AGN jet feedback in galaxy clusters: the case for cosmic ray heating

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in collaboration with

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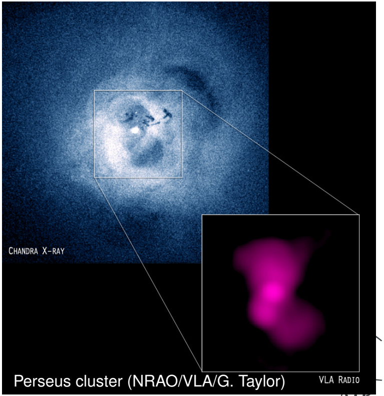
Extragalactic jets on all scales - launching, propagation, termination, Heidelberg, June 2021

Feedback by active galactic nuclei

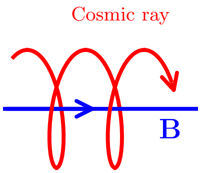
Paradigm: accreting super-massive black holes at galaxy cluster centers launch relativistic jets, which provide energetic feedback to balance cooling $\Rightarrow$ **but how?**

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



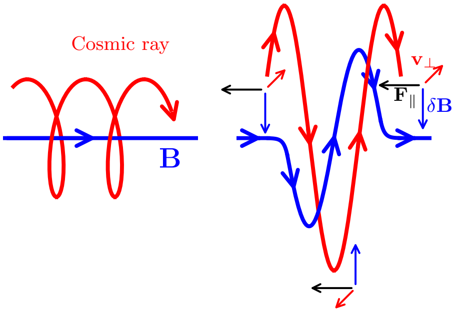
Perseus cluster (NRAO/VLA/G. Taylor)

Interactions of cosmic rays and magnetic fields



sketch: Jacob

Interactions of cosmic rays and magnetic fields

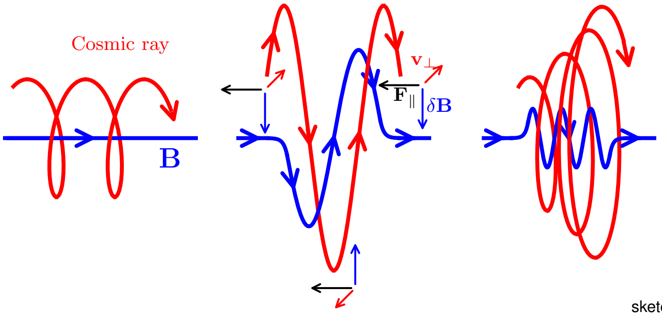


sketch: Jacob

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

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

Interactions of cosmic rays and magnetic fields

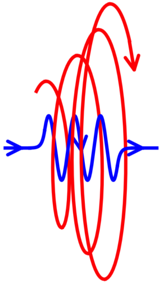


sketch: Jacob

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

Cosmic ray Alfvén wave heating

- **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



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

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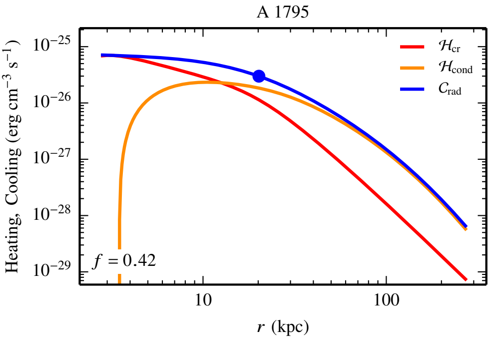
Case study A1795: heating and cooling



Jacob & CP (2016a)

