Cosmic rays in clusters of galaxies – Tuning in to the non-thermal Universe

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in collaboration with

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Outline

1. Cosmic rays in galaxy clusters
   - Introduction and motivation
   - Cluster simulations and cosmic ray physics
   - Cosmic ray pressure feedback
2. Particle acceleration processes
   - Diffusive shock acceleration
   - Stochastic acceleration
   - Particle reactions
3. Non-thermal cluster emission
   - Radiative processes
   - Unified model of radio halos and relics
   - High-energy gamma-ray emission

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Outline

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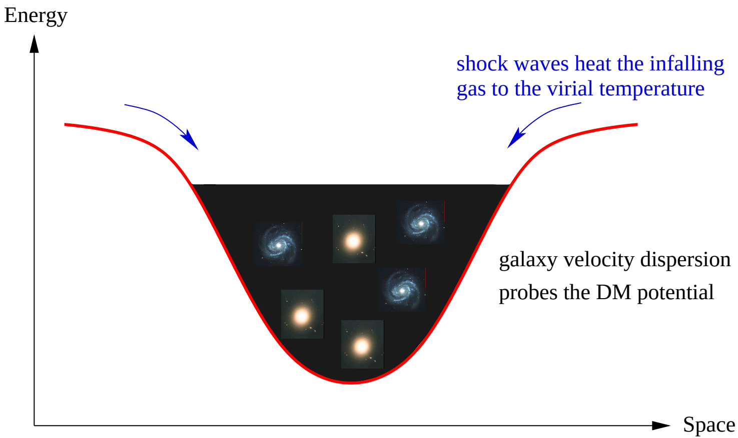
A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:



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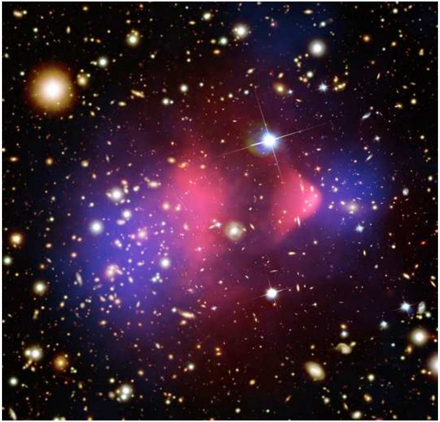
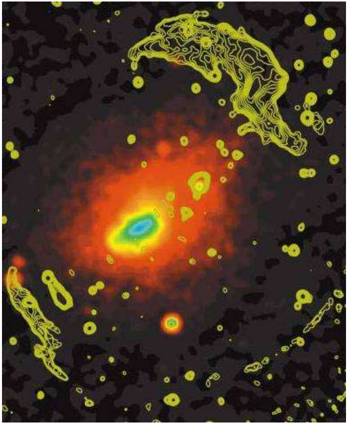
. . . and how the observer's Universe looks like



1E 0657-56 ("Bullet cluster")

(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

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

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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.
   - Non-thermal cluster emission will enable constructing a 'gold sample' for cosmology using orthogonal information on the dynamical cluster activity.
2. What can we learn from non-thermal cluster emission?
   - Understanding mechanism of diffuse radio and non-thermal X-ray emission of clusters.
   - Estimating the cosmic ray pressure contribution.
   - Fundamental physics: diffusive shock acceleration, large scale magnetic fields, and turbulence.

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Literature for the talk

- Pfrommer, 2007, arXiv:0707.1693, *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
- Pfrommer, Enßlin, Springel, 2007, arXiv:0707.1707, *Simulating cosmic rays in clusters of galaxies – II. A unified model for radio halos and relics with predictions of the γ-ray emission*
- Pfrommer, Enßlin, Springel, Jubelgas, and Dolag, 2007, MNRAS, 378, 385, *Simulating cosmic rays in clusters of galaxies, I. effects on the Sunyaev-Zel'dovich effect and the X-ray emission*
- Pfrommer, Springel, Enßlin, Jubelgas 2006, MNRAS, 367, 113, *Detecting shock waves in cosmological smoothed particle hydrodynamics simulations*
- Enßlin, Pfrommer, Springel, and Jubelgas, in press, astro-ph/0603484, *Cosmic ray physics in calculations of cosmological structure formation*
- Jubelgas, Springel, Enßlin, and Pfrommer, astro-ph/0603485, *Cosmic ray feedback in hydrodynamical simulations of galaxy formation*

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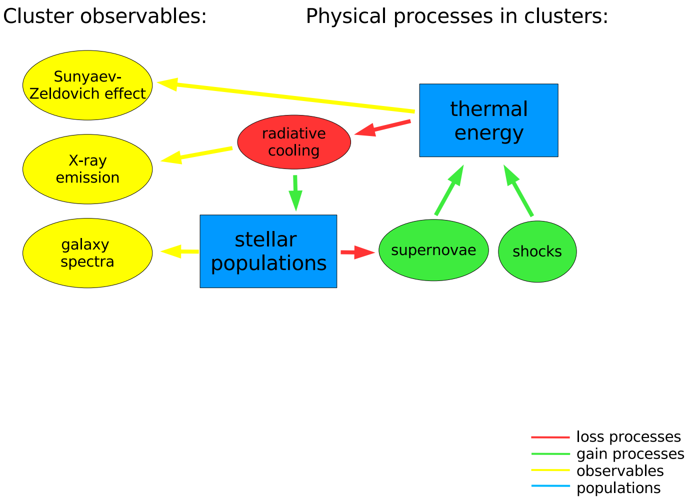
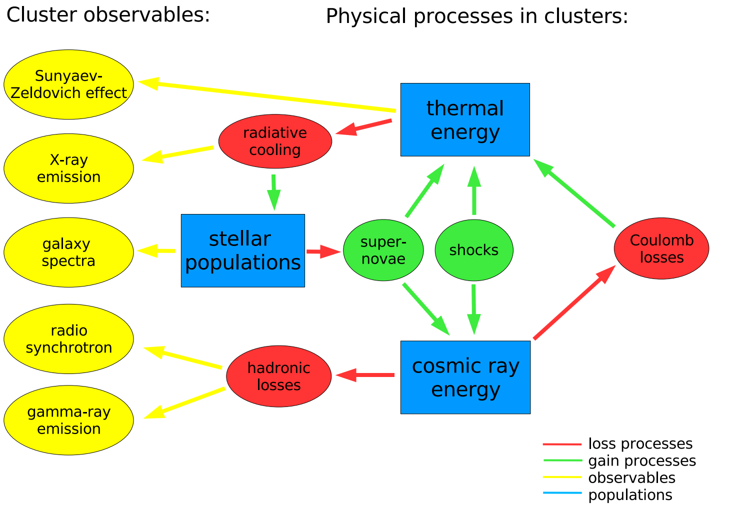
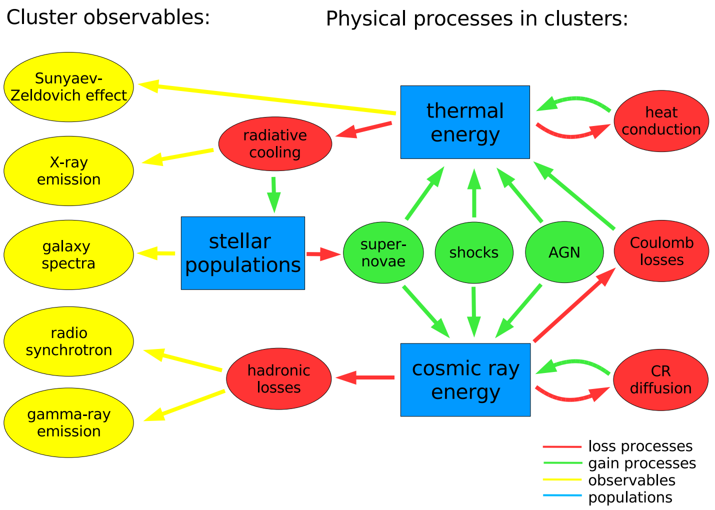
Radiative simulations – flowchart



Radiative simulations with cosmic ray (CR) physics



Radiative simulations with extended CR physics



Previous numerical work on cosmic rays in clusters

COSMOCR: A numerical code for cosmic ray studies in computational cosmology (Miniati, 2001):

- advantages: good resolution in momentum space
- drawbacks: CR pressure not accounted for in EoM, insufficient spatial resolution (grid code), non-radiative gas physics

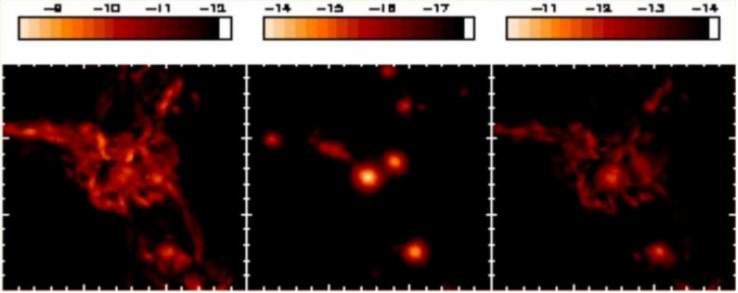


Figure: Hard X-rays, thermal X-rays, γ-rays, adopted from Miniati (2003)

Our 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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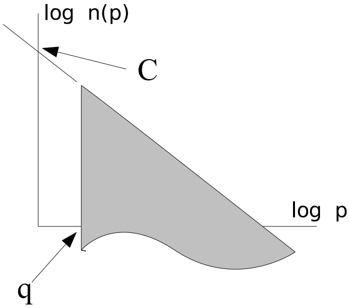
CR spectral description



