Cosmic Rays in Galaxy Clusters – Simulations and Reality

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in collaboration with

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Outline

1. Cosmological structure formation shocks
   - Observations
   - Cosmological galaxy cluster simulations
   - Mach number distribution

2. Simulating cosmic rays
   - Formalism
   - Cosmic ray pressure
   - Cosmological implications

3. Diffuse radio emission in clusters
   - Non-thermal processes in clusters
   - Shock related emission
   - Hadronically induced emission
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Shocks in galaxy clusters

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.)
consistent picture of non-thermal processes in galaxy clusters (radio, soft/hard X-ray, \(\gamma\)-ray emission) → illuminating the process of structure formation → history of individual clusters: cluster archeology

fundamental plasma physics complementary to SNRs:
- diffusive shock acceleration for intermediate Mach numbers
- origin and evolution of large scale magnetic fields
- nature of turbulent models

understanding the non-thermal pressure distribution to address biases of thermal cluster observables (gold sample of clusters for precision cosmology)

nature of dark matter: annihilation signal vs. cosmic ray (CR) induced \(\gamma\)-rays
Radiative simulations with GADGET – flowchart

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

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

CP, Enßlin, Springel (2008)
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 energy
- Stellar populations
- Supernovae
- Shock
- Coulomb losses
- Cosmic ray energy
- Hadronic losses

CP, Enßlin, Springel (2008)
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
- CR diffusion
- hadronic losses
- gamma-ray losses
- heat conduction

CP, Enßlin, Springel (2008)
Previous numerical work on Mach number statistics

- Miniati et al. (2000, 01, 02, 03): Eulerian approach, coarse resolution, passive CR evolution, NT cluster emission
- Ryu et al. (2003, 07, 08), Kang et al. 2005: Eulerian Mach number statistics (post-proc.), vorticity and magnetic field generation
- Pfrommer et al. (2006, 07, 08): Lagrangian approach, Mach number statistics (on the fly), self-consistent CR evolution, NT cluster emission
- Skillman et al. 2008: Eulerian AMR, Mach number statistics (post-proc.)
- Hoeft et al. 2008: Lagrangian approach, Mach number statistics (post-proc.)

→ increasing number of papers recently, with more expected to come that focus on the non-thermal emission from clusters and topics related to cosmic magnetic fields (as we enter a new era of multi-frequency experiments).
Detecting shock waves in SPH – Idea

Using the entropy conserving formalism with the entropic function $A(s) = P \rho^{-\gamma}$ (Springel & Hernquist 2002):

$$\frac{A_2}{A_1} = \frac{A_1 + dA_1}{A_1} = 1 + \frac{f_h h}{M_1 c_1 A_1} \frac{dA_1}{dt} = \frac{P_2}{P_1} \left( \frac{\rho_1}{\rho_2} \right)^\gamma$$

$$\frac{\rho_2}{\rho_1} = \frac{(\gamma + 1)M_1^2}{(\gamma - 1)M_1^2 + 2}$$

$$\frac{P_2}{P_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{\gamma + 1}$$

- SPH shock is broadened to a scale of the order of the smoothing length $h$, i.e. $f_h h$, and $f_h \sim 2$
- approximate instantaneous particle velocity by pre-shock velocity (denoted by $v_1 = M_1 c_1$)
Detecting shock waves in SPH – Details

1. Broad Mach number distributions \( f(\mathcal{M}) = \frac{d^2 u_{th}}{dt \, d \log \mathcal{M}} \)
because particle quantities within the (broadened) shock front do not correspond to those of the pre-shock regime.
   Solution: introduce decay time \( \Delta t_{\text{dec}} = f_h h / (\mathcal{M}_1 c) \), meanwhile the Mach number is set to the maximum (only allowing for its rise in the presence of multiple shocks).

