Cosmic Rays in Galaxy Clusters: Simulations and Perspectives

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in collaboration with

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Outline

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Observational properties of galaxy clusters

Exploring complementary methods for studying cluster formation

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

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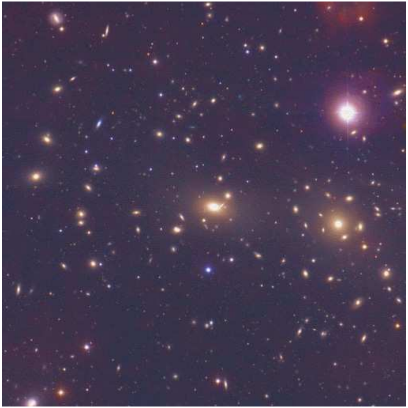
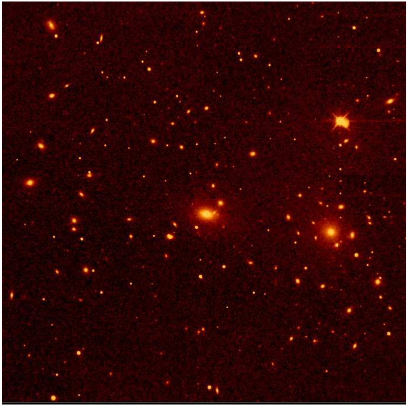
Coma cluster: member galaxies



optical emission,

(credit: Kitt Peak)



infra-red emission,

(credit: ISO)

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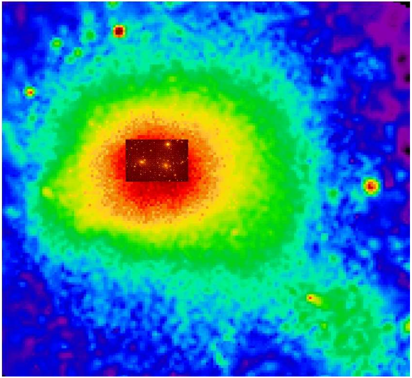
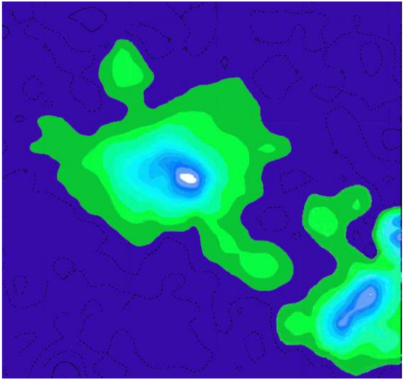
Coma cluster: (non-)thermal plasma



thermal X-ray emission,

(credit: S.L. Snowden/MPE/ROSAT)



radio synchrotron emission,

(credit: B.Deiss/Effelsberg)

Dynamical picture of cluster formation

- structure formation in the ΛCDM universe predicts the hierarchical build-up of dark matter halos from small scales to successively larger scales
- clusters of galaxies currently sit atop this hierarchy as the largest objects that have had time to collapse under the influence of their own gravity
- cluster are dynamically evolving systems that have not finished forming and equilibrating, $\tau_{\text{dyn}} \sim 1$ Gyr

$\rightarrow$ two extreme dynamical states of galaxy clusters: **merging clusters** and **cool core clusters**, which are relaxed systems where the central gas develops a dense cooling core due to the short thermal cooling times

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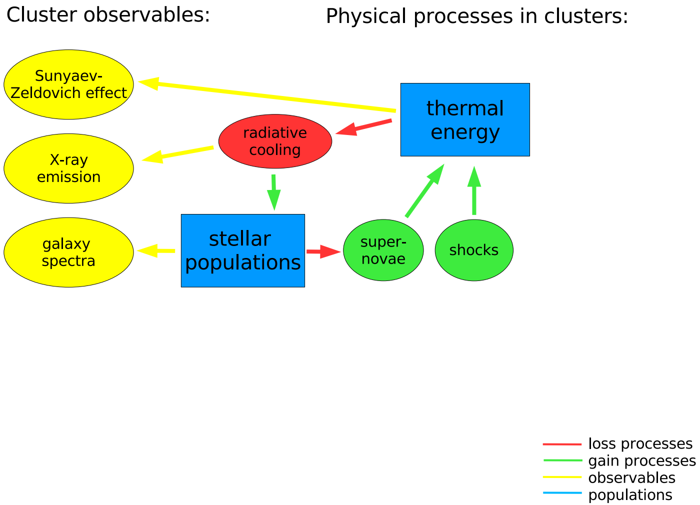
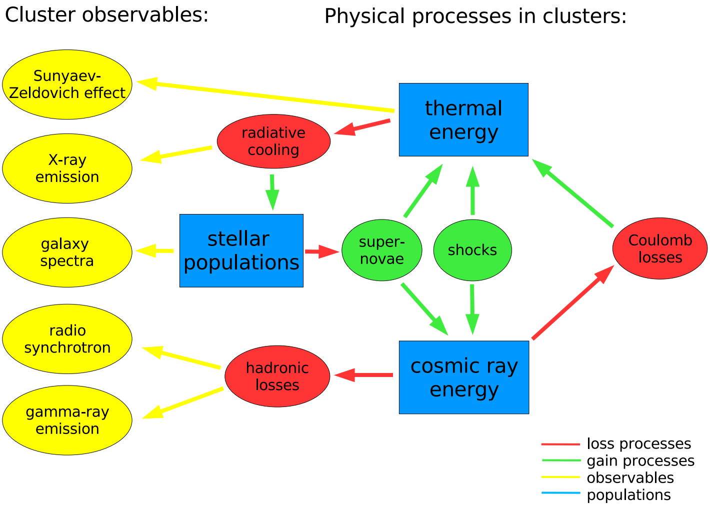
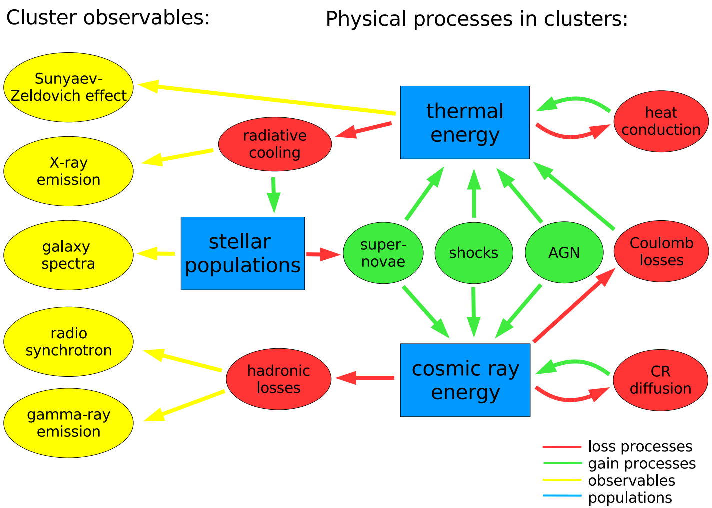
Radiative simulations – flowchart



Radiative simulations with cosmic ray (CR) physics



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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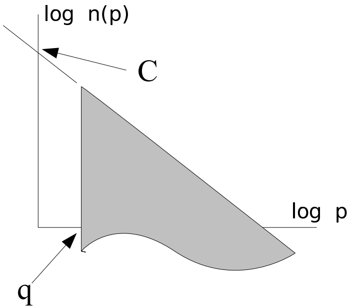
CR spectral description



