High-energy Observations of Galaxy Clusters

What did we learn and what will we learn?

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THE HIGH-ENERGY WINDOW

GALAXY & AGN OUTFLOWS, SHOCKS, TURBULENCE

Primary & re-accelerated $e$

Radio Synchrotron & X-ray Inverse Compton

Neutrinos
(e.g., Berezinsky, Blasi & Ptuskin 1997, FZ et al. 2015)

Gamma rays

see Brunetti & Jones (2014) for a review and Gianfranco's talk

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HARD X RAYS

INVERSE COMPTON EMISSION REMAINS ELUSIVE

(e.g., Rephaeli et al. 2008; Ajello et al. 2009, 2010; Wik et al. 2012; Wik et al. 2014; Gastaldello et al. 2014)

Current limits:

$B > 0.5 \mu G$ for halos, and $B > 1 \mu G$ for relics

Recent tantalizing residuals: Botteon et al. on El Gordo, and Sarazin et al. on A 3667

Hitomi-like instrument is needed to give a significant step forward...

Bartels, FZ & Ando (2015)
DETECTION OF GAMMA RAYS

From space, e.g., Fermi Large Area Telescope

Pair-production

From the ground, e.g., MAGIC, HESS, VERITAS

Imaging Cherenkov Technique
**GAMMA RAYS: 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); 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)
MAGIC OBSERVATIONS OF PERSEUS

250 HOURS OBSERVATIONS 2009-2014

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

MAGIC OBSERVATIONS OF PERSEUS

Perseus

constraints on $<X_{\text{CR}}>$

with EBL absorption

$\frac{<P_{\text{CR}}>/<P_{\text{th}}>}{R/R_{200}}$

$\alpha$  $<X_{\text{no-EBL,CR,\text{max}}}^{\text{no-EBL}}>[\%]$  $<X_{\text{CR,\text{max}}}^{\text{no-EBL}}>[\%]$

2.1       0.5                  0.7
2.2       0.8                  1.1
2.3       1.7                  2.3
2.5       11.4                 15.2

IF COSMIC RAYS ARE NOT CENTRALLY PEAKED OR HAVE A SOFT SPECTRA CONSTRAINTS GET LOOSE…
Assuming radio emission of hadronic origin: for $\alpha_p \approx 2.2$, limits imply $B_0 > 5-8 \mu G$.

\[ B(R) = B_0 \left( \frac{\rho_{\text{gas}}(R)}{\rho_{\text{gas},0}} \right)^{\alpha_B} \]
MAGIC OBSERVATIONS OF PERSEUS

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

FERMI-LAT OBSERVATIONS

60-month gamma-ray Sky > 1 GeV

Image credit: NASA/DOE/Fermi-LAT Collaboration
FERMI-LAT OBSERVATIONS

4-YEAR COMBINED LIKELIHOOD OF 50 HIFLUGCS CLUSTERS

$P_{CR}/P_{TH} < 1.4\%$ + EMISSION FROM A400, A1367, A3112

Fermi Coll. (2014)

see also Huber et al. (2013), Prokhorov & Churazov (2014), Griffin et al. (2014)
THE COMA CLUSTER

No detection $\Rightarrow$ flux upper limits $\Rightarrow$

$\Rightarrow$ Coma giant radio halo \textbf{cannot} be hadronic

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

Things changed with \textbf{Pass8 Fermi-LAT data (6 years)}

Low-significance residual emission

Bounds on CRs in agreement with previous works

\textbf{Fermi coll. (2015)}
THE COMA CLUSTER RELOADED

Brunetti, Zimmer & FZ (in prep.)

Brunetti et al. (2012)

Bonafeede et al. (2010)

Fermi-LAT

RM

Reacceleration

$B_0 (\mu G)$ vs $\eta$

$B_0 (\mu G)$ vs $\eta_B$

$\delta = 2.45$

$\delta = 2.3$

$\delta = 2.1$
Gamma-ray observations start to constrain physical parameters in re-acceleration scenarios.
NON-DETECTIONS CHALLENGE THE STANDARD PICTURE OF DIFFUSIVE SHOCK ACCELERATION UNLESS $B \gg 10 \mu G$

**FERMI-LAT & RADIO RELICS**

Vazza & Brüggen (2014)

Vazza et al. (2015)
AN ALTERNATIVE ANALYSIS

D³PO INFEERENCE ALGORITHM WITHIN THE FRAMEWORK OF INFORMATION FIELD THEORY


They detect significant emission toward the direction of several clusters.

Remains to be seen if diffuse and if associated with the ICM or point-sources...

Selig et al. (2015)
GAMMA-RAY 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
CHERENKOV TELESCOPE ARRAY

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 main editor
At least a factor of 4 improvement on current MAGIC constraints on Perseus

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

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

• CR P/E $< 10$ AT ODDS WITH DSA UNLESS MAGNETIC FIELD AT RELICS $>> 10 \mu G$

• Coma radio emission cannot be hadronic (with FR-derived magnetic field) + WE ARE LIMITING RE-ACCELERATION SCENARIOS

• IF Perseus mini-halo hadronic, $B_0 > 5–8 \mu G$
FUTURE PROSPECTS

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

CTA can detect/improve significantly on Perseus and test $B_0 > 20 \, \mu G$

Fermi successors around 100 MeV – 1 GeV are the key for CR protons, re-acceleration scenarios, and constrains on magnetic fields with gamma rays

Knödlseder (2016)