Cosmic Rays in Clusters of Galaxies – Tuning in to the Non-Thermal Universe

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in collaboration with

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Sep 26, 2007 / Cosmic Matter, Universität Würzburg

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Outline

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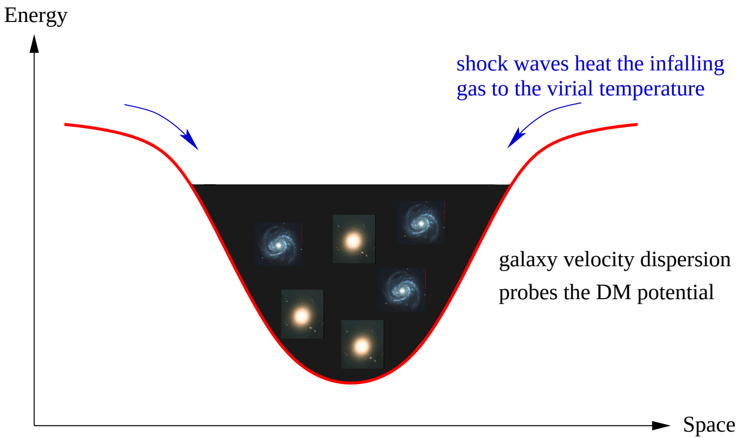
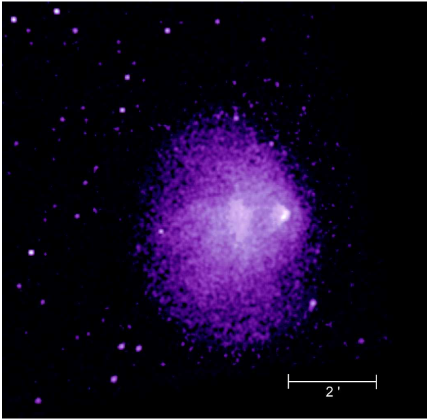
A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

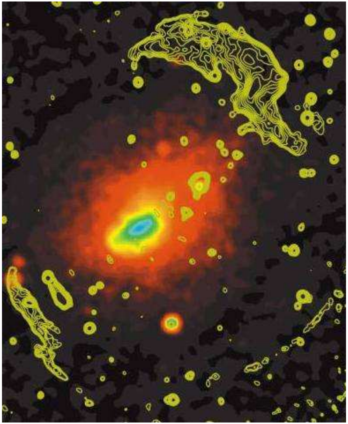


. . . and how the observer's Universe looks like



1E 0657-56 ("Bullet cluster")

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



Abell 3667

(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Observational properties of galaxy clusters

Each frequency window is sensitive to different processes and cluster properties:

- optical: gravitational lensing of background galaxies, galaxy velocity dispersion measure gravitational mass
- X-ray: thermal plasma emission, $F_X \propto n_{\mathrm{th}}^2 \sqrt{T_{\mathrm{th}}}$ $\rightarrow$ thermal gas with abundances, cluster potential, substructure
- Sunyaev-Zel'dovich effect: IC up-scattering of CMB photons by thermal electrons, $F_{\mathrm{SZ}} \propto p_{\mathrm{th}}$ $\rightarrow$ thermal gas pressure, cluster velocity, high-z clusters
- radio synchrotron halos: $F_{\mathrm{synchro}} \propto \varepsilon_B \varepsilon_{\mathrm{CRe}}$ $\rightarrow$ magnetic fields, CR electrons, shock waves
- diffuse γ-ray emission: $F_\gamma \propto n_{\mathrm{th}} n_{\mathrm{CRp}}$ $\rightarrow$ CR protons

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Why should we care about cosmic rays in clusters?

It allows us to explore complementary windows to cluster cosmology

1. Is high-precision cosmology possible using clusters?
   - Non-equilibrium processes such as cosmic ray pressure and turbulence possibly modify thermal X-ray emission and Sunyaev-Zel'dovich effect.
   - Cosmic ray pressure can modify the scaling relations → bias of cosmological parameters, or increase of the uncertainties if we marginalize over the 'unknown cluster physics' (cluster self-calibration)
2. What can we learn from non-thermal cluster emission?
   - Estimating the cosmic ray pressure contribution.
   - Constructing a 'gold sample' for cosmology using orthogonal information on the dynamical cluster activity.
   - Fundamental physics: diffusive shock acceleration, large scale magnetic fields, and turbulence.

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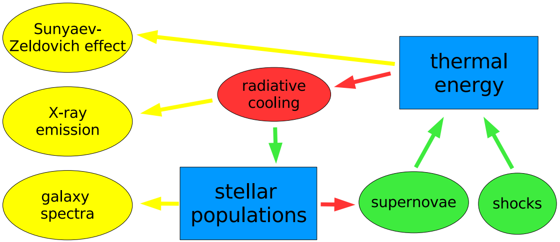
Radiative simulations – flowchart

Cluster observables: Physical processes in clusters:



loss processes
gain processes
observables
populations

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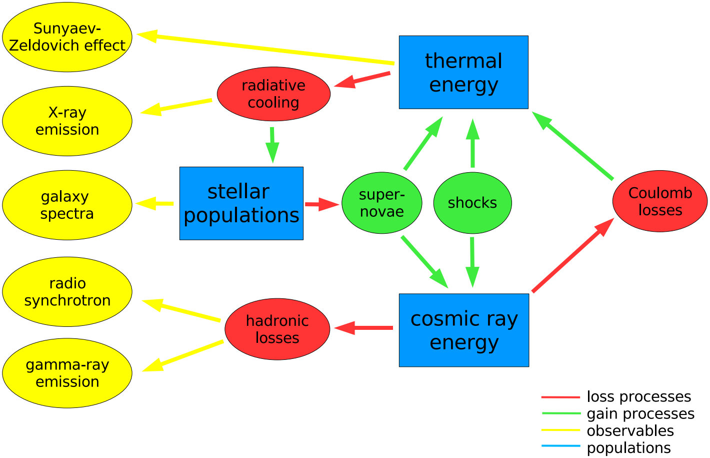
Radiative simulations with cosmic ray (CR) physics

Cluster observables: Physical processes in clusters:



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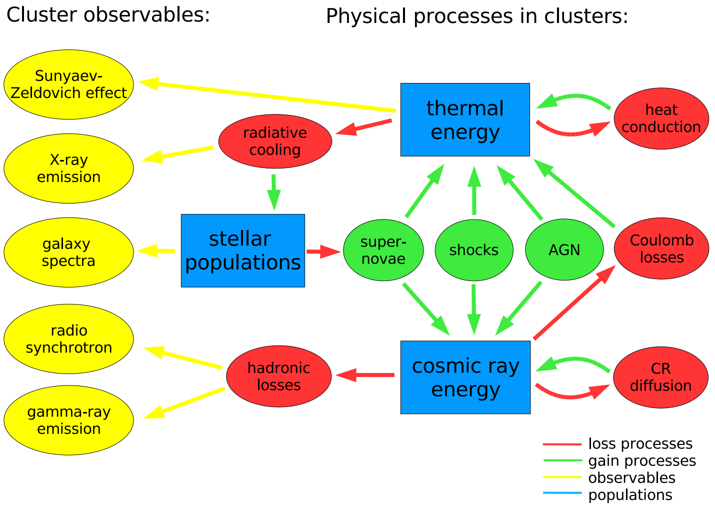
Radiative simulations with extended CR physics



Philosophy and description

An accurate description of CRs should follow the evolution of the spectral energy distribution of CRs as a function of time and space, and keep track of their dynamical, non-linear coupling with the hydrodynamics.

