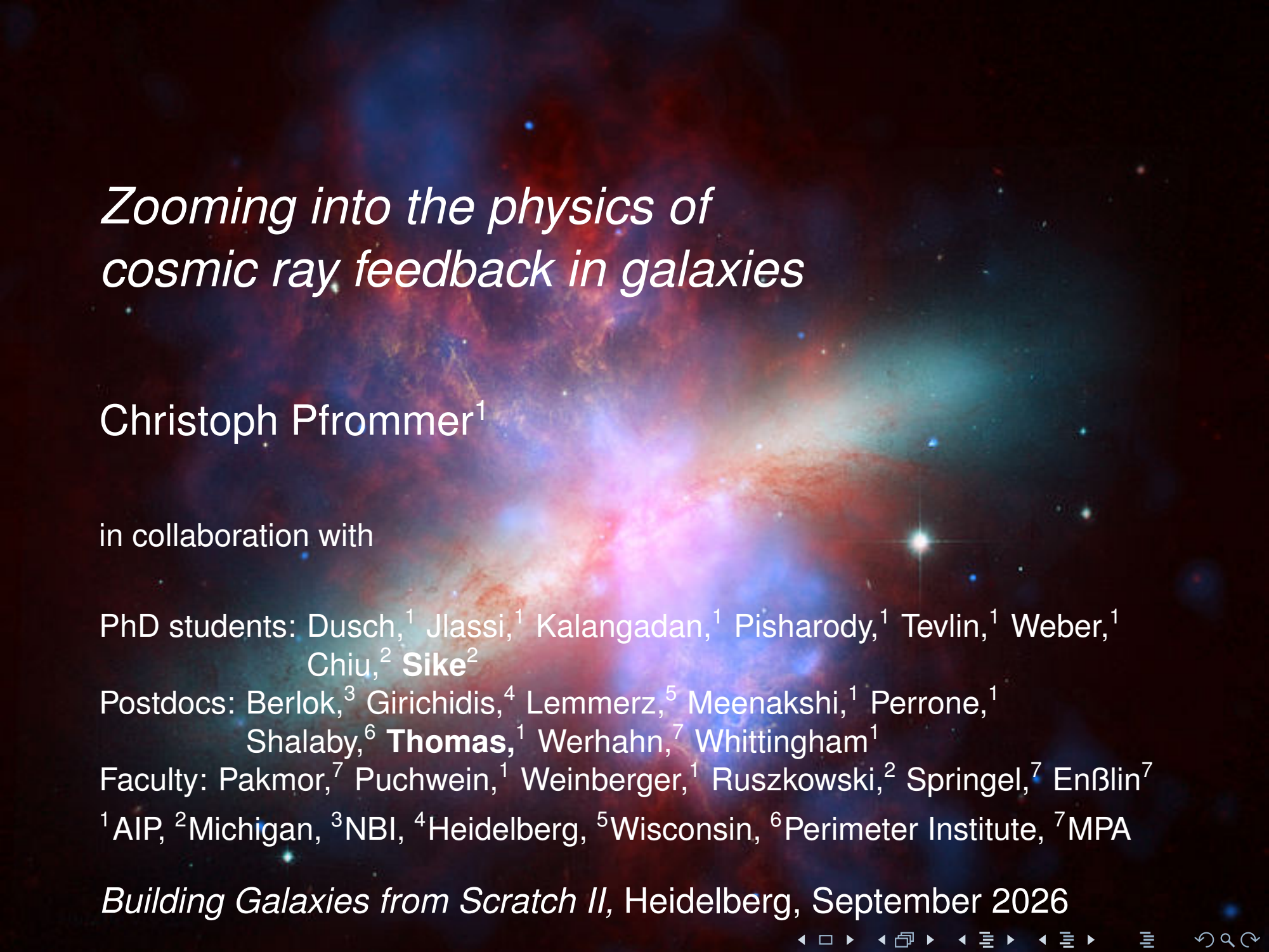


Zooming into the physics of cosmic ray feedback in galaxies

Christoph Pfrommer[1]

in collaboration with

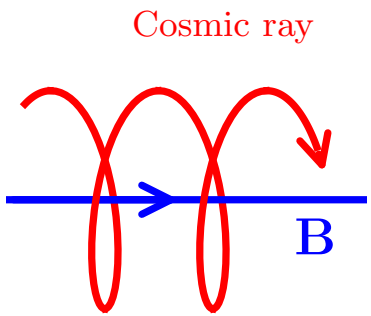
PhD students: Dusch,[1] Jlassi,[1] Kalangadan,[1] Pisharody,[1] Tevlin,[1] Weber,[1] Chiu,[2] **Sike**[2]
Postdocs: Berlok,[3] Girichidis,[4] Lemmerz,[5] Meenakshi,[1] Perrone,[1] Shalaby,[6] **Thomas,**[1] Werhahn,[7] Whittingham[1]
Faculty: Pakmor,[7] Puchwein,[1] Weinberger,[1] Ruszkowski,[2] Springel,[7] Enßlin[7]

[1]AIP, [2]Michigan, [3]NBI, [4]Heidelberg, [5]Wisconsin, [6]Perimeter Institute, [7]MPA

