

Bridging microscopic and macroscopic cosmic ray transport in galaxies

Christoph Pfrommer[1]

in collaboration with

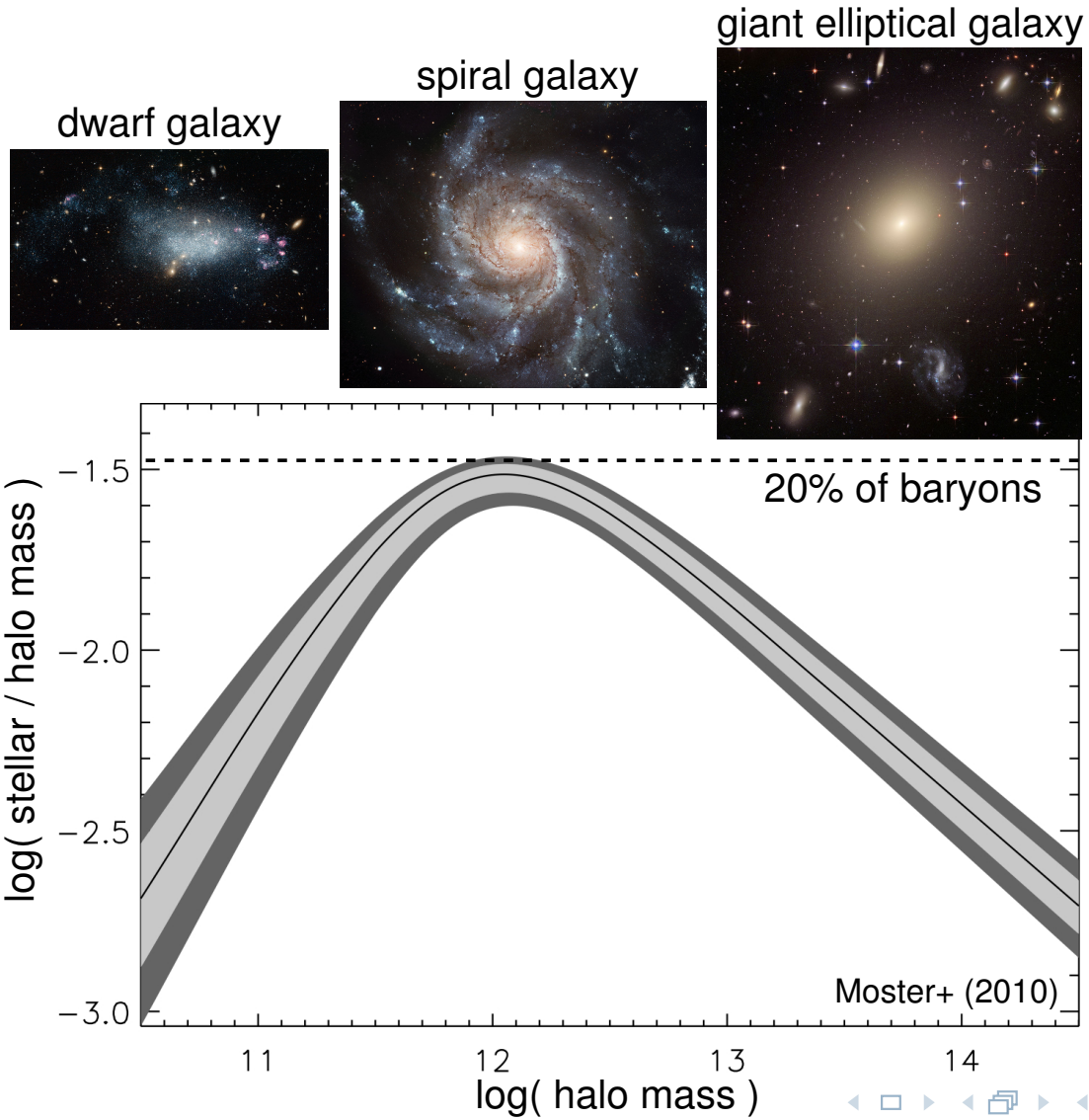
PhD students: Dusch,[1] Jlassi,[1] Kalangadan,[1] Pisharody,[1] Tevlin,[1] Weber,[1] Chiu,[2] Sike[2]
Postdocs: Berlok,[3] Girichidis,[4] **Lemmerz,**[5] Meenakshi,[1] Perrone,[1] Shalaby,[6] **Thomas,**[1] Werhahn,[7] Whittingham[1]
Faculty: Pakmor,[7] Puchwein,[1] Weinberger,[1] Ruszkowski,[2] Springel,[7]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

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

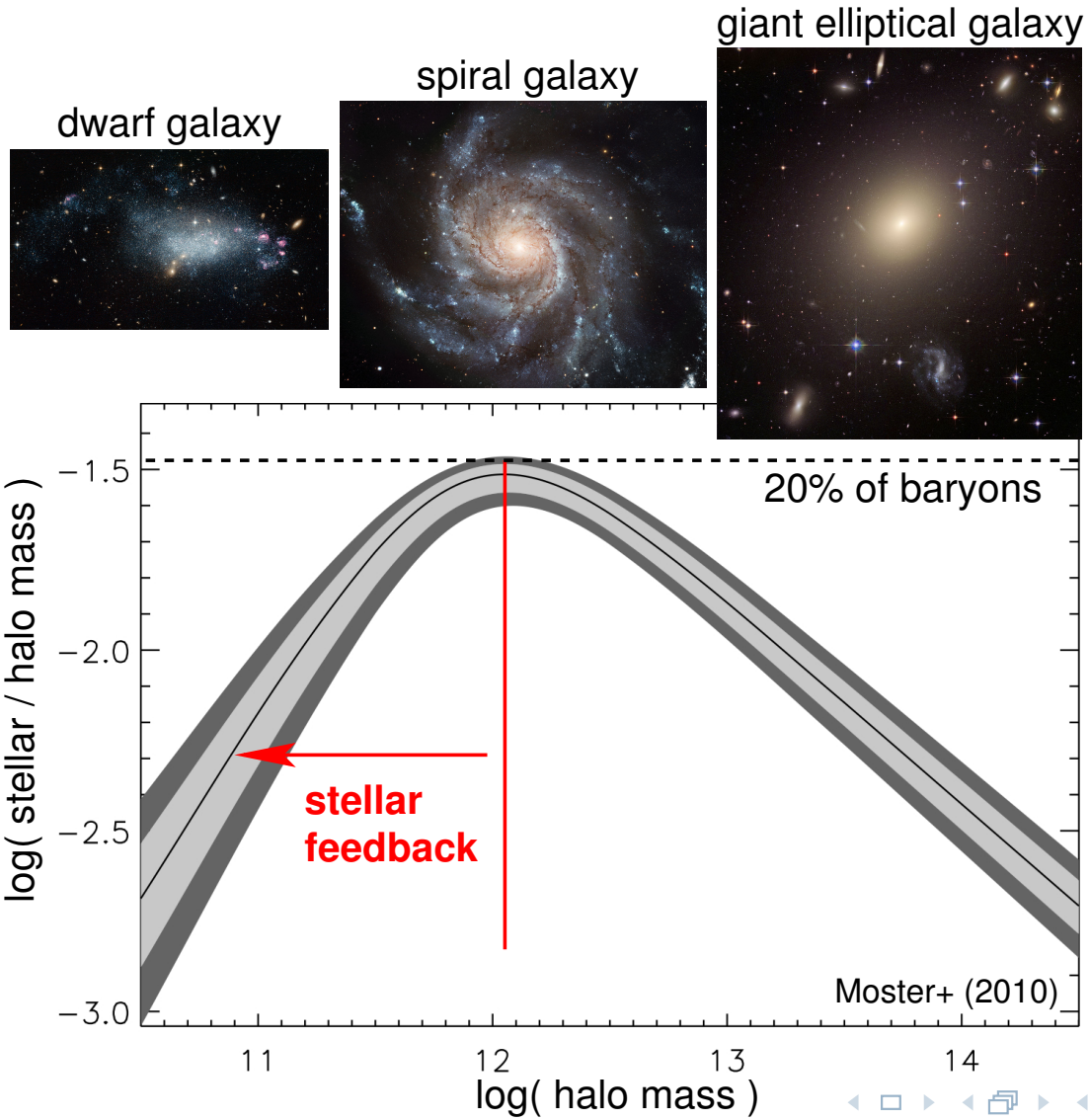
PohlFest, DESY Zeuthen, 2026



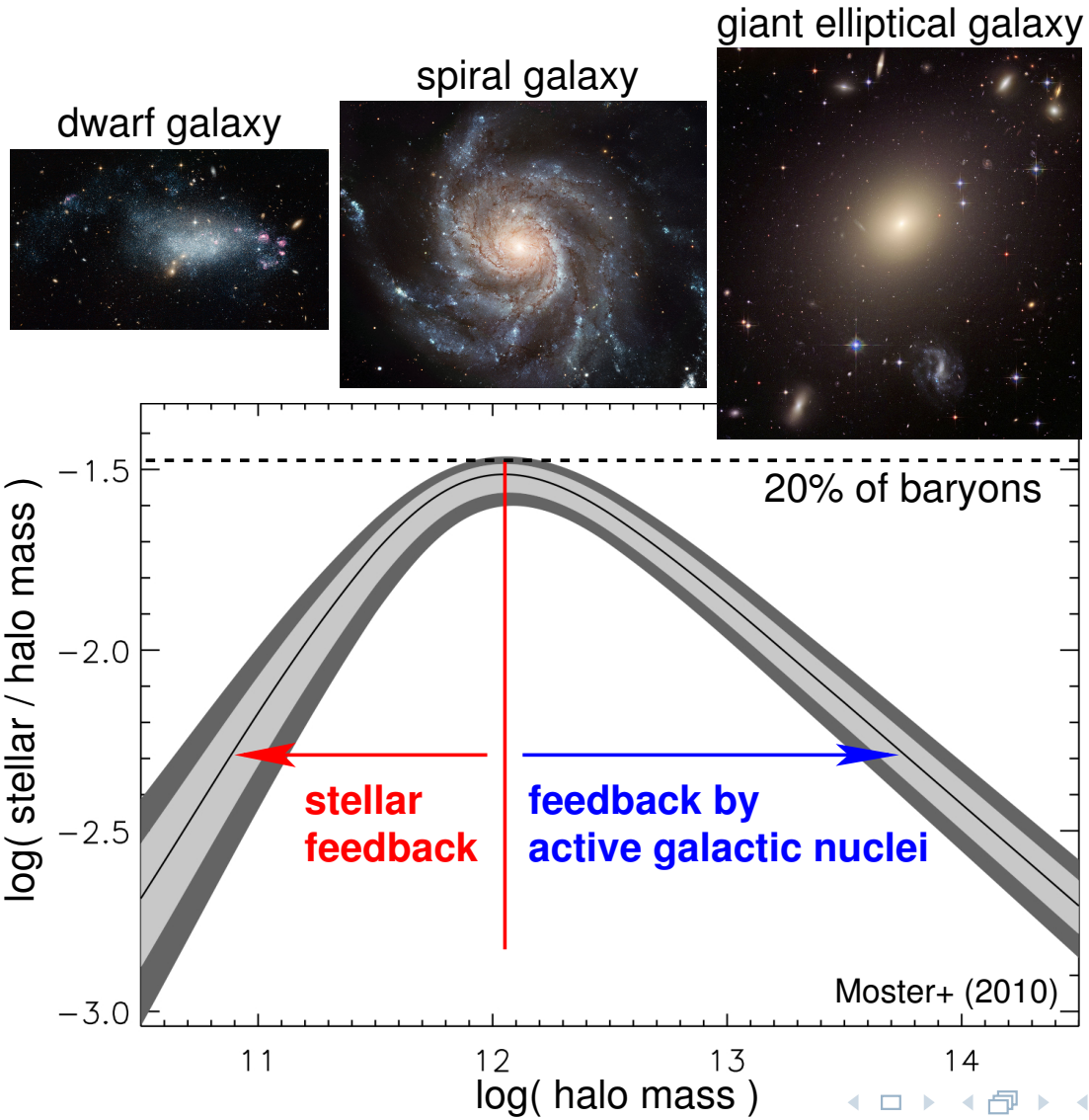
Puzzles in galaxy formation



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

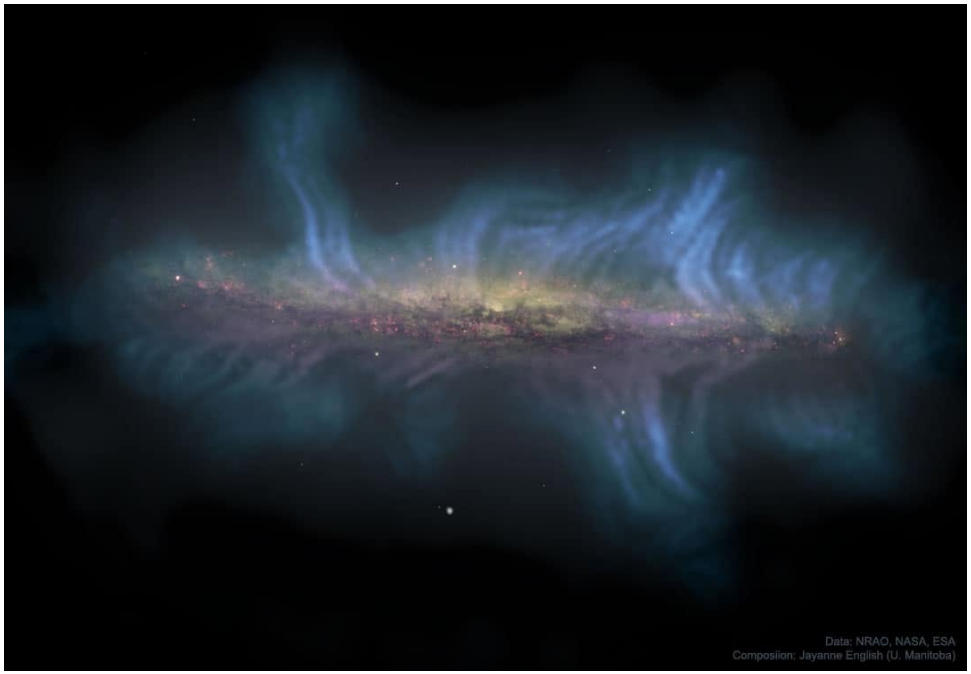
NASA/JPL-Caltech/STScI/CXC/UofA

- 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"

