Title: Cosmic Rays and Cluster Cosmology - A Critical Review

Date: Nov 10, 2006 02:30 PM

URL: http://pirsa.org/06110050

Abstract:

Outline

1. Introduction to galaxy clusters
   - Properties of galaxy clusters
   - Physical processes in simulations
   - Cosmic ray physics
2. Cosmic rays in cosmological simulations
   - Cosmic ray acceleration
   - Radiative high-resolution cluster simulations
   - Modified X-ray emission and Sunyaev-Zel'dovich effect
3. Cosmological implications of cosmic rays
   - Modified X-ray scaling relations
   - Fisher matrix analysis
   - Degeneracies of cosmological parameters

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

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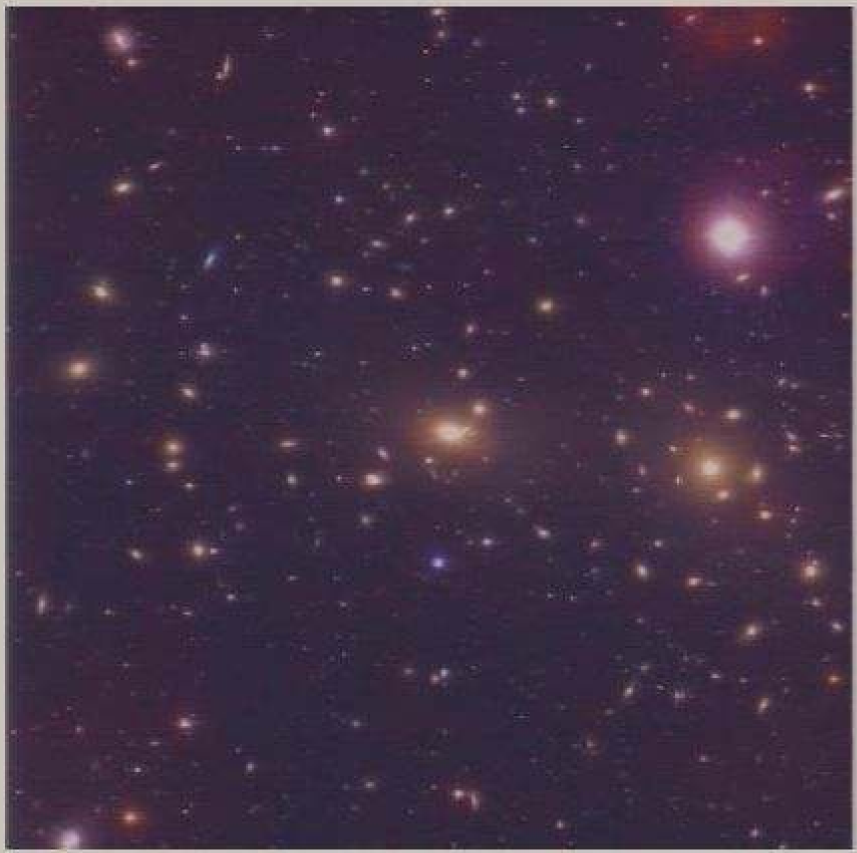
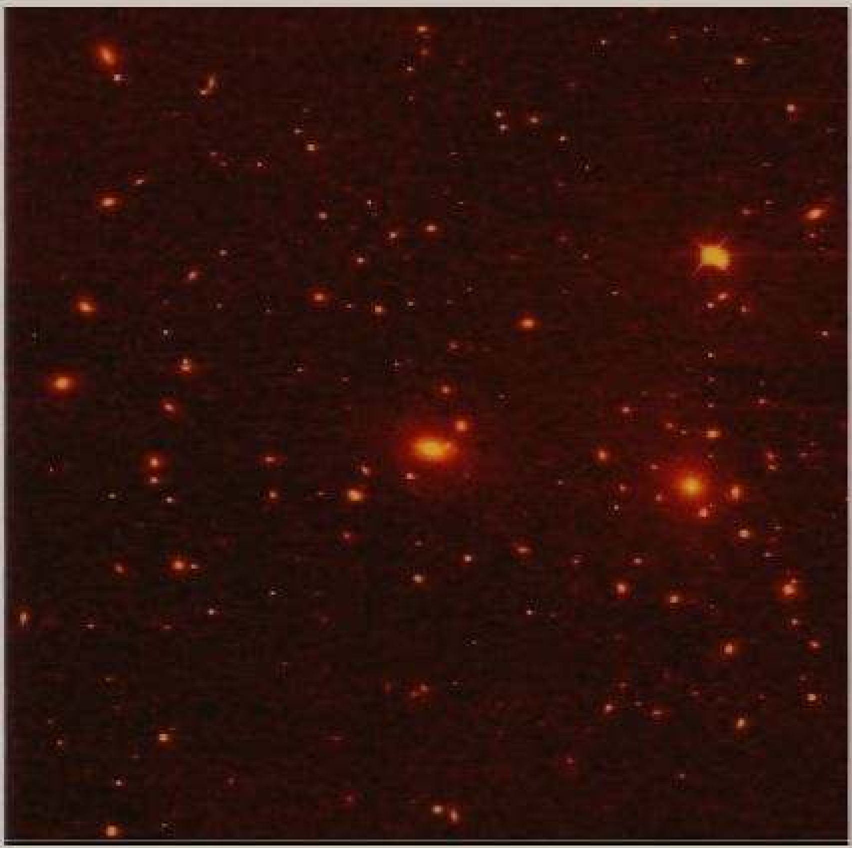
Coma cluster: member galaxies



optical emission,

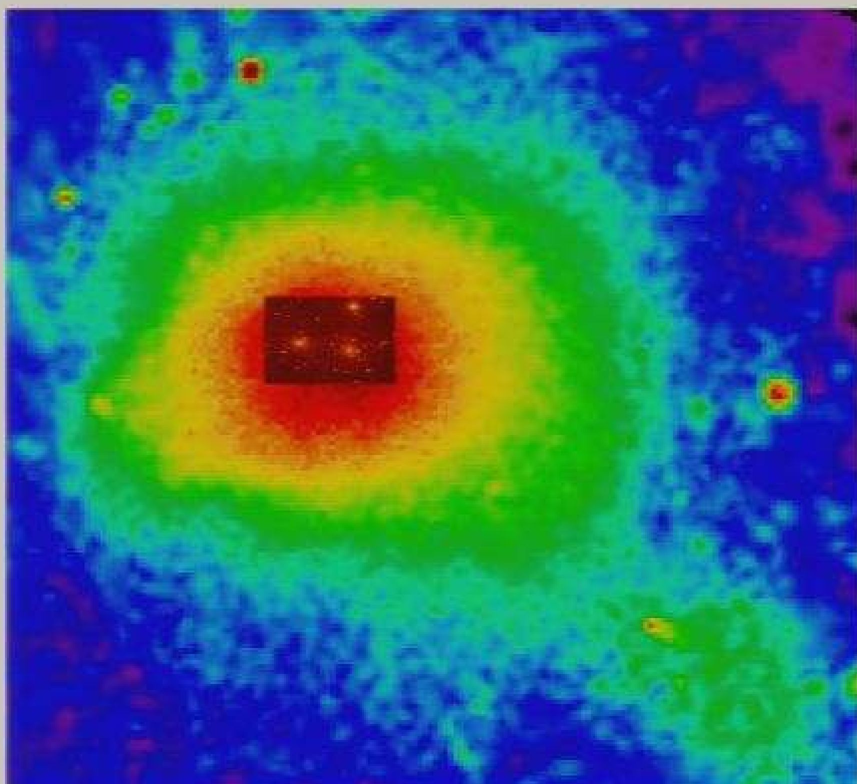
(credit: Kitt Peak)



infra-red emission,

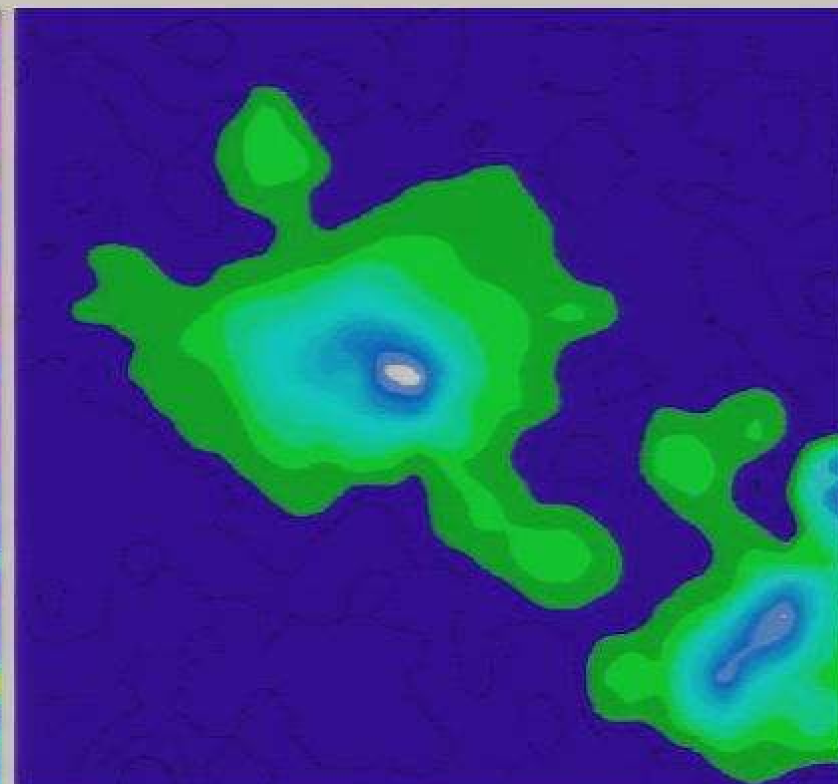
(credit: ISO)

Coma cluster: (non-)thermal plasma



thermal X-ray emission,

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



radio synchrotron emission,

(credit: B.Deiss/Effelsberg)

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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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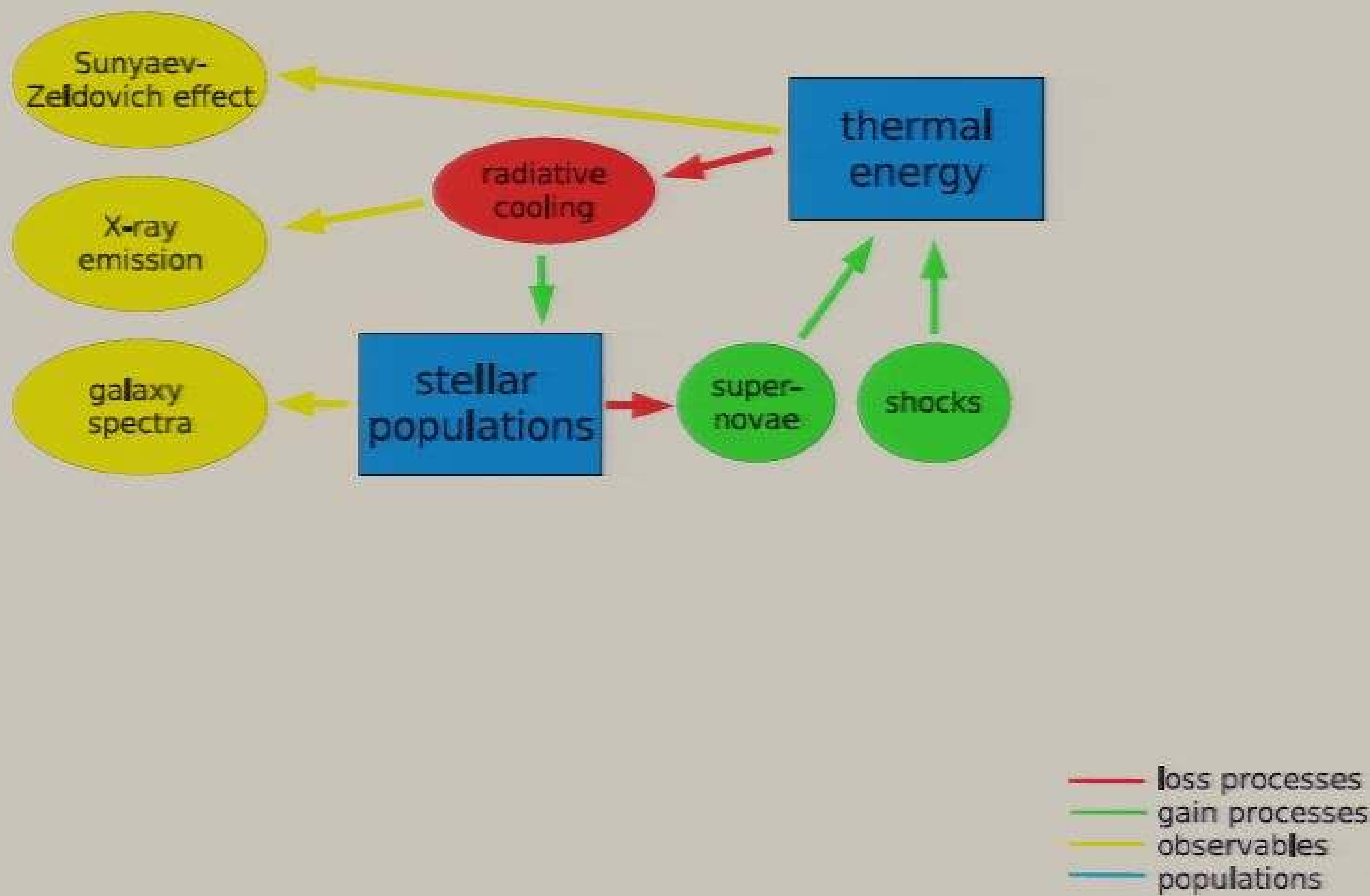
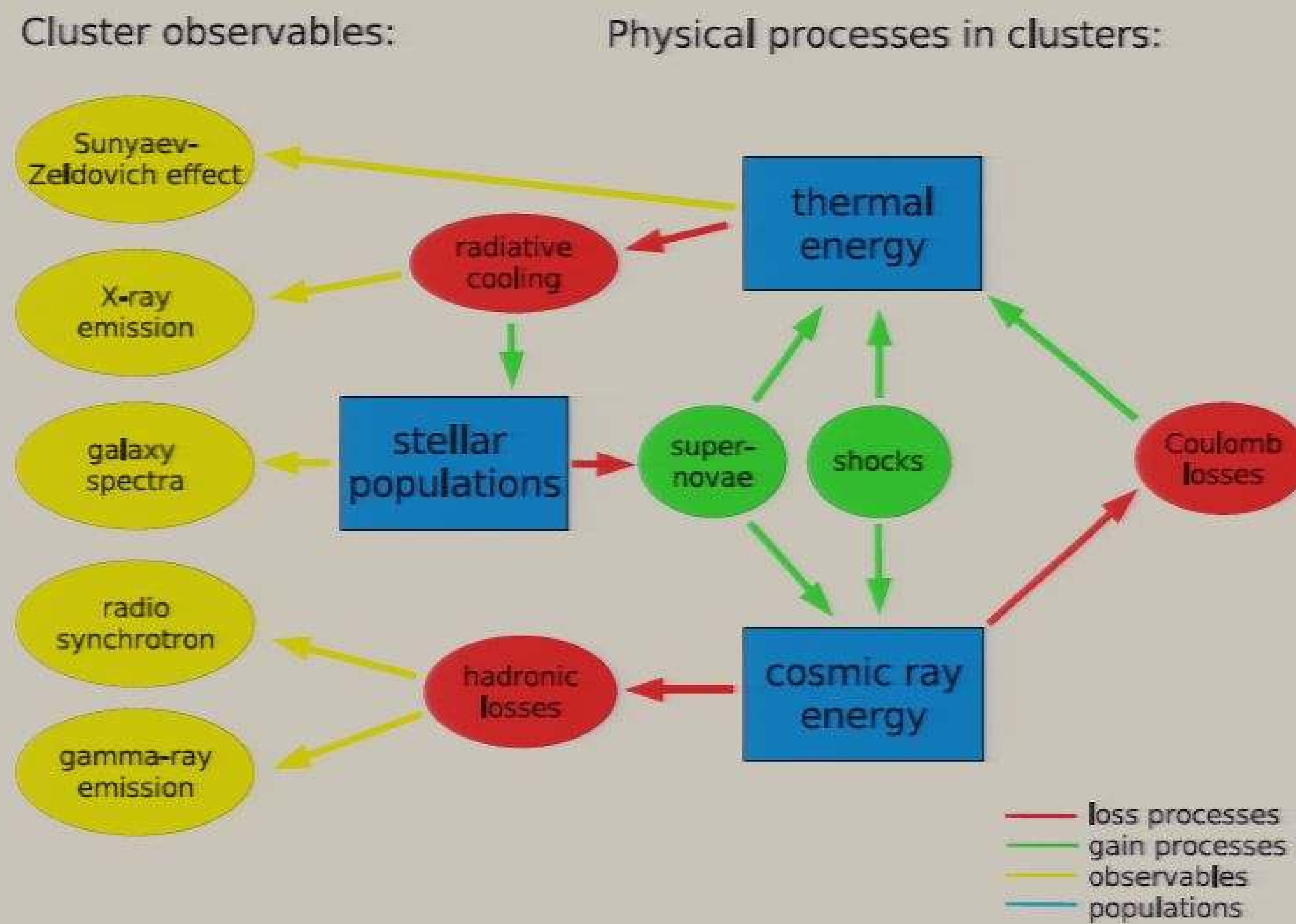
Radiative simulations – flowchart

