Cosmic Rays in Galaxy Formation: Acceleration, Transport, and Feedback

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in collaboration with

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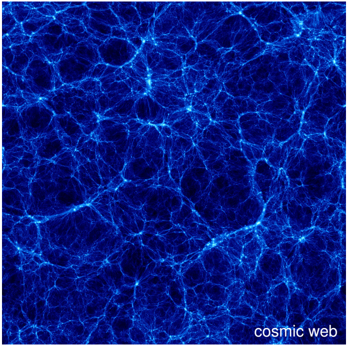
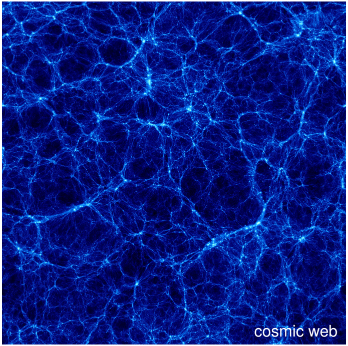
Connecting Micro & Macro Scales in Astrophysical Plasmas, KITP '19

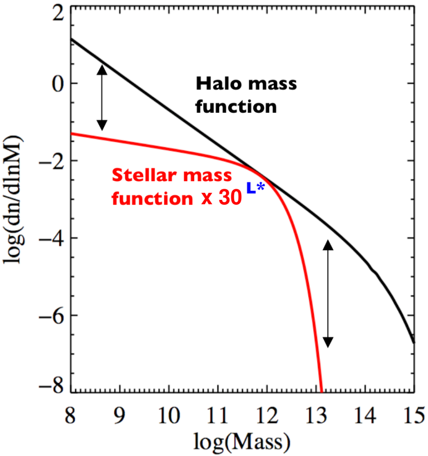
Does plasma physics matter in galaxy formation?

Galaxy formation in dark matter halos

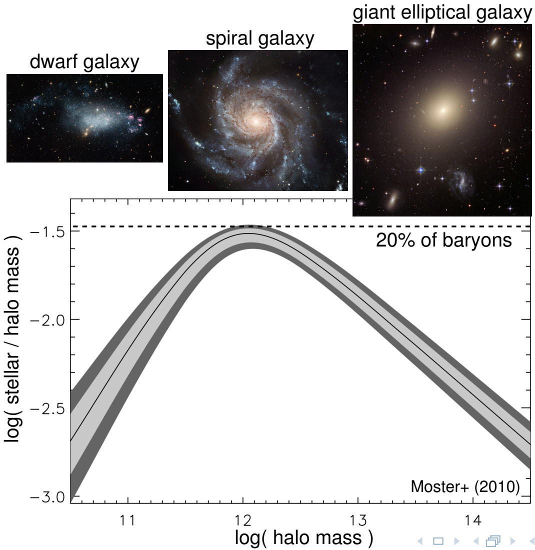


Galaxy formation in dark matter halos



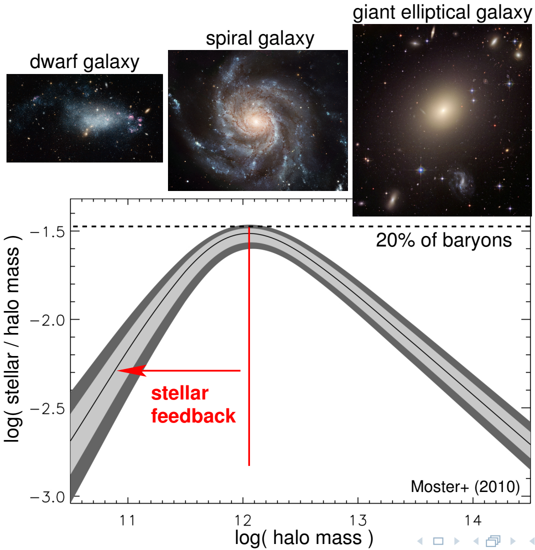


Puzzles in galaxy formation

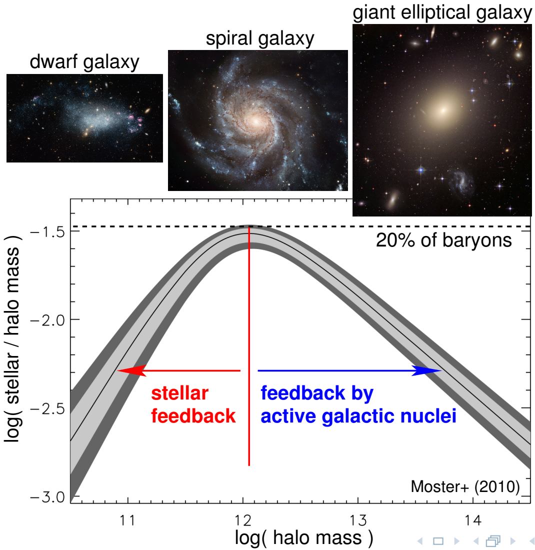


AIP

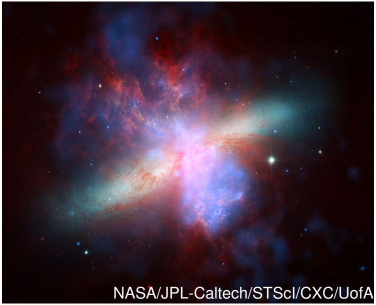
Puzzles in galaxy formation



Puzzles in galaxy formation



How are galactic winds driven?



super wind in M82

- thermal pressure provided by supernovae or AGNs?
- radiation pressure and photoionization by massive stars and QSOs?
- cosmic-ray pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

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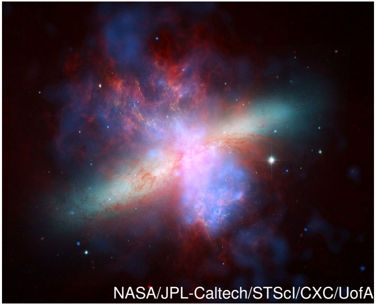

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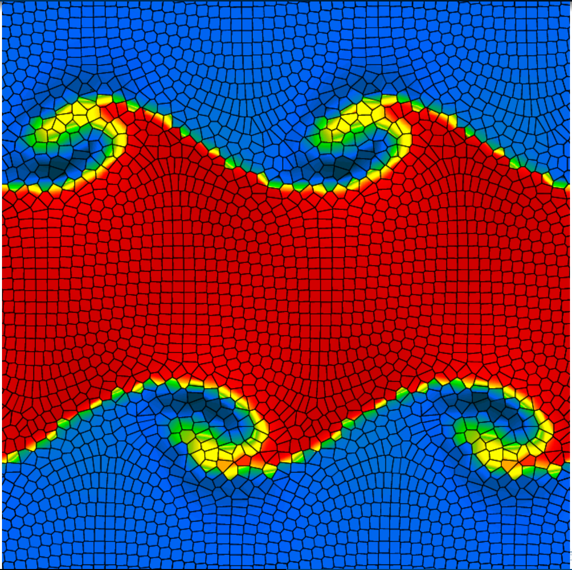
observed energy equipartition between cosmic rays, thermal gas and magnetic fields not a coincidence
→ suggests self-regulated feedback loop with CR driven winds

Outline

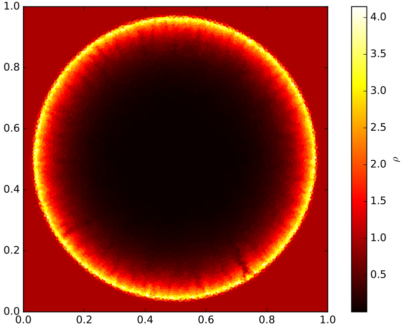
1. Cosmic ray acceleration
   - Introduction
   - Proton acceleration
   - Electron acceleration
2. Cosmic ray transport
   - The picture
   - CR hydrodynamics
   - Numerical solutions
3. Cosmic ray feedback
   - Modeling physics
   - Galaxy simulations
   - Cosmological simulations

Cosmological moving-mesh code AREPO (Springel 2010)

