Astro2020 Science White Paper

Exploring Beyond-the-Standard-Model Physics with TeV Gamma-rays

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☑ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: Observation of new physics beyond the Standard Model of particle physics would revolutionize the way we see the world. Such effects are often best searched for in the most energetic regions of space and on cosmic scales. Even small effects of new physics can reveal themselves when considered at the highest energies, over large volumes of space, and aggregated over millions of light-years. Here, we consider three well-motivated beyond-the-Standard-Model searches for which the next generation of high-energy observatories will be well-suited: dark matter in the forms of primordial black holes and axion-like particles and violations of Lorentz invariance.
The majority of the material is drawn from *Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere* [10]. If you'd like to cite results presented in this white paper, please cite the original paper.

1 Introduction

High-energy gamma-ray observations have the potential to probe fundamental physics at energy scales not accessible by earthbound accelerators as well as search for particle physics phenomena in environments much more extreme than those found on Earth. These observations enable the search for theoretical physics which goes beyond the Standard Model of particle physics. Dark matter in the form of primordial black holes or axion-like particles is readily searched for in the vast volumes of space and the high energy-density of astrophysical bodies. Grand unified theories of physics often allow for violations of Lorentz invariance, which is most easily tested over cosmic distances and at TeV or even PeV energies.

The High Altitude Water Cherenkov (HAWC) observatory, located in Mexico, uses water Cherenkov tanks to observe the extensive air showers created by $>$100 GeV photons interacting in the atmosphere. By being located in the Southern Hemisphere, a future HAWC-like observatory would be better situated than HAWC to observe the multitude of astrophysical sources near the center of the Milky Way galaxy. Additionally, a future detector would be expected to have an order of magnitude better sensitivity than HAWC, through larger detector area and other improvements such as going to higher altitude [10]. Here we consider some of the advancements that can be made in beyond-the-Standard-Model physics with such a wide field-of-view TeV Gamma-ray observatory in the Southern Hemisphere. In particular, we focus on primordial black holes, axion-like particles, and violations of Lorentz invariance.

2 Primordial Black Holes

Primordial black holes (PBH) are theoretical black holes which may have been formed in the early stages of the Universe [18]. Their mass spectrum depends on the formation mechanism and spans a large mass range. Black holes with low enough mass are expected to evaporate completely through the radiation of particles and energy at the Hawking temperature [28]. The lifetime of a PBH is

$$\tau \approx 4.55 \times 10^{-28} (M_{\mathrm{BH}}/1\mathrm{g})^3 \ \mathrm{s} \ . \tag{1}$$

That is, a PBH with an initial mass of $\sim 5 \times 10^{14}$ g in the early universe would have an evaporation time of roughly the current age of the universe [34]. In the latest stage of evaporation, the PBH emits particles at increasingly higher energies which are detectable by atmospheric or water Cherenkov detectors [43].

Gamma-ray observatories can therefore search for PBHs by looking for bursts of high-energy gamma-rays created by the last seconds of PBH evaporation. Upper limits on the local density of such evaporating PBHs have been reported by the Milagro observatory [2] and are expected to be improved by an order of magnitude by HAWC. These analyses – and related ones by atmospheric Cherenkov observatories – search for spatially-localized and short-time bursts of gamma-ray events unrelated to an astrophysical source. The choice of the time window for these searches is a compromise between signal and background, with typical time windows being 1–30 s.

The luminosity of a PBH burst decreases as the squared distance to the PBH. However, at larger distances, the number of PBHs with given luminosity is expected to *increase* as the cube of the distance. Therefore, an observatory's sensitivity to PBHs scales as the 3/2 power of its gamma-ray sensitivity. The sensitivity of a next-generation water Cherenkov observatory would be expected to be roughly ten times more sensitive than the current HAWC observatory. Assuming no PBH burst detection, the upper limit on the local rate of PBH explosion would thus be expected to improve by more than a factor of 30 compared to the HAWC limits, reaching the level of $\lesssim 130\,\mathrm{pc}^{-3}\mathrm{yr}^{-1}$.

