Bridging microscopic and macroscopic cosmic ray transport in galaxies

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in collaboration with

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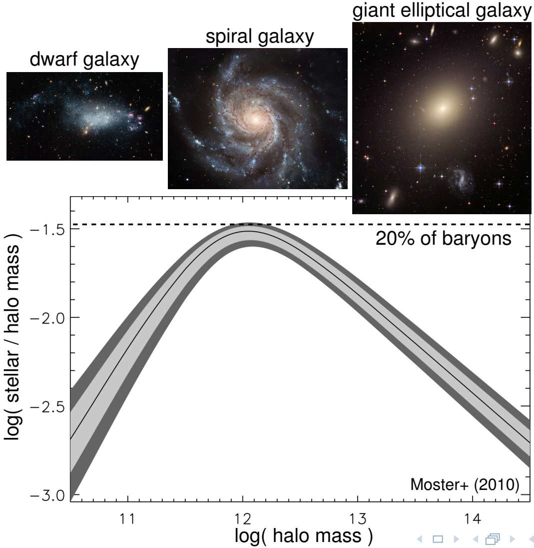
Unifying Cosmic Ray Research, Princeton 2026

Puzzles in galaxy formation



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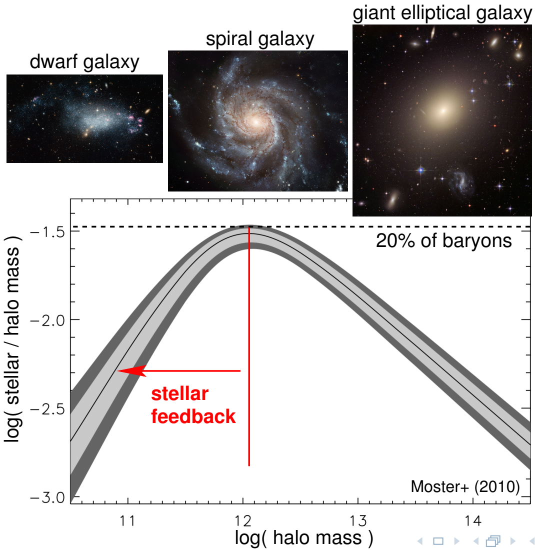

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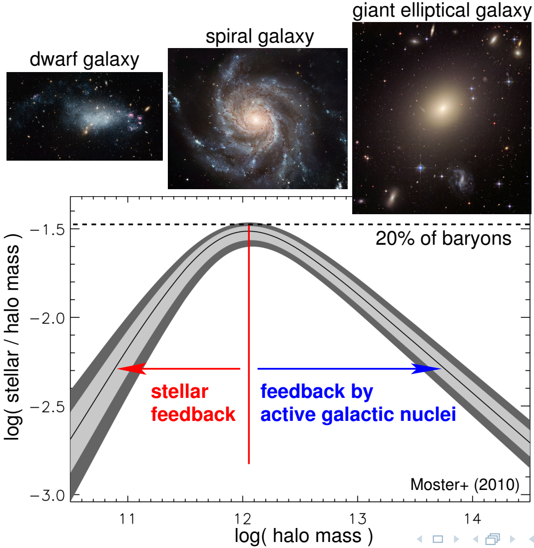
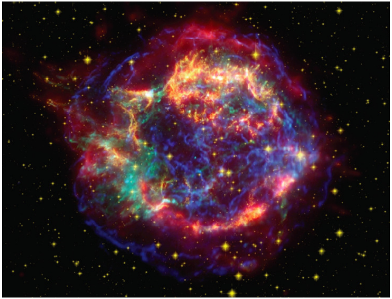


Stellar feedback drives galactic winds



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/O.Krause et al.

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields

AIP

Stellar feedback drives galactic winds

super wind in M82

NASA/JPL-Caltech/STScI/CXC/UofA

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Stellar feedback drives galactic winds

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NASA/JPL-Caltech/STScI/CXC/UofA

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields
- star formation and supernovae drive gas out of galaxies by galactic super winds
- critical for understanding the physics of galaxy formation $\rightarrow$ may explain puzzle of low star conversion efficiency in dwarf galaxies

How are galactic winds driven?

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?

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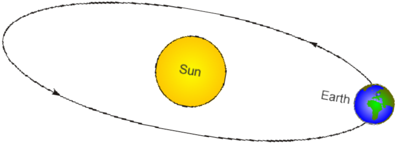
- pressure of cosmic rays (CRs) that are accelerated at supernova shocks?
- energy density of CRs, magnetic fields, and ISM turbulence all similar
  $\Rightarrow$ important feedback agent

Cosmic ray transport: an extreme multi-scale problem

Milky Way-like galaxy:

$$r_{\rm gal} \sim 10^4\ \rm pc$$



gyro-orbit of GeV CR:

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

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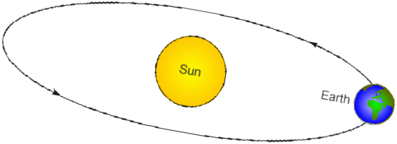

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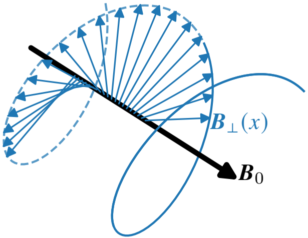
$\Rightarrow$ **link kinetic plasma physics to macroscopic MHD models on galactic scales!**

Zweibel (2017), Thomas & CP (2019)

What is gyro resonance?

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

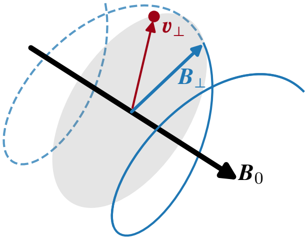


What is gyro resonance?

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

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

Ω_{cr} gyration frequency



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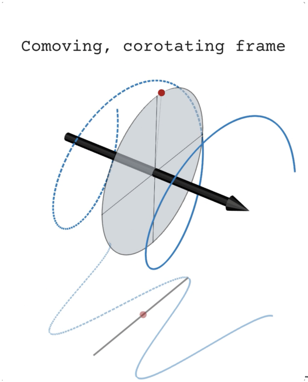

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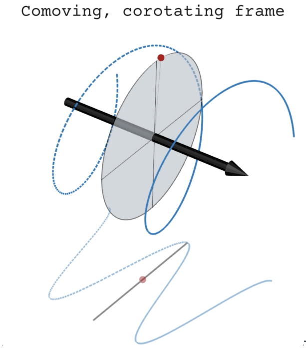
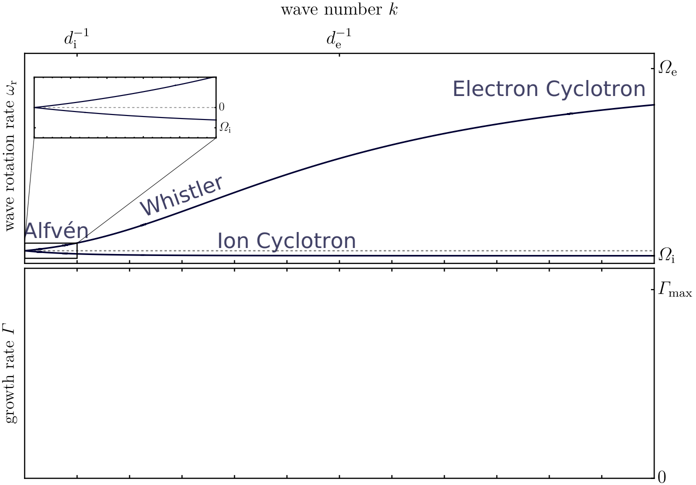
Resonant wave appears **static** to CR!



test particle without interactions!

