Feedback in galaxy formation

Christoph Pfrommer[1]

in collaboration with

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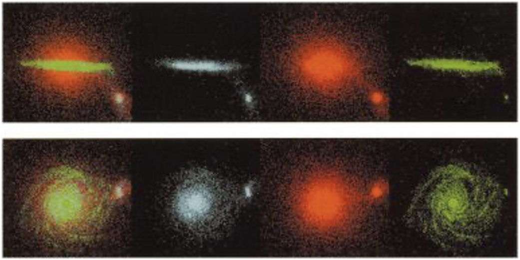
Postdocs: Berlok,[3] Girichidis,[4] **Lemmerz,**[5] Meenakshi,[1] Perrone,[1] Shalaby,[6] **Thomas,**[1] Werhahn,[7] Whittingham[1]
Faculty: Pakmor,[7] Puchwein,[1] Weinberger,[1] Ruszkowski,[2] Springel,[7] Enßlin[7]

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

MatthiasFest, AIP Potsdam, 2026



The formation of disc galaxies in a cosmological context: structure and kinematics

Matthias Steinmetz[1,2]★ and Ewald Müller[1]†

[1]Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, 85748 Garching bei München, Germany

[2]Institut für Astronomie und Astrophysik der Universität Kiel, Olshausenstrasse 40, 24098 Kiel, Germany

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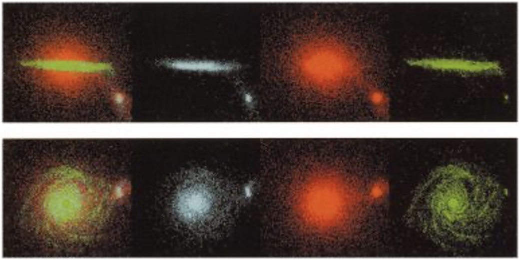
The modelling of feedback processes in cosmological simulations of disc galaxy formation

Franziska Piontek★ and Matthias Steinmetz

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany



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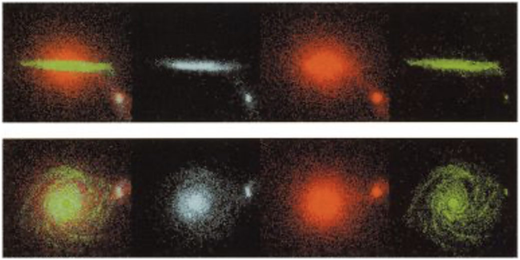
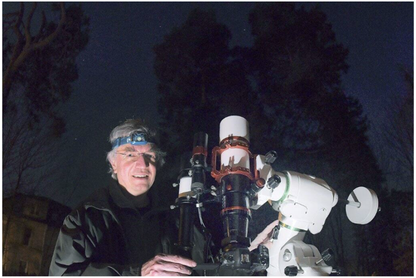
🧑‍🔬 Steinmetz simulations (1990s)

Matthias Steinmetz was one of the pioneers of **cosmological SPH simulations of galaxy formation**,
These are among the first simulations that produced **realistic-looking disk galaxies in a cosmological context** (though still with issues like angular momentum loss). (from ChatGPT)





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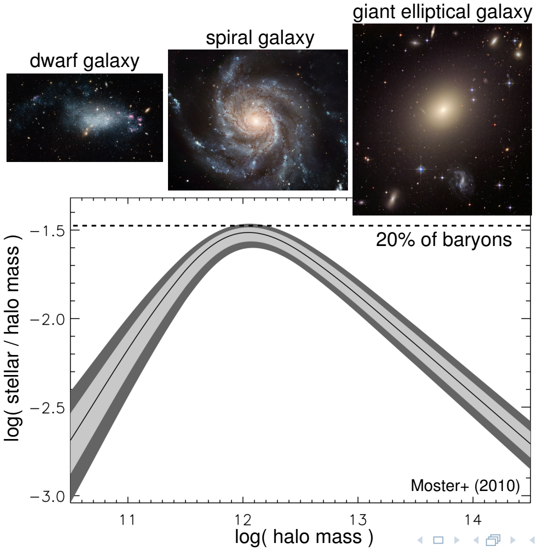
Puzzles in galaxy formation



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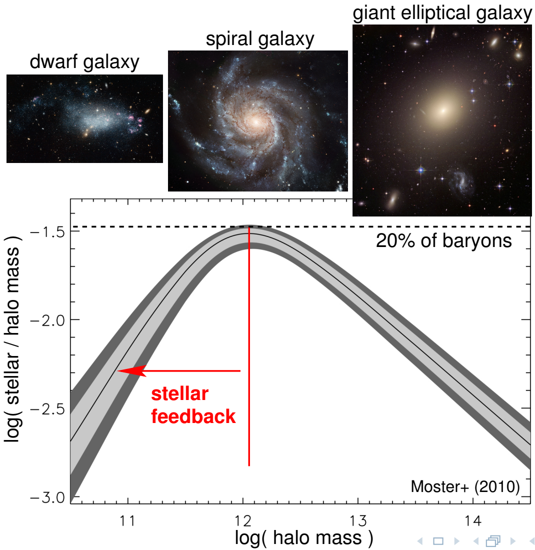

