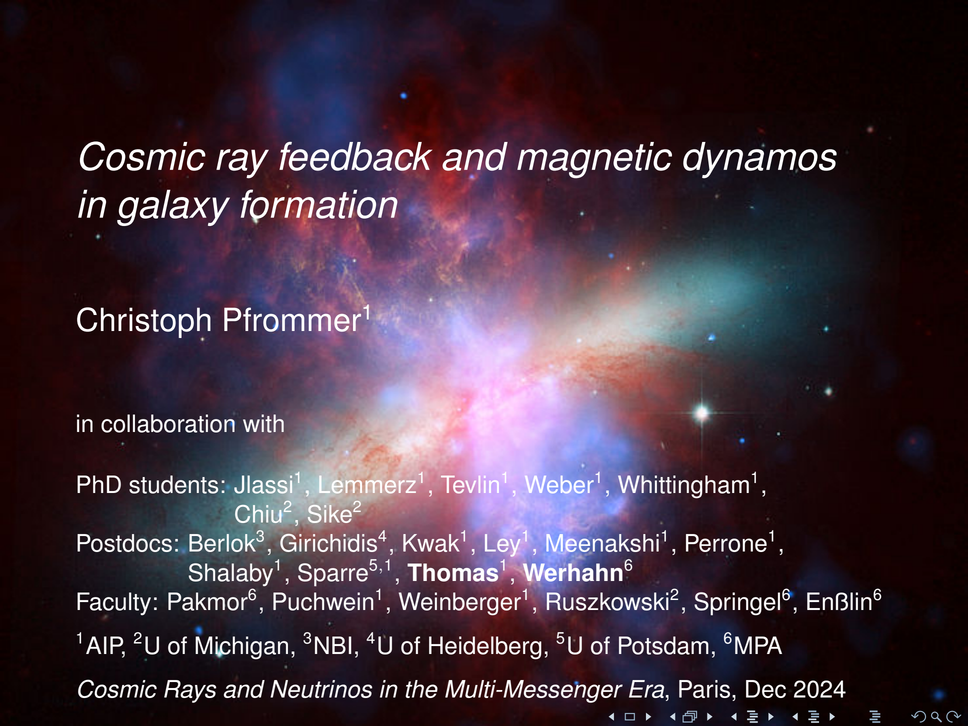


Cosmic ray feedback and magnetic dynamos in galaxy formation

Christoph Pfrommer[1]

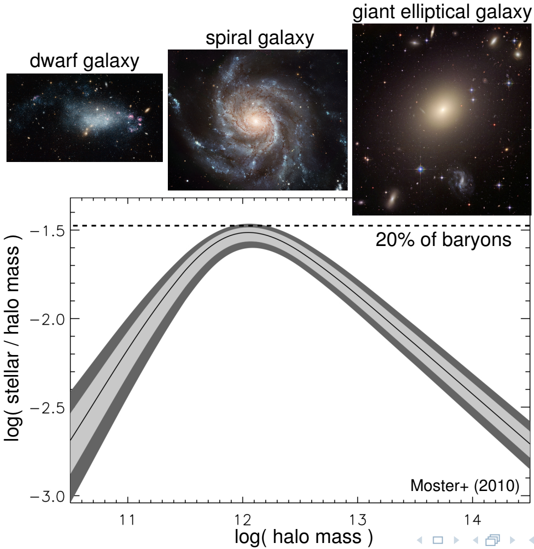
in collaboration with

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

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

Cosmic Rays and Neutrinos in the Multi-Messenger Era, Paris, Dec 2024

Puzzles in galaxy formation



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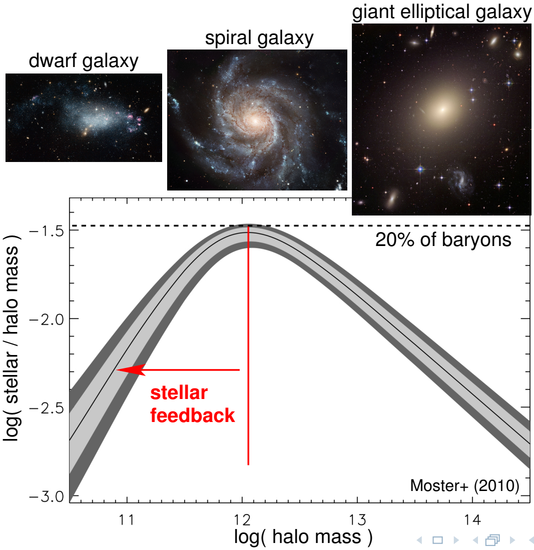

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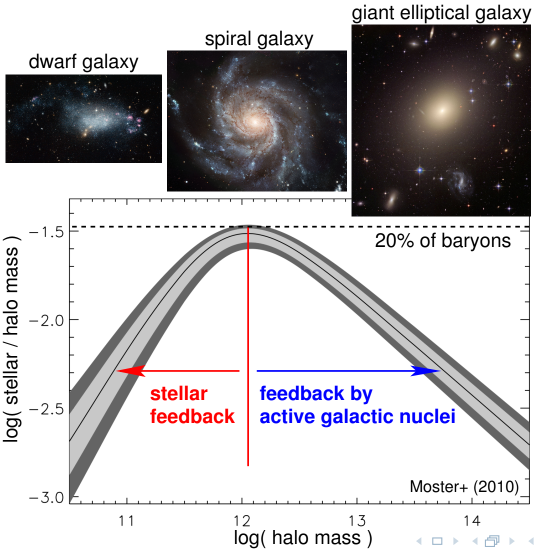
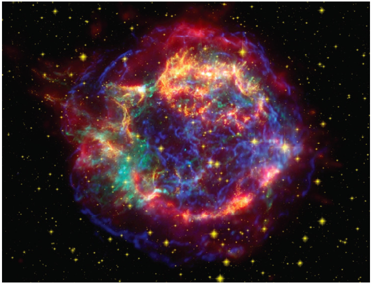


Stellar feedback



supernova Cassiopeia A

X-ray: NASA/CXC/SAO; Optical: NASA/STScI;
Infrared: NASA/JPL-Caltech/Steward/Krause

- galactic supernova remnants drive shock waves, turbulence, accelerate electrons + protons, amplify magnetic fields

Stellar feedback through 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

Stellar feedback through 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 → may explain puzzle of low star conversion efficiency in dwarf galaxies

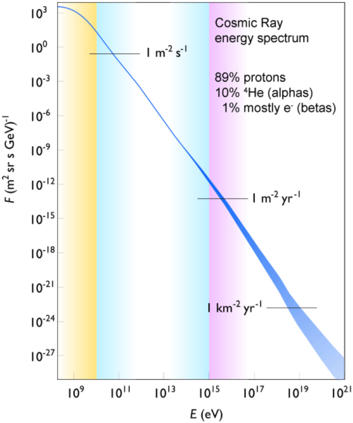
Stellar feedback: processes

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?