We seek a compromise between

- capturing as many physical properties as possible
- requiring as little computational resources as necessary

Assumptions:

- protons dominate the CR population
- a momentum power-law is a typical spectrum
- CR energy & particle number conservation

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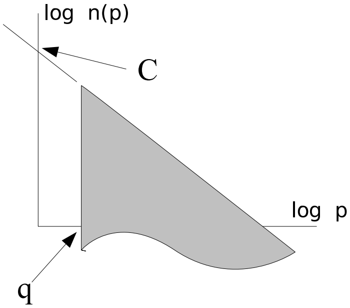
CR spectral description



$$p = P_\mathrm{p}/m_\mathrm{p}\,c$$

$$f(p) = \frac{dN}{dp\,dV} = C\,p^{-\alpha}\theta(p-q)$$

$$q(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{1}{3}} q_0$$

$$C(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{\alpha+2}{3}} C_0$$

$$n_\mathrm{CR} = \int_0^\infty \mathrm{d}p\,f(p) = \frac{C\,q^{1-\alpha}}{\alpha-1}$$

$$P_\mathrm{CR} = \frac{m_\mathrm{p}c^2}{3}\int_0^\infty \mathrm{d}p\,f(p)\,\beta(p)\,p$$

$$= \frac{C\,m_\mathrm{p}c^2}{6}\,\mathcal{B}_{\frac{1}{1+q^2}}\left(\frac{\alpha-2}{2},\frac{3-\alpha}{2}\right)$$

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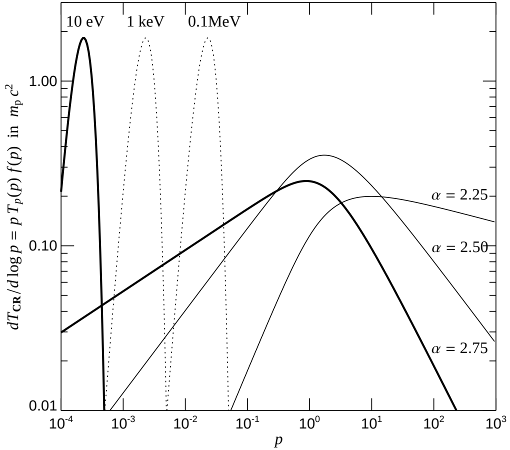
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:



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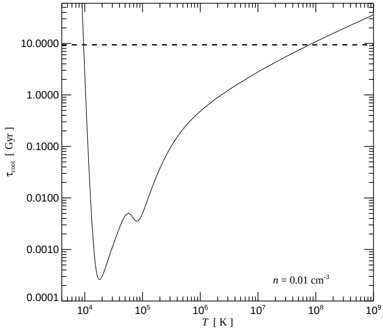
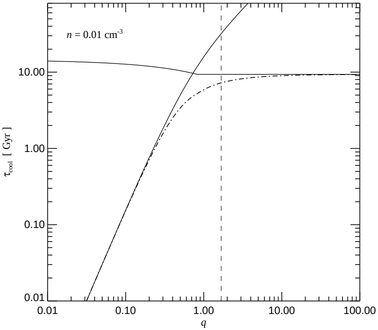
Cooling time scales of CR protons

Cooling of primordial gas:

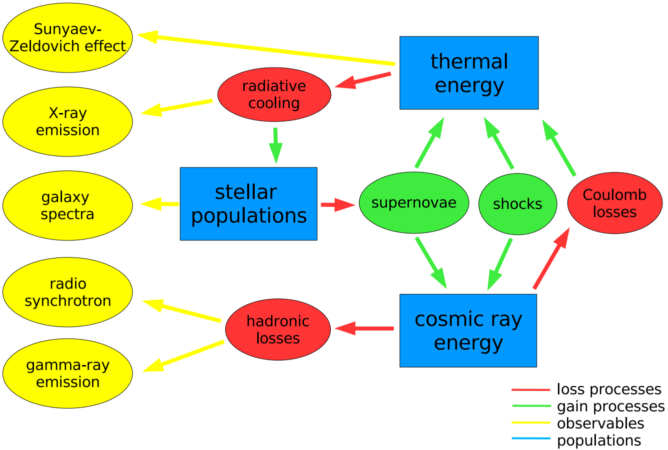


Cooling of cosmic rays:



Radiative simulations with CR physics

Cluster observables: Physical processes in clusters:



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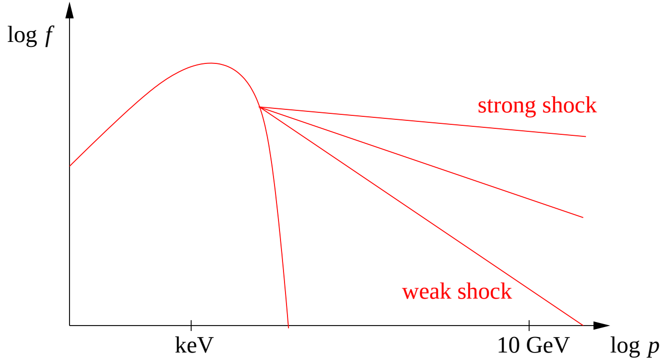
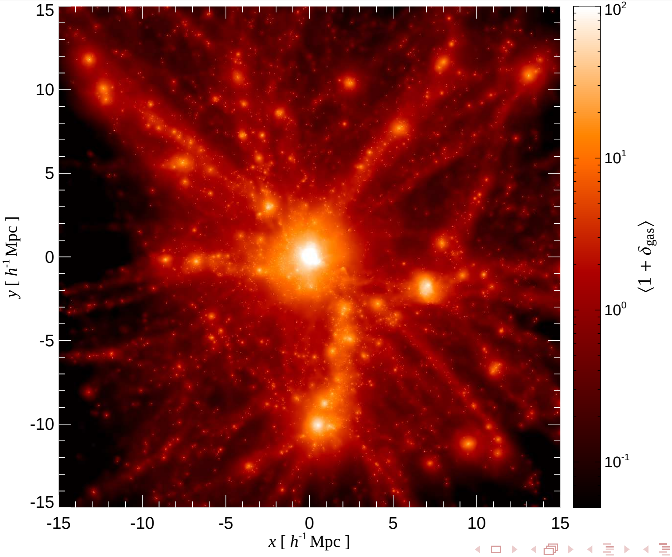
Diffusive shock acceleration – Fermi 1 mechanism

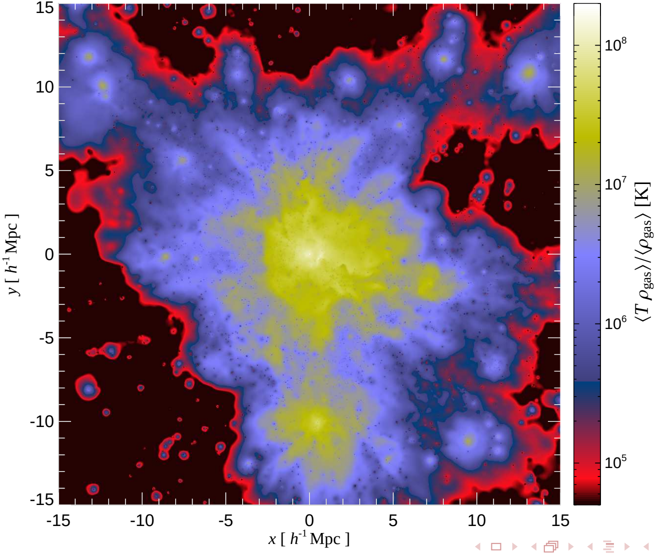
Spectral index depends on the Mach number of the shock, $\mathcal{M} = \upsilon_{\text{shock}}/c_{\text{s}}$:



Radiative cool core cluster simulation: gas density



Mass weighted temperature



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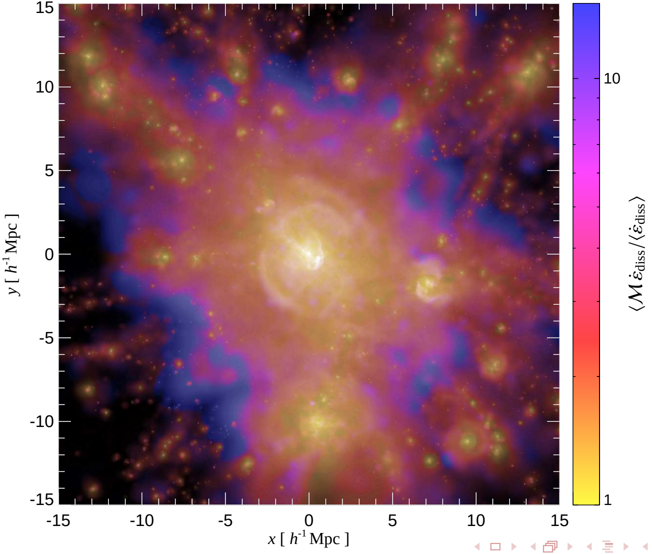
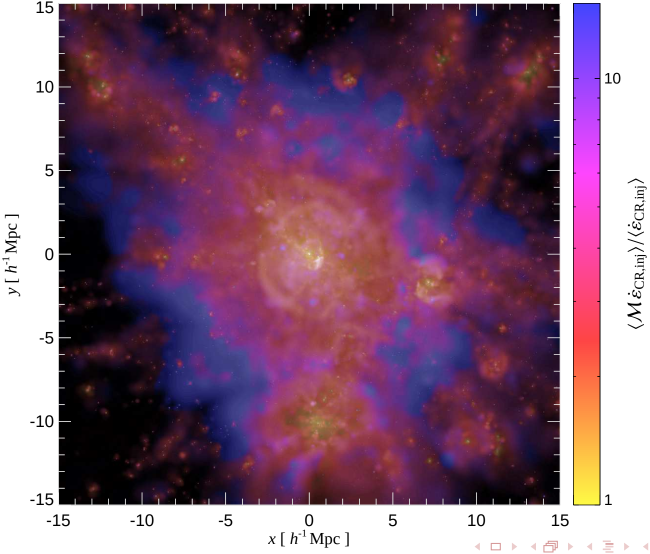
Mach number distribution weighted by $\varepsilon_{\mathrm{diss}}$



Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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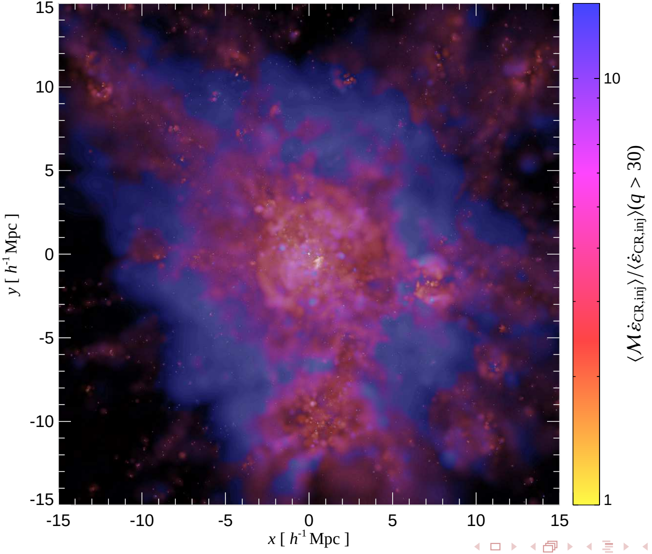
Mach number distribution weighted by $\varepsilon_{\rm CR,inj}(q > 30)$



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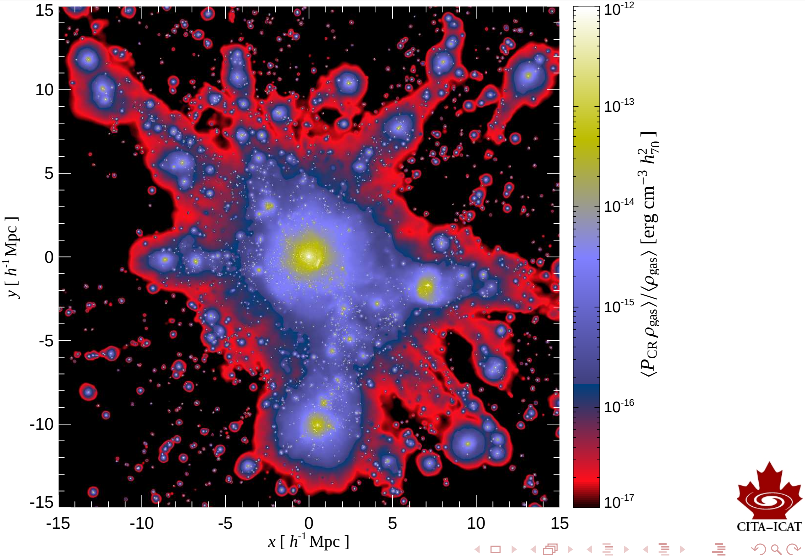
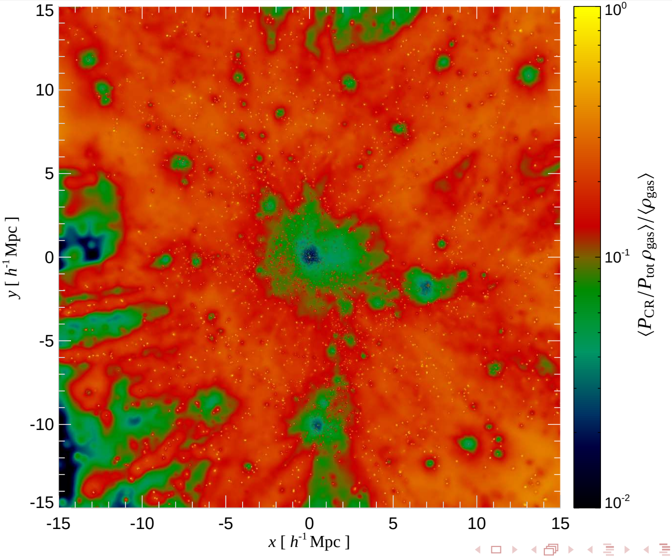
CR pressure $P_{\rm CR}$



