Particle Acceleration and Radiation from Galaxy Clusters

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in collaboration with

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Cosmological simulations with cosmic rays
- Motivation and observations
- Cosmological galaxy cluster simulations
- Non-thermal processes in clusters

Gamma-ray emission from clusters
- Spectra and morphology
- Predictions for Fermi and IACT’s
- MAGIC observations of Perseus

Diffuse radio emission in clusters
- The cosmic magnetized web
- Properties of cluster magnetic fields
- Cluster turbulence
Outline

1. Cosmological simulations with cosmic rays
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Cosmological structure formation shock physics complementary to interplanetary and SNR shocks:

- probing unique regions of DSA parameter space:
  - Mach numbers $\mathcal{M} \sim 2 \ldots 10$ with ‘infinitely’ extended (Mpc) and lasting (Gyr) shocks (observationally accessible @ $z = 0$)
  - plasma-$\beta$ factors of $\beta \sim 10^2 \ldots 10^5$

- origin and evolution of large scale magnetic fields and nature of turbulent models in a ‘cleaner environment’ (1-phase medium)

- 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
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.)
Radiative simulations with GADGET – flowchart

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

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

CP, Enßlin, Springel (2008)
Diffusive shock acceleration – Fermi 1 mechanism (1)

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

\[
\log f \quad \text{keV} \quad 10 \text{ GeV} \quad \log p
\]
CR proton energy injection efficiency, \( \zeta_{\text{inj}} = \frac{\varepsilon_{\text{CR}}}{\varepsilon_{\text{diss}}} \):

\[
\begin{align*}
\text{Mach number } \mathcal{M} \\
\infty & & 3 & & \sqrt{5} & & \sqrt{11/3} & & \sqrt{3} \\
\text{CR energy injection efficiency } \zeta_{\text{inj}} \\
\end{align*}
\]

- \( kT_2 = 10 \text{ keV} \)
- \( kT_2 = 0.3 \text{ keV} \)
- \( kT_2 = 0.01 \text{ keV} \)
Radiative cool core cluster simulation: gas density

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

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

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

\[ \times 10^n \]

\[ \times 10^{n+1} \]

\[ \times 10^{n+2} \]

\[ \times 10^{-1} \]

\[ \times 10^{0} \]

\[ \times 10^{1} \]

\[ \times 10^{2} \]
Mass weighted temperature

\[ \langle T \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle \, [K] \]
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Mach number distribution weighted by $\varepsilon_{\text{CR, inj}}$
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CR pressure $P_{CR}$

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

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

\[ \rho_{\text{gas}} \]

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

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

\[ 10^{-15} \quad 10^{-10} \quad 10^{-5} \quad 10^0 \quad 10^5 \quad 10^{10} \]

\[ 10^{-15} \quad 10^{-10} \quad 10^{-5} \quad 10^0 \quad 10^5 \quad 10^{10} \]

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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

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

hadronic reaction
Multi messenger approach for non-thermal processes

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

hadronic reaction
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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 ($\nu \sim (15 - 240)$ MHz)
- Simbol-X/NuSTAR: future hard X-ray satellites ($E \sim (1 - 100)$ keV)
- Fermi $\gamma$-ray space telescope ($E \sim (0.1 - 300)$ GeV)
- Imaging air Čerenkov telescopes ($E \sim (0.1 - 100)$ TeV)
Non-thermal emission from clusters
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CR proton and $\gamma$-ray spectrum (Pinzke & CP 2009)
Hadronic $\gamma$-ray emission, $E_\gamma > 100$ GeV

$S_\gamma(E_\gamma > 100 \text{ GeV}) \left[ \text{ph cm}^{-2} \text{s}^{-1} \right]$

$10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$

$x$ [Mpc] $y$ [Mpc]

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

Spectra and morphology
Predictions for Fermi and IACT's
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Total $\gamma$-ray emission, $E_{\gamma} > 100$ GeV

\begin{align*}
S_{\text{total}} (E_{\gamma} > 100 \text{ GeV}) \, [\text{ph cm}^{-2} \text{s}^{-1}] \\
10^{-12} &< 10^{-11} < 10^{-10} < 10^{-9} < 10^{-8}
\end{align*}
Correlation between thermal X-ray and $\gamma$-ray emission

Correlation with pion decay/sec. IC emission, X-ray and secondary emission $\propto n^2$
(CP, Enßlin, Springel 2008)

Correlation with primary IC emission, correlation space substructure
$\rightarrow$ oblique curved shocks; $B$-generation!
Photon index $\Gamma$ - variations on large scales

$\Gamma_{100 \text{ MeV}}^{1 \text{ GeV}}$ (Fermi): pion bump (center)
transition to pIC (strong accretion shocks)

$\Gamma_{100 \text{ MeV}}^{1 \text{ TeV}}$ (IACT's): pion-decay (center)
pIC (accretion shocks, cutoff $E_{\text{max}}$)
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Universal CR spectrum in clusters

Normalized CR spectrum shows universal concave shape → governed by hierarchical structure formation and the implied distribution of Mach numbers that a fluid element had to pass through in cosmic history (Pinzke & CP 2009).
Cosmological simulations with cosmic rays
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An analytic model for the cluster $\gamma$-ray emission
Comparison: simulation vs. analytic model, $M_{\text{vir}} \simeq (10^{14}, 10^{15}) M_\odot$

