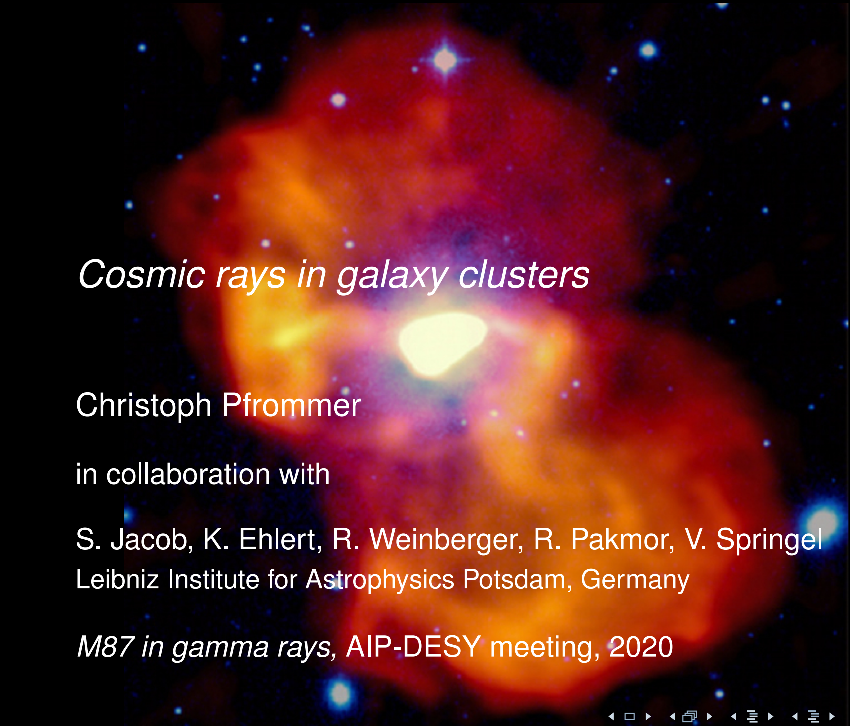


Cosmic rays in galaxy clusters

Christoph Pfrommer

in collaboration with

S. Jacob, K. Ehlert, R. Weinberger, R. Pakmor, V. Springel
Leibniz Institute for Astrophysics Potsdam, Germany

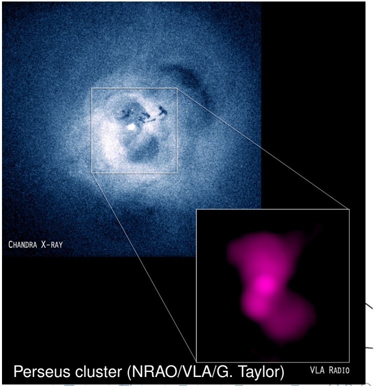
M87 in gamma rays, AIP-DESY meeting, 2020

Outline

1. Cosmic ray feedback
   - Observations of M87
   - Cosmic ray heating
2. Diversity of cool cores
   - Steady state solutions
   - Cosmic rays in jets

Radio mode feedback by AGN

Paradigm: super-massive black holes with $M \sim (10^9 \ldots 10^{10})\mathrm{M}_\odot$ co-evolve with their hosting cD galaxies at the centers of galaxy clusters; they launch relativistic jets that blow bubbles and provide energetic feedback to balance cooling



Perseus cluster (NRAO/VLA/G. Taylor)

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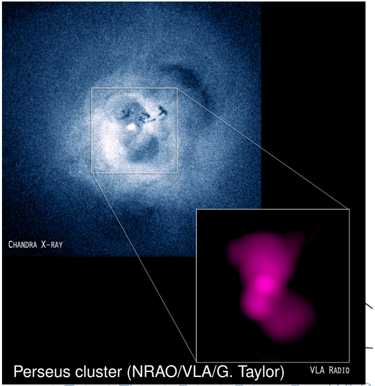
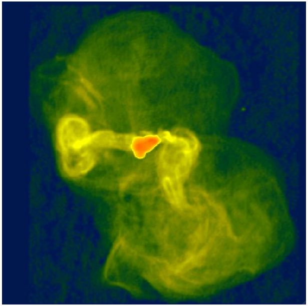
Paradigm: super-massive black holes with $M \sim (10^9 \ldots 10^{10}) M_\odot$ co-evolve with their hosting cD galaxies at the centers of galaxy clusters; they launch relativistic jets that blow bubbles and provide energetic feedback to balance cooling

- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- jet interaction with magnetized cluster medium $\rightarrow$ turbulence
- jet accelerates relativistic particles (cosmic rays, CRs) $\rightarrow$ release from bubbles provides source of heat
- self-regulated heating mechanism to avoid overcooling



Perseus cluster (NRAO/VLA/G. Taylor)

Messier 87 at radio wavelengths



$\nu = 1.4$ GHz (Owen+ 2000)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!

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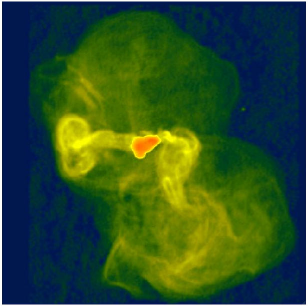
Messier 87 at radio wavelengths



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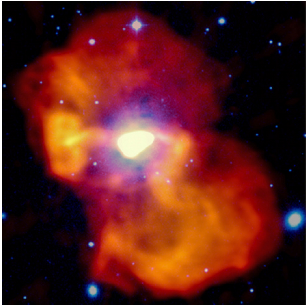


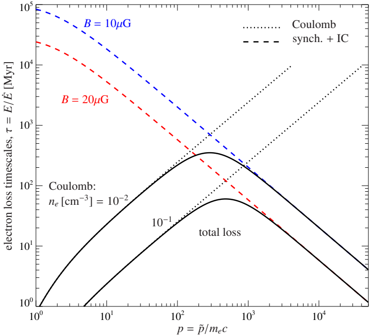
$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!
- LOFAR: halo confined to same region at all frequencies and no low-ν spectral steepening $\rightarrow$ puzzle of "missing fossil electrons"

