BCAS Vol.33 No.3 2019

Prospects on Testing Lorentz Invariance Violation with LHAASO Observations

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Einstein's theory of special relativity is an important cornerstone of modern physics, with a wide application in the fields of astronomy and fundamental physics. It is therefore crucial to test the validity of the basic assumptions of special relativity, such as Lorentz invariance. While laboratory tests are subject to various conditions, some high-energy astrophysical phenomena, with their extreme features, have been the best testbeds for testing the assumption of Lorentz invariance. But we would need high performance telescopes, such as the ongoing Large High Altitude Air Shower Observatory (LHAASO) project located at 4,400 meters of altitude in the Sichuan province of China, to help us capture these astrophysical phenomena.

1. Space and Time Are not Continuous, but Come in Discrete Pieces?

More than one hundred years ago, most people thought of matter as continuous. Although some philosophers and scientists had long suspected that had matter be decomposed into small enough pieces, they might turn out to consist of tiny atoms, very few thought the existence of atoms could even be verified. Now we have been able to obtain the image of a single atom and have carefully studied the particles that make up it. The

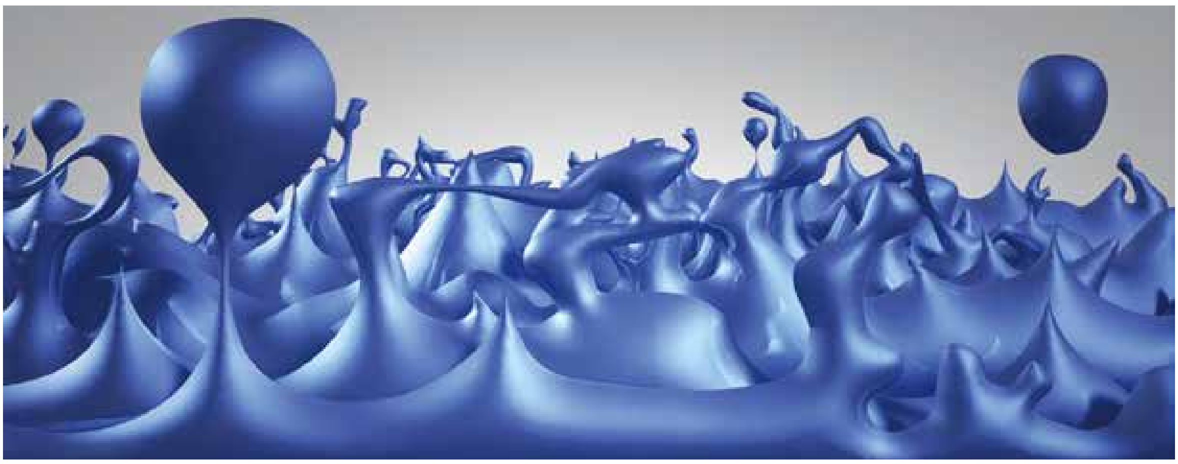

Figure 1. A cartoon picture of the foamy structure of space-time at extremely tiny scales. (Credit: NASA/CXC/M. Weiss)

discreteness of matter has become old news.

Similarly, space and time are usually considered to be continuous, but we are wondering if space and time are also made of discrete pieces. In fact, physicists and mathematicians have been exploring this issue for several decades. Is space continuous, or is it more like a piece of cloth, knitted with individual fibers? If we could probe into small enough scales, would we see "atoms" of space, inseparable pieces of volume that can not be divided into anything smaller? For time, does the natural world change continuously, or does it evolve in a series of tiny steps, acting like a digital computer? To understand the spatial structure on the very smallest size scale, scientists have developed some quantum theories of gravity that predict the granularity of space and time. These theories suggest that space comes in discrete pieces, the smallest length of which is about a Planck length, or 10^{-35} meter. Time proceeds in discrete ticks of about a Planck time, or 10^{-44} second. In these theories, space and time are not continuous, but are quantized. Space-time passes like a frame-by-frame film playing, which looks like to be continuous, but actually moves at an imperceptible tiny unit. If we gradually enlarge a region of space, space-time appears discontinuous and chaotic (see Figure 1). That is, quantum fluctuations in the space-time metric would make it appear "foamy" on short time and distance scales.