AIP

Review on cosmic ray feedback

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

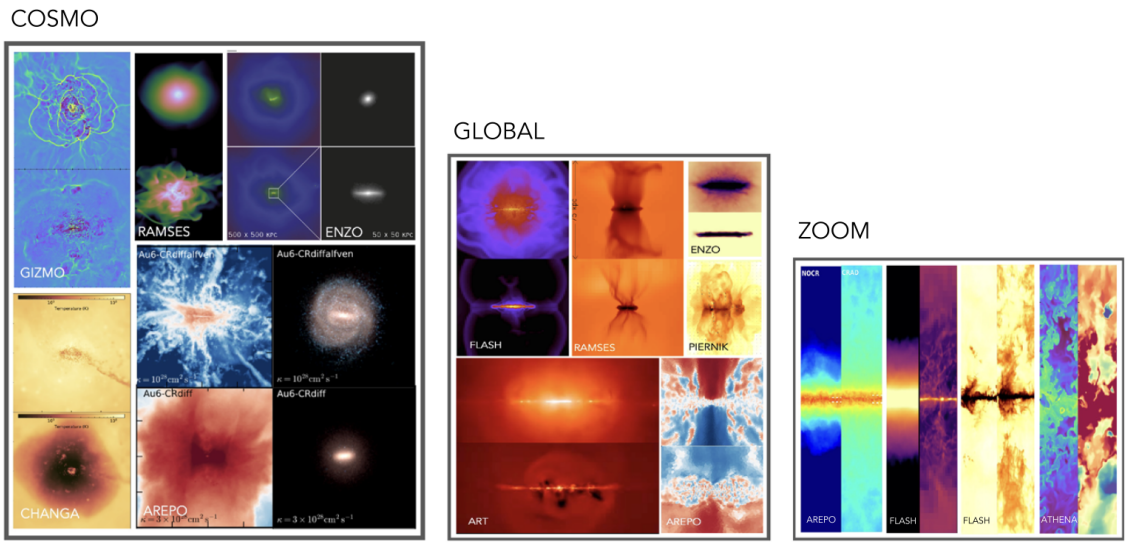
REVIEW ARTICLE

Check for updates

Cosmic ray feedback in galaxies and galaxy clusters

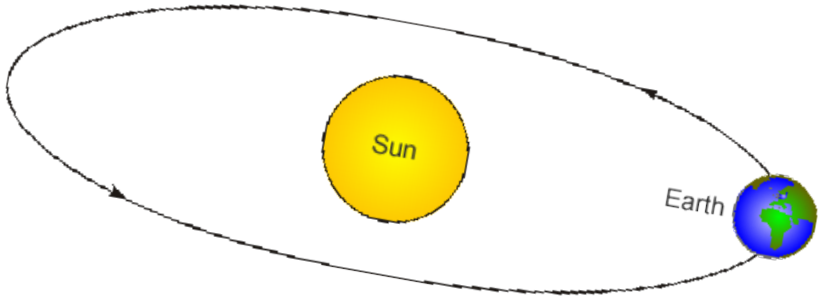
A pedagogical introduction and a topical review of the acceleration, transport, observables, and dynamical impact of cosmic rays

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



Cosmic ray transport: an extreme multi-scale problem





Milky Way-like galaxy:

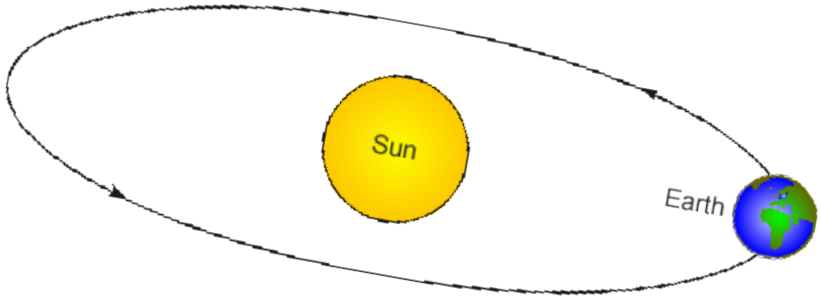
$$r_{\mathrm{gal}} \sim 10^4 \text{ pc}$$

gyro-orbit of GeV CR:

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

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:

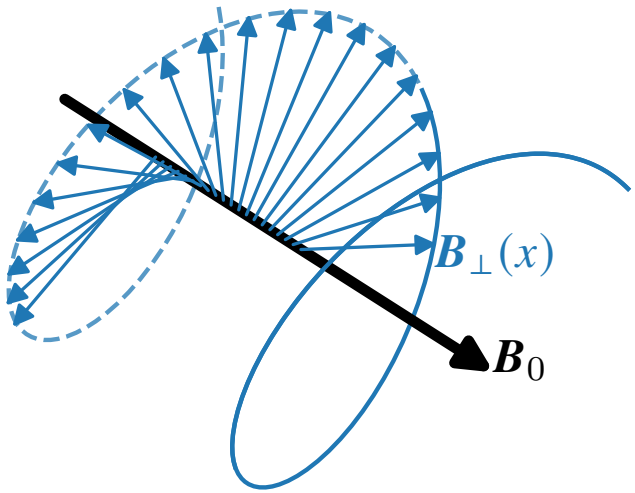
$$r_{\mathrm{cr}} = \frac{p_\perp}{e\,B_{\mu\mathrm{G}}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

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

Zweibel (2017), Thomas & CP (2019)

What is gyro resonance?

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

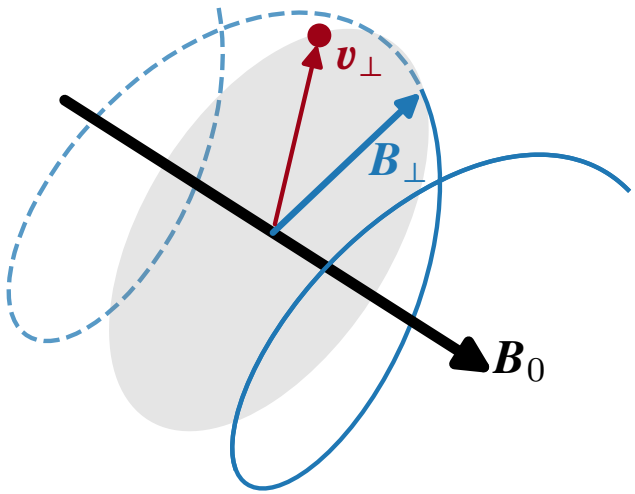


What is gyro resonance?

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

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

Ω_{cr} gyration frequency



AIP

What is gyro resonance?

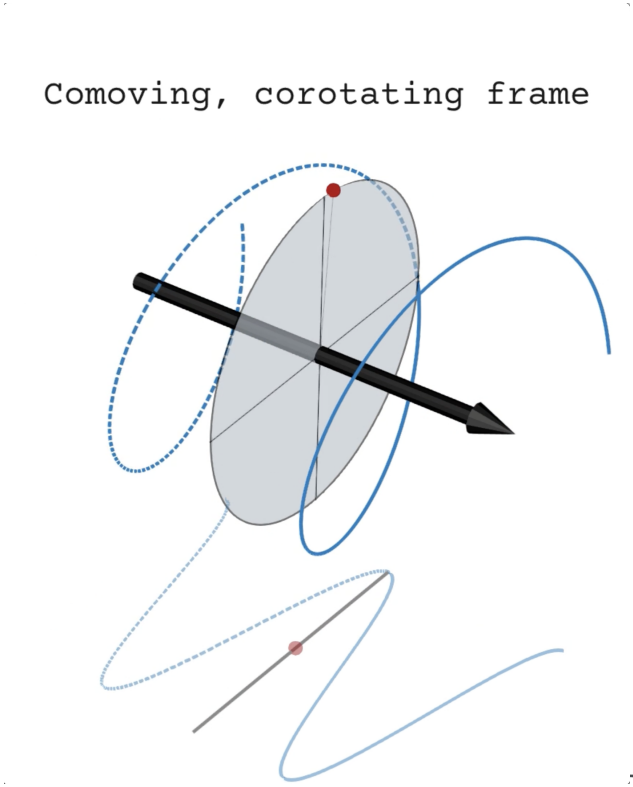
plane wave: $\exp(-ik(x - v_{\text{wave}}t))$

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 $\boldsymbol{B}_0$

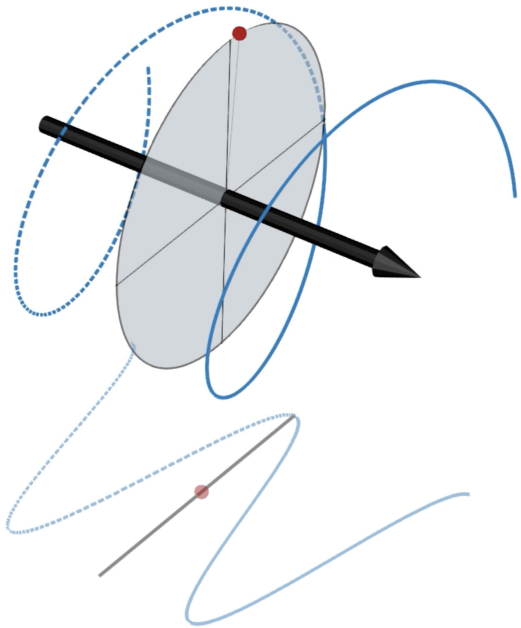
Ω_{cr} gyration frequency

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!

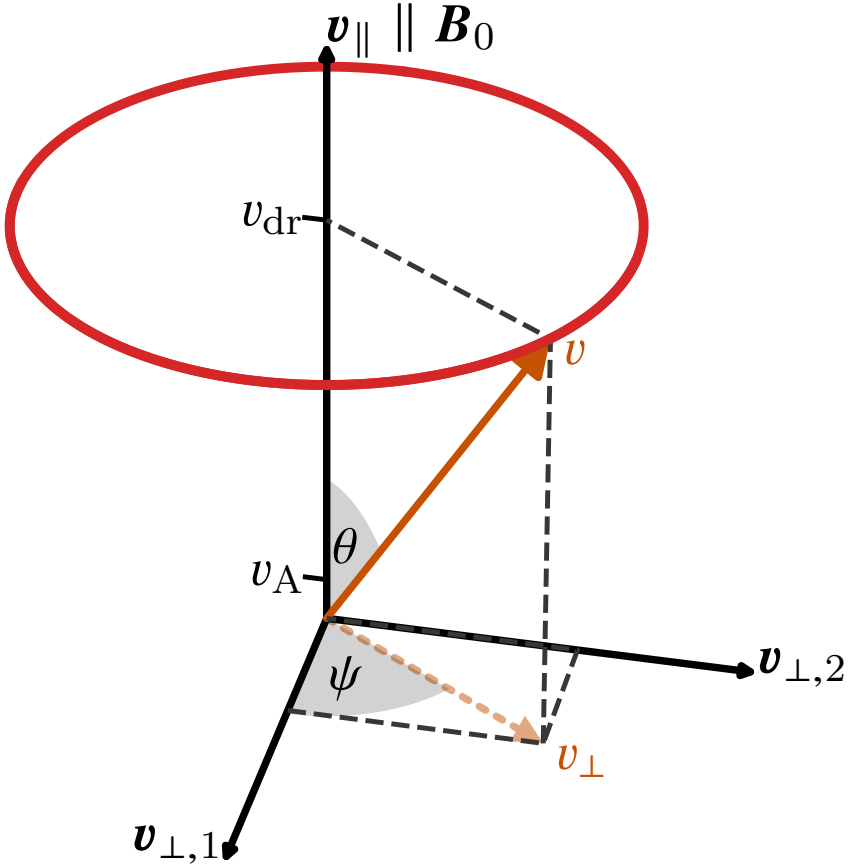
Comoving, corotating frame



test particle without interactions!

