

Cosmic rays in clusters of galaxies – Tuning in to the non-thermal Universe

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in collaboration with

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Seminar, Caltech



Outline

- 1 **Cosmic rays in galaxy clusters**
 - Introduction and motivation
 - Cluster simulations and cosmic ray physics
 - Cosmic ray pressure feedback
- 2 **Particle acceleration processes**
 - Diffusive shock acceleration
 - Stochastic acceleration
 - Particle reactions
- 3 **Non-thermal cluster emission**
 - Radiative processes
 - Unified model of radio halos and relics
 - High-energy gamma-ray emission



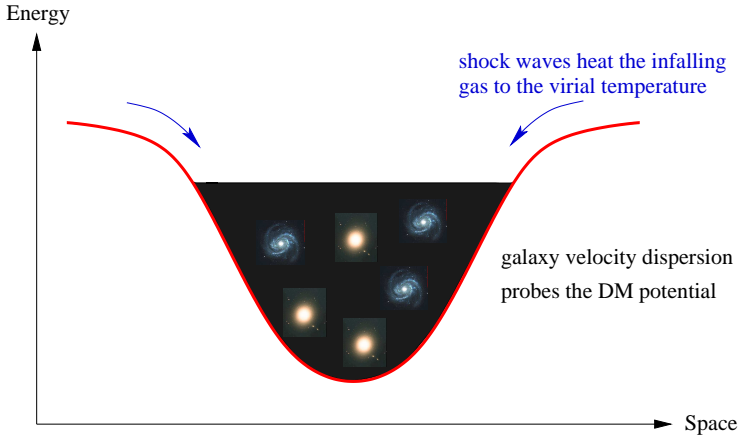
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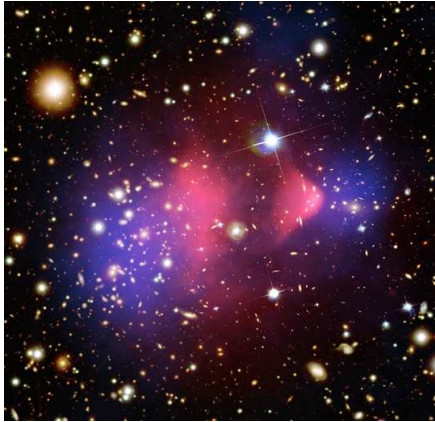


A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

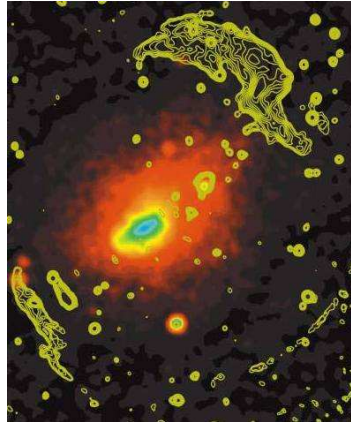


... and how the observer's Universe looks like



1E 0657-56 ("Bullet cluster")

(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

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.
 - Non-thermal cluster emission will enable constructing a **'gold sample' for cosmology** using orthogonal information on the dynamical cluster activity.
- 2 What can we learn from **non-thermal cluster emission**?
 - Understanding mechanism of **diffuse radio and non-thermal X-ray** emission of clusters.
 - Estimating the **cosmic ray pressure contribution**.
 - **Fundamental physics**: diffusive shock acceleration, large scale magnetic fields, and turbulence.



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Literature for the talk

- Pfrommer, 2007, arXiv:0707.1693, *Simulating cosmic rays in clusters of galaxies – III. Non-thermal scaling relations and comparison to observations*
- Pfrommer, Enßlin, Springel, 2007, arXiv:0707.1707, *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, in press, 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*



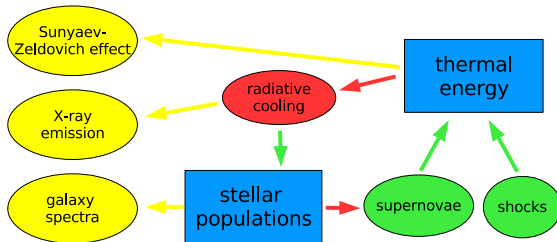
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Radiative simulations – flowchart

Cluster observables:

Physical processes in clusters:

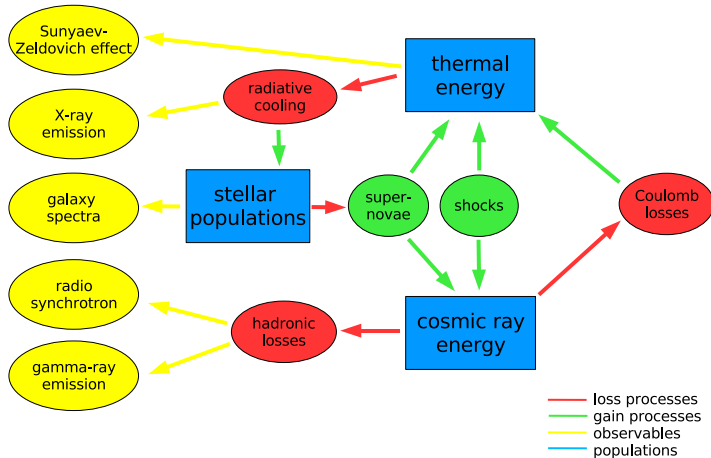


— loss processes
— gain processes
— observables
— populations

Radiative simulations with cosmic ray (CR) physics

Cluster observables:

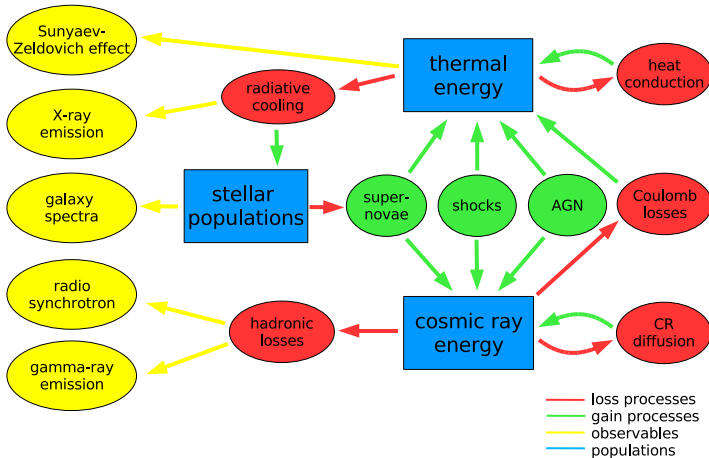
Physical processes in clusters:



Radiative simulations with extended CR physics

Cluster observables:

Physical processes in clusters:



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

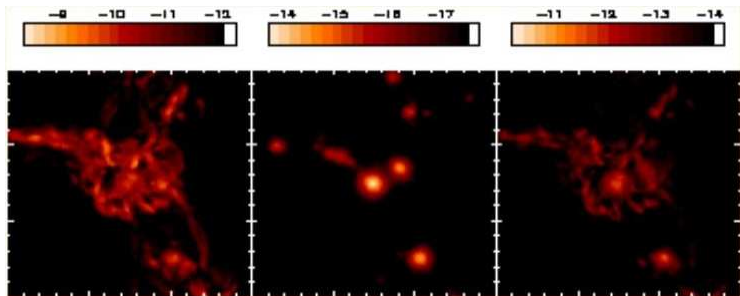


Figure: Hard X-rays, thermal X-rays, γ -rays, adopted from Miniati (2003)

Our 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

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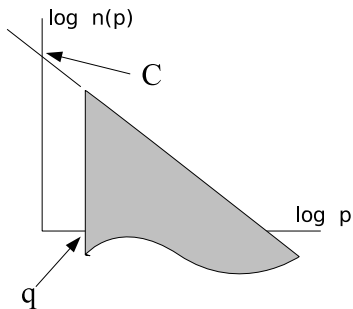
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CR spectral description



$$p = P_p / m_p c$$

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

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

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

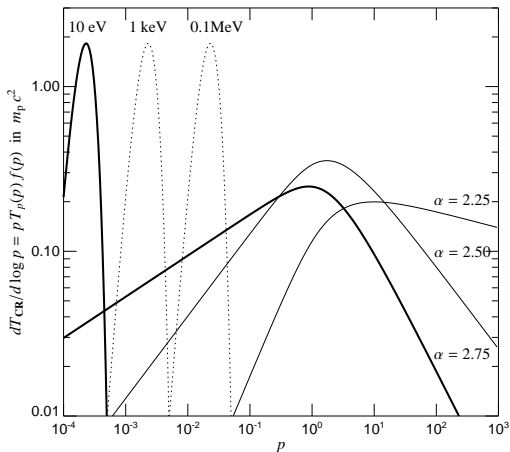
$$n_{\text{CR}} = \int_0^{\infty} dp f(p) = \frac{C q^{1-\alpha}}{\alpha-1}$$

$$P_{\text{CR}} = \frac{m_p c^2}{3} \int_0^{\infty} dp f(p) \beta(p) p$$

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

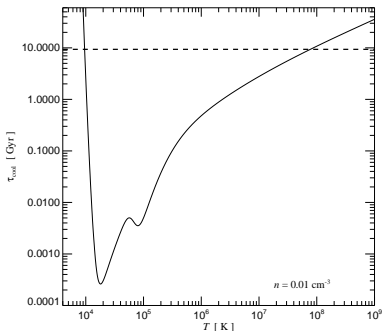
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:

