Impact of Cosmic Ray Transport on Galactic Winds

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9 August 2017

IMPACT OF COSMIC RAY TRANSPORT ON GALACTIC WINDS

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Draft version July 17, 2017

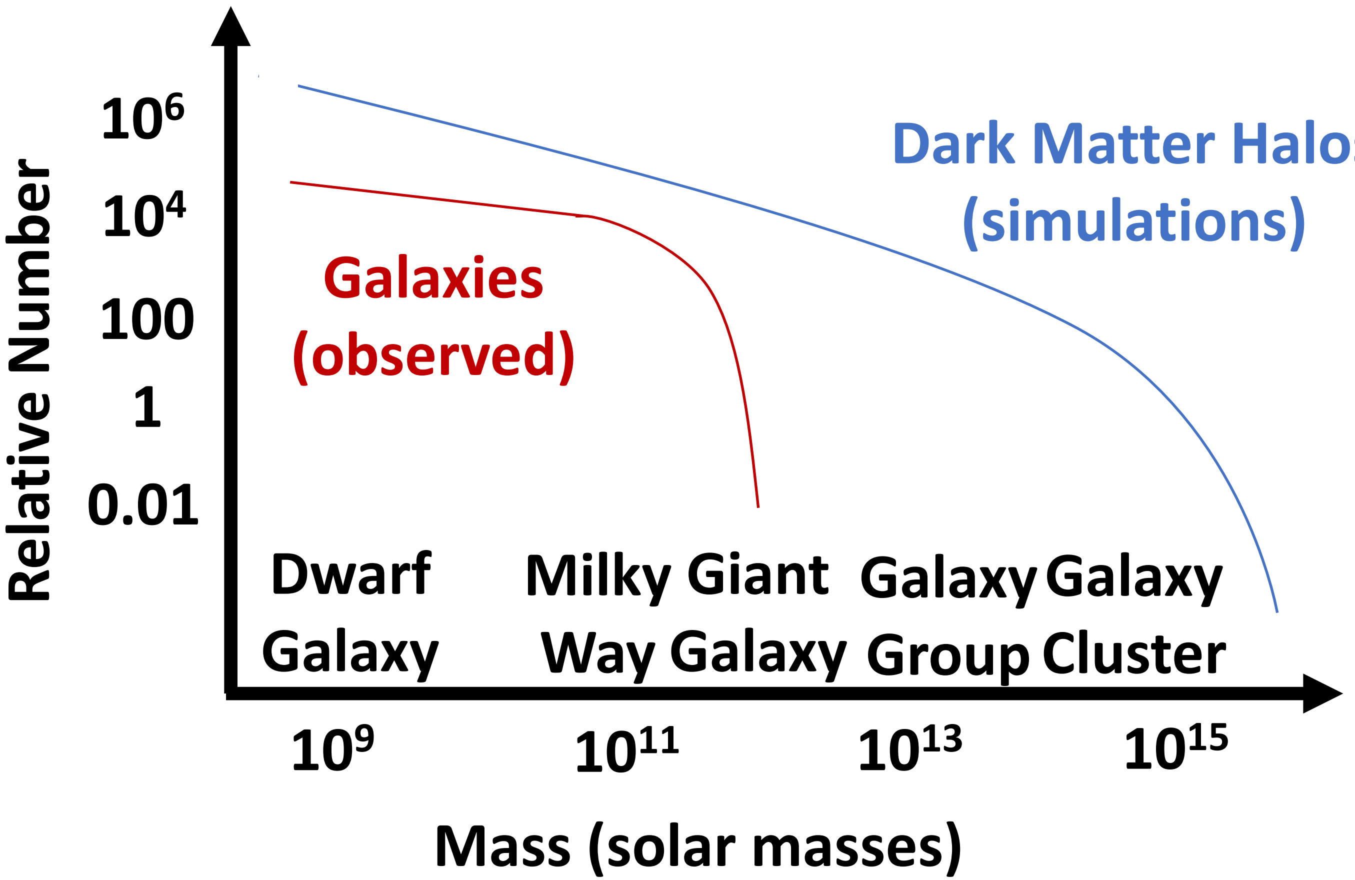
ABSTRACT

The role of cosmic rays generated by supernovae and young stars has very recently begun to receive significant attention in studies of galaxy formation and evolution due to the realization that cosmic rays can efficiently accelerate galactic winds. Microscopic cosmic ray transport processes are fundamental for determining the efficiency of cosmic ray wind driving. Previous studies focused on modeling of cosmic ray transport either via constant diffusion coefficient or via streaming proportional to the Alfvén speed. However, in predominantly cold, neutral gas, cosmic rays can propagate faster than in the ionized medium and the effective transport can be substantially larger; i.e., cosmic rays can decouple from the gas. We perform three-dimensional magnetohydrodynamical simulations of patches of galactic disks including the effects of cosmic rays. Our simulations include the decoupling of cosmic rays in the cold, neutral interstellar medium. We find that, compared to the ordinary diffusive cosmic ray transport case, accounting for the decoupling leads to significantly different wind properties such as the gas density and temperature, significantly broader spatial distribution of cosmic rays, and larger wind speed. These results have implications for X-ray, γ-ray and radio emission, and for the magnetization and pollution of the circumgalactic medium by cosmic rays.

