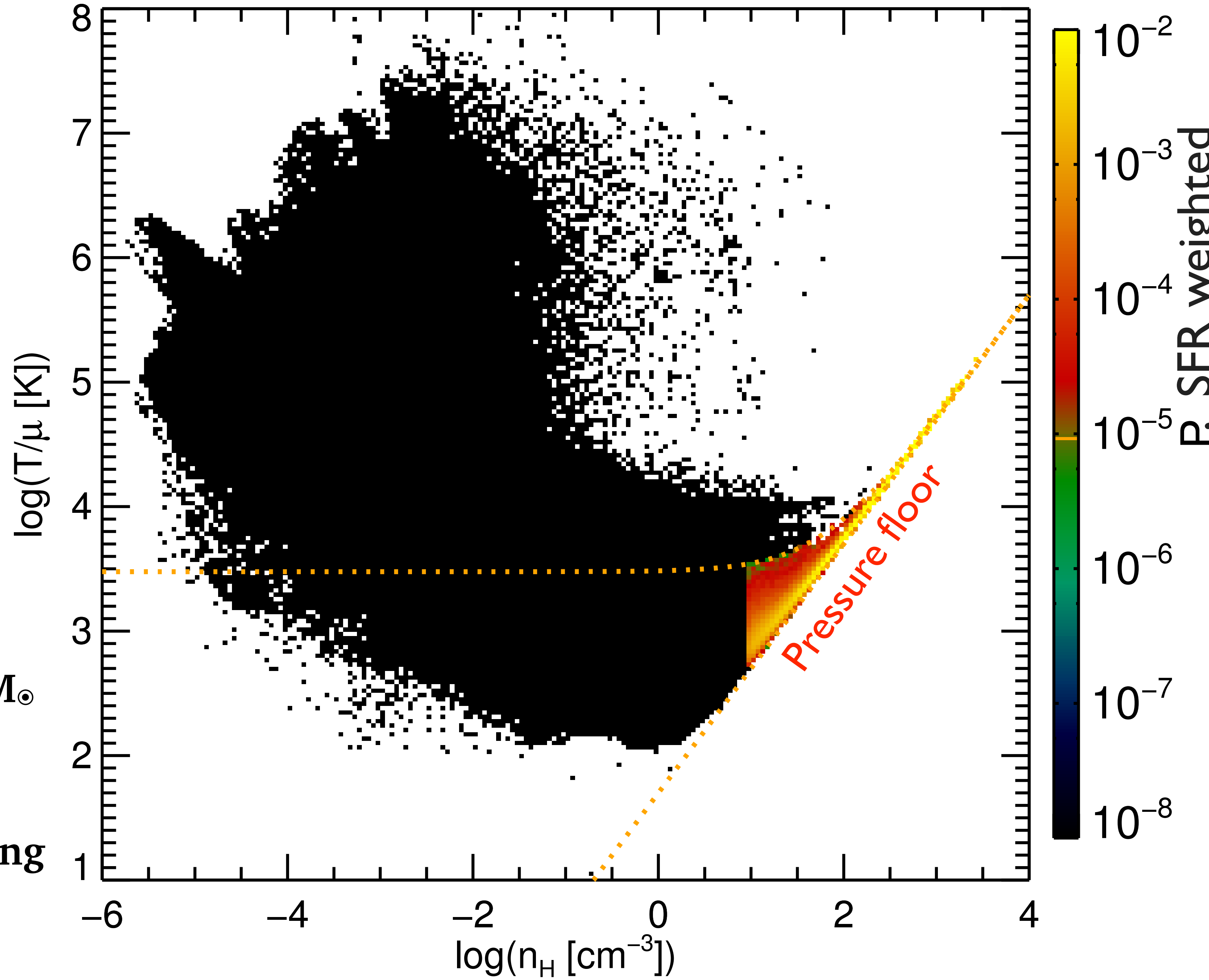
Simulation settings and physics

-18 pc resolution

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

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

2%



-Stellar particle mass: $m_☆$=600 $M_⊙$
-Chabrier IMF: η_{SN}=0.2
-Instantaneous SN at 10 Myr
-Non-equilibrium H and He cooling
-Metal cooling down to ~100 K
-Z = 0.1 $Z_⊙$, no yield

SN recipe 1:
Stochastic thermal feedback

Stochastic thermal feedback

adapted to AMR from Dalla Vecchia & Schaye (2012)

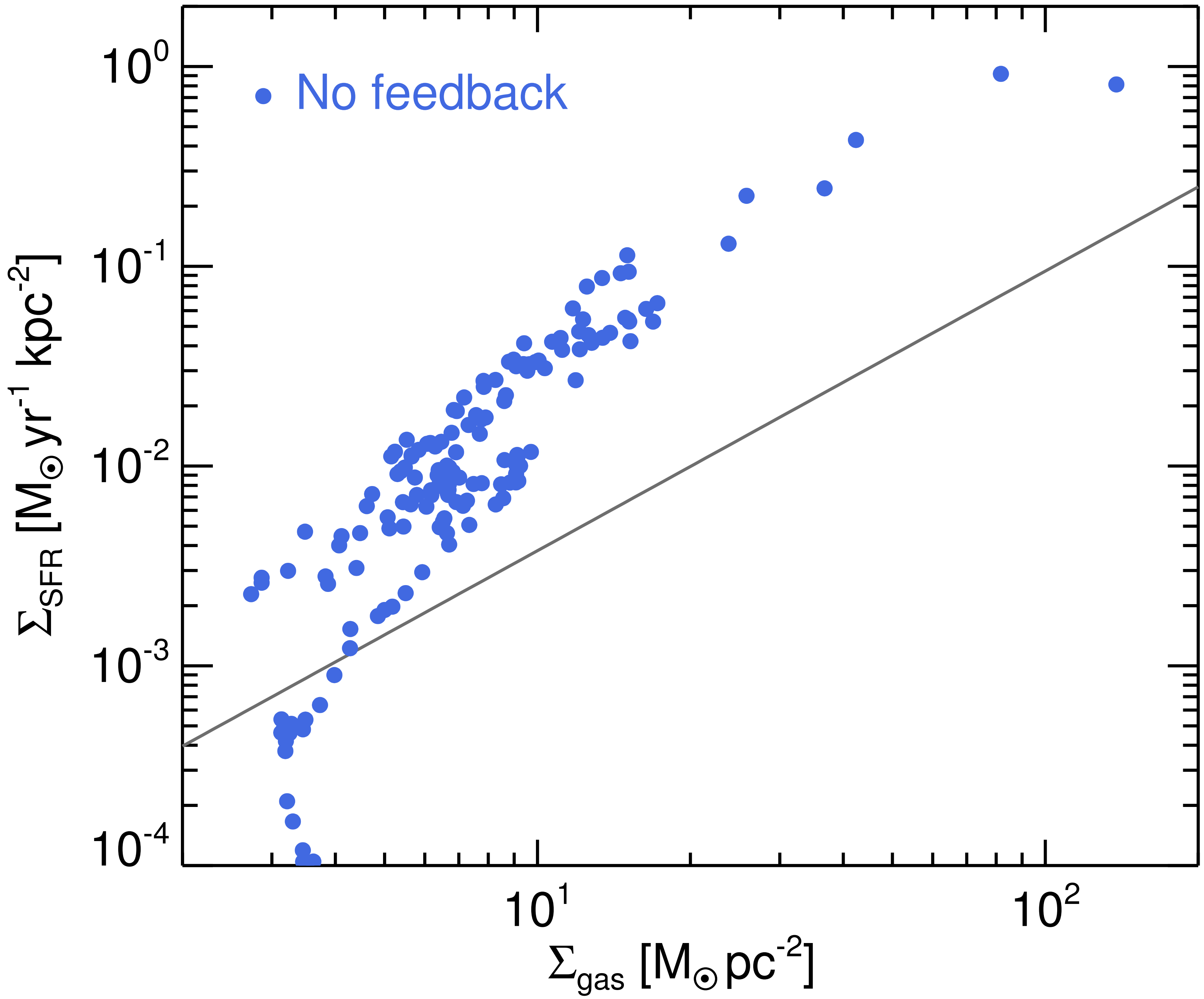
Overcooling problem: short cooling time compared to time step

Solution:
Increase cooling time by depositing *more* energy.

One feedback parameter: $\Delta T_{\rm min} \approx 10^7$ - 10^9 K
=SN heating

The *probability* for a SN is then:
$$\frac{\text{available energy}}{\text{required energy}} = \frac{E_{\rm SN}}{E_{\rm cell}(\Delta T_{\rm min})}$$

Stochastic feedback: Kennicutt Schmidt relation
over disk annuli, at 250 Myr



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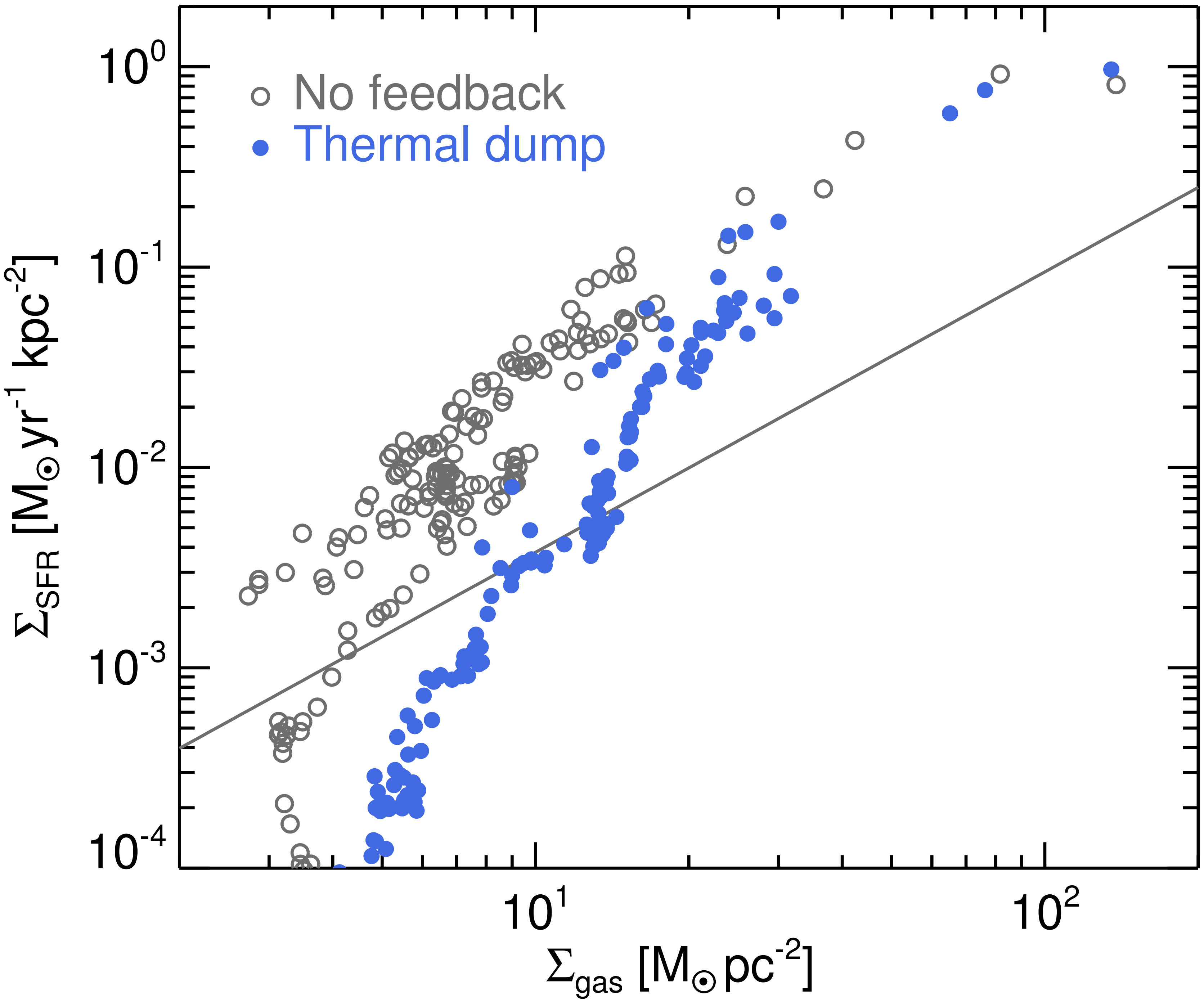

