Computational methods for simulating cosmic ray feedback

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in collaboration with

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Outline

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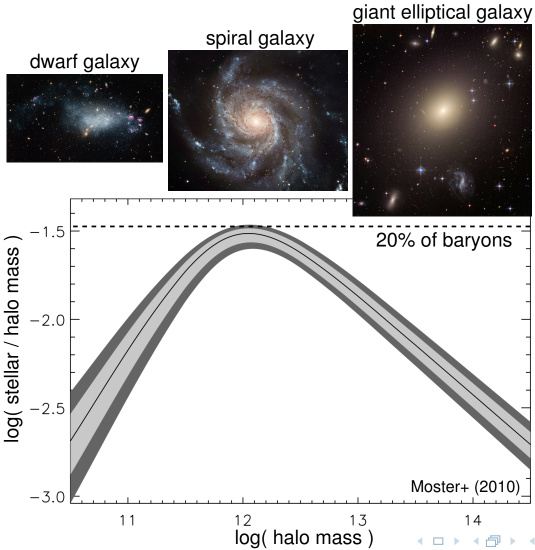
2. Computational methods
   - CR diffusion
   - CR streaming
   - CR hydrodynamics
3. Galaxy formation simulations
   - Modeling physics
   - Galaxy simulations
   - AGN jet simulations

Puzzles in galaxy formation


Puzzles in galaxy formation



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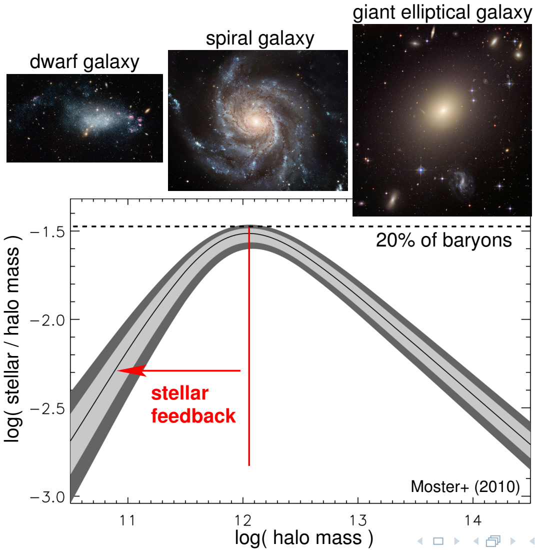
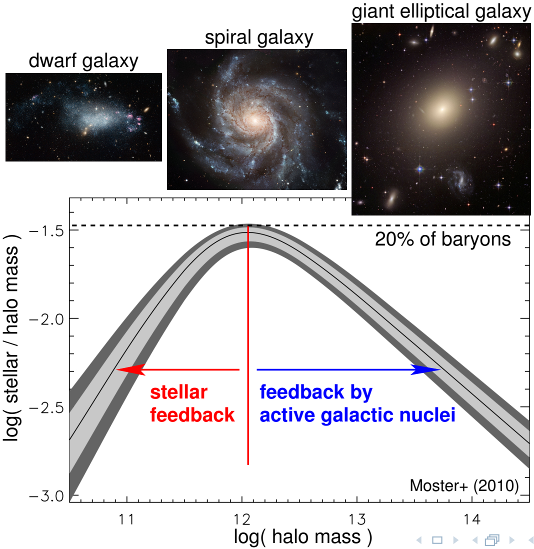
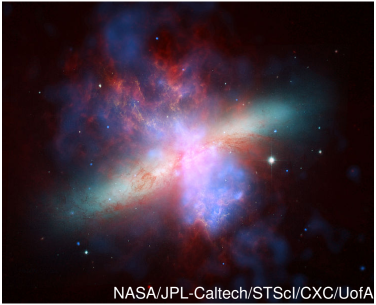


Puzzles in galaxy formation



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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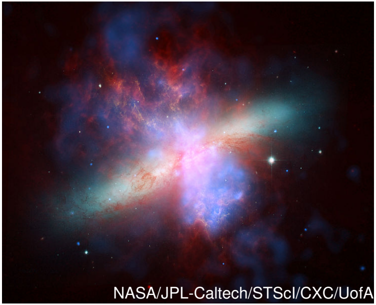

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- thermal pressure provided by supernovae or AGNs?
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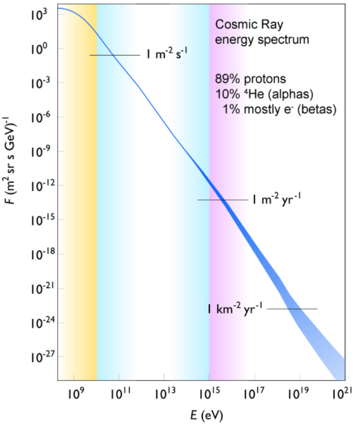
- cosmic-ray pressure and Alfvén wave heating of CRs accelerated at supernova shocks?

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

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

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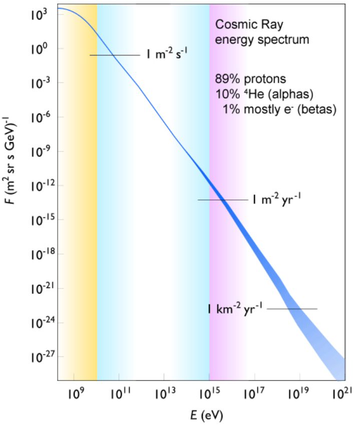

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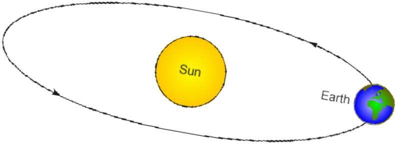
- spans more than 33 decades in flux and 12 decades in energy
- "knee" indicates characteristic maximum energy of galactic accelerators
- CRs beyond the "ankle" have extra-galactic origin
- energy density of cosmic rays, magnetic fields, and turbulence in the interstellar gas all similar

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

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

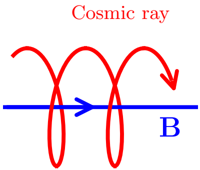
gyro-orbit of GeV cosmic ray:

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

⇒ 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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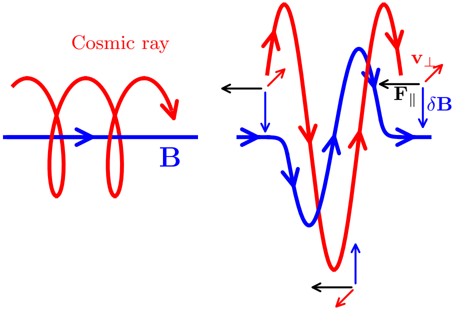

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- **gyro resonance:** $\omega - k_\parallel v_\parallel = n\Omega$

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

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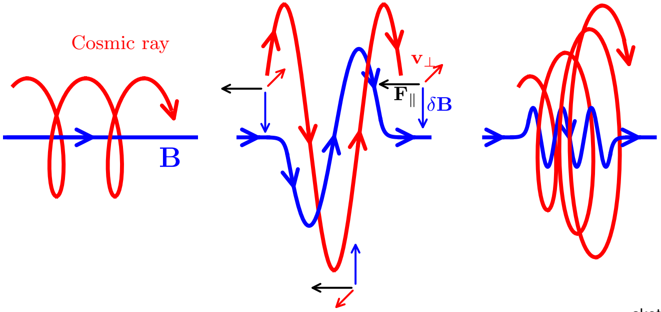

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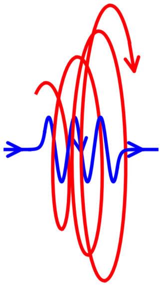
- **gyro resonance:** $\omega - k_{\|} v_{\|} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields → isotropization of CR momenta

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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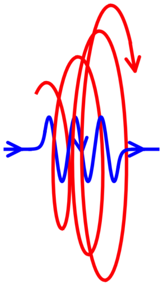

