SEARCHING FOR TRACES OF PLANCK-SCALE PHYSICS WITH HIGH ENERGY NEUTRINOS

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Special Relativity = Lorentz Invariance

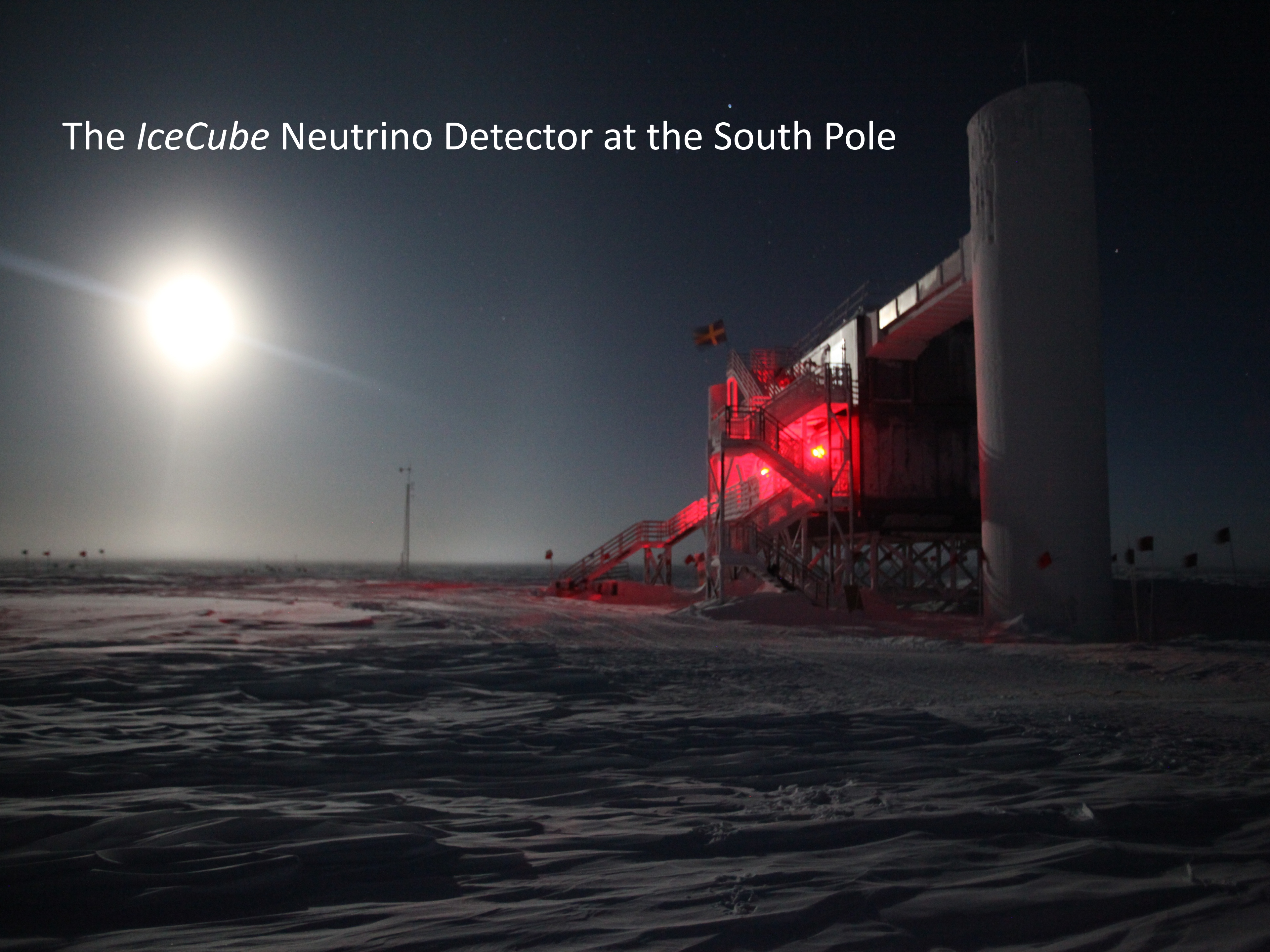
The reasons for looking for Lorentz invariance violation (LIV) come from the incompatibility of relativity and quantum mechanics, particularly at very small length scales.

One consequence of LIV can be a difference in the maximum velocities of particles from the speed of light, *e.g.*, “superluminal” velocities, and changes in energy thresholds for particle interactions.