Dispersion relation of resonant CR interactions



Shalaby+ (2023)

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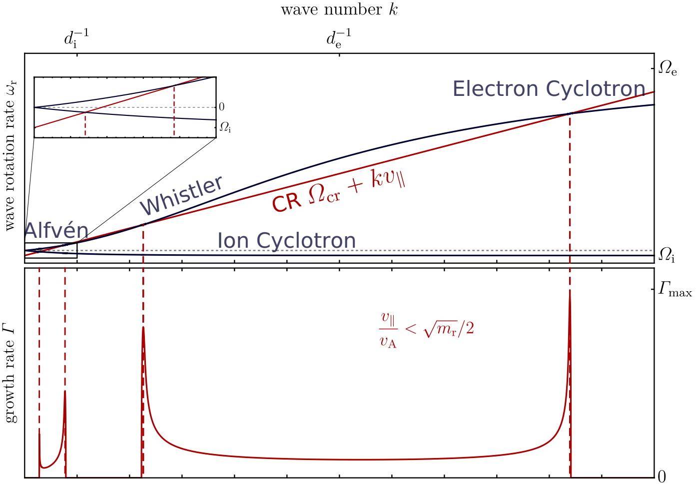

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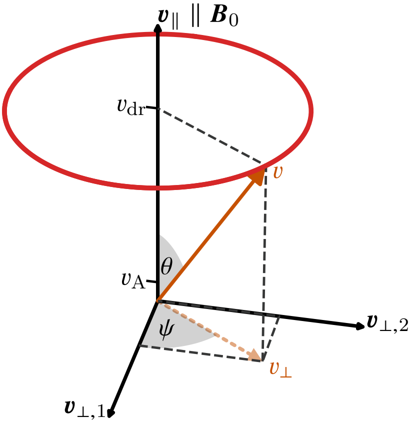
Idealized setup to understand physics



- 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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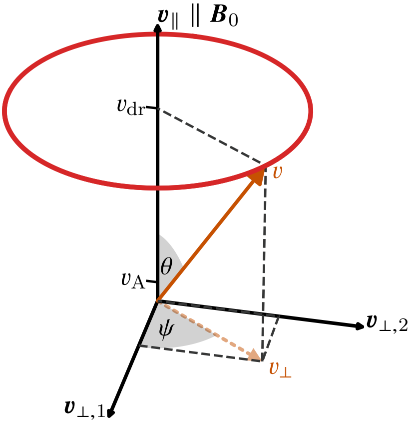
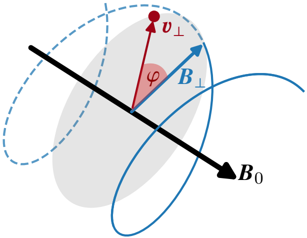


- gyrotropic ring distribution of CR ions with single pitch angle and energy
- neutralizing CR electron beam at same drift speed but $v_\perp = 0$
- background ion and electron fluid with Landau closure
- fluids coupled to particle-in-cell (PIC) CRs via Maxwell's equations

(Lemmerz+ 2024)

The mechanism of CR-driven instabilities – 1

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



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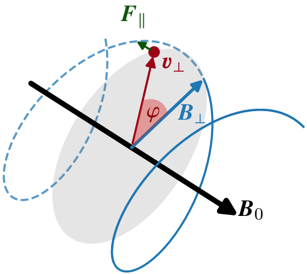

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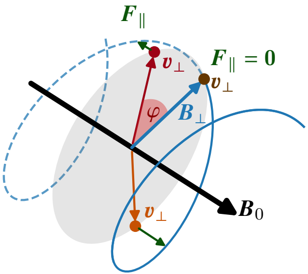

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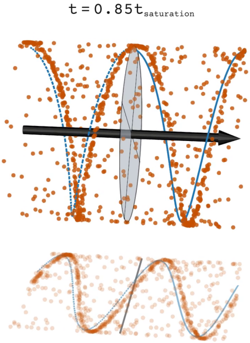

fluid-PIC simulation (Lemmerz+ 2025)

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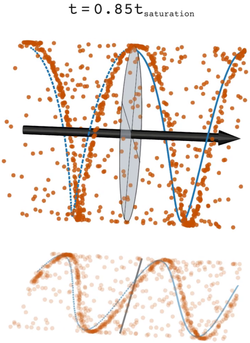
- CR trapping in Lorentz force potential saturates instability



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The mechanism of CR-driven instabilities – 2

- combine CR and magnetic phase angles, ψ_{cr} and ψ_B:

$$\varphi(x,t) = \psi_{\mathrm{cr}}(t) - \psi_B(x,t)$$

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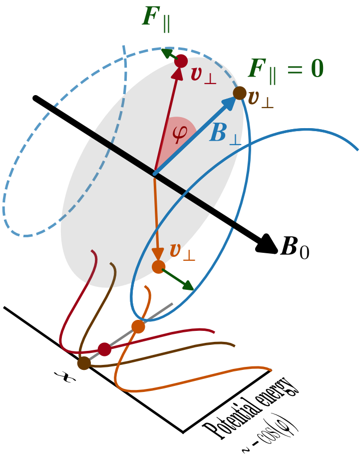
- evolution of relative CR gyrophase φ obeys pendulum equation:

$$\varphi(t) = -\Omega_{\mathrm{cr}} t + k \int_0^t v'_{\parallel}(\tau)\mathrm{d}\tau + \varphi_0,$$

$$\frac{\partial \varphi(t)}{\partial t} = -\Omega_{\mathrm{cr}} + k v'_{\parallel}(t),$$

$$\frac{\partial^2 \varphi(t)}{\partial t^2} = -k \frac{q B_{\perp}(t) v_{\perp}(t)}{\gamma' m} \sin \varphi(t)$$

The mechanism of CR-driven instabilities – 3



- saturation of CR streaming instability via CR trapping in Lorentz force potential: new idea for CR transport

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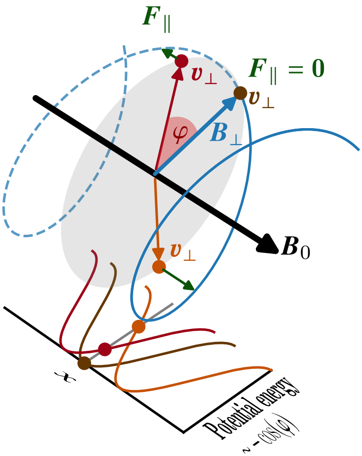

- saturation of CR streaming instability via CR trapping in Lorentz force potential: new idea for CR transport (Lemmerz+ 2025)
- particle trapping observed in the solar wind and modelled in PIC simulations (Hoshino & Terasawa 1985, Gary+ 1986, Zachary+ 1989)

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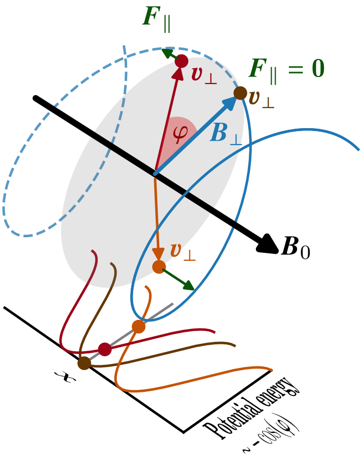
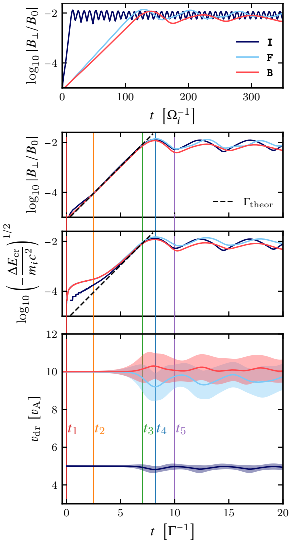


- saturation of CR streaming instability via CR trapping in Lorentz force potential: new idea for CR transport (Lemmerz+ 2025)
- particle trapping observed in the solar wind and modelled in PIC simulations (Hoshino & Terasawa 1985, Gary+ 1986, Zachary+ 1989)
- phase bunching also happens in a free-electron laser (however, electrons are trapped in potential of the ponderomotive force)

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

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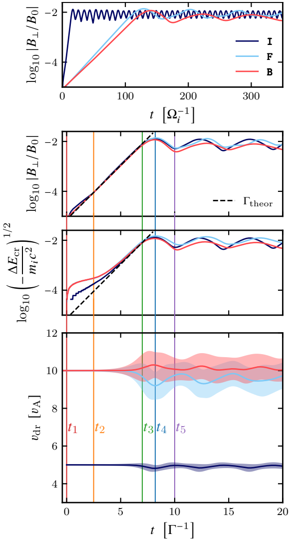

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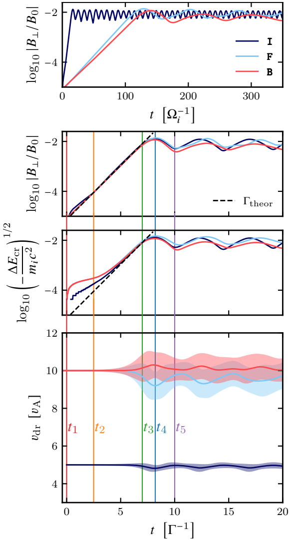
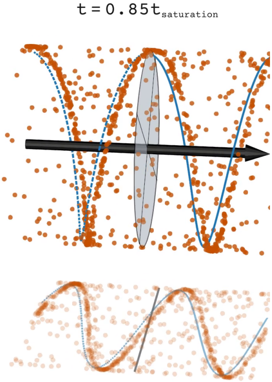


