Bridging microscopic and macroscopic cosmic ray transport in galaxies

Christoph Pfrommer[1]

in collaboration with

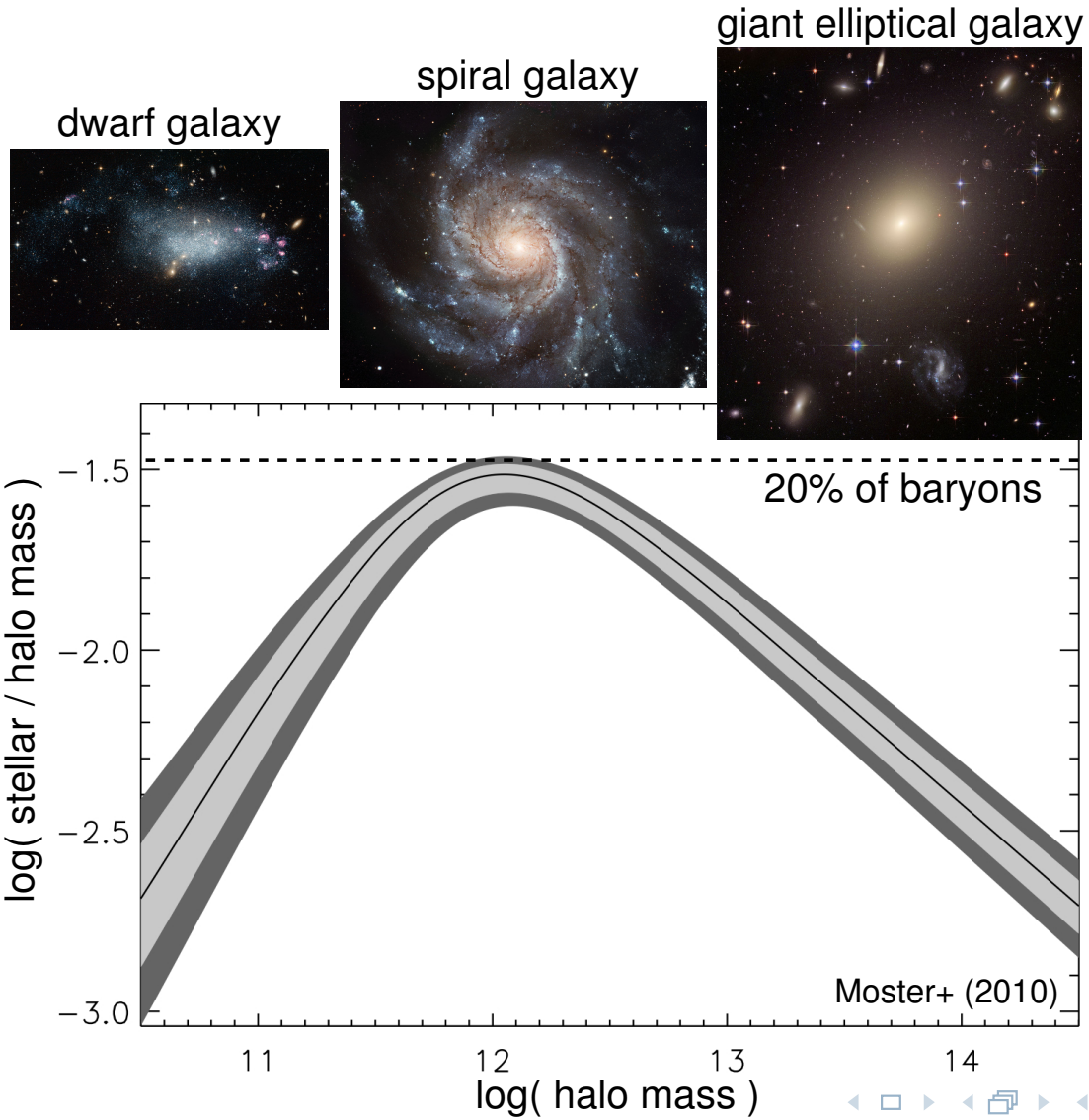
PhD students: Dusch,[1] Jlassi,[1] Kalangadan,[1] Pisharody,[1] Tevlin,[1] Weber,[1] Chiu,[2] Sike[2]
Postdocs: Berlok,[3] Girichidis,[4] **Lemmerz,**[5] Meenakshi,[1] Perrone,[1] Shalaby,[6] **Thomas,**[1] Werhahn,[7] Whittingham[1]
Faculty: Pakmor,[7] Puchwein,[1] Weinberger,[1] Ruszkowski,[2] Springel,[7]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

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

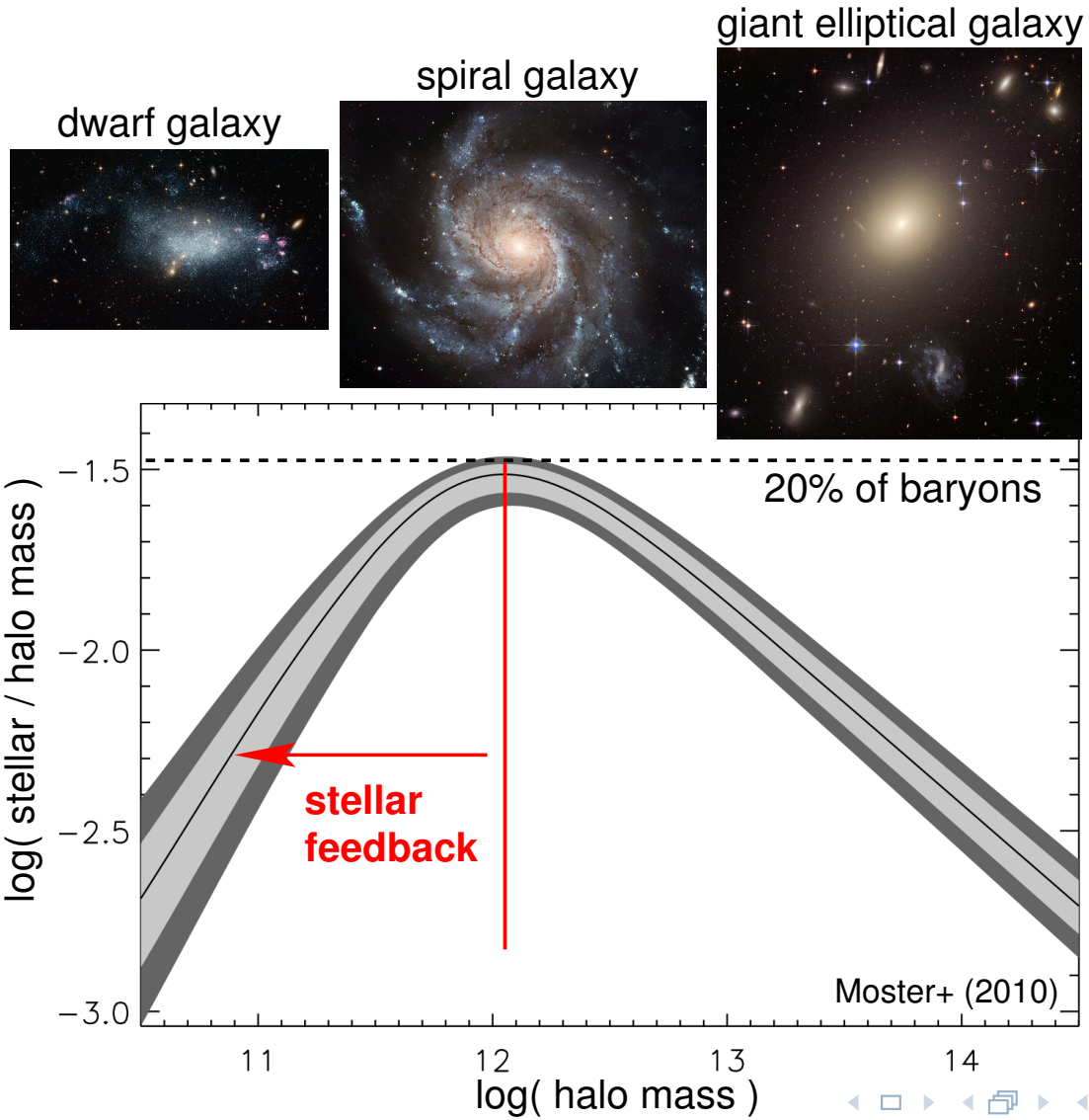
Annual Meeting of the German Astronomical Society, Garching, 2026



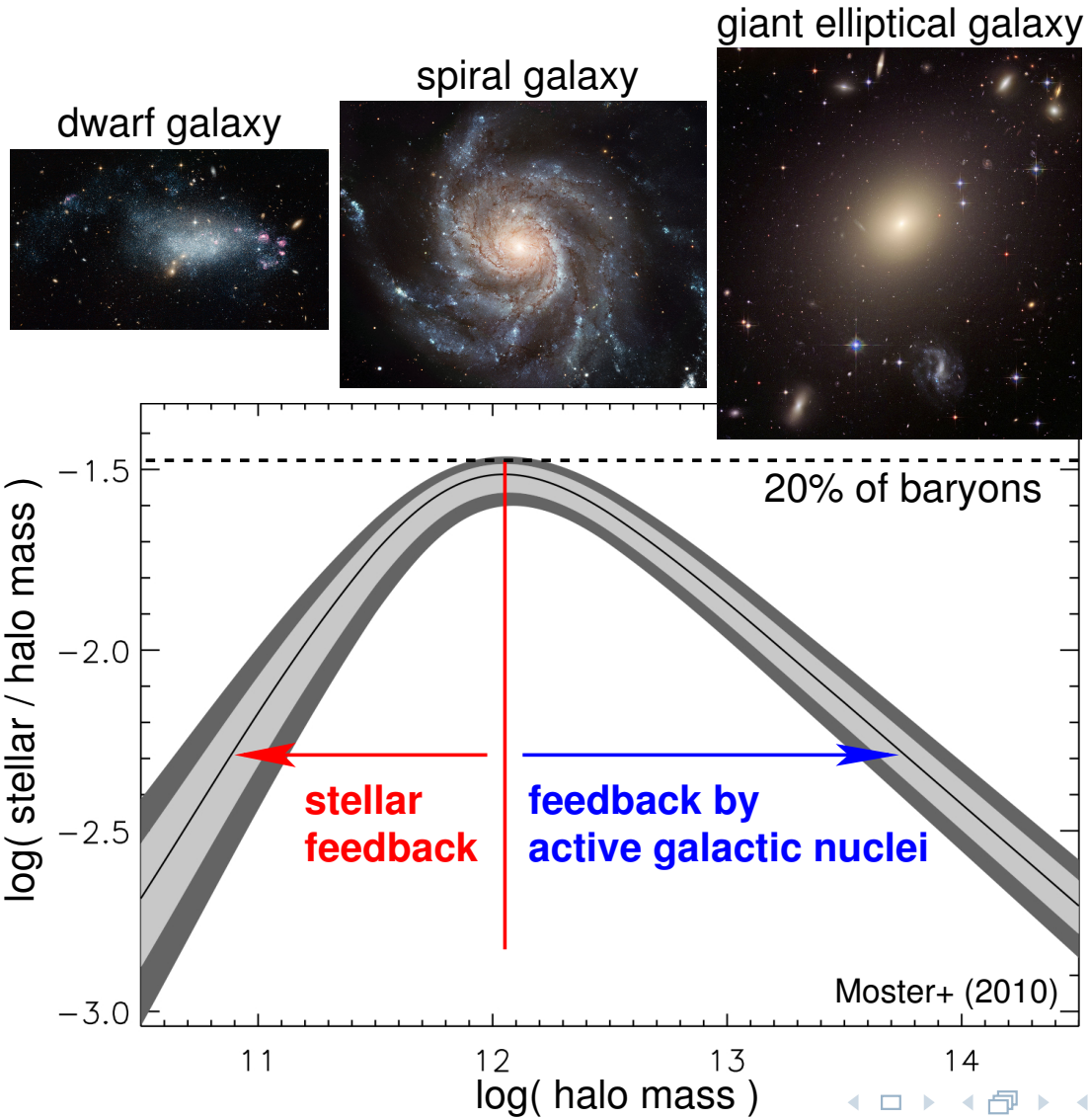
Puzzles in galaxy formation



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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

