How cosmic rays shape galaxies

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in collaboration with

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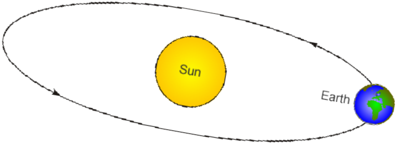
New Perspectives on Galactic Magnetism, Newcastle – Jun 2019

Outline

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

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

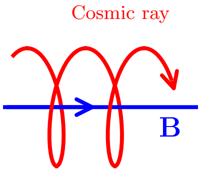
gyro-orbit of GeV cosmic ray:

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

$\Rightarrow$ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

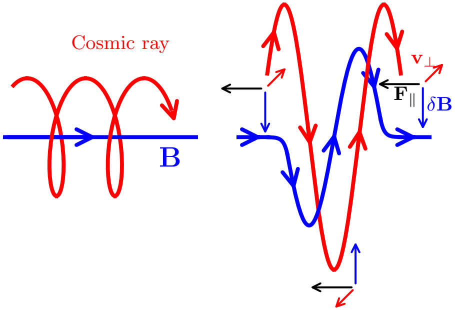
Zweibel (2017), Jiang & Oh (2018), Thomas & CP (2018)

Interactions of CRs and magnetic fields



sketch: Jacob

Interactions of CRs and magnetic fields



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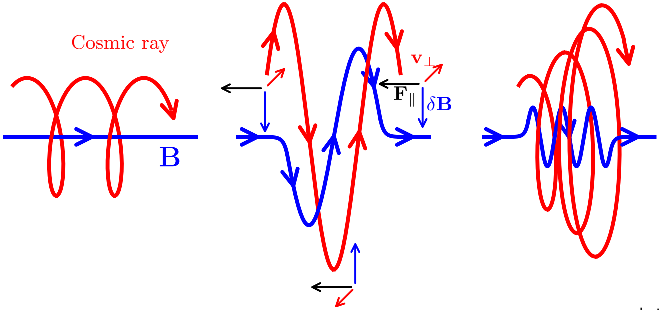
- **gyro resonance:** $\omega - k_\| v_\| = n\Omega$

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

Interactions of CRs and magnetic fields

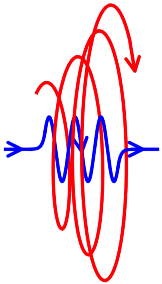


sketch: Jacob

- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields $\to$ isotropization of CR momenta

CR streaming and diffusion

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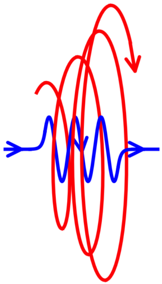

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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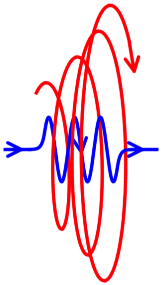
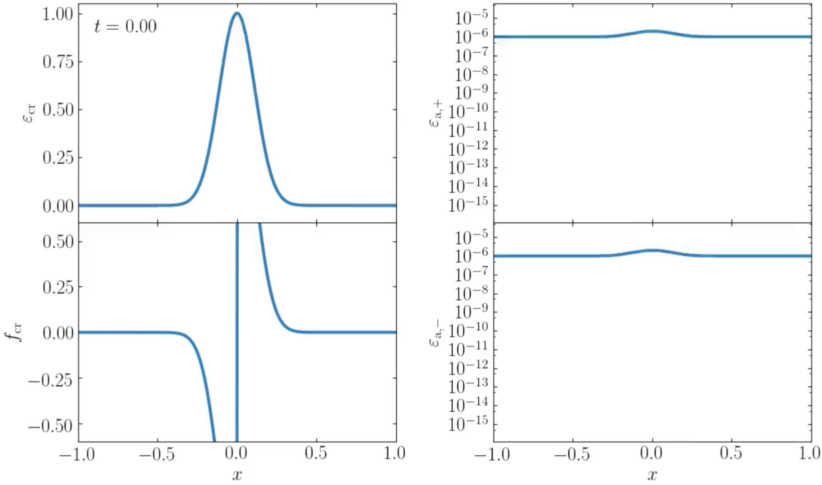


$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

Non-equilibrium CR streaming and diffusion

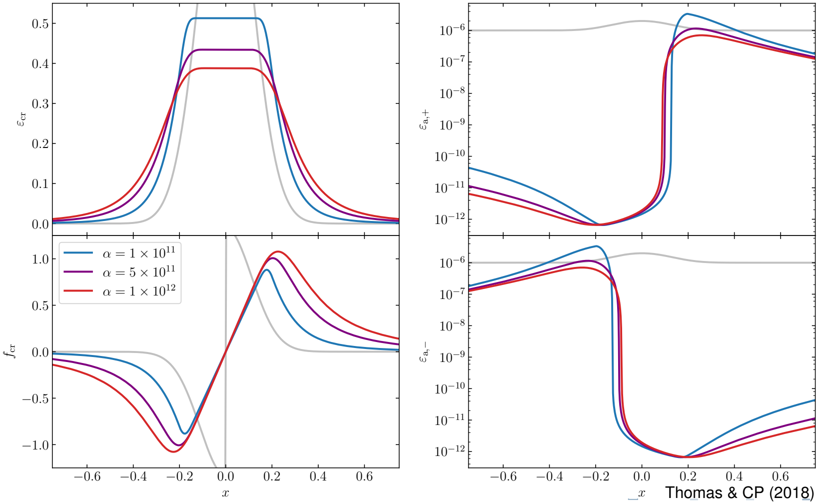
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