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

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

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

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

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

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

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

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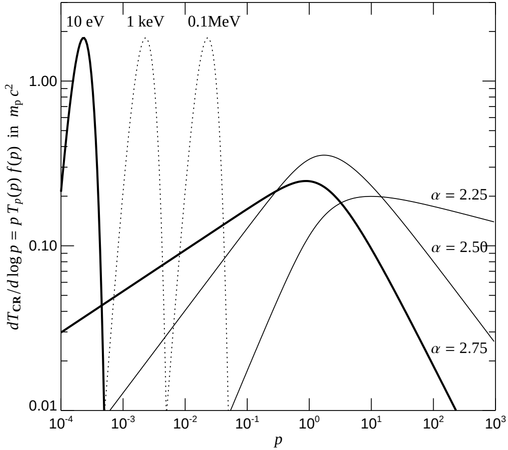
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:



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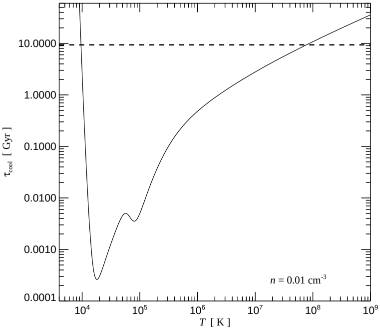
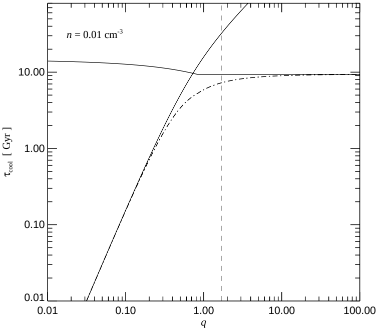
Cooling time scales of CR protons

Cooling of primordial gas:



Cooling of cosmic rays:



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Outline

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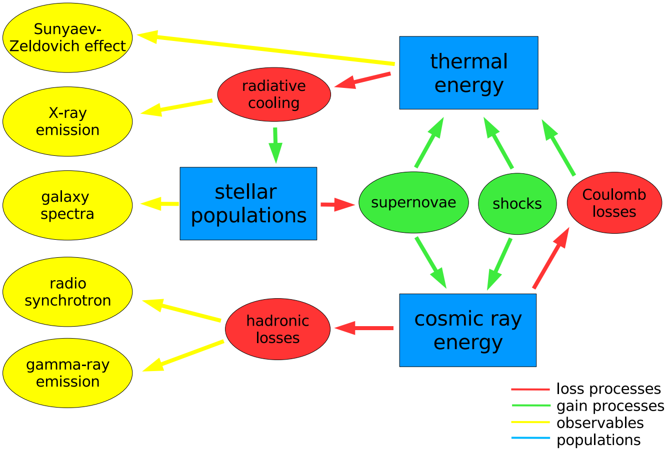
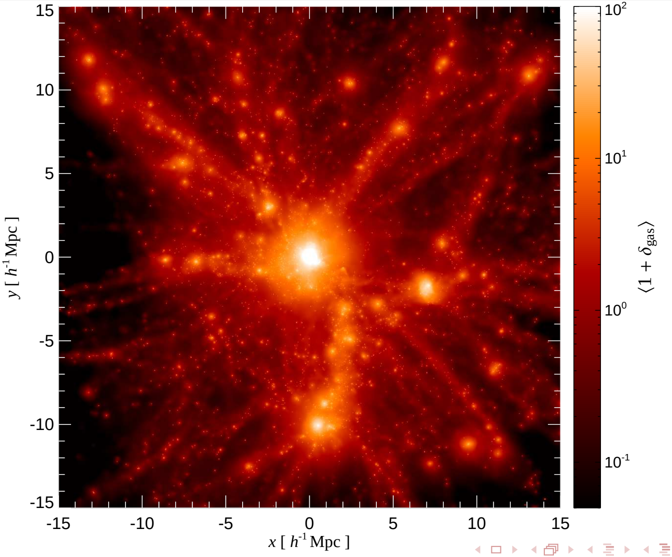
Radiative simulations with CR physics

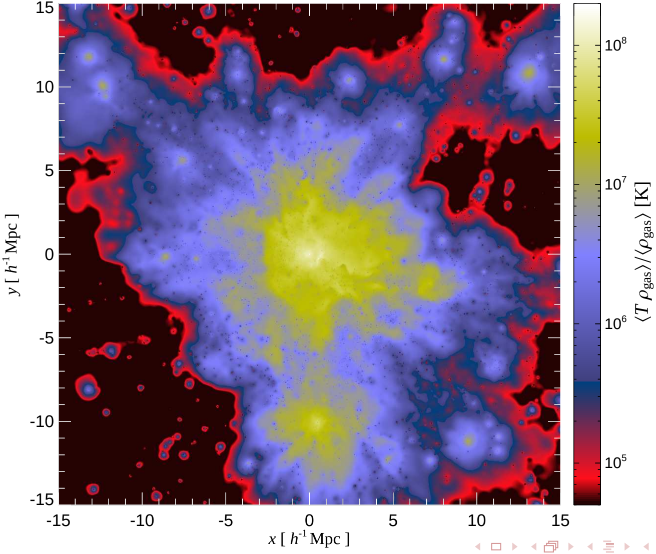
Cluster observables: Physical processes in clusters:



Radiative cool core cluster simulation: gas density



Mass weighted temperature



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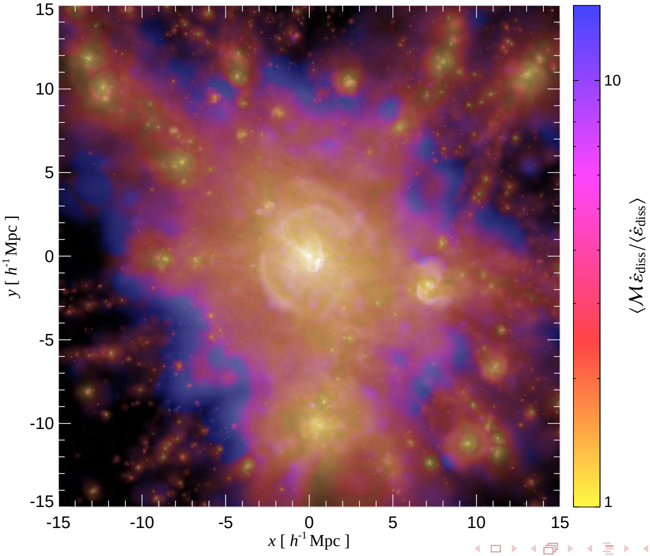
Mach number distribution weighted by $\varepsilon_{\text{diss}}$



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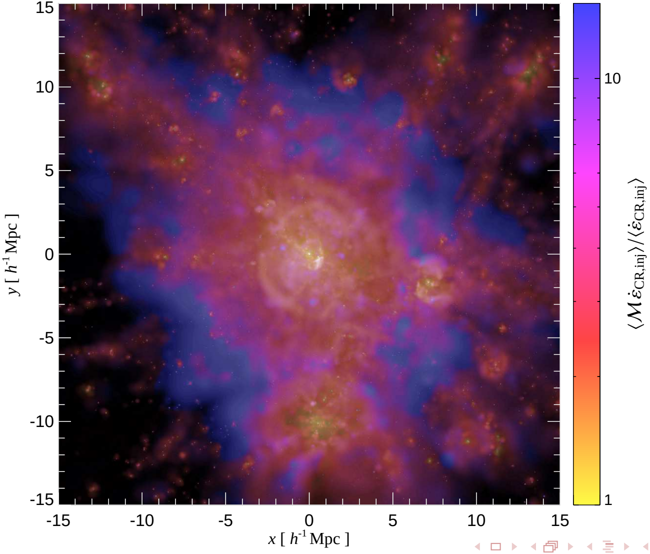
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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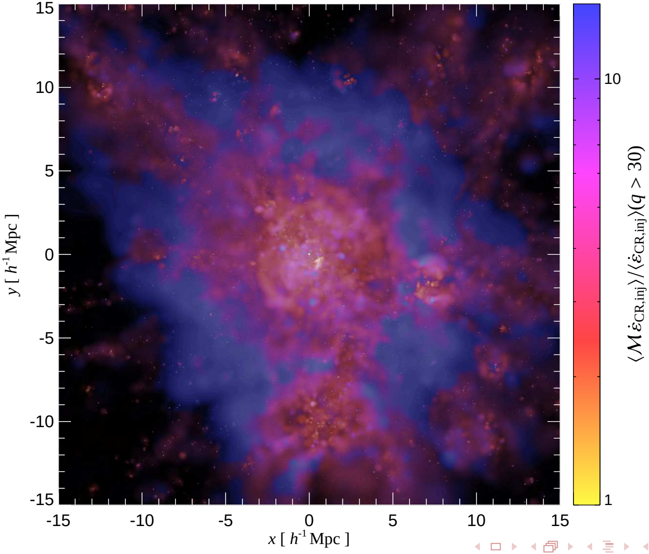
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



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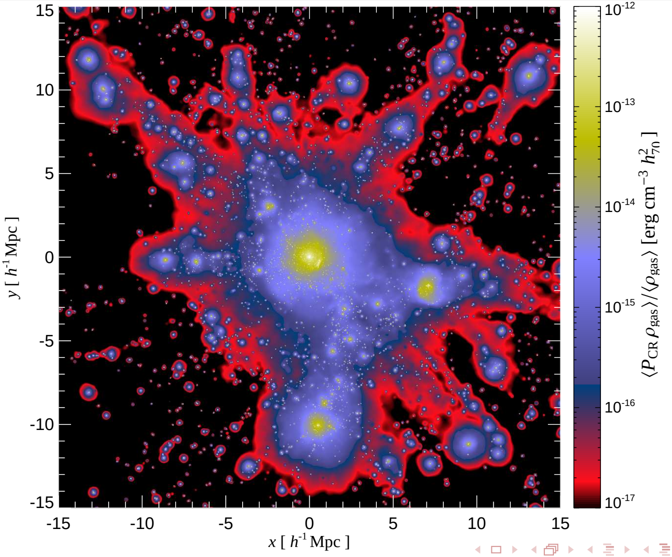
CR pressure $P_{\rm CR}$



