Cosmic rays and the interstellar medium

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in collaboration with

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R. Pakmor[2], K. Schaal, C. Simpson[3], V. Springel[2]

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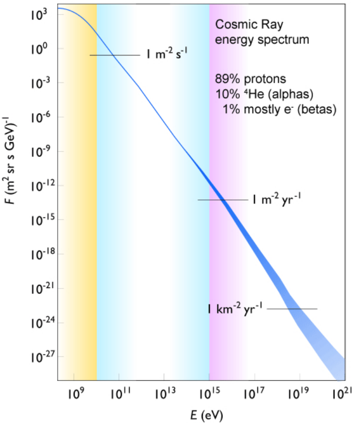
The Interstellar Medium of Galaxies, Leiden – Nov 2018

Outline

1. Introduction
   - Cosmic rays
   - ISM outflows
   - Cosmic ray transport
2. Interstellar medium
   - Supernova explosions
   - Particle acceleration
   - ISM simulations
3. Simulating galaxy formation
   - Cosmic ray advection
   - Cosmic ray diffusion
   - Radio and γ rays

Outline

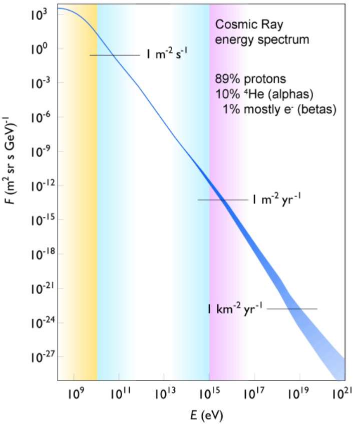
Galactic cosmic ray spectrum



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

Galactic cosmic ray spectrum



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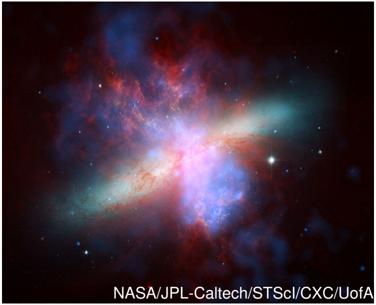
- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

How are outflows from the ISM 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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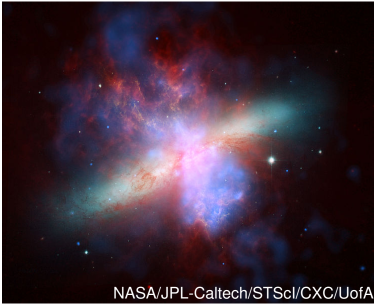

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- thermal pressure provided by supernovae or AGNs?
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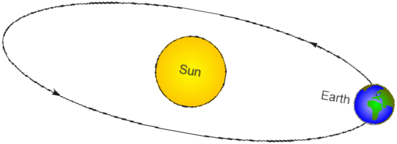
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
→ suggests self-regulated feedback loop with CR driven winds

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

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

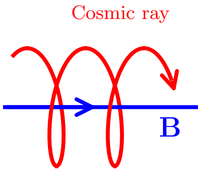
gyro-orbit of GeV cosmic ray:

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

$\Rightarrow$ 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

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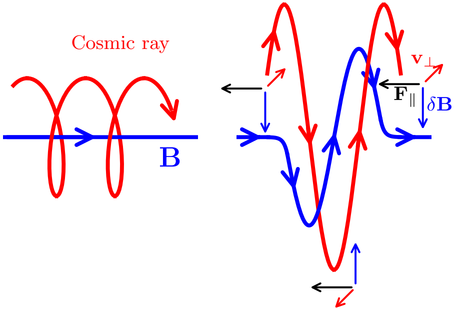

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- **gyro resonance:** $\omega - k_{||} v_{||} = n\Omega$

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

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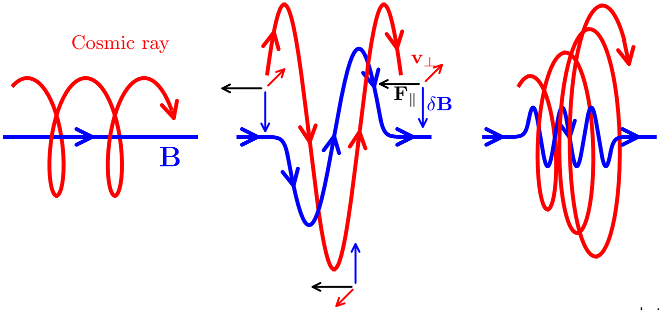
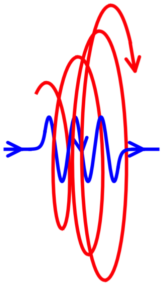


sketch: Jacob

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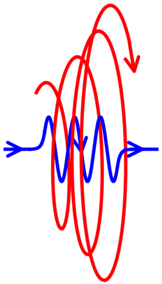

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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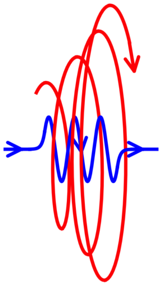

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

CR transport (steady-state flux)

- total CR velocity $\boldsymbol{v}_{\mathrm{cr}} = \boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\mathrm{gas}}$)

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- CRs stream down their own pressure gradient relative to the gas

$$\boldsymbol{v}_{\rm st} = \boldsymbol{v}_{\rm A} \frac{\bar{\nu}_+ - \bar{\nu}_-}{\bar{\nu}_+ + \bar{\nu}_-},$$

AIP

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$$\boldsymbol{v}_{\rm st} = \boldsymbol{v}_{\rm A} \frac{\bar{\nu}_+ - \bar{\nu}_-}{\bar{\nu}_+ + \bar{\nu}_-}, \quad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di} \boldsymbol{b} \frac{\boldsymbol{b} \cdot \nabla \varepsilon_{\rm cr}}{\varepsilon_{\rm cr}}, \quad \kappa_{\rm di} = \frac{c^2}{3(\bar{\nu}_+ + \bar{\nu}_-)}$$

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- energy equations with $\varepsilon = \varepsilon_{\rm th} + \rho v^2/2$:

$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla}\cdot\left[(\varepsilon + P_{\rm th} \qquad)\boldsymbol{v}\right] = 0$$

