Cosmic ray heating in cool core clusters

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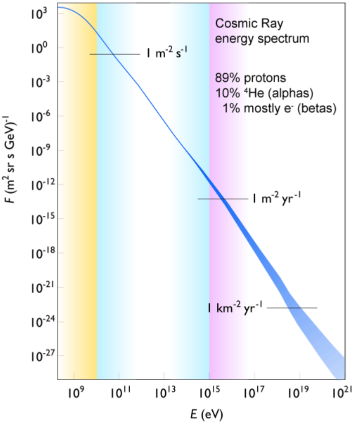
Galactic cosmic ray spectrum



data compiled by Swordy

- power-law momentum spectrum with 33 decades in flux and 12 decades in energy
- likely origin: diffusive shock acceleration at supernova remnants ($E \lesssim 10^{17}$ eV)

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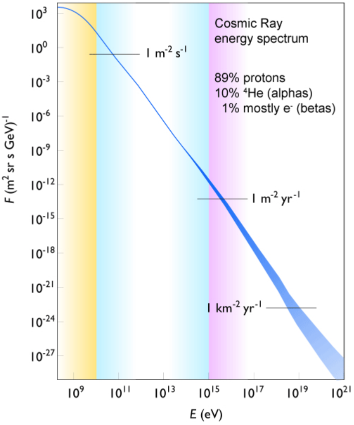

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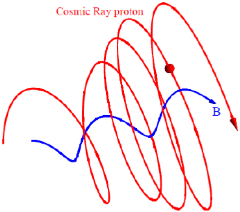
- power-law momentum spectrum with 33 decades in flux and 12 decades in energy
- likely origin: diffusive shock acceleration at supernova remnants ($E \lesssim 10^{17}$ eV)
- pressure of cosmic rays (CRs), magnetic fields, and turbulence in the interstellar gas all similar:

  → CR pressure in cluster cores?
  → impact of CRs on cooling gas and star formation in ellipticals?

Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\rm cr} > v_{\rm waves}$ with respect to the gas, CR excite Alfvén waves
  - scattering off this wave field limits the CRs' bulk speed $\ll c$
  - wave damping: transfer of CR energy and momentum to the thermal gas



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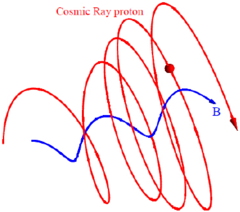

→ **CRs exert a pressure on the thermal gas by means of scattering off Alfvén waves and heat the surrounding gas**
→ cool-core heating (Loewenstein+ 1991, Guo & Oh 2008, C.P. 2013)

CR transport

- total CR velocity $\boldsymbol{v}_{\rm cr} = \boldsymbol{v} + \boldsymbol{v}_{\rm st} + \boldsymbol{v}_{\rm di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\rm gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering by MHD waves (both transports are along the local direction of $\boldsymbol{B}$):

$$\boldsymbol{v}_{\rm st} = -v_{\rm A} \frac{\boldsymbol{\nabla} P_{\rm cr}}{|\boldsymbol{\nabla} P_{\rm cr}|} \text{ with } v_{\rm A} = \sqrt{\frac{\boldsymbol{B}^2}{4\pi\rho}}, \qquad \boldsymbol{v}_{\rm di} = -\kappa_{\rm di} \frac{\boldsymbol{\nabla} P_{\rm cr}}{P_{\rm cr}},$$