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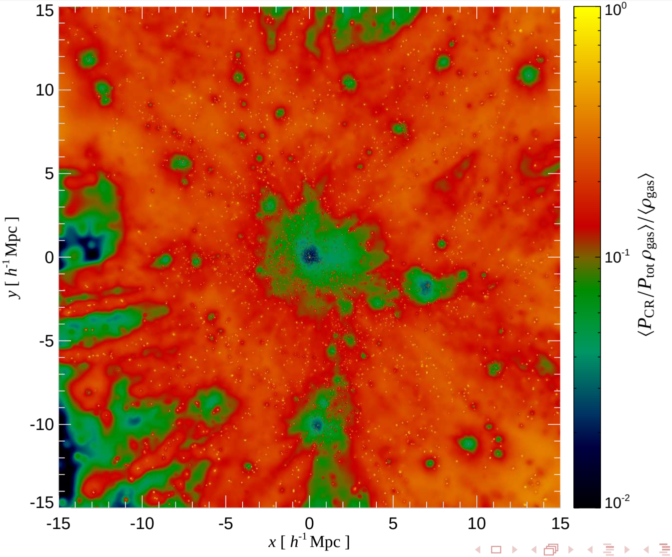
Relative CR pressure $P_{\rm CR}/P_{\rm total}$



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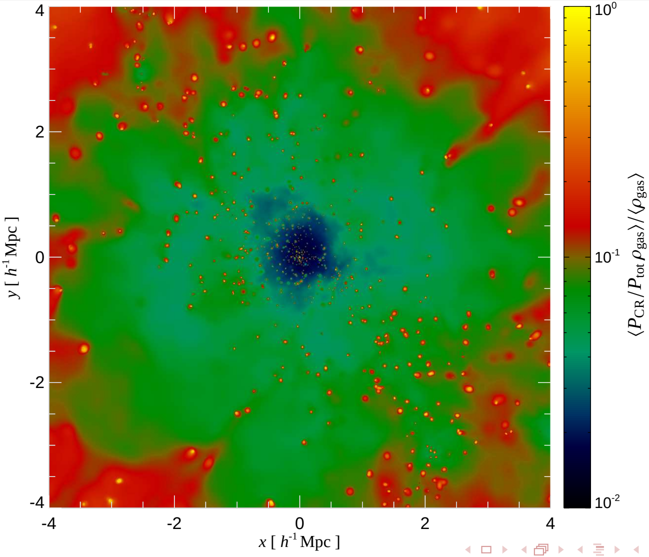
Relative CR pressure $P_{\rm CR}/P_{\rm total}$



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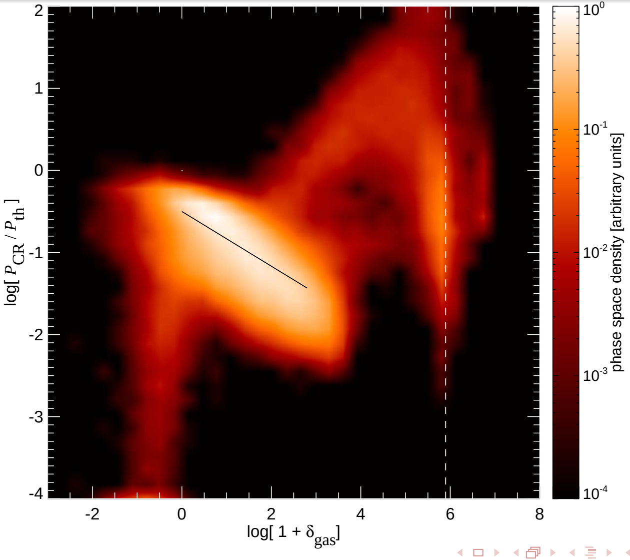
Phase-space diagram of radiative cluster simulation



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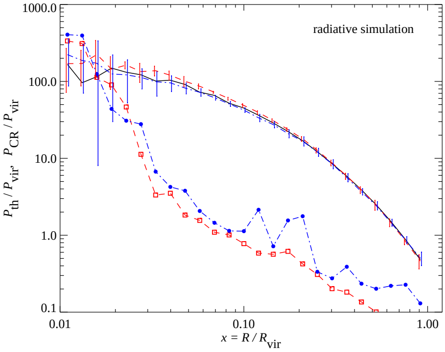
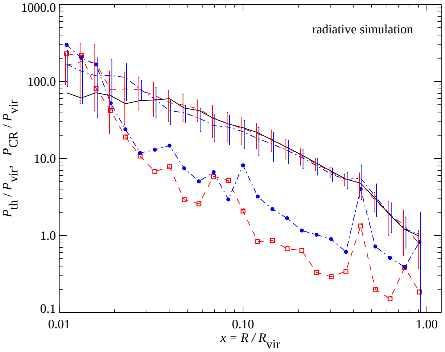
Radiative simulations: pressure profile



Cool core cluster sample.



Merging cluster sample.

red: only structure formation shock CRs,

blue: structure formation & SNe CRs.

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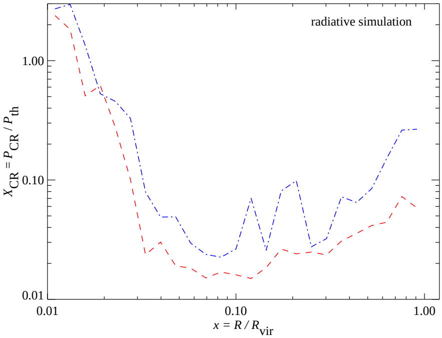
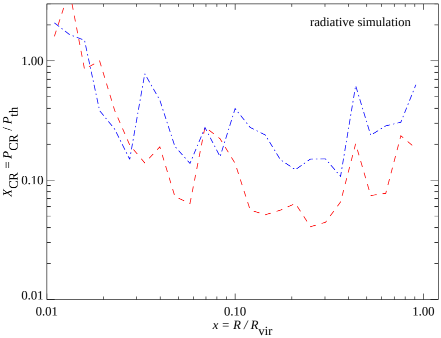
Radiative simulations: relative CR pressure profile





Cool core cluster sample.

Merging cluster sample.

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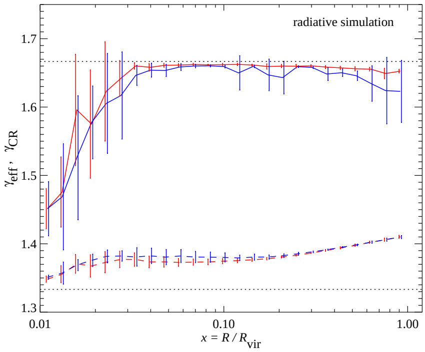
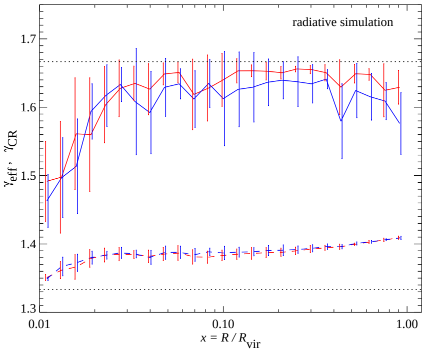
Radiative simulations: adiabatic index profile



Cool core cluster sample.



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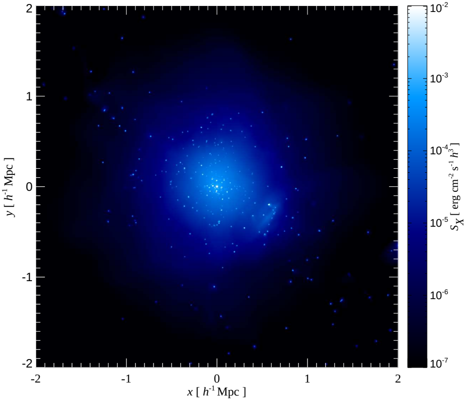
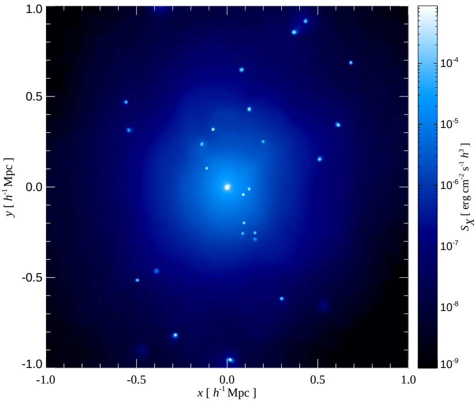
Thermal X-ray emission



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



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

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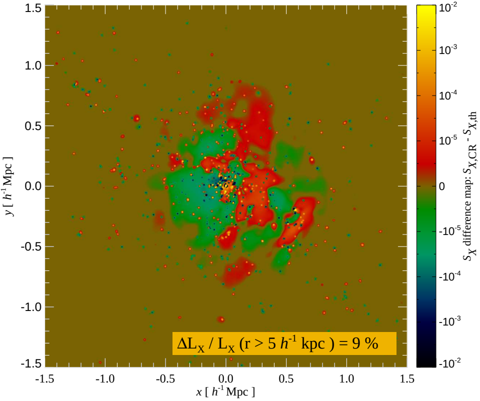
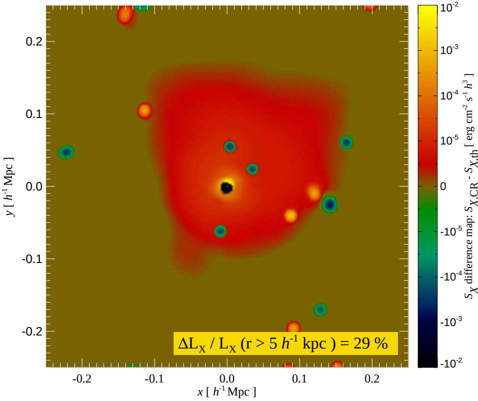
Difference map of S_X: $S_{X,\mathrm{CR}} - S_{X,\mathrm{th}}$





