Cosmic ray feedback in hydrodynamical simulations of galaxy and structure formation

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Canadian Institute for Theoretical Astrophysics, Toronto

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Outline

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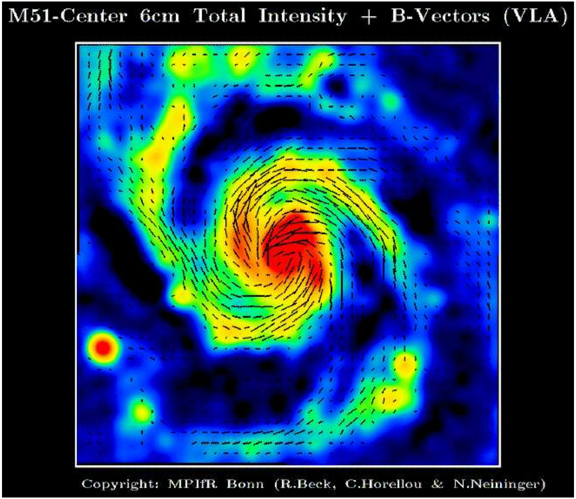
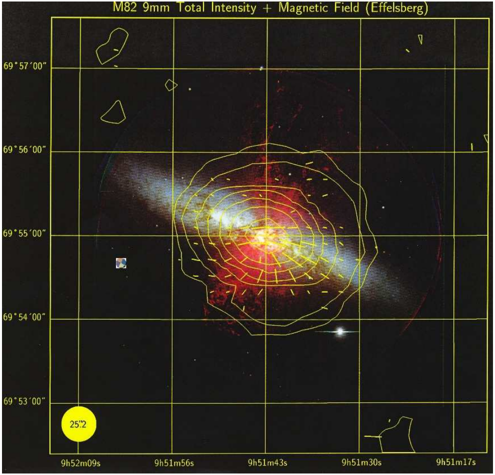
M51: cosmic ray electron population



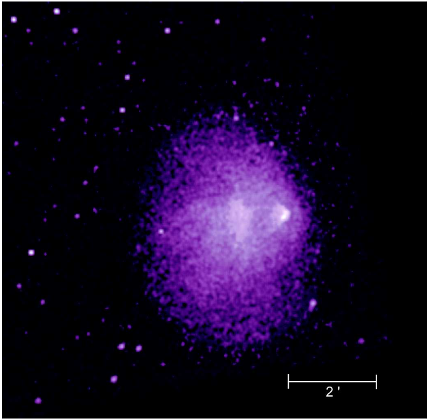
Fletcher, Beck, Berkhuijsen und Horellou, in prep.

M82: optical disk, H-α wind, & CR electron halo



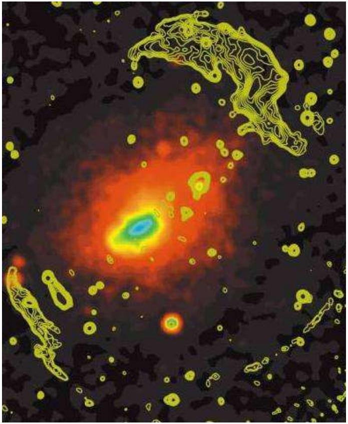
Thierbach, Wielebinski, Neininger (2004, unpublished)

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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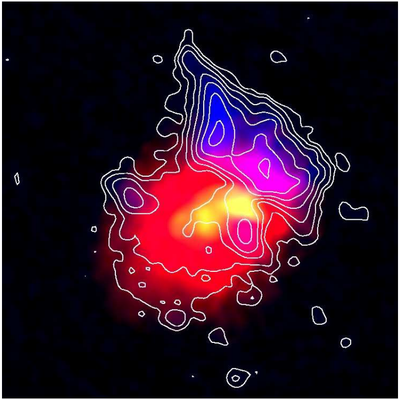
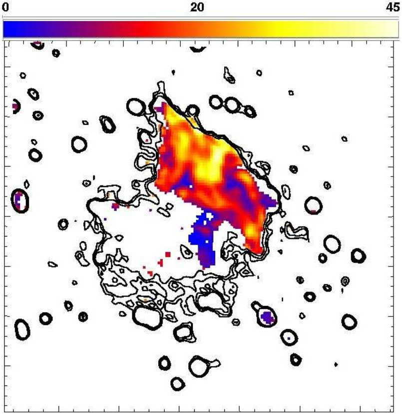
Abell 2256: giant radio relic & small halo



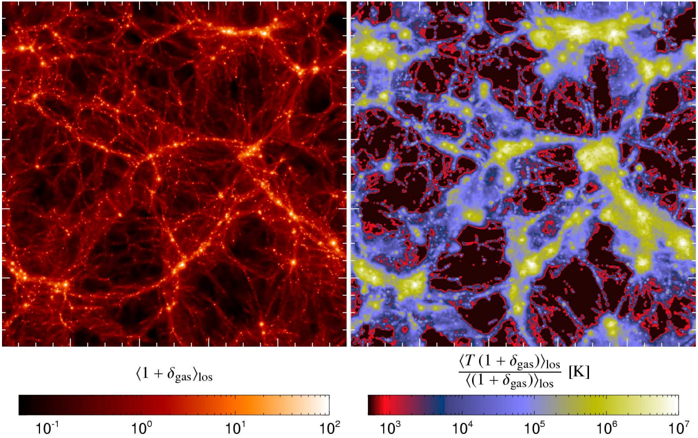
X-ray (red) & radio (blue, contours)



fractional polarisation in color

Clarke & Enßlin (2006)

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.