Solution to the "missing fossil electrons" problem

solution:

- Coulomb cooling removes fossil electrons
  $\rightarrow$ efficient mixing of CR electrons and protons with dense cluster gas
  $\rightarrow$ predicts γ rays from CRp-p interactions:
  $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$



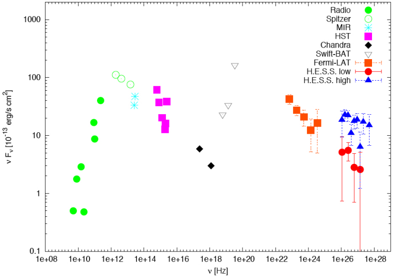
Pfrommer (2013)

The gamma-ray picture of M87

- high state is time variable
  $\rightarrow$ jet emission
- low state:
  (1) steady flux

  (2) γ-ray spectral index (2.2)
  $=$ CRp index
  $=$ CRe injection index as probed by LOFAR

  (3) spatial extension is under investigation



Rieger & Aharonian (2012)

$\rightarrow$ **confirming this triad would be smoking gun for first γ-ray signal from a galaxy cluster!**

AGN feedback = cosmic ray heating (?)

hypothesis: low state γ-ray emission traces π^0 decay within cluster

- cosmic rays excite Alfvén waves that dissipate the energy $\rightarrow$ heating rate

$$\mathcal{H}_{\mathrm{cr}} = |\boldsymbol{v}_{\mathrm{A}} \cdot \nabla P_{\mathrm{cr}}|$$

(Loewenstein+ 1991, Guo & Oh 2008, Enßlin+ 2011, Wiener+ 2013, CP 2013)

- calibrate P_{cr} to γ-ray emission and $\boldsymbol{v}_{\mathrm{A}}$ to radio/X-ray emission
$\rightarrow$ spatial heating profile

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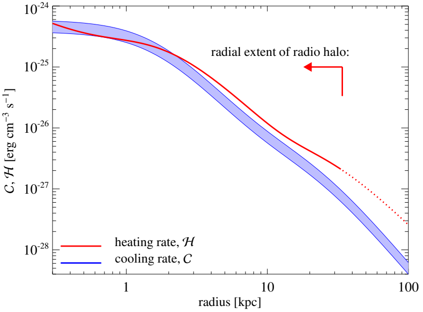

Pfrommer (2013)

$\rightarrow$ cosmic-ray heating matches radiative cooling (observed in X-rays) and may solve the famous “cooling flow problem” in galaxy clusters!

How universal is CR heating in cool core clusters?

- no γ rays observed from other clusters $\rightarrow P_{\rm cr}$ unconstrained
- **strategy:**

  (1) construct large sample of 39 cool cores

  (2) search for spherically symmetric, steady-state solutions:

  CR heating ($\mathcal{H}_{\rm cr}$) $+$ conductive heating ($\mathcal{H}_{\rm th}$) $\approx$ cooling ($\mathcal{C}_{\rm rad}$)

  (3) calculate hadronic radio and γ-ray flux $\mathcal{F}_{\rm had}$ and compare to observed fluxes $\mathcal{F}_{\rm obs}$

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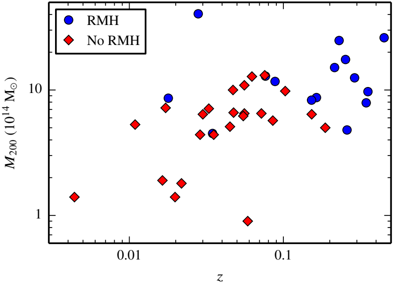
  (3) calculate hadronic radio and γ-ray flux $\mathcal{F}_{\mathrm{had}}$ and compare to observed fluxes $\mathcal{F}_{\mathrm{obs}}$
- **consequences:**
  $\Rightarrow$ if $\mathcal{H}_{\mathrm{cr}} + \mathcal{H}_{\mathrm{th}} \approx \mathcal{C}_{\mathrm{rad}}$ $\forall$ r and $\mathcal{F}_{\mathrm{had}} \leq \mathcal{F}_{\mathrm{obs}}$:
  successful CR heating model that is locally stable at 1 keV
  $\Rightarrow$ otherwise ***CR heating ruled out*** as dominant heating source

Sample selection

select 39 cool cores (CCs):

- brightest 23 CCs from X-ray flux-limited sample (HIFLUGCS) that are also in ACCEPT
- 10 high-resolution Chandra data (Vikhlinin+ 2006)
- 15 clusters with radio-mini halos (RMHs) (Giacintucci+ 2014)
- add Virgo + A2597



Jacob & Pfrommer (2017a)

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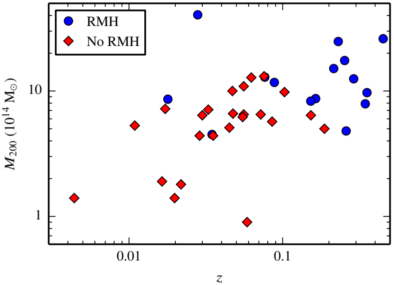

Jacob & Pfrommer (2017a)

⇒ RMH clusters show selection bias towards high-z and being more massive (fixed surface brightness limit)

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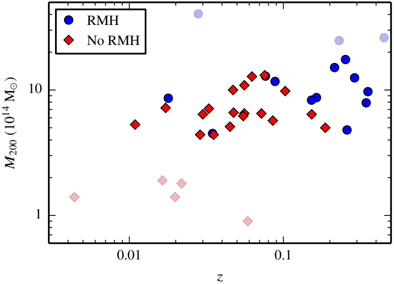

Jacob & Pfrommer (2017a)

