Cosmic rays and galactic winds

Christoph Pfrommer[1]

in collaboration with

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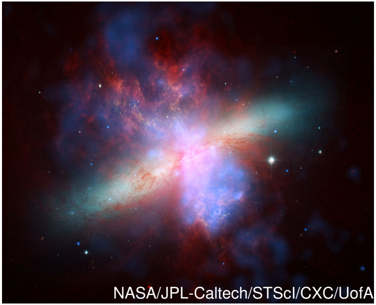
Three elephants in the γ-ray sky, Garmisch-Partenkirchen – 2017

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 (CR) pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

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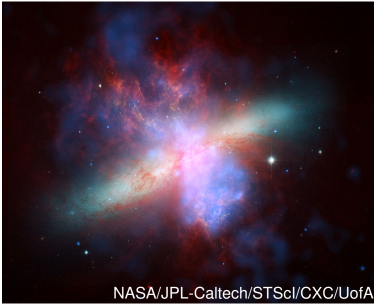

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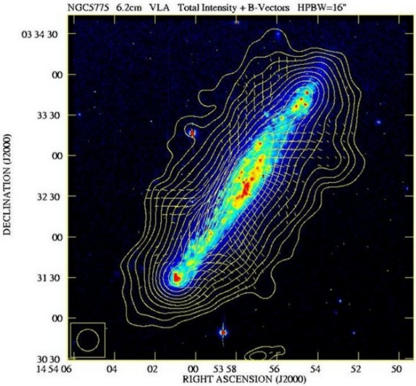
observed energy equipartition between cosmic rays, thermal gas and magnetic fields
→ suggests self-regulated feedback loop with CR driven winds

Why are CRs important for wind formation?

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



Tüllmann+ (2000)

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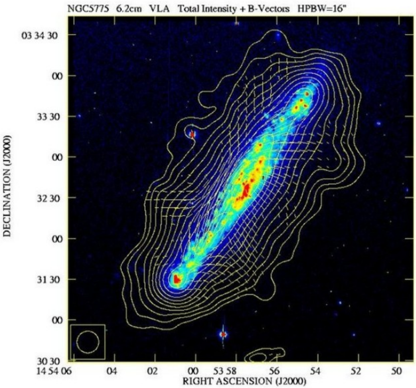
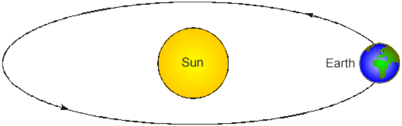


Tüllmann+ (2000)

- 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

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:

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

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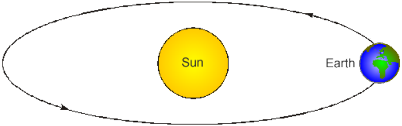

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$\Rightarrow$ need to develop a **fluid theory for a collisionless, non-Maxwellian component!**

Cosmic ray interactions with the plasma

individual particles:

- ***electrons/positrons:***
  - synchrotron
  - inverse Compton
  - bremsstrahlung
- ***ions:***
  - hadronic interaction $\rightarrow \gamma$ rays, ν, $e^{\pm}$
  - collisional ionization and Coulomb heating of the interstellar medium by MeV particles

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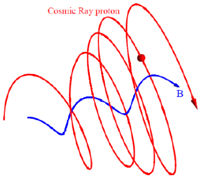
collective:

- ***microscales:*** kinetic instabilities and damping
- ***mesoscales:*** structure of collisionless shocks
- ***macroscales:*** interstellar, circumgalactic, intracluster plasma dynamics
  - outflows
  - equilibrium + stability
  - collisionless heating

Cosmic ray transport: two pictures

self-confinement:

- Alfvén waves are generated by streaming cosmic rays themselves
- gyroresonant interaction $\omega - k\, v_{\|} = \pm n\, \omega_{\rm c}, \quad n \in \mathbb{Z}$
- grow rate balanced by (non-linear Landau & turbulent) damping



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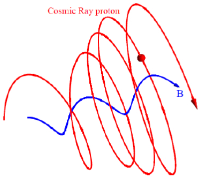
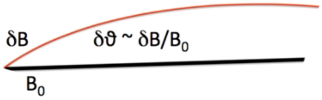


extrinsic confinement:

- waves are present as part of a turbulent cascade
- random walk of particles with nearly elastic scatterings
- diffusion process with scattering frequency

$$\nu \sim \frac{\langle (\delta\vartheta)^2 \rangle}{\delta t} \sim \omega_c \left(\frac{\delta B}{B_0} \right)^2$$



Cosmic-ray transport: streaming vs. diffusion

- 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, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\rm st} = -\boldsymbol{v}_{\rm A} \frac{\boldsymbol{b} \cdot \nabla P_{\rm cr}}{|\boldsymbol{b} \cdot \nabla P_{\rm cr}|}, \qquad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di} \boldsymbol{b} \frac{\boldsymbol{b} \cdot \nabla \varepsilon_{\rm cr}}{\varepsilon_{\rm cr}},$$

