Cosmic rays in galaxy clusters: transport and feedback

Christoph Pfrommer[1]

in collaboration with

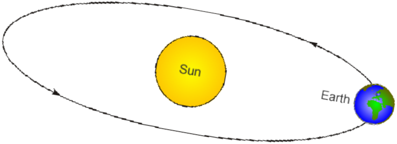
T. Thomas[1], K. Ehlert[1], S. Jacob[2], R. Weinberger[3], R. Pakmor[4], V. Springel[4]

[1]AIP, [2]HITS, [3]Harvard, [4]MPA

ICM Physics and Modeling, MPA/ESO, Garching, Oct 2018

Outline

Cosmic ray feedback: an extreme multi-scale problem



Milky Way-like galaxy:

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

gyro-orbit of GeV cosmic ray:

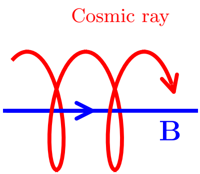
$$r_{\rm cr} = \frac{p_\perp}{e\,B_{\mu\rm G}} \sim 10^{-6} \text{ pc} \sim \frac{1}{4} \text{ AU}$$

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

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

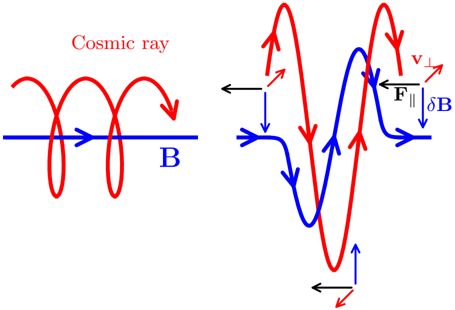
AIP

Interactions of CRs and magnetic fields



sketch: Jacob

Interactions of CRs and magnetic fields



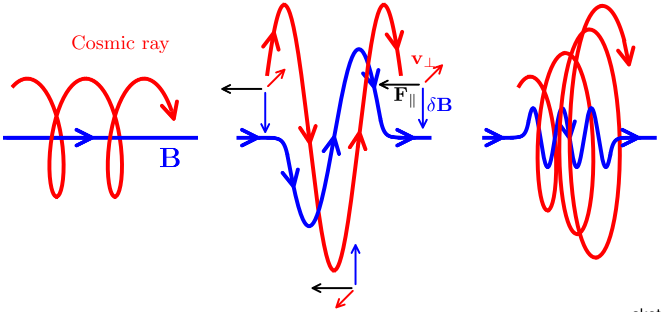
sketch: Jacob

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

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

AIP

Interactions of CRs and magnetic fields



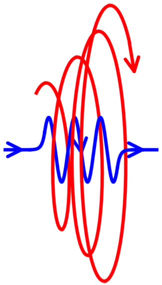
sketch: Jacob

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

  Doppler-shifted MHD frequency is a multiple of the CR gyrofrequency
- CRs scatter on magnetic fields → isotropization of CR momenta

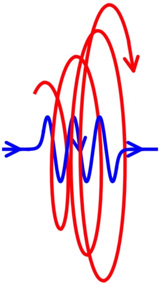
CR streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\mathrm{cr}} > v_{\mathrm{A}}$, 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 $\sim v_{\mathrm{A}}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



CR streaming and diffusion

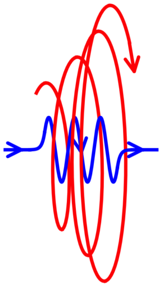
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm A}$, CR flux excites and amplifies an Alfvén wave field in resonance with the gyroradii of CRs
  - scattering off of this wave field limits the (GeV) CRs' bulk speed $\sim v_{\rm A}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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

CR streaming and diffusion

- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\mathrm{cr}} > v_{\mathrm{A}}$, 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 $\sim v_{\mathrm{A}}$
  - wave damping: transfer of CR energy and momentum to the thermal gas