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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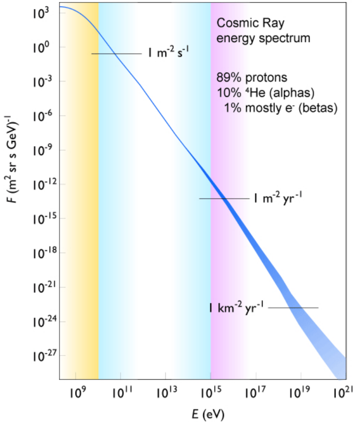

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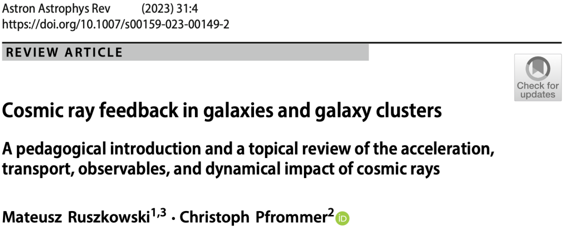
- spans more than 33 decades in flux and 12 decades in energy
- “knee” indicates characteristic maximum energy of galactic accelerators
- CRs beyond the “ankle” have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar
  $\Rightarrow$ important feedback agent

Review on cosmic ray feedback



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

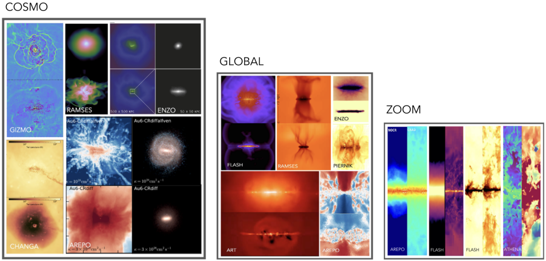
REVIEW ARTICLE

Check for updates

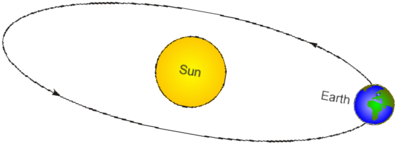
Cosmic ray feedback in galaxies and galaxy clusters

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:

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

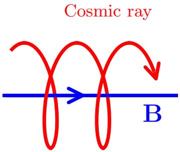
gyro-orbit of GeV CR:

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

⇒ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

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

Interactions of CRs and magnetic fields



sketch: Jacob & CP

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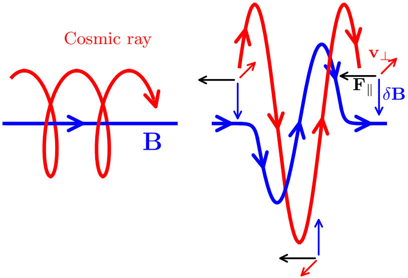

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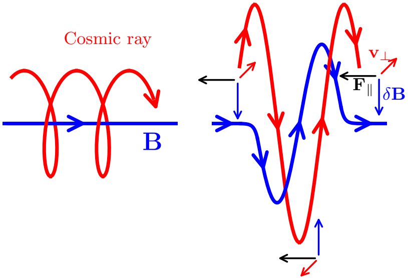

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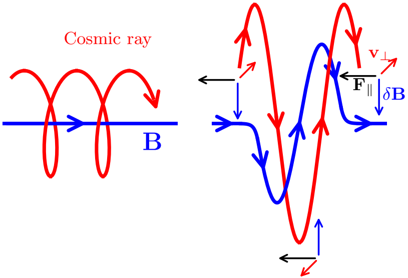

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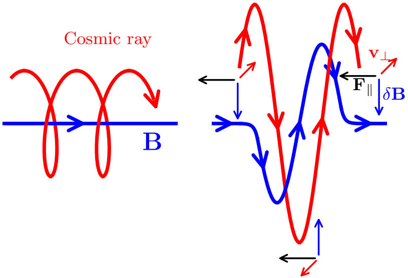

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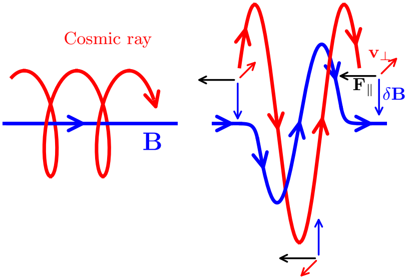
- work out **Lorentz forces on CRs** in wave frame: $\boldsymbol{F}_\mathrm{L} = q\frac{\boldsymbol{v} \times \boldsymbol{B}}{c}$
- Lorentz force depends on **relative phase of CR gyro orbit and wave:**
  - sketch: decelerating Lorentz force along CR orbit → $p_\parallel$ decreases
  - phase shift by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

Interactions of CRs and magnetic fields



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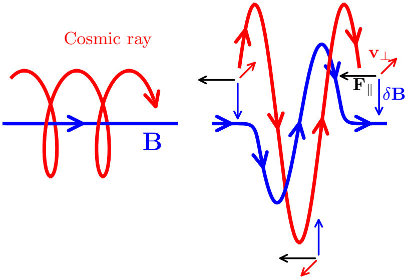

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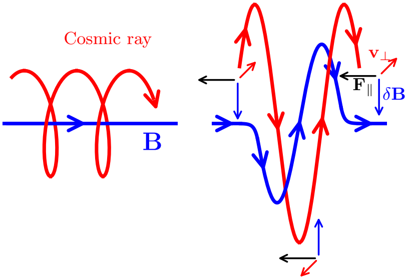

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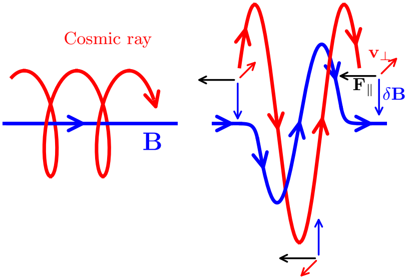
- this increases the CR pitch angle cosine $\mu = \cos\theta = \frac{\boldsymbol{B}}{|\boldsymbol{B}|} \cdot \frac{\boldsymbol{p}}{|\boldsymbol{p}|}$

Interactions of CRs and magnetic fields



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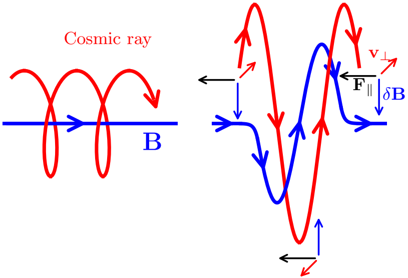
$$L_\parallel = r_\mathrm{g} = \frac{p_\perp c}{qB}$$

Interactions of CRs and magnetic fields



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

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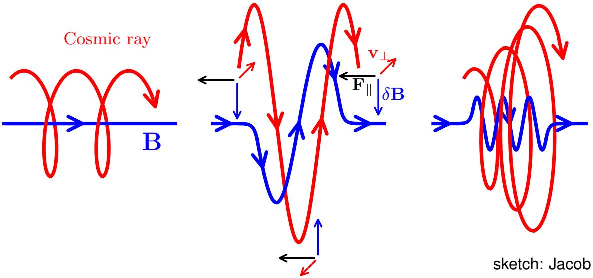

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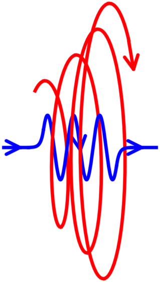
Cosmic ray streaming and diffusion

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



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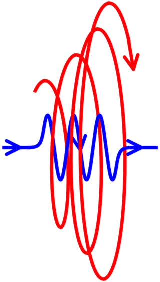

→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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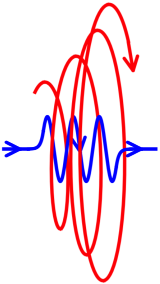
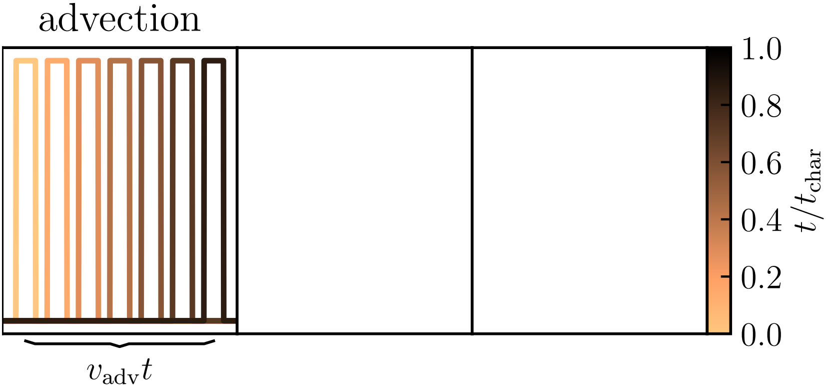