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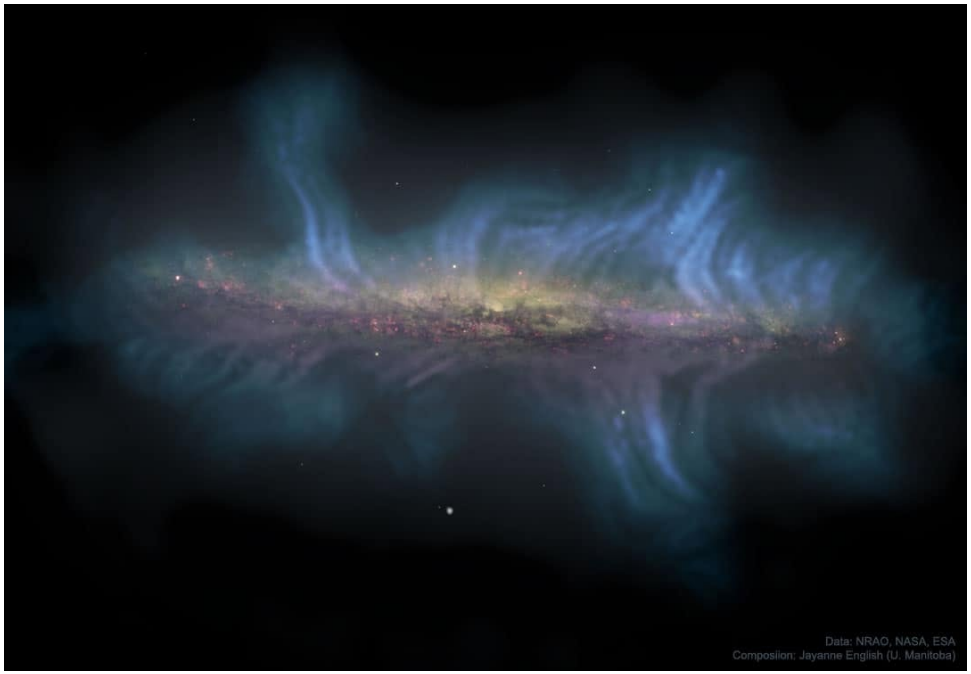
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- energy density of CRs, magnetic fields, and ISM turbulence all similar
  $\Rightarrow$ important feedback agent

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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"

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Review on cosmic ray feedback

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

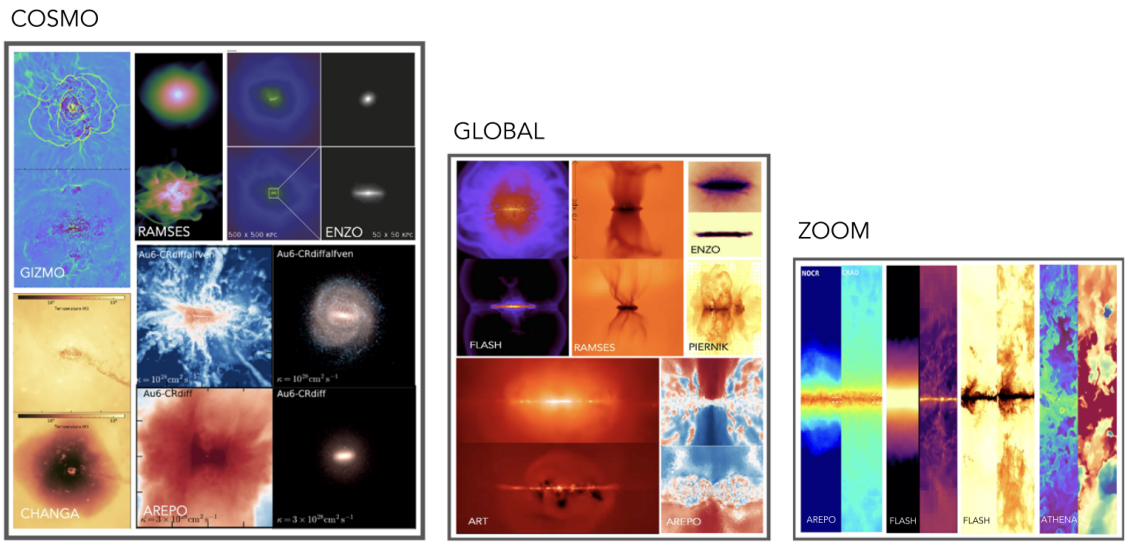
REVIEW ARTICLE

Check for updates

Cosmic ray feedback in galaxies and galaxy clusters

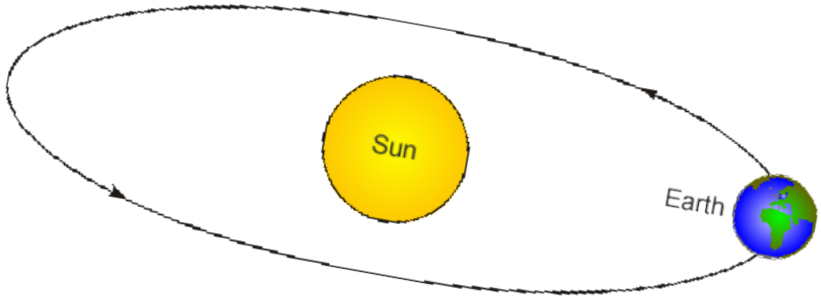
A pedagogical introduction and a topical review of the acceleration, transport, observables, and dynamical impact of cosmic rays

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



Cosmic ray transport: an extreme multi-scale problem





Milky Way-like galaxy:

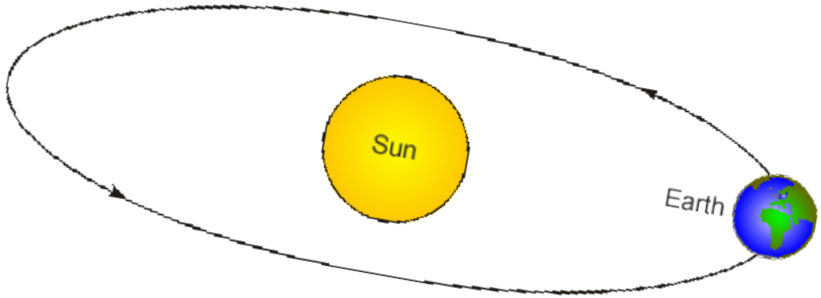
$$r_{\mathrm{gal}} \sim 10^4 \text{ pc}$$

gyro-orbit of GeV CR:

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

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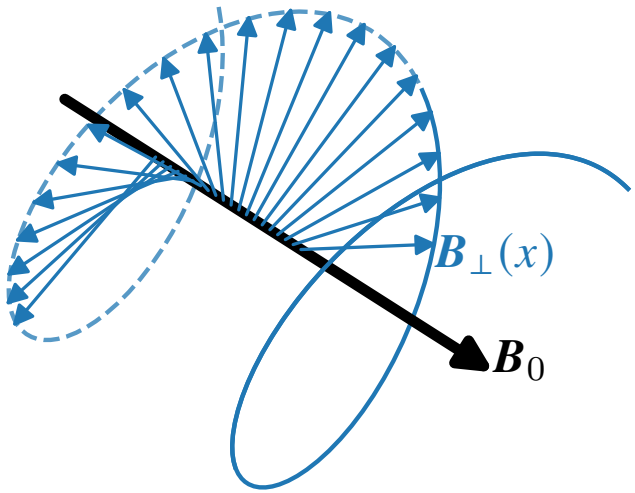
$$r_{\mathrm{cr}} = \frac{p_\perp}{e\,B_{\mu\mathrm{G}}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

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

Zweibel (2017), Thomas & CP (2019)

What is gyro resonance?

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

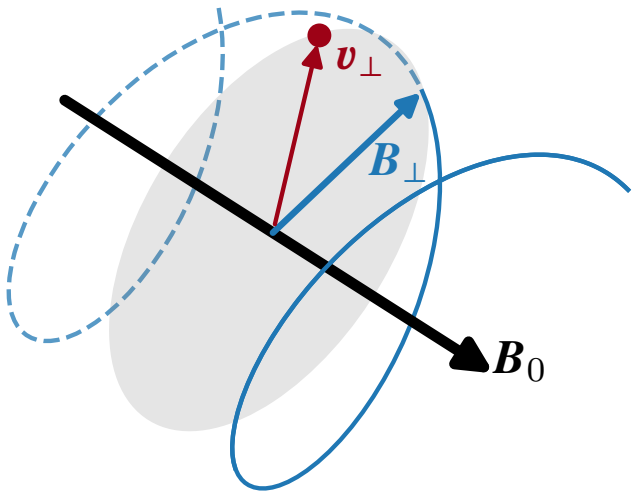


What is gyro resonance?

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

Ω_{cr} gyration frequency



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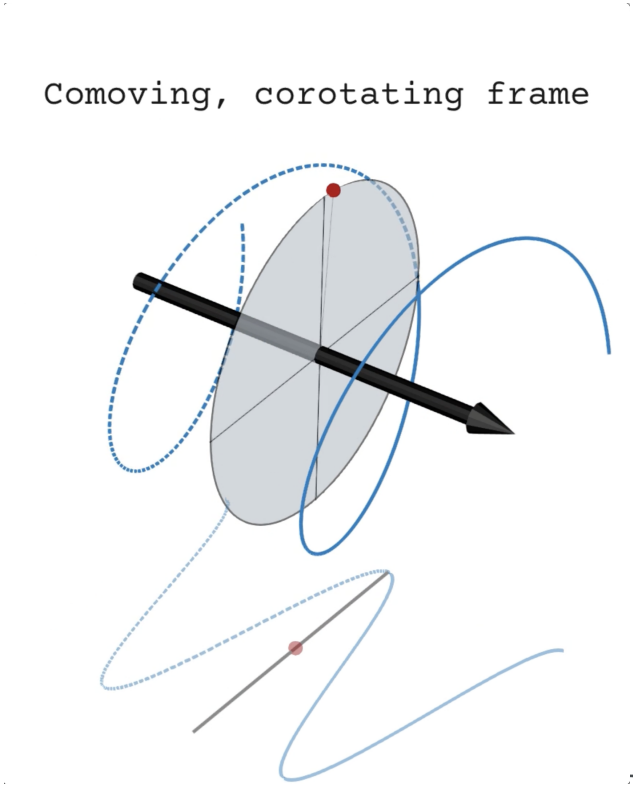
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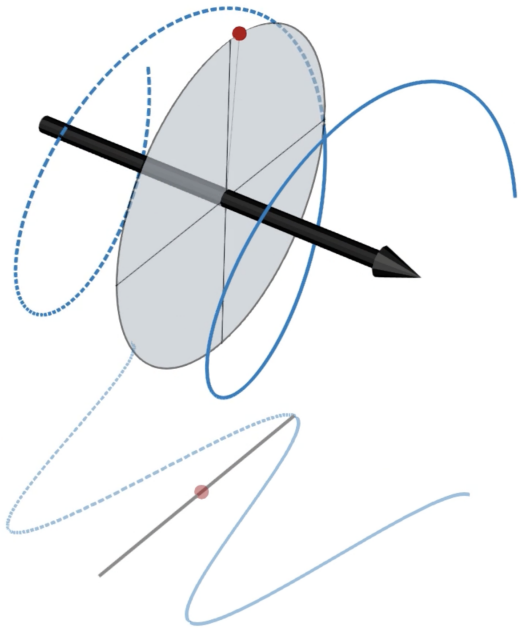
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Resonant wave appears **static** to CR!

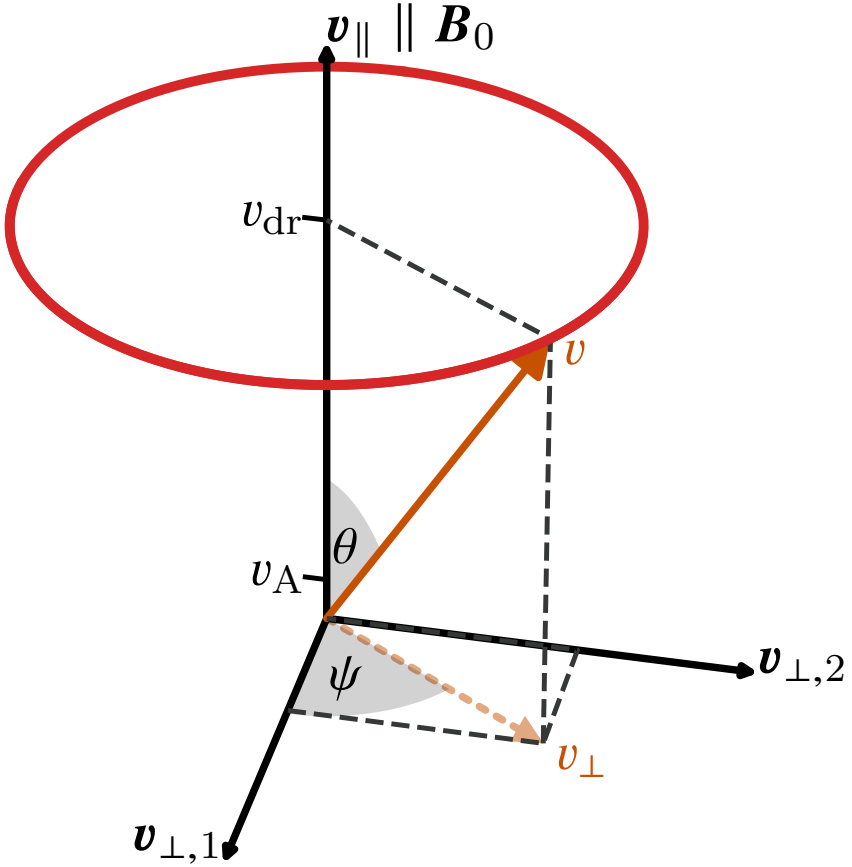
Comoving, corotating frame



test particle without interactions!