Experiment	Burst Rate Upper Limit	Optimal Search Duration	Reference
Milagro	36000 $\mathrm{pc}^{-3}\mathrm{yr}^{-1}$	1s	[2]
VERITAS	22200 $\mathrm{pc}^{-3}\mathrm{yr}^{-1}$	30s	[13]
HESS	14000 $\mathrm{pc}^{-3}\mathrm{yr}^{-1}$	30s	[26]
Fermi-LAT	7200 $\mathrm{pc}^{-3}\mathrm{yr}^{-1}$	1.26×10^8s	[5]
HAWC (pred.)	4059 $\mathrm{pc}^{-3}\mathrm{yr}^{-1}$	10s	[2]
Next-Gen Observatory	130 $\mathrm{pc}^{-3}\mathrm{yr}^{-1}$	10s	Estimated

Table 1: The PBH burst-rate densities searched by the current generation of experiments, compared to the capabilities of a next-generation observatory with 10 times the sensitivity of HAWC. Note that the optimal search duration specifies the methodology of the search (optimizing for signal while minimizing background) rather than being a physical PBH parameter.

3 Axion-like Particles

Axion-like Particles (ALPs) are hypothesized in many theories beyond the Standard Model [30]. They are similar to axions (which were theorized to solve the "Strong CP Problem" in particle physics [40]), except their mass and coupling strength to photons are independent. ALPs would be produced non-thermally in the early Universe and could constitute some or all of the dark matter that exists today [14]. These particles could also be formed today through high-energy interactions of photons.

A next-generation HAWC-like observatory will have competitive sensitivity at very high energies ($>$10 TeV), making it well equipped to search for ALP gamma-ray signatures. One potential ALP signature would be the detection of $\gtrsim$30 TeV photons from a hard-spectrum extragalactic source. Very high energy photons produced in extragalactic sources are difficult to observe at Earth since they become attenuated through interactions with the Extragalactic Background Light (EBL). However, gamma-rays produced at the source could convert into ALPs in its strong magnetic fields or the intergalactic magnetic field. These ALPs would then travel to us without EBL attenuation. They would convert back into gamma rays in the Milky Way's magnetic field and then be detected at Earth [29, 37]. In this way, $\gtrsim$30 TeV photons could be detected that would have been attenuated by the EBL without the intermediate conversion to ALPs.

To search for ALPs in this way requires hard-spectrum extragalatic sources. Several such sources are present in the Southern Hemisphere; e.g. PKS 0447-439 (z = 0.343) [4, 38] and 1RXS J023832.6-311658 (z = 0.232) [24]. Observations of many sources of this nature by a wide field-of-view observatory would also allow for a stacked analysis to improve the search. For a concrete example, here we consider 1RXS J023832.6-311658. We match an EBL-corrected [22] spectrum to the observed spectrum [25] to produce the expected observed emission in Fig 1. We include the case where no ALPs are produced at the source and the case where ALPs are produced assuming an ALP mass of $m_a = 5$neV and ALP-photon coupling constant of $g_{a,\gamma} = 5 \times 10^{-11}\mathrm{GeV}^{-1}$ (values that are consistent with current ALP constraints [9]). Also shown are the anticipated sensitivity curves of CTA-South [42] for 50 hours of observation and a hypothetical HAWC-like array with 10x better sensitivity than

