Simulating galaxy clusters – A review of thermal and non-thermal processes

Christoph Pfrommer

Canadian Institute for Theoretical Astrophysics, Canada

July, 3 2007 / Cosmology Summer Workshop, Santa Fe

CITA–ICAT

Outline

CITA–ICAT

Outline

CITA–ICAT

Dynamical picture of cluster formation

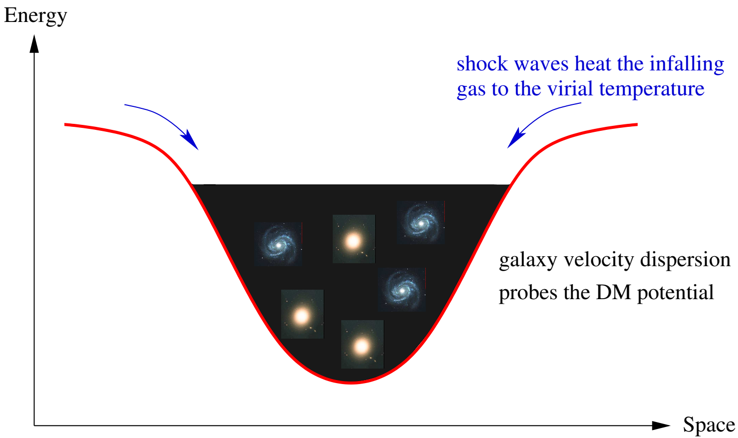
- structure formation in the ΛCDM universe predicts the hierarchical build-up of dark matter halos from small scales to successively larger scales
- clusters of galaxies currently sit atop this hierarchy as the largest objects that have had time to collapse under the influence of their own gravity
- cluster are dynamically evolving systems that have not finished forming and equilibrating, $\tau_{\rm dyn} \sim 1$ Gyr

$\rightarrow$ two extreme dynamical states of galaxy clusters: **merging clusters** and **cool core clusters**, which are relaxed systems where the central gas develops a dense cooling core due to the short thermal cooling times

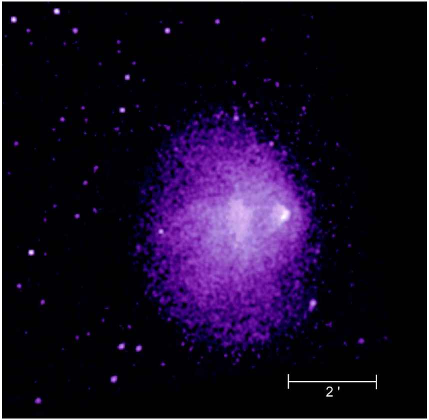
CITA–ICAT

A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

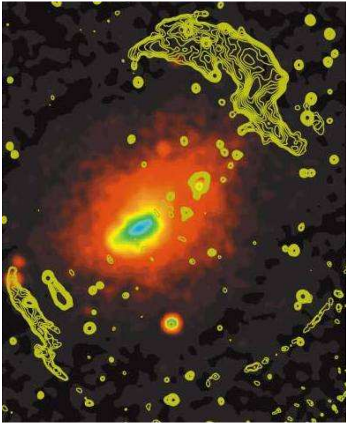


. . . and how the observer's Universe looks like



1E 0657-56 ("Bullet cluster")

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



Abell 3667

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

CITA–ICAT

Numerically modeling clusters – Dark matter (DM)

- Non-interacting DM is described by the collisionless Boltzmann equation coupled to the Poisson equation in an expanding background Universe:

  $$\frac{\mathrm{d}}{\mathrm{d}t} f(\boldsymbol{r}, \boldsymbol{v}, t) \equiv \dot{f} + (\boldsymbol{v}\nabla) f - \nabla\Phi\nabla_{\boldsymbol{v}} f = 0,$$

  $$\Delta\Phi(\boldsymbol{r}, t) = 4\pi G \int f(\boldsymbol{r}, \boldsymbol{v}, t)\mathrm{d}\boldsymbol{v},$$

  $f(\boldsymbol{r}, \boldsymbol{v}, t)$ denotes the distribution function in phase space.
- *N-body simulations* are particularly suited to solve these equations since phase space density is sampled by a large number N of tracer particles which are integrated along characteristic curves of the collisionless Boltzmann equation. The accuracy of this approach depends on a sufficiently high number of particles.

CITA–ICAT

Numerically modeling clusters – Dark matter (DM)

- Non-interacting DM is described by the collisionless Boltzmann equation coupled to the Poisson equation in an expanding background Universe:

$$\frac{\mathrm{d}}{\mathrm{d}t} f(\boldsymbol{r},\boldsymbol{v},t) \equiv \dot{f} + (\boldsymbol{v}\nabla)f - \nabla\Phi\nabla_{\boldsymbol{v}} f = 0,$$

$$\Delta\Phi(\boldsymbol{r},t) = 4\pi G \int f(\boldsymbol{r},\boldsymbol{v},t)\mathrm{d}\boldsymbol{v},$$

  $f(\boldsymbol{r},\boldsymbol{v},t)$ denotes the distribution function in phase space.

- *N-body simulations* are particularly suited to solve these equations since phase space density is sampled by a large number N of tracer particles which are integrated along characteristic curves of the collisionless Boltzmann equation. The accuracy of this approach depends on a sufficiently high number of particles.

CITA–ICAT

Numerically modeling clusters – (1) Gas

- The intra-cluster medium (ICM) is most simply modeled as an ideal inviscid gas which is coupled to dark matter through its gravitational interaction.
- The hydrodynamics of the gas is governed by the continuity equation, the Euler equation, and the conservation equation for the thermal energy u:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla \boldsymbol{v} = 0,$$

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi,$$

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\boldsymbol{v} - \frac{\Lambda(u,\rho)}{\rho},$$

  $\Lambda(u,\rho)$ describes external sinks or sources of heat for the gas.
- The equation of state $P = (\gamma - 1)\rho u$ closes the above system of coupled differential equations.

CITA–ICAT

Numerically modeling clusters – (1) Gas

- The intra-cluster medium (ICM) is most simply modeled as an ideal inviscid gas which is coupled to dark matter through its gravitational interaction.
- The hydrodynamics of the gas is governed by the continuity equation, the Euler equation, and the conservation equation for the thermal energy u:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\boldsymbol{v} = 0,$$
$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi,$$
$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\boldsymbol{v} - \frac{\Lambda(u,\rho)}{\rho},$$

$\Lambda(u,\rho)$ describes external sinks or sources of heat for the gas.

- The equation of state $P = (\gamma - 1)\rho u$ closes the above system of coupled differential equations.

CITA–ICAT

Numerically modeling clusters – (1) Gas

- The intra-cluster medium (ICM) is most simply modeled as an ideal inviscid gas which is coupled to dark matter through its gravitational interaction.
- The hydrodynamics of the gas is governed by the continuity equation, the Euler equation, and the conservation equation for the thermal energy u:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\boldsymbol{v} = 0,$$
$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi,$$
$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\boldsymbol{v} - \frac{\Lambda(u,\rho)}{\rho},$$

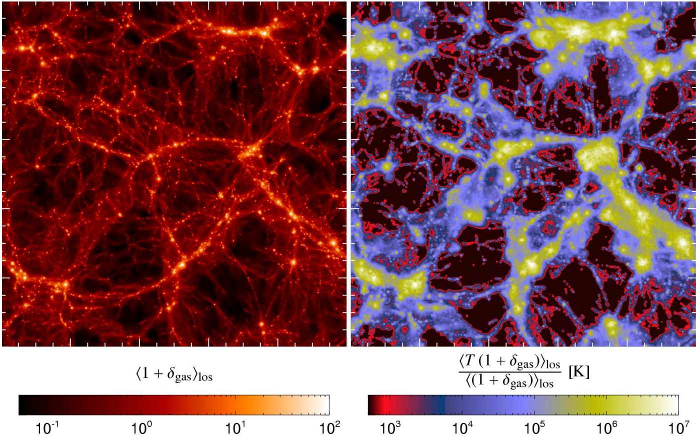
  $\Lambda(u,\rho)$ describes external sinks or sources of heat for the gas.
- The equation of state $P = (\gamma - 1)\rho u$ closes the above system of coupled differential equations.

Numerically modeling clusters – (2) Gas

- Cluster are dynamically evolving, non-linear objects → requires 3D simulations of the hydrodynamics coupled with N-body techniques for the DM.
- Numerical discretization requires compromises to solve for the hydrodynamics:
  1) Discretizing space → Eulerian approach: adaptive mesh refinement (AMR) simulations
  2) Discretizing mass → Lagrangian approach: smoothed particle hydrodynamics (SPH) simulations
- Each method has its drawbacks and limitations → choose the better suited method for the problem under consideration!
- None of these methods is 'better' or superior over the other!

CITA–ICAT

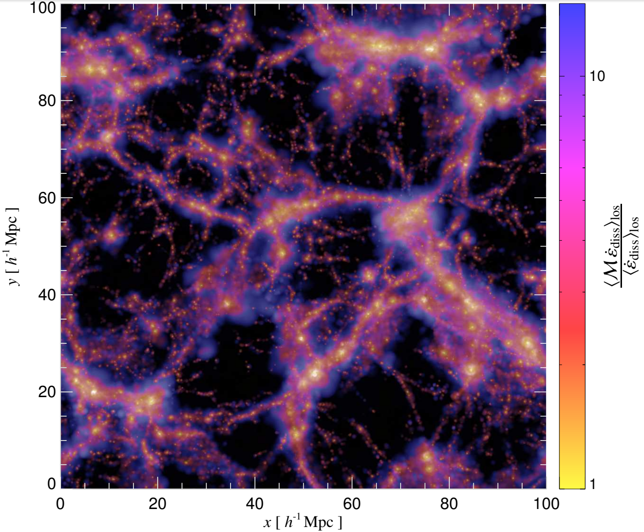
Gravitational heating by shocks



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

CITA–ICAT

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



CITA–ICAT

Volume rendered shock surfaces

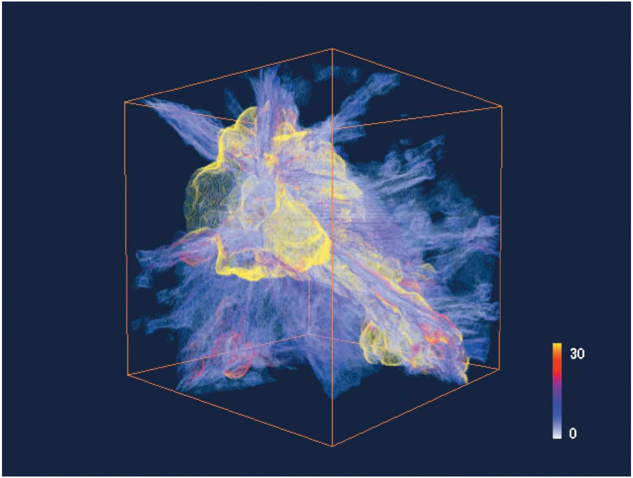
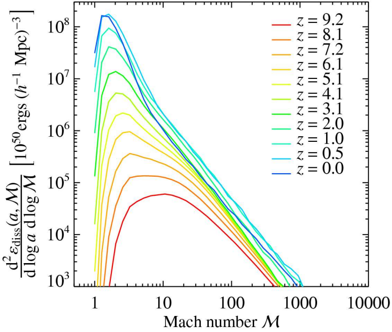


Figure: from Ryu et al. (2003)

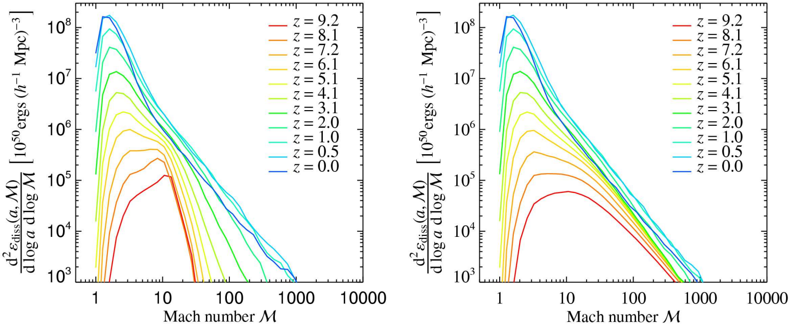
Cosmological Mach number statistics



- 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 reionisation



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

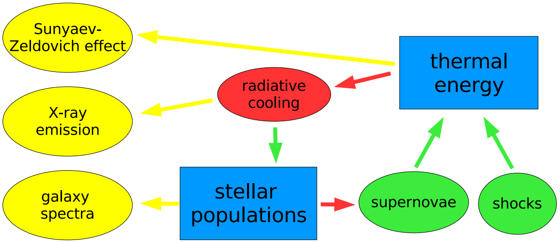
CITA–ICAT

Outline

CITA–ICAT

Radiative processes in simulations – flowchart

Cluster observables: Physical processes in clusters:



loss processes
gain processes
observables
populations

CITA–ICAT

Cluster scaling relations

- Observable-mass relations are one of the key ingredients for deriving cosmological constraints using upcoming large cluster surveys.
- X-ray and SZE observable-mass relations ($\Delta = 200$):

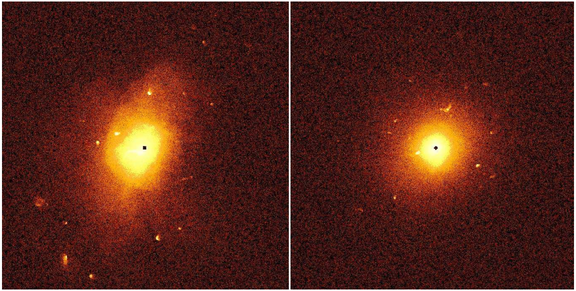
$$\begin{aligned} T_{\rm gas} &\propto M_\Delta / R_\Delta \propto M_\Delta^{2/3} E(z)^{2/3}, \\ SZ\ flux &\propto \int P_{\rm gas}\, \mathrm{d}l\, \mathrm{d}\Omega \propto f_{\rm gas} M_\Delta^{5/3} E(z)^{-2/3}, \end{aligned}$$

using $M_\Delta \equiv (4\pi/3)\, R_\Delta^3 \Delta\, \rho_{\rm crit}(z)$, $E(z) \equiv H(z)/H_0$

- Questions:
How does galaxy formation affect global cluster properties?
How do simulations compare to observations?

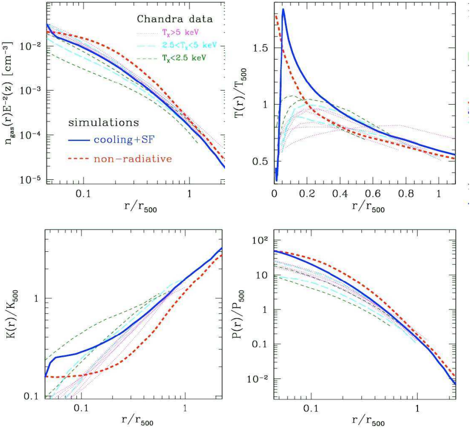
Chandra mock observations

- Generate ‘Chandra data’ for clusters from high-resolution simulations and reduce with real data analysis pipeline (Rasia et al. 2005, Nagai et al. 2006)
- Results:
  $\longrightarrow$ hydrostatic mass biased low at R_{500} due to turbulent pressure
  $\longrightarrow$ temperatures accurate to $\sim$ 10%



unrelaxed versus relaxed cluster (Nagai, Kravtsov, & Vikhlinin 2006)

Profiles of the intra-cluster medium

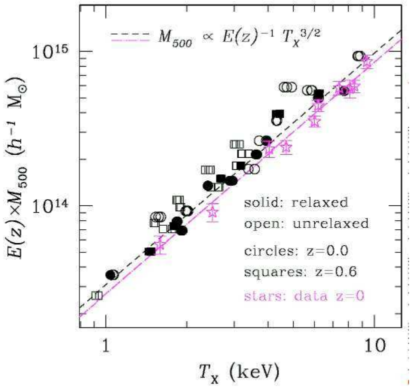


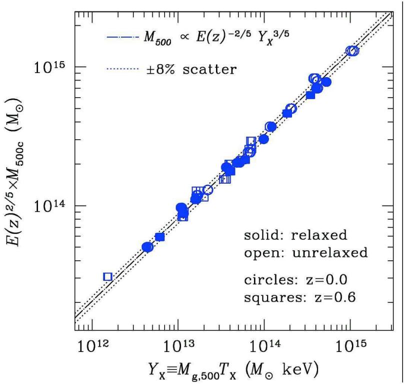
- red line: mean profile for relaxed clusters in non-radiative simulations
- blue band: mean profile for relaxed clusters in simulations with cooling and star formation
- thin dashed lines: profiles of Chandra clusters of different temperatures

(Nagai, Kravtsov, & Vikhlinin 2006)

CITA–ICAT

X-ray scaling relations





Scatter in $M - T_X$ is $\sim$ 20% in mass at a given T_X (driven by unrelaxed systems).

