Cosmic rays in galaxy clusters: transport and feedback

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in collaboration with

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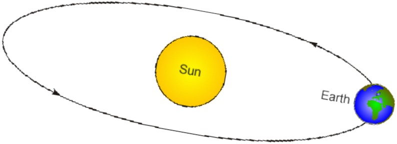
Physics of the ICM: Theory and Computation, Budapest, March, 2019

Outline

1. Cosmic ray transport
   - Introduction
   - CR hydrodynamics
2. AGN feedback
   - Steady-state models
   - Cosmic rays in jets

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

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

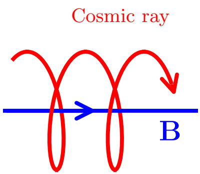
gyro-orbit of GeV cosmic ray:

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

$\Rightarrow$ 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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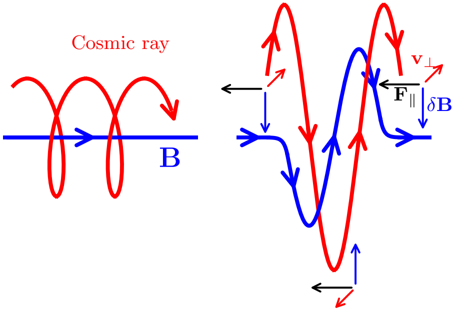

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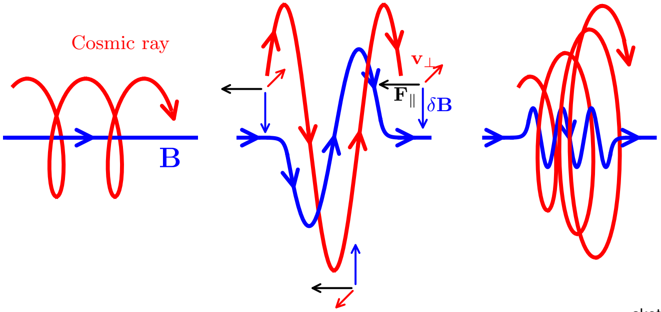
- **gyro resonance:** $\omega - k_{\|} v_{\|} = n\Omega$
  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency

Interactions of CRs and magnetic fields



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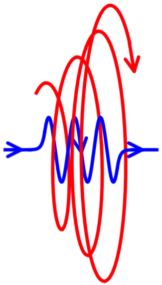
- **gyro resonance:** $\omega - k_\parallel v_\parallel = n\Omega$

  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 $v_{cr} > v_A$, 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 $\sim v_A$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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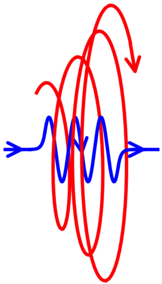

$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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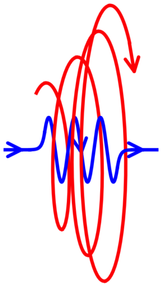
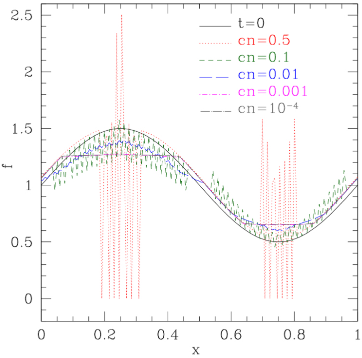


→ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

Modeling CR streaming
A challenging hyperbolic/parabolic problem



Sharma+ (2010)

- streaming equation (no heating):

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

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

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

Modeling CR streaming

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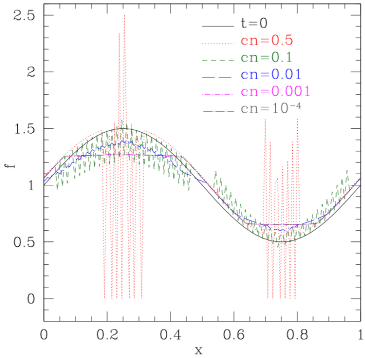

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- idea: regularize equations, similar to adding artificial viscosity

Modeling CR streaming – regularization

- 1D streaming equation (no heating):

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

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

- 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

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• resolved $\boldsymbol{B}$, strong scattering	CR streaming with $\boldsymbol{v}_\mathrm{a}$	Thomson scattering ($\tau \gg 1$) $\rightarrow$ advection with $\boldsymbol{v}$

