Cosmic Rays in Clusters of Galaxies – Tuning in to the Non-Thermal Universe

Christoph Pfrommer

Canadian Institute for Theoretical Astrophysics, Canada

June 25-29, 2007 / Tracing Cosmic Evolution with Clusters of Galaxies: Six Years Later, Sesto, Italy

CITA–ICAT

Why should we care about cosmic rays in clusters?

It allows us to explore complementary windows to cluster cosmology

1. Is high-precision cosmology possible using clusters?
   - Non-equilibrium processes such as cosmic ray pressure and turbulence possibly modify thermal X-ray emission and Sunyaev-Zel'dovich effect.
   - Cosmic ray pressure can modify the scaling relations → bias of cosmological parameters, or increase of the uncertainties if we marginalize over the 'unknown cluster physics' (cluster self-calibration)
2. What can we learn from non-thermal cluster emission?
   - Estimating the cosmic ray pressure contribution.
   - Constructing a 'gold sample' for cosmology using orthogonal information on the dynamical cluster activity.
   - Fundamental physics: diffusive shock acceleration, large scale magnetic fields, and turbulence.

CITA–ICAT

Why should we care about cosmic rays in clusters?

It allows us to explore complementary windows to cluster cosmology

1. Is high-precision cosmology possible using clusters?
   - Non-equilibrium processes such as cosmic ray pressure and turbulence possibly modify thermal X-ray emission and Sunyaev-Zel'dovich effect.
   - Cosmic ray pressure can modify the scaling relations $\rightarrow$ bias of cosmological parameters, or increase of the uncertainties if we marginalize over the 'unknown cluster physics' (cluster self-calibration)
2. What can we learn from non-thermal cluster emission?
   - Estimating the cosmic ray pressure contribution.
   - Constructing a 'gold sample' for cosmology using orthogonal information on the dynamical cluster activity.
   - Fundamental physics: diffusive shock acceleration, large scale magnetic fields, and turbulence.

CITA–ICAT

Take home messages of this talk

1. Characteristics of the CR pressure in clusters:
   - CR proton pressure traces the time integrated non-equilibrium activities of clusters and is modulated by recent dynamical activities.
   - The pressure of primary, shock-accelerated CR electrons resembles current accretion and merging shocks in the virial regions.
2. Unified model for the generation of giant radio halos, radio mini-halos, and relics:
   - Giant radio halos are dominated in the center by secondary synchrotron emission.
   - Transition to the radio emission from primary electrons in the cluster periphery.
3. Predicted sample of γ-ray clusters for GLAST: test of the presented scenario

CITA–ICAT

Take home messages of this talk

1. Characteristics of the CR pressure in clusters:
   - CR proton pressure traces the time integrated non-equilibrium activities of clusters and is modulated by recent dynamical activities.
   - The pressure of primary, shock-accelerated CR electrons resembles current accretion and merging shocks in the virial regions.
2. Unified model for the generation of giant radio halos, radio mini-halos, and relics:
   - Giant radio halos are dominated in the center by secondary synchrotron emission.
   - Transition to the radio emission from primary electrons in the cluster periphery.
3. Predicted sample of γ-ray clusters for GLAST: test of the presented scenario

CITA–ICAT

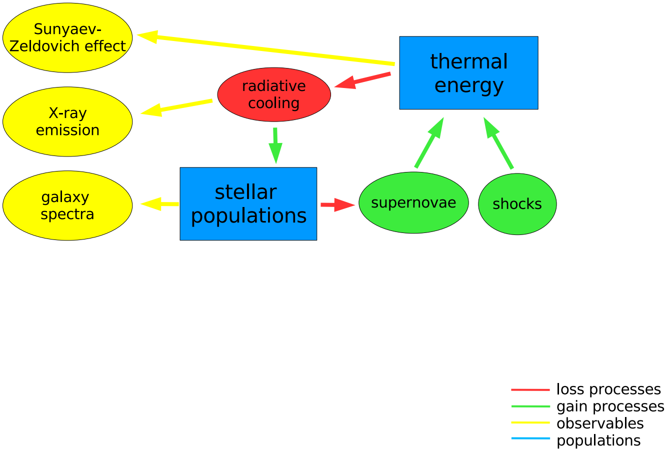
Take home messages of this talk

1. Characteristics of the CR pressure in clusters:
   - CR proton pressure traces the time integrated non-equilibrium activities of clusters and is modulated by recent dynamical activities.
   - The pressure of primary, shock-accelerated CR electrons resembles current accretion and merging shocks in the virial regions.
2. Unified model for the generation of giant radio halos, radio mini-halos, and relics:
   - Giant radio halos are dominated in the center by secondary synchrotron emission.
   - Transition to the radio emission from primary electrons in the cluster periphery.
3. Predicted sample of γ-ray clusters for GLAST: test of the presented scenario

CITA–ICAT

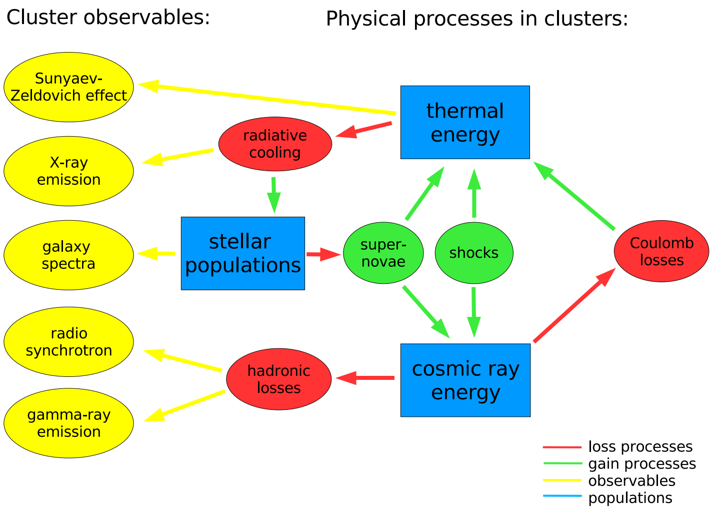
Radiative simulations – flowchart

Cluster observables: Physical processes in clusters:



CITA–ICAT

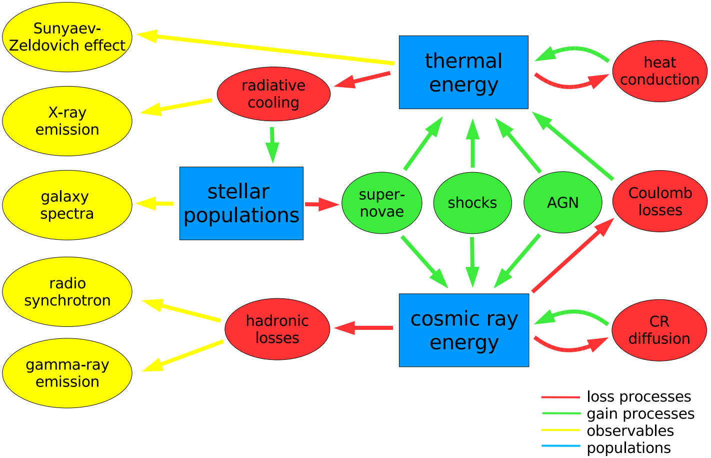
Radiative simulations with cosmic ray (CR) physics



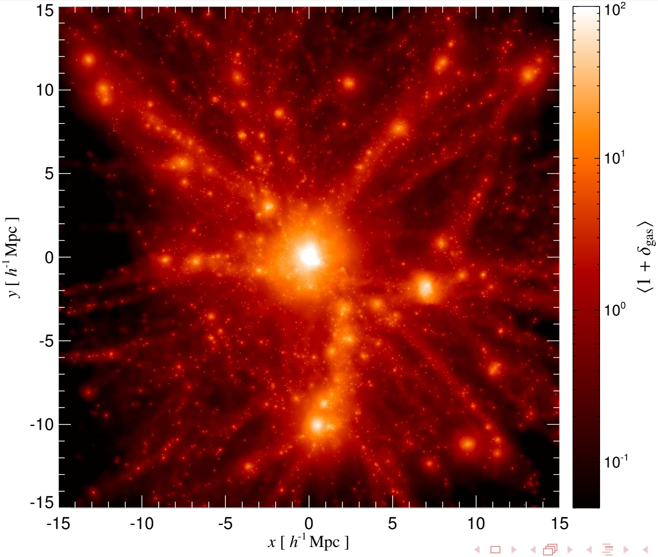
CITA–ICAT

Radiative simulations with extended CR physics

Cluster observables: Physical processes in clusters:

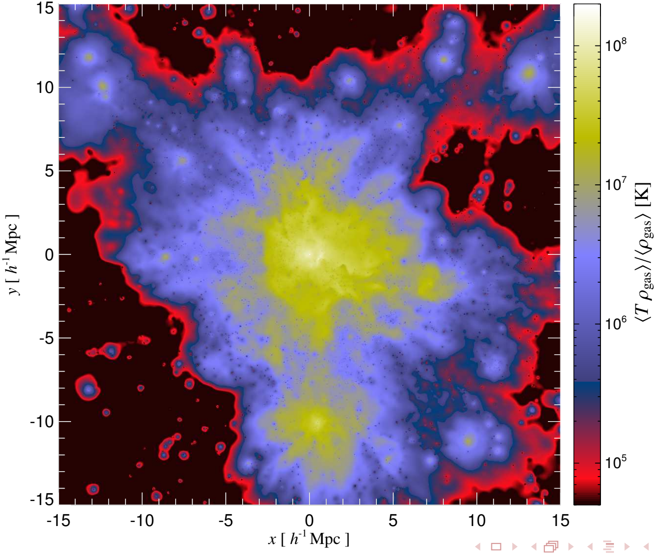


Radiative cool core cluster simulation: gas density



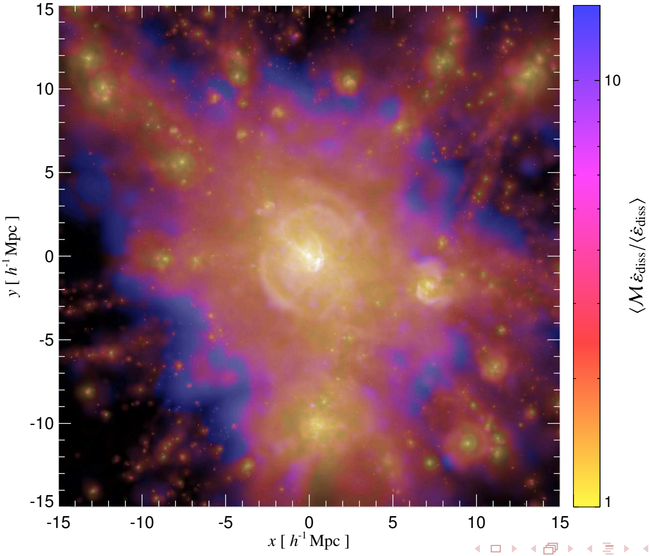
CITA–ICAT

Mass weighted temperature



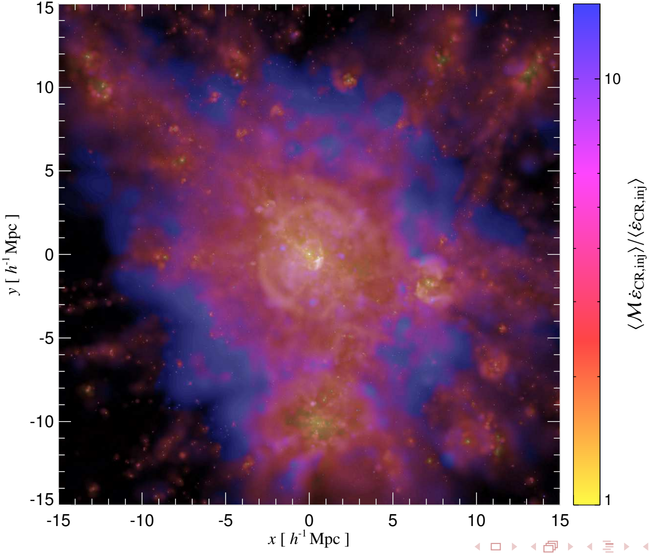
CITA–ICAT

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



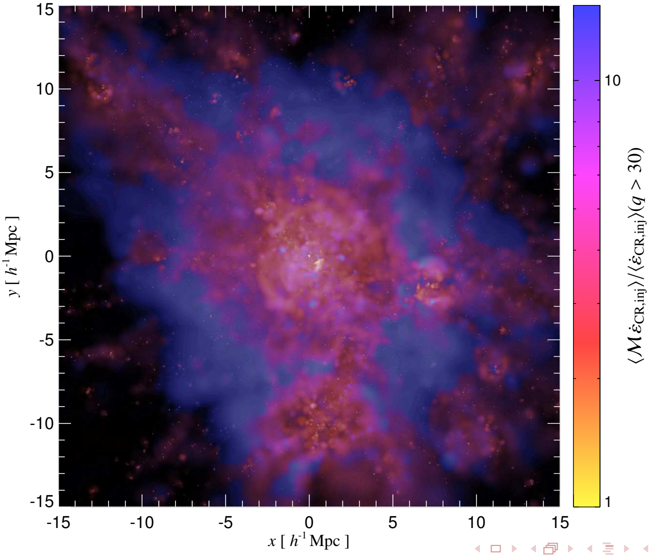
CITA–ICAT

Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}$



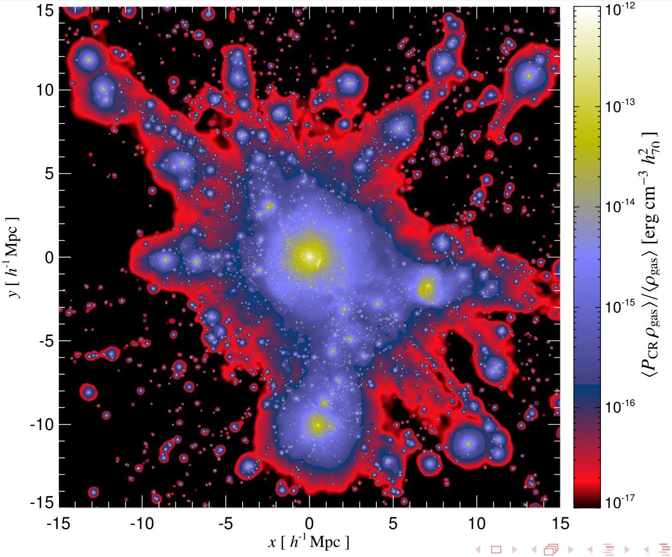
CITA–ICAT

Mach number distribution weighted by $\varepsilon_{\mathrm{CR,inj}}(q > 30)$

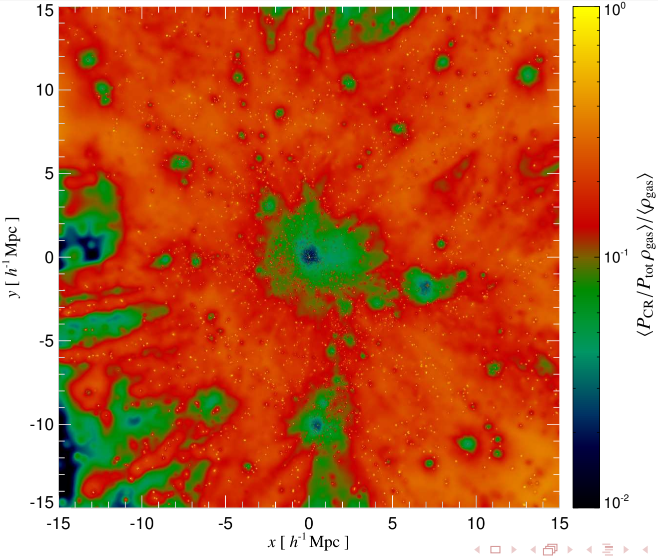


CITA–ICAT

CR pressure P_{CR}

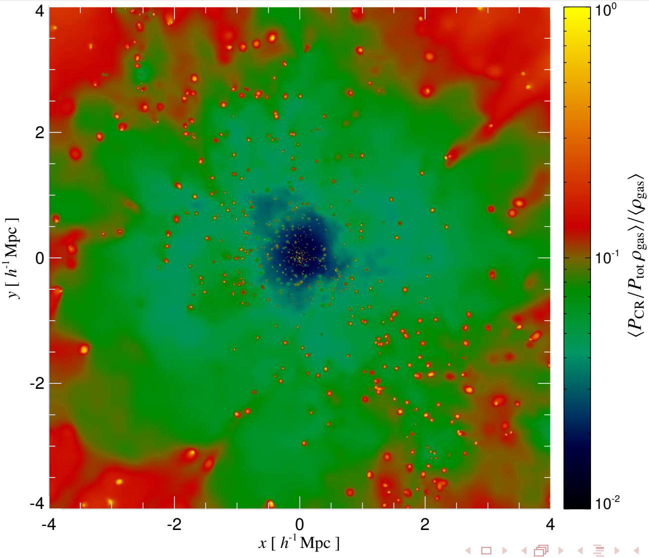


Relative CR pressure P_{CR}/P_{total}



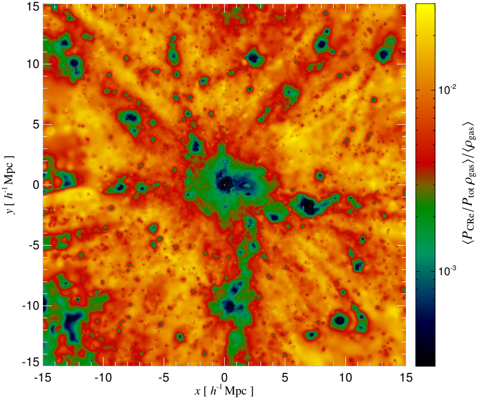
CITA–ICAT

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

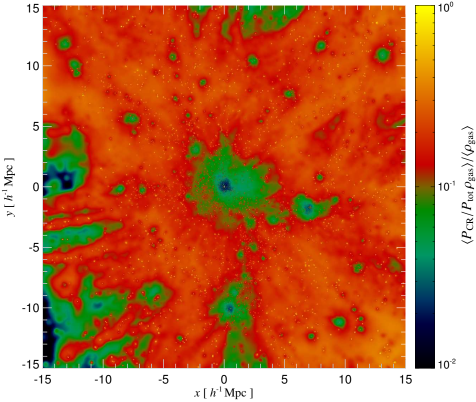


CITA–ICAT

CR electron versus CR proton pressure



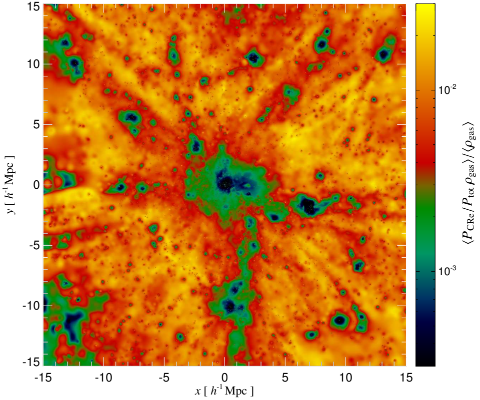
Relative pressure of primary CR electrons.



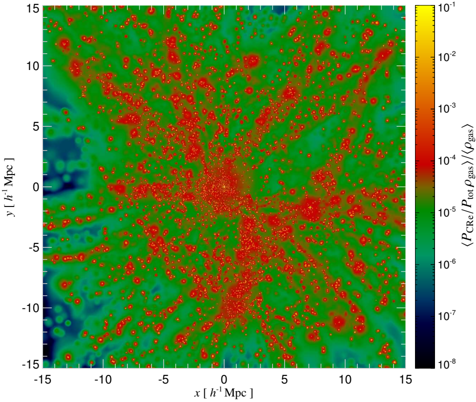
Relative pressure of CR protons.

CITA–ICAT

Primary versus secondary CR electrons



Relative pressure of *primary* CR electrons.



Rel. pressure of *secondary* CR electrons.

CITA–ICAT

