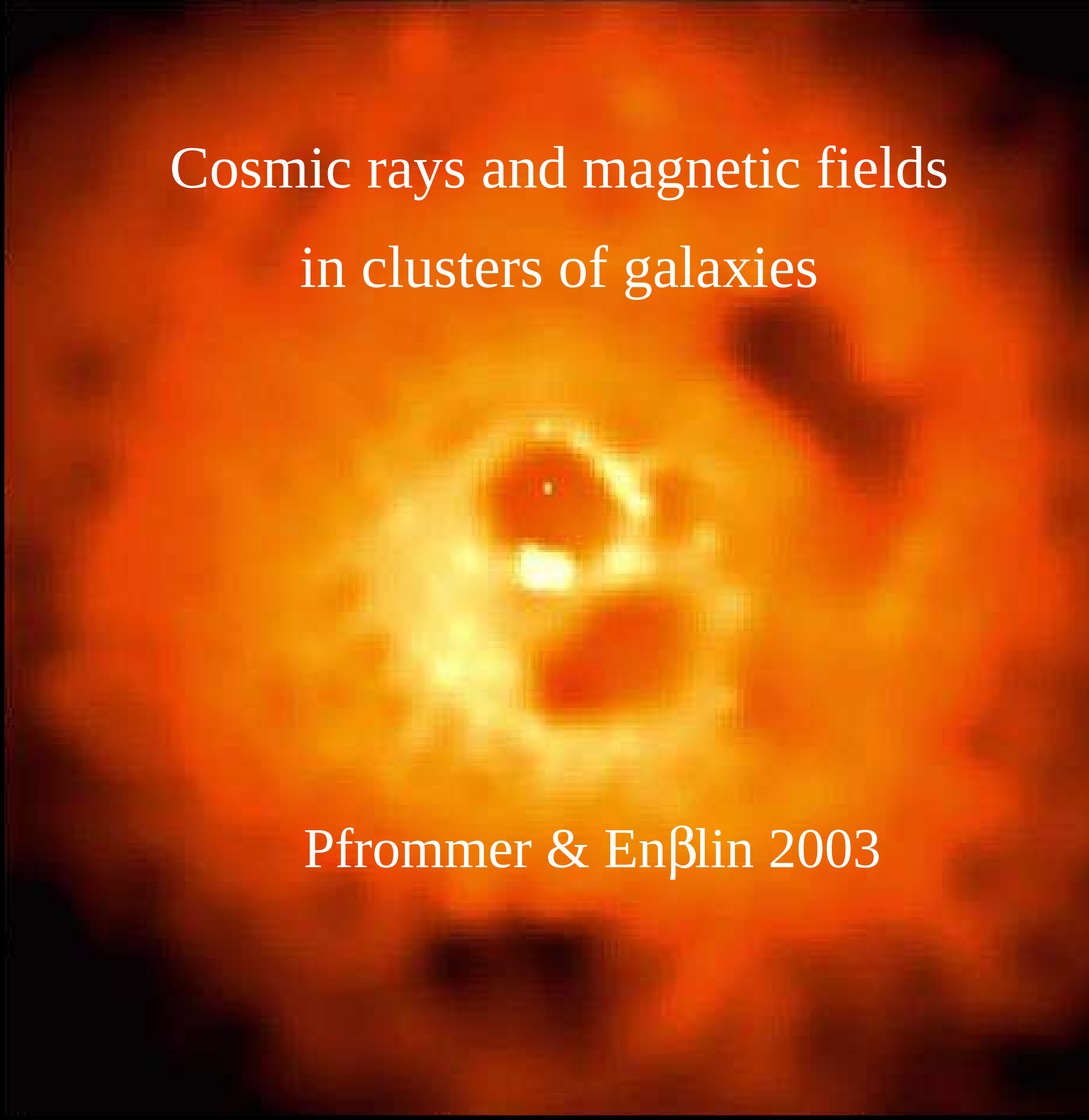
Cosmic rays and magnetic fields in clusters of galaxies



Pfrommer & Enβlin 2003

Outline of the Talk

A) Introduction and Motivation

1.) Galactic CR versus CR in galaxy clusters

2.) Acceleration mechanism of CRp

3.) Hadronic CRp interactions in the ICM

B) CRp in nearby clusters of galaxies

1.) Gamma−ray emission induced by CRp

2.) Hadronic origin of radio (mini−)halos

3.) Estimating cluster magnetic fields

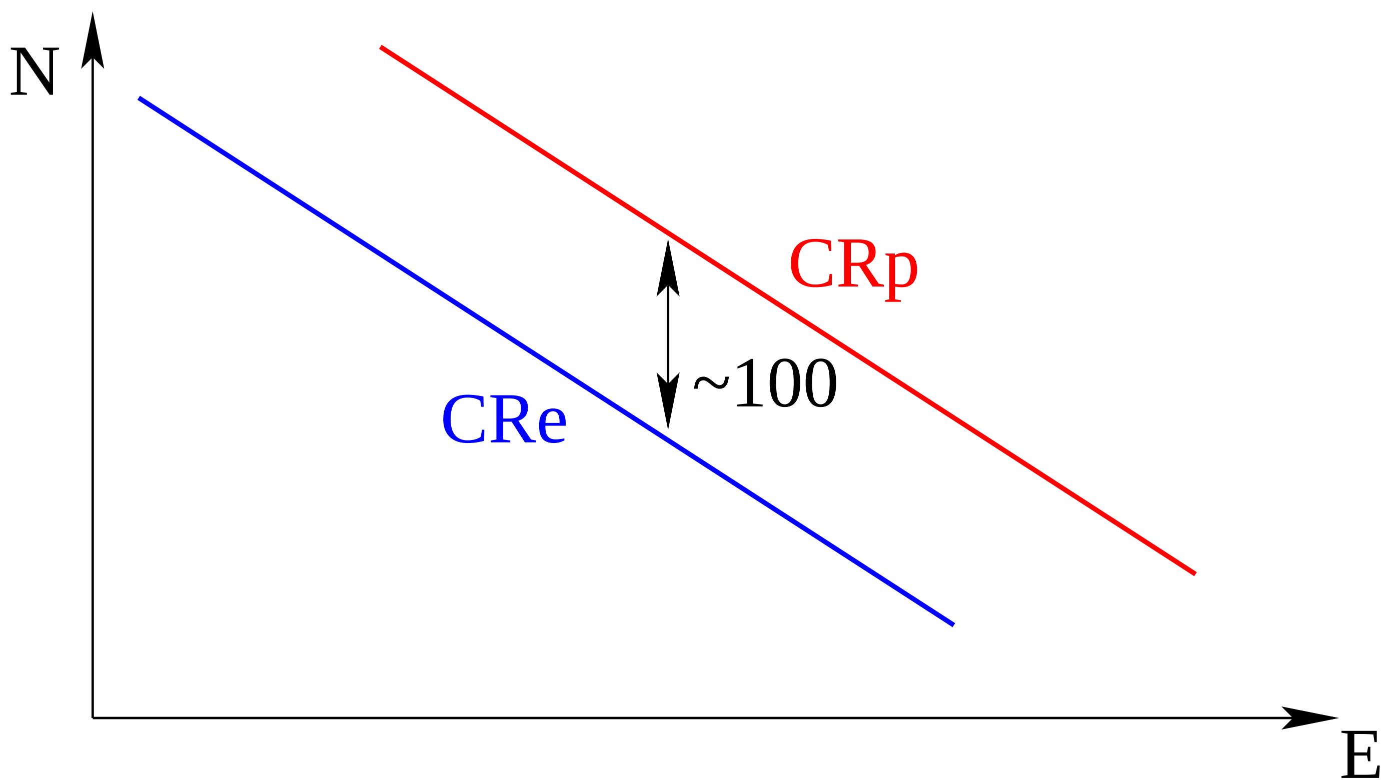
C) Conclusions

What are Galactic cosmic rays?

- relativistic particles: electrons, protons, α, ...

  electrons → CRe   protons → CRp

- $v \sim c \longrightarrow E > \mathrm{GeV} \gg m\,c^2$



Galactic cosmic rays cont.'d:

Typical lifetimes and losses of CR:

- escape of CR: $\sim 10^7\,\mathrm{yr}$ − radioactive clocks

- Energy losses:

  CRe: synchrotron, inverse Compton (IC), Coulomb

  CRp: inelastic collisions, Coulomb

Cosmic rays in clusters of galaxies:

Typical lifetimes and losses of CR:

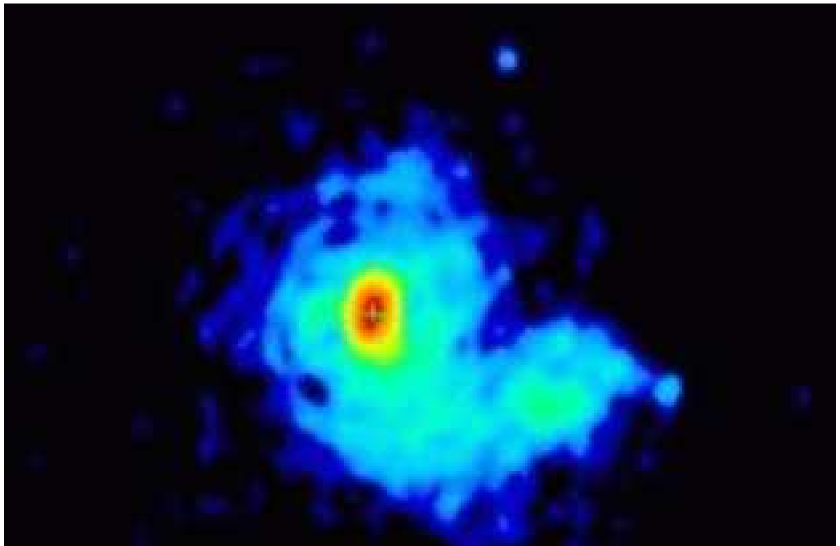
- escape of CR: $\longrightarrow$ impossible due to magnetic fields

- Energy losses: $E \sim 10$ GeV

CRe: synchrotron, IC: $\tau \sim 10^8$yr

CRp: inelastic collisions, Coulomb:

$\tau \sim 10^{10}$yr ~ Hubble time


Credit: Pedlar et al. (1990)

$\longrightarrow$ CRp can maintain a clusterwide distribution through diffusion

CRe are observed in clusters of galaxies!

CRp?

- Do they exist there?
- How many are there?
- Which implications would a significant population have?

Cosmological implications of CRp

- modification of the energy budget of clusters
- pressure balance $\longrightarrow$ change of the ICM evolution
- modification of hydrostatic mass estimates
- ICM heating (cooling flow problem)

Main injection mechanisms of CRp into the ICM:

- CRp acceleration at structure formation and accretion shocks:

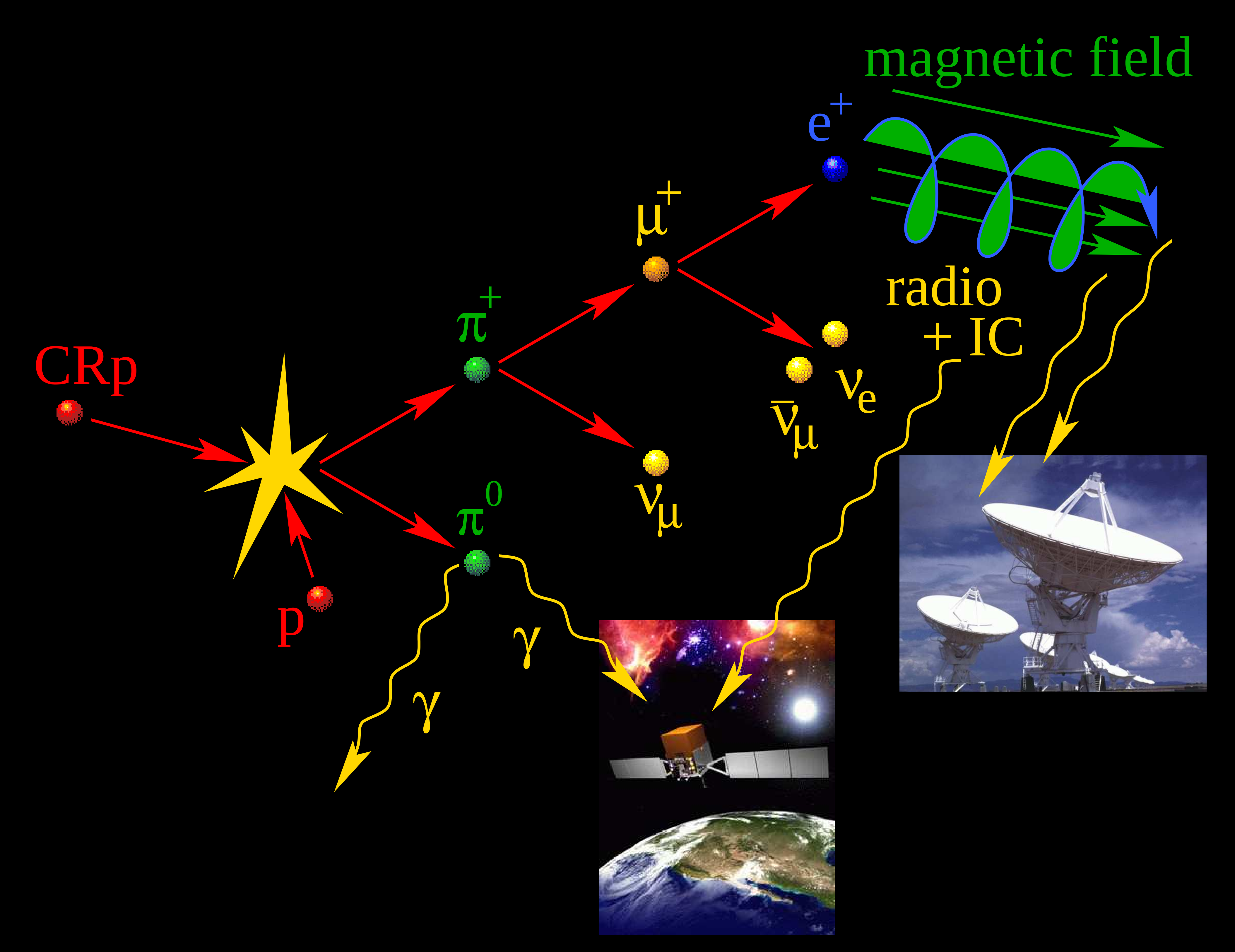
  Energy dissipation at the shock front → thermal energy
  → CRp acceleration

- Supernova driven galactic winds advect and inject CRp into the ICM

- CRp diffusion away from an AGN/radio galaxy into the ICM

How can we observe CRp in clusters of galaxies?

