Astroparticle Physics Connections to the Quantum Gravity Problem

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Introduction

The Universe can be used as a formidable laboratory for high-energy physics. In contrast to particle physics at colliders where the experimental environment is well controlled, astroparticle physics deals with elementary particles in “natural” environments where diverse astrophysical processes are at play. While this can introduce an additional level of complexity in the physical interpretation of data, the particle energies achievable by cosmic accelerators are beyond the capabilities of man-made accelerators (see Fig. 1) and these high-energy particles propagate over cosmological distances, offering unique opportunities to address fundamental physics aspects.

The question of quantum gravity (QG) remains unanswered, as no consistent theory combining quantum field theory and general relativity have been found so far. Theories of QG have been developed based on mathematical consistency arguments but the lack of observational evidence due to the extremely small expected effects renders very difficult to properly test and guide such speculative theories. This situation is changing as more and more efforts are put into developing a phenomenology of QG, searching for viable experimental tests in various fields, and astroparticle physics offers many attractive possibilities. We briefly present here selected astroparticle aspects relevant in the experimental search for QG mainly focused on Planck-scale tests of Lorentz symmetry, in the perspective of current and future experimental facilities.

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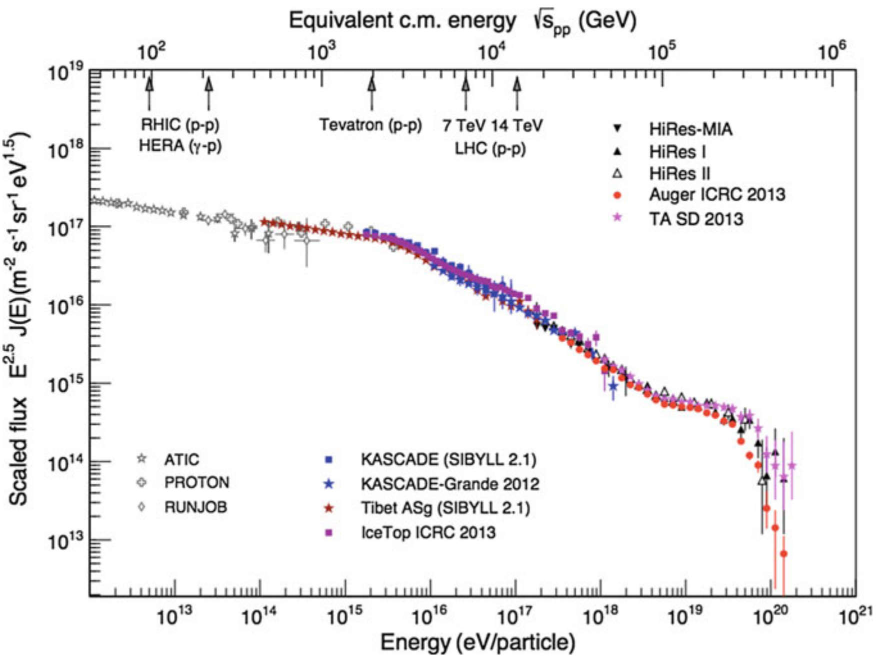

Fig. 1 Measurements of the all-particle cosmic ray spectrum (mainly protons). For comparison the center of mass energy reached at proton collider experiments is shown on the *upper horizontal axis*. Compilation of data by R. Engel, shown at RICAP16 conference

Lorentz Invariance Violation and Modified Dispersion Relations

A feature appearing in some approaches to QG is Lorentz invariance violation (LIV). Lorentz symmetry is a pillar of special relativity and has been established to be an exact symmetry of Nature up to the precision of current experiments. This symmetry is related to the scale-free nature of Minkowski spacetime, consequently the discretization of spacetime and the emergence of a fundamental length scale could mean that Lorentz symmetry is finally not an exact symmetry of Nature [11]. Such a fundamental scale is thought to be around the Planck scale (Planck length $l_{Pl} = \sqrt{\hbar G/c^3} \simeq 1.6 \times 10^{-35}$m, and Planck energy $E_{Pl} = \sqrt{\hbar c^5/G} \simeq 1.2 \times 10^{28}$eV). These quantities constructed using the fundamental physics constants for special relativity (c), quantum mechanics ($\hbar$) and gravitation (G), are the length and energy scales at which relativistic quantum effects of the gravitational interaction are expected to become significant.

Although Planck energy seems experimentally out of reach it has been recognized that LIV could leave distinctive signatures at lower energies, resulting in qualitatively new or distorted phenomena, and that Planck scale sensitivity to LIV could be achieved with already available astrophysical data [4] [3].