Non-thermal emission from clusters

Exploring the memory of structure formation

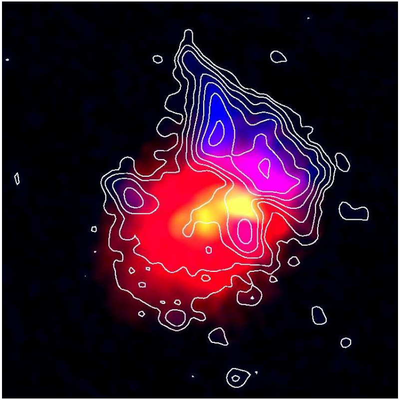
The thermal plasma lost most information on how cosmic structure formation proceeded due to the dissipative processes. The thermal observables, X-ray emission and the Sunyaev-Zel'dovich effect, tell us only very indirectly (if at all) about the cosmic history. In contrast, non-thermal processes retain their cosmic memory since their particle population is not in equilibrium $\rightarrow$ cluster archaeology.

How can we read out this information about non-thermal populations?
$\rightarrow$ new era of multi-frequency experiments, e.g.:

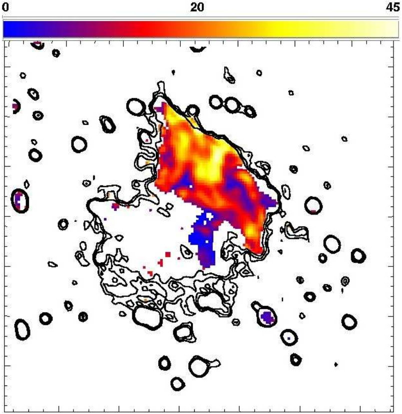
- LOFAR, GMRT, MWA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Glast: international high-energy γ-ray space mission ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes (TeV photon energies)

CITA–ICAT

Abell 2256: giant radio relic & small halo



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



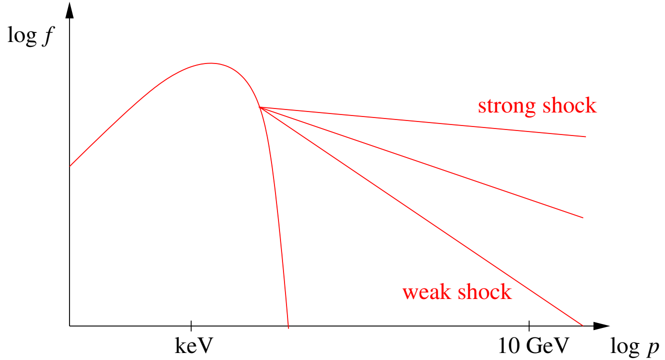
fractional polarization in color

Clarke & Enßlin (2006)

CITA–ICAT

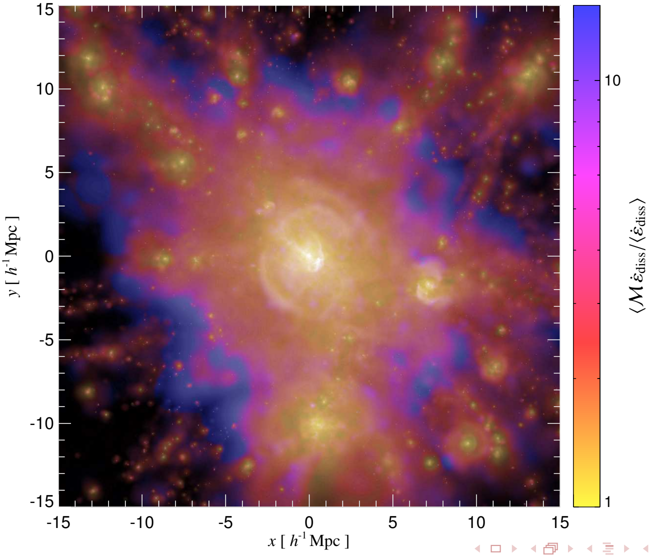
Diffusive shock acceleration – Fermi 1 mechanism

