Cosmic ray feedback in galaxy formation: the multi-scale challenge

Christoph Pfrommer[1]

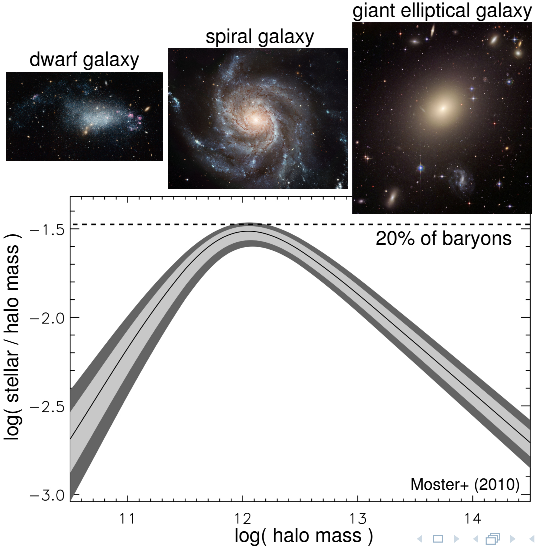
in collaboration with

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

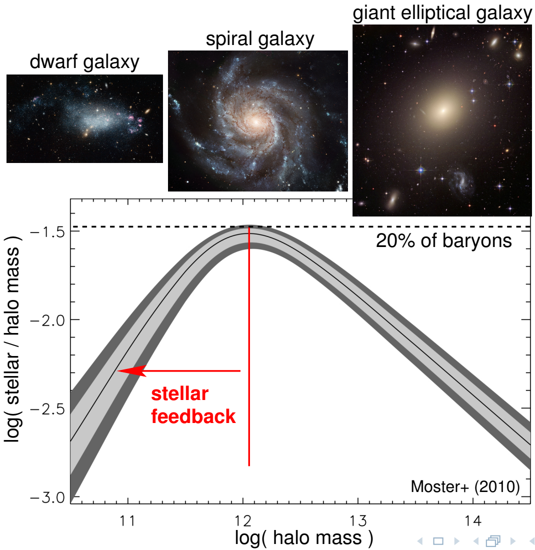
[1]AIP, [2]Michigan, [3]NBI, [4]Heidelberg, [5]Wisconsin, [6]Perimeter Institute, [7]MPA

Cosmic turbulence and magnetic fields, Corsica 2025

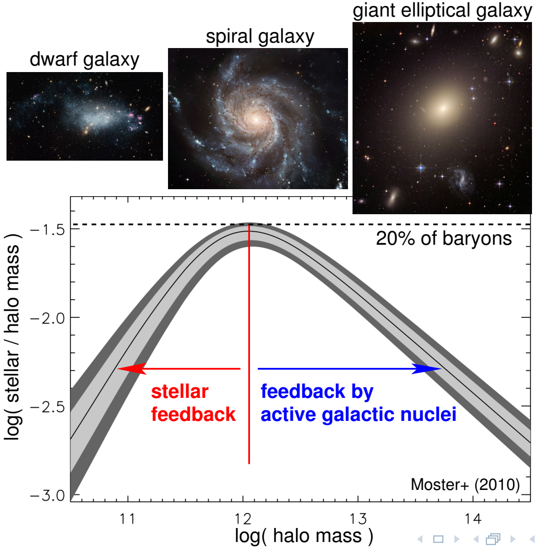
Puzzles in galaxy formation



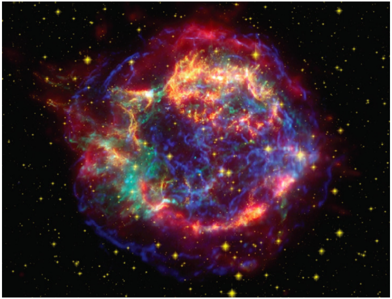
Puzzles in galaxy formation



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?

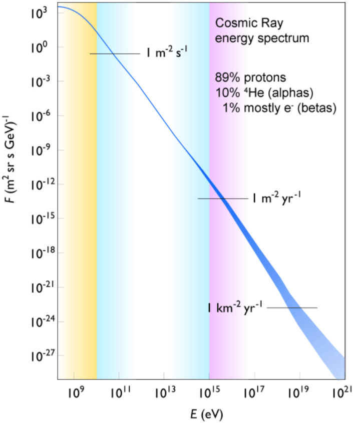
How are galactic winds driven?

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

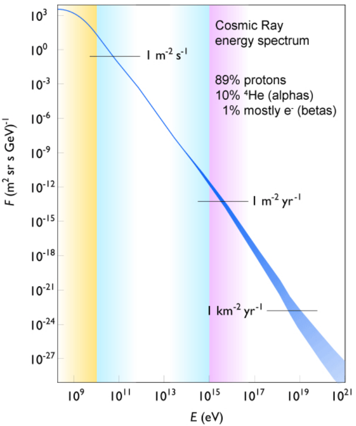
Galactic cosmic ray spectrum



data compiled by Swordy

- 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



data compiled by Swordy

- 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
- 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

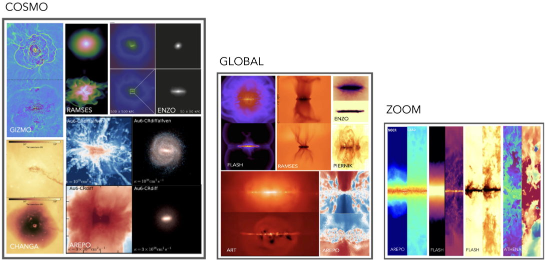
REVIEW ARTICLE

Check for updates

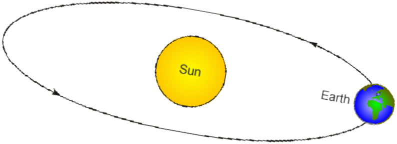
Cosmic ray feedback in galaxies and galaxy clusters

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

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



Cosmic ray transport: an extreme multi-scale problem



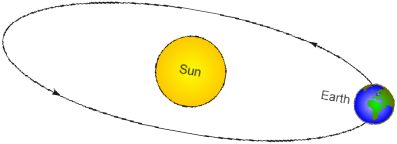
Milky Way-like galaxy:

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

gyro-orbit of GeV CR:

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

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:

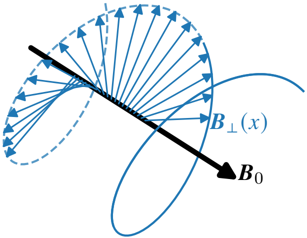
$$r_{\rm cr} = \frac{p_\perp}{e\,B_{\mu\mathrm{G}}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

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

Zweibel (2017), Thomas & CP (2019)

What is gyro resonance?

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

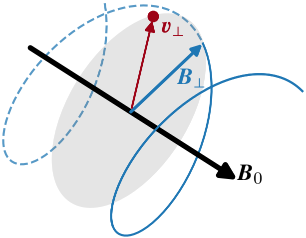


What is gyro resonance?

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

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

Ω_{cr} gyration frequency



What is gyro resonance?

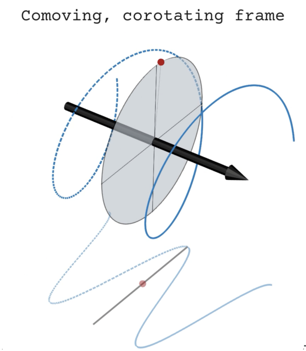
plane wave: $\exp(-\mathrm{i}k(x - v_{\mathrm{wave}}t))$

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

Ω_{cr} gyration frequency

resonance condition:

$$\overbrace{\Omega_{\mathrm{cr}}}^{\text{gyration}} + \overbrace{kv_{\|}}^{\text{Doppler shift}} = \overbrace{kv_{\mathrm{wave}}}^{\text{wave frequency}}$$



What is gyro resonance?

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

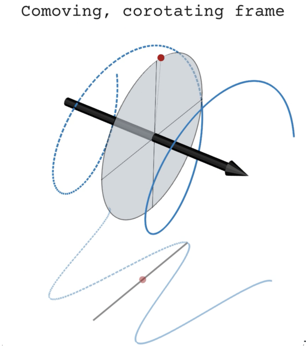
cosmic ray: $v_{||}$ movement along $\boldsymbol{B}_0$

$\Omega_{\rm cr}$ gyration frequency

resonance condition:

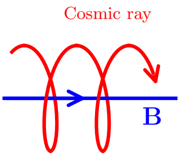
$$\overbrace{\Omega_{\rm cr}}^{\text{gyration}} + \overbrace{kv_{||}}^{\text{Doppler shift}} = \overbrace{kv_{\rm wave}}^{\text{wave frequency}}$$

Resonant wave appears **static** to CR!



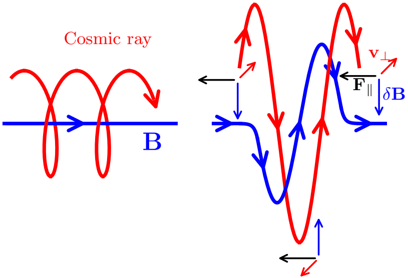
test particle without interactions!

