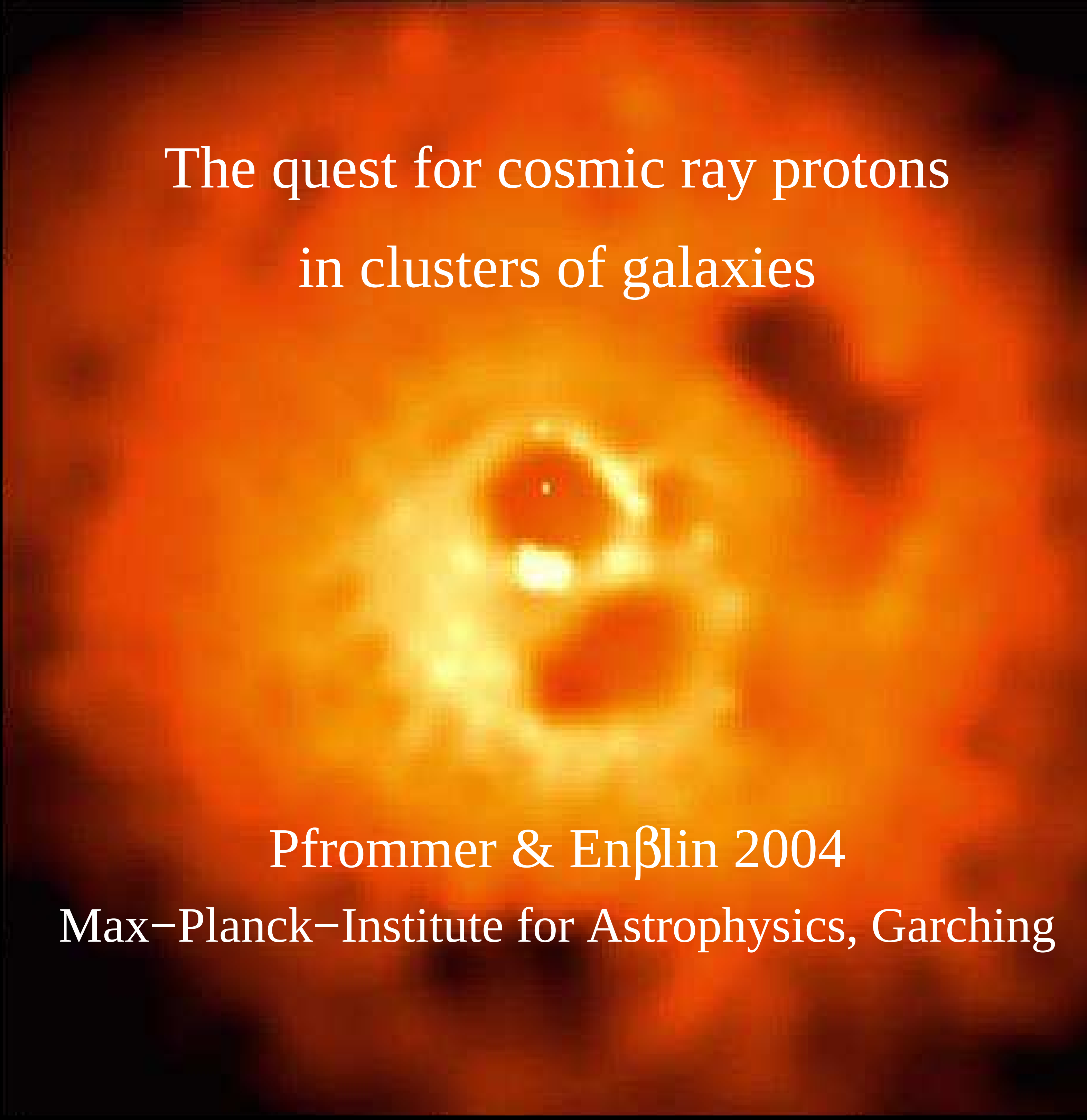
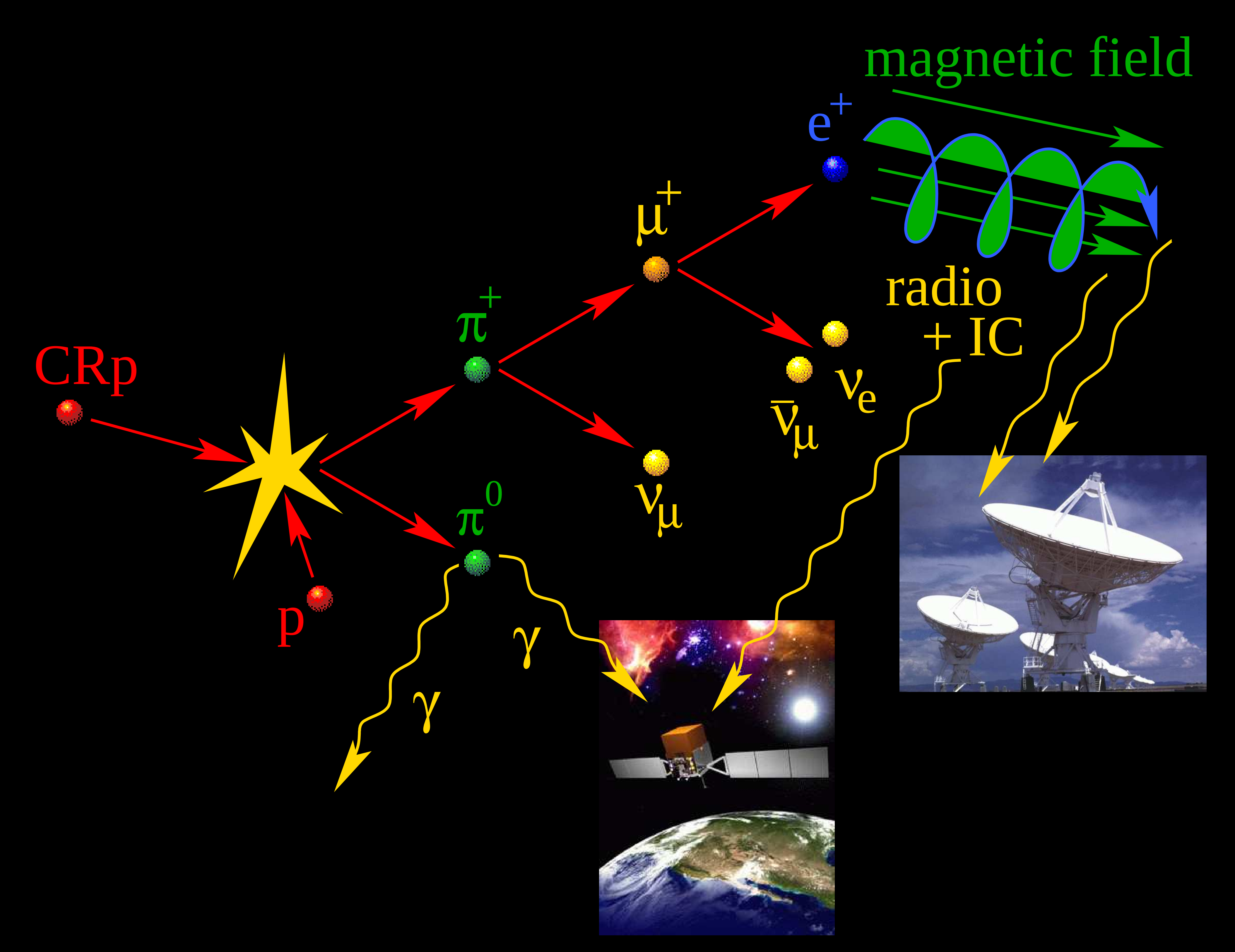


The quest for cosmic ray protons in clusters of galaxies

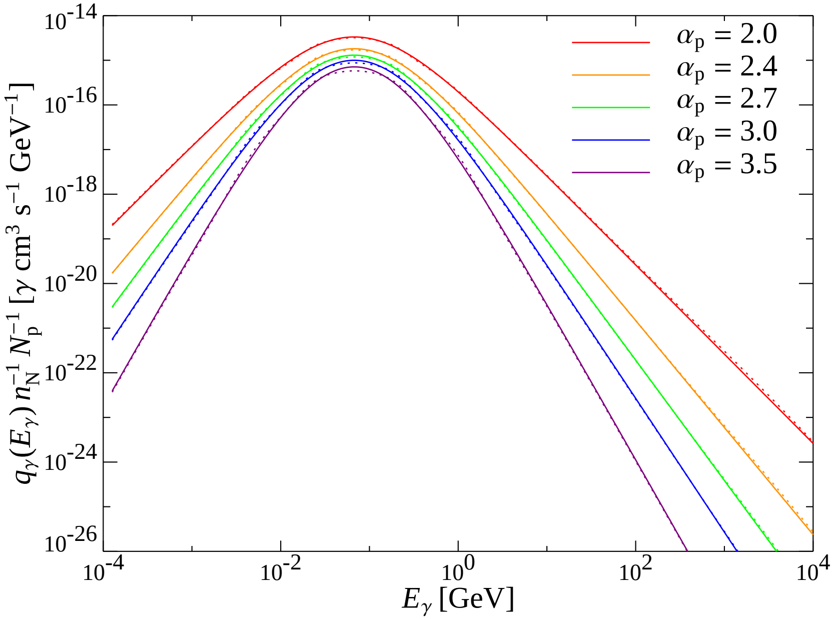
Pfrommer & Enβlin 2004
Max−Planck−Institute for Astrophysics, Garching

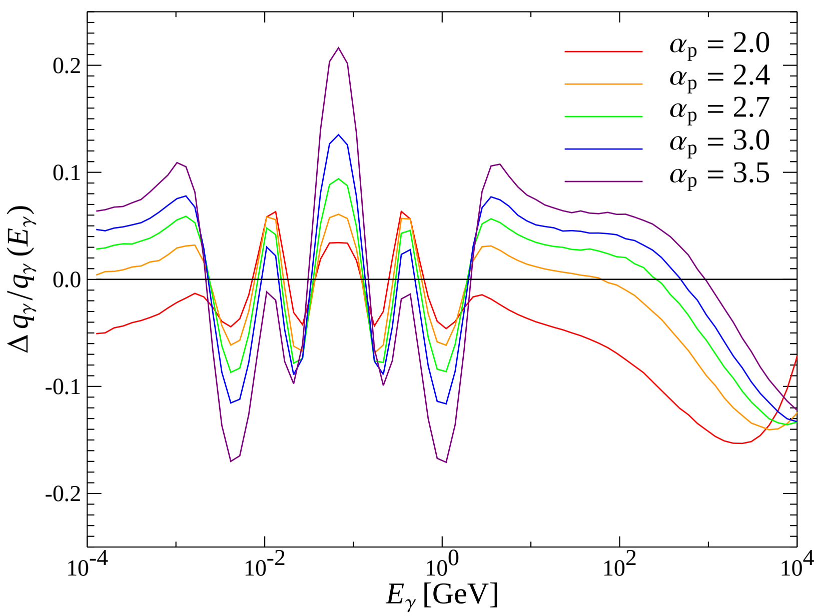


magnetic field
e+
μ+
π+
CRp
radio
+ IC
ν̄μ
νe
νμ
π0
p
γ
γ

Gamma ray source function

Pfrommer & Enßlin 2004:





- CRp population:

$$f_p(\mathbf{r}, p_p) = \frac{\tilde{n}_{CRp}(\mathbf{r})\, c}{\mathrm{GeV}} \left(\frac{p_p\, c}{\mathrm{GeV}}\right)^{-\alpha_p}$$

- Pion decay induced differential gamma−ray source function:

$$q_\gamma(\mathbf{r}, E_\gamma) \simeq \sigma_{pp}\, c\, n_N(\mathbf{r})\, 2^{2-\alpha_\gamma} \frac{\tilde{n}_{CRp}(\mathbf{r})}{\mathrm{GeV}} \times$$

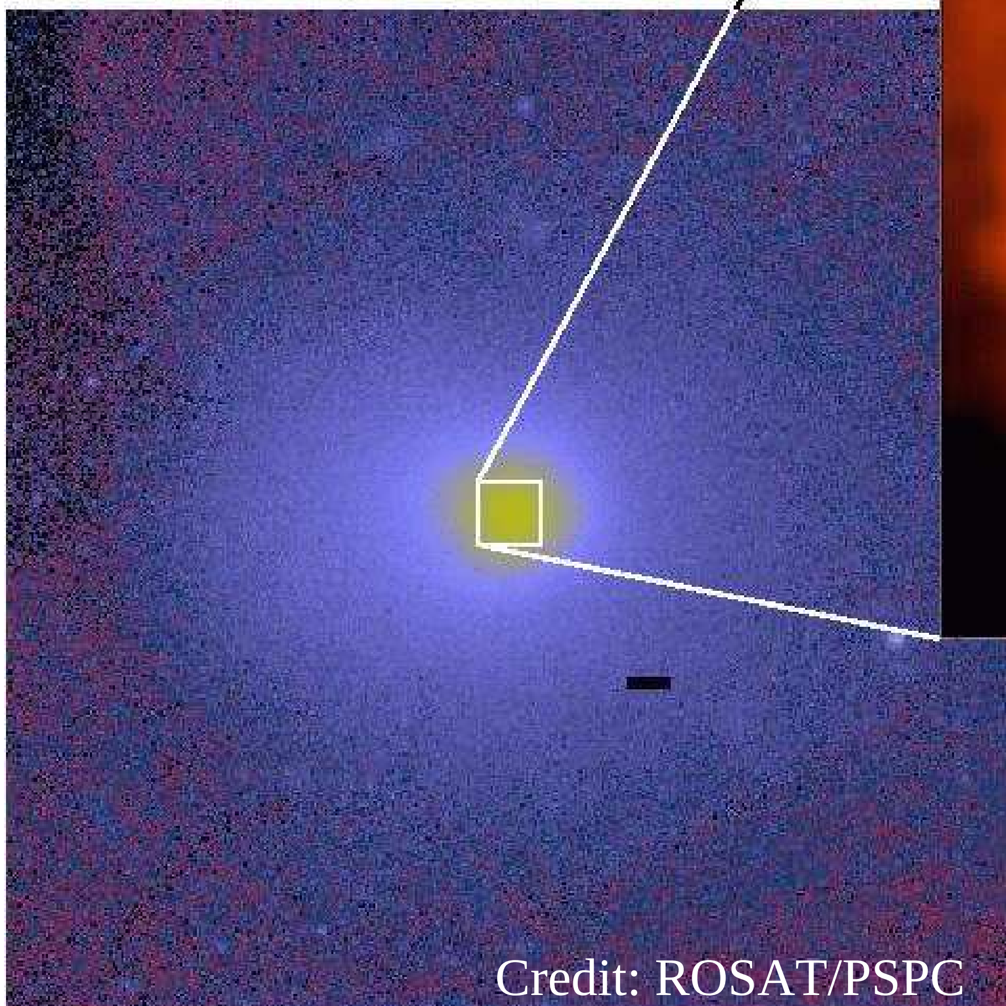
$$\frac{4}{3\,\alpha_\gamma} \left(\frac{m_{\pi^0} c^2}{\mathrm{GeV}}\right)^{-\alpha_\gamma} \left[\left(\frac{2\,E_\gamma}{m_{\pi^0}\, c^2}\right)^{\delta_\gamma} + \left(\frac{2\,E_\gamma}{m_{\pi^0}\, c^2}\right)^{-\delta_\gamma}\right]^{-\alpha_\gamma/\delta_\gamma}$$

