Cosmic Rays and Cluster Cosmology: A Critical Review

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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: $F_{sy} \propto \varepsilon_B \varepsilon_{CRe} \rightarrow$ magnetic fields, CR electrons, shock waves
- diffuse γ-ray emission: $F_\gamma \propto n_{th} n_{CRp} \rightarrow$ CR protons

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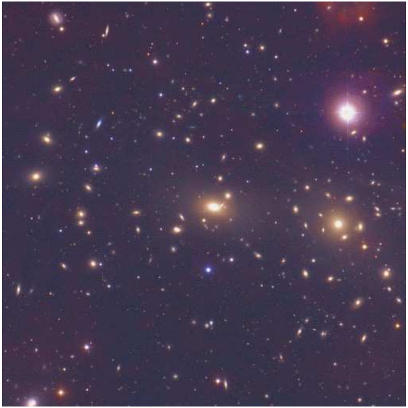
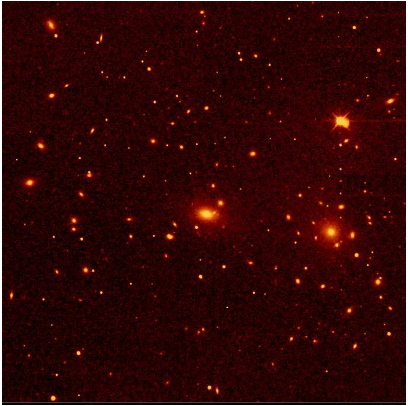
Coma cluster: member galaxies



optical emission,

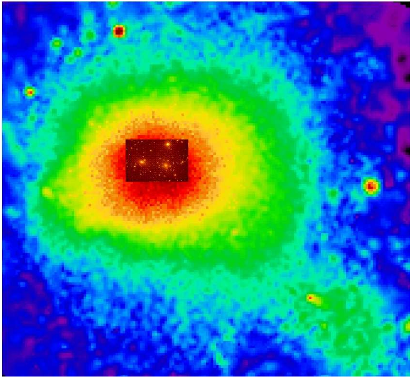
(credit: Kitt Peak)



infra-red emission,

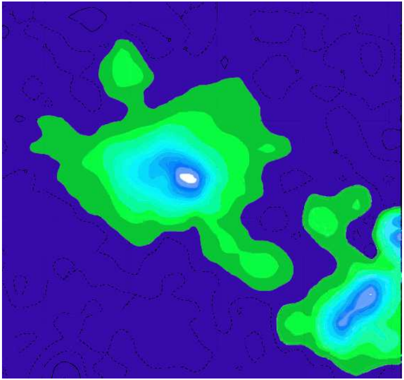
(credit: ISO)

