Radio mode theory: mechanical versus cosmic-ray heating

Christoph Pfrommer

Heidelberg Institute for Theoretical Studies, Germany

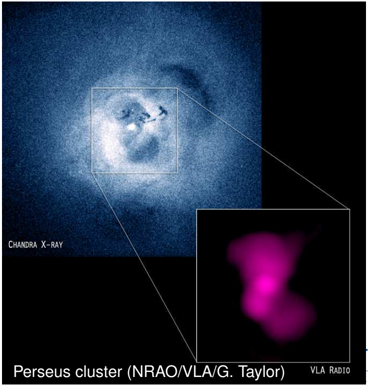
Jul 15, 2014 / *Quenching and Quiescence,* MPIA

Outline

1. Radio mode theory
   - The big picture
   - MHD interactions
   - Open questions
2. Cosmic ray feedback
   - Cosmic ray physics
   - Observations of M87
   - Alfvén-wave heating

Radio mode feedback by AGN

Paradigm: super-massive black holes with $M \sim (10^9 \dots 10^{10})\mathrm{M}_\odot$ co-evolve with their hosting cD galaxies at the centers of galaxy clusters. They launch relativistic jets that blow bubbles, potentially providing energetic feedback to balance cooling. Key points:

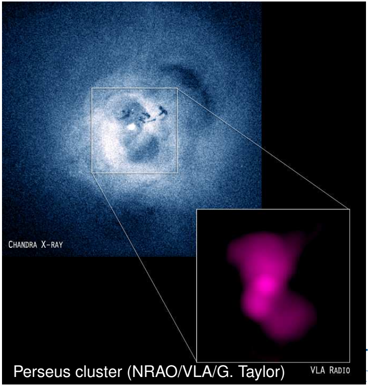


Perseus cluster (NRAO/VLA/G. Taylor)

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, potentially providing energetic feedback to balance cooling. Key points:

- energy source: release of non-gravitational energy due to accretion on a black hole and its spin
- jet-ICM interaction and rising of the bubbles: magnetic draping, cosmic ray confinement, entrainment of ICM plasma, duty cycle
- heating mechanism:
  1.) self-regulated to avoid overcooling
  2.) thermally stable to explain T floor
  3.) low energy coupling efficiency



Perseus cluster (NRAO/VLA/G. Taylor)

AGN feedback – energetics

- gravitational binding energy: $E_{\mathrm{grav}} = M\sigma^2$,
  $M - \sigma$ relation: $M_{\mathrm{BH}} \sim M/500$
- available BH energy to be extracted is $E \sim 0.1 M_{\mathrm{BH}} c^2$

AGN feedback – energetics

- gravitational binding energy: $E_{\text{grav}} = M\sigma^2$,
  $M - \sigma$ relation: $M_{\text{BH}} \sim M/500$
- available BH energy to be extracted is $E \sim 0.1\, M_{\text{BH}} c^2$
- it follows

$$\frac{E}{E_{\text{grav}}} = 0.1\,\frac{M_{\text{BH}}}{M}\left(\frac{c}{\sigma}\right)^2 \sim 200\left(\frac{300\ \text{km/s}}{\sigma}\right)^2$$

→ there is more than enough energy available for AGN feedback!

AGN feedback – thermodynamics

- relativistic jets displace the ICM at the location of the cavities, i.e. they do *pdV* work against the ICM, as well as supply internal energy to the cavities
- total energy required to create the cavity equals its enthalpy

$$H = U + PV = \frac{1}{\gamma_b - 1} PV + PV = \frac{\gamma_b}{\gamma_b - 1} PV = 4PV, \text{ with } \gamma_b = 4/3$$

AGN feedback – thermodynamics

- relativistic jets displace the ICM at the location of the cavities, i.e. they do *pdV* work against the ICM, as well as supply internal energy to the cavities
- total energy required to create the cavity equals its enthalpy

$$H = U + PV = \frac{1}{\gamma_b - 1} PV + PV = \frac{\gamma_b}{\gamma_b - 1} PV = 4PV, \text{ with } \gamma_b = 4/3$$

