Cosmological shock waves and cosmic rays in hydrodynamical cluster simulations

Christoph Pfrommer[1]

in collaboration with

Volker Springel[2], Torsten Enßlin[2], Martin Jubelgas[2]

[1]Canadian Institute for Theoretical Astrophysics, Canada

[2]Max-Planck Institute for Astrophysics, Germany

August, 10 2006
Heating versus cooling conference, MPA Garching

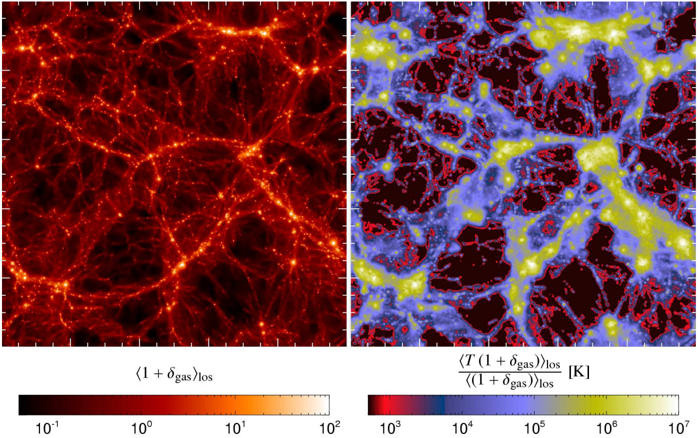
CITA–ICAT

Outline

1. Introduction
    - Violent structure formation
    - Cosmic rays in GADGET
2. Cosmological shock waves
    - Motivation
    - Cosmological simulations
3. Cosmic rays in coooling core clusters
    - Radiative high-resolution cluster simulations
    - Modified X-ray emission and Sunyaev-Zel'dovic effect
    - Cosmic ray induced emission processes

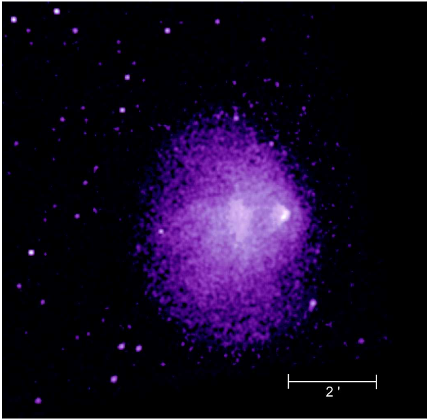
CITA–ICAT

Gravitational heating by shocks



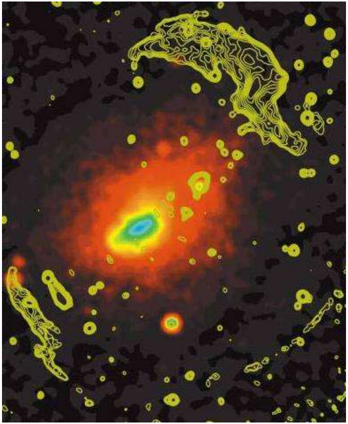
The "cosmic web" today. *Left:* the projected gas density in a cosmological simulation. *Right:* gravitationally heated intracluster medium through cosmological shock waves.

Observations of cluster shock waves



1E 0657-56 (“Bullet cluster”)

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



Abell 3667

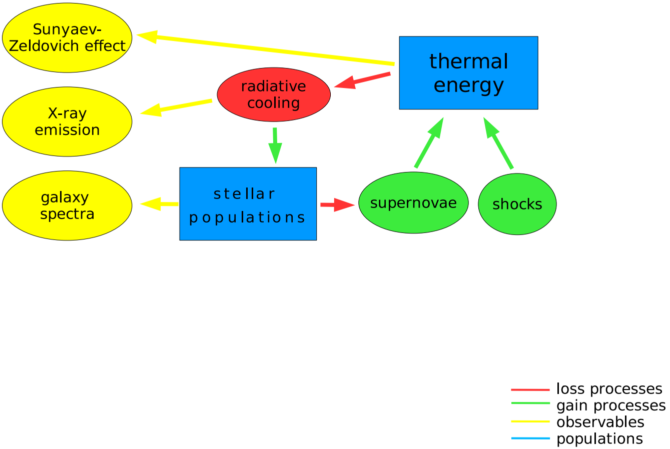
(Radio: Austr.TC Array. X-ray: ROSAT/PSPC.)

