Cosmic rays in hydrodynamical simulations of galaxy clusters

Christoph Pfrommer[1]

in collaboration with

Volker Springel[2], Torsten Enßlin[2], Martin Jubelgas[2]
Dick Bond[1], Jon Sievers[1]

[1]Canadian Institute for Theoretical Astrophysics, Canada

[2]Max-Planck Institute for Astrophysics, Germany

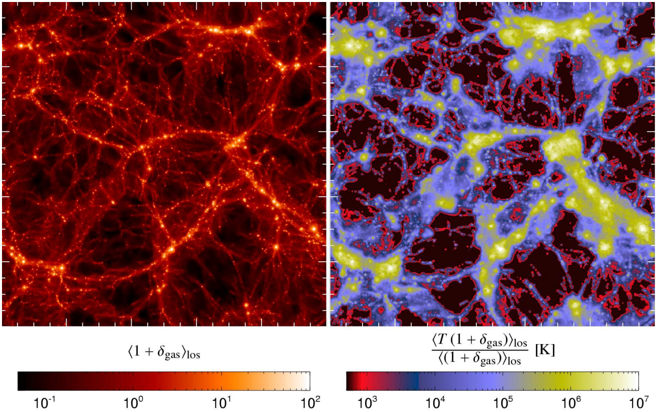
Jul. 2 2006 / "Annual meeting of CASCA", Calgary

CITA–ICAT

Outline

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 intergalactic medium through cosmological shock waves.

CITA–ICAT

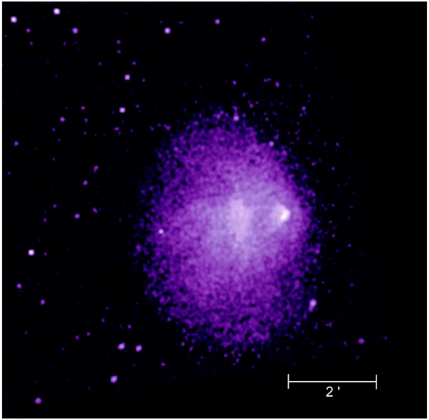
Motivation for cosmic rays in galaxy clusters

Cosmological structure formation shocks, active galactic nuclei in galaxy clusters and supernova feedback on galactic scales accelerate cosmic rays through diffusive shock acceleration:

- how is the intra-cluster medium affected by cosmic rays?
- what are the cosmological implications of cosmic rays?
- is precission cosmology possible with galaxy clusters in the presence of those astrophysical complications?
- simulating realistic cosmic ray distributions within galaxy clusters provides detailed predictions for the expected radio synchrotron and γ-ray emission

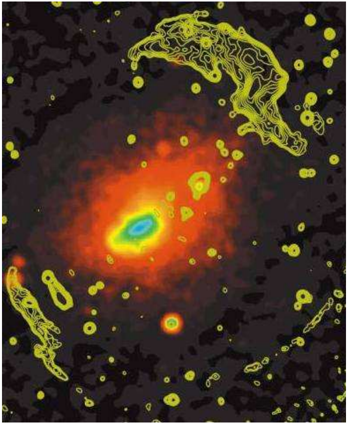
CITA–ICAT

Observations of cluster shock waves



1E 0657-56 (“Bullet cluster”)

