Cosmic rays in the Milky Way: transport, feedback and observations

Christoph Pfrommer[1]

in collaboration with

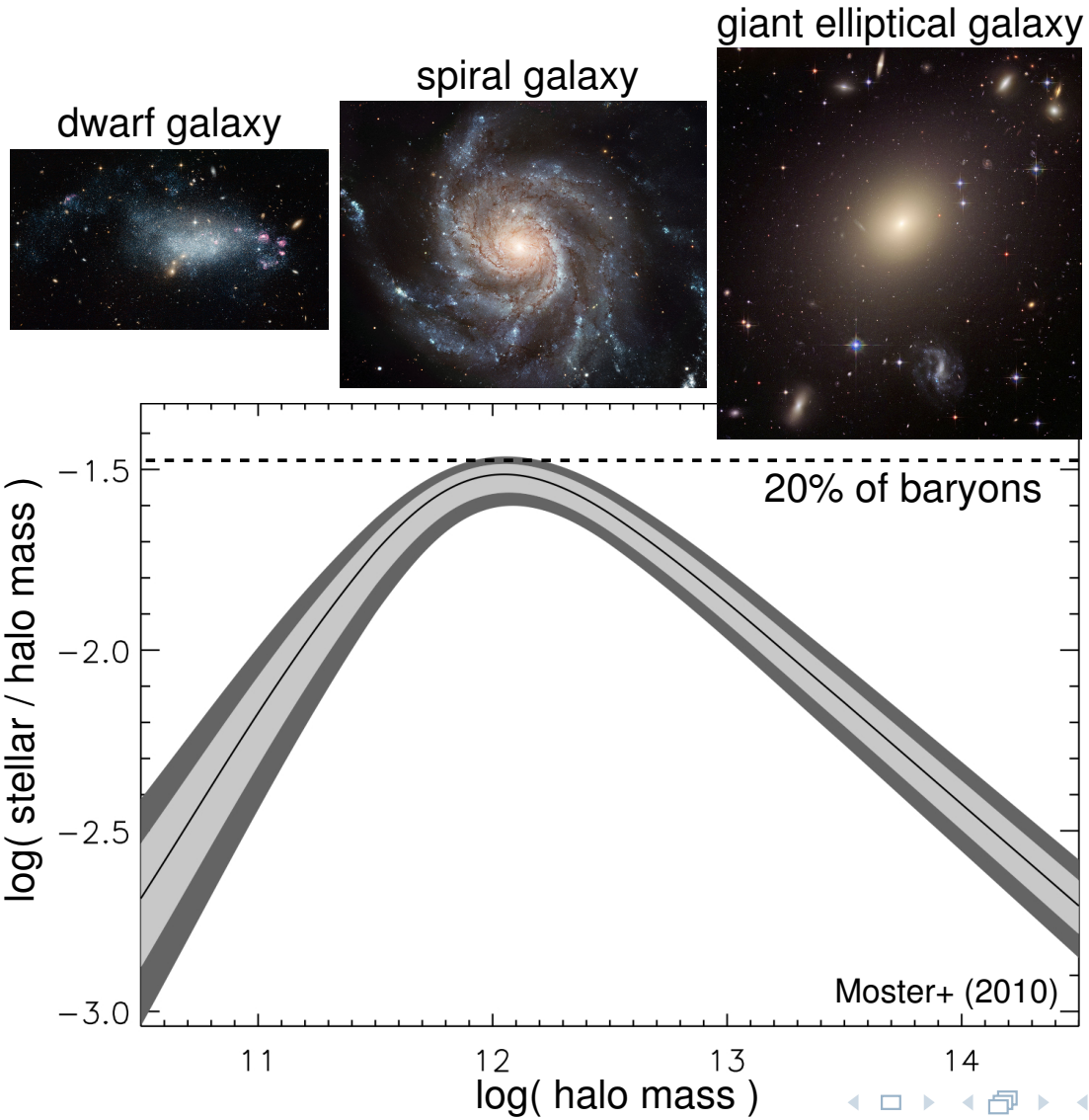
PhD students: Dusch,[1] Jlassi,[1] Kalangadan,[1] Pisharody,[1] Tevlin,[1] Weber,[1] Chiu,[2] **Sike**[2]
Postdocs: Berlok,[3] Girichidis,[4] **Lemmerz,**[5] Meenakshi,[1] Perrone,[1] Shalaby,[6] **Thomas,**[1] Werhahn,[7] Whittingham[1]
Faculty: Pakmor,[7] Puchwein,[1] Weinberger,[1] Ruszkowski,[2]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

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

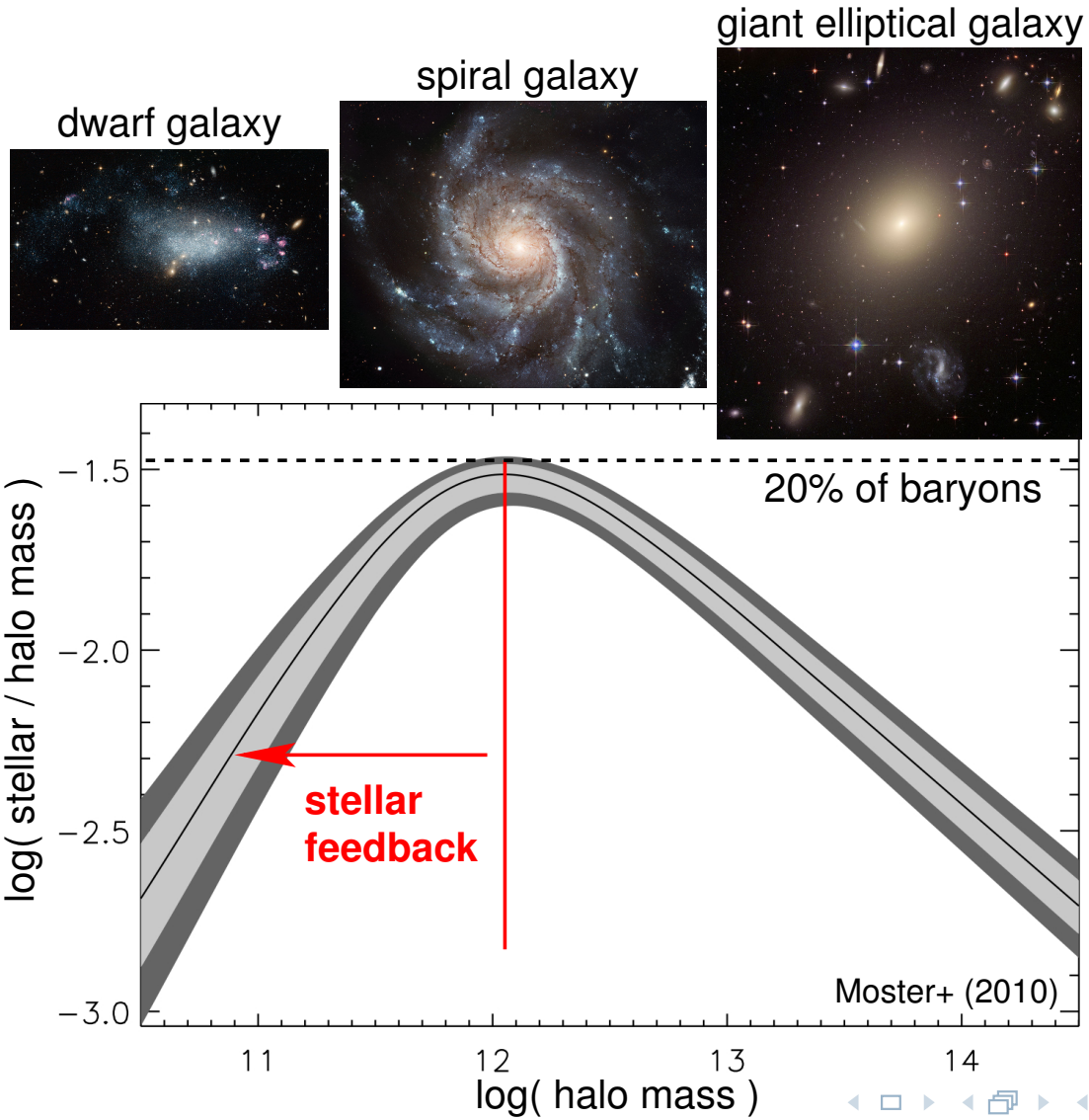
MW-Atlas meeting, Aachen, August 2026



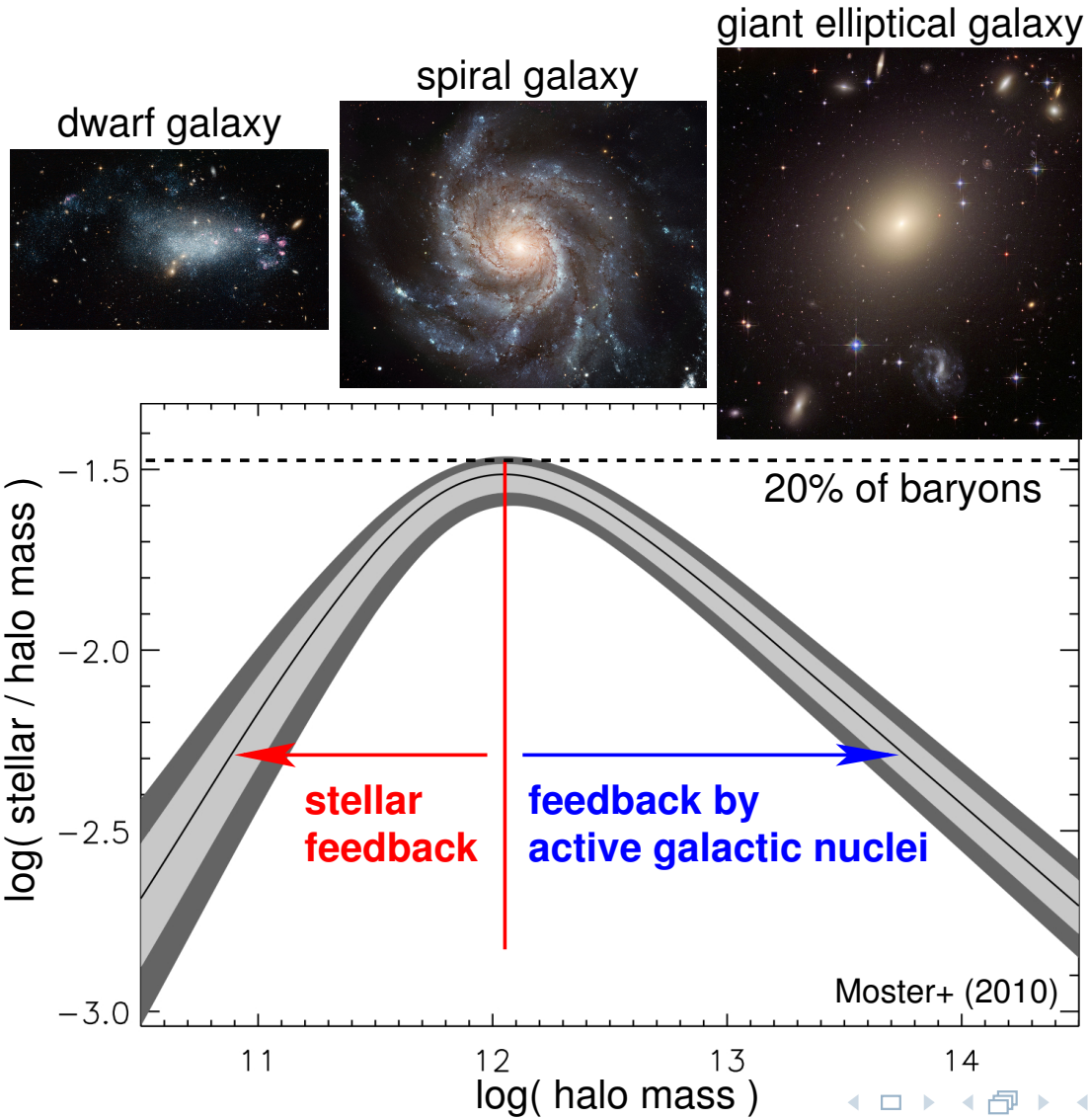
Puzzles in galaxy formation



Puzzles in galaxy formation



Puzzles in galaxy formation



How does stellar feedback drive galactic winds?



super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

- thermal pressure provided by supernovae or active galactic nuclei?
- radiation pressure and photoionization by massive stars and quasars?
- pressure of cosmic rays (CRs) that are accelerated at supernova shocks?

AIP

How does stellar feedback drive galactic winds?



super wind in M82

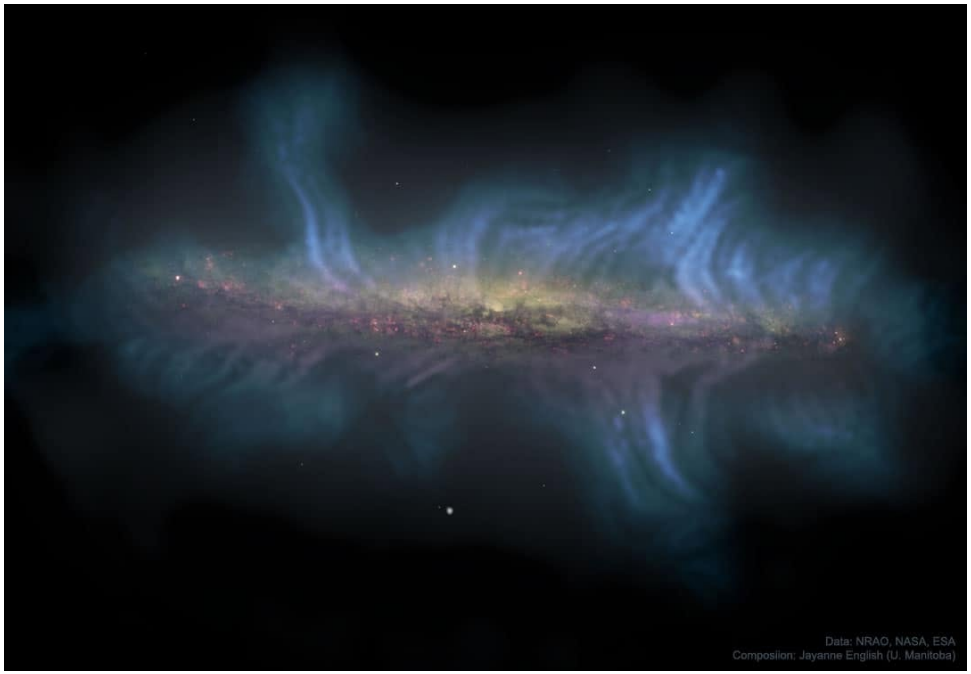
NASA/JPL-Caltech/STScI/CXC/UofA

- thermal pressure provided by supernovae or active galactic nuclei?
- radiation pressure and photoionization by massive stars and quasars?
- pressure of cosmic rays (CRs) that are accelerated at supernova shocks?
- energy density of CRs, magnetic fields, and ISM turbulence all similar
  $\Rightarrow$ important feedback agent

AIP

Why can cosmic rays drive galactic winds?

Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface



NRAO/NASA/ESA/Hubble/English

- escape of CRs into halo due to open field lines at wind launching site
- CR pressure drops less quickly than thermal pressure ($P_{\rm cr} \propto \rho^{4/3}$)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind $\rightarrow$ "CR battery"



Review on cosmic ray feedback

Astron Astrophys Rev (2023) 31:4
https://doi.org/10.1007/s00159-023-00149-2

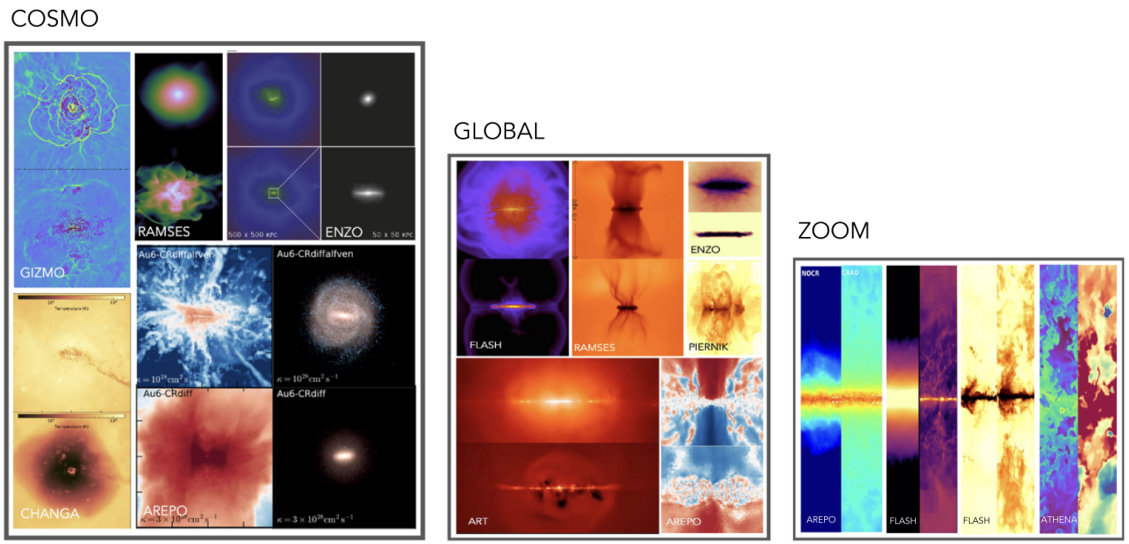
REVIEW ARTICLE

Check for updates

Cosmic ray feedback in galaxies and galaxy clusters

A pedagogical introduction and a topical review of the acceleration, transport, observables, and dynamical impact of cosmic rays

Mateusz Ruszkowski[1,3] · **Christoph Pfrommer**[2]

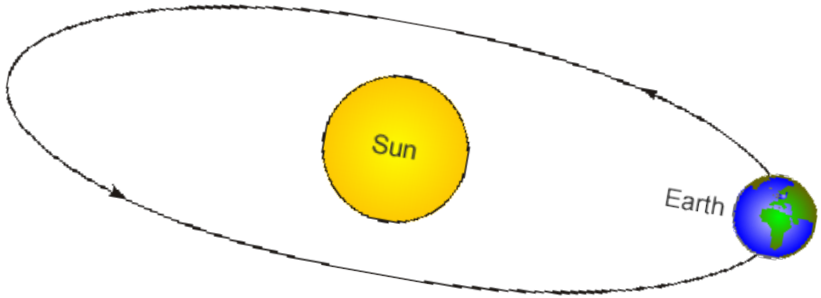


Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

$$r_{\mathrm{gal}} \sim 10^4 \text{ pc}$$



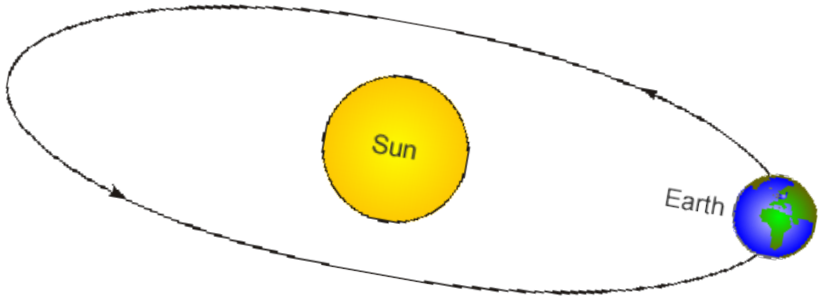
gyro-orbit of GeV CR:

$$r_{\mathrm{cr}} = \frac{p_\perp}{e\,B_{\mu\mathrm{G}}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

AIP

Cosmic ray transport: an extreme multi-scale problem





Milky Way-like galaxy:

$$r_{\mathrm{gal}} \sim 10^4 \text{ pc}$$

gyro-orbit of GeV CR:

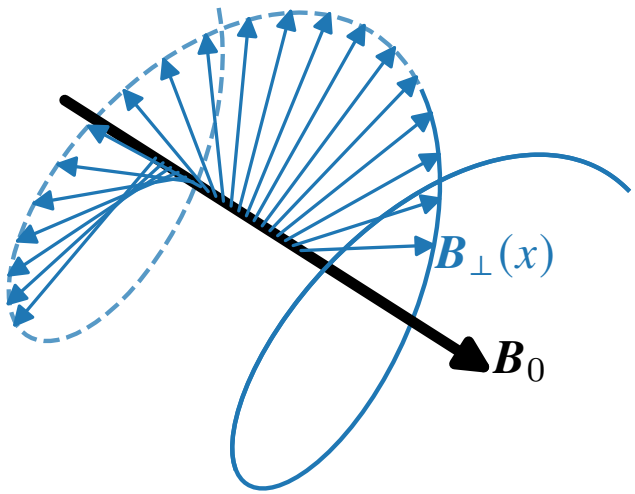
$$r_{\mathrm{cr}} = \frac{p_\perp}{e\,B_{\mu\mathrm{G}}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

$\Rightarrow$ **link kinetic plasma physics to macroscopic MHD models on galactic scales!**

Zweibel (2017), Thomas & CP (2019)

What is gyro resonance?

plane wave: $\exp(-\mathrm{i}k(x - v_{\mathrm{wave}}t))$

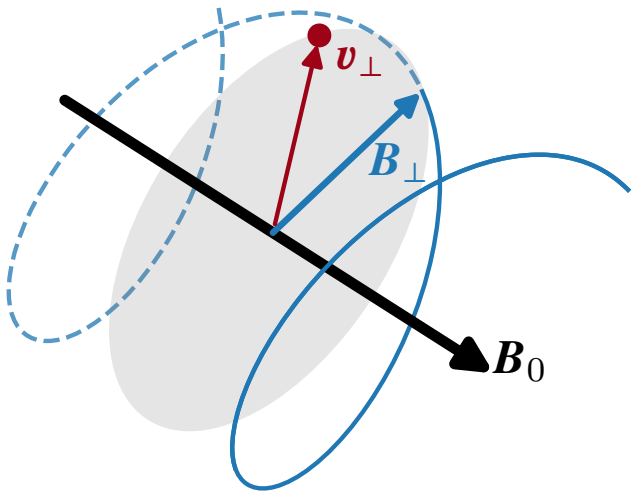


What is gyro resonance?

plane wave: $\exp(-\mathrm{i}k(x - v_{\mathrm{wave}}t))$

cosmic ray: $v_{||}$ movement along $\boldsymbol{B}_0$

Ω_{cr} gyration frequency



What is gyro resonance?

