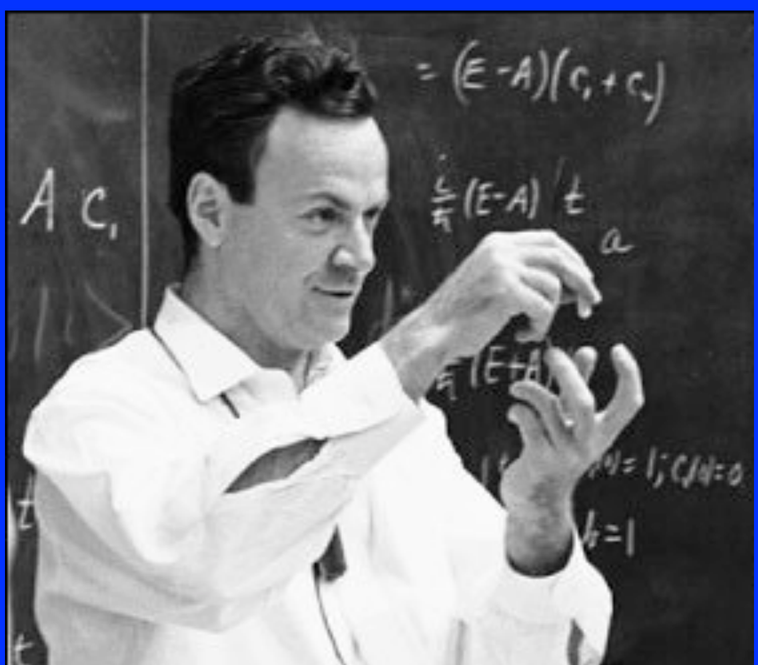
COSMIC HIGH ENERGY INTERACTIONS: TESTING LORENTZ INVARIANCE

F. W. STECKER
NASA Goddard Space Flight Center

"Today we say that the law of relativity is supposed to be true at all energies, but someday somebody may come along and say how stupid we were. We do not know where we are 'stupid' until we 'stick our neck out'…And the only way to find out that we are wrong is to find out what *our predictions are. It is absolutely necessary to make constructs."*

- Richard Feynman

(Feynman lectures in physics)



Planck Scale Physics and Lorentz Invariance Violation

Suggestions for Lorentz invariance violation (LIV) come from:

- *need to cut off UV divergences of QFT & BH entropy*
- *tentative calculations in various QG scenarios, e.g.*
    - *semiclassical spin-network calculations in Loop QG*
    - *string theory tensor VEVs*
    - *non-commutative geometry*
    - *some brane-world backgrounds*

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 and cosmic rays and cosmic neutrinos provide the highest observable energies in the universe.*
- *Planck scale (10^{-35} m) physics such as quantum gravity may lead to the breaking or deformation of Lorentz invariance with traces at high energy.*

Theoretical Frameworks for Lorentz Invariance Violation (LIV)

→ ▪ Effective Field Theory (EFT, SME)

▪ Deformed Special Relativity (DSR)

▪ Stochastic space-time "foam"

▪ Loop Quantum Gravity (LQG)

▪ String inspired models (D-branes)

▪ Emergent space-time

Some Astrophysical Tests of Lorentz Invariance Violation:

- Threshold for annihilation of γ-rays through e^+e^- production by interactions with intergalactic low energy photons and by vacuum decay of photons into e^+e^- pairs

- Time-of-flight of γ-rays from cosmologically distant sources

- Vacuum birefringence

- Modification of the "GZK" spectrum of ultrahigh energy cosmic rays produced by photomeson interactions with the CMB

- Pair production by high energy superluminal neutrinos

Coleman-Glashow Formalism

- For simplicity, assume rotational symmetry in a preferred rest frame, i.e., that of the cosmic background radiation (CBR). Only boosts are modified by Lorentz invariance violation.*

- Our motion with respect to the CBR is small, $\beta = O(10^{-3})$.

- Small perturbative departures from Lorentz invariance are then parametrized in terms of a fixed timelike 4-vector vacuum field, a "spurion field" (analogous to a Higgs field) added to the Lagrangian and proportional to a small quantity ε.

*Admitting rotational anisotropy involves a full tensor treatment, (see Colladay and Kostelecky 1998).

Consider the Free Particle Lagrangian $\mathcal{L} = \partial_\mu \mathbf{\Psi}^* \mathbf{Z} \partial^\mu \mathbf{\Psi} - \mathbf{\Psi}^* \mathbf{M}^2 \mathbf{\Psi}$

Add a small Lorentz violating term $\mathcal{L} \Rightarrow \mathcal{L} + \partial_i \mathbf{\Psi}^* \epsilon \partial^i \mathbf{\Psi}$

Where ϵ is dimensionless an $[\epsilon, \mathbf{M}^2] \neq 0$

(Note that $\partial_\mu \mathbf{\Psi}^* \epsilon \partial^\mu \mathbf{\Psi}$ is Lorentz invariant. Thus a small Lorentz violating perturbative term $\partial_i \mathbf{\Psi}^* \epsilon \partial^i \mathbf{\Psi}$ is equivalent to the Lorentz violating term $\partial_0 \mathbf{\Psi}^* \epsilon \partial^0 \mathbf{\Psi}$ containing only timelike derivatives.)

This gives a new propagator $-iD^{-1} = \left(p_{(4)}^2 - m^2\right) + \epsilon p^2$

So that $p_{(4)}^2 = E^2 - p^2 \Rightarrow m^2 + \epsilon p^2$

Which can be rewritten in the "conventional" form $E^2 = p^2 + m^2$

Where $m \Rightarrow \dfrac{m}{(1+\epsilon)^2} \simeq m(1-2\epsilon)$

And $c \Rightarrow 1 - \epsilon/2$

Thus the maximum attainable particle velocity has changed by $\epsilon/2$.

γ-Ray Astrophysics Limits on LIV

Let us characterize Lorentz invariance violation by the parameter $\delta = \varepsilon/2$ such that

$$c_e \equiv c_\gamma (1 + \delta)$$

(S. Coleman & S.L. Glashow 1999).

If $\delta > 0$, the γ-ray photon propagator in the case of pair production

$$\gamma + \gamma \rightarrow e^+ + e^-$$

is changed by the quantity $\varepsilon p_\gamma^2 = -2E_\gamma^2 \delta$

And the threshold energy condition is given by

$$2\omega E_\gamma (1 - \cos\theta) > 4m_e^2 + 2E_\gamma^2 \delta$$

γ-Ray Astrophysics Limits on LIV from the Crab Nebula

Since, from the threshold energy condition,

$$2\omega E_\gamma(1-\cos\theta) > 4m_e^2 + 2E_\gamma^2\delta$$

the decay

$$\gamma \rightarrow e^+ + e^-$$

would be allowed for $E_g > m_e\,(2/\,|\delta|)^{1/2}$ where $\delta < 0$

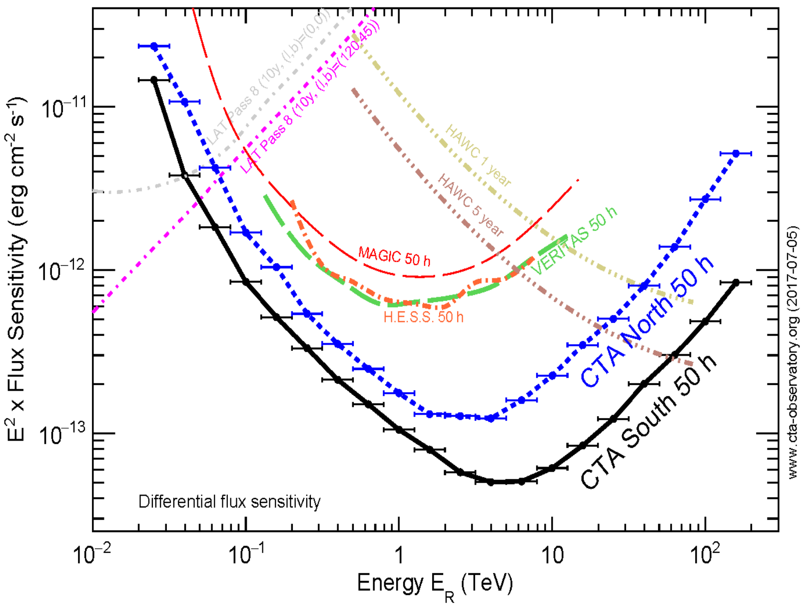
the observation of 50 TeV γ-rays from the Crab Nebula that have not decayed puts an upper limit on $|\delta|$ of

$$|\delta| < 2 \times 10^{-16}$$

(FWS & Glashow 2001).

CTA Detections of γ-rays above 50 TeV would give better constraints on LIV !

