Cosmic ray feedback in hydrodynamical simulations of galaxy and structure formation

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Outline

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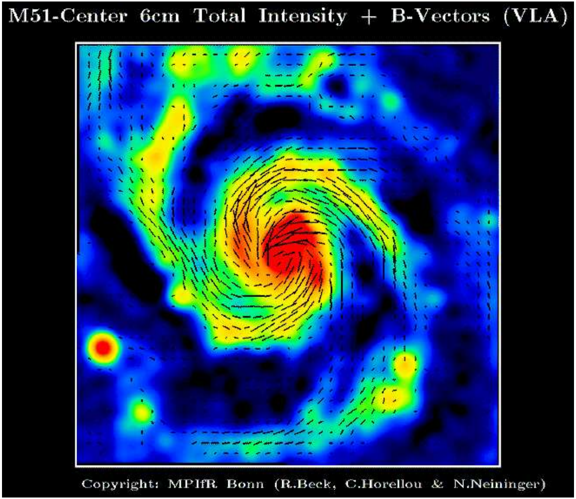
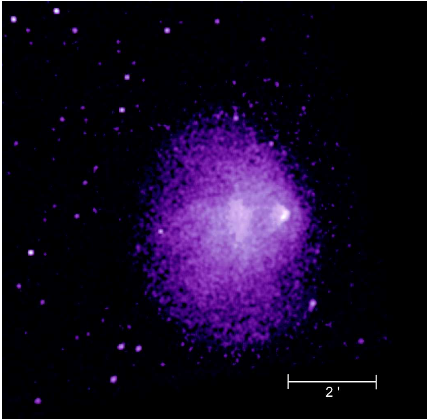
M51: cosmic ray electron population



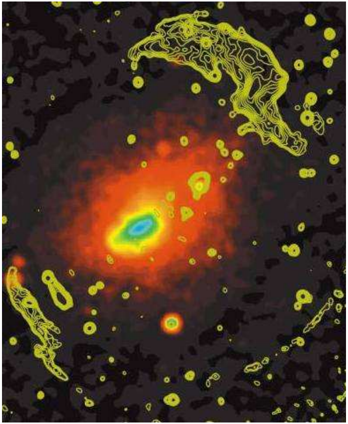
Fletcher, Beck, Berkhuijsen und Horellou, in prep.

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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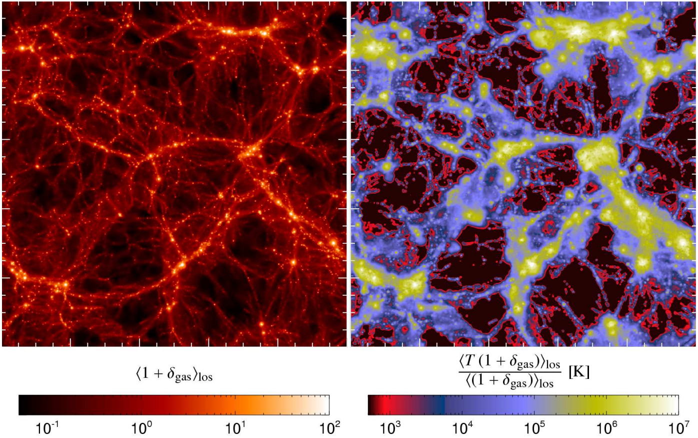
Gravitational heating by shocks



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

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Cosmic rays in GADGET– collaboration

The talk is based on the following papers:

- *Detecting shock waves in cosmological smoothed particle hydrodynamics simulations*,
  Pfrommer, Springel, Enßlin, & Jubelgas
  2006, MNRAS, 367, 113, astro-ph/0603483
- *Cosmic ray physics in calculations of cosmological structure formation*
  Enßlin, Pfrommer, Springel, & Jubelgas
  astro-ph/0603484
- *Cosmic ray feedback in hydrodynamical simulations of galaxy formation*
  Jubelgas, Springel, Enßlin, & Pfrommer
  astro-ph/0603485

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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 possible

Assumptions:

- protons dominate the CR population
- a momentum power-law is a typical spectrum
- CR energy & particle number conservation

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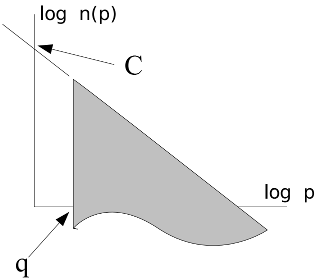
Philosophy and description

- CRs are coupled to the thermal gas by magnetic fields.
- We assume a single power-law CR spectrum: momentum cutoff q, normalization C, spectral index α (constant).
  $\longrightarrow$ determines CR energy density and pressure uniquely



The CR spectrum can be expressed by three adiabatic invariants, which scale only with the gas density. Non-adiabatic processes are mapped into changes of the adiabatic constants using mass, energy and momentum conservation.

