Cosmic ray feedback in galaxies

Christoph Pfrommer[1]

in collaboration with

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Perrone,[1] Shalaby,[6] **Thomas,**[1] Werhahn,[7] Whittingham[1]
Faculty: Pakmor,[7] Puchwein,[1] Weinberger,[1] Ruszkowski,[2] Springel,[7] Enßlin[7]

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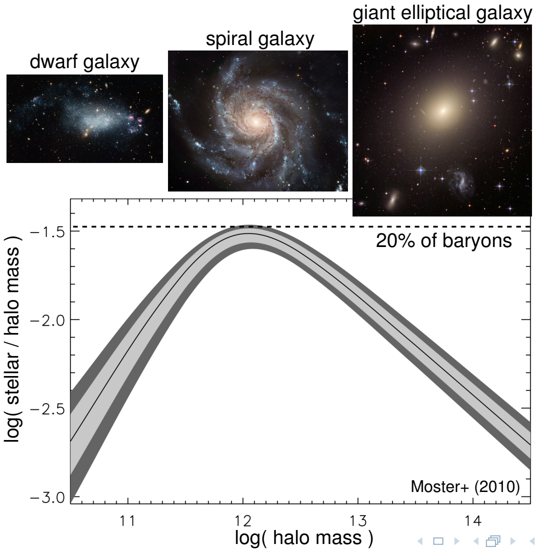
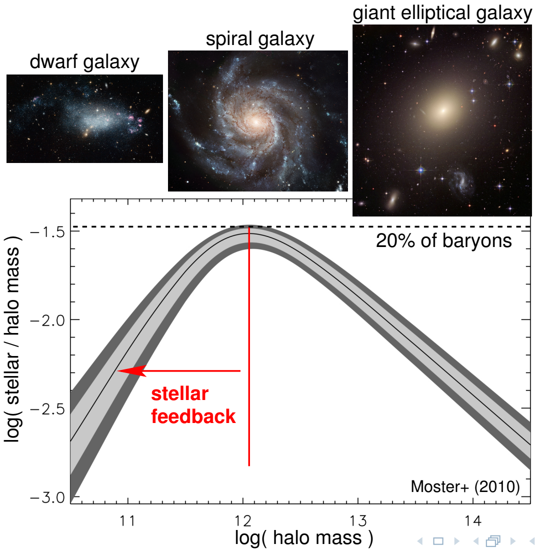
Annual Meeting of the German Astronomical Society, Görlitz, 2025

Puzzles in galaxy formation

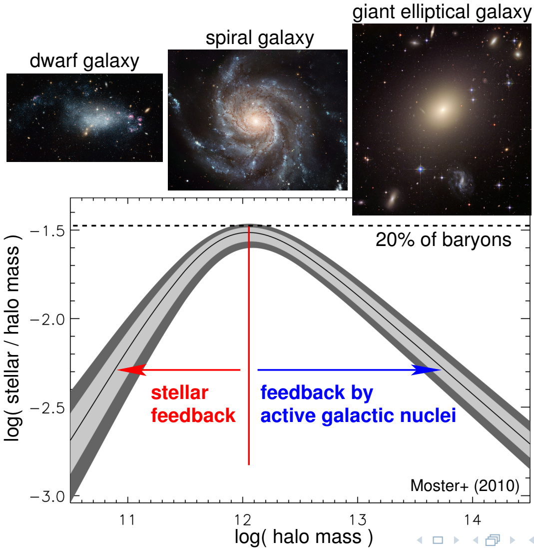
Puzzles in galaxy formation



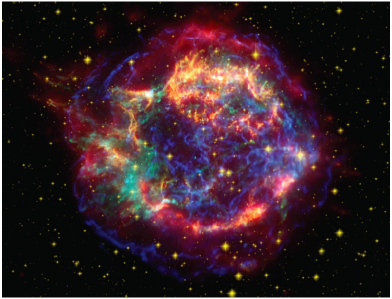
Puzzles in galaxy formation



Puzzles in galaxy formation



Feedback by 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

Feedback by galactic winds

super wind in M82

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

Feedback by galactic winds

super wind in M82

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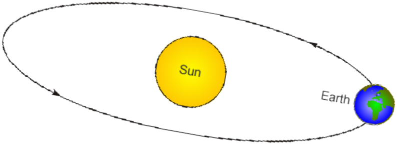
- pressure of cosmic rays (CRs) that are accelerated at supernova shocks?
- energy density of CRs, magnetic fields, and ISM turbulence all similar
  $\Rightarrow$ important feedback agent

Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

gyro-orbit of GeV CR:

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

$\Rightarrow$ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

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

Review on cosmic ray feedback

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

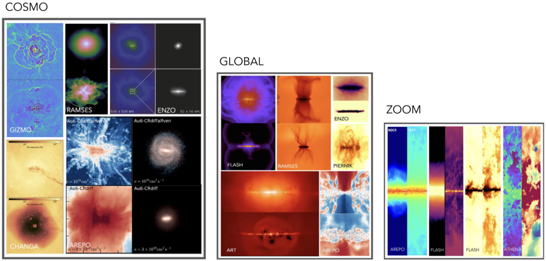
REVIEW ARTICLE

Check for updates

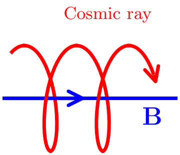
Cosmic ray feedback in galaxies and galaxy clusters