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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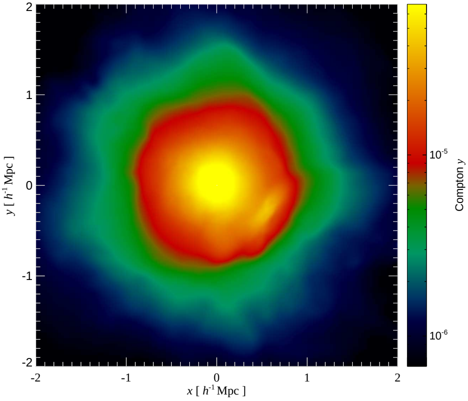
Compton y parameter in radiative cluster simulation



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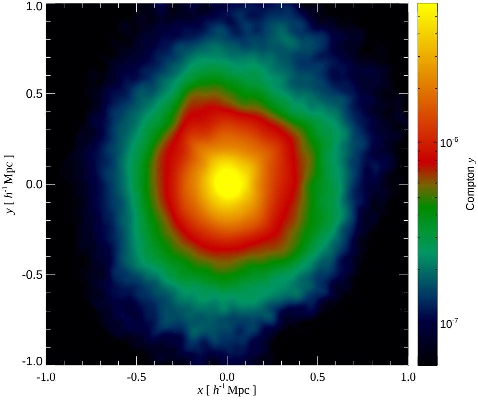
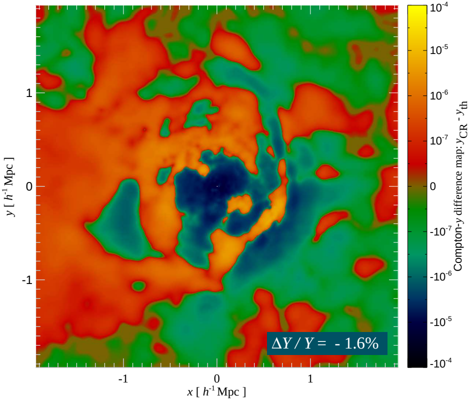


small cool core cluster, $M_{\rm vir} \simeq 10^{14} M_\odot / h$

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



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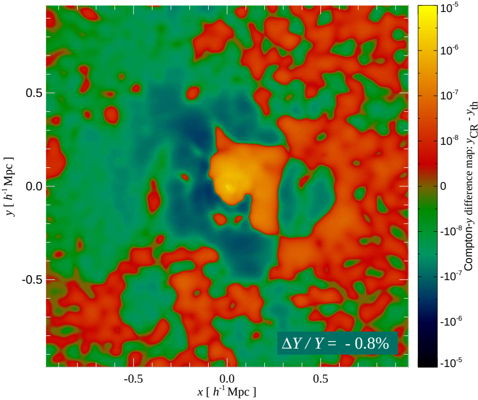

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Outline

Particle acceleration processes

particles are acclerated via:

- adiabatic compression
- diffusive shock acceleration (Fermi I)
- stochastic acceleration by plasma waves (Fermi II)
- particle reactions (pp $\rightarrow \pi \rightarrow \mu\nu \rightarrow e\nu\nu$)

particles are de-accelerated via:

- adiabatic expansion
- radiative cooling (synchrotron, inverse Compton, bremsstrahlung, hadronic interactions)
- non-radiative cooling (Coulomb interactions)

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Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:

- a collisionless shock wave
- magnetic fields to confine energetic particles
- plasma waves to scatter energetic particles $\rightarrow$ particle diffusion
- supra-thermal particles

mechanism:

- supra-thermal particles diffuse upstream across shock wave
- each shock crossing energizes particles through momentum transfer from recoil-free scattering off the macroscopic scattering agents
- momentum increases exponential with number of shock crossings
- number of particles decreases exponential with number of crossings

$\rightarrow$ power-law CR distribution

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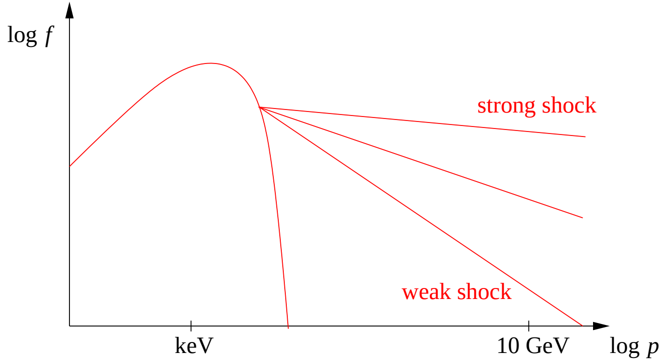
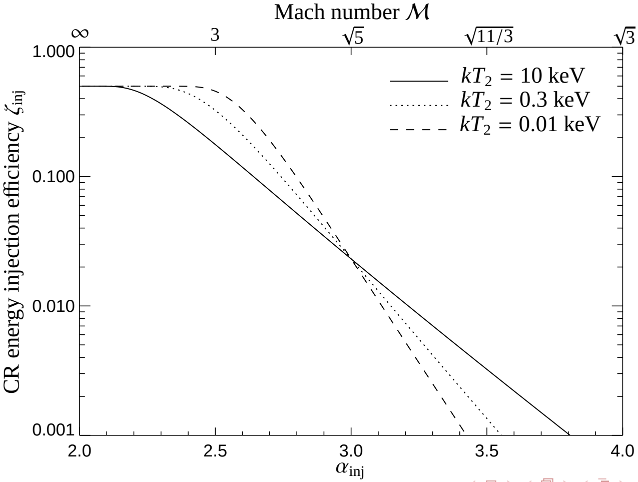
Diffusive shock acceleration – Fermi 1 mechanism (2)

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

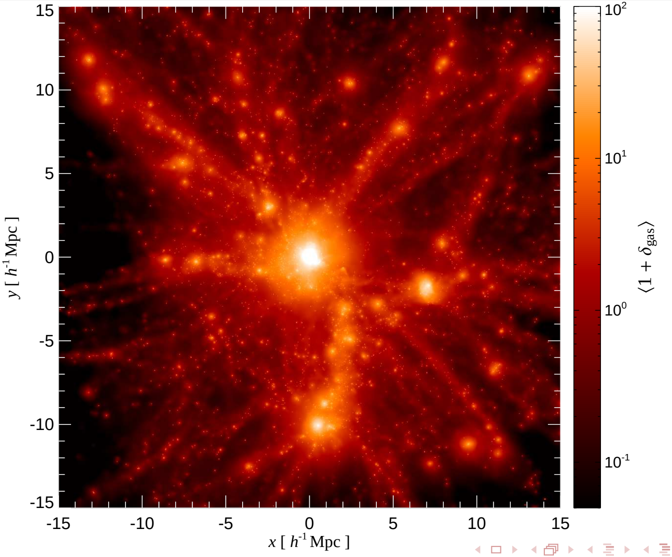


Diffusive shock acceleration – efficiency (3)

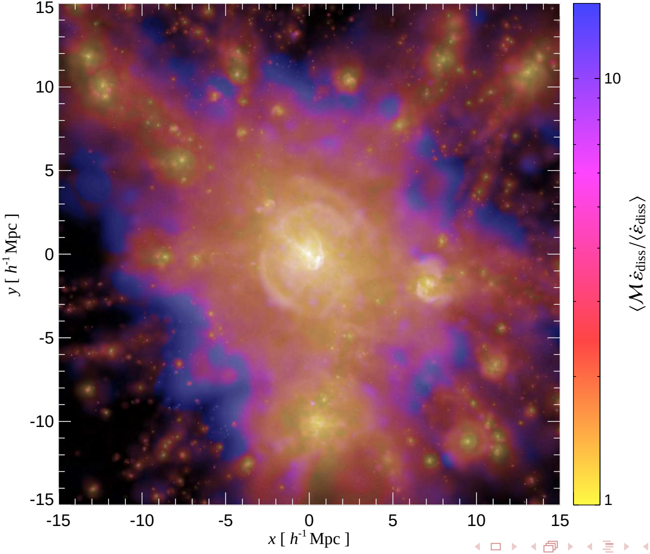
CR proton energy injection efficiency, $\zeta_{\rm inj} = \varepsilon_{\rm CR}/\varepsilon_{\rm diss}$:



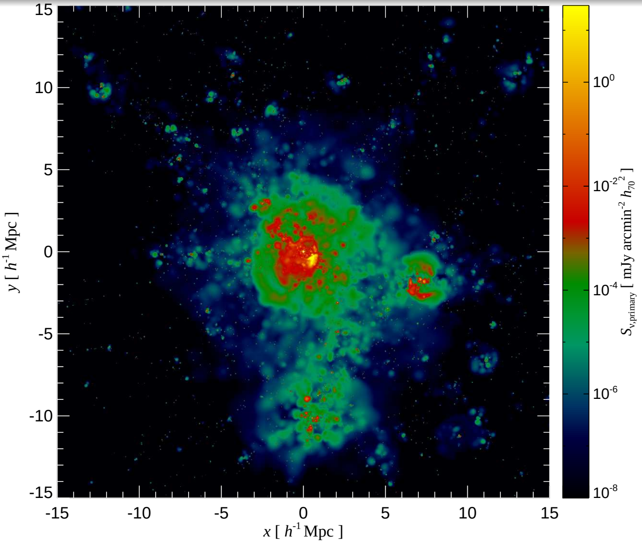
Radiative cool core cluster simulation: gas density



Cosmic web: Mach number



Radio web: primary CRe (1.4 GHz)