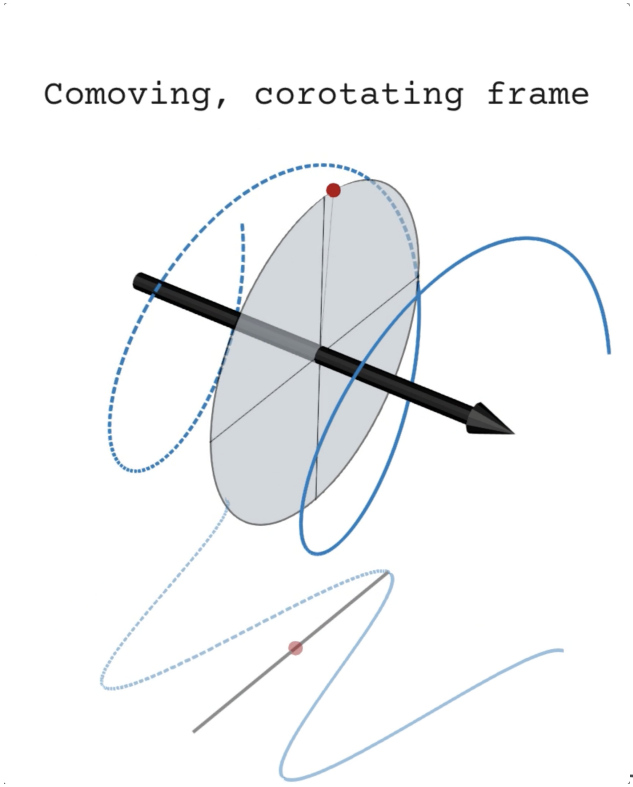
plane wave: $\exp(-ik(x - v_{\text{wave}}t))$

cosmic ray: $v_{\parallel}$ movement along $\boldsymbol{B}_0$

Ω_{cr} gyration frequency

resonance condition:

$$\overbrace{\Omega_{\text{cr}}}^{\text{gyration}} + \overbrace{kv_{\parallel}}^{\text{Doppler shift}} = \overbrace{kv_{\text{wave}}}^{\text{wave frequency}}$$



What is gyro resonance?

plane wave: $\exp(-ik(x - v_{\text{wave}}t))$

cosmic ray: $v_{\parallel}$ movement along $\boldsymbol{B}_0$

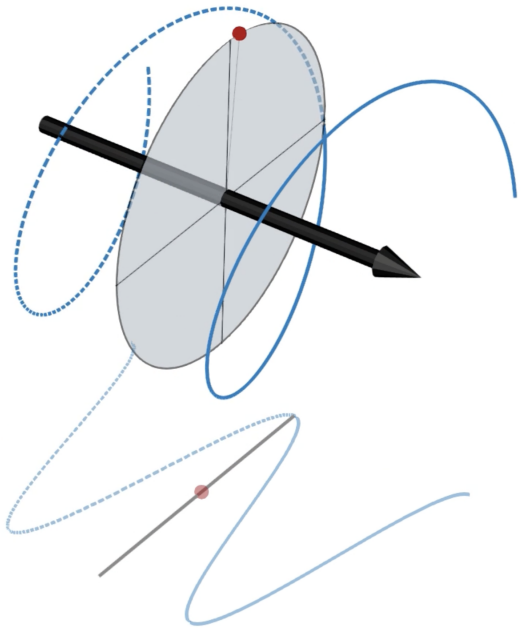
Ω_{cr} gyration frequency

resonance condition:

$$\overbrace{\Omega_{\text{cr}}}^{\text{gyration}} + \overbrace{kv_{\parallel}}^{\text{Doppler shift}} = \overbrace{kv_{\text{wave}}}^{\text{wave frequency}}$$

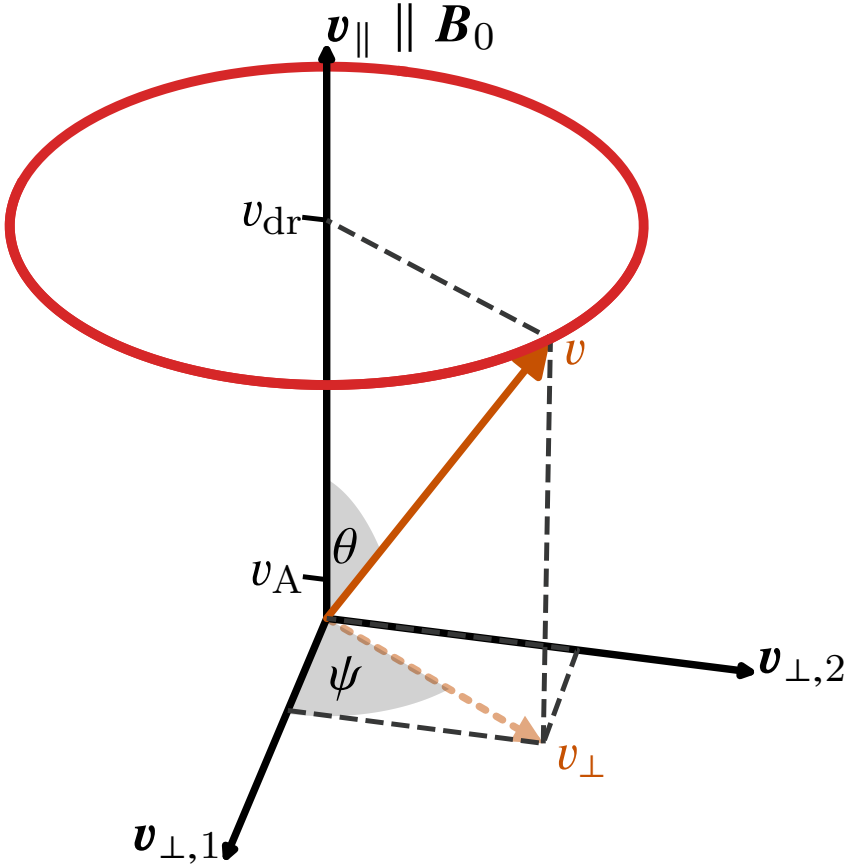
Resonant wave appears **static** to CR!

Comoving, corotating frame



test particle without interactions!

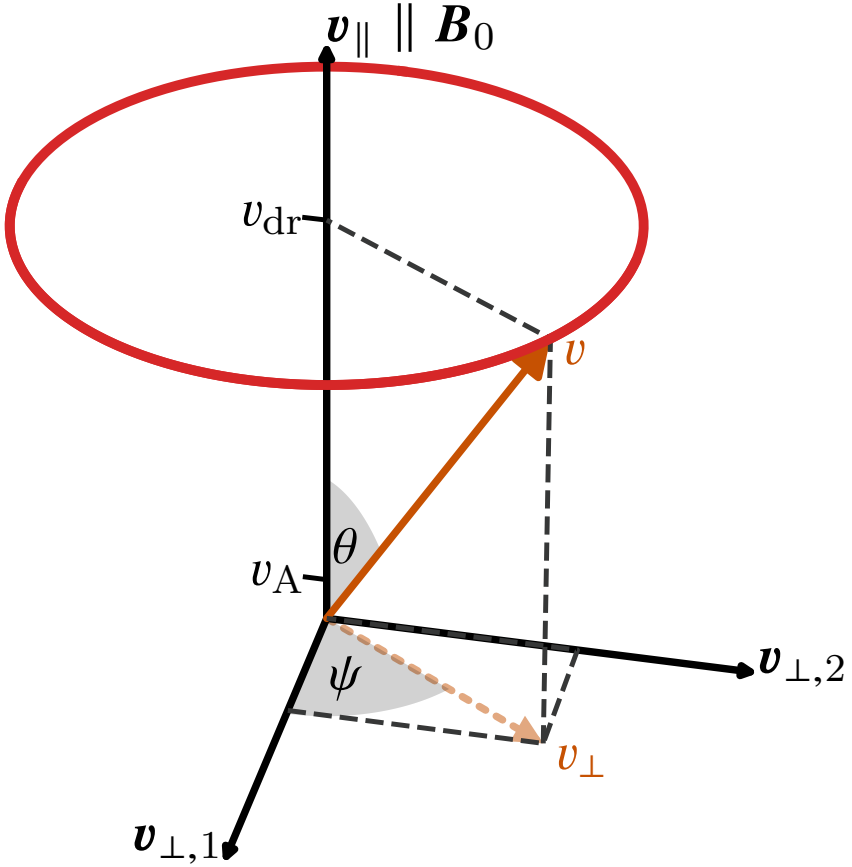
Idealized setup to understand physics



- gyrotropic ring distribution of CR ions with single pitch angle and energy
- neutralizing CR electron beam at same drift speed but $v_\perp = 0$

AIP

Idealized setup to understand physics



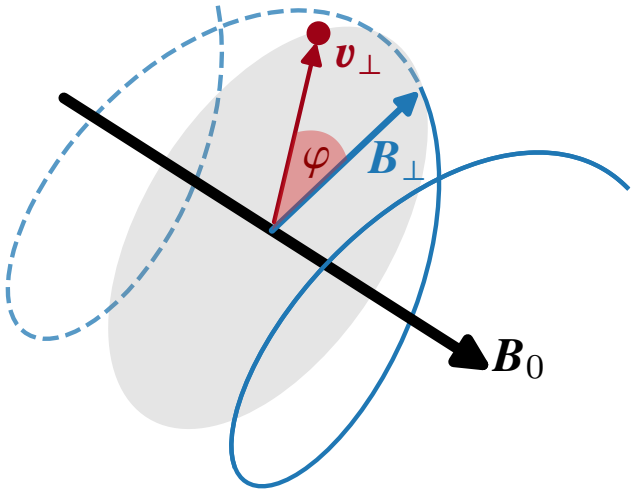
- gyrotropic ring distribution of CR ions with single pitch angle and energy
- neutralizing CR electron beam at same drift speed but $v_\perp = 0$
- background ion and electron fluid with Landau closure
- fluids coupled to particle-in-cell (PIC) CRs via Maxwell's equations

(Lemmerz+ 2024)

AIP

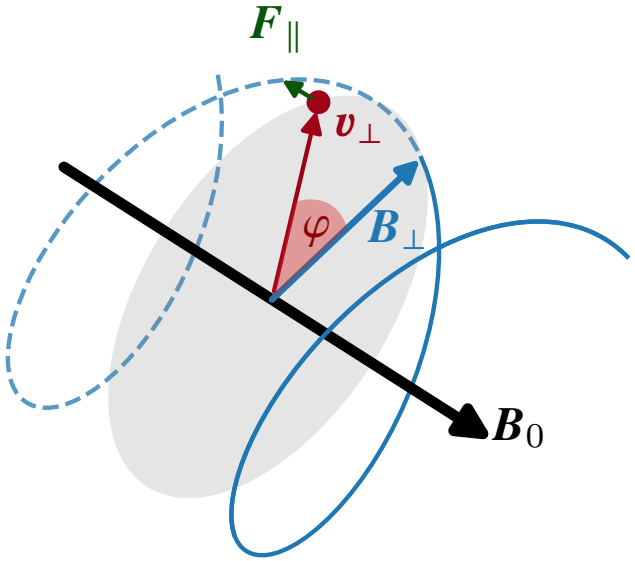
The mechanism of CR-driven instabilities

- ***goal:*** understand collective behaviour of many CRs



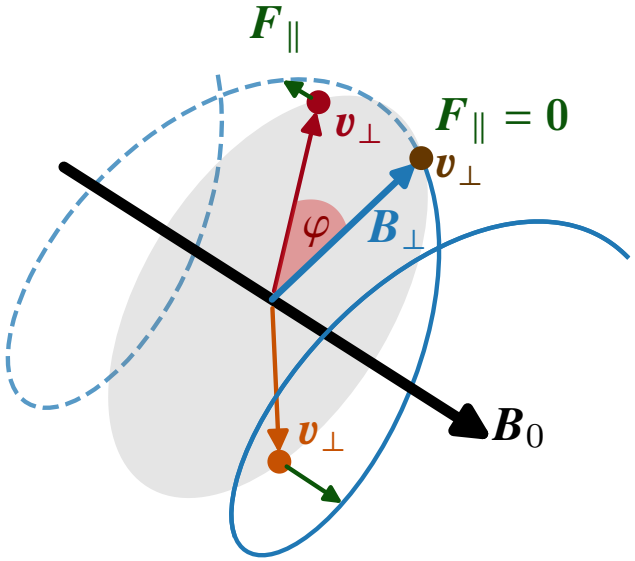
The mechanism of CR-driven instabilities

- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field



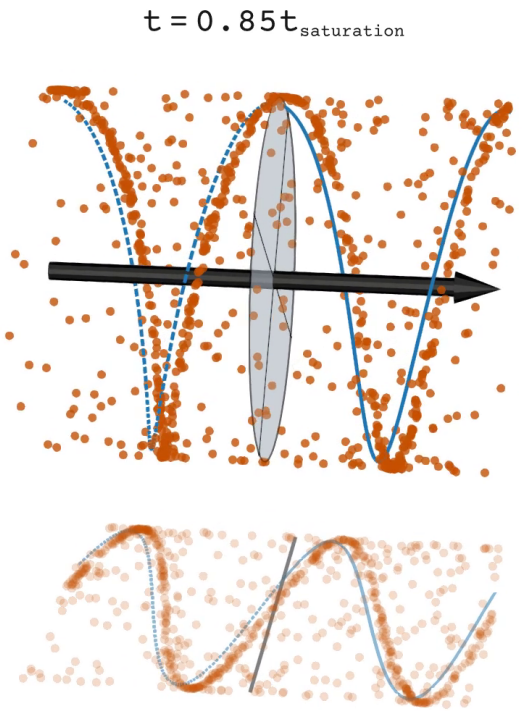
The mechanism of CR-driven instabilities

- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field
- CRs align rotational phase with plasma wave



The mechanism of CR-driven instabilities

- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field
- CRs align rotational phase with plasma wave
- CR current wave interacts with electro-magnetic wave

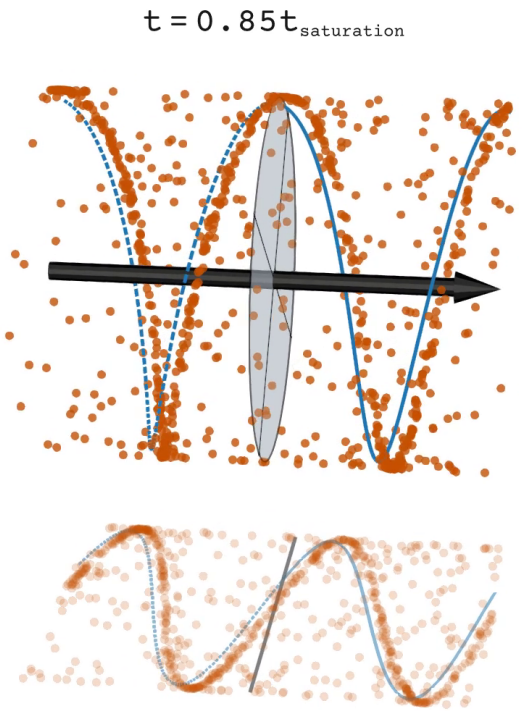


fluid-PIC simulation (Lemmerz+ 2025)

AIP

The mechanism of CR-driven instabilities

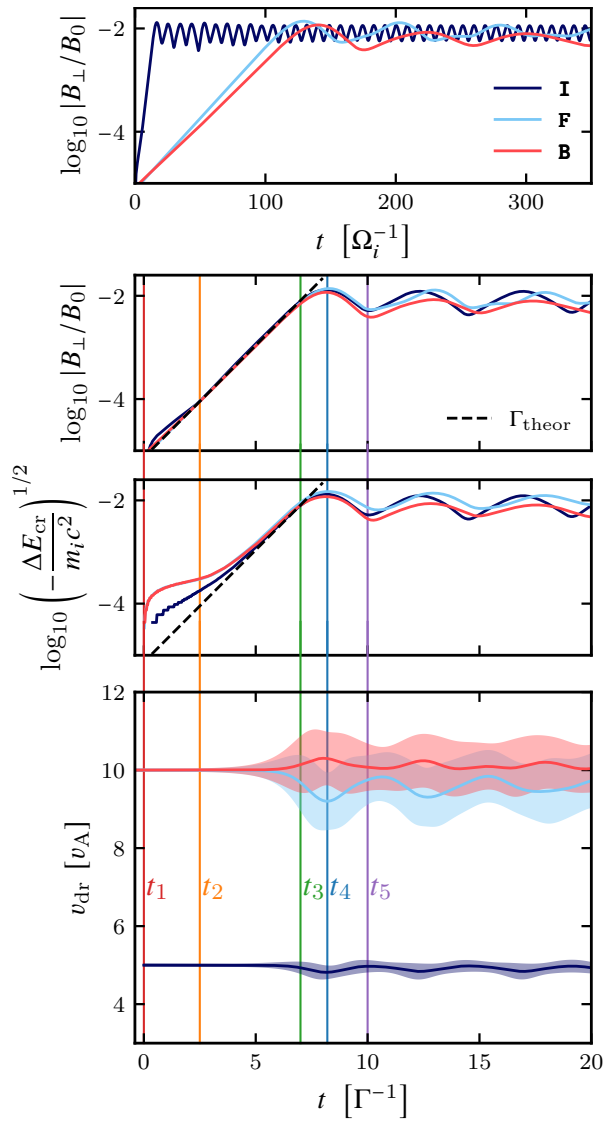
- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field
- CRs align rotational phase with plasma wave
- CR current wave interacts with electro-magnetic wave
- CR trapping in Lorentz force potential saturates instability



fluid-PIC simulation (Lemmerz+ 2025)