→ How many CRp are there?



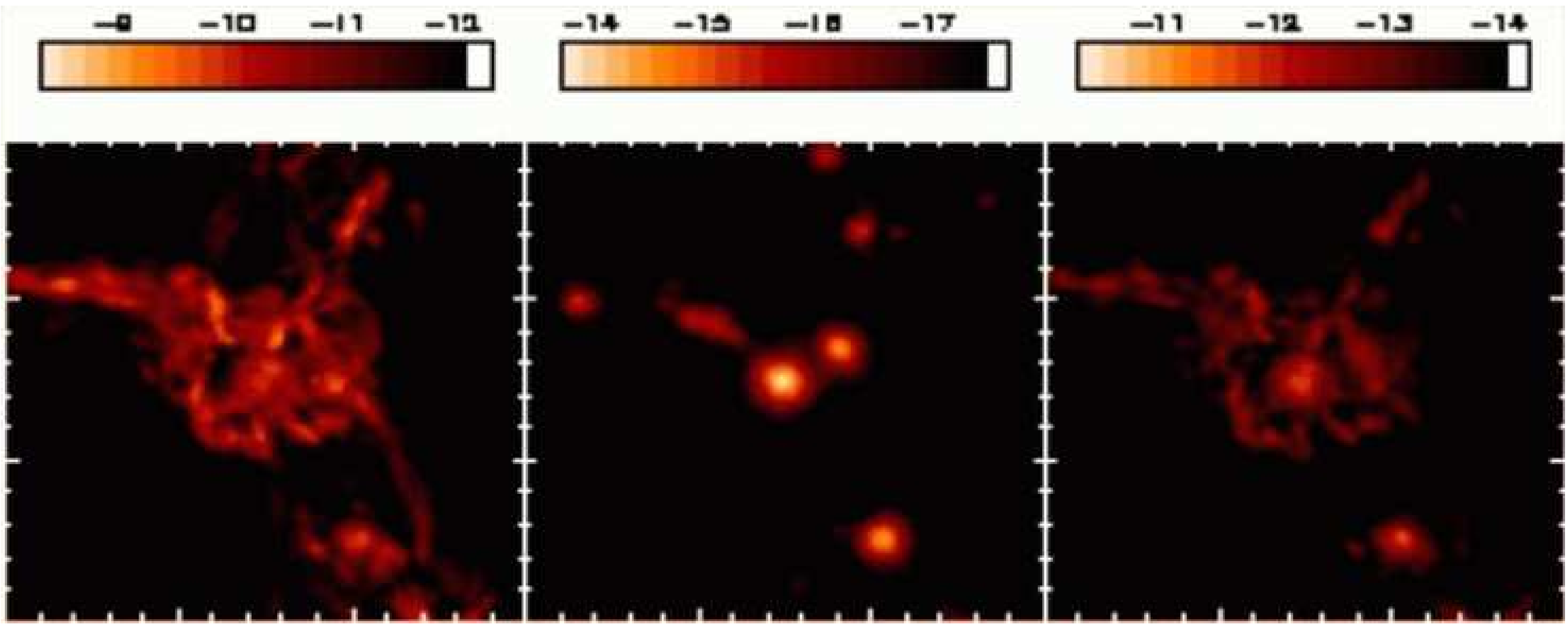
magnetic field
e+
μ+
π+
CRp
p
π0
νμ
ν̄μ
νe
radio
+ IC
γ
γ

Simulation of CR emission processes in galaxy clusters

Hard X−ray: F(> 100 keV)

Thermal X−ray:

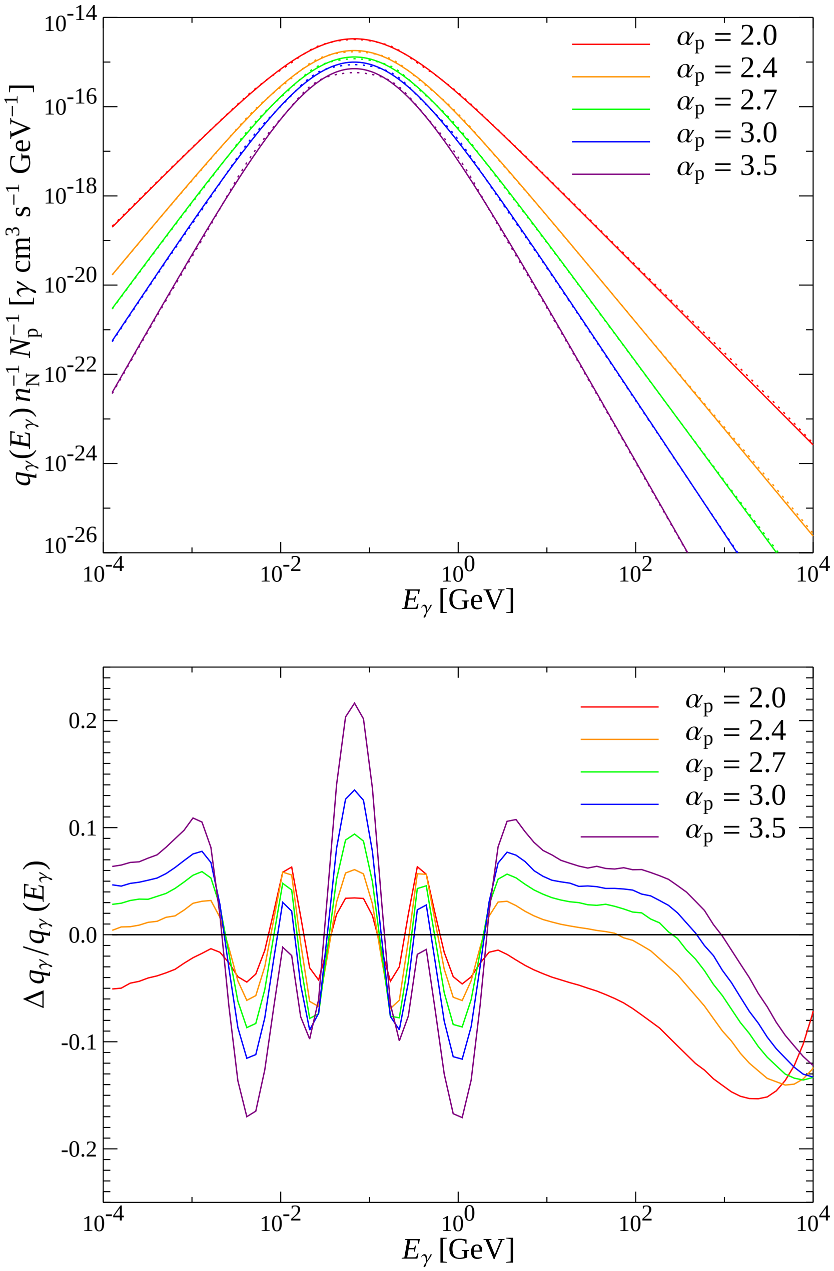
γ−ray: F(> 100 MeV)



Miniati 2003, MNRAS

Gamma ray source function

Pfrommer & Enßlin 2003:



- 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:

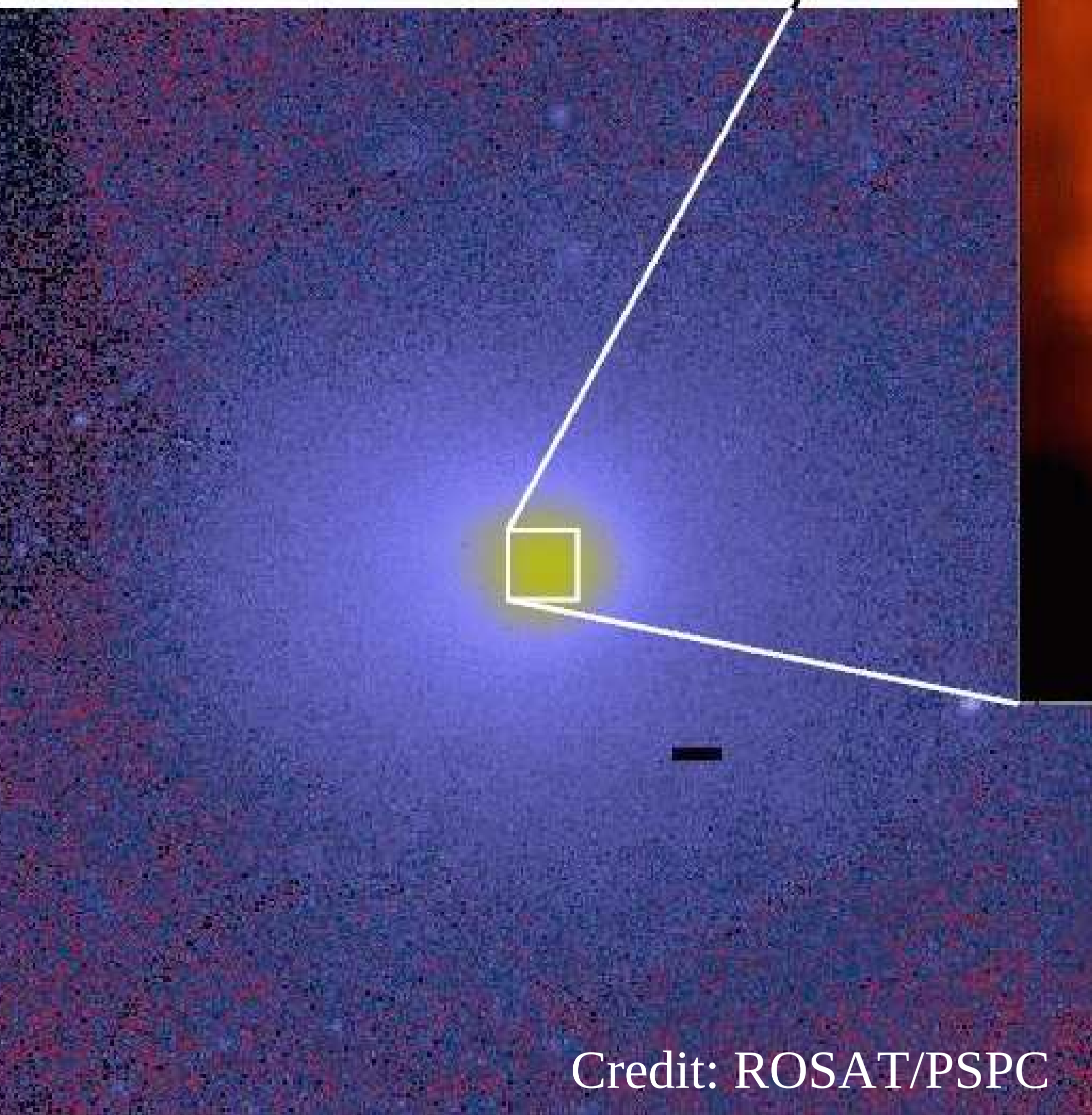
$$q_\gamma(\mathbf{r}, E_\gamma) \simeq \sigma_{pp}\, c\, n_N(\mathbf{r})\, 2^{2-\alpha_\gamma} \frac{\tilde{n}_{CRp}(\mathbf{r})}{\mathrm{GeV}} \times$$