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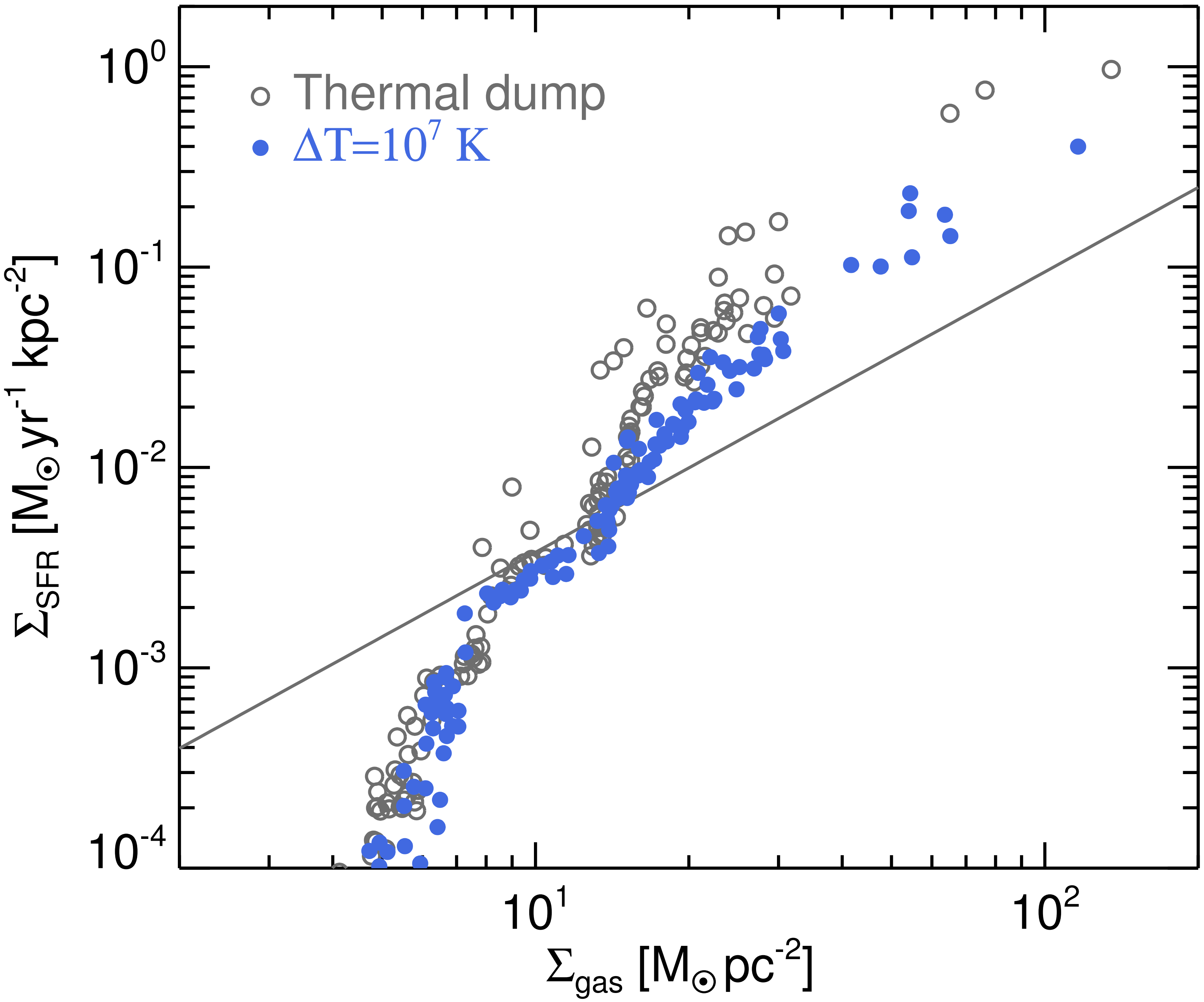

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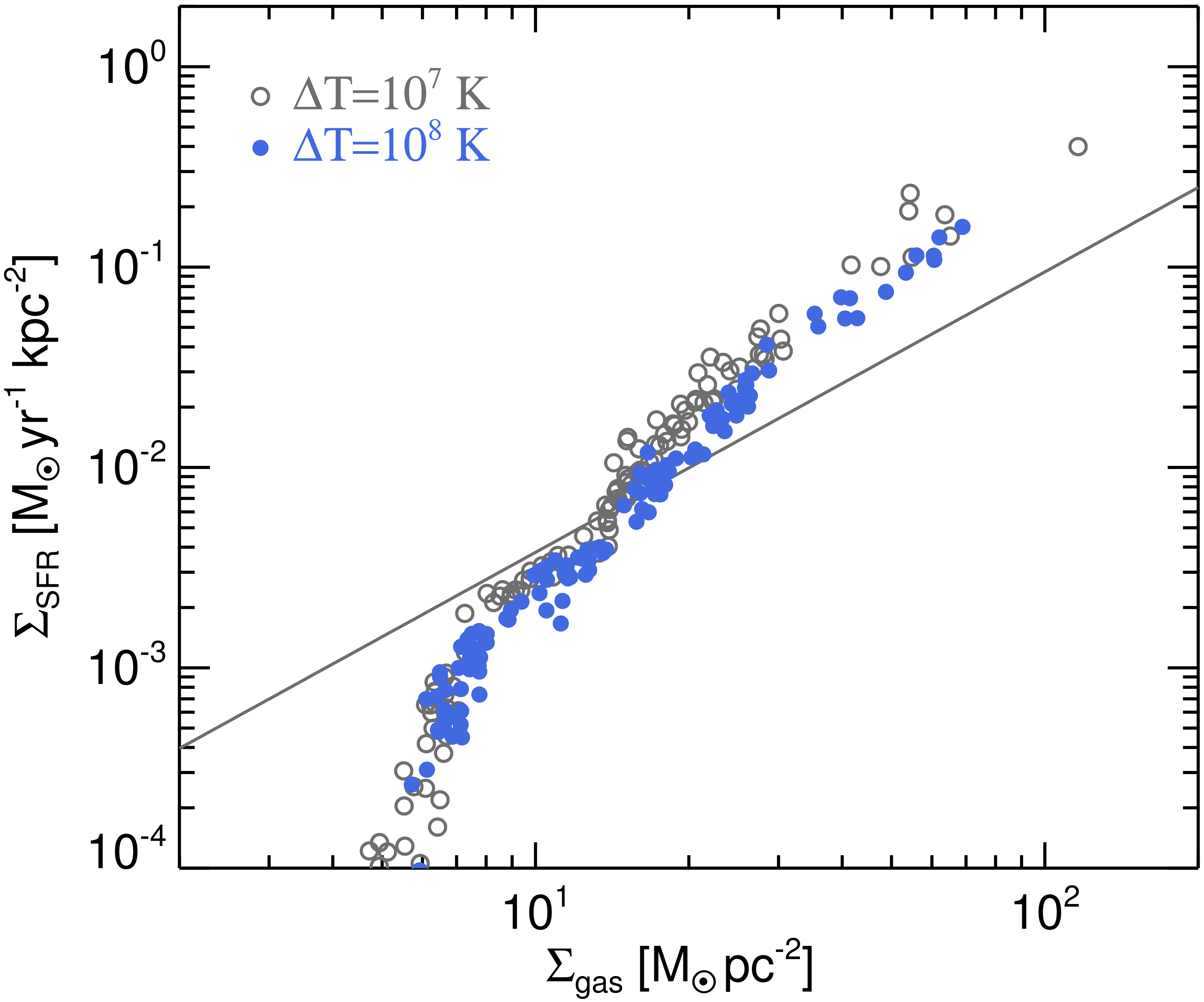

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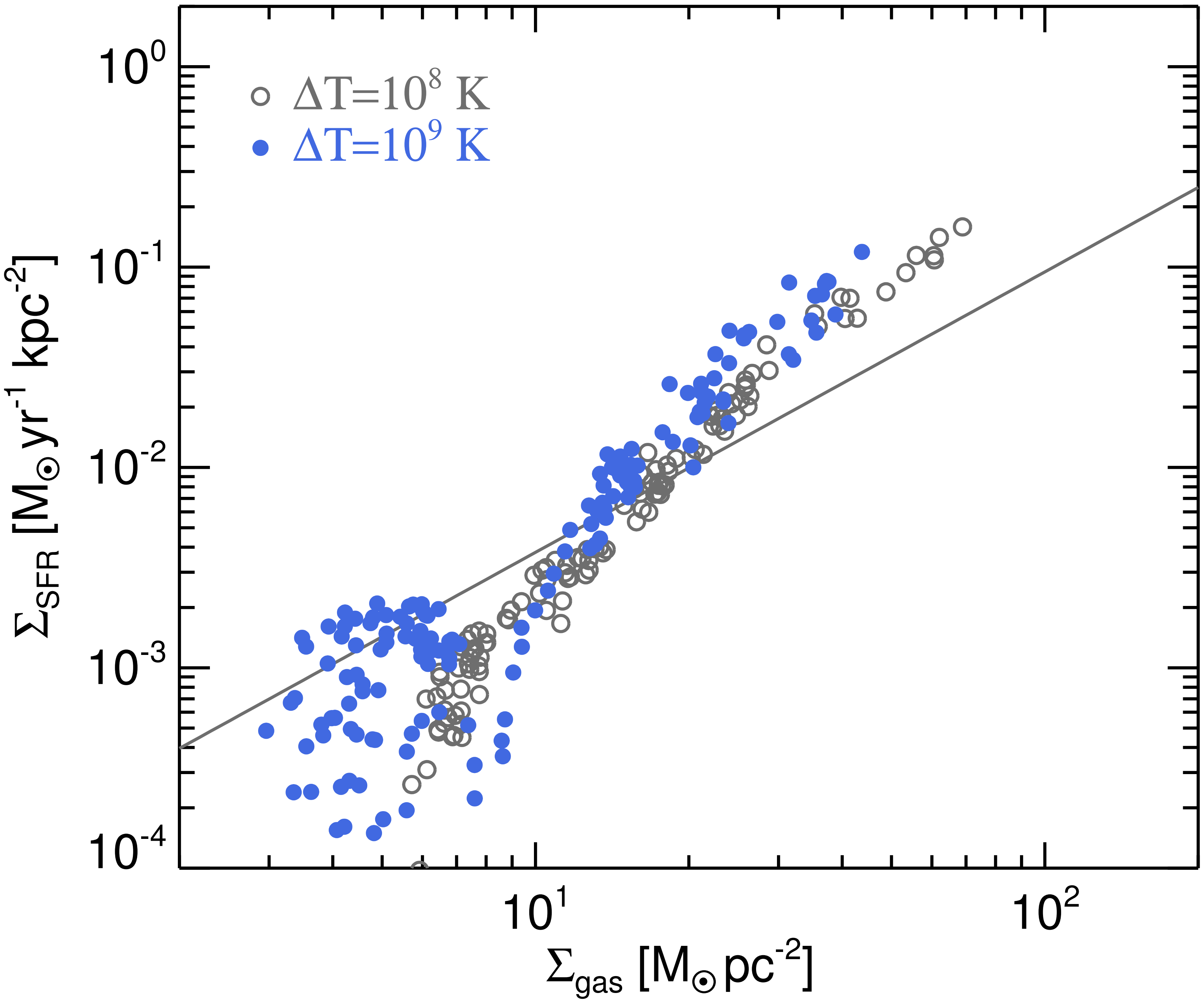

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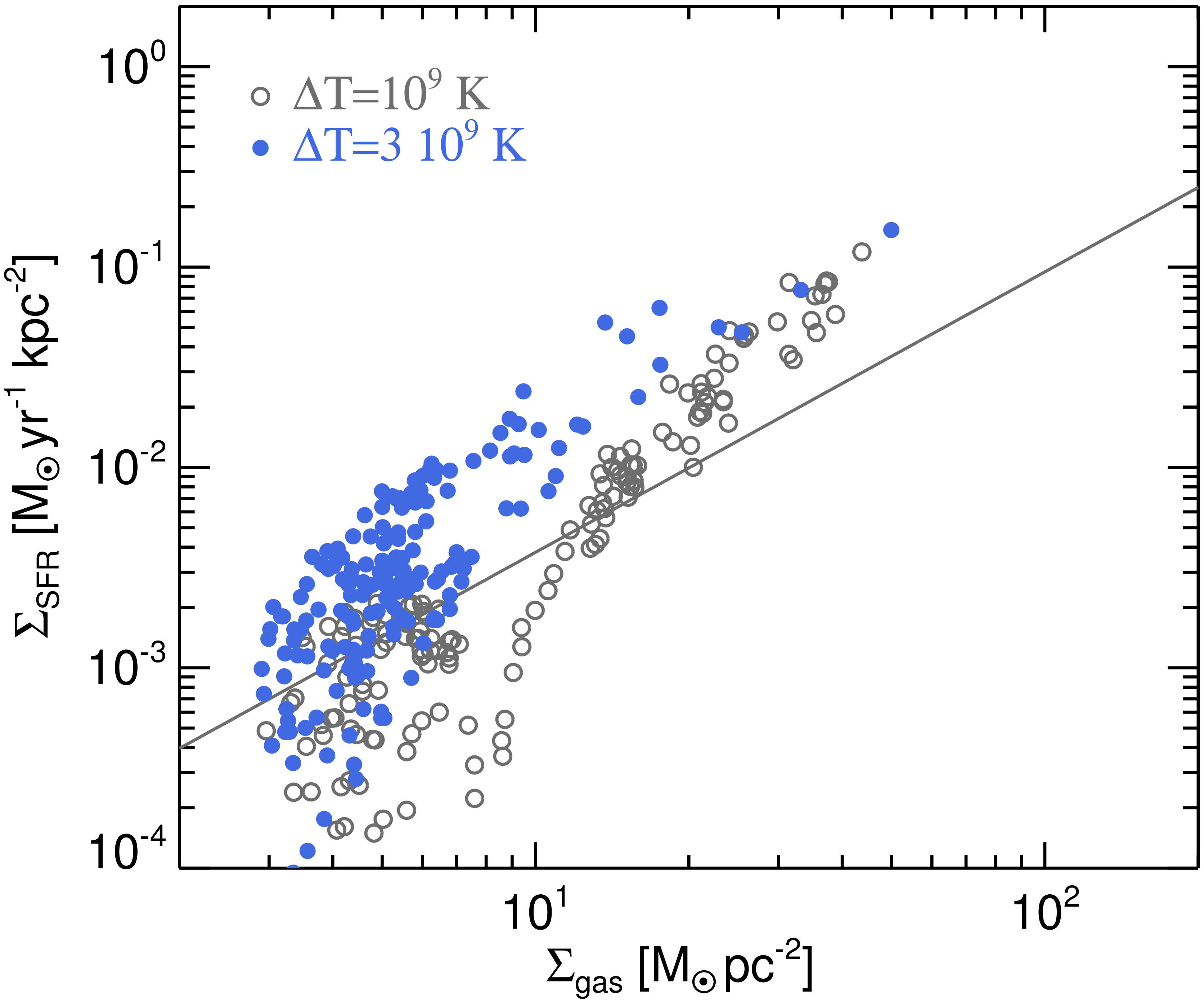