Keywords: cosmic rays – galaxies: evolution – cosmic rays – galaxies: star formation

https://arxiv.org/pdf/1707.04579.pdf

Missing Baryons in $L < L_*$ halos: Stellar Feedback Driven Galactic Winds



M82

Ohyama+ 2002

Cosmic Rays (CR)

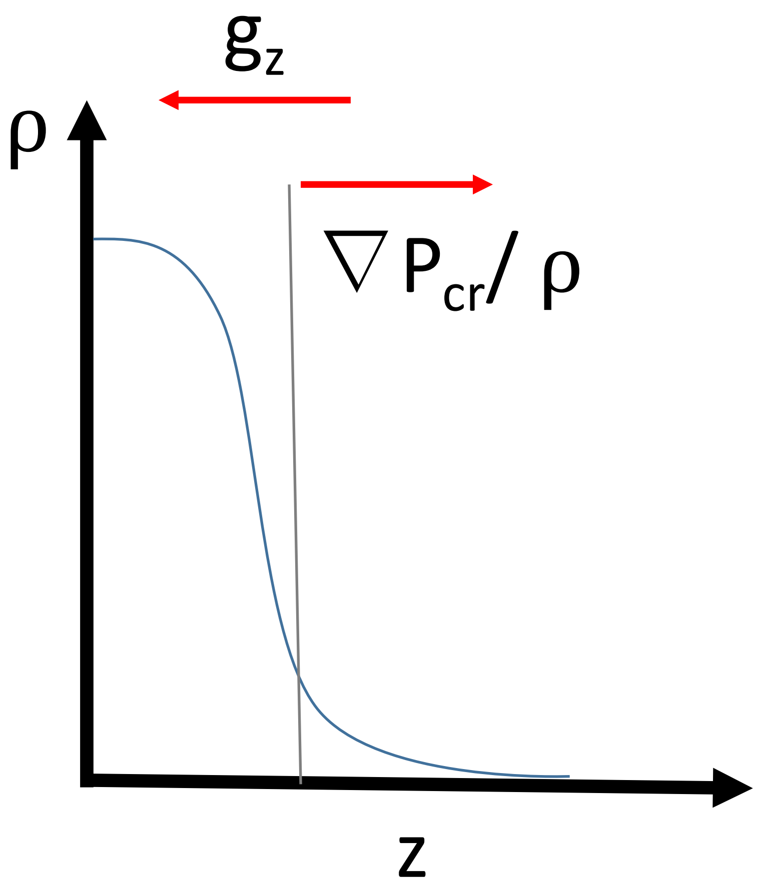
- Accelerated by diffusive shock acceleration in SNR shocks (Blandford & Eichler 1987; Caprioli 2015)

- $U_{dyn} \sim U_B \sim U_{CR}$ in the ISM (Cox 2005)

- 10^{-3} TeV CR: dominate CR pressure in ISM (Grenier, Black, & Strong 2015)

