Simulating Cosmic Ray Feedback in the Resolved ISM: Star Formation and Outflows

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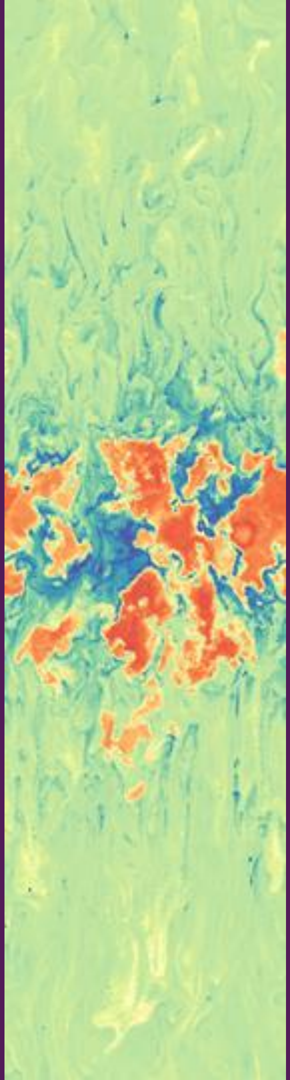
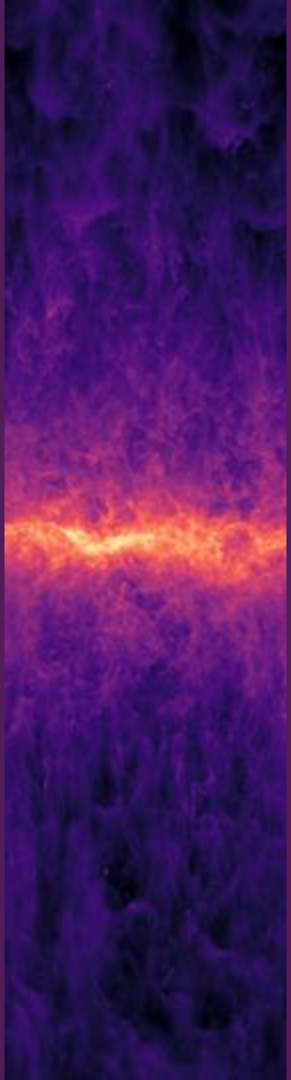
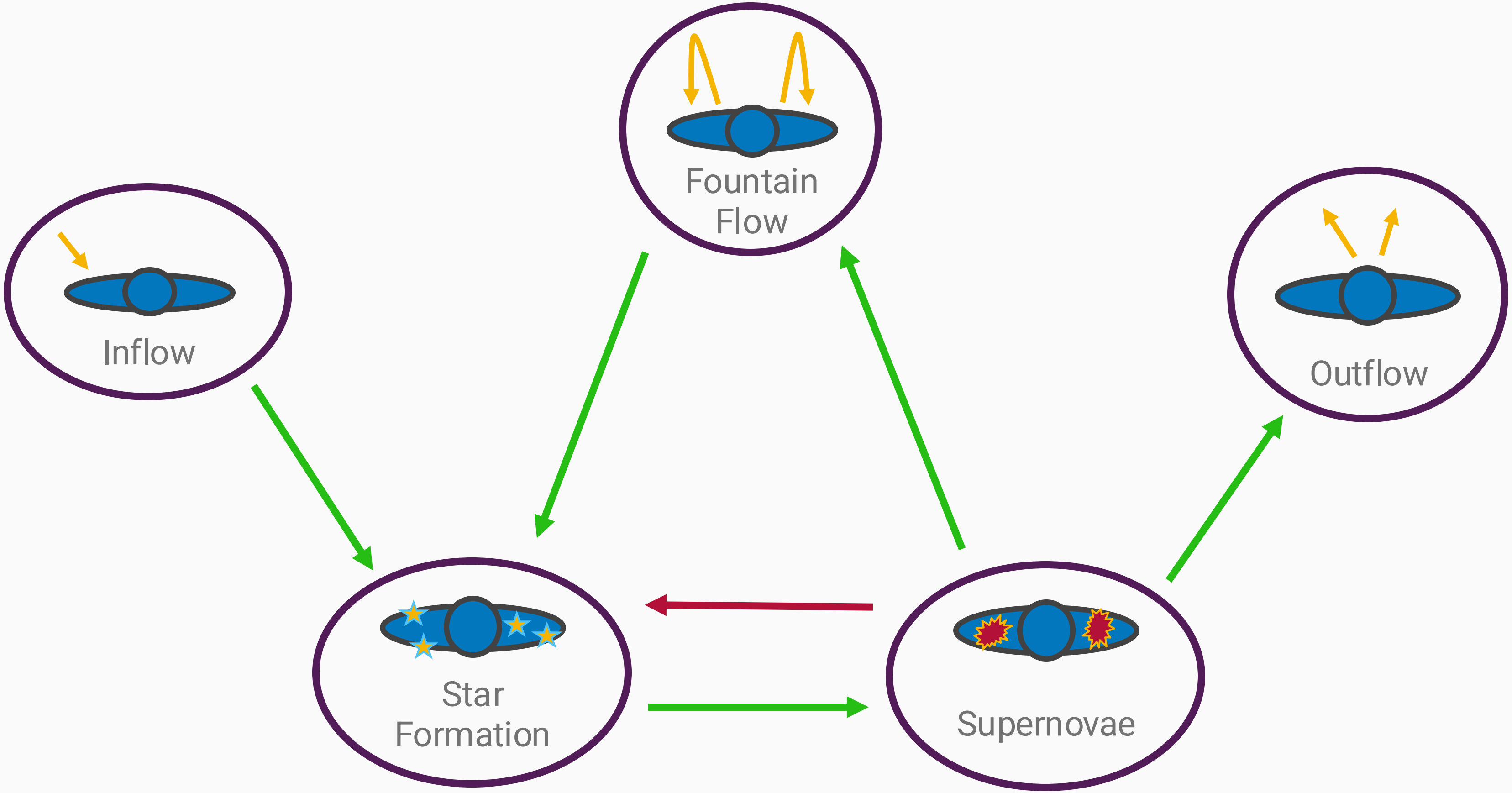
Rencontres du Vietnam TMEX 2025, January 8th, 2025