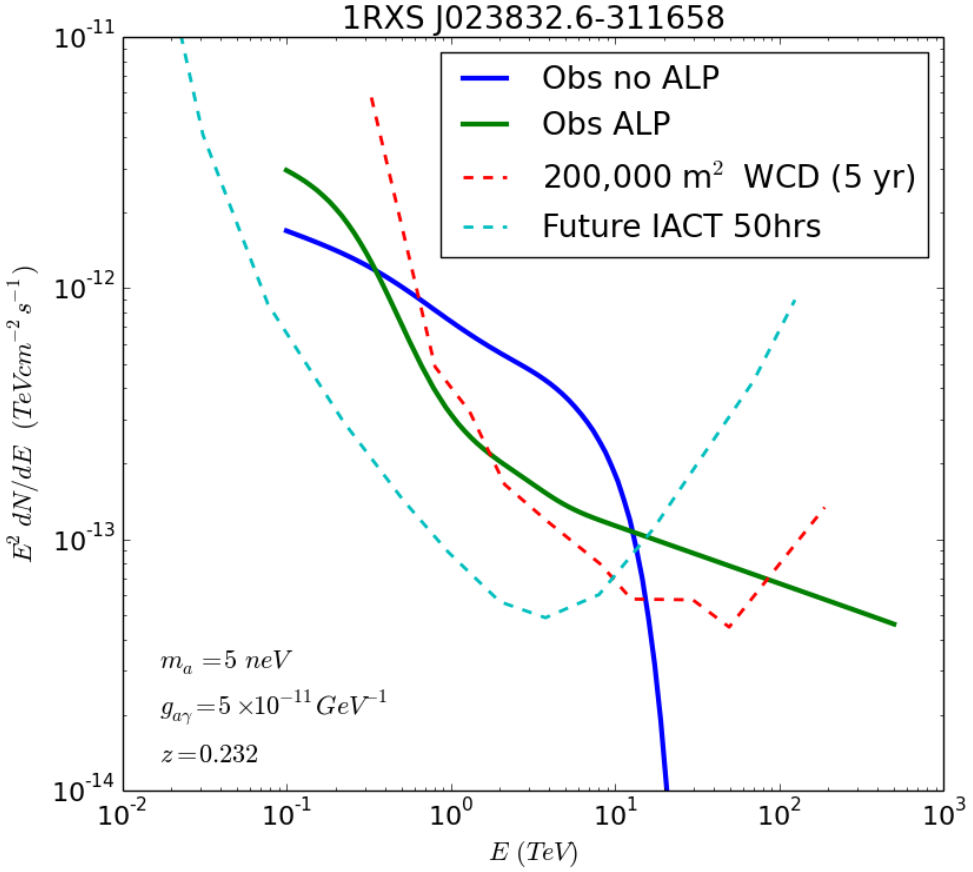

Figure 1: Expected observed spectrum from RXS J023832-311658 without and with ALPs created at the source. Also shown are the sensitivity curves for CTA-South (50 hours) and an array with 10 times better sensitivity than HAWC with 5 years of observation.

HAWC. Because such an observatory's sensitivity would be optimized for E $>$10 TeV, the difference between a cutoff or flattening of the observed spectrum would be clearly distinguishable. It should be noted that ALP conversions could also produce sharp spectral features in the observed spectrum of extragalactic sources [3, 9]. However, excellent energy resolution ($\lesssim 10\%$) is needed to resolve these features.

4 Testing Lorentz Invariance with the Highest-Energy Photons

Precise measurements of very-high-energy photons can be used as a test of the Lorentz symmetry [1, 8, 15, 20, 32, 33, 35, 44, 45]. As with any other fundamental principle, exploring its limits of validity has been an important motivation for theoretical and experimental research. Moreover, some Lorentz invariance violation (LIV) can be motivated as a possible consequence of theories beyond the Standard Model, such as quantum gravity or string theory [11, 12, 16, 17, 19, 21, 23, 31, 39, 41].
It has been shown that LIV can cause photons of sufficient energy to become unstable and