CTA Will Test LIV at Higher Energies

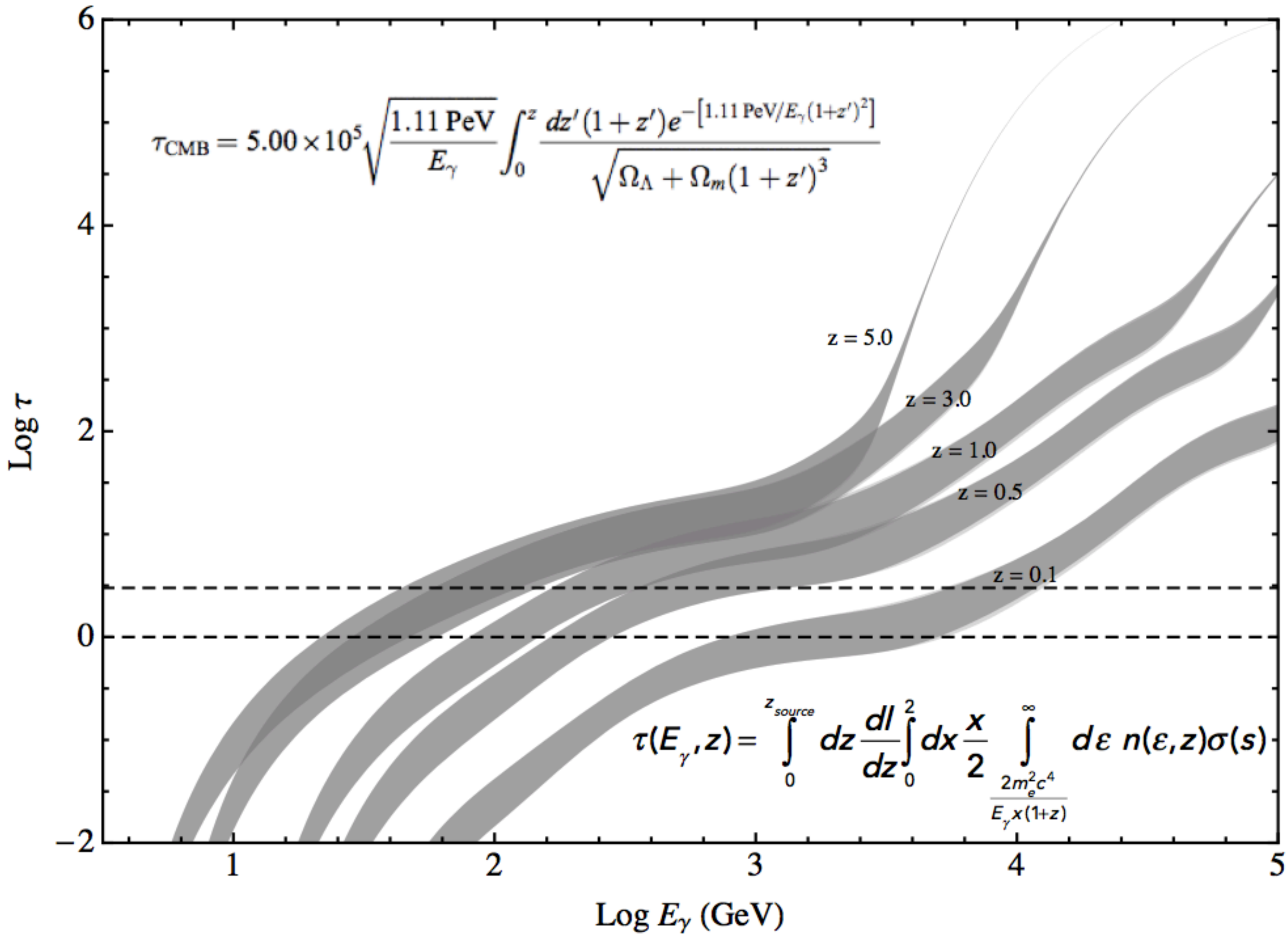


"Sweetspot" in sensitivity curve at multi-TeV energies

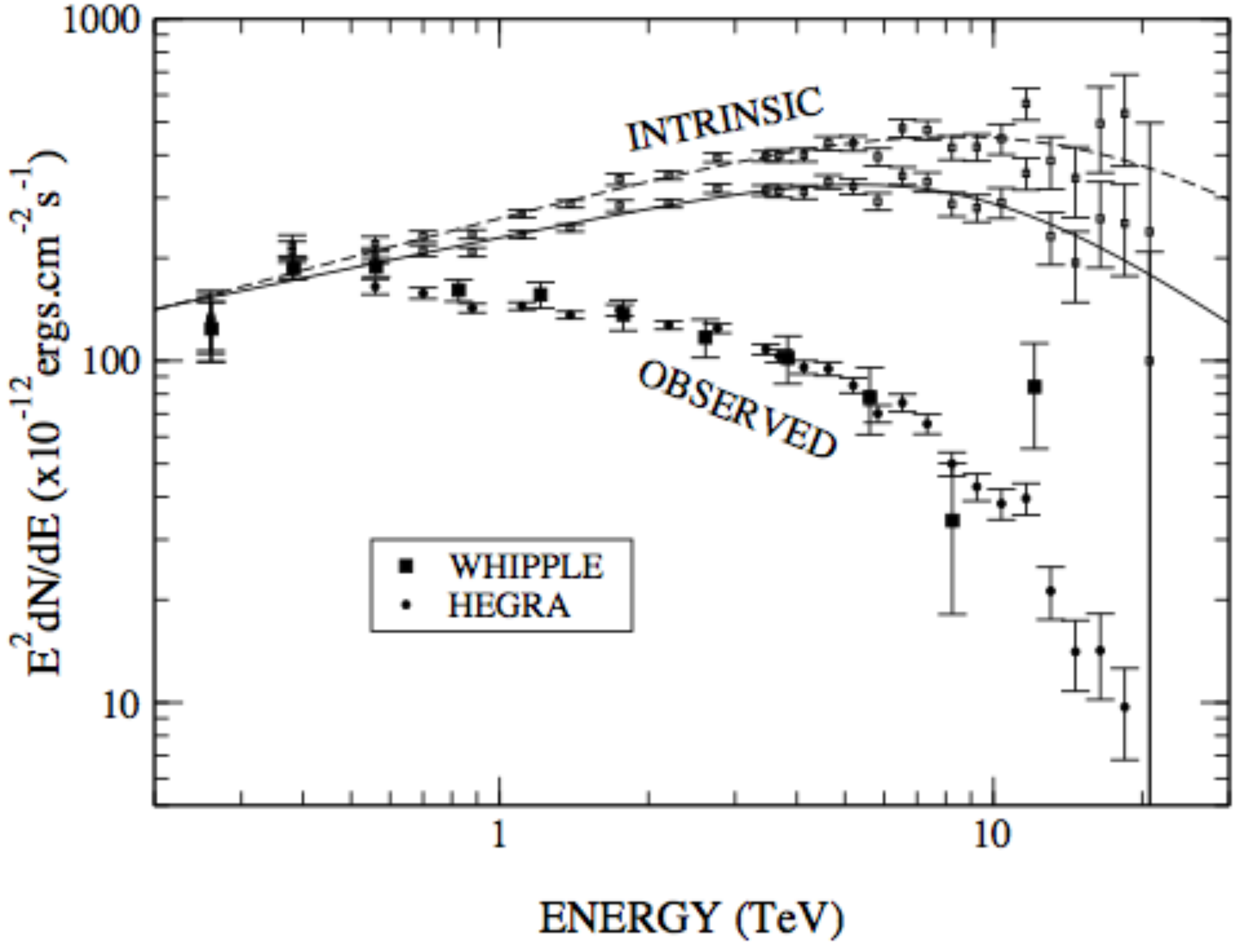
Constraints on Lorentz invariance violation (LIV) from spectral observations of very high energy γ-rays from blazars

γ-ray opacity through pair production interactions with photons from galaxies:

$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$



Flaring Spectrum of Mrk 501
(de Jager & FWS 2002)



Deabsorbed Mrk 501 Spectrum and SSC Model Fit
(Konopelko et el. 2003)

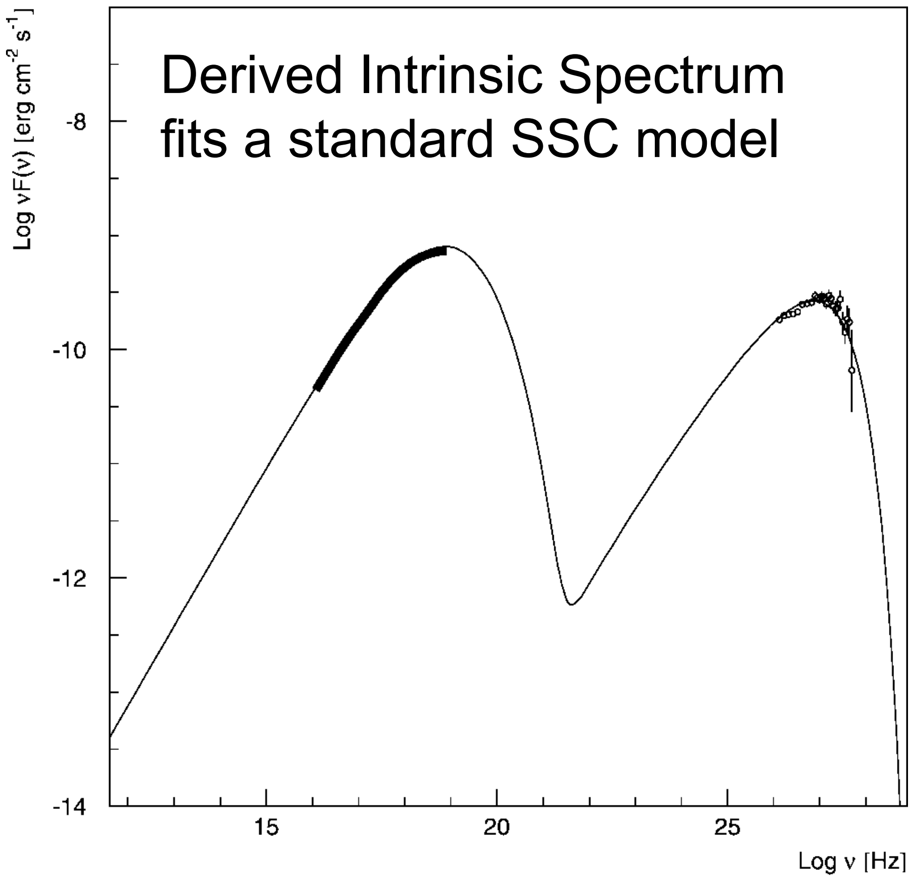


FIG. 7.—Combined X-ray/TeV γ-ray spectrum of Mrk 501 together with the best-fit SSC model.

γ-Ray Limit on LIV from Blazar Absorption from Coleman-Glashow Modified Threshold

$$2\omega E_\gamma(1-\cos\theta) > 4m_e^2 + 2E_\gamma^2\delta$$

The pair production threshold is raised significantly if

$$\delta > \frac{2m_e^2}{E_\gamma^2}.$$

The existence of electron-positron pair production for γ-ray energies up to ~20 TeV in the spectrum of Mkn 501 therefore gives an upper limit on δ at this energy scale of

$$\delta < 1.3 \times 10^{-15}$$

(FWS & S.L. Glashow 2001).

Limit on the Quantum Gravity Scale (FWS 2003)

For pair production, $\gamma + \gamma \rightarrow e^+ + e^-$ the electron (& positron) energy $E_e \sim E_\gamma / 2$. Introducing an additional QG term in the dispersion relation, p^3/M_{QG}, we find

$$\delta = \frac{E_\gamma}{2M_{QG}} - \frac{2m^2}{E_\gamma^2},$$

And the threshold energy from FWS and S. Glashow (2001)

$$\frac{E_\gamma^2 \delta}{2} \leq \frac{m^2}{E_\gamma} \qquad \text{reduces to} \qquad M_{QG} \geq \frac{E_\gamma^3}{8m^2}$$

Since pair production occurs for energies of at least E_γ = 20 TeV, we then find the numerical constraint on the quantum gravity scale

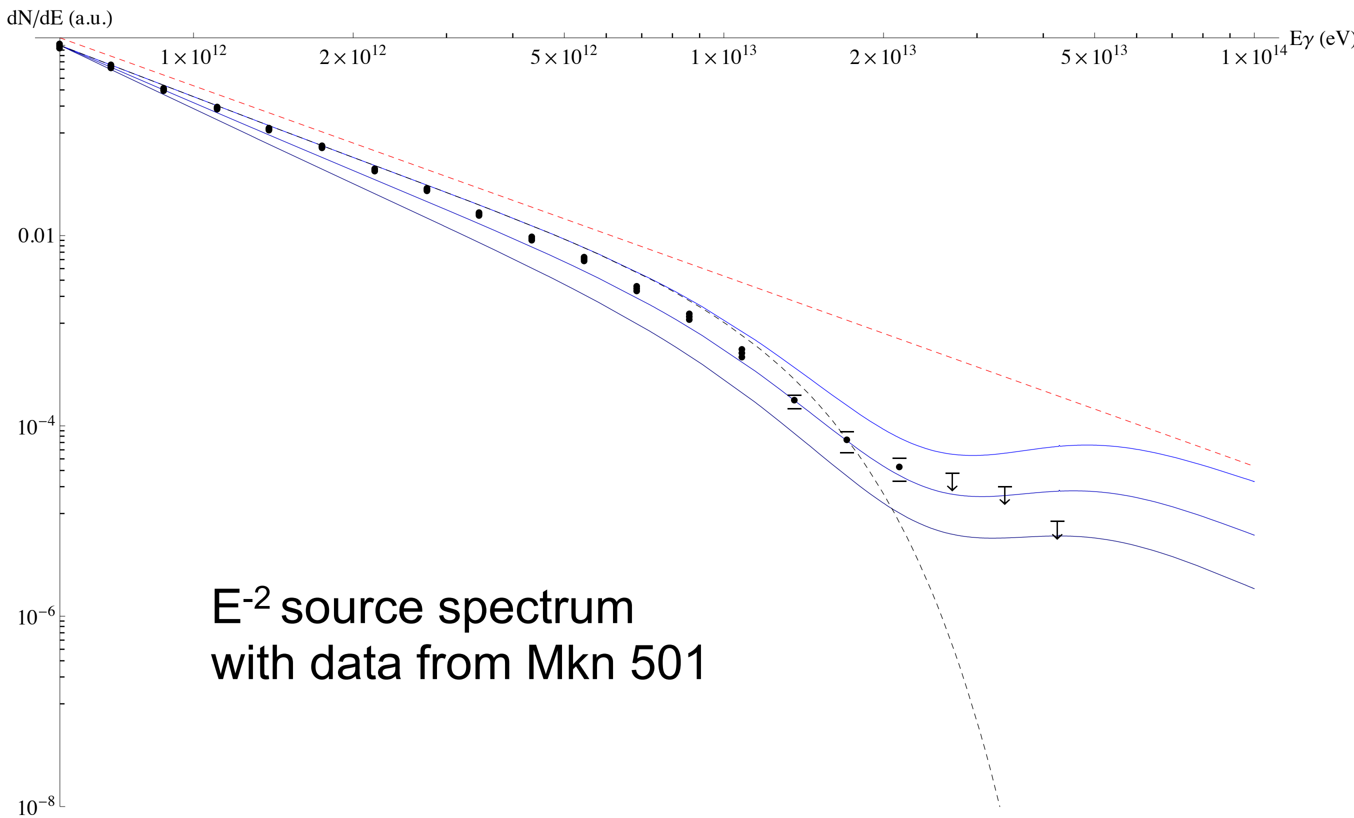
$$M_{QG} > 0.3\ M_{Planck}$$

Biteau & Williams (2015) find $M_{QG} > 0.65\ M_{Planck}$

For $M_{QG} = M_{Pl} = 1.2 \times 10^{19}$ GeV/c^2

- $E_\gamma^3/8m^2 = 2.9 \times 10^{13}$ eV = 29 TeV

Jacob & Piran 2008: Fig 4



CTA will test LIV at higher energies !

γ-ray time-of-flight constraint

Some classes of quantum gravity models postulate or imply a photon velocity dispersion relation with a pertubative term which may be linear with energy and with no birefringence (e.g. , Amelino-Camelia et al. 1998 and the D-brane model of Ellis et al. 2008).

$$v_\gamma = c\,[1 - (E_\gamma/M_{QG})]$$

Constraints from blazar flares and GRBs (short GRBs are best):

$$\Delta t = 20\ ms\ (M_{Planck}/M_{QG})\ d_{Gpc}\ \Delta E_{GeV}$$

where we might expect $(M_{Planck}/M_{QG}) = \xi = 1$

"Constraints on Lorentz Invariance Violation with Fermi-LAT Observations of GRBs"

V. Vasileiou, F. Piron,
J. Cohen-Tanugi (LUPM Montpellier)
A.Jacholkowska,
J. Bolmont, C. Couturier (LPNHE Paris)
J. Granot (Open Univ. of Israel)
F. Stecker (NASA GSFC)
F. Longo (INFN Trieste).

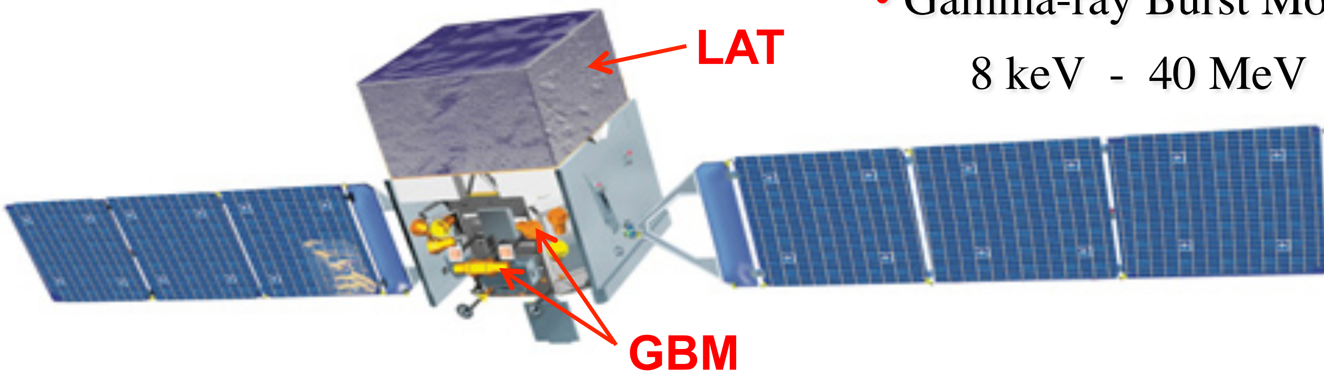
Phys. Rev. D, 87, 122001 (2013)

Limits on LIV from
Energy-Dependent Time Delay Limits
from GRB 090510

Fermi γ-ray Space Telescope:

Two *Fermi* instruments:

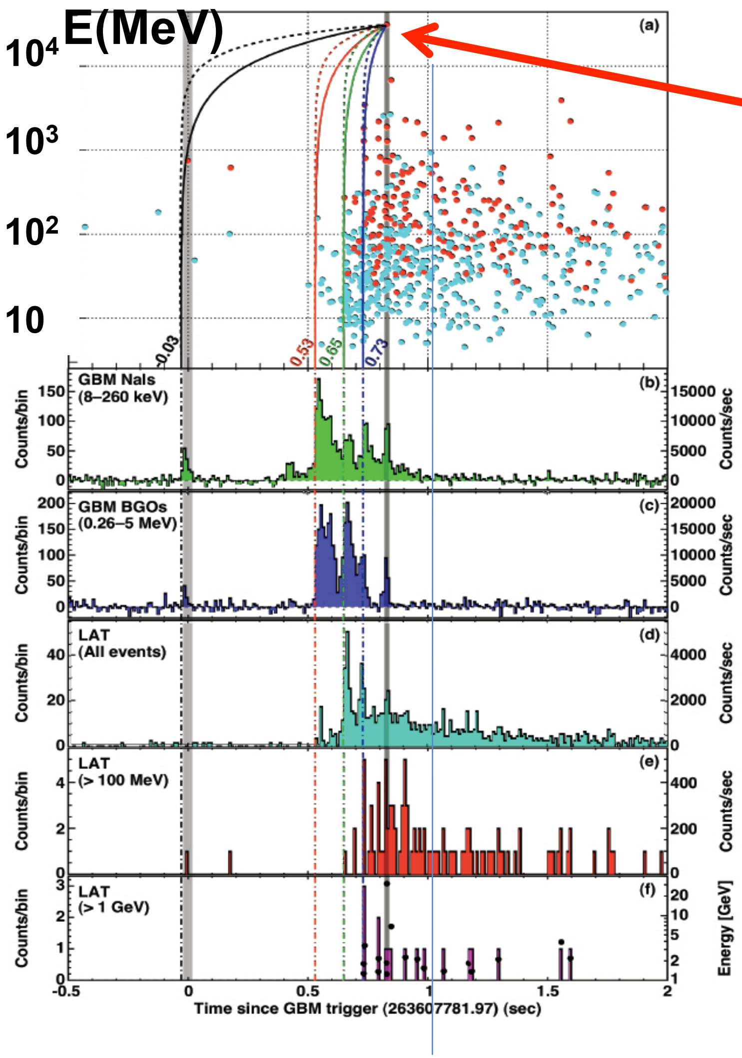
- Large Area Telescope (LAT)
  20 MeV - >300 GeV
- Gamma-ray Burst Monitor (GBM)
  8 keV - 40 MeV



The Fermi-LAT consists of three subsystems:

- An anti coincidence detector consisting of segmented plastic scintillators for cosmic-ray background rejection.
- A tracker consisting of silicon strip detectors and tungsten foil converters for determining the identification and direction of γ-rays.
- An imaging calorimeter consisting of cesium iodide scintillators.

31 GeV photon from GRB 090510



31 GeV photon : 860 ms after the Trigger from the GBM (largest possible Δt gives the most conservative result)

This is the highest energy observed from short GRB

Thus, this photon can be used to constrain both the bulk Lorentz factor of the relativistic jet and Lorentz Invariance Violation (LIV)

If

$$v_\gamma = c\,[1 - (E_\gamma/M_{QG})]$$

the *Fermi* *GBM/LAT* Timing Results imply

$$M_{QG} > \mathcal{O}(10)\ M_{Planck}$$

- *But we would expect that for a quantum theory of gravity* $M_{QG} \leq M_{Planck}$ *(e.g., Ellis et al. 2008).*

- *Maybe Horava-Lifshitz (2009) Quantum Gravity (see Pospelov & Shang 2012).*

EFT of LIV implying birefringence effects from E/M_{pl} scale velocity modifications (Meyers & Pospelov 2003)

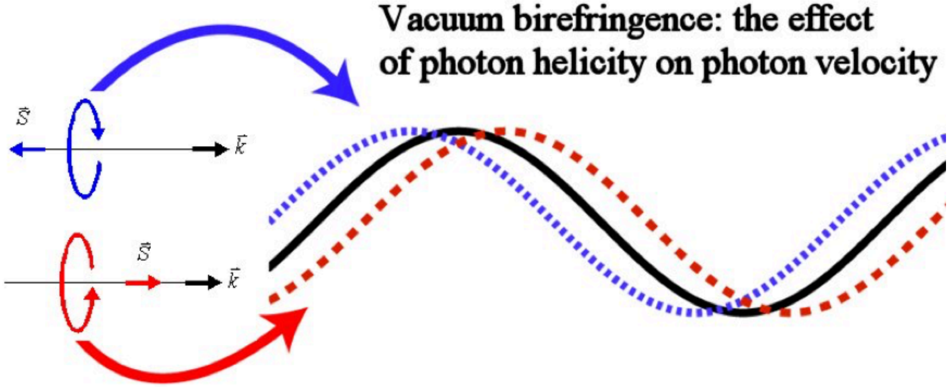
In the effective field theory (EFT) formalism, a dimension 5 LIV Term added to the EM Lagrangian that is both gauge and rotation invariant, not reducible to lower order, and suppressed by one power of the Planck mass

$$\Delta\mathcal{L}_\gamma = \frac{\xi}{M_{Pl}} n^a F_{ad} n \cdot \partial (n_b \tilde{F}^{bd})$$

gives dispersion relations where photons of opposite helicity propagate at different speeds (vacuum birefringence).

$$\omega^2 \;=\; k^2 \pm \xi\, k^3/M_{Pl}$$

This results in the destruction of polarization from linearly polarized cosmic photon sources if the difference between the rotated angles of polarized photons is greater than $\pi/2$.



Constraints on ξ with LIV term $(\xi/M_{planck})k^3$

If polarization is detected from a source at redshift z, this yields the constraint

$$|\xi| < \frac{\pi M_{Pl}}{\int_0^z dz' [k_2(z')^2 - k_1(z')^2] |dL_P(z')/dz'|} \tag{5}$$

where $k_{1,2}(z') = k_{1,2}[1 + z']$, and $k_{1,2} \equiv k_{1,2}(z' = 0)$ and

$$\left|\frac{dL_P}{dz'}\right| = \frac{c}{H_0} \frac{1}{(1+z')\sqrt{\Omega_\Lambda + (1+z')^3 \Omega_m}}. \tag{6}$$

Defining

$$\mathcal{D} = \frac{c}{H_0} \int_0^z dz' \frac{(1+z')}{\sqrt{\Omega_\Lambda + (1+z')^3 \Omega_m}} \tag{7}$$

it follows from Eqs. (5)–(7) and the definitions of $k_{1,2}(z')$ that

$$|\xi| < \frac{\pi M_{Pl}}{\mathcal{D}\left(k_2^2 - k_1^2\right)}, \tag{8}$$

Vacuum birefringence constraint

Polarized soft γ-ray emission from the region of the Crab Nebula pulsar yields

$|\xi| =< 9 \times 10^{-10}$ Maccione et al. 2008

Polarized X-rays from GRBs yield

$|\xi| < \mathcal{O}(10^{-15})$ FWS 2011, Laurent et al. 2011, Toma et al. 2012,

and the latest from GRB 140206A, $z = 2.74$,

$|\xi| < 1 \times 10^{-16}$ Goetz et al. 2014.

Sensitivity to vacuum birefringence from LIV is proportional to (redshift weighted) source distance and the square of the photon energy: Go to polarization detectors sensitive to higher energies to further test LIV!

Photomeson Production by Cosmic Microwave Background Photons Interacting with Ultrahigh Energy Cosmic Rays (UHECRs)

$$\gamma_{CMB} + p \rightarrow \Delta \rightarrow N + \pi$$

produces a "GZK Cutoff" in the UHECR Spectrum

But Cosmic Photomeson Interactions can be Modified by the Effects of LIV

UHECR Attenuation by the 2.7K CBR
(FWS 1968)

$$s \sim \omega E_p$$

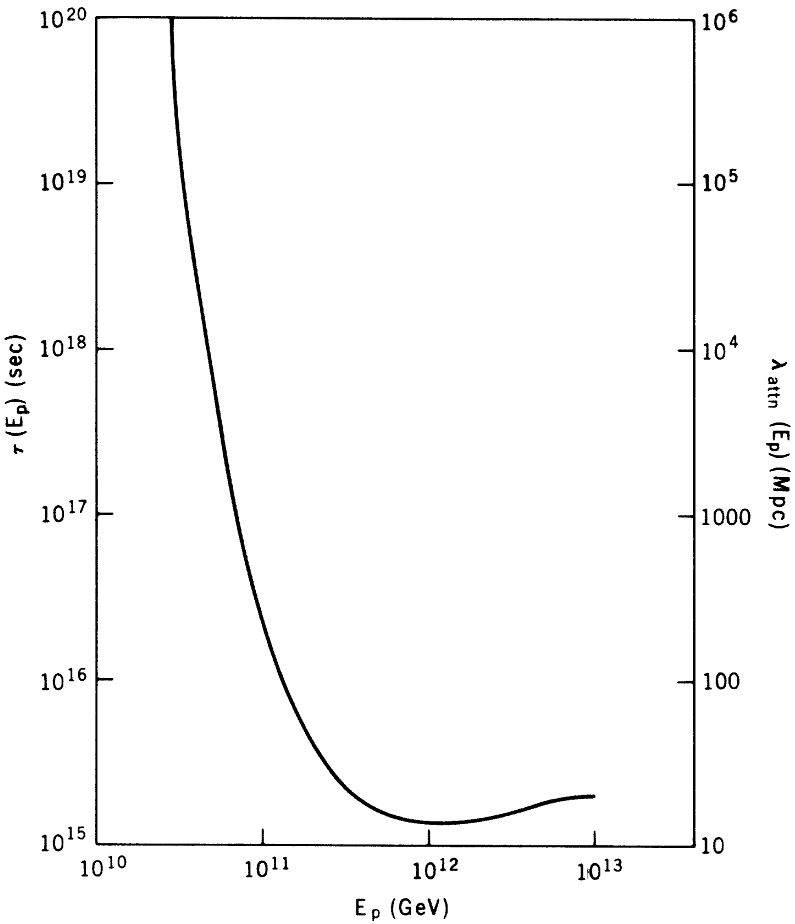


FIG. 2. Characteristic lifetime and attenuation mean free path for high-energy protons as a function of energy.

LIV Modified Interaction Threshold

Let us consider the photomeson production process leading to the GZK effect. Near threshold, where single pion production dominates,

$$\mathrm{p} + \gamma \to \mathrm{p} + \pi. \tag{7}$$

Using the normal Lorentz invariant kinematics, the energy threshold for photomeson interactions of UHECR protons of initial laboratory energy E with low energy photons of the CBR with laboratory energy ω, is determined by the relativistic invariance of the square of the total four-momentum of the proton–photon system. This relation, together with the threshold inelasticity relation $E_\pi = m/(M+m)E$ for single pion production, yields the threshold conditions for head on collisions in the laboratory frame

$$4\omega E = m(2M+m) \tag{8}$$

for the proton, and

$$4\omega E_\pi = \frac{m^2(2M+m)}{M+m} \tag{9}$$

in terms of the pion energy, where M is the rest mass of the proton and m is the rest mass of the pion [17].

If LI is broken so that $c_\pi > c_p$, it follows from equations (3), (6) and (9) that the threshold energy for photomeson is altered because the square of the four-momentum is shifted from its LI form so that the threshold condition in terms of the pion energy becomes[5]

$$4\omega E_\pi = \frac{m^2(2M+m)}{M+m} + 2\delta_{\pi\mathrm{p}} E_\pi^2 \tag{10}$$

Equation (10) is a quadratic equation with real roots only under the condition

$$\delta_{\pi\mathrm{p}} \leqslant \frac{2\omega^2(M+m)}{m^2(2M+m)} \simeq \omega^2/m^2. \tag{11}$$

Defining $\omega_0 \equiv kT_{\mathrm{CBR}} = 2.35 \times 10^{-4}$ eV with $T_{\mathrm{CBR}} = 2.725 \pm 0.02$ K, equation (11) can be rewritten

$$\delta_{\pi\mathrm{p}} \leqslant 3.23 \times 10^{-24} \left(\frac{\omega}{\omega_0}\right)^2. \tag{12}$$

Modifying Photomeson Interactions with LIV

- With LIV, different particles, i, can have different maximum attainable velocities c_i. *(S. Coleman and S. Glashow 1999)*

- The higher the value of $\boldsymbol{\delta}$, the higher the photon energy $\boldsymbol{\omega}$ required for the interactions to occur.

- Since $s \sim \omega E_p$, and there is a peak in the photomeson cross section at a fixed value of s corresponding to the $\boldsymbol{\Delta}$-resonance energy, interactions occur for higher energy CMB photons and corresponding lower values of E_p near the GZK "cutoff" energy, but are suppressed at higher values of E_p .