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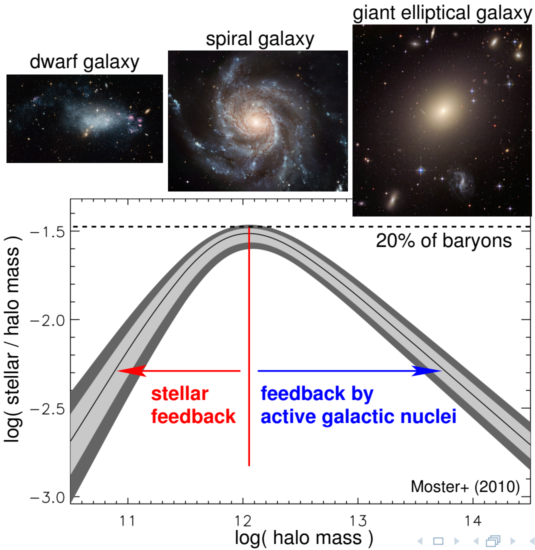


How does stellar feedback drive galactic winds?

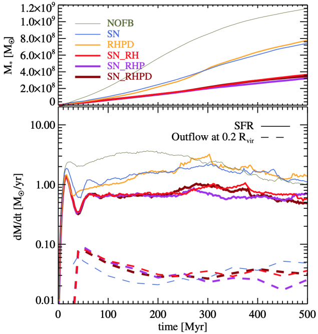
super wind in M82

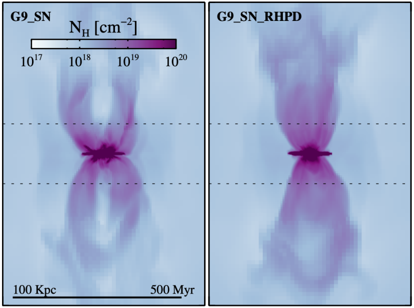
NASA/JPL-Caltech/STScI/CXC/UofA

- thermal pressure provided by supernovae or active galactic nuclei?
- radiation pressure and photoionization by massive stars and quasars?

AIP

Radiation feedback





Rosdahl+ (2015)

- similar outflow rates for SN-only models and full SN+radiation models
- radiation heating (RH) suppresses star formation as much as SN feedback
- radiation pressure not efficient in suppressing SFR at resolved τ_{IR}
- artificially boosting τ_{IR} reduces star formation by smoothing the gas rather than by generating stronger outflows

AIP

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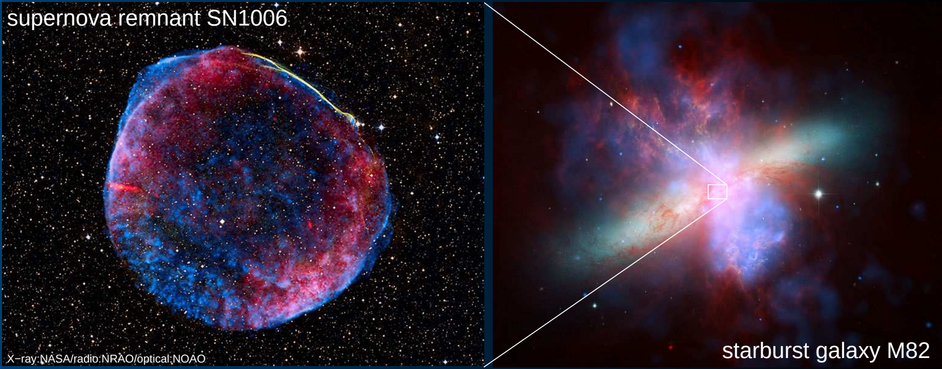
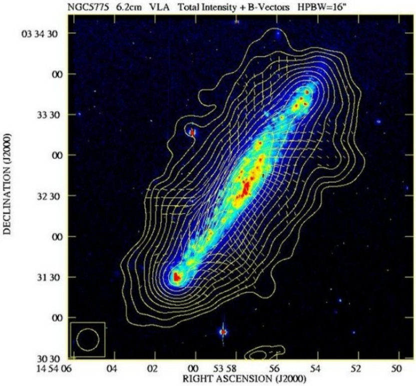
- thermal pressure provided by supernovae or active galactic nuclei?
- radiation pressure and photoionization by massive stars and quasars?
- pressure of cosmic rays (CRs) that are accelerated at supernova shocks?
- energy density of CRs, magnetic fields, and ISM turbulence all similar
  $\Rightarrow$ important feedback agent

Cosmic ray feedback



Why can cosmic rays drive galactic winds?