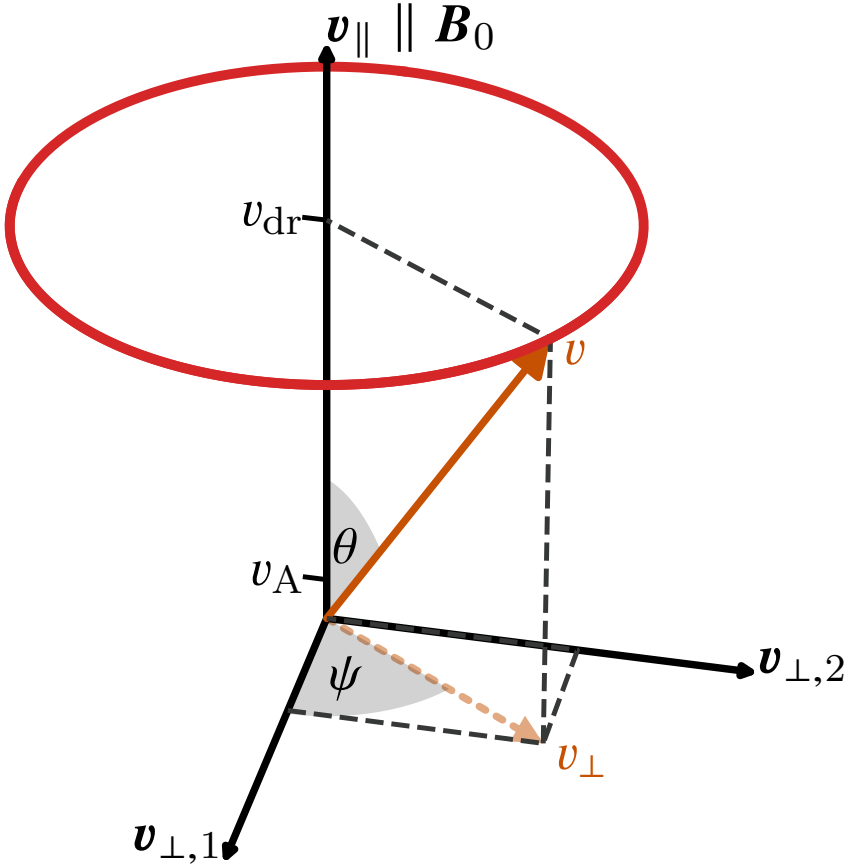
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Idealized setup to understand physics



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

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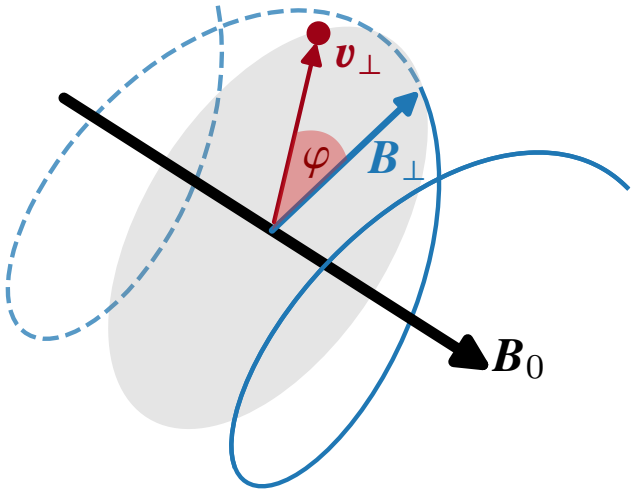
- gyrotropic ring distribution of CR ions with single pitch angle and energy
- neutralizing CR electron beam at same drift speed but $v_\perp = 0$
- background ion and electron fluid with Landau closure
- fluids coupled to particle-in-cell (PIC) CRs via Maxwell's equations

(Lemmerz+ 2024)

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The mechanism of CR-driven instabilities

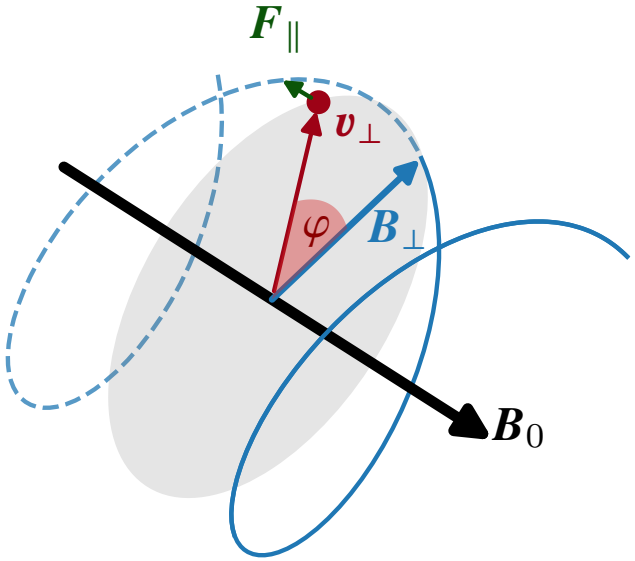
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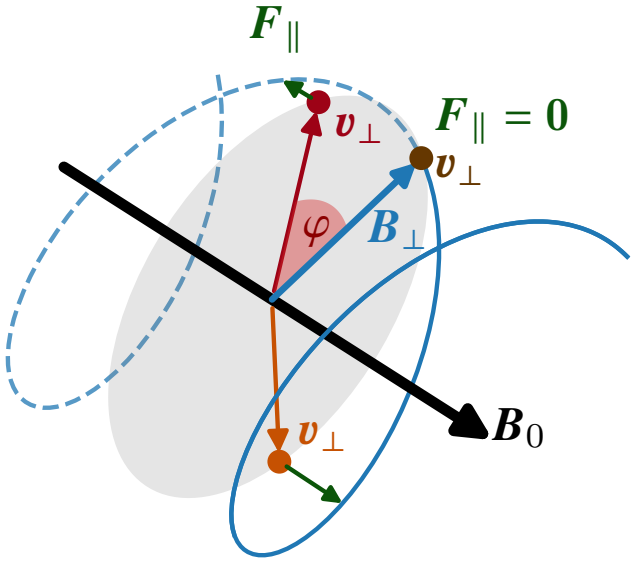
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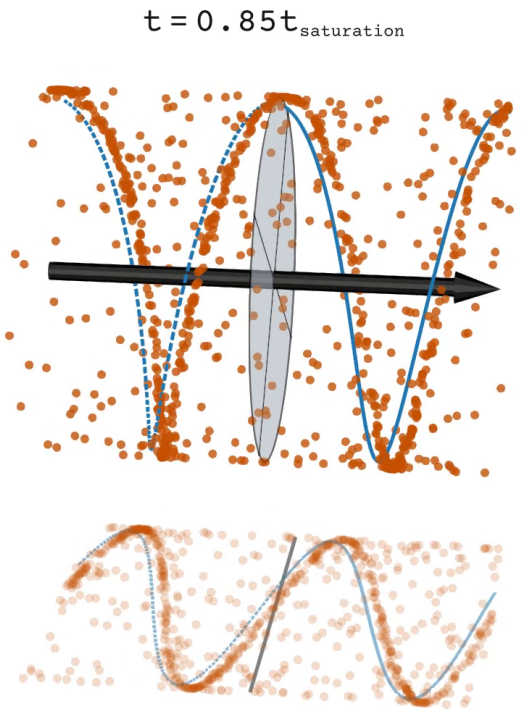
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The mechanism of CR-driven instabilities

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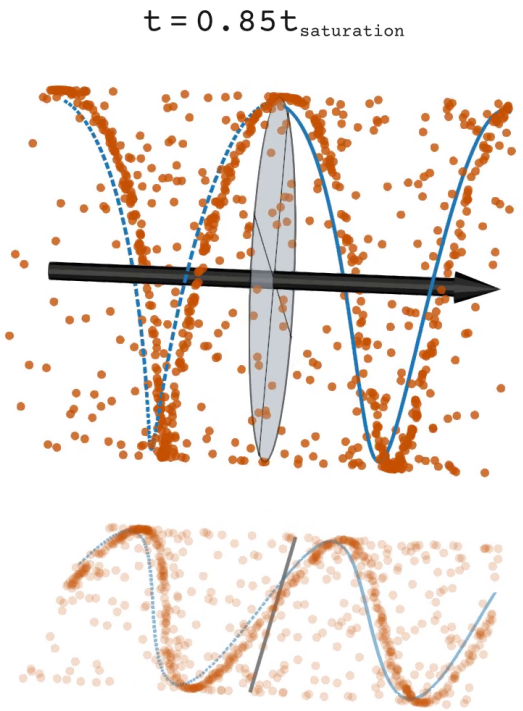


fluid-PIC simulation (Lemmerz+ 2025)

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The mechanism of CR-driven instabilities

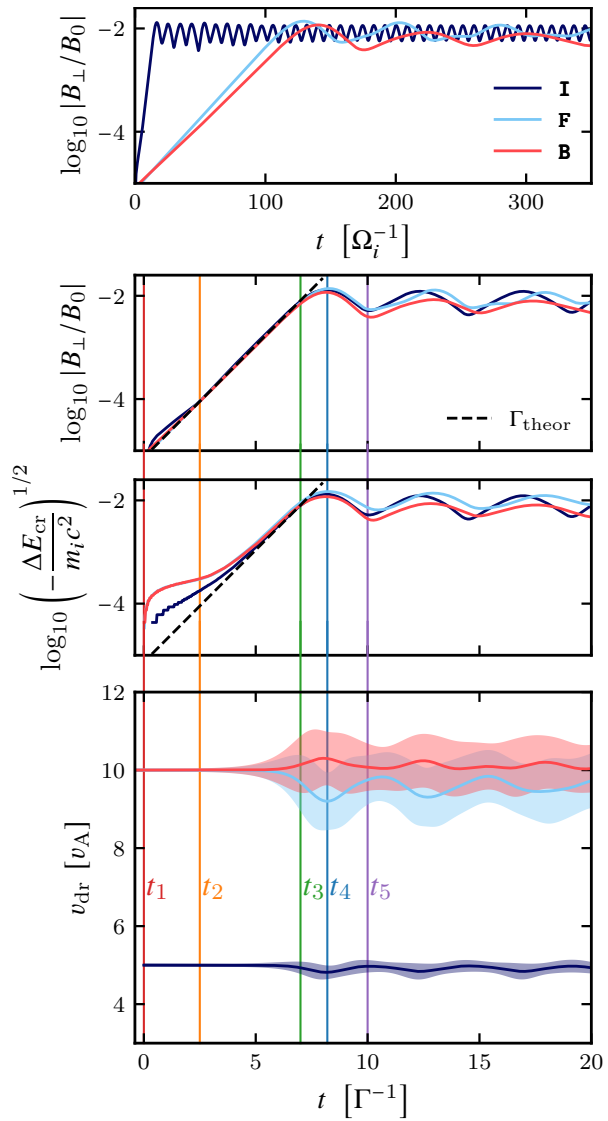
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- CR trapping in Lorentz force potential saturates instability



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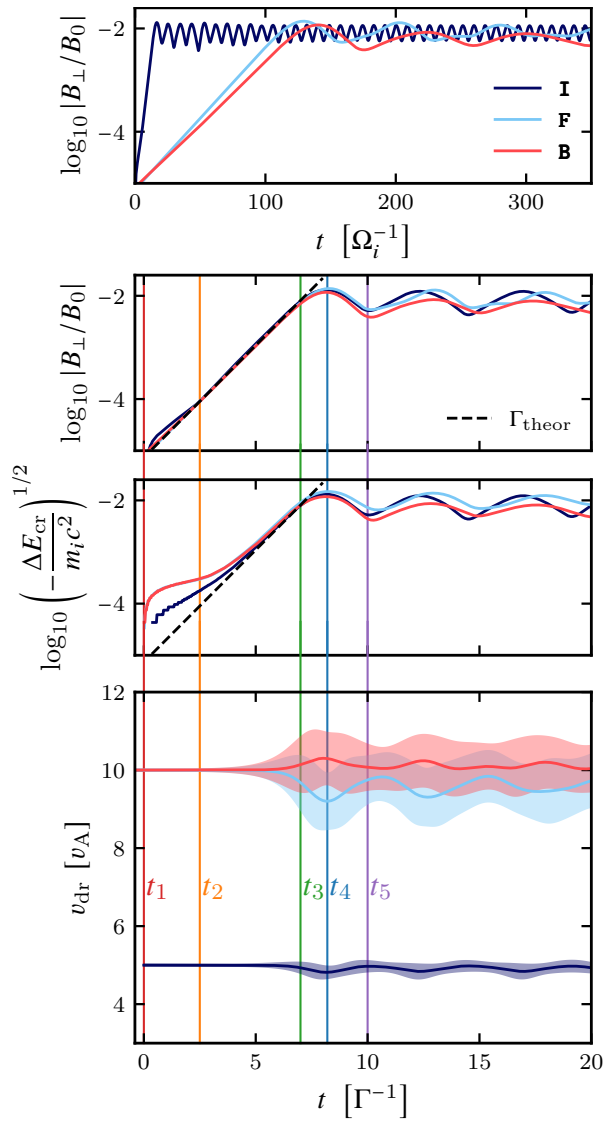
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Resonant wave growth and CR energy loss



