# *Cosmic ray transport and galaxy simulations*

Christoph Pfrommer[1]

in collaboration with

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Perrone,[1] Shalaby,[6] **Thomas,**[1] **Werhahn,**[7] Whittingham[1]
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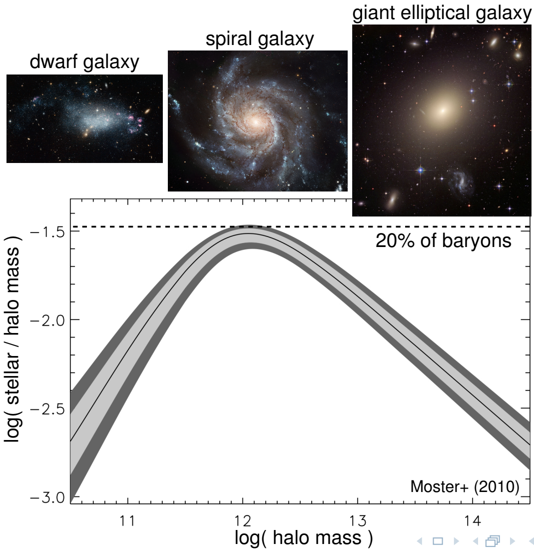
[1]AIP, [2]Michigan, [3]NBI, [4]Heidelberg, [5]Wisconsin, [6]Perimeter Institute, [7]MPA

*Milky Way Atlas Meeting,* Crete 2025

# Puzzles in galaxy formation

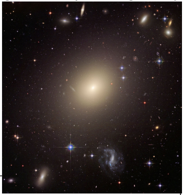


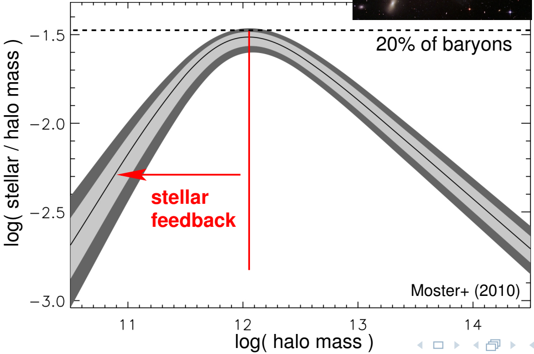
# Puzzles in galaxy formation

dwarf galaxy

spiral galaxy

giant elliptical galaxy





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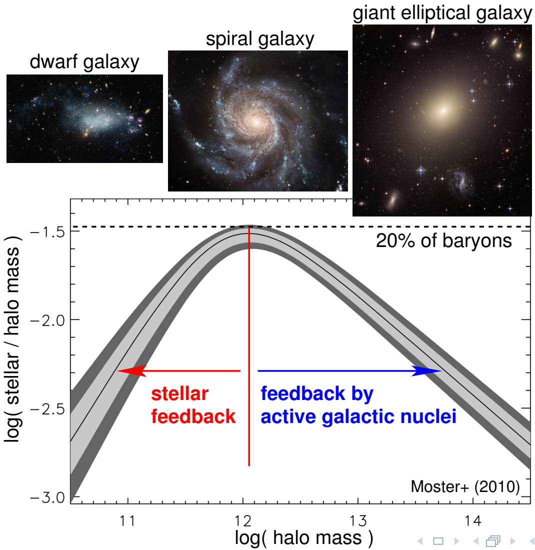
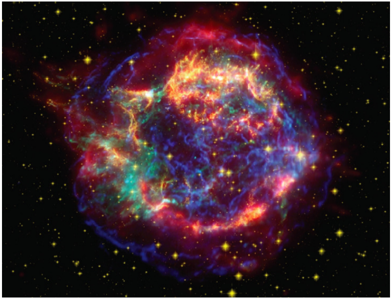


# Feedback by galactic winds



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

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# Feedback by galactic winds

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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

AIP

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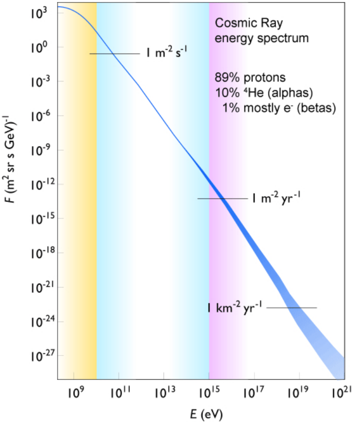
- energy density of CRs, magnetic fields, and ISM turbulence all similar
  $\Rightarrow$ important feedback agent

# 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

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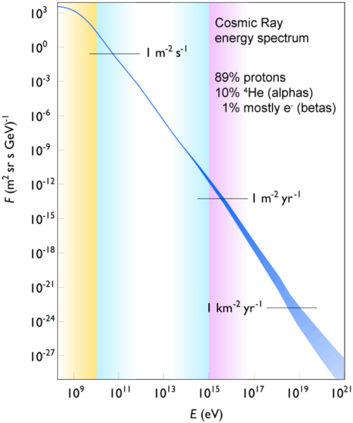


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- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays is dominated by GeV energies
  $\Rightarrow$ grey approach sufficient for feedback studies (Girichidis+ 2024)

AIP

# Review on cosmic ray feedback

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

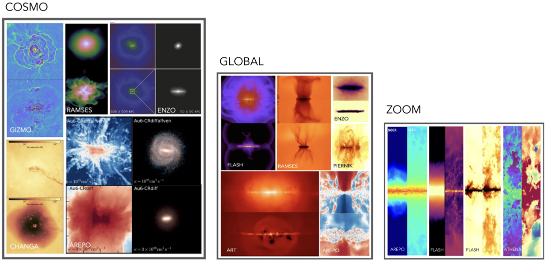
REVIEW ARTICLE

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]**

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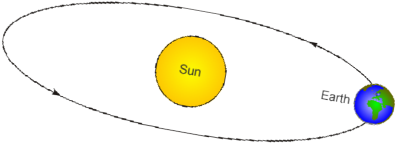
# Cosmic ray transport: an extreme multi-scale problem

Milky Way-like galaxy:

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




gyro-orbit of GeV CR:

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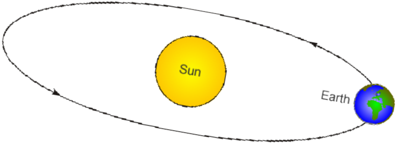


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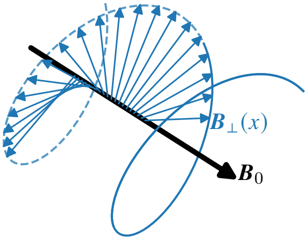
⇒ **link kinetic plasma physics to macroscopic MHD models on galactic scales!**

Zweibel (2017), Thomas & CP (2019)

# What is gyro resonance?

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




Lemmerz+ (2025)

# What is gyro resonance?

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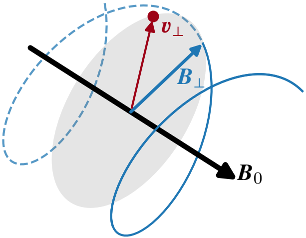
cosmic ray: $v_{||}$ movement along $\boldsymbol{B}_0$

$\Omega_{\mathrm{cr}}$ gyration frequency

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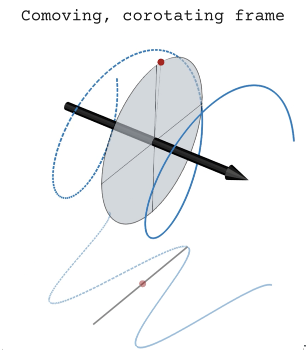


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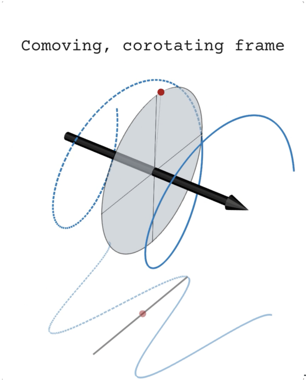
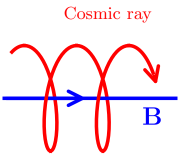
**Resonant** wave appears **static** to CR!




test particle without interactions!

Lemmerz+ (2025)

# Interactions of CRs and magnetic fields




sketch: Jacob & CP

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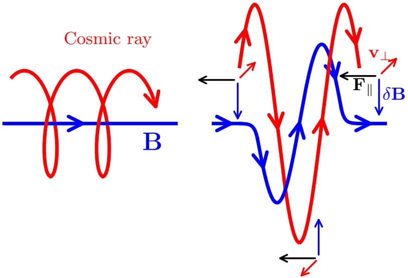


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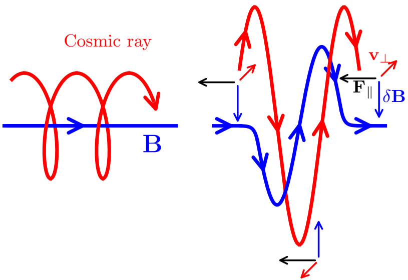


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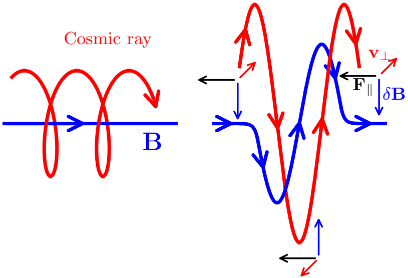


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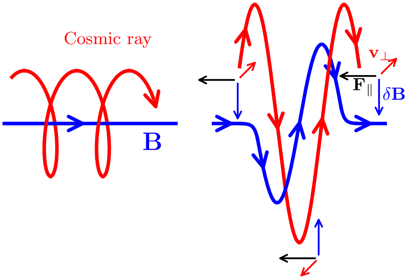


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- work out **Lorentz forces on CRs** in wave frame: $\boldsymbol{F}_\mathrm{L} = q\frac{\boldsymbol{v} \times \boldsymbol{B}}{c}$
- Lorentz force depends on **relative phase of CR gyro orbit and wave:**
  - sketch: decelerating Lorentz force along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