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]



Interactions of CRs and magnetic fields



sketch: Jacob & CP

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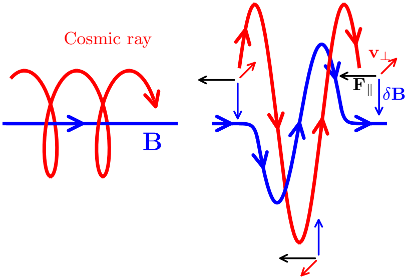

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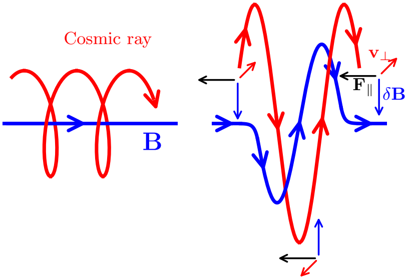

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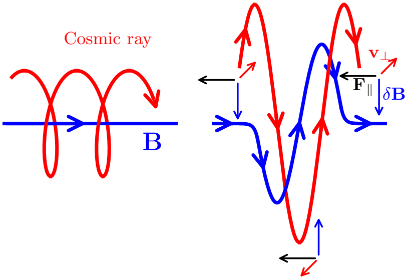

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- work out **Lorentz forces on CRs** in wave frame: $\boldsymbol{F}_\mathrm{L} = q\frac{\boldsymbol{v} \times \boldsymbol{B}}{c}$

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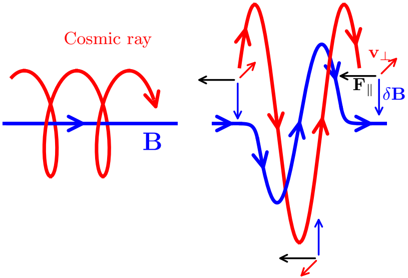

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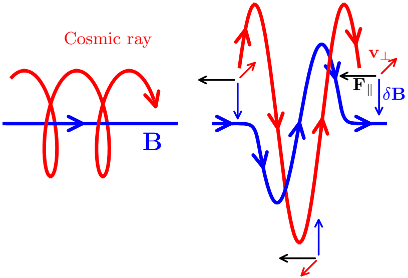
- work out **Lorentz forces on CRs** in wave frame: $\boldsymbol{F}_\mathrm{L} = q\frac{\boldsymbol{v} \times \boldsymbol{B}}{c}$
- Lorentz force depends on **relative phase of CR gyro orbit and wave:**
  - sketch: decelerating Lorentz force along CR orbit $\rightarrow p_\parallel$ decreases
  - phase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

Interactions of CRs and magnetic fields



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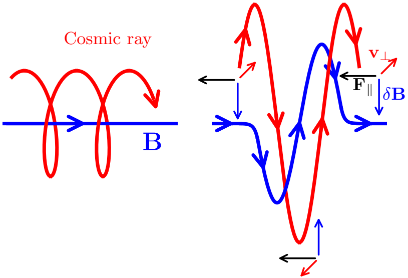
- **only electric fields can** provide work on charged particles and **change their energy**

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

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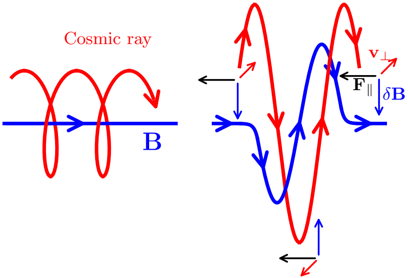

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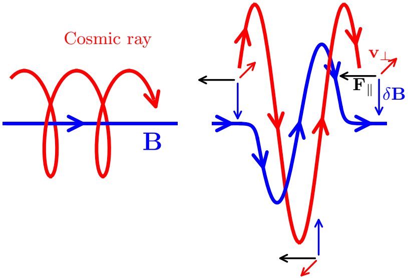
- this increases the CR pitch angle cosine $\mu = \cos\theta = \frac{\boldsymbol{B}}{|\boldsymbol{B}|} \cdot \frac{\boldsymbol{p}}{|\boldsymbol{p}|}$

AIP

Interactions of CRs and magnetic fields



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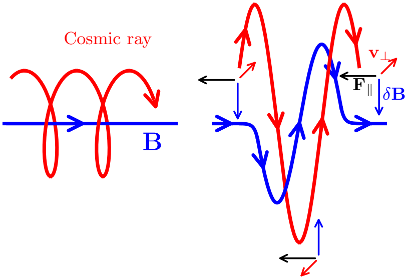
- **CRs resonantly interact with Alfvén waves** so that the wavelength equals the gyro-radius:

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

Interactions of CRs and magnetic fields



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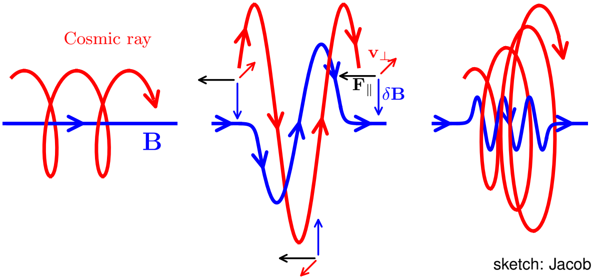
  Doppler-shifted MHD frequency is a multiple n of the CR gyrofrequency

Interactions of CRs and magnetic fields



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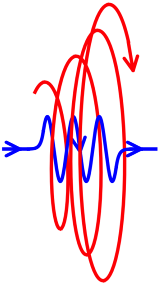
Cosmic ray streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{cr} > v_a$, 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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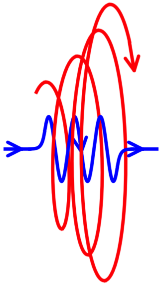

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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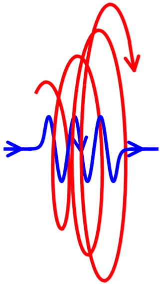
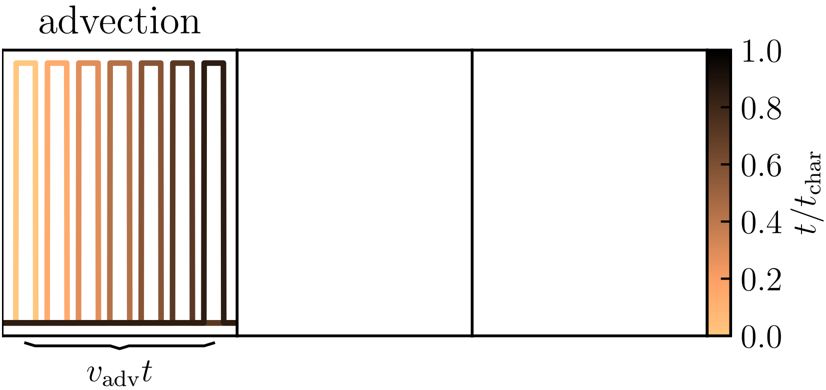


→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

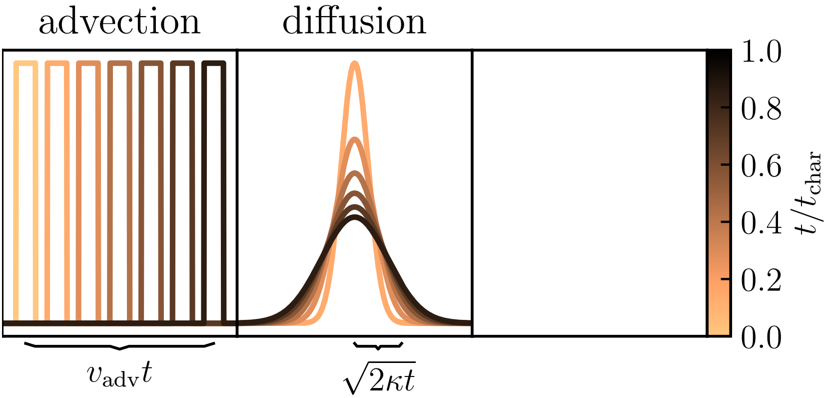
weak wave damping: strong coupling → CR stream with waves
strong wave damping: less waves to scatter → CR diffusion prevails

Modes of CR propagation



Thomas, CP, Enßlin (2020)

Modes of CR propagation



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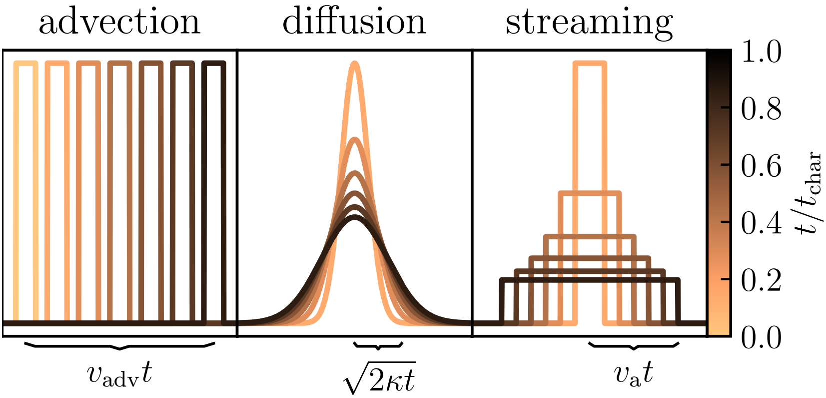