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

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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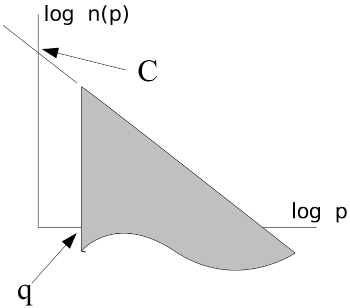
CR spectral description



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

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

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

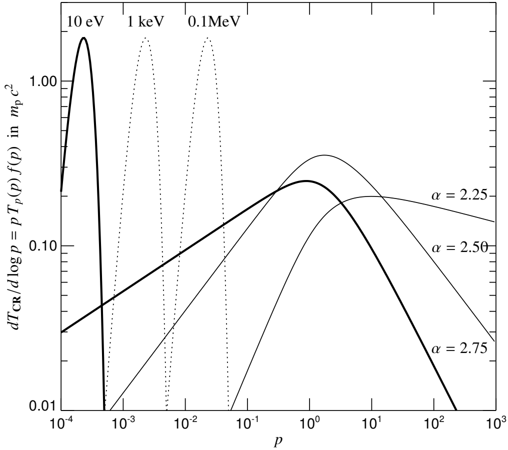
$$C(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{\alpha+2}{3}} C_0$$

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

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

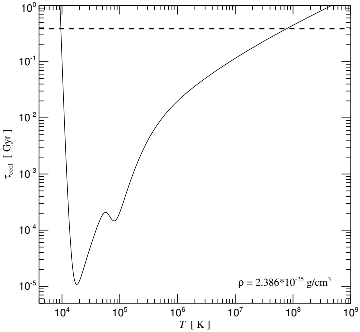
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:

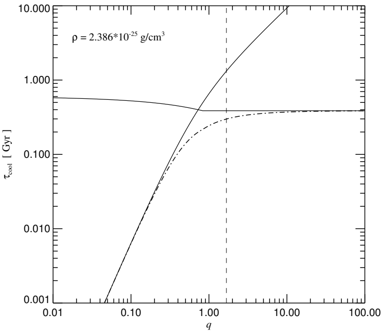


Radiative cooling

Cooling of primordial gas:



Cooling of cosmic rays:



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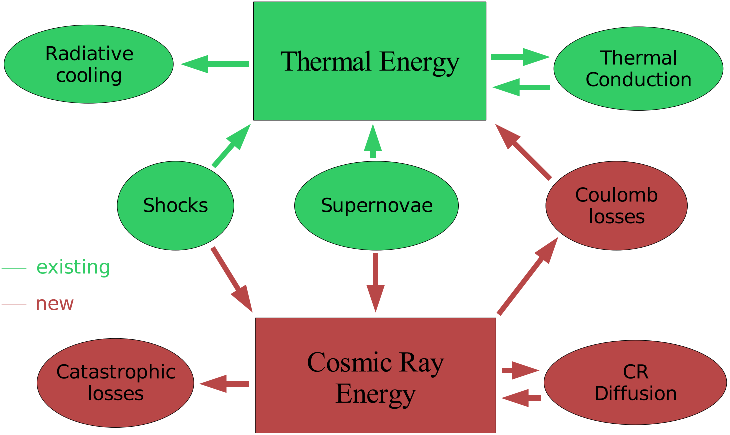
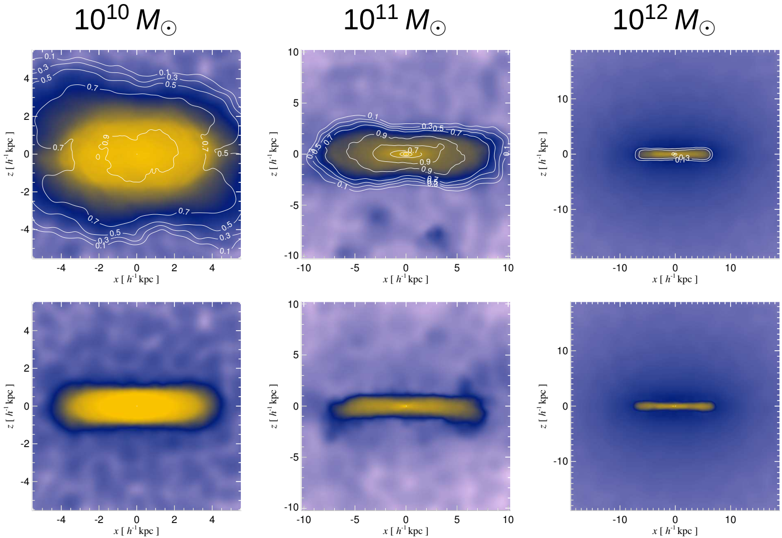
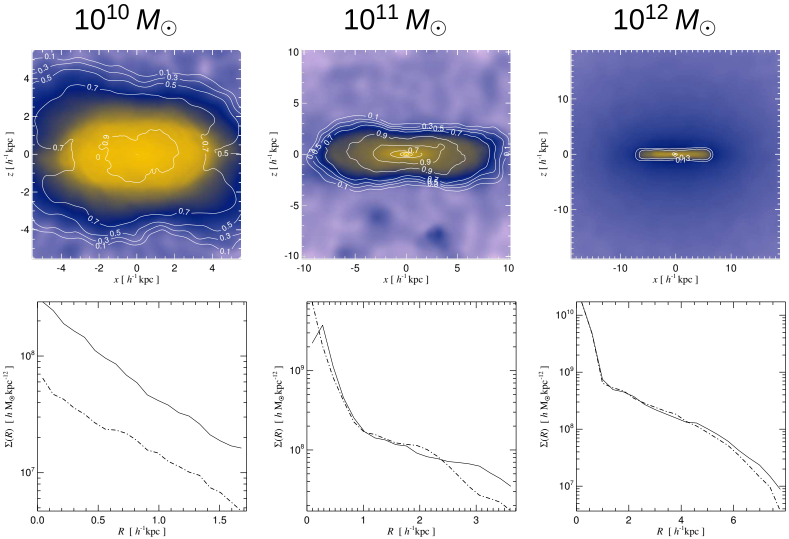
Cosmic rays in GADGET– flowchart