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

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

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

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

$$n_\mathrm{CR} = \frac{C\,q^{1-\alpha}}{\alpha-1}$$

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

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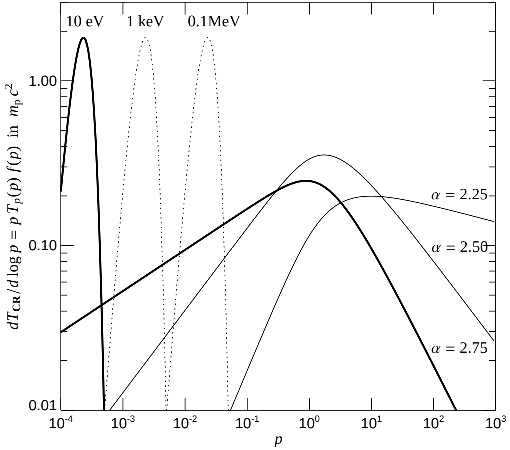
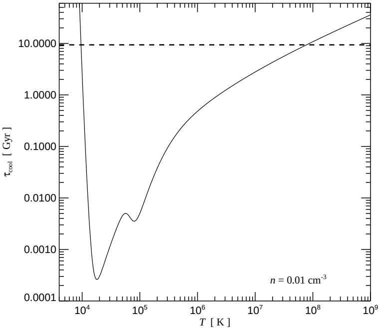
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:

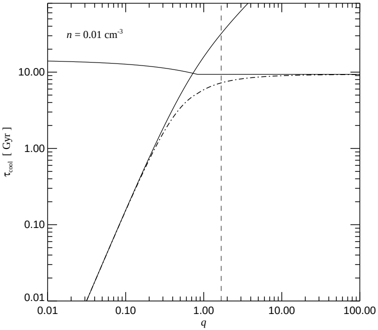


Radiative cooling

Cooling of primordial gas:



Cooling of cosmic rays:



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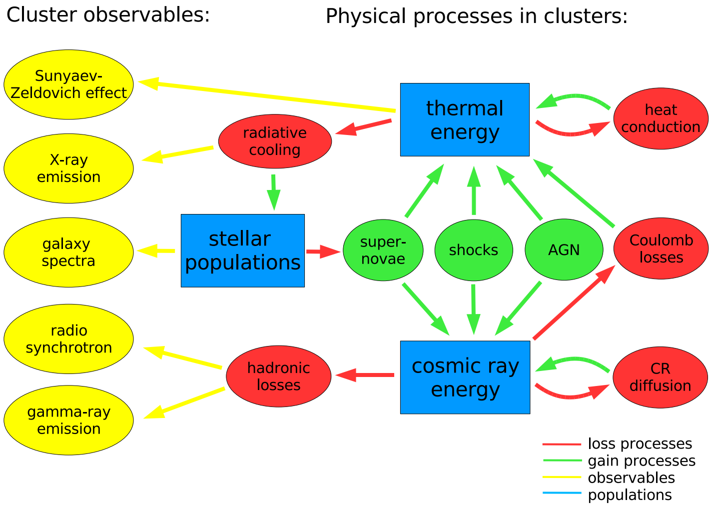
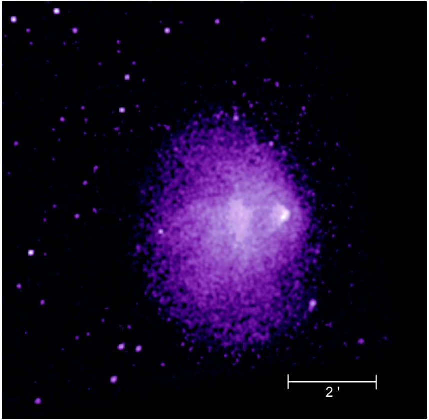
Cosmic rays in clusters – flowchart

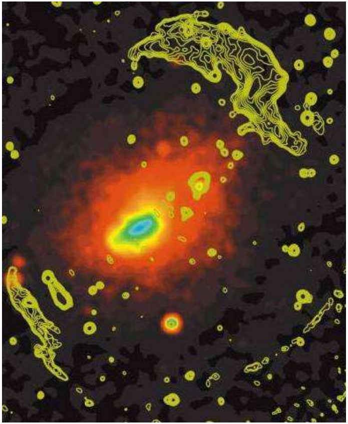


Observations of cluster shock waves



1E 0657-56 ("Bullet cluster")

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



Abell 3667

(radio: Austr.TC Array. X-ray: ROSAT/PSPC.)

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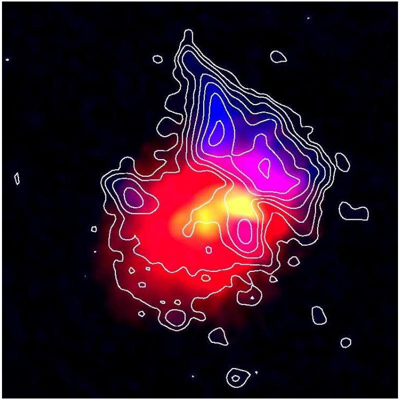
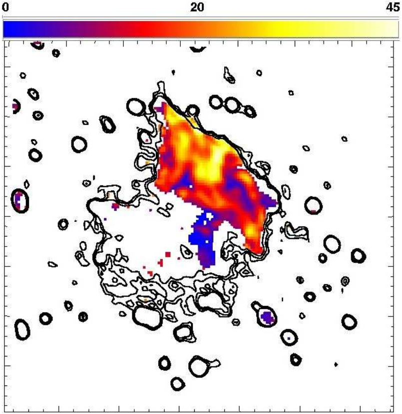
Abell 2256: giant radio relic & small halo



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



fractional polarization in colour

Clarke & Enßlin (2006)

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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 → 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

→ power-law CR distribution

Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:

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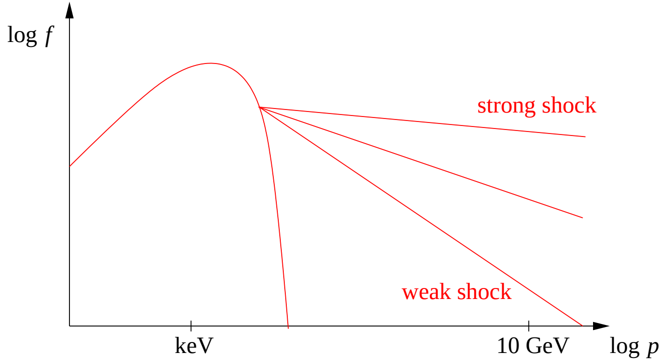
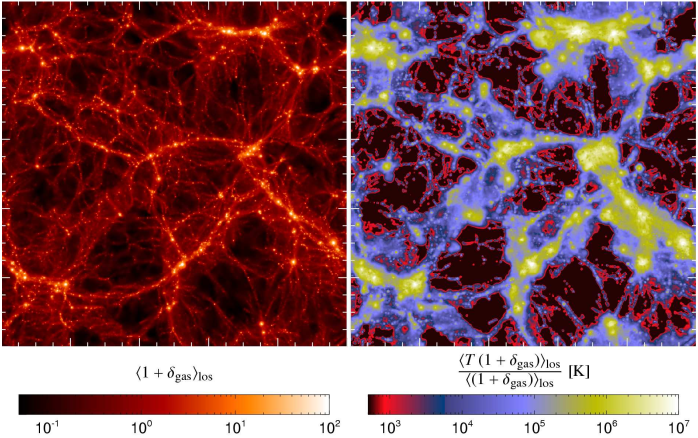
$\rightarrow$ **power-law CR distribution**