→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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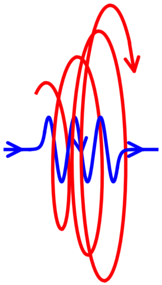

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weak wave damping: strong coupling → CR stream with waves
strong wave damping: less waves to scatter → CR diffusion prevails

CR transport (steady-state flux)

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

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

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$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla} \cdot [(\varepsilon + P_{\rm th} + P_{\rm cr}) \boldsymbol{v}] = P_{\rm cr} \boldsymbol{\nabla} \cdot \boldsymbol{v} - \boldsymbol{v}_{\rm st} \cdot \boldsymbol{\nabla} P_{\rm cr}$$

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

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

Outline

CR diffusion

- isotropic CR diffusion (unresolved tangled magnetic fields):

$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{f}_{\mathrm{iso}} = 0 \qquad \text{with} \qquad \boldsymbol{f}_{\mathrm{iso}} = -\kappa \boldsymbol{\nabla} \varepsilon_{\mathrm{cr}}$$

$\Rightarrow$ energy conserving and extremum preserving

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$\Rightarrow$ energy conserving and extremum preserving

- anisotropic CR diffusion (resolved magnetic fields in MHD simulations):

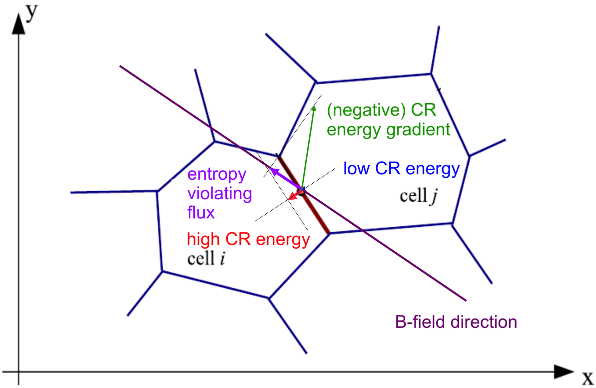
$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{f}_{\mathrm{aniso}} = 0 \qquad \text{with} \qquad \boldsymbol{f}_{\mathrm{aniso}} = -\kappa \boldsymbol{b} \left(\boldsymbol{b} \cdot \boldsymbol{\nabla} \varepsilon_{\mathrm{cr}} \right)$$

$\Rightarrow$ also energy conserving and extremum preserving

Discretization schemes for anisotropic CR diffusion

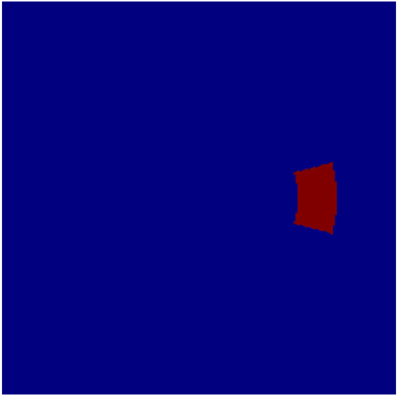
The entropy constraint can be easily violated in simple linear discretization schemes

$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \nabla \cdot \boldsymbol{f}_{\mathrm{aniso}} = 0 \quad \text{with} \quad \boldsymbol{f}_{\mathrm{aniso}} = -\kappa \boldsymbol{b} \left(\boldsymbol{b} \cdot \nabla \varepsilon_{\mathrm{cr}} \right)$$



Anisotropic CR diffusion

- diffusion of CR energy density along magnetic field lines
- implemented on unstructured mesh in AREPO
- implicit solver with local time stepping
- conserves CR energy and preserves extrema



Pakmor, CP, Simpson, Kannan, Springel (2016)

CR streaming vs. diffusion: estimates

- CRs cannot be transported faster than the Alfvén speed over macroscopic distances:

$$v_{\mathrm{di}} \equiv \kappa \frac{|\nabla P_{\mathrm{cr}}|}{\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}}} \overset{!}{<} v_{\mathrm{a}}$$

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- what happens as CRs are released from a supernova remnant?

$$v_{\rm di} \sim \frac{\kappa}{4L_{\rm cr}} \sim 10^3 \text{ km s}^{-1} \; \kappa_{28} L_{\rm cr,10\ pc}^{-1} \sim 100 v_{\rm a}$$

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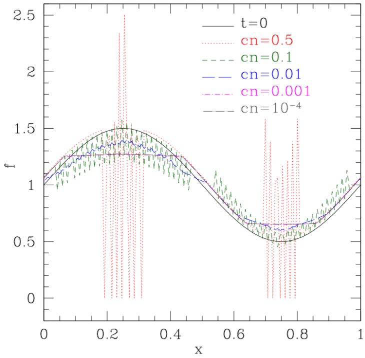
$\Rightarrow$ flux-limited CR diffusion: prohibitively expensive because of von-Neumann-type time step constraint ($\Delta t \propto \Delta x^2/\kappa$), even for implicit solvers

$\Rightarrow$ simulate CR streaming!

Modeling CR streaming
A challenging hyperbolic/parabolic problem



Sharma+ (2010)

- streaming equation (no heating):

$$\frac{\partial \varepsilon_{cr}}{\partial t} + \boldsymbol{\nabla} \cdot [(\varepsilon_{cr} + P_{cr})\boldsymbol{v}_{st}] = 0$$

$$\boldsymbol{v}_{st} = -\mathrm{sgn}(\boldsymbol{B} \cdot \boldsymbol{\nabla} P_{cr})\boldsymbol{v}_a$$

- CR streaming $\sim$ CR advection with the Alfvén speed
- at local extrema, CR energy can overshoot and develop unphysical oscillations

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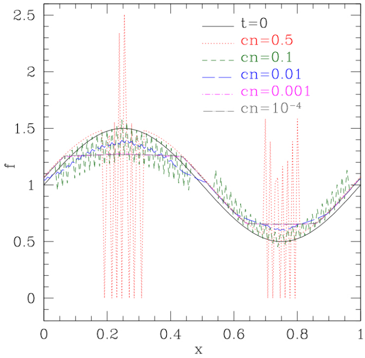

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- idea: regularize equations, similar to adding artificial viscosity

Modeling CR streaming – regularization

- 1D streaming equation (no heating):

$$\frac{\partial \varepsilon_{\rm cr}}{\partial t} + \frac{\partial}{\partial x}\left[(\varepsilon_{\rm cr} + P_{\rm cr})v_{\rm st}\right] = 0$$

$$v_{\rm st} = -v_{\rm a}\mathrm{sgn}\left(\frac{\partial \varepsilon_{\rm cr}}{\partial x}\right) \quad \rightarrow \quad \tilde{v}_{\rm st} = -v_{\rm a}\tanh\left(\frac{1}{\delta}\frac{\partial \varepsilon_{\rm cr}}{\partial x}\right)$$

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- regularized 1D streaming equation (no heating):

$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \frac{\partial}{\partial x}\left[\tilde{v}_{\mathrm{st}}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\right] =$$

$$\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \tilde{v}_{\mathrm{st}}\frac{\partial}{\partial x}(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}}) - \kappa_{\mathrm{reg}}\frac{\partial^2 \varepsilon_{\mathrm{cr}}}{\partial x^2} = 0,$$

where $\kappa_{\mathrm{reg}} = v_{\mathrm{a}}\gamma_{\mathrm{cr}}\varepsilon_{\mathrm{cr}}\frac{1}{\delta}\mathrm{sech}^2\left(\frac{1}{\delta}\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial x}\right)$ (Sharma+ 2010)

- regularized equation is advective at gradients and diffusive at extrema

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- regularized equation is advective at gradients and diffusive at extrema
- ***but:*** *numerical diffusion dominates for CR sources on a background*

Analogies of CR and radiation hydrodynamics

CRs and radiation are relativistic fluids

regime	CR transport	radiation HD analogy
• tangled $\boldsymbol{B}$, strong scattering	CR diffusion	diffusive transport in clumpy medium
• resolved $\boldsymbol{B}$, 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 with $\tau \gtrsim 1$
• no scattering	CR propagation with c	vacuum propagation

