Lorentz invariance violation and γ -ray propagation: Detectability by very-high-energy γ -detectors

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Several models of (quantum) gravity predict tiny violations of Lorentz Invariance (LI) at microscopic (Planckian) scales, which increase with the energy of the probe and amplified with the distance of the source. Thus, astrophysical/cosmological energetic probes provide the best test grounds of LI. The talk reviews the status and prospects of such tests, using high-energy cosmic γ detectors. The Čerenkov Telescope Array (CTA) is an excellent experimental tool for making such tests with sensitivities exceeding those possible using other detectors.

Keywords: Lorentz invariance violation; high energy astrophysics; gamma-ray detectors.

1. Introduction and Motivation

A century after Einstein's proposal for *General Relativity* (GR), Quantum Theory and Gravity still remain hard to reconcile, despite considerable effort. GR is a classical theory, which respects Lorentz Invariance (LI) locally, as a result of the strong equivalence principle. However, from the quantum-mechanical point of view, the vacuum, which is the lowest-energy state of a physical system, should be regarded as a medium that may have virtual structure, even if it is devoid of physical particles. As such, it may have non-trivial effects on particle propagation, even if LI is an underlying (classical) principle. This effect is, of course, familiar in the cases of photons propagating through plasmas at high temperatures or superconductors at low temperatures.

Wheeler argued, generalising arguments on uncertainty principles of quantum mechanics, that space-time would no longer appear flat at distance scales $\Delta x \sim 1/M_P = 10^{-35}$ m ($M_P = 1/\sqrt{G_N} \sim 10^{19}$ GeV, the Planck mass scale, with G_N the gravitational constant), possibly with the appearance of topological fluctuations as well as non-topological irregularities. Heuristic models of such quantum-gravity space-time foam have been proposed^{2–10}, in which microscopic fluctuations of space-time are responsible for inducing a medium characterised by a non-trivial 'index of refraction', which in several of these models is proportional to some integer power of the energy E of the probe. Simple models suggest that the photon group velocity might deviate linearly from that of light in Lorentz-invariant vacua:

$$v_g \equiv \frac{\partial E}{\partial p} \sim 1 - \frac{E_\gamma}{M_1}, \quad (1)$$

where M_1 is some large mass scale that might be $\mathcal{O}(M_P)$.

However, M_1 could depend on other parameters of the microscopic theory, as is the case, for instance, of some string-inspired models of foam³, based on

non-perturbative structures existing in various dimensions, notably D-brane worlds (membrane-like structures, to which open strings end, one of which may represent our universe) and D-particles (point-like D-brane defects of mass M_s/g_s , with M_s the string scale, in the range $\mathcal{O}(10) \text{ TeV} \leq M_s \leq M_P$, and $g_s < 1$ the string coupling)¹¹. Time-space stringy uncertainties come into play in such models¹², leading to mechanisms involving absorption and re-emission of the photon by the defect. This slows down the photon (as in conventional media), leading to a linear energy dependence of the refractive index, with $M_1 \sim M_s/g_s\eta(z)$ being in general redshift z dependent in case of inhomogeneous D-particle defect populations¹² with the linear densities of D-particles $\eta(z)$ being phenomenological parameters to be constrained by cosmological/astrophysical observations¹³.

This qualitative picture has several important, generic features: (i) The refractive index η (defined through the photon phase velocity $v_{\text{ph}} = p/E = c/\eta$) should be *larger than unity*, corresponding to *subluminal* propagation of energetic photons^{3 a}. (ii) The quantum-gravity-induced refractive index, in contrast to the ordinary material medium case, should *increase* with energy, which might be expected on general grounds, since gravitational interactions are in general proportional to some power of G_N . (iii) The interactions of different particle types with the space-time foam would *not* be universal, in general, so they would have different refractive indices. In the specific case of the photon, there is no conserved quantum number to impose a selection rule inhibiting its absorption and re-emission by a space-time excitation modelled by a D-particle. On the other hand, the interaction of a charged particle such as an electron with these excitations might well be inhibited¹⁵ (D-particles do not carry electric charges). A similar argument applies to the proton, with the added complication that it is a composite particle, further complicating the discussion. The case of the neutrino is different again: it has no electric charge, and lepton number is not expected to be absolutely conserved at the scale of quantum gravity. On the other hand, as a fermion the neutrino could not simply be absorbed by a space-time defect unless they occur in boson-fermion doublets *à la* supersymmetry.