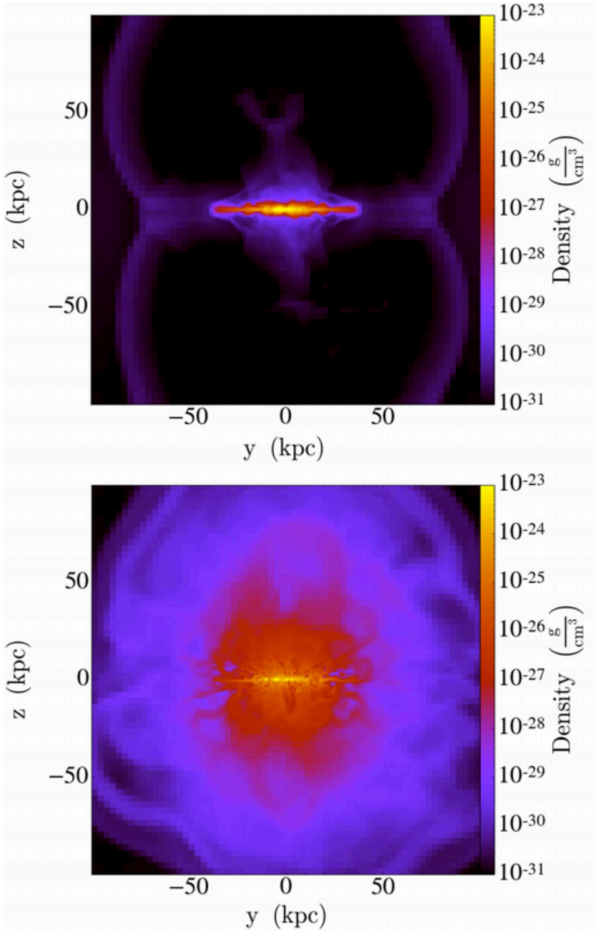
How Do CR Drive a Wind

- CR cool slowly
- CR exert a force on the gas = $\nabla P_{cr} / \rho$



CR Driven Galactic Winds

Ruszkowski+ 2017: CR transport can significantly boost wind driving



Advection
No diffusion

Streaming

CR Enhanced Transport By The Decoupling Mechanism

- CR transport inhibited by perturbations.
- Damping of perturbations -> faster transport!
- We consider ion-neutral damping.
- We model the enhanced transport as a boosted diffusion coefficient in cool regions

Simulation Setup

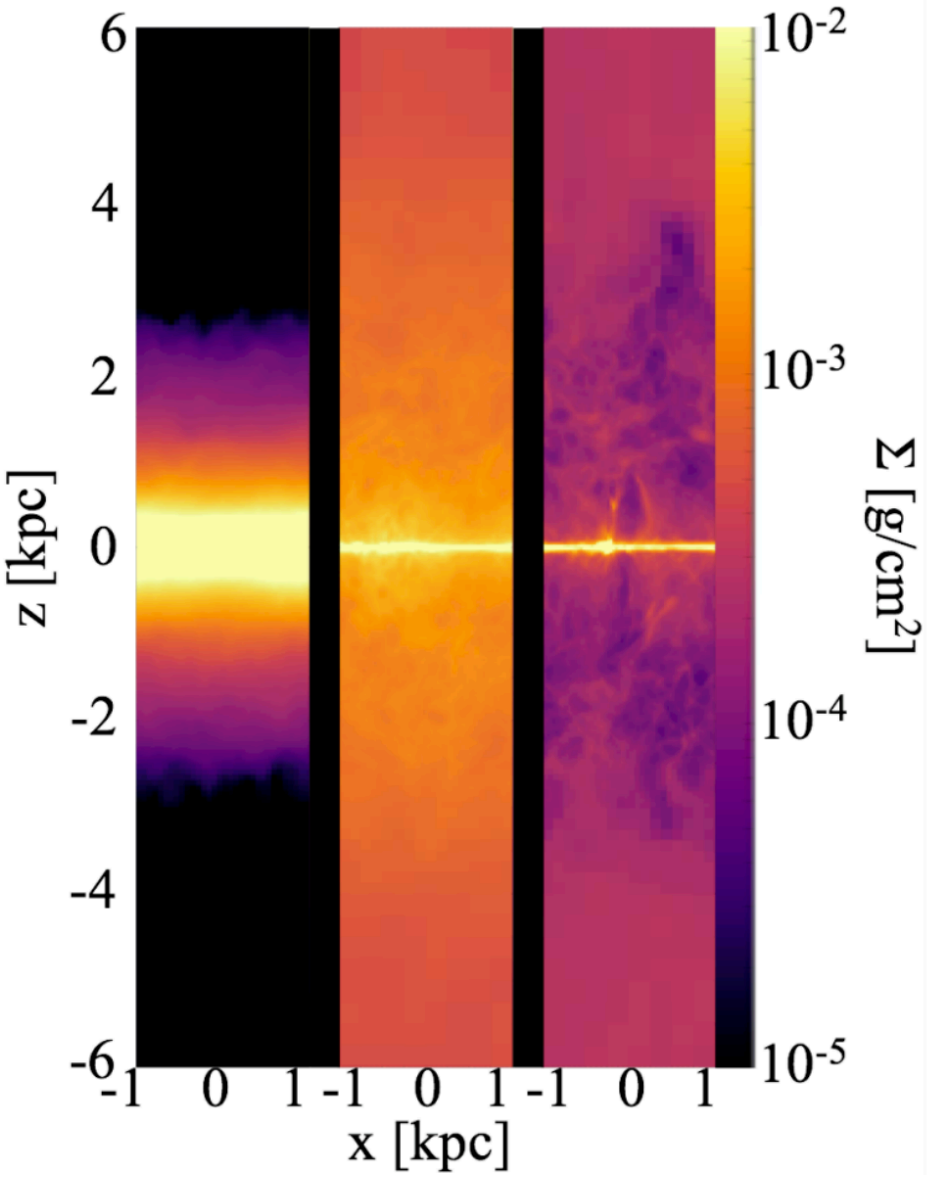
- Slab of ISM: 2 kpc x 2 kpc x 40 kpc
- Boundary Conditions: Periodic x Periodic x Diode