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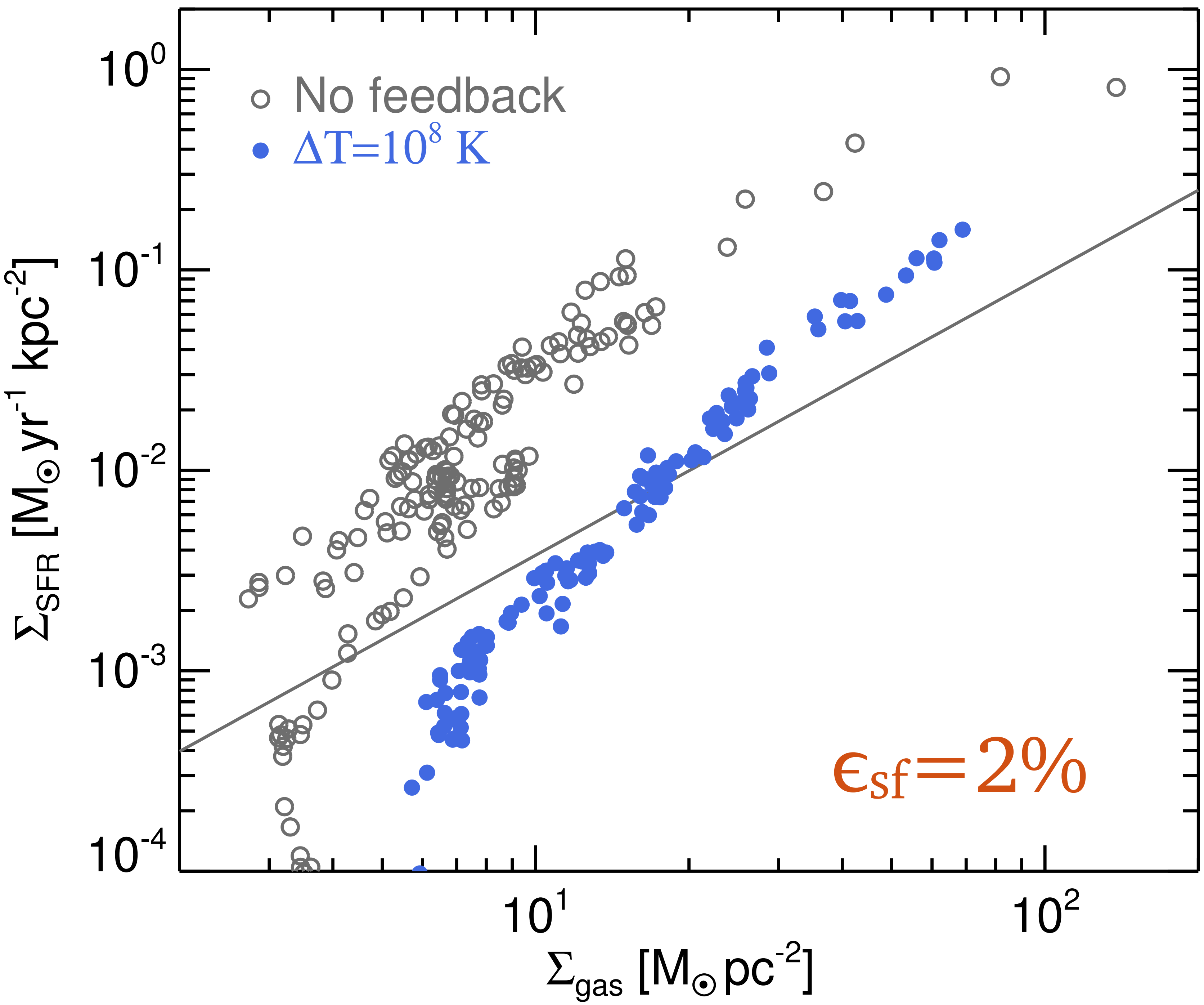
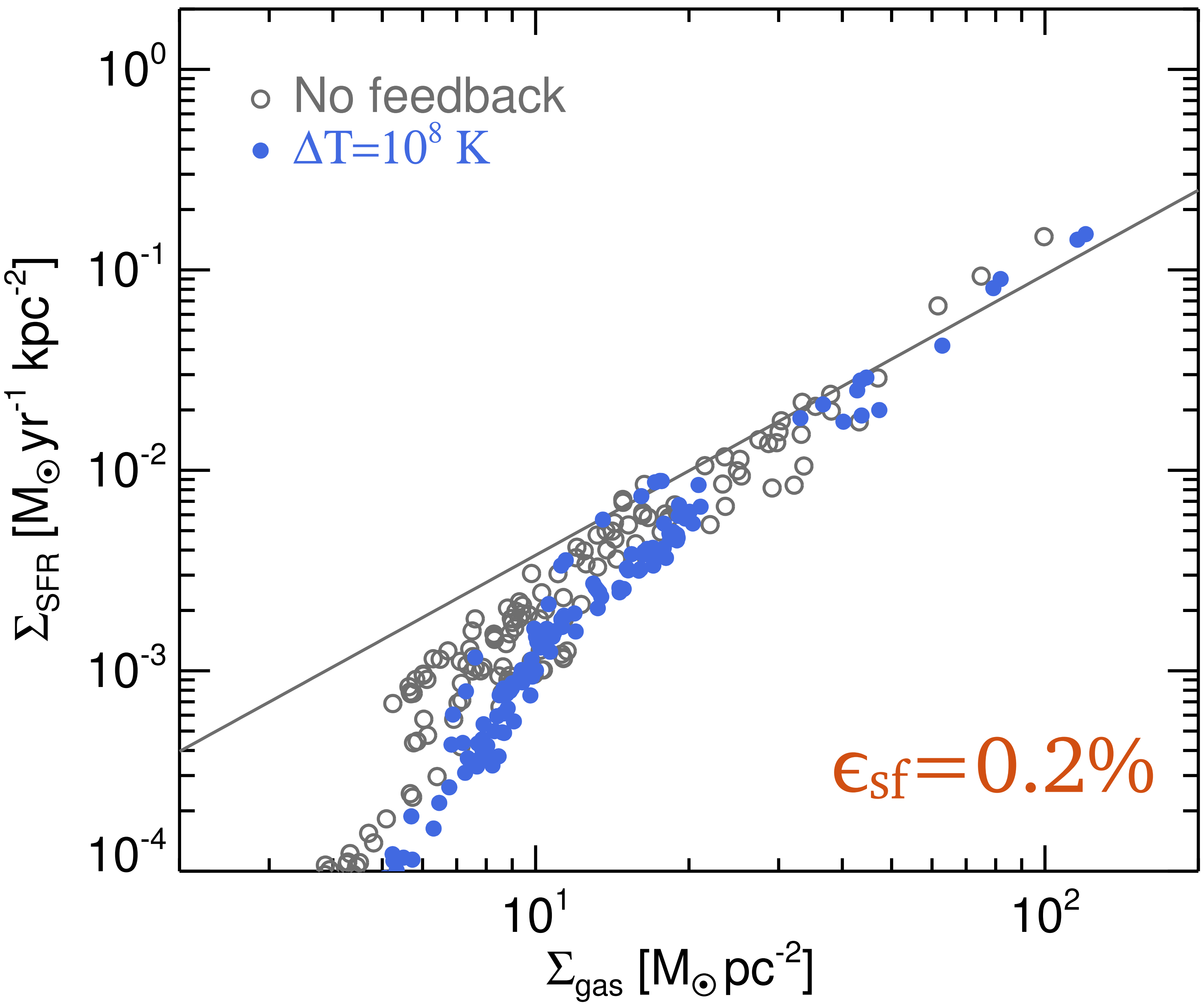


No agreement with observed KS relation…
but can change SF efficiency

Stochastic feedback: Kennicutt Schmidt relation



but can change SF efficiency…

<u>but</u> only way to get agreement is to cancel any feedback

SN recipe II:
Kinetic feedback

Kinetic feedback

Implemented in RAMSES by Dubois (2008)

Problem: Sedov blast unresolved

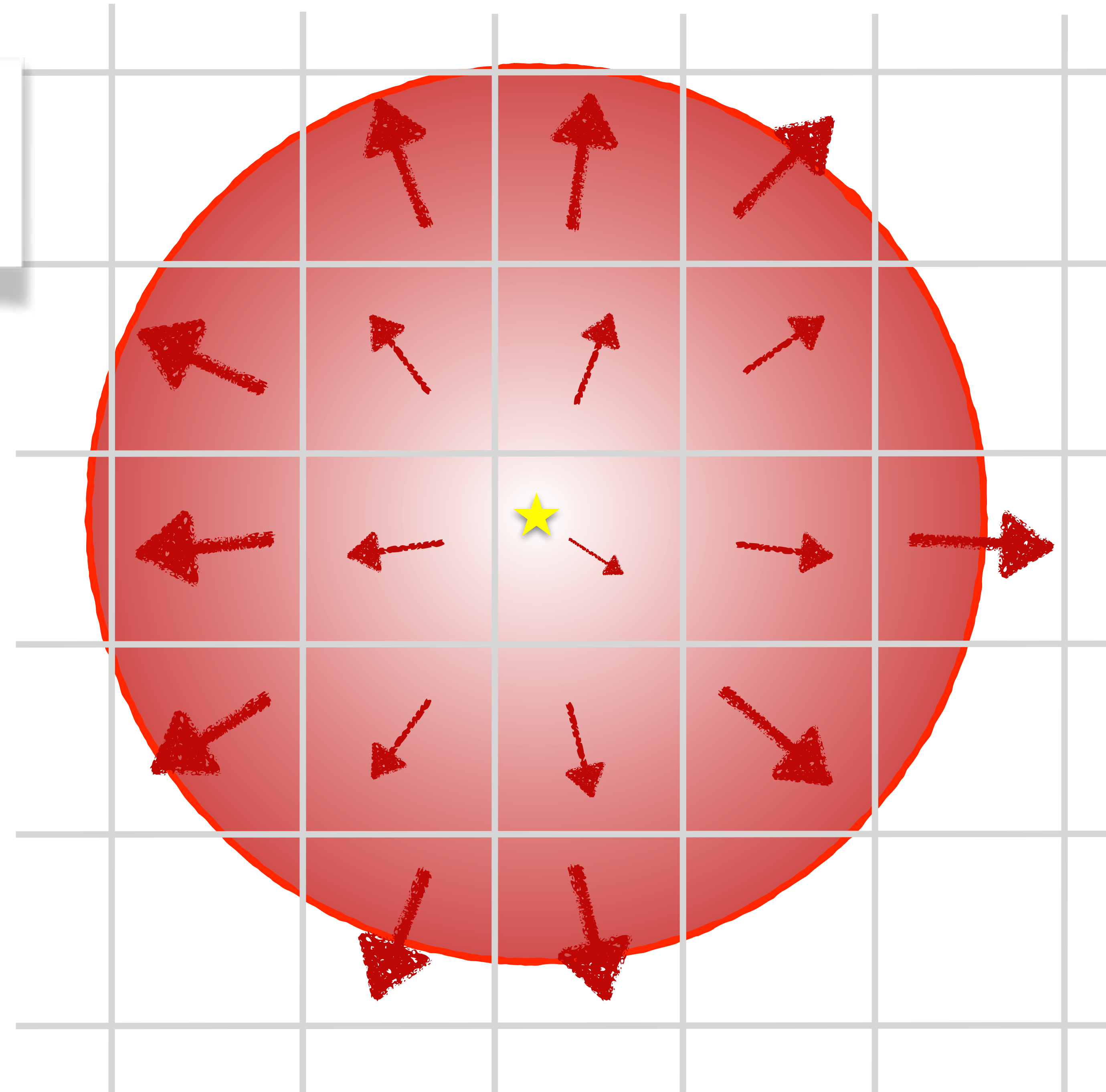
Solution: Skip Sedov blast — mimic the result

