BIG-BANG THEORY AND HIGH ENERGY ASTROPHYSICS

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The BIG cosmological questions:

- What happened at, or “near”, the “moment” of the big-bang (new physics)?

- Can we ever learn about it?

- Can we find out now about the earliest moments of the big bang?

IN THE BEGINNING ?

THE PLANCK SCALE, λ_{Planck} -- NOT THE "SINGULARITY " -- IS *THE* CRITICAL POINT!

General Relativity (GR)and Quantum Theory (QT) effects are equally strong at the Planck time.

$$t_{Planck} = \lambda_{Planck}/c = (Gh/c^5)^{1/2}$$

$= 5 \times 10^{-44}$ s after the initial singularity.

Do physics, space, and time, as we understand them, exist before t_{Planck} ?

BUT IN THE END ---

We need to reconcile GR and QT for the real "Big-Bang Theory"

- Grand Finale!

POSSIBLE CLUE:

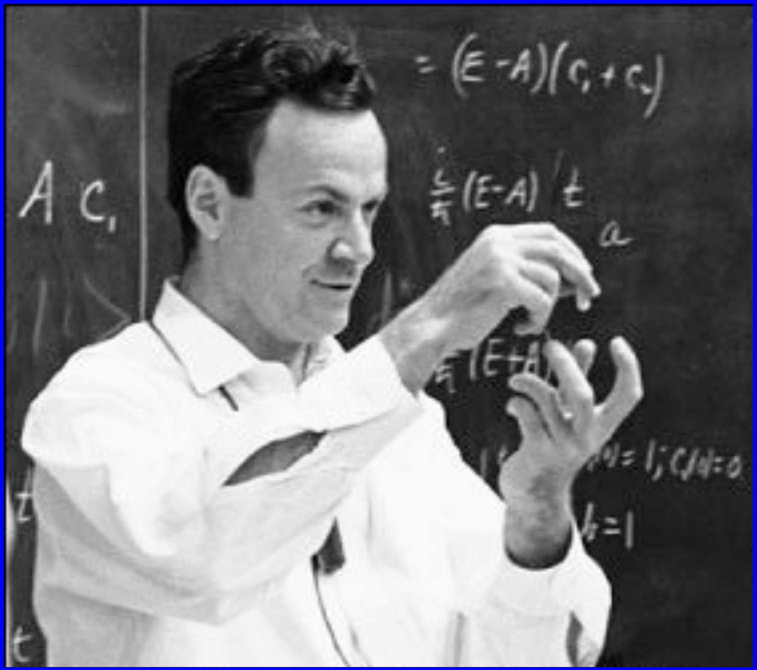
Use high energy astrophysical observations to search for Lorentz invariance violation from Planck-scale physics.

- *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 provide the highest observable energies in the universe.*
- *But there is a scale! At the Planck scale, λ_{Planck} (~10^{-35} m), E_{Planck} (~10^{19} GeV) physics such as quantum gravity may lead to the breaking or deformation of Lorentz invariance with traces at high energy.*

"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*

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

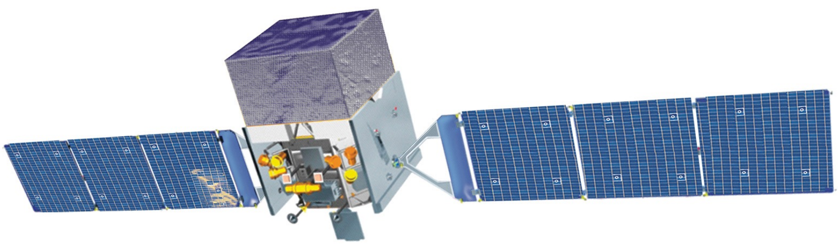
- Modification of the "GZK" spectrum of ultrahigh energy cosmic rays produced by photomeson interactions with the CMB

- Pair production *in vacuo* by high energy superluminal neutrinos


Cosmic γ-rays are produced by
active galactic nuclei (blazars)

γ-ray Telescopes:

Fermi **Space Telescope and Air Cherenkov Telescopes**



Fermi Space Telescope
(GeV energies)

Future Cherenkov Telescope Array
(TeV energies)