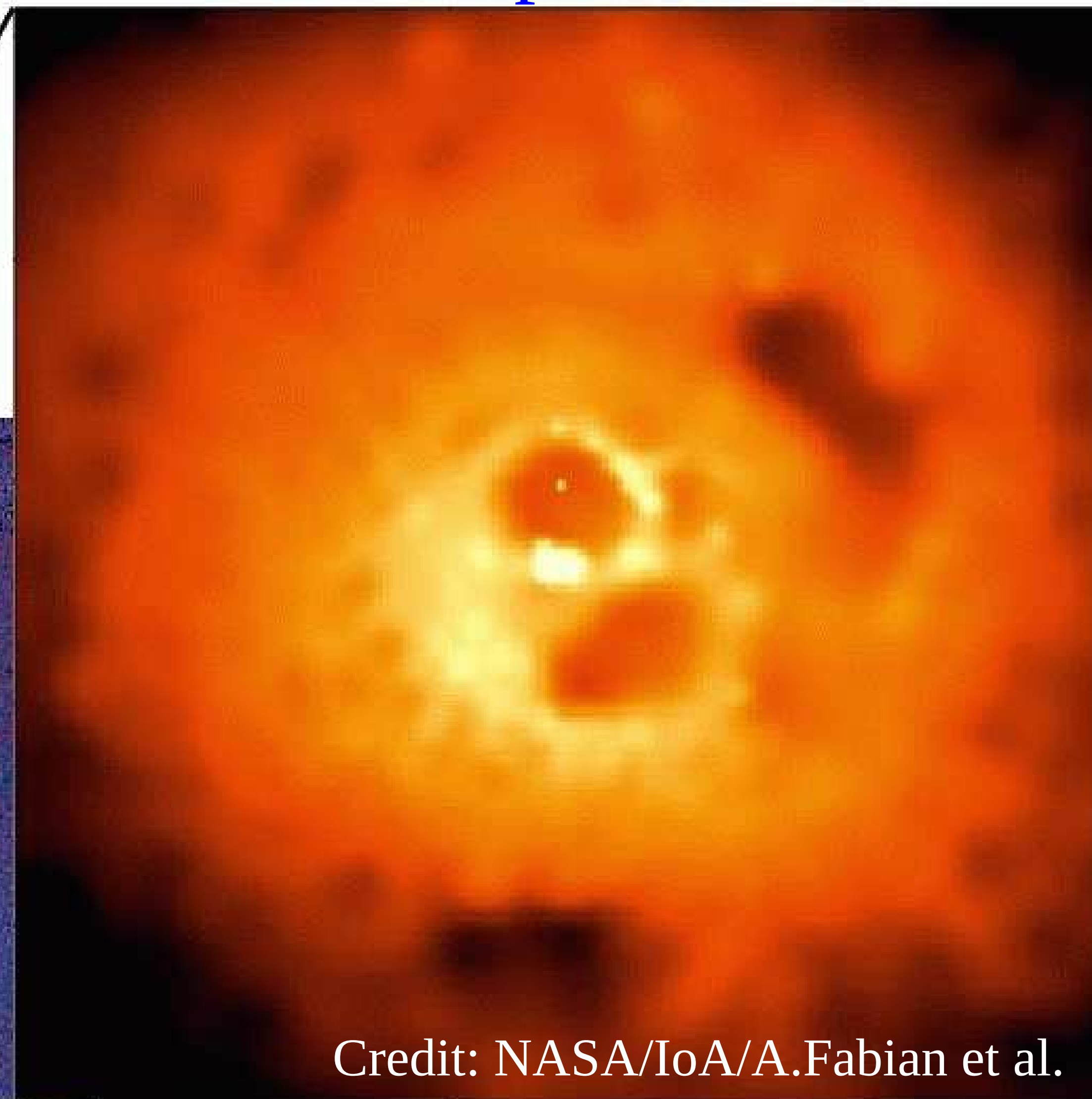
$$\frac{4}{3\,\alpha_\gamma} \left(\frac{m_{\pi^0}\, c^2}{\mathrm{GeV}}\right)^{-\alpha_\gamma} \left[\left(\frac{2\,E_\gamma}{m_{\pi^0}\, c^2}\right)^{\delta_\gamma} + \left(\frac{2\,E_\gamma}{m_{\pi^0}\, c^2}\right)^{-\delta_\gamma}\right]^{-\alpha_\gamma/\delta_\gamma}$$

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

Cooling flow clusters are efficient CRp detectors!

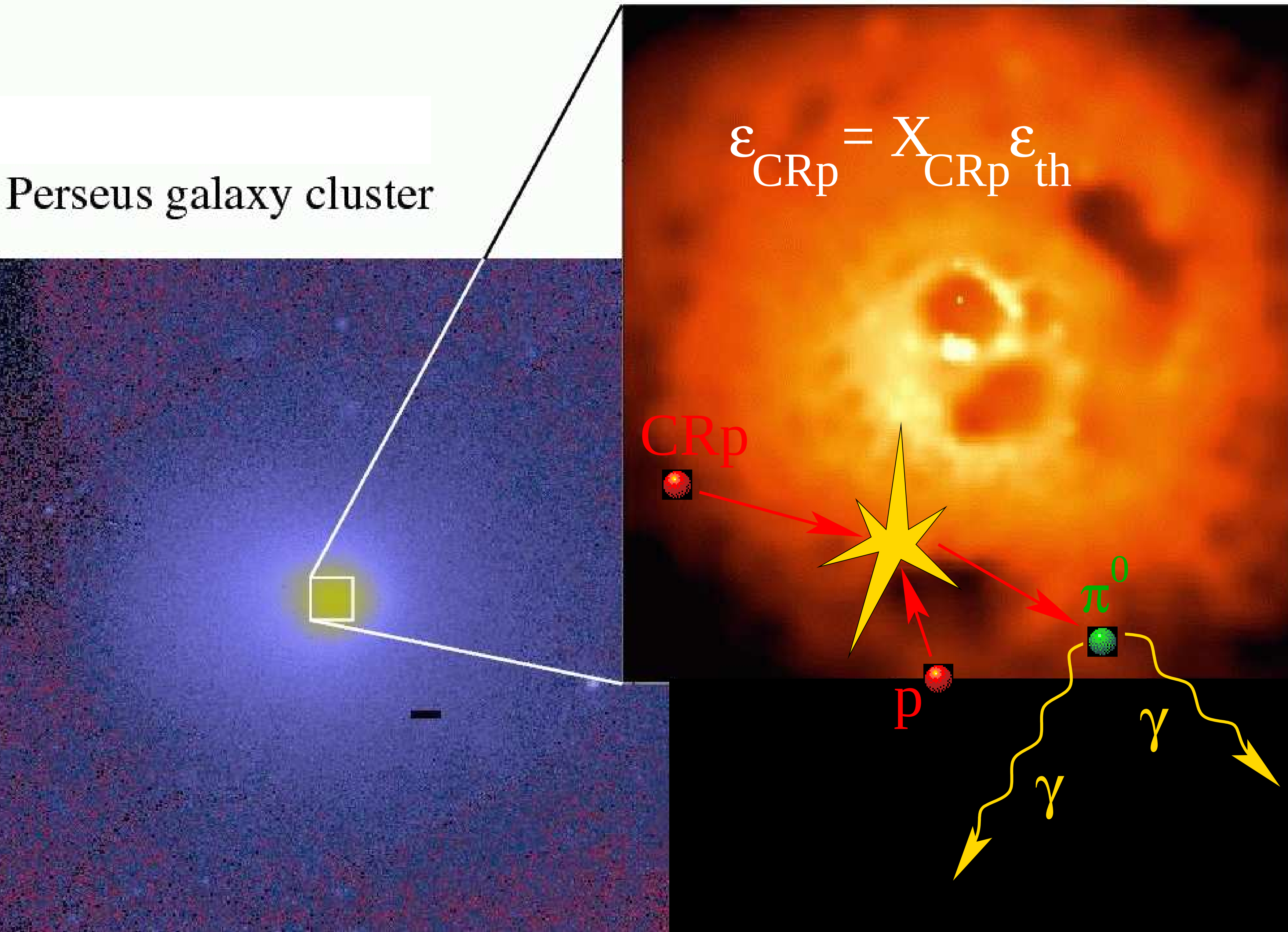
ROSAT observation:
Perseus galaxy cluster





Chandra observation:
central region of Perseus

Cooling flow 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

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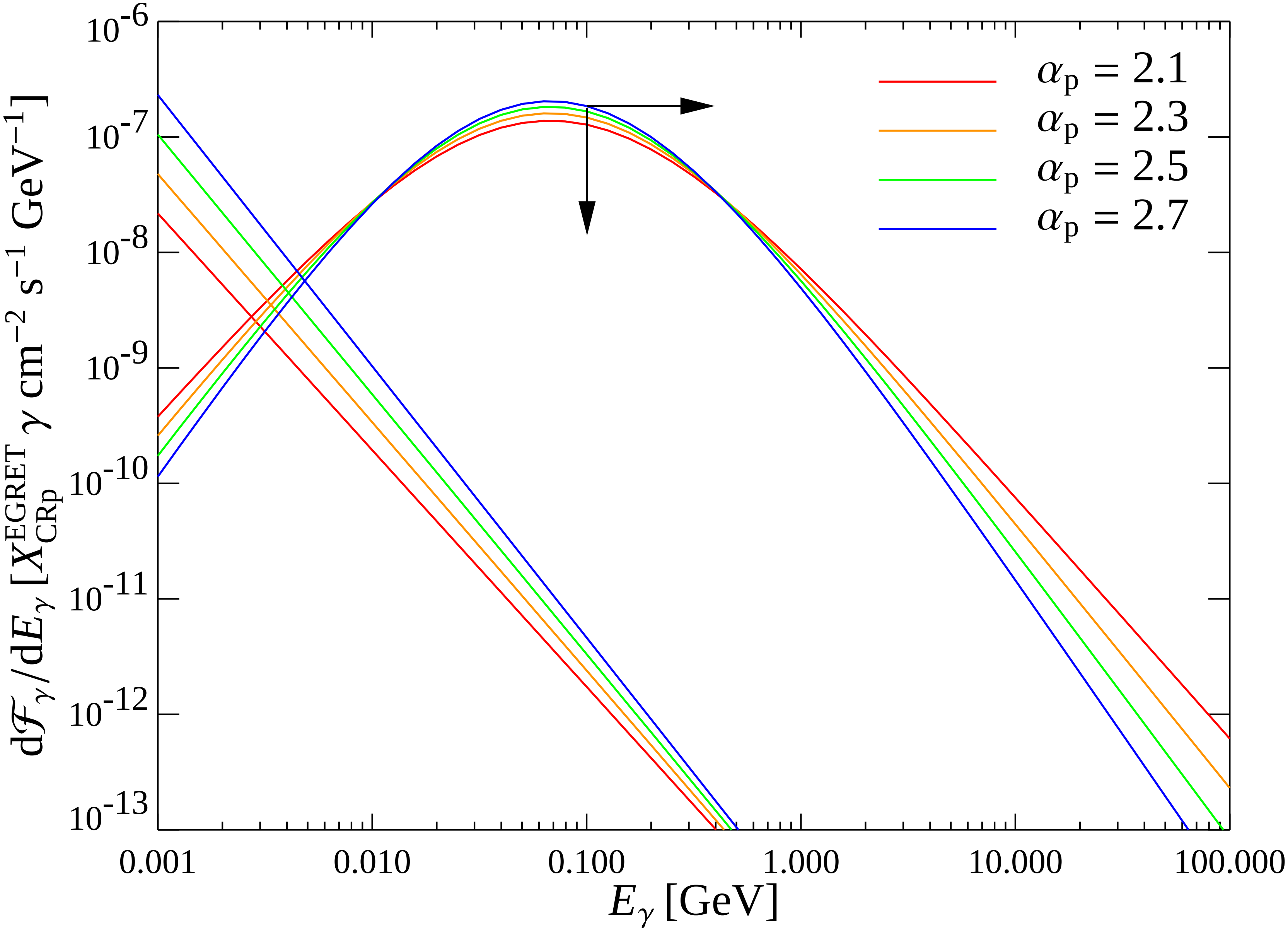
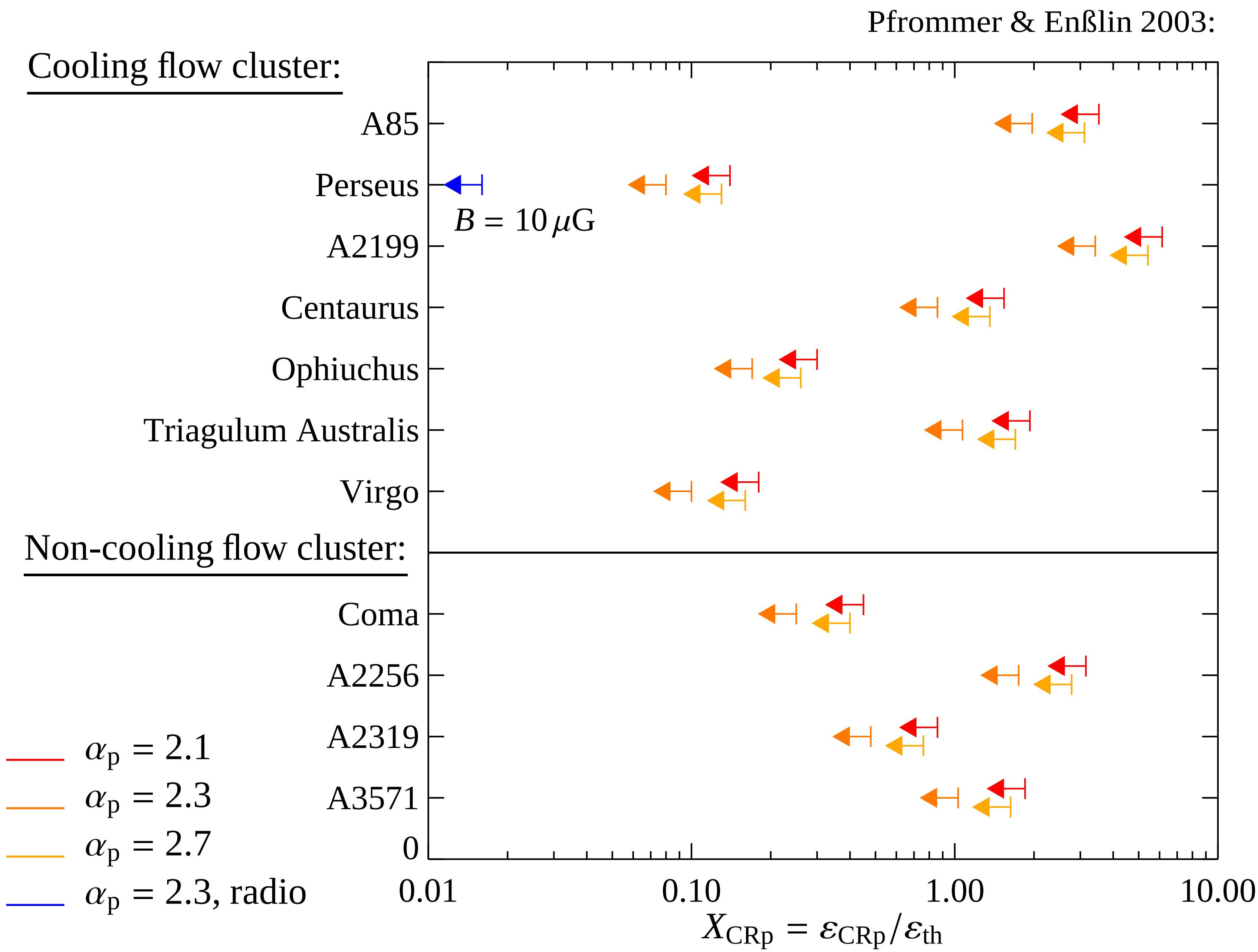


