

Cosmic ray feedback in galaxy formation

Christoph Pfrommer¹

in collaboration with

PhD students: Dusch,¹ Jlassi,¹ Tevlin,¹ Weber,¹ Chiu,² Sike²

Postdocs: Berlok,³ Girichidis,⁴ Lemmerz,⁵ Meenakshi,¹

Perrone,¹ Shalaby,⁶ **Thomas**,¹ Werhahn,⁷ Whittingham¹

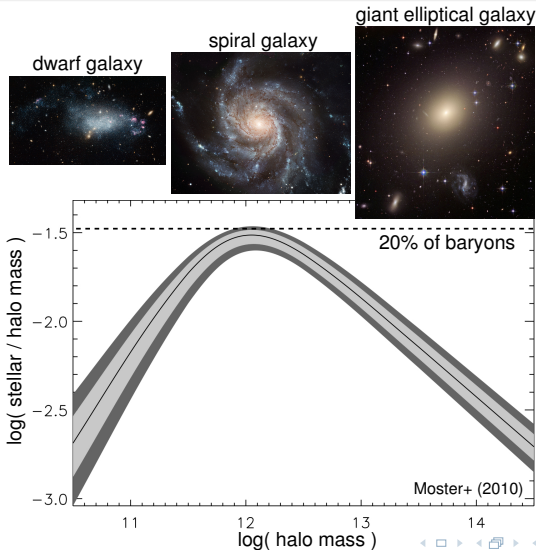
Faculty: Pakmor,⁷ Puchwein,¹ Weinberger,¹ Ruszkowski,² Springel,⁷ Enßlin⁷

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

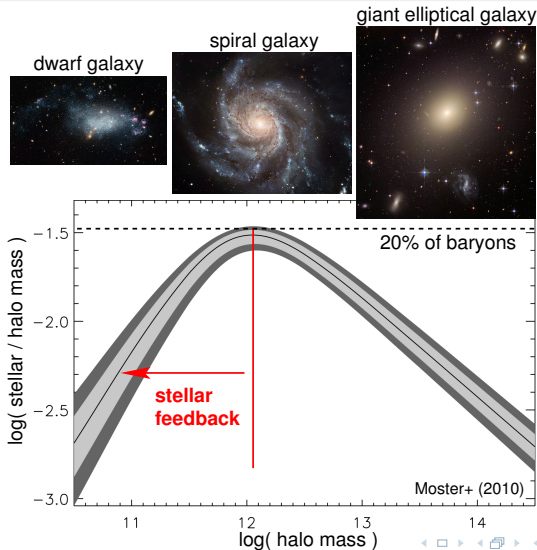
Confronting Simulations with the Real Universe, Napa Valley 2026



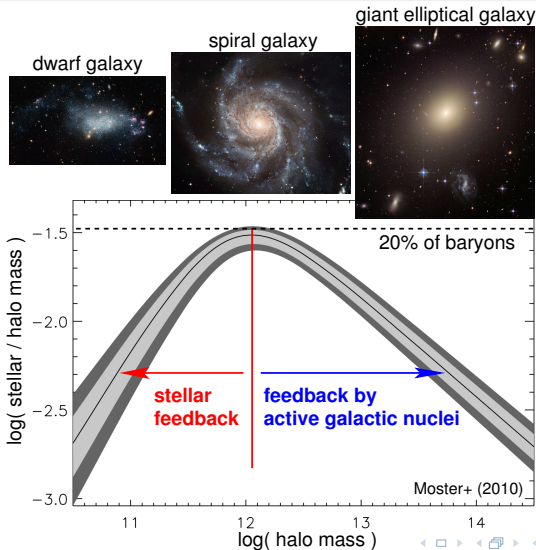
Puzzles in galaxy formation



Puzzles in galaxy formation



Puzzles in galaxy formation



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?

How are galactic winds driven?

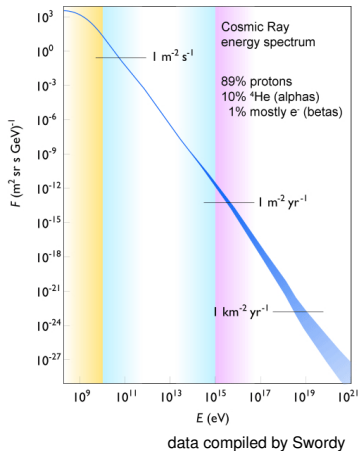


super wind in M82

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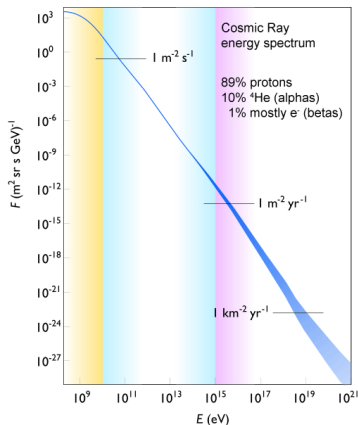
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- **radiation pressure and photoionization** by massive stars and quasars?
- **pressure of cosmic rays (CRs)** that are accelerated at supernova shocks?
- **energy density of CRs, magnetic fields, and ISM turbulence all similar**
⇒ CR feedback important!