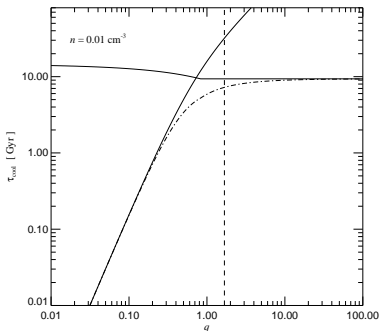


Cooling time scales of CR protons

Cooling of primordial gas:



Cooling of cosmic rays:



Outline

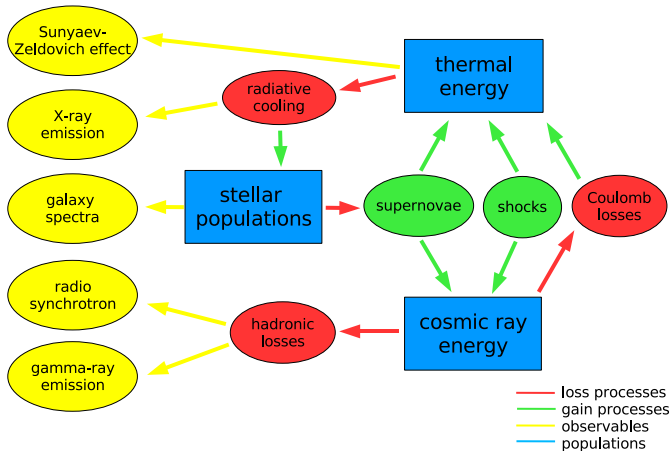
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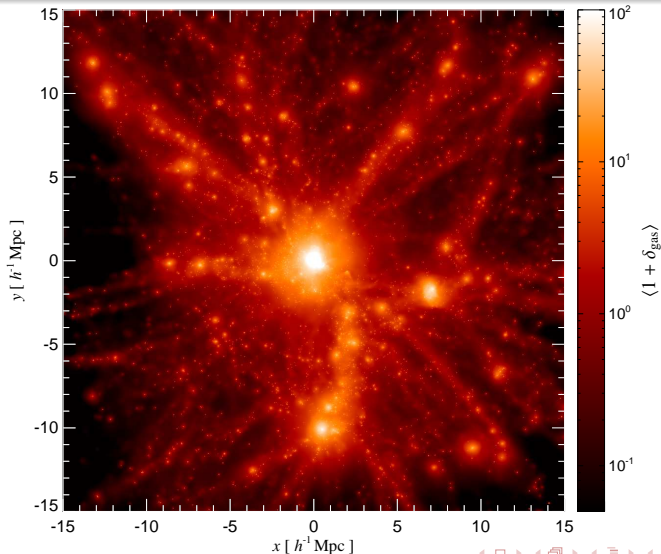
Radiative simulations with CR physics

Cluster observables:

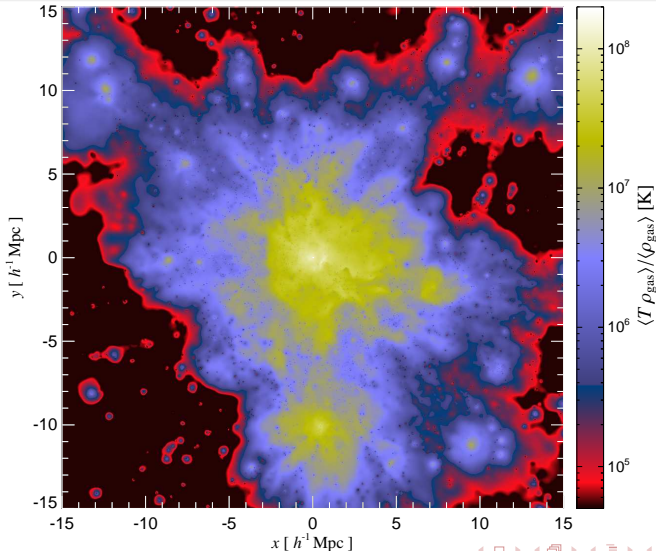
Physical processes in clusters:



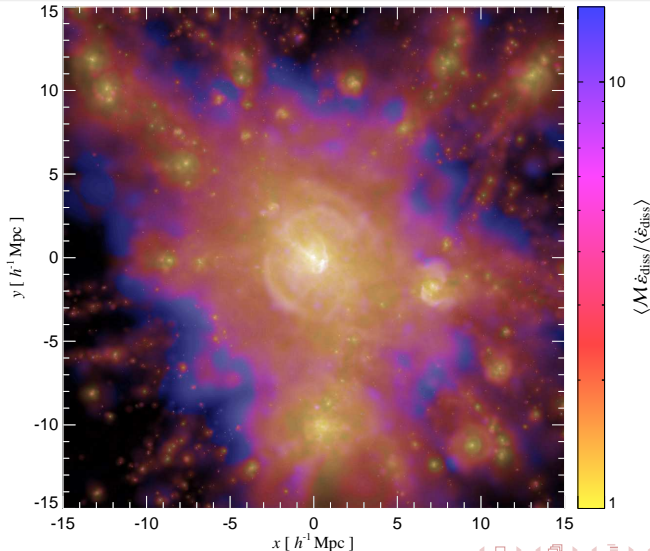
Radiative cool core cluster simulation: gas density



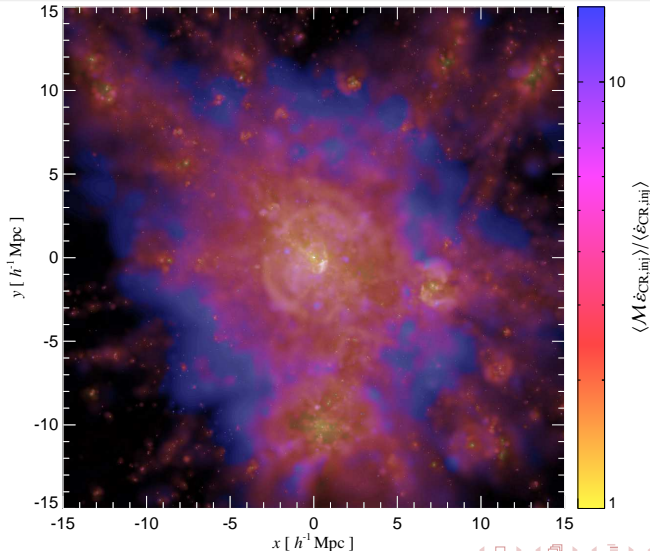
Mass weighted temperature



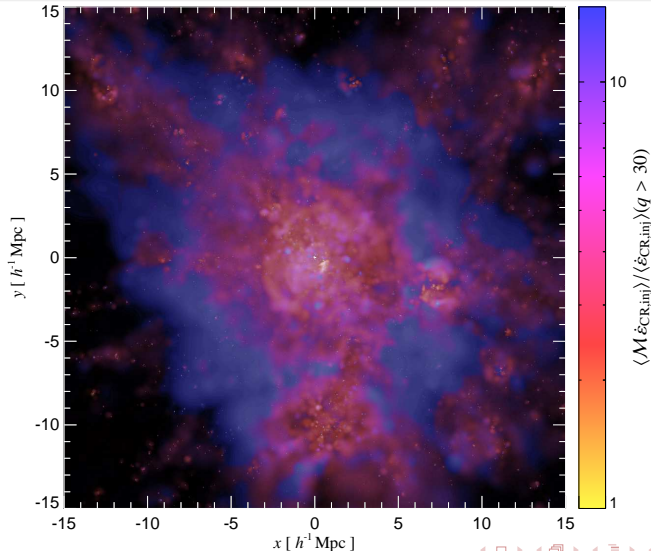
Mach number distribution weighted by ϵ_{diss}



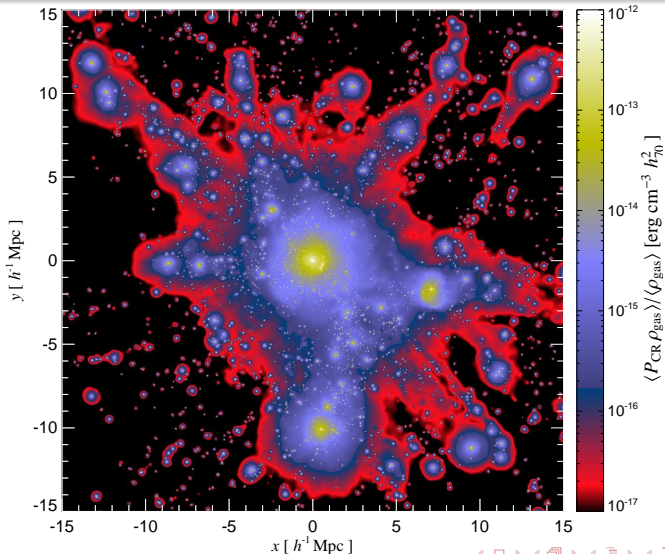
Mach number distribution weighted by $\varepsilon_{\text{CR},\text{inj}}$