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$$\begin{aligned}
\frac{\partial\varepsilon}{\partial t} + \boldsymbol{\nabla}\cdot\left[(\varepsilon + P_{\rm th} + P_{\rm cr})\boldsymbol{v}\right] &= P_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} - \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr} \\
\frac{\partial\varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla}\cdot\left[P_{\rm cr}\boldsymbol{v}_{\rm st} + \varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})\right] &= -P_{\rm cr}\boldsymbol{\nabla}\cdot\boldsymbol{v} + \boldsymbol{v}_{\rm st}\cdot\boldsymbol{\nabla}P_{\rm cr}
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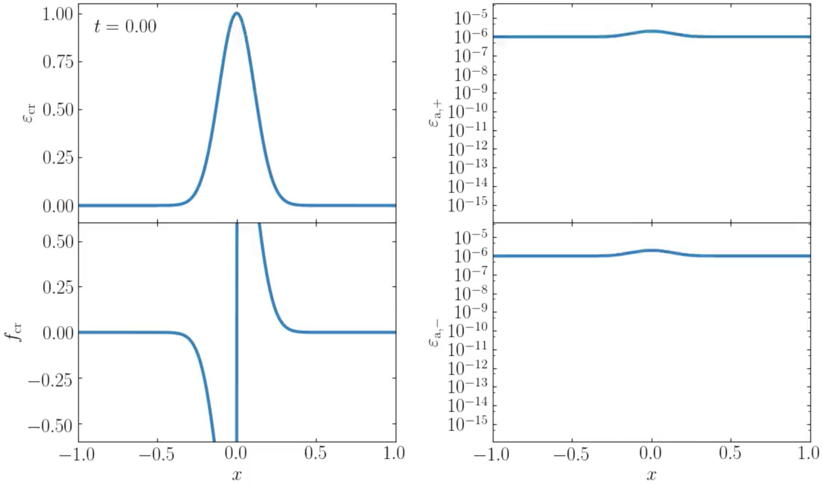
$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla} \cdot [P_{\rm cr} \boldsymbol{v}_{\rm st} + \varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})] = -P_{\rm cr} \boldsymbol{\nabla} \cdot \boldsymbol{v} + \boldsymbol{v}_{\rm st} \cdot \boldsymbol{\nabla} P_{\rm cr}$$

$$\Longleftrightarrow \quad \frac{\partial \varepsilon_{\rm cr}}{\partial t} + \boldsymbol{\nabla} \cdot [\varepsilon_{\rm cr}(\boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di})] = -P_{\rm cr} \boldsymbol{\nabla} \cdot (\boldsymbol{v} + \boldsymbol{v}_{\rm st})$$

Non-equilibrium CR streaming and diffusion

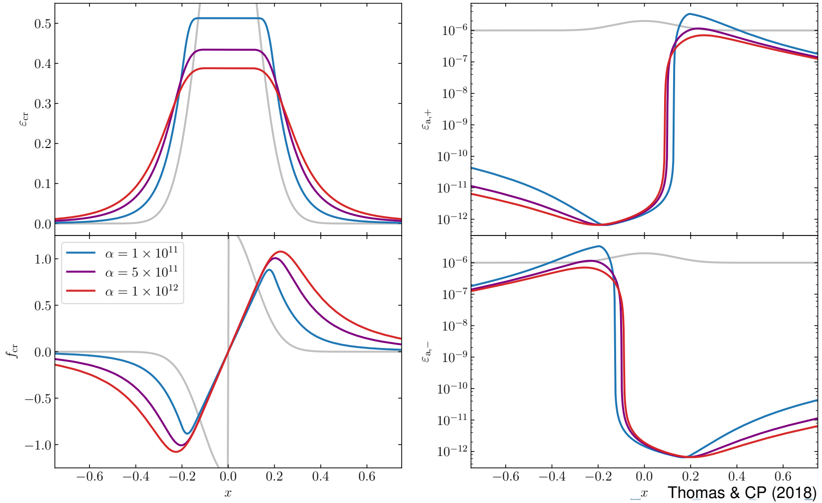
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution

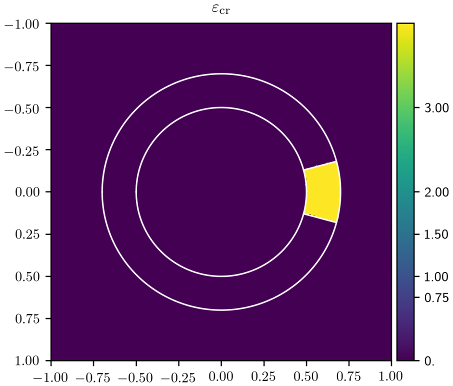


Thomas & CP (2018)

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.)

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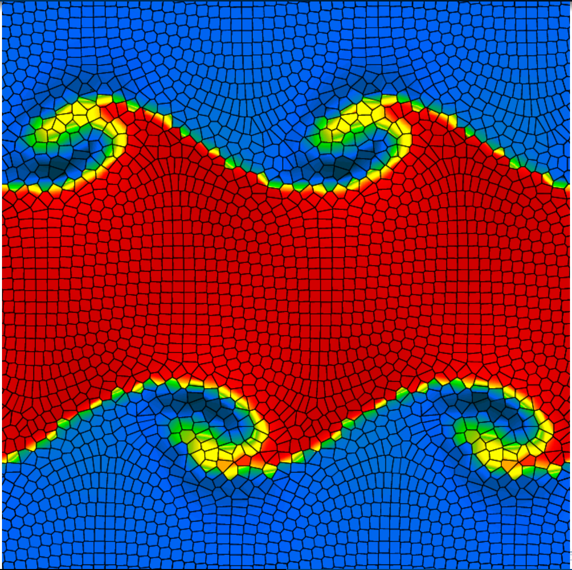
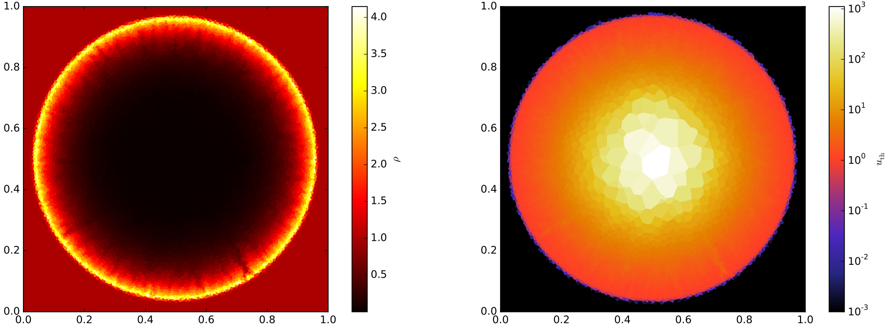
Cosmological moving-mesh code AREPO (Springel 2010)