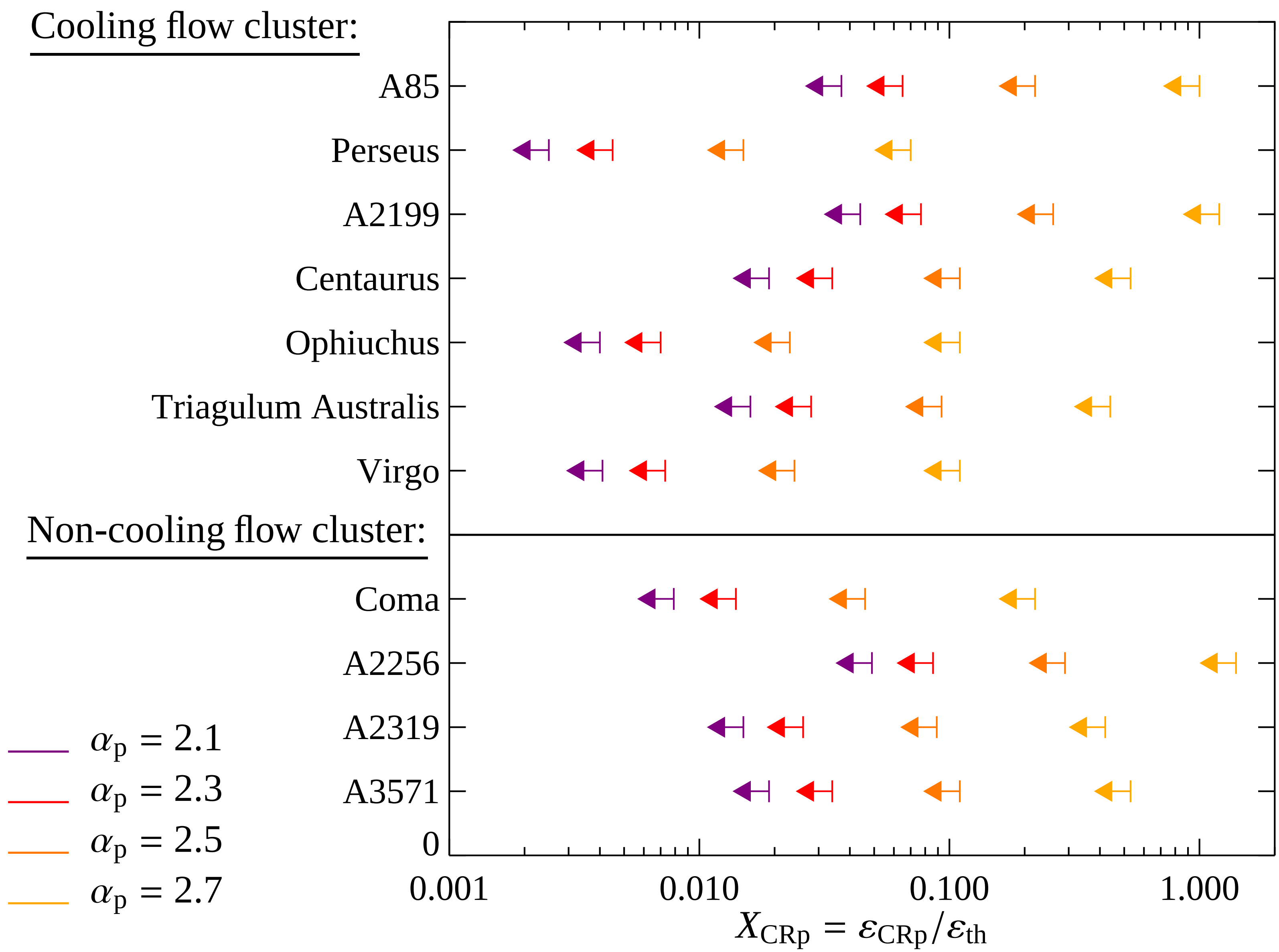
Upper limits on X_CRp using EGRET limits:



Expected limits on X_CRp using Cerenkov telescopes:

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

Pfrommer & Enßlin 2003:



HEGRA – M87: TeV position

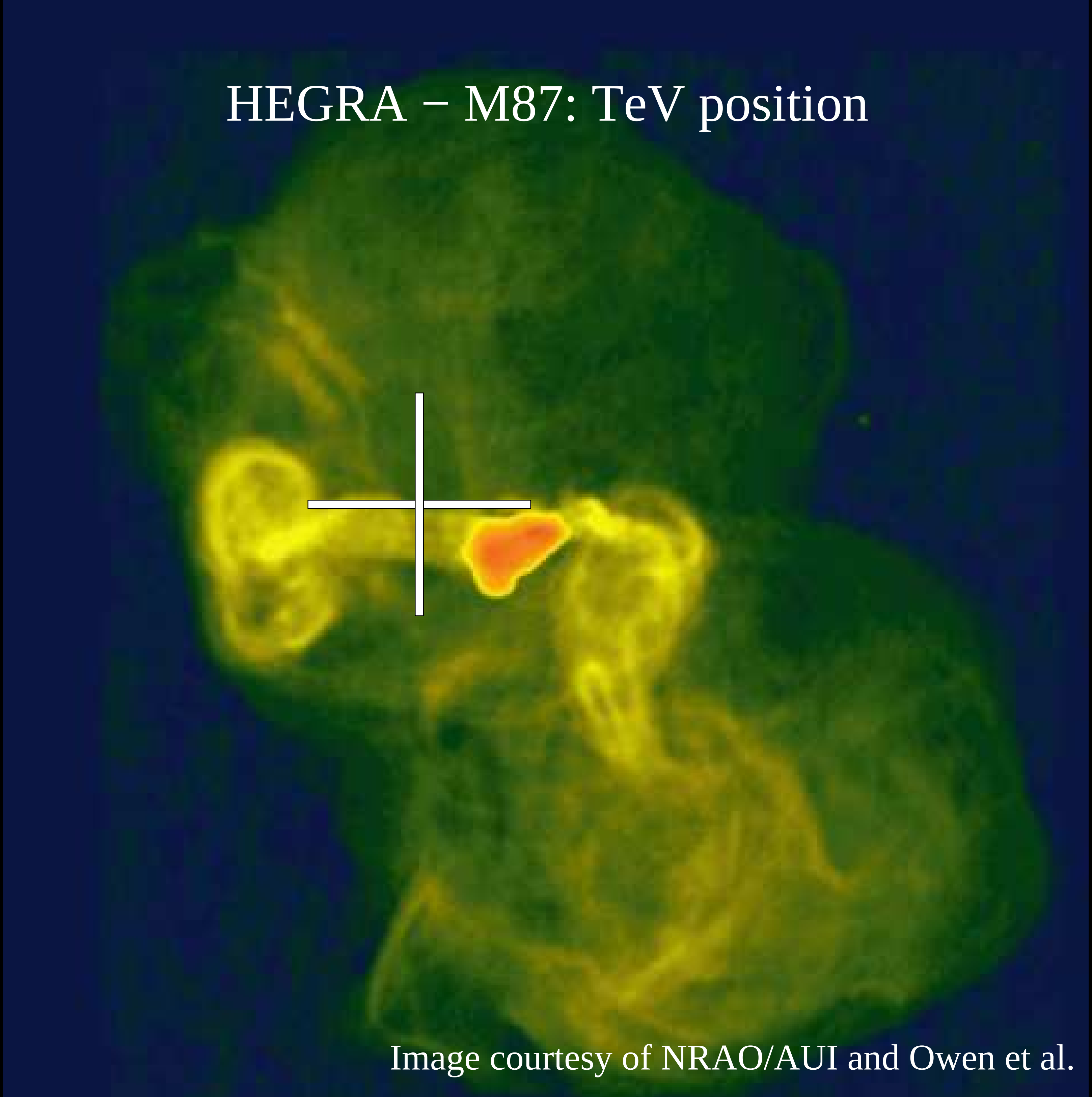


Image courtesy of NRAO/AUI and Owen et al.

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

- Processed radiation of the relativistic outflow (jet):

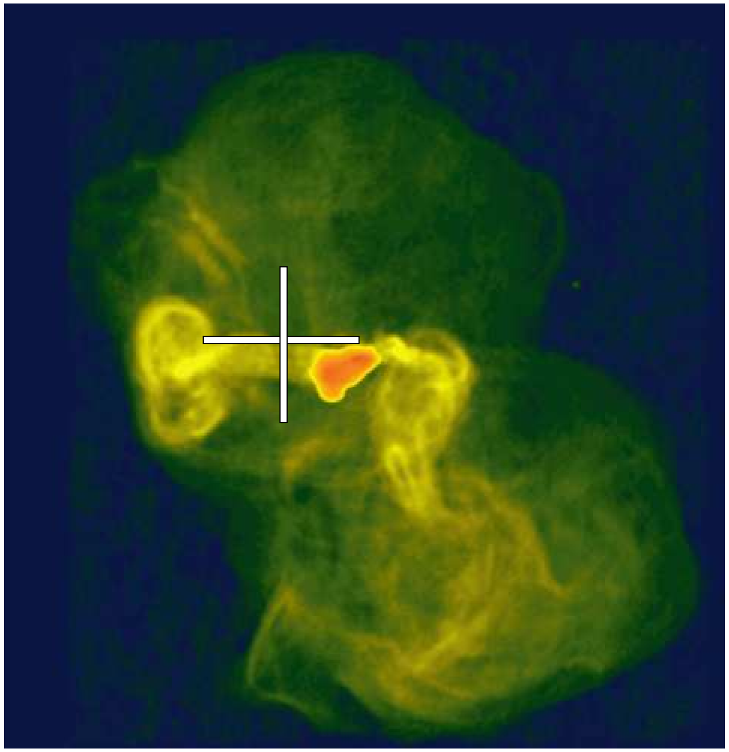
  e.g. IC upscattering of CMB photons by CRe (jet), SSC scenario

- Dark matter annihilation or decay processes

- Hadronically originating gamma−rays:

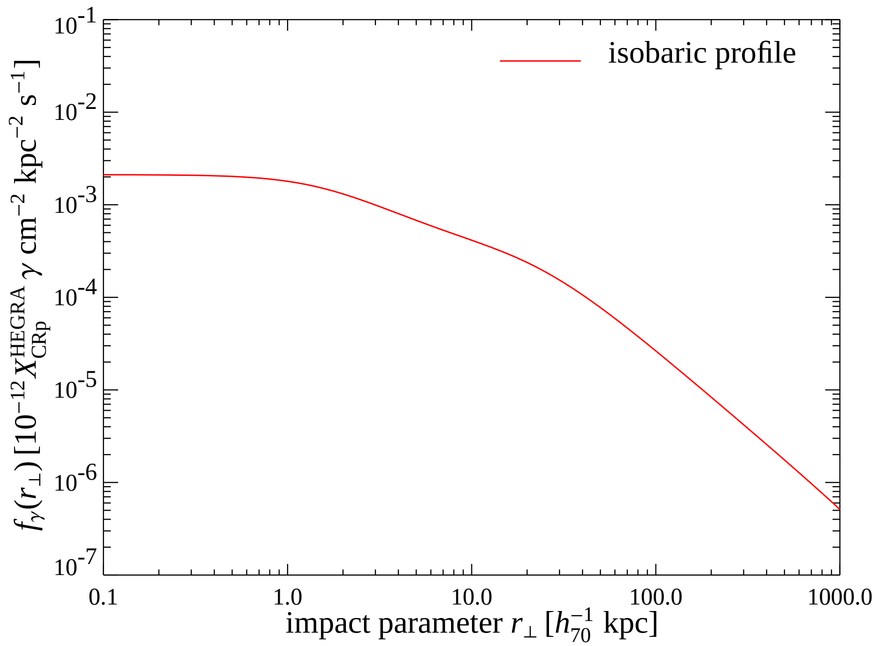
  Assuming CRp power−law distribution and a model for the CRp spatial distrib.

