The Quest for Gamma-rays in Cluster of Galaxies

Simulations and Observations

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OVERVIEW

• Motivation: Gammas in Clusters
• Constrained Simulations
• *Fermi*-LAT All-Sky Maps
• MAGIC Observations of the Perseus Galaxy Cluster
• Future Work
Cluster of Galaxies

Largest gravitationally bound systems in the Universe!

Typical mass of $10^{14} - 10^{15} \, M_\odot$, radius of few Mpc and distance of 100 Mpc

They are expected to contain substantial populations of cosmic-rays (CR) which acceleration through the cluster environment can yield a significant $\gamma$-ray emission

About 80% of their mass is in form of dark matter (DM), therefore, clusters are good candidates where to search for a DM-induced $\gamma$-ray emission
Motivation: Dark Matter

EVIDENCES

Rotational Curves

Lensing

Bullet Cluster

CMB Anisotropies

ΛCDM

73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.
Motivation: Dark Matter

EVIDENCES

We do not know what DM is... BUT we know that the DM particle should:

• be **NOT – BARYONIC**
• be **COLD**, i.e. non-relativistic speeds
• have **NEUTRAL ELECTRICAL** and **COLOUR CHARGES**
• interact only via **GRAVITATIONAL** and **WEAK** forces
• be **MASSIVE** enough to account for the total matter content
• has **LONG-LIFE** to be present since the early Universe
• be consistent with present observations and constraints

WIMPs: Weakly Interacting Massive Particles
Direct products of decay or annihilation of DM particles are model dependent. HOWEVER, the decay and hadronisation of these products result in [...] γ-rays:

\[ \Phi(E > E_0) = J(\Psi) \cdot \Phi^{PP}(E > E_0) \]

**ASTROPHYSICAL FACTOR:**
- DM distribution
- instrument PSF smearing

**PARTICLE PHYSICS FACTOR:**
- DM mass and cross section
- γ-ray spectrum
Constrained simulations are a particular case of cosmological N-body simulations in which observational data are used to set the initial conditions, reproducing in this way the main features visible on the sky such as the Virgo, Coma and Perseus clusters, and the Great Attractor \( \rightarrow \) we use that to obtain realistic all-sky DM maps of the Local Universe.

Klypin et al. 2003

\textbf{BOX } 160h^{-1} \text{Mpc} \text{ by A. Klypin [ART]}
DM decay “luminosity” all-sky map in Cartesian projection and galactic coordinates

\[ L_1 = \sum \frac{m_p}{4\pi d^2} \]

Cuesta et al. 2011
DM annihilation “luminosity” all-sky map in Cartesian projection and galactic coordinates

\[ L_i = \sum m_p \rho_i / 4\pi d_i^2 \]

Cuesta et al. 2011
**Fermi All-Sky DM Maps**

**THE SATELLITE**

- *Fermi* satellite was successfully launched on 11\textsuperscript{th} June 2008
- It constantly surveys the sky between 100 MeV and 300 GeV
- After 1 year of operation, more than 1400 point-like sources have been detected by LAT, while the previous γ-ray satellite, EGRET, discovered 270 sources in almost 10 years of operation!

*Fermi* is revolutionising our vision of the γ-ray Universe
The DM density and density-squared maps are taken as input for the \textit{Fermi} observation simulation tool to obtain 5-year observation photon count maps:

- we use the routine \texttt{gtobssim} of \textit{Fermi} Science Tool (v9r15p2)
- we consider the \textbf{real} instrument response function
- we take into account the extragalactic & galactic background as released by the \textit{Fermi} collaboration

Running the \textit{Fermi} simulations, we also use as input \textbf{two different} DM particle physics models:

- 100 GeV \textit{neutralino}
  - b-bbar channel
  - SUSY “bino-like” LSP
  - $<\sigma v> = 1 \times 10^{-23}$ cm$^3$ s$^{-1}$
  - $\tau = 1 \times 10^{26}$ s

- 1.6 TeV particle
  - $\mu^+\mu^-$ channel
  - fits PAMELA $e^\pm$ data
  - $<\sigma v> = 5.8 \times 10^{-23}$ cm$^3$ s$^{-1}$
  - $\tau = 3 \times 10^{26}$ s
By running *Fermi* observation simulation (5-year survey) we properly take into account the **REAL** backgrounds and instrument response → **S/N maps**

*Cuesta et al. 2011*
By running *Fermi* observation simulation (5-year survey) we properly take into account the REAL backgrounds and instrument response → **S/N maps**