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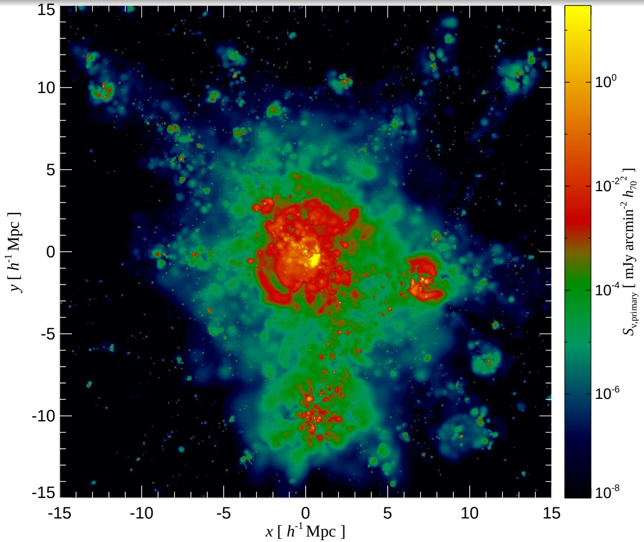
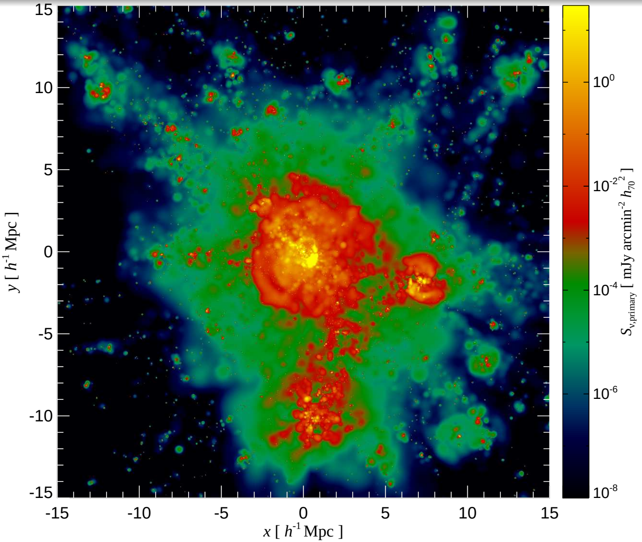
Radio web: primary CRe (150 MHz)



Radio web: primary CRe (15 MHz)



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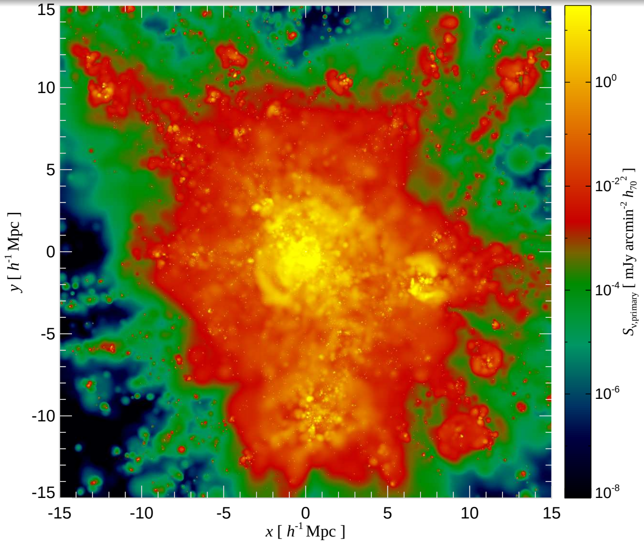
Radio web: primary CRe (15 MHz), slower magnetic decline



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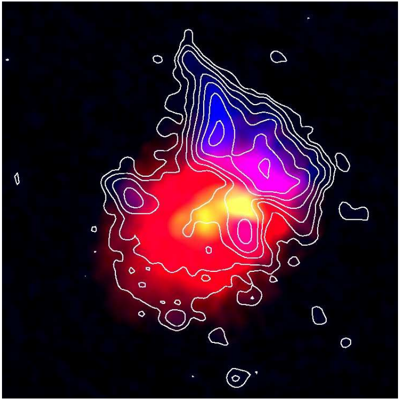
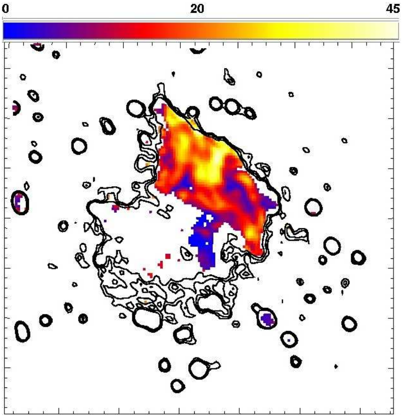
Abell 2256: giant radio relic & small halo



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



fractional polarization in color

Clarke & Enßlin (2006)

Outline

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Stochastic acceleration: recipe (1)

conditions:

- super-thermal or better relativistic particles
- magnetic fields to confine them
- high level of plasma waves to scatter them via gyro-resonances

mechanism:

- head on wave-particle collision energises particle
- tail on wave-particle collision de-energise particle
- statistically more head-on than tail-on collisions

$\rightarrow$ net energy gain due to diffusion in momentum space
advantage: plamsa waves are everywhere!

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Stochastic acceleration: recipe (1)

conditions:

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mechanism:

- head on wave-particle collision energises particle
- tail on wave-particle collision de-energise particle
- statistically more head-on than tail-on collisions

→ net energy gain due to diffusion in momentum space
advantage: plamsa waves are everywhere!

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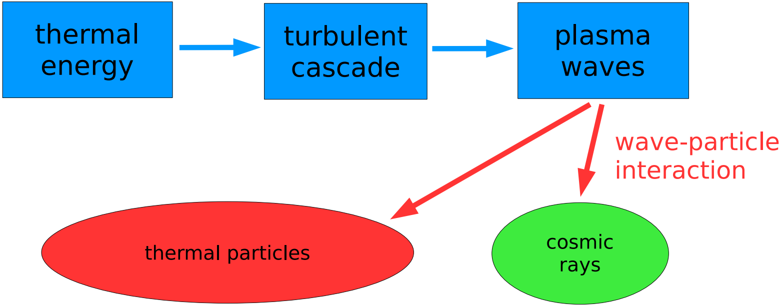
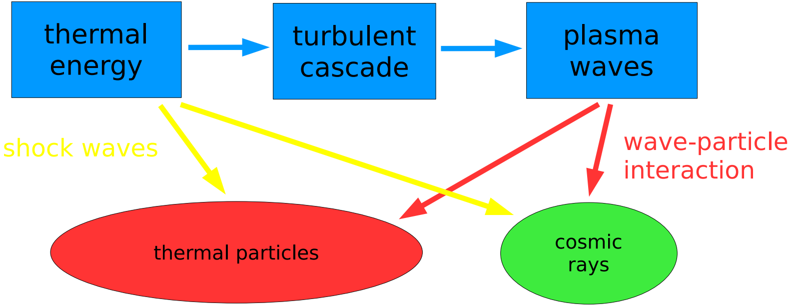
Stochastic acceleration: cartoon (2)



Stochastic acceleration: cartoon (2)



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Stochastic acceleration: problems (3)

problems:

- low efficiency (2nd order in ratio of wave to particle velocity)
- waves like to cascade to small scales
- small-scale waves dissipate into the thermal pool
- wave energy budget is usually tight
- at locations with high wave density (e.g. shocks), more efficient acceleration mechanism may be in operation (e.g. DSA)

nevertheless: cluster radio halos may be due to stochastic re-acceleration of 0.2 MeV electrons (e.g. Brunetti et al.)

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Outline

1. Cosmic rays in galaxy clusters
   - Introduction and motivation
   - Cluster simulations and cosmic ray physics
   - Cosmic ray pressure feedback
2. Particle acceleration processes
   - Diffusive shock acceleration
   - Stochastic acceleration
   - Particle reactions
3. Non-thermal cluster emission
   - Radiative processes
   - Unified model of radio halos and relics
   - High-energy gamma-ray emission

Particle reactions

relativistic proton populations can often be expected, since

- acceleration mechanisms work for protons . . .
  - . . . as efficient as for electrons (adiabatic compression) or
  - . . . more efficient than for electrons (DSA, stochastic acc.)
- galactic CR protons are observed to have 100 times higher energy density than electrons
- CR protons are very inert against radiative losses and therefore long-lived ($\sim$ Hubble time in galaxy clusters, longer outside)

$\longrightarrow$ an energetic CR proton population should exist in clusters

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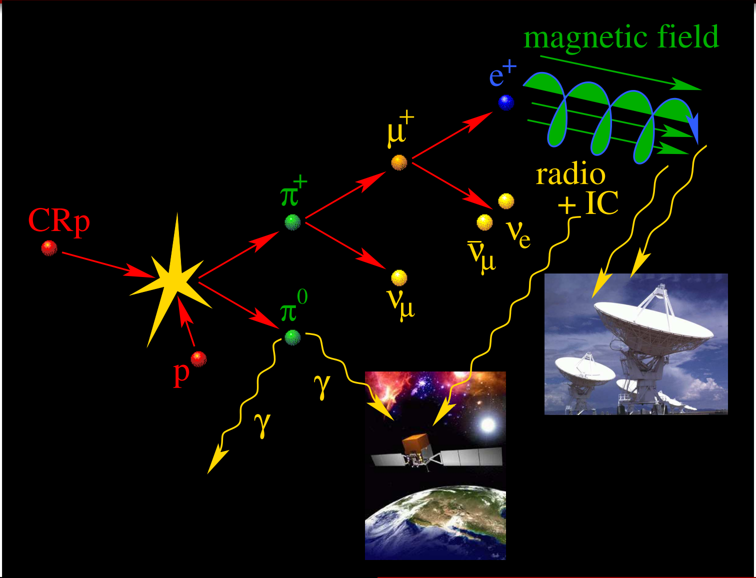
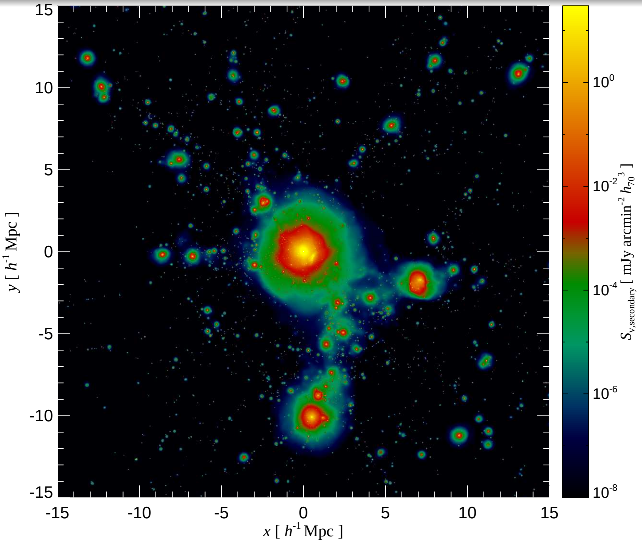
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