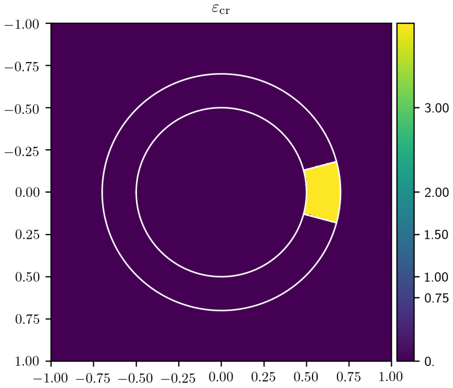


Thomas & CP (2018)

Anisotropic CR streaming and diffusion – AREPO

CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics

- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving

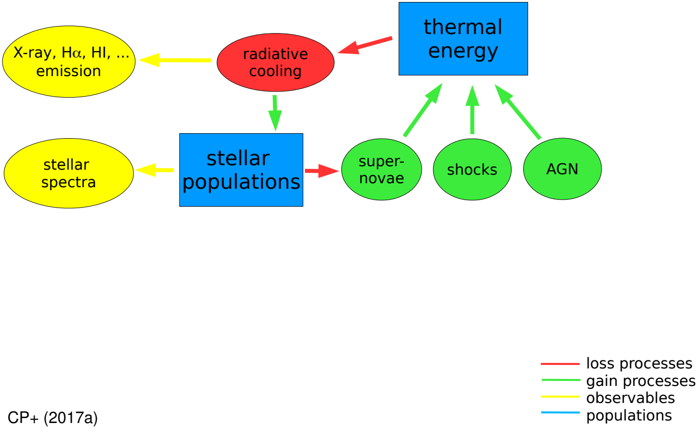


Thomas, Pakmor, CP (in prep.)

Simulations – flowchart

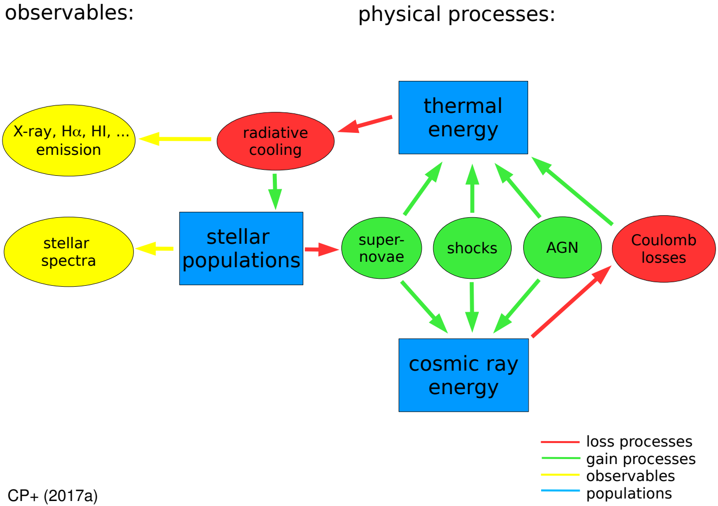
observables:

physical processes:



CP+ (2017a)

Simulations with cosmic ray physics



CP+ (2017a)

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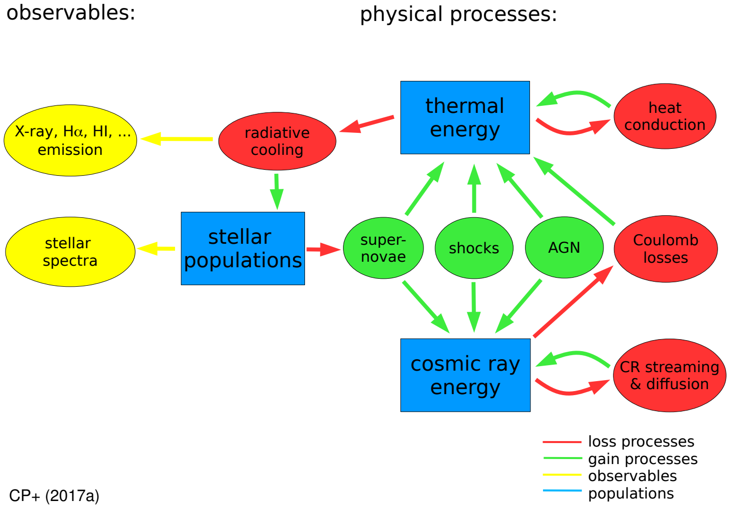