⇒ RMH clusters show selection bias towards high-z and being more massive (fixed surface brightness limit)

⇒ study ***sub-sample that is unbiased in*** M_{200} and ***entire sample***

Governing equations

- conservation of mass, momentum, thermal and CR energy:

$$
\begin{aligned}
\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\boldsymbol{\nabla}\cdot\boldsymbol{v} &= 0 \\
\rho\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} &= -\boldsymbol{\nabla}\left(P_{\mathrm{th}} + P_{\mathrm{cr}}\right) - \rho\boldsymbol{\nabla}\phi \\
\frac{\mathrm{d}e_{\mathrm{th}}}{\mathrm{d}t} + \gamma_{\mathrm{th}}e_{\mathrm{th}}\boldsymbol{\nabla}\cdot\boldsymbol{v} &= -\boldsymbol{\nabla}\cdot\boldsymbol{F}_{\mathrm{th}} + \mathcal{H}_{\mathrm{cr}} - \rho\mathcal{L} \\
\frac{\mathrm{d}e_{\mathrm{cr}}}{\mathrm{d}t} + \gamma_{\mathrm{cr}}e_{\mathrm{cr}}\boldsymbol{\nabla}\cdot\boldsymbol{v} &= -\boldsymbol{\nabla}\cdot\boldsymbol{F}_{\mathrm{cr}} - \mathcal{H}_{\mathrm{cr}} + S_{\mathrm{cr}}
\end{aligned}
$$

- Lagrangian derivative $\mathrm{d}/\mathrm{d}t = \partial/\partial t + \boldsymbol{v}\cdot\boldsymbol{\nabla}$
- equations of state:

$$
\begin{aligned}
P_{\mathrm{th}} &= (\gamma_{\mathrm{th}} - 1)e_{\mathrm{th}} \\
P_{\mathrm{cr}} &= (\gamma_{\mathrm{cr}} - 1)e_{\mathrm{cr}}
\end{aligned}
$$

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Governing equations

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\end{aligned}
$$

- gravitational potential $\phi = -\frac{GM_{\mathrm{s}}}{r}\ln\left(1 + \frac{r}{r_{\mathrm{s}}}\right) + v_{\mathrm{c}}^2 \ln\left(\frac{r}{r_0}\right)$
- radiative cooling $\rho\mathcal{L} = n_{\mathrm{e}}^2\left(\Lambda_{\mathrm{l}} + \Lambda_{\mathrm{b}} T^{1/2}\right)$
- CR source $S_{\mathrm{cr}} = -\frac{\nu\varepsilon_{\mathrm{cr}}\dot{M}c^2}{4\pi r_{\mathrm{cr}}^3}\left(\frac{r}{r_{\mathrm{cr}}}\right)^{-3-\nu}\left(1 - e^{-(r/r_{\mathrm{cr}})^2}\right)$

AIP

Governing equations

- conservation of mass, momentum, thermal and CR energy:

$$\frac{d\rho}{dt} + \rho\nabla\cdot\boldsymbol{v} = 0$$
$$\rho\frac{d\boldsymbol{v}}{dt} = -\nabla\left(P_{\mathrm{th}} + P_{\mathrm{cr}}\right) - \rho\nabla\phi$$
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$$\frac{de_{\mathrm{cr}}}{dt} + \gamma_{\mathrm{cr}}e_{\mathrm{cr}}\nabla\cdot\boldsymbol{v} = -\nabla\cdot\boldsymbol{F}_{\mathrm{cr}} - \mathcal{H}_{\mathrm{cr}} + S_{\mathrm{cr}}$$

- thermal heat flux $\boldsymbol{F}_{\mathrm{th}} = -\kappa\nabla T$
- CR streaming flux $\boldsymbol{F}_{\mathrm{cr}} = (e_{\mathrm{cr}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{st}}$ with $\boldsymbol{v}_{\mathrm{st}} = -v_{\mathrm{A}}\frac{\nabla P_{\mathrm{cr}}}{|\nabla P_{\mathrm{cr}}|}$
- CR heating rate $\mathcal{H}_{\mathrm{cr}} = -\boldsymbol{v}_{\mathrm{st}}\cdot\nabla P_{\mathrm{cr}}$

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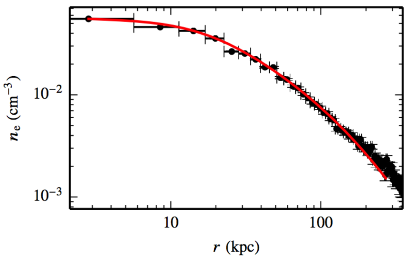
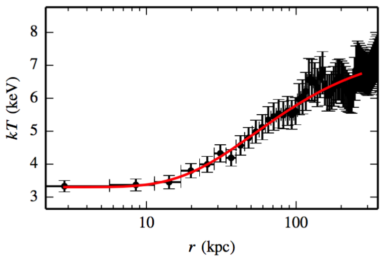
Case study A1795: density and temperature

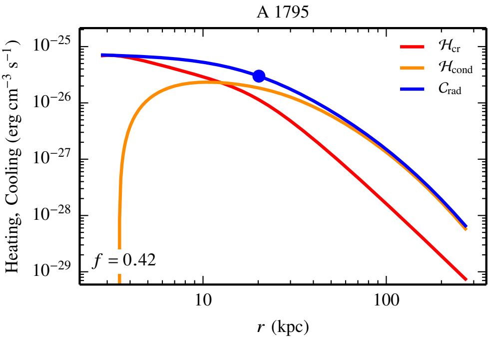




Jacob & Pfrommer (2017a)

- beautiful match of steady-state solutions to observed profiles
- pure NFW mass profile in A1795