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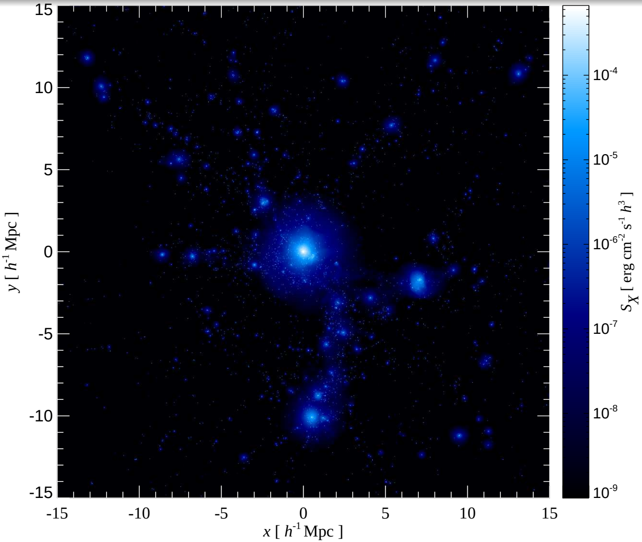
Thermal X-ray emission



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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 → cluster archaeology.

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

- LOFAR, GMRT, MWA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Simbol-X: future hard X-ray satellite ($E \simeq (0.5 - 70)$ keV)
- GLAST: high-energy γ-ray space mission ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes (TeV photon energies)

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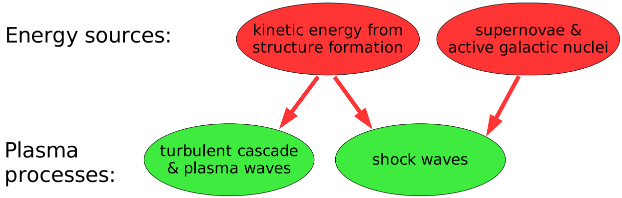
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



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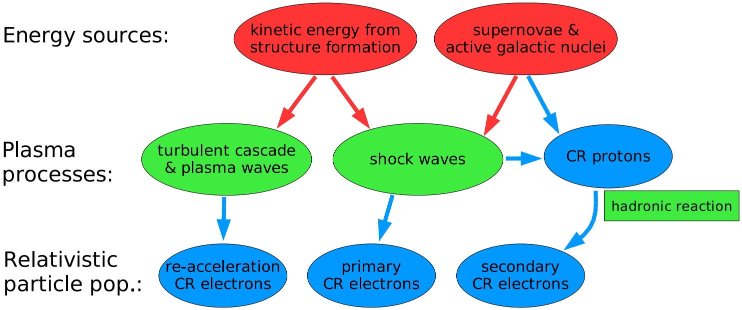

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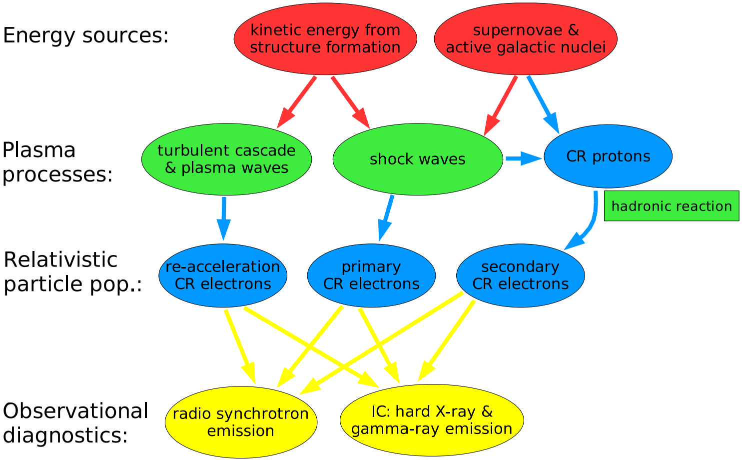

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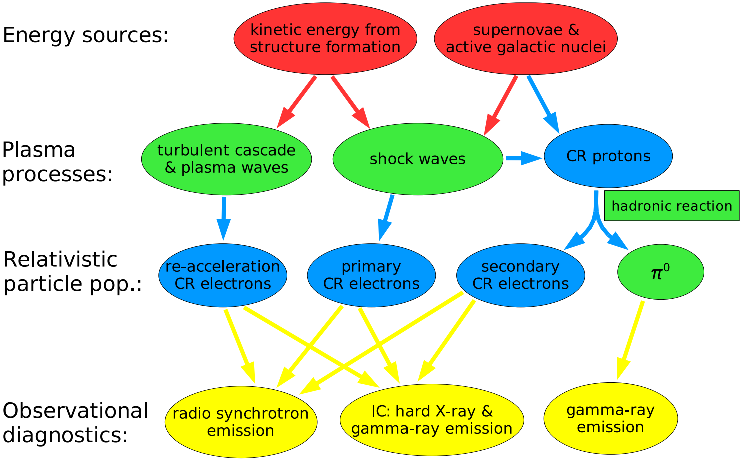

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Outline

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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 $\rightarrow$ selection effect).
- Cluster experiences major merger: two leading shock waves are produced that become stronger as they break at the shallow peripheral cluster potential $\rightarrow$ 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 $\rightarrow$ 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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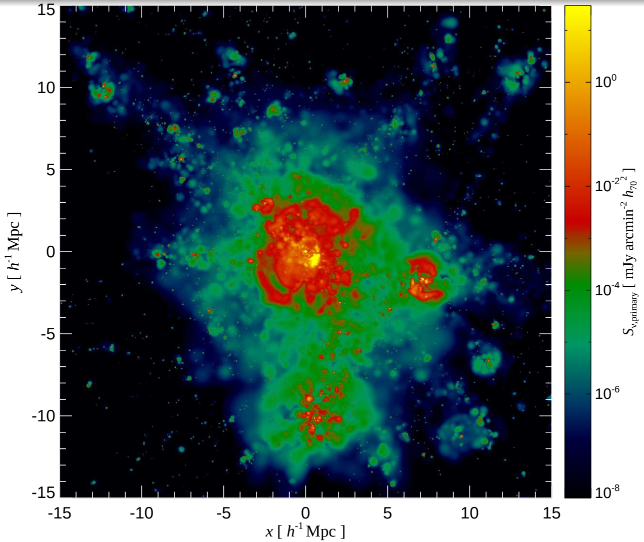
Radio gischt: primary CRe (150 MHz)



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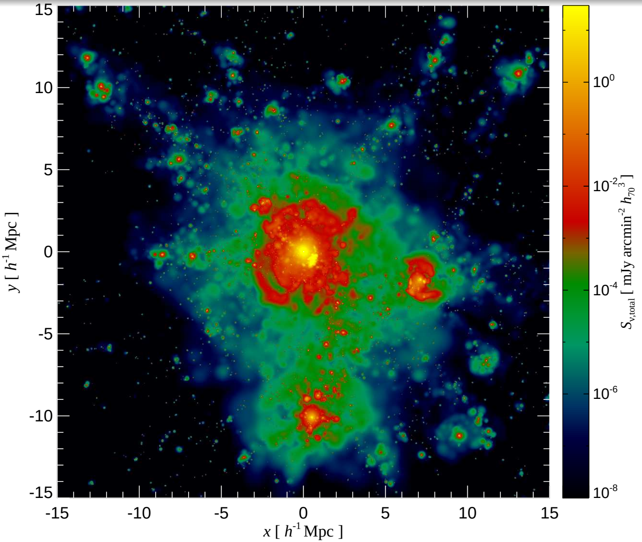
Radio gischt + central hadronic halo = giant radio halo



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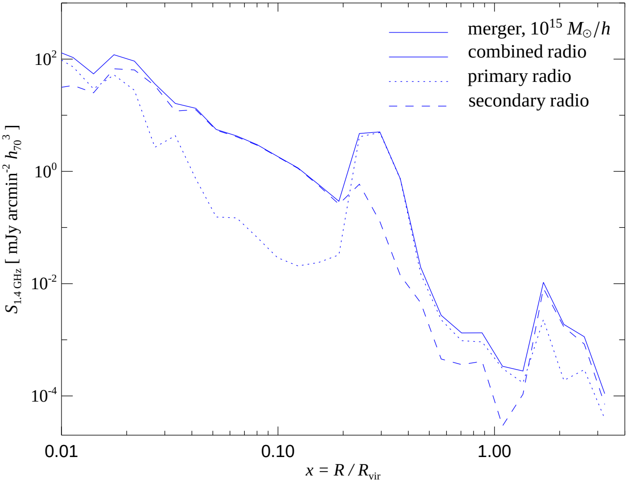
Giant radio halo profile