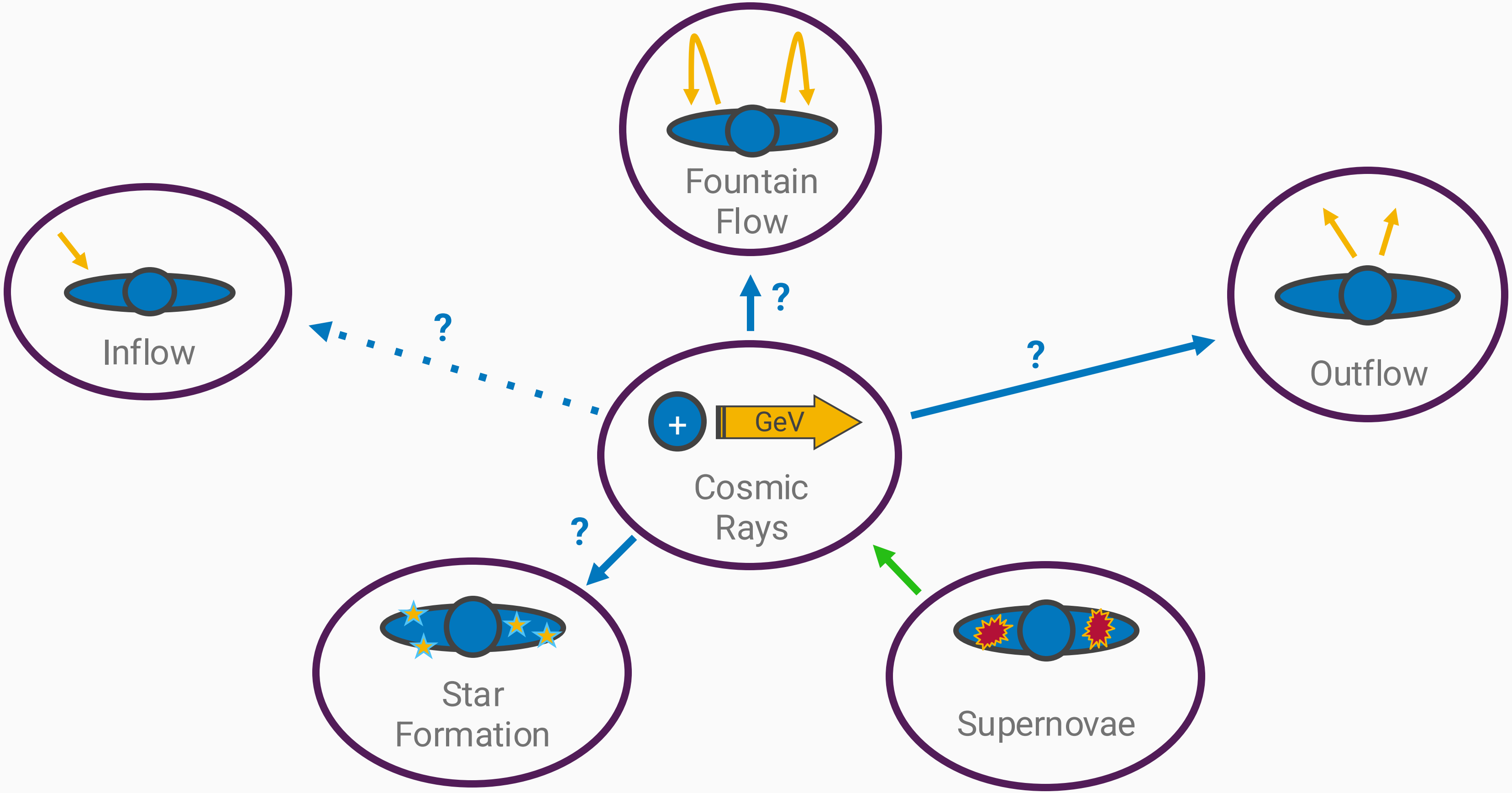


Quick review of galactic feedback

Galactic Feedback (Before Cosmic Rays)

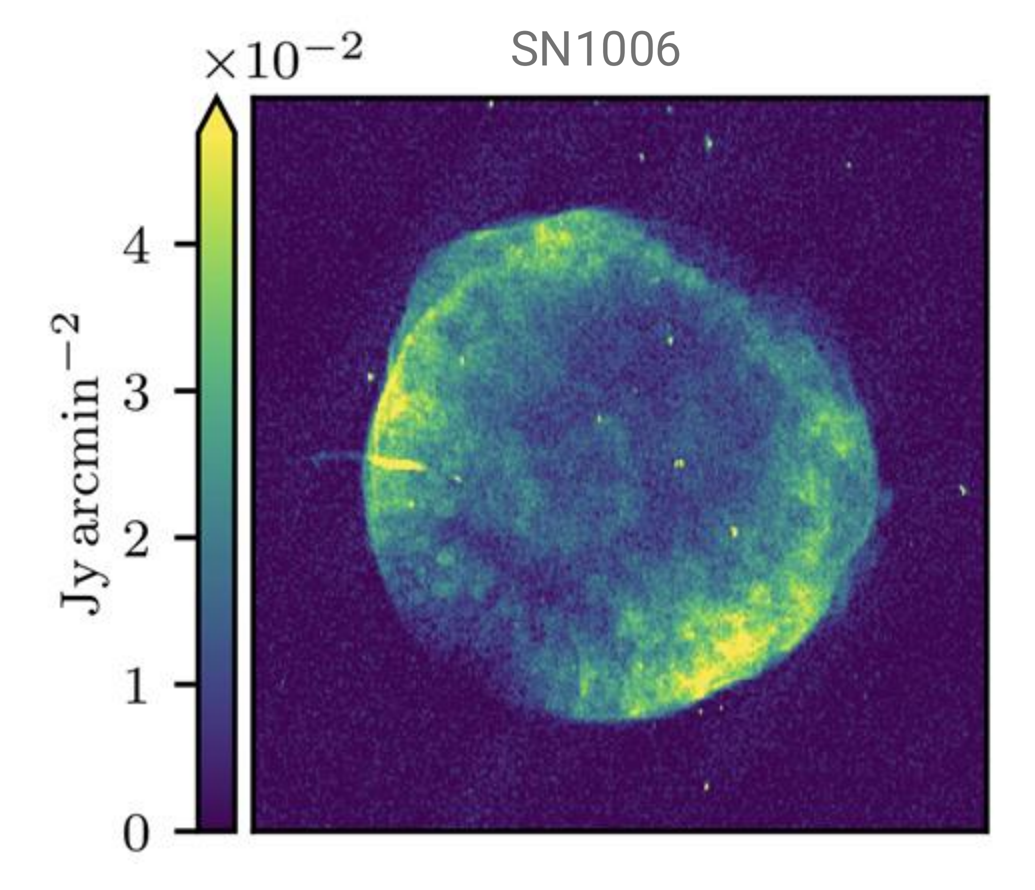


Galactic Feedback (With Cosmic Rays)



What do *I* mean by Cosmic Ray (CR)?

- Relativistic, charged particles found throughout the universe.
- Accelerated at shock fronts around supernova remnants.
- **~GeV protons are dynamically significant**, often traced by electrons that are observable in the radio.



Winner et. al. (2019), with data from Dyer et. al. (2009)

Cosmic Rays in Galaxies

- Equipartition with other energy densities in the ISM.
- Provide a source of **pressure**, contribute to heating, drive molecular chemistry, trace magnetic field topology.
- Notably, **cosmic rays can exchange momentum and energy with the gas over long time and distance scales.**

Table 1.3 Energy densities in the local ISM[a]

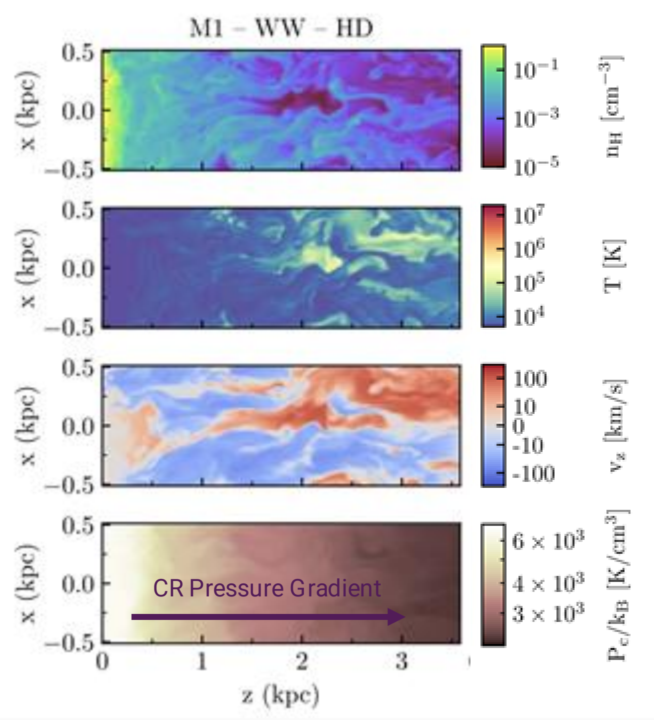
Type	Energy density ($eV\ cm^{-3}$)
Cosmic microwave background	0.2606
Thermal energy	0.4
Turbulent kinetic energy	0.2
Far-infrared from dust	0.3
Starlight	0.6
Magnetic energy	0.9
Cosmic rays	1.4

[a] *Data from Draine 2011, Table 1.5 and Table 12.1*

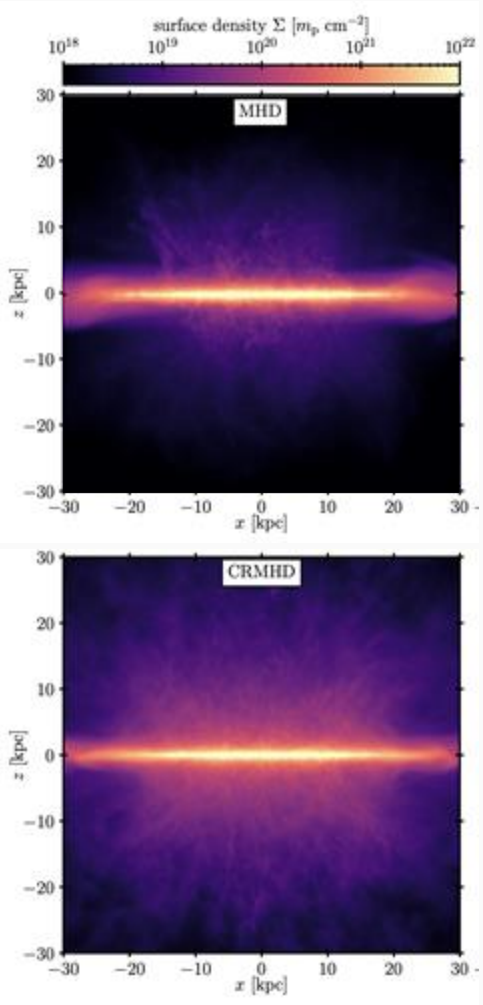
Ryden & Pogge: Interstellar and Intergalactic Medium (2021) with data adapted from Draine (2011), with cosmic ray data from Voyager measurements (Webber & Yushak 1983).

