Intergalactic electromagnetic cascades in the magnetized Universe as a tool of astroparticle physics

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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)
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 $\gamma\gamma \to e^+e^-$

IC — inverse Compton $e^-\gamma \to e^-'\gamma'$ or $e^+\gamma \to e^+'\gamma'$

AGN — active galactic nucleus

SED — spectral energy distribution


Topics to discuss

1. Secondary (cascade) $\gamma$-rays from UHE protons/nuclei emitted by blazars
2. Background for axion-like particle searches from (purely) EM cascades
3. EGMF parameter sensitivity for Fermi LAT and CTA
4. Spectrum and angular distribution of cascade $\gamma$-rays from nearby extragalactic sources in context of DM searches
5. What has changed after the recent Fermi LAT work (astro-ph/1804.08035)?


Synchrotron losses in voids are, as a rule, negligible given the contemporary upper limits on the EGMF (Pshirkov et al., Phys. Rev. Lett., 116, 191302 (2016))

Our calculations where $z$ is not indicated are for $z = 0.186$
A possible explanation: $\gamma$-ALP conversion in magnetic field

Kartavtsev et al., JCAP, 01, 024 (2017)
1. Secondary (cascade) γ-rays from UHE protons/nuclei emitted by blazars

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

These secondary (cascade) γ-rays are the product of the GZK process / pair production on nuclei
Intergalactic hadronic cascade model (HCM)

Most of these authors concluded that the hadronic cascade model can explain the high-energy anomaly.
“Basic” HCM: all observable γ-rays are from protons/nuclei and protons do not meet any obstacle on their way.

“Universal spectrum” (Berezinsky & Smirnov 1975, BK16)

\[ \Gamma = 1.85 \pm 0.1 \]

\[ \Gamma = 1.60 \pm 0.1 \]
A slice of large-scale EGMF (~10 nG, 1 Mpc) at least every 50 Mpc!
(Oikonomou et al., 2014) → 10 deg deflection of protons

\[ \delta \approx \frac{BZe}{E} \sqrt{\frac{Ll_c}{2}} \approx 1^\circ \frac{B}{nG} \frac{40 \text{ EeV}}{E/Z} \frac{\sqrt{Ll_c}}{\text{Mpc}} \] (Harari et al., 2016)
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)!
“Intermediate” HCM: all observable $\gamma$-rays --- from protons/nuclei but the proton beam is terminated at $z_c$. Observable SEDs are for $z_c = 0, 0.02, 0.05, 0.10, 0.15, 0.18$. 

![Graph showing SEDs for different $z_c$ values]
“Rule of thumb”: take the universal spectrum of a purely electromagnetic cascade, but at a location L/2 closer to the observer
Effective opacity decrease is \( \frac{25 \text{ Mpc}}{(700-800 \text{ Mpc})} = 0.03 \)
To compare with EBL intensity uncertainty: \(+ -30\%\)
(e.g. Korochkin & Rubtsov, astro-ph/1712.06579)
Conclusion: the effective decrease of opacity is not significant
A more realistic hadronic cascade model
(calculation technique: following B06, test asymptotics: BK16)

Blue circles denote strong magnetic fields around the object and on the way to the observer.
(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 $z_c$. 

Primary protons/nuclei
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); $z = 0.14$)
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.
2. 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>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H 1426+428</td>
<td>0.129</td>
<td>1999-2000</td>
<td>Aharonian et al. (2003)</td>
</tr>
<tr>
<td>3</td>
<td>H 1426+428</td>
<td>0.129</td>
<td>2001</td>
<td>Horan et al. (2002)</td>
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<tr>
<td>4</td>
<td>1ES 0229+200</td>
<td>0.140</td>
<td>2005-2006</td>
<td>Aharonian et al. (2007a)</td>
</tr>
<tr>
<td>5</td>
<td>1ES 0229+200</td>
<td>0.140</td>
<td>2010-2012</td>
<td>Aliu et al. (2014)</td>
</tr>
<tr>
<td>6</td>
<td>1ES 1218+304</td>
<td>0.182</td>
<td>2012-2013</td>
<td>Madhavan et al. (2013)</td>
</tr>
<tr>
<td>7</td>
<td>1ES 1101-232</td>
<td>0.186</td>
<td>2004-2005</td>
<td>Aharonian et al. (2007b)</td>
</tr>
<tr>
<td>8</td>
<td>1ES 1101-232</td>
<td>0.186</td>
<td>2004-2005</td>
<td>Aharonian et al. (2006)</td>
</tr>
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<td>9</td>
<td>1ES 0347-121</td>
<td>0.188</td>
<td>Aug.-Dec. 2006</td>
<td>Aharonian et al. (2007c)</td>
</tr>
<tr>
<td>10</td>
<td>1ES 0414+009</td>
<td>0.287</td>
<td>2005-2009</td>
<td>Abramowski A. et al. (2012)</td>
</tr>
</tbody>
</table>
Things to explain:

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

2) $\sim$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 $\sim$20% magnetically broadened cascade (MBC) flux at $\sim$1 degree scale at $\sim$1 GeV (Chen et al., Phys. Rev. Lett., 115, 211103 (2015))
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 $\approx 4/3 \Gamma_e^2 E_{CMB} << E_{\gamma_0}$
   (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
The high-energy excess option
The low-energy excess option
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. Electromagnetic cascade model predicts up to 3 times more flux at $E=8$ TeV.
3. EGMF parameter sensitivity for Fermi LAT and CTA (cf. Meyer et al. (2016), see section 5 for their assumptions)
The Cherenkov Telescope Array (CTA): low threshold (20 GeV), improved sensitivity and angular resolution
EGMF constraints following NS09 and the main regimes of intergalactic EM cascade development

- Pair halo (PH)
- Asymmetric cascade
- Turbulent field regime
- Magnetically broadened cascade (MBC)
“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!
Sensitivity to the EGMF parameters: “magnetic cutoff” method, CTA+ Fermi LAT. 1ES 1218+304, (B = 1 fG, L = 1 Mpc).
Sensitivity to the EGMF parameters: MBC method, CTA+ Fermi LAT
Sensitivity to the EGMF parameters: “magnetic cutoff” method, only CTA
Sensitivity to the EGMF parameters: MBC method, only CTA. **Conclusion:** a space telescope is needed.
4. Spectrum and angular distribution of cascade γ-rays from nearby extragalactic sources in context of DM searches

Their motivation: “the streetlight effect” (эффект Ходжи Насреддина) (Esmaili et al. JCAP, 12, 054 (2014))

Blanco et al., JCAP, 04, 060 (2018): highly non-standard scenarious with very heavy (>100 TeV) annihilating dark matter (overcoming usual upper bounds on mass).

Our work: applicable to any source of gamma-rays in nearby extragalactic objects
Example: Blanco et al. (2018)

\[ \sin \Theta \simeq \frac{l}{r_l} \simeq 0.3 \left( \frac{B}{10^{-11} \text{ G}} \right) \left( \frac{100 \text{ TeV}}{E_e} \right)^2 \]
The (l/r) ratio was severely underestimated!! → no MBC observable
(Black: Thomson regime approximation, red: approximation of Khangulyan et al. (2014))
Observable spectrum: $E_{\gamma_0} = 100$ TeV, $L = 16.8$ Mpc
In fact, the “pair halo regime” is realised (instead of the MBC regime). If $E_\gamma^0 \sim 1-3$ PeV, the observer can see a cloud of angular extension $\sim (8 \text{ kpc} + 10 \text{ kpc})/(80 \text{ kpc}) = 0.2 \text{ rad}$. For Virgo, if $E_\gamma^0 = 100$ TeV, $\sim (1 \text{ Mpc})/(16.8 \text{ Mpc}) = 0.06 \text{ rad}$.
5. Any room for intergalactic cascade models after 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 σ”
There is no room for the cascade component in their fit!
Conclusion: their results are mainly driven by their assumptions!!
Conclusions (1)

1. For intergalactic hadronic cascade models of blazar emission, it is very important to account for realistic structure of the EGMF “strong component”. For realistic models of this component the development of EM cascades from primary protons/nuclei does not modify the effective opacity of the Universe significantly.

2. The development of EM cascades from primary $\gamma$-rays may, in principle, qualitatively explain all known “anomalies”. A very strong anomaly, however, could not be produced by this mechanism. The most severe test of the intergalactic electromagnetic cascade model is variability.
3. While measuring EGMF, CTA should be supplemented by a space-based telescope such as Fermi LAT.

4. MBC/PH boundary (on magnetic field) moves up for the case of nearby extragalactic objects due to higher electron energy. Thomson regime formulas are not applicable in this case!

5. No evidence for strong (0.1 pG) EGMF in voids from Fermi LAT so far, even for stable sources.
Additional slides
We consider point-like extragalactic sources (for the most part beamed). Primary $\gamma$-rays absorb on EBL (and for $E_{\gamma 0} > 100 \text{ TeV}/(1+z)$ --- on CMB) photons (model SEDs of EBL: Inoue et al., ApJ, 768, 197 (2013))
SED of EBL at $z=2$ (according to F17).