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, $\tau_{\mathrm{dyn}} \sim 1$ 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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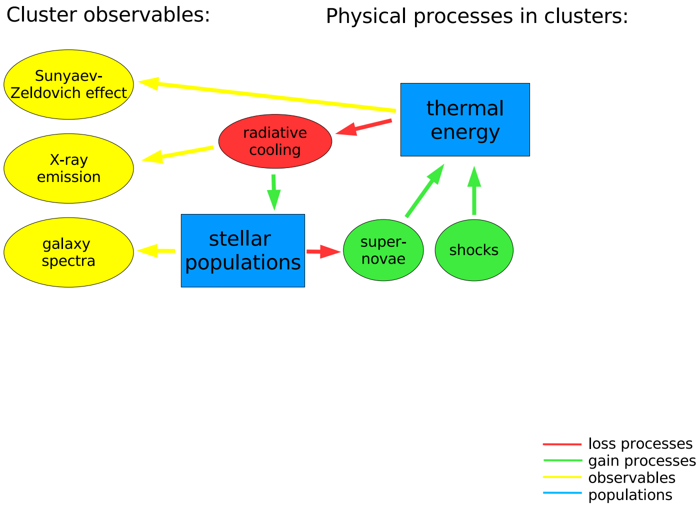
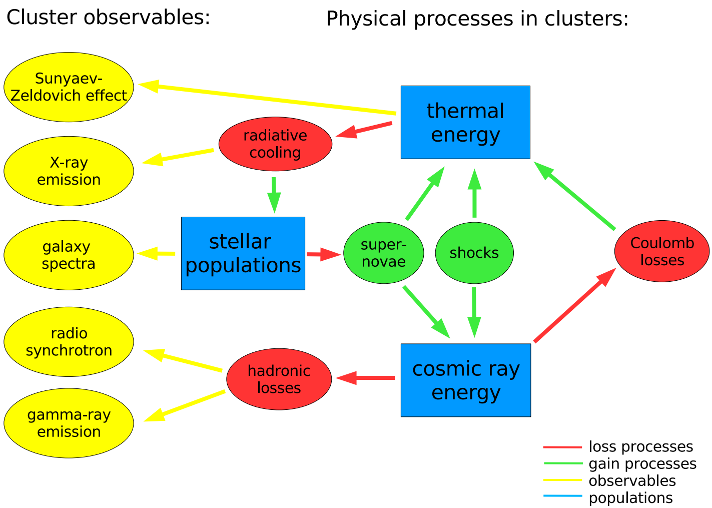
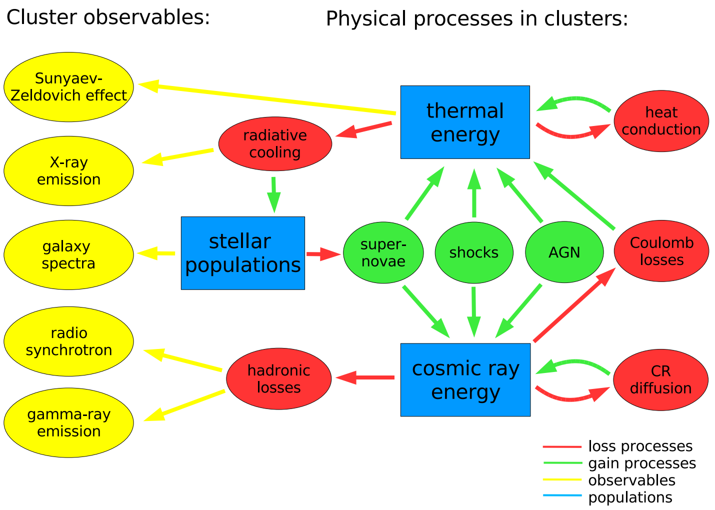
Radiative simulations – flowchart



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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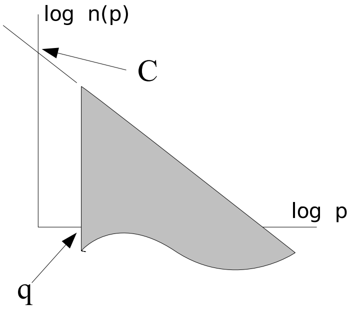
CR spectral description



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

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

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

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

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

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

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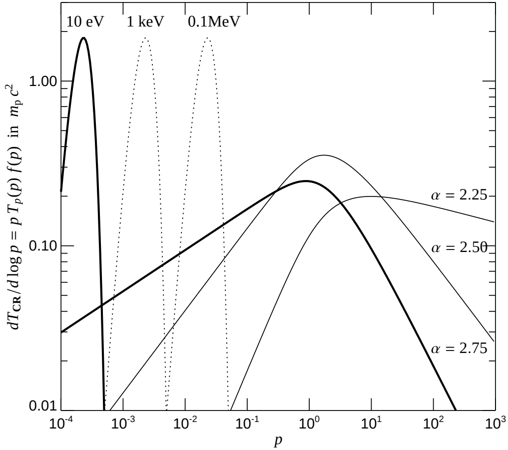
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:



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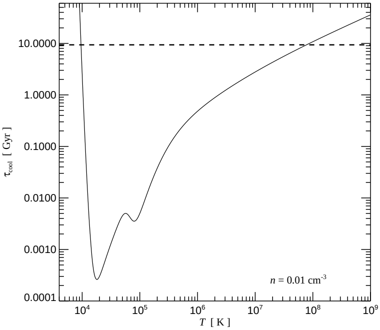
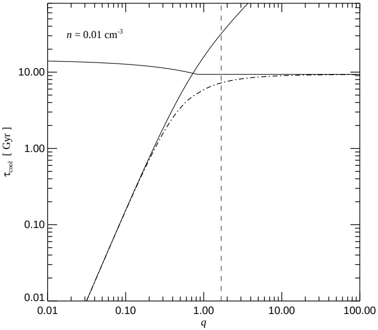
Radiative cooling