Cosmic Ray-Driven Galactic Winds

- CRs drive an outflow by establishing a pressure gradient.
- CR-driven winds are able to lift more material into the CGM than thermally-driven winds.



Armillotta et al. (2024)



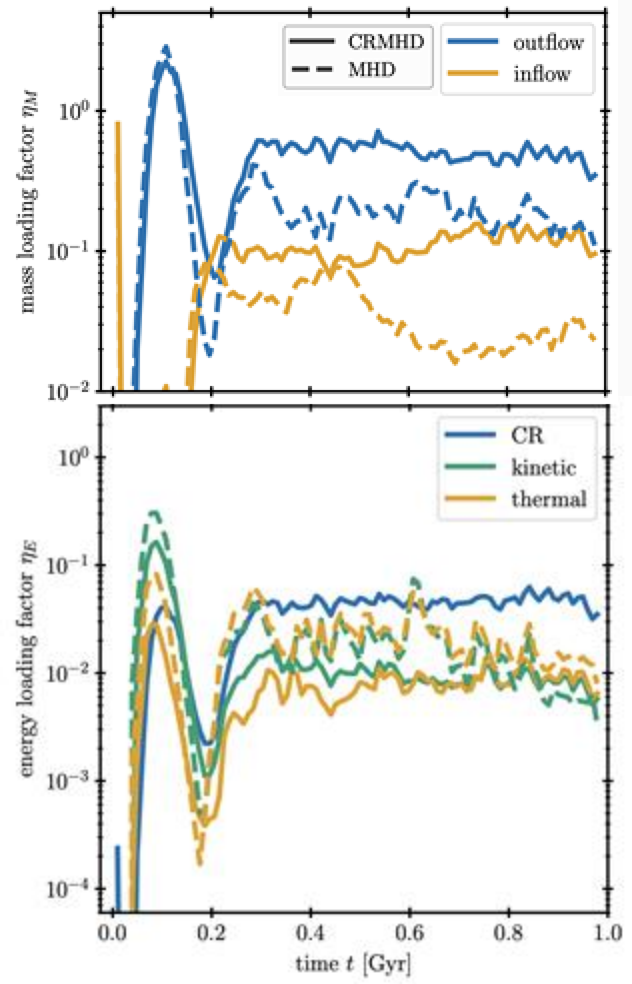
Thomas et al. (2024)

Outflow Diagnostics

- Mass and energy loading factors tell us about the efficacy of feedback in driving outflows.
- CR-driven winds have higher mass loading factors than pure MHD winds, and also primarily contain energy as CRs.

$$\eta_{\rm M} = \frac{\dot{M}_{\rm out}}{\rm SFR}$$

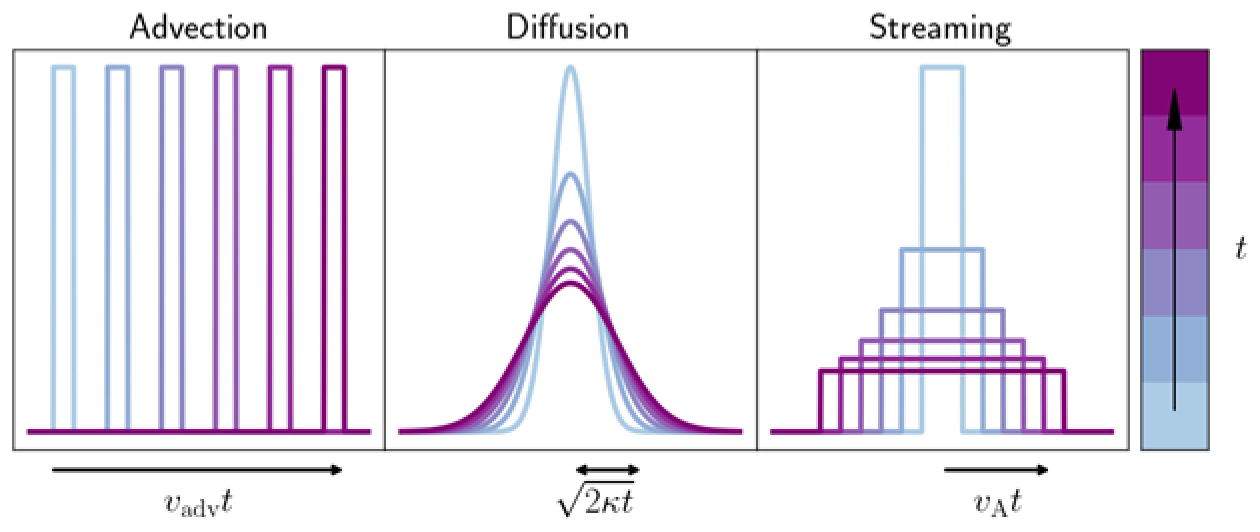
$$\eta_{\rm E} = \left(\frac{10^{51}\ {\rm erg}}{100\ {\rm M}_\odot}\ {\rm SFR}\right)^{-1} \dot{E}_{\rm out}$$



Thomas et al. (2024)

GeV Cosmic Ray Transport

CR Transport

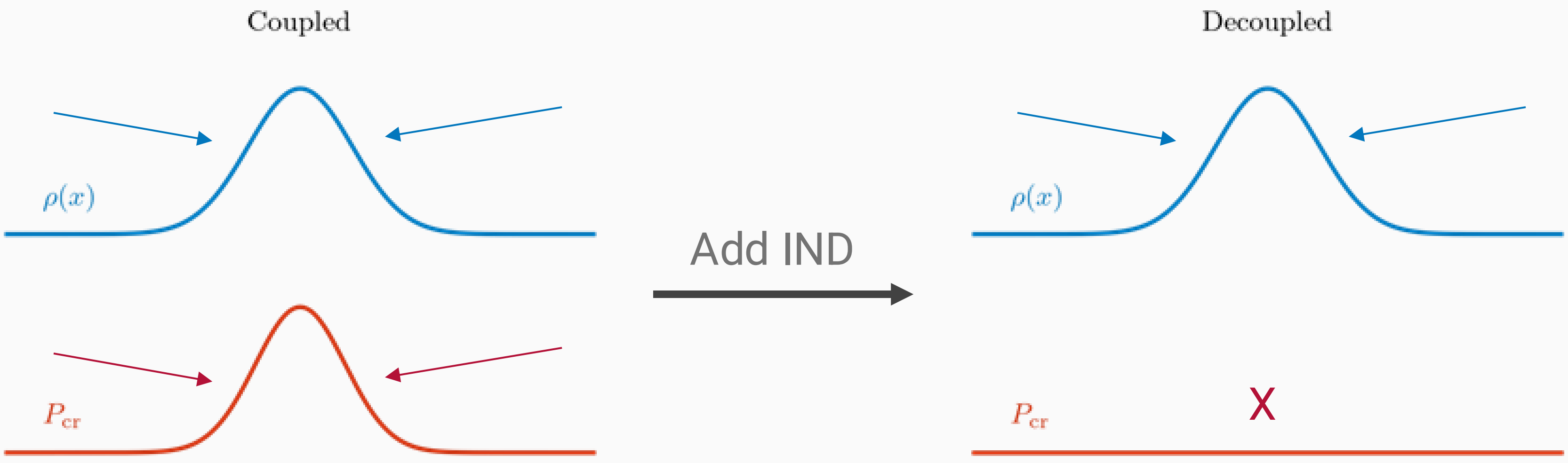


Adapted from Thomas et. al. 2020

- Advection, diffusion, and streaming are regulated by magnetic fields and Alfvén waves.
- **Energy is transported along magnetic fields at** $v \approx v_{\rm A} \ll c$
- Real CR transport is a combination of these modes.