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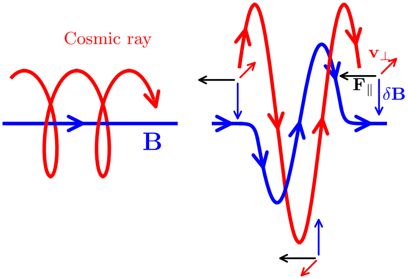


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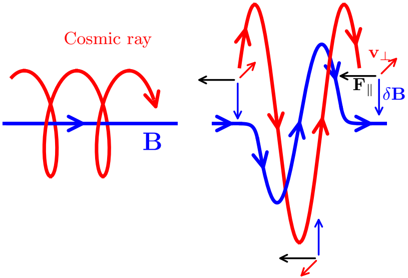


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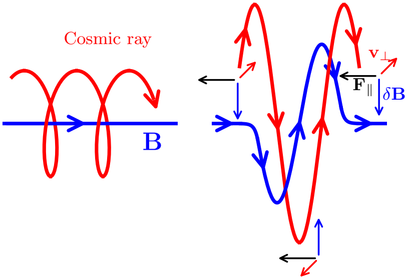


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- this increases the CR pitch angle cosine $\mu = \cos\theta = \frac{\boldsymbol{B}}{|\boldsymbol{B}|} \cdot \frac{\boldsymbol{p}}{|\boldsymbol{p}|}$

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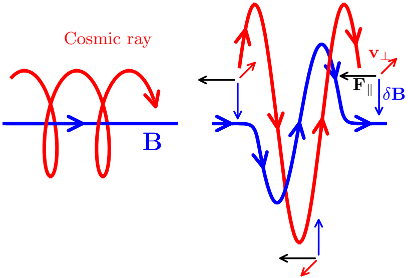


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$$L_\parallel = r_\mathrm{g} = \frac{p_\perp c}{qB}$$

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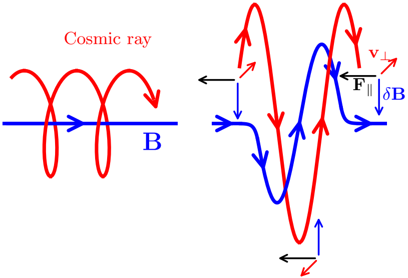


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Doppler-shifted MHD frequency is a multiple $n$ of the CR gyro frequency

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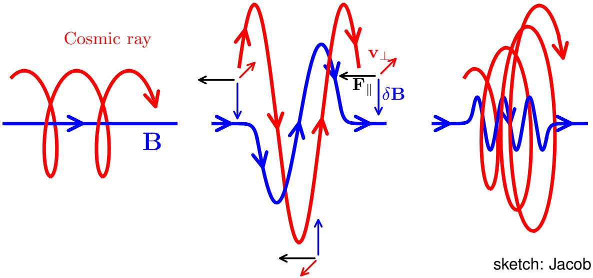


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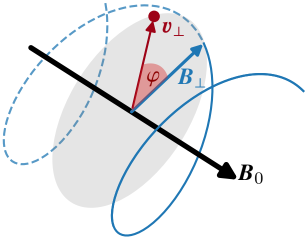
# The mechanism of CR-driven instabilities

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

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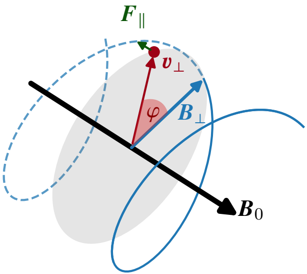

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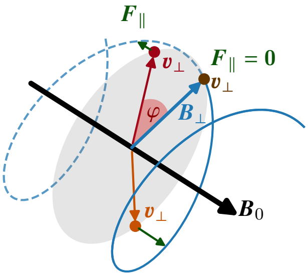

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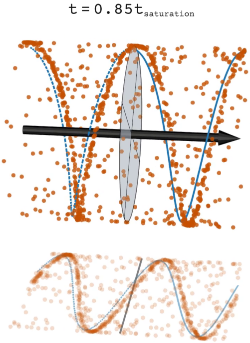


fluid-PIC simulation (Lemmerz+ 2025)

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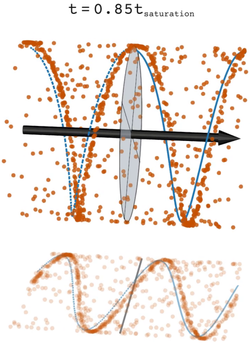
- CR trapping in Lorentz force potential saturates instability

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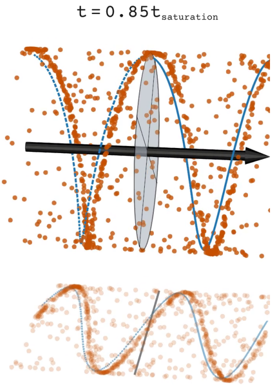
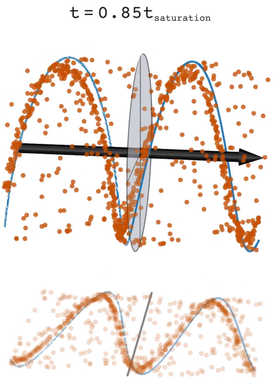
# Growth of forward and backward moving waves




forward Alfvén,
Whistler

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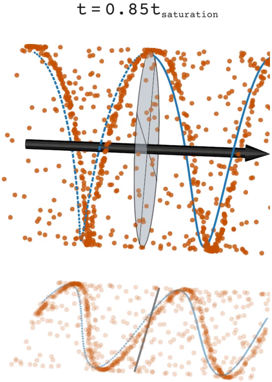


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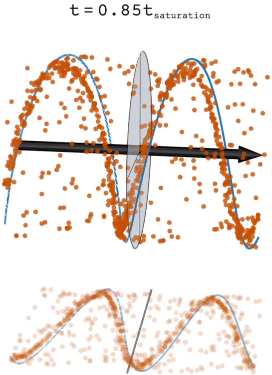


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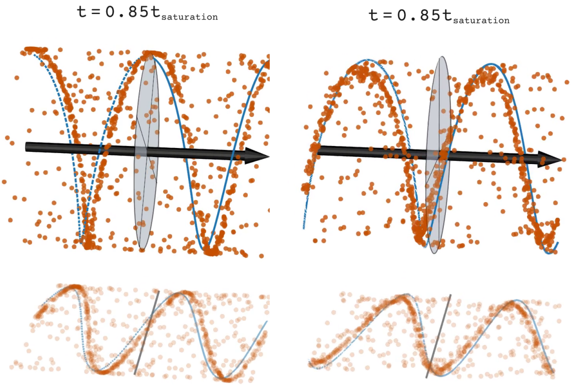


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***bunching theory:***

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- biased CR scattering, favors wave growth

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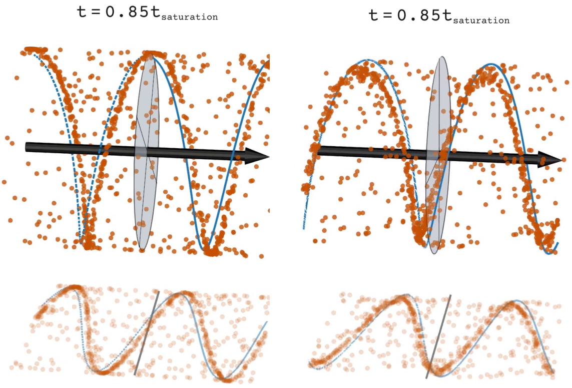


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***traditional, quasilinear theory:***

- assumes uniform $\varphi$
- 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
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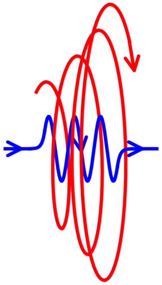
  - wave damping: transfer of CR energy and momentum to the thermal gas



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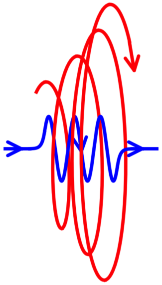

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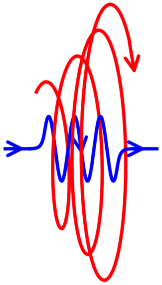
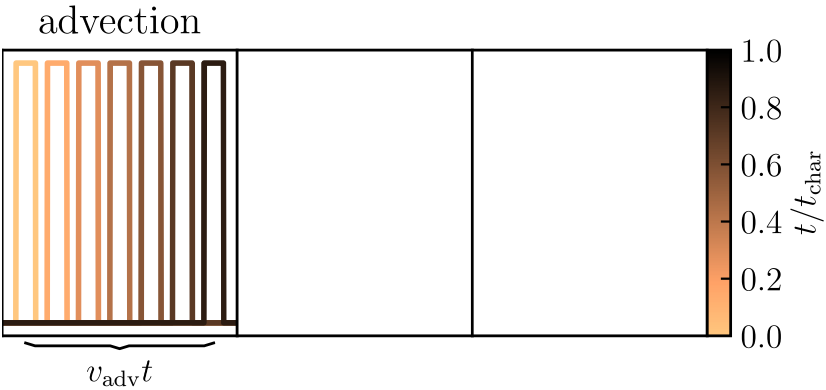


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

# Modes of CR propagation




Thomas, CP, Enßlin (2020)

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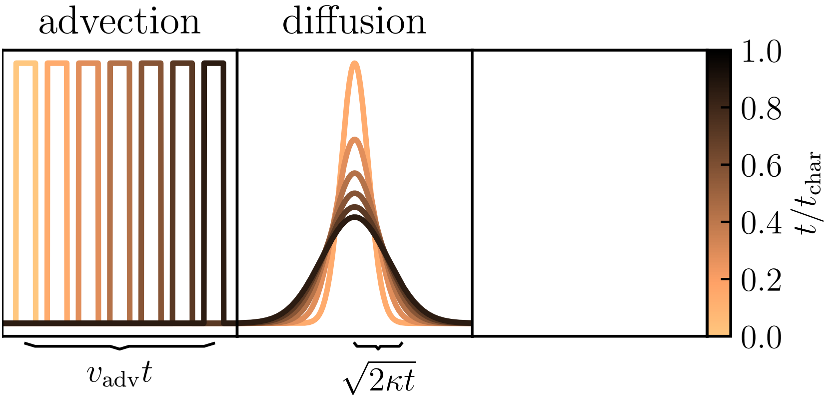


