The quest for cosmic ray protons in clusters of galaxies

"Astrophysical Seminar"

Universität Würzburg

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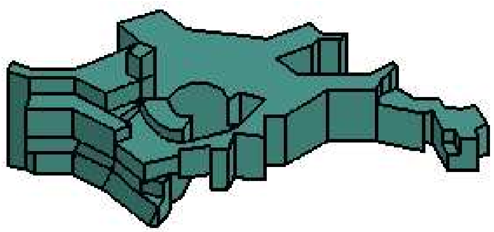


Outline

A.) Introduction and motivation
  1.) cosmic rays in galaxies and clusters of galaxies
  2.) cosmological implications
  3.) hadronic cosmic ray proton interactions in the ICM

B.) Cosmic rays in nearby clusters of galaxies
  1.) γ-ray emission induced by cosmic ray protons
  2.) minimum energy criterion: preferred CR profiles

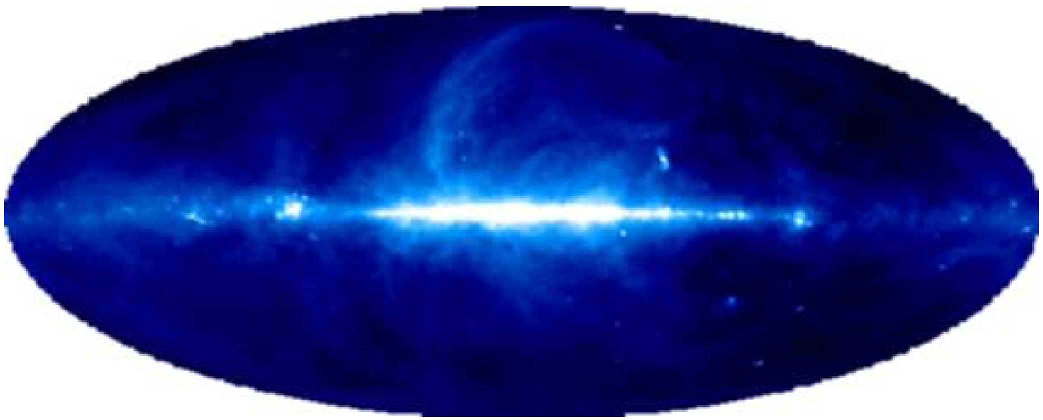
C.) Cosmic rays in the simulation code GADGET
  1.) philosophy and description
  2.) first results

D.) Conclusions

Galactic cosmic rays

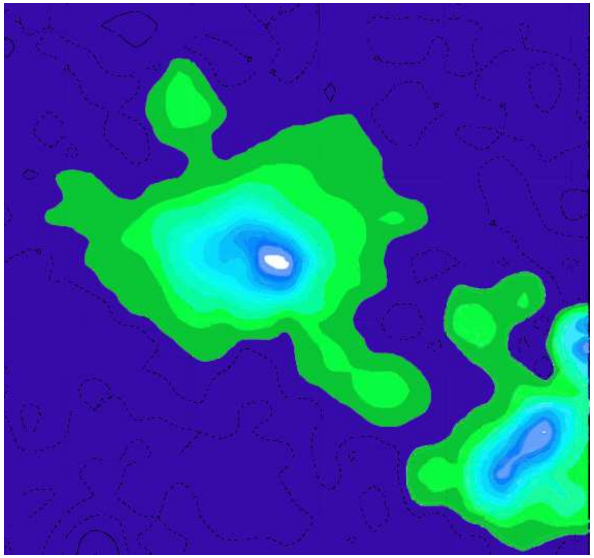
Galactic cosmic rays are dynamically important:

- 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 $E_{\rm CRp} > 2 \times 10^{16}$ 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

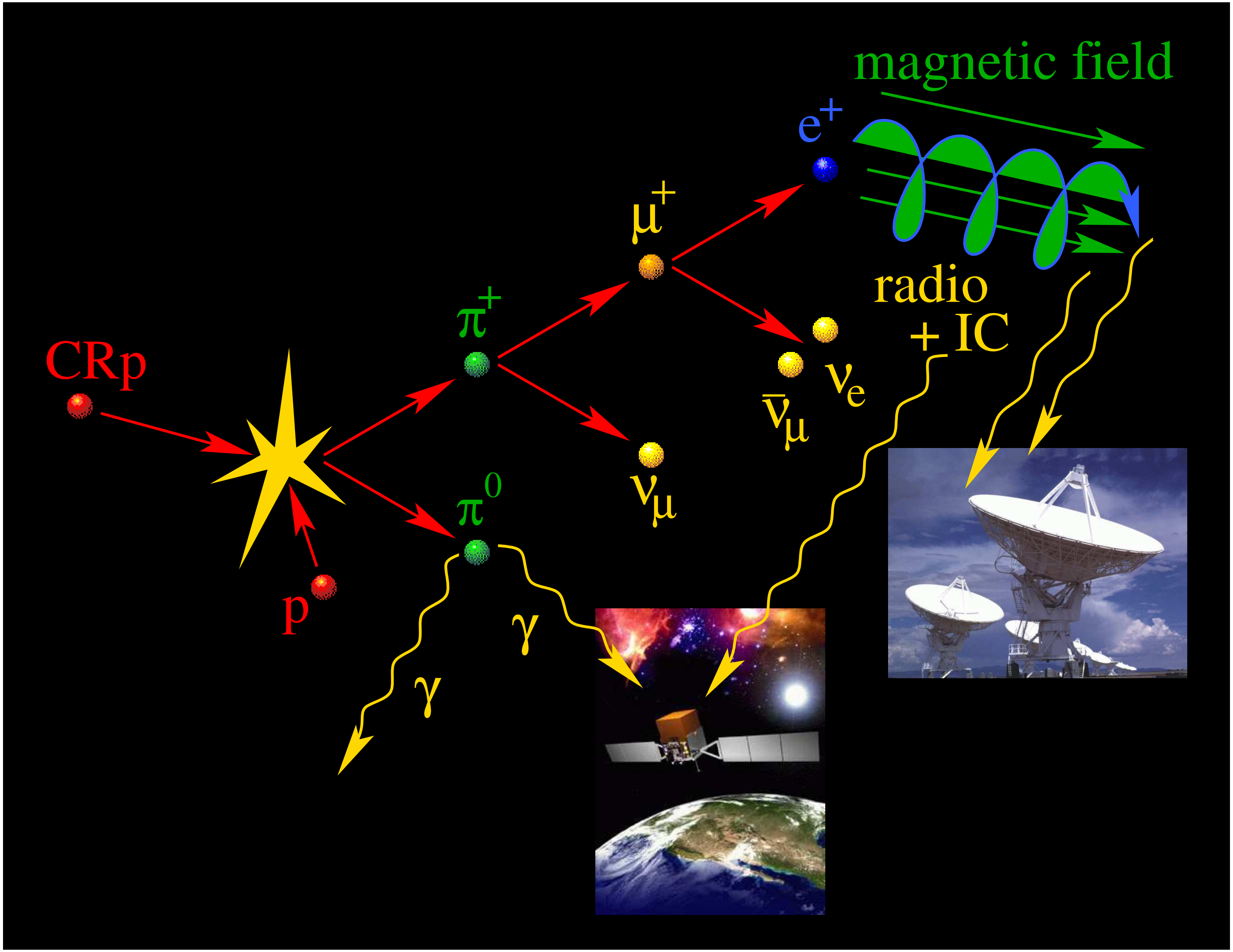


Coma cluster: radio halo, $\nu = 1.4$ GHz, $2.5° \times 2.0°$
(Credit: Deiss/Effelsberg)

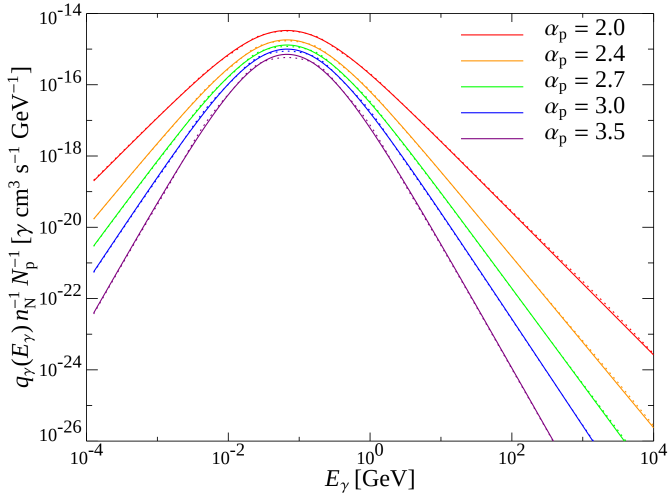
Cosmological implications

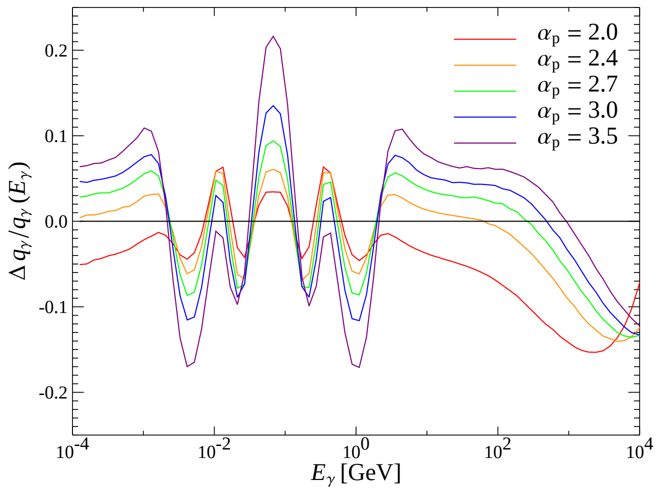
- cosmic rays provide an additional pressure component:
  $\longrightarrow$ modifications of the hydrostatic mass estimates
  $\longrightarrow$ additional heating of the ICM (cooling flow problem)
- the equation of state of cosmic rays is 'softer' than the thermal component ($\gamma_{\mathrm{CRp}} \sim \frac{4}{3}$):
  $\longrightarrow$ 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
  $\longrightarrow$ prevents the ICM from overcooling

Hadronic cosmic ray proton interaction



Gamma-ray source function





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

$$q_\gamma \propto \left[\left(\frac{2\,E_\gamma}{m_{\pi^0}c^2}\right)^{\delta} + \left(\frac{2\,E_\gamma}{m_{\pi^0}c^2}\right)^{-\delta}\right]^{-\alpha/\delta}$$

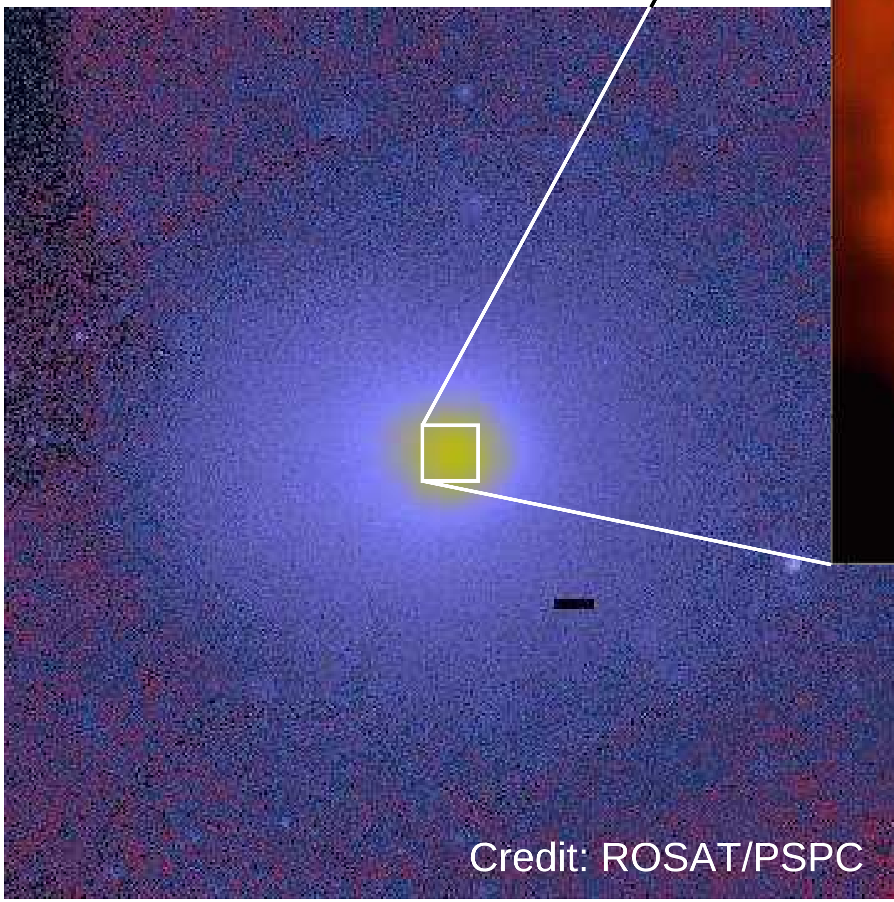
- below: relative deviation of our analytic approach to simulated γ-ray spectra