Cluster observables: Physical processes in clusters:



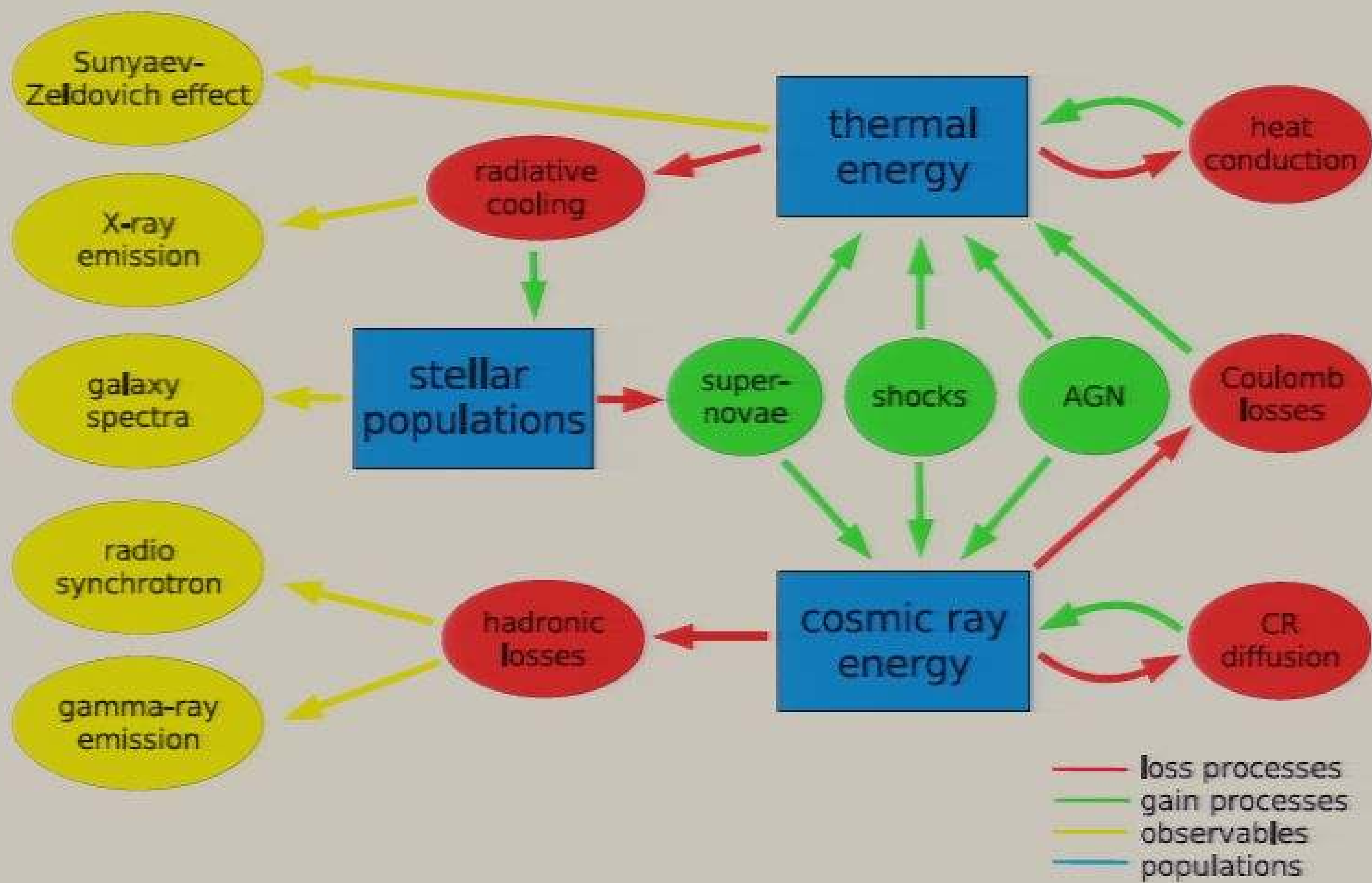
Radiative simulations with cosmic ray (CR) physics



Radiative simulations with extended CR physics

Cluster observables:

Physical processes in clusters:



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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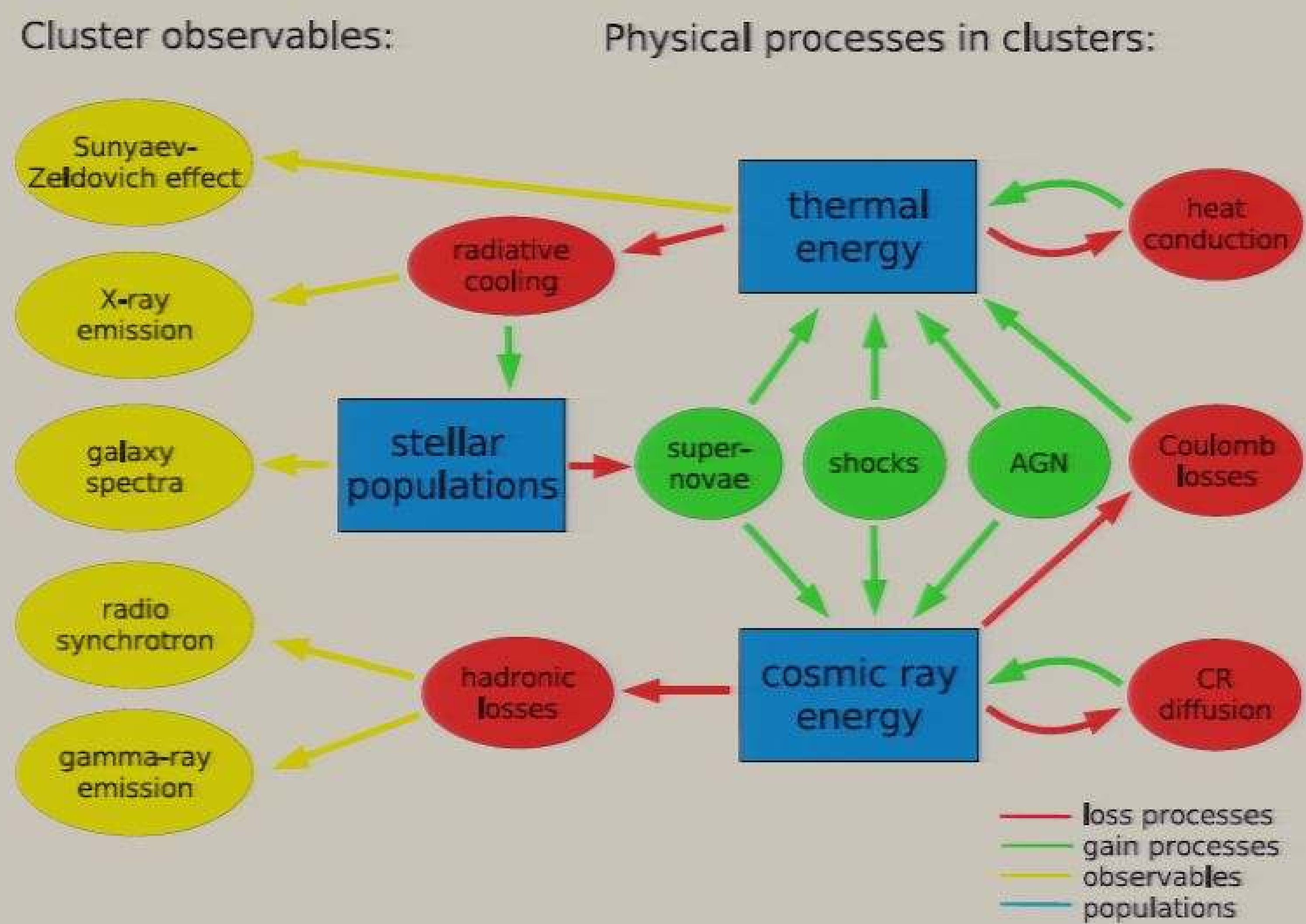
Radiative simulations with extended CR physics



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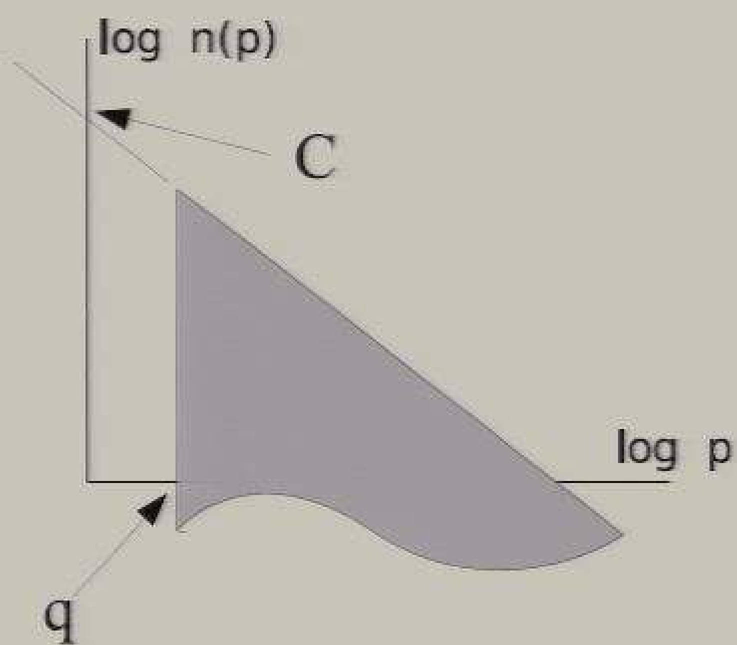
CR spectral description



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

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

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

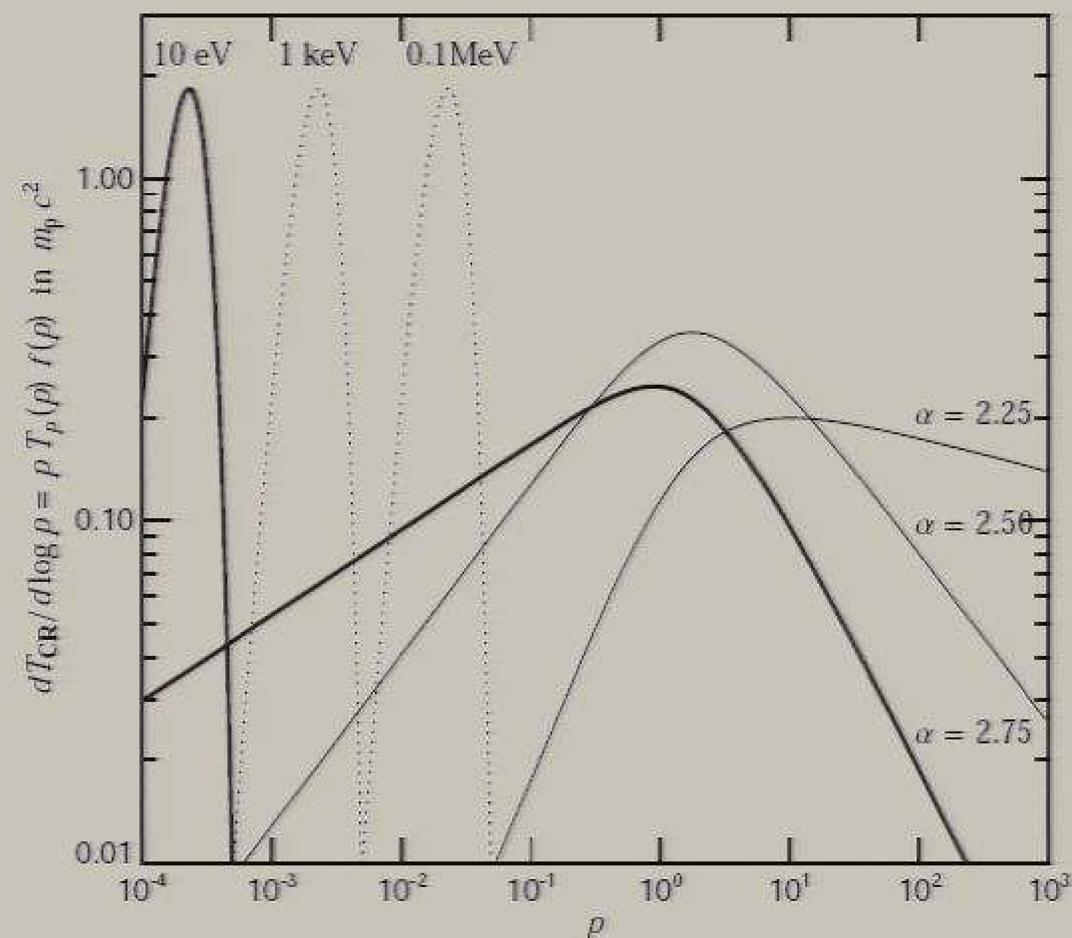
$$n_{\rm CR} = \frac{C\,q^{1-\alpha}}{\alpha-1}$$

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

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

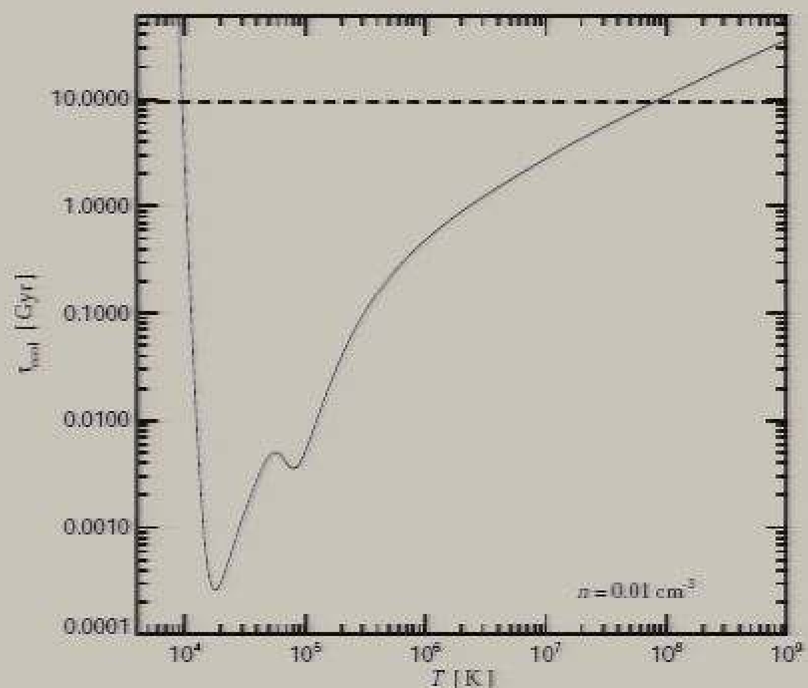
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:

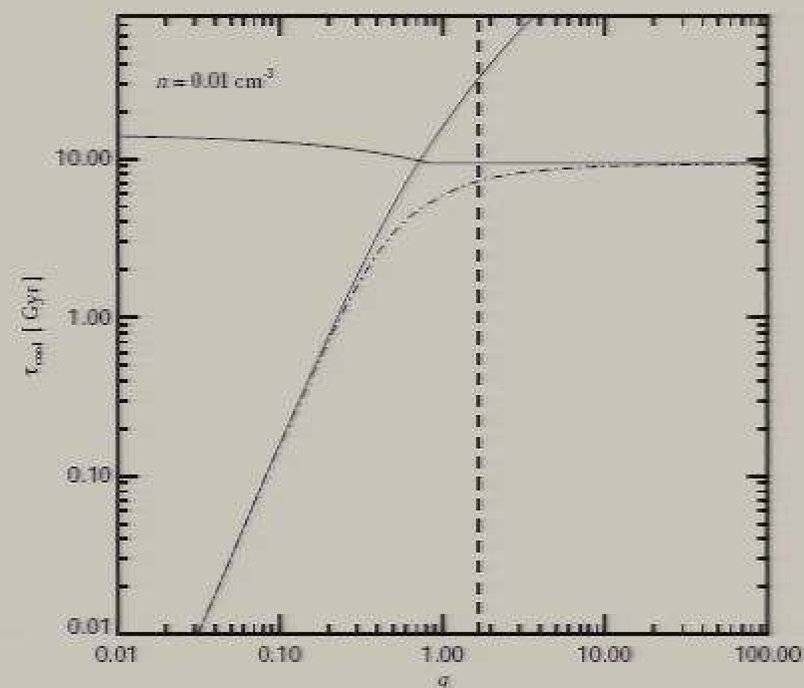


Radiative cooling

Cooling of primordial gas:



Cooling of cosmic rays:



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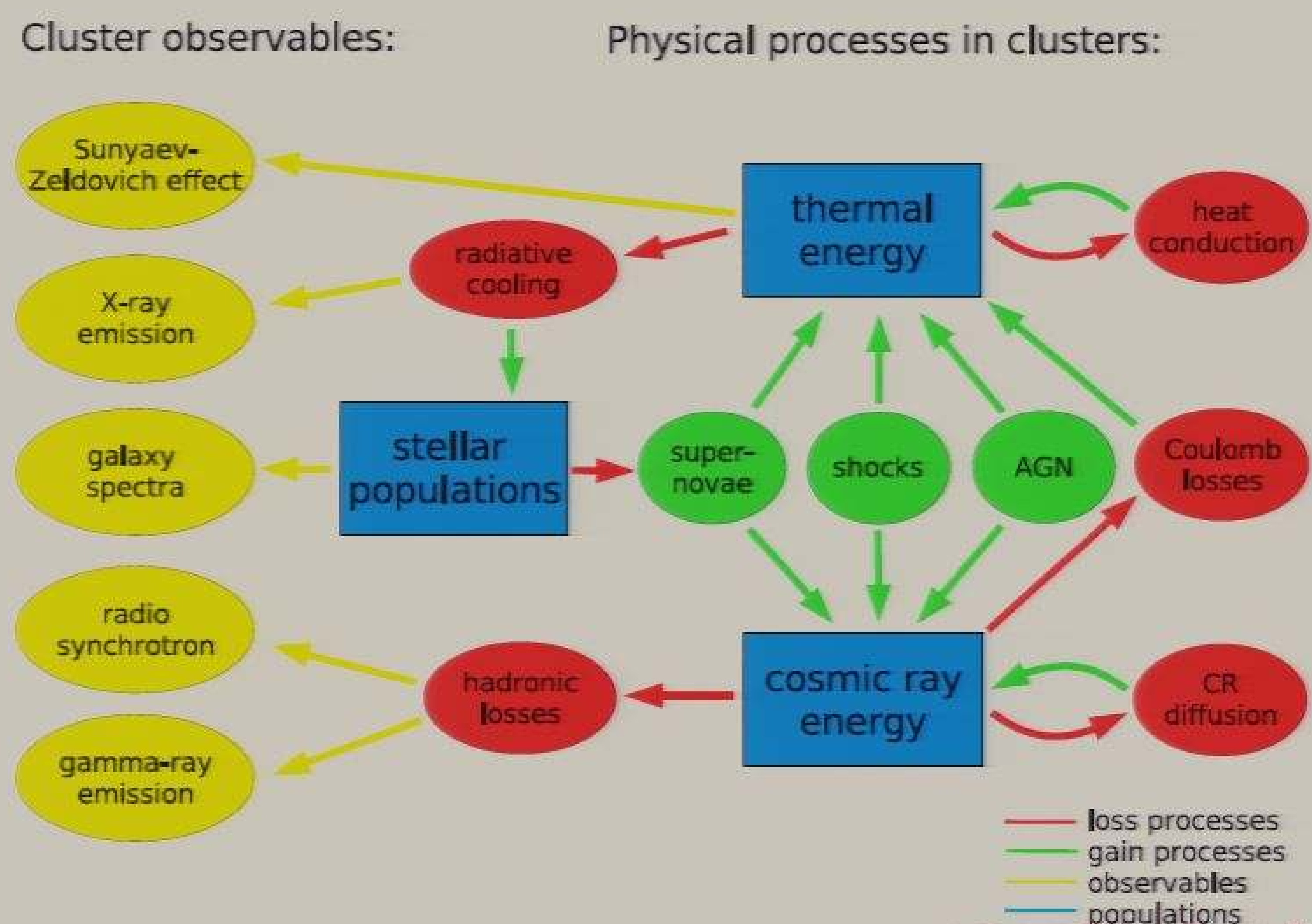
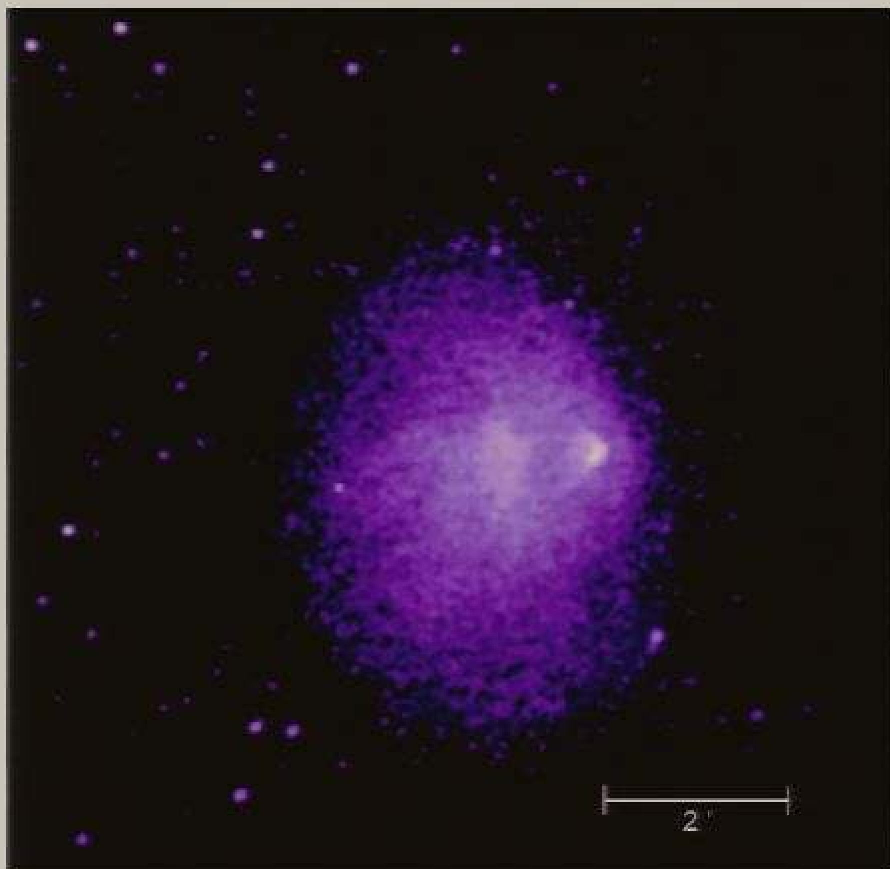
Cosmic rays in clusters – flowchart

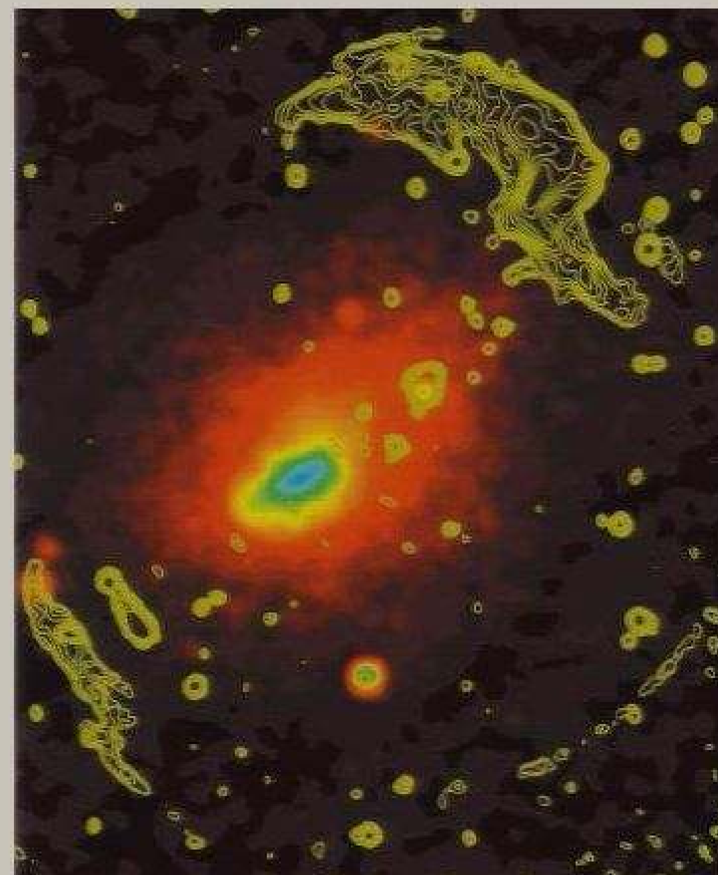


Observations of cluster shock waves



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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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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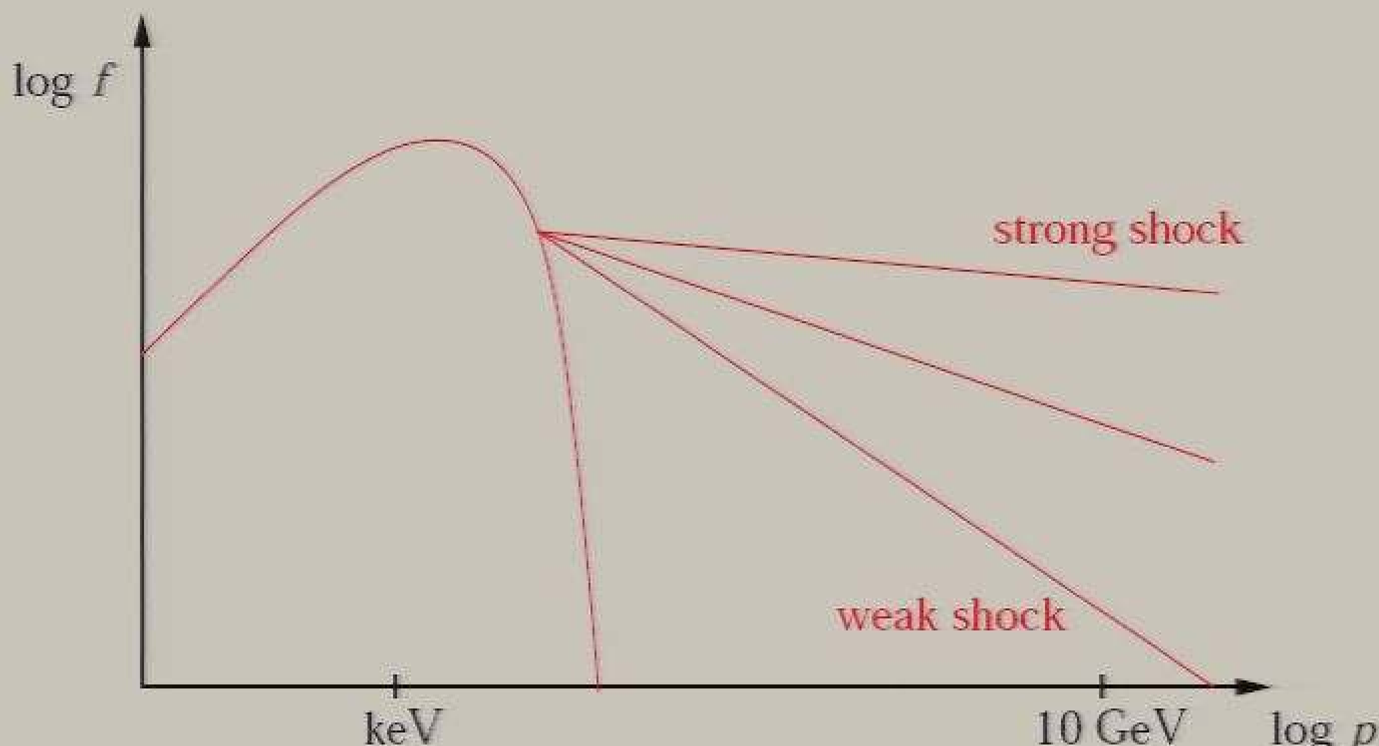
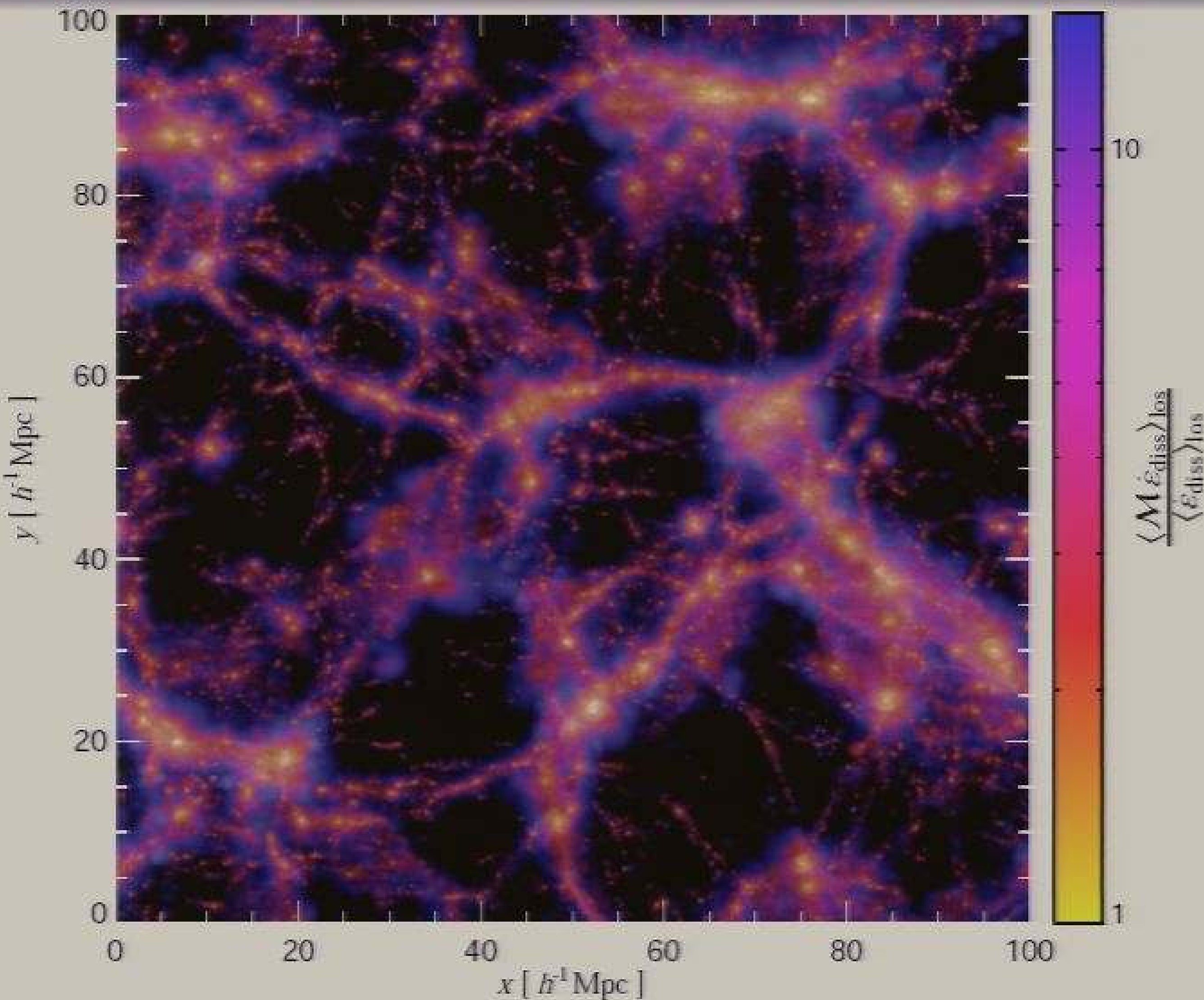
Diffusive shock acceleration – Fermi 1 mechanism (2)