CITA–ICAT

Radiative simulations – flowchart

Cluster observables:

Physical processes in clusters:



Sunyaev-Zeldovich effect

X-ray emission

galaxy spectra

radiative cooling

thermal energy

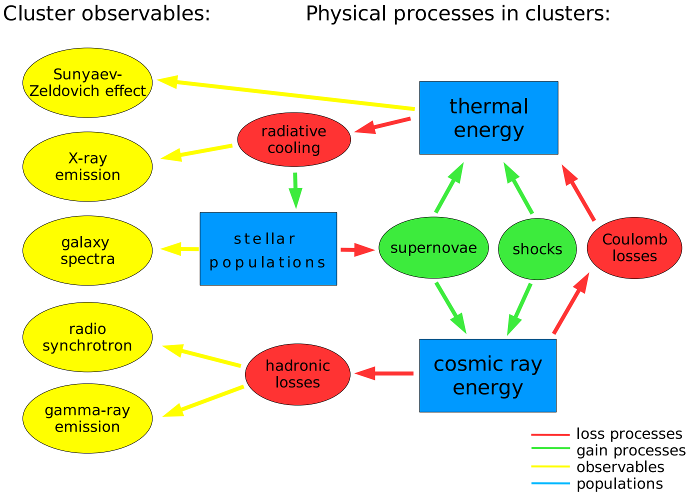
stellar populations

supernovae

shocks

🟥 loss processes
🟩 gain processes
🟨 observables
🟦 populations

Radiative simulations with cosmic rays



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

CITA–ICAT

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

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

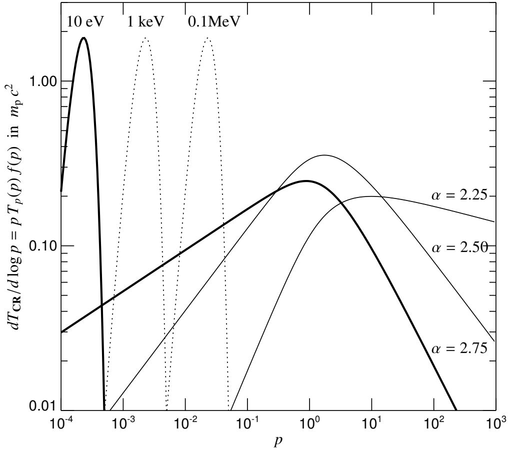
Assumptions:

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

CITA–ICAT

Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:



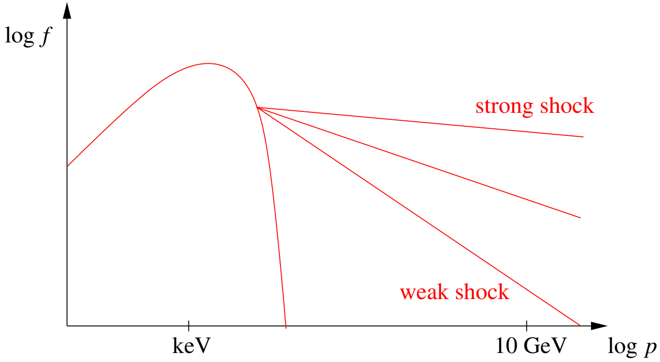
Motivation for studying shock waves:

- cosmological shocks dissipate gravitational energy into thermal gas energy: where and when is the gas heated, and which shocks are mainly responsible for it?
- 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