Sedov explosion

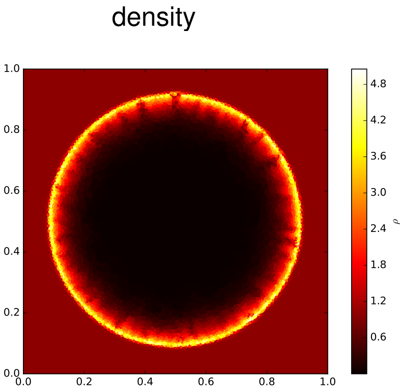
density

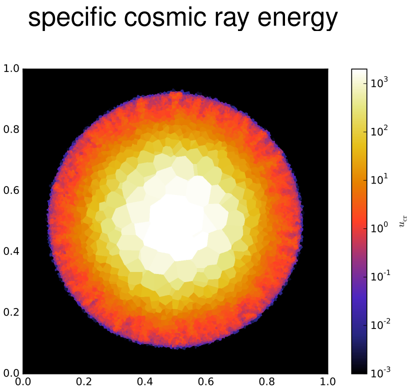
specific thermal energy



CP, Pakmor, Schaal, Simpson, Springel (2017a)

Sedov explosion with CR acceleration

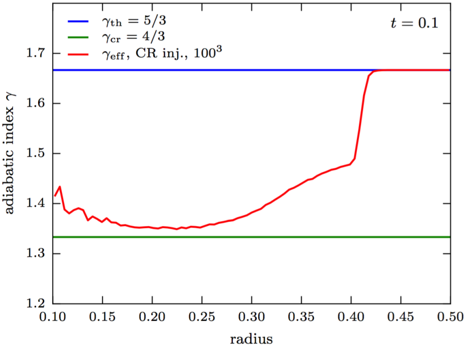




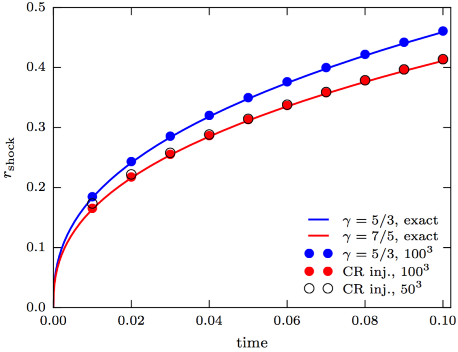
CP, Pakmor, Schaal, Simpson, Springel (2017a)

Sedov explosion with CR acceleration

adiabatic index



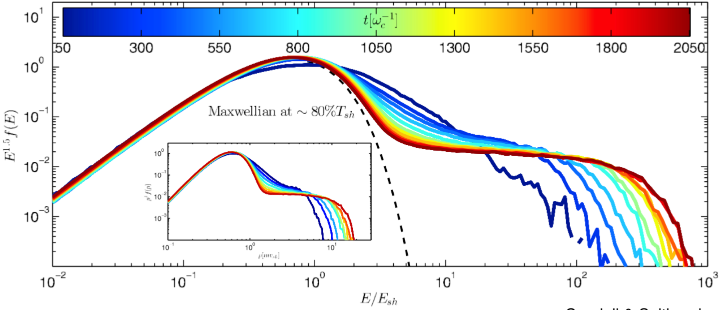
shock evolution



CP, Pakmor, Schaal, Simpson, Springel (2017a)

Ion spectrum

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



Caprioli & Spitkovsky (2014)

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

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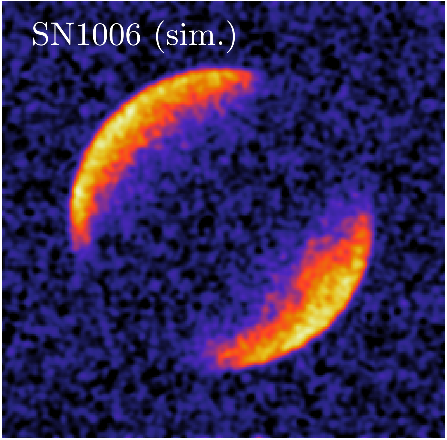
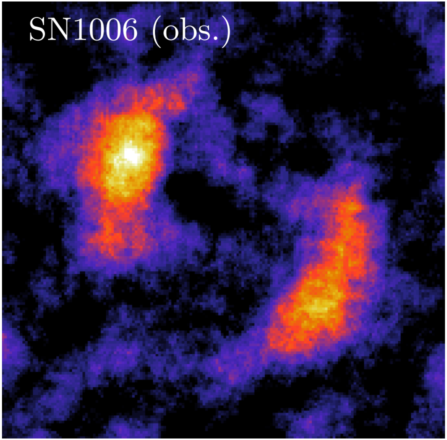
TeV γ rays from shell-type SNRs: SNR 1006

AREPO simulation



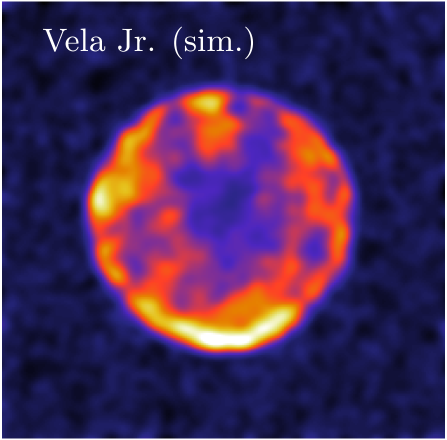
H.E.S.S. observation



Pais, CP, Ehlert (2018)

TeV γ rays from shell-type SNRs: Vela Junior

AREPO simulation



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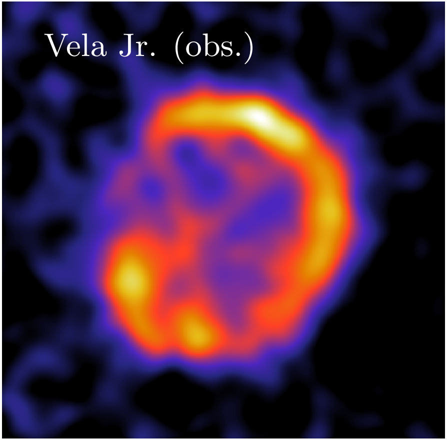
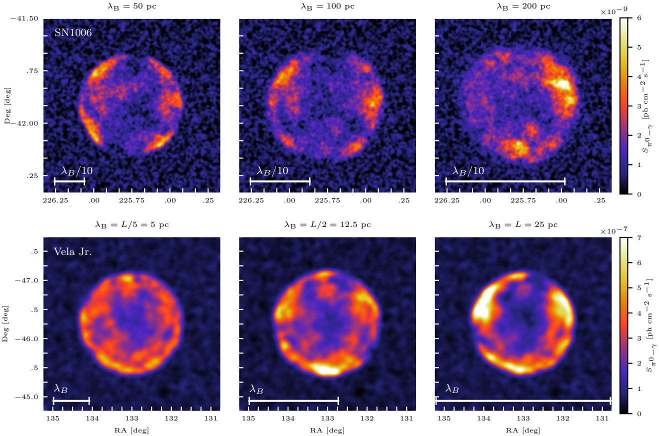