Diffusive shock acceleration – Fermi 1 mechanism (2)

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

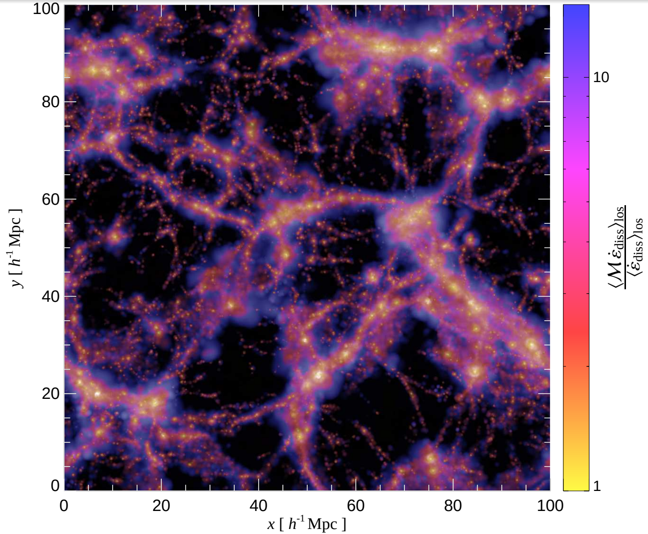


Gravitational heating by shocks



The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves.

Cosmological Mach numbers: weighted by $\varepsilon_{\rm diss}$



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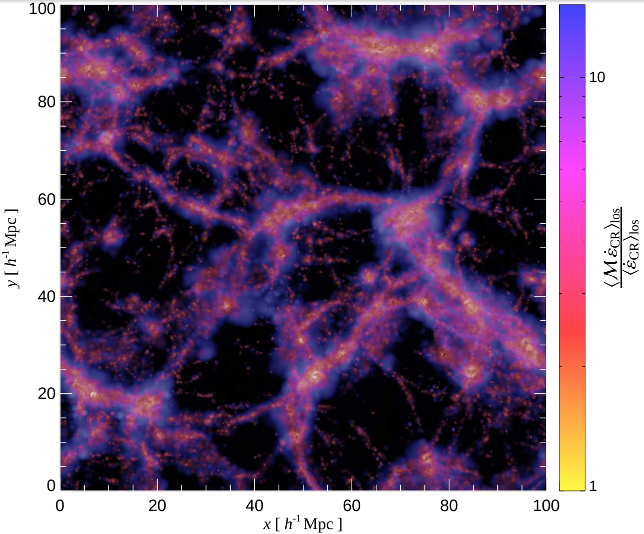
Cosmological Mach numbers: weighted by $\varepsilon_{\mathrm{CR}}$



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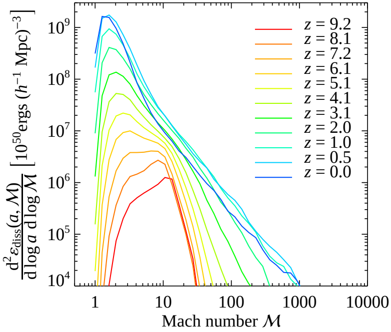
Cosmological Mach number statistics



- more energy is dissipated at later times
- mean Mach number decreases with time

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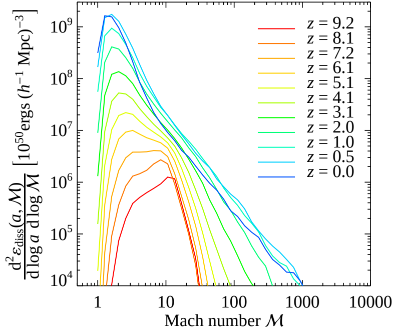
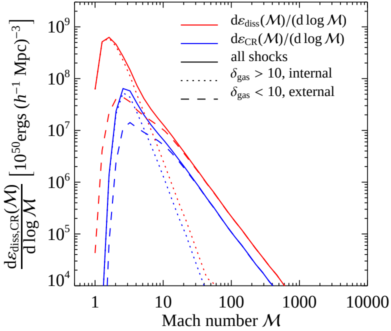
Cosmological statistics: CR acceleration





- more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks
- non-radiative simulations: injected CR energy inside cluster makes up only a small fraction of the total dissipated energy

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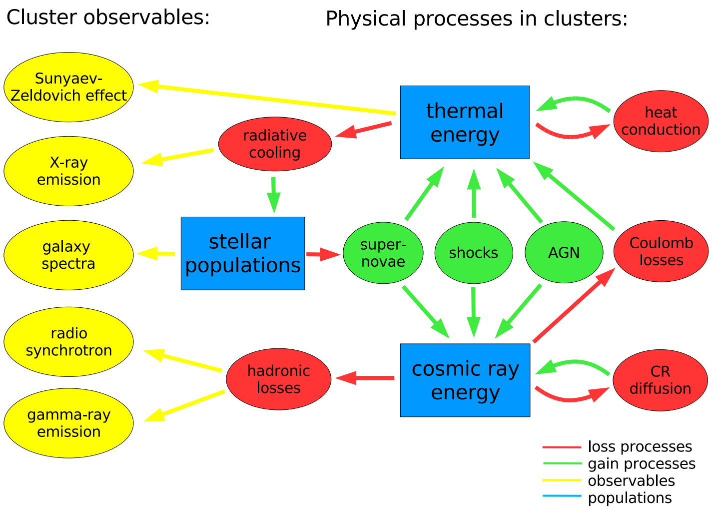
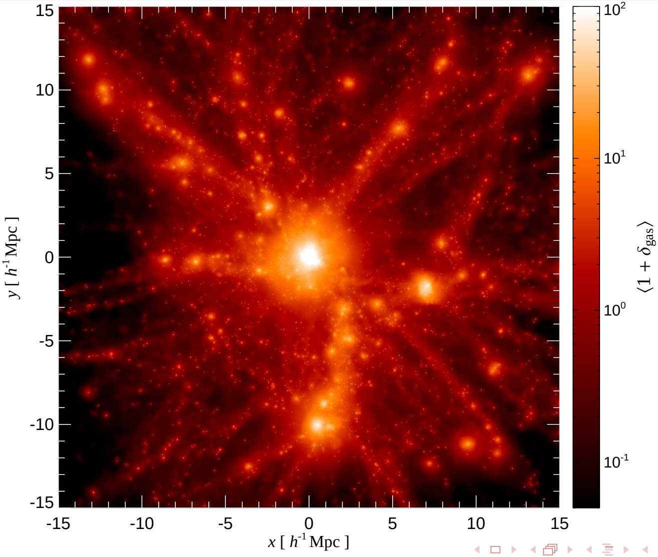
Radiative simulations with extended CR physics



Radiative cool core cluster simulation: gas density



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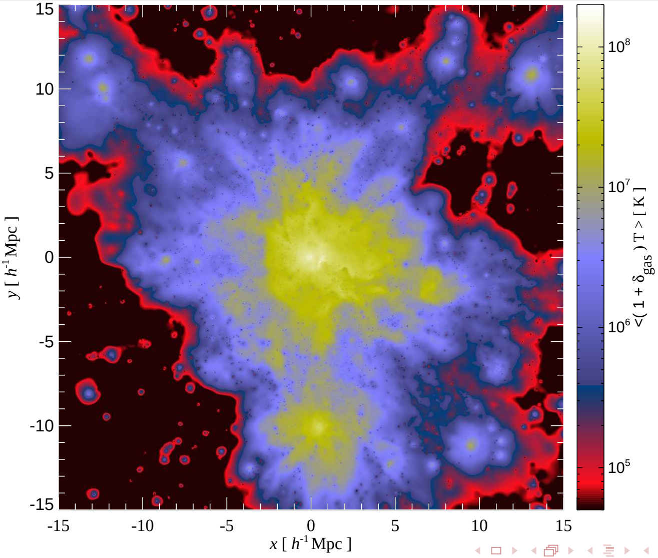
Mass weighted temperature