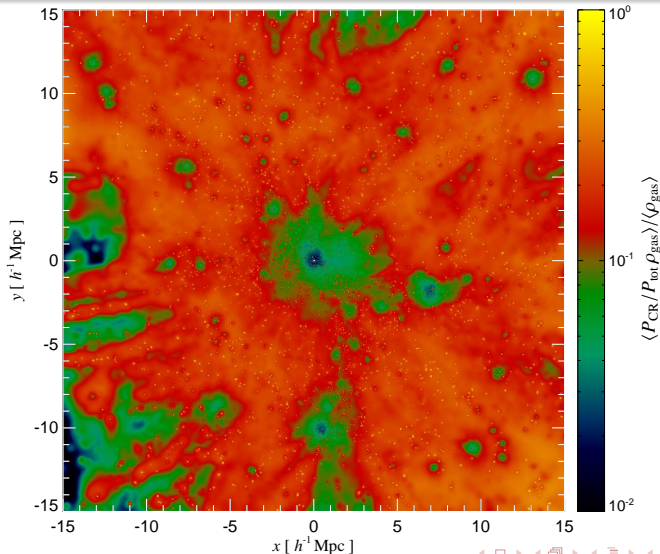
Mach number distribution weighted by $\varepsilon_{\text{CR, inj}}(q > 30)$



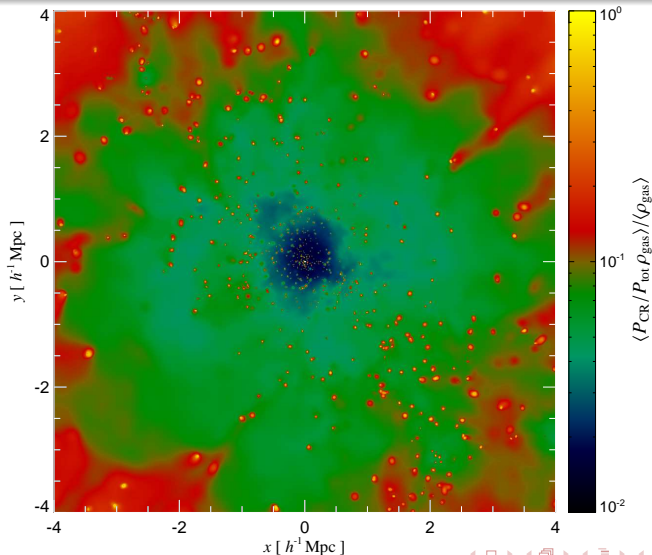
CR pressure P_{CR}



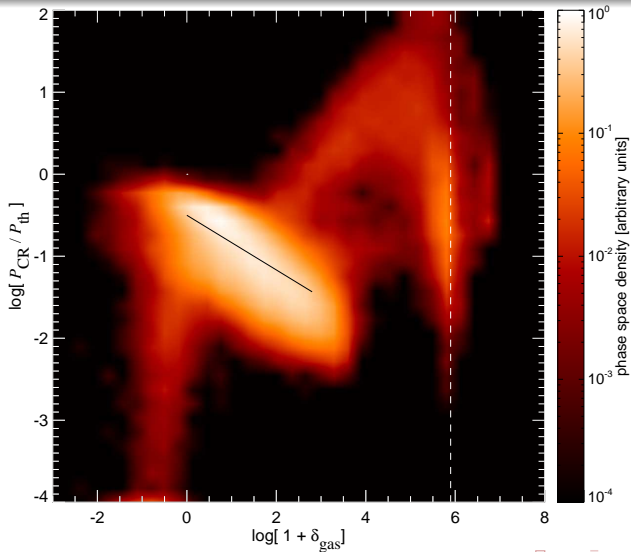
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$



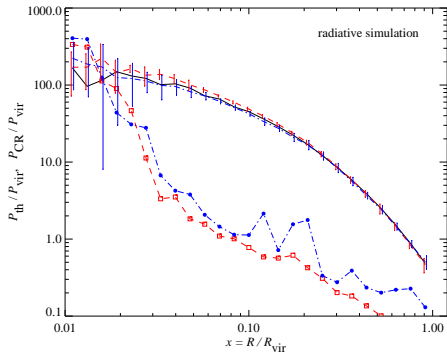
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$



Phase-space diagram of radiative cluster simulation



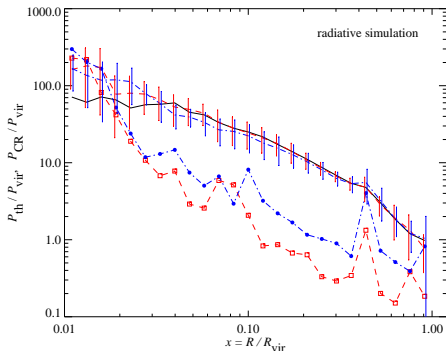
Radiative simulations: pressure profile



Cool core cluster sample.

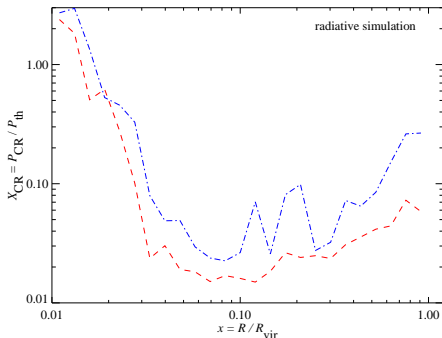
red: only structure formation shock CRs,

blue: structure formation & SNe CRs.



Merging cluster sample.

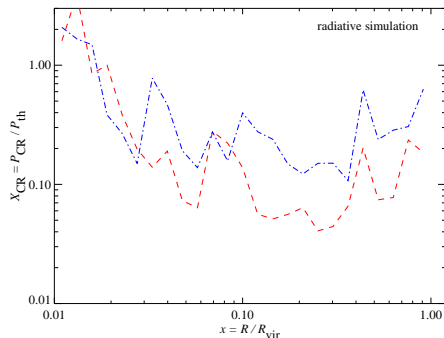
Radiative simulations: relative CR pressure profile



Cool core cluster sample.

red: only structure formation shock CRs,

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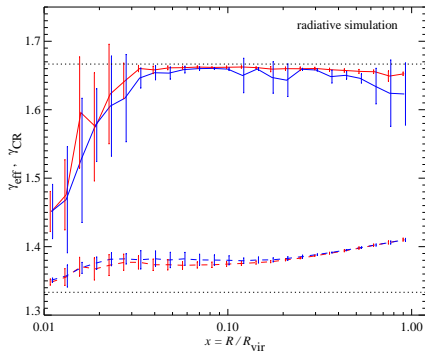


Merging cluster sample.



CITA-ICAT

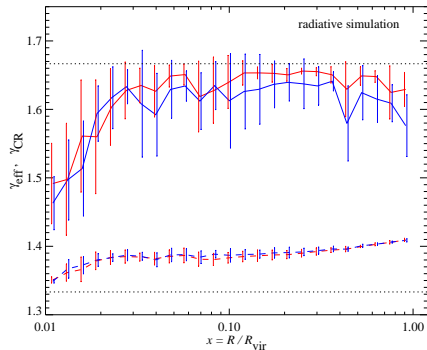
Radiative simulations: adiabatic index profile



Cool core cluster sample.

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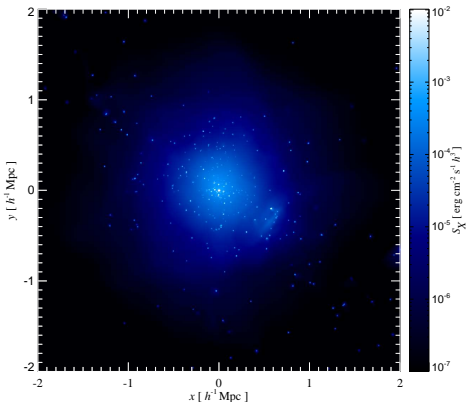
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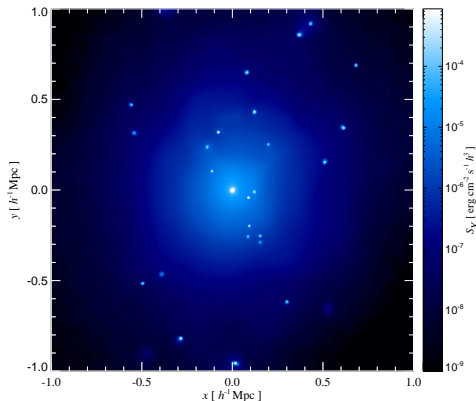
Merging cluster sample.