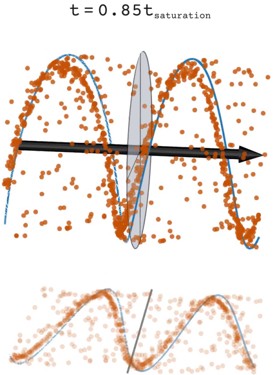
- exponential wave growth in fluid-PIC simulations that excite whistlers (via intermediate-scale instability, **I**), backward (**B**) and forward (**F**) Alfvén waves
- energy gain by waves exactly balances CR energy loss to the unstable modes
- mean CR drift speed, $v_{\rm dr}$, slows down for forward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

AIP

Growth of forward and backward moving waves



forward Alfvén,
Whistler



backward Alfvén

Lemmerz+ (2025)

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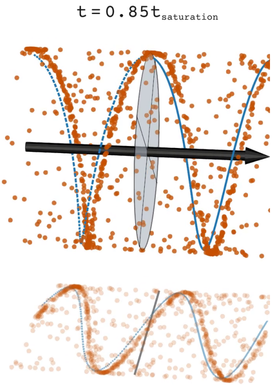

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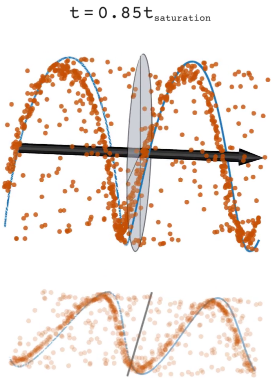

backward Alfvén

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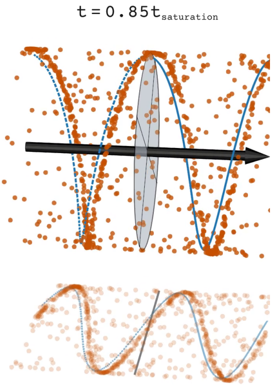
Growth of forward and backward moving waves



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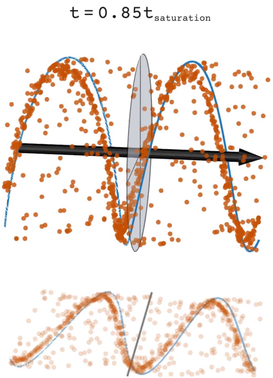

backward Alfvén

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bunching theory:

- *bunching* in CR gyro phase
- biased CR scattering, favors wave growth

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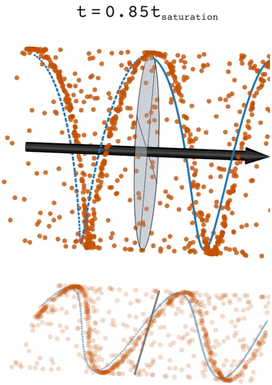
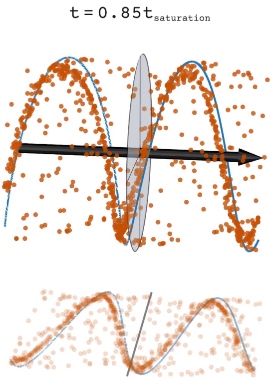


forward Alfvén, Whistler



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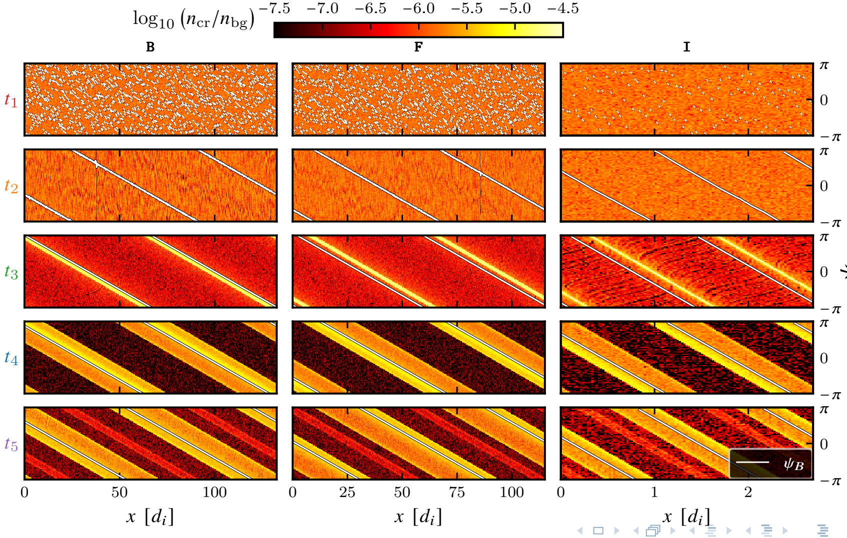
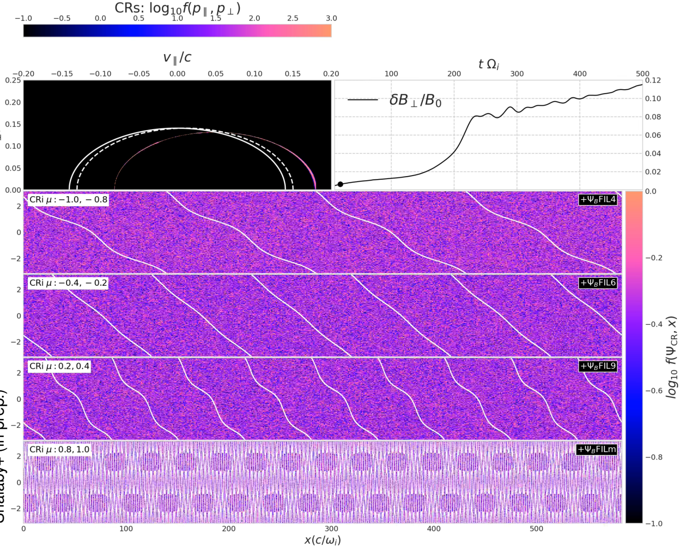
traditional, quasilinear theory:

- assumes uniform φ
- diffusive scattering, no backward wave growth

CR phase bunching critical for instablity growth



Cosmic ray-driven instability with shell distribution



Shalaby+ (in prep.)

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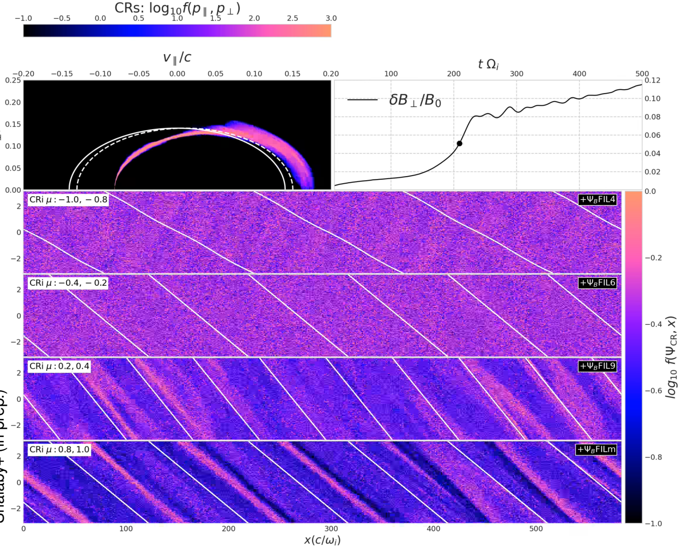

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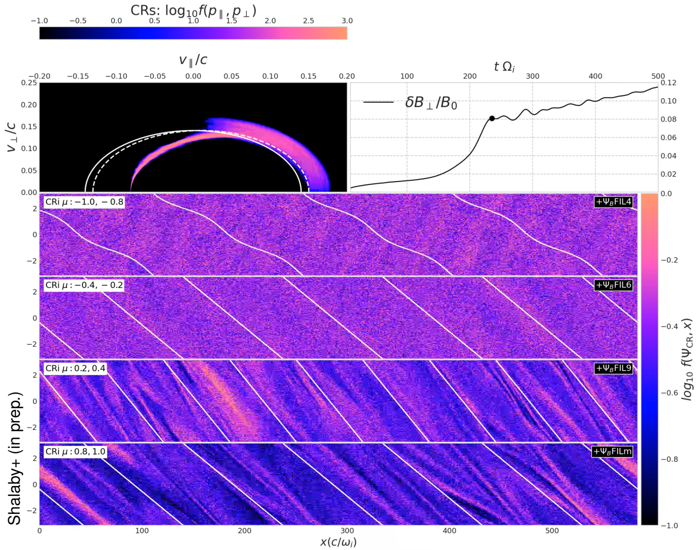

