

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

Christoph Pfrommer¹

in collaboration with

Torsten Enßlin², Volker Springel²

¹Canadian Institute for Theoretical Astrophysics, Canada

²Max-Planck Institute for Astrophysics, Germany

Nov 1, 2007 / ACKS Seminar, Stanford University



Outline

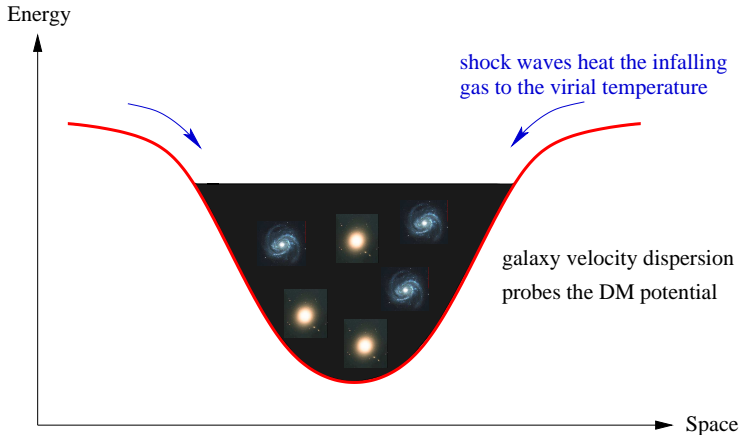
- 1 **Cosmic rays in galaxy clusters**
 - Introduction and motivation
 - Cluster simulations and cosmic ray physics
 - Cosmic ray pressure feedback
- 2 **Particle acceleration processes**
 - Diffusive shock acceleration
 - Stochastic acceleration
 - Particle reactions
- 3 **Non-thermal cluster emission**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

Outline

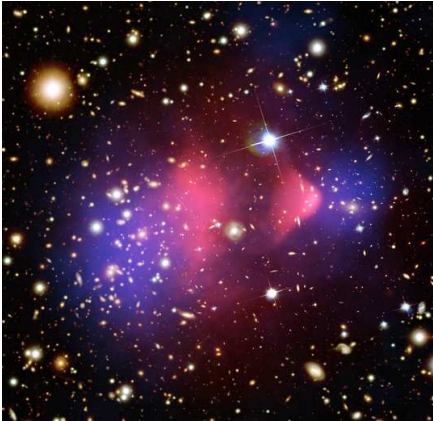
- 1 **Cosmic rays in galaxy clusters**
 - Introduction and motivation
 - Cluster simulations and cosmic ray physics
 - Cosmic ray pressure feedback
- 2 Particle acceleration processes
 - Diffusive shock acceleration
 - Stochastic acceleration
 - Particle reactions
- 3 Non-thermal cluster emission
 -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

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

Galaxy clusters are dynamically evolving dark matter potential wells:

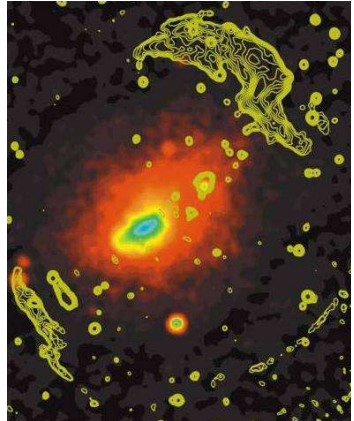


...and how the observer's Universe looks like



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.



Why should we care about cosmic rays in clusters?

It allows us to explore complementary windows to cluster cosmology

- ❶ 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.
- ❷ 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.



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*

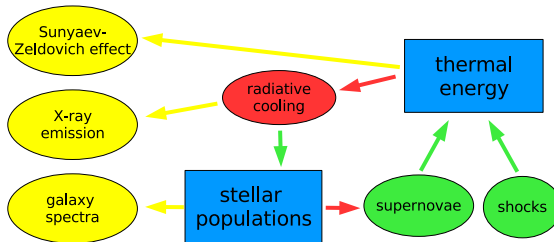
Outline

- 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

Radiative simulations – flowchart

Cluster observables:

Physical processes in clusters:

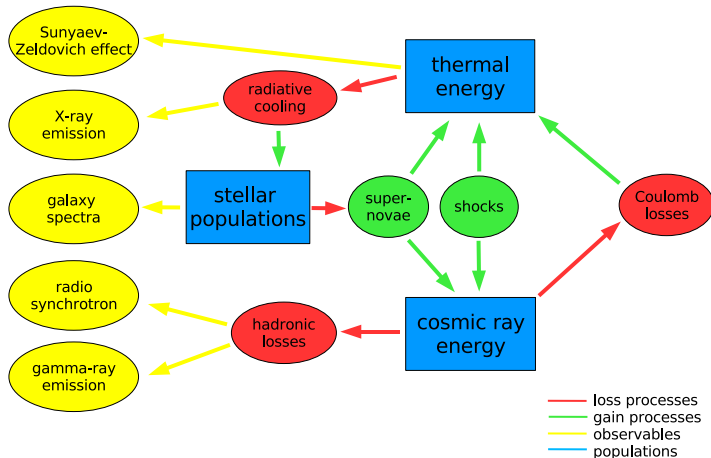


— loss processes
— gain processes
— observables
— populations

Radiative simulations with cosmic ray (CR) physics

Cluster observables:

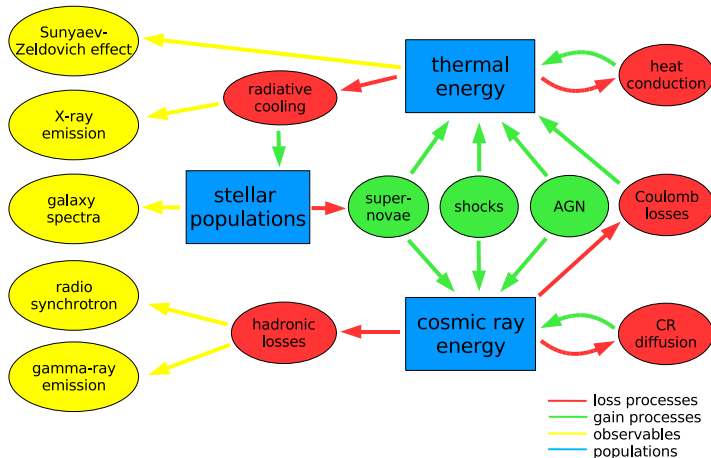
Physical processes in clusters:



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

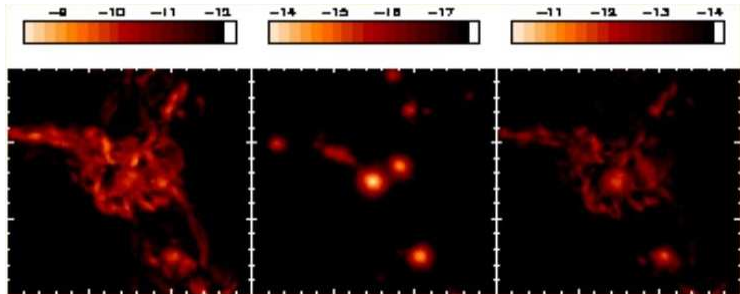


Figure: Hard X-rays, thermal X-rays, γ -rays, adopted from Miniati (2003)

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

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

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.

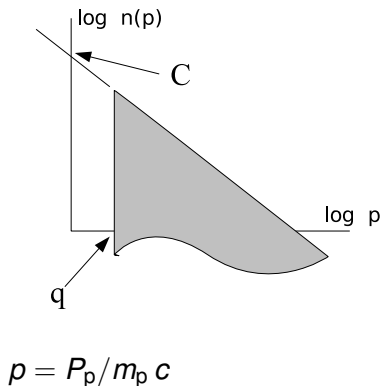
We seek a compromise between

- 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

CR spectral description



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

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

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

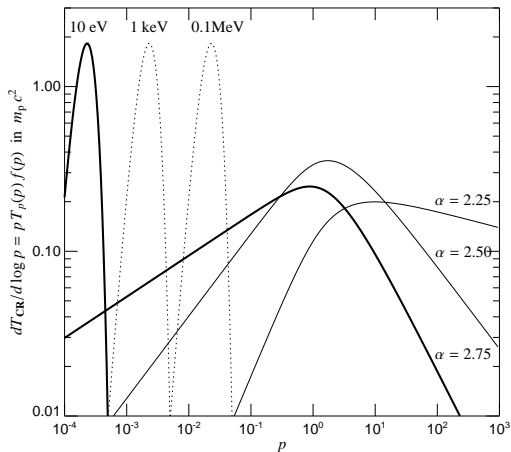
$$n_{\text{CR}} = \int_0^{\infty} dp f(p) = \frac{C q^{1-\alpha}}{\alpha-1}$$

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

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

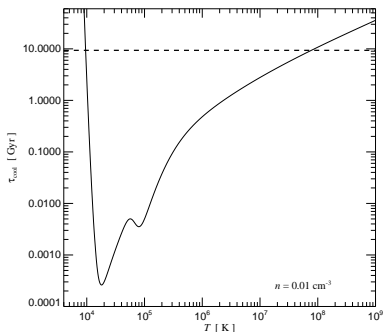
Thermal & CR energy spectra

Kinetic energy per logarithmic momentum interval:

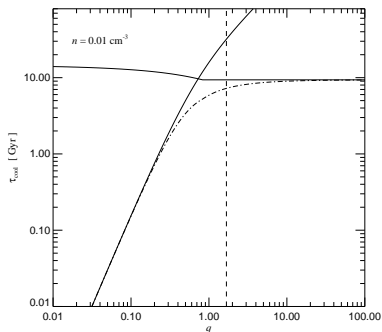


Cooling time scales of CR protons

Cooling of primordial gas:



Cooling of cosmic rays:



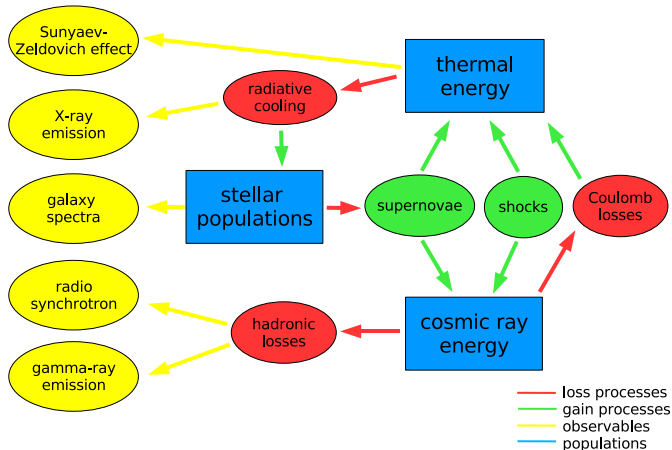
Outline

- 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

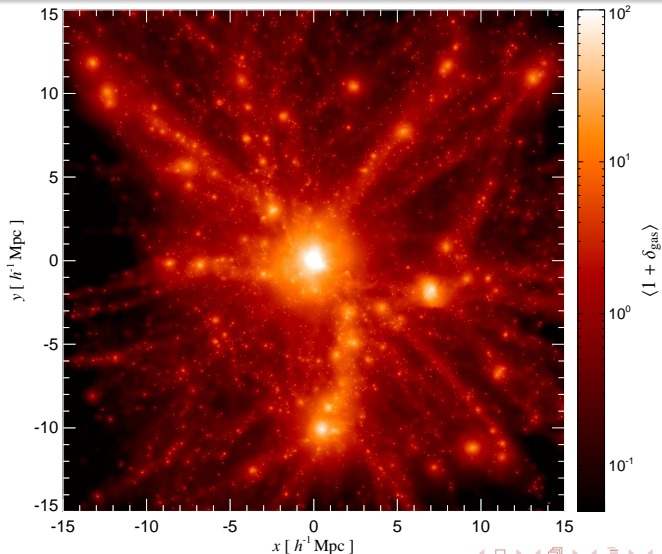
Radiative simulations with CR physics

Cluster observables:

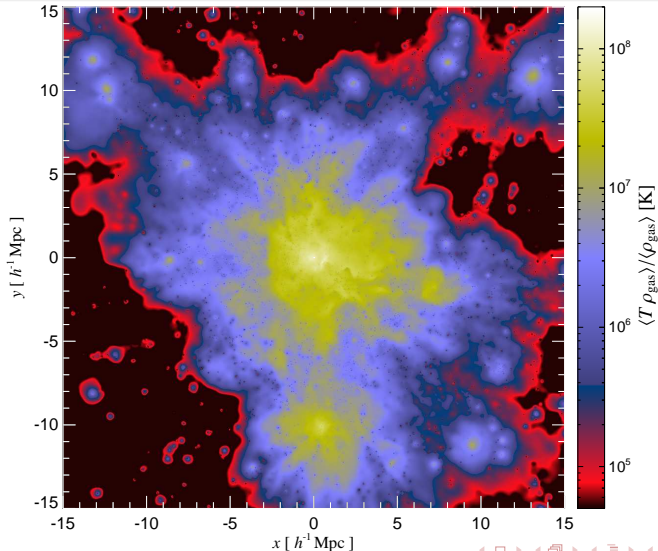
Physical processes in clusters:



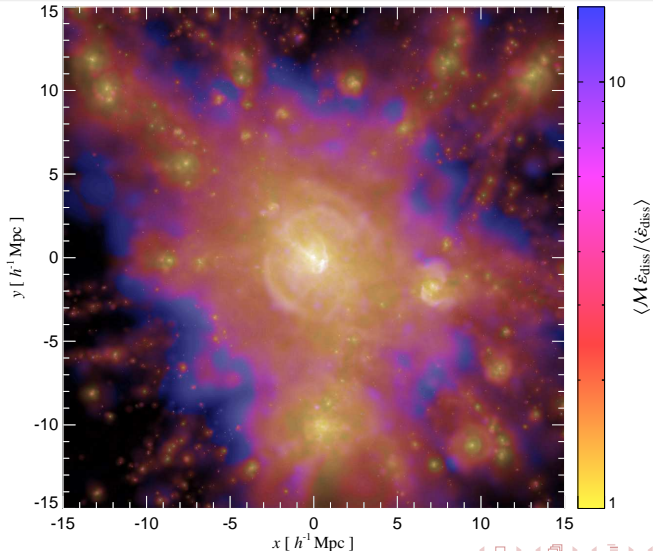
Radiative cool core cluster simulation: gas density



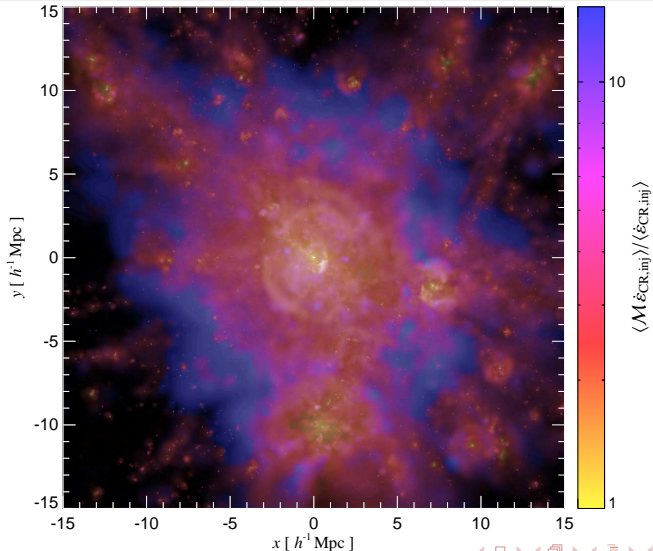
Mass weighted temperature



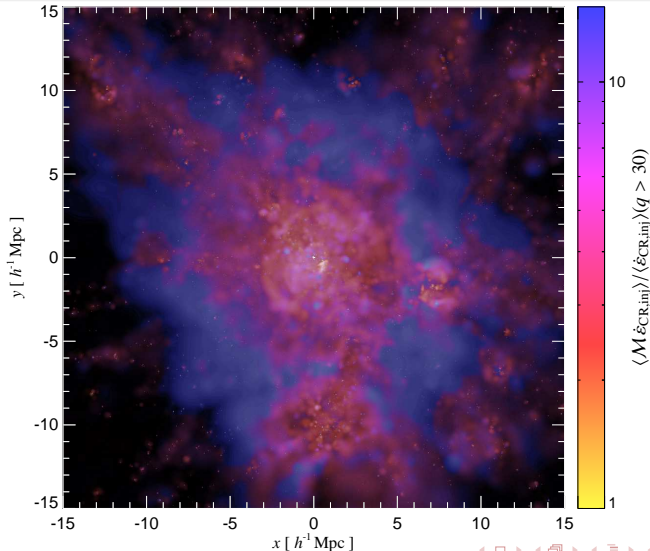
Mach number distribution weighted by $\varepsilon_{\text{diss}}$



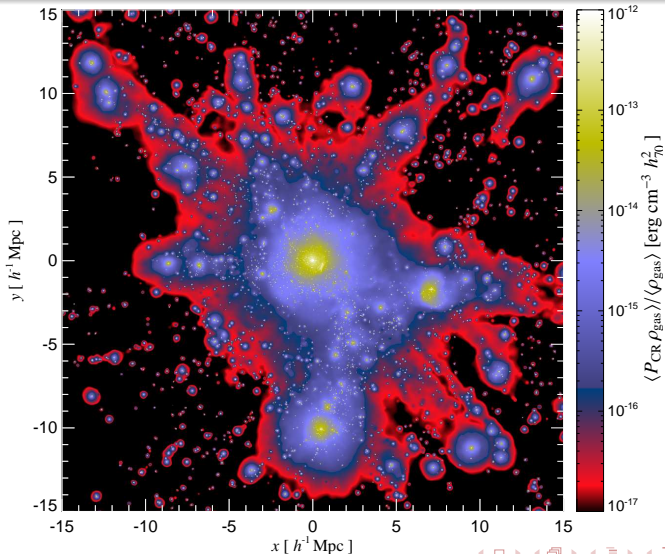
Mach number distribution weighted by $\varepsilon_{\text{CR},\text{inj}}$