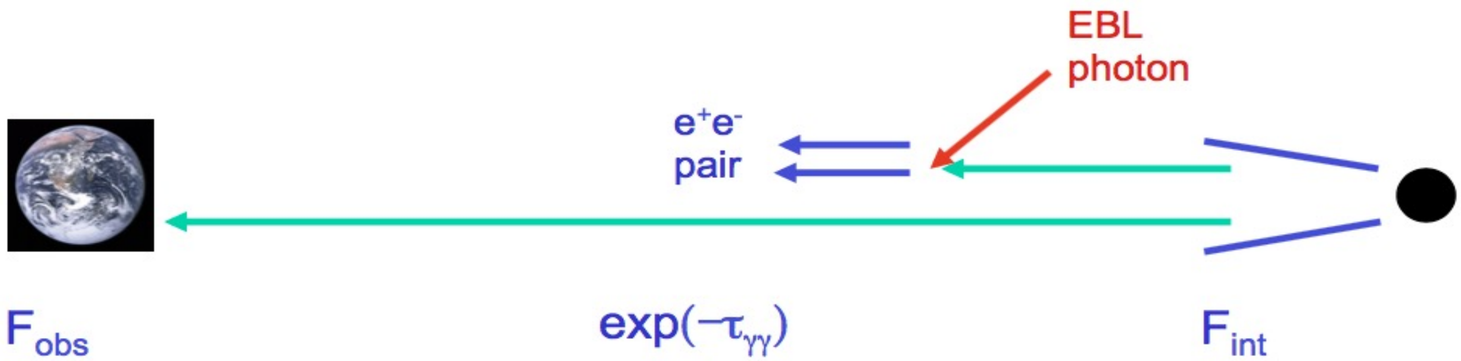
Fermi Launch: June 11, 2008

Gamma-ray Opacity of the Universe

$$F_{\gamma,obs} = F_{\gamma,source}\, exp\, [-\tau\, (E,z)]$$

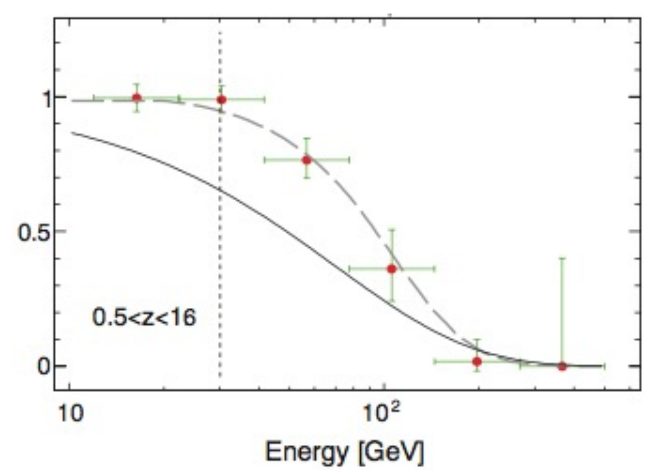
γ-ray Opacity from e^-e^+ Pair Production →

- *γ-ray extinction through mutual annihilation with intergalactic UV-IR photons*

