Probing Lorentz Invariance Violation

with high-energy astrophysical neutrinos

*based on PRD **87** 116009 (2013)*

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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 bremsstrahlung of electron-positron pairs ($\nu \to \nu\, e^+\, e^-$).
- The three 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:

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

Lorentz Invariance Violation

Quantum gravity effects are expected at the Planck scale

$$M_{PL} = \sqrt{\hbar c/G_N} \approx 1.22 \times 10^{13} \text{PeV}/c^2$$

Earth-based experiments: 4×10^{-3} PeV per beam (LHC, 2012)

Cosmic-rays: 6×10^{4} PeV (GZK cutoff at HiRes, 2007)

Nonetheless:

Low-energy Relic Signatures of QG:
e.g. Liberati and Maccione 2009 *for a recent review*

- Quantum decoherence and state collapse
- QG imprint on initial cosmological perturbations
- Cosmological variation of couplings
- TeV black holes that are related to extra dimensions
- Violation of discrete symmetries
- Violation of spacetime symmetries
- ...

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- **Violation of spacetime symmetries**
- ...

Lorentz Invariance Violation

Lorentz invariance is a key hypothesis of the CPT theorem.

Anti-CPT Theorem — Greenberg 2002

In any unitary, local, relativistic point-particle field theory:

CPT breaking ⇒ Lorentz 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

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

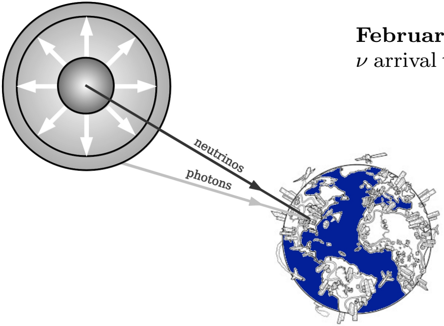
Limit from SN1987A

Core collapse (Type II) supernova:

Neutrino emission: It occurs simultaneously with core collapse.

few hours later

Emission of visible light: It occurs only after the shock wave reaches the stellar surface.



February 23, 1987:
ν arrival time - γ arrival time = *few hours*

$$d = 163\,000\,\text{ly}$$

$$\Delta t_\nu = d/v_\nu$$
$$\Delta t_\gamma = d/c\,d$$

Limit from SN1987A:

$$\delta \lesssim 4 \times 10^{-9}$$

LIV Processes

Superluminal propagation allows for processes otherwise kinematically forbidden:

LIV Processes (neutrino sector) — Cohen & Glashow 2011

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

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

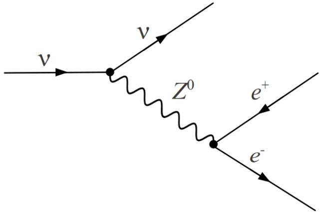
Decay Law

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

$\nu \to \nu\,\nu\,\bar{\nu}$ is neglected (it brings only minor modifications).

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

If $\nu \to \nu\,e^+\,e^-$ is forbidden (threshold effects) $\nu \to \nu\gamma$ is anyway operational and a channel for energy losses, although two orders of magnitude less efficient (W-loop diagram...) than $\nu \to \nu\,e^+e^-$.



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

Energy Treshold Cohen & Glashow 2011

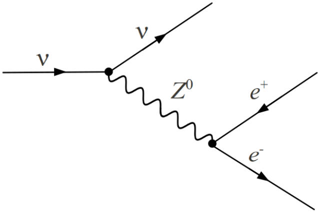
$$E_\nu > \frac{2\, m_e}{\sqrt{\delta}} \simeq \mathrm{PeV}\sqrt{10^{-18}/\delta}$$

LI conservation is assumed in the electron sector.