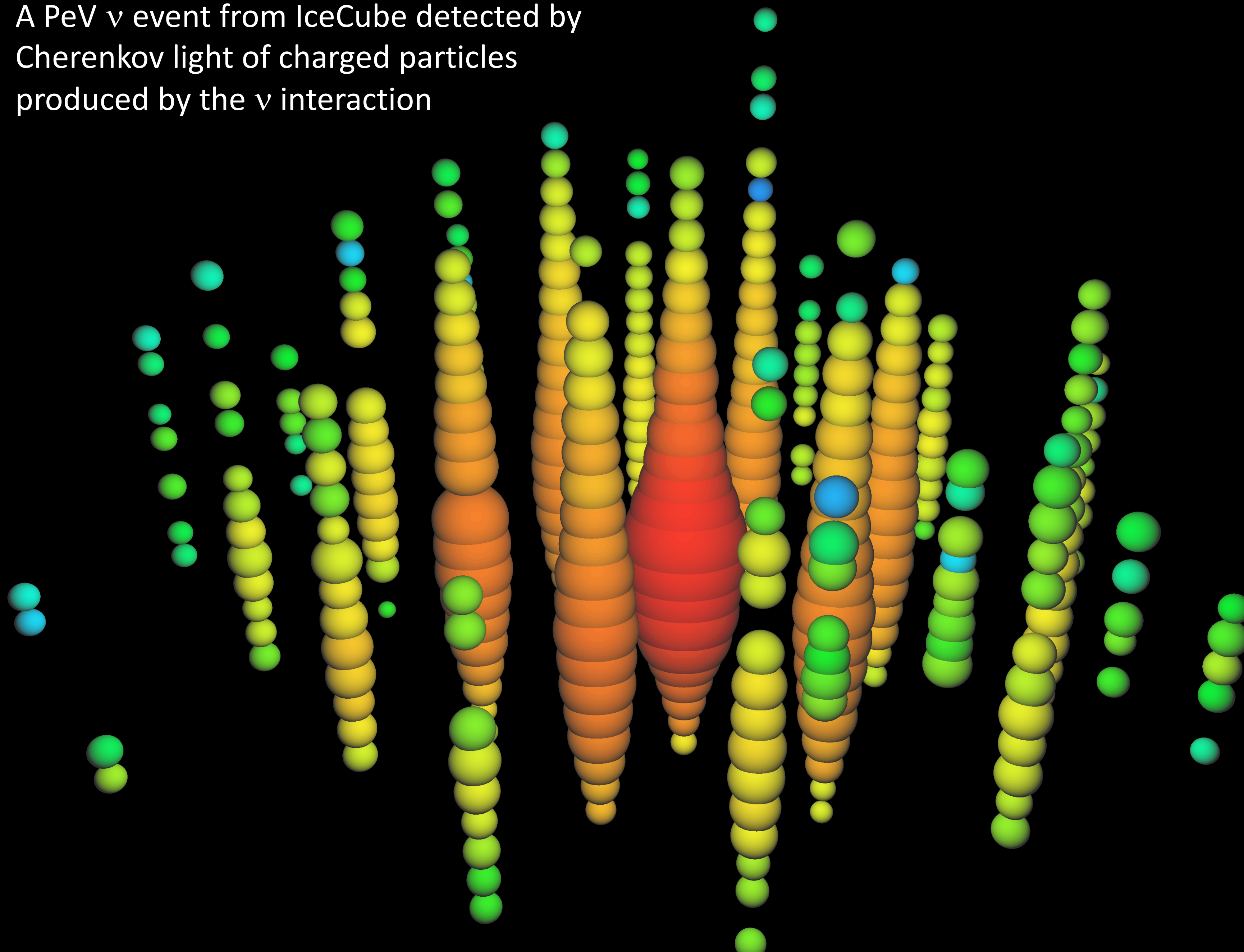
Why high energy neutrinos?

- *Both high energy γ-rays and neutrinos result from the decay of pions produced in hadronic interactions in astrophysical sources.*
- *γ-rays above ~TeV energies coming from all but the closest extragalactic sources are annihilated by interactions with low energy photons emitted by galaxies. Above ~PeV energies no extragalactic γ-rays can reach us owing to interactions with cosmic microwave background photons.*
- *However, neutrinos reach us from throughout the Universe. The cross section for neutrino interactions grows as E^2 up to energies ~100 TeV. Also, above ~100 TeV, the flux of astrophysical neutrinos stands out above the atmospheric foreground.*
- *Thus, there is a natural transition region above the multi-TeV energy range where neutrino astronomy comes into its own!*