The above-described space-time foam effects are amplified by the distance the probe has travelled from emission to observation. Combined with the feature that the quantum-gravity-induced refractive index increases with the energy of the probe, this implies that distant, rapidly-varying astrophysical/cosmological sources of high-energy γ rays could provide some of the most sensitive probes of some models of Lorentz invariance (LI)². Such tests of LI, or searches for LI Violation (LIV), may be pursued from a purely phenomenological point of view¹⁶, prompted by, but not limited to, specific heuristic models, specifically by testing for a possible deviation δv from the speed of light in the propagation of energetic photons that increases as some power of energy: $\delta v/c \sim -(E/M_n)^n$, in particular $n = 1$ or 2 .

^aThe fact that photons should not travel faster than c can be argued independently on general grounds: if they did, they would emit gravitational Čerenkov radiation and lose energy unacceptably quickly¹⁴.

The current status and prospects for such tests will be the subject of the next sections of this review, which is dedicated to the occasion that the year 2015 has been officially declared as *the year of light*. The talk focuses on studies of cosmic light in order to extract fundamental properties of space time. As discussed in Ref. 17 and reviewed below, Čerenkov Telescope Array (CTA)¹⁸ will be uniquely well placed to carry these tests to the next level of sensitivity¹⁹.

2. Current Tests of Lorentz Invariance with Cosmic Photons

It was proposed in Ref. 2 that one can probe Lorentz violation by searching for the smearing of transient features in high-energy γ emissions from astrophysical sources. To the extent that such sources are not monochromatic, the observations at Earth of photons in such emissions would be retarded by amounts increasing with energy, and (approximately) coincident arrival times of photons with different energies can be used to constrain the parameters M_n . It is clear that the figure of merit for such studies is $L\Delta(E^n)/\Delta t$, where L is the distance of the source and Δt is the time-scale of transient emissions. Candidate astrophysical sources include pulsars, Active Galactic Nuclei (AGN) and Gamma Ray Bursters (GRB).

Two cautionary comments are in order. One is that the spectra of transient emissions from many astrophysical sources become harder with time. Thus, a higher-energy photon may be relatively more likely to have been emitted later, potentially polluting any search for a Lorentz-violating refractive index. It is therefore essential to devise tools for discriminating between retardation effects at source and during propagation. In principle, this could be done by comparing the smearing of sources at different distances, since any propagation effect would increase with L whereas (in the absence of evolutionary effects) source effects should be L -independent. However, this strategy entails the observation of emissions from a number of sources at different distances, and presupposes the existence of a class of ‘standard lighthouses’ sharing common time structures in their high-energy emissions. Observations of GRBs are more copious than observations of time structures in emissions from AGNs, but neither are very uniform ‘standard lighthouses’. The second comment is that any statistical separation between source and propagation effects would need to be extraordinarily convincing, which suggests that corroborating evidence from at least two classes of sources should be required, e.g., both GRBs and AGNs, with a statistically significant set of data.

Early studies of Lorentz violation, furnished by different types of astrophysical sources, including the Crab Pulsar and AGN Markarian 421^{2,20,21}, provided a sensitivity to $M_1 \sim 4 \times 10^{16}$ GeV²¹. However, these pioneering studies had relatively low statistics and distances from observation points, and were not able to disentangle source and propagation effects. The first study to attempt this by combining data from several different sources at different distances was made using a sample of GRB emissions observed by BATSE and OSSE⁴. Subsequent upgraded fits, analyzing emissions from 35 GRBs with measured redshifts $z \leq 6.29$ observed

by the BATSE, HETE and SWIFT instruments, yielded the robust lower limit $M_1 \gtrsim 1.4 \times 10^{16}$ GeV at the 95% CL²², despite a strong correlation between the source and propagation parameters in the fit.