Spectral index depends on the Mach number of the shock, $\mathcal{M} = \upsilon_{\text{shock}}/c_{\text{s}}$:



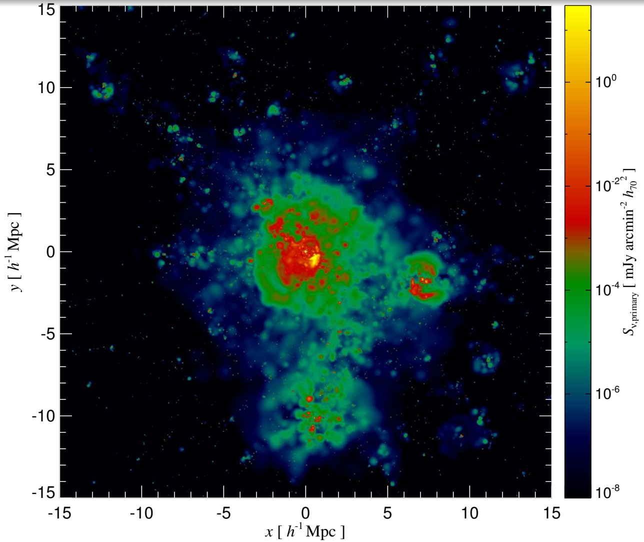
CITA–ICAT

Cosmic web: Mach number



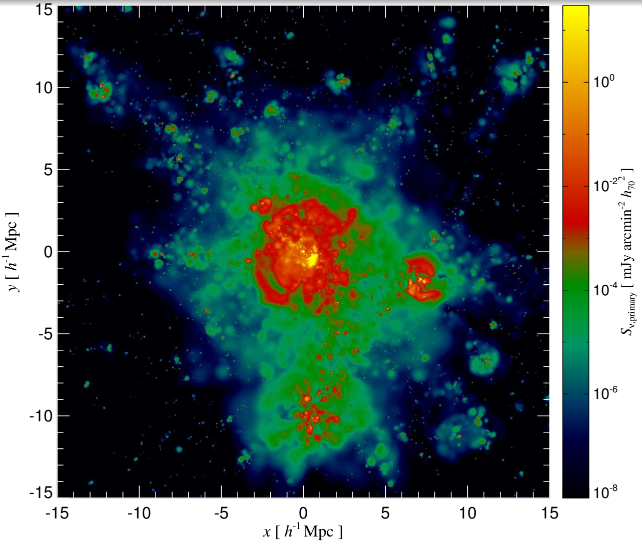
CITA–ICAT

Radio web: primary CRe (1.4 GHz)



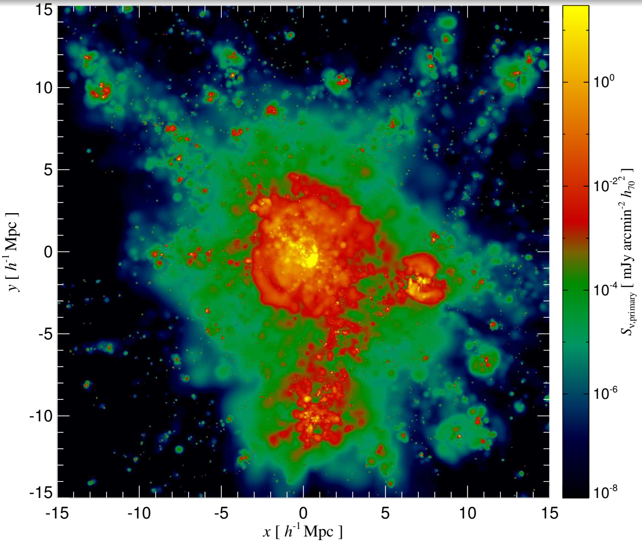
CITA–ICAT

Radio web: primary CRe (150 MHz)



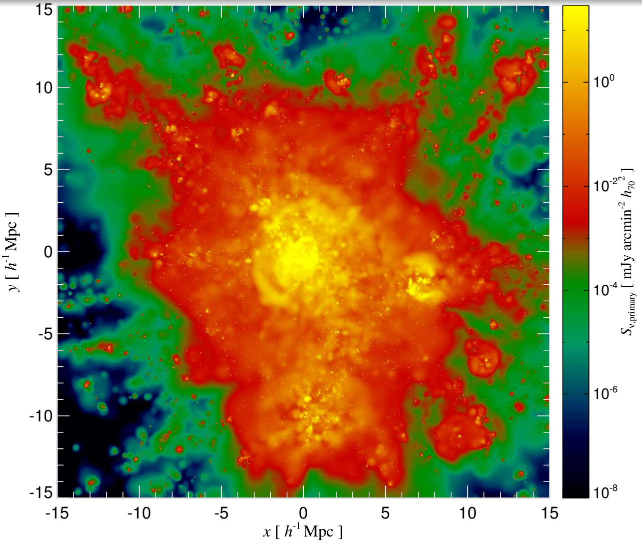
CITA–ICAT

Radio web: primary CRe (15 MHz)