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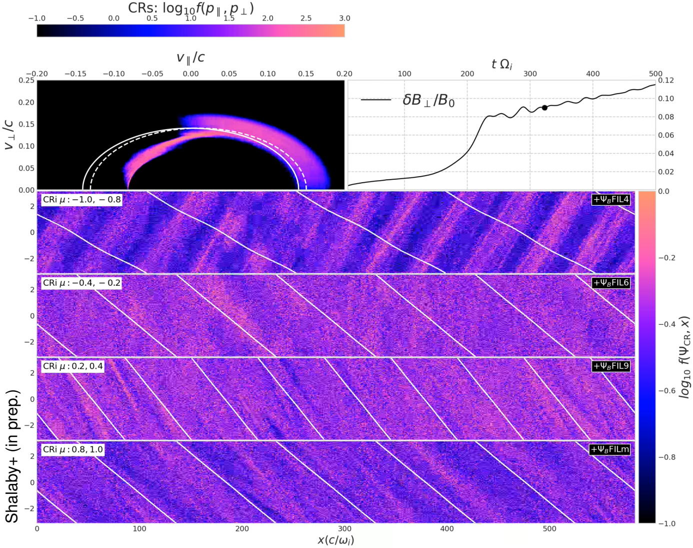

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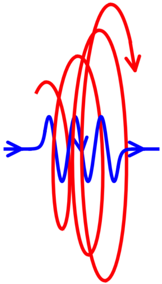
Cosmic ray streaming and diffusion

- **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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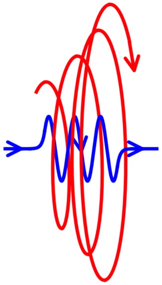

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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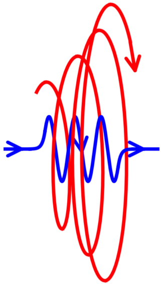
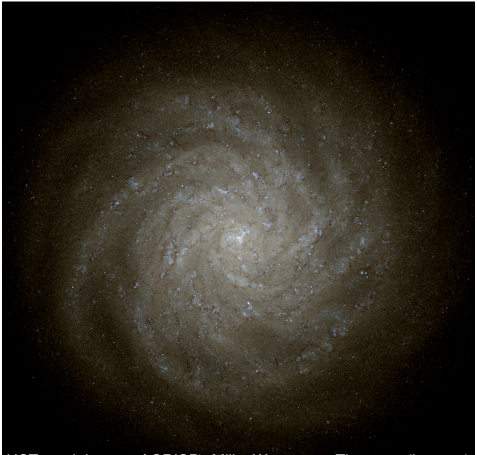


→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

weak wave damping: strong coupling → CR stream with waves
strong wave damping: less waves to scatter → CR diffusion prevails

Cosmic ray transport in galaxies



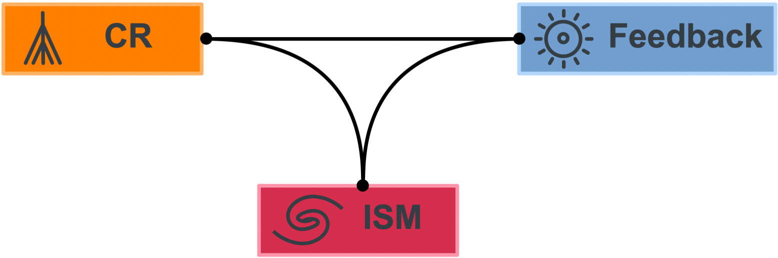
HST mock image of CRISPy Milky Way Thomas+ (in prep.)

- 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)

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

Feedback

CR

ISM

Chemistry

- 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

CR

ISM

Feedback

- 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

Feedback

ISM

CR

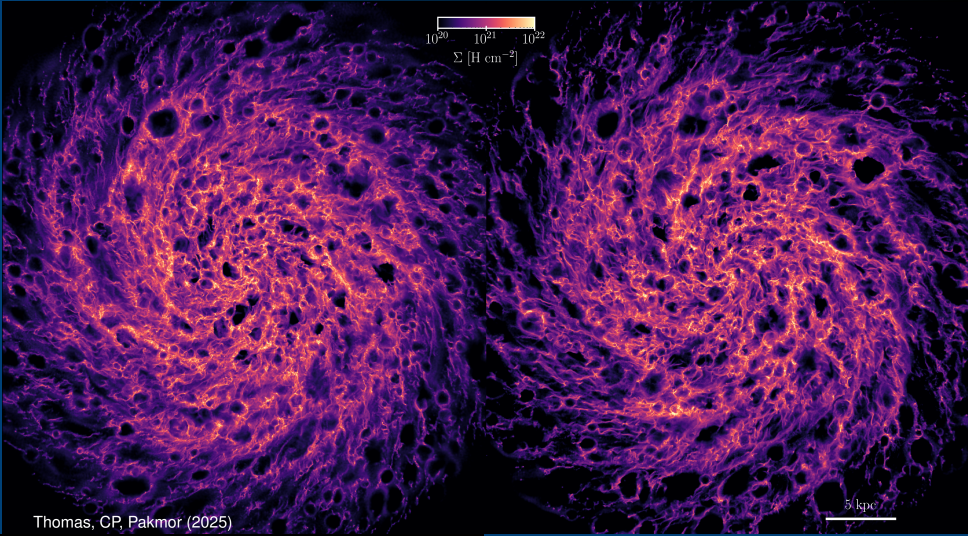
- Novel CR hydrodynamics
  coarse graining plasma physics
- CR ionization
  impacting **Chemistry**
- CR microphysics

Follow $\varepsilon_{\mathrm{cr}}$ and v_{cr}

Self-consistently evolve κ_{cr}

Thomas, CP, Pakmor (2025)