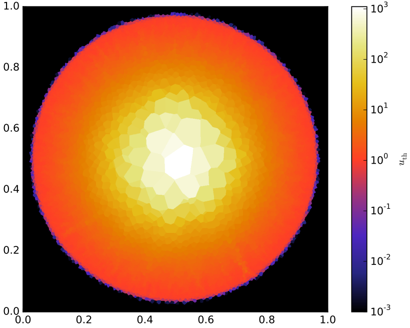


Sedov explosion

density



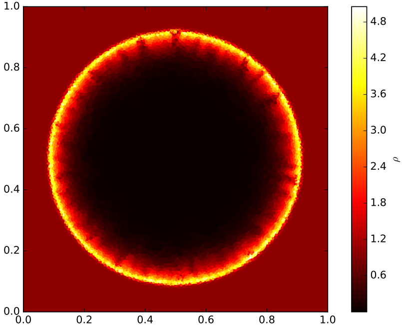
specific thermal energy



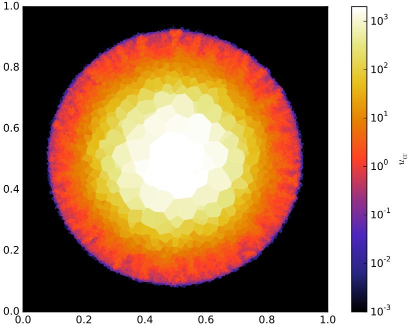
CP+ (2017a)

Sedov explosion with CR acceleration

density



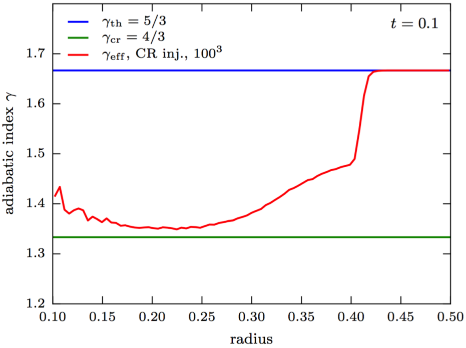
specific cosmic ray energy



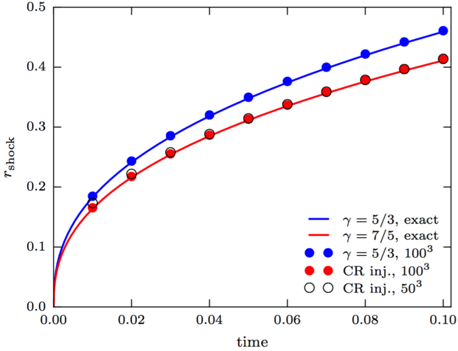
CP+ (2017a)

Sedov explosion with CR acceleration

adiabatic index



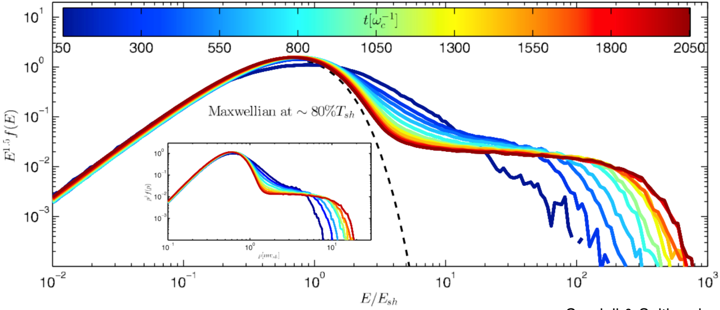
shock evolution



CP+ (2017a)

Ion spectrum

Non-relativistic *parallel shock* in long-term hybrid simulation

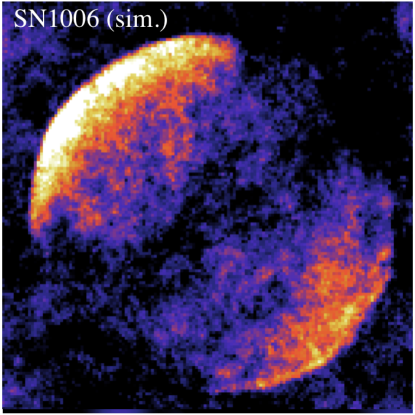


Caprioli & Spitkovsky (2014)

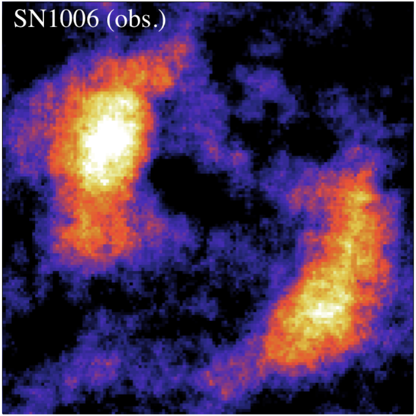
- quasi-parallel shocks ($\boldsymbol{B} \parallel \boldsymbol{n}_s$) accelerate ions
- quasi-perpendicular shocks ($\boldsymbol{B} \perp \boldsymbol{n}_s$) cannot
- model magnetic obliquity in AREPO simulations

TeV γ rays from shell-type SNRs: SN 1006

AREPO simulation



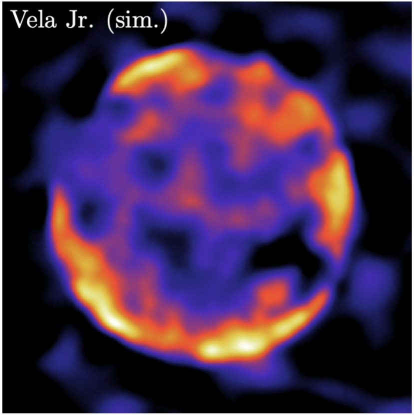
H.E.S.S. observation



Pais, CP (in prep.)

TeV γ rays from shell-type SNRs: Vela Junior

AREPO simulation



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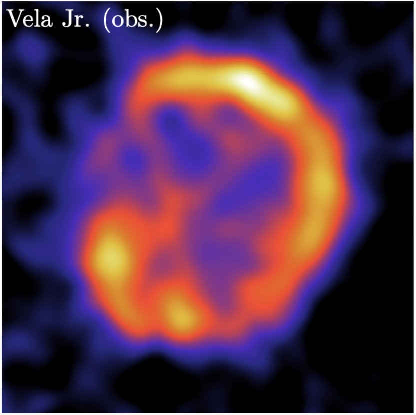
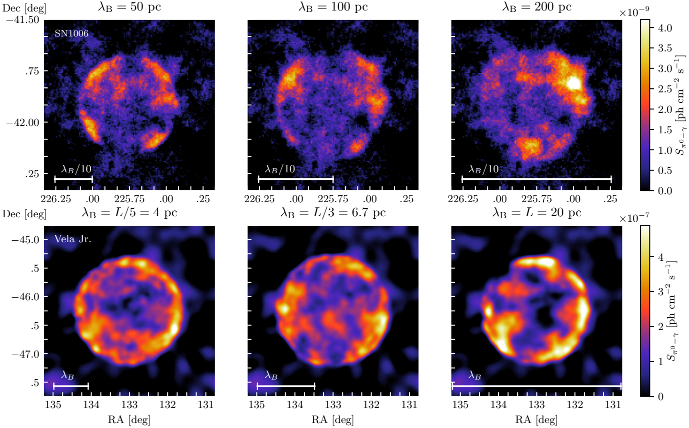


Pais, CP (in prep.)

TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN1006 and Vela Junior

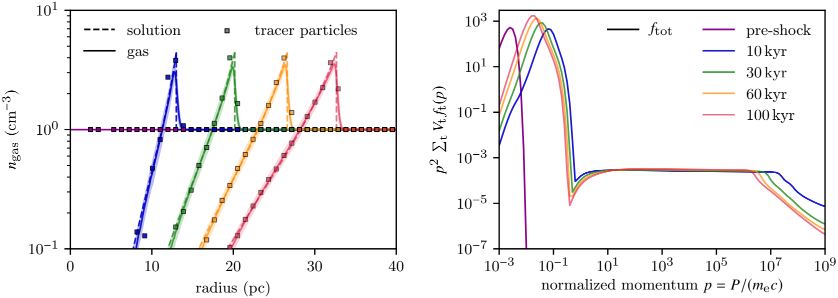


Pais, CP, Ehlert, Werhahn (2019)

SNR 1006: $\lambda_B > 200^{+10}_{-60}$ pc Vela Junior: $\lambda_B = 8^{+15}_{-6}$ pc

Electron acceleration at supernova remnants

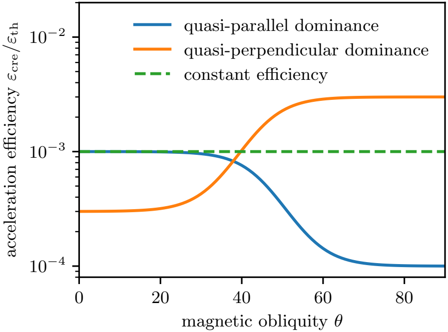
Solve Fokker Planck equation for electrons on Lagrangian trajectories



Winner, CP, Girichidis, Pakmor (2019)

- find shock surface at each timestep, model Bell-amplified ***B*** field
- inject CR electron power-law spectrum (account for numerically broadened shock)
- follow Coulomb, synchrotron and inverse Compton cooling
- model radio, X-ray and inverse Compton emission

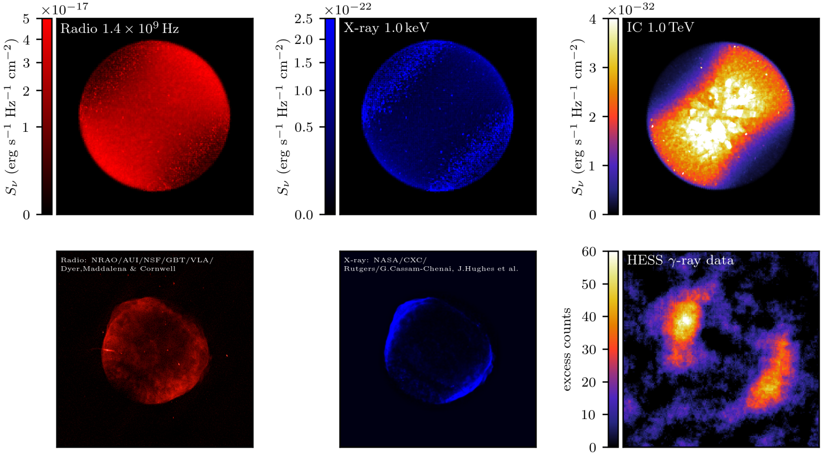
Electron acceleration efficiency



- quasi-perp. shocks ($\boldsymbol{B} \perp \boldsymbol{n}_{\mathrm{s}}$) inject and accelerate(?) electrons (Xu+ 2019)
- quasi-parallel shocks ($\boldsymbol{B} \parallel \boldsymbol{n}_{\mathrm{s}}$) inefficiently accelerate electrons alongside ions (Park+ 2015)
- how can we test these PIC results?

Testing electron acceleration with global SNR sim's

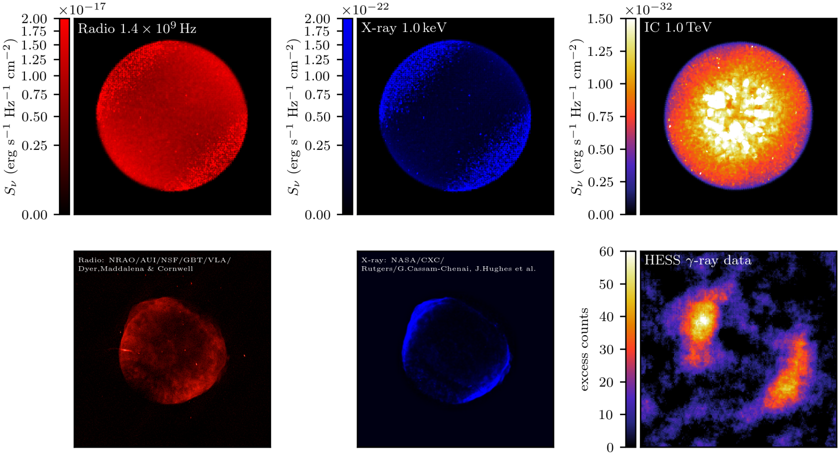
Preferred quasi-perpendicular e^- acceleration: radio, X-ray and IC in SN1006



Winner, CP, Girichidis, Werhahn (in prep.)

Testing electron acceleration with global SNR sim's

Constant e^- acceleration efficiency: radio, X-ray and IC in SN1006



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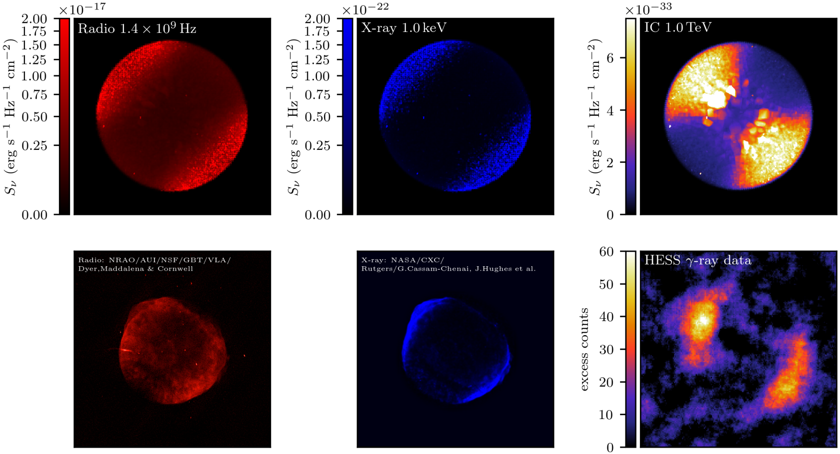
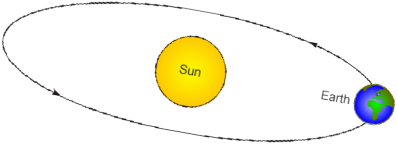
Testing electron acceleration with global SNR sim’s

Preferred quasi-parallel e^- acceleration: radio, X-ray and IC in SN1006



Winner, CP, Girichidis, Werhahn (in prep.)

Cosmic ray transport: an extreme multi-scale problem



Milky Way-like galaxy:

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

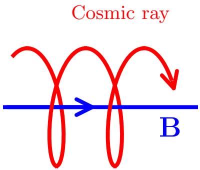
gyro-orbit of GeV cosmic ray:

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

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

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

Interactions of CRs and magnetic fields



sketch: Jacob

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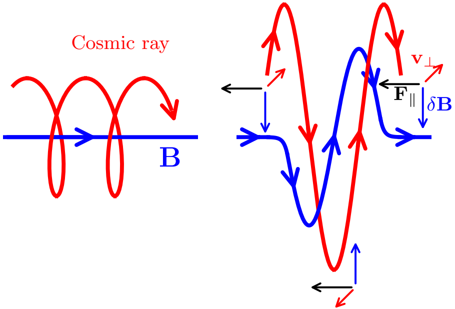

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- **gyro resonance:** $\omega - k_\parallel v_\parallel = n\Omega$

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

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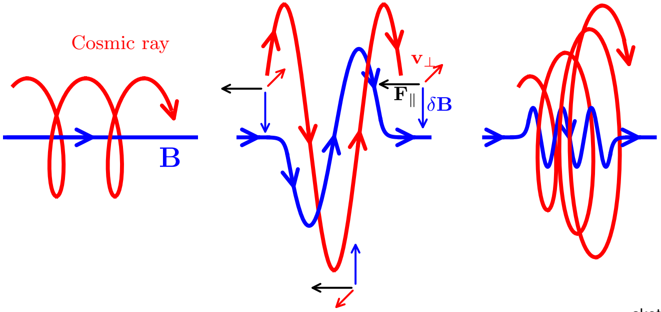
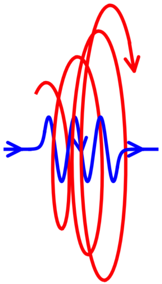


sketch: Jacob

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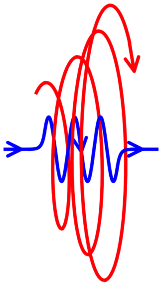

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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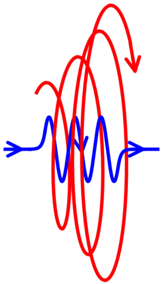

