Intergalactic gamma-ray propagation: basic ideas, processes, and constraints

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Some abbreviations and definitions

\( E_{\gamma_0} \) — primary energy of a \( \gamma \)-ray (source restframe)
\( E_{p_0} \) — primary energy of a proton (source restframe)
\( z \) — redshift; \( \tau \) — \( \gamma\gamma \) pair production optical depth; \( \gamma \) — spectral power-law index (when \( \gamma \) is a number)

HE — high-energy (\( E>100 \) MeV); VHE — very high energy (\( E>100 \) GeV);
UHE — ultra high energy (\( E>1 \) EeV)
EBL — extragalactic background light; EGMF — extragalactic magnetic field
CMB — cosmic microwave background

PP — pair production \( \gamma\gamma \rightarrow e^+e^- \)
IC — inverse Compton \( e^-\gamma \rightarrow e^-'\gamma' \) or \( e^+\gamma \rightarrow e^+\gamma' \)
AGN — active galactic nucleus
SED — spectral energy distribution

This talk is mostly based on:


In this work we use for our simulations three MC codes:
Kachelriess et al., Comp. Phys. Comm., 183, 1036 (2012)
Fitoussi et al., MNRAS, 466, 3472 (2017)
and our own code ECS (from “electromagnetic cascade spectrum”) (astro-ph/1705.05360)
The Cherenkov Telescope Array (CTA): low threshold (20 GeV), improved sensitivity and angular resolution (Acharya et al., special APh issue (2013))
High-energy anomaly (HM12, H16): colored symbols denote absorption-corrected data (significance: originally 4.2 $\sigma$). A similar effect: Rubtsov & Troitsky, JETP. Lett., 100, 355 (2014) ($\sim$12 $\sigma$).

A possible explanation: $\gamma$-ALP conversion in magnetic field


Kartavtsev et al., JCAP, 01, 024 (2017)


Extragalactic gamma-ray propagation models

1. Absorption-only model
   - Pair production (PP)
   - Adiabatic losses (AL)

2. Cascade models
   - 2a. Electromagnetic cascade model
     - Inverse Compton (IC)
     - PP, AL
   - 2b. Hadronic cascade model
     - Bethe-Heitler pair production (BHPP)
     - Photohadronic processes (PHP)
     - PP, AL, IC

3. Exotic models
   - 3a. Axion-like particle oscillation
   - 3b. Lorentz invariance violation
   - 3c. Exotic primaries, etc.
EGMF constraints following Durrer & Neronov (2013) and the main regimes of intergalactic EM cascade development

Magnetically broadened cascade (MBC)

Faraday rotation
Hubble radius
Turbulence damping
(Still) non-observation of cascade component

Many claims of strong constraints/detection inside the black frame
Things to explain:

1) a possible high-energy anomaly (HM12 – 4.2 σ; Rubtsov & Troitsky, JETP. Lett., 100, 355 (2014) ~12 σ)
   Troitsky, Talk at the Mount Elbrus Conference (2017):
   improved analysis, Z~9-10 σ even for Inoue et al. EBL model
   Really strong anomaly, exotic solutions
   such as ALPs are probably required

2) ~2-4 times higher flux of some blazars pointing towards the voids
   (indication for intergalactic EM cascade?) (Furniss. et al., MNRAS, 446, 2267 (2015))

3) indication for ~20% magnetically broadened cascade (MBC) flux at
“Strong” (in terms of EM cascade) EGMF from astro-ph/1804.08035?

Their results on the EGMF:
1. $B > 3 \times 10^{-16}$ G for $\lambda > 10$ kpc even for highly variable sources,
2. $B > 3 \times 10^{-13}$ G for $\lambda > 10$ kpc and stable sources

Their conclusion: “This improves previous limits by several orders of magnitude.”

No MBC/PH was found
Still the result of Chen et al. (2015) on MBC is not excluded directly
It is rather noted that systematics does not allow to prove the existence of the MBC/PH
One of their assumptions: “Accounting for the cascade contribution does not change the best-fit spectrum of the central point source in the entire Fermi-LAT energy band by more than 5 $\sigma$”
There is no room for the cascade component in their fit!
Conclusion: their results are mainly driven by their assumptions!!
“Magnetic cutoff” (cf. -1 spectrum of Neronov et al.). 1ES 1218+304, B = 1 fG, L = 1 Mpc. The PSF radius depends on energy! Variability studies are extremely important!
Secondary (cascade) $\gamma$-rays from UHE protons/nuclei emitted by blazars

Motivation (e.g. Uryson, JETP, 86, 213 (1998)):
Effectively moving the source of $\gamma$-rays closer to the observer

These secondary (cascade) $\gamma$-rays are the product of the GZK process / pair production on nuclei
(Greisen, Phys. Rev. Lett., 16, 748 (1966);
Zatsepin & Kuzmin, JETP Lett., 4, 78 (1966))
A slice of large-scale EGMF (~10 nG, 1 Mpc) at least every 50 Mpc!
(Oikonomou et al., 2014) → 10 deg deflection of protons

\[
\delta \approx \frac{BZe}{E} \sqrt{\frac{Ll_c}{2}} \approx 1^\circ \frac{B}{\text{nG}} \frac{40 \text{ EeV}}{E/Z} \frac{\sqrt{Ll_c}}{\text{Mpc}}
\]

(Harari et al., 2016)
“Intermediate” HCM: all observable γ-rays --- from protons/nuclei but the proton beam is terminated at $z_c$. Observable SEDs for $z_c = 0, 0.02, 0.05, 0.10, 0.15, 0.18$
Constraints on hadronic cascade models (the case of 1ES 0229+200, $z=0.14$). $B_0 =$ magnetic field strength in the center of the cluster, $z_c =$ the termination redshift of the proton beam, in color: significance of exclusion.
If the anomaly at high energies can be explained by (purely) EM cascades?