2. What Is a Quantum Theory of Gravity?

First of all, let's look at the background of the introduction of a quantum theory of gravity. Up to date, humans have discovered four fundamental forces in physics: gravity, electromagnetism, strong interaction, and weak interaction. The theory of quantum mechanics was formulated in the early 20th century. Quantum theory successfully describes the behavior of microscopic particles, completely changing our understanding of material structure and interaction. Except for gravity, other three fundamental forces can be well described within the context of quantum mechanics. The most accurate theory to describe the gravitational interaction of macroscopic matter is Einstein's theory of general relativity. In this theory, the gravitational force arises as a consequence of space-time being curved by the presence of matter. Since quantum mechanics and general relativity have each been fantastically well confirmed by experiments, they have been the two major theory pillars of modern physics.

At present, what physicists are trying to do is to combine four fundamental interactions and to create a grand unified theory that can describes everything. Quantum gravity is such a kind of theory that wants to put quantization into general relativity and to unify four fundamental interactions including gravity. However, how to apply the concept of quantum theory into the framework of general relativity is still an open question. Quantum theory and Einstein's theory of general relativity are like two separated kings, who rule their own kingdoms very well and have no conflicts between them – not until one day, the two kings are invited to discuss the possibility of establishing a united kingdom, which turns out to be too difficult. Besides the linguistic barrier, many other things can not be combined. Although quantum mechanics and general relativity are not fully integrated, it is believed that there is a more fundamental theory of quantum gravity that can uniformly describes gravity and quantum physics. Current popular models of quantum gravity include string theory, loop quantum gravity, double special relativity, and so on. If readers are interested in these models, they can refer to relevant references.

3. The Assumption of Lorentz Invariance

Lorentz invariance mirrors the fundamental symmetry of Einstein's special relativity, which indicates that the physical laws of a non-accelerating physical system are invariant when this system undergoes Lorentz transformation. However, deviations from Lorentz invariance at the Planck energy scale $E_{\rm Planck}\approx 1.22\times 10^{19}$ GeV (or at the Planck length 10^{-35} meter) are predicted in various quantum gravity theories attempting to unify quantum mechanics and general relativity. Thus, precision test of Lorentz invariance can be pointing to a correct path to the unified theoretical model. Over the past few years, a lot of researches on Lorentz invariance violation (LIV) have been carried on in the field of high-energy astrophysics.

As described in Section 1, many quantum gravity models predict that at small spatial scales space-time is no longer smooth, but presents "foamy". The propagation of light through this space-time foam might exhibit a non-trivial dispersion relation in a vacuum. In this bumpy space-time, high-energy photons with shorter wavelengths should be slower than low-energy photons with longer wavelengths (some other models expect that high-energy photons travel faster than low-energy photons, referred to as the "superluminal" case), see Figure 2. As a consequence of LIV, the speed for the propagation of photons would become energy-dependent, instead of a constant speed of light in a vacuum. Since photons with higher energies are more likely to interact with the foamy structure of space-time at small spatial scales, they propagate slower than those with lower energies. The LIV induced modifications to the photon dispersion relation can be expressed as $\left|\frac{v}{c}-1\right| \approx \left(\frac{E}{E_{QG,n}}\right)^n (n+1)/2$, where $E_{QG,n}$ denotes the quantum gravity energy scale. Since it is generally expected for quantum gravity to manifest itself fully at the Planck scale, the Planck energy scale is a natural threshold at which Lorentz invariance is predicted to be broken. If the derived quantum gravity energy scale is bigger than the Planck energy scale, we can exclude deviations from Lorentz invariance, and then exclude those quantum gravity models that predicting the existence of LIV.

Due to the photon dispersion relation, two photons with different energies emitted simultaneously from the same source would arrive on Earth at different times. The arrival time differences are $\Delta t = \left(\frac{\Delta E}{E_{QG,1}}\right) d/c$ for the linear (n=1), and $\Delta t=(\Delta E/E_{QG,2})^2 3d/2c$ for the quadratic (n=2) LIV effects, respectively. Here ΔE is the energy difference and d is the distance of the source. One can see from these two equations that sources with shorter time delays, higher frequencies, and longer distances would set more stringent limits on the quantum gravity energy scales.