Scatter in $M - Y_X$ is $\sim$ 8% $\rightarrow$ why is there an anti-correlation between $M_{\mathrm{gas},500}$ and T_X?

CITA–ICAT

Problems

Current Lagrangian (SPH) as well as Adaptive Eulerian (AMR) approaches face the same problems → lack of our physical understanding

- over-cooled cluster core regions out to $r \simeq 0.2\,R_{200}$
- too numerous gaseous substructures
- external regions: non-thermal pressure support (CRs, turbulence)
- influence of the clusters dynamical state on the scaling properties (especially the nature of the scatter)

Cluster self-calibration in its most general approach won't allow us to improve on statistical uncertainties of cosmological parameters.

CITA–ICAT

Solution

Hybrid self-calibration:

- Combining thermal and non-thermal observables simultaneously in observation space to solve for the virial mass.
- Imposing Bayesian priors on the functional properties of the scaling relations and the non-cosmological redshift evolution derived from hydrodynamical simulations.

$\longrightarrow$ cosmological motivation to study and understand feedback processes

CITA–ICAT

Outline

CITA–ICAT

Feedback

feedback n -s often attrib:

1. the return to the input of a part of the output of a machine, system, or process
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify it
3. the solution of all problems in galaxy formation and cluster physics

CITA–ICAT

Feedback

feedback n -s often attrib:

1. the return to the input of a part of the output of a machine, system, or process
2. the partial reversion of the effects of a given process to its source or to a preceding stage so as to reinforce or modify it
3. the solution of all problems in galaxy formation and cluster physics

CITA–ICAT

Different feedback processes in the ICM

Incomplete and biased list of cluster feedback processes in addition to the usually considered cooling and star formation:

1. cosmic ray (CR) pressure
2. magnetic fields
3. AGN ‘radio mode’ feedback
4. turbulent pressure support
5. galactic outflows
6. physical viscosity
7. heat conduction
8. . . .

CITA–ICAT

Different feedback processes in the ICM

1. cosmic ray (CR) pressure:
   where: cluster center and outskirts, WHIM
   what: quenching of cooling flows (Cen 2005), excitation of Hα-filaments (Ruszkowski et al. 2007), bias of hydrostatic masses, X-ray/SZ emission (Pfrommer et al. 2007), suppression of the low-mass end of the galaxy luminosity function (Jubelgas et al. 2007)
2. magnetic fields
3. AGN 'radio mode' feedback
4. turbulent pressure support
5. galactic outflows
6. physical viscosity
7. heat conduction
8. ...

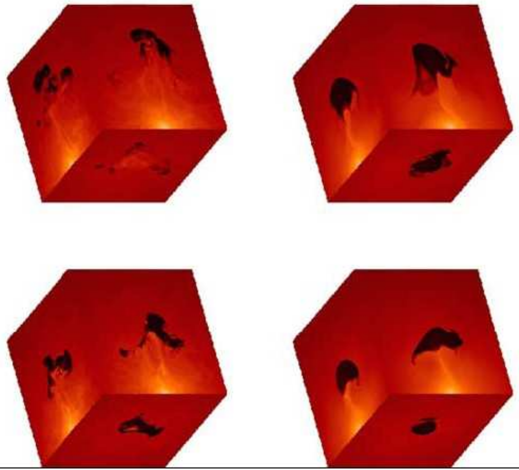
CITA–ICAT

Different feedback processes in the ICM

1. cosmic ray (CR) pressure
2. magnetic fields:
   where: at the interface of different phases of the ICM (bubbles, cold fronts) and at cluster centers
   what: suppresses hydrodynamic instabilities (Kelvin-Helmholtz, Rayleigh-Taylor) and thermal conduction across interface (Asai et al. 2007, Lyutikov 2007, Ruszkowski et al. 2007, Dursi & Pfrommer 2007), responsible for cluster synchrotron emission (Dolag & Enßlin 2000)
3. AGN ‘radio mode’ feedback
4. turbulent pressure support
5. galactic outflows
6. physical viscosity
7. heat conduction
8. ...

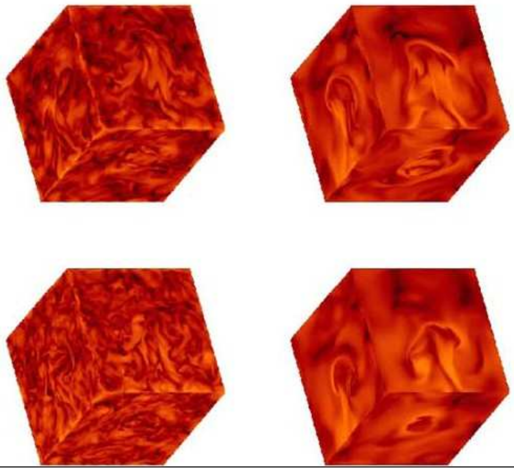
CITA–ICAT

Magnetic draping at bubbles: density



log ρ, non-draping versus draping case (Ruszkowski et al. 2007)

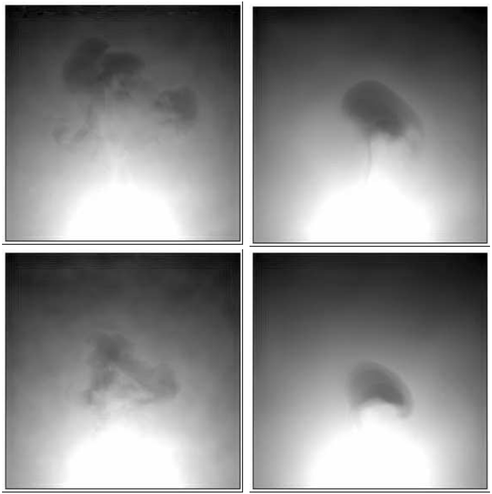
Magnetic draping at bubbles: magnetic pressure



$\log B^2$, non-draping versus draping case (Ruszkowski et al. 2007)

CITA–ICAT

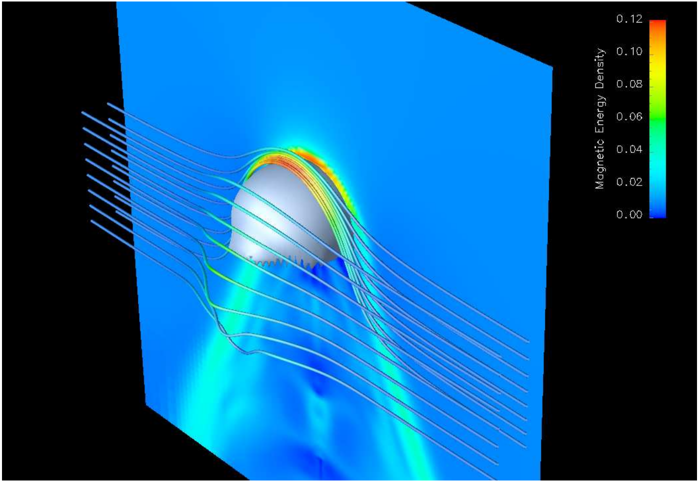
Magnetic draping at bubbles: X-ray emission



S_X, non-draping versus draping case (Ruszkowski et al. 2007)

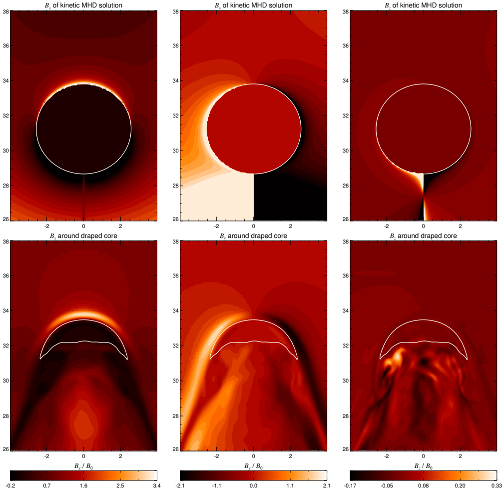
CITA–ICAT

Magnetic draping at cold fronts: physics



Magnetic pressure and field lines (Dursi & Pfrommer in prep.)

Magnetic draping at cold fronts: comparison to theory



Magnetic field: analytics versus AMR (Dursi & Pfrommer in prep.)

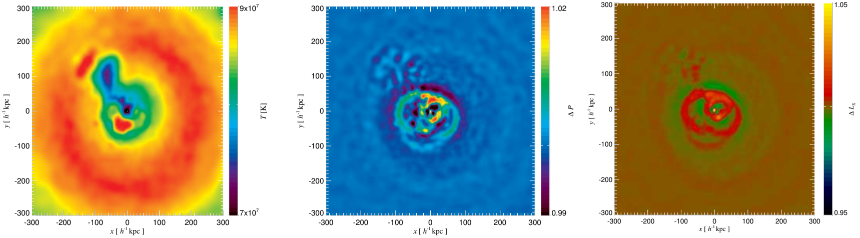
Different feedback processes in the ICM

1. cosmic ray (CR) pressure
2. magnetic fields
3. AGN 'radio mode' feedback:
   where: cluster center/cD galaxy
   what: quenching of cooling flows (e.g., Churazov et al. 2001, Sijacki & Springel 2006, Heinz et al. 2006), suppression of the high-mass end of the luminosity function, down-sizing and color bimodality of galaxies (Croton et al. 2006, de Lucia & Blaizot 2006)
4. turbulent pressure support
5. galactic outflows
6. physical viscosity
7. heat conduction
8. . . .

CITA–ICAT

AGN ‘radio mode’ feedback

Mass-weighted temperature, pressure, X-ray brightness (unsharp masked):



- central bubbles have mushroom-like morphologies and are uplifting residual cool material
- bubbles generate sound waves and weak shocks (heating mechanism unclear, depends on physical viscosity)

  (Sijacki & Springel 2006)

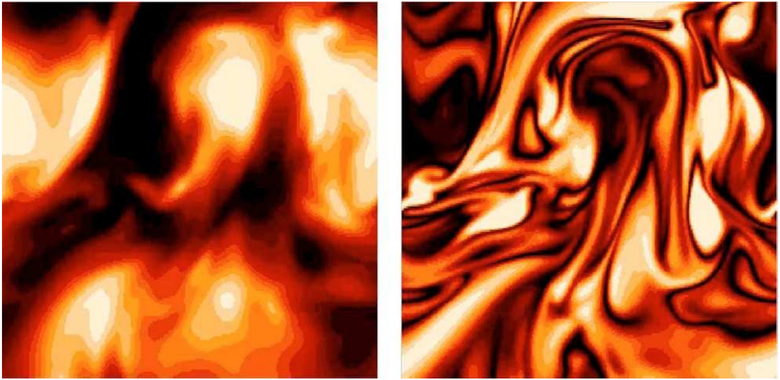
CITA–ICAT

Different feedback processes in the ICM

1. cosmic ray (CR) pressure
2. magnetic fields
3. AGN ‘radio mode’ feedback
4. turbulent pressure support:
   where: ICM, at particular at outskirts (Schekochihin & Cowley 2006)
   what: bias of hydrostatic masses (Rasia et al. 2005, Kravtsov et al. 2006), quenching of cooling flows (Enßlin & Vogt 2006), source of CRs (Brunetti & Lazarian 2007)
5. galactic outflows
6. physical viscosity
7. heat conduction
8. ...

CITA–ICAT

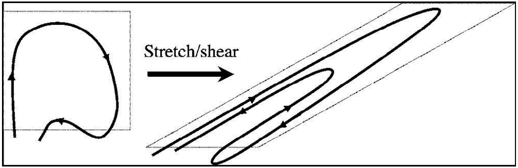
MHD turbulence in clusters

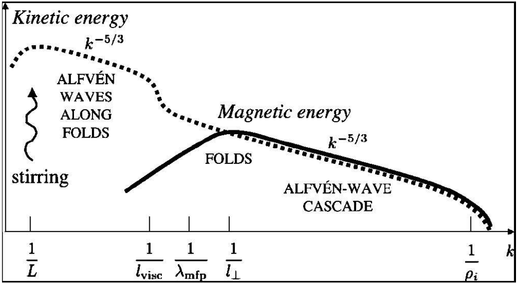


cross-section of $|\boldsymbol{u}|$ and $|\boldsymbol{B}|$ in the saturated dynamo state (Schekochihin & Cowley 2006)

CITA–ICAT

MHD turbulence in clusters



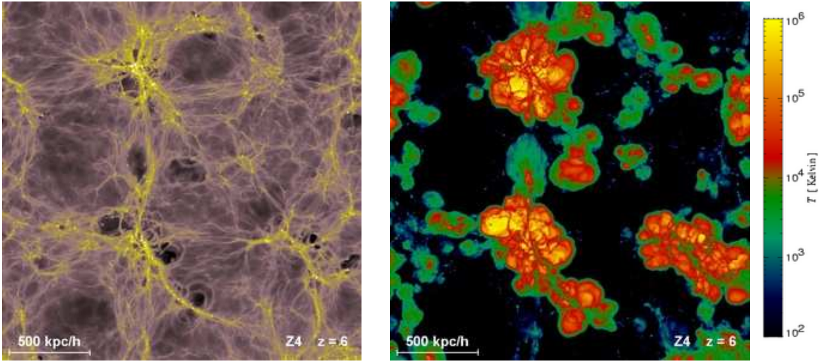


(Schekochihin & Cowley 2006)

Different feedback processes in the ICM

1. cosmic ray (CR) pressure
2. magnetic fields
3. AGN ‘radio mode’ feedback
4. turbulent pressure support
5. galactic outflows:
   where: cluster center & around galaxies
   what: metal enrichment of the IGM (Springel & Hernquist 2002), entropy source of the ICM
6. physical viscosity
7. heat conduction
8. …

Galactic Outflows



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).

CITA–ICAT

Different feedback processes in the ICM

1. cosmic ray (CR) pressure
2. magnetic fields
3. AGN ‘radio mode’ feedback
4. turbulent pressure support
5. galactic outflows
6. physical viscosity:
   where: ICM
   what: change of bubbles properties, additional entropy generation mode, effective gas stripping (Sijacki & Springel 2006)
7. heat conduction
8. ...

CITA–ICAT

Physical viscosity – Navier Stokes equation

- Unlike ideal gases which are isentropic outside of shock waves, entropy conservation does not hold for viscous fluids: Euler equation → generalized Navier-Stokes equation:

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi + \frac{\nabla\hat{\boldsymbol{\sigma}}}{\rho},$$

where the viscous stress tensor, or 'rate-of-strain tensor' is

$$\hat{\sigma}_{ik} = \eta\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\frac{\partial v_l}{\partial x_l}\right) + \zeta\delta_{ik}\frac{\partial v_l}{\partial x_l},$$

η is the coefficient of shear viscosity, and ζ represents the bulk viscosity coefficient.

