Cosmic rays in clusters of galaxies

Exploring a different window to clusters

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Outline

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1. Introduction and motivation
   - Cosmic rays in galaxies and clusters
   - Cosmological implications
   - Hadronic cosmic ray proton interaction
2. Cosmic rays in nearby clusters of galaxies
   - γ-ray emission
   - Cluster radio halos
   - Minimum energy condition

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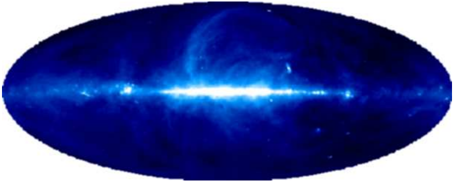
Galactic cosmic rays

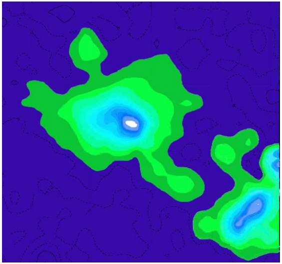
Galactic cosmic rays are dynamically important:

- the pressure contained in cosmic ray protons and magnetic fields each contributes at least as much pressure as the thermal gas
- escape time of cosmic rays from the galactic disc $\sim 10^7$ years (radioactive clocks)
- energy losses:
  CRe: synchrotron, inverse Compton, Coulomb
  CRp: inelastic collisions, Coulomb



Cosmic rays in clusters of galaxies

- predictions for the CR pressure span between 10% and 50% of the cluster's pressure budget
- escape of cosmic ray protons only possible for energies $E_{\mathrm{CRp}} > 2 \times 10^{16}$ eV
- energy losses (for particles with $E \sim 10$ GeV):
  CRe: synchrotron, inverse Compton: $\tau \sim 10^{8}$ yr
  CRp: inelastic collisions, Coulomb losses: $\tau \sim 10^{10}$ yr $\sim$ Hubble time



Coma cluster: radio halo,
$\nu = 1.4$ GHz, $2.5^{\circ} \times 2.0^{\circ}$
(Credit: Deiss/Effelsberg)

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Cosmological implications

- cosmic ray related observables: complementary information of the clusters dynamical state
- cosmic rays provide an additional pressure component:
  $\longrightarrow$ modifications of the hydrostatic mass estimates
- the equation of state of cosmic rays is 'softer' than the thermal component ($\gamma_{\mathrm{CRp}} \sim \frac{4}{3}$):
  $\longrightarrow$ effects on the baryonic halo profile
  $\longrightarrow$ modification of the ICM evolution (entropy distribution)
- the cosmic ray energy reservoir is cooling differently than the thermal:
  $\longrightarrow$ influence on energetic feedback and star formation

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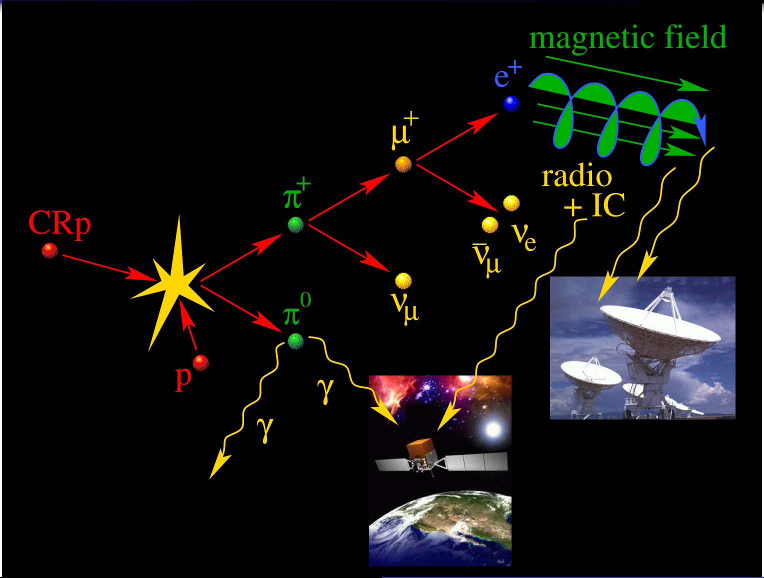
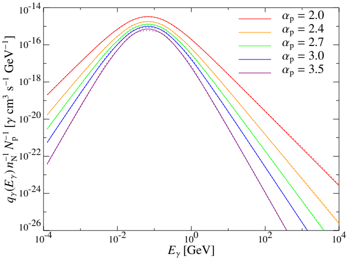
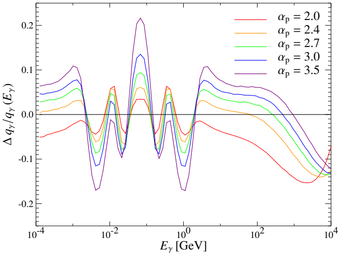
Hadronic cosmic ray proton interaction