Relative CR pressure $P_{\rm CR}/P_{\rm total}$



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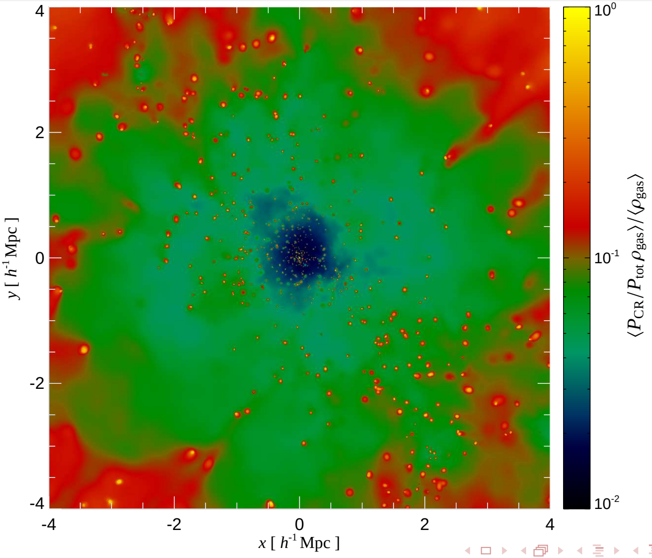
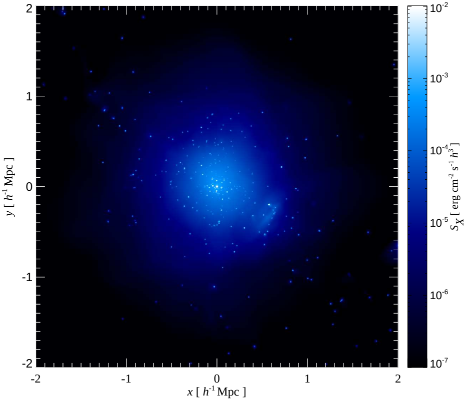
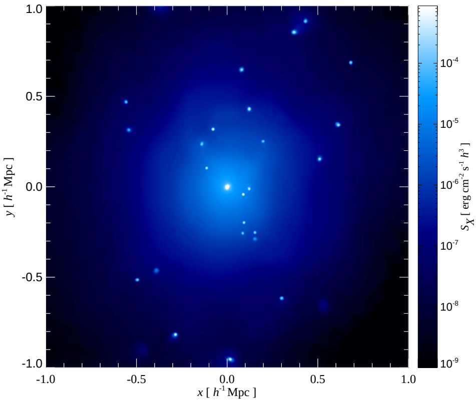


Thermal X-ray emission



large merging cluster, $M_{\rm vir} \simeq 10^{15} M_\odot / h$



small cool core cluster, $M_{\rm vir} \simeq 10^{14} M_\odot / h$

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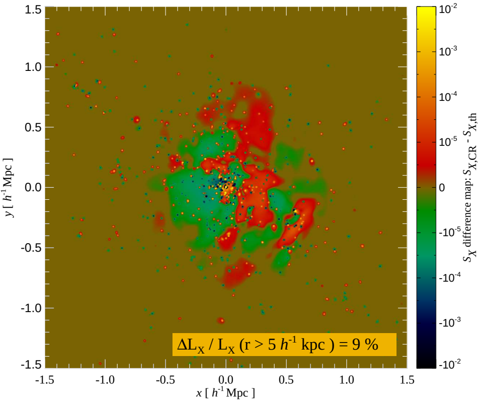
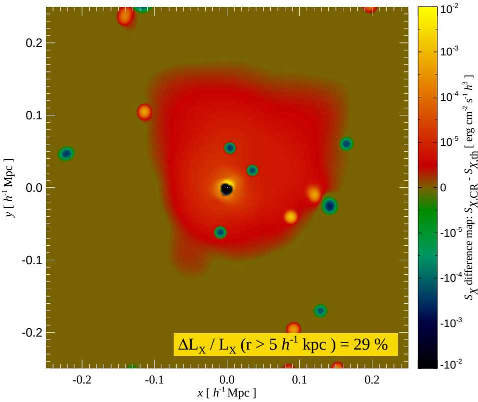
Difference map of S_X: $S_{X,\mathrm{CR}} - S_{X,\mathrm{th}}$





large merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_\odot / h$
$\rightarrow$ contributes to the scatter in the $M - L_X$ scaling relation

cool core cluster, $M_{\mathrm{vir}} \simeq 10^{14} M_\odot / h$
$\rightarrow$ systematic increase of L_X for small cool core clusters

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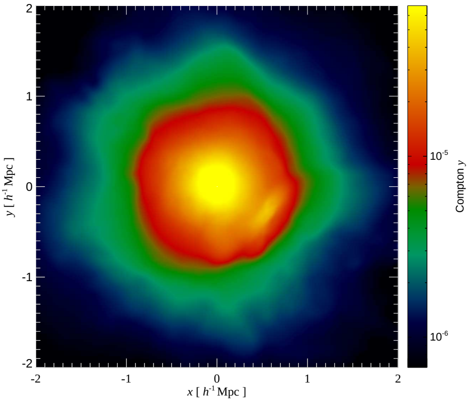
Compton y parameter in radiative cluster simulation



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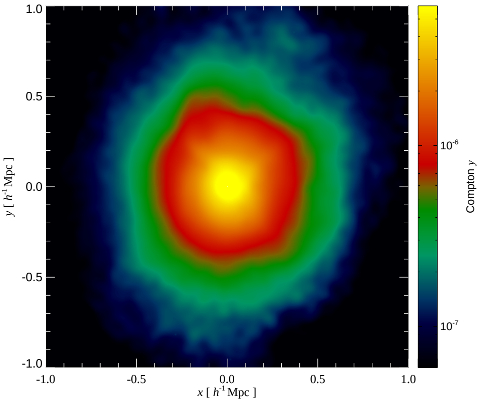

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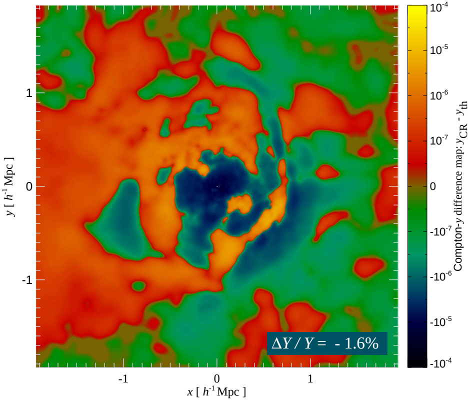
Compton y difference map: $y_{\mathrm{CR}} - y_{\mathrm{th}}$



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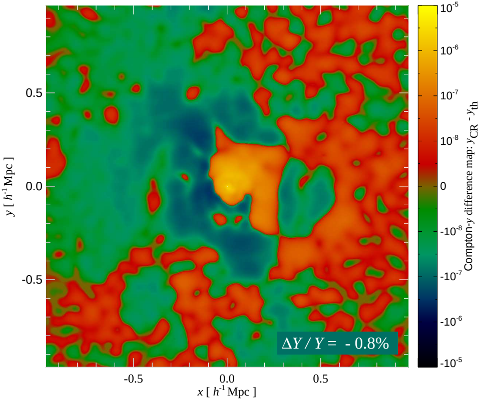

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Non-thermal emission from clusters

Exploring the memory of structure formation

The thermal plasma lost most information on how cosmic structure formation proceeded due to the dissipative processes. The thermal observables, X-ray emission and the Sunyaev-Zel'dovich effect, tell us only very indirectly (if at all) about the cosmic history. In contrast, non-thermal processes retain their cosmic memory since their particle population is not in equilibrium $\rightarrow$ cluster archaeology.