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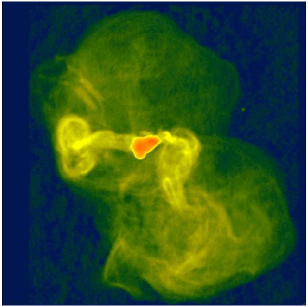
- energy equations with $\varepsilon = \varepsilon_{\mathrm{th}} + \rho v^2/2$ (neglecting CR diffusion):

$$\begin{aligned}
\frac{\partial \varepsilon}{\partial t} + \boldsymbol{\nabla} \cdot [(\varepsilon + P_{\mathrm{th}} + P_{\mathrm{cr}})\boldsymbol{v}] &= P_{\mathrm{cr}} \boldsymbol{\nabla} \cdot \boldsymbol{v} + |\boldsymbol{v}_{\mathrm{st}} \cdot \boldsymbol{\nabla} P_{\mathrm{cr}}| \\
\frac{\partial \varepsilon_{\mathrm{cr}}}{\partial t} + \boldsymbol{\nabla} \cdot (\varepsilon_{\mathrm{cr}} \boldsymbol{v}) + \boldsymbol{\nabla} \cdot [(\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{st}}] &= -P_{\mathrm{cr}} \boldsymbol{\nabla} \cdot \boldsymbol{v} - |\boldsymbol{v}_{\mathrm{st}} \cdot \boldsymbol{\nabla} P_{\mathrm{cr}}|
\end{aligned}$$

Messier 87 at radio wavelengths



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

- expectation: low frequencies sensitive to fossil electrons ($E \sim 100$ MeV) → time-integrated activity of AGN feedback!

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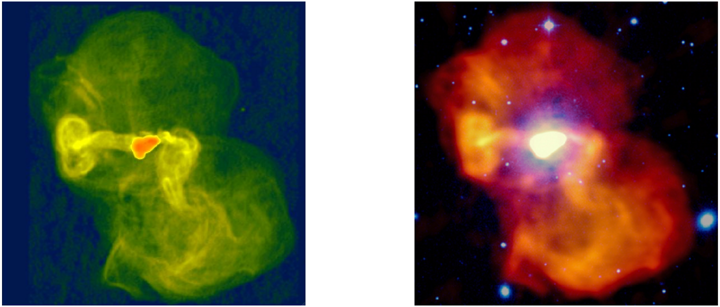

$\nu = 1.4$ GHz (Owen+ 2000)

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

- expectation: low frequencies sensitive to fossil electrons ($E \sim 100$ MeV) → time-integrated activity of AGN feedback!
- LOFAR: halo confined to same region at all frequencies and no low-ν spectral steepening → 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)

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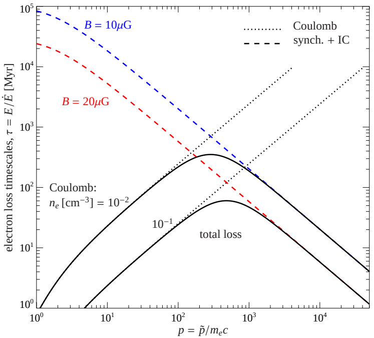
- Coulomb cooling removes fossil electrons
  $\rightarrow$ efficient mixing of CR electrons and protons with dense cluster gas
  $\rightarrow$ predicts γ rays from CRp-p interactions: $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$



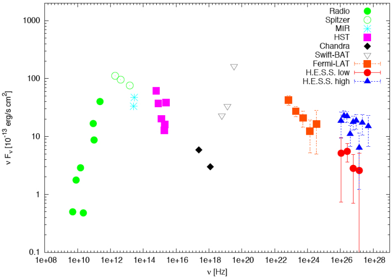
C.P. (2013)

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 (?)



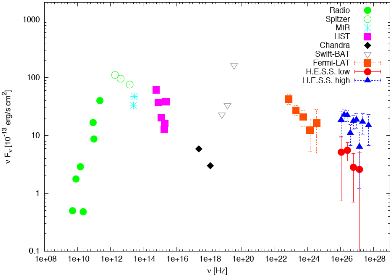
Rieger & Aharonian (2012)

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

Estimating the CR pressure in M87

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

- X-ray data → n and T profiles
- assume $X_{\rm cr} = P_{\rm cr}/P_{\rm th} = \text{const.}$ (self-consistency requirement)
- $F_\gamma \propto \int \mathrm{d}V\, P_{\rm cr}\, n$ enables to estimate $X_{\rm cr} = 0.31$ (allowing for Coulomb cooling with $\tau_{\rm Coul} = 40\,\text{Myr}$)