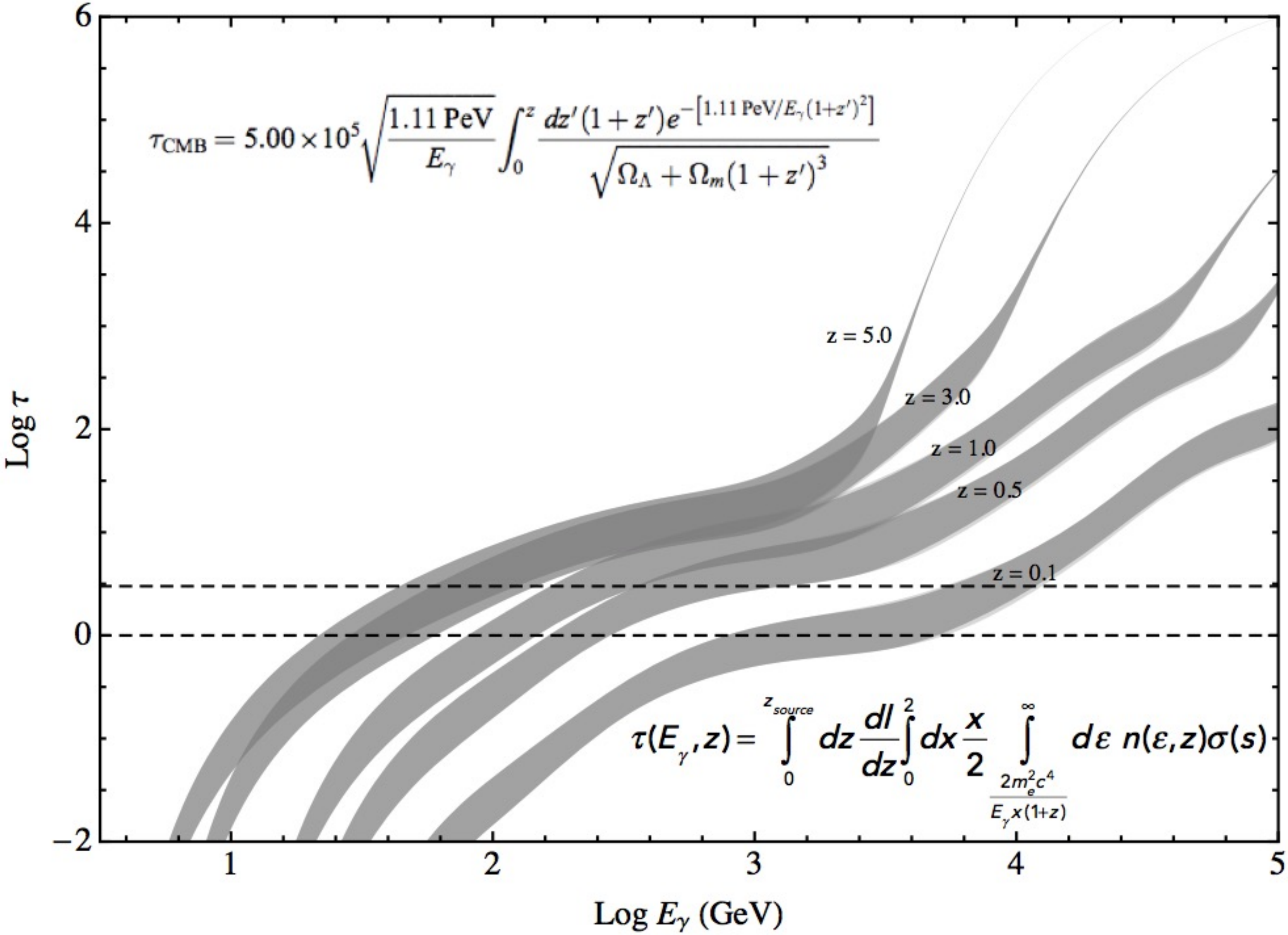


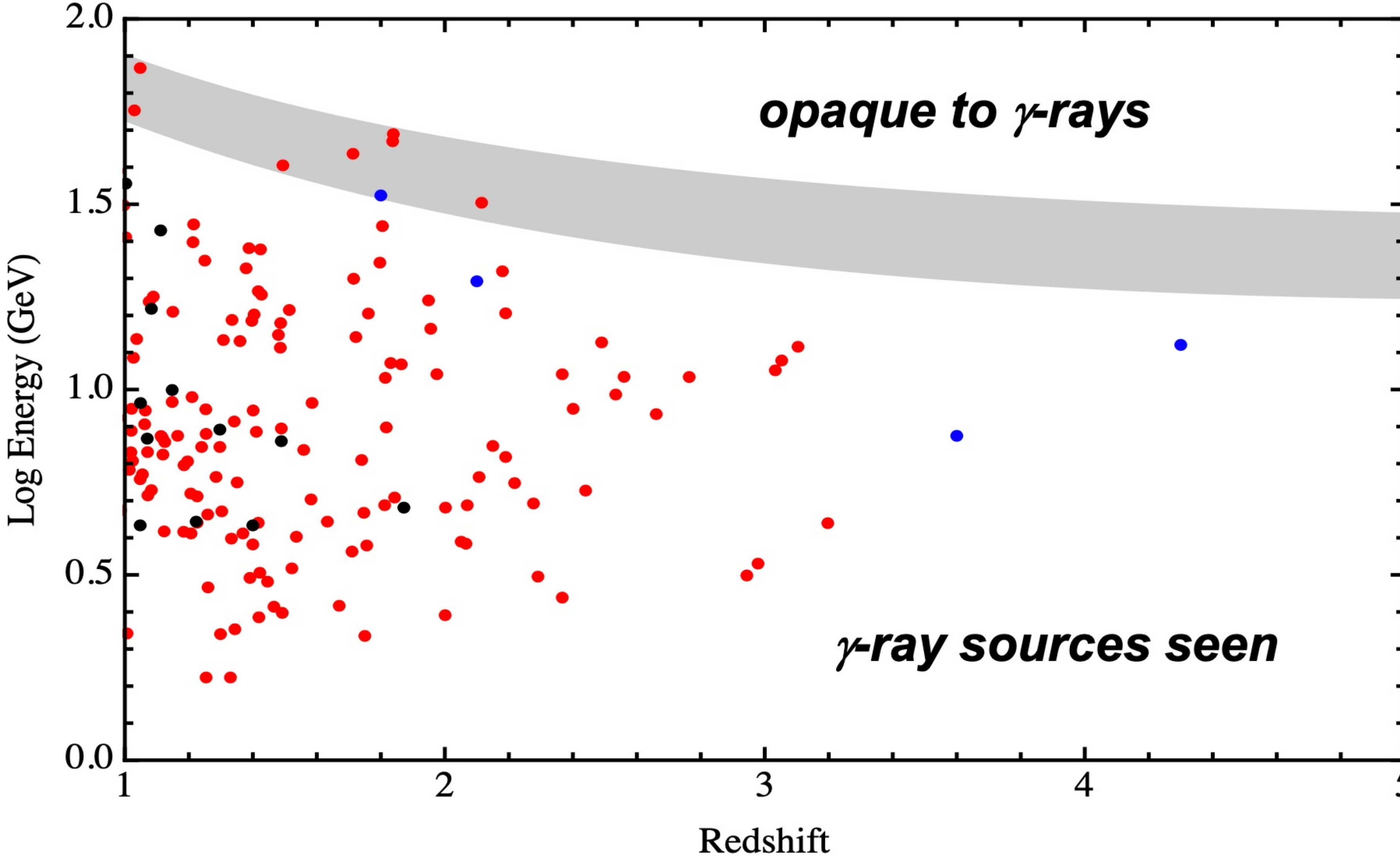
absorption = distance x photon density x cross section

$$\tau_{\gamma\gamma}(E, z_s) = c \int_0^{z_s} dz \left|\frac{dt}{dz}\right| \int_{\epsilon_{\min}}^{\infty} d\epsilon \; n_{\rm EBL}(\epsilon; z) \; \sigma_{\gamma\gamma}(E, \epsilon)$$



γ-ray opacity through pair production versus energy





opaque to γ-rays
γ-ray sources seen
Log Energy (GeV)
Redshift
2.0
1.5
1.0
0.5
0.0
1
2
3
4
5

LIV Test #1

Increased 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

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

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).

