HAWC potential to observe Lorentz Invariance Violation

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Summary

The framework of relativistic quantum-field theories requires Lorentz Invariance. Many theories of quantum gravity, on the other hand, include violations of Lorentz Invariance at small scales and high energies. This generates a lot of interest in establishing limits on such effects, and, if possible, observing them directly. Gamma-ray observatories provide a tool to probe parts of the parameter space of models of Lorentz Invariance Violation that is not accessible in terrestrial laboratories and man-made accelerators. Transients, especially gamma-ray bursts, are a particularly promising class of events to search for such phenomena. By combining cosmological distances with high energy emission and short duration, emitting photons up to 30 GeV in less than a second, one can measure the energy dependence of the speed of photons to one part in 10^{16}. We will discuss the potential of HAWC to detect effects of the violation of Lorentz Invariance and place its sensitivity in the context of existing limits.

Motivation

- **Relativistic Quantum Field Theories** combine **Special Relativity** and **Quantum Mechanics**. They require **Lorentz Invariance** for consistency
- Gravity has **not been successfully integrated** with Quantum Mechanics into a complete, consistent Field Theory.
- Models of Quantum Gravity (**QG**) exist, many of which predict **Lorentz Invariance Violation** (**LIV**)
- New, unique scale, the **Planck Scale**, is considered the natural scale for QG:

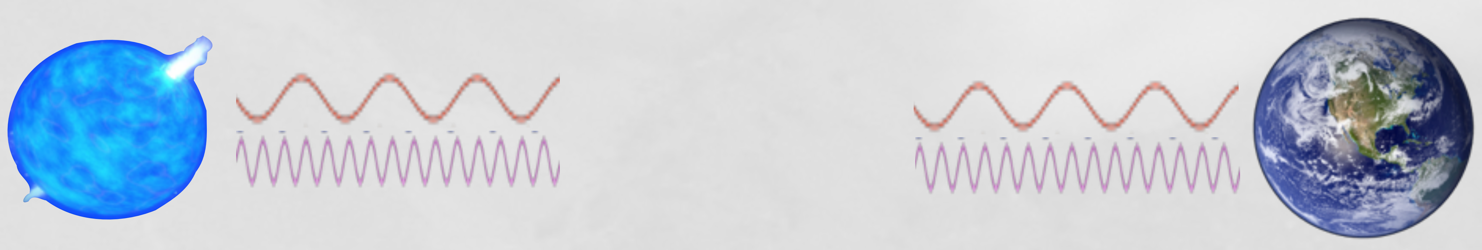
$$m_{\mathrm{pl}} = \sqrt{\hbar c/G} \approx 10^{19}\,\mathrm{GeV}$$

- **Not directly observable** in the laboratory or contemporary universe.
- **Indirect observations** using low energy effects in the laboratory or in astro-particle scenarios could be possible

Observation: Difference in arrival time

Constant speed of light

Photons **emitted simultaneously** will **arrive simultaneously**



Energy dependent speed of light

The velocity of photons and therefore their travel time could depend on their energy: Photons **emitted simultaneously** will **arrive at different times**

Variable speed of light

- One possible realisation of LIV is by having a **variable speed of light**.
- **Gamma ray observatories**, including **HAWC**, are well suited for studying this kind of scenarios

Leading Term

$$v \approx c\left(1 + \frac{n+1}{2}\left(\frac{E_\gamma}{E_{\mathrm{QG}}^{(n)}}\right)^n\right)$$

E_γ photon energy

$E_{\mathrm{QG}}^{(n)}$ QG parameter, to be studied

The order of the leading term depends on the model.

- Theoretically well motivated: $n = 1$ and $n = 2$.

Propagation time

Nearby objects

E.g., Pulsars

$$\Delta t = \frac{(n+1)d}{2c}\frac{\Delta E^n}{\left(E_{\mathrm{QG}}^{(n)}\right)^n} \approx \frac{(n+1)d}{2c}\frac{E_{\max}^n}{\left(E_{\mathrm{QG}}^{(n)}\right)^n}$$

where d the distance to the object and $\Delta E^n = E_{\max}^n - E_{\min}^n \approx E_{\max}^n$.

Distant objects

E.g., Gamma Ray Bursts (GRB) or AGN flares

- Have to take into account **curvature** and **red-shift** along path

$$\Delta t = \frac{n+1}{2}H_0^{-1}\frac{E_{\max}^n}{\left(E_{\mathrm{QG}}^{(n)}\right)^n}\int_0^z \frac{(1+z')^n}{h(z')}\,\mathrm{d}z'$$

with $h(z) = \sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}$ and $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$.

Existing lower limits for $E_{\mathrm{QG}}^{(n)}$ and potential of HAWC

Source	Experiment	Limit on $E_{\mathrm{QG}}^{(1)}$	Limit on $E_{\mathrm{QG}}^{(2)}$	Distance	Δt	$E_{\max}$
Crab	VERITAS	$1.7 \cdot 10^{17}$ GeV	$7 \cdot 10^{9}$ GeV	2.2 kpc	100 μs	120 GeV
GRB090510	Fermi/LAT	$9.1 \cdot 10^{19}$ GeV	$1.3 \cdot 10^{11}$ GeV	$z = 0.903$	combined methods	
PKS 2155-304	H.E.S.S.	$2.1 \cdot 10^{18}$ GeV	$6.4 \cdot 10^{10}$ GeV	$z = 0.116$	likelihood fit	
PG 1553+113	H.E.S.S., Fermi/LAT	$4.3 \cdot 10^{17}$ GeV	$2.1 \cdot 10^{10}$ GeV	$z = 0.49 \pm 0.04$	combined analysis	
HAWC Pulsar ref.	HAWC	10^{17} GeV	$9 \cdot 10^{9}$ GeV	2 kpc	1 ms	500 GeV
HAWC GRB ref.	HAWC	$4.9 \cdot 10^{19}$ GeV	$1.1 \cdot 10^{11}$ GeV	$z = 1$	1 s	100 GeV

Best published lower limits on $E_{\mathrm{QG}}^{(n)}$ from **pulsar**, **GRB**, and **AGN** flare observations. **Estimated potential** of HAWC to set limits for reference scenarios for **pulsar** and **GRB** observations. The reference scenarios use only the difference of the arrival between the highest and lowest energy photon. More sophisticated analysis are expected to produce more stringent limits.

Potential limits: GRB

- Reference scenario motivated by **GRB090510** and **GRB130427A**
- HAWC can observe **higher energy** photons than Fermi/LAT
- **Large field of view** (> 2 sr) and **large duty cycle** (> 90%) increase HAWC's chances of detecting an interesting GRB, compared to Air Cherenkov Telescopes (ACT)

Reference scenario motivated by Fermi/LAT observation.

Combined analysis with other experiments should potentially improve limits further.

Potential limits: Pulsars

- **Large field of view** (> 2 sr) and **large duty cycle** (> 90%) allow for long-term monitoring of a large number of potential sources.
- HAWC pulsar search and monitoring under development.
- Reference scenario might be too optimistic about $E_{\gamma,\max}$ and too pessimistic about time resolution of structures.

Pulsars are not setting the most stringent limits. It is nevertheless interesting to study all possible channels.

Potential limits: AGN flares

HAWC limits expected to be, at best, comparable to limits from Air Cherenkov Telescopes.

Unless:

- Early detection proves relevant: **Large field of view** (> 2 sr) increases HAWC's chances here
- Event hard to observe for ACT's: HAWC's **large duty cycle** (> 90%) increases chance of observation

Observations with ACT expected to be more detailed

Will need better analysis than ΔE vs Δt.

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