Non-thermal Emission in Galaxy Clusters: from Radio to Gamma-Rays

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In collaboration with Francisco Prada (IAA-CSIC, IFT-UAM/CSIC), Christoph Pfrommer (HITS) and others

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OUTLINE

• Galaxy Clusters and their Non-thermal Emission
• Cosmic Rays (CR) and Dark Matter (DM)
• Gamma-ray MAGIC Observations of Perseus
• Future Prospects & Work
Clusters of Galaxies

Largest gravitationally bound systems in the Universe with mass of $10^{14} - 10^{15} \, M_\odot$ and radius of few Mpc

Actively evolving objects

Cosmic energy reservoirs

Expected to contain substantial populations of CRs and DM

Powerful cosmological tools to test models on the origin and evolution of the Universe

Can generate non-thermal emission from radio to gamma-ray frequencies

via thermal X-ray emission and Sunyaev-Zel’dovich (SZ) effect

27/09/2012 Fabio Zandanel (IAA-CSIC)
Non-thermal Diffuse Radio Emission

Diffuse radio synchrotron emission is observed in many clusters probing the presence of relativistic electron populations permeating the ICM.

Radio Relics
- at the cluster periphery
- irregular morphology
- highly polarized
- seems to trace structure formation shocks

Radio (Mini-)Halos (RHs)
- at the cluster center
- regular morphology
- un-polarized
- similar to thermal X-ray emission

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CIZA J2242.8+5301
van Weeren et al. (2010)

Coma
Giant Radio Halo
(size is ≈ 2 Mpc)
Deiss et al. (1997)

thermal X-ray
ROSAT/PSPC
CRs in Clusters – Processes & Emission

from Pfrommer et al. 2008

energy and particle sources

structure formation

AGNs and supernovae

acceleration processes

turbulence

Shock waves

relativistic populations

CR electrons re-acceleration

primary CR electrons

from Pfrommer et al. 2008
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Expected emission

Synchrotron radio

IC hard X-ray and gamma-ray
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HADRONIC INTERACTIONS

AGNs and supernovae

CR protons

from Pfrommer et al. 2008

primary CR electrons

secondary CR electrons

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γ0

gamma-ray
RH Models – How to discriminate?

**HADRONIC MODEL**
Radio emitting electrons produced in CR pp hadronic interactions with the ICM (e.g. Enßlin et al. 2011)

π⁰ decay directly to gamma-rays “not” predicted by re-acceleration model (or at a much lower level, see e.g. Brunetti et al. 2012)

**RE-ACCELERATION MODEL**
Electrons accelerated during powerful states of ICM turbulence as after a merger (e.g. Brunetti & Lazarian 2011)

radio population studies but large samples are needed \(\rightarrow\) LOFAR survey

observations with IACTs and *Fermi*
Direct products of DM annihilation or decay are model dependent. However, the decay and hadronisation of these products result (among others) in gamma-rays. A peculiar gamma-ray spectrum, a smoking gun for DM.
Why Clusters?

The Milky Way center and dwarf spheroidal satellite (dSph) galaxies are “classic” targets; clusters have recently attracted the attention of DM seekers: **80% of their mass is DM** and we expect **very high fluxes** from them.

DM Density and Density Squared All-Skymaps **freely available on-line** at http://www.clues-project.org/articles/darkmattermaps.html.

**Cuesta, Jeltema, FZ, Profumo et al. (2010)**
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Sanchez-Conde, Cannoni, FZ, Gomez & Prada (2011)
[see also Pinzke, Pfrommer & Bergstrom (2011)]
Gamma-rays are detected by recording the images created on a PMT pixelized camera by the Cherenkov light produced in the particle cascades induced in the atmosphere by CRs from space.
The MAGIC Telescopes

Major Atmospheric Gamma Imaging Cherenkov

• Cameras FoV: 3.5 deg
• Energy Threshold: 50 GeV
• Angular Resolution: 0.1 deg @ 300 GeV
• Energy Resolution: 15% @ 1 TeV
• Sensitivity: 0.7% Crab Nebula (>600 GeV, 5σ in 50 h)
Perseus Galaxy Cluster

• $M = 7.7 \times 10^{14} \, M_\odot$
• $D = 77.7 \, \text{Mpc} \,(z = 0.018)$
• Brightest X-ray cluster in the sky
• Massive central cooling flow
• Radio mini-halo

• Hydrodynamic simulations of Pinzke & Pfrommer (2010) indicate it as best target for gammas from CR interactions with ICM

• 80% of cluster mass is DM, good target for DM indirect searches

• Central radio galaxy NGC1275
MAGIC-I Observation

“MAGIC Gamma-ray Telescope Observation of the Perseus Cluster of Galaxies: Implications for Cosmic rays, Dark Matter and NGC1275”
Aleksić et al. (FZ & Pfrommer as corresponding authors)
APJ 710, 634, 2010