Building Galaxies from Scratch II, Heidelberg, September 2026

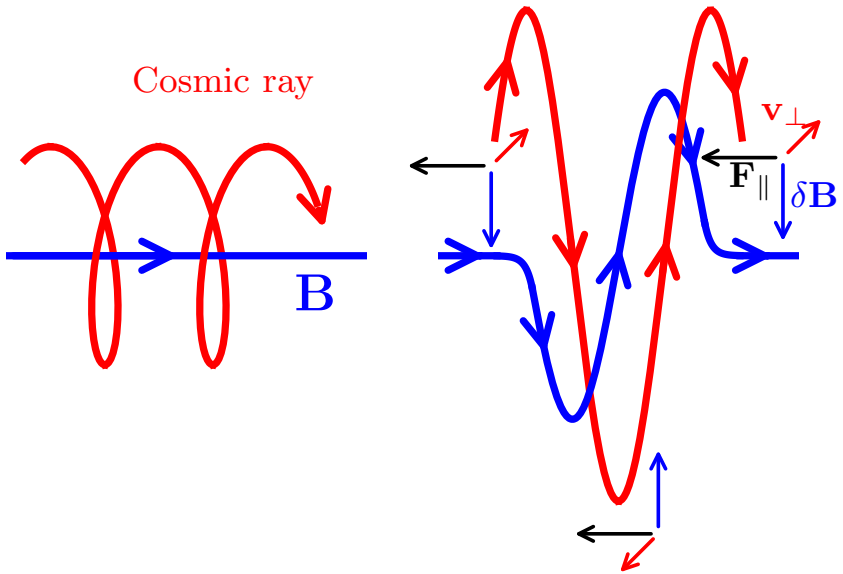


Interactions of CRs and magnetic fields



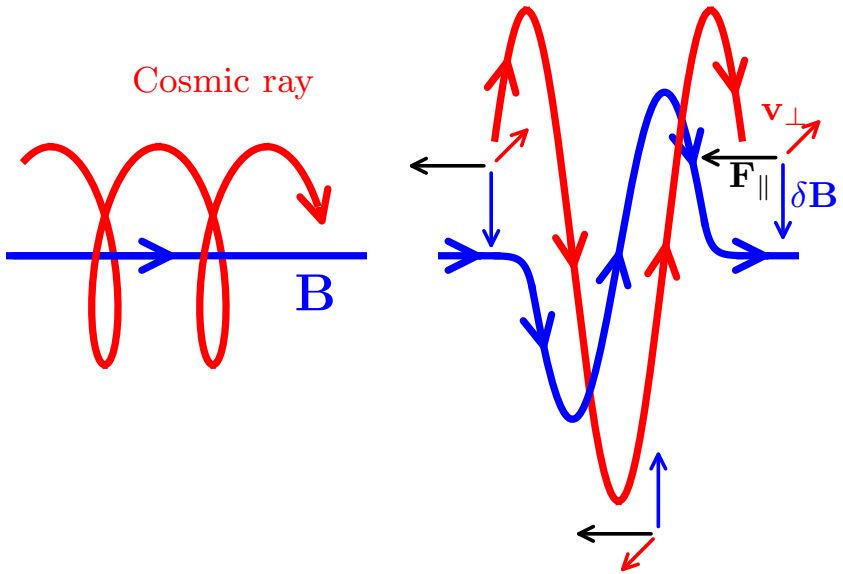
sketch: Jacob & CP

Interactions of CRs and magnetic fields



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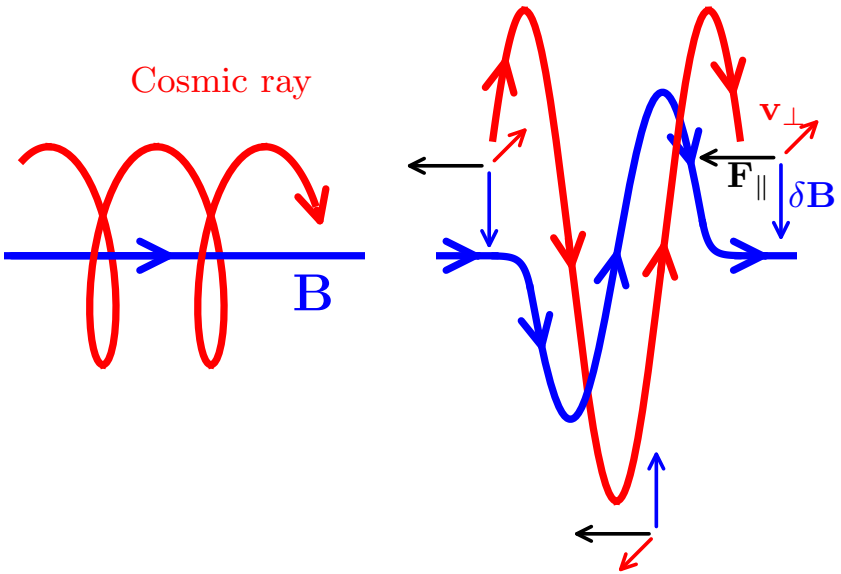
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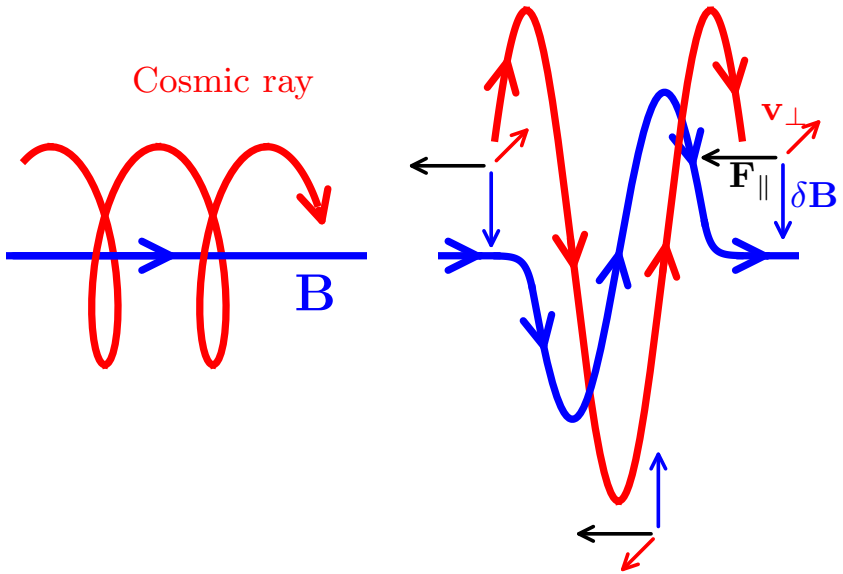


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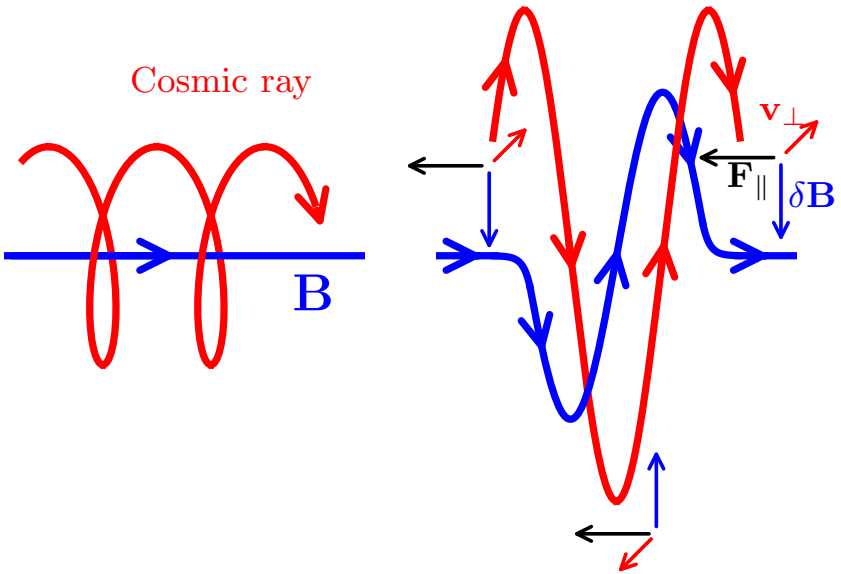
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- Lorentz force depends on **relative phase of CR gyro orbit and wave:**
  - sketch: decelerating Lorentz force along CR orbit $\rightarrow p_\parallel$ decreases
  - phase shift by 180°: accelerating Lorentz force $\rightarrow p_\parallel$ increases

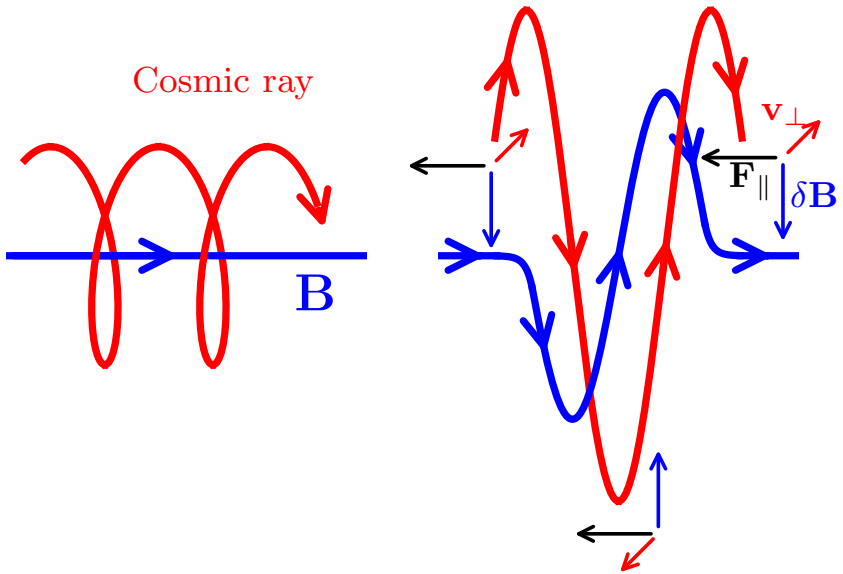
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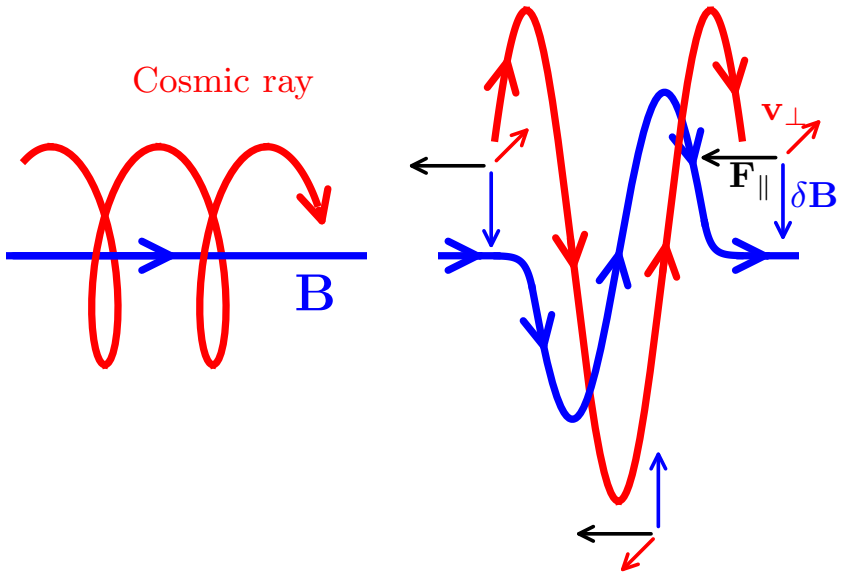
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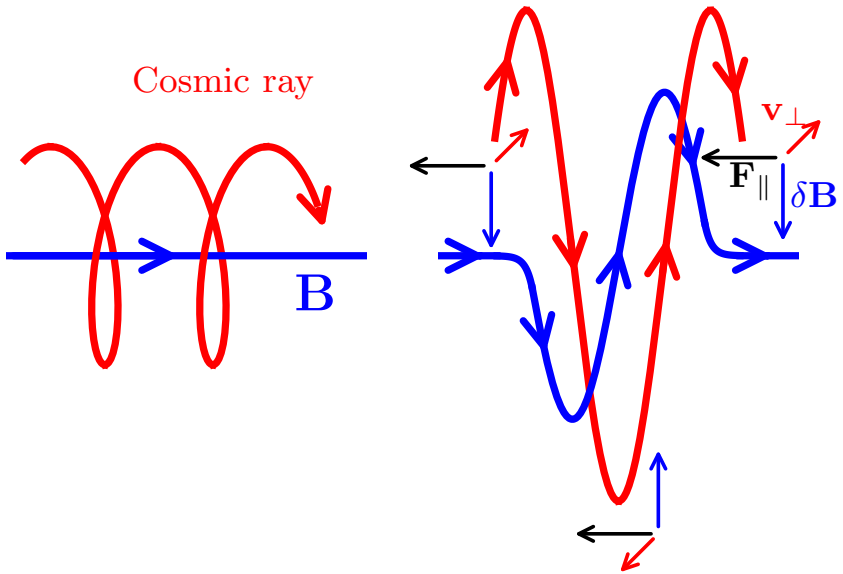


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- this increases the CR pitch angle cosine $\mu = \cos\theta = \frac{\boldsymbol{B}}{|\boldsymbol{B}|} \cdot \frac{\boldsymbol{p}}{|\boldsymbol{p}|}$

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Interactions of CRs and magnetic fields