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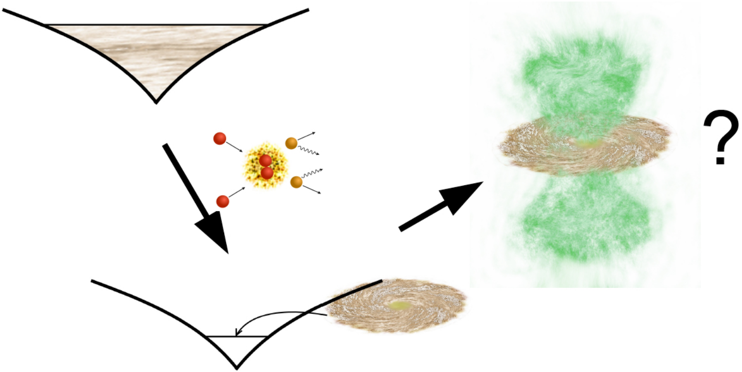
- CR streaming adiabatically transports CR energy with $\sim v_{\rm A}$
  CR diffusion irreversibly disperses the CR energy

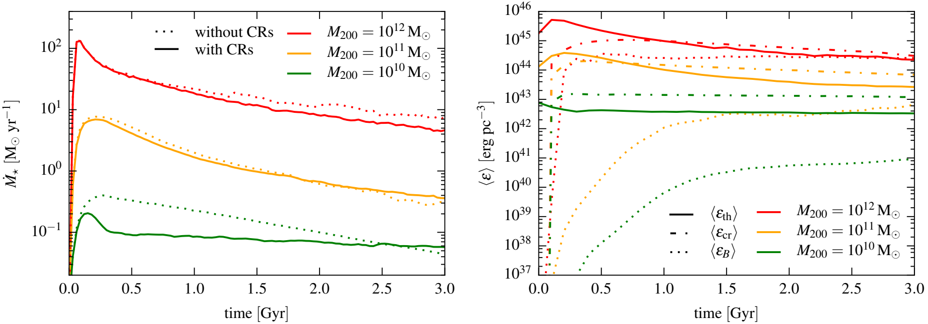
Galaxy simulation setup: 1. cosmic ray advection



C.P., Pakmor, Schaal, Simpson, Springel (2017)
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



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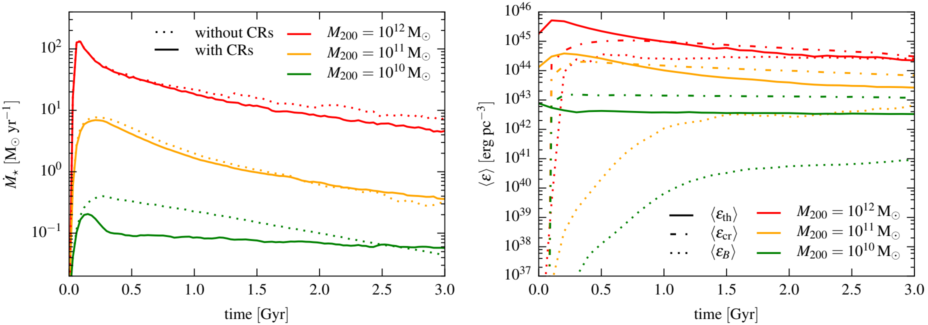

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- CR pressure feedback suppresses SFR more in smaller galaxies

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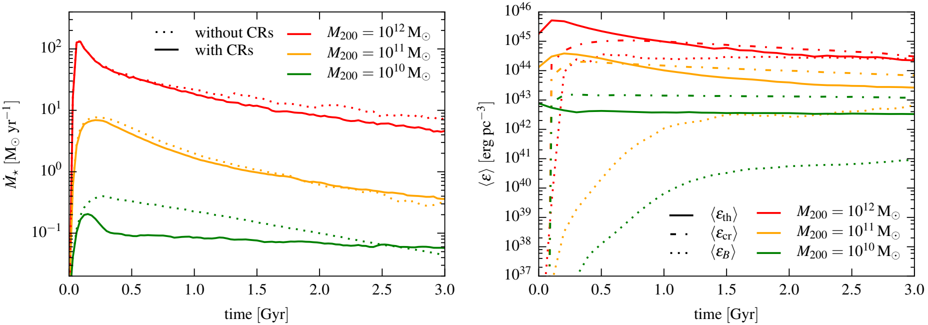

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- energy budget in disks is dominated by CR pressure

