AGN feedback: mechanical versus cosmic-ray heating

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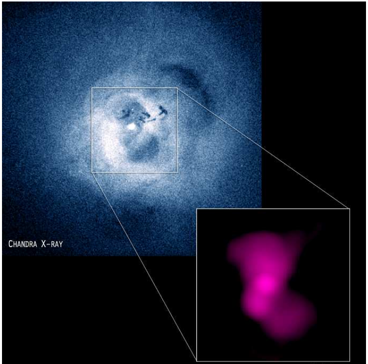
Outline

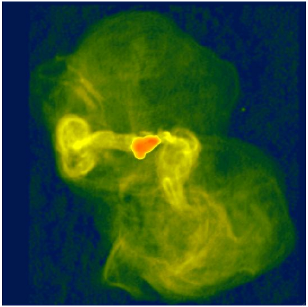
Radio mode feedback by AGN: open questions

- energy source:
  release of non-gravitational accretion energy of a black hole
- jet-ICM interaction and rising bubbles:
  1.) magnetic draping → amplification
  2.) CR confinement vs. release
  3.) excitation of turbulence
- heating mechanism:
  1.) self-regulated to avoid overcooling
  2.) thermally stable to explain T floor
  3.) low energy coupling efficiency
- cosmic ray heating:
  1.) are CRs efficiently mixed into the ICM?
  2.) is the CR heating rate sufficient to balance cooling?
  3.) how universal is this heating mechanism in cool cores?

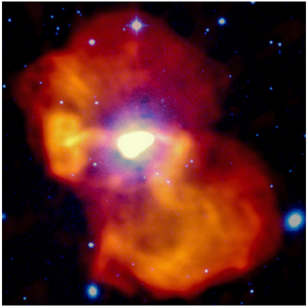


Perseus cluster (NRAO/VLA/G. Taylor)

Messier 87 at radio wavelengths



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



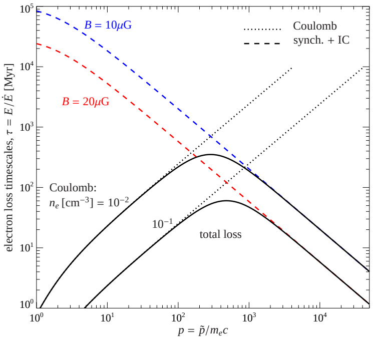
$\nu = 140$ MHz (LOFAR/de Gasperin+ 2012)

- 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”

Solutions to the “missing fossil electrons” problem

solutions:

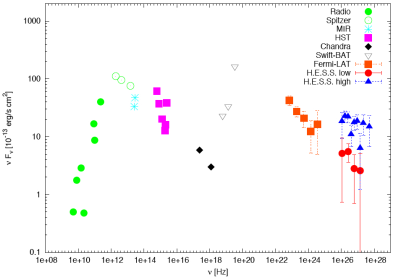
- special time: M87 turned on $\sim$ 40 Myr ago after long silence
  $\Leftrightarrow$ conflicts order unity duty cycle inferred from stat. AGN feedback studies (Birzan+ 2012)
- Coulomb cooling removes fossil electrons
  $\rightarrow$ efficient mixing of CR electrons and protons with dense cluster gas
  $\rightarrow$ predicts γ rays from CRp-p interactions:
  $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$



C.P. (2013)

The gamma-ray picture of M87

- high state is time variable
  → 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 (?)



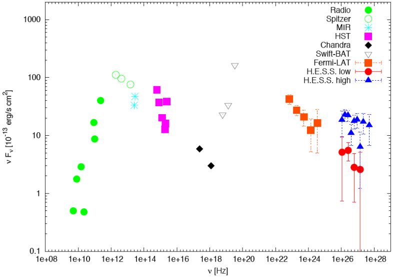
Rieger & Aharonian (2012)

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

Estimating the cosmic-ray pressure in M87

hypothesis: low state of γ-ray emission traces π^0 decay in ICM:

- X-ray data $\rightarrow$ n and T profiles
- assume steady-state CR streaming: $P_{\mathrm{cr}} \propto \rho^{\gamma_{\mathrm{cr}}/2} \propto P_{\mathrm{th}}$
- $F_\gamma \propto \int \mathrm{d}V\, P_{\mathrm{cr}} n$ enables to estimate $X_{\mathrm{cr}} = P_{\mathrm{cr}}/P_{\mathrm{th}} = 0.31$ (allowing for Coulomb cooling with $\tau_{\mathrm{Coul}} = 40\,\mathrm{Myr}$)