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



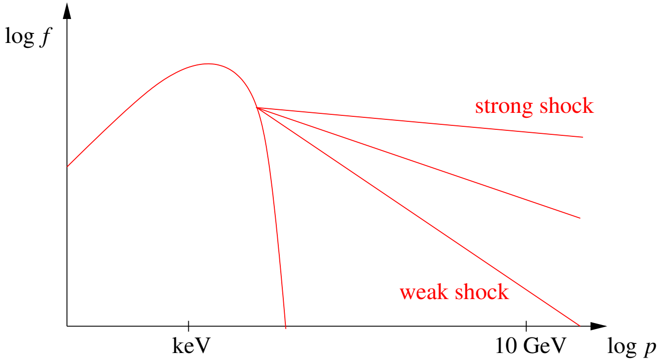
Abell 3667

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

CITA–ICAT

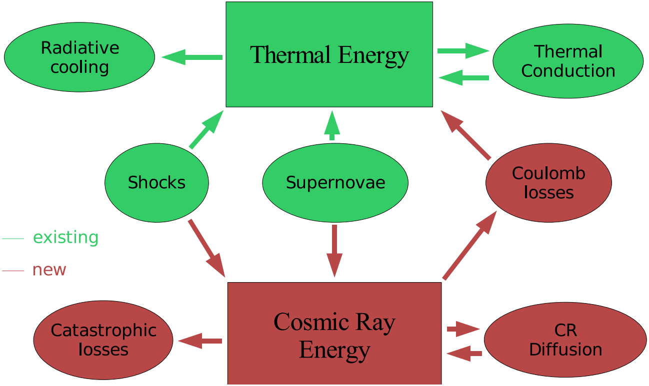
Diffusive shock acceleration – Fermi 1 mechanism

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.

