Probing Lorentz Invariance Violation

with high-energy astrophysical neutrinos

based on arXiv:1303.5843

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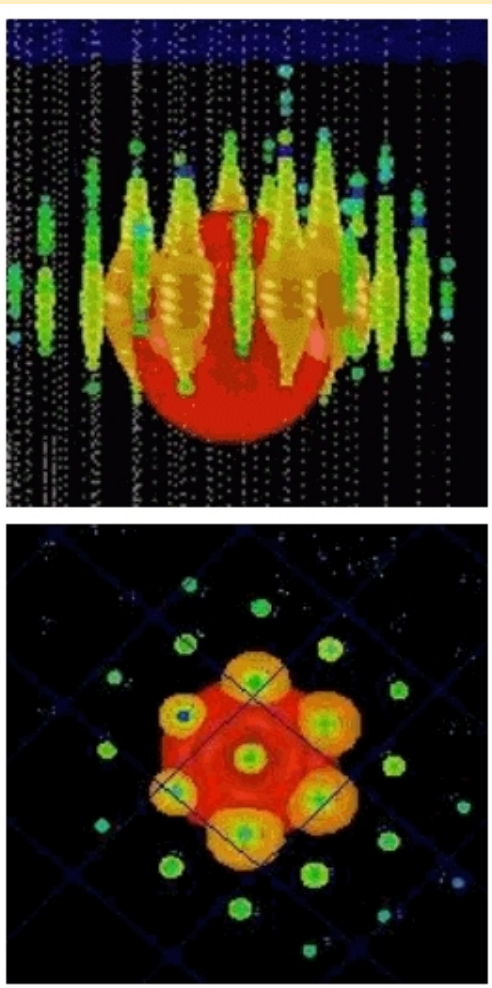
Outline

- Lorentz invariance violation (LIV) might be generated by quantum-gravity (QG) effects.
- As a consequence, particles may not travel at the universal speed of light.
- In particular, superluminal extragalactic neutrinos would rapidly lose energy via the bremssthralung of electron-positron pairs ($\nu \to \nu\, e^+\, e^-$).
- The two PeV cascade neutrino events recently detected by IceCube –if attributed to extragalactic diffuse events– can place *the strongest bound* on LIV in the neutrino sector:

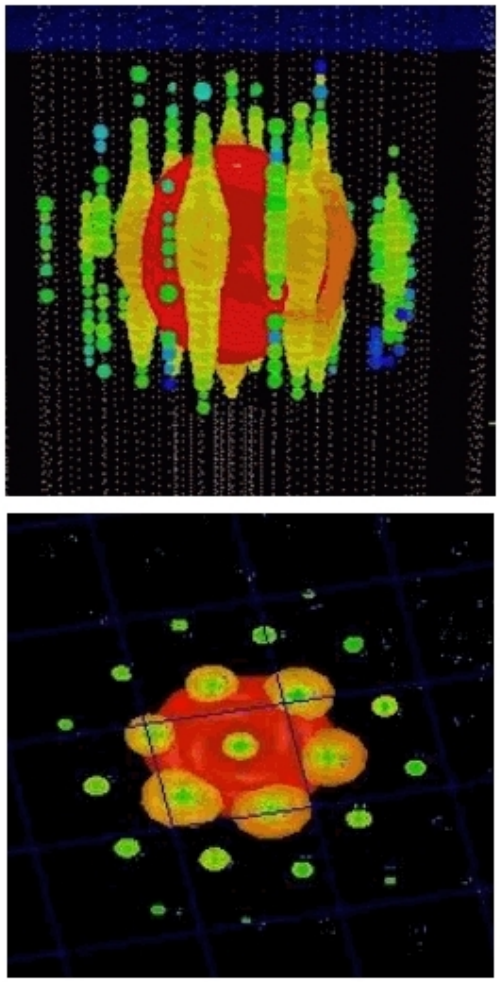
$$\delta = (v^2 - 1) < \mathcal{O}(10^{-18})$$

The IceCube experiment has recently reported the detection of two cascade ν events with energy 1.1 and 1.3 PeV. The origin of these events is not settled.

AUGUST 9TH, 2011



JANUARY 3RD, 2012



CONVENTIONAL ATMOSPHERIC νS

The flux is too low at PeV energies. Unlikely.

COSMOGENIC νS

Lack of higher energy events. Unlikely.

PROMPT ATMOSPH. νS

Lack of correlation between the two events and hits in the IceTop surface array. Unlikely.

CHOLIS & HOOPER 2012

Diffuse Extragalactic Flux?

There is also another intriguing experimental indication:

IceCube Analysis of Neutrino-Induced Muon Track Events

- The sample is dominated by conventional atmospheric neutrinos. *But...*
- Data marginally prefer (1.8 σ) an extra component at $E > 100\,\text{TeV}$
- The extrapolation of this best-fit flux to PeV scale is in perfect agreement with two observed PeV cascade events

The hypothesis that these two neutrinos could be the first indication of a diffuse extragalactic astrophysical flux at the PeV scale appears at the same time the **most likely** *and the* **most exciting** *one.*

Lorentz Invariance Violation

Lorentz invariance might be **violated** in a candidate theory of QG. As a consequence highly boosted energetic particles might propagate at speed greater than the speed of light.