CR Transport: Damping Processes

- CRs are confined by Alfvén waves, Alfvén waves are damped.
- Nonlinear Landau damping (NLLD) is energy loss from beat waves, **sets universal coupling**.
- Ion neutral damping (IND) is ~frictional loss from ion/neutral collisions, **decouples CRs from neutral regions**.



The Questions:

- How does CR feedback affect the steady-state SFR and galactic outflow?
- How do CRs interact with multiphase gas in the wind?
- **Does ion-neutral damping prevent CRs from providing effective feedback?**

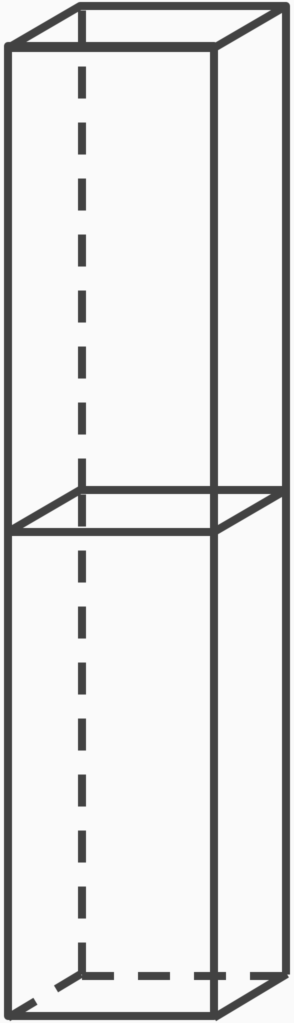
Model

ISM Tallbox

- Use AREPO (Springel 2010)
- 1 kpc * 1 kpc * 8 kpc
- Σgas = 10 Msun / pc^2
- 10 Msun resolution in the ISM
- ~3 pc resolution in the wind
- Live MHD, stellar feedback
- Nonequilibrium ionization model CRISP

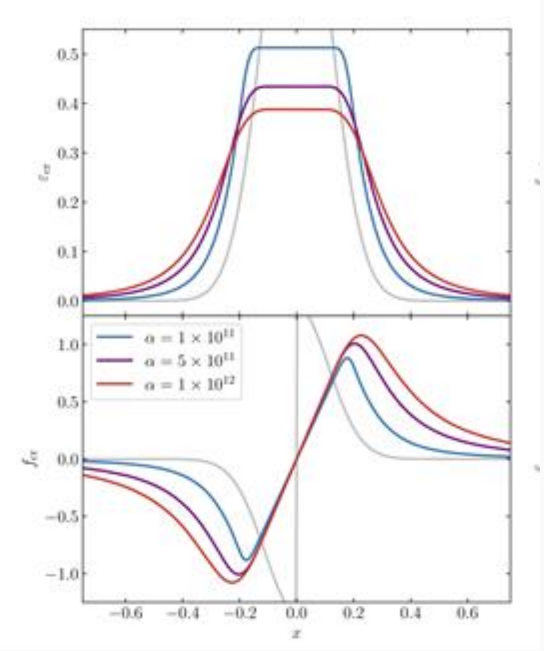
Face-on spiral galaxy NGC 3982, NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

Edge-on spiral galaxy NGC 5907, ESA/Hubble & NASA, R. de Jong. Acknowledgement: Judy Schmidt (Geckzilla)

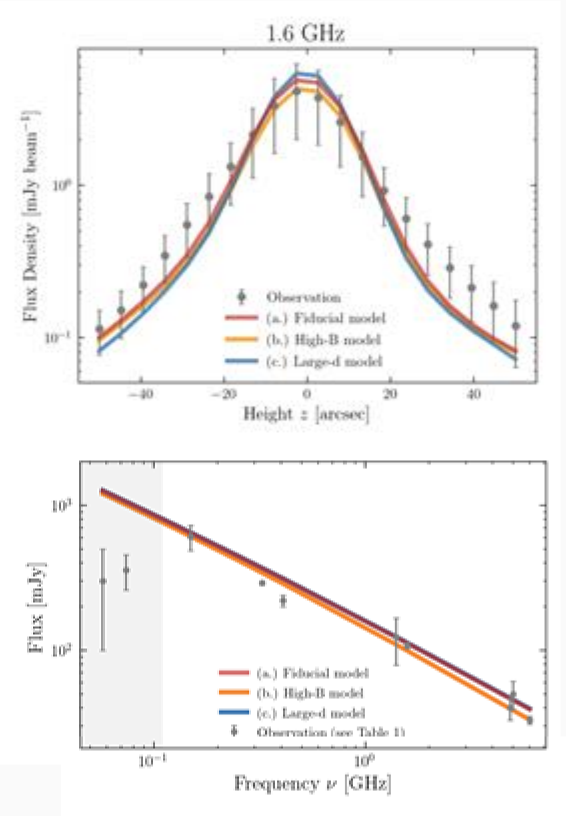


Alfvén-Wave Regulated CRMHD

- Thomas & Pfrommer (2019)
- Two-moment model which follows advection + streaming + diffusion and both NLLD and IND calculated on-the-fly.
- Matches radio observations well.



Thomas & Pfrommer (2019)



Chiu et al. (2024)

4 Cases

- (“MHD”): No CRs
- (“CR-A”): CRs with only advection
- (“CR-NL”): CRs with two-moment CRMHD (advection + streaming + diffusion) and only NLLD. **Uniform coupling of CRs to gas.**
- (“CR-NL-IN”): CRs with two-moment CRMHD (advection + streaming + diffusion) and both NLLD and IND. **Full physics; CRs decouple from neutral gas.**

Results

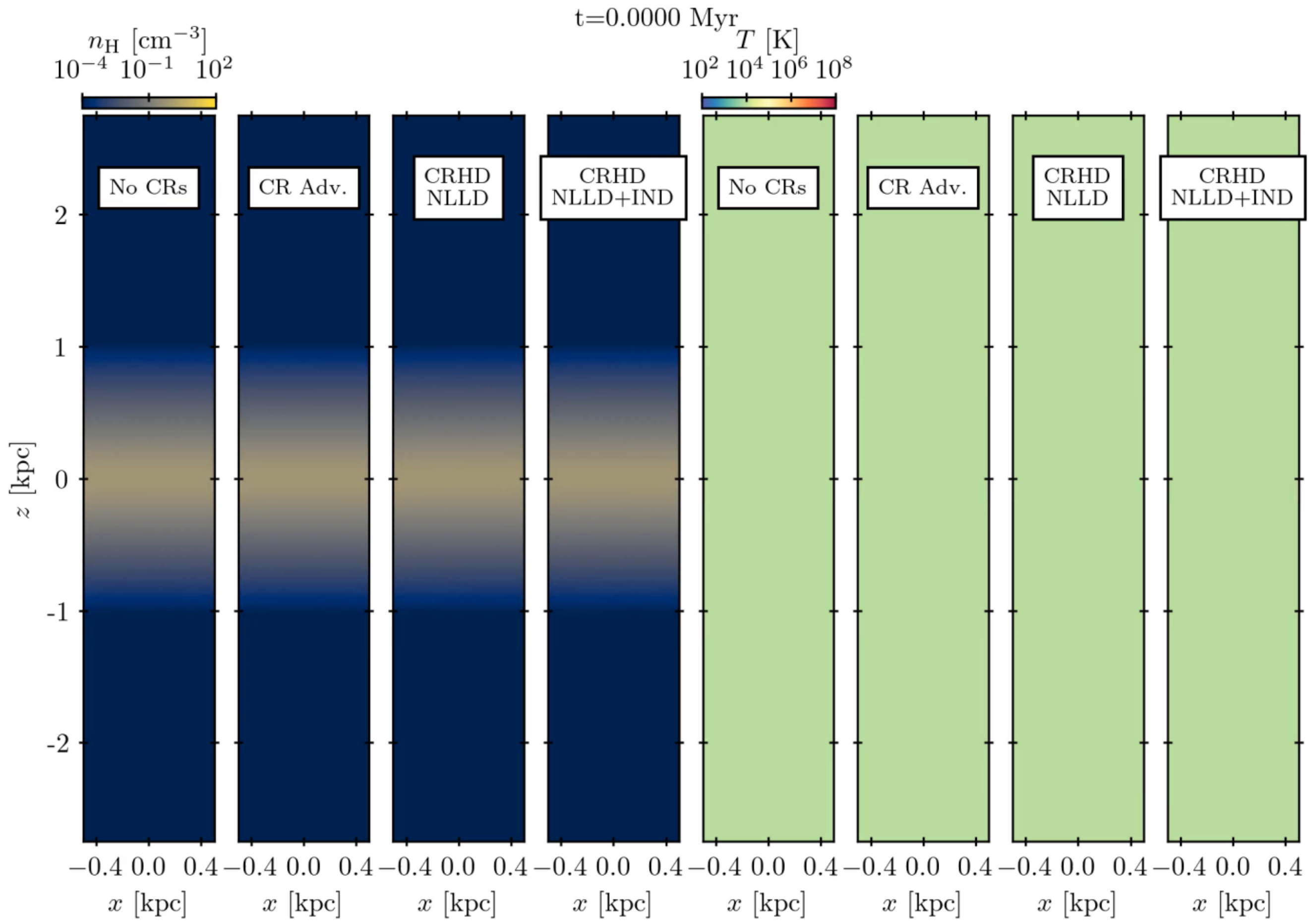
arXiv:2410.06988 (astro-ph)