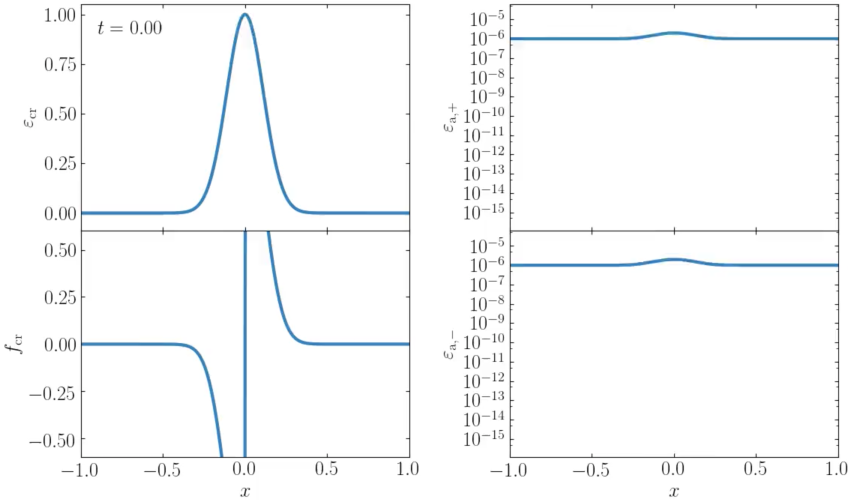
$\rightarrow$ *CRs exert pressure on thermal gas via scattering on Alfvén waves*

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

AIP

Non-equilibrium CR streaming and diffusion

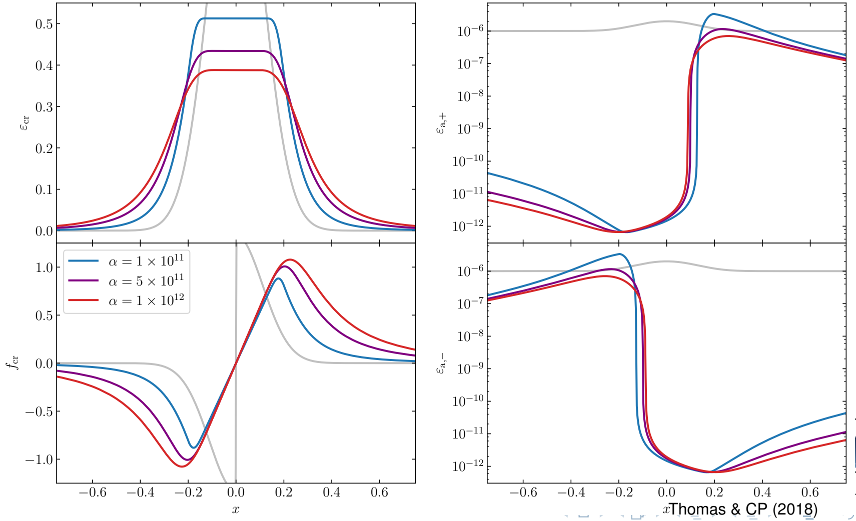
Coupling the evolution of CR and Alfvén wave energy densities



Thomas & CP (2018)

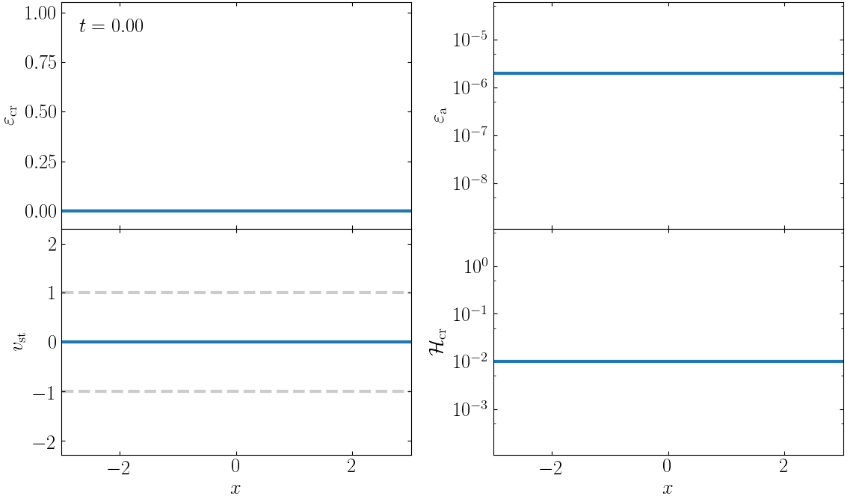
Non-equilibrium CR streaming and diffusion

Varying damping rate of Alfvén waves modulates the diffusivity of solution



Thomas & CP (2018)