Thermal X-ray emission

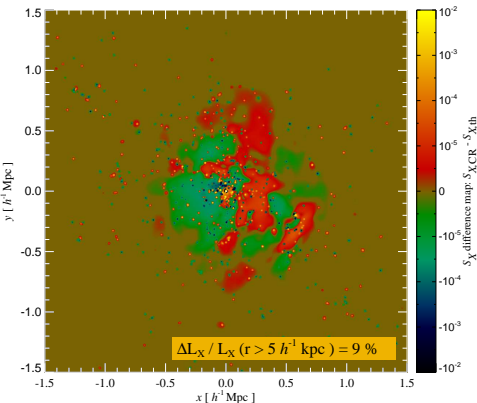


large merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$

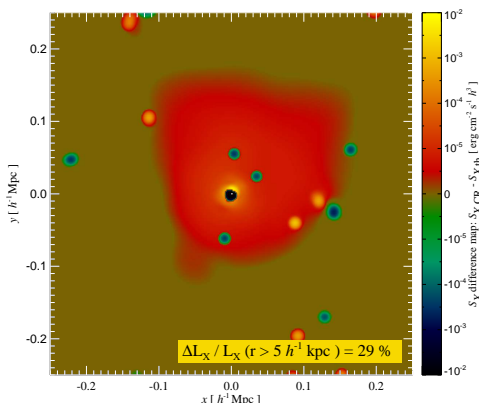


small cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$

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

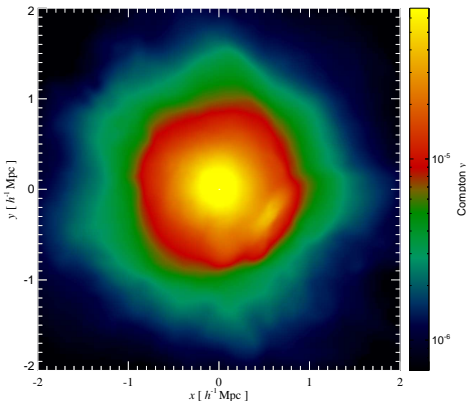


large merging cluster, $M_{vir} \simeq 10^{15} M_\odot / h$
 → contributes to the scatter in the $M - L_X$ scaling relation

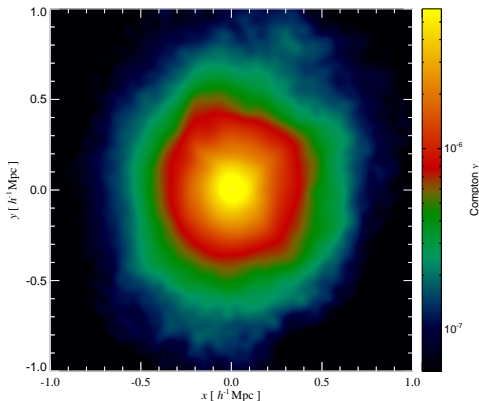


cool core cluster, $M_{vir} \simeq 10^{14} M_\odot / h$
 → systematic increase of L_X for small cool core clusters

Compton y parameter in radiative cluster simulation

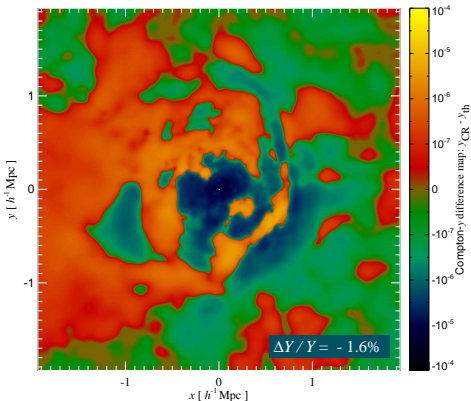


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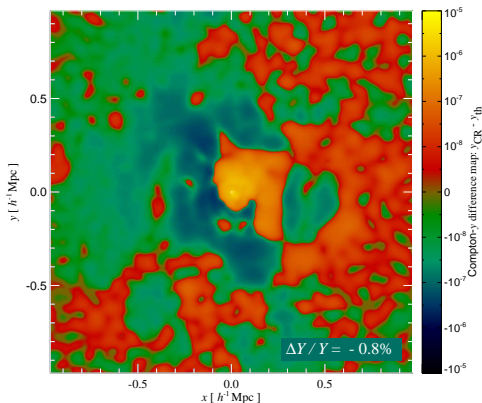


small cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$

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



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



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

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Particle acceleration processes

particles are accelerated via:

- adiabatic compression
- diffusive shock acceleration (Fermi I)
- stochastic acceleration by plasma waves (Fermi II)
- particle reactions ($pp \rightarrow \pi \rightarrow \mu\nu \rightarrow e\nu\nu$)

particles are de-accelerated via:

- adiabatic expansion
- radiative cooling (synchrotron, inverse Compton, bremsstrahlung, hadronic interactions)
- non-radiative cooling (Coulomb interactions)

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Diffusive shock acceleration – Fermi 1 mechanism (1)

conditions:

- a collisionless shock wave
- magnetic fields to confine energetic particles
- plasma waves to scatter energetic particles → 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

→ power-law CR distribution

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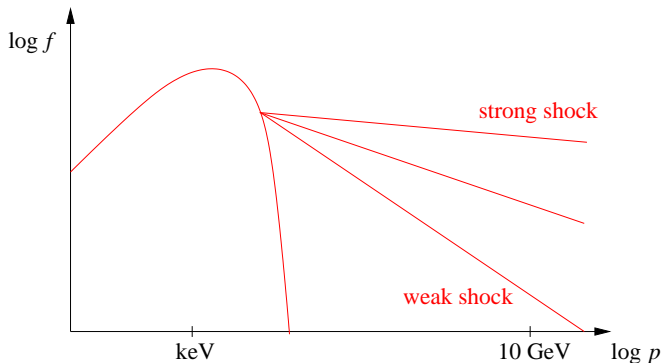
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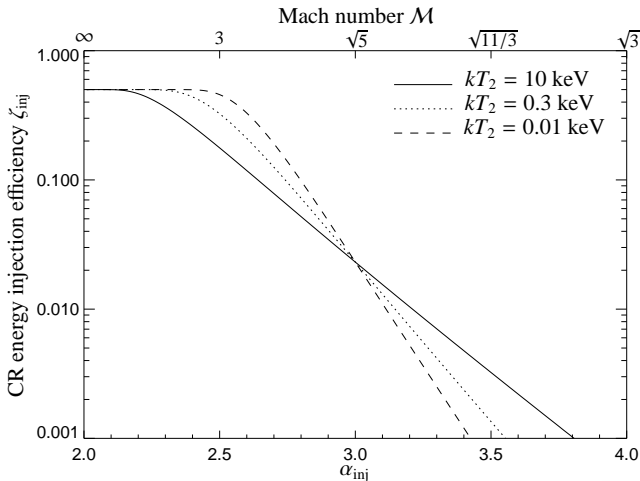
Diffusive shock acceleration – Fermi 1 mechanism (2)

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

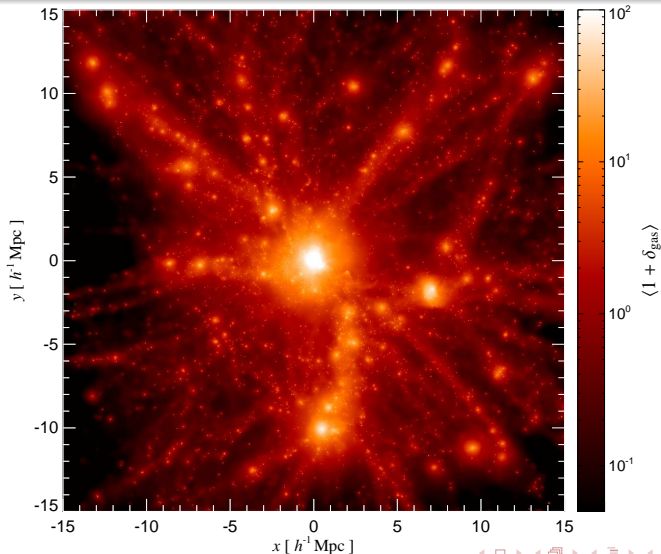


Diffusive shock acceleration – efficiency (3)

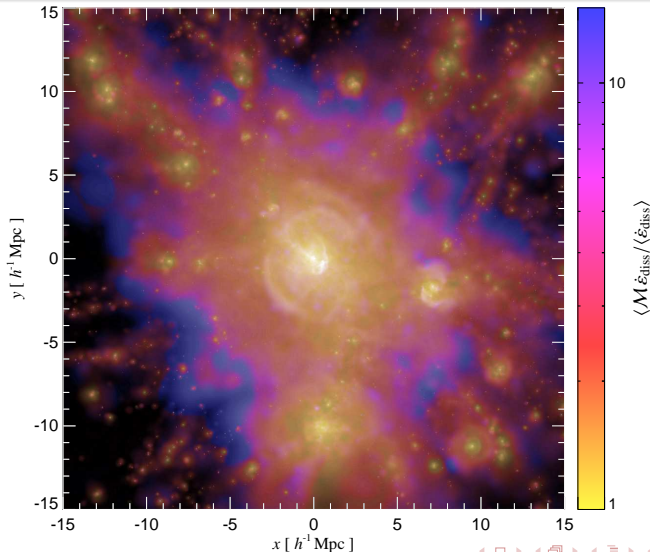
CR proton energy injection efficiency, $\zeta_{\text{inj}} = \varepsilon_{\text{CR}}/\varepsilon_{\text{diss}}$:



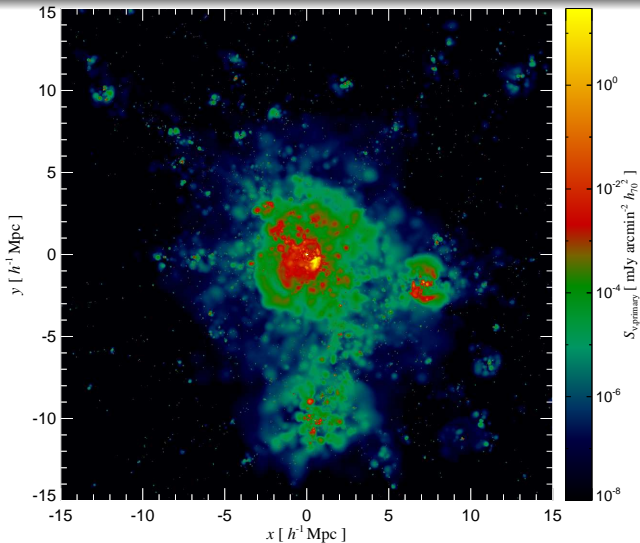
Radiative cool core cluster simulation: gas density



