

Probing cosmic ray feedback in galaxies through radio emission

Christoph Pfrommer¹

in collaboration with

PhD students: Dusch,¹ Jlassi,¹ Kalangadan,¹ Pisharody,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

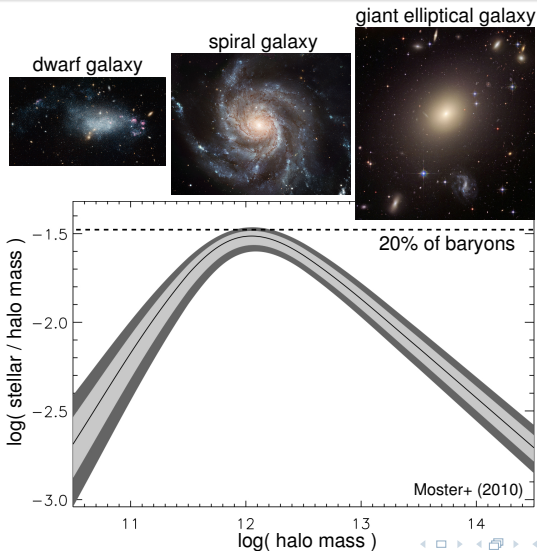
Faculty: Pakmor,⁷ Puchwein,¹ Weinberger,¹ Ruszkowski,² Springel,⁷ Enßlin⁷

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

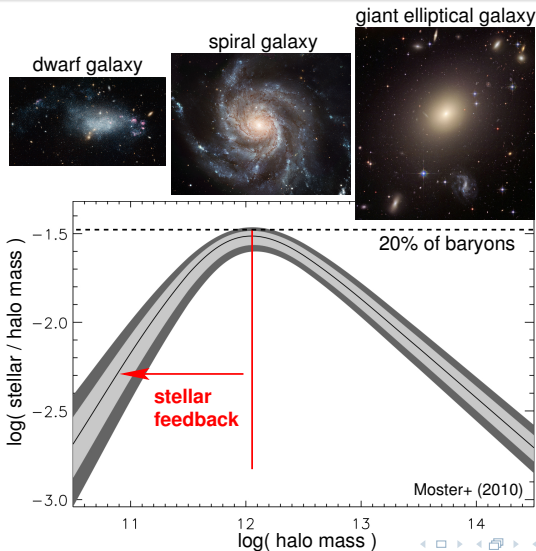
Cosmic-Ray Transport Workshop, The Ohio State University, 2026



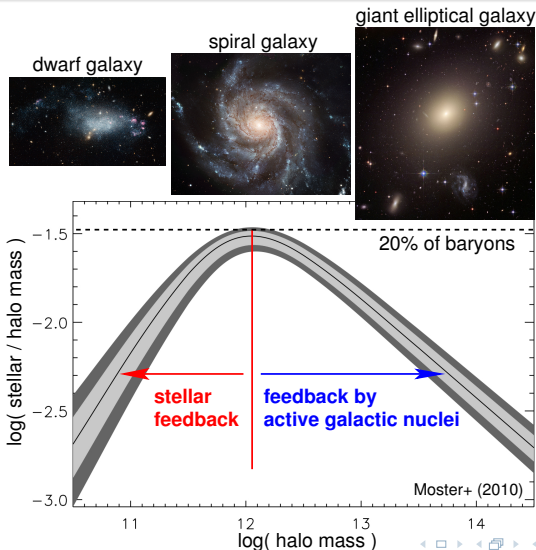
Puzzles in galaxy formation



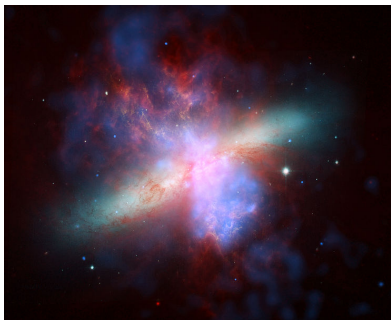
Puzzles in galaxy formation



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?

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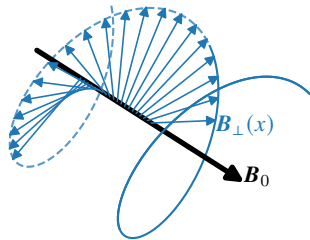
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- **energy density of CRs, magnetic fields, and ISM turbulence all similar**
⇒ important feedback agent

What is gyro resonance?

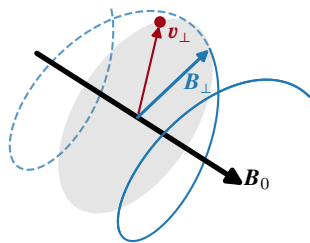
plane wave: $\exp(-ik(x - v_{\text{wave}}t))$



What is gyro resonance?

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cosmic ray: v_{\parallel} movement along \mathbf{B}_0
 Ω_{cr} gyration frequency



What is gyro resonance?

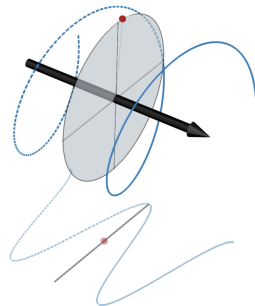
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resonance condition:

$$\underbrace{\Omega_{\text{cr}}}_{\text{gyration}} + \underbrace{kv_{\parallel}}_{\text{Doppler shift}} = \underbrace{kv_{\text{wave}}}_{\text{wave frequency}}$$

Comoving, corotating frame



What is gyro resonance?

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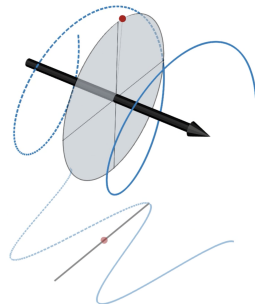
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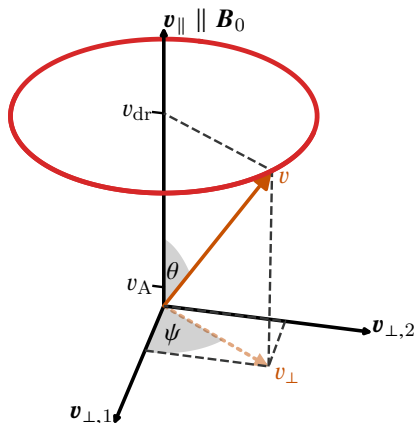
Resonant wave appears **static** to CR!

Comoving, corotating frame



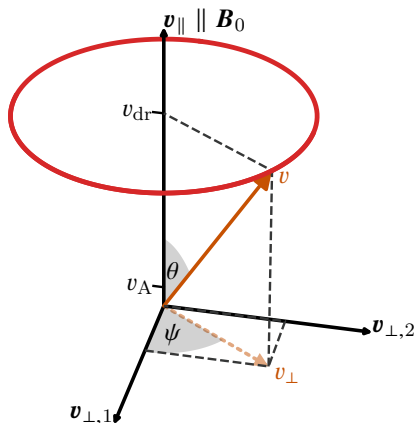
test particle without interactions!

