The Quest for Gamma-rays in Clusters of Galaxies

Simulations and Observations

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OVERVIEW

• Galaxy Clusters, Cosmic Rays and Dark Matter

• Emission Predictions using N-body Simulations

• MAGIC Observations of the Perseus Galaxy Cluster

• Future Prospects & Work
Cluster of Galaxies

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

Actively evolving objects

Cosmic energy reservoirs

Expected to contain substantial populations of cosmic rays (CR)

About 80% of their mass is in form of dark matter (DM)

can generate non-thermal emission from radio to gamma-ray frequencies
Cluster of Galaxies
SHOCKS, RADIO RELICS & (MINI-)HALOS

- Abell 3667
  - Röttigering (1997)

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

- Coma
  - Giant Radio Halo
    - (size is about 1 Mpc)
    - Deiss (Effelsberg)

- Perseus
  - Radio Mini - Halo
    - (size is about 200 kpc)
    - Pedlar et al. (1990)

- thermal X-ray
  - ROSAT/PSPC
  - CHANDRA
Cosmic Rays in Clusters
NON-THERMAL PROCESSES & EMISSION

energy and particle sources
acceleration processes
relativistic populations
expected emission

structure formation

AGNs and supernovae

CR protons

CR electrons
reacceleration

primary CR electrons

secondary CR electrons

synchrotron radio

IC hard X-ray and gamma-ray

gamma-ray

HADRONIC INTERACTIONS

from Pfrommer et al. 2008
Cluster cosmological simulations of *Pfrommer et al. (2008)* and *Pinzke & Pfrommer (2010)* reproduce the observed synchrotron radio (mini-)halo emission and predict the gamma-ray emission. The dominant component results from CR hadronic interactions.
In the last years, many evidences for DM existence have been accumulated (e.g. rotational curves, lensing, Bullet cluster, CMB anisotropies).

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

- be **NOT** - BARYONIC
- be **COLD** (non-relativistic when decoupling) or **WARM**
- have **NEUTRAL ELECTRIC** and **COLOR CHARGES**
- interact only via **GRAVITATIONAL** force

**WIMPs: Weakly Interacting Massive Particles**
Direct products of annihilation or decay of DM particles are model dependent, however, decay and hadronisation of these products result in:

- high-energy neutrinos
- relativistic electrons, protons and anti-particles
- $\gamma$-rays (via $\pi^0 \rightarrow \gamma \gamma$, internal bremsstrahlung, line emission)

and low-energy photons through the interaction of $e^-$ with $B$ (synchrotron), with interstellar material (bremsstrahlung), with CMB (inverse Compton).

The multi-wavelength interpretation of the non-thermal emission observed in clusters can put strong constraints on DM models (see e.g. Colafrancesco, Profumo & Ullio 2006; Pérez-Torres, Zandanel et al. 2009; Colafrancesco, Marchegiani & Giommi 2010).
The Milky Way center and dwarf spheroidal satellite galaxies are “classic” targets, but clusters have recently attracted the attention of DM astro-seekers: we expect very high fluxes from them!

Sanchez-Conde, Cannoni, Zandanel, Gomez & Prada (2011)

Pinzke, Pfrommer & Bergström (2011)
DM Gamma-ray Emission in the Local Universe

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

ASTROPHYSICAL FACTOR:
- DM distribution
- instrument PSF, \( \Delta E \), effective area

PARTICLE PHYSICS FACTOR:
- DM mass and cross section
- gamma-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. We use that to obtain realistic all-sky DM maps of the Local Universe.

Klypin et al. (2003)

BOX $160h^{-1}$ Mpc, $1024^3$ particles, ART

www.clues-project.org
Constrained Simulations
THE ALL-SKY DM MAPS

DM decay all-sky map in Cartesian projection and galactic coordinates

\[ \Sigma \frac{m_p}{4\pi d_i^2} \]

Cuesta, Jeltema, Zandanel et al. (2011)
DM \textit{annihilation} all-sky map in Cartesian projection and galactic coordinates

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

Cuesta, Jeltema, Zandanel et al. (2011)
**Fermi** satellite was successfully launched on 11\(^{th}\) June 2008.

- It constantly surveys the sky between 20 MeV and 300 GeV.
- After 1 year of operation, >1400 point-like sources have been detected by LAT, while EGRET discovered 270 sources in almost 10 years of operation!

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

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

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

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

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

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

Cuesta, Jeltema, Zandanel 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**
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*
- S/N is not very sensitive to the area of the considered region
- filamentary structure

**DM Annihilation:** we did not find 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

and you are strongly encouraged to use it!
The idea now is to calculate the CR-induced radio and gamma-ray emission of galaxy clusters and groups (approximately $M > 10^{13} M_\odot$) using N-body simulations of the Local Universe and adopting the hadronic model supported by simulations of Cosmic Rays in Clusters.