AIP

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• weak scattering	CR streaming and diffusion	flux-limited diffusion with $\tau \sim 1$

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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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- ***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)

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

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

Alfvén-wave regulated CR transport

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

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

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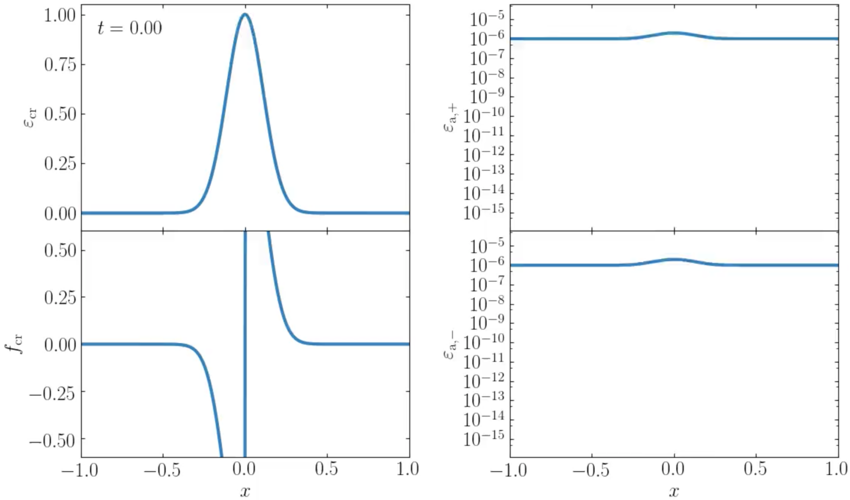
Non-equilibrium CR streaming and diffusion

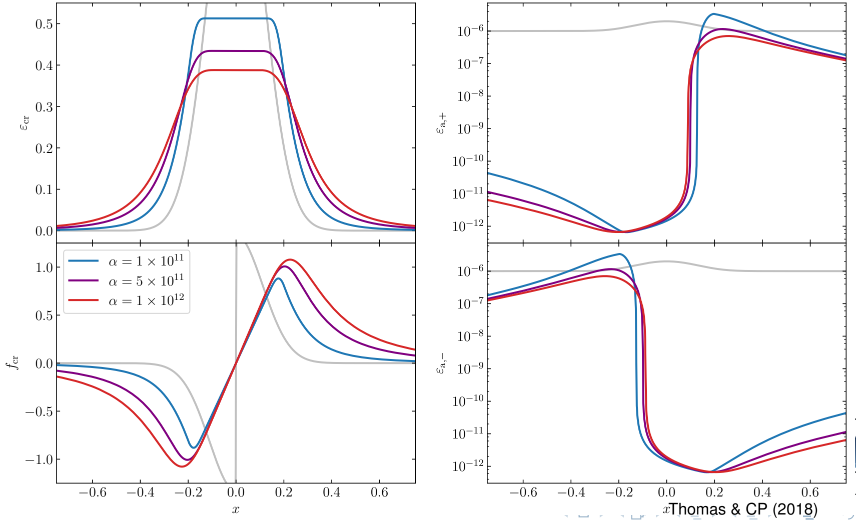
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

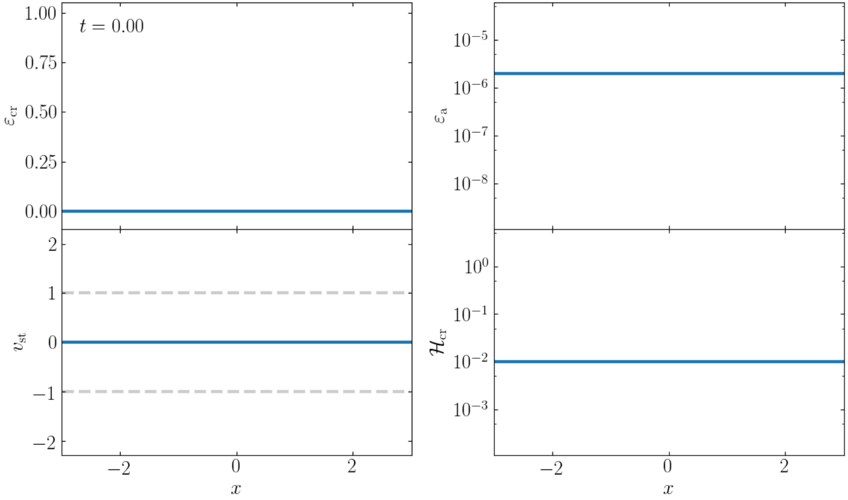
Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2018)