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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 $\bar{\nu}_\pm / c^2 = 1/(3\kappa_\pm)$
- lab-frame equ's for CR energy and momentum density, ε_cr and $\boldsymbol{f}_\mathrm{cr}/c^2$ (Thomas & CP 2018):

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

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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):

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

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

CR vs. radiation hydrodynamics

- Alfvén wave velocity in lab frame: $\boldsymbol{w}_\pm = \boldsymbol{v} \pm \boldsymbol{v}_\mathrm{a}$,
  CR scattering frequency $\bar{\nu}_\pm / c^2 = 1/(3\kappa_\pm)$
- lab-frame equ's for CR energy and momentum density, ε_cr and $\boldsymbol{f}_\mathrm{cr}/c^2$ (Thomas & CP 2018):

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

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

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

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

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

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

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 density $\varepsilon_{\mathrm{a},\pm}$ (Thomas & CP 2018)

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

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

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

Alfvén-wave regulated CR transport

- comoving equ's for CR energy and momentum density, ε_cr and f_cr/c^2 and Alfvén-wave energy density $\varepsilon_{\mathrm{a},\pm}$ (Thomas & CP 2018)
  $\rightarrow$ pseudoforces (e.g., adiabatic changes)

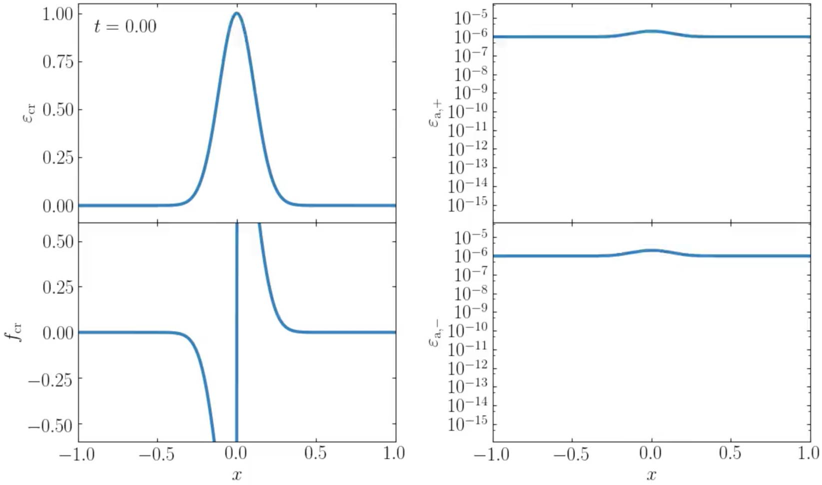
$$\frac{\partial \varepsilon_\mathrm{cr}}{\partial t} + \boldsymbol{\nabla}\cdot\left[\boldsymbol{v}(\varepsilon_\mathrm{cr}+P_\mathrm{cr}) + \boldsymbol{b} f_\mathrm{cr}\right] = \boldsymbol{v}\cdot\boldsymbol{\nabla} P_\mathrm{cr} - \frac{v_\mathrm{a}}{3\kappa_+}\left[f_\mathrm{cr} - v_\mathrm{a}(\varepsilon_\mathrm{cr}+P_\mathrm{cr})\right]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

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

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

Non-equilibrium CR streaming and diffusion

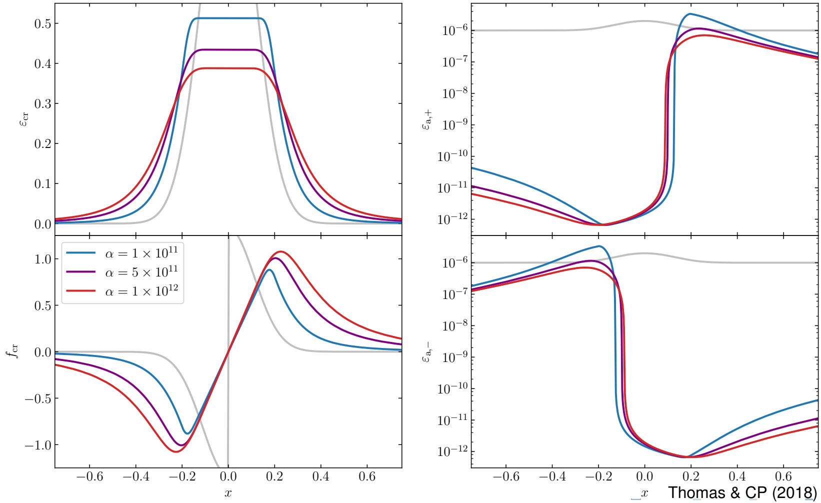
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

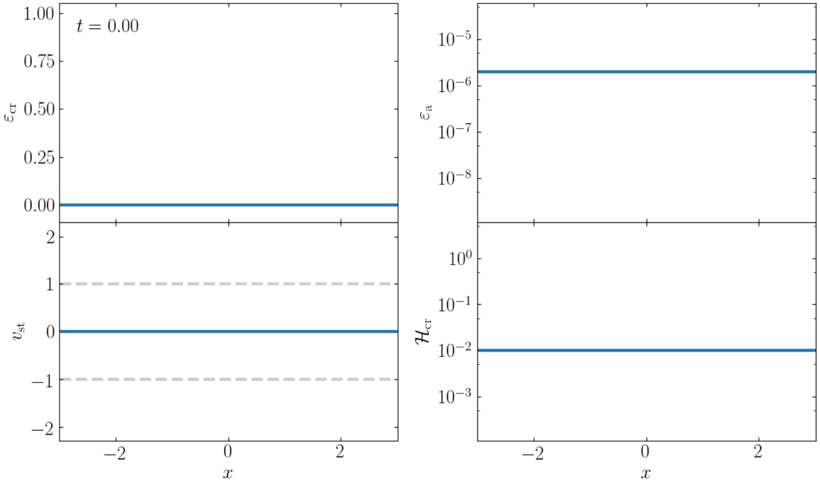
Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2018)

Steady CR source: CR Alfvén wave heating

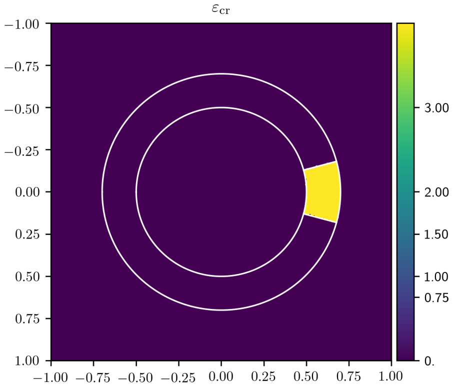


Thomas & CP (2018)

Anisotropic CR streaming and diffusion – AREPO

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

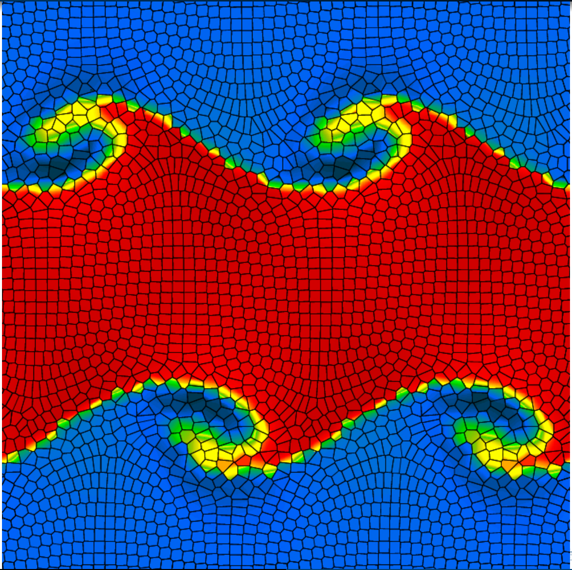
- CR streaming and diffusion along magnetic field lines in the self-confinement picture
- moment expansion similar to radiation hydrodynamics
- accounts for kinetic physics: non-linear Landau damping, gyro-resonant instability, . . .
- Galilean invariant and causal transport
- energy and momentum conserving



Thomas, Pakmor, CP (in prep.)