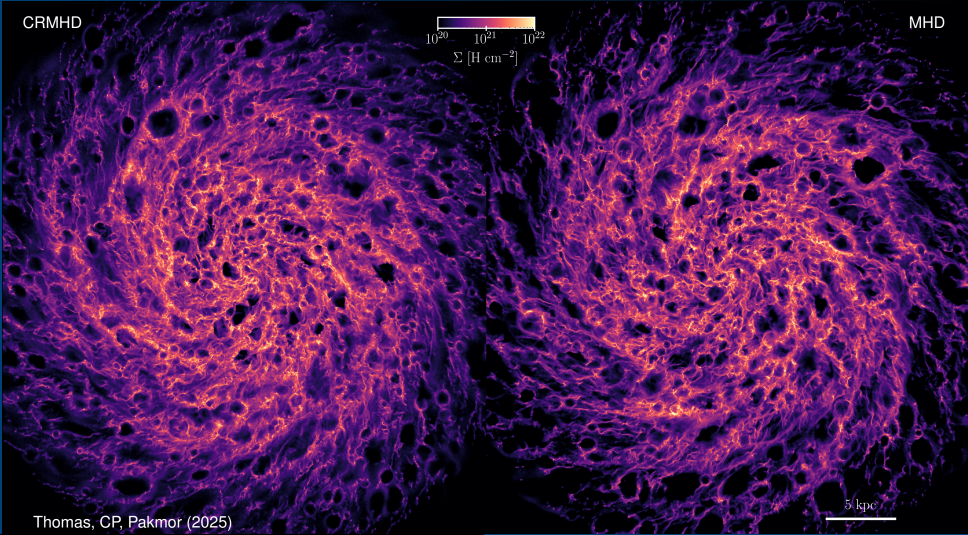
Multi-phase ISM modeling



Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

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



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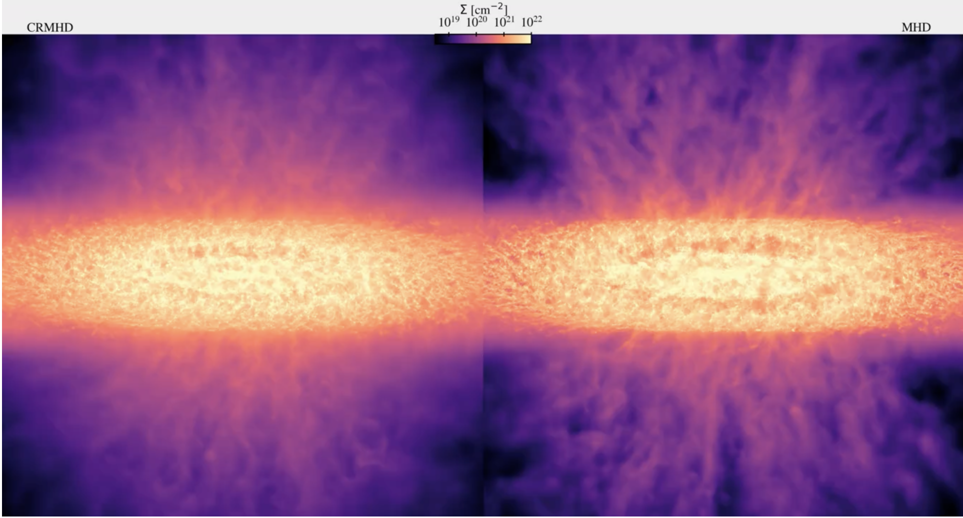
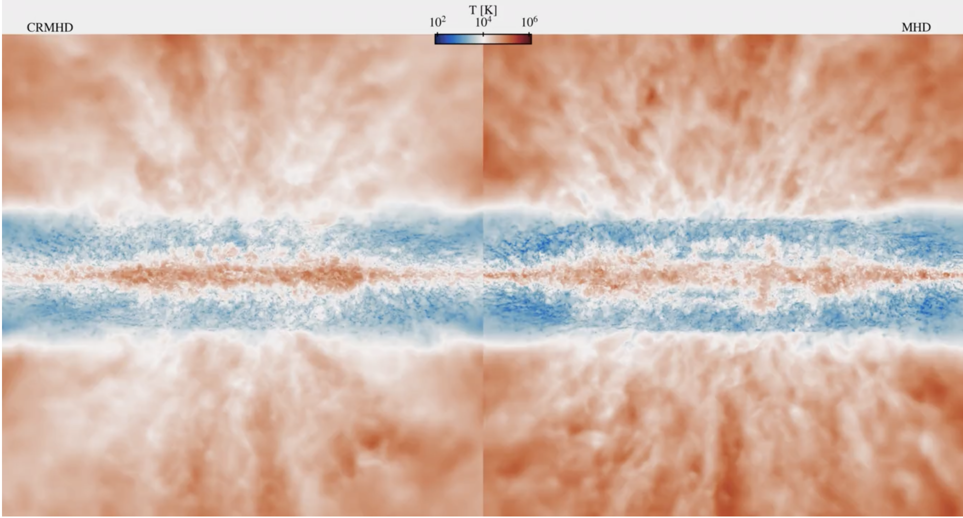
Simulated Milky Way: surface density

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



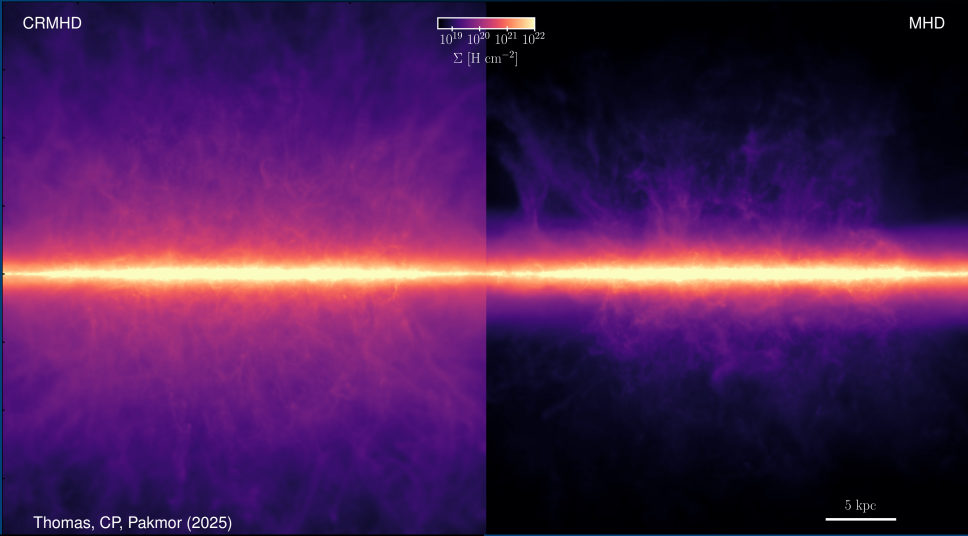
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter

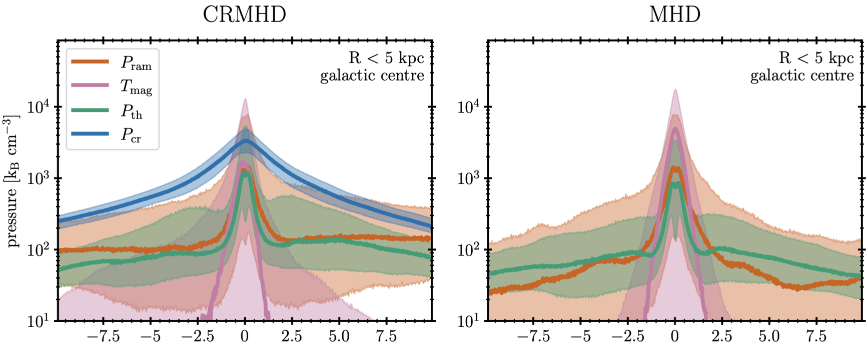


Multi-phase ISM modeling

Cosmic rays make galactic winds much denser



Cosmic ray driven wind: mechanism

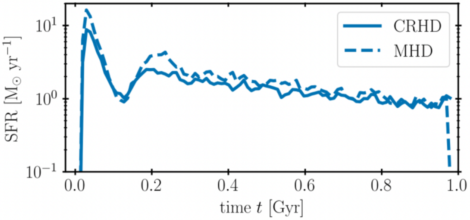


Thomas, CP, Pakmor (2025)

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

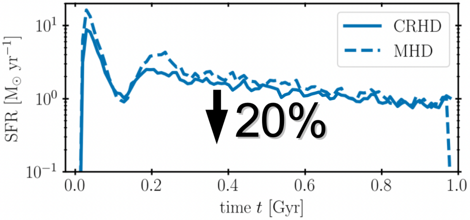
$$|\nabla P_{\rm cr} + \nabla P_{\rm th}| > \rho |\nabla \Phi|$$

Mass and energy loading factors



Thomas, CP, Pakmor (2025)

Mass and energy loading factors



Thomas, CP, Pakmor (2025)

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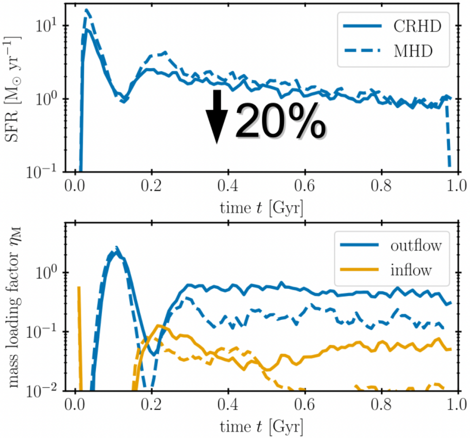

Thomas, CP, Pakmor (2025)

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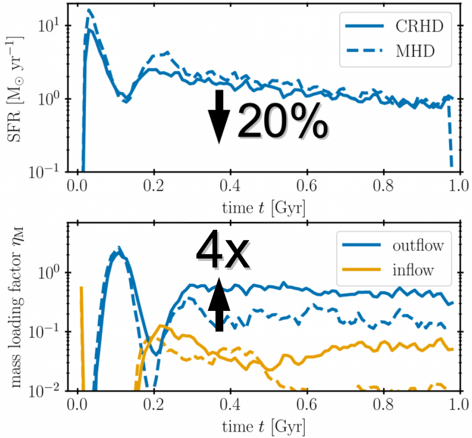

Thomas, CP, Pakmor (2025)

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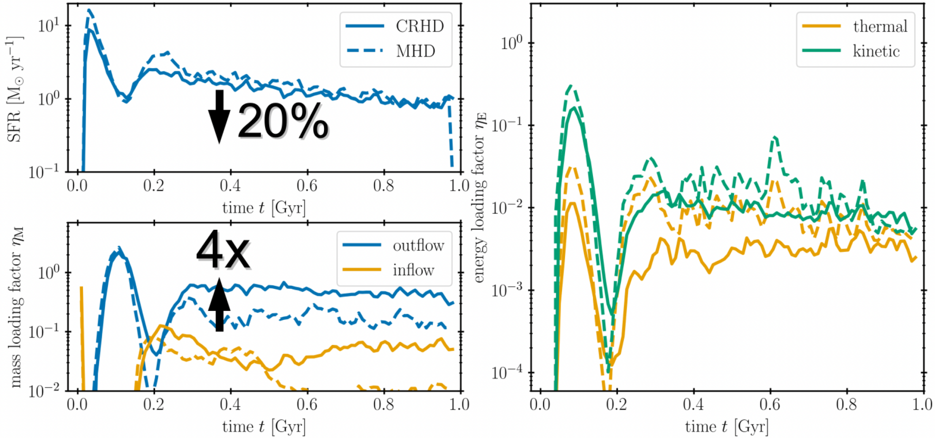

Thomas, CP, Pakmor (2025)