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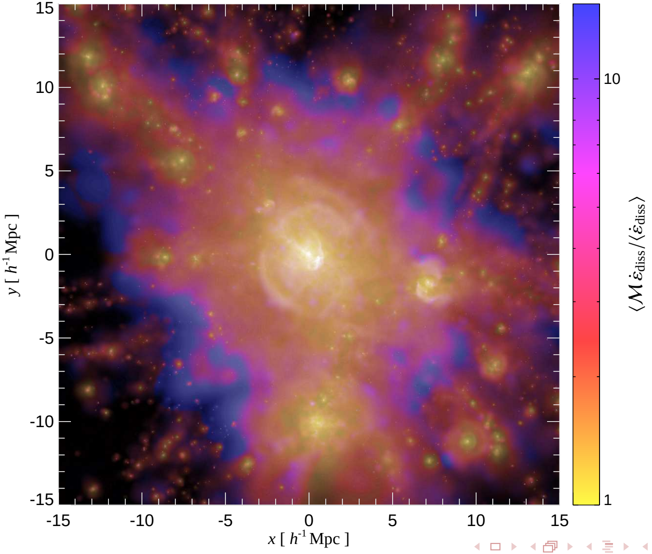
Mach number distribution weighted by $\varepsilon_{\mathrm{diss}}$



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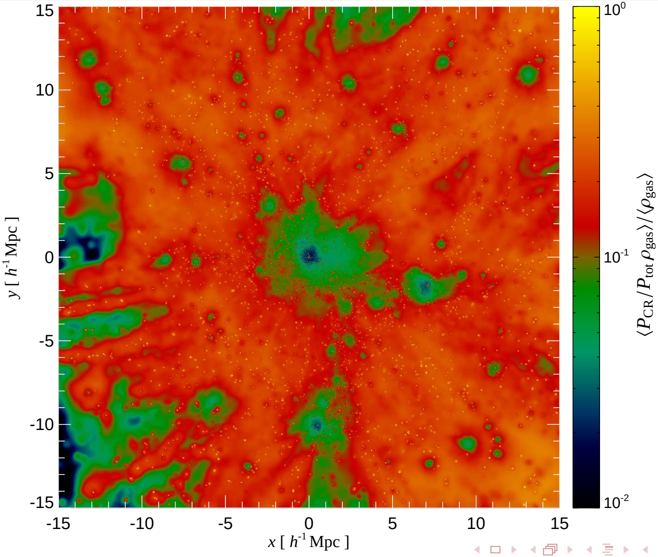
Relative CR pressure $P_{\rm CR}/P_{\rm total}$



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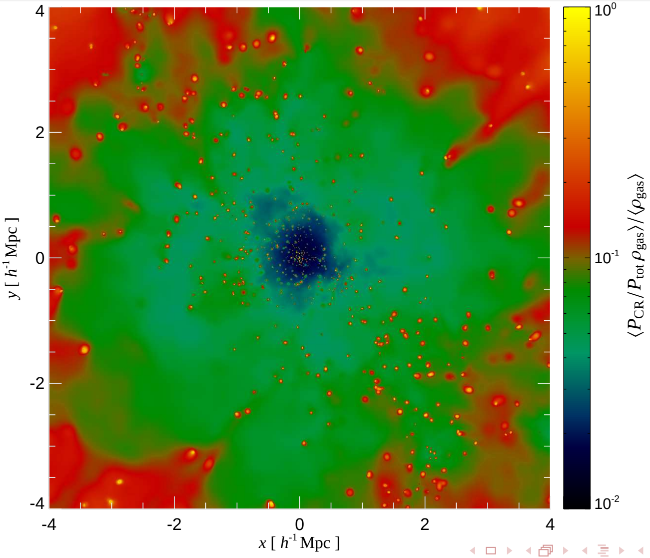

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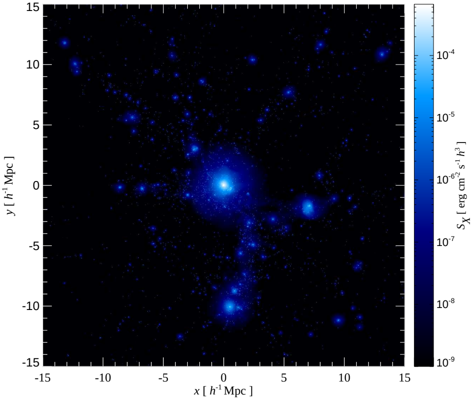
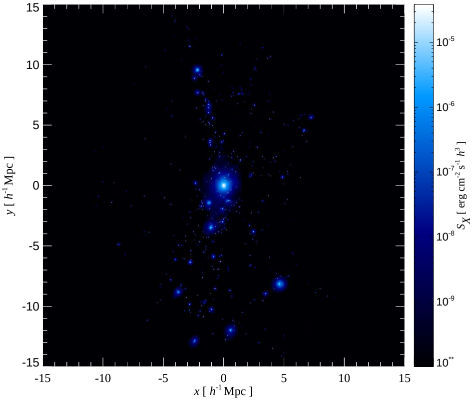
Thermal X-ray emission



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



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

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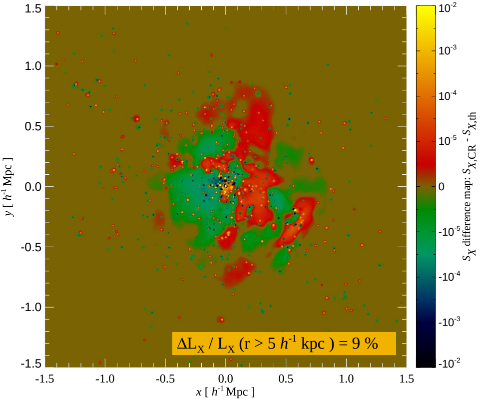
Difference map of S_X: $S_{X,\mathrm{CR}} - S_{X,\mathrm{th}}$



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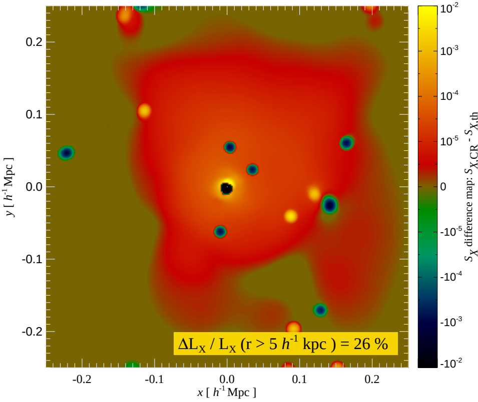