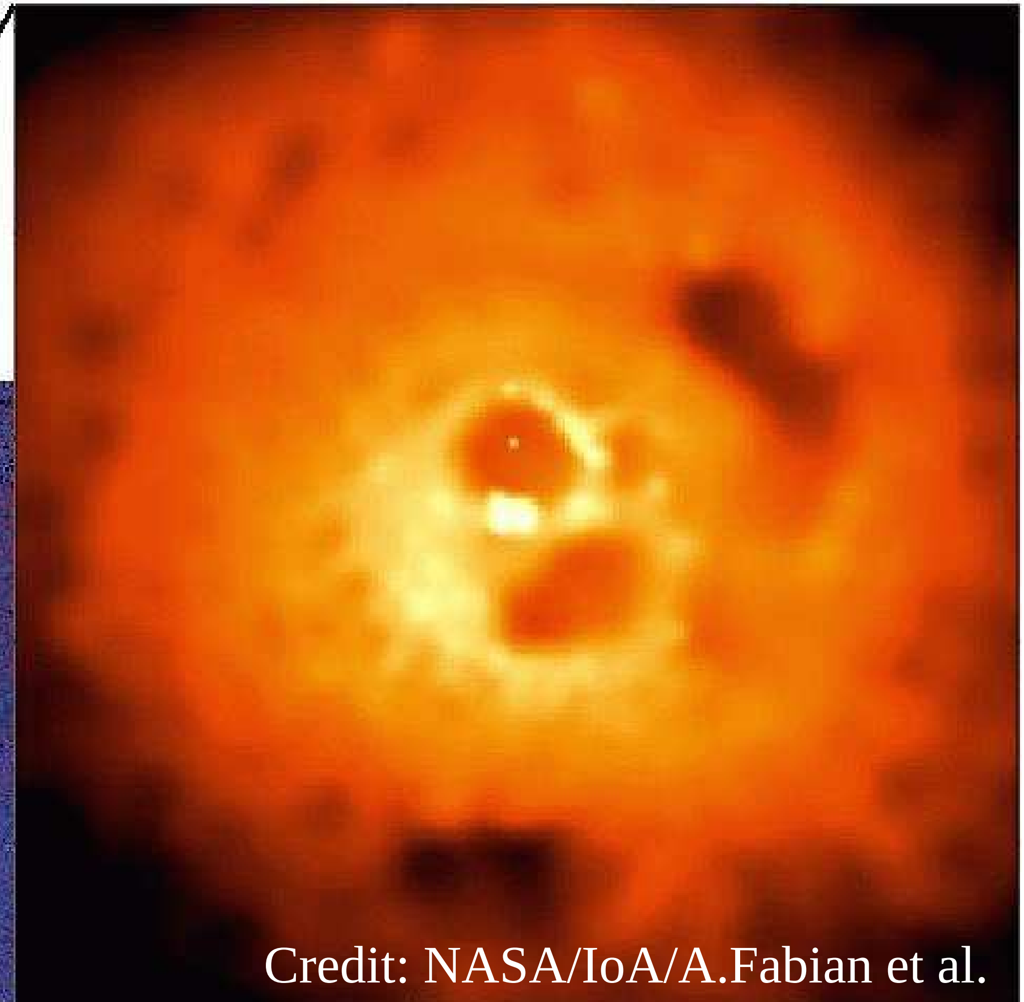
- Relative deviation of our analytic approach to simulated gamma−ray spectra.

Cool core clusters as efficient CRp detectors

ROSAT observation:

Perseus galaxy cluster

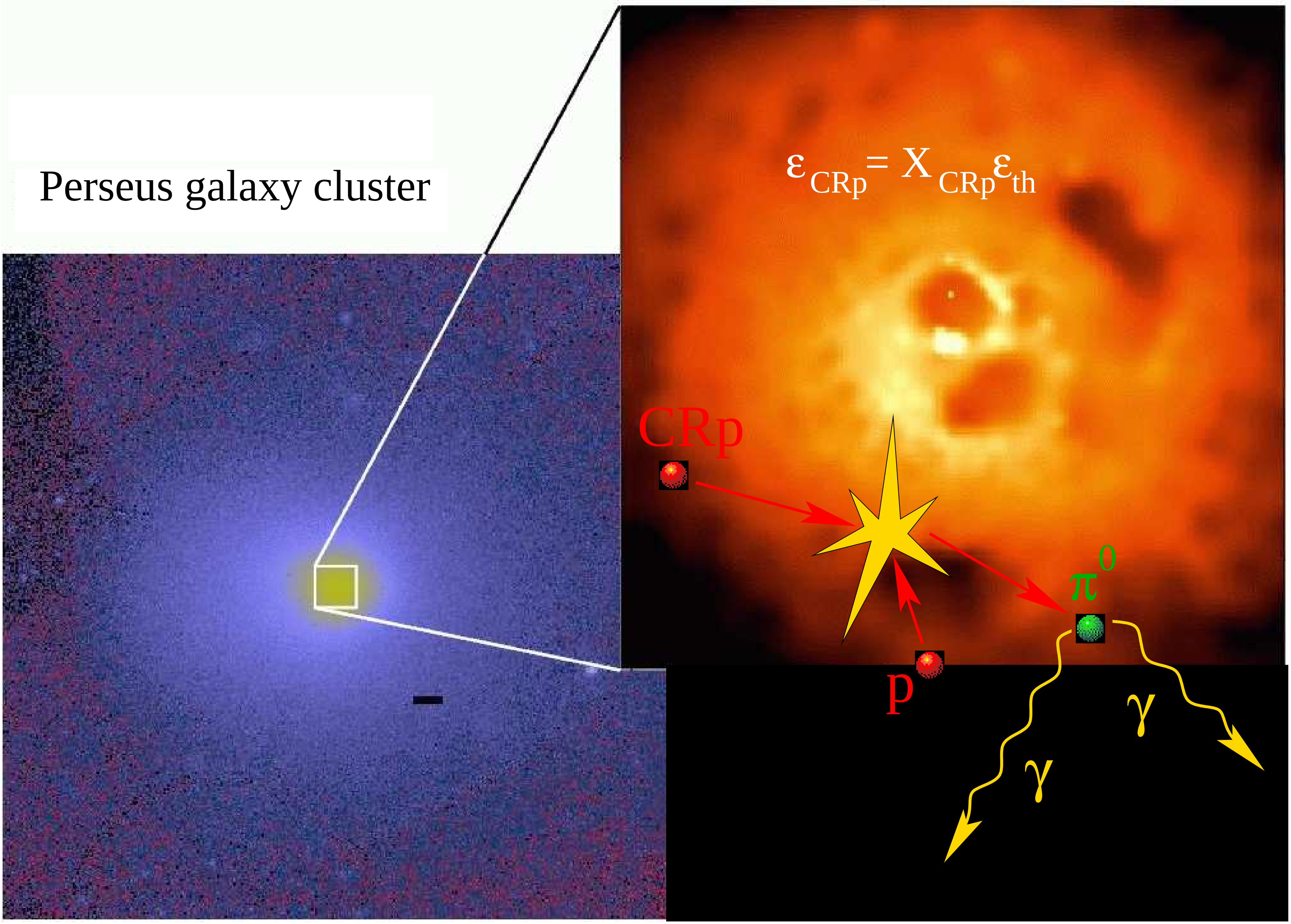




Chandra observation:

central region of Perseus

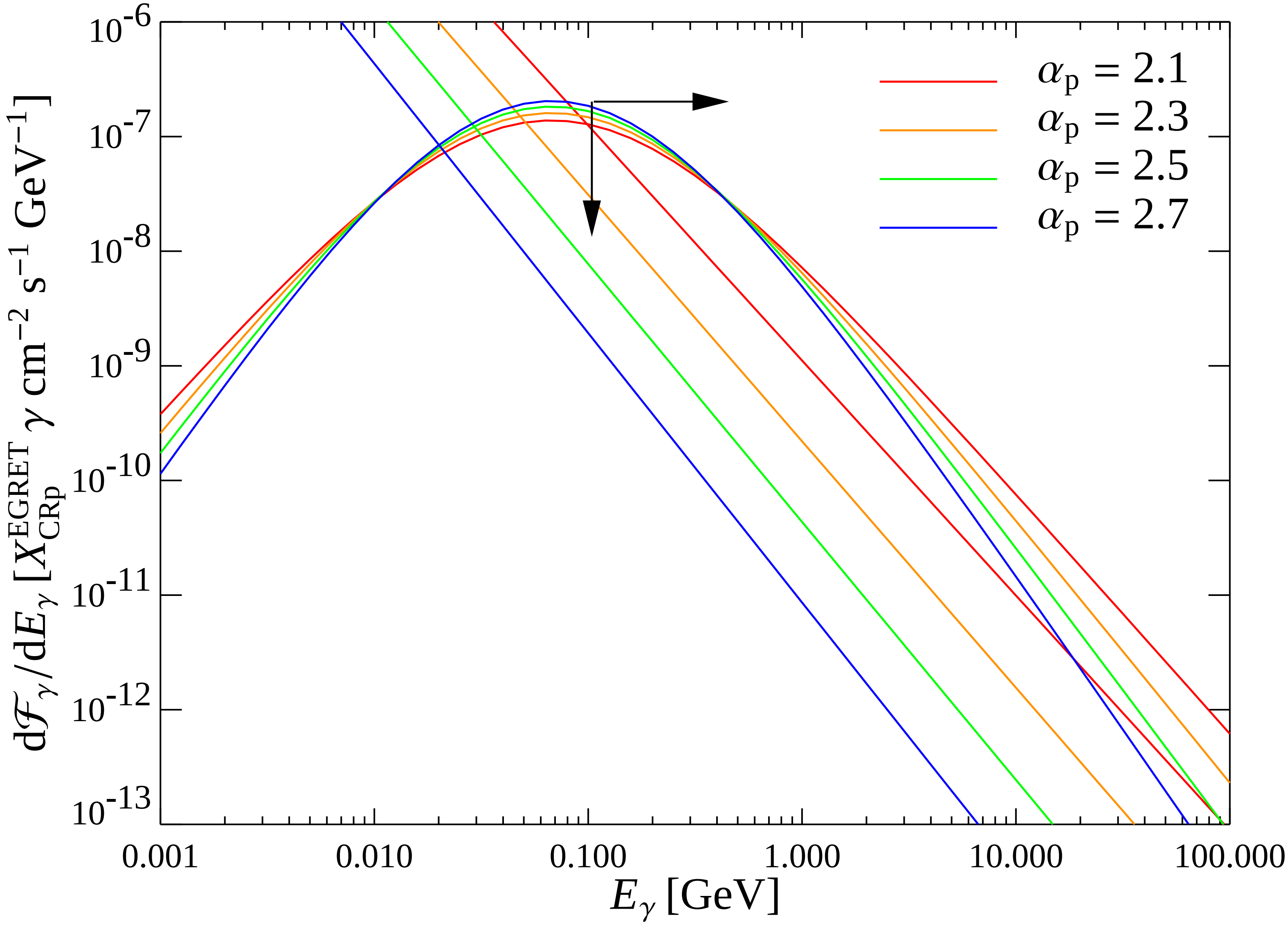
Cool core cluster model of CRp detection



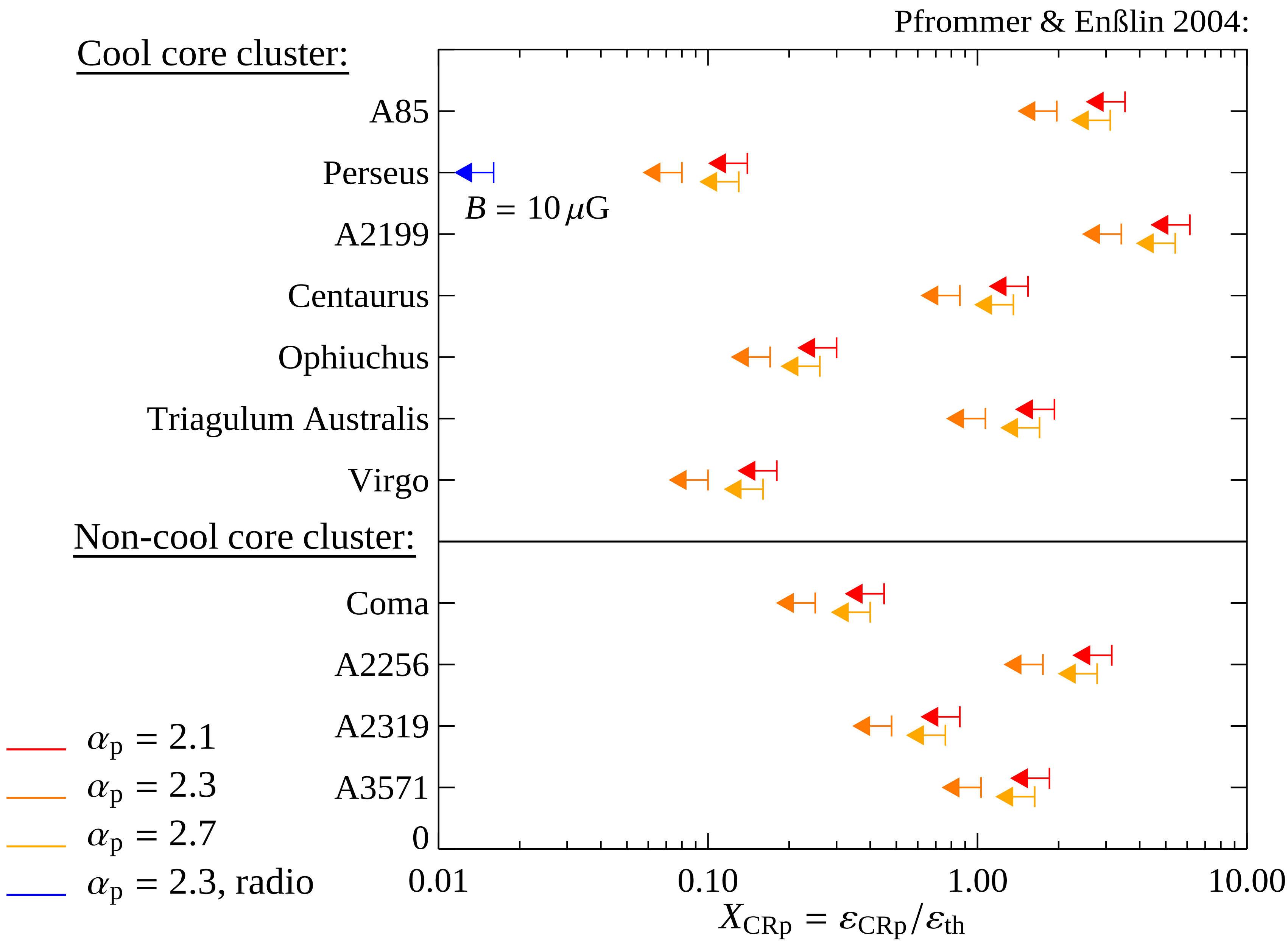
Gamma ray flux of Perseus galaxy cluster

Inverse Compton emission of secondary CRe (B = 0),
pion decay induced gamma ray emission:

Pfrommer & Enßlin 2004:

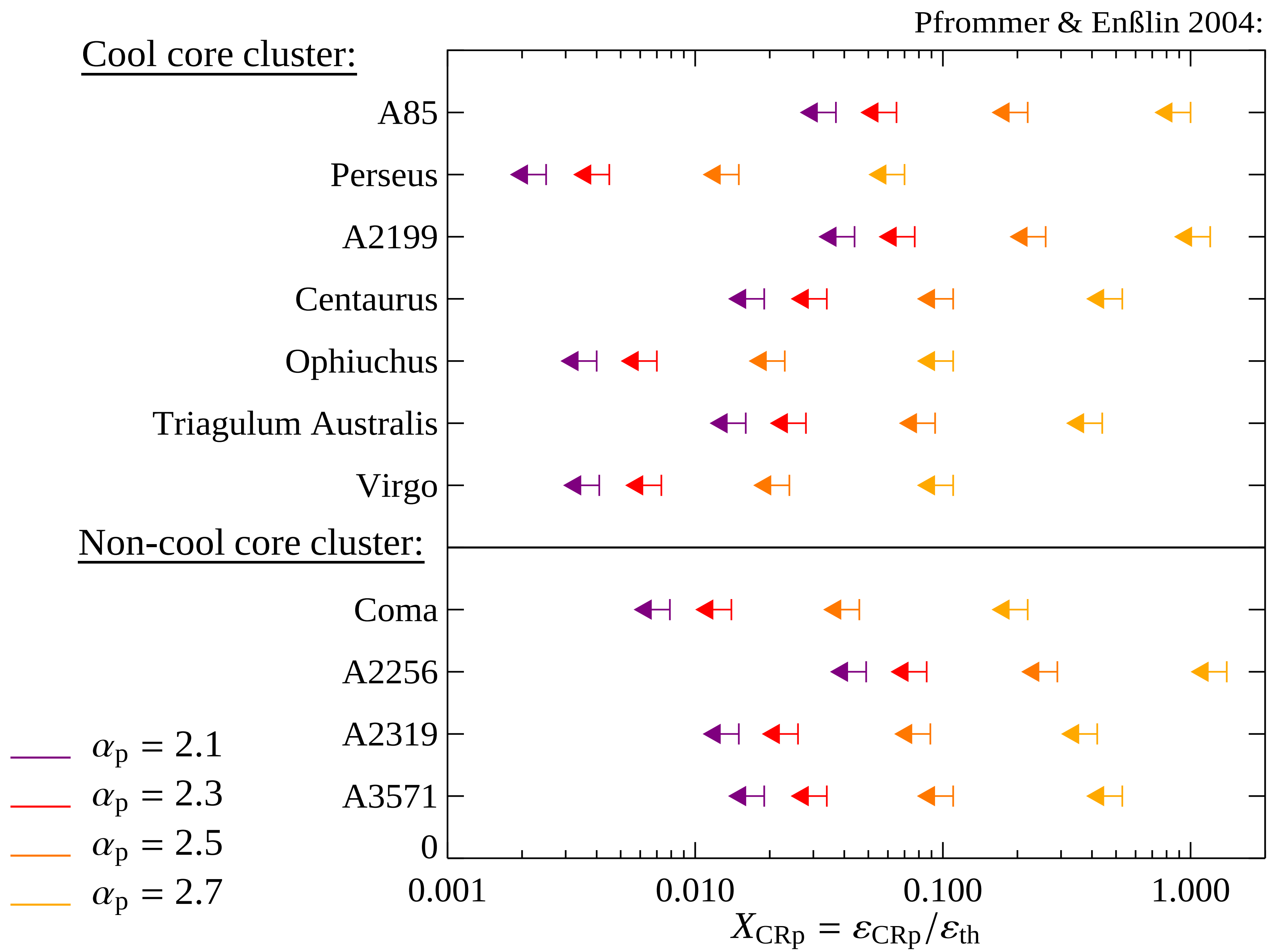


Upper limits on X_CRp using EGRET limits



Expected limits on X_CRp using Cerenkov telescopes

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



HEGRA – M87: TeV CoG position

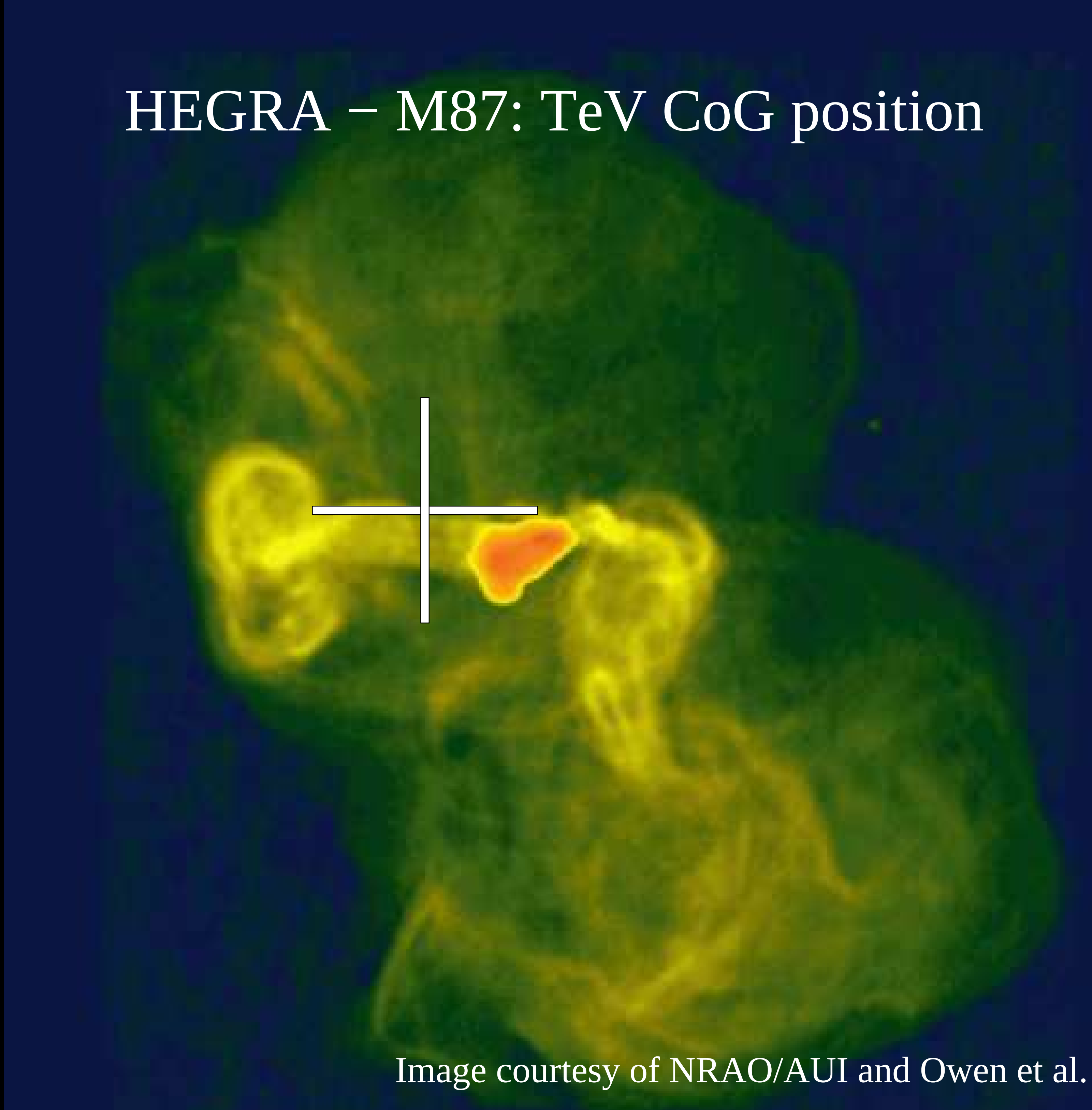


Image courtesy of NRAO/AUI and Owen et al.

What is the origin of the M 87 gamma−ray emission?

- Processed radiation of the relativistic outflow (jet):

  e.g. IC up−scattering of CMB photons by CRes (jet), SSC scenario
  (e.g. Bai & Lee 2001)

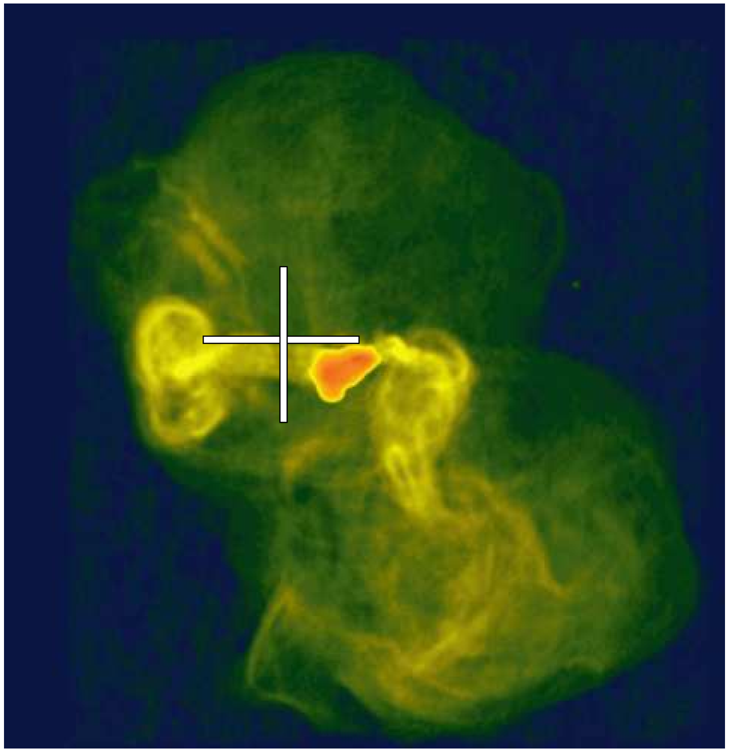
- Dark matter annihilation or decay processes (Baltz et al. 2000)

- Hadronically originating gamma−rays:

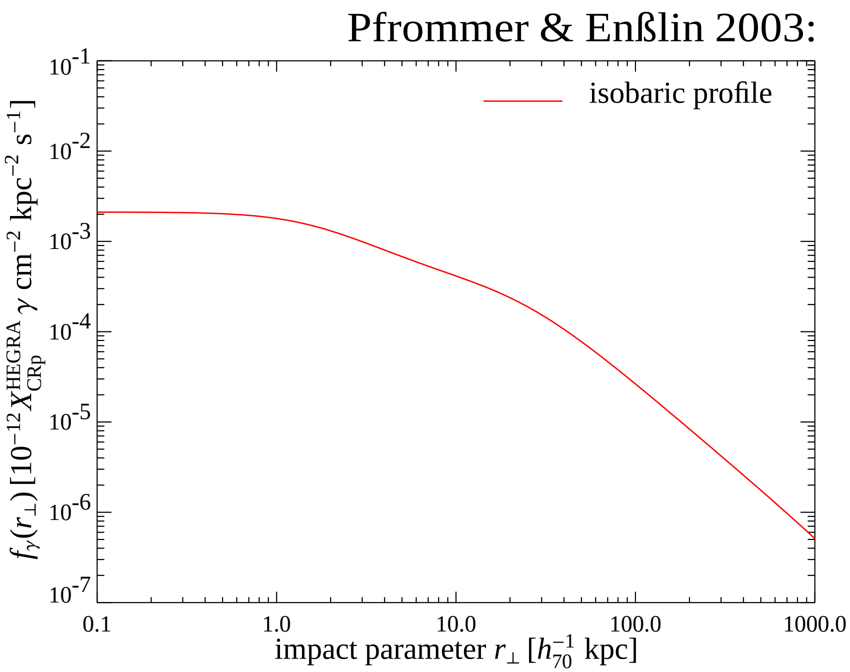
  Assuming CRp power−law distribution and a model for the CRp spatial distrib.

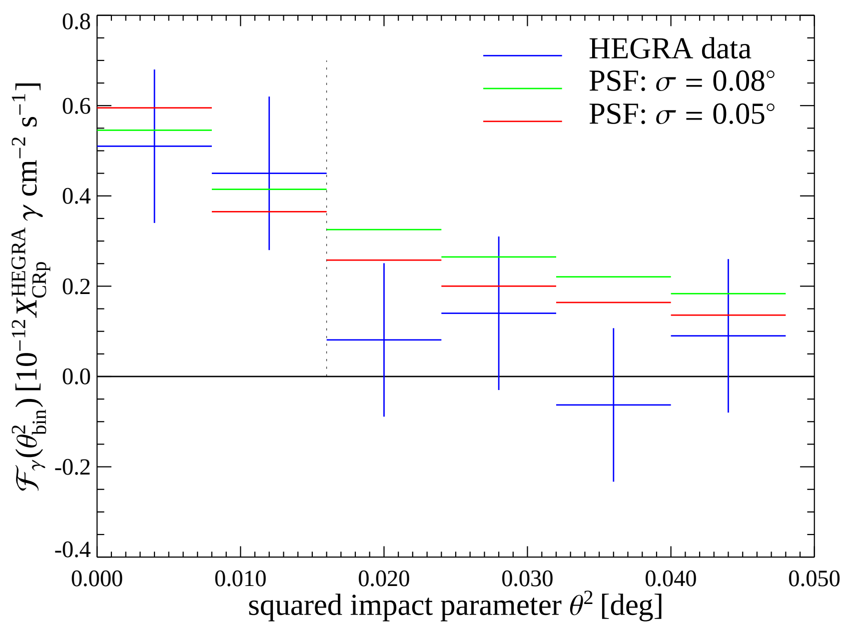
  → measurement of the CRp population in ICM/ISM of M 87!

  (Pfrommer & Enßlin 2003)



Gamma ray flux profile of M 87 (Virgo)





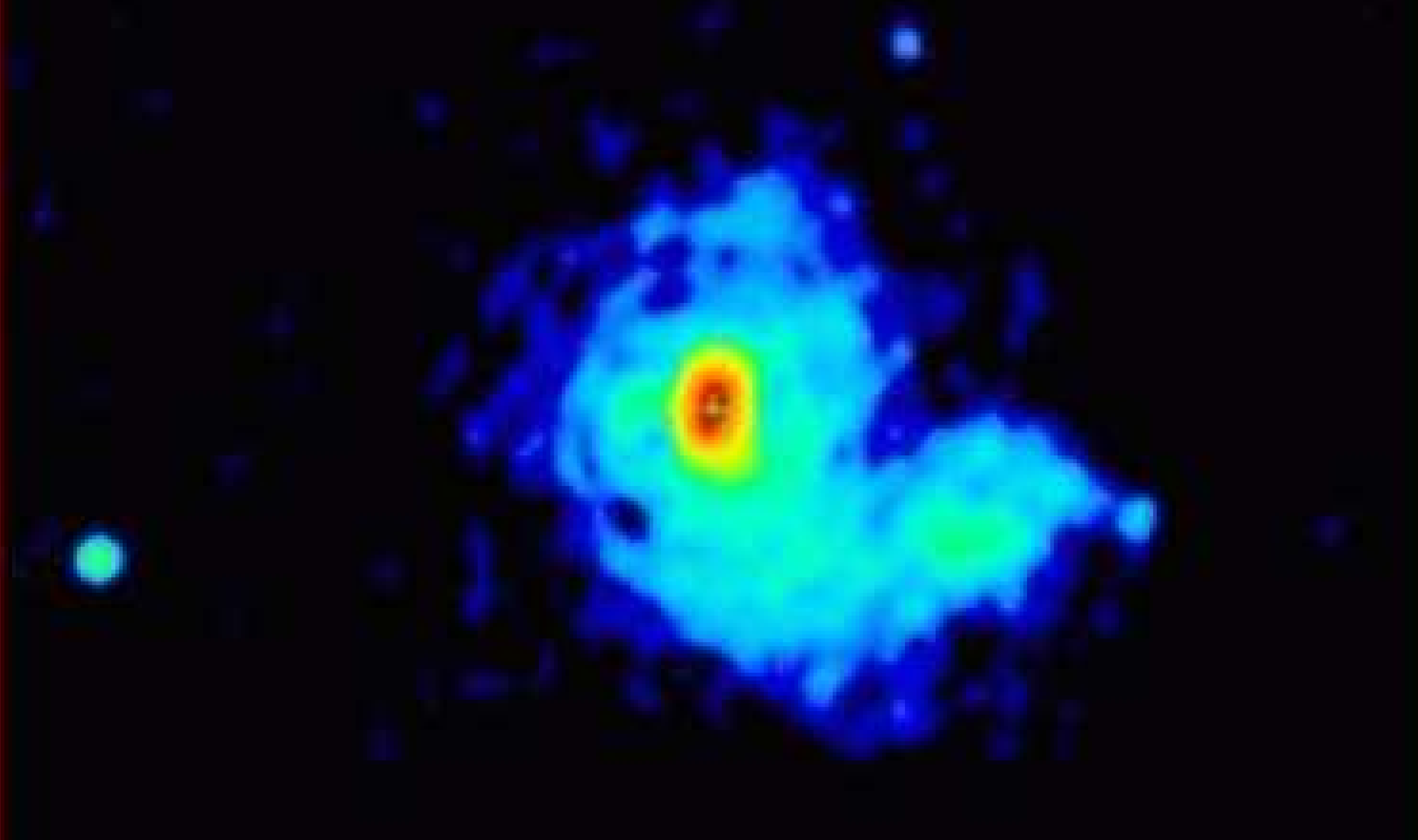
Top:

- modeled gamma−ray surface flux profile
- normalized to the HEGRA flux (>730 GeV) within the two innermost datapoints

Bottom:

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

Perseus Radio Mini−Halo @ 1.4 GHz



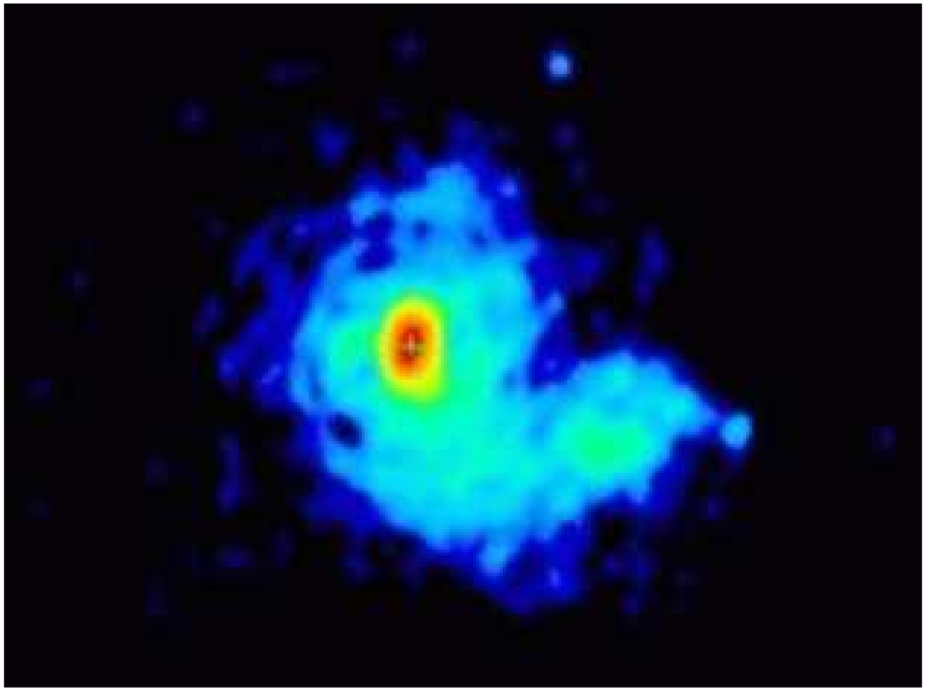
Credit: Pedlar et al. (1990)

What is the origin of radio mini−halos?

Synchrotron emission by CRes, but which population?

- Directly accelerated CRes at structure formation or merger shocks ⟶ diffusion length scales too short! (Sarazin 1999)
- Reaccelerated CRes (in situ) by magnetic turbulence in the ICM (Jaffe 1977, Gitti et al. 2002)
- Hadronically originating CRes: (Dennison 1980, Vestrand 1982)

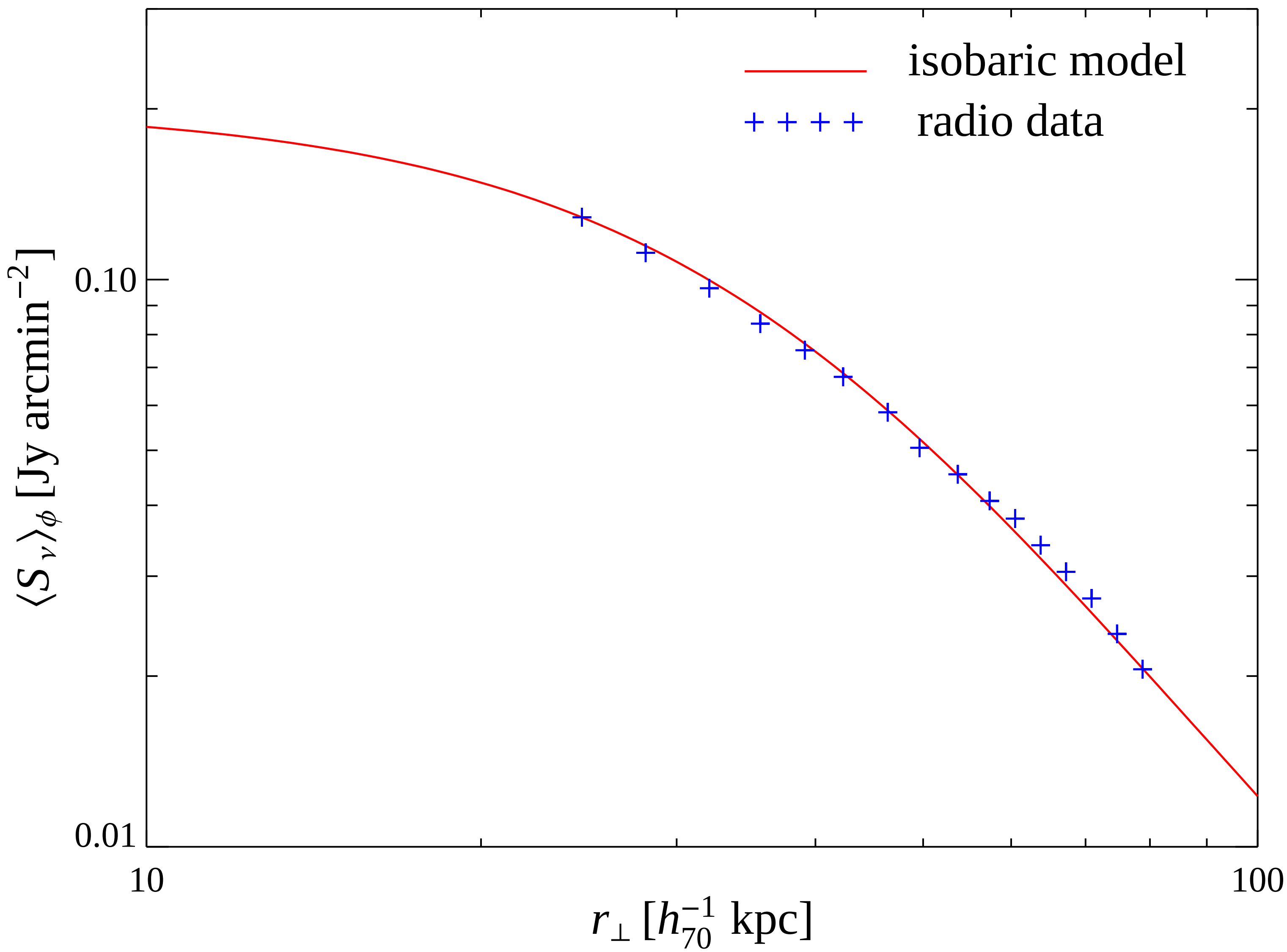
Assuming a mag. field strength ⟶ measure/upper limit of CRp population in ICM (Pfrommer & Enβlin 2004)



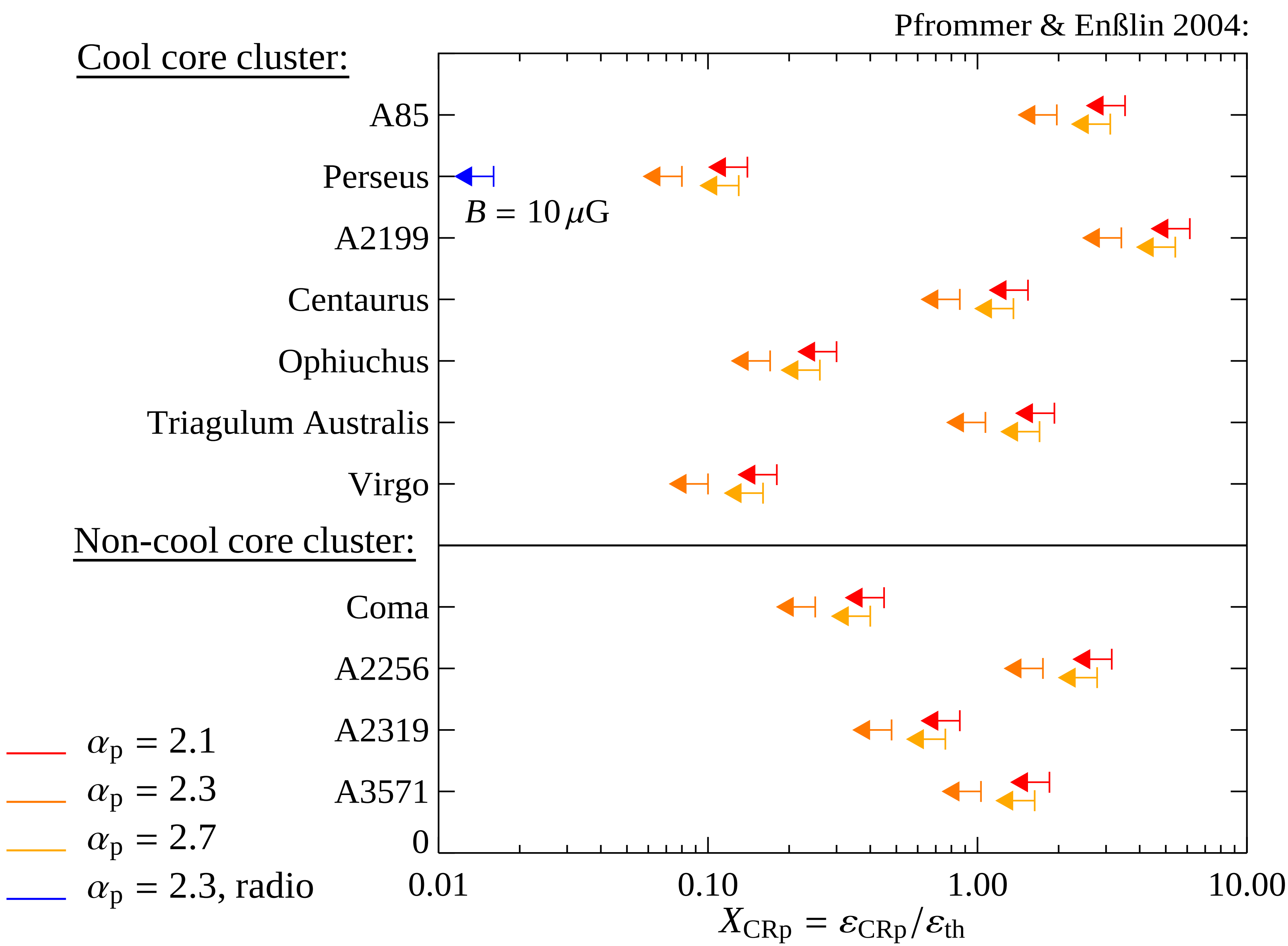
Brightness profile of Perseus radio mini−halo:

Synchrotron radiation of hadronically originating CRe

Pfrommer & Enßlin 2004:



Upper limits on X_CRp using EGRET limits



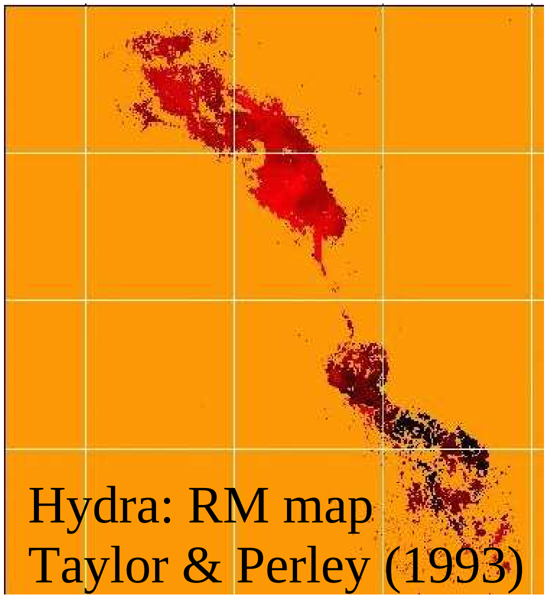
Magnetic fields in clusters

- Rotation measure of polarised radio sources behind cluster magnetic fields:

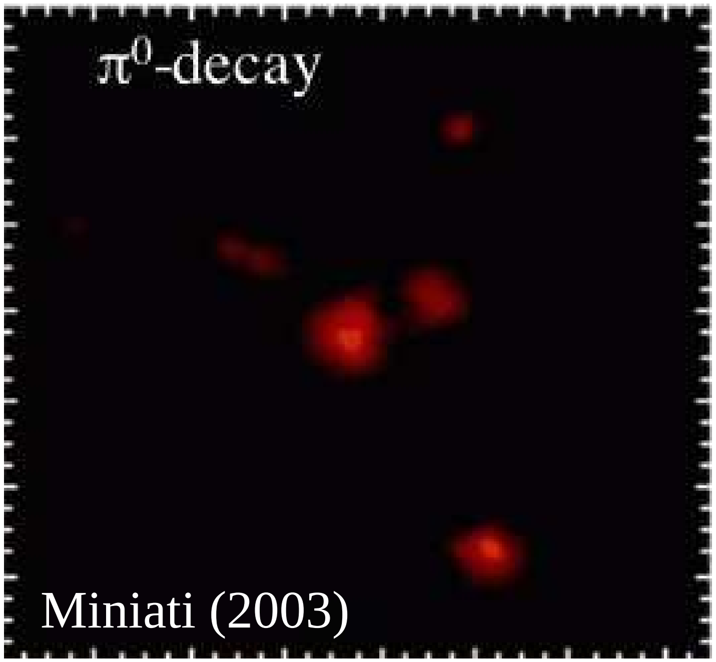
  ⟶ not every cluster exhibits suitable radio lobes