Radio halos in disks: CRs and magnetic fields exist at the disk-halo interface



Tüllmann+ (2000)

- CR pressure drops less quickly than thermal pressure ($P \propto \rho^{\gamma}$)
- CRs cool less efficiently than thermal gas
- CR pressure energizes the wind $\rightarrow$ "CR battery"
- poloidal ("open") field lines at wind launching site $\rightarrow$ CR-driven Parker instability

Review on cosmic ray feedback

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

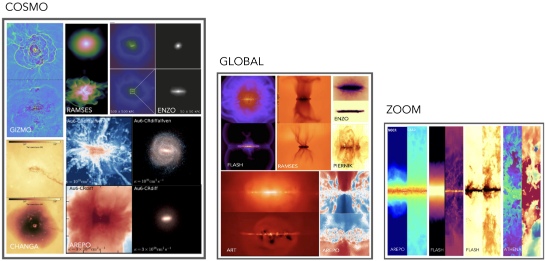
REVIEW ARTICLE

Check for updates

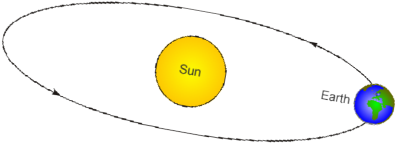
Cosmic ray feedback in galaxies and galaxy clusters

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:

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

gyro-orbit of GeV CR:

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

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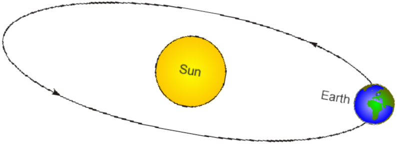

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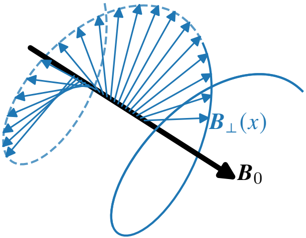
$\Rightarrow$ **link kinetic plasma physics to macroscopic MHD models on galactic scales!**

Zweibel (2017), Thomas & CP (2019)

What is gyro resonance?

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



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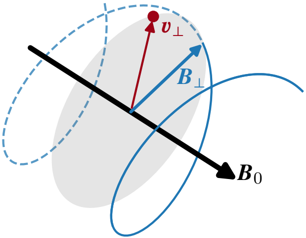
cosmic ray: $v_{||}$ movement along $\boldsymbol{B}_0$

Ω_{cr} gyration frequency



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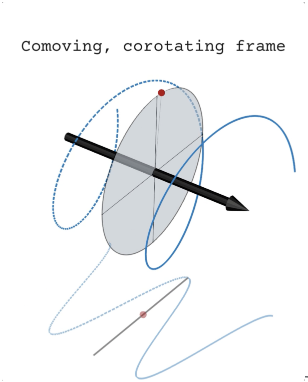

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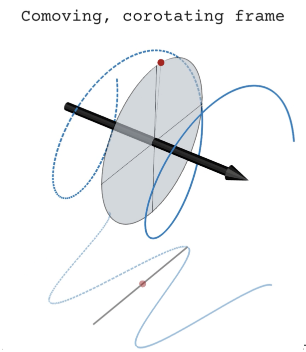
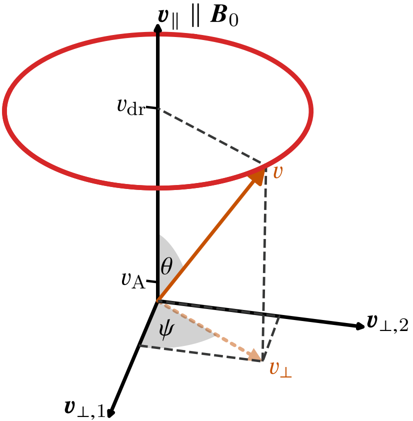
Resonant wave appears **static** to CR!



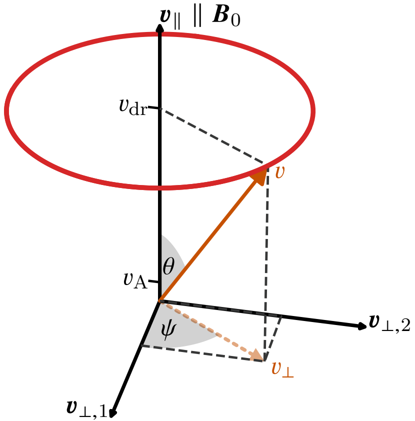
test particle without interactions!

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

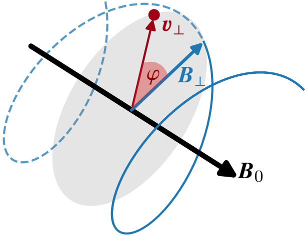


- gyrotropic ring distribution of CR ions with single pitch angle and energy
- neutralizing CR electron beam at same drift speed but $v_{\perp} = 0$
- background ion and electron fluid with Landau closure
- fluids coupled to particle-in-cell (PIC) CRs via Maxwell's equations

(Lemmerz+ 2024)

The mechanism of CR-driven instabilities

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



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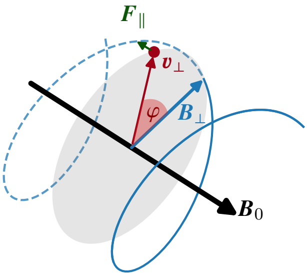