The observation of cosmic photons with much higher energies lead to significant improvement on the sensitivity of LI tests. Fig. 1 compares the sensitivities of different experiments to the time-lag/energy ratio $\Delta t/E$ as functions of:¹³

$$K(z) \equiv \frac{1}{(1+\hat{z})} \int_0^z \frac{(1+\hat{z})d\hat{z}}{h(\hat{z})}, \quad (2)$$

where the Hubble expansion rate $h(\hat{z}) = \sqrt{\Omega_\Lambda + \Omega_M(1+\hat{z})^3}$, which measures the distance of the source from the observation point. As seen in Fig. 1, greater sensitivities to $\Delta t/E$, and hence M_1 , have been found in two analyses of AGN flares. The first was a flare of γ -rays with energies $\lesssim 10$ TeV from Markarian 501 at $z = 0.034$ observed by the MAGIC telescope, which had sensitivity to $M_1 \sim 2 \times 10^{17}$ GeV²³. The second was a flare of γ -rays with energies $\lesssim 1$ TeV from PKS 2155-304 at redshift $z = 0.116$ observed by the H.E.S.S. telescope, which yielded sensitivity to $M_1 \sim 2 \times 10^{18}$ GeV²⁴. Several factors contributed to the greater sensitivity of this observation: the higher redshift, the higher range of γ energies and the larger statistics. All of these are features that CTA may hope to improve further, principally by virtue of its much greater collection power.

Fig. 1. Comparison of data on delays Δt in the arrival times of energetic gamma rays from various astrophysical sources with models in which the velocity of light is reduced by an amount linear in the photon energy. The graph plots on a logarithmic scale the quantity $\Delta t/E$ and a function of the red-shift, $K(z)$, which is essentially the distance of the source from the observation point. From Ref. 13.

The principal competition for these AGN observations is currently provided by Fermi GBM/LAT measurements of energetic γ -rays from GRBs. As also seen in Fig. 1, the most sensitive of these to date has been provided by observations²⁵ of GRB 090510 at $z = 0.90$, in particular the observation of a single photon with $E_\gamma \sim 31$ GeV. The sensitivity to M_1 inferred from this single photon depends

whether one assumes (most conservatively) that it was not emitted before the start of any detectable emission below 1 MeV, $M_1 \sim 1.4 \times 10^{19}$ GeV, or that it was not emitted before the start of emission above 1 GeV, $M_1 \sim 1.2 \times 10^{20}$ GeV, or (most aggressively) that it was associated with the nearest 1 MeV emission spike, in which case the sensitivity is to $M_1 \sim 1.2 \times 10^{21}$ GeV²⁵. This remarkable sensitivity is traceable in part to the cosmological redshift and the fine time structure, which are typical of GRB emissions, as well as to the observation of a very-high-energy γ -ray from a GRB. It should be mentioned that one can still fit the GRB 090510 data together with the rest of fig. 1 data within a refractive index scheme obtained from an inhomogeneous D-particle foam models^{12,13}.

There have also been attempts to take into account microscopic astrophysical mechanisms for photon acceleration in GRB models, together with quantum-gravity-induced propagation effects. The intrinsic time delay Δ_{intr} between emissions of low and high energy photons using, *e.g.* the magnetic jet model for acceleration²⁶, has been implemented together with linear LIV Violation effects in a unified scenario both for long and short Fermi-detected GRBs²⁷. The total time delay in such analyses between low and high energy photons is given by the sum $\Delta_{\text{intr}} + \Delta_{\text{LIV}}$, where the second term contains the LIV refractive index effects, suppressed by the scale M_1 . Such studies yield $M_1 \sim 10^{20}$ GeV, mainly due to the inclusion in the data of the GRB 090510.

The previous paragraphs focused on the possibility of a photon speed decreasing linearly with energy, where the finer time structure of GRB emissions gives them an advantage over AGN emissions. However, the situation is different when one considers a quadratic dependence: $\delta v \sim -(E/M_2)^2$. In this case, the higher energies seen in AGN emissions confer on them a significant advantage. For example, the MAGIC data on Markarian 501 yield a sensitivity to $M_2 \sim 2.6 \times 10^{10}$ GeV²³ and those on PKS 2155-304 are sensitive to $M_2 \sim 6.4 \times 10^{10}$ GeV²⁴, with which the observations of GRB 090510²⁵ are not competitive.