→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

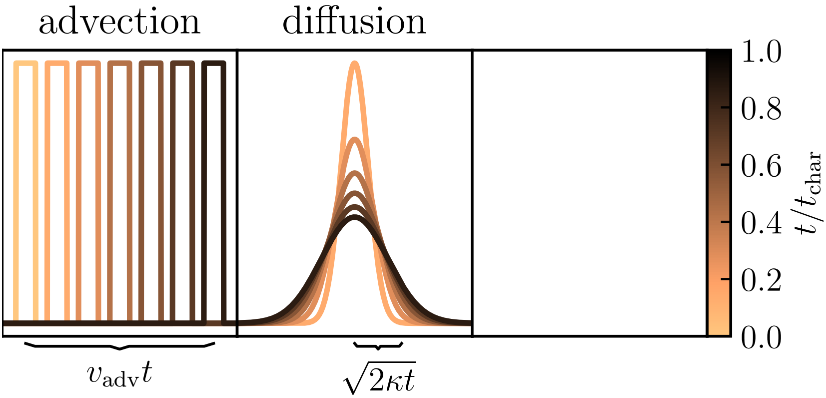
weak wave damping: strong coupling → CR stream with waves
strong wave damping: less waves to scatter → CR diffusion prevails

Modes of CR propagation



Thomas, CP, Enßlin (2020)

Modes of CR propagation



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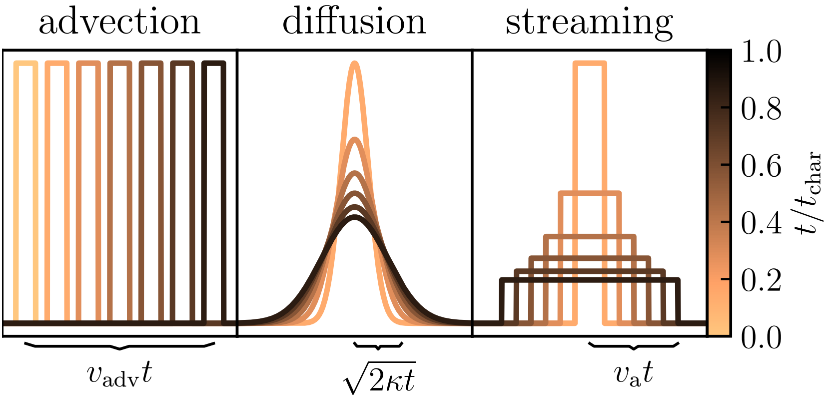

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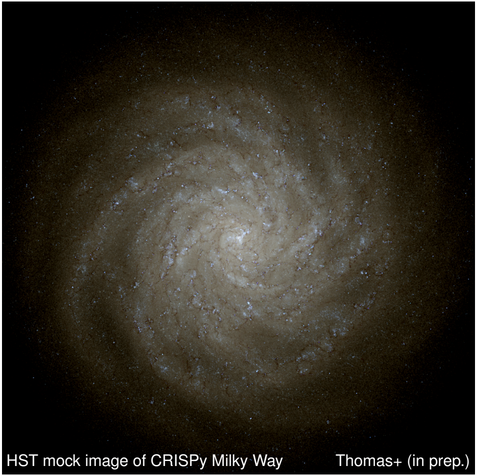
Cosmic ray transport in galaxies

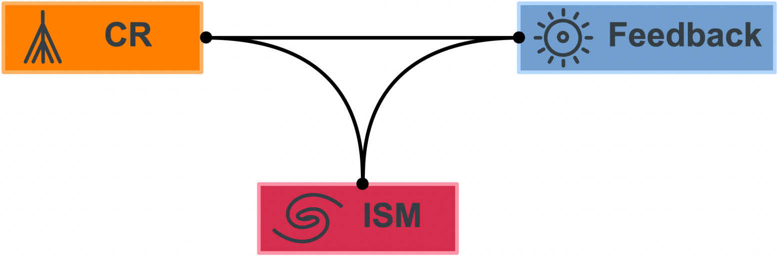

HST mock image of CRISPy Milky Way Thomas+ (in prep.)

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

Multi-phase ISM modeling

CRISP framework

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



Thomas, CP, Pakmor (2024)

Multi-phase ISM modeling

CRISP framework

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

Feedback

CR

ISM

Chemistry

- Full H – H_2 – He chemistry
  sets ionization degree
- First ionization stages of C – O – Si
  low temperature cooling
- Photoelectric heating by dust

Thomas, CP, Pakmor (2024)

Multi-phase ISM modeling

CRISP framework

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

CR

ISM

Feedback

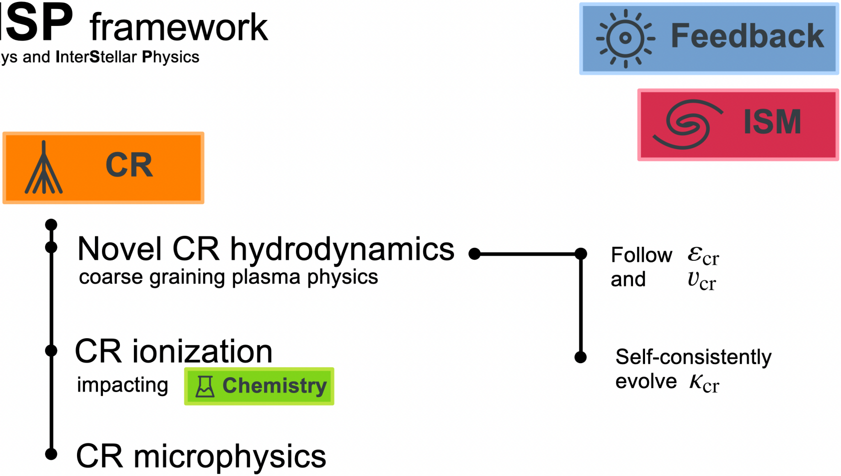
- Improved SNe treatment (manifestly isotropic)
  and stellar winds
- FUV NUV OPT radiation fields (reverse ray tracing)
  absorbed by dust – impacting **Chemistry**
- Metal enrichment

Thomas, CP, Pakmor (2024)

Multi-phase ISM modeling

CRISP framework

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



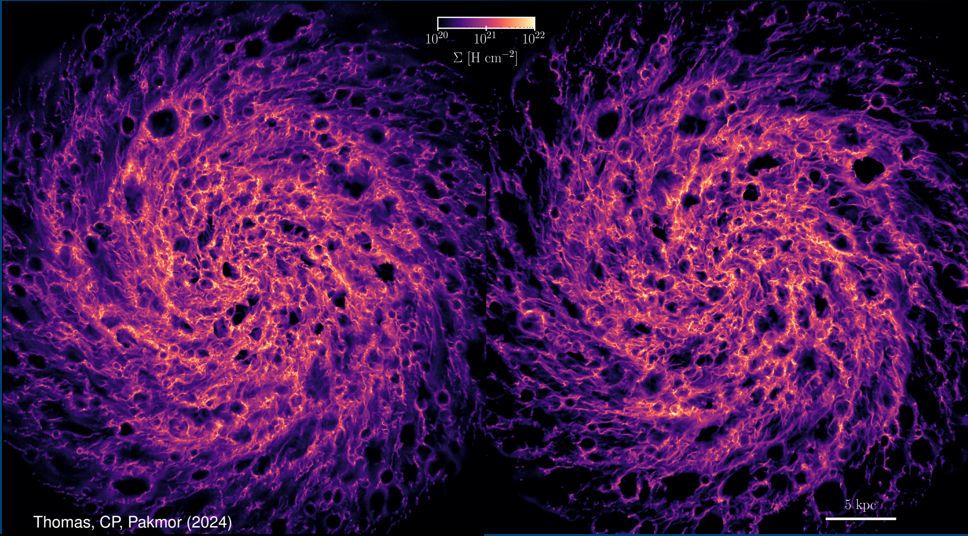
- Novel CR hydrodynamics
  coarse graining plasma physics
- CR ionization
  impacting Chemistry
- CR microphysics