The LHAASO project is a new generation multi-component instrument, with the aim to study the origin of high-energy cosmic rays, the evolution of high-energy celestials, and new frontier physics. Two LHAASO detectors can be used to make gamma-ray observations,

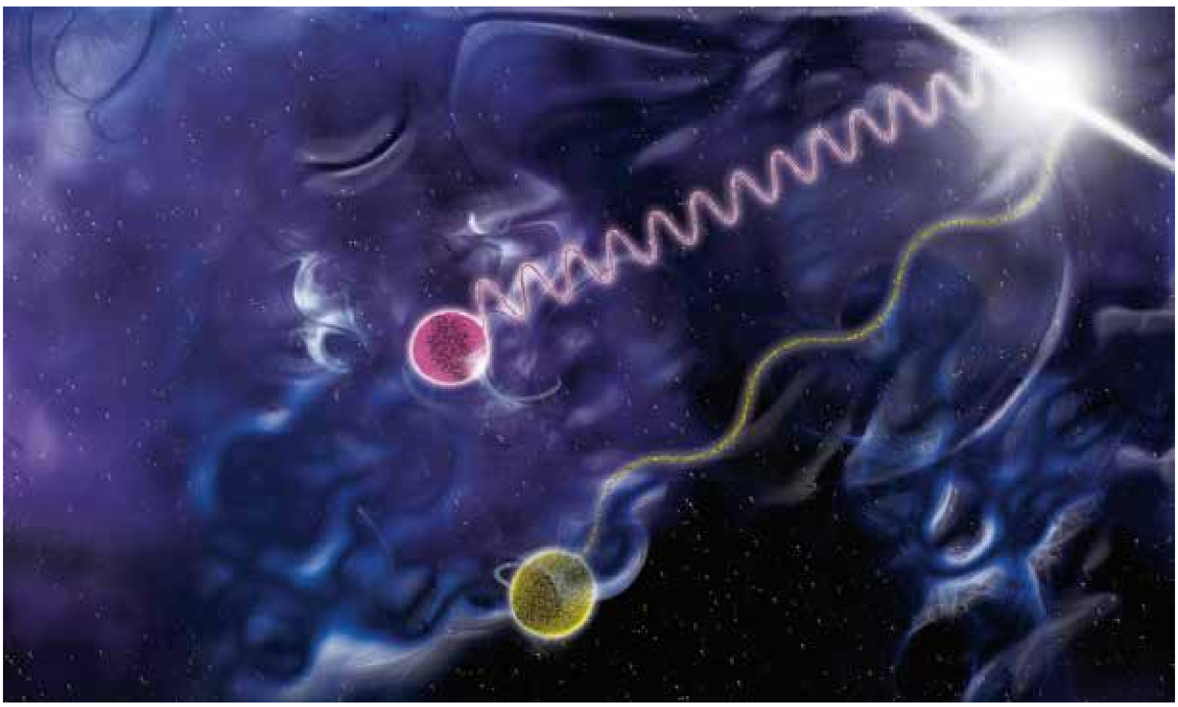

Figure 2. A cartoon picture shows two photons with different energies travel at different velocities in the bubble-like space-time. (Credit: NASA/Sonoma State University/Aurore Simonnet)

covering the energy range from about 10^{11} to 10^{15} eV. Its Water Cerenkov Detector Array (WCDA) can detect photons in the energy range between ~0.1 to 10 TeV, and the Kilo-Meter Square Array (KM2A) can detect photons with energies higher than 10 TeV. LHAASO is the most sensitive instrument to observe gamma-ray emissions above 30 TeV. Obviously, with higher sensitive and wider energy ranges, LHAASO will be able to detect more and more high-energy gamma-ray emission sources. With these abundant observational information, more stringent limits on LIV could be expected in the era of LHAASO.

4. Astrophysical Tests of LIV in History

Lorentz invariance can be tested by comparing the arrival-time differences of photons with different energies originating from the same astrophysical source. Note that the time-of-flight method applies to the situation that these two photons with different energies are emitted simultaneously from the source. So far, some high-energy astrophysical phenomena, such as gamma-ray bursts and blazars, have been widely used to test Lorentz invariance.

4.1Gamma-ray bursts

Gamma-ray bursts (GRBs) are powerful flashes of high-energy photons occurring at cosmological distances. According to their duration times, GRBs are usually classified into long GRBs (with durations longer than 2 second) and short GRBs (with durations shorter than 2 second). As the most energetic explosions in the universe, GRBs can be detected up to very high redshifts.

