Cosmological shock waves in SPH simulations

Exploring cosmic ray feedback

Christoph Pfrommer

Canadian Institute for Theoretical Astrophysics, Toronto

Mar. 20 2006 / "Contents and Structures of the Universe", Rencontres de Moriond

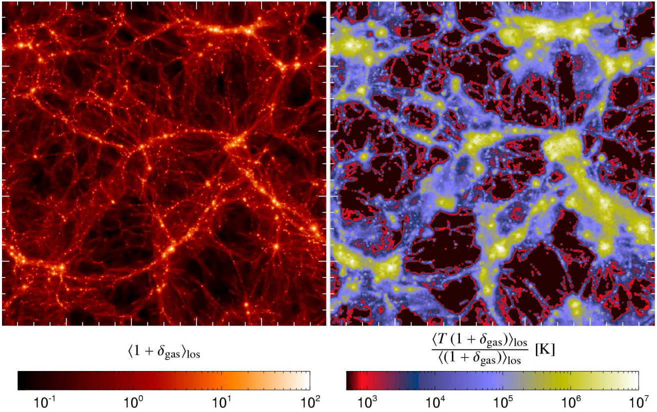
CITA–ICAT

Outline

1. Cosmological shock waves
   - Cosmic rays in GADGET
   - Mach number finder
   - Cosmological and cluster simulations
2. Cosmic rays in galaxy clusters
   - Cluster radio halos
   - Energetically preferred CR pressure profiles
   - CR pressure influences Sunyaev-Zel'dovic effect

CITA–ICAT

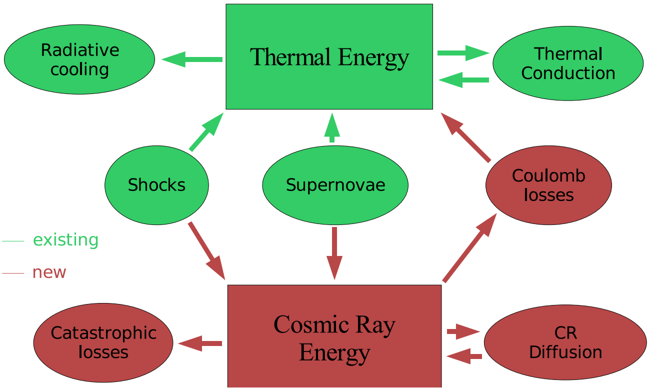
Cosmic rays in GADGET (Pfrommer, Springel, Enßlin, Jubelgas, 2006, MNRAS)



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

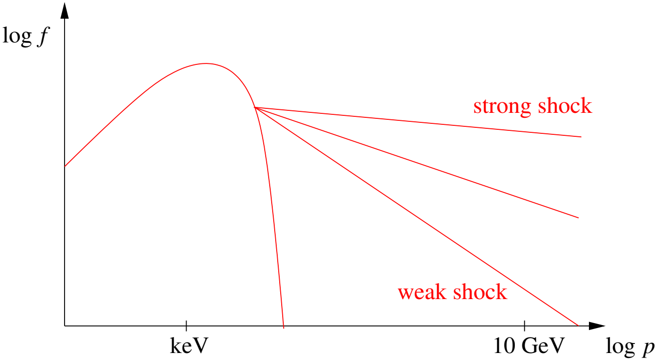
CITA–ICAT

Cosmic rays in GADGET– flowchart



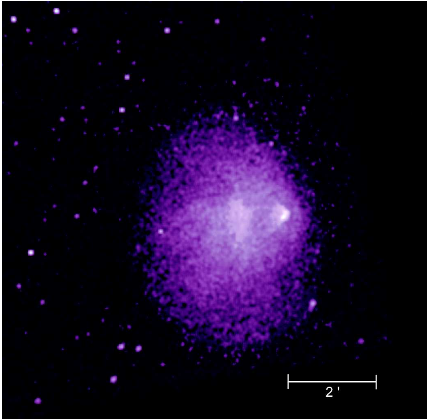
Diffusive shock acceleration – Fermi 1 mechanism

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.