Steady CR source: CR Alfvén wave heating

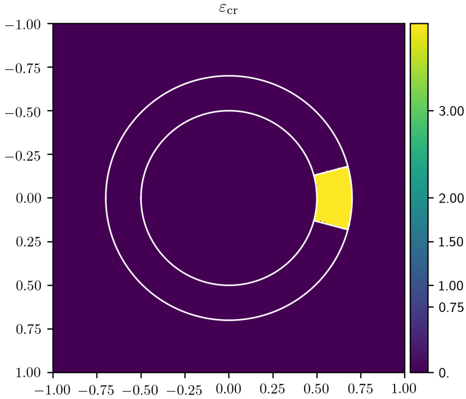


Thomas & CP (2018)

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

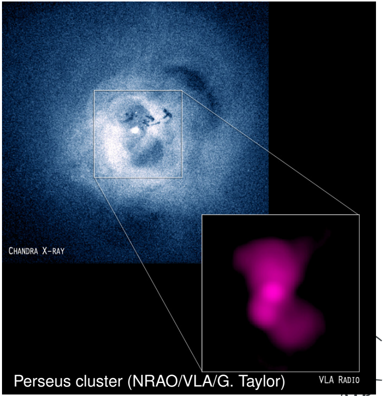


Thomas, Pakmor, CP (in prep.)

Feedback by active galactic nuclei

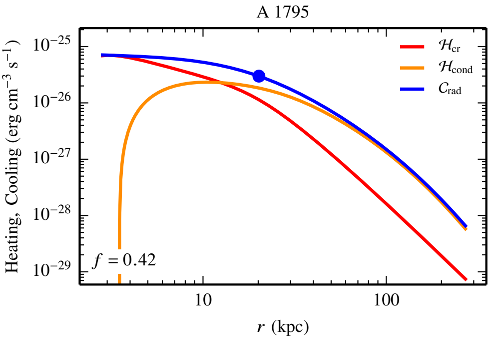
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling ⇒ **but how?**

- 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

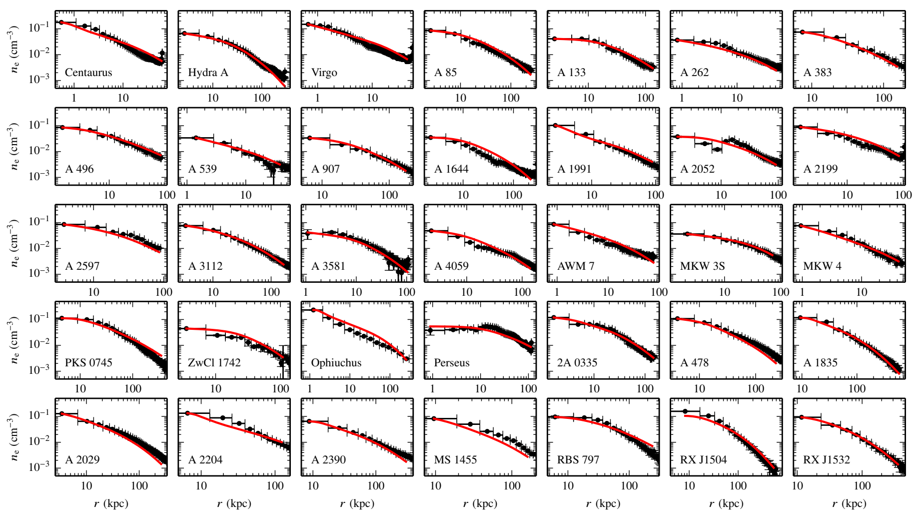


Jacob & CP (2016a)