Parameters:

$r_{bubble} \approx$ 150 pc

$\eta_W \approx$ 1-10 = wind mass loading

V_W from energy conservation



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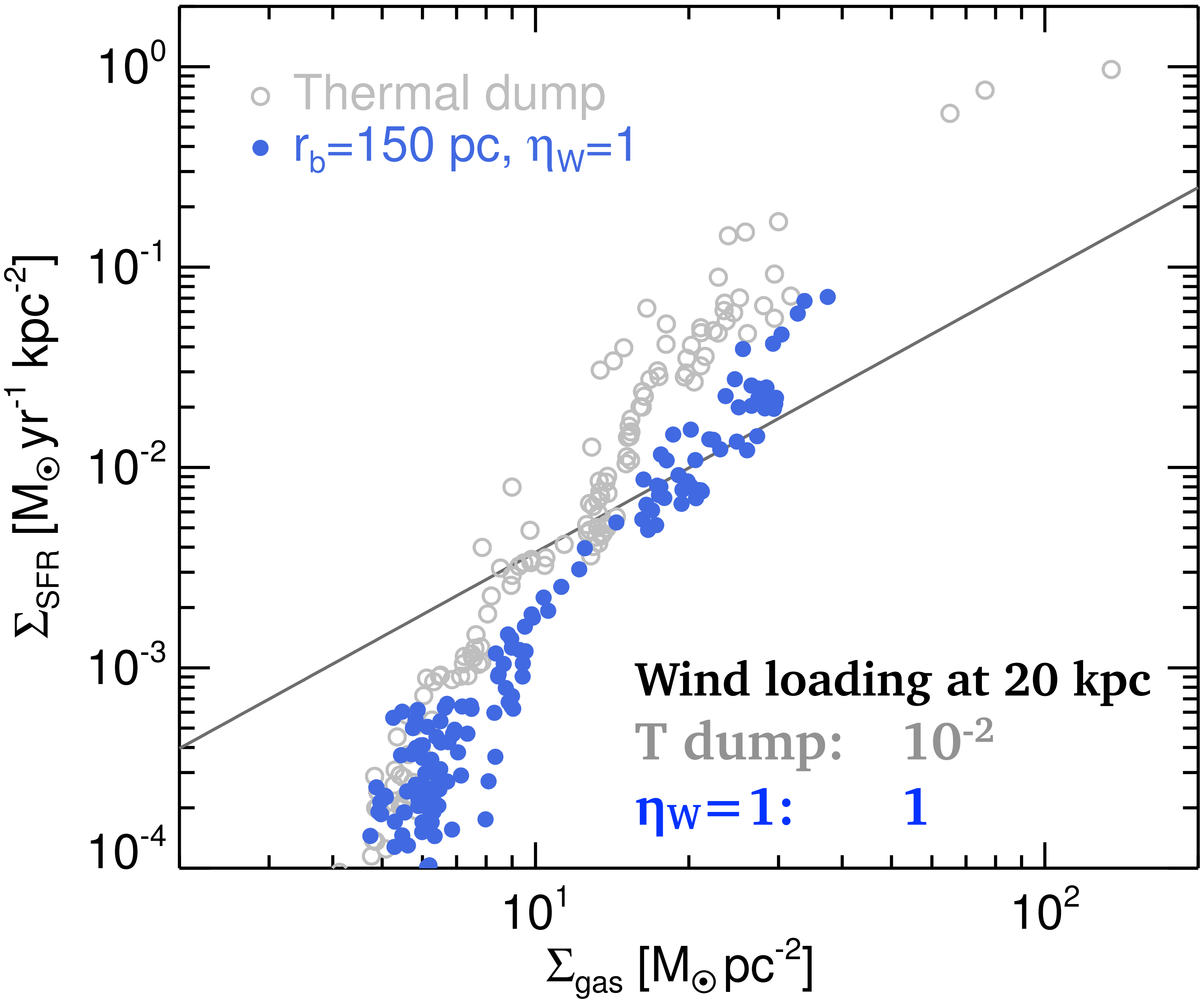
Kinetic feedback: Kennicutt Schmidt relation



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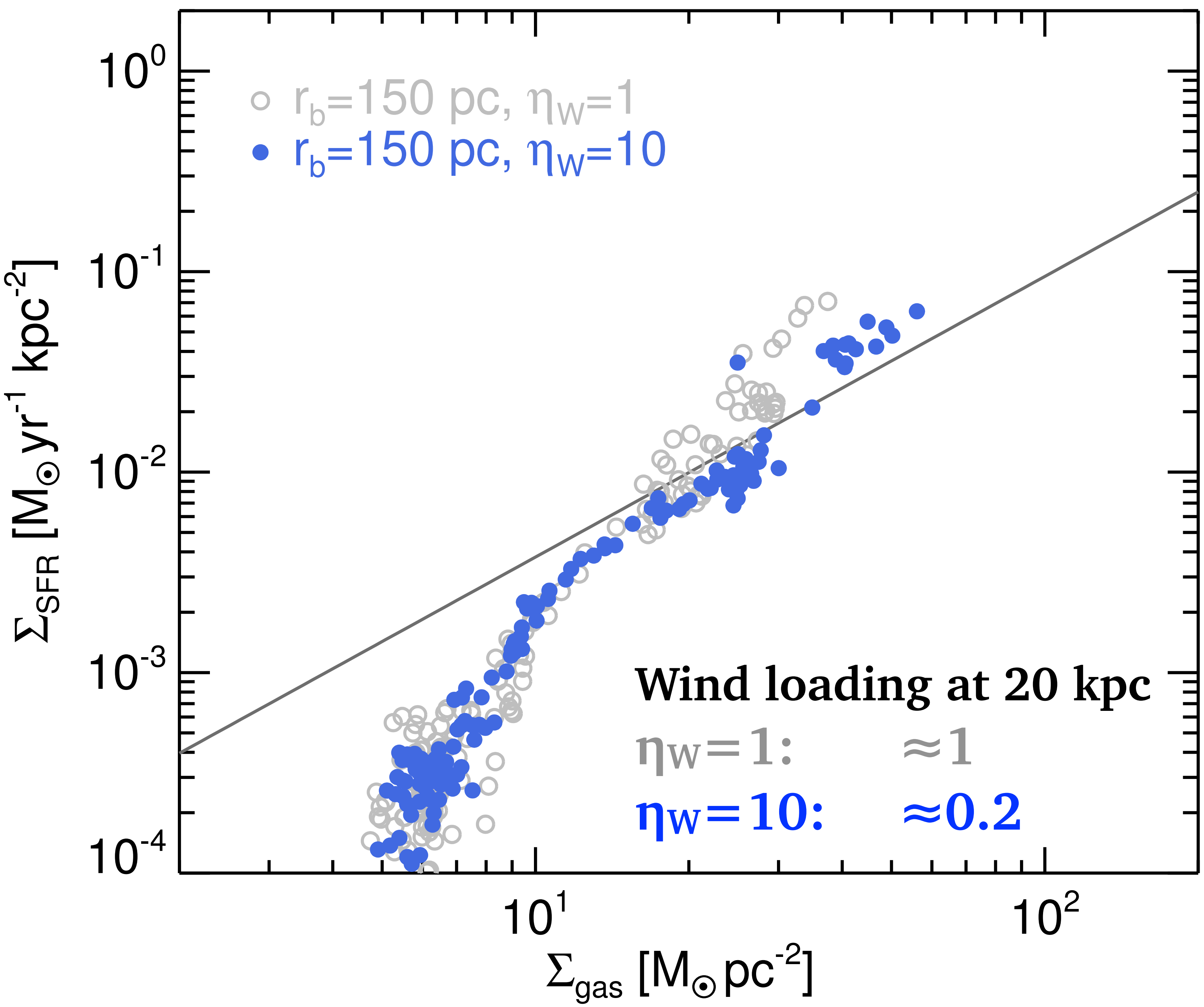
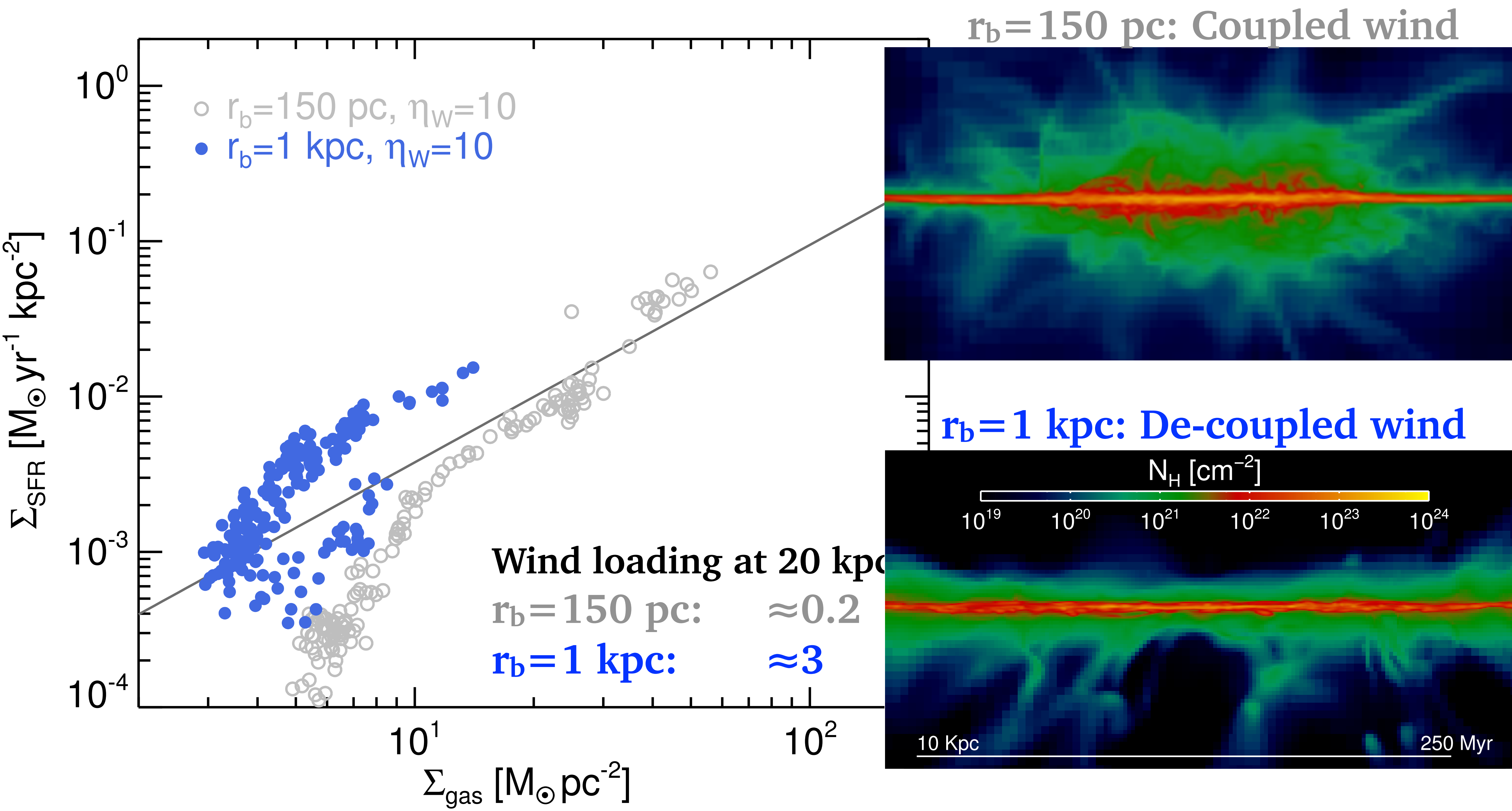


Kinetic feedback: Kennicutt Schmidt relation



SN recipe III: Delayed cooling

Delayed cooling

Implemented in RAMSES by R. Teyssier

Overcooling problem:
cooling time is short compared to time step, and SN energy disappears before gas reacts

Solution:
Turn off cooling long enough to allow gas to react

Physical meaning:

- SN activity maintains an unresolved non-thermal ***turbulence***
- Decays on unresolved sound-crossing time — hydro solver maintains it on larger scales