Idealized setup to understand physics



- gyrotropic ring distribution of CR ions with single pitch angle and energy
- neutralizing CR electron beam at same drift speed but $v_{\perp} = 0$

Idealized setup to understand physics

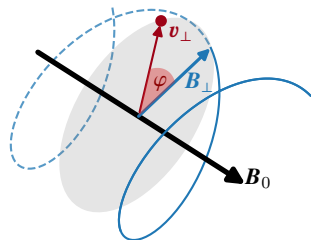


- gyrotropic ring distribution of CR ions with single pitch angle and energy
- neutralizing CR electron beam at same drift speed but $v_{\perp} = 0$
- background ion and electron fluid with Landau closure
- fluids coupled to particle-in-cell (PIC) CRs via Maxwell's equations

(Lemmerz+ 2024)

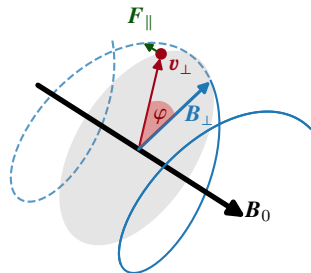
The mechanism of CR-driven instabilities

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



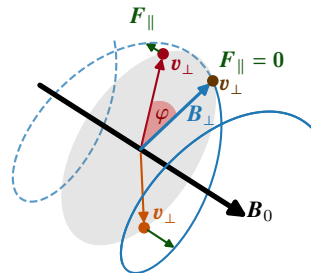
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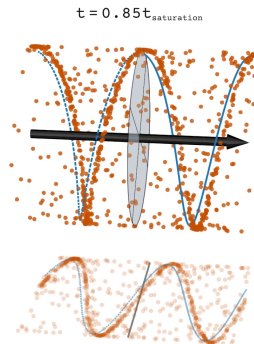
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The mechanism of CR-driven instabilities

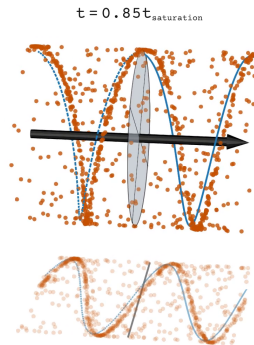
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fluid-PIC simulation (Lemmerz+ 2025)

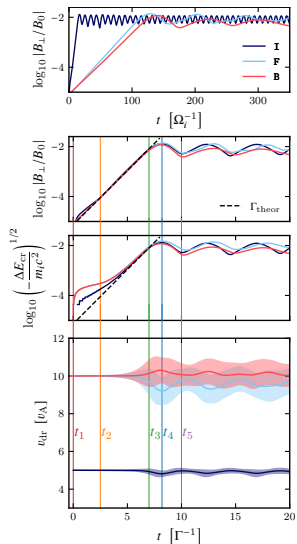
The mechanism of CR-driven instabilities

- **goal:** understand collective behaviour of many CRs
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- CR current wave interacts with electro-magnetic wave
- CR trapping in Lorentz force potential saturates instability



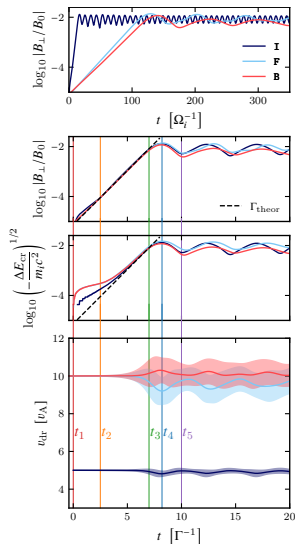
fluid-PIC simulation (Lemmerz+ 2025)

Resonant wave growth and CR energy loss



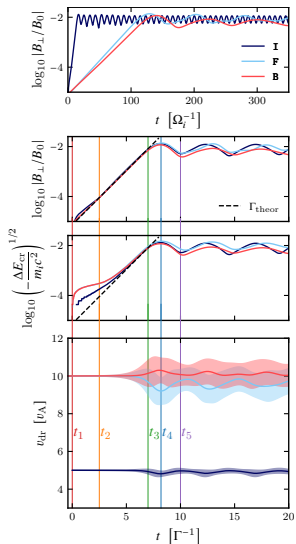
- exponential wave growth in fluid-PIC simulations that excite whistlers (via intermediate-scale instability, **I**), backward (**B**) and forward (**F**) Alfvén waves

Resonant wave growth and CR energy loss



- **exponential wave growth in fluid-PIC simulations** that excite whistlers (via intermediate-scale instability, **I**), backward (**B**) and forward (**F**) Alfvén waves
- **energy gain by waves exactly balances CR energy loss** to the unstable modes

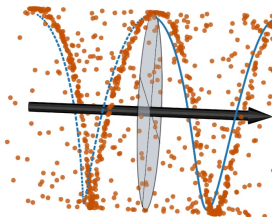
Resonant wave growth and CR energy loss



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- energy gain by waves exactly balances CR energy loss to the unstable modes
- mean CR drift speed, v_{dr} , slows down for forward waves (**F** and **I**) and accelerates for backward waves (**B**): saturation at $v_{\text{dr}} > v_A$ for gyrotropic CR ring distribution

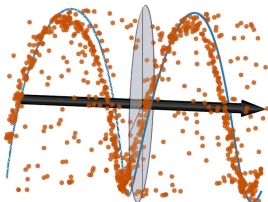
Growth of forward and backward moving waves

$t = 0.85 t_{\text{saturation}}$

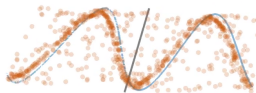
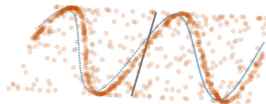


forward Alfvén,
Whistler

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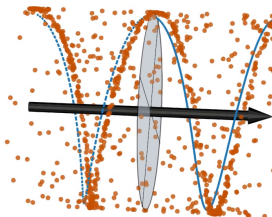


backward Alfvén
Lemmerz+ (2025)



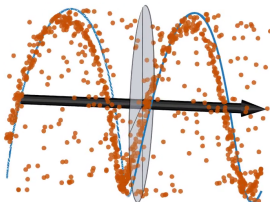
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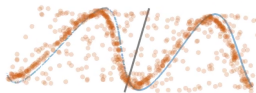
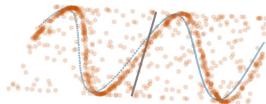


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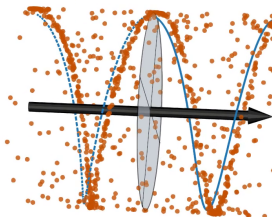


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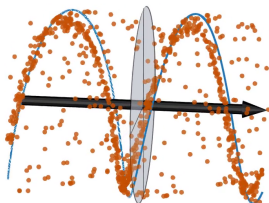
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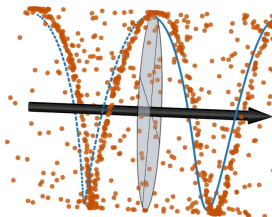
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bunching theory:

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

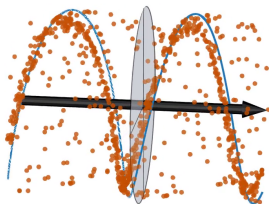
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Lemmerz+ (2025)

bunching theory:

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traditional, quasilinear theory:

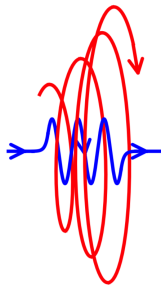
- assumes uniform φ
- diffusive scattering, no backward wave growth

Cosmic ray streaming and diffusion

● CR streaming instability:

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

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

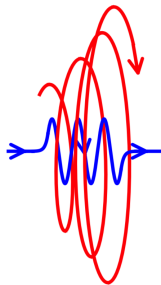


Cosmic ray streaming and diffusion

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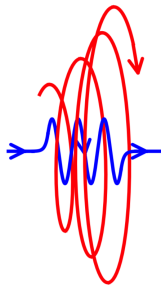
→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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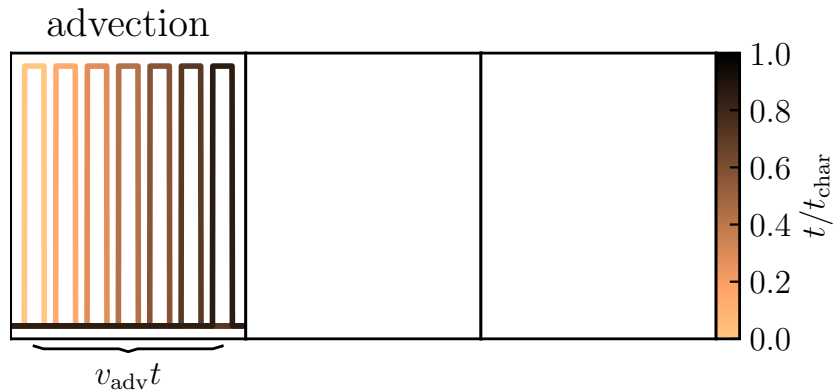