Thanks to their short duration times, cosmological distances, and very high-energy photons, GRBs have been viewed as the most promising sources for probing the LIV effect. In 2008, the high-energy emission of long GRB 080916C was detected by the Fermi Large Area Telescope (LAT). Abdo *et al*. (2009a) used the time lag of 16.5 s between the highest energy (13.2 GeV) photon and MeV photons from GRB 080916C to constrain the linear LIV energy scale and presented a strict limit of 1.3×10^{18} GeV, improving previous limits by at least one order of magnitude. But this limit is still one order of magnitude below the Planck energy scale (1.22×10^{19} GeV). Compared to long GRBs, short GRBs with shorter duration times are more favorable to constrain Lorentz invariance. By analyzing the arrival time delay (much less than 1 s) between a 31 GeV photon and the low-energy (trigger) photons from short GRB 090510, Abdo *et al*. (2009b) set the best so far limit on the linear LIV energy scale, yielding $E_{QG,1}$>(1–10)E_{Planck}. We can see that the linear LIV case can be ruled out by GRB 090510. Subsequently, Vasileiou *et al*. (2013) used three different techniques to constrain the degree of dispersion observed in four GRBs, improving the latest constraints by Fermi by a factor of ~2.

Although the limits on LIV have reached high precision, most were based on the rough time lag of a single highest-energy photon. It is necessary to consider using the true time lags of high-quality and high-energy light curves in different energy multi-photon bands to constrain the LIV effect. Furthermore, the method of the flight-time difference used for testing LIV is hindered by our ignorance concerning the intrinsic time lag that

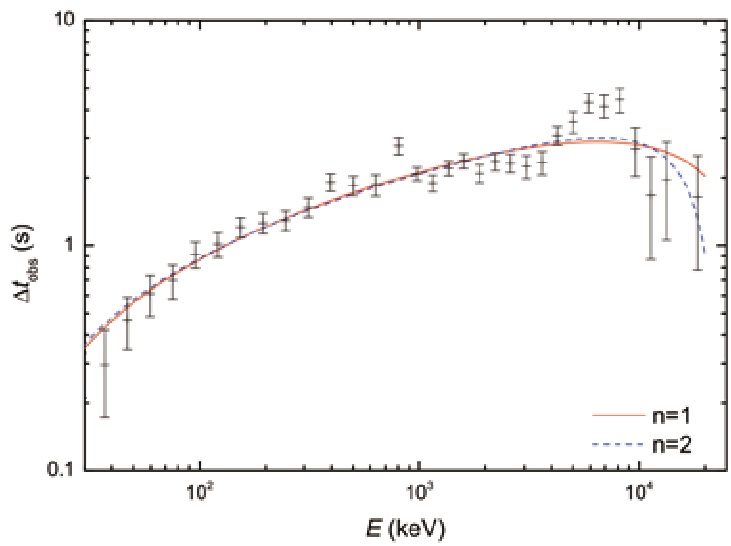

Figure 3. Energy dependence of the observed spectral lag (relative to the softest band), and the best-fit theoretical curves: (solid line) the linear LIV model; (dashed line) the quadratic LIV model. [Image adopted from Wei *et al*. (2017)]

depends on the unknown emission mechanism of GRBs. Most previous studies concentrated on the time delay induced by LIV and neglecting the intrinsic time lag, which would impact the reliability of the resulting constraints on LIV. The first attempt to disentangle the intrinsic time delay problem was presented by Ellis *et al*. (2006). They proposed working on a statistical sample of GRBs at a range of different redshifts, and formulated the problem in terms of a linear regression analysis where the intercept represents the average intrinsic time lag of different GRBs, and the slope corresponds to the quantum gravity energy scale related to the LIV effect. In 2017, Wei *et al*. (2017) first proposed that GRB 160625B, the only burst to date with a well-defined transition from positive to negative lags, provides a good opportunity to put new constraints on LIV. Using multi-photon energy bands they considered the contributions to the observed spectral lag from both the intrinsic time lag and the lag by the LIV effect, and assuming the intrinsic time lag to have a positive dependence on the photon energy, they obtained robust limits on LIV by directly fitting the spectral lag data of GRB 160625B (see Figure 3). In addition, they gave, for the first time, a reasonable formulation of the intrinsic energy-dependent time lag. The strategy of analysis proposed in this work is novel: it has some reference value to the emerging field of quantum-gravity phenomenology, and it allows to place conservative limits, which are a much bigger asset for the development of the field than the usual "conditional limits".