- only $1PV$ is directly available for mechanical work on the surroundings ($3PV$ is stored as internal energy); work done by 2 bubbles in one outburst

$$W = PV = 2\,\frac{4}{3}\pi r_b^3\, n_\mathrm{ICM} kT \sim 10^{59}\,\mathrm{erg}$$

with $r_b \sim 20\,\mathrm{kpc}$, $n_\mathrm{ICM} \sim 10^{-2}\,\mathrm{cm}^{-3}$, $kT \sim 3\,\mathrm{keV}$

AGN feedback – luminosity

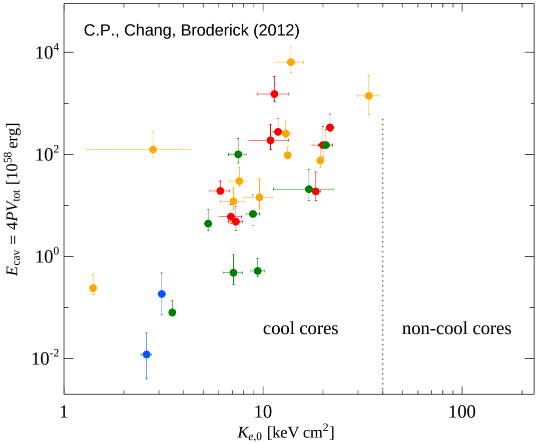
- energy release time scale is of order the sound crossing time ∼ buoyant rise time ∼ refill time of displaced bubble volume $\sim 3 \times 10^7$ yr
- AGN heating rate

$$L_{\text{AGN}} \sim \frac{PV}{t_{\text{buoy}}} \sim \frac{10^{59}\,\text{erg}}{10^{15}\,\text{s}} \sim 10^{44}\,\frac{\text{erg}}{\text{s}} \sim L_X$$

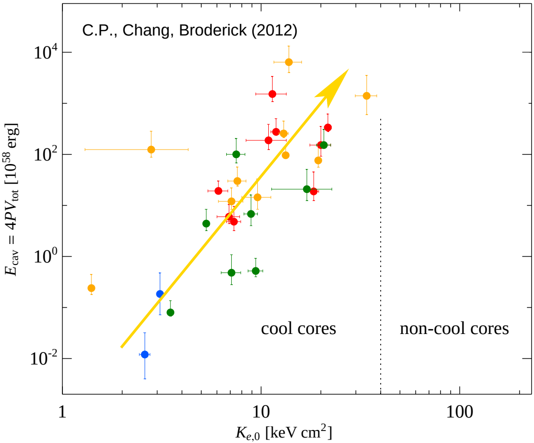
i.e. comparable to the X-ray luminosity

→ necessary condition for balancing X-ray cooling losses and increasing the core entropy $K_e = kT/n_e^{2/3}$ of the ambient ICM!

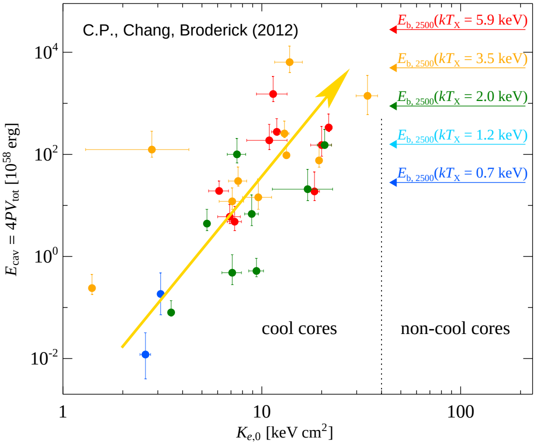
How efficient is heating by AGN feedback?



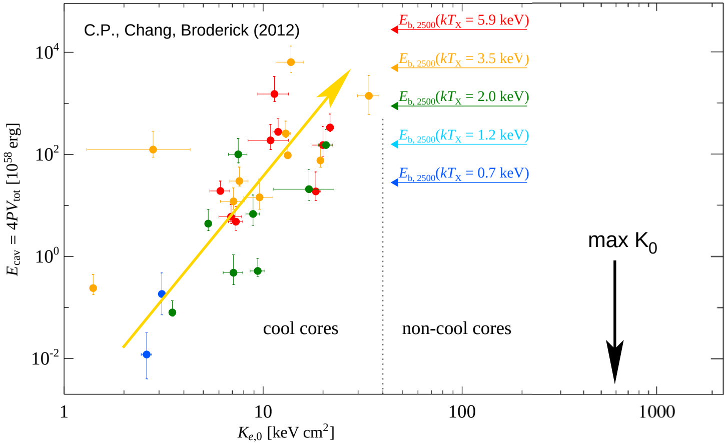
How efficient is heating by AGN feedback?