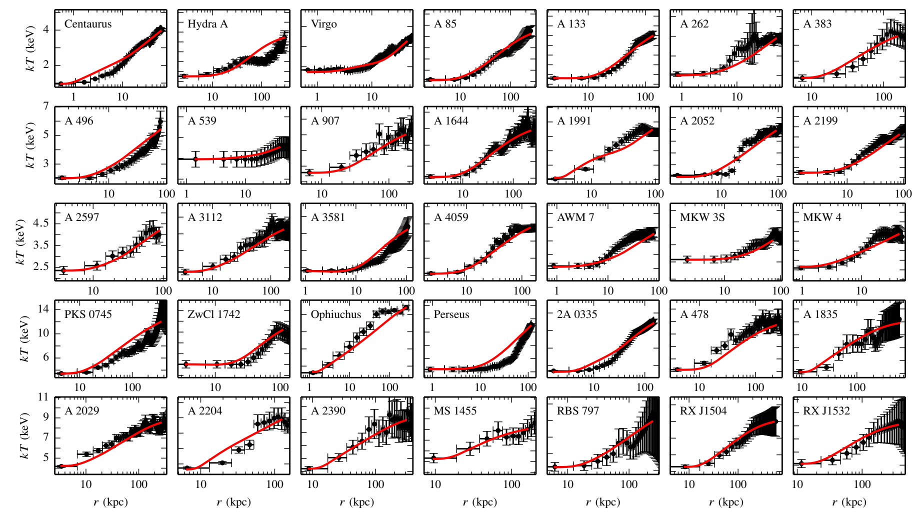
- CR heating dominates in the center
- conductive heating takes over at larger radii, $\kappa = 0.42\kappa_{\mathrm{Sp}}$
- $\mathcal{H}_{cr} + \mathcal{H}_{cond} \approx \mathcal{C}_{rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}

AIP

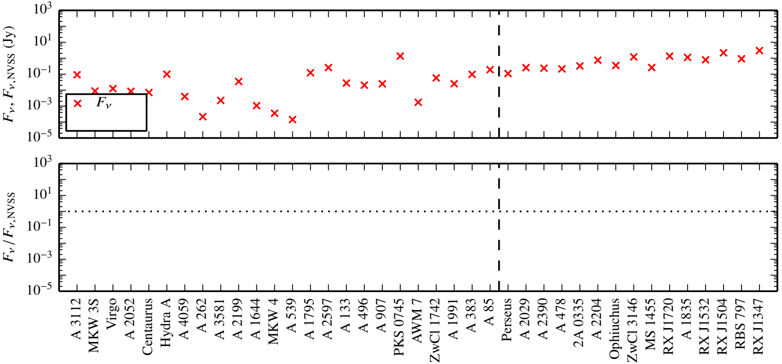
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

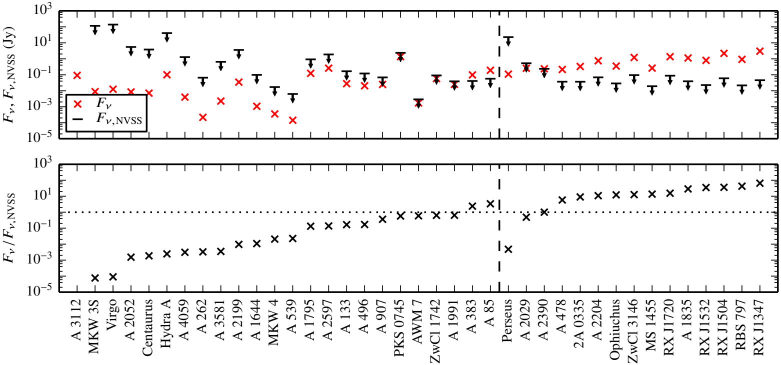


Hadronically induced radio emission



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

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

↘

radio mini halo

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

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

↘

radio mini halo

How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

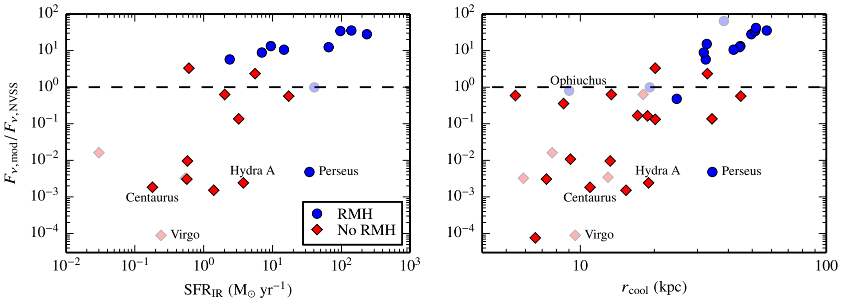
↑ ↓

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

↘

radio mini halo

Self-regulated heating/cooling cycle in cool cores



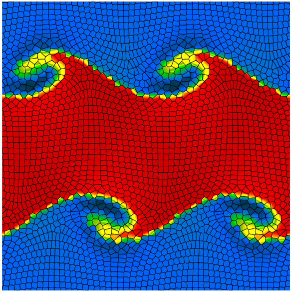
Jacob & CP (2017b)