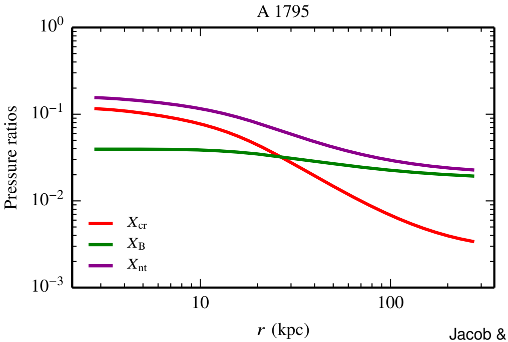
Case study A1795: heating and cooling



Jacob & Pfrommer (2017a)

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

Case study A1795: CR and B pressure ratios



Jacob & Pfrommer (2017a)

- define $X_{cr} = P_{cr}/P_{th}$, $X_B = P_B/P_{th}$, $X_{nt} = P_{nt}/P_{th}$

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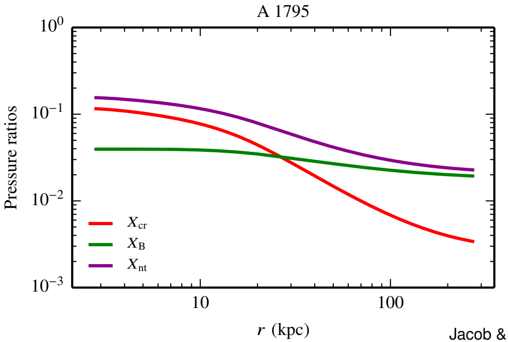

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- define $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$, $X_B = P_B/P_{\rm th}$, $X_{\rm nt} = P_{\rm nt}/P_{\rm th}$
- $X_{\rm cr} \approx$ const. in center: $\Delta\varepsilon_{\rm th} = -\tau_{\rm A}\,\boldsymbol{v}_{\rm st}\cdot\nabla P_{\rm cr} \approx P_{\rm cr} = X_{\rm cr}P_{\rm th}$

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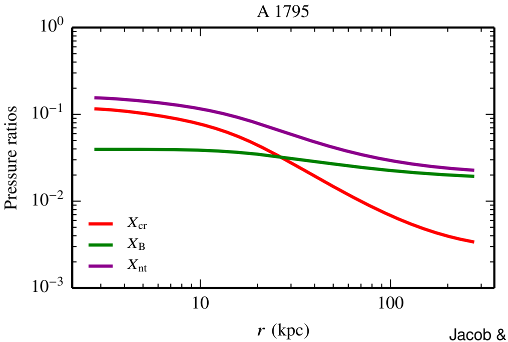
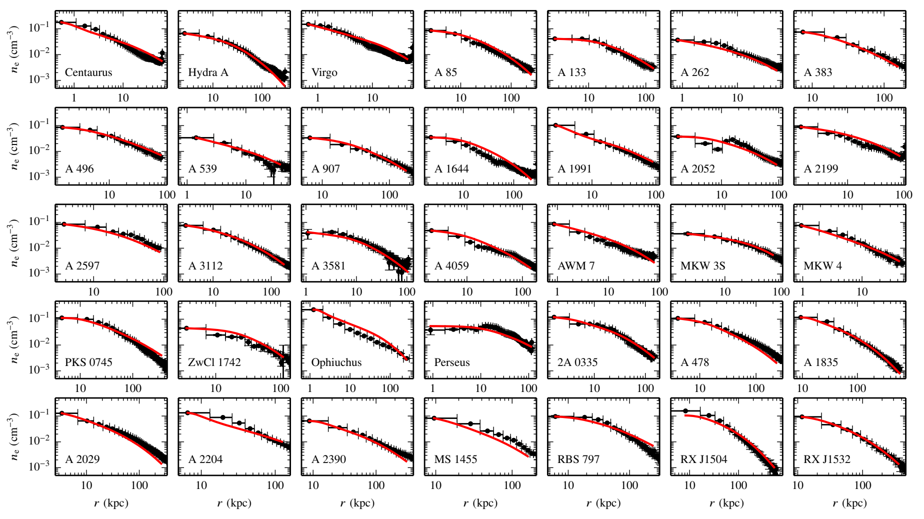


Jacob & Pfrommer (2017a)

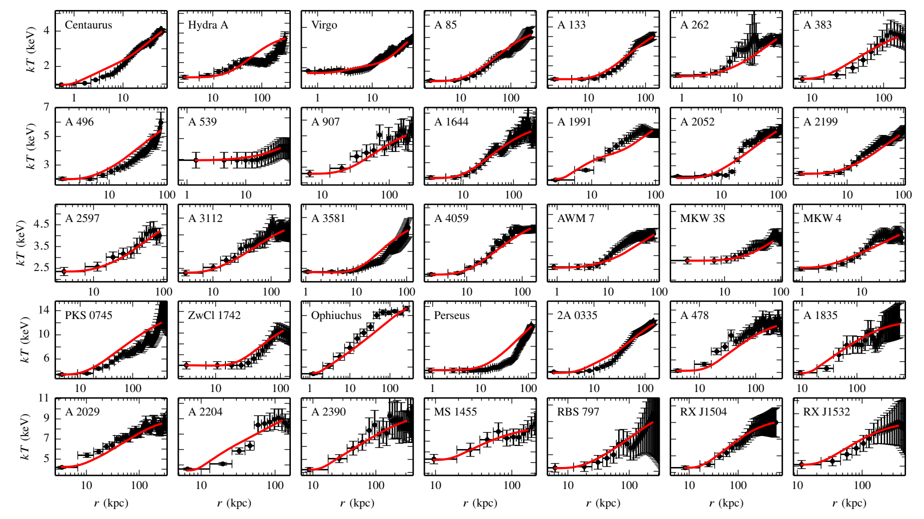
- define $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$, $X_B = P_B/P_{\rm th}$, $X_{\rm nt} = P_{\rm nt}/P_{\rm th}$
- $X_{\rm cr} \approx$ const. in center: $\Delta\varepsilon_{\rm th} = -\tau_{\rm A}\boldsymbol{v}_{\rm st}\cdot\nabla P_{\rm cr} \approx P_{\rm cr} = X_{\rm cr}P_{\rm th}$
- adopt B model from Faraday rotation studies:

$$B = 10\,\mu\mathrm{G}\times\left(n/0.01\,\mathrm{cm}^{-3}\right)^{0.5}$$

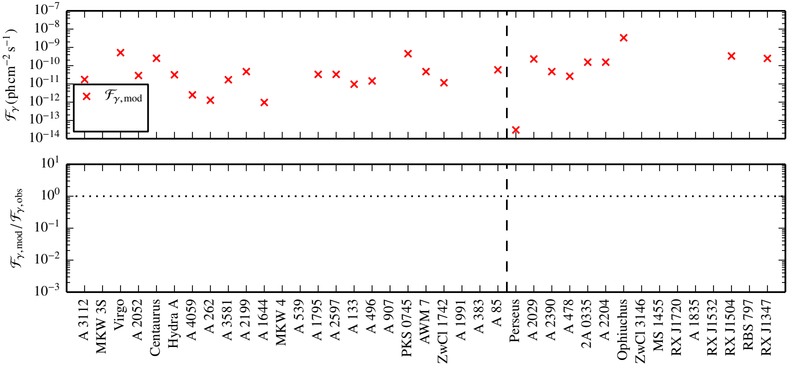
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

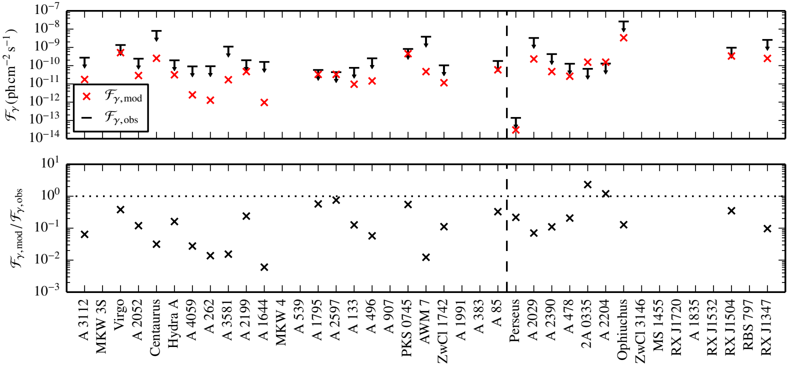


Hadronic gamma-ray emission



Jacob & Pfrommer (2017b)

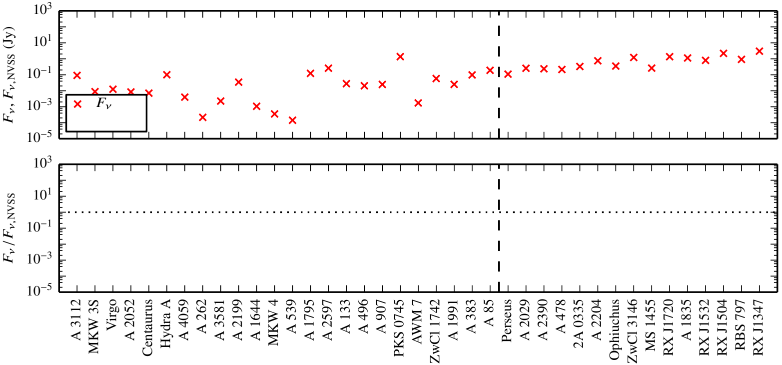
Hadronic gamma-ray emission: observational limits



Jacob & Pfrommer (2017b)

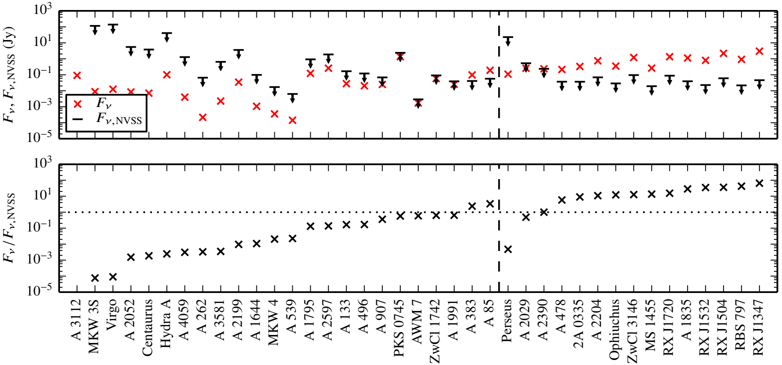
- predictions close to observational limits
- sensitivity not sufficient to be constraining

Hadronically induced radio emission



Jacob & Pfrommer (2017b)

Hadronically induced radio emission: NVSS limits



Jacob & Pfrommer (2017b)

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

How can we explain these results?

- self-regulated feedback cycle driven by CRs

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- self-regulated feedback cycle driven by CRs

AGN injects CRs

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- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

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↓

CRs stream outwards and become too dilute to heat the cluster

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AGN injects CRs → CR heating balances cooling

↓

CRs stream outwards and become too dilute to heat the cluster

↘

radio mini halo

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How can we explain these results?