Isolated galaxies – projections



Isolated galaxies – stellar profiles



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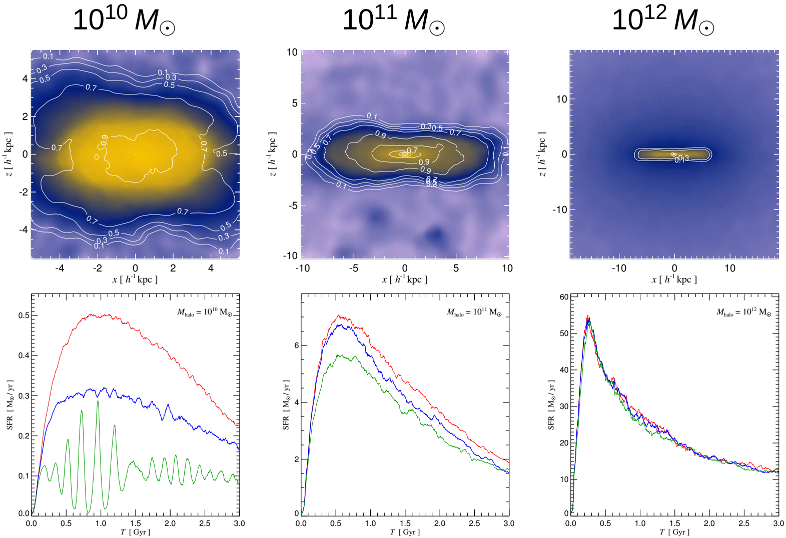
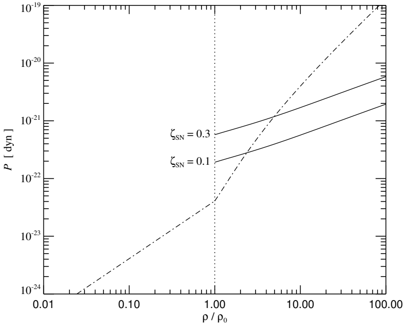
Isolated galaxies – star formation history



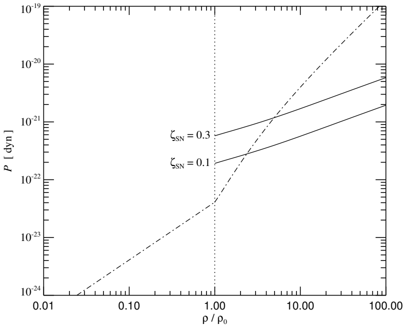
Effective equation of state

Supernova heating balances cooling

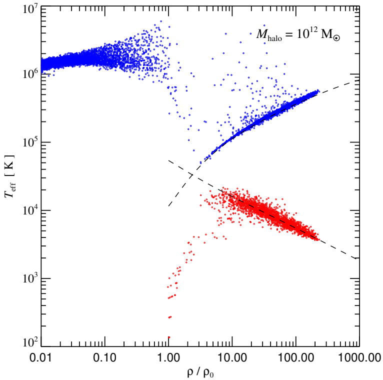


Effective equation of state & phase space distribution

Supernova heating balances cooling

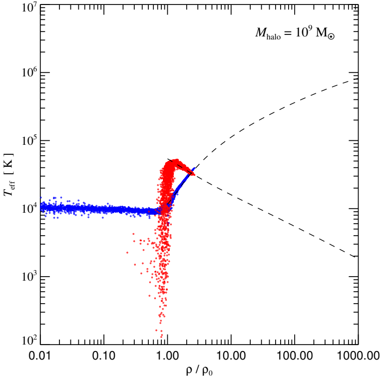


$10^{12} M_\odot$ galaxy

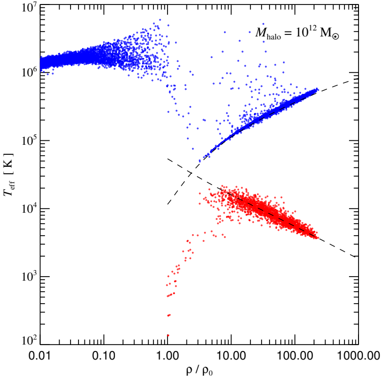


Effective equation of state & phase space distribution

$10^9\, M_\odot$ galaxy



$10^{12}\, M_\odot$ galaxy



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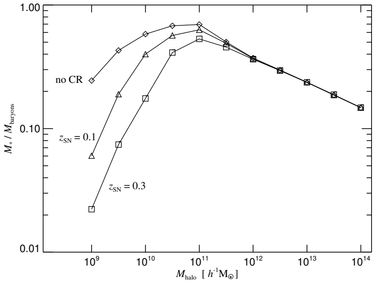
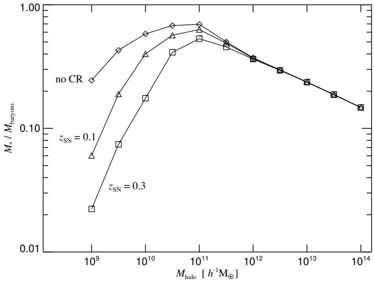
Quenching of dwarf galaxies

Star formation efficiency suppressed in small halos:

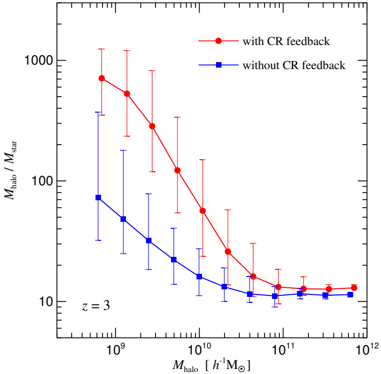


Quenching of dwarf galaxies

Star formation efficiency suppressed in small halos:



Averaged mass-to-light ratio:



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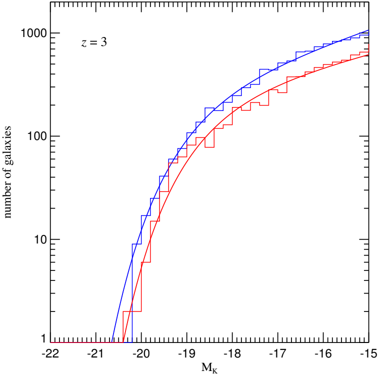
Quenching of small galaxies