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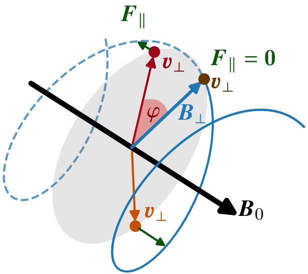

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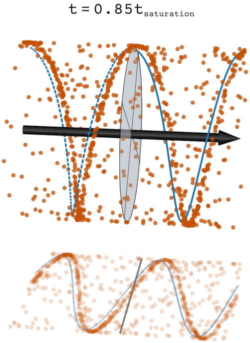

fluid-PIC simulation (Lemmerz+ 2025)

The mechanism of CR-driven instabilities

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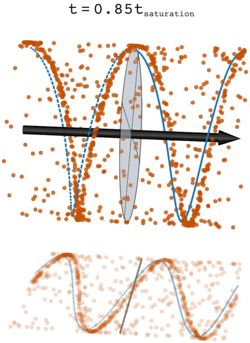
- CR current wave interacts with electro-magnetic wave
- CR trapping in Lorentz force potential saturates instability



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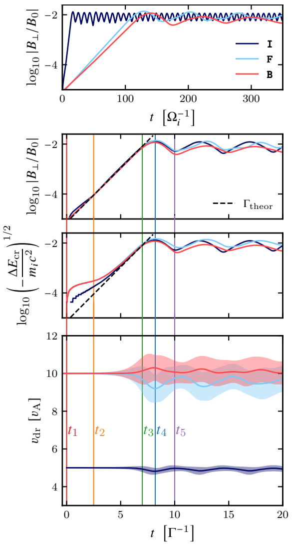
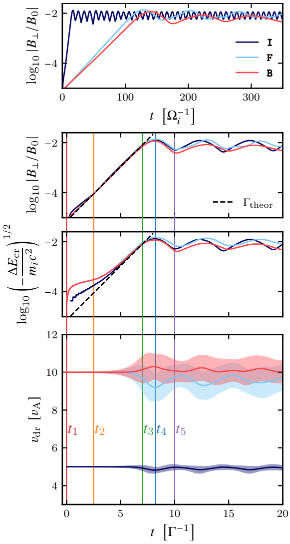
Resonant wave growth and CR energy loss



- 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



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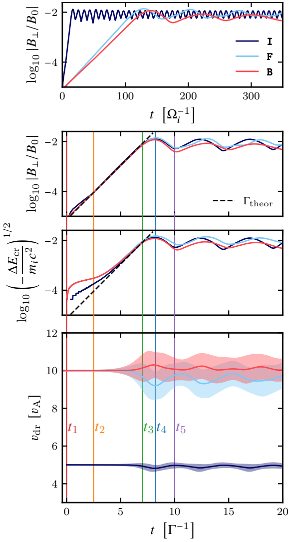
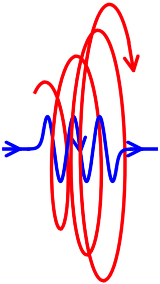


- exponential wave growth in fluid-PIC simulations that excite whistlers (via intermediate-scale instability, **I**), backward (**B**) and forward (**F**) Alfvén waves
- energy gain by waves exactly balances CR energy loss to the unstable modes
- mean CR drift speed, $v_{\rm dr}$, slows down for forward waves (**F** and **I**) and accelerates for backward waves (**B**): saturation at $v_{\rm dr} > v_{\rm A}$ for gyrotropic CR ring distribution

AIP

Cosmic ray streaming and diffusion

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



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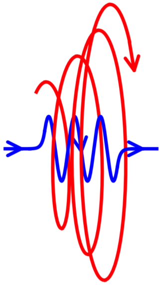

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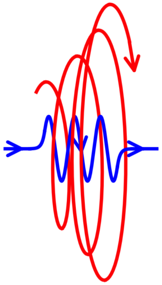
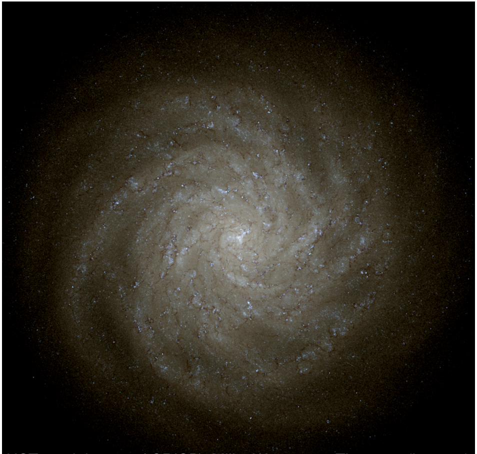


→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

Cosmic ray transport in galaxies

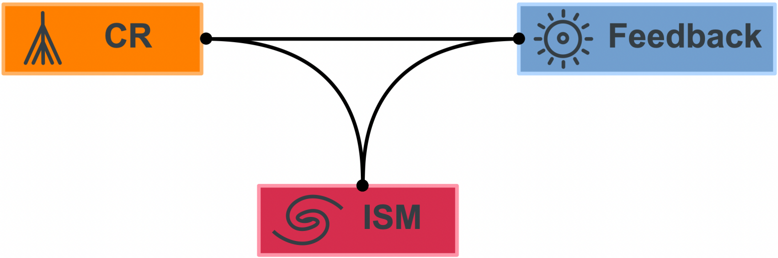

HST mock image of CRISPy Milky Way Thomas+ (in prep.)