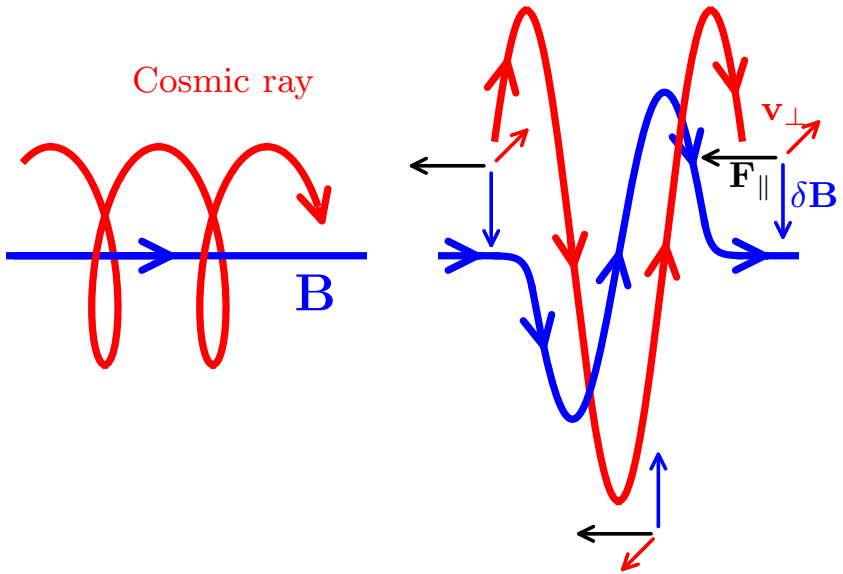


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- **CRs resonantly interact with Alfvén waves** so that the wavelength equals the gyro-radius:

$$L_\parallel = r_\mathrm{g} = \frac{p_\perp c}{qB}$$

Interactions of CRs and magnetic fields



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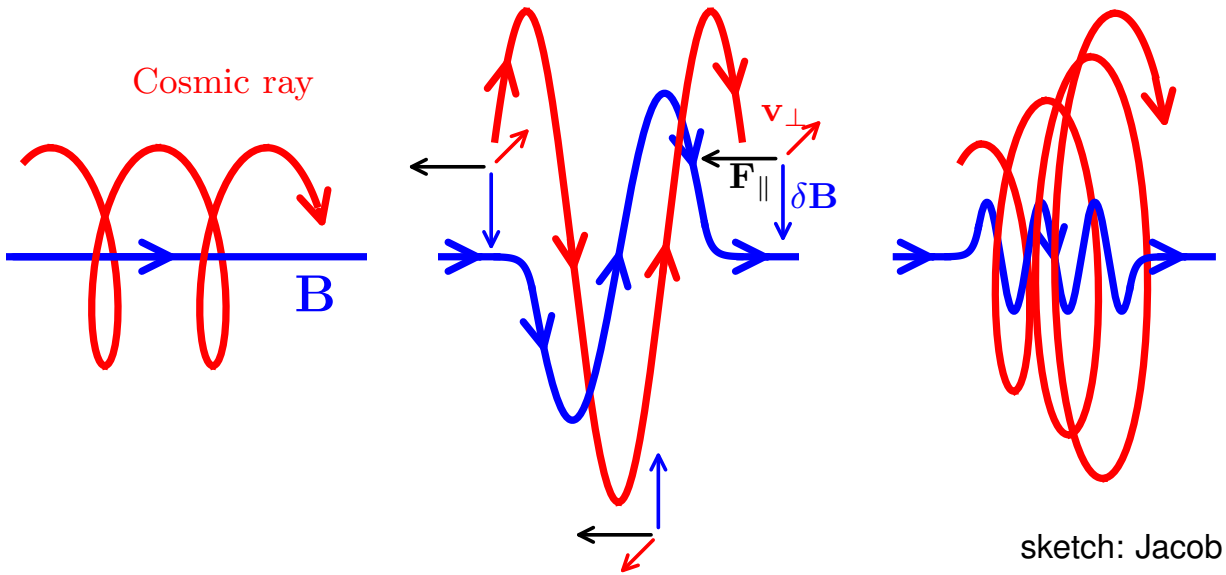
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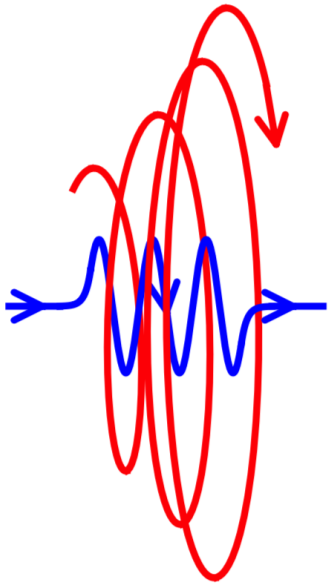
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Cosmic ray streaming and diffusion

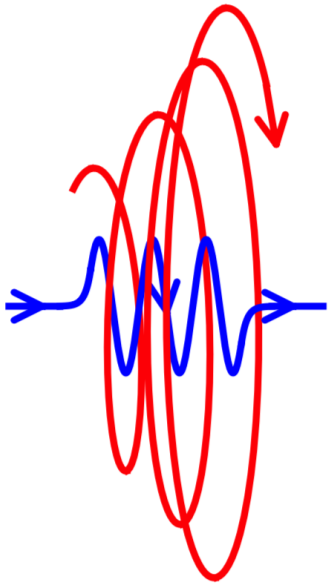
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  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)
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  - wave damping: transfer of CR energy and momentum to the thermal gas



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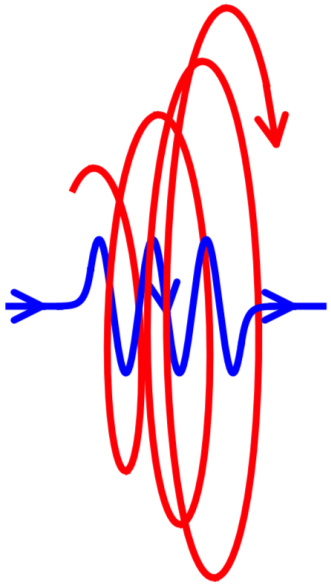
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$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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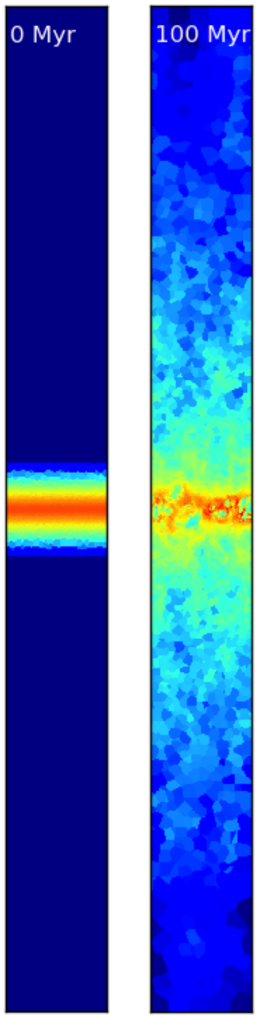
$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

weak wave damping: strong coupling $\rightarrow$ CR stream with waves
strong wave damping: less waves to scatter $\rightarrow$ CR diffusion prevails

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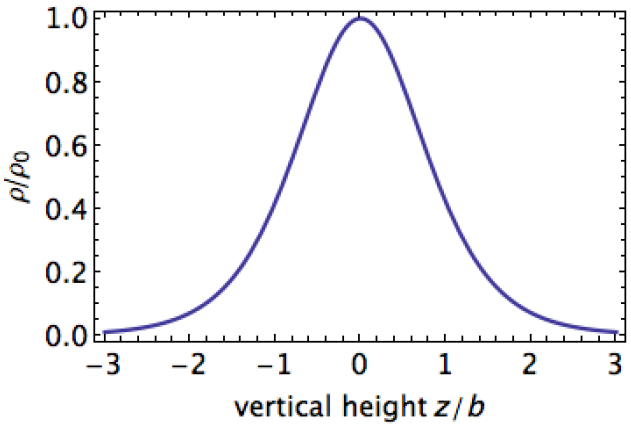
CR feedback in the multi-phase interstellar medium

Explore how CR transport impacts on galactic outflows – stratified box simulations



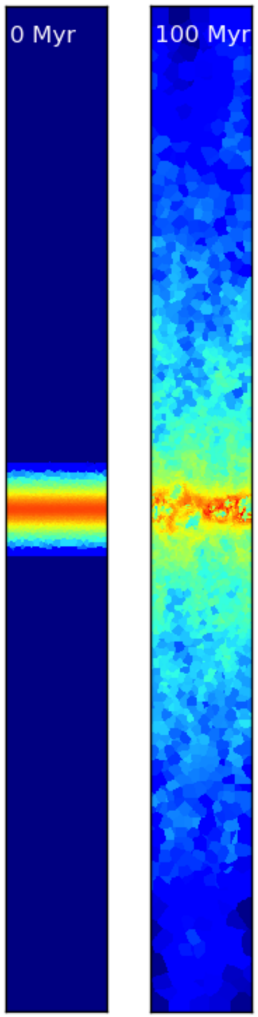
- isothermal disk with $T_0 = 10^4$ K
- hydrostatic equilibrium:

$$f_g \nabla^2 \Phi = 4\pi G \rho$$



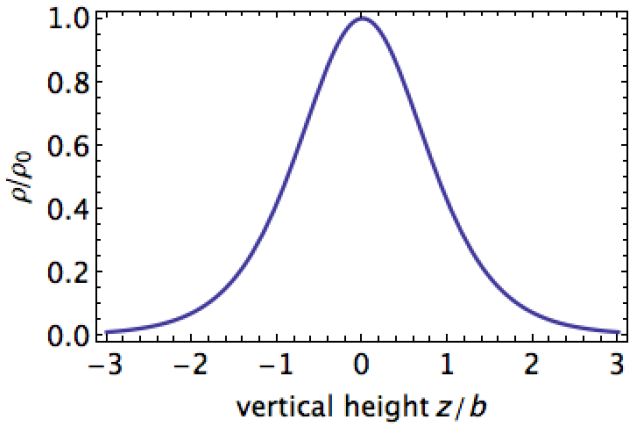
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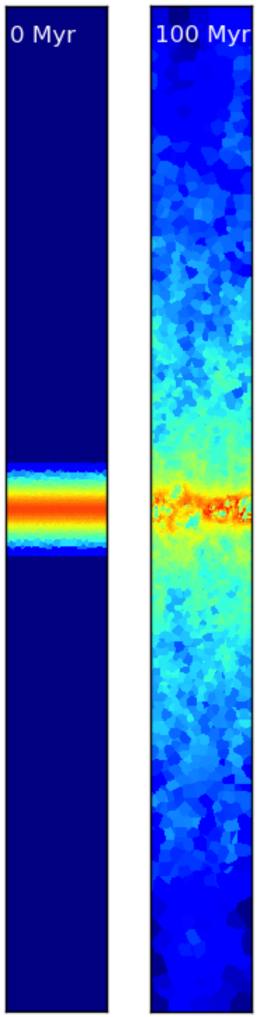


- self-gravity; turbulent stirring for 50 Myrs
- CRISP framework with non-equilibrium chemistry (Thomas, CP, Pakmor 2014)
- attenuated FUV stellar radiation field
- MHD with small magnetic seed field (Pakmor+ 2011)
- cosmic ray physics (Thomas & CP 2019, Thomas+ 2021)