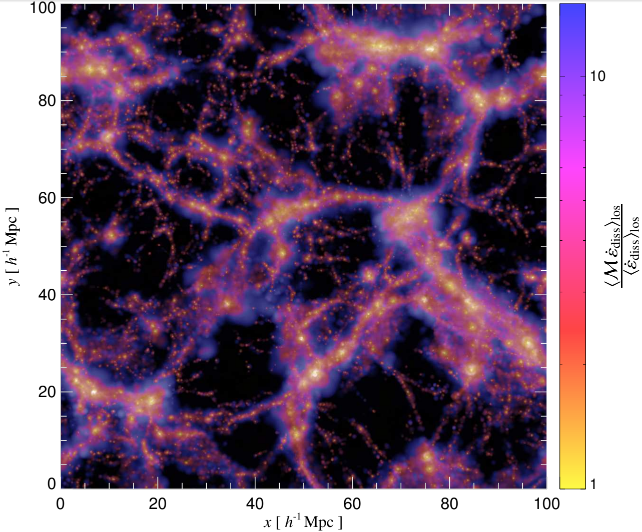
CITA–ICAT

Diffusive shock acceleration – Fermi 1 mechanism

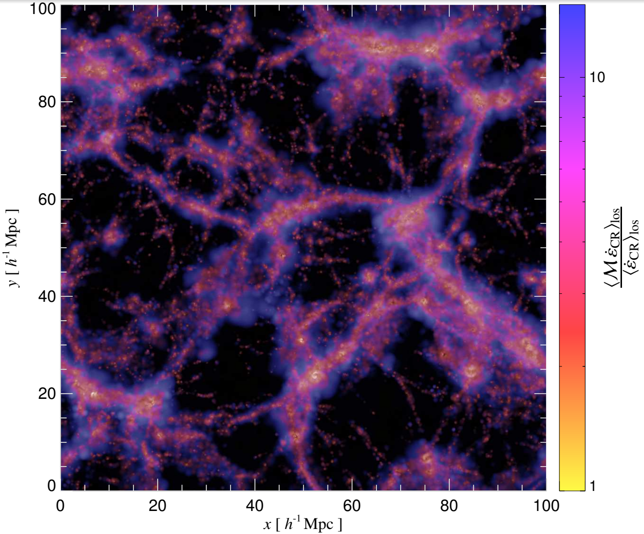
Cosmic rays gain energy $\Delta E/E \propto \upsilon_1 - \upsilon_2$ through bouncing back and forth the shock front. Accounting for the loss probability $\propto \upsilon_2$ of particles leaving the shock downstream leads to power-law CR population.