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

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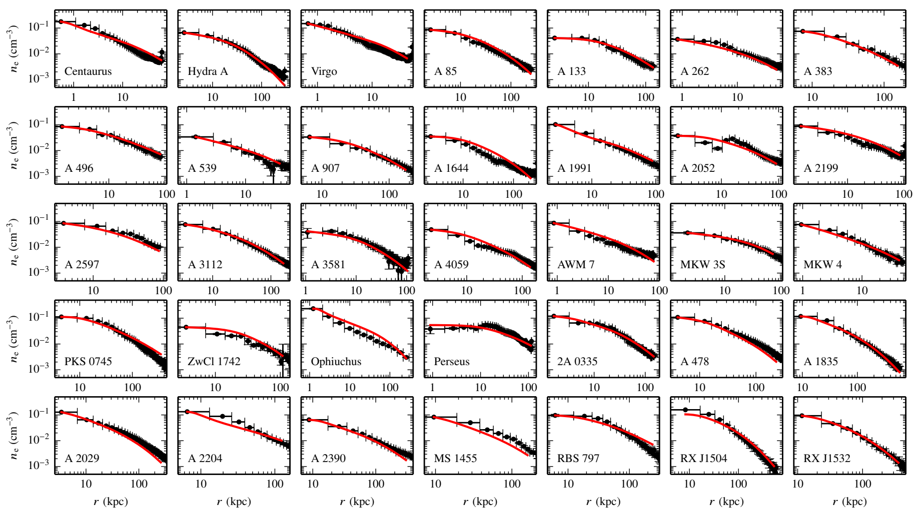
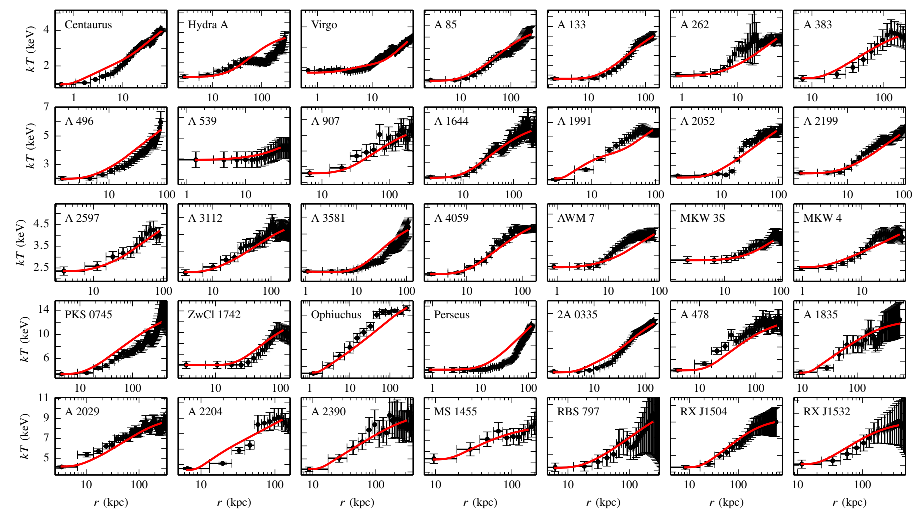
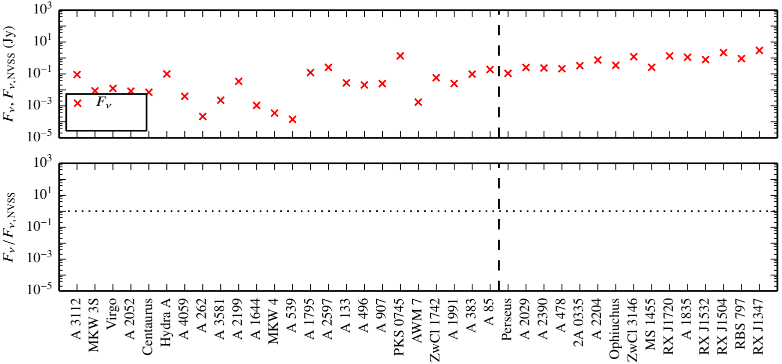
Gallery of solutions: density profiles