→ CRs exert pressure on thermal gas via scattering on Alfvén waves

weak wave damping: strong coupling → CR stream with waves

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

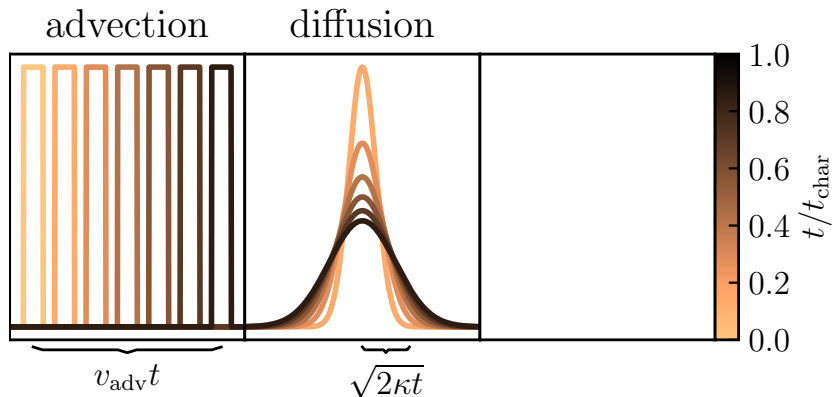
Modes of CR propagation



Thomas, CP, EnBlin (2020)



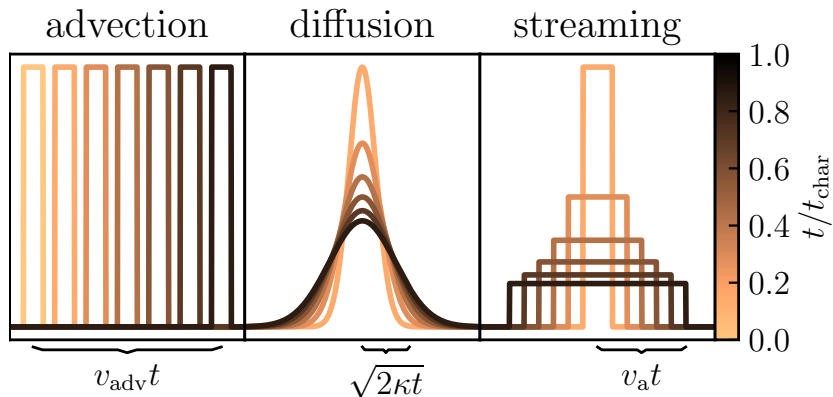
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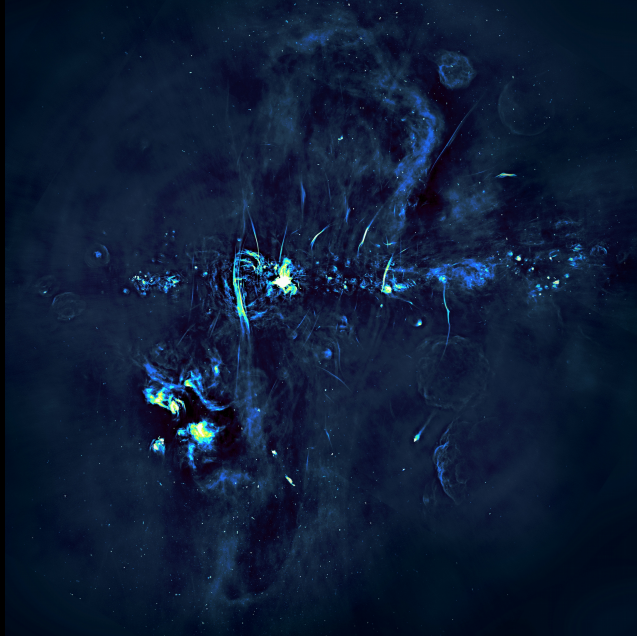


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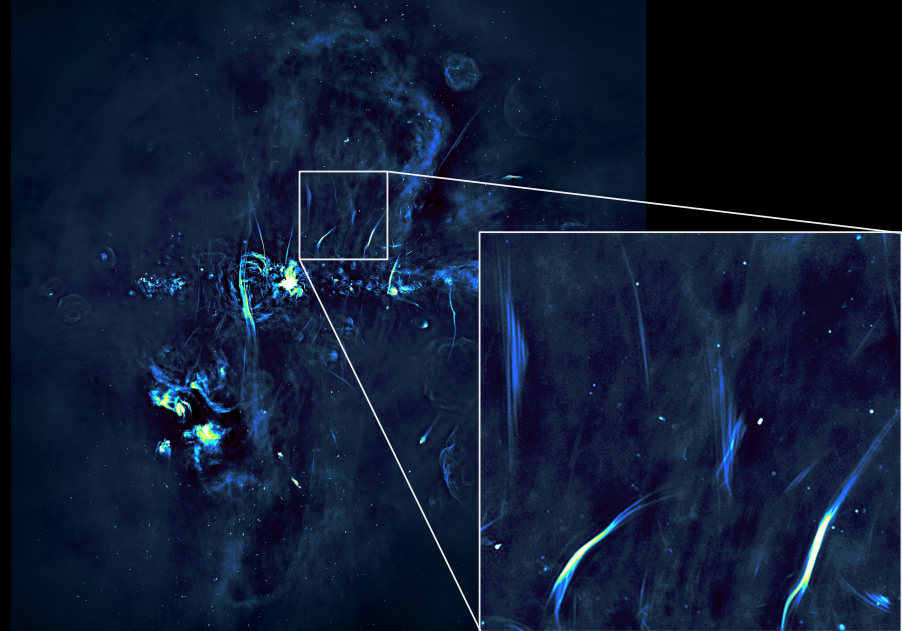
MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



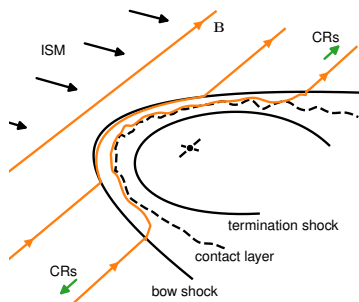
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Radio synchrotron harps: the model

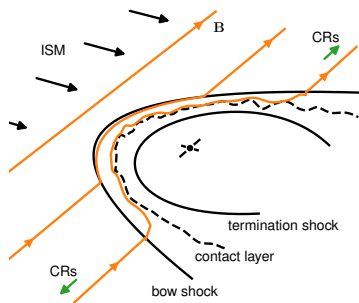
shock acceleration scenario



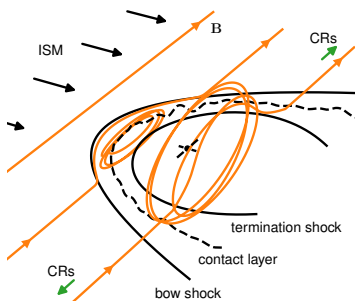
Thomas, CP, Enßlin (2020)

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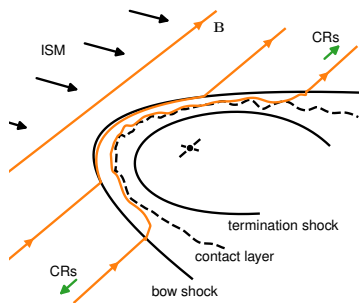
magnetic reconnection at pulsar wind



Thomas, CP, Enßlin (2020)

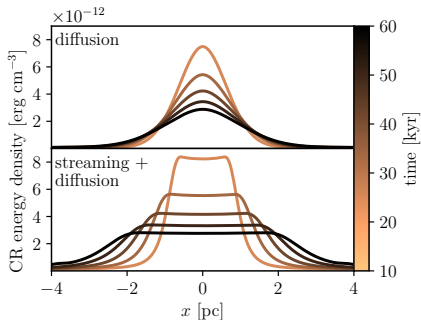
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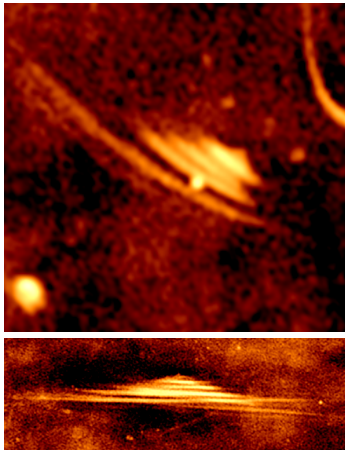