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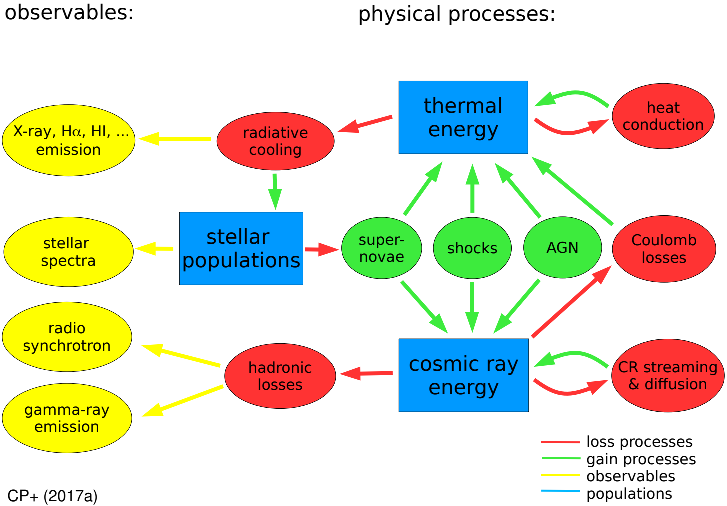
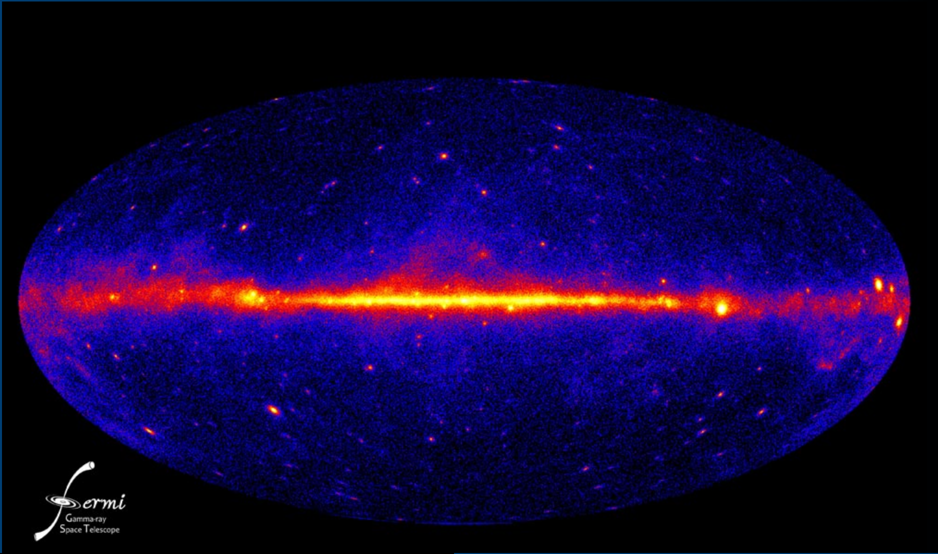
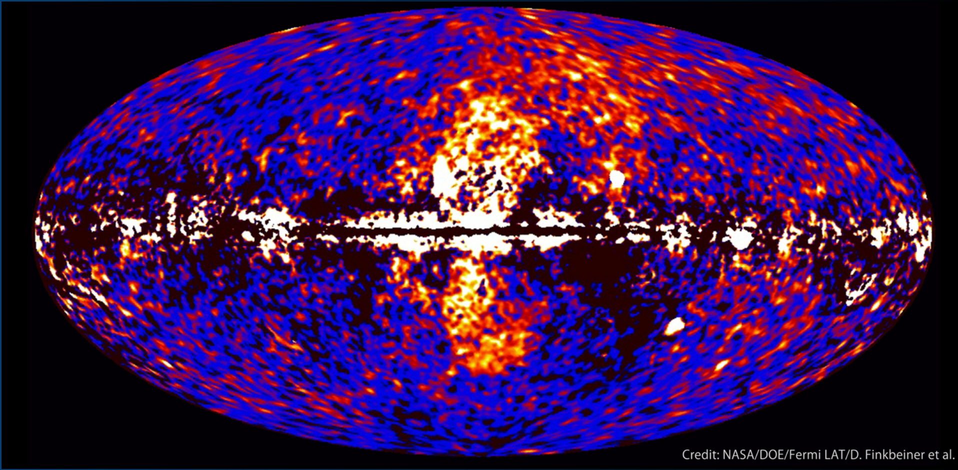


CP+ (2017a)

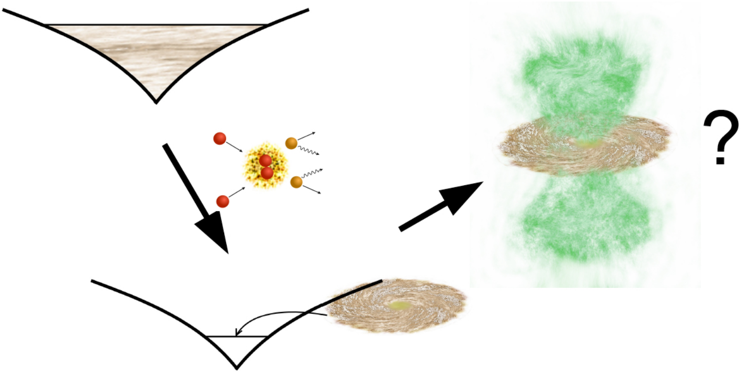
Gamma-ray emission of the Milky Way



Galactic wind in the Milky Way?
Fermi gamma-ray bubbles



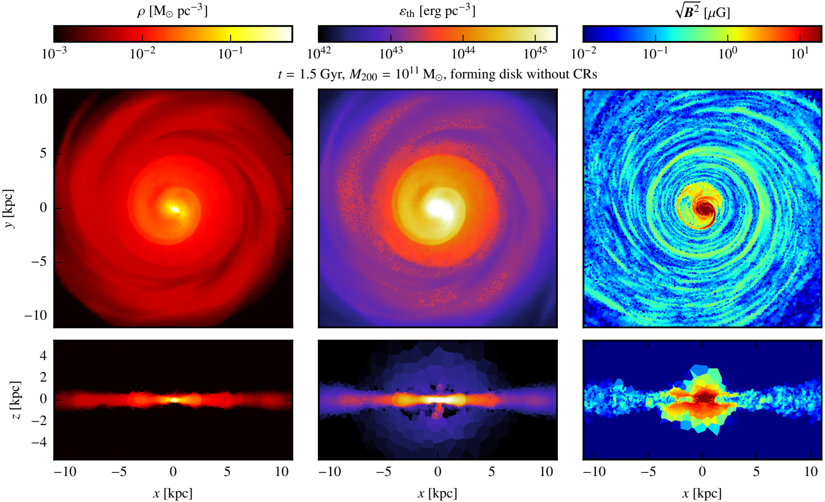
Galaxy simulation setup: 1. cosmic ray advection