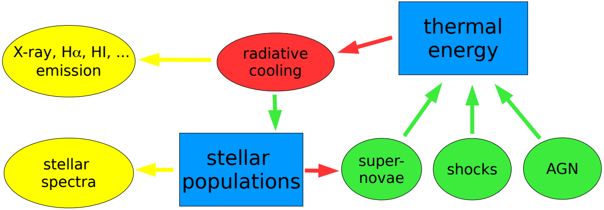
Outline

Cosmological moving-mesh code AREPO (Springel 2010)



Simulations – flowchart

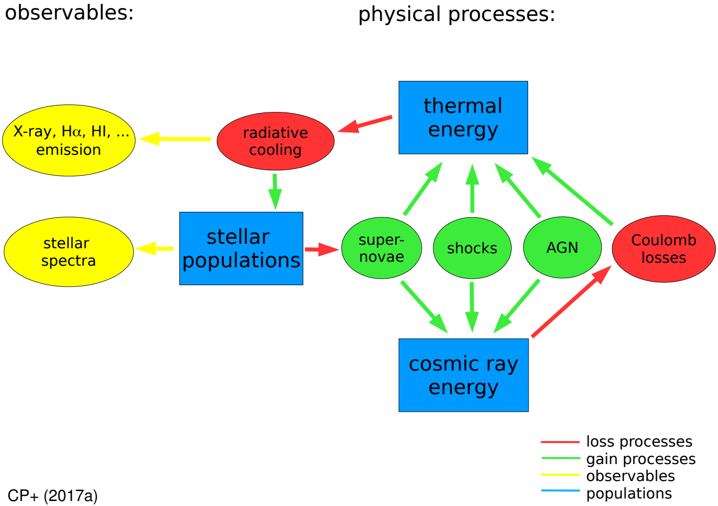
observables: physical processes:



loss processes
gain processes
observables
populations

CP+ (2017a)

Simulations with cosmic ray physics

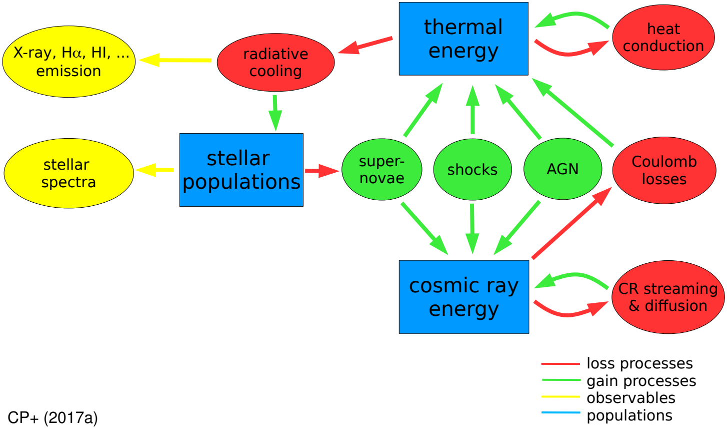


CP+ (2017a)

Simulations with cosmic ray physics

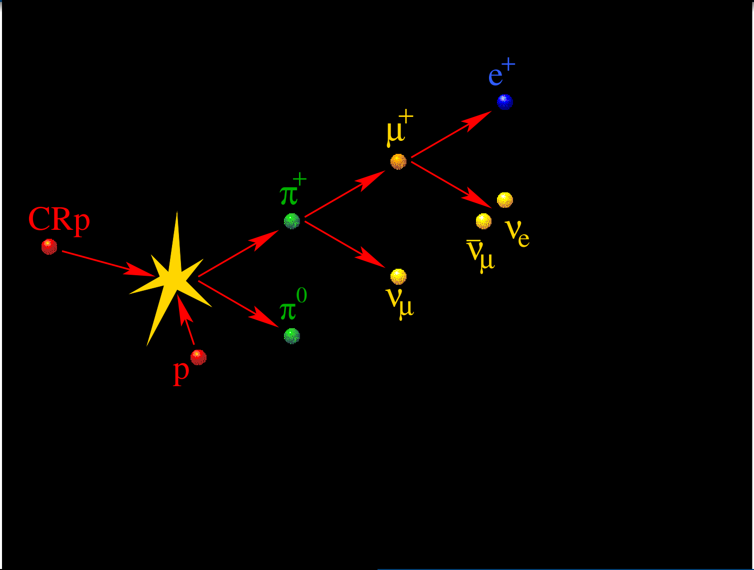
observables:

physical processes:

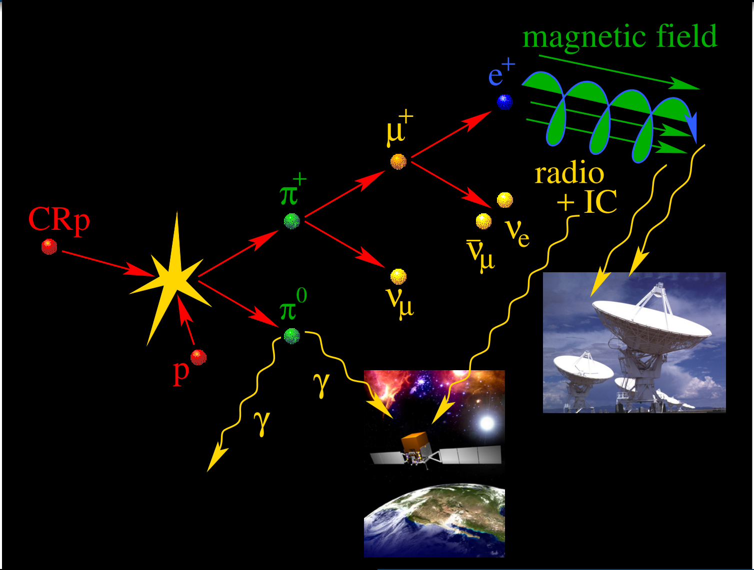


CP+ (2017a)

Hadronic cosmic ray proton interaction



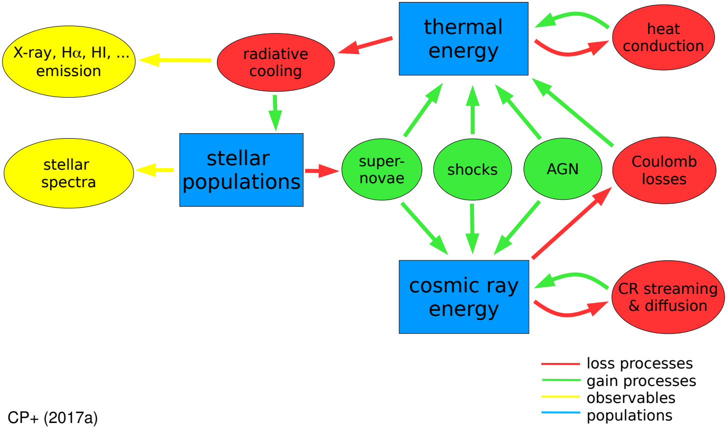
Hadronic cosmic ray proton interaction



Simulations with cosmic ray physics

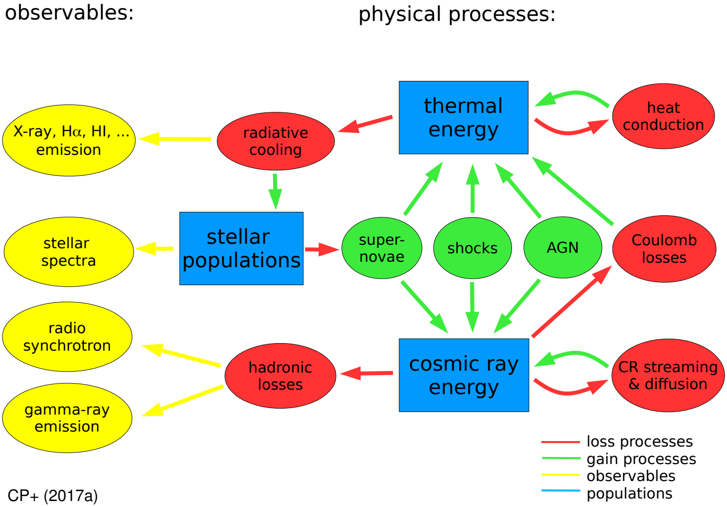
observables:

physical processes:



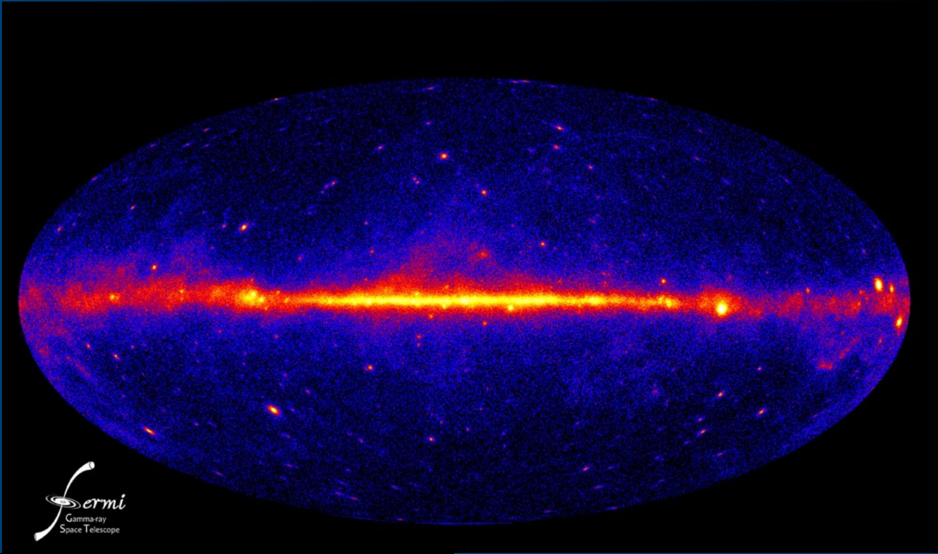
CP+ (2017a)

Simulations with cosmic ray physics



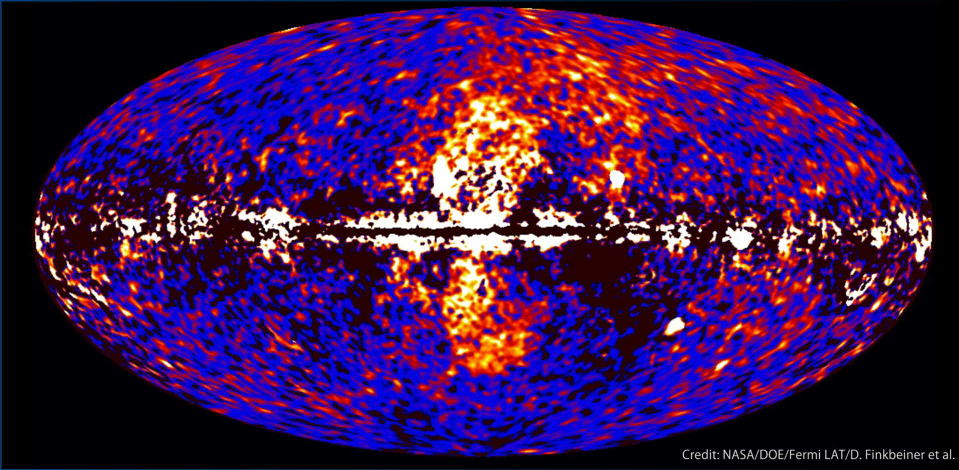
CP+ (2017a)

Gamma-ray emission of the Milky Way



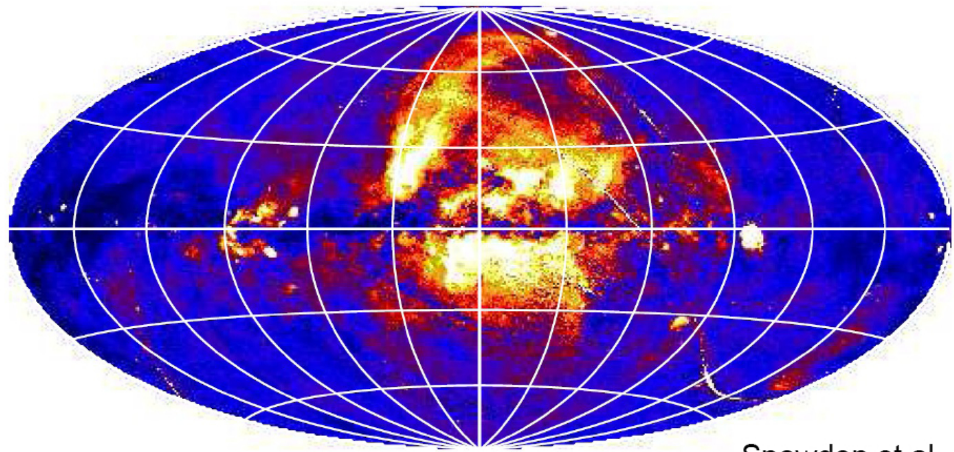
Galactic wind in the Milky Way?

Fermi gamma-ray bubbles



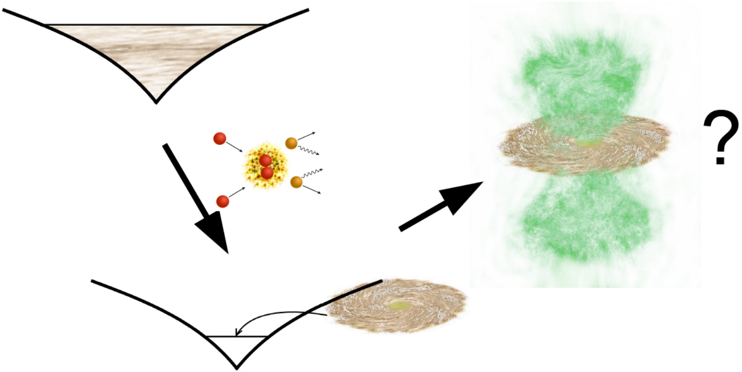
Galactic wind in the Milky Way?

Diffuse X-ray emission in our Galaxy



Snowden et al.,

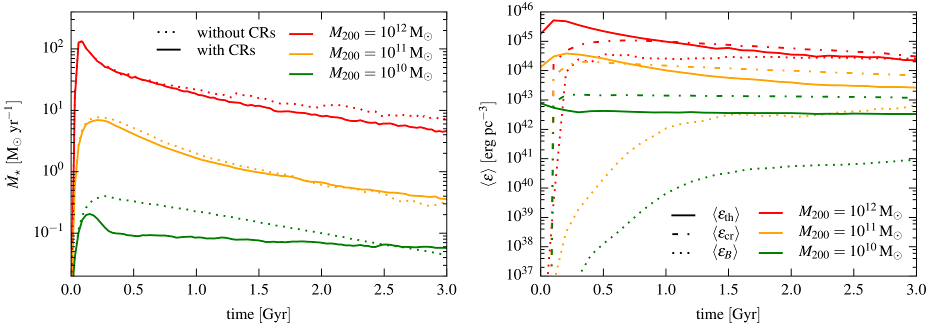
Galaxy simulation setup: 1. cosmic ray advection