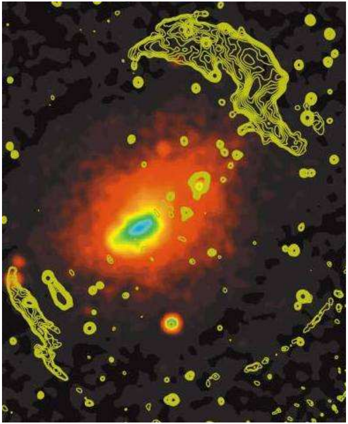
CITA–ICAT

Observations of cluster shock waves



1E 0657-56 (“Bullet cluster”)

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



Abell 3667

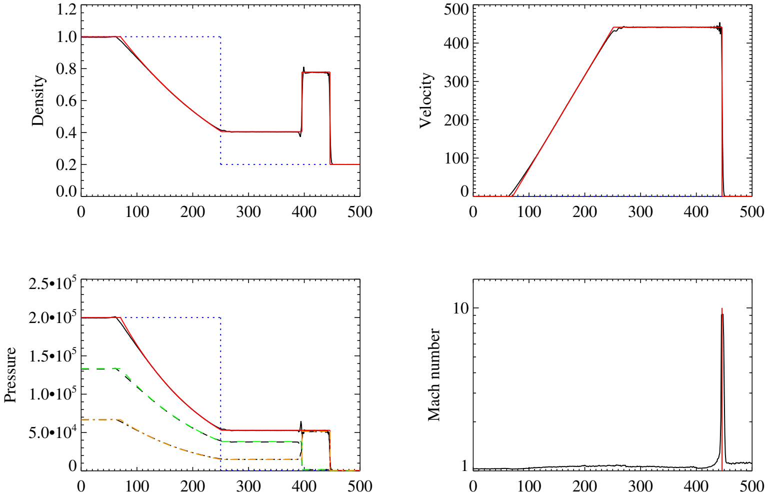
(Radio: Austr.TC Array. X-ray: ROSAT/PSPC.)

CITA–ICAT

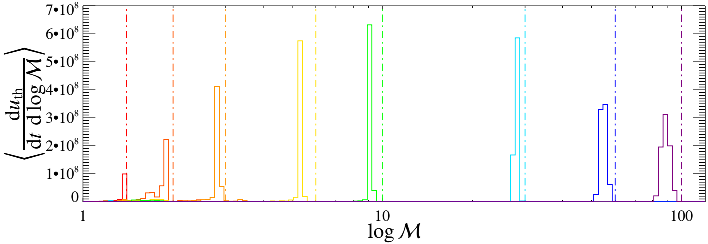
Motivation for the Mach number finder

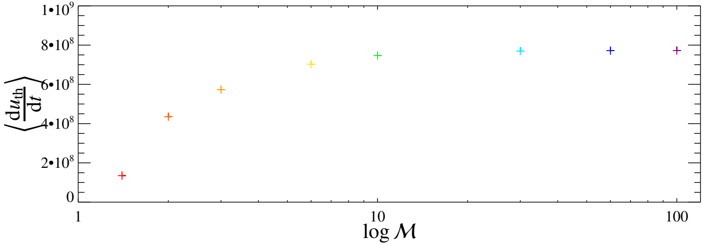
- cosmological shocks dissipate gravitational energy into thermal gas energy: where and when is the gas heated, and which shocks are mainly responsible for it?
- shock waves are tracers of the large scale structure and contain information about its dynamical history (warm-hot intergalactic medium)
- 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