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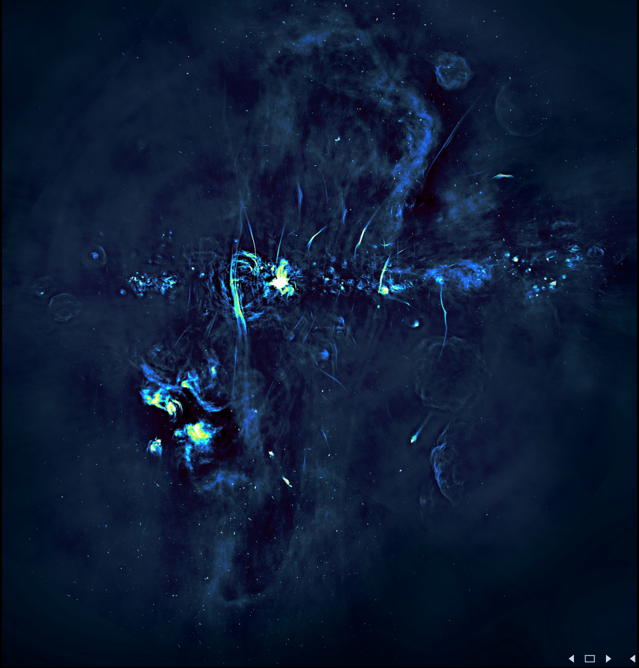
MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



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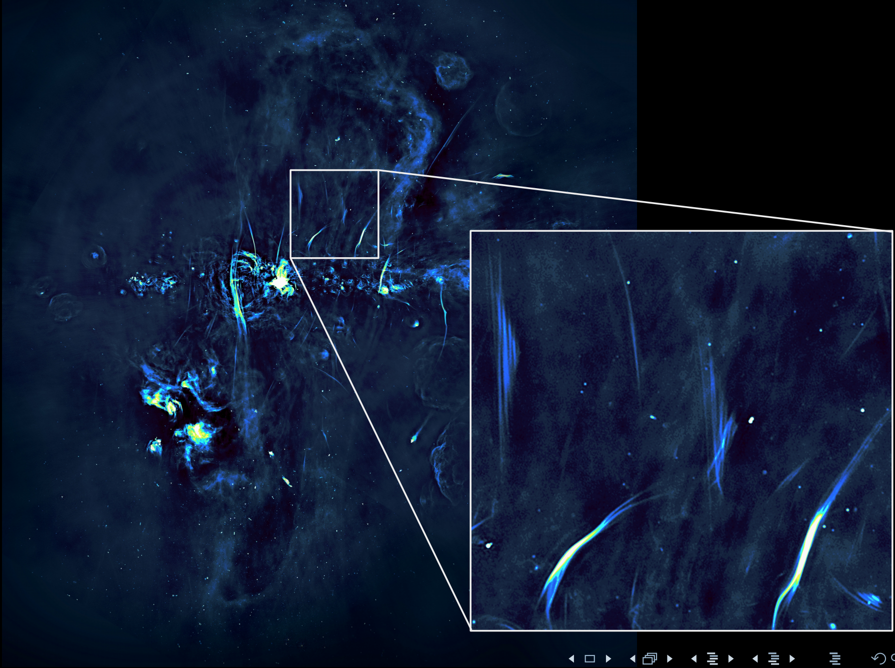
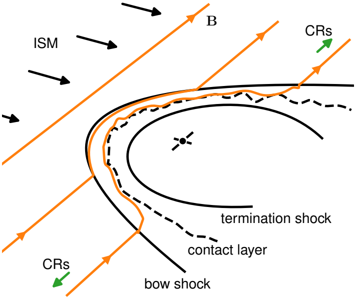


Radio synchrotron harps: the model

shock acceleration scenario



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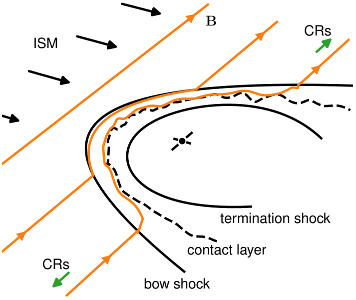
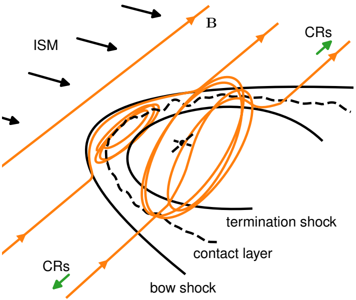


magnetic reconnection at pulsar wind



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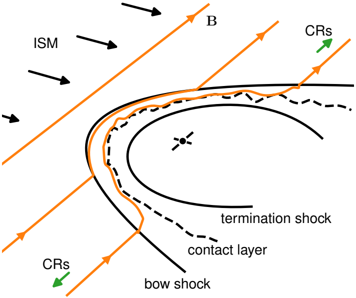
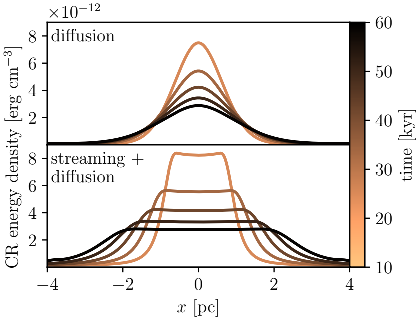
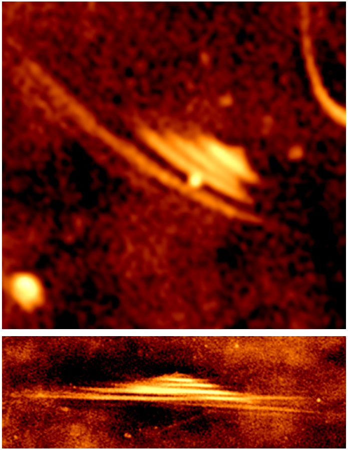