- Energy conservation law → general heat transfer equation:

$$\rho T\frac{\mathrm{d}S}{\mathrm{d}t} = \nabla(\kappa\nabla T) + \frac{1}{2}\eta\,\hat{\sigma}_{\alpha\beta}\hat{\sigma}_{\alpha\beta} + \zeta(\nabla\boldsymbol{v})^2$$

This equation expresses how much entropy is generated by the internal friction of the gas and by the heat conducted into the considered volume element.

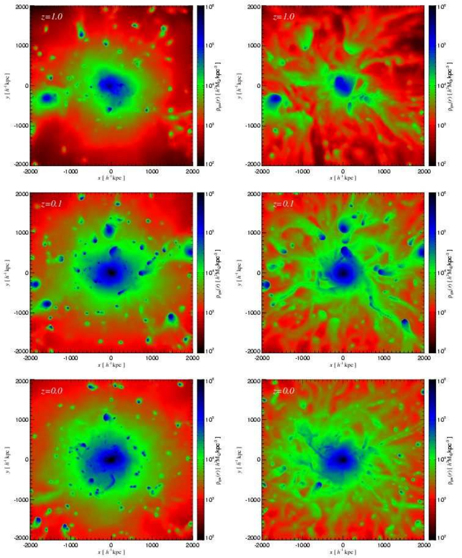
CITA–ICAT

Physical viscosity – Navier Stokes equation

- Unlike ideal gases which are isentropic outside of shock waves, entropy conservation does not hold for viscous fluids: Euler equation → generalized Navier-Stokes equation:
$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi + \frac{\nabla\hat{\boldsymbol{\sigma}}}{\rho},$$
where the viscous stress tensor, or 'rate-of-strain tensor' is
$$\hat{\sigma}_{ik} = \eta\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i} - \frac{2}{3}\delta_{ik}\frac{\partial v_l}{\partial x_l}\right) + \zeta\delta_{ik}\frac{\partial v_l}{\partial x_l},$$
η is the coefficient of shear viscosity, and ζ represents the bulk viscosity coefficient.
- Energy conservation law → general heat transfer equation:
$$\rho T\frac{\mathrm{d}S}{\mathrm{d}t} = \nabla(\kappa\nabla T) + \frac{1}{2}\eta\,\hat{\sigma}_{\alpha\beta}\hat{\sigma}_{\alpha\beta} + \zeta(\nabla\,\boldsymbol{v})^2$$
This equation expresses how much entropy is generated by the internal friction of the gas and by the heat conducted into the considered volume element.

CITA–ICAT

Gas stripping in viscous medium



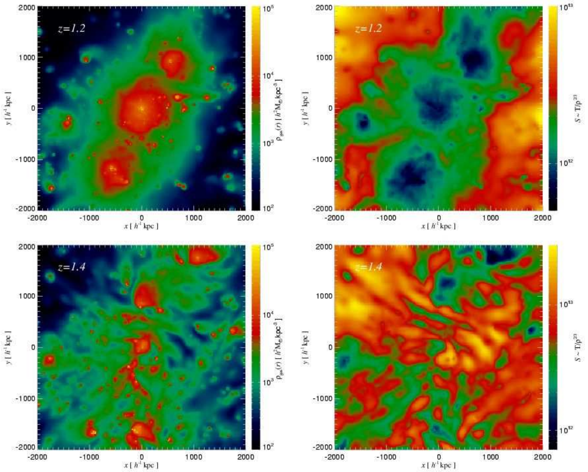
- Projected gas density maps of a non-radiative cluster simulation at redshifts $z = 1.0$, $z = 0.1$ and $z = 0.0$
- left: no physical viscosity, right: including Braginskii shear viscosity suppressed by a factor 0.3
- friction forces induced by viscosity remove more gas from infalling structures when they enter the massive halo $\rightarrow$ pronounced gaseous tails

(Sijacki & Springel 2006)

CITA–ICAT

Generation of entropy bridges in viscous medium

gas density and entropy in radiative cluster simulation



(Sijacki & Springel 2006)

Different feedback processes in the ICM

1. cosmic ray (CR) pressure
2. magnetic fields
3. AGN ‘radio mode’ feedback
4. turbulent pressure support
5. galactic outflows
6. physical viscosity
7. heat conduction:
   where: ICM
   what: re-distribution of thermal energy, quenching of cooling flows (Narayan & Medvedev 2001, Jubelgas et al. 2004, Dolag et al. 2004)
8. ...

CITA–ICAT

Outline

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

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.

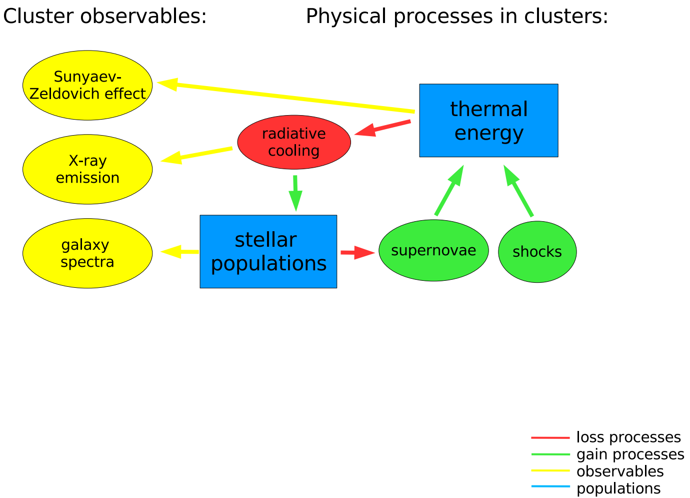
CITA–ICAT

Literature for the following topics

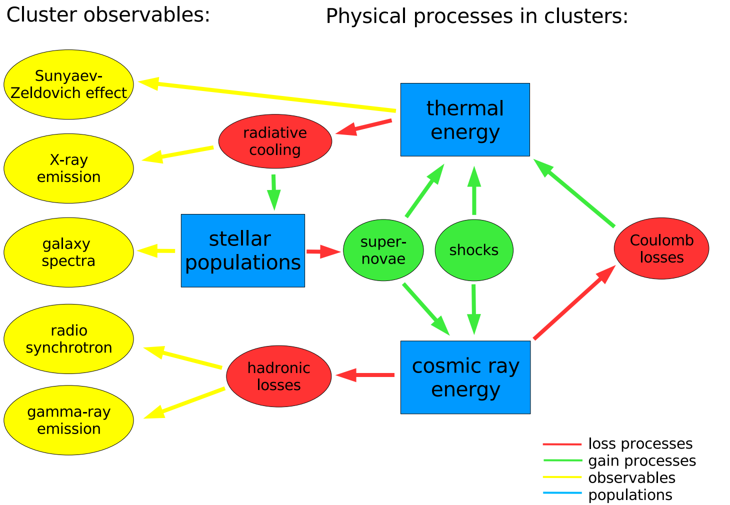
- Pfrommer, 2007, in prep.,
  Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations
- Pfrommer, Enßlin, Springel, 2007, in prep.,
  Simulating cosmic rays in clusters of galaxies – II. A unified model for radio halos and relics with predictions of the γ*-ray emission*
- Pfrommer, Enßlin, Springel, Jubelgas, and Dolag, 2007, MNRAS, 378, 385,
  Simulating cosmic rays in clusters of galaxies, I. effects on the Sunyaev-Zel'dovich effect and the X-ray emission
- Pfrommer, Springel, Enßlin, Jubelgas 2006, MNRAS, 367, 113,
  Detecting shock waves in cosmological smoothed particle hydrodynamics simulations
- Enßlin, Pfrommer, Springel, and Jubelgas, astro-ph/0603484,
  Cosmic ray physics in calculations of cosmological structure formation
- Jubelgas, Springel, Enßlin, and Pfrommer, astro-ph/0603485,
  Cosmic ray feedback in hydrodynamical simulations of galaxy formation

CITA–ICAT

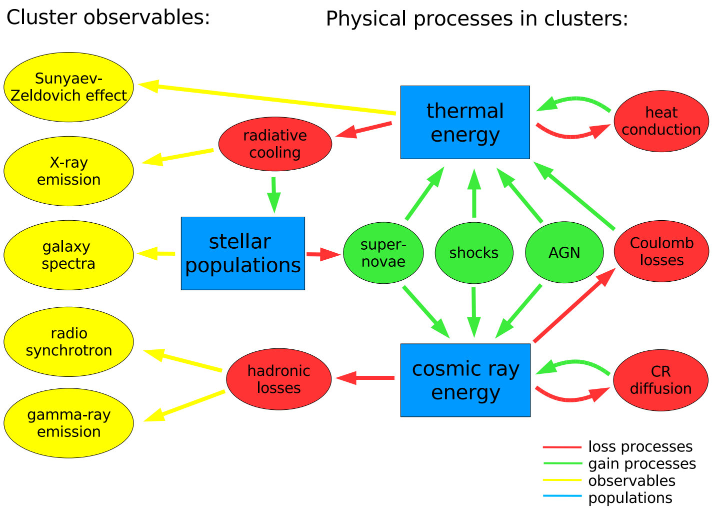
Radiative simulations – flowchart



Radiative simulations with cosmic ray (CR) physics



Radiative simulations with extended CR physics



Previous numerical work on cosmic rays in clusters

COSMOCR: A numerical code for cosmic ray studies in computational cosmology (Miniati, 2001):

- advantages: good resolution in momentum space
- drawbacks: CR pressure not accounted for in EoM, insufficient spatial resolution (grid code), non-radiative gas physics

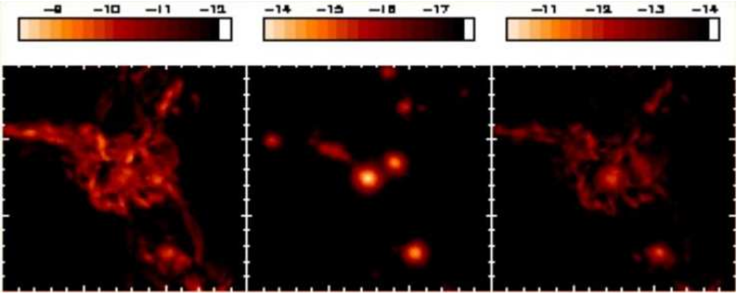


Figure: Hard X-rays, thermal X-rays, γ-rays, adopted from Miniati (2003)

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 necessary

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 necessary

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

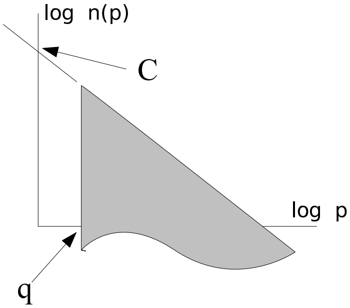
- capturing as many physical properties as possible
- requiring as little computational resources as necessary

Assumptions:

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

CITA–ICAT

CR spectral description



$$p = P_\mathrm{p}/m_\mathrm{p}\,c$$

$$f(p) = \frac{dN}{dp\,dV} = C\,p^{-\alpha}\theta(p-q)$$

$$q(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{1}{3}} q_0$$

$$C(\rho) = \left(\frac{\rho}{\rho_0}\right)^{\frac{\alpha+2}{3}} C_0$$

$$n_\mathrm{CR} = \int_0^\infty \mathrm{d}p\, f(p) = \frac{C\,q^{1-\alpha}}{\alpha-1}$$

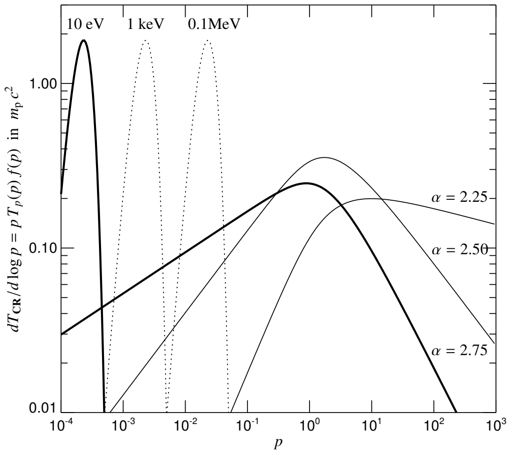
$$P_\mathrm{CR} = \frac{m_\mathrm{p}c^2}{3}\int_0^\infty \mathrm{d}p\, f(p)\,\beta(p)\,p$$

$$= \frac{C\,m_\mathrm{p}c^2}{6}\,\mathcal{B}_{\frac{1}{1+q^2}}\left(\frac{\alpha-2}{2},\frac{3-\alpha}{2}\right)$$

CITA–ICAT

Thermal & CR energy spectra

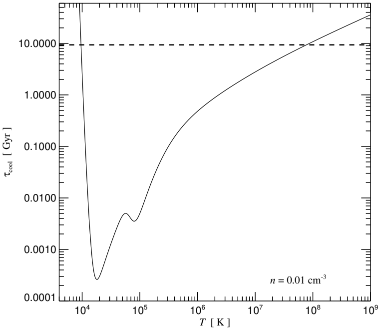
Kinetic energy per logarithmic momentum interval:



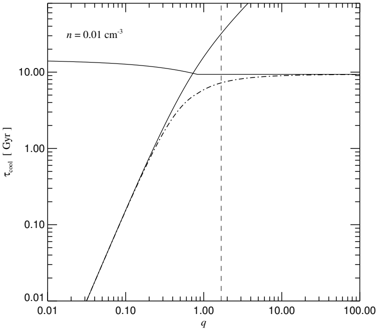
CITA–ICAT

Cooling time scales of CR protons

Cooling of primordial gas:



Cooling of cosmic rays:



CITA–ICAT

Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:

- a collisionless shock wave
- magnetic fields to confine energetic particles
- plasma waves to scatter energetic particles $\longrightarrow$ particle diffusion
- supra-thermal particles

mechanism:

- supra-thermal particles diffuse upstream across shock wave
- each shock crossing energizes particles through momentum transfer from recoil-free scattering off the macroscopic scattering agents
- momentum increases exponential with number of shock crossings
- number of particles decreases exponential with number of crossings

$\longrightarrow$ power-law CR distribution

CITA–ICAT

Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:

- a collisionless shock wave
- magnetic fields to confine energetic particles
- plasma waves to scatter energetic particles $\longrightarrow$ particle diffusion
- supra-thermal particles

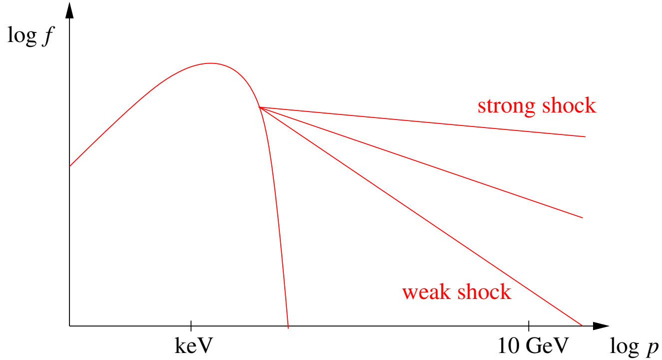
mechanism:

- supra-thermal particles diffuse upstream across shock wave
- each shock crossing energizes particles through momentum transfer from recoil-free scattering off the macroscopic scattering agents
- momentum increases exponential with number of shock crossings
- number of particles decreases exponential with number of crossings