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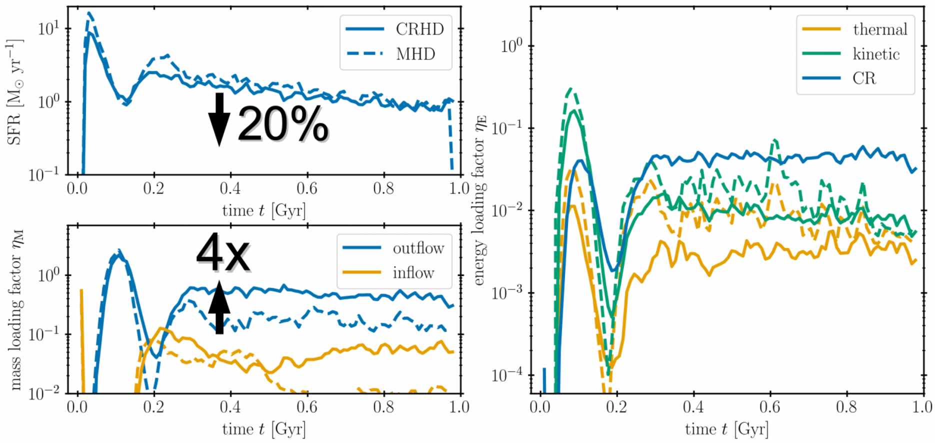
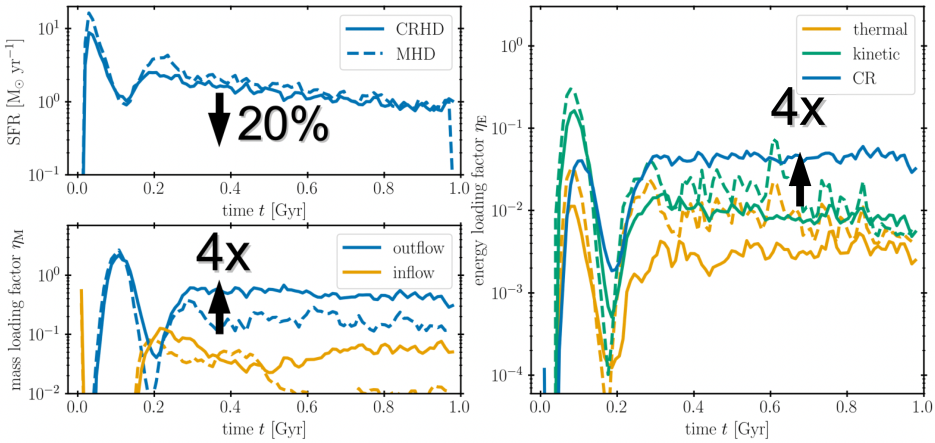


Thomas, CP, Pakmor (2025)

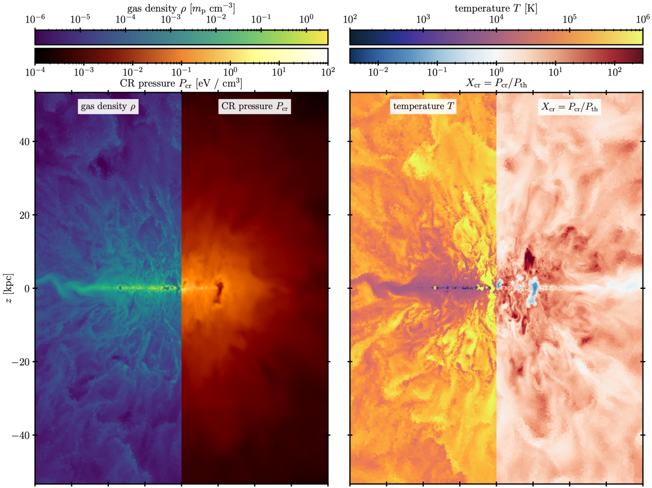
Mass and energy loading factors



Thomas, CP, Pakmor (2025)

CRs in the circumgalactic medium (CGM)

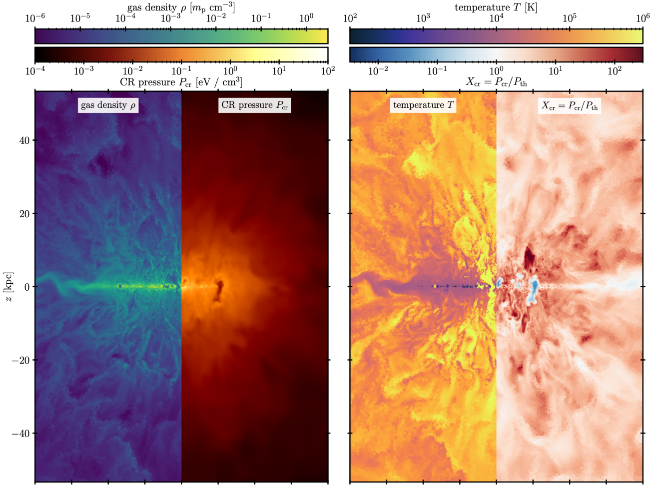
CR pressure dominates in the CGM ($X_{\rm cr} = P_{\rm cr}/P_{\rm th} > 1$)



Thomas, CP, Pakmor (2025)

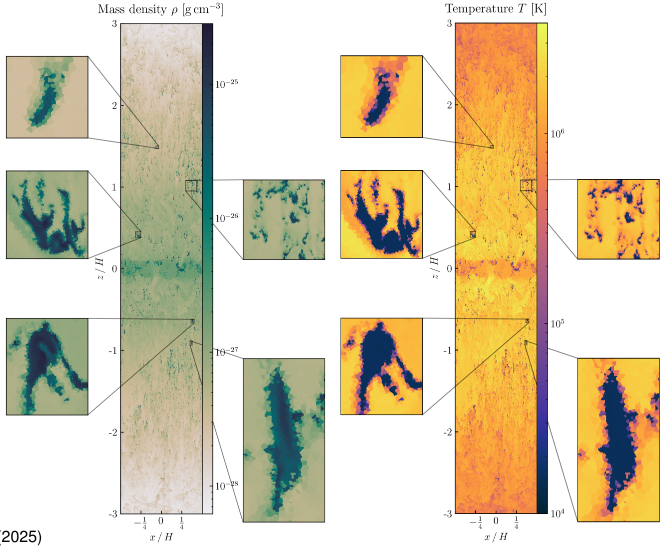
CRs in the circumgalactic medium (CGM)

CR pressure dominates in the CGM ($X_{cr} = P_{cr}/P_{th} > 1$): what about thermal instability?



Thomas, CP, Pakmor (2025)

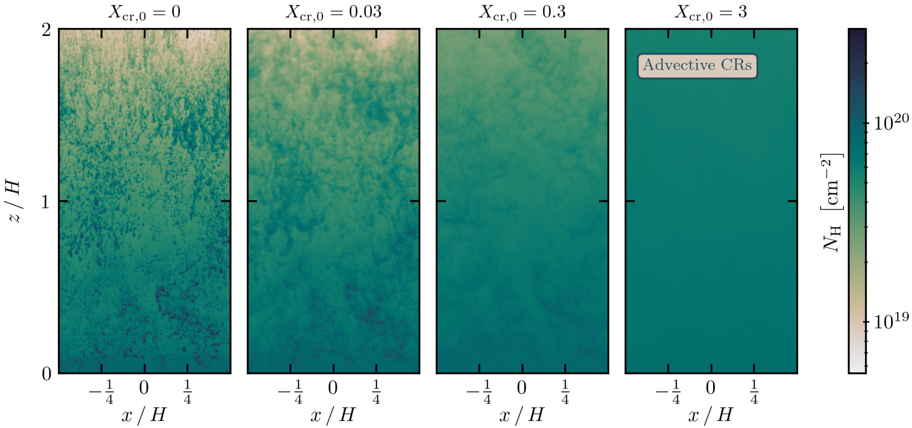
Thermal instability in the circumgalactic medium



Weber+ (2025)

Thermal instability with purely advective CRs

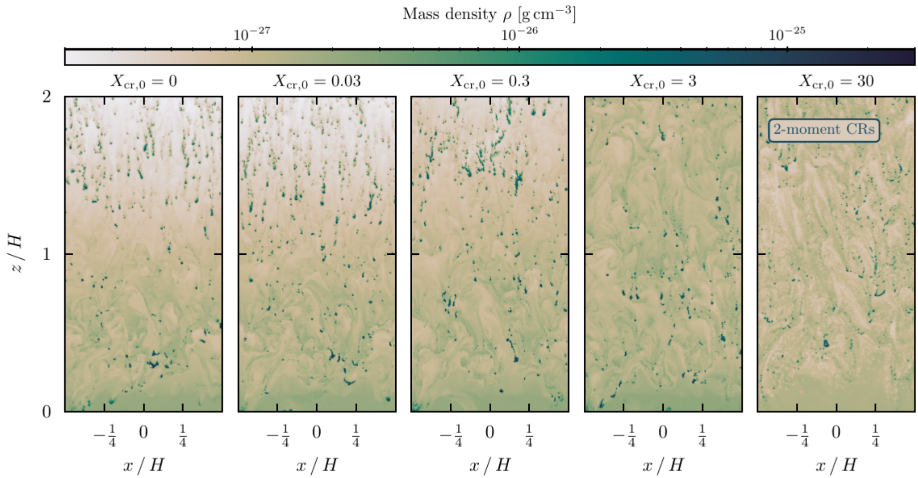
Increasing CR pressure to the right prevents radiative cooling and condensation



