Cosmic rays in galaxy clusters and cosmological shock waves

Going beyond gas physics

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Outline

1. Non-equilibrium processes in clusters
   - Introduction
   - Cluster radio halos
   - Minimum energy condition
2. Cosmic rays in GADGET
   - Importance of cosmic ray feedback
   - Philosophy and description
3. Cosmological shock waves
   - Observations of cluster shocks
   - Mach number finder
   - Cosmological simulations
   - Cluster simulations

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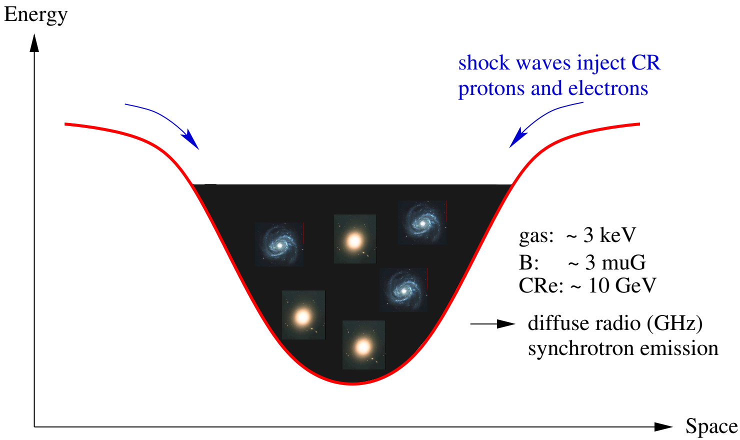
Galaxy clusters

Galaxy clusters are dynamically evolving dark matter potential wells:



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

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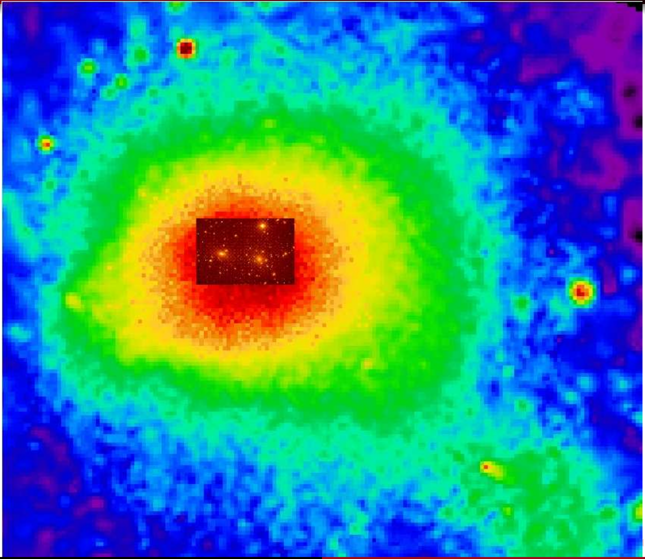
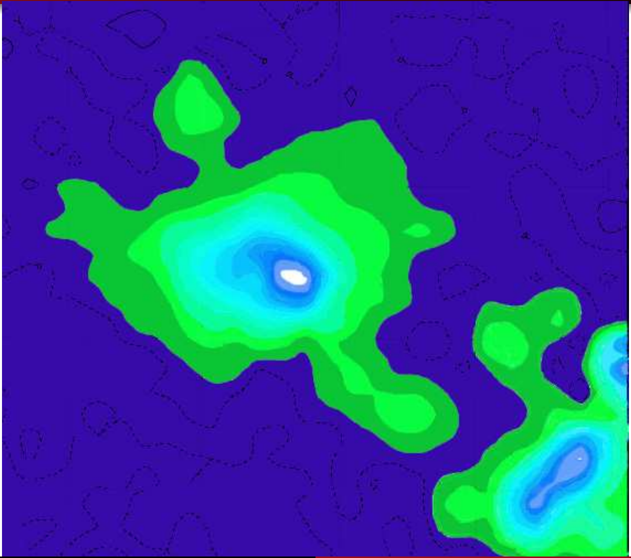
Coma cluster: optical emission

Coma cluster: infra-red emission

Coma cluster: X-ray emission



Coma cluster: radio synchrotron emission



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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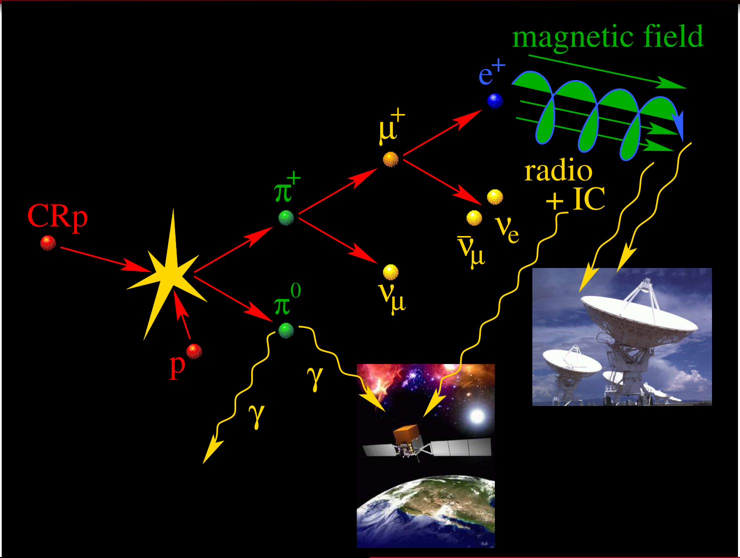
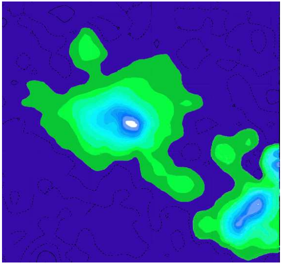
Hadronic cosmic ray proton interaction