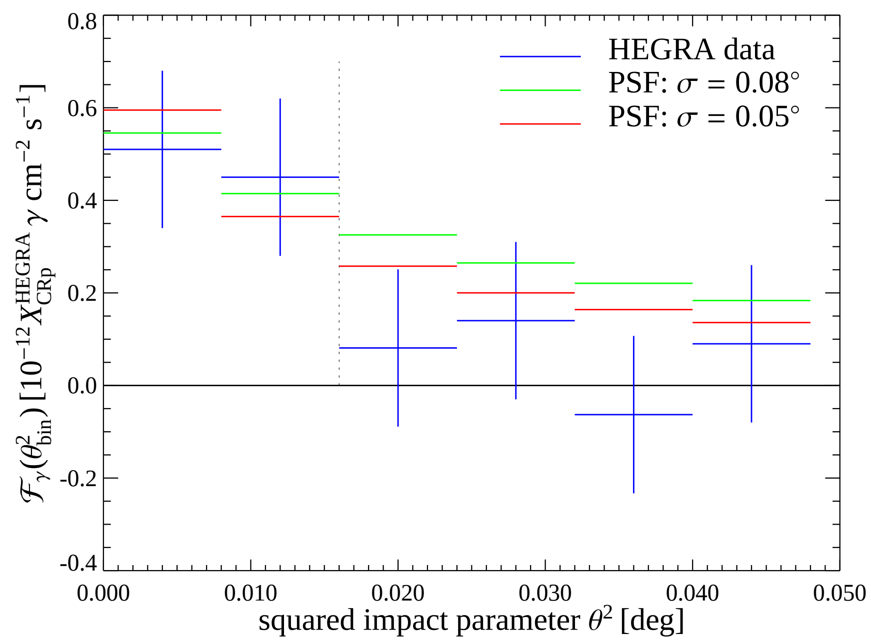
  ⟶ measurement of the CRp population in ICM/ISM of M 87!



Gamma ray flux profile of M 87 (Virgo):

Pfrommer & Enßlin 2003:





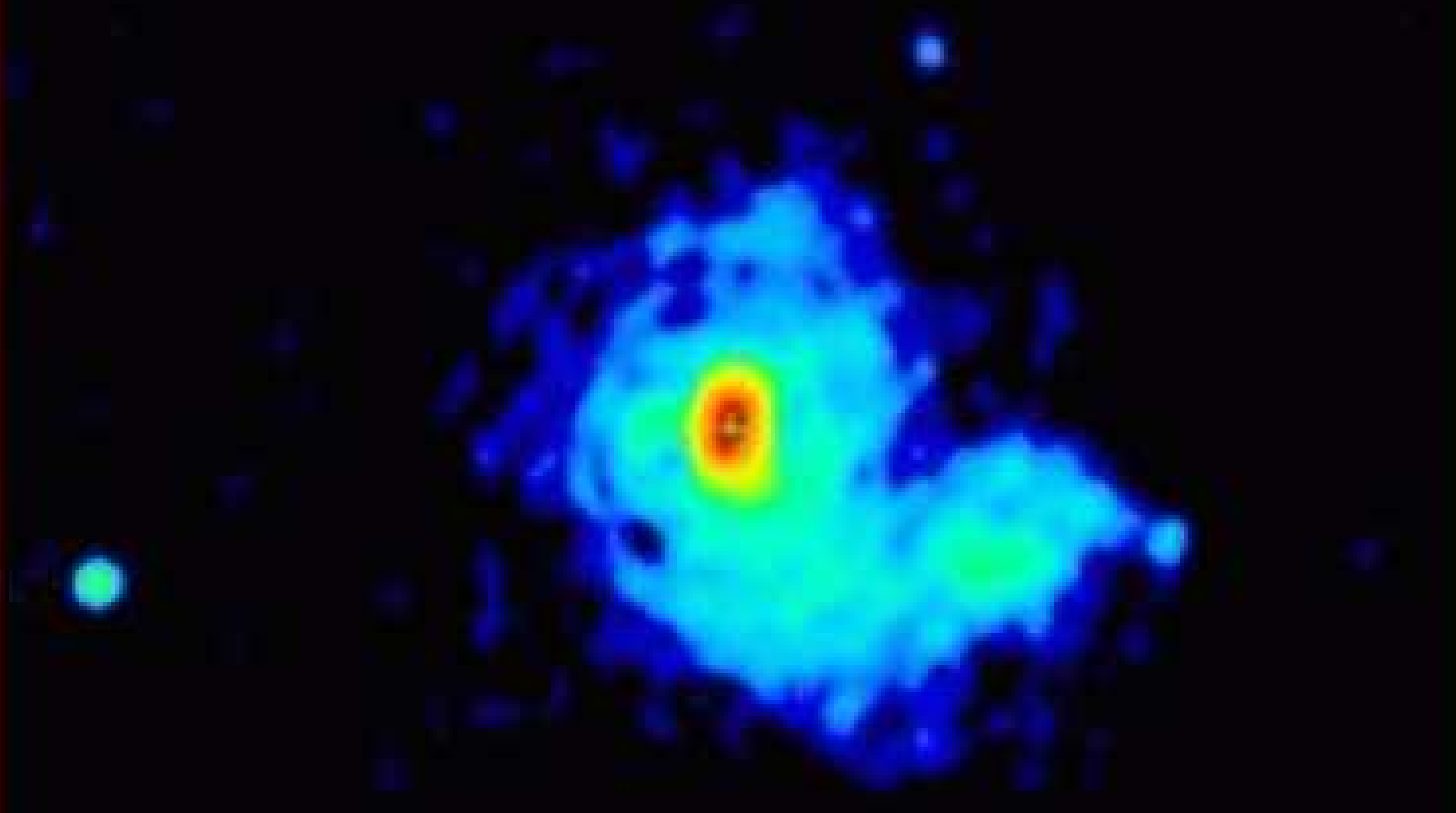
Top:

- 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)

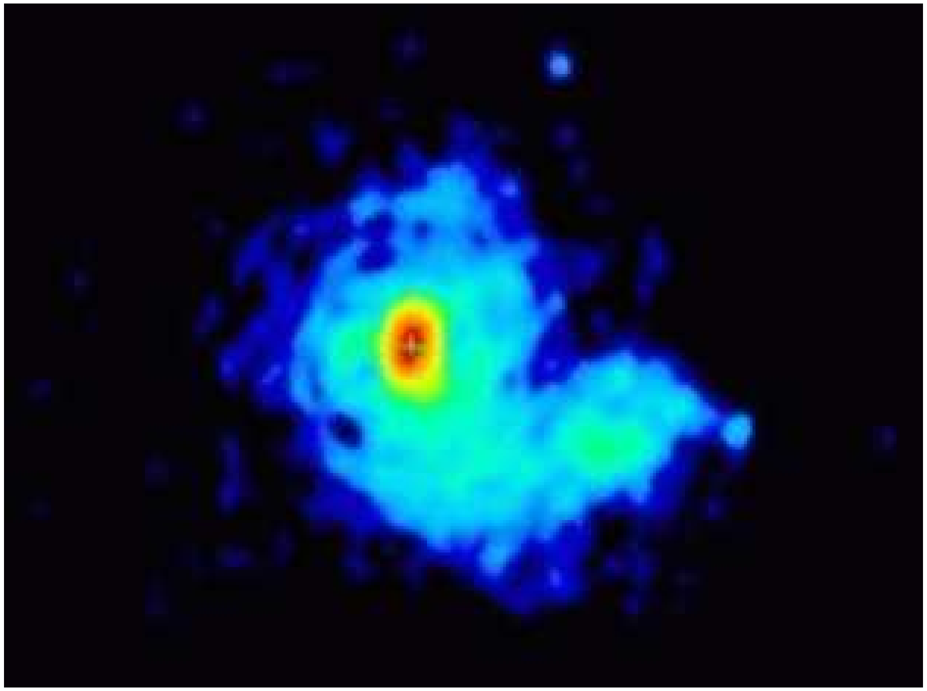
What is the origin of radio mini−halos?

Synchrotron emission by CRe, but which population?

- Directly accelerated CRe at structure formation or merger shocks ⟶ diffusion length scales too short!
- Reaccelerated CRe (in situ) by magnetic turbulence in the ICM
- Hadronically originating CRe:

Assuming a mag. field strength

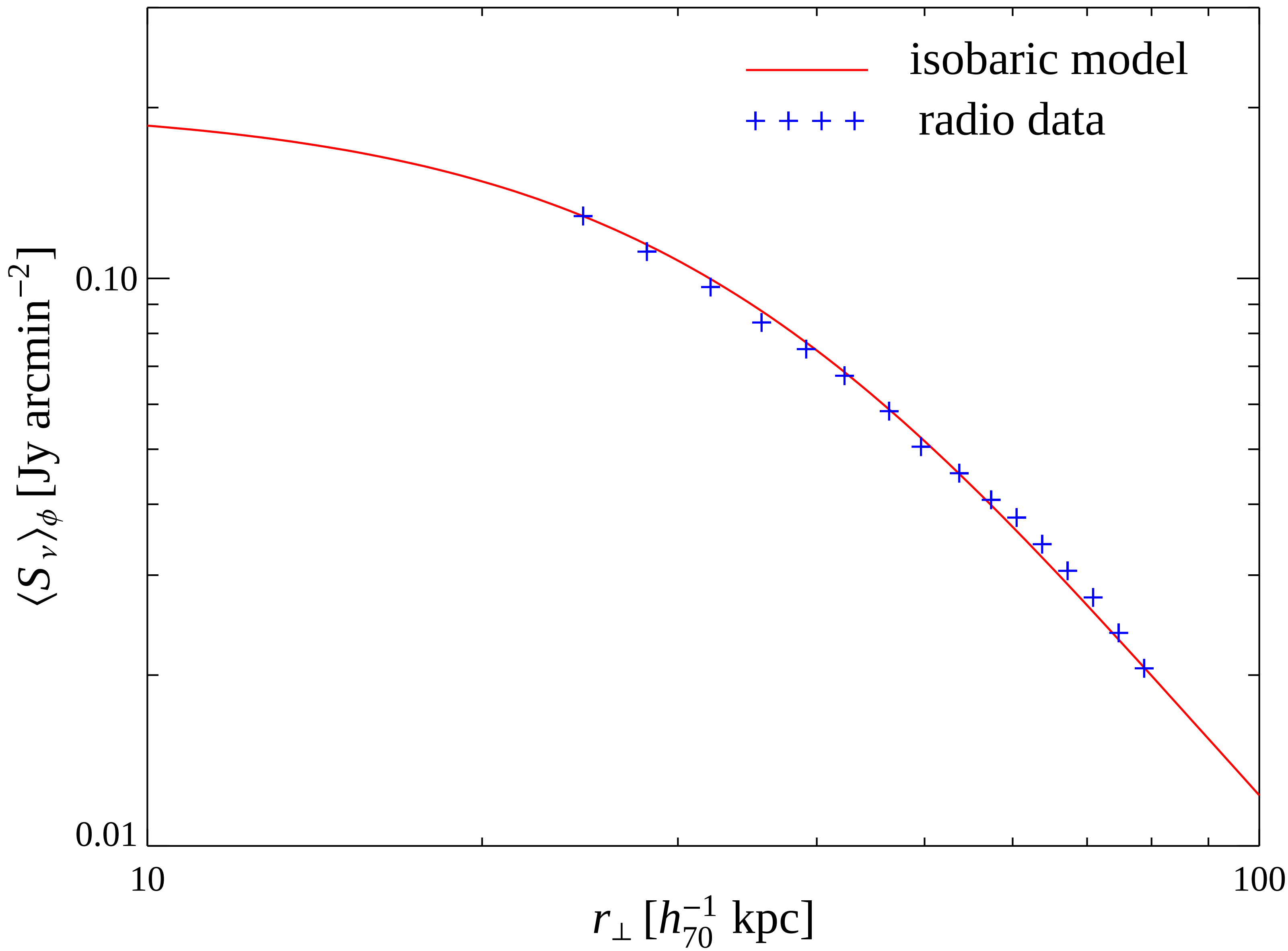
⟶ measure/upper limit of CRp population in ICM