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

Analogies of CR and radiation hydrodynamics

CRs and radiation are relativistic fluids

regime	CR transport	radiation HD analogy
• tangled ***B***, strong scattering	CR diffusion	diffusive transport in clumpy medium
• resolved ***B***, strong scattering	CR streaming with $\boldsymbol{v}_\mathrm{a}$	Thomson scattering ($\tau \gg 1$) $\rightarrow$ advection with $\boldsymbol{v}$
• weak scattering	CR streaming and diffusion	flux-limited diffusion/ M1 closure ($\tau \gtrsim 1$)
• no scattering	CR propagation with c	vacuum propagation

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

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

but: *CR hydrodynamics is charged RHD*

$\rightarrow$ ***take gyrotropic average and account for anisotropic transport***

CR vs. radiation hydrodynamics

- Alfvén wave velocity in lab frame: $\boldsymbol{w}_\pm = \boldsymbol{v} \pm \boldsymbol{v}_\mathrm{a}$,
  CR scattering frequency $\bar{\nu}_\pm = c^2/(3\kappa_\pm)$
- lab-frame equ's for CR energy and momentum density, ε_cr and $\boldsymbol{f}_\mathrm{cr}/c^2$ (Thomas & CP 2019):

$$\frac{\partial \varepsilon_\mathrm{cr}}{\partial t} + \boldsymbol{\nabla}\cdot\boldsymbol{f}_\mathrm{cr} = -\boldsymbol{w}_\pm \cdot \frac{\boldsymbol{bb}}{3\kappa_\pm}\cdot\left[\boldsymbol{f}_\mathrm{cr} - \boldsymbol{w}_\pm(\varepsilon_\mathrm{cr} + P_\mathrm{cr})\right] - \boldsymbol{v}\cdot\boldsymbol{g}_\mathrm{Lorentz} + S_\varepsilon$$

$$\frac{1}{c^2}\frac{\partial \boldsymbol{f}_\mathrm{cr}}{\partial t} + \boldsymbol{\nabla}\cdot\mathbf{P}_\mathrm{cr} = -\frac{\boldsymbol{bb}}{3\kappa_\pm}\cdot\left[\boldsymbol{f}_\mathrm{cr} - \boldsymbol{w}_\pm(\varepsilon_\mathrm{cr} + P_\mathrm{cr})\right] - \boldsymbol{g}_\mathrm{Lorentz} + \boldsymbol{S}_f$$

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- lab-frame equ's for radiation energy and momentum density, ε and $\boldsymbol{f}/c^2$ (Mihalas & Mihalas, 1984, Lowrie+ 1999):

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{f} = -\sigma_\mathrm{s} \boldsymbol{v} \cdot \left[\boldsymbol{f} - \boldsymbol{v} \cdot (\varepsilon \mathbf{1} + \mathbf{P})\right] + S_\mathrm{a}$$

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$$\frac{1}{c^2}\frac{\partial \boldsymbol{f}}{\partial t} + \boldsymbol{\nabla}\cdot\mathbf{P} = -\sigma_\mathrm{s}\left[\boldsymbol{f} - \boldsymbol{v}\cdot(\varepsilon\mathbf{1}+\mathbf{P})\right] + S_\mathrm{a}\boldsymbol{v}$$

- ***problem:*** *CR lab-frame equation requires resolving rapid gyrokinetics!*

AIP

Alfvén-wave regulated CR transport

- comoving equ's for CR energy and momentum density, $\varepsilon_{\mathrm{cr}}$ and f_{cr}/c^2 and Alfvén-wave energy densities $\varepsilon_{\mathrm{a},\pm}$ (Thomas & CP 2019)

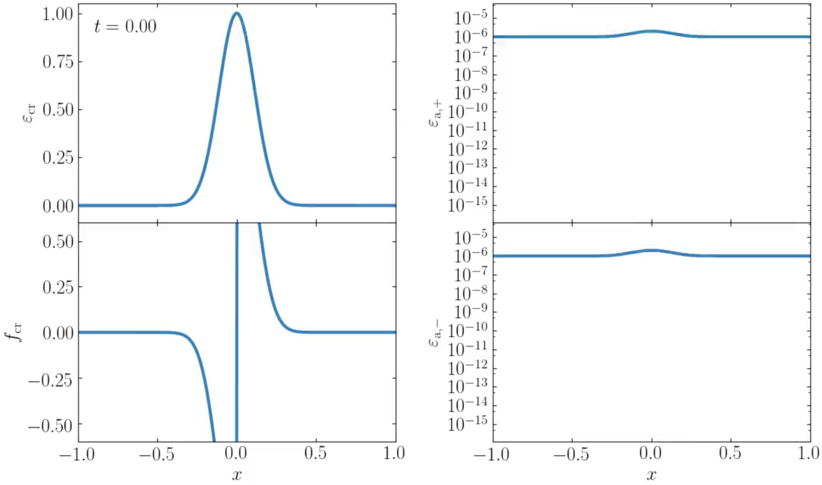
$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla}\cdot\left[\boldsymbol{v}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}}) + \boldsymbol{b} f_{\mathrm{cr}}\right] = \boldsymbol{v}\cdot\boldsymbol{\nabla} P_{\mathrm{cr}} - \frac{v_{\mathrm{a}}}{3\kappa_+}\left[f_{\mathrm{cr}} - v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\right] + \frac{v_{\mathrm{a}}}{3\kappa_-}\left[f_{\mathrm{cr}} + v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\right],$$

$$\frac{\partial f_{\mathrm{cr}}/c^2}{\partial t} + \boldsymbol{\nabla}\cdot\left(\boldsymbol{v} f_{\mathrm{cr}}/c^2\right) + \boldsymbol{b}\cdot\boldsymbol{\nabla} P_{\mathrm{cr}} = -(\boldsymbol{b}\cdot\boldsymbol{\nabla}\boldsymbol{v})\cdot(\boldsymbol{b} f_{\mathrm{cr}}/c^2) - \frac{1}{3\kappa_+}\left[f_{\mathrm{cr}} - v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\right] - \frac{1}{3\kappa_-}\left[f_{\mathrm{cr}} + v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\right],$$

$$\frac{\partial \varepsilon_{\mathrm{a},\pm}}{\partial t} + \boldsymbol{\nabla}\cdot\left[\boldsymbol{v}(\varepsilon_{\mathrm{a},\pm} + P_{\mathrm{a},\pm}) \pm v_{\mathrm{a}}\boldsymbol{b}\varepsilon_{\mathrm{a},\pm}\right] = \boldsymbol{v}\cdot\boldsymbol{\nabla} P_{\mathrm{a},\pm} \pm \frac{v_{\mathrm{a}}}{3\kappa_\pm}\left[f_{\mathrm{cr}} \mp v_{\mathrm{a}}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\right] - S_{\mathrm{a},\pm}.$$

Non-equilibrium CR streaming and diffusion

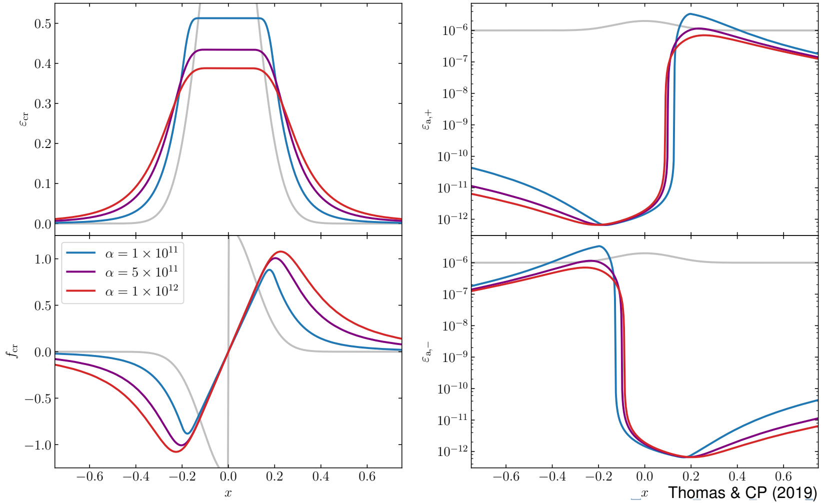
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2019)