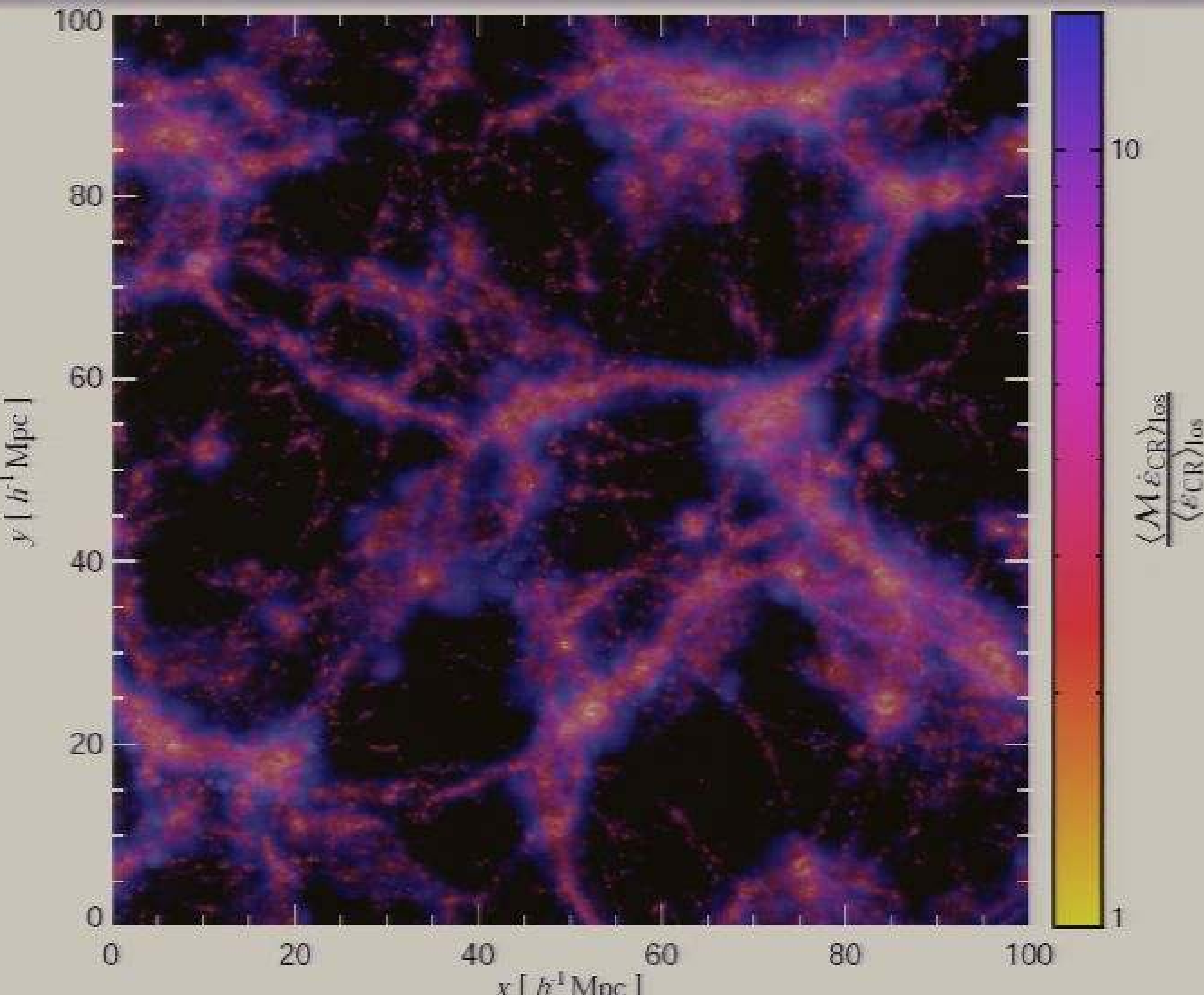
Spectral index depends on the Mach number of the shock, $\mathcal{M} = \upsilon_{\text{shock}}/c_{\text{s}}$:



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



Cosmological Mach numbers: weighted by ε_{CR}



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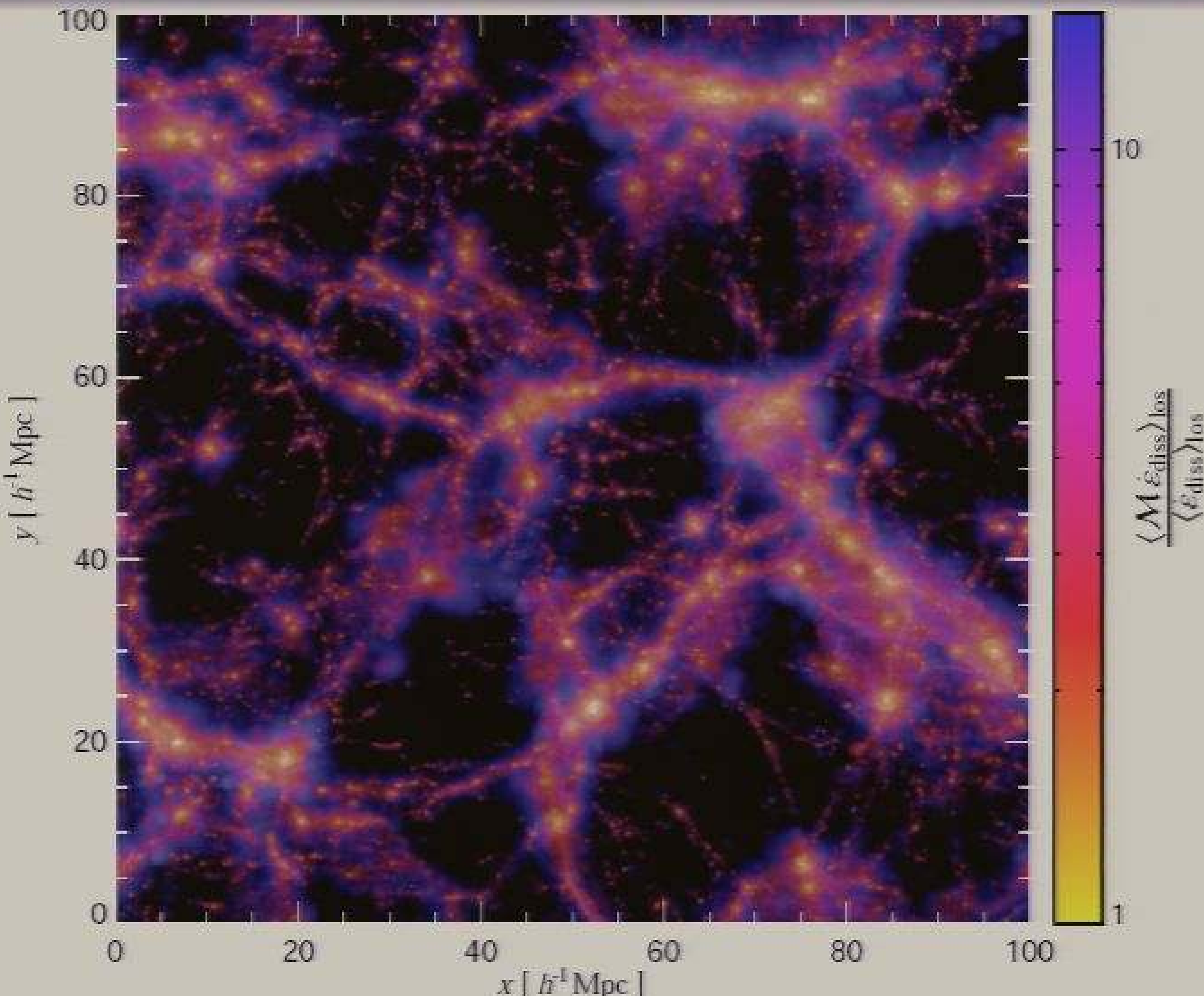

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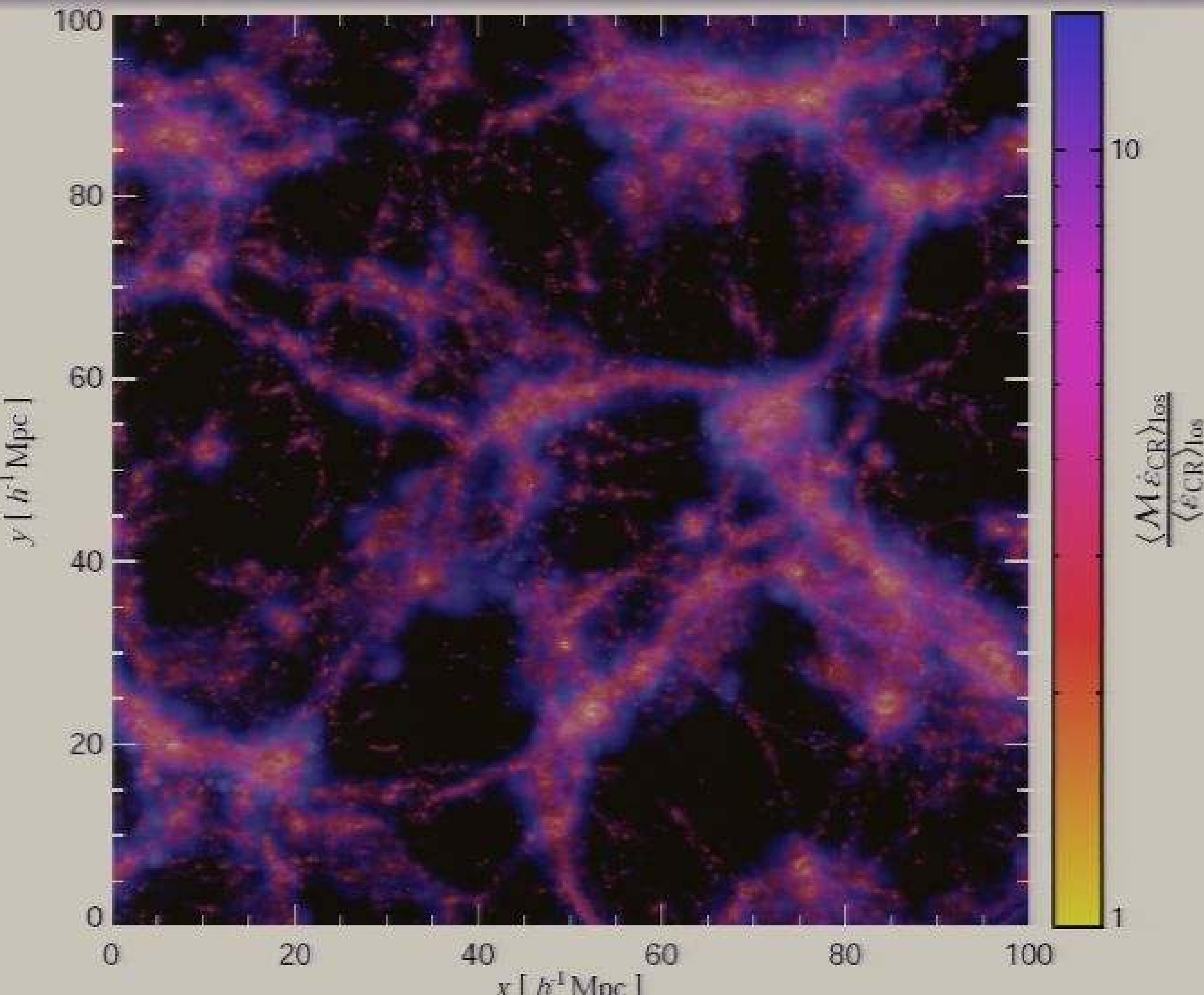

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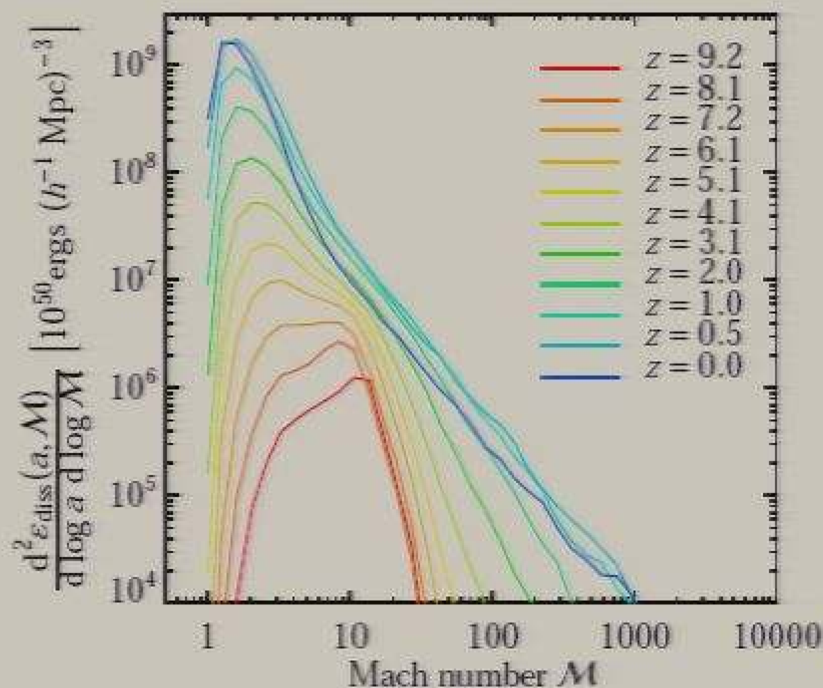
Cosmological Mach number statistics



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

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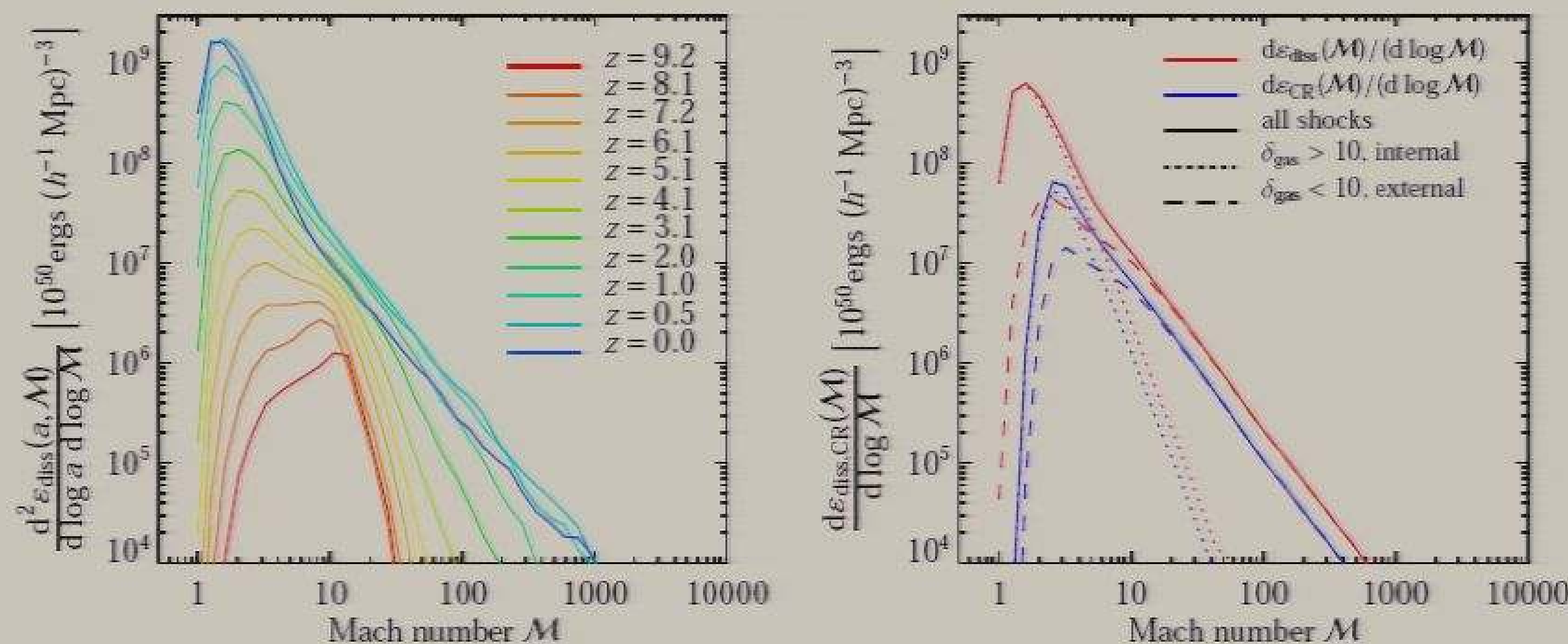
Cosmological statistics: CR acceleration