Pais, CP, Ehlert (2018)

TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN1006 and Vela Junior



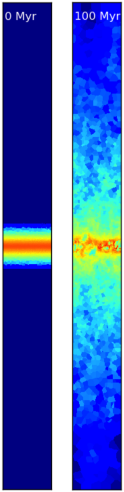
Pais, CP, Ehlert (2018)

SNR 1006: $\lambda_B > 200^{+10}_{-60}$ pc

Vela Junior: $\lambda_B = 8^{+15}_{-6}$ pc

A model for the multi-phase interstellar medium

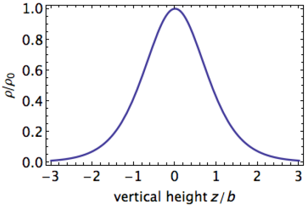
Explore supernovae-driven outflows at high resolution – stratified box simulations



Simpson+ (2016)

- isothermal disk with $T_0 = 10^4$ K
- hydrostatic equilibrium:

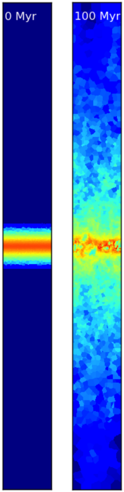
$$f_g \nabla^2 \Phi = 4\pi G \rho$$



- self-gravity
- atomic & molecular cooling network, self-shielding (Glover & Clark 2012, Smith+ 2014)
- MHD with small magnetic seed field (Pakmor+ 2011)
- cosmic ray physics (CP+ 2017a, Pakmor+ 2016)

Supernova feedback

Explore supernovae-driven outflows at high resolution – stratified box simulations



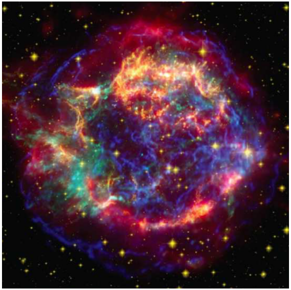
Simpson+ (2016)

- star formation rate:

$$\dot{M}_{*,i} = \epsilon \frac{M_i}{t_{\mathrm{dyn},i}}$$

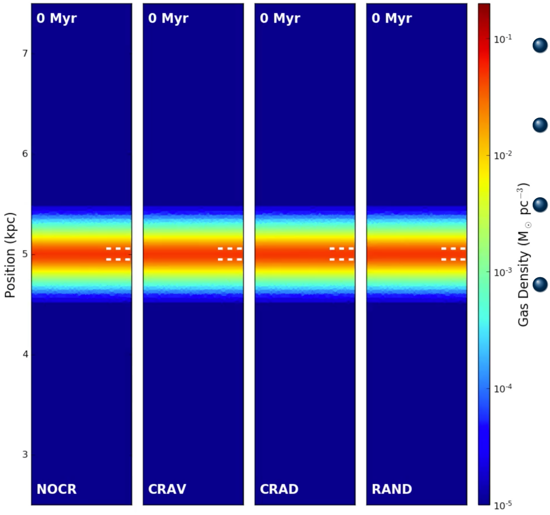
- supernova rate:

$$\dot{M}_{\mathrm{SN},i} = \dot{M}_{*,i} \frac{1.8\ \mathrm{events}}{100\ \mathrm{M}_\odot}$$



- supernova energy $E_{\mathrm{SN}} = 10^{51}$ erg distributed over 32 nearest neighbors
- input in form of thermal, kinetic, or cosmic ray energy

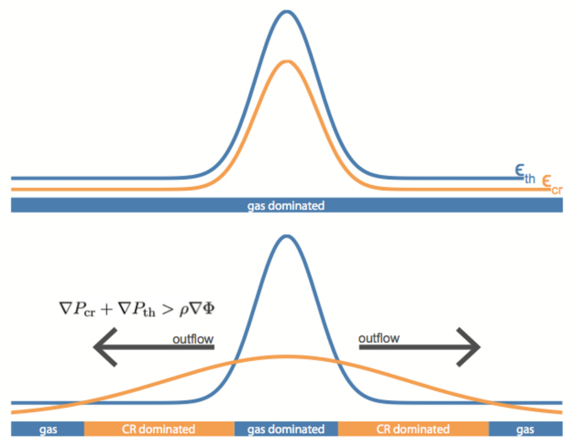
Interstellar medium – turbulence and outflows



Simpson+ (2016)

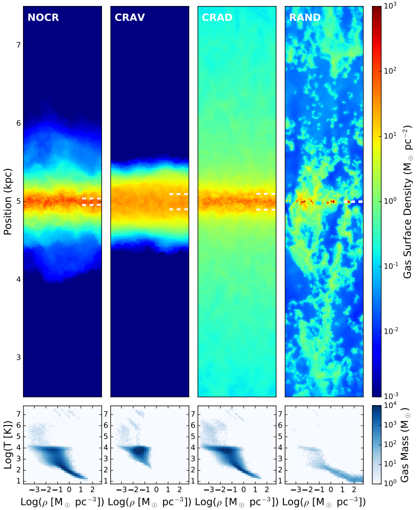
- NOCR: purely thermal SNe
- CRAV: CR advection, $\{f_{cr}, f_{th}\} = \{0.1, 0.9\}$
- CRAD: anisotropic CR diffusion
- RAND: random injection

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)

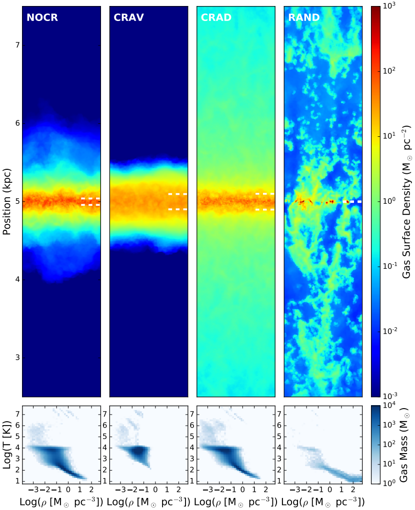
Interstellar medium – turbulence and outflows



Simpson+ (2016)

- diffusing CRs (CRAD) launch outflows with similar mass loadings as randomly placed feedback models (RAND)

Interstellar medium – turbulence and outflows



Simpson+ (2016)

- diffusing CRs (CRAD) launch outflows with similar mass loadings as randomly placed feedback models (RAND)
- different forcing: CR pressure gradient (CRAD) vs. kinetic pressure gradients propelling a ballistic outflow (RAND)
  → velocity and clumpiness differ