Interactions of CRs and magnetic fields



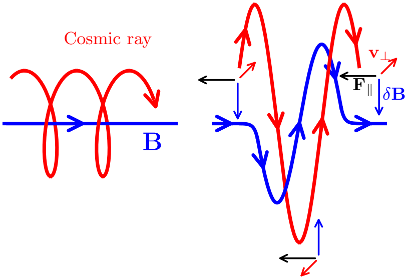
sketch: Jacob & CP

Interactions of CRs and magnetic fields



sketch: Jacob & CP

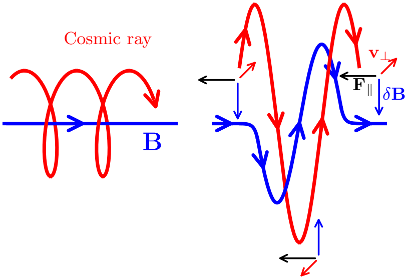
Interactions of CRs and magnetic fields



sketch: Jacob & CP

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

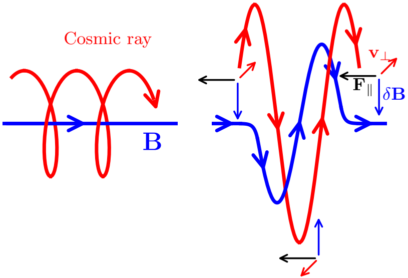
Interactions of CRs and magnetic fields



sketch: Jacob & CP

- **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: $\boldsymbol{F}_\mathrm{L} = q\frac{\boldsymbol{v} \times \boldsymbol{B}}{c}$

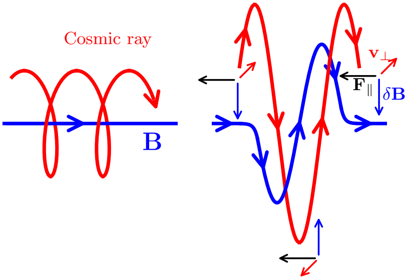
Interactions of CRs and magnetic fields



sketch: Jacob & CP

- **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: $\boldsymbol{F}_\mathrm{L} = q\frac{\boldsymbol{v} \times \boldsymbol{B}}{c}$
- 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

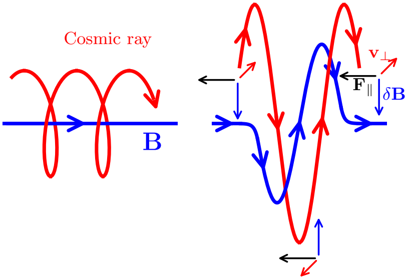
Interactions of CRs and magnetic fields



sketch: Jacob & CP

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

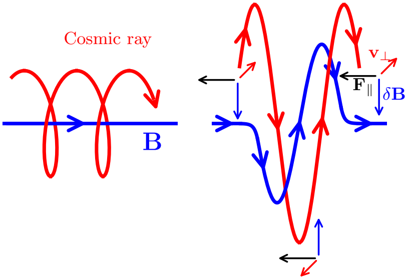
Interactions of CRs and magnetic fields



sketch: Jacob & CP

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

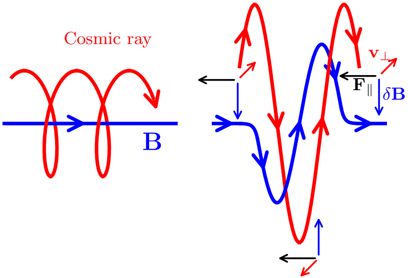
Interactions of CRs and magnetic fields



sketch: Jacob & CP

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

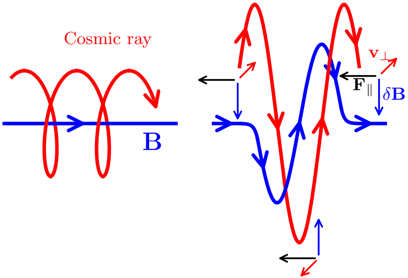


sketch: Jacob & CP

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

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

Interactions of CRs and magnetic fields



sketch: Jacob & CP

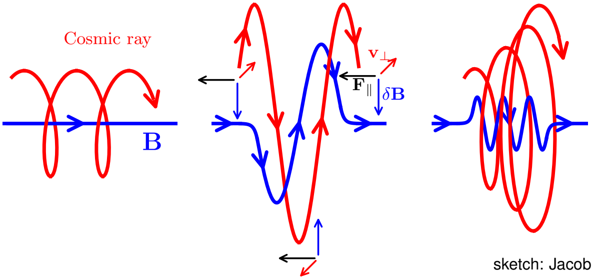
- **CRs resonantly interact with Alfvén waves** so that the wavelength equals the gyro-radius:

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

- **gyro resonance:** $\omega - k_{\parallel} v_{\parallel} = n\Omega_{\mathrm{cr}} = n\frac{qB}{\gamma m_{\mathrm{i}} c}$

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

Interactions of CRs and magnetic fields



sketch: Jacob & CP

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

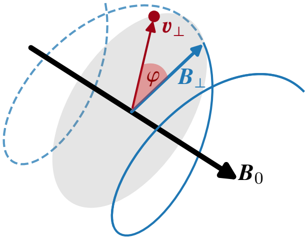
$$L_\parallel = r_\mathrm{g} = \frac{p_\perp c}{qB}$$

- **gyro resonance:** $\omega - k_\parallel v_\parallel = n\Omega_\mathrm{cr} = n\frac{qB}{\gamma m_\mathrm{i} c}$

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

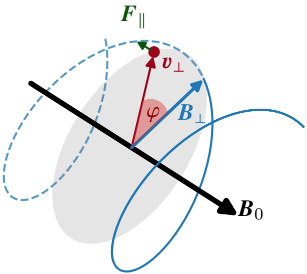
The mechanism of CR-driven instabilities

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



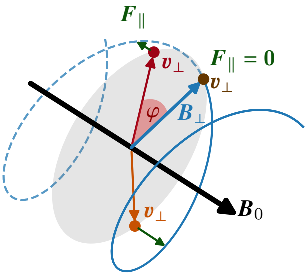
The mechanism of CR-driven instabilities

- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field



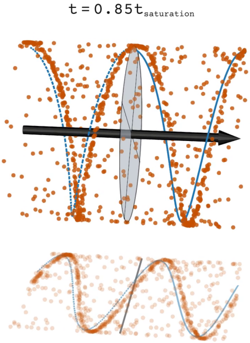
The mechanism of CR-driven instabilities

- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field
- CRs align rotational phase with plasma wave



The mechanism of CR-driven instabilities

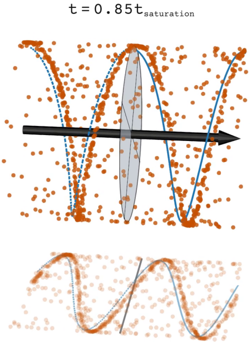
- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field
- CRs align rotational phase with plasma wave
- CR current wave interacts with electro-magnetic wave



fluid-PIC simulation (Lemmerz+ 2025)

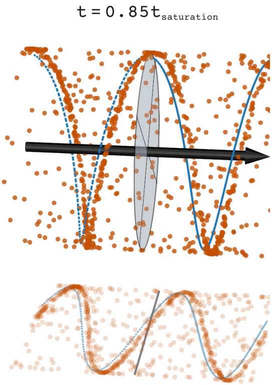
The mechanism of CR-driven instabilities

- ***goal:*** understand collective behaviour of many CRs
- parallel Lorentz force accelerates CRs towards closest wave field
- CRs align rotational phase with plasma wave
- CR current wave interacts with electro-magnetic wave
- CR trapping in Lorentz force potential saturates instability

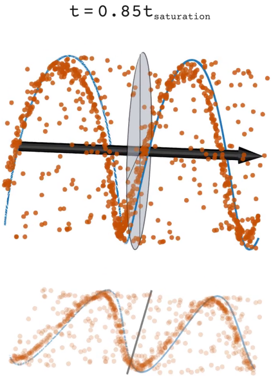


fluid-PIC simulation (Lemmerz+ 2025)

Growth of forward and backward moving waves



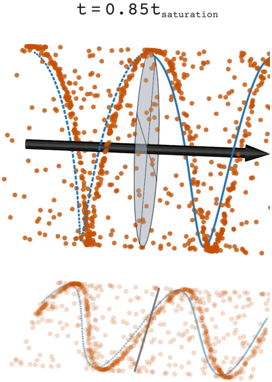
forward Alfvén,
Whistler



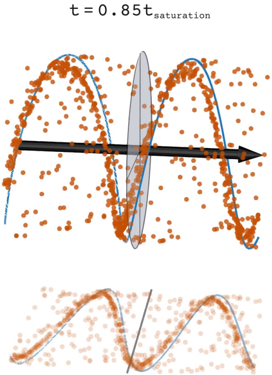
backward Alfvén

Lemmerz+ (2025)

Growth of forward and backward moving waves



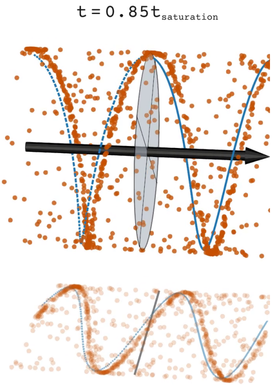
forward Alfvén, Whistler



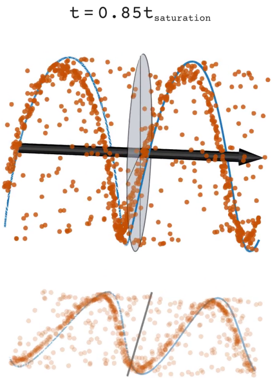
backward Alfvén

Lemmerz+ (2025)

Growth of forward and backward moving waves



forward Alfvén,
Whistler



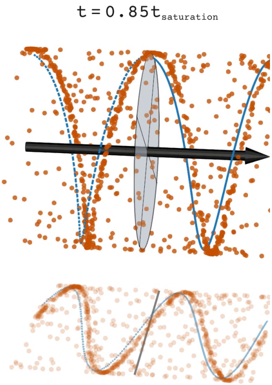
backward Alfvén

Lemmerz+ (2025)

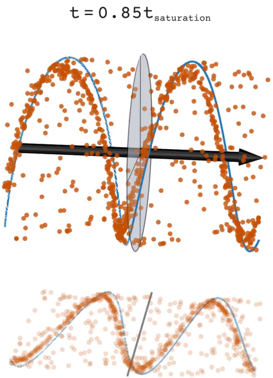
bunching theory:

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

Growth of forward and backward moving waves



forward Alfvén, Whistler



backward Alfvén

Lemmerz+ (2025)

bunching theory:

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

traditional, quasilinear theory:

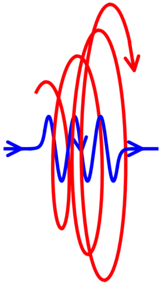
- assumes uniform φ
- diffusive scattering, no backward wave growth

Cosmic ray streaming and diffusion

- **CR streaming instability:**

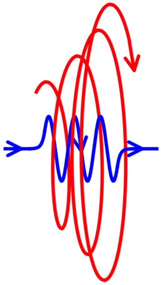
  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)

  - 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



Cosmic ray streaming and diffusion

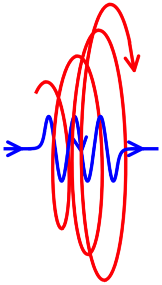
- **CR streaming instability:**
  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)
  - if $v_{\mathrm{cr}} > v_{\mathrm{a}}$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed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



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

Cosmic ray streaming and diffusion

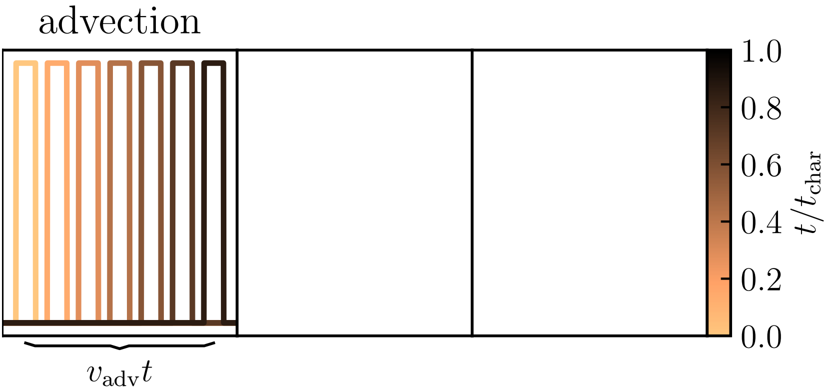
- **CR streaming instability:**
  Kulsrud & Pearce (1969), Shalaby+ (2021, 2023), Lemmerz+ (2025)
  - if $v_{\mathrm{cr}} > v_{\mathrm{a}}$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed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



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

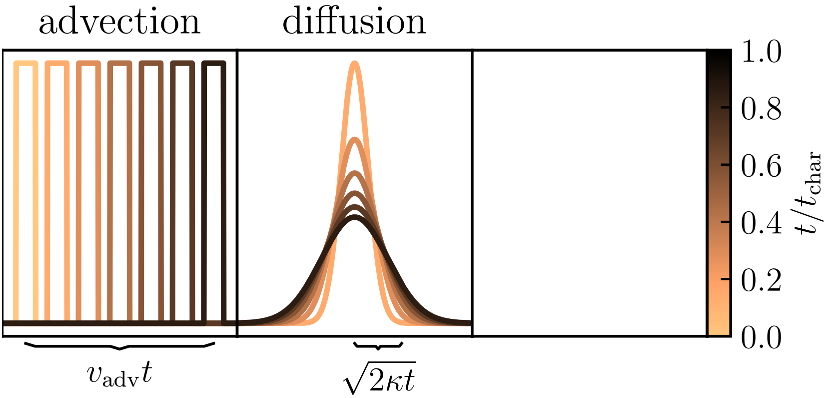
weak wave damping: strong coupling $\rightarrow$ CR stream with waves
strong wave damping: less waves to scatter $\rightarrow$ CR diffusion prevails

Modes of CR propagation



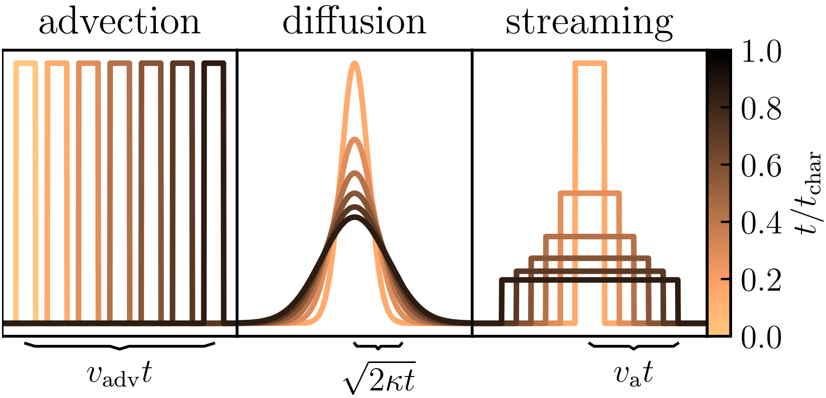
Thomas, CP, Enßlin (2020)

Modes of CR propagation



Thomas, CP, Enßlin (2020)

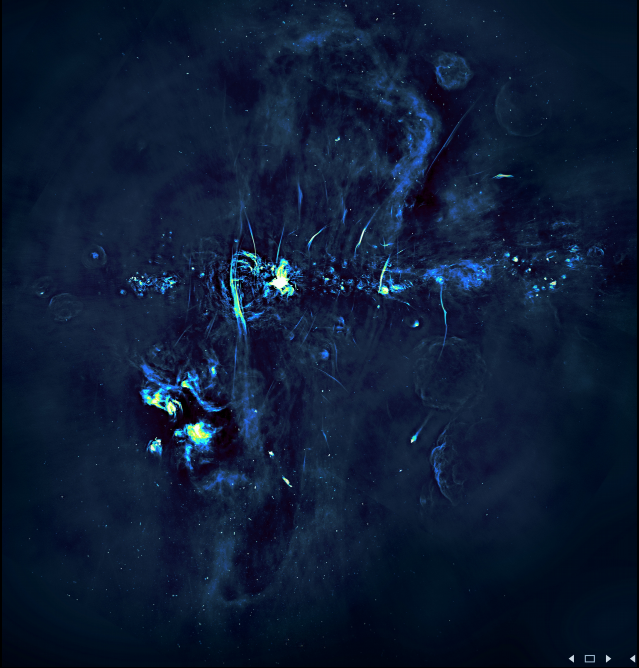
Modes of CR propagation



Thomas, CP, Enßlin (2020)

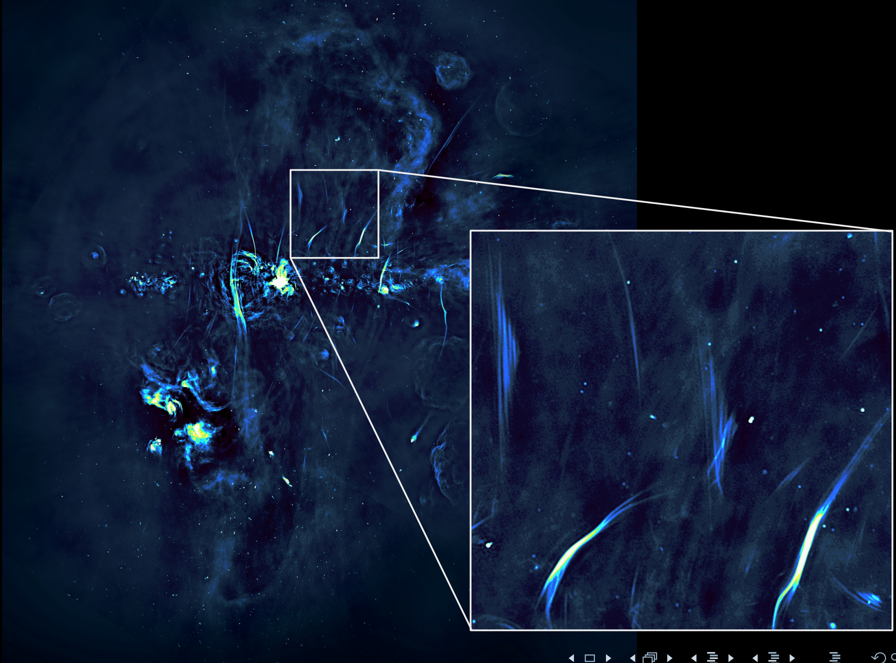
MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



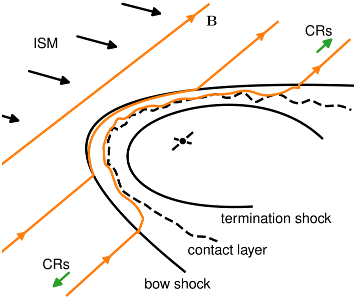
MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



Radio synchrotron harps: the model

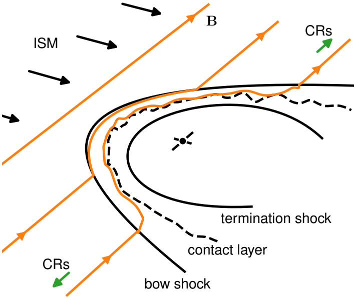
shock acceleration scenario



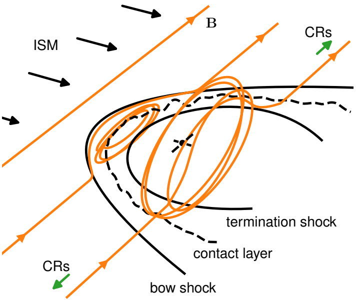
Thomas, CP, Enßlin (2020)