Steady CR source: CR Alfvén wave heating

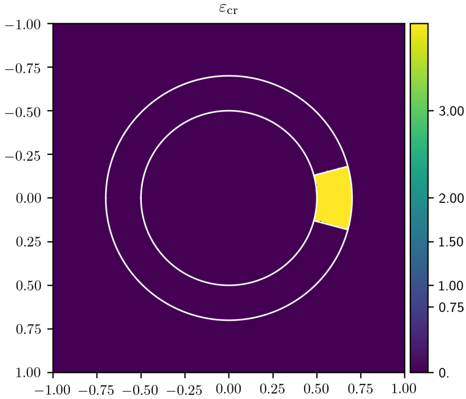


Thomas & CP (2018)

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

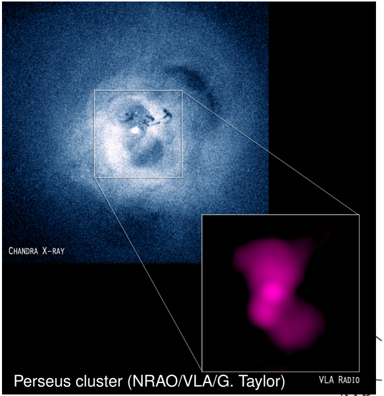


Thomas, Pakmor, CP (in prep.)

Feedback by active galactic nuclei

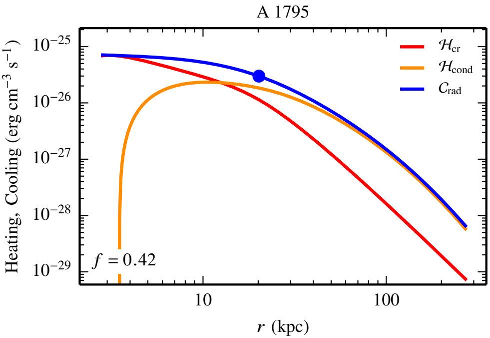
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling ⇒ **but how?**

- Jacob & CP (2017a,b): study large sample of 40 cool core clusters
- spherically symmetric steady-state solutions where cosmic ray heating balances radiative cooling



Perseus cluster (NRAO/VLA/G. Taylor)

