Cosmic ray feedback in galaxy formation

Christoph Pfrommer[1]

in collaboration with

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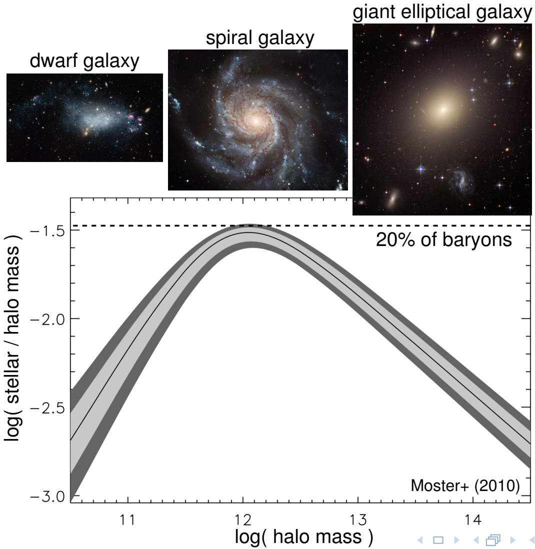
Perrone,[1] Shalaby,[5] **Thomas,**[1] Werhahn,[6] Whittingham[1]
Faculty: Pakmor,[6] Puchwein,[1] Weinberger,[1] Ruszkowski,[2] Springel,[6] Enßlin[6]

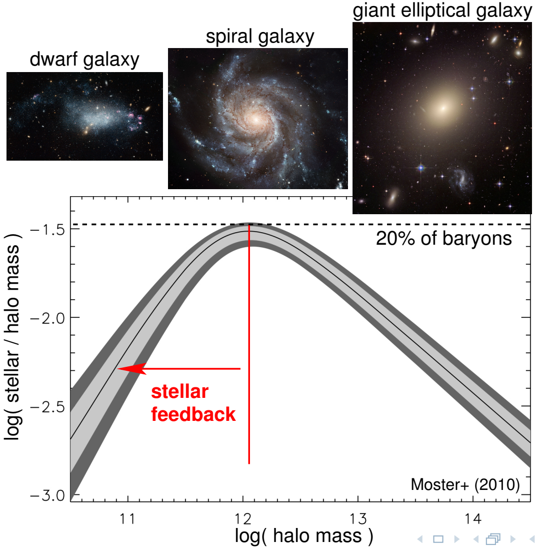
[1]AIP, [2]U of Michigan, [3]NBI, [4]U of Heidelberg, [5]Perimeter Institute, [6]MPA

The Midwest Magnetic Fields Workshop 2025, Madison, July 2025

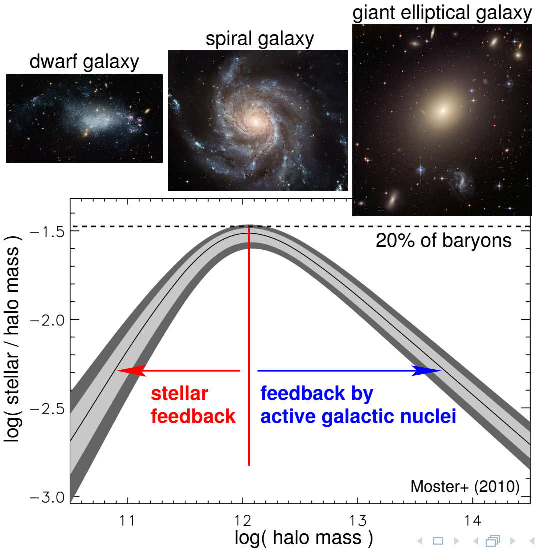
Puzzles in galaxy formation



Puzzles in galaxy formation



Puzzles in galaxy formation



Stellar feedback

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?

Review on cosmic ray feedback

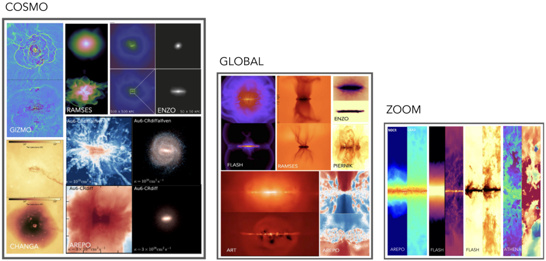
Astron Astrophys Rev (2023) 31:4
https://doi.org/10.1007/s00159-023-00149-2

REVIEW ARTICLE

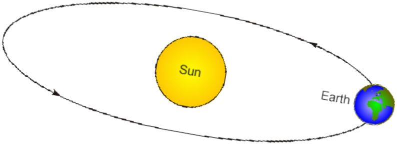
Cosmic ray feedback in galaxies and galaxy clusters

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

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



Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

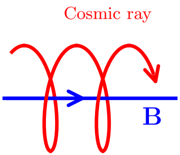
gyro-orbit of GeV CR:

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

$\Rightarrow$ 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

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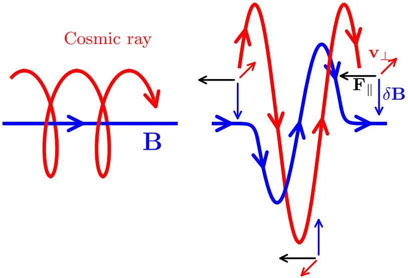

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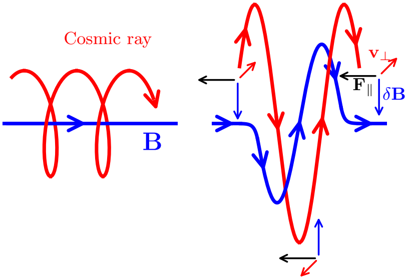

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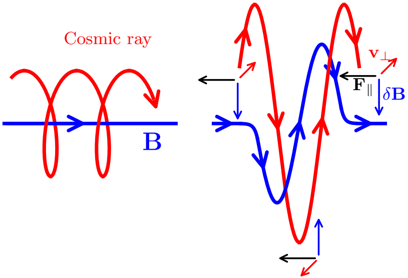
Interactions of CRs and magnetic fields



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

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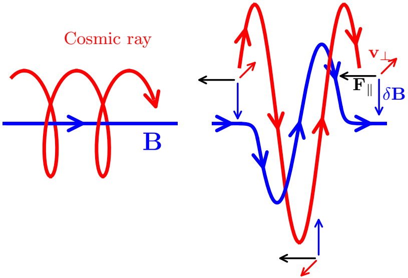

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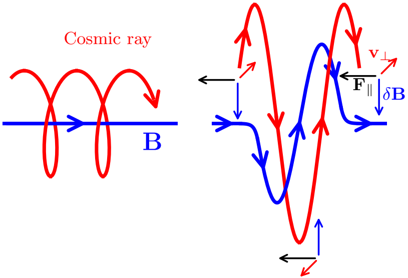
- work out **Lorentz forces on CRs** in wave frame: $\boldsymbol{F}_\mathrm{L} = q\frac{\boldsymbol{v} \times \boldsymbol{B}}{c}$
- Lorentz force depends on **relative phase of CR gyro orbit and wave:**
  - sketch: decelerating Lorentz force along CR orbit $\rightarrow p_\parallel$ decreases
  - phase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

AIP

Interactions of CRs and magnetic fields



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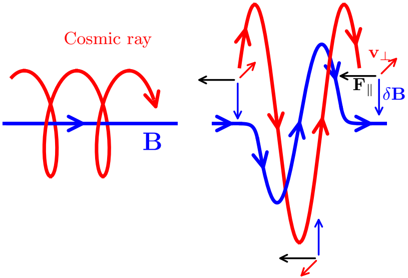
- **only electric fields can** provide work on charged particles and **change their energy**

Interactions of CRs and magnetic fields



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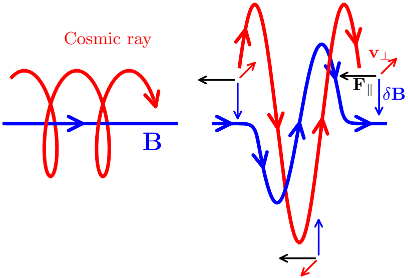
- **in Alfvén wave frame, where $E = 0$, CR energy is conserved:** $p^2 = p_\parallel^2 + p_\perp^2 =$ const. so that decreasing $p_\parallel$ causes $p_\perp$ to increase

Interactions of CRs and magnetic fields



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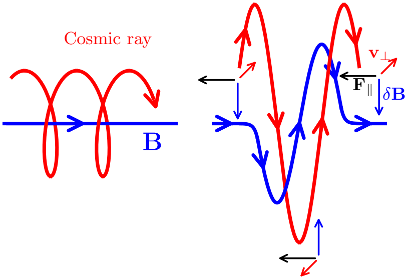
- **in Alfvén wave frame, where $E = 0$, CR energy is conserved:** $p^2 = p_{\|}^2 + p_{\perp}^2 =$ const. so that decreasing $p_{\|}$ causes $p_{\perp}$ to increase
- this increases the CR pitch angle cosine $\mu = \cos\theta = \frac{\boldsymbol{B}}{|\boldsymbol{B}|} \cdot \frac{\boldsymbol{p}}{|\boldsymbol{p}|}$