Luminosity function (z=3):



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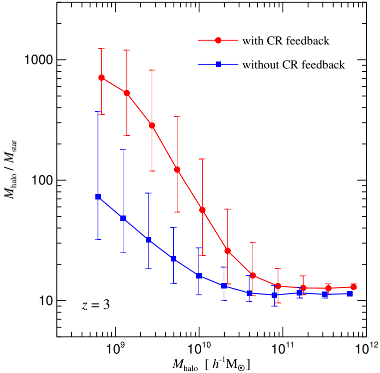
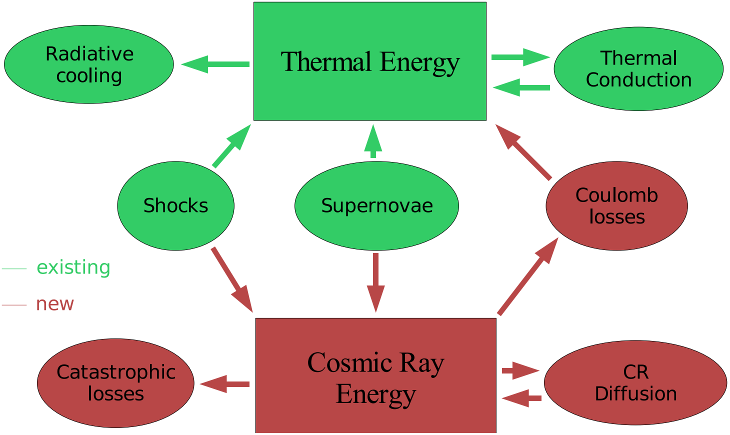
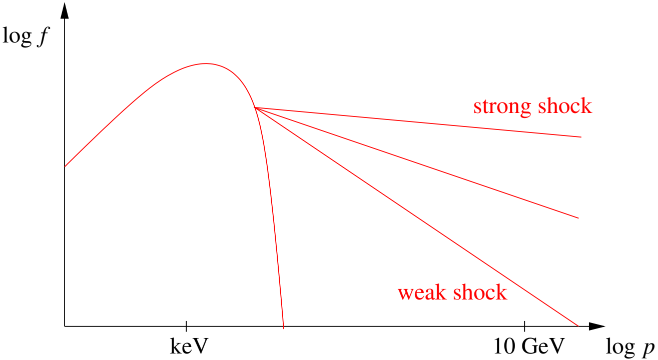


Cosmic rays in GADGET– flowchart



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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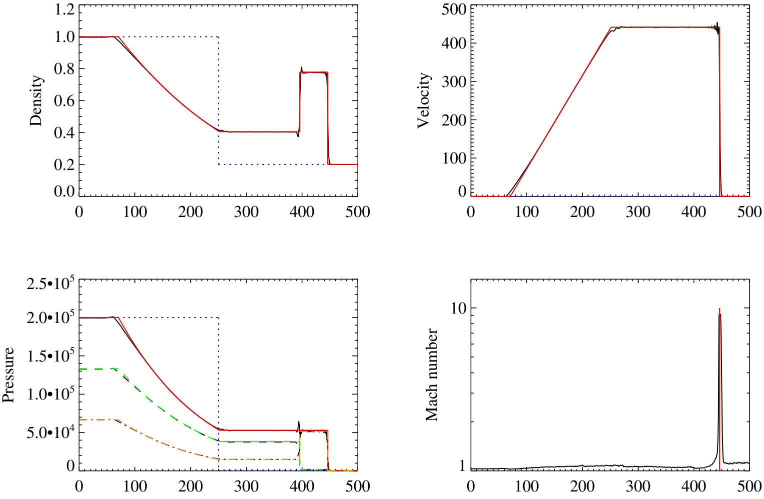
Idea of the Mach number finder in SPH

- SPH shock is broadened to a scale of the order of the smoothing length h, i.e. $f_h h$, and $f_h \sim 2$
- approximate instantaneous particle velocity by pre-shock velocity (denoted by $\upsilon_1 = \mathcal{M}_1 c_1$)

Using the entropy conserving formalism of Springel & Hernquist 2002 ($A(s) = P\rho^{-\gamma}$ is the entropic function):

$$
\begin{aligned}
\frac{A_2}{A_1} &= \frac{A_1 + \mathrm{d}A_1}{A_1} = 1 + \frac{f_h h}{\mathcal{M}_1 c_1 A_1}\frac{\mathrm{d}A_1}{\mathrm{d}t} = \frac{P_2}{P_1}\left(\frac{\rho_1}{\rho_2}\right)^{\gamma} \\
\frac{\rho_2}{\rho_1} &= \frac{(\gamma+1)\mathcal{M}_1^2}{(\gamma-1)\mathcal{M}_1^2 + 2} \\
\frac{P_2}{P_1} &= \frac{2\gamma\mathcal{M}_1^2 - (\gamma-1)}{\gamma+1}
\end{aligned}
$$