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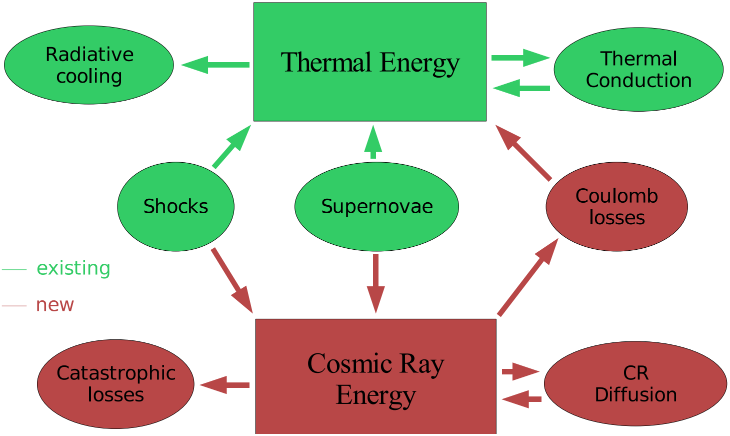
Cosmic rays in GADGET– flowchart



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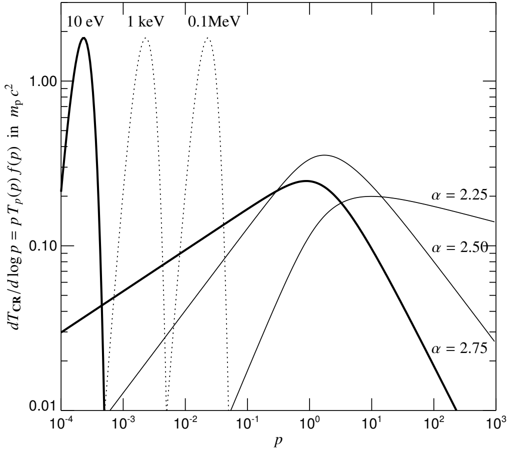
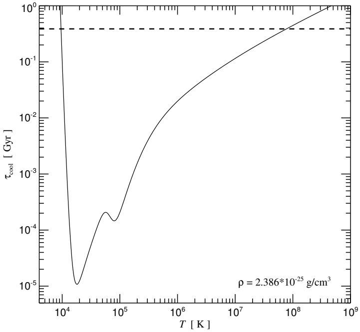
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:

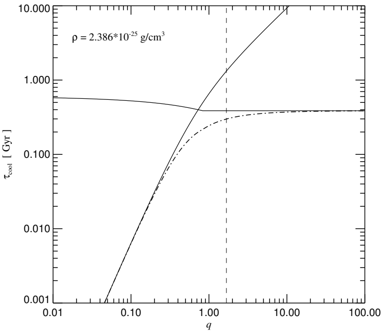


Radiative cooling

Cooling of primordial gas:



Cooling of cosmic rays:



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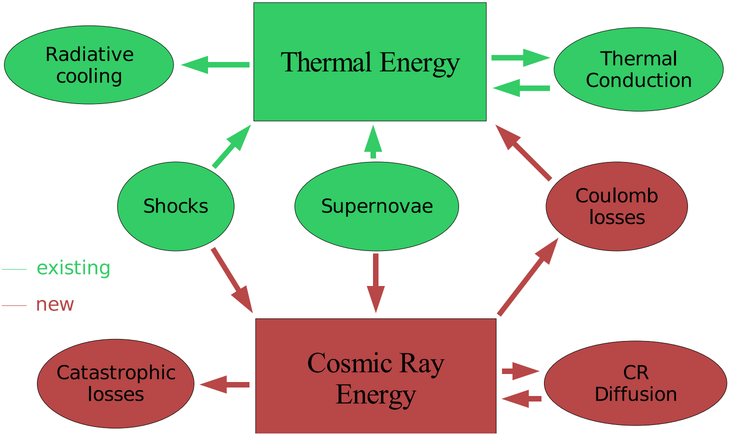
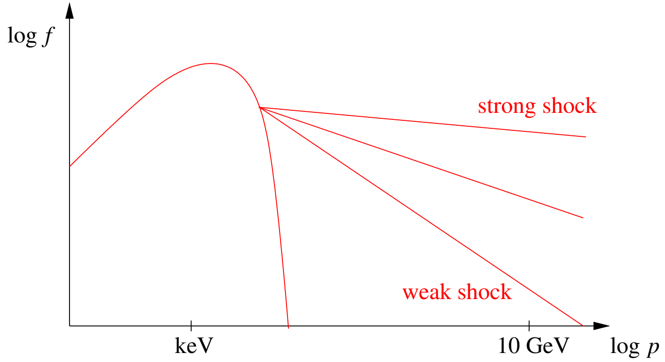
Cosmic rays in GADGET– flowchart



Diffusive shock acceleration – Fermi 1 mechanism

Cosmic rays gain energy $\Delta E/E \propto \upsilon_1 - \upsilon_2$ through bouncing back and forth the shock front. Accounting for the loss probability $\propto \upsilon_2$ of particles leaving the shock downstream leads to power-law CR population.