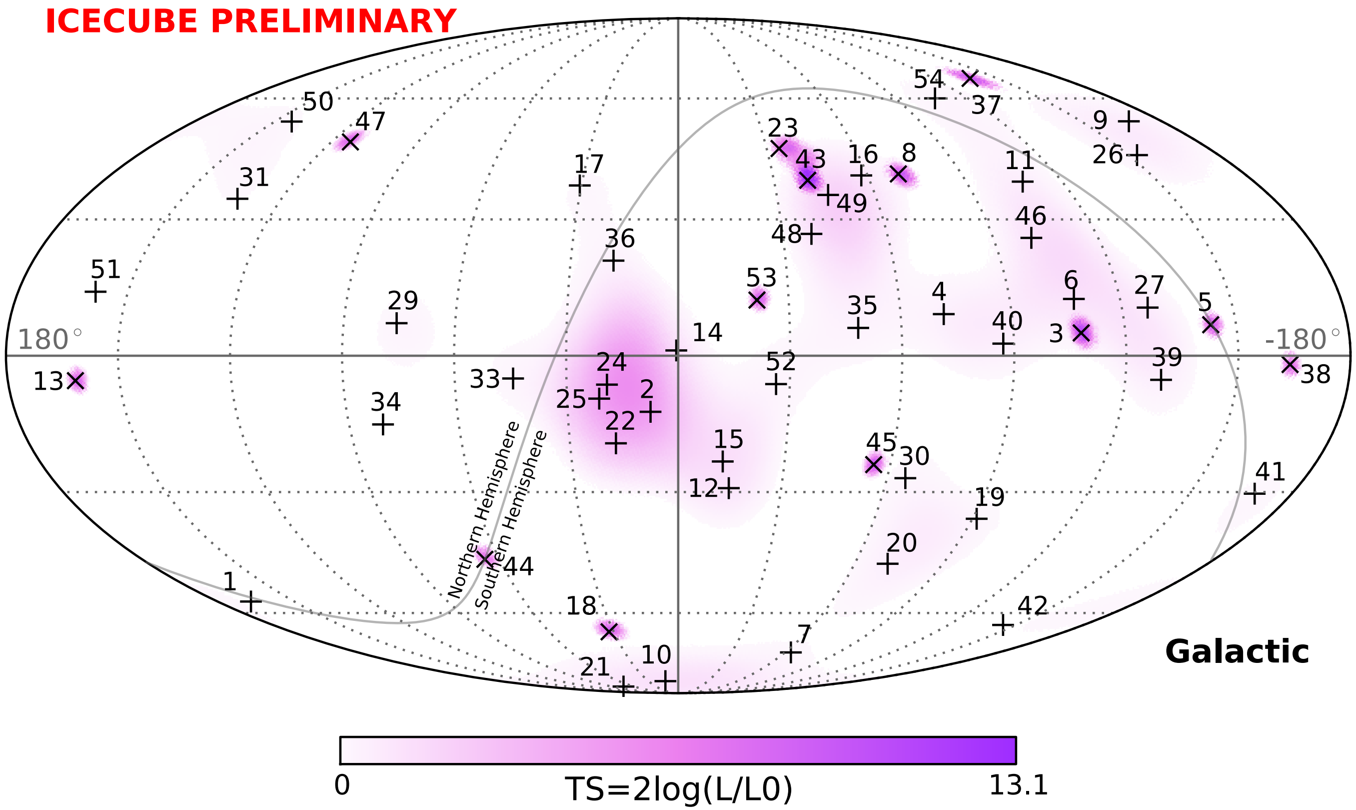
The *IceCube* Neutrino Detector at the South Pole



A PeV ν event from IceCube detected by
Cherenkov light of charged particles
produced by the ν interaction



The isotropic arrival distribution of cosmic neutrinos indicates that most are of extragalactic origin.

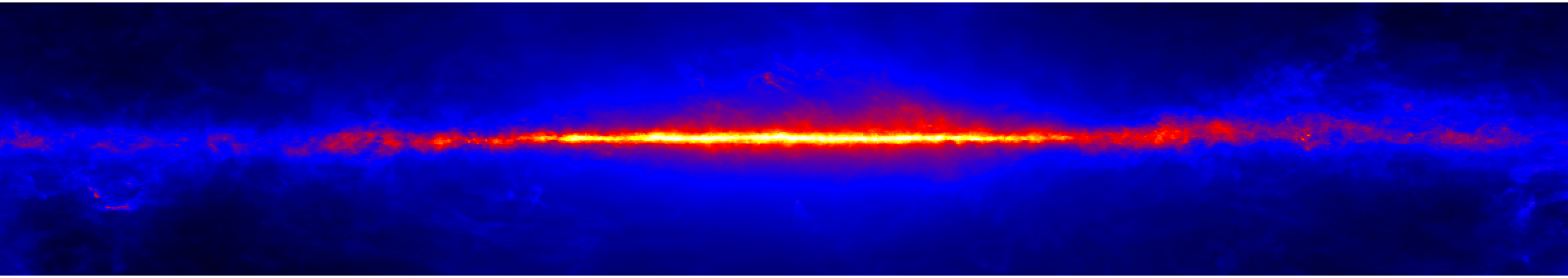


The Celestial Distribution of *IceCube* Astrophysical Neutrinos in Galactic Coordinates.

x: Muon Tracks, < 1.5° a.r, (+): Cascades, ~15° a.r.

A *galactic* ν distribution should resemble a sharper version of the *Fermi* 5 year γ-ray skymap (see below), of secondary but without sources, since both are from secondary π decay