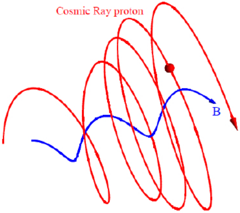


Rieger & Aharonian (2012)

$\rightarrow$ in agreement with non-thermal pressure constraints from dynamical potential estimates (Churazov+ 2010)

Interactions of cosmic rays and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm A}$, CR current provides steady driving force, which 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



→ **CRs exert a pressure on the thermal gas by means of scattering off of Alfvén waves**

Cosmic-ray transport

- total CR velocity $\boldsymbol{v}_{\mathrm{cr}} = \boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\mathrm{gas}}$)
- CRs are advected with the flux-frozen $\boldsymbol{B}$ field in the gas
- CRs stream adiabatically down their own pressure gradient relative to the gas:

$$\boldsymbol{v}_{\mathrm{st}} = -v_{\mathrm{A}}\, \boldsymbol{b} \frac{\boldsymbol{b} \cdot \nabla P_{\mathrm{cr}}}{|\boldsymbol{b} \cdot \nabla P_{\mathrm{cr}}|} \quad \text{with} \quad \boldsymbol{b} = \frac{\boldsymbol{B}}{|\boldsymbol{B}|} \quad \text{and} \quad v_{\mathrm{A}} = \sqrt{\frac{\boldsymbol{B}^2}{4\pi\rho}}$$

- CRs diffuse in the wave frame due to pitch angle scattering by MHD waves:

$$\boldsymbol{v}_{\mathrm{di}} = -\kappa_{\mathrm{di}}\, \boldsymbol{b} \frac{\boldsymbol{b} \cdot \nabla P_{\mathrm{cr}}}{P_{\mathrm{cr}}},$$

Cosmic-ray heating vs. radiative cooling (1)

CR Alfvén-wave heating:

(Loewenstein, Zweibel, Begelman 1991, Guo & Oh 2008, Enßlin+ 2011)

$$\mathcal{H}_{\rm cr} = -\boldsymbol{v}_A \cdot \boldsymbol{\nabla} P_{\rm cr} = -v_A \left(X_{\rm cr} \nabla_r \langle P_{\rm th} \rangle_\Omega + \frac{\delta P_{\rm cr}}{\delta l} \right)$$

- Alfvén velocity $v_A = B/\sqrt{4\pi\rho}$ with $B \sim B_{\rm eq}$ from LOFAR and ρ from X-ray data
- $X_{\rm cr}$ inferred from γ rays
- $P_{\rm th}$ from X-ray data
- pressure fluctuations $\delta P_{\rm cr}/\delta l$ (e.g., due to weak shocks of $\mathcal{M} \simeq 1.1$)

radiative cooling:

$$\mathcal{C}_{\rm rad} = n_e n_i \Lambda_{\rm cool}(T, Z)$$

- cooling function $\Lambda_{\rm cool}$ with $Z \simeq Z_\odot$, all quantities determined from X-ray data

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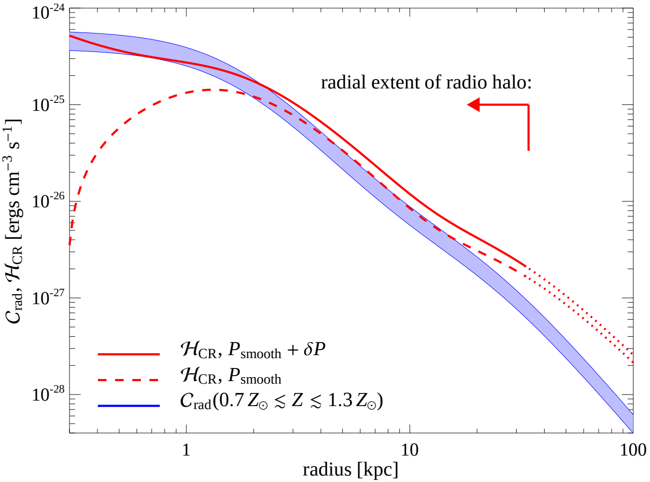
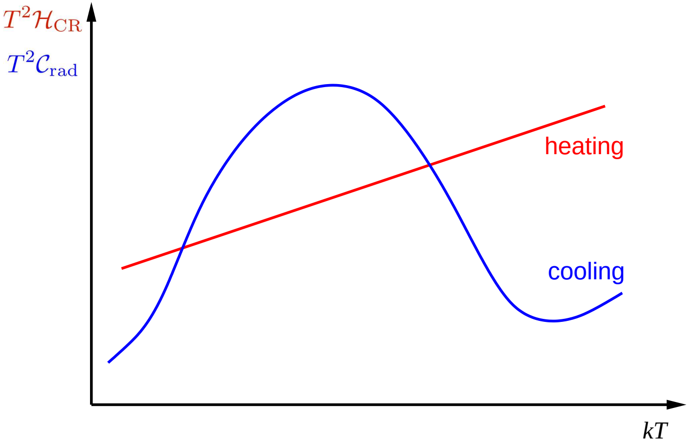
Cosmic-ray heating vs. radiative cooling (2)