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Motivation for the Mach number finder

- cosmological shocks dissipate gravitational energy into thermal gas energy: where and when is the gas heated, and which shocks are mainly responsible for it?
- shock waves are tracers of the large scale structure and contain information about its dynamical history (warm-hot intergalactic medium)
- shocks accelerate cosmic rays through diffusive shock acceleration at structure formation shocks: what are the cosmological implications of such a CR component, and does this influence the cosmic thermal history?
- simulating realistic CR distributions within galaxy clusters provides detailed predictions for the expected radio synchrotron and γ-ray emission

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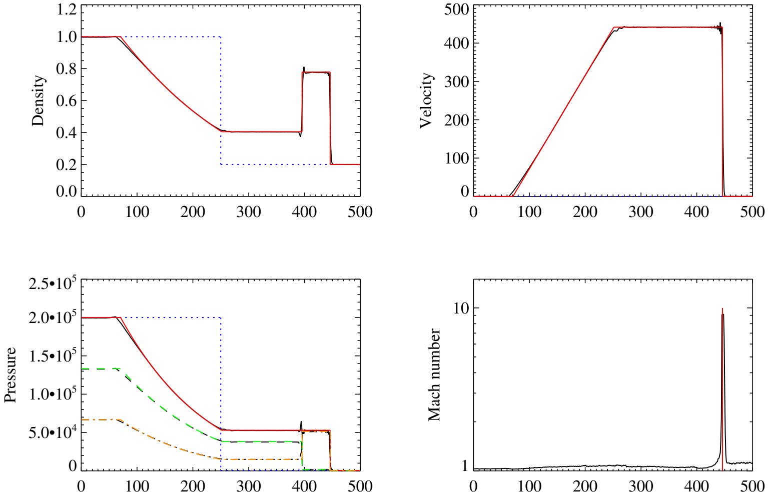
Shock tube (CRs & gas, $\mathcal{M} = 10$): thermodynamics



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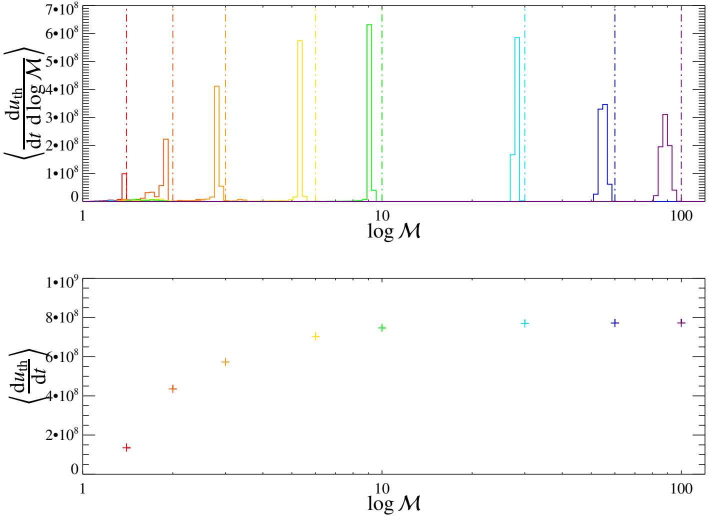
Shock tube (CRs & gas): Mach number statistics



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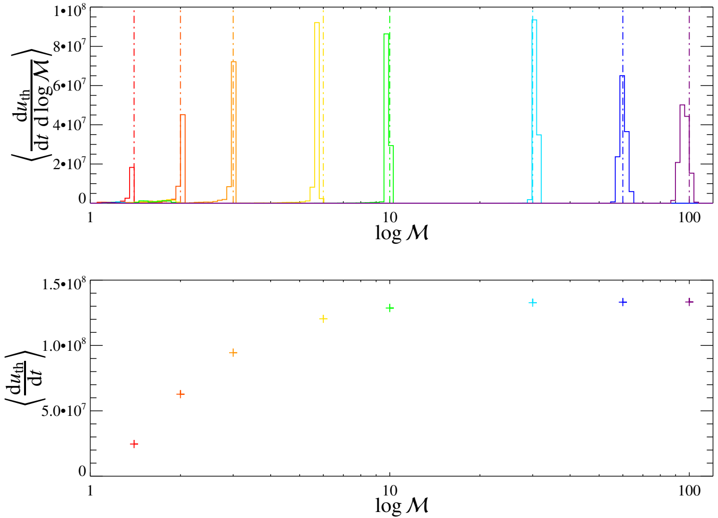
Shock tube (th. gas): Mach number statistics