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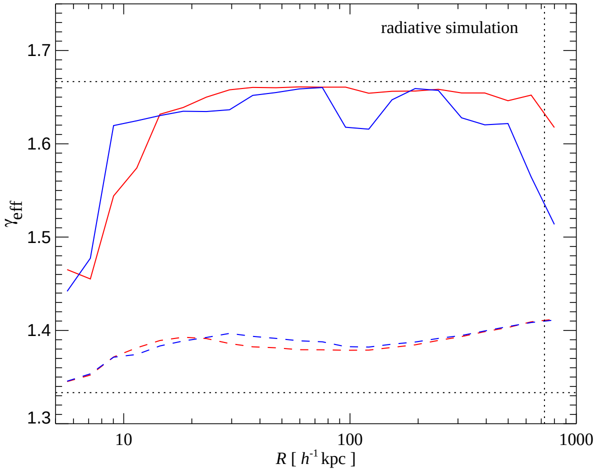
Softer effective adiabatic index of composite gas



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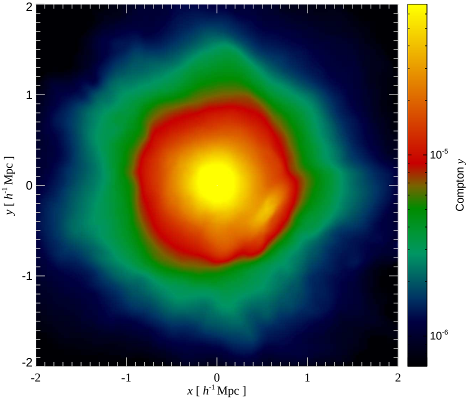
Compton y parameter in radiative cluster simulation



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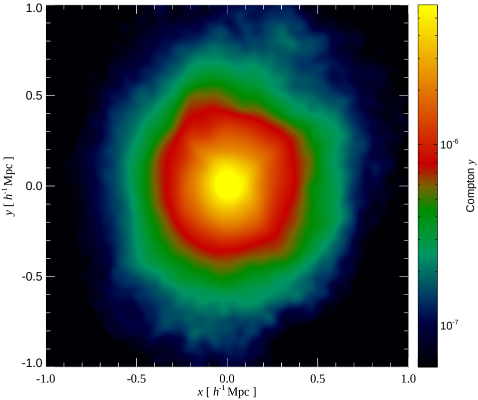

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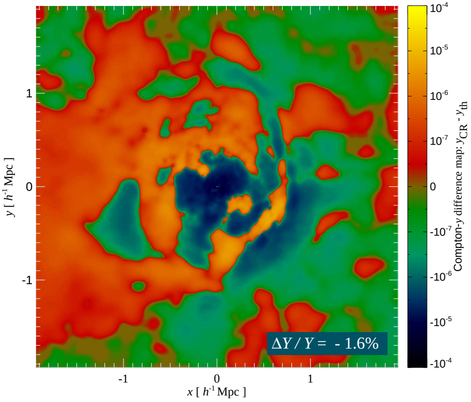
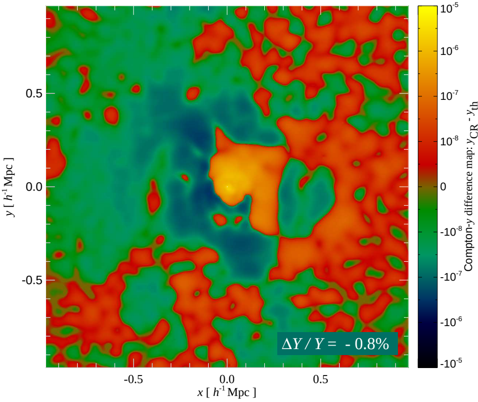
Compton y difference map: $y_{\mathrm{CR}} - y_{\mathrm{th}}$





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

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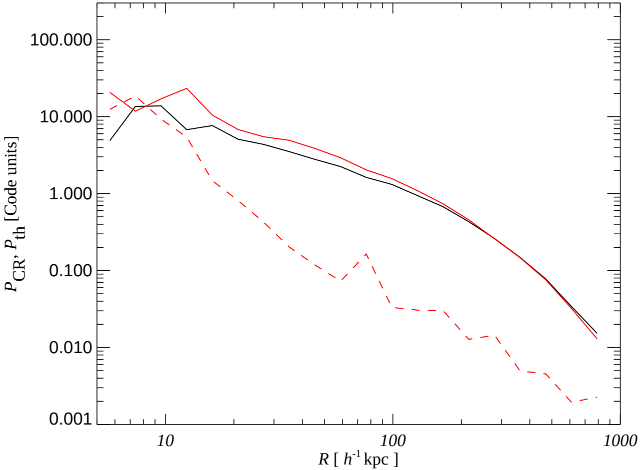
Pressure profiles with and without CRs



Non-thermal emission from clusters

Exploring the memory of structure formation

So far, we were asking how the CR pressure modifies thermal cluster observables such as the X-ray emission and the Sunyaev-Zel'dovich effect of clusters. These processes tell us only very indirectly (if at all) about the history of structure formation. In contrast, non-thermal processes retain their cosmic memory since their particle population is not in equilibrium.

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

- LOFAR: European interferometric array of radio telescopes at low frequencies ($\nu \simeq (10 - 240)$ MHz)
- Astrosat: Indian satellite that images soft and hard X-rays ($E \simeq (0.3 - 100)$ keV)
- Glast: international high-energy γ-ray space mission ($E \simeq (0.02 - 300)$ GeV)

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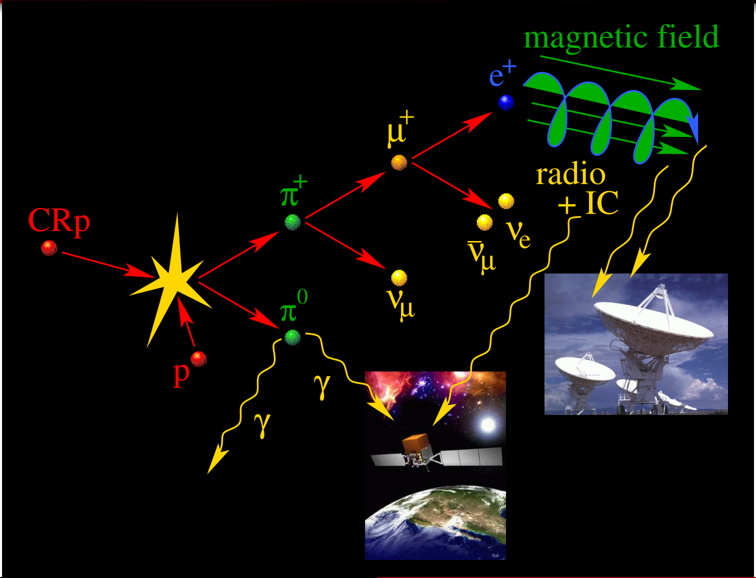
Hadronic cosmic ray proton interaction



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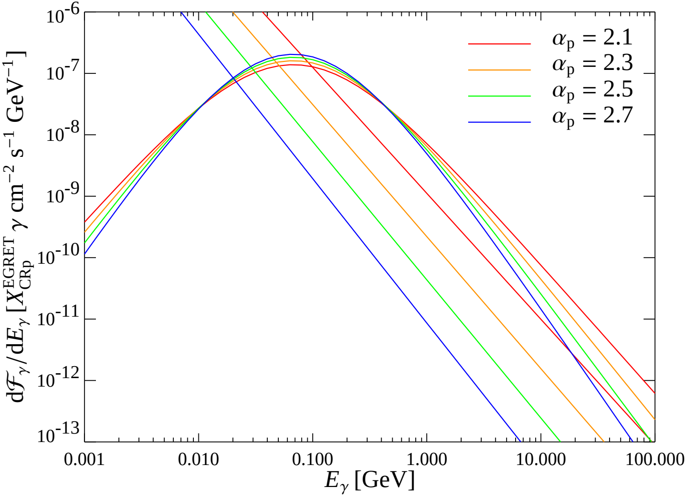
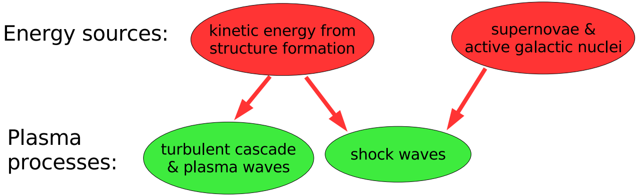
Expected hadronic γ-ray flux of the Perseus cluster