Global thermal equilibrium on all scales in M87



C.P. (2013)

Local stability analysis (1)



- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

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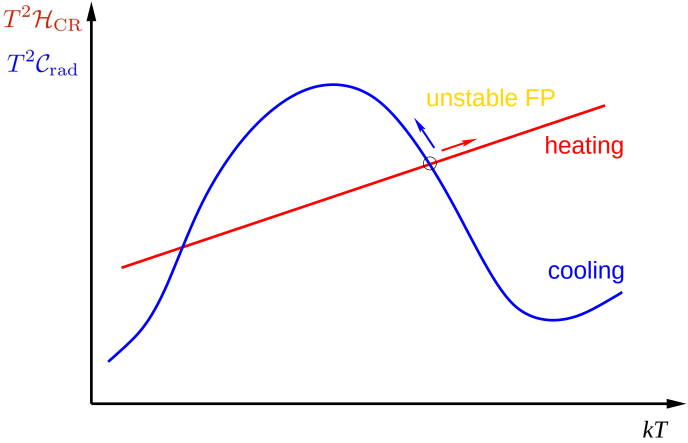

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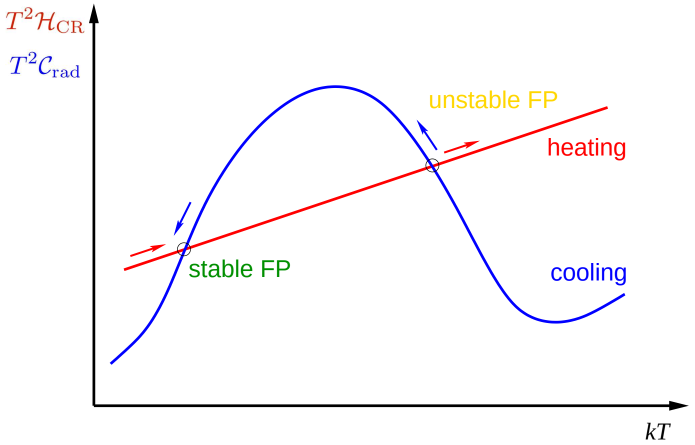

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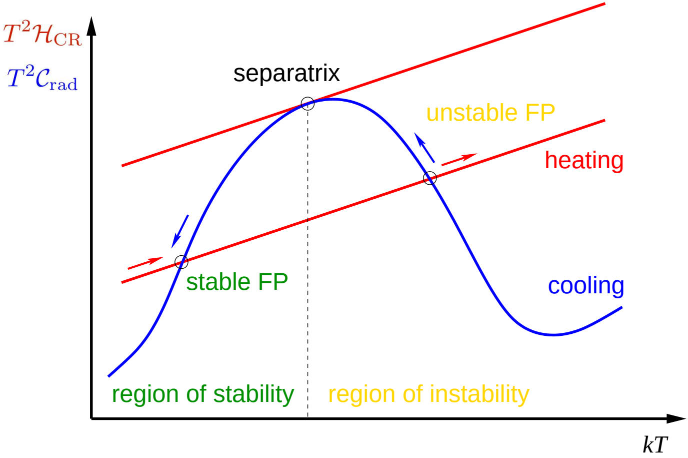