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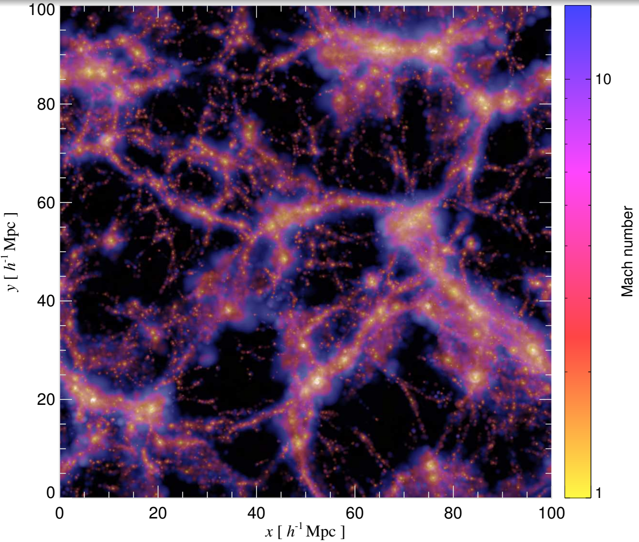
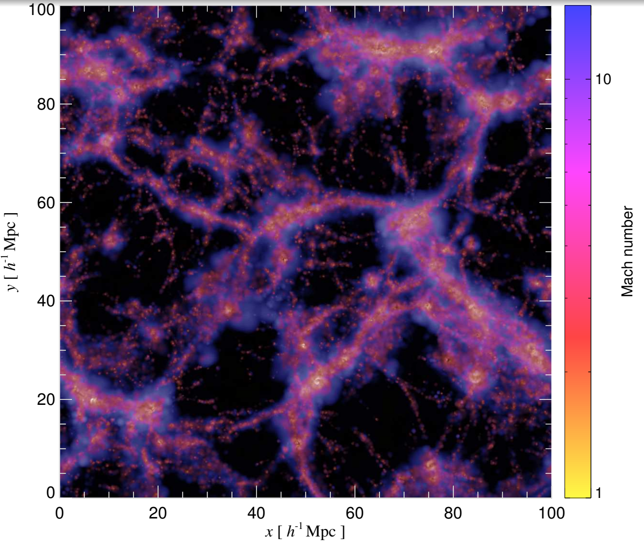
Cosmological Mach numbers: weighted by $\varepsilon_{\mathrm{diss}}$



Cosmological Mach numbers: weighted by ε_{CR}



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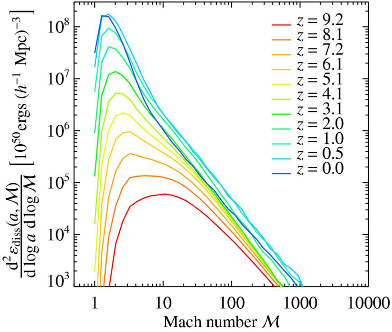
Cosmological Mach number statistics



- more energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks
- more energy is dissipated at later times
- mean Mach number decreases with time

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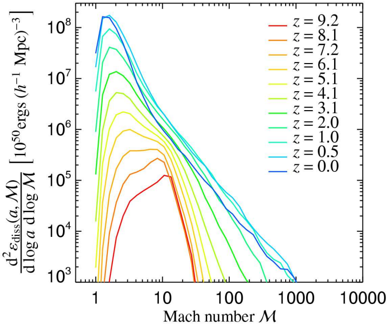
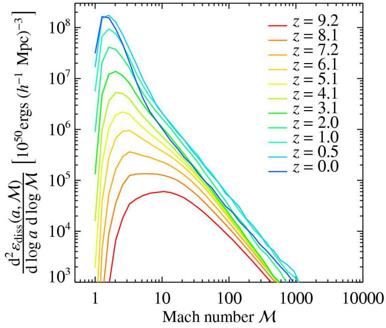
Cosmological statistics: influence of reionization





- reionization epoch at $z_{\text{reion}} = 10$ suppresses efficiently strong shocks at $z < z_{\text{reion}}$ due to jump in sound velocity
- cosmological constant causes structure formation to cease

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Radio halos as window for non-equilibrium processes