- 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

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



Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework

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

Feedback

CR

ISM

Chemistry

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

Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework

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

CR

ISM

Feedback

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

Thomas, CP, Pakmor (2025)

Multi-phase ISM modeling

CRISP framework

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

Feedback

ISM

CR

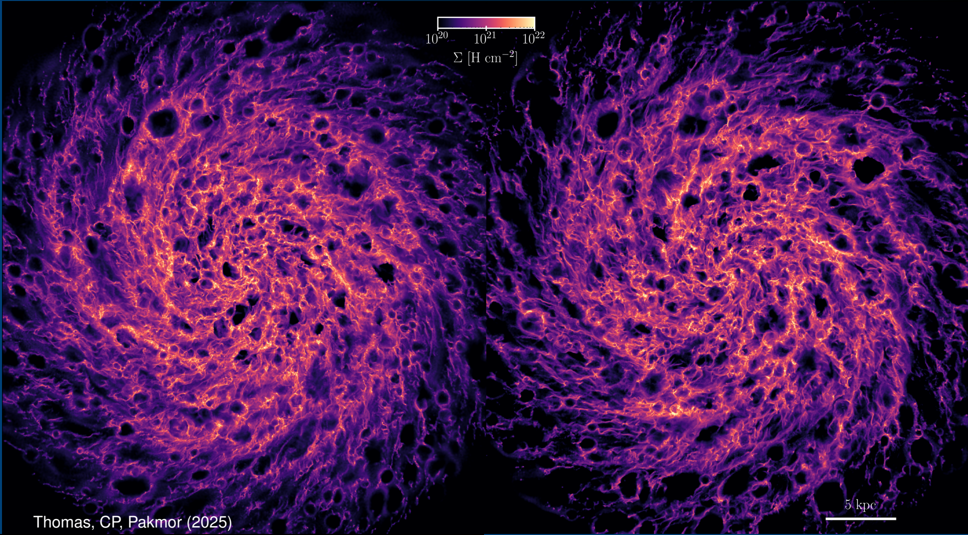
- Novel CR hydrodynamics
  coarse graining plasma physics
- CR ionization
  impacting **Chemistry**
- CR microphysics

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

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

Thomas, CP, Pakmor (2025)

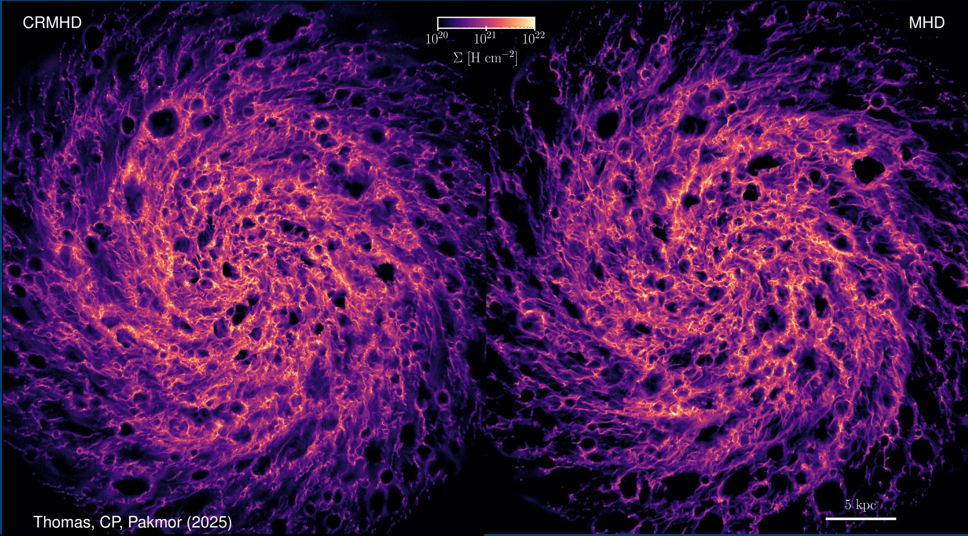
Multi-phase ISM modeling



Thomas, CP, Pakmor (2025)