Thomas, CP, Enßlin (2020)

CR diffusion vs. streaming + diffusion



Radio synchrotron harps: testing CR propagation



Haywood+ (Nature, 2019)

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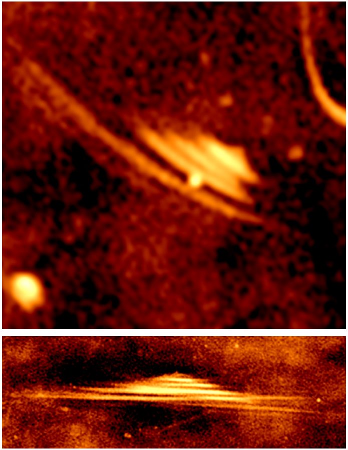

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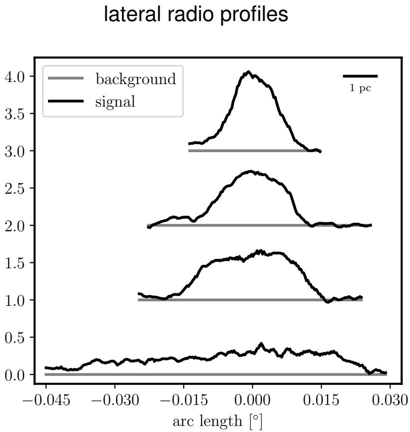

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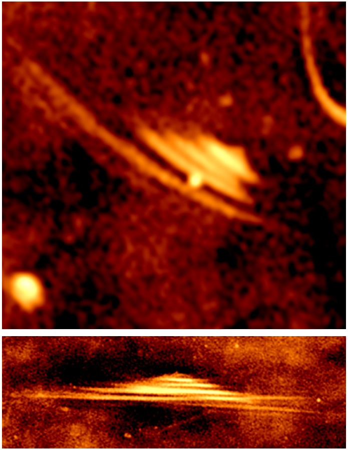

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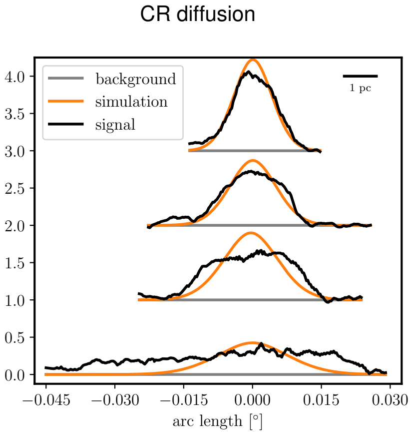

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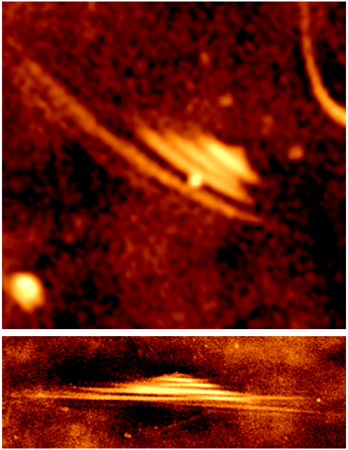

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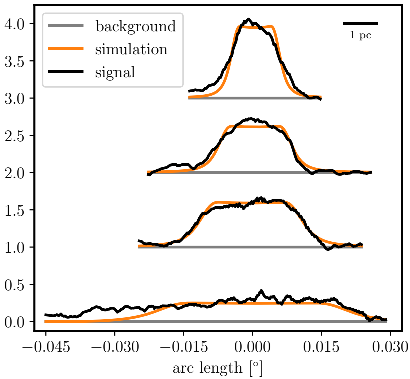
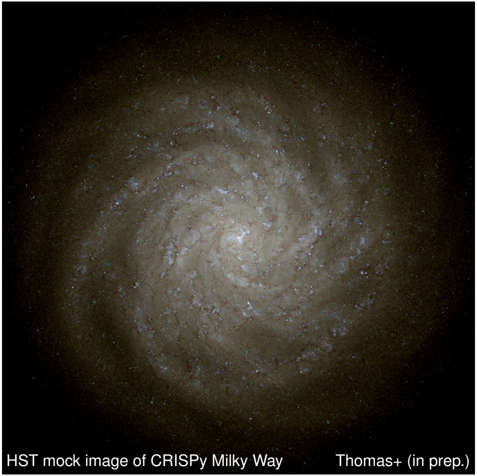


Thomas, CP, Enßlin (2020)