- isobaric perturbations to global thermal equilibrium
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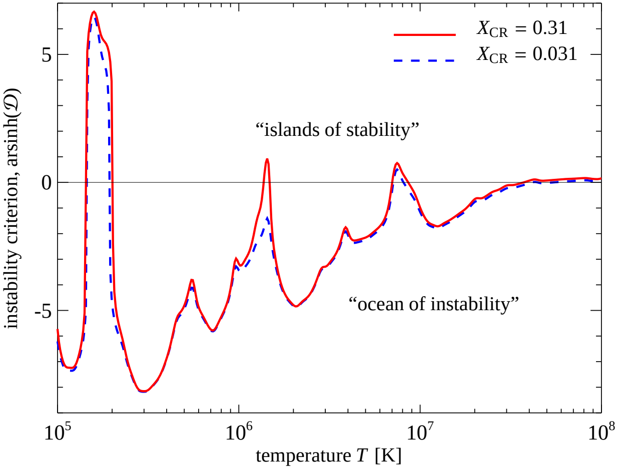
Local stability analysis (2)

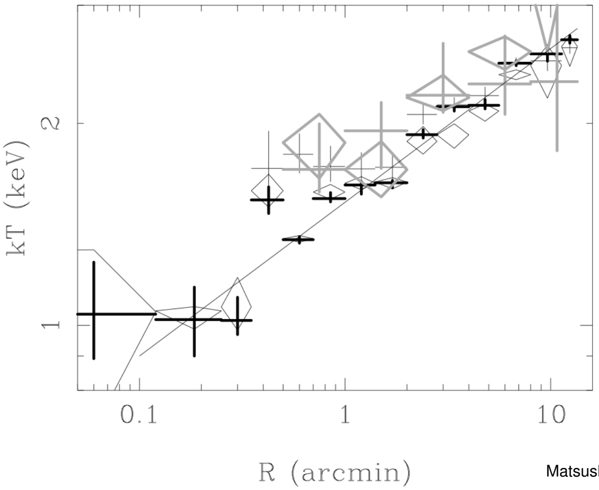
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

Virgo cluster cooling flow: temperature profile

X-ray observations confirm temperature floor at $kT \simeq 1$ keV



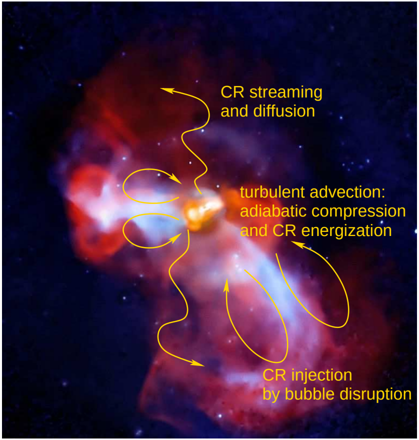
Matsushita+ (2002)

Emerging picture of CR feedback by AGNs

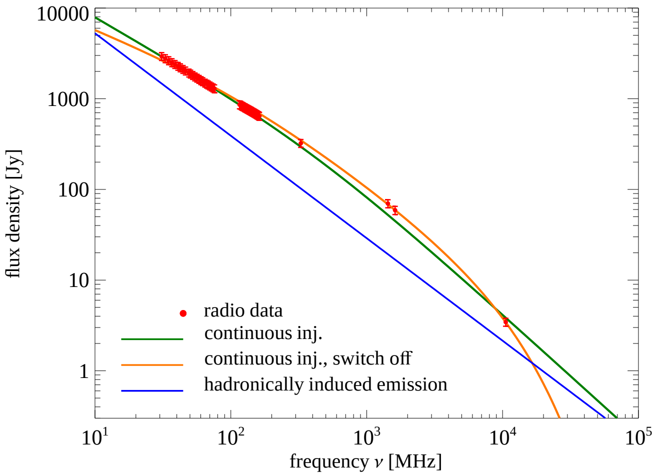
(1) during buoyant rise of bubbles: CRs diffuse and stream outward
→ CR Alfvén-wave heating

(2) if bubbles are disrupted, CRs are injected into the ICM and caught in a turbulent downdraft that is excited by the rising bubbles
→ CR advection with flux-frozen field
→ adiabatic CR compression and energizing: $P_{\rm cr}/P_{\rm cr,0} = \delta^{4/3} \sim 20$ for compression factor $\delta = 10$