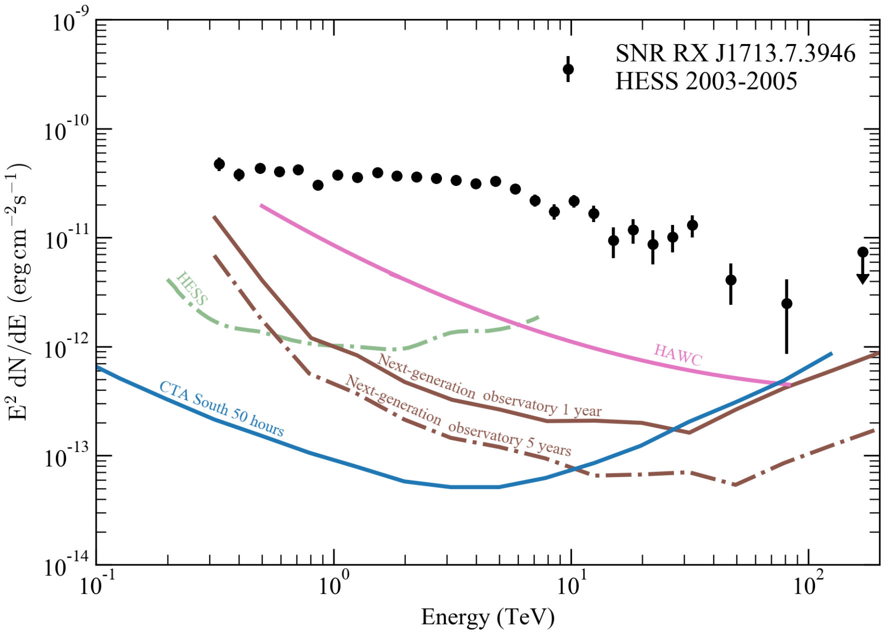

Figure 2: The RXJ1713.7-3946 source reported by H.E.S.S. [27] with the differential sensitivity threshold of H.E.S.S. and HAWC Experiments and the estimated thresholds of CTA and an array with 10 times the HAWC area (Next-generation observatory) at 1 and 5 years. Galactic sources like this supernova remnant are more readily found in a Southern Hemisphere sky, with the Galactic Center pass overhead. With the known high-energy flux, sources like this one are likely candidates for a future observatory to stringently limit LIV.

decay rapidly [36]. This strongly restricts the propagation of photons to very short distances from the source, with the photons decaying well before the can arrive at Earth. LIV is usually parameterized as an isotropic correction to the photon dispersion relation:

$$E_\gamma^2 - p_\gamma^2 = \pm \frac{E_\gamma^{n+2}}{(E_{LIV}^{(n)})^n}, \tag{2}$$

where $E_{\mathrm{LIV}}^{(n)}$ is the Lorentz invariance violation energy scale at leading order n. Superluminal effects in Eq. (2) allow photon decay, $\gamma \to e^- e^+$, above a certain energy threshold, such that no photons above that threshold should reach the Earth from astrophysical distances. Hence, a direct limit to $E_{\mathrm{LIV}}^{(n)}$ can be established by the observation of high-energy photons with energy E_γ, given by

$$E_{\mathrm{LIV}}^{(n)} > E_\gamma \left[\frac{E_\gamma^2 - 4m_{e^-}^2}{4m_{e^-}^2} \right]^{1/n} \quad . \tag{3}$$

Constraints to the LIV energy scale have been established by looking at the highest-energy photons from the Crab nebula [6] and SNR RX J1713.7-3946 [7]. However, higher limits are expected from observations of the Crab nebula by HAWC [35]. With a next-generation observatory, even stronger limits to $E_{\mathrm{LIV}}^{(n)}$ can be obtained from the known high-energy source RXJ1713.7-3946.

Fig. 2 shows the H.E.S.S. observations for RX J1713.7-3946 from 2003 to 2005 [27], where the last two energy bins at 47.19 TeV and 81.26 TeV have been reported with $\sigma = 2.5$ and 1.5, respectively, so the possibility of significant observations to hundreds of TeV are reasonable.