Rieger & Aharonian (2012)

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

Cosmic-ray heating vs. radiative cooling (1)

CR Alfvén-wave heating:

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

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

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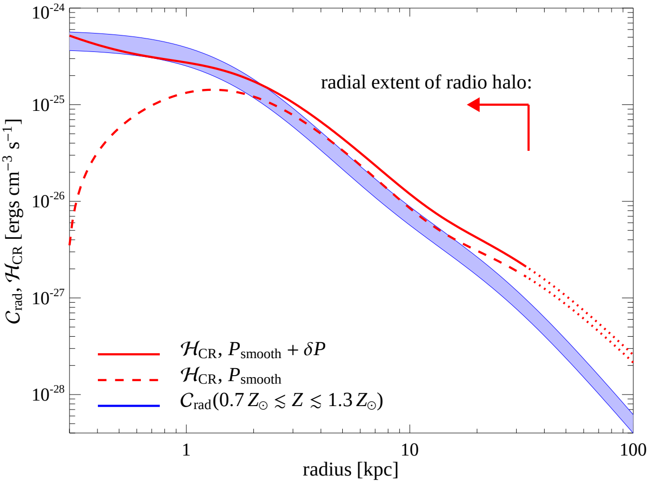
radiative cooling:

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

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

Cosmic-ray heating vs. radiative cooling (2)

Global thermal equilibrium on all scales in M87



C.P. (2013)

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- central temperature profile rises slowly: $T \propto r^{\alpha}$, with $\alpha \lesssim 0.3$
- assume $v_A =$ const. and $P_{\rm cr} \propto P_{\rm th}$ (required for self-consistency):

$$\begin{aligned} \mathcal{H}_{\rm cr} &\propto \frac{\partial}{\partial r} P_{\rm th} \propto \frac{\partial}{\partial r} r^{\alpha-1} \propto r^{\alpha-2} \\ \mathcal{C}_{\rm rad} &\propto n^2 \propto r^{-2} \end{aligned}$$

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(1) identical radial profiles expected for $T \simeq \text{const.}$ ($\alpha \simeq 0$)

(2) for a smoothly rising temperature profile, heating is slightly favored over cooling at larger radii → onset of cooling is smoothly modulated from the outside in

Cosmic-ray heating vs. radiative cooling

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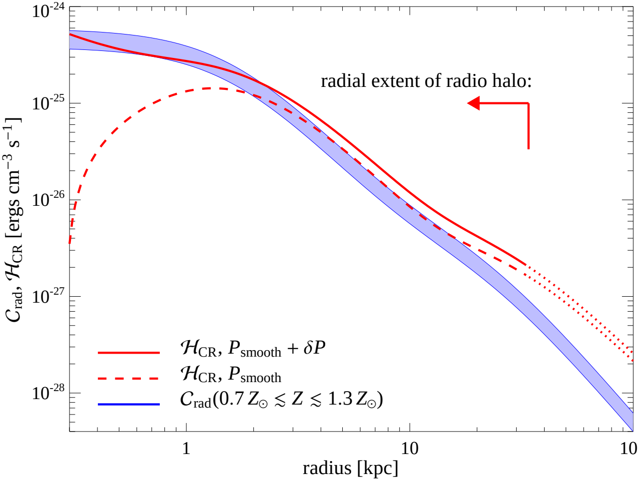

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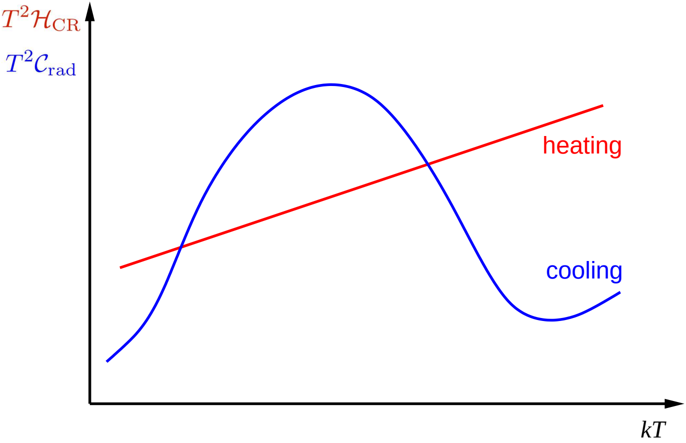
Local stability analysis (1)