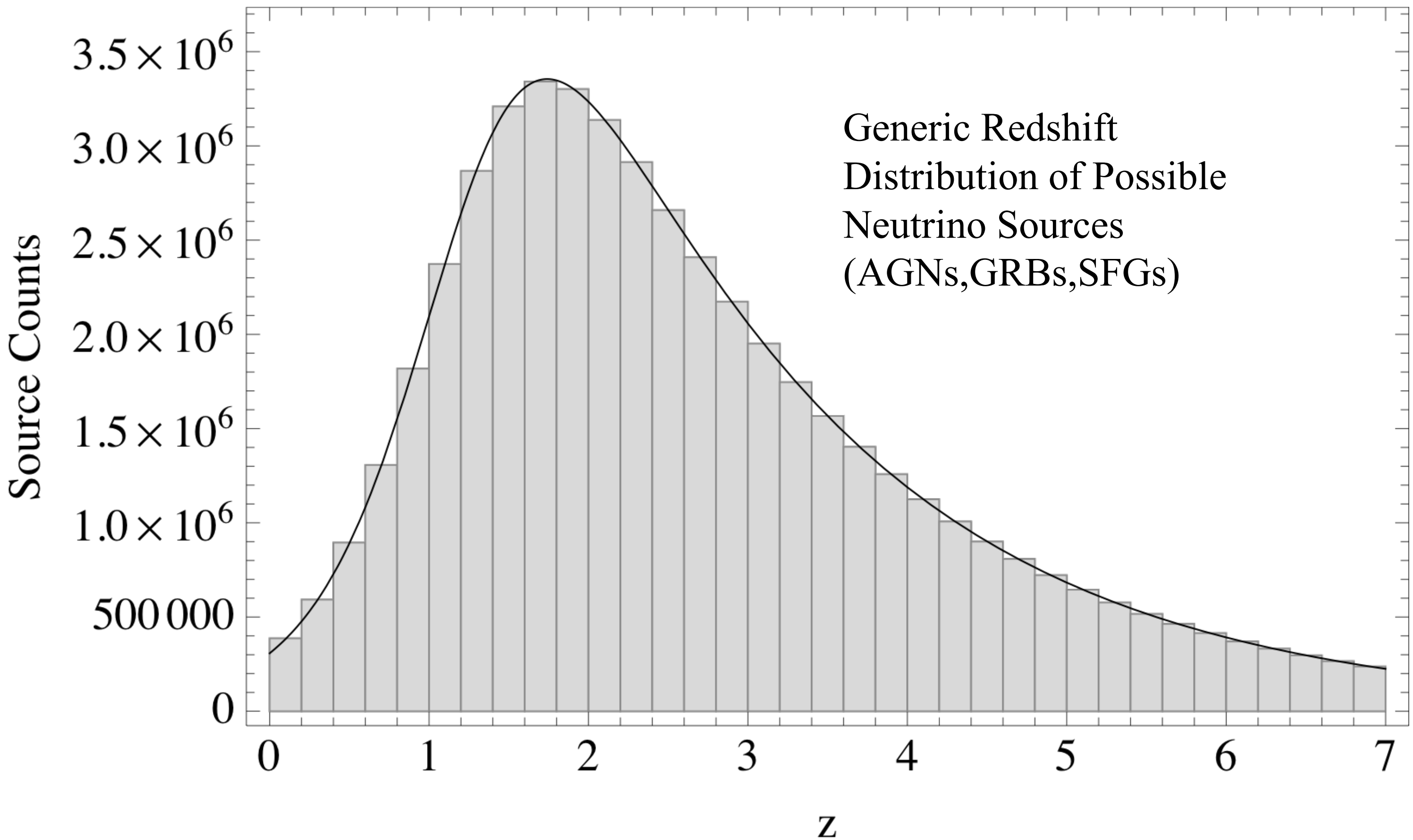
(FWS 1979) .



IceCube PeV Neutrinos are Extragalactic!

Since they come from large distances, they are sensitive to energy loss processes.

Redshift Distribution of Possible Extragalactic Neutrino Sources



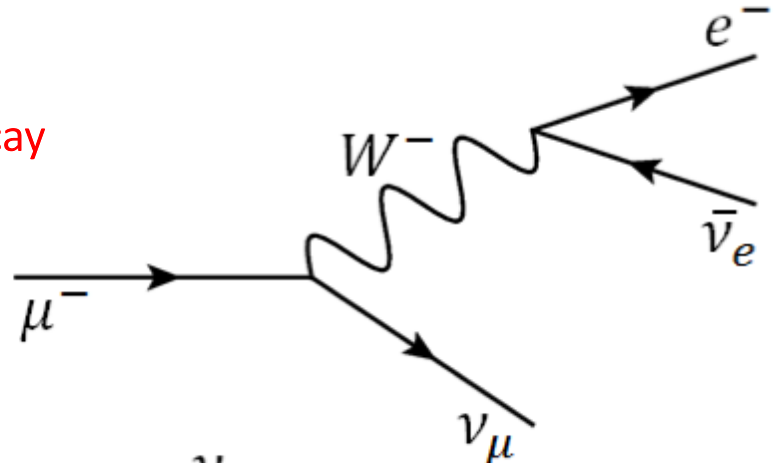
$$D = \frac{c}{H_0}\int_0^z \frac{dz'}{(1+z')\sqrt{\Omega_\Lambda + \Omega_M(1+z')^3}}$$

Energy Loss Rates from Allowed Interactions of Superluminal Neutrinos *in vacuo*

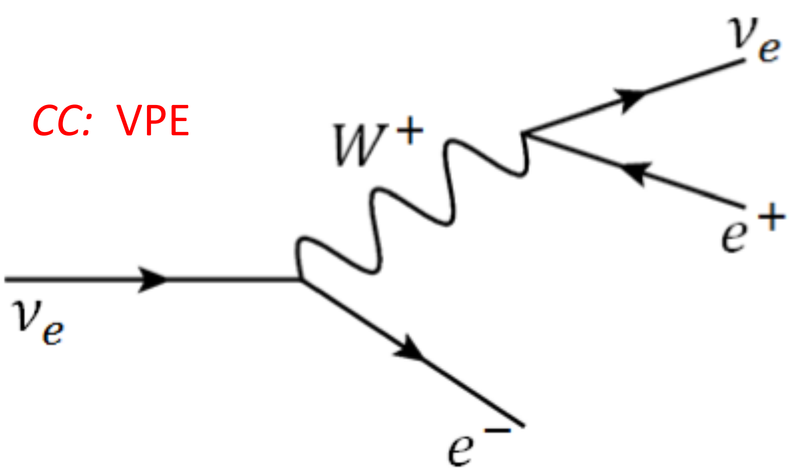
Using the effective field theory formalism called the *Standard Model Extension (SME)* that incorporates LIV, we have calculated the effect of vacuum pair emission (VPE), neutrino splitting, and redshift on extragalactic superluminal neutrinos and compared it with the spectral data from 3 years of observations of cosmic neutrinos using the IceCube detector array.

