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

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in collaboration with

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Outline

1. Cosmic rays in galaxy clusters
   - Introduction and motivation
   - Cluster simulations and cosmic ray physics
   - Cosmic ray pressure feedback

2. Unified model of radio halos and relics
   - Radio emission from primary electrons
   - Hadronically produced radio emission
   - Towards a holistic view of cluster radio emission

3. Gamma-ray emission from clusters
   - Gamma-ray morphology
   - Gamma-ray scaling relations
   - Predicted cluster sample for GLAST
Galaxy clusters are dynamically evolving dark matter potential wells:

- Shock waves heat the infalling gas to the virial temperature.
- Galaxy velocity dispersion probes the DM potential.
Cosmic rays in galaxy clusters
Unified model of radio halos and relics
Gamma-ray emission from clusters

Introduction and motivation
Cluster simulations and cosmic ray physics
Cosmic ray pressure feedback

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

1E 0657-56 ("Bullet cluster")
(NASA/SAO/CXC/M.Markevitch et al.)

Abell 3667
(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

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Cosmic Rays in Galaxy Clusters
Each frequency window is sensitive to different processes and cluster properties:

- **optical**: gravitational lensing of background galaxies, galaxy velocity dispersion measure gravitational mass
- **X-ray**: thermal plasma emission, $F_X \propto n_{th}^2 \sqrt{T_{th}} \rightarrow$ thermal gas with abundances, cluster potential, substructure
- **Sunyaev-Zel’dovitch effect**: IC up-scattering of CMB photons by thermal electrons, $F_{SZ} \propto p_{th} \rightarrow$ thermal gas pressure, cluster velocity, high-z clusters
- **radio synchrotron halos**: $F_{\text{synchro}} \propto \varepsilon_B \varepsilon_{\text{CR e}} \rightarrow$ magnetic fields, CR electrons, shock waves
- **diffuse $\gamma$-ray emission**: $F_{\gamma} \propto n_{th} n_{\text{CR p}} \rightarrow$ CR protons
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Why should we care about cosmic rays in clusters?
It allows us to explore complementary windows to cluster cosmology

1. Is high-precision cosmology possible using clusters?
   - Non-equilibrium processes such as cosmic ray pressure and turbulence possibly modify thermal X-ray emission and Sunyaev-Zel’dovich effect.
   - Cosmic ray pressure can modify the scaling relations \(\rightarrow\) bias of cosmological parameters, or increase of the uncertainties if we marginalize over the ‘unknown cluster physics’ (cluster self-calibration)

2. What can we learn from non-thermal cluster emission?
   - Estimating the cosmic ray pressure contribution.
   - Constructing a ‘gold sample’ for cosmology using orthogonal information on the dynamical cluster activity.
   - Fundamental physics: diffusive shock acceleration, large scale magnetic fields, and turbulence.
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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:
- Radiative cooling
- Stellar populations
- Supernovae
- Cosmic ray energy
- Hadronic losses
- 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:
- Thermal energy
- Radiative cooling
- Stellar populations
- Supernovae
- Shocks
- AGN
- Coulomb losses
- Cosmic ray energy
- Hadronic losses
- CR diffusion
- Heat conduction

Loss processes: Red
Gain processes: Green
Observables: Yellow
Populations: Blue

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Cosmic Rays in Galaxy Clusters
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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**CR spectral description**

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

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

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

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

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

\[ = \frac{C \, m_p c^2}{6} \, \beta^{\frac{1}{1+q^2}} \left( \frac{\alpha - 2}{2}, \frac{3-\alpha}{2} \right) \]
Kinetic energy per logarithmic momentum interval:

\[
\frac{dT_{\text{CR}}}{d\log p} = p T(p) f(p) \quad \text{in } m_p c^2
\]