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

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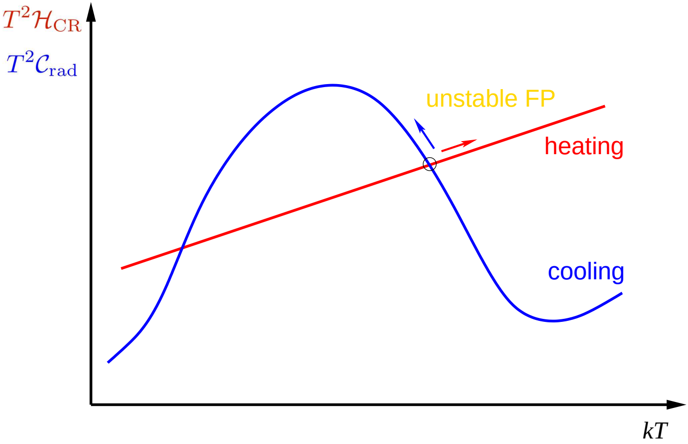

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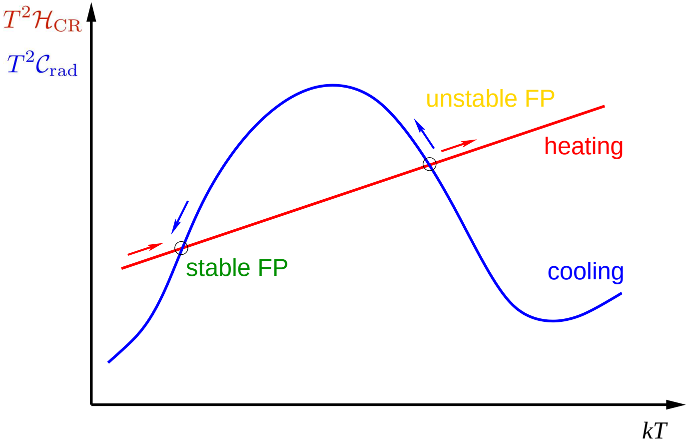

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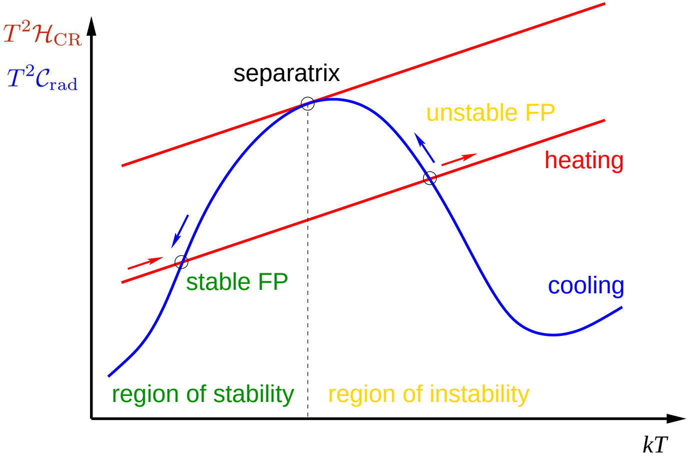

