Cosmic Rays in Galaxy Clusters: Simulations and Perspectives

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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.
- Improving cluster self-calibration with a hybrid approach: combining (non-)thermal properties in observation space with Bayesian prior on the functional scaling properties derived from hydrodynamical simulations.

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.
Thought provoking impulses
Exploring 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.
   - Improving cluster self-calibration with a hybrid approach: combining (non-)thermal properties in observation space with Bayesian prior on the functional scaling properties derived from hydrodynamical simulations.

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.
Cosmic rays in galaxy clusters
Non-thermal emission from clusters
Cosmic ray pressure in galaxy clusters
Modified X-ray emission and SZ effect
Cosmological implications of cosmic rays

Radiative simulations – flowchart

Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- galaxy spectra

Physical processes in clusters:
- radiative cooling
- thermal energy
- stellar populations
- supernovae
- shocks

Legend:
- red: loss processes
- green: gain processes
- yellow: observables
- blue: populations

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Cosmic Rays in Galaxy Clusters
Radiative simulations with cosmic ray (CR) physics

Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- Galaxy spectra
- Radio synchrotron
- Gamma-ray emission

Physical processes in clusters:
- Stellar populations
- Radiative cooling
- Supernovae
- Shocks
- Cosmic ray energy
- Coulomb losses

Loss processes:
- Red

Gain processes:
- Green

Observables:
- Yellow

Populations:
- Blue
Radiative simulations with extended CR physics

Cluster observables:
- Sunyaev-Zeldovich effect
- X-ray emission
- Galaxy spectra
- Radio synchrotron
- Gamma-ray emission

Physical processes in clusters:
- Radiative cooling
- Stellar populations
- Supernovae
- Shocks
- AGN
- Coulomb losses
- Cosmic ray energy
- CR diffusion

Processes:
- Loss processes
- Gain processes
- Observables
- Populations

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Cosmic Rays in Galaxy Clusters
Radiative cool core cluster simulation: gas density

\[ \langle 1 + \delta_{\text{gas}} \rangle \]

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Cosmic Rays in Galaxy Clusters
Mass weighted temperature

\[ \frac{\langle T \rho_{\text{gas}} \rangle}{\langle \rho_{\text{gas}} \rangle} \text{[K]} \]

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Mach number distribution weighted by $\epsilon_{\text{diss}}$
Mach number distribution weighted by $\varepsilon_{\text{CR}, \text{inj}}$
Mach number distribution weighted by $\varepsilon_{\text{CR, inj}}(q > 30)$
CR pressure $P_{\text{CR}}$
Cosmic rays in galaxy clusters
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Relative CR pressure $P_{CR}/P_{total}$

$x \ [h^{-1} \text{Mpc}]$
$y \ [h^{-1} \text{Mpc}]$

$P_{CR}/P_{total} = \frac{\langle P_{CR}/\rho_{gas} \rangle}{\langle \rho_{gas} \rangle}$
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$
Relative pressure of primary CR electrons.

Relative pressure of CR protons.
Primary versus secondary CR electrons

Relative pressure of *primary* CR electrons.

Rel. pressure of *secondary* CR electrons.
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**Thermal X-ray emission**

![Graph showing thermal X-ray emission from large merging and small cool core clusters.]

- **Large merging cluster**, $M_{\text{vir}} \approx 10^{15} M_\odot / h$
- **Small cool core cluster**, $M_{\text{vir}} \approx 10^{14} M_\odot / h$

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Cosmic Rays in Galaxy Clusters
Difference map of $S_X$: $S_{X,CR} - S_{X,th}$

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

**cool core cluster**, $M_{\text{vir}} \approx 10^{14} M_\odot / h$
→ systematic increase of $\Delta L_X \approx 40\%$
for cool core clusters
Softer effective adiabatic index of composite gas
Compton $y$ parameter in radiative cluster simulation

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

small cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot / h$
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Compton $y$ difference map: $y_{\text{CR}} - y_{\text{th}}$

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

small cool core cluster, $M_{\text{vir}} \approx 10^{14} M_\odot / h$
Pressure profiles with and without CRs
CR feedback lowers the effective mass threshold for X–ray flux–limited cluster sample
The number density of massive clusters is exponentially sensitive to the amplitude of the initial Gaussian fluctuations, whose normalization we usually describe using $\sigma_8$, the rms fluctuations of overdensity within spheres of $8 \, h^{-1}$ Mpc.