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

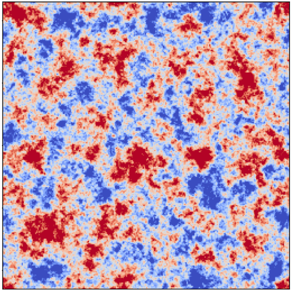
MHD jet simulations



AREPO: unstructured-mesh

- MHD moving-mesh code AREPO
- NFW cluster potential

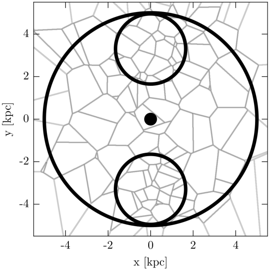
MHD jet simulations



initial magnetic field

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

MHD jet simulations

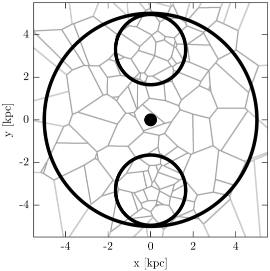


AREPO: jet injection region

(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 modelling

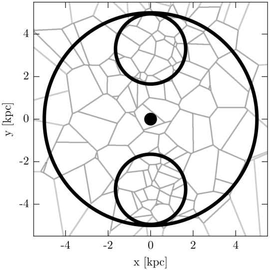


AREPO: jet injection region

(Weinberger+ 2017)

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

Cosmic ray modelling



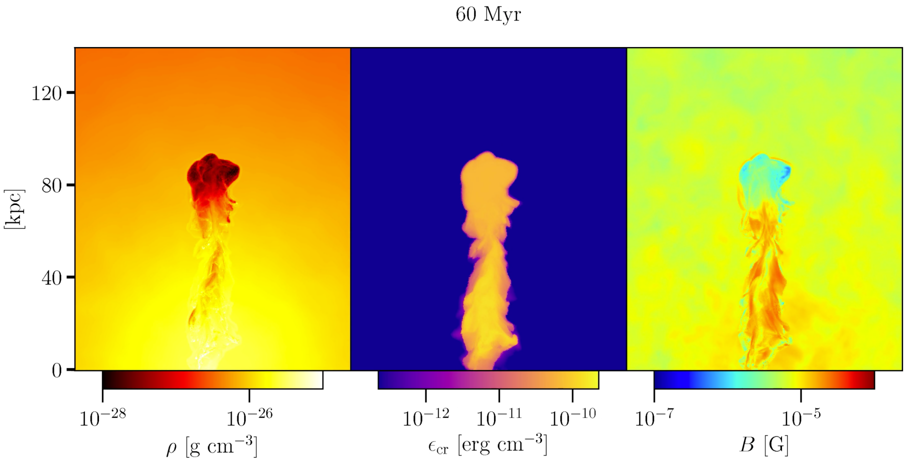
AREPO: jet injection region

(Weinberger+ 2017)

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

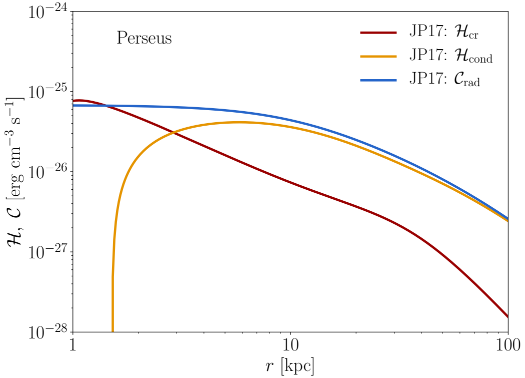
AIP

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



Ehlert, Weinberger, CP+ (2018)

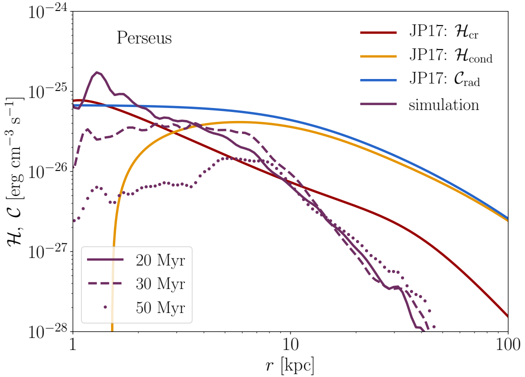
Perseus cluster – heating vs. cooling: theory