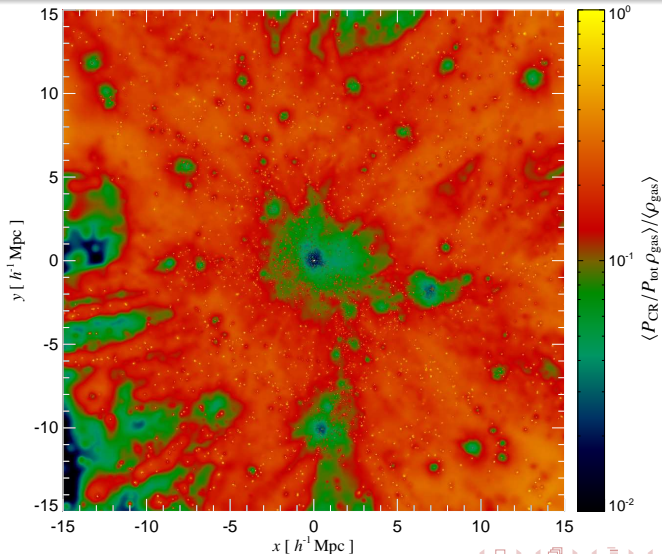
Mach number distribution weighted by $\varepsilon_{\text{CR},\text{inj}}(q > 30)$



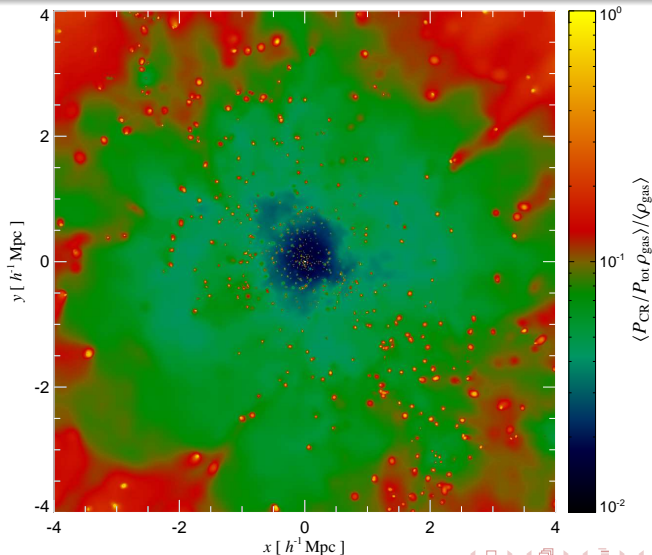
CR pressure P_{CR}



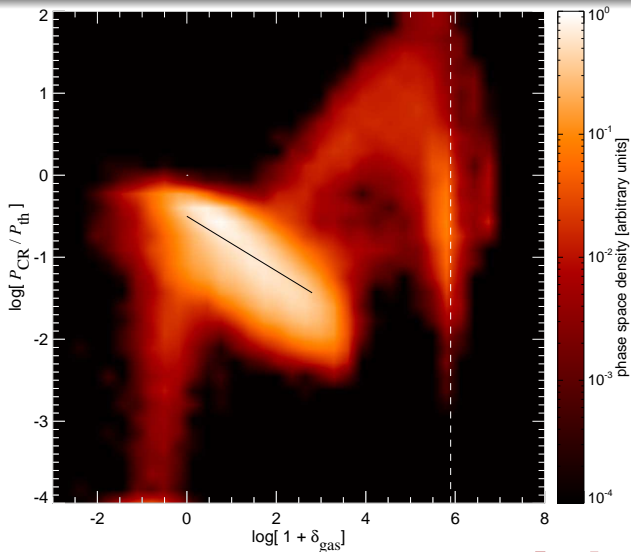
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$



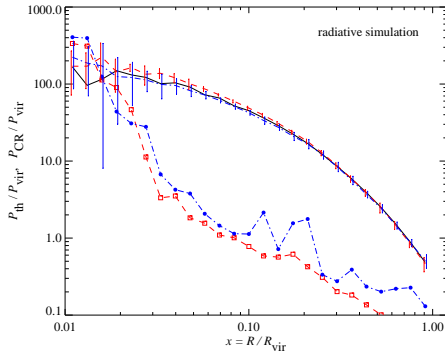
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$



Phase-space diagram of radiative cluster simulation

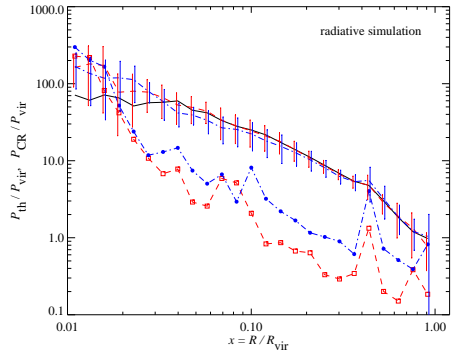


Radiative simulations: pressure profile



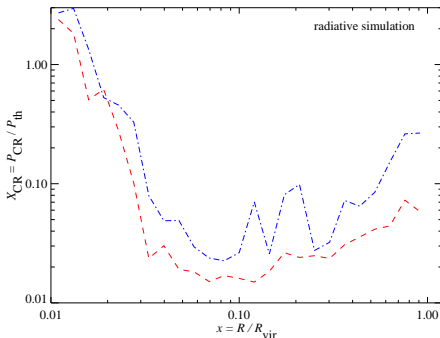
Cool core cluster sample.

red: only structure formation shock CRs,
blue: structure formation & SNe CRs.



Merging cluster sample.

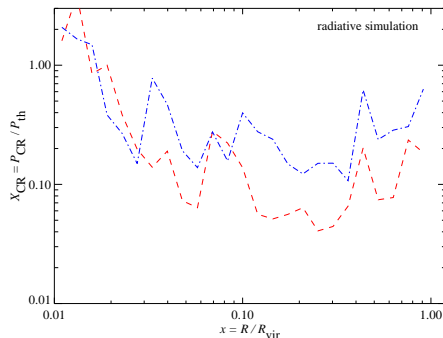
Radiative simulations: relative CR pressure profile



Cool core cluster sample.

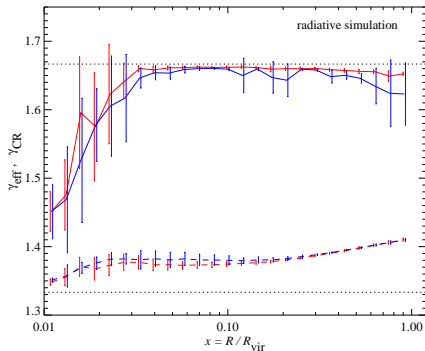
red: only structure formation shock CRs,

blue: structure formation & SNe CRs.



Merging cluster sample.

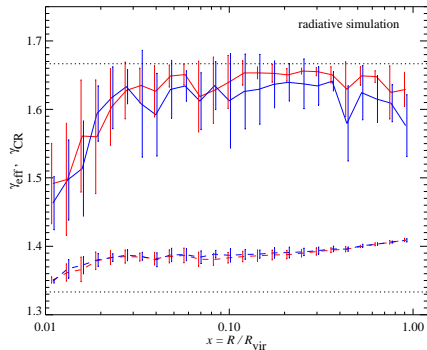
Radiative simulations: adiabatic index profile



Cool core cluster sample.

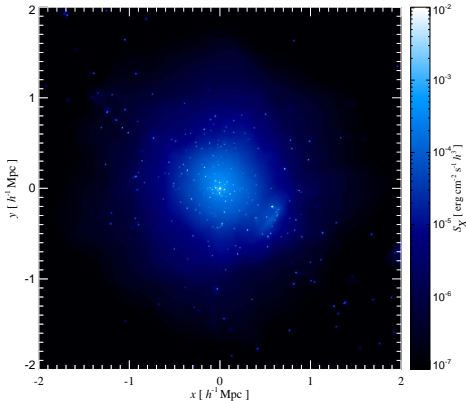
red: only structure formation shock CRs,

blue: structure formation & SNe CRs.

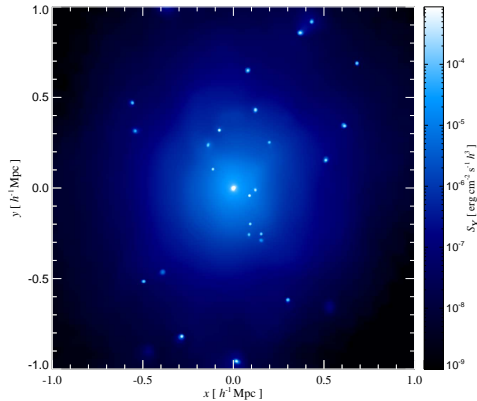


Merging cluster sample.