How can we read out this information about non-thermal populations? $\rightarrow$ new era of multi-frequency experiments, e.g.:

- LOFAR, GMRT, MWA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Glast: international high-energy γ-ray space mission ($E \simeq (0.1 - 300)$ GeV)
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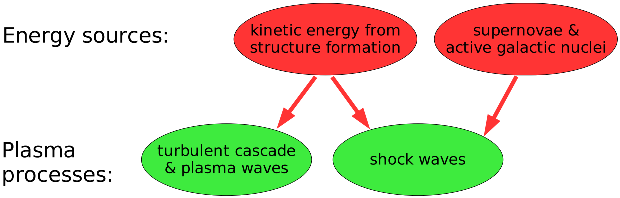
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



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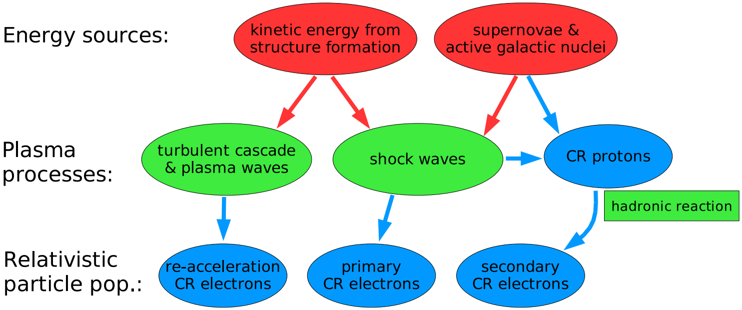

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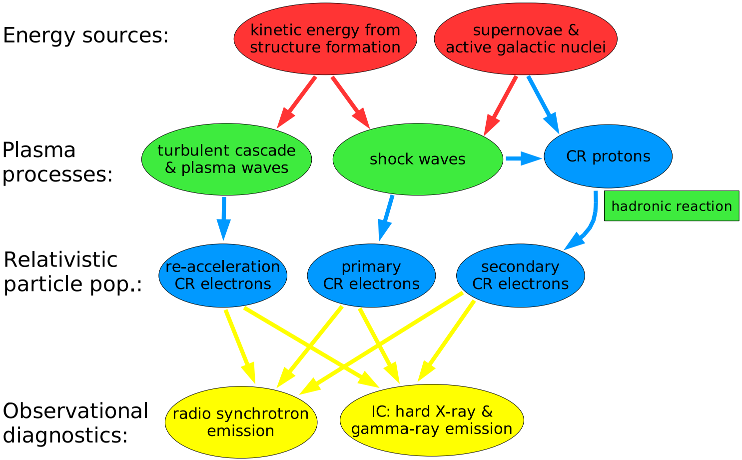

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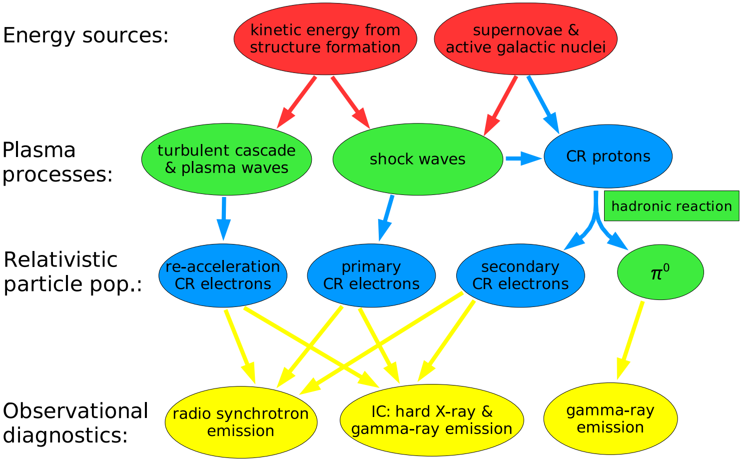

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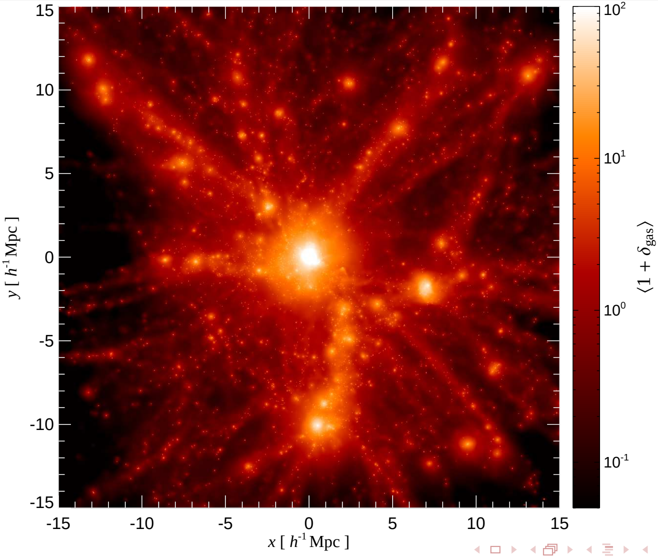

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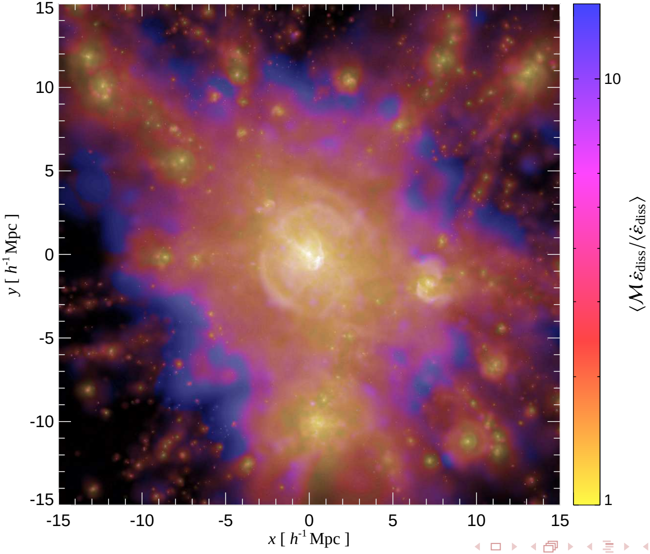
Cosmic web: Mach number



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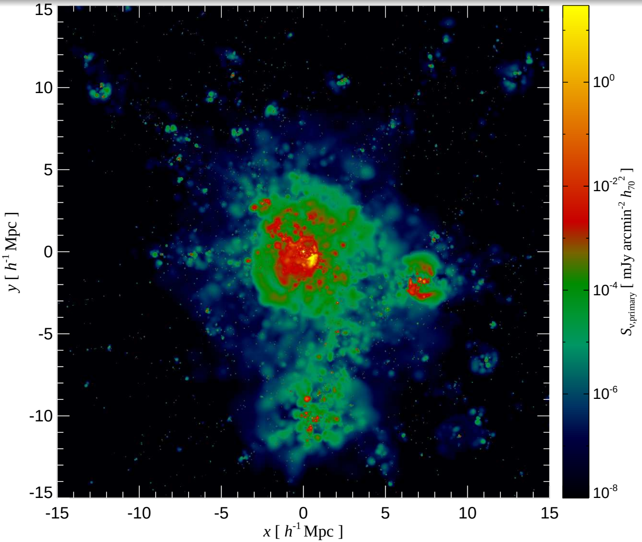
Radio web: primary CRe (1.4 GHz)