Gamma-ray source function





- CRp population: $f_{\rm CRp} \propto p^{-\alpha}$
- π^0-decay induced γ-ray source function q_γ:

$$q_\gamma \propto \left[\left(\frac{2\,E_\gamma}{m_\pi c^2}\right)^{\delta} + \left(\frac{2\,E_\gamma}{m_\pi c^2}\right)^{-\delta}\right]^{-\alpha/\delta}$$

- below: relative deviation of our analytic approach to simulated γ-ray spectra

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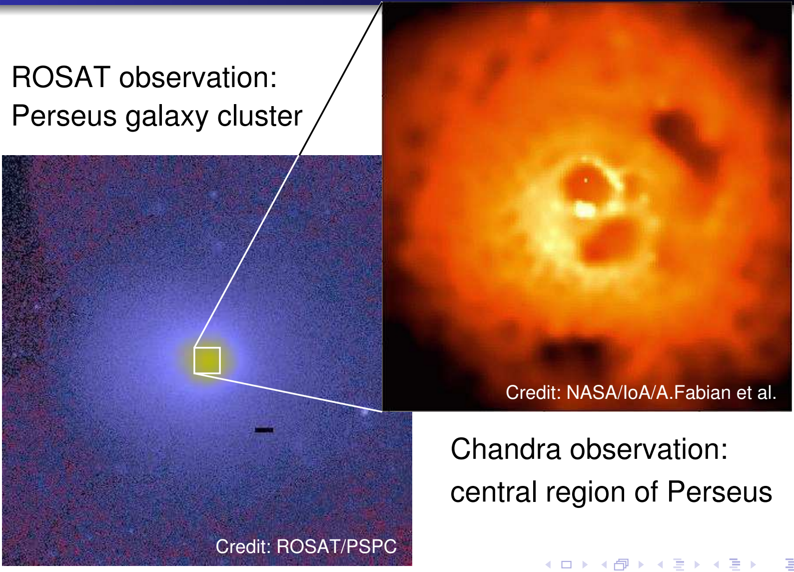
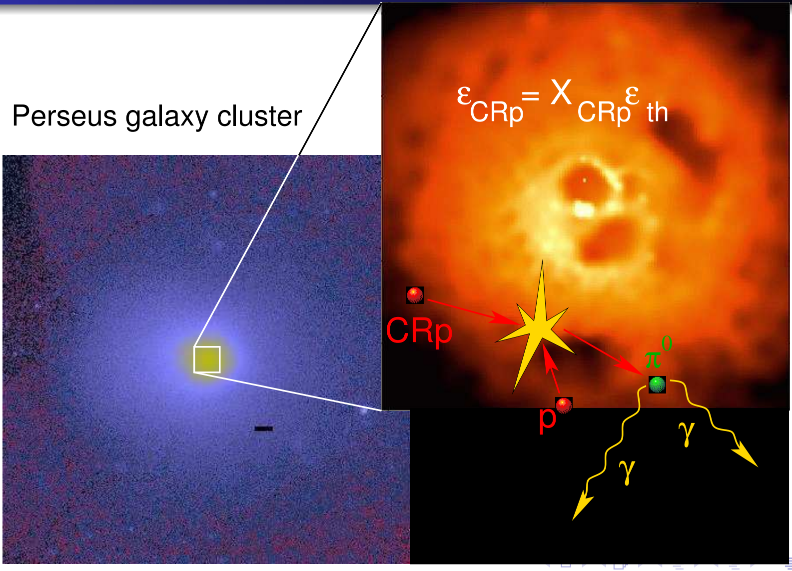
Cooling core clusters are efficient CRp detectors