Gallery of solutions: temperature profiles

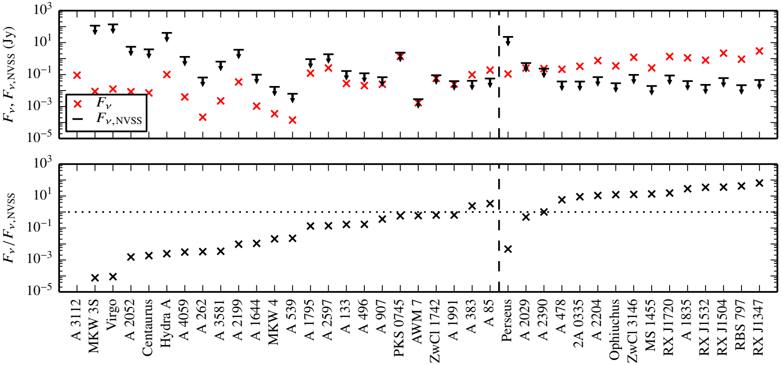


Hadronically induced radio emission



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)

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How can we explain these results?

- self-regulated feedback cycle driven by CRs

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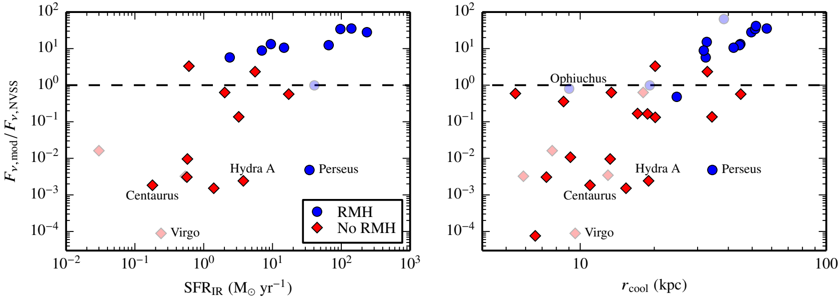
CRs stream outwards and become too dilute to heat the cluster ← cluster cools and triggers AGN activity

↑

↘ 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

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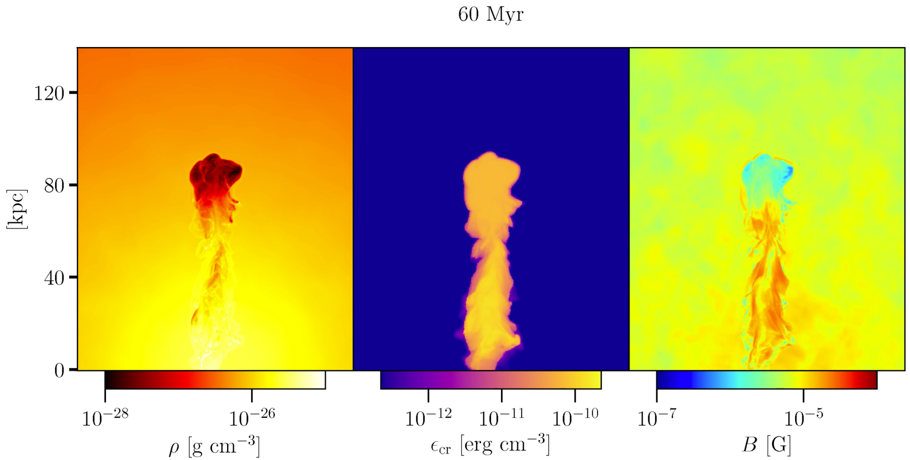
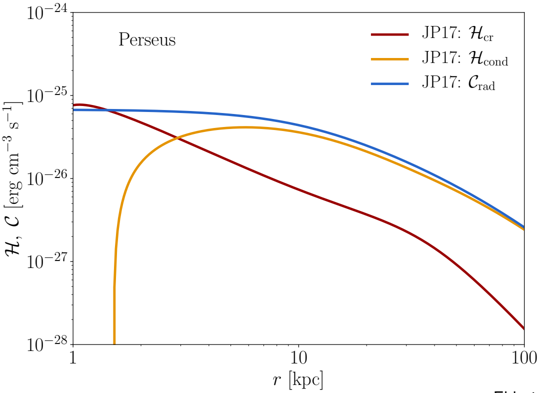
Jet simulation: gas density, CR energy density, *B* field



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 $\mathrm{M}_\odot\ \mathrm{yr}^{-1}$