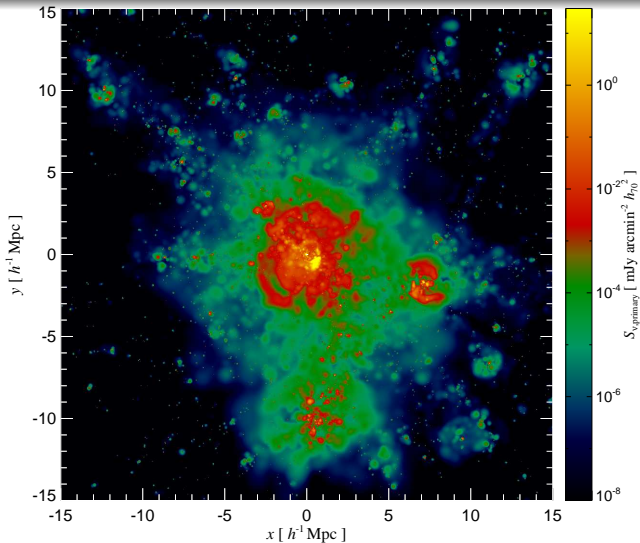
Cosmic web: Mach number



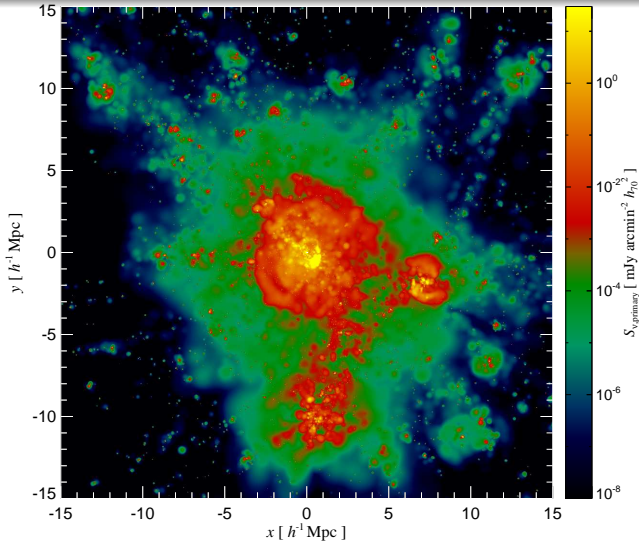
Radio web: primary CRe (1.4 GHz)



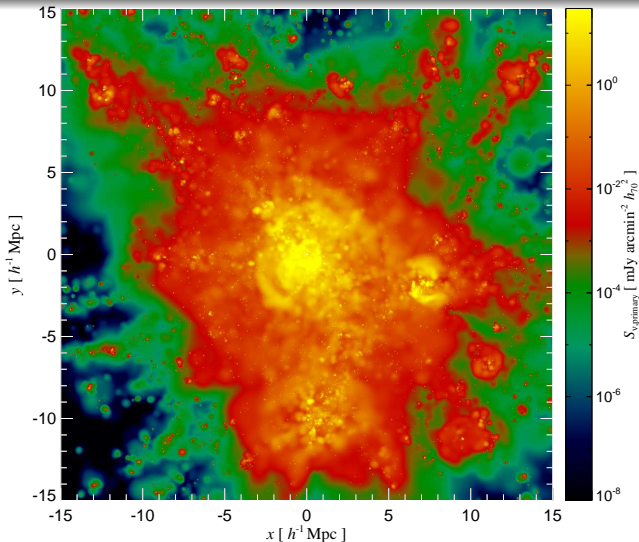
Radio web: primary CRe (150 MHz)



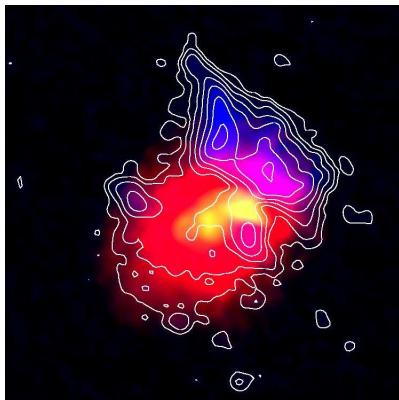
Radio web: primary CRe (15 MHz)



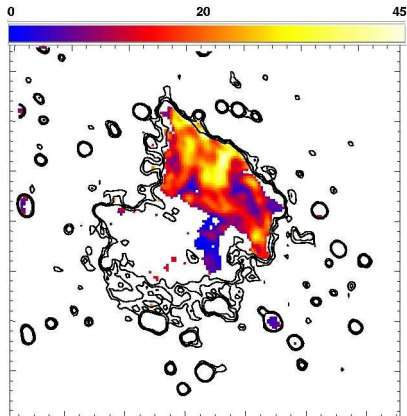
Radio web: primary CRe (15 MHz), slower magnetic decline



Abell 2256: giant radio relic & small halo



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



fractional polarization in color

Clarke & Enßlin (2006)

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Stochastic acceleration: recipe (1)

conditions:

- super-thermal or better relativistic particles
- magnetic fields to confine them
- high level of plasma waves to scatter them via gyro-resonances

mechanism:

- head on wave-particle collision energises particle
- tail on wave-particle collision de-energise particle
- statistically more head-on than tail-on collisions

→ net energy gain due to diffusion in momentum space
advantage: plasma waves are everywhere!



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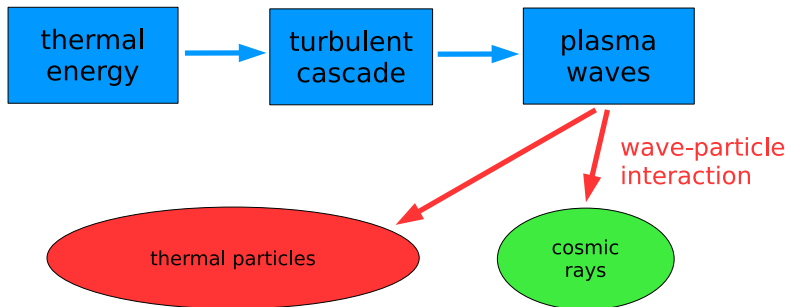
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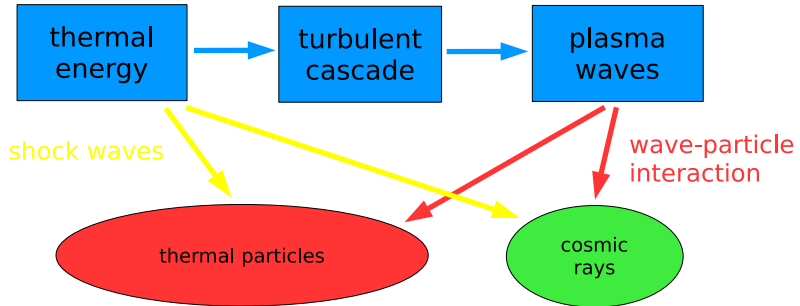
→ net energy gain due to diffusion in momentum space
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Stochastic acceleration: cartoon (2)



Stochastic acceleration: cartoon (2)



Stochastic acceleration: problems (3)

problems:

- low efficiency (2nd order in ratio of wave to particle velocity)
- waves like to cascade to small scales
- small-scale waves dissipate into the thermal pool
- wave energy budget is usually tight
- at locations with high wave density (e.g. shocks), more efficient acceleration mechanism may be in operation (e.g. DSA)

nevertheless: cluster radio halos may be due to stochastic re-acceleration of 0.2 MeV electrons (e.g. Brunetti et al.)