Galactic cosmic ray spectrum



- spans more than 33 decades in flux and 12 decades in energy
- “knee” indicates characteristic maximum energy of galactic accelerators
- CRs beyond the “ankle” have extra-galactic origin

Galactic cosmic ray spectrum



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- “knee” indicates characteristic maximum energy of galactic accelerators
- CRs beyond the “ankle” have extra-galactic origin
- energy density of cosmic rays is dominated by GeV energies
 \Rightarrow grey approach sufficient for feedback studies (Girichidis+ 2024)

Review on cosmic ray feedback

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

REVIEW ARTICLE

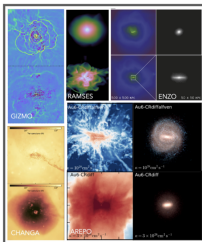


Cosmic ray feedback in galaxies and galaxy clusters

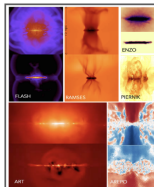
A pedagogical introduction and a topical review of the acceleration, transport, observables, and dynamical impact of cosmic rays

Mateusz Ruszkowski^{1,3} · Christoph Pfrommer²

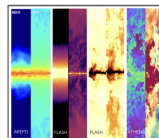
COSMO



GLOBAL



ZOOM

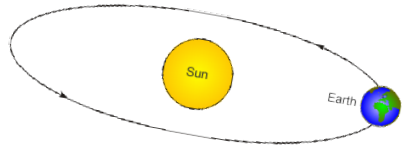


Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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



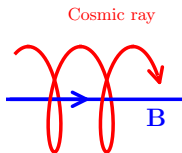
gyro-orbit of GeV CR:

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

⇒ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

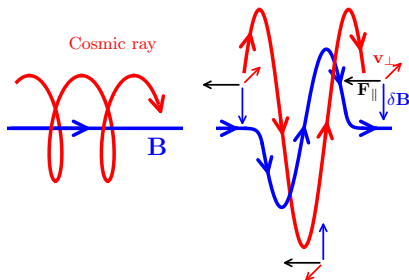
Zweibel (2017), Jiang & Oh (2018), Thomas & CP (2019)

Interactions of CRs and magnetic fields



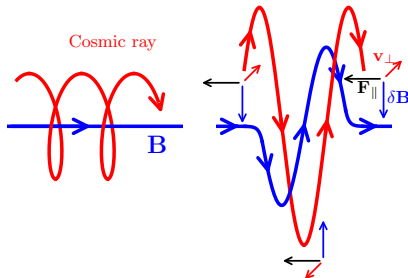
sketch: Jacob & CP

Interactions of CRs and magnetic fields



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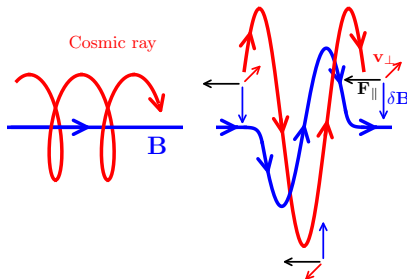
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- **electric fields vanish in the Alfvén wave frame:** $\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$

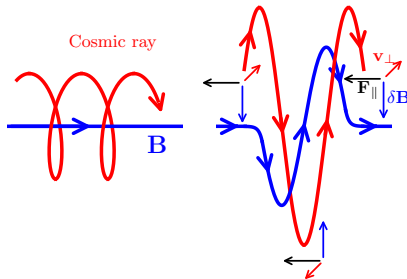
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- **electric fields vanish in the Alfvén wave frame:** $\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$
- **work out Lorentz forces on CRs in wave frame:** $\mathbf{F}_L = q \frac{\mathbf{v} \times \mathbf{B}}{c}$

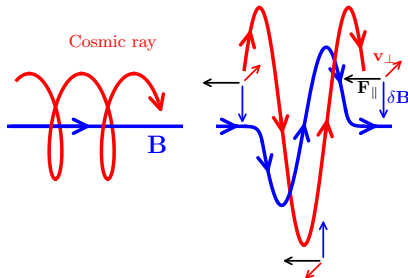
Interactions of CRs and magnetic fields



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- work out **Lorentz forces on CRs** in wave frame: $\mathbf{F}_L = q \frac{\mathbf{v} \times \mathbf{B}}{c}$
- Lorentz force depends on **relative phase of CR gyro orbit and wave:**
 - sketch: decelerating Lorentz force along CR orbit $\rightarrow p_{\parallel}$ decreases
 - phase shift by 180° : accelerating Lorentz force $\rightarrow p_{\parallel}$ increases

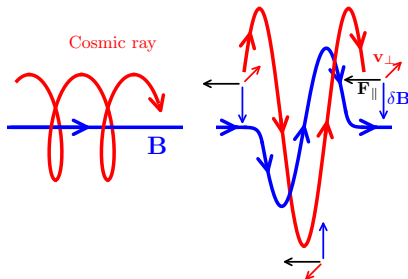
Interactions of CRs and magnetic fields



sketch: Jacob & CP

- **only electric fields can provide work on charged particles and change their energy**