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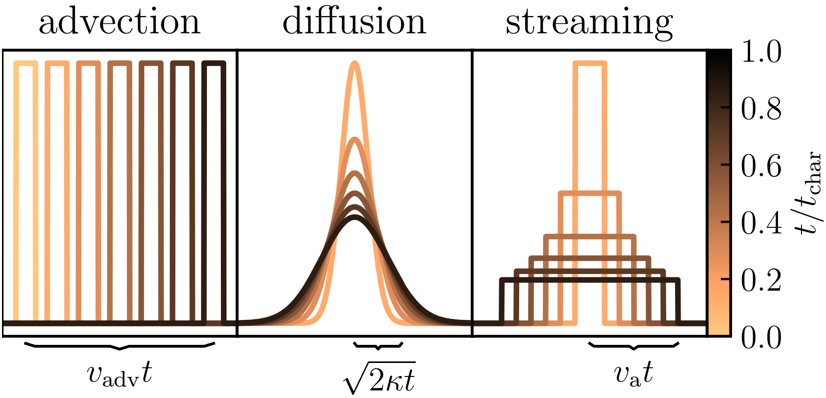


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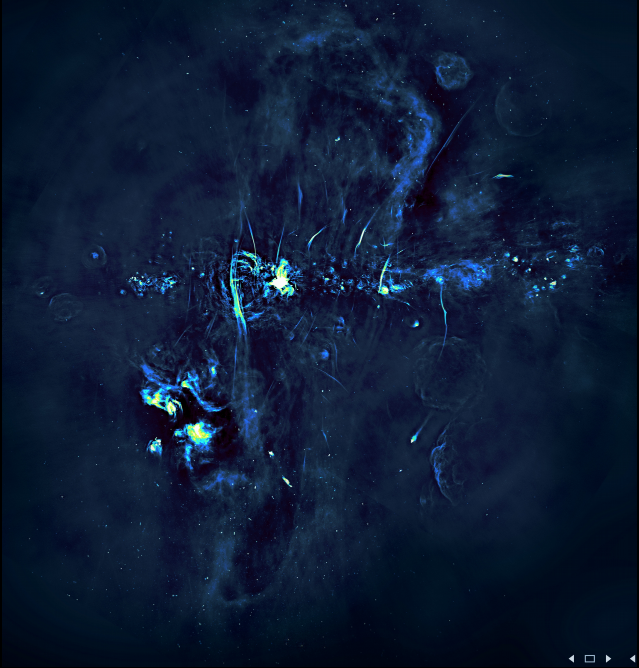
# MeerKAT image of the Galactic Center

Haywood+ (Nature, 2019)



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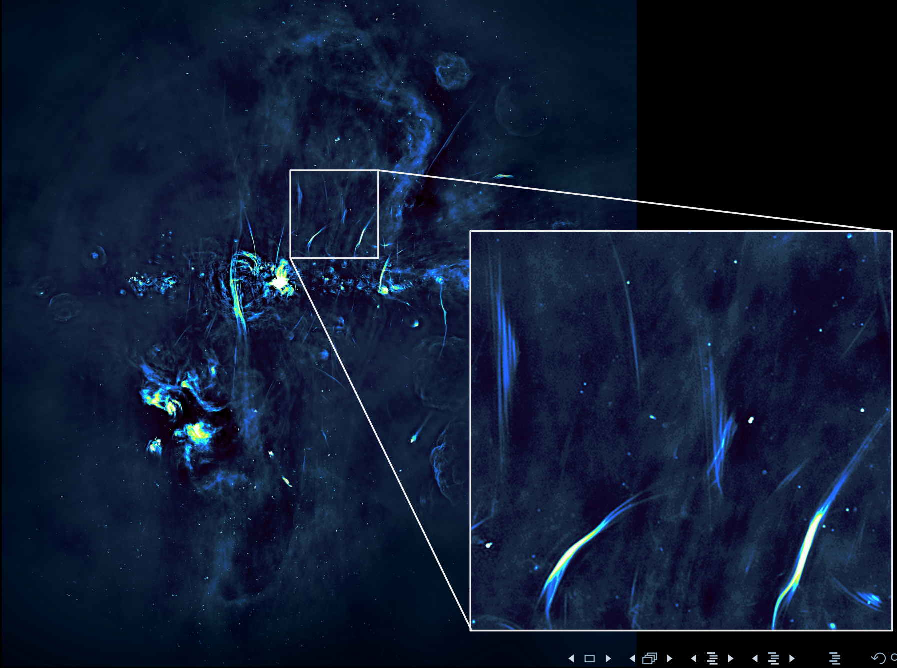
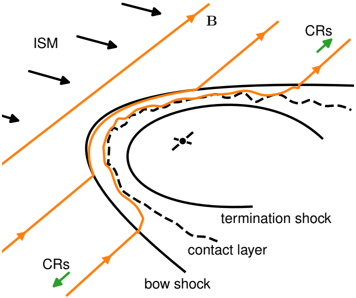


# Radio synchrotron harps: the model

shock acceleration scenario




Thomas, CP, Enßlin (2020)

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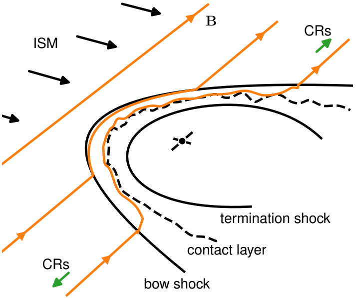
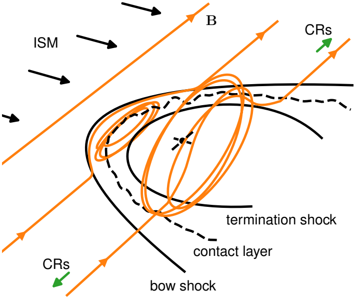



magnetic reconnection at pulsar wind




Thomas, CP, Enßlin (2020)

# Radio synchrotron harps: the model

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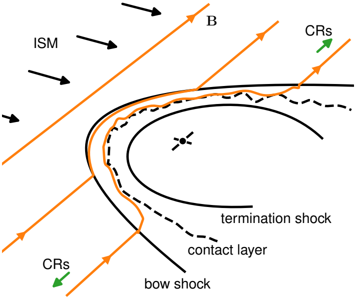
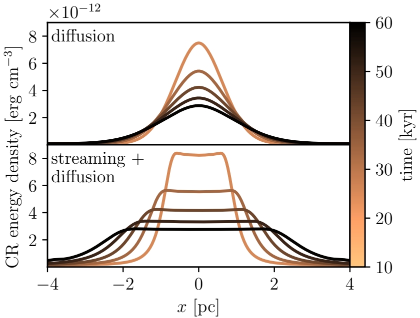
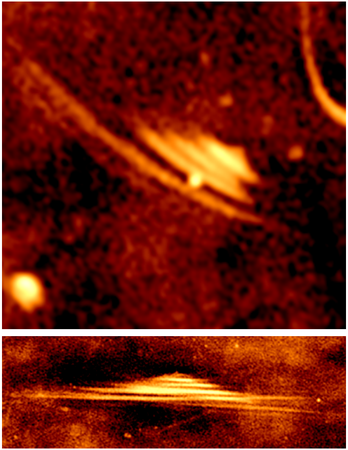



Thomas, CP, Enßlin (2020)

CR diffusion vs. streaming + diffusion



# Radio synchrotron harps: testing CR propagation



Haywood+ (Nature, 2019)

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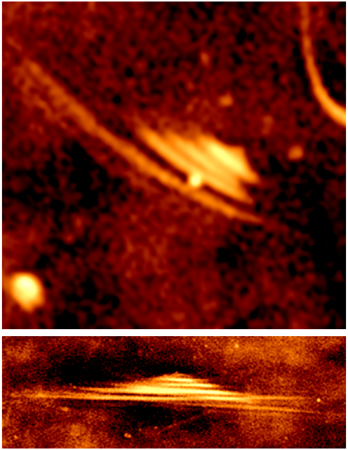
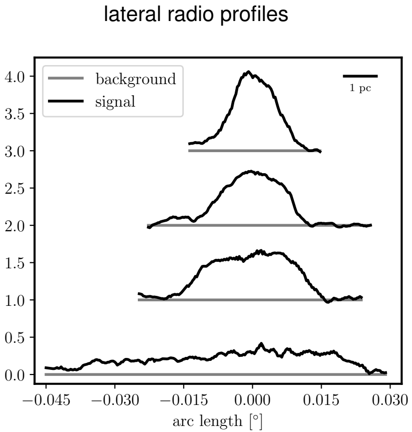


Haywood+ (Nature, 2019)




Thomas, CP, Enßlin (2020)

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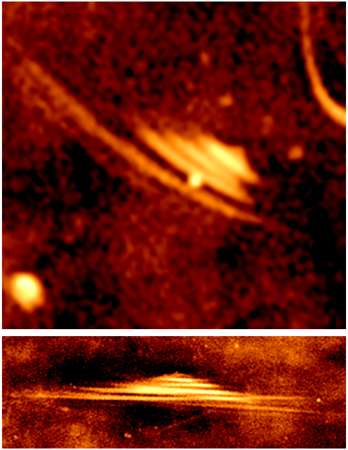
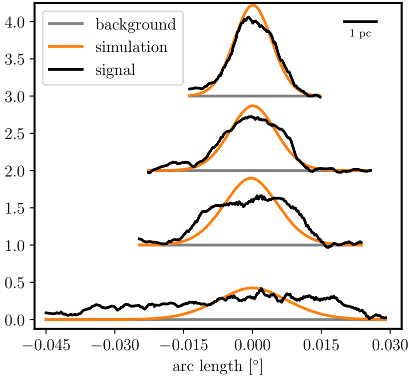