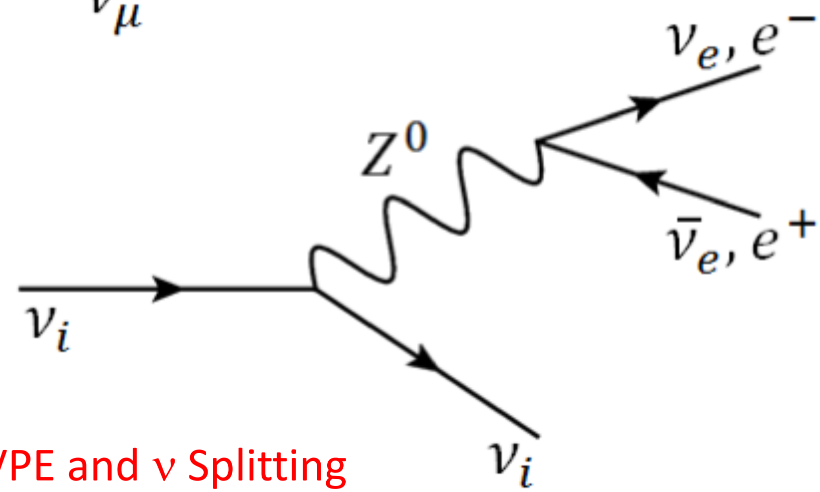
VPE and Neutrino Splitting

c.f., muon decay



CC: VPE





NC: VPE and ν Splitting

Assume the neutrino to be traveling at a *fractional velocity* δ *above c.* We then assume that the higher order terms in SME Lagrangian are described by operators of mass dimension *[d]* suppressed by *n = [d] – 4* factors of the Planck mass, M_{Pl}. Using the definition $\delta = \kappa_n (E_\nu / M_{Pl})^n$, the neutrino energy loss rate from VPE above a threshold energy $E_{th} = m_e (2/\delta)^{1/2}$ is then

$$\Gamma = \frac{G_F^2}{192\pi^3}[(1-2s_W^2)^2 + (2s_W^2)^2]\zeta_n \kappa_n^3 \frac{E_\nu^{3n+5}}{M_{\rm Pl}^{3n}}, \qquad (18)$$

where s_W is the sine of the Weinberg angle ($s_W^2 = 0.231$) and the ζ_n's are numbers of order 1 [20].

The loss rate from neutrino splitting is three times larger (3 flavors).