How efficient is heating by AGN feedback?

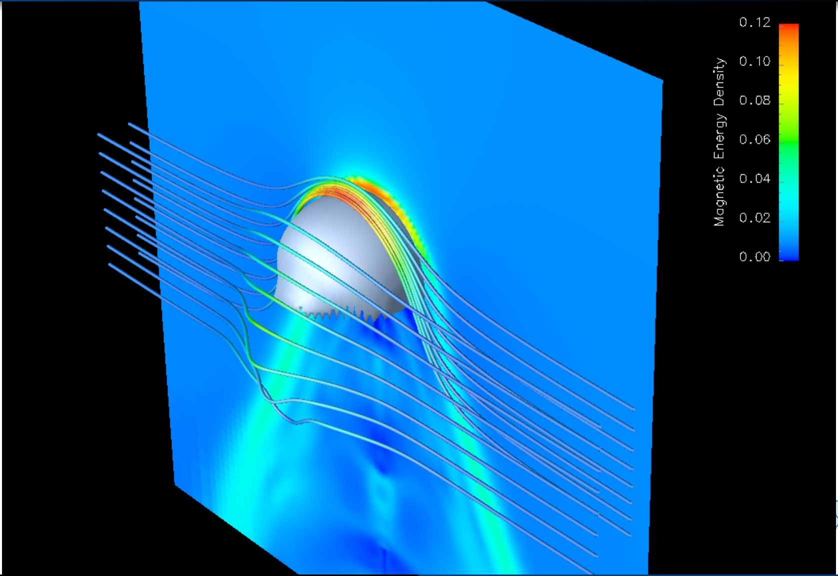


How efficient is heating by AGN feedback?



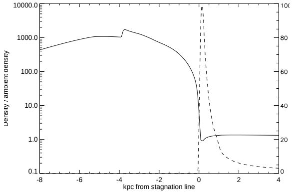
AGNs cannot transform CC to NCC clusters (on a buoyancy timescale)

Magnetic draping around rising bubbles



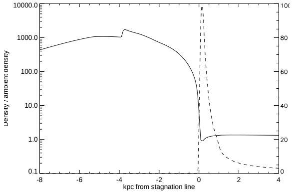
What is magnetic draping?

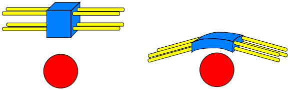
- is magnetic draping (MD) similar to ram pressure compression?
  → no density enhancement for MD
    - analytical solution of MD for incompressible flow
    - ideal MHD simulations *(right)*



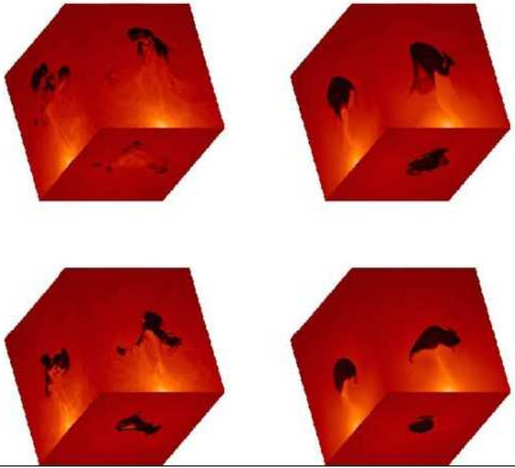
What is magnetic draping?

