Thermal Supernova Feedback and Multiphase Galactic Outflow

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Introduction: Supernova Feedback

- Supernova feedback (SN FB) drive outflow and quench star formation.
- SN scale (~ 10 pc) is unresolved in galaxy simulations (kpc-Mpc scale).
- What do we need to model?

Credit: X-ray: NASA/CXC/JHU/D.Strickland; Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team; IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

SN Feedback Model: Kinetic & Thermal

- Two forms of feedback: **Kinetic** & **Thermal**

	Kinetic FB	**Thermal FB**
Physical meaning	SNR gives momentum to ISM	Shock heating by SN ejecta
Roles	Drive **turbulence**, **Expel gas** out from galaxy	Produce **hot outflow**, **Transport metals** out from galaxy
Difficulty in low reso.	Unresolved cooling length, Unresolved thin shell formation (Due to low **spatial resolution**)	Unresolved cooling mass (Due to low **mass resolution**)
Previous works	Kimm & Cen (2014); Rosdahl et al. (2017); Hopkins et al. (2018)	Stinson et al. (2006); Dalla Vecchia & Schaye (2012); Keller et al. (2014)

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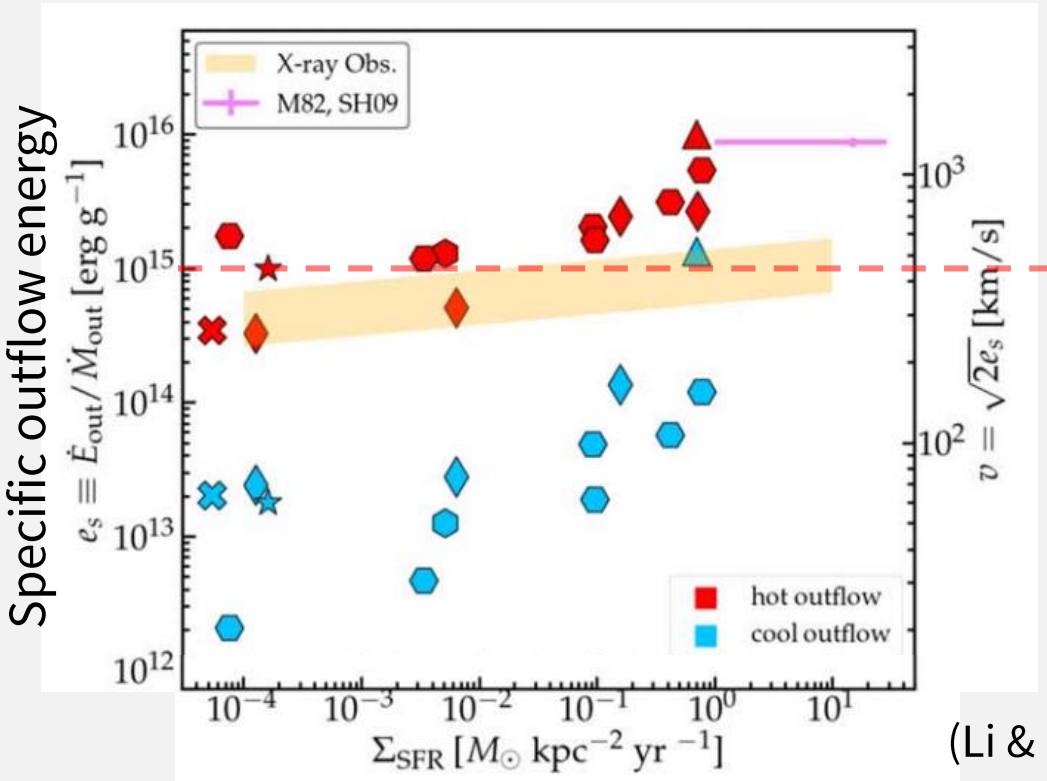
<u>Motivation of this work:</u>

- Develop a SN FB model **considering both** { **kinetic FB** / **thermal FB** ⟸ **Today's topic**
- First, model SN FB based on **pc-scale simulations**.
- Second, implement the results into a galactic-scale simulation.

Result from small-box simulations

- **How to assign thermal energy?**
- When **cooling mass** is unresolved, thermal feedback is **ineffective (overcooling problem)**.