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



Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



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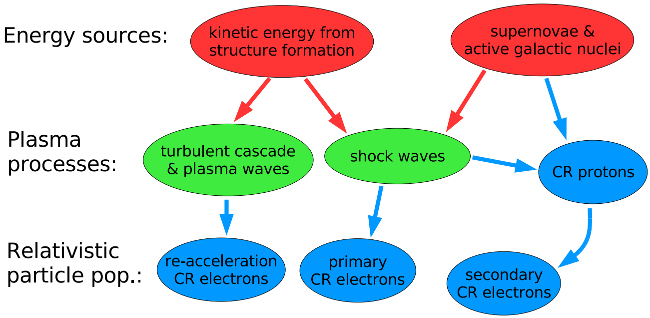

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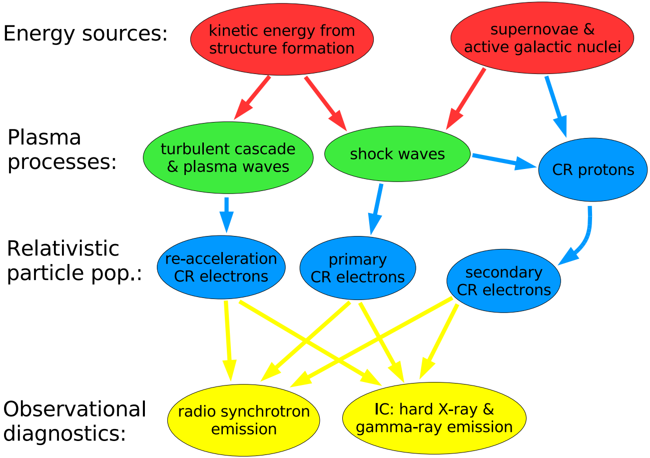

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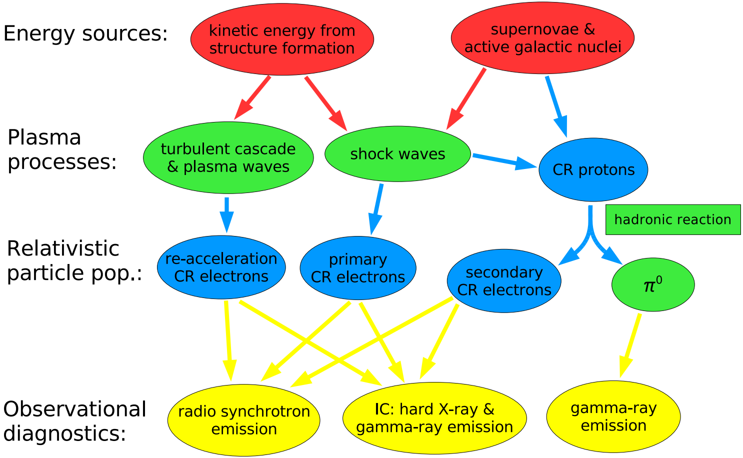

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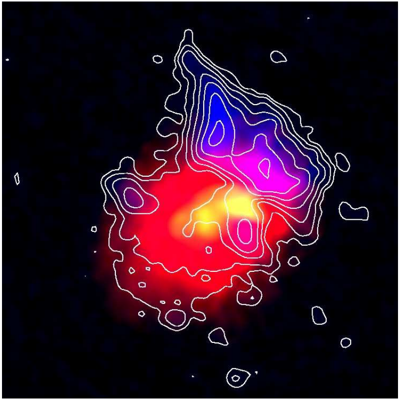
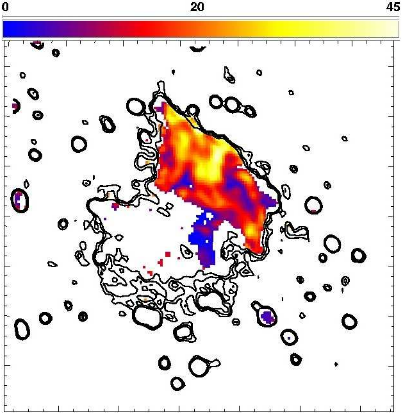
Abell 2256: giant radio relic & small halo



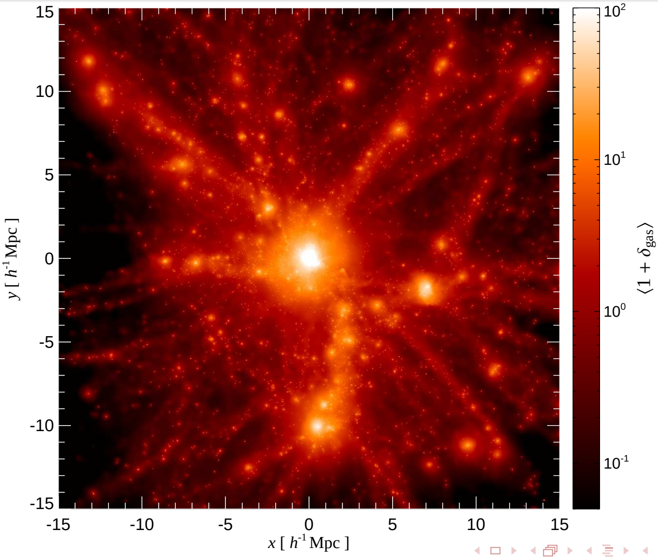
X-ray (red) & radio (blue, contours)



fractional polarization in colour

Clarke & Enßlin (2006)

Cosmic web: density



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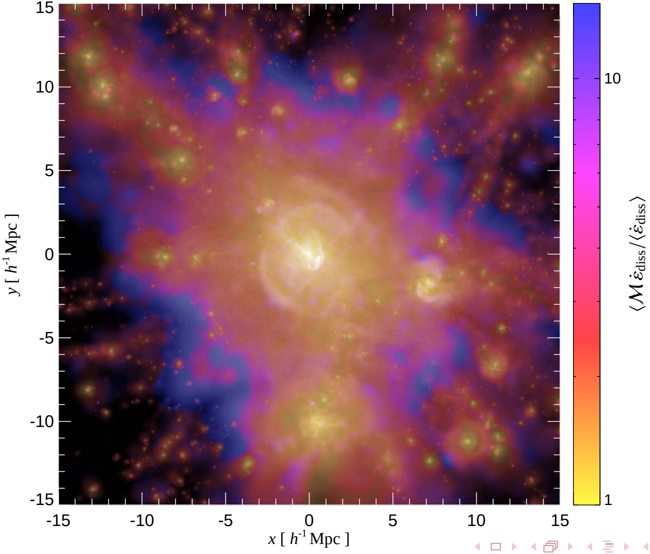
Cosmic web: Mach number