- 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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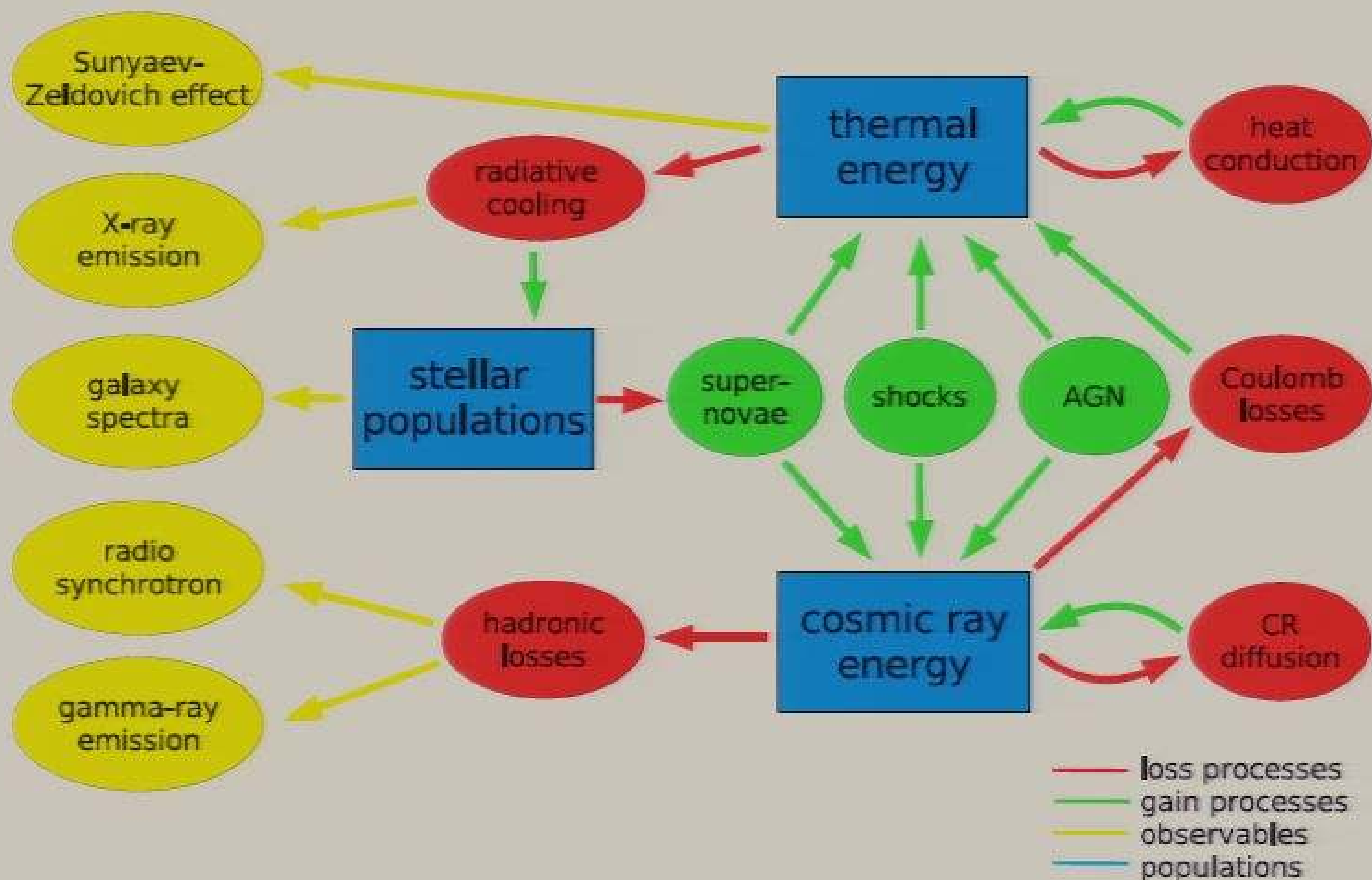
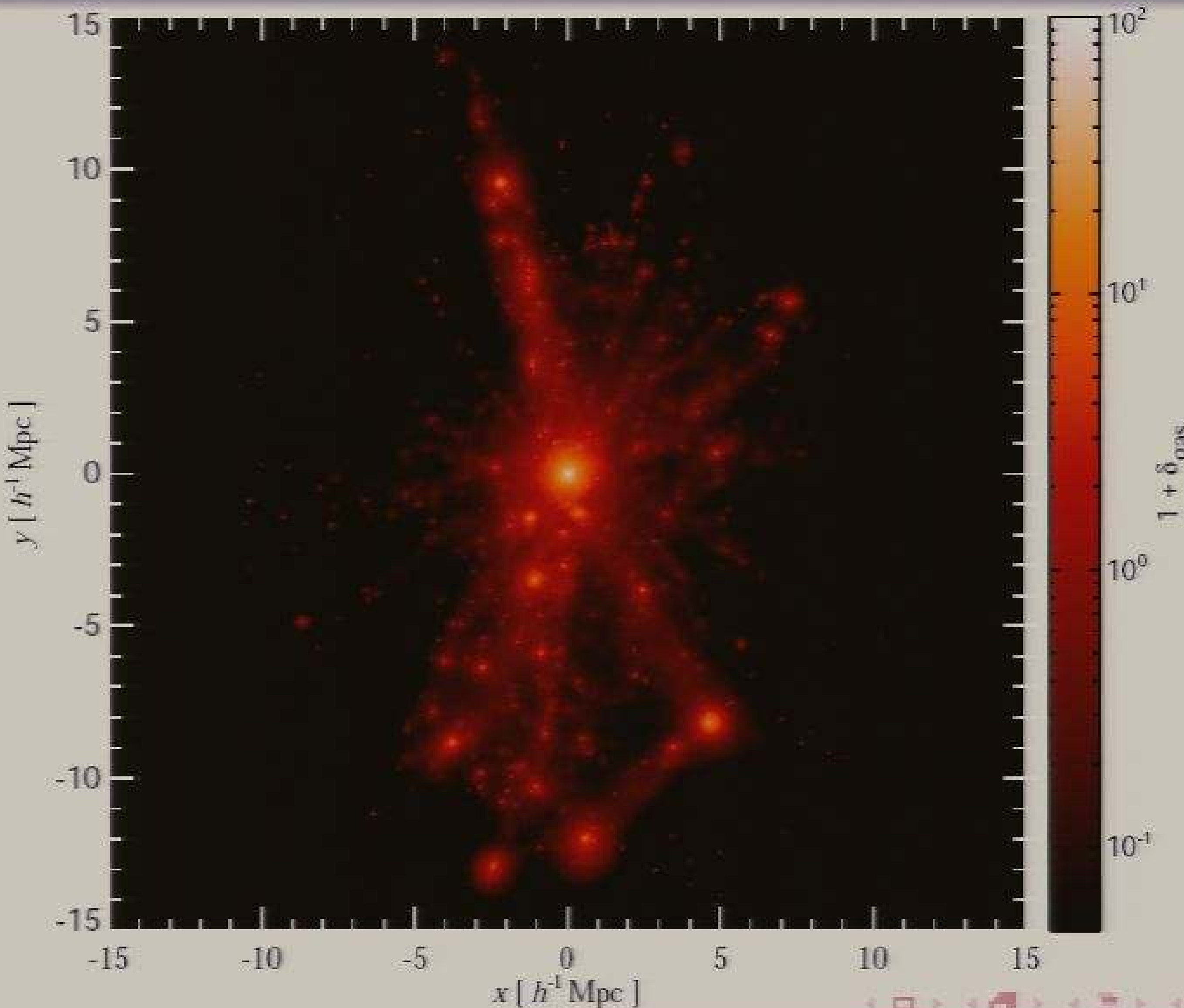
Radiative simulations with extended CR physics

Cluster observables: Physical processes in clusters:



Radiative cool core cluster simulation: gas density



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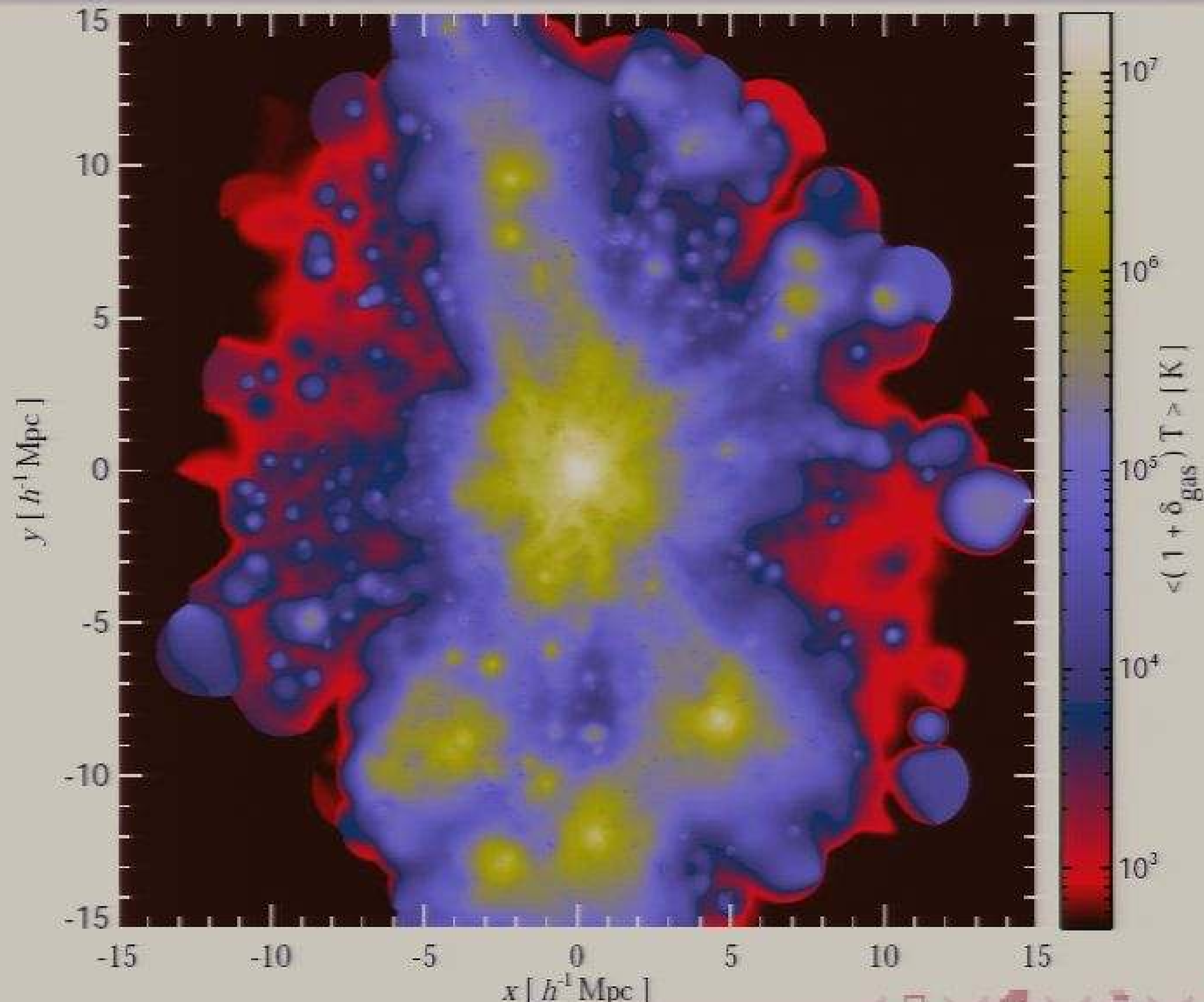
Mass weighted temperature



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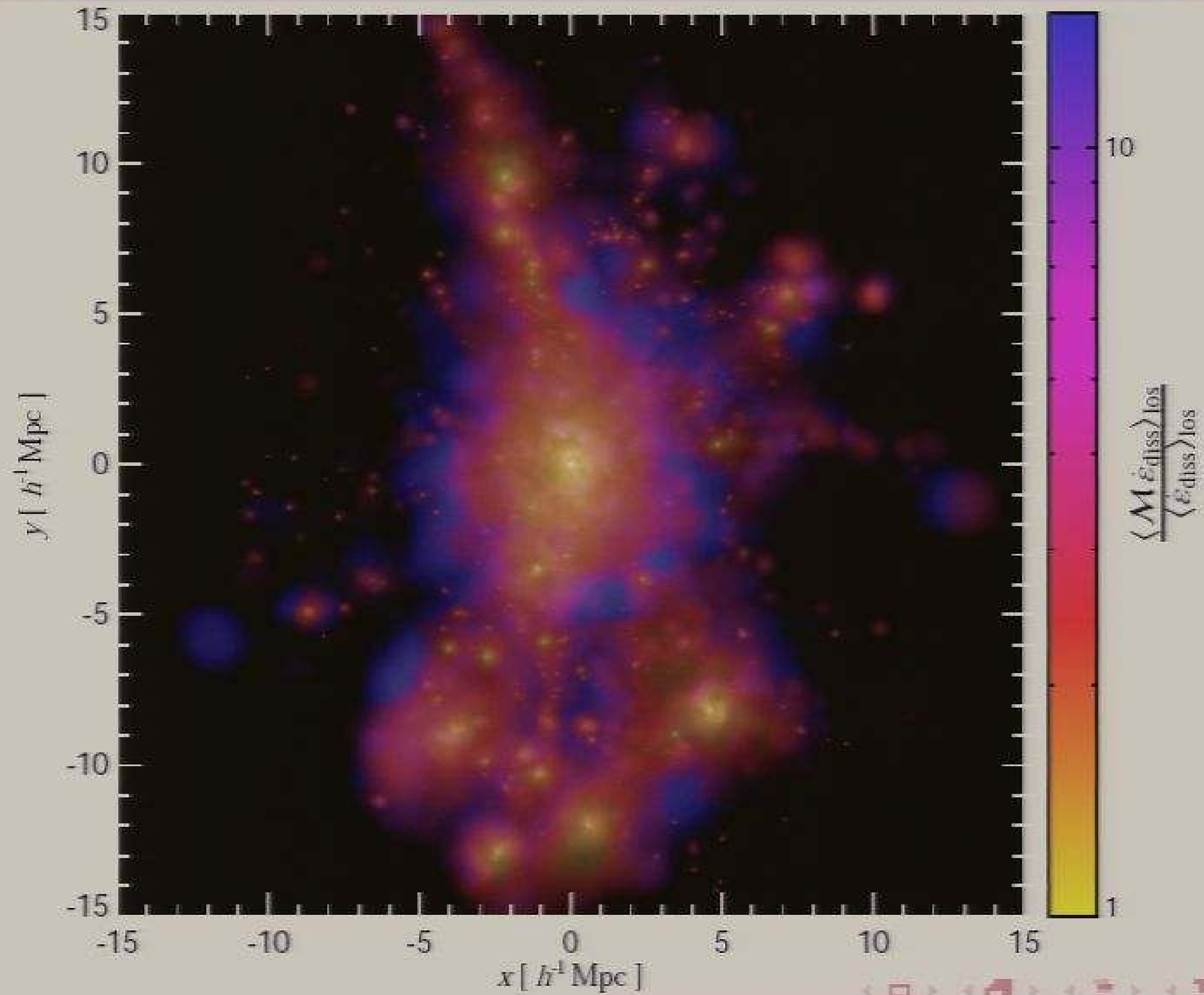
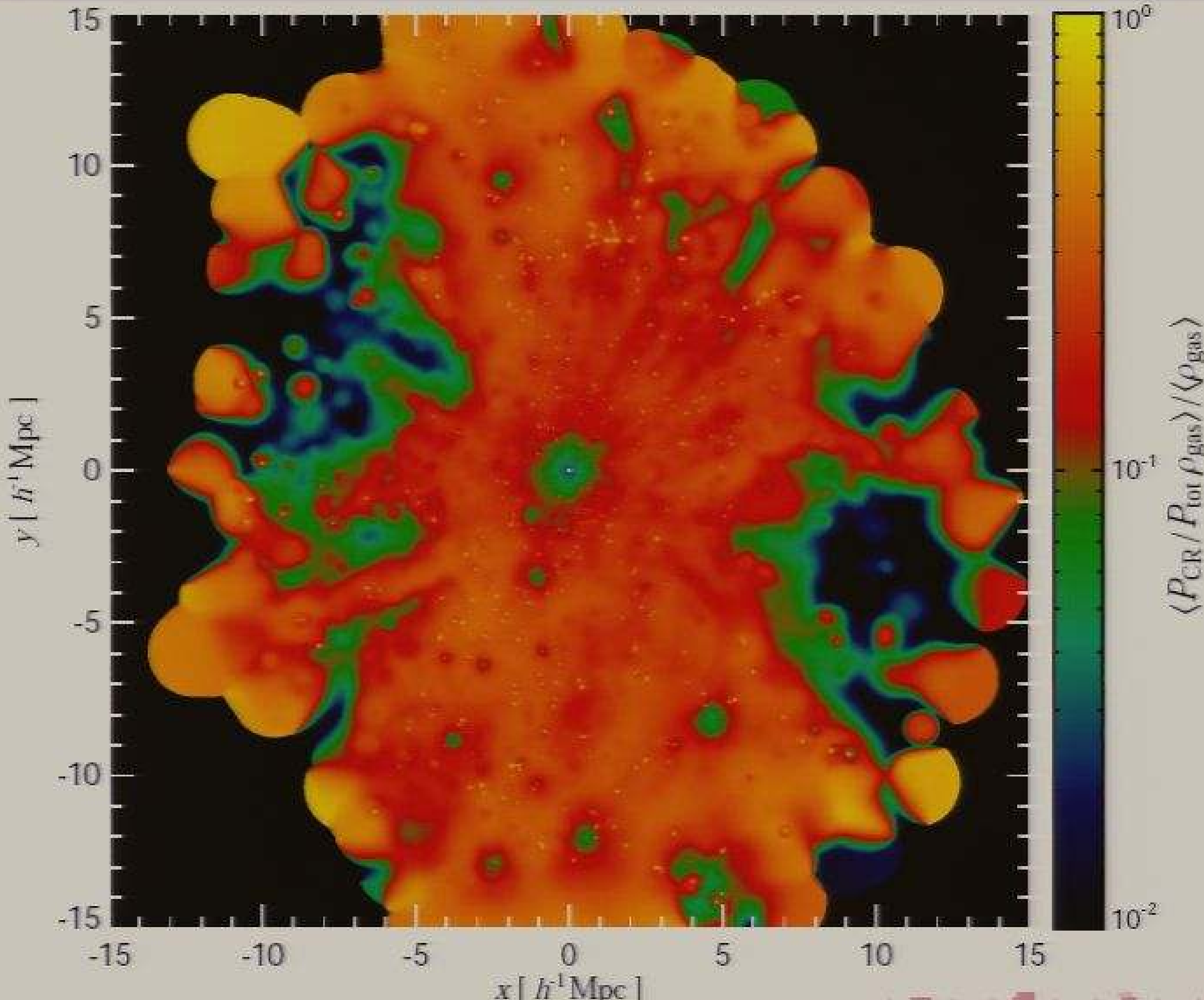
Mach number distribution weighted by $\varepsilon_{\rm diss}$