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Particle reactions

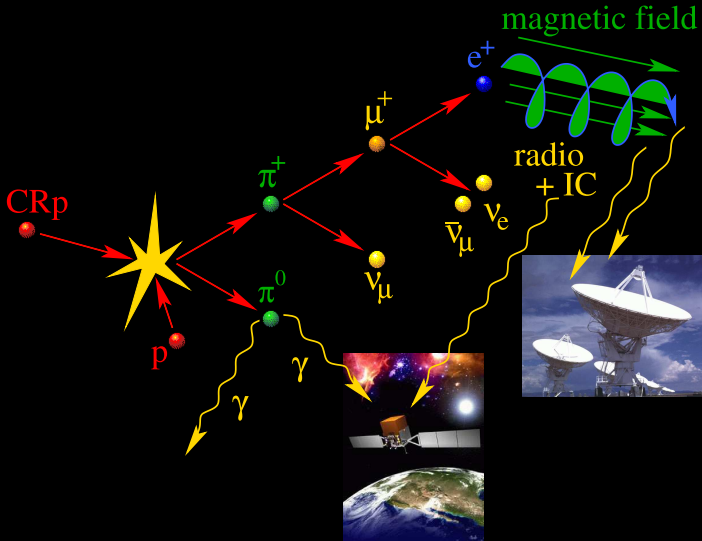
relativistic **proton** populations can often be expected, since

- acceleration mechanisms work for protons ...
 - ... as efficient as for electrons (adiabatic compression) or
 - ... more efficient than for electrons (DSA, stochastic acc.)
- galactic CR protons are observed to have 100 times higher energy density than electrons
- CR protons are very inert against radiative losses and therefore long-lived (\sim Hubble time in galaxy clusters, longer outside)

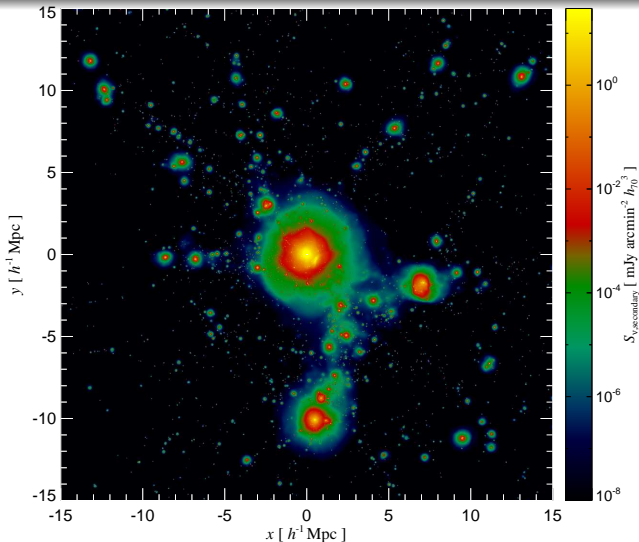
→ an energetic **CR proton** population should exist in clusters



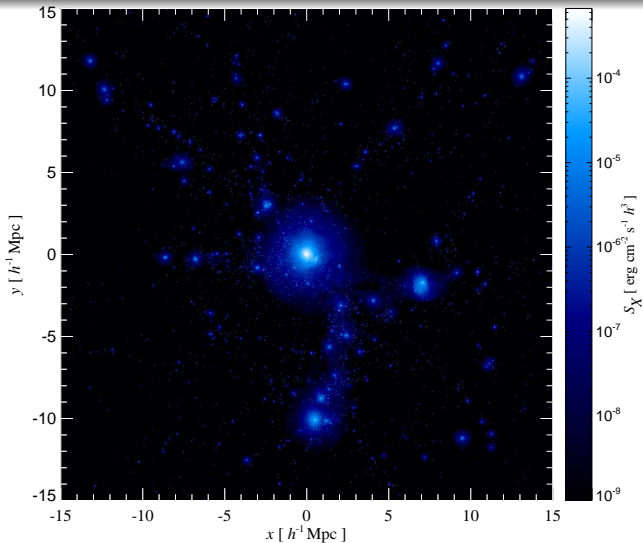
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



Thermal X-ray emission



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- 3 **Non-thermal cluster emission**
 - **Radiative processes**
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 - High-energy gamma-ray emission



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)



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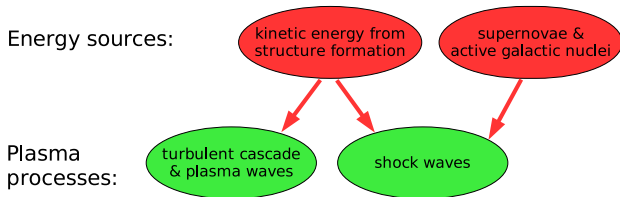
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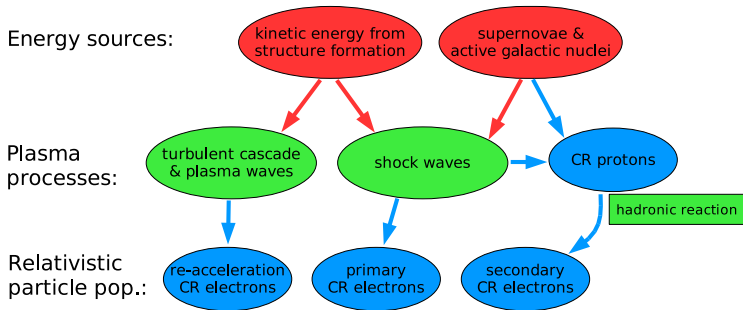
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



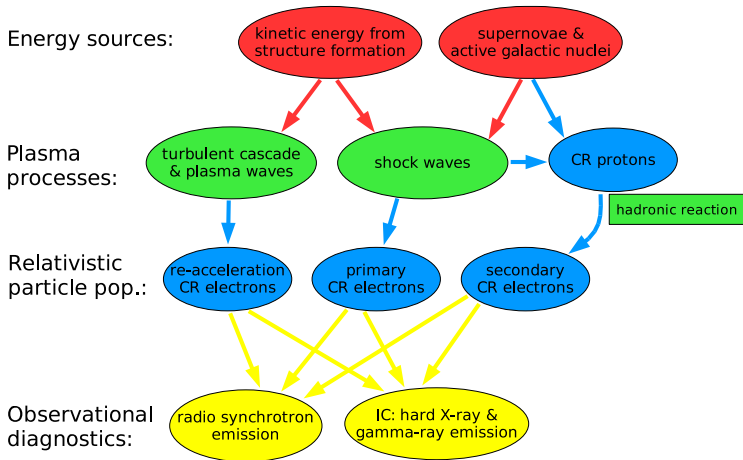
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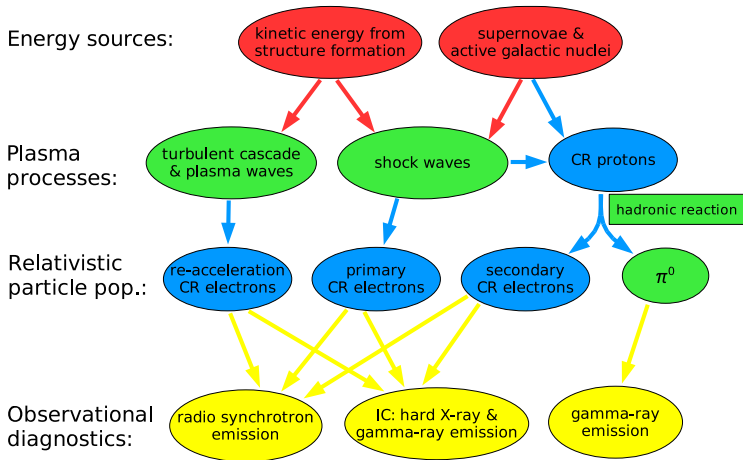
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Previous models for giant radio halos in clusters

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.

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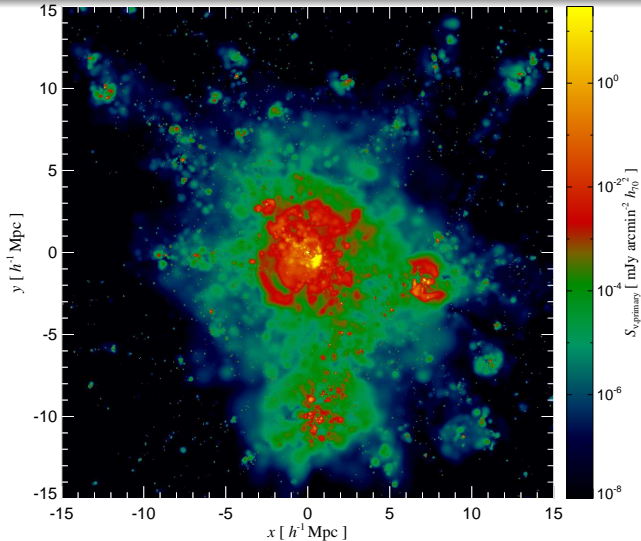
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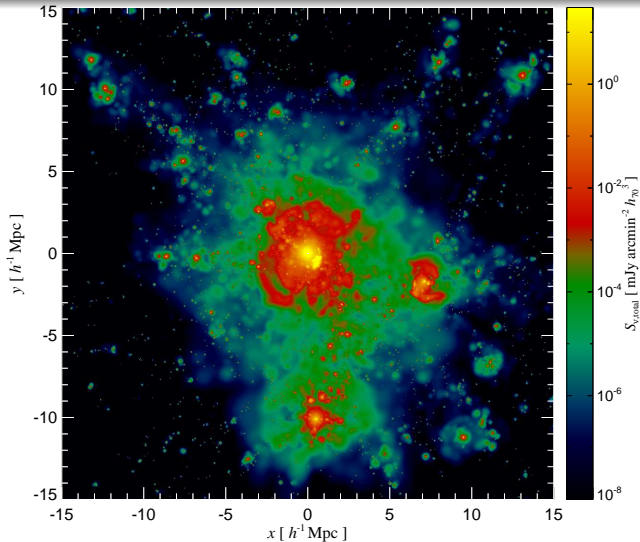
Radio gischt: primary CRe (150 MHz)