CR feedback in the multi-phase interstellar medium

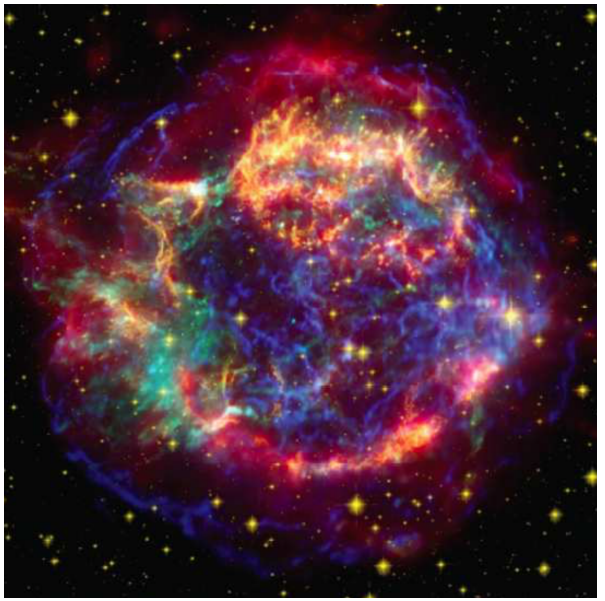
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- supernova rate:

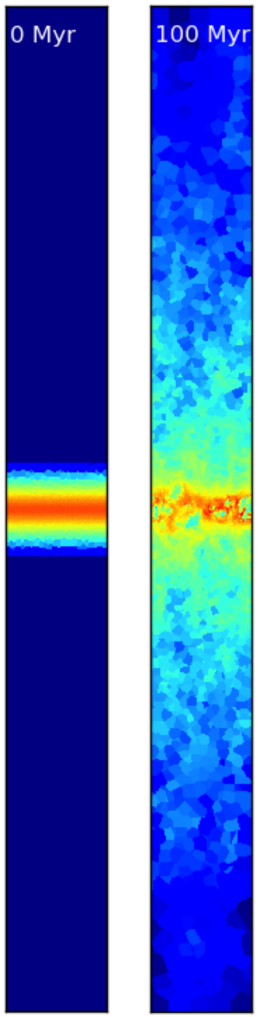
$$\dot{M}_{\mathrm{SN},i} = \dot{M}_{\star,i} \frac{1 \text{ event}}{100 \text{ M}_\odot}$$

- CR-to-thermal energy injection rate = 5 %



CR feedback in the multi-phase interstellar medium

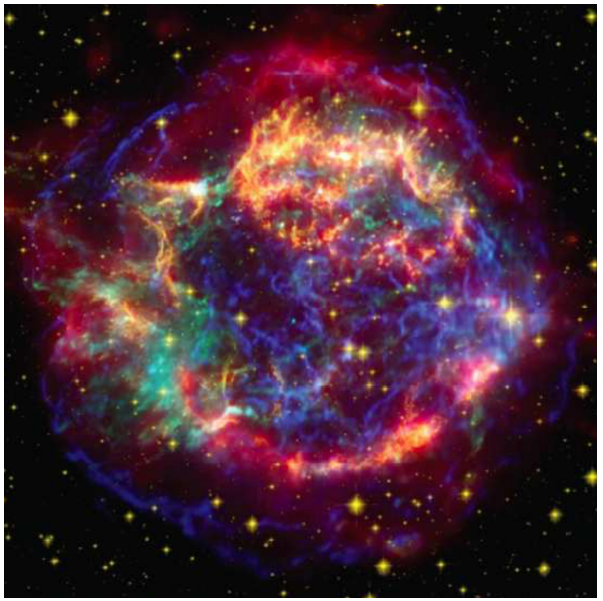
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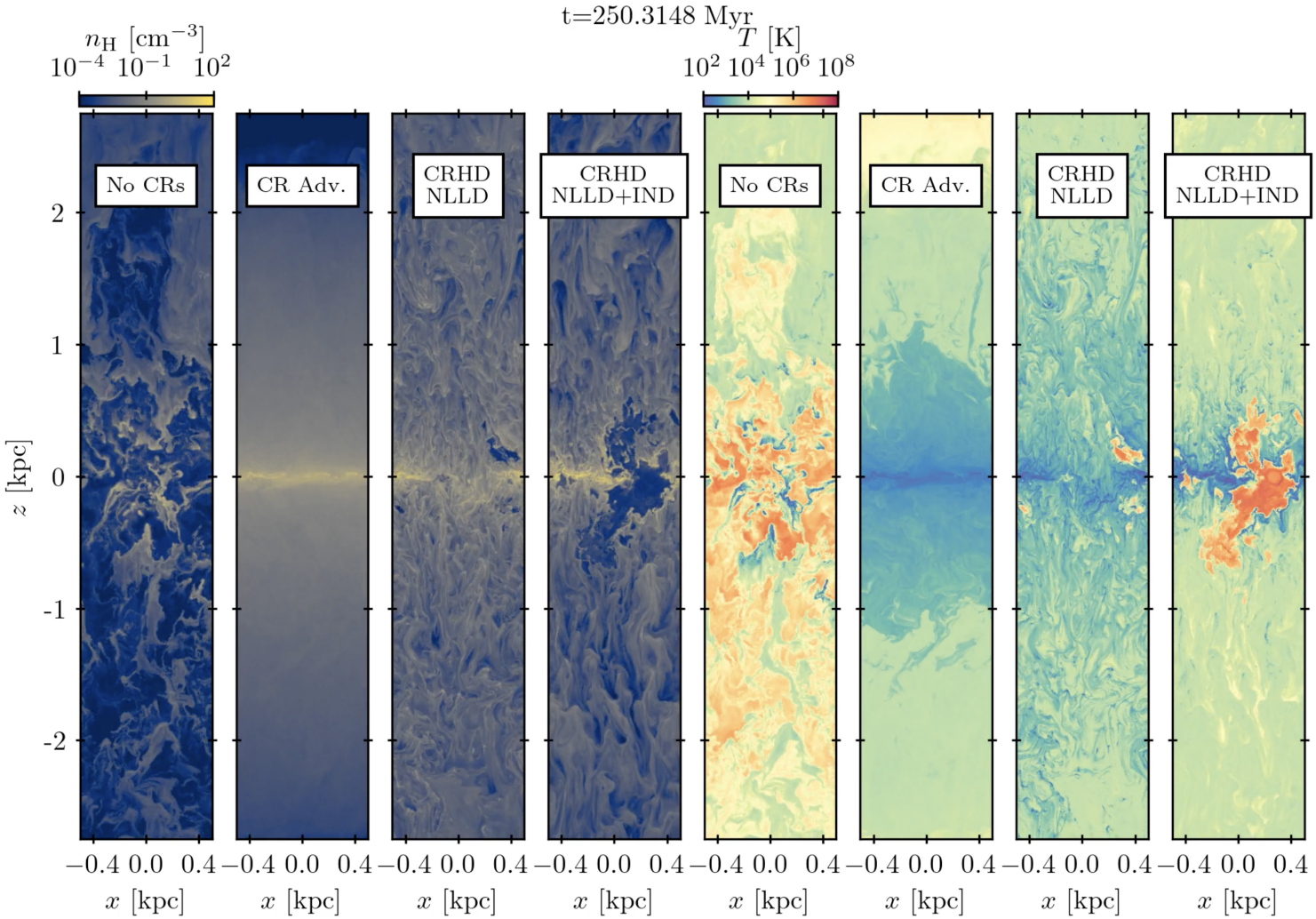
- CR-to-thermal energy injection rate = 5 %
- comparing 4 models:
  - pure MHD
  - CR advection
  - CR transport with non-linear Landau (NL) damping (strong CR coupling)
  - CR transport with NL and ion-neutral damping (weak CR coupling in dense ISM)



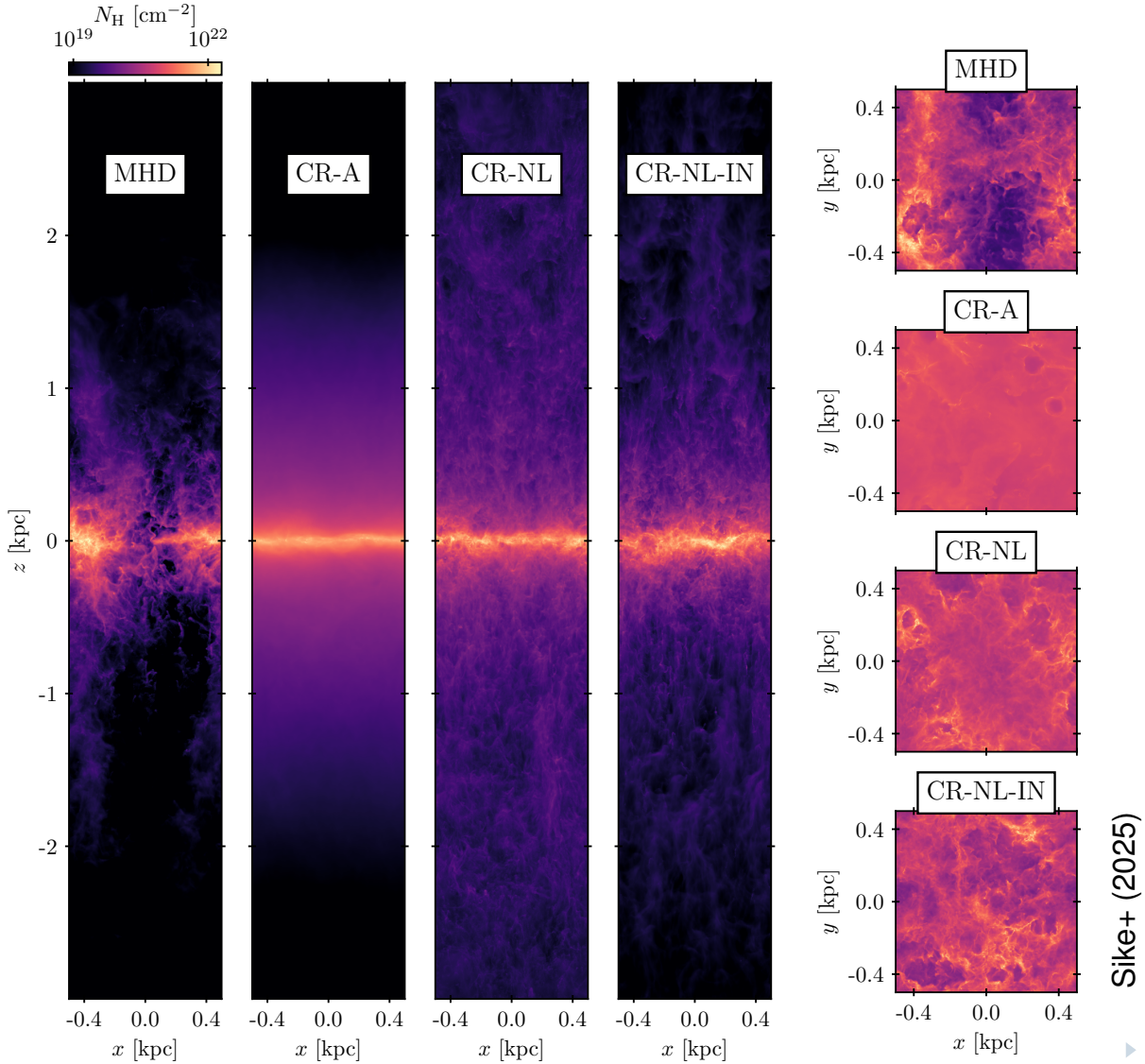
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ISM tallbox: density and temperature