$T \sim 5 \times 10^6$ K

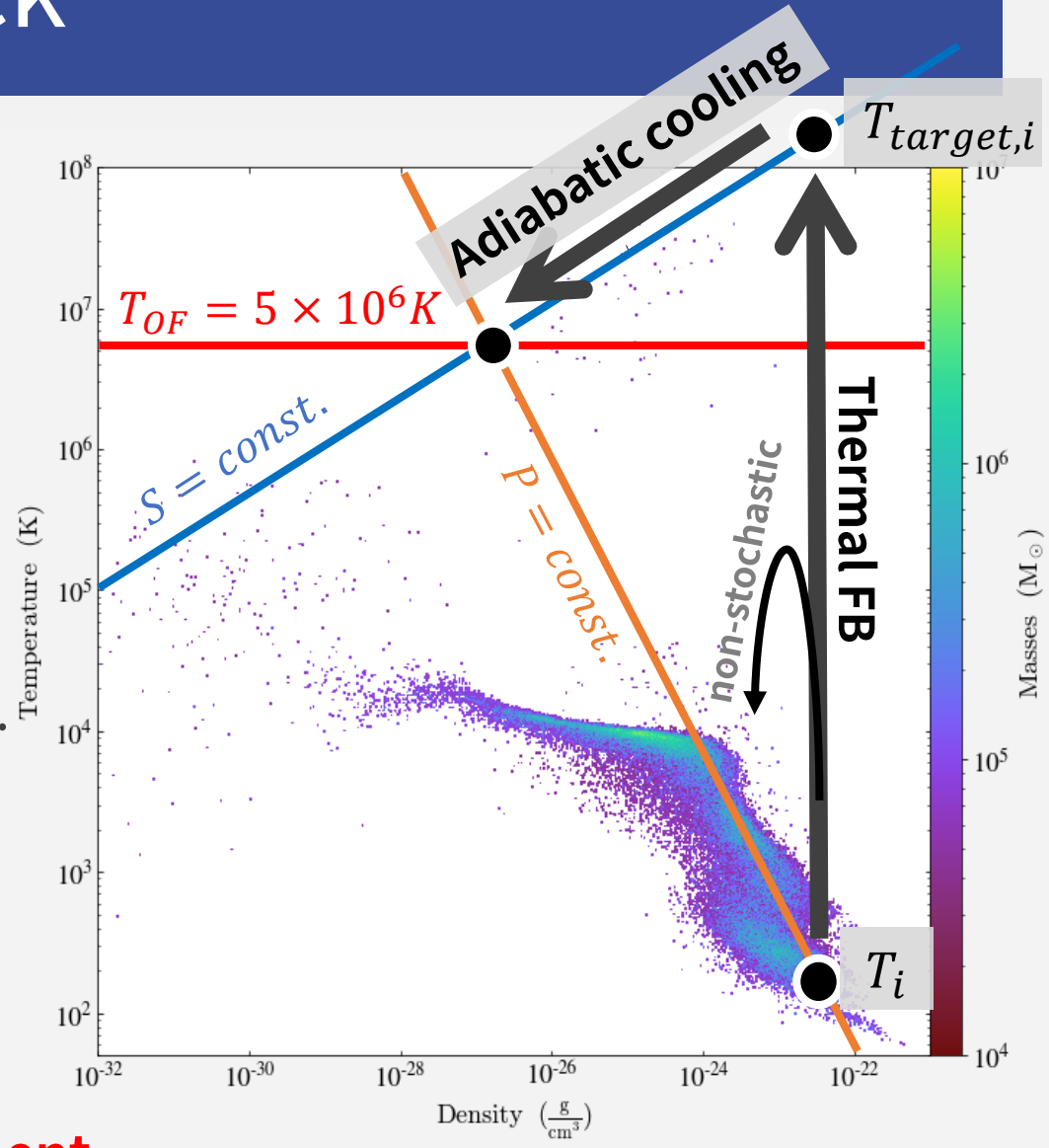
$\left(T = \frac{\mu m_p}{k_B} e_s\right)$

(Li & Bryan 2019)

High-resolution small-box simulations show **temperature of hot outflow is typically 5×10^6 K.**