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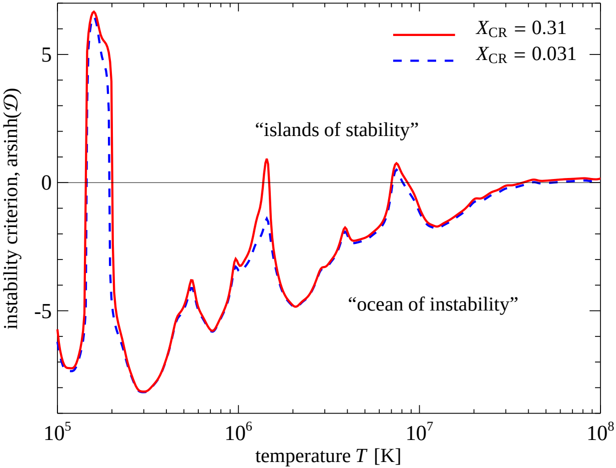
Local stability analysis (2)

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



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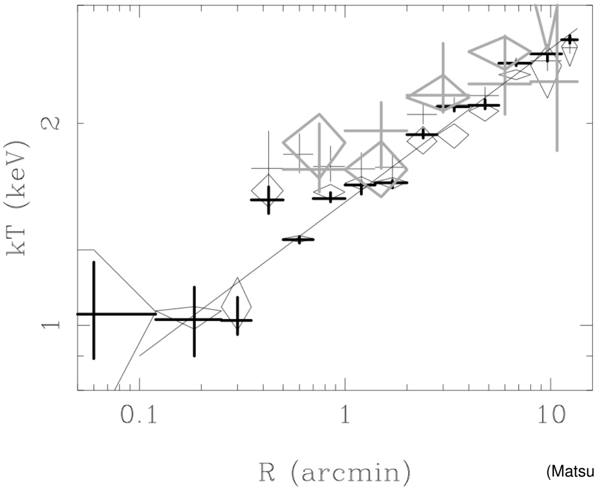
Virgo cluster cooling flow: temperature profile

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



(Matsushita+ 2002)

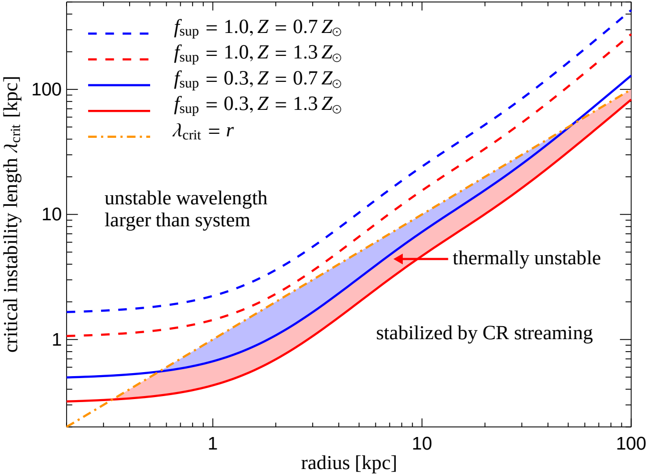
Critical length scale of the instability ($\sim$ Fields length)

- CR streaming transfers energy to a given gas parcel
- line and bremsstrahlung emission radiate energy from the parcel
- limiting size of unstable gas parcel since CR Alfvén-wave heating smoothes out temperature inhomogeneities on small scales:

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

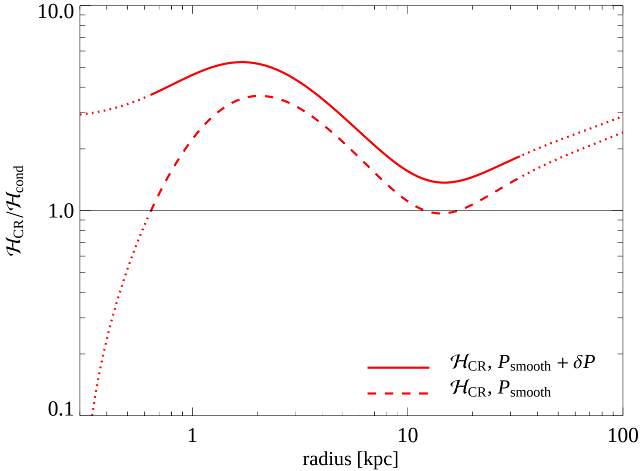
- however: unstable wavelength needs to be supported by the system → constraint on magnetic suppression factor f_s