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}

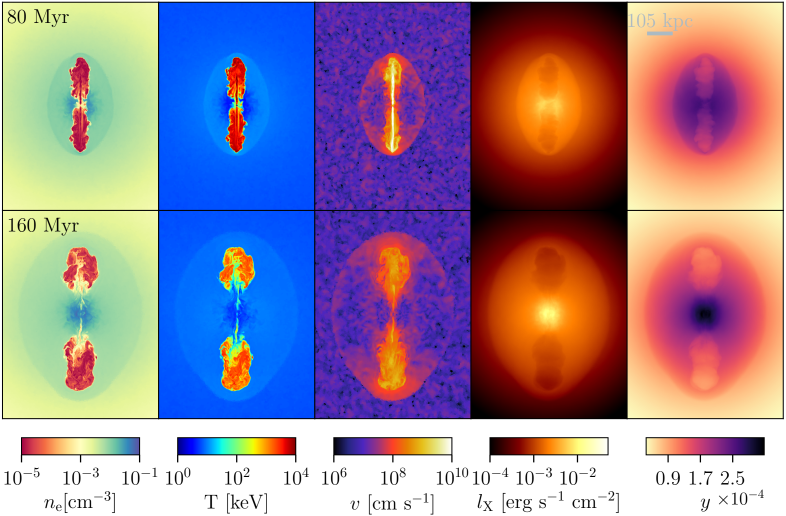
Perseus cluster – heating vs. cooling: simulations



Ehlert, Weinberger, CP+ (2018)

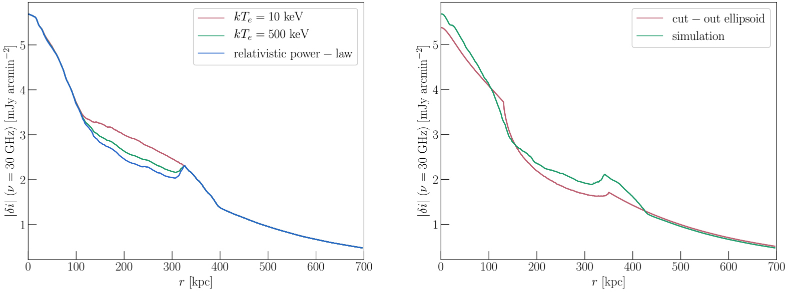
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Modelling the major outburst in MS 0735



Ehlert, CP+ (in prep.)

SZ effect of bubbles – profiles



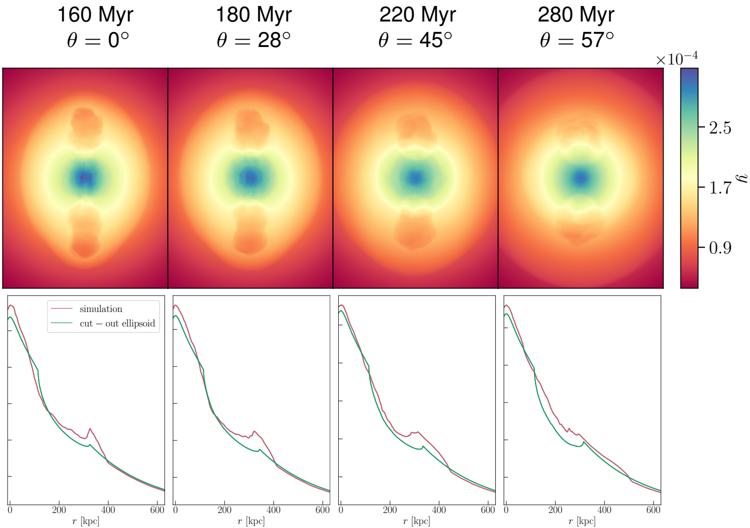
different bubble fillings:

thermal vs. relativistic content

Ehlert, CP+ (in prep.)