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

Self-consistently
evolve κ_{cr}

Thomas, CP, Pakmor (2024)

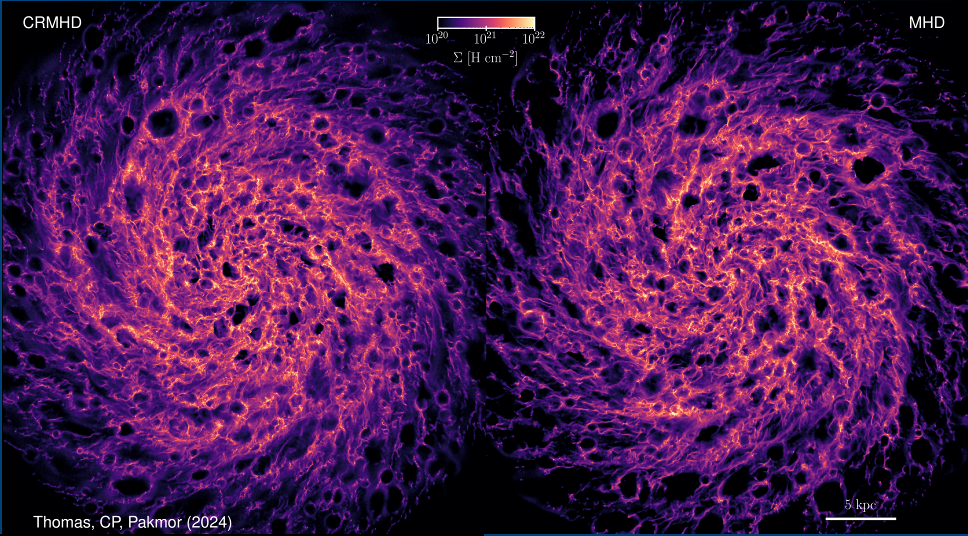
Multi-phase ISM modeling



Thomas, CP, Pakmor (2024)

Multi-phase ISM modeling

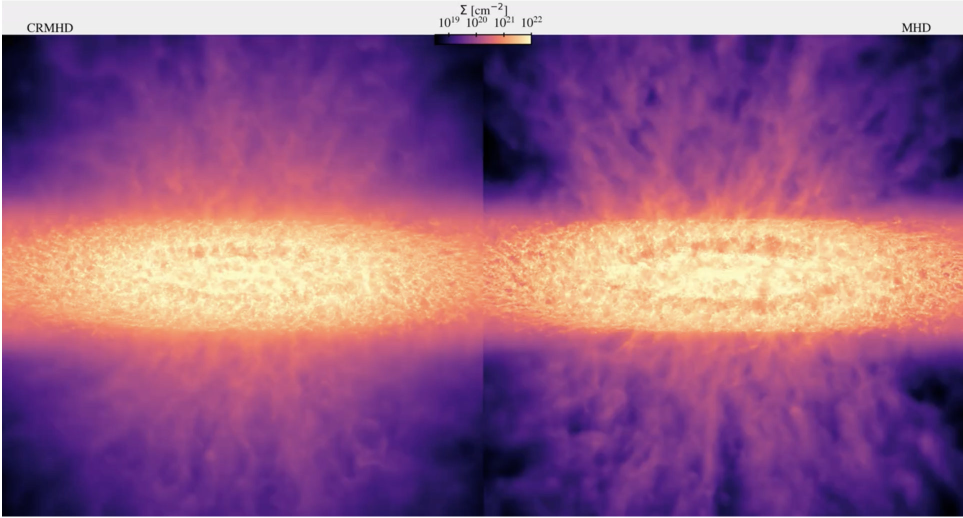
Cosmic rays barely affect the ISM because ion-neutral damping erases Alfvén waves



Thomas, CP, Pakmor (2024)

Simulated Milky Way: surface density

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



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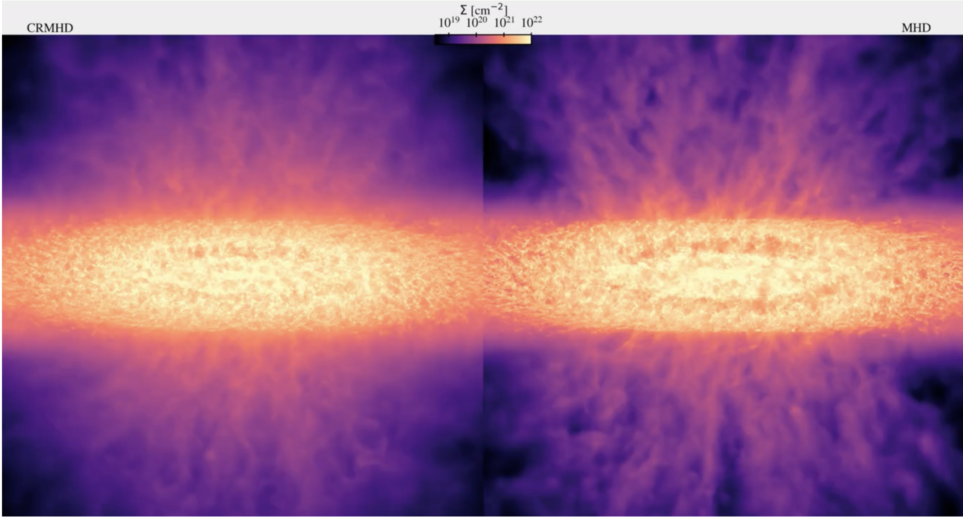
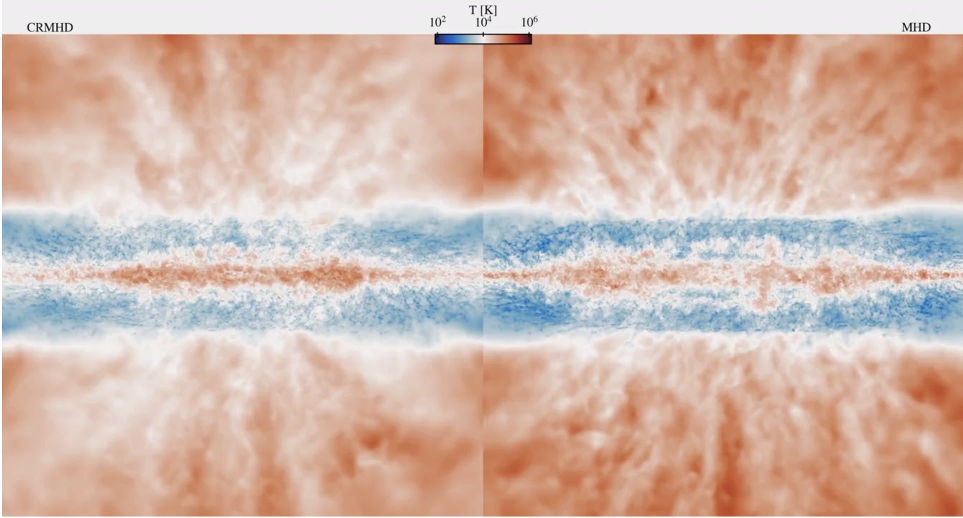


Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter



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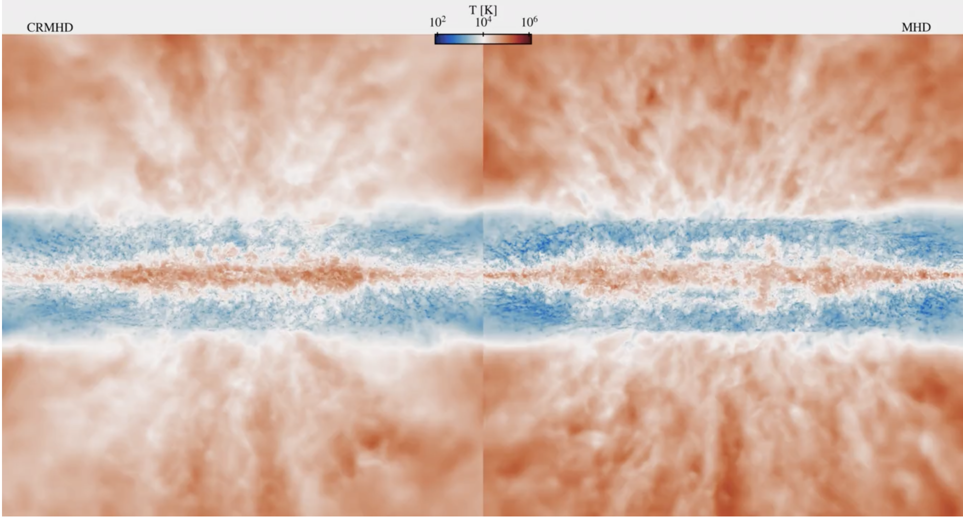
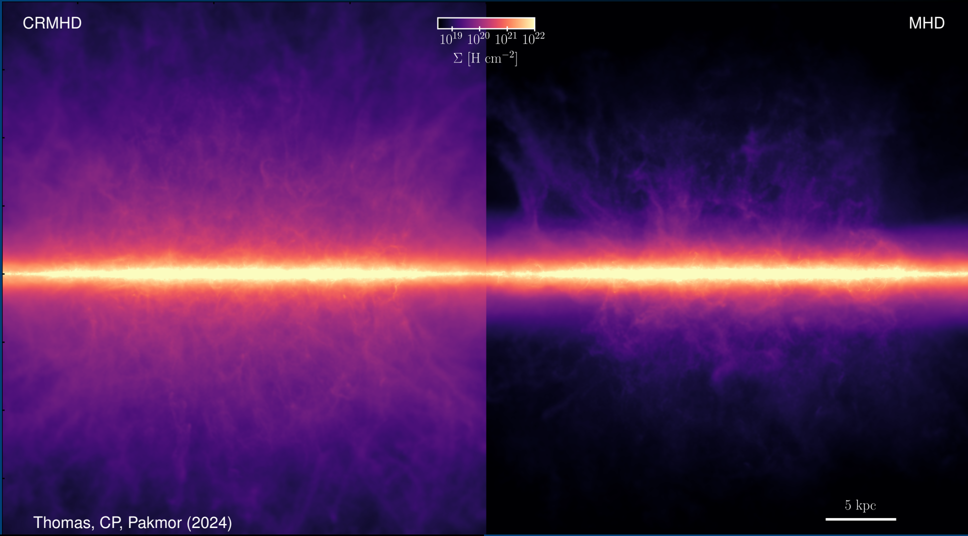


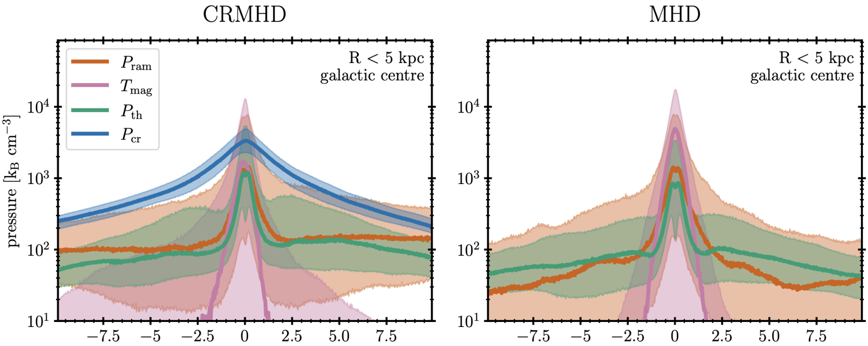
Multi-phase ISM modeling

Cosmic rays make galactic winds much denser



Thomas, CP, Pakmor (2024)

Cosmic ray driven wind: mechanism

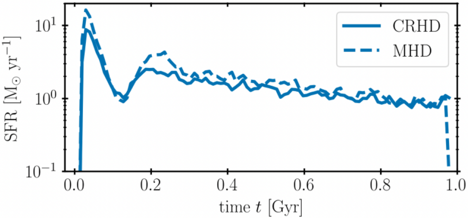


Thomas, CP, Pakmor (2024)

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

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

Mass and energy loading factors



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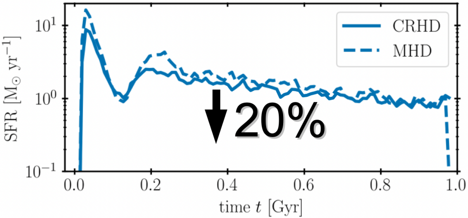

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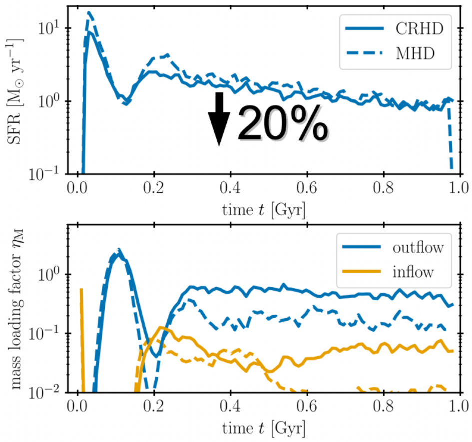

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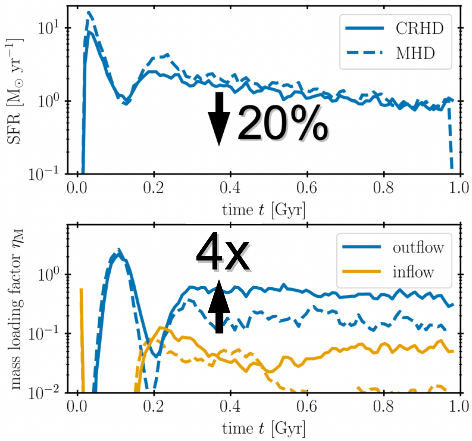

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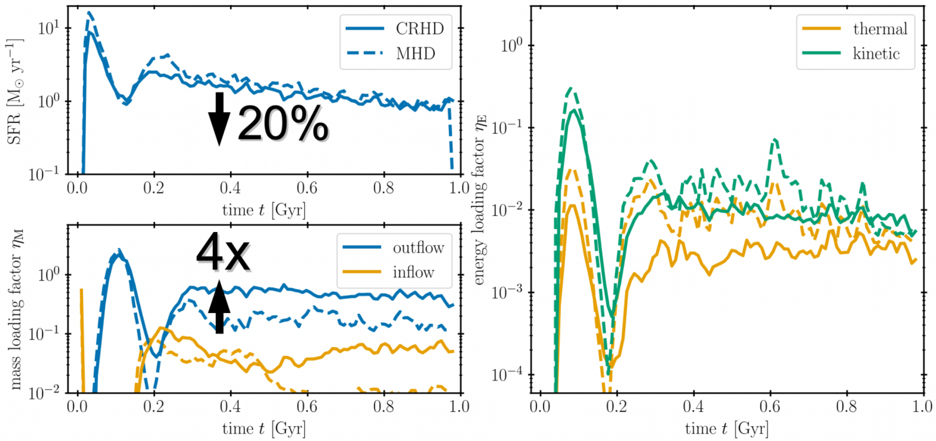