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

γ-Ray Astrophysics Limit on LIV from Blazar Absorption Features

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

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

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

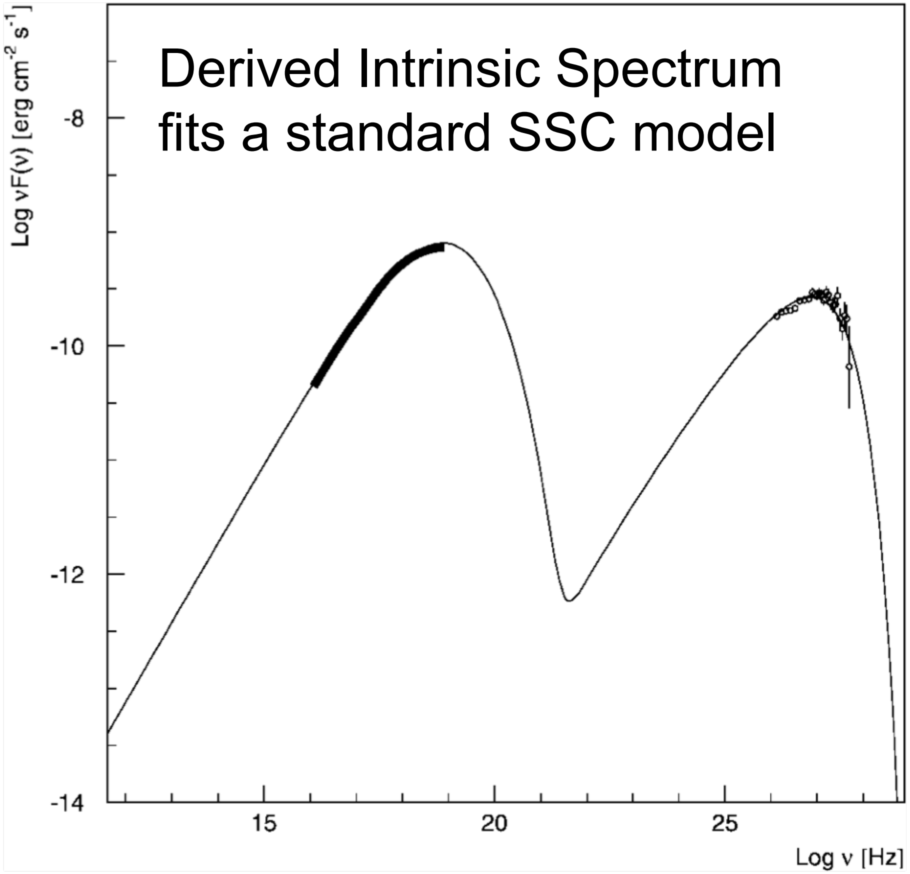


FIG. 7.—Combined X-ray/TeV γ-ray spectrum of Mrk 501 together with the best-fit SSC model.

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 the AGN Mkn 501 gives an upper limit on δ at this energy scale of

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

(FWS & Sheldon 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)

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

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

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

LIV Test #2

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

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):

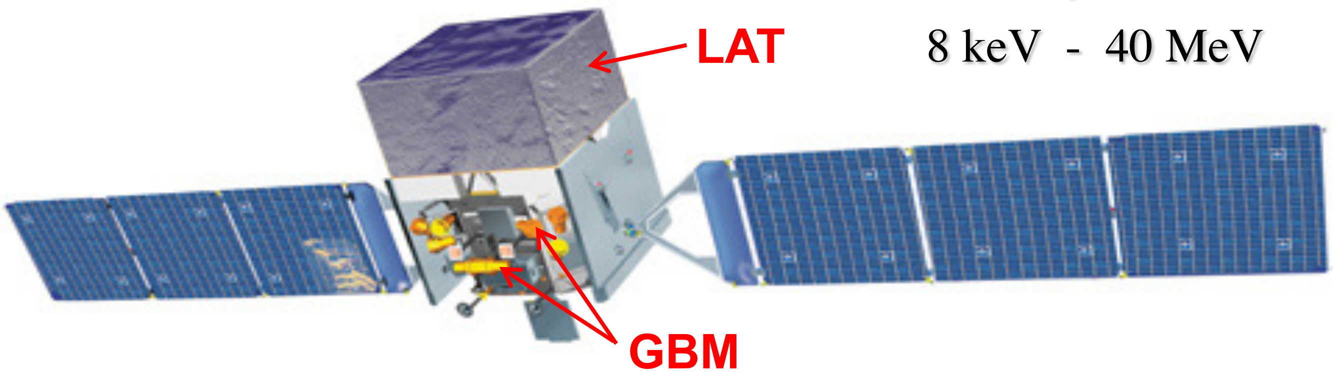
$$\Delta t = 20\ ms\ (M_{Planck}/M_{QG})\ d_{Gpc}\ \Delta E_{GeV}$$

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

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.