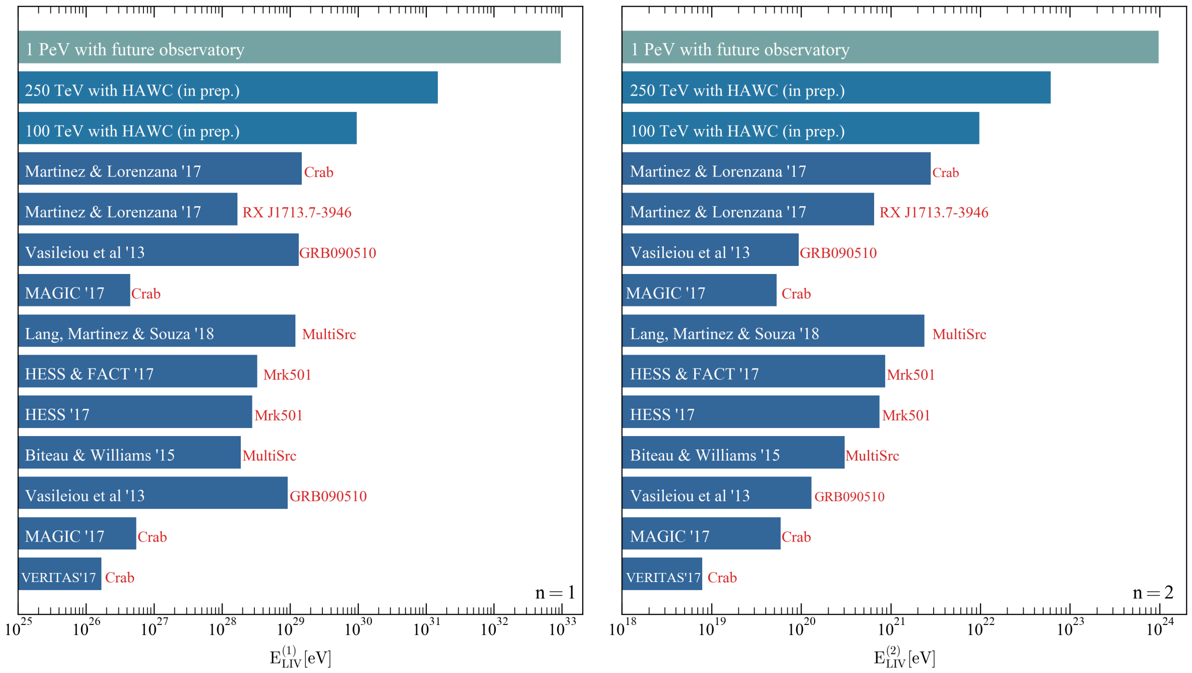

Figure 3: The strongest E_{LIV} limits from LIV searches, energy-dependent time delays, pair-production threshold shifts and photon decay into electron-positron pairs (from bottom to top, see Refs. [1, 8, 15, 20, 32, 33, 35, 44, 45]). The leading limits from HAWC are based on constraining photons above 250 TeV in a Galactic source (work in prep.). If a future observatory were able to improve the photon constraints from such sources to PeV energies, these limits would be further improved by orders of magnitude (shown in gray).

As a reference, preliminary HAWC limits to LIV energy scale at leading order n=1 and 2 are presented in Fig. (3), from limits on gamma-ray energies of $>$100 TeV (for the Crab nebula) and $>$250 TeV (for a hard-spectrum Galactic source). The higher energy of a detected gamma-ray and the narrower its energy uncertainty, the more stringent the constraints on $E^{(n)}_{\mathrm{LIV}}$ would be. Thus, instruments optimized at the highest energies, such as the next-generation observatory, would be optimal instruments to search for LIV signatures. With a high-energy sensitivity nearly an order of magnitude better than HAWC, a future observatory would enable potential measurements of photons up to PeV energies, constraining LIV by orders of magnitude more than the current-generation HAWC observatory.

5 Conclusions

The search for new physics beyond the Standard Model is a high priority for the future of particle physics. It is in these searches for the unknown that a wide field-of-view, higher-energy observatory truly shines. Evaporating PBHs could occur at any location at any time; high uptime and large field-of-view are needed to catch these rare events. The extension of spectral features to the highest energies for ALP searches requires an observatory with high-energy sensitivity. Searches for LIV require high-energy sensitivity for the lever-arm to see features beyond the Planck scale. Sensitivity to unexplored regions of the sky at energies never before detected can lead to surprises – the possibility for new physics in the cosmos.

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