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



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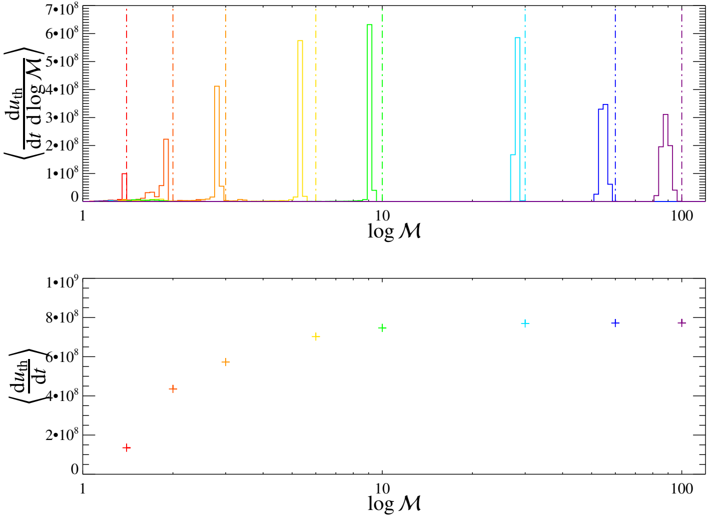
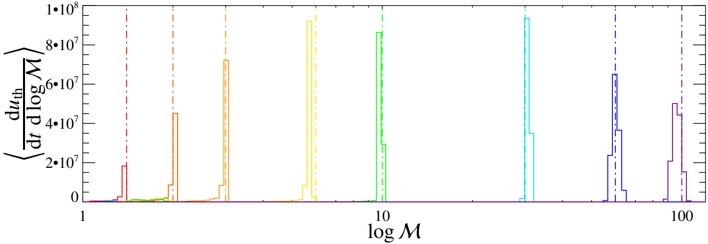
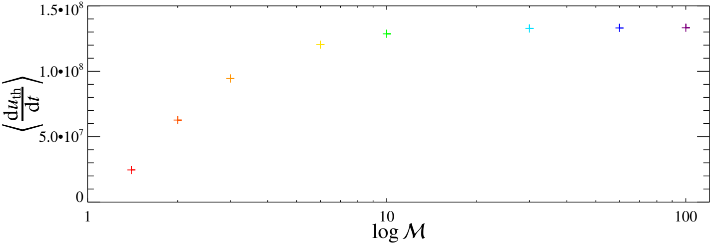
Shock tube (CRs & gas): Mach number statistics

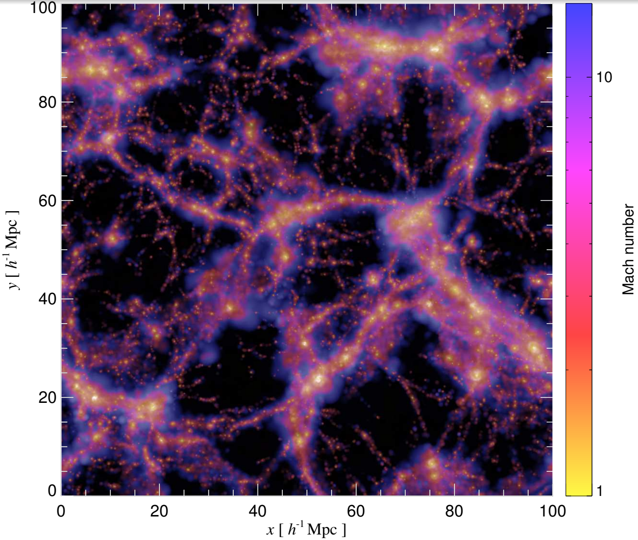


Shock tube (th. gas): Mach number statistics





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



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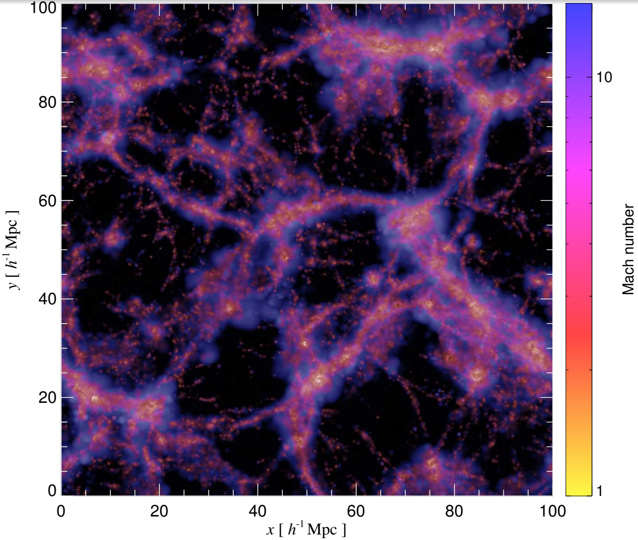
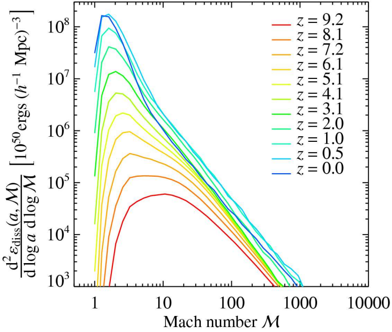
Cosmological Mach numbers: weighted by $\varepsilon_{\rm CR}$

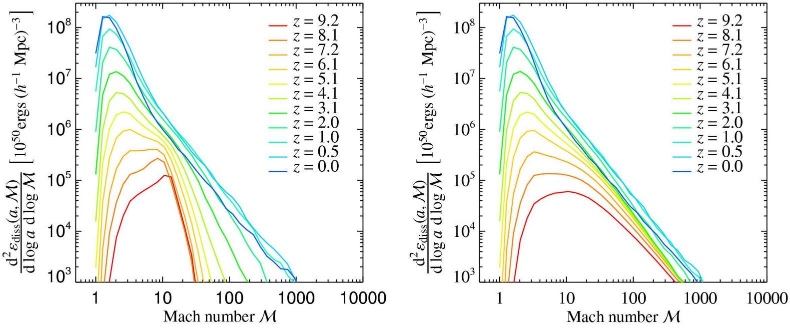


Cosmological Mach number statistics



- 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

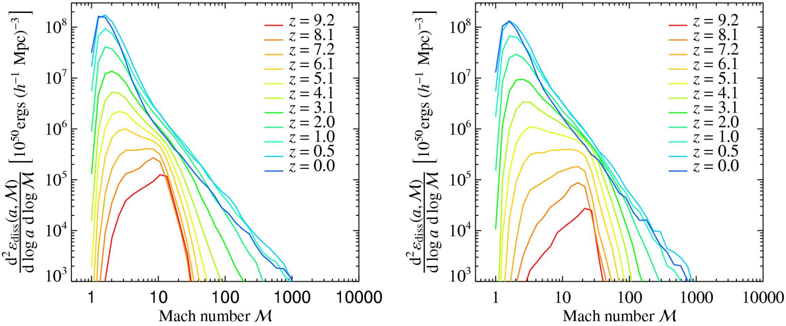
Cosmological statistics: influence of reionization