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

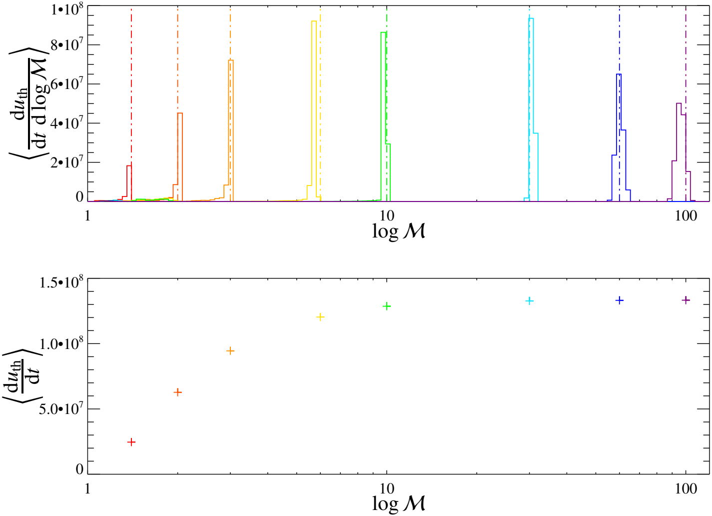


Shock tube (CRs & gas): Mach number statistics

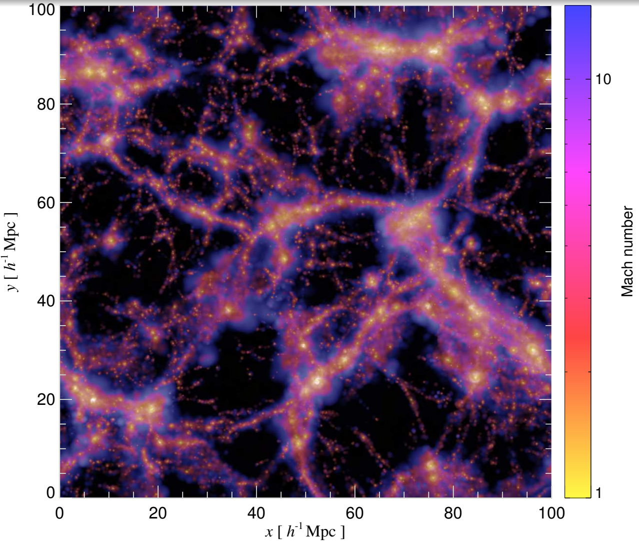




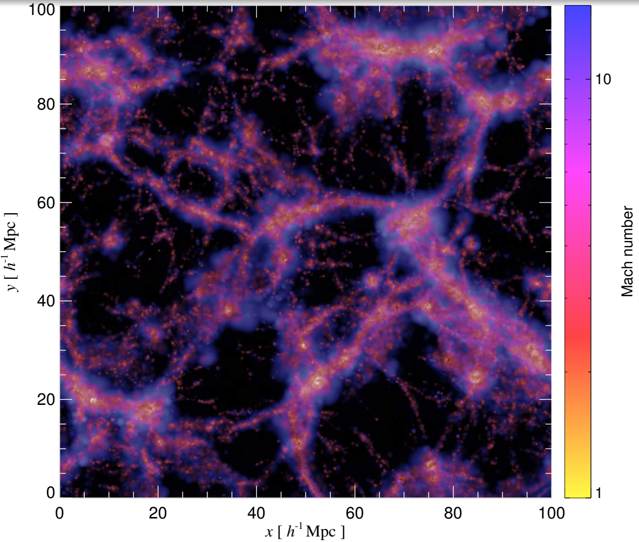
Shock tube (th. gas): Mach number statistics



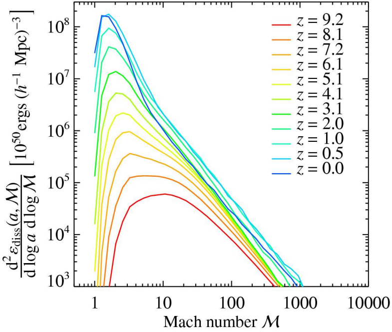
Cosmological Mach numbers: weighted by $\varepsilon_{\mathrm{diss}}$