Radio synchrotron harps: the model

shock acceleration scenario



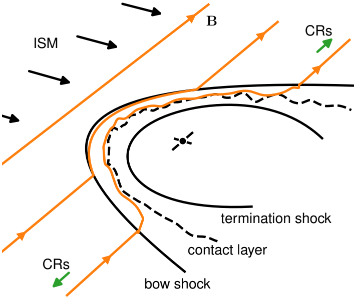
magnetic reconnection at pulsar wind



Thomas, CP, Enßlin (2020)

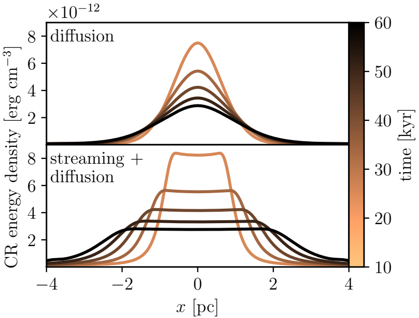
Radio synchrotron harps: the model

shock acceleration scenario

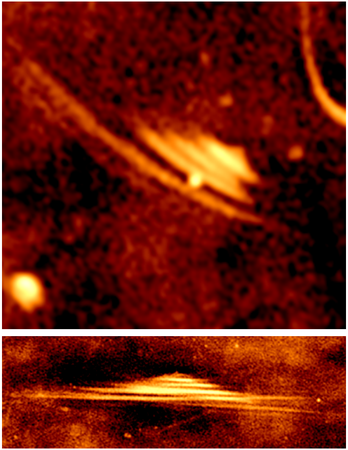


Thomas, CP, Enßlin (2020)

CR diffusion vs. streaming + diffusion

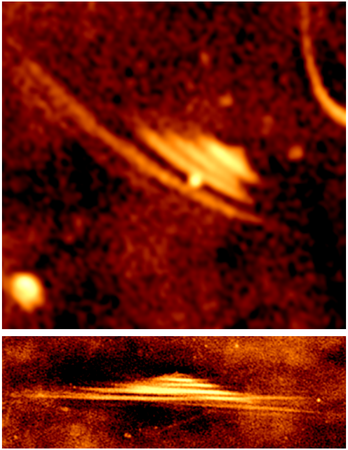


Radio synchrotron harps: testing CR propagation

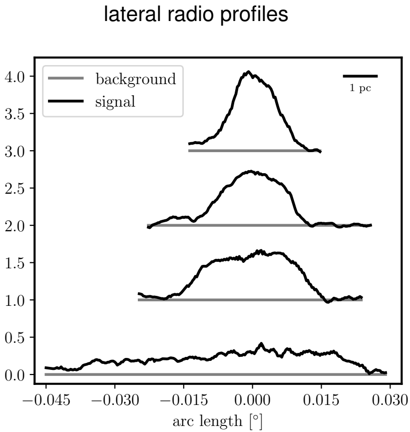


Haywood+ (Nature, 2019)

Radio synchrotron harps: testing CR propagation

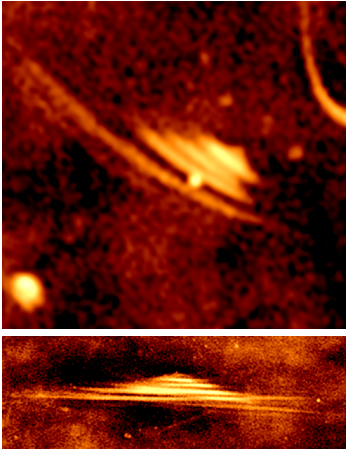


Haywood+ (Nature, 2019)

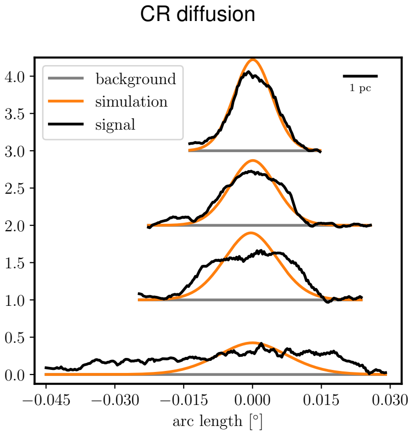


Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation

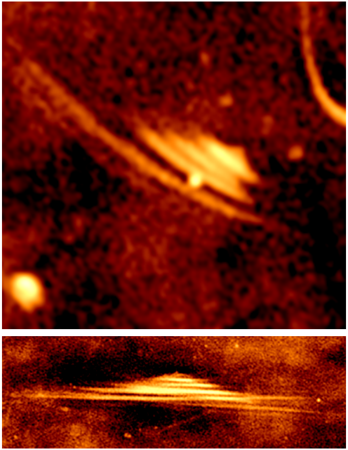


Haywood+ (Nature, 2019)



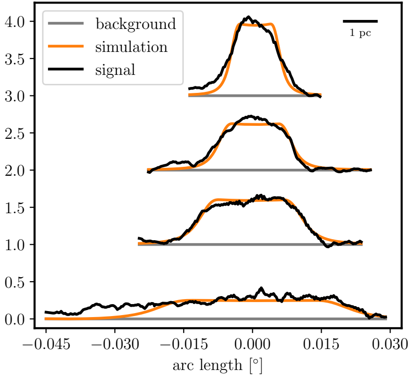
Thomas, CP, Enßlin (2020)

Radio synchrotron harps: testing CR propagation



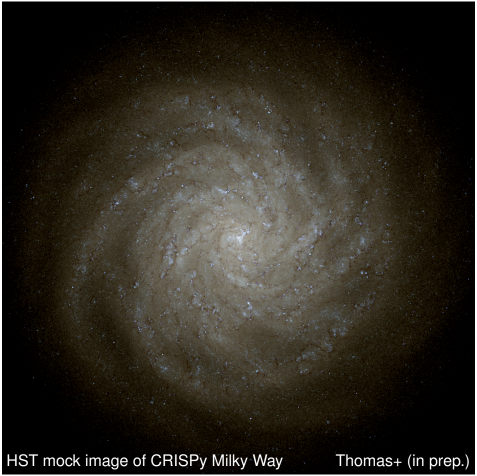
Haywood+ (Nature, 2019)

CR streaming and diffusion



Thomas, CP, Enßlin (2020)

Cosmic ray transport in galaxies

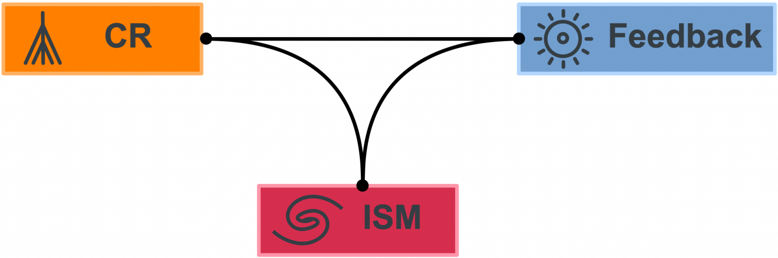


- CR transport in galaxies demands modeling non-linear Landau damping (in warm/hot phase) and ion-neutral damping (in disk)
- this requires resolving the multi-phase structure of the ISM
- development of CRISP framework (**C**osmic **R**ays and **I**nter**S**tellar **P**hysics, Thomas+ 2025)

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 Inter**S**tellar **P**hysics

Feedback

ISM

CR

Novel CR hydrodynamics
coarse graining plasma physics

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

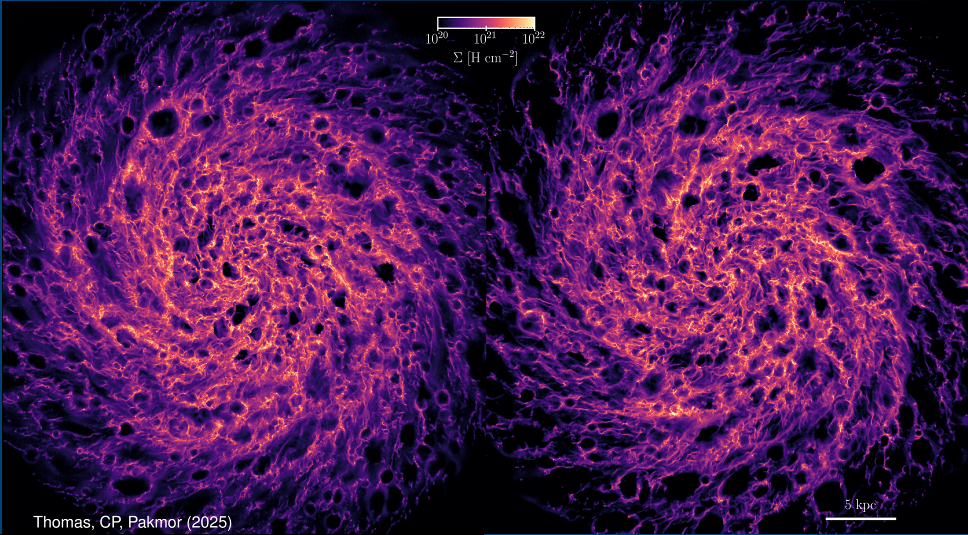
CR ionization
impacting **Chemistry**

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

CR microphysics

Thomas, CP, Pakmor (2025)