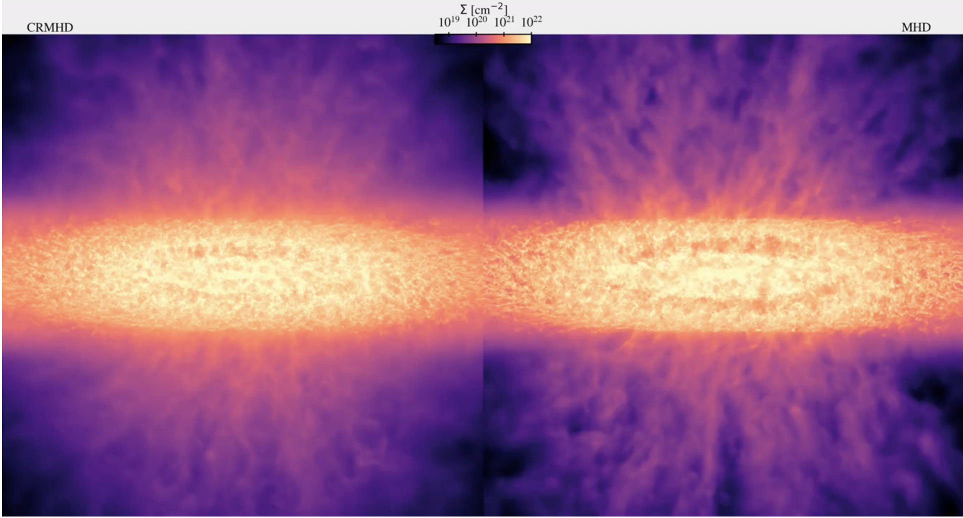
Multi-phase ISM modeling

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



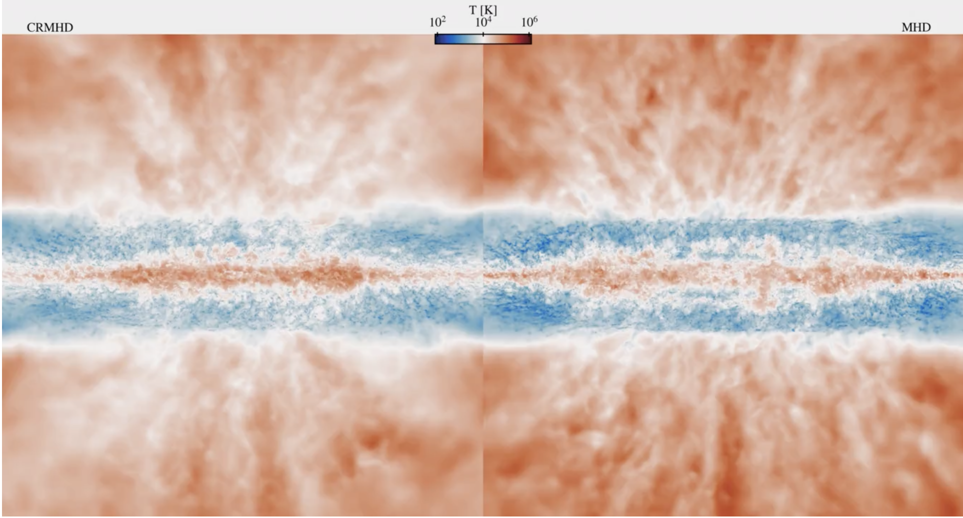
Simulated Milky Way: surface density

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



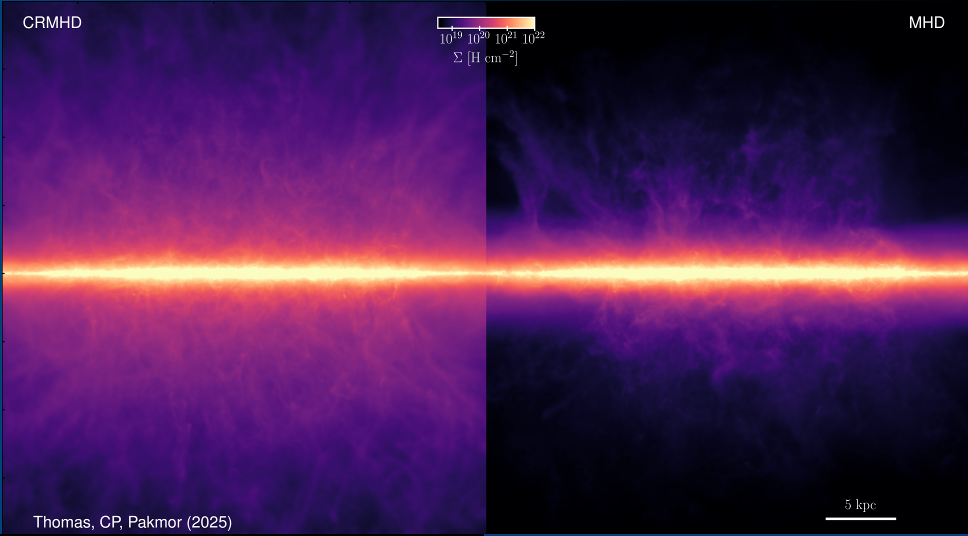
Simulated Milky Way: temperature

Galactic winds without cosmic rays are much hotter

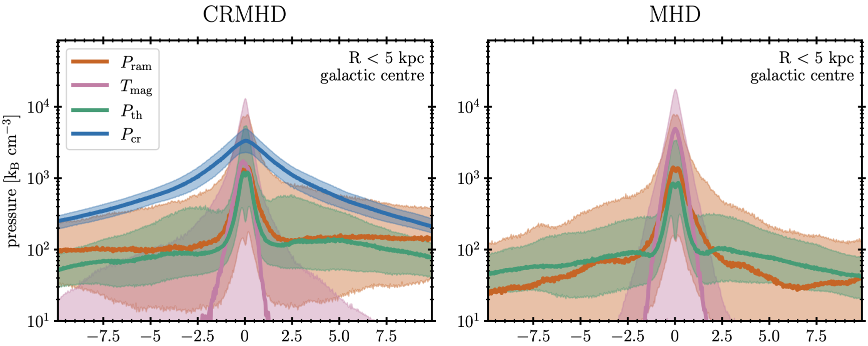


Multi-phase ISM modeling

Cosmic rays make galactic winds much denser



Cosmic ray driven wind: mechanism

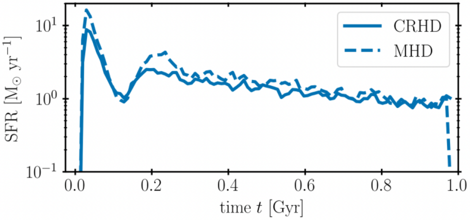