Critical length scale of the instability (∼ Fields length)



C.P. (2013)

CR heating dominates over thermal conduction



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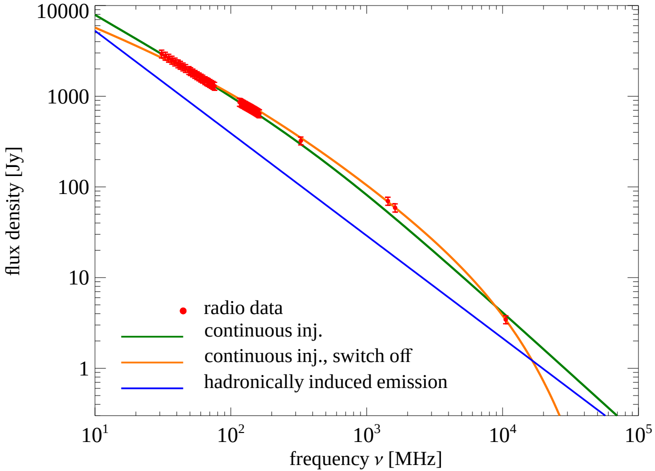
Prediction: flattening of high-ν radio spectrum



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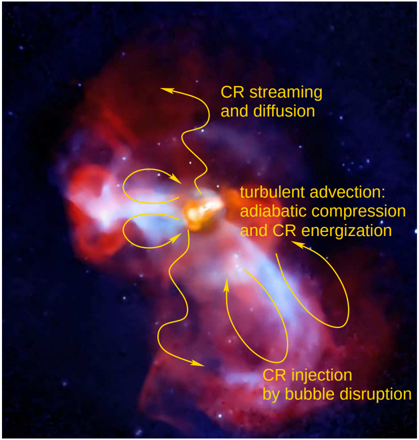
Emerging picture of CR feedback by AGNs

(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: $P_{\mathrm{cr}}/P_{\mathrm{cr},0} = \delta^{4/3} \sim 20$ for compression factor $\delta = 10$

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



Conclusions on AGN feedback by cosmic-ray heating

- LOFAR puzzle of “missing fossil electrons” 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 radio halo ($r < 35$ kpc)
- local thermal stability analysis predicts observed temperature floor at $kT \simeq 1$ keV

outlook: simulate steaming CRs coupled to MHD, cosmological cluster simulations, improve γ-ray and radio observations . . .

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.

Self-consistent CR pressure in steady state

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

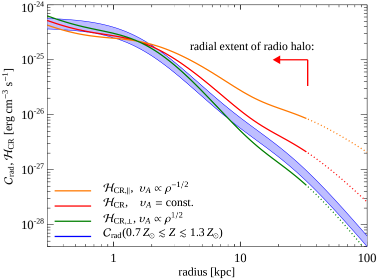
  $$\Delta\varepsilon_{\mathrm{th}} = -\tau_A \boldsymbol{v}_A \cdot \nabla P_{\mathrm{cr}} \approx P_{\mathrm{cr}} = X_{\mathrm{cr}} P_{\mathrm{th}},$$

  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_{cr} is a necessary condition if CR streaming is the dominant heating process

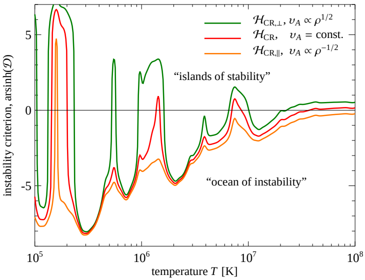
→ **thermal pressure profile adjusts to that of the streaming CRs!**

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 $v_A = \mathrm{const.}$
- $\alpha_B = 0$ for collapse along ***B***, implying $v_{A,\parallel} \propto \rho^{-1/2}$
- $\alpha_B = 1$ for collapse perpendicular to ***B***, implying $v_{A,\perp} \propto \rho^{1/2}$