Pfrommer et al. (2008), Pinzke & Pfrommer (2010)

Secondary CRe (which dominates over the primary CRe) produce synchrotron radio emission and decay directly to gamma-rays.
We use the semi-analytical model of Pinzke & Pfrommer (2010). We can calculate the CR-induced radio and gamma-ray emission of any cluster, once we know its:

- mass, radius and distance
- gas density (radial distribution)

from N-body cosmological simulations
Cosmic Rays in Clusters

THE SIMULATION

MultiDark Run 1

Simulation (ART) with 2024$^3$ particles in a box of 1 $h^{-1}$ Gpc on a side done with WMAP5

Prada et al. (2011)

tons of clusters: 109997 halos above $10^{13}$ $M_\odot$, 88 above $10^{15}$ $M_\odot$
**Problem:** how do we assign a gas density $\rho(r)$ to halos?

**Solution:** we construct a phenomenological model based on real gas profiles from REXCESS (Croston et al. 2008) and we scale them at all masses using the observed $f_{\text{gas}}$-M relation (Sun et al. 2009).
To check if we reconstruct correctly enough the gas density profile, we calculate the thermal bremsstrahlung X-ray emission and compare it with the observations.

![Graph showing a scatter plot with a linear fit]

**OUR PHENOMENOLOGICAL MODEL**

Mantz et al. (2010)

**PRELIMINARY**

Zandanel et al., in prep.
To check if we reconstruct correctly enough the gas density profile, we calculate the thermal bremsstrahlung X-ray emission and compare it with the observations.

\[
\text{Log}(\frac{dn}{dL_{\text{X_{BOl}}}}) [\text{h}^5 \text{Mpc}^{-3} (10^{44} \text{ erg s}^{-1})]
\]

PRELIMINARY
Zandanel et al., in prep.

OUR PHENOMENOLOGICAL MODEL
Ebeling et al. (1997)
To check if we reconstruct correctly enough the gas density profile, we calculate the thermal bremsstrahlung X-ray emission and compare it with the observations.

Log\left( \frac{dn}{dL_{\chi_{\text{BOL}}}^2} \right) [h^5 \text{Mpc}^{-3} (10^{44} \text{ erg s}^{-1})^{-1}]$

$\text{from HIFLUGCS L-M relation (slope}=1.8) [\text{slope}_{\text{MANTZ}}=1.6]$

Ebeling et al. (1997)

PRELIMINARY
Zandanel et al., in prep.
To check if we reconstruct correctly enough the gas density profile, we calculate the thermal bremsstrahlung X-ray emission and compare it with the observations.

Reproducing correctly the thermal X-ray emission, we can safely apply our phenomenological gas model to obtain realistic radio and gamma-ray predictions.

WORK IN PROGRESS ...
MAGIC stays for **Major Atmospheric Gamma Imaging Cherenkov**

It detects gamma-rays by recording the images created on a PMT pixelized camera by the Cherenkov light produced in the particle cascades 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 CR, DM and central AGN
No excess found in 25 hours (Nov – Dec 2008)
Only upper limits
ASTROPHYSICAL FACTOR:
- NFW profile
- $M = 7.7 \times 10^{14} \, M_\odot$
- $c = 6$ (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

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

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

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

Boost factors of the order of $10^4$ are needed to match the typically expected DM gamma-ray flux
MAGIC (integral) flux upper limits are a factor of 2 higher than the CR emission model which permits to constrain the CR-to-thermal pressure to < 4% - 8%.

Minimum gamma-ray flux

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. (Sitarek, Zandanel & Lombardi as corresponding authors)
APJ Letters 723, 207, 2010

→ 40 hours of stereo data (Oct 2009 - Feb 2010)

SERENDIPITOUS DISCOVERY!
NEW STEREO Observation of Perseus: NGC1275 detection!

MAGIC Collaboration, ATel#2916

PRELIMINARY

+ NGC 1275
* IC 310

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

DM boost factor constrained to $\leq 10^4$

Upper limits on CR-induced emission are a factor of 2 higher than the CR emission model which permits to constrain the CR-to-thermal pressure of the cluster to $< 4\%$ for the cluster center and to $< 8\%$ for the whole cluster.

With a hundred hours of stereo observation we will be able to seriously probe the hadronic model for radio halos... Meanwhile, we detected IC310 and NGC1275!
Future Prospects & Work

Simulations
Theory
Phenomenology

Observations

• Nearby extragalactic objects are very promising targets for DM studies
• The CR-induced emission will be studied in detail using a large cluster sample from N-body simulations
• The DM and CR-induced emission have to be studied together and using a multi-wavelength approach
• MAGIC is performing a deep STEREO observation campaign of the Perseus cluster of galaxies
• Soon we will be able to probe the CR emission models... Stay tuned!
Final Remarks

All these efforts go in the direction of obtaining a complete and consistent picture of the non-thermal processes in galaxy clusters, of understanding the underlying plasma astrophysics, the nature of dark matter and the structure formation itself.
Thanks!