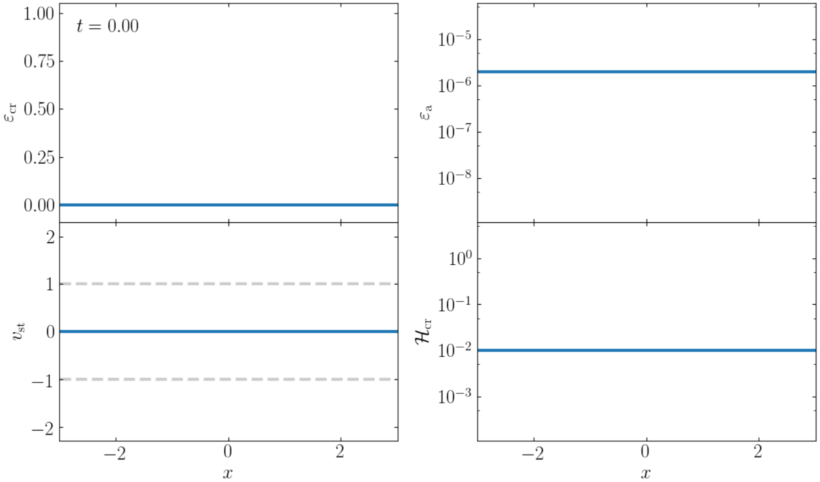
Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2019)

Steady CR source: CR Alfvén wave heating

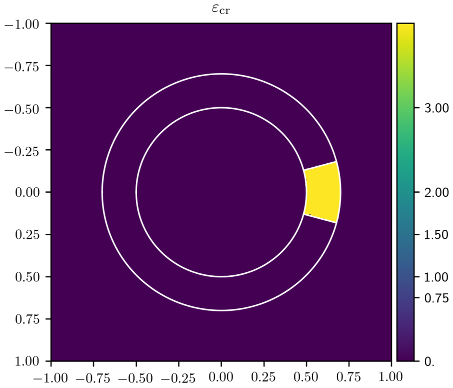


Thomas & CP (2019)

Anisotropic CR streaming and diffusion – AREPO

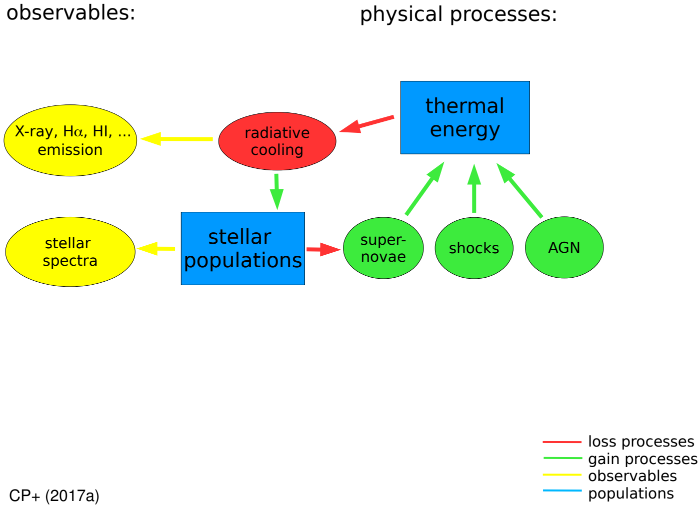
CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics

- 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



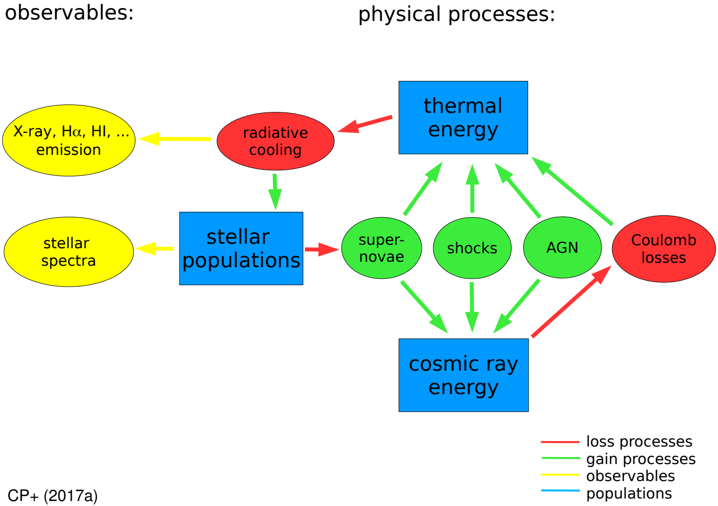
Thomas, Pakmor, CP (in prep.)

Simulations – flowchart



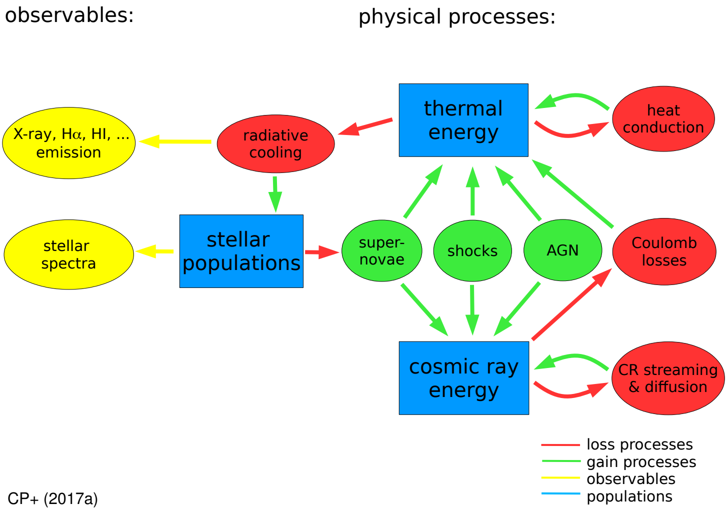
CP+ (2017a)

Simulations with cosmic ray physics



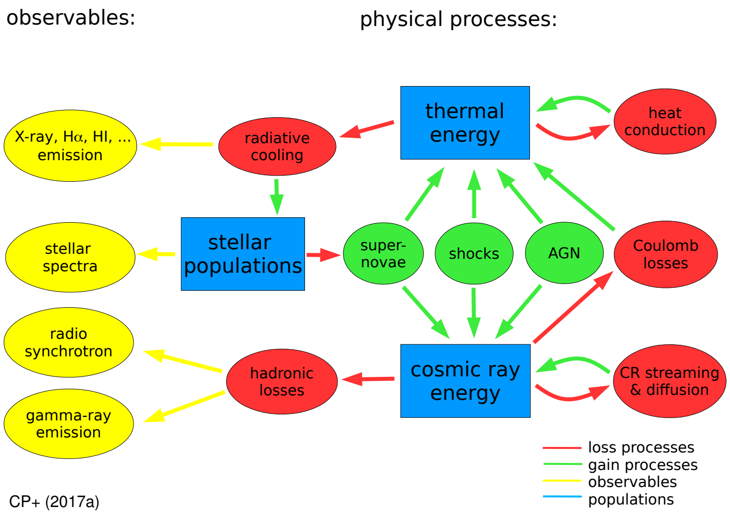
CP+ (2017a)

Simulations with cosmic ray physics



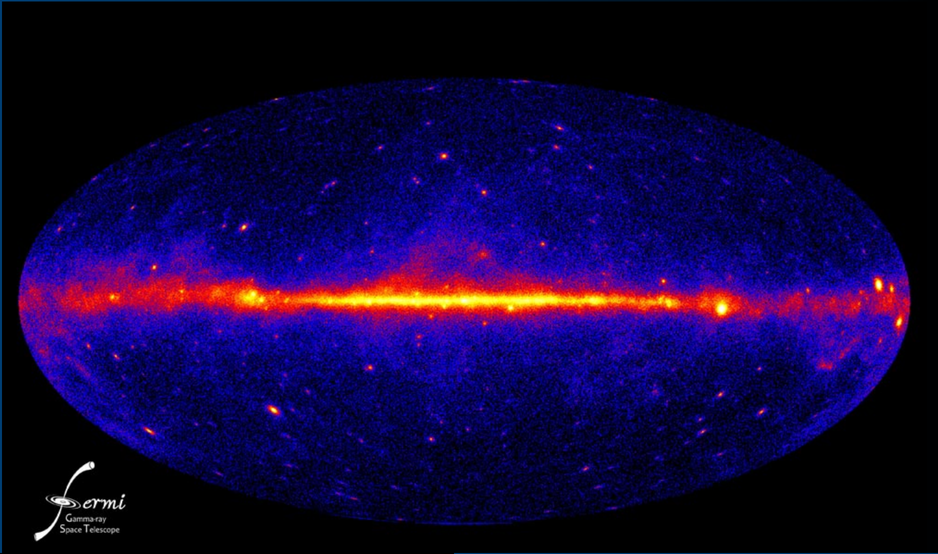
CP+ (2017a)

