Cosmic Rays in Galaxy Clusters: Simulations and Perspectives

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Collaborators

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- Nick Battaglia, Dick Bond, Jon Sievers (CITA)
- Subha Majumdar (TIFR, India)

Thought provoking impulses

Exploring 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.
   - Improving cluster self-calibration with a hybrid approach: combining (non-)thermal properties in observation space with Bayesian prior on the functional scaling properties derived from hydrodynamical simulations.
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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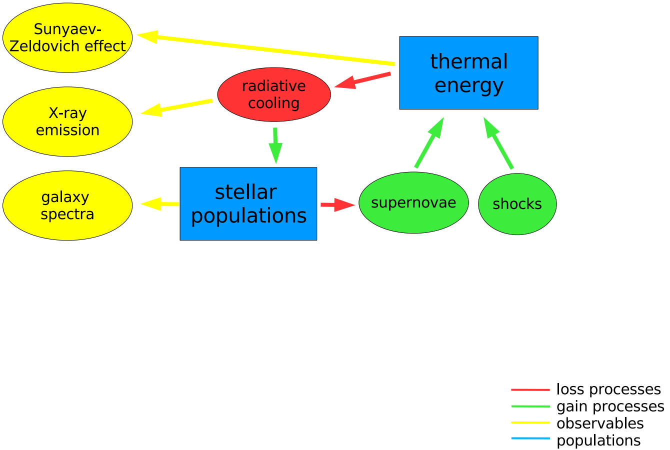
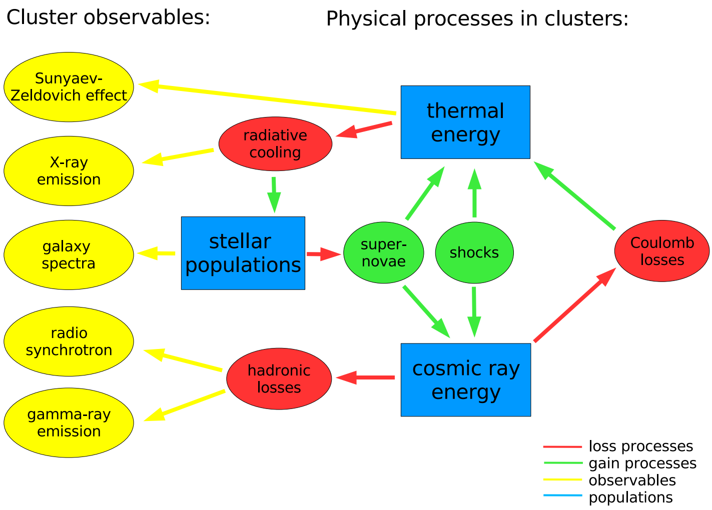
Radiative simulations – flowchart

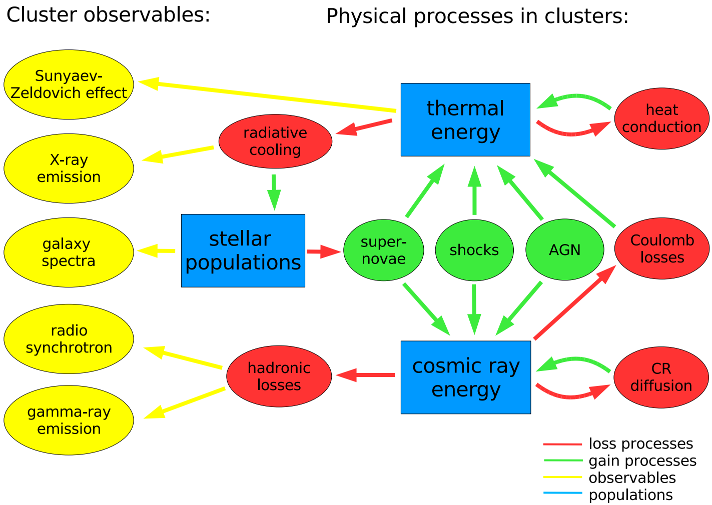
Cluster observables: Physical processes in clusters:



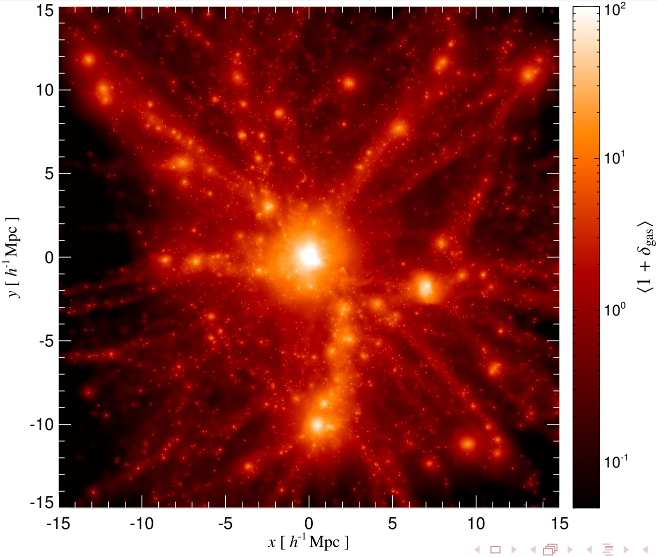
Radiative simulations with cosmic ray (CR) physics



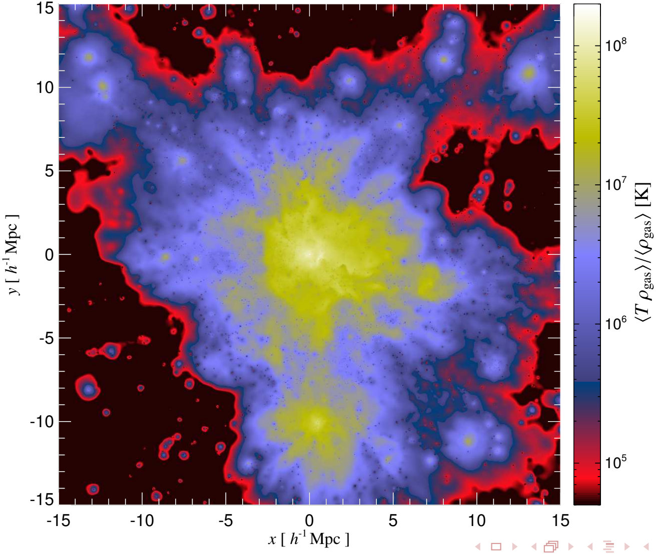
Radiative simulations with extended CR physics



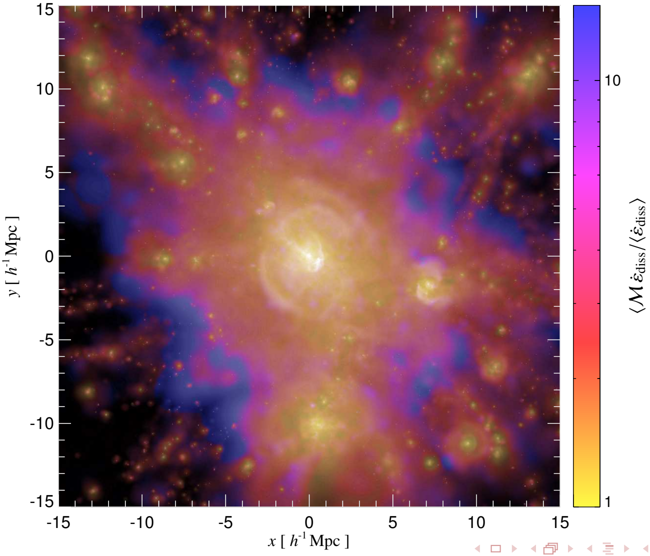
Radiative cool core cluster simulation: gas density