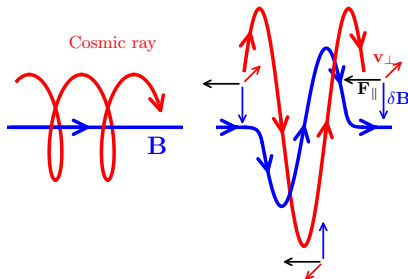
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- **only electric fields can provide work on charged particles and change their energy**
- **in Alfvén wave frame, where $E = 0$, CR energy is conserved:**
 $p^2 = p_{\parallel}^2 + p_{\perp}^2 = \text{const.}$ so that decreasing p_{\parallel} causes p_{\perp} to increase

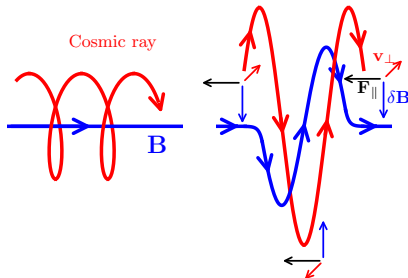
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 $p^2 = p_{\parallel}^2 + p_{\perp}^2 = \text{const.}$ so that decreasing p_{\parallel} causes p_{\perp} to increase
- this increases the CR pitch angle cosine $\mu = \cos \theta = \frac{B}{|B|} \cdot \frac{p}{|p|}$

Interactions of CRs and magnetic fields

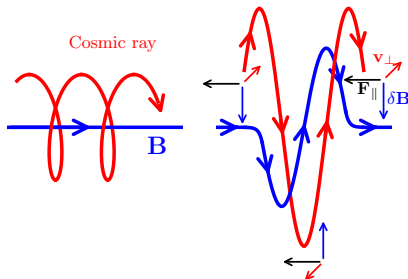


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- **CRs resonantly interact with Alfvén waves** so that the wavelength equals the gyro-radius:

$$L_{\parallel} = r_g = \frac{p_{\perp} c}{qB}$$

Interactions of CRs and magnetic fields



sketch: Jacob & CP

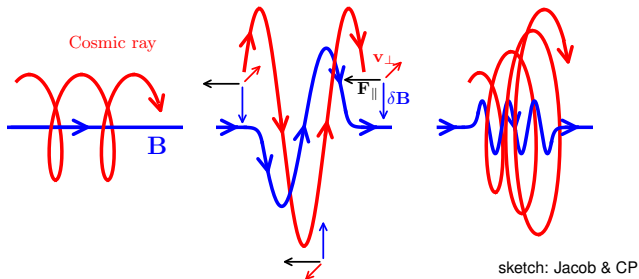
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Doppler-shifted MHD frequency is a multiple n of the CR gyrofrequency

Interactions of CRs and magnetic fields



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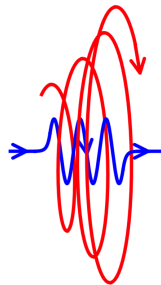
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Cosmic ray streaming and diffusion

● CR streaming instability:

Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)

- if $v_{\text{cr}} > v_a$, 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**

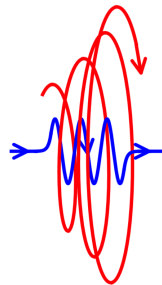


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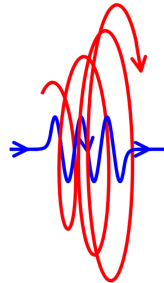
→ CRs exert pressure on thermal gas via scattering on Alfvén waves

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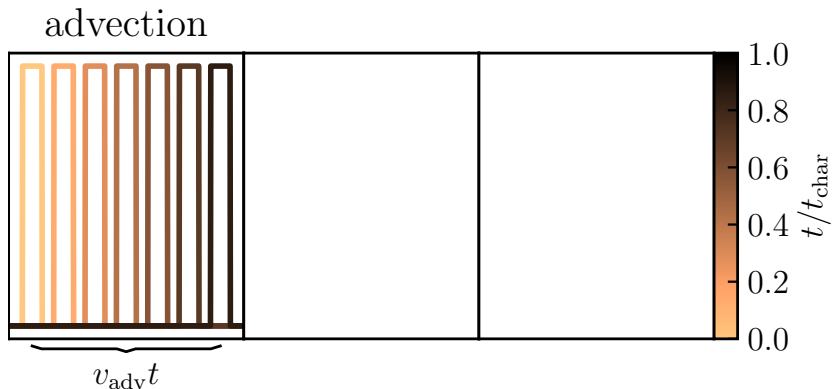