- is magnetic draping (MD) similar to ram pressure compression?
  → no density enhancement for MD
  - analytical solution of MD for incompressible flow
  - ideal MHD simulations *(right)*
- is magnetic flux still frozen into the plasma?
  yes, but plasma is pulled into the direction of the field lines while field lines get stuck at the obstacle



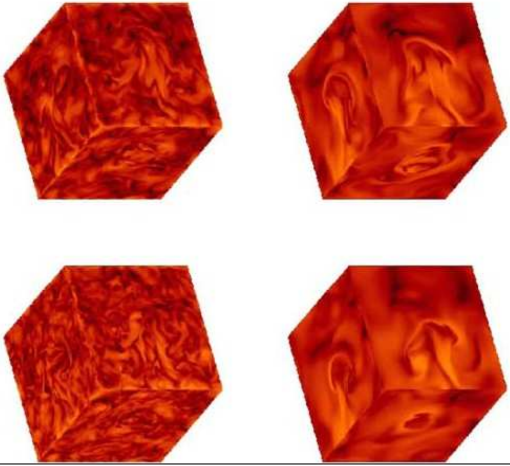


Magnetic draping at bubbles: density



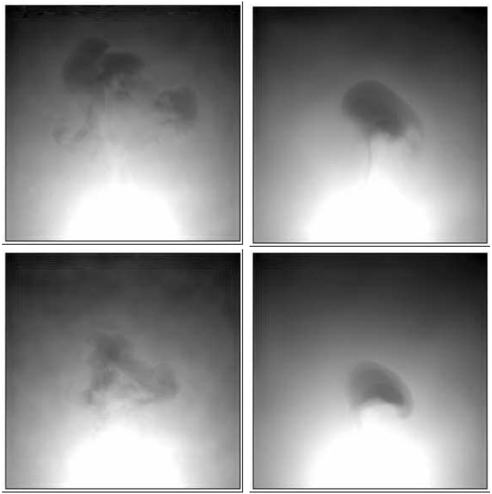
log ρ, non-draping versus draping case (Ruszkowski et al. 2007)

Magnetic draping at bubbles: magnetic pressure



log B^2, non-draping versus draping case (Ruszkowski et al. 2007)

Magnetic draping at bubbles: X-ray emission



S_X, non-draping versus draping case (Ruszkowski et al. 2007)

Conditions for magnetic draping

- ambient plasma sufficiently ionized such that flux freezing condition applies
- super-Alfvénic motion of a cloud through a weakly magnetized plasma: $\mathcal{M}_A^2 = \beta\gamma\mathcal{M}^2/2 > 1$
- magnetic coherence across the "cylinder of influence":

$$\frac{\lambda_B}{R} \gtrsim \frac{1}{\mathcal{M}_A} \sim 0.1 \times \left(\frac{\beta}{100}\right)^{-1/2} \quad \text{for sonic motions,}$$

R denotes the curvature radius of the working surface at the stagnation line

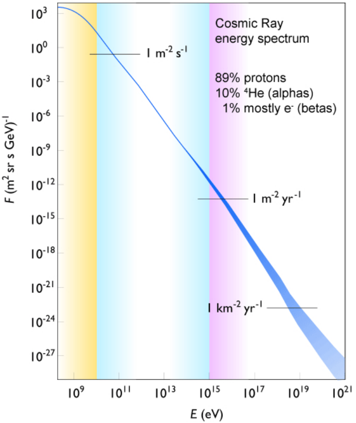
C.P. & Dursi (2010), Dursi & C.P. (2008)

Open questions on radio mode AGN feedback

- how is accretion output thermalized?
  - dissipation of waves, turbulence, releasing potential energy, thermal conduction, cosmic-ray heating
- is heating/cooling balance thermally stable?
  - no: turbulence dissipation, conduction
  - yes: cosmic-ray heating
- how is the accretion rate tuned?
  - cooling radius (30 kpc) $\sim 10^8$ Schwarzschild radius
  - Schwarzschild radius

$$r_{\mathrm{SMBH}} = \frac{2GM_{\mathrm{SMBH}}}{c^2} \simeq 10^{15} \left(\frac{M_{\mathrm{SMBH}}}{5 \times 10^9 \,\mathrm{M}_\odot} \right) \mathrm{cm}$$

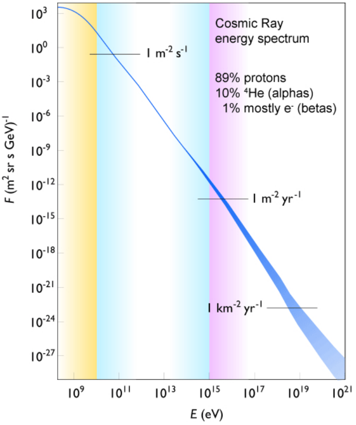
Galactic cosmic ray spectrum



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)

Galactic cosmic ray spectrum



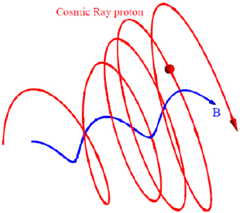
data compiled by Swordy

- 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)
- pressure of cosmic rays, 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?