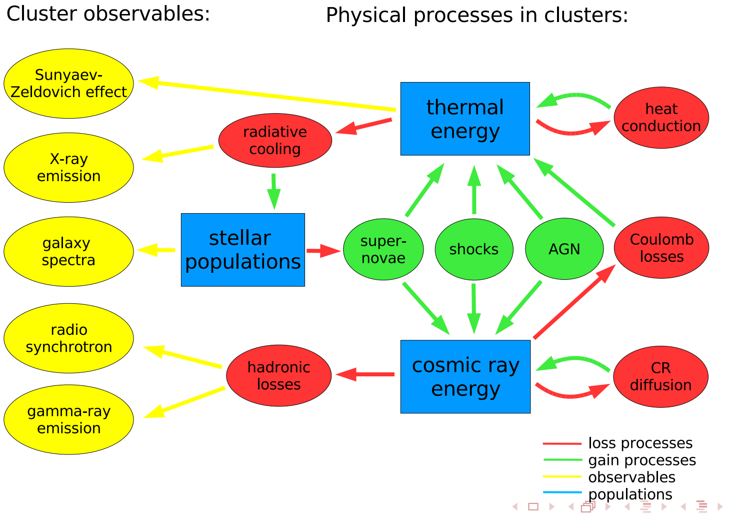
Cooling of primordial gas:



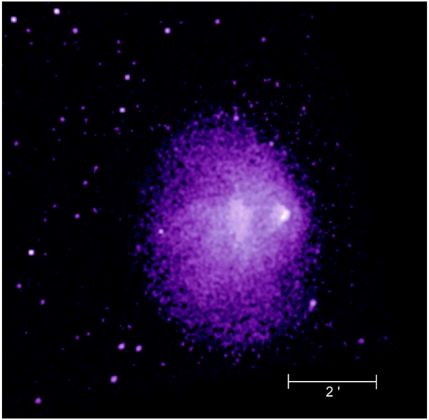
Cooling of cosmic rays:



Cosmic rays in clusters – flowchart

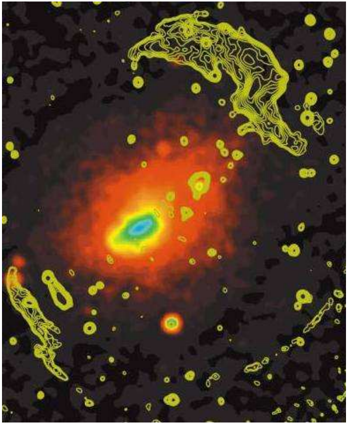


Observations of cluster shock waves



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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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

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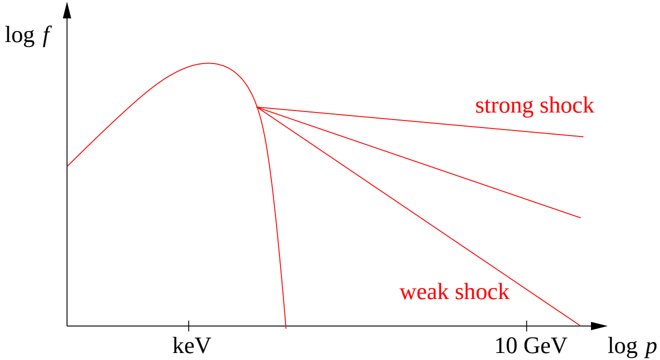
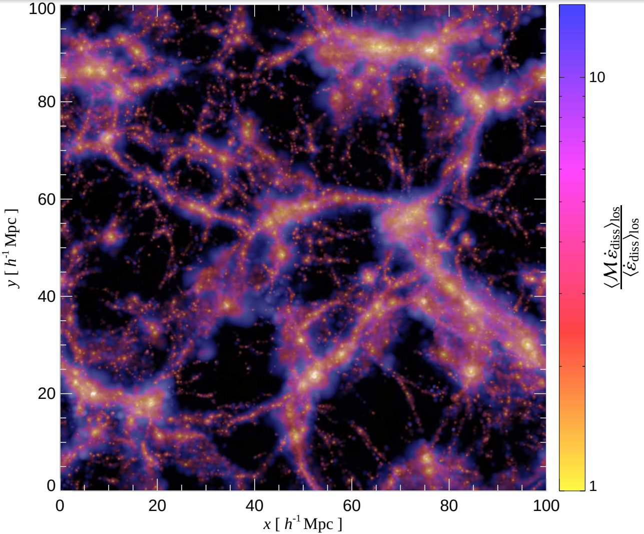
Diffusive shock acceleration – Fermi 1 mechanism (2)