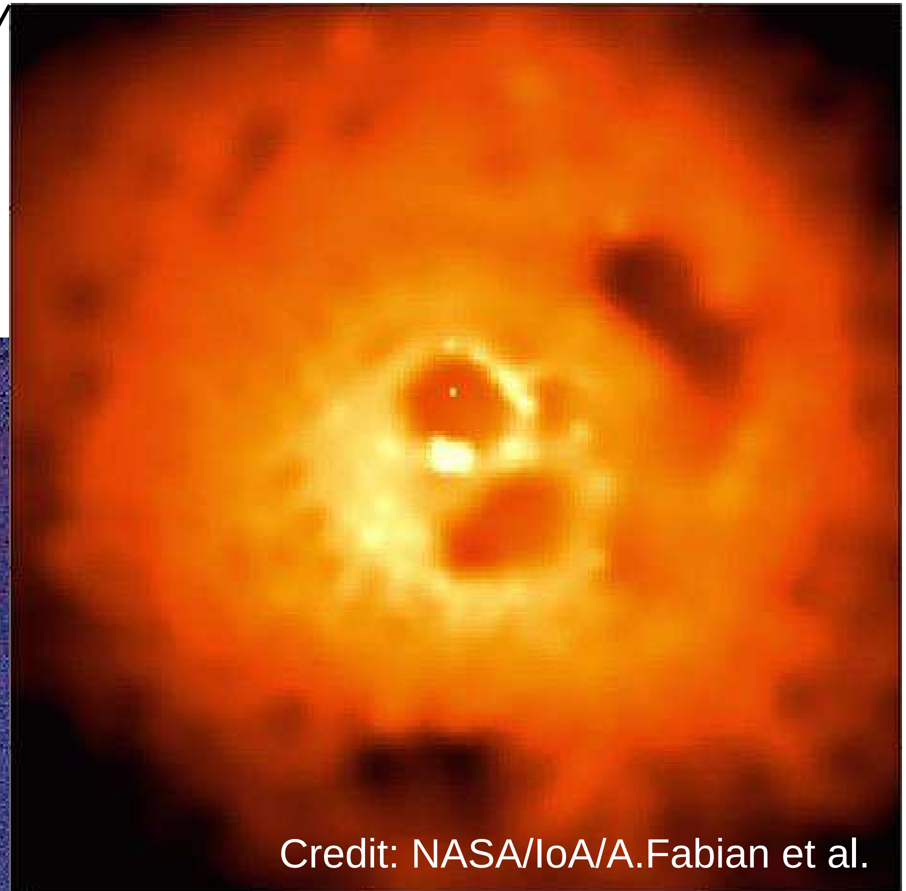
this and the following work:

Pfrommer & Enßlin 2003, 2004

Cooling core clusters are efficient CRp detectors

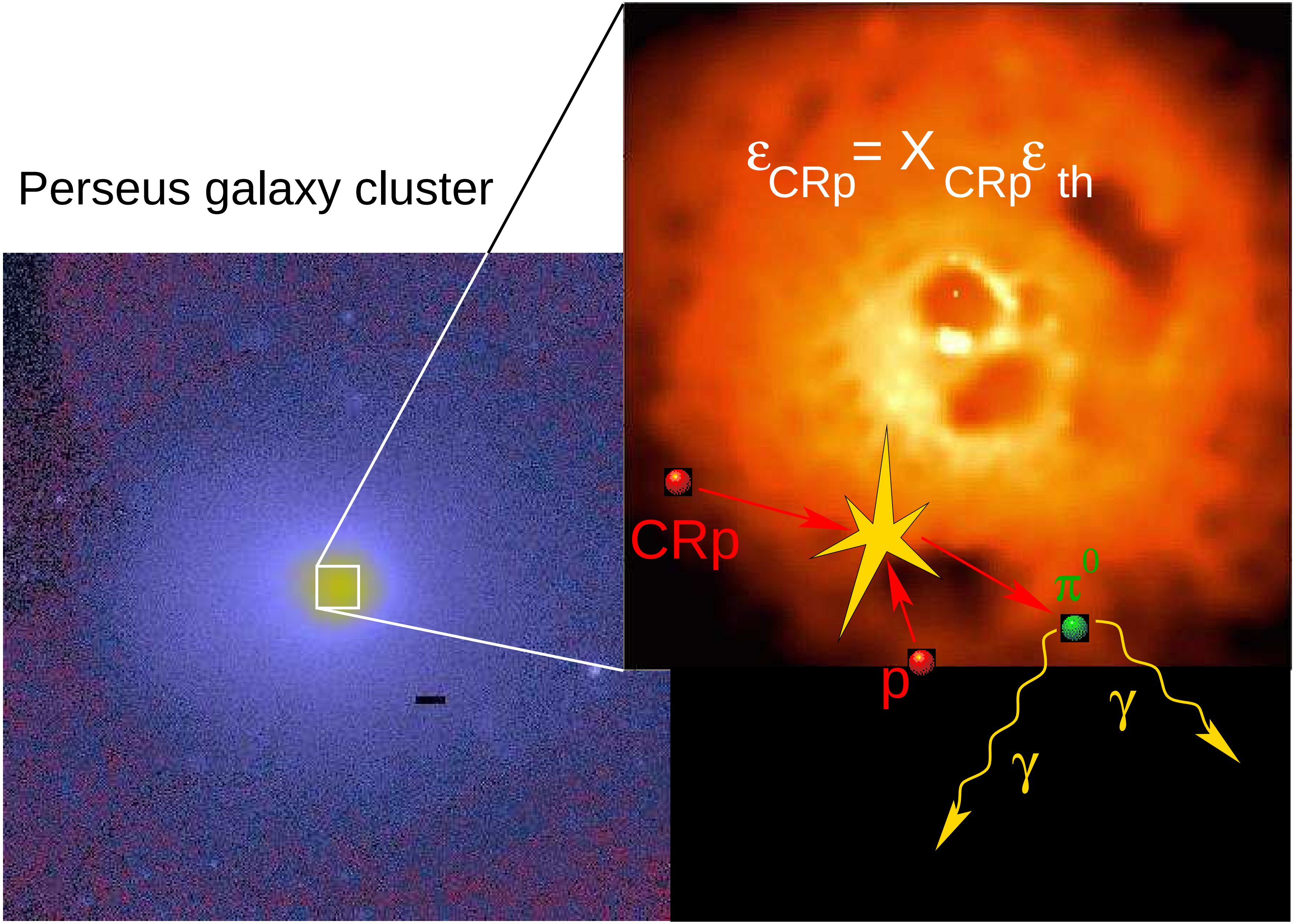
ROSAT observation:
Perseus galaxy cluster





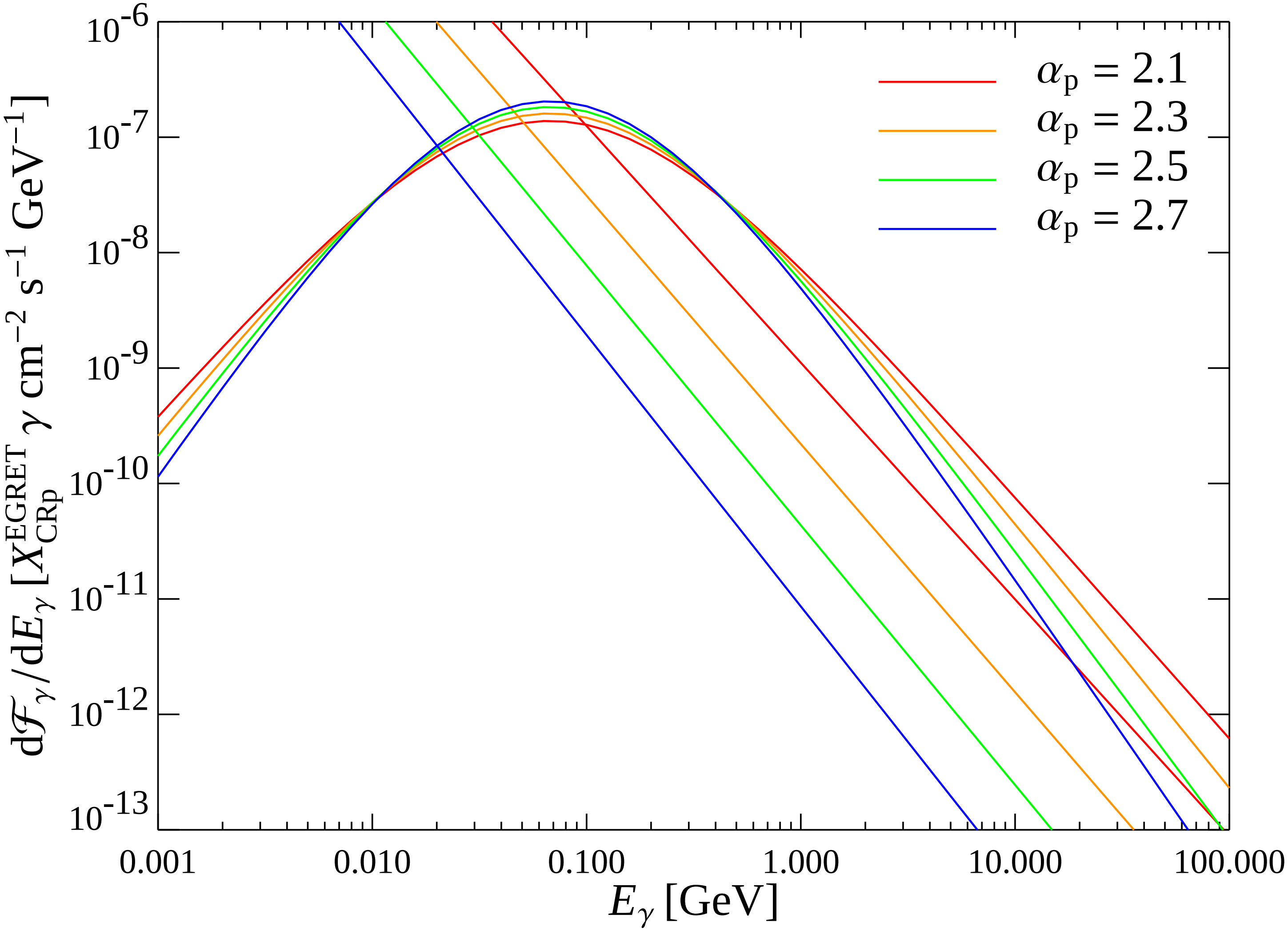
Chandra observation:
central region of Perseus