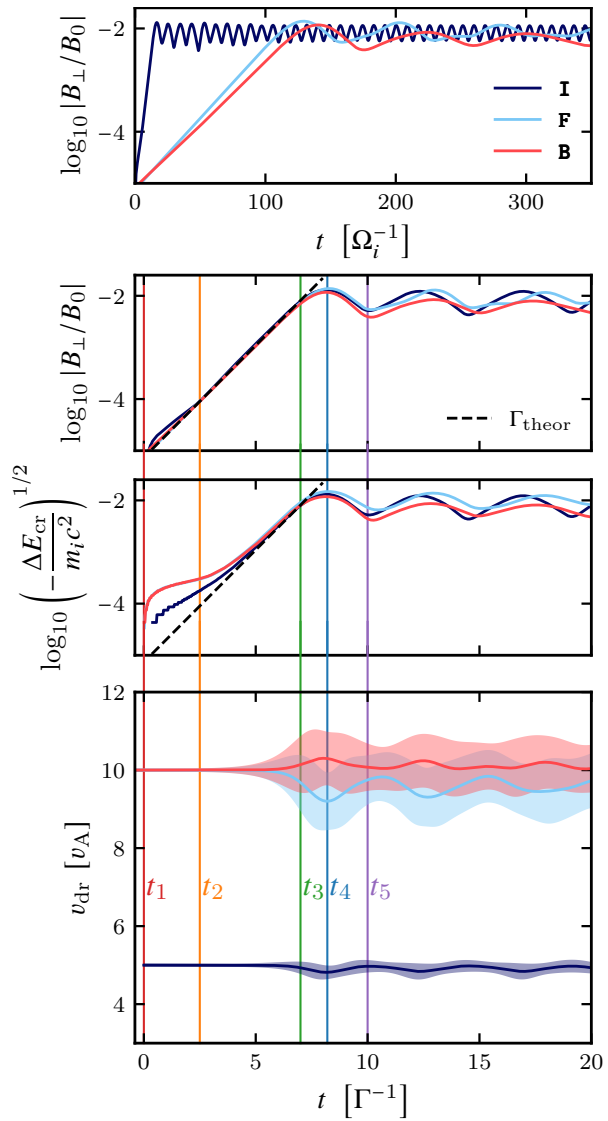
AIP

Resonant wave growth and CR energy loss



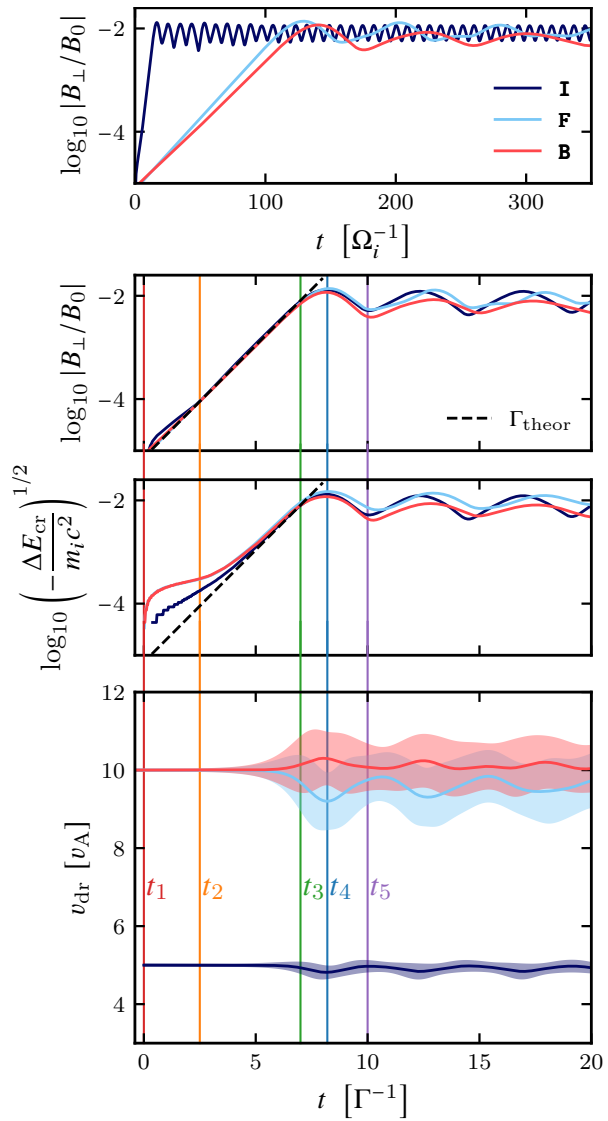
- exponential wave growth in fluid-PIC simulations that excite whistlers (via intermediate-scale instability, `I`), backward (`B`) and forward (`F`) Alfvén waves

Resonant wave growth and CR energy loss



- exponential wave growth in fluid-PIC simulations that excite whistlers (via intermediate-scale instability, `I`), backward (`B`) and forward (`F`) Alfvén waves
- energy gain by waves exactly balances CR energy loss to the unstable modes

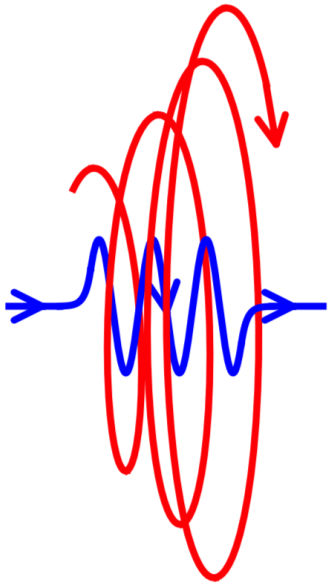
Resonant wave growth and CR energy loss



- exponential wave growth in fluid-PIC simulations that excite whistlers (via intermediate-scale instability, **I**), backward (**B**) and forward (**F**) Alfvén waves
- energy gain by waves exactly balances CR energy loss to the unstable modes
- mean CR drift speed, $v_{\rm dr}$, slows down for forward waves (**F** and **I**) and accelerates for backward waves (**B**): saturation at $v_{\rm dr} > v_{\rm A}$ for gyrotropic CR ring distribution

Cosmic ray streaming and diffusion

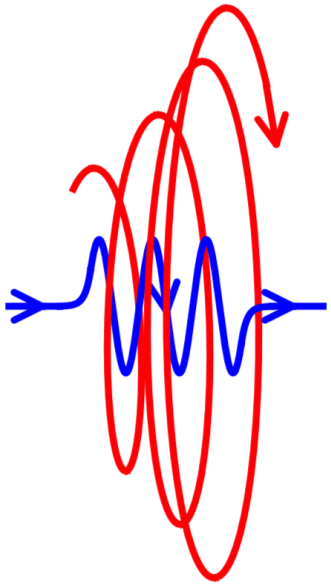
- **CR streaming instability:**
  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)
  - if $v_{\rm cr} > v_{\rm a}$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm a}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



AIP

Cosmic ray streaming and diffusion

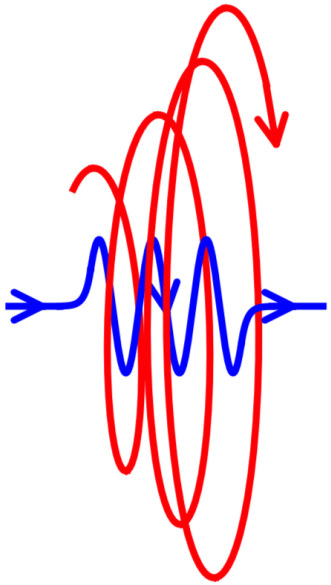
- **CR streaming instability:**
  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)
  - if $v_{\rm cr} > v_{\rm a}$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm a}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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

Cosmic ray streaming and diffusion

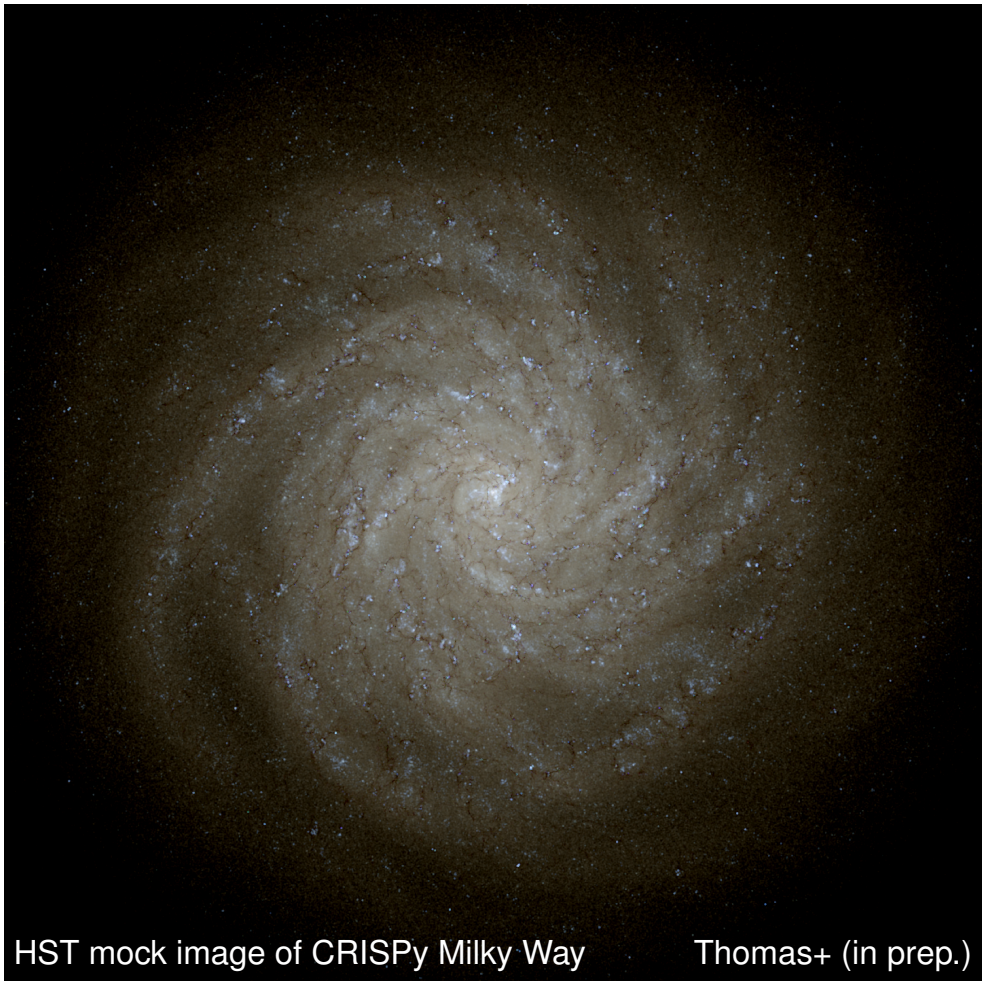
- **CR streaming instability:**
  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)
  - if $v_{cr} > v_a$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_a$
  - wave damping: transfer of CR energy and momentum to the thermal gas



$\rightarrow$ *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

Cosmic ray transport in galaxies


HST mock image of CRISPy Milky Way Thomas+ (in prep.)

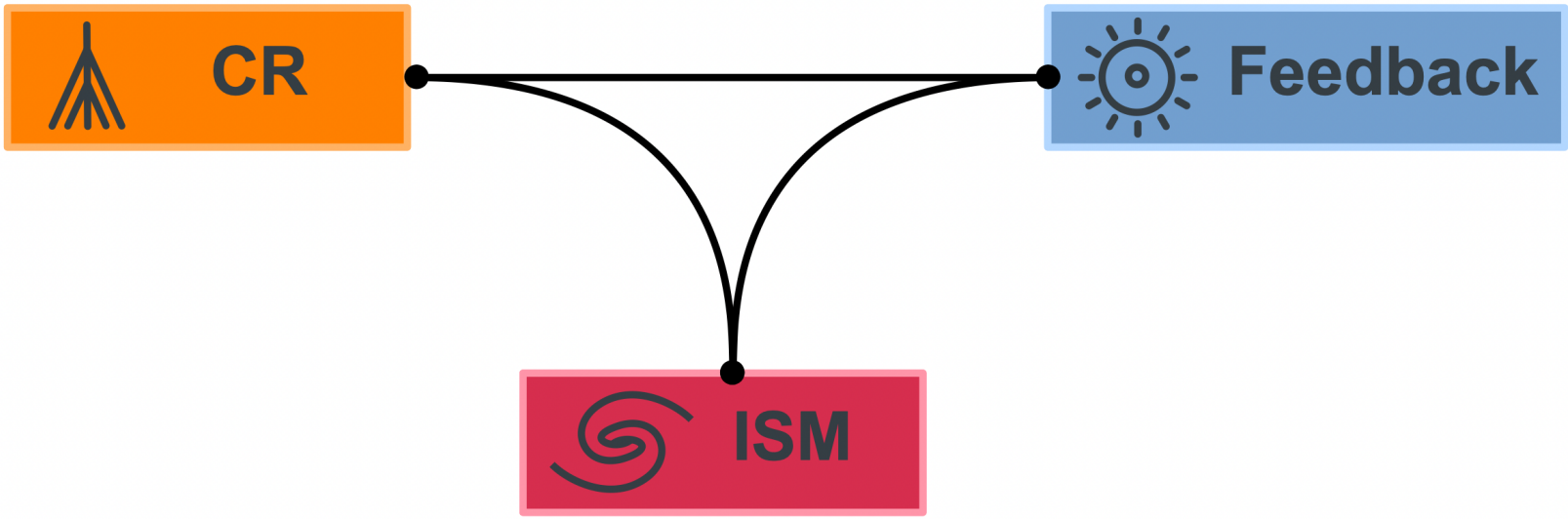
- CR transport in galaxies demands modeling non-linear Landau damping (in warm/hot phase) and ion-neutral damping (in disk)
- this requires resolving the multi-phase structure of the ISM
- development of CRISP framework (**C**osmic **R**ays and **I**nter**S**tellar **P**hysics, Thomas+ 2025)

AIP

Multi-phase ISM modeling

CRISP framework

Cosmic **R**ays and **I**nter**S**tellar **P**hysics



Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework
Cosmic **R**ays and **I**nter**S**tellar **P**hysics









- Full H – H_2 – He chemistry
  sets ionization degree
- First ionization stages of C – O – Si
  low temperature cooling
- Photoelectric heating by dust

Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework

Cosmic **R**ays and **I**nter**S**tellar **P**hysics







- Improved SNe treatment (manifestly isotropic)
  and stellar winds
- FUV NUV OPT radiation fields (reverse ray tracing)
  absorbed by dust — impacting Chemistry
- Metal enrichment

Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework

Cosmic **R**ays and **I**nter**S**tellar **P**hysics

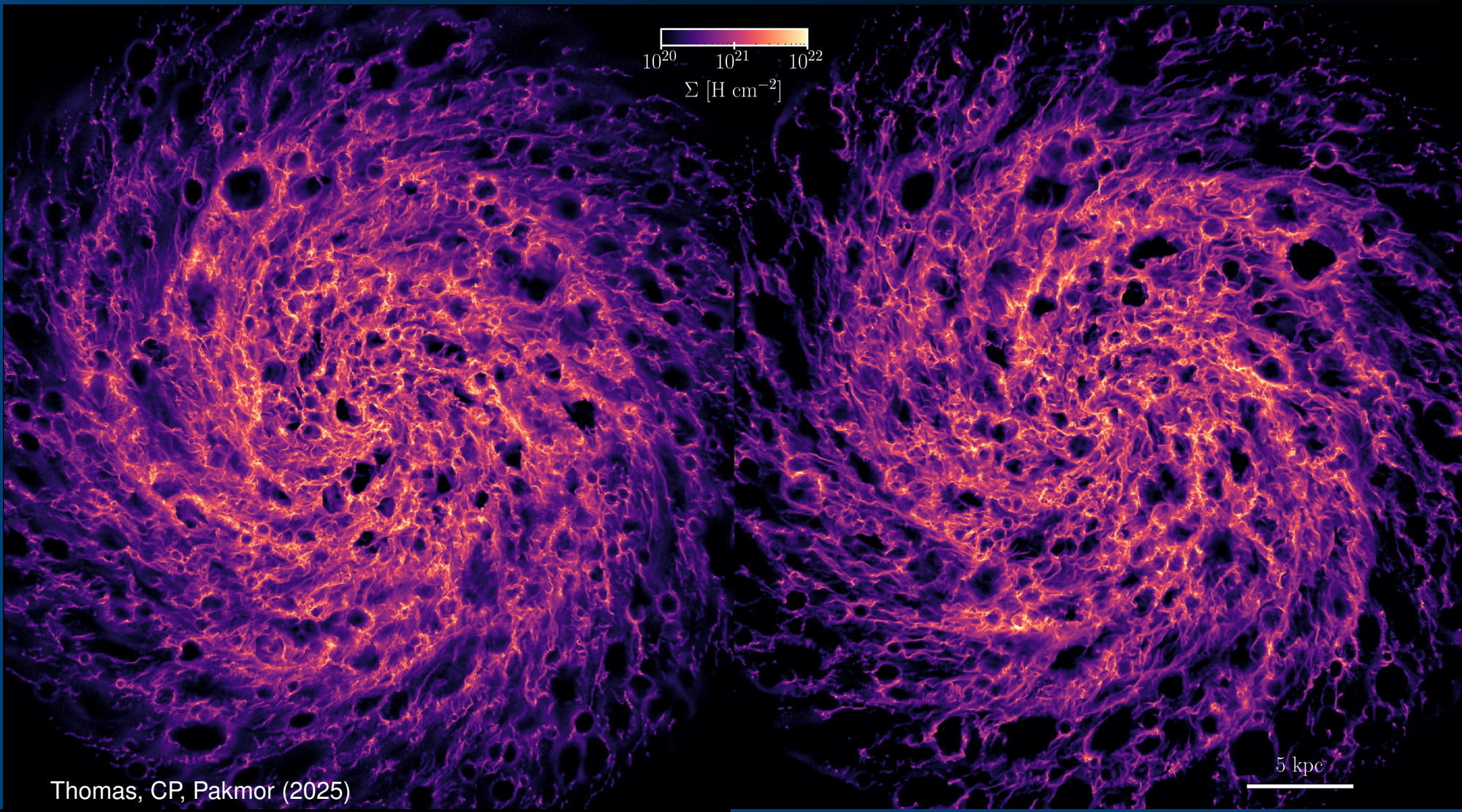




- **Novel CR hydrodynamics**
  coarse graining plasma physics
  - Follow $\varepsilon_{\rm cr}$ and $v_{\rm cr}$
  - Self-consistently evolve $\kappa_{\rm cr}$
- **CR ionization**
  impacting Chemistry
- **CR microphysics**

Thomas, CP, Pakmor (2025)