$\longrightarrow$ power-law CR distribution

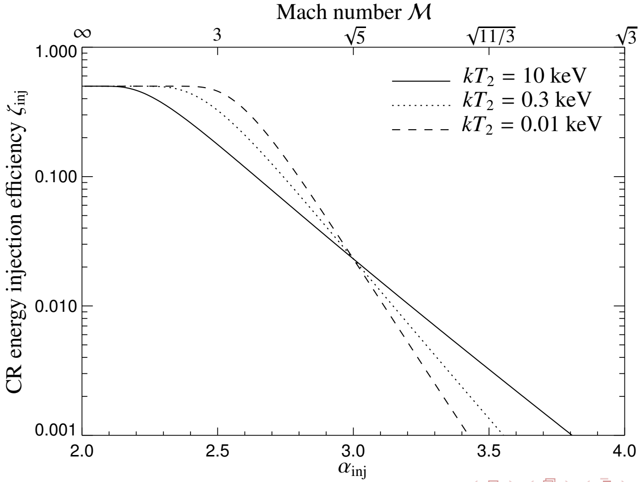
Diffusive shock acceleration – Fermi 1 mechanism (2)

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



Diffusive shock acceleration – efficiency (3)

CR proton energy injection efficiency, $\zeta_{\mathrm{inj}} = \varepsilon_{\mathrm{CR}}/\varepsilon_{\mathrm{diss}}$:

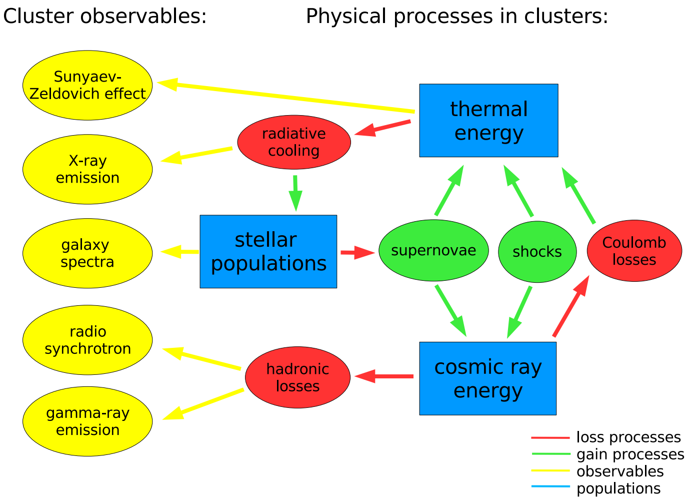


Outline

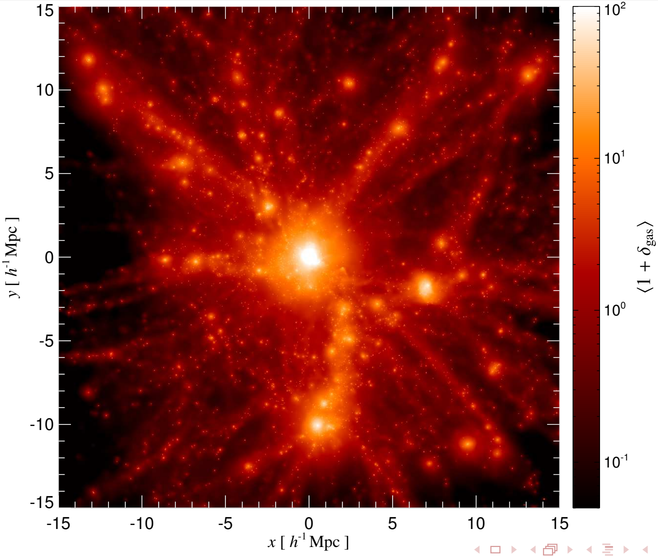
1. Thermal plasma in galaxy clusters
   - Introduction
   - Thermal cluster observables
   - Feedback processes in the ICM
2. Cosmic rays in galaxy clusters
   - Cosmic ray physics
   - Cosmic ray pressure feedback
   - Cosmological implications of cosmic rays
3. Non-thermal cluster emission
   - Radiative processes
   - Unified model of radio halos and relics
   - High-energy gamma-ray emission

CITA–ICAT

Radiative simulations with CR physics

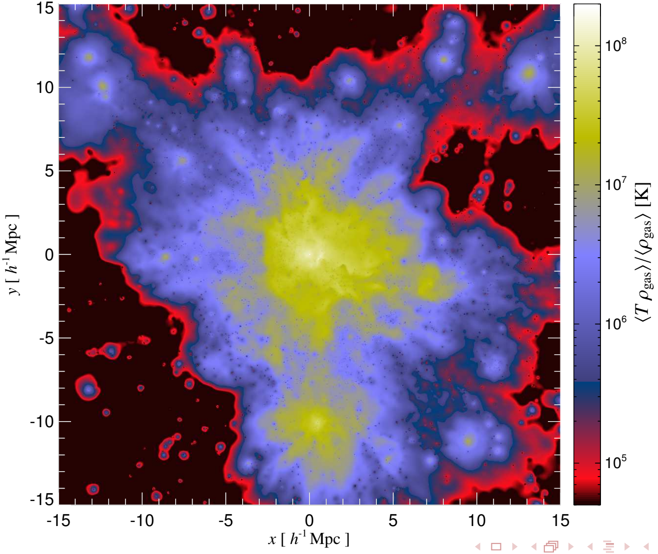


Radiative cool core cluster simulation: gas density



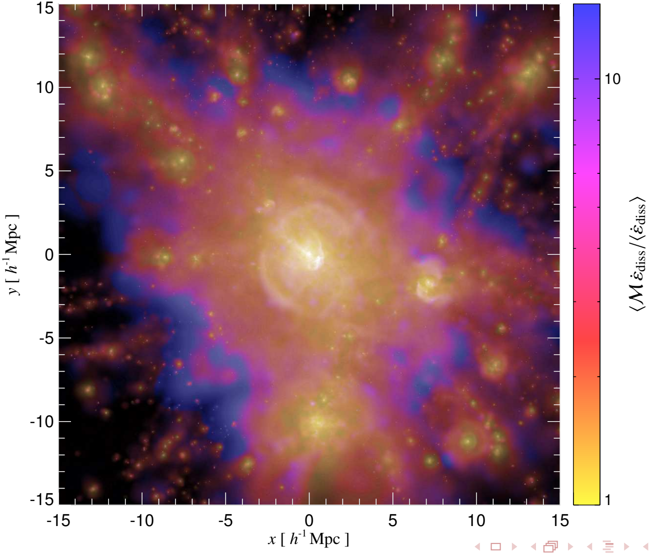
CITA–ICAT

Mass weighted temperature



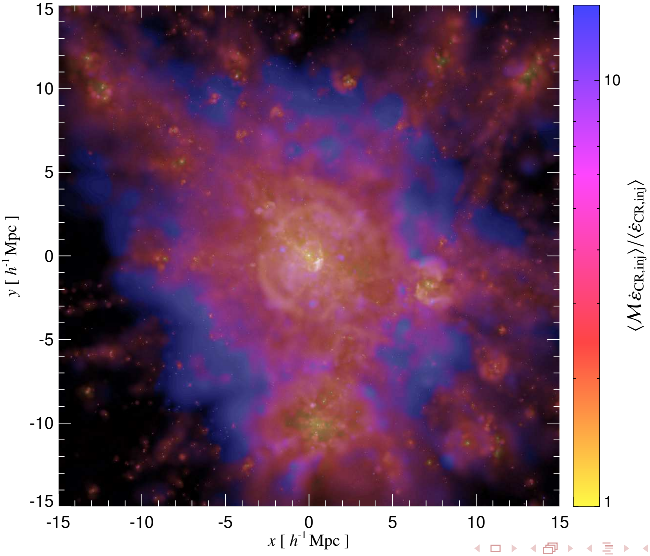
CITA–ICAT

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



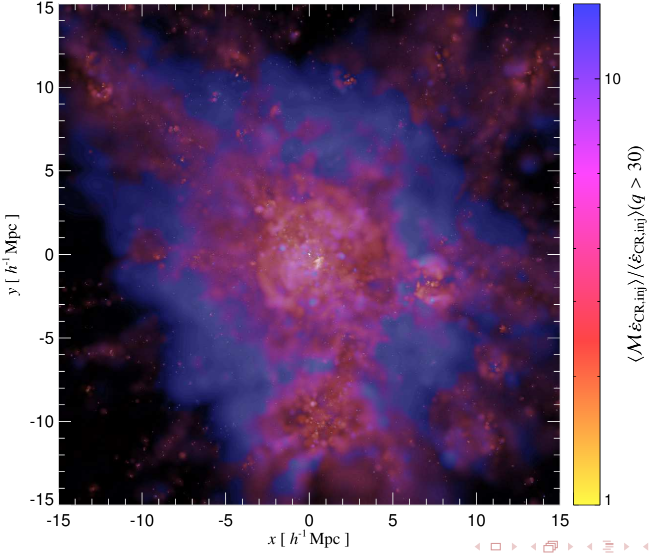
CITA–ICAT

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



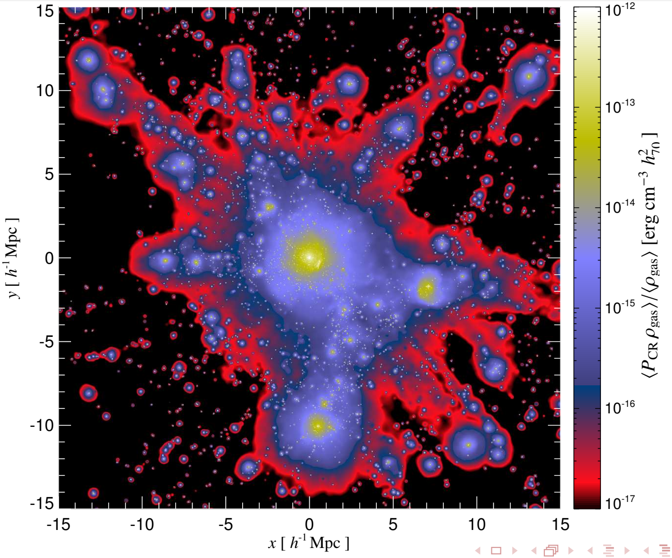
CITA–ICAT

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



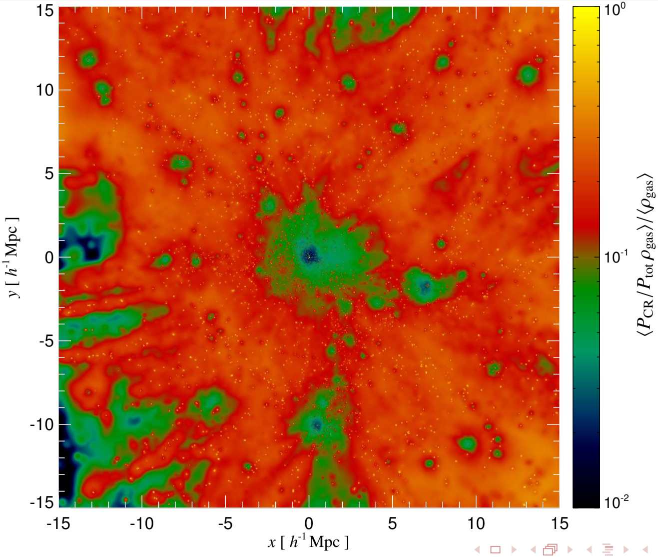
CITA–ICAT

CR pressure P_{CR}



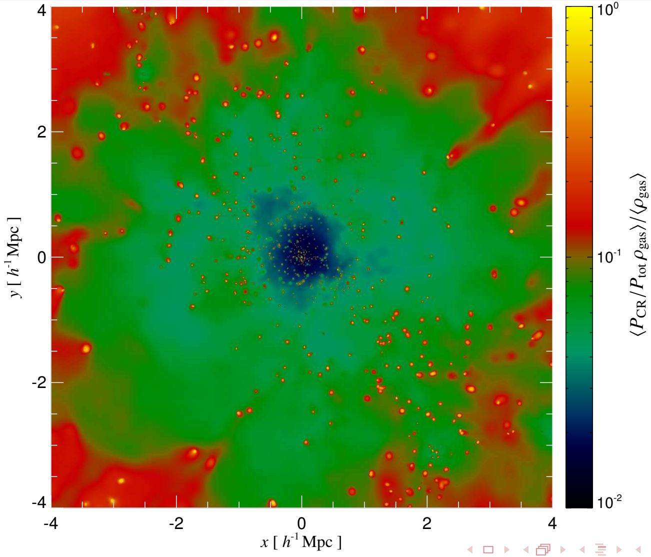
CITA–ICAT

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



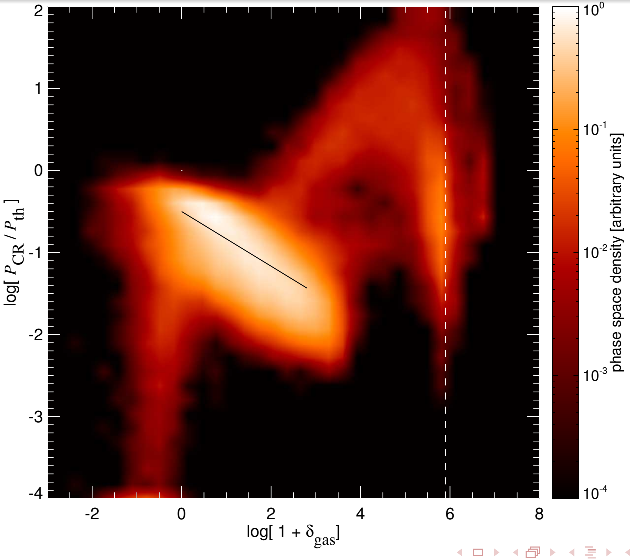
CITA–ICAT

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

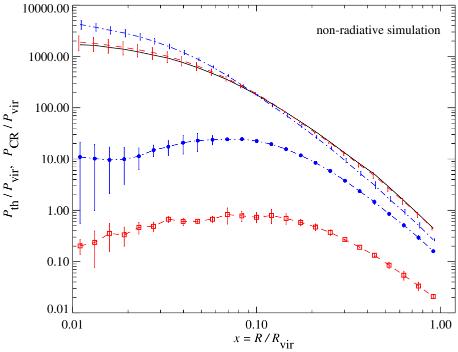


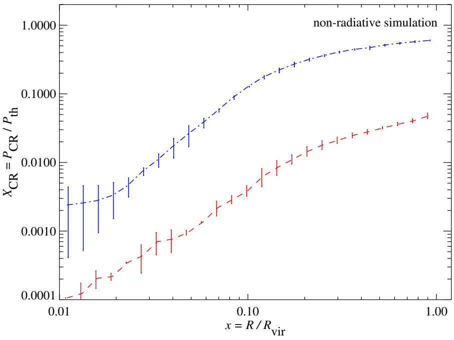
CITA–ICAT

Phase-space diagram of radiative cluster simulation



Profiles: non-radiative simulations





Thermal & CR pressure

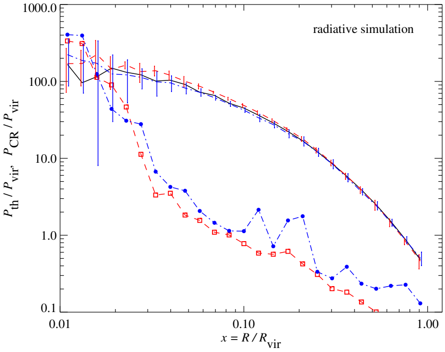
Relative CR pressure, $X_{CR} = P_{CR}/P_{th}$.