Mass weighted temperature



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



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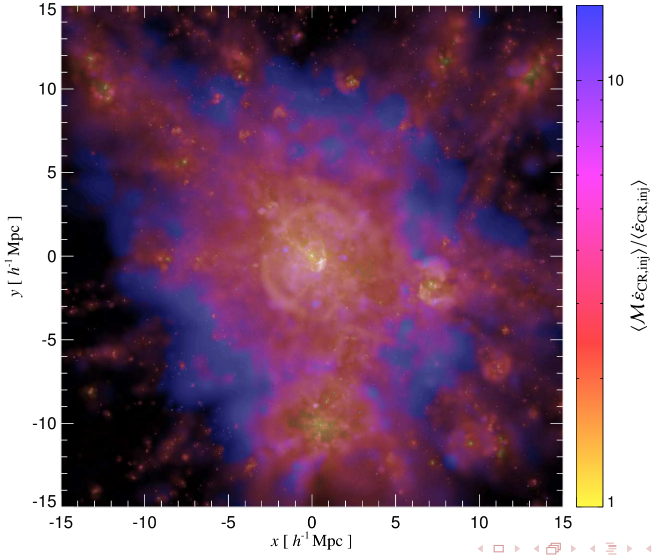
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



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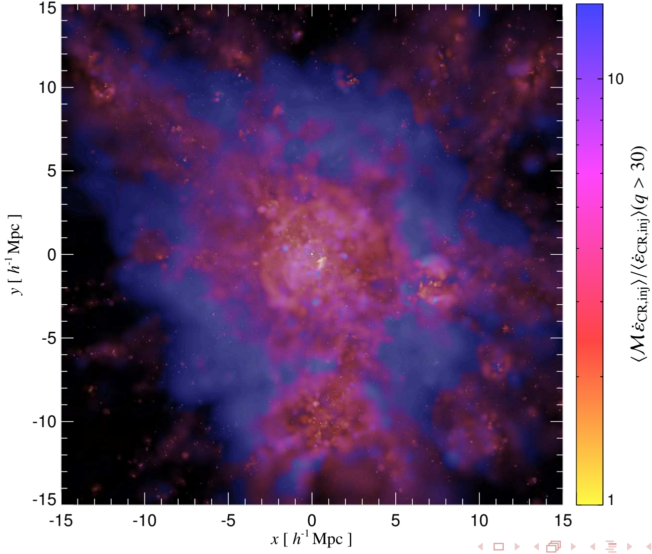
Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$



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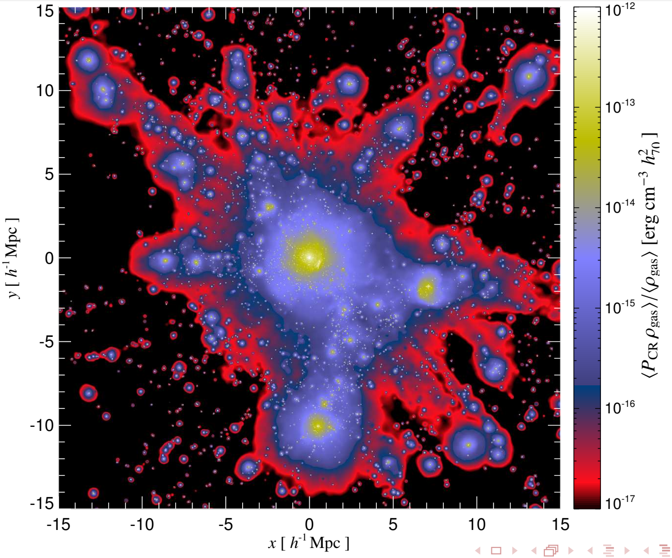
CR pressure $P_{\rm CR}$



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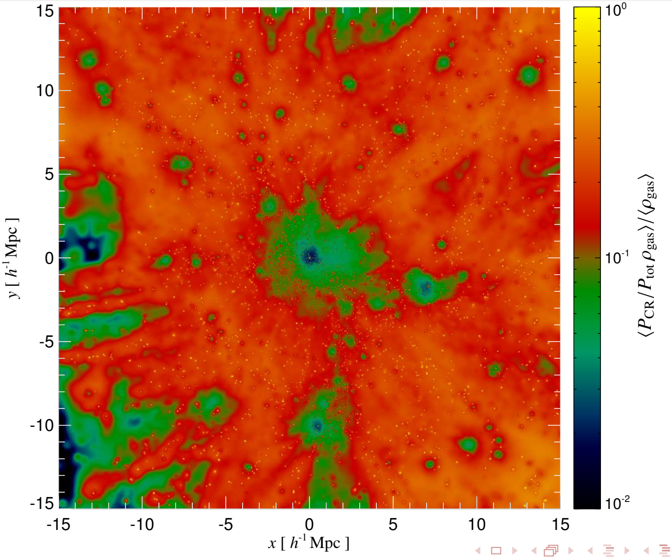
Relative CR pressure P_{CR}/P_{total}



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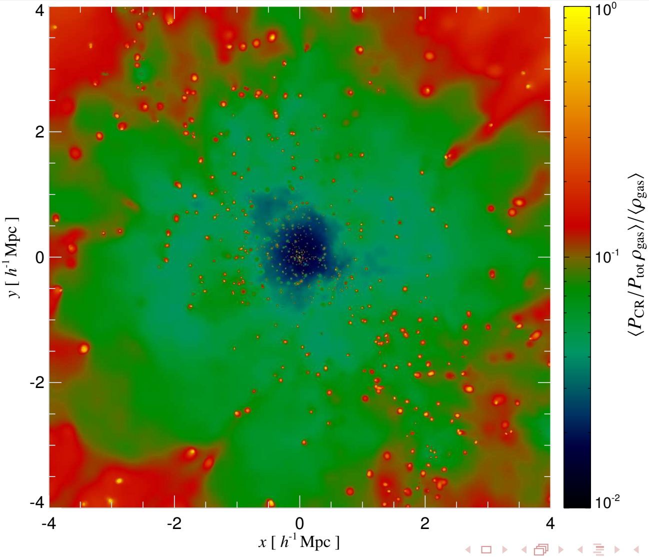
Relative CR pressure $P_{\rm CR}/P_{\rm total}$



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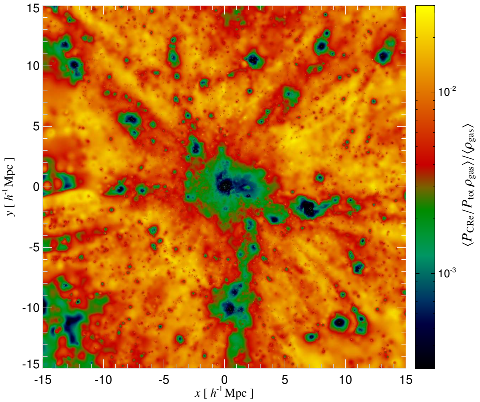
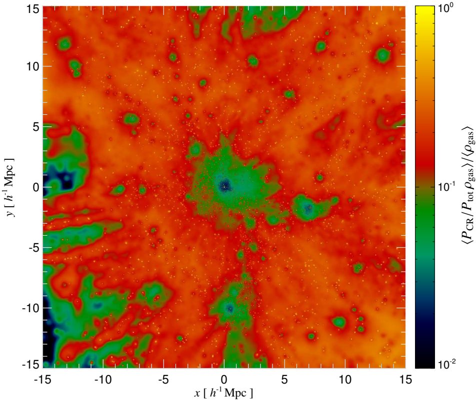
CR electron versus CR proton pressure





Relative pressure of primary CR electrons.