(3) CR escape and outward streaming → CR Alfvén-wave heating



Prediction: flattening of high-ν radio spectrum

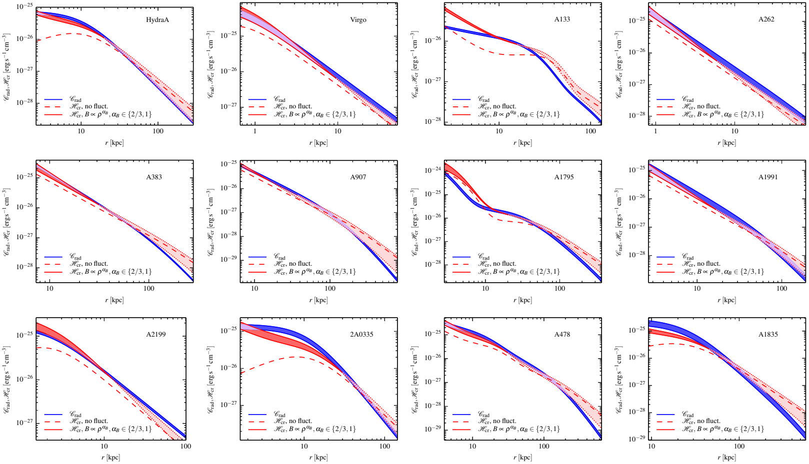


C.P. (2013)

How universal is CR heating in cool core clusters?

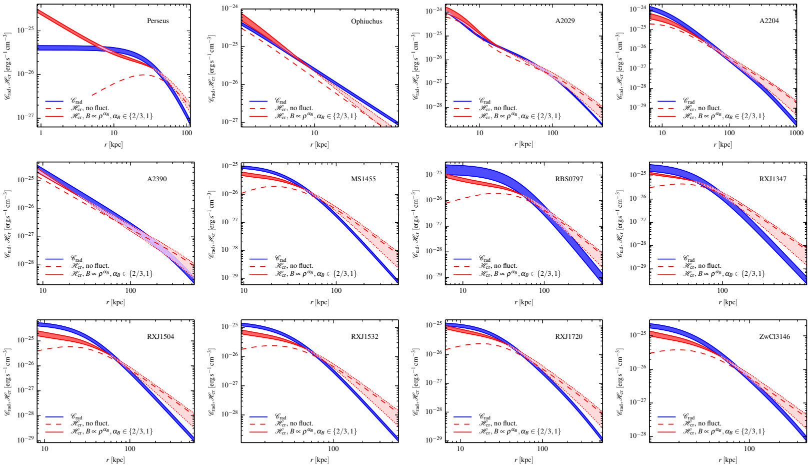
- no γ rays observed from other clusters $\rightarrow$ $P_{\rm cr}$ unconstrained
- **strategy:** construct sample of 24 cool cores
  (1) assume $\mathcal{H}_{\rm cr} = \mathcal{C}_{\rm rad}$ at $r = r_{\rm cool,\,1\,Gyr}$
  (2) assume steady-state CR streaming: $P_{\rm cr} \propto \rho^{\gamma_{\rm cr}/2}$
  (3) adopt B model from Faraday rotation studies:
  $B = 40\,\mu{\rm G} \times \left(n/0.1\,{\rm cm}^{-3}\right)^{\alpha_B}$ where $\alpha_B \in \{2/3, 1\}$
  (4) calculate hadronic radio and γ-ray emission and compare to observations
- **consequences:**
  $\Rightarrow$ if $\mathcal{H}_{\rm cr} = \mathcal{C}_{\rm rad}\ \forall\ r$ and hadr. emission below observational limits: successful CR heating model that is locally stabilized at $\sim$ 1 keV
  $\Rightarrow$ otherwise CR heating ruled out as dominant heating source

Cosmic-ray heating in cool core clusters (1)



Jacob & C.P. (in prep.)

Cosmic-ray heating in cool core clusters (2)



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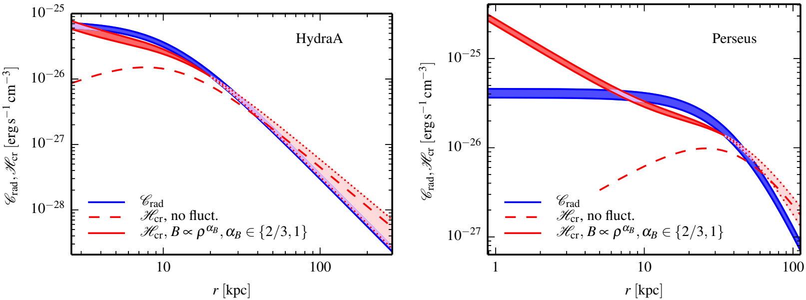
Cosmic-ray heating in Hydra A vs. Perseus

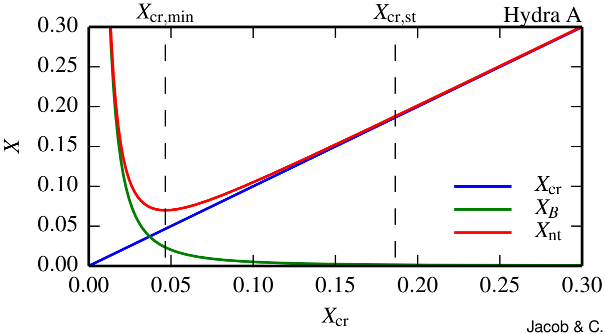


Jacob & C.P. (in prep.)