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

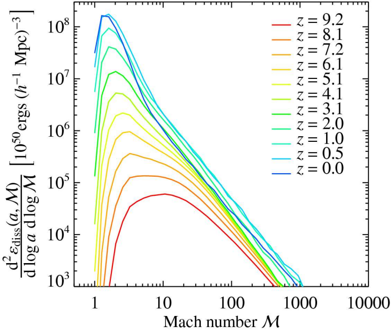


Cosmological Mach numbers: weighted by $\varepsilon_{\rm CR}$



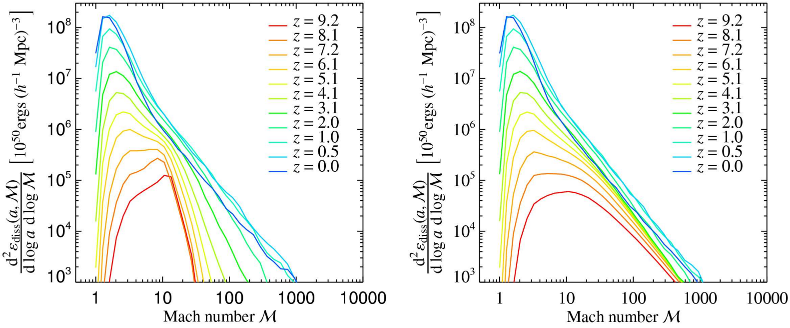
CITA–ICAT

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

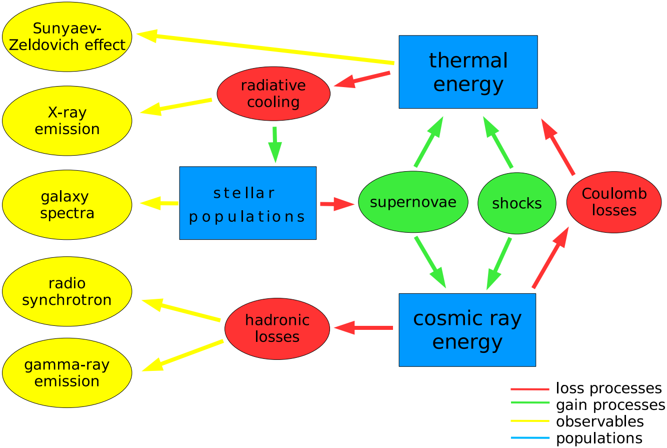


- reionization epoch at $z_{\rm reion} = 10$ suppresses efficiently strong shocks at $z < z_{\rm reion}$ due to jump in sound velocity
- cosmological constant causes structure formation to cease

CITA–ICAT

Cosmic rays in galaxy clusters

Cluster observables: Physical processes in clusters:



Sunyaev-Zeldovich effect

X-ray emission

galaxy spectra

radio synchrotron

gamma-ray emission

radiative cooling

stellar populations

hadronic losses

thermal energy

supernovae

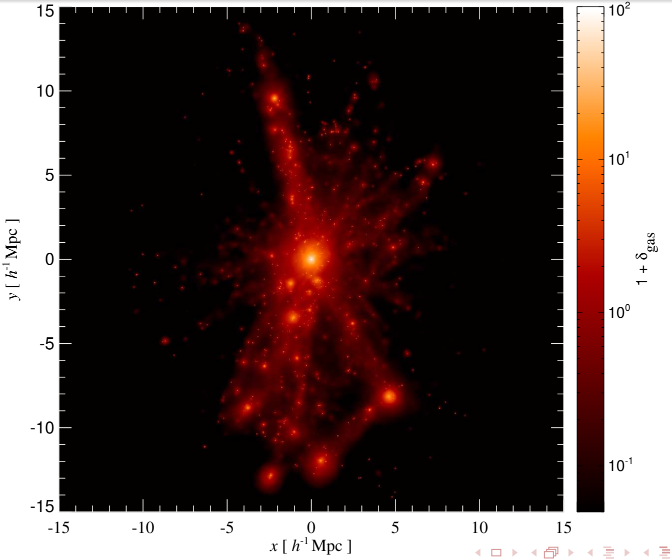
shocks

Coulomb losses

cosmic ray energy

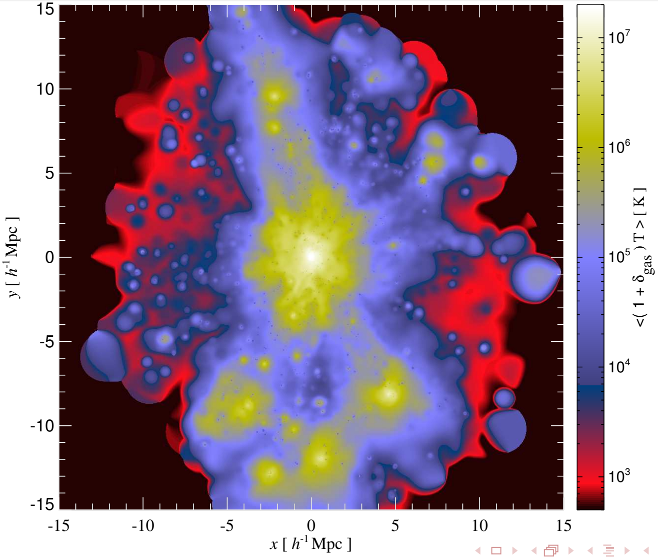
- 🟥 loss processes
- 🟩 gain processes
- 🟨 observables
- 🟦 populations