Thermal X-ray emission

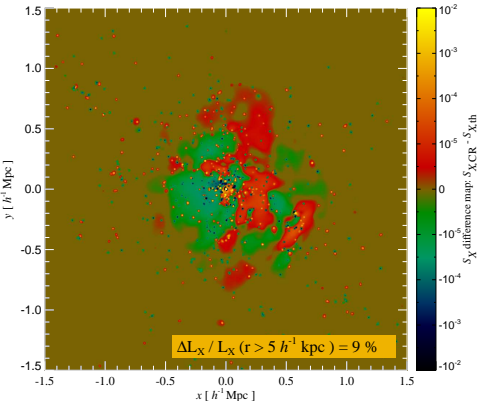


large merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$

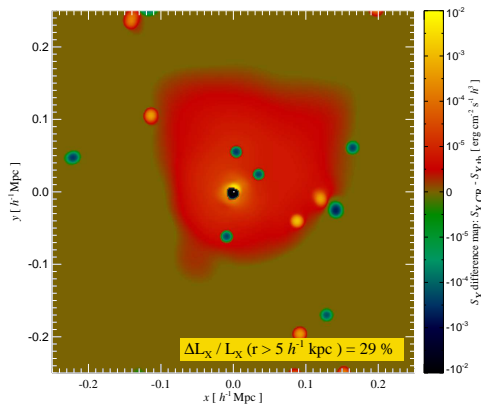


small cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$

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

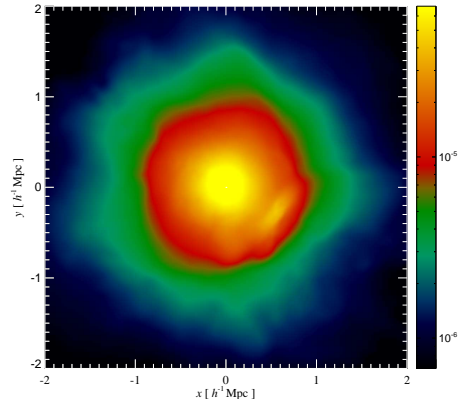


large merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$
→ contributes to the **scatter in the $M - L_X$ scaling relation**

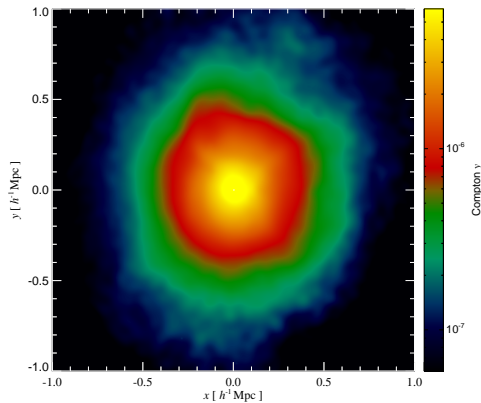


cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$
→ **systematic increase of L_X for small cool core clusters**

Compton y parameter in radiative cluster simulation

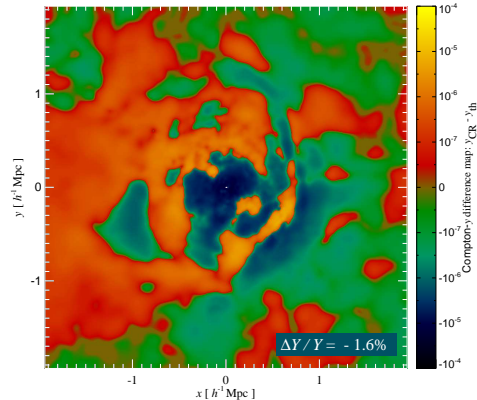


large merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$

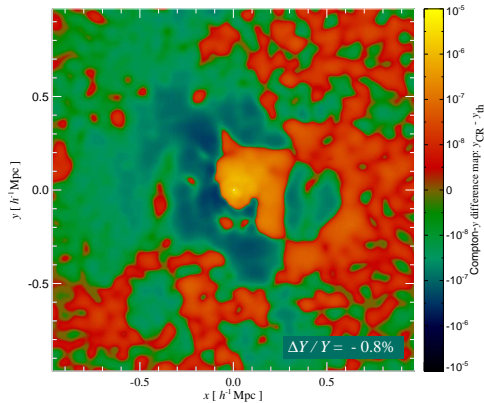


small cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$

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, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$

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

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)

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)

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

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

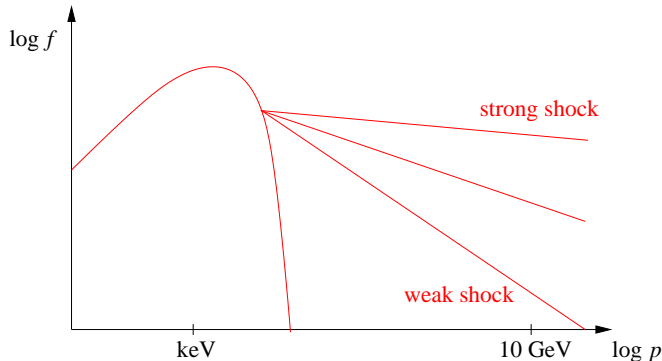
mechanism:

- 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

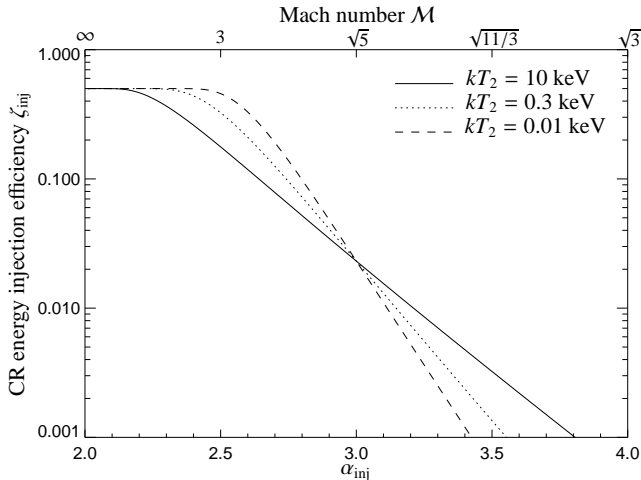
Diffusive shock acceleration – Fermi 1 mechanism (2)

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

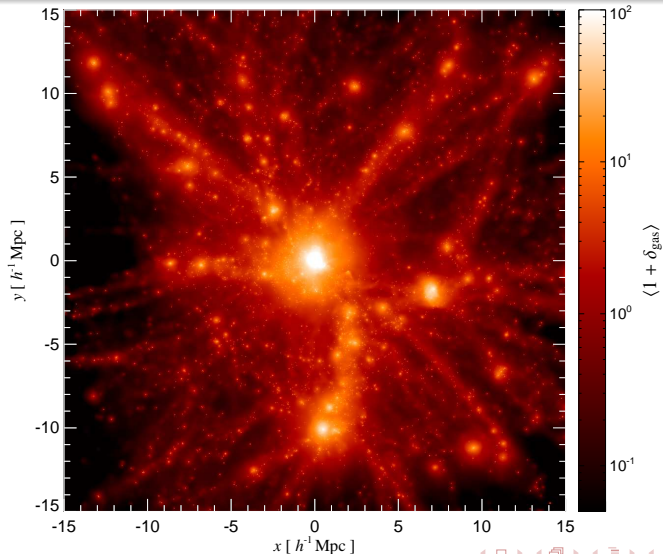


Diffusive shock acceleration – efficiency (3)

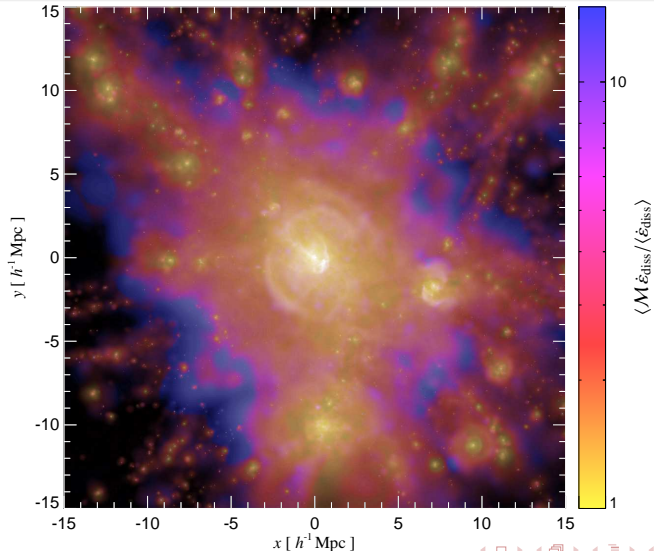
CR proton energy injection efficiency, $\zeta_{\text{inj}} = \varepsilon_{\text{CR}}/\varepsilon_{\text{diss}}$:



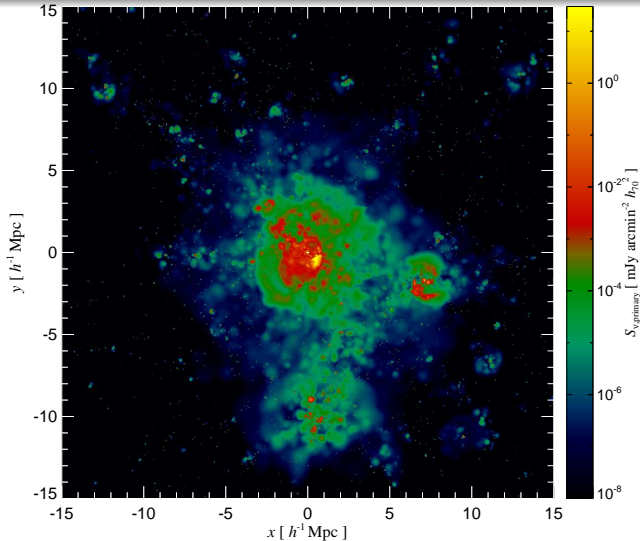
Radiative cool core cluster simulation: gas density



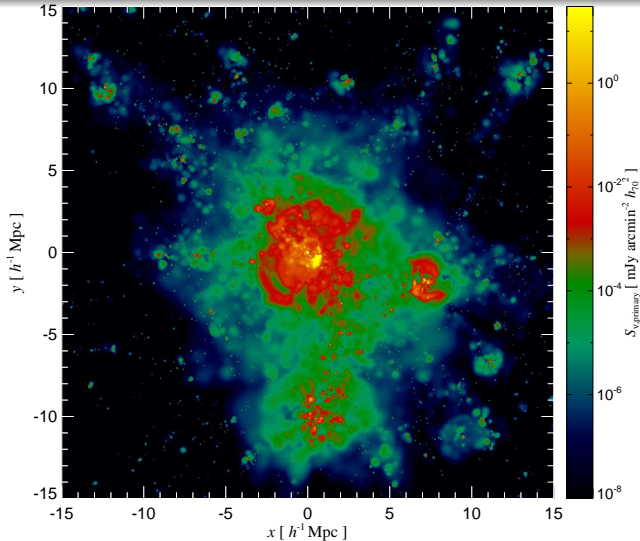
Cosmic web: Mach number



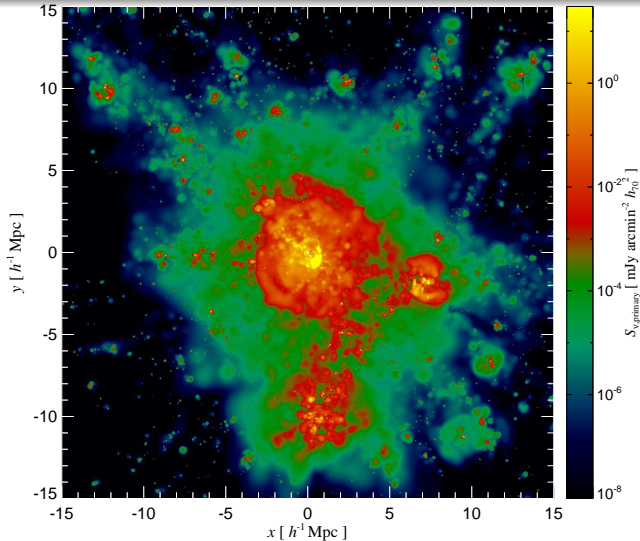
Radio web: primary CRe (1.4 GHz)



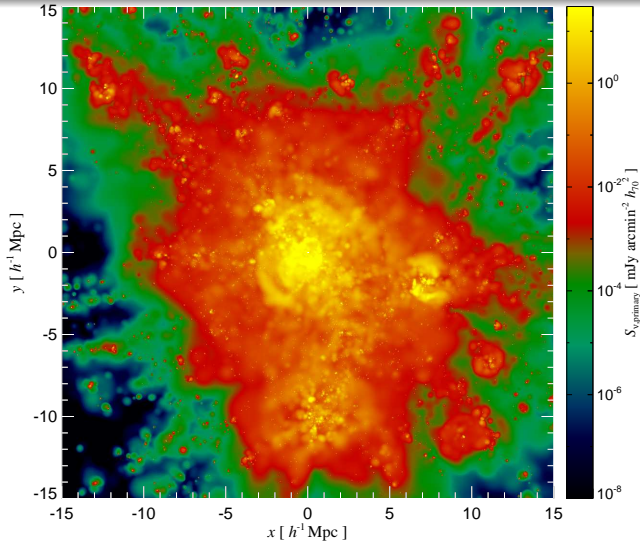
Radio web: primary CRe (150 MHz)



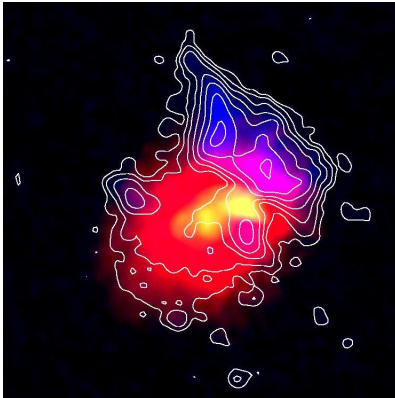
Radio web: primary CRe (15 MHz)



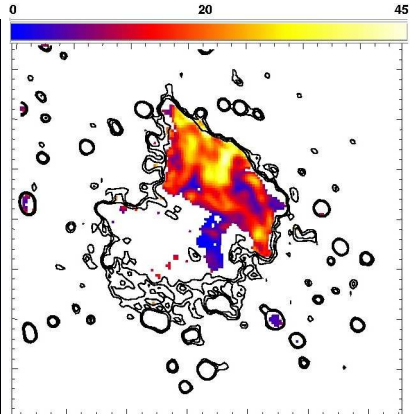
Radio web: primary CRe (15 MHz), slower magnetic decline



Abell 2256: giant radio relic & small halo



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



fractional polarization in color

Clarke & Enßlin (2006)

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

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!

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

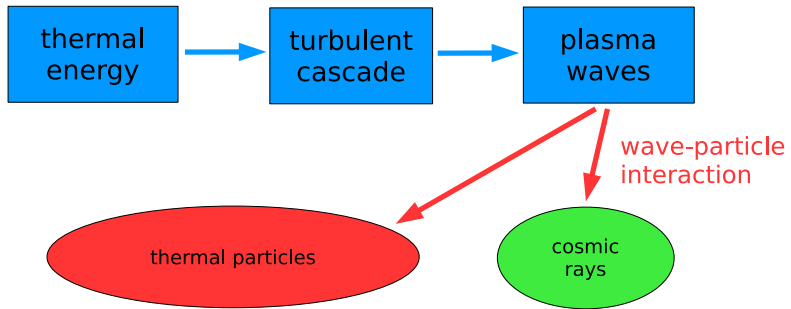
mechanism:

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

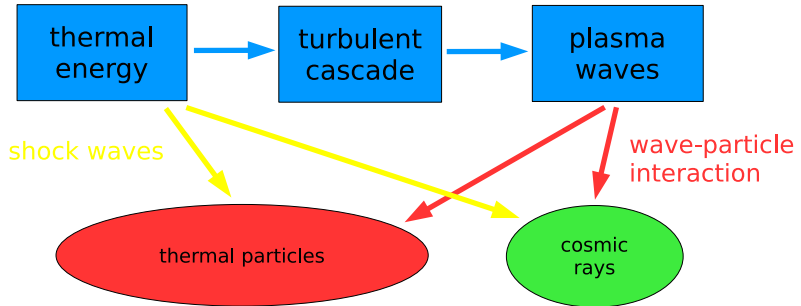
→ net energy gain due to diffusion in momentum space
advantage: plasma waves are everywhere!



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.)

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

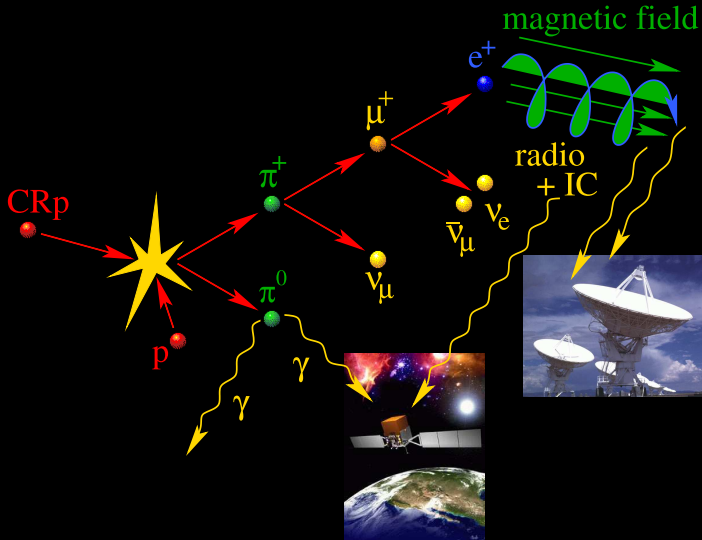
Particle reactions

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

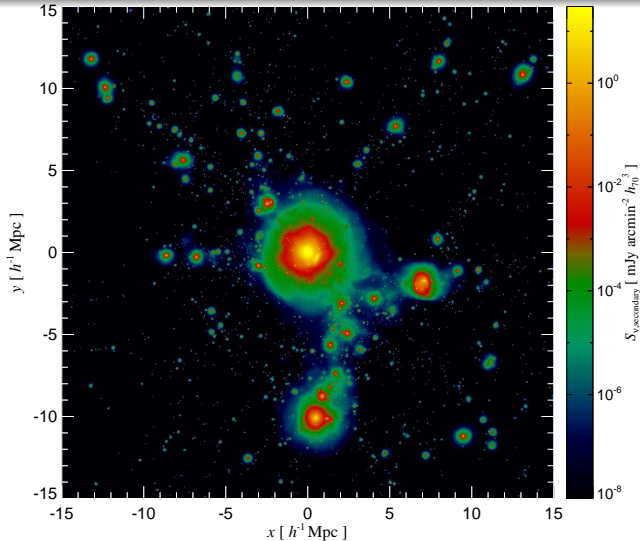
- acceleration mechanisms work for protons ...
 - ... as efficient as for electrons (adiabatic compression) or
 - ... more efficient than for electrons (DSA, stochastic acc.)
- galactic CR protons are observed to have 100 times higher energy density than electrons
- CR protons are very inert against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