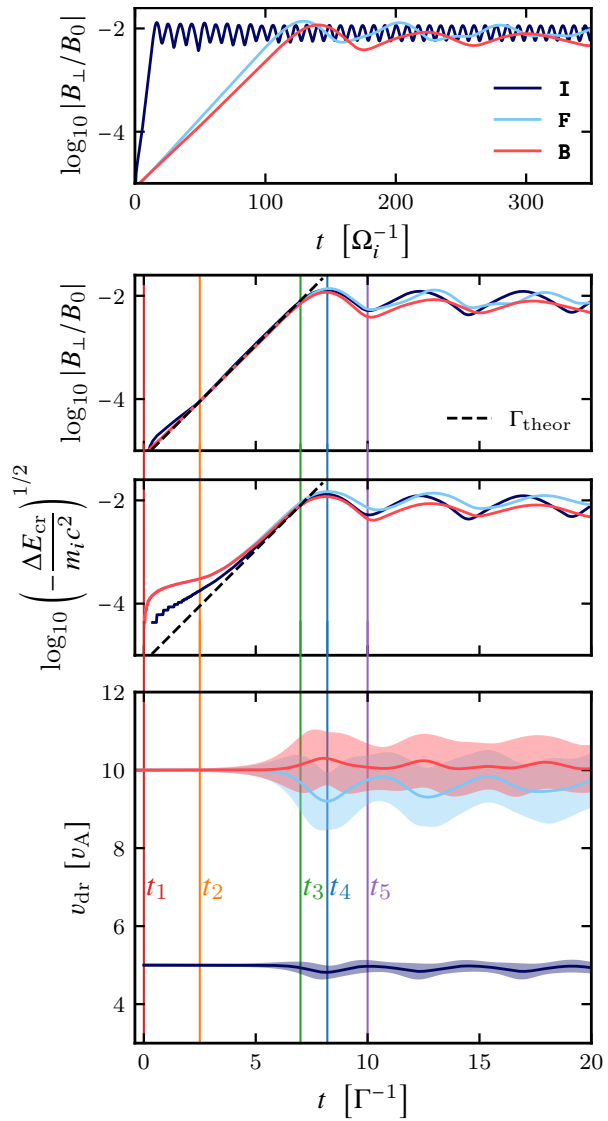
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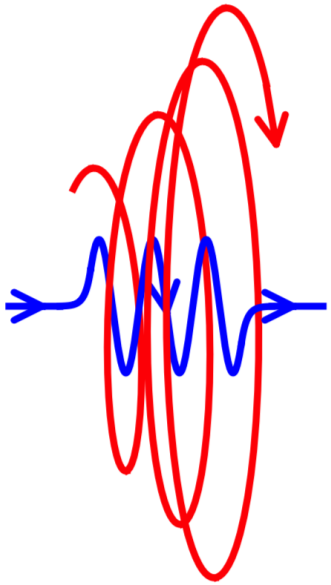
Resonant wave growth and CR energy loss



- 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

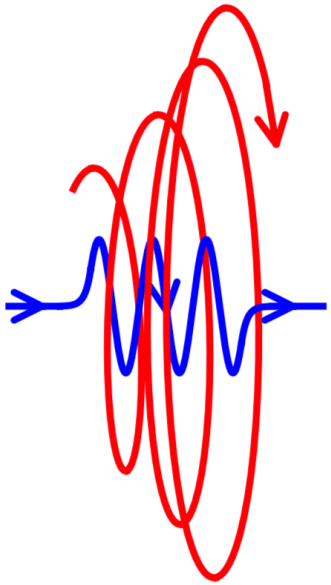
- **CR streaming instability:**
  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)
  - if $v_{\rm cr} > v_{\rm a}$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm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



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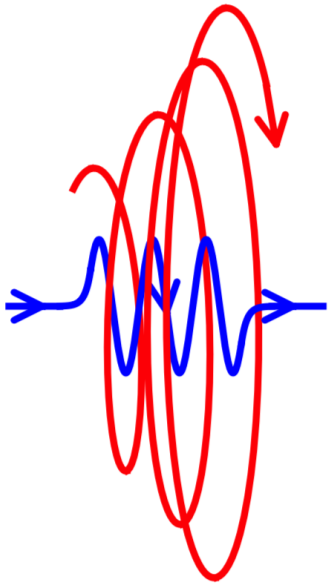
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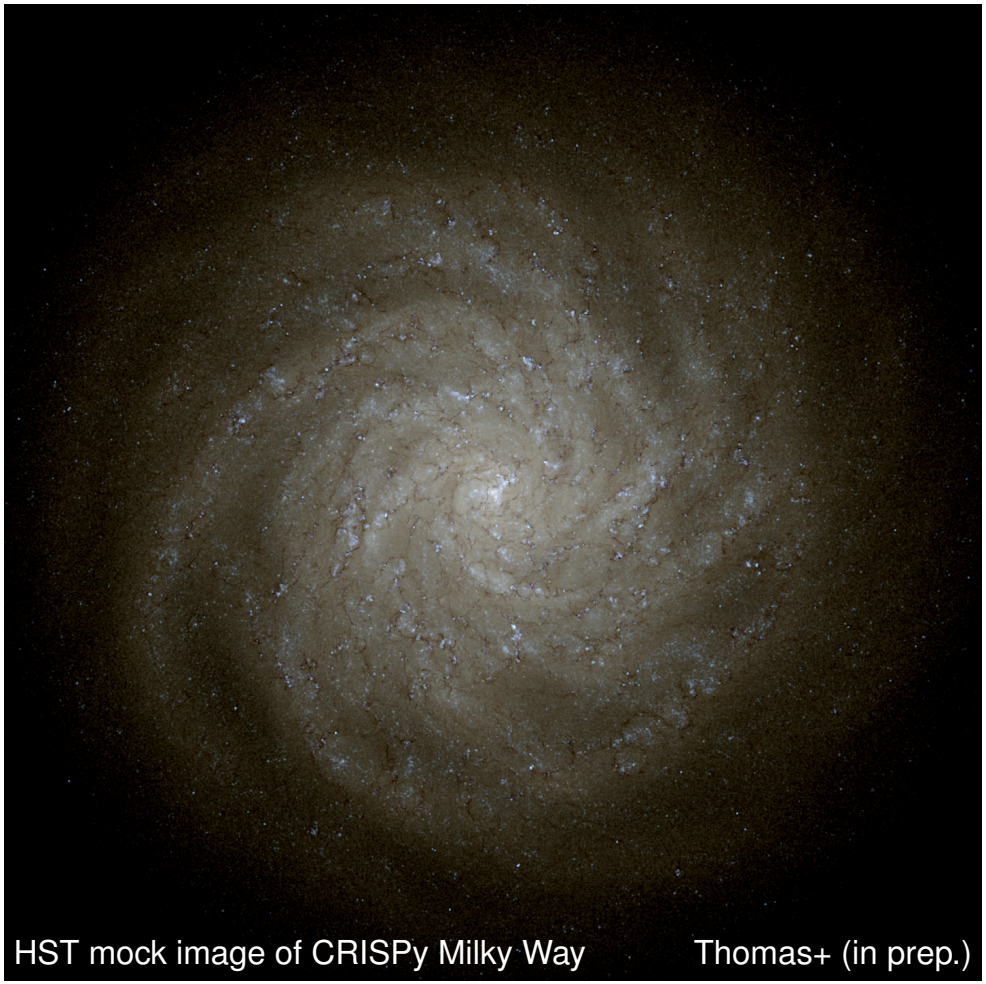


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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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Cosmic ray transport in galaxies


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

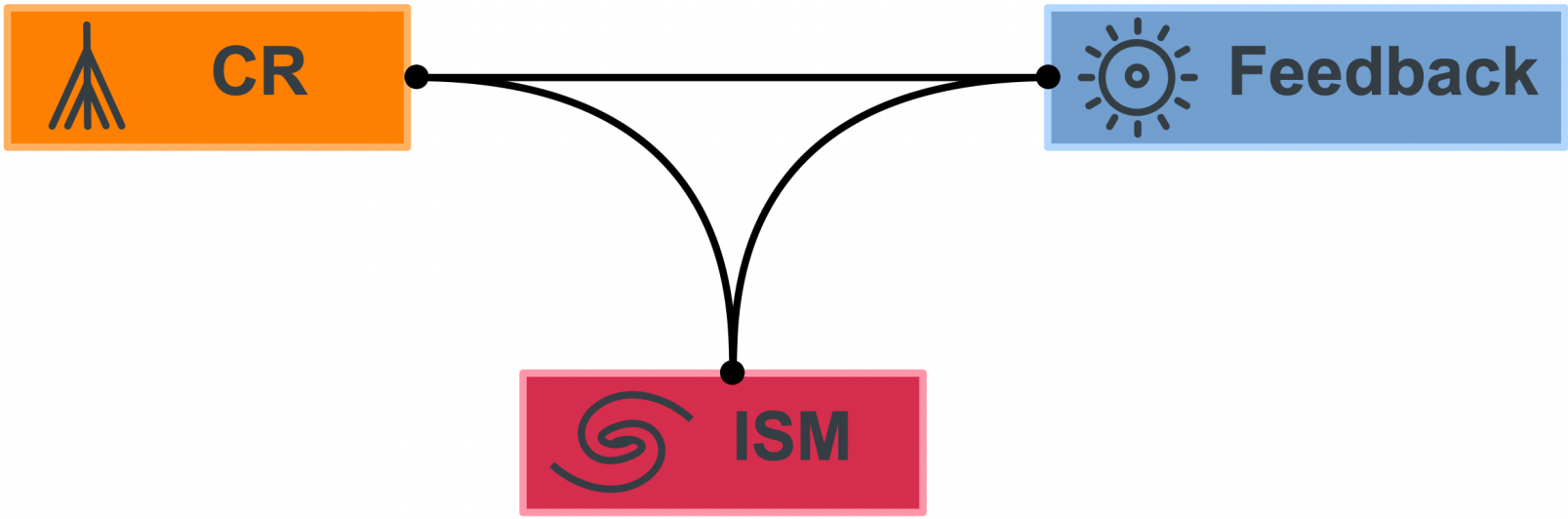
- CR transport in galaxies demands modeling non-linear Landau damping (in warm/hot phase) and ion-neutral damping (in disk)
- this requires resolving the multi-phase structure of the ISM
- development of CRISP framework (**C**osmic **R**ays and **I**nter**S**tellar **P**hysics, Thomas+ 2025)

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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