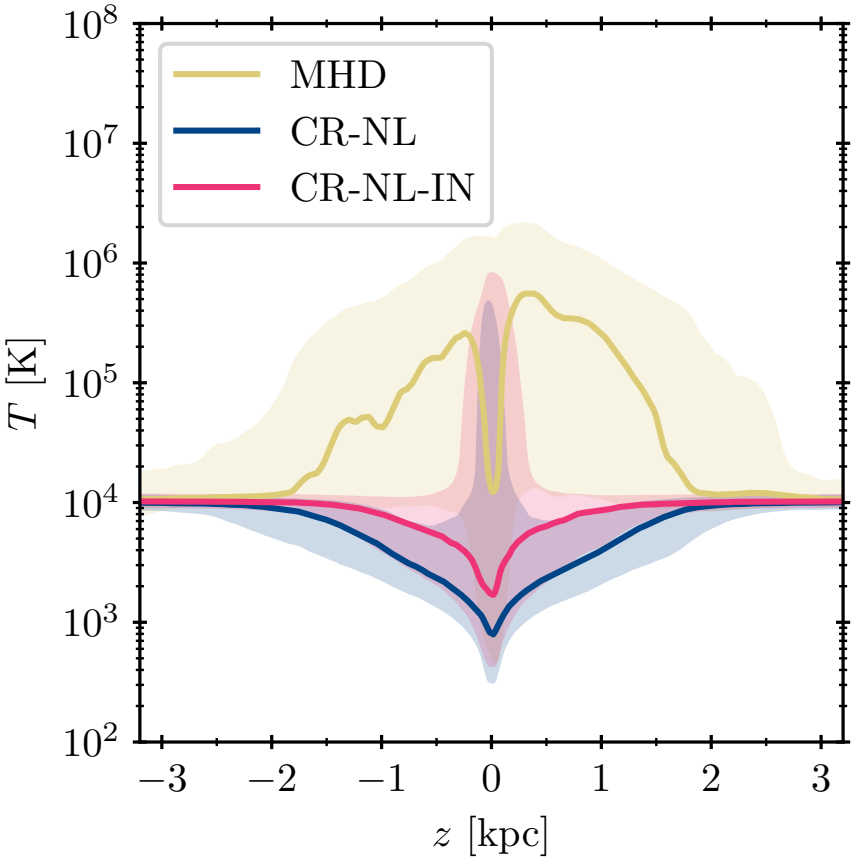
Comparing models: MHD, CR advection, full CR transport (different wave damping)



ISM column densities



Characteristics of supernovae- vs. CR-driven winds

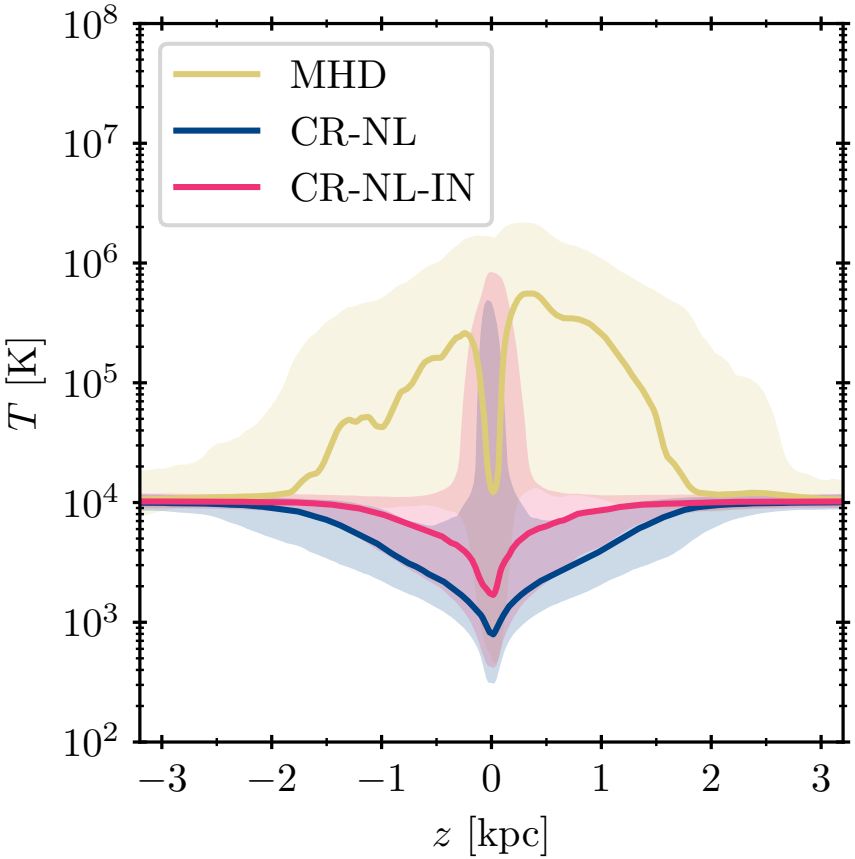


Sike+ (2025)

- MHD: thermal/kinetic pressure from SNe mainly propell galactic fountains that self-regulate the ISM
- CRs drive colder and denser galactic winds

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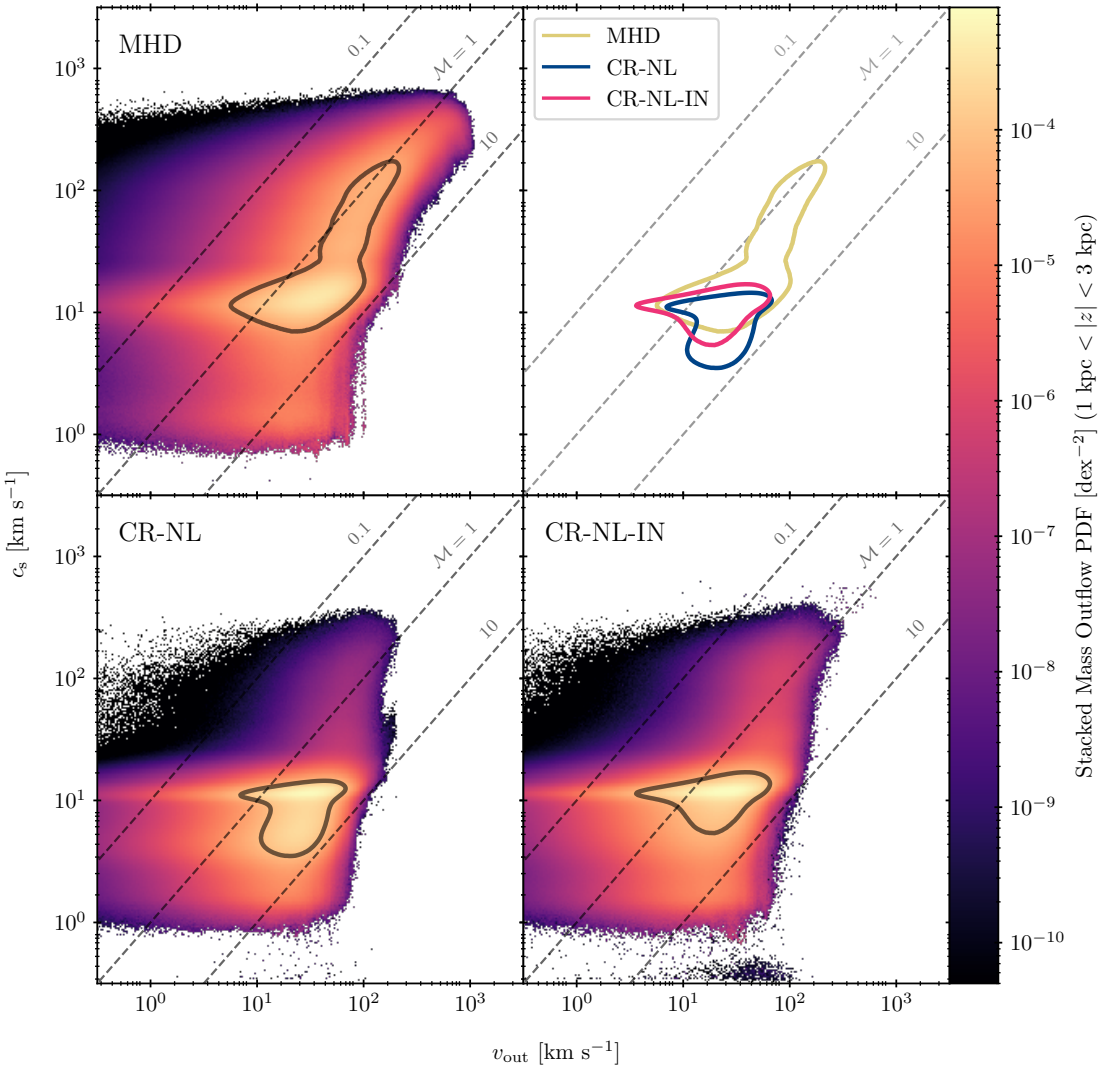