Cooling core cluster model of CRp detection

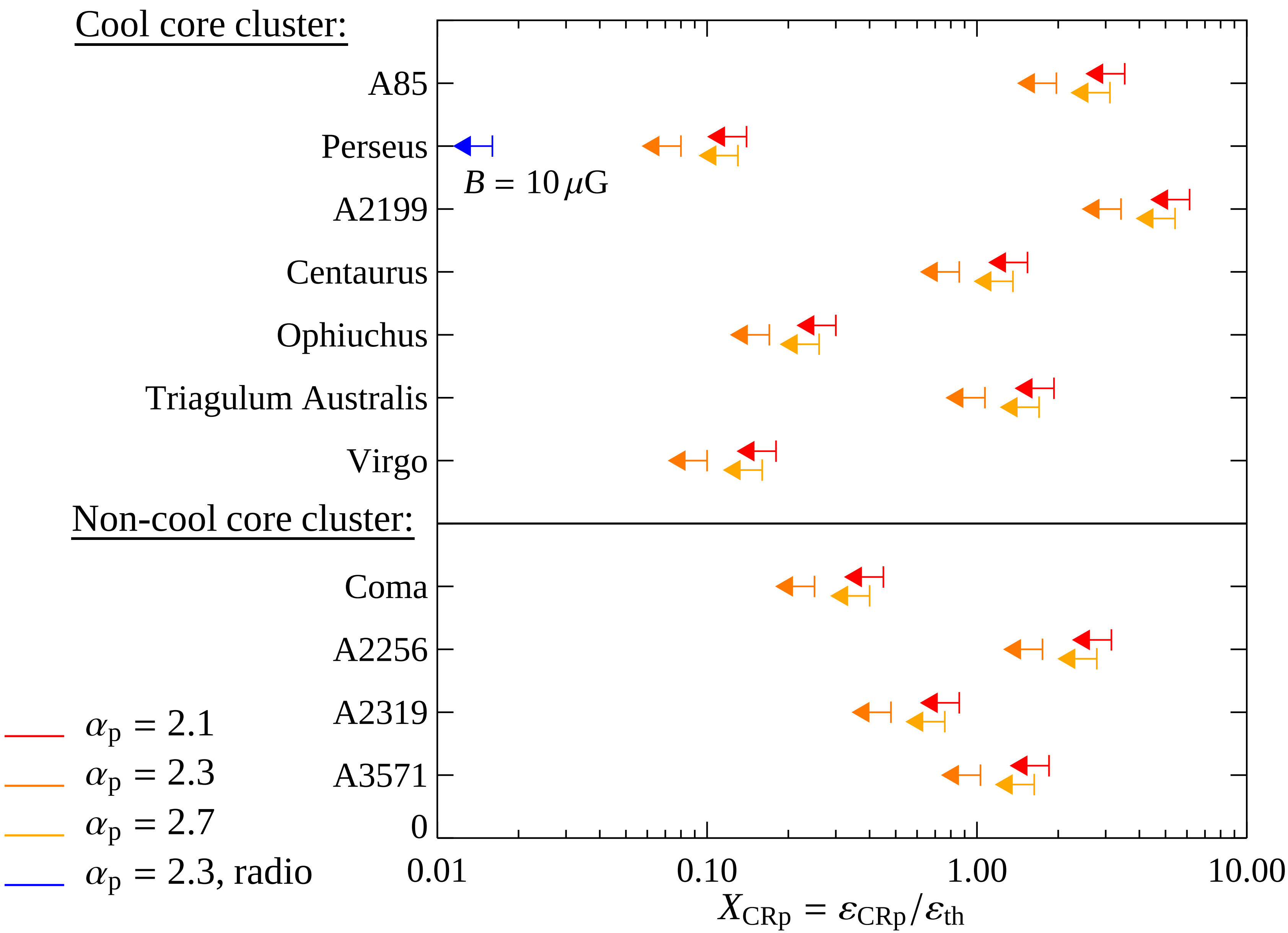


Gamma-ray flux of the Perseus galaxy cluster

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

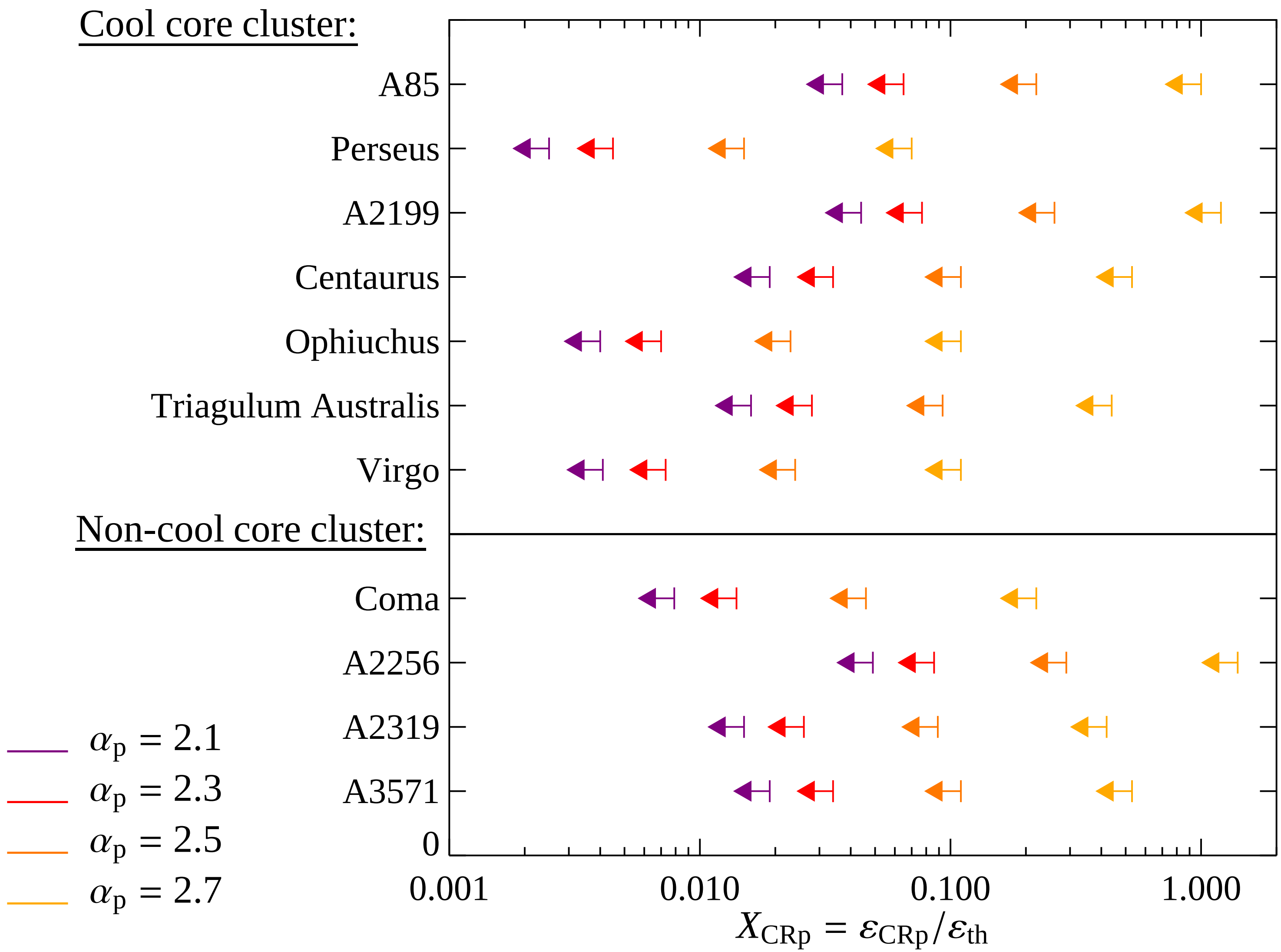


Upper limits on X_{CRp} using EGRET limits

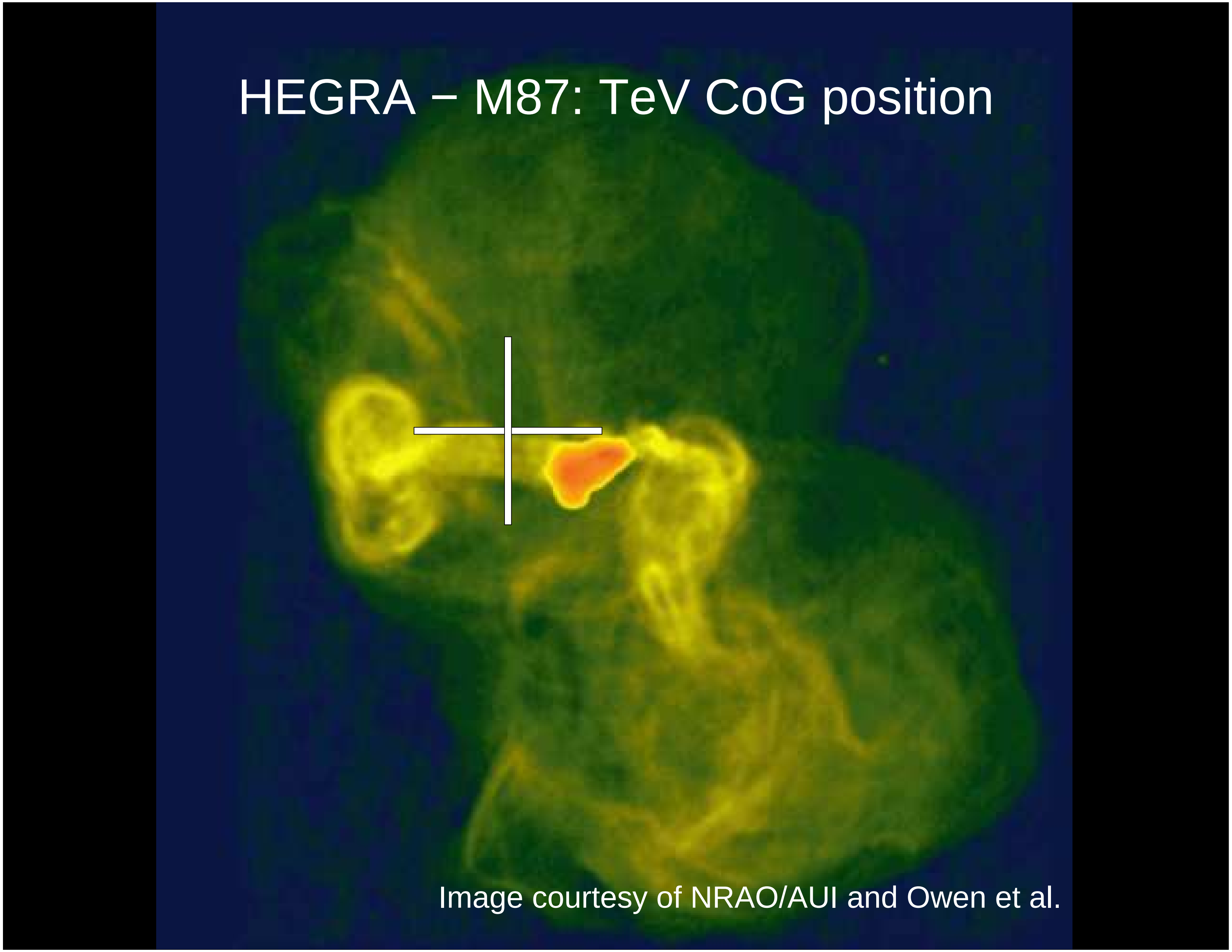


Expected limits on $X_{\rm CRp}$ using Čerenkov telescopes

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

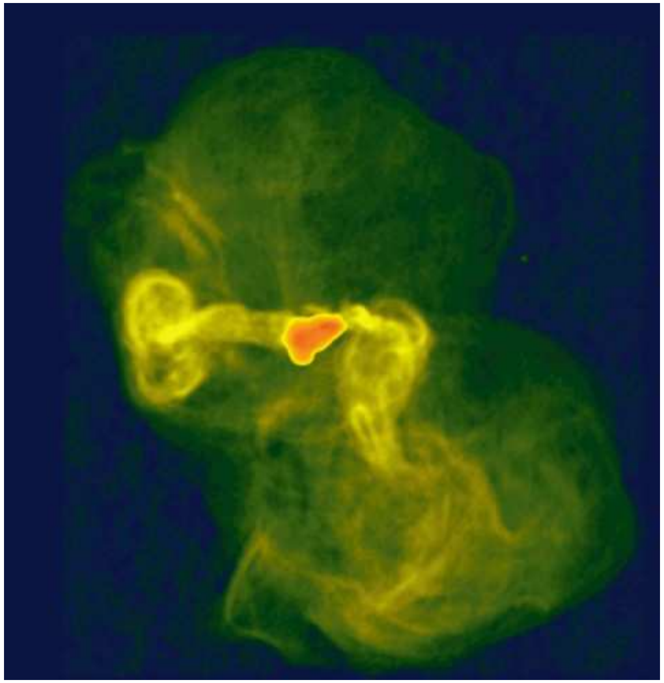


HEGRA detection of γ-rays from M 87

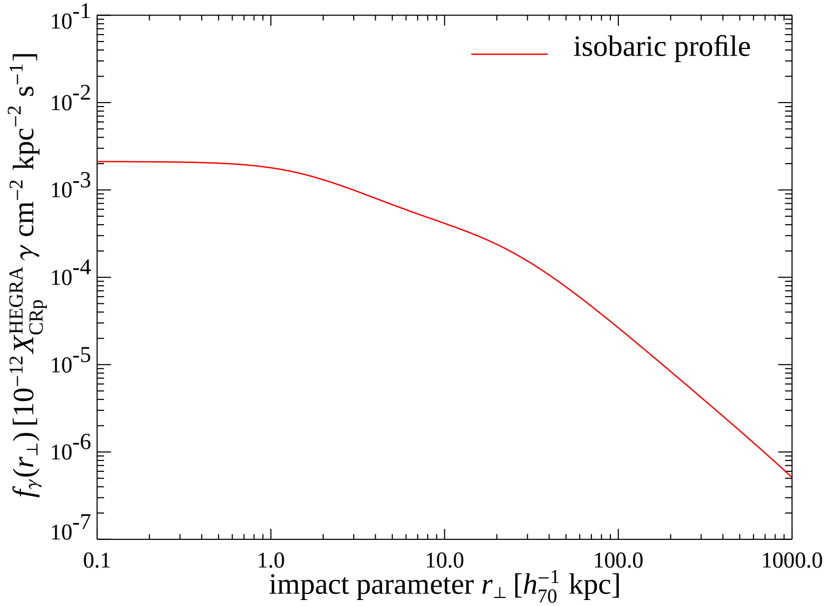


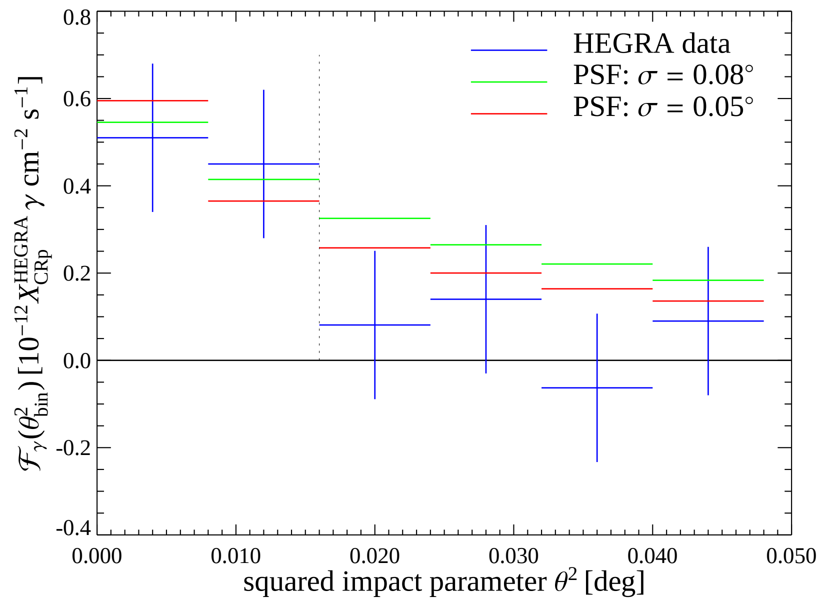
What is the origin of the M 87 γ-ray emission?