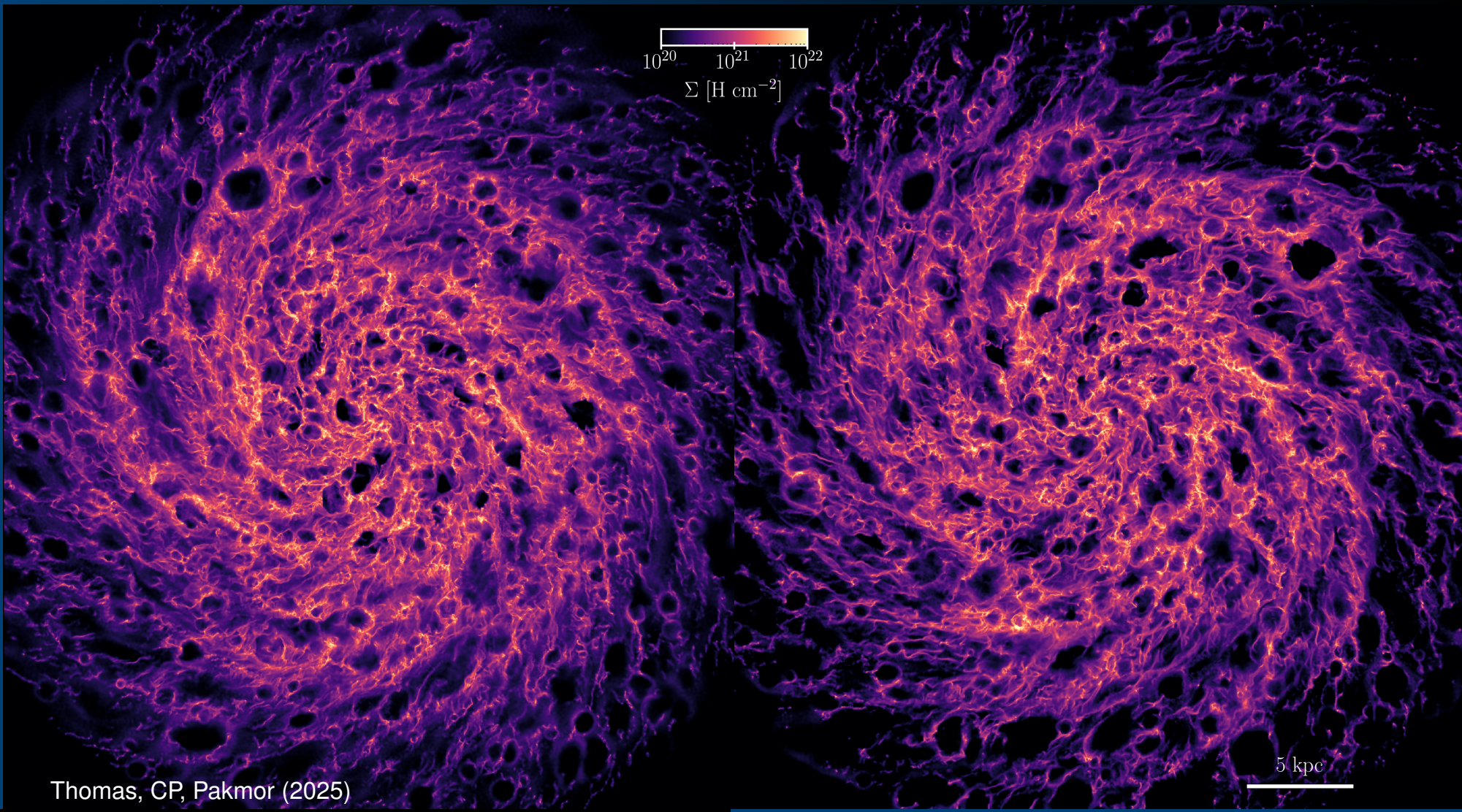




- **Novel CR hydrodynamics**
  coarse graining plasma physics
  - Follow $\varepsilon_{\rm cr}$ and $v_{\rm cr}$
  - Self-consistently evolve $\kappa_{\rm cr}$
- **CR ionization**
  impacting **Chemistry**
- **CR microphysics**

Thomas, CP, Pakmor (2025)

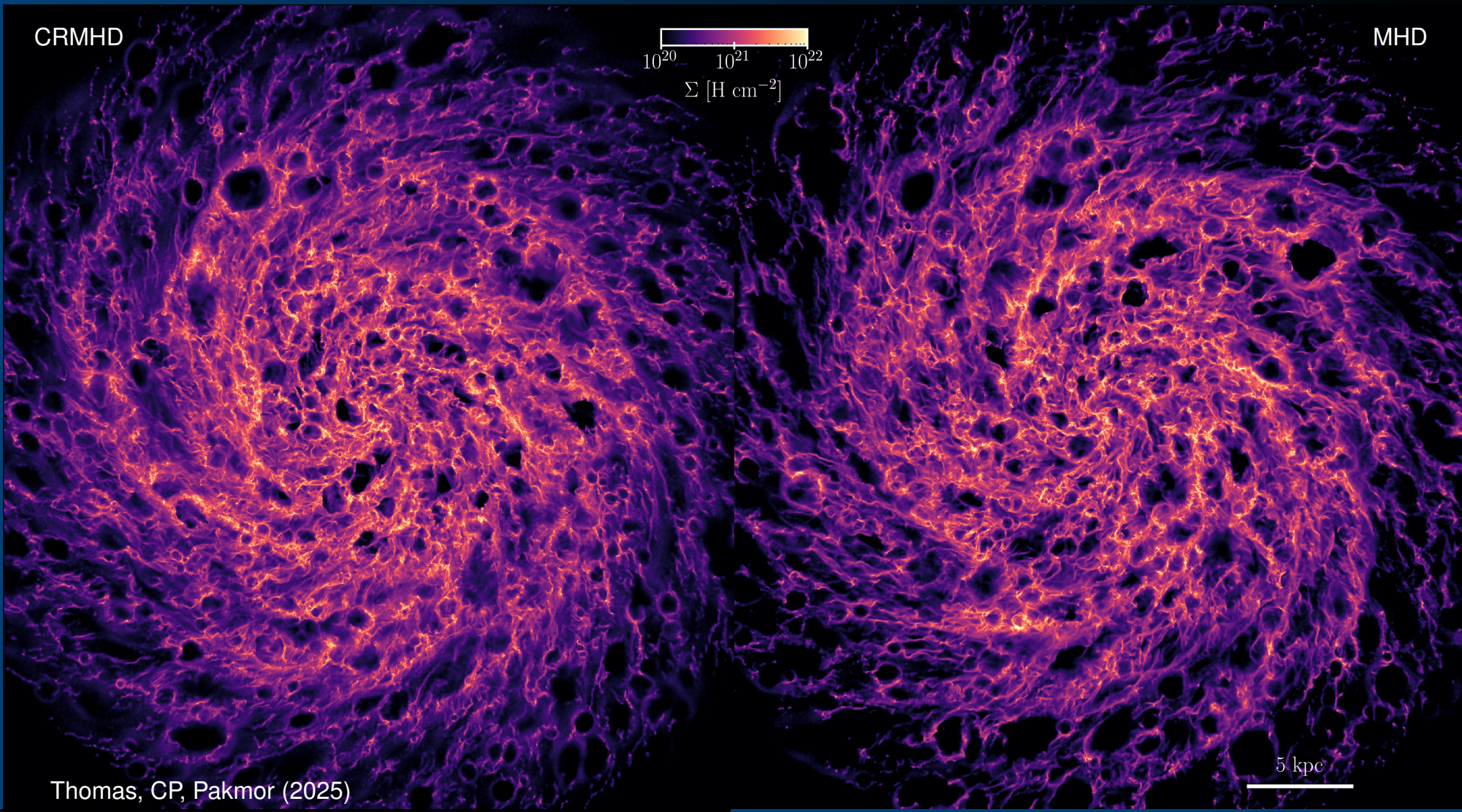
Multi-phase ISM modeling



Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

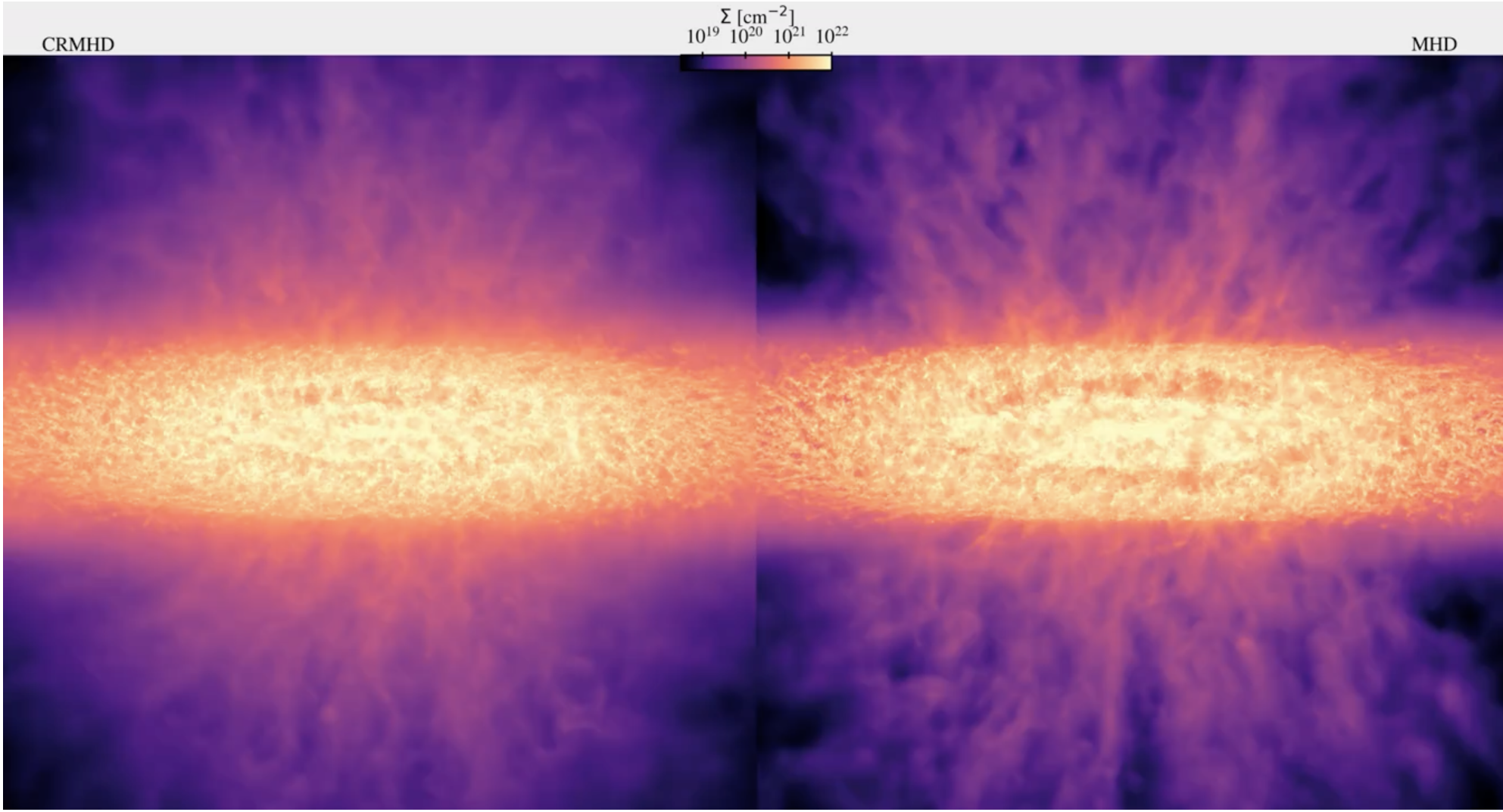
Cosmic rays barely affect the ISM because ion-neutral damping erases Alfvén waves



Thomas, CP, Pakmor (2025)