→ an energetic CR proton population should exist in clusters

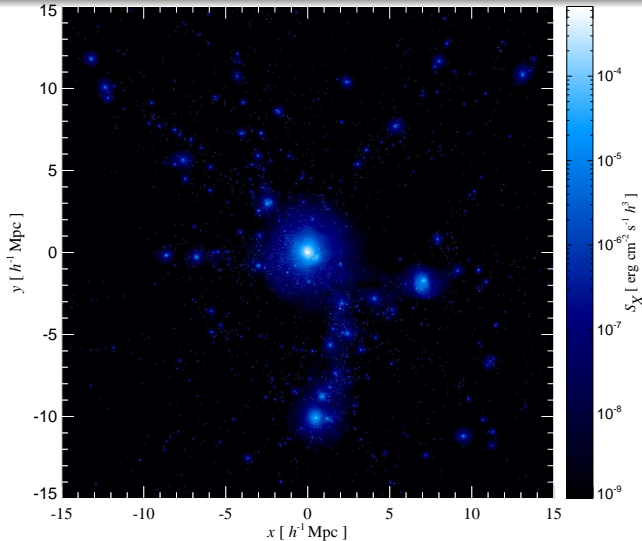
Hadronic cosmic ray proton interaction



Cluster radio emission by hadronically produced CRe



Thermal X-ray emission



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

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)

Non-thermal emission from clusters

Exploring the memory of structure formation

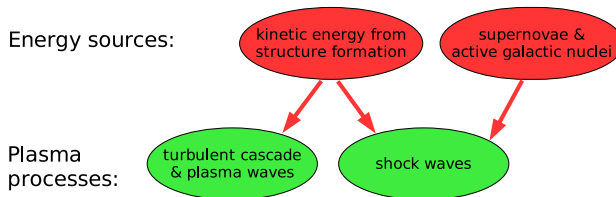
The **thermal plasma lost most information** on how cosmic structure formation proceeded due to the dissipative processes. The thermal observables, X-ray emission and the Sunyaev-Zel'dovich effect, tell us only very indirectly (if at all) about the cosmic history. In contrast, **non-thermal processes 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)

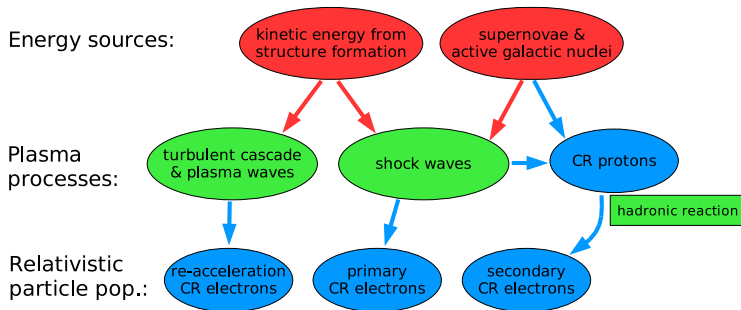
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



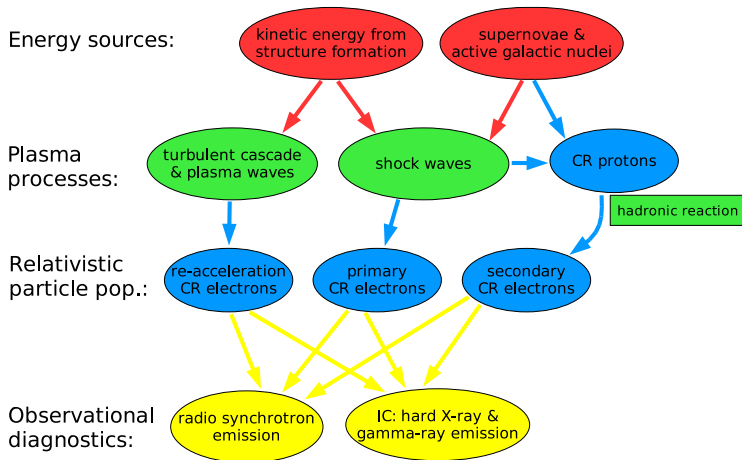
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



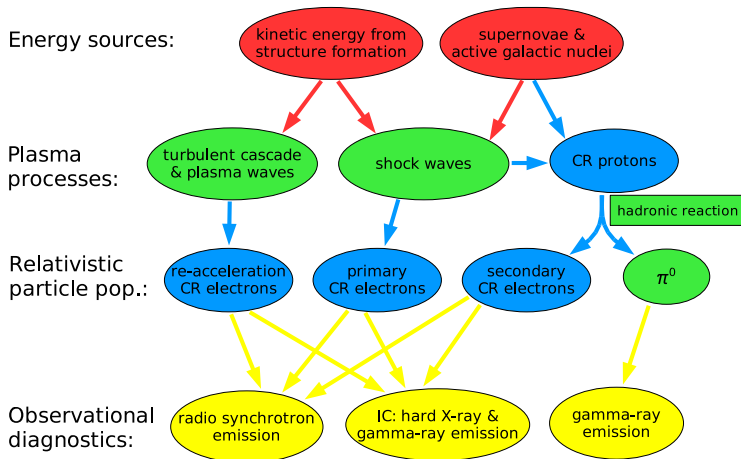
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:



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

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.



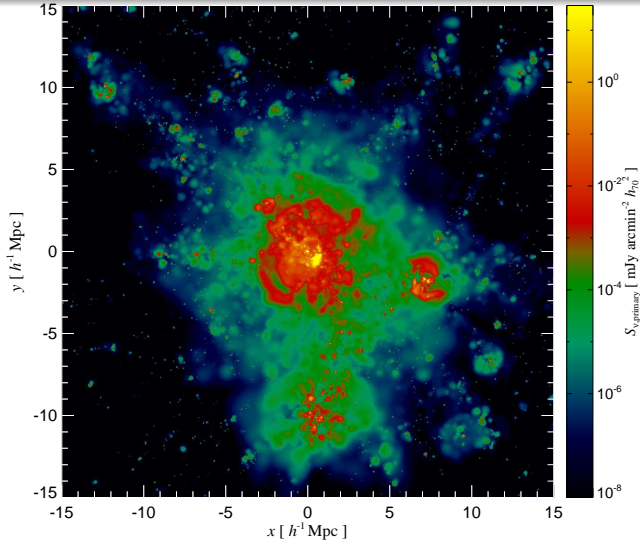
Unified model of radio halos and relics

Cluster radio emission varies with dynamical stage of a cluster:

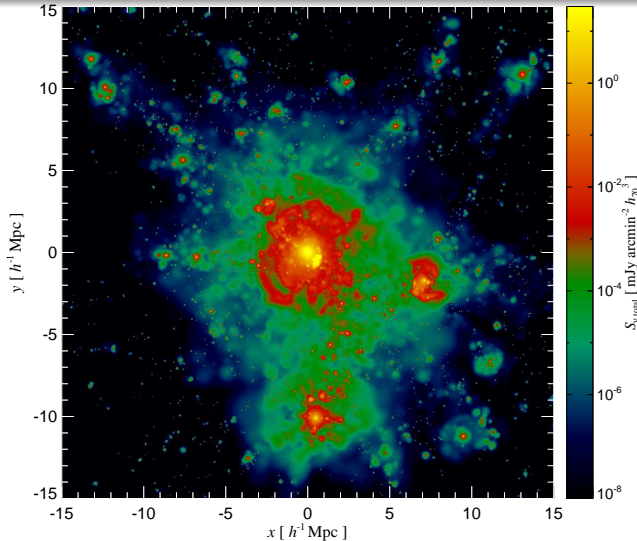
- Cluster relaxes and develops cool core: **radio mini-halo develops** due to hadronically produced CR electrons, magnetic fields are adiabatically compressed (cooling gas triggers **radio mode feedback of AGN** that outshines mini-halo → selection effect).
- Cluster experiences **major merger**: two 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.