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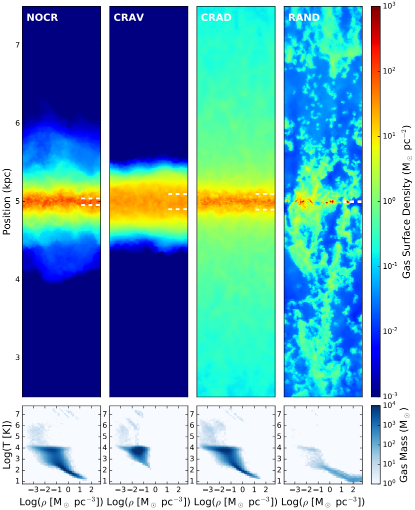

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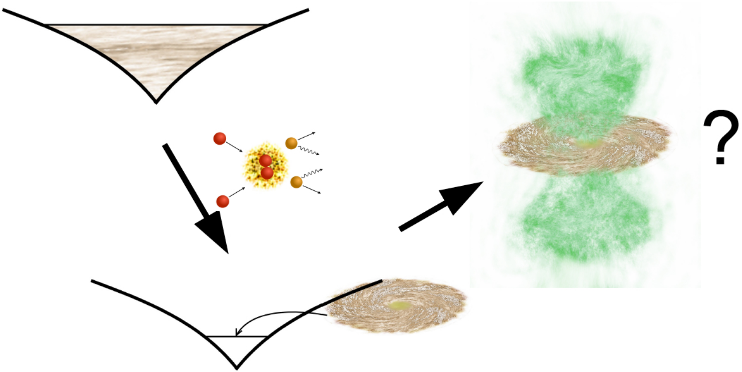
- different forcing: CR pressure gradient (CRAD) vs. kinetic pressure gradients propelling a ballistic outflow (RAND)
  $\rightarrow$ velocity and clumpiness differ
- CR + turbulent pressure self-regulate ISM $\rightarrow$ scale height $h_{1/2} \approx 100$ pc; ISM in RAND collapses to dense phase

$\Rightarrow$ **CR physics is essential for correctly modeling the ISM!**

Outline

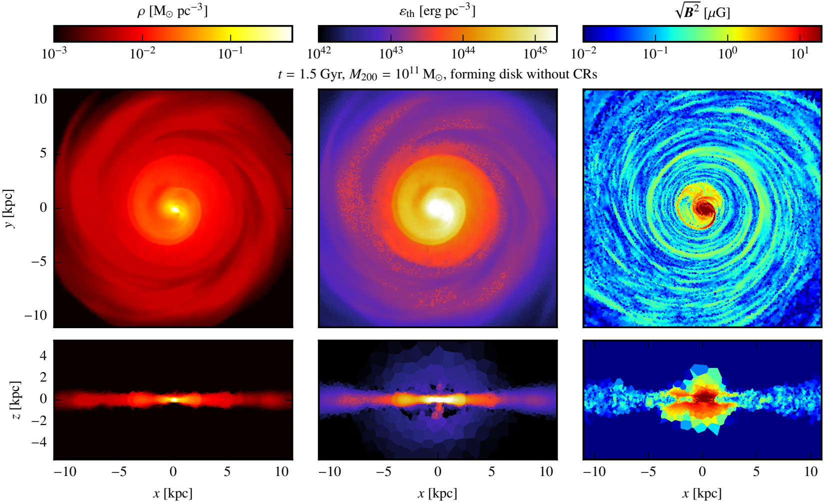
Galaxy simulation setup: 1. cosmic ray advection



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



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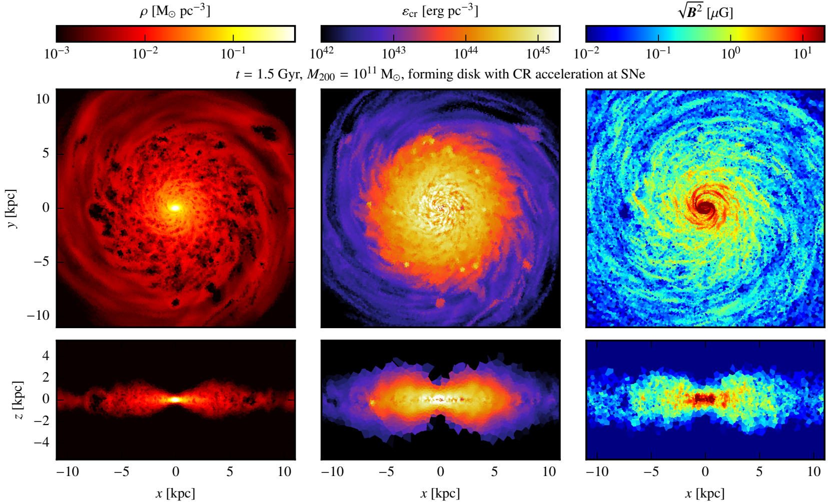
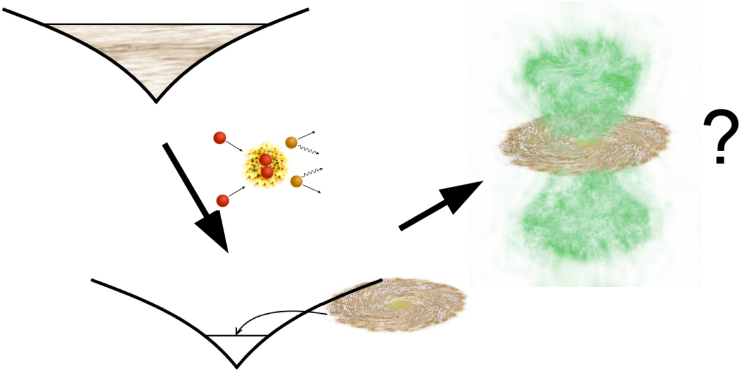


CP, Pakmor, Schaal, Simpson, Springel (2017a)

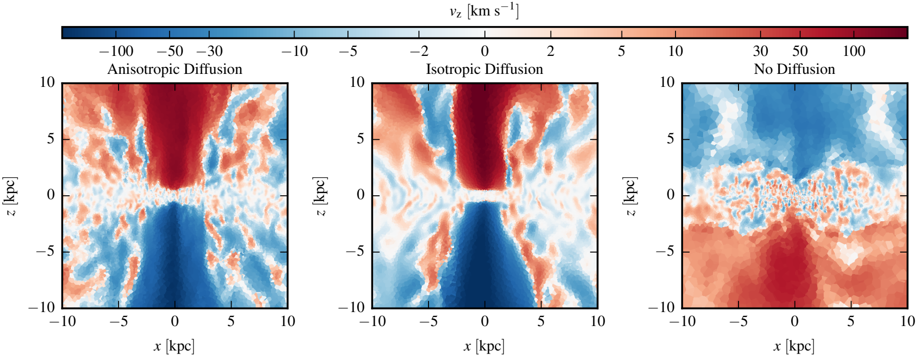
Galaxy simulation setup: 2. cosmic ray diffusion