- 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)





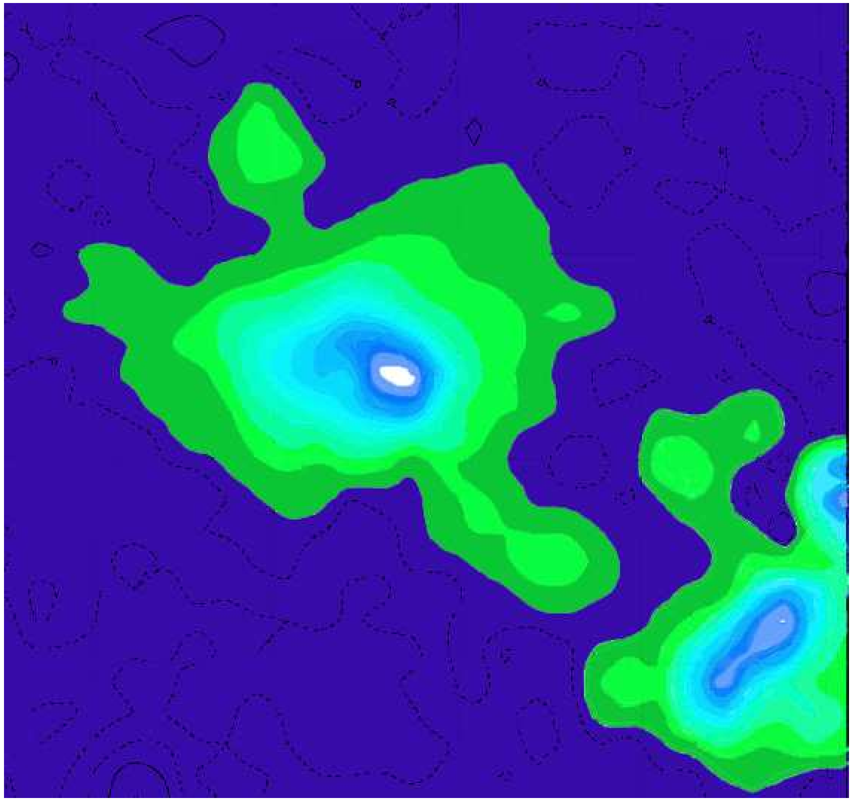
top:

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

bottom:

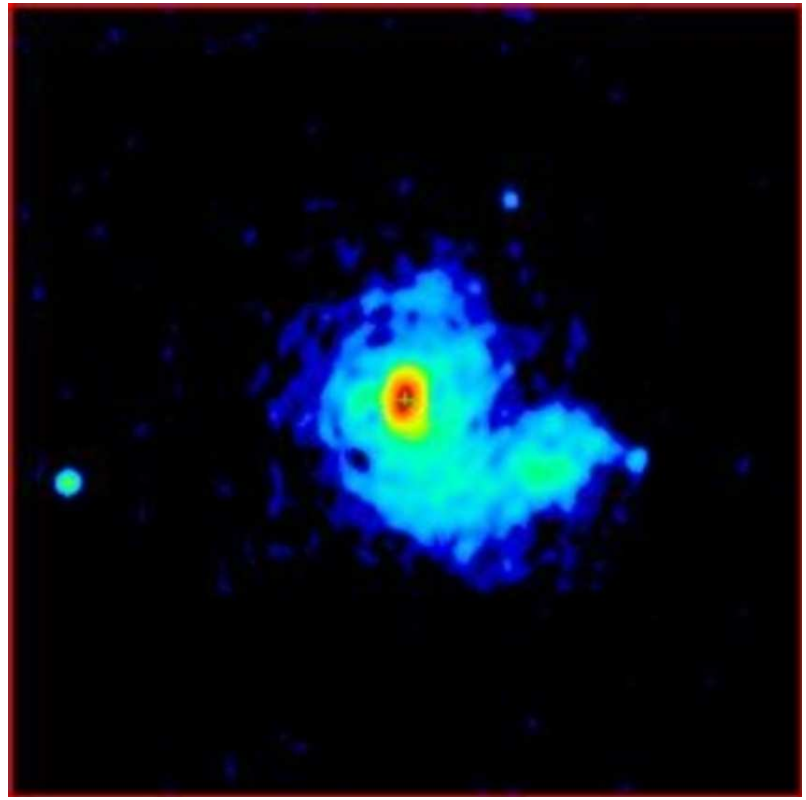
- comparison of detected to simulated γ-ray flux profiles which are convolved with two different widths of the PSF

Radio (mini-)halos: Coma and Perseus



Coma radio halo, $\nu = 1.4$ GHz, largest emission diameter ~ 3 Mpc

(Credit: Deiss/Effelsberg)

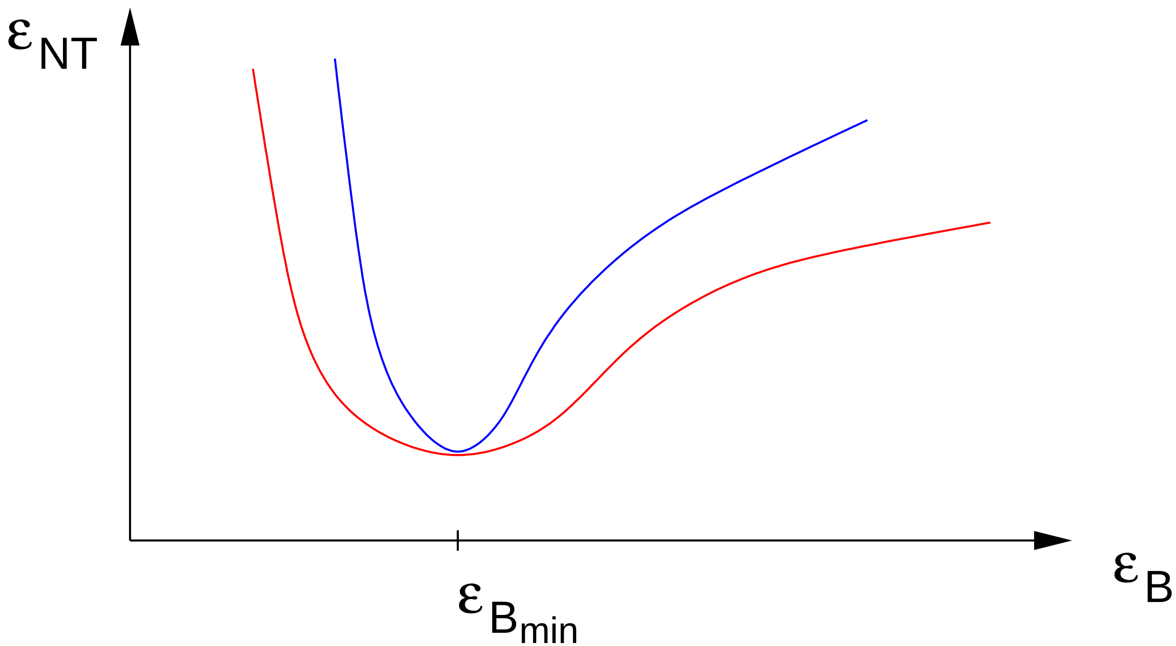


Perseus mini-halo, $\nu = 1.4$ GHz, largest emission size ~ 0.5 Mpc

(Credit: Pedlar/VLA)