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



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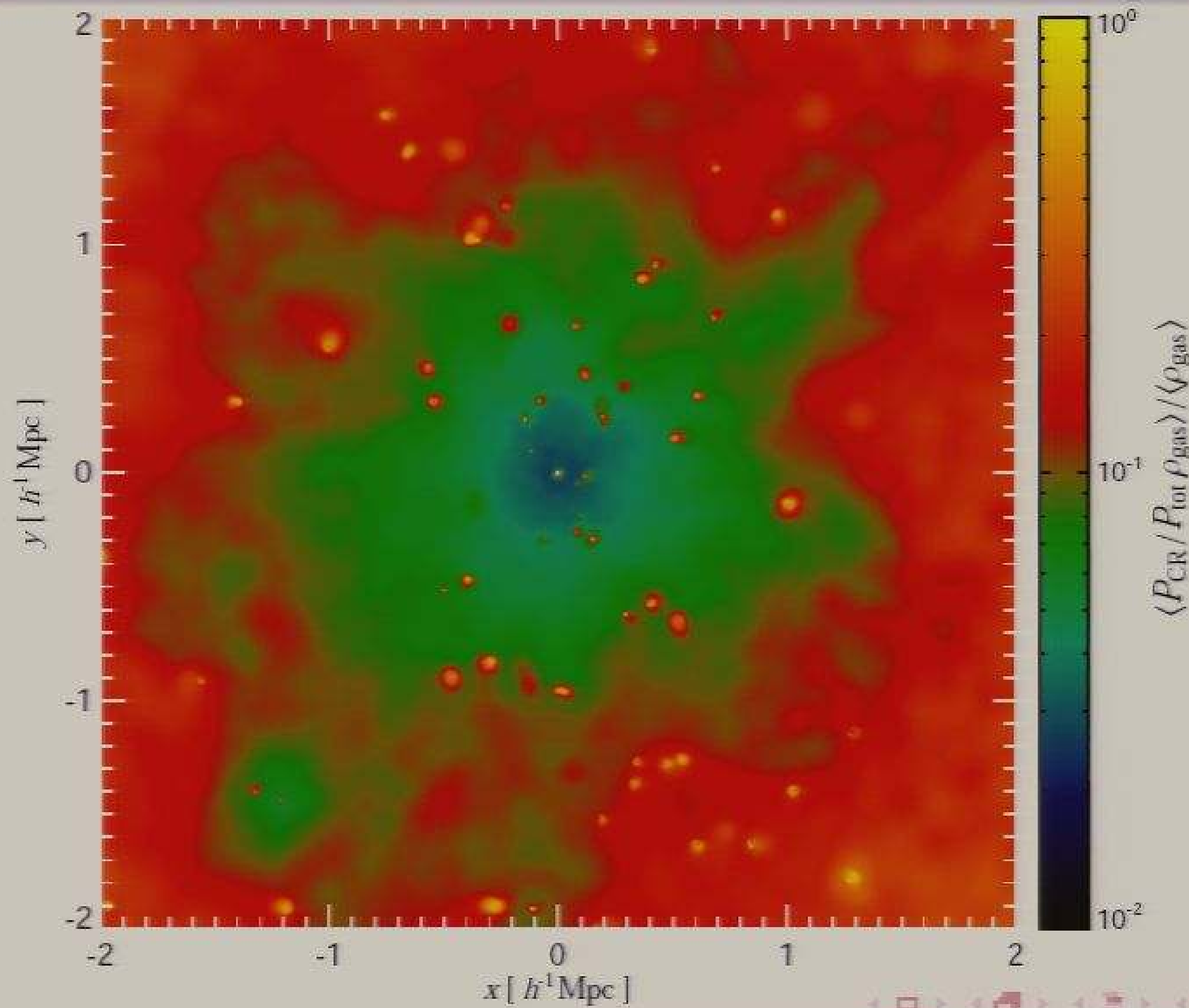
Relative CR pressure P_{CR}/P_{total}



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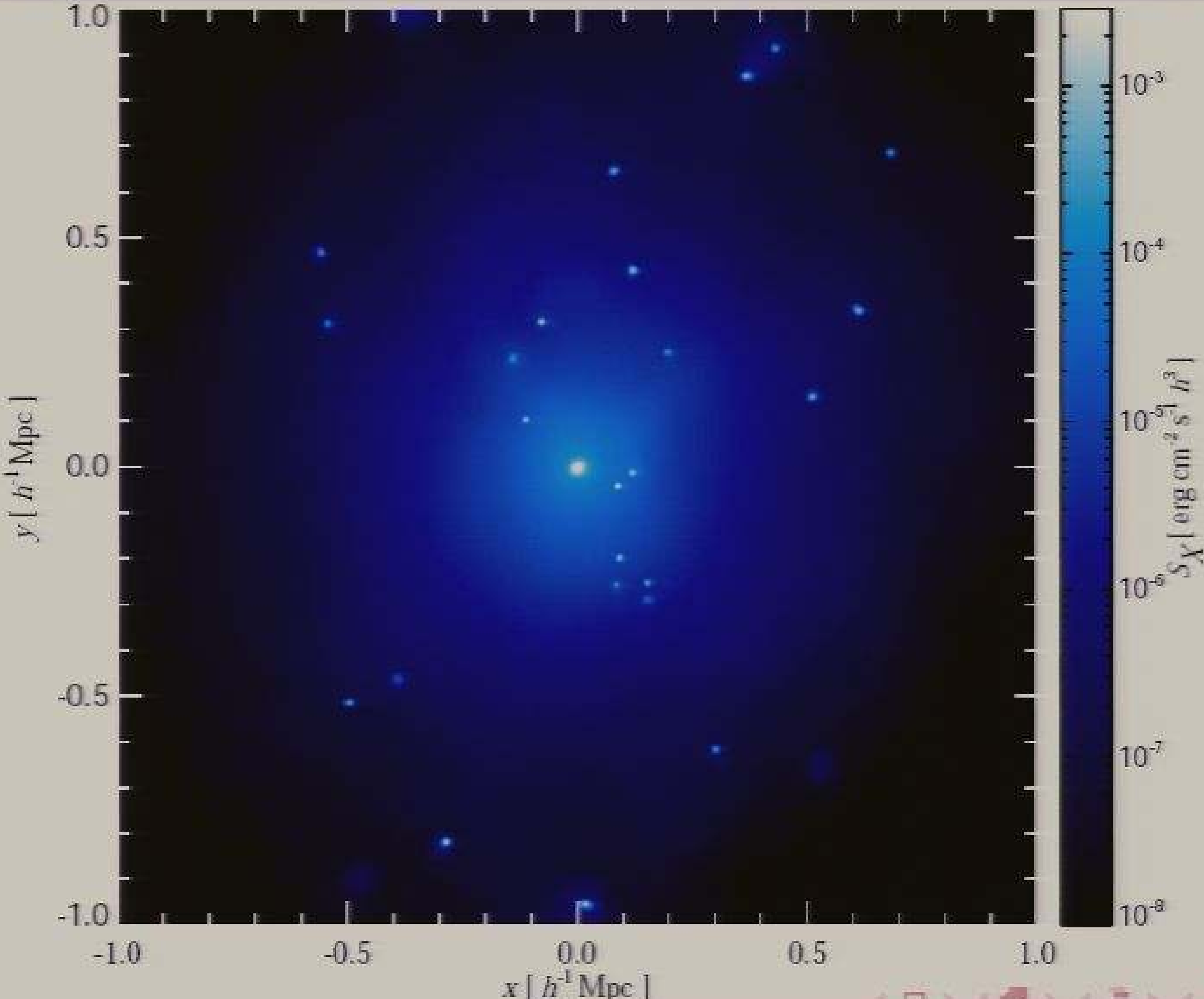
Thermal X-ray emission



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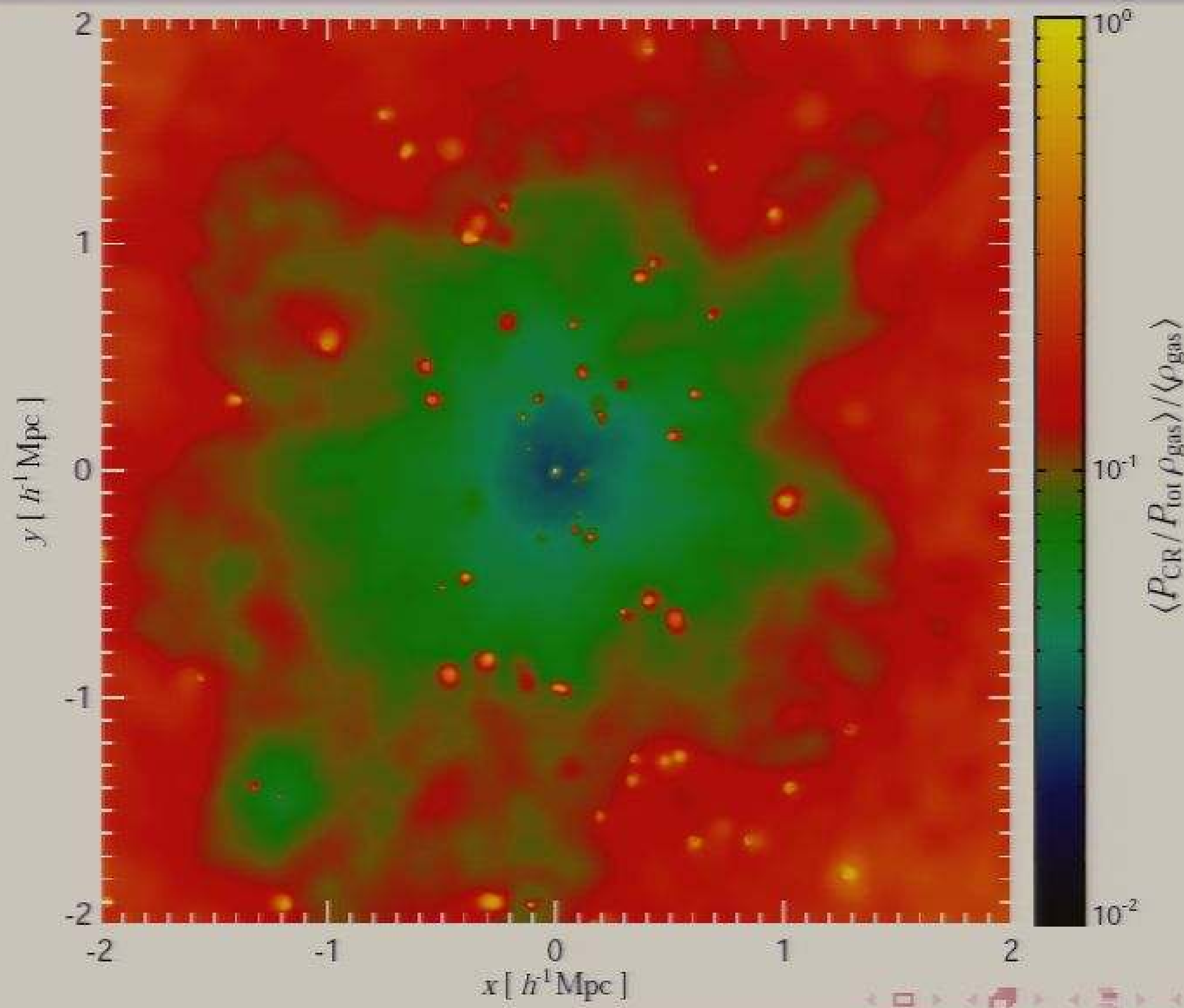

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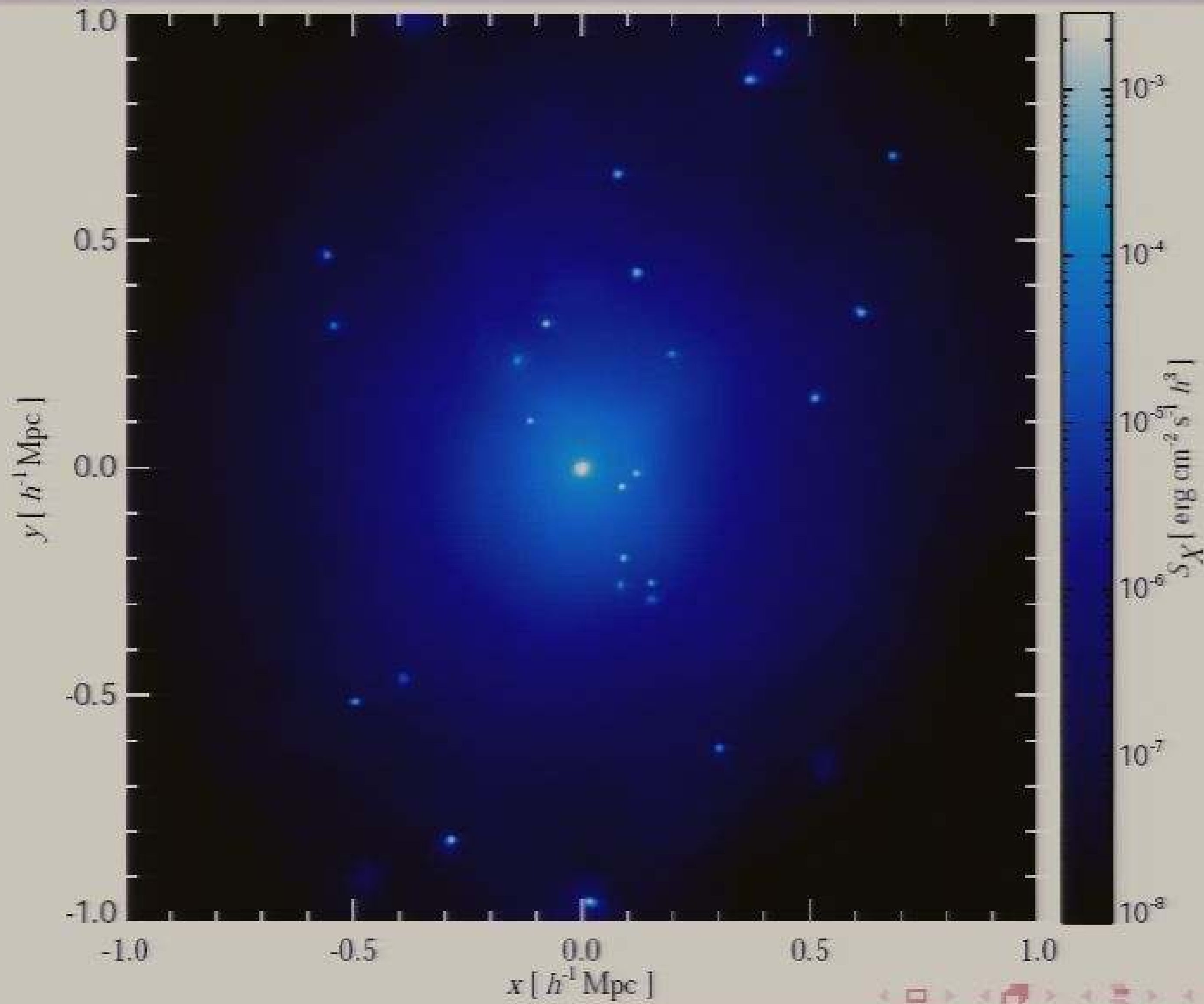
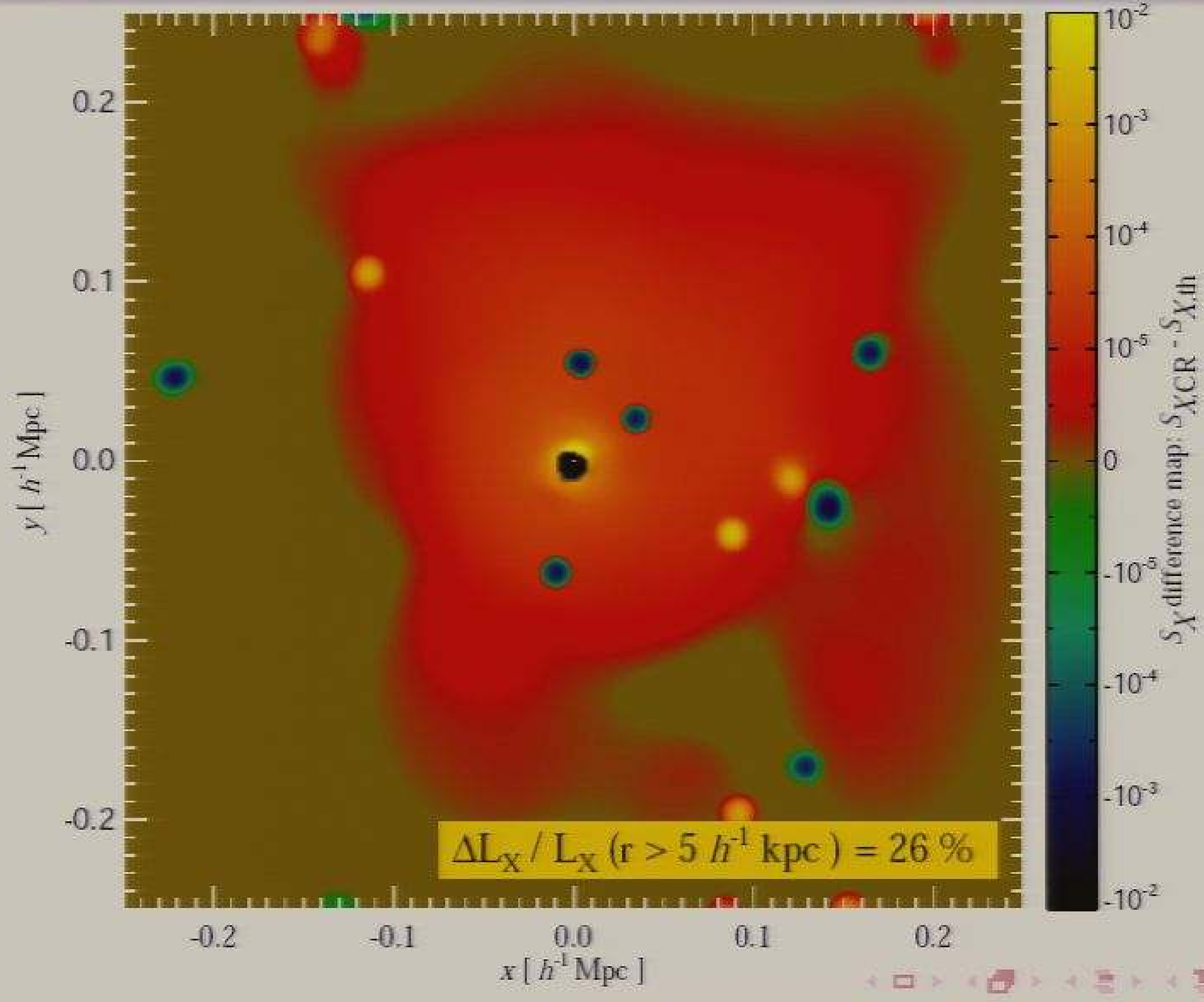