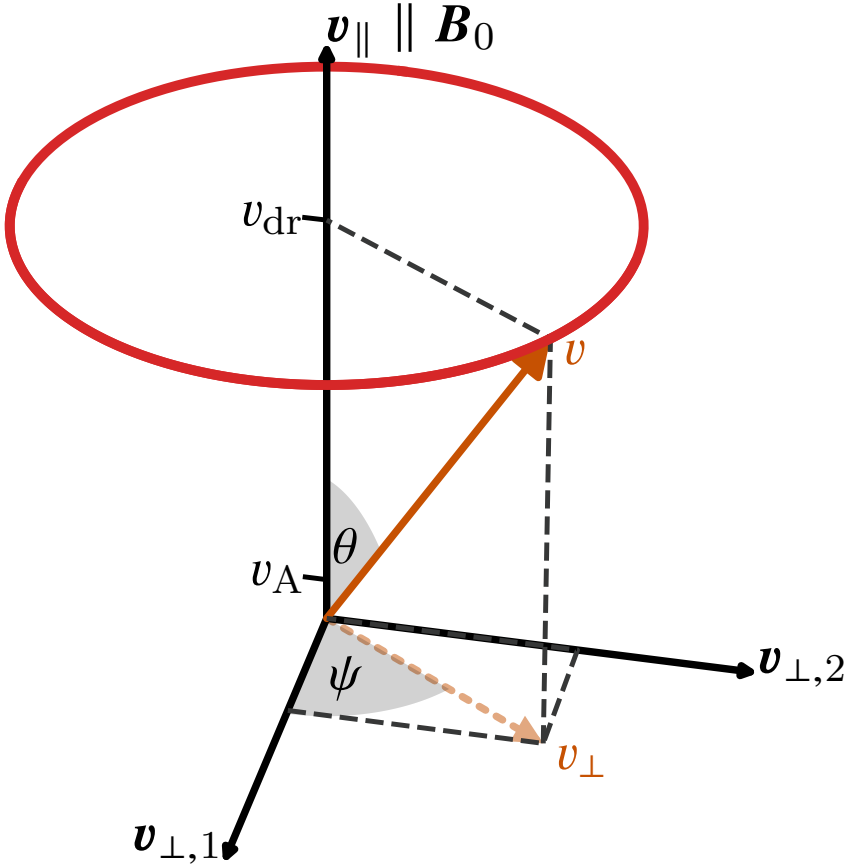
AIP

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 $v_\perp = 0$

Idealized setup to understand physics



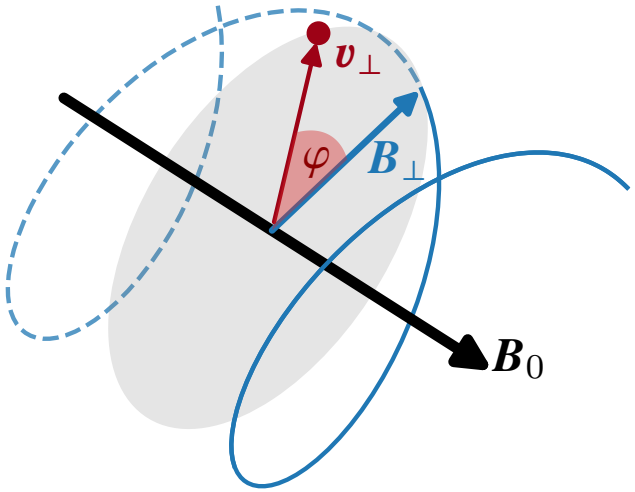
- gyrotropic ring distribution of CR ions with single pitch angle and energy
- neutralizing CR electron beam at same drift speed but $v_\perp = 0$
- background ion and electron fluid with Landau closure
- fluids coupled to particle-in-cell (PIC) CRs via Maxwell's equations

(Lemmerz+ 2024)

AIP

The mechanism of CR-driven instabilities

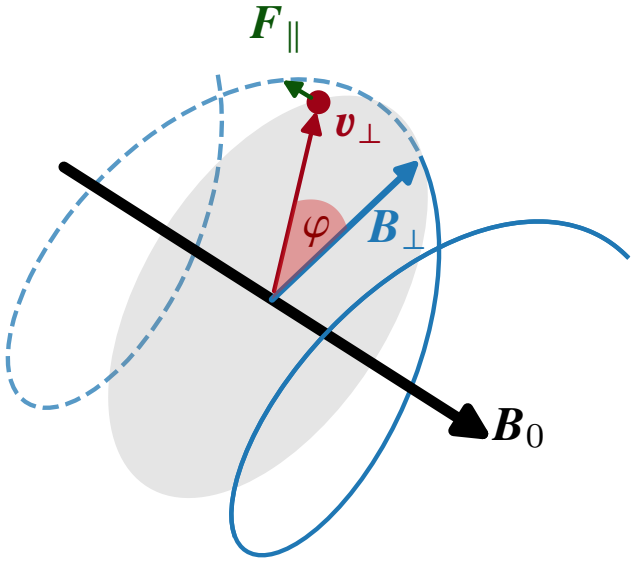
- ***goal:*** understand collective behaviour of many CRs



AIP

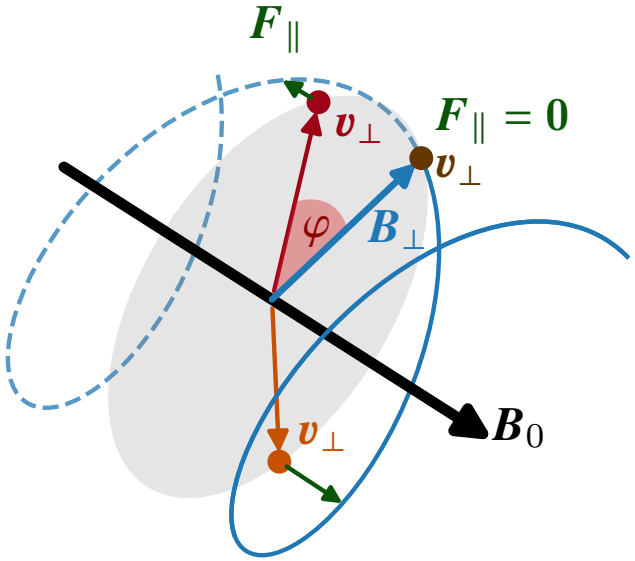
The mechanism of CR-driven instabilities

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



The mechanism of CR-driven instabilities

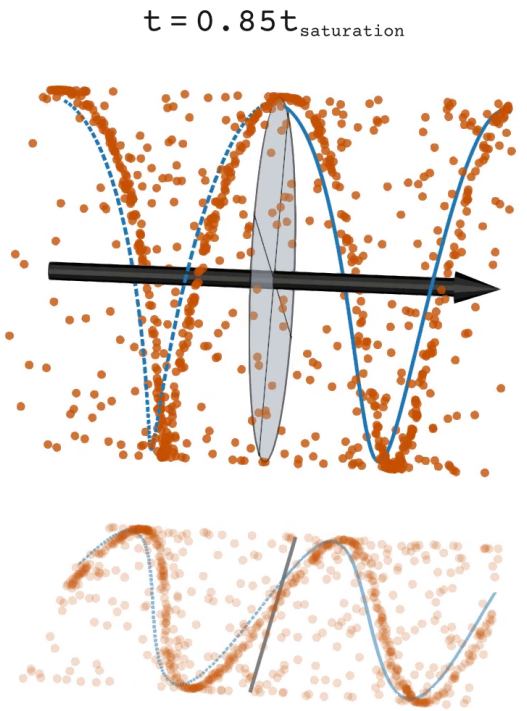
- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field
- CRs align rotational phase with plasma wave



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

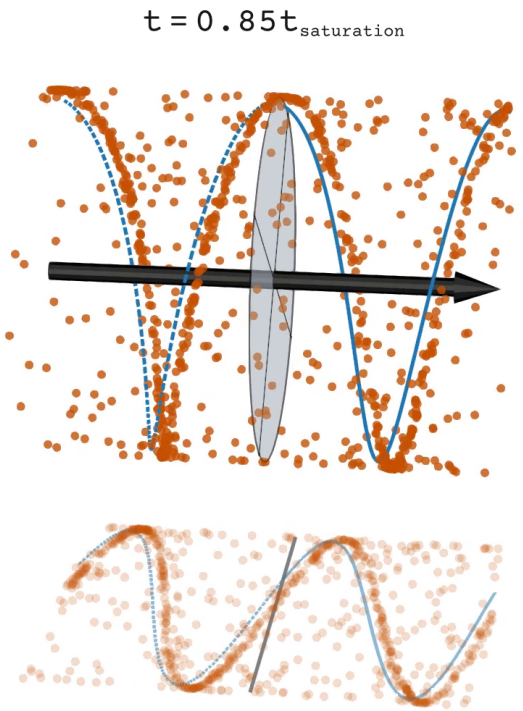


fluid-PIC simulation (Lemmerz+ 2025)

AIP

The mechanism of CR-driven instabilities

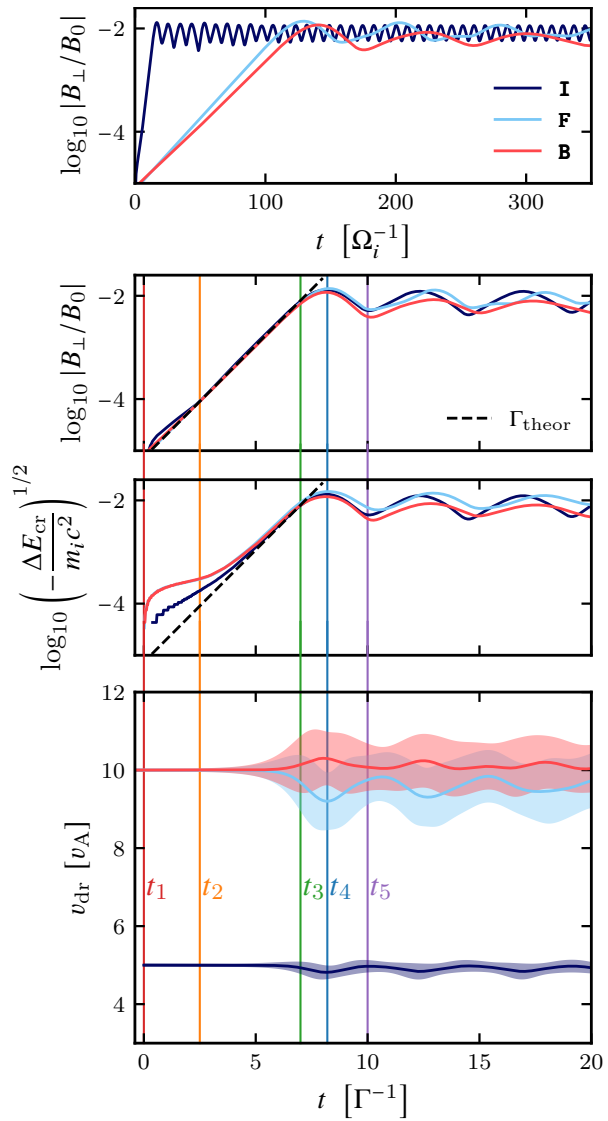
- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field
- CRs align rotational phase with plasma wave
- CR current wave interacts with electro-magnetic wave
- CR trapping in Lorentz force potential saturates instability



fluid-PIC simulation (Lemmerz+ 2025)