Cosmic rays in clusters of galaxies

What do we know about CRs?

- predictions for the CR pressure span between 10% and 50% of the cluster's pressure budget
- escape of cosmic ray protons only possible for energies $E_{\mathrm{CRp}} > 2 \times 10^{16}$ eV
- energy losses (for particles with $E \sim 10$ GeV):
  CRe: synchrotron, inverse Compton: $\tau \sim 10^8$ yr
  CRp: inelastic collisions, Coulomb losses: $\tau \sim 10^{10}$ yr $\sim$ Hubble time



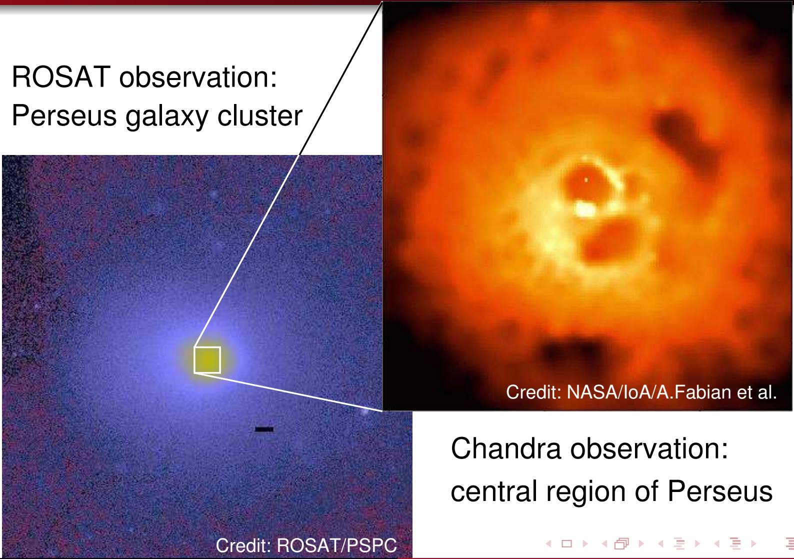
Coma cluster: radio halo,

$\nu = 1.4$ GHz, $2.5^\circ \times 2.0^\circ$

(Credit: Deiss/Effelsberg)

Cooling core clusters are efficient CRp detectors

ROSAT observation:
Perseus galaxy cluster



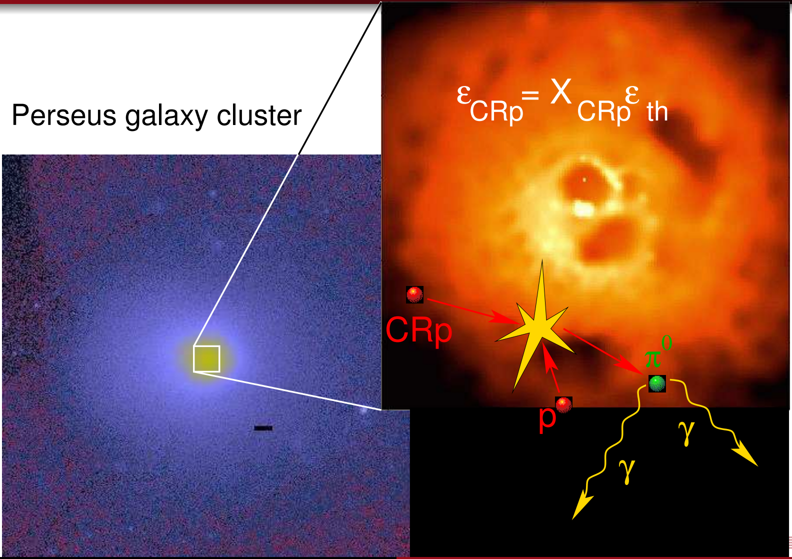
Credit: NASA/IoA/A.Fabian et al.