Decay Rate Cohen & Glashow 2011

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

Bremsstrahlung of Electron-Positron Pairs



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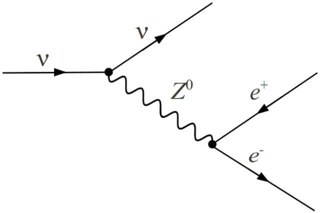

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Counterargument against OPERA's Claim

In July 2012 the OPERA Collaboration reported evidence of superluminal neutrino propagation:

CERN:

CNGS: ν_μ pulses with mean energy 17.5 GeV

730 km

LNGS:

OPERA: neutrinos are detected 60 ns earlier than expected

OPERA's Anomaly — Adam et al. 2012

IF neutrinos travel faster than light: $\delta = 5 \times 10^{-5}$

Counterargument — Cohen & Glashow 2011

$\nu \to \nu\, e^+\, e^-$ treshold:	140 MeV
decay rate:	$\Gamma = 1.69\ \mathrm{m}^{-1}$
energy loss per process:	$\sim 78\%$

No neutrino of 17.5 GeV should have been detected at all!

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LNGS:

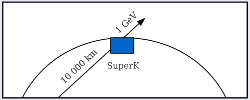
OPERA: neutrinos are detected 60 ns earlier than expected

- The OPERA collaboration then announced the identification of two sources of error.
- In particular, a faulty connection in the optical fiber cable that brings the external GPS signal to the experiment master clock.
- Systematic error of about 70 ns in the determination of the time of flight of neutrinos.

Recent Constraints

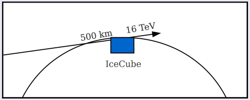
Super-Kamiokande, 1 GeV — Ashie et. al. 2005, Coehen & Glashow 2011

probes: upward-going atmospheric νs
energy: 1 GeV
baseline: 10 000 km
bound: $\delta < 1.4 \times 10^{-8}$



IceCube, 16 TeV — Abbasi et. al. 2011, Coehen & Glashow 2011

probes: upward-going atmospheric νs
energy: 16 TeV
baseline: 500 km
bound: $\delta < 1.7 \times 10^{-11}$



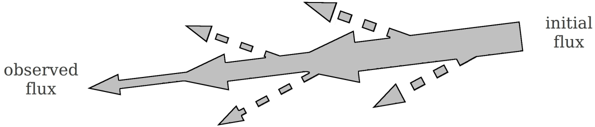
Re-Analyis of CR Propagation in the Atmosphere — Cowsik et al. 2012

Self-consistent re-analysis of CR propagation in the atmosphere including: (*i*) ν superluminal effects on μ and π decay; (*ii*) and the energy losses due to the Cohen-Glashow process; (*iii*) comprehensive and up to date data from underground detectors.

bound: $\delta < 10^{-13}$

PeV Neutrinos: Heuristic Argument

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



Decay Rate — Cohen & Glashow 2011

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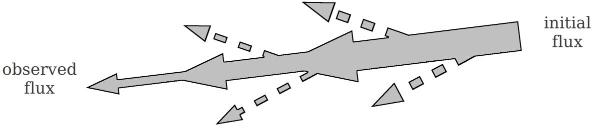
Treshold

$$\delta \gtrsim 10^{-18} E_{\rm PeV}^{-2}$$

In order for this process to be effective ($\Gamma L \gtrsim 1$) for **PeV extragalactic** νs ($L \sim$ Mpc), it must be

$$\delta \gtrsim 10^{-18}$$

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



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Treshold

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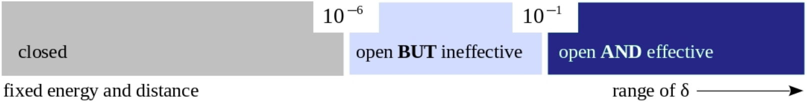
GeV galactic neutrinos ($L \sim 10$ kpc):



PeV Neutrinos: Heuristic Argument

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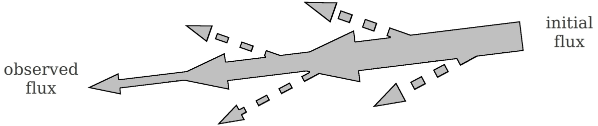

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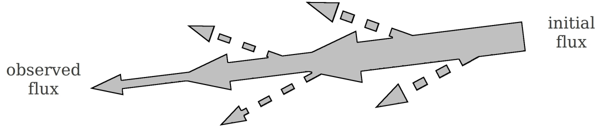
Treshold

$$\delta \gtrsim 10^{-18} E^{-2}_{\text{PeV}}$$

PeV extragalactic neutrinos ($L \sim 1$ Mpc):