- $\alpha = 2.25$
- $\alpha = 2.50$
- $\alpha = 2.75$

Graph showing the distribution of kinetic energy per logarithmic momentum interval for different values of $\alpha$. The graph has a logarithmic scale for momentum (\(p\)) on the x-axis and a linear scale for energy density (\(T_{\text{CR}}\)) on the y-axis.
Cooling time scales of CR protons

Cooling of primordial gas:

\[ \tau_{\text{cool}} \ [\text{Gyr}] \]

\[ n = 0.01 \text{ cm}^{-3} \]

\[ T \ [\text{K}] \]

0.0001
0.0010
0.0100
0.1000
1.0000
10.0000

Cooling of cosmic rays:

\[ \tau_{\text{cool}} \ [\text{Gyr}] \]

\[ n = 0.01 \text{ cm}^{-3} \]

\[ q \]

0.01
0.10
1.00
10.00
100.00

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Diffusive shock acceleration – Fermi 1 mechanism

Spectral index depends on the Mach number of the shock,
\[ M = \frac{v_{\text{shock}}}{c_s} \]

- Strong shock
- Weak shock

\[
\log p \quad \log f
\]

- keV
- 10 GeV
Radiative cool core cluster simulation: gas density

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

\[ \langle T \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle \,[\text{K}] \]
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Mach number distribution weighted by $\varepsilon_{\text{CR, inj}}$
Mach number distribution weighted by $\varepsilon_{\text{CR,inj}}(q > 30)$
Cosmic rays in galaxy clusters
Unified model of radio halos and relics
Gamma-ray emission from clusters

Introduction and motivation
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CR pressure $P_{CR}$
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Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$

$\langle P_{\text{CR}}/P_{\text{tot}}\rho_{\text{gas}} \rangle/\langle \rho_{\text{gas}} \rangle$
Relative CR pressure $P_{\text{CR}}/P_{\text{total}}$

\[ \langle P_{\text{CR}}/P_{\text{tot}} \rho_{\text{gas}} \rangle/\langle \rho_{\text{gas}} \rangle \]
Thermal X-ray emission

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

small cool core cluster, $M_{\text{vir}} \approx 10^{14} M_{\odot}/h$
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 $L_X$ for small cool core clusters
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Compton $y$ parameter in radiative cluster simulation

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

small cool core cluster, $M_{\text{vir}} \simeq 10^{14} M_\odot/h$
**Cosmic rays in galaxy clusters**

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

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

**small cool core cluster, $M_{vir} \approx 10^{14} M_\odot / h$**
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 ($\nu \approx (15 - 240) \text{ MHz}$)
- **Glast**: international high-energy $\gamma$-ray space mission ($E \approx (0.1 - 300) \text{ GeV}$)
- **Imaging air Čerenkov telescopes**: (TeV photon energies)
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- Imaging air Čerenkov telescopes (TeV photon energies)
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
Cosmic rays in galaxy clusters
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Relativistic particle pop.: 
- re-acceleration CR electrons
- primary CR electrons
- secondary CR electrons

CR protons
hadronic reaction
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- Re-acceleration
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**Observational diagnostics:**
- Radio synchrotron emission
- IC: hard X-ray & gamma-ray emission
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Cosmic Rays in Galaxy Clusters
Cosmic rays in galaxy clusters
Unified model of radio halos and relics
Gamma-ray emission from clusters
Radio emission from primary electrons
Hadronically produced radio emission
Towards a holistic view of cluster radio emission

Cosmic web: Mach number

\[ \langle \dot{M}_{\text{diss}} / \langle \dot{\varepsilon}_{\text{diss}} \rangle \]
Radio web: primary CR (1.4 GHz)

\[ S_{\text{\nu,primary}} \left[ \text{mJy arcmin}^{-2} h_{70}^{-2} \right] \]

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

\[ 10^{-8} \quad 10^{-6} \quad 10^{-4} \quad 10^{-2} \quad 10^{0} \]