2. Weak shocks imply large values of \( \Delta t_{\text{dec}} \):
   Solution: \( \Delta t_{\text{dec}} = \min[f_h h / (\mathcal{M}_1 c), \Delta t_{\text{max}}] \)

3. Strong shocks with \( \mathcal{M} > 5 \) are slightly underestimated because there is no universal shock length.
   Solution: recalibrate strong shocks!
Shock tube: thermodynamics

1. Density
2. Velocity
3. Pressure
4. Mach number
Cosmological structure formation shocks
Simulating cosmic rays
Diffuse radio emission in clusters
Mach number distribution

Shock tube: Mach number statistics

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Cosmological structure formation shocks
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Shock tube (CRs & gas)

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Shock tube (CRs & gas): Mach number statistics

\[ \frac{d n_{\text{th}}}{d \log M} \]

\[ \langle d u_{\text{th}}/dt \rangle \langle d \log M \rangle \]
Cosmological shock statistics

- More energy is dissipated at later times
- Mean Mach number decreases with time
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Simulating cosmic rays
Diffuse radio emission in clusters

Cosmological shock statistics: influence of reionization

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

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Mach number dependent injection efficiency of CRs favors medium Mach number shocks ($M \gtrsim 3$) for the injection, and even stronger shocks when accounting for Coulomb interactions.

More energy is dissipated in weak shocks internal to collapsed structures than in external strong shocks.
Spectral index depends on the Mach number of the shock, \( \mathcal{M} = \frac{\nu_{\text{shock}}}{c_s} \):

\[ \log f \]

\[ \begin{array}{c|c}
\text{keV} & 10 \text{ GeV} \\
\hline
\text{strong shock} & \log p \\
\text{weak shock} & \log p \\
\end{array} \]
CR proton energy injection efficiency, $\zeta_{\text{inj}} = \varepsilon_{\text{CR}}/\varepsilon_{\text{diss}}$:
Cosmological structure formation shocks
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Cosmological Mach numbers: weighted by $\mathcal{E}_{\text{diss}}$

![Cosmological Mach numbers weighted by $\mathcal{E}_{\text{diss}}$](image-url)
Cosmological Mach numbers: weighted by $\varepsilon_{CR}$
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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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CR spectral description

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

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

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

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

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

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

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

\( \alpha = 2.25 \)
\( \alpha = 2.50 \)
\( \alpha = 2.75 \)

\[ 10 \text{ eV} \quad 1 \text{ keV} \quad 0.1 \text{ MeV} \]
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Simulating cosmic rays
Diffuse radio emission in clusters

Cooling time scales of CR protons

Cooling of primordial gas:

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

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

Cooling of cosmic rays:

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

\[ n = 0.01 \text{ cm}^{-3} \]
Radiative cool core cluster simulation: gas density

\[
\langle1 + \delta_{\text{gas}}\rangle
\]

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Mass weighted temperature

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

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Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Mach number distribution weighted by $\varepsilon_{\text{CR, inj}}$
Mach number distribution weighted by $\varepsilon_{CR, inj}(q > 30)$
Cosmological structure formation shocks
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Formalism
Cosmic ray pressure
Cosmological implications

CR pressure $P_{\text{CR}}$

\[
\langle P_{\text{CR}} \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle [\text{erg cm}^{-3} h_{270}^{-2}]
\]

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

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

\[
\langle P_{CR}/P_{\text{tot}} \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle
\]

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CR phase-space diagram: final distribution @ $z = 0$

- Formalism
  - Cosmic ray pressure
  - Cosmological implications

**Graph Description:**
- **x-axis:** $\log[1 + \delta_{\text{gas}}]$
- **y-axis:** $\log[\frac{P_{\text{CR}}}{P_{\text{th}}}]$
- **Colorbar:** Phase space density [arbitrary units]

**Graph Details:**
- The graph shows the distribution of cosmic ray pressure relative to the thermal pressure in the gas at a redshift of $z = 0$.
- The color gradient indicates the density of phase space, with darker colors representing higher density.