Simulations with cosmic ray physics



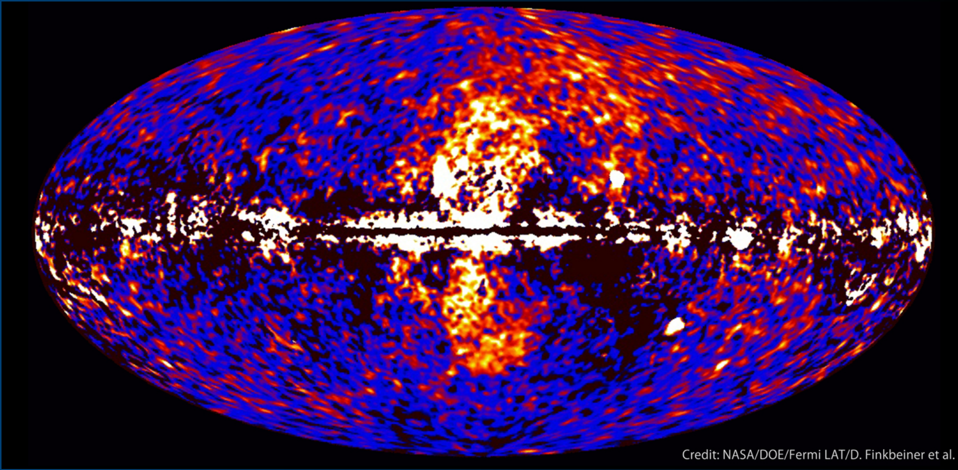
CP+ (2017a)

Gamma-ray emission of the Milky Way

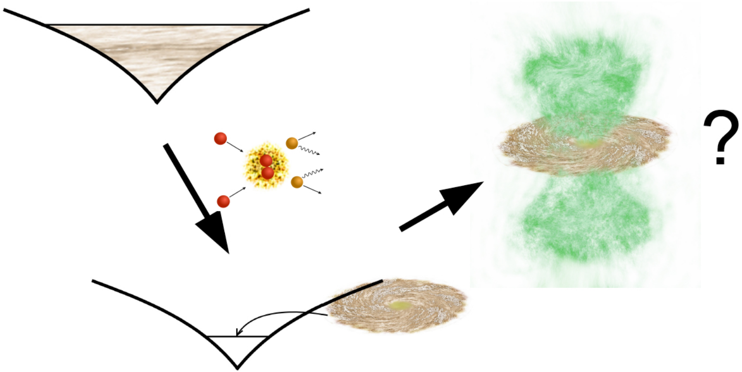


Galactic wind in the Milky Way?

Fermi gamma-ray bubbles



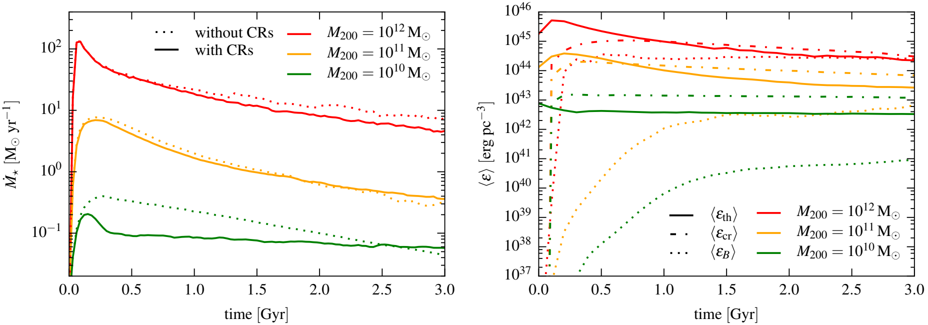
Galaxy simulation setup: 1. cosmic ray advection



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

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

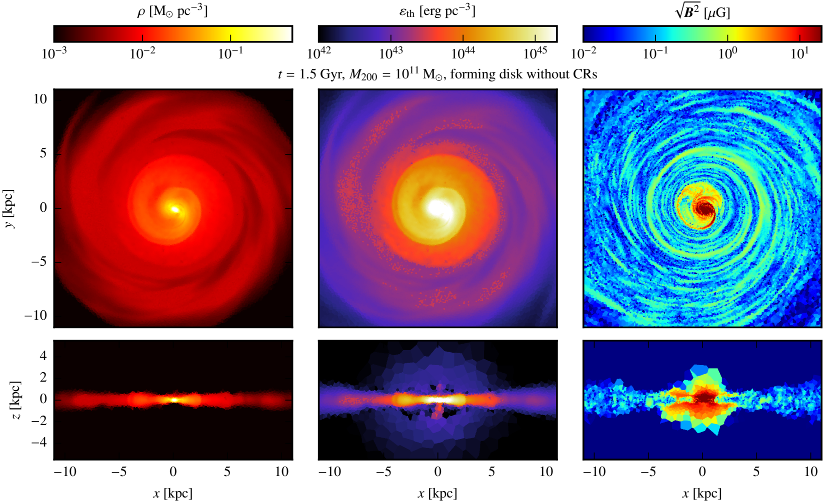
Time evolution of SFR and energy densities



CP+ (2017a)

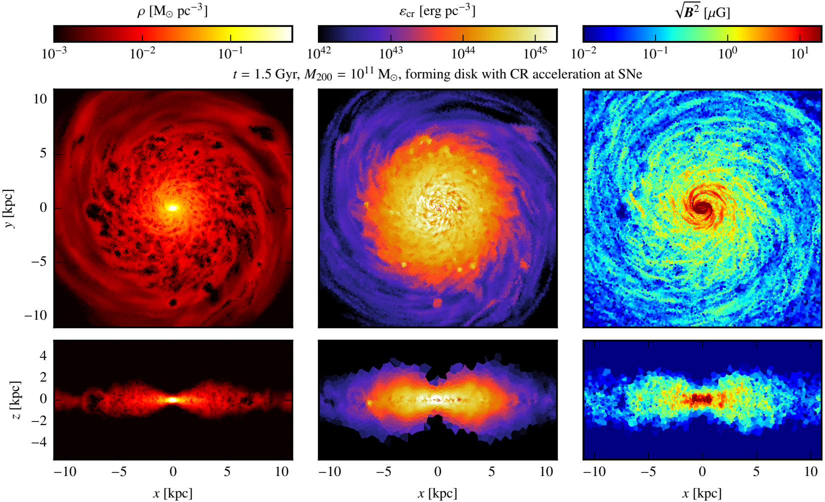
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



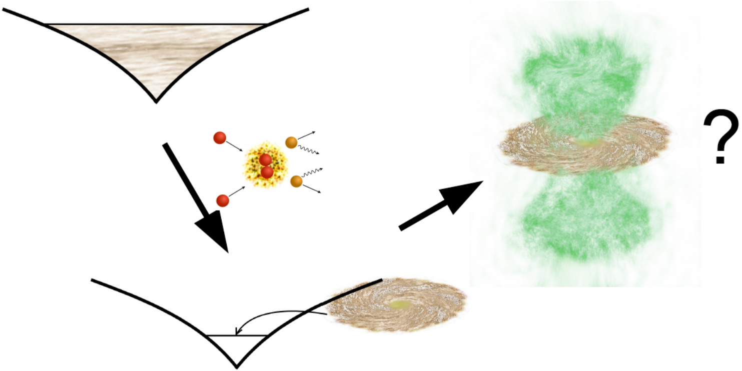
CP+ (2017a)

MHD galaxy simulation with CRs



CP+ (2017a)