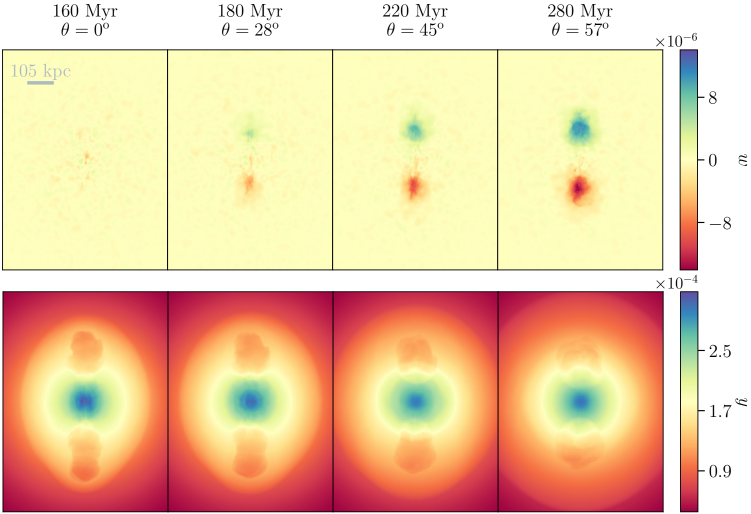
analytical model vs. simulation

SZ effect of bubbles: inclination-distance degeneracy



Ehlert, CP+ (in prep.)

Kinetic vs. thermal SZ effect



Ehlert, CP+ (in prep.)

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

AIP

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

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

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

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
- simulating SZE of bubbles: determine relativistic filling
  but: pressure enhancements, jet inclinations, kSZ

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

This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No CRAGSMAN–646955).

Literature for the talk

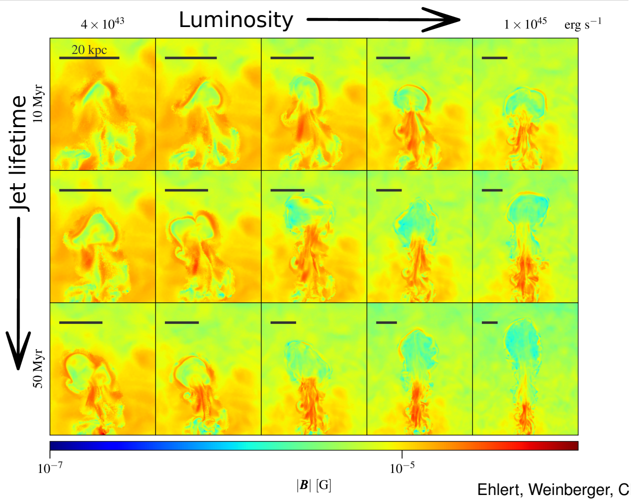
Cosmic ray transport:

- Thomas, Pfrommer, *Cosmic-ray hydrodynamics: Alfvén-wave regulated transport of cosmic rays,* 2018.

Cosmic ray feedback in galaxy clusters:

- Jacob & Pfrommer, *Cosmic ray heating in cool core clusters I: diversity of steady state solutions*, 2017a, MNRAS.
- Jacob & Pfrommer, *Cosmic ray heating in cool core clusters II: self-regulation cycle and non-thermal emission*, 2017b, MNRAS.
- Ehlert, Weinberger, Pfrommer, Pakmor, Springel, *Simulations of the dynamics of magnetised jets and cosmic rays in galaxy clusters,* 2018, MNRAS.

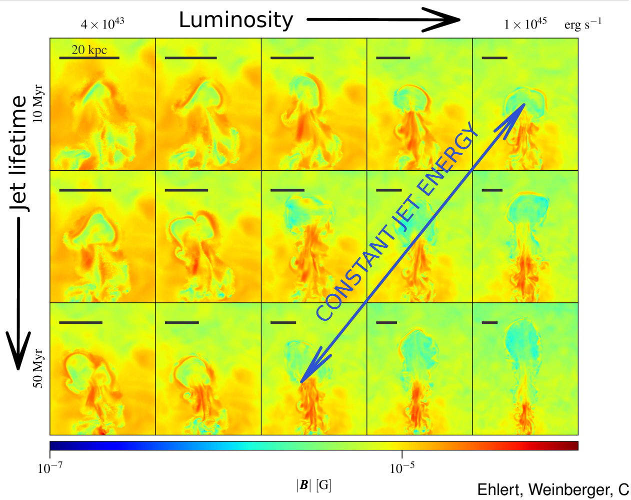
Magnetic field structure



Ehlert, Weinberger, CP+ (2018)