CP, Pakmor, Schaal, Simpson, Springel (2017a)
Simulating cosmic ray physics on a moving mesh

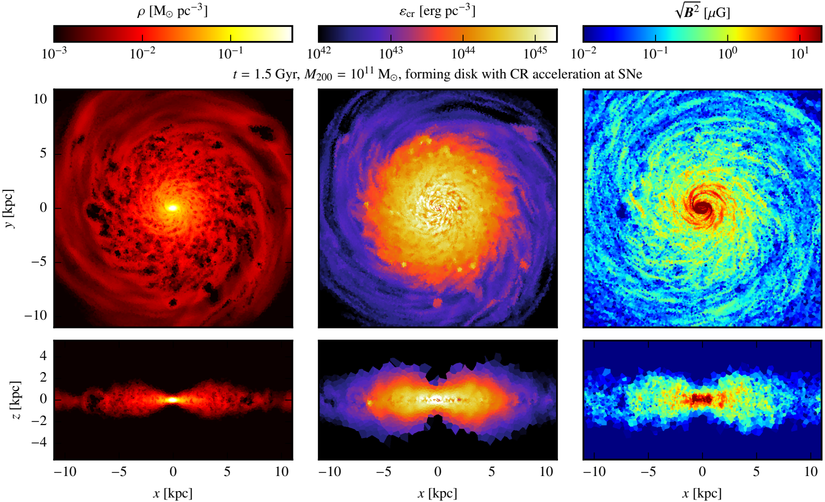
MHD + cosmic ray advection: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

MHD galaxy simulation without CRs



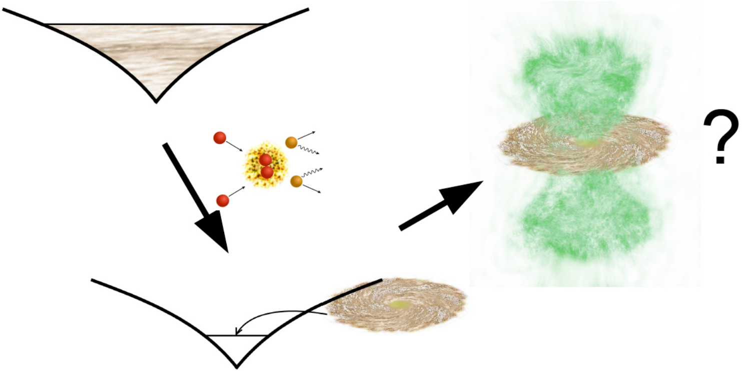
CP+ (2017a)

MHD galaxy simulation with CRs



CP+ (2017a)

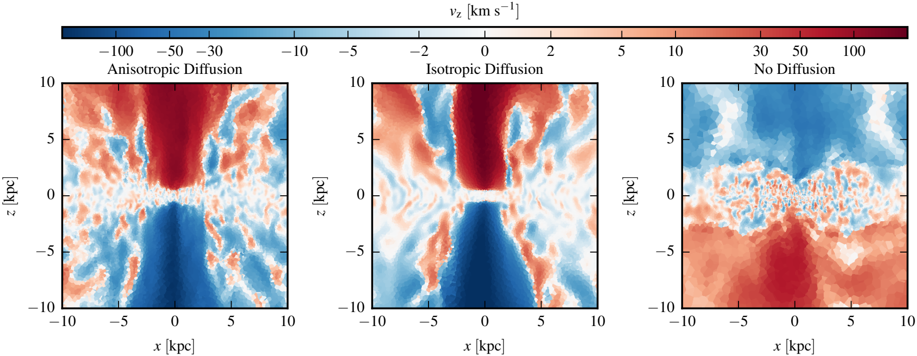
Galaxy simulation setup: 2. cosmic ray diffusion



Pakmor, CP, Simpson, Springel (2016)
Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies

MHD + CR advection + diffusion: $10^{11}\,M_\odot$

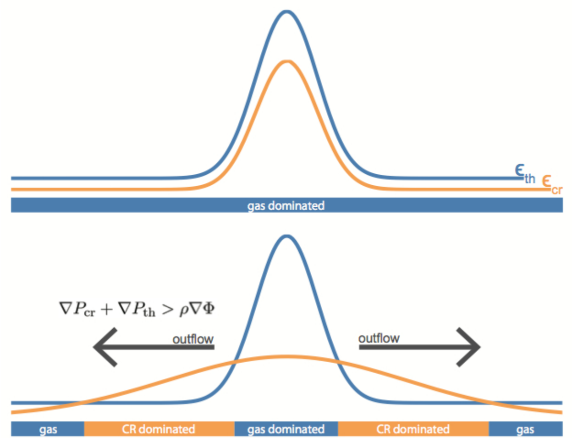
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