Difference map of S_X: $S_{X,CR} - S_{X,th}$



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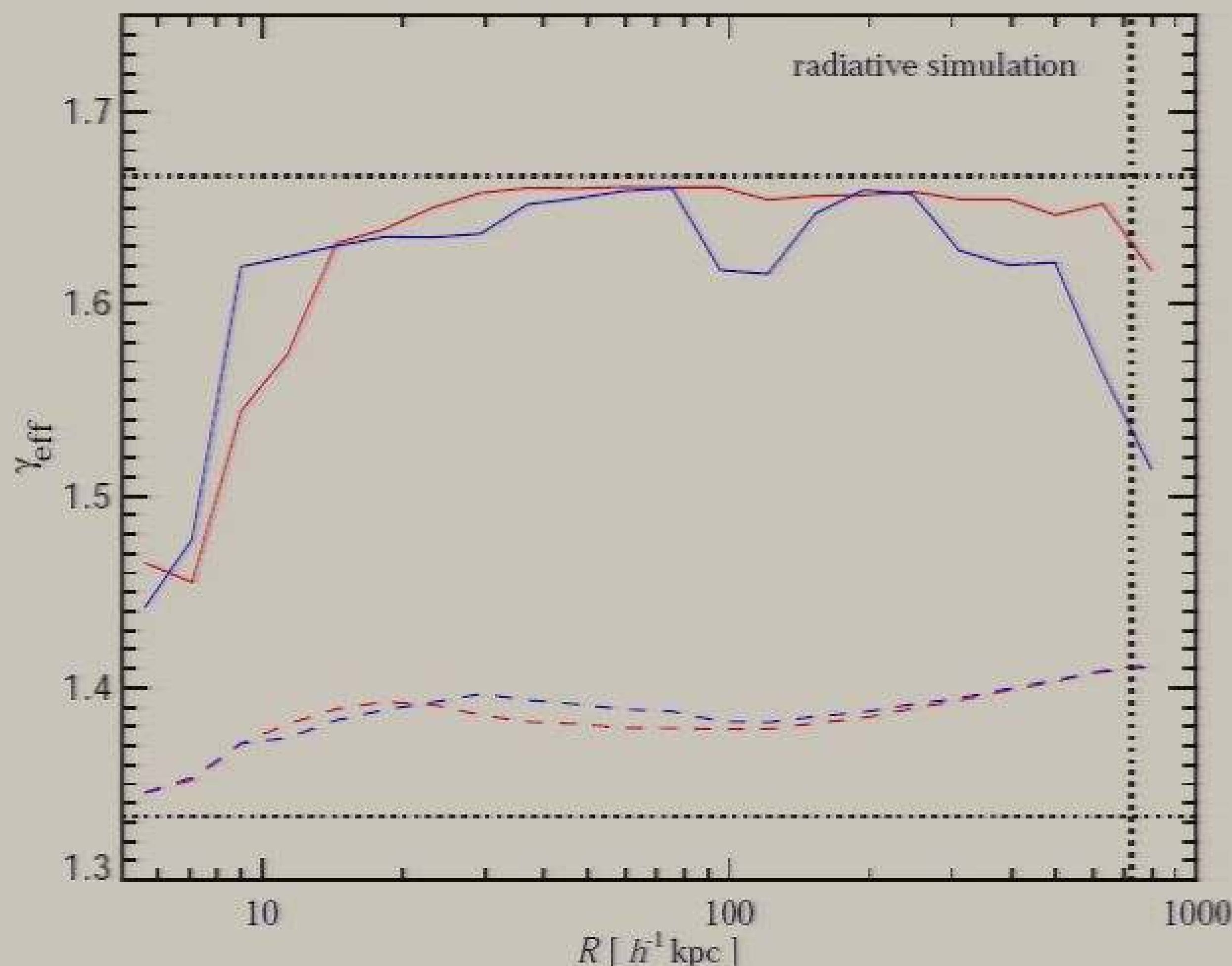
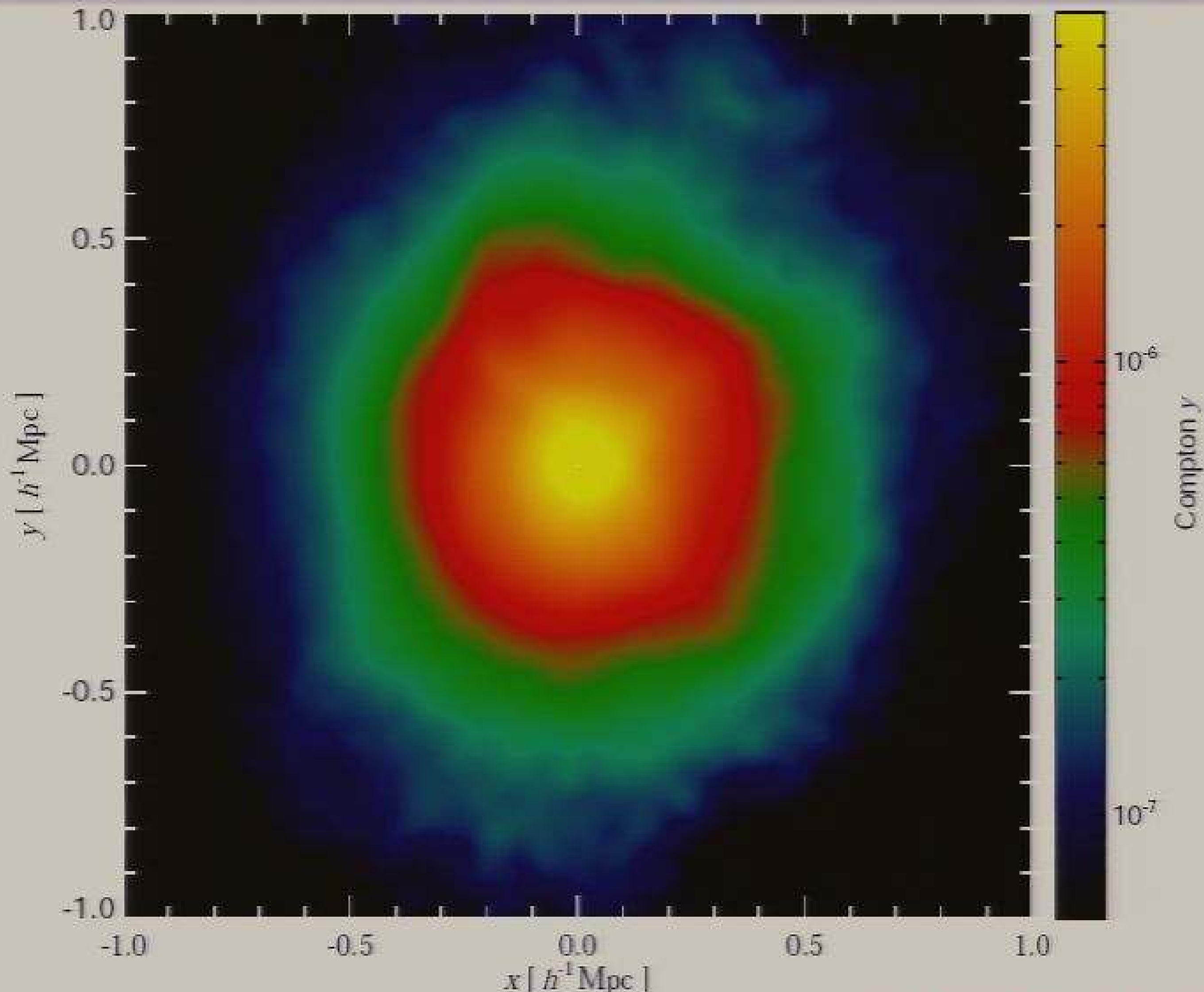
Softer effective adiabatic index of composite gas



Compton y parameter in radiative cluster simulation



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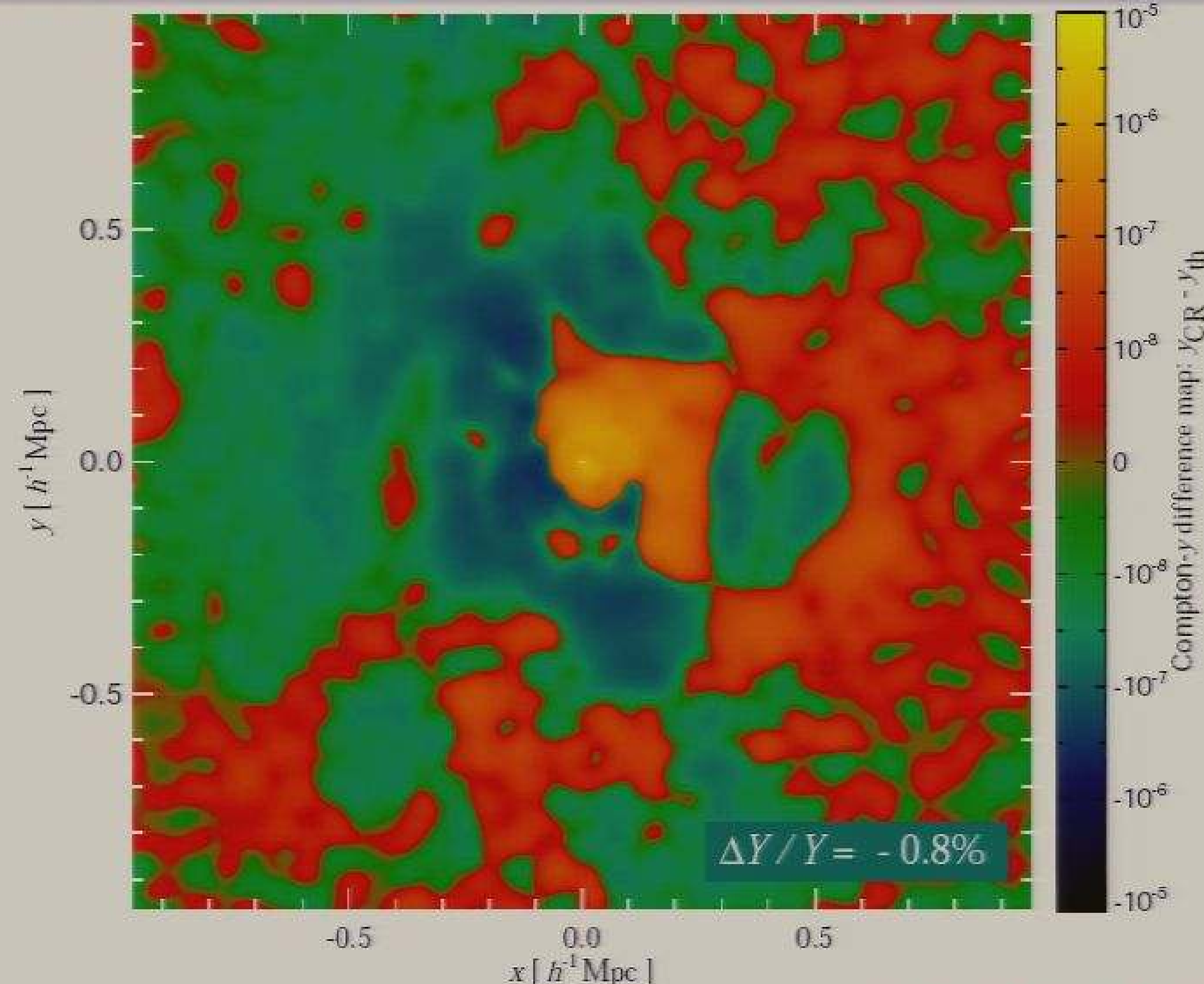
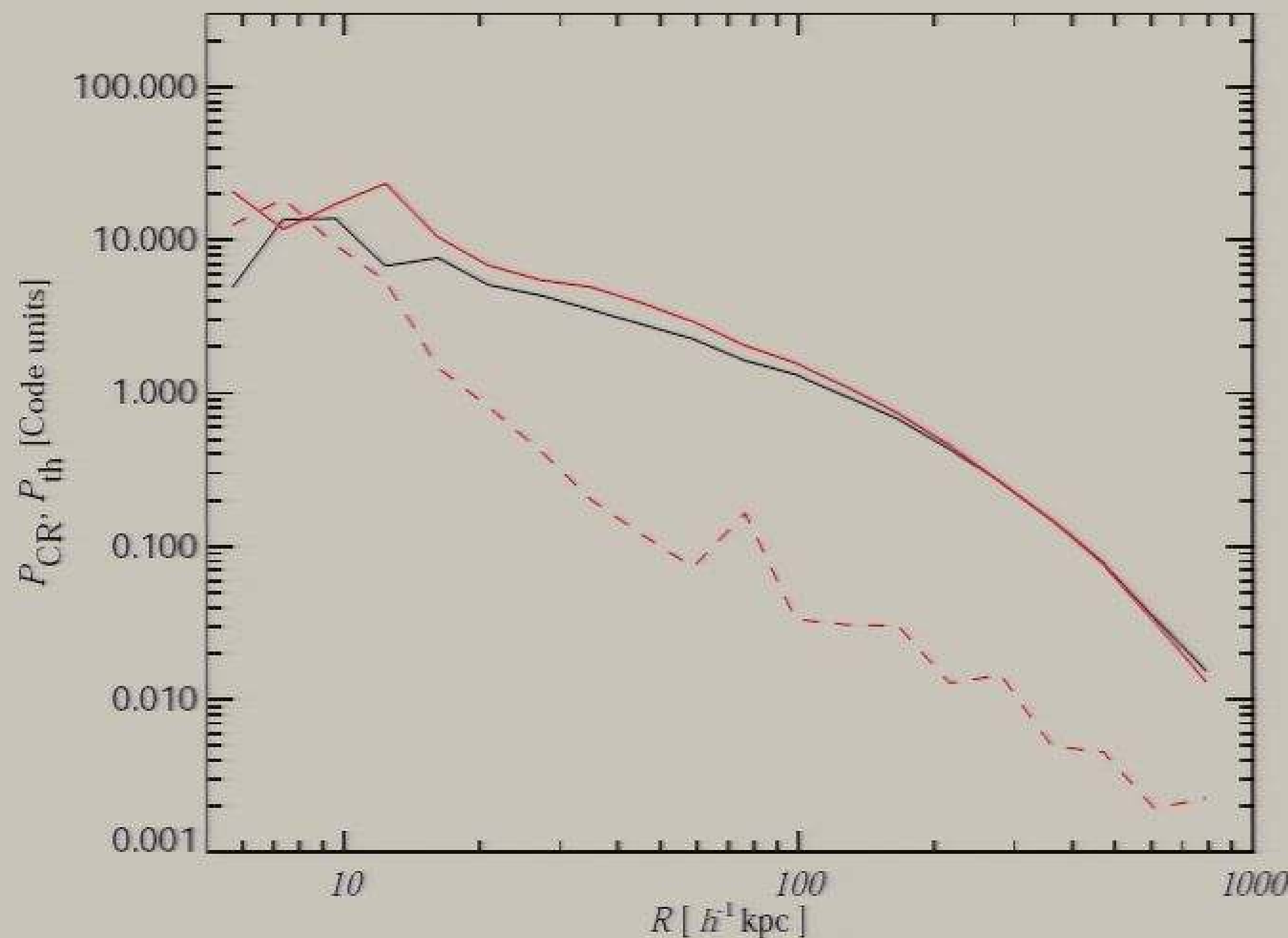
Compton y difference map: $y_{\mathrm{CR}} - y_{\mathrm{th}}$