Cosmic ray transport in galaxies

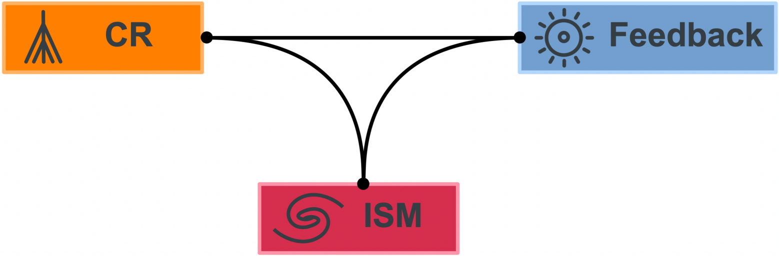


- CR transport in galaxies demands modeling non-linear Landau damping (in warm/hot phase) and ion-neutral damping (in disk)
- this requires resolving the multi-phase structure of the ISM
- development of CRISP framework (**C**osmic **R**ays and **I**nter**S**tellar **P**hysics, Thomas+ 2024)

A model for the multi-phase interstellar medium

CRISP framework

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



Thomas, CP, Pakmor (2024)

A model for the multi-phase interstellar medium

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)

A model for the multi-phase interstellar medium

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)

A model for the multi-phase interstellar medium

CRISP framework

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

Feedback

ISM

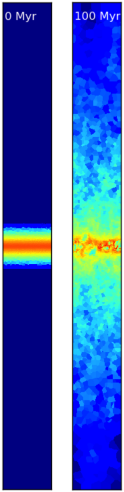
CR

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

Thomas, CP, Pakmor (2024)

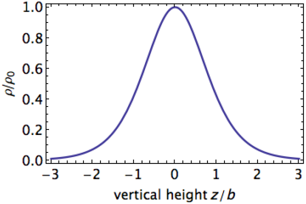
CR feedback in the multi-phase interstellar medium

Explore how CR transport impacts on galactic outflows – stratified box simulations



- isothermal disk with $T_0 = 10^4$ K
- hydrostatic equilibrium:

$$f_g \nabla^2 \Phi = 4\pi G \rho$$



AIP

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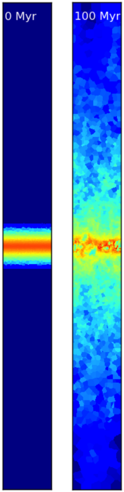

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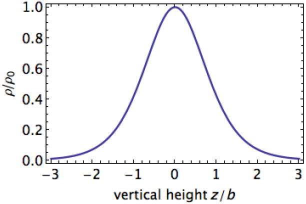

- self-gravity; turbulent stirring for 50 Myrs
- CRISP framework with non-equilibrium chemistry (Thomas, CP, Pakmor 2014)
- attenuated FUV stellar radiation field
- MHD with small magnetic seed field (Pakmor+ 2011)
- cosmic ray physics (Thomas & CP 2019, Thomas+ 2021)

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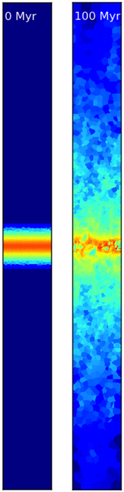
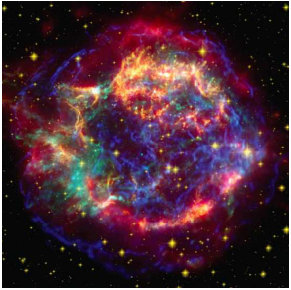


- supernova rate:

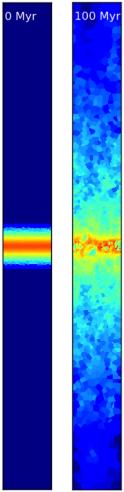
$$\dot{M}_{\mathrm{SN},i} = \dot{M}_{\star,i} \frac{1\ \mathrm{event}}{100\ \mathrm{M}_\odot}$$

- CR-to-thermal energy injection rate = 5 %



CR feedback in the multi-phase interstellar medium

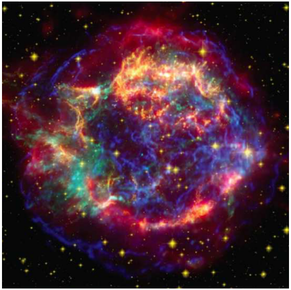
Explore how CR transport impacts on galactic outflows – stratified box simulations



- supernova rate:

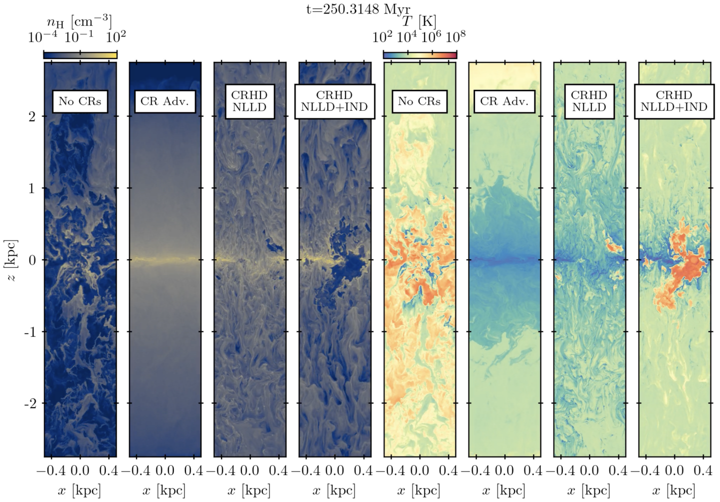
$$\dot{M}_{\mathrm{SN},i} = \dot{M}_{\star,i} \frac{1\ \mathrm{event}}{100\ \mathrm{M}_\odot}$$