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} $M_{\odot}$

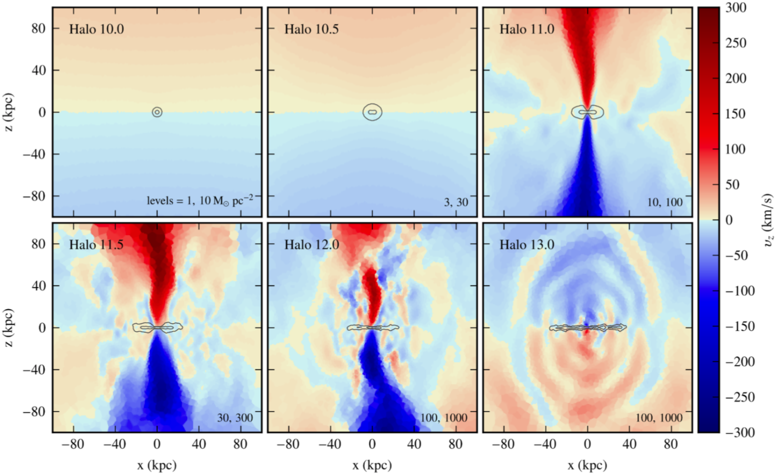
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

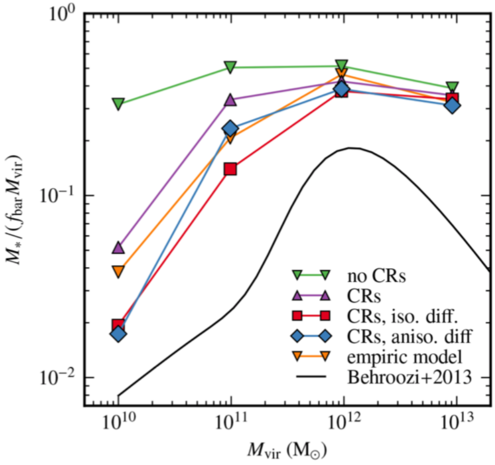
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

CR-driven winds: dependence on halo mass



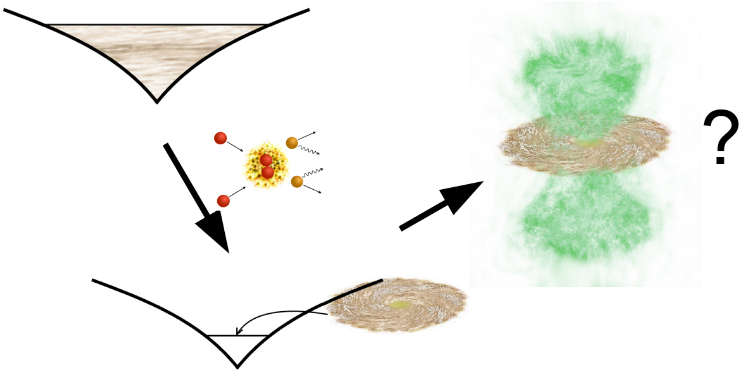
Jacob+ (2018)

CR-driven winds: suppression of star formation



Jacob+ (2018)

Galaxy simulation setup: 3. non-thermal emission

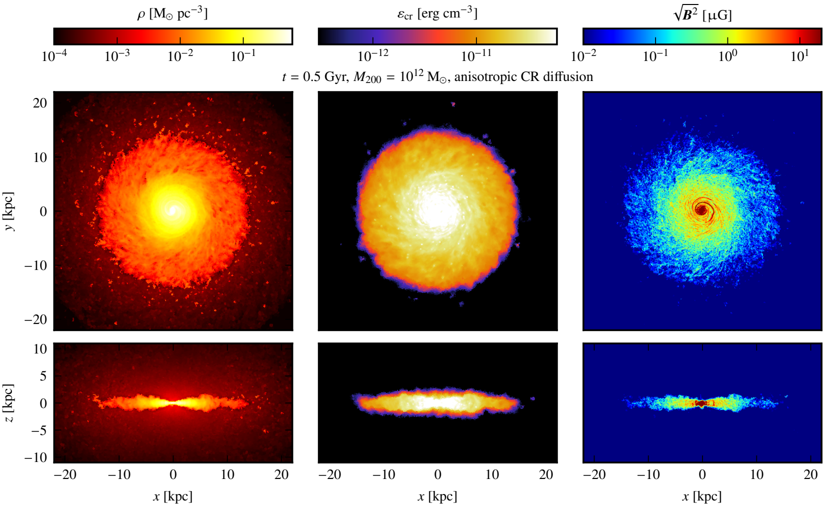


CP, Pakmor, Simpson, Springel (2017b, 2018)

Simulating radio synchrotron and gamma-ray emission in galaxies

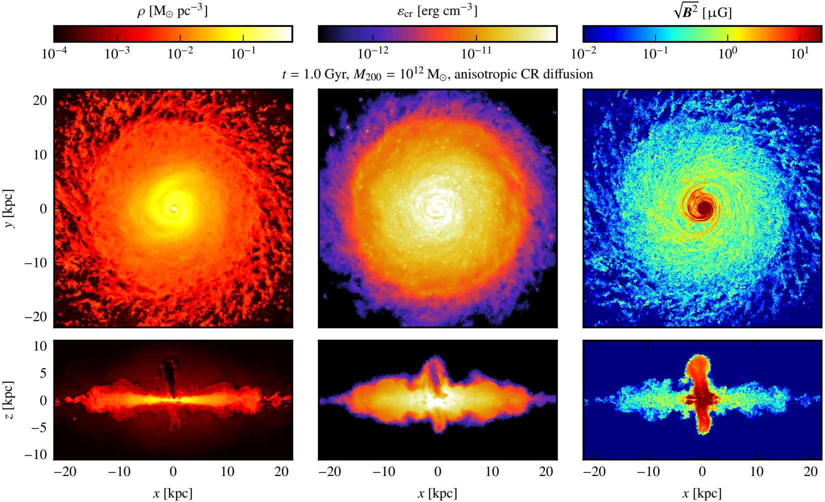
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}$ $M_\odot$