2 populations of cool cores emerging:

- pop 1 (Hydra A, Virgo, ...): $\mathcal{H}_{\rm cr} = \mathcal{C}_{\rm rad} \rightarrow$ CR heated?
- pop 2 (Perseus, Ophiuchus, ...): $\mathcal{H}_{\rm cr} \neq \mathcal{C}_{\rm rad}$: host radio-mini halos!

Non-thermal pressure balance

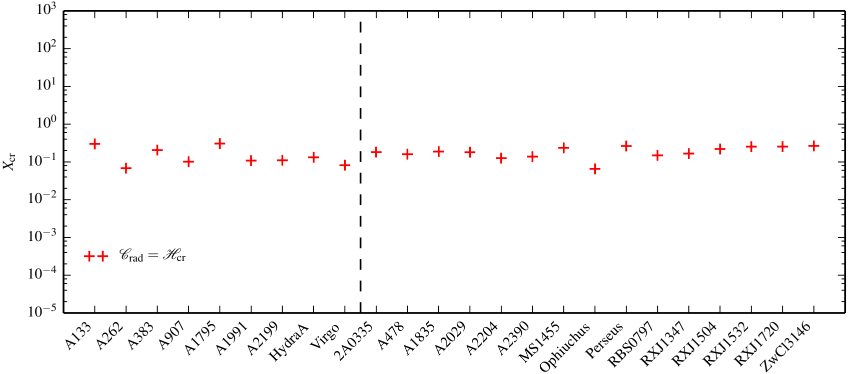


Jacob & C.P. (in prep.)

- define $X_{\rm cr} = P_{\rm cr}/P_{\rm th}$ and $X_B = P_B/P_{\rm th}$
- CR heating rate: $\mathcal{H}_{\rm cr} = -\boldsymbol{v}_A \cdot \nabla P_{\rm cr} \propto X_B^{0.5} X_{\rm cr}$
- non-thermal pressure at fixed heating rate:

$$X_{\rm nt} \equiv (X_B + X_{\rm cr})_{\mathcal{H}_{\rm cr}} = A X_{\rm cr}^{-2} + X_{\rm cr} \quad \rightarrow \quad X_{\rm cr,min} = (2A)^{1/3}$$

Hadronic emission: radio and γ rays



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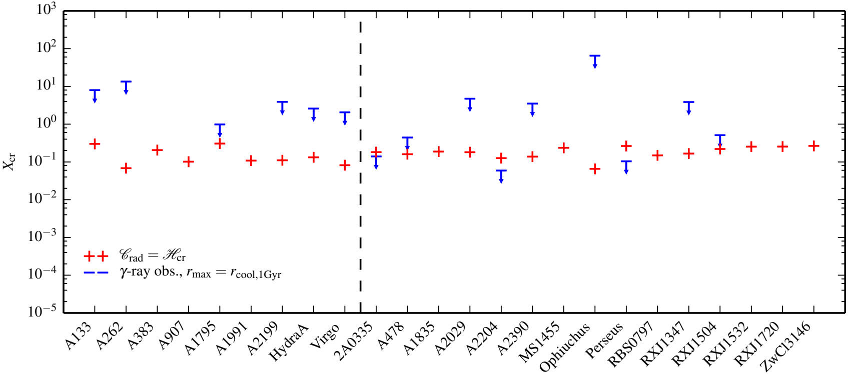

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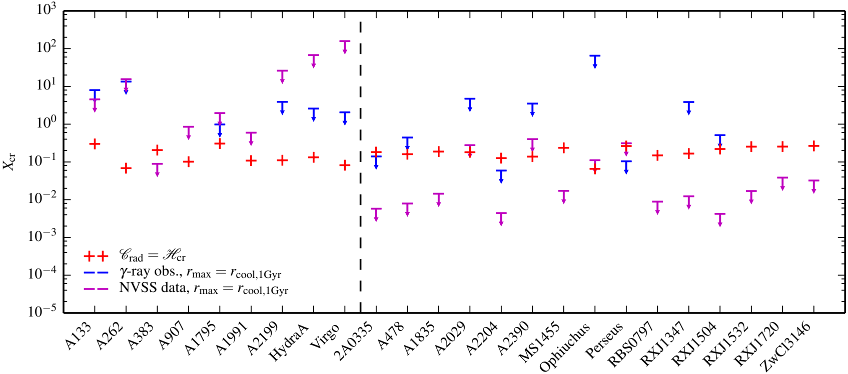