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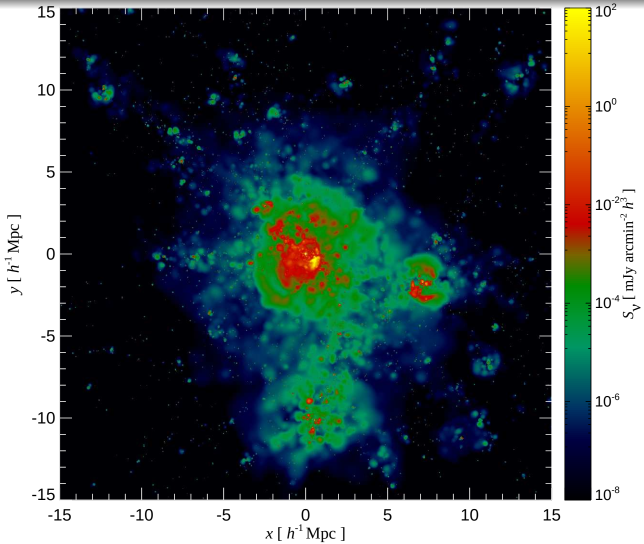
Radio web: primary CRe (1.4 GHz)



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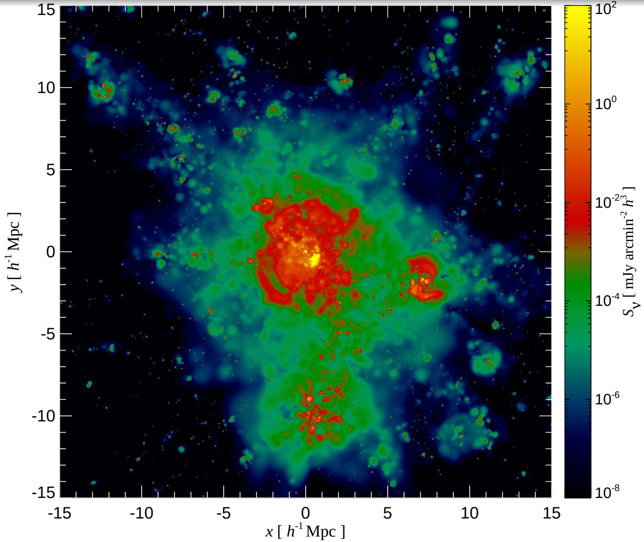
Radio web: primary CRe (150 MHz)



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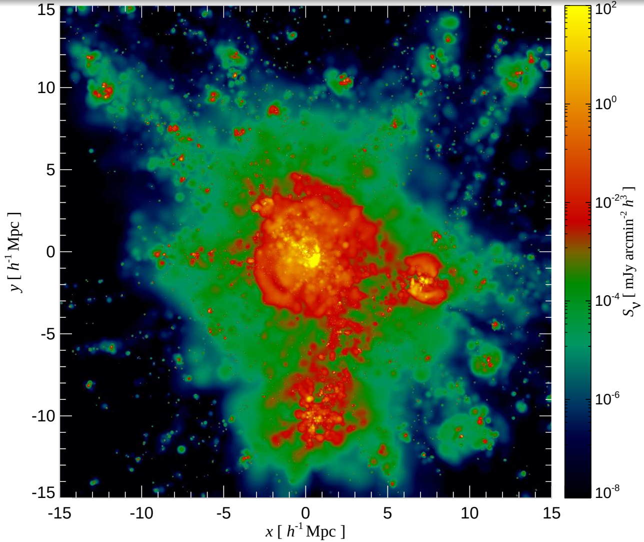
Radio web: primary CRe (15 MHz)



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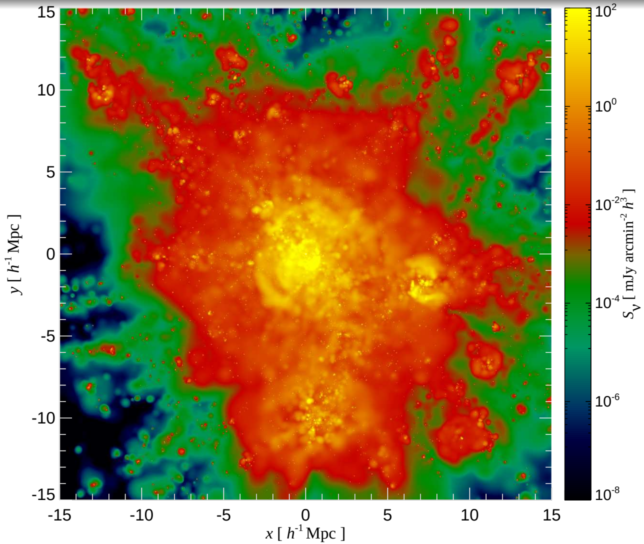
Radio web: primary CRe (15 MHz), slower magnetic decline



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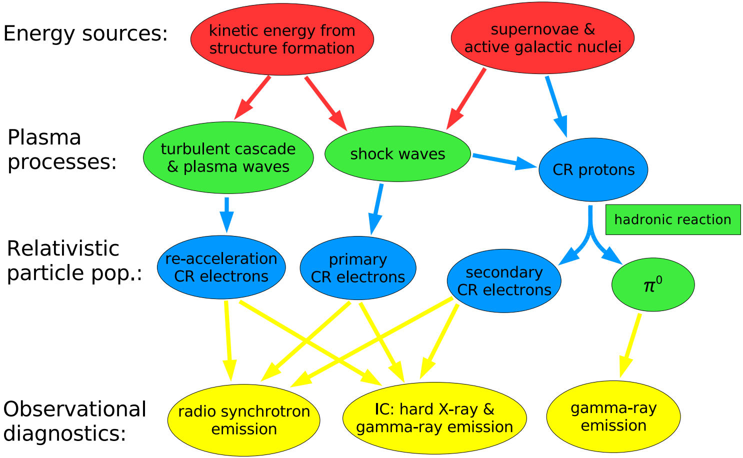
Models for radio synchrotron halos in clusters

Halo characteristics: smooth unpolarized radio emission at scales of 3 Mpc.
Different CR electron populations:

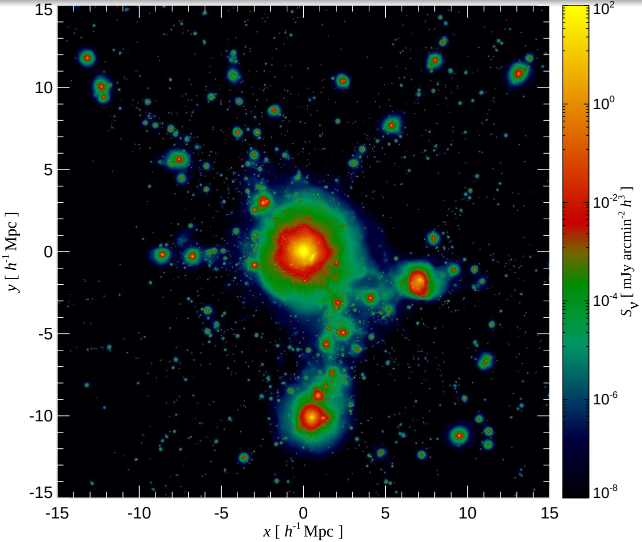
- Primary accelerated CR electrons: synchrotron/IC cooling times too short to account for extended diffuse emission
- Re-accelerated CR electrons through resonant interaction with turbulent Alfvén waves: possibly too inefficient, no first principle calculations (Jaffe 1977, Schlickeiser 1987, Brunetti 2001)
- Hadronically produced CR electrons in inelastic collisions of CR protons with the ambient gas (Dennison 1980, Vestrad 1982, Miniati 2001, Pfrommer 2004)

Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



Radio halos: secondary CRe (150 MHz)