ROSAT observation:
Perseus galaxy cluster



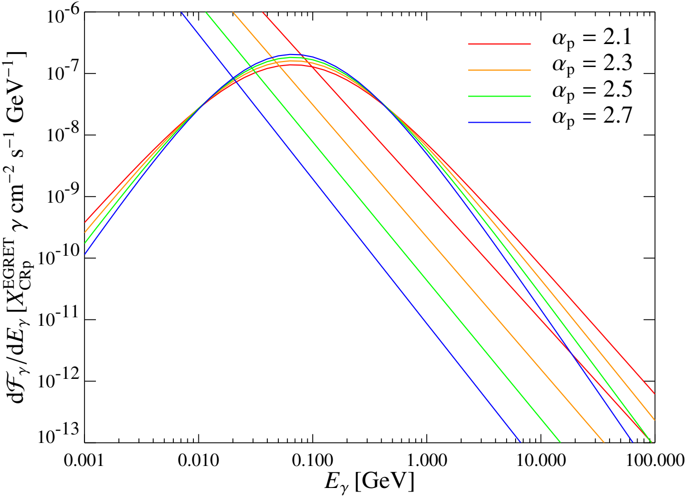
Chandra observation:
central region of Perseus

Cooling core cluster model of CRp detection



Gamma-ray flux of the Perseus galaxy cluster

IC emission of secondary CRes ($B = 0$), π^0-decay induced γ-ray emission:



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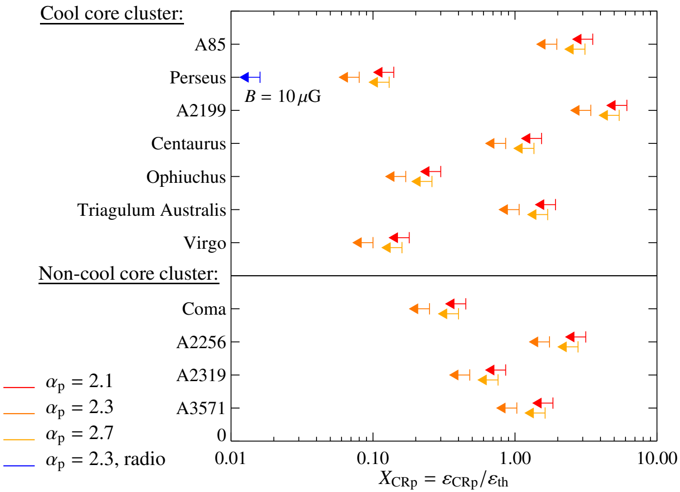
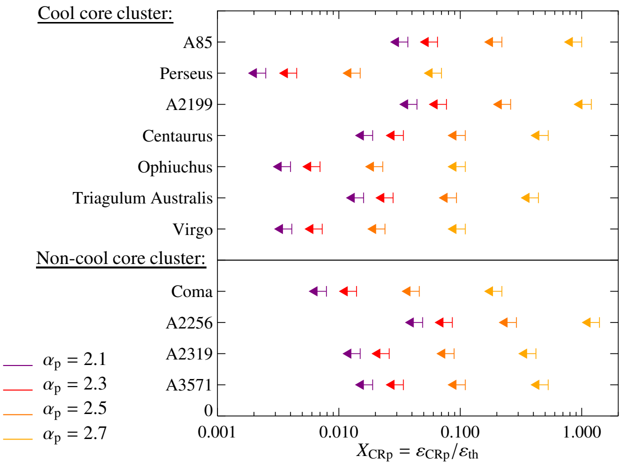
Upper limits on X_{CRp} using EGRET limits



Expected limits on X_{CRp} using Čerenkov telescopes

Sensitivity: $\mathcal{F}_{\gamma,\,\mathrm{exp}}(E > E_{\mathrm{thr}}) = 10^{-12}\,\gamma\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ (E_{\mathrm{thr}}/100\ \mathrm{GeV})^{1-\alpha}$



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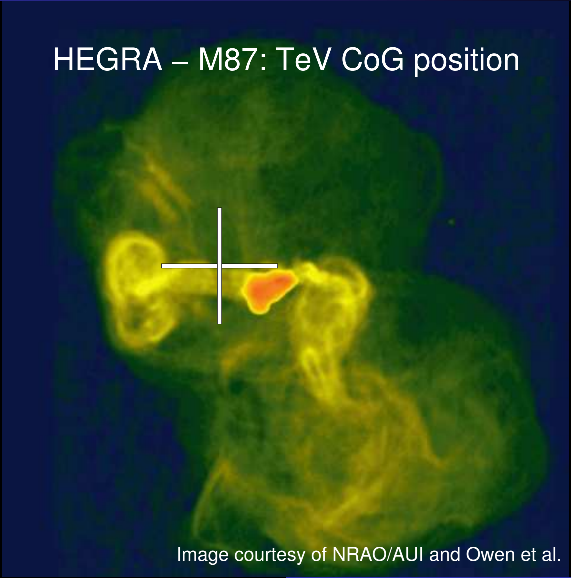
HEGRA detection of γ-rays from M 87