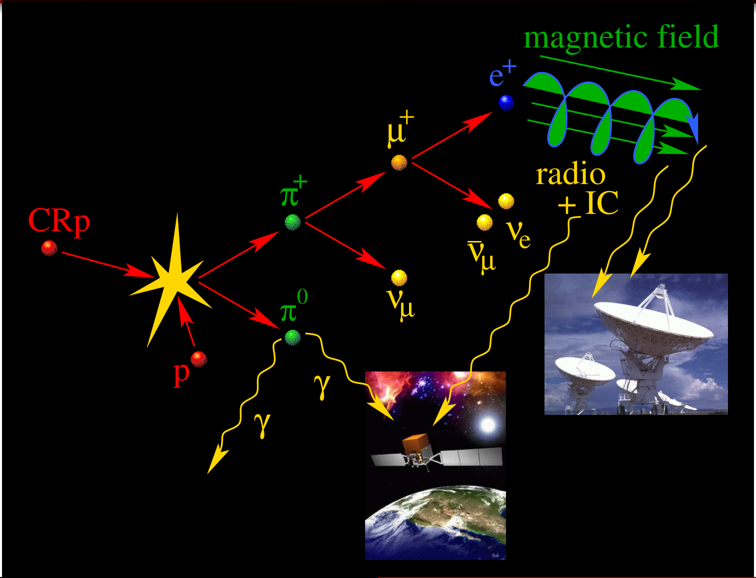
CITA–ICAT

Radio web: primary CRe (15 MHz), slower magnetic decline

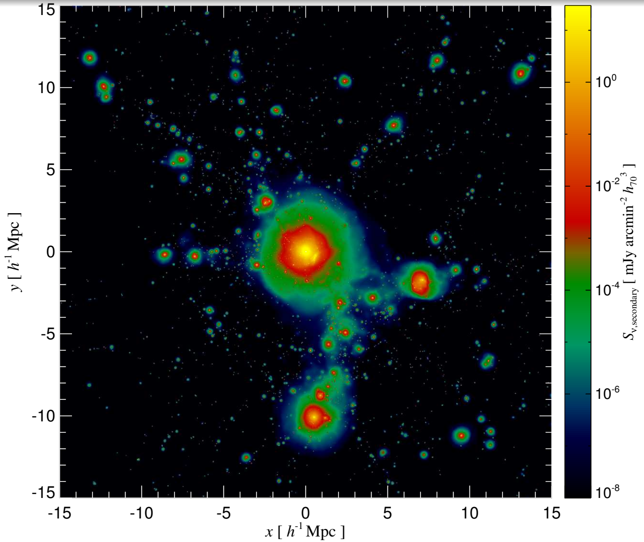


CITA–ICAT

Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



CITA–ICAT

Previous models for giant radio halos in clusters

Radio halos show a smooth unpolarized radio emission at Mpc-scales. How are they generated?

- Primary accelerated CR electrons: synchrotron/IC cooling times too short to account for extended diffuse emission.
- Continuous in-situ acceleration of pre-existing CR electrons either via interactions with magneto-hydrodynamic waves, or through turbulent spectra (Jaffe 1977, Schlickeiser 1987, Brunetti 2001, Brunetti & Lazarian 2007).
- Hadronically produced CR electrons in inelastic collisions of CR protons with the ambient gas (Dennison 1980, Vestrad 1982, Miniati 2001, Pfrommer 2004).

All of these models face theoretical short-comings when comparing to observations.

Unified model of radio halos and relics

Cluster radio emission varies with dynamical stage of a cluster:

- Cluster relaxes and develops cool core: radio mini-halo develops due to hadronically produced CR electrons, magnetic fields are adiabatically compressed (cooling gas triggers radio mode feedback of AGN that outshines mini-halo → selection effect).
- Cluster experiences major merger: two leading shock waves are produced that become stronger as they break at the shallow peripheral cluster potential → shock-acceleration of primary electrons and development of radio relics.
- Generation of morphologically complex network of virializing shock waves. Lower sound speed in the cluster outskirts lead to strong shocks → irregular distribution of primary electrons, MHD turbulence amplifies magnetic fields.
- Giant radio halo develops due to (1) boost of the hadronically generated radio emission in the center (2) irregular radio 'gischt' emission in the cluster outskirts.

Unified model of radio halos and relics

Cluster radio emission varies with dynamical stage of a cluster:

- Cluster relaxes and develops cool core: radio mini-halo develops due to hadronically produced CR electrons, magnetic fields are adiabatically compressed (cooling gas triggers radio mode feedback of AGN that outshines mini-halo → selection effect).
- Cluster experiences major merger: two leading shock waves are produced that become stronger as they break at the shallow peripheral cluster potential → shock-acceleration of primary electrons and development of radio relics.
- Generation of morphologically complex network of virializing shock waves. Lower sound speed in the cluster outskirts lead to strong shocks → irregular distribution of primary electrons, MHD turbulence amplifies magnetic fields.
- Giant radio halo develops due to (1) boost of the hadronically generated radio emission in the center (2) irregular radio 'gischt' emission in the cluster outskirts.

CITA–ICAT

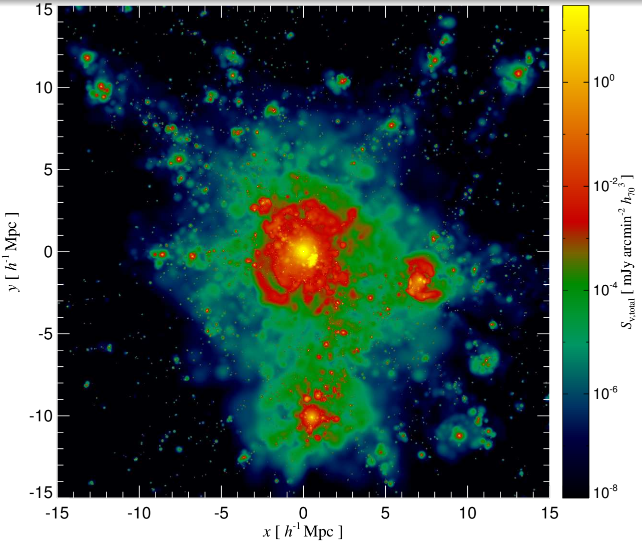
Unified model of radio halos and relics

Cluster radio emission varies with dynamical stage of a cluster:

- Cluster relaxes and develops cool core: radio mini-halo develops due to hadronically produced CR electrons, magnetic fields are adiabatically compressed (cooling gas triggers radio mode feedback of AGN that outshines mini-halo $\rightarrow$ selection effect).
- Cluster experiences major merger: two leading shock waves are produced that become stronger as they break at the shallow peripheral cluster potential $\rightarrow$ shock-acceleration of primary electrons and development of radio relics.
- Generation of morphologically complex network of virializing shock waves. Lower sound speed in the cluster outskirts lead to strong shocks $\rightarrow$ irregular distribution of primary electrons, MHD turbulence amplifies magnetic fields.
- Giant radio halo develops due to (1) boost of the hadronically generated radio emission in the center (2) irregular radio 'gischt' emission in the cluster outskirts.