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



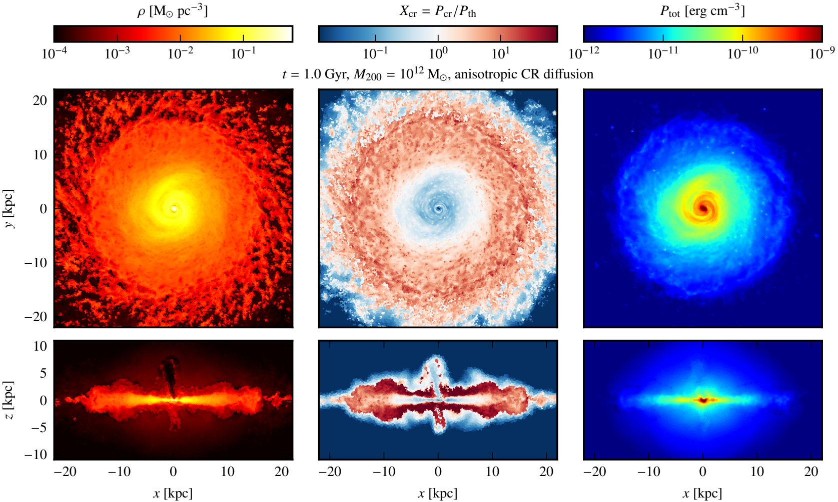
CP+ (2017b, 2018)

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



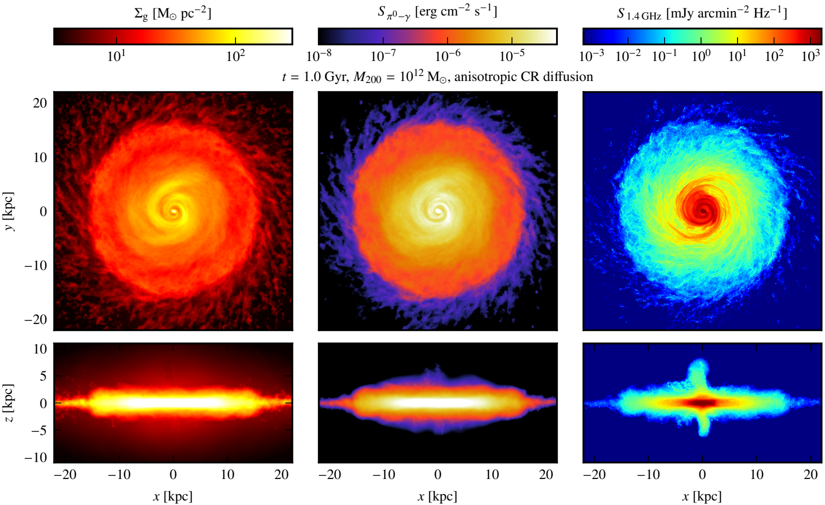
CP+ (2017b, 2018)

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



CP+ (2017b, 2018)

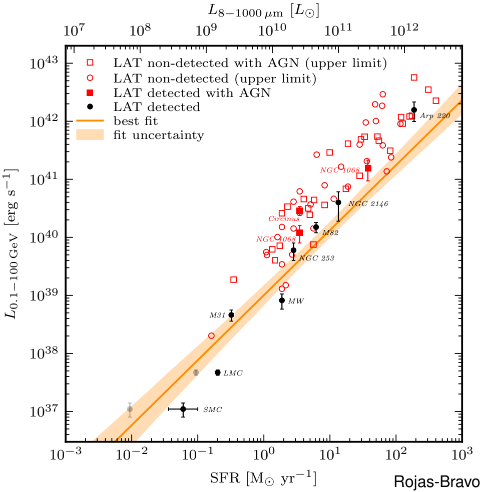
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, 2018)

Far infra-red – gamma-ray correlation

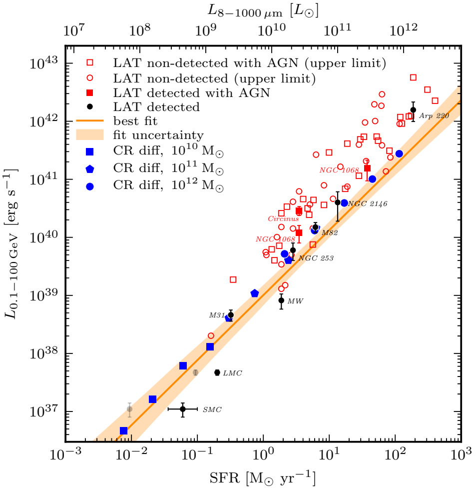
Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays

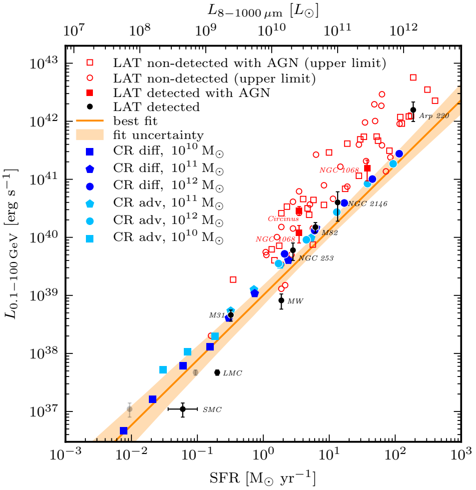


CP+ (2017b)

AIP

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



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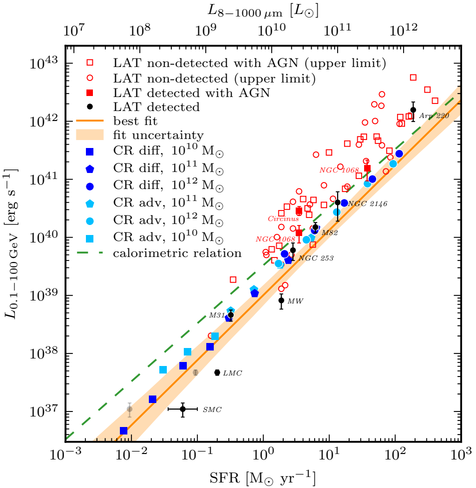

CP+ (2017b)

Conclusions on CR feedback in galaxies and clusters

- CR pressure feedback slows down star formation
- outflows from the ISM are naturally explained by CR diffusion & streaming
- $L_{\mathrm{FIR}} - L_{\gamma}$ and $L_{\mathrm{FIR}} - L_{\mathrm{radio}}$ correlations enable us to test the calorimetric assumption and magnetic dynamo theories

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**

AIP

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).

AIP

Literature for the talk – 1

Cosmic ray acceleration and transport:

- Thomas, Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2018.
- Pais, Pfrommer, Ehlert, *Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants,* 2018.
- Pais, Pfrommer, Ehlert, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics,* 2018, MNRAS.

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.
- Jacob, Pakmor, Simpson, Springel, Pfrommer, *The dependence of cosmic ray driven galactic winds on halo mass,* 2018, MNRAS.