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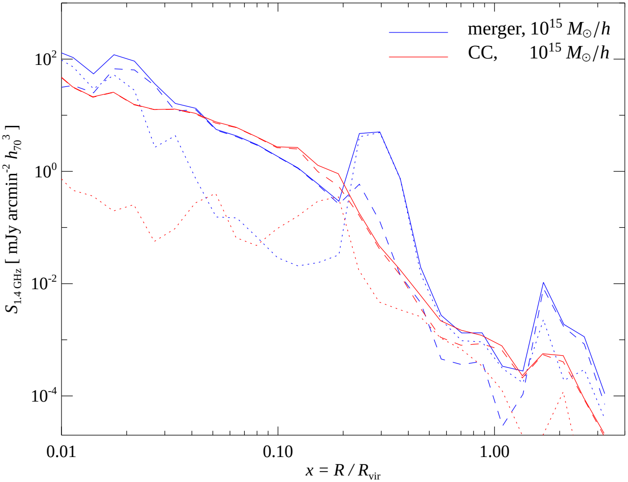
Giant radio halo vs. mini-halo



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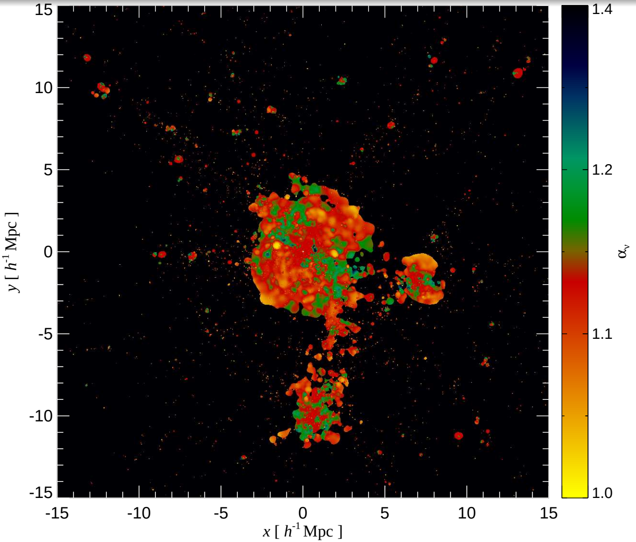
Radio relics + halos: spectral index



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

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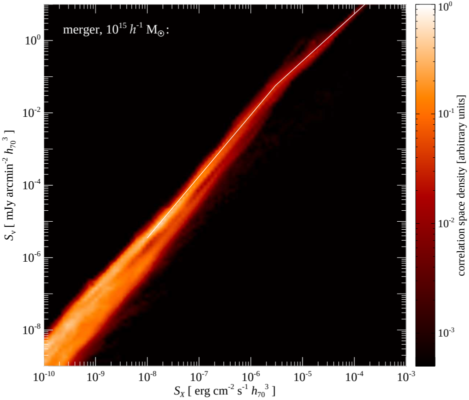
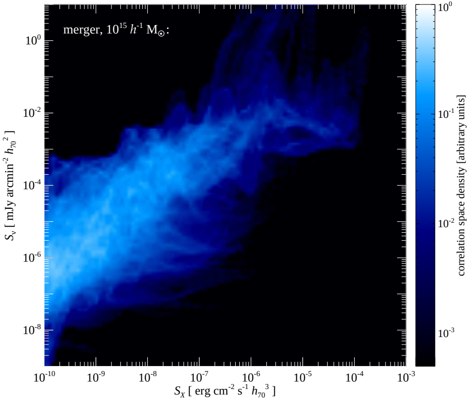
Correlation between X-ray and synchrotron emission



Correlation with secondary 'halo' emission,

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



Correlation with primary 'relic' emission,

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

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Outline

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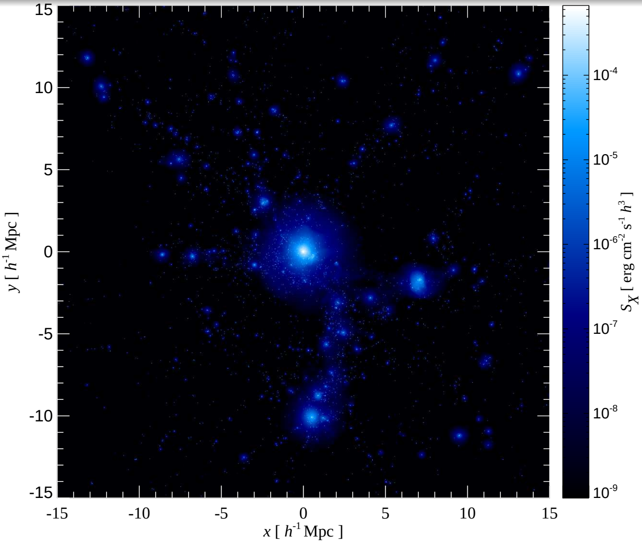
Thermal X-ray emission



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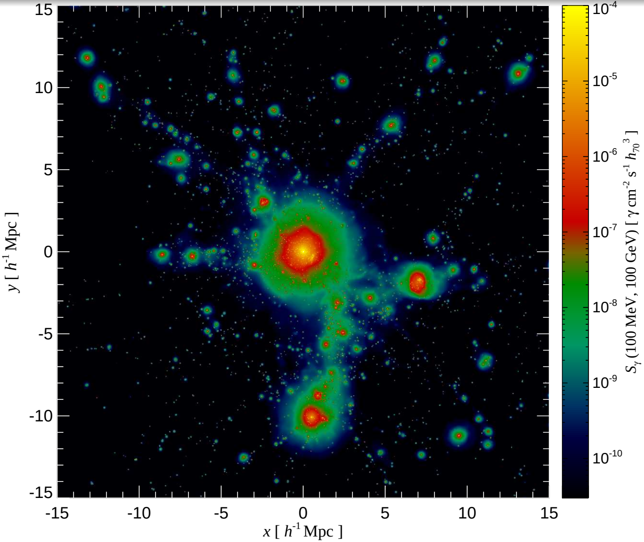
Hadronic γ-ray emission, $E_\gamma > 100$ MeV



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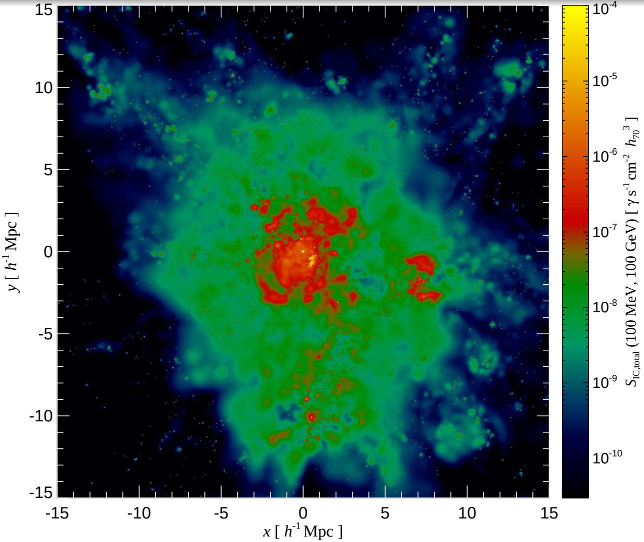
Inverse Compton emission, $E_{\rm IC} > 100$ MeV



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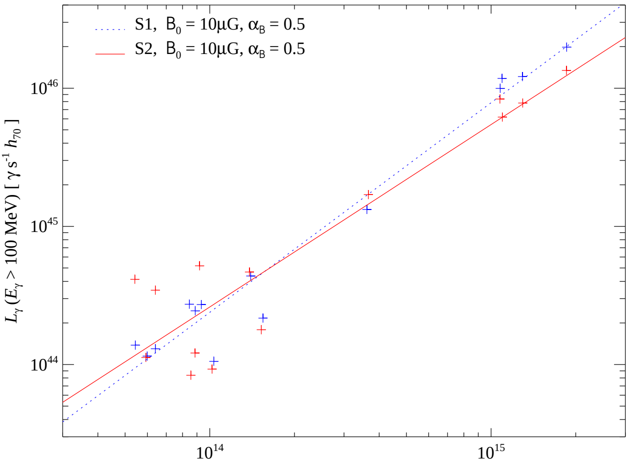
Gamma-ray scaling relations



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

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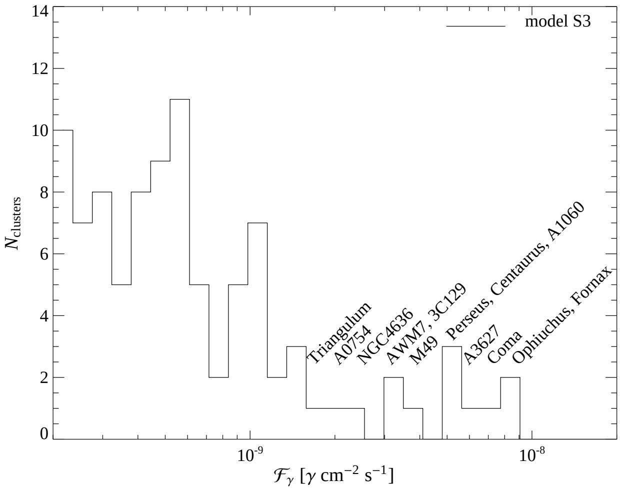
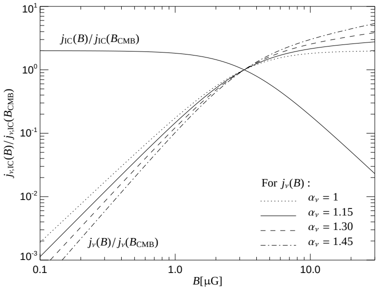
Predicted cluster sample for GLAST



Minimum γ-ray flux in the hadronic model (1)



Synchrotron emissivity of high-energy, steady state electron distribution is independent of the magnetic field for $B \gg B_{CMB}$!