**DM annihilation (b-bbar channel)**

*Cuesta et al. 2011*
The most promising clusters for DM studies are the ones at high-galactic latitude (e.g. Virgo, Coma)

**DM Decay:**
- nearby clusters and filamentary regions could be detected by *Fermi* in a 5-year survey and the satellite can improve the present DM decay constraints (e.g. recent Dugger, Jeltema, Profumo 2010)
- S/N is not very sensitive to the area of the region under analysis, making possible analysis of few-degrees areas (masking away the point-like sources)
- filamentary structure of the cosmic web constitutes a new interesting target for DM indirect searches: this is the first time that filaments are considered as DM targets

**DM Annihilation:** we did not found strong evidences in favour of an extra-galactic detection, but we cannot exclude this possibility considering that we are not using any type of boost factor!
The density and density-squared maps are available on-line in fits format:

http://www.clues-project.org/articles/darkmattermaps.html

you are strongly encouraged to use it!

20/01/2011

Fabio Zandanel (IAA - CSIC)
MAGIC stays for **Major Atmospheric Gamma Imaging Cherenkov**

It detects γ-rays by recording the images created on a PMT pixelized camera by the Cherenkov light produced in the particle cascades (air showers) induced in the atmosphere by cosmic-rays from space...
• Cameras FoV: 3.5 deg
• Angular Resolution: 0.06 deg
• Energy Threshold: 50 GeV
• Energy Resolution: 15% above 300 GeV
• Sensitivity: 0.8% Crab Nebula (5σ in 50 h)
• Angular Resolution: 0.1 deg
• Energy Threshold: 60 GeV
• Energy Resolution: 25%
• Sensitivity: 1.6% Crab Nebula
PERSEUS characteristics:

- Mass is $M = 7.7 \times 10^{14} M_\odot$
- Distance is 77.7 Mpc ($z = 0.018$)
- Brightest X-ray cluster in the sky
- Massive central cooling flow
- Radio mini-halo (diffuse synchrotron emission)
- Central radio galaxy NGC1275

Interest triggered by DM, CR and central AGN

Sijbring 1993
“MAGIC Gamma-ray Telescope Observation of the Perseus Cluster of Galaxies: Implications for Cosmic rays, Dark Matter and NGC1275”
Aleksić et al. APJ 710, 634, 2010

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

<table>
<thead>
<tr>
<th>Integral flux upper limits above 100 GeV</th>
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<tbody>
<tr>
<td>$\Gamma$</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>-1.5</td>
</tr>
<tr>
<td>-2.2</td>
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<tr>
<td>-2.5</td>
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</tbody>
</table>
\[ \Phi(E > E_0) = J(\Psi) \cdot \Phi^{PP}(E > E_0) \]

ASTROPHYSICAL FACTOR:
- NFW profile
- \( M = 7.7 \times 10^{14} \text{M}_\odot \)
- \( c = 6 \) (Bullock et al. 2001)

PARTICLE PHYSICS FACTOR: one of the most optimistic model as in Sánchez-Conde et al. (2007), in the minimal super-symmetric model (MSSM) scenario

\[
\begin{align*}
F_{TH}(> 100 \text{ GeV}) &\approx 1.4 \times 10^{-16} \text{ cm}^{-2}\text{s}^{-1} \\
F_{UL}(> 100 \text{ GeV}) &= 4.63 \times 10^{-12} \text{ cm}^{-2}\text{s}^{-1}
\end{align*}
\]

Boost factors of the order of \(10^4\) are needed to match the typically expected DM \(\gamma\)-ray flux
Motivation: Cosmic Rays

CLUSTER PARTICLE ACCELERATION

energy (and particle) sources
structure formation
AGNs and supernovae
acceleration process
CR protons
relativistic populations
HADRONIC INTERACTIONS WITH ICM
emission
primary CR electrons
synchrotron radio
IC hard X-ray and γ-ray
secondary CR electrons
π^0
γ-ray

20/01/2011
Fabio Zandanel (IAA - CSIC)
We used the clusters cosmological simulation of *Pfrommer et al. (2008)* to predict γ-ray emission from clusters and select our target (*Perseus*). The simulation principally includes diffuse shock acceleration and supernovae injection.

**Gamma-ray luminosity is dominated by the pion-decay induced emission**

The emission is enhanced in cool-core clusters (as Perseus)

*Aleksić et al. 2010*
MAGIC (integral) flux upper limits are a factor of 2 higher than the most optimistic CR emission model.

Minimum $\gamma$-ray flux: at this level a negative detection seriously challenges the hadronic model for radio halos.

Aleksić et al. 2010

CR models as in Pinzke & Pfrommer (2010)
NEW STEREO Observation of Perseus: IC310 detection!