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Radio web: primary CRe (150 MHz)
Radio web: primary CRe (15 MHz)
Radio web: primary CRe (15 MHz), slower magnetic decline

\[ S_{\nu,\text{primary}} \left[ \text{mJy arcmin}^{-2} h_{70}^{-2} \right] \]

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

\[ y [ h^{-1} \text{Mpc}] \]
Abell 2256: giant radio relic & small halo

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

fractional polarization in color

Clarke & Enßlin (2006)
Cosmic rays and radiative processes

Relativistic populations and radiative processes in clusters:

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Hadronic cosmic ray proton interaction

Cosmic rays in galaxy clusters
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Cluster radio emission by hadronically produced CRe

![Graph showing radio emission intensity as a function of position in a galaxy cluster. The intensity is plotted on a logarithmic scale ranging from $10^{-15}$ to $10^{0}$ mJy arcmin$^{-2}$. The x-axis represents the position in $h^{-1}$ Mpc, and the y-axis also represents position in $h^{-1}$ Mpc. The intensity increases from blue to red, with red indicating higher intensity.]
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).


All of these models face theoretical short-comings when comparing to observations.
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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Unified model of radio halos and relics

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CITA–ICAT
Radio gischt: primary CRe (150 MHz)
Radio gischt + central hadronic halo = giant radio halo

\[ S_{\nu, \text{total}} \left[ \text{mJy arcmin}^{-2} h_{70}^{3/2} \right] \]

\[ y \left[ h^{-1} \text{Mpc} \right] \]
\[ x \left[ h^{-1} \text{Mpc} \right] \]
Giant radio halo profile

- Merger, $10^{15} M_{\odot}/h$
- Combined radio
- Primary radio
- Secondary radio

$S_{1.4\,\text{GHz}}$ [mJy arcmin$^{-2} h_{70}^{-3}$]

$x = R / R_{\text{vir}}$

- $10^{-4}$
- $10^{-2}$
- $10^0$
- $10^2$

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Cosmic Rays in Galaxy Clusters
Giant radio halo vs. mini-halo

$S_{1.4\,\text{GHz}}$ [mJy arcmin$^{-2}$ $h_{70}^{-3}$]

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$x = R / R_{\text{vir}}$

merger, $10^{15} M_{\odot}/h$

CC, $10^{15} M_{\odot}/h$
Radio relics + halos: spectral index

\[ \alpha \nu \]

\[ x \left[ h^{-1} \text{Mpc} \right] \]

\[ y \left[ h^{-1} \text{Mpc} \right] \]

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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
Cosmic rays in galaxy clusters
Unified model of radio halos and relics
Gamma-ray emission from clusters

Gamma-ray morphology
Gamma-ray scaling relations
Predicted cluster sample for GLAST

Thermal X-ray emission

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Hadronic $\gamma$-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

\[ L(\gamma; E_\gamma > 100 \text{ MeV}) \left[ \gamma \text{s}^{-1} h_{70} \right] \]

\[ S_1, B_0 = 10 \mu \text{G}, \alpha_B = 0.5 \]

\[ S_2, B_0 = 10 \mu \text{G}, \alpha_B = 0.5 \]
Cosmic rays in galaxy clusters
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Predicted cluster sample for GLAST

- Ophiuchus, Fornax
- Coma
- A3627
- Perseus, Centaurus, A1060
- M49
- 3C129
- NGC4636
- A0754
- AWM7
- Triangulum
- A0754
- Fγ [γ cm⁻² s⁻¹]

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Cosmic Rays in Galaxy Clusters
Summary

1. Characteristics of the CR pressure in clusters:
   - CR proton pressure traces the time integrated non-equilibrium activities of clusters and is modulated by recent dynamical activities.
   - The pressure of primary, shock-accelerated CR electrons resembles current accretion and merging shocks in the virial regions.

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

3. We predict GLAST to detect $\sim$ ten $\gamma$-ray clusters: test of the presented scenario