[Submitted on 9 Oct 2024]

Cosmic Ray–Driven Galactic Winds with Resolved ISM and Ion–Neutral Damping

Brandon Sike, Timon Thomas, Mateusz Ruszkowski, Christoph Pfrommer, Matthias Weber

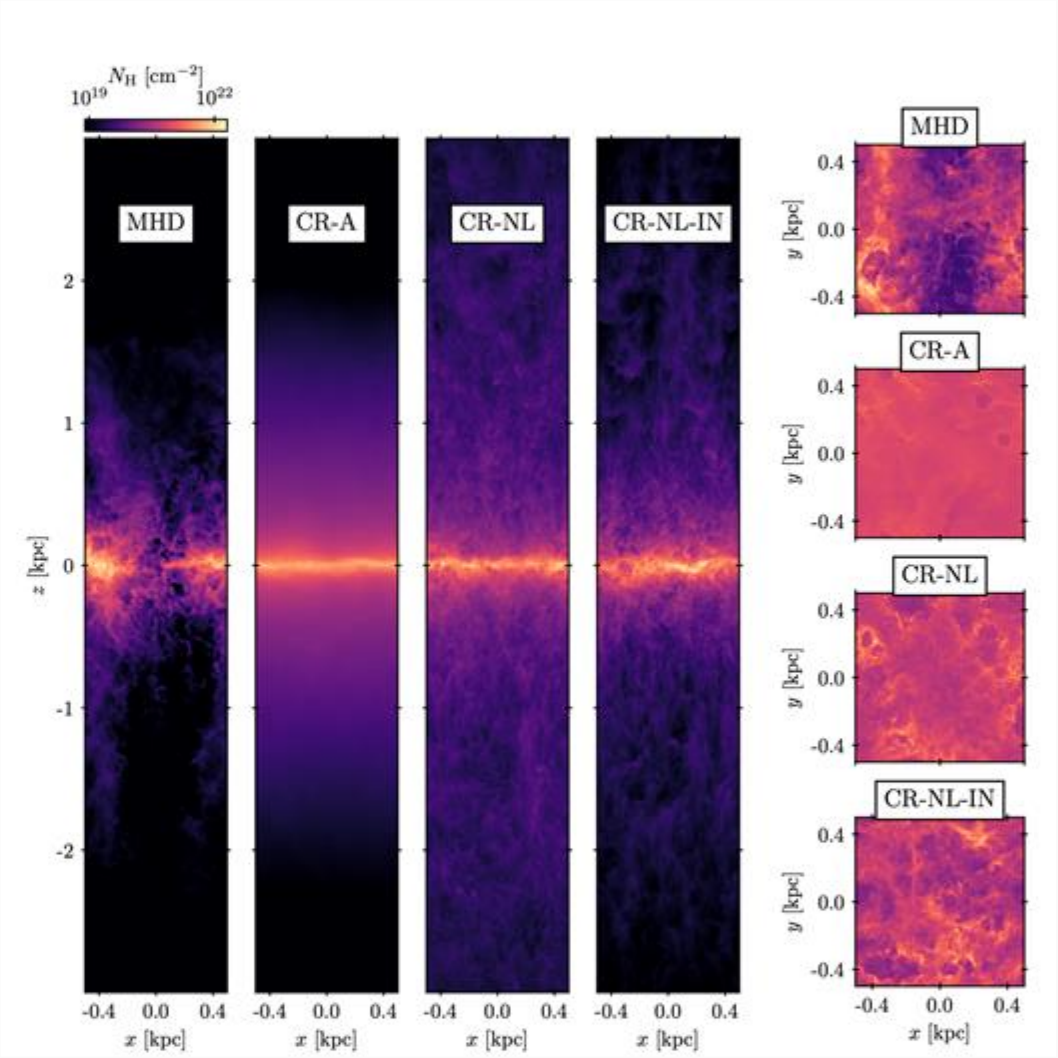
Comments: 27 pages, 13 figures. Submitted to ApJ


t=0.0000 Myr
n_H [cm^{-3}]
10^{-4} 10^{-1} 10^{2}
T [K]
10^{2} 10^{4} 10^{6} 10^{8}
No CRs
CR Adv.
CRHD NLLD
CRHD NLLD+IND
No CRs
CR Adv.
CRHD NLLD
CRHD NLLD+IND
z [kpc]
x [kpc]

Animation

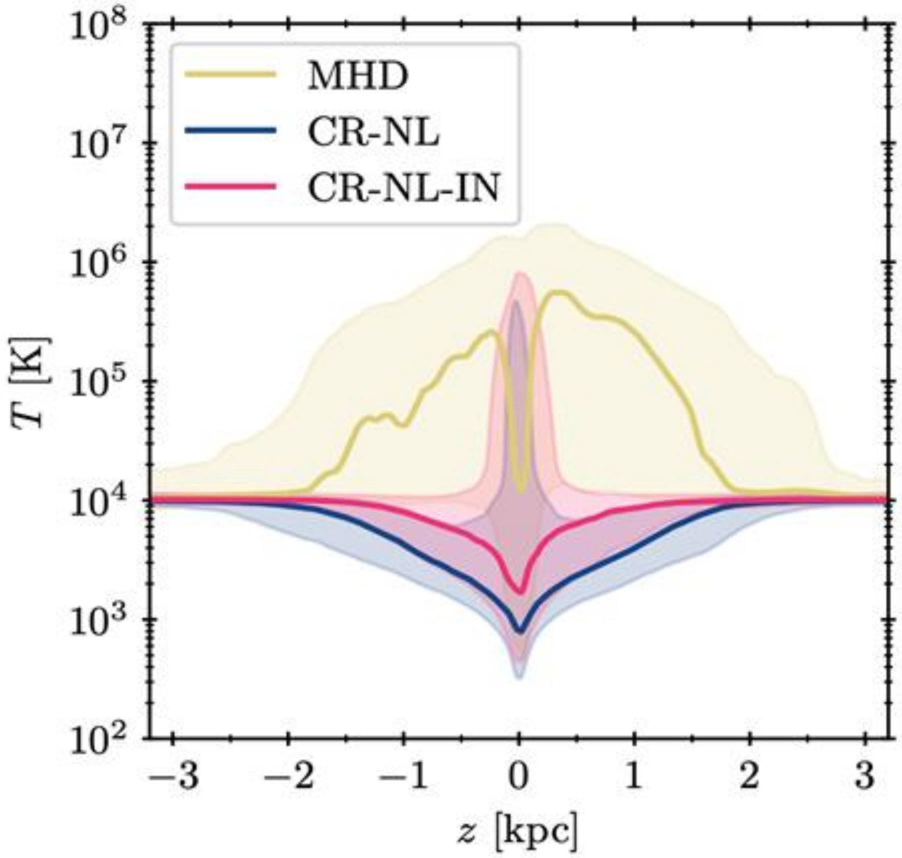
Column Density

- CRs cause the wind to display higher column densities.
- Pure MHD case has the most visible excavation due to large regions of low-density, SN-heated gas.