**Annotations:**
- The graph includes lines indicating specific pressure ratios.

**Legend:**
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- Cosmic Rays in Galaxy Clusters
Cosmological structure formation shocks
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Diffuse radio emission in clusters

CR pressure and hydrostatic masses
Non-radiative simulations: mean and $\sigma$ over cluster sample

CR pressure profile:

Difference in hydrostatic masses:

\[ \rho_{\text{gas}} \frac{dP_{\text{tot}}}{dr} = - \frac{G M(< r)}{r^2}, \text{ where } P_{\text{tot}} = P_{\text{th}} + P_{\text{nth}} \] (CP & Majumdar in prep.)

- “turbulence” dominates $\Delta M$-bias, CR pressure only secondary effect on $\Delta M$
CR pressure and hydrostatic masses
Radiative simulations with star formation: mean and $\sigma$ over cluster sample

CR pressure profile:

\[
X_{\text{CR}} = \frac{P_{\text{CR}}}{P_{\text{th}}} \]

Difference in hydrostatic masses:

\[
\left( \frac{M_{\text{hydrostatic}}}{M_{\text{true}}} - 1 \right) / M_{\text{true}} \quad (x < X_{\text{CR}})
\]

- $\rho_{\text{gas}}^{-1} \frac{dP_{\text{tot}}}{dr} = -\frac{GM(<r)}{r^2}$, where $P_{\text{tot}} = P_{\text{th}} + P_{\text{nth}}$ (CP & Majumdar in prep.)
- “turbulence” dominates $\Delta M$-bias, CR pressure only secondary effect on $\Delta M$
large merging cluster, $M_{\text{vir}} \approx 10^{15} M_\odot / h$

small cool core cluster, $M_{\text{vir}} \approx 10^{14} M_\odot / h$
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, $M_{\text{vir}} \approx 10^{14} M_\odot / h$
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Multi messenger approach for non-thermal 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
Multi messenger approach for non-thermal 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
- CR protons
- hadronic reaction
Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:

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

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

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

hadronic reaction
Multi messenger approach for non-thermal processes

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- Re-acceleration
- Primary
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Hadronic reaction

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Cosmic web: Mach number

\[
\langle \frac{\dot{M}_{\text{diss}}}{\dot{\epsilon}_{\text{diss}}} \rangle
\]
Radio gischt (relics): primary CR$_e$ (1.4 GHz)
Radio gischt: primary CRe (150 MHz)
Radio gischt: primary CRe (15 MHz)
Radio gischt: primary CRe (15 MHz), slower magnetic decline
Structure formation shocks triggered by a recent merger of a large galaxy cluster.

red/yellow: shock-dissipated energy,
blue/contours: 150 MHz radio gischt emission from shock-accelerated CRs
Battaglia, CP, Sievers, Bond, Enßlin (2008):

By suitably combining the observables associated with diffuse polarized radio emission at low frequencies ($\nu \sim 150$ MHz, GMRT/LOFAR/MWA/LWA), we can probe

- the strength and coherence scale of magnetic fields on scales of galaxy clusters,
- the process of diffusive shock acceleration of electrons,
- the existence and properties of the WHIM,
- the exploration of observables beyond the thermal cluster emission which are sensitive to the dynamical state of the cluster.
Population of faint radio relics in merging clusters
Probing the large scale magnetic fields

Finding radio relics in 3D cluster simulations using a friends-of-friends finder with an emission threshold → relic luminosity function

radio map with GMRT emissivity threshold

"theoretical" threshold (towards SKA)
Relic luminosity function – theory

Relic luminosity function is very sensitive to large scale behavior of the magnetic field and dynamical state of cluster:

\[
\log\left(\frac{J}{J_0}\right), \quad J_0 = 1 \text{ erg Hz s ster}
\]

varying magnetic decline with radius

varying overall normalization of the magnetic field

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Rotation measure (RM)

RM maps and power spectra have the potential to infer the magnetic pressure support and discriminate the nature of MHD turbulence in clusters:

Left: RM map of the largest relic, right: Magnetic and RM power spectrum comparing Kolmogorow and Burgers turbulence models.
Giant radio halo in the Coma cluster

- thermal X-ray emission
  (Snowden/MPE/ROSAT)
- radio synchrotron emission
  (Deiss/Effelsberg)

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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 77, Schlickeiser 87, Brunetti et al. 01, 04, Brunetti & Blasi 05, Brunetti & Lazarian 07, ...).

