PERSEUS AND COMA

What did we learn from gamma-ray observations and what will we learn

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NON-THERMAL PROCESSES

STRUCTURE FORMATION

OUTFLOWS FROM GALAXIES & AGN

TURBULENCE (Fermi II)

SHOCK WAVES (Fermi I)

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
SYNCHROTRON RADIO EMISSION

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

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

• **Impact on cluster environment** \( \frac{P_{CR}}{P_{TH}} \)?
SYNCHROTRON RADIO EMISSION

ASSUMING RADIO IS MAINLY OF “HADRONIC” ORIGIN (INCLUDING RE-ACCELERATED SECONDARIES):

RADIO $\Rightarrow$ SYNCHROTRON $\Rightarrow$ SECONDARY ELECTRONS
MAGNETIC FIELD

GAMMA RAYS & NEUTRINOS $\Rightarrow$ PION DECAYS $\Rightarrow$ PROTONS
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)

**Gamma rays are fundamental as they:**

- **Directly prove the CR proton content**
- **Indirectly test (re-)acceleration scenarios and magnetic fields beyond what can be done with radio data alone**
WHY COMA AND PERSEUS

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

1.4 GHz – Pedlar et al. (1990)

1.4 GHz – Deiss et al. (1997)

Pinzke & Pfrommer (2010)

note: cool-core = high ICM target density for p-p interactions

see also, e.g., Kushnir & Waxman (2009), Pinzke et al. (2011), Brunetti et al. (2012), Fujita & Ohira (2012), FZ et al. (2014), Vazza et al. (2016)
WHY COMA AND PERSEUS

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

Caveats:

• Radio power known
• Mass and gas density known
• Cosmic-ray spatial and spectral distribution unknown and heavily model dependent \(\rightarrow\) This affects modeling but also target selection!

See also, e.g., Kushnir & Waxman (2009), Pinzke et al. (2011), Brunetti et al. (2012), Fujita & Ohira (2012), FZ et al. (2014), Vazza et al. (2016)
GAMMA RAYS: WHERE WE STAND

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

Reimer et al. (2003) ... ; 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); Prokhorov (2014); Vazza & Brüggen (2014); Griffin et al. (2014); Selig et al. (2015); Vazza et al. (2015); Branchini et al. (2017); Brunetti, Zimmer & FZ (2017)

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

Spectrum of central radio galaxy NGC 1275

We see the cutoff of the emission and the source is not detected anymore above few hundred GeV

MAGIC COLL. (2014)

MAGIC COLL. (2016)
MAGIC OBSERVATIONS OF PERSEUS

Test models with different CR spatial and spectral distributions and tune them to radio including losses due to the star and dust light in the cluster center.

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

Perseus constraints on \( <X_{CR}> \) with EBL absorption

IF COSMIC RAYS ARE NOT CENTRALLY PEAKED OR HAVE A SOFT SPECTRA CONSTRAINTS GET LOOSE...

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>( \langle X_{CR,max}^{no-EBL} \rangle ) [%]</th>
<th>( \langle X_{CR,max} \rangle ) [%]</th>
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</thead>
<tbody>
<tr>
<td>2.1</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>2.2</td>
<td>0.8</td>
<td>1.1</td>
</tr>
<tr>
<td>2.3</td>
<td>1.7</td>
<td>2.3</td>
</tr>
<tr>
<td>2.5</td>
<td>11.4</td>
<td>15.2</td>
</tr>
</tbody>
</table>

MAGIC OBSERVATIONS OF PERSEUS

FOR $\alpha_p \leq 2.1$, HADRONIC ORIGIN OF RADIO EMISSION IS EXCLUDED INDEPENDENTLY FROM B

MINIMUM GAMMA-RAY FLUX:

$$L_{\gamma} = C_{\gamma} \int dV n_{\text{CR}} n_{\text{ICM}},$$

$$L_{\nu} = C_{\nu} \int dV n_{\text{CR}} n_{\text{ICM}} \frac{\varepsilon_{\text{B}}^{(\alpha_{\nu}+1)/2}}{\varepsilon_{\text{CMB}} + \varepsilon_{\text{SD}} + \varepsilon_{\text{B}}}$$

$$F_{\gamma, \text{min}} \approx \frac{C_{\gamma} L_{\nu}}{C_{\nu} 4\pi D_{\text{lum}}^2}$$

1.4 GHz – Pedlar et al. (1990)
327 MHz – Gitti et al. (2002)

Perseus
$$F_{\gamma, \text{min}} (\varepsilon_B >> \varepsilon_{\text{CMB}} + \varepsilon_{\text{SD}})$$
with EBL absorption

$\alpha = 2.1$ ————
$\alpha = 2.2$ ————
$\alpha = 2.3$ ————
$\alpha = 2.5$ ————


10/07/2017

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FERMI-LAT OBSERVATIONS

60-month gamma-ray Sky > 1 GeV

Image credit: NASA/DOE/Fermi-LAT Collaboration
THE COMA CLUSTER

ANALYSIS OF 5.25-YEAR (Pass7rep) \textit{Fermi}-LAT data

FZ & Ando (2014)

\[ P_{CR}/P_{TH} < 0.6 - 2.7 \ (17) \% \]
THE COMA CLUSTER

ANALYSIS OF 5.25-YEAR (PASS7REP) FERMI-LAT DATA

HALO

RELIC

FZ & ANDO (2014)