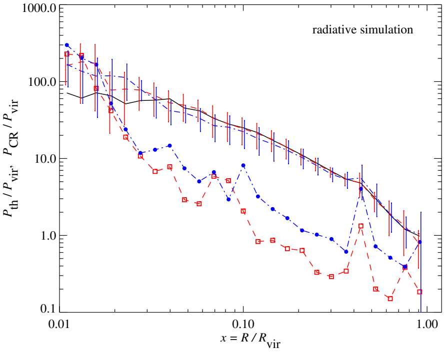
red: Mach number dependent CR injection,

blue: fixed acceleration efficiency (too simplistic).

CITA–ICAT

Radiative simulations: pressure profile





Cool core cluster sample.

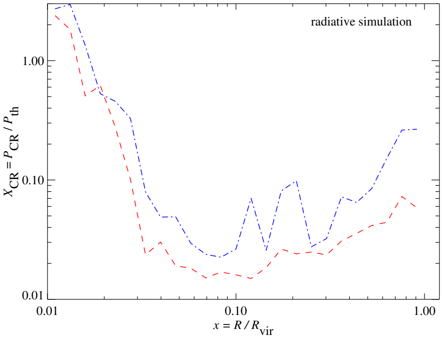
Merging cluster sample.

red: only structure formation shock CRs,

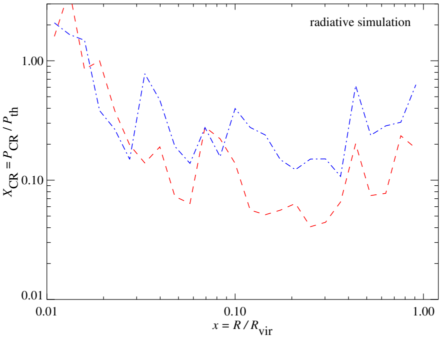
blue: structure formation & SNe CRs.

CITA–ICAT

Radiative simulations: relative CR pressure profile



Cool core cluster sample.



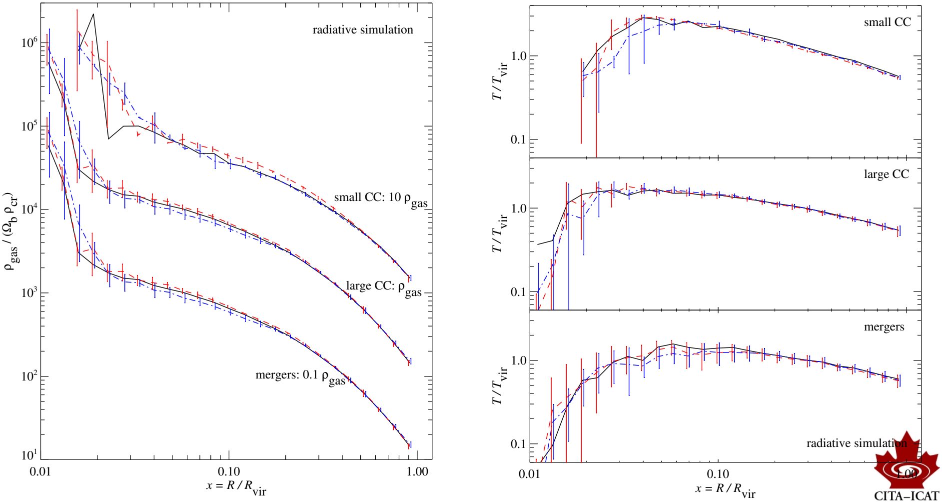
Merging cluster sample.

red: only structure formation shock CRs,

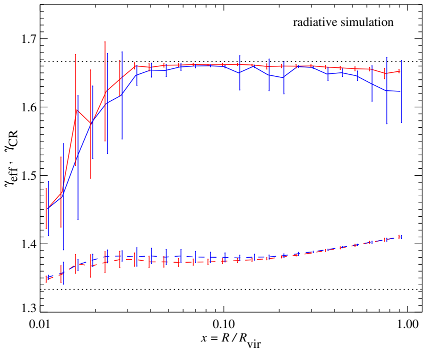
blue: structure formation & SNe CRs.

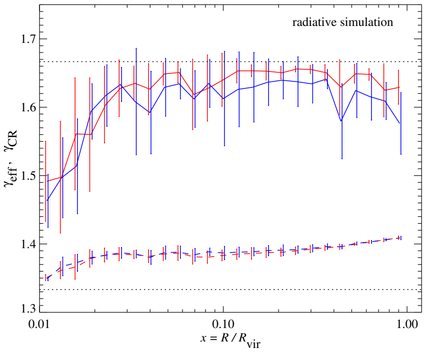
CITA–ICAT

Radiative simulations: density and temperature profile



Radiative simulations: adiabatic index profile





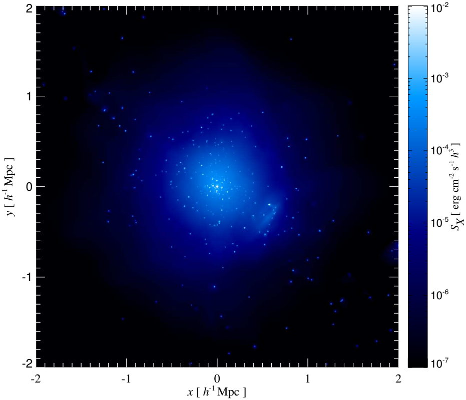
Cool core cluster sample.

Merging cluster sample.

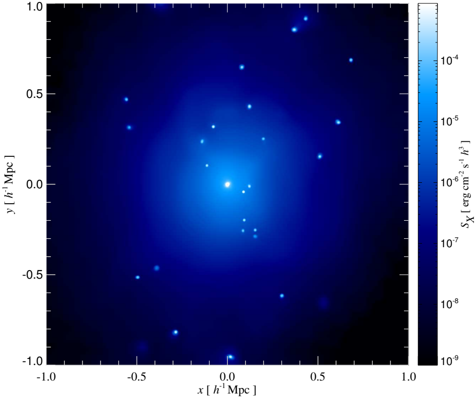
red: only structure formation shock CRs,

blue: structure formation & SNe CRs.

Thermal X-ray emission



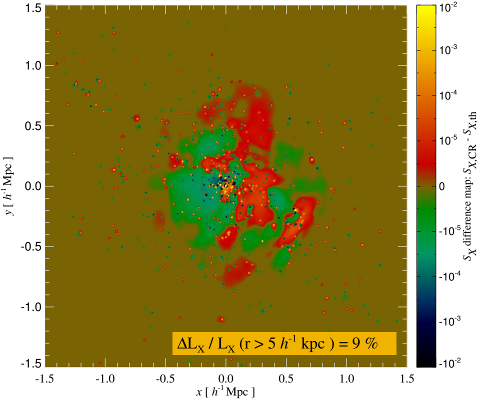
large merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_{\odot}/h$

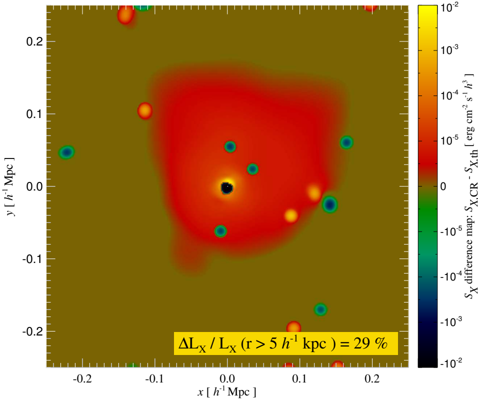


small cool core cluster, $M_{\mathrm{vir}} \simeq 10^{14} M_{\odot}/h$

CITA–ICAT

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



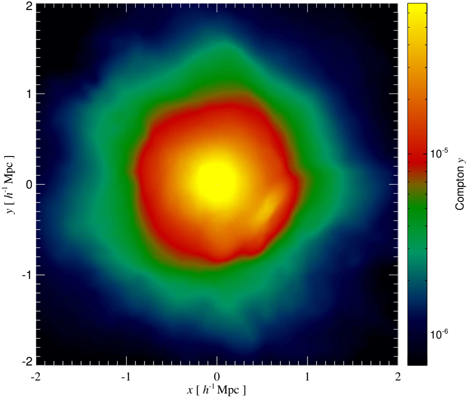


large merging cluster, $M_{vir} \simeq 10^{15} M_\odot / h$
$\rightarrow$ contributes to the scatter in the $M - L_X$ scaling relation

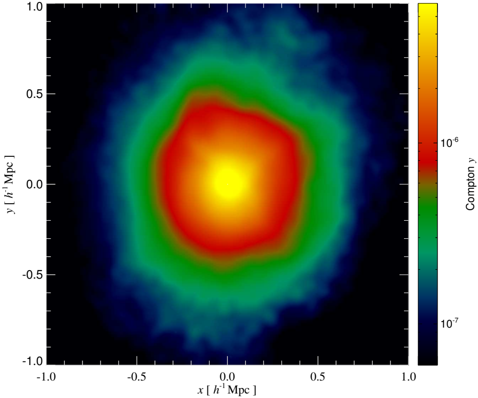
cool core cluster, $M_{vir} \simeq 10^{14} M_\odot / h$
$\rightarrow$ systematic increase of L_X for small cool core clusters

CITA–ICAT

Compton y parameter in radiative cluster simulation



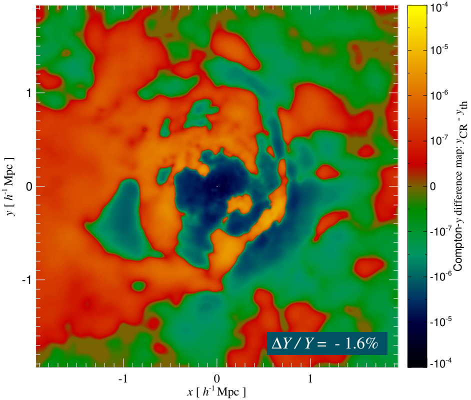
large merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_{\odot}/h$



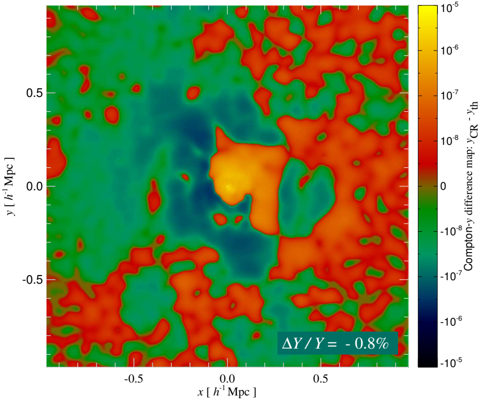
small cool core cluster, $M_{\mathrm{vir}} \simeq 10^{14} M_{\odot}/h$

CITA–ICAT

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



large merging cluster, $M_{\mathrm{vir}} \simeq 10^{15} M_\odot / h$



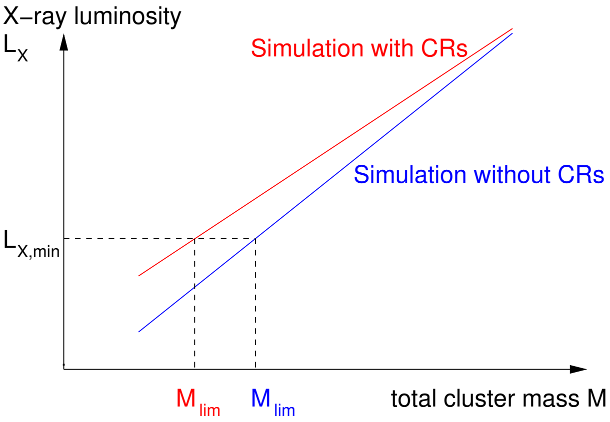
small cool core cluster, $M_{\mathrm{vir}} \simeq 10^{14} M_\odot / h$

CITA–ICAT

Outline

CITA–ICAT

Modified X-ray scaling relations (with Subha Majumdar)



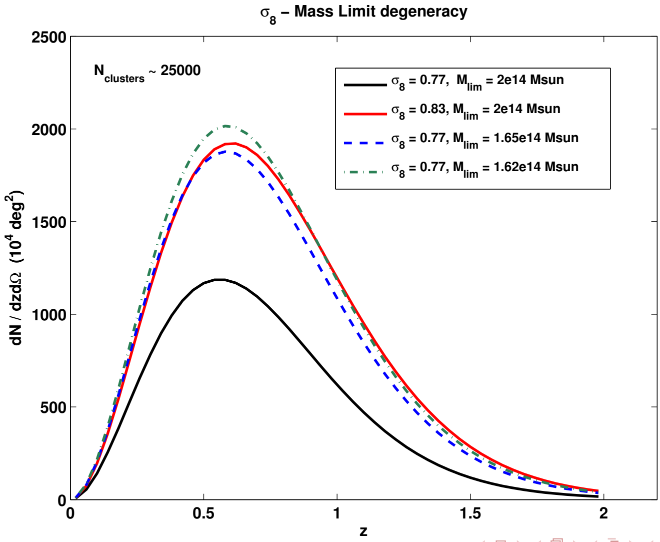
→ CR feedback lowers the effective mass threshold for X–ray flux–limited cluster sample

Degeneracies of the cluster redshift distribution (1)

- The number density of massive clusters is exponentially sensitive to the amplitude of the initial Gaussian fluctuations, whose normalization we usually describe using σ_8, the *rms* fluctuations of overdensity within spheres of $8\,h^{-1}$ Mpc.
- The cluster redshift distribution $\mathrm{d}n/\mathrm{d}z$ is increased by a lower effective mass threshold M_{lim} in a survey or by increasing σ_8 respectively Ω_{m} $\rightarrow$ degeneracies of cosmological parameters with respect to cluster physics.

CITA–ICAT

Degeneracies of the cluster redshift distribution (2)



Fisher matrix analysis (1)

Survey Fisher matrix information for a data set:

$$F_{ij} \equiv -\left\langle \frac{\partial^2 \ln \mathcal{L}}{\partial p_i \, \partial p_j} \right\rangle = \sum_n \frac{\partial N_n}{\partial p_i} \frac{\partial N_n}{\partial p_j} \frac{1}{N_n},$$

where $\mathcal{L}$ is the likelihood for an observable (proportional to $\mathrm{d}N/\mathrm{d}z$ for the redshift distribution), p_i describes our parameter set, the sum extends over the redshift bins, and N_n represents the number of surveyed clusters in each redshift bin n (statistically independent, Poisson distributed).

The inverse F_{ij}^{-1} describes the best attainable covariance matrix $[C_{ij}]$ (assuming Gaussianity) for measurement of the parameters considered. The diagonal terms of $[C_{ij}]$ then give the uncertainties of each of our parameters.