Sike+ (2025)

- MHD: thermal/kinetic pressure from SNe mainly propell galactic fountains that self-regulate the ISM
- CRs drive colder and denser galactic winds
- weak non-linear Landau (NL) damping tightly couples CRs to the ambient plasma
  $\Rightarrow$ strong CR driven winds
- NL and strong ion-neutral damping decouple CRs in the cold and warm ISM
  $\Rightarrow$ weaker winds

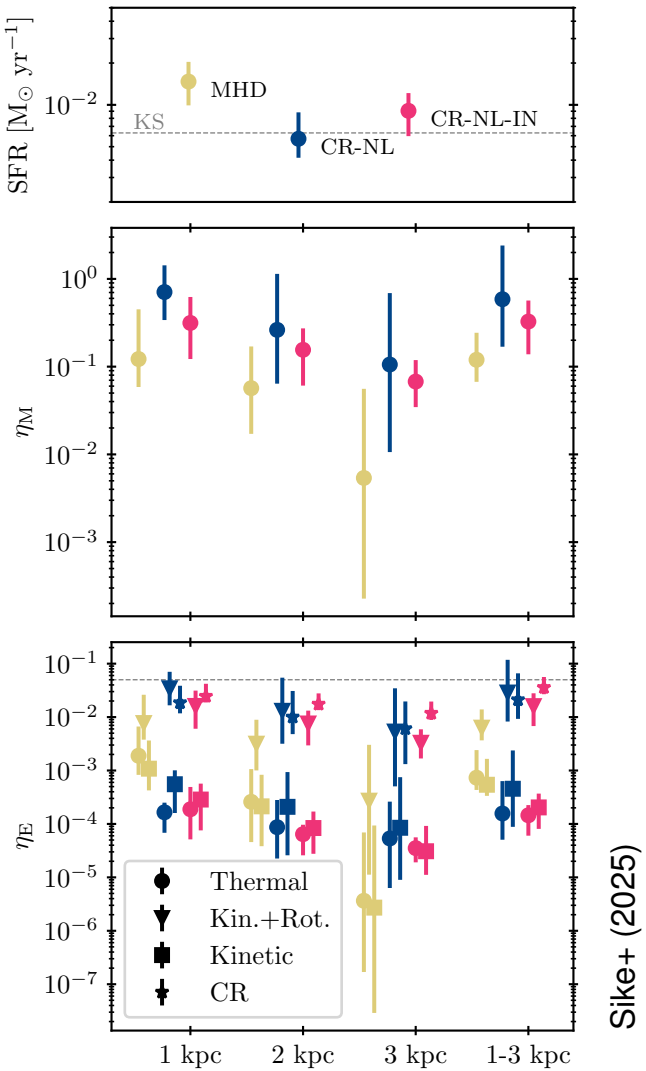
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Phase structure of outflowing material



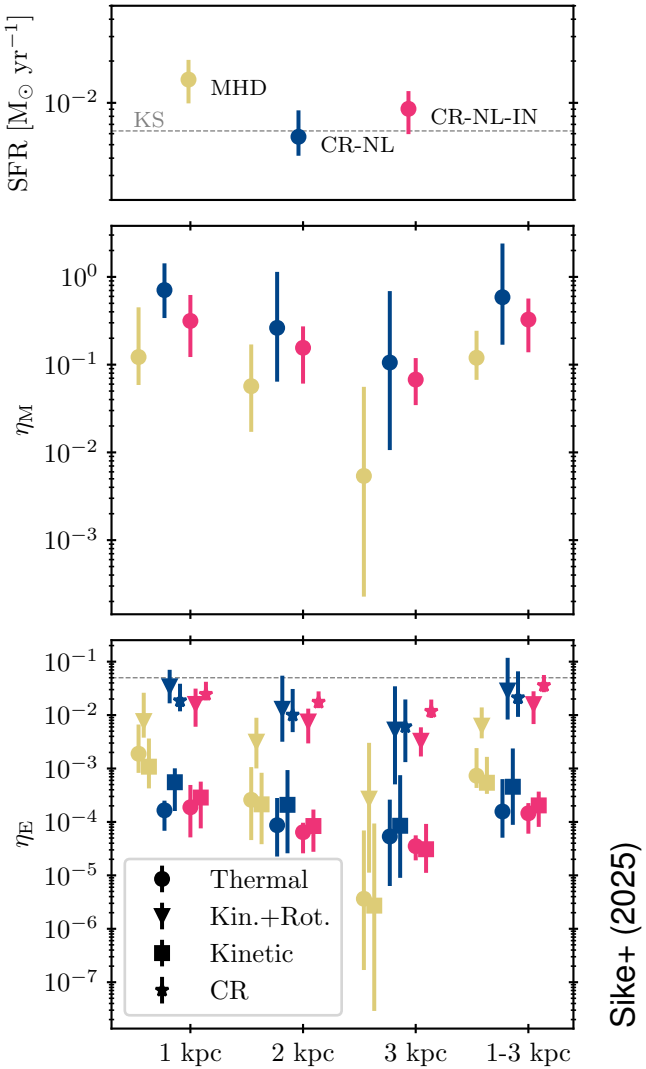
Sike+ (2025)

Mass and energy loading factors



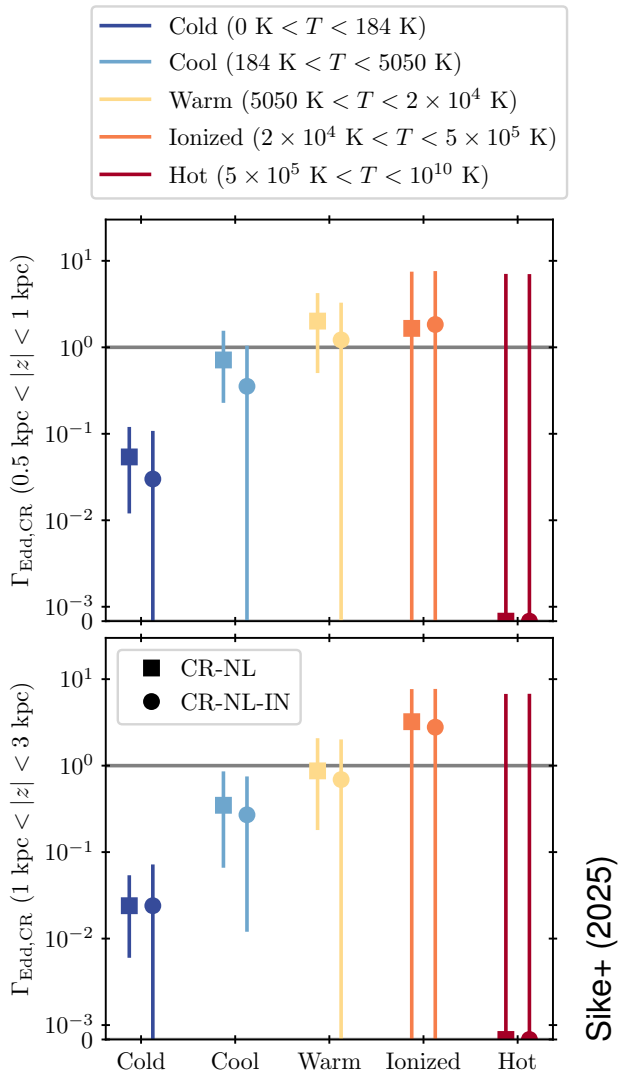
- MHD fountains self-regulate the ISM: mass/energy loading factors decrease steeply with height
- CR-driven mass loading factors 3-5 time larger than MHD case

Mass and energy loading factors



- MHD fountains self-regulate the ISM: mass/energy loading factors decrease steeply with height
- CR-driven mass loading factors 3-5 time larger than MHD case
- most of CR energy transported to the wind while other energy forms are quickly dissipated
- CR energy loading comparable to kinetic energy loading with rotational boost ($\boldsymbol{v}_{\mathrm{kin+rot}} = \boldsymbol{v} + \boldsymbol{v}_{\mathrm{rot}}$)

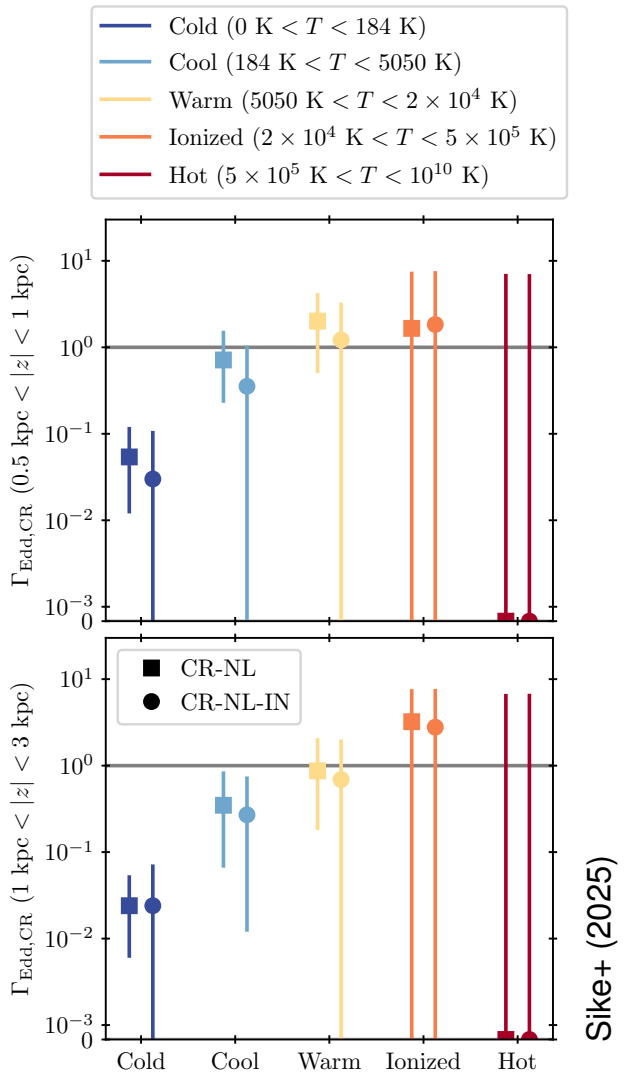
CR Eddington factors for different ISM phases