Relative pressure of CR protons.

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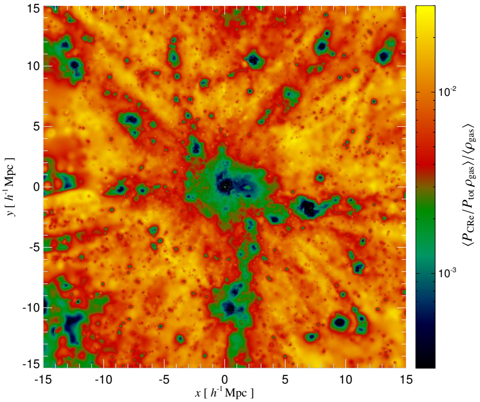
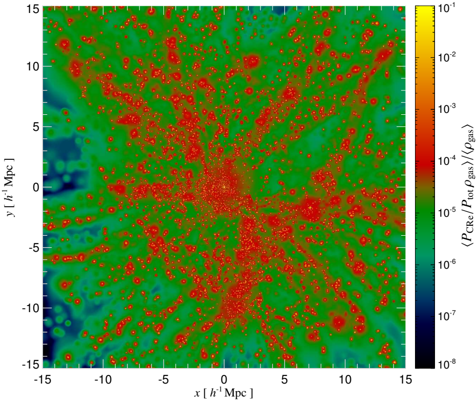
Primary versus secondary CR electrons



Relative pressure of *primary* CR electrons.



Rel. pressure of *secondary* CR electrons.

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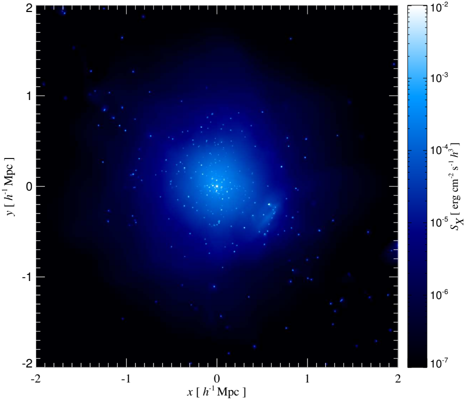
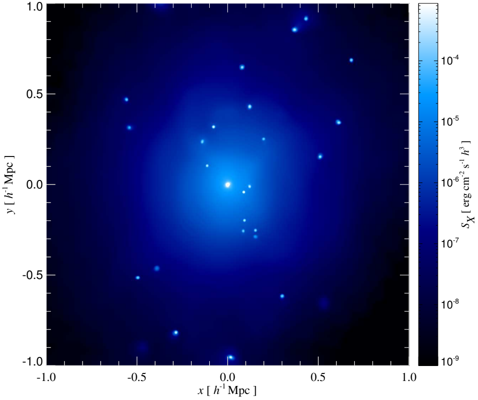
Thermal X-ray emission



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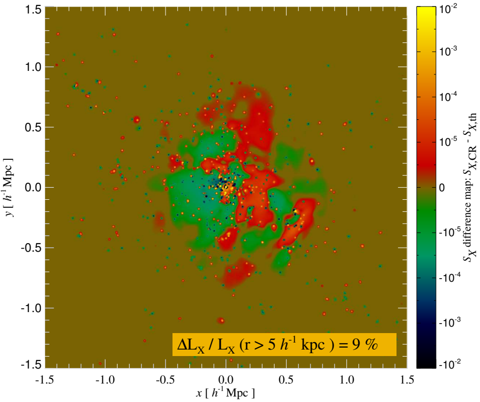
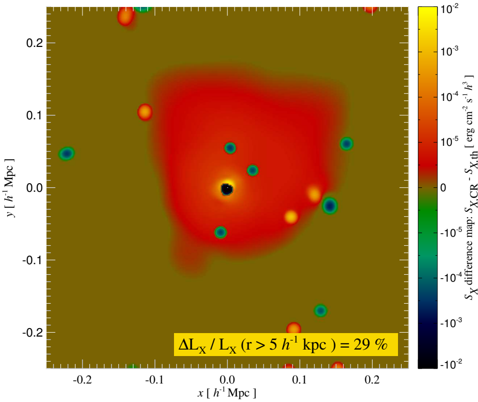
Difference map of S_X: $S_{X,\mathrm{CR}} - S_{X,\mathrm{th}}$



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 $\Delta L_X \simeq 40\%$ for cool core clusters

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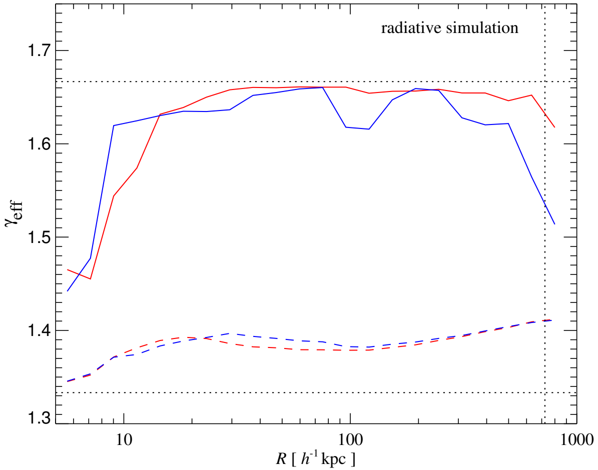
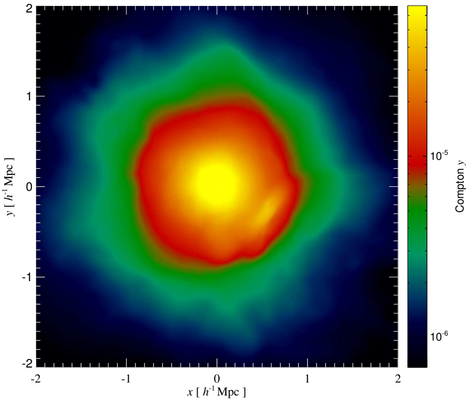
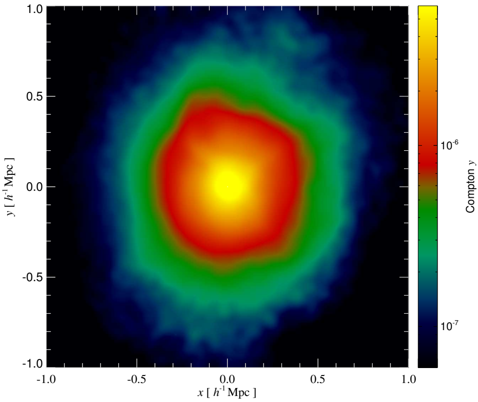
Softer effective adiabatic index of composite gas