Stochastic Thermal Feedback

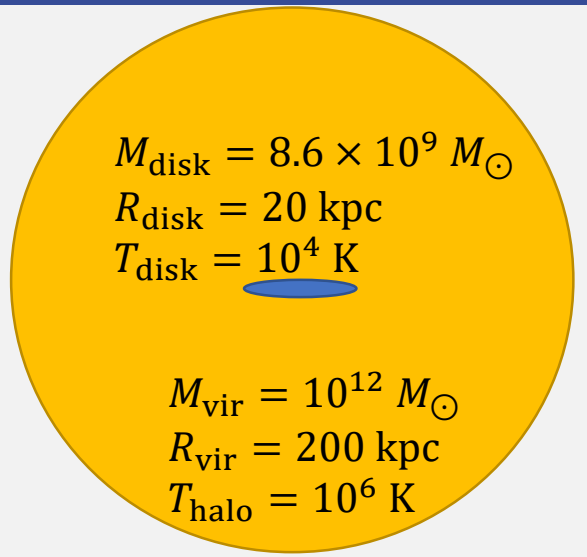
- Updated **stochastic thermal feedback model** (Dalla Vecchia & Schaye 2012).
- Consider an effect of **adiabatic cooling** to reproduce hot outflow with $T_{OF} \sim 5 \times 10^6 K$,
- Assume pressure equilibrium between outflow and ISM, the **target temperature is** $T_{\mathrm{target},i} = T_{\mathrm{OF}}^{5/3}\, T_i^{-2/3}$.
- Inject thermal energy $\Delta E_i = \frac{m_i}{\mu m_p} k_B T_{\mathrm{target},i}$ stochastically.
- Total thermal feedback energy is $0.7 E_{SN}$.
- **Cooling is always on**.



Heats gas up to high temperature by stochastic treatment

Isolated Galaxy Test: Setup

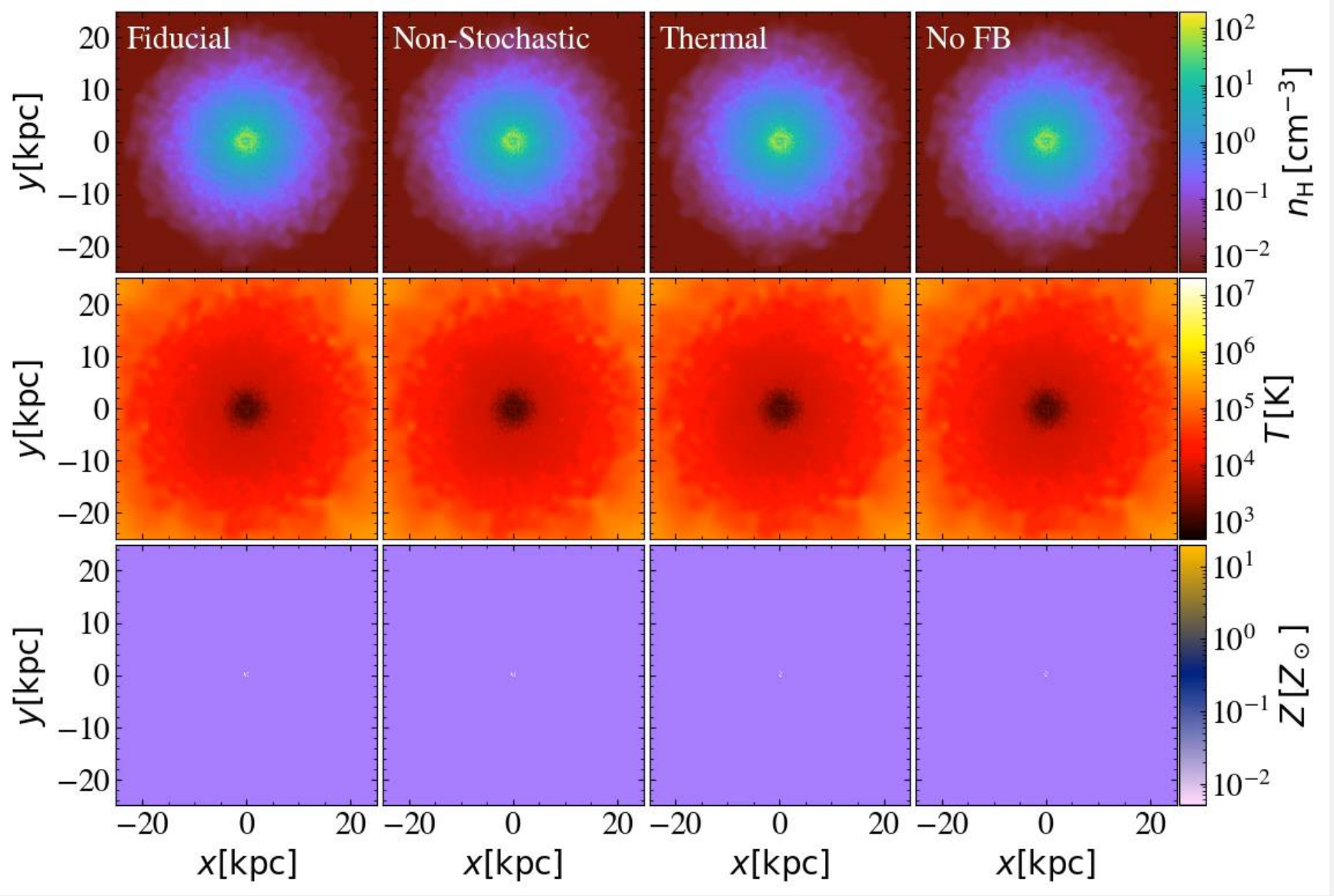
- Isolated galaxy simulation using GADGET3-Osaka (Shimizu+ 2019).
- Initial condition: AGORA disk (Kim+ 2014) + gas halo (Shin+ 2021)
  - Milky-way-mass disk galaxy
  - $m_{gas} = 8.6 \times 10^4\ M_\odot, m_{DM} = 1.3 \times 10^7\ M_\odot$
- Evolved to 1 Gyr.