Interactions of CRs and magnetic fields

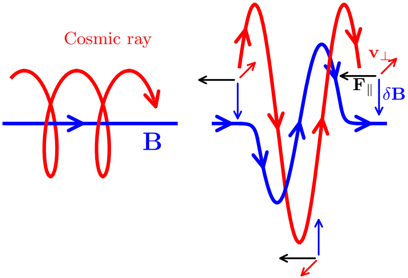


sketch: Jacob & CP

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

$$L_\parallel = r_\mathrm{g} = \frac{p_\perp c}{qB}$$

Interactions of CRs and magnetic fields



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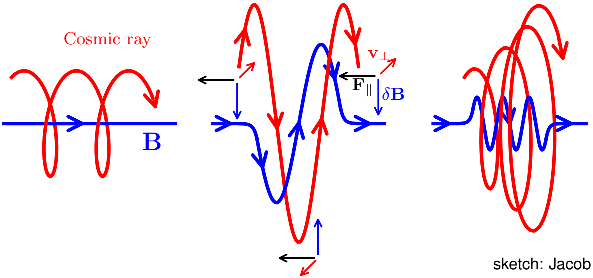
  Doppler-shifted MHD frequency is a multiple n of the CR gyrofrequency

Interactions of CRs and magnetic fields



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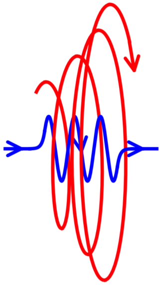
Cosmic ray streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - 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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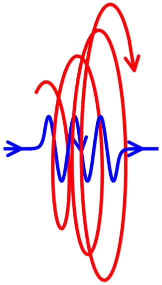

→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

Cosmic ray streaming and diffusion

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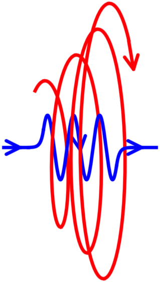
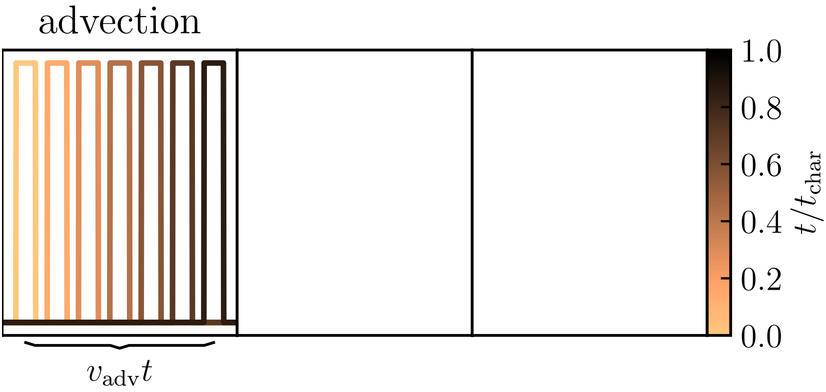


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

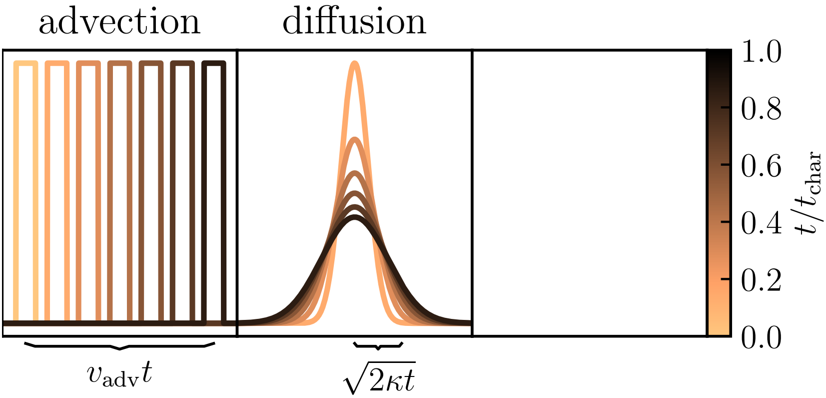
weak wave damping: strong coupling $\rightarrow$ CR stream with waves
strong wave damping: less waves to scatter $\rightarrow$ CR diffusion prevails

Modes of CR propagation



Thomas, CP, Enßlin (2020)

Modes of CR propagation



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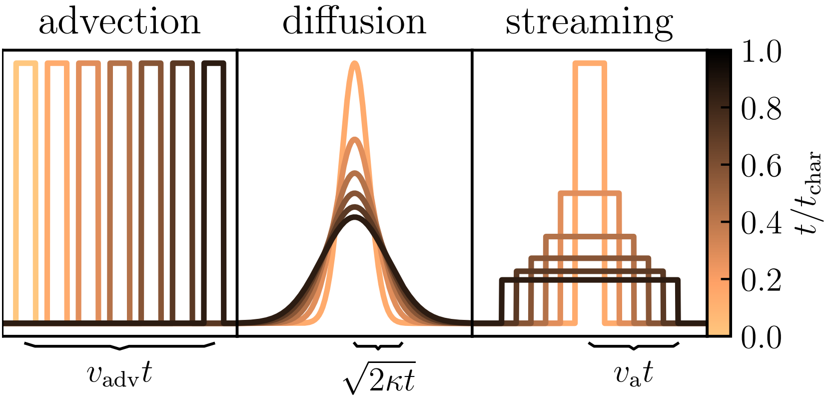