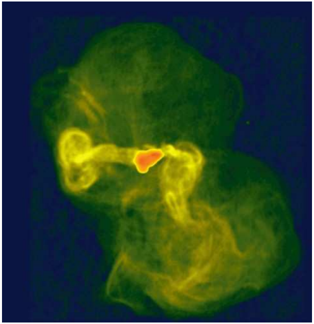


What is the origin of the M 87 γ-ray emission?

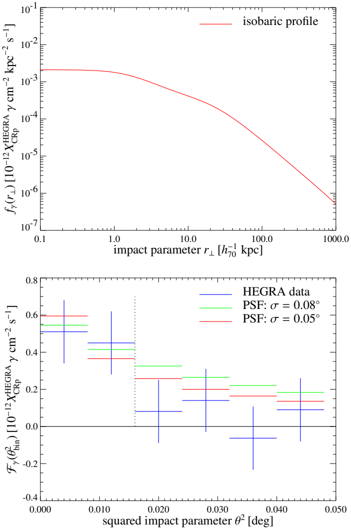
- processed radiation of the relativistic outflow (jet): e.g. IC up-scattering of CMB photons by CRes (jet), SSC scenario (Bai & Lee 2001)
- dark matter annihilation or decay processes (Baltz et al. 2000)
- Hadronically originating γ-rays:

  assuming a CRp power law distribution and a model for the CRp spatial distribution

  $\rightarrow$ measurement of the CRp population of the ICM/ISM of M87! (Pfrommer & Enßlin 2003)



Gamma-ray flux profile of M 87 (Virgo)



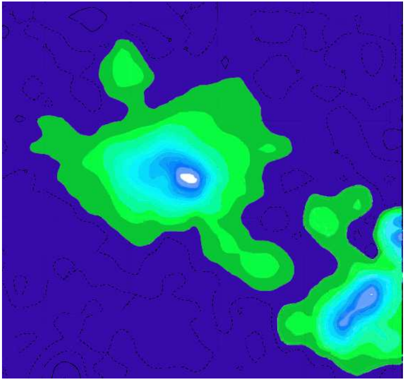
top:

- modeled γ-ray surface flux profile
- normalized to the HEGRA flux ($>$ 730 GeV) within the two innermost data points

bottom:

- comparison of detected to simulated γ-ray flux profiles which are convolved with two different widths of the PSF

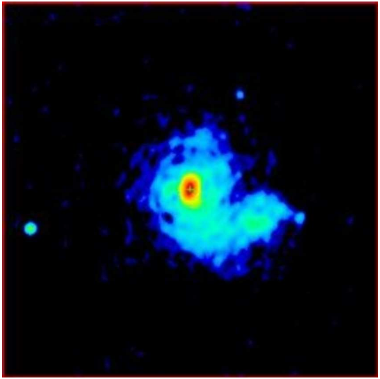
Radio halos: Coma and Perseus



Coma radio halo, $\nu = 1.4$ GHz,

largest emission diameter ~ 3 Mpc

(Credit: Deiss/Effelsberg)



Perseus mini-halo, $\nu = 1.4$ GHz,

largest emission size ~ 0.5 Mpc

(Credit: Pedlar/VLA)

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Models for radio synchrotron halos in clusters

Halo characteristics: smooth unpolarized radio emission at scales of 3 Mpc.
Different CR electron populations:

- Primary accelerated CR electrons: synchrotron/IC cooling times too short to account for extended diffuse emission
- Re-accelerated CR electrons through resonant interaction with turbulent Alfvén waves: possibly too inefficient, no first principle calculations (Jaffe 1977, Schlickeiser 1987, Brunetti 2001)
- Hadronically produced CR electrons in inelastic collisions of CR protons with the ambient gas (Dennison 1980, Vestrad 1982, Miniati 2001, Pfrommer 2004)