- CR Eddington factors:

$$\Gamma_{\mathrm{Edd,CR}} \equiv -\frac{a_{\mathrm{CR},z}}{a_{\mathrm{grav}}}, \qquad a_{\mathrm{CR},z} = \frac{\nabla P_{\mathrm{CR}} \cdot \boldsymbol{e}_z}{\rho}$$

CR Eddington factors for different ISM phases

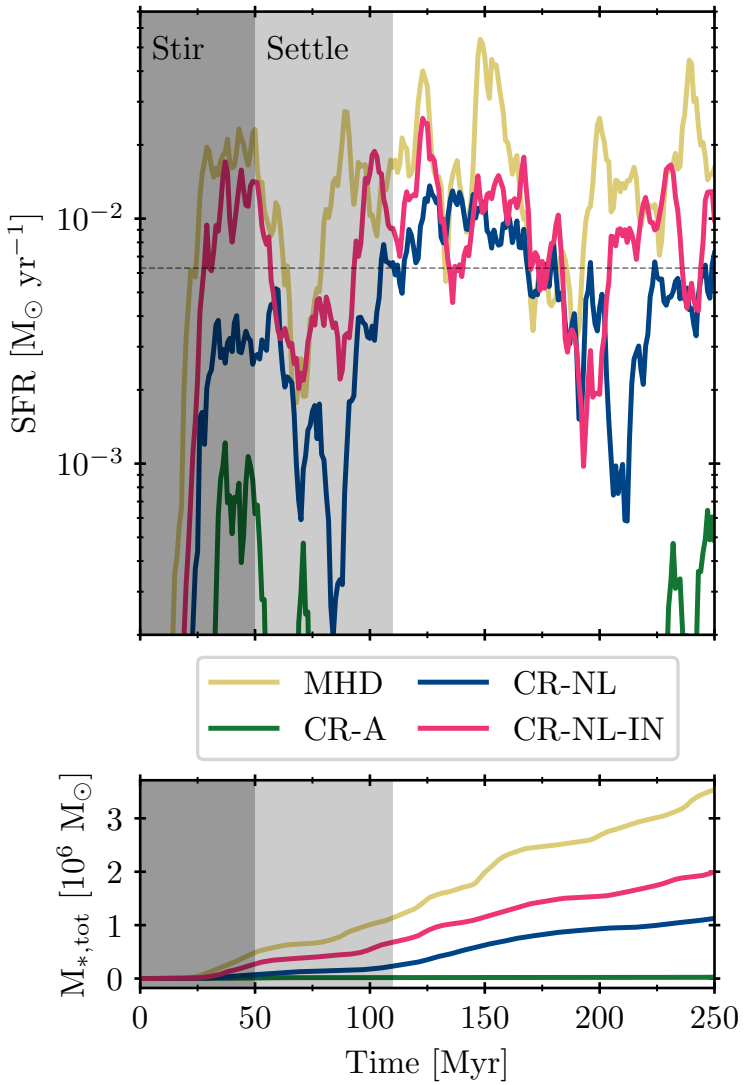


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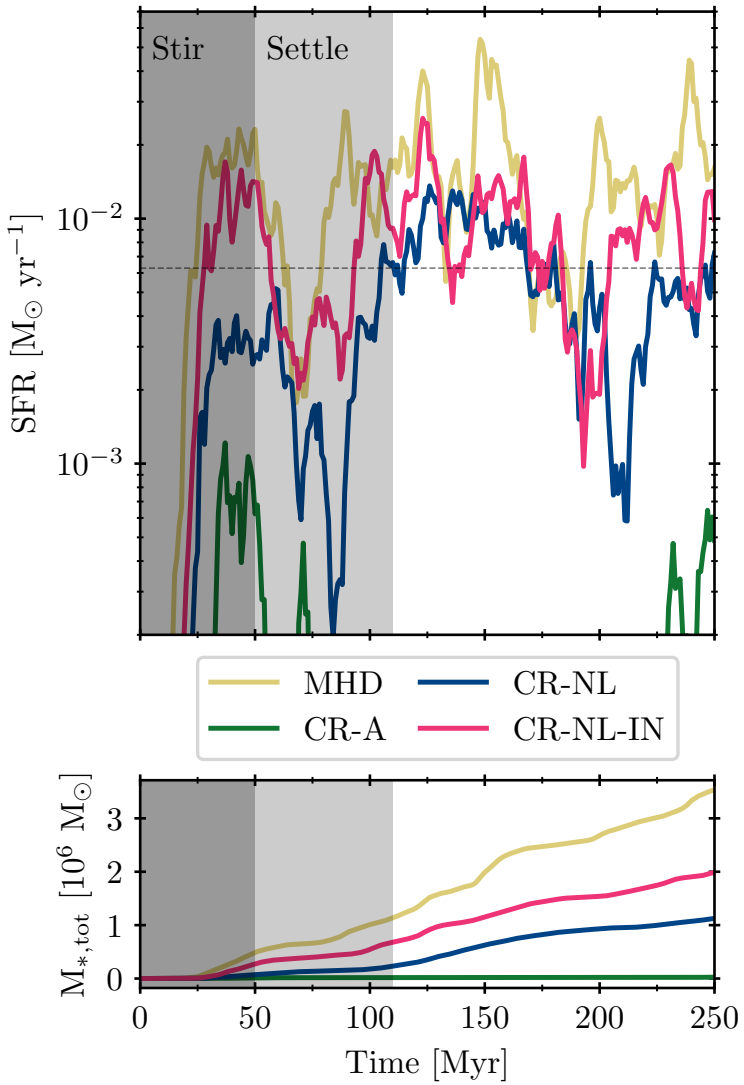
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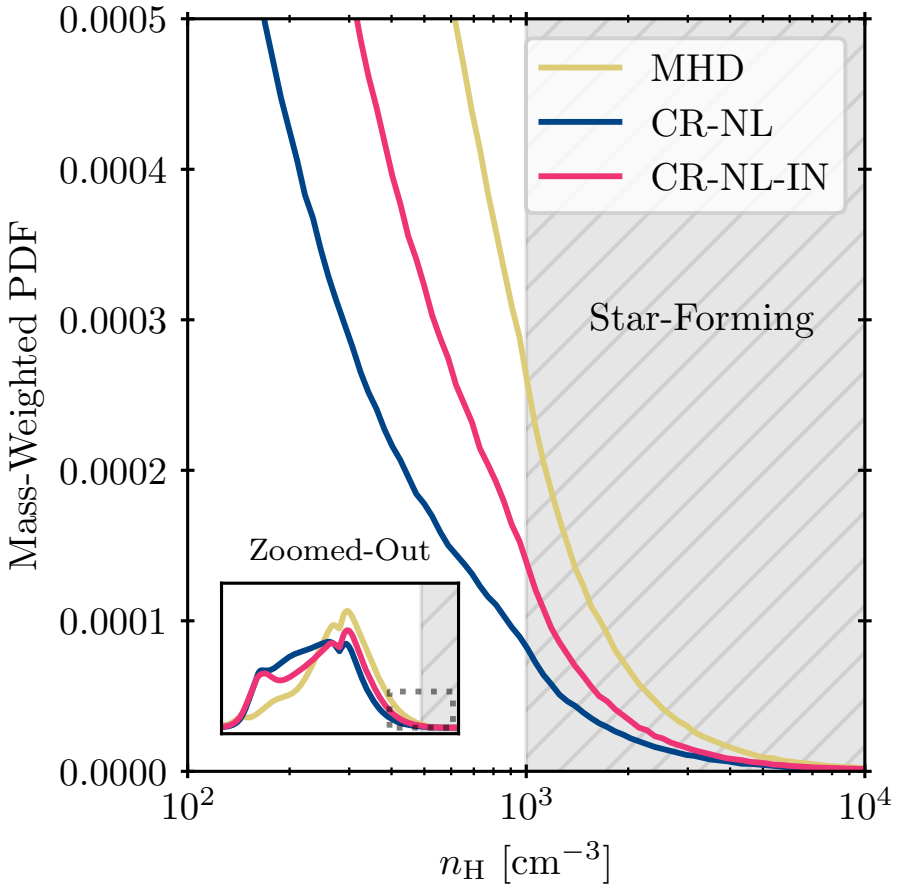
- CRs supply no momentum to the hot phase
- CRs accelerate warm and ionized gas to launch a wind
- CRs support the cool and cold phases against freefall but do not actively drive them out