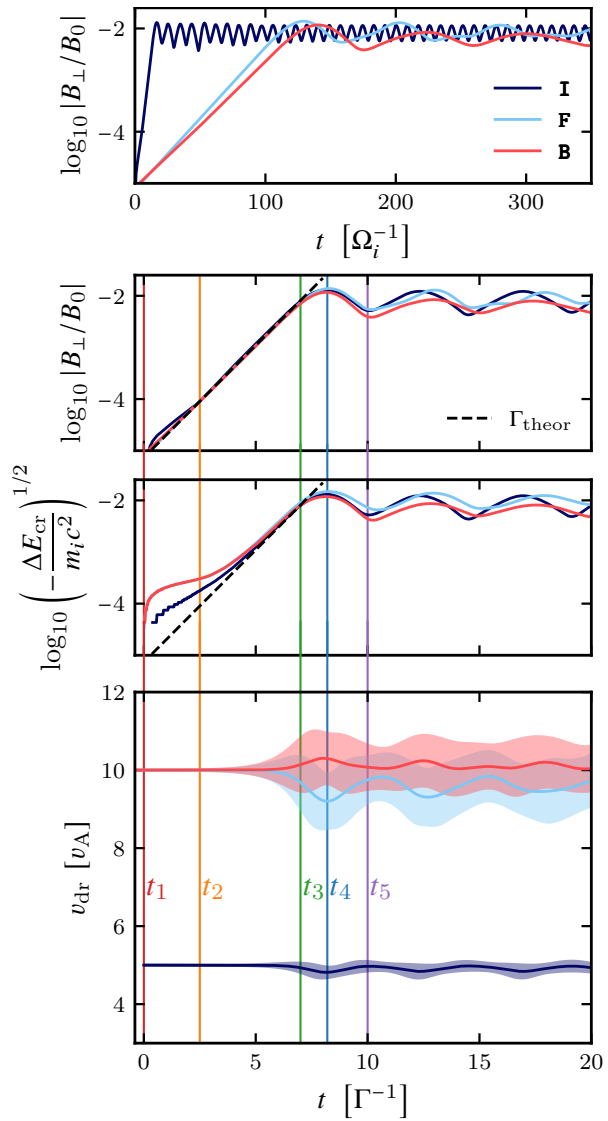
AIP

Resonant wave growth and CR energy loss



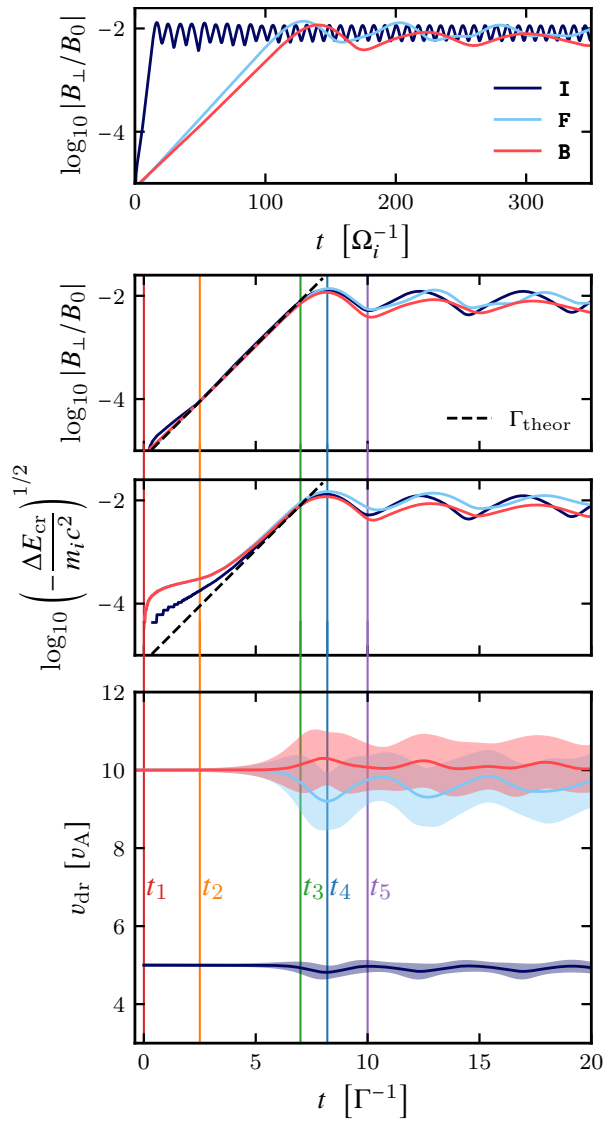
- exponential wave growth in fluid-PIC simulations that excite whistlers (via intermediate-scale instability, `I`), backward (`B`) and forward (`F`) Alfvén waves

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

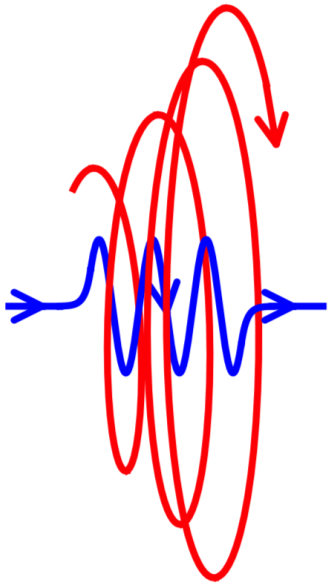
Resonant wave growth and CR energy loss



- 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

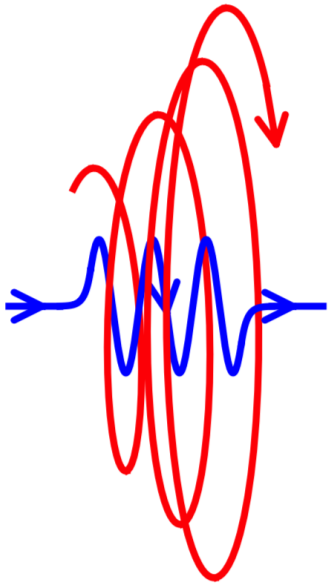
- **CR streaming instability:**
  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)
  - if $v_{\rm cr} > v_{\rm a}$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm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



AIP

Cosmic ray streaming and diffusion

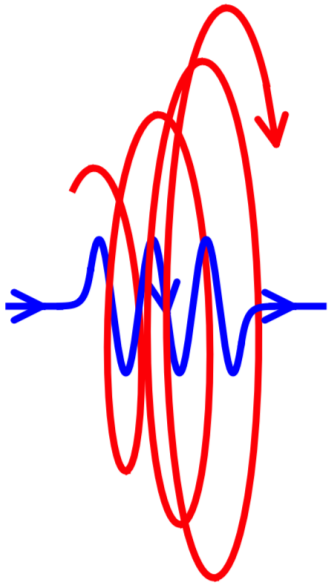
- **CR streaming instability:**
  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)
  - if $v_{\rm cr} > v_{\rm a}$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm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

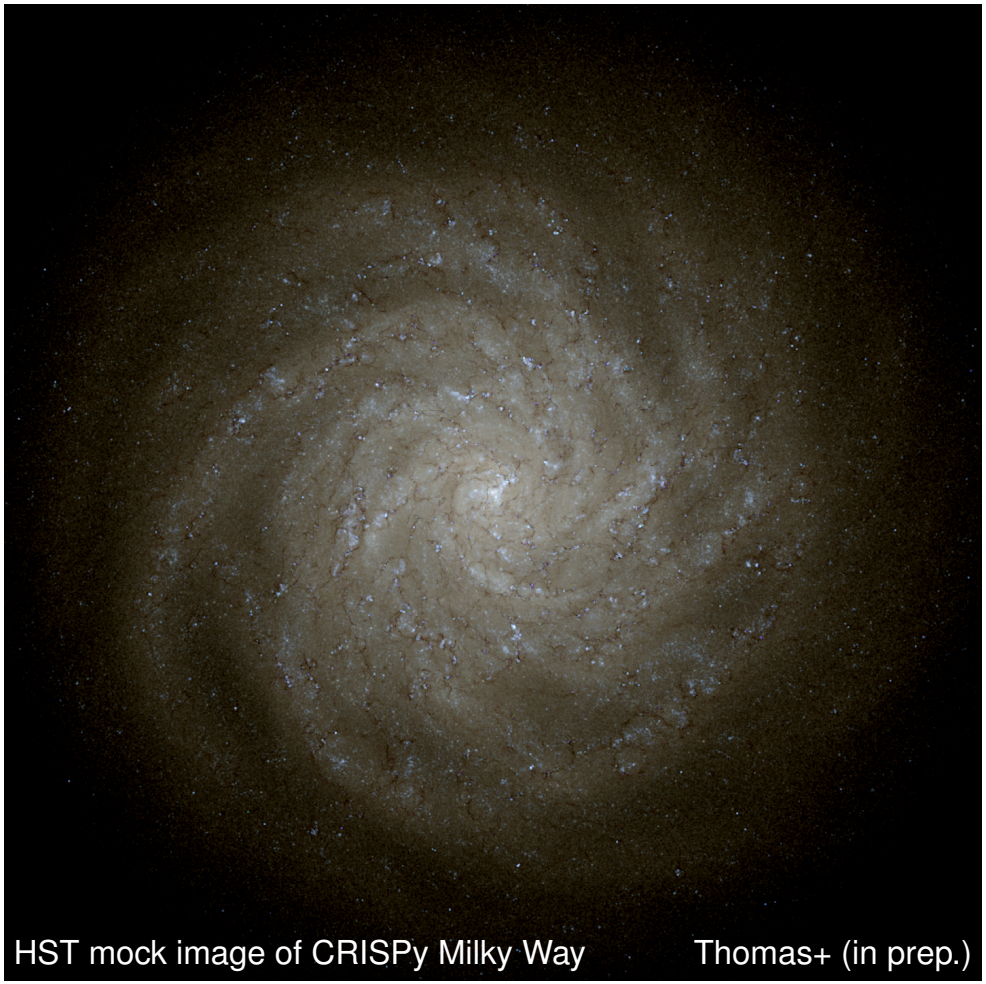


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

AIP

Cosmic ray transport in galaxies


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

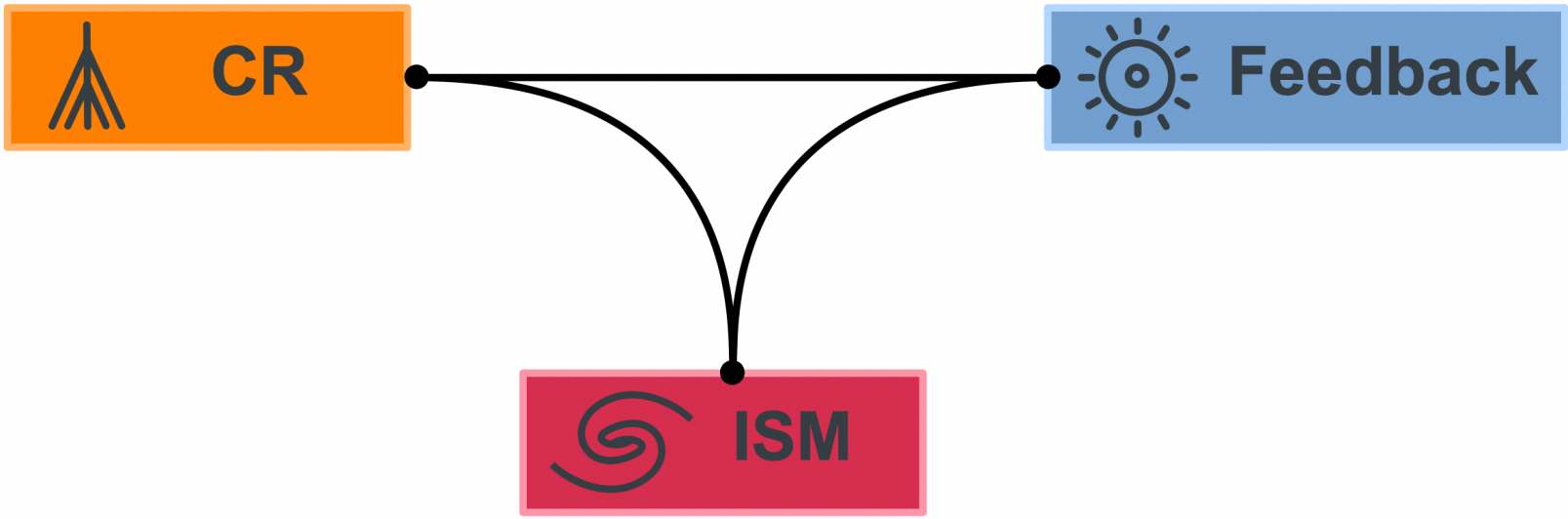
- CR transport in galaxies demands modeling non-linear Landau damping (in warm/hot phase) and ion-neutral damping (in disk)
- this requires resolving the multi-phase structure of the ISM
- development of CRISP framework (**C**osmic **R**ays and **I**nter**S**tellar **P**hysics, Thomas+ 2025)