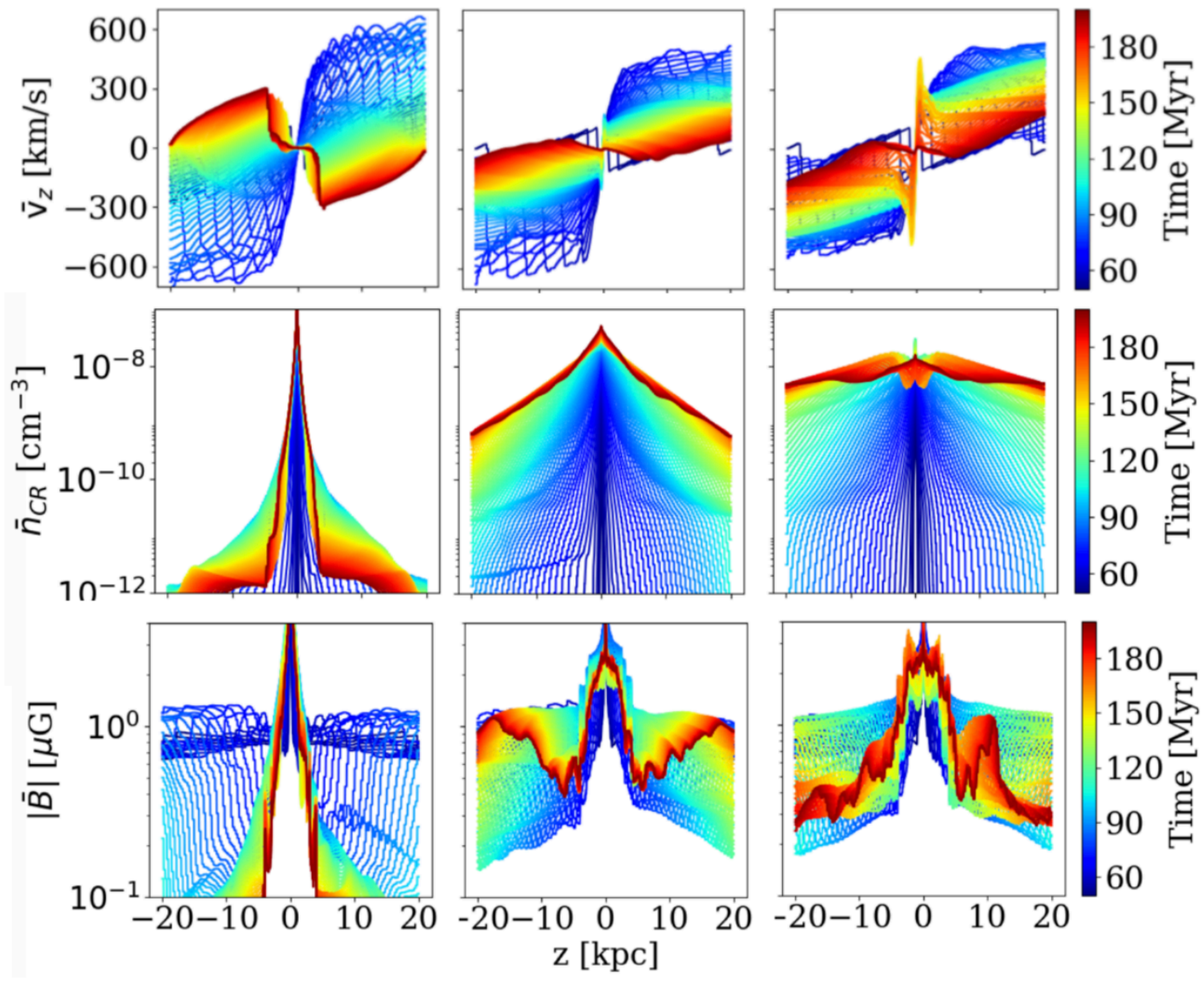
- NFW dark matter halo (10^{12} $M_{\odot}$)
- Gas surface density = 100 $M_{\odot}/pc^2$
- Physics
  - self-gravity of the gas, radiative cooling, star formation and feedback, magnetic fields, cosmic rays

Results: Mass Column Density

time = 170 Myr

arXiv 1707.04579




600
300
0
−300
−600
$\bar{v}_z$ [km/s]
10^{-8}
10^{-10}
10^{-12}
$\bar{n}_{CR}$ [cm^{-3}]
10^{0}
10^{-1}
$|\bar{B}|$ [μG]
−20 −10 0 10 20
z [kpc]
60
90
120
150
180
Time [Myr]

Results

- We observe hot evacuated bubbles in decoupling simulations.
  - Enhanced soft x-ray emission in edge-on galaxies?
- Simulations with decoupling have much higher n_{CR} in the halo.
  - Extended radio emission?
- With decoupling, the wind is much faster but lower density which conspire to produce similar mass loading factors.