- Idea: combine hadronically induced gamma−ray and synchrotron emission

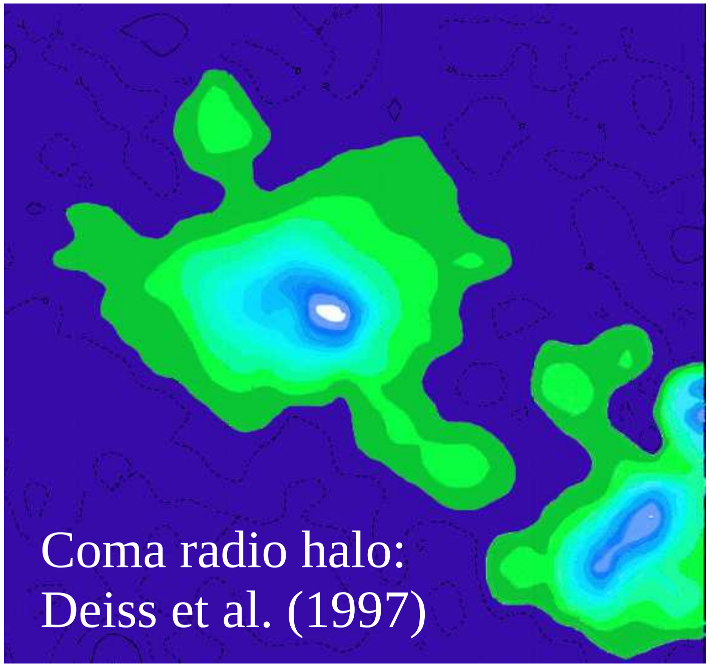
  ⟶ upper limit on magnetic field strength



Hydra: RM map
Taylor & Perley (1993)



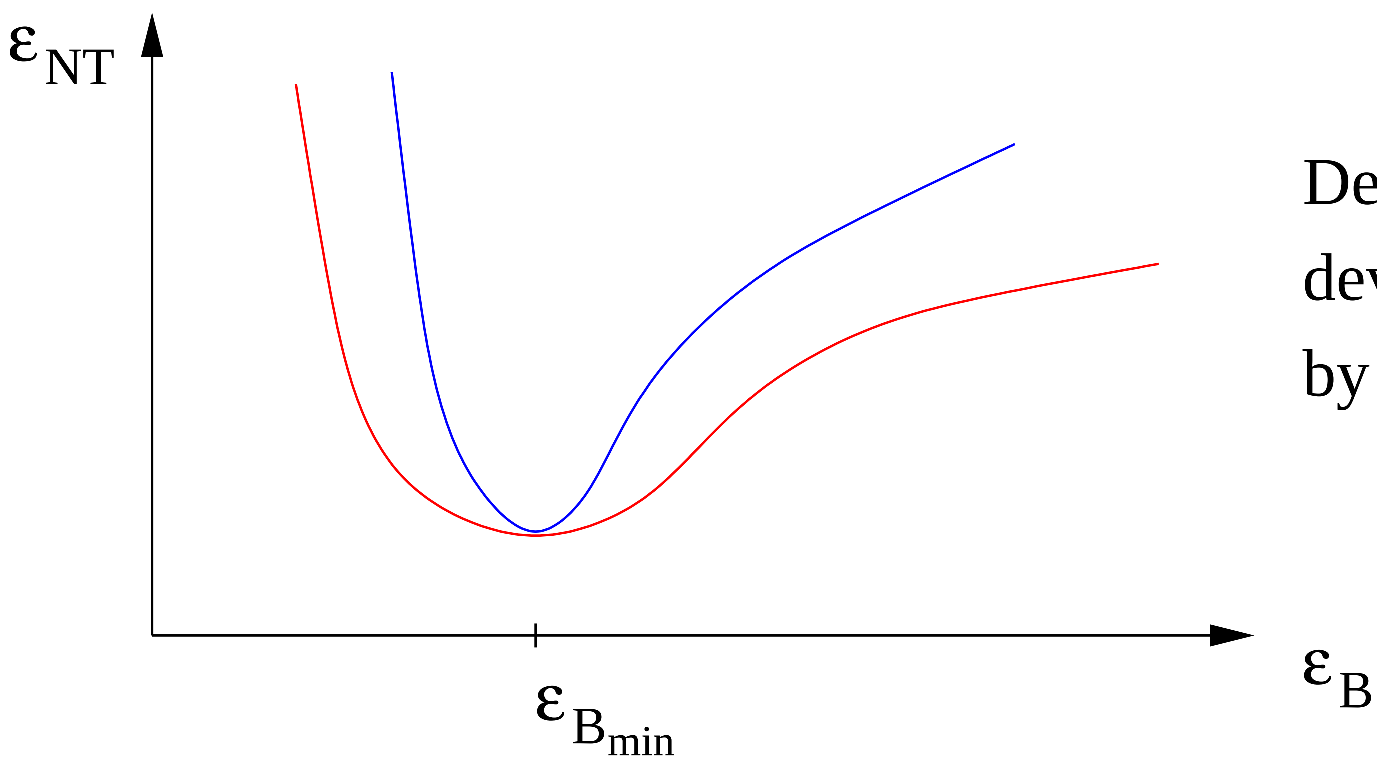
Miniati (2003)



Coma radio halo:
Deiss et al. (1997)

Minimum energy criterion (MEC): the idea

- $\varepsilon_{\rm NT} = \varepsilon_B + \varepsilon_{\rm CRp} + \varepsilon_{\rm CRe}$ ⟶ Minimum criterion: $\left.\frac{\partial \varepsilon_{\rm NT}}{\partial \varepsilon_B}\right|_{j_\nu} \overset{!}{=} 0$
- classical MEC: $\varepsilon_{\rm CRp} = k_{\rm p} \varepsilon_{\rm CRe}$
- hadronical MEC: $\varepsilon_{\rm CRp} \propto (\varepsilon_B + \varepsilon_{\rm CMB})\varepsilon_B^{-(\alpha_\nu+1)/2}$

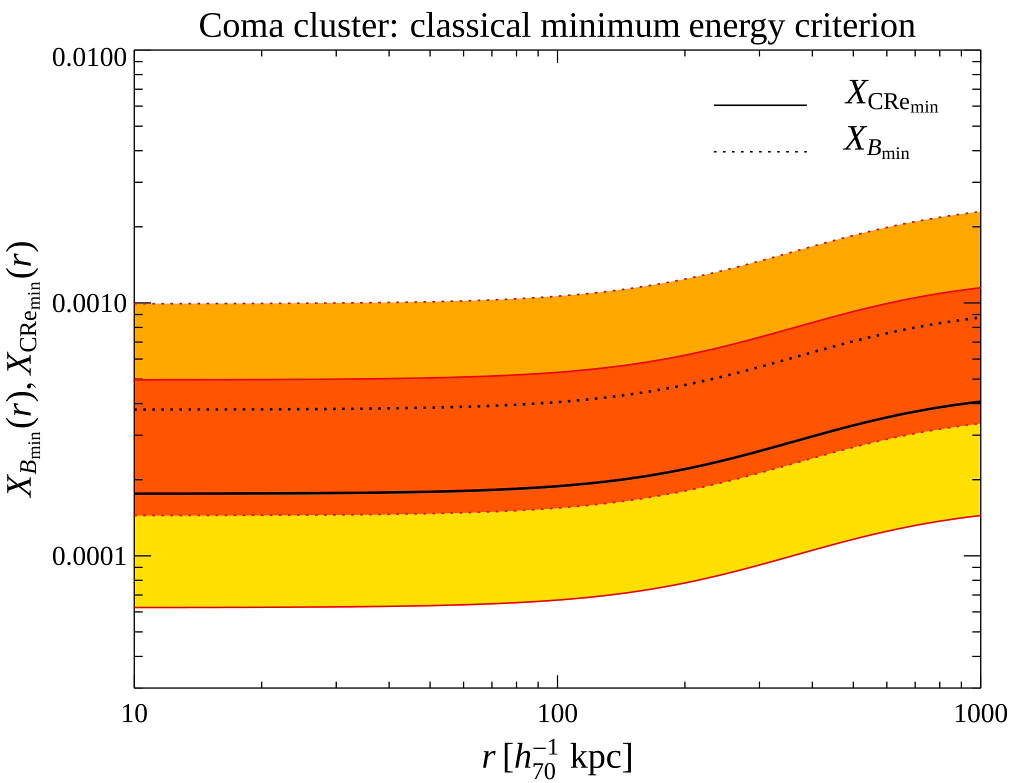


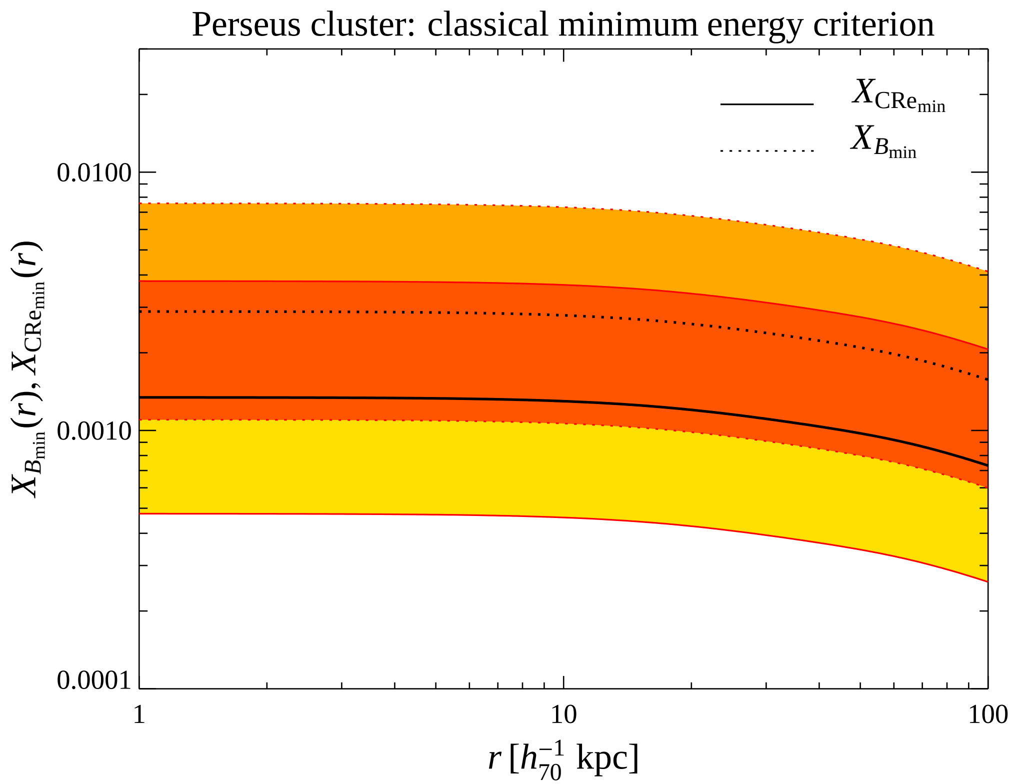
Defining tolerance levels:
deviation from minimum
by one e−fold

Classical minimum energy criterion

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

Pfrommer & Enβlin 2004:





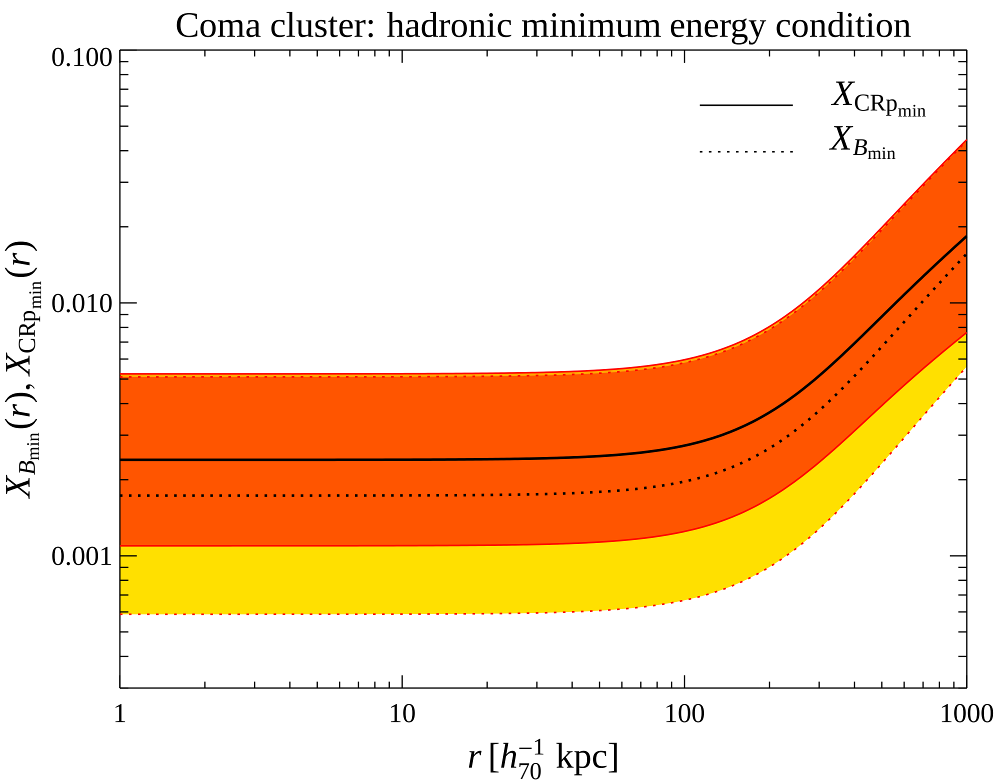
$$B_{\mathrm{Coma}} = 1.1^{+0.7}_{-0.4}\,\mu\mathrm{G}$$

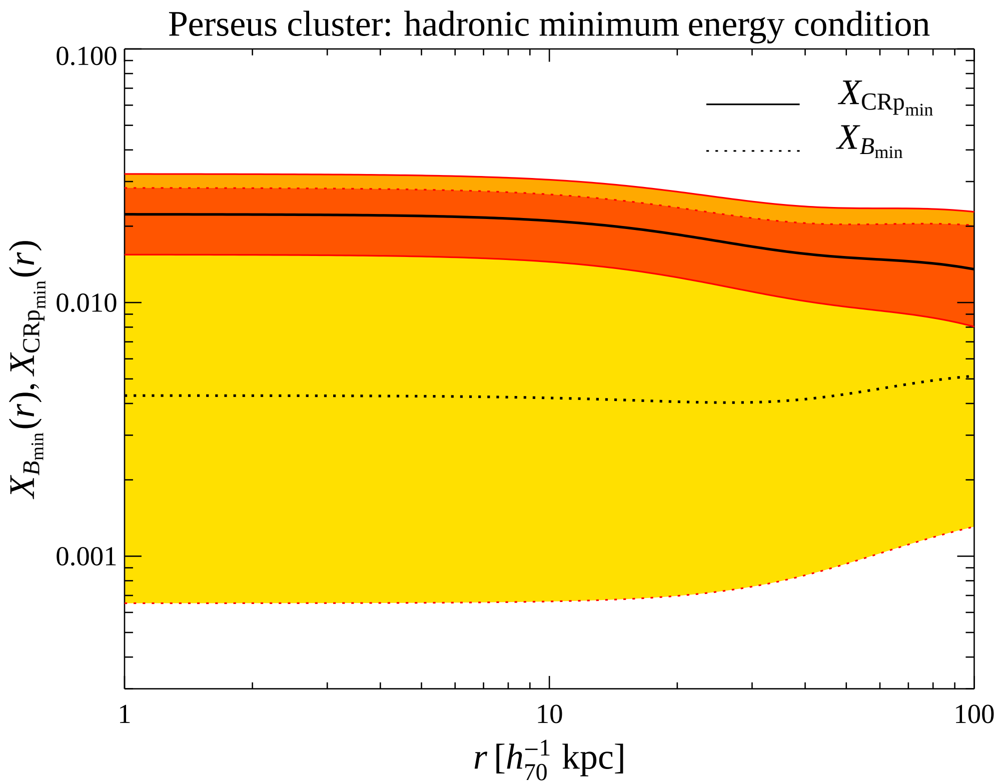
$$B_{\mathrm{Perseus}} = 7.2^{+4.5}_{-2.8}\,\mu\mathrm{G}$$