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



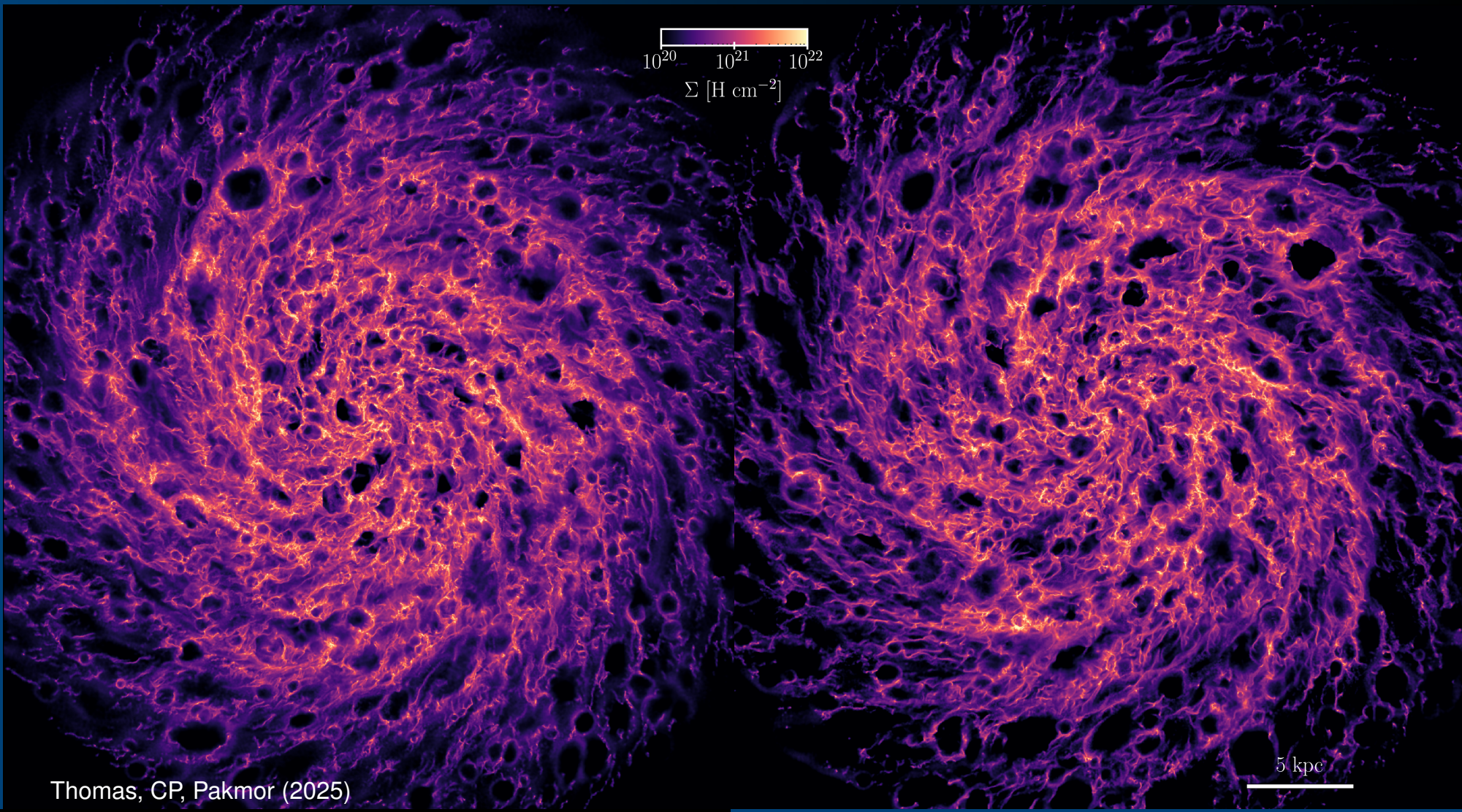




- **Novel CR hydrodynamics**
  coarse graining plasma physics
  - Follow $\varepsilon_{\rm cr}$ and $v_{\rm cr}$
  - Self-consistently evolve $\kappa_{\rm cr}$
- **CR ionization**
  impacting **Chemistry**
- **CR microphysics**

Thomas, CP, Pakmor (2025)

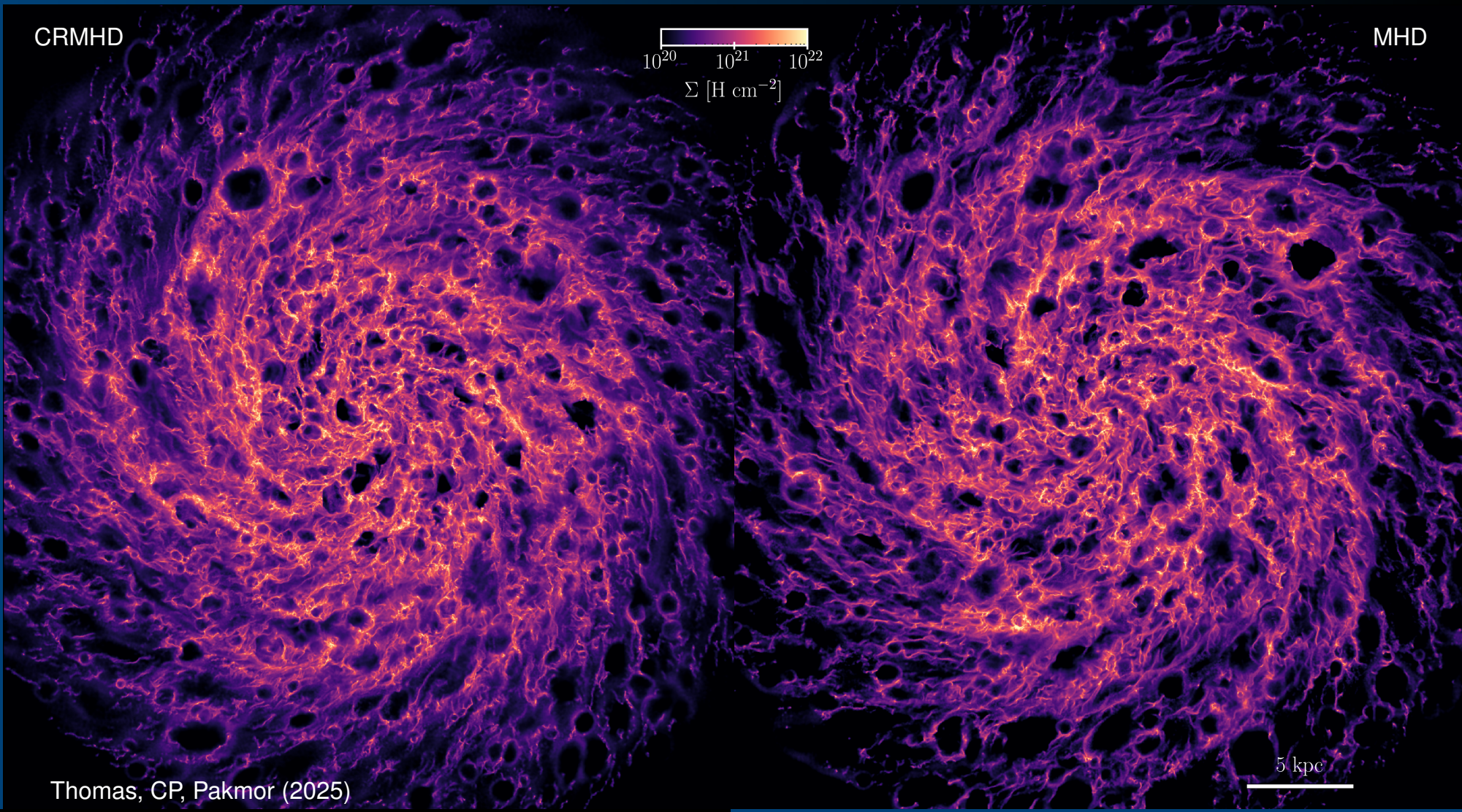
Multi-phase ISM modeling



Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

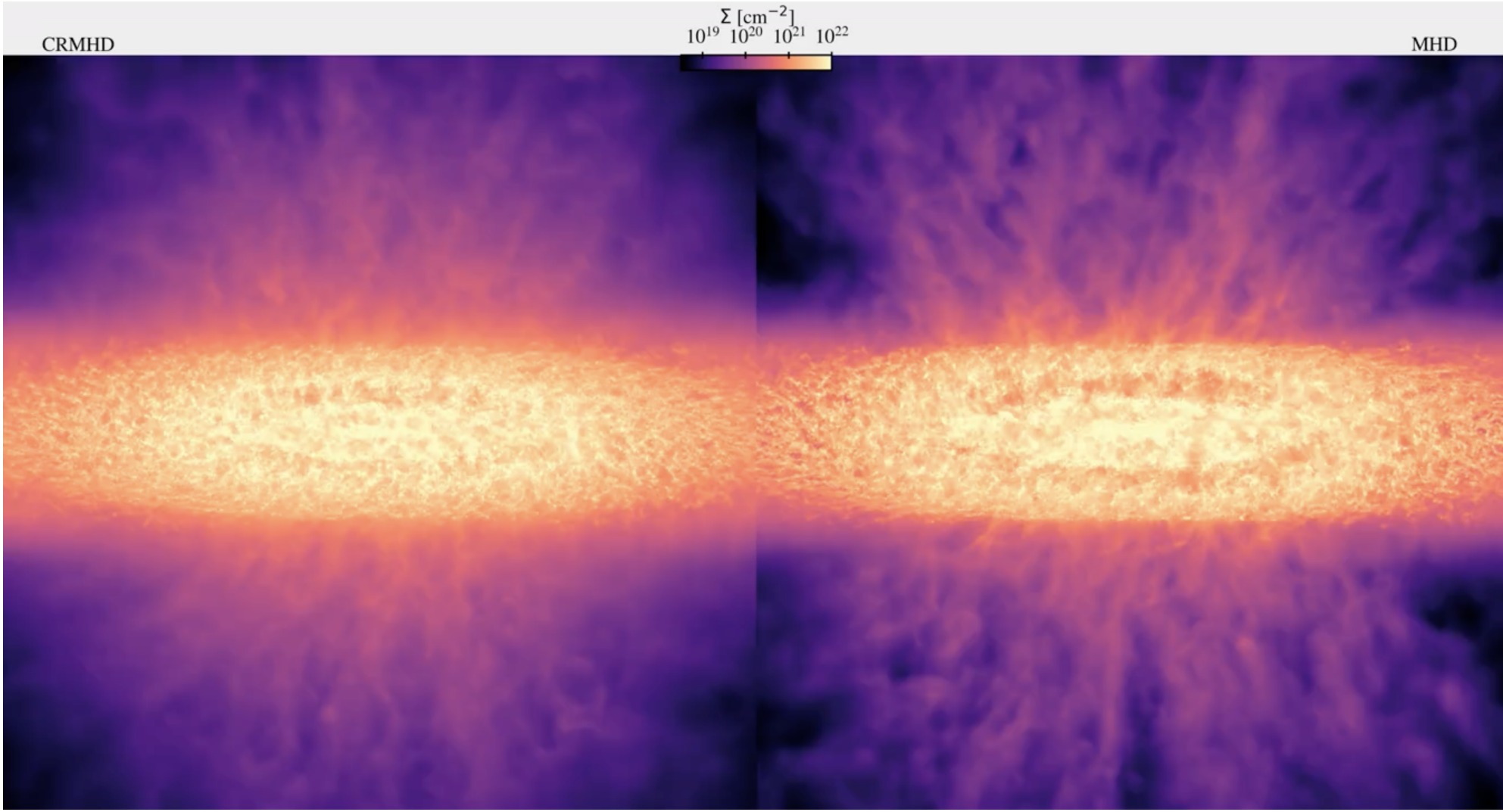
Cosmic rays barely affect the ISM because ion-neutral damping erases Alfvén waves



Thomas, CP, Pakmor (2025)