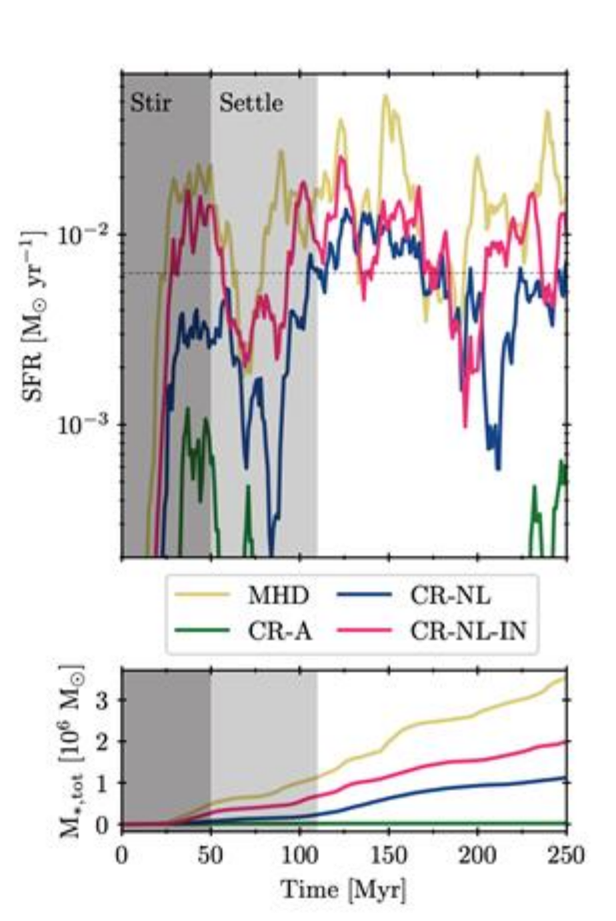
Temperature Profiles

- MHD is the hottest; supernovae-driven.
- CRs in CR-NL can couple to cold gas in the wind, CRs in CR-NL-IN cannot.
- **IND makes the wind moderately warmer**.



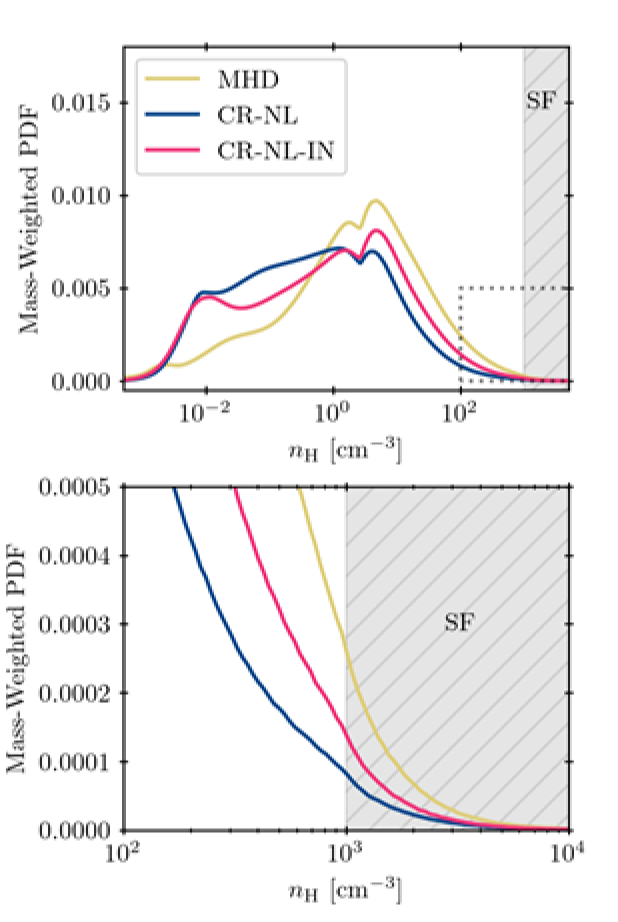
Star Formation Rate

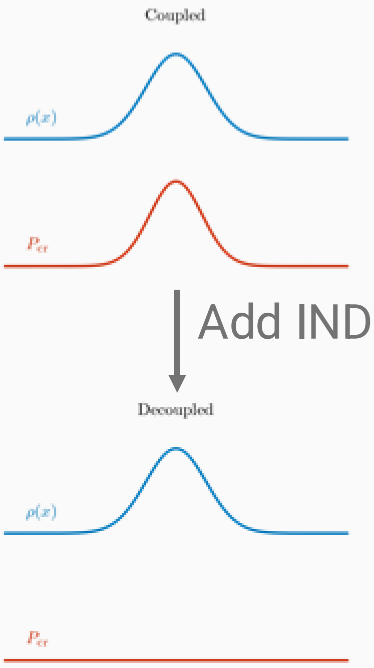
- From highest to lowest: MHD, CR-NL-IN, CR-NL, CR-A.
- **IND reduces the impact of CRs on the SFR.**
- CRs in CR-A are extremely effective at preventing star formation, so we ignore that case.



Star Forming Conditions

- Trend in amount of star-forming gas here mirrors the SFRs from the previous slide.
- CRs reduce the amount of star-forming gas.
- **IND decouples CRs from dense, neutral gas, allowing gas to reach star-forming densities with less resistance.**