→ CRs exert pressure on thermal gas via scattering on Alfvén waves

weak wave damping: strong coupling → CR stream with waves

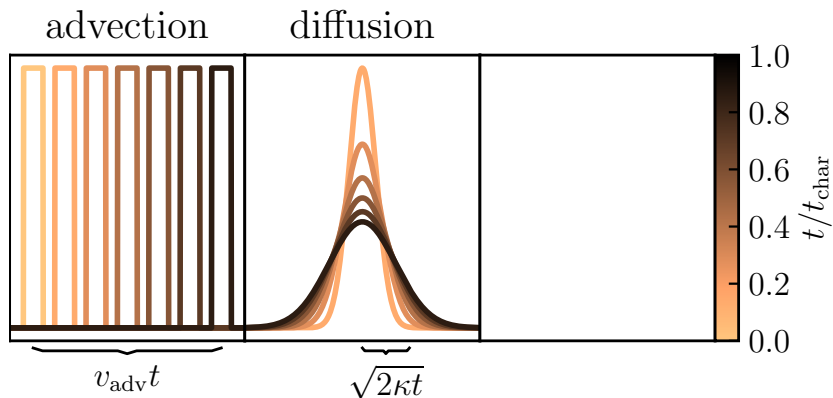
strong wave damping: less waves to scatter → CR diffusion prevails

Modes of CR propagation



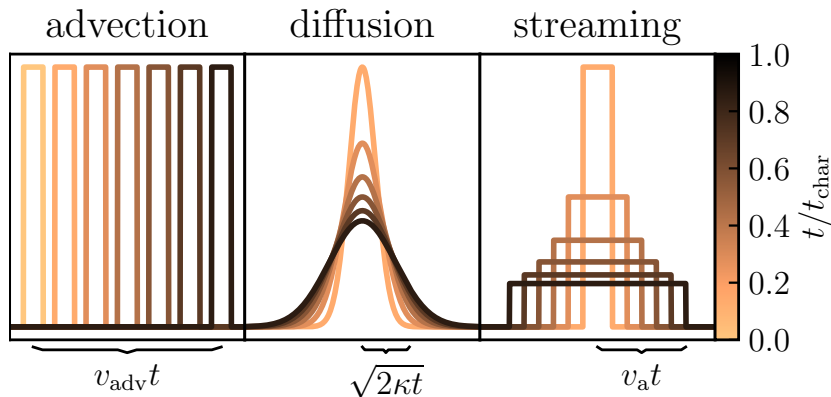
Thomas, CP, Enßlin (2020)

Modes of CR propagation



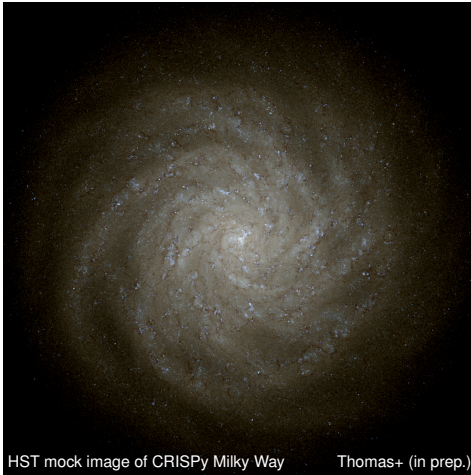
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Modes of CR propagation



Thomas, CP, Enßlin (2020)

Cosmic ray transport in galaxies

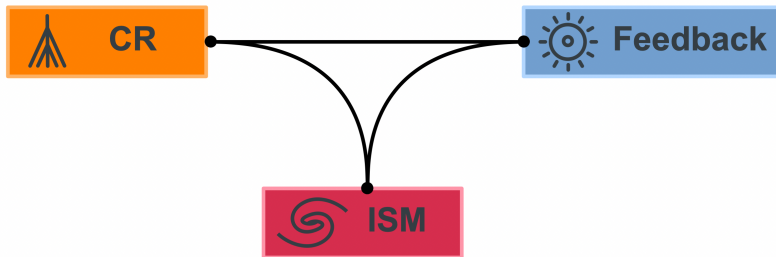


- CR transport in galaxies demands modeling **non-linear Landau damping (in warm/hot phase)** and **ion-neutral damping (in disk)**
- this requires resolving the **multi-phase structure of the ISM**
- development of CRISP framework (**Cosmic Rays and InterStellar Physics**, Thomas+ 2025)

Multi-phase ISM modeling

CRISP framework

Cosmic Rays and InterStellar Physics



Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework

Cosmic Rays and InterStellar Physics



Feedback



CR



ISM

Chemistry



- Full H – H₂ – 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 Rays and InterStellar Physics




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 Rays and InterStellar Physics