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



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



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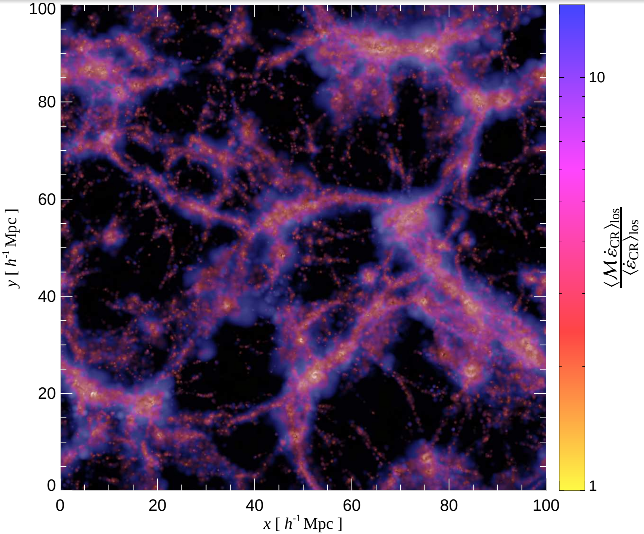
Cosmological Mach numbers: weighted by $\varepsilon_{\mathrm{CR}}$



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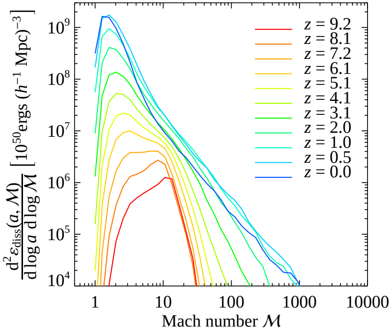
Cosmological Mach number statistics



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

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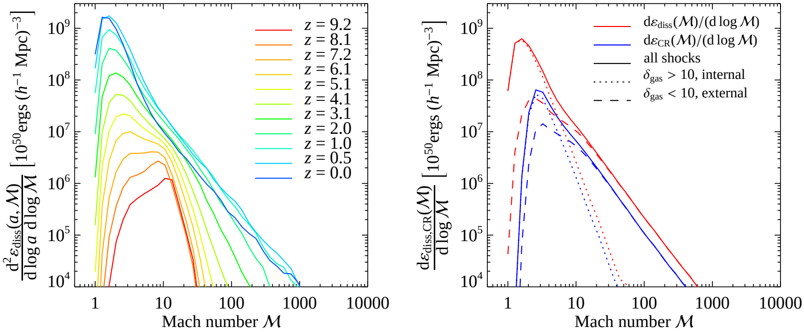
Cosmological statistics: CR acceleration



- 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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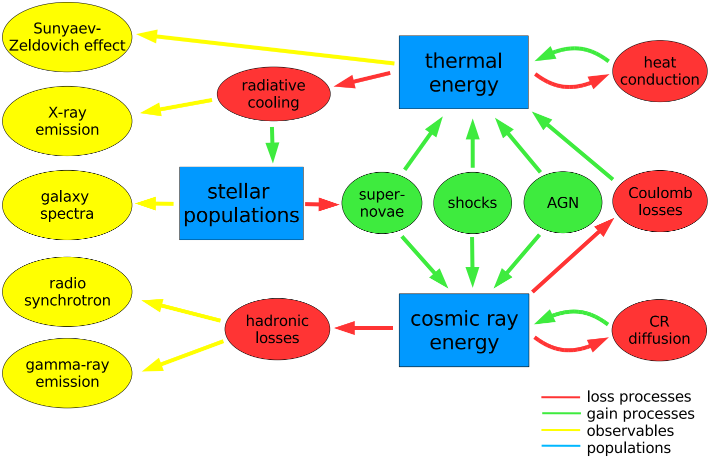
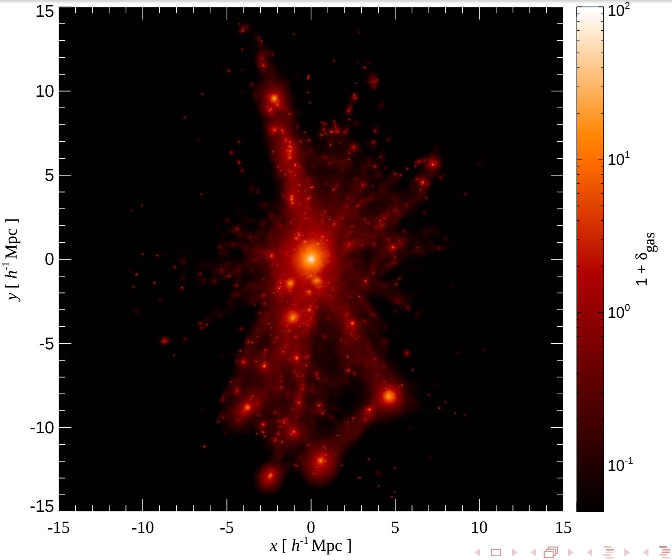
Radiative simulations with extended CR physics