A generic and effective approach to introduce LIV effects consists of adding an extra term in the energy-momentum dispersion relation of particles, of the form [10]

$$E^2 = m^2c^4 + p^2c^2\left[1 \pm \left(\frac{pc}{\xi E_{Pl}}\right)^n\right], \quad (1)$$

where E, m, p are respectively the energy, mass, and momentum of the particle, ξ is a dimensionless parameter comparing the LIV scale to Planck scale (parameter possibly depending on the type of particle), and n is the leading order of the perturbation, the simplest natural possibility being $n = 1$.

The consideration of such modified dispersion relations with no other modification to the theory may not necessarily be valid in a fully consistent framework but this toy-model approach to LIV permits the exploration of a rich phenomenology in astroparticle physics. Two aspects that have been actively explored are time delays in the arrival time of high energy photons that could be the sign of an energy-dependent speed of light, and propagation anomalies for the most energetic cosmic rays or photons that could be due to the modification of the energy threshold of particle interactions.

Time-of-Flight Studies

The realization of Eq. 1 in Nature would induce a energy-dependent velocity for photons. Consequently, photons with an energy difference ΔE emitted simultaneously and propagating over a distance l would acquire an arrival time difference Δt with respect to the standard Lorentz invariant scenario

$$\Delta t \simeq \frac{\Delta E}{\xi E_{Pl}}\frac{l}{c}, \quad (2)$$

where we see that this time-lag is most likely to be observable when E and l are large. The ideal experimental setup to test this effect would then consist of a beam of photons with an energy spectrum going up to very high energies placed at the furthest possible distance from the observer and suddenly turned on in order to compare the arrival time of photons in different energy bands. Such a situation is approximately realized in the observations γ rays coming from γ-ray bursts (GRB) at cosmological distances or during the flares of active galaxy nuclei (AGN). The progresses of γ-ray astronomy over the last decade have allowed significant progresses in that direction.

In the GeV band (high-energy γ-ray astronomy, $E_\gamma > 100$ MeV) the Fermi satellite has observed hundreds of GRBs since it began science operations in 2008. Bright and energetic GRBs with a known redshift (emission distance) can be used to put limits on the LIV scale. The best constraint to date comes from GRB 090510, with a limit up to $\xi \gtrsim 7$ [7] for the case in which higher energetic photons are slowed down (minus sign of the perturbation in Eq. 1) with $n = 1$ (configuration we will call subluminal linear LIV). The analysis of other GRBs have led to lower constraints, and in some cases results even suggest a linear energy-dependent correction to the velocity of photons like in the case of GRB 160509A with $\xi \simeq 0.03$ [15]. The apparent tension between those results and the ones obtained with other methods (see below) can be explained considering intrinsic energy-dependent variability in the γ-ray emission processes of some GRBs. In the TeV band (very high-energy γ-ray astronomy, $E_\gamma > 100$ GeV) the current generation of ground-based atmospheric Cherenkov telescopes (like HESS, MAGIC or VERITAS) has observed flares of AGN with rapid and intense flux variations. In particular the exceptional flare of PKS 2155-304 observed by HESS led to the limit $\xi \gtrsim 0.2$.

Time-of-flight studies with γ rays will benefit from the accumulation of data and population studies of both AGNs and GRBs will allow to disentangle intrinsic energy-dependent variability or other systematic effects from genuine LIV.

Photons and neutrinos could be affected by LIV differently. Testing such an idea now starts to be possible with the advent of sensitive high-energy neutrino experiments like IceCube, the south pole neutrino observatory. Although no astrophysical neutrino event have yet been associated with a γ-ray source, correlation studies of neutrinos with GRBs start to be feasible [2] and time-of-flight studies with neutrinos are an exciting and largely unexplored territory (not to mention the infamous 2011 OPERA anomaly, which turned out to be due to an instrumental effect).

Modification of Reaction Thresholds

Another consequence of Eq. 1 concerns the modification of the energy threshold of interactions between the most energetic particles propagating over extragalactic distances and low energy background photons.

Soon after the discovery of the cosmic microwave background (CMB) in 1964 it was realized that such a low-energy background radiation (Fig. 2) filling the Universe could act as a target material for high-energy particles, reducing their mean free path of propagation. For protons, the critical energy at which the the interaction with a CMB photon allow the resonant creation of pions through the reaction $p + \gamma \to \Delta^+ \to p + \pi^0$ is $E_{GZK} \sim 5 \times 10^{19}$ eV. The observed cosmic ray spectrum is then expected to be rapidly suppressed around E_{GZK}, feature known as the GZK cut-off [9, 16]. In the case of Planck-scale LIV this threshold energy is affected (either enhanced or suppressed depending on the sign of the perturbation in Eq. 1) and the observations of anomalies could be attributed to LIV. While early results showed some signs of absence of the GZK cut-off, the recent results from the Pierre Auger Observatory unambiguously show a suppression of the cosmic ray flux at energies above 4×10^{19} eV [1] suggesting that the GZK prediction of spectral steepening have been verified, leading to stringent constraints on LIV for protons up to $\xi \gtrsim 10^4$