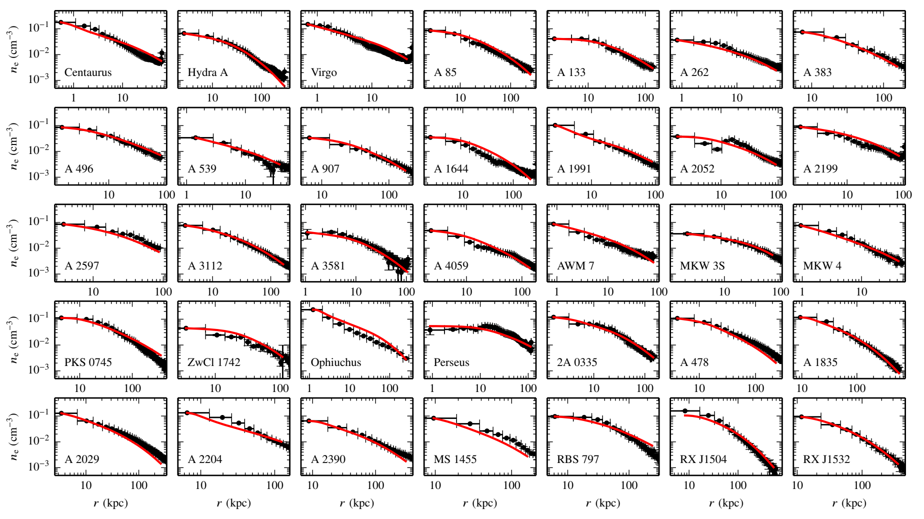
Case study A1795: heating and cooling



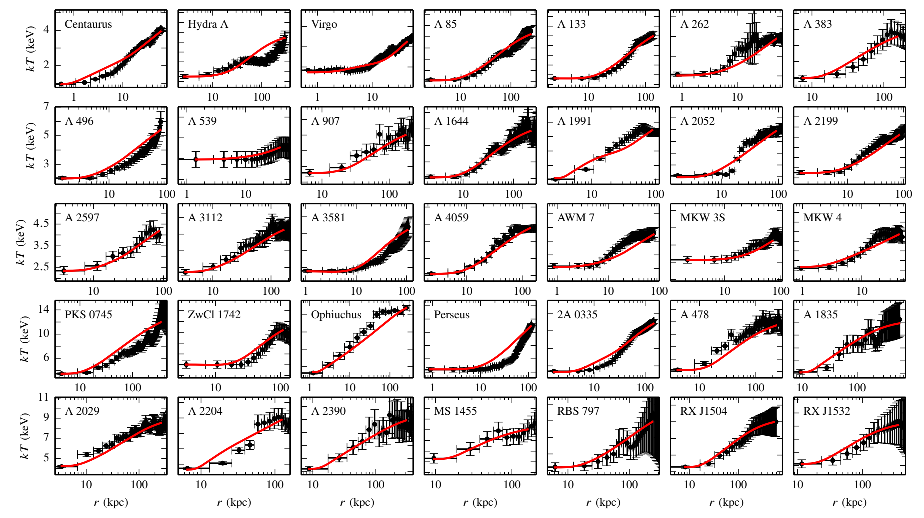
Jacob & CP (2016a)

- CR heating dominates in the center
- conductive heating takes over at larger radii, $\kappa = 0.42\kappa_{\rm Sp}$
- $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm cond} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

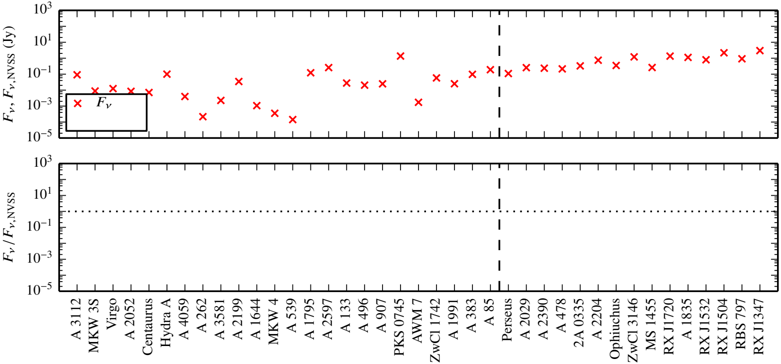
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

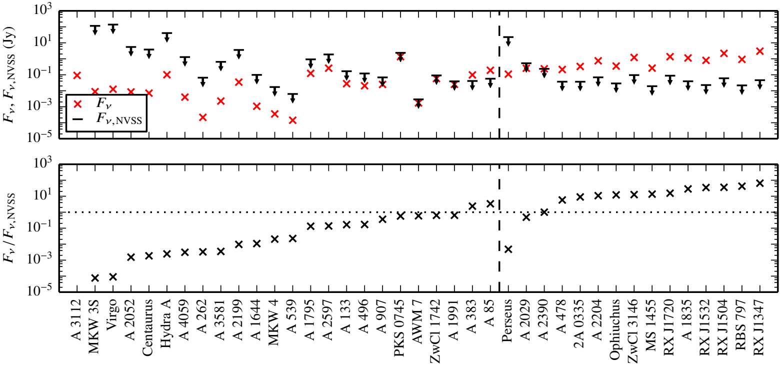


Hadronically induced radio emission



Jacob & CP (2017b)

Hadronically induced radio emission: NVSS limits



Jacob & CP (2017b)

- continuous sequence in $F_{\nu,\mathrm{pred}}/F_{\nu,\mathrm{NVSS}}$
- CR heating viable solution for non-RMH clusters
- CR heating solution ruled out in radio mini halos (RMHs)

How can we explain these results?