“KESHET-LIKE” RING: FLUX UPPER LIMITS ARE ONE ORDER OF MAGNITUDE LOWER THAN CLAIMED FLUX

No detection $\Rightarrow$ Flux upper limits $\Rightarrow$

$\Rightarrow$ Coma giant radio halo cannot be hadronic

$\Rightarrow$ CR proton contribution to radio emission < 60%
DIFFUSE GAMMA-RAY AND NEUTRINO BACKGROUND

Fluxes for all clusters using mass function and gamma-ray luminosity – mass relation respecting constraints from radio to gamma rays

$B >> B_{CMB}$

$\alpha_p = 2$
$\alpha_p = 2.2$
$\alpha_p = 2.4$

$\log_{10} N(>F_{1.4\,GHz})$ [#/sky]

$\log_{10} F_{1.4\,GHz}$ [mJy]

$+\,$ NVSS (0.044 < z < 0.2)

FZ, Tamborra, Gabici & Ando (2015)
DIFFUSE GAMMA-RAY AND NEUTRINO BACKGROUND

Fluxes for all clusters using mass function and gamma-ray luminosity – mass relation respecting constraints from radio to gamma rays

\[ B = 0.5 \mu \text{G} \]

\[ \alpha_p = 2 \]

\[ \log_{10} N > N_F(1.4 \text{GHz}) \] vs \[ \log_{10} F_{1.4 \text{GHz}} \] (mJy)

\[ \log_{10} E^2 dN/dE \] (GeV cm$^{-2}$ s$^{-1}$) vs \[ \log_{10} E \] (GeV)

FZ, Tamborra, Gabici & Ando (2015)
This refers to $\sim 0.1\%$ contribution to the extragalactic background.

A 10% contribution as claimed by some authors would overshoot angular power spectrum measurements!
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**

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Fermi coll. (2016)
THE COMA CLUSTER RELOADED

Brunetti, Zimmer & FZ (2017; submitted)

Bonafede et al. (2010)

Brunetti et al. (2012)

Fermi–LAT

RM

Reacceleration

$B_0(\mu G)$

$\eta$

$\eta_B$

$\delta=2.45$

$\delta=2.3$

$\delta=2.1$
Gamma-ray observations start to constrain physical parameters in re-acceleration scenarios.
Cosmic-ray content is not well constrained in the outskirts of clusters!
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)
CROSS-CORRELATION OF GAMMA RAYS AND CLUSTER CATALOGUES

They detect a signal between extragalactic gamma-ray background and several cluster catalogues.

Again, remains to be seen if diffuse and if associated with the ICM or point-sources...

Branchini et al. (2017)
GAMMA-RAY FUTURE PROSPECTS

Knödlseder (2016)

ComPair
CHERENKOV TELESCOPE ARRAY

www.cta-observatory.org

North hemisphere – La Palma

South hemisphere – Paranal
CHERENKOV TELESCOPE ARRAY

Project Phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Construction</td>
<td>Current Phase</td>
</tr>
<tr>
<td>Pre-Production</td>
<td>2018-2020</td>
</tr>
<tr>
<td>Production</td>
<td>2020-2024</td>
</tr>
</tbody>
</table>

First Pre-Production Telescopes On Site

Current Phase

Pre-Construction

Collect International Agreement Signatures & Secure Financial Investment ➔ Financial Threshold Reached

Oct 2016 ➔ Site Infrastructure Preparations ➔ Site Infrastructure Begins ➔ CTA Offices Open in Bologna ➔ Final Legal Entity Defined

10/07/2017

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CHERENKOV TELESCOPE ARRAY

Key science project on clusters of galaxies
Perseus is the most promising target for CTA

CTA consortium (in prep.) – FZ as main editor
Perseus diffuse
(< 0.15 deg)

MAGIC 2016 - upper limits
CTA 300 h - detection
CTA 300 h - upper limits
centrally peaked $B_0 = 10 \, \mu G$
$B_0 = 20 \, \mu G$
extended $B_0 = 10 \, \mu G$
$B_0 = 20 \, \mu G$
$F_{\text{min}} \alpha_p = -2.3$
Simulated gamma-ray flux for 100 hr of observation of the Perseus cluster assuming models with $B_0 = 10 \, \mu G$

CTA consortium (in prep.) – FZ as main editor
A factor of 6 improvement on current MAGIC constraints on Perseus.

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

CTA consortium (in prep.) – FZ as main editor
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 IN THE LAST YEARS

MAIN RESULTS:

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

• COMA RADIO EMISSION CANNOT BE HADRONIC (WITH FR-DERIVED MAGNETIC FIELD) + WE ARE LIMITING RE-ACCELERATION SCENARIOS

• IF PERSEUS IS HADRONIC: $\alpha_p > 2.1$, $B_0 > 5–8 \mu G$

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

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

CTA can detect / improve significantly on Perseus:
- Test hadronic origin for $\alpha_p \leq 2.3 + B_0 \geq 20 \mu G$
- $P_{cr}/P_{th} < 0.1 - 2.5 \%$ (peaked CRs) to $< 5\%$ (flat CRs)

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

THANKS!