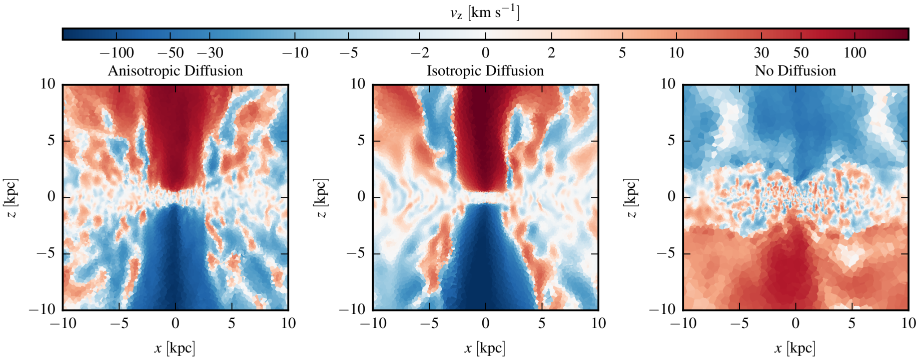
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

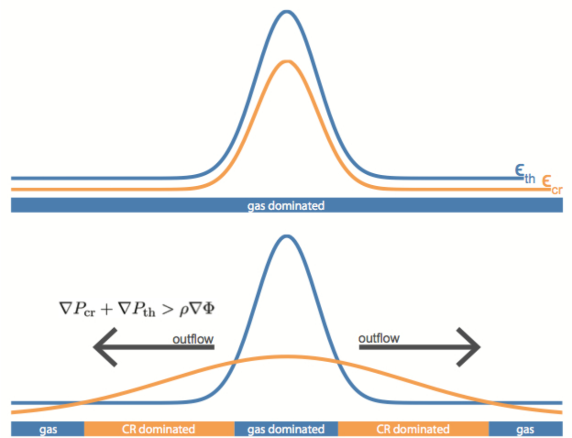
MHD galaxy simulation with CR diffusion



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)

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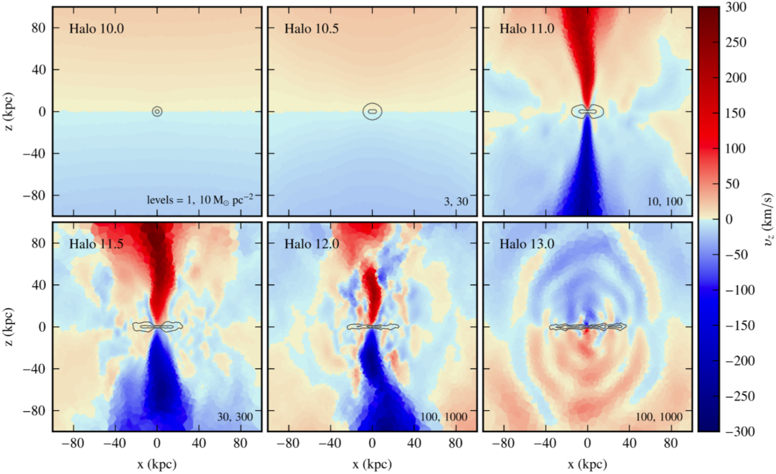
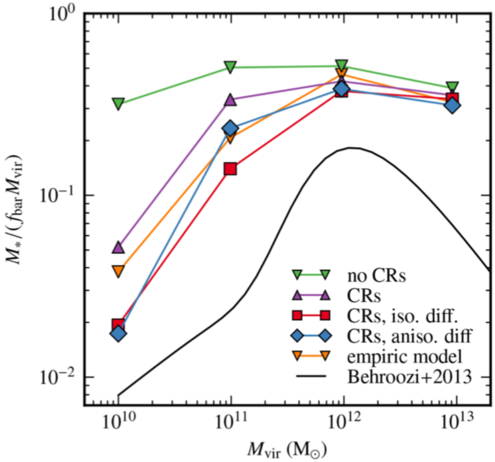
CR-driven winds: dependence on halo mass



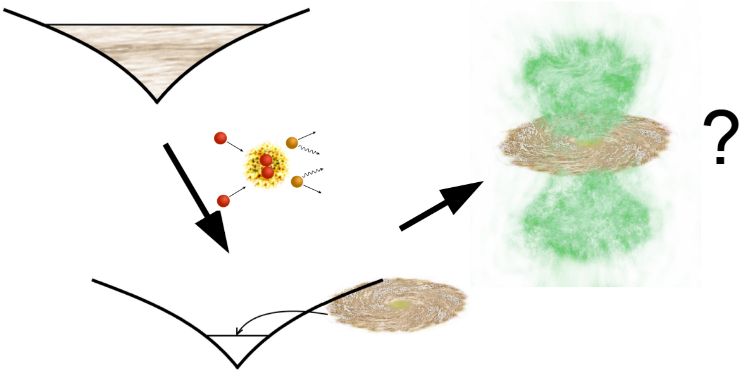
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

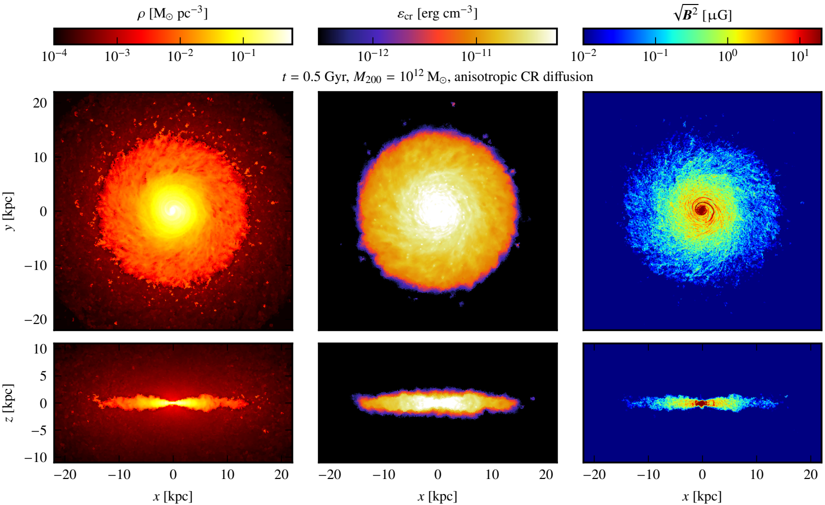
Galaxy simulation setup: 3. non-thermal emission



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

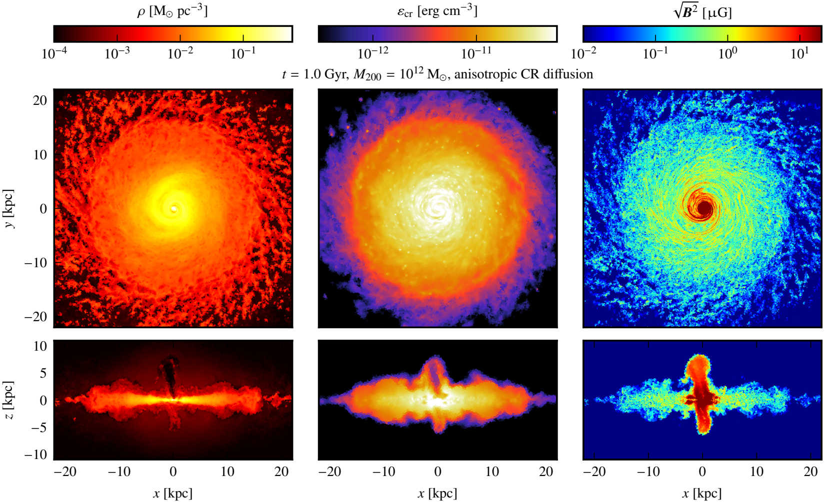
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ M_\odot$

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



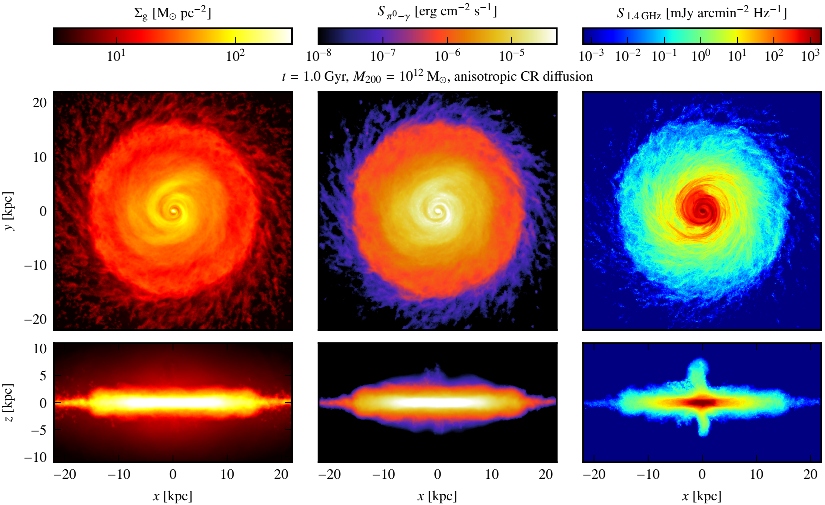
CP+ (2017b, in prep.)