Compton y parameter in radiative cluster simulation



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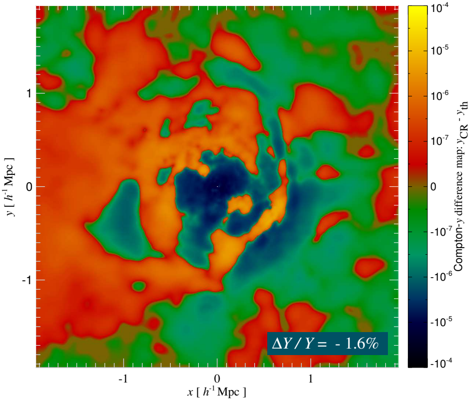
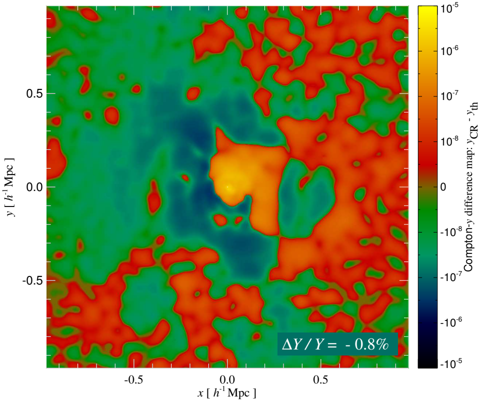
Compton y difference map: $y_{\rm CR} - y_{\rm th}$



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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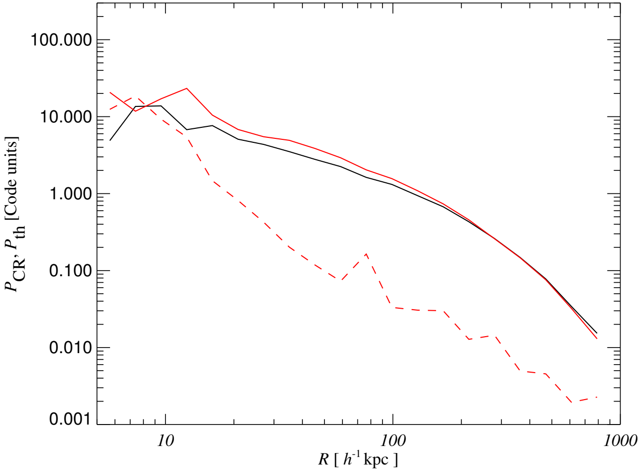
Pressure profiles with and without CRs



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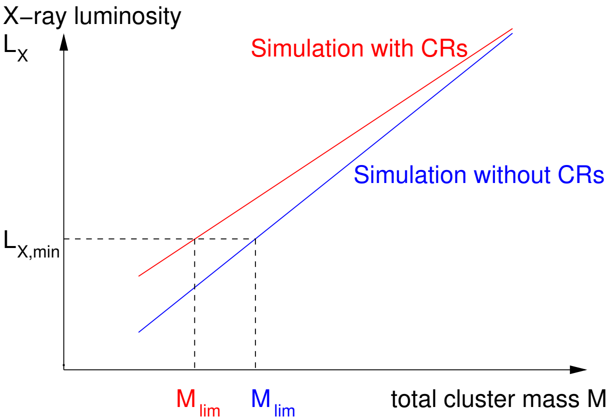
Modified X-ray scaling relations (with Subha Majumdar)



→ CR feedback lowers the effective mass threshold for X–ray flux–limited cluster sample

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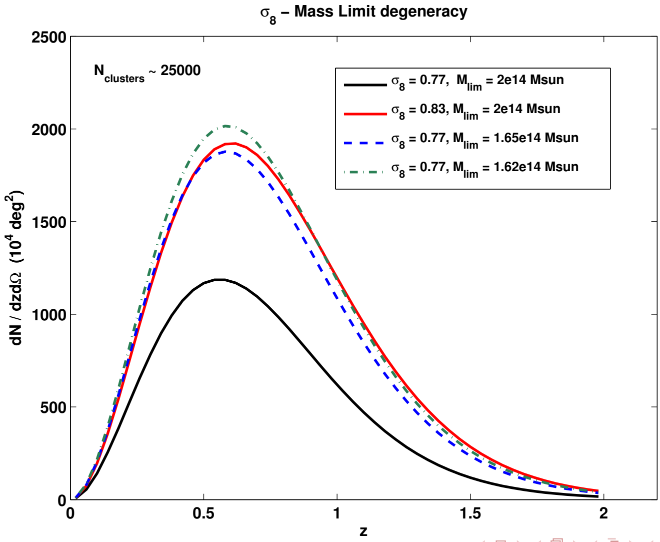
Degeneracies of the cluster redshift distribution (1)

- The number density of massive clusters is exponentially sensitive to the amplitude of the initial Gaussian fluctuations, whose normalization we usually describe using σ_8, the *rms* fluctuations of overdensity within spheres of $8\,h^{-1}$ Mpc.
- The cluster redshift distribution $\mathrm{d}n/\mathrm{d}z$ is increased by a lower effective mass threshold M_{lim} in a survey or by increasing σ_8 respectively $\Omega_{\mathrm{m}} \rightarrow$ degeneracies of cosmological parameters with respect to cluster physics.

Degeneracies of the cluster redshift distribution (2)



Fisher matrix analysis

Assumed survey details:

- survey area $A = 10^4$ square degrees ($1/4$ of the sky)
- redshift range: $0 < z < 2$
- bolometric X-ray flux limit $F_\mathrm{X} = 2.5 \times 10^{-13}$ erg s^{-1} cm^{-2}
- sample size: 25000 clusters

Fisher matrix preliminaries:

- free parameters: 2 parameters of the scaling relations: slope and normalization, Ω_m, Ω_b, n_s, h, σ_8
- priors: flat Universe, WMAP prior on $h = 72 \pm 5$

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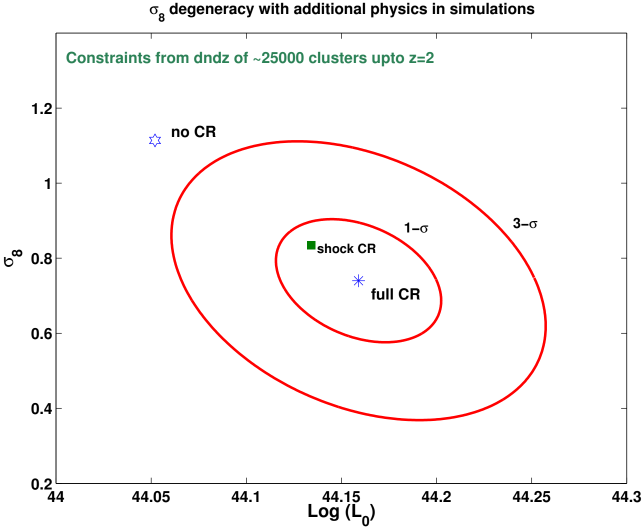
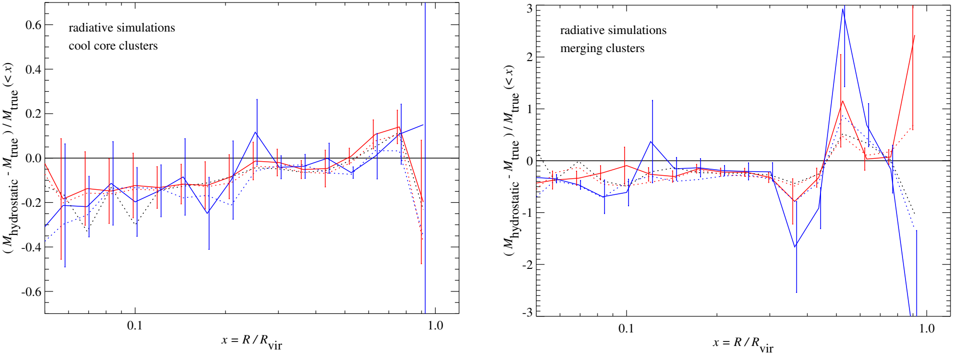
Degeneracy of σ_8 with cosmic ray physics (preliminary)