Minimum energy criterion (MEC): the idea

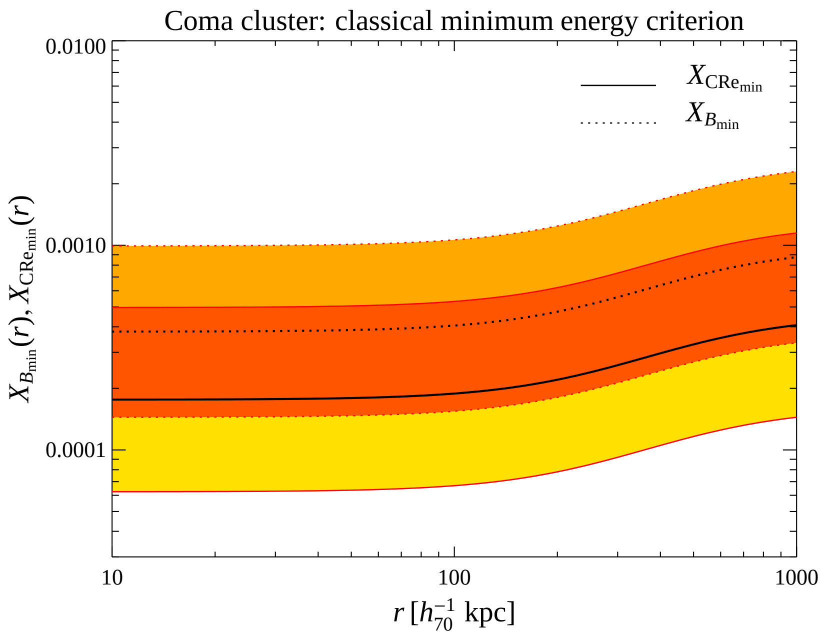
- $\varepsilon_{\mathrm{NT}} = \varepsilon_B + \varepsilon_{\mathrm{CRp}} + \varepsilon_{\mathrm{CRe}}$
  $\rightarrow$ minimum energy criterion: $\left.\frac{\partial \varepsilon_{\mathrm{NT}}}{\partial \varepsilon_B}\right|_{j_\nu} \stackrel{!}{=} 0$
- classical MEC: $\varepsilon_{\mathrm{CRp}} = k_{\mathrm{p}}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

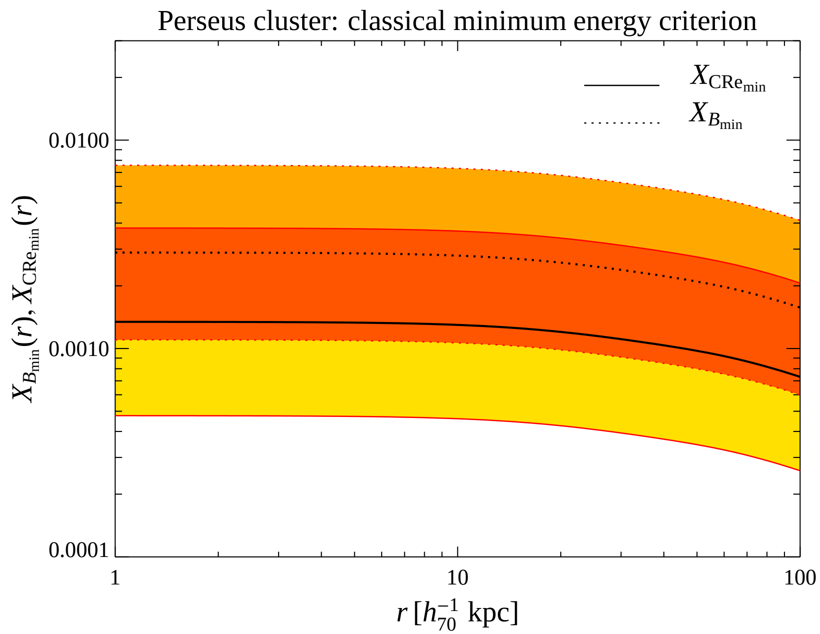


defining tolerance levels: deviation from minimum by one e-fold

Classical minimum energy criterion

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

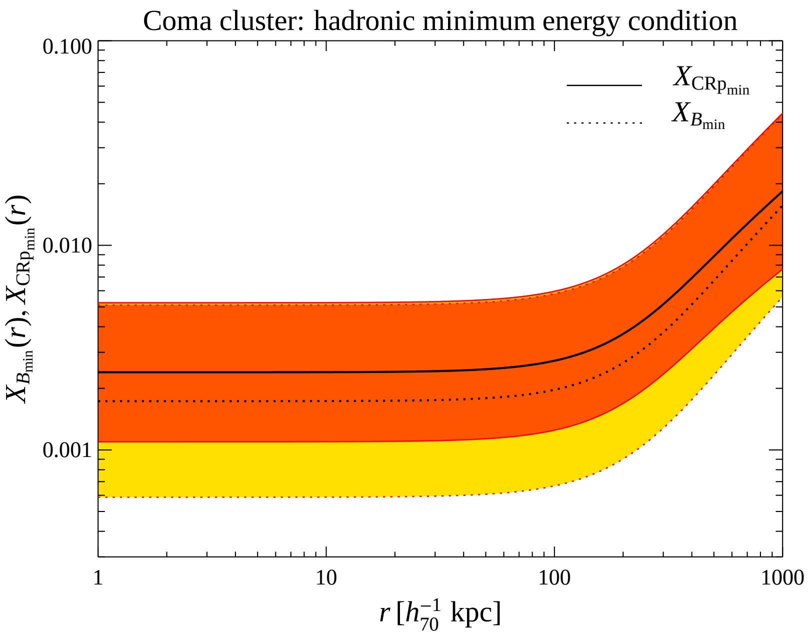


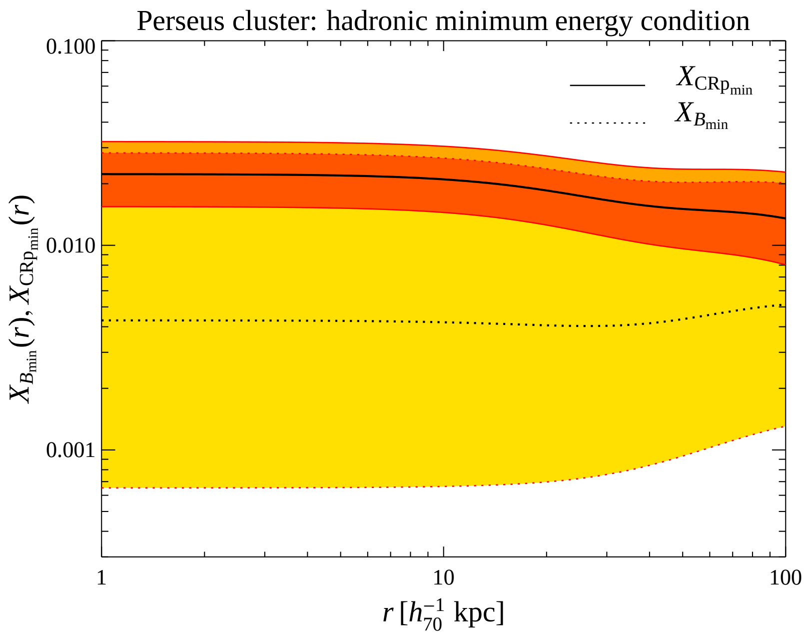


$$B_{\mathrm{Coma}}(0) = 1.1^{+0.7}_{-0.4}\mu\mathrm{G} \qquad B_{\mathrm{Perseus}}(0) = 7.2^{+4.5}_{-2.8}\mu\mathrm{G}$$

Hadronic minimum energy criterion

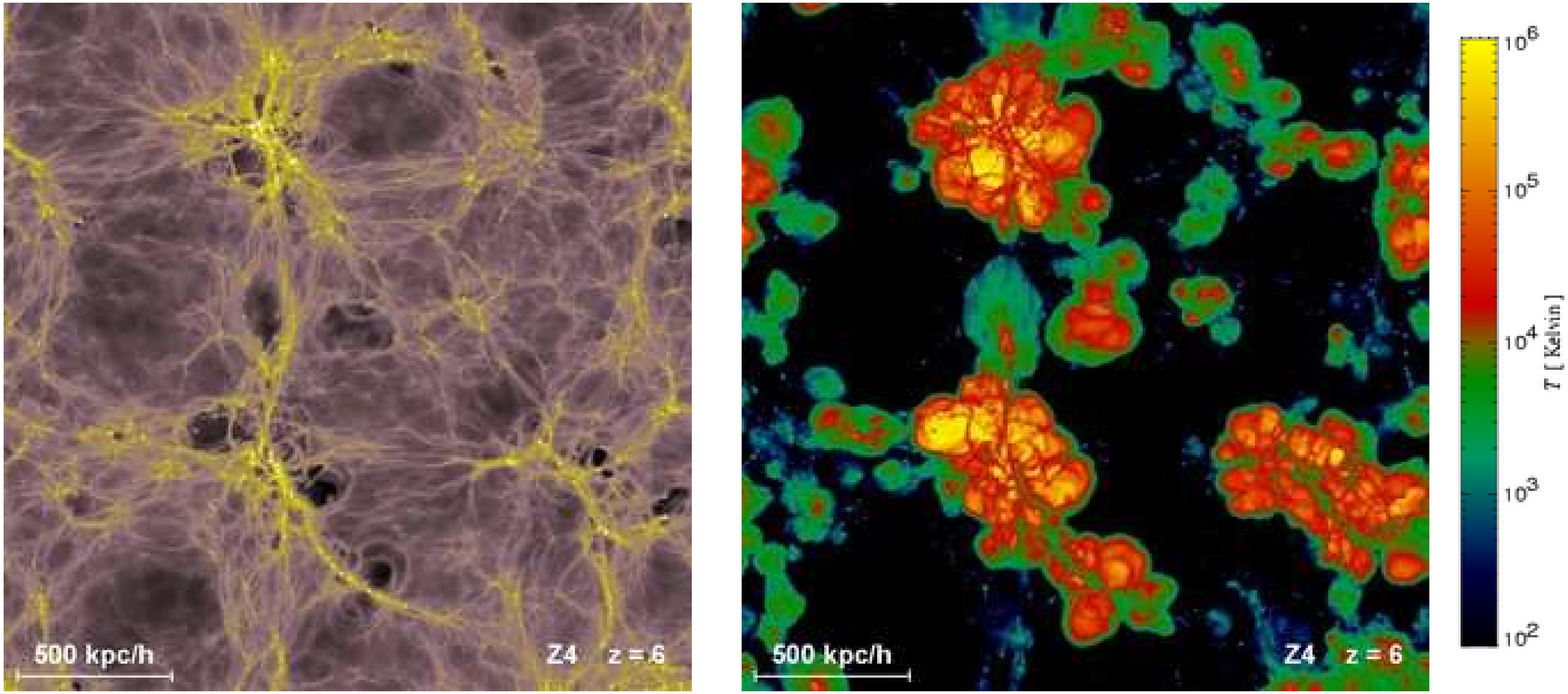
$$X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\mathrm{th}}}(r)$$





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

Cosmic rays in GADGET



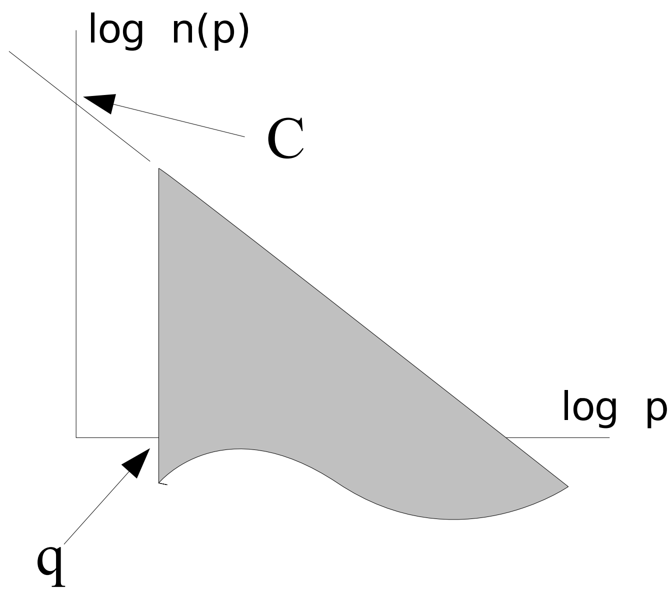
A galactic outflow seen at high redshift. Left: the projected gas density around some of the first star forming galaxies. Right: generated bubbles of hot gas, as seen in the temperature map (Springel & Hernquist 2002).