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

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

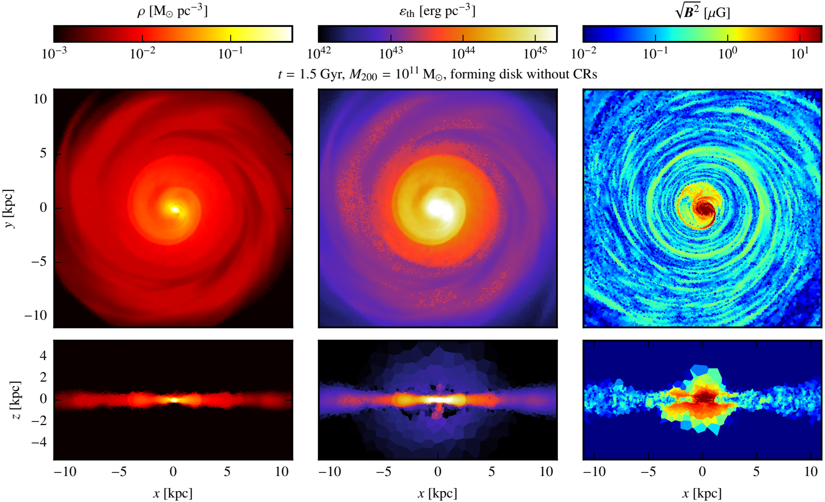
Time evolution of SFR and energy densities



CP+ (2017a)

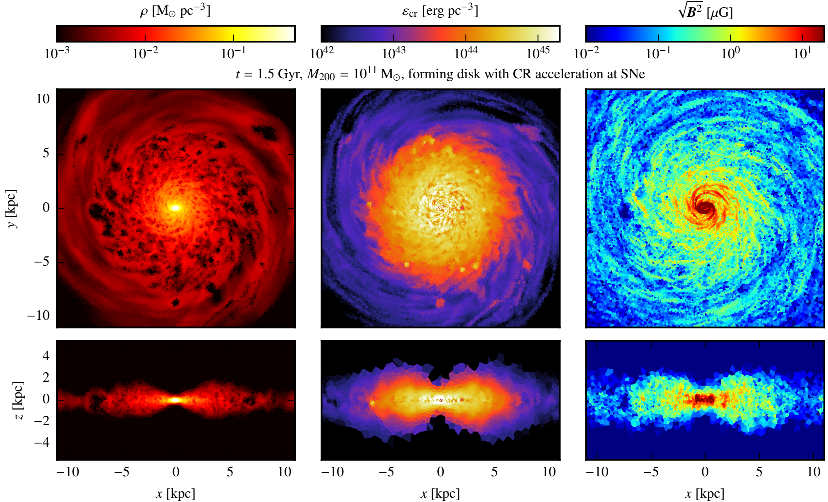
- CR pressure feedback suppresses SFR more in smaller galaxies
- energy budget in disks is dominated by CR pressure
- magnetic dynamo faster in Milky Way galaxies than in dwarfs

MHD galaxy simulation without CRs



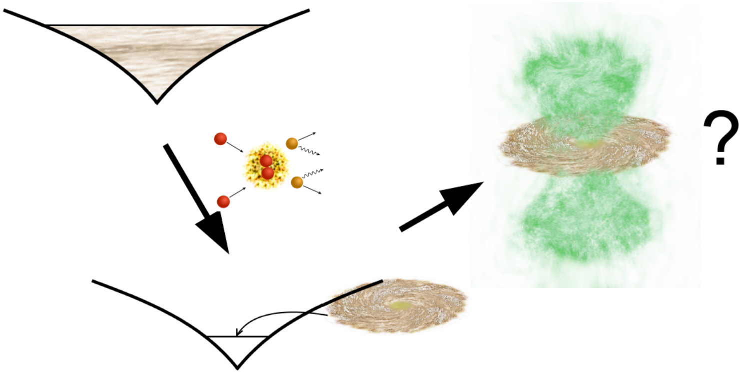
CP+ (2017a)

MHD galaxy simulation with CRs



CP+ (2017a)

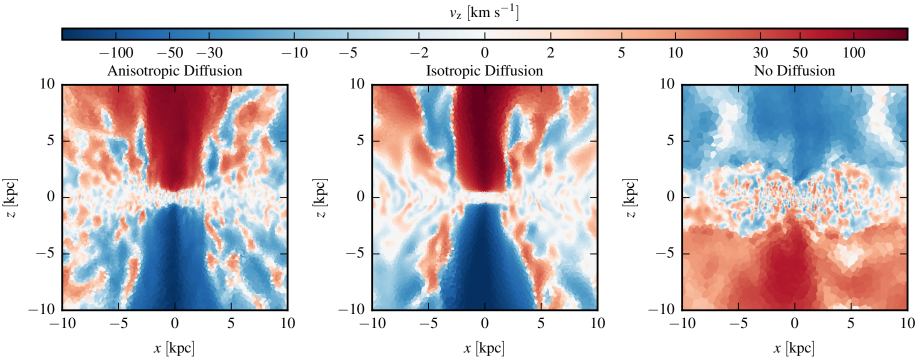
Galaxy simulation setup: 2. cosmic ray diffusion



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

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

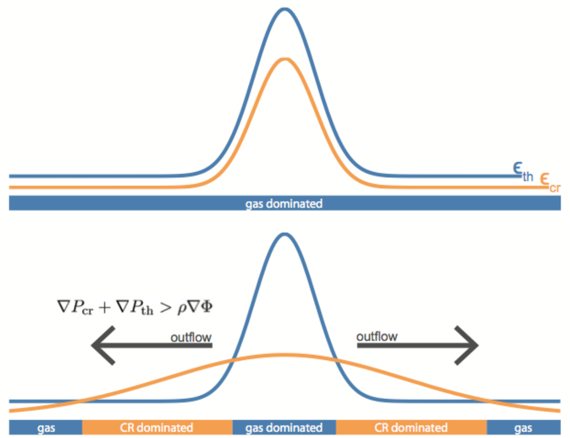
MHD galaxy simulation with CR diffusion



Pakmor, CP, Simpson, Springel (2016)

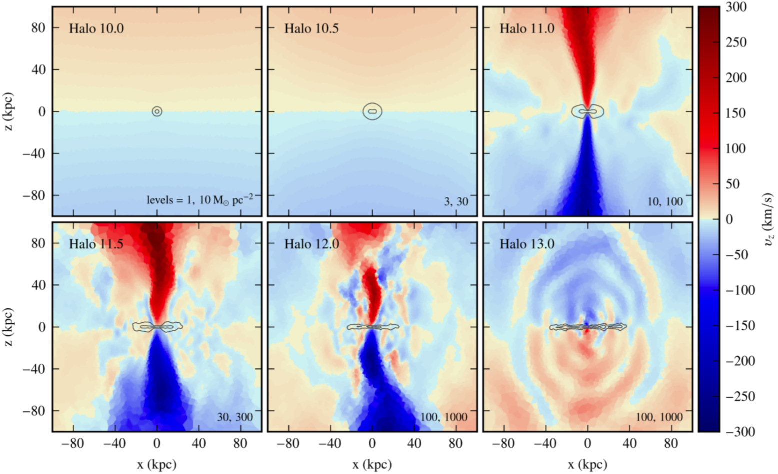
- CR diffusion launches powerful winds
- simulation without CR diffusion exhibits only weak fountain flows

Cosmic ray driven wind: mechanism



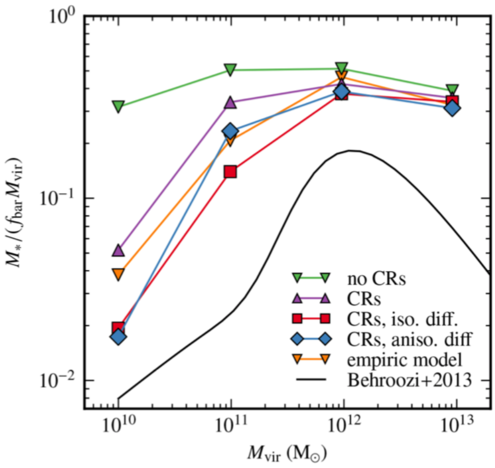
CR streaming in 3D simulations: Uhlig, CP+ (2012), Ruszkowski+ (2017)
CR diffusion in 3D simulations: Jubelgas+ (2008), Booth+ (2013), Hanasz+ (2013), Salem & Bryan (2014), Pakmor, CP+ (2016), Simpson+ (2016), Girichidis+ (2016), Dubois+ (2016), CP+ (2017b), Jacob+ (2018)