Credit: ROSAT/PSPC

Chandra observation:
central region of Perseus

Cooling core cluster model of CRp detection

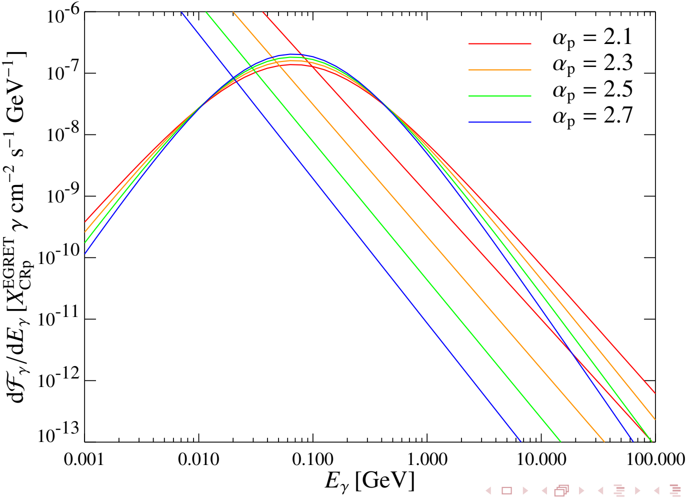
Perseus galaxy cluster



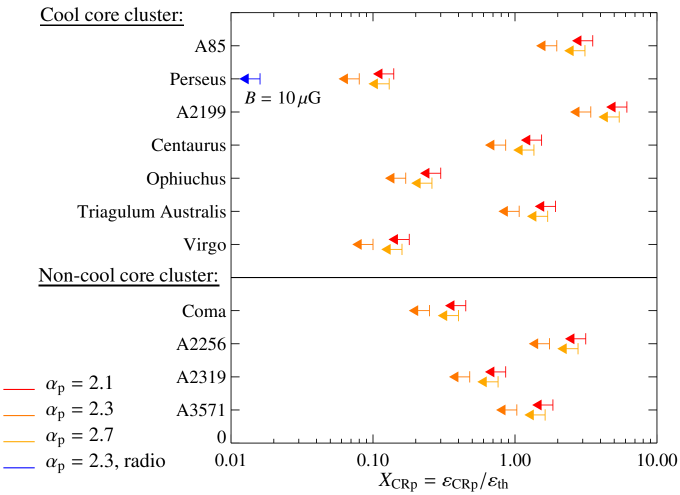
$$\varepsilon_{\mathrm{CRp}} = X_{\mathrm{CRp}}\, \varepsilon_{\mathrm{th}}$$

Gamma-ray flux of the Perseus galaxy cluster

IC emission of secondary CRes ($B = 0$), π^0-decay induced γ-ray emission:



Upper limits on X_{CRp} using EGRET limits



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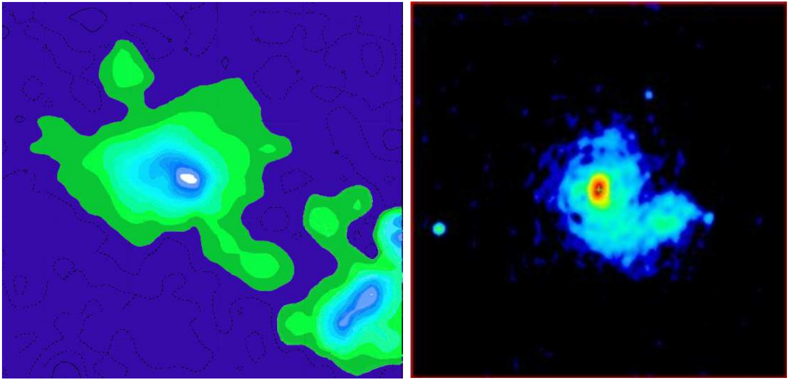
Radio halos: Coma and Perseus



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

largest emission diameter ~ 3 Mpc

(Credit: Deiss/Effelsberg)

Perseus mini-halo, $\nu = 1.4$ GHz,

largest emission size ~ 0.5 Mpc

(Credit: Pedlar/VLA)

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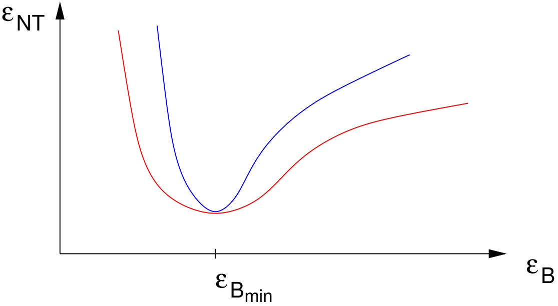
Minimum energy criterion (MEC): the idea

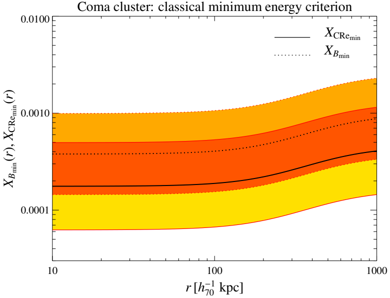
- $\varepsilon_{\mathrm{NT}} = \varepsilon_B + \varepsilon_{\mathrm{CRp}} + \varepsilon_{\mathrm{CRe}}$
  $\rightarrow$ minimum energy criterion: $\left.\frac{\partial \varepsilon_{\mathrm{NT}}}{\partial \varepsilon_B}\right|_{j_\nu} \overset{!}{=} 0$
- classical MEC: $\varepsilon_{\mathrm{CRp}} = k_{\mathrm{p}} \varepsilon_{\mathrm{CRe}}$
- hadronic MEC: $\varepsilon_{\mathrm{CRp}} \propto (\varepsilon_B + \varepsilon_{\mathrm{CMB}})\, \varepsilon_B^{-(\alpha_\nu+1)/2}$