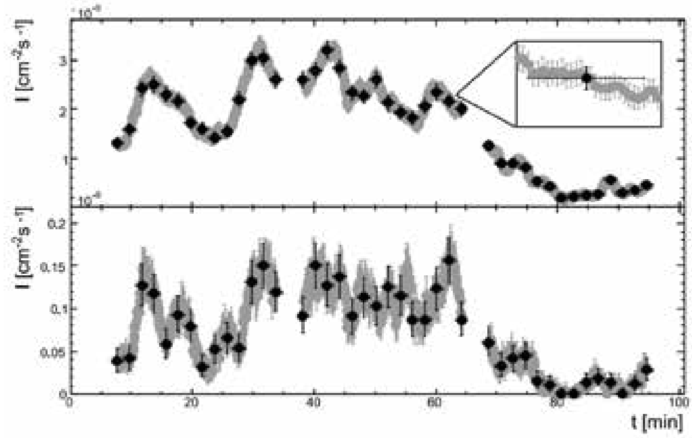

Figure 4. The integral flux VHE light curves observed on July 28, 2006 from PKS 2155-304 by H.E.S.S. between 200 and 800 GeV (upper panel) and >800 GeV (lower panel). [Image adopted from Aharonian *et al*. (2008)]

4.2 TeV blazars

Among the extragalactic very-high-energy (VHE) gamma-rays (E>100 GeV) known to date, the so-called TeV sources, most are blazars. Blazars are an extreme subclass of active galactic nuclei, which can be further classified into flat spectrum radio quasars if they have strong emission lines and BL Lacertae objects if they have weak or no emission lines. Blazars are characterized by broadband non-thermal emissions extending from radio up to high-energy and VHE gamma-rays, and a display of violent variability on different timescales from minutes to years. The broadband radiation originates within a relativistic jet that is oriented very close to the line of sight.

Because of their rapid flux variation, cosmological distances, and VHE photons in the TeV range, TeV blazars have also been deemed as an effective probe to study the LIV effect. It should be underlined that testing LIV with both GRBs and TeV blazars is of fundamental interest. GRBs can be observed at very large distances (up to z~8), but with very limited statistics of photons above a few tens of GeV. On the contrary, TeV blazars can be well detected by ground-based telescopes with large statistics of photons above a few tens of TeV. But due to the absorption of high-energy photons by extragalactic background light, TeV observations are limited to sources at low redshifts. Thus, GRBs and TeV blazars are mutually complementary in constraining LIV, and they enable us to test different energy and redshift ranges.

To date, the best limit on LIV obtained with blazars is from the observations of PKS 2155-304. On 28 July, 2006, the H.E.S.S. collaboration detected a VHE flare of the active galaxy PKS 2155-304. By analyzing the time delay from the 200800 GeV and >800 GeV light curves of PKS 2155-304 (see Figure 4) and adopting its redshift of z = 0.116, Aharonian *et al*. (2008) showed that the limits on the quantum gravity energy scale are $E_{QG,1}>7.2\times10^{17}$ GeV for the linear, and $E_{QG,2}>1.4\times10^{9}$ GeV for the quadratic LIV effects, respectively. Subsequently, H.E.S.S. Collaboration *et al*. (2011) used a more sensitive analysis method to determine the time lag between two light curves of PKS 2155-304. The previous limits on the linear and quadratic terms are improved by up to $E_{QG,1}>2.1\times10^{18}$GeV and $E_{QG,2}>6.4\times10^{10}$ GeV, respectively.

5. Prospects on Testing LIV with LHAASO Observations

In this section, we will discuss the potential of LHAASO to observe GRBs and TeV blazars, and predict the potential of these observations to test the LIV effect.