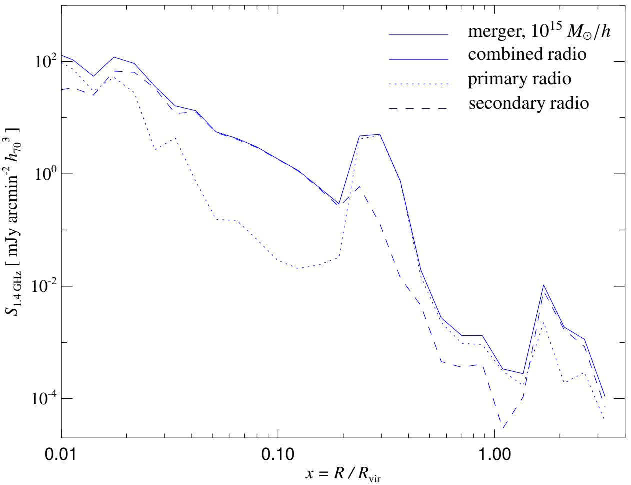
CITA–ICAT

Radio gischt + central hadronic halo = giant radio halo

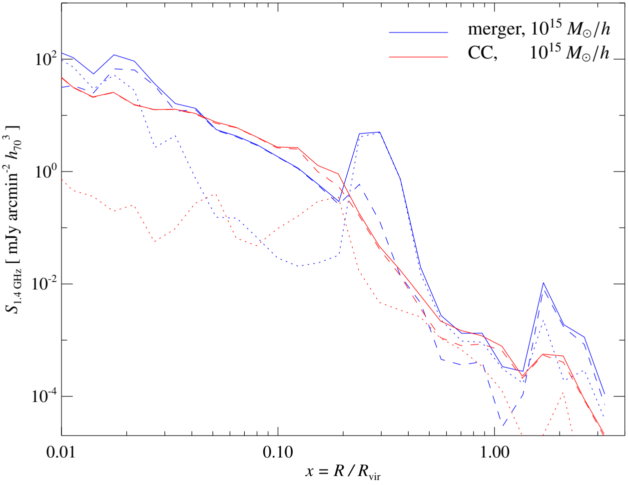


CITA–ICAT

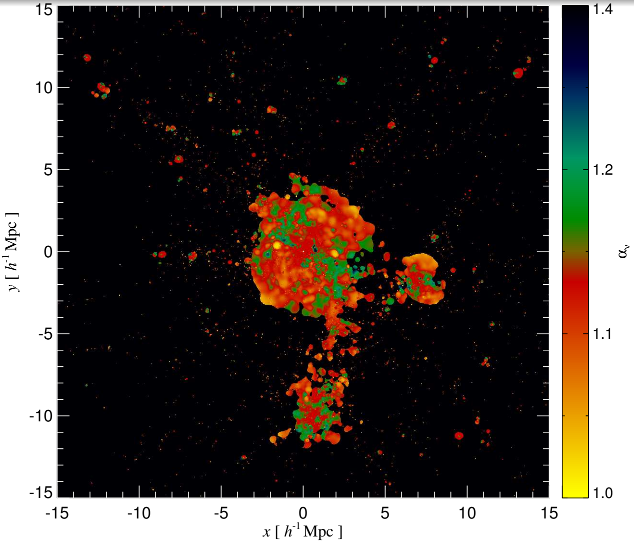
Giant radio halo profile



Giant radio halo vs. mini-halo



Radio relics + halos: spectral index



CITA–ICAT

Observational properties of diffuse radio emission

What cluster radio observations demand:

- Giant radio halos: homogeneous spherical morphology (similar to X-ray emission), larger variation of the spectral index in the peripheral regions, steep radio spectrum ($\alpha_\nu \simeq 1.3$), Faraday depolarized synchrotron emission
- Radio mini-halos: occur in cooling core clusters, homogeneous spherical morphology in the cooling region, Faraday depolarized synchrotron emission, steep radio spectrum
- Radio relics: occur in merging clusters, inhomogeneous morphology, peripheral cluster regions, flat radio spectrum ($\alpha_\nu \simeq 1.1$), polarized synchrotron emission

CITA–ICAT

Low-frequency radio emission from clusters

Window into current and past structure formation

Our unified model accounts for . . .

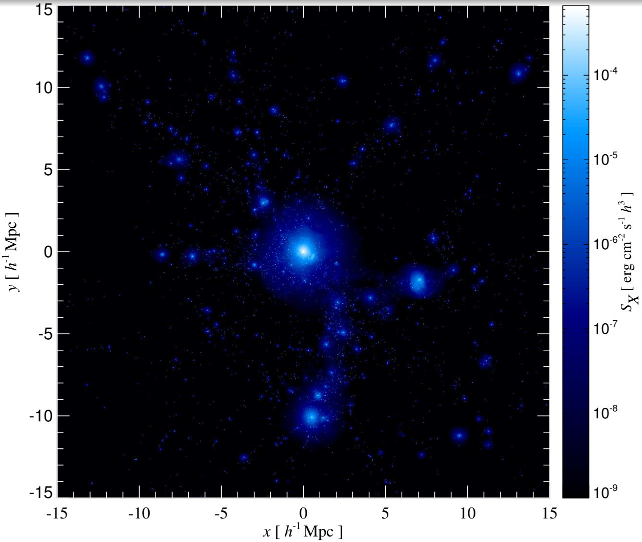
- correlation between merging clusters and giant halos, occurrence of mini-halos in cool core clusters
- observed luminosities of halos/relics for magnetic fields derived from Faraday rotation measurements
- observed morphologies, variations, spectral and polarization properties in radio halos/relics