Weber+ (2025), see also Butsky+ (2020)

Thermal instability with CR streaming and diffusion

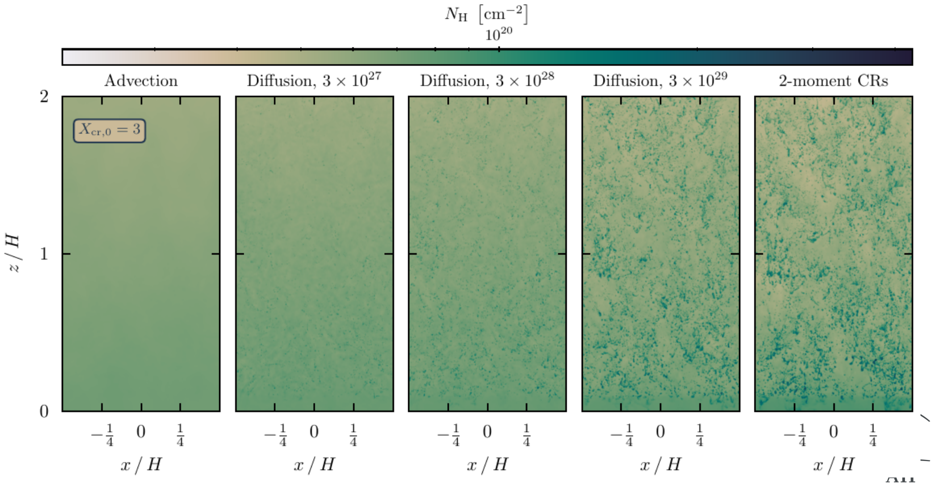
Increasing CR pressure (toward the right) has no effect on condensation: why?



Weber+ (2025)

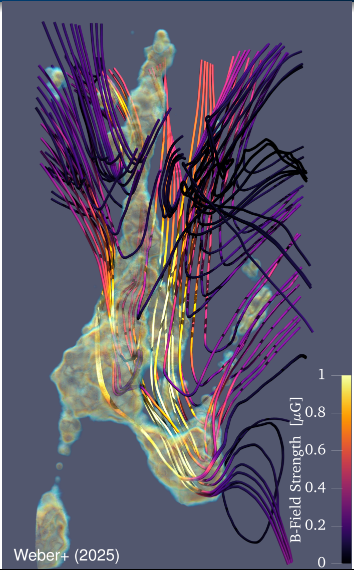
Thermal instability with different CR transport models

Increasing CR transport speed (toward the right) enhances gas condensation



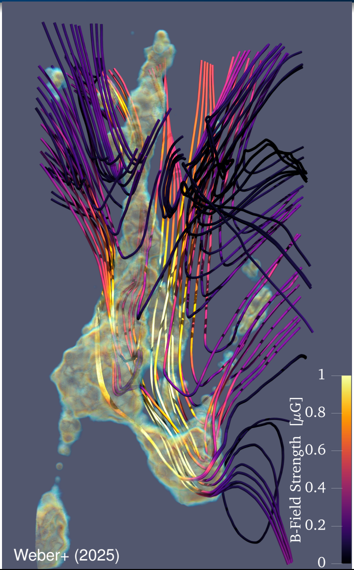
Weber+ (2025)

Zooming in onto a condensing cold cloud



- complex magnetic field topology in and around a descending, condensing cloud governs CR transport
- magnetic field lines connect cloud interior to the ambient plasma

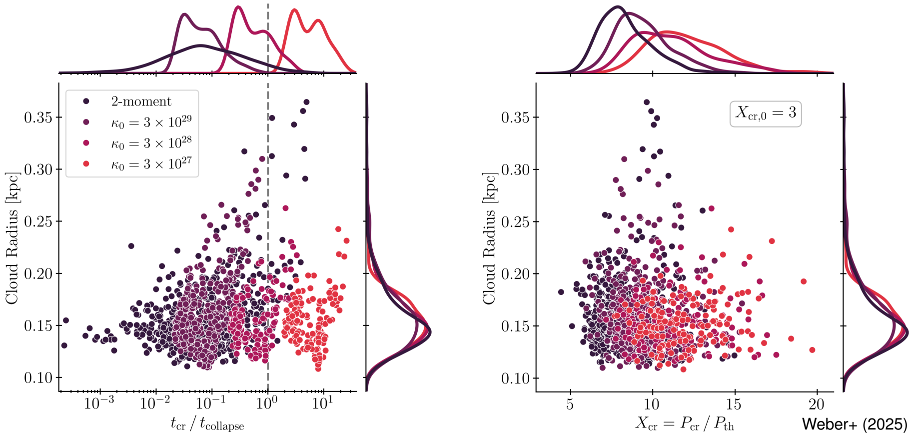
Zooming in onto a condensing cold cloud



- complex magnetic field topology in and around a descending, condensing cloud governs CR transport
- magnetic field lines connect cloud interior to the ambient plasma
- radiative cooling compresses CR and magnetic energy density by a factor $\sim$100
- emerging CR gradients and amplified magnetic fields enable rapid CR escape from the compressed cloud

AIP

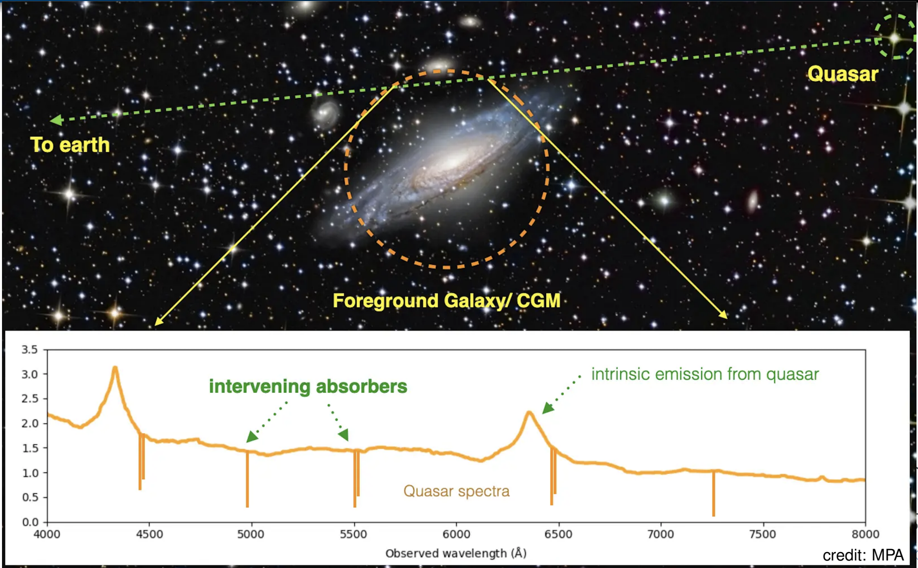
CR escape times for different transport speeds



Weber+ (2025)

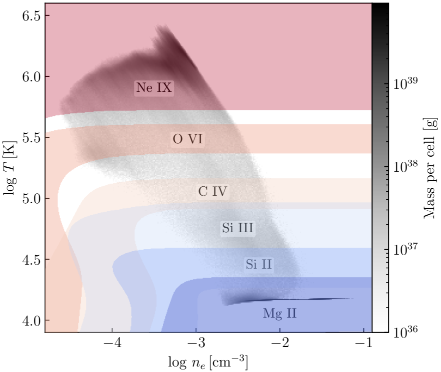
- CR escape time < collapse time for faster CR transport
- smaller CR pressure support in clouds with faster CR transport

Probing the multiphase CGM with absorption lines



credit: MPA

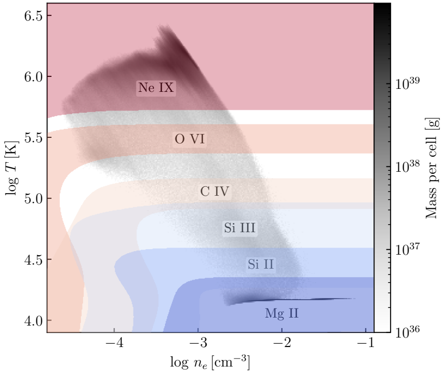
Probing the CGM with ionic tracers

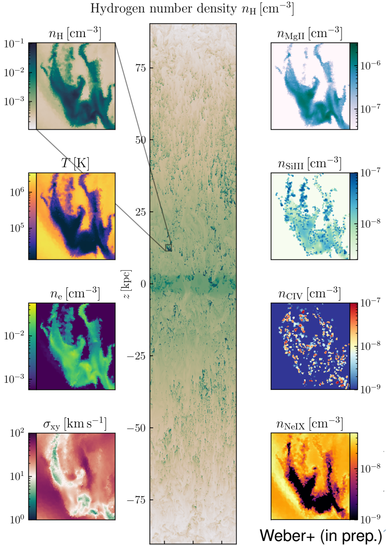


- different ionic species probe different CGM phases

Weber+ (in prep.)