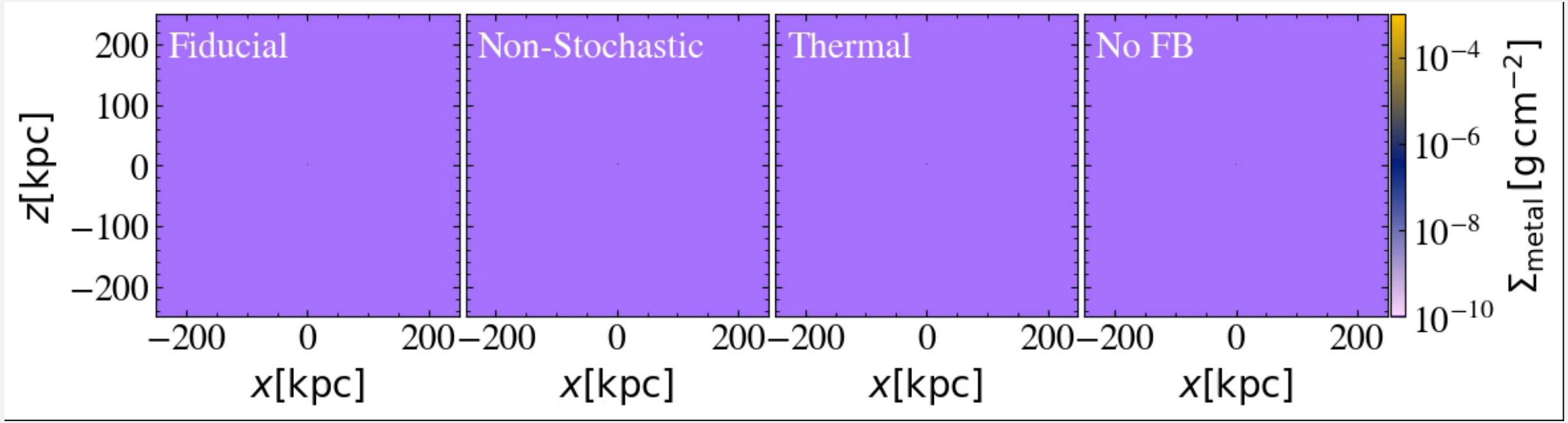
Name	Description	Purpose
Fiducial	Fiducial (momentum FB + stochastic thermal FB)	
Non-stochastic	Thermal energy is distributed without stochastic treatment	To evaluate the **stochastic treatment**
Thermal	Only stochastic thermal FB	To evaluate the **effect of kinetic FB**
No FB	No feedback	Reference

Isolated Galaxy Test: Face-on Movie

- **Without kinetic FB,** gas can easily **collapse** and the disk becomes **clumpy**. (Thermal & No FB)
- **Hot bubbles** are created by stochastic treatment (Fiducial & Thermal)
- Hot gas in No FB run is due to projection effect.