Star Formation and Feedback

- Star Formation Criteria (all must simultaneously be true)
  - $n_{gas} > 10\ cm^{-3}$
  - $\nabla \cdot \mathbf{u}_g < 0$
  - $t_{cool} < t_{dyn}$ or $T < 300$ K
  - $M_{cell} > M_{jeans}$

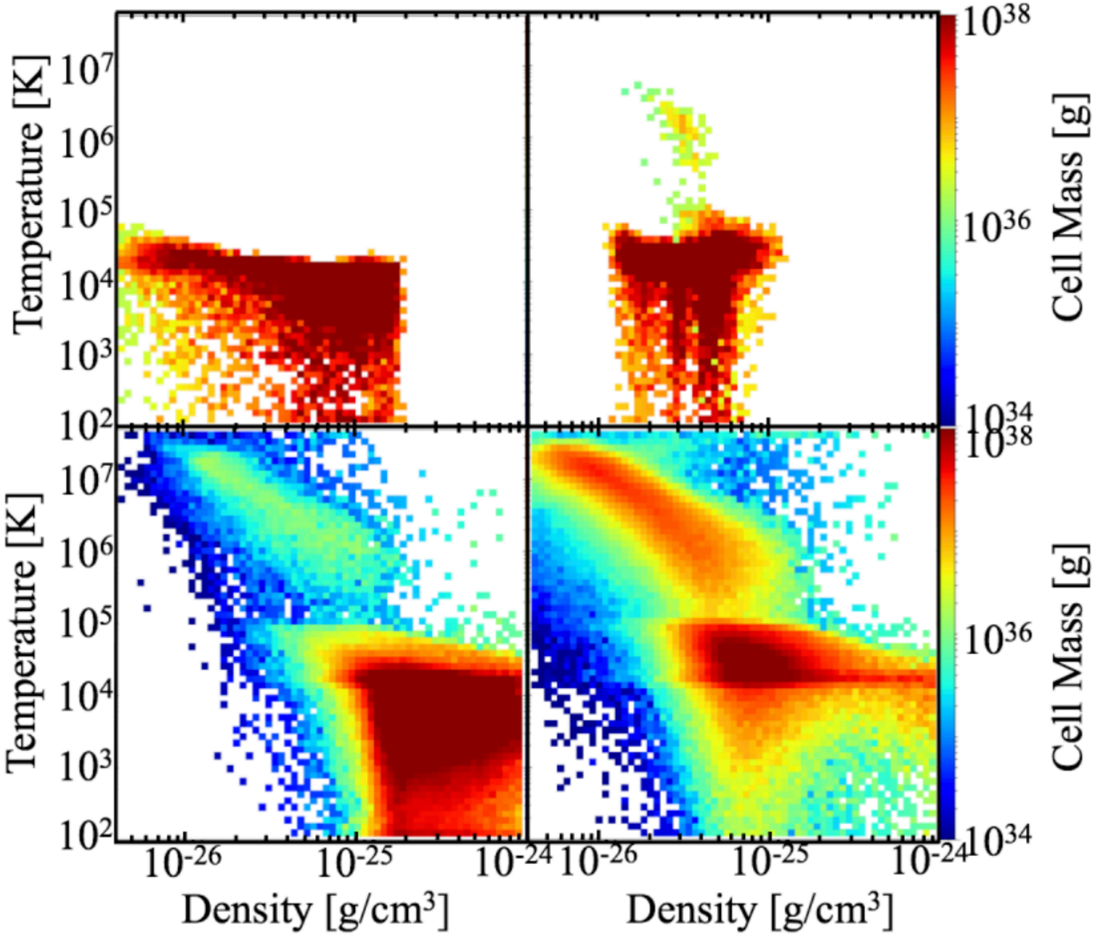
- SN Feedback
  - SN energy = 10^{51} erg
  - 10% of SN energy -> CR
  - 90% of SN energy -> Thermal