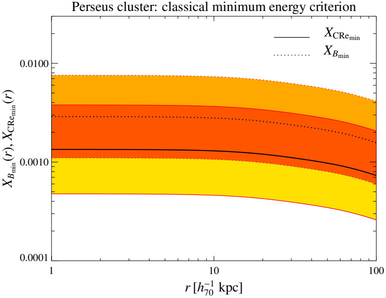


defining tolerance levels: deviation from minimum by one e-fold

Classical minimum energy criterion

$$X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\mathrm{th}}}(r)$$

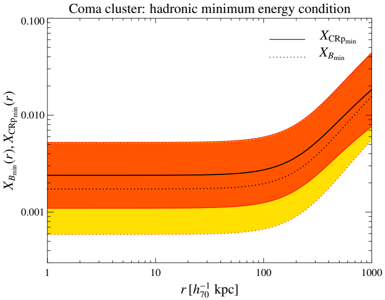


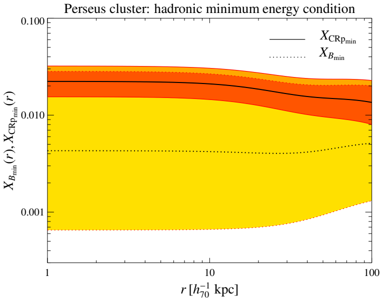


$$B_{\mathrm{Coma}}(0) = 1.1^{+0.7}_{-0.4}\,\mu\mathrm{G} \qquad B_{\mathrm{Perseus}}(0) = 7.2^{+4.5}_{-2.8}\,\mu\mathrm{G}$$

Hadronic minimum energy criterion

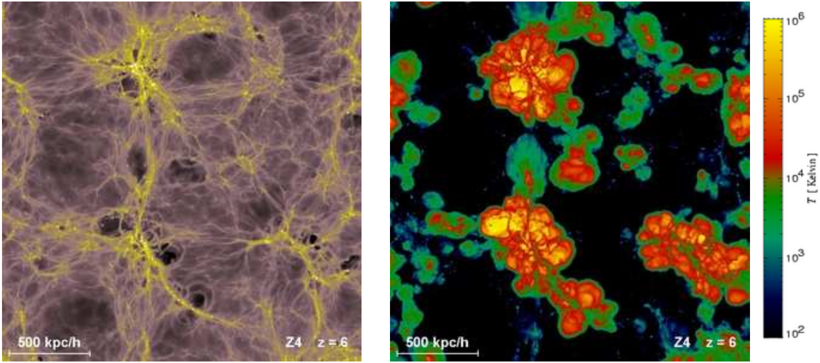
$$X_{\mathrm{CRp}}(r) = \frac{\varepsilon_{\mathrm{CRp}}}{\varepsilon_{\mathrm{th}}}(r), \quad X_B(r) = \frac{\varepsilon_B}{\varepsilon_{\mathrm{th}}}(r)$$


Coma cluster: hadronic minimum energy condition


Perseus cluster: hadronic minimum energy condition

$$B_{\mathrm{Coma}}(0) = 2.4^{+1.7}_{-1.0}\,\mu\mathrm{G} \qquad B_{\mathrm{Perseus}}(0) = 8.8^{+13.8}_{-5.4}\,\mu\mathrm{G}$$

Cosmic rays in GADGET (Enßlin, Jubelgas, Pfrommer, Springel)



A galactic outflow seen at high redshift. Left: the projected gas density around some of the first star forming galaxies. Right: generated bubbles of hot gas, as seen in the temperature map (Springel & Hernquist 2002).

Potential effects of cosmic ray feedback

Mostly speculations so far

- Feedback on galactic scales:
  - Regulation of star formation efficiency due to extra CR pressure.
  - Driving Galactic outflows due to buoyant rise of CRs in star forming regions.
  - radiative cooling losses of galaxies altered by different CR cooling times → gas flow in halos might be affected.
- Feedback on larger scales:
  - Changing the total baryonic fraction that ends up in collapsed structures due to effects of different CR cooling times and equation of state.
  - CRs might change the absorption properties at high redshift.

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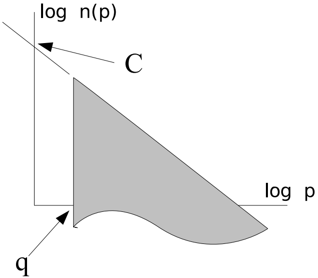
Philosophy and description

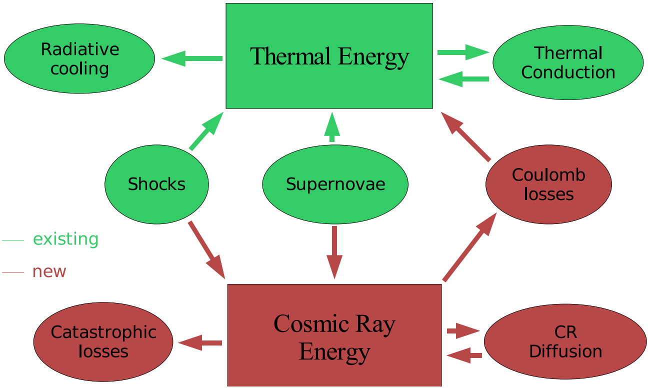
Our model describes the CR physics by three adiabatic invariants

- 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).
  $\rightarrow$ determines CR energy density and pressure



In adiabatic processes, q and C scale only with the density. Non-adiabatic processes are mapped into changes of the adiabatic constants q_0 and C_0.