Radiative cool core cluster simulation: gas density

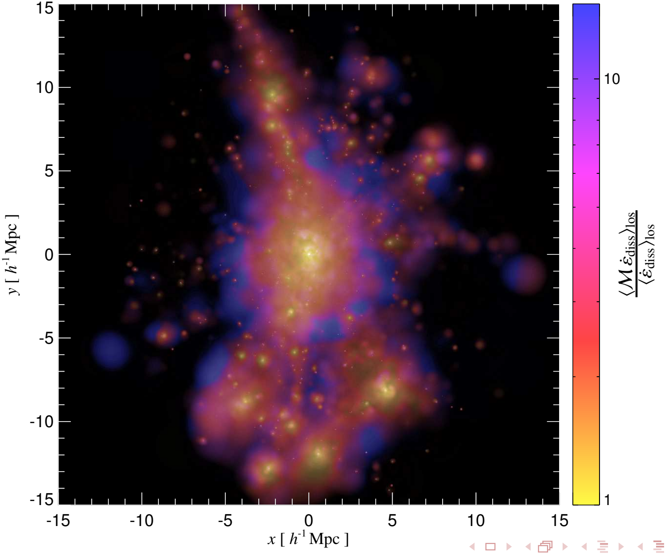


CITA–ICAT

Mass weighted temperature

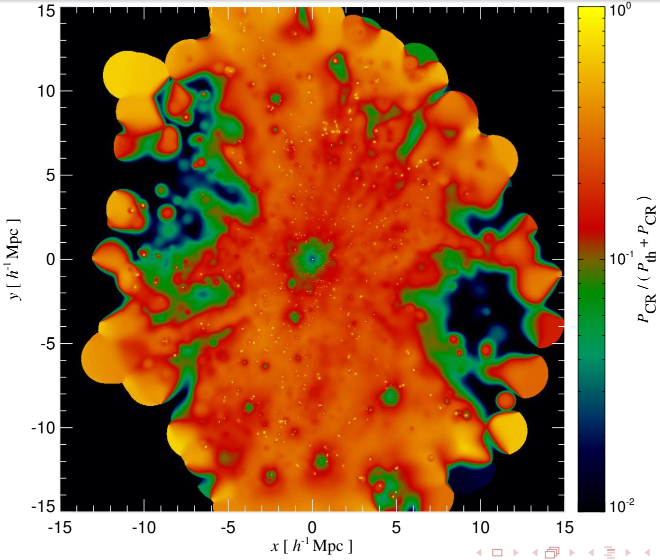


Mach number distribution weighted by $\varepsilon_{\text{diss}}$

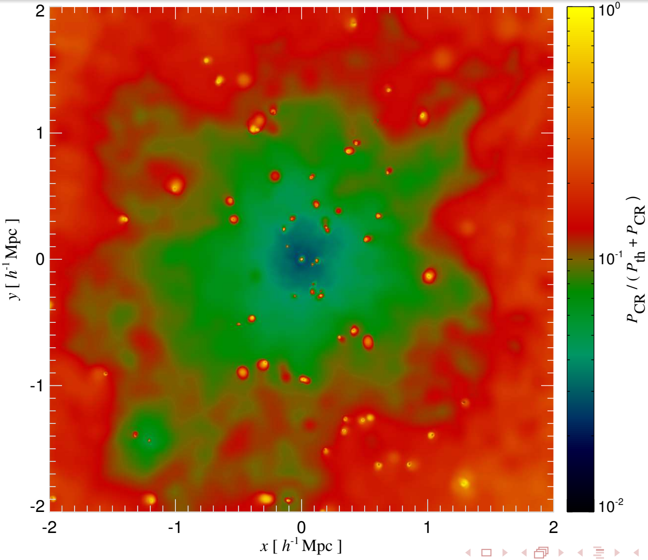


CITA–ICAT