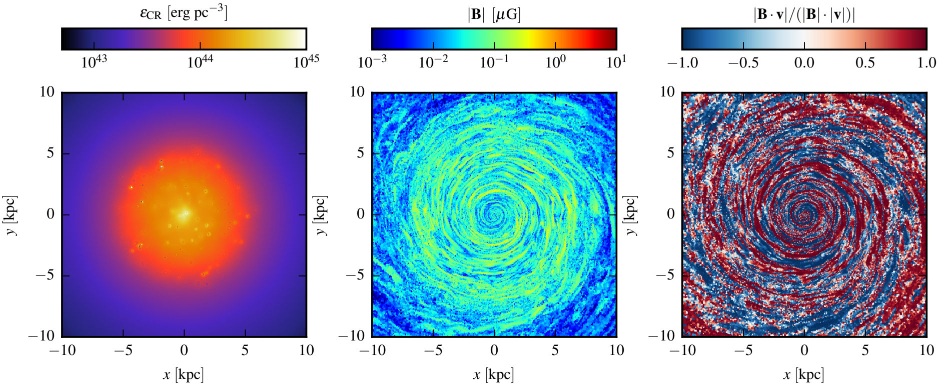
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

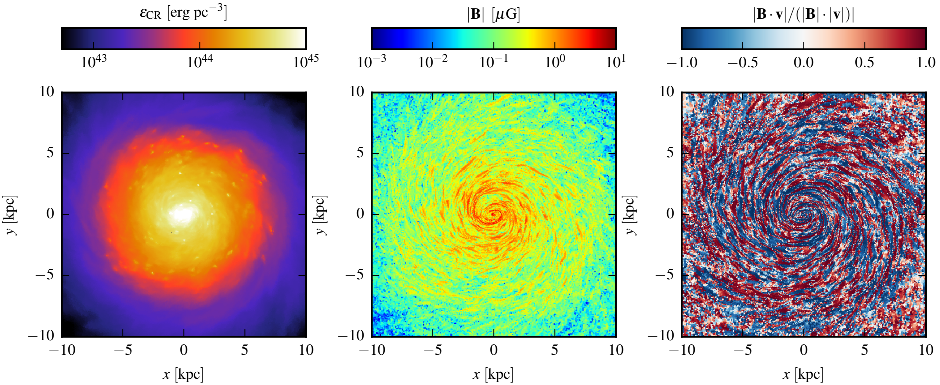
MHD galaxy simulation with CR isotropic diffusion



Pakmor, CP, Simpson, Springel (2016)

- CR diffusion strongly suppresses SFR
- strong outflow quenches magnetic dynamo to yield $B \sim 0.1\ \mu$G

MHD galaxy simulation with CR anisotropic diffusion

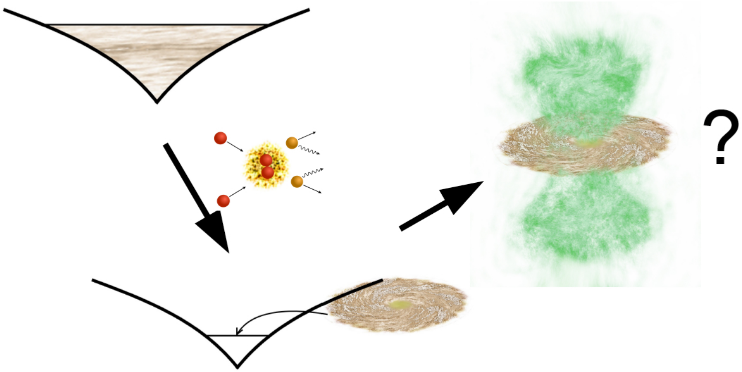


Pakmor, CP, Simpson, Springel (2016)

- anisotropic CR diffusion also suppresses SFR
- reactivation of magnetic dynamo: growth to observed strengths

AIP

Galaxy simulation setup: 3. non-thermal emission

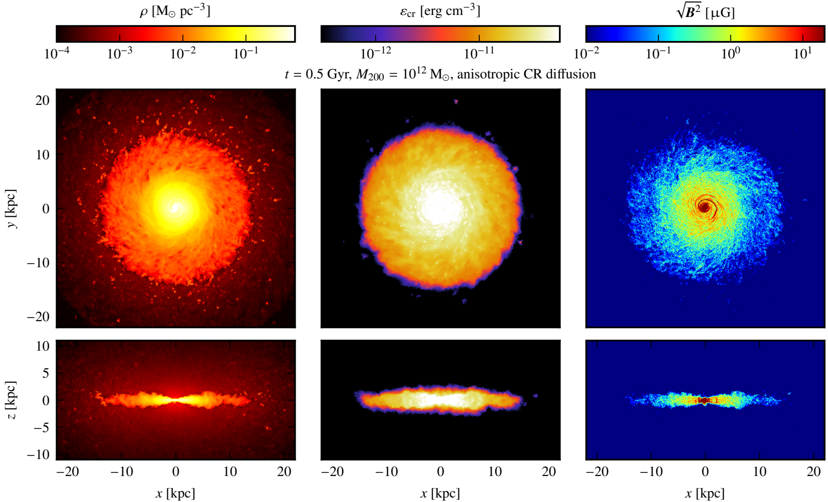


CP, Pakmor, Simpson, Springel (2017b, in prep.)
Simulating radio synchrotron and gamma-ray emission in galaxies

MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

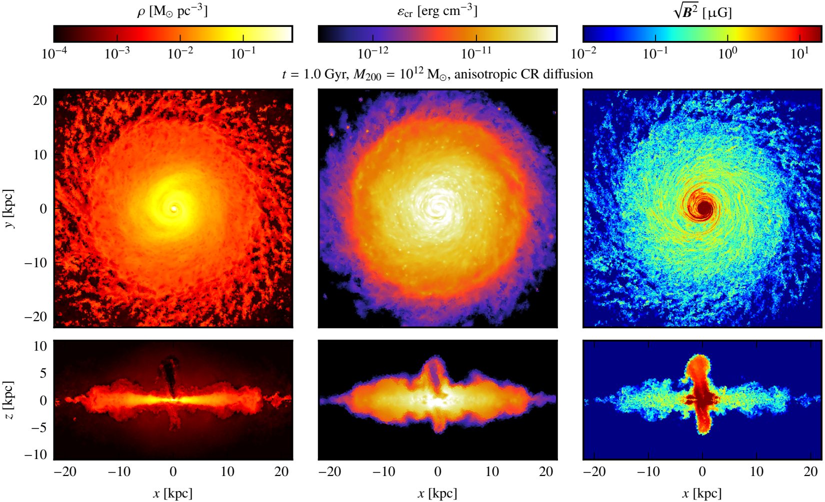
AIP

Simulation of Milky Way-like galaxy, $t = 0.5$ Gyr



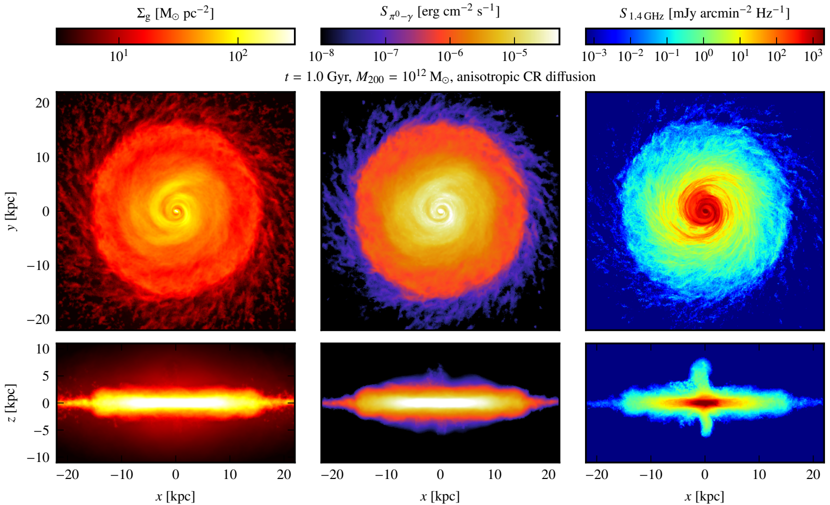
CP+ (2017b, in prep.)

Simulation of Milky Way-like galaxy, $t = 1.0$ Gyr



CP+ (2017b, in prep.)

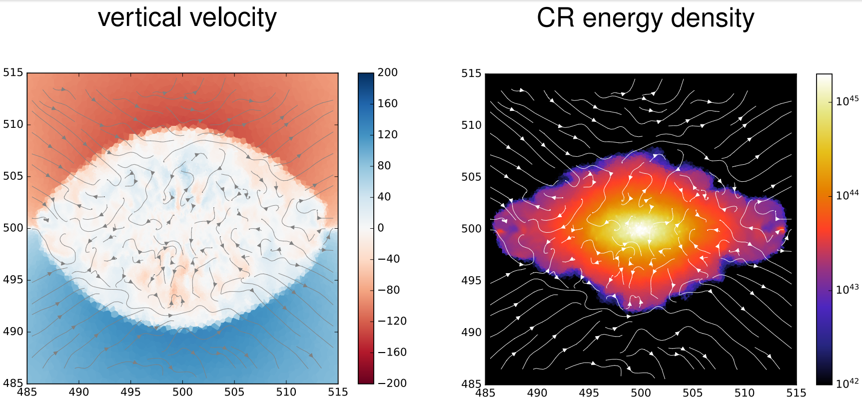
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, in prep.)

Radio synchrotron polarization

Isolated galaxy simulation, $M_{200} = 10^{11}\,\mathrm{M}_\odot$, $t = 0.5$ Gyr



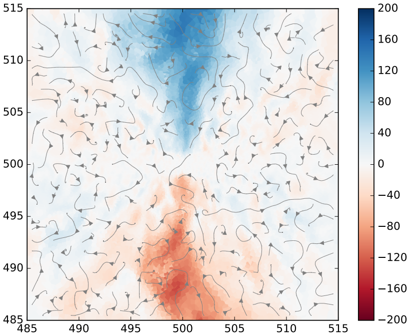
- arrows: projected polarized synchrotron emission at 5 GHz