Cosmic rays in GADGET– flowchart



Thermal Energy

Radiative cooling

Thermal Conduction

Shocks

Supernovae

Coulomb losses

— existing

— new

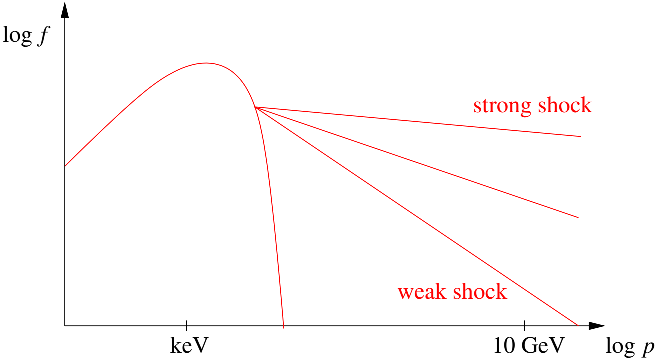
Cosmic Ray Energy

Catastrophic losses

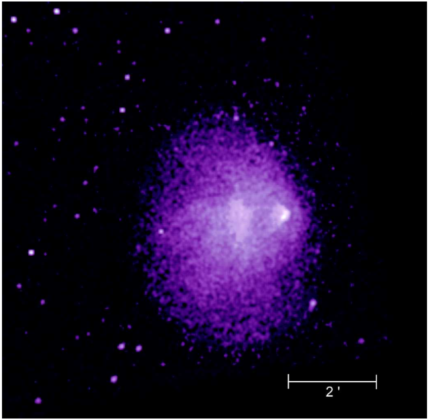
CR Diffusion

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.

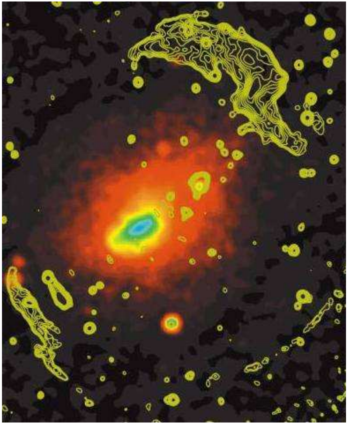


Observations of cluster shock waves



1E 0657-56 (“Bullet cluster”)

(NASA/SAO/CXC/M.Markevitch et al.)



Abell 3667

(Radio: Austr.TC Array. X-ray: ROSAT/PSPC.)

Applications for a shock finder in SPH simulations

- cosmological shocks dissipate gravitational energy into thermal gas energy
- shock waves are tracers of the large scale structure and contain information about its dynamical history (warm-hot intergalactic medium)
- shocks accelerate energetic particles (cosmic rays) through diffusive shock acceleration at structure formation shocks
- cosmic ray injection by supernova remnants (when combined with radiative dissipation and star formation)
- shock-induced star formation in the interstellar medium

Idea of the Mach number finder

- 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 $\upsilon_1 = \mathcal{M}_1 c_1$)

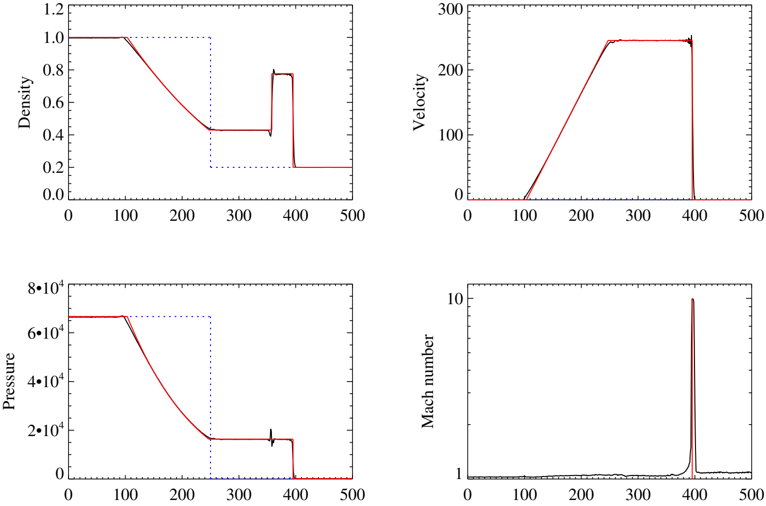
Using the entropy conserving formalism of Springel & Hernquist 2002 ($A(s) = P\rho^{-\gamma}$ is the entropic function):