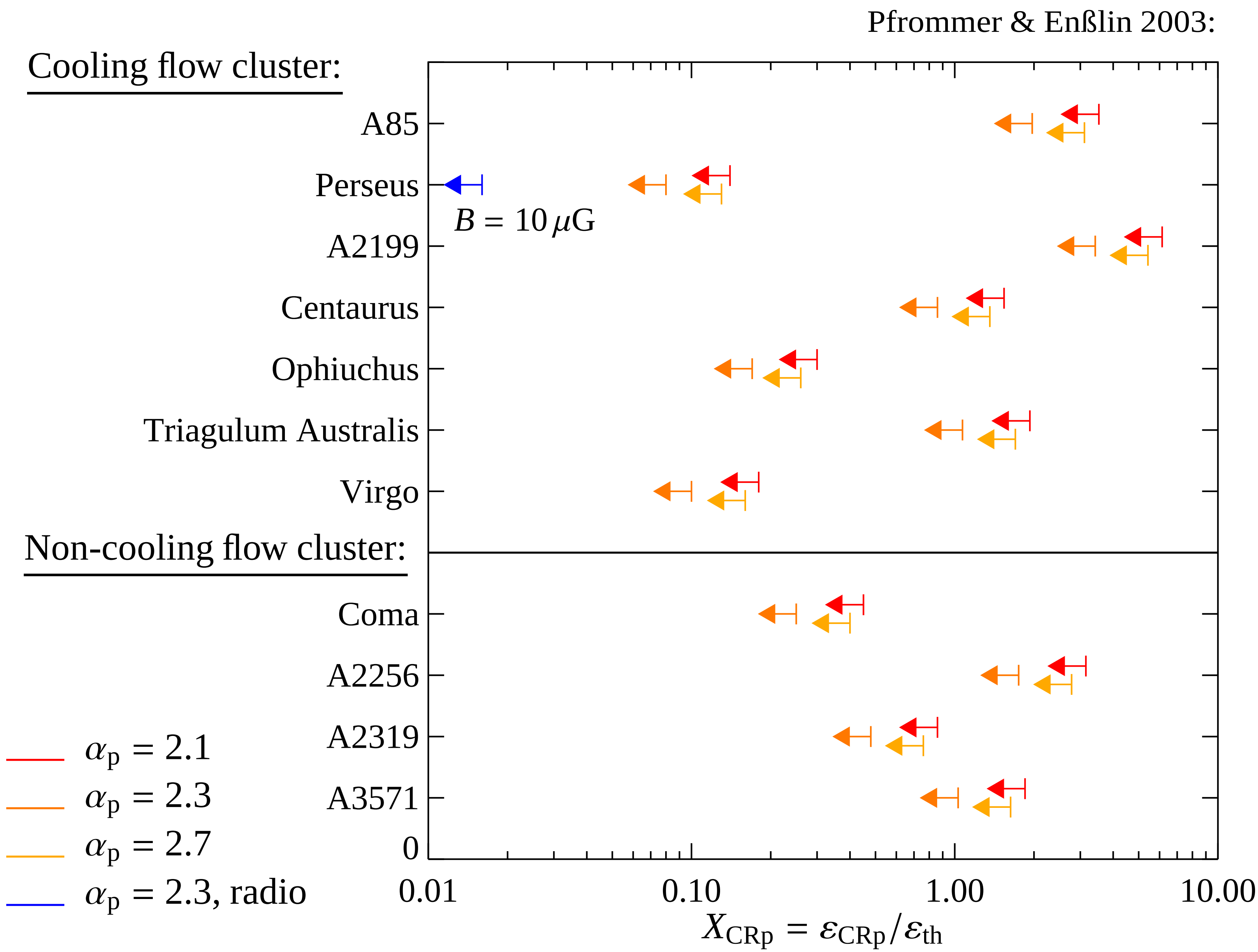
Brightness profile of Perseus radio mini−halo:

Synchrotron radiation of hadronically originating CRe

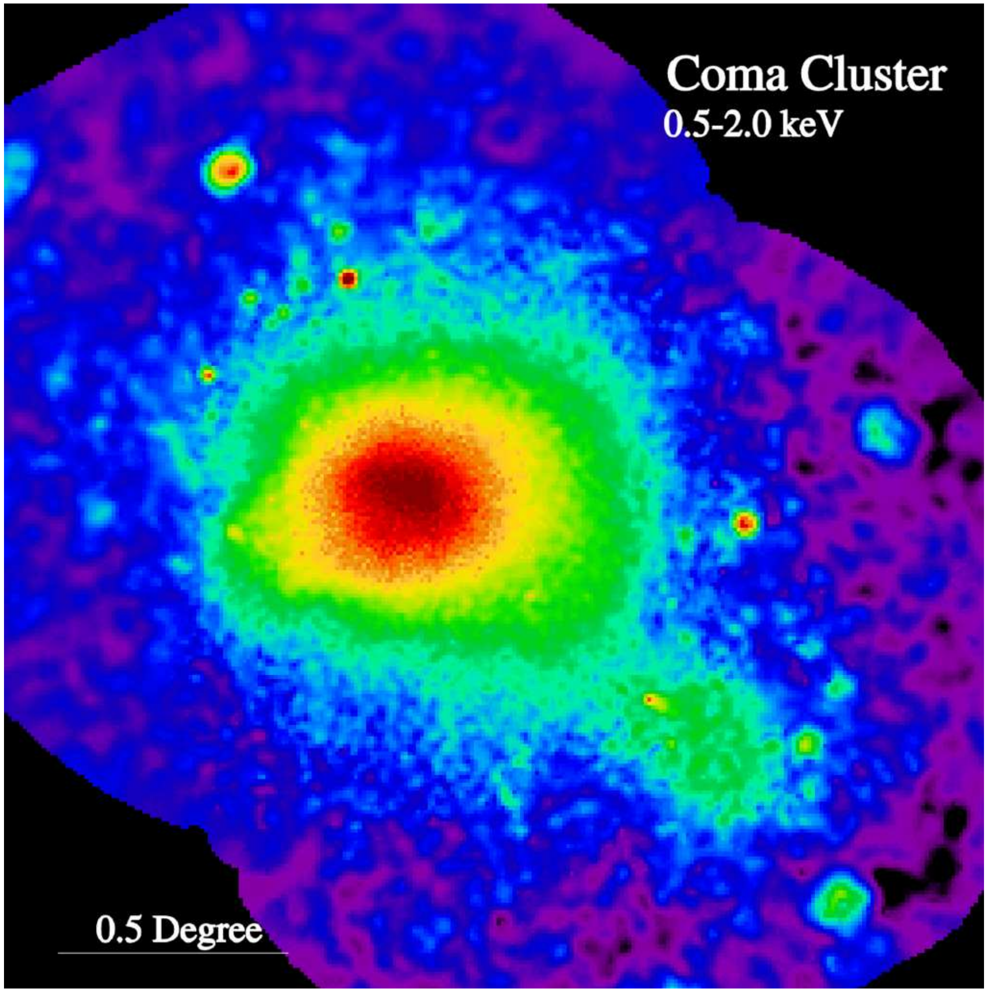
Pfrommer & Enßlin 2003:

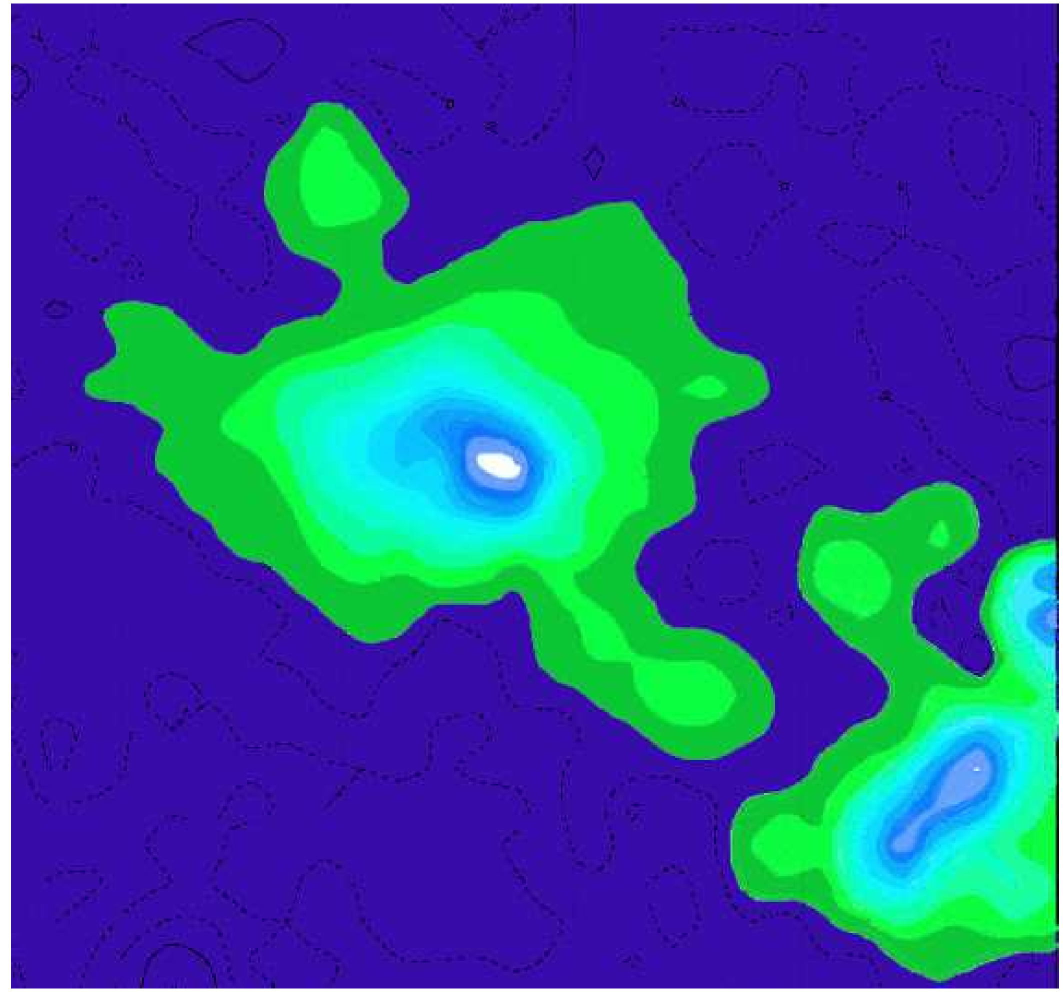


Upper limits on X_CRp using EGRET limits:



Coma galaxy cluster





ROSAT−PSPC: 2.7° x 2.5°

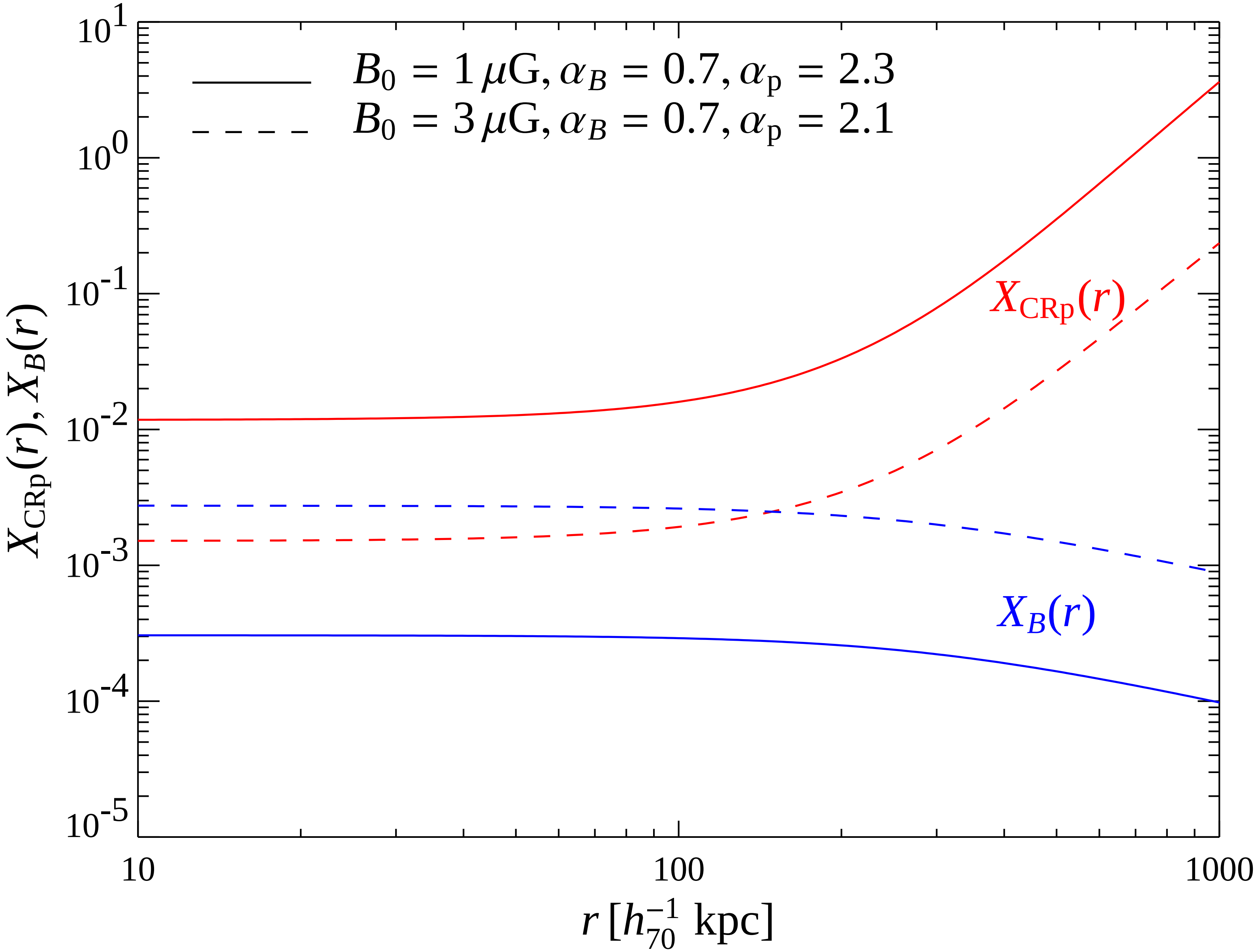
Credit: ROSAT/MPE/Snowden

Radio halo, 1.4 GHz: 2.5° x 2.0°

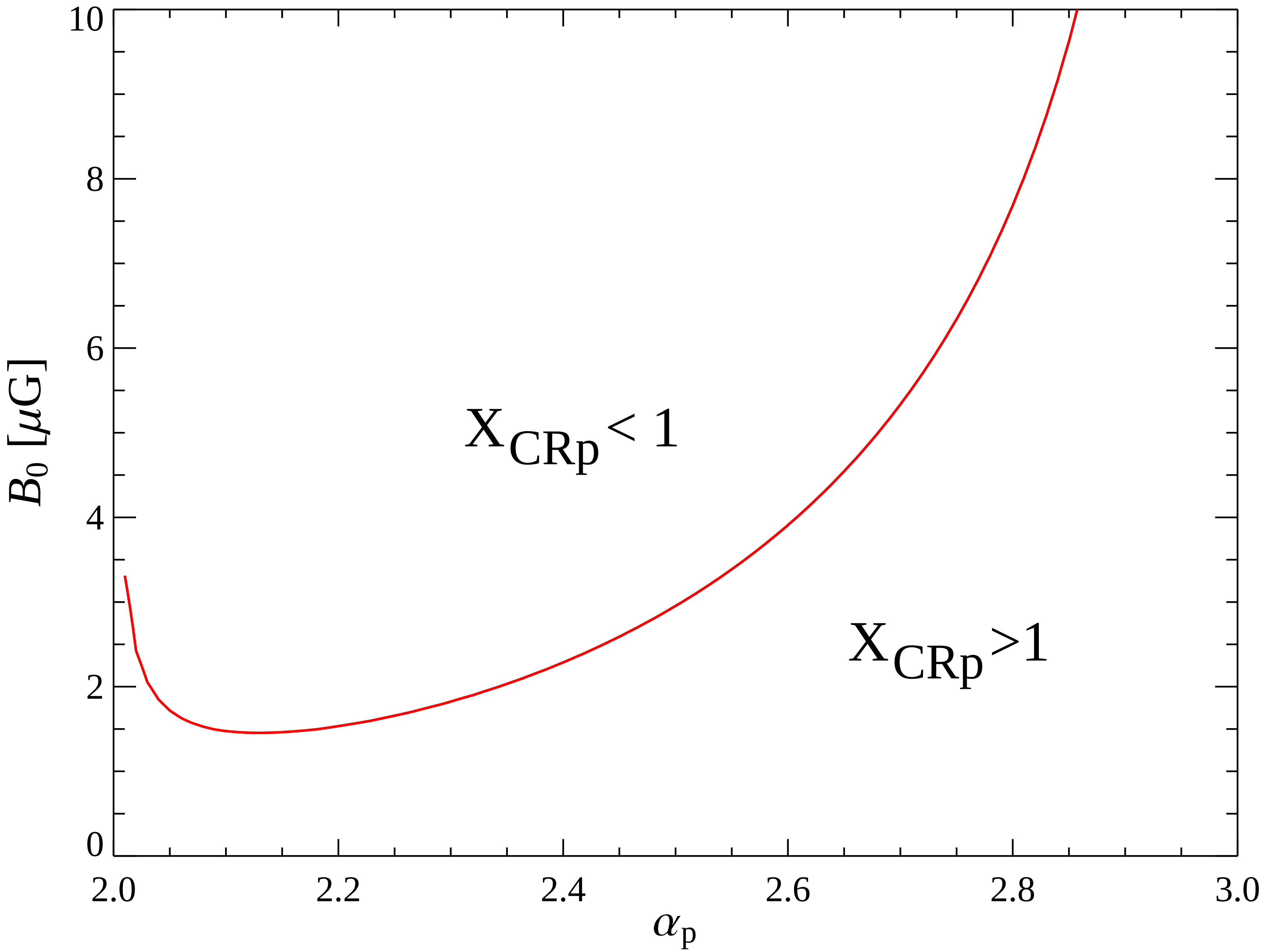
Credit: B.Deiss/Effelsberg

Radio halo in Coma galaxy cluster

$$f_p(r, p_p) \propto p_p^{-\alpha_p}, \qquad B(r) = B_0 \left[\frac{n_e(r)}{n_e(0)}\right]^{\alpha_B}, \qquad X_{CRp}(r) = \frac{\varepsilon_{CRp}}{\varepsilon_{th}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{th}}(r)$$



Parameter study on the hadronic origin of the Coma radio halo



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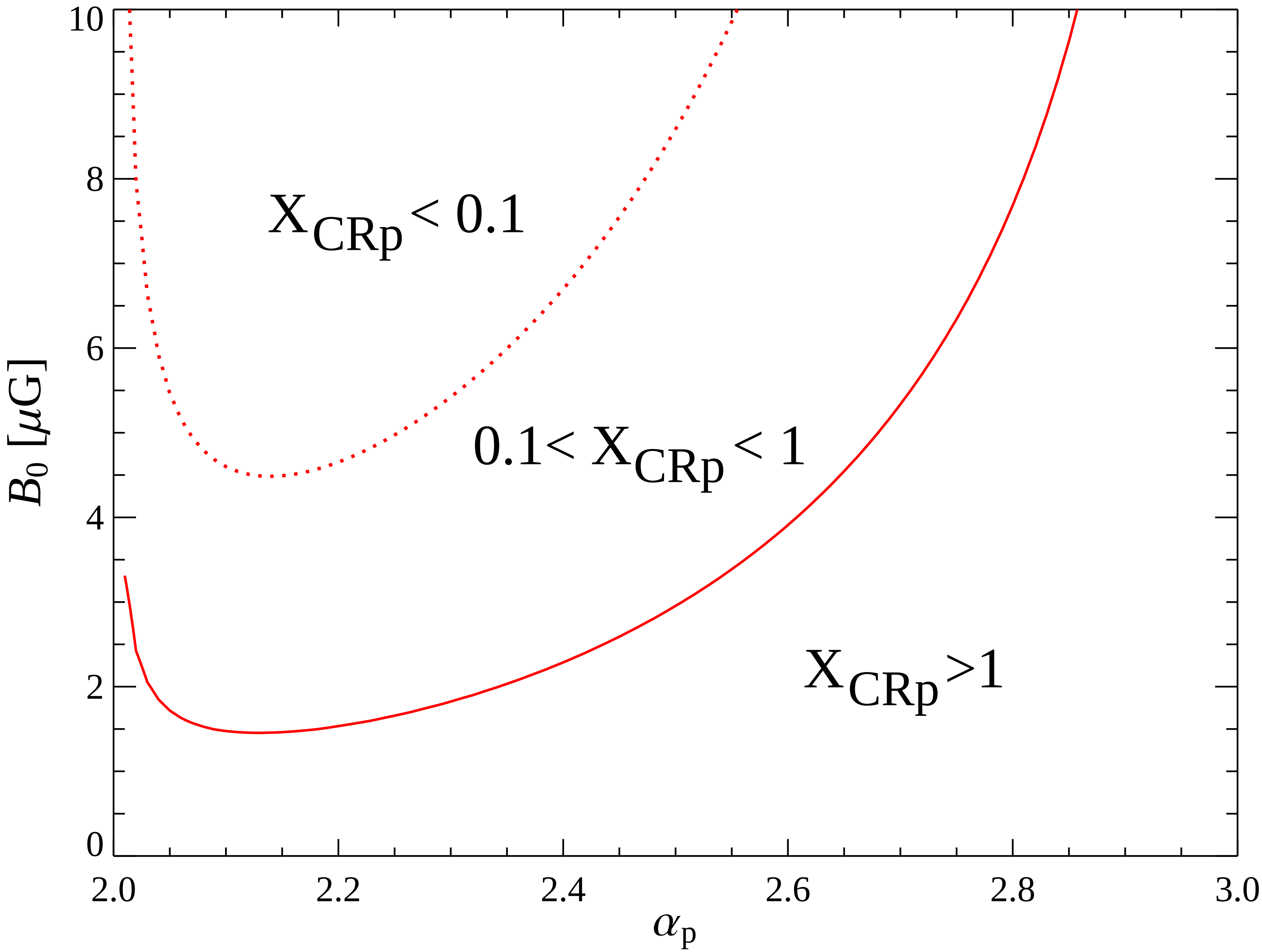

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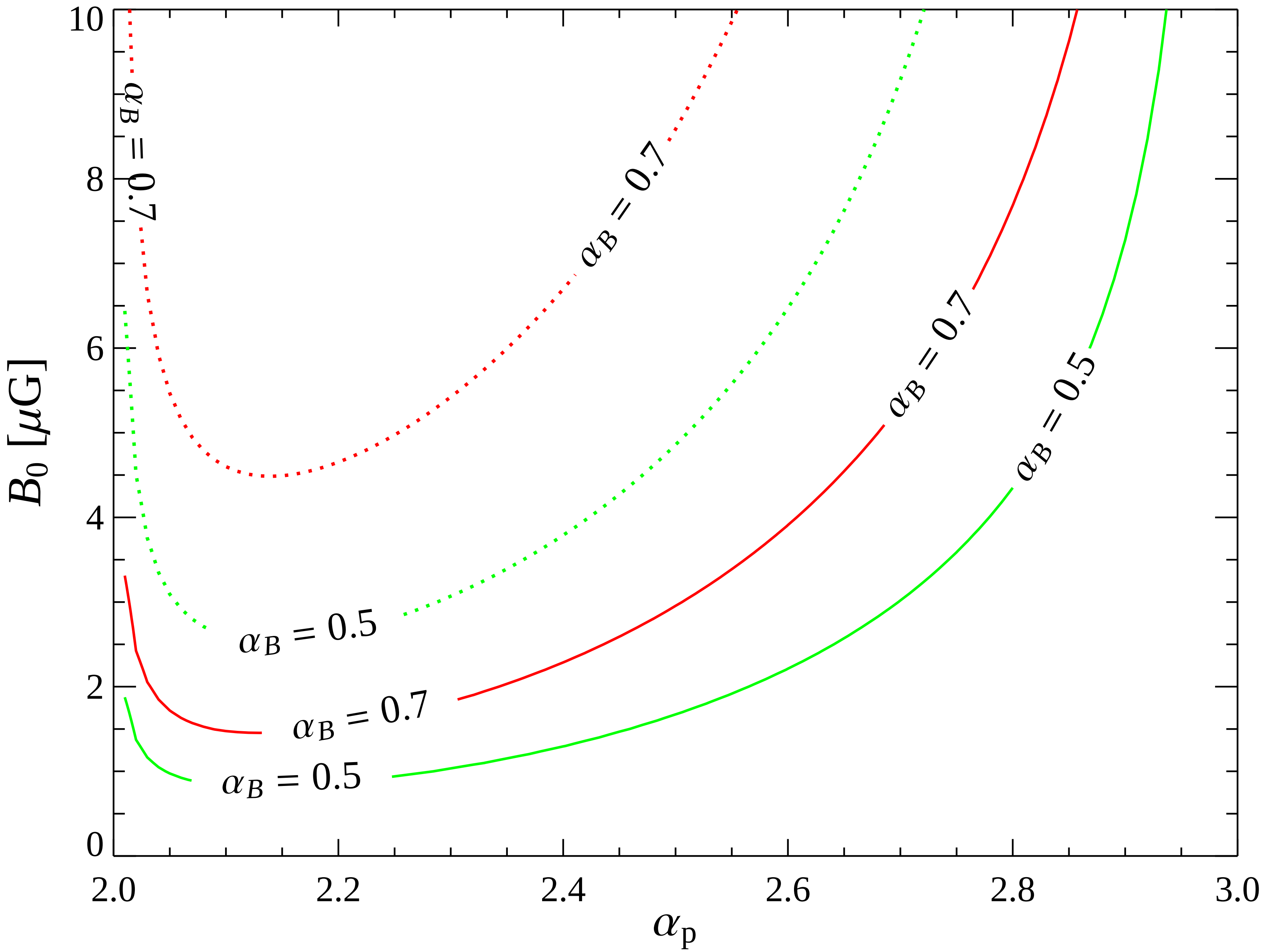
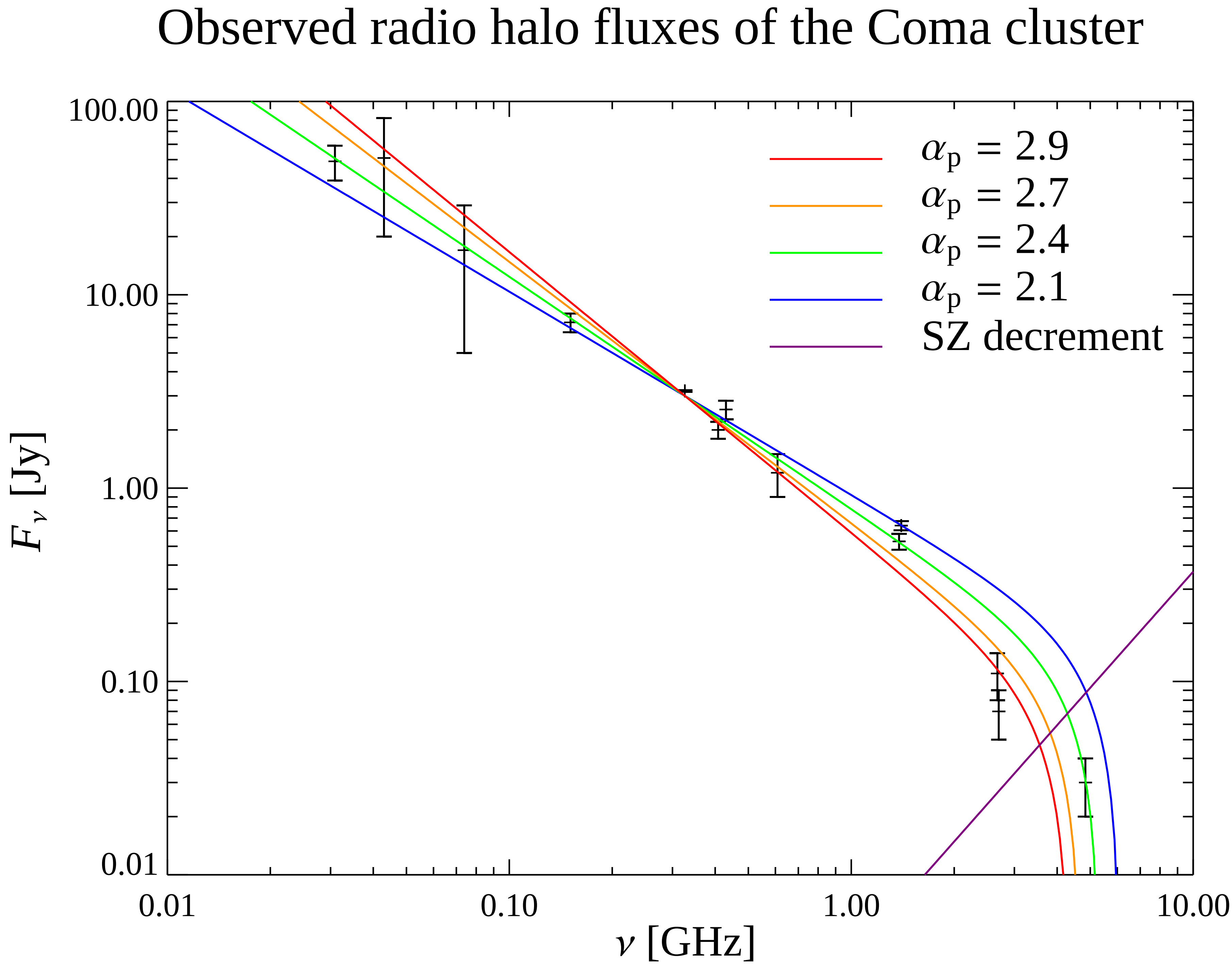