Parametrization

$$\delta = v^2 - 1\,, \qquad v = \frac{\partial E}{\partial p}\,, \qquad E = p(1 + \delta/2)$$

Neutrino sector:

Limit from SN1987A — Stodolsky 1988

Flight delay of the γ with respect to ν of a few hours:

$$\delta < 4 \times 10^{-9} \qquad (\text{at } E_\nu \sim 10 \text{ MeV})$$

LIV allows processes otherwise kinematically forbidden:

LIV processes — Cohen & Glashow 2011

– neutrino Cherenkov radiation ($\nu \to \nu\,\gamma$)
– neutrino splitting ($\nu \to \nu\,\nu\,\bar{\nu}$)
– bremssthralung of electron-positron pairs ($\nu \to \nu\,e^+\,e^-$)

Bremsstrahlung of Electron-Positron Pairs

All these processes would produce a depletion of the high-energy neutrino fluxes during their propagation

Decay Law

$$\text{observed flux} = e^{-\Gamma L} \text{ initial flux}$$

Neutrino pair production ($\nu \to \nu\, e^+\, e^-$) has been recognized as the fastest energy-loss process for LIV neutrinos.

Counterargument against OPERA's Claim — Cohen & Glashow 2011

Baseline experiment. Known baseline, initial and observed fluxes.

Strongest bound on LIV νs — Cowsik et al. 2012

$\delta \lesssim 10^{-13}$, from the observation of upward going atmospheric ν showers ($L \simeq 500$ km), measured at $E \gtrsim 100$ TeV at IceCube.

Bremsstrahlung of Electron-Positron Pairs

For $\delta > 0$ the process $\nu \to \nu\, e^+\, e^-$ is kinematically allowed provided that

Energy Treshold — Cohen & Glashow 2011

$$E_\nu \gtrsim \frac{2\, m_e}{\sqrt{v_\nu^2 - v_e^2}} \simeq \frac{2\, m_e}{\sqrt{\delta}} \simeq \mathrm{PeV}\sqrt{10^{-18}/\delta}$$

LI conservation is assumed in the electron sector.

Decay Rate — Cohen & Glashow 2011

$$\Gamma_{e^\pm} = \frac{1}{14}\frac{G_F^2 E^5 \delta^3}{192\,\pi^3} = 2.55 \times 10^{53} \delta^3 E_{\mathrm{PeV}}^5 \ \mathrm{Mpc}^{-1}$$

The process $\nu \to \nu\, \nu\, \bar{\nu}$ is neglected, because it brings only minor modifications.

NOTES: If $\nu \to \nu\, e^+\, e^-$ is forbidden because of threshold effects, $\nu \to \nu\gamma$ is anyway operational and a channel for energy losses, although two to three orders of magnitude less efficient than $\nu \to \nu\, e^+ e^-$.

A New Stringent Bound

Assumptions made: *a*) PeV neutrinos are generated in extragalactic sources; *b*) The above processes are effective.

Unnecessary assumptions: *a*) Astrophysical sources; *b*) production mechanism.

CR Interaction Length onto CMB Photons *e.g.* Lee 1996

$e^{\pm}$	few kpc	inverse-Compton scattering (ICS)
γ	$\lesssim 10$ kpc	pair production

ICS photons accumulate a γ-ray flux at energies below $\mathcal{O}(100)$ GeV. In our case:

Diffuse Flux from IceCube Pev νs Ishihara @ Neutrino Conf. 2012

$$E_\nu^2 \frac{d\varphi_E}{dE} \sim 10^{-8}\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

This flux is already quite close to the

Waxman-Bahcall benchmark νs Waxman & Bahcall 1998

$$E_\nu^2 \frac{d\varphi_E}{dE} = 2 \times 10^{-8}\text{GeV cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

A New Stringent Bound

VERY conservatively we impose

$$e^{-\Gamma L} = \frac{\text{observed flux}}{\text{initial flux}} \lesssim 10^{-2}$$

- Assuming that the channel $\nu \to \nu\, e^+ e^-$ is open, we get

$$\delta^3\, L_{\rm Mpc} < 1.8 \times 10^{-53}\,.$$

- For the simplest scenario of cosmologically distant sources, a reasonable value is $L \sim \mathcal{O}(10^3)\,$Mpc:

$$\delta \lesssim \mathcal{O}(10^{-19})$$

  which means that **the pair-production mechanism can't be operational**.

- Under these hypothesis the actual bound is thus $\delta < \mathcal{O}(10^{-18})$.

In general:

$$\delta \lesssim 10^{-18} \times \text{Max}\left[\frac{2.7}{E_{\rm PeV}^{5/3}\; L_{\rm Mpc}^{1/3}},\, E_{\rm PeV}^{-2}\right],$$

A New Stringent Bound

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NOTES: $\nu \to \nu\gamma$ is kinematically accessible to PeV neutrinos even for $\delta < \mathcal{O}(10^{-18})$. It is easy to check that it leads to a slightly weaker (albeit of comparable order of magnitude) bound.

Conclusions

- We have derived a very **stringent bound on LIV** in the neutrino sector, $\delta < \mathcal{O}(10^{-18})$, from the observations of two PeV scale IceCube events and remarkably few assumptions on the underlying astrophysical sources.
- We assumed that the two PeV IceCube events are due to an **extragalactic** flux ($L \sim$ Gpc).
- Once **additional information** will be available (e.g. number density and redshift distribution of the sources) an improved calculation will be possible.
- We have shown that the curent lack of these details **doesn't affects the bound** very much (as it scales as the cubic root of L).
- In summary, we have argued that a confirmation of the extragalactic astrophysical nature of the PeV events detected by IceCube would not only open a new window to the high-energy universe, but also allow a significant jump in tests of **fundamental physics** .