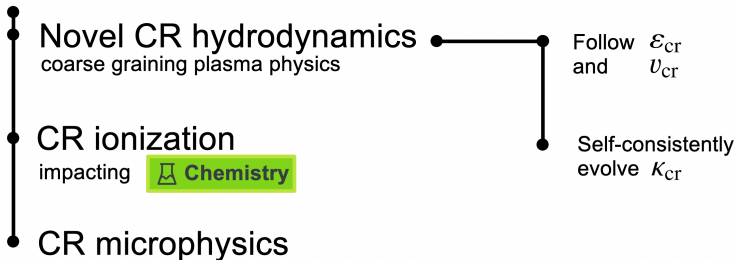
Feedback



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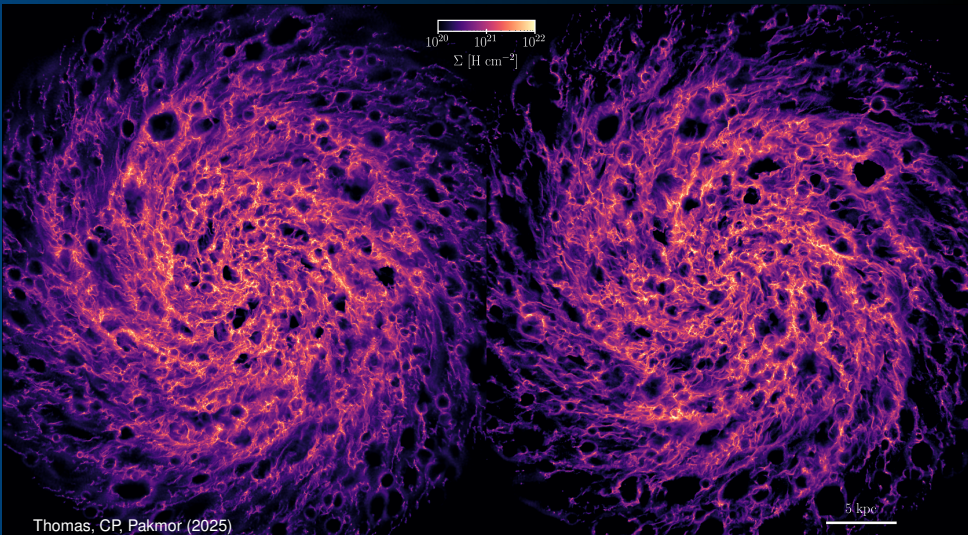


CR



Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling



Thomas, CP, Pakmor (2025)

Christoph Pfrommer

Cosmic ray feedback in galaxy formation

Multi-phase ISM modeling

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

CRMHD

MHD

10^{20} 10^{21} 10^{22}
 Σ [H cm^{-2}]

5 kpc

Thomas, CP, Pakmor (2025)

Christoph Pfrommer

Cosmic ray feedback in galaxy formation

Simulated Milky Way: surface density

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

CRMHD

$\Sigma \text{ [cm}^{-2}\text{]}$
 $10^{19} \quad 10^{20} \quad 10^{21} \quad 10^{22}$

MHD

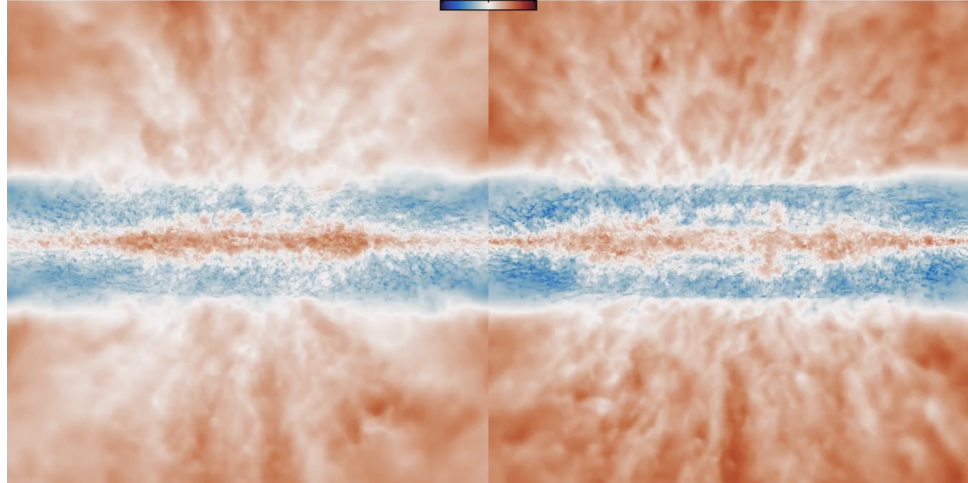
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter

CRMHD

T [K]
 10^2 10^4 10^6

MHD



Multi-phase ISM modeling

Cosmic rays make galactic winds much denser

CRMHD

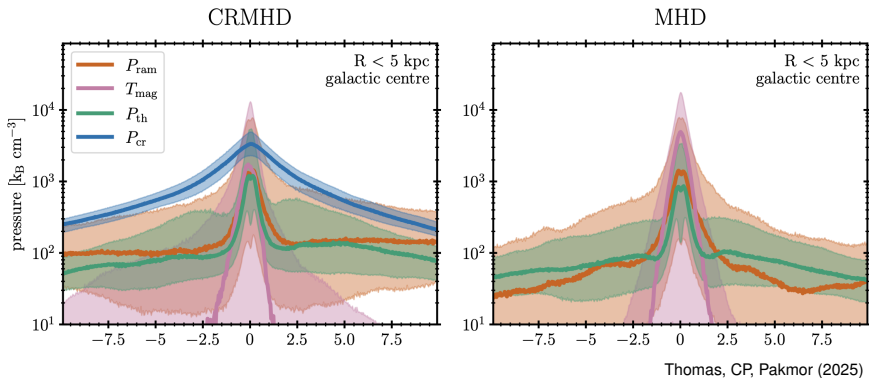
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Thomas, CP, Pakmor (2025)