CITA–ICAT

Fisher matrix analysis (2)

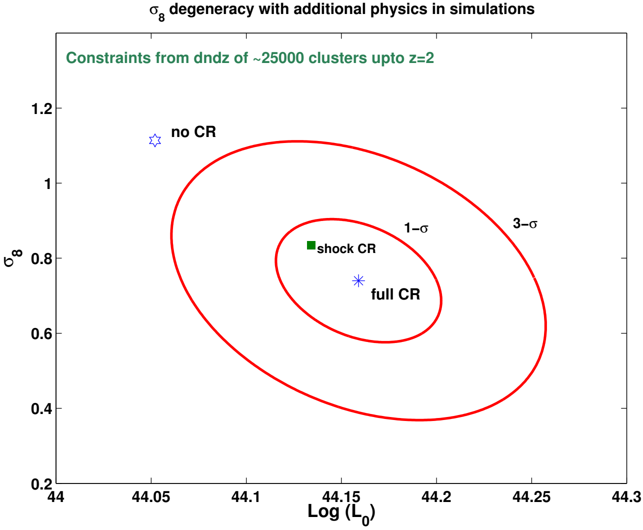
Assumed survey details:

- survey area $A = 10^4$ square degrees ($1/4$ of the sky)
- redshift range: $0 < z < 2$
- bolometric X-ray flux limit $F_\mathrm{X} = 2.5 \times 10^{-13}$ erg s^{-1} cm^{-2}
- sample size: 25000 clusters

Fisher matrix preliminaries:

- free parameters: 2 parameters of the scaling relations: slope and normalization, Ω_m, Ω_b, n_s, h, σ_8
- priors: flat Universe, WMAP prior on $h = 72 \pm 5$

Degeneracy of σ_8 with cosmic ray physics (preliminary)

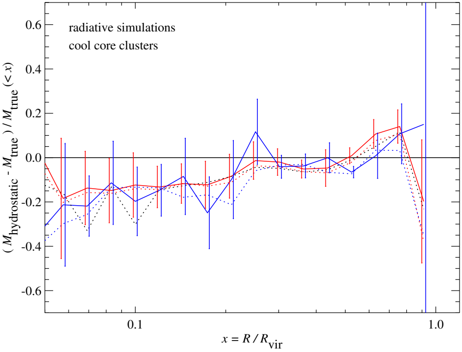


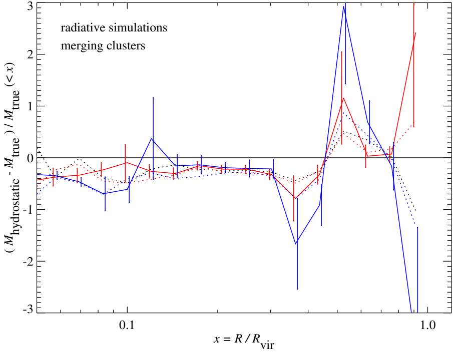
CITA–ICAT

Hydrostatic mass profiles

Influence of turbulence and CR pressure

Relative mass difference $(M_{\text{hydrostatic}} - M_{\text{true}})/M_{\text{true}}$:





$$\frac{1}{\rho_{\text{gas}}}\frac{\mathrm{d}P_{\text{tot}}}{\mathrm{d}r} = -\frac{G\,M(<r)}{r^2}, \text{ and } P_{\text{tot}} = P_{\text{th}} + P_{\text{nth}} + P_{\text{turb}}.$$

CITA–ICAT

Outline

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 → cluster archaeology.

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

- LOFAR, GMRT, MWA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Simbol-X: future hard X-ray satellite ($E \simeq (0.5 - 70)$ keV)
- GLAST: high-energy γ-ray space mission ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes (TeV photon energies)

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.

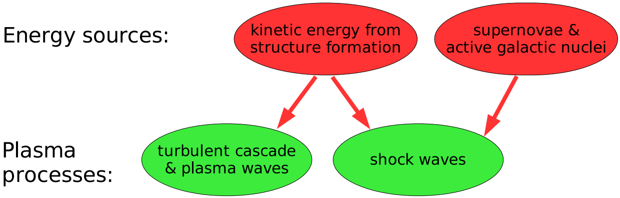
How can we read out this information about non-thermal populations? $\rightarrow$ new era of multi-frequency experiments, e.g.:

- LOFAR, GMRT, MWA: interferometric array of radio telescopes at low frequencies ($\nu \simeq (15 - 240)$ MHz)
- Simbol-X: future hard X-ray satellite ($E \simeq (0.5 - 70)$ keV)
- GLAST: high-energy γ-ray space mission ($E \simeq (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes (TeV photon energies)

CITA–ICAT

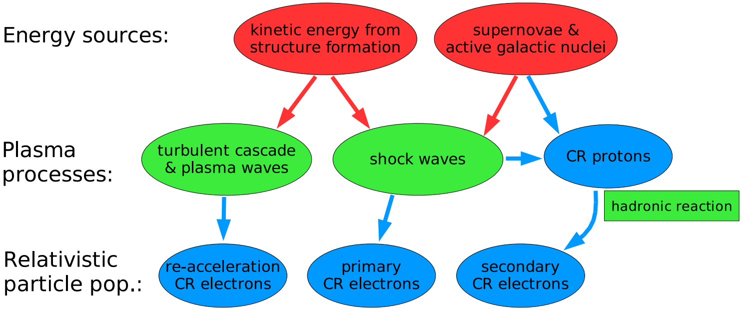
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



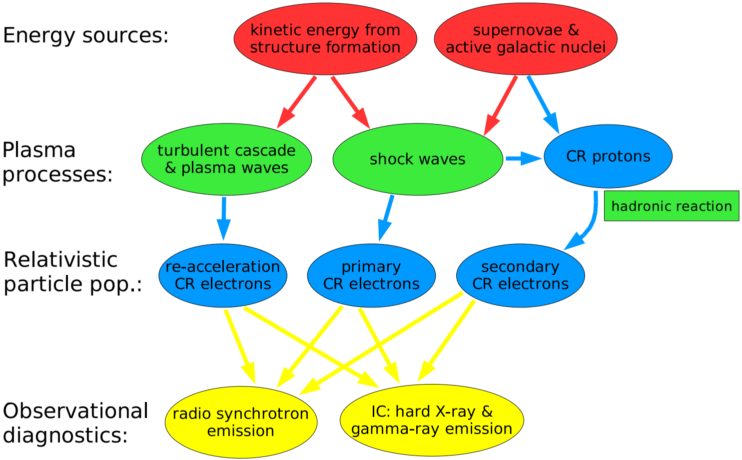
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



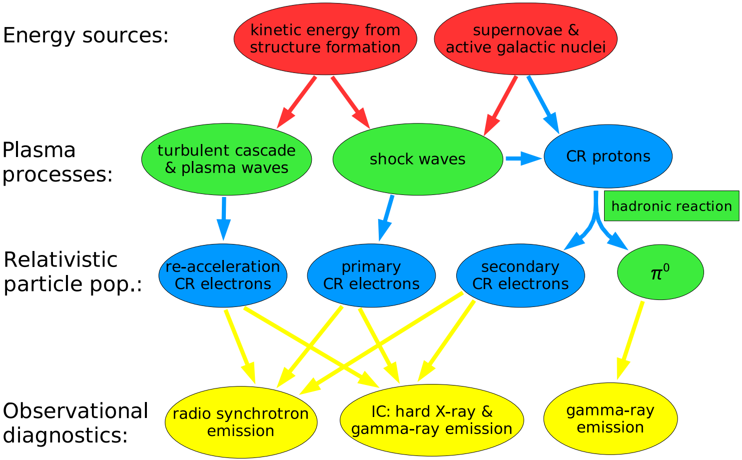
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:

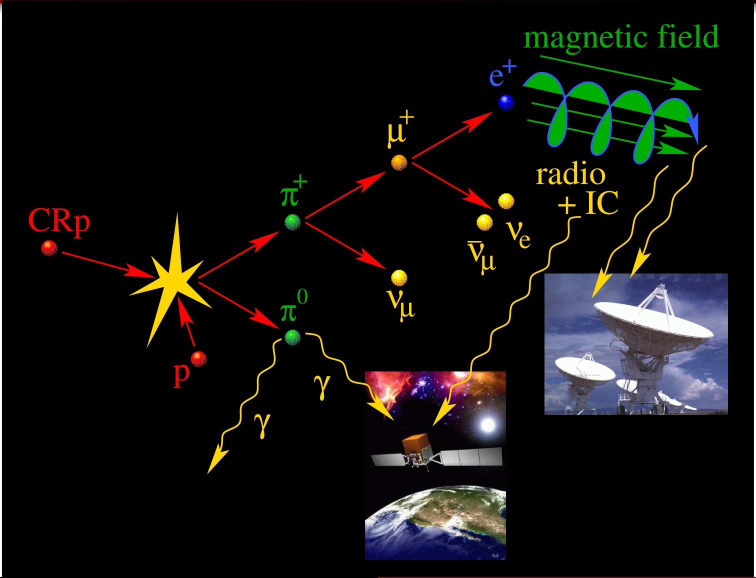


Cosmic rays and radiative processes

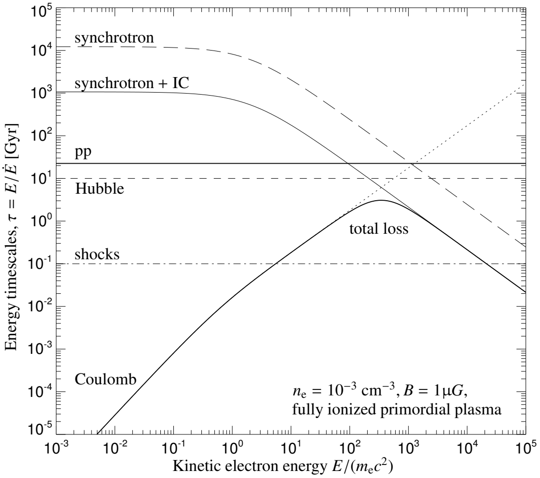
Relativistic populations and radiative processes in clusters:



Hadronic cosmic ray proton interaction



Cooling time scales of CR electrons

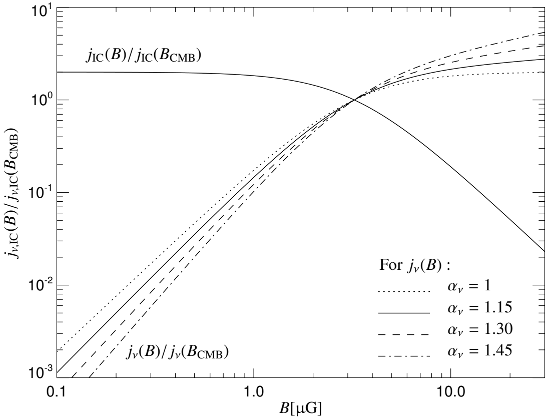


Equilibrium distribution of CR electrons

- CR electron injection balances IC/synchrotron cooling:
$$\frac{\partial}{\partial E_\mathrm{e}}\left[\dot{E}_\mathrm{e}(E_\mathrm{e}) f_\mathrm{e}(E_\mathrm{e})\right] = s_\mathrm{e}(E_\mathrm{e})\,.$$
- For $\dot{E}_\mathrm{e}(p) < 0$, this equation is solved by
$$f_\mathrm{e}(E_\mathrm{e}) = \frac{1}{|\dot{E}_\mathrm{e}(E_\mathrm{e})|}\int_{E_\mathrm{e}}^{\infty} \mathrm{d}E'_\mathrm{e} s_\mathrm{e}(E'_\mathrm{e})\,.$$
- At high energies, IC/synchrotron losses dominate:
$$-\dot{E}_\mathrm{e}(E_\mathrm{e}) = \frac{4\,\sigma_\mathrm{T}\,c}{3\,m_\mathrm{e}^2\,c^4}\left[\varepsilon_B + \varepsilon_\mathrm{ph}\right]\,E_\mathrm{e}^2.$$
- CR electrons can either be produced by structure formation shocks, or in hadronic CR proton interactions $\rightarrow$ source function s_e.

CITA–ICAT

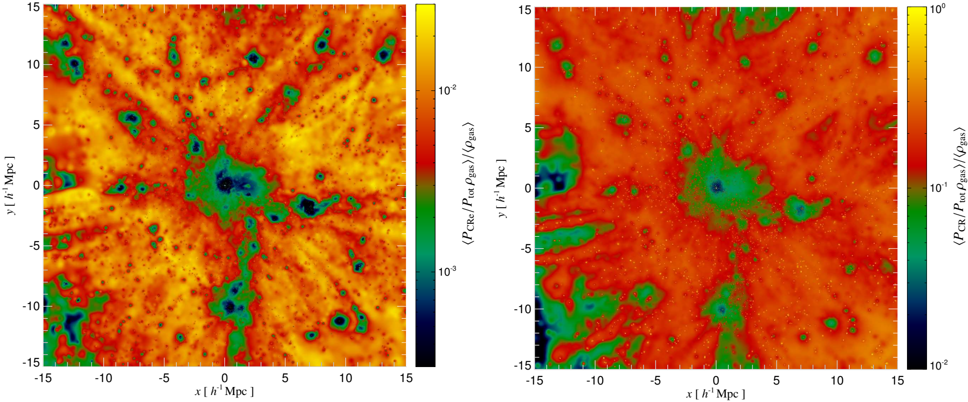
Synchrotron versus IC emissivity



IC cooling regime: leftwards of $B_\mathrm{CMB} \simeq 3.2\,(1+z)^2\,\mu\mathrm{G}$,
synchrotron cooling regime: rightwards of B_CMB.

CITA–ICAT

CR electron versus CR proton pressure

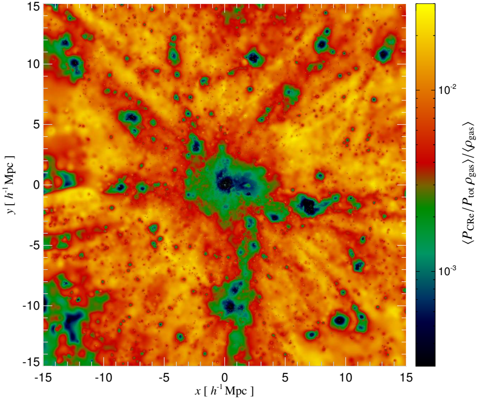


Relative pressure of primary CR electrons.

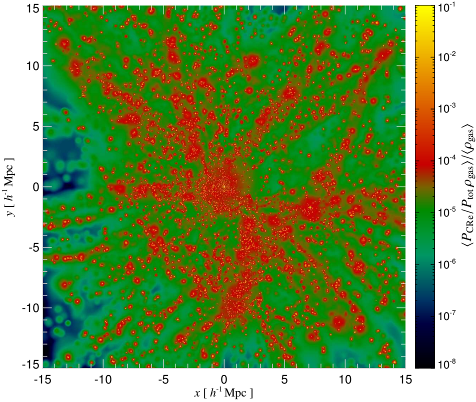
Relative pressure of CR protons.

CITA–ICAT

Primary versus secondary CR electrons



Relative pressure of *primary* CR electrons.



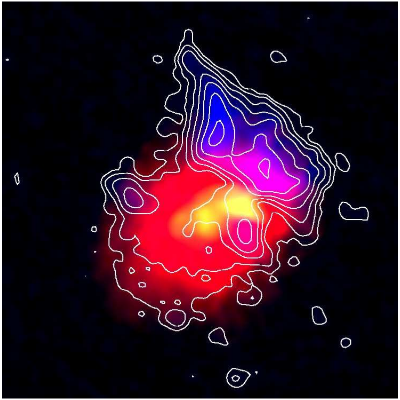
Rel. pressure of *secondary* CR electrons.