Recently, the MAGIC telescopes first detected the GRB 190114C in the TeV energy domain (Mirzoyan *et al*. 2019). The GRB observation of MAGIC shows a clear excess of gamma-ray emission with high significance in the first 20 min (starting about 50 s after the Swift trigger time) for energies >300 GeV. The successful detection of TeV emission from GRB 190114C makes us believe that more GRBs with VHE gamma-ray photons would be detected by LHAASO in the future. The Water Cerenkov Detector Array (WCDA), covering the energy range from 0.1 to 10 TeV, can be more useful for detecting >100 GeV photons from GRBs. The total area of WCDA is about 78,000 m^2. But the effective area of WCDA depends on the energy and zenith angle of the photon, which might be reduced to be about 3,000 m^2 for >100 GeV gamma-ray detection. With an effective area of 3,000 m^2, that is nearly 3,000 times larger than Fermi/LAT, LHAASO-WCDA can reach a much higher sensitivity at >100 GeV energy band. Fermi/LAT have already detected ~100 GeV photons from GRBs, and such high-energy photons are entirely within the reach of LHAASO-WCDA. Assuming GRBs have power-law spectra $dN(E)/dE \propto E^{-\beta}$ with a photon index $\beta \approx 2.0$, we can detect $N(>E)=\int_E^{\infty} dN(E)/dE \times dE$ photons per unit detector area. From this we can estimate the number ratio between photons above 100 GeV and those above 1 GeV: $\frac{N(>100\,\mathrm{GeV})}{N(>1\mathrm{GeV})}=100^{1-\beta}=0.01$. Assuming Fermi/LAT can detect 10 photons above 1 GeV for one high-energy burst, 0.1 photons above 100 GeV can then be detected by LAT. Hence, the number of >100 GeV photons detected by LHAASO-WCDA should be 3000. With large statistics for high-energy photons, high-energy (>100 GeV) light curves with excellent temporal resolutions can be constructed.

As mentioned above, the LIV limits from the high-energy photons observed by Fermi/LAT have reached high precision. The linear LIV has been excluded by the highest energy photon of short GRB 090510, but such a severe constraint has no support from other long GRBs. Generally speaking, a long GRB observed by Fermi/LAT would have an observed time delay of ~10 s (*i.e.*, the time lag between the arrival time of the highest energy photon and the trigger time of low-energy photons), a redshift of z=1. The maximum observed photon energy is ~50 GeV. In this case, it is possible for Fermi/LAT to set a limit of 2.5×10^{18} GeV for the linear term $E_{QG,1}$ and 5.4×10^{11} GeV for the quadratic term $E_{QG,2}$. We use the sources studied by Fermi/LAT to construct reference scenarios for the LHAASO-WCDA and establish its potential to set limits on LIV. The scenario for setting limits on LIV from GRBs is motivated by the excellent detection performance of LHAASO-WCDA. Our reference scenario is a long burst with Δt = 1 s at a redshift of z = 1, with a maximum observed photon energy of 500 GeV, within the detecting range of LHAASO-WCDA. Such a burst is certainly detectable by LHAASO-WCDA if it occurs in its field of view. The time delay assumed in this scenario is based on the fact that LHAASO-WCDA has the ability to detect hundreds to thousands of high energy photons (>100 GeV) from GRBs and high-quality, high-energy light curves with high temporal resolutions will be possible. In this scenario, it is possible for LHAASO-WCDA to set a limit of 2.5×10^{20} GeV for the linear term $E_{QG,1}$ and 5.4×10^{11} GeV for the quadratic term $E_{QG,2}$, improving current results by 1–2 orders of magnitude.

As the most sensitive instrument in the 30 TeV–1 PeV energy range, LHAASO will be capable of continuously surveying the gamma-ray sky for steady and transient sources, and have the potential to discover more and more TeV blazars. Similar to GRBs, high-quality, high-energy light curves from TeV blazars can be constructed by LHAASO, and then the true time delay between light curves of different energies can be extracted. With the future TeV source catalogue of LHAASO, we can select those TeV blazars with higher energies, shorter time delays, and longer distances to further improve the LIV limits.

6. Summary

Possible violations of Lorentz invariance have been investigated for a long time using the observed time delays of GRBs as well as TeV blazars. The current high-energy data of GRBs are mainly collected from the observations of Fermi/LAT. Due to the limited-area of space-based detector, however, only a few high-energy GRB photons have been detected by LAT. With a much larger detector area, LHAASO has the potential to detect more high-energy photons from one GRB than Fermi/LAT, making it possible to construct high-energy light curves with high temporal resolutions. By analyzing the light curves between the highest energy band and the low energy band that occurring at nearly the same time, we can reduce the observed time delay between different energy bands, and then improve the LIV limits with higher accuracy. In addition, LHAASO would be able to detect more TeV blazars with high-quality light curves in the TeV gamma-ray survey. If TeV blazars with higher energies, shorter time delays, and longer distances can be detected by LHAASO, much more competitive limits on LIV can be set.

In summary, using observations of GRBs and TeV blazars, LHAASO might bring forth notable advancements on the LIV tests.

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