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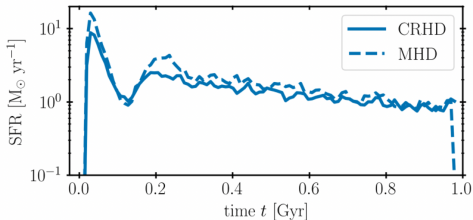
Cosmic ray driven wind: mechanism



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

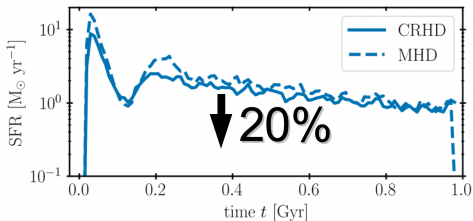
$$|\nabla P_{\text{cr}} + \nabla P_{\text{th}}| > \rho |\nabla \phi|$$

Mass and energy loading factors



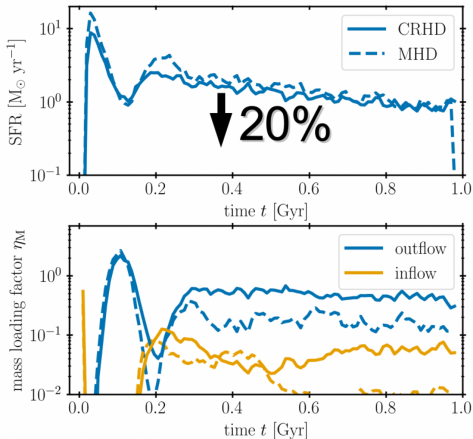
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



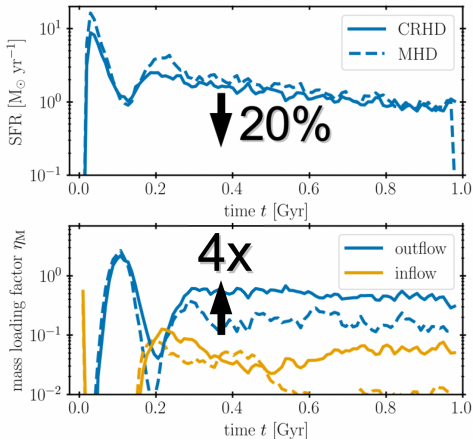
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



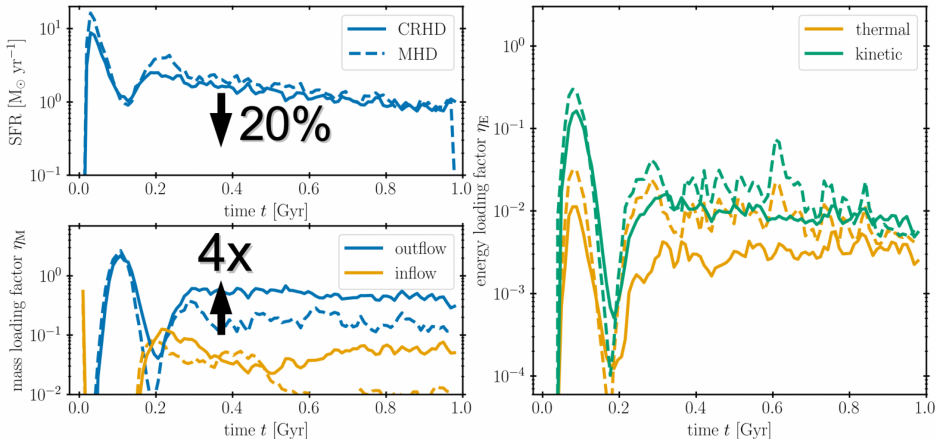
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



Thomas, CP, Pakmor (2025)

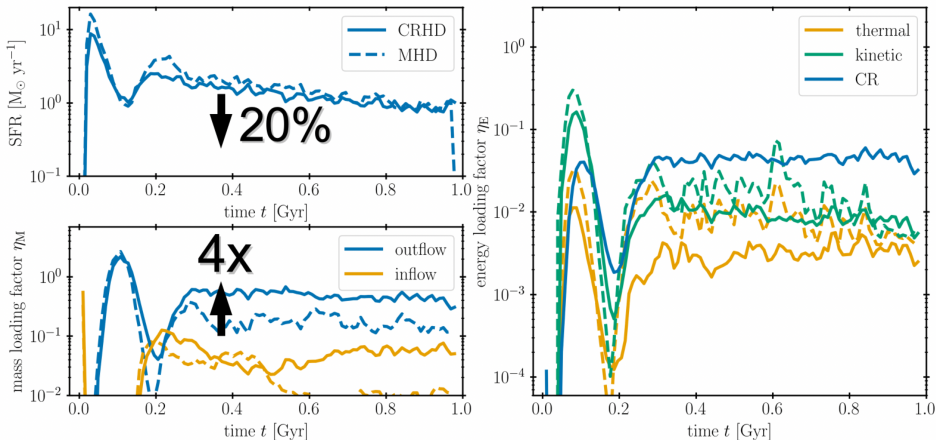
Mass and energy loading factors



Thomas, CP, Pakmor (2025)