Thomas, CP, Enßlin (2020)

CR diffusion vs. streaming + diffusion

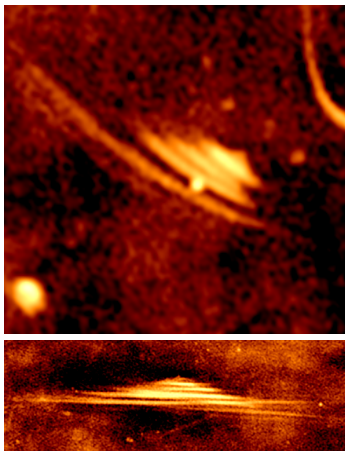


Radio synchrotron harps: testing CR propagation



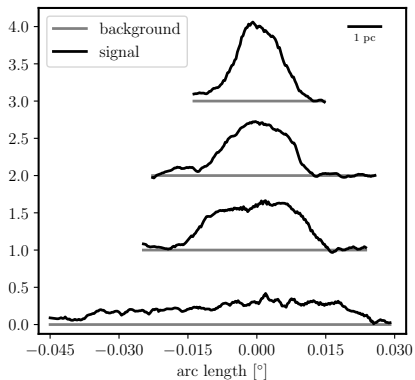
Haywood+ (Nature, 2019)

Radio synchrotron harps: testing CR propagation



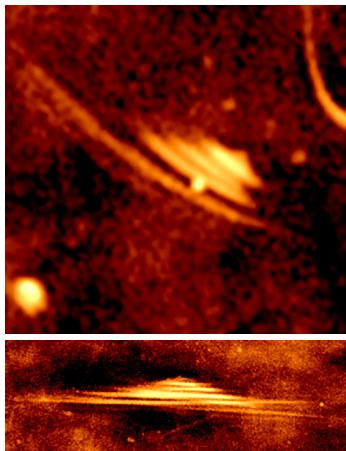
Haywood+ (Nature, 2019)

lateral radio profiles



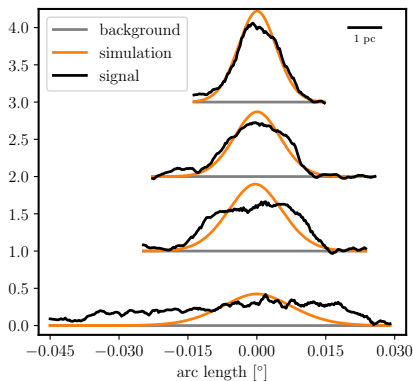
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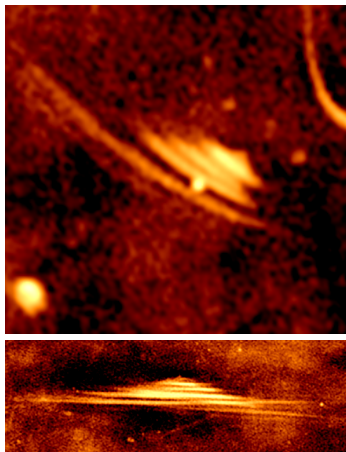
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CR diffusion



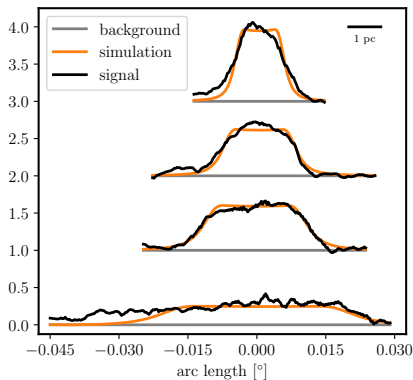
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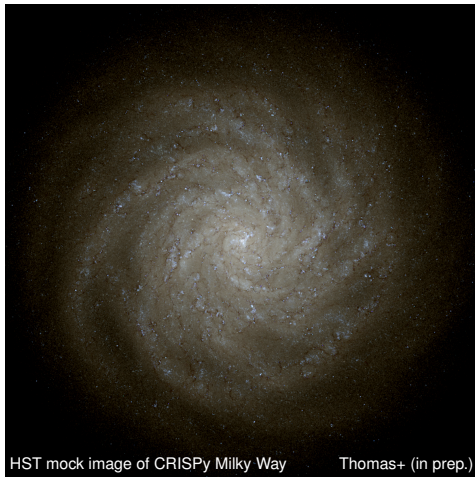
Haywood+ (Nature, 2019)

CR streaming and diffusion



Thomas, CP, Enßlin (2020)

Cosmic ray transport in galaxies

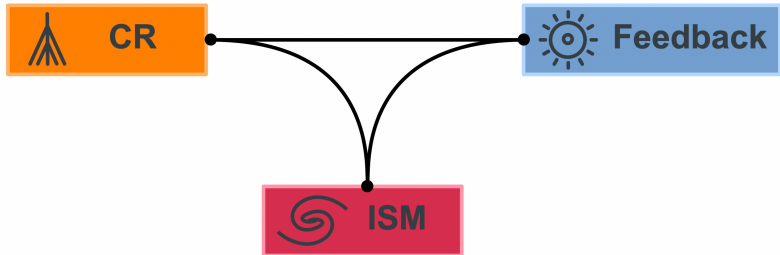


- CR transport in galaxies demands modeling **non-linear Landau damping (in warm/hot phase)** and **ion-neutral damping (in disk)**
- this requires resolving the **multi-phase structure of the ISM**
- development of CRISP framework (**Cosmic Rays and InterStellar Physics**, Thomas+ 2025)

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



- 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



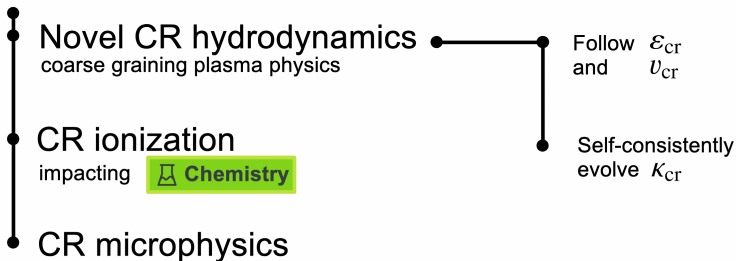
Feedback



ISM



CR

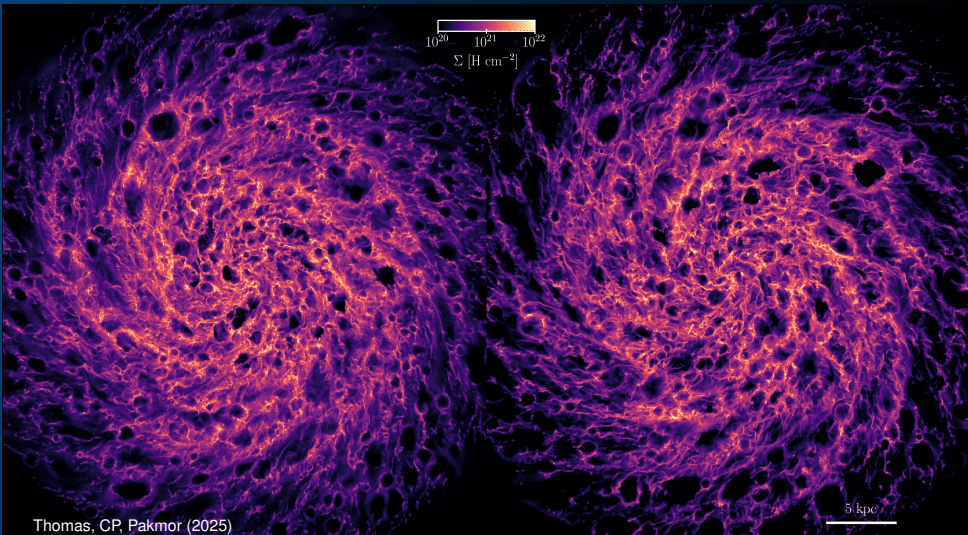


Thomas, CP, Pakmor (2025)