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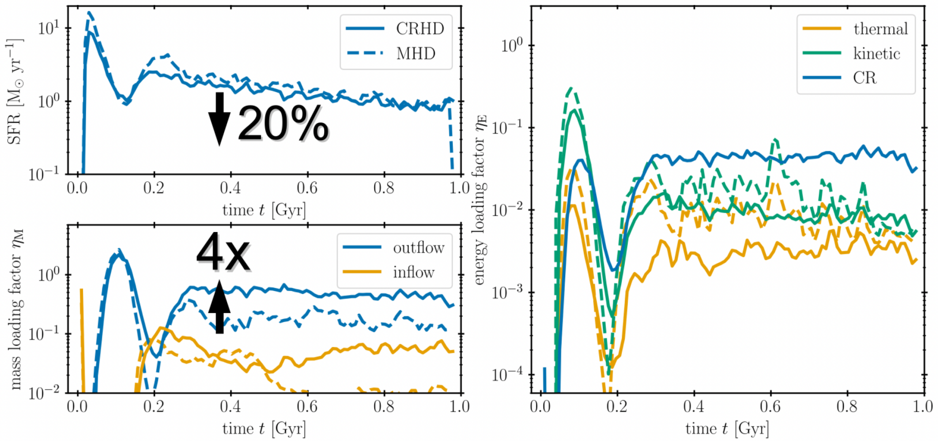

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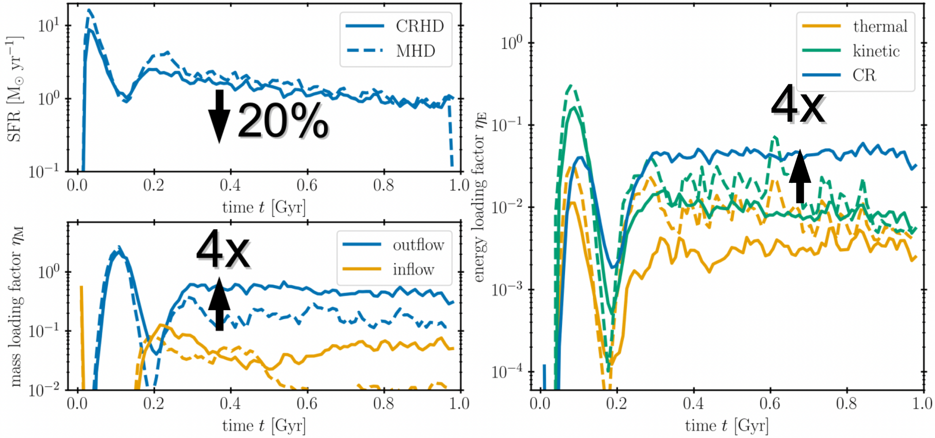

Thomas, CP, Pakmor (2024)

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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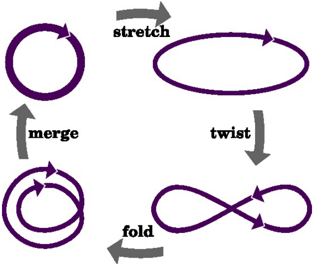
- ***Growth.*** A small-scale (fluctuating) dynamo is an MHD process, in which the kinetic (turbulent) energy is converted into magnetic energy: the mechanism relies on magnetic fields to become stronger when the field lines are stretched



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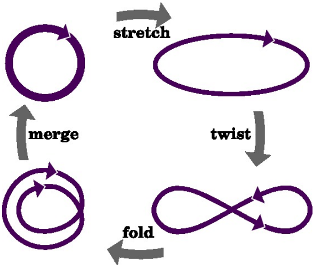
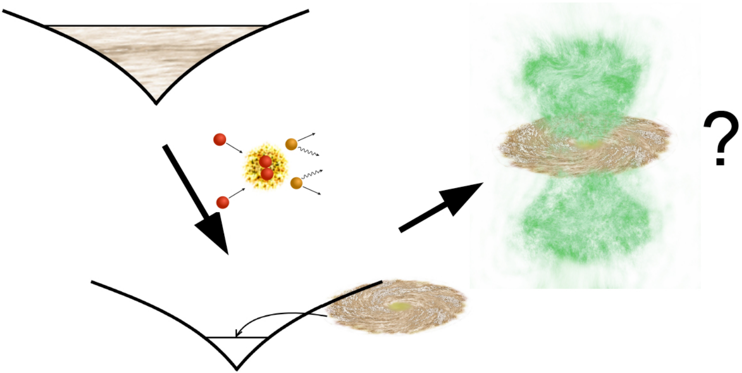
- ***Saturation.*** Field growth stops at a sizeable fraction of the turbulent energy when magnetic forces become strong enough to resist the stretching and folding motions



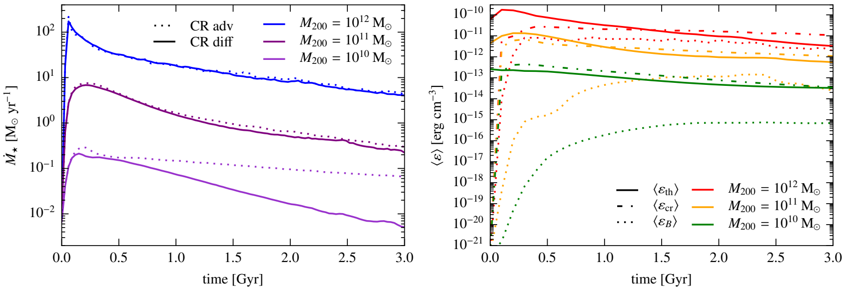
Galactic magnetic dynamo



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

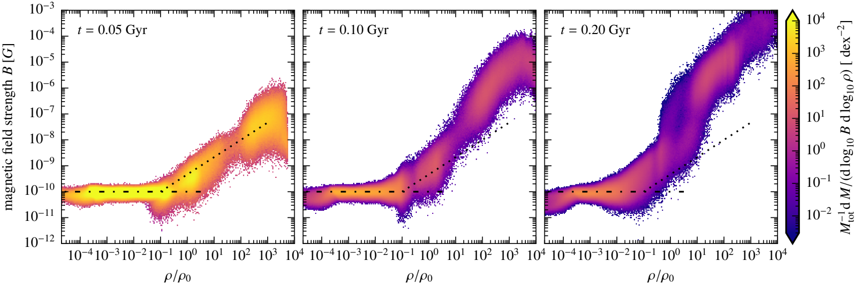
Time evolution of SFR and energy densities



CP+ (2022)

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

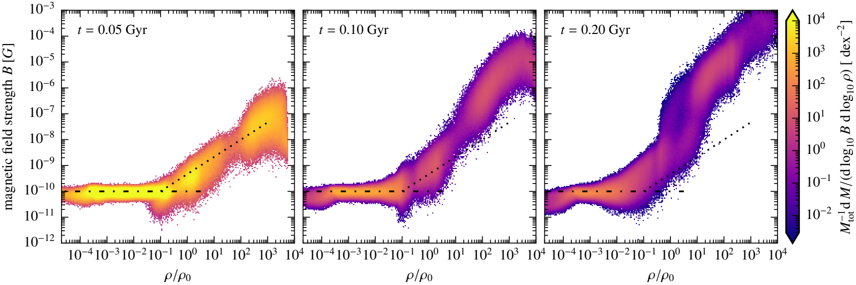
Identifying different growth phases



CP+ (2022)

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

Identifying different growth phases



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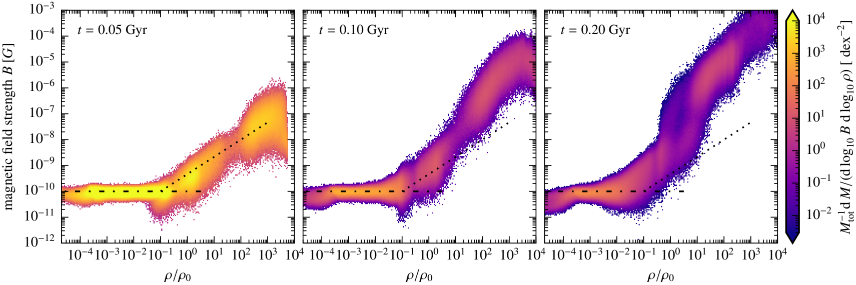

