Gamma-ray Observations of Galaxy Clusters

Current constraints and future prospects

Fabio Zandanel

(Gravitation AstroParticle Physics Amsterdam)

TeV Particle Astrophysics 2016 – CERN – 12-16/09/2016
CLUSTERS OF GALAXIES

Largest gravitationally bound structures in the Universe with $10^{14} - 10^{15} \, M_\odot$ and Mpc radii

5% are galaxies, 15% is a hot (keV) gas, and 80% is dark matter

See Voit (2005) and Brunetti & Jones (2014) for reviews
NON-THERMAL PROCESSES

STRUCTURE FORMATION
- TURBULENCE (Fermi II)
- SHOCK WAVES (Fermi I)

OUTFLOWS FROM GALAXIES & AGN
- COSMIC-RAY PROTONS

HADRONIC INTERACTIONS
- RE-ACCELERATED ELECTRONS
- PRIMARY ELECTRONS
- SECONDARY ELECTRONS

SYNCHROTRON EMISSION
- INVERSE-COMPTON EMISSION
- GAMMA RAYS & NEUTRINOS

adapted from Pfrommer et al. (2008) – see Brunetti & Jones (2014) for a review

13/09/2016 Fabio Zandanel (GRAPPA) 3
SYNCHROTRON RADIO EMISSION

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

GIANT HALOS
COMA
1.4 GHz – Deiss et al. (1997)

MINI HALOS
PERSEUS
1.4 GHz – Pedlar et al. (1990)

• **Origin** of radio-emitting electrons and magnetic fields?

• **Contribution of** cosmic-ray protons?

• **Impact on cluster environment** \((P_{cr}/P_{th})\)?
WHERE WE STAND

SPACE-BASED OBSERVATIONS (~100 MeV – 100 GeV)

Reimer et al. (2003, EGRET); Fermi-LAT (2010a-b, 2014, 2015, 2016); Jeltema & Profumo (2011); Han et al. (2012); Ando & Nagai (2012); Brunetti et al. (2012); Huber et al. (2013); FZ & Ando (2014); Prokhorov & Churazov (2014); Vazza & Brüggen (2014); Griffin et al. (2014); Selig et al. (2015) [D$^3$Po]; Vazza et al. (2015)

GROUND-BASED OBSERVATIONS (>100 GeV)

Perkins et al. (2006); Perkins (2008); HESS Coll. (2009a-b, 2012); Domainko et al. (2009); Galante et al. (2009); Kiuchi et al. (2009); VERITAS Coll. (2009, 2012); MAGIC Coll. (2010, 2012, 2016)

Brunetti & Jones (2014)
WHY COMA AND PERSEUS!

Most massive and closest clusters hosting the brightest diffuse synchrotron radio emission

- Why Coma and Perseus
- Most massive and closest clusters hosting the brightest diffuse synchrotron radio emission
- Cool-core cluster merging cluster
- Coma
- 1.4 GHz – Deiss et al. (1997)
- Perseus
- 1.4 GHz – Pedlar et al. (1990)

- Pinzke & Pfrommer (2010)
- Note: cool-core = high ICM target density for p-p interactions

See also Kushnir & Waxman (2009), Pinzke et al. (2011), Brunetti et al. (2012), FZ et al. (2014), Vazza et al. (2016)
HESS and VERITAS OBSERVATIONS OF COMA

HESS Coll. (2009)

VERITAS Coll. (2012)

$P_{CR}/P_{TH} < 16\% \ (\alpha_p \approx 2.2) \rightarrow < 2\% \ \text{WITH FERMI}$

$B_0 > 2-5.5 \ \mu G$

SEE ALSO KESHEt et al. (2012/2014)
MAGIC OBSERVATIONS OF PERSEUS

250 HOURS OBSERVATIONS 2009-2014

(MAGIC Coll. 2010a-b, 2012a-b, 2014a-b; in collaboration with Pinzke & Pfrommer)

(MAGIC Coll. 2016) – P. Colin and FZ as Corr. Authors
MAGIC OBSERVATIONS OF PERSEUS

For $\alpha_p \leq 2.1$, hadronic origin of radio emission is excluded.