Cosmological Mach numbers: weighted by ε_{CR}



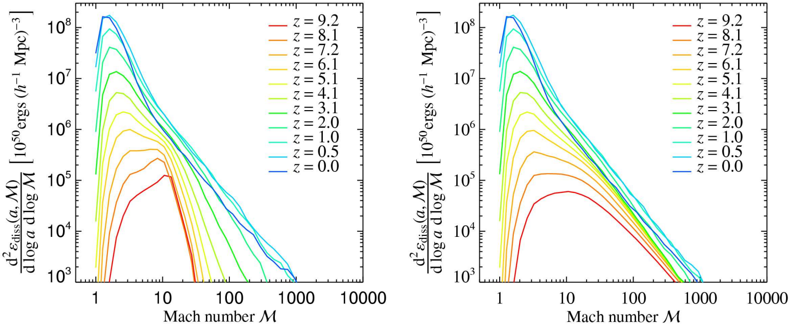
Cosmological Mach number statistics



- 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

CITA–ICAT

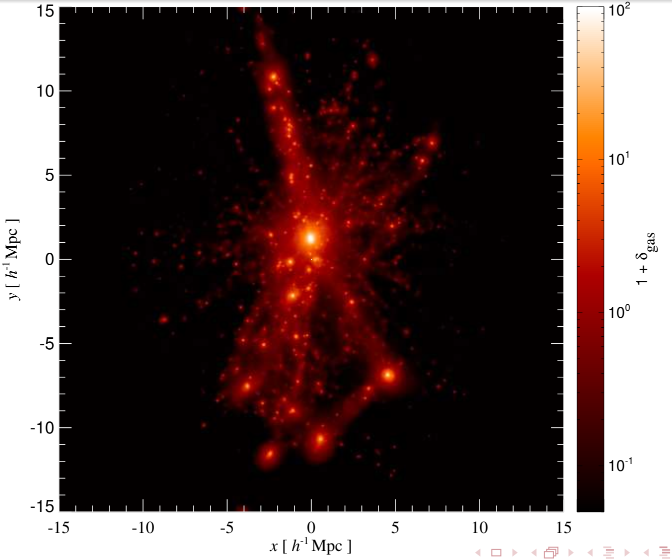
Cosmological statistics: influence of reionization



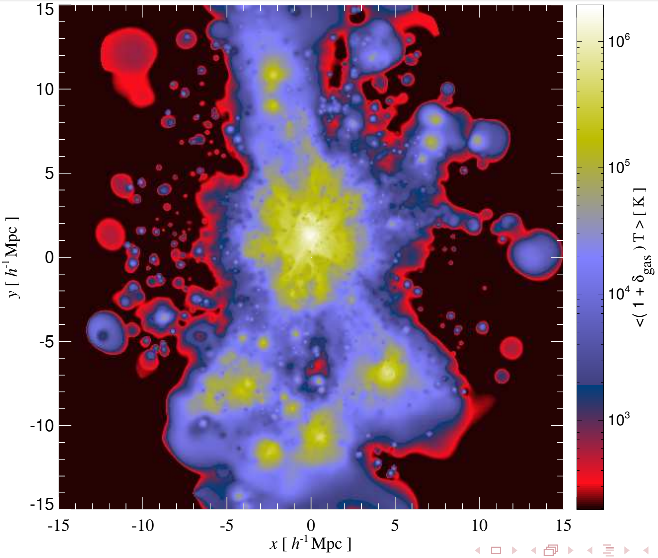
- reionization epoch at $z_{\text{reion}} = 10$ suppresses efficiently strong shocks at $z < z_{\text{reion}}$ due to jump in sound velocity
- cosmological constant causes structure formation to cease