Synchrotron luminosity:

$$L_\nu = A_\nu \int dV\, n_{CR} n_{gas} \frac{\varepsilon_B^{(\alpha_\nu+1)/2}}{\varepsilon_{CMB} + \varepsilon_B}$$

$$\rightarrow A_\nu \int dV\, n_{CR} n_{gas} \quad (\varepsilon_B \gg \varepsilon_{CMB})$$

γ-ray luminosity:

$$L_\gamma = A_\gamma \int dV\, n_{CR} n_{gas}$$

$\rightarrow$ minimum γ-ray flux:

$$\mathcal{F}_{\gamma,\min} = \frac{A_\gamma}{A_\nu} \frac{L_\nu}{4\pi D^2}$$

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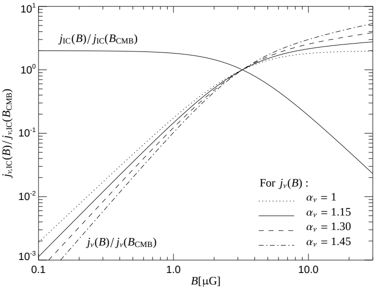
Minimum γ-ray flux in the hadronic model (1)



Synchrotron emissivity of high-energy, steady state electron distribution is independent of the magnetic field for $B \gg B_{\rm CMB}$!

Synchrotron luminosity:

$$L_\nu = A_\nu \int \mathrm{d}V\, n_{\rm CR} n_{\rm gas} \frac{\varepsilon_B^{(\alpha_\nu+1)/2}}{\varepsilon_{\rm CMB} + \varepsilon_B}$$

$$\to A_\nu \int \mathrm{d}V\, n_{\rm CR} n_{\rm gas} \quad (\varepsilon_B \gg \varepsilon_{\rm CMB})$$

γ-ray luminosity:

$$L_\gamma = A_\gamma \int \mathrm{d}V\, n_{\rm CR} n_{\rm gas}$$

$\to$ **minimum γ-ray flux:**

$$\mathcal{F}_{\gamma,\rm min} = \frac{A_\gamma}{A_\nu} \frac{L_\nu}{4\pi D^2}$$

Minimum γ-ray flux in the hadronic model (2)

Minimum γ-ray flux ($E_\gamma > 100$ MeV) for the Coma cluster:

CR spectral index	2.0	2.3	2.6	2.9
$\mathcal{F}_\gamma$ $[10^{-10}\gamma\, cm^{-2} s^{-1}]$	0.8	1.6	3.4	7.1

- These limits can be made even tighter when considering energy constraints, $P_B < P_{\text{gas}}/20$ and B-fields derived from Faraday rotation studies, $B_0 = 3\,\mu$G: $\mathcal{F}_{\gamma,\text{COMA}} \gtrsim 2 \times 10^{-9}\gamma\, cm^{-2} s^{-1} = \mathcal{F}_{\text{GLAST, 2yr}}$
- Non-detection by GLAST seriously challenges the hadronic model.
- Potential of measuring the CR accleration efficiency for diffusive shock accleration.

Summary – 1. CR pressure feedback

1. Characteristics of the CRs in clusters:
   - CR proton pressure: time integrated non-equilibrium activities of clusters, modulated by recent mergers.
   - Primary CR electron pressure: resembles current accretion and merging shocks in the virial regions.
2. CR pressure modifies the ICM in merging clusters and cooling core regions:
   - Galaxy cluster X-ray emission is enhanced up to 35%, systematic effect in low-mass cooling core clusters.
   - Integrated Sunyaev-Zel'dovich effect remains largely unchanged while the Compton-y profile is more peaked.
   - GLAST should see hadronic γ-ray emission from clusters: measurement of CR protons and origin of radio halos.

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Summary – 2. Non-thermal cluster emission

1. 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.
2. LOFAR/GMRT are expected to see the radio web emission: origin of cosmic magnetic fields.
3. We predict GLAST to detect $\sim$ ten γ-ray clusters: test of the presented scenario

$\longrightarrow$ exciting experiments allow a complementary view on structure formation as well as fundamental physics!

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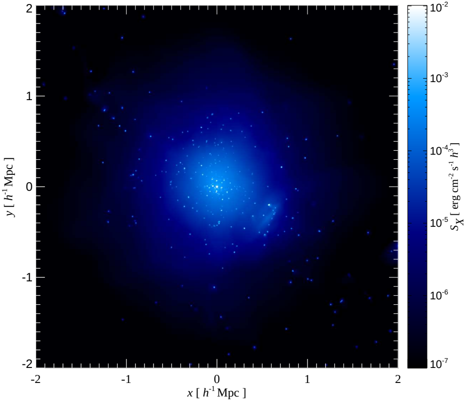
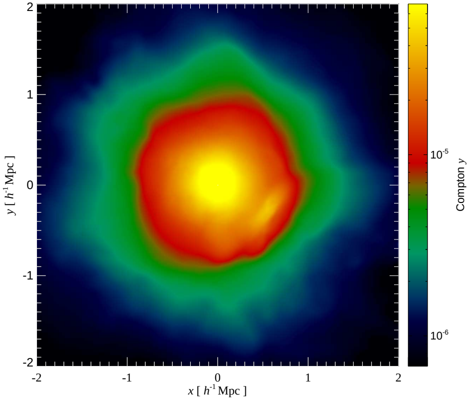
Thermal cluster observables (1)



Thermal bremsstrahlung emission,

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



Sunyaev-Zel'dovich effect,

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

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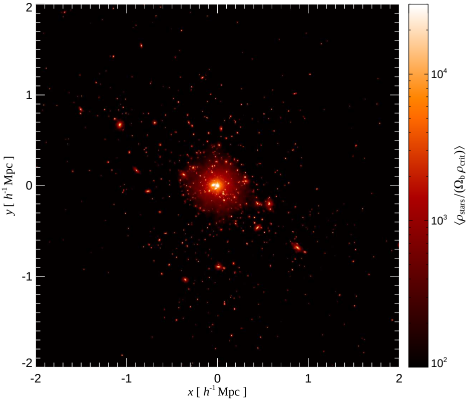
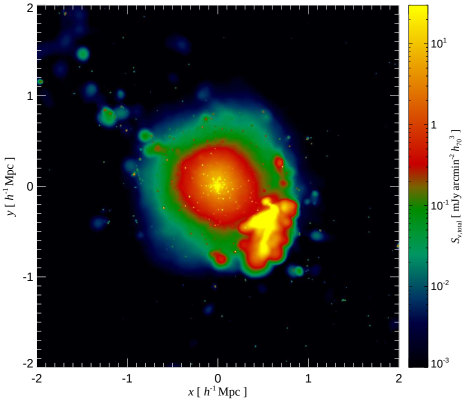
Optical and radio synchrotron cluster observables (1)



Stellar mass density (“cluster galaxies”), merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_\odot/h$



Radio halo and relic emission, merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_\odot/h$

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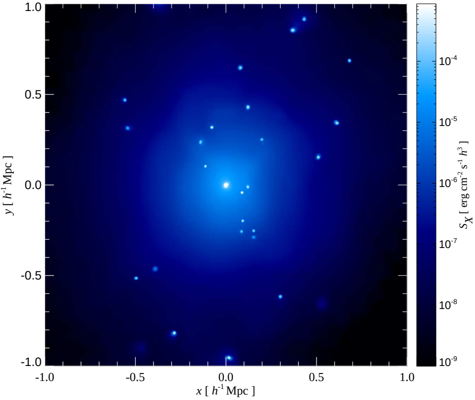
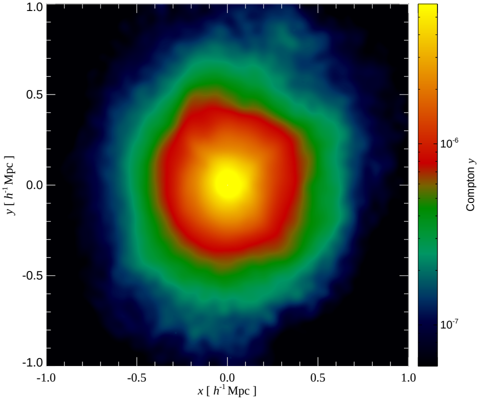
Thermal cluster observables (2)



Thermal bremsstrahlung emission,

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



Sunyaev-Zel'dovich effect,

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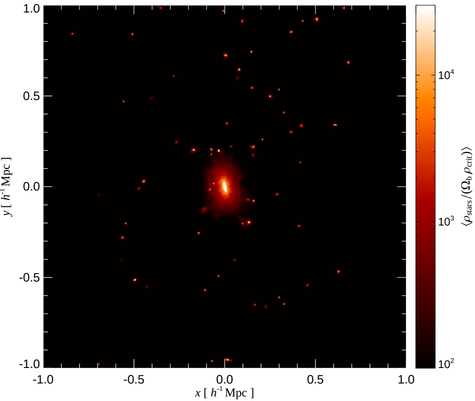

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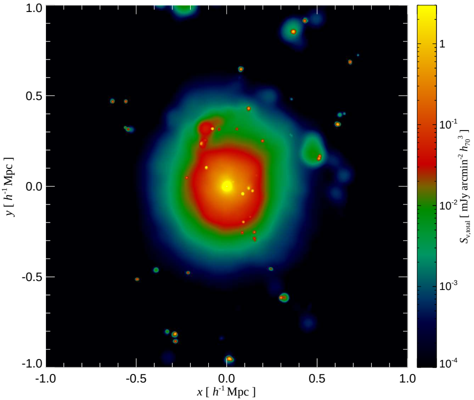

Radio halo and relic emission,

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