For $\alpha_p \approx 2.2$, limits imply $B_0 > 5–8 \mu G$.
4-YEAR COMBINED LIKELIHOOD OF 50 HI FLOGCS CLUSTERS

\[ \frac{P_{\text{CR}}}{P_{\text{TH}}} < 1.4\% + \text{EMISSION FROM A400, A1367, A3112} \]

FERMI Coll. (2014)

THE COMA CLUSTER

ANALYSIS OF 5.25-YEAR (Pass7rep) Fermi-LAT data

FZ & Ando (2014)

$P_{\text{CR}}/P_{\text{TH}} < 0.6-2.7\%$
THE COMA CLUSTER

Coma giant radio halo cannot be (uniquely) of hadronic origin

CR proton contribution to radio emission < 60%
THE COMA CLUSTER RELOADED

Things changed with **Pass8 Fermi-LAT data (6 years)**

**Low-significance residual emission**

**Bounds on CRs in agreement with previous works**

---

**Fermi coll. (2015)**
THE COMA CLUSTER RELOADED

Coma giant radio halo cannot be of hadronic origin BUT

COSMIC-RAY PROTONS → TURBULENCE (FERMI II) → RE-ACCELERATED SECONDARY ELECTRONS AND PROTONS → SYNCHROTRON EMISSION

HADRONE INTERACTIONS

SECONDARY ELECTRONS

See, e.g., Brunetti & Lazarian (2011), Brunetti et al. (2012), Pinzke et al. (2015), and Brunetti & Jones (2014) for a review

GAMMA RAYS & NEUTRINOS

13/09/2016

Fabio Zandanel (GRAPPA)
Gamma-ray observations start to constrain physical parameters in re-acceleration scenarios !!!
Non-detections challenge the standard picture of diffusive shock acceleration unless $B \gg 10 \mu G$

See also Kang and Ryu (2013), Kang et al. (2014), Guo et al. (2014), Caprioli & Spitkovsky (2014)

Vazza & Brüggen (2014)

Vazza et al. (2015)
FUTURE PROSPECTS

Knödlseder (2016)

![Graph showing energy sensitivity vs energy for various gamma-ray telescopes. The graph includes lines for INTEGRAL/SPI, COMPTEL, AdEPT, HARPO, e-ASTROGAM, Fermi, MAGIC, ARGO-YBJ, MILAGRO, H.E.S.S., CTA, LHASSO-W, HAWC, HISSCORE, and LHASSO-K.](image-url)
FUTURE PROSPECTS

Knödlseder (2016)
CHERENKOV TELESCOPE ARRAY

www.cta-observatory.org

Project Phases

Pre-Construction Phase
Finish End of 2016

Pre-Production Phase
2017 - 2018

Production Phase
2019 - 2024

First Telescopes on Site (earliest) 2017
Key Science project on Clusters of Galaxies

Perseus is the most promising target for CTA

Perseus simulated gamma-ray flux > 100 GeV for 100 hours observation

Preliminary – CTA consortium (in prep.) – FZ as editor for clusters
At least a factor of 4 improvement on current MAGIC constraints on Perseus.

For $\alpha_p \approx 2.2$, we will test $B_0 > 20 \mu G$.

Present Radio Constraints (GMRT)

MAGIC Perseus (2016)

Fermi-LAT (2014)

CTA Perseus 300 hr

Preliminary – CTA consortium (in prep.) – FZ as editor for clusters
TAKE AWAY MESSAGE

WE DO EXPECT CR PROTONS IN CLUSTERS, ALSO TO BE RE-ACCELERATED BY TURBULENCE

GAMMA-RAY NON-DETECTIONS ARE ONE OF THE MOST IMPORTANT ADVANCEMENTS

MAIN RESULTS:

• \( P_{CR}/P_{TH} < 1\% \left( \alpha_p = 2.1 \right) \) TO \(< 10\% \left( \alpha_p = 2.5 \right) \), LARGER IF CR NOT CENTRALLY PEAKED...

• CR P/E < 10 AT ODDS WITH DSA, BUT ACCELERATION EFFICIENCY MODEL DEPENDENT

• COMA RADIO EMISSION CANNOT BE HADRONIC + WE ARE LIMITING RE-ACCELERATION SCENARIOS

• CR IN CLUSTERS CONTRIBUTE \(< 1 – 10\% \) TO EGRB AND NEUTRINO FLUXES (SEE, E.G., FZ ET AL. 2015)
FUTURE PROSPECTS

**Fermi-LAT 10 years** + Improved/Alternative analysis (e.g., D³PO)

**CTA can detect / improve significantly on Perseus**

More work on p-\(\gamma\) emission at accretion shocks (Inoue et al. 2005, Vannoni et al. 2011) is desirable for CTA prospects...

**Fermi successors around 100 MeV – 1 GeV are the key both for CR protons and re-acceleration scenarios**

CROSS-CORRELATION OF **Fermi** with cluster catalogues (see Monday talk by Marco Regis) !!!

![Graph showing sensitivity vs. energy for various gamma-ray detectors](image_url)