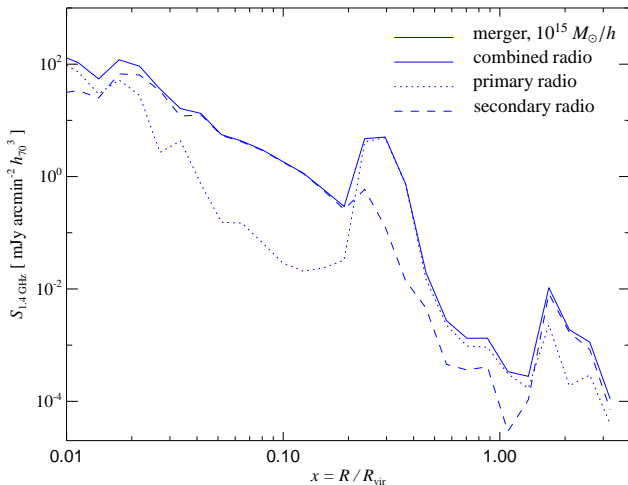
Cosmic rays in galaxy clusters
Particle acceleration processes
Non-thermal cluster emission

Radiative processes
Unified model of radio halos and relics
High-energy gamma-ray emission

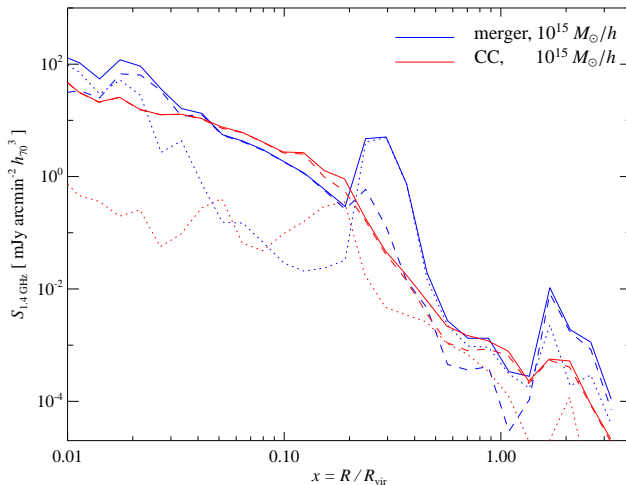
Radio gischt + central hadronic halo = giant radio halo



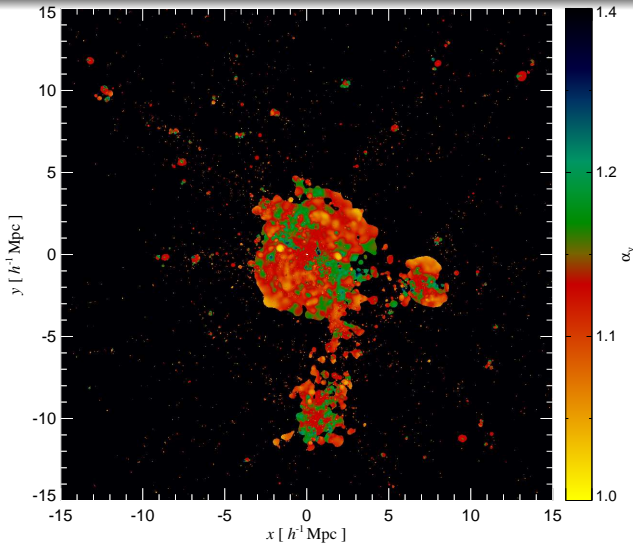
Giant radio halo profile



Giant radio halo vs. mini-halo



Radio relics + halos: spectral index



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



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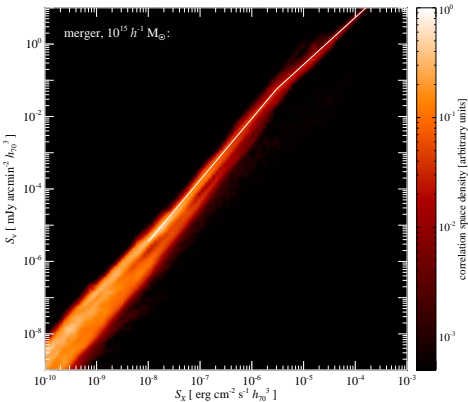
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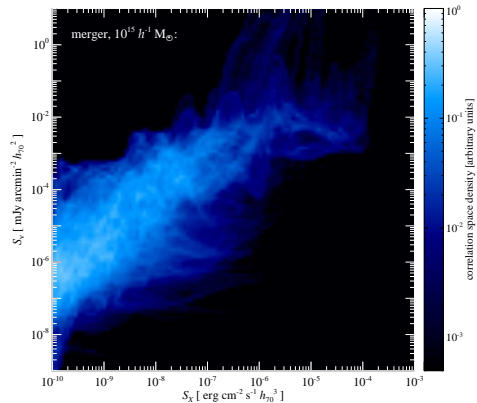
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Correlation between X-ray and synchrotron emission



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



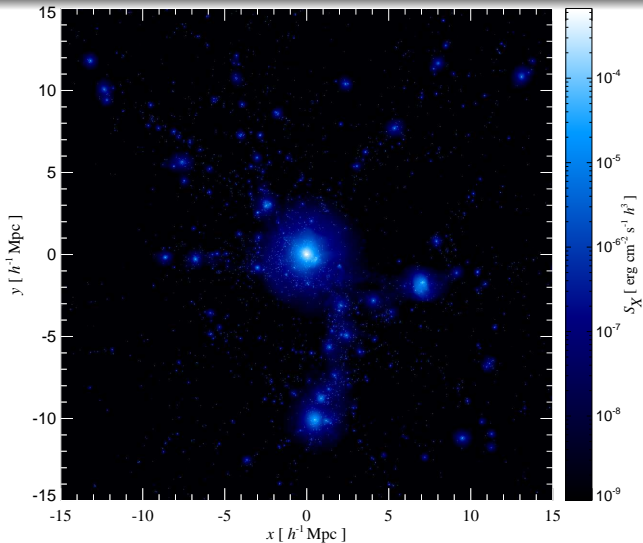
Correlation with primary 'relic' emission,
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Outline

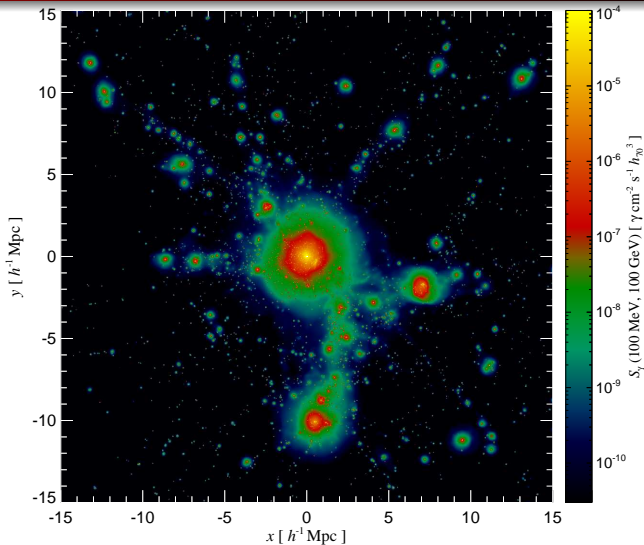
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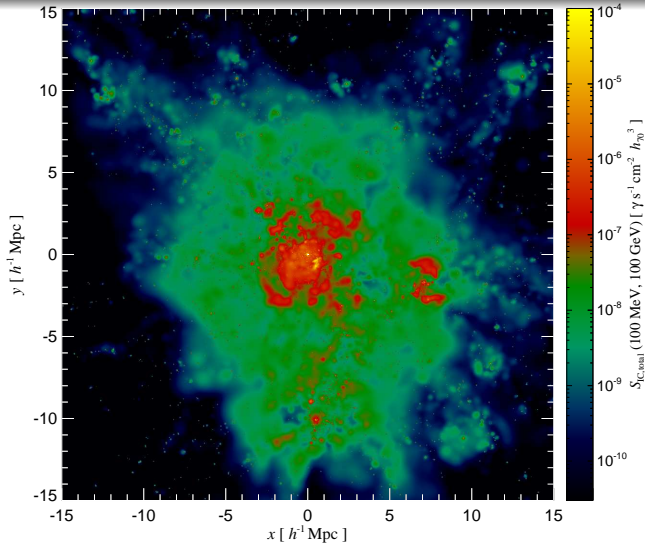
Thermal X-ray emission



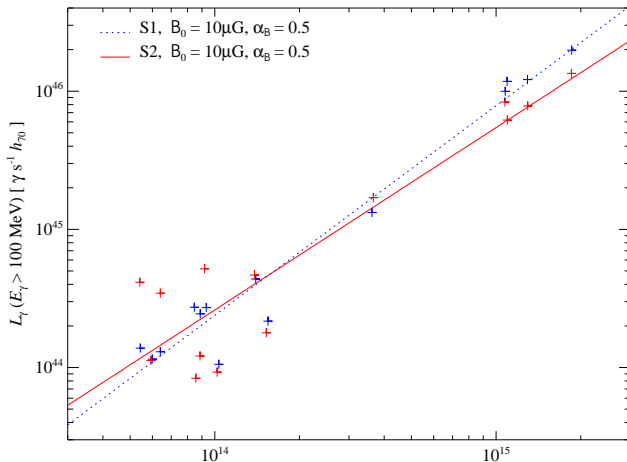
Hadronic γ -ray emission, $E_\gamma > 100$ MeV