CITA–ICAT

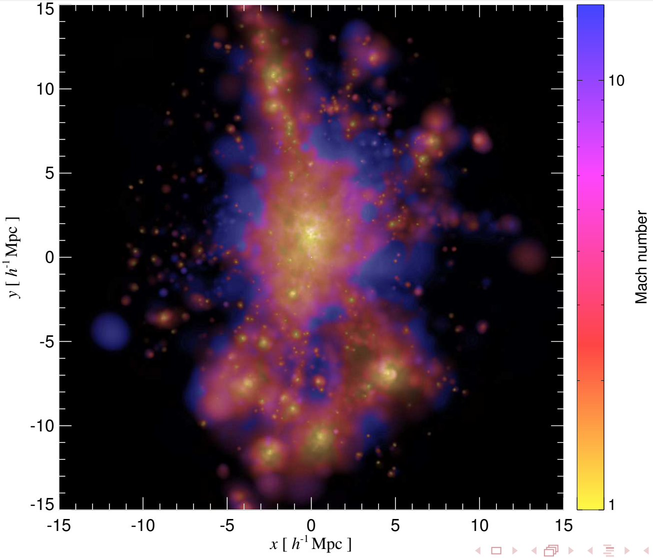
Adiabatic cluster simulation: gas density



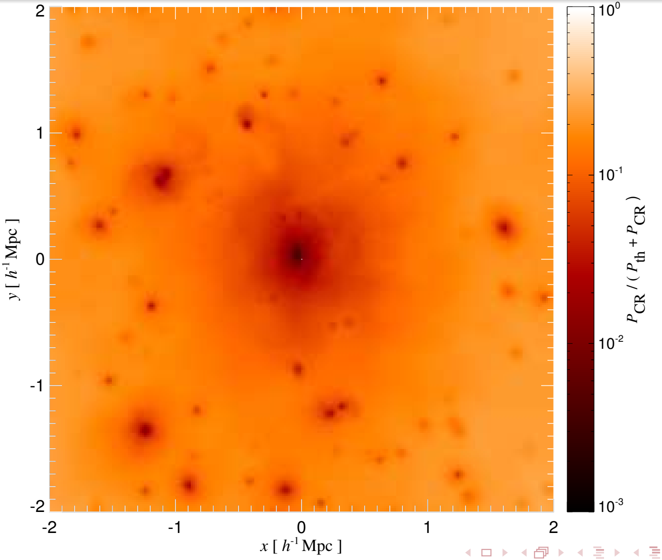
Mass weighted temperature



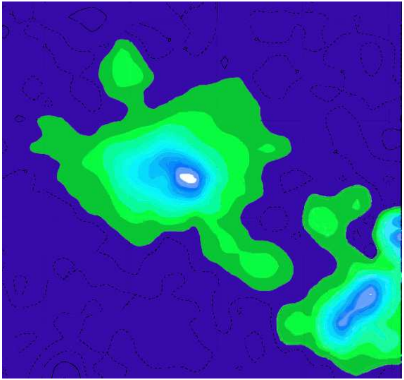
Mach number distribution weighted by $\varepsilon_{\rm diss}$



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



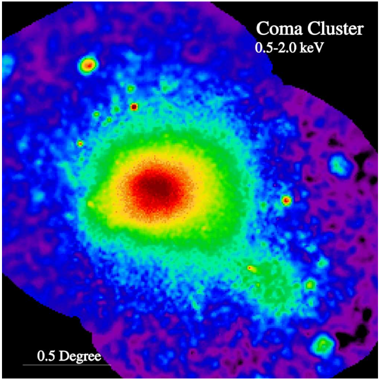
Radio halos as window for non-equilibrium processes



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)