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

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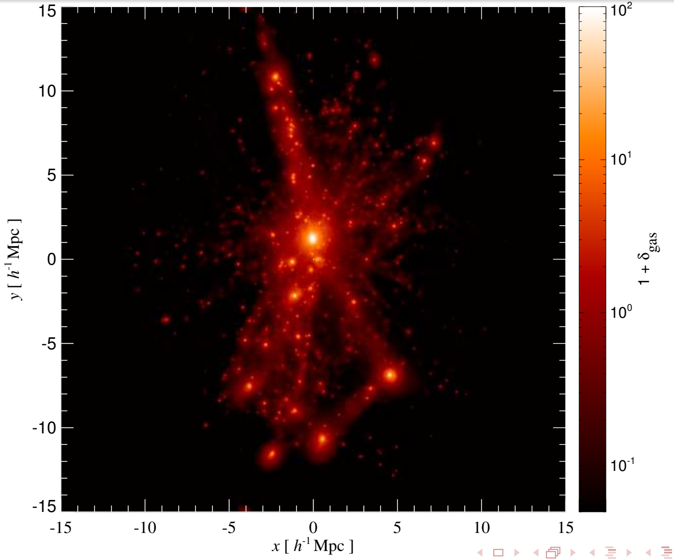
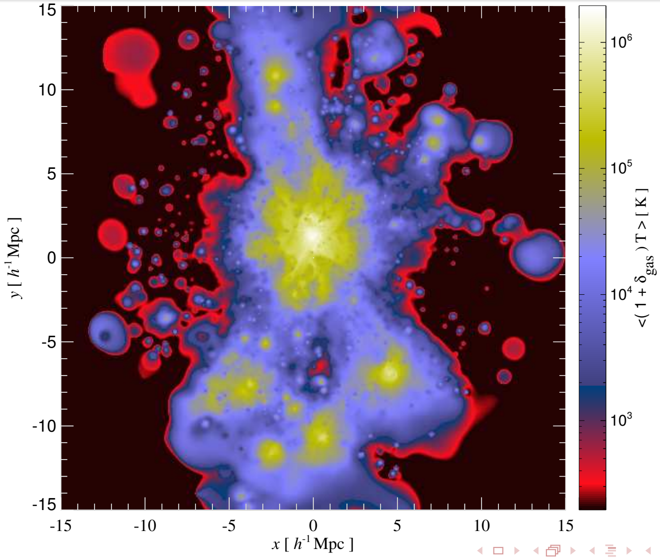
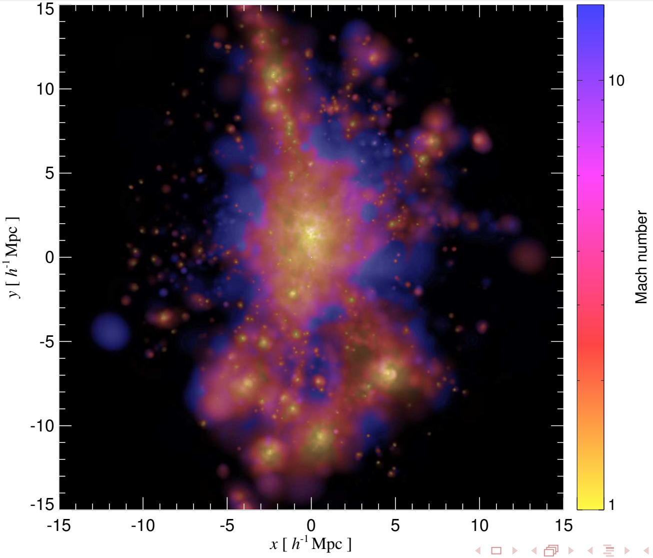
Adiabatic cluster simulation: gas density



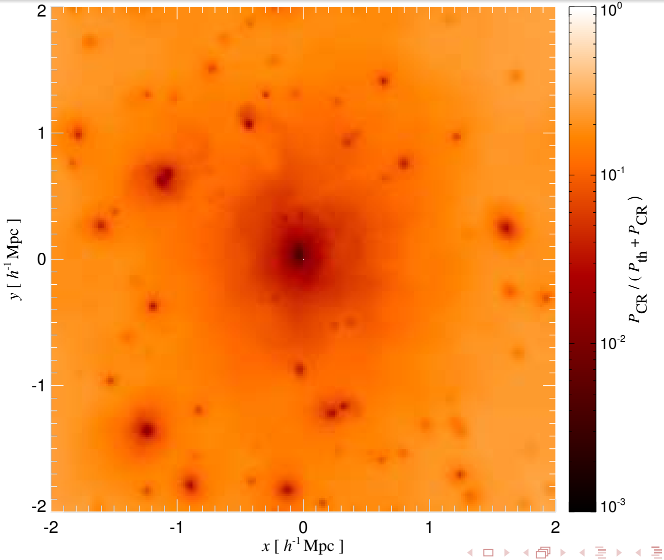
Mass weighted temperature



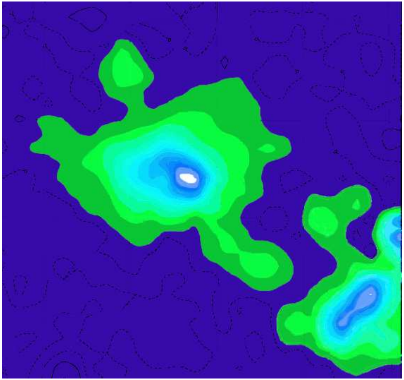
Mach number distribution weighted by $\varepsilon_{\mathrm{diss}}$