How we can make use of this information:

- Radio relics: produced by primary accelerated CR electrons at formation shocks → probes current dynamical, non-equilibrium activity of forming structures (shocks and magnetic fields)
- Central radio halos: produced by secondary CR electrons in hadronic CR proton interactions → tracing time-integrated non-equilibrium activity, modulated by recent dynamical activities

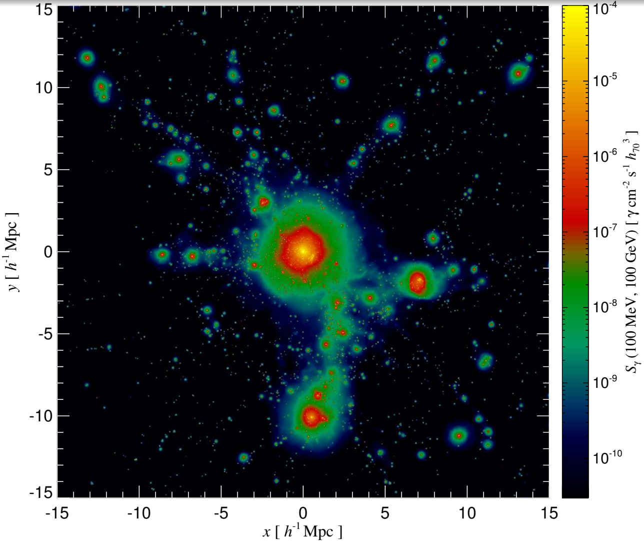
CITA–ICAT

Thermal X-ray emission



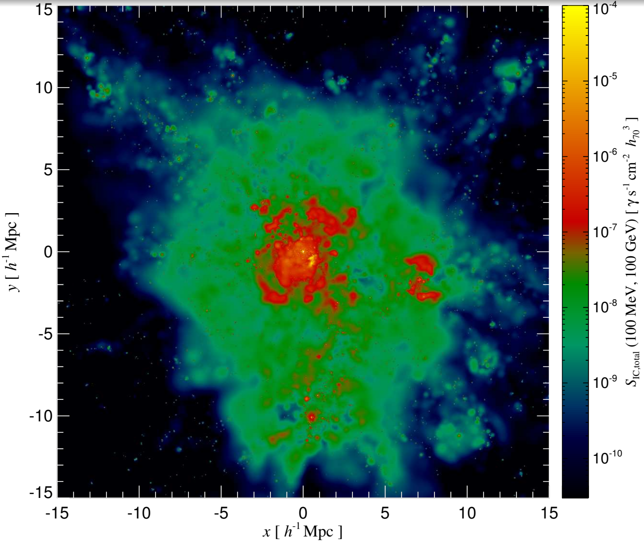
CITA–ICAT

Hadronic γ-ray emission, $E_\gamma > 100$ MeV



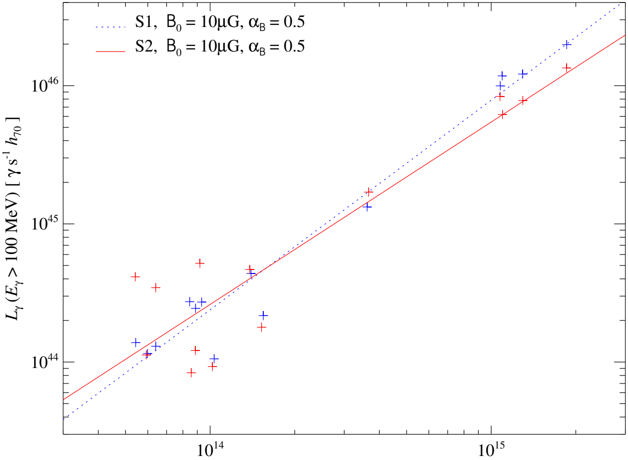
CITA–ICAT

Inverse Compton emission, $E_{IC} > 100$ MeV



CITA–ICAT

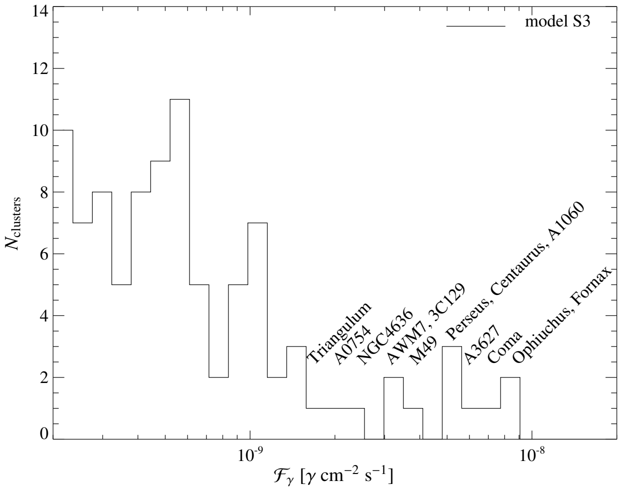
Gamma-ray scaling relations



Scaling relation + complete sample of the brightest X-ray clusters (HIFLUCGS) → predictions for GLAST

CITA–ICAT

Predicted cluster sample for GLAST



CITA–ICAT

Summary

1. Characteristics of the CR pressure in clusters:
   - CR proton pressure traces the time integrated non-equilibrium activities of clusters and is modulated by recent dynamical activities.
   - The pressure of primary, shock-accelerated CR electrons resembles current accretion and merging shocks in the virial regions.
2. Unified model for the generation of giant radio halos, radio mini-halos, and relics:
   - Giant radio halos are dominated in the center by secondary synchrotron emission.
   - Transition to the radio emission from primary electrons in the cluster periphery.
3. We predict GLAST to detect $\sim$ ten γ-ray clusters: test of the presented scenario

CITA–ICAT