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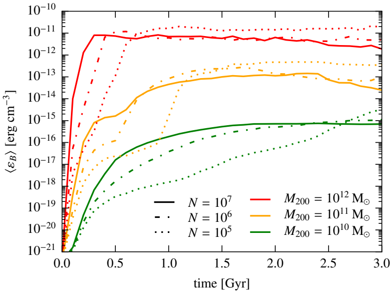
- *2nd phase:* additional growth at high density ρ with small dynamical times $t_\mathrm{dyn} \sim (G\rho)^{-1/2}$
- *3rd phase:* growth migrates to lower ρ on larger scales $\propto \rho^{-1/3}$

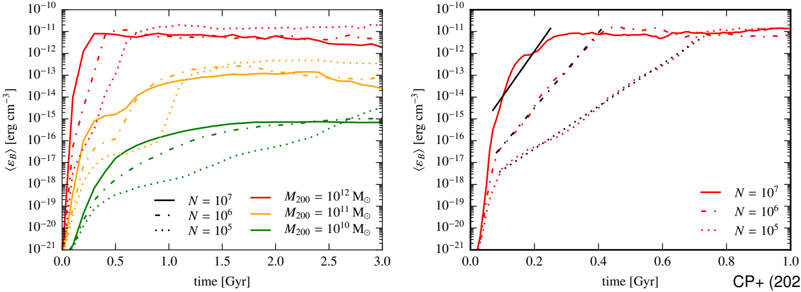
Studying growth rate with numerical resolution



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



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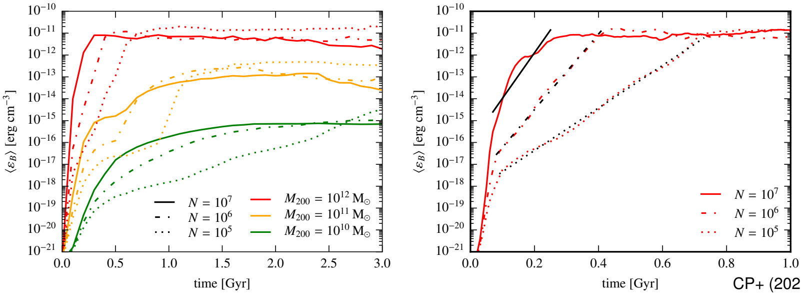
Studying growth rate with numerical resolution

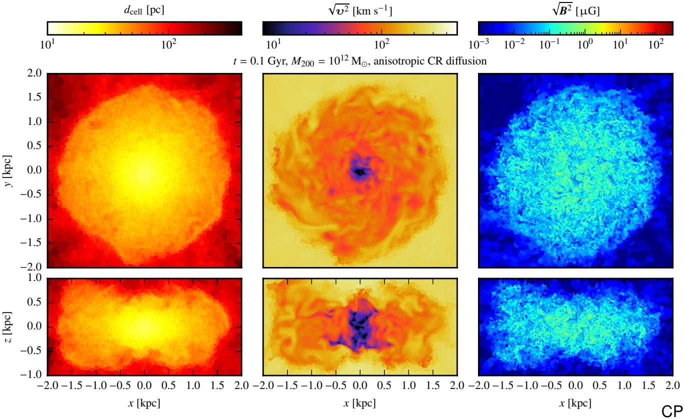


CP+ (2022)

- ***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

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

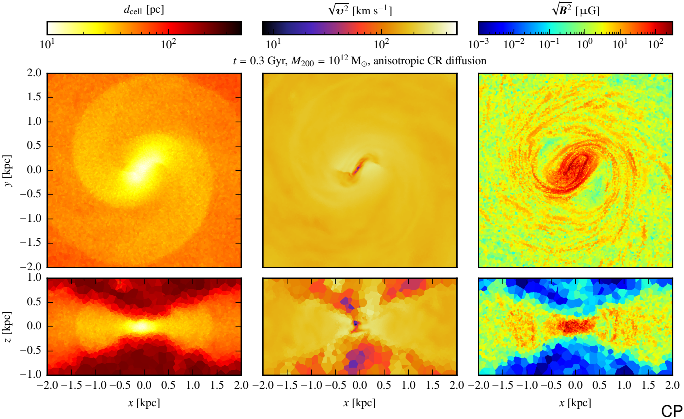
Exponential field growth in kinematic regime



CP+ (2022)

- ***corrugated accretion shock*** dissipates kinetic energy from gravitational infall, injects vorticity that decays into turbulence, and drives a small-scale dynamo

Dynamo saturation on small scales while λ_B increases

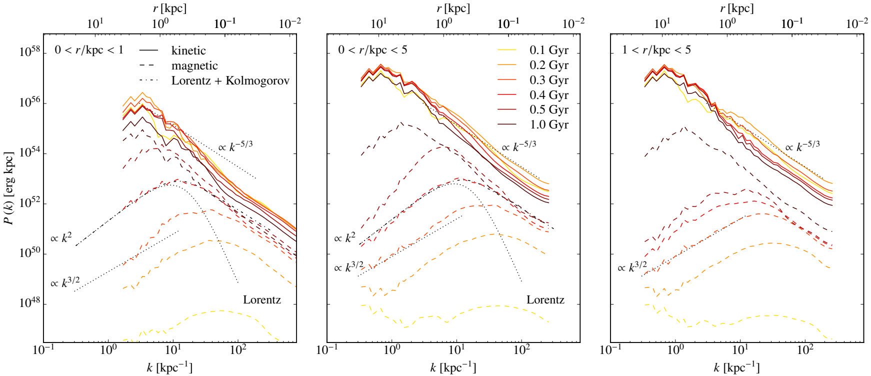


CP+ (2022)

- ***supersonic velocity shear*** between the rotationally supported cool disk and hotter CGM: excitation of Kelvin-Helmholtz body modes that interact and drive a small-scale dynamo

Kinetic and magnetic power spectra

Fluctuating small-scale dynamo in different analysis regions

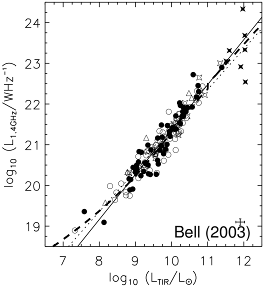


CP+ (2022)

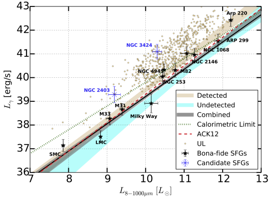
- $E_B(k)$ superposition of form factor and turbulent spectrum
- pure turbulent spectrum outside steep central B profile

Non-thermal emission in star-forming galaxies

- ***previous theoretical modeling:***
  - one-zone steady-state models
    (Lacki+ 2010, 2011, Yoast-Hull+ 2013)
  - 1D transport models (Heesen+ 2016)
  - static Milky Way models
    (Strong & Moskalenko 1998, Evoli+ 2008, Kissmann 2014)



Bell (2003)



Ajello+ (2020)

Non-thermal emission in star-forming galaxies

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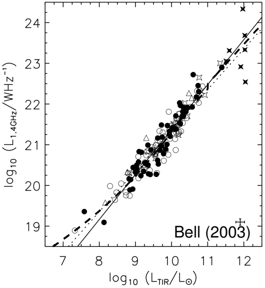
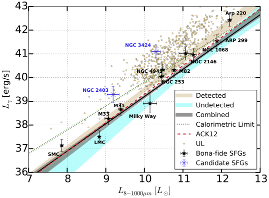
    (Lacki+ 2010, 2011, Yoast-Hull+ 2013)
  - 1D transport models (Heesen+ 2016)
  - static Milky Way models
    (Strong & Moskalenko 1998, Evoli+ 2008, Kissmann 2014)
- ***our theoretical modeling:***
  - run MHD-CR simulations of galaxies at different halos masses and SFRs
  - model steady-state CRs: protons, primary and secondary electrons
  - model all radiative processes from radio to gamma rays
  - gamma rays: understand pion decay and leptonic inverse Compton emission
  - radio: understand magnetic dynamo, primary and secondary electrons