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



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Treshold

$$\delta \gtrsim 10^{-18} E_{\mathrm{PeV}}^{-2}$$

What if δ is slightly bigger? e.g. $\delta \to 2\,\delta$

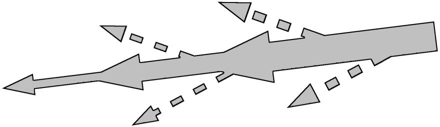
Γ scales like δ^3, then

$$\Delta\delta \sim \mathcal{O}(1) \quad \Rightarrow \quad \Delta(\text{initial flux}) \sim \mathcal{O}(10^3)$$

(the observed flux is kept constant)

PeV Neutrinos: Heuristic Argument

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



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Treshold

$$\delta \gtrsim 10^{-18} E_{\text{PeV}}^{-2}$$

What if δ is much bigger? e.g. $\delta \to 10\,\delta$

Γ scales like δ^3, then

$\Delta\delta \sim \mathcal{O}(10)$ $\Rightarrow$ **totally unphysical!** $\Delta(\text{initial flux}) \sim \mathcal{O}(10^{434})$

(the observed flux is kept constant)

PeV Neutrinos: Heuristic Argument

Expectations:

The observation of PeV **extragalactic** neutrinos can put bounds on δ as strong as 10^{-18} with little or none assumption on their source.

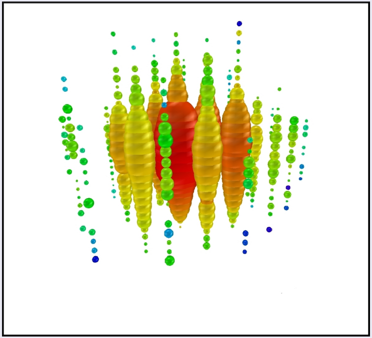
To make this argument more robust:

- Detection of PeV neutrinos
- Arguments in favour of their extragalactic origin
  – in the best scenario, the identification of the source
- A physical argument to constraint the initial flux
  – either a theoretical model for the source or
  – indirect constraints on the associated secondary emission

After the first two years of data taking (May 2010 – May 2012) the IceCube collaboration reported the detection of two cascade ν events with PeV energy:

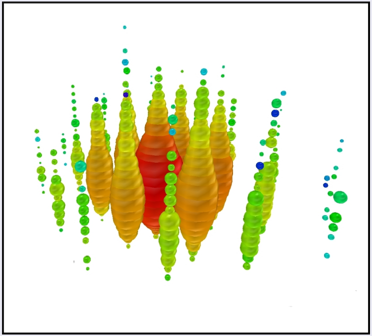
AUGUST 9TH, 2011

$$1.04^{+0.13}_{-0.14}\ \text{PeV}$$



JANUARY 3RD, 2012

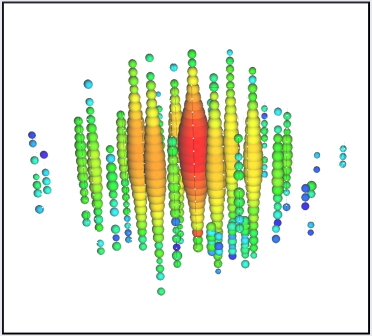
$$1.14^{+0.14}_{-0.13}\ \text{PeV}$$



The full 988-day sample (May 2014) reported the detection of a third PeV cascade event:

December 4th, 2012

$$2.00\,^{+0.24}_{-0.26}\ \text{PeV}$$



Atmospheric Neutrinos?

Enberg *et al.* 2008

Collisions of cosmic rays with atmospheric nuclei produce many unstable hadrons:

Pions

Predominantly.

neutrinos:
They dominate at the lowest energies.

Kaons

Small fraction.

neutrinos:
They dominate at intermediate energies.

Mesons and Baryons with Heavy Quarks (Charm)

Very small fraction.