Pressure profiles with and without CRs



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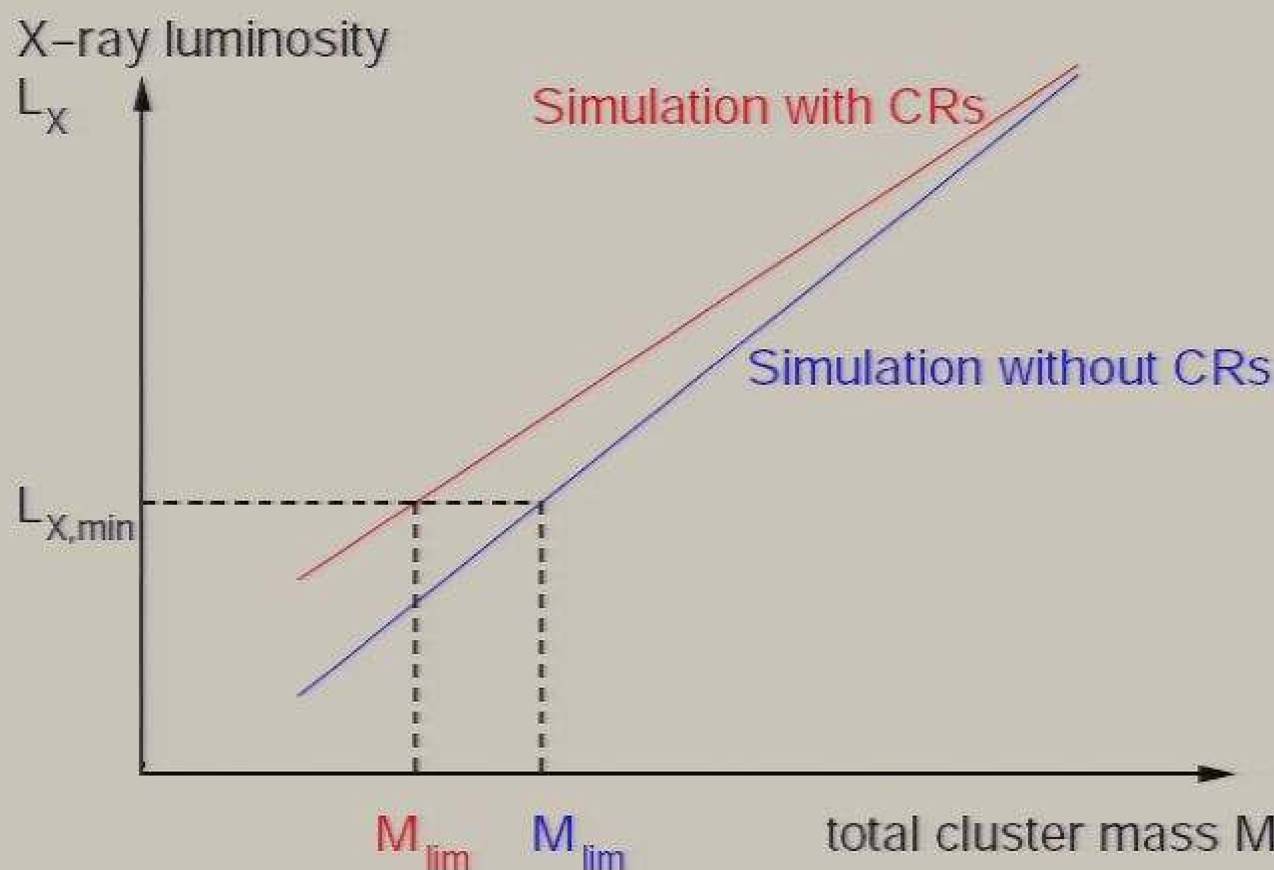
Modified X-ray scaling relations



→ 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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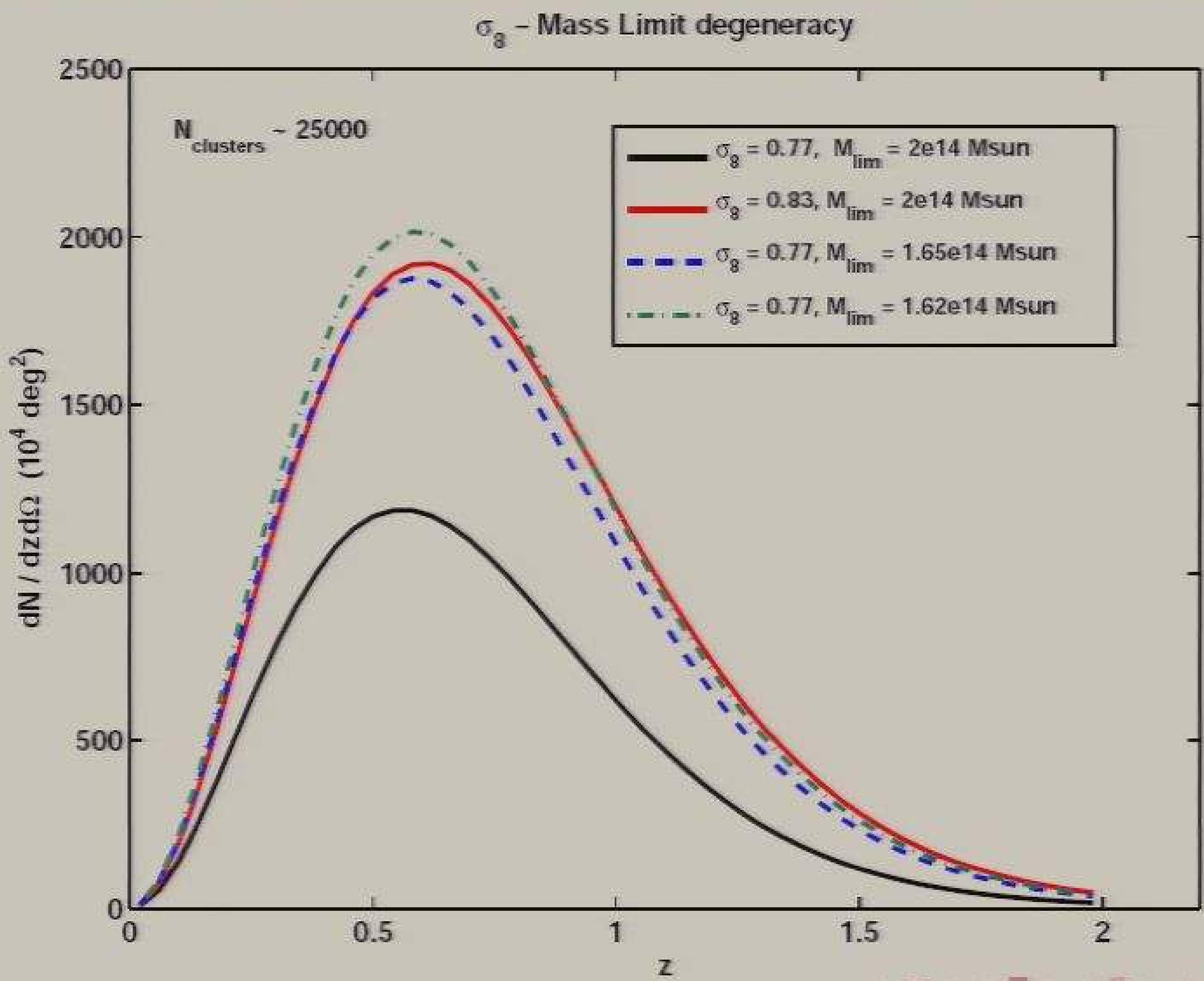
Degeneracies of the cluster redshift distribution (2)



Fisher matrix analysis (1)

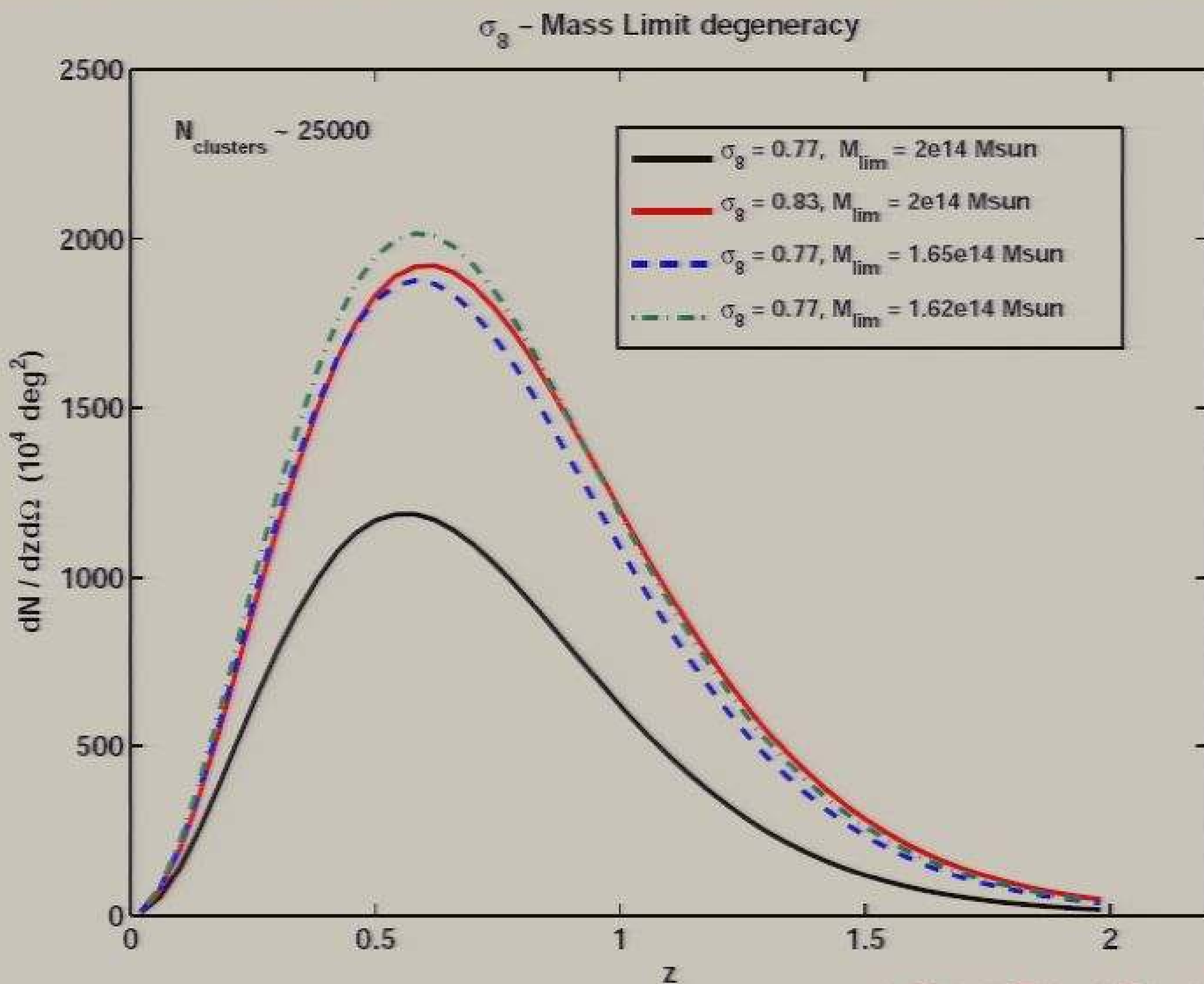
Survey Fisher matrix information for a data set:

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

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.

Degeneracies of the cluster redshift distribution (2)



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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 $h = 72 \pm 5$

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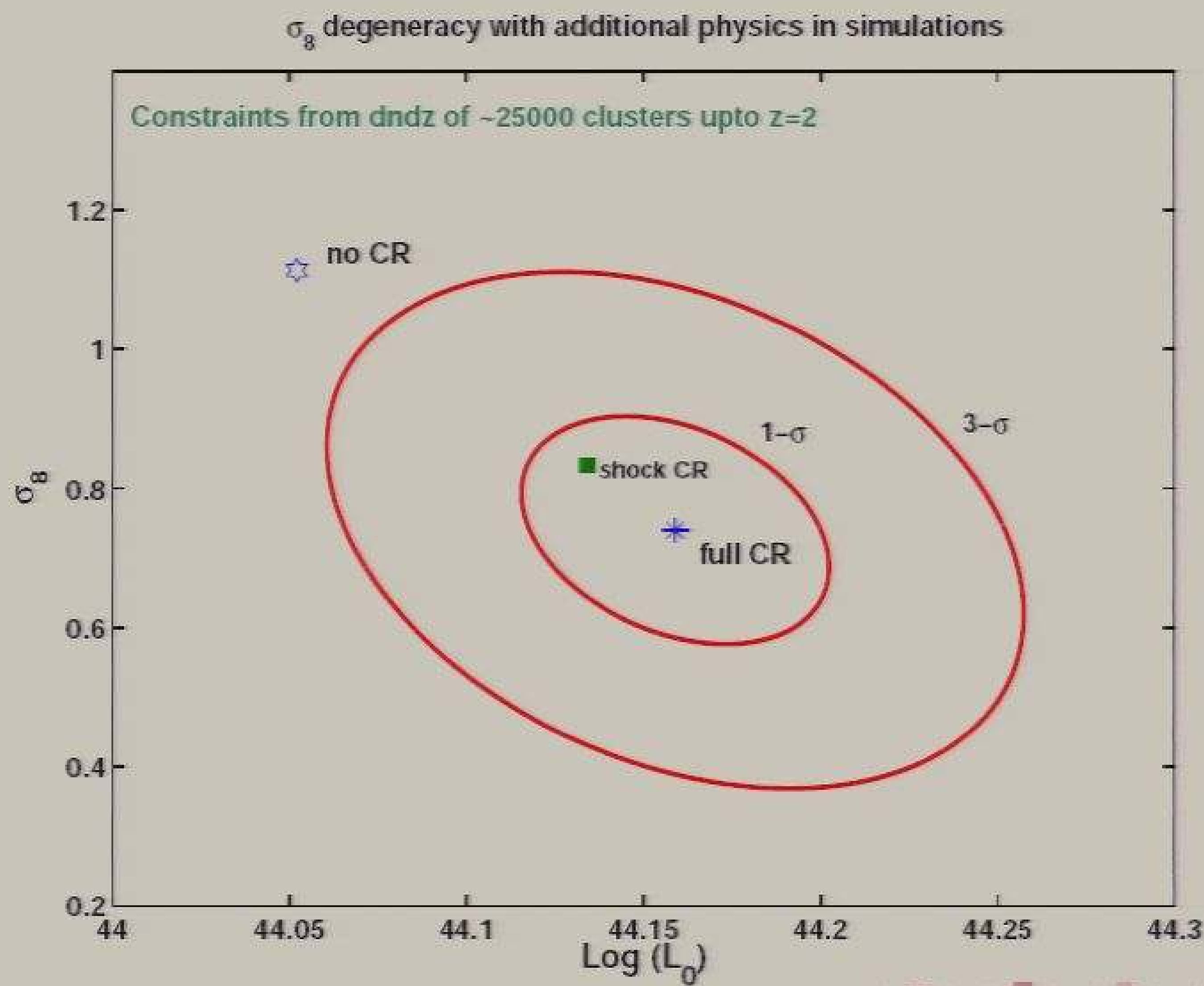
Degeneracy of σ_8 with cosmic ray physics (preliminary)



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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