$\Rightarrow$ Faraday depolarization effects negligible

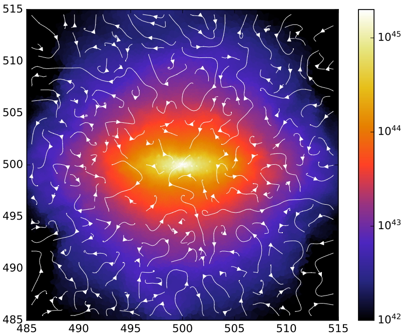
Radio synchrotron polarization

Isolated galaxy simulation, $M_{200} = 10^{11}\,\mathrm{M}_\odot$, $t = 1.0$ Gyr

vertical velocity



CR energy density



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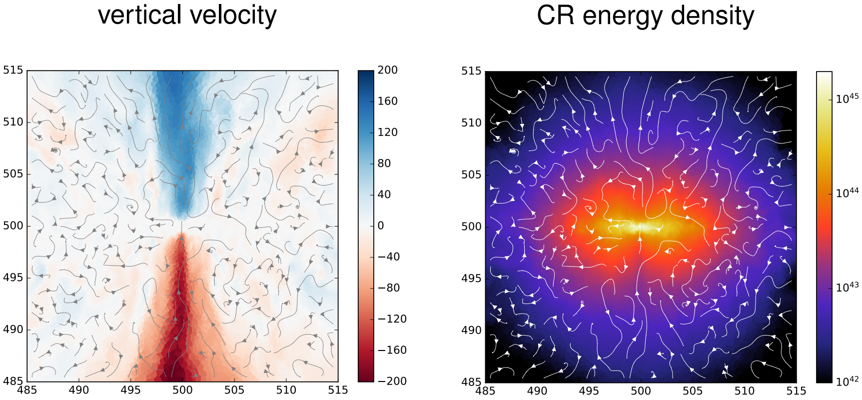
Radio synchrotron polarization

Isolated galaxy simulation, $M_{200} = 10^{11}\,\mathrm{M}_\odot$, $t = 1.5$ Gyr

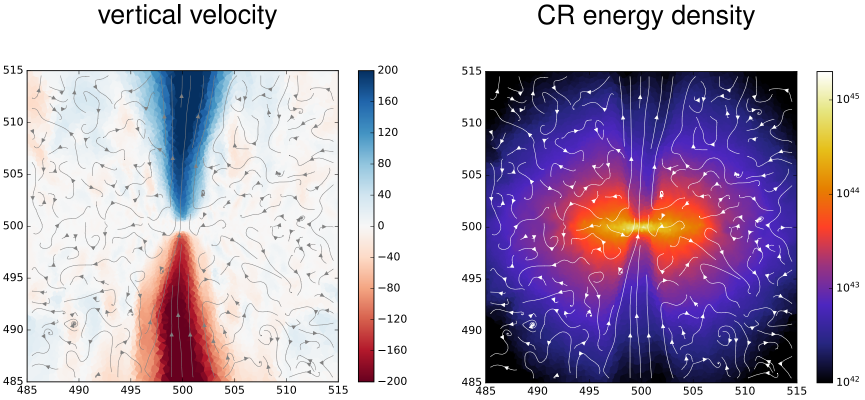


- arrows: projected polarized synchrotron emission at 5 GHz

$\Rightarrow$ Faraday depolarization effects negligible

Radio synchrotron polarization

Isolated galaxy simulation, $M_{200} = 10^{11}\ \mathrm{M}_\odot$, $t = 2.0$ Gyr



- arrows: projected polarized synchrotron emission at 5 GHz

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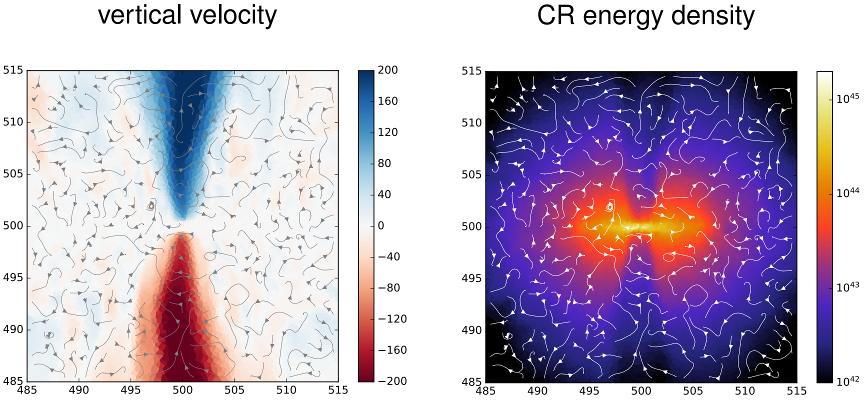
Radio synchrotron polarization

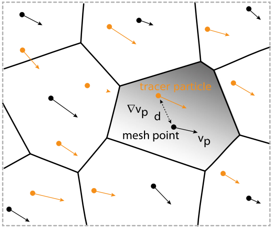
Isolated galaxy simulation, $M_{200} = 10^{11}\ \mathrm{M}_\odot$, $t = 2.0$ Gyr