CITA–ICAT

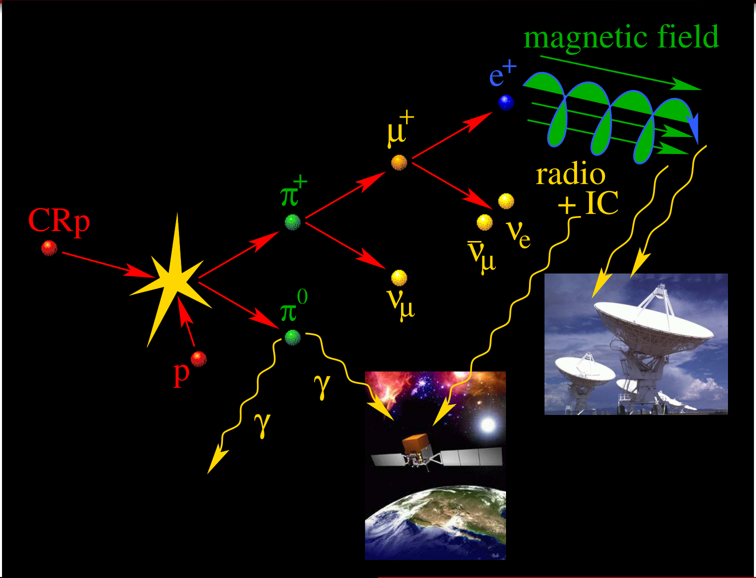
Models for radio synchrotron halos in clusters

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)

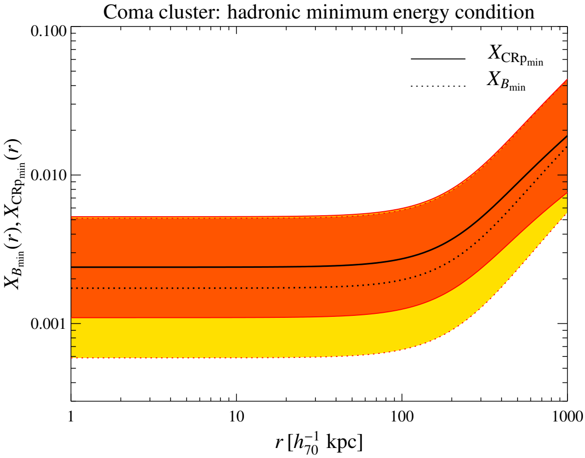
CITA–ICAT

Hadronic cosmic ray proton interaction



CITA–ICAT

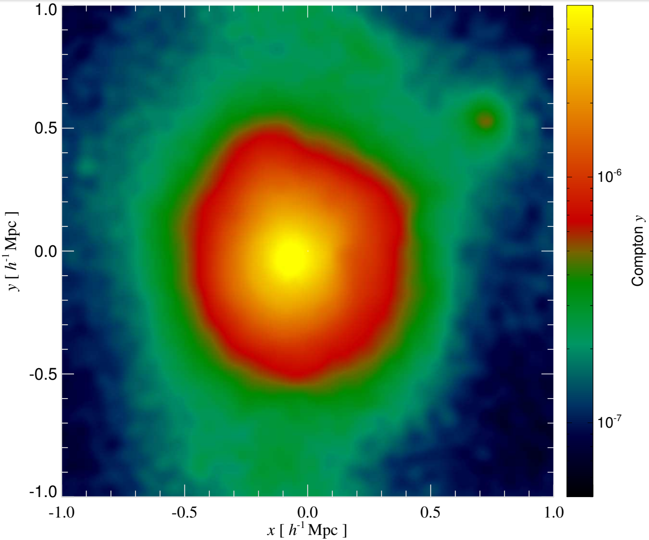
Energetically preferred CR pressure profiles