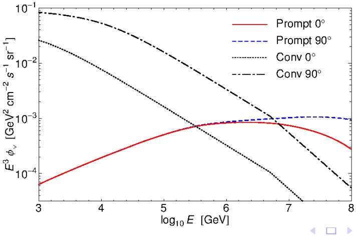
neutrinos:
They dominate at the highest energies ($E_\nu >$ PeV).

Conventional Atmospheric νs

Strong zenith-angle dependence, due to the varying depth of atmosphere.

Prompt Atmospheric νs

Closer to isotropic.



Atmospheric Neutrinos?

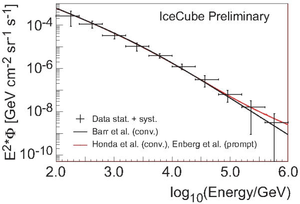
The origin of these events is not settled. But: (2 year analyis)

Atmospheric Neutrino Background
Gaisser 2012

Expected background events in 615.9 days:

$$(3.8 \pm 0.4(\text{stat})\,^{+2.1}_{-3.8}(\text{syst})) \times 10^{-2} \text{ from pions}$$

$$(1.2 \pm 0.1(\text{stat})\,^{+1.0}_{-0.7}(\text{syst})) \times 10^{-2} \text{ from kaons}$$



Promt Atmospheric Neutrino Background
Enberg *et al.* 2008

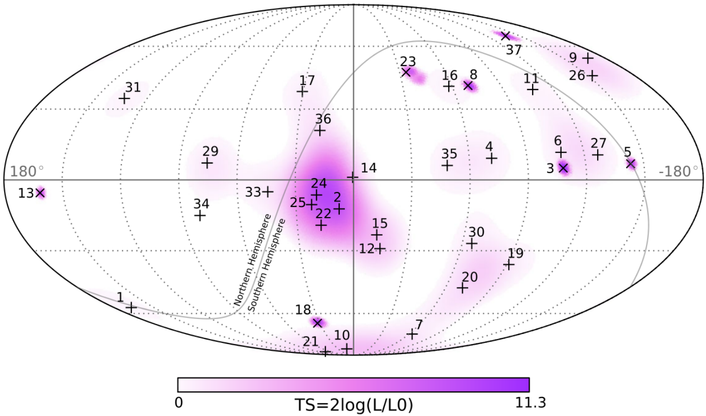
Adding prompt atmospheric neutrinos from decays of charmed mesons:

$$(8.2 \pm 0.4(\text{stat})\,^{+4.1}_{-5.7}(\text{syst})) \times 10^{-2}$$

The hypothesis that two events in two years are fully explained by atmospheric background including the prompt atmospheric neutrinos had a p value of 2.9×10^{-3} $(2.8\,\sigma)$.

NOTES: The prompt component has large theoretical uncertainties. But even using an extreme prompt flux which covers a potential unknown contribution from intrinsic charm the two events were not atmospheric at $(2.3\,\sigma)$.

34 More Events



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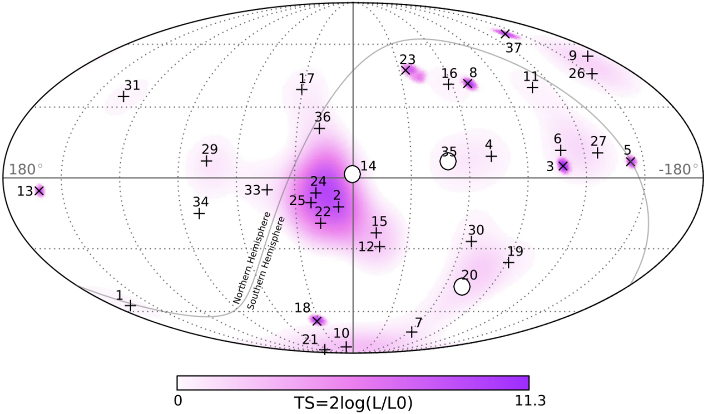