Cosmic ray transport
Galaxy formation

Multi-phase interstellar medium
Cosmic ray driven winds
Radio emission

Multi-phase ISM modeling



Thomas, CP, Pakmor (2025)

Christoph Pfrommer

Probing cosmic ray feedback through radio emission

Cosmic ray transport
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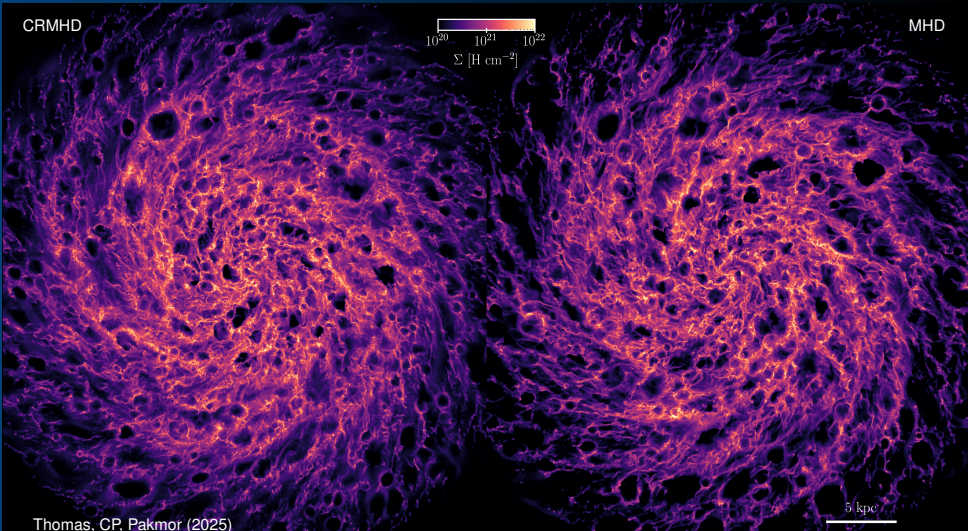
Multi-phase ISM modeling

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}]



Thomas, CP, Pakmor (2025)

Christoph Pfrommer

Probing cosmic ray feedback through radio emission

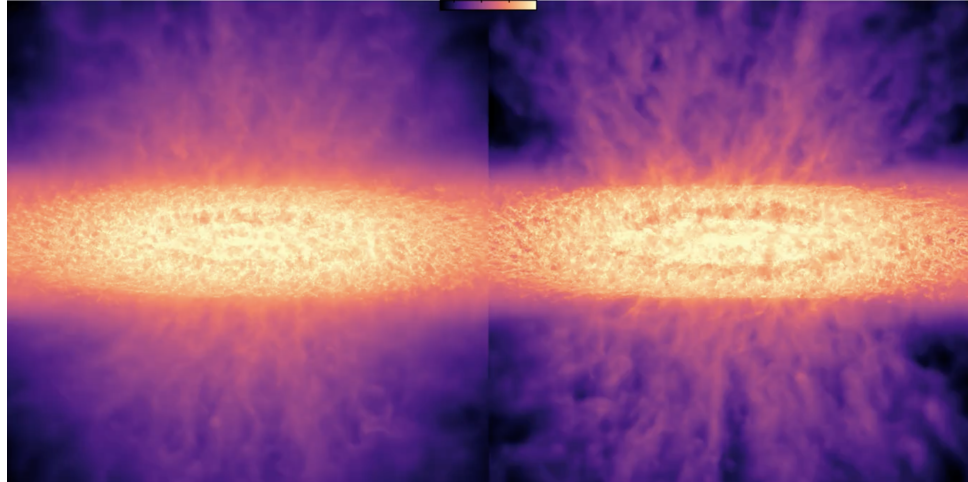
Simulated Milky Way: surface density

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

CRMHD

Σ [cm^{-2}]
 10^{19} 10^{20} 10^{21} 10^{22}

MHD



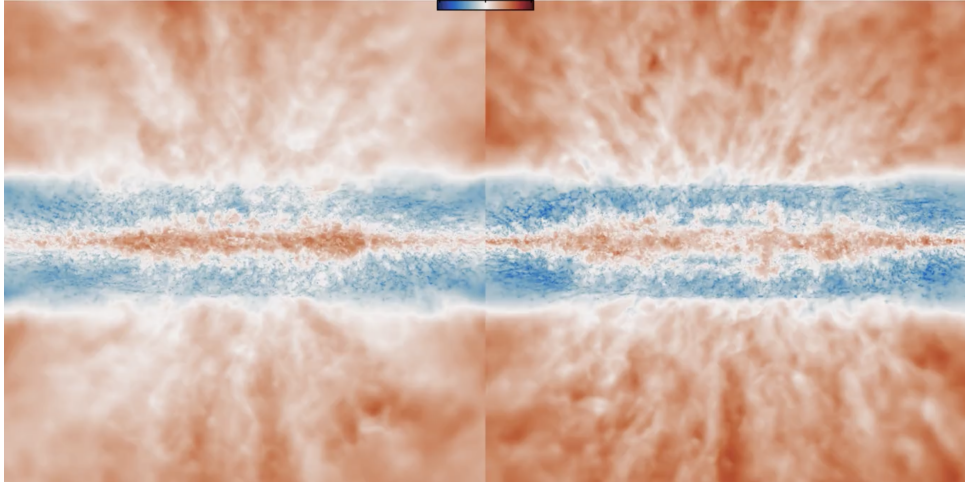
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter

CRMHD

10^2 T [K] 10^6

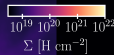
MHD



Multi-phase ISM modeling

Cosmic rays make galactic winds much denser

CRMHD



MHD

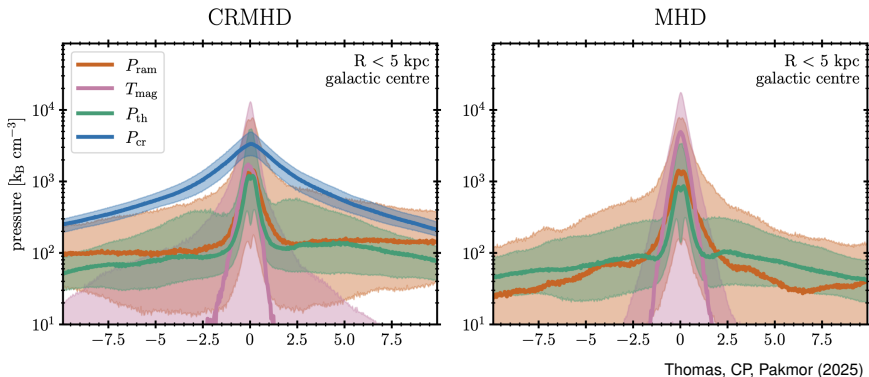
Thomas, CP, Pakmor (2025)

Christoph Pfrommer

5 kpc

Probing cosmic ray feedback through radio emission

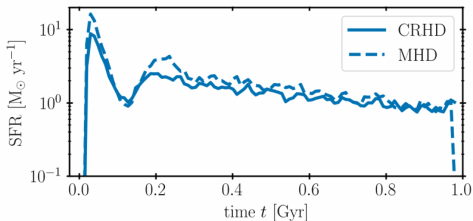
Cosmic ray driven wind: mechanism



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

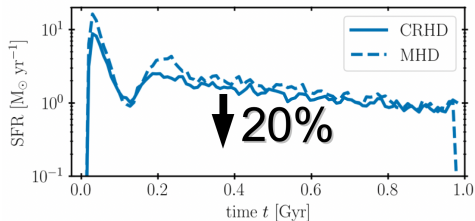
$$|\nabla P_{\text{cr}} + \nabla P_{\text{th}}| > \rho |\nabla \Phi|$$