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



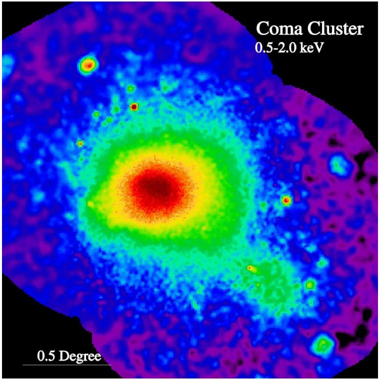
Radio halos as window for non-equilibrium processes



Coma radio halo, $\nu = 1.4$ GHz,

largest emission diameter ~ 3 Mpc

($2.5^\circ \times 2.0^\circ$, credit: Deiss/Effelsberg)



Coma thermal X-ray emission,

($2.7^\circ \times 2.5^\circ$, credit: ROSAT/MPE/Snowden)

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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)

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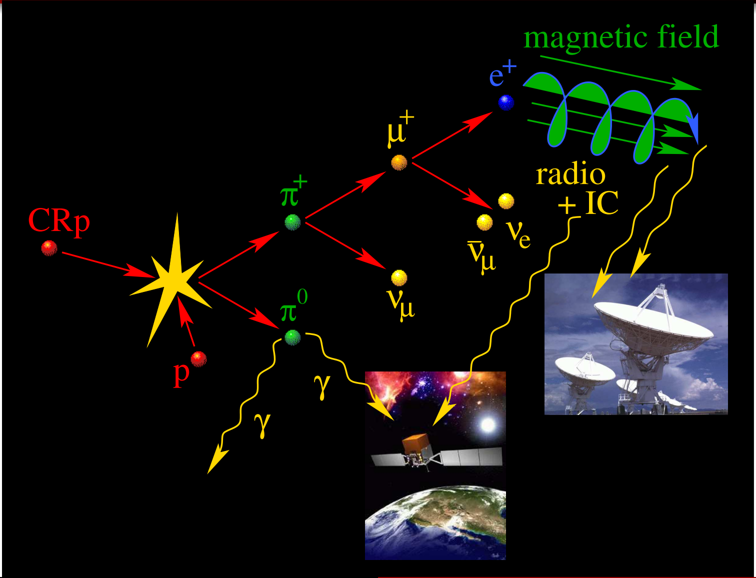
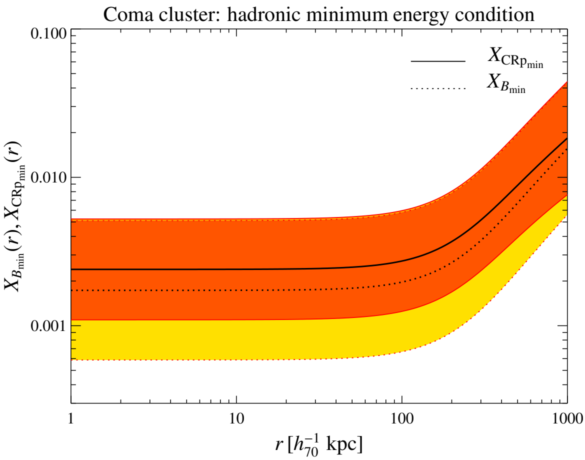
Hadronic cosmic ray proton interaction



Energetically preferred CR pressure profiles



$$X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\mathrm{th}}}(r) \quad \rightarrow \quad B_{\mathrm{Coma,\,min}}(0) = 2.4^{+1.7}_{-1.0}\,\mu\mathrm{G}$$