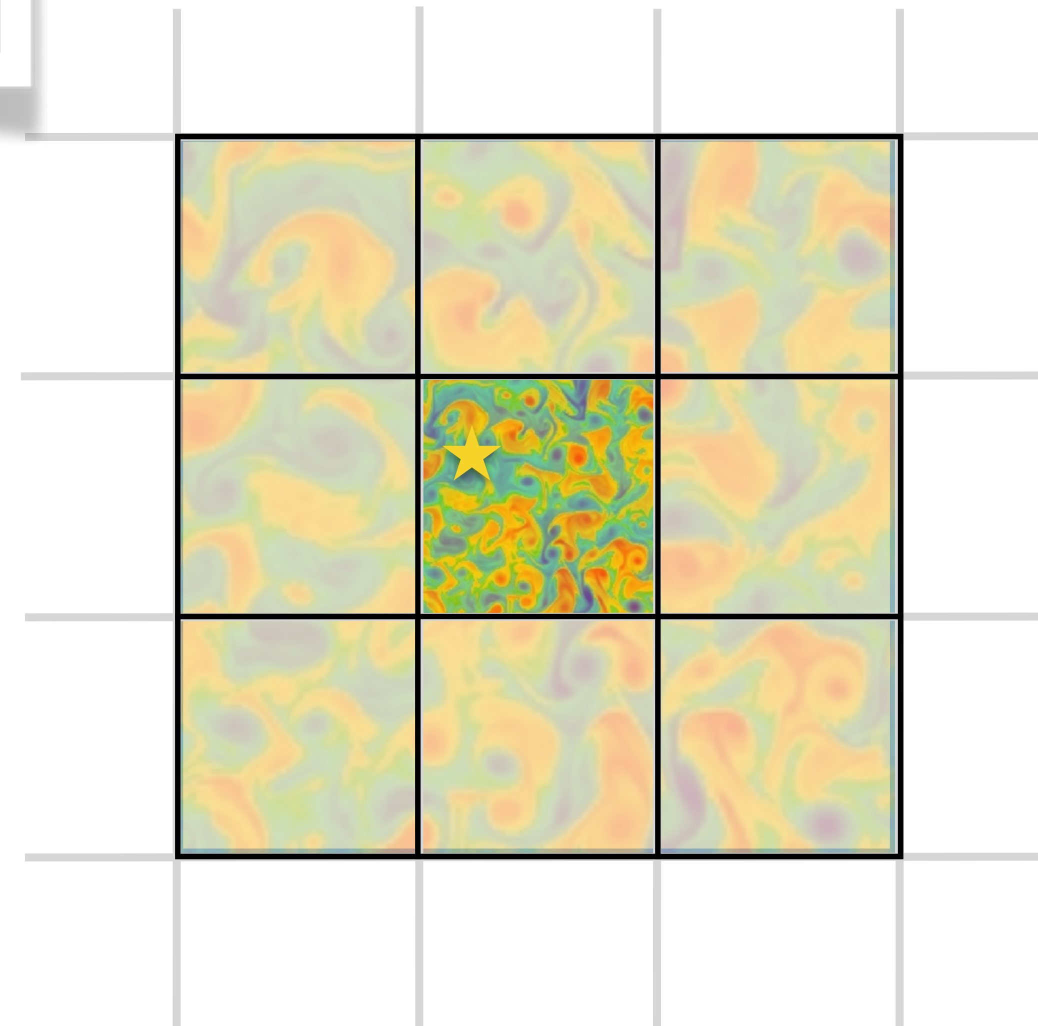
Delayed cooling

Method:

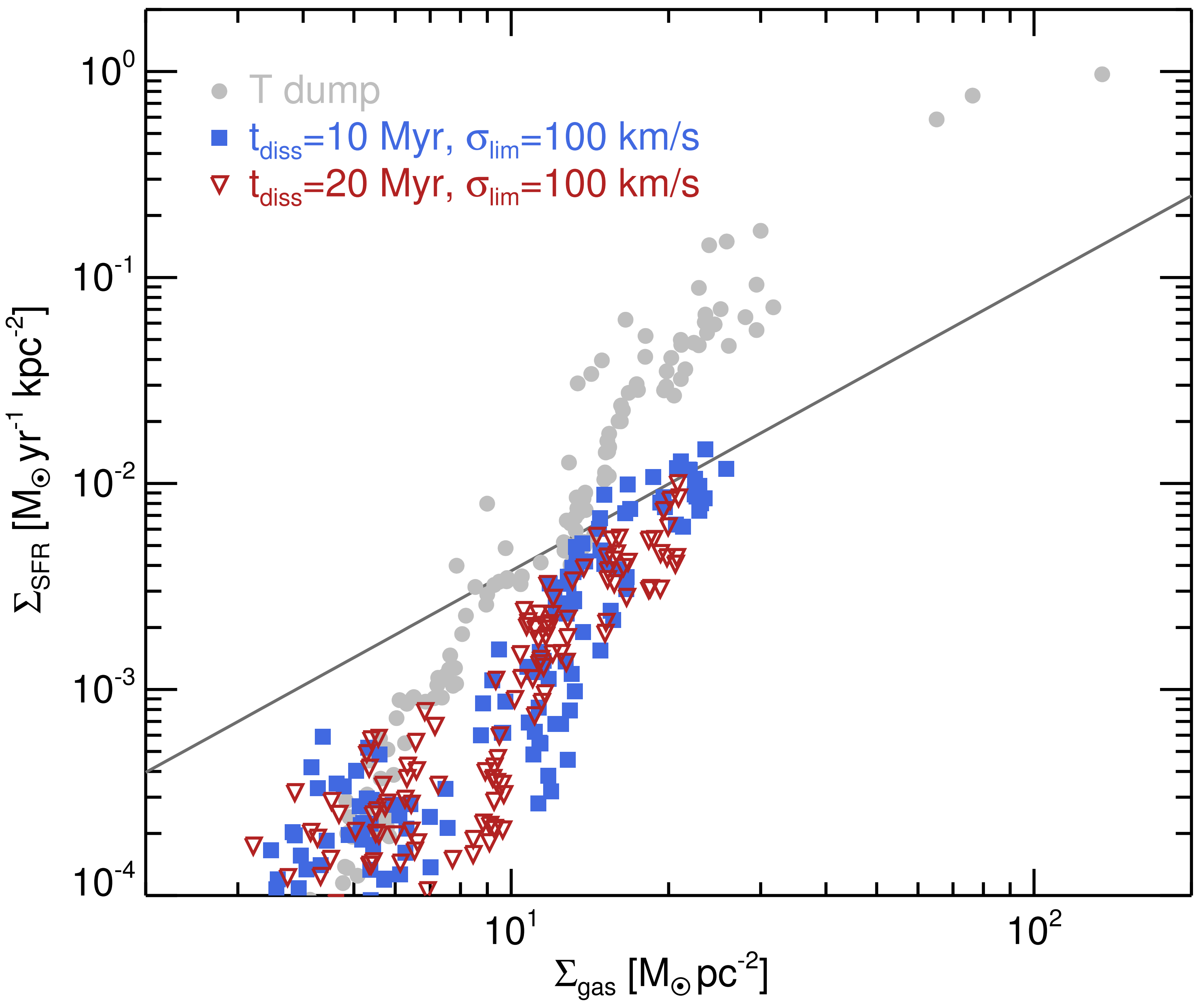
- Inject SN energy, but also a turbulent energy tracer, σ_{turb}, which moves with the gas.
- Turn off cooling where $\sigma_{turb} > \sigma_{min}$
- Decay σ_{turb} on a timescale t_{diss}

Parameters:

- $t_{diss} \approx$ **10 Myr,** depending on simulation
- $\sigma_{min} \approx$ **100 km/s** (1/50 of SN velocity)



Delayed cooling: results



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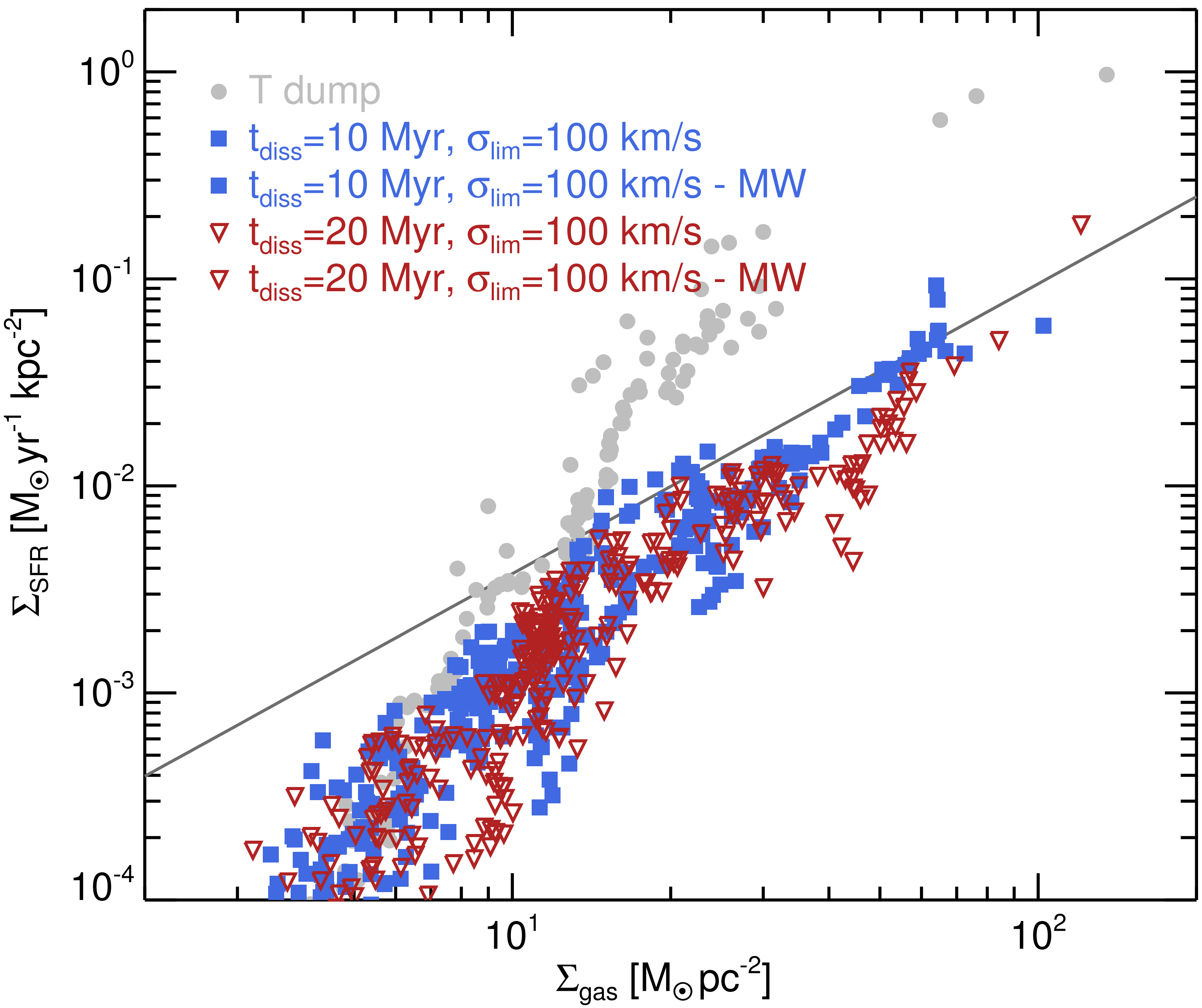
Delayed cooling: results



SN recipes

Overcooling problem can be dealt with:

- suppressed SF, puffed up galaxies, outflows
- but perhaps not all at the same time

Recipes likely over-do SN feedback, but make up for lack of e.g.:

- Cosmic rays
- Stellar winds - early
- Radiation feedback - early

It is timely to look closer at those other processes:

- how do the actually work?
- are they fairly represented by current sub-grid recipes?