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

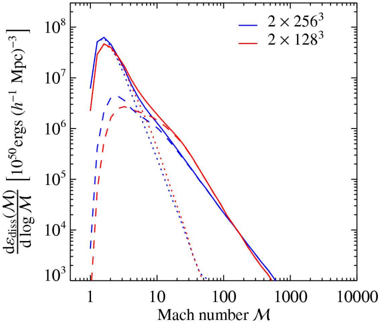
Cosmological statistics: resolution study

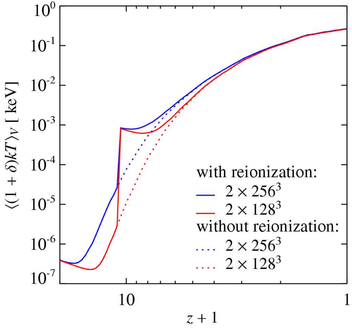
Differential distributions: 2×256^3 versus 2×128^3



- differential Mach number distributions are converged for $z < 3$
- at earlier epochs, weak internal shocks are missing in low resolution simulations

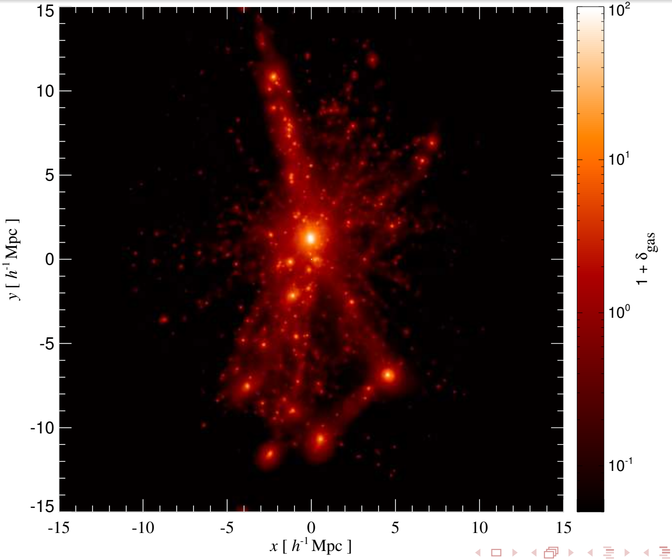
Cosmological statistics: resolution study





- in higher resolution simulations structure forms earlier
- integrated Mach number distribution converged

Adiabatic cluster simulation: gas density



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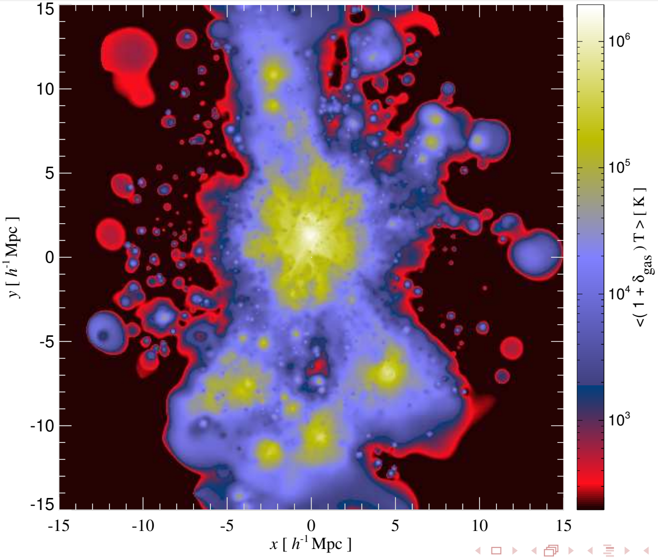
Mass weighted temperature



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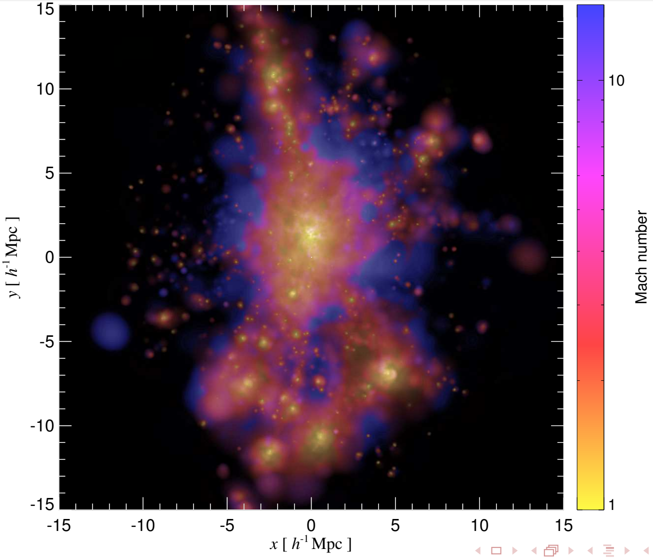
Mach number distribution weighted by $\varepsilon_{\mathrm{diss}}$