As mentioned in the introduction, Lorentz-violating effects on the propagation of different particle species are not expected to be universal, and sensitivities to (constraints on) Lorentz violation for electrons, protons and neutrinos are of independent interest in their own rights. We note, in particular, that broadband observations of electromagnetic radiation from the Crab Nebula restrict very severely any possible Lorentz violation for the electron, so that the corresponding $M_1^e \gg M_P$ ¹⁶. Important constraints on Lorentz violation for other particles are provided by observations of ultra-high-energy cosmic rays (UHECRs), via constraints on both conventional processes such as $p + \gamma \rightarrow p + \pi^0, n + \pi^+$ and unconventional processes such as $p \rightarrow p + \gamma, p + \pi^0$ that are forbidden by Lorentz invariance²⁸. There are also very stringent constraints¹⁶ on models that predict birefringence⁹, unlike the stringy models of Ref. 3. In the latter category belong also some models of (quantum) refractive index in parity-violating scalar dark matter interacting with photons²⁹.

3. Prospects for CTA and Complementarity with Other Detectors

High-energy astrophysics and related aspects of cosmology are the bread-and-butter science issues for the Čerenkov Telescope Array (CTA)¹⁸, but measurements related to fundamental physics can be easily accommodated in its research agenda^{17,19}. One such possibility is to use transient high-energy emissions from distant astrophysical objects observed by CTA to probe the validity of Lorentz invariance. The large collection area and acceptance of CTA will provide it with unique prospects for gathering data on astrophysical sources of energetic γ -rays, and hence new opportunities for probing Lorentz violation, due to its ability of reaching higher energies, larger redshifts and finer time structures. Indeed, CTA will : (i) be able to make much more detailed studies of known sources such as the AGNs Markarian 421, Markarian 501 and PKS 2155-304, which should provide higher-energy γ -rays as well as greater statistics, and might reveal smaller structures in their γ emissions, (ii) also be able to extend γ -ray observations to a larger family of less-luminous AGNs, including objects with similar intrinsic luminosities to known AGNs, but with larger redshifts, improving the sensitivity to Lorentz violation and providing a longer lever arm for separating source and propagation effects, apart, of course, from making possible more systematic studies of the source effects themselves, (iii) CTA may also detect a population of nearby objects with less intrinsic luminosity, which *a priori*, might have smaller emission regions and hence exhibit more rapid flux variations. Of course, it must be said that the improvements in sensitivity to Lorentz violation are somewhat uncertain, due to the stochastic properties of γ -ray emissions.

A typical spectral index $\Gamma : dN/dE_\gamma \sim (E_\gamma/E_0)^{-\Gamma}$ for AGN γ -ray emissions is $\Gamma \sim 2^{24}$, implying, e.g., that a collecting power ~ 100 greater than that of H.E.S.S. would be required to extend its observations of PKS 2155-304 to γ -rays with $\langle E_\gamma \rangle \sim 10$ TeV. Nevertheless, if this could be achieved, and assuming the observation of a transient structure in emissions with a similar time-scale, it would extend the sensitivity reported in Ref. 24 to $M_1 \sim 10^{19}$ GeV.

However, there is a potential limitation to what can be achieved with higher-energy γ -rays, since their mean free path for interaction with (and hence energy loss to) microwave and infrared background photons imposes an effective limit on the energies of photons emitted at large redshifts that can in fact be observed. For example, it is calculated that interactions with the cosmic microwave background would prevent the observations of photons with energies $E_\gamma > 100$ TeV emitted from more than a few Mpc away. The cosmic infrared background is less well determined but, as seen in Fig. 2, it is likely to absorb photons with $E_\gamma > 1$ TeV emitted by AGNs at distances larger than those of Markarian 421, Markarian 501 and PKS 2155-304³⁰. This was highlighted in Ref. 31 as an issue for the observation of ~ 20 -TeV γ -rays from Markarian 501 reported by HEGRA³². It was also noted in Ref. 31 that Lorentz violation might actually resolve this problem, though more mundane explanations are also possible³³.

Fig. 2. The horizon for high-energy photons interacting with the cosmic infrared and microwave backgrounds, shown as solid lines corresponding to various optical depths τ . The dashed and dot-dashed curves correspond to alternative models of the extragalactic background light. From Ref. 30.