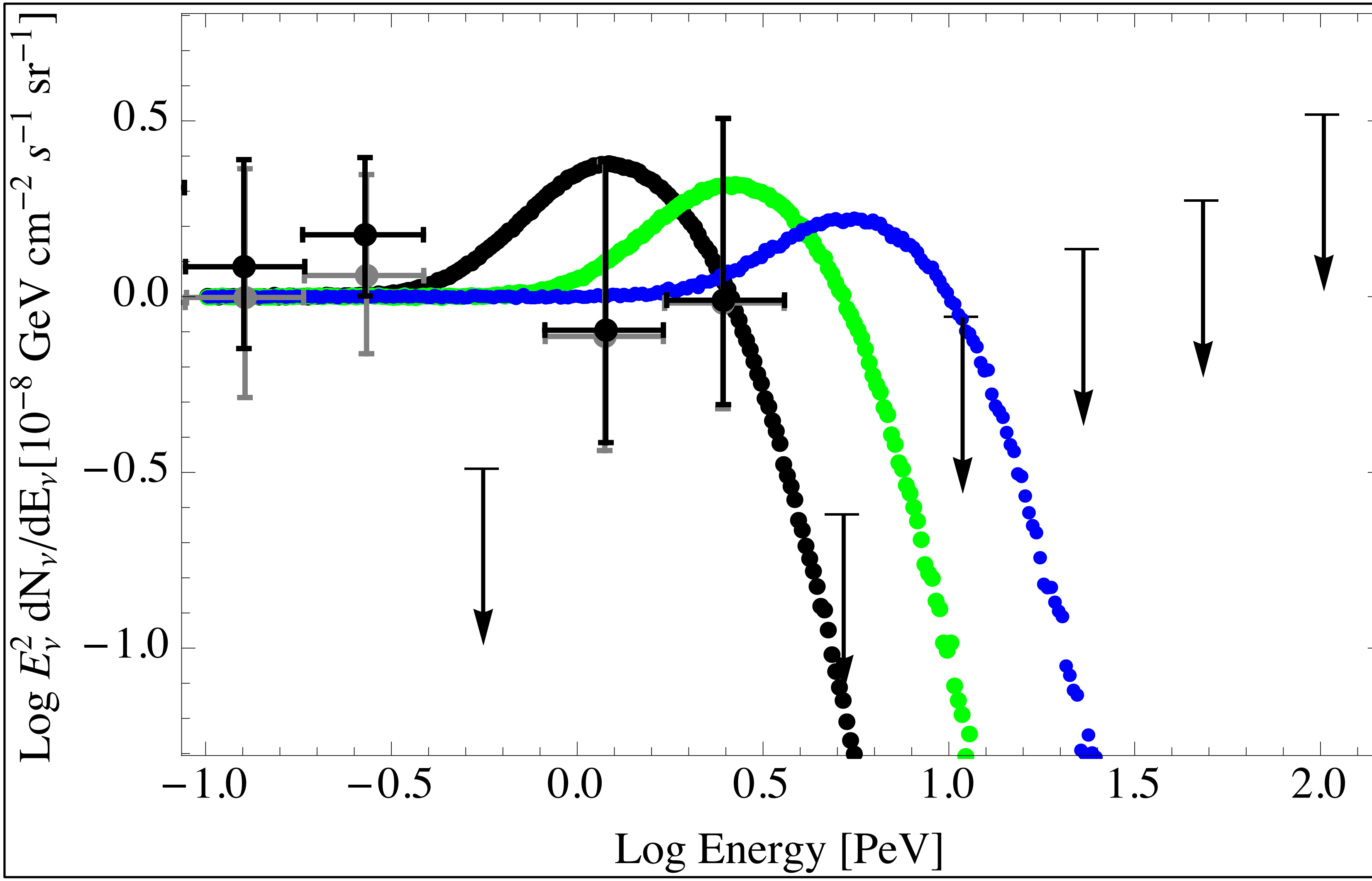
The energy loss from redshifting is

$$-(\partial \log E/\partial t)_{\rm redshift} = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}.$$

The very existence of PeV neutrino events can place dramatic limits on the velocity of superluminal neutrinos and the violation of Lorentz invariance.

This is because even very slightly superluminal neutrinos will lose energy by the Cherenkov radiation of lepton pairs *in vacuo*.

This process increases dramatically with energy and with the energy loss occurring over extragalactic distances.

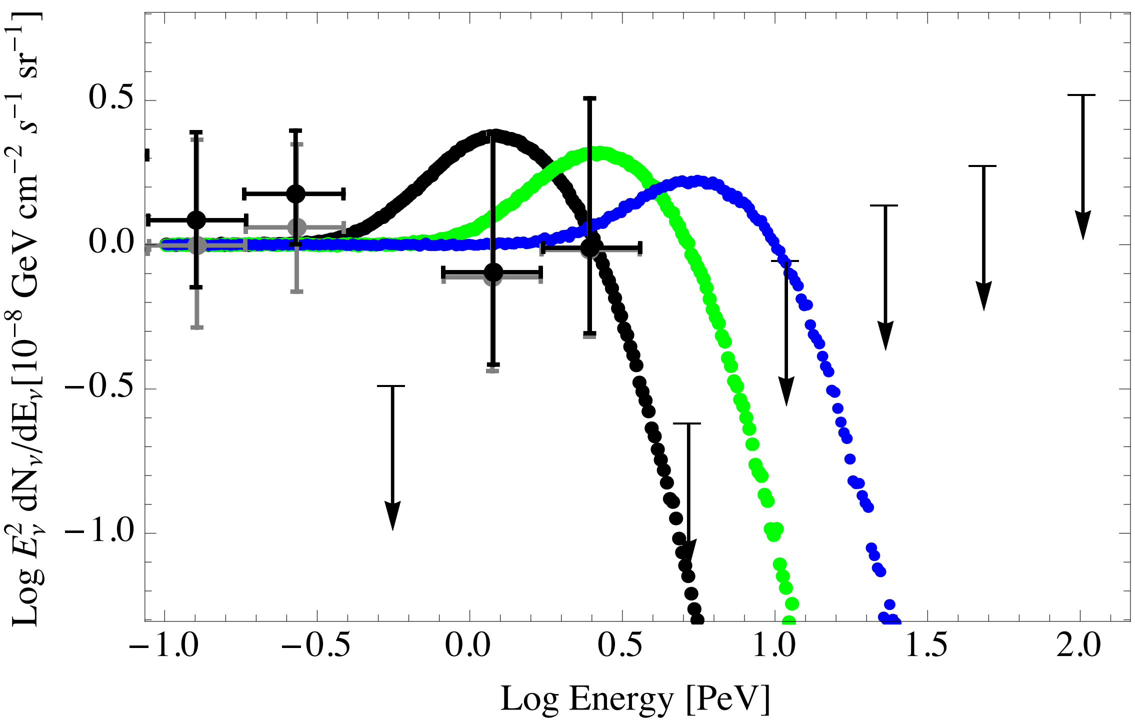


Predicted neutrino spectrum with $\delta = 10^{-20}$ shown in black. Other spectra are for $\delta < 10^{-20}$.