- **Hadronically produced CR electrons** in inelastic collisions of CR protons with the ambient gas (Dennison 80, Vestrad 82, Blasi & Colafrrancesco 99, Miniati 01, Pfrommer et al. 04, 08, ...).

All of these models face either theoretical short-comings when comparing to observations or their success has not been demonstrated in a cosmological framework.
Hadronic cosmic ray proton interaction

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Cluster radio emission by hadronically produced CRe
Thermal X-ray emission

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Radio gischt: primary CRe (150 MHz)

\[ S_{\nu, \text{primary}} [\text{mJy arcmin}^{-2} h^{70}_2] \]

-15 -10 -5 0 5 10 15

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

\( y [h^{-1}\text{Mpc}] \)
Radio gischt + central hadronic halo = giant radio halo

Cosmological structure formation shocks
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Cosmic Rays in Galaxy Clusters
Which one is the simulation/observation of A2256?

- **red/yellow**: thermal X-ray emission,
- **blue/contours**: 1.4 GHz radio emission with giant radio halo and relic
Observation – simulation of A2256

Clarke & Enßlin (2006)

CP, Battaglia, Pinzke, in prep.

red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic
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.
Non-thermal emission from clusters
Exploring the memory of structure formation

- **primary, shock-accelerated CR electrons** resemble current accretion and merging shock waves
- **CR protons/hadronically produced CR electrons** trace the time integrated non-equilibrium activities of clusters that is modulated by the recent dynamical activities

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

- **GMRT, LOFAR, MWA, LWA, SKA**: interferometric array of radio telescopes at low frequencies ($\nu \approx (15 - 240)$ MHz)
- **Simbol-X/NuSTAR**: future hard X-ray satellites ($E \approx (1 - 100)$ keV)
- **Fermi $\gamma$-ray space telescope**: ($E \approx (0.1 - 300)$ GeV)
- **Imaging air Čerenkov telescopes**: ($E \approx (0.1 - 100)$ TeV)
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- **Fermi \(\gamma\)-ray space telescope** \((E \simeq (0.1 - 300) \text{ GeV})\)
- **Imaging air Čerenkov telescopes** \((E \simeq (0.1 - 100) \text{ TeV})\)
In contrast to the thermal plasma, the non-equilibrium distributions of CRs preserve the information about their injection and transport processes and provide thus a unique window of current and past structure formation processes and fundamental plasma astrophysics!

1. **Cosmological hydrodynamical simulations** are indispensable for understanding non-thermal processes in galaxy clusters → illuminating the process of structure formation

2. **Adiabatic compression** disfavors the thermal pressure relative to the CR pressure: only small bias of hydrostatic masses and Sunyaev-Zel’dovich effect

3. **Unified model** for the generation of giant radio halos, radio mini-halos, and relics: interplay of primary and secondary synchrotron emission.
Literature for the talk

Brunetti et al. 2008, Nature, 455, 944:

colors: thermal X-ray emission, contours: diffuse radio emission, 
→ presence of radio structure at 610 MHz and their absence at three times higher/lower frequency is incompatible with synchrotron theory!
Brunetti et al. 2008, Nature, 455, 944:

**“radio halo” interpretation:**
- re-acceleration of relativistic electrons (Brunetti et al.)
- hadronic model inconsistent with spectra and morphology

**“radio relic” interpretations:**
- aged population of shock-accelerated electrons
- populations of several shock-compressed radio ghosts (aged radio lobes)

→ polarization is key to differentiate

• asterisks denote spectrum of the radio relic with $\alpha_\nu \sim 1.5$
• filled circles that of “radio halo” with $\alpha_\nu \sim 2.1$