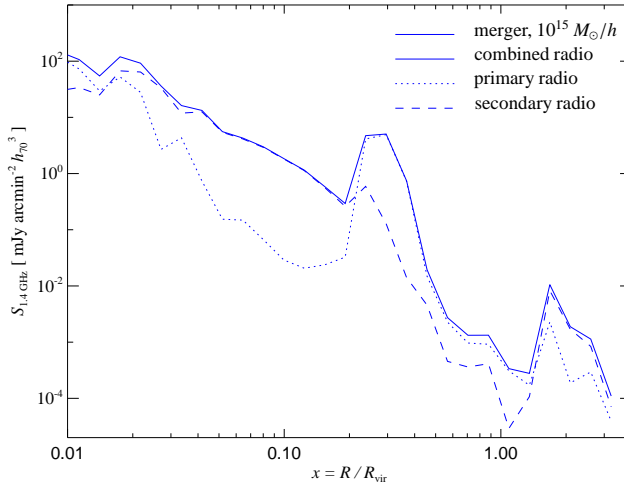
Radio gischt: primary CRe (150 MHz)



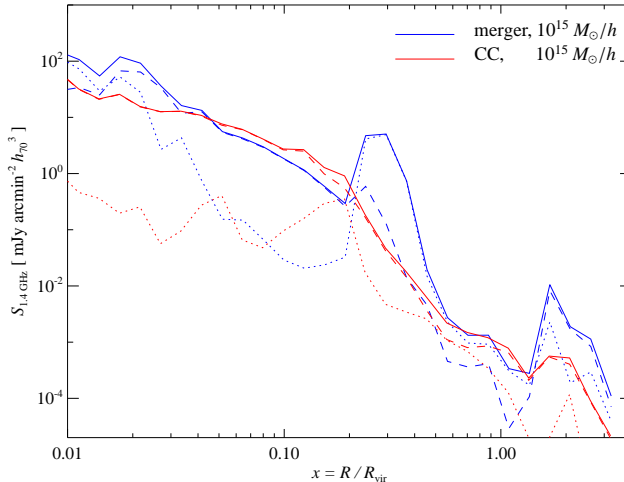
Radio gischt + central hadronic halo = giant radio halo



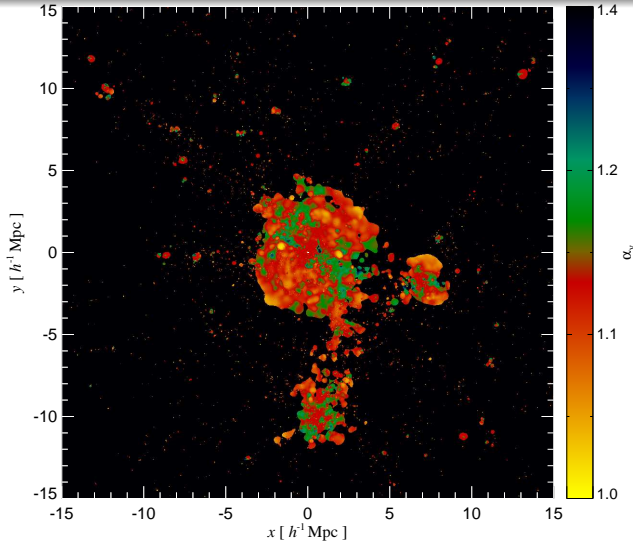
Giant radio halo profile



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

Low-frequency radio emission from clusters

Window into current and past structure formation

Our unified model accounts for ...

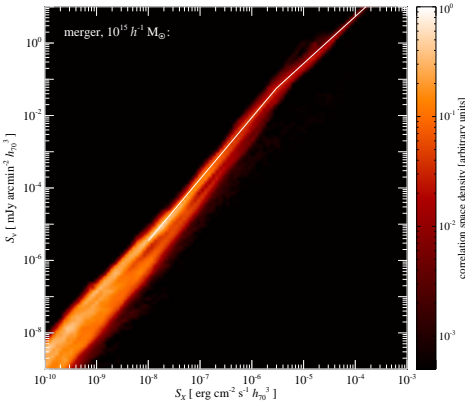
- **correlation between merging clusters and giant halos**, occurrence of mini-halos in cool core clusters
- observed luminosities of halos/relics for magnetic fields derived from Faraday rotation measurements
- **observed morphologies, variations, spectral and polarization** properties in radio halos/relics

How we can make use of this information:

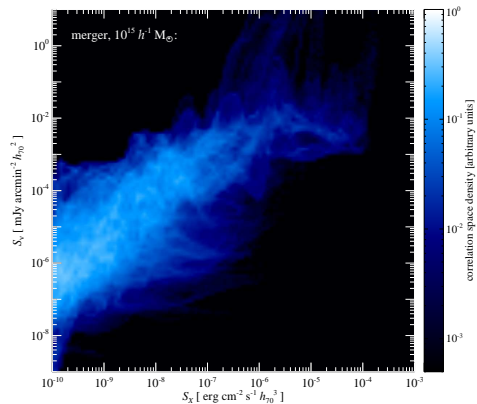
- **Radio relics**: produced by primary accelerated CR electrons at formation shocks → probes **current dynamical, non-equilibrium activity** of forming structures (shocks and magnetic fields)
- **Central radio halos**: produced by secondary CR electrons in hadronic CR proton interactions → tracing **time-integrated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



Correlation between X-ray and synchrotron emission



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

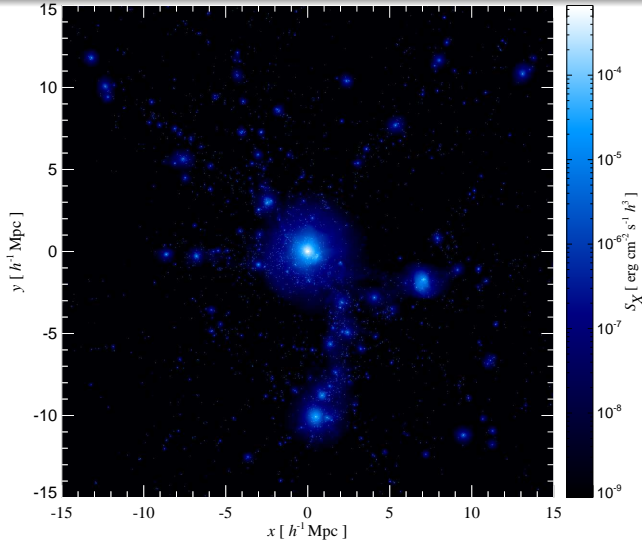


Correlation with primary 'relic' emission,
merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot}/h$

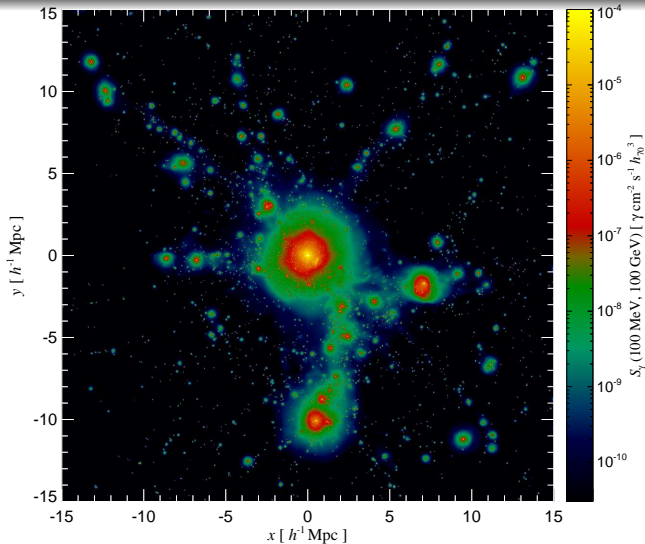
Outline

- 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**

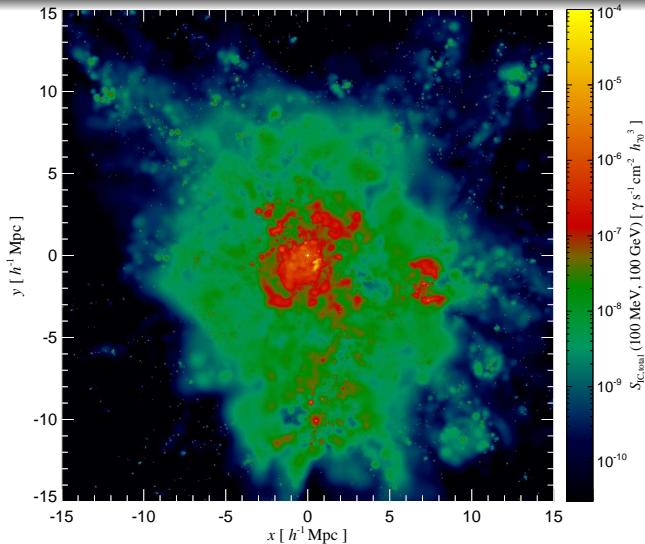
Thermal X-ray emission



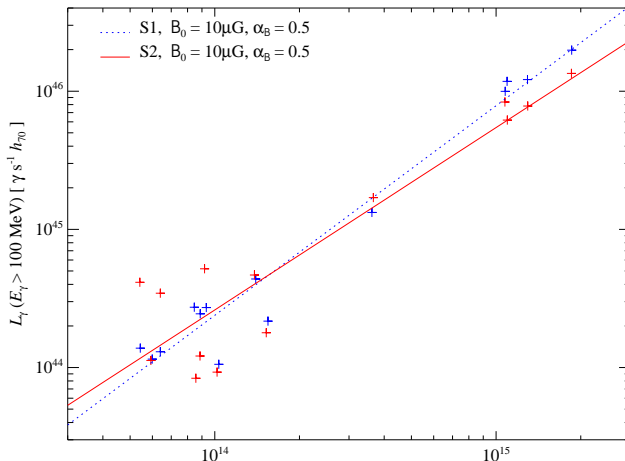
Hadronic γ -ray emission, $E_\gamma > 100$ MeV