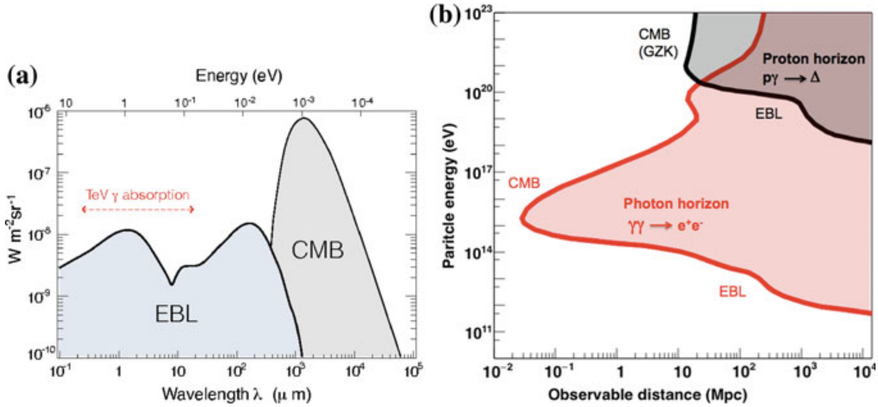

Fig. 2 *Left*: Energy distribution of low energy background photon fields in the Universe, see text (Courtesy of H. Dole). *Right*: Corresponding photon (*red*) and proton (*black*) energy-dependent horizon defined as their mean free path of propagation in Mpc (1 pc $\simeq$ 3.26 light-years)

[6] although this bound is dependent on the mass composition of the most energetic events which may not be exclusively protons but also heavier nuclei.

An interesting alternative possibility to study the GZK cut-off could be to look for the ultra-high energy neutrinos resulting from the decay of pions created in the GZK reaction. A reduction of the interaction rate due to LIV would induce a reduction of the associated neutrino flux [14]. Experiments like the ARIANNA radio array will have the sensitivity to detect these so-called cosmogenic neutrinos, possibly offering an additional way to put constraints on Planck-scale LIV.

For high-energy γ rays, background fields like the CMB also induce a reduction of the mean free path due to the electron-positron pair creation reaction $\gamma\gamma \rightarrow e^+e^-$ (see Fig. 3). The energy threshold for this reaction is reached when $E_{\gamma_{HE}} \simeq \frac{m_e^2}{E_{\gamma_{LE}}}$. For a low-energy photon at the typical CMB energy $E_{\gamma_{LE}}$, the required γ-ray energy $E_{\gamma_{HE}}$ exceeds several hundreds of TeV. This energy range is slightly beyond the capabilities of the currently operating γ-ray experiments and no such ultra-energetic γ rays have been detected so far. However, the CMB is not the only low-energy background photon field filling the extragalactic medium ; the integrated starlight of the Universe and its reprocessing by interstellar dust gives rise to what is called the extraglactic background light (EBL) made of photons in the optical and infrared energy bands. Attenuation due to pair creation on the EBL affects TeV γ-ray fluxes, which is precisely the maximum sensitivity range of atmospheric Cherenkov telescopes detecting the EBL attenuation effect in the energy spectra of AGNs with a high significance. An exceptional flare of the nearby AGN Mrk 501 in 2014 have allowed the measurement by HESS of a spectrum extending significantly up to 20 TeV in agreement with our current knowledge of the EBL [12], leading to the limit $\xi \gtrsim 2$ in the case of linear subluminal LIV perturbations affecting only photons.

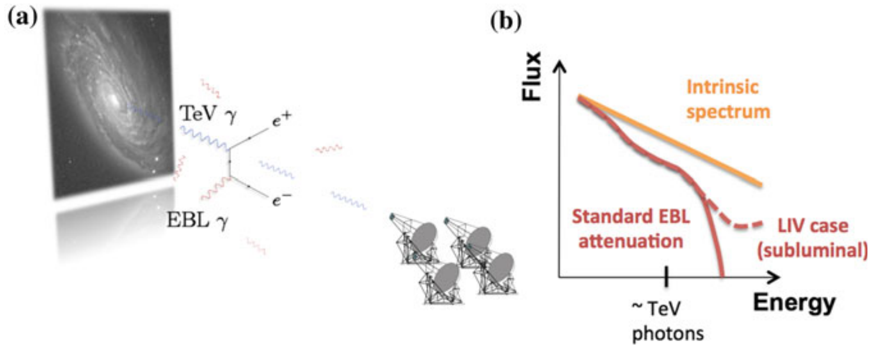

Fig. 3 *Left*: Illustration of the EBL pair production process for TeV photons propagating from an AGN. *Right*: Illustration of the principle allowing LIV constraints via the non-observation of deviation with respect to standard attenuation in the measured spectrum of a TeV γ-ray source