Hadronic minimum energy criterion

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

Pfrommer & Enβlin 2004:

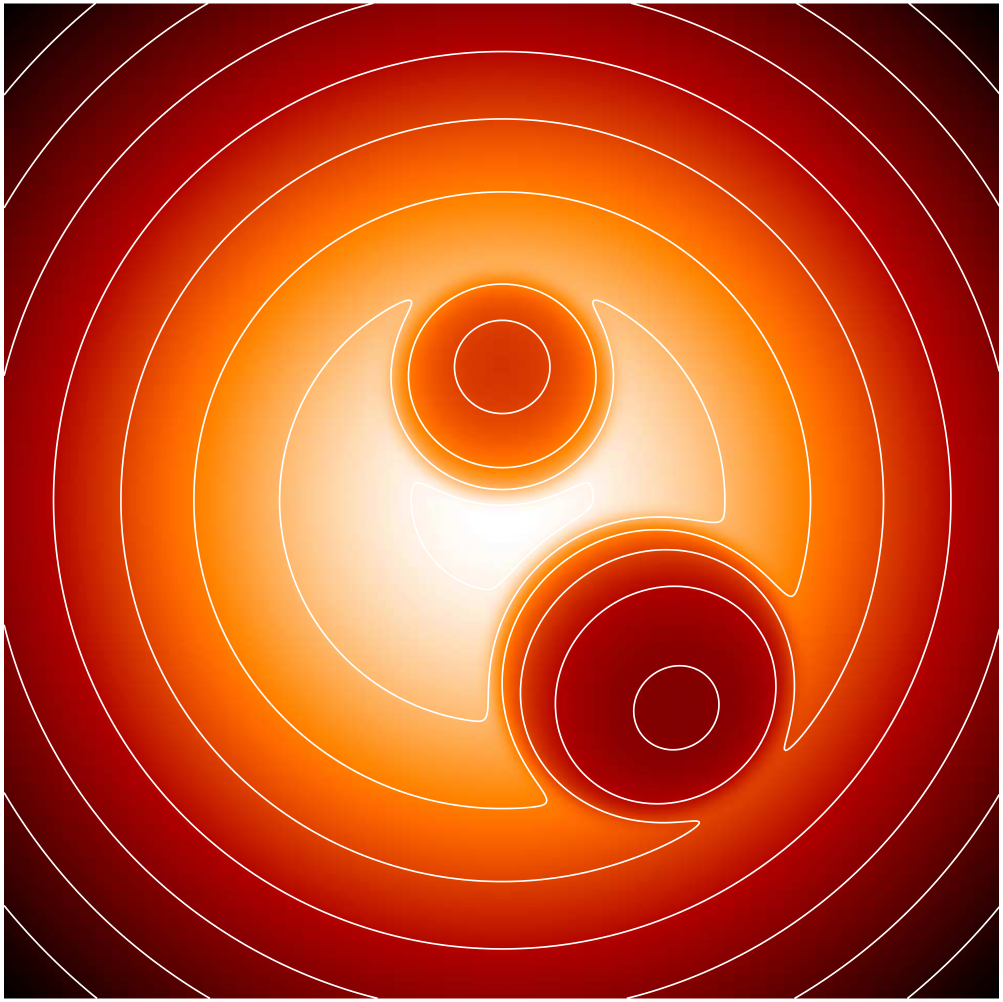


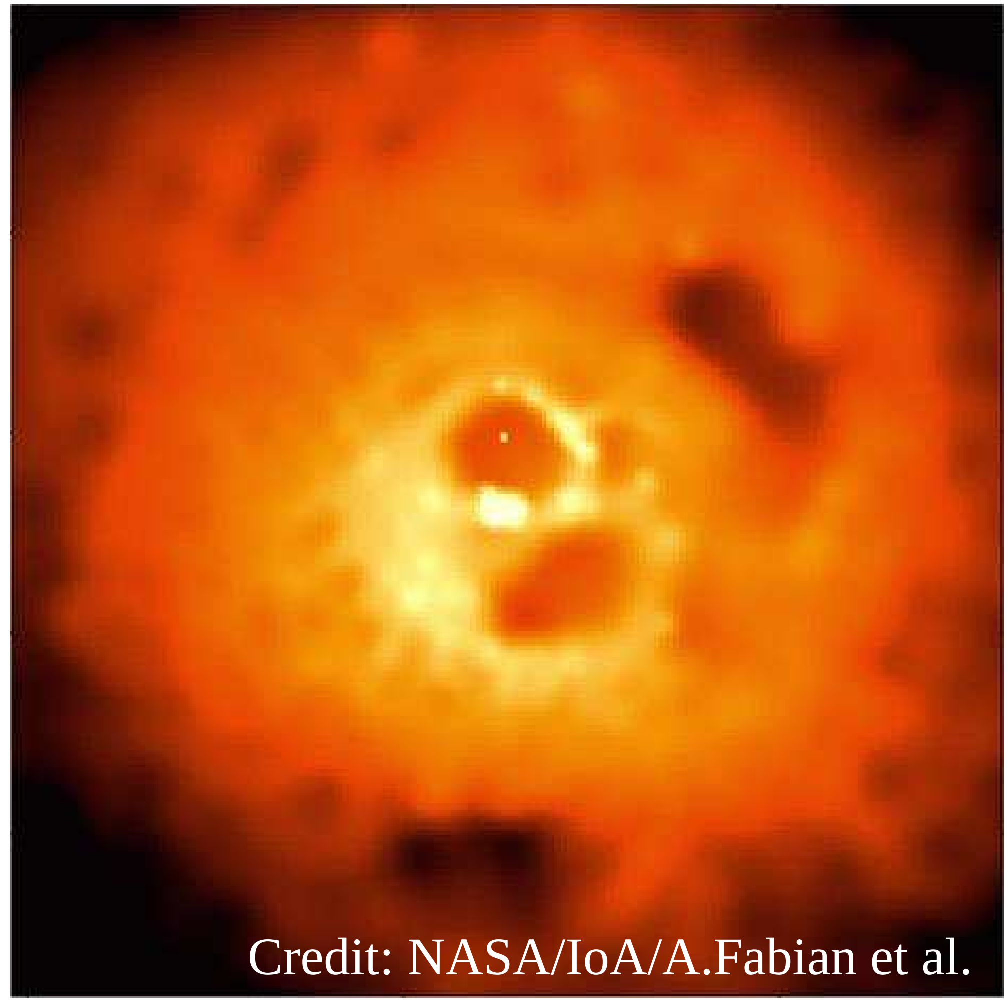


$$B_{\rm Coma} = 2.4^{+1.7}_{-1.0}\,\mu{\rm G}$$

$$B_{\rm Perseus} = 8.8^{+13.8}_{-5.4}\,\mu{\rm G}$$

Sunyaev−Zel'dovich effect of radio plasma bubbles





sim. ALMA E, 144 GHz: 2.5' x 2.5'

Thermal X−ray: 6' x 6'

SZE ⟶ radio bubble composition

Scientific motivation for SZ observations of plasma bubbles

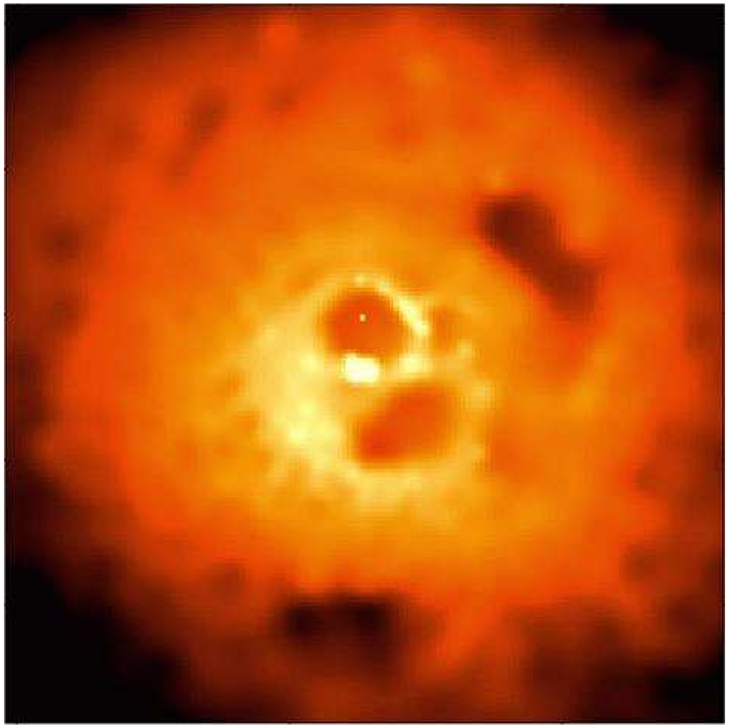
- Inferring the dynamically important composition of radio plasma bubbles and ghost cavities (later evolutional stage):

  relativistic ⟷ trans−relativistic ⟷ hot thermal composition

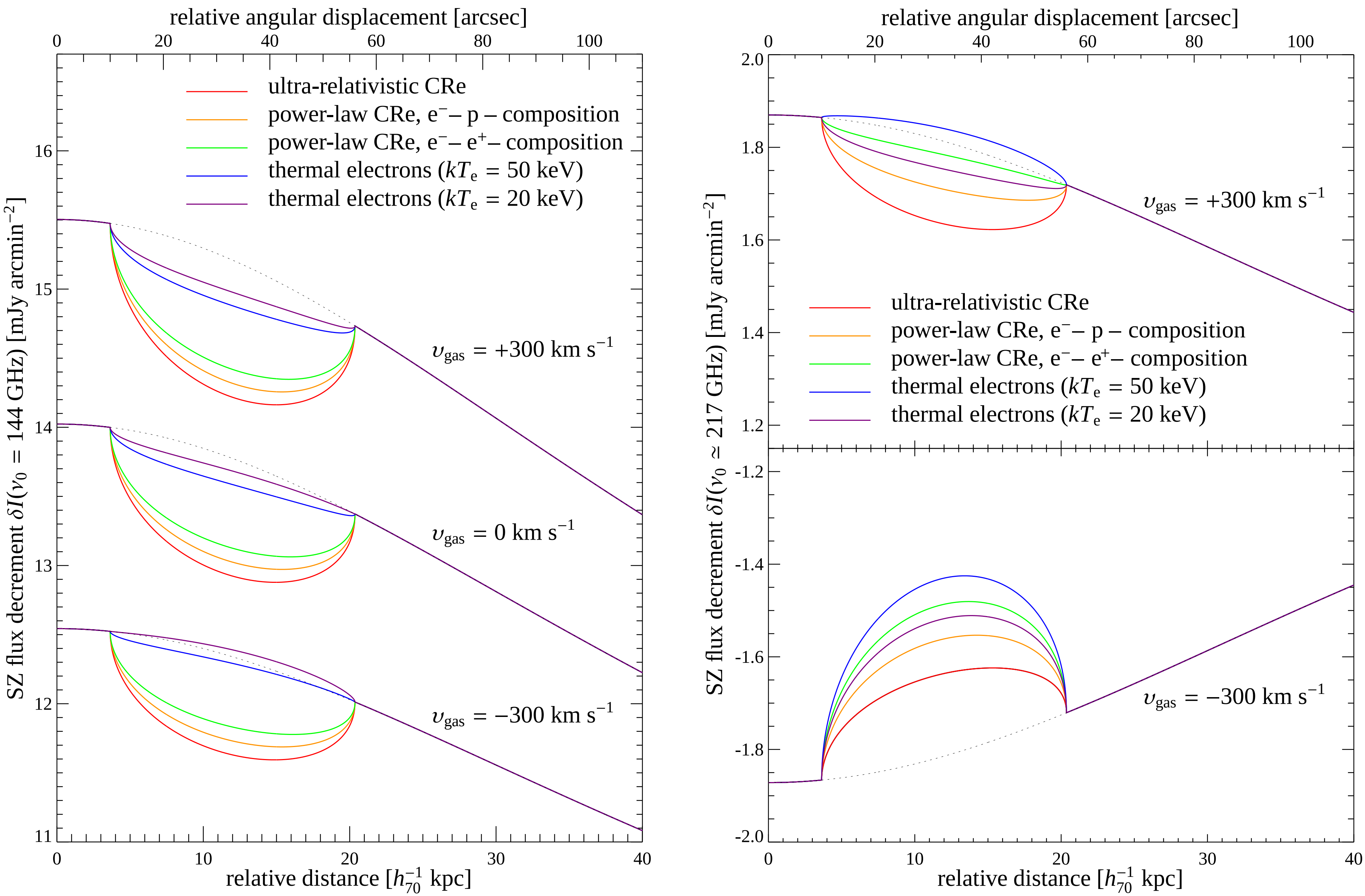
- Composition of AGN jets:

  hadronic ⟷ electron/positron scenario

- Detection of plasma bubbles in outskirt cluster regions compared to X−ray observations



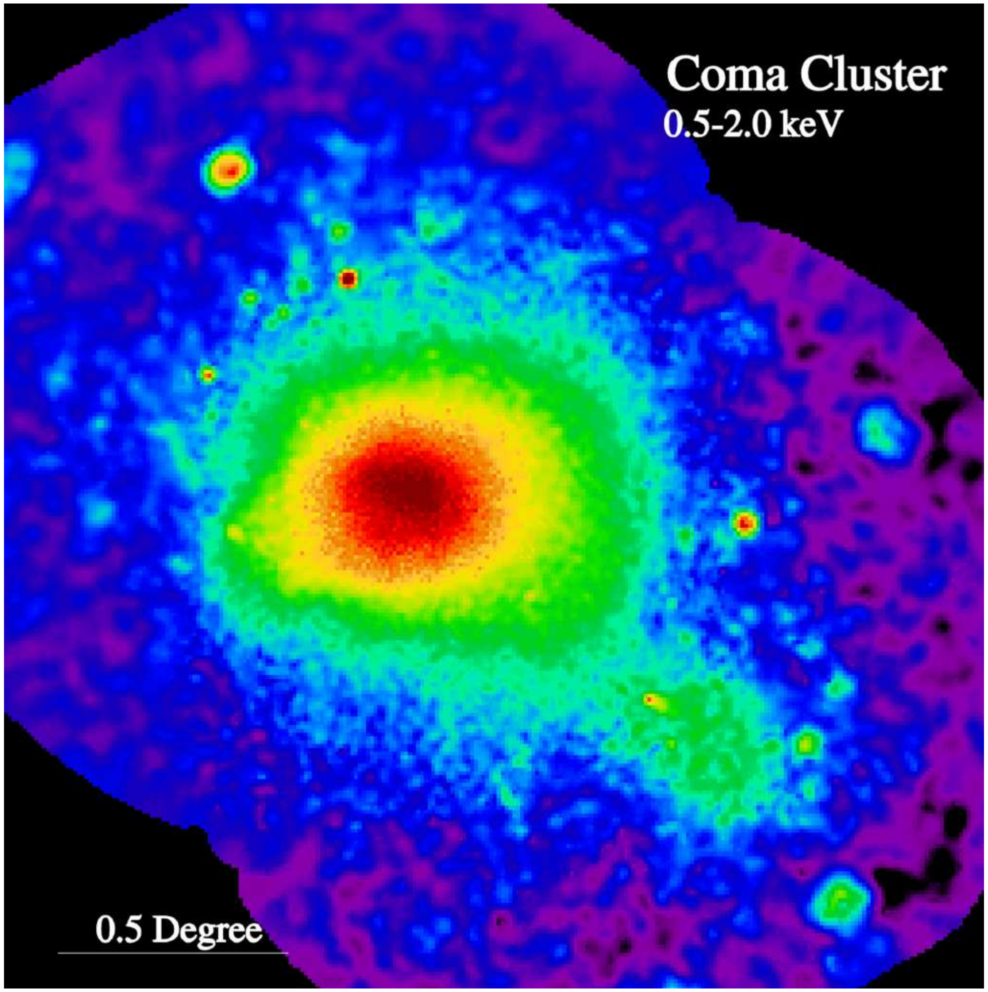
Unveiling the composition of radio plasma bubbles