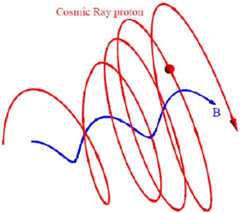
Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\text{cr}} > v_{\text{waves}}$ 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



Interactions of CRs and magnetic fields

- CRs scatter on magnetic fields → isotropization of CR momenta
- **CR streaming instability:** Kulsrud & Pearce 1969
  - if $v_{\mathrm{cr}} > v_{\mathrm{waves}}$ 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



→ **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 $\boldsymbol{v}_{\mathrm{cr}} = \boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} + \boldsymbol{v}_{\mathrm{di}}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_{\mathrm{gas}}$)
- 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 $\boldsymbol{B}$):

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

CR transport

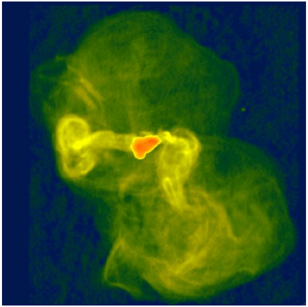
- total CR velocity $\boldsymbol{v}_\mathrm{cr} = \boldsymbol{v} + \boldsymbol{v}_\mathrm{st} + \boldsymbol{v}_\mathrm{di}$ (where $\boldsymbol{v} \equiv \boldsymbol{v}_\mathrm{gas}$)
- CRs stream down their own pressure gradient relative to the gas, CRs diffuse in the wave frame due to pitch angle scattering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

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

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

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

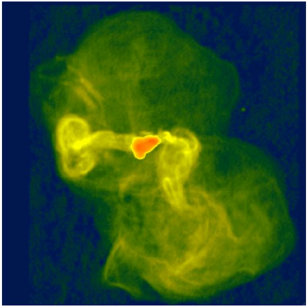
Messier 87 at radio wavelengths



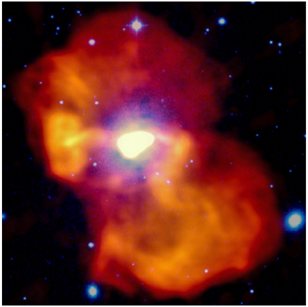
$\nu = 1.4$ GHz (Owen+ 2000)

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

Messier 87 at radio wavelengths



$\nu = 1.4$ 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

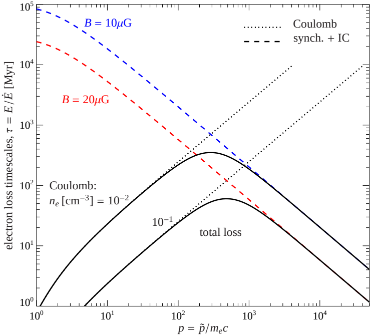
solutions:

- 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)

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:
  $p + p \rightarrow \pi^0 + \ldots \rightarrow 2\gamma + \ldots$



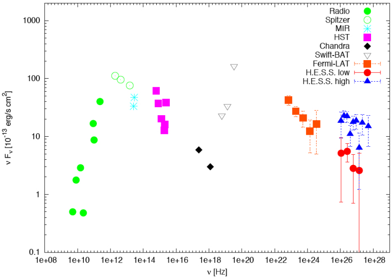
C.P. (2013)

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 (?)