Typical arguments:
1. Secondary electrons acquire energy $E_e = E_{\gamma 0}/2$
2. These electrons interact mainly on dense CMB
3. Therefore, cascade photon energy $\approx 4/3 \Gamma_e^2 E_{\text{CMB}} << E_{\gamma 0}$
   (example: 100 GeV for $E_{\gamma 0} = 10$ TeV)
4. Therefore, intergalactic EM cascade can not explain the anomaly at high energy

Electromagnetic cascade model of blazar emission
Background for axion-like particle searches from (purely) EM cascades

Motivation:
primary spectrum is not known, especially for the case of “extreme TeV blazars” --- active galactic nuclei with hard primary spectrum and low-amplitude slow variability!!

<table>
<thead>
<tr>
<th>N</th>
<th>Source</th>
<th>z</th>
<th>Observational period</th>
<th>Reference</th>
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<tr>
<td>1</td>
<td>H 1426+428</td>
<td>0.129</td>
<td>1999-2000</td>
<td>Aharonian et al. (2003)</td>
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<tr>
<td>3</td>
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<td>2001</td>
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<td>4</td>
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<td>5</td>
<td>1ES 0229+200</td>
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<td>2010-2012</td>
<td>Aliu et al. (2014)</td>
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<tr>
<td>6</td>
<td>1ES 1218+304</td>
<td>0.182</td>
<td>2012-2013</td>
<td>Madhavan et al. (2013)</td>
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<tr>
<td>7</td>
<td>1ES 1101-232</td>
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<td>2004-2005</td>
<td>Aharonian et al. (2007b)</td>
</tr>
<tr>
<td>8</td>
<td>1ES 1101-232</td>
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<td>2004-2005</td>
<td>Aharonian et al. (2006)</td>
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<td>1ES 0347-121</td>
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<td>Aug.-Dec. 2006</td>
<td>Aharonian et al. (2007c)</td>
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<td>1ES 0414+009</td>
<td>0.287</td>
<td>2005-2009</td>
<td>Abramowski A. et al. (2012)</td>
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</table>
The high-energy excess option
The low-energy excess option.
All known anomalies are explained in a unified way!
Electromagnetic cascade model \((z = 0.188)\). SED shape at low energy is concealed by the cascade component ("EM cascade masquerade").
The ratio of best-fit model spectra for electromagnetic cascade model and the absorption-only model. Prospects for CTA: stat. Uncertainty 10 % at 3 TeV, 40 % at 6 TeV.

- **Dip**, $\tau \sim 1$
- **Enhancement**, $\tau \sim 2$-$3$
- **Bump**, $\tau \sim 5$ (!!)
- **Cutoff**, $\tau > 5$
EGMF parameter sensitivity for Fermi LAT and CTA (cf. Meyer et al. (2016))

We use 1ES 1218+304 as our source
Sensitivity to the EGMF parameters: MBC method, CTA+ Fermi LAT

1) Limited sensitivity to correlation length
2) Angular information is significant!
3) For weak EGMF (~1 fG; 1 Mpc) Fermi LAT data are significant!
Conclusions (1)

1. No evidence for strong (0.1 pG) EGMF in voids from Fermi LAT so far, even for stable sources. Intergalactic cascade models are still alive!

2. The development of EM cascades from primary protons/nuclei does not modify the effective opacity of the Universe significantly.

3. The development of EM cascades from primary $\gamma$-rays may, in principle, qualitatively explain all known “anomalies” (if they do exist!). “Extreme” versions of this model are testable with CTA!
4. While measuring the EGMF:
   a) Constraining the correlation length is difficult
   b) Angular information is significant
   c) For a weak EGMF (~1 fG) CTA should be supplemented by a space-based telescope such as Fermi LAT.
Additional slides
Color: the ratio of the likelihood of the extended-emission hypothesis to that of the null hypothesis (the PSF) (Chen et al., Phys. Rev. Lett., 115, 211103 (2015), p-value~ 0.01), EGMF: B= 0.01-1 fG
Hard-spectra Fermi LAT blazars tend to be located towards the voids in the large scale structure (Furniss. et al., MNRAS, 446, 2267 (2015) (F15), significance ~2.5 $\sigma$)
In these cases, observed flux is usually much higher (F15, significance ~2.5 $\sigma$); $x$: voidiness runs from 0 to 1. EGMF-dependent effects?
“Delta-plot”, cascade spectra for primary monoenergetic emission (histograms: ELMAG (KD10 EBL), symbols: ECS (G12 EBL))
Most of these authors concluded that the hadronic cascade model can explain the high-energy anomaly.
Blue circles denote strong magnetic fields around the object and on the way to the observer.
Primary luminosity and spectrum: Tavecchio, MNRAS, 438, 3255 (2014) (primary proton luminosity is limited by magnetic field density)
The source is embedded in a galaxy cluster (Meyer et al., Phys. Rev. D, 87, 035027 (2013)), central magnetic field $B_0$.
The proton beam may encounter another cluster at $z_c$.
Towards a more realistic intergalactic hadronic cascade model!

\[
\sin(\theta_n) = \sin(\delta) \frac{L_\gamma(E_{\gamma_{n-1}}, z_s)}{L_s}
\]

Observable angles >1 deg, well beyond HESS/CTA PSF (~0.1 deg)!
Observable intensity drops as $B_0$ grows from 1 nG (black)/10 nG (red) to 10 mkG (experimental data: Aliu et al., ApJ, 782, 13 (2014); $z = 0.14$)
Sensitivity to the EGMF parameters: “magnetic cutoff” method, CTA+ Fermi LAT
Constraints on gamma-ALP mixing
Point spread function (PSF) width for various instruments