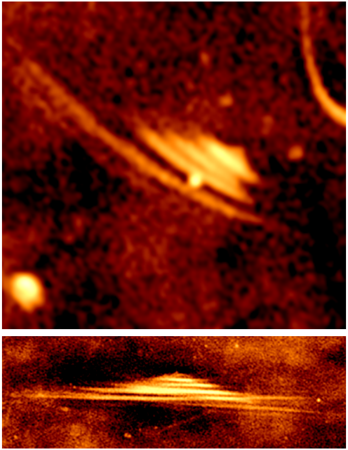
Haywood+ (Nature, 2019)

CR diffusion



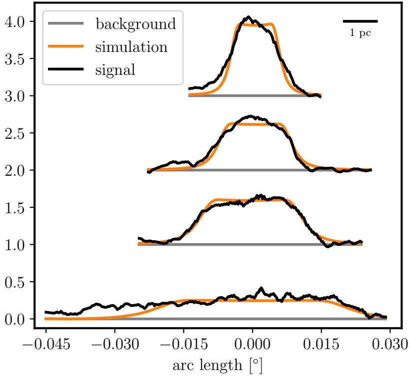

Thomas, CP, Enßlin (2020)

# Radio synchrotron harps: testing CR propagation



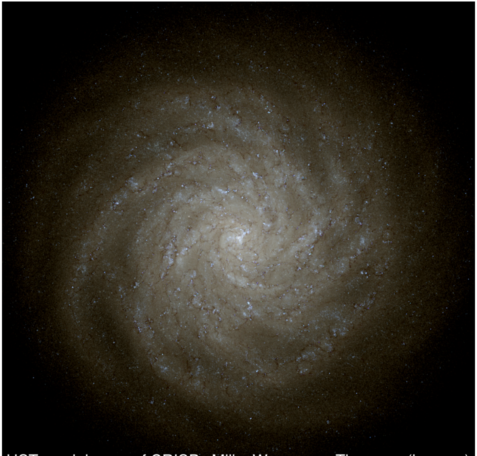
Haywood+ (Nature, 2019)

CR streaming and diffusion




Thomas, CP, Enßlin (2020)

# Cosmic ray transport in galaxies



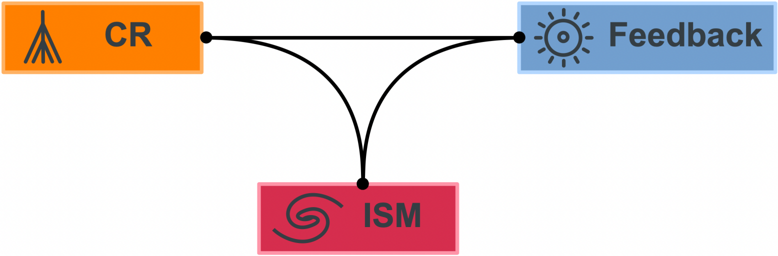
HST mock image of CRISPy Milky Way Thomas+ (in prep.)

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

# Multi-phase ISM modeling

## CRISP framework

**C**osmic **R**ays and **I**nter**S**tellar **P**hysics




Thomas, CP, Pakmor (2025)

# Multi-phase ISM modeling

## CRISP framework

**C**osmic **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

**C**osmic **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

**C**osmic **R**ays and **I**nter**S**tellar **P**hysics

**Feedback**

**ISM**

**CR**

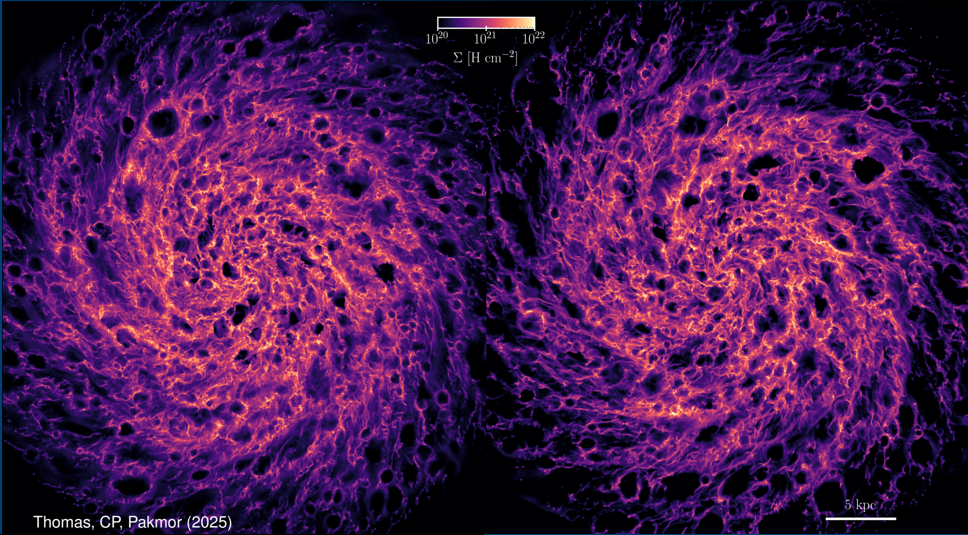
- Novel CR hydrodynamics
  coarse graining plasma physics
- CR ionization
  impacting **Chemistry**
- CR microphysics

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

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

Thomas, CP, Pakmor (2025)

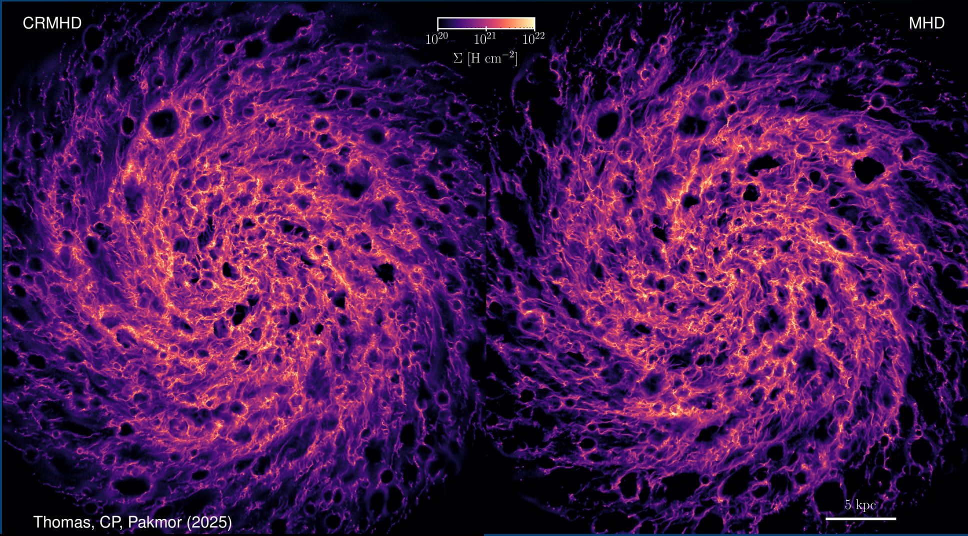
# Multi-phase ISM modeling




Thomas, CP, Pakmor (2025)

# Multi-phase ISM modeling

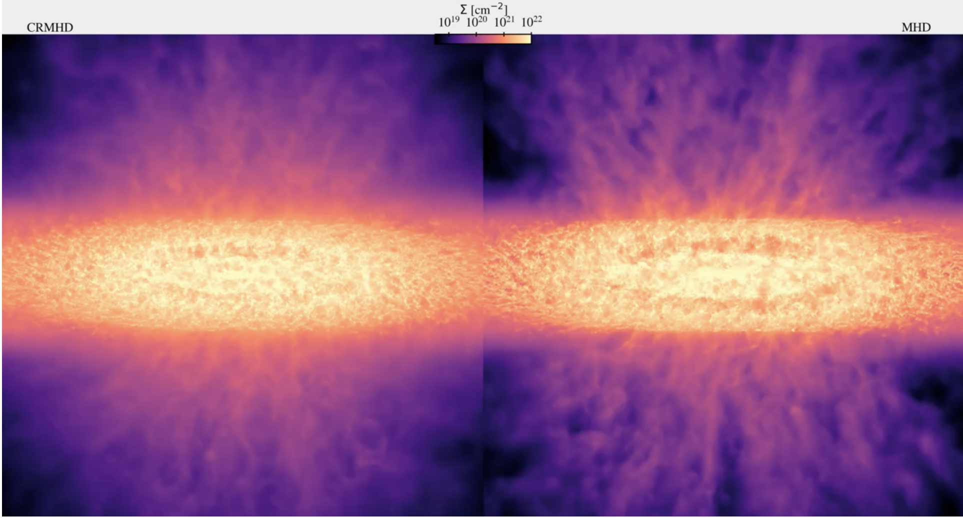
## Cosmic rays barely affect the ISM because ion-neutral damping erases Alfvén waves




Thomas, CP, Pakmor (2025)