At 6.3 PeV, there is a "Glashow resonance" for high energy electron antineutrinos interacting with electrons in the ice,

$$\bar{\nu}_e + e^- \rightarrow W^- \rightarrow shower.$$

If the neutrino spectrum extended to this energy without a cutoff, 3 to 4 events of 6.3 PeV energy should have been seen. No events at this energy have been seen by *IceCube*, supporting the cutoff effect.



Conclusions

• We have shown that neutrino velocities cannot exceed *c* by more than 1 part in 10^{20}.

• Larger future neutrino detectors such as *IceCube-Gen2* will enable more sensitive tests of Lorentz invariance violation in the neutrino sector.

• Should future cosmic neutrino observations confirm a cutoff in the neutrino spectrum at PeV energies *and* find a significant bump in the spectrum just below the cutoff, this would be an indication that ν's are slightly superluminal and of a violation of Lorentz invariance.

Supplemental Slides

Why use high energy astrophysical observations to search for Lorentz invariance violation?

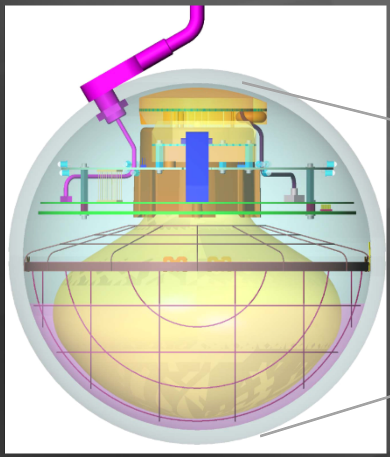
- *Lorentz invariance implies scale-free spacetime.*
- *The group of Lorentz transformations is unbounded.*
- *Very large boosts probe physics at ultra-short distance intervals, λ.*
- *To probe physics at these distance intervals, particularly the nature of space and time, we need to go to ultrahigh energies $E = 1/\lambda$.*
- *Cosmic γ-rays, neutrinos, and cosmic rays provide the highest observable energies in the universe.*
- *Planck scale ($1/M_{pl} = 10^{-35}$ m) physics such as quantum gravity may lead to the breaking or deformation of Lorentz invariance with traces at high energy.*

Superluminal Neutrinos: One Test of Lorentz Invariance Violation

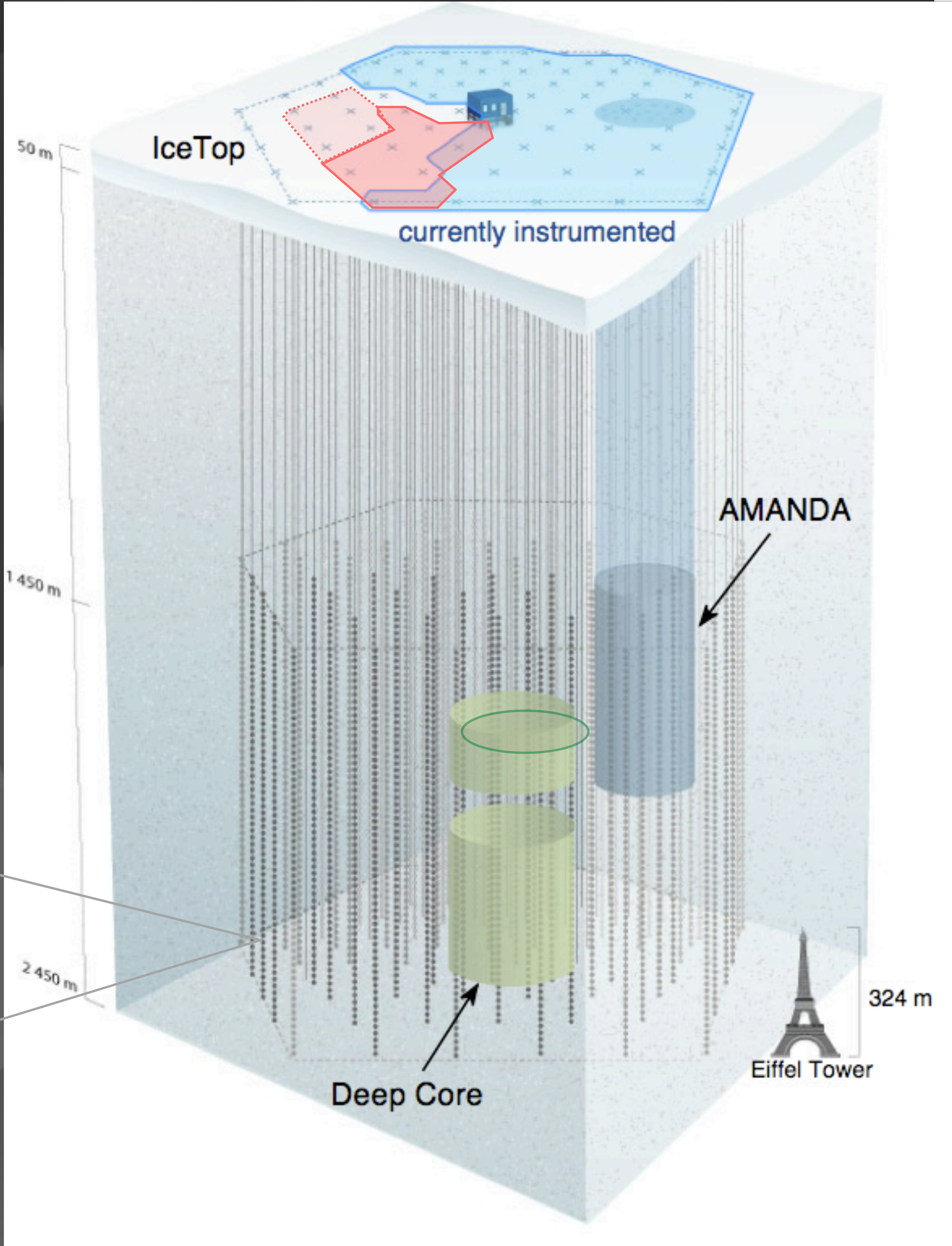
"Superluminal Neutrinos", *i.e.*, neutrinos traveling faster than *c*, thus violating Lorentz invariance (LIV), have been a topic of interest, particularly since a false report of them some years ago.