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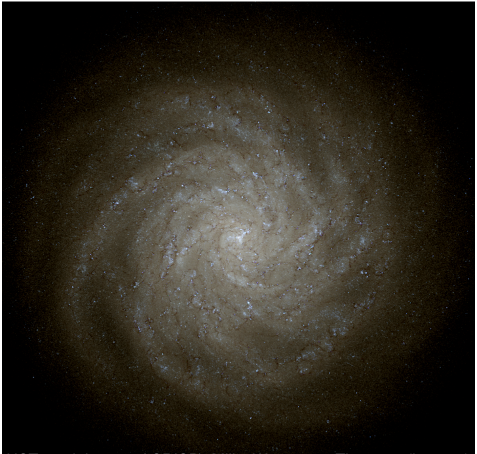
Cosmic ray transport in galaxies

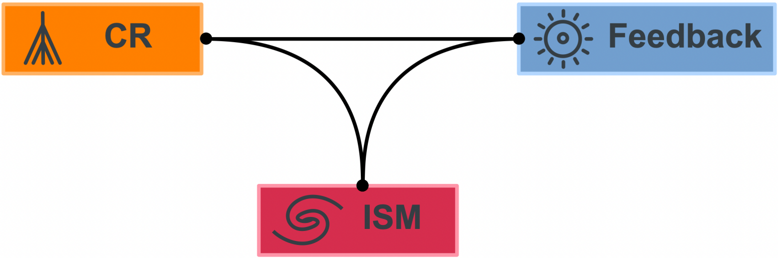

HST mock image of CRISPy Milky Way Thomas+ (in prep.)

- 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+ 2024)

Multi-phase ISM modeling

CRISP framework

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



Thomas, CP, Pakmor (2024)

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 (2024)

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 (2024)

Multi-phase ISM modeling

CRISP framework

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

Feedback

ISM

CR

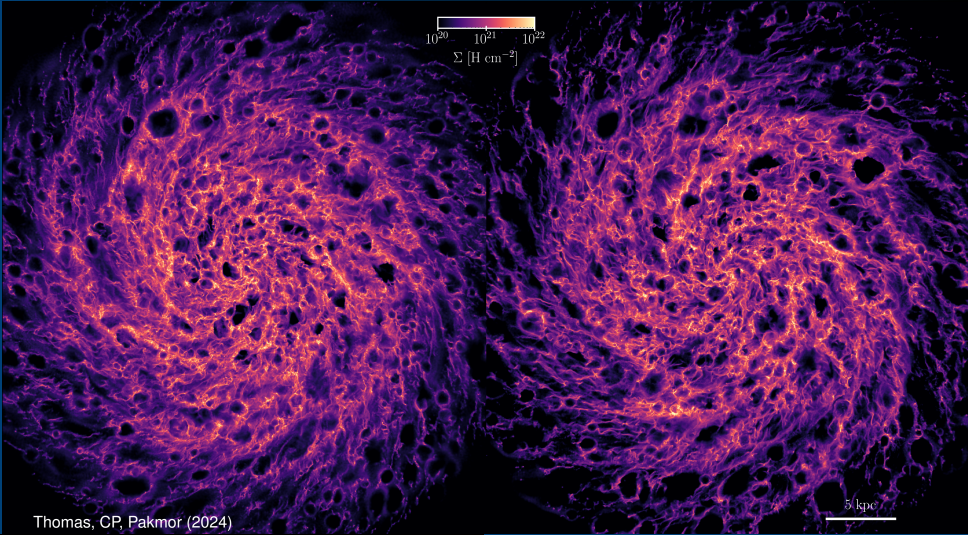
- Novel CR hydrodynamics
  coarse graining plasma physics
- CR ionization
  impacting **Chemistry**
- CR microphysics

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

Self-consistently evolve $\kappa_{\rm cr}$

Thomas, CP, Pakmor (2024)