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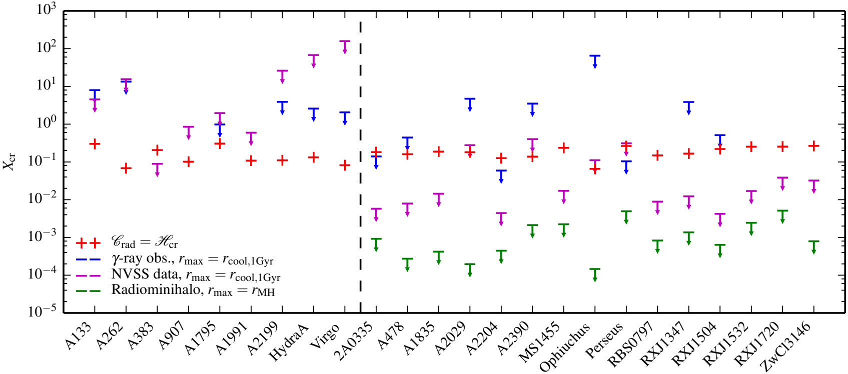
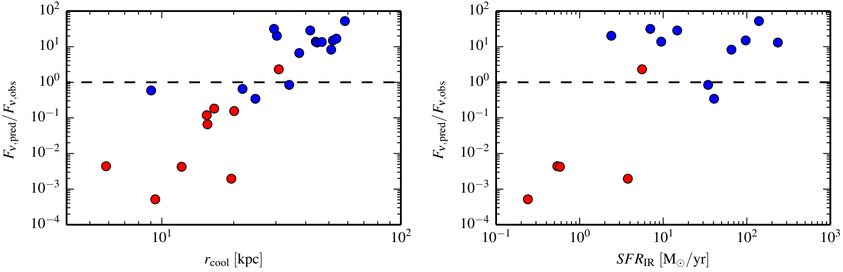
Hadronic emission: radio and γ rays



Jacob & C.P. (in prep.)

- CR heating solution ruled out in radio mini-halos ($\mathcal{H}_{\rm cr} \neq \mathcal{C}_{\rm rad}$)!

Correlations in cool cores



Jacob & C.P. (in prep.)

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

- $F_{\nu,\mathrm{obs}} > F_{\nu,\mathrm{pred}}$: strong radio source = abundant injection of CRs
- peaked CC profile ($r_{\mathrm{cool}} \lesssim 20$ kpc) and simmering star formation: cosmic-ray(?) heating is effectively balancing cooling
- large star formation rates: heating out of balance

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Conclusions on AGN feedback by cosmic-ray heating

cosmic-ray heating in M87:

- LOFAR puzzle of “missing fossil electrons” in M87 solved by mixing with dense cluster gas and Coulomb cooling
- predicted γ rays identified with low state of M87 $\rightarrow$ estimate CR-to-thermal pressure of $X_{\mathrm{cr}} = 0.31$
- CR Alfvén wave heating balances radiative cooling on all scales within the central radio halo ($r < 35$ kpc)
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

diversity of cool cores:

- *peaked 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

Literature for the talk

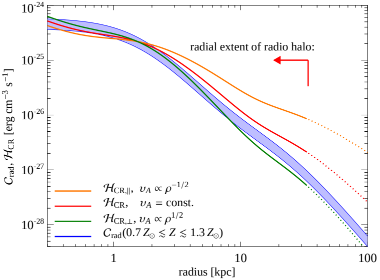
AGN feedback by cosmic rays:

- 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, 779, 10.
- Jacob & Pfrommer, *Diversity in cool core clusters: implications for cosmic-ray heating*, in prep.