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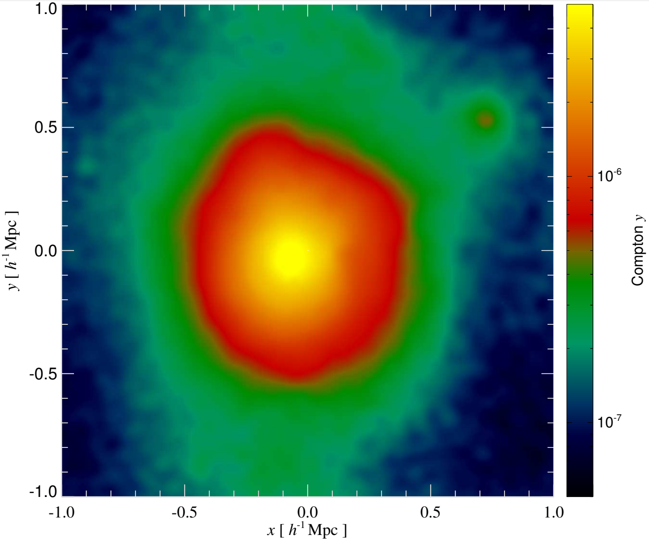
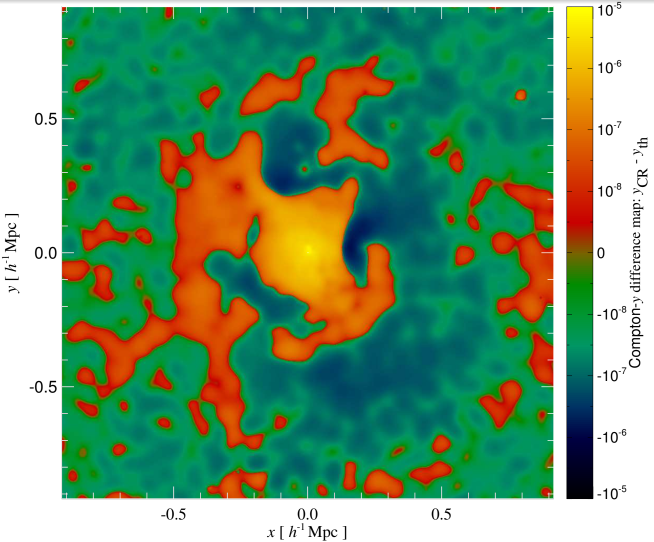
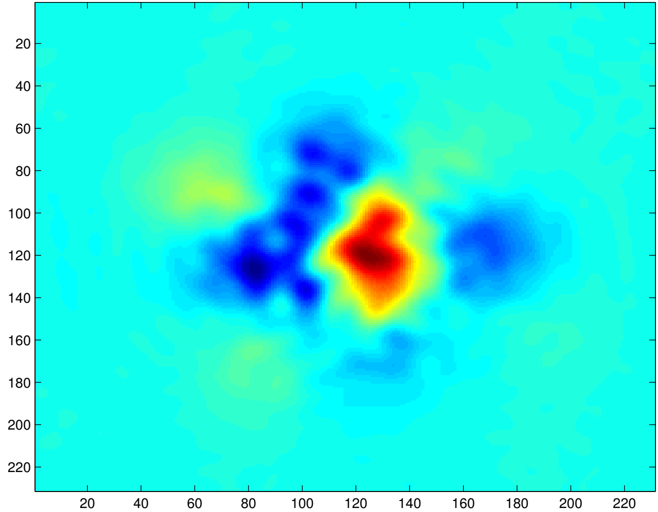
Compton y parameter in radiative cluster simulation



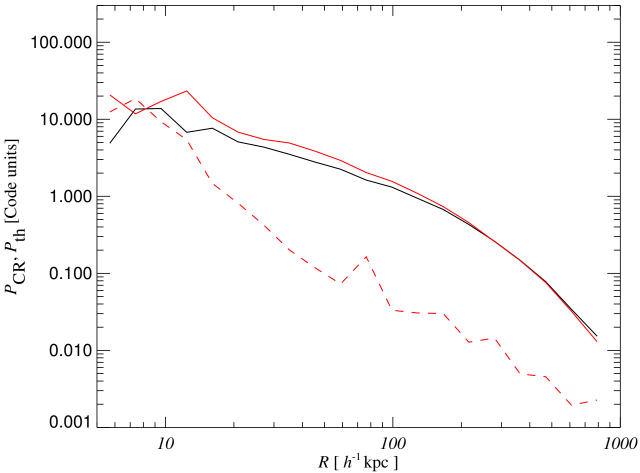
Compton y difference map: $y_{CR} - y_{th}$



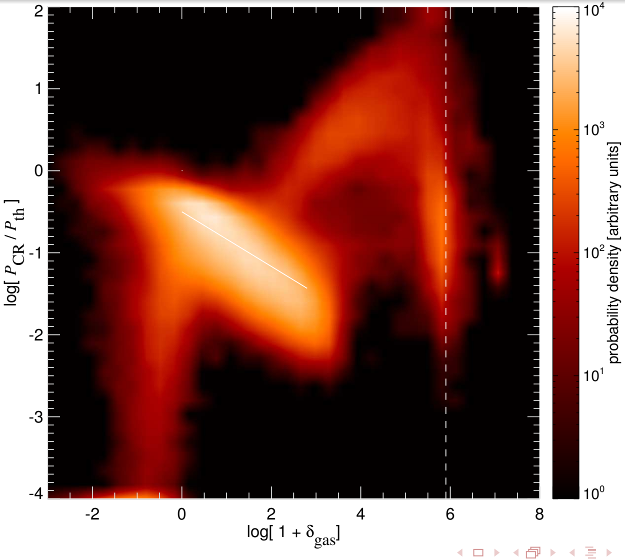
Simulated CBI observation of $y_{\mathrm{CR}} - y_{\mathrm{th}}$ (with Sievers & Bond)