Probing the CGM with ionic tracers



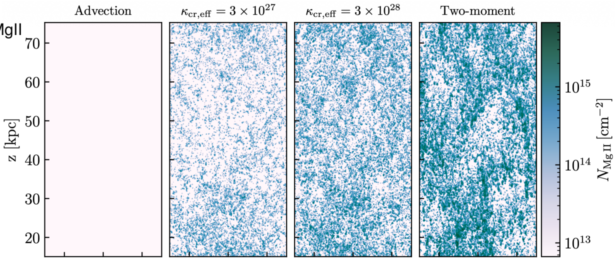


Weber+ (in prep.)

- different ionic species probe different CGM phases

Column densities for different CR transport speeds

Cold gas tracer: MgII

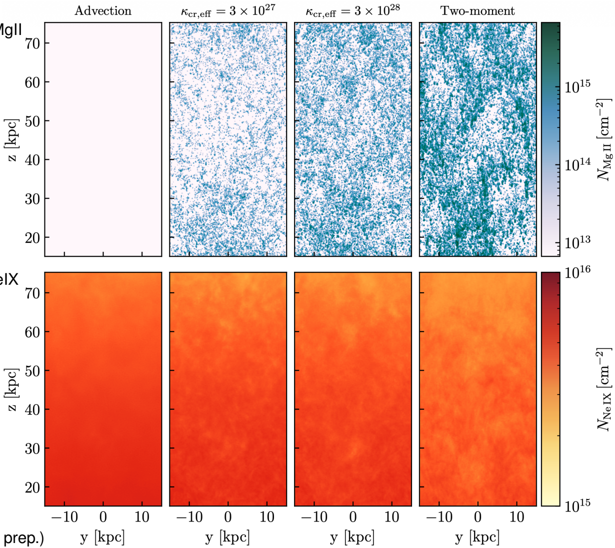


Weber+ (in prep.)

Column densities for different CR transport speeds

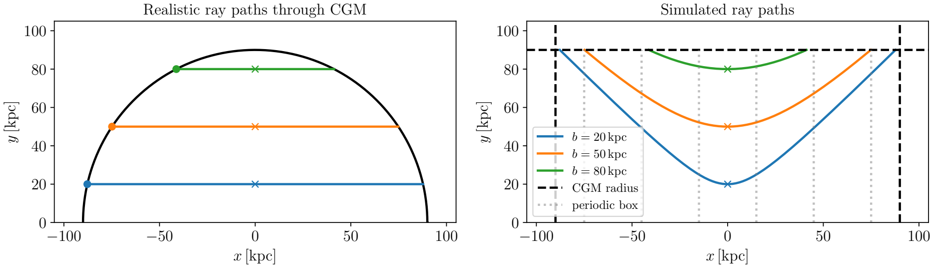
Cold gas tracer: MgII

Hot gas tracer: NeIX



Weber+ (in prep.)

Producing synthetic absorption spectra from tall boxes

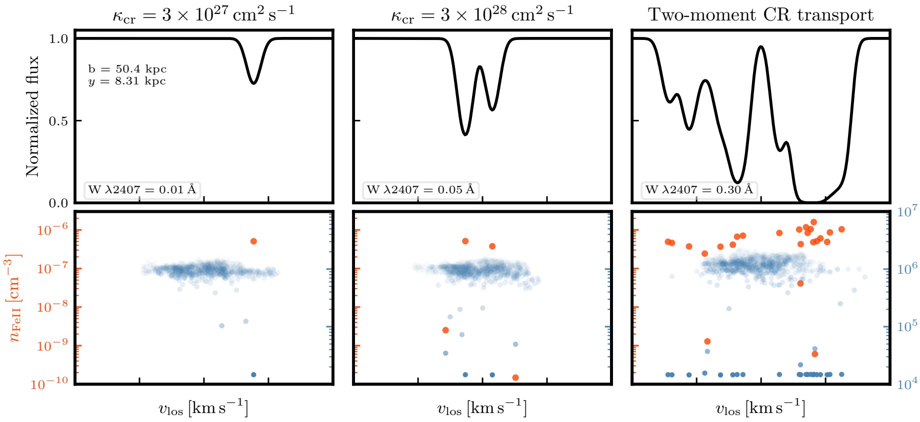


Weber+ (in prep.)

- radiative CR-MHD simulation run in plane-parallel geometry
- cast parabolic sightlines through periodically replicated boxes to recover realistic velocity structure (for line broadening), at the expense of somewhat overextended path lengths

Synthetic absorption spectra along one sightline

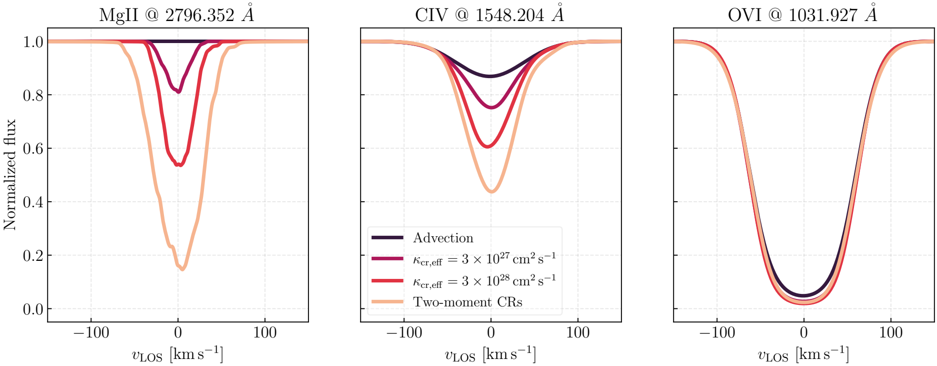
Line profiles enable constraints on CR transport speeds



Weber+ (in prep.)

Mean absorption spectra with varying CR transport

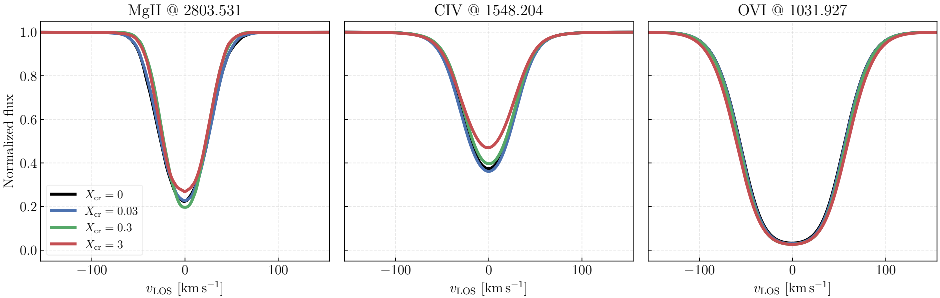
Strength and width of cold/warm absorption lines increases for faster CR transport



Weber+ (in prep.)

Mean absorption spectra with varying CR pressure

Strength and width of absorption lines independent of CR pressure support



Weber+ (in prep.)

Conclusions

CR-driven plasma instabilities:

- 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

Conclusions

CR-driven plasma instabilities:

- 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

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 and increases mass and energy loading factors

AIP

Conclusions

CR-driven plasma instabilities:

- CR-driven plasma-instabilities grow and saturate via phase bunching ⇒ sets CR transport speed and feedback strength
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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 and increases mass and energy loading factors

Thermal instability in the circumgalactic medium with CRs:

- 2-moment CR transport predicts fast CR escape from condensing clouds ⇒ multi-phase circumgalactic medium
- absorption-line spectra enable constraining CR transport speed

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:

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- 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 CGM:

- 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.
- Weber, Thomas, Pfrommer, Pakmor, *CRexit: how different cosmic ray transport modes affect thermal instability in the circumgalactic medium,* 2025, A&A, 698, A125.