- self-regulated feedback cycle driven by CRs

AGN injects CRs → CR heating balances cooling

↓

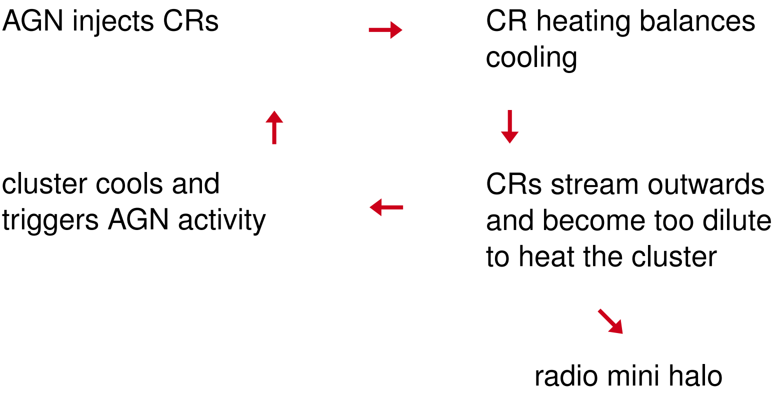
cluster cools and triggers AGN activity ← CRs stream outwards and become too dilute to heat the cluster

↘

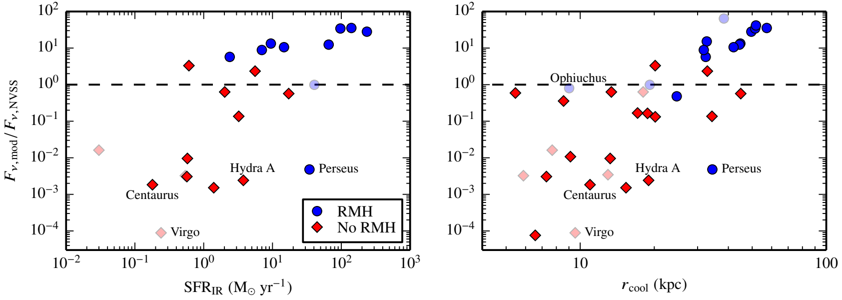
radio mini halo

How can we explain these results?

- self-regulated feedback cycle driven by CRs



Self-regulated heating/cooling cycle in cool cores

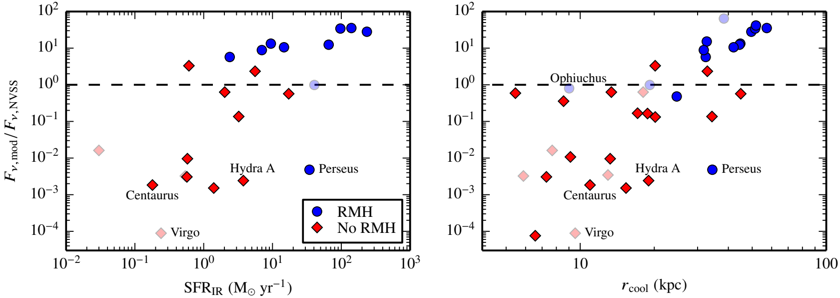


Jacob & Pfrommer (2017b)

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

Self-regulated heating/cooling cycle in cool cores



Jacob & Pfrommer (2017b)

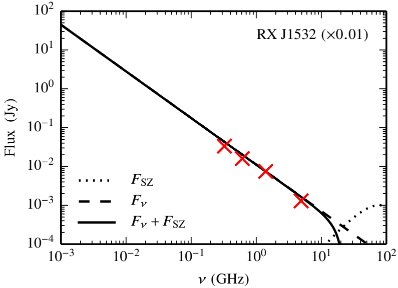
possibly CR-heated cool cores vs. radio mini halo clusters:

- simmering SF: CR heating is effectively balancing cooling
- abundant SF: heating/cooling out of balance
- $F_{\nu,\mathrm{obs}} > F_{\nu,\mathrm{pred}}$: strong radio source = abundant injection of CRs

  $\Rightarrow$ predicting existence of **radio micro halos** in CR heated clusters

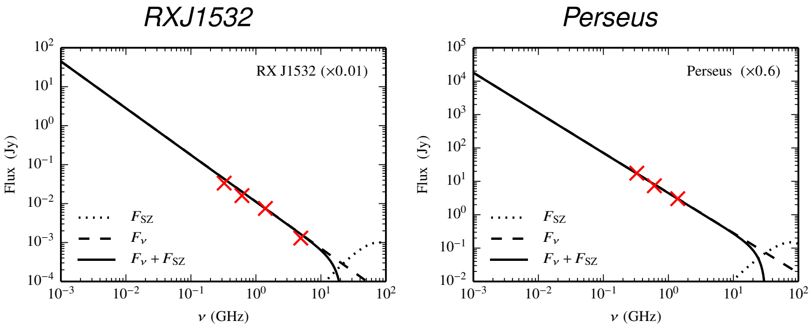
Radio mini halos

RXJ1532



- radio mini halos may be of hadronic origin: CR protons from AGN that have streamed outwards and cooled via Alfvén-wave excitation
- *RXJ1532:* dying radio mini halo

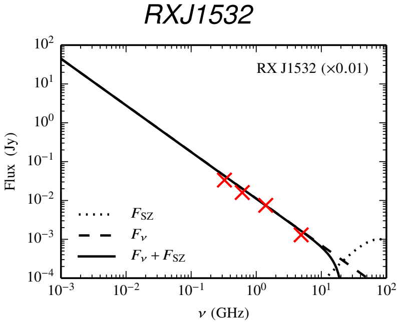
Radio mini halos

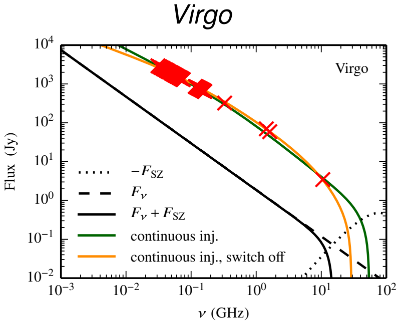


Jacob & Pfrommer (2017a)

- radio mini halos may be of hadronic origin: CR protons from AGN that have streamed outwards and cooled via Alfvén-wave excitation
- *RXJ1532:* dying radio mini halo
  Perseus: transitional object, was CR heated until recently