CR-driven winds: dependence on halo mass



Jacob+ (2018)

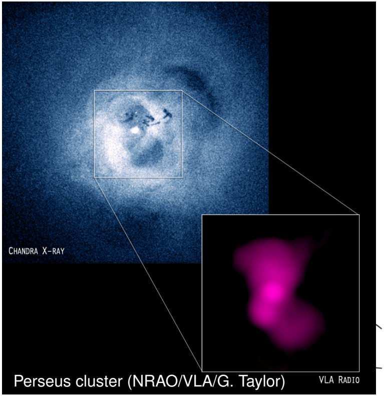
CR-driven winds: suppression of star formation



Jacob+ (2018)

Feedback by active galactic nuclei

Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling ⇒ **but how?**

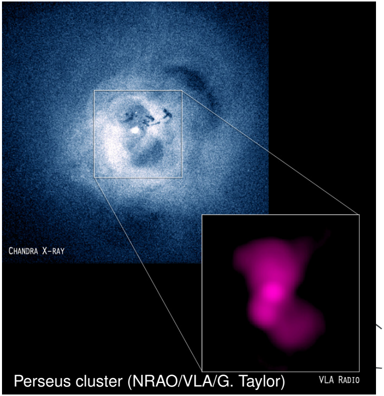


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling

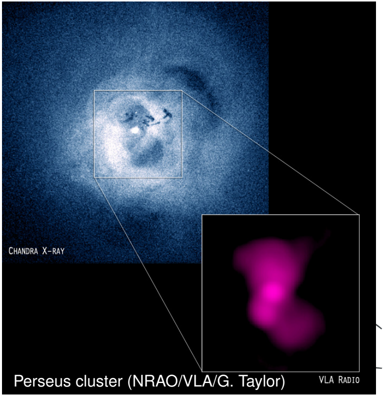


Perseus cluster (NRAO/VLA/G. Taylor)

Feedback by active galactic nuclei

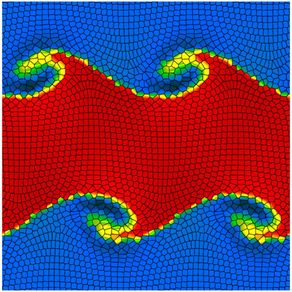
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling ⇒ **but how?**

- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- self-regulated heating mechanism to avoid overcooling
- jet interaction with magnetized cluster medium → turbulence
- jet accelerates cosmic rays → release from bubbles provides source of heat



Perseus cluster (NRAO/VLA/G. Taylor)

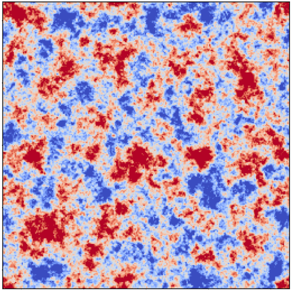
MHD jet simulations



AREPO: unstructured-mesh

- MHD moving-mesh code AREPO
- NFW cluster potential

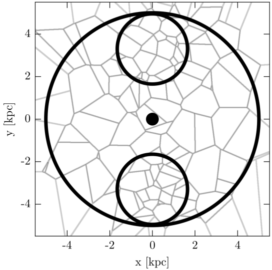
MHD jet simulations



initial magnetic field

- MHD moving-mesh code AREPO
- NFW cluster potential
- external turbulent magnetic field (Kolmogorov)

MHD jet simulations

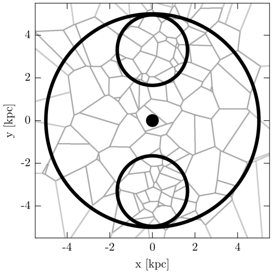


AREPO: jet injection region

(Weinberger+ 2017)

- MHD moving-mesh code AREPO
- NFW cluster potential
- external turbulent magnetic field (Kolmogorov)
- jet module
  - prepare low-density state in pressure equilibrium
  - inject kinetic energy, ***B***, and CRs
  - refine to sustain density contrast

Cosmic ray modeling



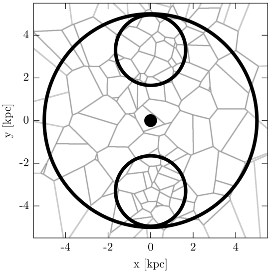
AREPO: jet injection region

(Weinberger+ 2017)

- subgrid CR acceleration:
  - reality: internal shocks
  - code: $E_{cr}/E_{th} \geq 0.5$

AIP

Cosmic ray modeling

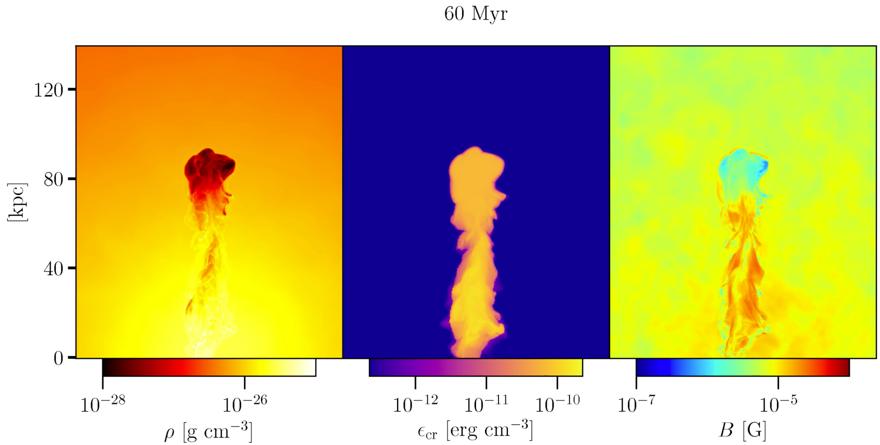


AREPO: jet injection region

(Weinberger+ 2017)

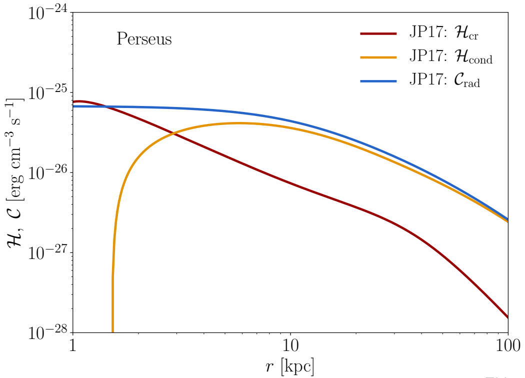
- subgrid CR acceleration:
  - reality: internal shocks
  - code: $E_{cr}/E_{th} \geq 0.5$
- CR transport:
  - CRs are advected
  - emulate CR streaming ≈ anisotropic CR diffusion & Alfvén cooling

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



Ehlert, Weinberger, CP+ (2018)

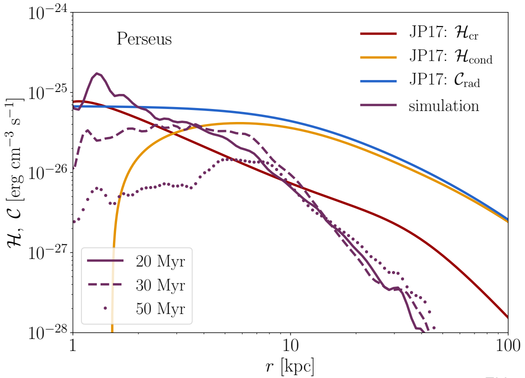
Perseus cluster – heating vs. cooling: theory



Ehlert, Weinberger, CP+ (2018)