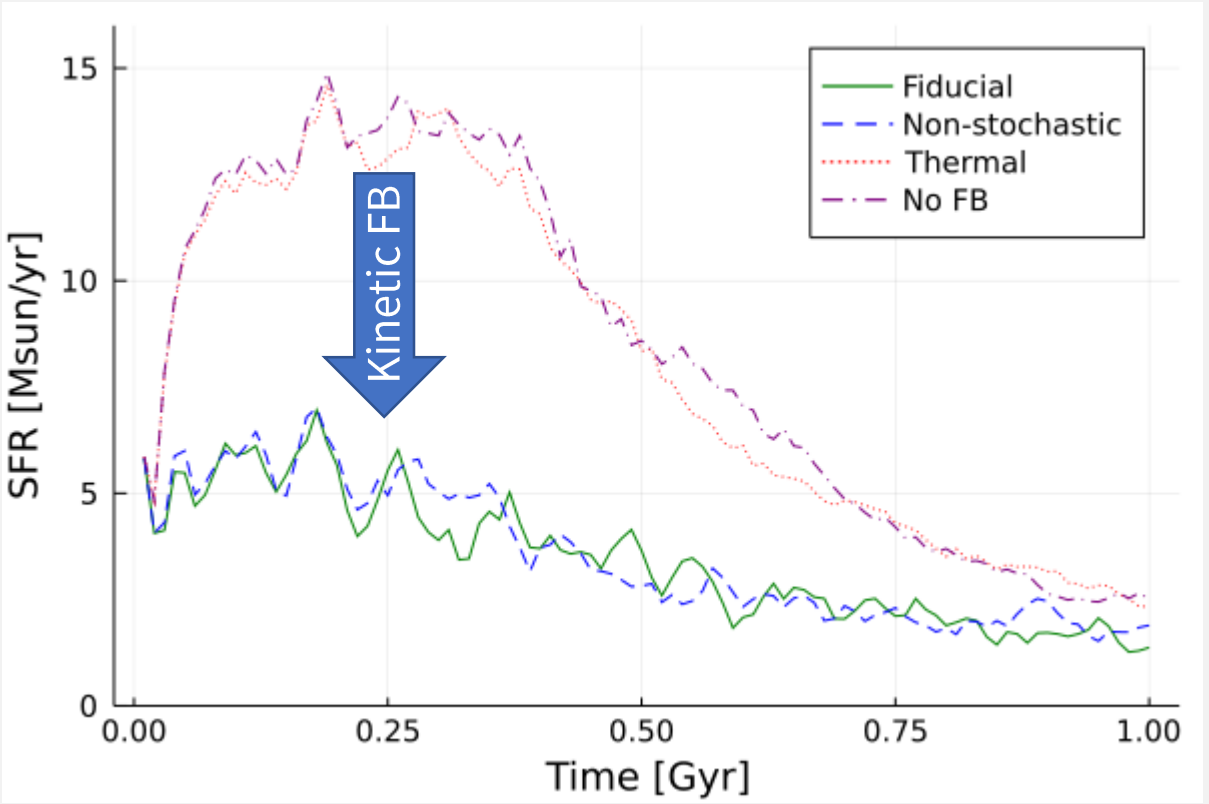


Isolated Galaxy Test: Edge-on Metal Outflow



- Outflow by stochastic thermal feedback **transports metals up to R_{vir}** $(= 200\ \mathrm{kpc})$.
- Gases kicked by kinetic feedback **fall back** to the galaxy.