Cluster observables: Physical processes in clusters:



Radiative cool core cluster simulation: gas density



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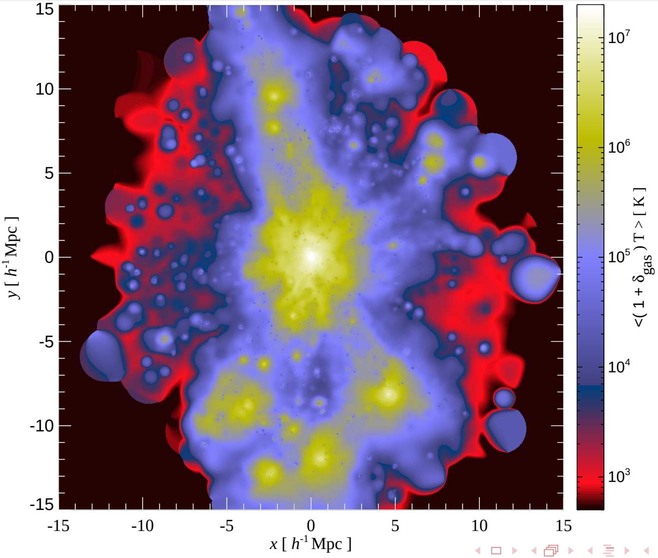
Mass weighted temperature



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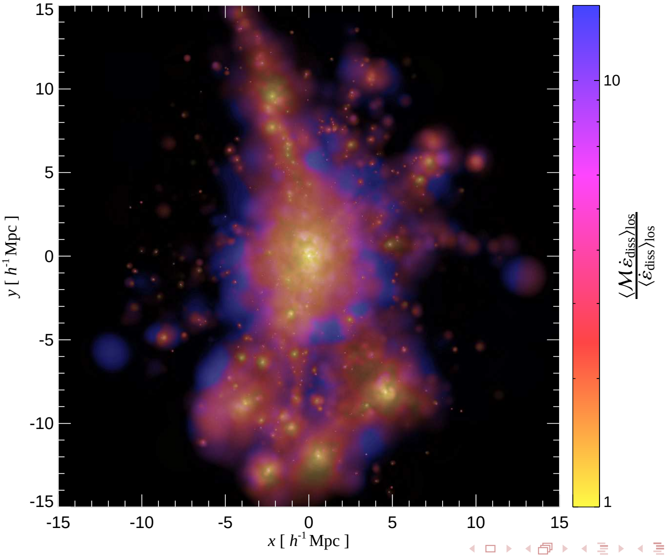
Mach number distribution weighted by $\varepsilon_{\rm diss}$



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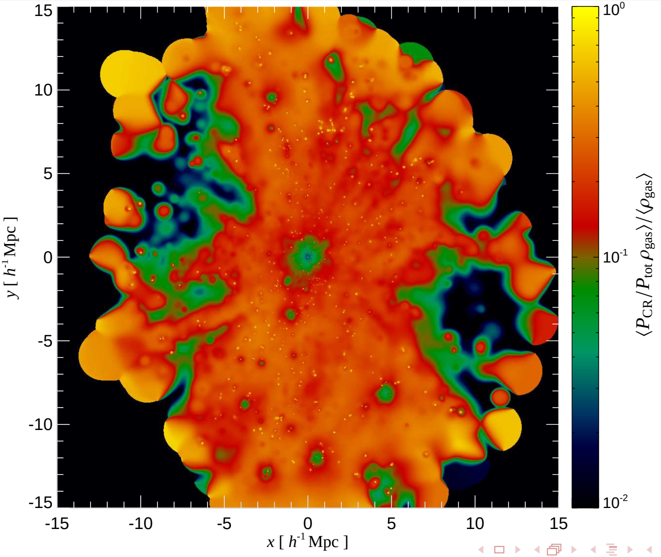
Relative CR pressure P_{CR}/P_{total}