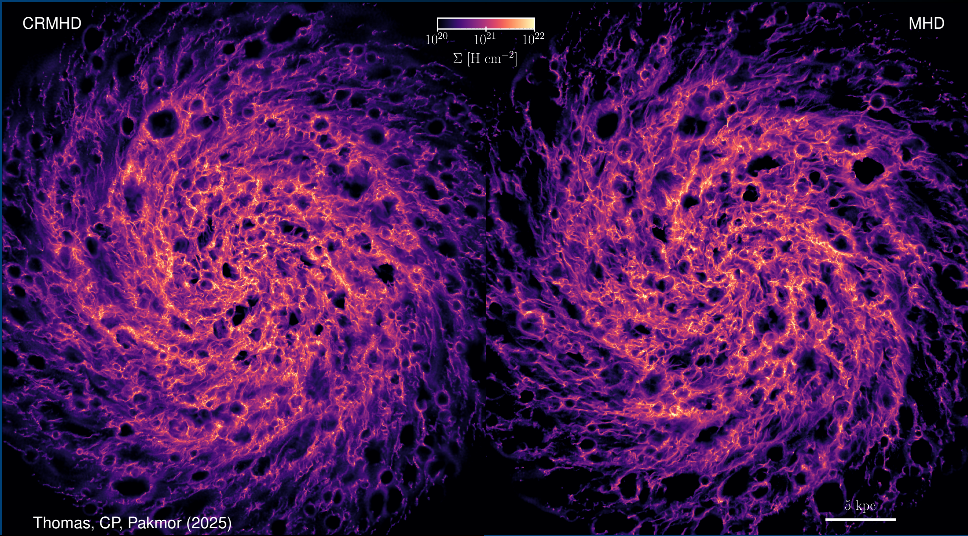
Multi-phase ISM modeling



Thomas, CP, Pakmor (2025)

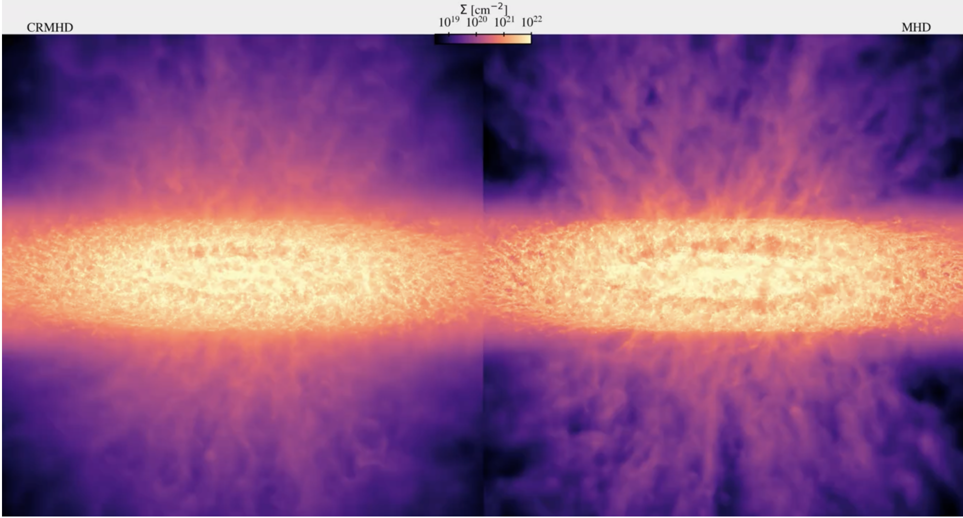
Multi-phase ISM modeling

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



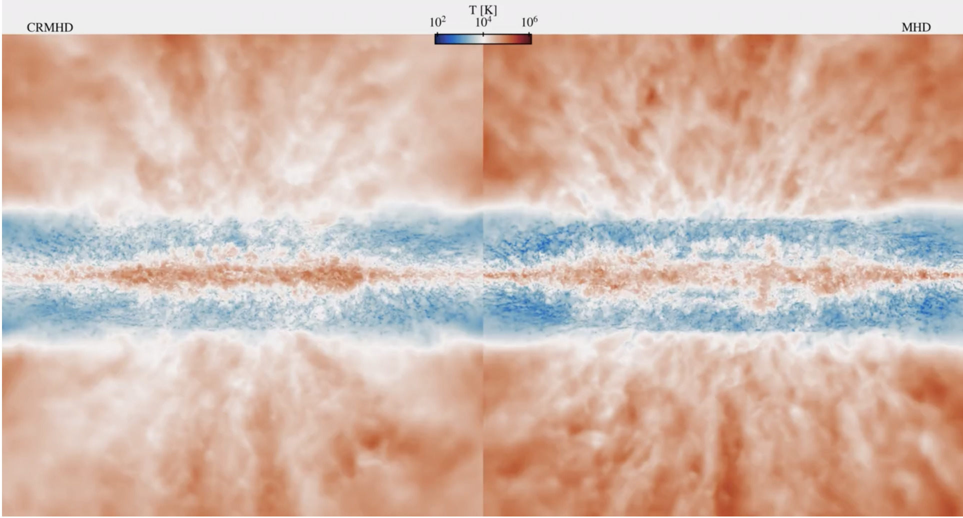
Simulated Milky Way: surface density

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



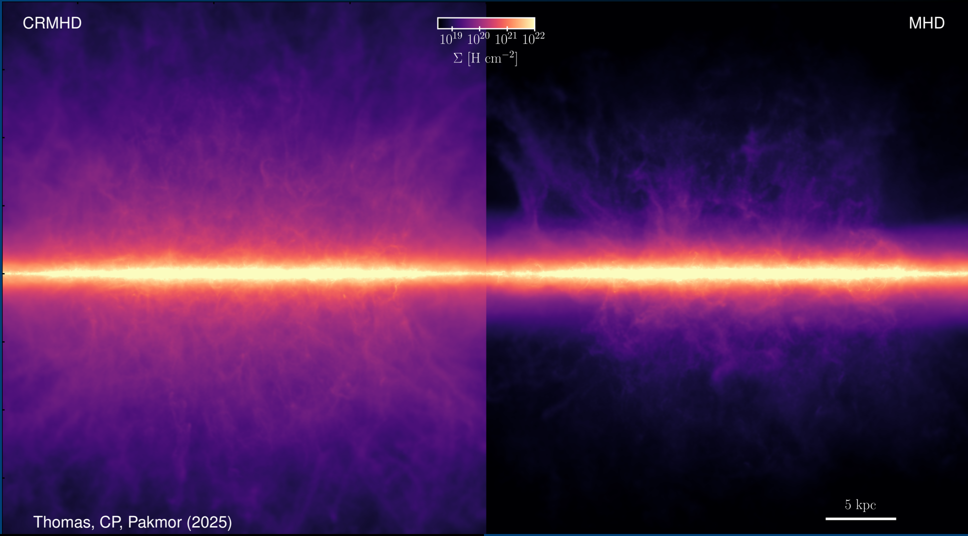
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter

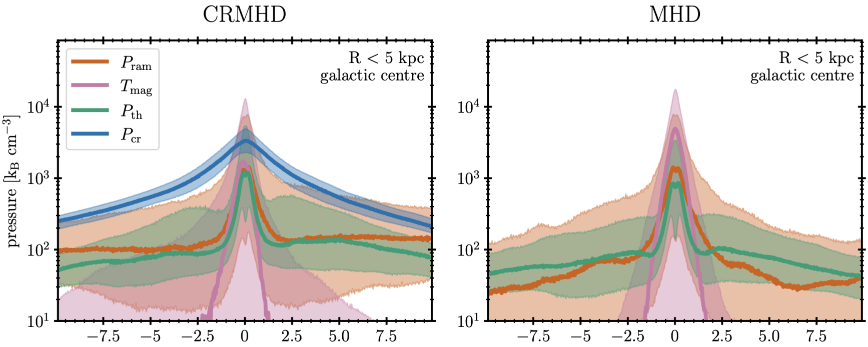


Multi-phase ISM modeling

Cosmic rays make galactic winds much denser



Cosmic ray driven wind: mechanism

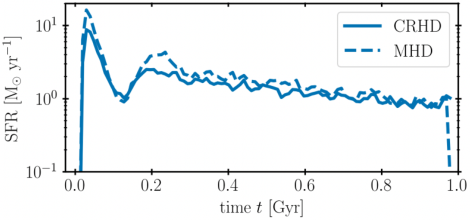


Thomas, CP, Pakmor (2025)

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

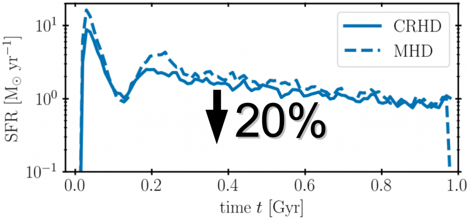
$$|\nabla P_{\mathrm{cr}} + \nabla P_{\mathrm{th}}| > \rho |\nabla \Phi|$$

Mass and energy loading factors



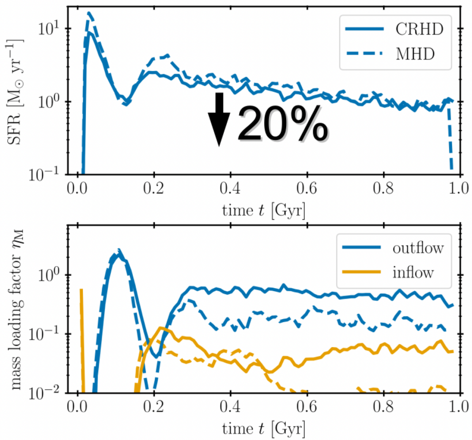
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



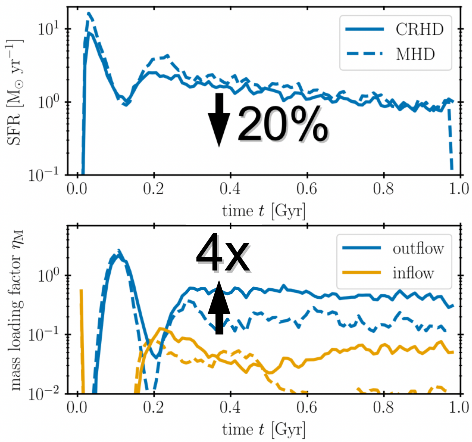
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