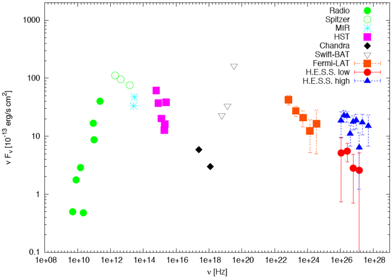


Rieger & Aharonian (2012)

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

Estimating the CR pressure in M87

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



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 $\mathcal{M} \simeq 1.1$)

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 $\mathcal{M} \simeq 1.1$)

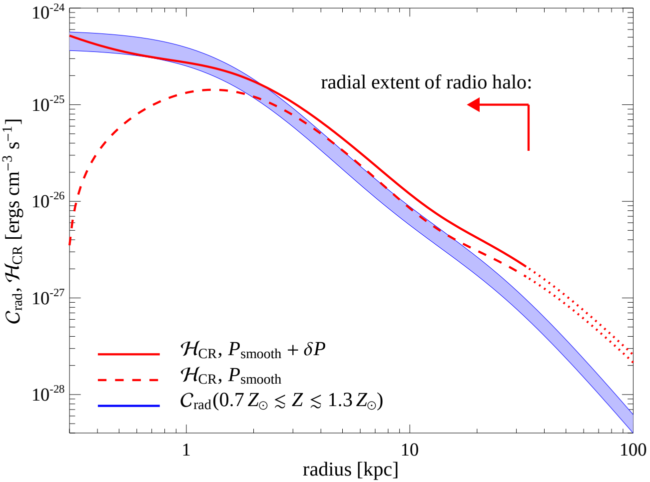
radiative cooling:

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

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

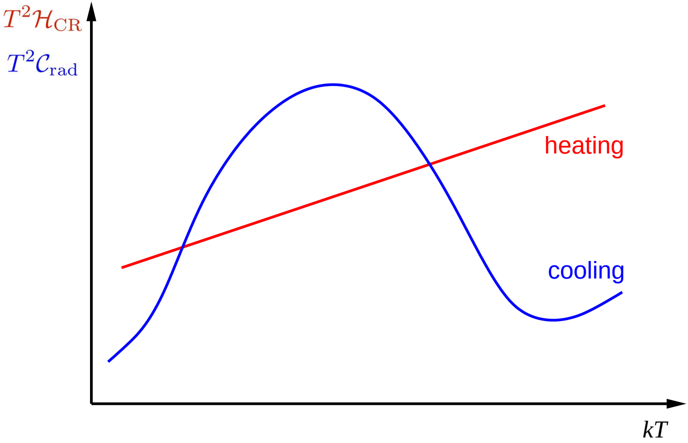
Cosmic-ray heating vs. radiative cooling (2)

Global thermal equilibrium on all scales in M87



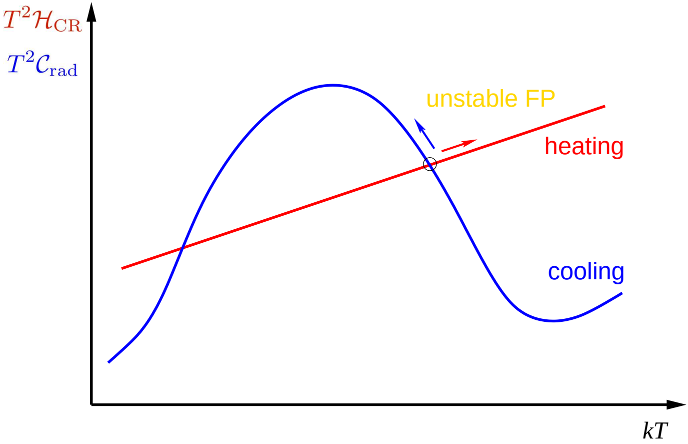
C.P. (2013)

Local stability analysis (1)



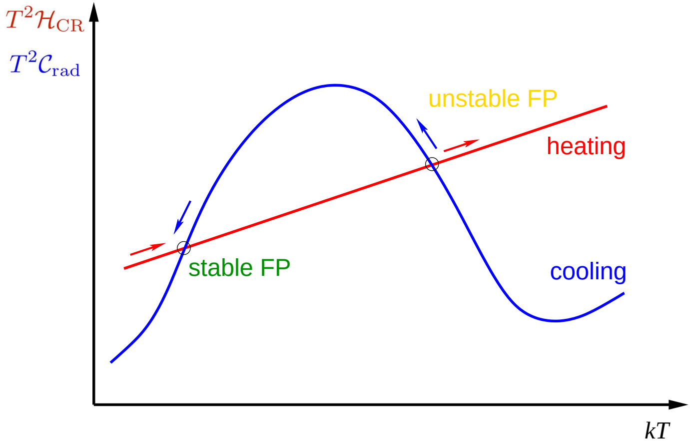
- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