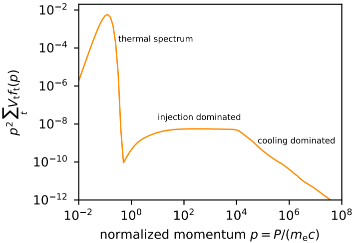


- arrows: projected polarized synchrotron emission **at 100 MHz**

$\Rightarrow$ Faraday depolarization effects **important**

CREST - Cosmic Ray Electron Spectra evolved in Time





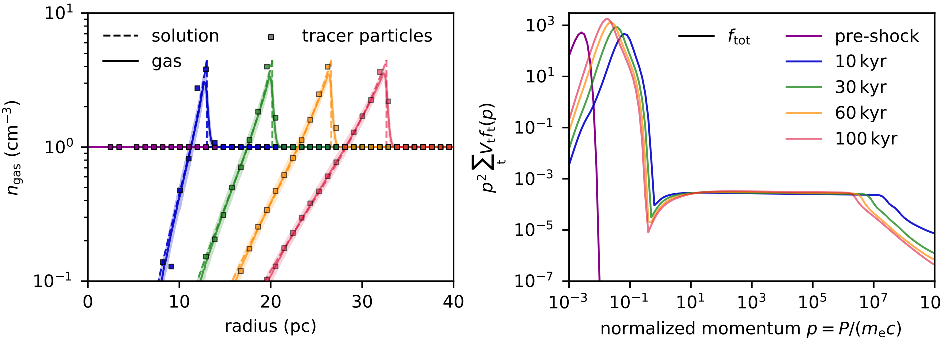
CREST code (Winner+ 2019)

- post-processing MHD simulations
- on Lagrangian particles
  - adiabatic processes
  - Coulomb and radiative losses
  - Fermi-I (re-)acceleration
  - Fermi-II reacceleration
  - secondary electrons

Link to observations

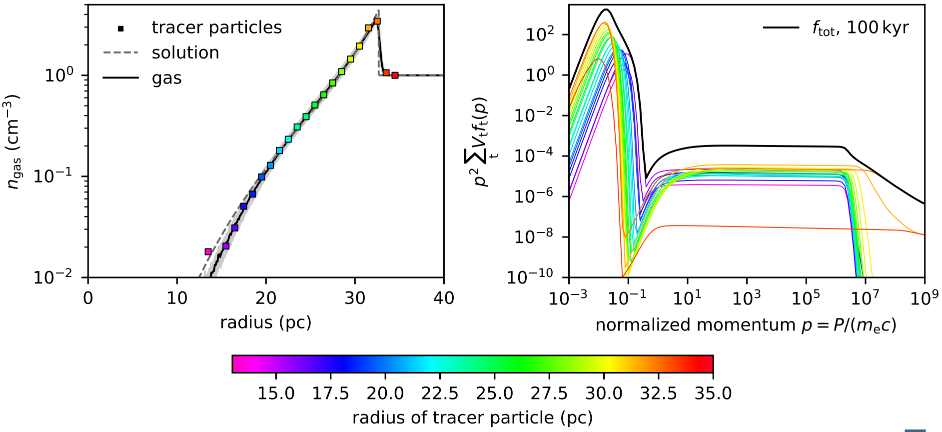
- radio synchrotron
- inverse Compton γ-ray

Sedov–Taylor blast wave: spectral evolution



$E_0 = 10^{51}$ erg, $n_{\rm gas} = 1\,{\rm cm}^{-3}$, $T_0 = 10^4$ K, $B = 1\,\mu$G

Sedov–Taylor blast wave: radial contribution



Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR diffusion/streaming
- anisotropic CR diffusion necessary for efficient galactic dynamo: observed field strengths of $B \sim 10\,\mu$G
- more realistic radio modelling with CREST

Conclusions on CR feedback in galaxies and clusters

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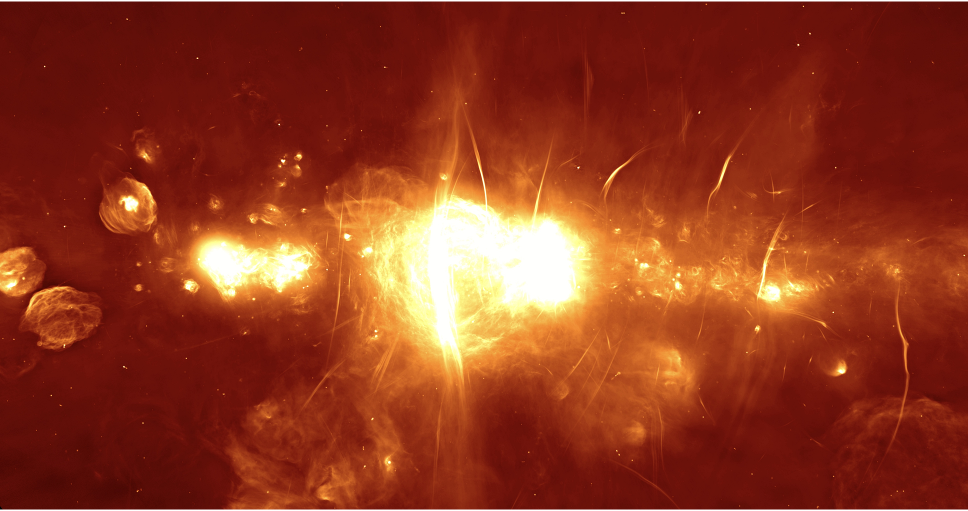
outlook: improved modeling of plasma physics, follow CR spectra, cosmological settings

need: comparison to resolved radio/γ-ray observations $\rightarrow$ **SKA/CTA**

CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter 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 CRAGSMAN–646955).

MeerKAT: Galactic center region



Literature for the talk

Cosmic ray feedback in galaxies:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, MNRAS.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.
- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2019, MNRAS.

Non-thermal radio and gamma-ray emission in galaxies:

- Pfrommer, Pakmor, Simpson, Springel, *Simulating Gamma-ray Emission in Star-forming Galaxies,* 2017b, ApJL.
- Winner, Pfrommer, Girichidis, Pakmor, *Evolution of cosmic ray electron spectra in magnetohydrodynamical simulations*, 2019, subm.