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

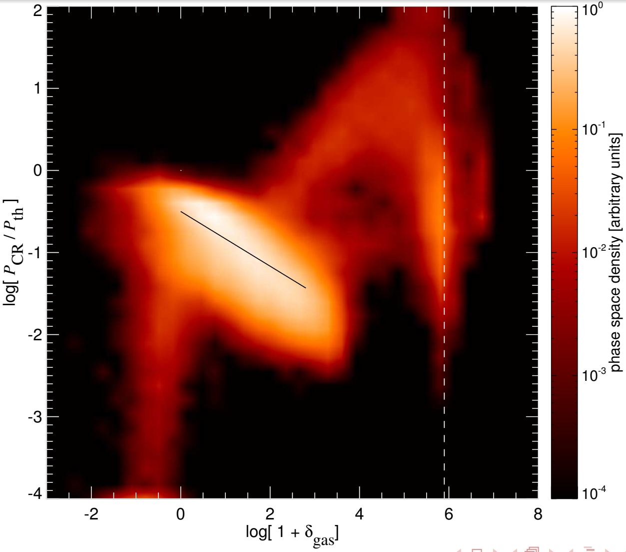


Relative CR pressure $P_{\rm CR}/P_{\rm total}$

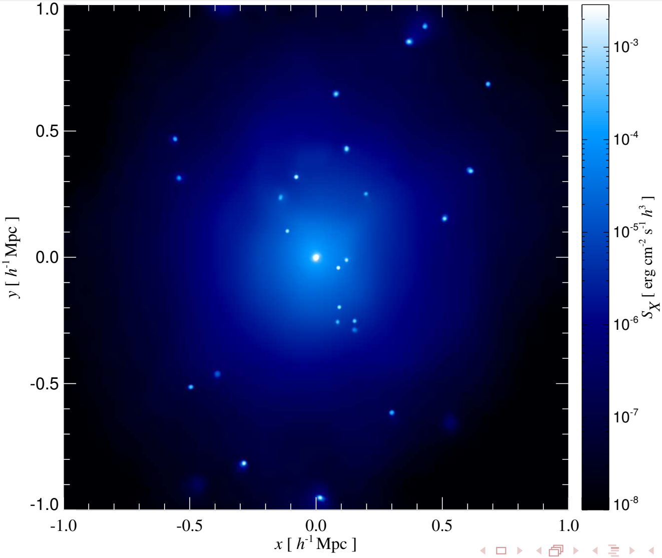


CITA–ICAT

Phase-space diagram of radiative cluster simulation

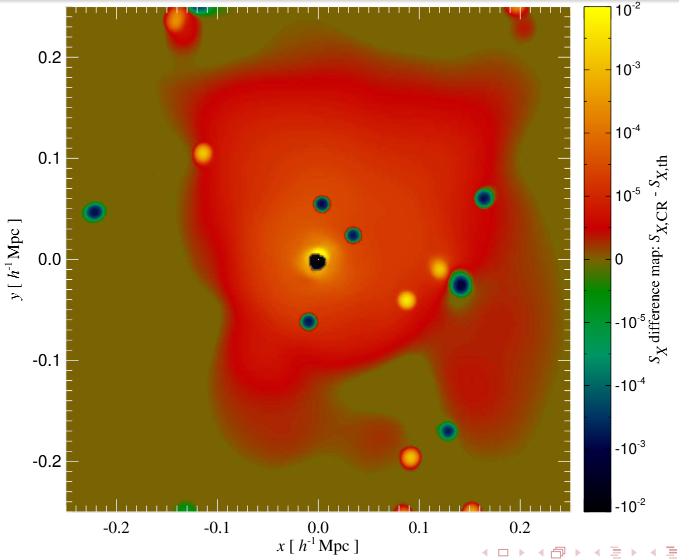