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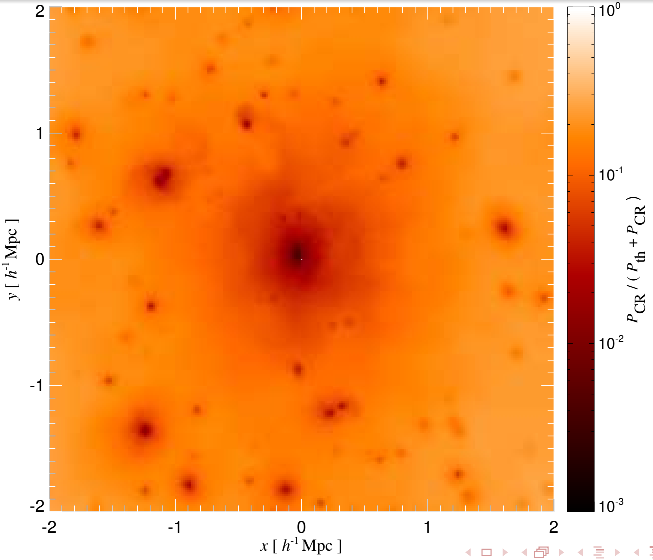
Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



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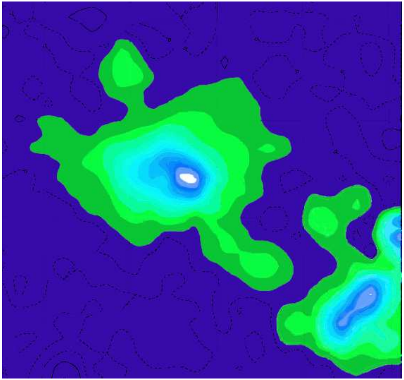
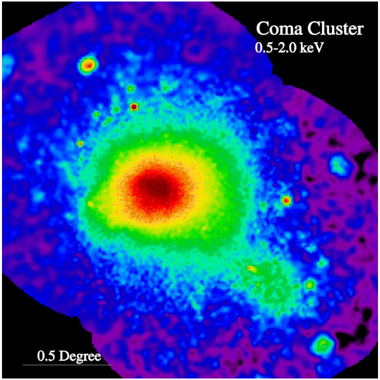
Radio halos as window for non-equilibrium processes



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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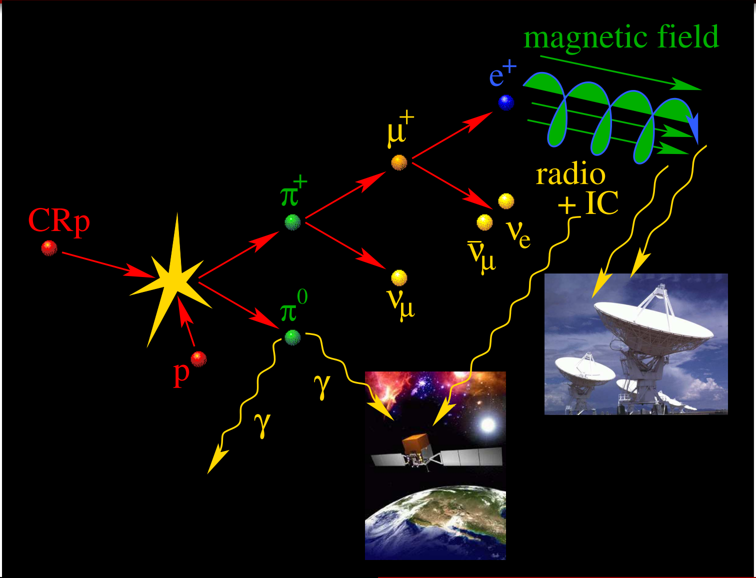
Models for radio synchrotron halos in clusters

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

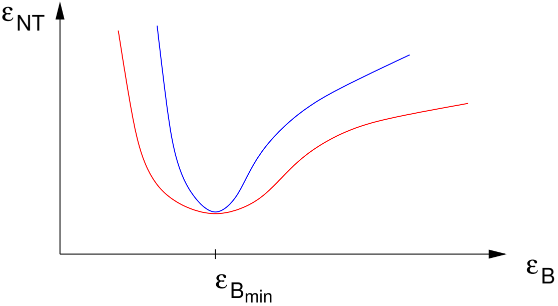
- Primary accelerated CR electrons: synchrotron/IC cooling times too short to account for extended diffuse emission
- Re-accelerated CR electrons through resonant interaction with turbulent Alfvén waves: possibly too inefficient, no first principle calculations (Jaffe 1977, Schlickeiser 1987, Brunetti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

Hadronic cosmic ray proton interaction



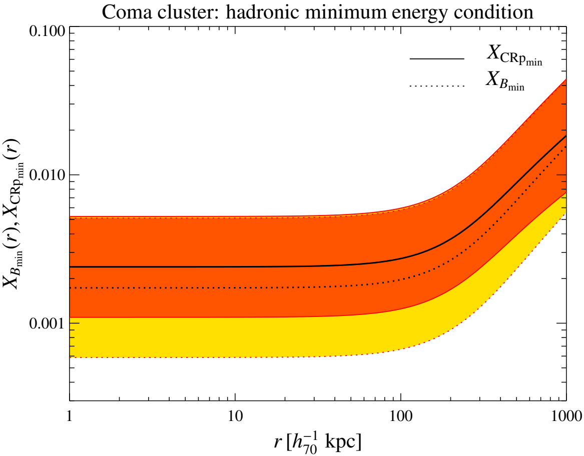
Minimum energy criterion (MEC): the idea

- What is the energetically least expensive distribution of non-thermal energy density ε_NT given the observed synchrotron emissivity?
- $\varepsilon_\mathrm{NT} = \varepsilon_B + \varepsilon_\mathrm{CRp} + \varepsilon_\mathrm{CRe}$
  $\rightarrow$ minimum energy criterion: $\left.\frac{\partial \varepsilon_\mathrm{NT}}{\partial \varepsilon_B}\right|_{j_\nu} \overset{!}{=} 0$