Local stability analysis (1)



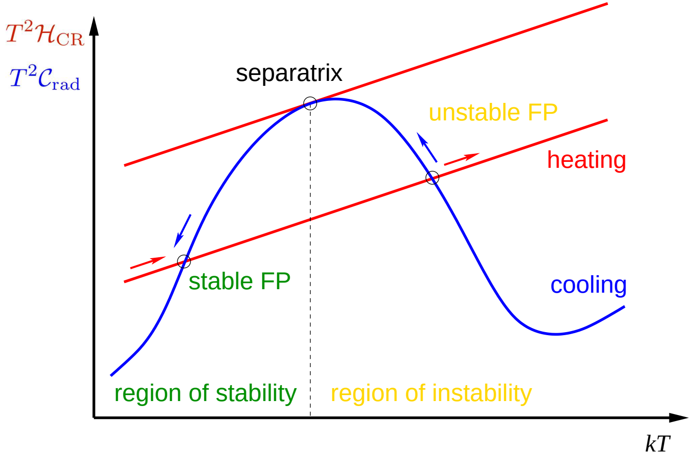
- isobaric perturbations to global thermal equilibrium
- CRs are adiabatically trapped by perturbations

Local stability analysis (1)



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

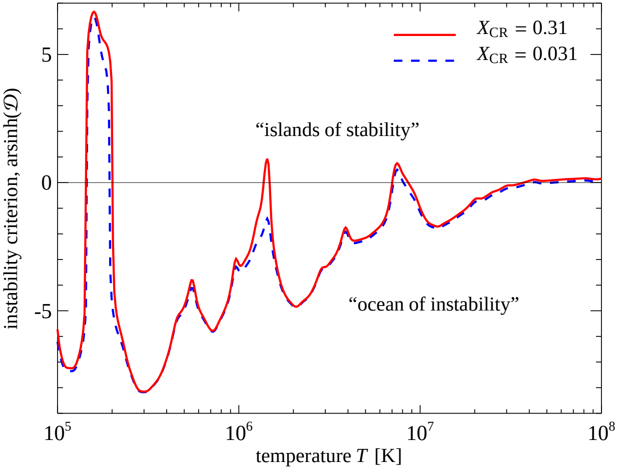
Local stability analysis (1)



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

Local stability analysis (2)

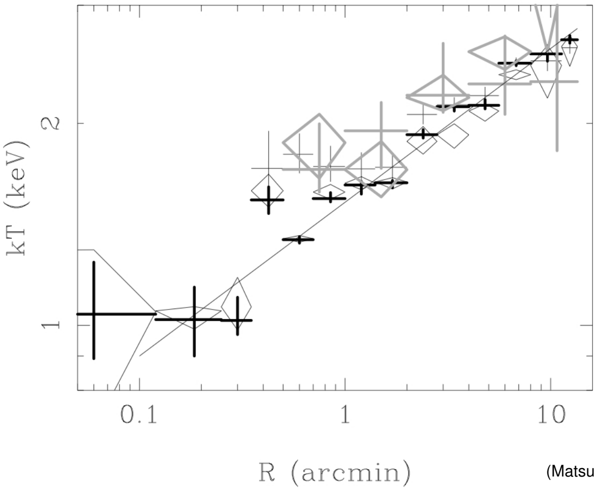
Theory predicts observed temperature floor at $kT \simeq 1$ keV



C.P. (2013)

Virgo cluster cooling flow: temperature profile

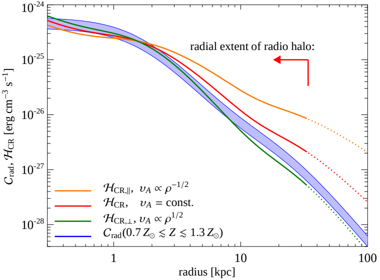
X-ray observations confirm temperature floor at $kT \simeq 1$ keV