The same issue arises in considering the potential for observing emissions from larger redshifts. For example, it is seen in Ref. 30, assuming conventional Lorentz-invariant kinematics, that only photons with $E_\gamma \lesssim 300$ GeV are likely to be observable in emissions from $z \sim 1$. Nevertheless, if one assumes that a structure similar to that observed by H.E.S.S. in emissions from PKS 2155-304 were to be observed in TeV-scale emissions from an AGN with $z \sim 1$, which might be possible with the collecting power of CTA, this would also give sensitivity to $M_1 \sim 10^{19}$ GeV¹⁷. Detailed feasibility studies for CTA sensitivity to Lorentz-violating effects on the γ -ray horizon can be found in Ref. 34.

Alternatively, one may consider the possibility of observing transient emissions with shorter time-scales than those observed from AGNs so far, which might exist for a variety of astrophysical reasons¹⁷. Although the magnitudes of any small-time-scale fluctuations are likely also to be of smaller amplitude than those observed from, e.g., PKS 2155-304 observed by H.E.S.S., nevertheless, if the larger statistics obtainable with CTA were to reveal structures with time-scales an order of magnitude shorter than that observed from PKS 2155-304, but with similar energies and from similar redshifts, sensitivity to $M_1 \sim 10^{19}$ GeV $\sim M_P$, the characteristic mass-scale of quantum gravity, might again be attained.

The principal competition for CTA in probing Lorentz violation with photons will be provided by experiments studying emissions from GRBs, such as Fermi GBM/LAT. However, since a refractive index $\eta \sim E_\gamma/M_1$ yields a time delay proportional to $K(z)$ (2), which is significantly nonlinear at large redshifts, there is no great advantage in sources with $z > 1$. Rather, consolidation of the sensitivity attained with GRB 090510 will require significantly more statistics of comparably energetic photons, which are currently in short supply with the Fermi satellite. Moreover, establishment of a solid limit on M_1 (either lower or upper) would require concordant measurements with different classes of sources, with their different source effects, e.g., both GRBs and AGNs.

It should also be emphasized that CTA will come into its own when the sensitivity to a possible quadratic dependence of the speed on energy is considered, in view of its ability to measure photons of much higher energies than those typical of GRB emissions. Another point worth remembering is that, in at least some models of space-time foam, such as the inhomogeneous D-particle foam model^{3,13}, the refractive index may vary with redshift. In order to avoid this ambiguity, one should compare with measurements of AGNs those of emissions from GRBs with similar redshifts $z = \mathcal{O}(0.1)$. The sensitivity to Lorentz violation provided by GRBs in this z range is currently significantly less than that attained with AGN measurements.

As already mentioned, there is no direct comparison between photon probes of Lorentz violation and probes using other particles. Specifically, we would not expect similar effects for charged particles such as electrons, protons and neutrinos ν ¹⁷.

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References

1. J. A. Wheeler and K. W. Ford, *Geons, black holes, and quantum foam : a life in physics* (Norton, New York, 1998) ISBN 0-393-04642-7.
2. G. Amelino-Camelia, J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, S. Sarkar, *Nature* **393** , 763 (1998); G. Amelino-Camelia, J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, *Int. J. Mod. Phys. A* **12** , 607 (1997).
3. J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, *Gen. Rel. Grav.* **32** , 127 (2000); J. R. Ellis, N. E. Mavromatos, M. Westmuckett, *Phys. Rev. D* **70** , 044036 (2004); *ibid.* **71** , 106006 (2005).
4. J. R. Ellis, K. Farakos, N. E. Mavromatos, V. A. Mitsou, D. V. Nanopoulos, *Astrophys. J.* **535** , 139 (2000) .
5. L. Gonzalez-Mestres, arXiv:physics/9712005; arXiv:physics/9708028.
6. R. Gambini, J. Pullin, *Phys. Rev. D* **59** , 124021 (1999).
7. G. Amelino-Camelia, *Int. J. Mod. Phys. D* **11** , 35 (2002); J. Magueijo, L. Smolin, *Phys. Rev. Lett.* **88** , 190403 (2002).
8. V. A. Kostelecky, arXiv:hep-ph/9912528 and references therein.
9. R. C. Myers, M. Pospelov, *Phys. Rev. Lett.* **90** , 211601 (2003); J. Alfaro, L. F. Urrutia, *Phys. Rev. D* **81** , 025007 (2010).
10. P. Horava, *Phys. Rev. D* **79** , 084008 (2009); M. Visser, *ibid.* **80** , 025011 (2009).
11. J. Polchinski, *Phys. Rev. Lett.* **75** , 4724 (1995); hep-th/9611050.
12. J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, *Phys. Lett. B* **665** , 412 (2008); T. Li, N. E. Mavromatos, D. V. Nanopoulos, D. Xie, *ibid.* **679** , 407 (2009).
13. J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, *Int. J. Mod. Phys. A* **26** , 2243 (2011).
14. G. D. Moore and A. E. Nelson, *JHEP* **0109** , 023 (2001).