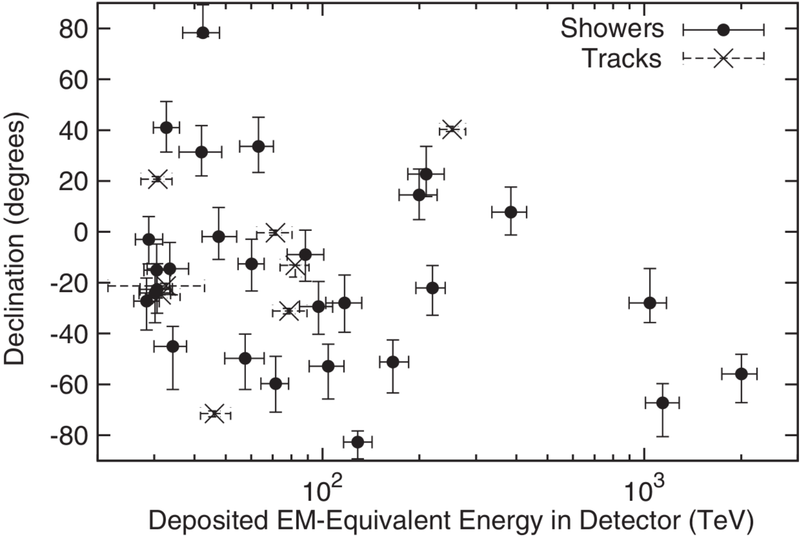
Showers
Tracks
80
60
40
20
0
-20
-40
-60
-80
Declination (degrees)
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)

37 Events

Main features:

Excess with Respect to the Background

The evidence for **extraterrestrial** neutrinos is now at the level of $\mathbf{5.7}\,\sigma$.

"Extraterrestrial" but "galactic"?

Arrival Directions

The arrival directions of the 37 events show no significant clustering.
In particular, **there is no statistical association with the galactic plane!**

Energy Spectrum

Up to 3 PeV the excess is compatible with an E^{-2} spectrum:

$$E_\nu^2 \frac{d\varphi_E}{dE} = (0.95 \pm 0.3) \times 10^{-8}\ \mathrm{GeV\ cm^{-2} s^{-1} sr^{-1}}$$

The extrapolated energy spectrum deduced from $\mathcal{O}(100)$ TeV events predicts three PeV neutrinos in three years.

A Novel Bound

Diffuse Flux from IceCube PeV νs — Aartsen *et al.* 2014

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Observed Integrated Energy Density:

$$\omega_\nu^{\text{obs}} = \frac{4\pi}{c} \int_{1\,\text{PeV}}^{3\,\text{PeV}} E \frac{d\varphi_E}{dE}\, \text{d}E \sim 10^{-9}\,\text{eV/cm}^3\,,$$

The initial ν energy density is depleted at the expense of ICS photons (Cohen & Glashow $e^{\pm}$ propagate only few kpc before scattering off the CMB) that populate a γ-ray flux between $E_1 \sim \mathcal{O}(1)$ GeV and $E_2 \mathcal{O}(100)$ GeV.
This flux is constrained by Fermi data:

(Integrated) Extra-Galactic Diffuse γ-ray Emission — Abdo *et al.* 2010

$$\omega_\gamma = \frac{4\pi}{c} \int_{E_1}^{E_2} E \frac{d\varphi_\gamma}{dE}\, \text{d}E \lesssim 5.7 \times 10^{-7}\,\text{eV/cm}^3\,.$$

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$$\text{initial flux} \lesssim 10^2 \text{ observed flux}$$

Reversing the previous argument:

$$\Delta(\text{flux}) < \mathcal{O}(10^3) \quad \Rightarrow \quad \Delta(\delta) < \mathcal{O}(1)$$

$$\delta \lesssim \mathcal{O}(10^{-18})$$

Conclusions

- A very **stringent bound on LIV** in the neutrino sector, $\delta \lesssim \mathcal{O}(10^{-18})$, has been derived from the observations of three PeV neutrinos at IceCube and remarkably few other assumptions.
- The main (only?) hypothesis being the **extragalactic** nature of the observed PeV flux.
- Once **additional information** will be available (e.g. number density and redshift distribution of the sources) an improved calculation will be possible.
- In summary, it has been argued that a confirmation of the extragalactic nature of the PeV events detected at IceCube would not only open a new window to the high-energy universe, but also allow a significant jump (six orders of magnitune) in testing **fundamental physics**.