LIV studies with cosmic rays or γ-rays represents the major part of QG-related searches in astroparticle physics. In addition to the above-mentioned observational constraints, other possible LIV effects can be investigated like vacuum Cherenkov effect, photon decay, or cut-off in the synchrotron emission of the Crab nebula which actually provide the most stringent constraints on anomalous dispersion relation for electrons. The interested reader can find more complete informations in reviews like [11].

Other Astroparticle Windows to QG

Spacetime Interferometry

One aspect of the quantum nature of spacetime could be its “foaminess" at a scale close to the Planck lenght. While this notion of spacetime foam remains loosely defined, the basic idea is that Planck-scale spatial uncertainties may induce path-length fluctuations in the propagation of particles and the associated phase shifts (increasing with energy) could accumulate over large distances, affecting the image formation of distant sources. Models of spacetime foam are characterized by a parameter α related to the path-length fluctuation δl for a source at distance l by $\delta l = l^{1-\alpha} l_{Pl}^{\alpha}$.

Recent studies have explored the potential effects of spacetime foam, predicting a possible energy-dependent image blurring of distant astronomical objects or even the total disappearance of images because of accumulated wavefront distortions on small scales. In such a framework the mere observation of TeV γ-ray point sources at a cosmological distance can be used to put significant constraints on models of spacetime foam with a lower bound $\alpha \gtrsim 0.7$ [13].

Fast TeV Transient Signals as White Holes Bursts?

QG may allow a black hole to tunnel into a white hole, and this transition may induce a detectable burst. This possibility have been recently explored in the context of loop QG theories [5] and within this framework the lifetime of a black hole would be shorter than the one given by Hawking evaporation. For stellar-mass black holes the typical lifetime is still far too long to expect the observation of such bursts but low-mass primordial black holes formed in the early universe—if they exist—could be bursting today at a high rate. This could open a new window for quantum-gravity phenomenology as such a white hole burst is predicted to be associated with a short (millisecond) emission of photons in two different channels: a low-energy signal with radio wavelengths reflecting the size of the black hole reaching a critical density, and a high-energy signal reflecting the typical medium temperature at the time of the black hole formation, which for the very early Universe corresponding to the black hole masses considered is around the TeV scale.

Experimental investigation of this idea could benefit from already existing studies on the search for primordial black hole bursts at TeV energies like in [8]. Moreover, the possibility that the low-energy signal could be associated with the intense fast radio bursts (FRBs) of unknown nature is tempting, although many conventional astrophysical scenarios are being developed to explain their origin, and more data will be needed for reliable interpretations. The observation of a simultaneous TeV counterpart to a FRB could spark more interest for this idea. In this perspective, the triggering strategies for TeV follow-up observations of rapid transients like FRBs with current and future Cherenkov telescopes arrays may provide interesting insights, together with wide field of view TeV monitoring experiments like the currently operating High Altitude Water Cherenkov (HAWC) Gamma-ray Observatory.

Conclusion

The study of the most energetic cosmic particles like protons photons or neutrinos offers an experimental connection to the QG problem and has to some extent already allowed to limit the reasonable possibilities that might arise from fundamental Planck scale physics. The non-detection of anomalies that could have been interpreted as evidence for LIV in a simple framework automatically discard QG theories where effects due to Planck scale linear perturbations show up too easily. In the near-future, the increase in statistics due to the accumulation of data from current experiments and the increase in sensitivity with the advent of new generations of experiments (like the Cherenkov Telescope Array) will strengthen the already-existing constraints, enable more complex analyses, and data may also reveal unexpected surprises. Moreover the birth of gravitational wave astronomy and the opening possibilities of multimessenger astronomy using altogether photons neutrinos and gravitational waves will provide very interesting insights in the experimental search for QG.

On the theory side, the development of models associated with a clear phenomenology is essential to maintain a reasonable predictive power of theories. Ideally, QG theories should be able to predict smoking-gun signals for which it is conceivable to arrive at experimental signatures that can be disentangled from systematic effects, either of instrumental or astrophysical origin. A close collaboration between theorists and experimentalists in the field will certainly allow the exploration of new exciting possibilities. In this perspective astroparticle physics could be an active and rich area in the experimental search for QG for the decades to come.

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