Thomas, CP, Pakmor (2025)

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

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

Mass and energy loading factors



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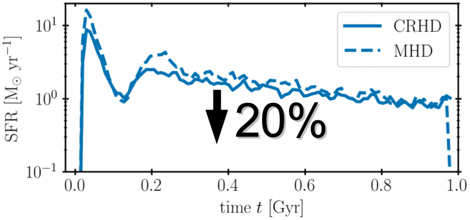
Mass and energy loading factors



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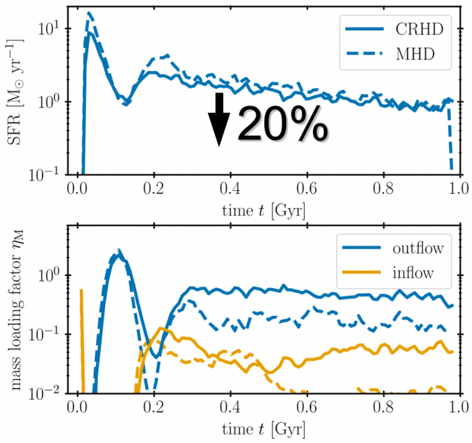
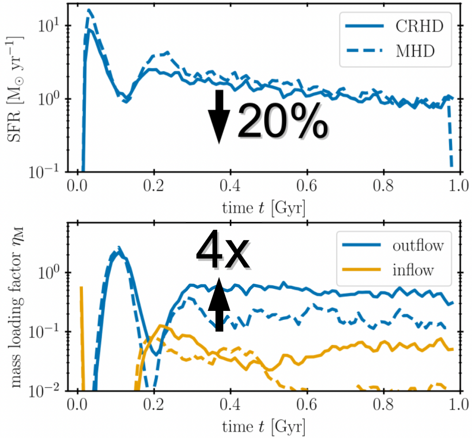
Mass and energy loading factors



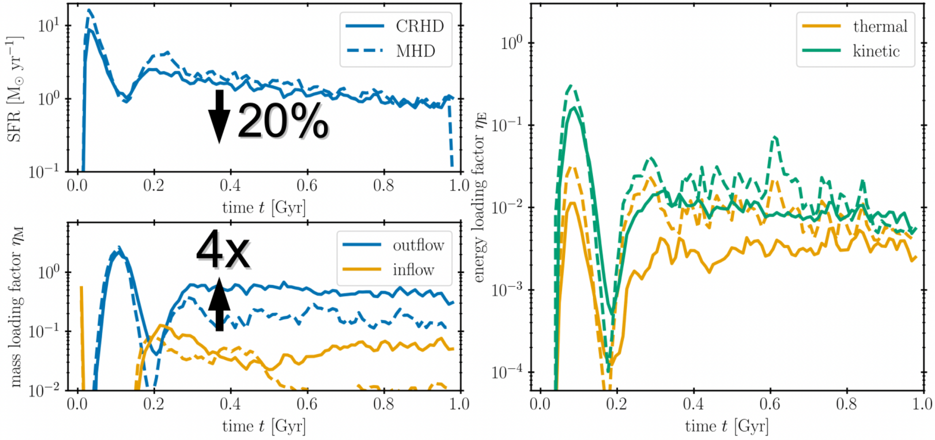
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