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

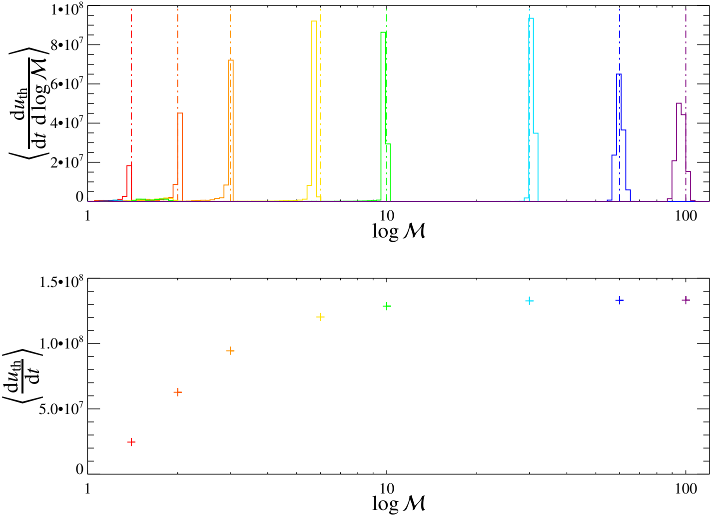
Complications of the numerical implementation

- Broad Mach number distributions $f(\mathcal{M}) = \frac{\mathrm{d}u_\mathrm{th}}{\mathrm{d}t\,\mathrm{d}\log\mathcal{M}}$ because particle quantities within the (broadened) shock front do not correspond to those of the pre-shock regime. Solution: introduce decay time $\Delta t_\mathrm{dec} = f_h h/(\mathcal{M}_1 c)$, meanwhile the Mach number is set to the maximum (only allowing for its rise in the presence of multiple shocks).
- Weak shocks imply large values of Δt_dec:
  Solution: $\Delta t_\mathrm{dec} = \min[f_h h/(\mathcal{M}_1 c), \Delta t_\mathrm{max}]$
- Strong shocks with $\mathcal{M} > 5$ are slightly underestimated because there is no universal shock length.
  Solution: recalibrate strong shocks!

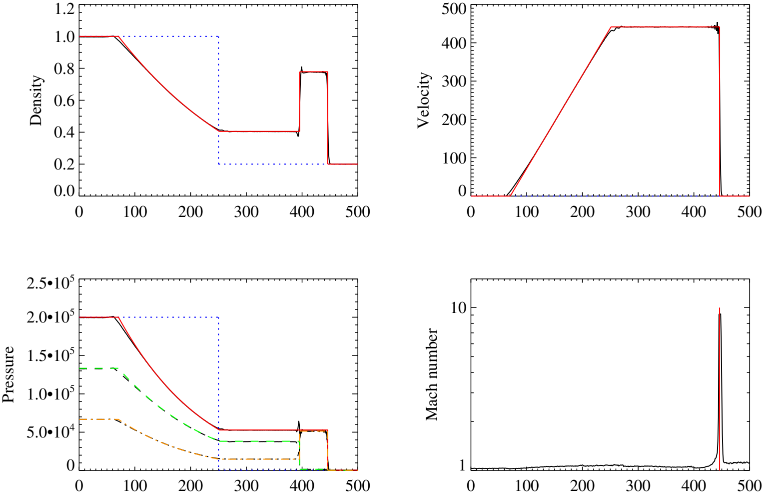
Shock tube ($\mathcal{M} = 10$): thermodynamics



Shock tube: Mach number statistics



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



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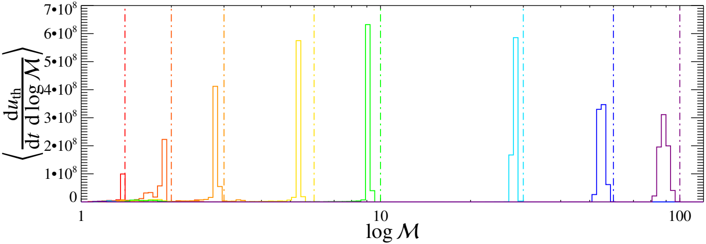
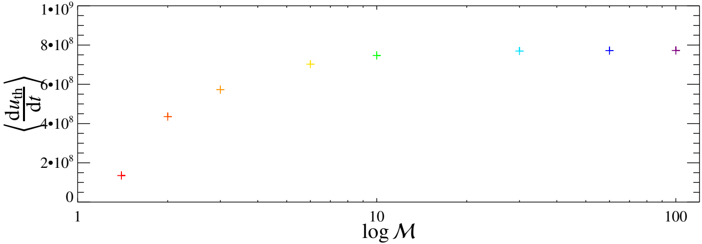
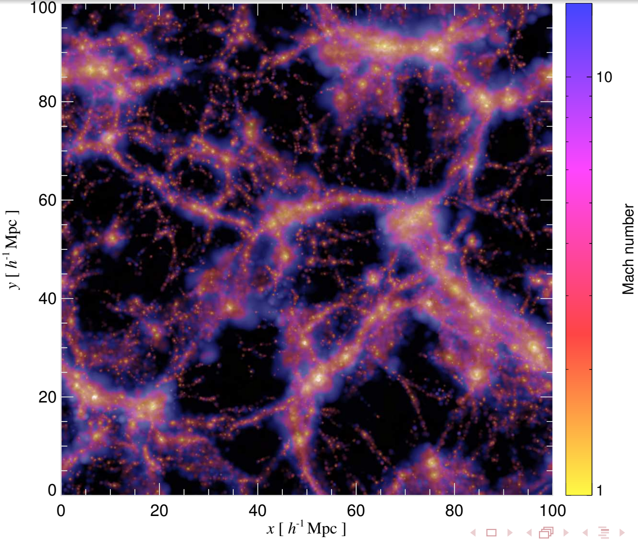