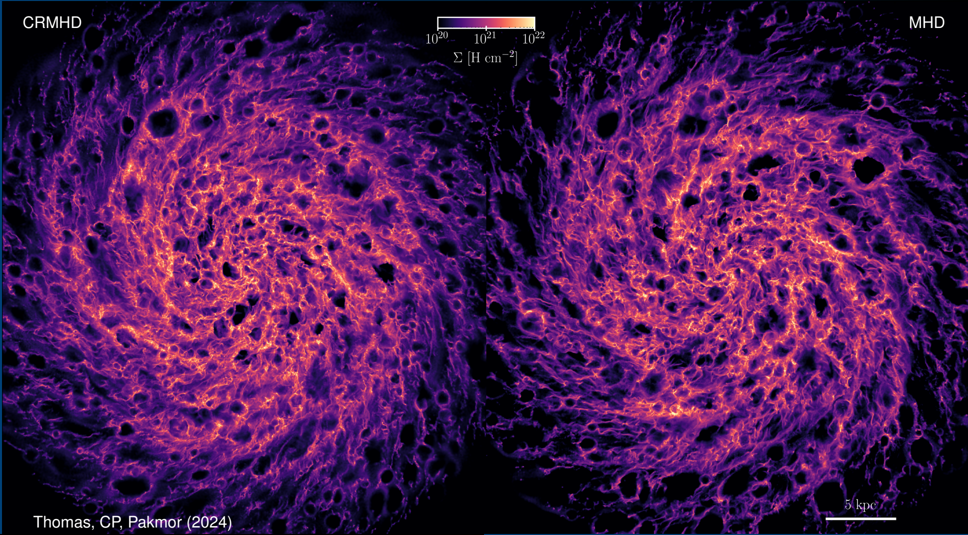
Multi-phase ISM modeling



Thomas, CP, Pakmor (2024)

Multi-phase ISM modeling

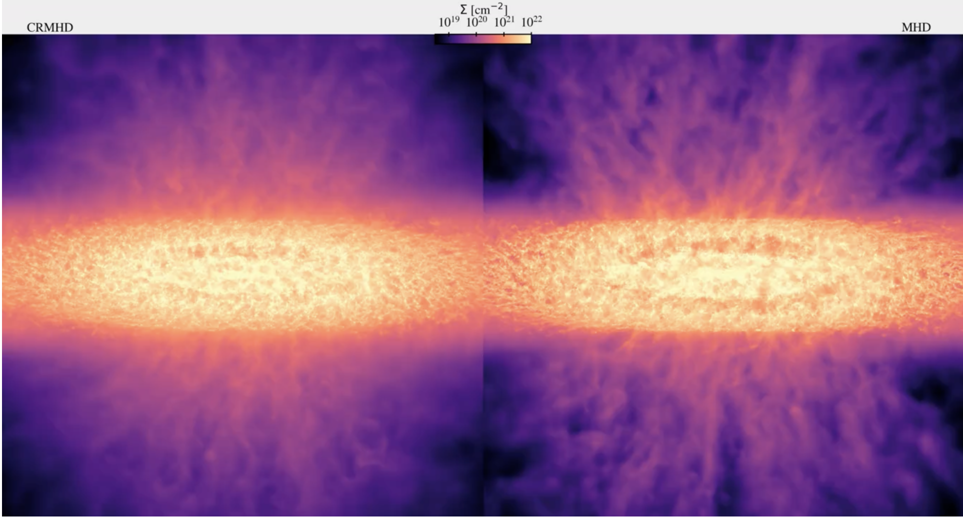
Cosmic rays barely affect the ISM because ion-neutral damping erases Alfvén waves



Thomas, CP, Pakmor (2024)