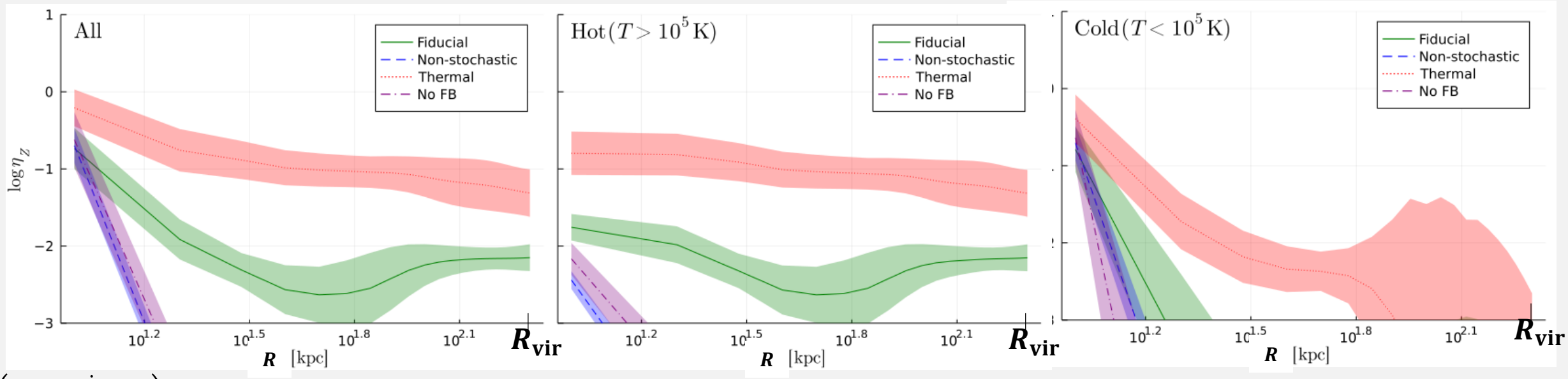
Isolated Galaxy Test: SFR



- Kinetic FB **suppresses** star formation (Fiducial vs. Thermal vs. No FB).
- Stochastic thermal feedback have **little effect** on star formation (Fiducial vs. Non-stochastic).

Isolated Galaxy Test: Outflow

Metal loading factor profile averaged over $t = 0.5 - 1$ Gyr.



$\left(\eta_Z = \frac{\dot{M}_{Z,out}}{\dot{M}_{Z,SN}}\right)$

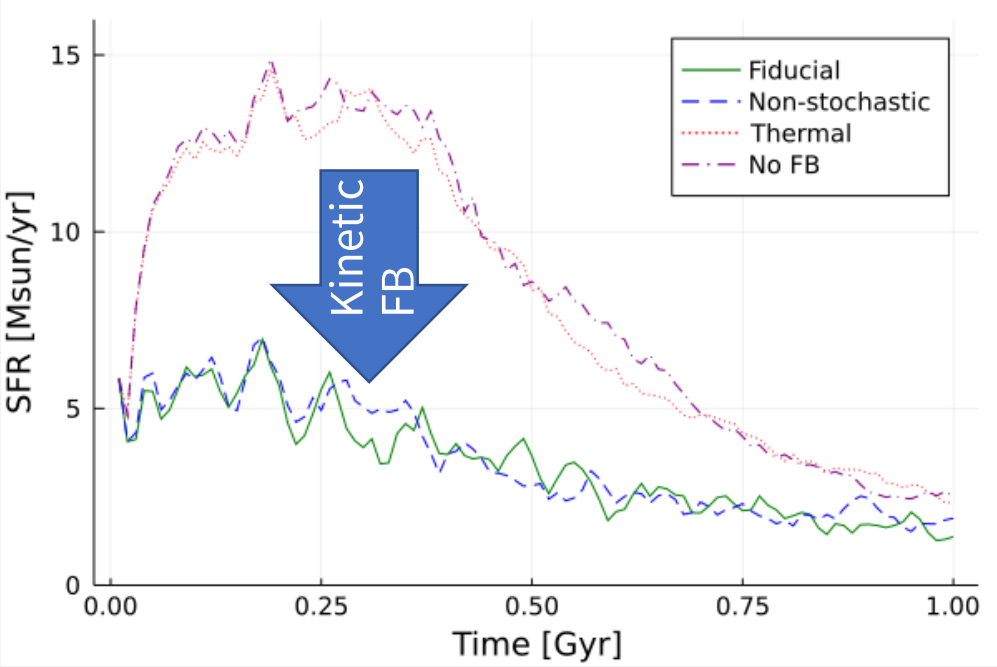
- **Stochastic thermal FB** produces **hot** ($T > 10^5$ K) **outflow** reaches $R_{\rm vir}$.
- Metals are transported by **hot outflow**.