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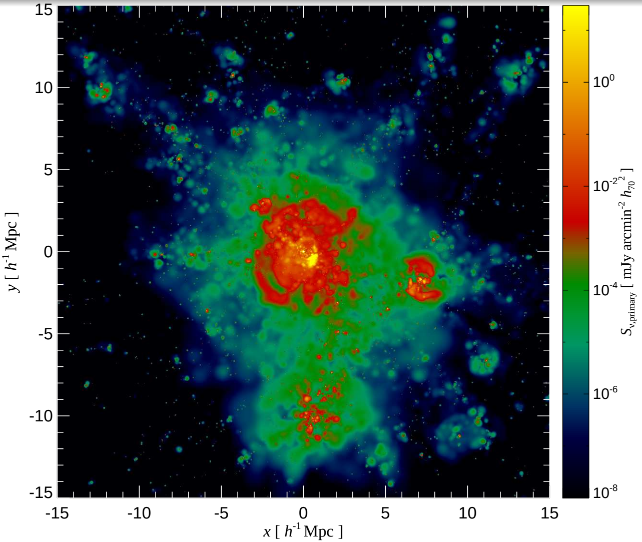
Radio web: primary CRe (150 MHz)



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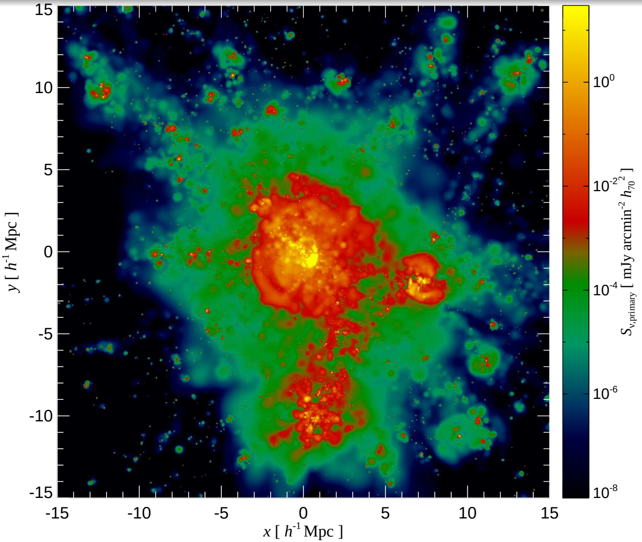
Radio web: primary CRe (15 MHz)



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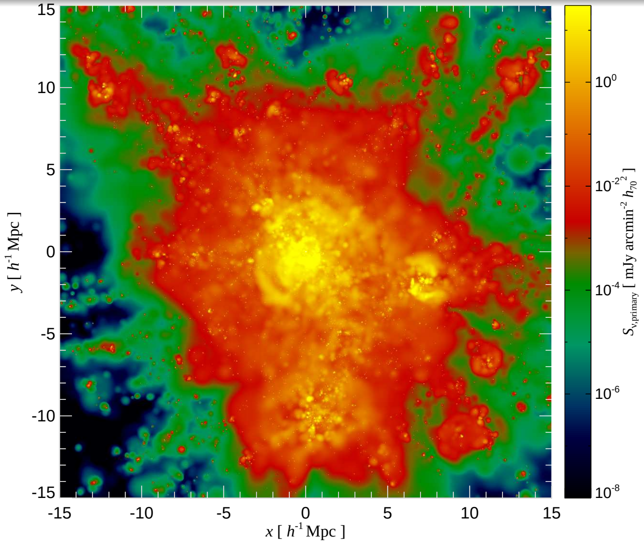
Radio web: primary CRe (15 MHz), slower magnetic decline



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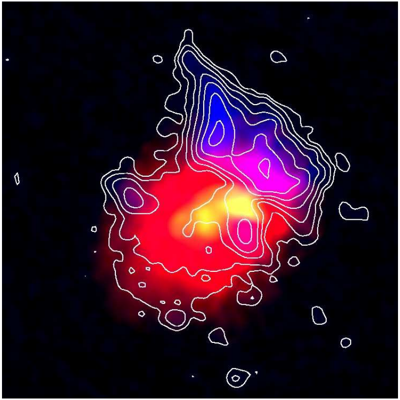
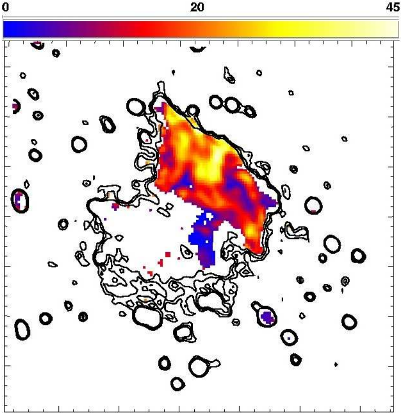
Abell 2256: giant radio relic & small halo



X-ray (red) & radio (blue, contours)



fractional polarization in color

Clarke & Enßlin (2006)

Cosmic rays and radiative processes

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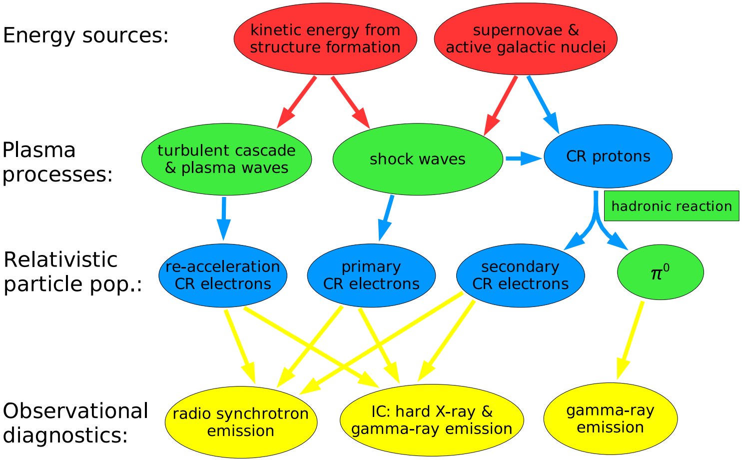

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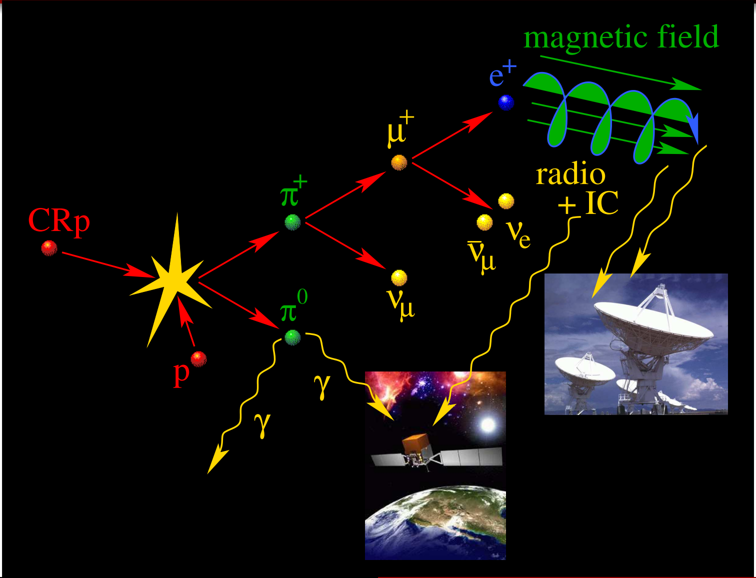
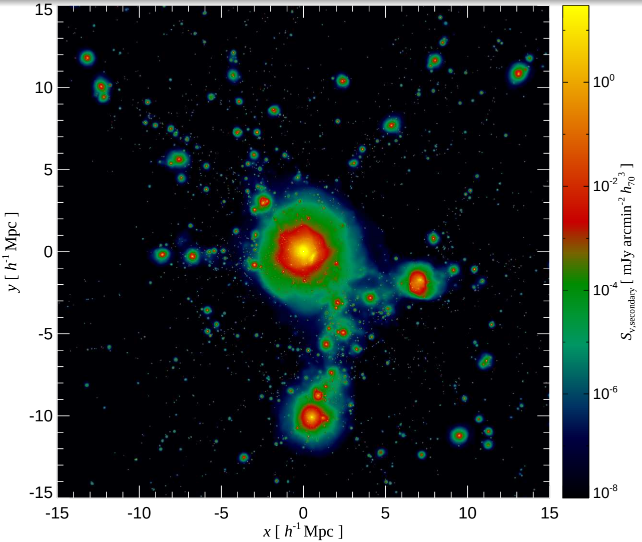
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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Previous models for giant radio halos in clusters

Radio halos show a smooth unpolarized radio emission at Mpc-scales. How are they generated?