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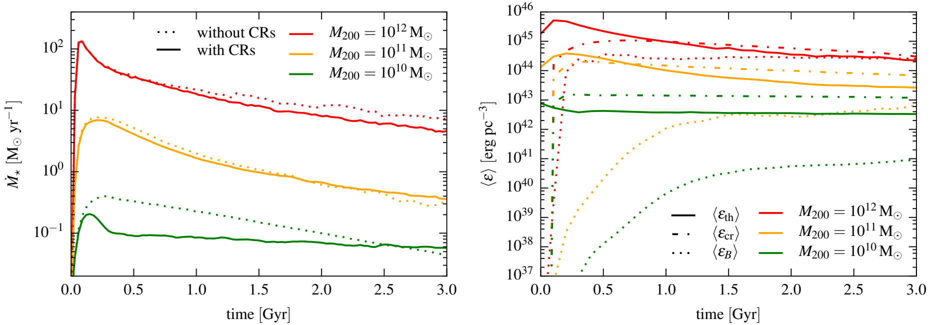
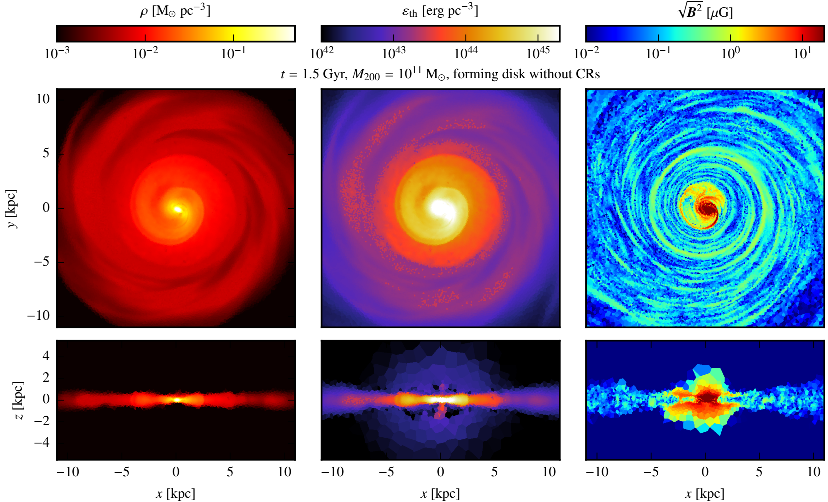
Time evolution of SFR and energy densities



C.P., Pakmor, Schaal, Simpson, Springel (2017)

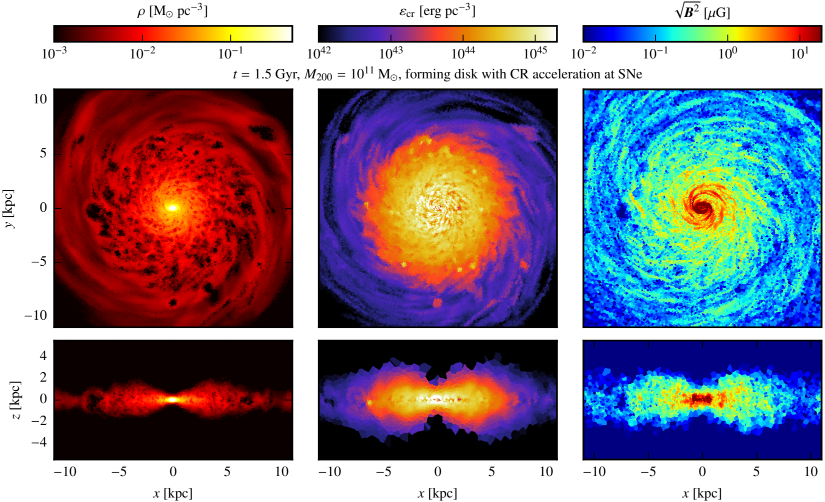
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



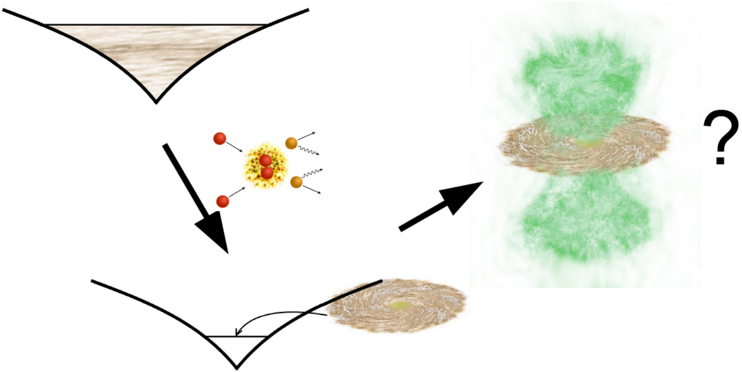
C.P., Pakmor, Schaal, Simpson, Springel (2017)

MHD galaxy simulation with CRs



C.P., Pakmor, Schaal, Simpson, Springel (2017)