Spatial $\gamma$-ray emission profile

Pion decay spectrum

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Gamma-ray scaling relations

Scaling relation + complete sample of the brightest X-ray clusters (HIFLUGCS) $\rightarrow$ predictions for Fermi and IACT's
Cosmological simulations with cosmic rays
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Predicted cluster sample for *Fermi* and IACT’s

black: optimistic model, including galactic ‘point sources’ that bias γ-ray flux high; red: realistic model, excluding galactic ‘point sources’
Predicted cluster sample for *Fermi* – brightest objects
MAGIC observations of Perseus
Upper limit on the TeV \( \gamma \)-ray emission from Perseus

assuming $f \propto p^{-\alpha}$ with $\alpha = 2.1$, $P_{\text{CR}} \propto P_{\text{th}}$:
$E_{\text{CR}} < 0.017E_{\text{th}} \rightarrow$ most stringent constraint on CR pressure!

upper limits consistent with cosmological simulations:
$F_{\text{upper limits}}(100\text{GeV}) = 3.5 F_{\text{sim}}$ (optimistic model)

simulation modeling of pressure constraint yields
$\langle P_{\text{CR}} \rangle / \langle P_{\text{th}} \rangle < 0.07 (0.14)$ for the core (entire cluster)

3 physical effects that resolve the apparent discrepancy:
- concave curvature ‘hides’ CR pressure at GeV energies
- galactic ‘point sources’ bias $\gamma$-ray flux high and pressure limits low (partly physical)
- relative CR pressure increases towards the outer parts (adiabatic compression and softer equation of state of CRs)
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Minimum $\gamma$-ray flux in the hadronic model

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

![Graph showing $j_{\nu}(B)/j_{\nu}(B_{\text{CMB}})$ vs. $B$ in $\mu G$.]

Synchrotron luminosity:

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

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

$\gamma$-ray luminosity:

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

$\rightarrow$ minimum $\gamma$-ray flux:

$$F_{\gamma,\text{min}} = \frac{A_{\gamma}}{A_{\nu}} \frac{L_{\nu}}{4\pi D^2}$$
Minimum $\gamma$-ray flux in the hadronic model

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

Synchrotron luminosity:

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

$$\rightarrow A_\nu \int dV n_{\text{CR}} n_{\text{gas}} \left( \varepsilon_B \gg \varepsilon_{\text{CMB}} \right)$$

$\gamma$-ray luminosity:

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

$\rightarrow$ minimum $\gamma$-ray flux:

$$F_{\gamma,\text{min}} = \frac{A_\gamma}{A_\nu} \frac{L_\nu}{4\pi D^2}$$
Minimum $\gamma$-ray flux in the hadronic model: *Fermi*

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

<table>
<thead>
<tr>
<th>CR spectral index</th>
<th>2.0</th>
<th>2.3</th>
<th>2.6</th>
<th>2.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_\gamma$ [$10^{-10}$ ph cm$^{-2}$ s$^{-1}$]</td>
<td>0.8</td>
<td>1.6</td>
<td>3.4</td>
<td>7.1</td>
</tr>
</tbody>
</table>

- These limits can be made even tighter when considering energy constraints, $P_B < P_{\text{gas}}/30$ and $B$-fields derived from Faraday rotation studies, $B_0 = 3 \, \mu\text{G}$:
  
  $$F_{\gamma,\text{COMA}} \gtrsim (1.1 \ldots 1.5) \times 10^{-9} \gamma \text{ cm}^{-2} \text{ s}^{-1} \lesssim F_{\text{Fermi}}, \text{2yr}$$

- Non-detection by Fermi seriously challenges the hadronic model.

- Potential of measuring the CR acceleration efficiency for diffusive shock acceleration.
Minimum $\gamma$-ray flux in the hadronic model: IACT’s

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

<table>
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<th>$\mathcal{F}_\gamma$ [$10^{-14}$ ph cm$^{-2}$s$^{-1}$]</th>
</tr>
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<tbody>
<tr>
<td>2.0</td>
<td>20.2</td>
</tr>
<tr>
<td>2.3</td>
<td>7.6</td>
</tr>
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<td>2.9</td>
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</table>

These limits can be made even tighter when considering energy constraints, $P_B < P_{gas}/30$, FRM $B$-fields with $B_0 = 3$ $\mu$G, and $\alpha_p < 2.3$ (caution: this assumes a power-law scaling):

$\mathcal{F}_{\gamma,COMA} \gtrsim (5.3 \ldots 7.6) \times 10^{-13} \gamma$ cm$^{-2}$s$^{-1}$

Potential of measuring the CR spectrum, the effective acceleration efficiency for diffusive shock acceleration, and relate this to the history of structure formation shock waves (Mach number distribution).
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Cosmic web: Mach number

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Radio gischt (relics): primary CRe (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 CRe
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 $\rightarrow$ relic luminosity function

radio map with GMRT emissivity threshold

“theoretical” threshold (towards SKA)
Relic luminosity function is very sensitive to large scale behavior of the magnetic field and dynamical state of cluster:

varying magnetic decline with radius

varying overall normalization of the magnetic field
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.
Conclusions

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 diffusive shock acceleration!

1. Universal distribution of CR protons determined by maximum shock acceleration efficiency $\zeta_{\text{max}}$ and adiabatic transport: mapping between the hadronic $\gamma$-ray emission and $\zeta_{\text{max}}$ → cosmological simulations are indispensable for exploring this (non-linear) map → spectral shape illuminates the process of structure formation

2. Primary radio (gischt) emission traces the magnetized cosmic web; sensitive to electron acceleration efficiency → Faraday rotation on polarized Mpc-sized relics allows determining the nature of the intra-cluster turbulence
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