- self-regulated feedback cycle driven by CRs

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radio mini halo

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cluster cools and triggers AGN activity ← CRs stream outwards and become too dilute to heat the cluster

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radio mini halo

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↑ ↓

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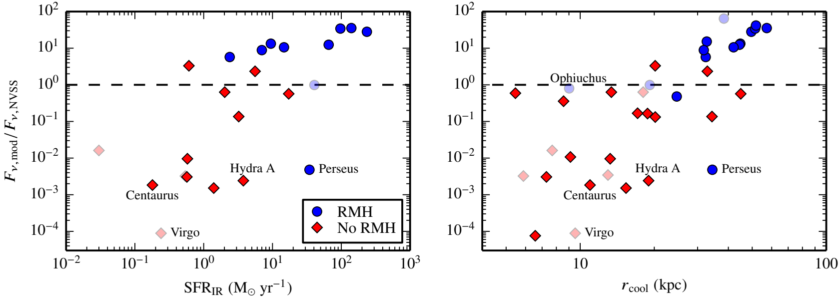
radio mini halo

Self-regulated heating/cooling cycle in cool cores



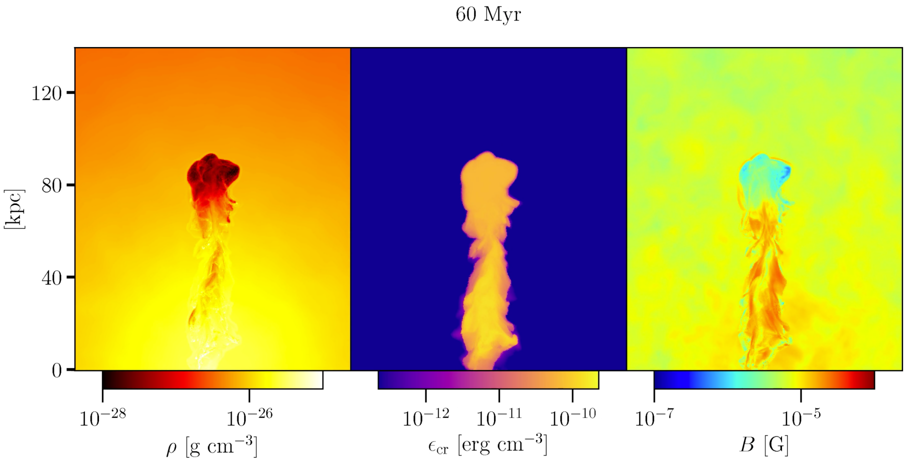
Jacob & CP (2017b)

possibly CR-heated cool cores vs. radio mini halo clusters:

- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance

AIP

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



Ehlert, Weinberger, CP+ (2018)

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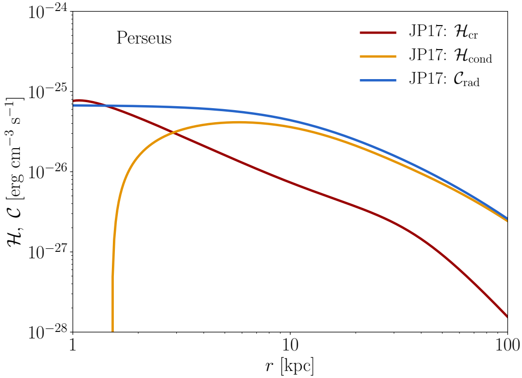
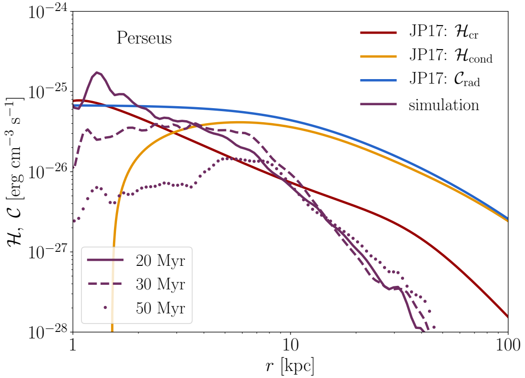
Perseus cluster – heating vs. cooling: theory



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

Conclusions on cosmic rays in 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

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AGN feedback and CRs:

- steady-state CR heating: self-regulated cooling-heating loop
- 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

Cosmic ray transport:

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

Cosmic ray feedback in galaxy clusters:

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- Ehlert, Weinberger, Pfrommer, Pakmor, Springel, *Simulations of the dynamics of magnetised jets and cosmic rays in galaxy clusters,* 2018, MNRAS.