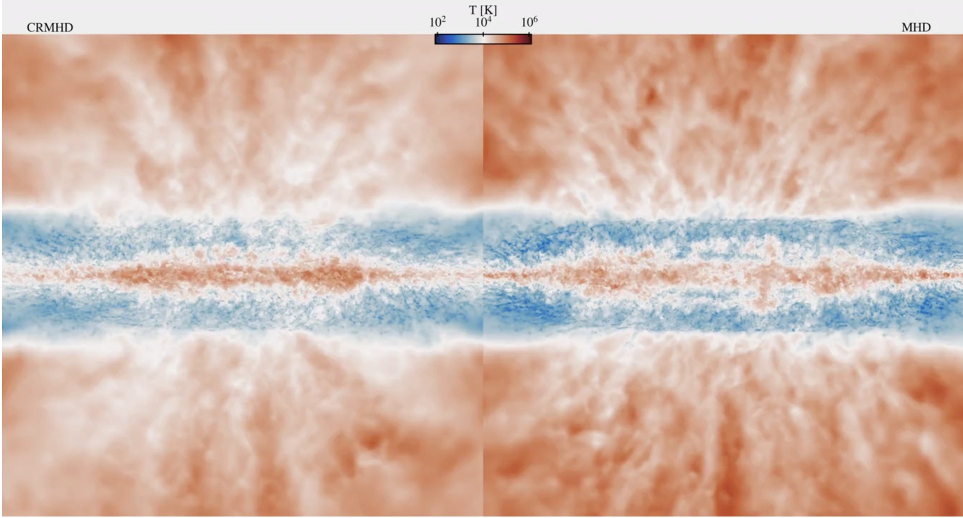
# Simulated Milky Way: surface density

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



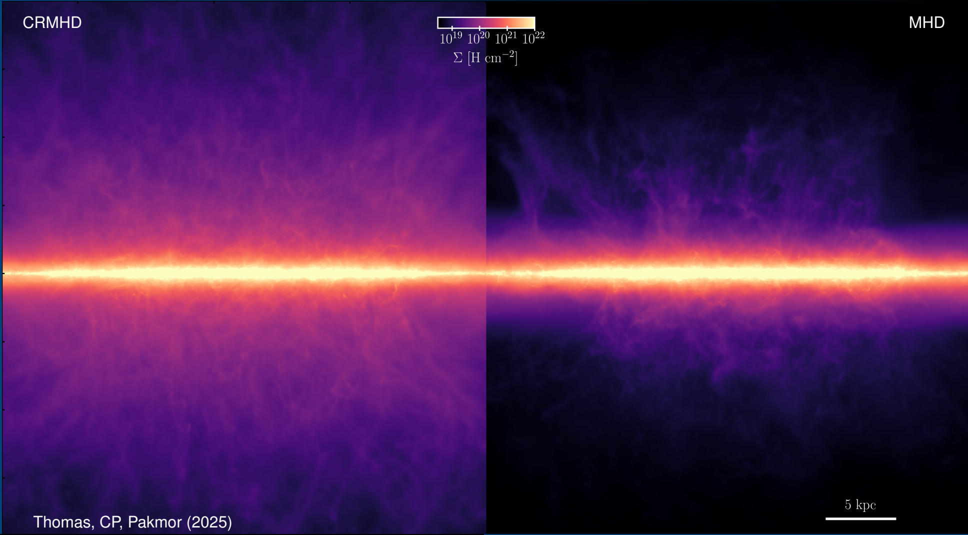
# Simulated Milky Way: temperature

## Galactic winds without cosmic rays are much hotter



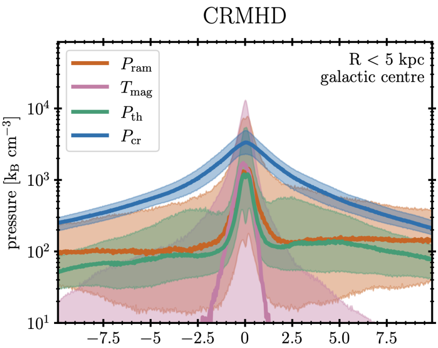
# Multi-phase ISM modeling

## Cosmic rays make galactic winds much denser




Thomas, CP, Pakmor (2025)

# Cosmic ray driven wind: mechanism

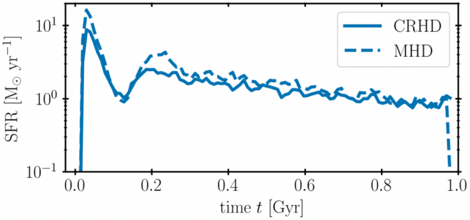



Thomas, CP, Pakmor (2025)

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

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

# Mass and energy loading factors




Thomas, CP, Pakmor (2025)

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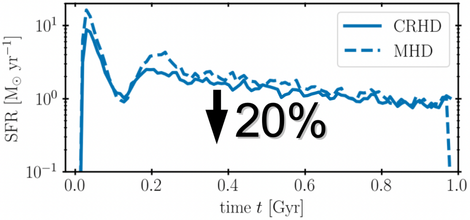


Thomas, CP, Pakmor (2025)

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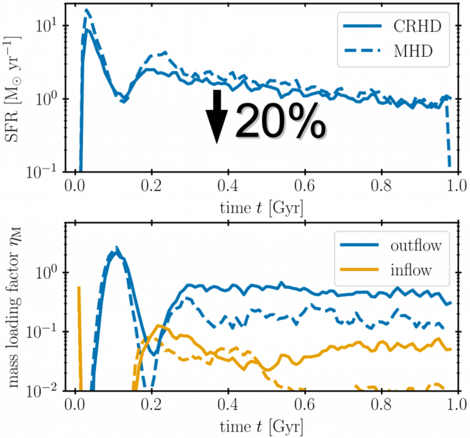


Thomas, CP, Pakmor (2025)

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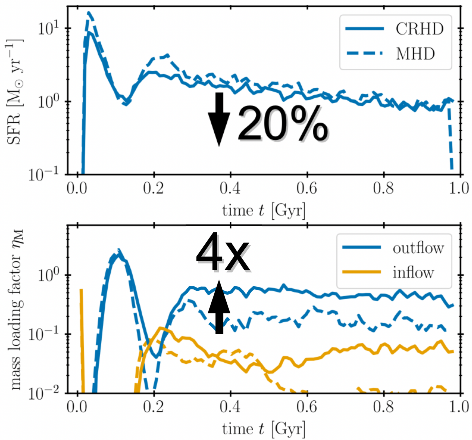


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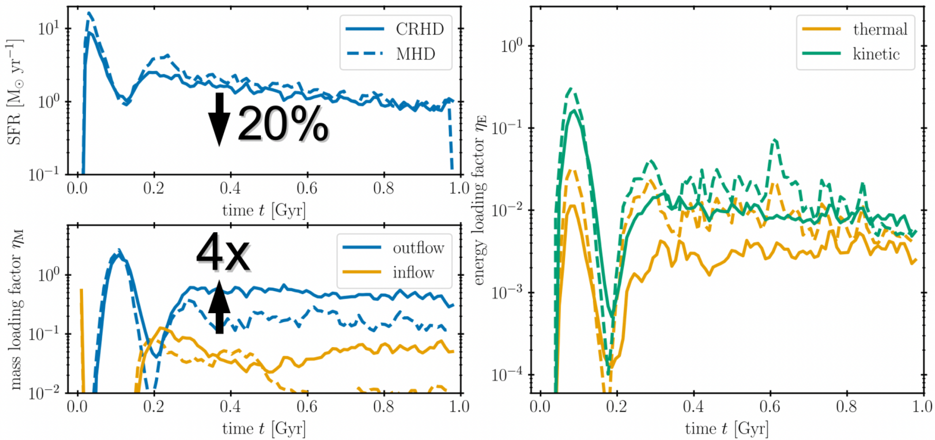


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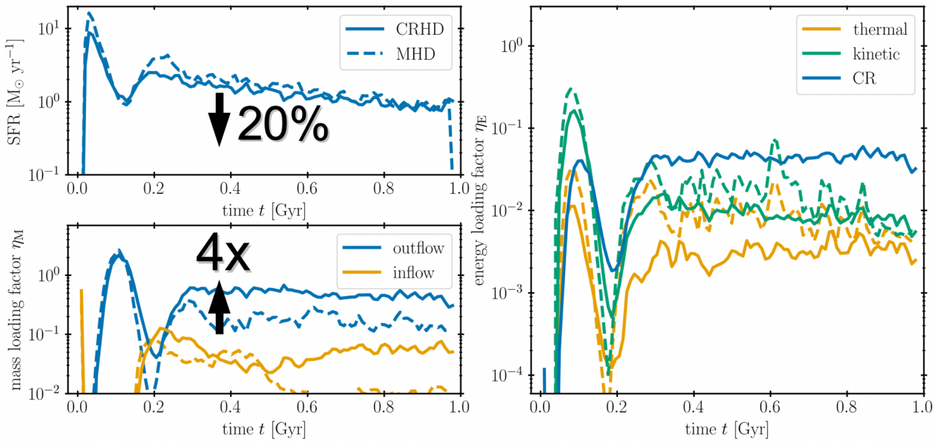


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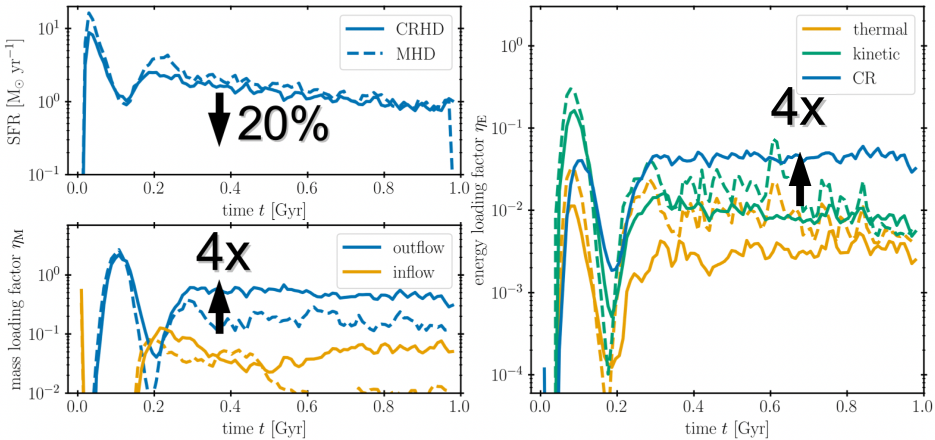
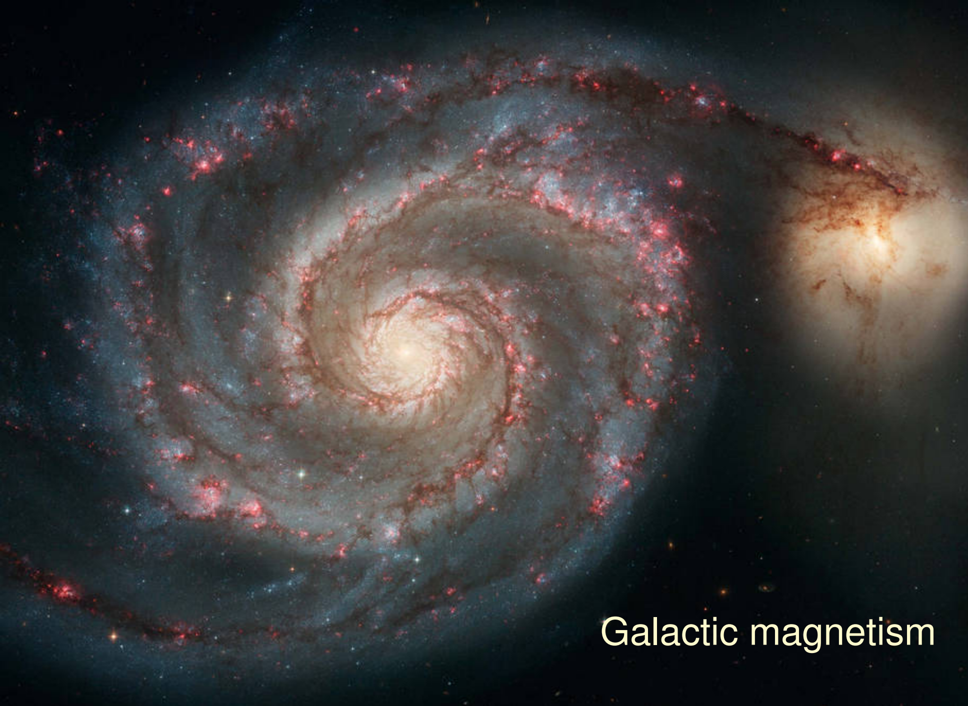