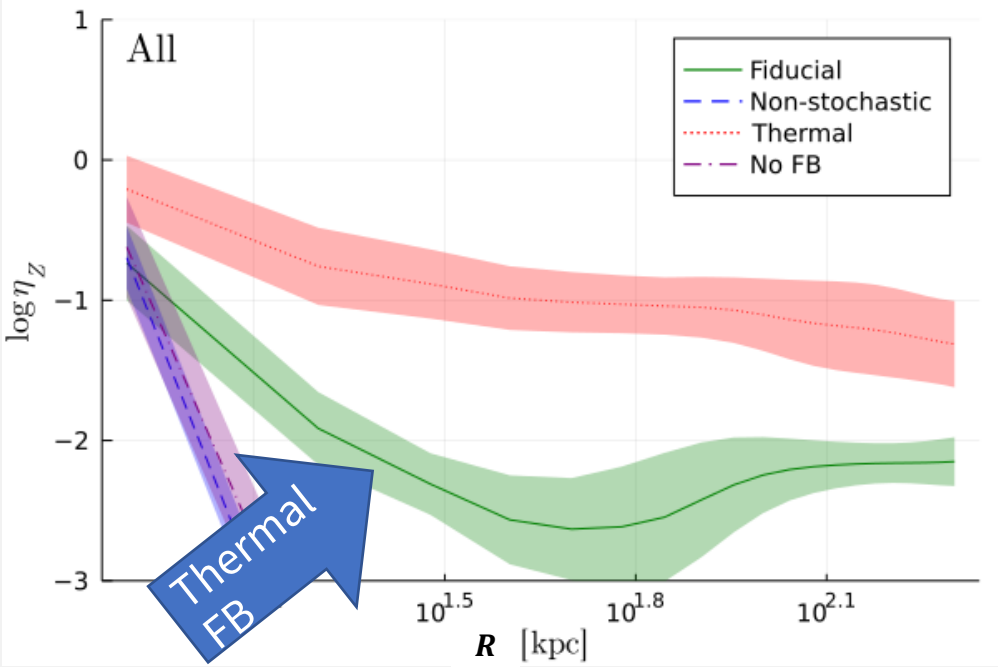
Summary

- Updated stochastic FB model to reproduce hot ($T = 5 \times 10^6$ K) outflow.

From isolated-galaxy test,

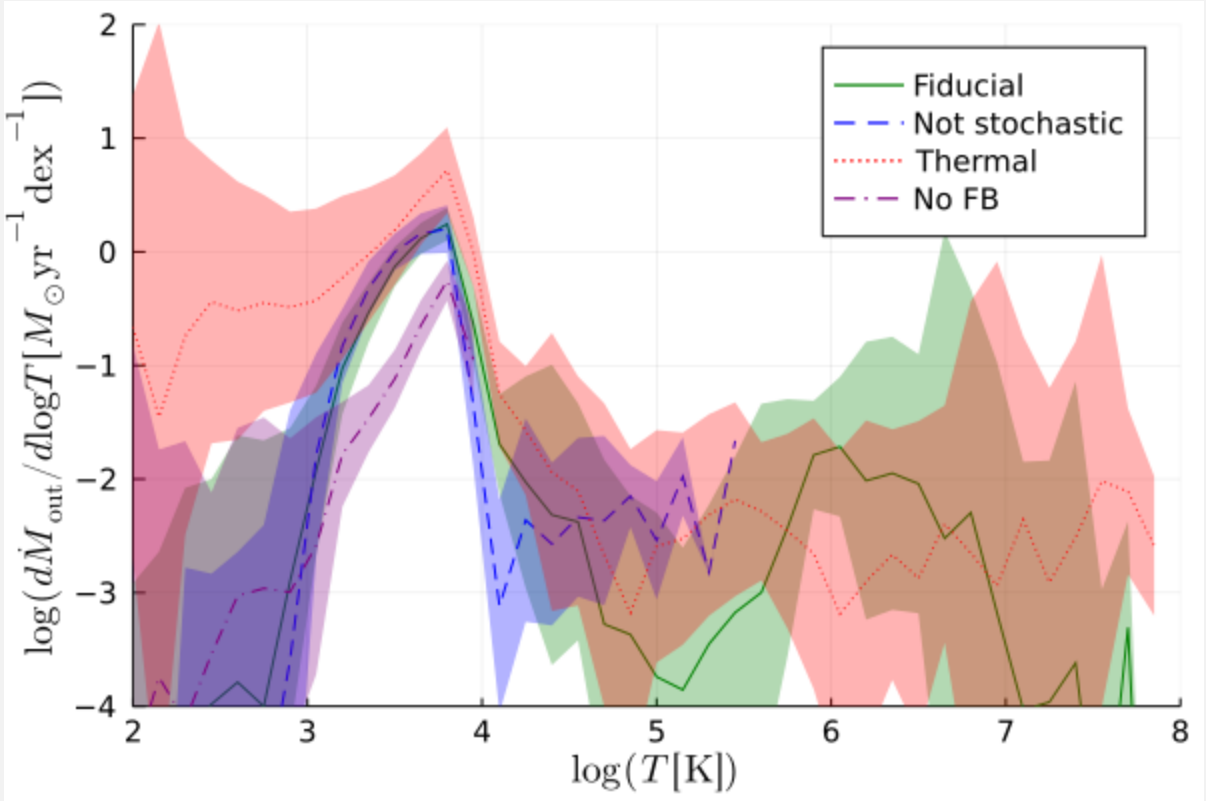
- Kinetic FB suppresses star formation.
- Stochastic thermal FB produce hot outflow and transport metals up to $R_{\rm vir}$.
- We will use this model in cosmological simulations.