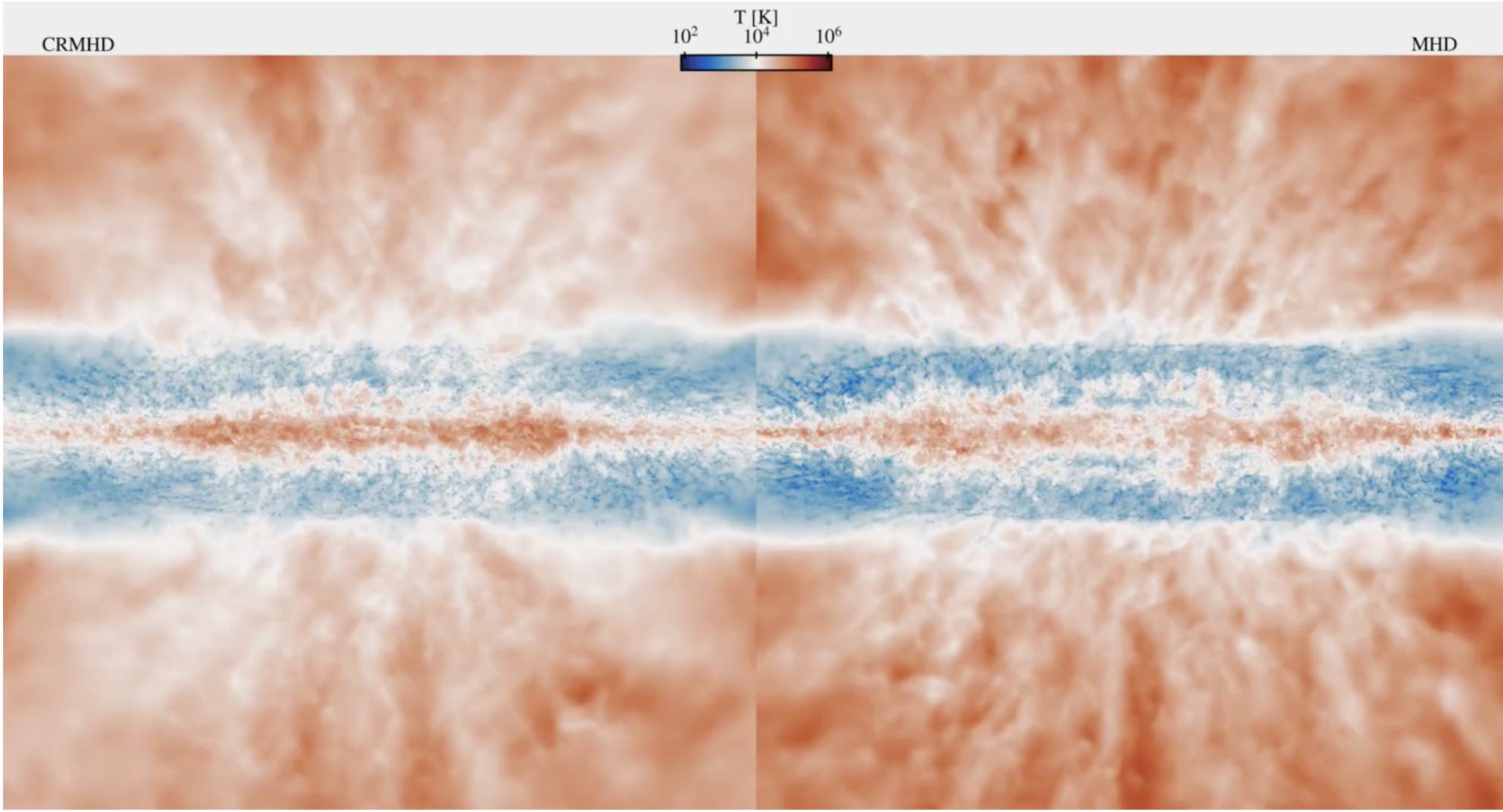
Simulated Milky Way: surface density

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



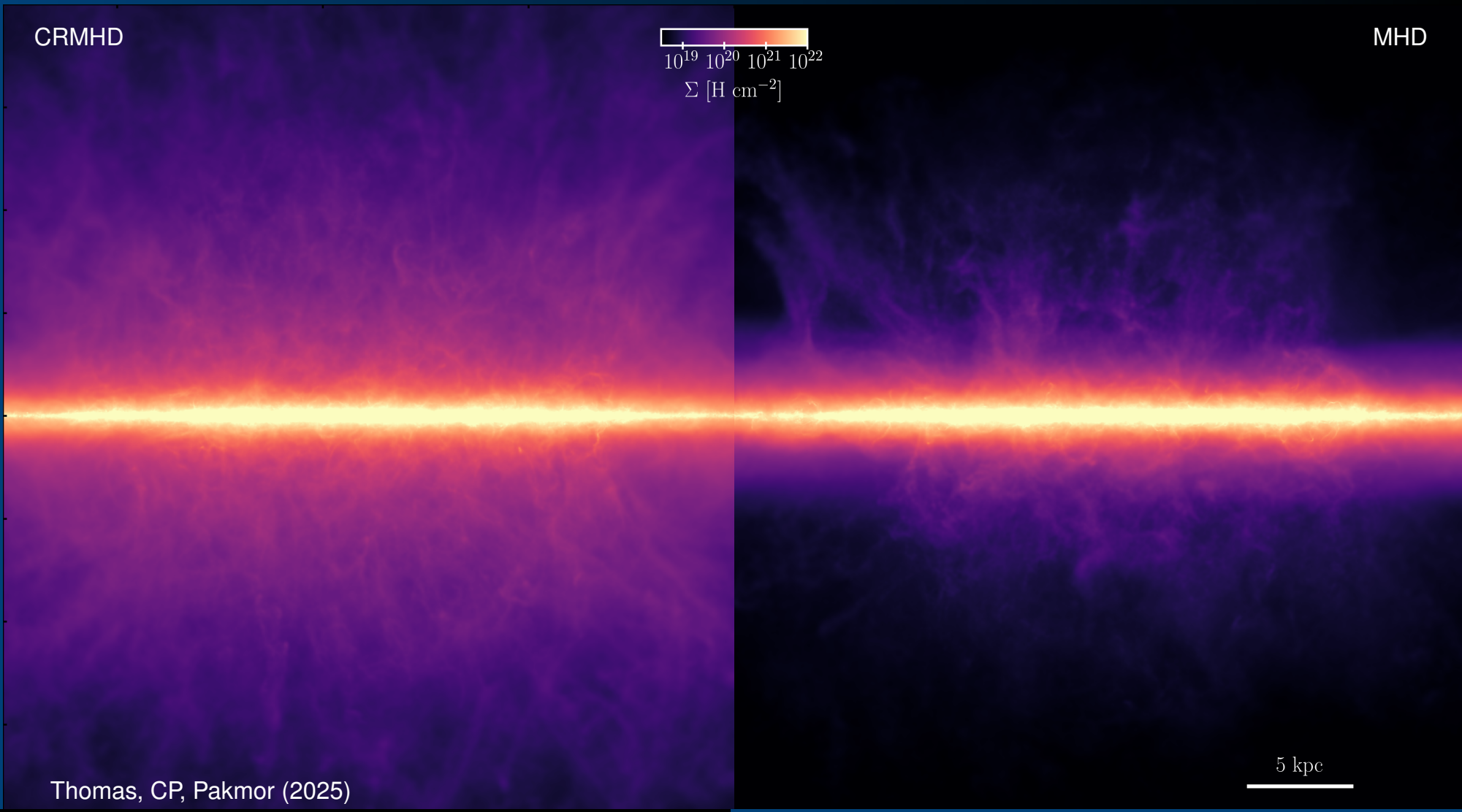
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter



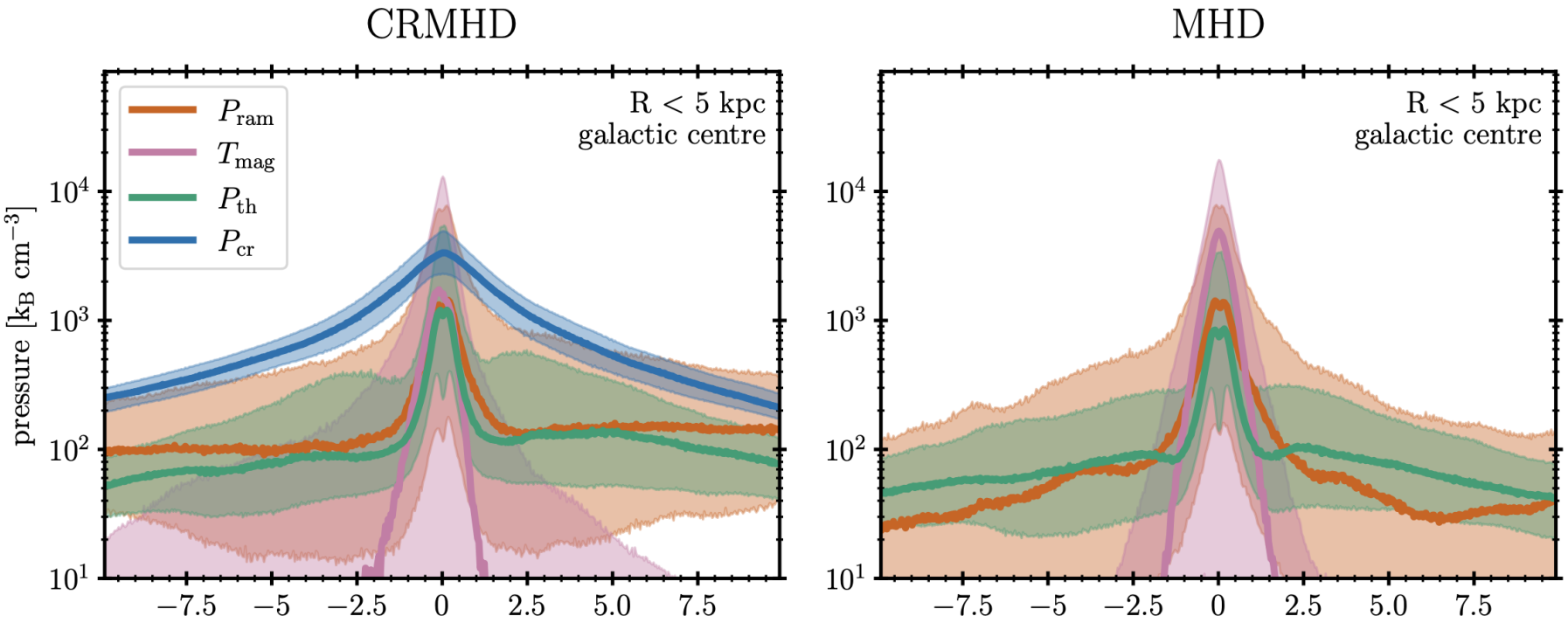
Multi-phase ISM modeling

Cosmic rays make galactic winds much denser



Thomas, CP, Pakmor (2025)

Cosmic ray driven wind: mechanism

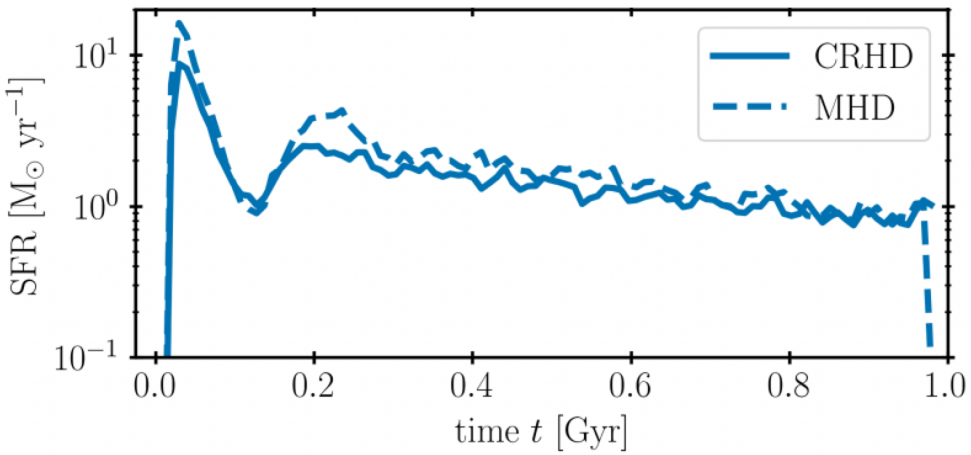


Thomas, CP, Pakmor (2025)