Caveat: large systematic uncertainty of EBL models at high $z$
Typical AGN geometry (left, 1) and SED of a MeV-GeV blazar (right, 2); SED of EBL for several models (bottom, 3)

3 EBL model KD10 is shown by red dashed line

Extreme TeV blazars: high-energy peak in the SED at E>1 TeV, usually weak variability
Extragalactic gamma-ray propagation models (more conservative first)

1. Absorption-only model: pair production + adiabatic losses
2. Electromagnetic cascade model: +IC
3. Hadronic cascade model: +EM cascades from UHE (>1 EeV) protons and nuclei
4. gamma-axion-like particle (ALP) oscillation

General idea: BEC (superposition of several photons) usually develop a shower in the atmosphere earlier wrt normal photons; this affects the parameters of the images and was ruled out experimentally
EGMF simulations: Vazza et al., Class. Quantum Grav., 34, 234001 (2017)
Interaction rates for $z = 0$ (different components). Black --- gamma (total); red --- gamma (EBL); green --- gamma (CMB); blue --- e (CMB); cyan --- e (EBL); magenta --- e (total)
E_0 < 100 \text{ TeV} \rightarrow \text{gamma-rays escape to voids}

E_0 = 10 \text{ TeV} \rightarrow E_{0e} \sim 5 \text{ TeV}; \text{ electrons produce cascade photons almost “in situ”}

E_{\text{casc}} \sim (E_{0e}/m_e)^2 E_{\text{CMB}} \sim 100 \text{ GeV} \rightarrow \text{cascade photons travel practically without absorption; voidiness < 1 is not an issue}
\[ D_\gamma(E'_\gamma, z) = 40 \frac{\kappa}{(1 + z)^2} \left[ \frac{E'_\gamma}{20 \text{ TeV}} \right]^{-1} \text{ Mpc}, \]

\[ L_{\text{att}}(E, z) = C \cdot L_t \frac{E_t}{(1 + z)^\alpha E} \left[ 1 + k \cdot \sin(a \cdot \log((1 + z)^\beta E) - b) \right] \]

\[ \gamma\text{-ray attenuation length:} \]

“original” and “refined”

NS09 approximation

\( z \) from 0 to 1

black: numerical calculation, red: fit
(both downscaled for \( z \geq 0 \))
Blazars are the brightest distant (\(z>0.03\)) extragalactic HE gamma-ray emitters (Ackermann et al., astro-ph/1702.00664 (2017)).


Synchrotron losses are not an issue; we do not account for any collective effects in \(e^+e^-\) beams.
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. $\gamma$ -- Axion-like particle oscillation
   - 3b. Lorentz invariance violation
   - 3c. Exotic primaries, etc.
The “absorption-only model”
Account for only the absorption (PP) of primary γ-rays and adiabatic losses

Nikishov, Sov. Phys. JETP, 14, 393 (1962)

The PP process signatures in blazar spectra were convincingly detected in:
Ackermann et al., Science, 338, 11 (2012);
Gamma-ray horizon (from HM12, EBL model: KD10)
Our own very modest contribution ($z=0.186, 1ES\ 1101-232$ observations from Aharonian et al., Nature, 440, 1018 2006) ~3σ indication (systematics included) for the anomaly was found (6 sources); almost all excess is due to extreme TeV blazars, and not to classical blazars such as Mkn421, Mkn 501 (Dzhatdoev, J. Phys. Conf. Ser., 632, 012035 (2015))
Constraints on gamma-ALP mixing
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 $\sim 2.5 \sigma$); $x$: voidiness runs from 0 to 1. EGMF-dependent effects?
“Delta-plot” \((z = 0.186, \text{ELMAG } 2.02)\): observable spectra for one-generation \((E_0 = 1 \text{ TeV}, 3 \text{ TeV}, 10 \text{ TeV})\) and universal regime \((100 \text{ TeV}, 1 \text{ PeV})\); transition regime \((30 \text{ TeV})\)
“Delta-plot”, cascade spectra for primary monoenergetic emission (histograms: ELMAG (KD10 EBL), symbols: ECS (G12 EBL))
Gamma-ray (solid) and positron (dashed) SEDs (KA08, $E_{p0} = 30$ EeV, $50$ EeV, $70$ EeV, $100$ EeV); relevant neutrino fluxes were accounted for (Kelner & Aharonian (2008)).
Impact of voidiness ($K = 1.0, 0.6, 0.4, 0.3, 0.2$). The source is 1ES 0229+200 ($z = 0.188$). The high-energy part is better fitted for $K < 0.6$, the low-energy part — for $K$ from 0.3 to 0.6.
The ratio of best-fit model spectra for electromagnetic cascade model and the absorption-only model
Constraints on the EGMF

No MBC, but it is still possible to observe pair-halo (PH)

The MBC solution
The ratio of the optical depth (blue — KD10 as implemented in ELMAG 2.02, black — G12 model) to the one for the original KD10 model. Solid — $z= 0.186$, dashed — $z= 0.287$. 
Spectral signatures of the electromagnetic cascade model: 1) high-energy cutoff, 2) “ankle” 3) “magnetic cutoff” 4) second ankle.
Arsioli & Chang A&A 598, A134 (2017) found a plenty of blazars with hard primary spectra in Fermi LAT data (of course, TS is usually lower than in the official Fermi LAT catalogues)