“Detection of very high energy gamma-ray emission from the Perseus cluster head-tail galaxy IC310 by the MAGIC telescopes”

Aleksić et al. APJ Letters 723, 207, 2010

⇒ 40 hours of stereo data (Oct 2009 – Feb 2010)
Discovery of Very High Energy Gamma-Ray Emission from NGC1275 by MAGIC

ATel #2916; Mose Mariotti (INFN and Univ. of Padova) on behalf of the MAGIC Collaboration on 10 Oct 2010; 15:00 UT

Distributed as an Instant Email Notice (Request for Observations)
Password Certification: Mose Mariotti (mariotti@pd.infn.it)

Subjects: Gamma Ray, >GeV, TeV, VHE, AGN, Blazars, Cosmic Rays

The MAGIC Collaboration reports the detection of Very High Energy (VHE) gamma-ray emission from a position consistent with NGC 1275, the central radio galaxy of the Perseus cluster of galaxies.

The MAGIC observations were carried out in stereoscopic mode starting from August 2010, accumulating 14 h of good quality data. Preliminary analysis using the standard analysis chain with an energy threshold of 100 GeV, shows an excess of 280 gamma-rays, corresponding to a statistical significance of 5.2 standard deviations. The observed flux is estimated to be ~3% of the Crab nebula flux above 100 GeV, and it decreases rapidly with energy. No signal is detected above 400 GeV.

The MAGIC VHE detection happened during a period of increased high gamma-ray activity of NGC 1275, as reported in July 2010 by the Fermi/LAT collaboration, ATel#2737, and continuing until October, according to an analysis of public Fermi/LAT data. MAGIC will continue observations of NGC1275. Observations at other wavelengths are encouraged.

MAGIC consists of two 17m diameter imaging air Cherenkov telescopes located on La Palma, Canary Islands, Spain. Questions regarding the MAGIC observations should be directed to Mose Mariotti (mose.mariotti@pd.infn.it)
No gamma-ray emission was detected above 80 GeV in 24.4 hours of observation of the Perseus cluster.

First work where cluster cosmological simulations and observational results are combined.

DM boost factor constrained to $\leq 10^4$ (within the assumed particle physics model with the neutralino as DM particle, but no substructures...)

With a hundred hours of (stereo) observation we should be able to catch some CR-induced $\gamma$ or to seriously probe the hadronic model for radio halos ... Meanwhile, we detected IC310 and NGC1275!
The idea is to produce an all-sky map of the CR-induced $\gamma$-ray emission, as for the DM case, for the galaxy clusters (and groups) (approximately $M > 10^{13} \, M_\odot$) in the Local Universe.

We use the semi-analytical model of Pinzke & Pfrommer (2010). Using a "simple" formula, we can calculate the CR-induced $\gamma$-ray emission of any cluster, once we know its:

- mass, radius and distance
- gas density (radial distribution)
**Problem**: we have N-body simulations of the Local Universe, i.e. only DM is included, so how do we assign a baryon gas density distribution $\rho(r)$ to a DM-simulated cluster?

**Our Solution**: we construct a phenomenological model based on real data from the HIFLUGCS sample (Reiprich & Böringher 2002, Chen et al. 2007), so we can assign to each cluster of the simulation, the quantities needed to get $\rho(r)$, modeled as a $\beta$-profile

$$\rho(r) = \rho_0 \left(1 + \frac{r^2}{r_c^2}\right)^{-3\beta/2}$$

- $\beta = 1$ (to match outer NFW)
- $r_c - M_{\text{vir}}$ relation
- $\rho_0 - M_{\text{vir}}$ relation

**FROM REAL DATA**
To check if we reconstruct correctly the gas density profile, we calculate the thermal bremsstrahlung X-ray emission $L_X$ for the clusters in the simulation and compare it with the observed $L_X - M_{\text{vir}}$ relation (Reiprich & Böringher 2002).

We can safely apply it to the $\gamma$-ray emission and be confident that we will obtain realistic results!

**Work in Progress**
Simulations
Theory

- the DM analysis should be complemented with the *galactic* component
- the potential of clusters for DM searches will be study in detail
- *cosmic-ray induced γ-ray all sky maps* are under construction! following the same strategy, we will see what *Fermi* will be able to do with galaxy clusters and groups

Observations

- *MAGIC* is performing a deep (STEREO!!!) observation campaign of the Perseus cluster of galaxies as it is a promising target for DM indirect searches, CR induced emission, and it contains plenty of interesting objects ... *STAY TUNED!*
Thanks!