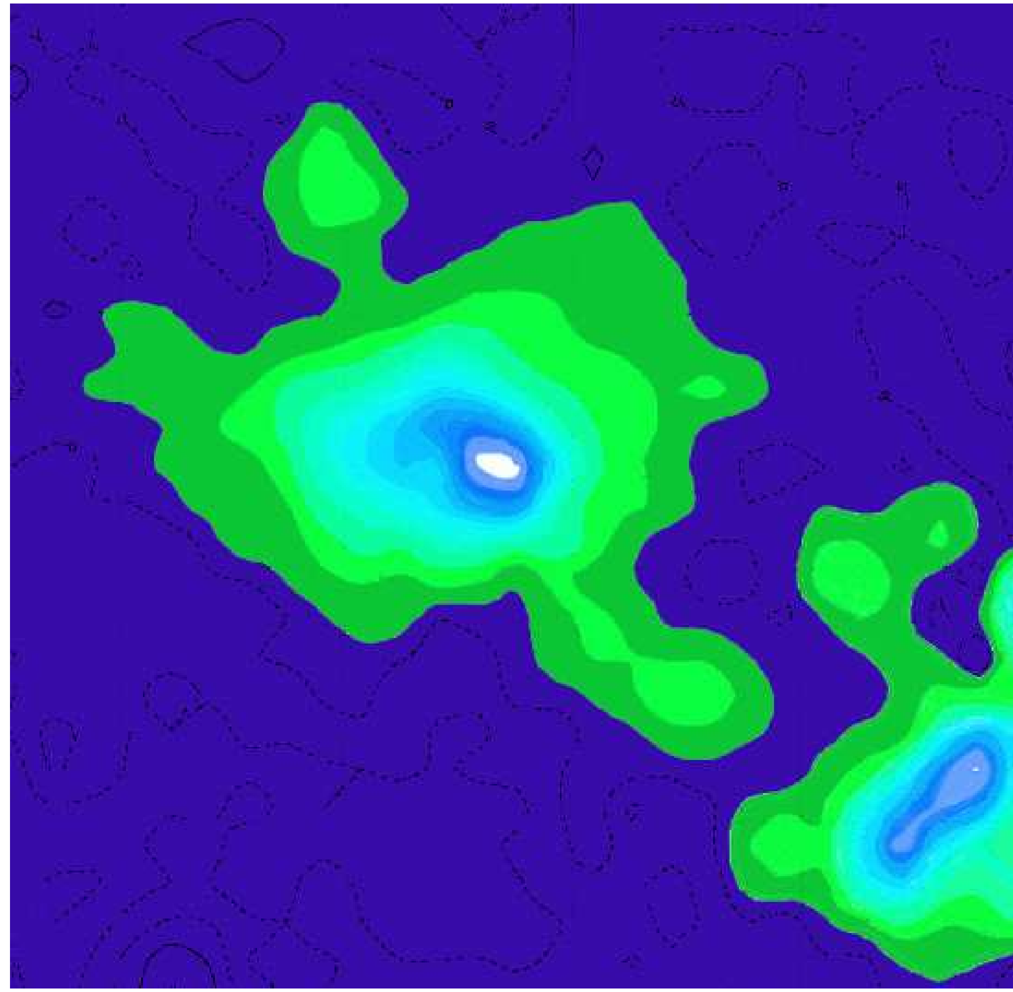


Conclusions

- Cool core clusters are efficient CRp detectors.
- Limits from γ −rays (EGRET): $X_{CRp} < 20\%$
- Radio emission of Perseus: $X_{CRp} \sim 2\%$
- Radio mini−halos (Perseus) seem to be of hadronic origin!
- M 87 gamma−ray emission is consistent with hadronic scenario!
- Hadronic minimum energy criterion can scrutinize the hadronic model.
- Sunyaev−Zel'dovich effect of radio plasma bubbles is able to unveil their composition.

Coma galaxy cluster





ROSAT−PSPC: 2.7° x 2.5°

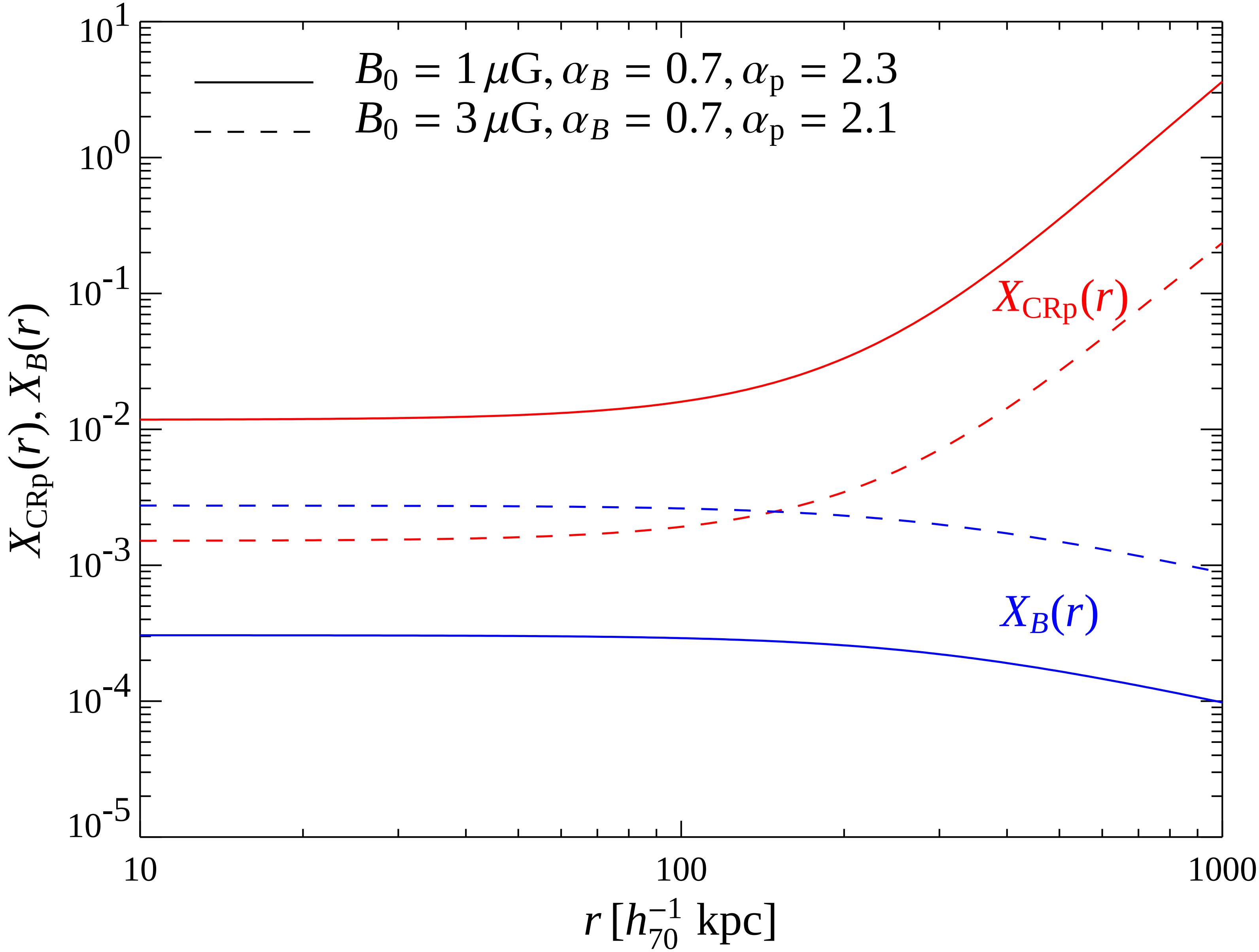
Credit: ROSAT/MPE/Snowden

Radio halo, 1.4 GHz: 2.5° x 2.0°

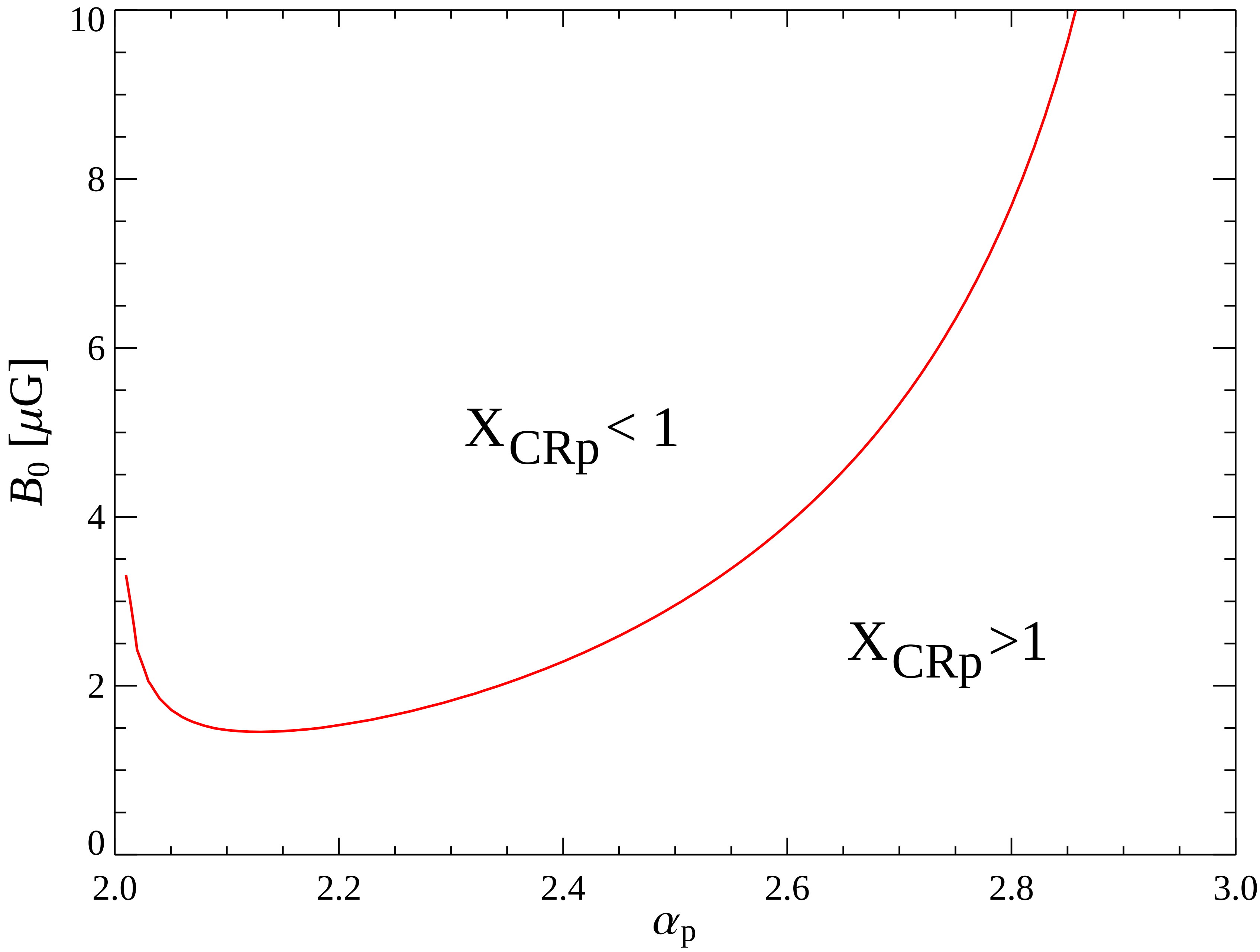
Credit: B.Deiss/Effelsberg

Radio halo in Coma galaxy cluster

$$f_{\rm p}(r, p_{\rm p}) \propto p_{\rm p}^{-\alpha_{\rm p}}, \qquad B(r) = B_0 \left[\frac{n_{\rm e}(r)}{n_{\rm e}(0)}\right]^{\alpha_B}, \qquad X_{\rm CRp}(r) = \frac{\varepsilon_{\rm CRp}}{\varepsilon_{\rm th}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\rm th}}(r)$$



Parameter study on the hadronic origin of the Coma radio halo



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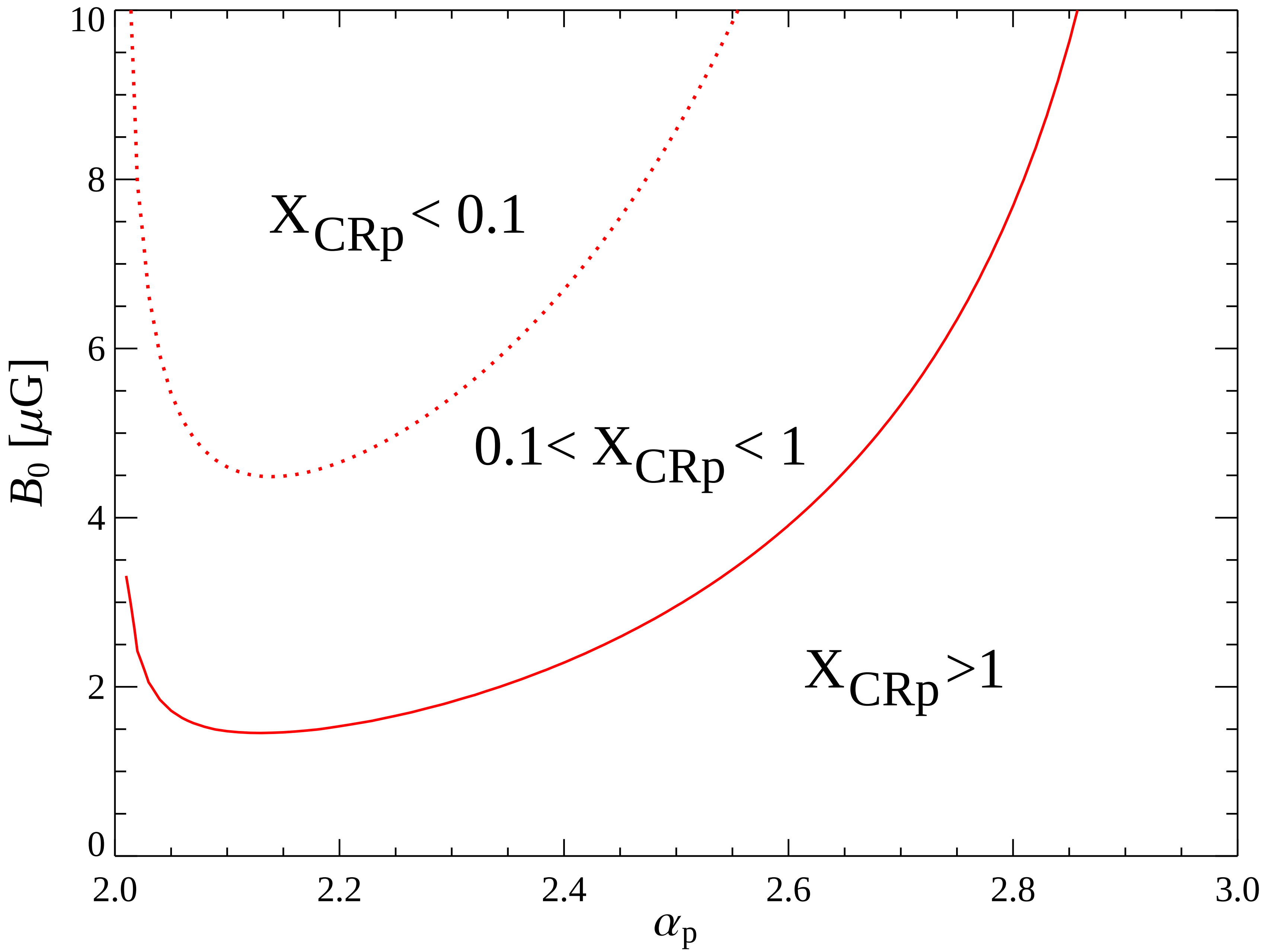