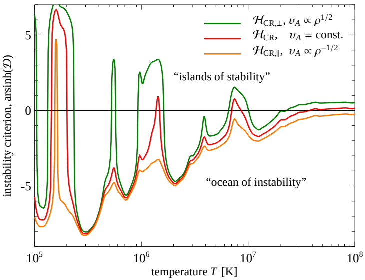
Additional slides

Impact of varying Alfvén speed on CR heating

global thermal equilibrium:



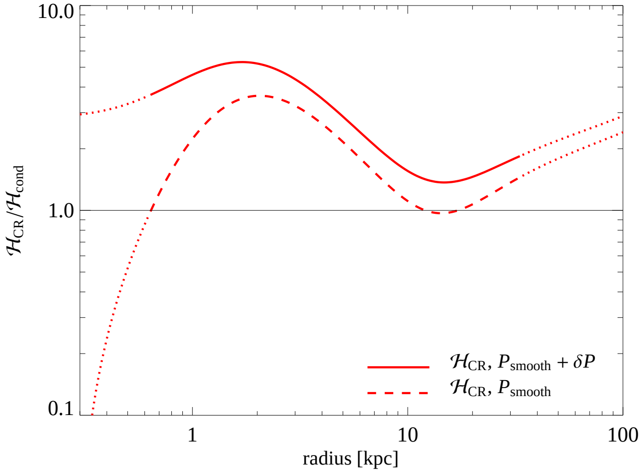
local stability criterion:



parametrize $B \propto \rho^{\alpha_B}$, which implies $v_A = B/\sqrt{4\pi\rho} \propto \rho^{\alpha_B - 1/2}$:

- $\alpha_B = 0.5$ is the geometric mean, implying $v_A = \text{const.}$
- $\alpha_B = 0$ for collapse along $\boldsymbol{B}$, implying $v_{A,\parallel} \propto \rho^{-1/2}$
- $\alpha_B = 1$ for collapse perpendicular to $\boldsymbol{B}$, implying $v_{A,\perp} \propto \rho^{1/2}$

CR heating dominates over thermal conduction



C.P. (2013)

Critical length scale of the instability ($\sim$ Fields length)

- CR streaming transfers energy to a gas parcel with the rate

$$\mathcal{H}_{\rm cr} = -\boldsymbol{v}_A \cdot \boldsymbol{\nabla} P_{\rm cr} \sim f_s v_A |\nabla P_{\rm cr}|,$$

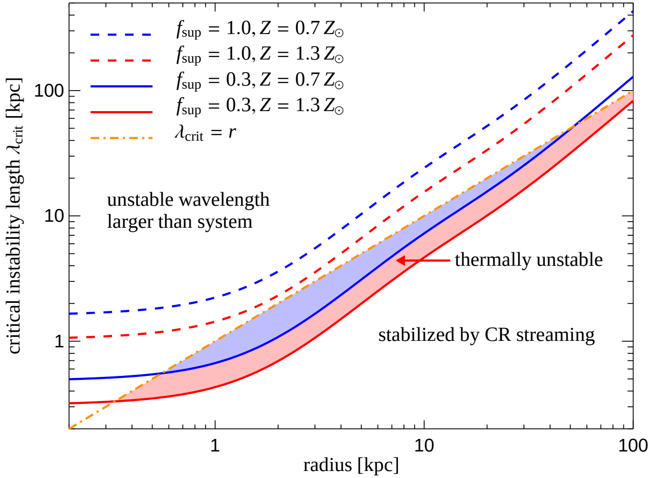
where f_s is the magnetic suppression factor

- line and bremsstrahlung emission radiate energy with a rate $\mathcal{C}_{\rm rad}$
- limiting size of unstable gas parcel since CR Alfvén-wave heating smoothes out temperature inhomogeneities on small scales:

$$\lambda_{\rm crit} = \frac{f_s v_A P_{\rm cr}}{\mathcal{C}_{\rm rad}}$$

- however: unstable wavelength must be supported by the system $\rightarrow$ constraint on magnetic suppression factor f_s

Critical length scale of the instability ($\sim$ Fields length)



C.P. (2013)

Self-consistent CR pressure in steady state

- CR streaming transfers energy per unit volume to the gas as

$$\Delta\varepsilon_{\rm th} = -\tau_A \boldsymbol{v}_A \cdot \nabla P_{\rm cr} \approx P_{\rm cr} = X_{\rm cr} P_{\rm th},$$

  where $\tau_A = \delta l / v_A$ is the Alfvén crossing time and δl the CR pressure gradient length
- comparing the first and last term suggests that a constant CR-to-thermal pressure ratio $X_{\rm cr}$ is a necessary condition if CR streaming is the dominant heating process

$\rightarrow$ **thermal pressure profile adjusts to that of the streaming CRs!**