Cosmic ray GADGET - Collaboration: Enßlin, Jubelgas, Pfrommer, Springel

Philosophy and description

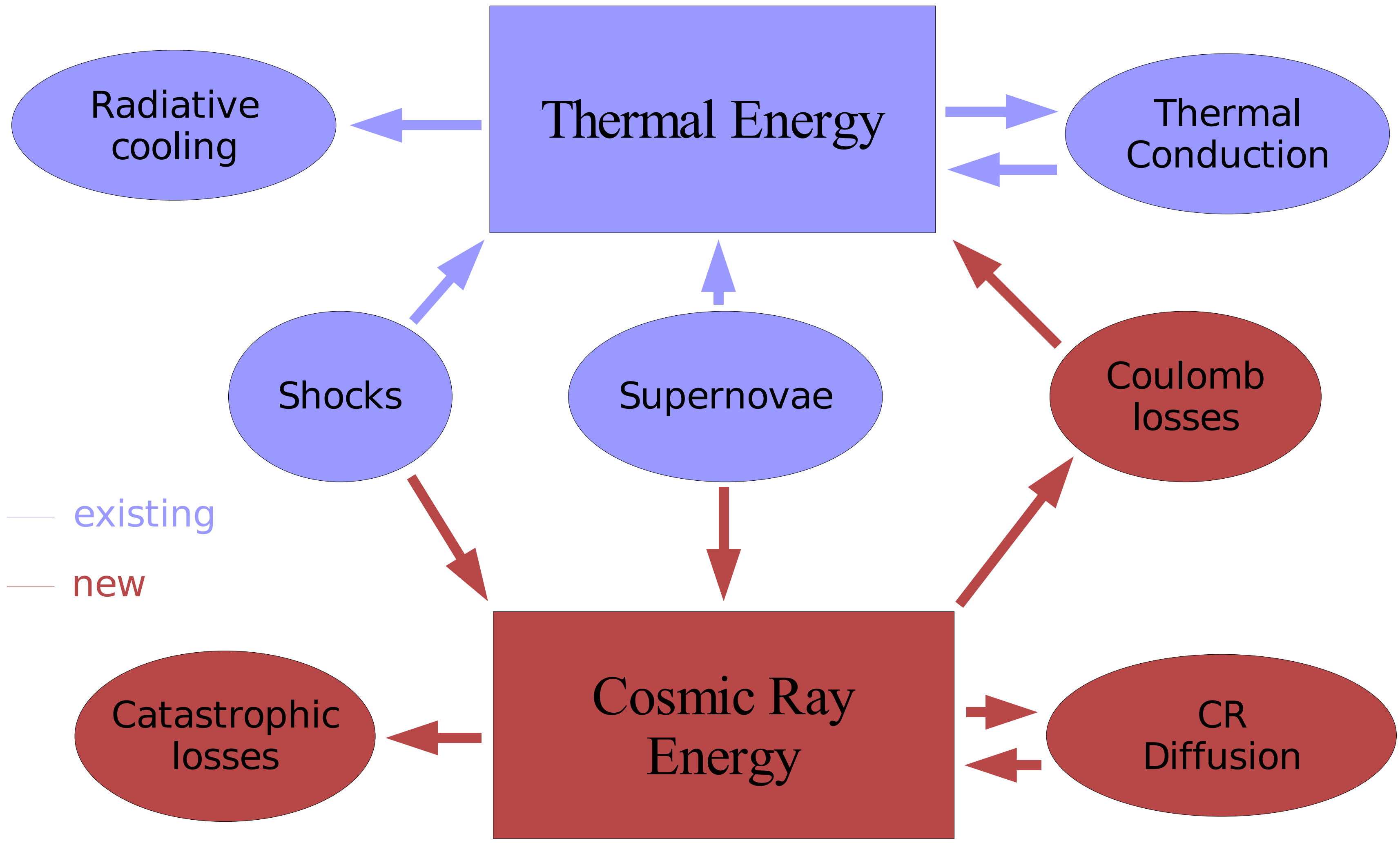
Our model describes the CR physics by two adiabatic invariants!

- CRs are coupled to the thermal gas by magnetic fields.
- We assume a single power-law CR spectrum: momentum cutoff q, normalization C, spectral index α (constant).
  $\longrightarrow$ determines CR energy density and pressure

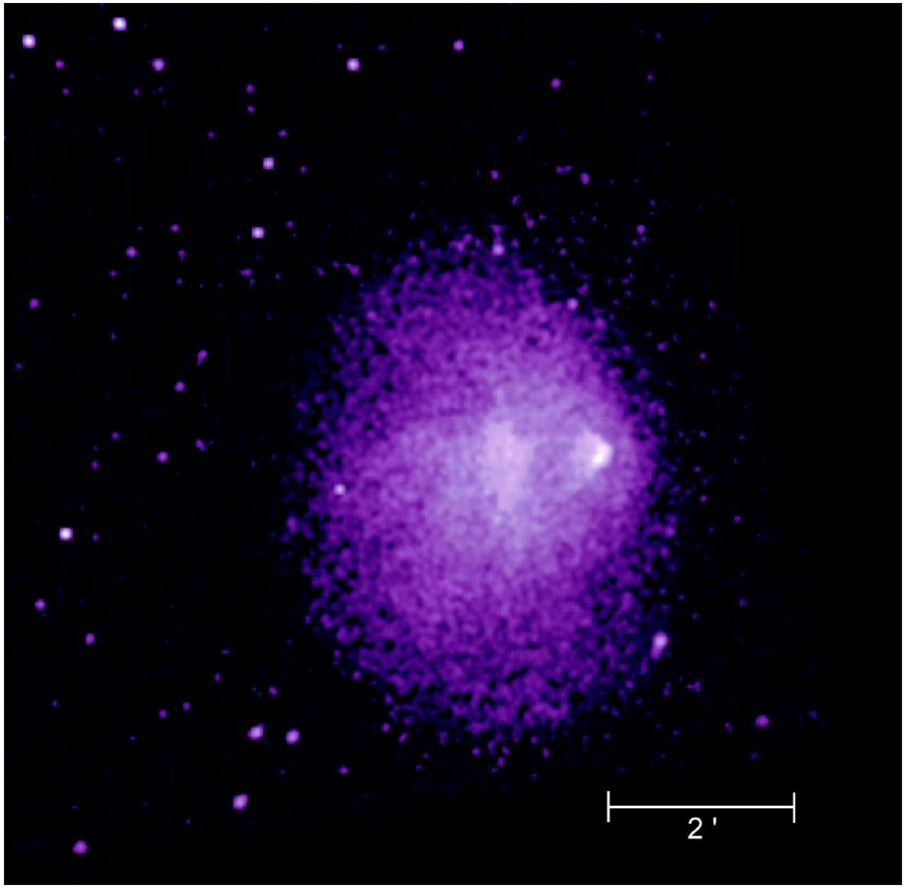


In adiabatic processes, q and C scale only with the density. Non-adiabatic processes are mapped into changes of the adiabatic constants q_0 and C_0.

Cosmic rays in GADGET – flowchart

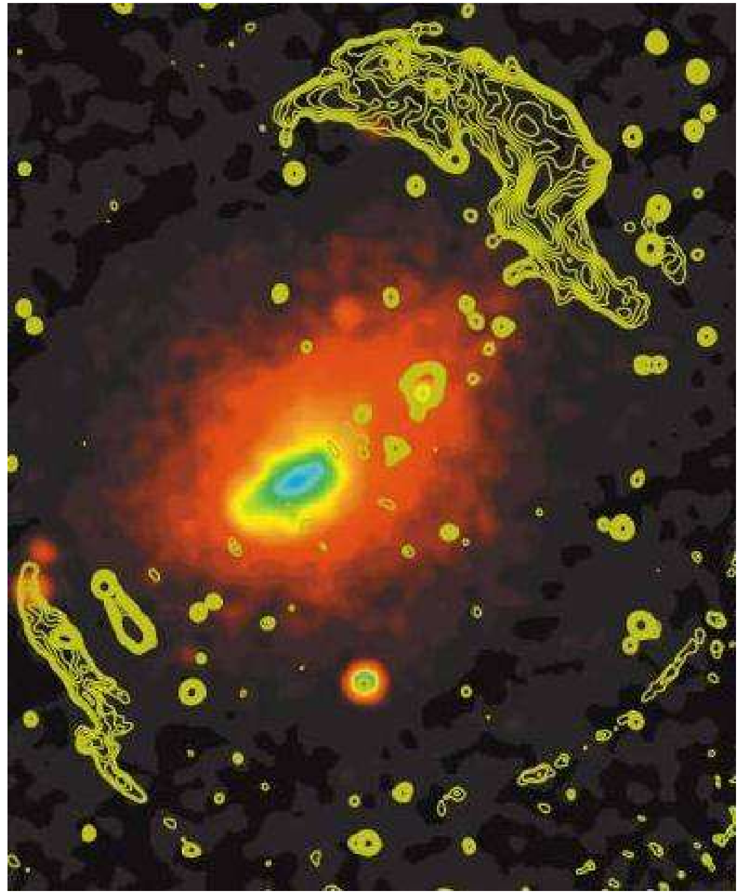


Shock waves in galaxy clusters



1E 0657-56 (“Bullet cluster”)

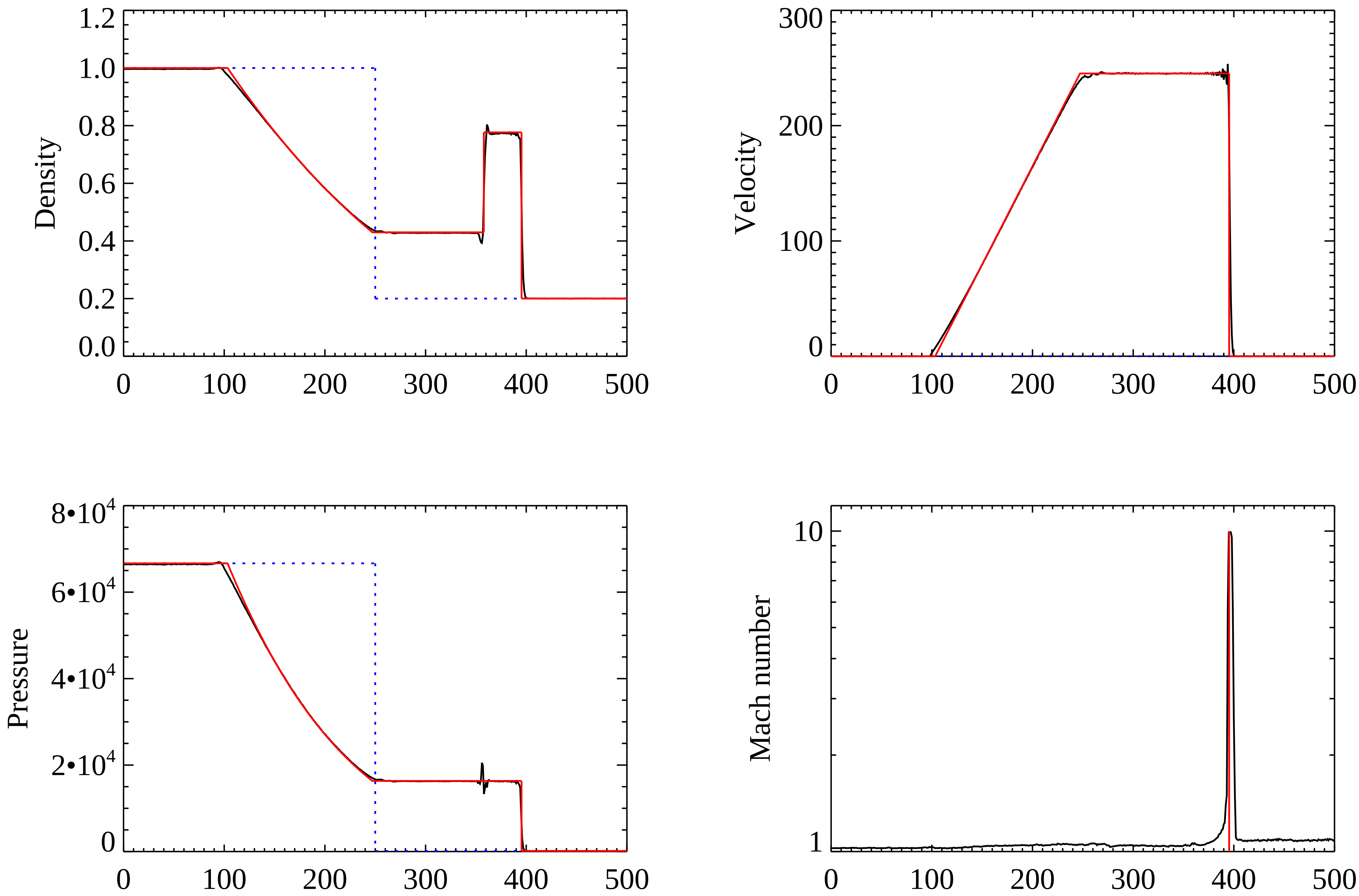
(NASA/SAO/CXC/M.Markevitch et al.)