Hydrostatic mass profiles

Influence of turbulence and CR pressure

Relative mass difference $(M_{\text{hydrostatic}} - M_{\text{true}})/M_{\text{true}}$:



$$\frac{1}{\rho_{\text{gas}}} \frac{\mathrm{d}P_{\text{tot}}}{\mathrm{d}r} = -\frac{G\,M(<r)}{r^2}, \text{ and } P_{\text{tot}} = P_{\text{th}} + P_{\text{nth}} + P_{\text{turb}}.$$

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?
$\longrightarrow$ new era of multi-frequency experiments, e.g.:

- LOFAR, GMRT: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ 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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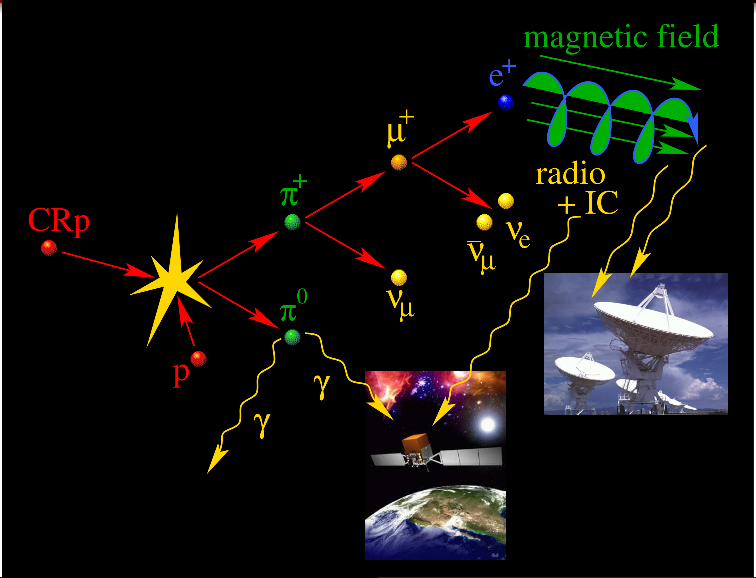
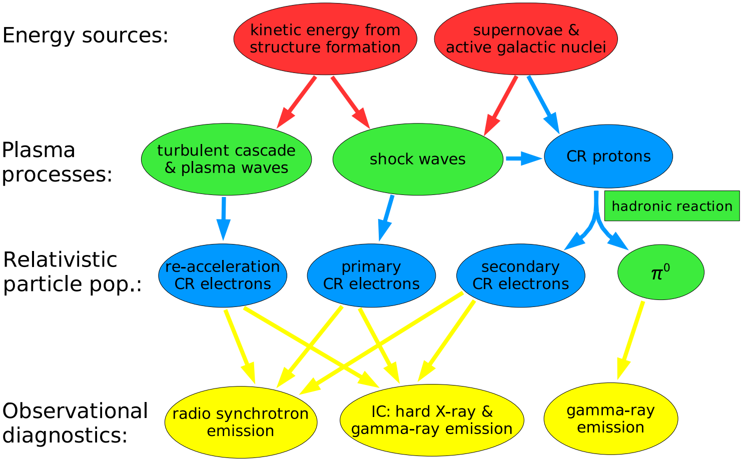
Hadronic cosmic ray proton interaction



Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



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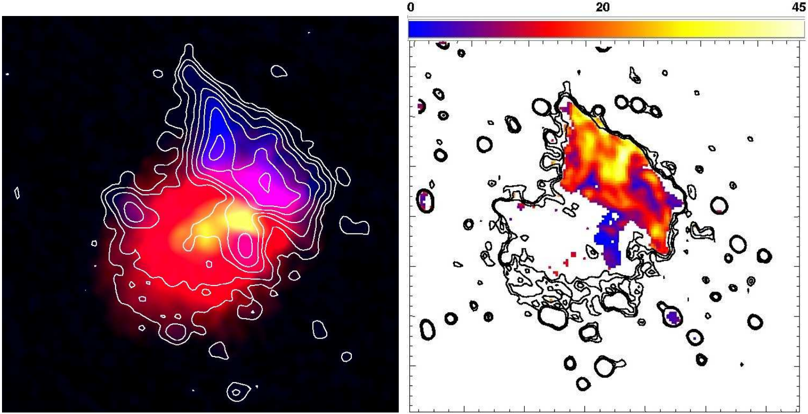
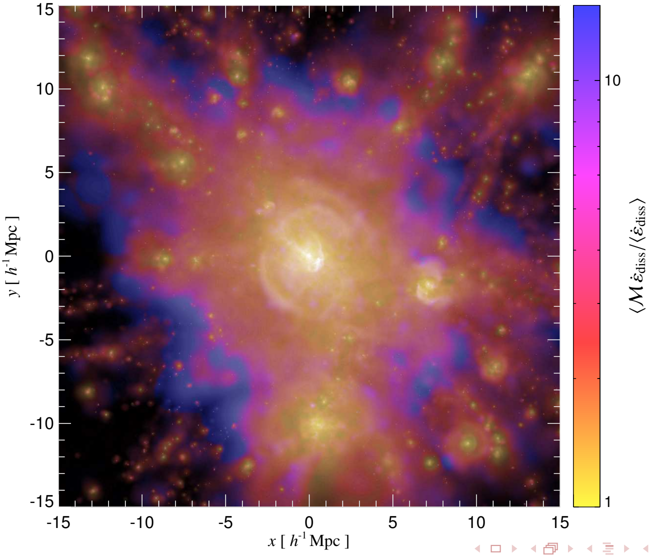
Abell 2256: giant radio relic & small halo



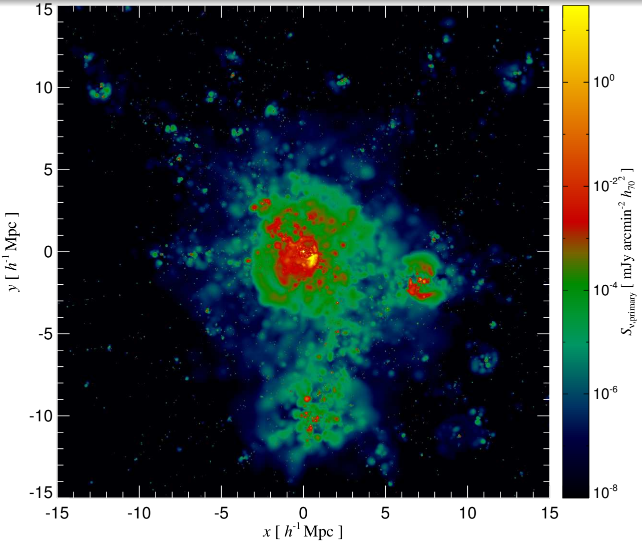
X-ray (red) & radio (blue, contours) fractional polarization in color

Clarke & Enßlin (2006)

Cosmic web: Mach number



Radio web: primary CRe (1.4 GHz)



