The Quest for Gamma-rays in Clusters of Galaxies

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OUTLINE

• The Latest & Largest Structures: Clusters of Galaxies

• Gamma-ray Emission from Structure Formation

• State-of-art of Observations

• Implications, Predictions & Future Prospects for CTA
Structure Formation

Non-baryonic Cold Dark Matter (DM) is the dominant matter in the Universe and drives the structure formation.

**Hierarchical Scenario:** structures grow via gravitational instability from initial small density fluctuations → large-scale structures grow through merging and accretion of smaller systems.

![SDSS Image](image1.png)

![Millennium Simulation Image](image2.png)
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 cosmic rays (CRs) and dark matter (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 effect
Observed Non-thermal Emission in Radio

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

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

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

Coma

Giant Halo
(size is ≈ 2 Mpc)
1.4GHz – Deiss et al. (1997)
CRs in Clusters – Processes & Emission

from Pfrommer et al. 2008

energy and particle sources

acceleration processes

relativistic populations

dependent on structure formation

- turbulence
- shock waves

AGNs and supernovae

expected emission

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AGNs and supernovae

structure formation

turbulence

primary CR electrons

shock waves
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CR protons

primary CR electrons

12/12/2013

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CR protons

primary CR electrons

secondary CR electrons

π^0

HADRONIC INTERACTIONS
CRs in Clusters – Processes & Emission

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energy and particle sources

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re-accelerated CR electrons

primary CR electrons

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π⁰
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HADRONIC INTERACTIONS

re-accelerated CR electrons

primary CR electrons

secondary CR electrons

expected emission

synchrotron radio

IC hard X-ray and gamma-ray

π^0

from Pfrommer et al. 2008
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HADRONIC INTERACTIONS

from Pfrommer et al. 2008

π^0

gamma-ray

from Pfrommer et al. 2008

from Pfrommer et al. 2008
“Reference” CR Model in Gamma-rays

Pinzke & Pfrommer (2010)

Most important energy and particle sources in the simulation are diffusive shock acceleration at cosmological structure formation shocks and supernovae injection.

Pion-decay dominates over primary and secondary IC emission.

This obeys to a universal CR spectrum and spatial distribution.

Characteristic pion-bump + spectral index of about 2.2 at TeV energies.
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Existing Gamma-ray Instruments

**Fermi-Large Area Telescope**

*NASA satellite*

- Constantly survey the sky (full coverage in 3 hours)
- 100 MeV – 300 GeV
- Angular resolution 0.1 deg @ 10 GeV
- Energy resolution 10% @ 10 GeV

**Imaging Atmospheric Cherenkov Telescopes**

- > 50 – 100 GeV
- Angular resolution 0.1 deg
- Energy resolution 15%

*Fermi 2-year skymap (Nolan et al. 2012)*
State of Art of Observations - IACTs

Best Constraints: **MAGIC observation campaign of the Perseus cluster of galaxies**

Total of 85 hours of data from Oct 2009 to Feb 2011

Deepest cluster observation ever at very high energy

MAGIC Coll. (2012) – FZ as corr. author
Predictions (Pinzke & Pfrommer 2010) were constrained for the first time
the maximum CR acceleration efficiency at shocks is < 50%
OR
significant CR propagation out of the cluster core

MAGIC Coll. (2012) – FZ as corr. author
Fermi Coll. stacked analysis of 50 HIFLUGCS clusters  
(arXiv:1308.5654)

maximum acceleration efficiency is $< 25\%$ + CR-to-thermal pressure $< 1.5\%$
State of Art of Observations - *Fermi*

*Fermi Coll.* stacked analysis of 50 HIFLUGCS clusters  
(arXiv:1308.5654)

see also Huber et al. (2013) and Prokhorov & Churazov (2013)
State of Art of Observations - *Fermi*

*Fermi* analysis of the Coma cluster of galaxies
FZ & Ando 2013, arXiv:1312.1493

Test different (diffuse) models:

- Point Source
- Disk
- Pinkze & Pfrommer (2010)
- FZ, Pfrommer & Prada (2012)
- Radio Relic template
- Ring-like template (Keshet et al. 2003)

→ NOT DETECTED (TS ≤ 2)
State of Art of Observations - *Fermi*

*Fermi* analysis of the *Coma* cluster of galaxies
FZ & Ando 2013, arXiv:1312.1493

- CR *protons* acceleration efficiency $< 15\%$
- CR *electrons* acceleration efficiency $< 1\%$
- CR-to-thermal pressure $< 1.5\%$
CR-to-thermal pressure < 1% ($\alpha_p = 2.1$) to < 10% ($\alpha_p = 2.5$)

Maximum CR proton acceleration efficiency << 50%

Gamma-ray Emission:

• CRp could have a very low acceleration efficiency

• CRp could diffuse/stream out of the cluster core

• CRp could have a different/varying spectral index

+ need to “match” the radio data where the magnetic field enters the game
Detectability – Predictions for CTA

Doro et al. (2013) for the CTA Collaboration – $\xi_p = 50\%$
Detectability – Predictions for CTA

Zandanel et al. (2013) - Mock Catalogs
Pinzke et al. (2011) - HIGFLUGCS - $\xi_p = 50\%$
Pinzke et al. (2011) - HIGFLUGCS - $\xi_p = 20\%$

$\log_{10} N(F_{>100\text{ GeV}})$

$\log_{10} F_{>100\text{ GeV}}$ [ph cm$^{-2}$ s$^{-1}$]

500 hr
100 hr
CTA 50 hr (5$\sigma$, PS)
What needs to be done now in CTA?

Model nearby clusters with available radio and X-ray data

Make detailed sensitivity study for CTA and select suitable targets

Promote clusters of galaxies as key science case (proprietary data), not only for CRs but also field galaxies and DM, within CTA and make sure that they are observed

→ Lots of science work to be done right now ←

Collaboration commitment is important as the required observation time is likely very high (> 100 hr)
Summary & Future Prospects

We **DO expect** CR protons to accumulate in clusters and electrons to be accelerated directly at accretion and merger shocks.

We **DO expect** a correspondent induced gamma-ray emission.

Emission may be much lower than thought before (CR acceleration efficiency, transport properties...)

**BEST SCENARIO** for CTA is to detect a handful of clusters.
Gamma-rays (*Fermi* & IACTs) are starting to put stringent constraints on various acceleration scenarios and on the CR content in clusters of galaxies. Detection of cluster gamma-ray emission would be a major scientific discovery!!!

Open up a new window to study:

- non-thermal processes in clusters
- high-energy physics in the largest structures
- DM, CR, ICM, and cluster magnetic field
- formation and evolution of clusters, and of the Universe itself
Thanks!