Appendix

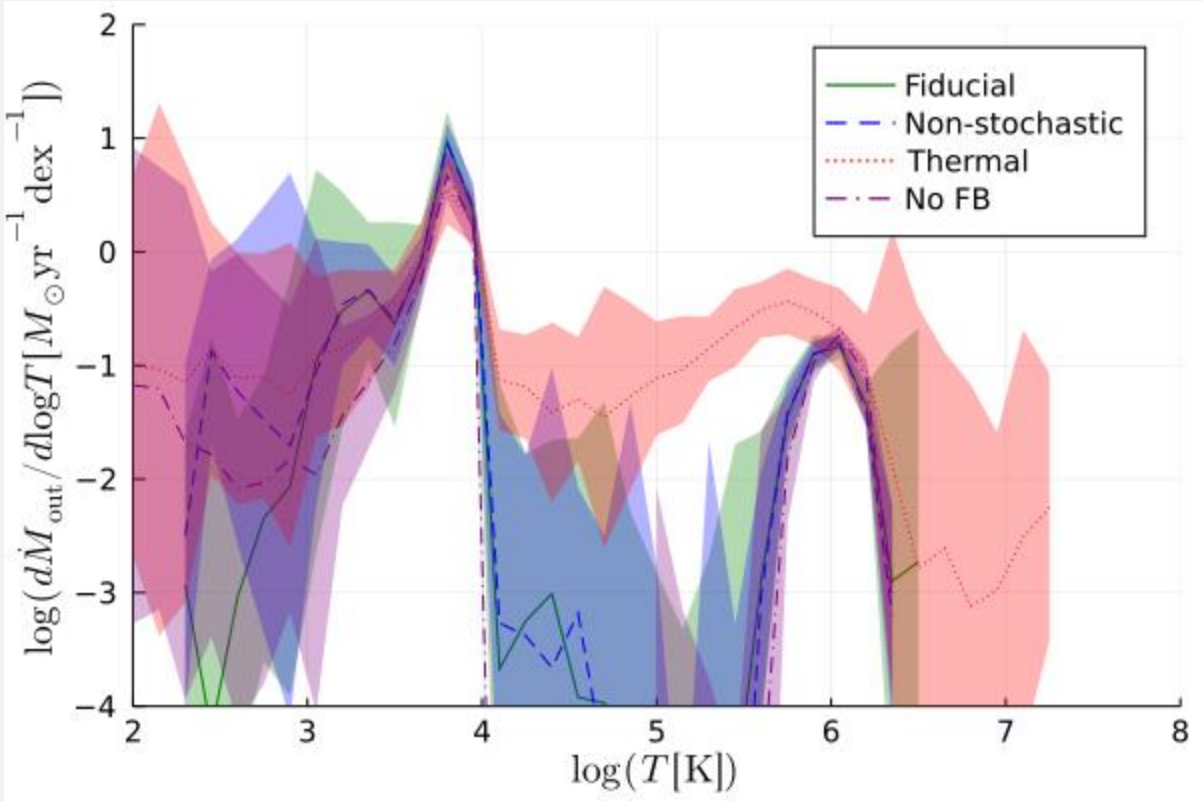
Outflow Temperature



- Runs **without** hot gas halo
- Hot outflow ($T = 10^{6-7}$ K) in fiducial run

$T_{OF} \sim 5 \times 10^6 K$ is reproduced.

Outflow Temperature (with hot gas halo)



- Runs **with** hot gas halo
- Hot outflow ($T = 10^{6-7}$ K) in all runs.