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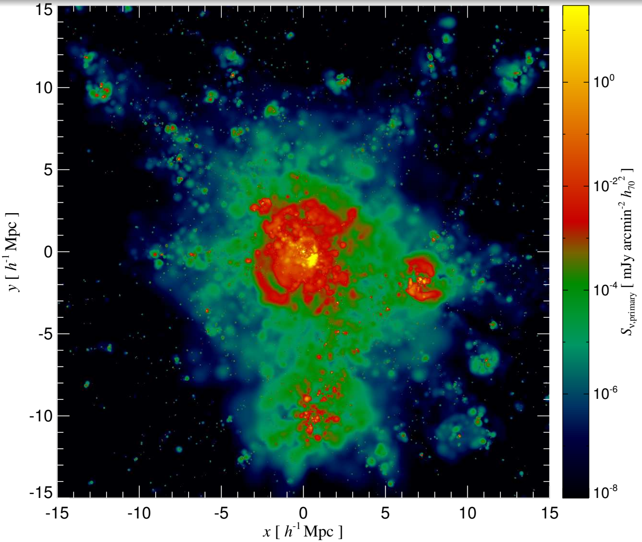
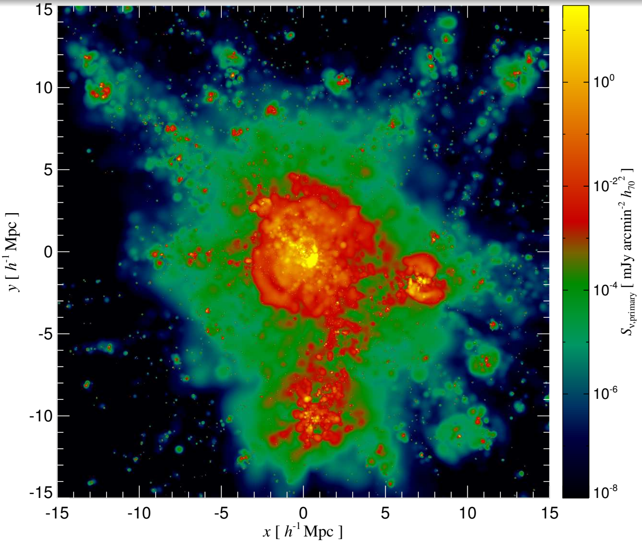
Radio web: primary CRe (150 MHz)



Radio web: primary CRe (15 MHz)



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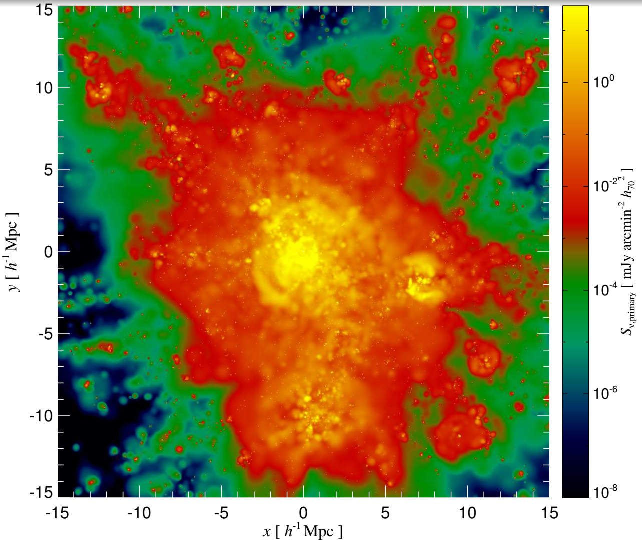
Radio web: primary CRe (15 MHz), slower magnetic decline



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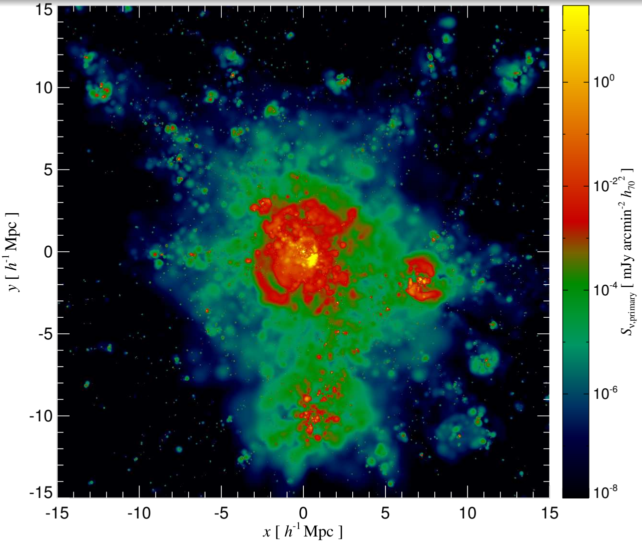
Exploring the magnetized radio web (with Battaglia, Sievers, Bond)



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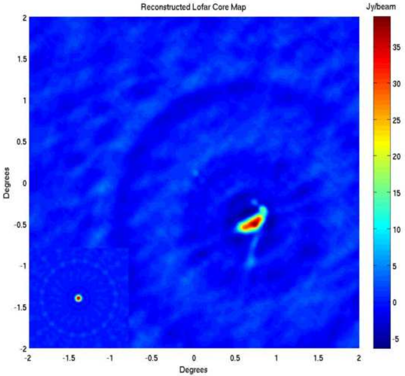
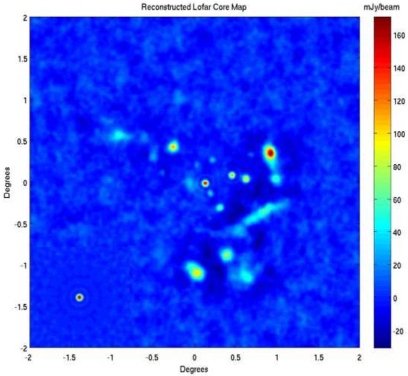
Simulated LOFAR observation (merging cluster at $z = 0.02$)



Reconstructed ‘dirty’ LOFAR core map.



Reconstructed ‘cleaned’ LOFAR map.

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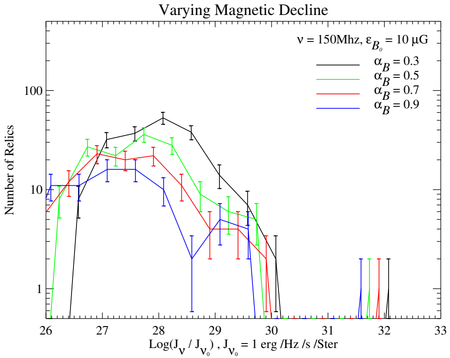
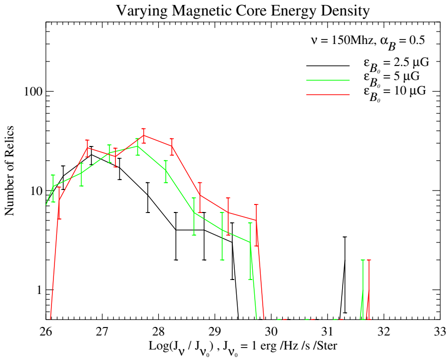
Radio relic luminosity function



Varying the magnetic decline, $\varepsilon_B \propto \varepsilon_{\mathrm{th}}^{2\alpha_B}$.



Varying the central magnetic field.