AIP

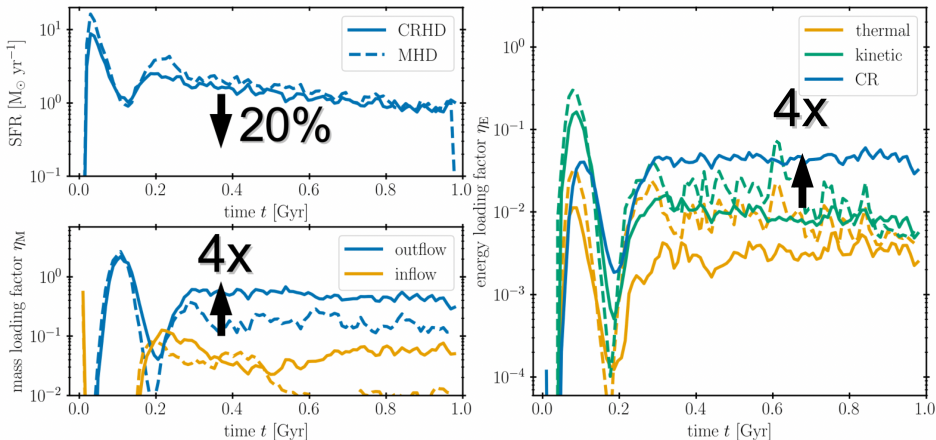
Mass and energy loading factors



Thomas, CP, Pakmor (2025)

AIP

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Conclusions for cosmic ray physics in galaxies

CR 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

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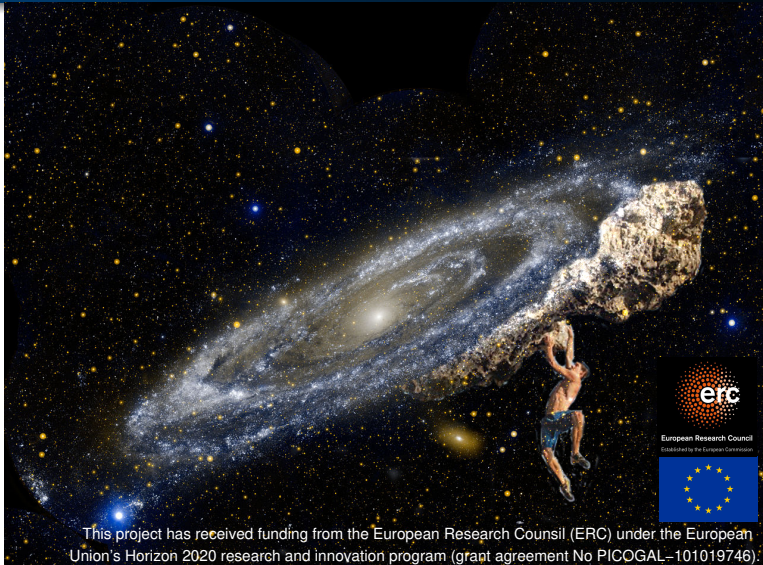
CR feedback in galaxy formation:

- CR feedback barely impacts ISM or 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 by 4

Introduction
Cosmic ray transport
Cosmic rays in galaxy formation

Multi-phase ISM
Cosmic ray driven winds
Mass and energy loading factors

PICO GAL: From Plasma Kinetics to COsmological GALaxy Formation



This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No PICO GAL-101019746).

Christoph Pfrommer

Cosmic ray feedback in galaxy formation



Literature for the talk

CR hydrodynamics and CR transport:

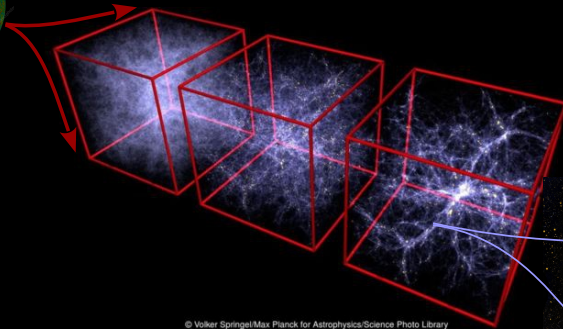
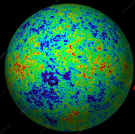
- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh*, 2017, MNRAS, 465, 4500.
- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays*, 2019, MNRAS, 485, 2977.
- Thomas, Pfrommer, Pakmor, *A finite volume method for two-moment cosmic-ray hydrodynamics on a moving mesh*, 2021, MNRAS, 503, 2242.
- Thomas, Pfrommer, Enßlin, *Probing Cosmic Ray Transport with Radio Synchrotron Harps in the Galactic Center*, 2020, ApJL, 890, L18.