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

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J. Cohen-Tanugi (LUPM Montpellier)
A.Jacholkowska,
J. Bolmont, C. Couturier (LPNHE Paris)
J. Granot (Open Univ. of Israel)
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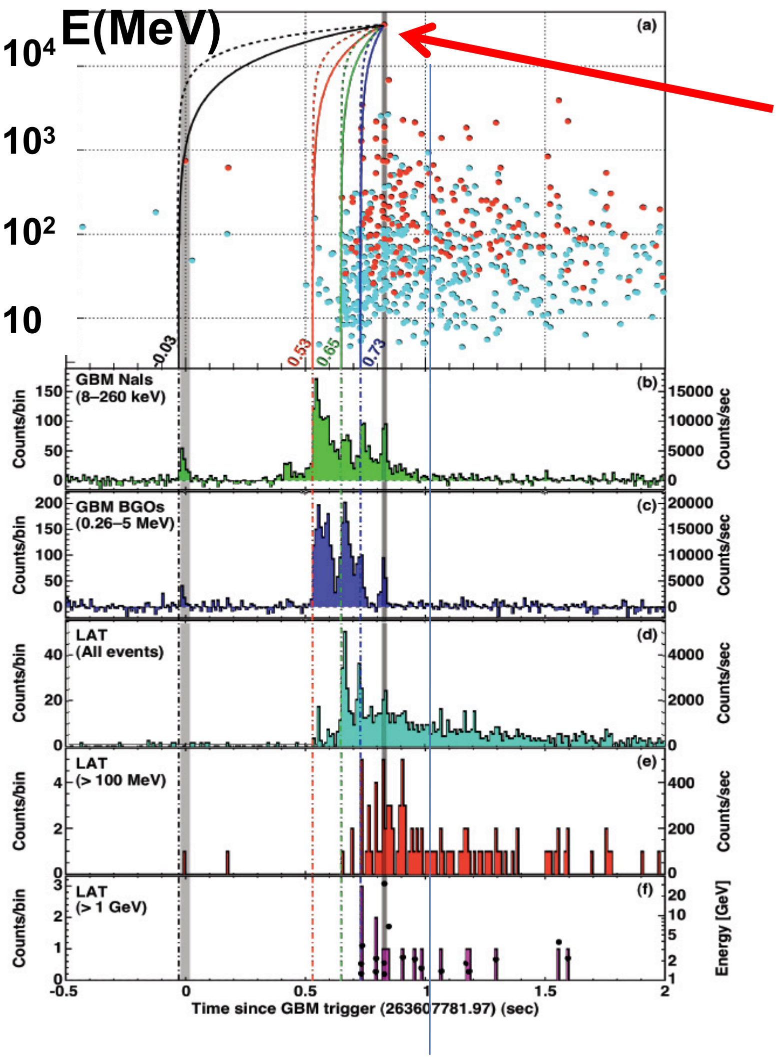
Phys. Rev. D, 87, 122001 (2013)

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

31 GeV photon from GRB 090510



31 GeV photon : 860 ms after the Trigger (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)

Fermi *GBM/LAT* Timing Results Imply

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

under the assumption: $v_\gamma = c\,[1 - (E_\gamma/M_{QG})]$.

- *But we would expect that for a "simple" 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).*

- *Or the simple assumption:* $v_\gamma = c\,[1 - (E_\gamma/M_{QG})]$

is not valid.

LIV Test #3

Vacuum birefringence

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 the Planck mass

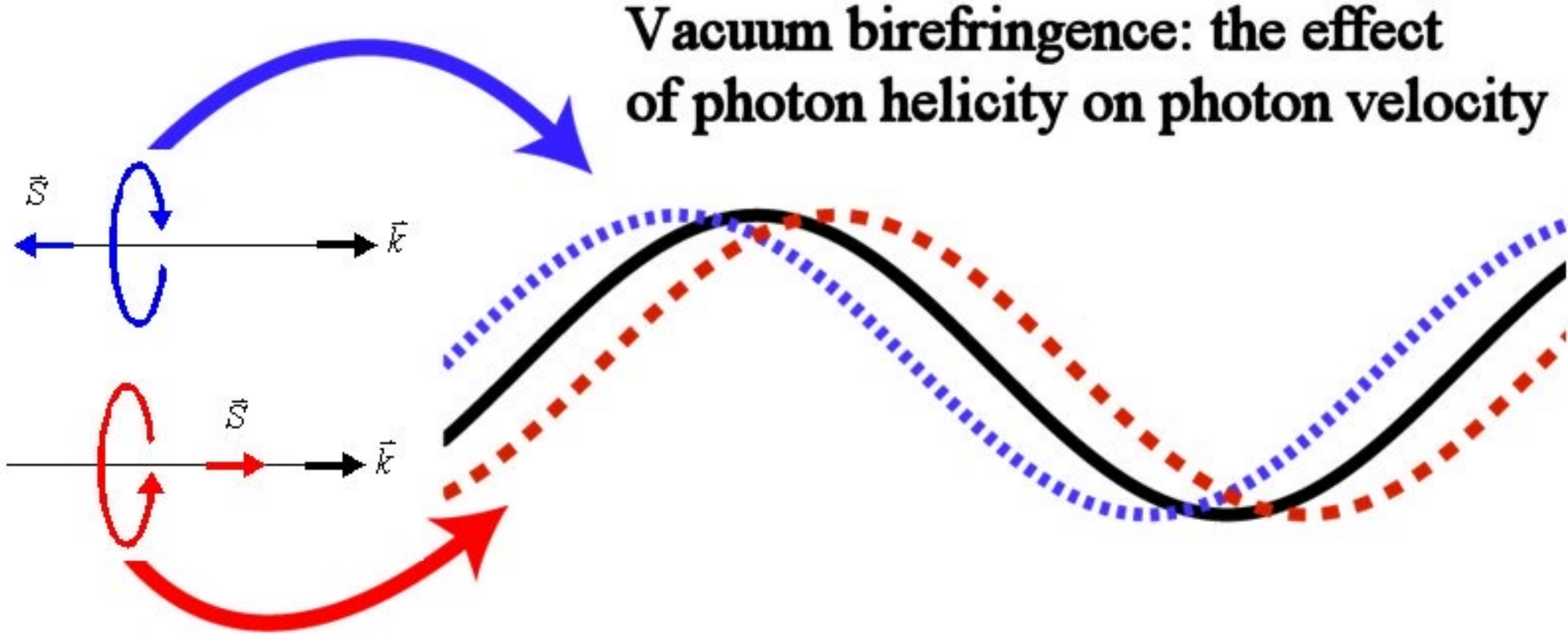
$$\Delta \mathcal{L}_{\gamma} = \frac{\xi}{M_{Pl}} n^a F_{ad} n \cdot \partial (n_b \tilde{F}^{bd})$$