Phase Plots at 170 Myr

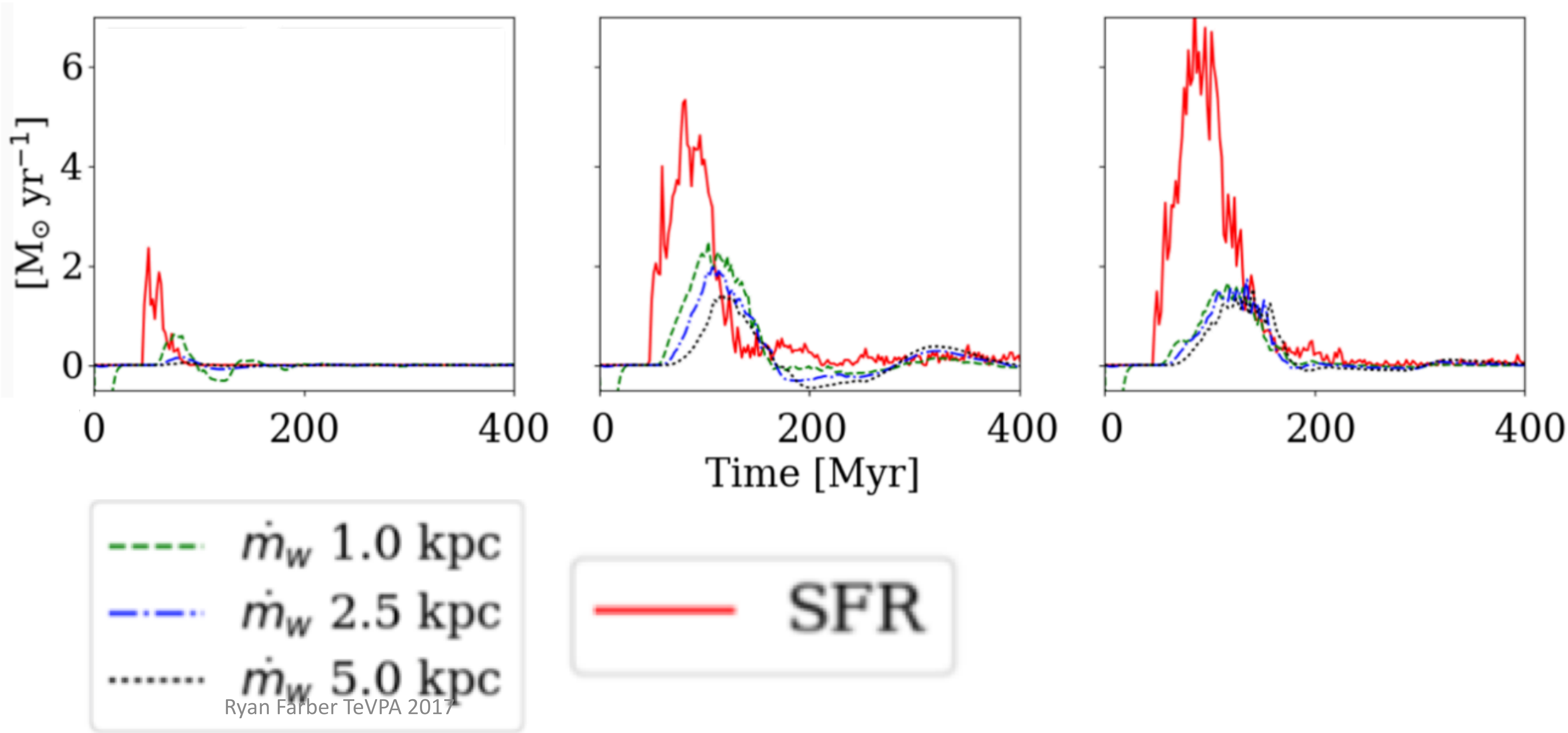
Diffusion Decoupling

|z| > 4 kpc

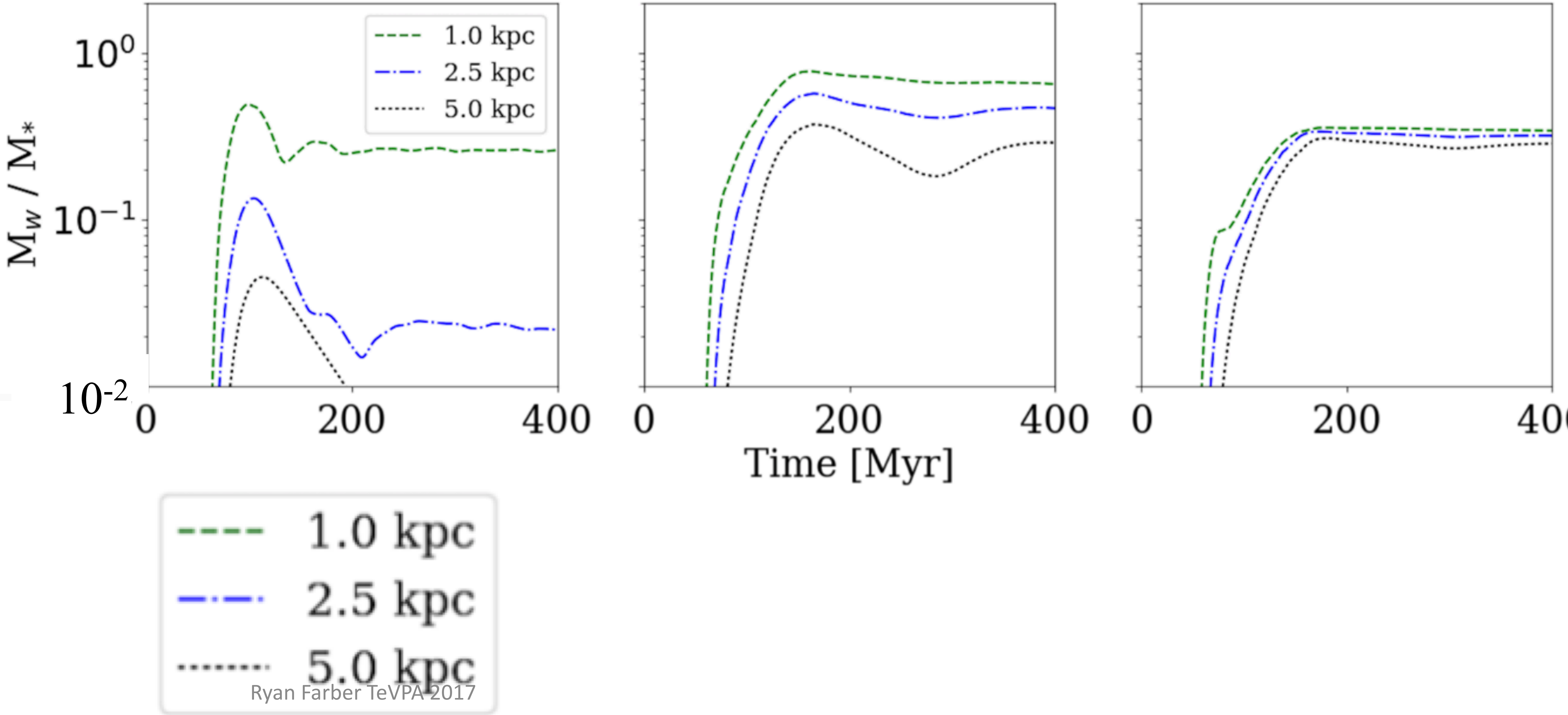
|z| < 4 kpc