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

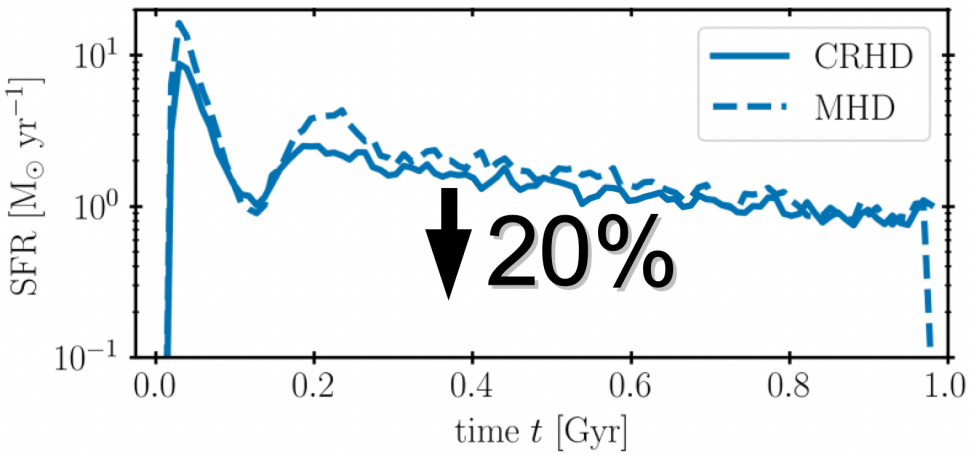
$$|\nabla P_{\rm cr} + \nabla P_{\rm th}| > \rho |\nabla \Phi|$$

Mass and energy loading factors



Thomas, CP, Pakmor (2025)

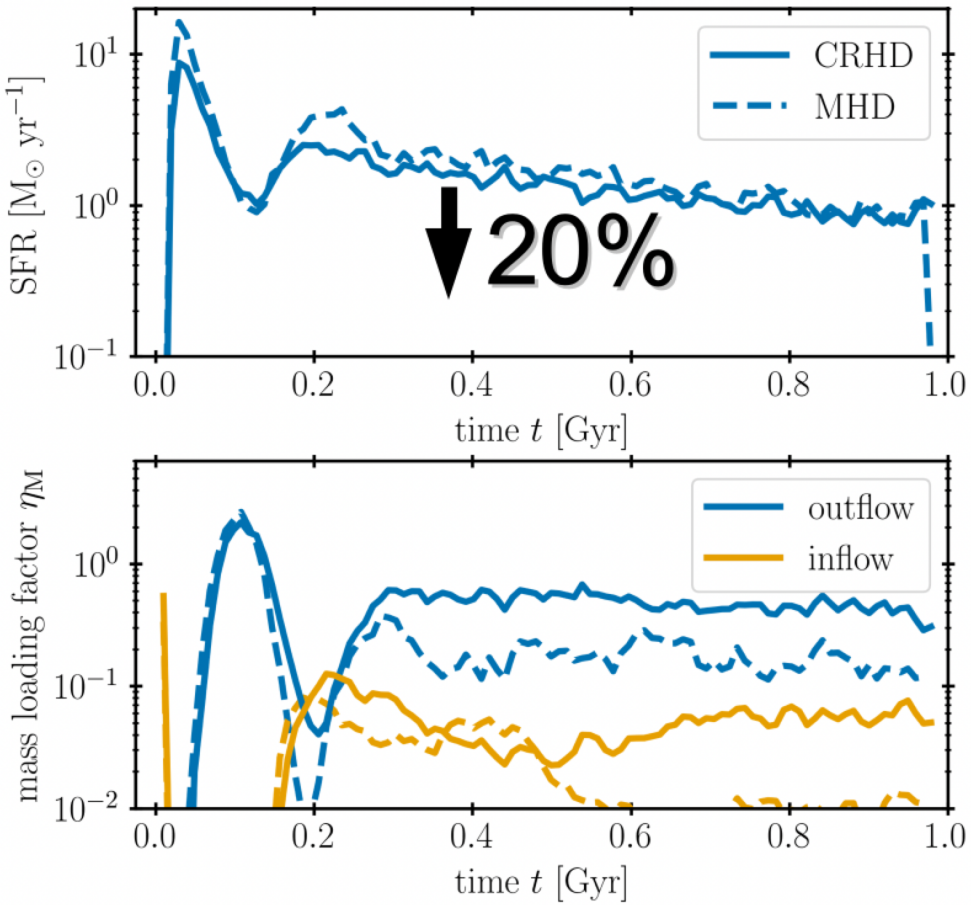
Mass and energy loading factors



Thomas, CP, Pakmor (2025)

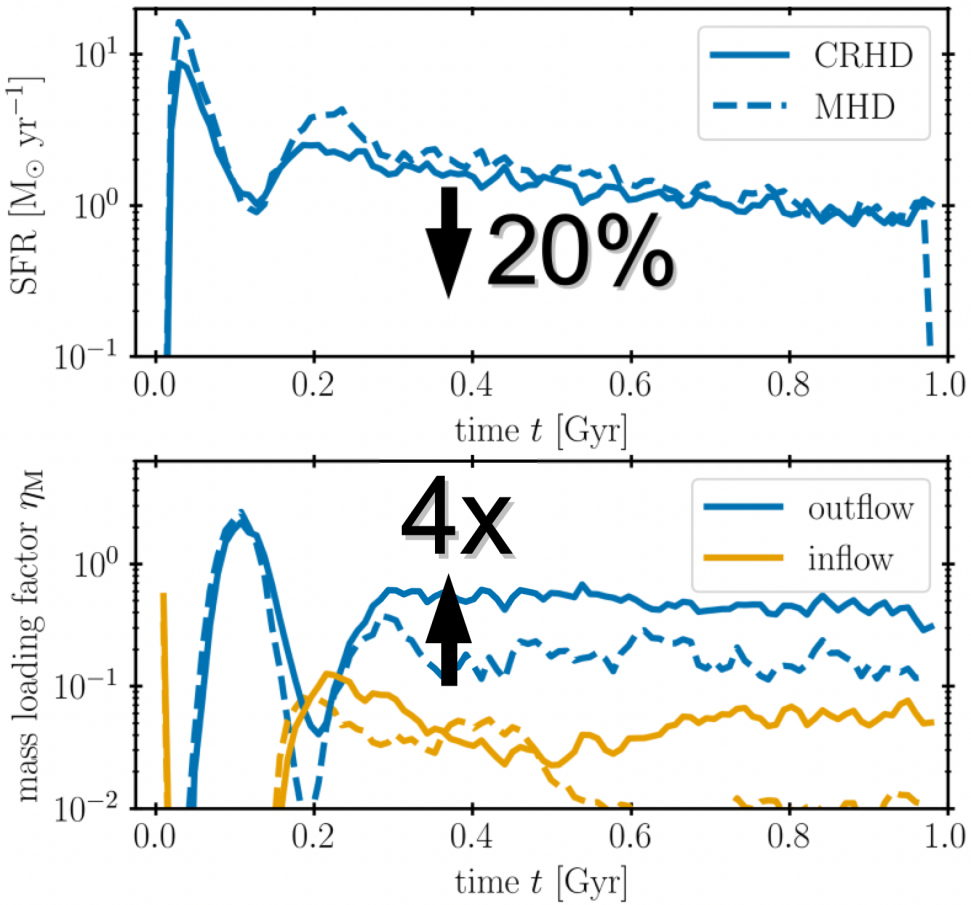
AIP

Mass and energy loading factors



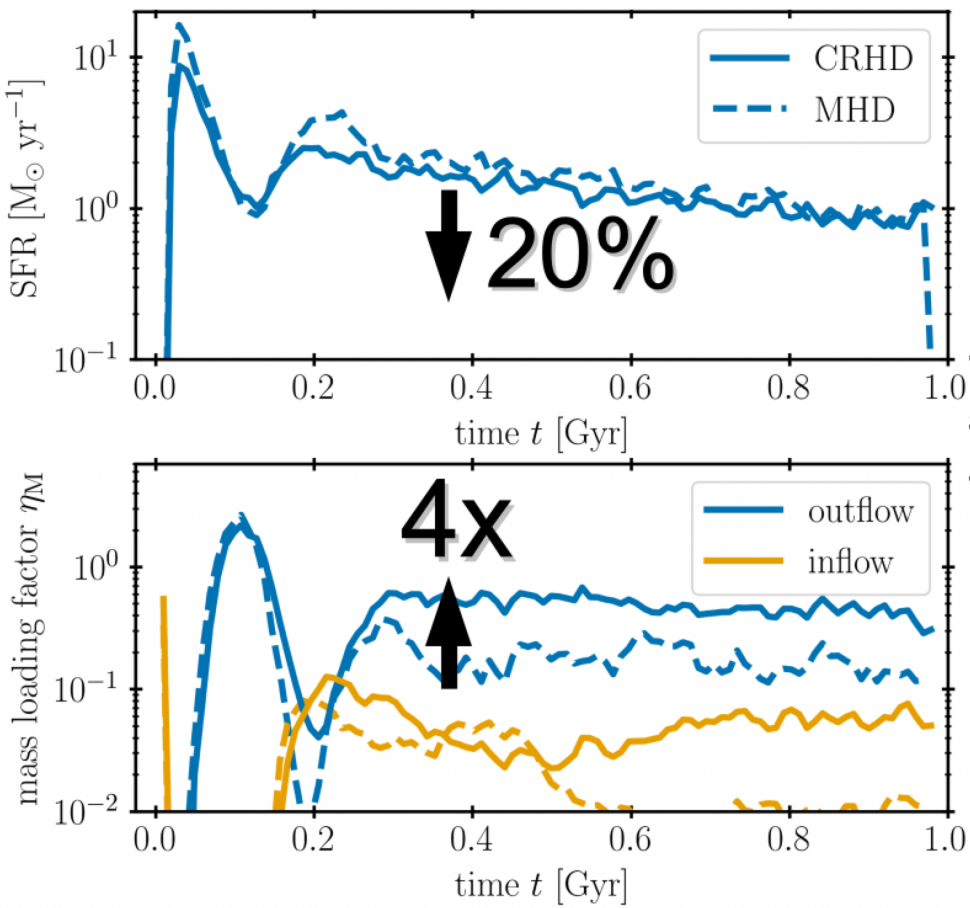
Thomas, CP, Pakmor (2025)

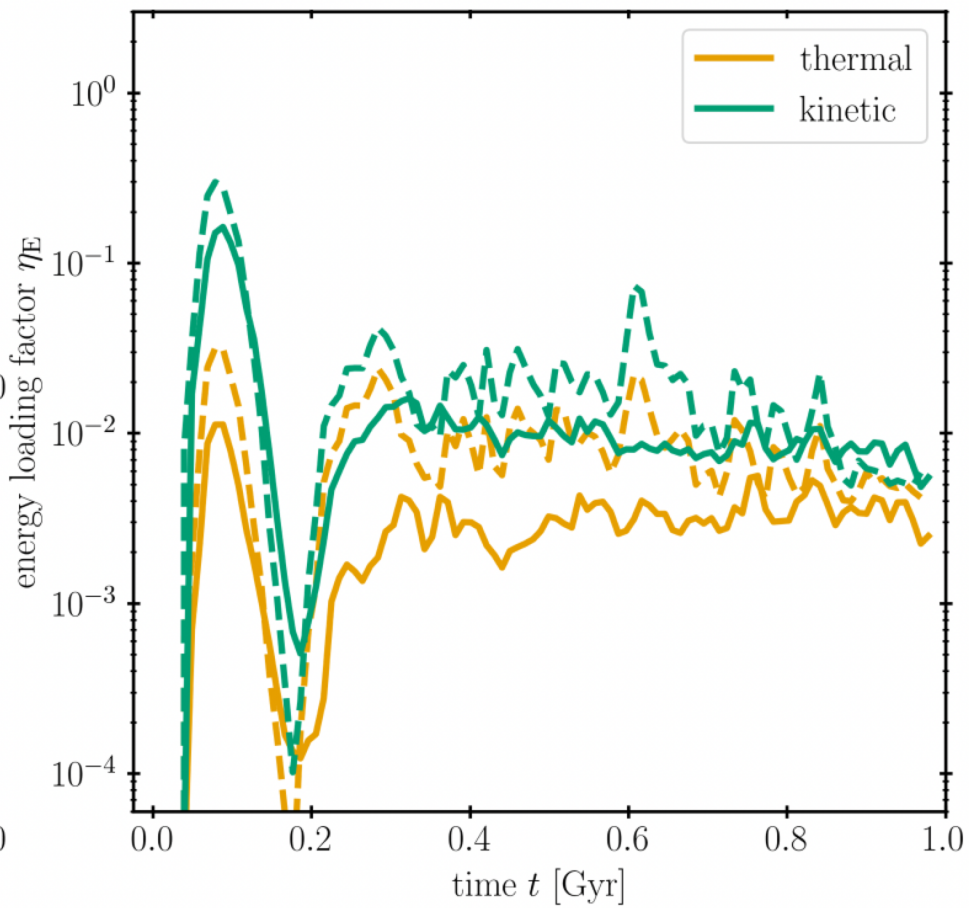
Mass and energy loading factors



Thomas, CP, Pakmor (2025)