CR feedback in galaxy formation:

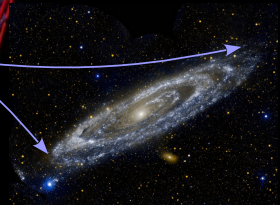
- Ruszkowski, Pfrommer, *Cosmic ray feedback in galaxies and galaxy clusters*, 2023, Astron Astrophys Rev, 31, 4.
- Thomas, Pfrommer, Pakmor, *Cosmic ray-driven galactic winds: transport modes of cosmic rays and Alfvén-wave dark regions*, 2023, MNRAS, 521, 3023.
- Thomas, Pfrommer, Pakmor, *Why are thermally- and cosmic ray-driven galactic winds fundamentally different?* 2025, A&A, 698, A104.

Additional slides

Cosmological galaxy formation



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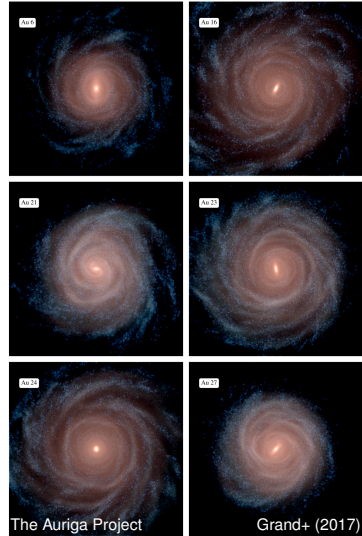
Cosmic rays in cosmological galaxy simulations

The galaxy formation model

- primordial and metal line cooling
- sub-resolution model for star formation (Springel+ 03)
- mass and metal return from stars to ISM
- cold dense gas stabilized by pressurized ISM
- thermal and kinetic energy from supernovae modeled by isotropic wind – launched outside of SF region
- black hole seeding and accretion model (Springel+ 05)
- thermal feedback from AGN in radio and quasar mode
- uniform magnetic field of 10^{-10} G seeded at $z = 128$

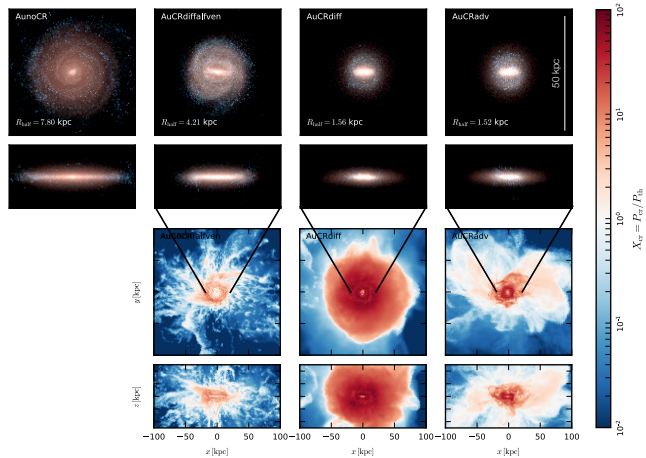
Simulation suite (Buck, CP+ 2020)

- 2 galaxies, baryons with $5 \times 10^4 M_{\odot} \sim 5 \times 10^6$ resolution elements in halo, 2×10^6 star particles
- 4 models with different CR physics for each galaxy:
 - no CRs
 - CR advection
 - + CR anisotropic diffusion
 - + CR Alfvén wave cooling



Cosmic rays in cosmological galaxy simulations

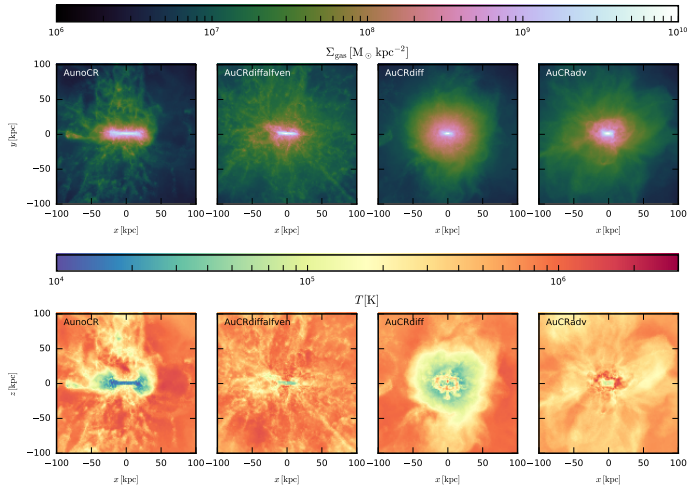
Auriga MHD models: CR transport changes disk sizes



Buck, CP, Pakmor, Grand, Springel (2020)

Cosmic rays in cosmological galaxy simulations

Auriga MHD models: CR transport modifies the circum-galactic medium



Buck, CP, Pakmor, Grand, Springel (2020)