Mass and energy loading factors



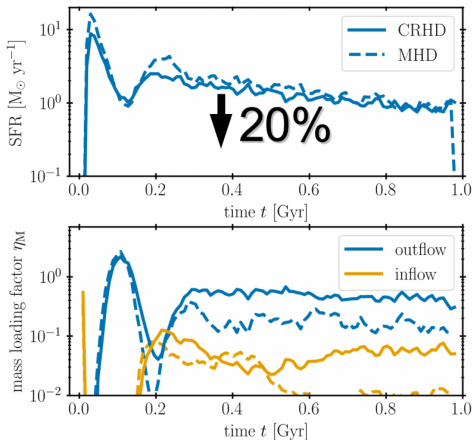
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



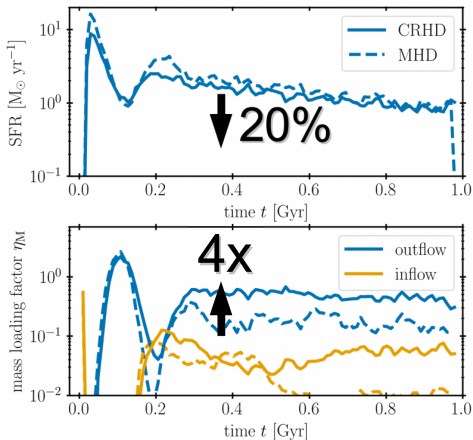
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



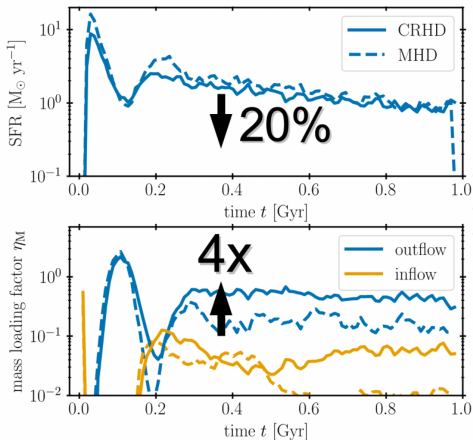
Thomas, CP, Pakmor (2025)

Mass and energy loading factors

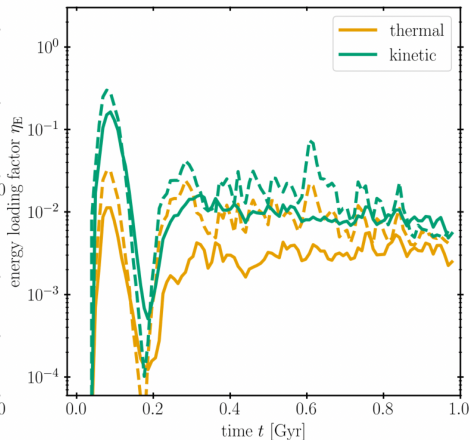


Thomas, CP, Pakmor (2025)

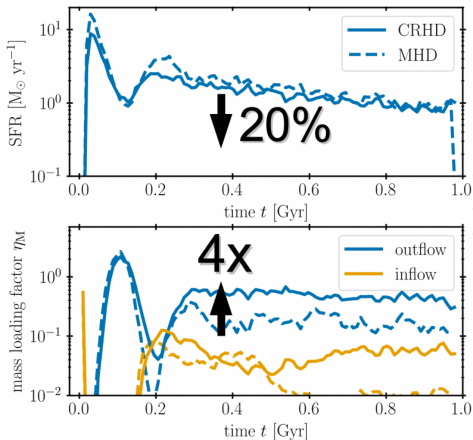
Mass and energy loading factors



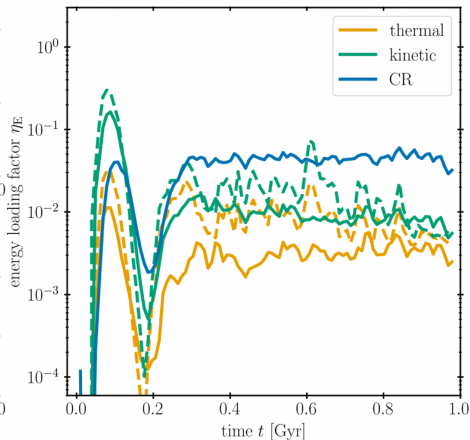
Thomas, CP, Pakmor (2025)



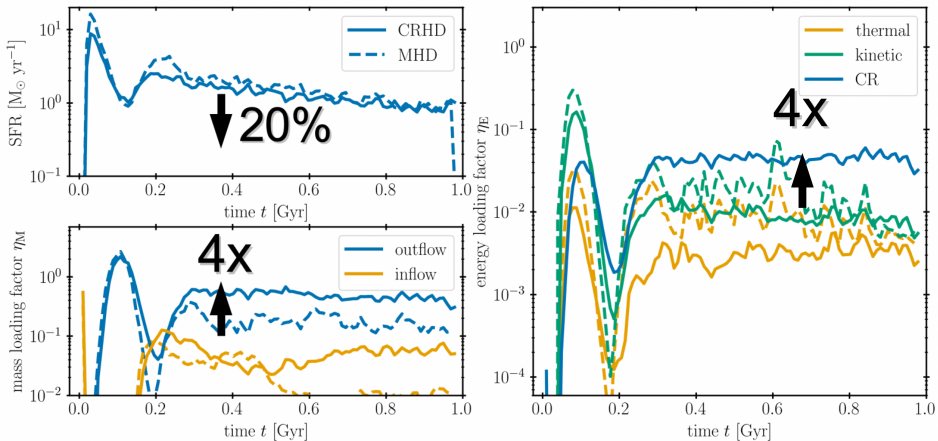
Mass and energy loading factors



Thomas, CP, Pakmor (2025)



Mass and energy loading factors



Thomas, CP, Pakmor (2025)

AIP

Steady-state cosmic ray spectra

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

$$\frac{N(E)}{\tau_{\text{esc}}} - \frac{d}{dE} [N(E)b(E)] = Q(E)$$

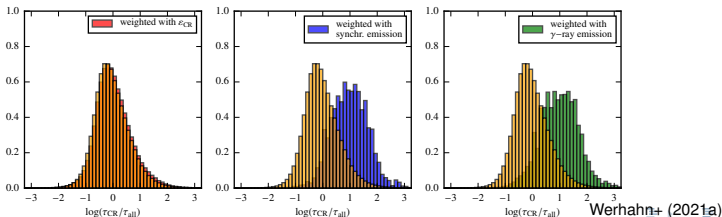
- **protons**: Coulomb, hadronic and escape losses (re-normalized to ε_{cr})
- **electrons**: Coulomb, bremsstr., IC, synchrotron and escape losses
 - primaries (re-normalized using $K_{\text{ep}} = 0.02$)
 - secondaries

Steady-state cosmic ray spectra

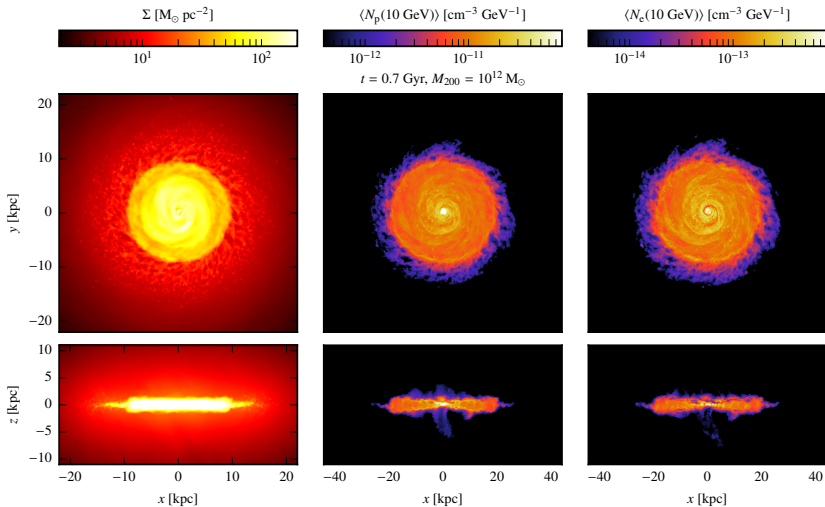
- solve the steady-state equation in every cell for each CR population:

$$\frac{N(E)}{\tau_{\text{esc}}} - \frac{d}{dE} [N(E)b(E)] = Q(E)$$

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

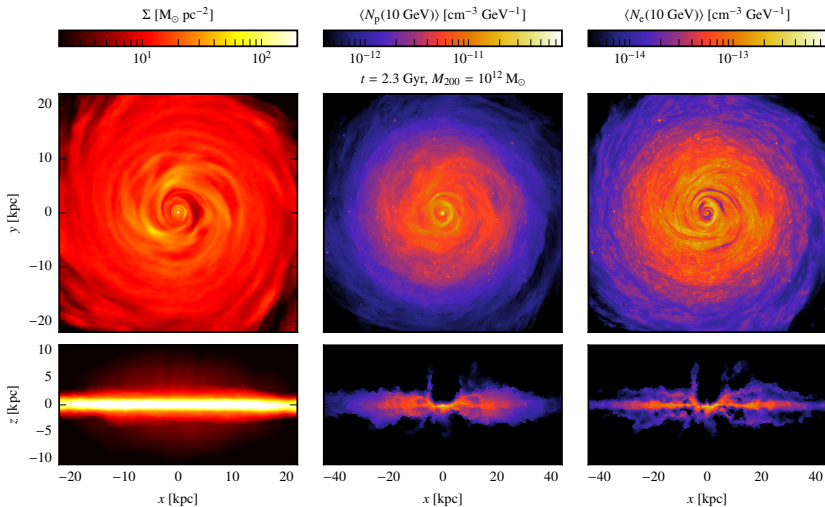


From a starburst galaxy to a Milky Way analogy



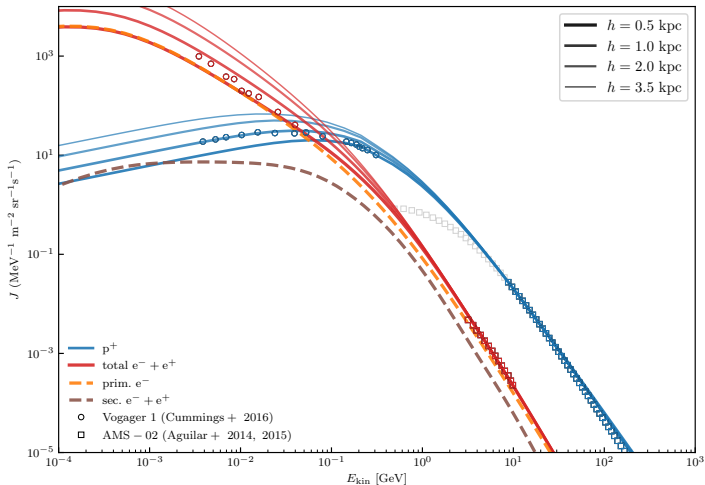
Werhahn, CP+ (2021a,b)

From a starburst galaxy to a Milky Way analogy



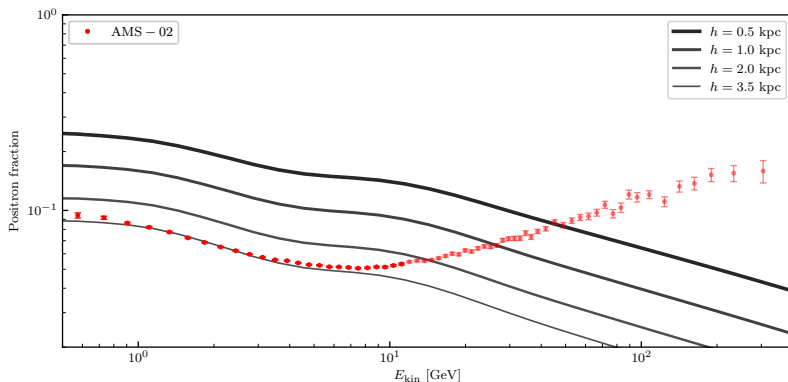
Werhahn, CP+ (2021a,b)

Comparing CR spectra to Voyager and AMS-02 data



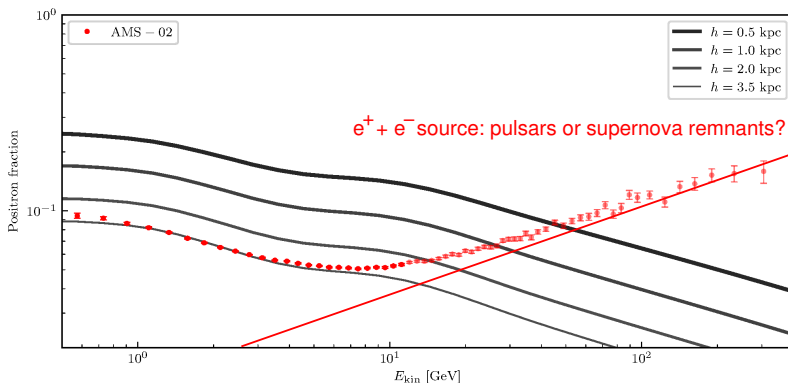
Werhahn, CP+ (2021a)

Comparing the positron fraction to AMS-02 data



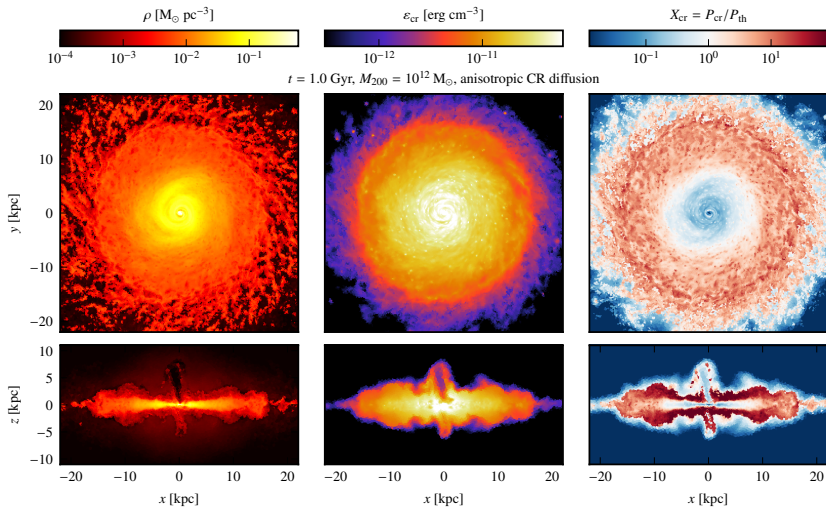
Werhahn, CP+ (2021a)

Comparing the positron fraction to AMS-02 data



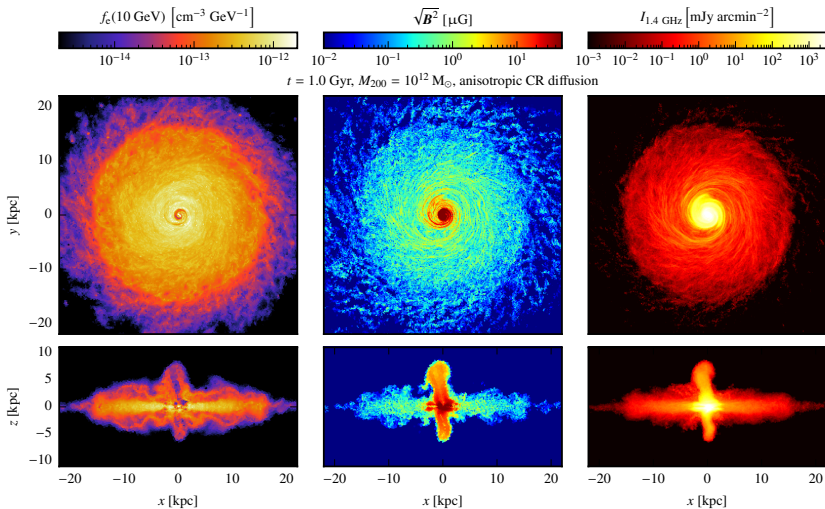
Werhahn, CP+ (2021a)

