The quest for high-energy \(\gamma\)-ray emission from galaxy clusters

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in collaboration with

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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

red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

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High-energy $\gamma$-ray emission from galaxy clusters
Cosmological hydrodynamical simulations are indispensable for understanding non-thermal processes in galaxy clusters → illuminating the process of structure formation

2 Predicted sample and properties of $\gamma$-ray clusters for GLAST and IACTs

3 Multi-messenger approach including radio synchrotron, hard X-ray IC, and HE $\gamma$-ray emission:
   - fundamental plasma physics: diffusive shock acceleration, large scale magnetic fields, and turbulence
   - nature of dark matter
   - gold sample of cluster for precision cosmology
Radiative simulations with CR physics

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

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

Loss processes: red
Gain processes: green
Observables: yellow
Populations: blue

Cosmic rays from structure formation shocks
Properties of γ-ray emission from clusters
Towards a holistic view on non-thermal processes
Cosmic rays from structure formation shocks
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Radiative cool core cluster simulation: gas density

$\langle 1 + \delta_{\text{gas}} \rangle$

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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 \( \varepsilon_{\text{diss}} \)

\[ \langle \dot{M}_{\varepsilon_{\text{diss}}} / \langle \dot{\varepsilon}_{\text{diss}} \rangle \rangle \]
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Mach number distribution weighted by $\varepsilon_{\text{CR, inj}}$

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CR pressure $P_{CR}$

![Image of CR pressure map with scale and units]

$\langle P_{CR} \rho_{\text{gas}} \rangle / \langle \rho_{\text{gas}} \rangle [\text{erg cm}^{-3} h_{70}^{2}]$

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Thermal X-ray emission

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Hadronic $\gamma$-ray emission, $E_\gamma > 100$ MeV
Cosmic rays from structure formation shocks
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Inverse Compton emission, $E_{IC} > 100$ MeV

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High-energy $\gamma$-ray emission from galaxy clusters
Total γ-ray emission, $E_\gamma > 100$ MeV

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Correlation between thermal X-ray and $\gamma$-ray emission

Correlation with pion decay/sec. IC emission,
merging cluster, $M_{\text{vir}} \sim 10^{15} M_{\odot} / h$

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

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High-energy $\gamma$-ray emission from galaxy clusters
Gamma-ray scaling relations

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

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Predicted cluster sample for GLAST

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

- $F_\gamma [\gamma \text{ cm}^{-2} \text{ s}^{-1}]$

Clusters:
- Ophiuchus, Fornax
- Coma
- A3627
- A1060
- M49
- AWM7
- NGC4636
- Perseus, Centaurus
- M75
- Triangulum

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Universal CR spectrum in clusters

Preliminary: normalized CR spectrum shows universal concave shape → governed mainly by hierarchical structure formation and adiabatic CR transport processes. (Pinzke & Pfrommer, in prep.)
Radiative cool core cluster simulation: gas density
Mass weighted temperature

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

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

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

\[ 10^8 \]

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High-energy \( \gamma \)-ray emission from galaxy clusters
Mach number distribution weighted by $\varepsilon_{\text{diss}}$
Hadronic $\gamma$-ray emission, $E_\gamma > 100$ GeV
Inverse Compton emission, $E_{\text{IC}} > 100$ GeV
Total $\gamma$-ray emission, $E_\gamma > 100$ GeV

$S_\gamma(100 \text{ GeV}, 100 \text{ TeV}) \left[ \gamma \text{ cm}^{-2} \text{s}^{-1} h_{70}^{-3} \right]$
Cosmic rays from structure formation shocks
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Photon index $\Gamma = 1.0$ for $1 \text{ TeV}$ and $100 \text{ GeV}$

$\alpha_{2D}$ (100 GeV, 1 TeV)

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

$\Gamma = \alpha + 1$ is the photon index.

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High-energy $\gamma$-ray emission from galaxy clusters
Smooth variation of $\Gamma$: inner parts dominated by pion decay, transition to primary IC from formation shocks at cluster periphery and WHIM

$\rightarrow$ bright prospects for DM annihilation! (Pinzke & Pfrommer, in prep.)
Cosmic rays from structure formation shocks
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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
- 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

High-energy $\gamma$-ray emission from galaxy clusters
Synchrotron emissivity of high-energy, steady state electron distribution is independent of the magnetic field for $B \gg B_{\text{CMB}}$!

**Synchrotron luminosity:**

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

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

**$\gamma$-ray luminosity:**

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

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

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

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>$\mathcal{F}_\gamma [10^{-10} \gamma cm^{-2} s^{-1}]$</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, $P_B < P_{\text{gas}}/20$ and $B$-fields derived from Faraday rotation studies, $B_0 = 3 \, \mu\text{G}$:
  $$\mathcal{F}_{\gamma, \text{COMA}} \gtrsim 2 \times 10^{-9} \gamma cm^{-2} s^{-1} = \mathcal{F}_{\text{GLAST}, 2\text{yr}}$$

- Non-detection by GLAST seriously challenges the hadronic model.
Cosmological hydrodynamical simulations are indispensable for understanding non-thermal processes in galaxy clusters → illuminating the process of structure formation

Brightest $\gamma$-ray clusters for GLAST and IACTs: Ophiuchus, Fornax, Coma, Norma, Perseus, Centaurus

Multi-messenger approach including radio synchrotron, hard X-ray IC, and HE $\gamma$-ray emission:
- fundamental plasma physics: diffusive shock acceleration, large scale magnetic fields, and turbulence
- nature of dark matter
- gold sample of cluster for precision cosmology


Pinzke, Pfrommer, in prep.

Pfrommer, Battaglia, Pinzke, in prep.