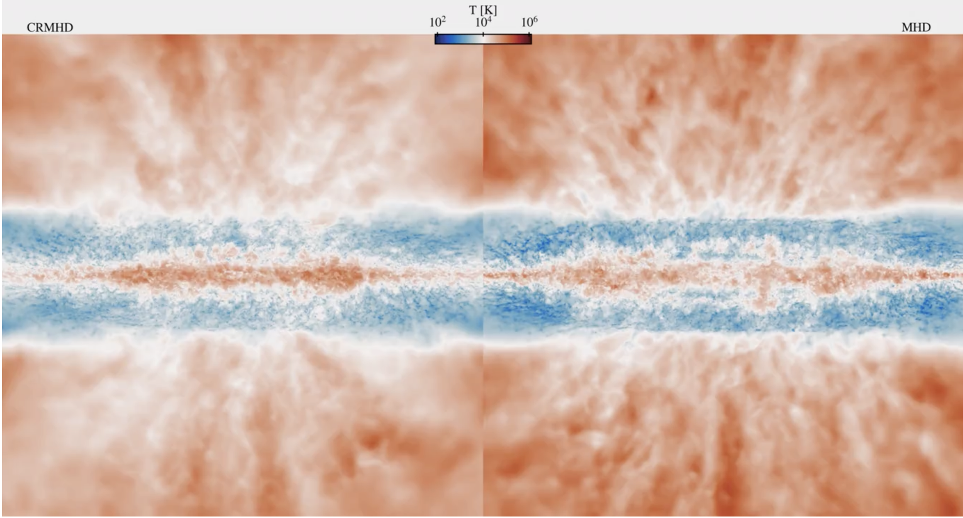
Simulated Milky Way: surface density

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



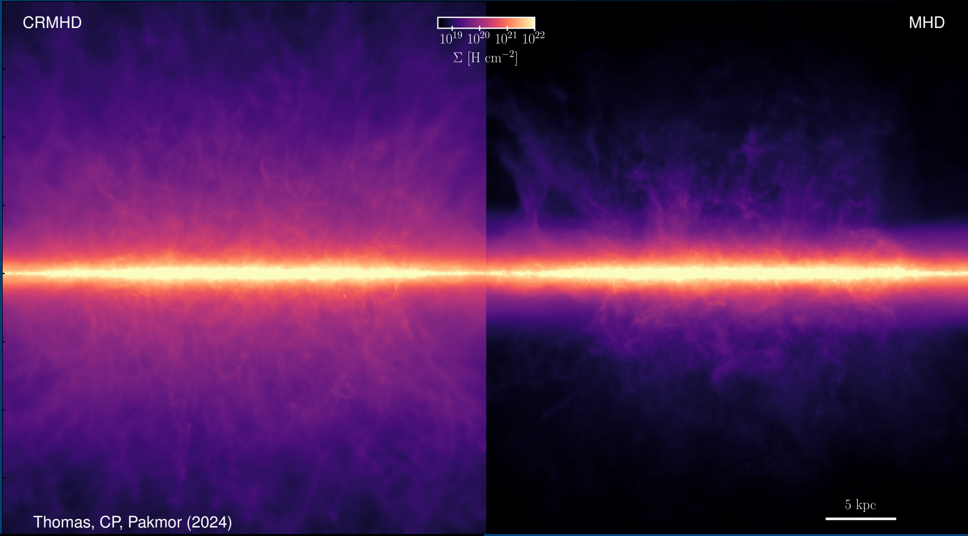
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter

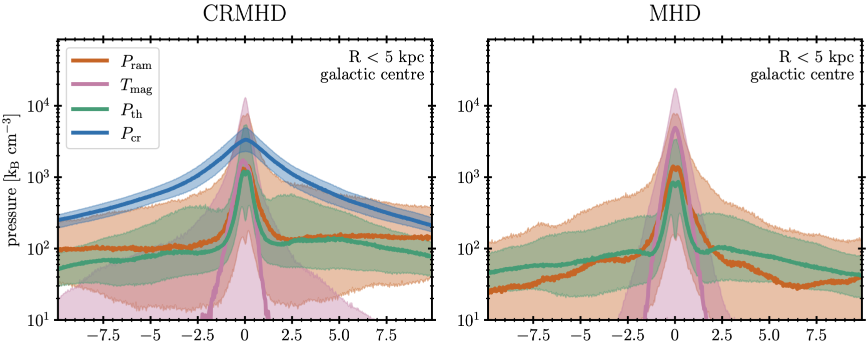


Multi-phase ISM modeling

Cosmic rays make galactic winds much denser



Cosmic ray driven wind: mechanism

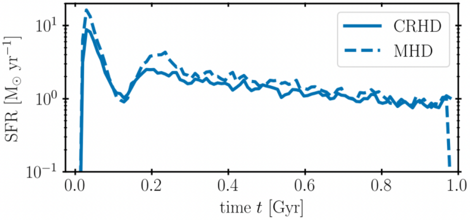


Thomas, CP, Pakmor (2024)

- 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



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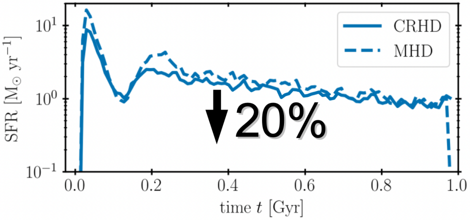

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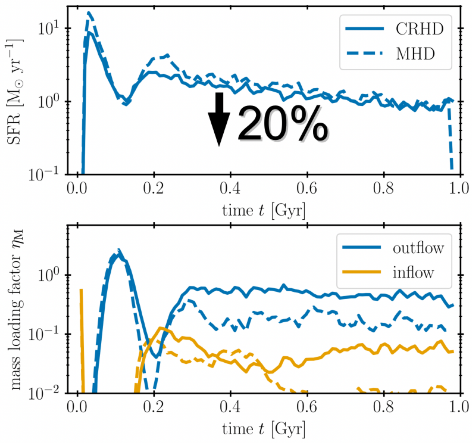

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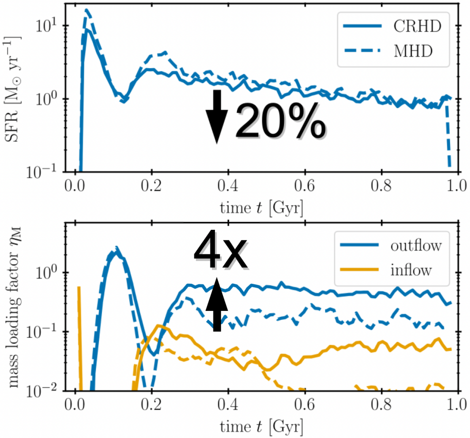