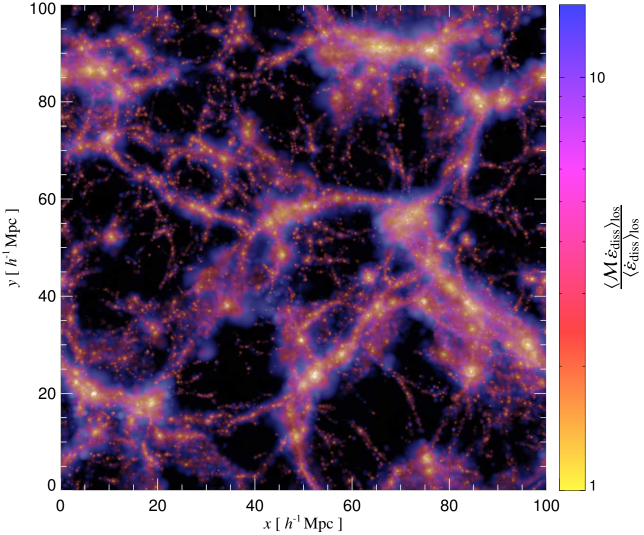


CITA–ICAT

Cosmic rays in GADGET– flowchart

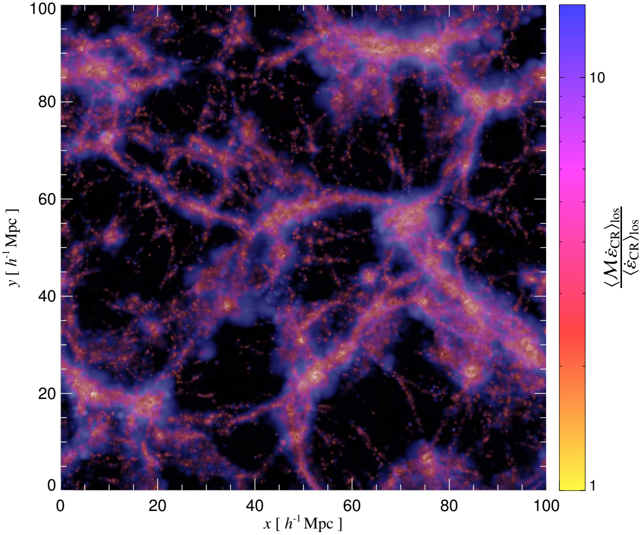


Cosmological Mach numbers: weighted by $\varepsilon_{\mathrm{diss}}$



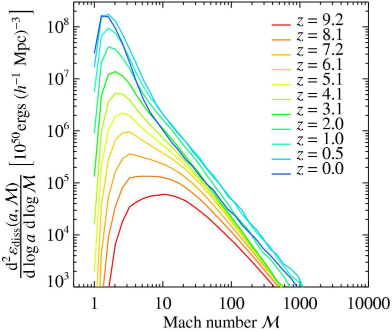
CITA–ICAT

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



CITA–ICAT

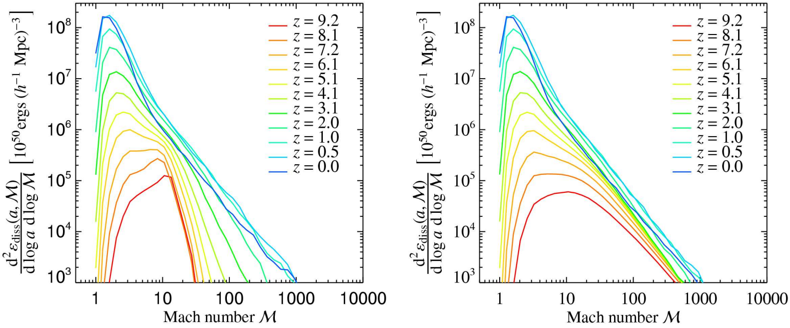
Cosmological Mach number statistics



- 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

CITA–ICAT

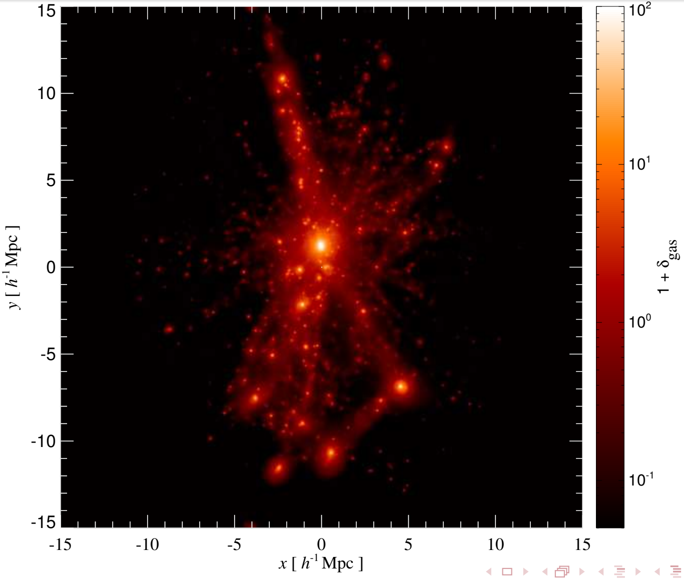
Cosmological statistics: influence of reionization



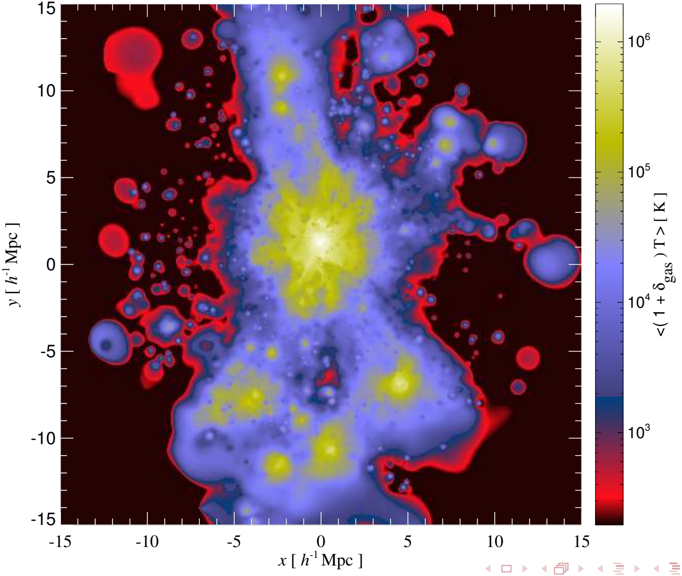
- reionization epoch at $z_{\text{reion}} = 10$ suppresses efficiently strong shocks at $z < z_{\text{reion}}$ due to jump in sound velocity
- cosmological constant causes structure formation to cease