Literature for the talk – 2

A multi-phase model of the interstellar medium:

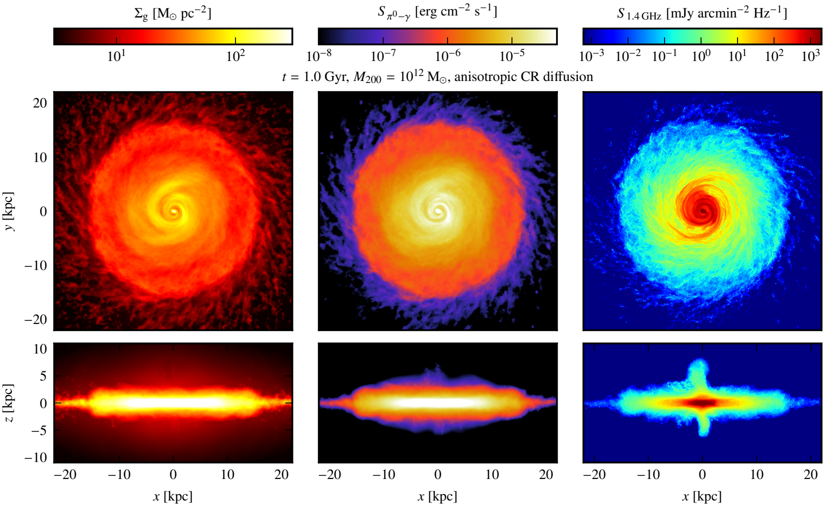
- Simpson, Pakmor, Marinacci, Pfrommer, Springel, Glover, Clark, Smith, *The role of cosmic ray pressure in accelerating galactic outflows,* 2016, ApJL.

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

- Pfrommer, Pakmor, Simpson, Springel, *Simulating Gamma-ray Emission in Star-forming Galaxies,* 2017b, ApJL.
- Pfrommer, Pakmor, Simpson, Springel, *Simulating Radio Synchrotron Emission in Galaxies: the Origin of the Far Infrared–Radio Correlation,* 2018.

Additional slides

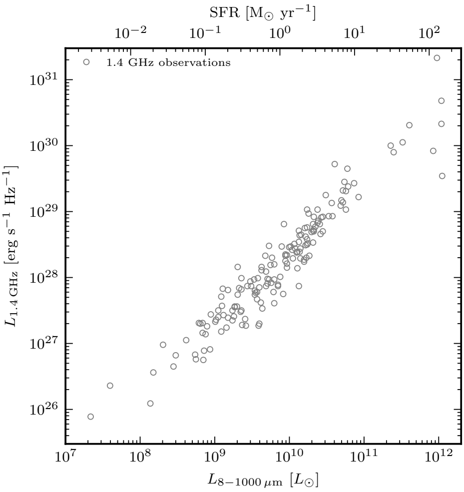
γ-ray and radio emission of Milky Way-like galaxy



CP+ (2017b, 2018)

Far infra-red – radio correlation

Universal conversion: star formation → cosmic rays → radio



Bell (2003)

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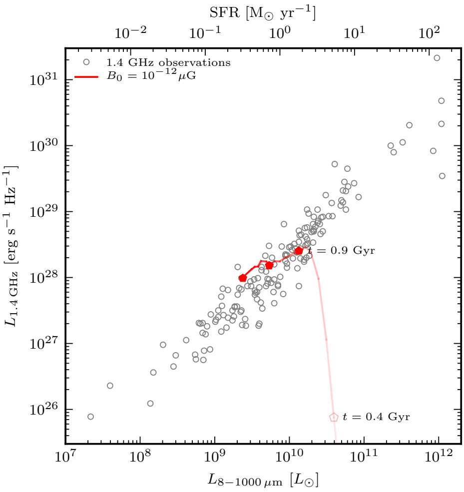

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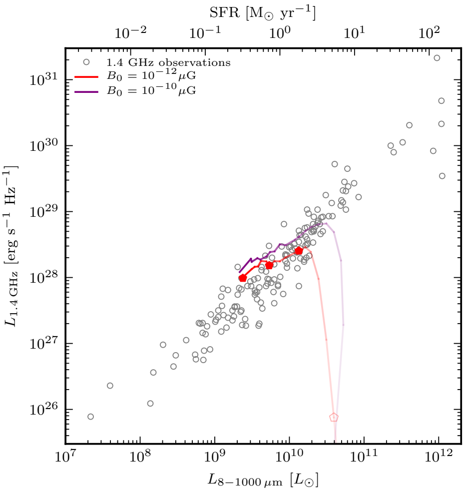

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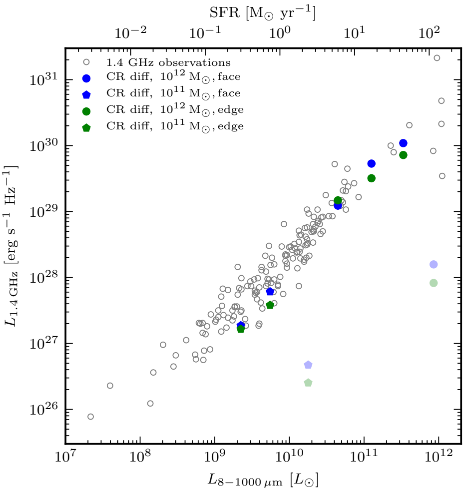

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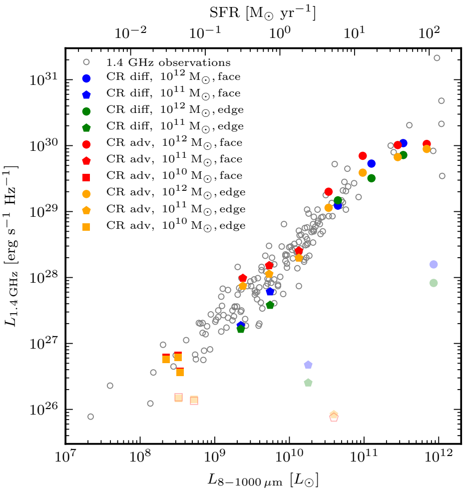

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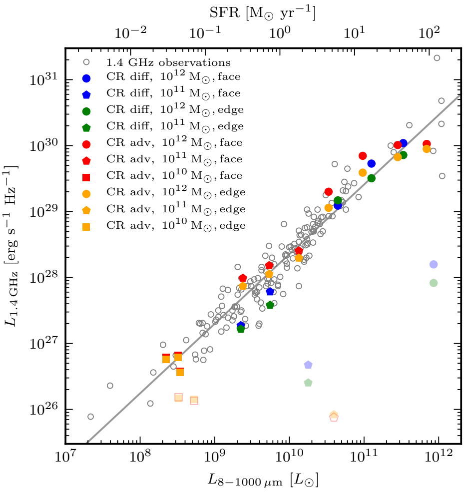

CP+ (2018)