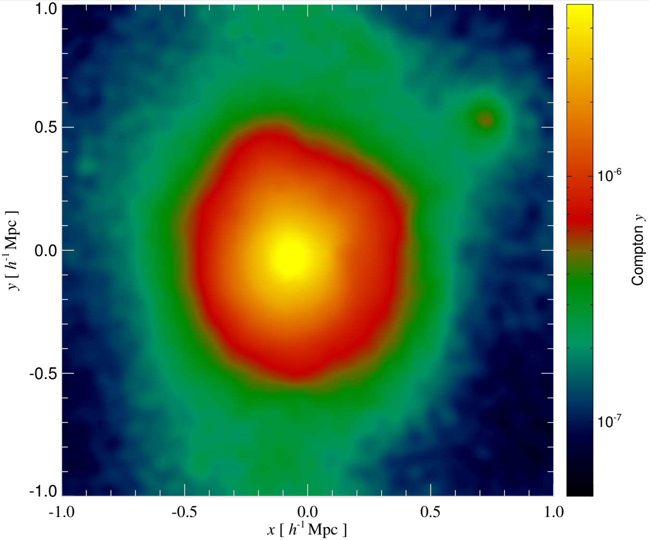
defining tolerance levels: deviation from minimum by one e-fold

Energetically preferred CR pressure profiles

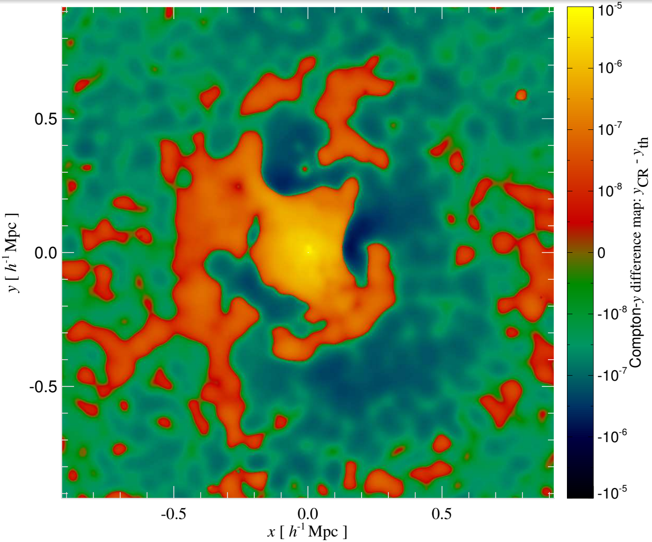


$$X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\mathrm{th}}}(r) \quad \rightarrow \quad B_{\mathrm{Coma,\,min}}(0) = 2.4^{+1.7}_{-1.0}\,\mu\mathrm{G}$$

Compton *y* parameter in radiative cluster simulation



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



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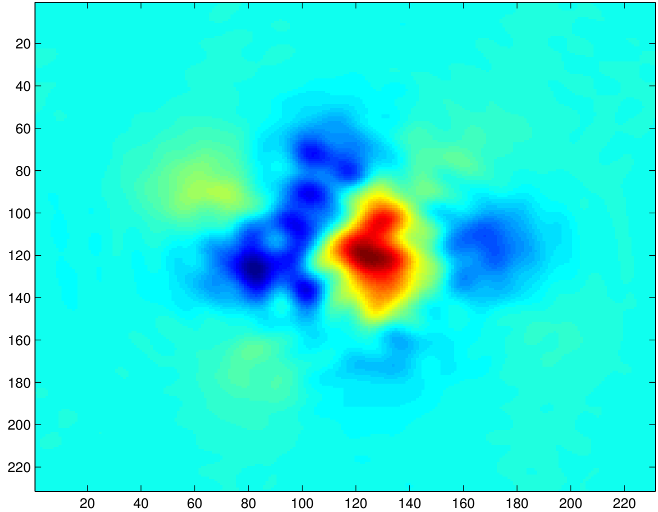
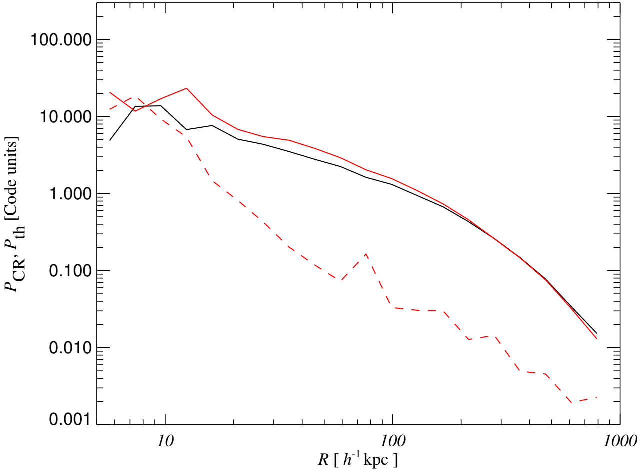
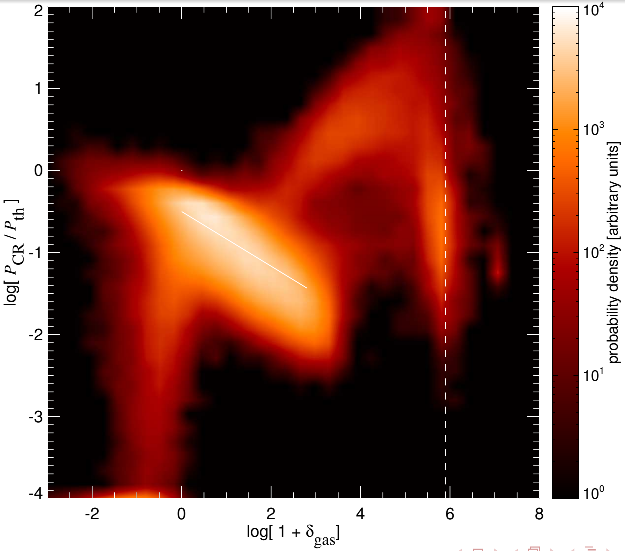
Simulated CBI observation of $y_{\rm CR} - y_{\rm th}$ (with Sievers & Bond)



Pressure profiles with and without CRs



Phase-space diagram of radiative cluster simulation



Summary

- Galaxy evolution: CRs significantly reduce the star formation efficiency in small galaxies
- 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

- 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

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