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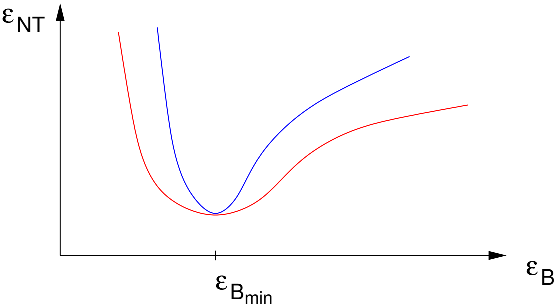
Minimum energy criterion (MEC): the idea

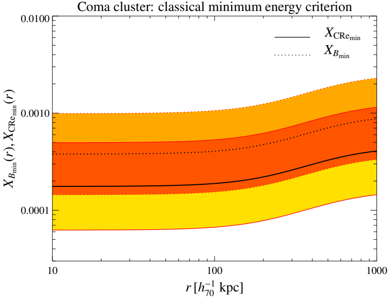
- $\varepsilon_{\mathrm{NT}} = \varepsilon_B + \varepsilon_{\mathrm{CRp}} + \varepsilon_{\mathrm{CRe}}$
  $\rightarrow$ minimum energy criterion: $\left.\frac{\partial \varepsilon_{\mathrm{NT}}}{\partial \varepsilon_B}\right|_{j_\nu} \overset{!}{=} 0$
- classical MEC: $\varepsilon_{\mathrm{CRp}} = k_{\mathrm{p}} \varepsilon_{\mathrm{CRe}}$
- hadronic MEC: $\varepsilon_{\mathrm{CRp}} \propto (\varepsilon_B + \varepsilon_{\mathrm{CMB}})\, \varepsilon_B^{-(\alpha_\nu+1)/2}$

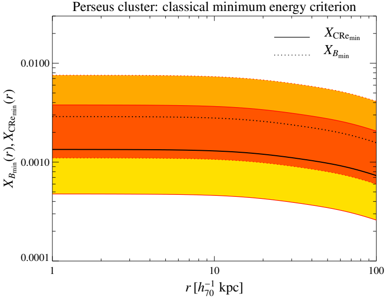


defining tolerance levels: deviation from minimum by one e-fold

Classical minimum energy criterion

$$X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\mathrm{th}}}(r)$$





$$B_{\mathrm{Coma}}(0) = 1.1^{+0.7}_{-0.4}\,\mu\mathrm{G} \qquad B_{\mathrm{Perseus}}(0) = 7.2^{+4.5}_{-2.8}\,\mu\mathrm{G}$$

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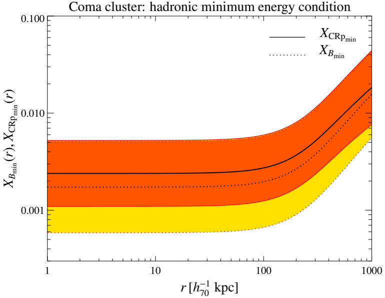
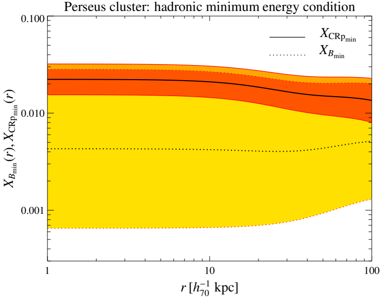
Hadronic minimum energy criterion

$$X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\mathrm{th}}}(r)$$





$$B_{\mathrm{Coma}}(0) = 2.4^{+1.7}_{-1.0}\,\mu\mathrm{G} \qquad B_{\mathrm{Perseus}}(0) = 8.8^{+13.8}_{-5.4}\,\mu\mathrm{G}$$

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Summary

1. Understanding non-thermal processes is crucial for using clusters as cosmological probes (high-z scaling relations).
2. Cosmic rays in nearby clusters of galaxies:
   - limits on CRps from γ-rays (EGRET): $X_{\mathrm{CRp}} = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}} < 20\%$
   - M 87 γ-ray emission is consistent with hadronic scenario
   - radio (mini)-halos seem to be of hadronic origin
3. Outlook: numerical simulations with GADGET
   - huge potential and predictive power of cosmological simulations $\rightarrow$ provides detailed γ-ray emission maps
   - Galaxy evolution: influence on energetic feedback, star formation, and galactic winds

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