Auger spectrum with curves for various amounts of LIV giving the limit:

$\delta_{\pi p} < 4.5 \times 10^{-23}$ (FWS & S. Scully 2009)

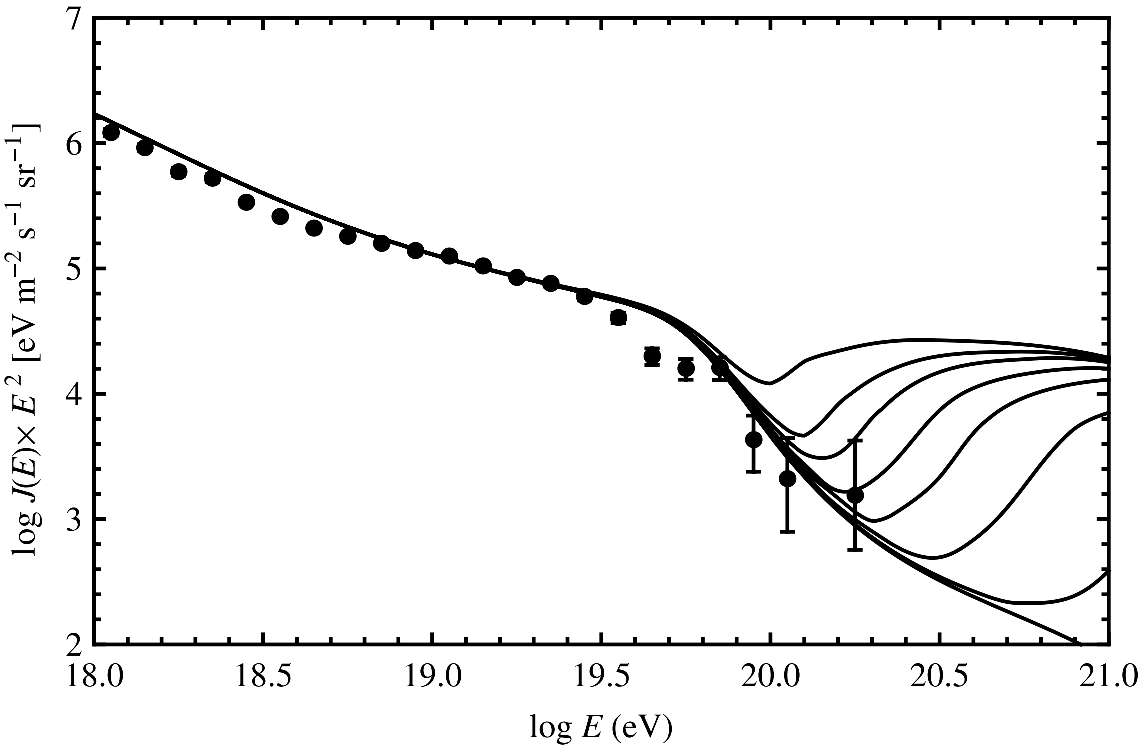


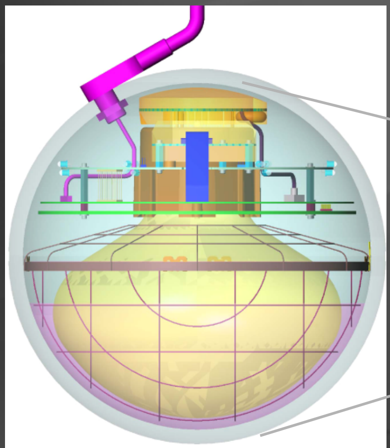
Figure 4. Comparison of the latest Auger data with calculated spectra for various values of $\delta_{\pi\mathrm{p}}$, taking $\delta_{\mathrm{p}} = 0$ (see text). From top to bottom, the curves give the predicted spectra for $\delta_{\pi\mathrm{p}} = 1 \times 10^{-22}$, 6×10^{-23}, 4.5×10^{-23}, 3×10^{-23}, 2×10^{-23}, 1×10^{-23}, 3×10^{-24} and 0 (no Lorentz violation) [44].

Constraints on $\delta_\nu > 0$ from the Recently Reported *IceCube* Detection of Cosmic PeV Neutrinos

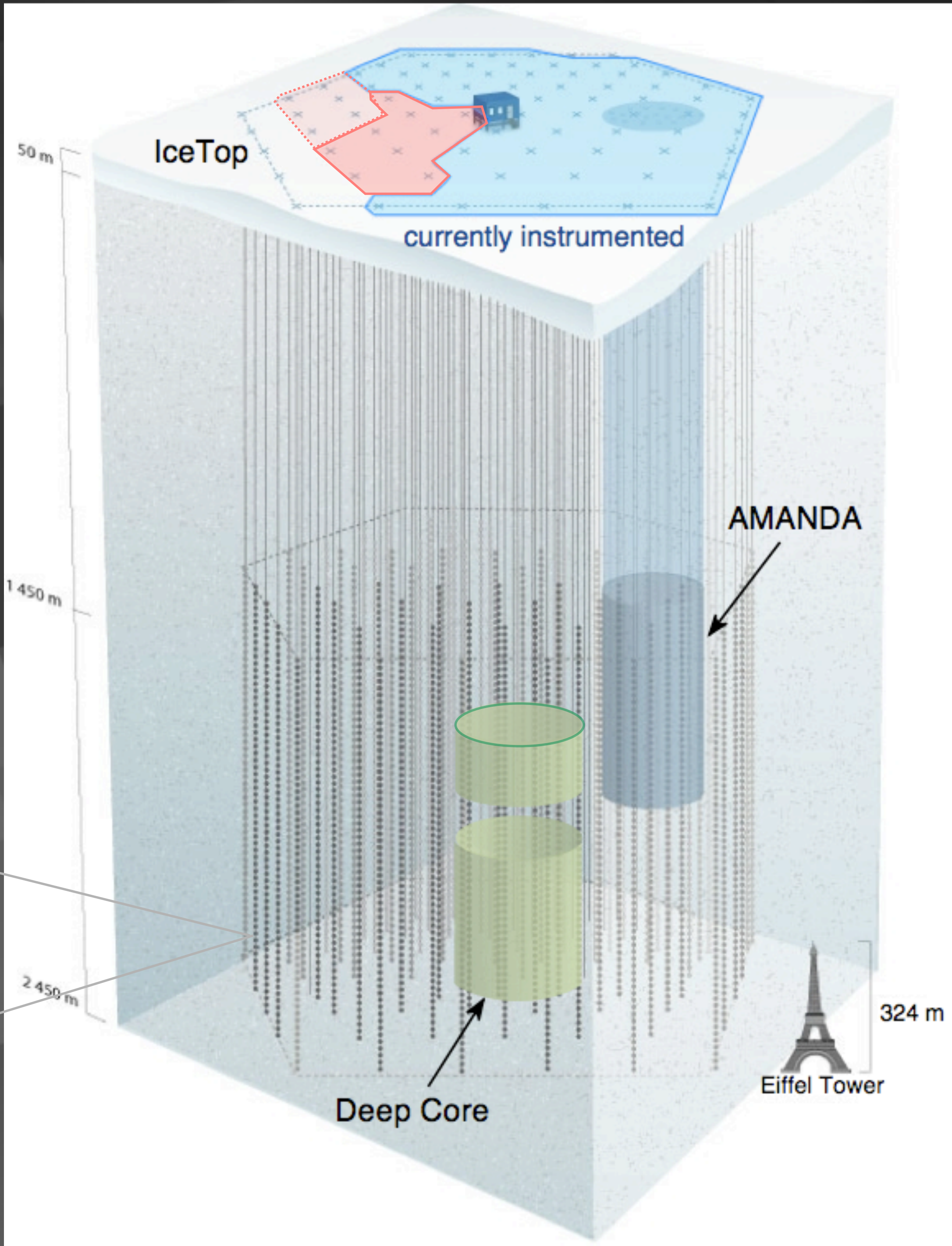
Ice Cube has detected three ν induced shower events with energies between *1* and 2 *PeV* *

*and a recent external event with E > 2.6 PeV.

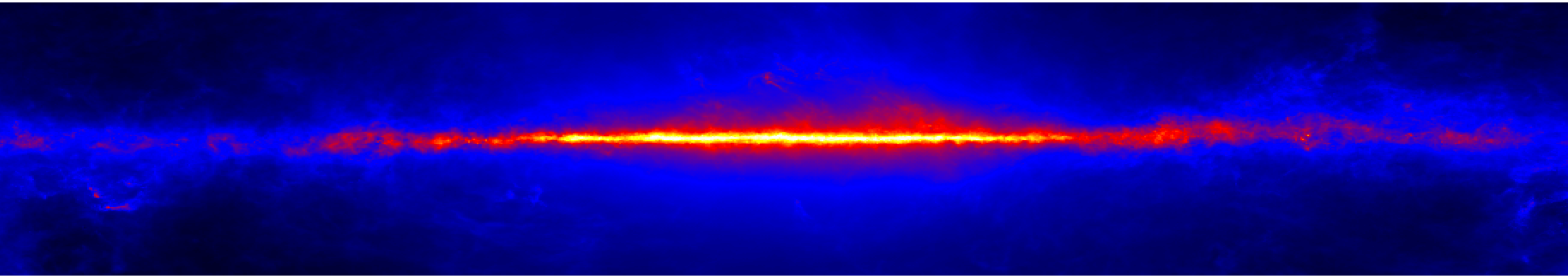
- *5160 optical sensors between 1.5 ~ 2.5 km*
- *detects > 200 neutrino-induced muons and ~ 2 x10^8 cosmic ray muons per day*



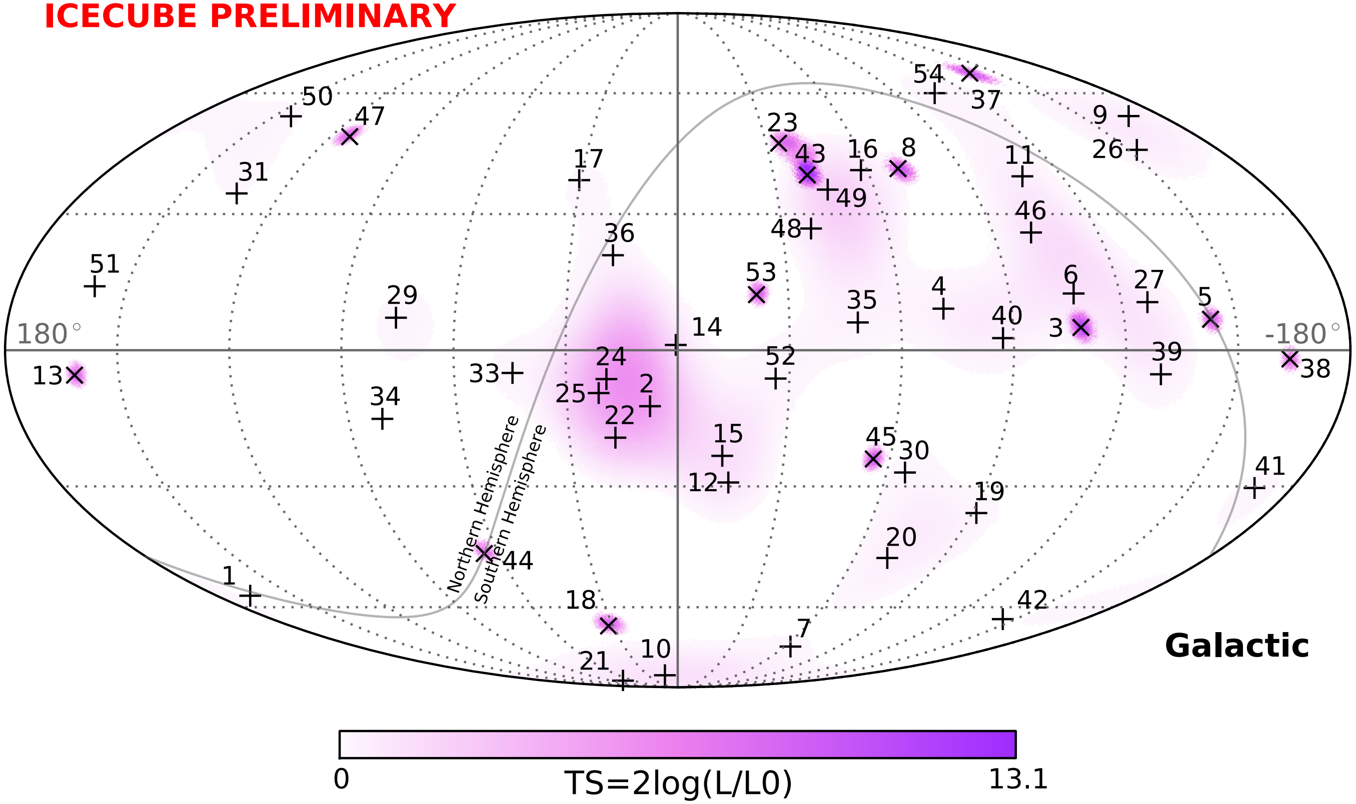
Digital Optical Module (DOM)



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) .



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^o a.r., (+): Cascades, ~15^o a.r.

Neutrino Energy Loss Processes for LIV with $\delta_\nu > 0$
(A. Cohen & S.L. Glashow 2011)

- $\nu \rightarrow \nu + \nu + \nu$

  Not relevant even for different flavors because oscillation data show that any difference in ν flavor velocities < 10^{-19}

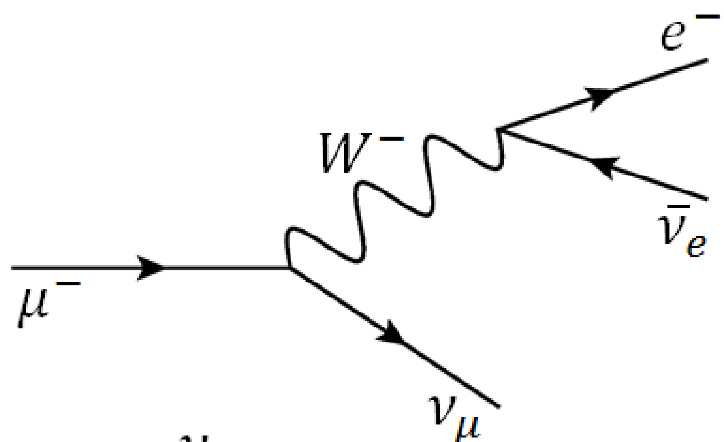
- $\nu \rightarrow \nu + e^+ + e^-$

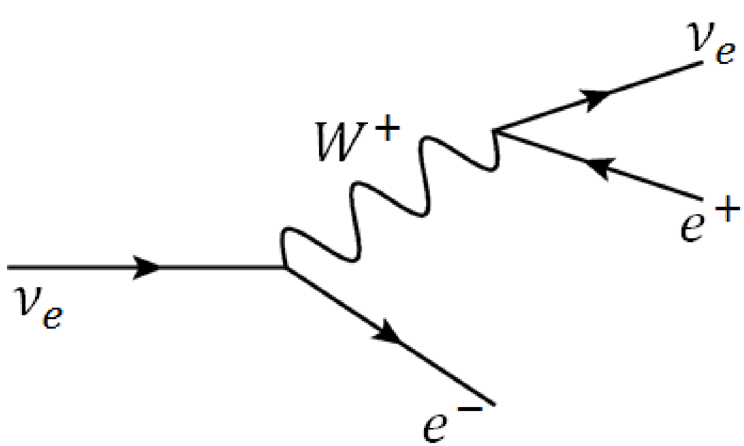
  Pair emission (Most Important Loss Process)

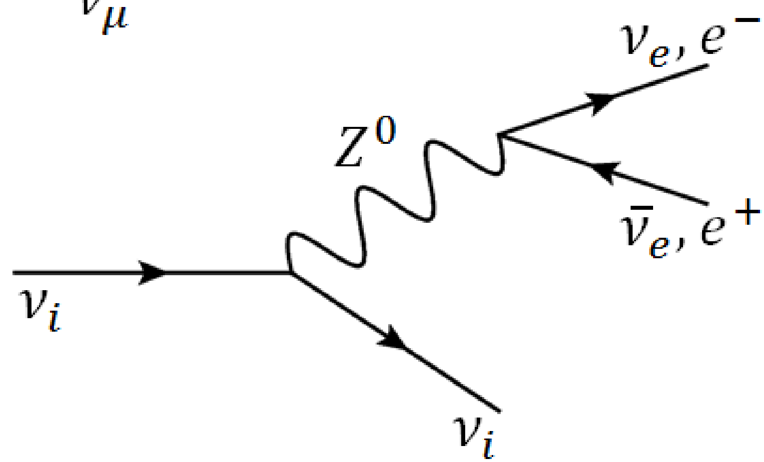
- $\nu \rightarrow \nu + \gamma$

  Less important than pair emission since the rate is down by α/π, requiring an extra e^+-e^- loop.