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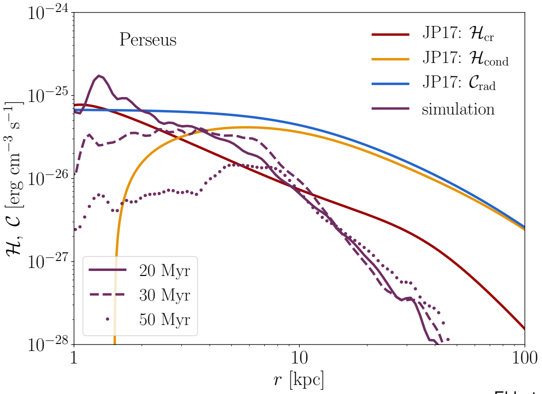
Perseus cluster – heating vs. cooling: simulations



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- 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 $\mathrm{M}_\odot$ yr^{-1}
- **simulated CR heating rate matches 1D steady state model**

Conclusions

large sample of cool cores ⇒ self-regulation cycle

- *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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MHD simulations of AGN jets

- cosmic ray heating is isotropic in cluster center
- cosmic ray heating balances cooling for AGN duty cycle

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

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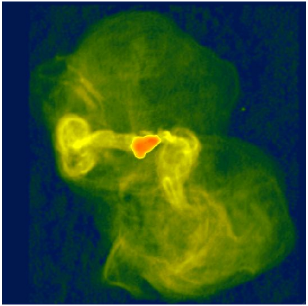
Literature for the talk

Cosmic ray feedback in galaxy clusters:

- Pfrommer, *Toward a comprehensive model for feedback by active galactic nuclei: new insights from M87 observations by LOFAR, Fermi and H.E.S.S.*, 2013, ApJ.
- 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.

Additional slides

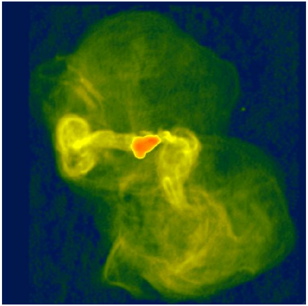
Feedback heating: M87 at radio wavelengths



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

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

Feedback heating: M87 at radio wavelengths



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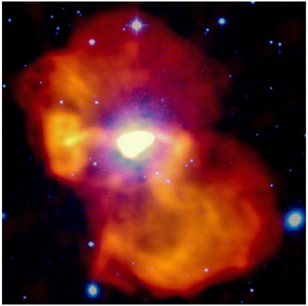


$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

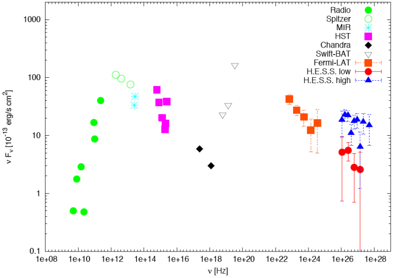
- high-ν: freshly accelerated CR electrons
  low-ν: fossil CR electrons $\rightarrow$ time-integrated AGN feedback!
- LOFAR: same picture $\rightarrow$ puzzle of "missing fossil electrons"
- solution: electrons are fully mixed with the dense cluster gas and cooled through Coulomb interactions

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

$$\mathcal{H}_{\rm cr} = -\boldsymbol{v}_A \cdot \boldsymbol{\nabla} P_{\rm cr}$$

- calibrate $P_{\rm cr}$ to γ-ray emission and $\boldsymbol{v}_A$ to radio and X-ray emission $\rightarrow$ spatial heating profile

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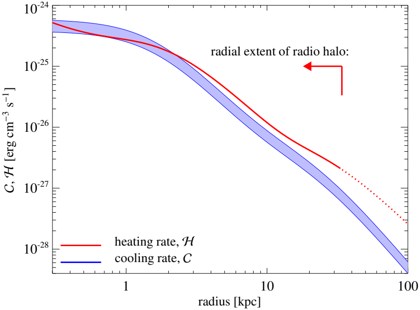

Pfrommer (2013)

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

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