- 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}

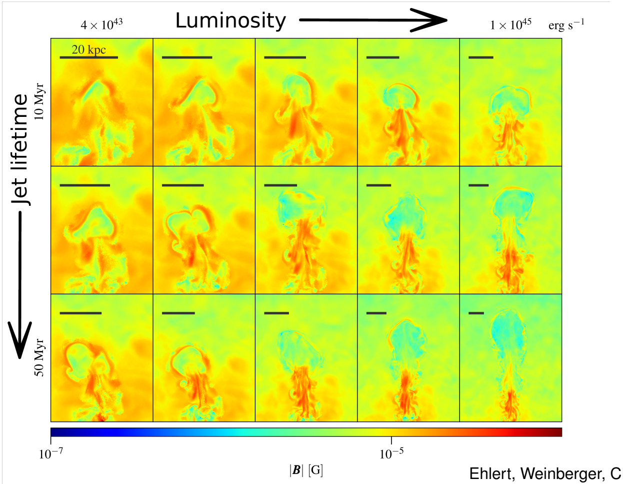
Perseus cluster – heating vs. cooling: simulations



Ehlert, Weinberger, CP+ (2018)

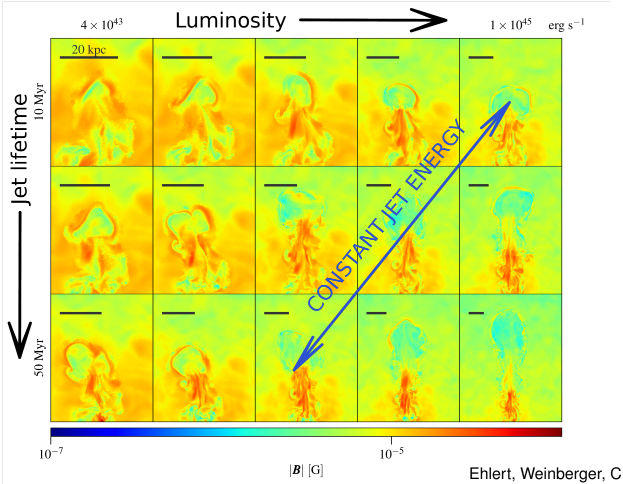
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Magnetic field structure



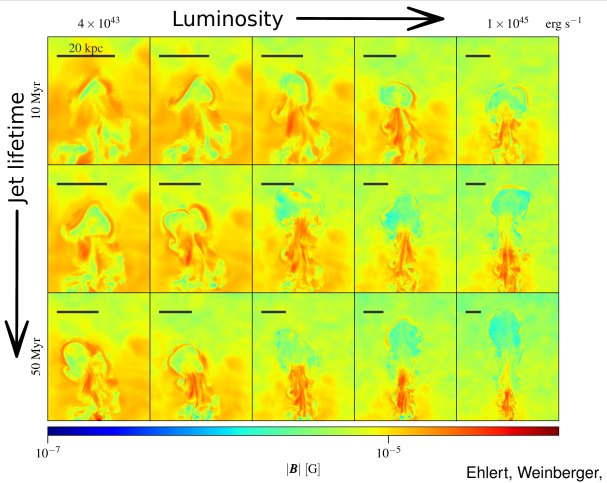
Ehlert, Weinberger, CP+ (2018)

Magnetic field structure



Ehlert, Weinberger, CP+ (2018)

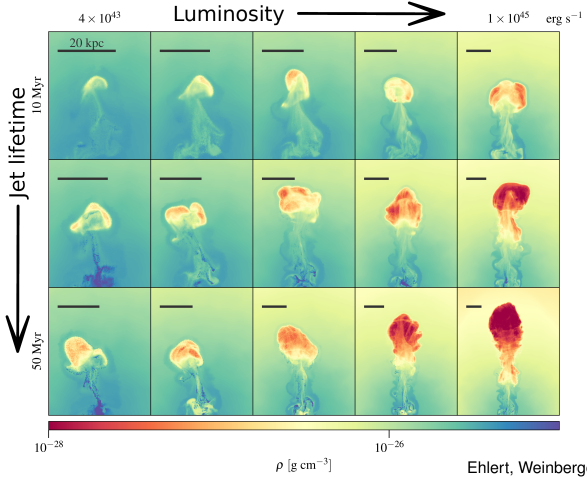
Magnetic field structure



Ehlert, Weinberger, CP+ (2018)

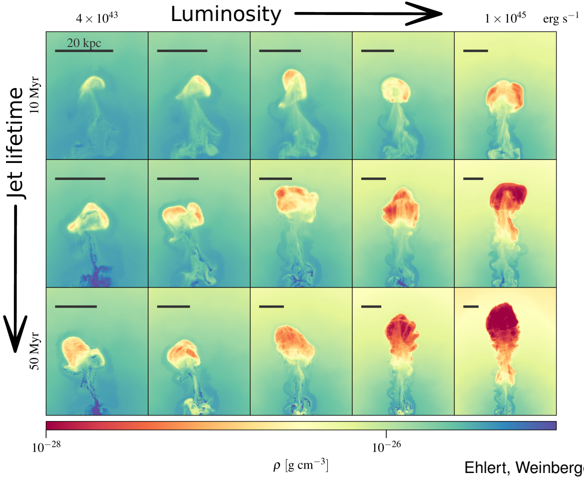
Magnetic enhancement and draping general feature

Jet morphology



Ehlert, Weinberger, CP+ (2018)

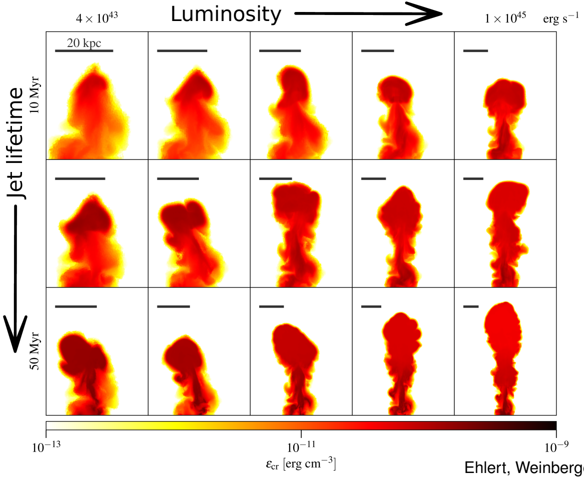
Jet morphology



Ehlert, Weinberger, CP+ (2018)

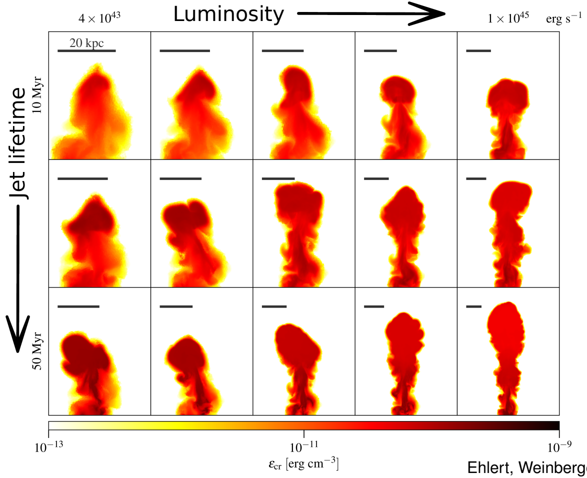
Low-energy/power jets mix more efficiently $\Rightarrow$ invisible in X-rays

CR distribution



Ehlert, Weinberger, CP+ (2018)

CR distribution



Ehlert, Weinberger, CP+ (2018)

CRs still present in low-energy/power jets

Conclusions on CR feedback in galaxies and clusters

CR hydrodynamics:

- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
- moment expansion similar to radiation hydrodynamics
- Galilean invariant, energy and momentum conserving

Conclusions on CR feedback in galaxies and clusters

CR hydrodynamics:

- novel theory of CR transport mediated by Alfvén waves and coupled to magneto-hydrodynamics
- moment expansion similar to radiation hydrodynamics
- Galilean invariant, energy and momentum conserving

CR feedback in galaxy formation:

- CR pressure feedback slows down star formation
- galactic winds are naturally explained by CR streaming and diffusion
- MHD simulations of AGN jets: CR heating can solve the "cooling flow problem" in galaxy clusters

CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtioN

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Literature for the talk

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