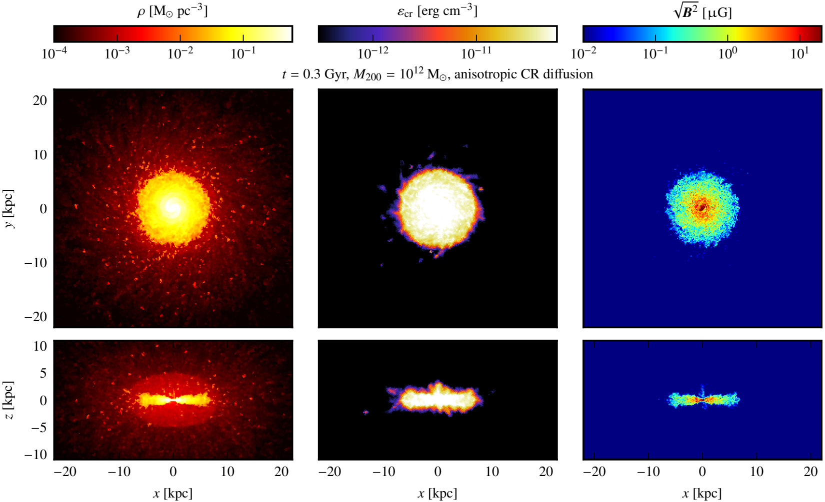
Galaxy simulation setup: 2. cosmic ray diffusion



C.P., Pakmor, Simpson, Springel (2017a,b)
Simulating radio synchrotron and gamma-ray emission in galaxies

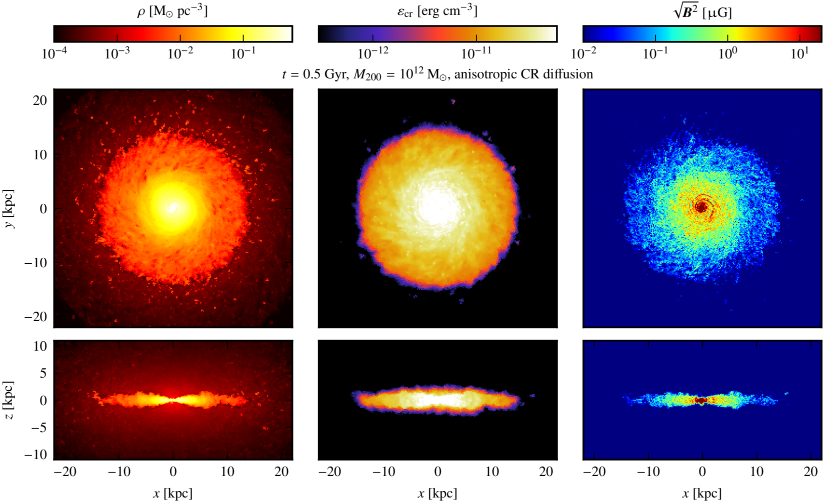
MHD + CR advection + diffusion: $\{10^{10}, 10^{11}, 10^{12}\}\ M_{\odot}$

Simulation of Milky Way-like galaxy, $t = 0.3$ Gyr



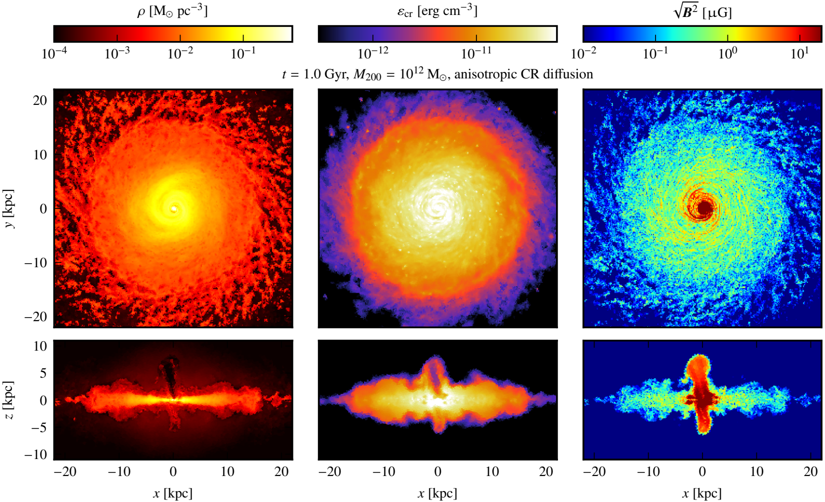
C.P.+ (2017a,b)

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



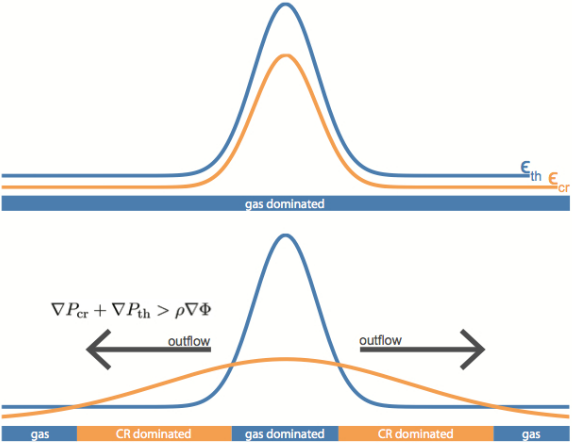
C.P.+ (2017a,b)

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



C.P.+ (2017a,b)

Cosmic ray driven wind: mechanism



CR streaming: Uhlig+ (2012), Wiener+ (2017), Ruszkowski+ (2017)
CR diffusion: Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor+ (2016), Simpson+ (2017), Girichidis+ (2016), C.P.+ (2017)