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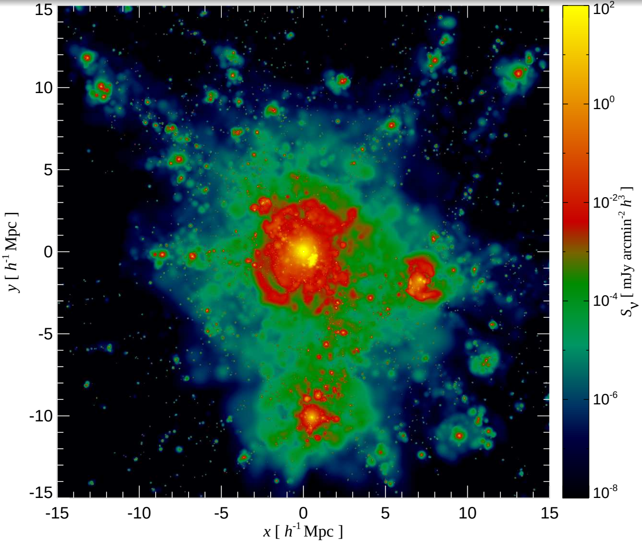
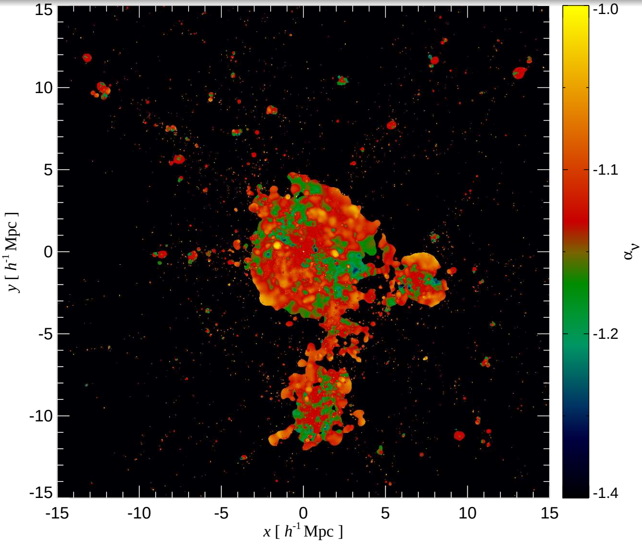
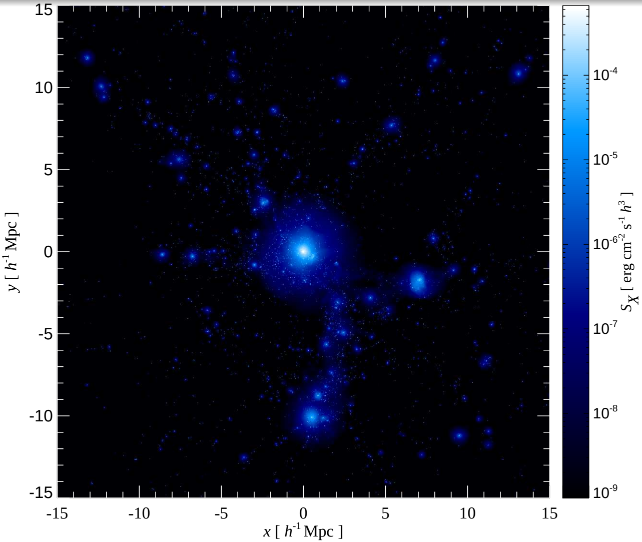
Radio web + halos 150 MHz



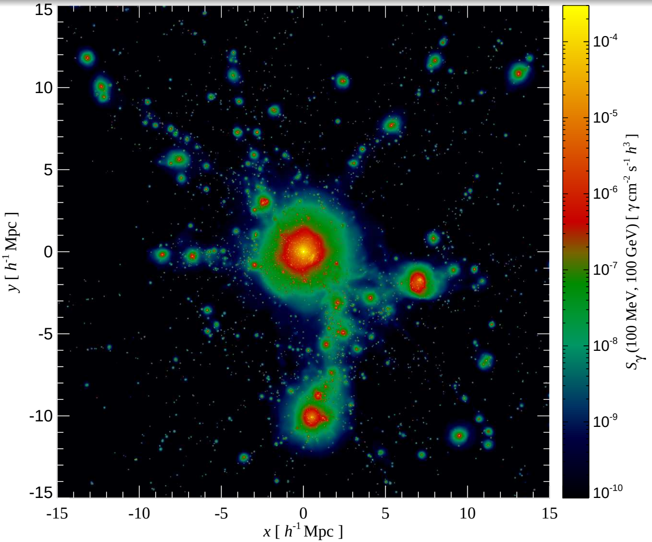
Radio web + halos: spectral index



Thermal X-ray emission



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



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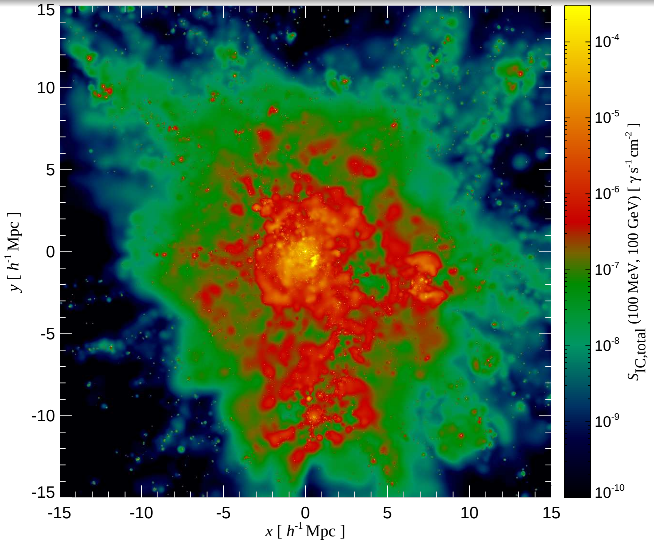
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ MeV



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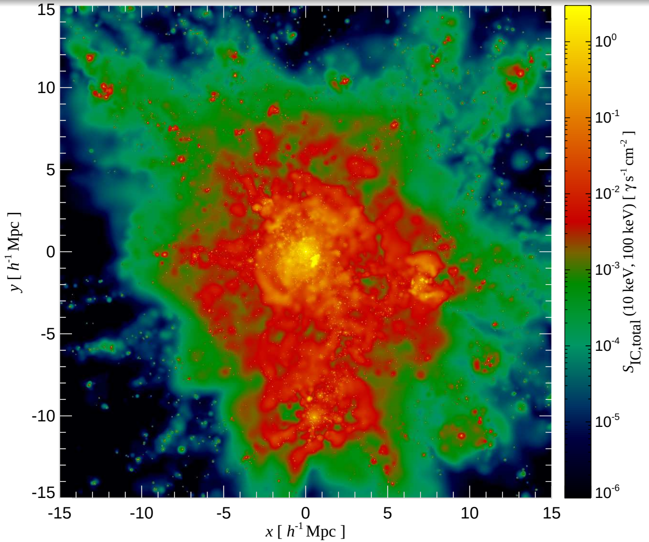
Inverse Compton emission, $E_{\mathrm{IC}} > 10$ keV



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Summary

CR physics modifies the intracluster medium 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.
- LOFAR is expected to see the radio web emission: origin of cosmic magnetic fields.
- Glast should see hadronic γ-ray emission from clusters: measurement of CR protons and origin of radio halos.

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

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