- CR-to-thermal energy injection rate = 5 %
- comparing 4 models:
  - pure MHD
  - CR advection
  - CR transport with non-linear Landau (NL) damping (strong CR coupling)
  - CR transport with NL and ion-neutral damping (weak CR coupling in dense ISM)

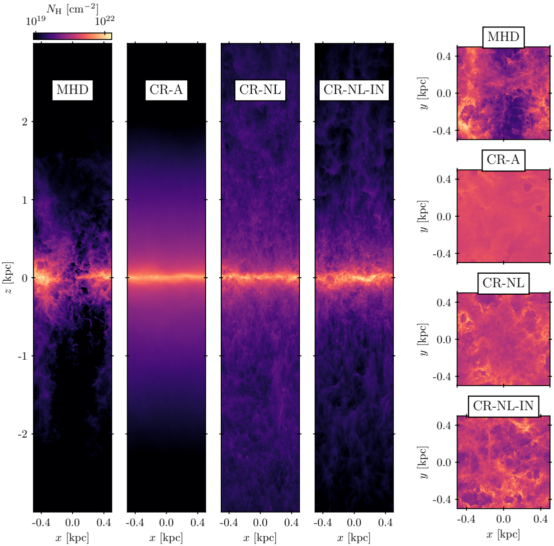


ISM tallbox: density and temperature

Comparing models: MHD, CR advection, full CR transport (different wave damping)

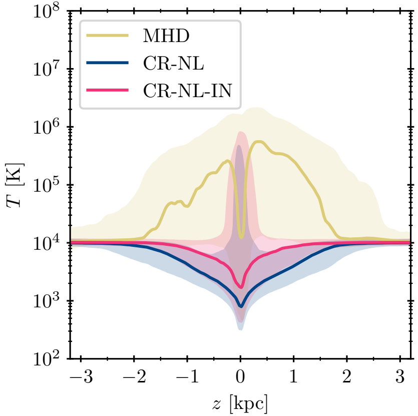


ISM column densities



Sike+ (2024)

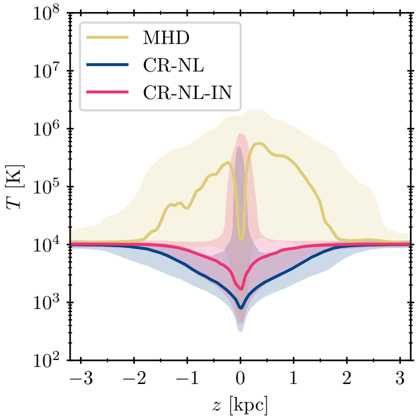
Characteristics of supernovae- vs. CR-driven winds



Sike+ (2024)

- MHD: thermal/kinetic pressure from SNe mainly propell galactic fountains that self-regulate the ISM
- CRs drive colder and denser galactic winds

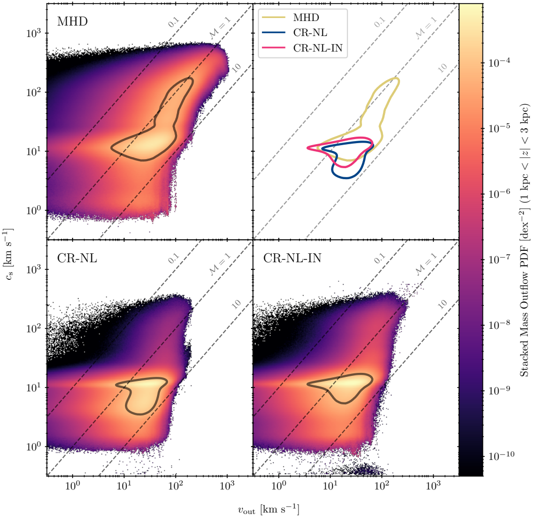
Characteristics of supernovae- vs. CR-driven winds



Sike+ (2024)

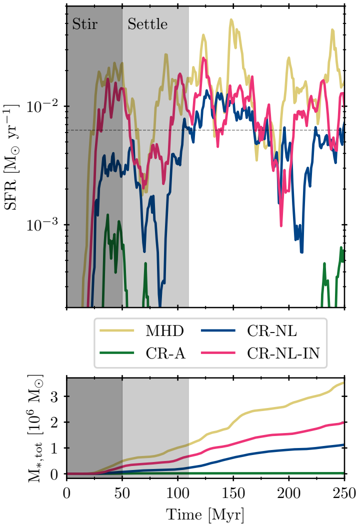
- MHD: thermal/kinetic pressure from SNe mainly propell galactic fountains that self-regulate the ISM
- CRs drive colder and denser galactic winds
- weak non-linear Landau (NL) damping tightly couples CRs to the ambient plasma $\Rightarrow$ strong CR driven winds
- NL and strong ion-neutral damping decouple CRs in the cold and warm ISM $\Rightarrow$ weaker winds