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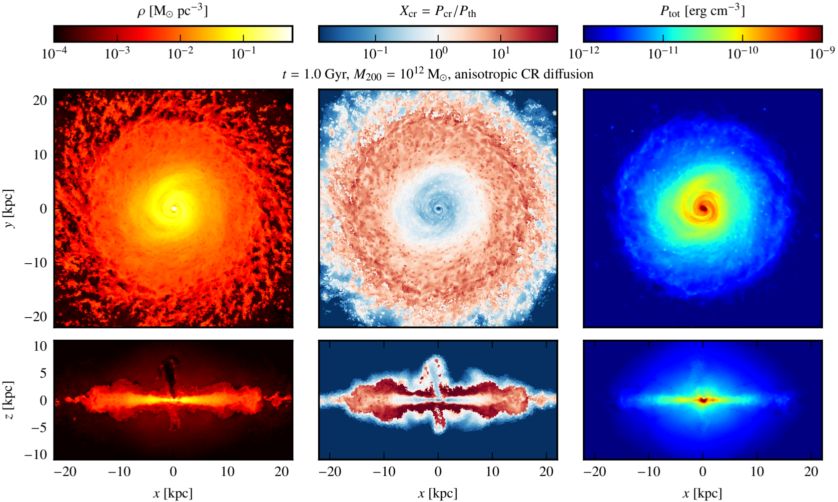

C.P.+ (2017a,b)

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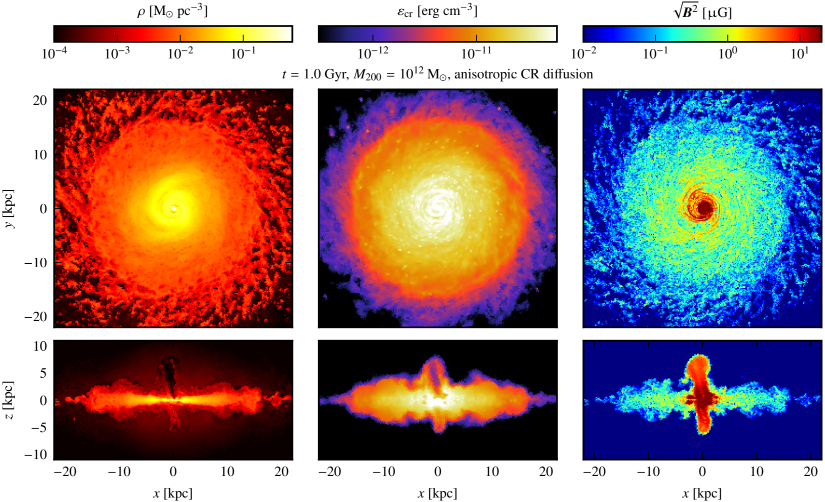
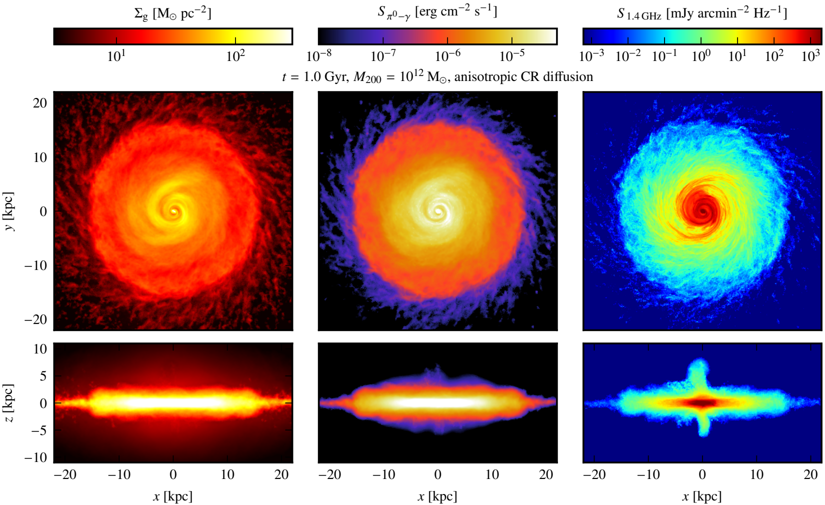


C.P.+ (2017a,b)

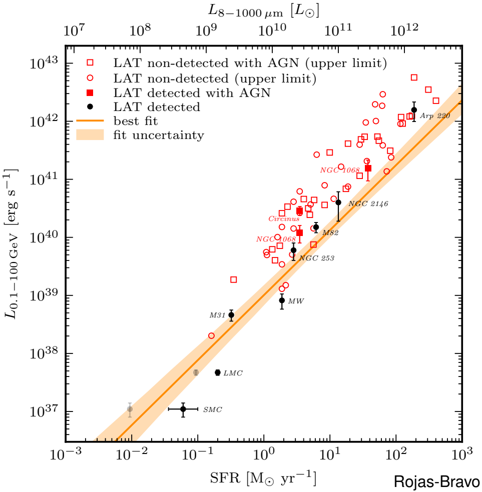
γ-ray and radio emission of Milky Way-like galaxy