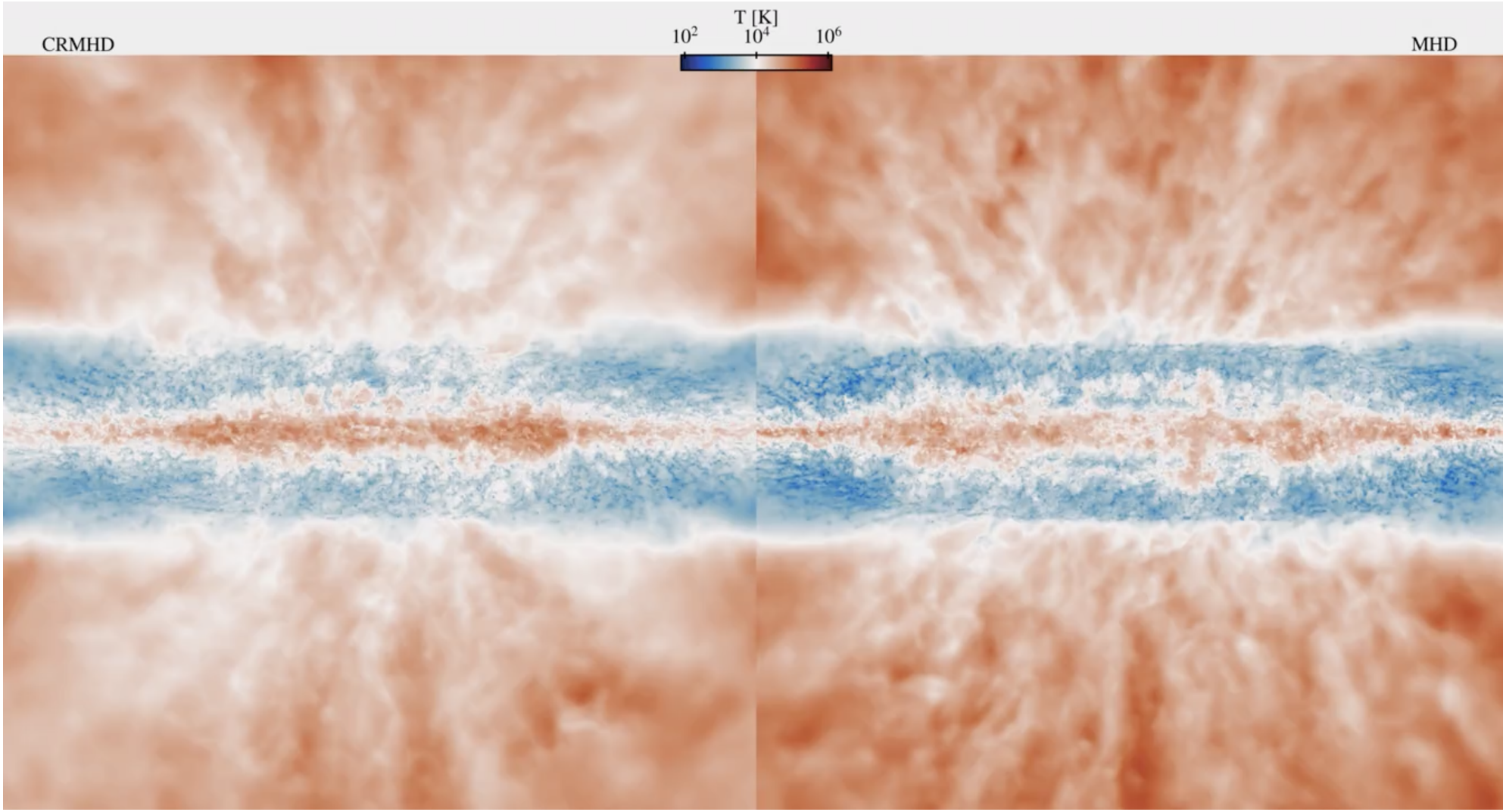
Simulated Milky Way: surface density

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



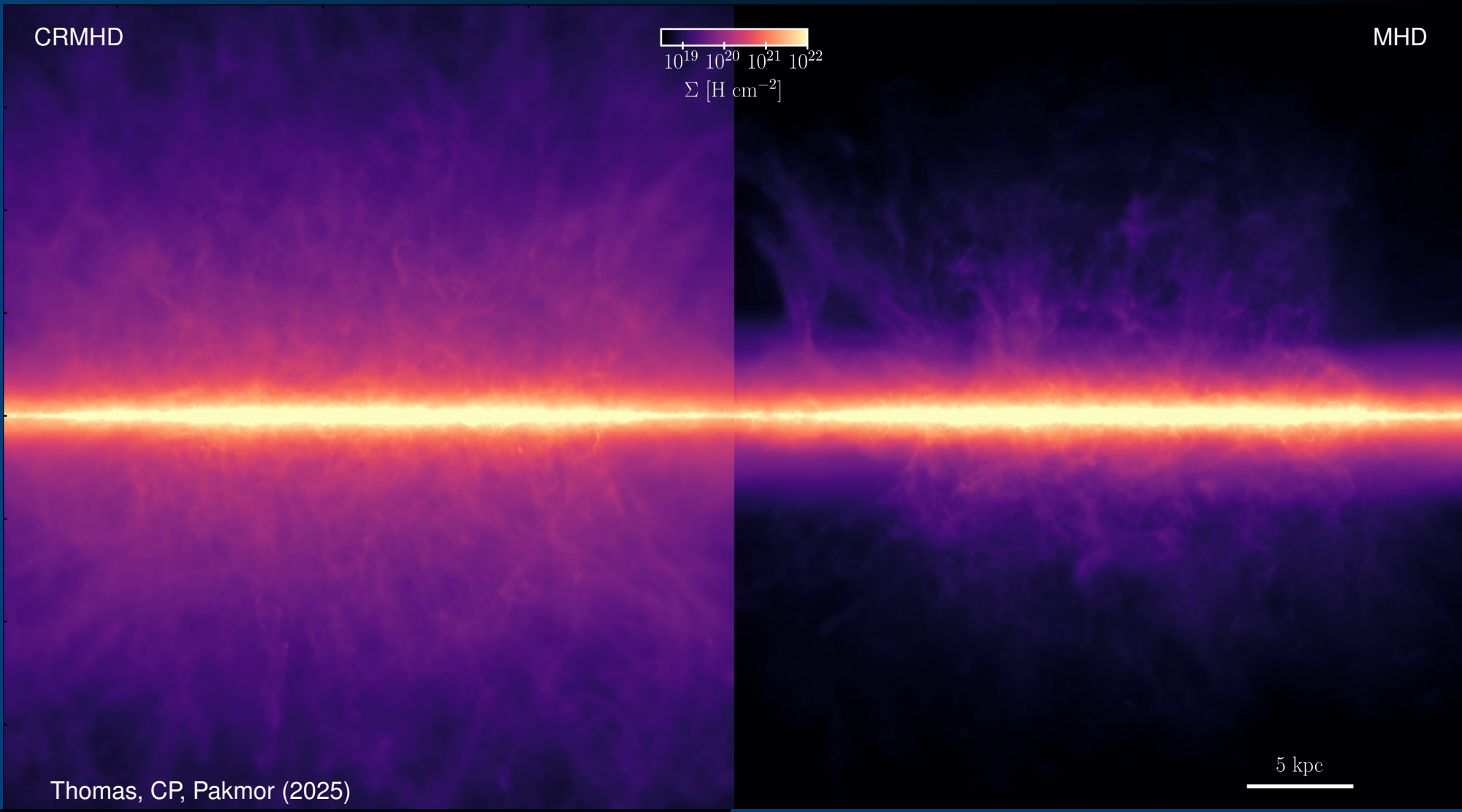
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter



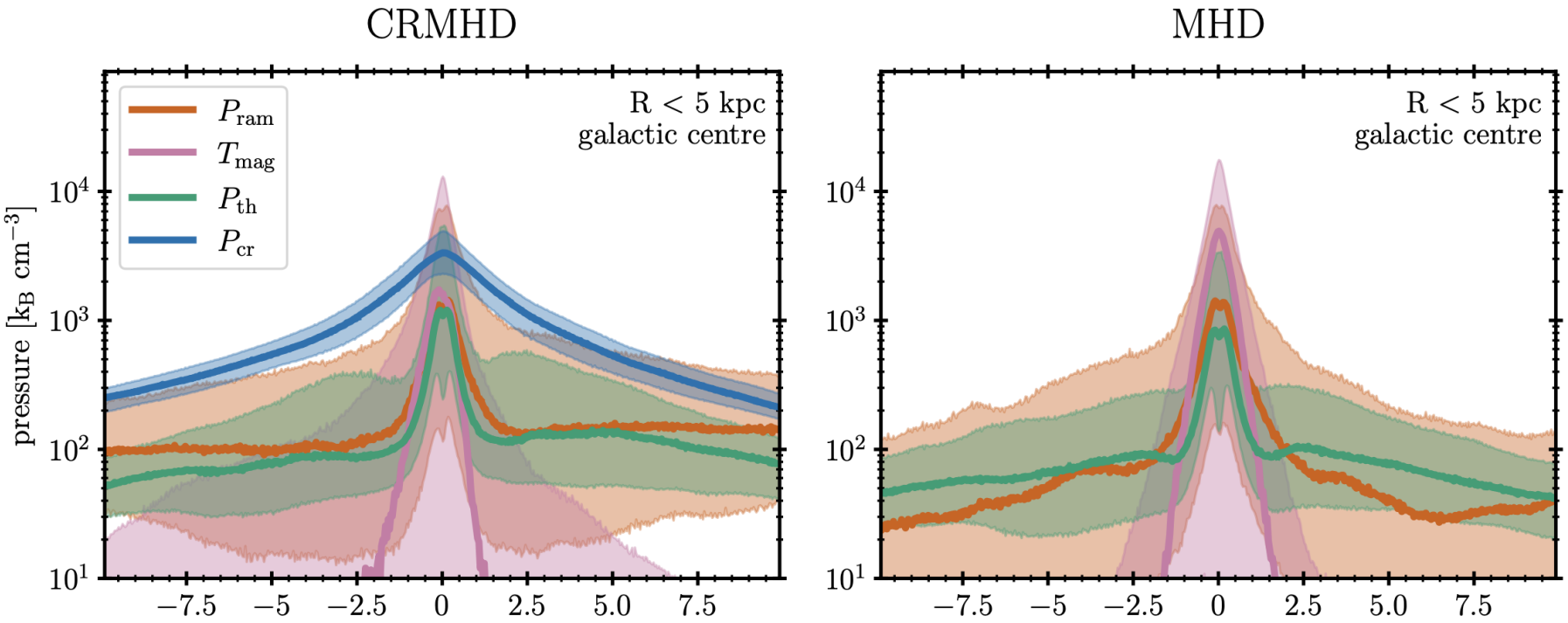
Multi-phase ISM modeling

Cosmic rays make galactic winds much denser



Thomas, CP, Pakmor (2025)

Cosmic ray driven wind: mechanism

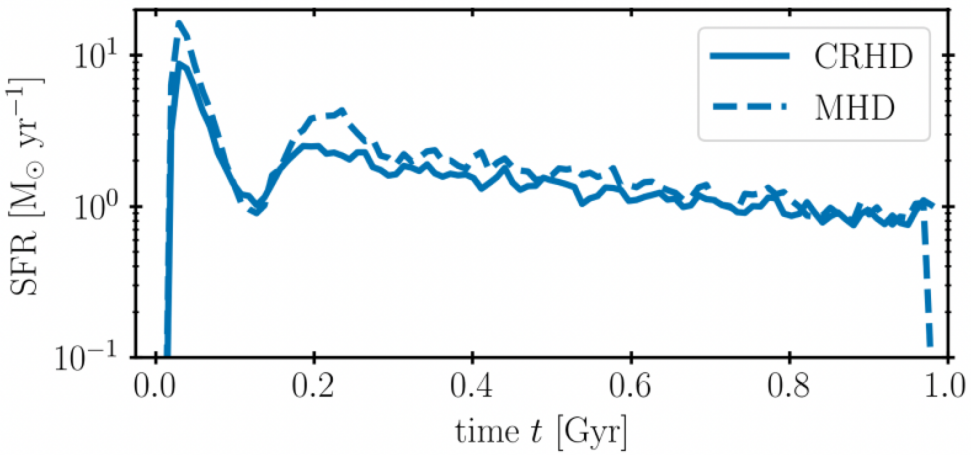


Thomas, CP, Pakmor (2025)

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

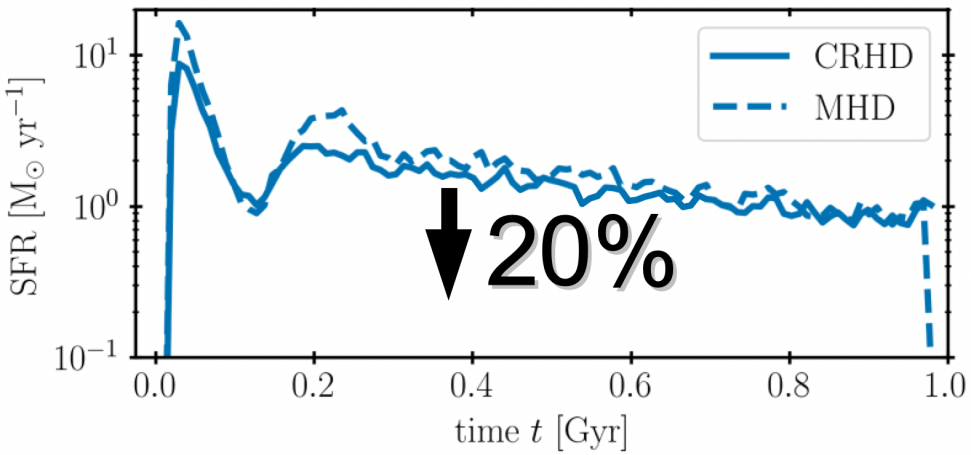
$$|\nabla P_{\rm cr} + \nabla P_{\rm th}| > \rho |\nabla \Phi|$$

Mass and energy loading factors



Thomas, CP, Pakmor (2025)