Ajello+ (2020)

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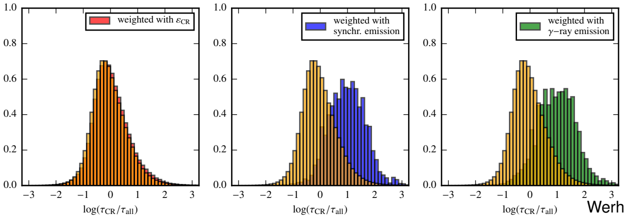
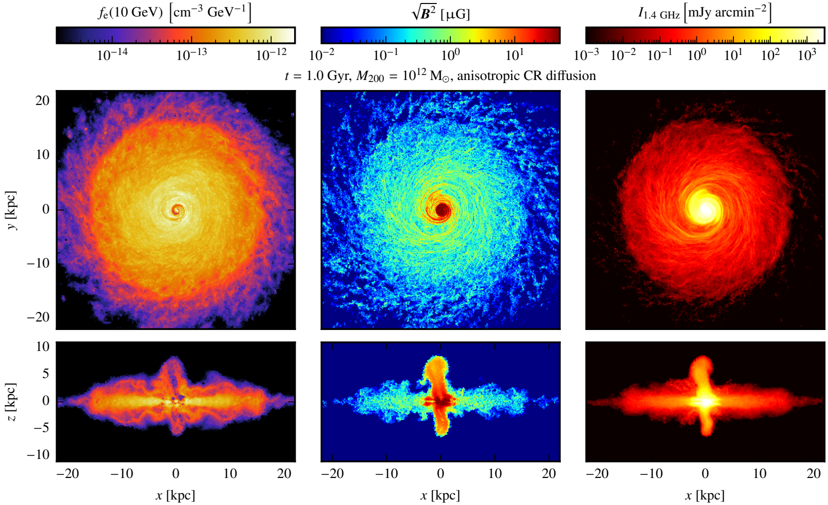
- electrons: Coulomb, bremsstr., IC, synchrotron and escape losses
  - primaries (re-normalized using $K_{\mathrm{ep}} = 0.02$)
  - secondaries
- steady state assumption is fulfilled in disk and in regions dominating the non-thermal emission but not at low densities, at SNRs and in outflows



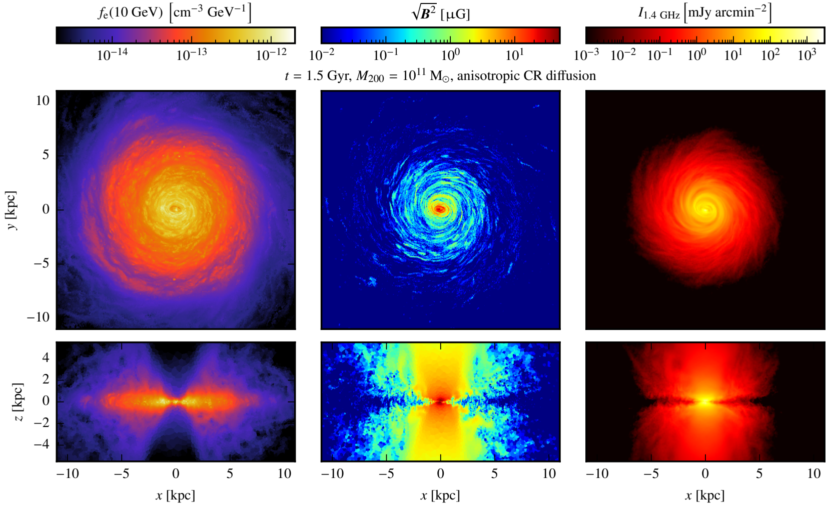
Werhahn+ (2021a)

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



CP+ (2022)

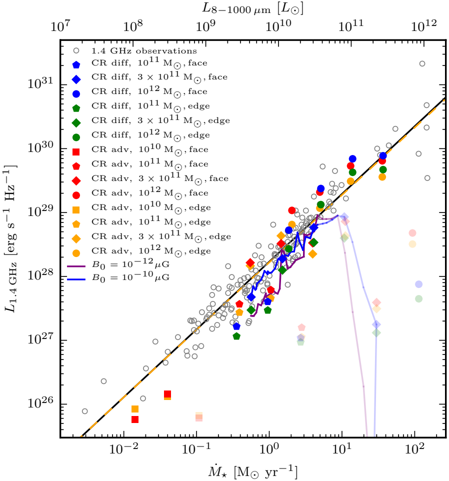
Simulated radio emission: 10^{11} $M_\odot$ halo



CP+ (2022)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



CP+ (2022)

Conclusions for cosmic ray physics in galaxies

CR feedback in galaxy formation:

- CR feedback barely impacts ISM or star formation because of strong ion-neutral damping in disk, which weakens CR coupling
- CR feedback drives powerful galactic winds
- CR feedback increases mass and energy loading factors by 4

Conclusions for cosmic ray physics in galaxies

CR feedback in galaxy formation:

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Galactic magnetic dynamo and radio emission:

- gravitational collapse drives fluctuating small-scale dynamo $\Rightarrow$ magnetic field growth
- magnetic fields saturate close to equipartition in Milky Way centers and sub-equipartition at larger radii and in dwarfs
- global $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ reproduced for galaxies with saturated magnetic fields, scatter due to viewing angle and CR transport

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 hydrodynamics and CR transport:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, MNRAS, 465, 4500.
- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2019, MNRAS, 485, 2977.
- Thomas, Pfrommer, Pakmor, *A finite volume method for two-moment cosmic-ray hydrodynamics on a moving mesh,* 2021, MNRAS, 503, 2242.
- Thomas, Pfrommer, Enßlin, *Probing Cosmic Ray Transport with Radio Synchrotron Harps in the Galactic Center,* 2020, ApJL, 890, L18.

CR feedback in galaxy formation:

- Ruszkowski, Pfrommer, *Cosmic ray feedback in galaxies and galaxy clusters,* 2023, Astron Astrophys Rev, 31, 4.
- Thomas, Pfrommer, Pakmor, *Cosmic ray-driven galactic winds: transport modes of cosmic rays and Alfvén-wave dark regions,* 2023, MNRAS, 521, 3023.
- Thomas, Pfrommer, Pakmor, *Why are thermally- and cosmic ray-driven galactic winds fundamentally different?* 2024, A&A, submitted.

Literature for the talk – 2

Galactic magnetic dynamo and radio emission:

- Pfrommer, Werhahn, Pakmor, Girichidis, Simpson, *Simulating radio synchrotron emission in star-forming galaxies: small-scale magnetic dynamo and the origin of the far infrared-radio correlation,* 2022, MNRAS, 515, 4229.
- Werhahn, Pfrommer, Girichidis, Puchwein, Pakmor, *Cosmic rays and non-thermal emission in simulated galaxies. I. Electron and proton spectra explain Voyager-1 data,* 2021a, MNRAS 505, 3273.
- Werhahn, Pfrommer, Girichidis, Winner, *Cosmic rays and non-thermal emission in simulated galaxies. II. γ-ray maps, spectra and the far infrared-γ-ray relation,* 2021b, MNRAS, 505, 3295.
- Werhahn, Pfrommer, Girichidis, *Cosmic rays and non-thermal emission in simulated galaxies. III. probing cosmic ray calorimetry with radio spectra and the FIR-radio correlation,* 2021c, MNRAS, 508, 4072.