Magnetic enhancement and draping general feature

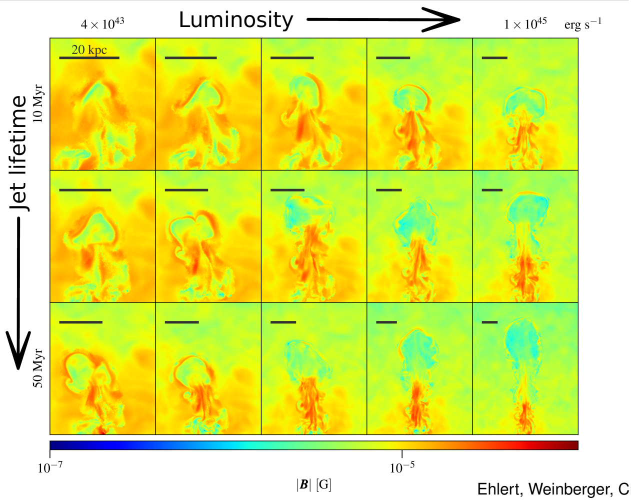
Magnetic field structure



Ehlert, Weinberger, CP+ (2018)

Magnetic enhancement and draping general feature

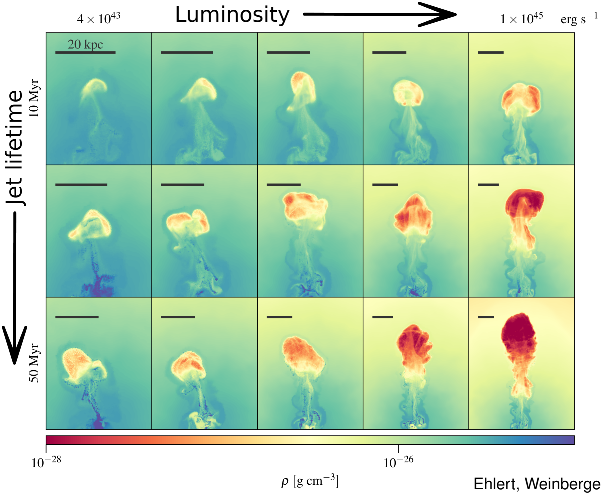
Magnetic field structure



Ehlert, Weinberger, CP+ (2018)

Magnetic enhancement and draping general feature

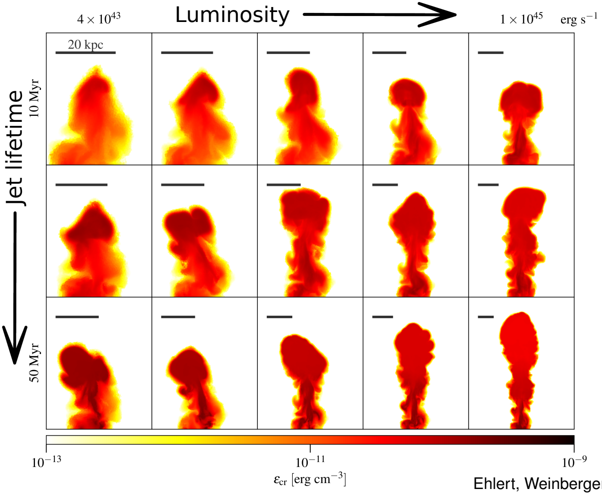
Jet morphology



Ehlert, Weinberger, CP+ (2018)

Low-energy/power jets mix more efficiently ⇒ invisible in X-rays

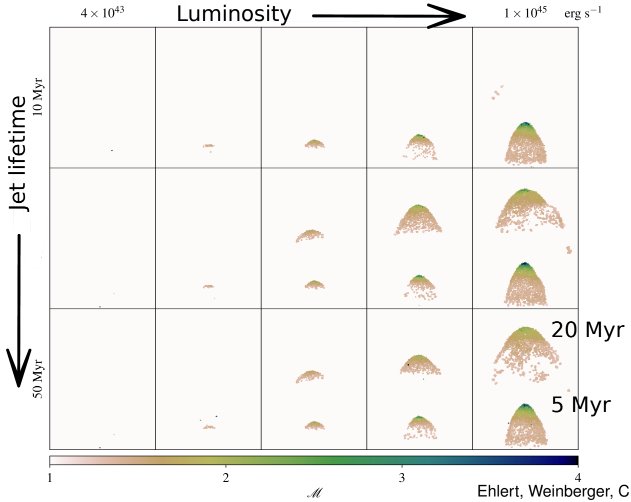
CR distribution



Ehlert, Weinberger, CP+ (2018)

CRs still present in low-energy/power jets

Jet Mach numbers



Ehlert, Weinberger, CP+ (2018)

Mach numbers generally low