CITA–ICAT

Adiabatic cluster simulation: gas density

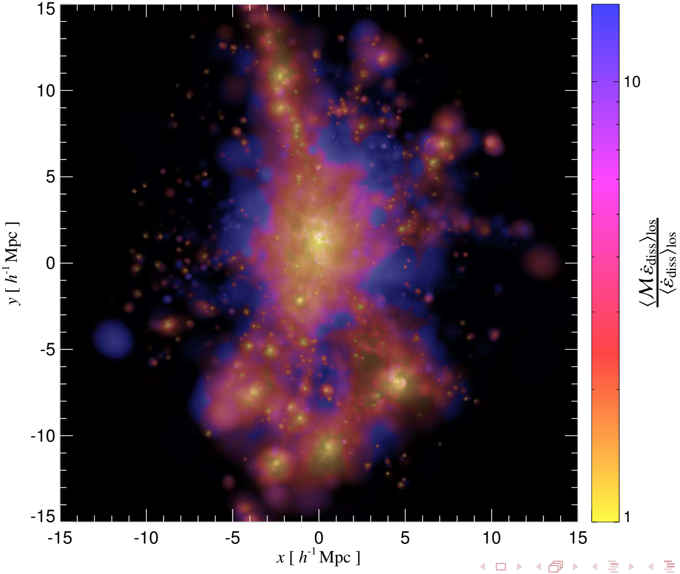


Mass weighted temperature

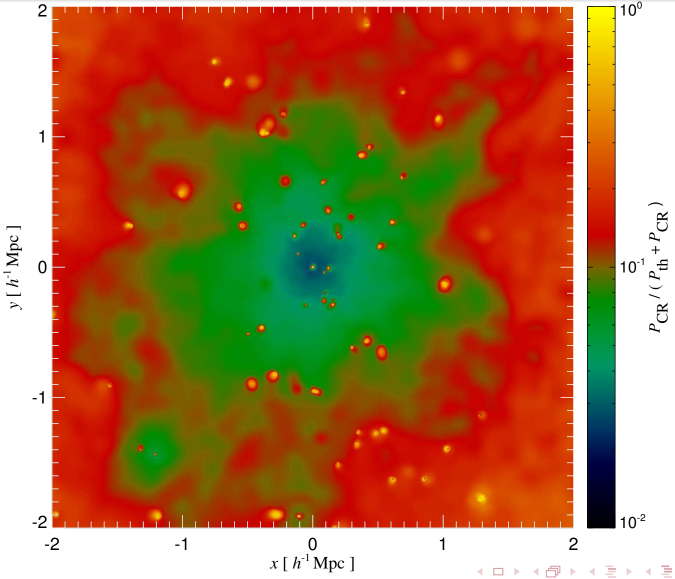


CITA–ICAT

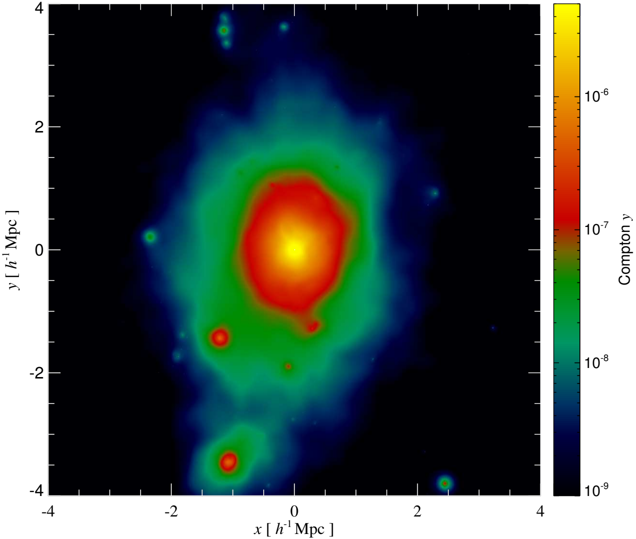
Mach number distribution weighted by $\varepsilon_{\mathrm{diss}}$