Vacuum Pair Emission (VPE) * *by Superluminal Neutrinos*







*A weak interaction version of Cherenkov radiation

Neutrino Threshold and Loss Rate from VPE:
(Cohen and Glashow 2011)

With VPE, neutrinos lose ~78% of their energy per pair emission.

$$\nu \rightarrow \nu + e^{+} + e^{-}$$

This is allowed if neutrinos are above a threshold energy

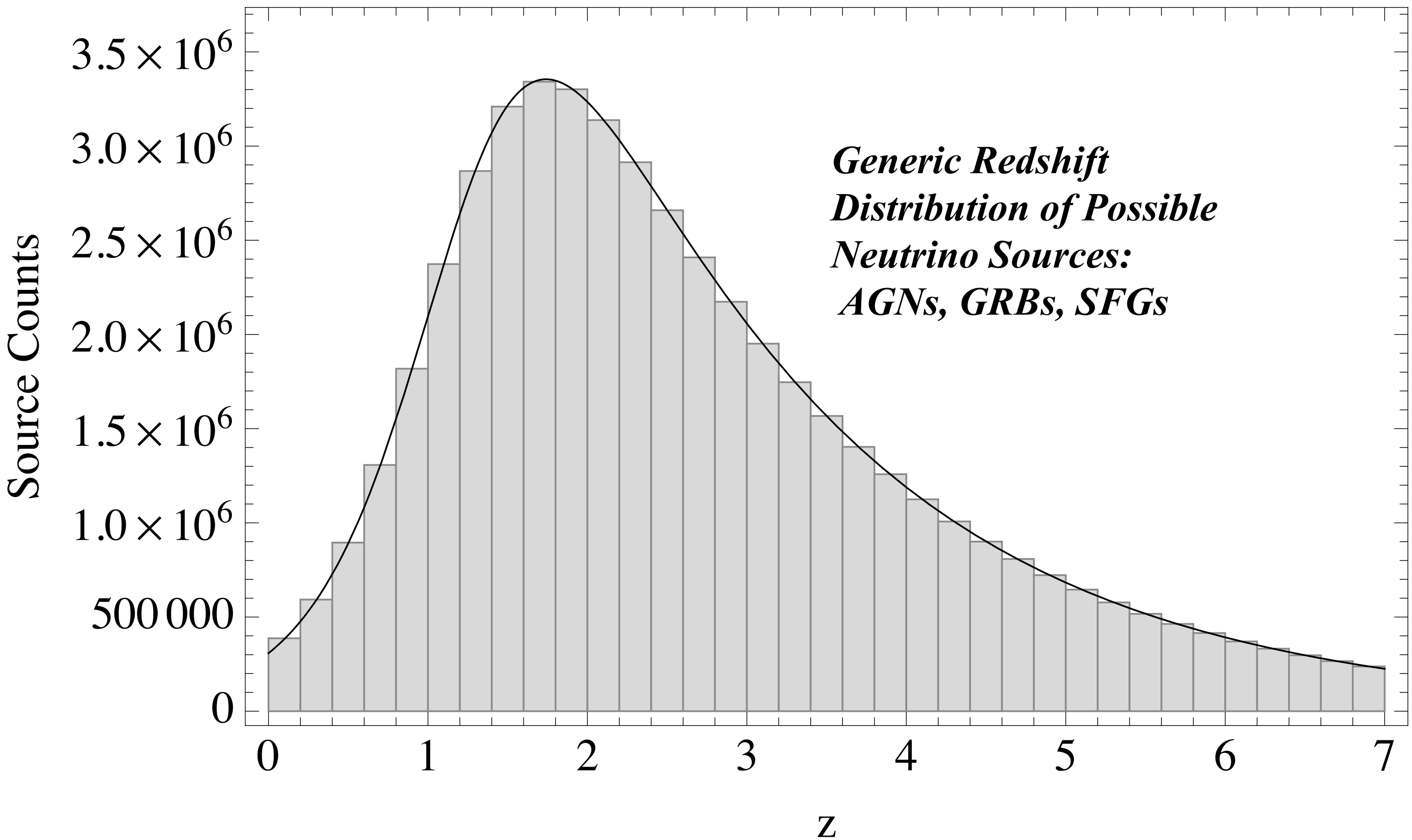
$$E_{\nu} > m_{e}\,[2/(|\delta_{\nu}-\delta_{e}|)]^{1/2},$$

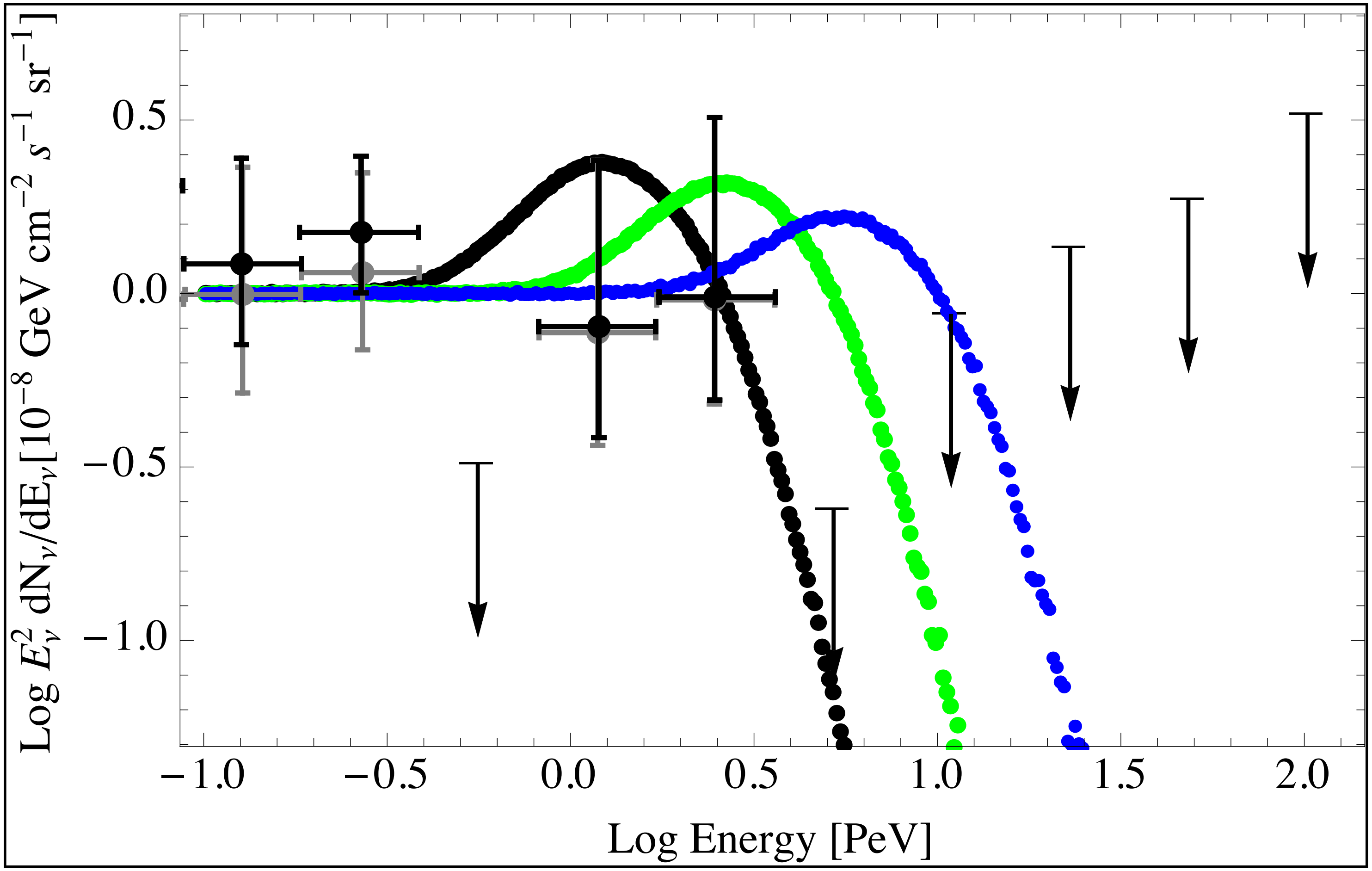
with $v_{\nu,e} = c_{\gamma}(1 + \delta_{\nu,e})$

The energy loss rate is given by

$$\frac{dE}{dx} = -k\,\frac{G_F^2}{192\pi^3}\,E^6\,\delta^3$$

Possible Extragalactic Neutrino Sources





Predicted ν spectrum with $\delta = 10^{-20}$ and EFT prediction with $[d] = 6$ in black.
Other spectra are for $\delta < 10^{-20}$ and $[d] = 6$. (FWS et al. 2016)

Conclusions for Neutrinos:
(FWS & Scully 2014, FWS et al. 2015)

• *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.*

Summary:

- The *Fermi* timing observations of GRB090510 are in tension with simple QG and D-brane model predictions of a retardation of photon velocity proportional to E/M_{QG} because they would require $M_{QG} > M_{Planck}$.
- More indirect results from γ-ray birefringence limits, the non-decay of 50 TeV γ-rays from the Crab Nebula, and the TeV spectra of nearby AGNs place severe limits on EFT LIV with [d] = 5 dominance.
- Observations of very high energy neutrinos by *IceCube* provide severe constraints on LIV in the neutrino sector.
- Observations of ultrahigh energy cosmic-rays provide extremely severe constraints on LIV.
- ***See other related talks at this meeting.***

Some Review Papers

D. Mattingly, *Living Rev. Relativity* **8** (2005) 5

T. Jacobson, S. Liberati and D, Mattingly, *Ann. Phys.* **321** (2006) 150

S. Liberati and L. Maccione, *Ann. Rev. Nuc. Part. Sci.* **59** (2009) 245

V. A. Kosteleck'y and N. Russell,`arXiv:0801.0287v7` (2014) Data Tables

F. W. Stecker, *Symmetry* **9,** 9100201, arXiv:1708.05672

Thank you!

Other Slides

Everything that is not forbidden is compulsory.
– Murray Gell-Mann

"Scientific values consist in…extending, or equivalently limiting , the domain of applicability of our concepts relating to matter, space, and time."

- Subramanian Chandrasekar

Fermi Launch: June 11, 2008

Analysis Uses Three Methods to Obtain τ_n and ξ_n

- *"Pair View" (PV)*

  Calculate the spectral lags between pairs of photons in a dataset.
  Find the peak in the distribution of pair lags as defined by τ_n.

- *"Sharpness Maximization Method" (SMM)*

  LIV smears light curve structure decreasing sharpness. Search for degree of dispersion that restores the sharpness.

- *"Maximum Likelihood Analysis" (ML)*

  Derive a model of GRB data with light curve template obtained from low enough energies for negligible LIV. Calculate likelihood of detecting each photon in the dataset given the model and maximize the likelihood to produce the best estimate of the time lags.