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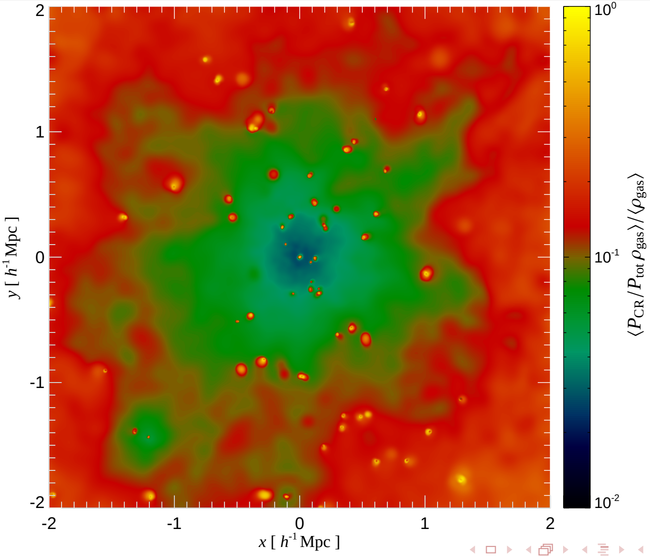

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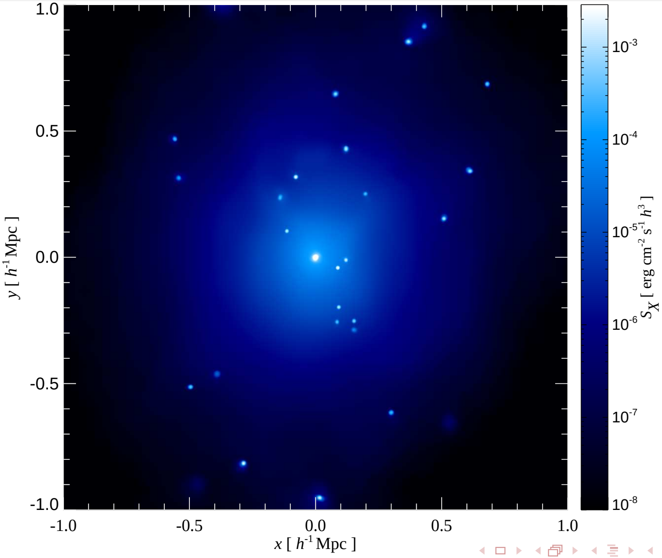
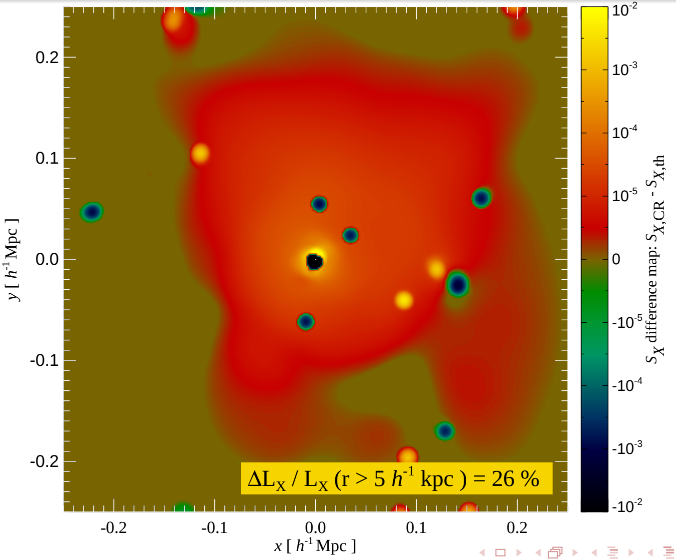
Thermal X-ray emission