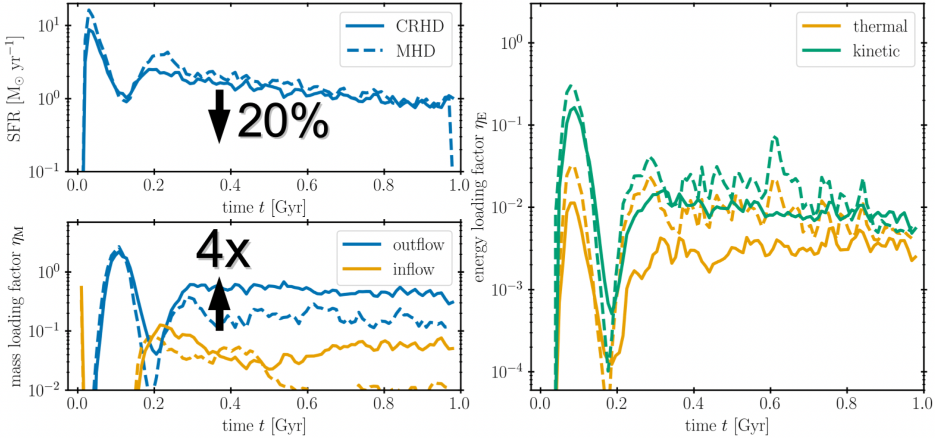
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



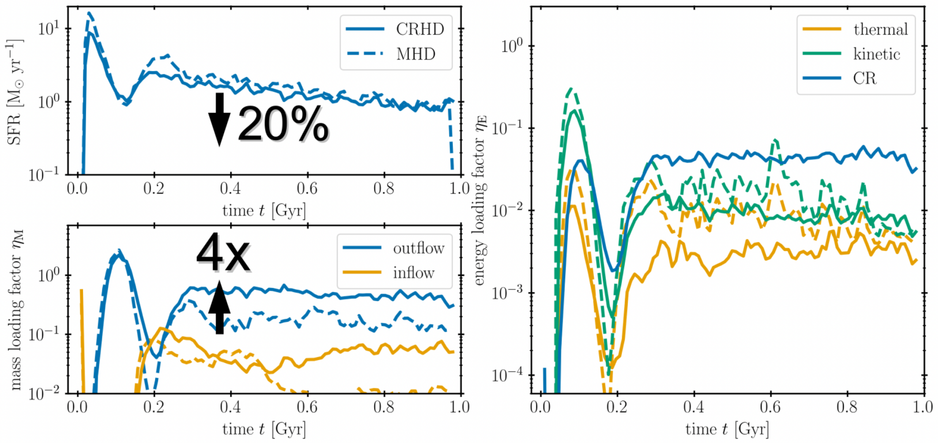
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



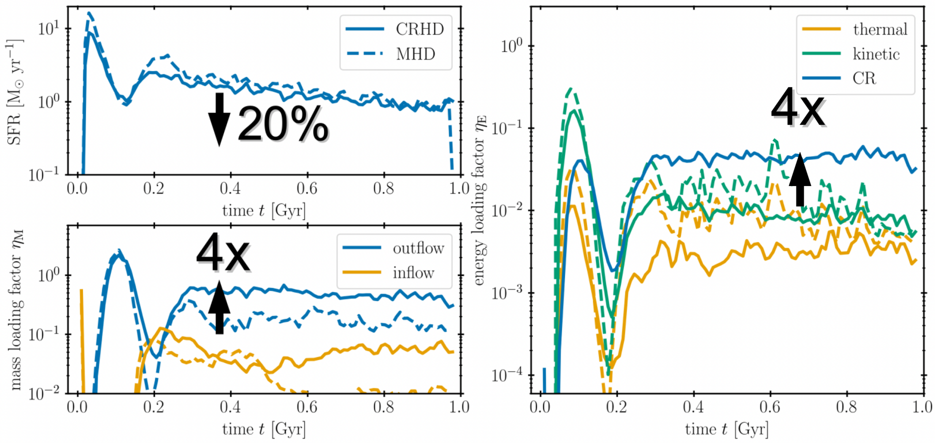
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



Thomas, CP, Pakmor (2025)

Mass and energy loading factors



Thomas, CP, Pakmor (2025)

Conclusions

Plasma instabilities and CR transport:

- Mechanism of CR-driven plasma-instabilities understood: important for setting CR transport speed and feedback strength
- 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

Conclusions

Plasma instabilities and CR transport:

- Mechanism of CR-driven plasma-instabilities understood: important for setting CR transport speed and feedback strength
- 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

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
- CR feedback increases mass and energy loading factors

UC SANTA BARBARA
Kavli Institute for Theoretical Physics

program dates: Jan 4 to Mar 11, 2027
application deadline: Nov 28, 2025

Cosmic Rays in Astrophysical Systems: From the Sun to Galaxies and Beyond

Coordinators: Greg Bryan, Christoph Pfrommer, Mateusz Ruszkowski, and Ellen Zweibel

Scientific Advisors: Eve Ostriker, Eliot Quataert, and Volker Springel

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, Lemmerz, Thomas, C. Pfrommer, *The mechanism of efficient electron acceleration at parallel non-relativistic shocks,* 2022, ApJ, 932, 86.
- 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.

AIP

Literature for the talk – 2

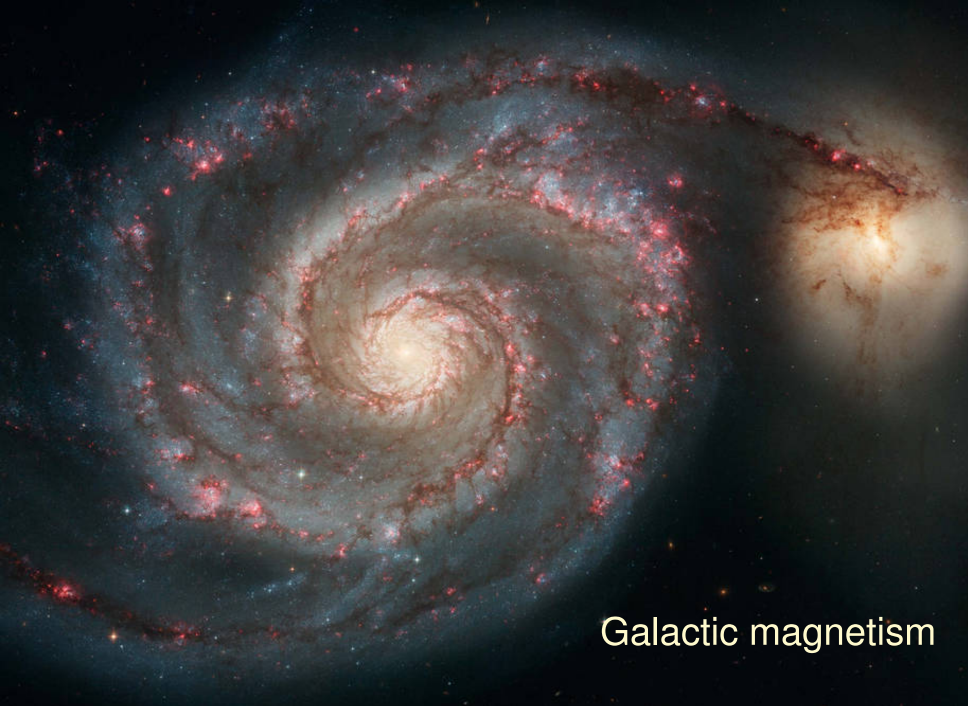
CR hydrodynamics and CR transport:

- 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



Galactic magnetism

Galactic magnetism

Origin and growth of magnetic fields

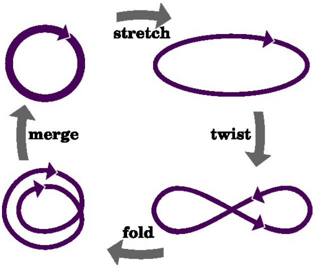
The general picture:

- ***Origin.*** Magnetic fields are generated by 1. electric currents sourced by a phase transition in the early universe or 2. by the Biermann battery

Origin and growth of magnetic fields

The general picture:

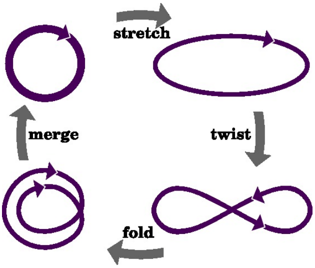
- ***Origin.*** Magnetic fields are generated by 1. electric currents sourced by a phase transition in the early universe or 2. by the Biermann battery
- ***Growth.*** A small-scale (fluctuating) dynamo is an MHD process, in which the kinetic (turbulent) energy is converted into magnetic energy: the mechanism relies on magnetic fields to become stronger when the field lines are stretched



Origin and growth of magnetic fields

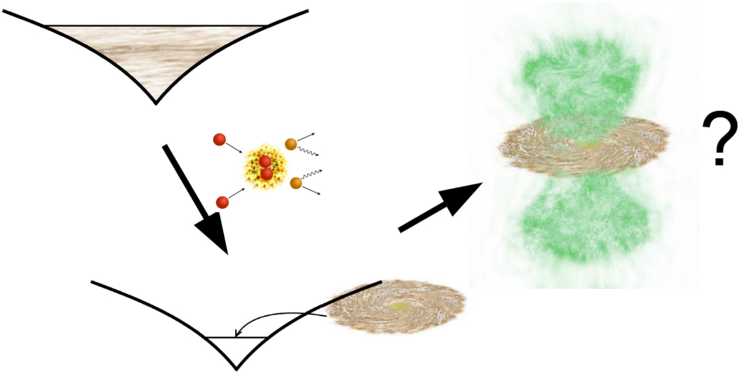
The general picture:

- ***Origin.*** Magnetic fields are generated by 1. electric currents sourced by a phase transition in the early universe or 2. by the Biermann battery
- ***Growth.*** A small-scale (fluctuating) dynamo is an MHD process, in which the kinetic (turbulent) energy is converted into magnetic energy: the mechanism relies on magnetic fields to become stronger when the field lines are stretched
- ***Saturation.*** Field growth stops at a sizeable fraction of the turbulent energy when magnetic forces become strong enough to resist the stretching and folding motions



AIP

Galaxy simulations with cosmic rays

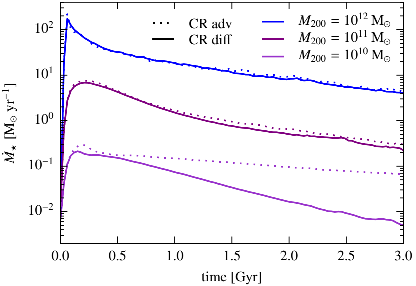


CP, Werhahn, Pakmor, Girichidis, Simpson (2022)
Simulating radio synchrotron emission in star-forming galaxies: small-scale magnetic dynamo and the origin of the far-infrared–radio correlation

MHD + cosmic ray advection + diffusion: $\{10^{10}, 10^{11}, 3\times10^{11}, 10^{12}\}\ \mathrm{M}_\odot$

AIP

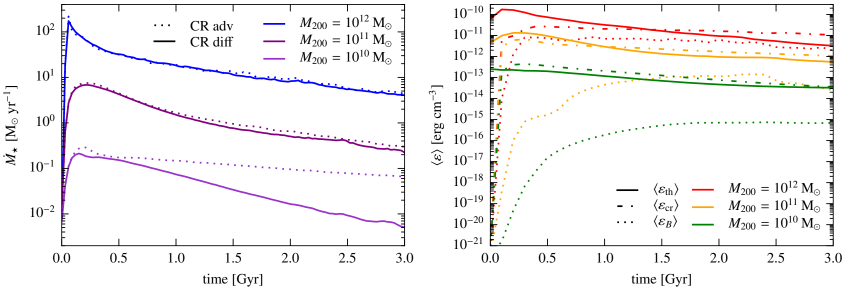
Time evolution of SFR and energy densities



CP+ (2022)

- cosmic ray (CR) pressure feedback suppresses SFR more in smaller galaxies

Time evolution of SFR and energy densities

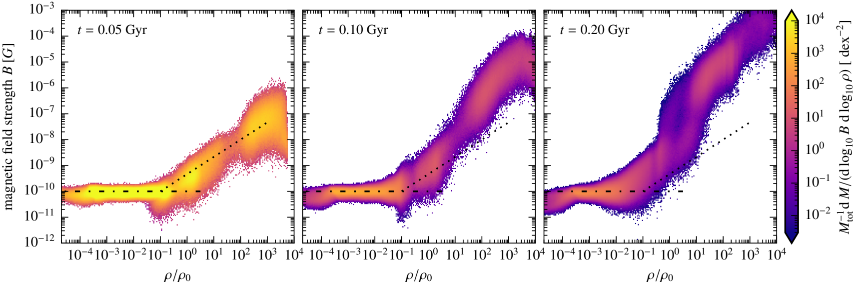


CP+ (2022)

- cosmic ray (CR) pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic growth faster in Milky Way galaxies than in dwarfs

AIP

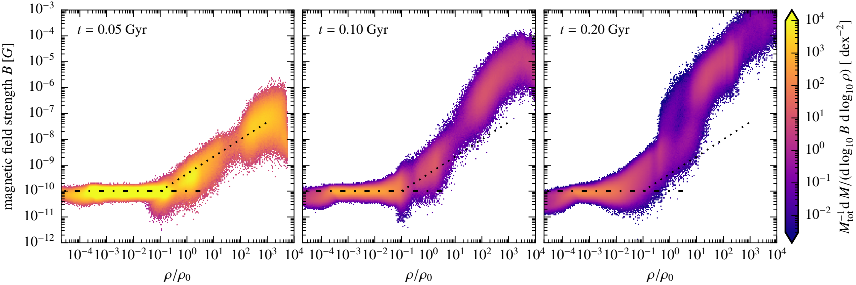
Identifying different growth phases



CP+ (2022)

- *1st phase:* adiabatic growth with $B \propto \rho^{2/3}$ (isotropic collapse)

Identifying different growth phases

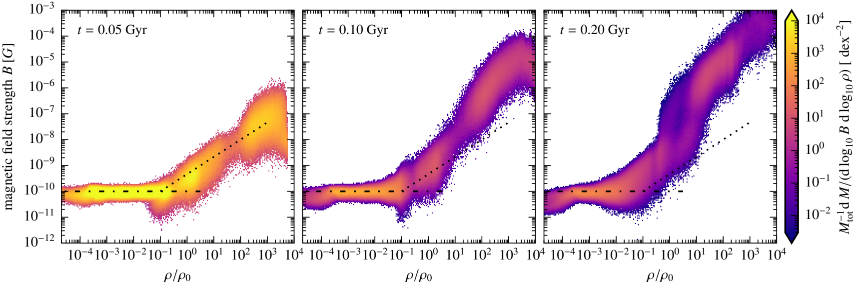


CP+ (2022)

- *1st phase:* adiabatic growth with $B \propto \rho^{2/3}$ (isotropic collapse)
- *2nd phase:* additional growth at high density ρ with small dynamical times $t_{\text{dyn}} \sim (G\rho)^{-1/2}$

AIP

Identifying different growth phases

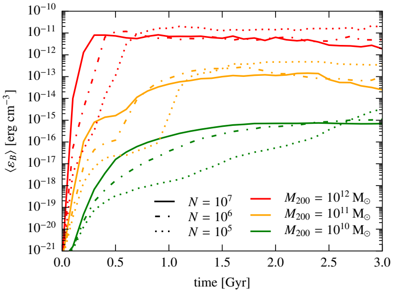


CP+ (2022)

- *1st phase:* adiabatic growth with $B \propto \rho^{2/3}$ (isotropic collapse)
- *2nd phase:* additional growth at high density ρ with small dynamical times $t_{\rm dyn} \sim (G\rho)^{-1/2}$
- *3rd phase:* growth migrates to lower ρ on larger scales $\propto \rho^{-1/3}$

AIP

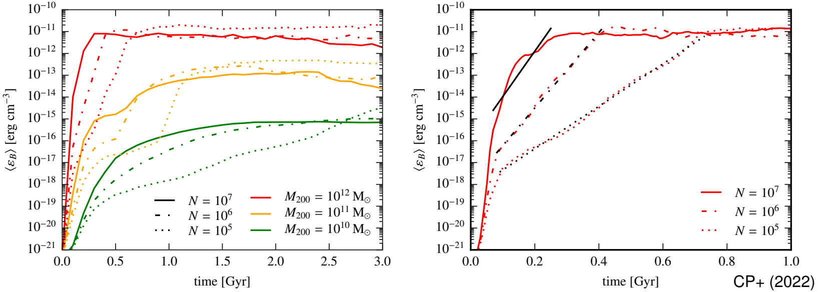
Studying growth rate with numerical resolution



CP+ (2022)

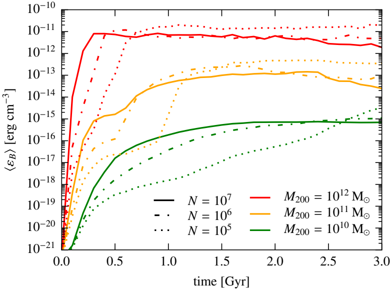
- ***faster magnetic growth in higher resolution simulations and larger halos,*** numerical convergence for $N \gtrsim 10^6$

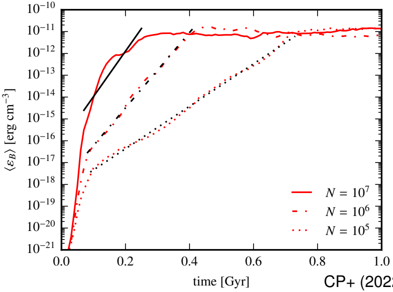
Studying growth rate with numerical resolution



- ***faster magnetic growth in higher resolution simulations and larger halos,*** numerical convergence for $N \gtrsim 10^6$
- *1st phase:* adiabatic growth (independent of resolution)

Studying growth rate with numerical resolution





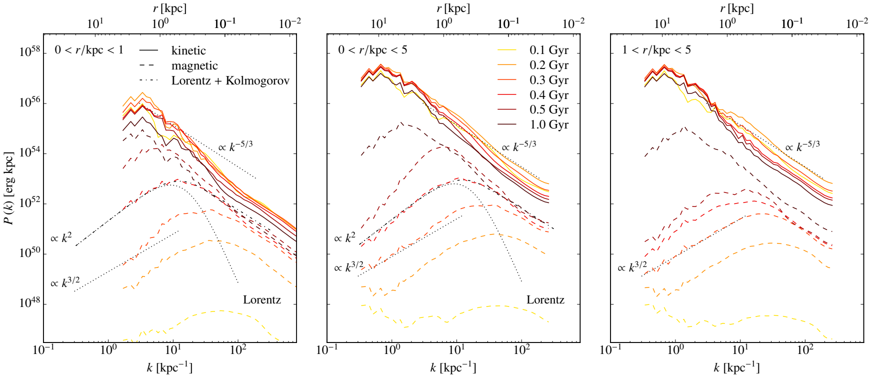
CP+ (2022)

- ***faster magnetic growth in higher resolution simulations and larger halos,*** numerical convergence for $N \gtrsim 10^6$
- *1st phase:* adiabatic growth (independent of resolution)
- *2nd phase:* small-scale dynamo with resolution-dep. growth rate

$$\Gamma = \frac{\mathcal{V}}{\mathcal{L}} \mathrm{Re}_{\mathrm{num}}^{1/2}, \quad \mathrm{Re}_{\mathrm{num}} = \frac{\mathcal{L}\mathcal{V}}{\nu_{\mathrm{num}}} = \frac{3\mathcal{L}\mathcal{V}}{d_{\mathrm{cell}}\, v_{\mathrm{th}}}$$