Predicting radio micro halos

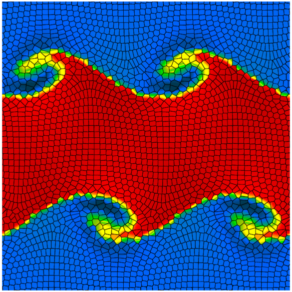




Jacob & Pfrommer (2017a)

- radio mini halos may be of hadronic origin: CR protons from AGN that have streamed outwards and cooled via Alfvén-wave excitation
- predicting radio micro halos of primary origin in CR-heated CCs: CR electrons that escaped from AGN; subdominant hadronic emission

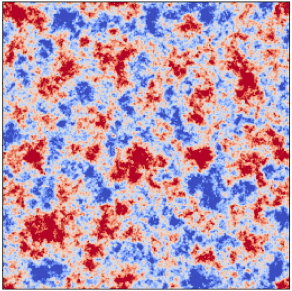
MHD jet simulations



AREPO: unstructured-mesh

- MHD moving-mesh code AREPO
- NFW cluster potential

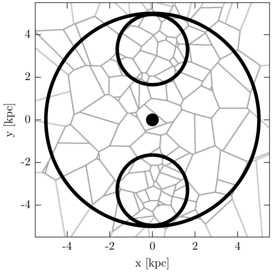
MHD jet simulations



initial magnetic field

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

MHD jet simulations

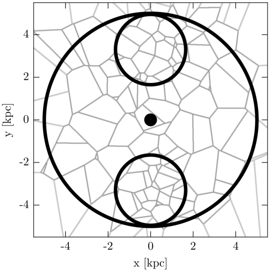


AREPO: jet injection region

(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: $E_{\mathrm{cr}}/E_{\mathrm{th}} \geq 0.5$

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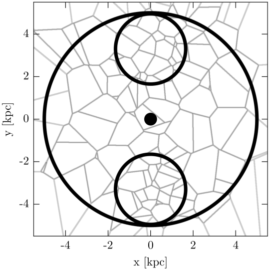

AREPO: jet injection region

(Weinberger+ 2017)

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

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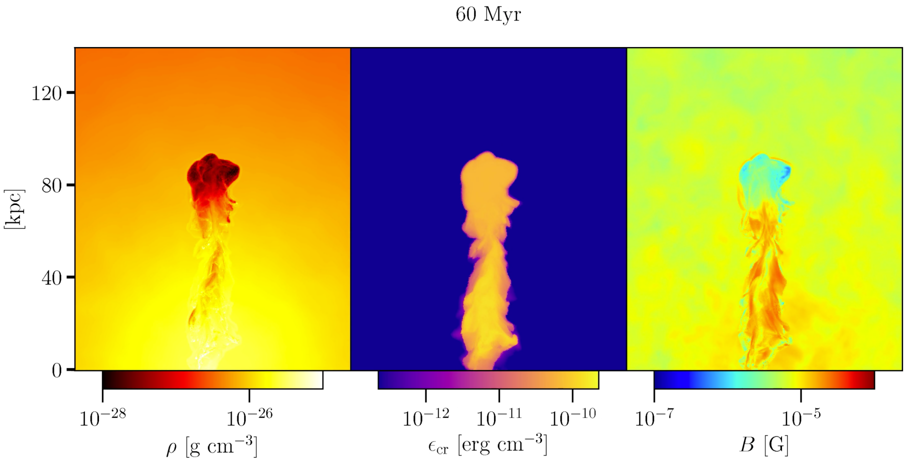
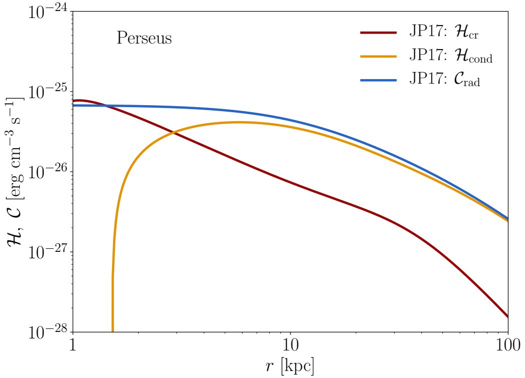
Jet simulation: gas density, CR energy density, *B* field



Ehlert, Weinberger, Pfrommer+ (2018)

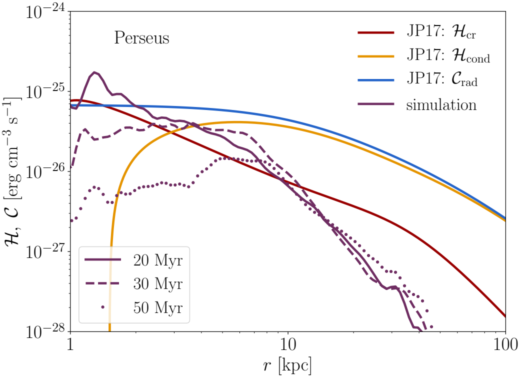
Perseus cluster – heating vs. cooling: theory



Ehlert, Weinberger, Pfrommer+ (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}

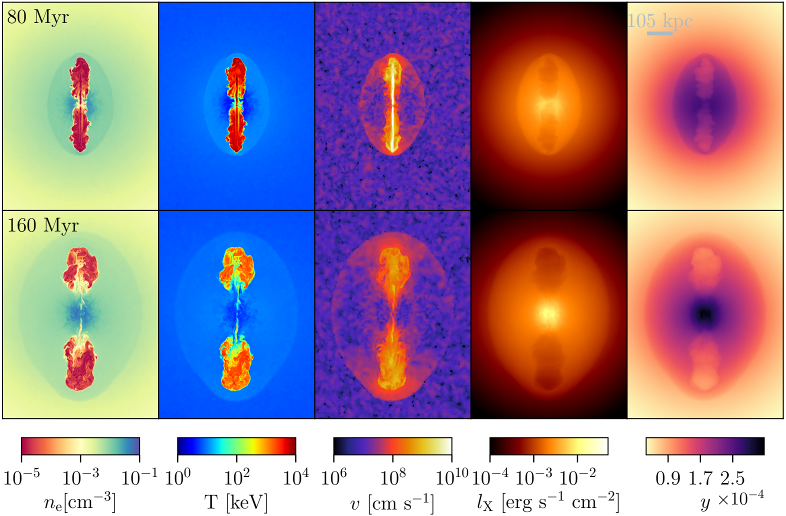
Perseus cluster – heating vs. cooling: simulations