Pressure profiles with and without CRs



Phase-space diagram of radiative cluster simulation

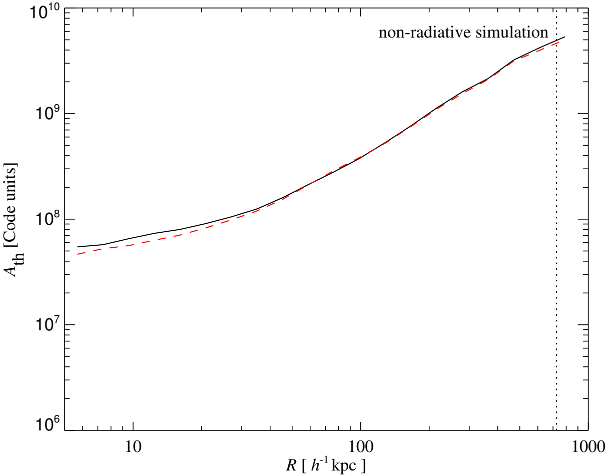


Preliminary emerging picture

Importance of central CR pressure relative to the gas pressure seems to depend on subtle interplay of the following effects:

- Presence of well developed cool core region
- Violent merger history of the cluster $\rightarrow$ resulting flat effective spectral index of CRs
- Cluster mass: ratio of CR-to-thermal cooling times changes with the cluster's virial temperature

Non-radiative simulation: entropy profile



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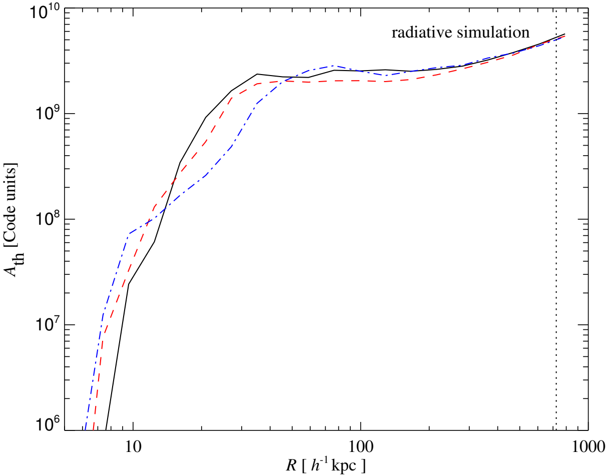
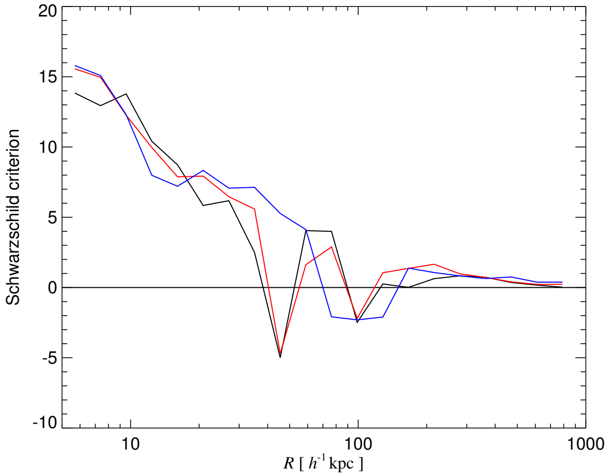
Radiative simulation: entropy profile

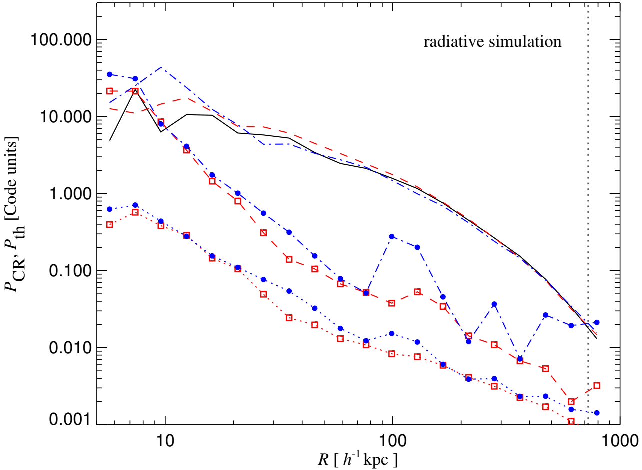


Radiative simulation: Schwazschild criterion



Cluster profile instable with respect to convection → effective mixing?

Generic CR pressure profile



Summary

- Understanding non-thermal processes is crucial for using clusters as cosmological probes (high-z scaling relations).
- Radio halos might be of hadronic origin as our simulations suggests $\longrightarrow$ tracer of structure formation
- Dynamical CR feedback influences Sunyaev-Zel'dovic effect

- Outlook
  - Galaxy evolution: CRs might influence energetic feedback, galactic winds, and disk galaxy formation
  - Huge potential and predictive power of cosmological CR simulations/Mach number finder $\longrightarrow$ provides detailed γ-ray/radio emission maps