Kinetic and magnetic power spectra

Fluctuating small-scale dynamo in different analysis regions

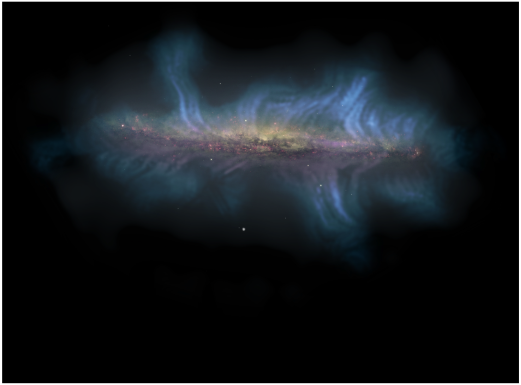


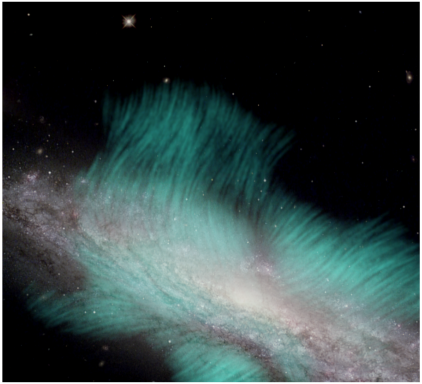
CP+ (2022)

- $E_B(k)$ superposition of form factor and turbulent spectrum
- pure turbulent spectrum outside steep central B profile

AIP

Galactic radio emission





Irwin+ (2024)

Steady-state cosmic ray spectra

- solve the steady-state equation in every cell for each CR population:

$$\frac{N(E)}{\tau_{\mathrm{esc}}} - \frac{\mathrm{d}}{\mathrm{d}E}\left[N(E)b(E)\right] = Q(E)$$

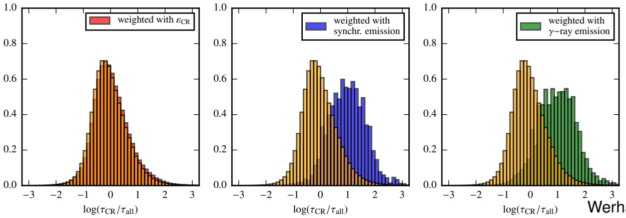
- protons: Coulomb, hadronic and escape losses (re-normalized to $\varepsilon_{\mathrm{cr}}$)
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\mathrm{ep}} = 0.02$)
  - secondaries

Steady-state cosmic ray spectra

- solve the steady-state equation in every cell for each CR population:

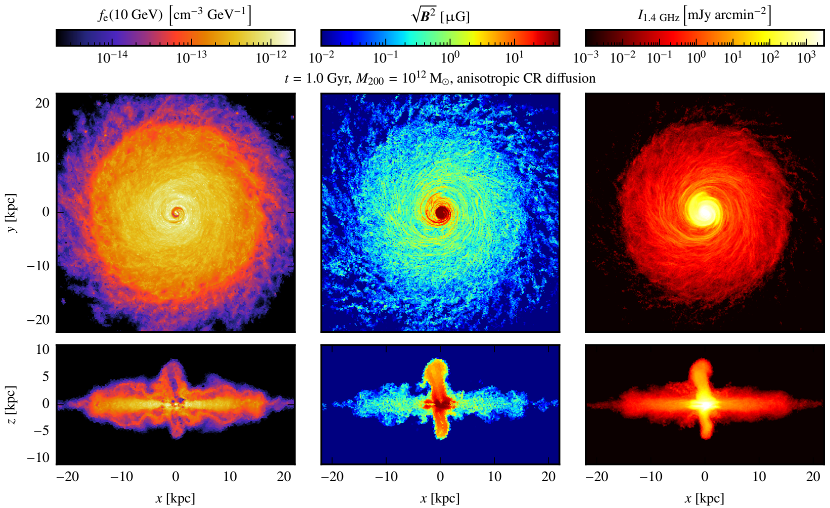
$$\frac{N(E)}{\tau_{\mathrm{esc}}} - \frac{\mathrm{d}}{\mathrm{d}E}\left[N(E)b(E)\right] = Q(E)$$

- protons: Coulomb, hadronic and escape losses (re-normalized to $\varepsilon_{\mathrm{cr}}$)
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\mathrm{ep}} = 0.02$)
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



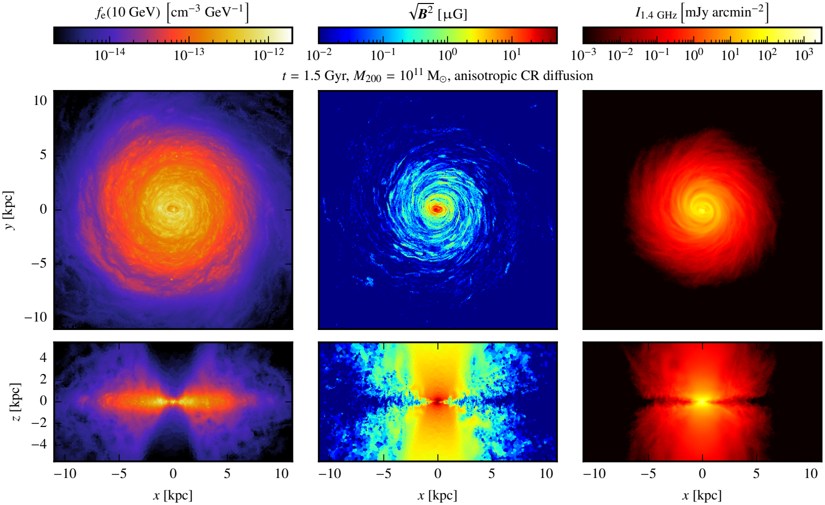
Werhahn+ (2021a)

Simulated radio emission: $10^{12}\,\mathrm{M}_\odot$ halo



CP+ (2022)

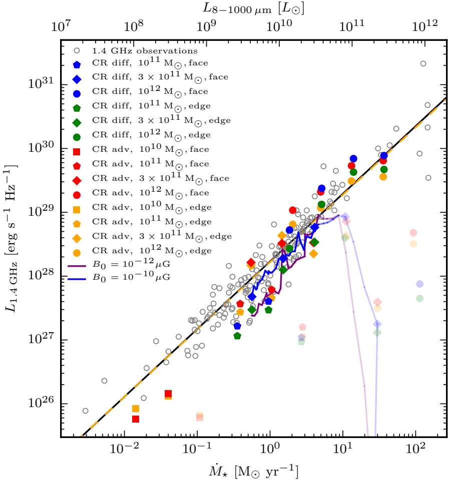
Simulated radio emission: 10^{11} M$_\odot$ halo



CP+ (2022)

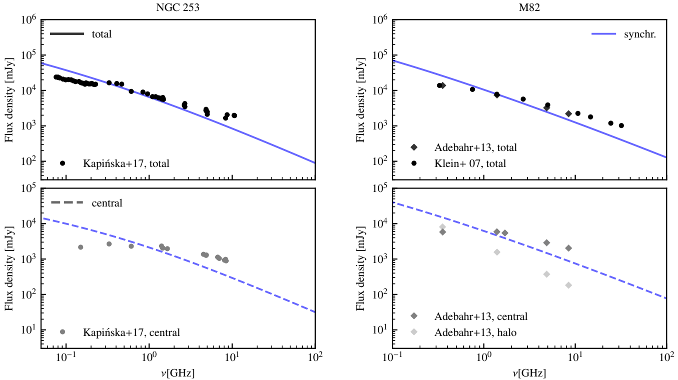
Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



CP+ (2022)

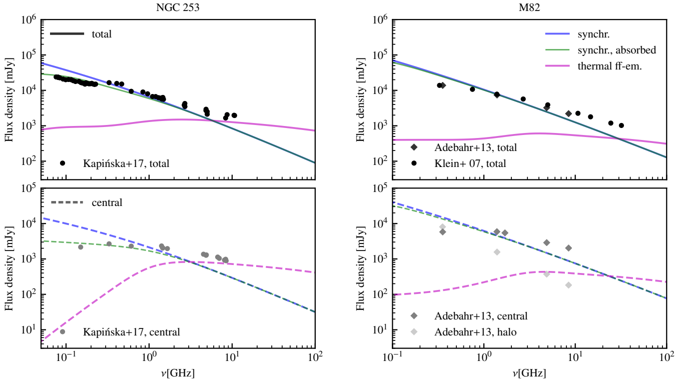
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)

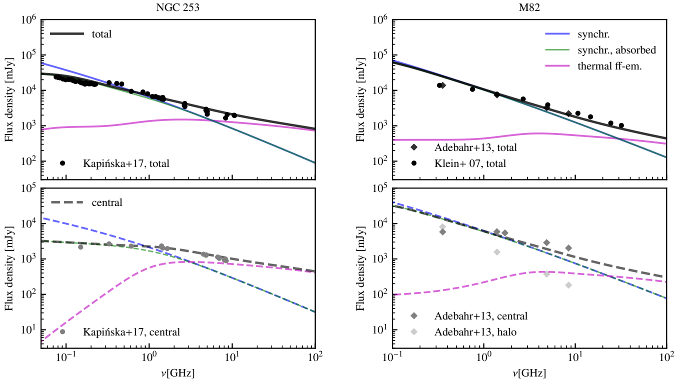
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν)

Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)
- synchrotron absorption (low-ν) and thermal free-free emission (high-ν) required to match (total and central) spectra

AIP