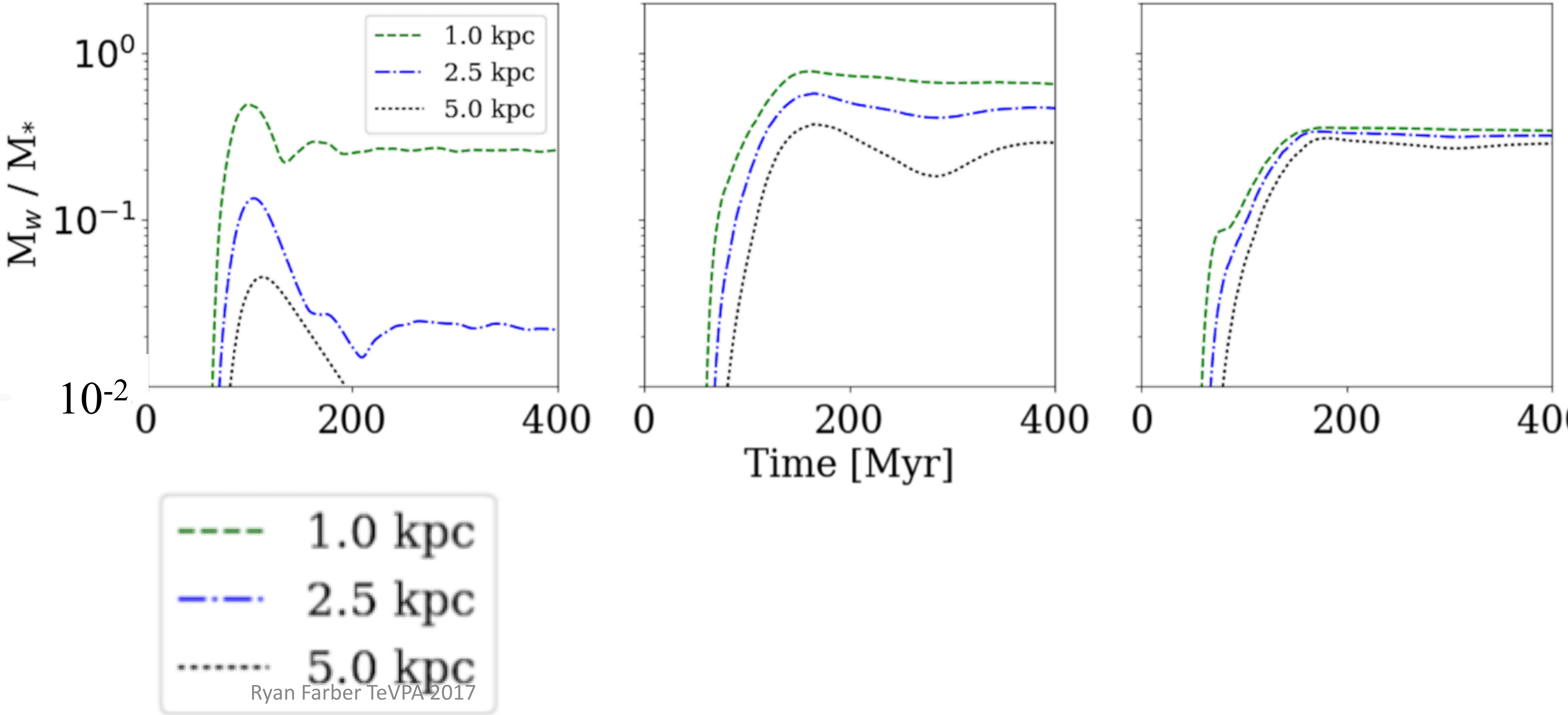
SFR, Mass Outflow Rate

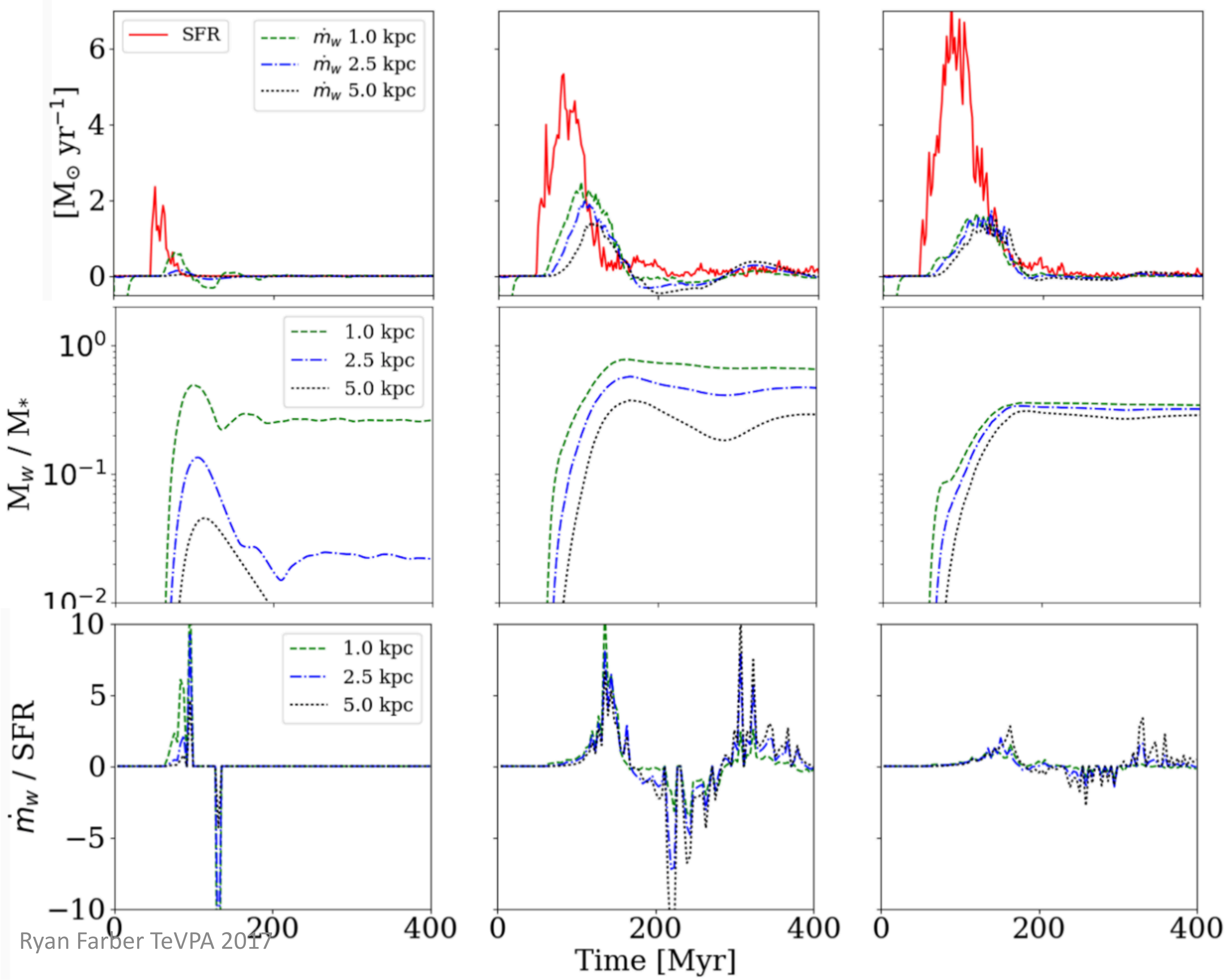


Integrated Mass Loading



Instantaneous Mass Loading




SFR
$\dot{m}_w$ 1.0 kpc
$\dot{m}_w$ 2.5 kpc
$\dot{m}_w$ 5.0 kpc
$[M_\odot\ yr^{-1}]$
1.0 kpc
2.5 kpc
5.0 kpc
M_w / M_*
1.0 kpc
2.5 kpc
5.0 kpc
$\dot{m}_w$ / SFR
Time [Myr]