15. J. R. Ellis, N. E. Mavromatos, A. S. Sakharov, *Astropart. Phys.* **20** , 669 (2004); J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, A. S. Sakharov, *Int. J. Mod. Phys. A* **19** , 4413 (2004).
16. S. R. Coleman, S. L. Glashow, *Phys. Rev.* **D59** , 116008 (1999); T. Jacobson, S. Liberati, D. Mattingly, *Nature* **424** , 1019 (2003); *Annals Phys.* **321** , 150 (2006); N. E. Mavromatos, *Int. J. Mod. Phys. A* **25**, 5409 (2010); S. Liberati, L. Maccione, *J. Phys. Conf. Ser.* **314** , 012007 (2011).
17. J. Ellis and N. E. Mavromatos, *Astropart. Phys.* **43**, 50 (2013).
18. G. Hermann [CTA Collaboration], *Nucl. Phys. Proc. Suppl.* **212-213** , 170 (2011).
19. M. K. Daniel *et al.* [CTA Consortium Collaboration], arXiv:1508.06622; *Nucl. Part. Phys. Proc.* **265-266**, 314 (2015).
20. P. Kaaret, *Astron. Astrophys.* **345**, L32 (1999).
21. S. D. Biller *et al.*, *Phys. Rev. Lett.* **83**, 2108 (1999).
22. J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, A. S. Sakharov, *Astron. Astrophys.* **402** , 409 (2003); J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos, A. S. Sakharov and E. K. G. Sarkisyan, *Astropart. Phys.* **25**, 402 (2006); [*Astropart. Phys.* **29**, 158](E) (2008).
23. J. Albert *et al.* [MAGIC Collaboration], J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, A. S. Sakharov and E. K. G. Sarkisyan, *Phys. Lett.* **B668**, 253 (2008).
24. A. Abramowski *et al.* [HESS Collaboration], *Astropart. Phys.* **34**, 738 (2011).
25. M. Ackermann *et al.* [Fermi GBM/LAT Collaboration], *Nature* **462** , 331 (2009); F. de Palma [Fermi-LAT and Fermi GBM Collaborations], *AIP Conf. Proc.* **1223** , 173 (2010).
26. Z. Bosnjak and P. Kumar, *Mon. Not. Roy. Astron. Soc.* **421**, 39 (2012).
27. Z. Chang, Y. Jiang and H. Lin, *Astropart. Phys.* **36**, 47 (2012).
28. M. Galaverni, G. Sigl, *Phys. Rev. Lett.* **100** , 021102 (2008); *Phys. Rev.* **D78** , 063003 (2008); L. Maccione, S. Liberati, G. Sigl, *Phys. Rev. Lett.* **105** , 021101 (2010).
29. S. Gardner and D. C. Latimer, *Phys. Rev. D* **82**, 063506 (2010); D. C. Latimer, *ibid.* **88**, 063517 (2013).
30. T. M. Kneiske and H. Dole, *Astron. Astrophys.* **515**, A19 (2010).
31. R. J. Protheroe, H. Meyer, *Phys. Lett.* **B493** , 1 (2000).
32. F. Aharonian *et al.* [HEGRA Collaboration], *Astrophys. J.* **546** , 898 (2001).
33. E. Dwek and F. Krennrich, *Astrophys. J.* **618**, 657 (2005) ; M. Orr, F. Krennrich and E. Dwek, *Astrophys. J.* **733**, 77 (2011).
34. M. Fairbairn, A. Nilsson, J. Ellis, J. Hinton and R. White, *JCAP* **1406**, 005 (2014).