CR feedback mildly suppresses star formation



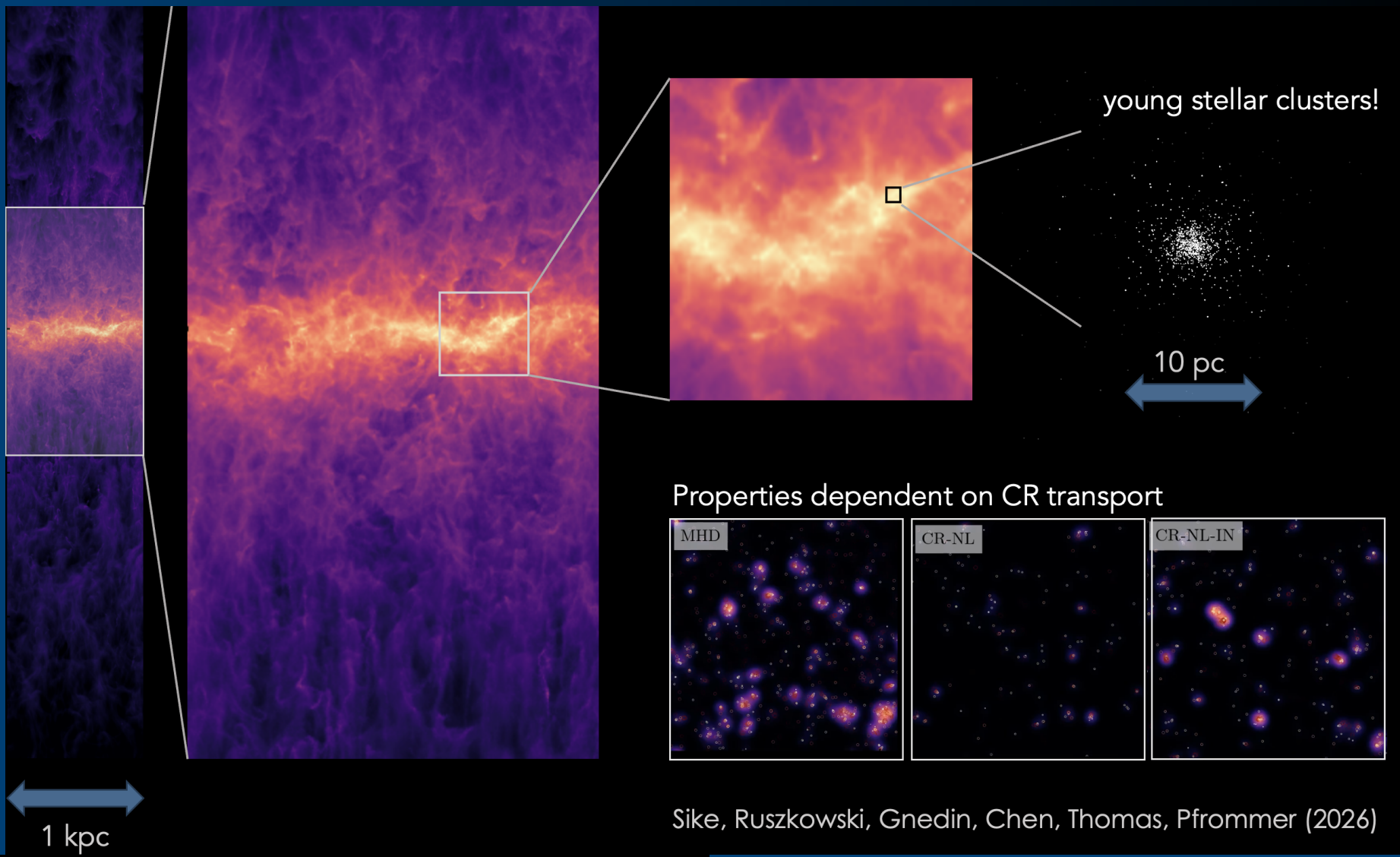
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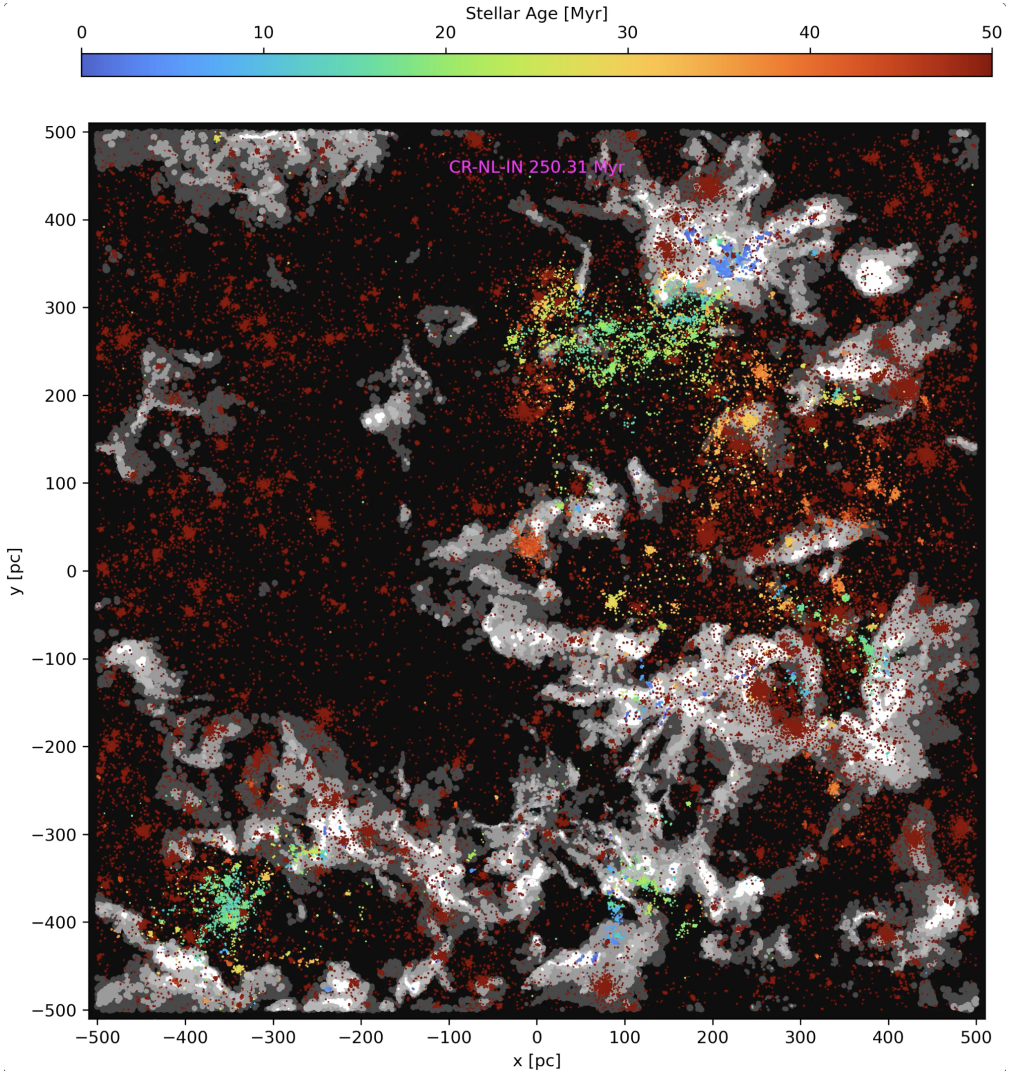
Sike+ (2025)

Molecular cloud and star cluster formation

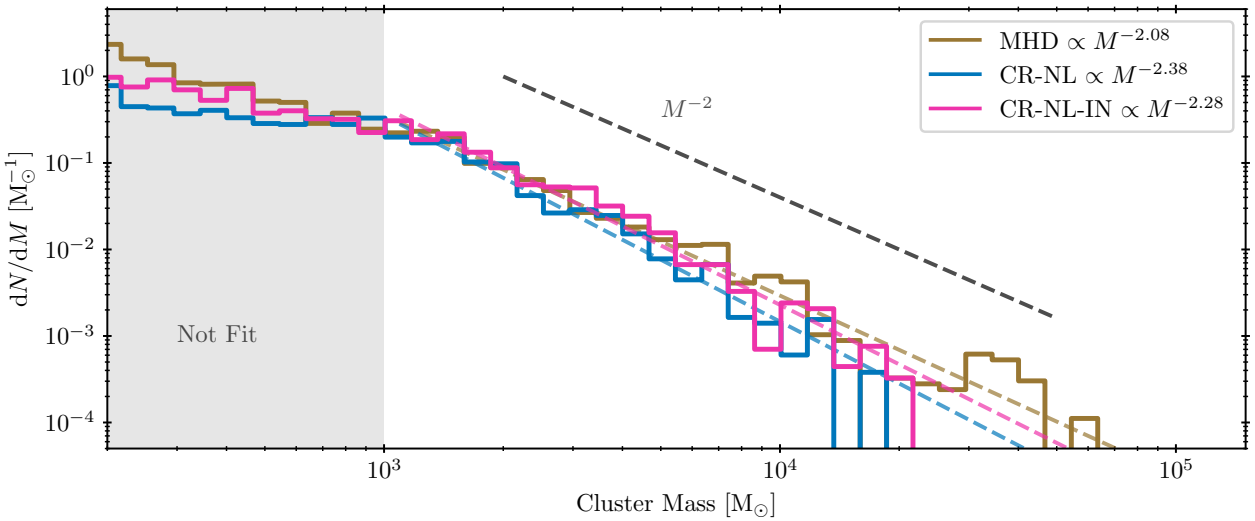


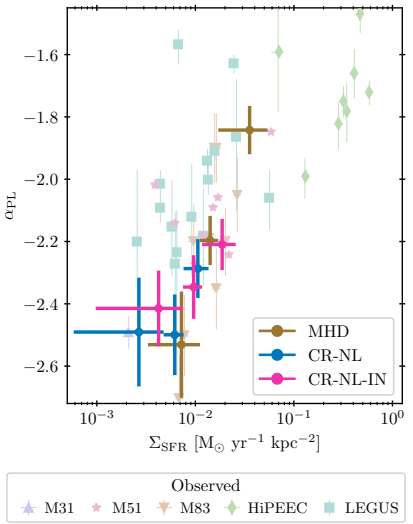
Sike, Ruszkowski, Gnedin, Chen, Thomas, Pfrommer (2026)

Molecular cloud and star cluster formation



Star cluster mass function





Sike+ (2026)

- star cluster mass function of young clusters similar for all models
- power-law slope agrees with observational data

Conclusions

CR feedback in the multi-phase ISM:

- CRISP models multiphase ISM with full CR physics
- CR feedback mildly suppresses star formation because of strong ion-neutral damping in disk, which weakens CR coupling
- CR feedback drives powerful galactic winds
- CR feedback increases mass and energy loading factors
- young star cluster mass function consistent with observations



PICOGAL: From Plasma KInetics to COsmological GALaxy Formation



This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No PICOGAL–101019746).

AIP

Literature for the talk

CR feedback in galaxy formation and the ISM:

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