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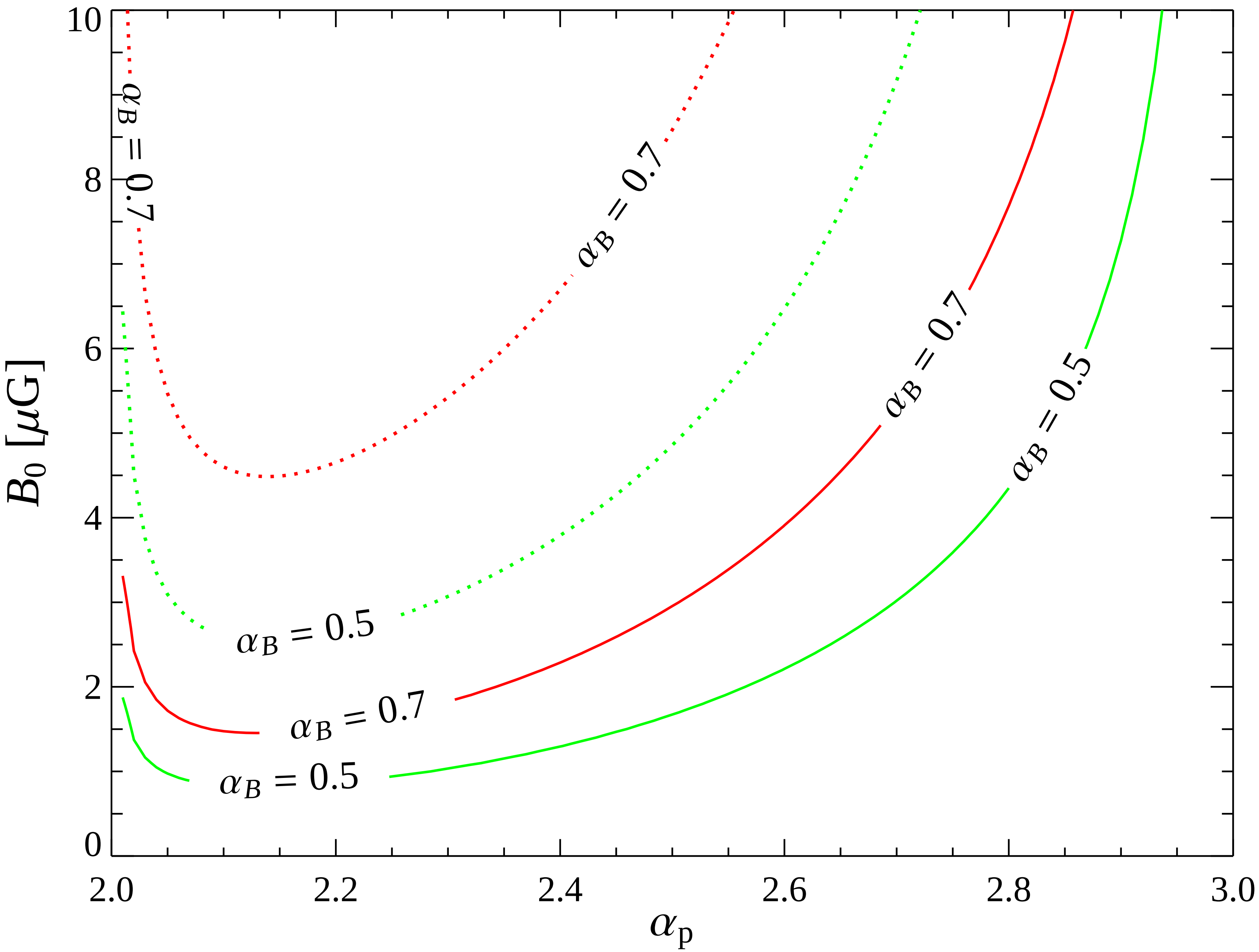
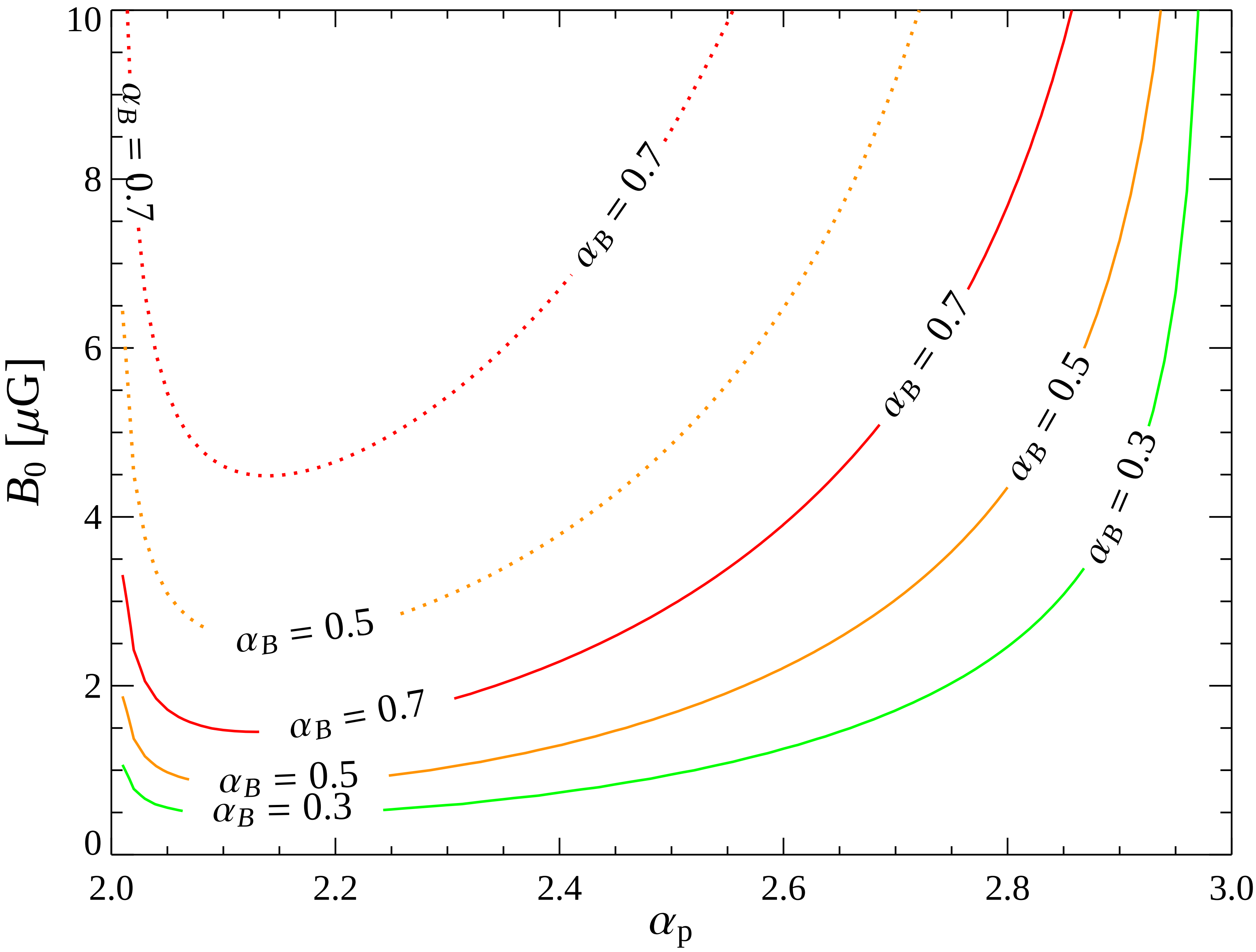
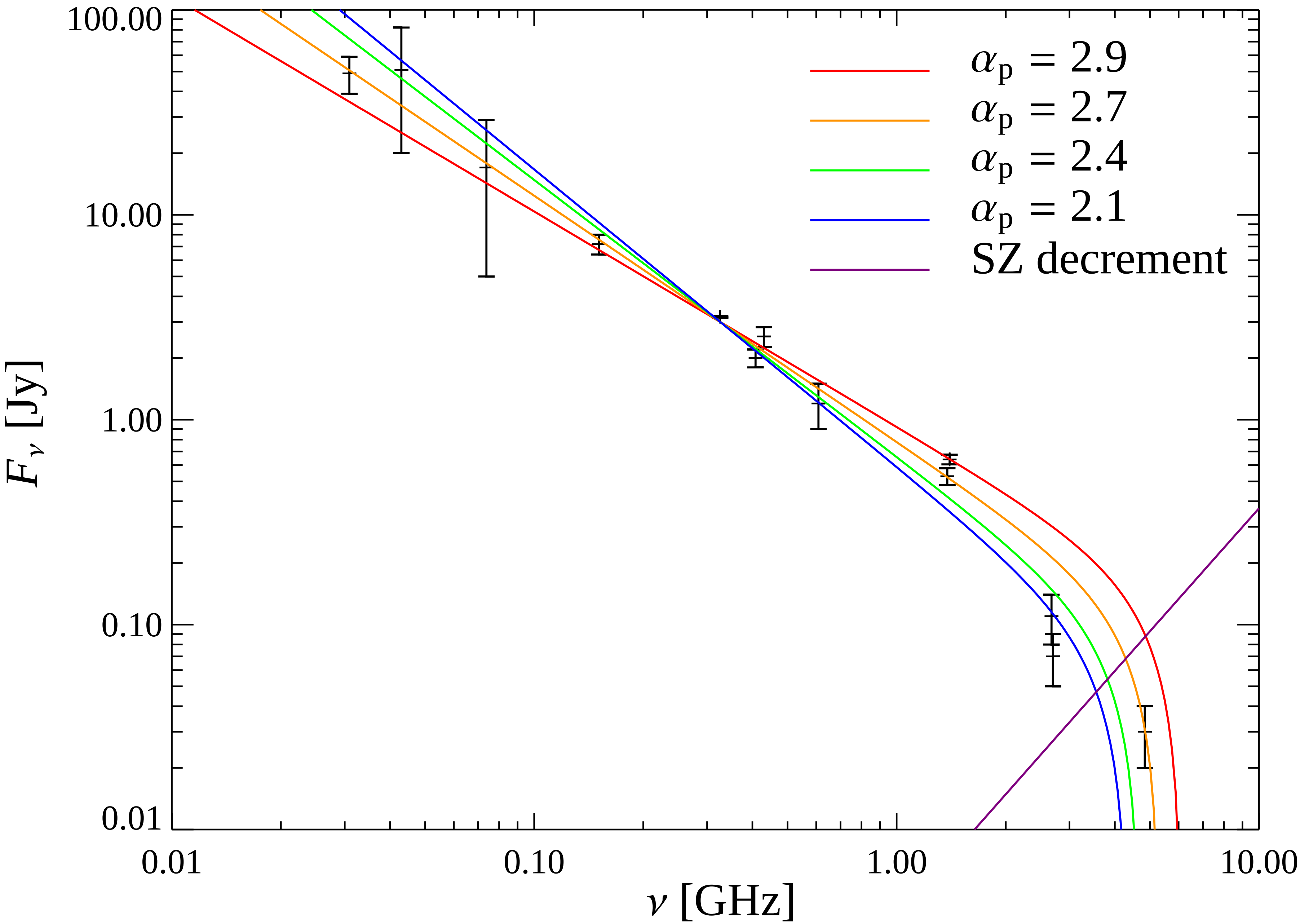


Parameter study on the hadronic origin of the Coma radio halo



Observed radio halo fluxes of the Coma cluster

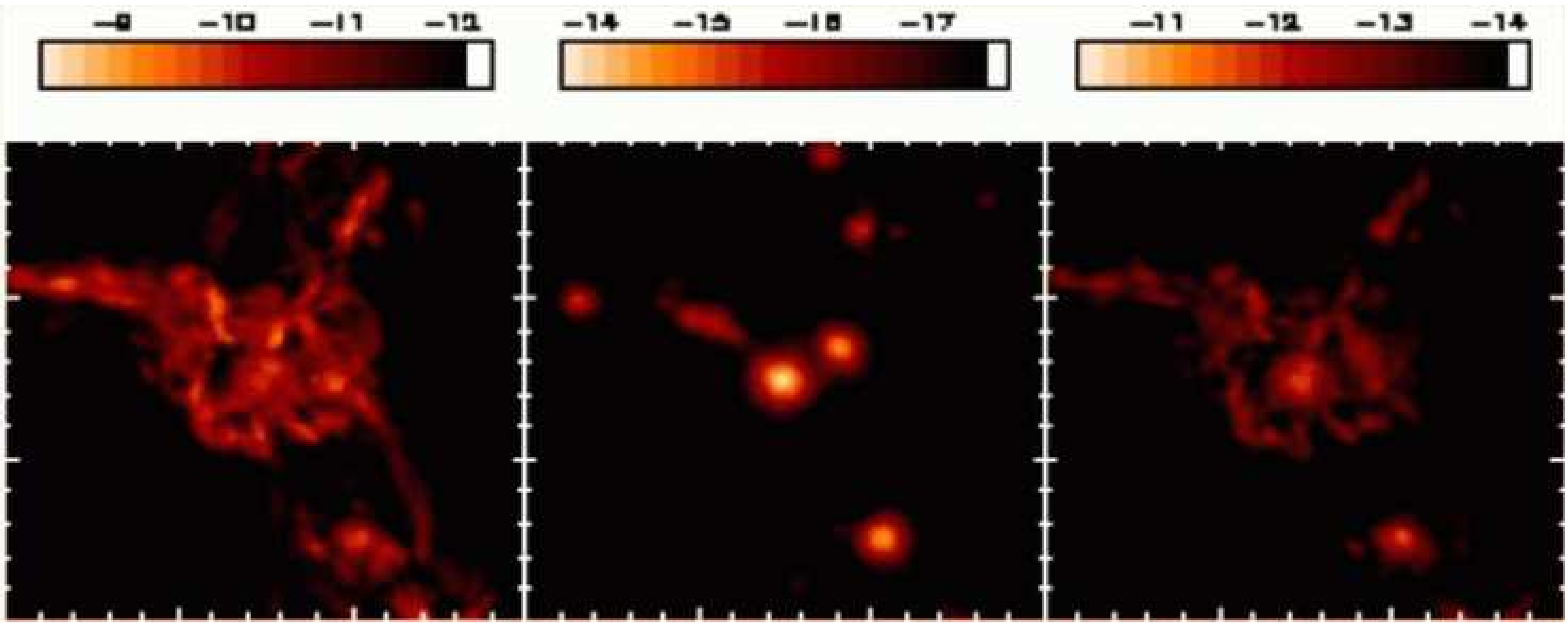


Simulation of CR emission processes in galaxy clusters

Hard X−ray: F(> 100 keV)

Thermal X−ray:

γ−ray: F(> 100 MeV)



Credit: Miniati (2003)

Simulation of CR emission processes

Secondary emission: Primary emission:

F(>100 keV)

F(>100 MeV)