Thomas, CP, Pakmor (2024)

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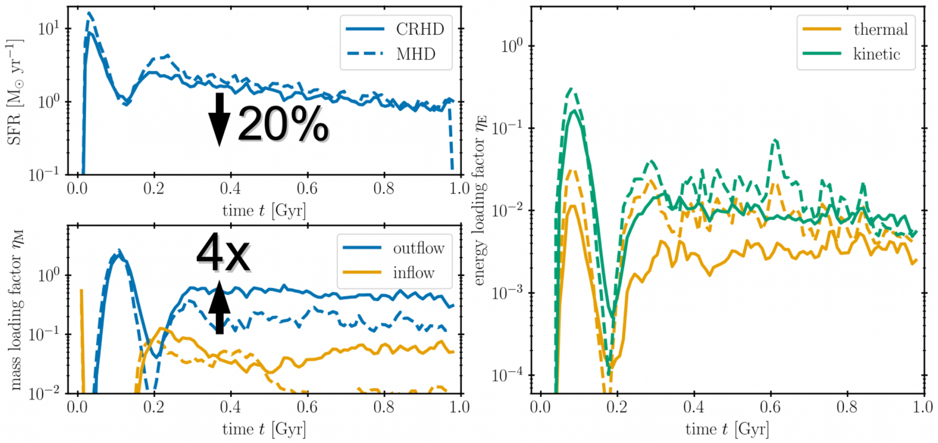

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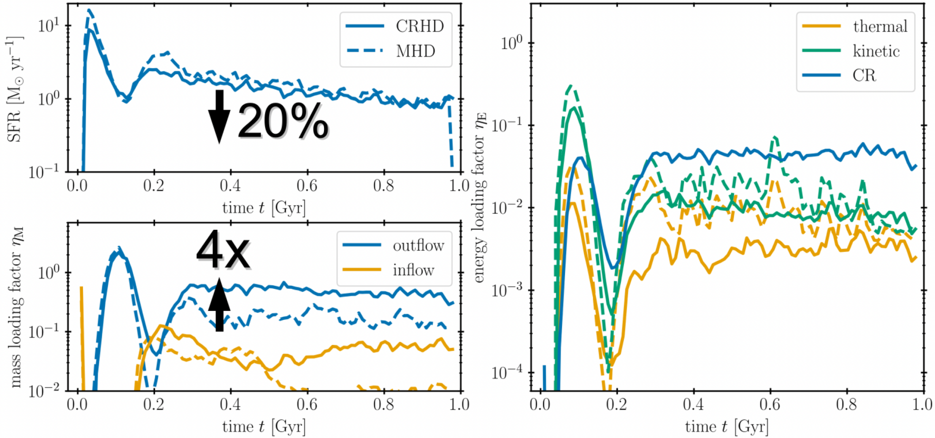

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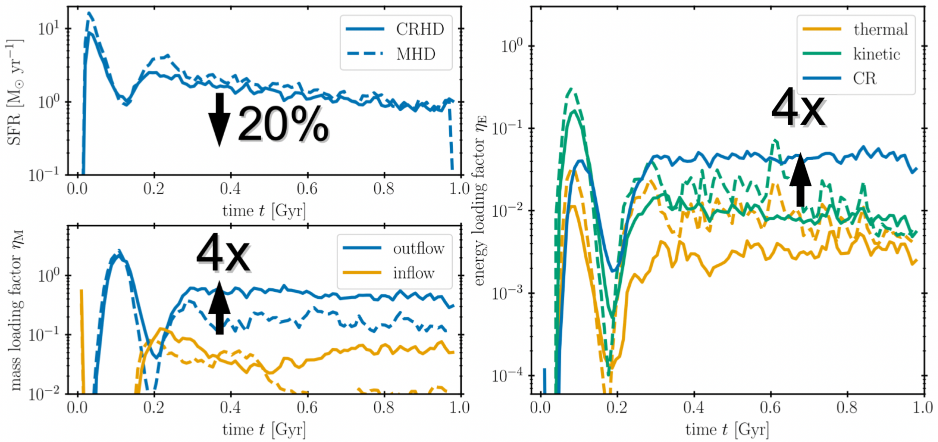
AIP

Mass and energy loading factors



Thomas, CP, Pakmor (2024)

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

Conclusions for cosmic ray physics in galaxies

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

CR feedback in 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

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

CR hydrodynamics and CR transport:

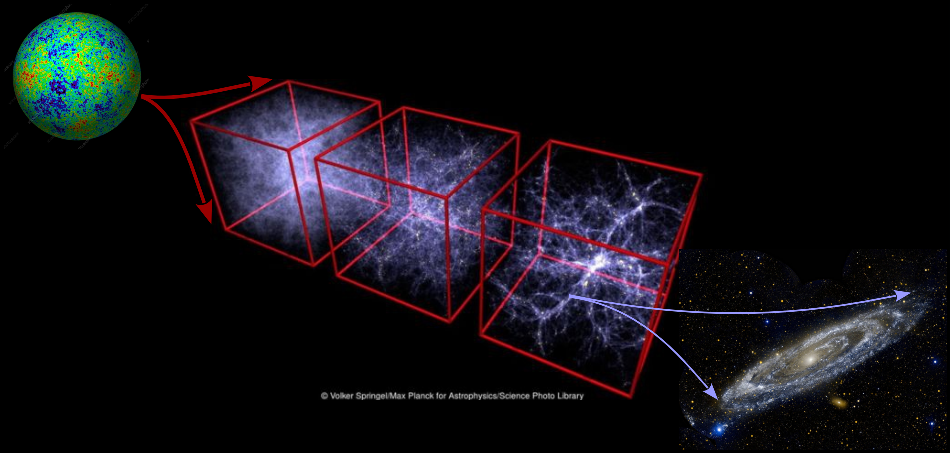
- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, MNRAS, 465, 4500.
- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2019, MNRAS, 485, 2977.
- Thomas, Pfrommer, Pakmor, *A finite volume method for two-moment 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?* 2024, A&A, submitted.

Additional slides

Cosmological galaxy formation



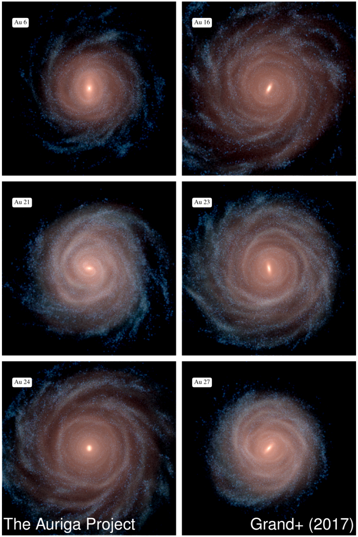
Cosmic rays in cosmological galaxy simulations

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)

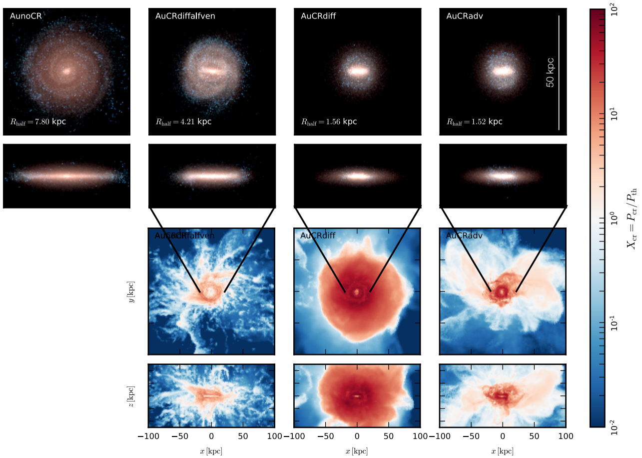
- 2 galaxies, baryons with $5 \times 10^4\,\mathrm{M}_\odot \sim 5 \times 10^6$ resolution elements in halo, 2×10^6 star particles
- 4 models with different CR physics for each galaxy:
  - no CRs
  - CR advection
  - + CR anisotropic diffusion
  - + CR Alfvén wave cooling



The Auriga Project Grand+ (2017)

Cosmic rays in cosmological galaxy simulations

Auriga MHD models: CR transport changes disk sizes

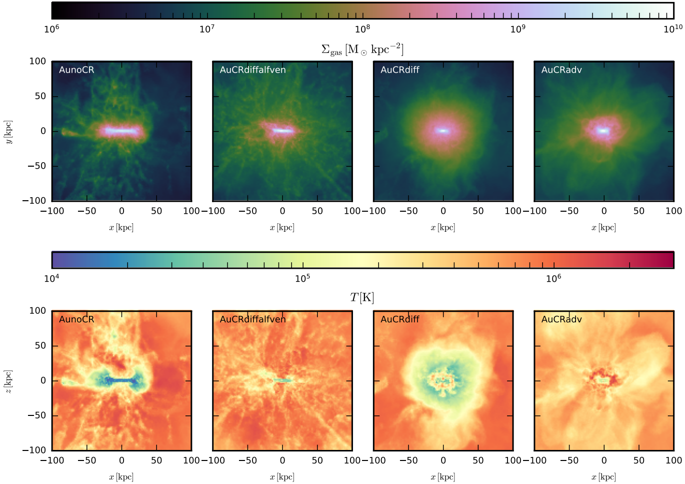


Buck, CP, Pakmor, Grand, Springel (2020)

AIP

Cosmic rays in cosmological galaxy simulations

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



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