- Primary accelerated CR electrons: synchrotron/IC cooling times too short to account for extended diffuse emission.
- Continuous in-situ acceleration of pre-existing CR electrons either via interactions with magneto-hydrodynamic waves, or through turbulent spectra (Jaffe 1977, Schlickeiser 1987, Brunetti 2001, Brunetti & Lazarian 2007).
- Hadronically produced CR electrons in inelastic collisions of CR protons with the ambient gas (Dennison 1980, Vestrad 1982, Miniati 2001, Pfrommer 2004).

All of these models face theoretical short-comings when comparing to observations.

Unified model of radio halos and relics

Cluster radio emission varies with dynamical stage of a cluster:

- Cluster relaxes and develops cool core: radio mini-halo develops due to hadronically produced CR electrons, magnetic fields are adiabatically compressed (cooling gas triggers radio mode feedback of AGN that outshines mini-halo → selection effect).
- Cluster experiences major merger: two leading shock waves are produced that become stronger as they break at the shallow peripheral cluster potential → shock-acceleration of primary electrons and development of radio relics.
- Generation of morphologically complex network of virializing shock waves. Lower sound speed in the cluster outskirts lead to strong shocks → irregular distribution of primary electrons, MHD turbulence amplifies magnetic fields.
- Giant radio halo develops due to (1) boost of the hadronically generated radio emission in the center (2) irregular radio 'gischt' emission in the cluster outskirts.

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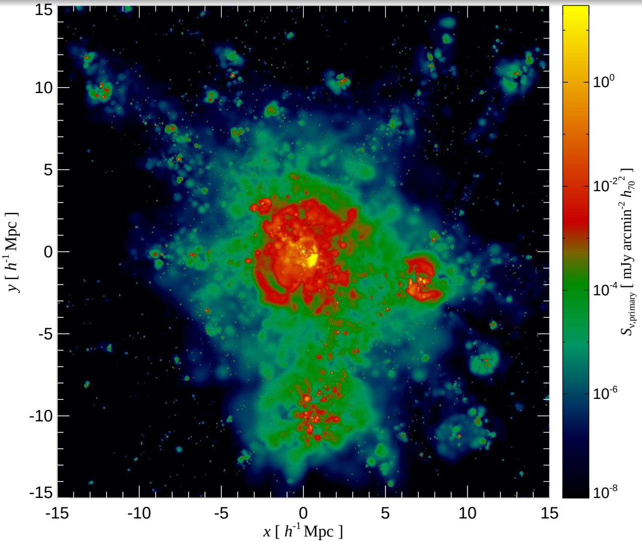
Radio gischt: primary CRe (150 MHz)



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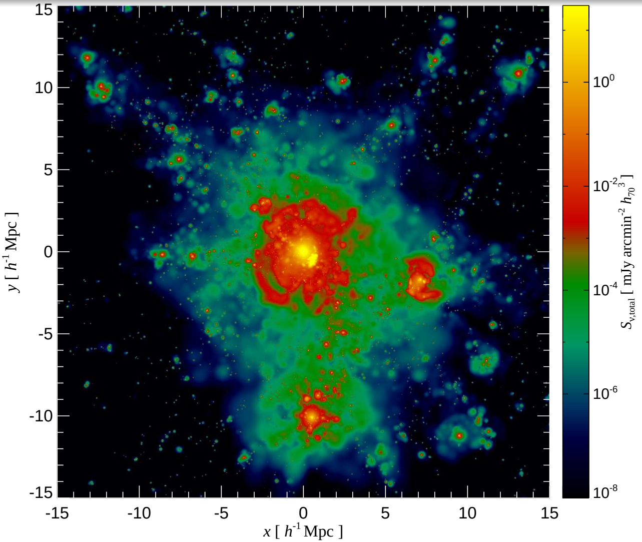
Radio gischt + central hadronic halo = giant radio halo



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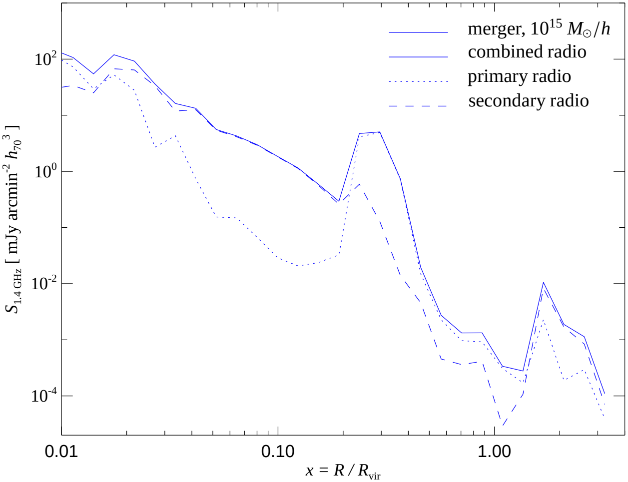
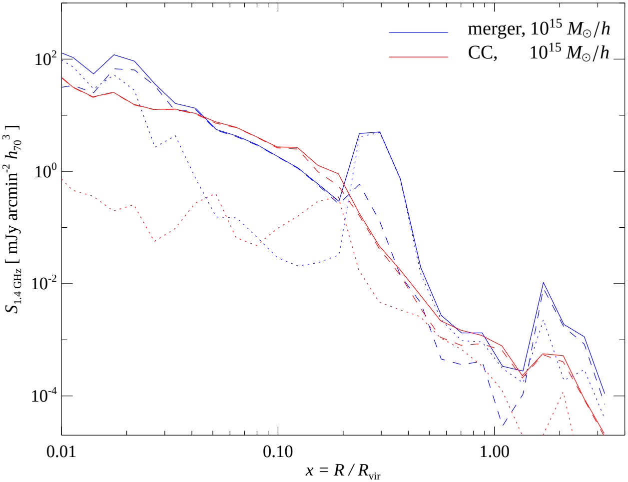
Giant radio halo profile



Giant radio halo vs. mini-halo



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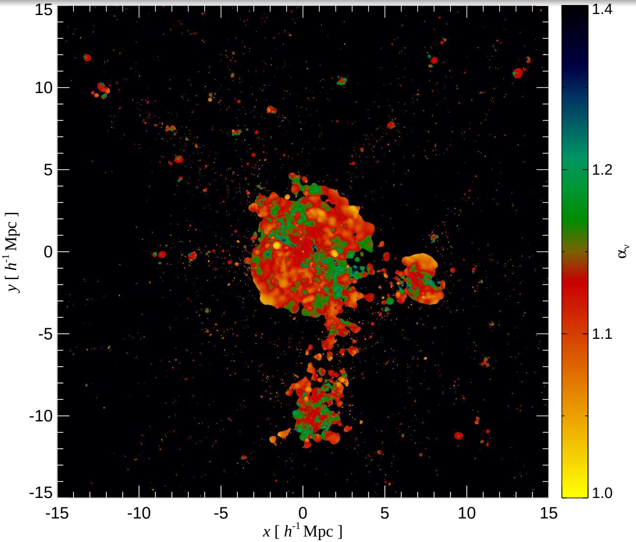
Radio relics + halos: spectral index