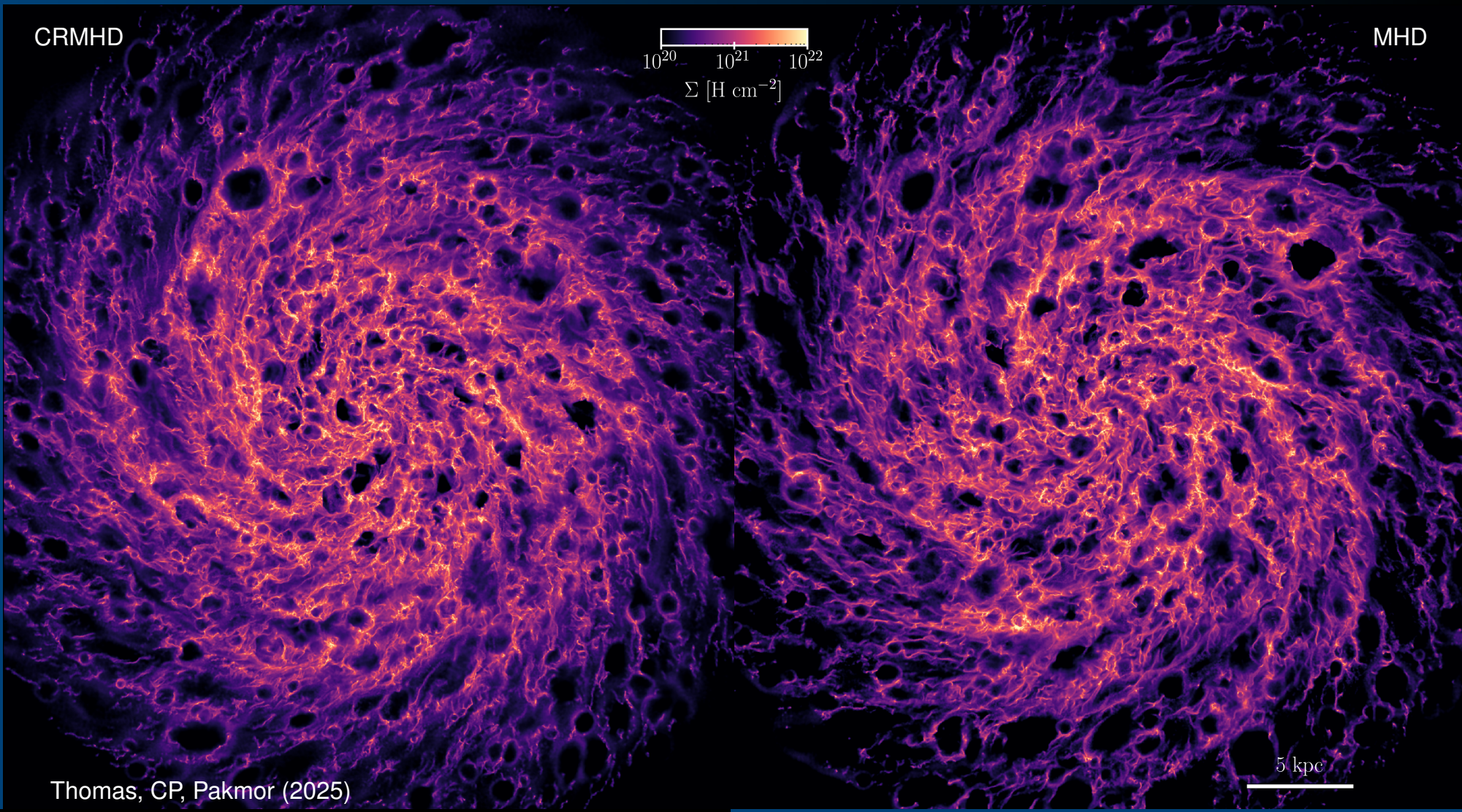
Multi-phase ISM modeling



Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

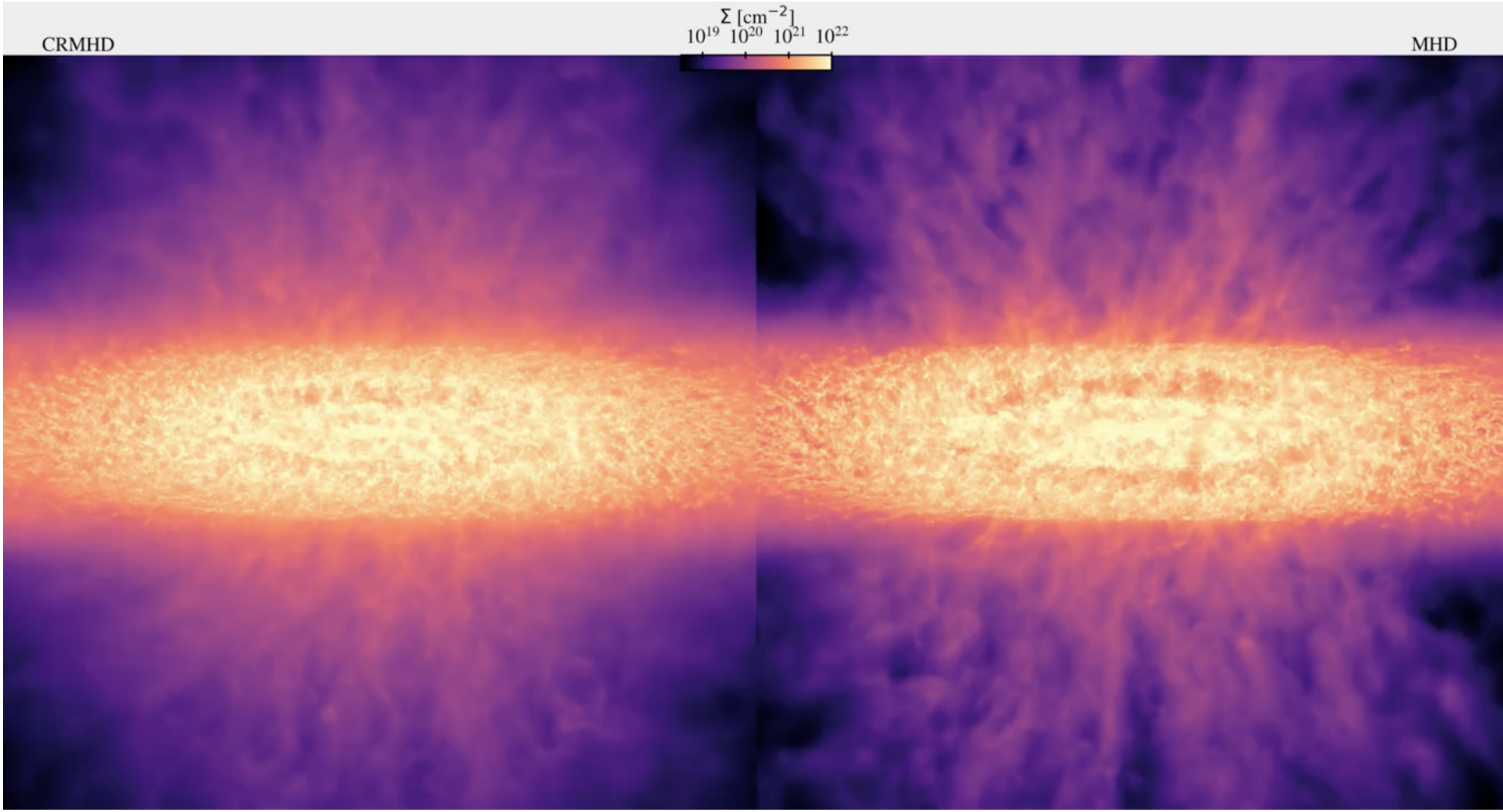
Cosmic rays barely affect the ISM because ion-neutral damping erases Alfvén waves



Thomas, CP, Pakmor (2025)

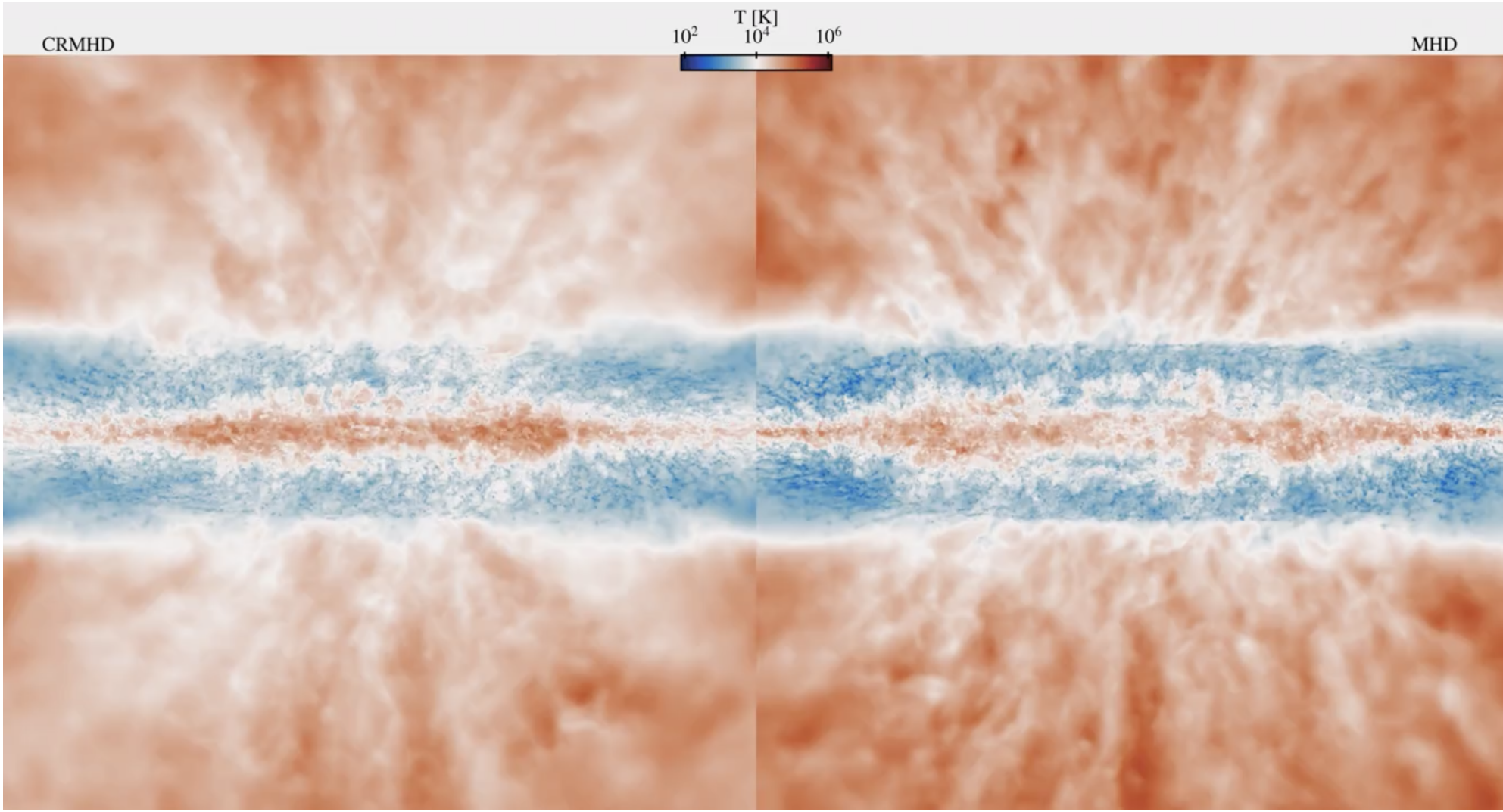
Simulated Milky Way: surface density

Cosmic rays drive galactic winds, ram pressure propells mainly galactic fountains



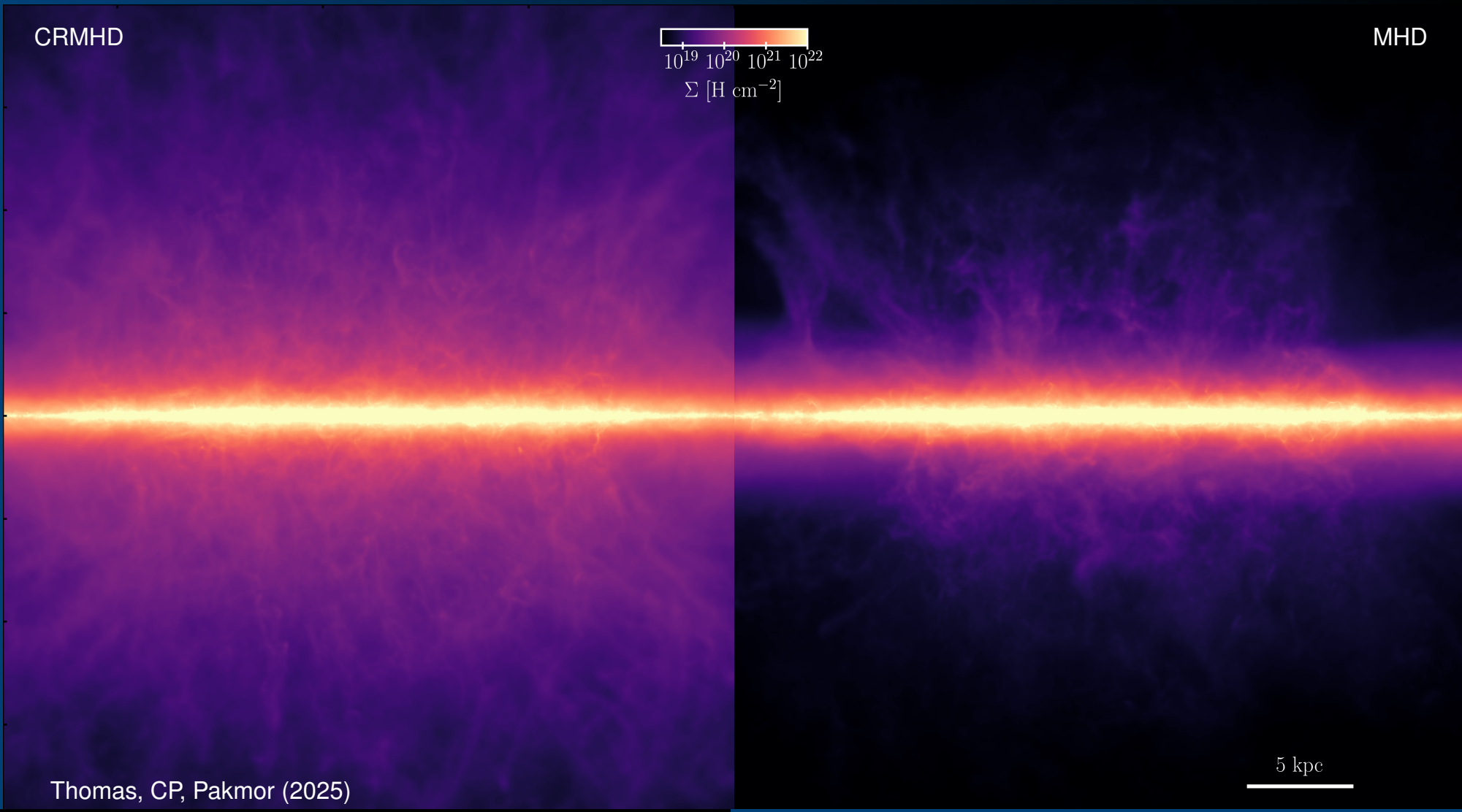
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter



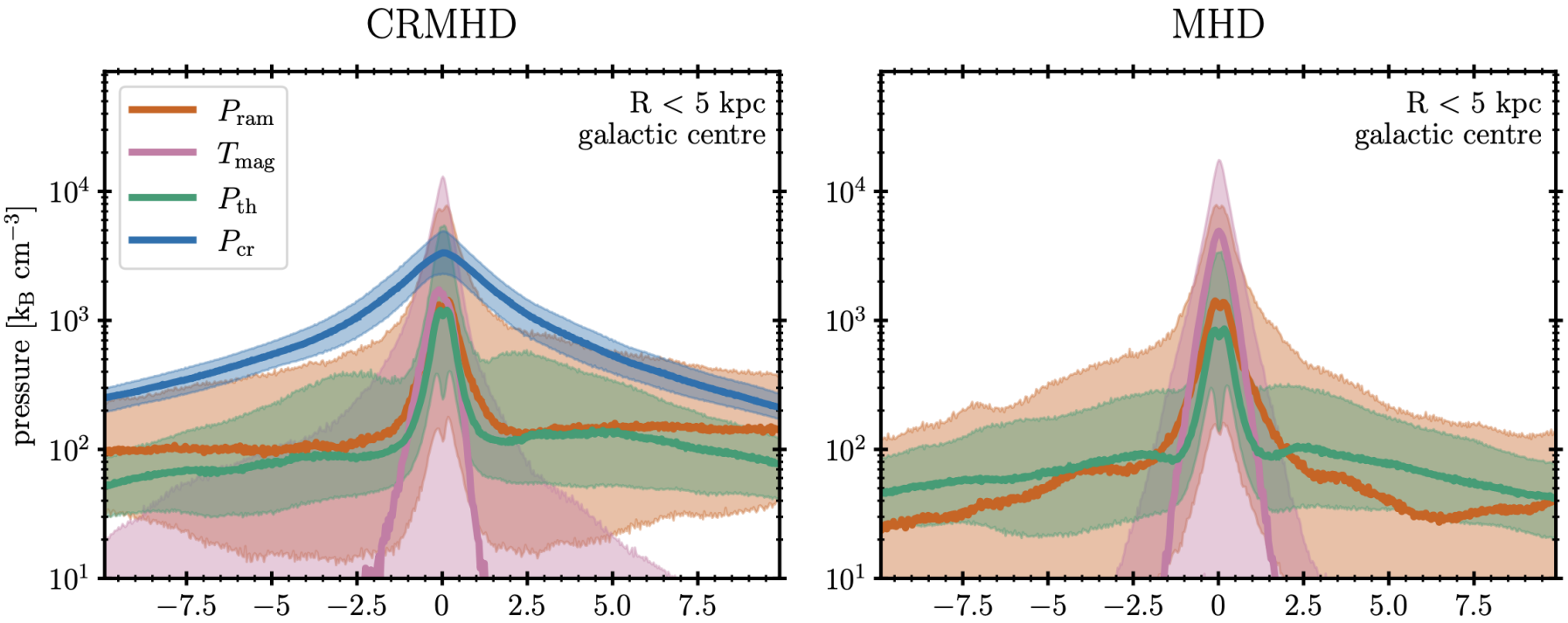
Multi-phase ISM modeling

Cosmic rays make galactic winds much denser



Thomas, CP, Pakmor (2025)

Cosmic ray driven wind: mechanism

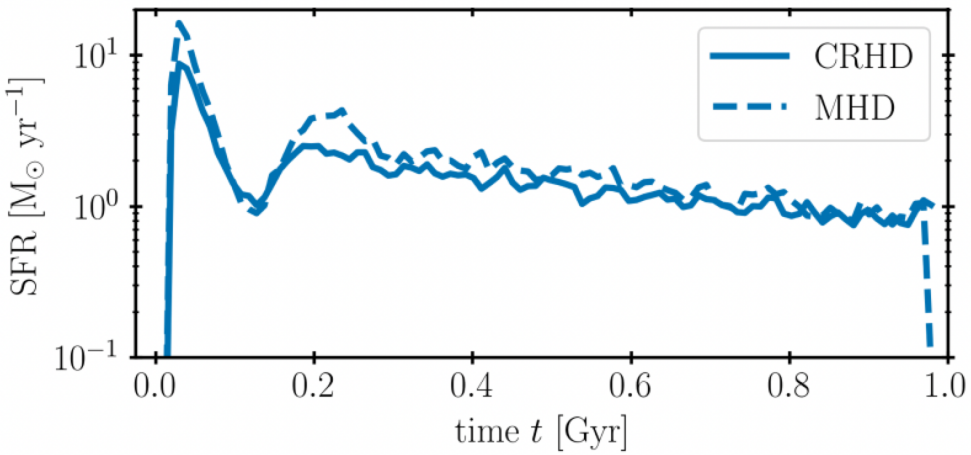


Thomas, CP, Pakmor (2025)

- CR pressure gradient dominates over thermal and ram pressure gradient and drives outflow:

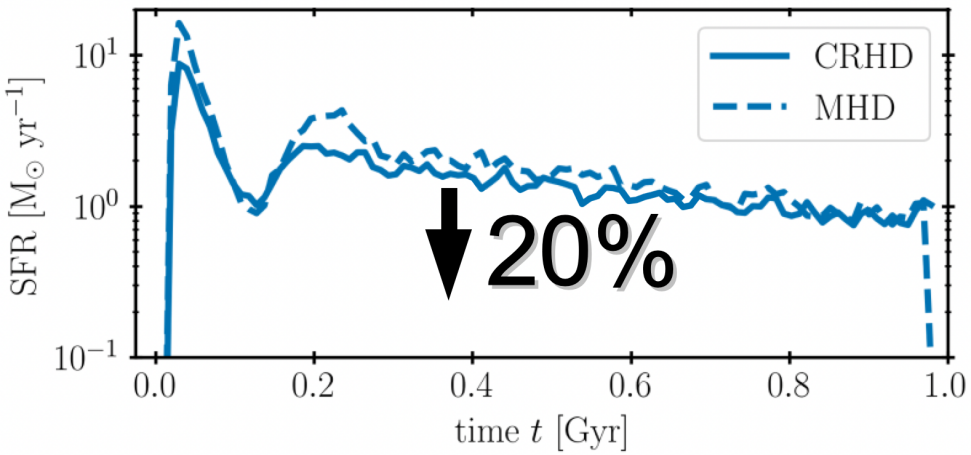
$$|\nabla P_{\rm cr} + \nabla P_{\rm th}| > \rho |\nabla \Phi|$$

Mass and energy loading factors



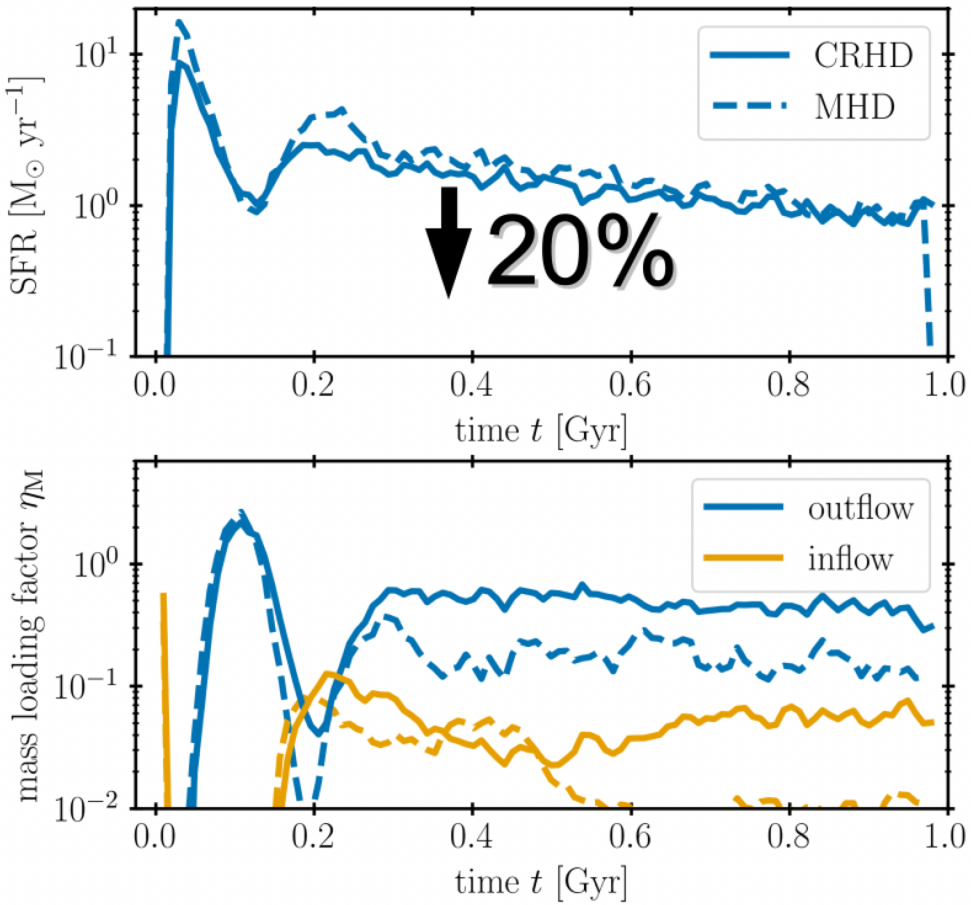
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