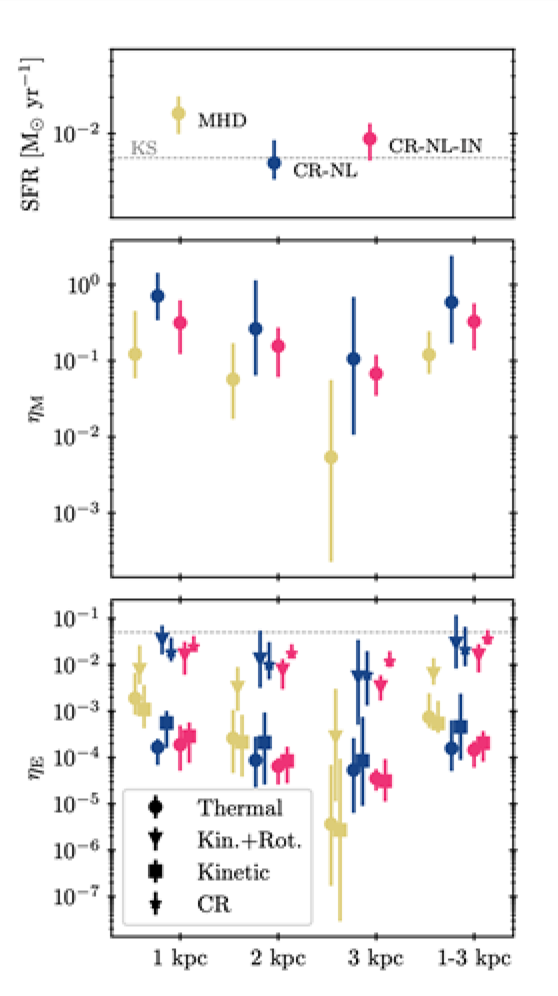




Outflow & Loading Factors

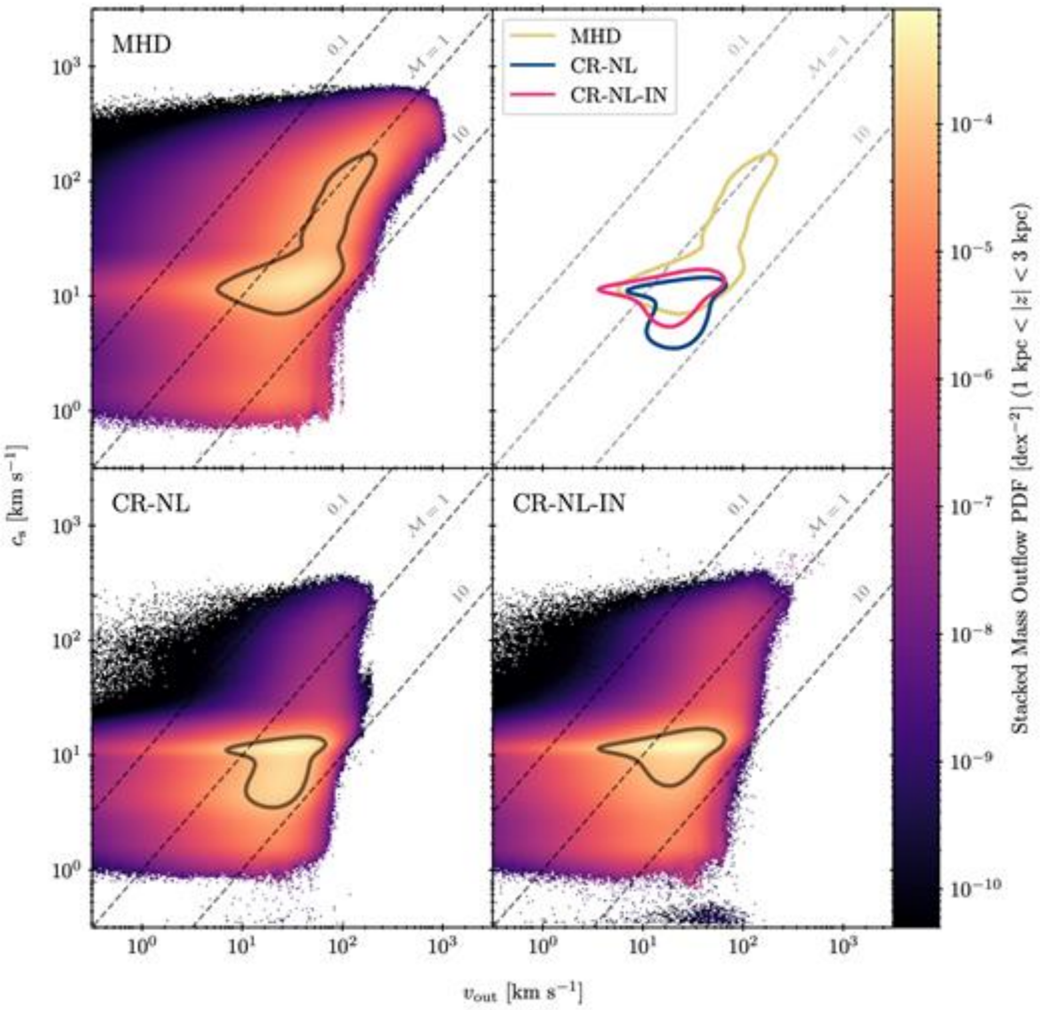
- MHD case has the lowest mass-loading factors, and the outflow becomes very weak by |z|=3kpc.
- SFRs are not different enough to explain the differences in mass loading factors.
- CR-driven winds have high CR energy loading factors.

$$\mathbf{v}_{\mathrm{kin.+rot.}} = \mathbf{v}_{\mathrm{sim}} + 220\ \mathrm{km\ s^{-1}}\ \mathbf{e}_x$$



Outflow Phase

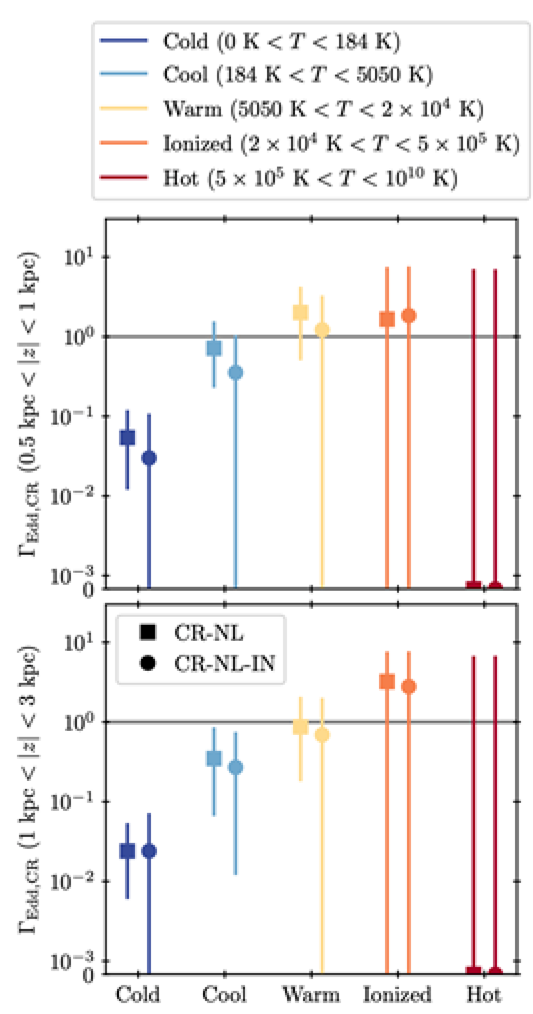
- Pure MHD outflow is the hottest and the fastest, but with lowest Mach numbers.
- CR-NL outflow is the coldest and has the highest Mach numbers.
- CR-NL-IN is cool/warm with intermediate Mach numbers.



Driving Multiphase Outflows

$$\Gamma_{\rm Edd,CR} = -a_{\rm CR,z}/a_{\rm grav}$$

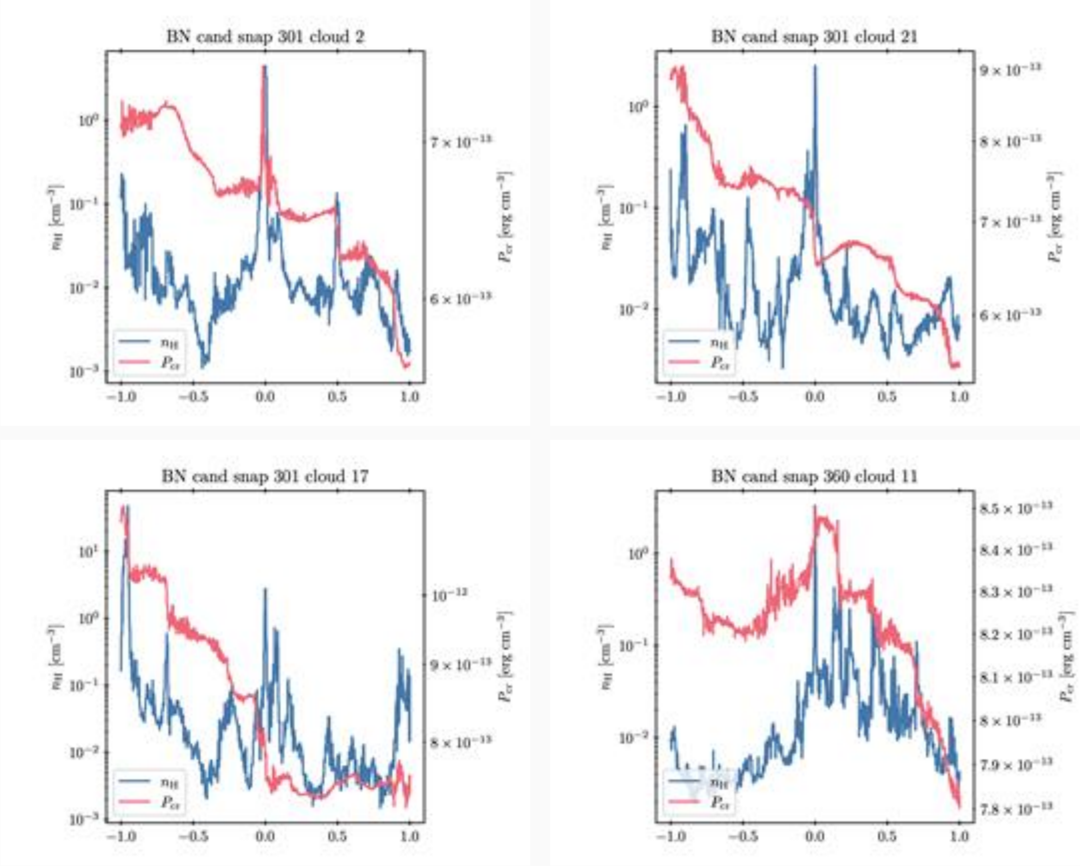
- CRs are best at accelerating warm & ionized gas, and bad at accelerating hot gas.
- CRs provide little outward acceleration to cool and cold gas in the wind.
- IND reduces the ability of CRs to accelerate gas, but not catastrophically.