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Low-frequency radio emission from clusters

Window into current and past structure formation

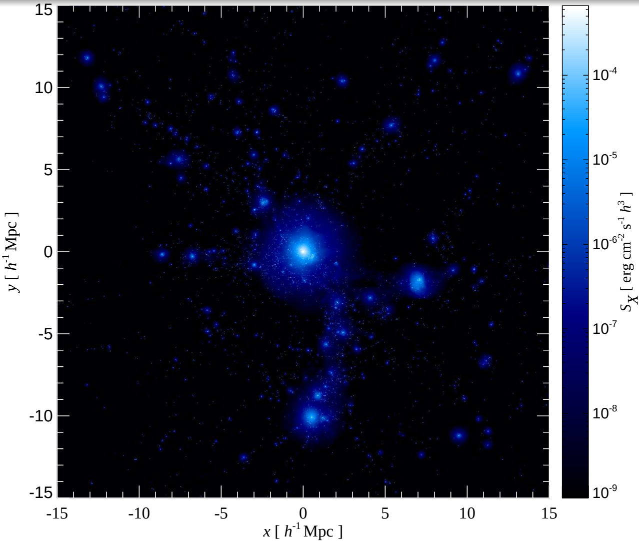
Our unified model accounts for . . .

- correlation between merging clusters and giant halos, occurrence of mini-halos in cool core clusters
- observed luminosities of halos/relics for magnetic fields derived from Faraday rotation measurements
- observed morphologies, variations, spectral and polarization properties in radio halos/relics

How we can make use of this information:

- Radio relics: produced by primary accelerated CR electrons at formation shocks → probes current dynamical, non-equilibrium activity of forming structures (shocks and magnetic fields)
- Central radio halos: produced by secondary CR electrons in hadronic CR proton interactions → tracing time-integrated non-equilibrium activity, modulated by recent dynamical activities

Thermal X-ray emission



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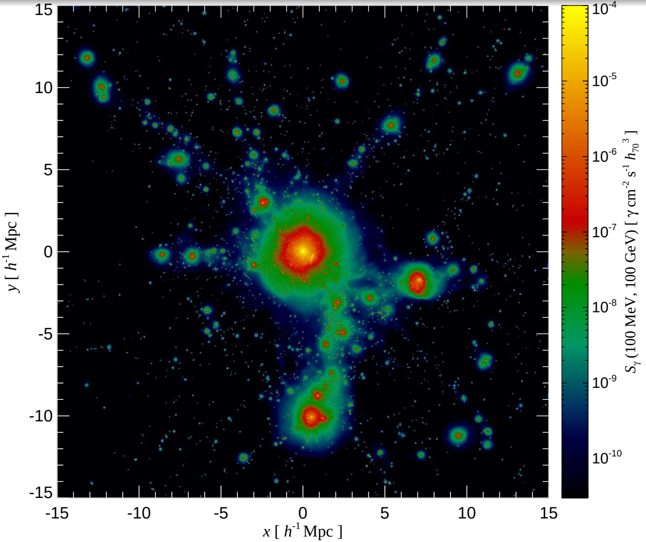
Hadronic γ-ray emission, $E_\gamma > 100$ MeV



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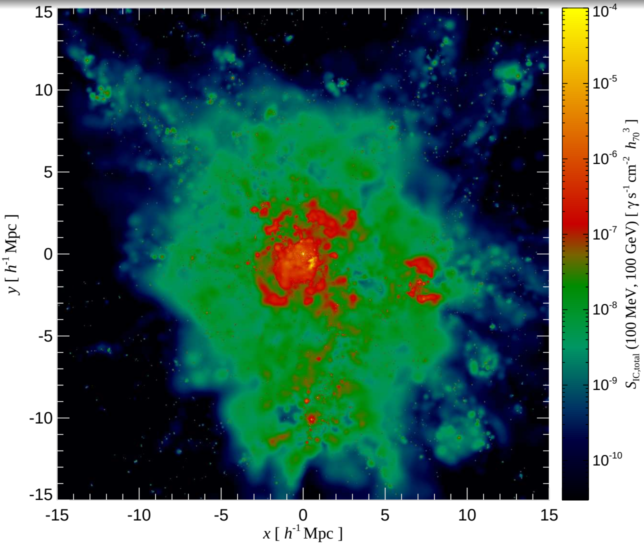
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ MeV



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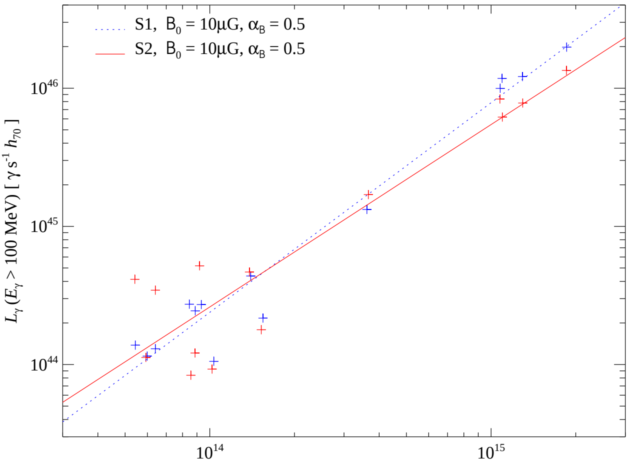
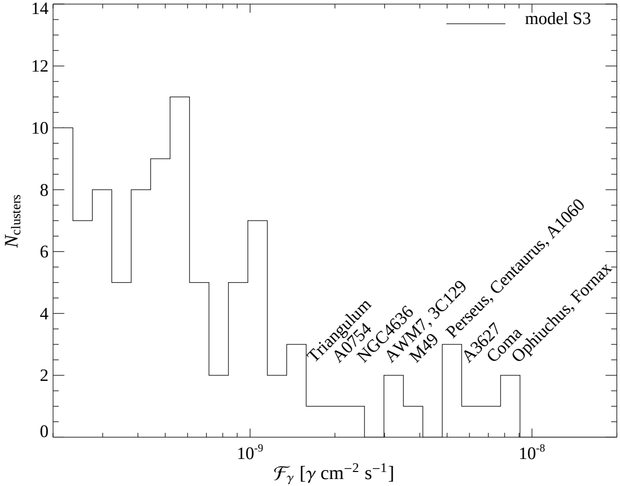
Gamma-ray scaling relations



Scaling relation + complete sample of the brightest X-ray clusters (HIFLUCGS) → predictions for GLAST

Predicted cluster sample for GLAST



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Summary

1. Characteristics of the CR pressure in clusters:
   - CR proton pressure traces the time integrated non-equilibrium activities of clusters and is modulated by recent dynamical activities.
   - The pressure of primary, shock-accelerated CR electrons resembles current accretion and merging shocks in the virial regions.
2. Unified model for the generation of giant radio halos, radio mini-halos, and relics:
   - Giant radio halos are dominated in the center by secondary synchrotron emission.
   - Transition to the radio emission from primary electrons in the cluster periphery.
3. We predict GLAST to detect $\sim$ ten γ-ray clusters: test of the presented scenario

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