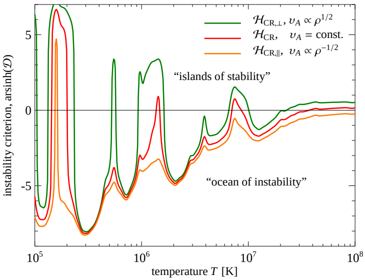
(Matsushita+ 2002)

Impact of varying Alfvén speed on CR heating

global thermal equilibrium:



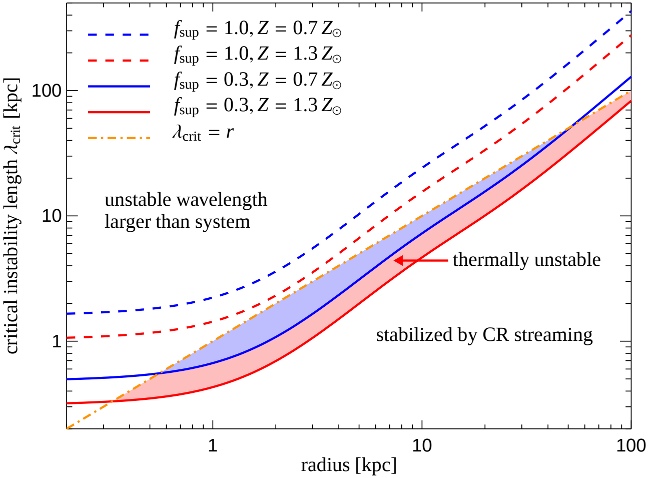
local stability criterion:



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

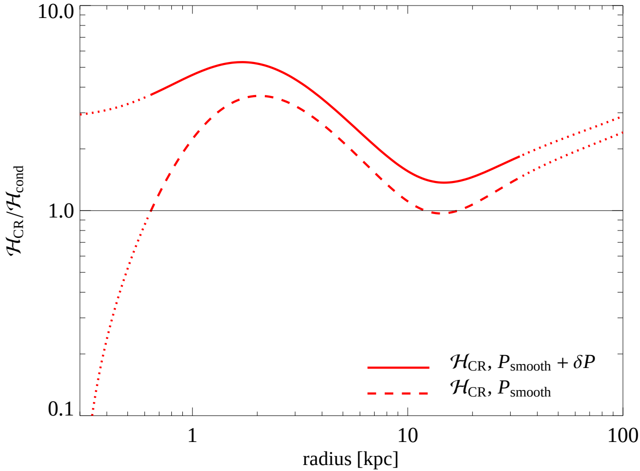
- $\alpha_B = 0.5$ is the geometric mean, implying $v_A = \text{const.}$
- $\alpha_B = 0$ for collapse along $\boldsymbol{B}$, implying $v_{A,\parallel} \propto \rho^{-1/2}$
- $\alpha_B = 1$ for collapse perpendicular to $\boldsymbol{B}$, implying $v_{A,\perp} \propto \rho^{1/2}$

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



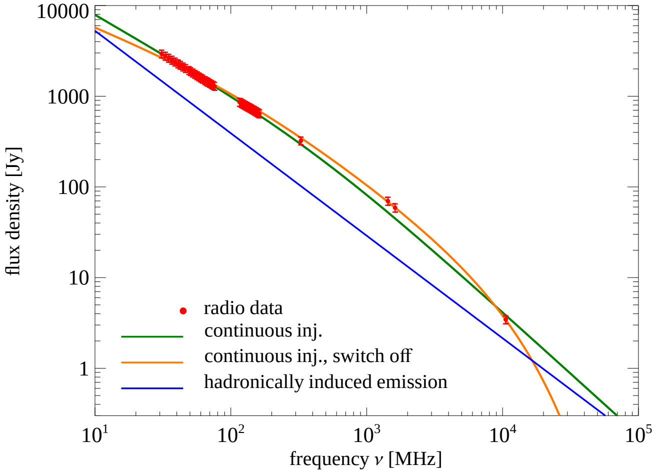
C.P. (2013)

CR heating dominates over thermal conduction



C.P. (2013)

Prediction: flattening of high-ν radio spectrum



C.P. (2013)

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 …

cf. Loewenstein et al. (1991), Guo & Oh (2008), Enßlin et al. (2011)

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.