Galaxy simulation with cosmic ray-driven wind



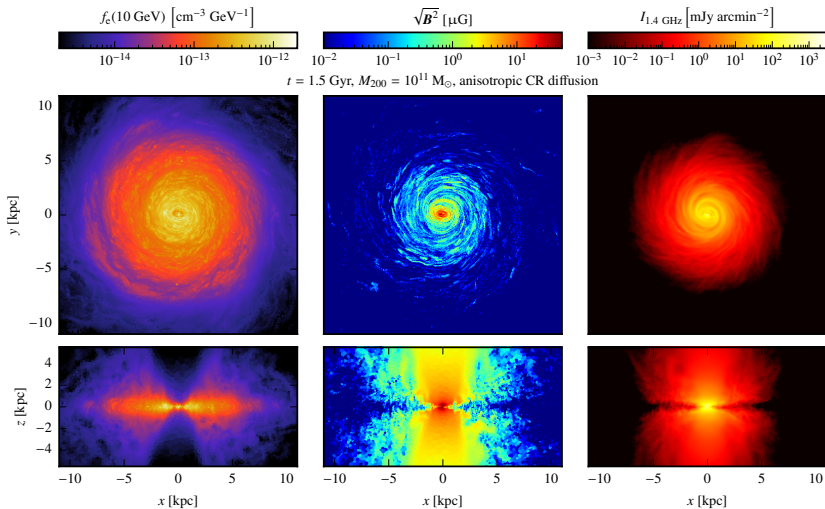
CP+ (2017)

Simulated radio emission: $10^{12} M_{\odot}$ halo



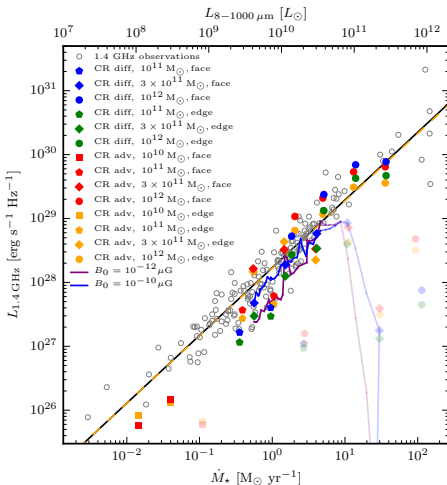
CP+ (2022)

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



Far infra-red – radio correlation

Universal conversion: star formation \rightarrow cosmic rays \rightarrow radio

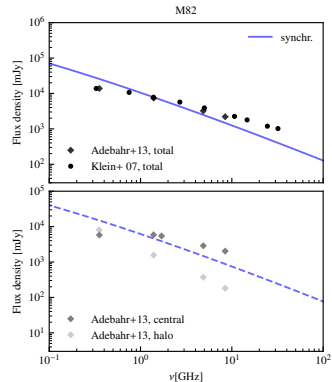
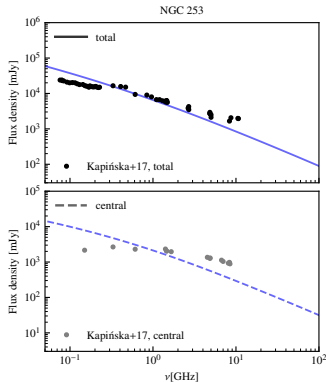


CP+ (2022)



AIP

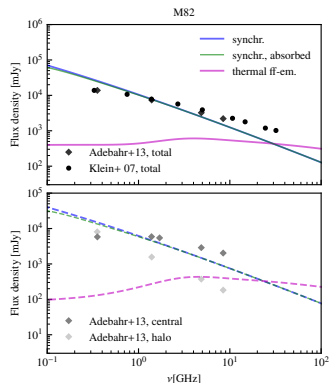
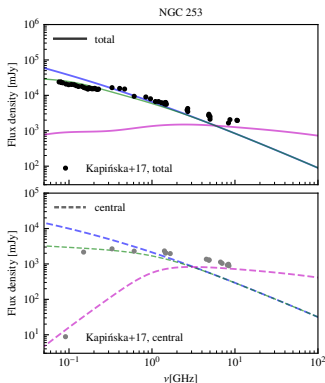
Radio-ray spectra of starburst galaxies



Werhahn, CP+ (2021c)

- **synchrotron spectra too steep** (cooling + diffusion losses)

Radio-ray spectra of starburst galaxies

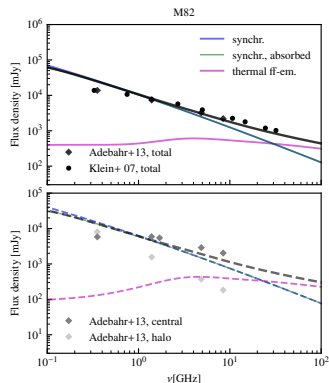
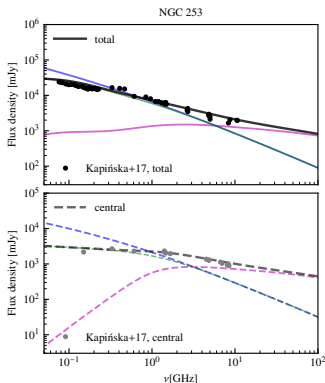


Werhahn, CP+ (2021c)

- **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

Conclusions

Plasma instabilities and CR transport:

- **Mechanism of CR-driven plasma-instabilities revised:** 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

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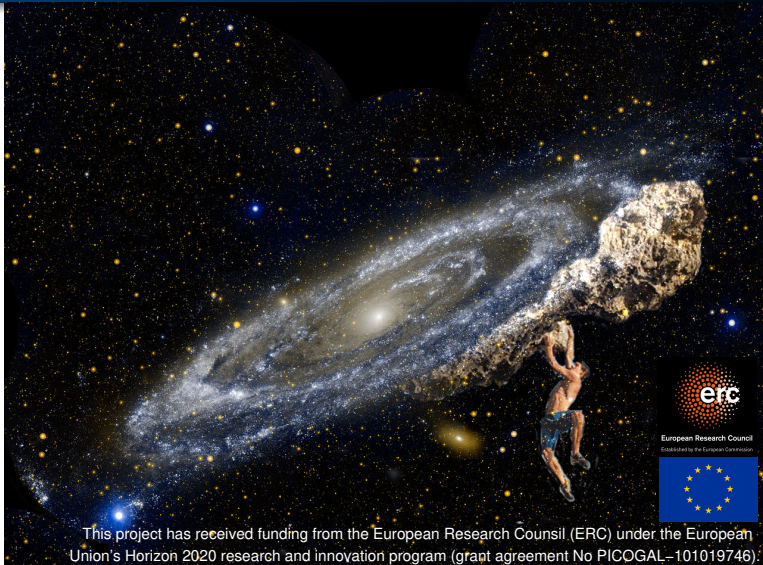
CR feedback in galaxy formation:

- **CR feedback mildly suppresses star formation** because of strong ion-neutral damping in disk, which weakens CR coupling
- **CR feedback drives powerful galactic winds**
- **global $L_{\text{FIR}} - L_{\text{radio}}$ reproduced for galaxies with saturated magnetic fields**, scatter due to viewing angle and CR transport

Cosmic ray transport
Galaxy formation

Multi-phase interstellar medium
Cosmic ray driven winds
Radio emission

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

Probing cosmic ray feedback through radio emission



Literature for the talk – 1

CR-driven plasma instabilities:

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- Shalaby, Lemmerz, Thomas, C. Pfrommer, *The mechanism of efficient electron acceleration at parallel non-relativistic shocks*, 2022, ApJ, 932, 86.
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Literature for the talk – 2

CR hydrodynamics and CR transport:

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- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays*, 2019, MNRAS, 485, 2977.
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- Thomas, Pfrommer, Pakmor, *Why are thermally- and cosmic ray-driven galactic winds fundamentally different?* 2025, A&A, 698, A104.

Literature for the talk – 3

Cosmic rays and non-thermal emission in galaxies:

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