Energy Related Relative Time Delay

Using a dispersion relation perturbation term of order n = dim - 4

$$E^2 - p^2 \simeq s_{\pm}\xi_n p^2 (\frac{p}{E_{Pl}})^n$$

with $s_{\pm} = \pm 1$, and further defining

$$\tau_n \equiv \frac{\Delta t}{E_h^n - E_l^n}$$

then

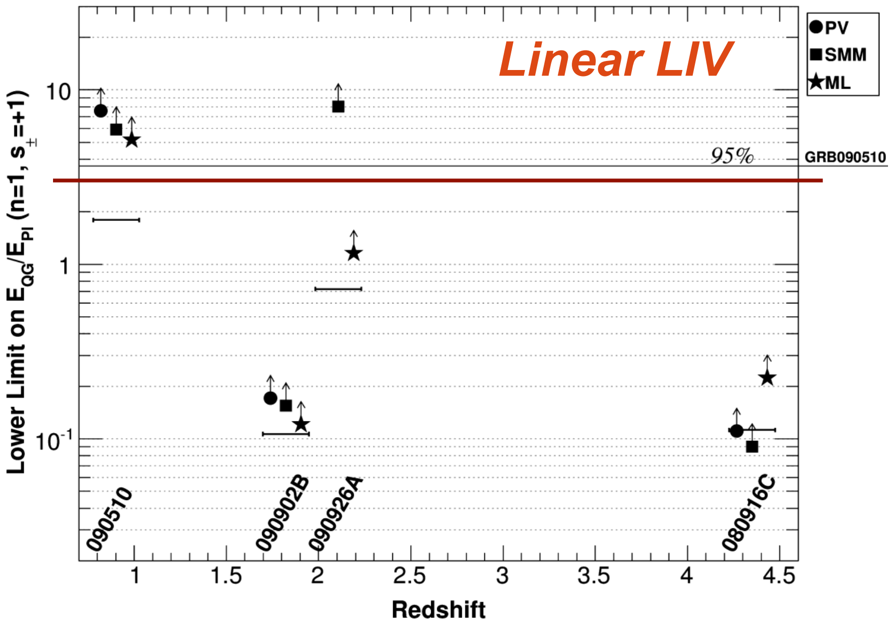
$$\tau_n \simeq \frac{(1+n)\xi_n}{2E_{Pl}c}\mathcal{D}_n$$

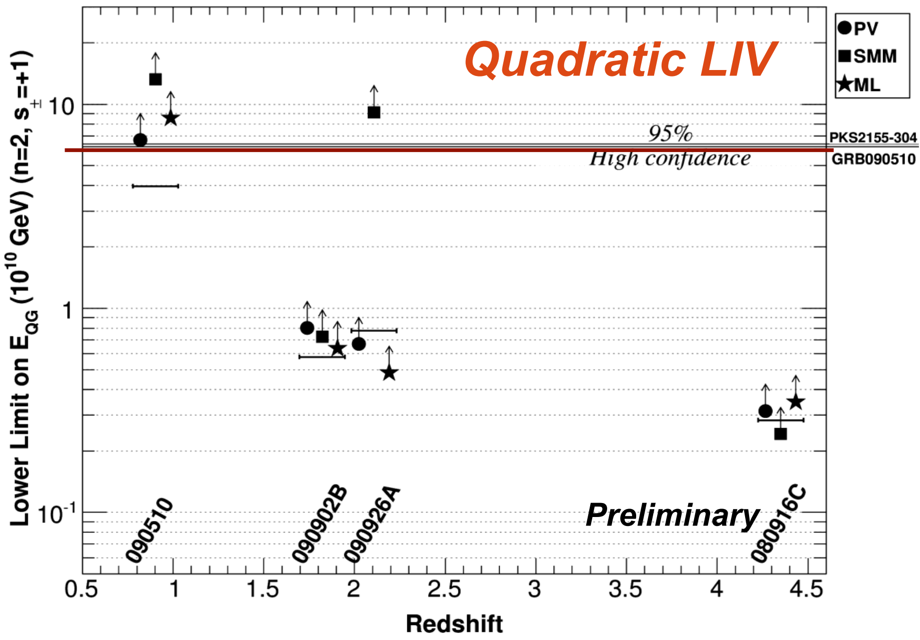
where

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

(Jacob & Piran 2008).

95% lower limits on EQG (subluminal case)





- We improve previous limits from time-of-flight by factor of
- ~ 2–4 depending on LIV type and CL:
- from GRB 090510
  - n=1: $E_{QG} \gtrsim 8\ E_{Pl}$
  - n=2: $E_{QG} \gtrsim 1.3 \times 10^{11}$ GeV

- **Horizontal bars** → our average constraint accounting for GRB-intrinsic effects
  - Still over the Planck scale for n=1: $E_{QG} \gtrsim 2\ E_{Pl}$
- **Markers** →our constraints not accounting for GRB-intrinsic effects

Uncertainties in *Lp-Ep* Relation and thus GRB Distance (Lyu et al. 2014)

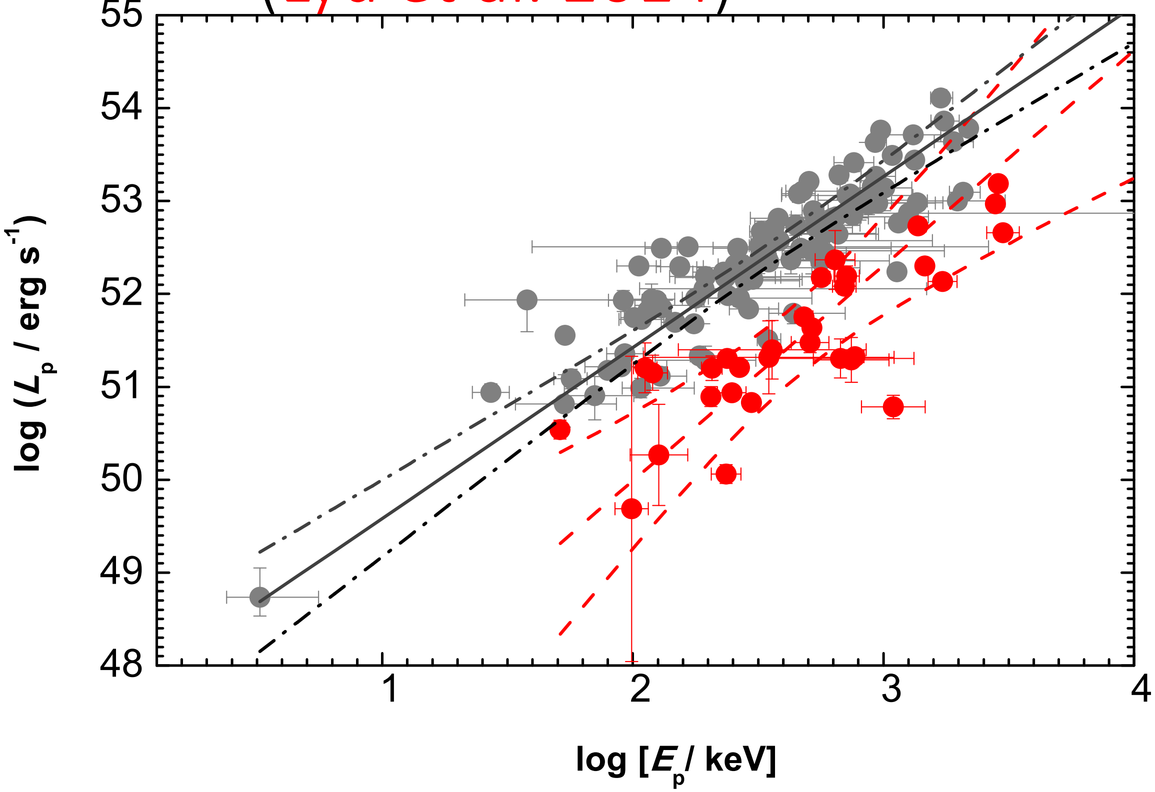
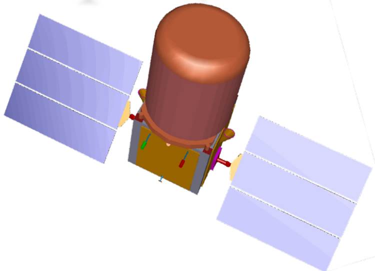


Fig. 1.— Relation between L_p and E_p derived from the time-integrated spectra of GRBs in our sample. The Yonetoku relation (grey dots) is also shown with a sample of GRBs from Yonetoku et al. (2010). Lines are the linear fit and its 3 σ confidence level to the data using the maximum likelihood method.

Advanced Energetic Pair Telescope (AdEPT)

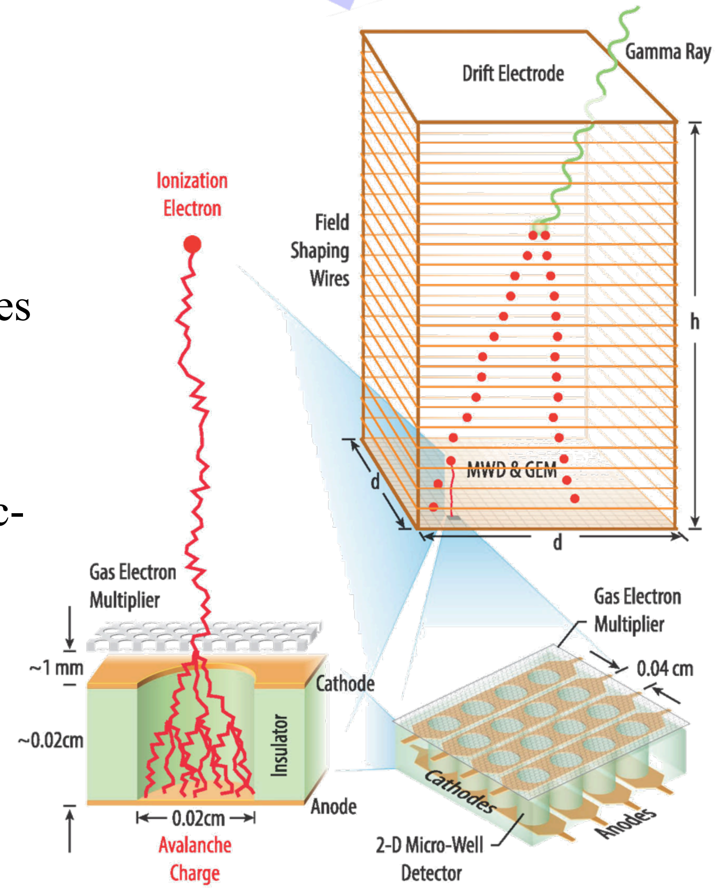


Medium-energy ~5-200 MeV γ-ray telescope

- High sensitivity and angular resolution
- Significant polarization sensitivity
- γ-ray imaging via triplet production
- *Thus, can provide a more sensitive test of vacuum birefringence*

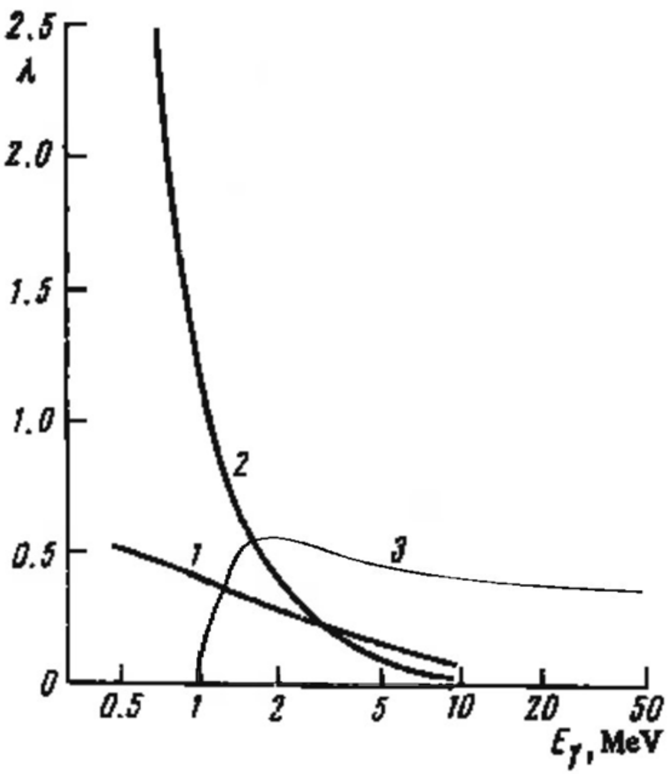
The keystone is the electron tracker, the *3-D Track Imager* (Hunter, et al. 2010)

- Large volume, *low density, gas* time-projection chamber enabling detection of γ-rays at lower energies than *Fermi*, acting as both a γ-ray convertor and a detection medium.
- Accurate tracking of all charged particles traversing the volume allows for γ-ray identification and cosmic-ray background rejection
- 3-D track imaging eliminates need for massive calorimeter and anti-coincidence shield