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



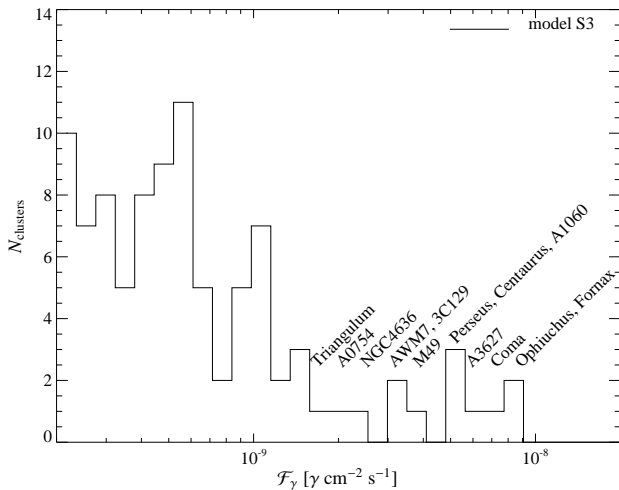
Gamma-ray scaling relations



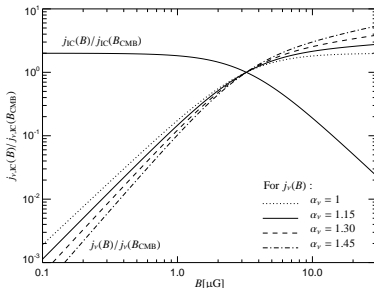
Scaling relation + complete sample of the brightest X-ray clusters (HIFLUCGS) → predictions for GLAST



Predicted cluster sample for GLAST



Minimum γ -ray flux in the hadronic model (1)



Synchrotron emissivity of high-energy, steady state electron distribution is independent of the magnetic field for $B \gg B_{\text{CMB}}$!

Synchrotron luminosity:

$$L_\nu = A_\nu \int dV n_{\text{CR}} n_{\text{gas}} \frac{\epsilon_B^{(\alpha_\nu+1)/2}}{\epsilon_{\text{CMB}} + \epsilon_B}$$

$$\rightarrow A_\nu \int dV n_{\text{CR}} n_{\text{gas}} \quad (\epsilon_B \gg \epsilon_{\text{CMB}})$$

γ -ray luminosity:

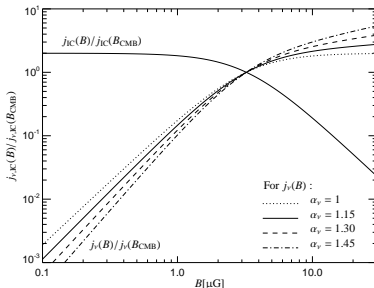
$$L_\gamma = A_\gamma \int dV n_{\text{CR}} n_{\text{gas}}$$

\rightarrow minimum γ -ray flux:

$$\mathcal{F}_{\gamma, \text{min}} = \frac{A_\gamma}{A_\nu} \frac{L_\nu}{4\pi D^2}$$



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Minimum γ -ray flux in the hadronic model (2)

Minimum γ -ray flux ($E_\gamma > 100$ MeV) for the Coma cluster:

CR spectral index	2.0	2.3	2.6	2.9
$\mathcal{F}_\gamma [10^{-10} \gamma \text{ cm}^{-2} \text{ s}^{-1}]$	0.8	1.6	3.4	7.1

- These limits can be made even tighter when considering energy constraints, $P_B < P_{\text{gas}}/20$ and B -fields derived from Faraday rotation studies, $B_0 = 3 \mu\text{G}$:

$$\mathcal{F}_{\gamma, \text{COMA}} \gtrsim 2 \times 10^{-9} \gamma \text{ cm}^{-2} \text{ s}^{-1} = \mathcal{F}_{\text{GLAST}}, 2\text{yr}$$

- Non-detection by GLAST seriously challenges the hadronic model.
- Potential of measuring the CR acceleration efficiency for diffusive shock acceleration.



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**.

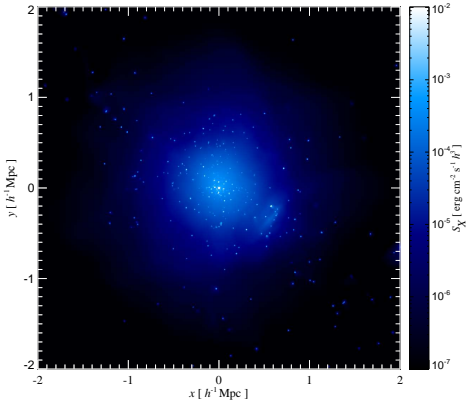
Summary – 2. Non-thermal cluster emission

- 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

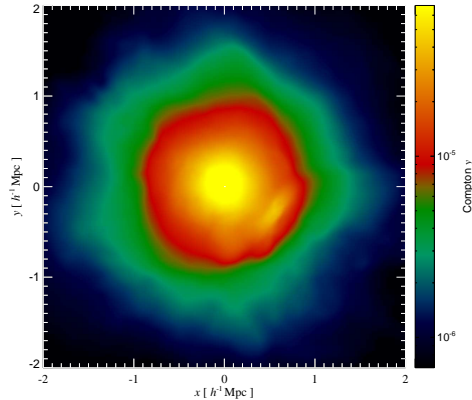
→ exciting experiments allow a **complementary view on structure formation** as well as **fundamental physics!**



Thermal cluster observables (1)

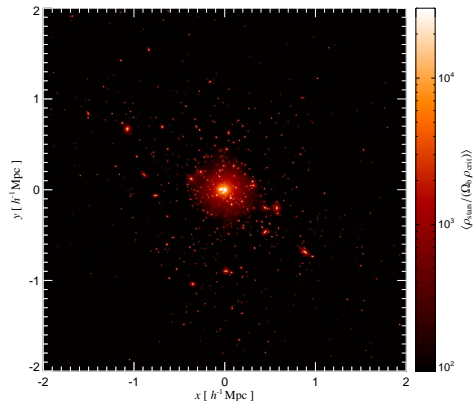


Thermal bremsstrahlung emission,
merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$

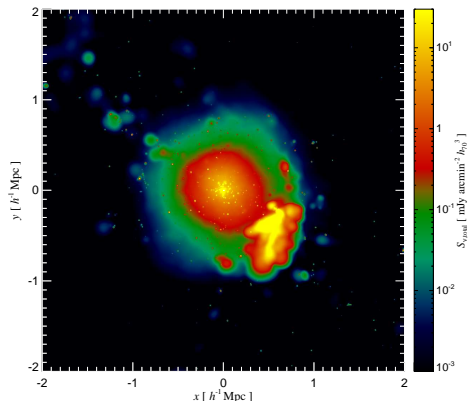


Sunyaev-Zel'dovich effect,
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Optical and radio synchrotron cluster observables (1)

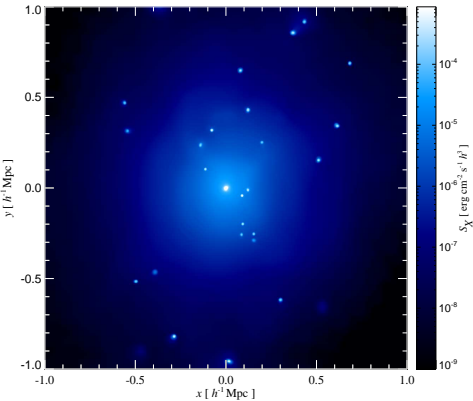


Stellar mass density (“cluster galaxies”),
merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$

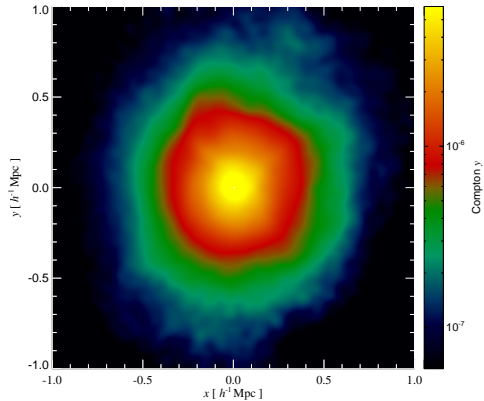


Radio halo and relic emission,
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Thermal cluster observables (2)

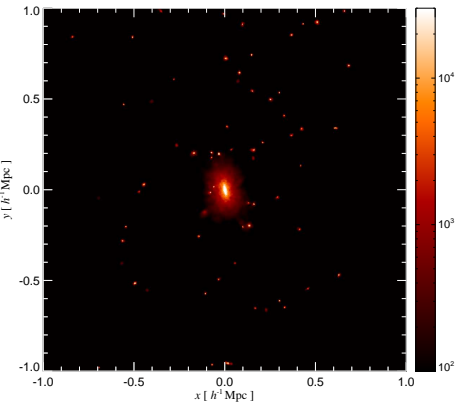


Thermal bremsstrahlung emission,
cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$

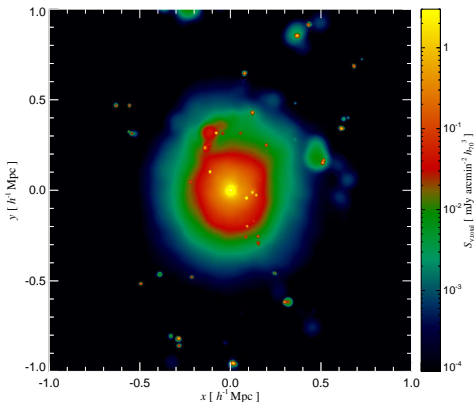


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