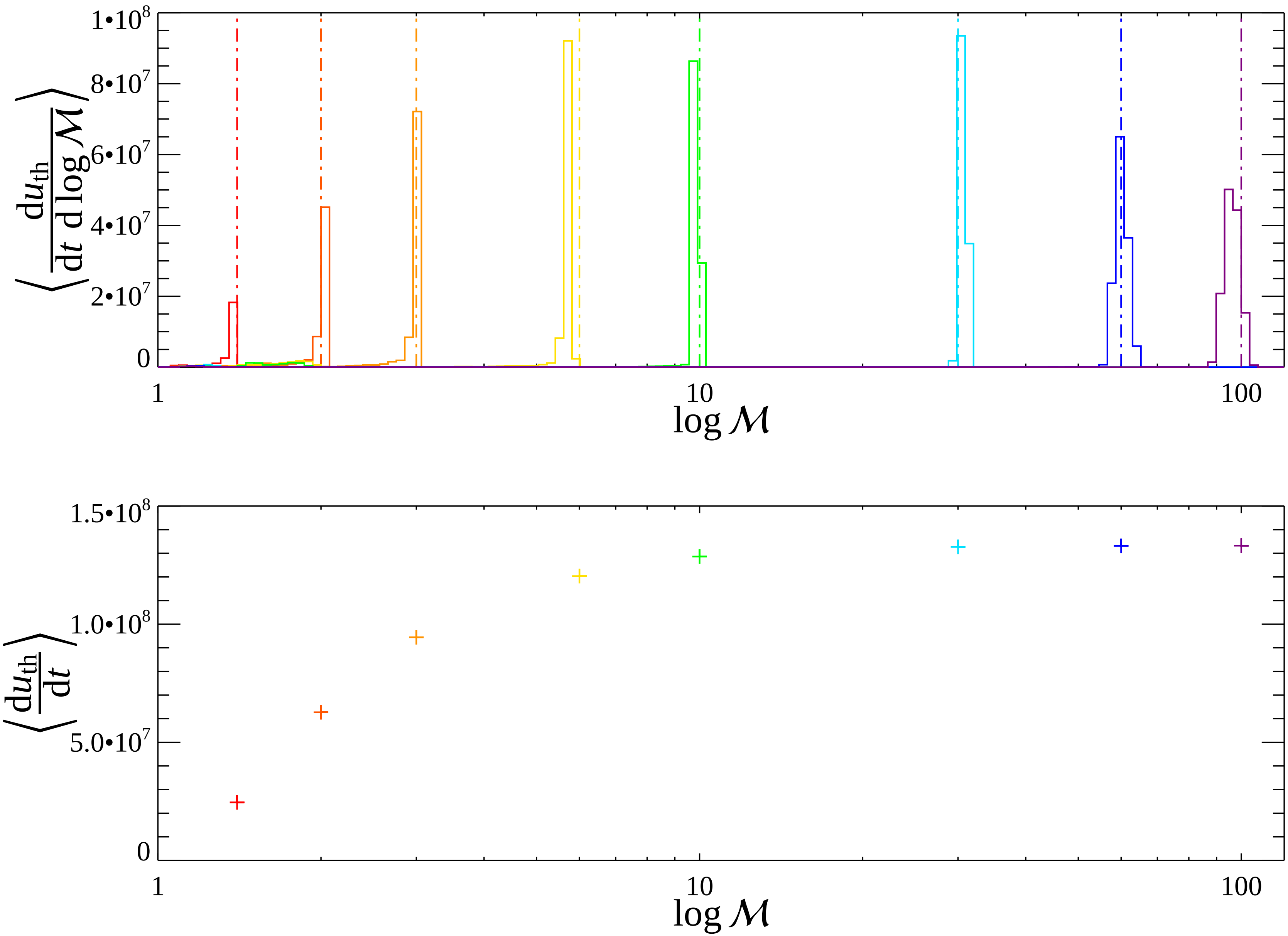
Abell 3667

(Radio: Australia Telescope Comp. Array. X-ray: ROSAT/PSPC.)