Radiation feedback, with radiation-hydrodynamics (RHD)

I. RHD method

II. Results: effect of adding stellar radiation

III. The nature of radiation feedback on a galactic scale
- Radiation heating?
- Radiation pressure?

The code: Ramses-RT

Radiation Hydrodynamics in RAMSES

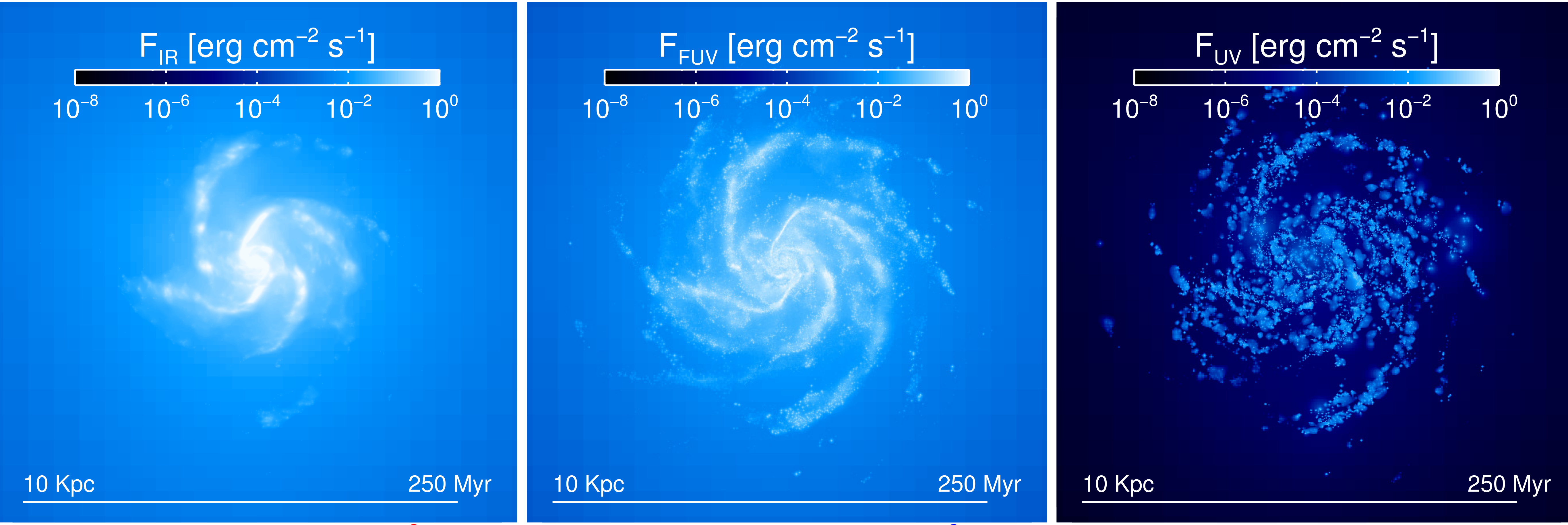
Rosdahl et al. (2013):

- Moment method radiative transfer (RT), with M1 closure
- Ionisation and heating of gas
- Radiation pressure added and tested
- Optically thick IR modelled with diffusion (hybrid method)

➡ IR trapping and multi-scattering on dust

Radiation bands
IR, FUV, 3xUV

On-the-fly stellar particle emission from SEDs: Bruzual & Charlot (2003)



$\kappa_{\rm dust} = 10 \times Z/Z_\odot \ {\rm cm}^2/{\rm g}$

$\kappa_{\rm dust} = 1000 \times Z/Z_\odot \ {\rm cm}^2/{\rm g}$

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$\sigma_{\rm HI} \approx \sigma_{\rm HeI} \approx 3 \ 10^{-18} \ {\rm cm}^2$

$\sigma_{\rm HeII} \approx 10^{-18} \ {\rm cm}^2$

IR can scatter indefinitely

➜ multiplication factor in IR pressure at high opacity

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Radiation feedback with RHD

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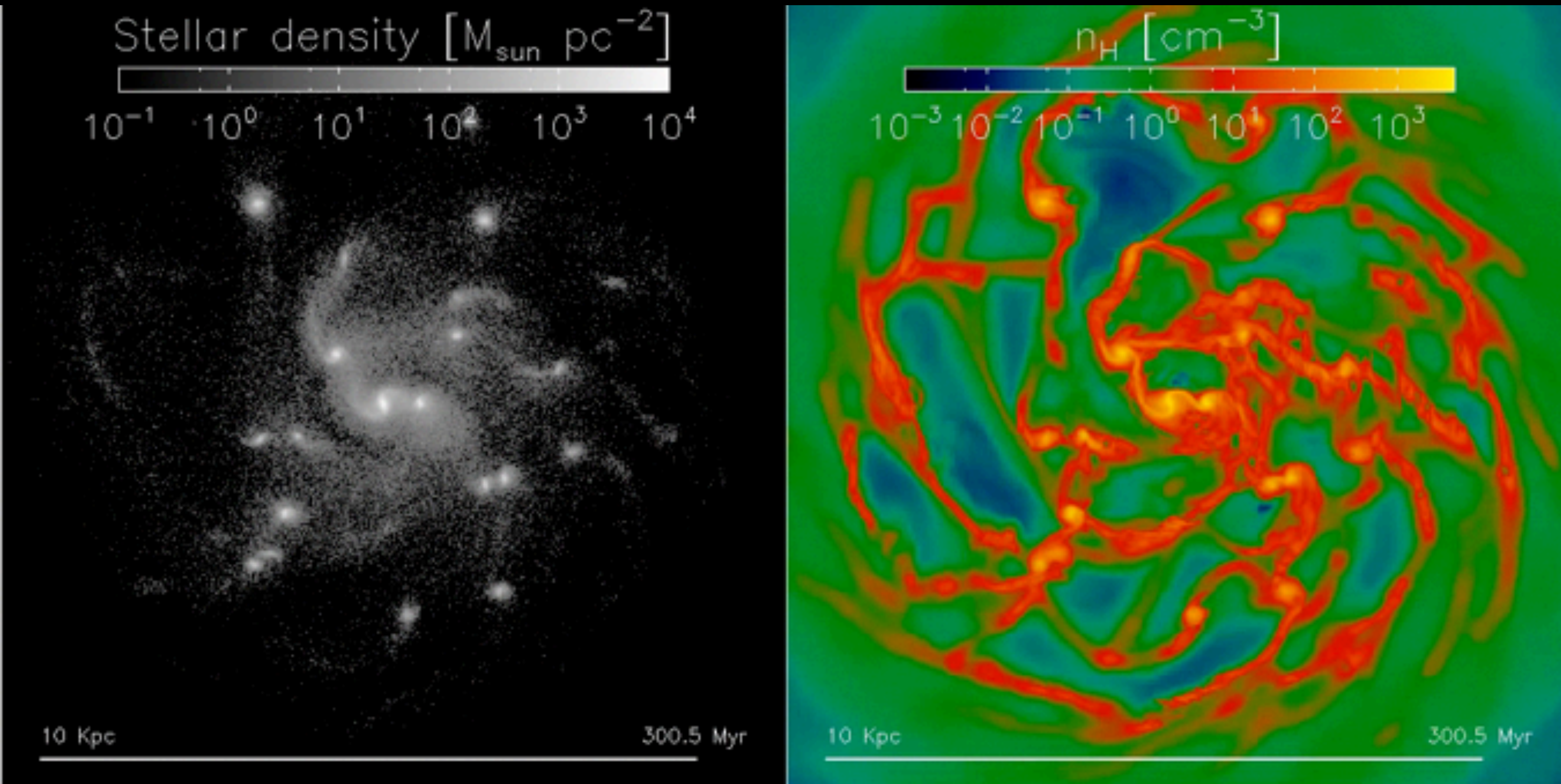
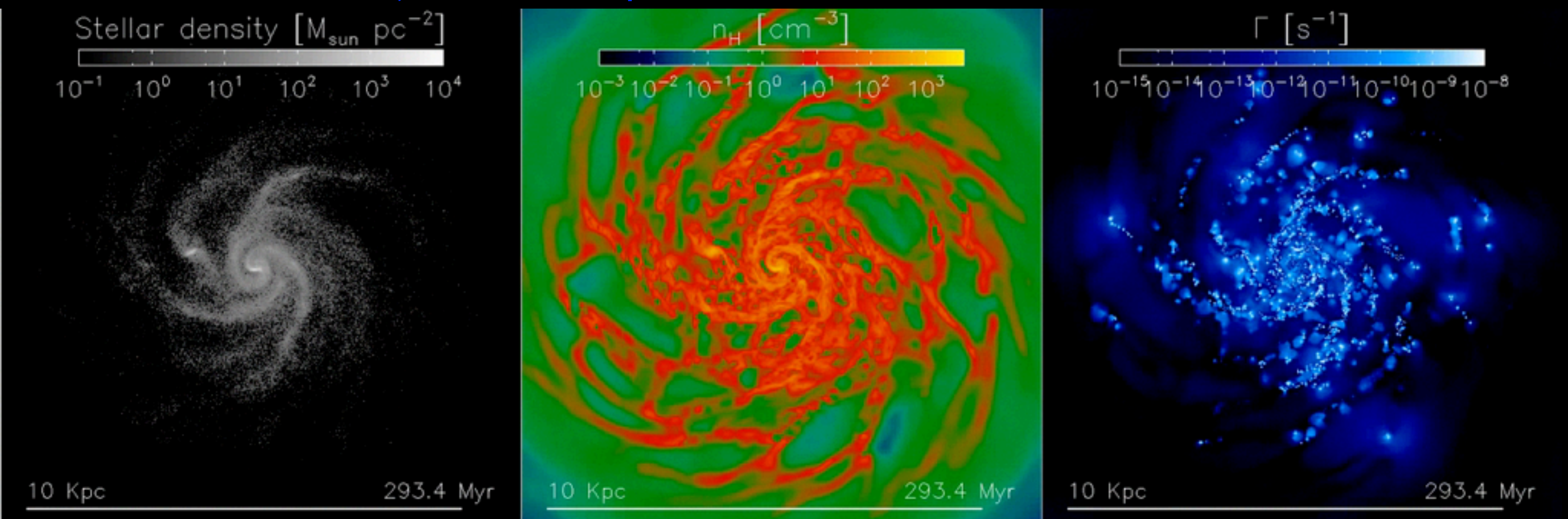
Results: Visual comparison: no RT versus RT



No RT...just thermal dump SNe



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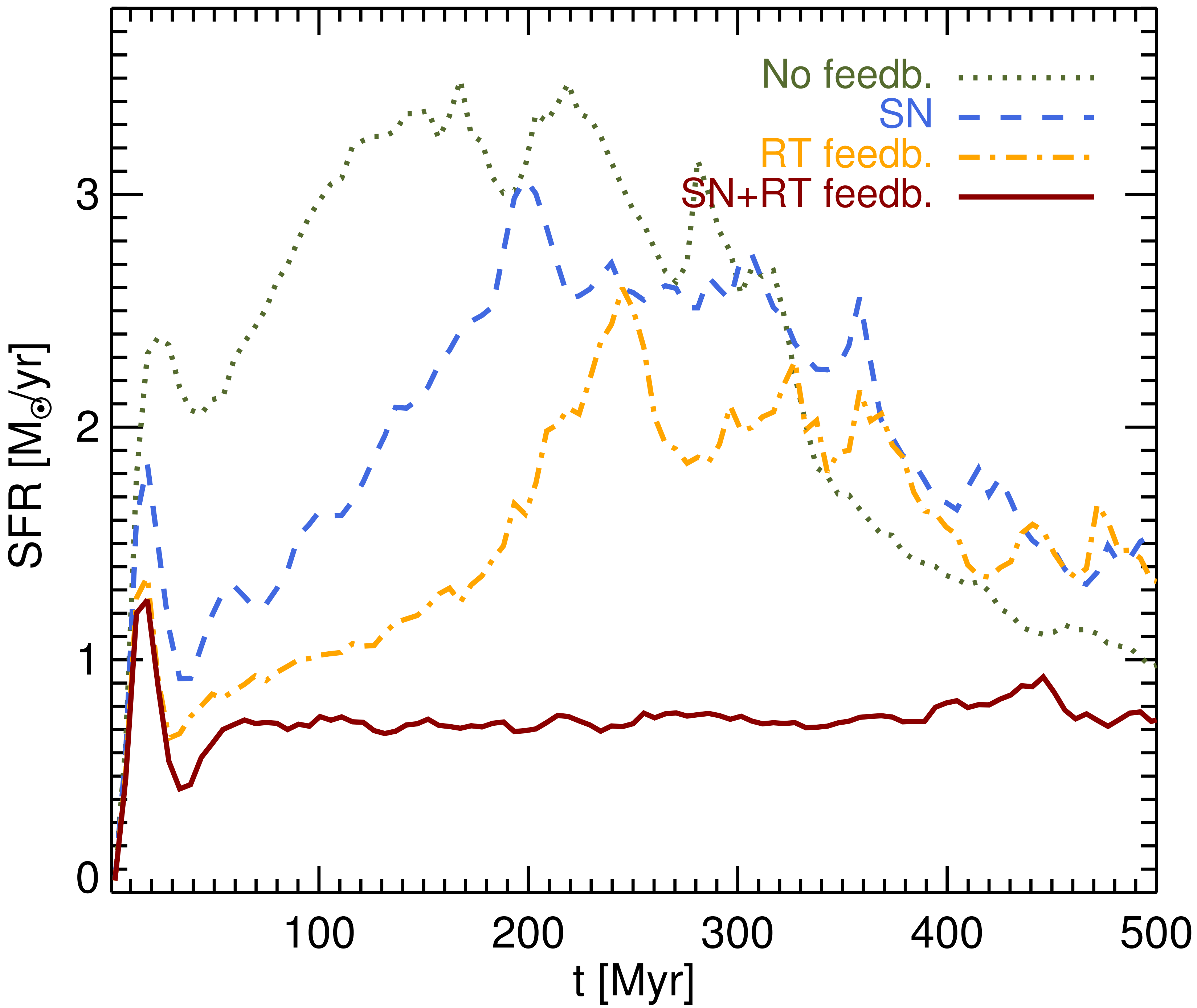
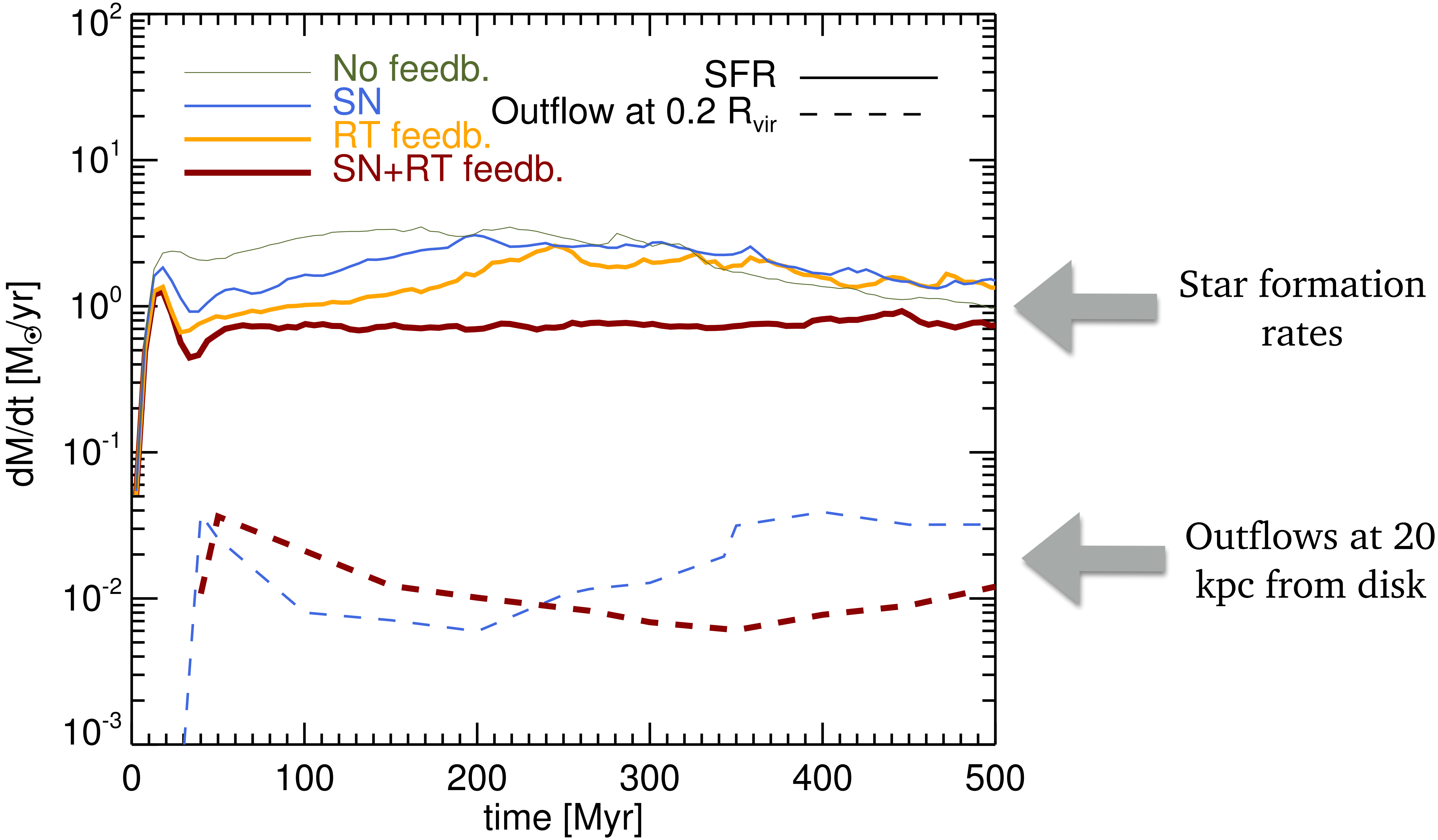
SNe + RT