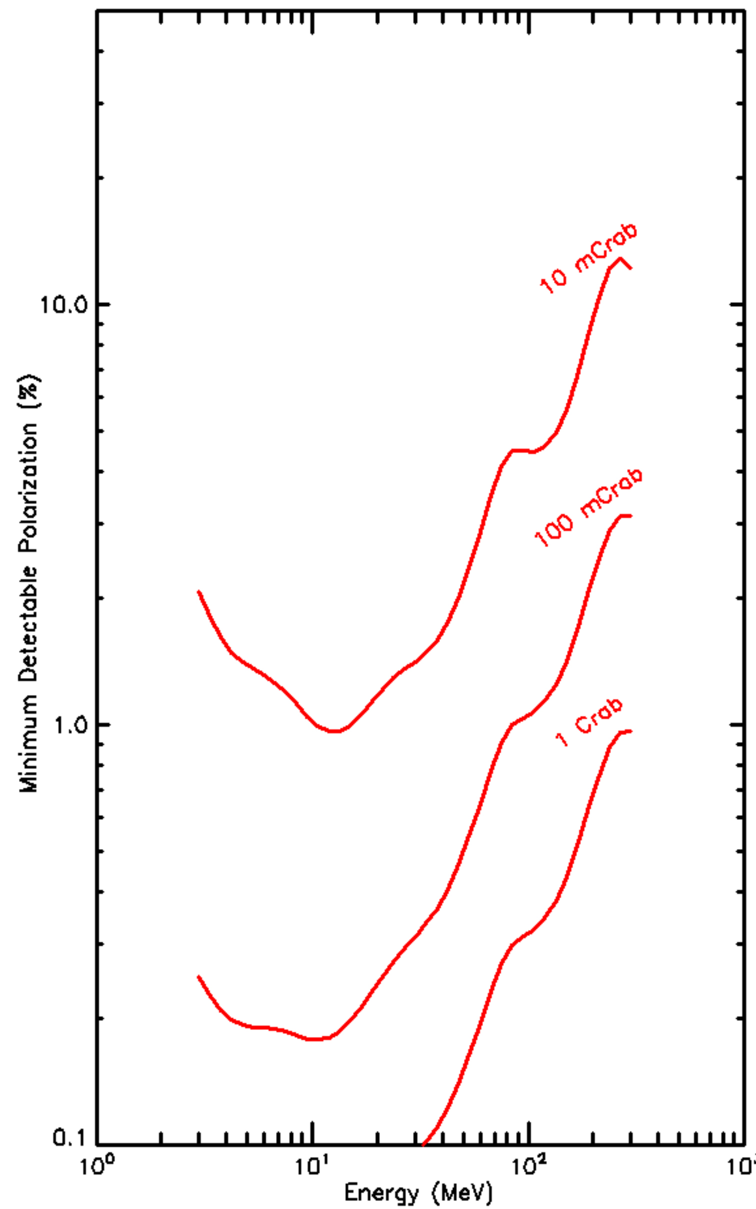


AdEPT Minimum Detectable Polarization

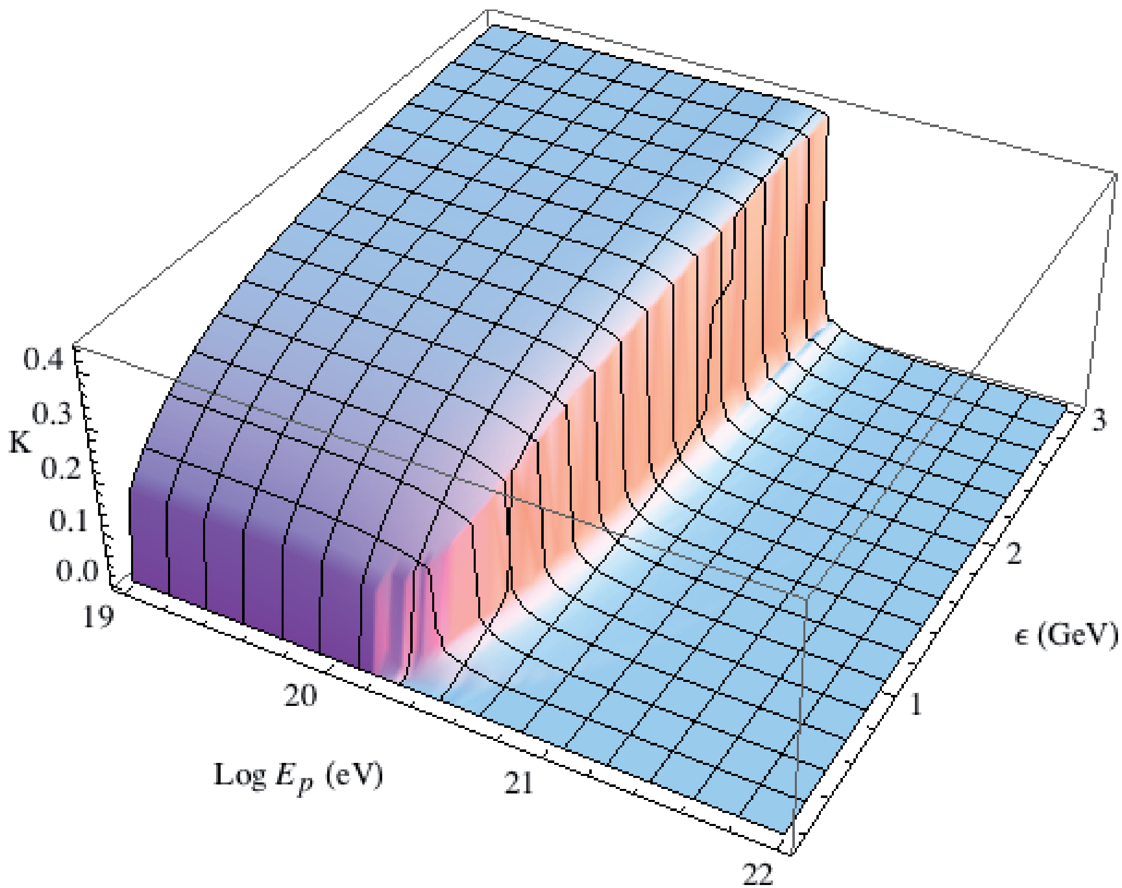
- A_{geom}=4x10^4 cm^2, T_{obs}=10^6 s, ΔE=E
- Modulation factor, λ = 0.35



The asymmetry λ as a function of the photon energy.
Curves: 1—Compton effect, 2—photoeffect, 3—pair production.
Adapted from : S.R. Kel'ner et al. Sov. J. Nucl. Phys. 21, 3, 1975



LIV Modified Proton Inelasticity for $\delta_{\pi p} = c_\pi - c_p = 3 \times 10^{-23}$



Upper Limit on *CPT*-Even Dimension 6 LIV Violating Term from *Auger* data:

dispersion relation for a particle of type ‘a’

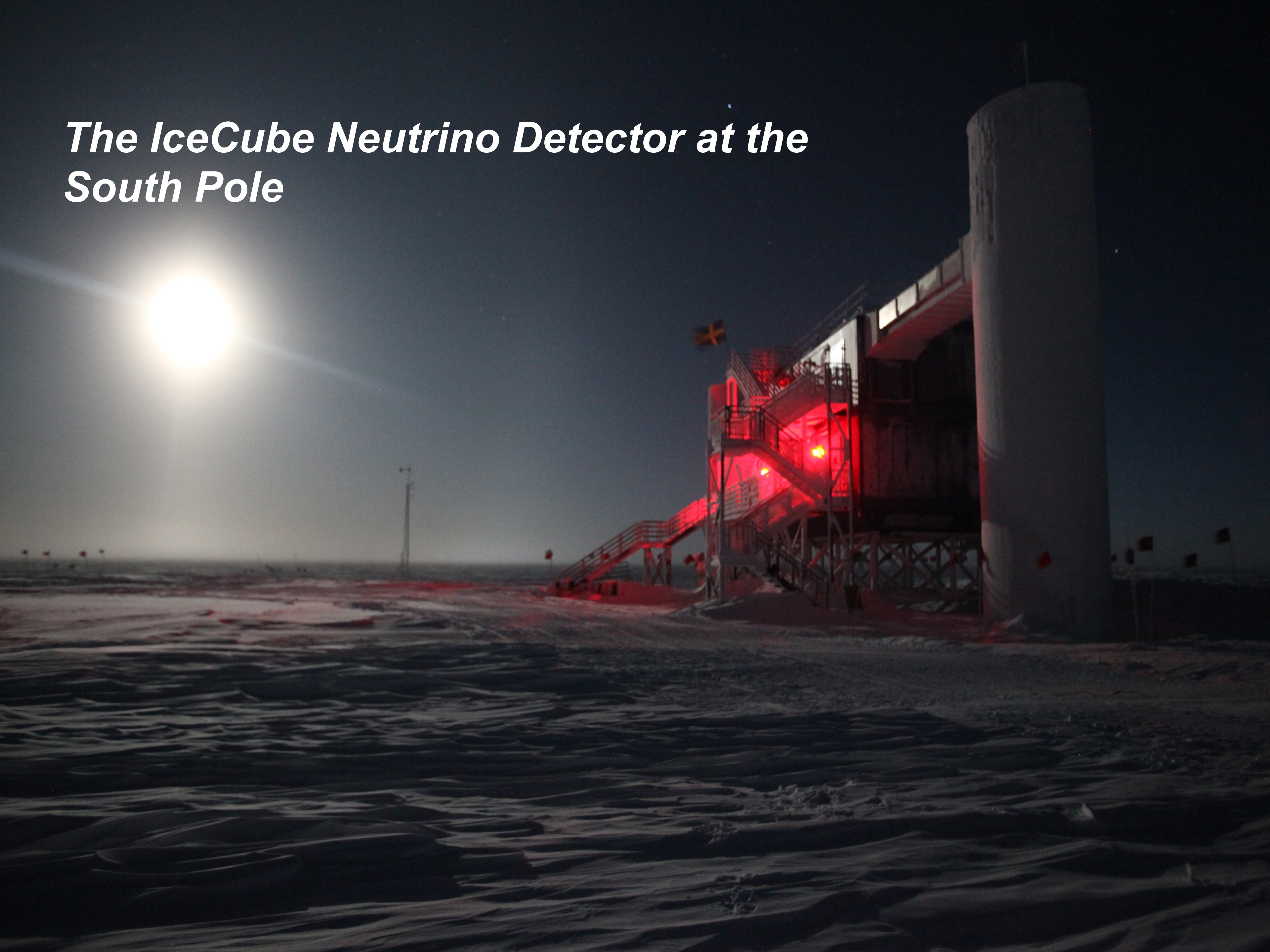
$$E_{\rm a}^2 = p_{\rm a}^2 + m_{\rm a}^2 + \eta_{\rm a}\left(\frac{p^4}{M_{\rm Pl}^2}\right).$$

FWS and S. Scully (2009) derived the relation

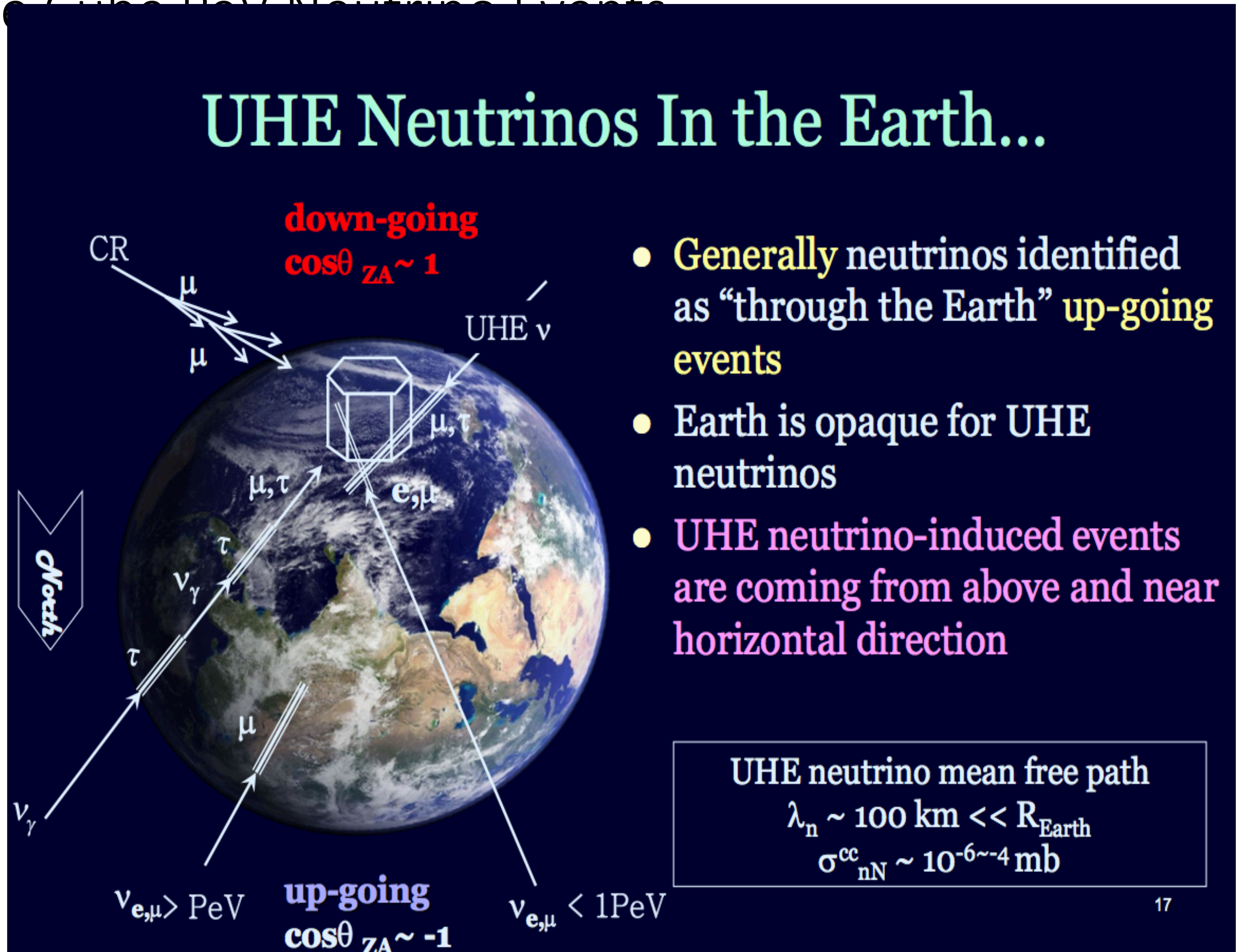
$$2\delta_{\pi \rm p} \simeq (\eta_\pi - 25\eta_{\rm p})\left(\frac{0.2E_{\rm f}}{M_{\rm Pl}}\right)^2$$

with fiducial energy $E_f = 10^{20}$ eV, yielding a limit $O(10^{-6})\ M_{Pl}^{-2}$ on the dim-6 term.

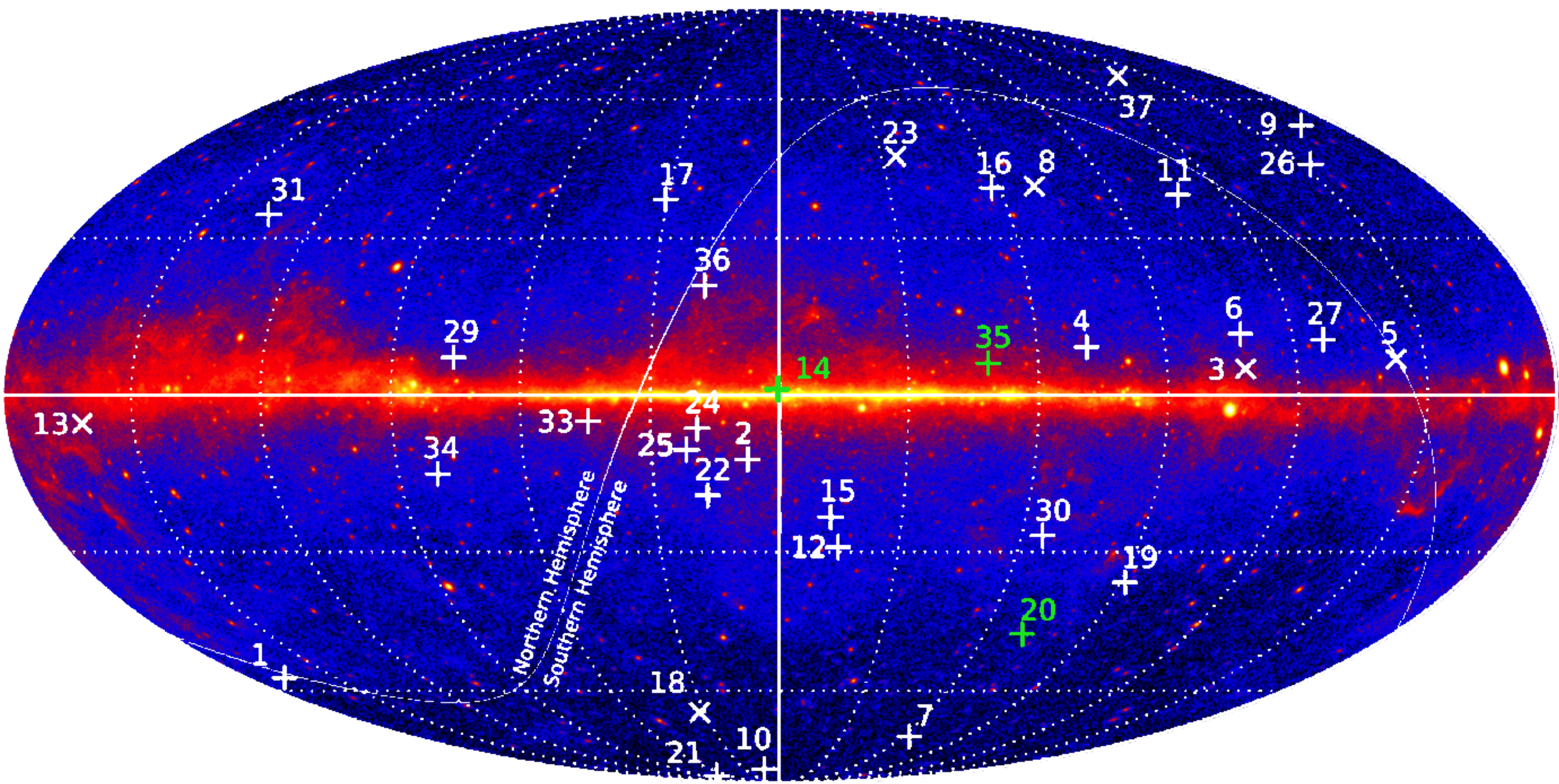
A similar result was obtained by Maccione et al. (2009) using a Monte Carlo technique.