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



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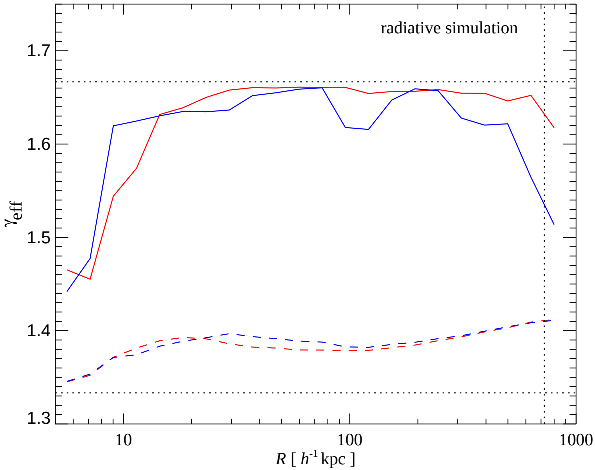
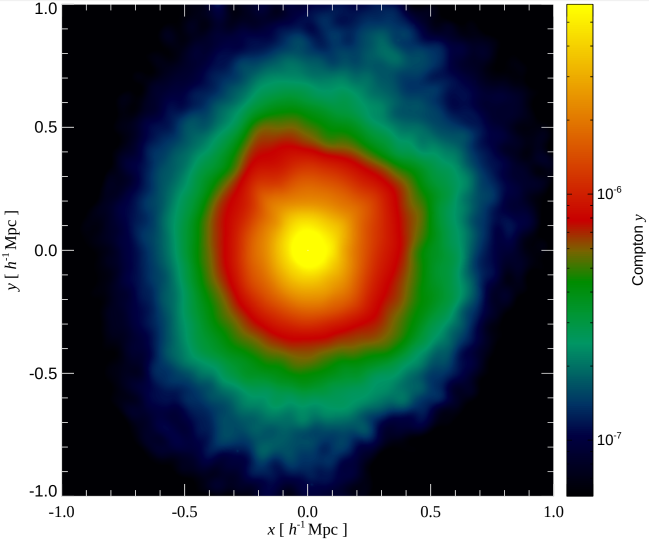
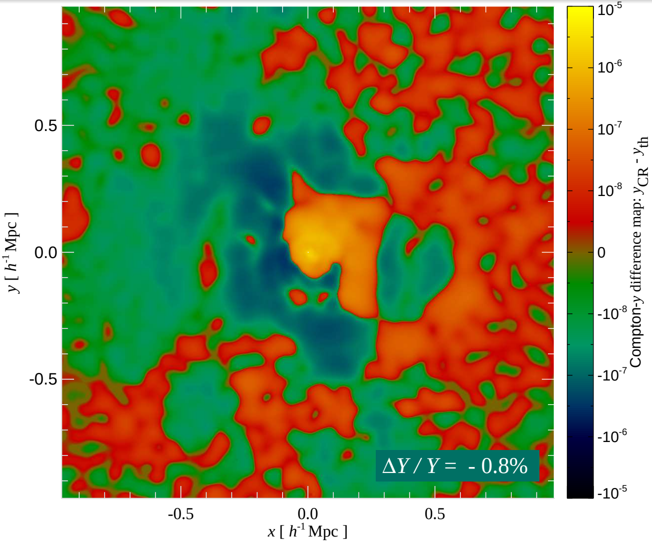
Softer effective adiabatic index of composite gas



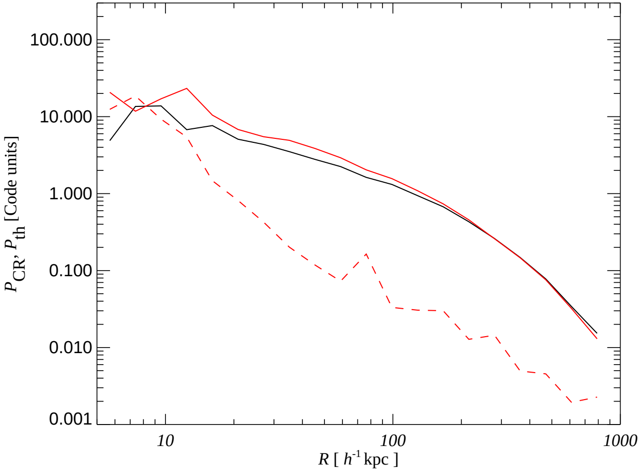
Compton y parameter in radiative cluster simulation



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



Pressure profiles with and without CRs



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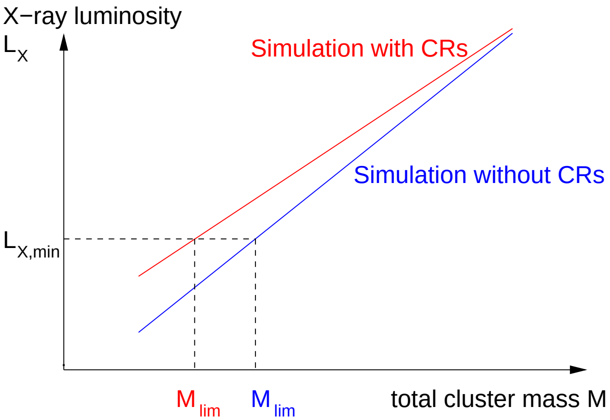
Modified X-ray scaling relations



→ 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 Ω_{m} $\rightarrow$ degeneracies of cosmological parameters with respect to cluster physics.