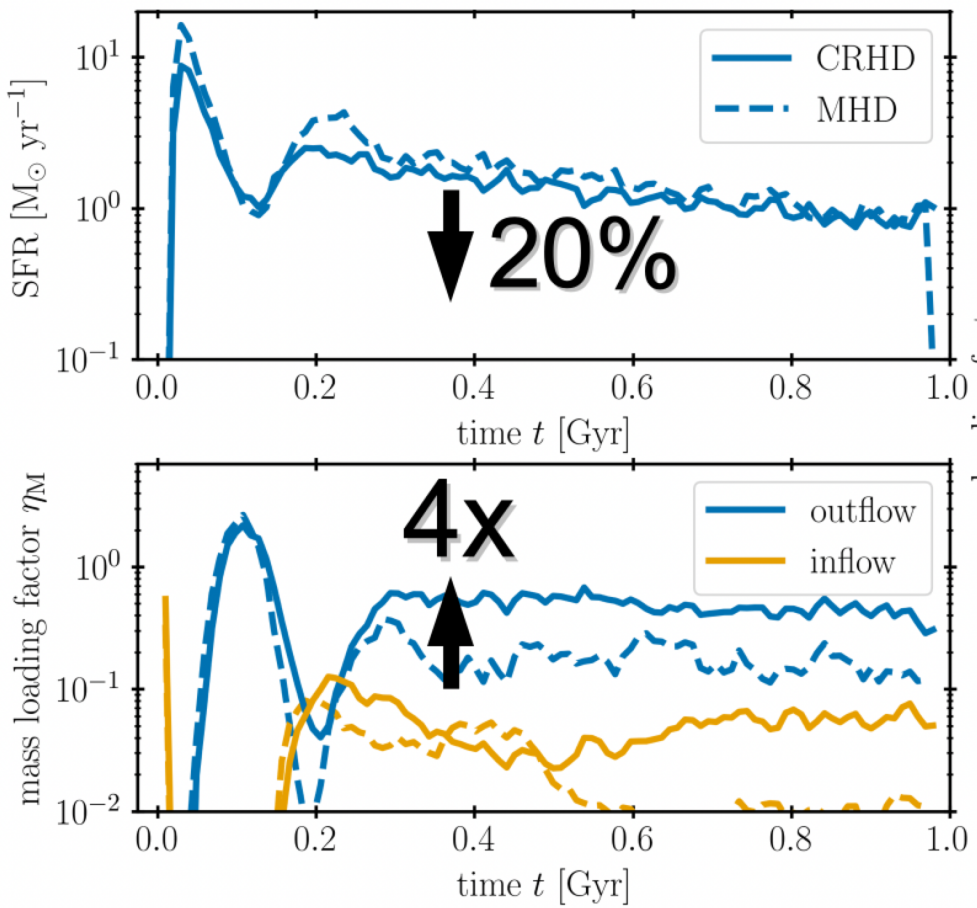
Mass and energy loading factors

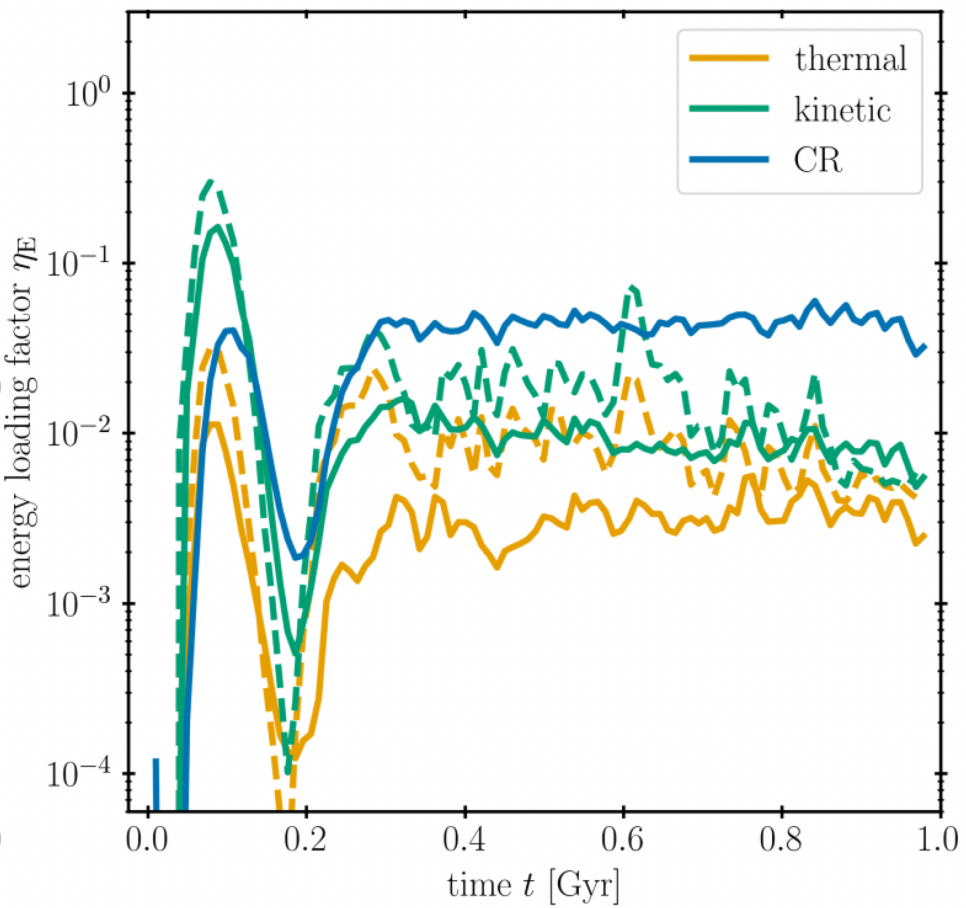




Thomas, CP, Pakmor (2025)

Mass and energy loading factors

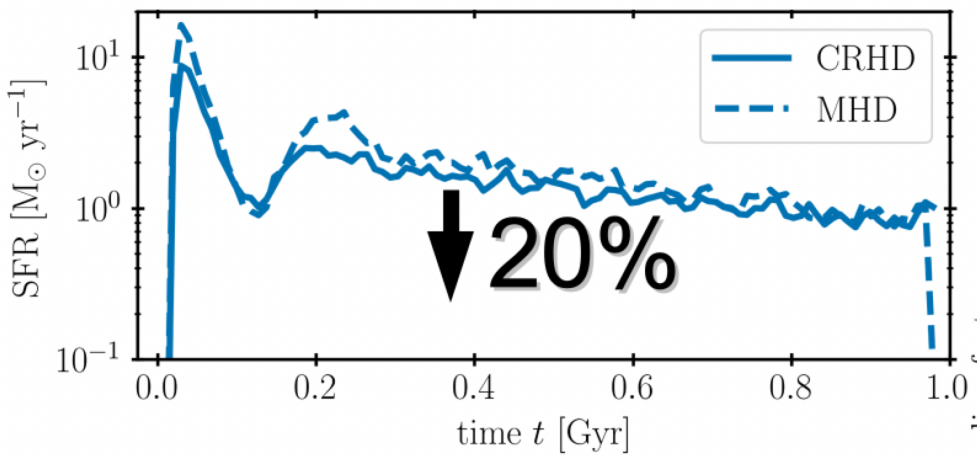


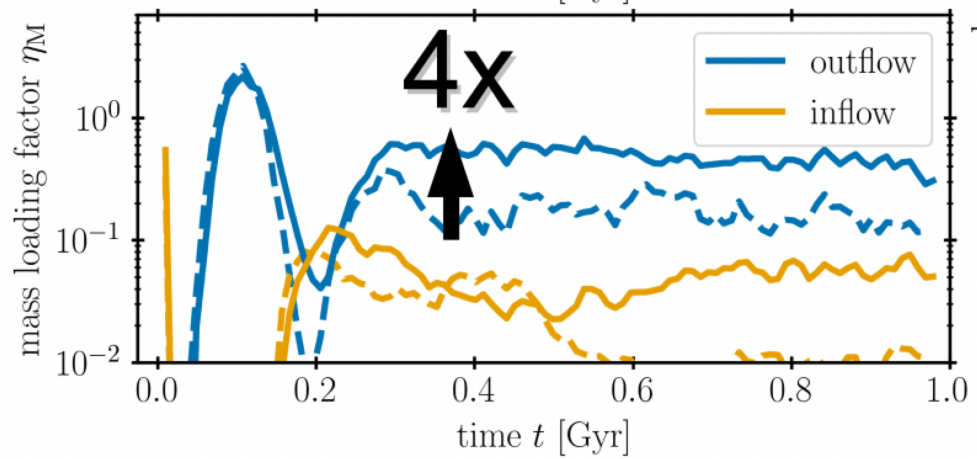


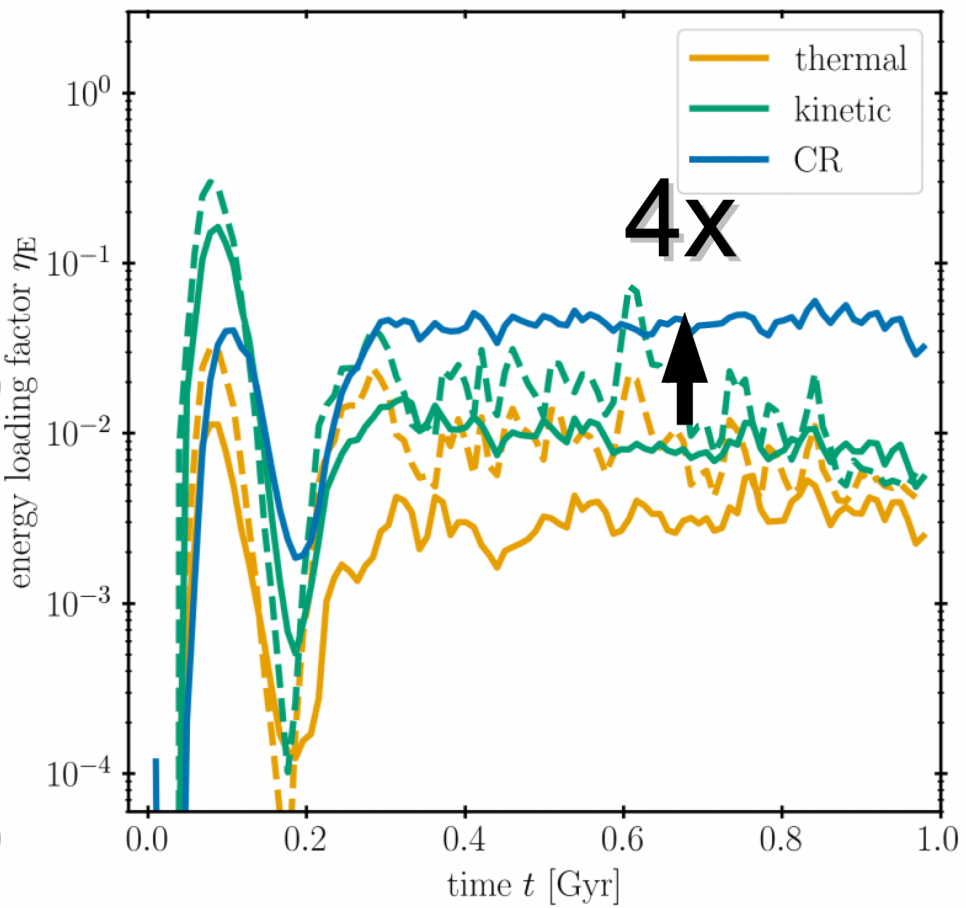
Thomas, CP, Pakmor (2025)

AIP

Mass and energy loading factors







Thomas, CP, Pakmor (2025)

AIP

Conclusions

Plasma instabilities and CR transport:

- CR-driven plasma-instabilities grow and saturate via phase bunching $\Rightarrow$ sets CR transport speed and feedback strength
- bunching theory extends traditional, quasilinear theory: growth of whistlers, forward and backward Alfvén waves
- self-generated diffusion coefficient emerges from CR-wave interactions



Conclusions

Plasma instabilities and CR transport:

- CR-driven plasma-instabilities grow and saturate via phase bunching $\Rightarrow$ sets CR transport speed and feedback strength
- bunching theory extends traditional, quasilinear theory: growth of whistlers, forward and backward Alfvén waves
- self-generated diffusion coefficient emerges from CR-wave interactions

CR feedback in galaxy formation:

- CR feedback mildly suppresses star formation because of strong ion-neutral damping in disk, which weakens CR coupling
- CR feedback drives powerful galactic winds



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.



Literature for the talk – 2

CR transport and feedback in galaxy formation:

- 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.