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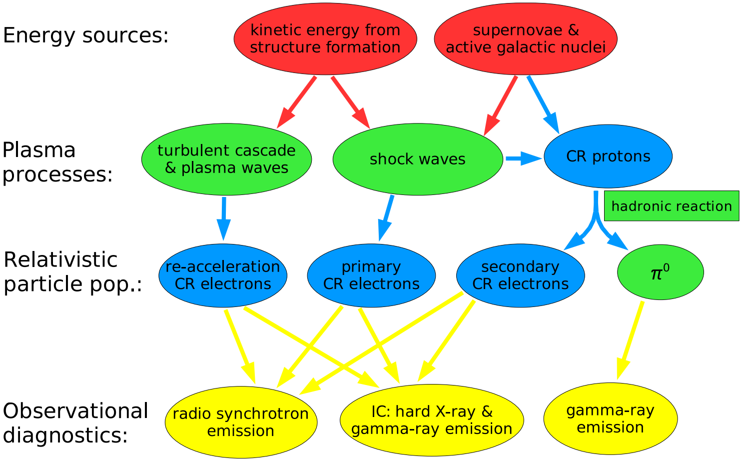
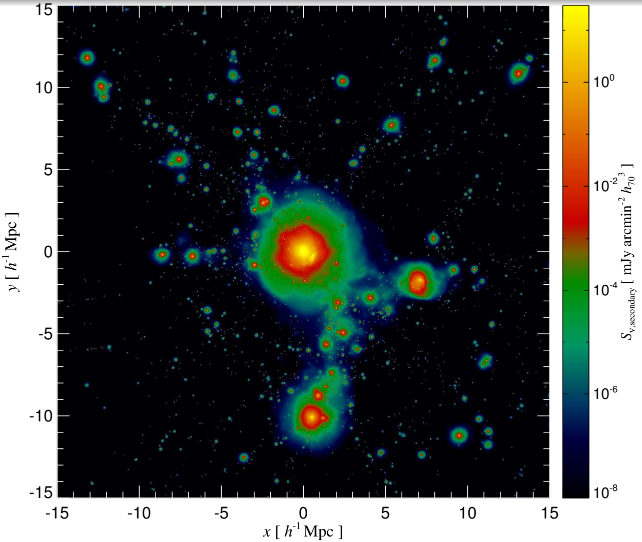
Radio halos: secondary CRe

Relativistic populations and radiative processes in clusters:



Radio halos: secondary CRe (150 MHz)



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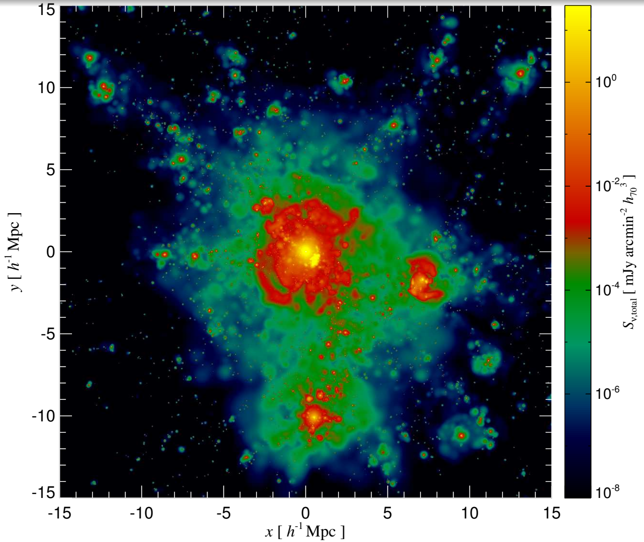
Radio relics + halos 150 MHz



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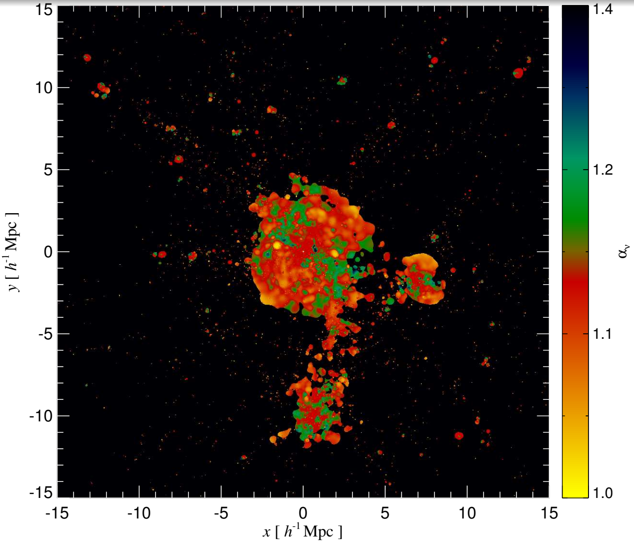
Radio relics + halos: spectral index



Low-frequency radio emission from clusters

Window into current and past structure formation

Observational properties of radio synchrotron emission:

- Radio relics: inhomogeneous morphology, peripheral cluster regions, polarized synchrotron emission, flat radio spectrum ($\alpha_\nu \simeq 1.1$)
- Radio (mini-) halos: homogeneous spherical morphology (similar to X-ray emission), Faraday depolarized synchrotron emission, steeper radio spectrum ($\alpha_\nu \simeq 1.3$)

What this tells us:

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

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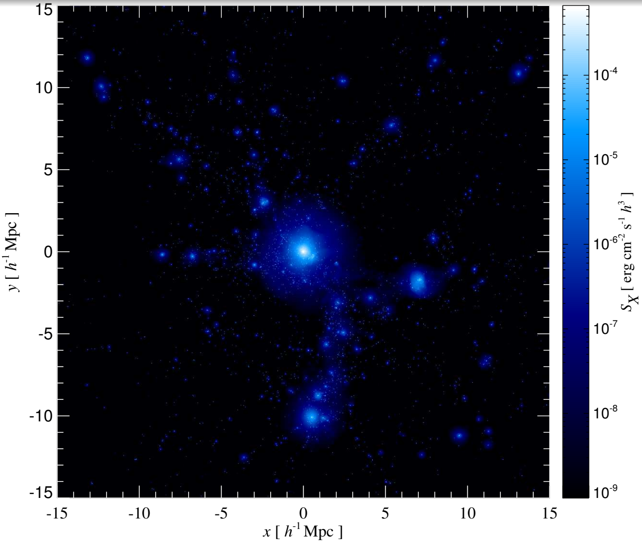
Thermal X-ray emission



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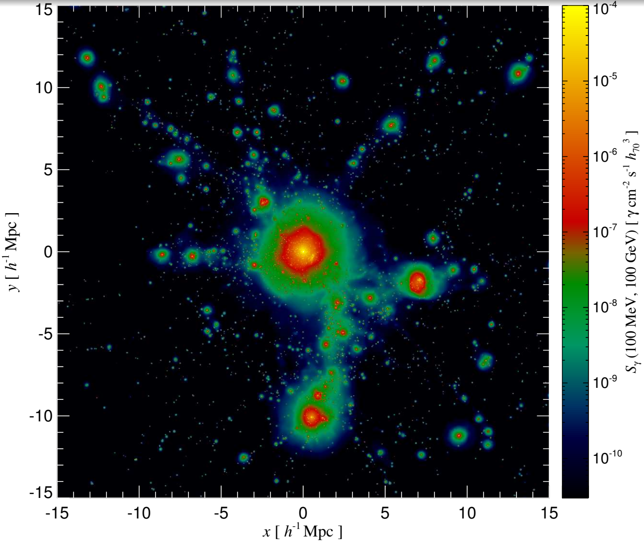
Hadronic γ-ray emission, $E_\gamma > 100$ MeV



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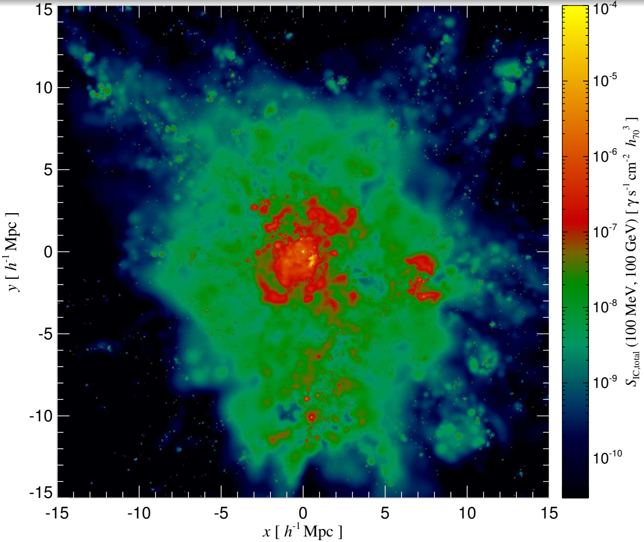
Inverse Compton emission, $E_{\mathrm{IC}} > 100$ MeV