Thermal X-ray emission



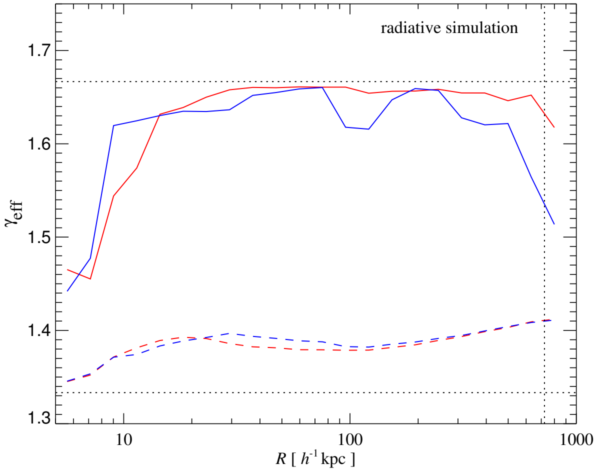
CITA–ICAT

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

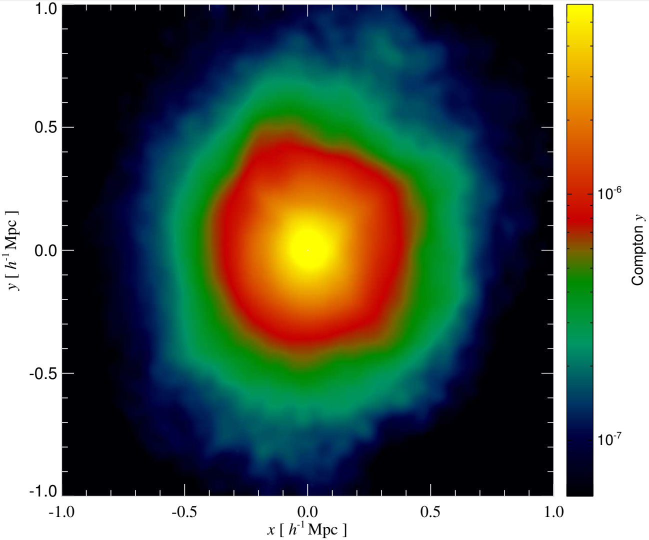


CITA–ICAT

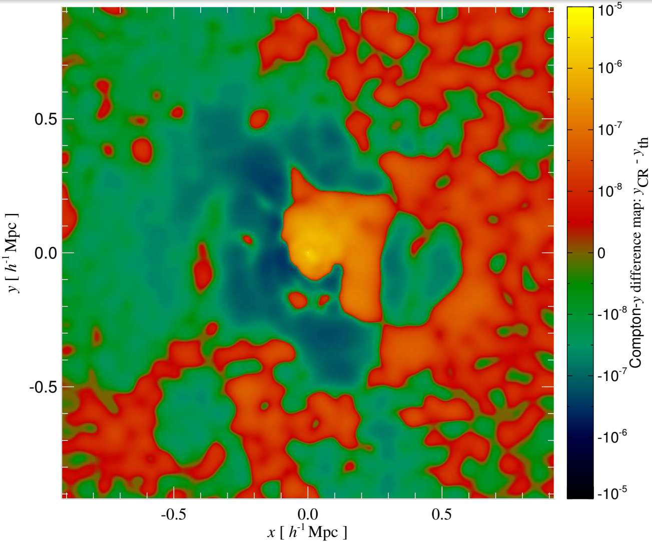
Softer effective adiabatic index of composite gas