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

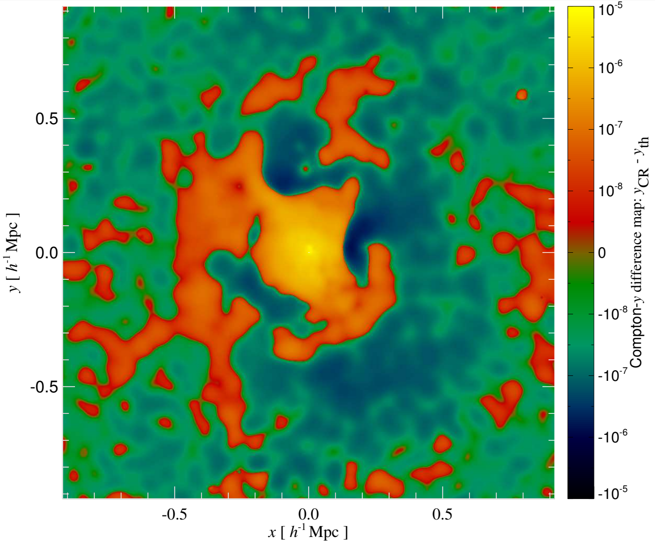


Compton y parameter in radiative cluster simulation



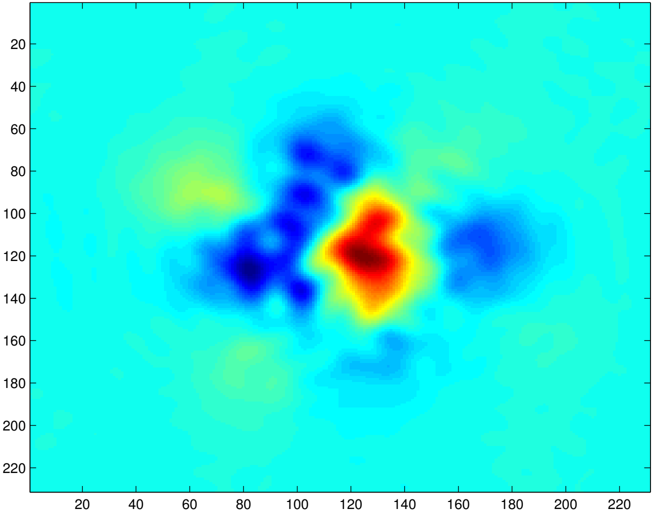
CITA–ICAT

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

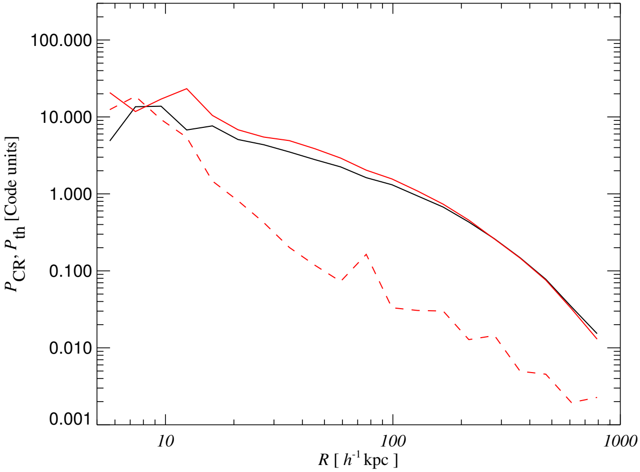


CITA–ICAT

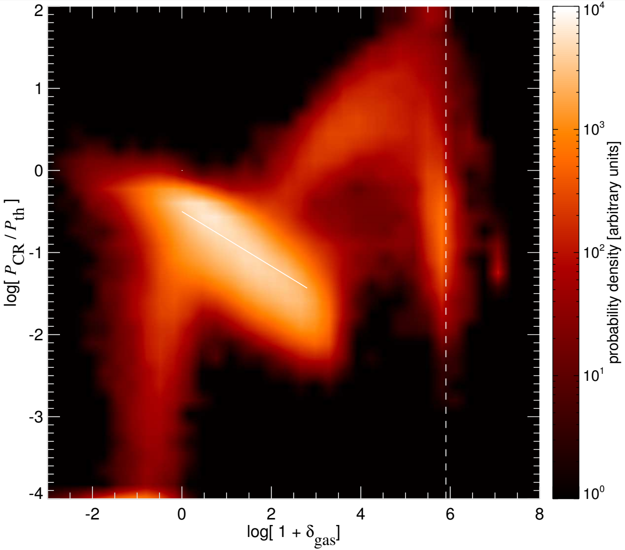
Simulated CBI observation of $y_{\mathrm{CR}} - y_{\mathrm{th}}$