In-Progress Work

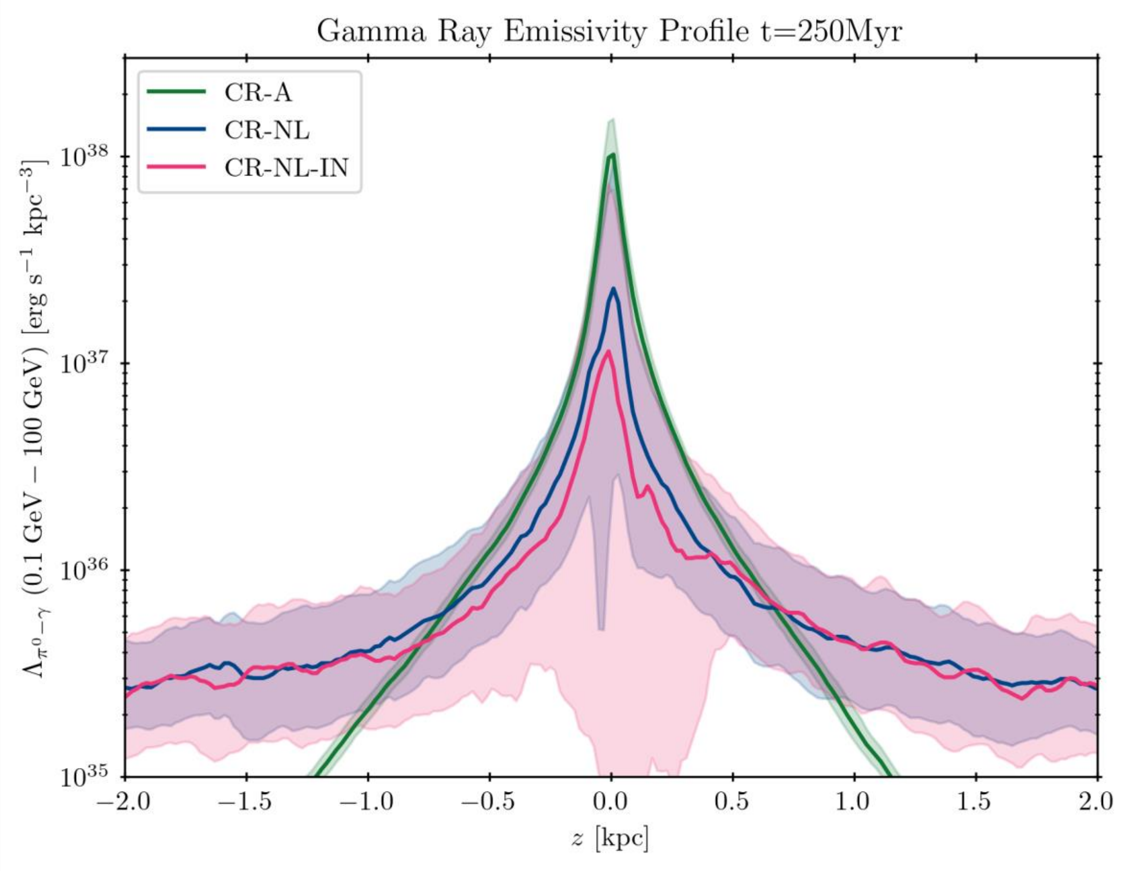
Cosmic Ray Bottlenecks

- CR pressure becomes flat between density peaks (cold clouds).
- CR pressure stairsteps at the cold clouds.
- Consequence of self-confined transport.
- Investigate observable properties, bottleneck demographics, and dynamical consequences (if any).



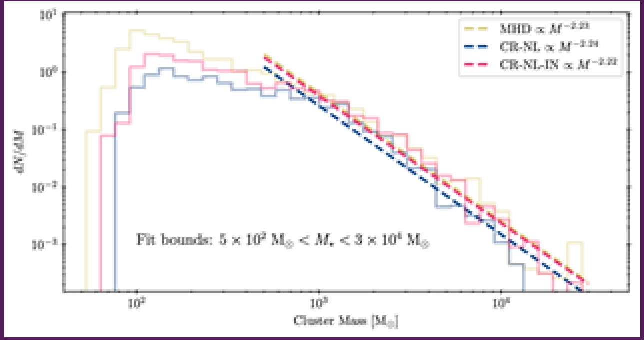
Gamma Rays and Calorimetry

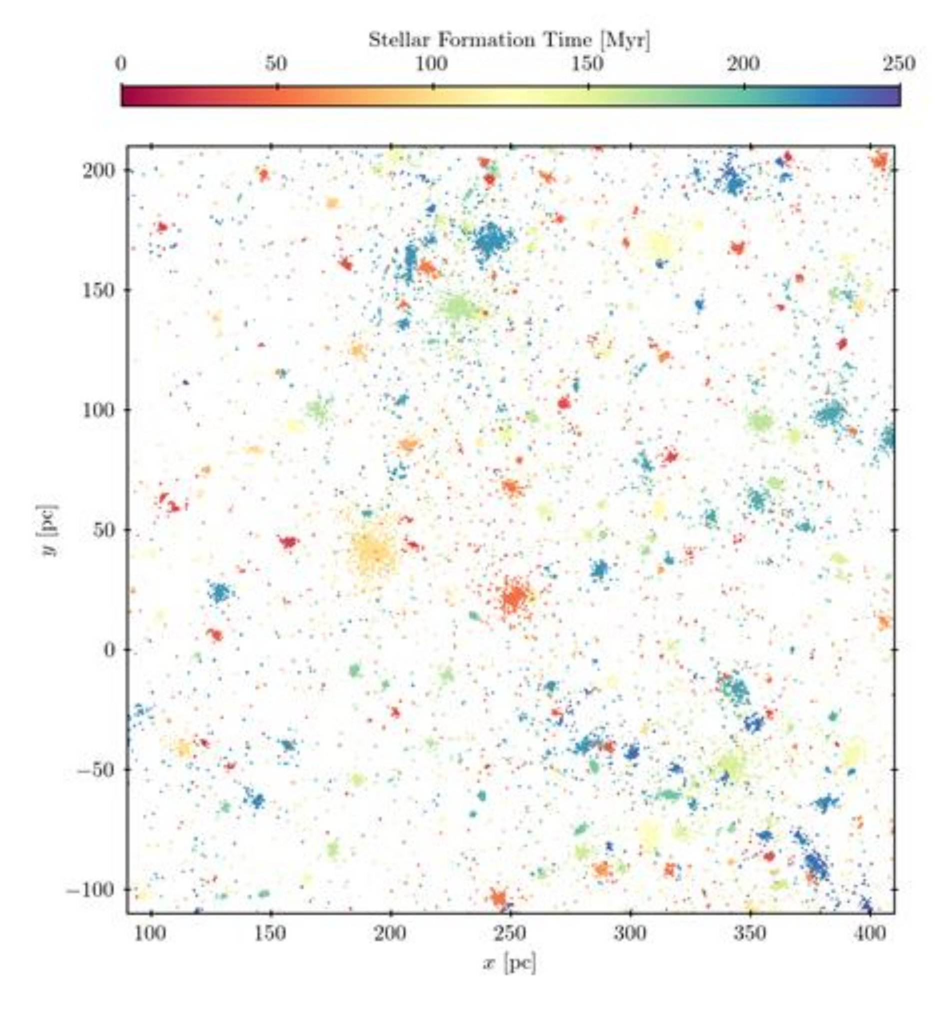
- IND decouples CRs from dense regions, implying decreased hadronic gamma ray emission.
- Less gamma ray “losses” means more CRs available for wind-driving.
- Investigate the effect of IND on gamma ray observables and CR proton calorimetry.



Star Clusters

- Mass resolution allows us to form bound star clusters of particles with similar ages.
- All models produce a similar (reasonable) mass function.
- Investigate the effect of CRs on star cluster properties.





Summary

- **Ion-neutral damping does not prevent CRs from providing effective feedback.**
- Ion-neutral damping reduces the effect of CRs on the SFR.
- Full-physics CR-driven wind is primarily warm with moderate mass loading and high CR energy loading.
- Also bottlenecks, gamma rays, and star clusters.

See astro.brsike.com/tmex2025 for slides and contact info.