Cosmological Mach numbers: weighted by $\varepsilon_{\mathrm{diss}}$



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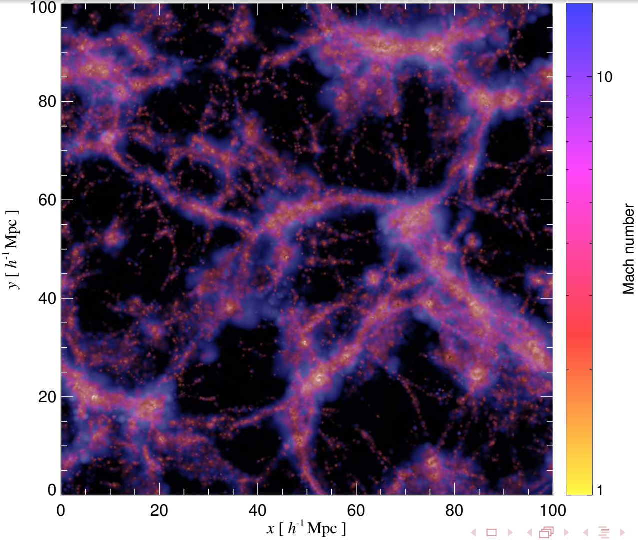

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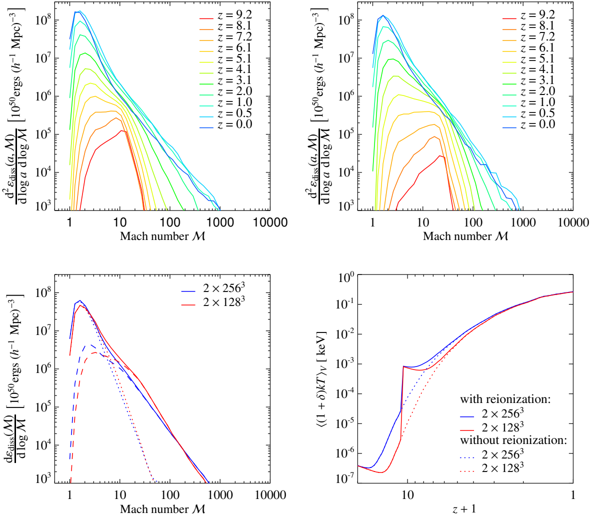
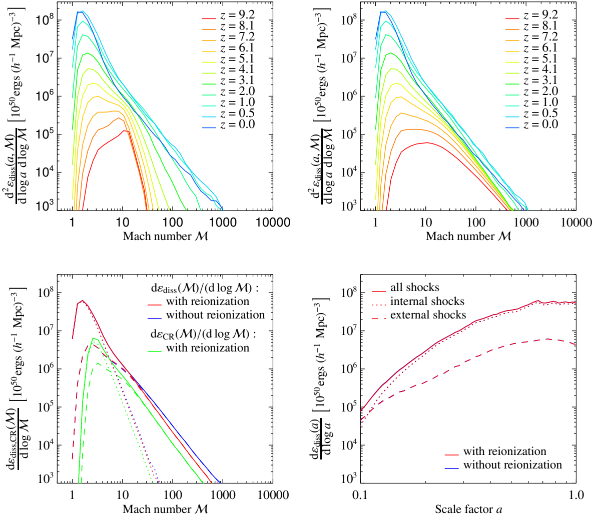
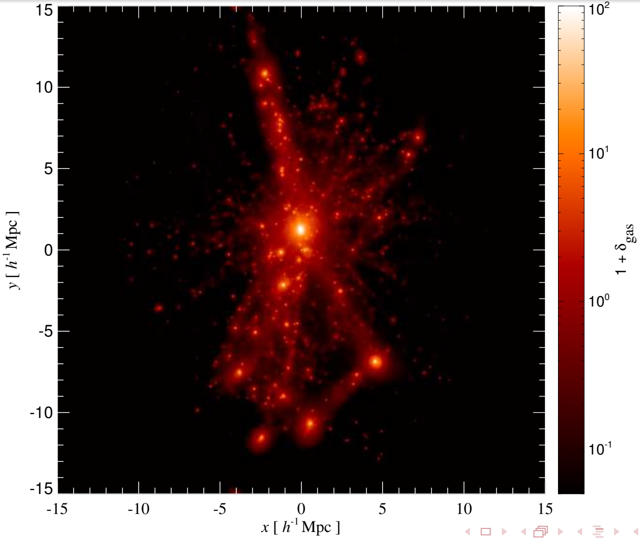
Cosmological statistics: resolution study