C.P.+ (2017a,b)

Far infra-red – gamma-ray correlation

Universal conversion: star formation → cosmic rays → gamma rays



Rojas-Bravo & Araya (2016)

Far infra-red – gamma-ray correlation

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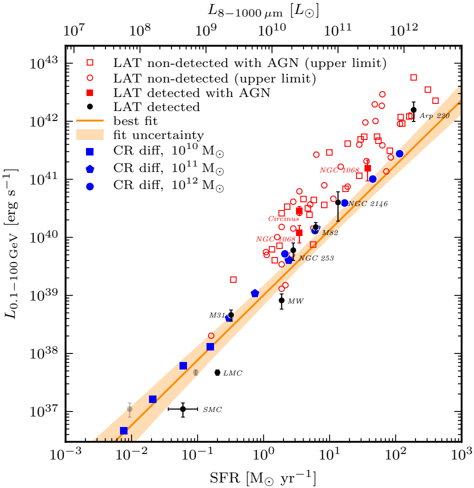

C.P.+ (2017a)

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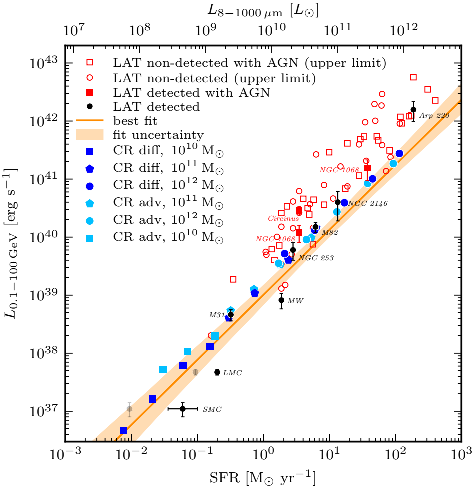

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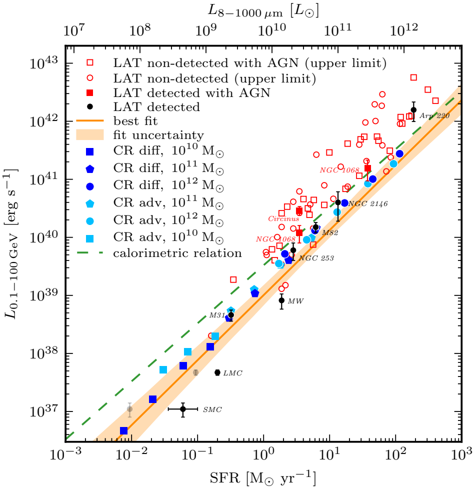
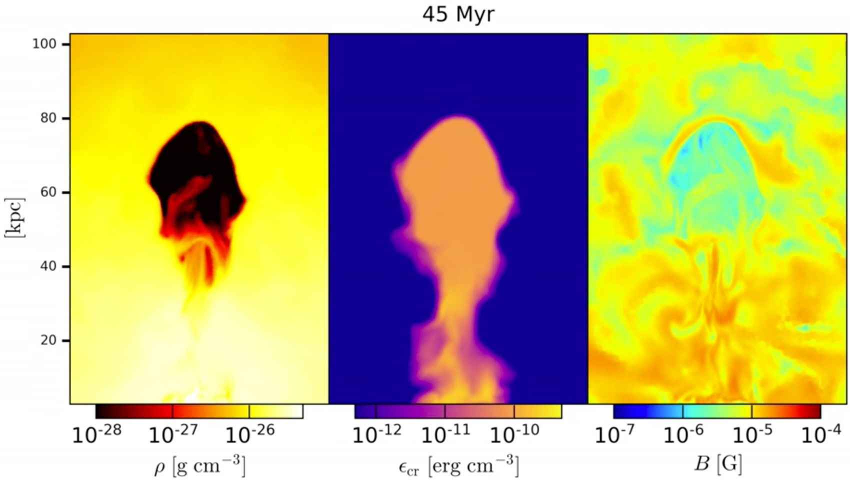


C.P.+ (2017a)

Jet simulation: gas density, CR energy density, *B* field



Ehlert+ in prep.

Open problems on cosmic ray-driven galactic winds

- improved plasma physics modeling of CR transport:
  streaming vs. diffusion
  → scaling of wind properties with halo mass ($\dot{M}$, $v_{\rm wind}$, ...)
  → magnetic dynamo (non-linear back-reaction on CR transport)

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- follow CR spectra:
  $\rightarrow$ improved cooling and (energy-dependent) transport

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  $\rightarrow$ which epoch? which halo mass?
  $\rightarrow$ active driver vs. preventive feedback?