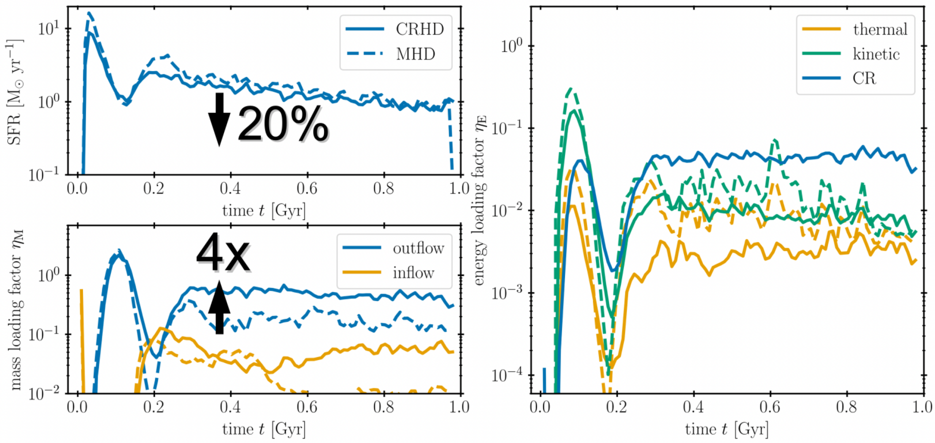
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



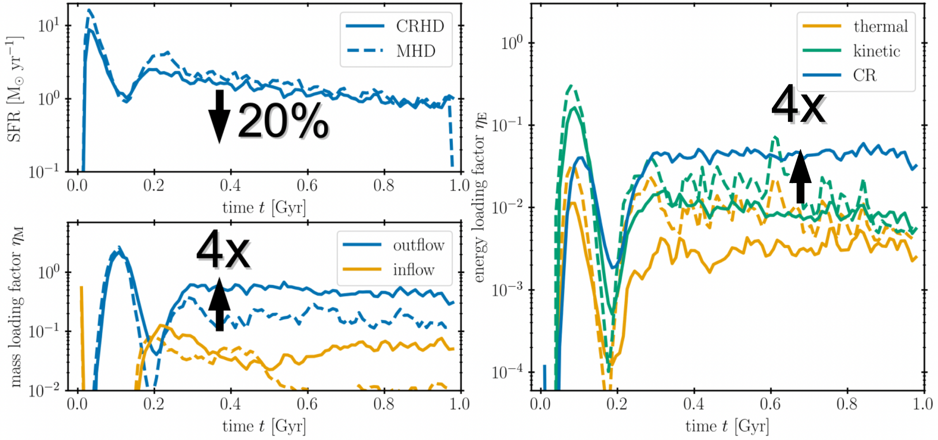
Thomas, CP, Pakmor (2025)

Mass and energy loading factors



Thomas, CP, Pakmor (2025)

Mass and energy loading factors



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Conclusions

Stellar feedback processes:

- Supernova feedback cannot drive galactic winds from disks but it can self-regulate the ISM
- Radiative feedback unable to drive winds in star-forming galaxies because photons leak out along underdense channels
- CR feedback drives powerful galactic winds and increases mass and energy loading factors

Conclusions

Stellar feedback processes:

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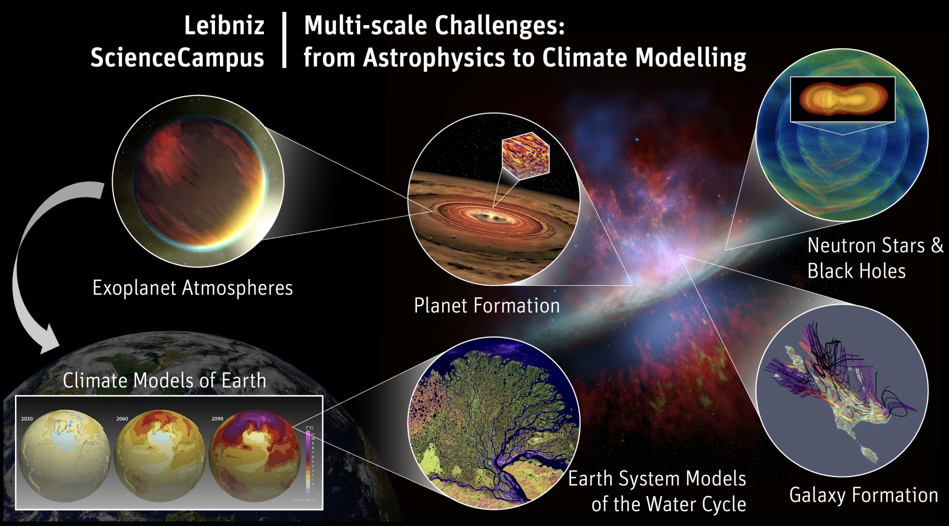
CR-driven plasma instabilities:

- CR-driven plasma-instabilities grow and saturate via phase bunching $\Rightarrow$ sets CR transport speed and feedback strength
- bunching theory extends traditional, quasilinear theory: growth of whistlers, forward and backward Alfvén waves
- self-generated diffusion coefficient emerges from CR-wave interactions

Bridging Astrophysics and Climate Modeling



PICOGAL: From Plasma KInetics to COsmological GALaxy Formation

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