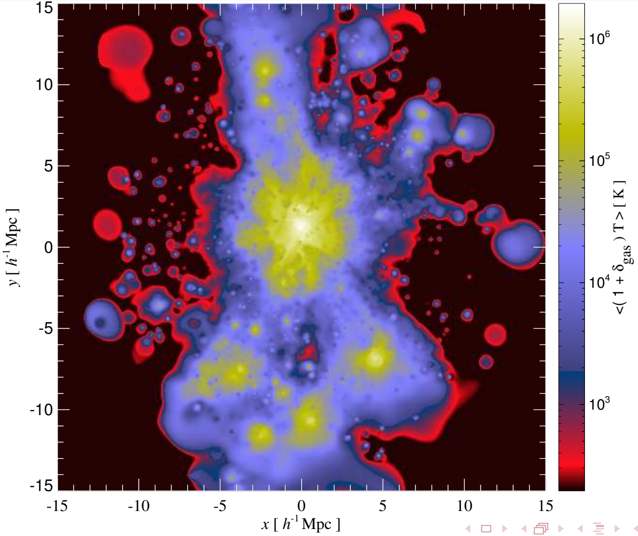
Cosmological statistics: influence of reionization



Adiabatic cluster simulation: gas density



Mass weighted temperature



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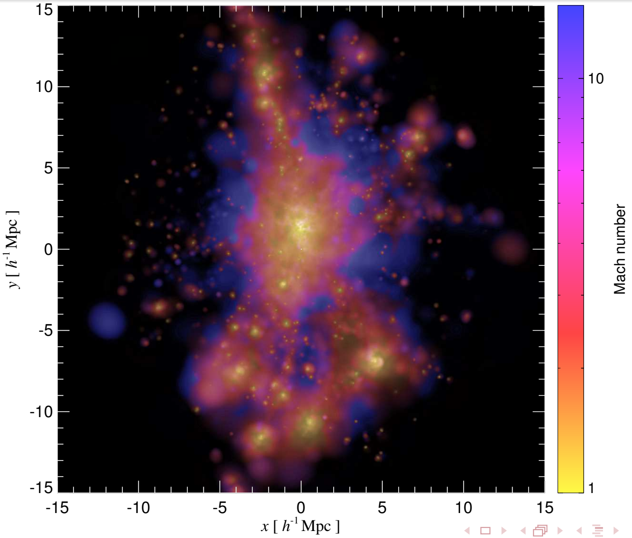
Mach number distribution weighted by $\varepsilon_{\rm diss}$



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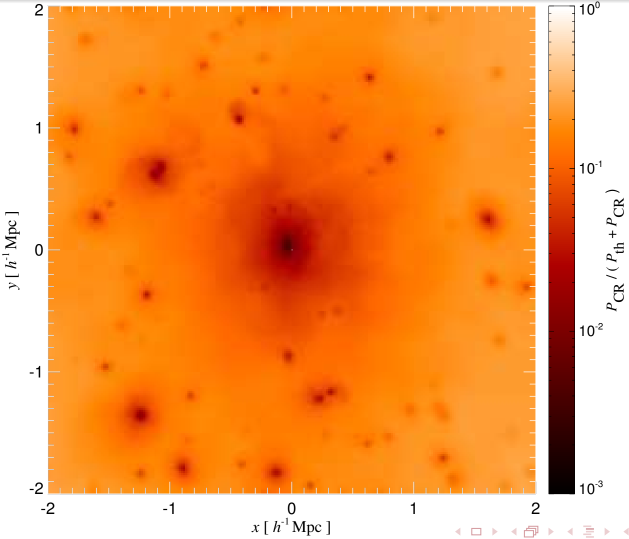
Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



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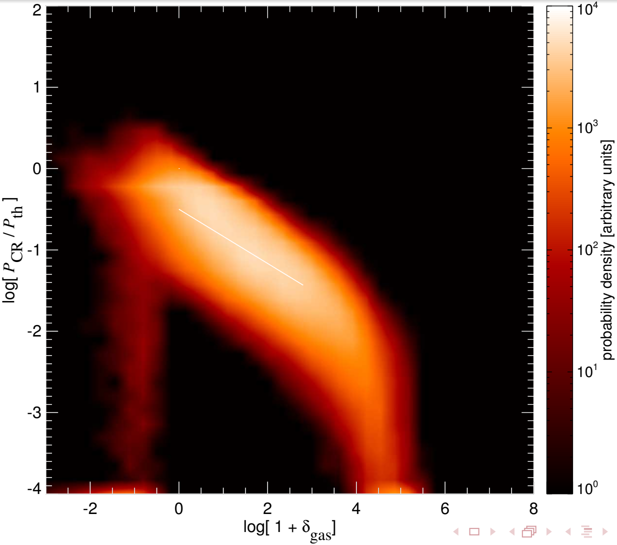
Equation of state for CRs



Summary

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- Radio halos might be of hadronic origin as our simulations suggests.
- Huge potential and predictive power of cosmological CR simulations/Mach number finder → provides detailed γ-ray/radio emission maps

- Outlook
  - Galaxy evolution: influence on energetic feedback, star formation, and galactic winds
  - Exploring the CR influence on the absorption properties at high redshift.

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