Pressure profiles with and without CRs



Phase-space diagram of radiative cluster simulation



CITA–ICAT

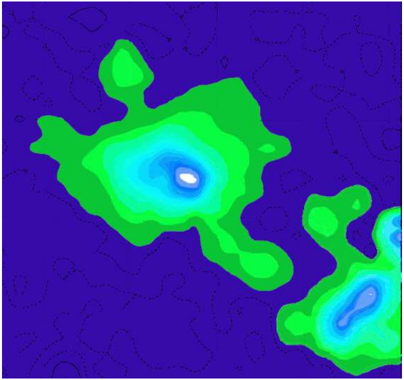
Summary

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

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

CITA–ICAT

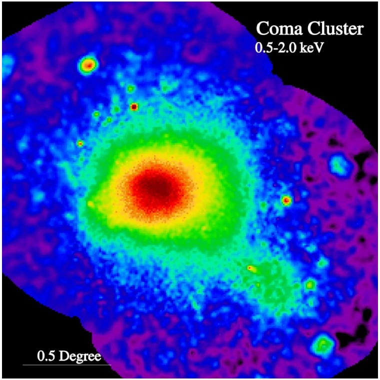
Radio halos as window for non-equilibrium processes



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

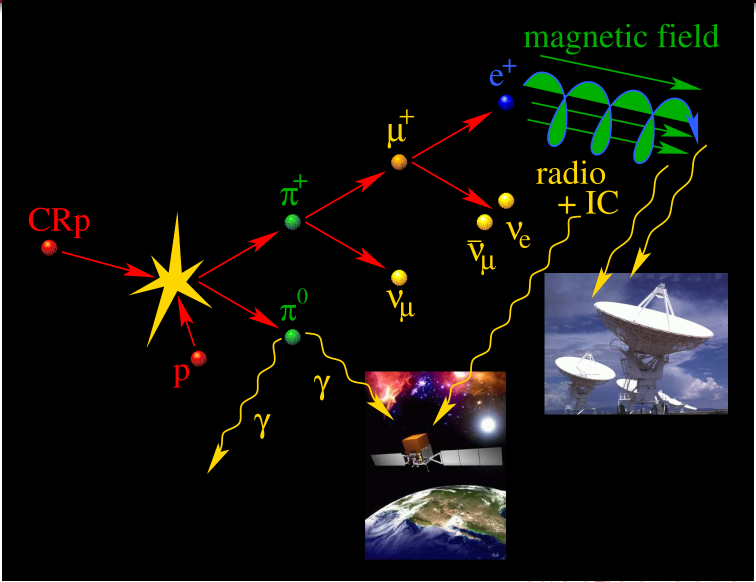
Models for radio synchrotron halos in clusters

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

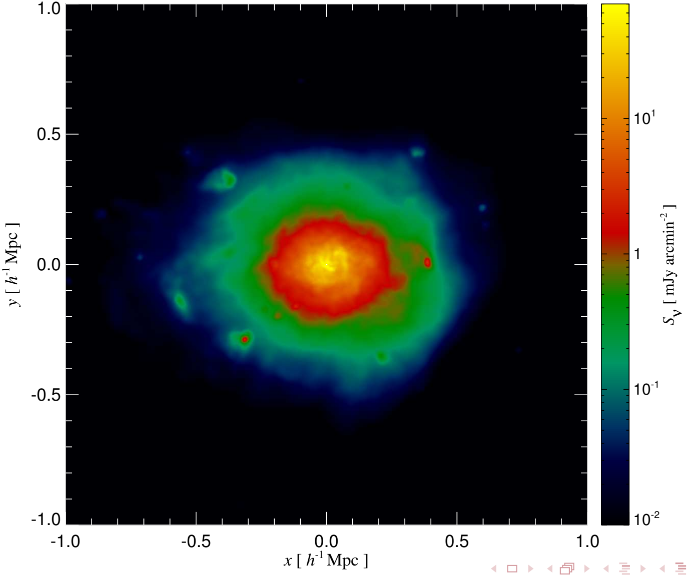
- Primary accelerated CR electrons: synchrotron/IC cooling times too short to account for extended diffuse emission
- Re-accelerated CR electrons through resonant interaction with turbulent Alfvén waves: possibly too inefficient, no first principle calculations (Jaffe 1977, Schlickeiser 1987, Brunetti 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



Simulated hadronically induced radio halo emission



CITA–ICAT

Simulated hadronically induced γ-ray emission