Thomas, CP, Pakmor (2025)



# 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

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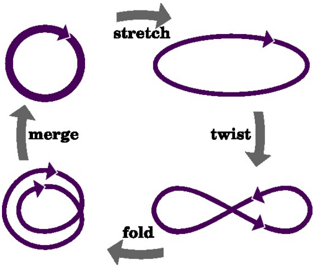


AIP

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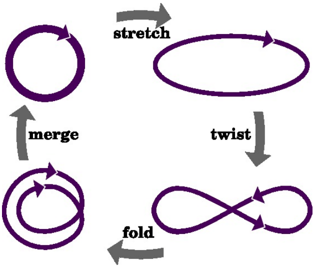
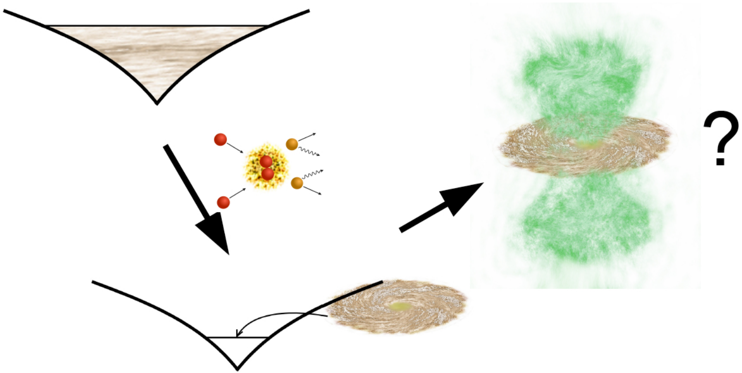
- ***Saturation.*** Field growth stops at a sizeable fraction of the turbulent energy when magnetic forces become strong enough to resist the stretching and folding motions



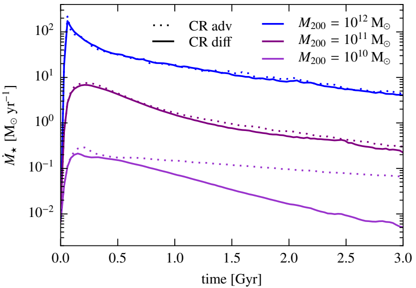
# Galactic magnetic dynamo




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: $\{10^{10}, 10^{11}, 3\times10^{11}, 10^{12}\}\ \mathrm{M}_\odot$

# Time evolution of SFR and energy densities




CP+ (2022)

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

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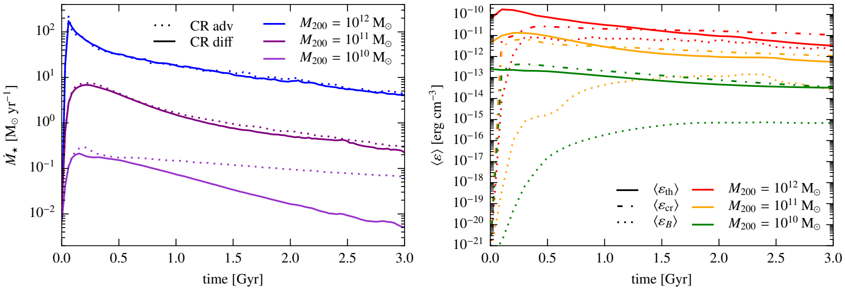
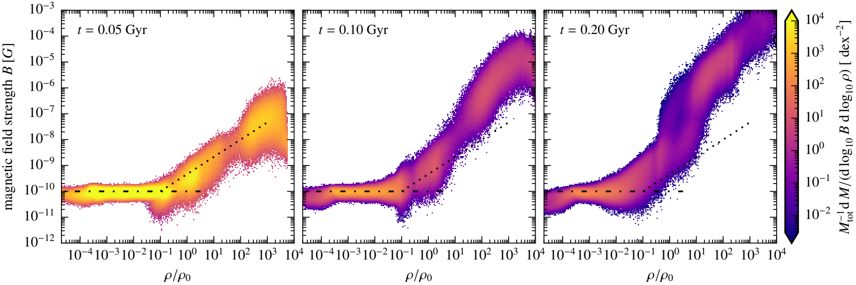



CP+ (2022)

- 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

# Identifying different growth phases




CP+ (2022)

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

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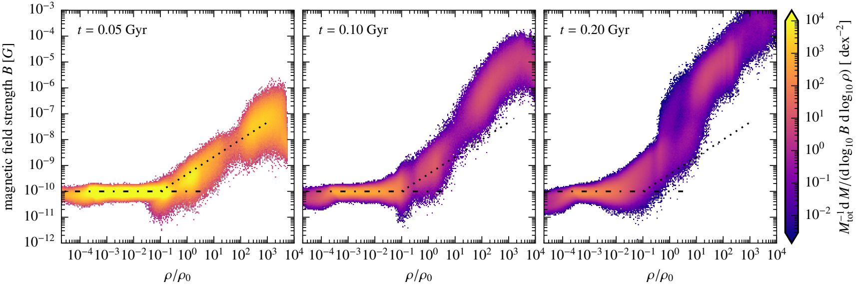


CP+ (2022)

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- *2nd phase:* additional growth at high density $\rho$ with small dynamical times $t_{\text{dyn}} \sim (G\rho)^{-1/2}$

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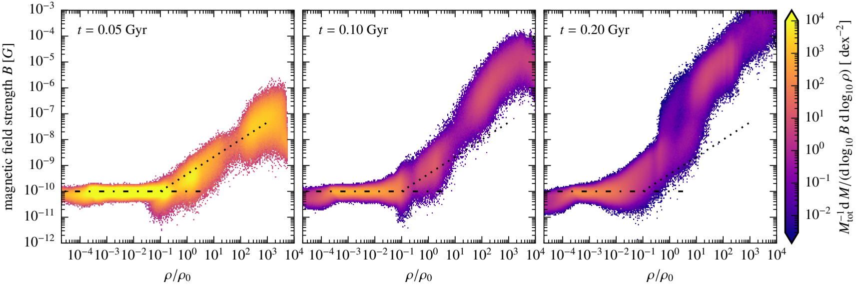


CP+ (2022)

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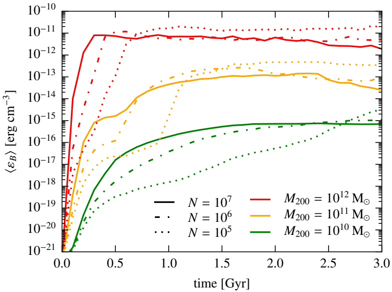
- *3rd phase:* growth migrates to lower $\rho$ on larger scales $\propto \rho^{-1/3}$

AIP

# Studying growth rate with numerical resolution




CP+ (2022)

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

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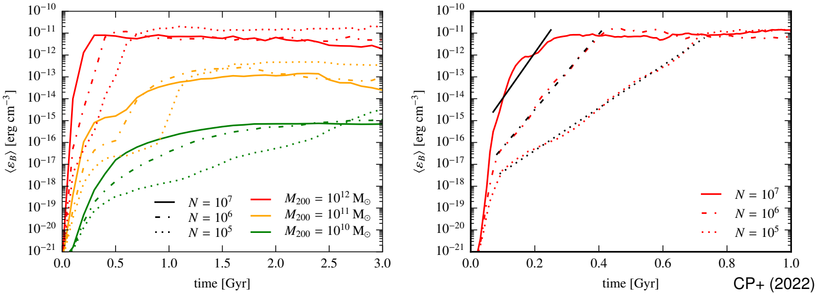


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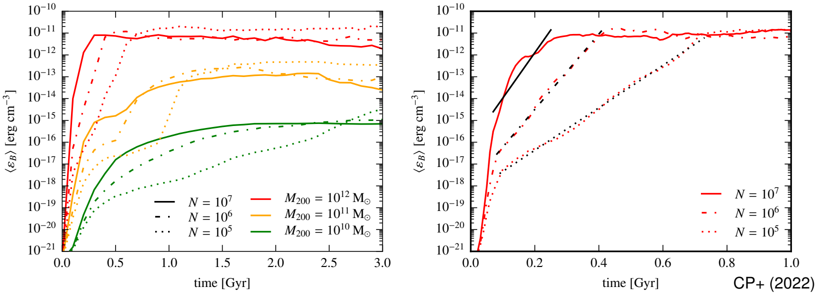