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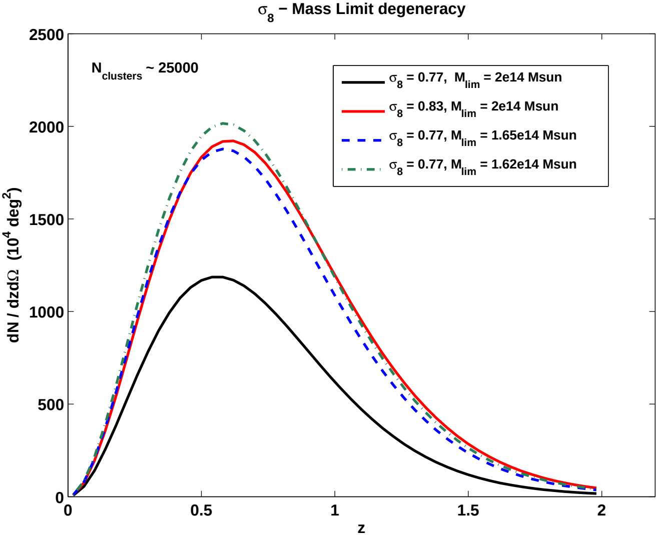
Degeneracies of the cluster redshift distribution (2)



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Fisher matrix analysis (1)

Survey Fisher matrix information for a data set:

$$F_{ij} \equiv -\left\langle \frac{\partial^2 \ln \mathcal{L}}{\partial p_i \, \partial p_j} \right\rangle = \sum_n \frac{\partial N_n}{\partial p_i} \frac{\partial N_n}{\partial p_j} \frac{1}{N_n},$$

where $\mathcal{L}$ is the likelihood for an observable (proportional to $\mathrm{d}N/\mathrm{d}z$ for the redshift distribution), p_i describes our parameter set, the sum extends over the redshift bins, and N_n represents the number of surveyed clusters in each redshift bin n (statistically independent, Poisson distributed).

The inverse F_{ij}^{-1} describes the best attainable covariance matrix $[C_{ij}]$ (assuming Gaussianity) for measurement of the parameters considered. The diagonal terms of $[C_{ij}]$ then give the uncertainties of each of our parameters.

Fisher matrix analysis (2)

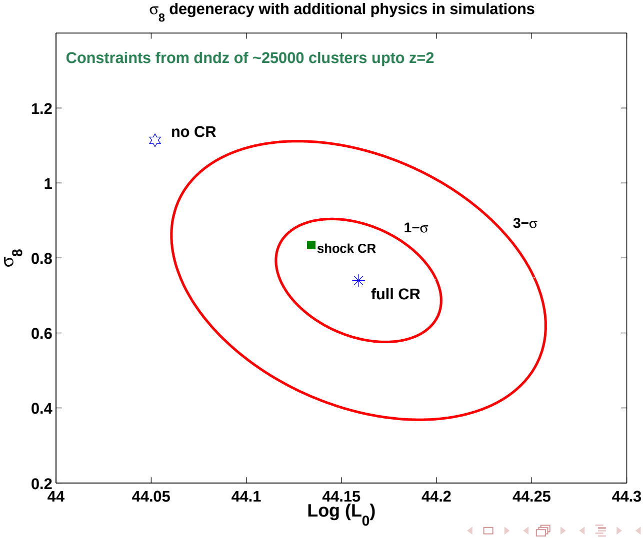
Assumed survey details:

- survey area $A = 10^4$ square degrees ($1/4$ of the sky)
- redshift range: $0 < z < 2$
- bolometric X-ray flux limit $F_X = 2.5 \times 10^{-13}$ 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 $h = 72 \pm 5$

Degeneracy of σ_8 with cosmic ray physics (preliminary)



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.
- Cosmological parameters such as σ_8 and Ω_m as derived from clusters are degenerate with cluster parameters.
- Understanding non-thermal processes is crucial for using clusters as cosmological probes (high-z scaling relations).

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