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



CP+ (2017b, in prep.)

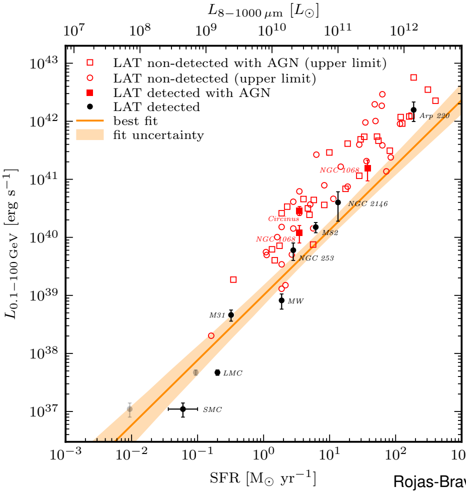
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, in prep.)

Far infra-red – gamma-ray correlation

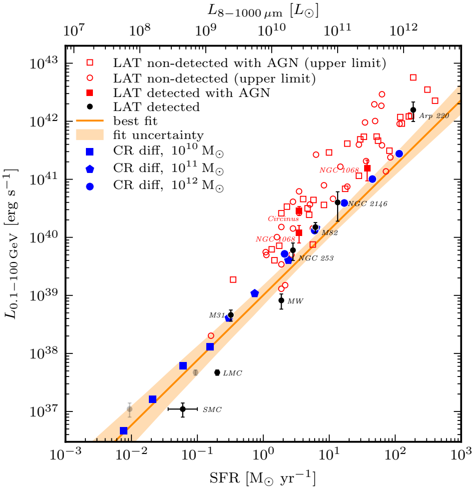
Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



CP+ (2017b)

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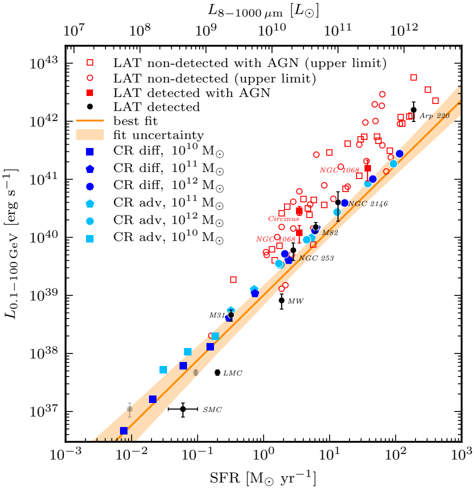

CP+ (2017b)

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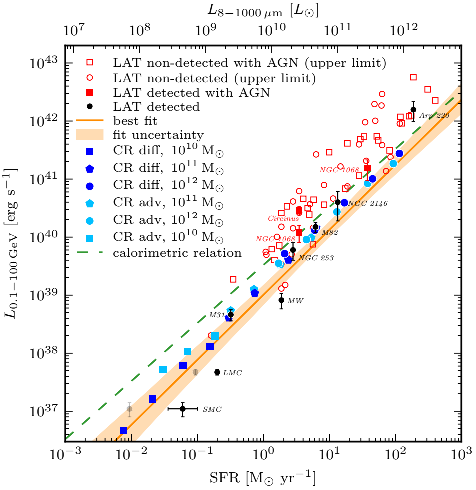
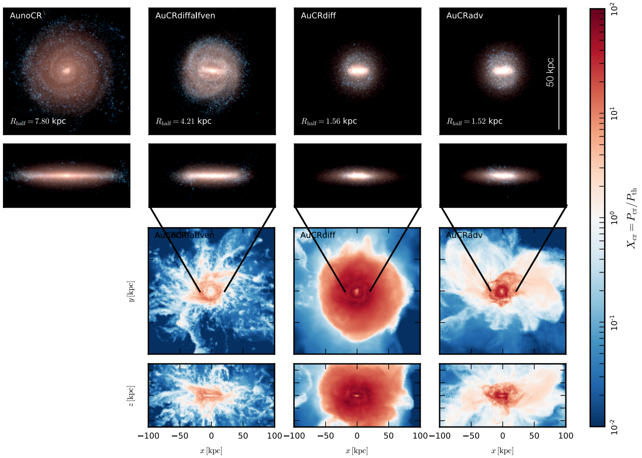


CP+ (2017b)

Cosmic rays in cosmological galaxy simulations

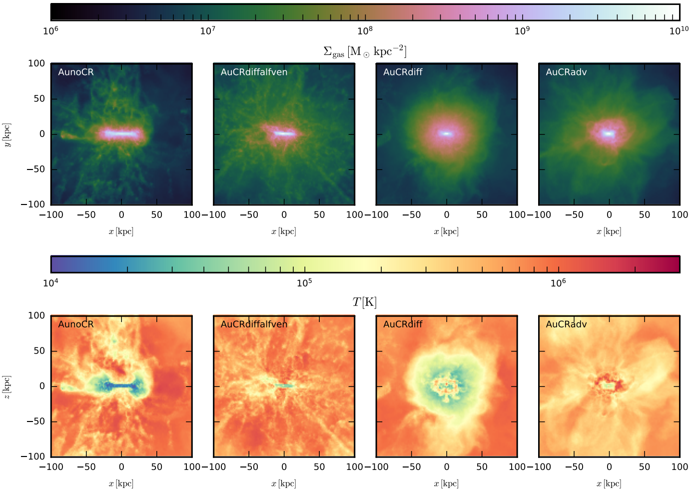
Auriga MHD models: CR transport changes disk sizes



Buck, CP, Pakmor+ (in prep.)

Cosmic rays in cosmological galaxy simulations

Auriga MHD models: CR transport modifies the circum-galactic medium



Buck, CP, Pakmor+ (in prep.)

Conclusions for cosmic ray physics in galaxies

CR acceleration:

- TeV shell-type SNRs probe magnetic coherence scale in ISM
- hybrid-PIC sim's of p^+ acceleration agree with global SNR sim's, more work needed for PIC sim's of e^- acceleration

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CR hydrodynamics:

- moment expansion similar to radiation hydrodynamics
- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics

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CR hydrodynamics:

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CR feedback in galaxy formation:

- CR pressure feedback slows down star formation
- galactic winds naturally explained by CR streaming and diffusion

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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).

Literature for the talk – 1

Cosmic ray transport:

- Thomas & Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2019, MNRAS.

Cosmic ray acceleration:

- Pais, Pfrommer, Ehlert, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics*, 2018, MNRAS.
- Pais, Pfrommer, Ehlert, Werhahn, *Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants*, 2019, subm.
- Winner, Pfrommer, Girichidis, Pakmor, *Evolution of cosmic ray electron spectra in magnetohydrodynamical simulations,* 2019, MNRAS
- Winner, Pfrommer, Girichidis, Werhahn, *Dissecting models for cosmic ray electron acceleration at Supernova remnants*, in prep.

Literature for the talk – 2

Cosmic ray feedback in galaxies:

- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.
- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017a, MNRAS.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating gamma-ray emission in star-forming galaxies,* 2017b, ApJL.
- Jacob, Pakmor, Simpson, Springel, Pfrommer, *The dependence of cosmic ray driven galactic winds on halo mass,* 2018, MNRAS.
- Buck, Pfrommer, Pakmor, Grand, Springel, *The effects of cosmic rays on the formation of Milky Way-like galaxies in a cosmological context,* in prep.