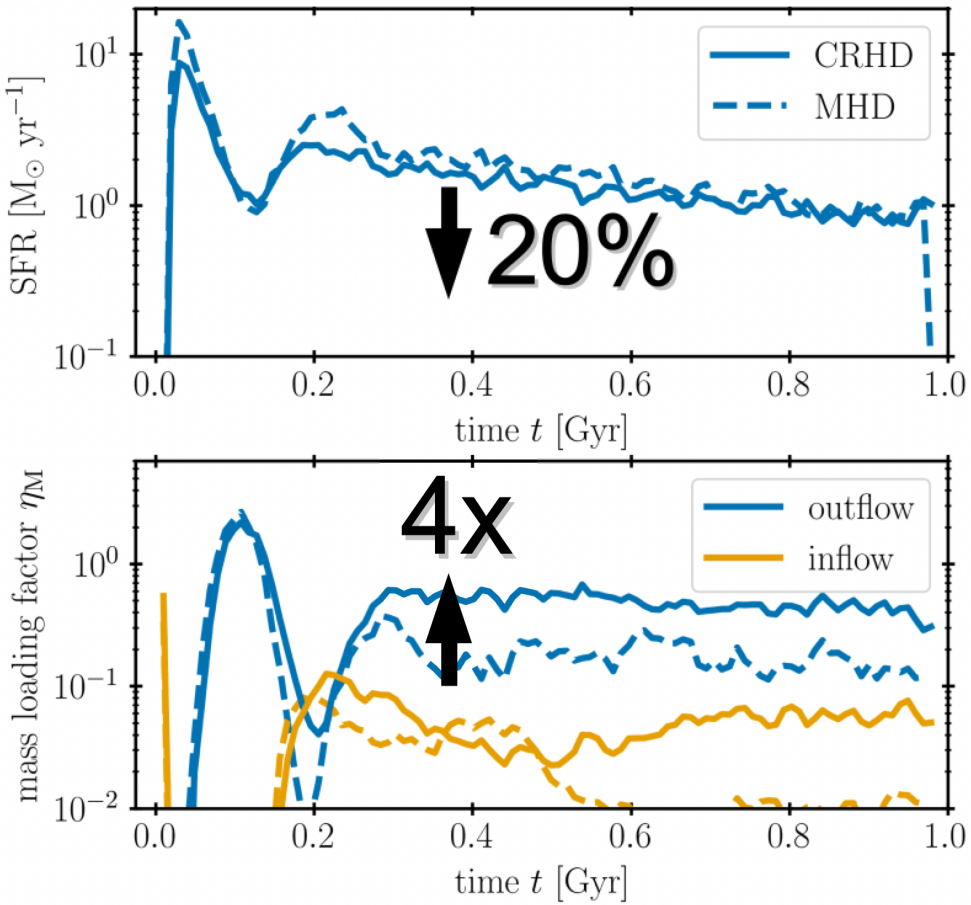
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



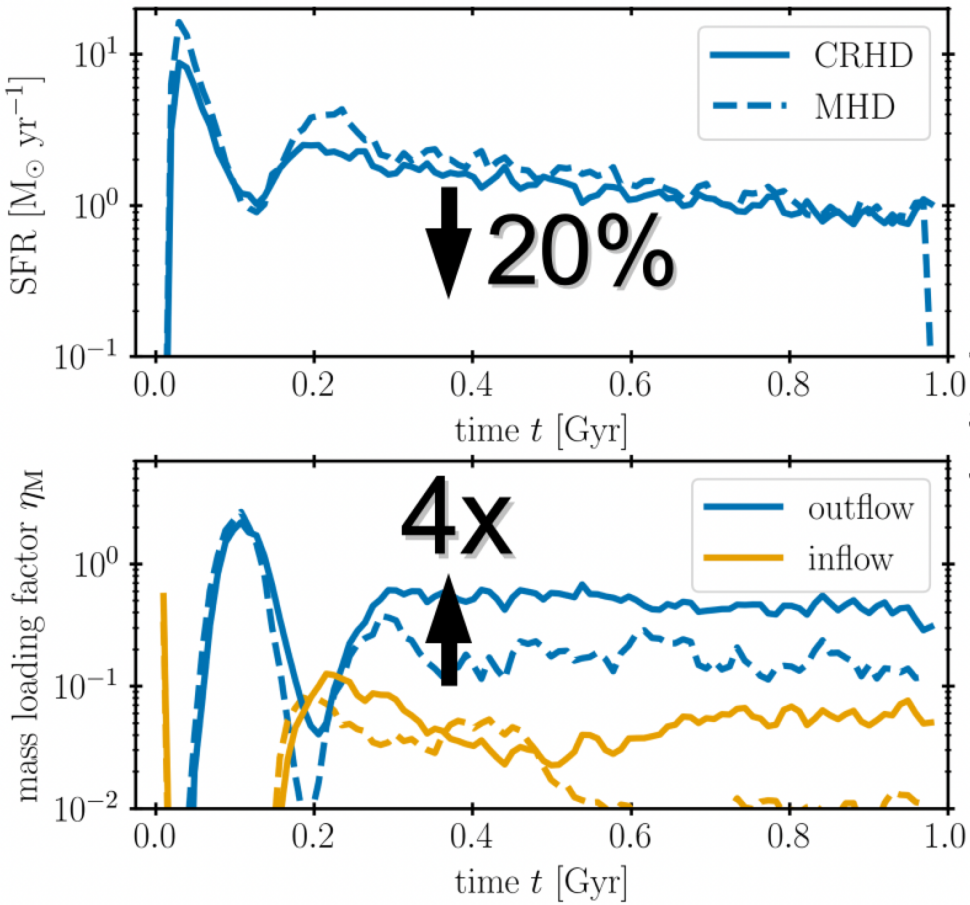
Thomas, CP, Pakmor (2025)

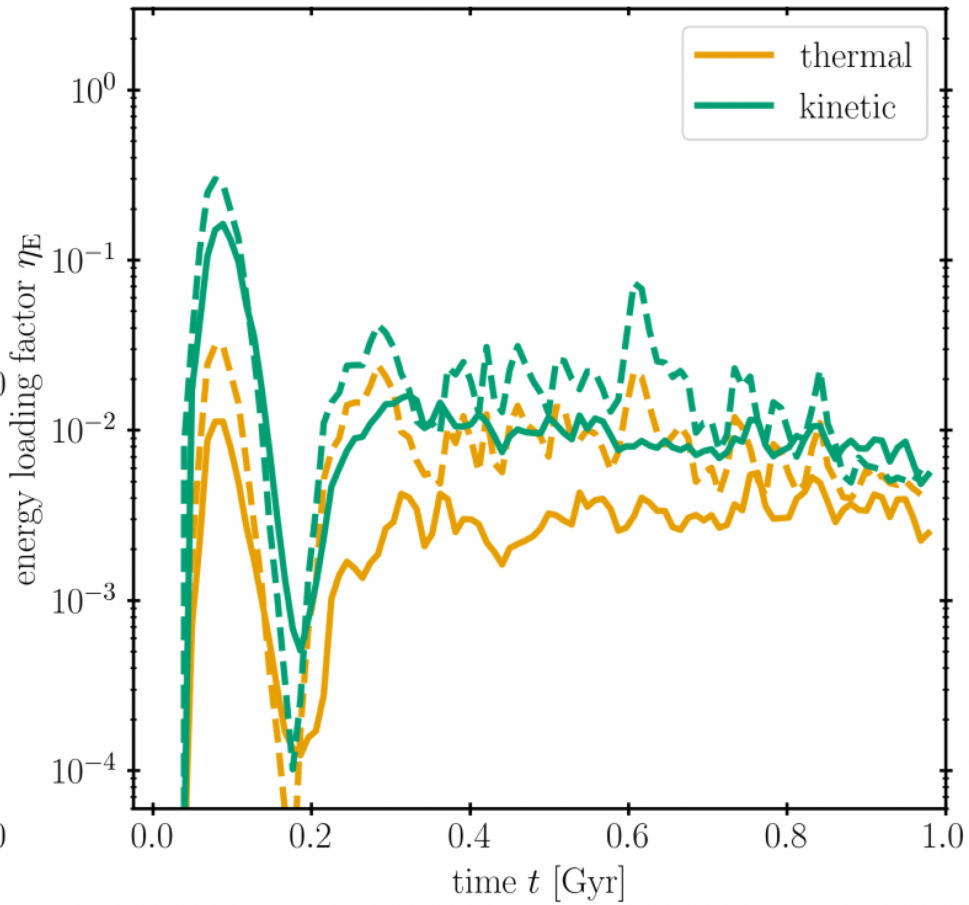
Mass and energy loading factors



Thomas, CP, Pakmor (2025)

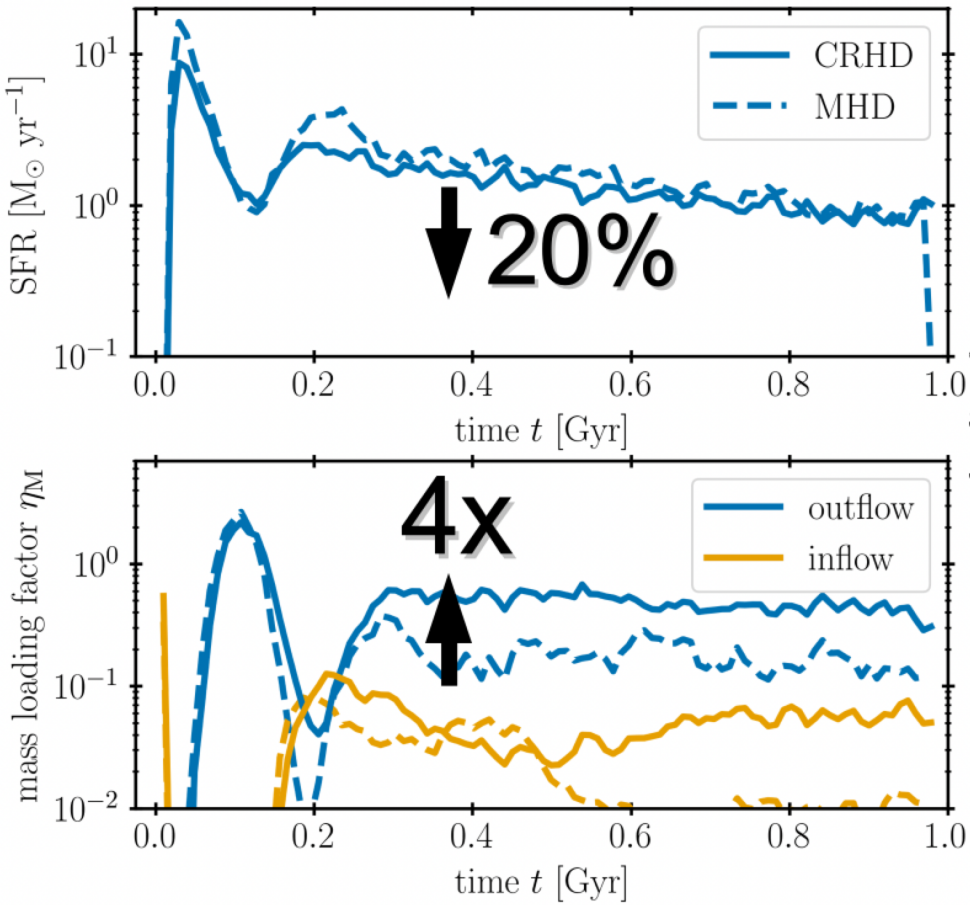
Mass and energy loading factors

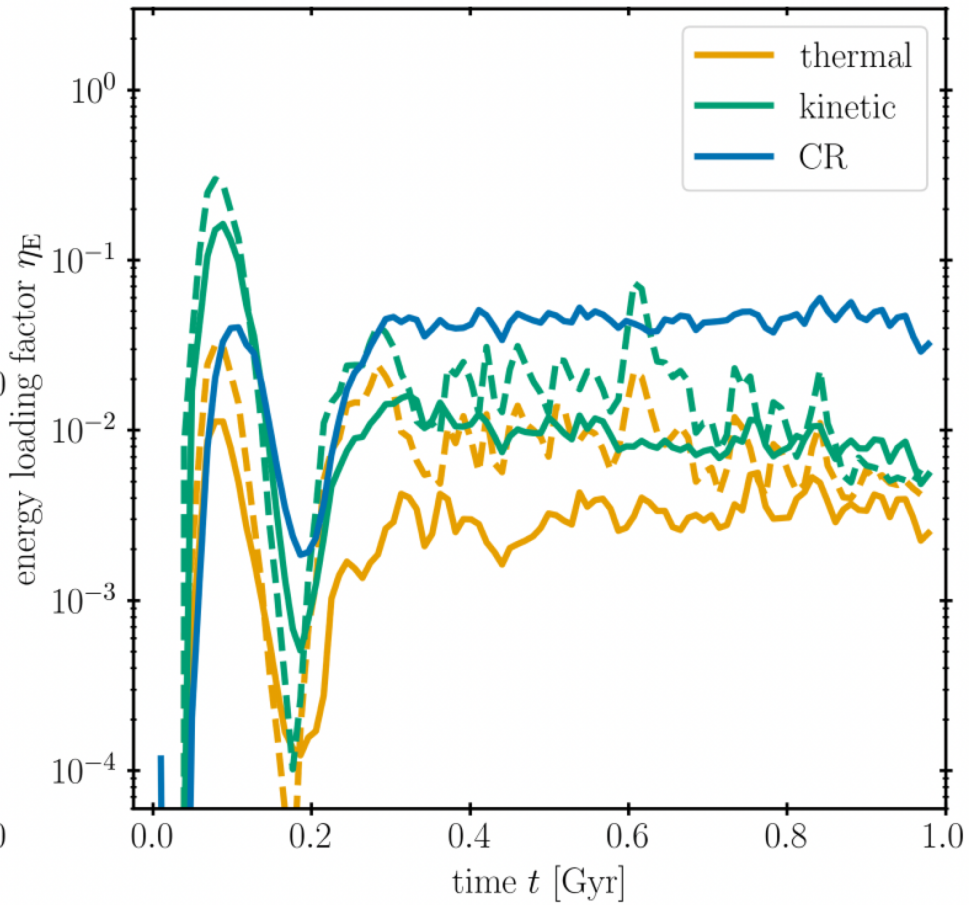




Thomas, CP, Pakmor (2025)

Mass and energy loading factors

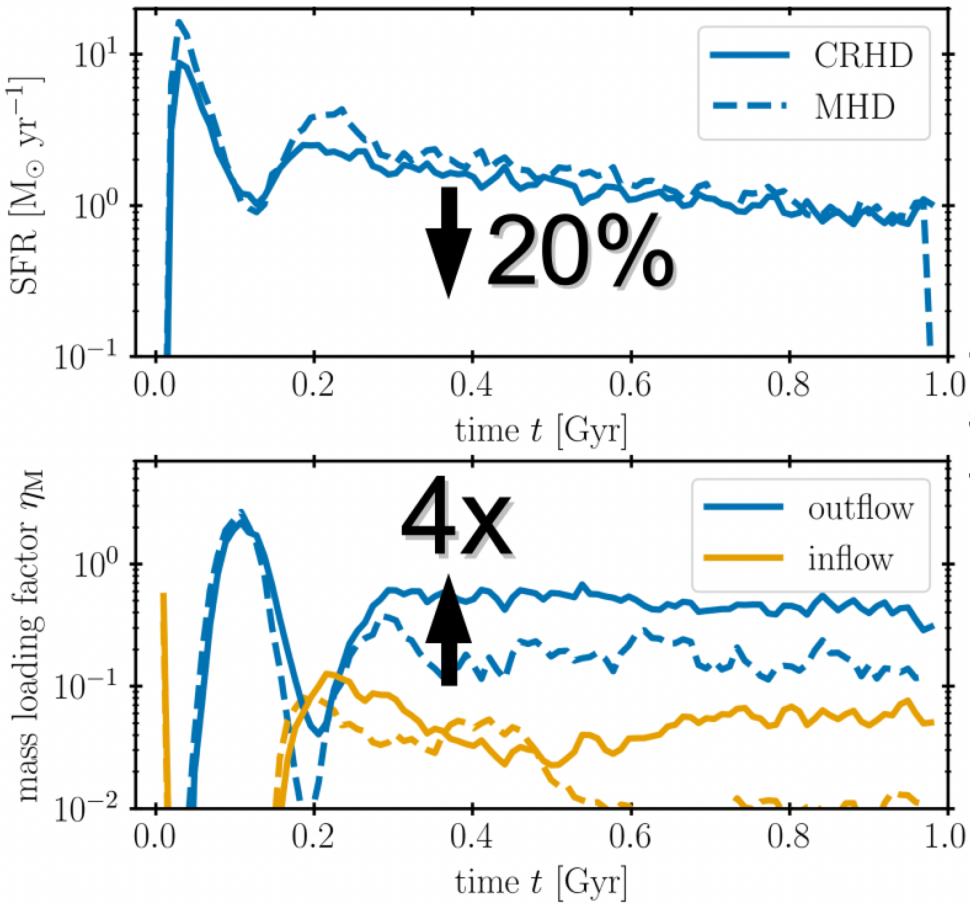


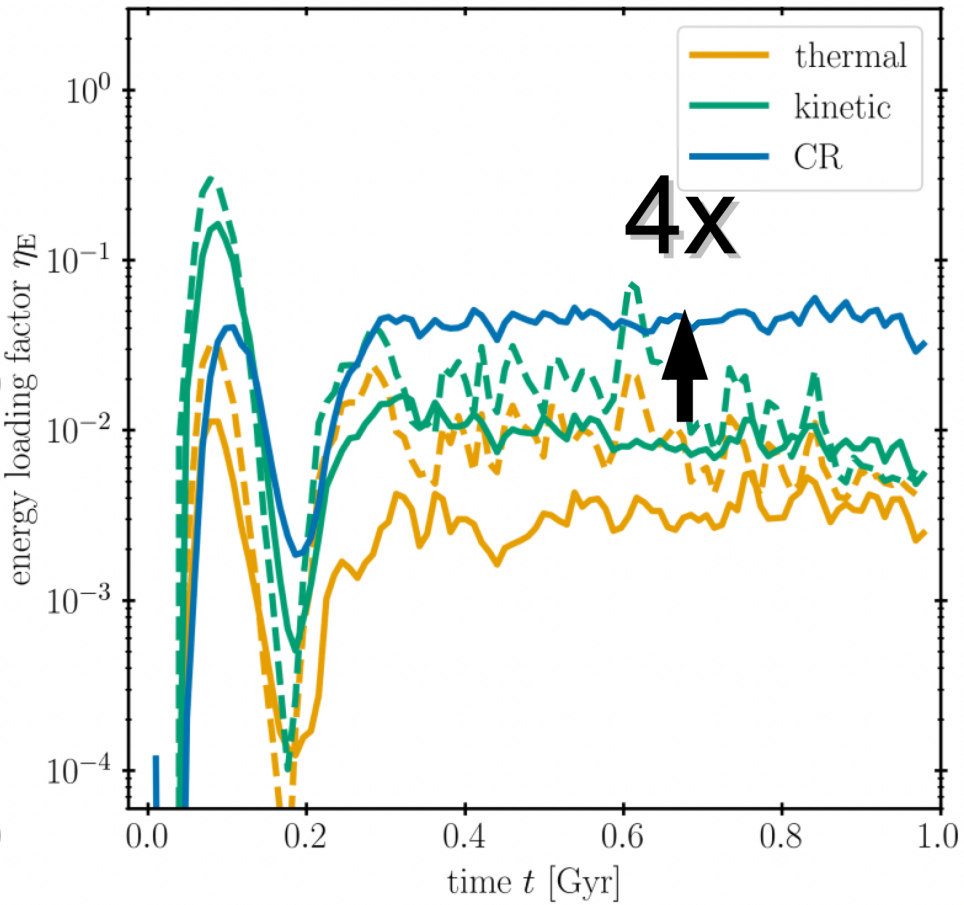


Thomas, CP, Pakmor (2025)