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- impact of cosmological environment

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

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

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

Cosmic-ray driven galactic winds:

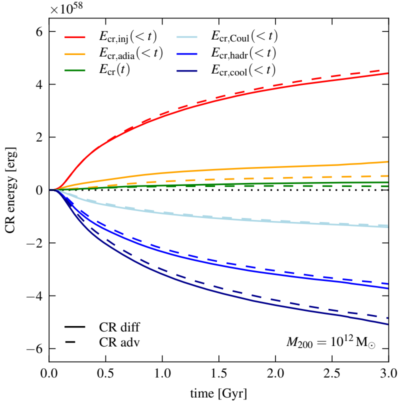
- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, MNRAS.
- Pakmor, Pfrommer, Simpson, Springel, *Galactic winds driven by isotropic and anisotropic cosmic ray diffusion in isolated disk galaxies,* 2016, ApJL.

AGN feedback by cosmic rays:

- Ehlert, Weinberger, Pfrommer, Springel, *Simulating active galactic nuclei feedback with cosmic rays,* in prep.

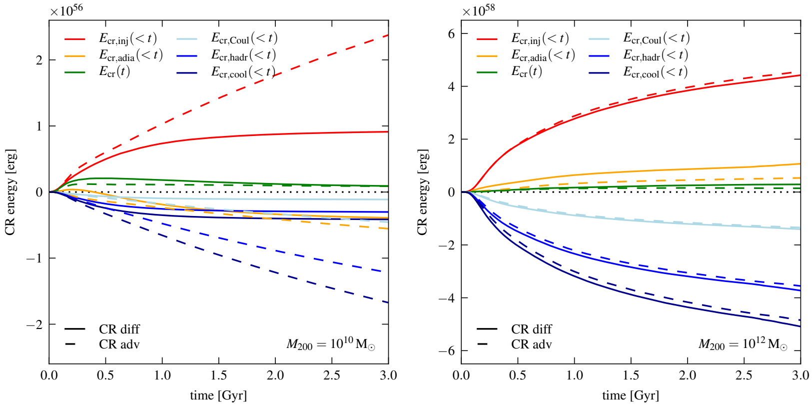
Additional slides

Time evolution of CR energies



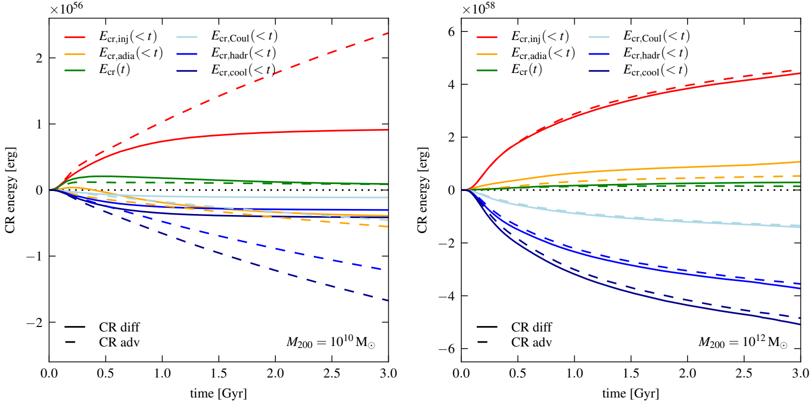
C.P.+ (2017a)

Time evolution of CR energies



C.P.+ (2017a)

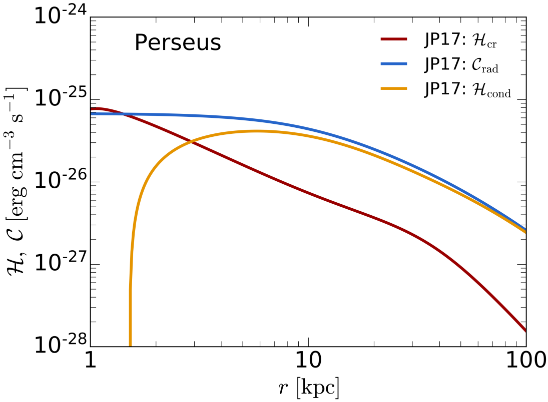
Time evolution of CR energies



C.P.+ (2017a)

- adiabatic CR losses are significant in small galaxies
  ⇒ deviation from calorimetric relation at small SFRs

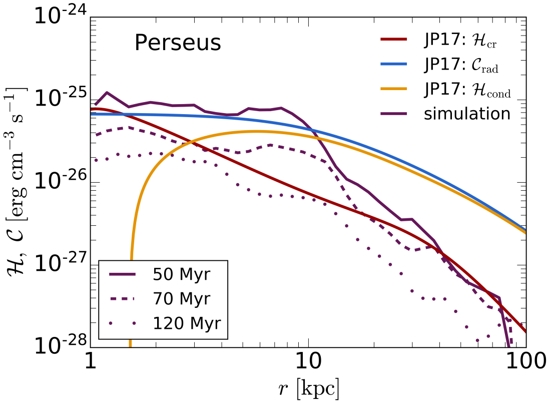
Perseus cluster – heating vs. cooling: theory



Ehlert+ in prep.

- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

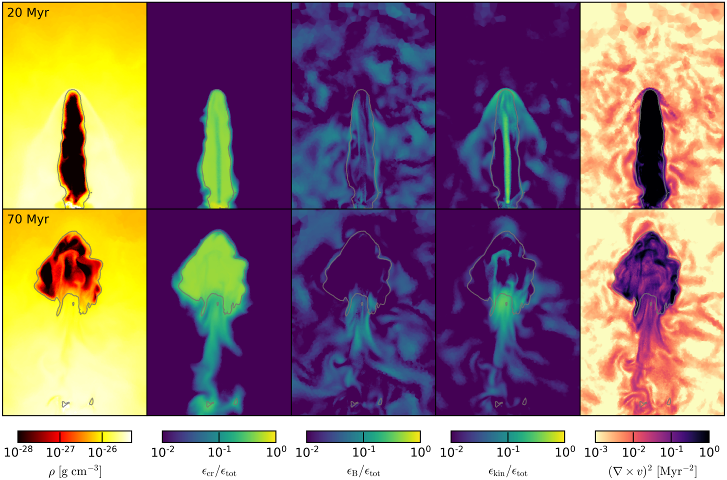
Perseus cluster – heating vs. cooling: simulations



Ehlert+ in prep.

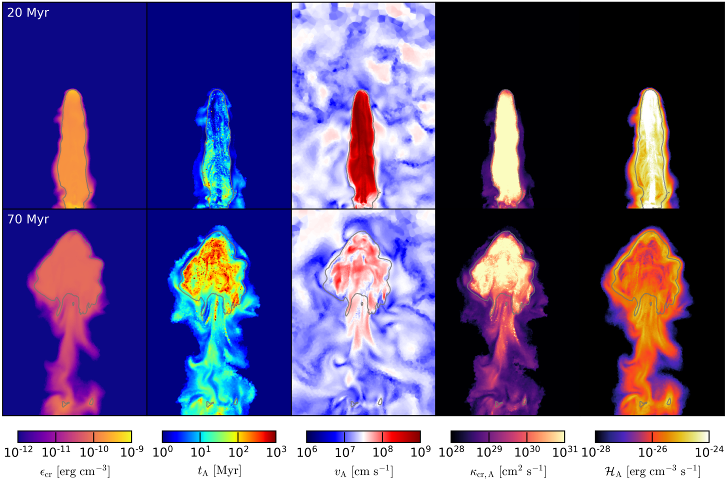
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

AGN Simulations: energy densities



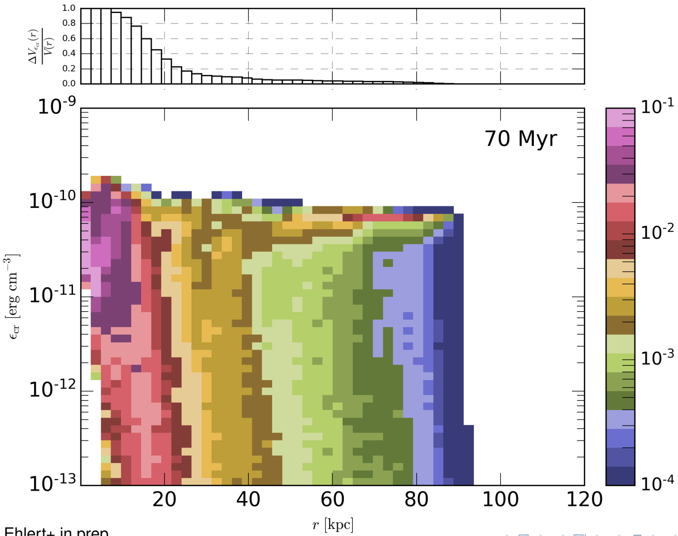
Ehlert+ in prep.

AGN Simulations: cosmic-ray transport



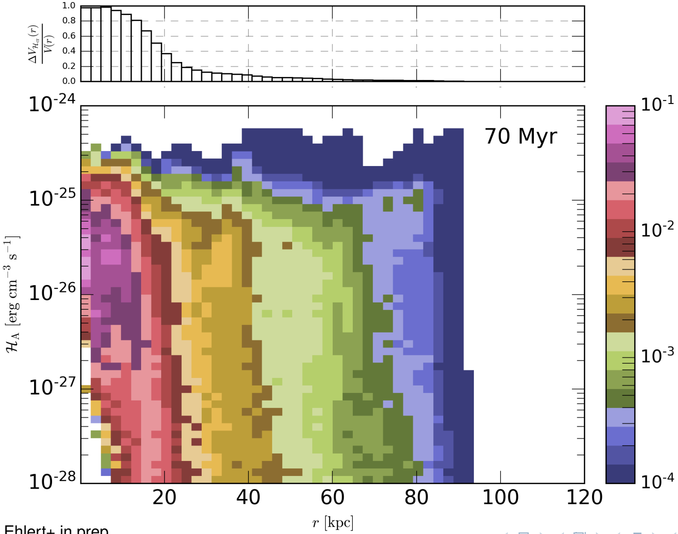
Ehlert+ in prep.

AGN Simulations: cosmic ray distribution



Ehlert+ in prep.

AGN Simulations: cosmic-ray heating rate



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