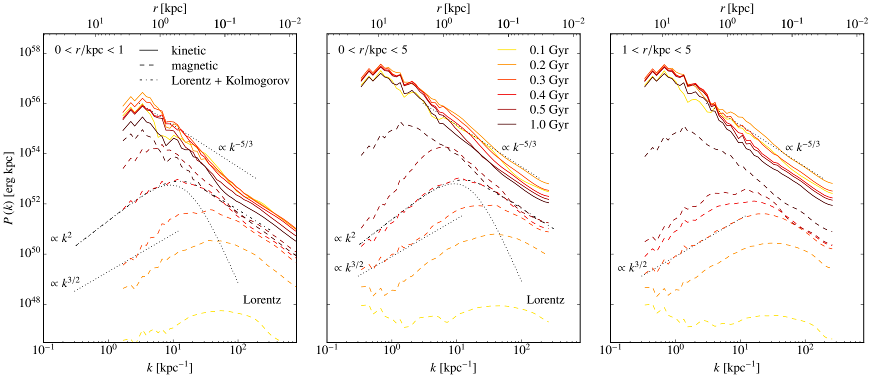

- ***faster magnetic growth in higher resolution simulations and larger halos,*** numerical convergence for $N \gtrsim 10^6$
- *1$^{st}$ phase:* adiabatic growth (independent of resolution)
- *2$^{nd}$ phase:* small-scale dynamo with resolution-dep. growth rate

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

AIP

# Kinetic and magnetic power spectra

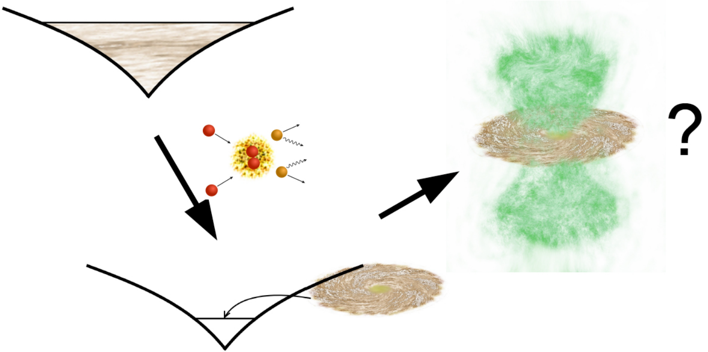
## Fluctuating small-scale dynamo in different analysis regions




CP+ (2022)

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

# Cosmic rays and non-thermal emission




Werhahn, CP, Girichidis+ (2021a,b,c)
*Cosmic rays and non-thermal emission in simulated galaxies*
MHD + CR advection + anisotropic diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$
steady-state spectra of CR protons, primary & secondary electrons

# Steady-state cosmic ray spectra

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

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

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

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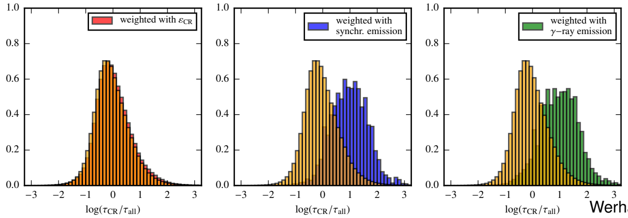
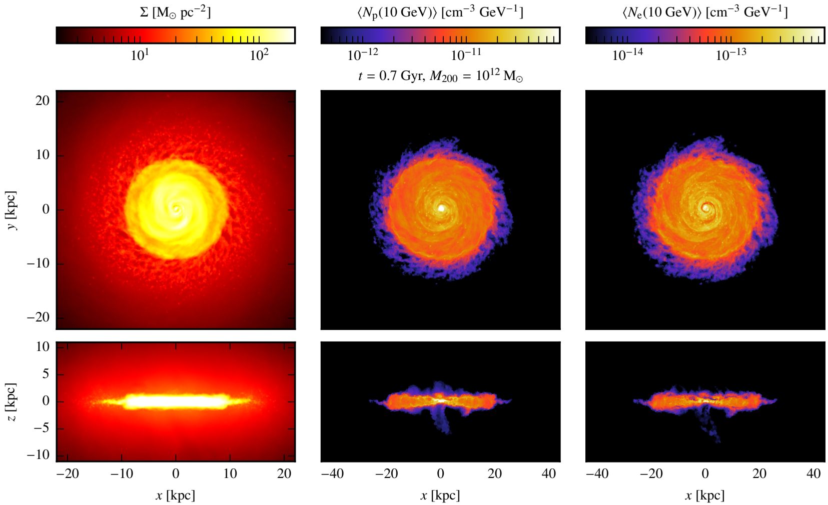
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\mathrm{ep}} = 0.02$)
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows




Werhahn+ (2021a)

# From a starburst galaxy to a Milky Way analogy




Werhahn, CP+ (2021a,b)

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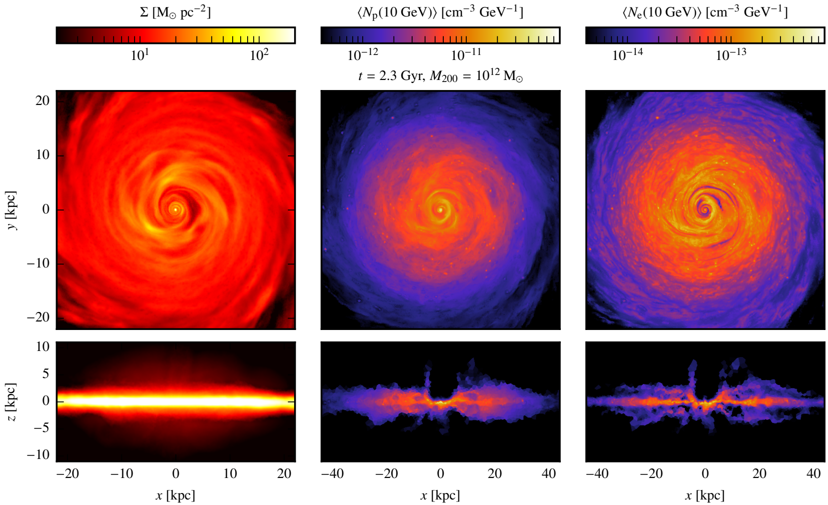
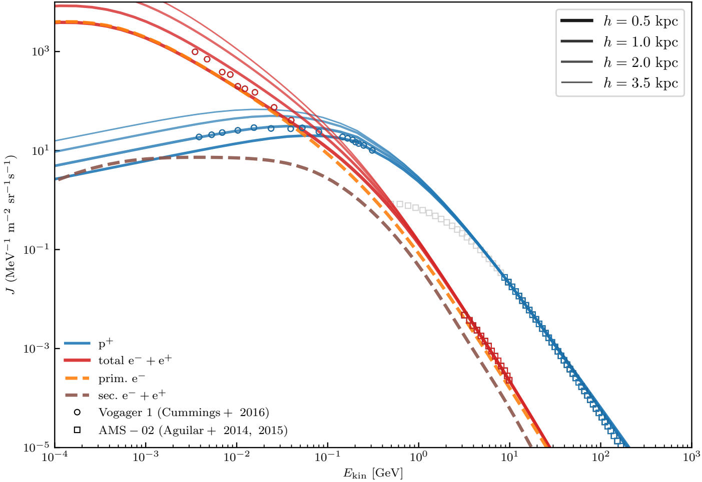


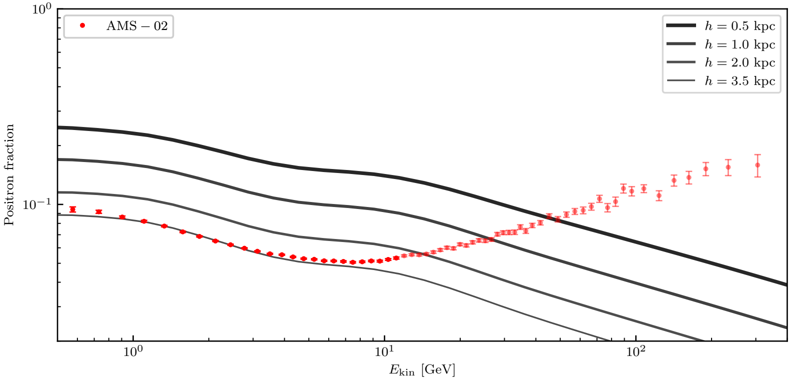

Werhahn, CP+ (2021a,b)

# Comparing CR spectra to Voyager and AMS-02 data




Werhahn, CP+ (2021a)

# Comparing the positron fraction to AMS-02 data




Werhahn, CP+ (2021a)

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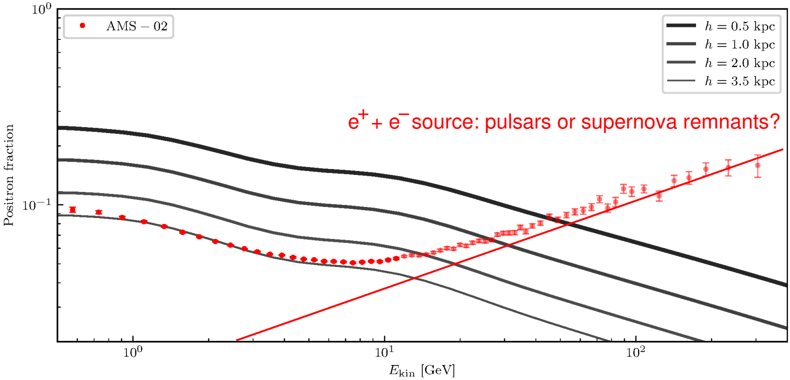
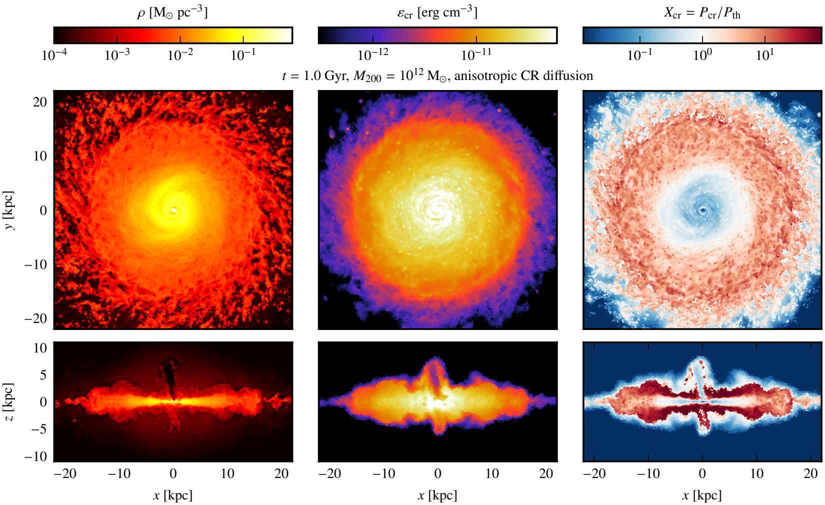