The cluster redshift distribution $dn/dz$ is increased by a lower effective mass threshold $M_{\text{lim}}$ in a survey or by increasing $\sigma_8$ respectively $\Omega_m \rightarrow$ degeneracies of cosmological parameters with respect to cluster physics.
Degeneracies of the cluster redshift distribution (2)

\[ \sigma_8 \text{ – Mass Limit degeneracy} \]

- \( N_{\text{clusters}} \approx 25000 \)
- \( \sigma_8 = 0.77, M_{\text{lim}} = 2\times10^{14} \text{ Msun} \)
- \( \sigma_8 = 0.83, M_{\text{lim}} = 2\times10^{14} \text{ Msun} \)
- \( \sigma_8 = 0.77, M_{\text{lim}} = 1.65\times10^{14} \text{ Msun} \)
- \( \sigma_8 = 0.77, M_{\text{lim}} = 1.62\times10^{14} \text{ Msun} \)
Fisher matrix analysis

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 $F_X = 2.5 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$
- sample size: 25000 clusters

Fisher matrix preliminaries:
- free parameters: 2 parameters of the scaling relations: slope and normalization, $\Omega_m$, $\Omega_b$, $n_s$, $h$, $\sigma_8$
- priors: flat Universe, WMAP prior on $h = 72 \pm 5$
Degeneracy of $\sigma_8$ with cosmic ray physics (preliminary)

Constraints from $dndz$ of ~25000 clusters up to $z=2$

- no CR
- full CR
- shock CR

$\sigma_8$ degeneracy with additional physics in simulations

Log($L_0$) vs $\sigma_8$ plot with contours for 1-$\sigma$ and 3-$\sigma$ confidence levels.

Constraints from $dndz$ of ~25000 clusters up to $z=2$.

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Hydrostatic mass profiles
Influence of turbulence and CR pressure

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

\[
\frac{1}{\rho_{\text{gas}}} \frac{dP_{\text{tot}}}{dr} = -\frac{GM(<r)}{r^2}, \quad \text{and} \quad P_{\text{tot}} = P_{\text{th}} + P_{\text{nth}} + P_{\text{turb}}.
\]
So far, we were asking how the CR pressure modifies thermal cluster observables such as the X-ray emission and the Sunyaev-Zel’dovich effect of clusters. These processes tell us only very indirectly (if at all) about the history of structure formation. In contrast, non-thermal processes retain their cosmic memory since their particle population is not in equilibrium.

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

- **LOFAR, GMRT**: interferometric array of radio telescopes at low frequencies ($\nu \sim (15 - 240) \text{ MHz}$)
- **Astrosat**: Indian satellite that images soft and hard X-rays ($E \sim (0.3 - 100) \text{ keV}$)
- **Glast**: international high-energy $\gamma$-ray space mission ($E \sim (0.02 - 300) \text{ GeV}$)
Hadronic cosmic ray proton interaction

- Cosmic ray proton (CRp)
- Protons (p) interact with a magnetic field
- Producing pions ($\pi^+$, $\pi^0$)
- Pions decay into muons ($\mu^+$), neutrinos ($\nu_\mu$, $\bar{\nu}_\mu$), and electrons ($e^+$), plus IC (inverse Compton) radiation
- $\gamma$ rays are produced by these interactions
- Inverse Compton scattering enhances gamma-ray emission
- Radio synchrotron emission is observed from the interactions

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Cosmic Rays in Galaxy Clusters
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:

Energy sources:
- kinetic energy from structure formation
- supernovae & active galactic nuclei

Plasma processes:
- turbulent cascade & plasma waves
- shock waves

Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons
- π^0

Observational diagnostics:
- radio synchrotron emission
- IC: hard X-ray & gamma-ray emission
- gamma-ray emission