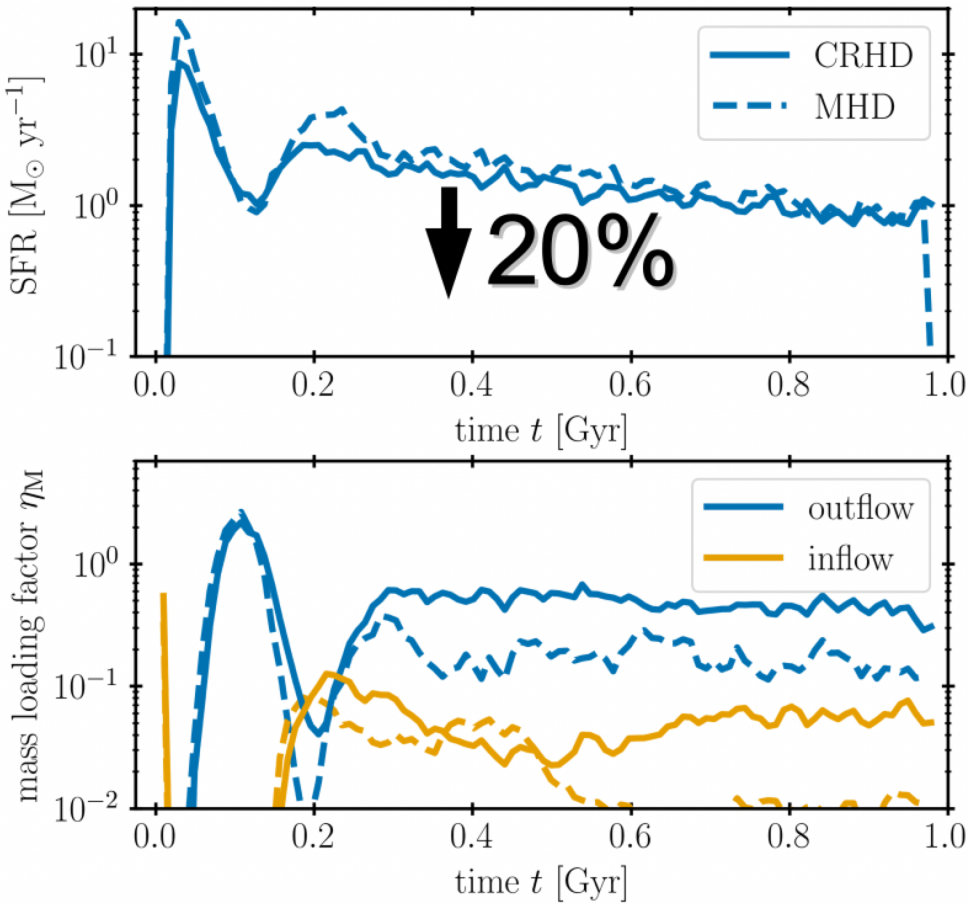
Mass and energy loading factors



Thomas, CP, Pakmor (2025)

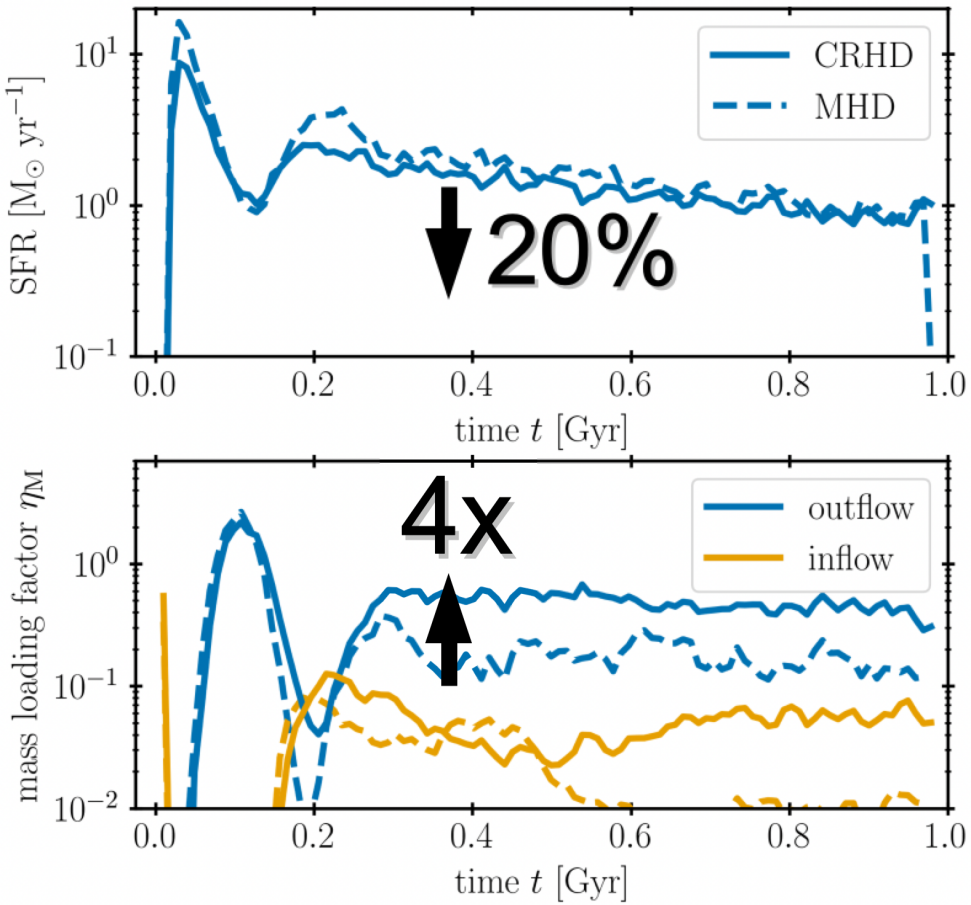
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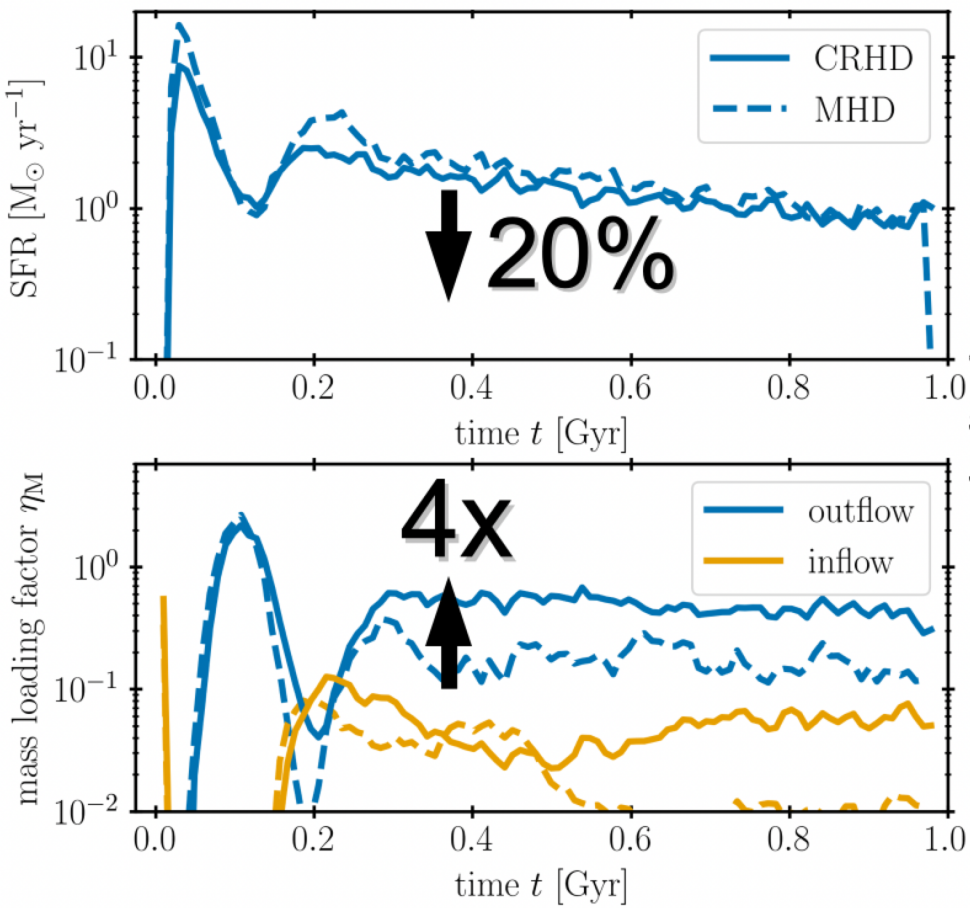
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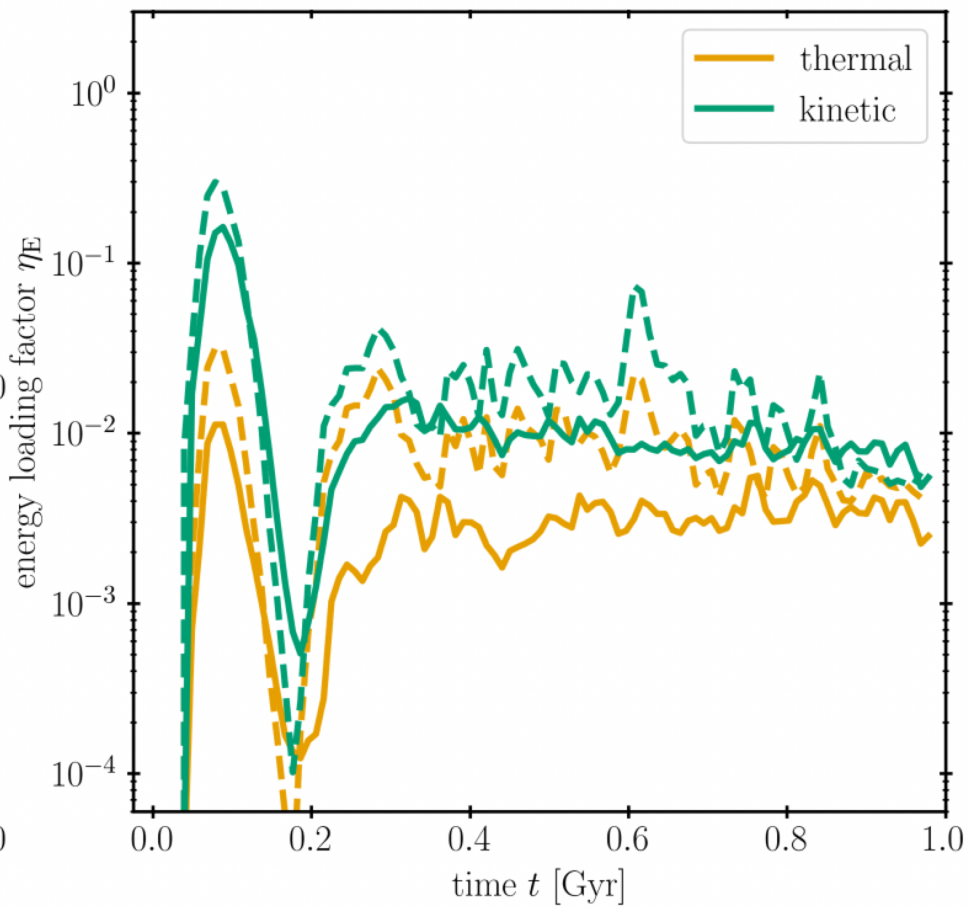
Mass and energy loading factors



Thomas, CP, Pakmor (2025)