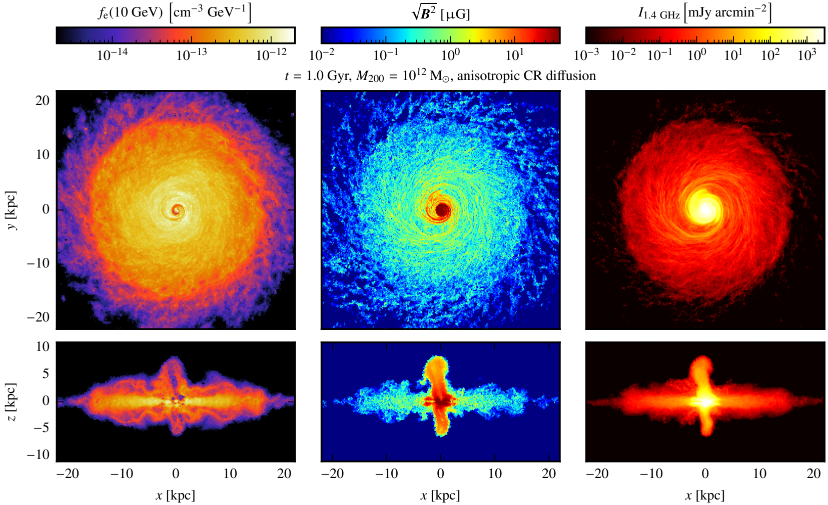

Werhahn, CP+ (2021a)

# Galaxy simulation with cosmic ray-driven wind



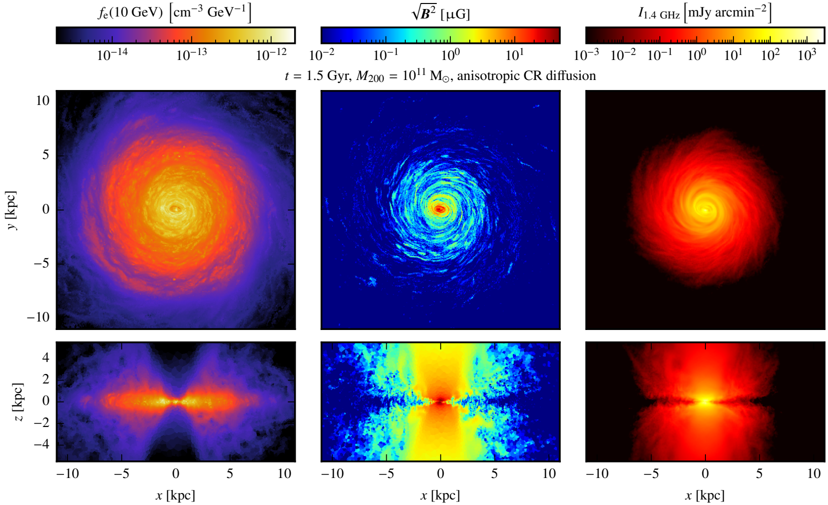

CP+ (2017)

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




CP+ (2022)

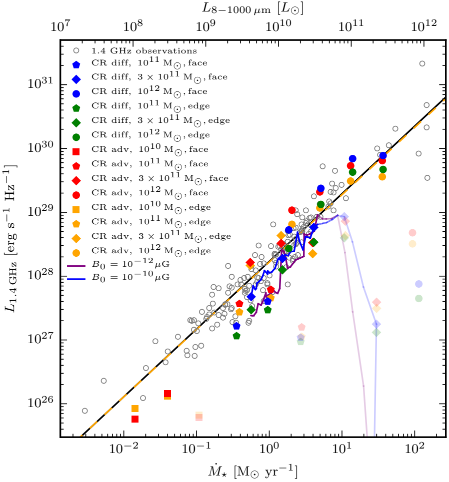
# Simulated radio emission: $10^{11}$ $M_\odot$ halo




CP+ (2022)

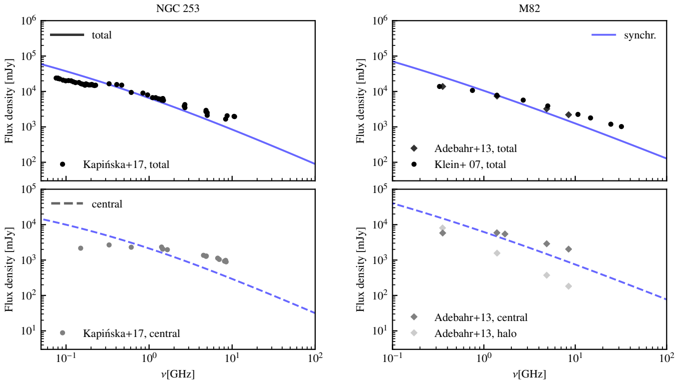
# Far infra-red – radio correlation

## Universal conversion: star formation → cosmic rays → radio




CP+ (2022)

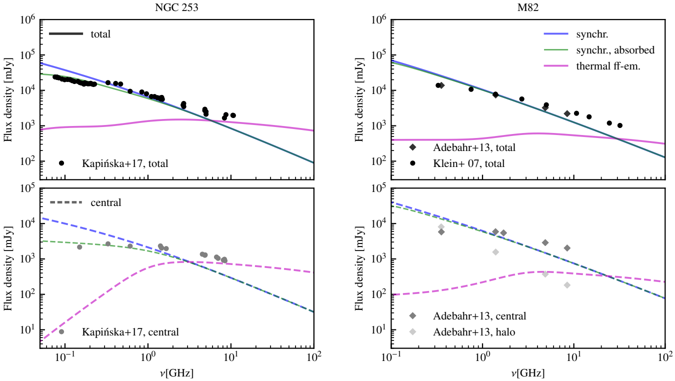
# Radio-ray spectra of starburst galaxies




Werhahn, CP+ (2021c)

- synchrotron spectra too steep (cooling + diffusion losses)

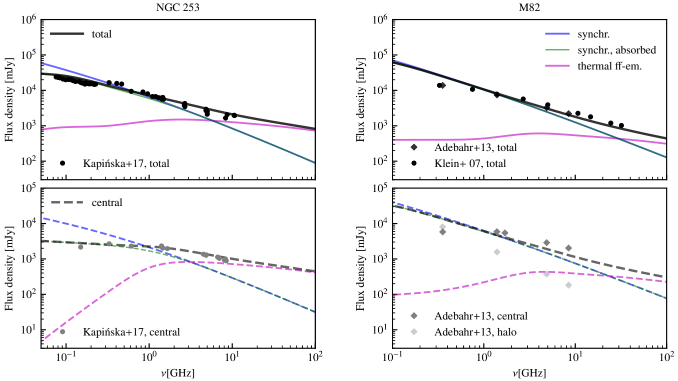
# Radio-ray spectra of starburst galaxies




Werhahn, CP+ (2021c)

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

# Radio-ray spectra of starburst galaxies




Werhahn, CP+ (2021c)

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

# 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

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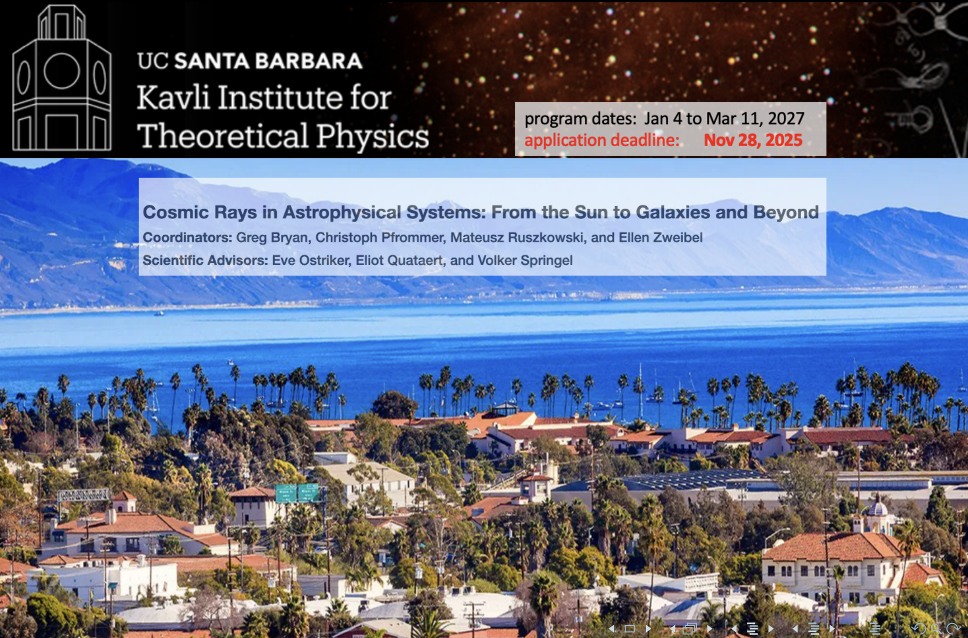
**CR feedback in galaxy formation:**

- 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 $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ reproduced for galaxies with saturated magnetic fields, scatter due to viewing angle and CR transport


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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# 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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## CR feedback in galaxy formation:

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- 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.

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## Cosmic rays and non-thermal emission in galaxies:

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