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

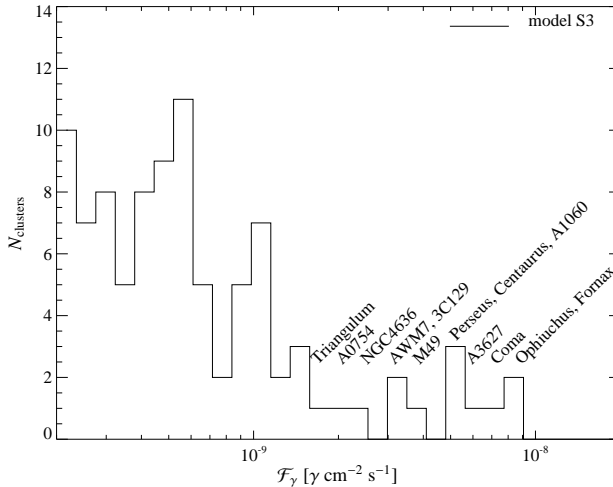


Gamma-ray scaling relations

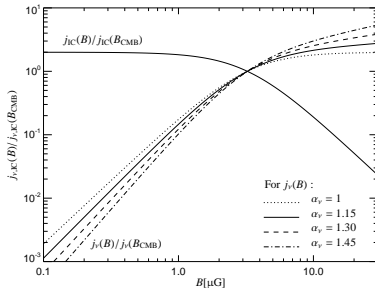


Scaling relation + complete sample of the brightest X-ray clusters (HIFLUCGS) → predictions for GLAST

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:

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

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

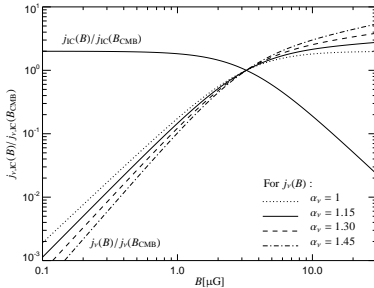
γ -ray luminosity:

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

\rightarrow minimum γ -ray flux:

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

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:

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

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

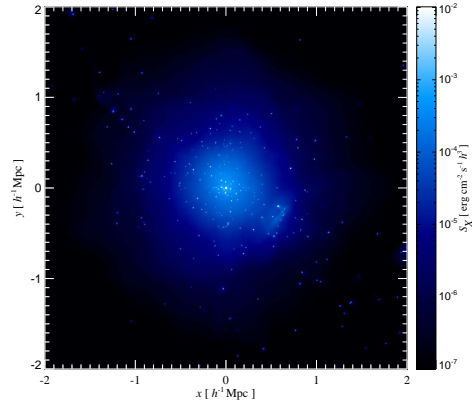
- ① Characteristics of the **CRs in clusters**:
 - **CR proton** pressure: **time integrated non-equilibrium activities** of clusters, modulated by recent mergers.
 - **Primary CR electron** pressure: resembles **current accretion and merging shocks** in the virial regions.
- ② **CR pressure modifies 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

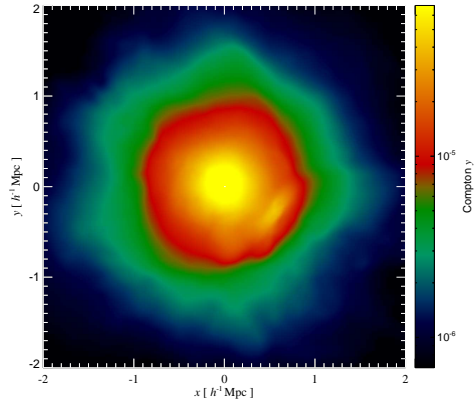
- ① **Unified model** for the generation of giant radio halos, radio mini-halos, and relics:
 - Giant radio halos are dominated in the **center by secondary synchrotron emission**.
 - Transition to the radio emission from **primary electrons in the cluster periphery**.
- ② **LOFAR/GMRT** are expected 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)

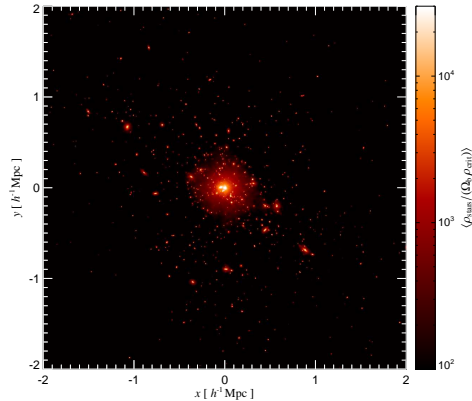


Thermal bremsstrahlung emission,
merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$

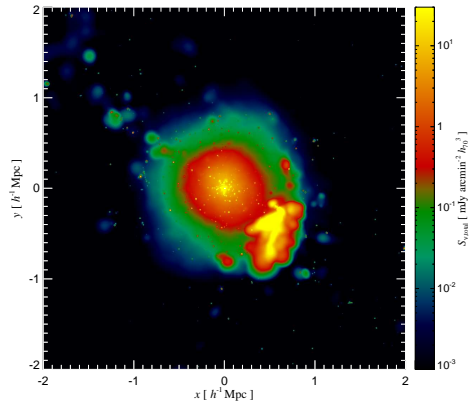


Sunyaev-Zel'dovich effect,
merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$

Optical and radio synchrotron cluster observables (1)

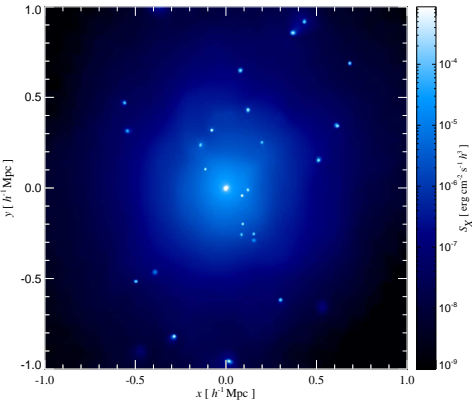


Stellar mass density ("cluster galaxies"),
merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$

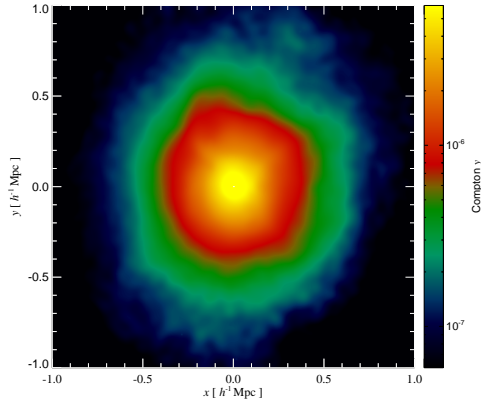


Radio halo and relic emission,
merging cluster, $M_{\text{vir}} \simeq 10^{15} M_{\odot} / h$

Thermal cluster observables (2)

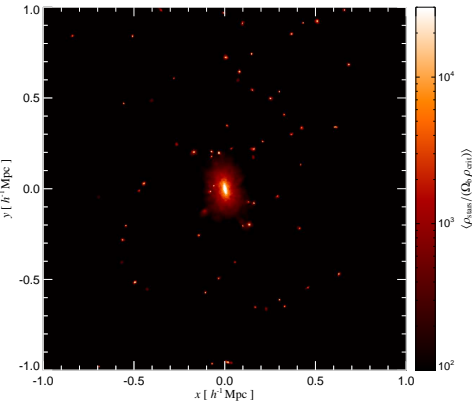


Thermal bremsstrahlung emission,
cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$

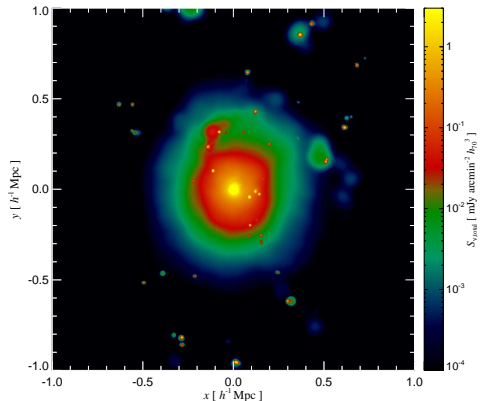


Sunyaev-Zel'dovich effect,
cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$

Optical and radio synchrotron cluster observables (2)



Stellar mass density ("cluster galaxies"),
cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$



Radio halo and relic emission,
cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_{\odot} / h$