• No excess found in 25 hours (Nov – Dec 2008)
• Only upper limits

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$F_{UL} \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$</th>
</tr>
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<tbody>
<tr>
<td>-1.5</td>
<td>4.63</td>
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<tr>
<td>-2.2</td>
<td>6.55</td>
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<tr>
<td>-2.5</td>
<td>7.52</td>
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</table>
**DM-induced emission**

considering one of the most optimistic model as in Sanchez-Conde et al. (2007) in the mSUGRA scenario

\[ F_{\text{TH}} (> 100 \text{ GeV}) \approx 1.4 \times 10^{-16} \text{ cm}^{-2} \text{s}^{-1} \]

\[ F_{\text{UL}} (> 100 \text{ GeV}) = 4.63 \times 10^{-12} \text{ cm}^{-2} \text{s}^{-1} \]

\[ \rightarrow \text{ need boost factor of the order of } 10^4 \]

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**CR-induced emission**

Upper limits are a factor of 2 higher than prediction which permit to constrain the CR-to-thermal pressure to < 4% - 8%
The STEREO observation campaign during 2009 – 2011 had given a very profitable scientific outcome:

“Detection of VHE gamma-ray emission from the Perseus cluster head-tail galaxy IC310”
Aleksić et al. (Sitarek, FZ & Lombardi)

“Detection of VHE gamma-ray emission from NGC1275 with the MAGIC telescopes”
Aleksić et al. (Lombardi, Colin, Hildebrand & FZ)
A&A 539, L2, 2012

“Constraining Cosmic Rays and Magnetic Fields in the Perseus Galaxy Cluster with TeV observations by the MAGIC telescopes”
Aleksić et al. (FZ, Pfrommer, Colin, Pinzke & Lombardi)
MAGIC Stereo Observation – IC310 & NGC1275

**IC310**
- 40 hours (Oct 2009 – Feb 2010)
- Very hard spectrum $\Gamma \approx -2$
- Year to month-scale variability
- Emission very likely located in the inner part of the jet

**NGC1275**
- 46 hours (Aug 2010 – Feb 2011)
- Spectrum $\Gamma \approx -4$, no emission above 600 GeV
- *Fermi* + MAGIC results suggest cutoff around tens of GeV
MAGIC Stereo Observation

Total of 85 hours of data from Oct 2009 to Feb 2011
Deepest cluster observation at very high energy ever

Constraints on CRs and magnetic fields above 630 GeV
DM analysis left for future work
Simulation predictions are constrained for the first time
the maximum CR acceleration efficiency at shocks is < 50%
OR
significant CR propagation out of the cluster core

CR models from Pinzke & Pfrommer (2010)
Assuming the hadronic model valid, constraints on the magnetic field can be obtained.

Minimum magnetic field, $B_{0,min}$ [$\mu$G]:

<table>
<thead>
<tr>
<th>$\alpha_B$</th>
<th>-2.1</th>
<th>-2.2</th>
<th>-2.3</th>
<th>-2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
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<td>0.5</td>
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<tr>
<td>0.7</td>
<td>13.1</td>
<td>9.16</td>
<td>7.08</td>
<td>4.68</td>
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</table>
We build a mock galaxy cluster catalog from the MDR1 N-body simulation by adopting a phenomenological gas density model for each cluster based on X-ray measurements that matches SZ and X-ray scaling relations and luminosity function.

Radio-emitting electrons are generated in hadronic CR-ICM proton interactions and our CR model derives from cosmological hydrodynamical simulations of cluster formation and additionally accounts for CR transport.

tons of clusters: 109997 halos above $10^{13} \, M_\odot$, 88 above $10^{15} \, M_\odot$

"On the Physics of Radio Halos: Scaling Relations and Luminosity Functions"
FZ, Pfrommer & Prada
submitted, ArXiv:1207.6410

freely available on-line at www.multidark.org
LOFAR Tier 1 at 120 MHz should detect about 3500 RHs above 0.5 mJy, under this model assumptions.
Conclusions and Future Work

• Perseus: deepest observation (85 hours) ever of a galaxy cluster at very high energies

• Detection of IC310 and NGC1275 galaxies

• For the first time, constraints on the physics of cluster hydrodynamic simulations: the maximum CR acceleration efficiency must be <50% or presence of significant CR propagation out of the cluster core

• CR-to-thermal pressure constrained to be less than few percents

• Assuming the hadronic model valid, $B_0 \geq 4 - 9 \mu G$

• DM boost factor constrained to $\leq 10^4$ with MAGIC-I observations

• Multi-frequency cluster mock catalogs reproducing observations (will be freely available on-line), hybrid hadronic model with effective CR transport parameterization reproducing observed characteristics of RHs $\rightarrow$ radio & gamma-ray predictions
Conclusions and Future Work

**Future Work**

- Further MAGIC (IACTs) observations of Perseus (clusters)
- Improve DM analyses
- Feasibility studies for CTA
- Further work on the hadronic model and CR transport
- Cluster population studies with future LOFAR survey sample
- Mock Catalogs + synergy with X-ray cluster samples (eROSITA)
Thanks!