AIP

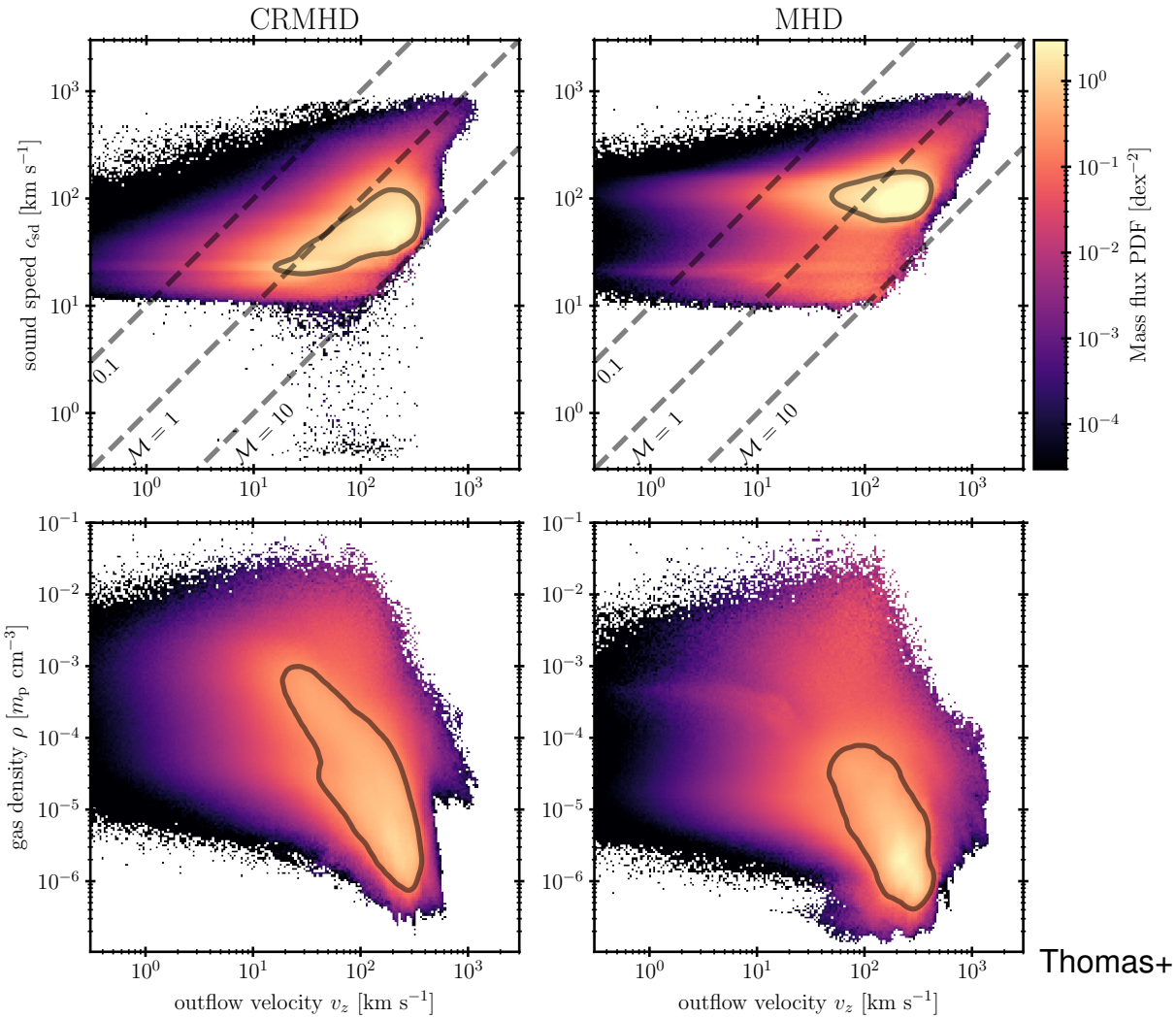
Mass and energy loading factors





Thomas, CP, Pakmor (2025)

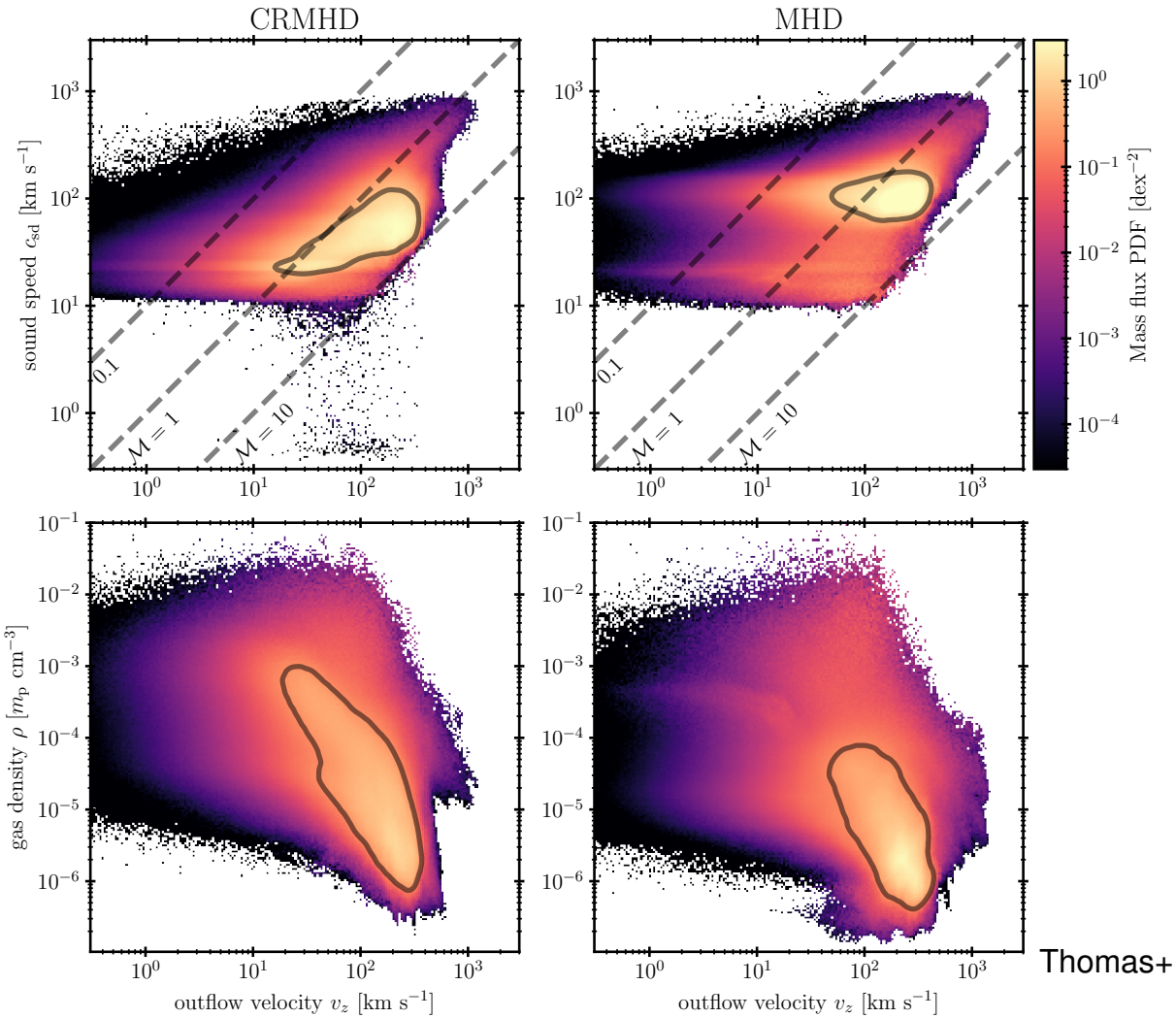
Phase structure of outflowing material



Thomas+ (2025)

Phase structure of outflowing material

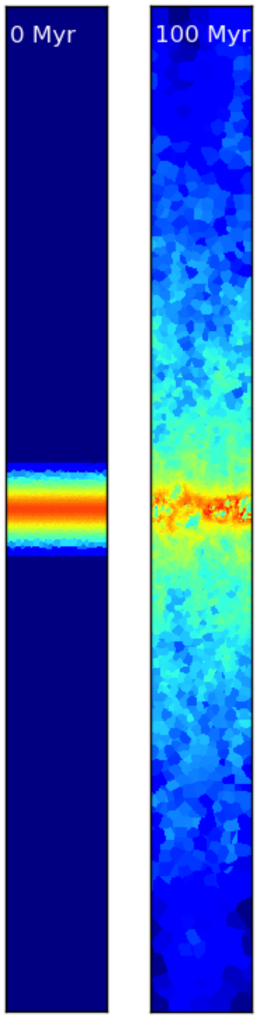
Missing cool phase in outflow: model shortcomings or insufficient resolution?



Thomas+ (2025)

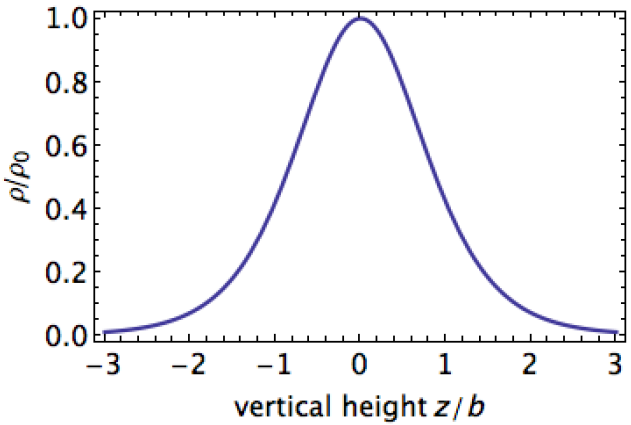
CR feedback in the multi-phase interstellar medium

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



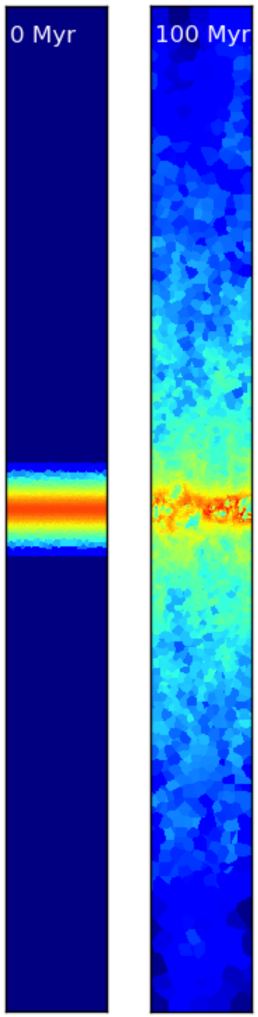
- isothermal disk with $T_0 = 10^4$ K
- hydrostatic equilibrium:

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



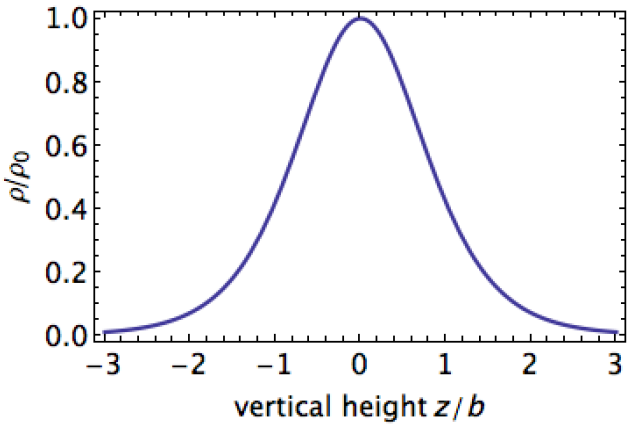
CR feedback in the multi-phase interstellar medium

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



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

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

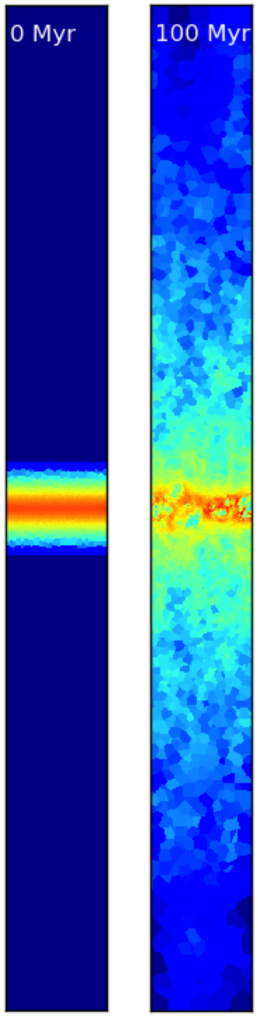


- self-gravity; turbulent stirring for 50 Myrs
- CRISP framework with non-equilibrium chemistry (Thomas, CP, Pakmor 2014)
- attenuated FUV stellar radiation field
- MHD with small magnetic seed field (Pakmor+ 2011)
- cosmic ray physics (Thomas & CP 2019, Thomas+ 2021)



CR feedback in the multi-phase interstellar medium

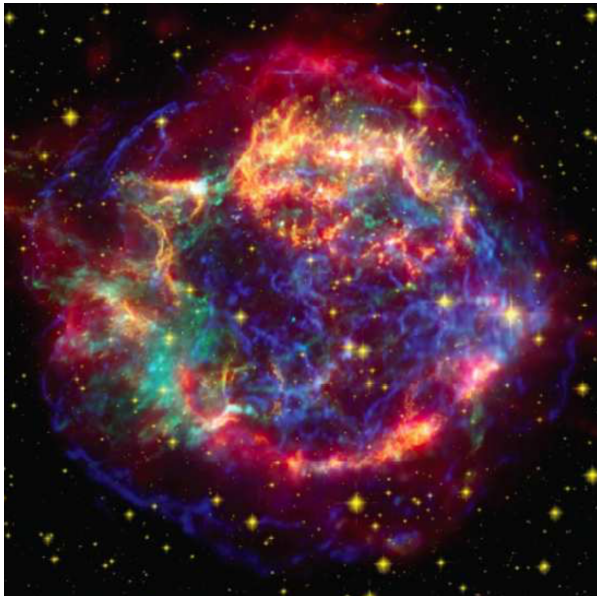
Explore how CR transport impacts on galactic outflows – stratified box simulations



- supernova rate:

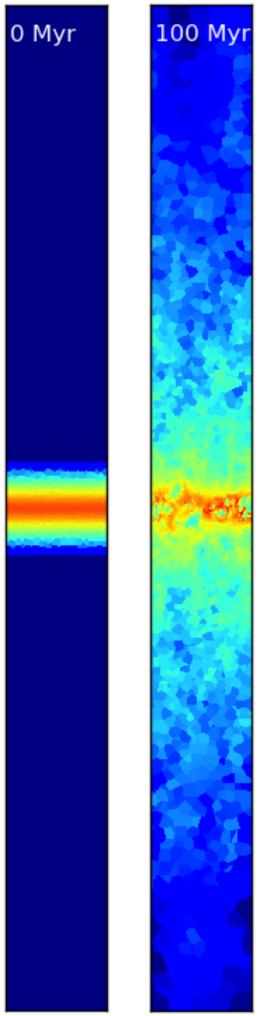
$$\dot{M}_{\mathrm{SN},i} = \dot{M}_{\star,i} \frac{1 \text{ event}}{100 \text{ M}_\odot}$$

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



CR feedback in the multi-phase interstellar medium

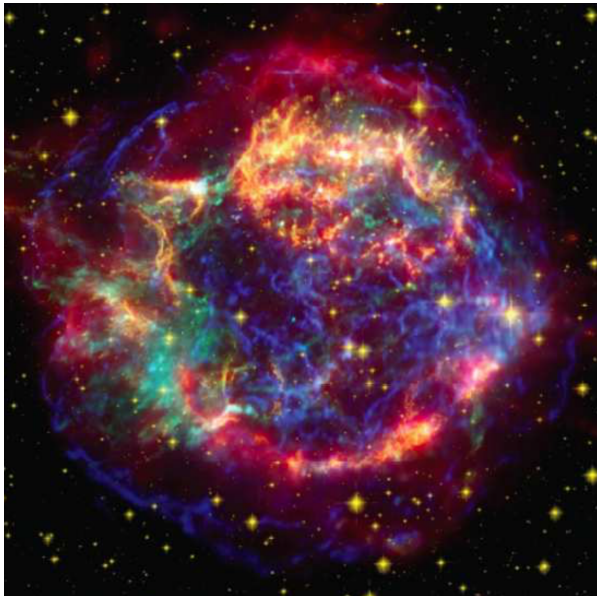
Explore how CR transport impacts on galactic outflows – stratified box simulations



- supernova rate:

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

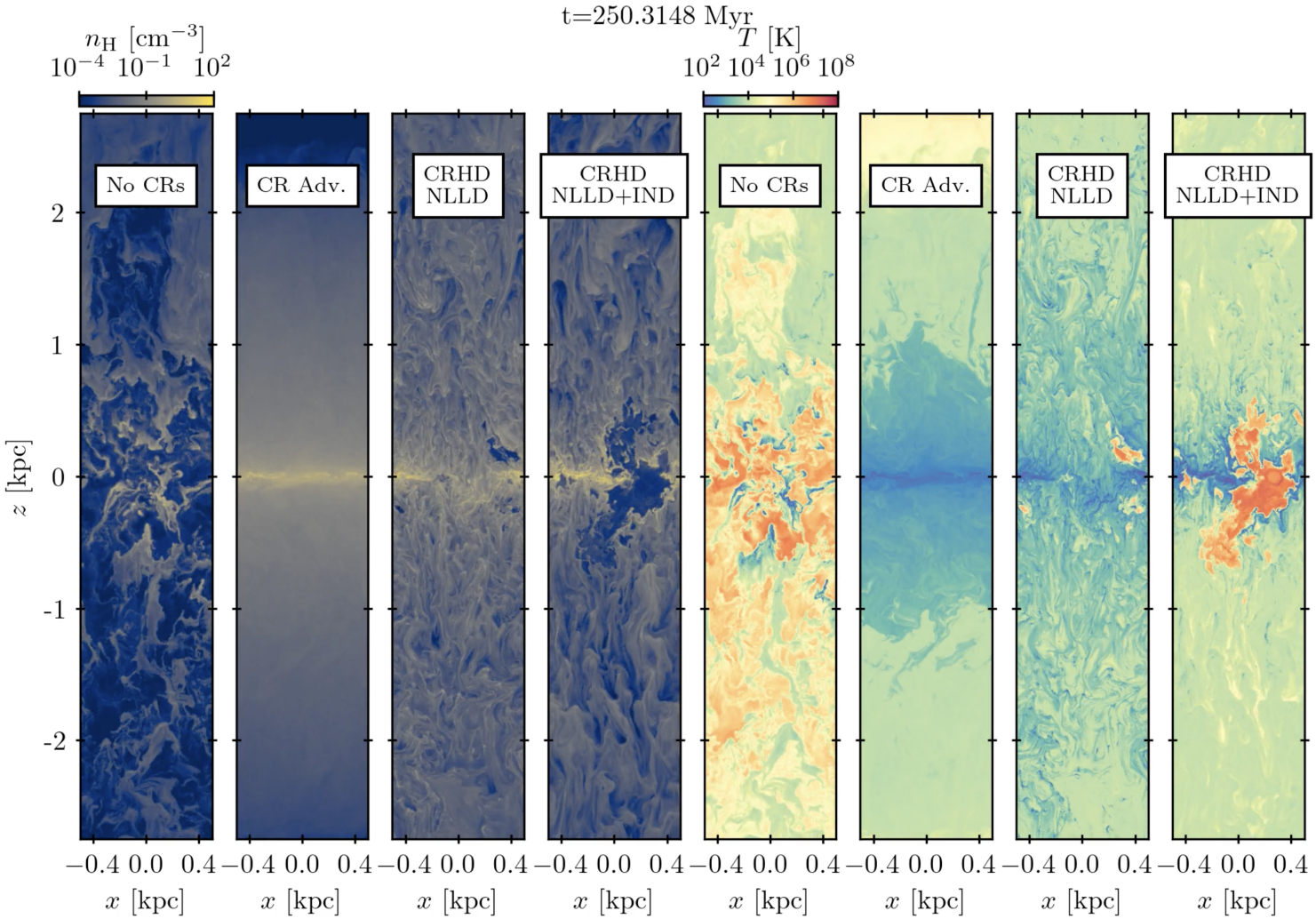
- CR-to-thermal energy injection rate = 5 %
- comparing 4 models:
  - pure MHD
  - CR advection
  - CR transport with non-linear Landau (NL) damping (strong CR coupling)
  - CR transport with NL and ion-neutral damping (weak CR coupling in dense ISM)