Compton y parameter in radiative cluster simulation

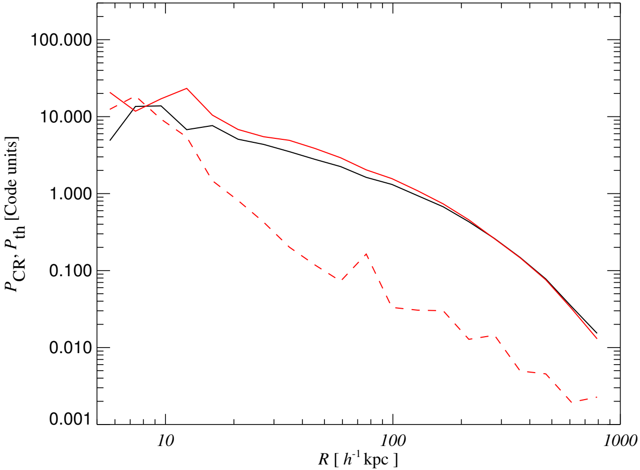


Compton y difference map: $y_{\mathrm{CR}} - y_{\mathrm{th}}$



CITA–ICAT

Pressure profiles with and without CRs

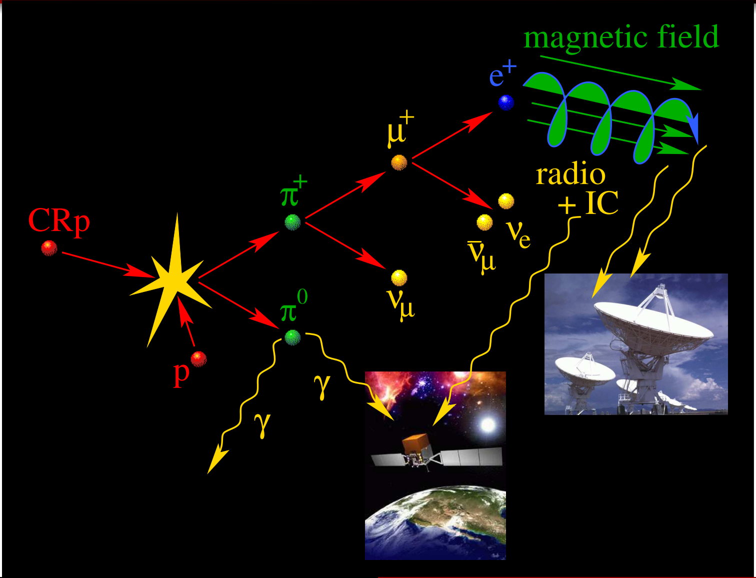


Models for radio synchrotron (mini-)halos in clusters

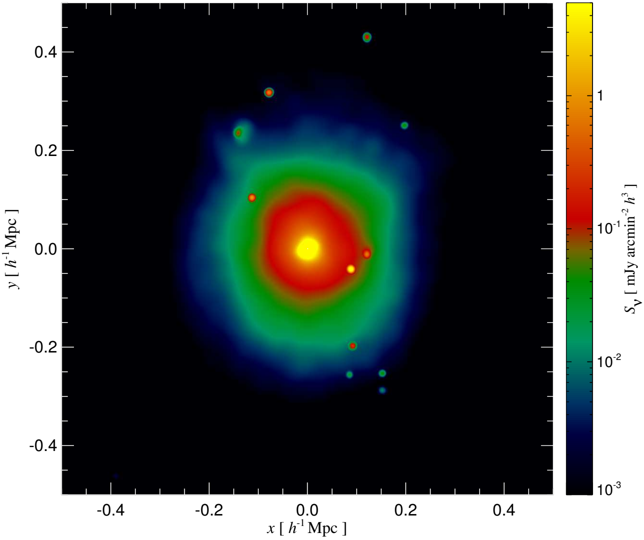
Different CR electron populations:

- 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)

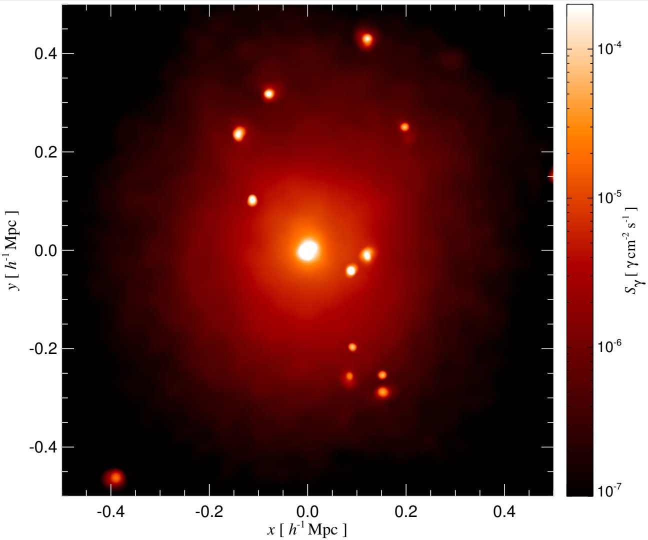
Hadronic cosmic ray proton interaction



Hadronically induced radio mini-halo emission



Hadronically induced γ-ray emission



CITA–ICAT

Summary

CR physics modifies the intracluster medium in cooling core regions:

- Galaxy cluster X-ray emission is enhanced up to 35%, predominantely in low-mass cooling core clusters.
- Integrated Sunyaev-Zel'dovich effect remains largely unchanged while the Compton-y profile is more peaked.
- Huge potential and predictive power of cosmological CR simulations $\rightarrow$ provides detailed γ-ray/radio emission maps
- Understanding non-thermal processes is crucial for using clusters as cosmological probes (high-z scaling relations).

CITA–ICAT