CITA–ICAT

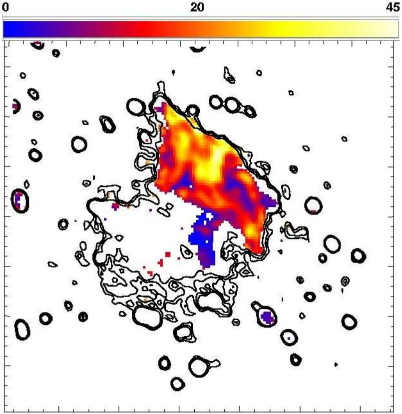
Outline

CITA–ICAT

Abell 2256: giant radio relic & small halo



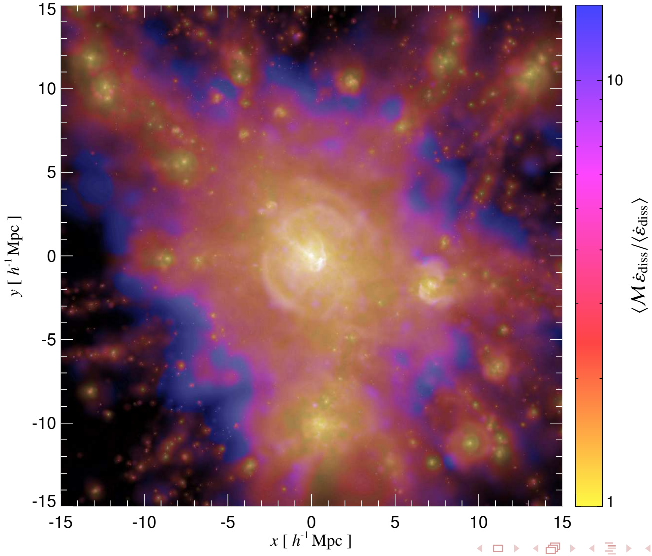
X-ray (red) & radio (blue, contours)



fractional polarization in color

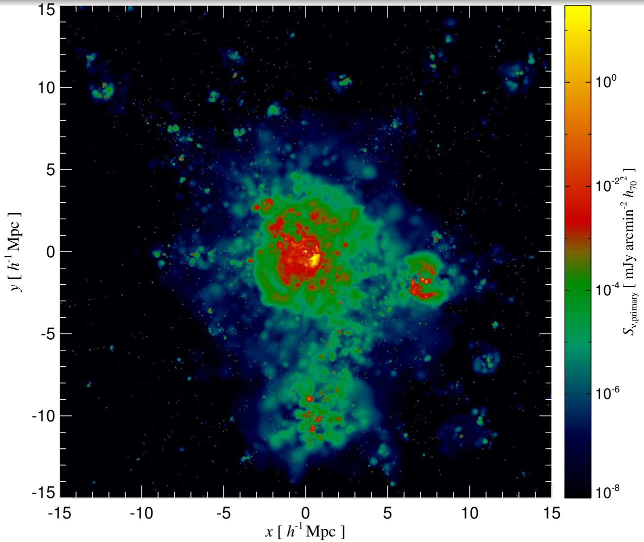
Clarke & Enßlin (2006)

Cosmic web: Mach number

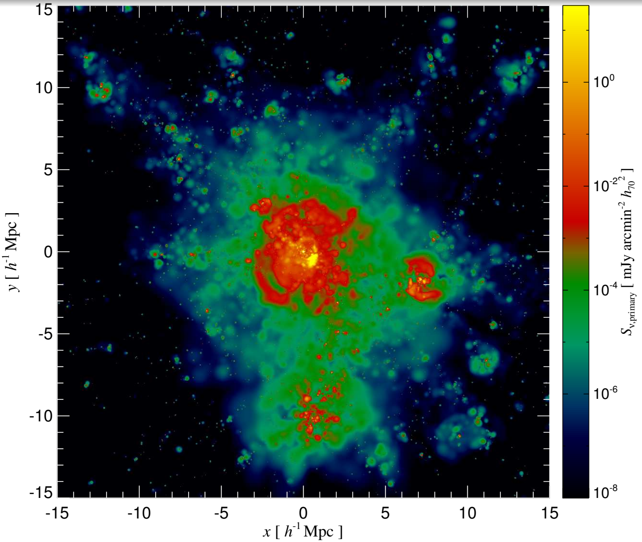


CITA–ICAT

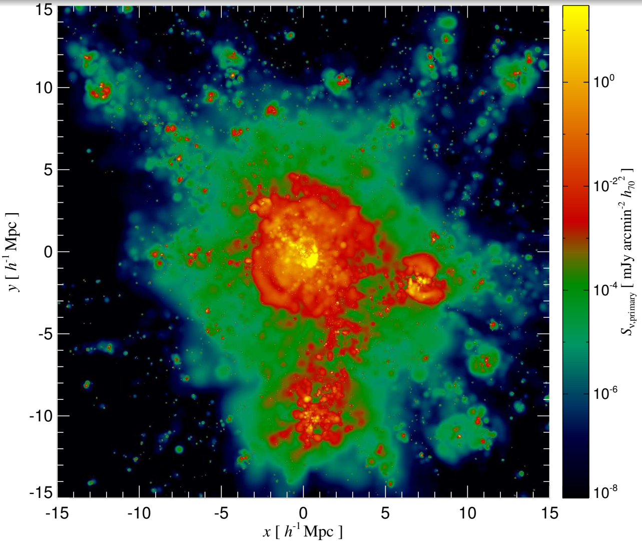
Radio web: primary CRe (1.4 GHz)



Radio web: primary CRe (150 MHz)

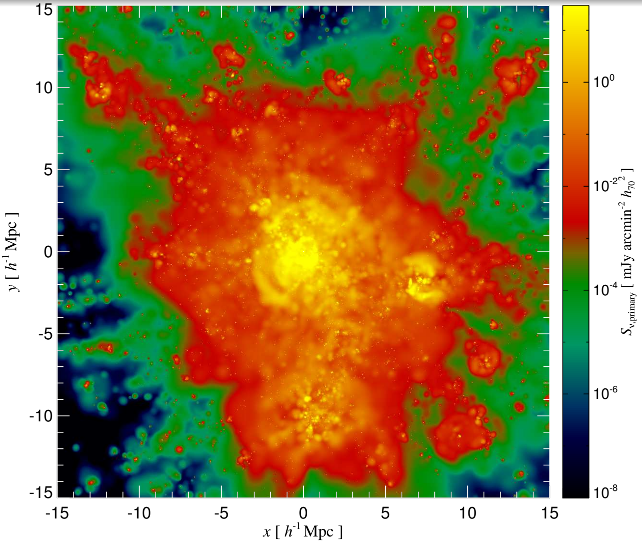


Radio web: primary CRe (15 MHz)



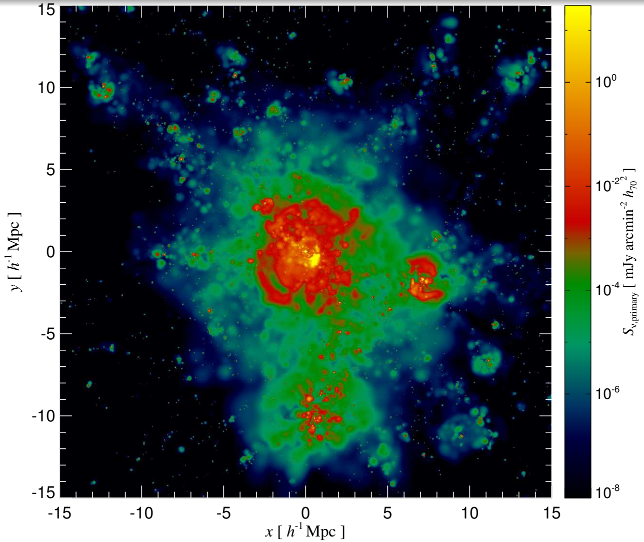
CITA–ICAT

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



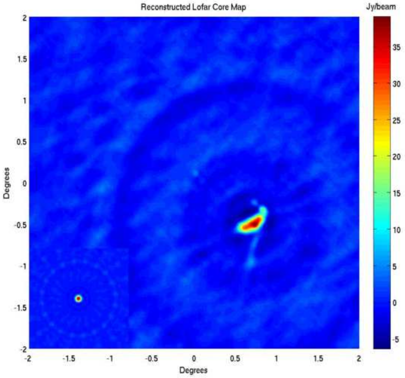
CITA–ICAT

Exploring the magnetized radio web (with Battaglia, Sievers, Bond)

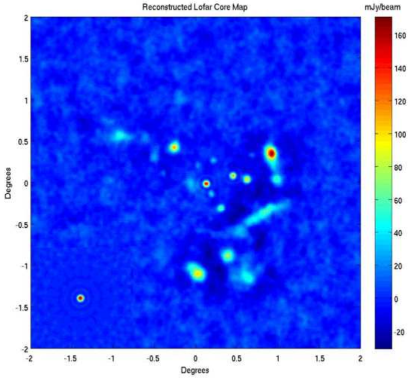


CITA–ICAT

Simulated LOFAR observation (merging cluster at $z = 0.02$)

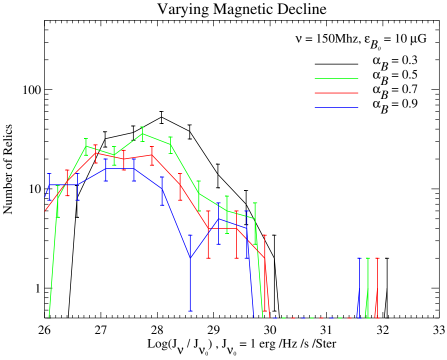


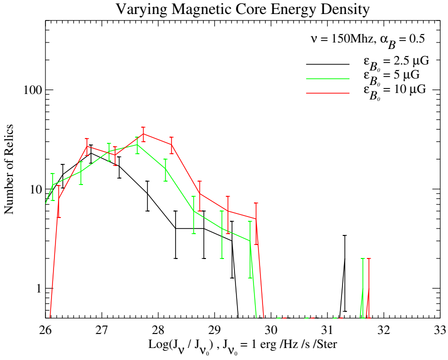
Reconstructed 'dirty' LOFAR core map.



Reconstructed 'cleaned' LOFAR map.

Radio relic luminosity function



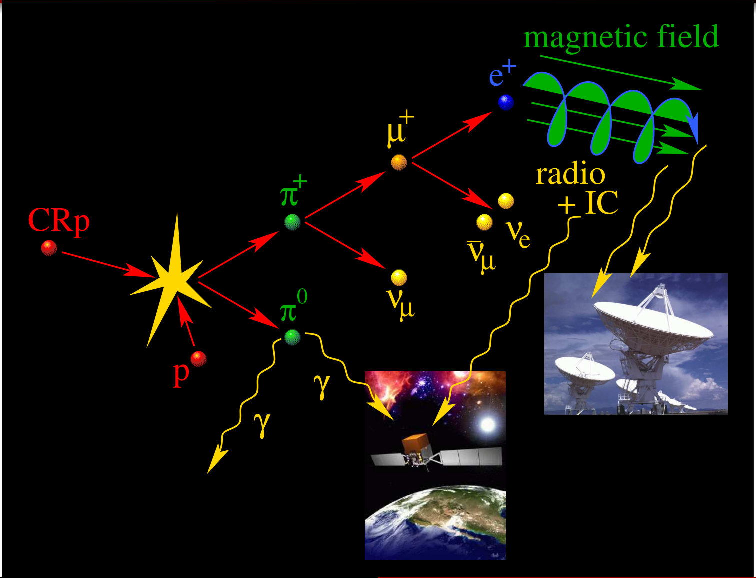


Varying the magnetic decline, $\varepsilon_B \propto \varepsilon_{\text{th}}^{2\alpha_B}$.

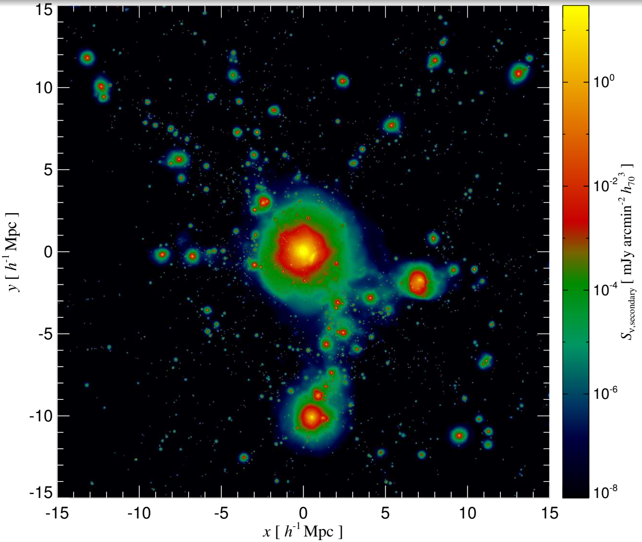
Varying the central magnetic field.

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

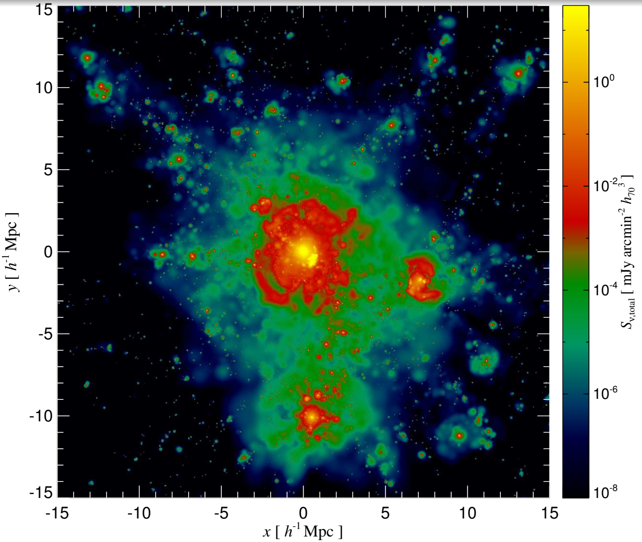
Unified model of radio halos and relics

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.

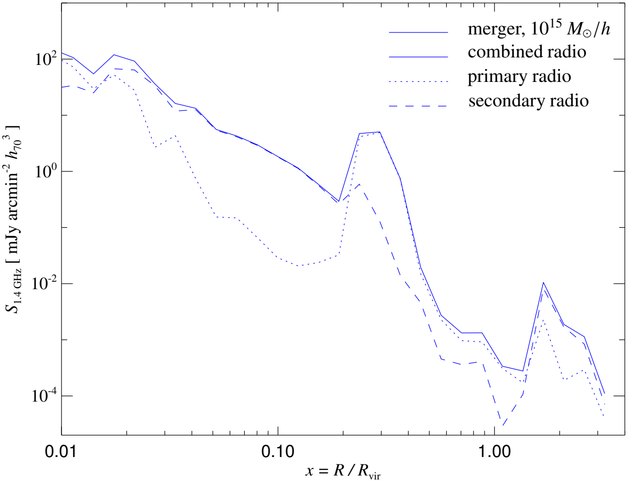
CITA–ICAT

Radio gischt + central hadronic halo = giant radio halo



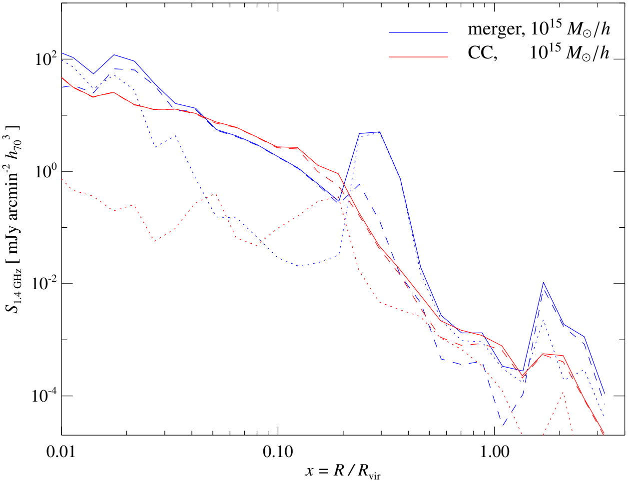
CITA–ICAT

Giant radio halo profile



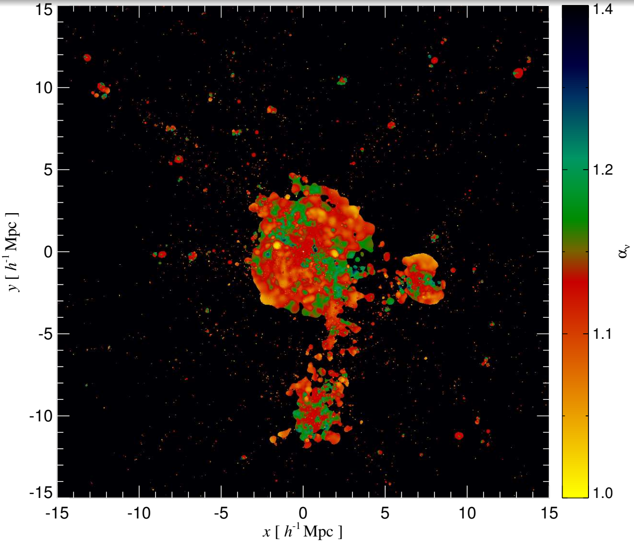
CITA–ICAT

Giant radio halo vs. mini-halo



CITA–ICAT

Radio relics + halos: spectral index



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

Low-frequency radio emission from clusters

Window into current and past structure formation

Our unified model accounts for . . .