Observed radio halo fluxes of the Coma cluster
αp = 2.9
αp = 2.7
αp = 2.4
αp = 2.1
SZ decrement
100.00
10.00
1.00
0.10
0.01
0.01
0.10
1.00
10.00
Fν [Jy]
ν [GHz]

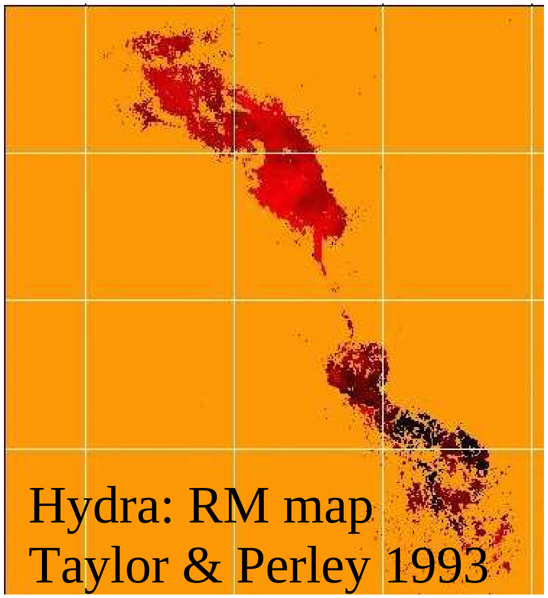
Magnetic fields in clusters

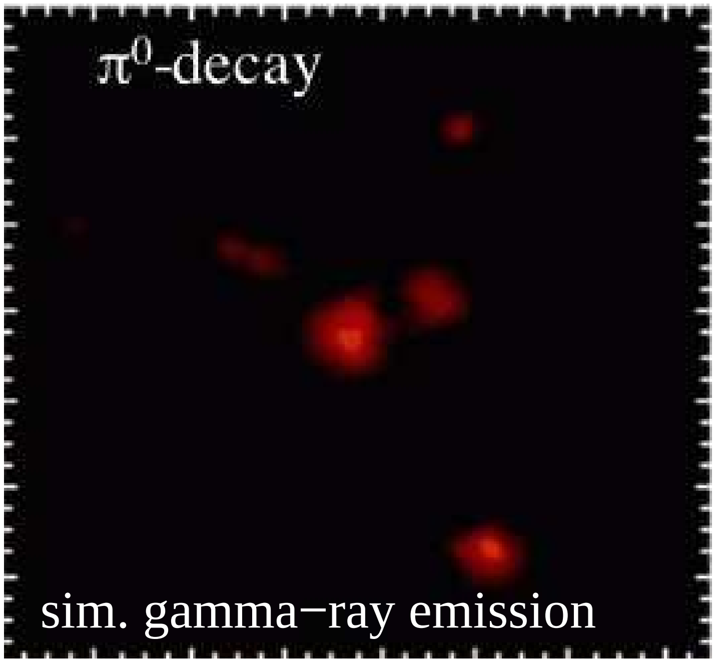
- Rotation measure of polarised radio sources behind cluster magnetic fields:

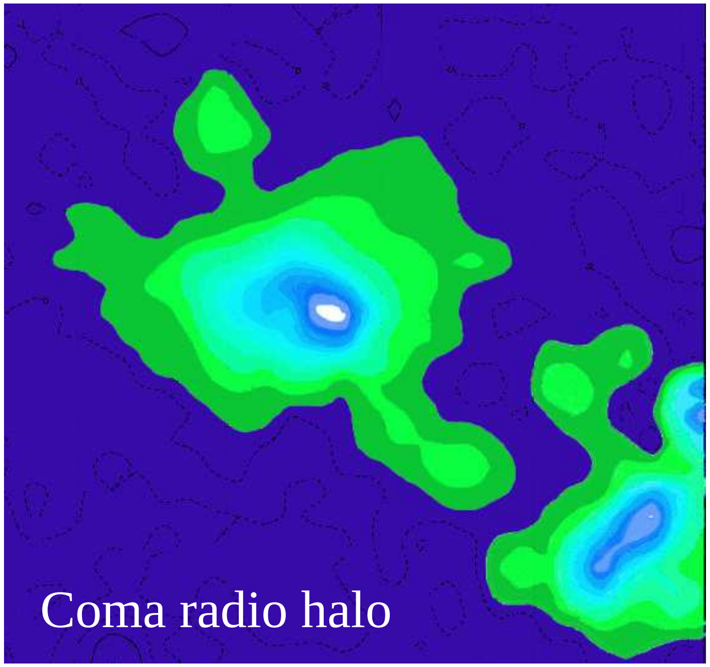
  → only finite window accessible

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

  → upper limit on magnetic field strength

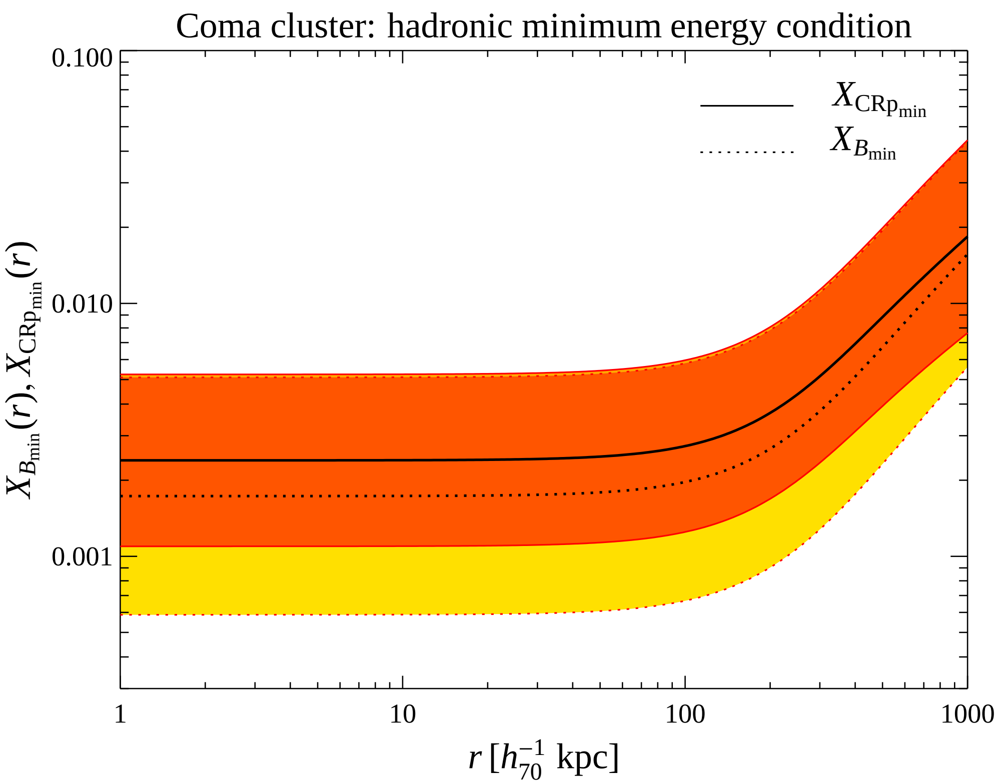


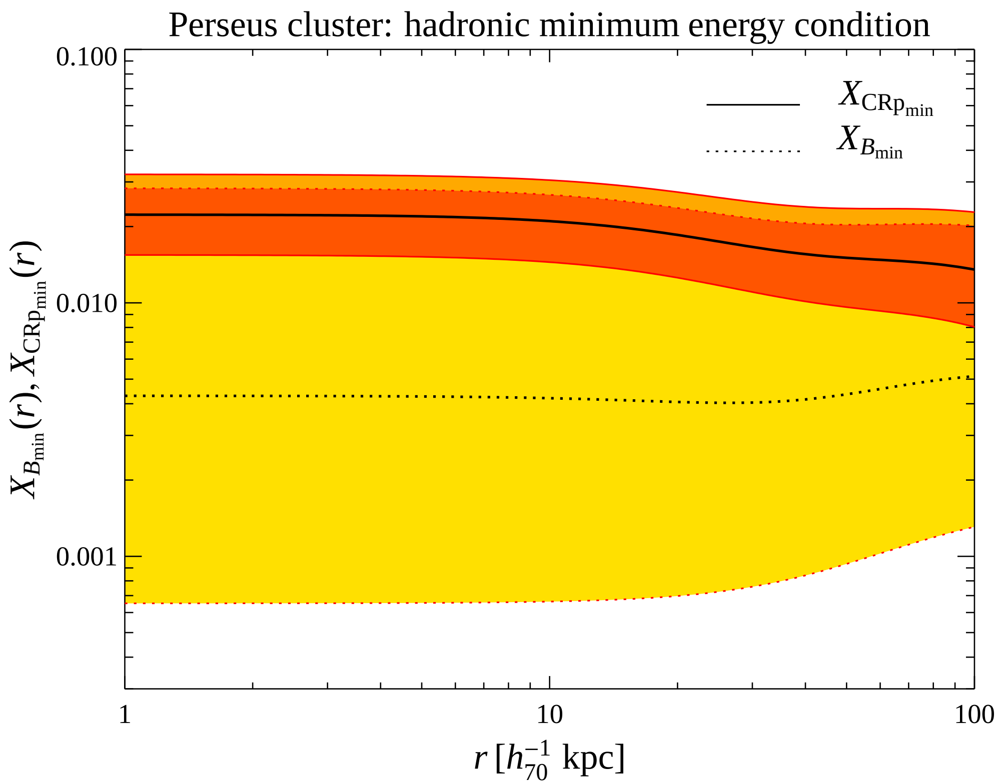




Hadronic minimum energy condition

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





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

Conclusions

Cosmic ray protons: $X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r)$

- M 87 gamma−ray emission is consistent with hadronic scenario!
- Limits from γ−rays (EGRET): $X_{\mathrm{CRp}} < 20\%$
- Radio emission of Perseus: $X_{\mathrm{CRp}} \sim 2\%$
- Radio mini−halos (Perseus) seem to be of hadronic origin!
- Hadronic origin of radio halos (Coma) can not be excluded

Simulation of CR emission processes

Secondary emission: Primary emission:

F(>100 keV)

F(>100 MeV)