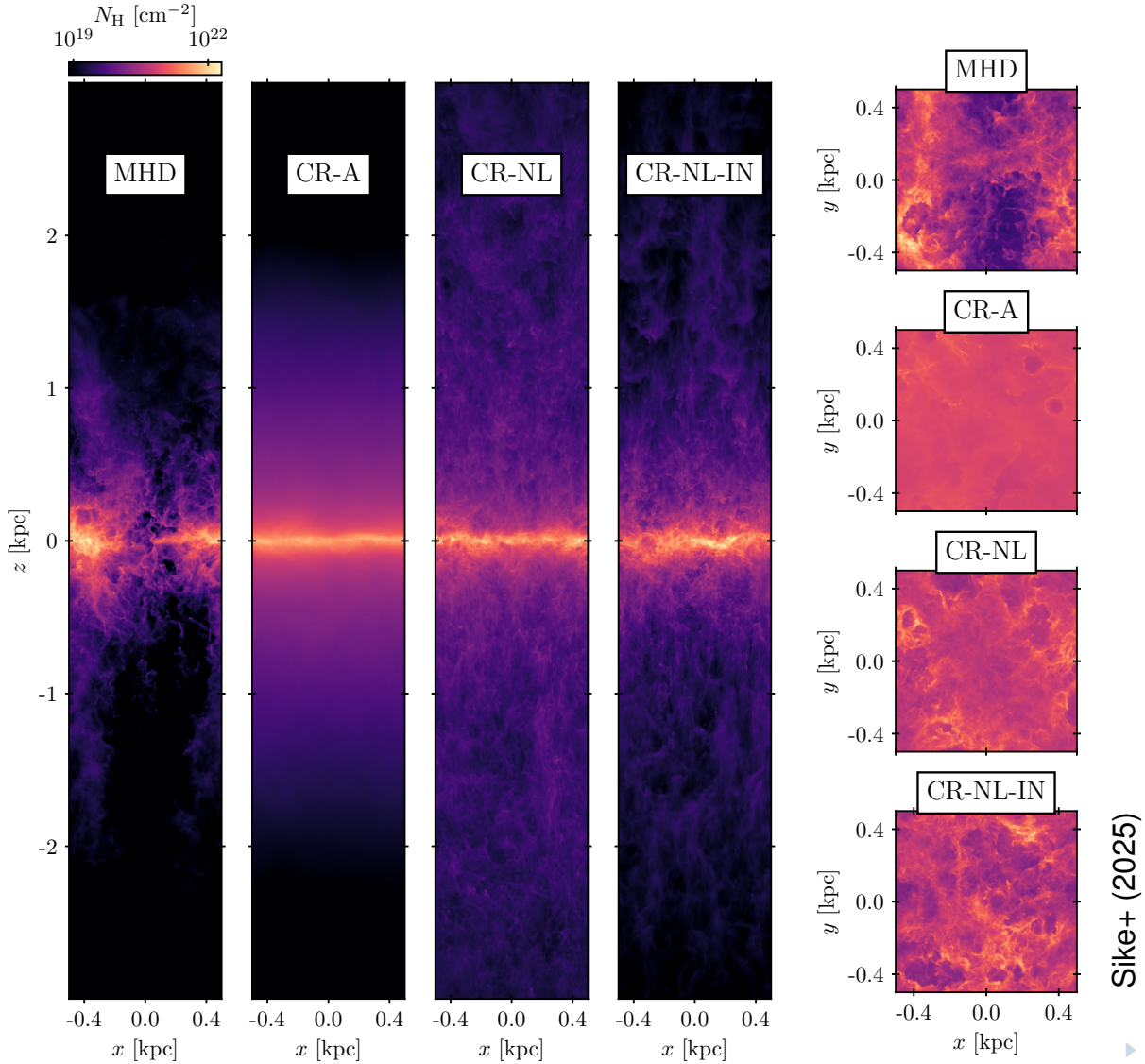
AIP

ISM tallbox: density and temperature

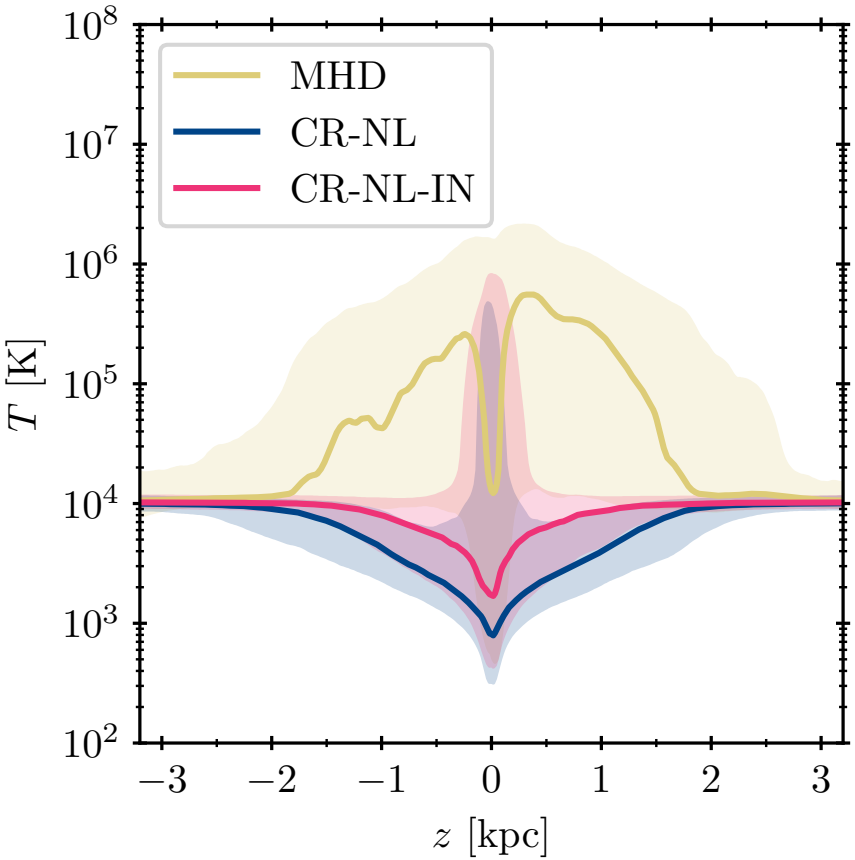
Comparing models: MHD, CR advection, full CR transport (different wave damping)



ISM column densities



Characteristics of supernovae- vs. CR-driven winds

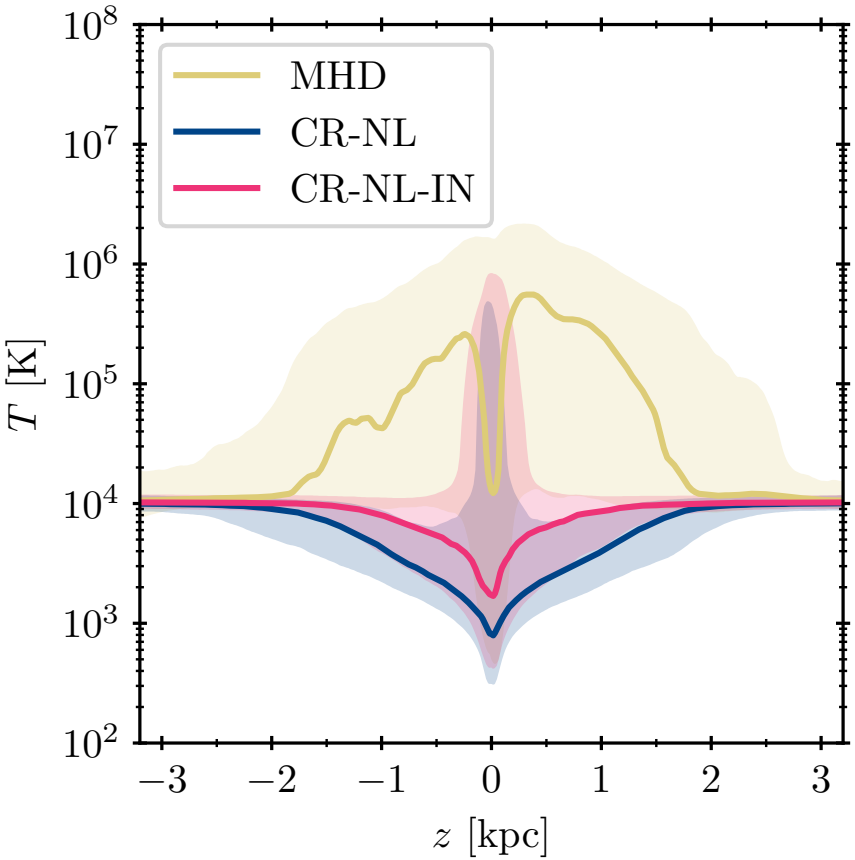


Sike+ (2025)

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

AIP

Characteristics of supernovae- vs. CR-driven winds

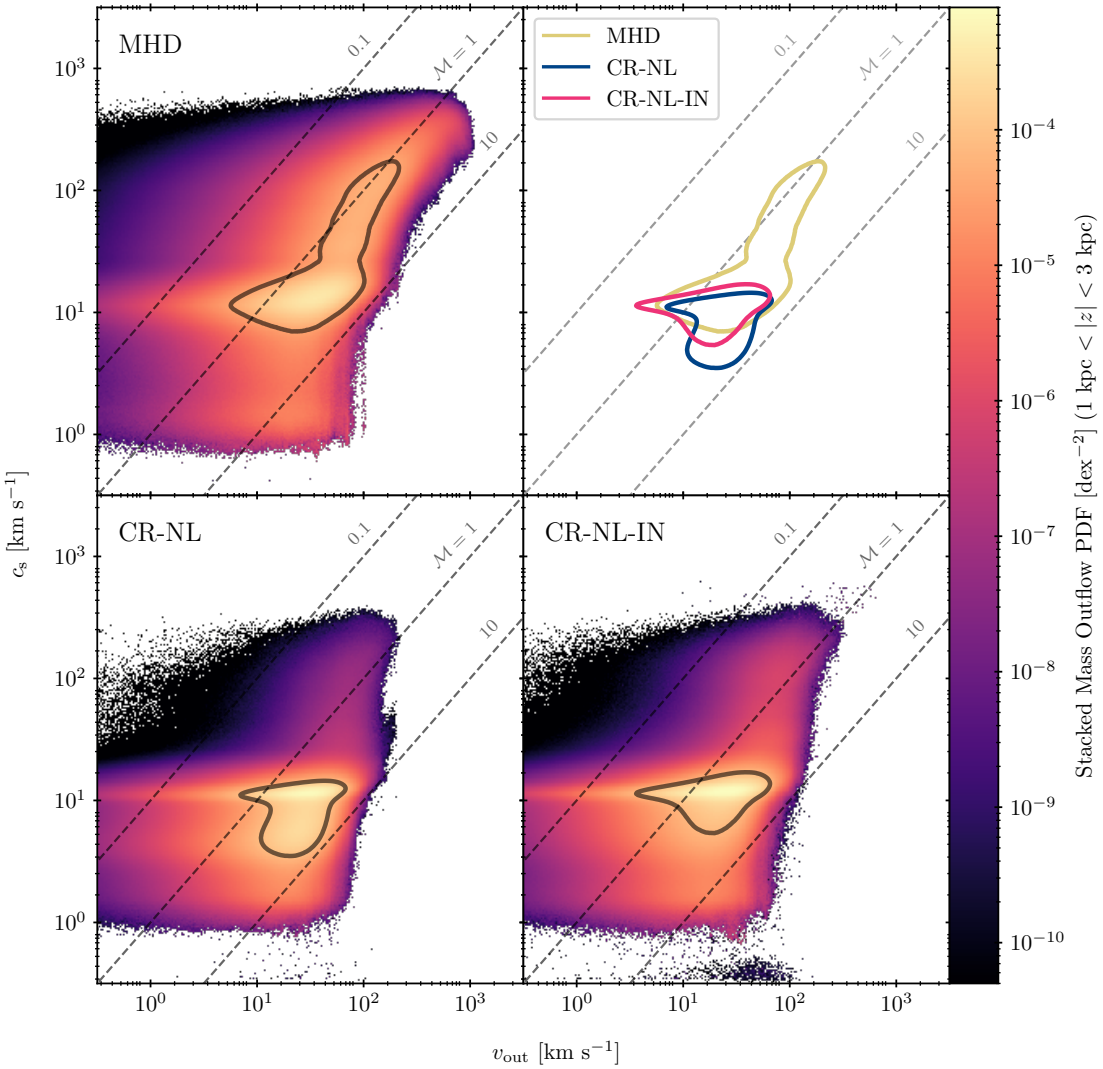


Sike+ (2025)

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

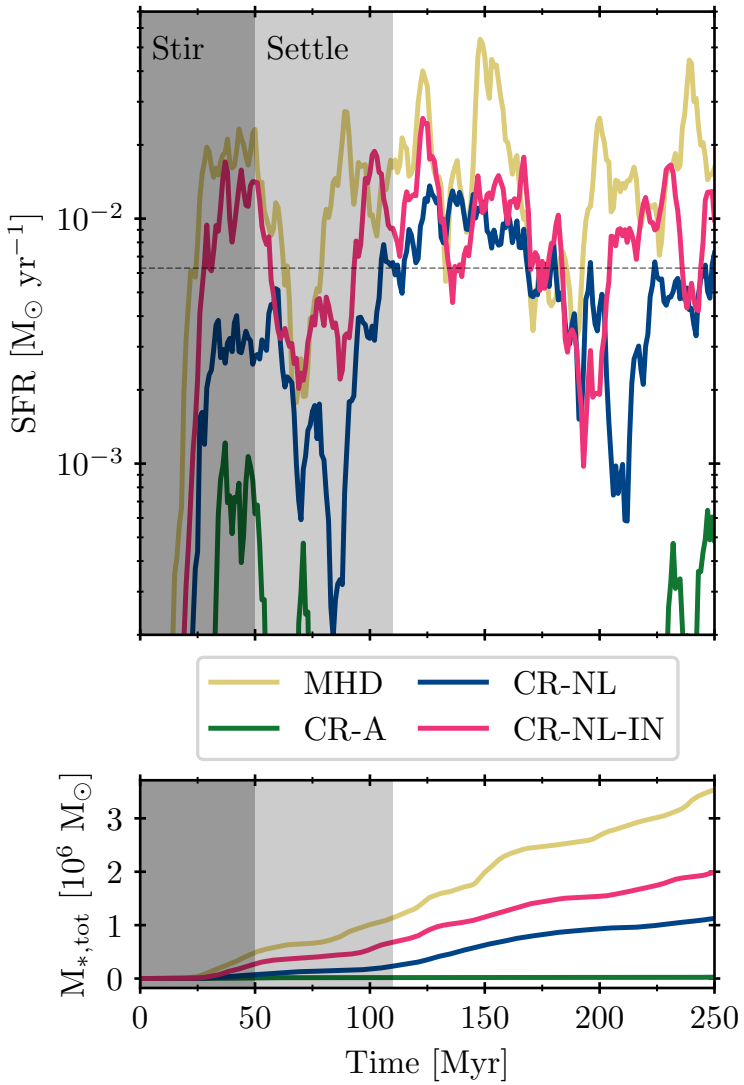
AIP

Phase structure of outflowing material

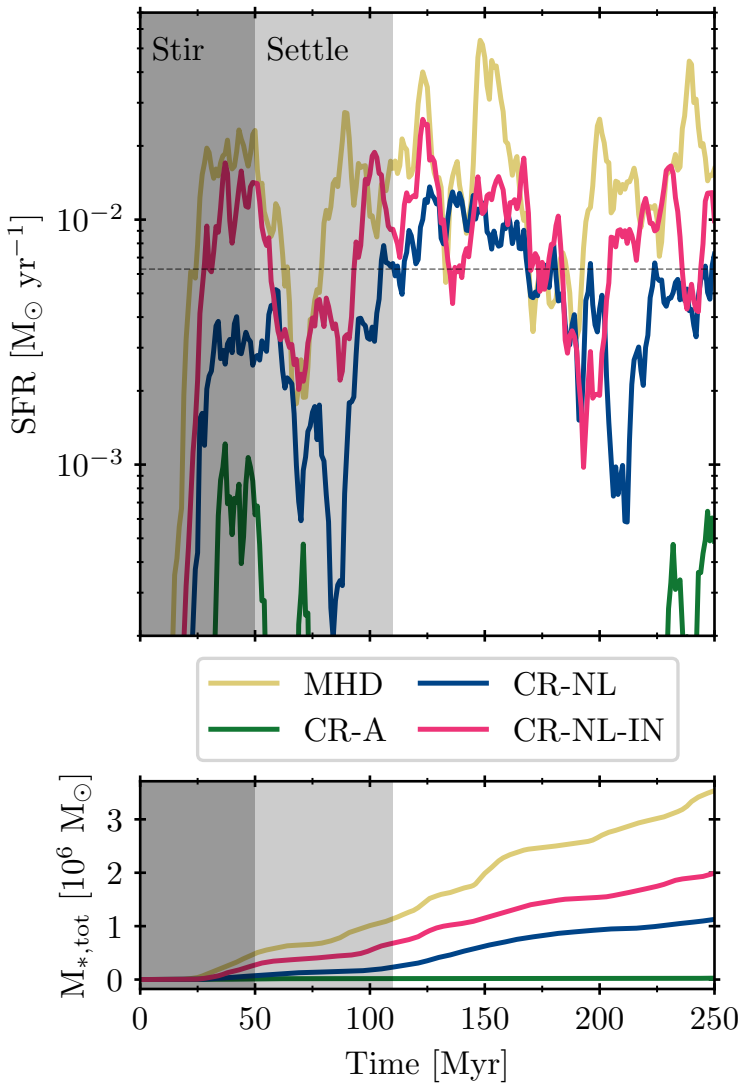


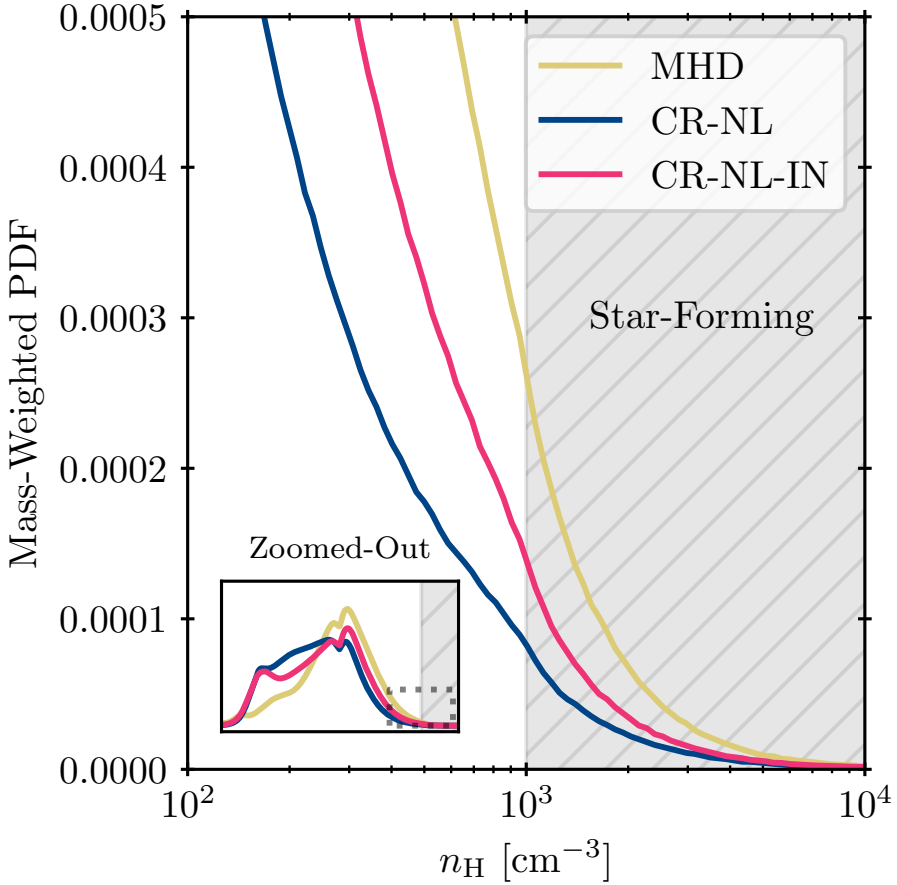
Sike+ (2025)