Effect of RT feedback on star formation rate

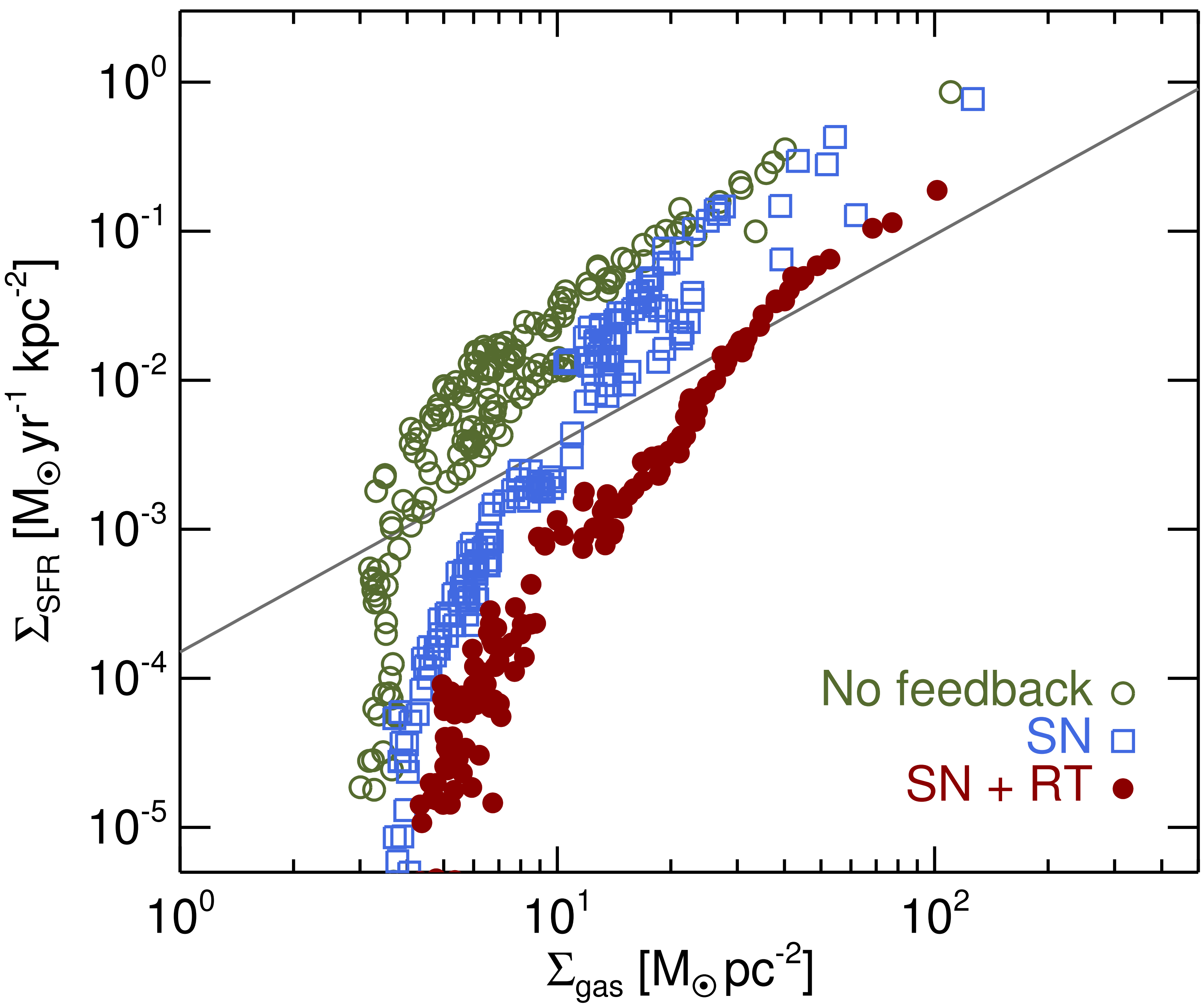


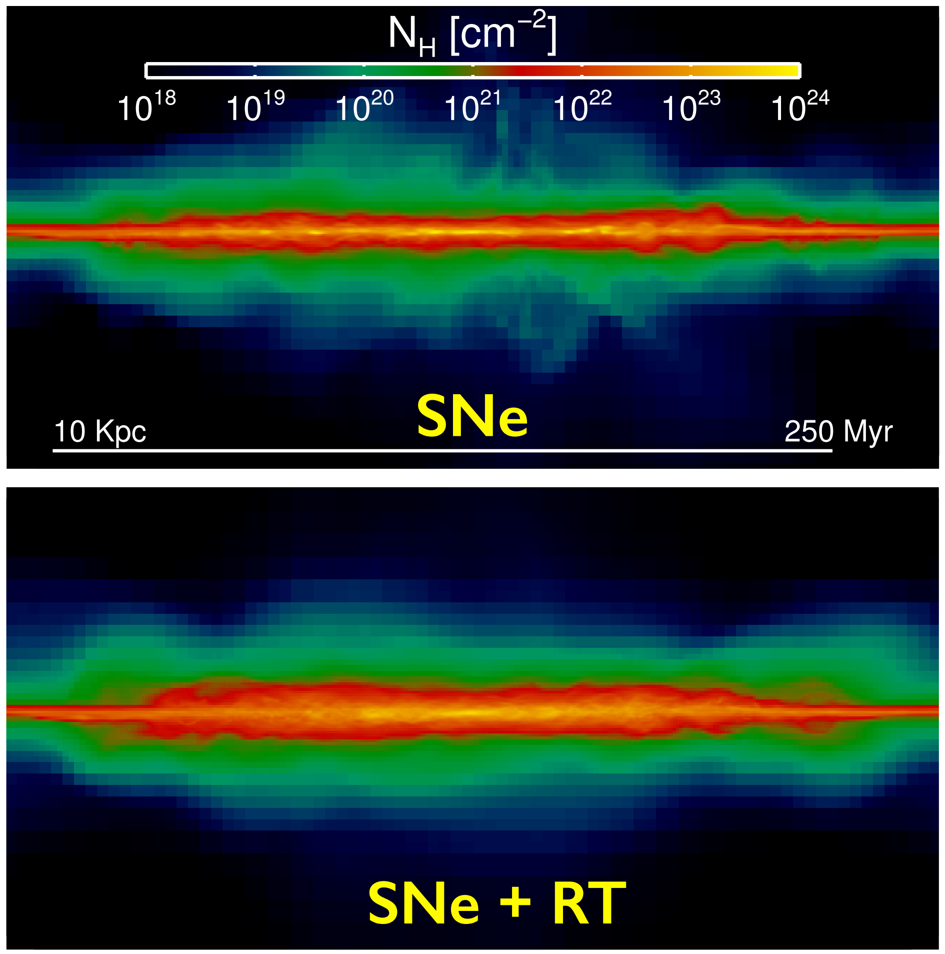
Effect of RT feedback on outflows



- **Radiation has little effect on outflows**

Effect on Kennicutt Schmidt relation: no RT versus RT





Galaxy is ‘puffed up’ by radiation

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Radiation feedback with RHD

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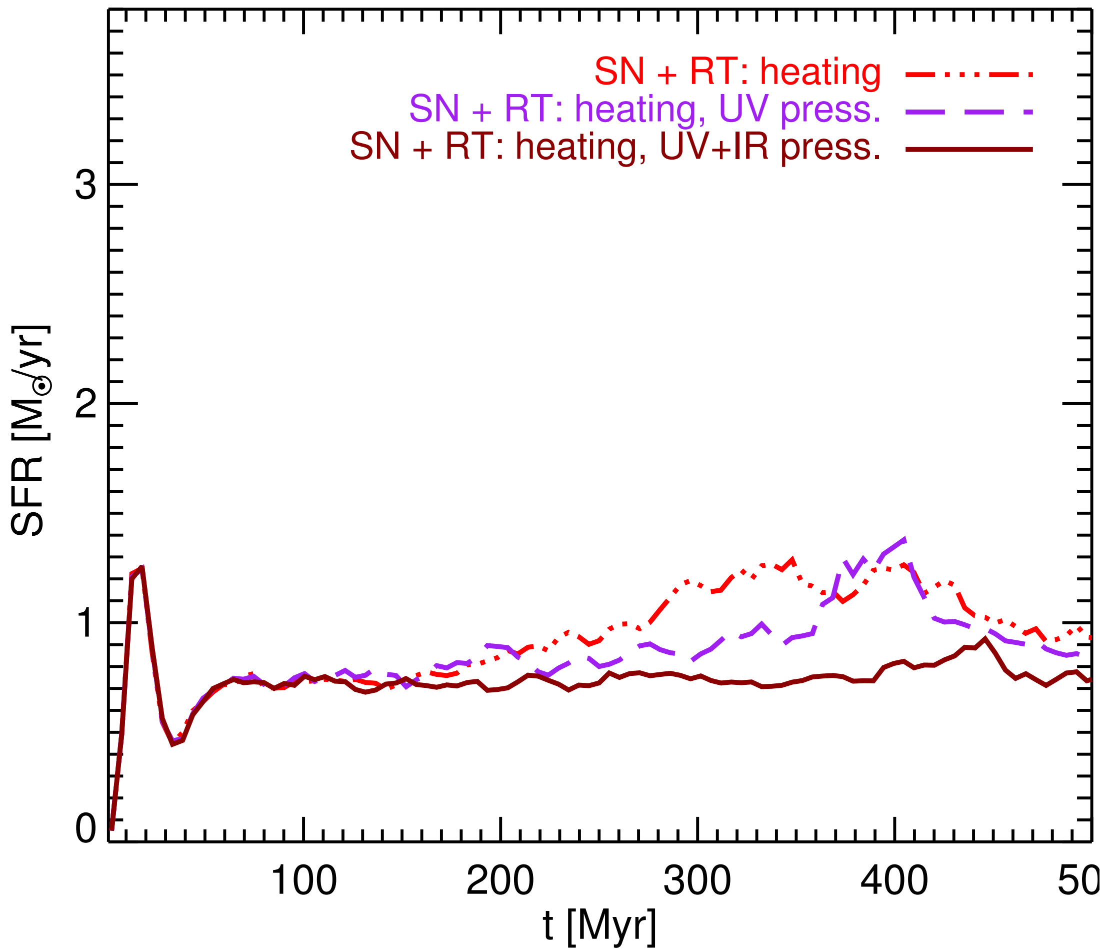
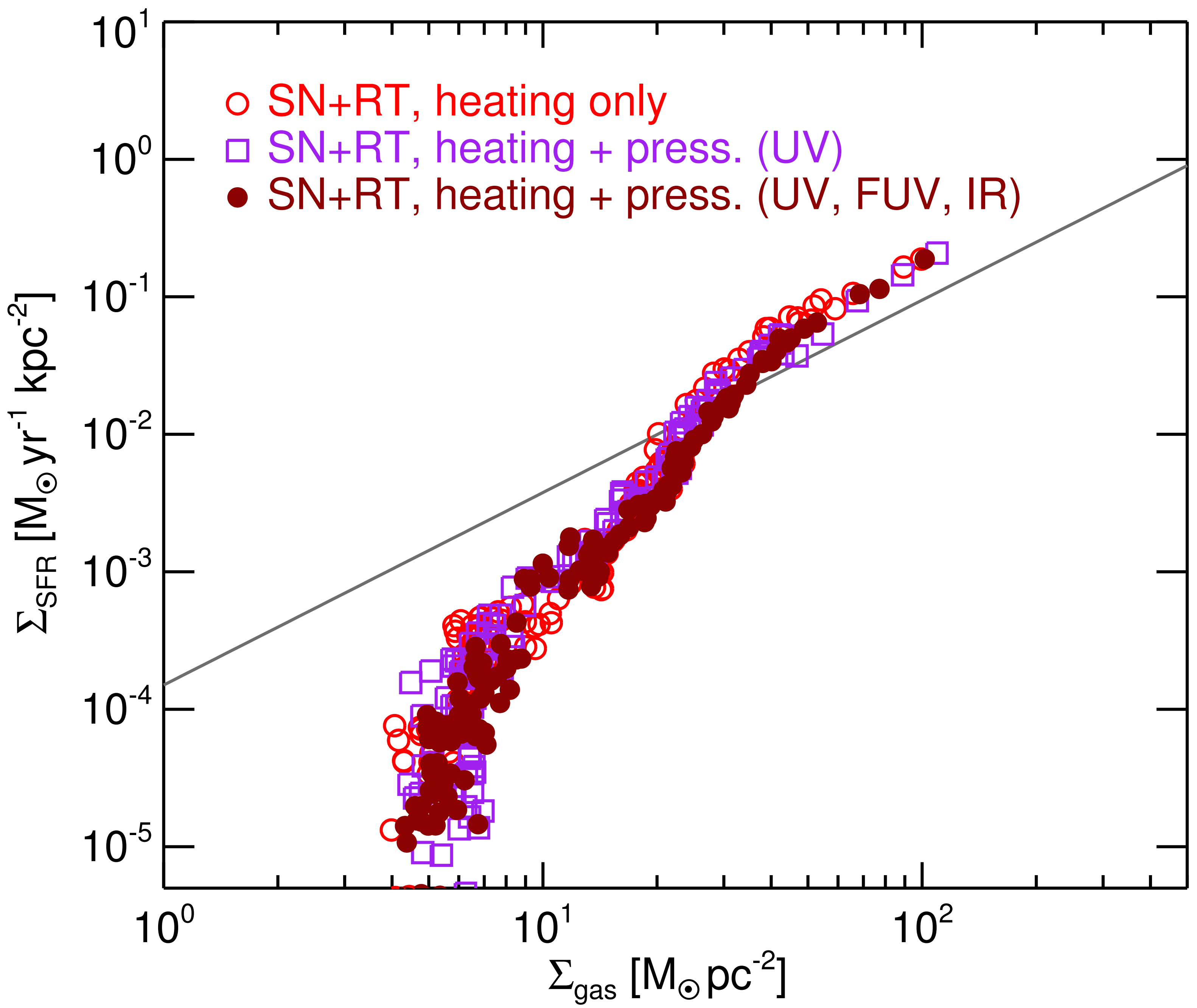
- Radiation pressure?

What is the nature of the the radiation feedback?

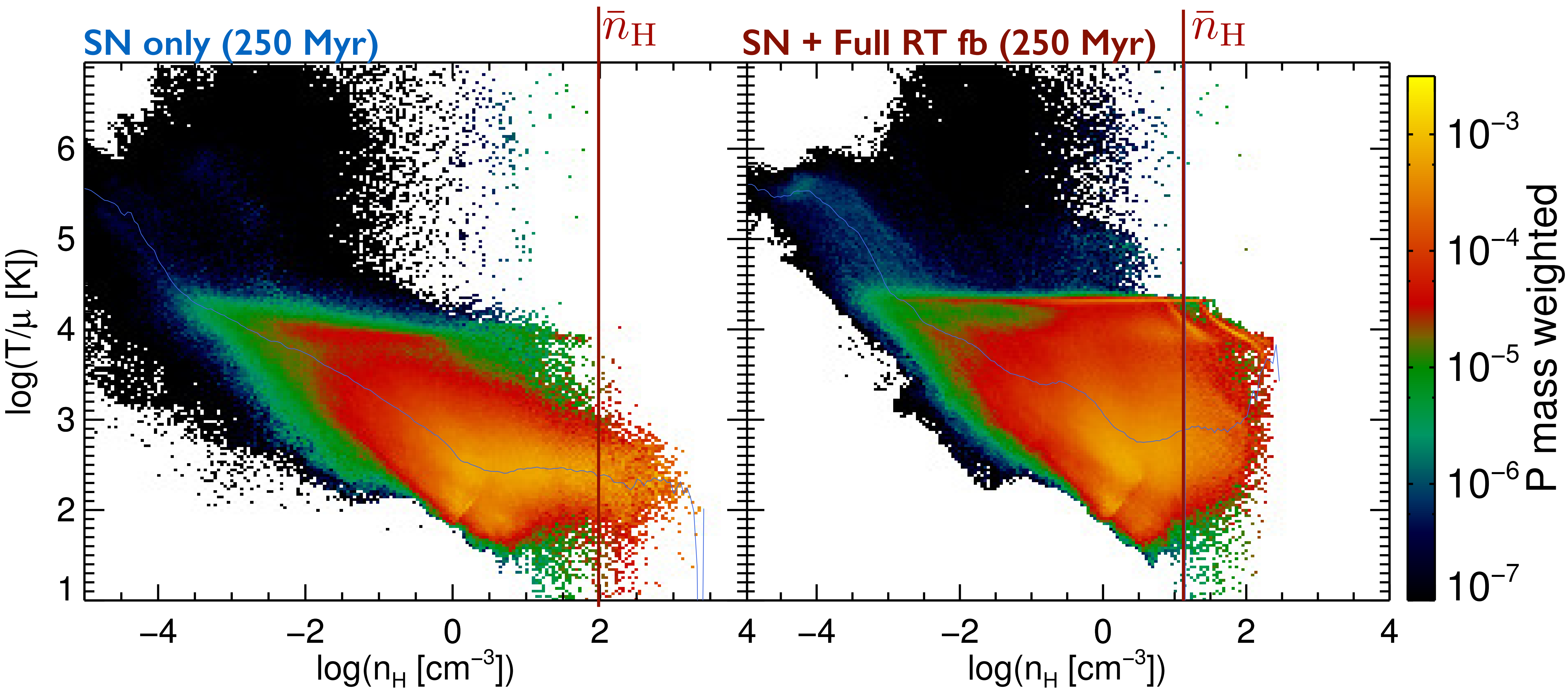




- **Radiation pressure is weak**
- **Radiation heating dominates**

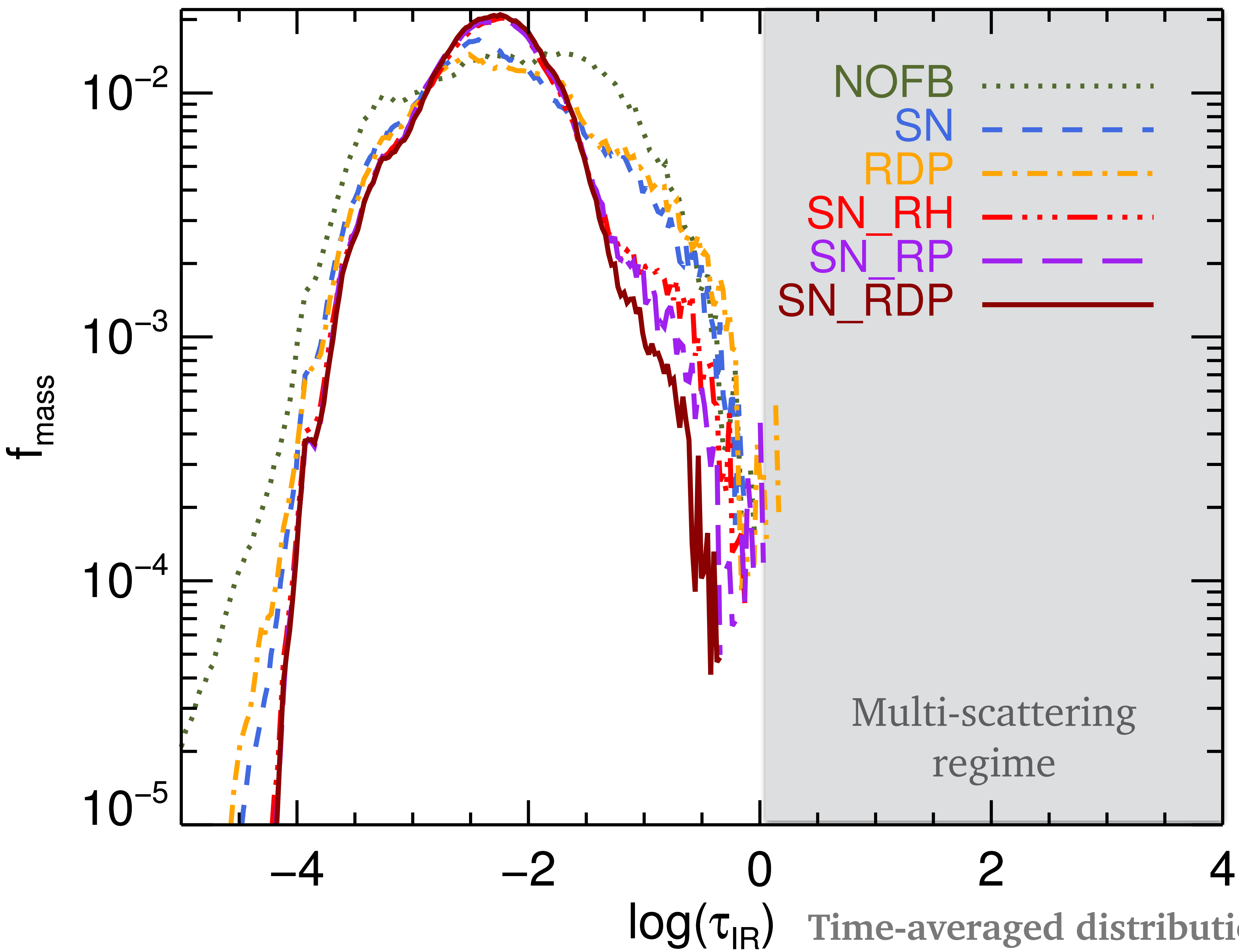
What is the nature of the the radiation feedback?

- Radiation pressure is weak
- Photoionisation heating dominates: expands the gas and prevents collapse



Radiation pressure…

Why is it weak?



No feedback
SN feedback
Rad. heating, dir + dust pressure
SN + rad. heating
SN + rad. heating and dir. pressure
SN + rad. heating, dir. + dust pressure

Time-averaged distribution of face-on dust optical depths

- **Recent works cite multi-scattering as a major contributor**
- **…but we do not have any**
- **Not to say that it doesn't exist — we just don't resolve it!**

Conclusions

- Radiation feedback is 'gentle' - not much like SN sub-grid recipes
- Main effect is heating -> lower density peaks

➡Next:

- How does radiation feedback combine with more efficient SN feedback recipes?
- How does it behave in more/less massive halos?
- Cosmological simulations