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

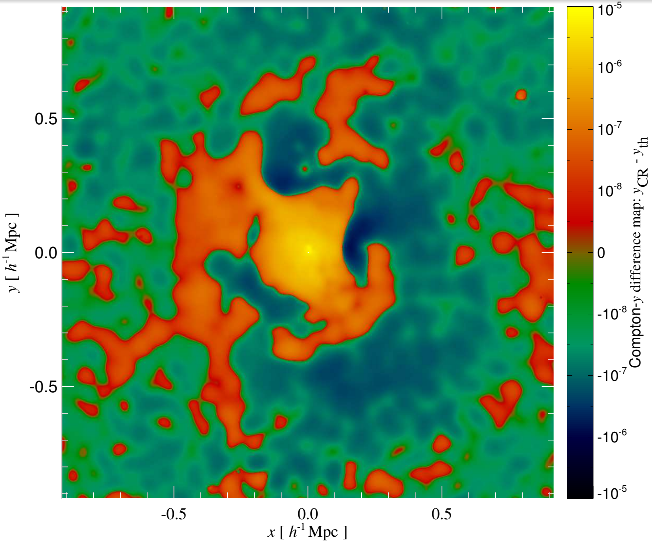
CITA–ICAT

Compton *y* parameter in radiative cluster simulation



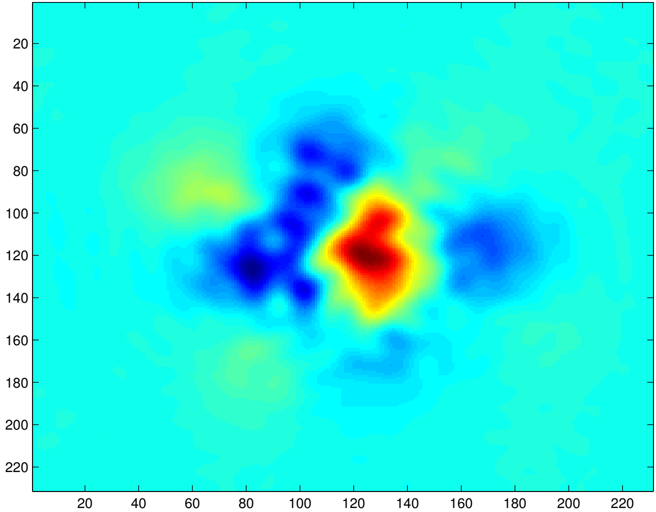
CITA–ICAT

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



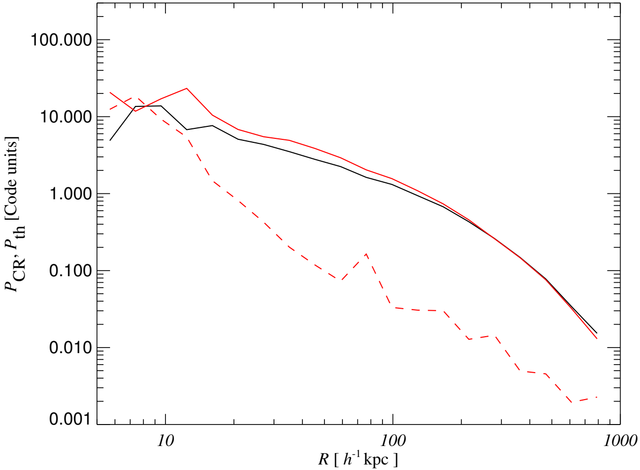
CITA–ICAT

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



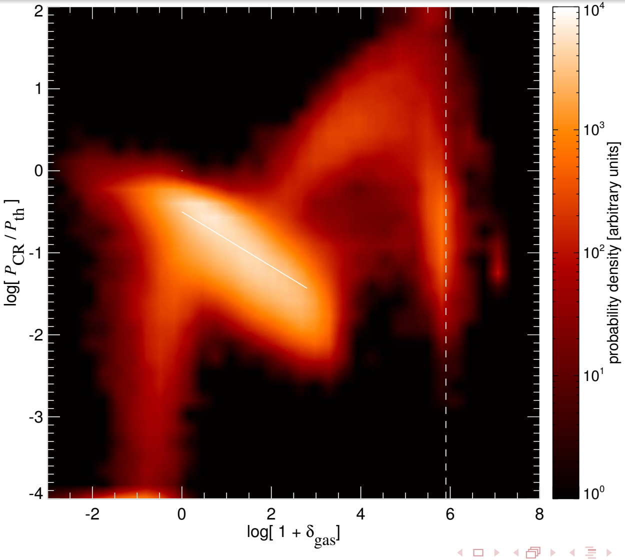
CITA–ICAT

Pressure profiles with and without CRs



CITA–ICAT

Phase-space diagram of radiative cluster simulation



CITA–ICAT

Summary

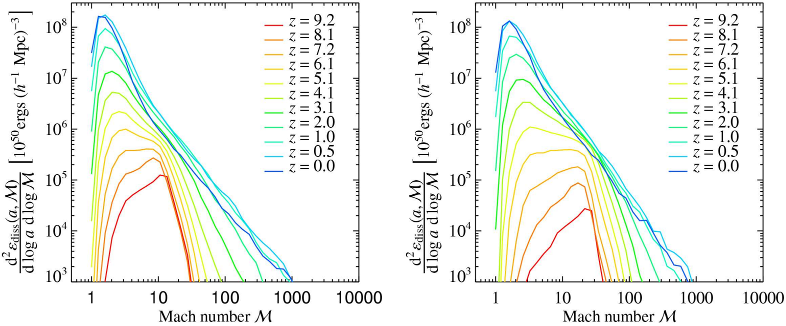
- Understanding non-thermal processes is crucial for using clusters as cosmological probes (high-z scaling relations).
- Radio halos might be of hadronic origin as our simulations suggests $\rightarrow$ tracer of structure formation
- Dynamical CR feedback influences Sunyaev-Zel'dovic effect

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

CITA–ICAT

Cosmological statistics: resolution study

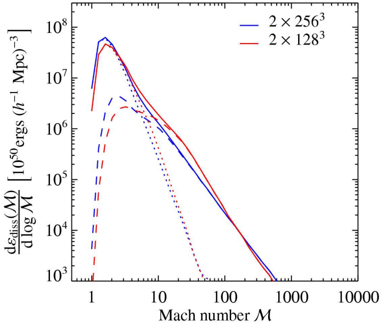
Differential distributions: 2×256^3 versus 2×128^3