CR feedback mildly suppresses star formation



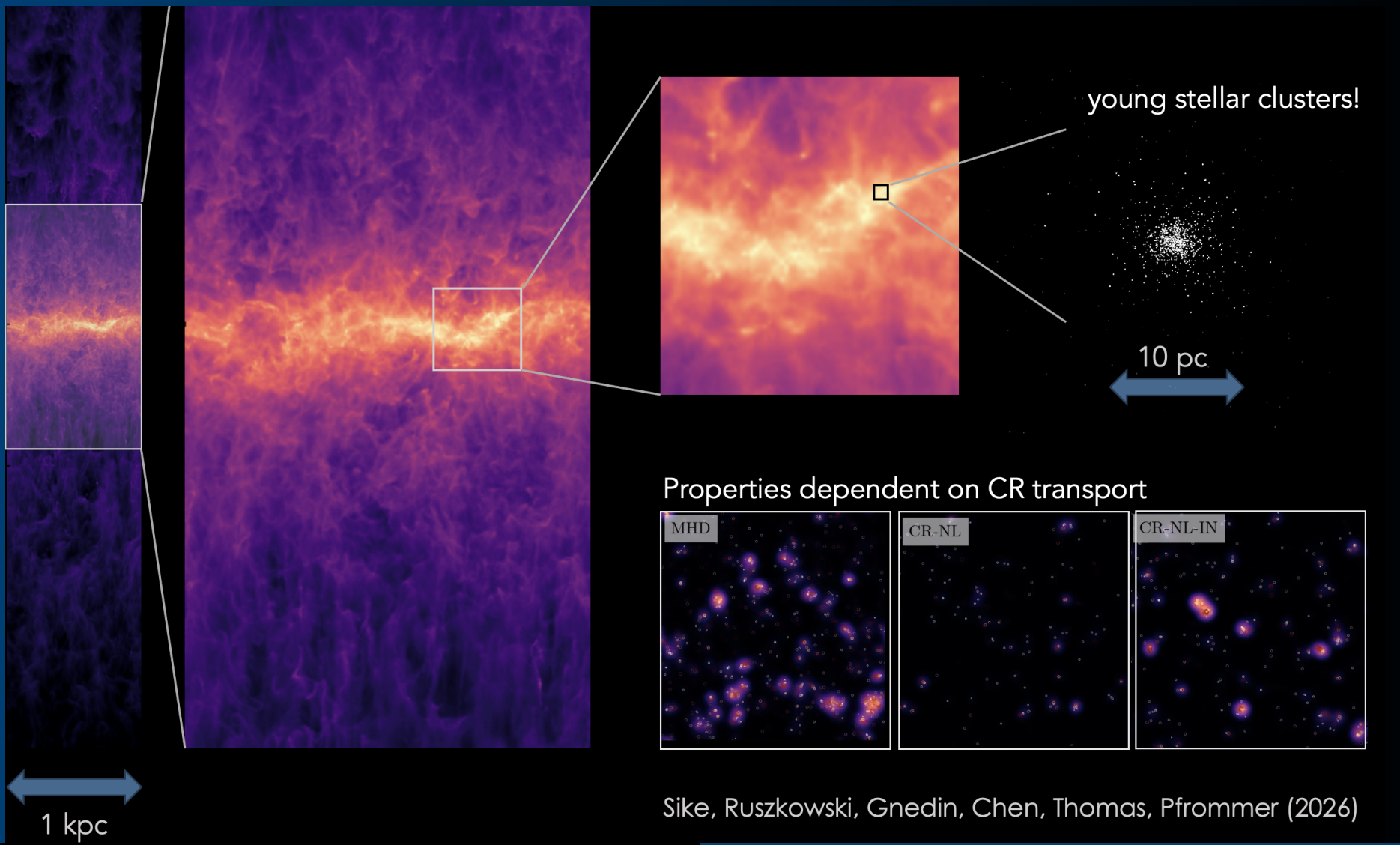
CR feedback mildly suppresses star formation





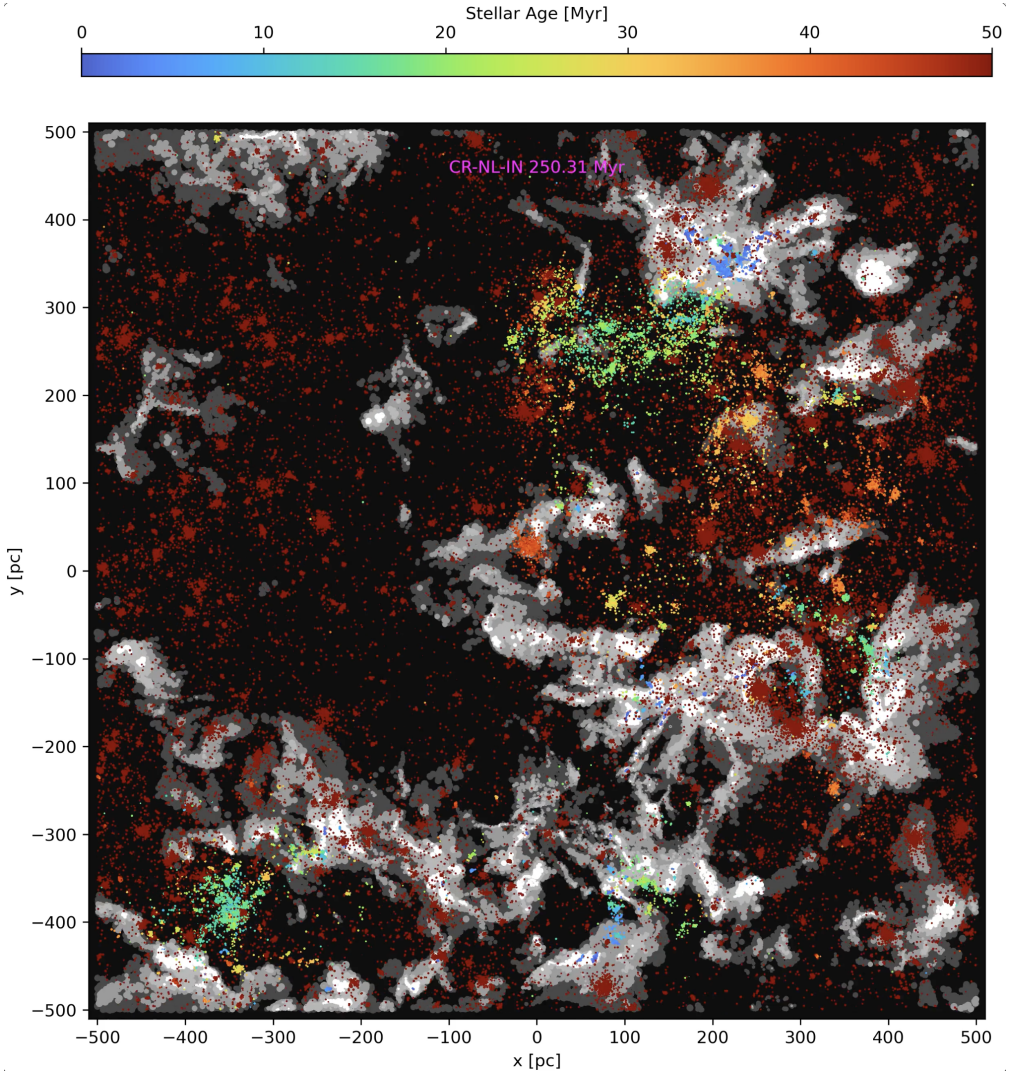
Sike+ (2025)

Molecular cloud and star cluster formation



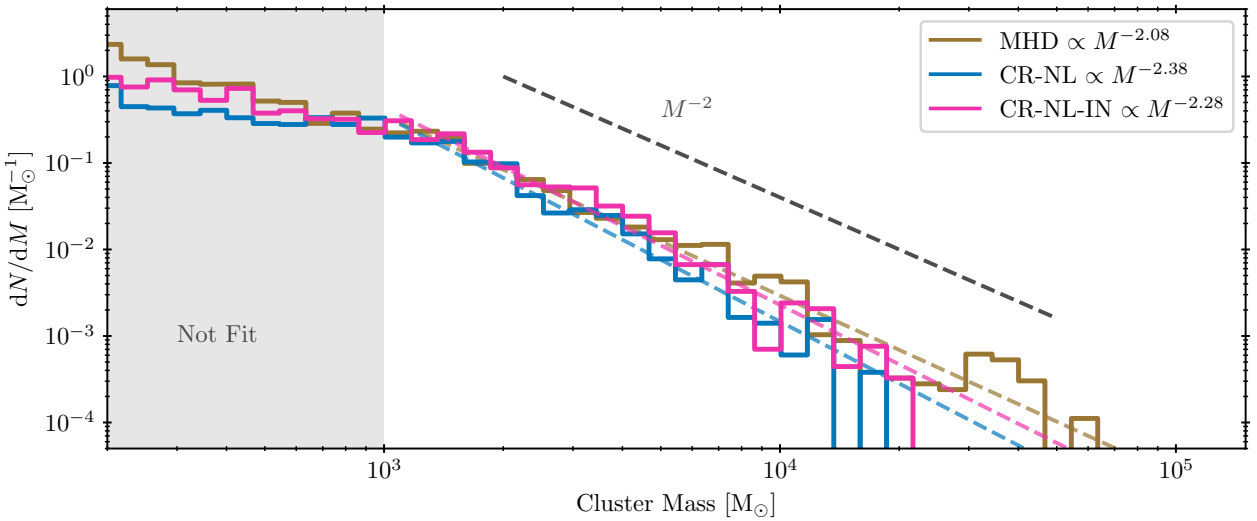
Sike, Ruszkowski, Gnedin, Chen, Thomas, Pfrommer (2026)

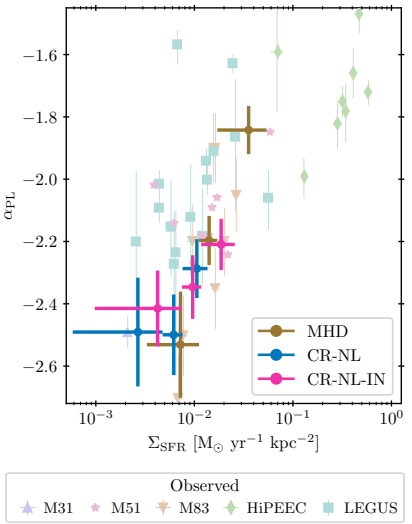
Molecular cloud and star cluster formation



Sike+ (2026)

Star cluster mass function

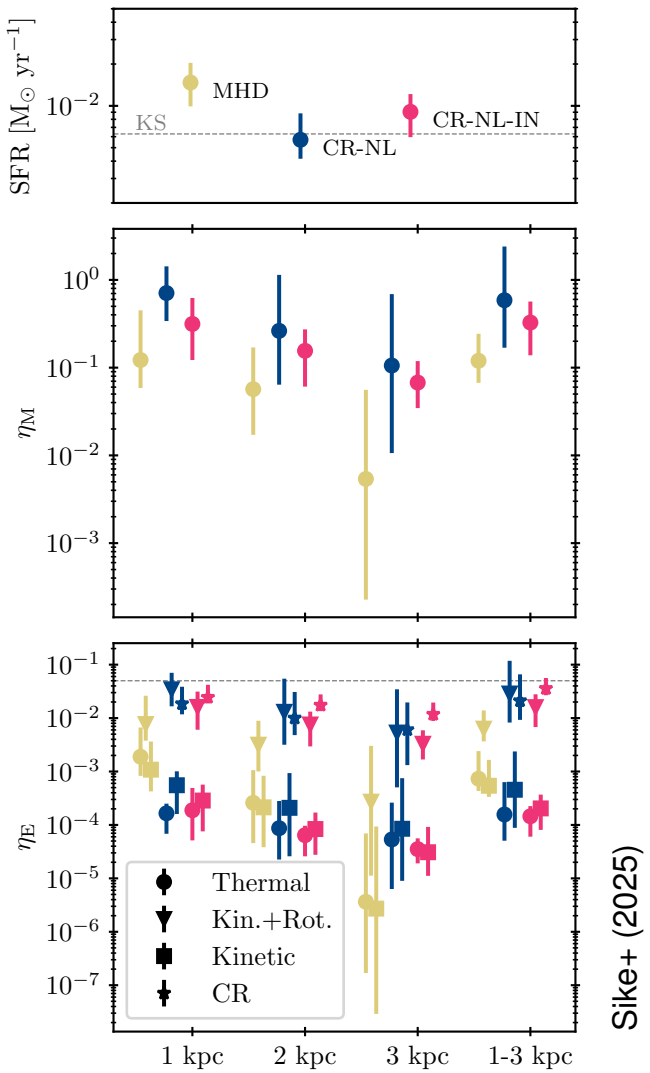




Sike+ (2026)

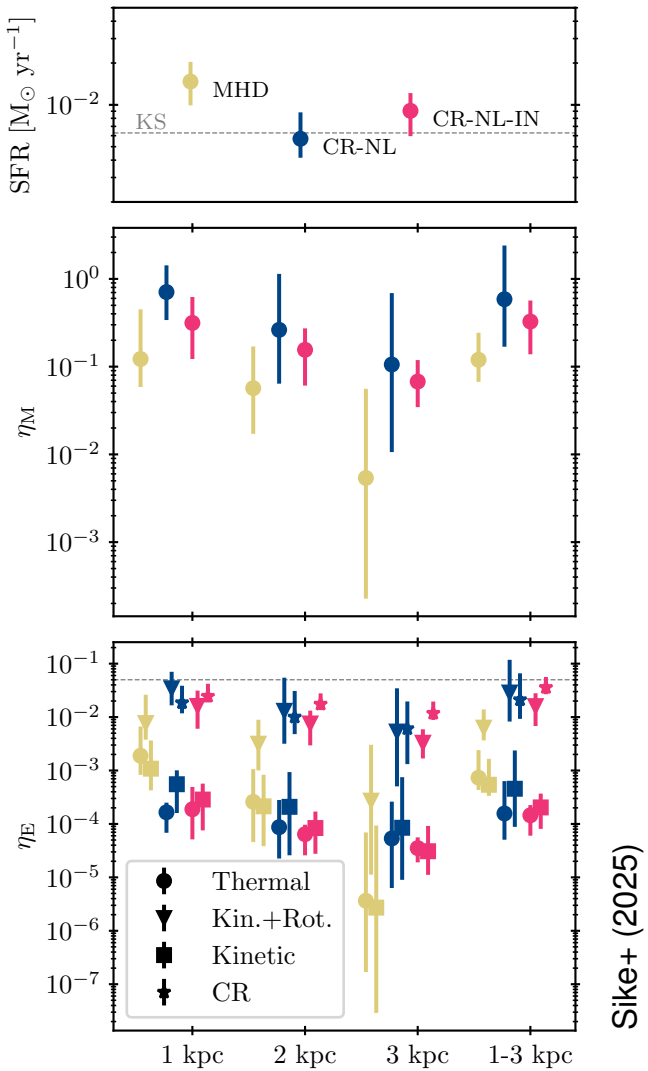
- star cluster mass function of young clusters similar for all models
- power-law slow agrees with observational data

Mass and energy loading factors



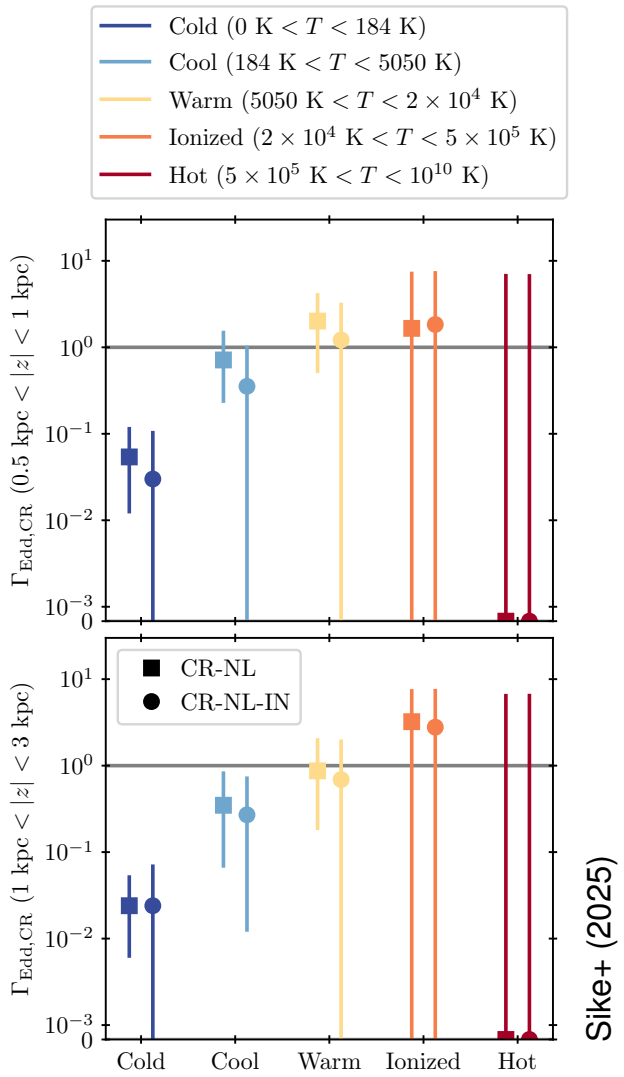
- MHD fountains self-regulate the ISM: mass/energy loading factors decrease steeply with height
- CR-driven mass loading factors 3-5 time larger than MHD case

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 ($\boldsymbol{v}_{\mathrm{kin+rot}} = \boldsymbol{v} + \boldsymbol{v}_{\mathrm{rot}}$)

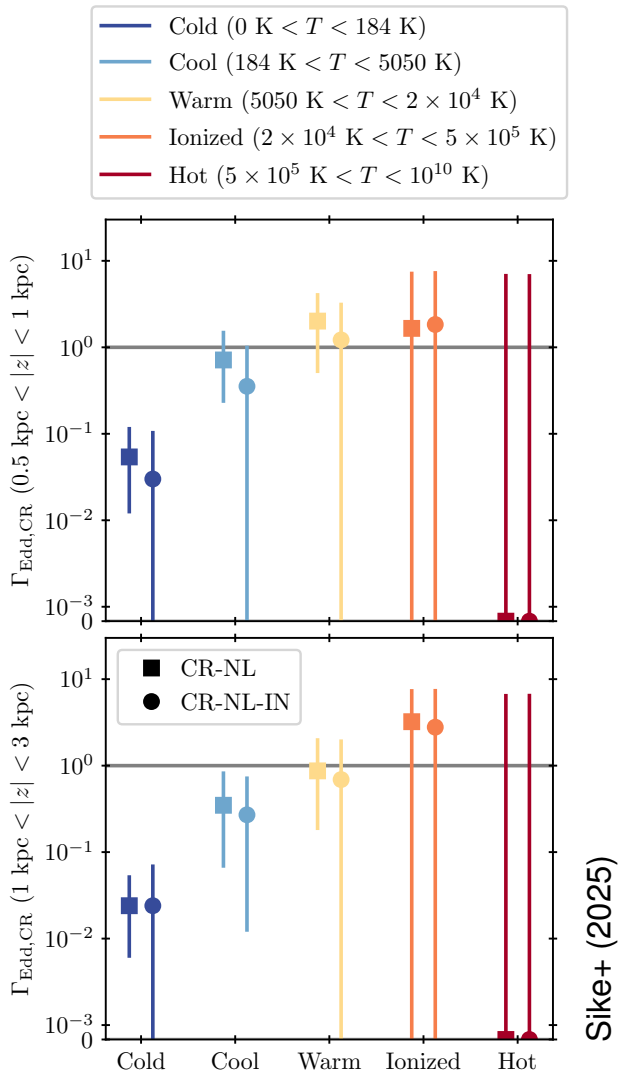
CR Eddington factors for different ISM phases



- 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



- CR Eddington factors:

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

- 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

Conclusions for cosmic ray physics in galaxies

CR magneto-hydrodynamics:

- novel theory of CR transport mediated by Alfvén waves developed and coupled to magneto-hydrodynamics
- self-generated diffusion coefficient emerges from CR-wave interactions

Conclusions for cosmic ray physics in galaxies

CR magneto-hydrodynamics:

- novel theory of CR transport mediated by Alfvén waves developed and coupled to magneto-hydrodynamics
- self-generated diffusion coefficient emerges from CR-wave interactions

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



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).

Literature for the talk – 1

CR-driven plasma instabilities:

- Shalaby, Thomas, Pfrommer, *A new cosmic ray-driven instability,* 2021, ApJ, 908, 206.
- Shalaby, Thomas, Pfrommer, Lemmerz, Bresci, *Deciphering the physical basis of the intermediate-scale instability,* 2023, JPP Letters, 89, 175890603.
- Lemmerz, Shalaby, Pfrommer, Thomas, *The theory of resonant cosmic ray-driven instabilities – Growth and saturation of single modes,* 2025, ApJ, 979, 34.

CR hydrodynamics:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, MNRAS, 465, 4500.
- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2019, MNRAS, 485, 2977.
- Thomas, Pfrommer, Pakmor, *A finite volume method for two-moment cosmic-ray hydrodynamics on a moving mesh,* 2021, MNRAS, 503, 2242.

AIP

Literature for the talk – 2

CR feedback in galaxy formation and the ISM:

- Ruszkowski, Pfrommer, *Cosmic ray feedback in galaxies and galaxy clusters,* 2023, Astron Astrophys Rev, 31, 4.
- Thomas, Pfrommer, Pakmor, *Cosmic ray-driven galactic winds: transport modes of cosmic rays and Alfvén-wave dark regions,* 2023, MNRAS, 521, 3023.
- Thomas, Pfrommer, Pakmor, *Why are thermally- and cosmic ray-driven galactic winds fundamentally different?* 2025, A&A, 698, A104.
- Thomas, Pfrommer, Pakmor, Lemmerz, Shalaby, *Effective cosmic ray diffusion in multiphase galactic environments,* 2026, A&A, in print, arXiv:2510.16125.
- Sike, Thomas, Ruszkowski, Pfrommer, Weber, *Cosmic Ray-Driven Galactic Winds with Resolved ISM and Ion-Neutral Damping, 2025, ApJ, 987, 204.*
- *Sike, Ruszkowski, Gnedin, Chen, Weber, Thomas, Pfrommer,* Resolving Star Cluster Formation in Galaxy Simulations with Cosmic Ray Feedback, 2026, ApJ, 1004 236.