The IceCube Neutrino Detector at the South Pole

IceCube PeV Neutrino Events



Fermi 5-year γ-ray Sky Map in Galactic Coordinates with *IceCube* Event Directions Superposed: PeV ν Events are in Green.



IceCube High Energy Neutrinos: Most or all are extragalactic!

(1) The arrival distribution of the observed 37 neutrinos is consistent with isotropy.

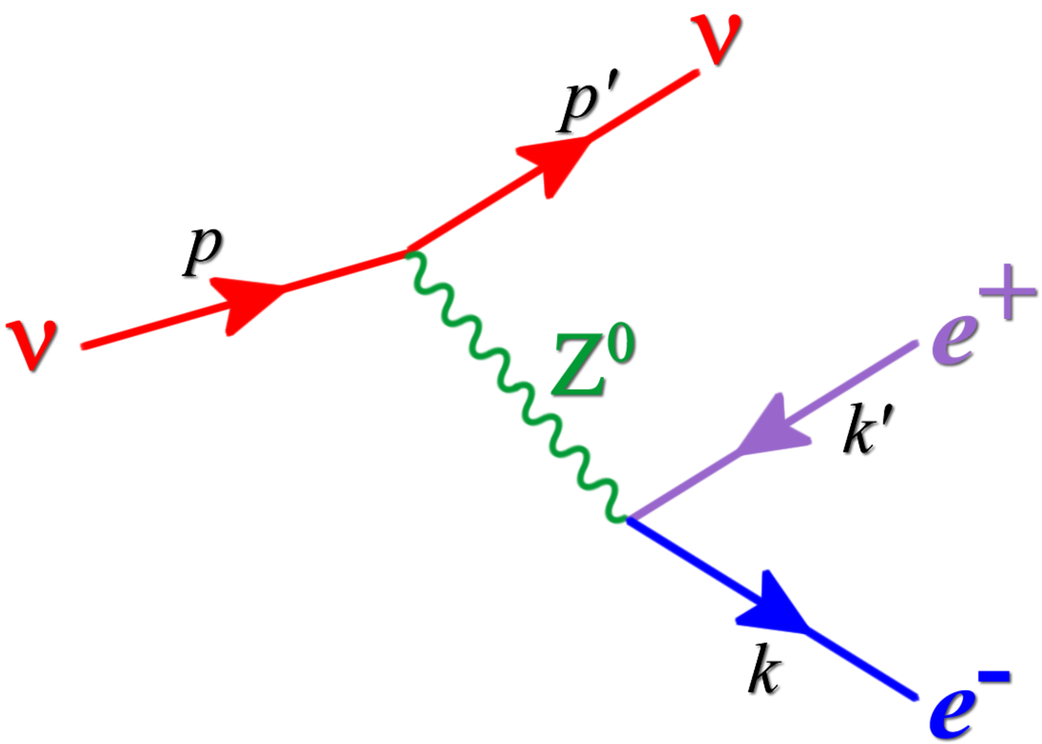
(2) The arrival distribution of galactic PeV neutrinos should be strongly confined to the galactic plane (Stecker 1979).

(2) The diffuse galactic ν flux (Stecker 1979) is expected to be well below that observed by *IceCube*.

(3) At least one of the $\sim$1 PeV ν's observed by IceCube (dubbed "Ernie") came from a direction off of the galactic plane. The highest energy ν gives the best constraint on superluminality.

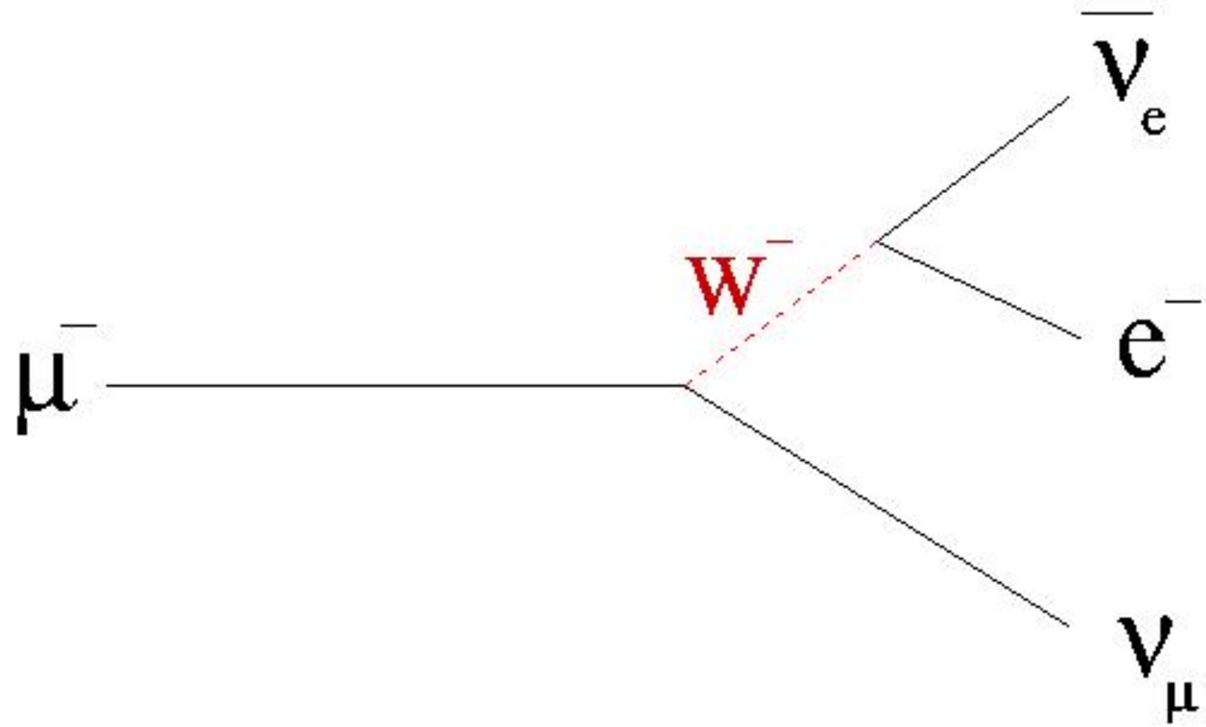
(4) Upper limits on diffuse galactic γ-rays in the TeV-PeV energy range imply that galactic neutrinos cannot account for the neutrino flux observed by *IceCube* (Ahlers and Murase 2014).

Vacuum Pair Emission (VPE) by Superluminal Neutrinos*



*A neutral current weak interaction version of Cherenkov radiation

μ Decay: $\Gamma \sim \gamma^{-1} G_F{}^2 m_\mu{}^5$



Dependence of VPE Rate on E_ν and $\delta_{\nu e}$

For muons with a Lorentz factor γ_μ in the observer's frame the decay rate is

$$\Gamma \propto \gamma_\mu{}^{-1} G_F^2 M_\mu^5 \tag{35}$$

where G_F is the Fermi constant equal to 1.16637×10^{-5} GeV^{-2}.

We can look at the right hand side of equation (4) as an effective energy-dependent mass-squared term in the dispersion relation. It then follows from equation (4), with $\delta_{\nu e} = \epsilon/2$, that by making the substitutions

$$M_\mu^2 \rightarrow 2\delta_{\nu e} E_\nu^2 \tag{36}$$

and

$$\gamma_\mu^2 \rightarrow \frac{E_\nu^2}{2\delta_{\nu e} E_\nu^2} = (2\delta_{\nu e})^{-1} \tag{37}$$

the rate for the VPE process is then

$$\Gamma \propto (2\delta_{\nu e})^{1/2} G_F^2 (2\delta_{\nu e} E_\nu^2)^{5/2} \tag{38}$$

which gives the proportionality

$$\Gamma \propto G_F^2\, \delta_{\nu e}^3 E_\nu^5 \tag{39}$$

Neutrino Pair Emission Energy Loss Rate Calculation:

Weak Interaction Lagrangian:

$$\mathcal{L} = \frac{4G_F}{\sqrt{2}} \bar{\nu_L} \gamma^\mu e \bar{e} \gamma_\mu \nu_L$$

Then calculate matrix element for the weak transition (messy).

The interaction rate is the integral over phase space and the (summed over spins) square of the matrix element, $\mathbf{M}$, preserving conservation of energy and momentum, but with

$P_\nu^2 = \delta E^2$ distorting the normal phase space.

$$\Gamma = \int (phase\ space) \delta^4 (P_\nu - p_e - P_{\bar{e}} - p_\nu) \sum |\mathbf{M}|^2$$

The final result is

$$\Gamma = k' \frac{G_F^2}{192\pi^3} E^5 \delta^3$$

Neutrino Spectra vs. $\delta_{\nu e}$

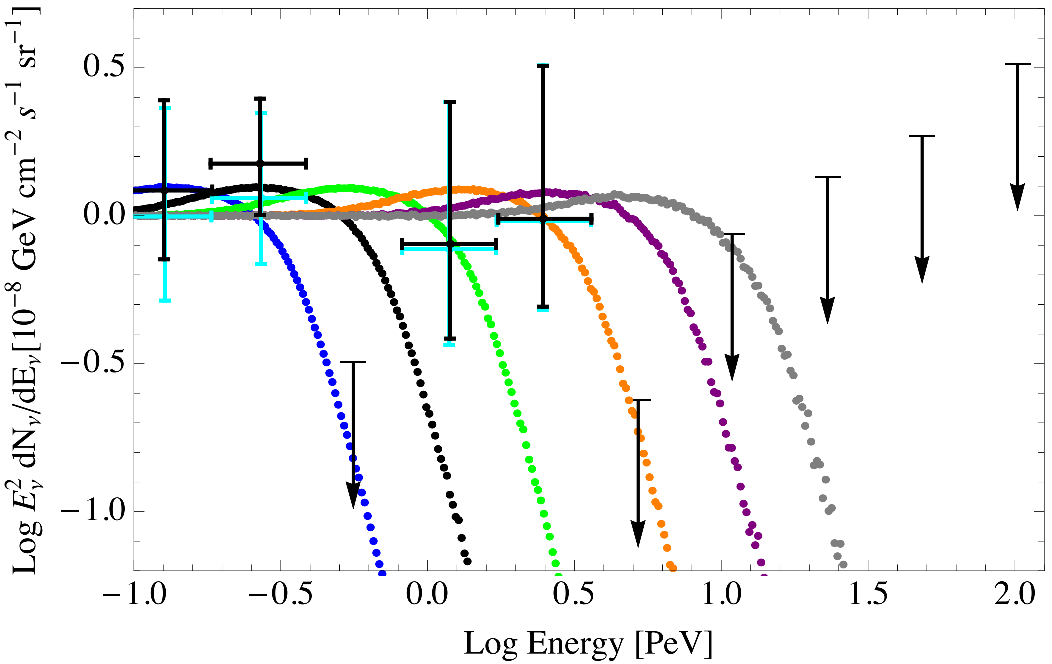


FIG. 3. Calculated neutrino spectra with VPE and redshifting compared with the IceCube data both including a subtraction of atmospheric charm ν's at the 90% C.L. (cyan) and omitting such a subtraction (black) [5]. Curves from left to right are spectra obtained with rest-frame threshold energies of 1, 2, 4, 10, 20 and 40 PeV. The corresponding values of $\delta_{\nu e}$ are given by equation (3).

Two interpretations of the cutoff in the neutrino spectrum

$\delta_\nu < (0.5 - 1) \times 10^{-20}$

This is the most conservative result since cutoff in the spectrum between 2 and 3 PeV can be caused by something else, e.g., a cutoff in the source spectrum.

$\delta_\nu = (0.5 - 1) \times 10^{-20}$

This would be an exciting result if the cutoff in the spectrum between 2 and 3 PeV is due to a very small amount of Lorentz invariance violation.

Our calculations either put the most stringent constraints by far to date on Lorentz invariance violation in the neutrino sector or may possibly indicate the existence of very slightly superluminal neutrinos and a correspondingly small amount of Lorentz invariance violation.

Neutrino LIV Conclusions
*(*FWS & Scully 2014, Phys. Rev. D 90, 043012*)*

For a rest-frame threshold energy of > 4 PeV from the IceCube event spectrum, as shown in the previous slide and with $\delta_e < 5 \times 10^{-21}$*, *we then find**

$$\delta_\nu < (0.5 - 1) \times 10^{-20}$$

**From Fermi observations of the Crab Nebula*

A PeV ν event from *IceCube*