Cosmic Rays in Galaxy Clusters
Abell 2256: giant radio relic & small halo

X-ray (red) & radio (blue, contours)  fractional polarization in color

Clarke & Enßlin (2006)
Cosmic rays in galaxy clusters
Non-thermal emission from clusters

Overview of non-thermal emission processes
Radio synchrotron emission
Gamma-ray emission

Cosmic web: Mach number

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Cosmic rays in galaxy clusters

Overview of non-thermal emission processes
Radio synchrotron emission
Gamma-ray emission

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
Exploring the magnetized radio web (with Battaglia, Sievers, Bond)
Simulated LOFAR observation (merging cluster at $z = 0.02$)

Reconstructed ‘dirty’ LOFAR core map.

Reconstructed ‘cleaned’ LOFAR map.
Varying the magnetic decline, $\varepsilon_B \propto \varepsilon_{\text{th}}^{2\alpha_B}$.

Varying the central magnetic field.
Radio halos: secondary CRe

Relativistic populations and radiative processes in clusters:

Energy sources:
- kinetic energy from structure formation
- supernovae & active galactic nuclei

Plasma processes:
- turbulent cascade & plasma waves
- shock waves
- CR protons

Relativistic particle pop.:
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons
- $\pi^0$

Observational diagnostics:
- radio synchrotron emission
- IC: hard X-ray & gamma-ray emission
- gamma-ray emission
Radio halos: secondary CRe (150 MHz)
Radio relics + halos 150 MHz

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Radio relics + halos: spectral index
Low-frequency radio emission from clusters
Window into current and past structure formation

Observational properties of radio synchrotron emission:

- **Radio relics**: inhomogeneous morphology, peripheral cluster regions, polarized synchrotron emission, flat radio spectrum \( \alpha_\nu \approx 1.1 \)

- **Radio (mini-) halos**: homogeneous spherical morphology (similar to X-ray emission), Faraday depolarized synchrotron emission, steeper radio spectrum \( \alpha_\nu \approx 1.3 \)

What this tells us:

- **Radio relics**: produced by primary accelerated CR electrons at formation shocks → probes current dynamical, non-equilibrium activity of forming structures (shocks and magnetic fields)

- **Radio halos**: produced by secondary CR electrons in hadronic CR proton interactions → tracing time-integrated non-equilibrium activity, modulated by recent dynamical activities
Cosmic rays in galaxy clusters
Non-thermal emission from clusters

Overview of non-thermal emission processes
Radio synchrotron emission
Gamma-ray emission

Thermal X-ray emission

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Hadronic $\gamma$-ray emission, $E_\gamma > 100$ MeV
Inverse Compton emission, $E_{IC} > 100$ MeV
Inverse Compton emission, $E_{IC} > 10$ keV
CR physics modifies the intracluster medium in merging clusters and cooling core regions:

- Galaxy cluster **X-ray emission is enhanced** up to 40%, systematic effect in cooling core clusters.
- Integrated **Sunyaev-Zel’dovich effect** remains largely unchanged while the Compton-$y$ profile is more peaked.
- **LOFAR/GMRT** are expected to see the **radio web emission**: origin of **cosmic magnetic fields**.
- **Glast** should see hadronic $\gamma$-ray emission from clusters: measurement of CR protons and origin of radio halos.

→ exciting experiments allow a **complementary view on structure formation** and teach us **fundamental physics**!
**Thermal cluster observables (1)**

- **Thermal bremsstrahlung emission**, merging cluster, $M_{\text{vir}} \sim 10^{15} M_\odot / h$
- **Sunyaev-Zel'dovich effect**, merging cluster, $M_{\text{vir}} \sim 10^{15} M_\odot / h$
Optical and radio synchrotron cluster observables (1)

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

Radio halo and relic emission, merging cluster, \( M_{\text{vir}} \approx 10^{15} M_\odot / h \)
Thermal bremsstrahlung emission, 
cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot / h$

Sunyaev-Zel'dovich effect, 
cool core cluster, $M_{\text{vir}} \sim 10^{14} M_\odot / h$
Stellar mass density ("cluster galaxies"),
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