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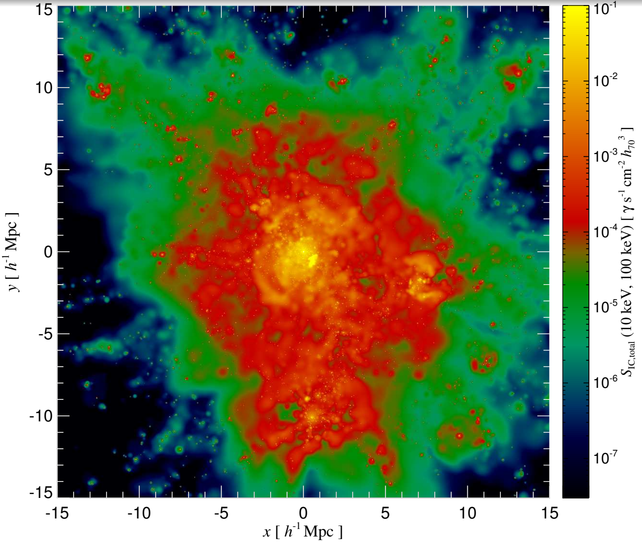
Inverse Compton emission, $E_{\mathrm{IC}} > 10$ keV



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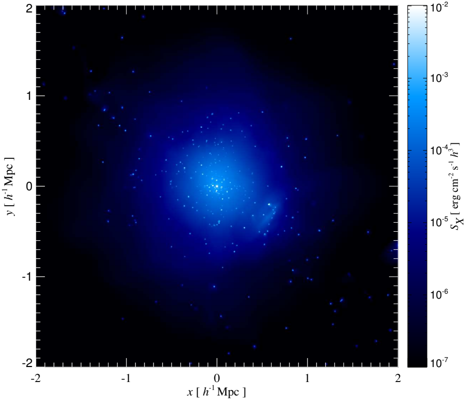
Summary

CR physics modifies the intracluster medium in merging clusters and cooling core regions:

- Galaxy cluster X-ray emission is enhanced up to 40%, systematic effect in cooling core clusters.
- Integrated Sunyaev-Zel'dovich effect remains largely unchanged while the Compton-y profile is more peaked.
- LOFAR/GMRT are 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.

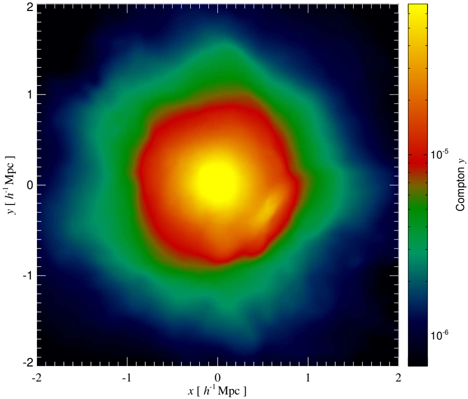
$\rightarrow$ exciting experiments allow a complementary view on structure formation and teach us fundamental physics!

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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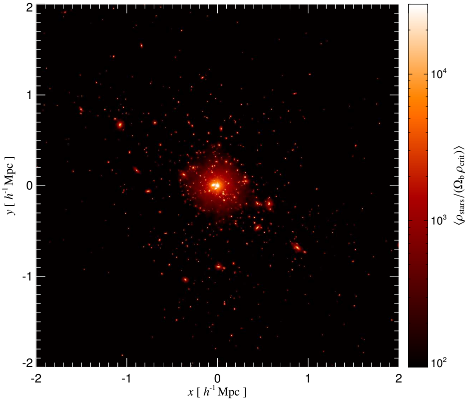
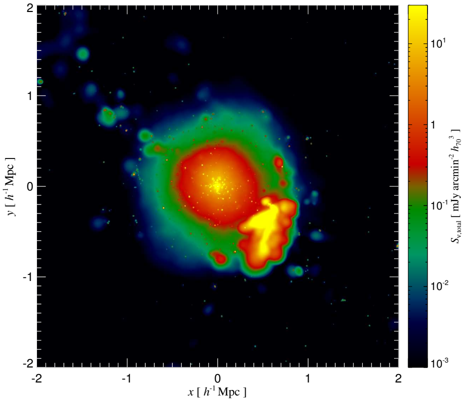
Optical and radio synchrotron cluster observables (1)



Stellar mass density ("cluster galaxies"),

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



Radio halo and relic emission,

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

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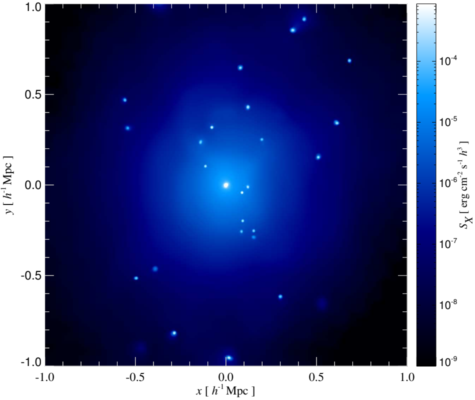
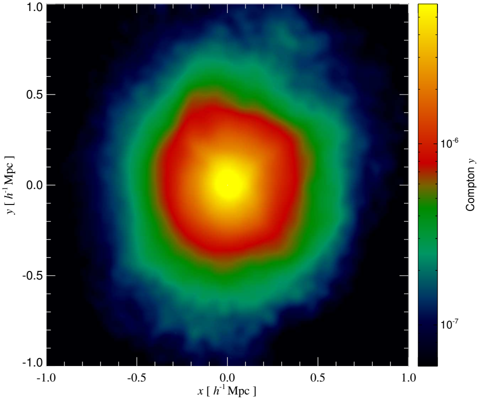
Thermal cluster observables (2)



Thermal bremsstrahlung emission,

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



Sunyaev-Zel'dovich effect,

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

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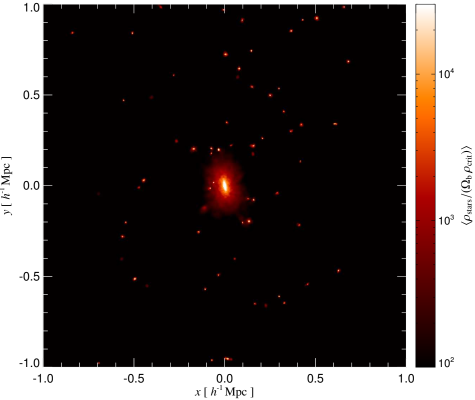
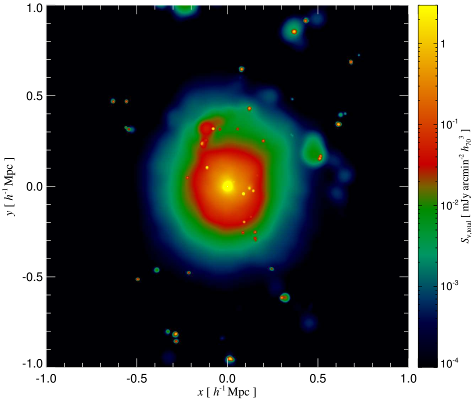
Optical and radio synchrotron cluster observables (2)



Stellar mass density (“cluster galaxies”),

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



Radio halo and relic emission,

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