IceCube Array

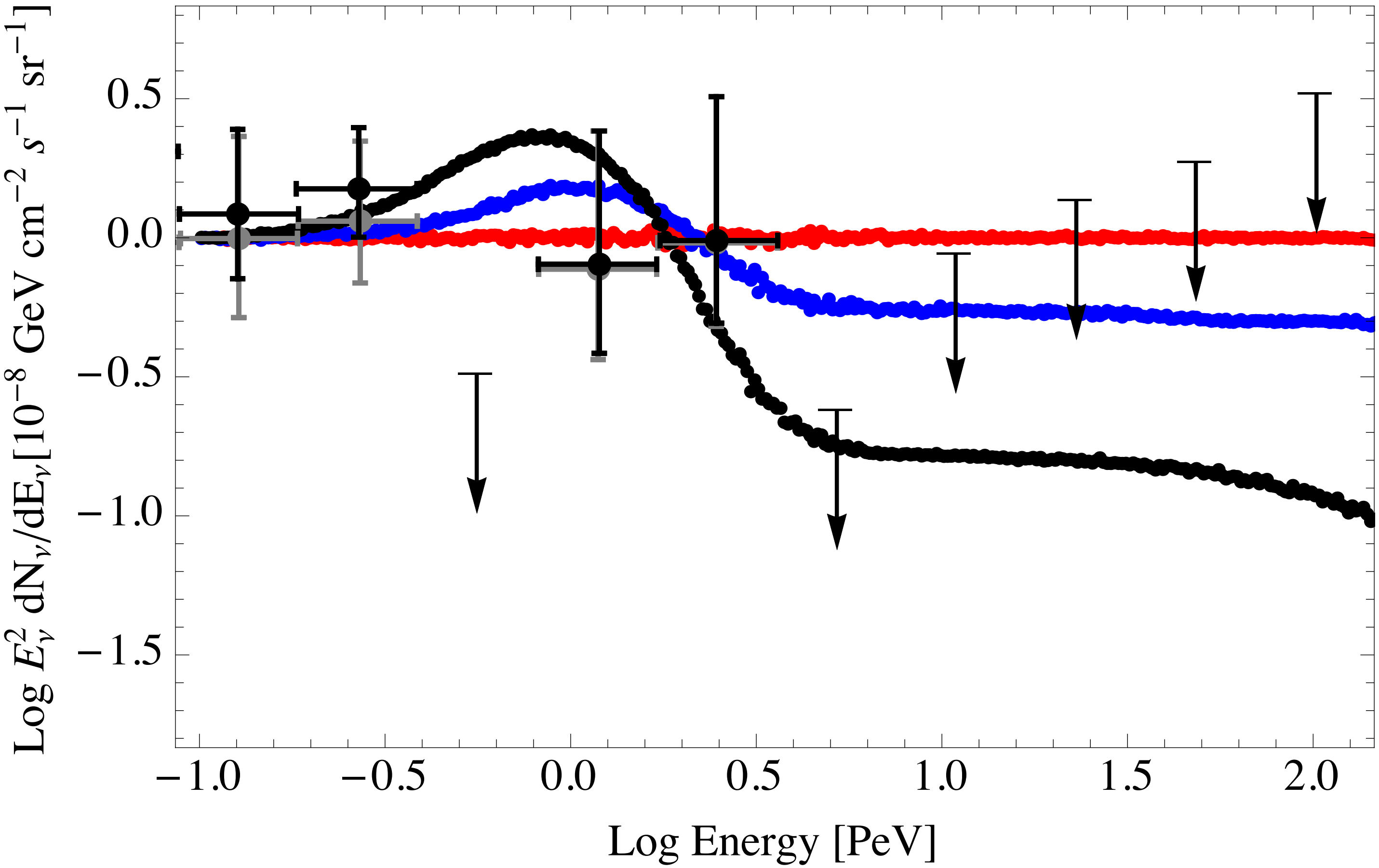
- 5160 optical sensors between 1.5 ~ 2.5 km
- detects > 200 neutrino-induced muons and ~ 2 x10^8 cosmic ray muons per day



Digital Optical Module (DOM)



Case with n = 1 dominance (CPT odd), no pronounced cutoff



Blue is a 50-50 mix of neutrinos and antineutrinos. Other curves are 0% and 100% of one kind of superluminal neutrinos. If one kind is superluminal, the other kind is subluminal because of CPT violation.