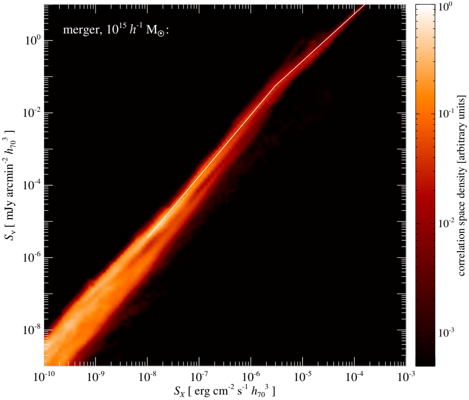
- correlation between merging clusters and giant halos, occurrence of mini-halos in cool core clusters
- observed luminosities of halos/relics for magnetic fields derived from Faraday rotation measurements
- observed morphologies, variations, spectral and polarization properties in radio halos/relics

How we can make use of this information:

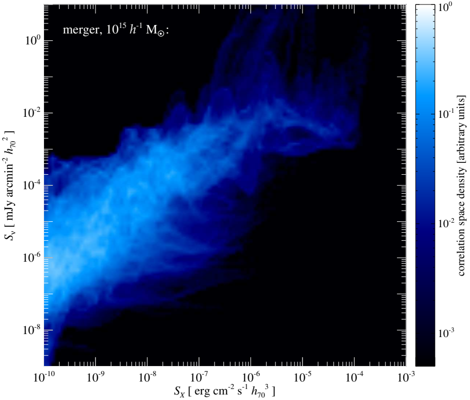
- Radio relics: produced by primary accelerated CR electrons at formation shocks $\rightarrow$ probes current dynamical, non-equilibrium activity of forming structures (shocks and magnetic fields)
- Central radio halos: produced by secondary CR electrons in hadronic CR proton interactions $\rightarrow$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

CITA–ICAT

Correlation between X-ray and synchrotron emission



Correlation with secondary 'halo' emission, merging cluster, $M_{\rm vir} \simeq 10^{15} M_\odot/h$



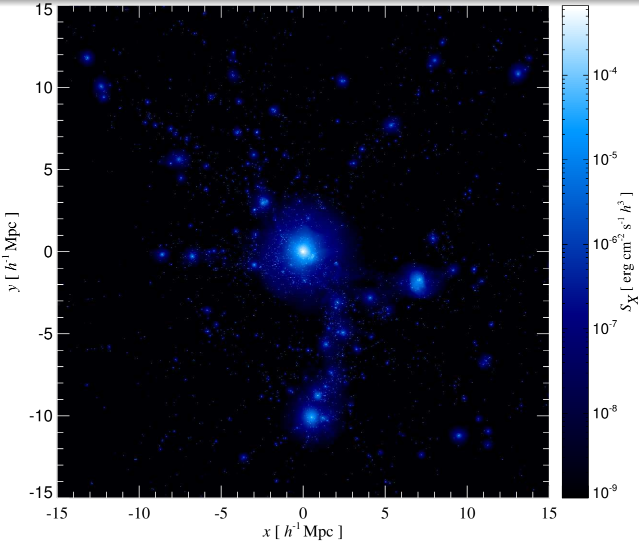
Correlation with primary 'relic' emission, merging cluster, $M_{\rm vir} \simeq 10^{15} M_\odot/h$

CITA–ICAT

Outline

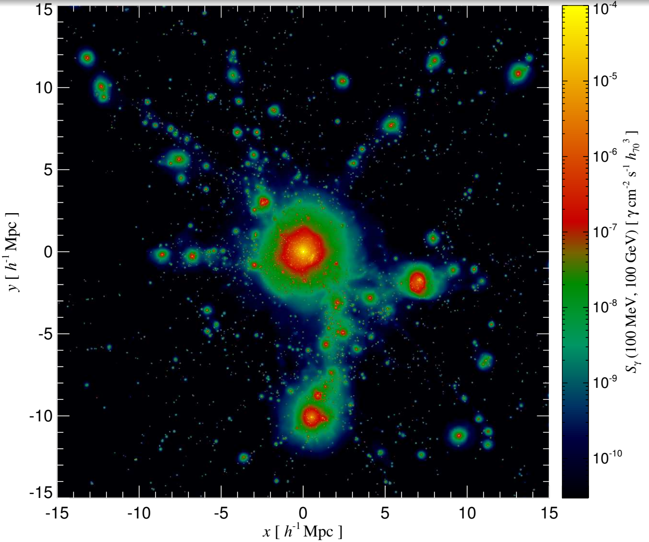
CITA–ICAT

Thermal X-ray emission



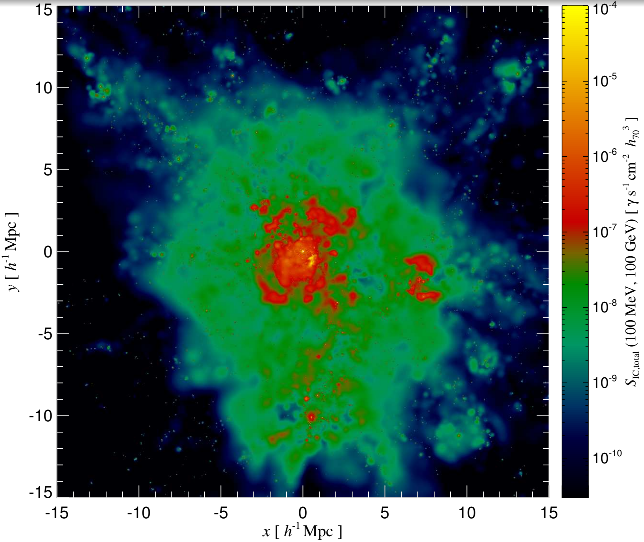
CITA–ICAT

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



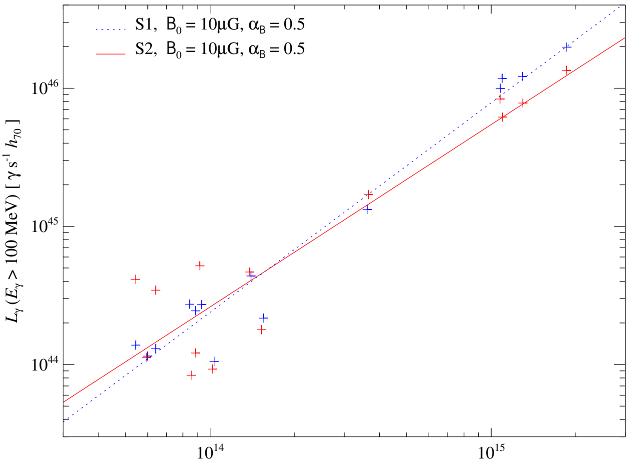
CITA–ICAT

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



CITA–ICAT

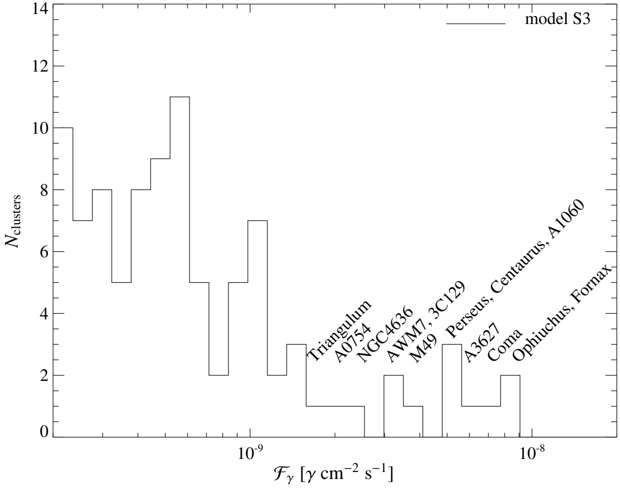
Gamma-ray scaling relations



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. CR pressure feedback

1. Characteristics of the CRs in clusters:
   - CR proton pressure: time integrated non-equilibrium activities of clusters, modulated by recent mergers.
   - Primary CR electron pressure: resembles current accretion and merging shocks in the virial regions.
2. CR pressure modifies the ICM in merging clusters and cooling core regions:
   - Galaxy cluster X-ray emission is enhanced up to 35%, systematic effect in low-mass cooling core clusters.
   - Integrated Sunyaev-Zel'dovich effect remains largely unchanged while the Compton-y profile is more peaked.
   - GLAST should see hadronic γ-ray emission from clusters: measurement of CR protons and origin of radio halos.

CITA–ICAT

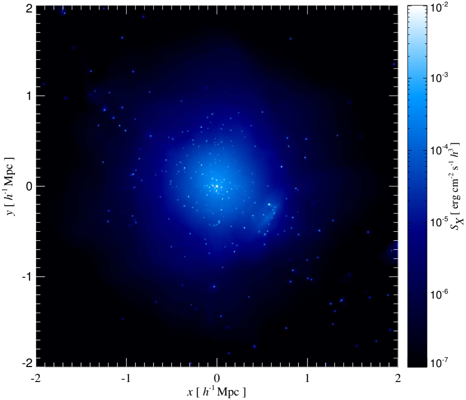
Summary – 2. Non-thermal cluster emission

1. 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.
2. LOFAR/GMRT are expected to see the radio web emission: origin of cosmic magnetic fields.
3. We predict GLAST to detect $\sim$ ten γ-ray clusters: test of the presented scenario

$\longrightarrow$ exciting experiments allow a complementary view on structure formation as well as fundamental physics!

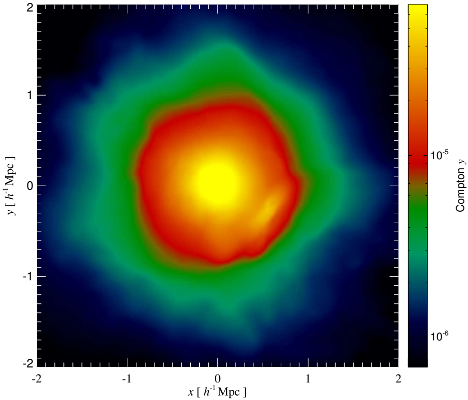
CITA–ICAT

Thermal cluster observables (1)



Thermal bremsstrahlung emission,

merging cluster, $M_{\rm vir} \simeq 10^{15} M_\odot / h$

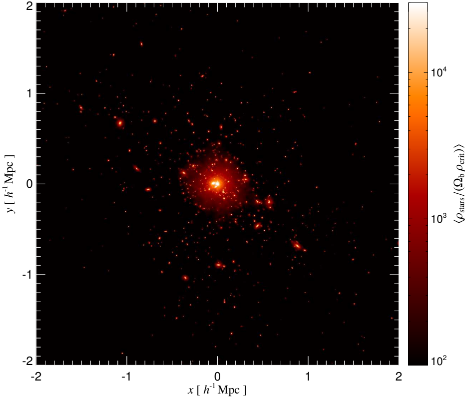


Sunyaev-Zel'dovich effect,

merging cluster, $M_{\rm vir} \simeq 10^{15} M_\odot / h$

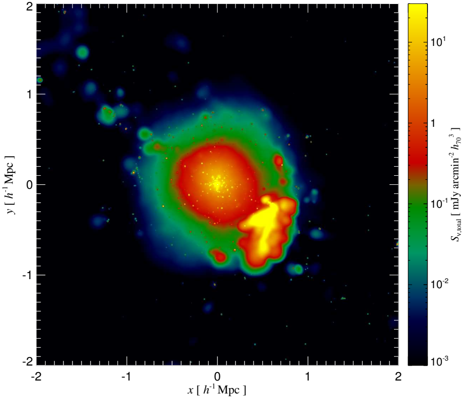
CITA–ICAT

Optical and radio synchrotron cluster observables (1)



Stellar mass density (“cluster galaxies”),

merging cluster, $M_{\rm vir} \simeq 10^{15} M_{\odot}/h$

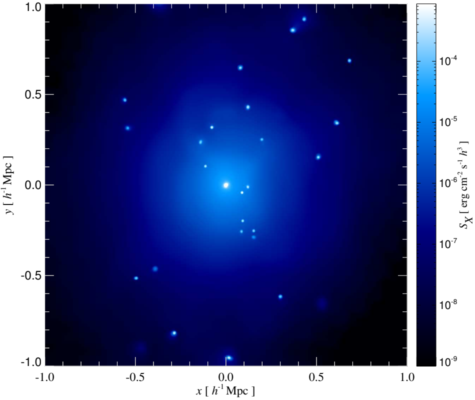


Radio halo and relic emission,

merging cluster, $M_{\rm vir} \simeq 10^{15} M_{\odot}/h$

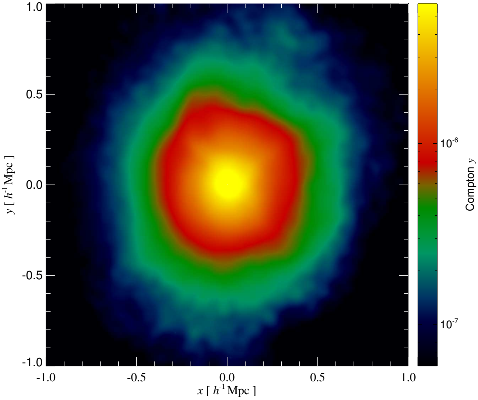
CITA–ICAT

Thermal cluster observables (2)



Thermal bremsstrahlung emission,

cool core cluster, $M_{\mathrm{vir}} \simeq 10^{14} M_\odot / h$

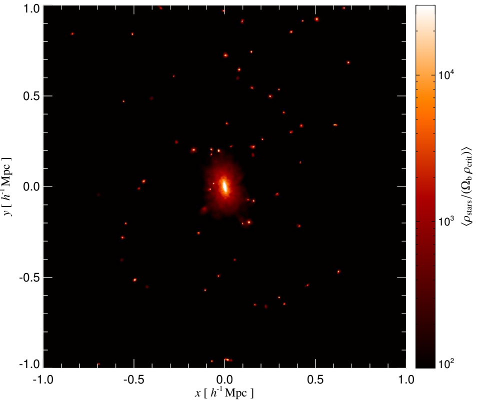


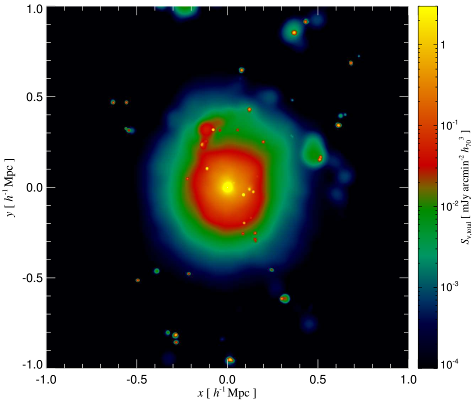
Sunyaev-Zel'dovich effect,

cool core cluster, $M_{\mathrm{vir}} \simeq 10^{14} M_\odot / h$

CITA–ICAT

Optical and radio synchrotron cluster observables (2)





Stellar mass density (“cluster galaxies”),

cool core cluster, $M_{vir} \simeq 10^{14} M_\odot / h$

Radio halo and relic emission,

cool core cluster, $M_{vir} \simeq 10^{14} M_\odot / h$

CITA–ICAT