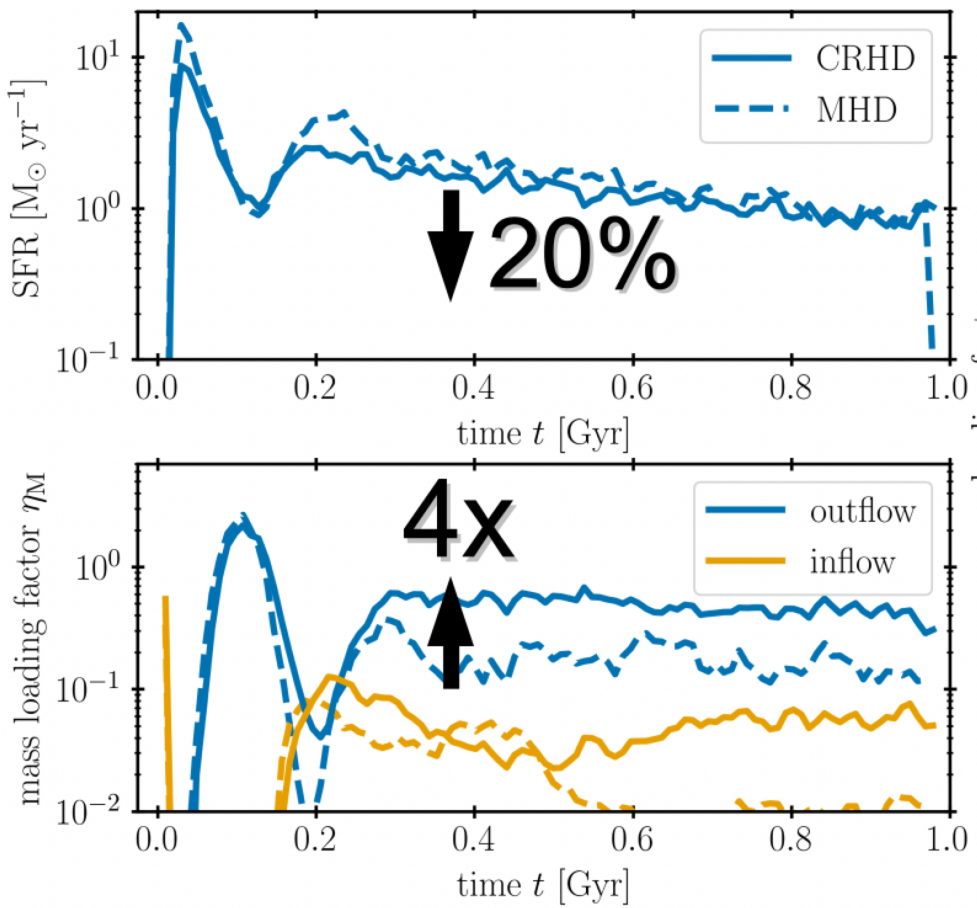
Mass and energy loading factors

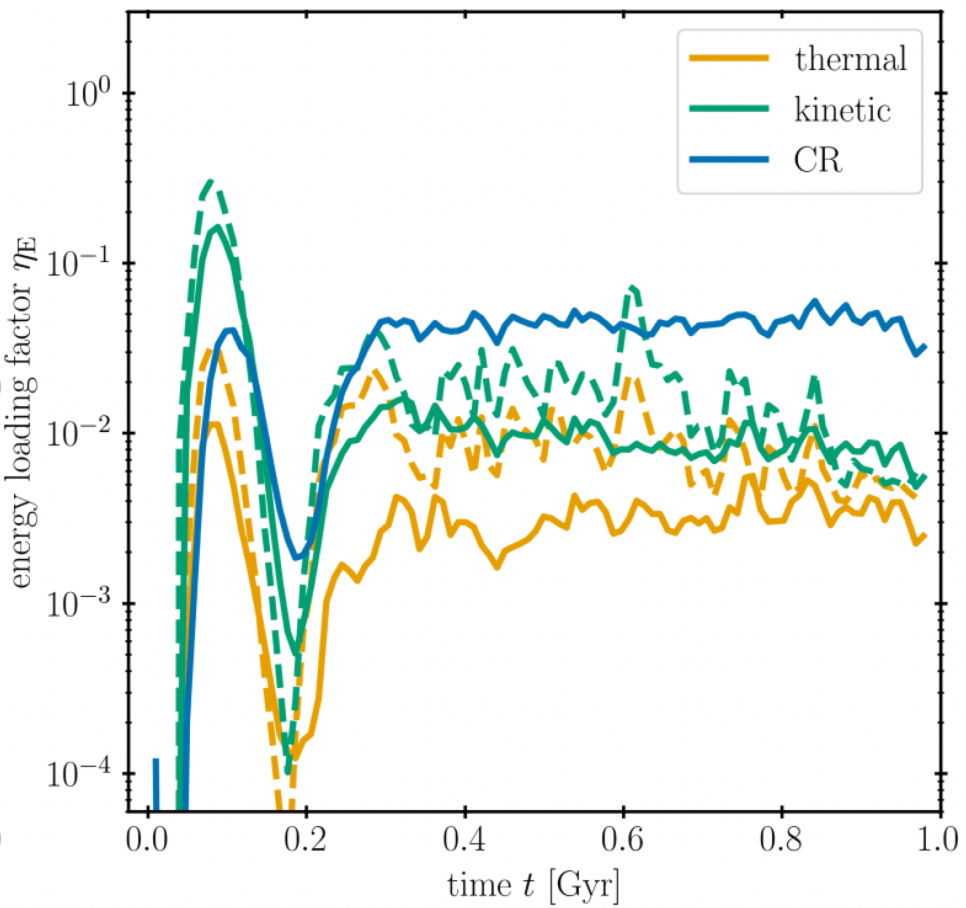




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Mass and energy loading factors

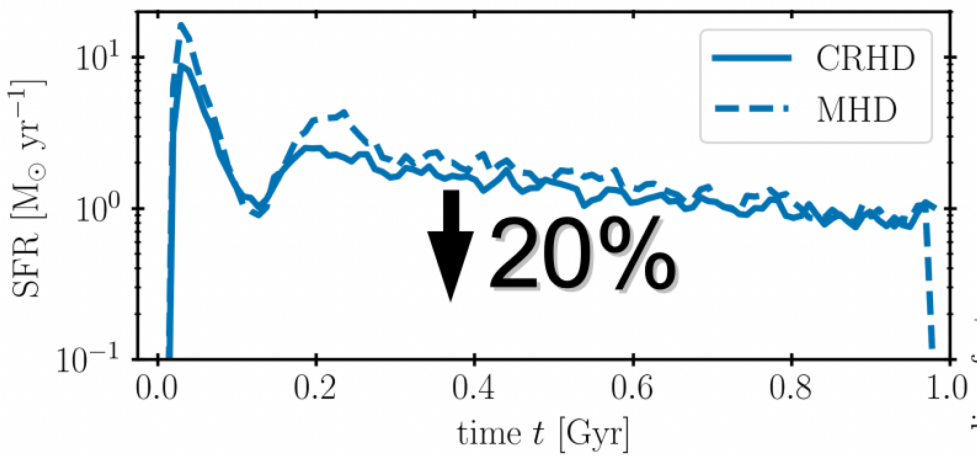


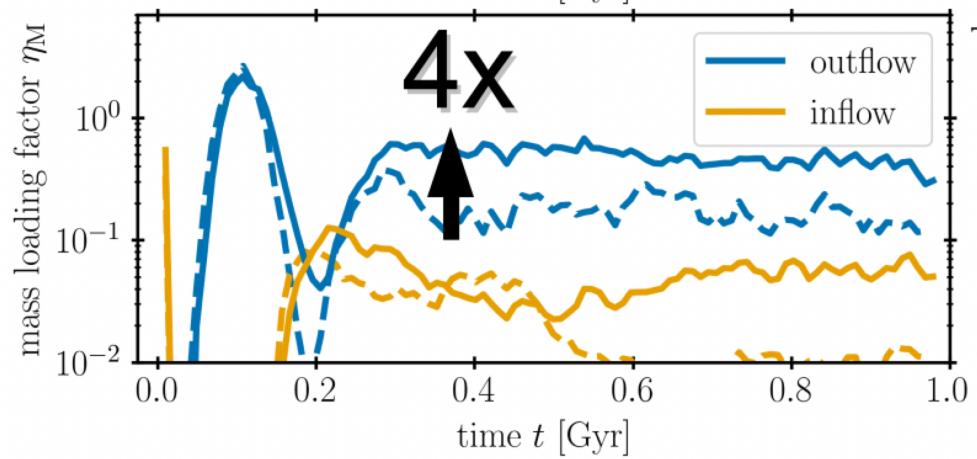


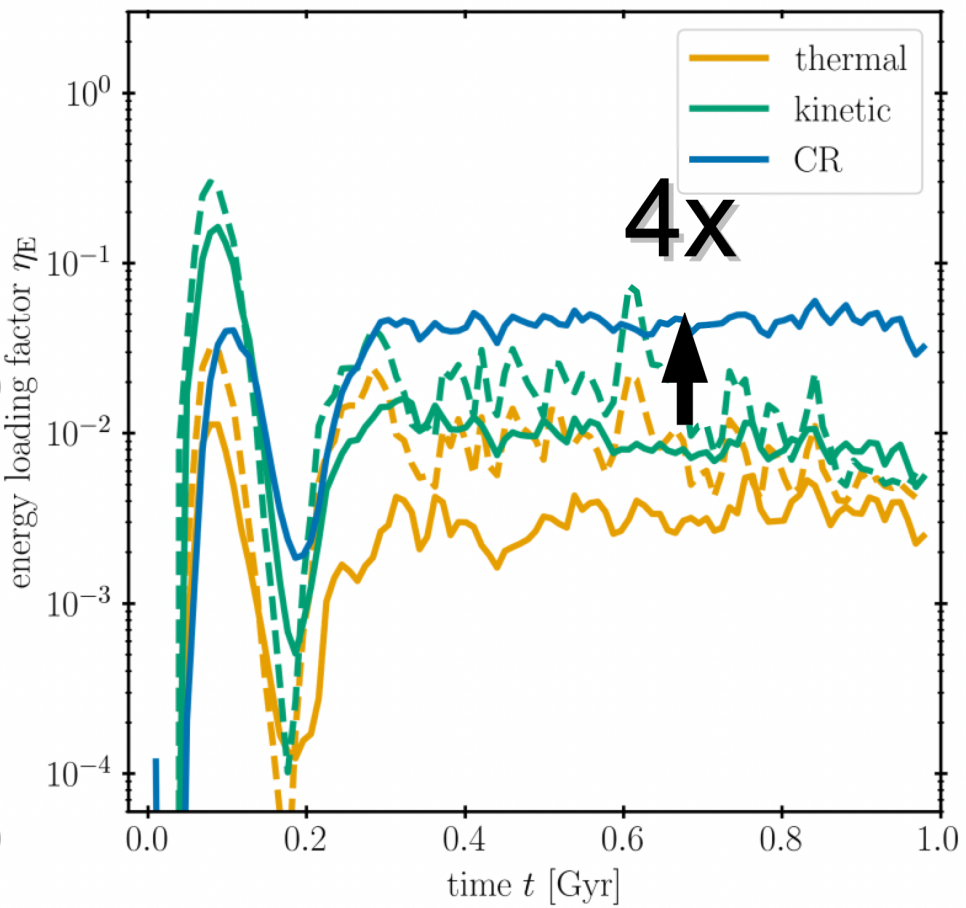
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Mass and energy loading factors







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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

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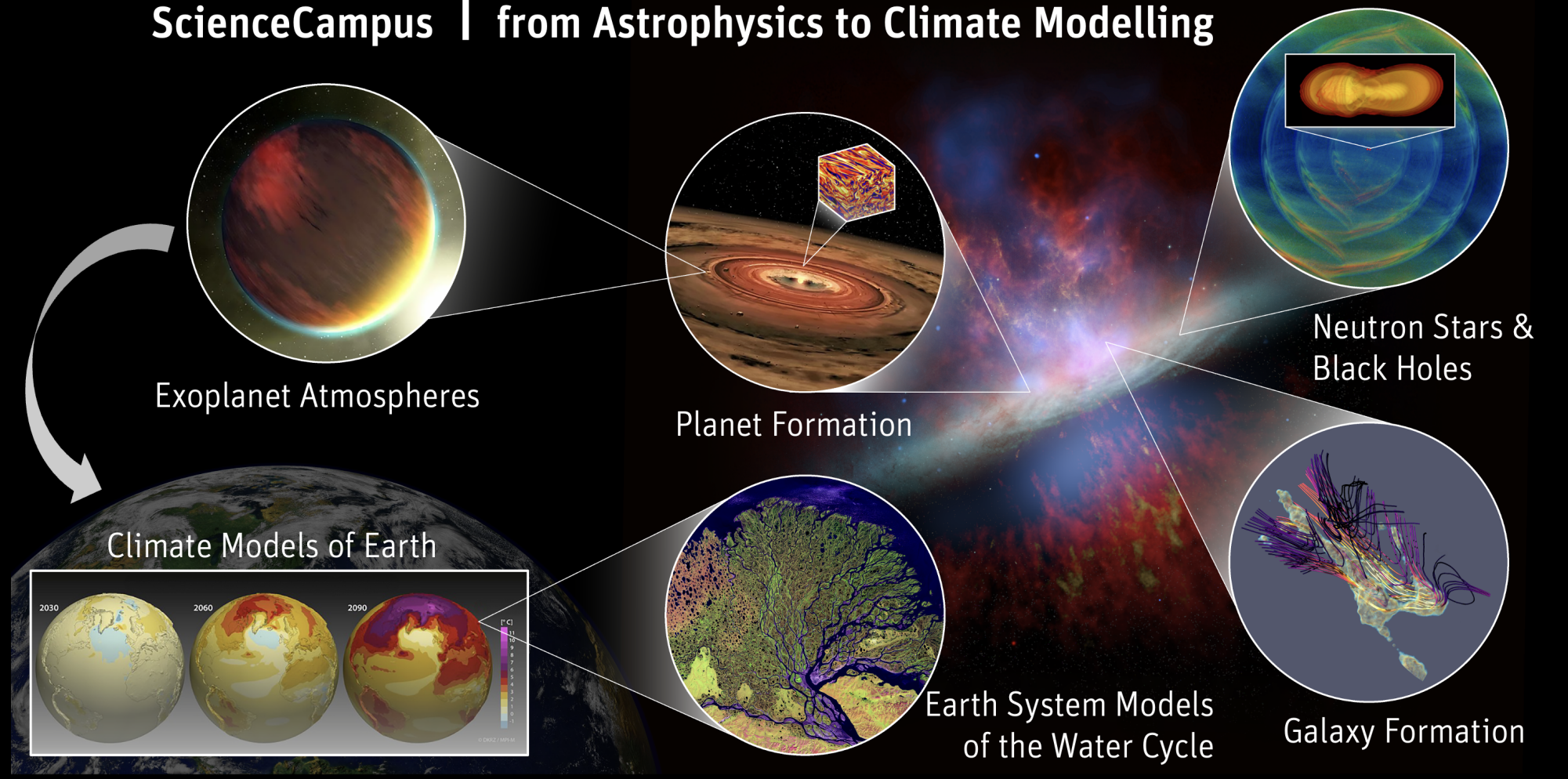
CR feedback in galaxy formation:

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



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PICOGAL: From Plasma KInetics to COsmological GALaxy Formation



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Literature for the talk – 1

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