Phase structure of outflowing material

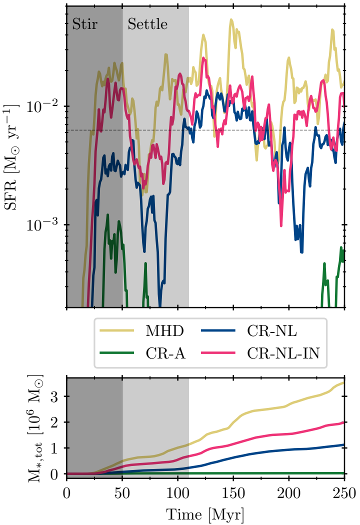


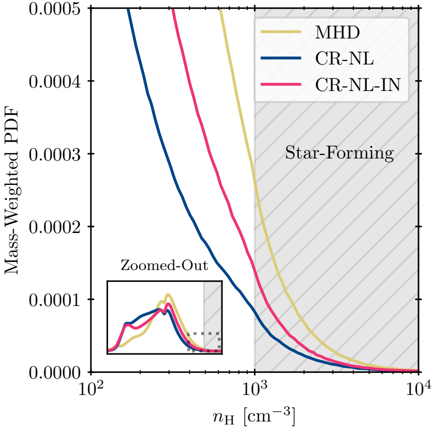
Sike+ (2024)

CR feedback mildly suppresses star formation



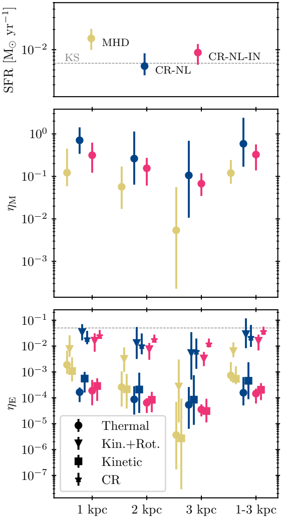
CR feedback mildly suppresses star formation





Sike+ (2024)

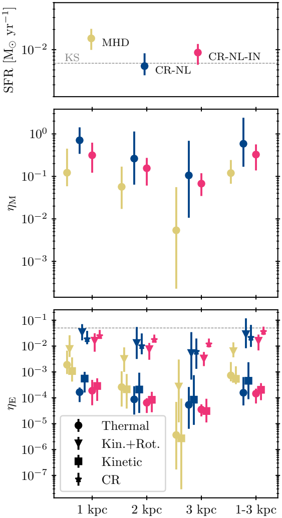
Mass and energy loading factors



Sike+ (2024)

- MHD fountains self-regulate the ISM: mass/energy loading factors decrease steeply with height
- CR-driven mass loading factors 3-5 time larger than MHD case

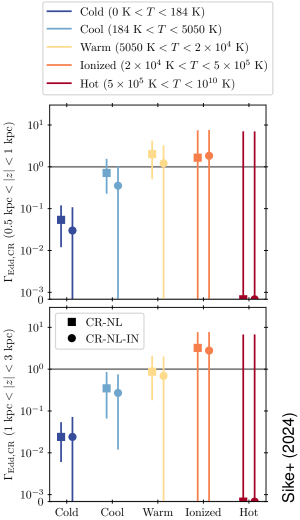
Mass and energy loading factors



Sike+ (2024)

- MHD fountains self-regulate the ISM: mass/energy loading factors decrease steeply with height
- CR-driven mass loading factors 3-5 time larger than MHD case
- most of CR energy transported to the wind while other energy forms are quickly dissipated
- CR energy loading comparable to kinetic energy loading with rotational boost ($\boldsymbol{v}_{\mathrm{kin+rot}} = \boldsymbol{v} + \boldsymbol{v}_{\mathrm{rot}}$)

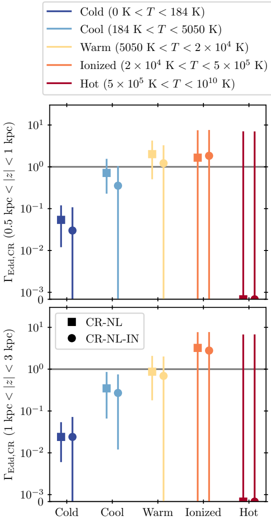
CR Eddington factors for different ISM phases



- CR Eddington factors:

$$\Gamma_{\mathrm{Edd,CR}} \equiv -\frac{a_{\mathrm{CR},z}}{a_{\mathrm{grav}}}, \quad a_{\mathrm{CR},z} = \frac{\nabla P_{\mathrm{CR}} \cdot \boldsymbol{e}_z}{\rho}$$

CR Eddington factors for different ISM phases



Sike+ (2024)

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- CRs supply no momentum to the hot phase
- CRs accelerate warm and ionized gas to launch a wind
- CRs support the cool and cold phases against freefall but do not actively drive them out

Conclusions for cosmic ray physics in galaxies

CR magneto-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: validated at radio harps

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CR feedback in the multi-phase ISM:

- CRISP models multiphase ISM with full CR physics
- CR feedback mildly suppresses 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

PICOGAL: From Plasma KInetics to COsmological GALaxy Formation

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Literature for the talk

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AIP