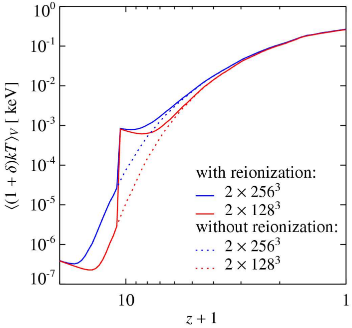


- more energy is dissipated at later times
- mean Mach number decreases with time
- differential Mach number distributions are converged for $z < 3$

CITA–ICAT

Cosmological statistics: resolution study





- in higher resolution simulations structure forms earlier
- more energy is dissipated in shocks internal to collapsed structures than in external shocks of pristine gas
- integrated Mach number distribution converged

CITA–ICAT

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):

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

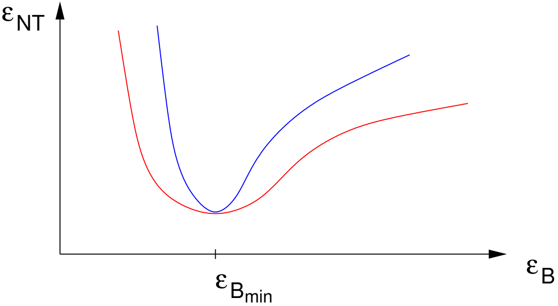
$$\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)\mathcal{M}_1^2}{(\gamma-1)\mathcal{M}_1^2 + 2}$$

$$\frac{P_2}{P_1} = \frac{2\gamma\mathcal{M}_1^2 - (\gamma-1)}{\gamma+1}$$

CITA–ICAT

Minimum energy criterion (MEC): the idea

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

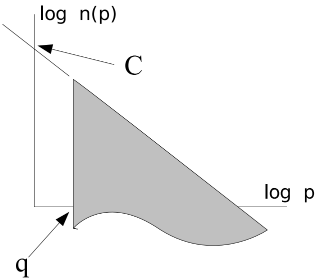


defining tolerance levels: deviation from minimum by one e-fold

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.

CITA–ICAT