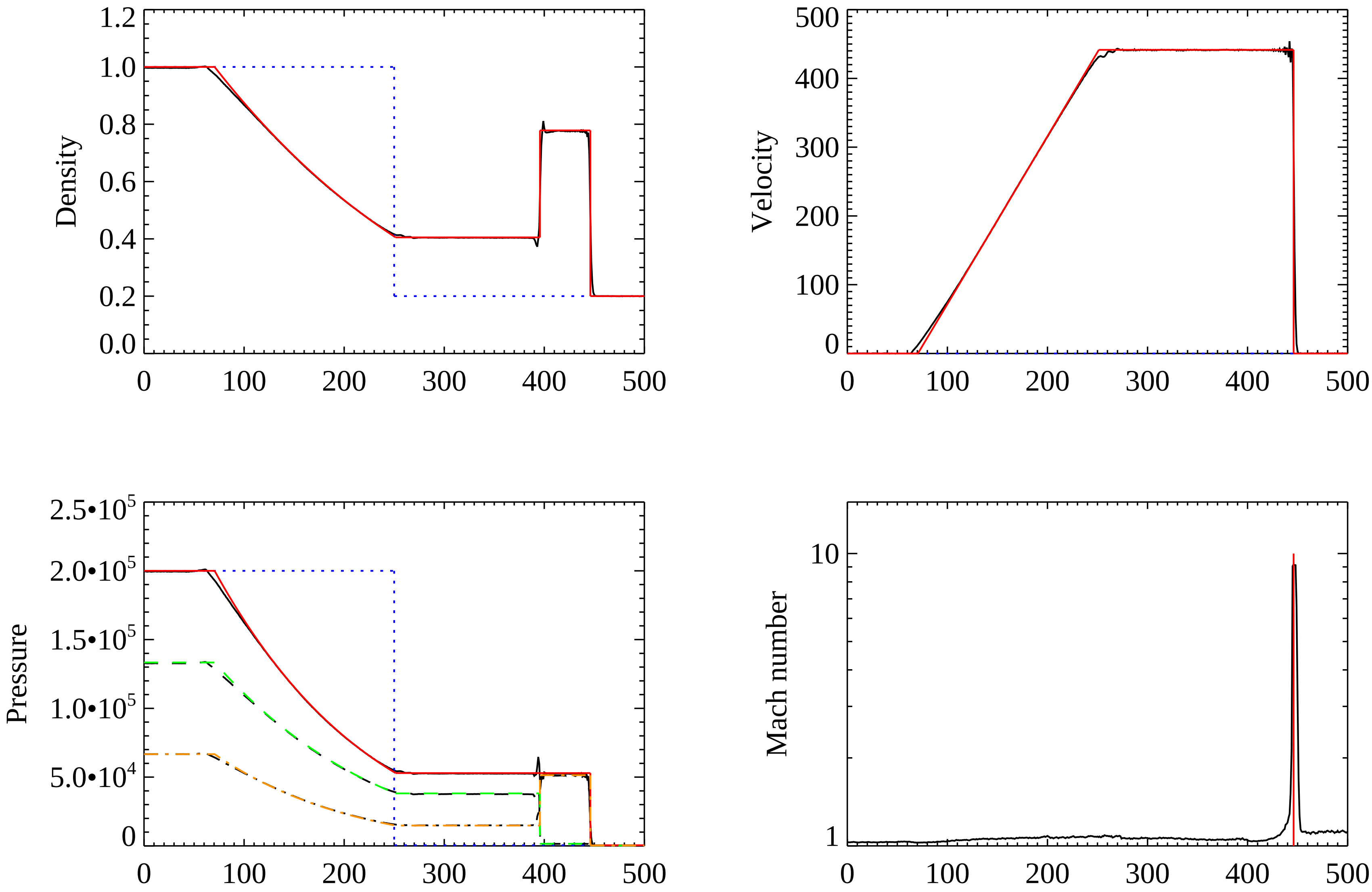
Shock tube: thermodynamics



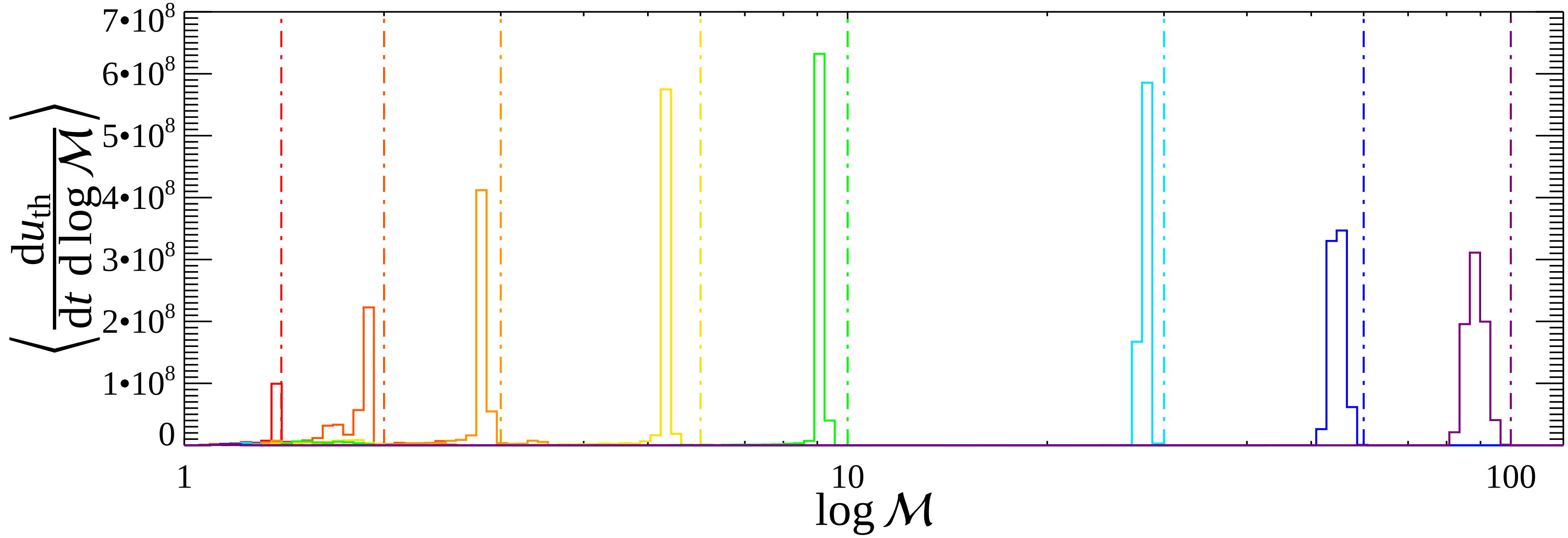
Shock tube: statistics

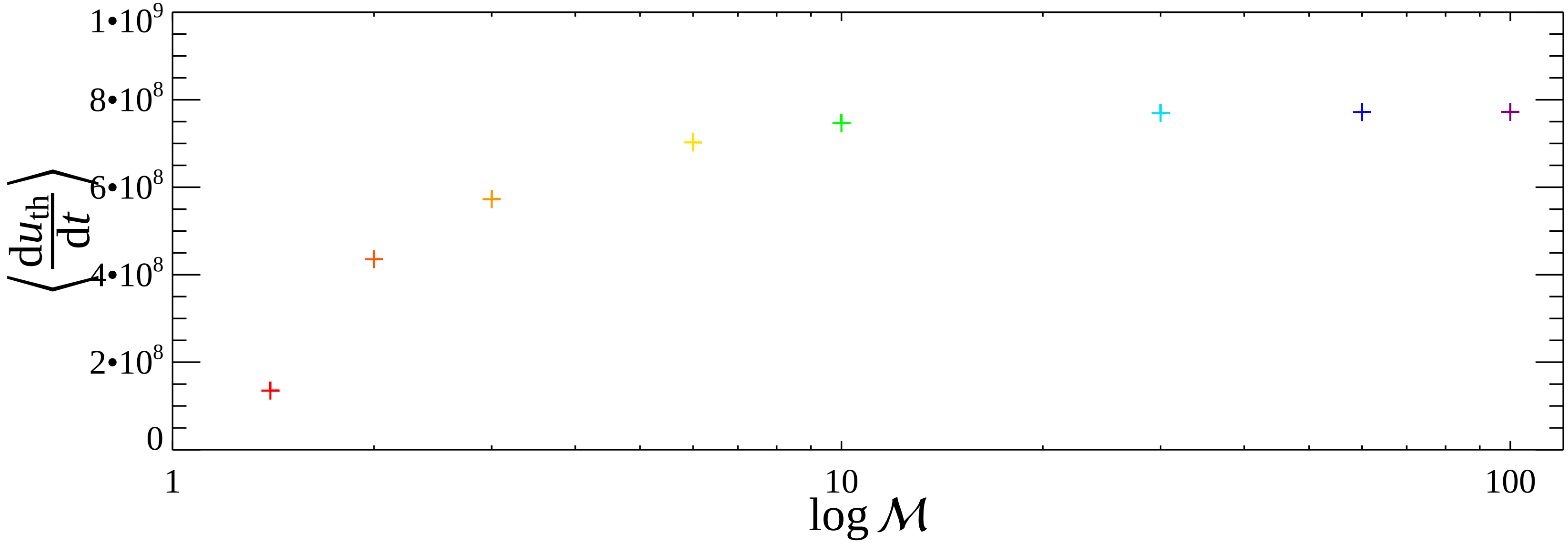


Shock tube (CRs & th. gas): thermodynamics

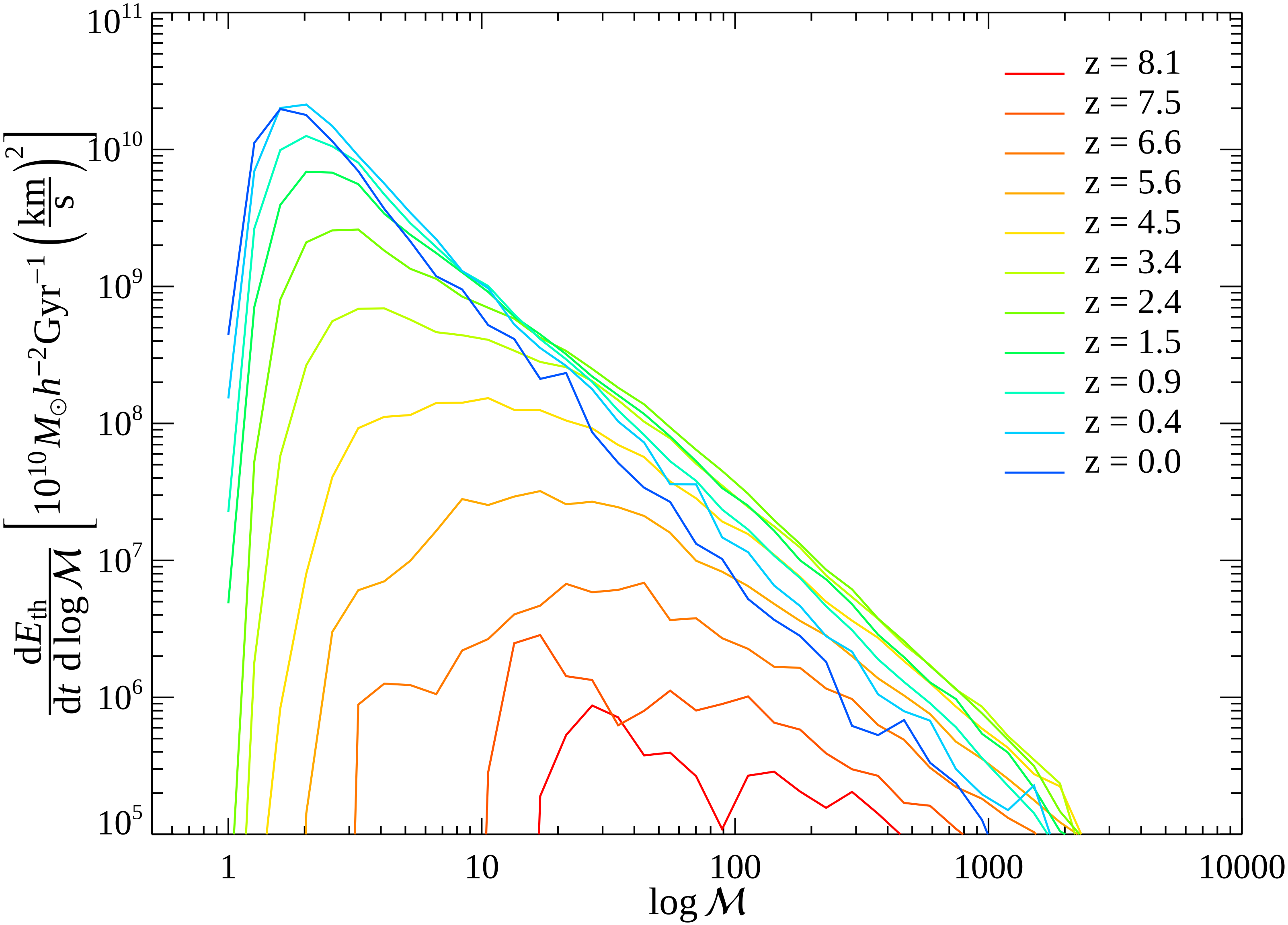


Shock tube (CRs & th. gas): statistics

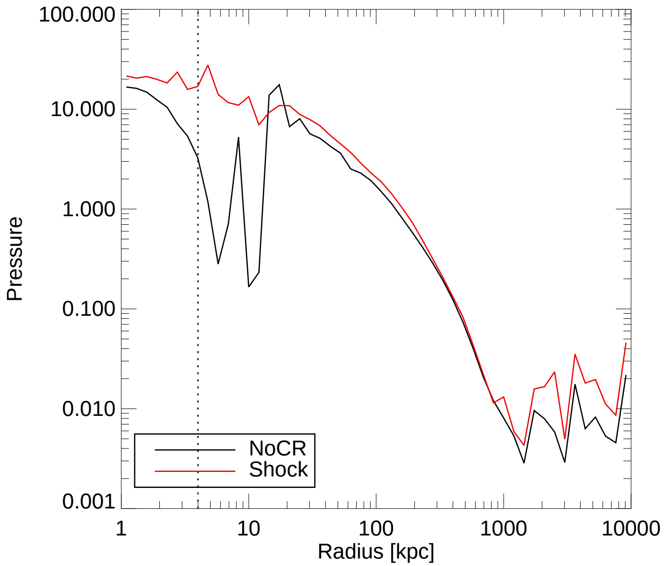


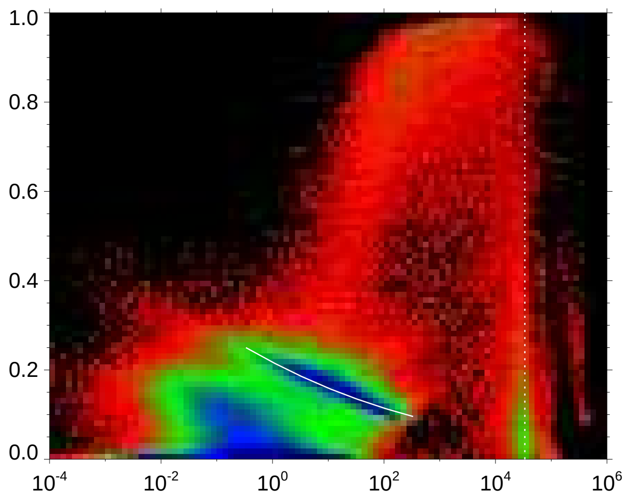


Cosmological simulation



Cosmic ray effects on cluster physics





Test case:

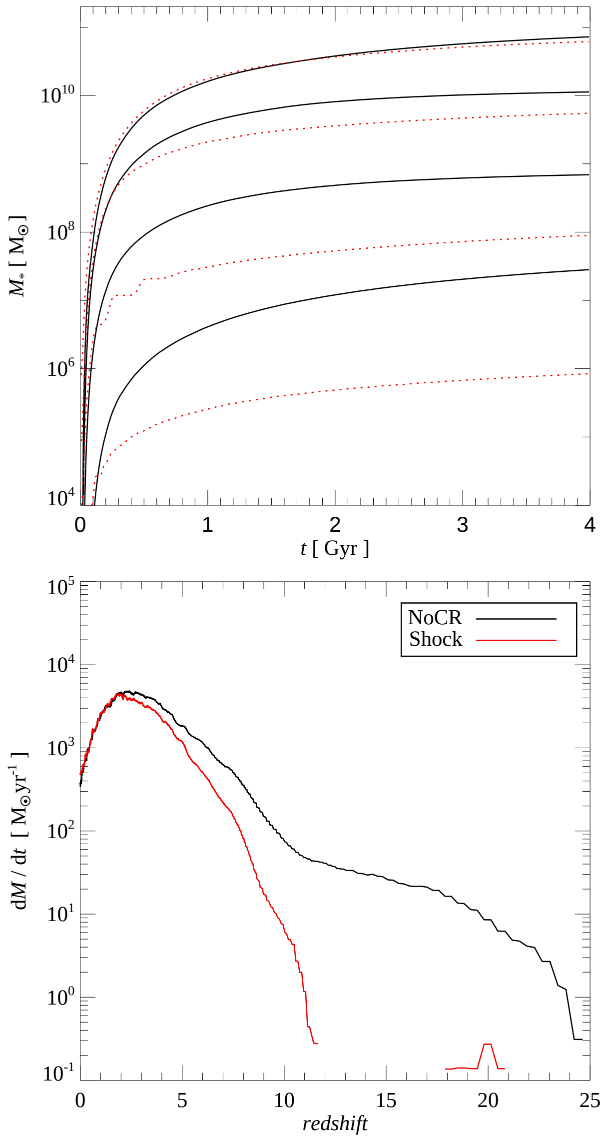
resimulation of a cosmologically evolving galaxy cluster with thermal gas, star formation (cooling processes and SN feedback) and CRs (shock injection)

Results:

- the composite gas (CRs & thermal gas) is easier compressible and thus leads to stronger radiative cooling processes
- clusters with shock-injected CRs show stronger matter concentration in central regions at z=0
- in dense regions, CRs represent an important pressure component (because thermal gas cools down with high efficiency)

Cosmic ray effects on galaxy evolution

Stellar mass as a function of time:



Test case:

simulation of a collapse of isolated gas spheres inside NFW dark matter profiles.

Results:

- global star formation efficiency is strongly dependent on the total halo mass: faint galaxies are strongly suppressed
- galaxy evolution in the hierarchical Universe: star formation rate effectively suppressed at early times (galaxy cluster simulation)

Conclusions

A.) Cosmic rays in nearby clusters of galaxies:

1.) limits on CRps from γ-rays (EGRET):
$X_{\mathrm{CRp}} = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}} < 20\%$

2.) M 87 γ-ray emission is consistent with hadronic scenario

3.) radio mini-halos (Perseus) seem to be of hadronic origin

B.) Cosmic rays in the simulation code GADGET

1.) huge potential and predictive power of cosmological simulations $\longrightarrow$ provides detailed γ-ray emission maps

2.) galaxy evolution: influence on energetic feedback, star formation, and galactic winds

3.) additional entropy floor at the cluster centers (cooling flow problem)