Ehlert, Weinberger, Pfrommer+ (2018)

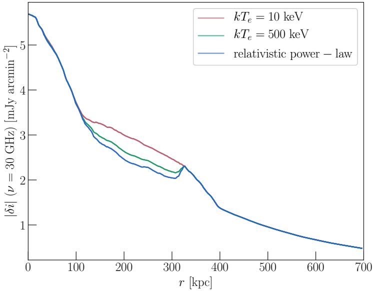
- CR and conductive heating balance radiative cooling: $\mathcal{H}_{\rm cr} + \mathcal{H}_{\rm th} \approx \mathcal{C}_{\rm rad}$: modest mass deposition rate of 1 $M_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

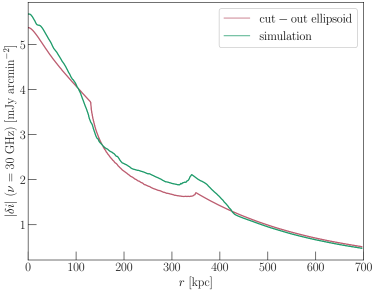
Modelling the major outburst in MS 0735



Ehlert, Pfrommer+ (2019)

SZ effect of bubbles – profiles





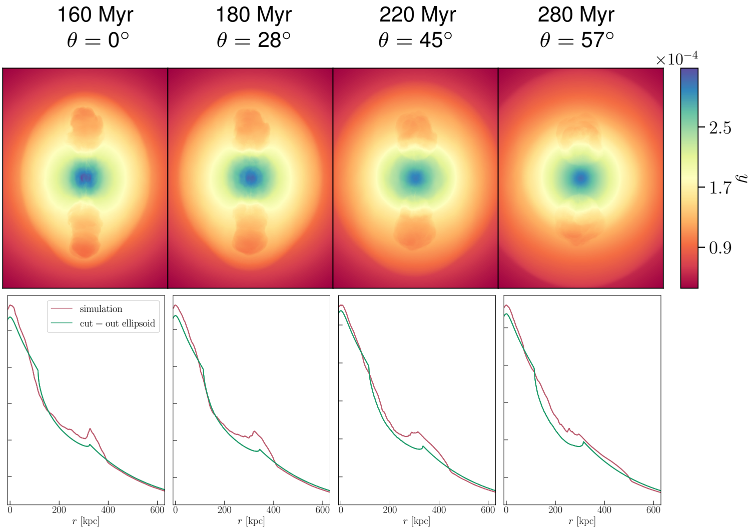
Ehlert, Pfrommer+ (2019)

different bubble fillings:

thermal vs. relativistic content

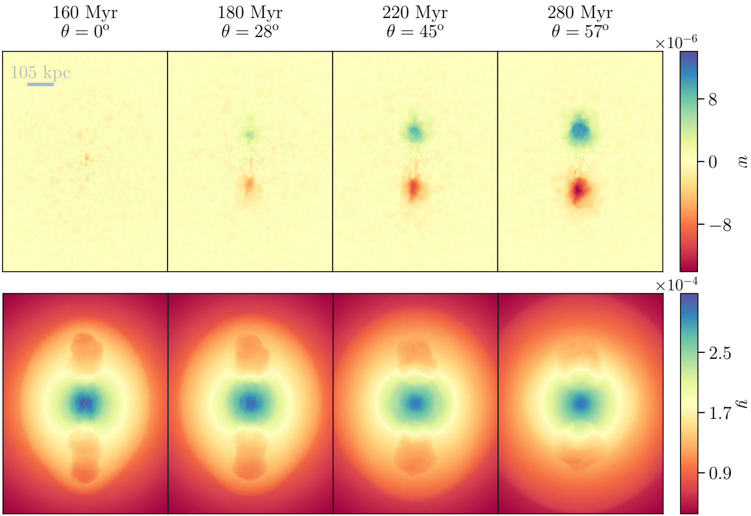
analytical model vs. simulation

SZ effect of bubbles: inclination-distance degeneracy



Ehlert, Pfrommer+ (2019)

Kinetic vs. thermal SZ effect



Ehlert, Pfrommer+ (2019)

Conclusions on AGN feedback by cosmic-ray heating

cosmic-ray heating in M87:

- radio and γ-ray data of M87 imply CR mixing with dense cluster gas with a CR-to-thermal pressure ratio of $X_{\mathrm{cr}} = 0.3$
- CR Alfvén wave heating balances radiative cooling on all scales within the central radio halo ($r < 35$ kpc)

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- *low-density cool cores:* possibly stably heated by cosmic rays
- *radio mini halo clusters:* cosmic-ray heating ruled out systems are strongly cooling and form stars at large rates

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AGN jet simulations:

- MHD simulations of AGN jets: CR heating can solve the "cooling flow problem" in galaxy clusters
- simulating Sunyaev-Zel'dovich effect of bubbles: determine relativistic filling

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).

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Literature for the talk

AGN feedback by cosmic rays:

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- Weinberger, Ehlert, Pfrommer, Pakmor, Springel, *Simulating the interaction of jets with the intra-cluster medium,* 2017, MNRAS, 470, 4530.
- Ehlert, Weinberger, Pfrommer, Pakmor, Springel, *Simulations of the dynamics of magnetised jets and cosmic rays in galaxy clusters,* 2018, MNRAS, 481, 2878.
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