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 $\pi/2$.

Vacuum Birefringence from LIV



Vacuum birefringence constraint on ξ with an added LIV term $(\xi/M_{planck})k^3$

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

LIV Test #4

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

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

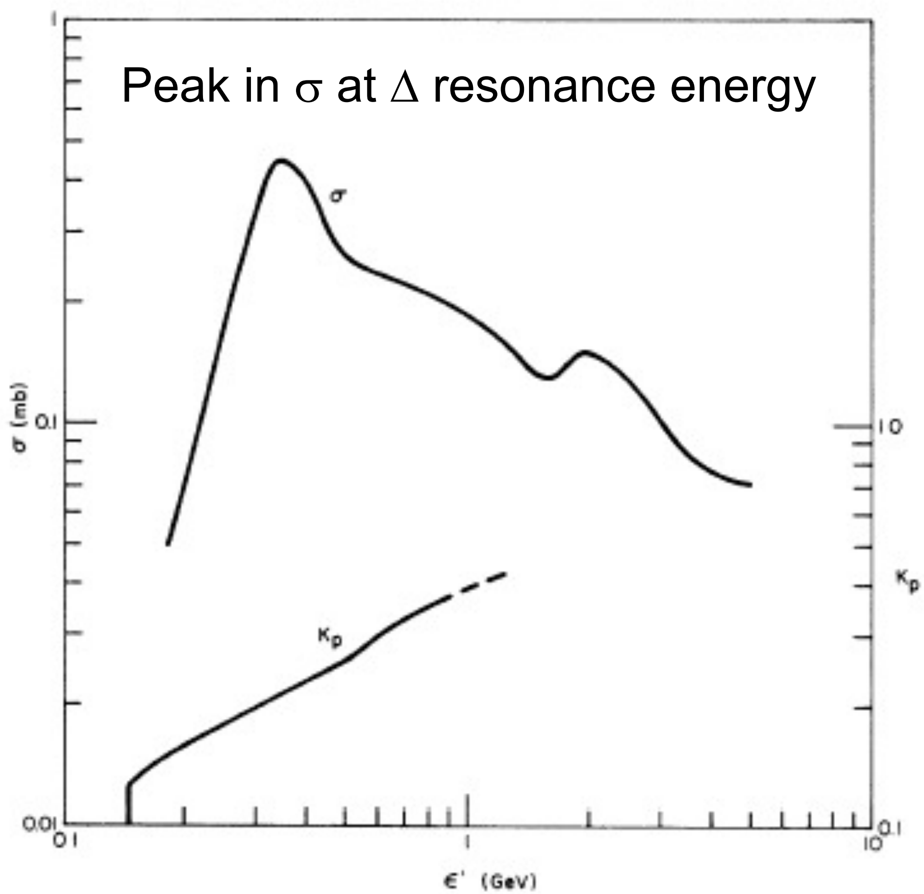


FIG. 1. Total photomeson production cross section and inelasticity as a function of gamma-ray energy in the proton rest system.

UHECR Attenuation (FWS 1968)

Since the Δ resonance in the cross section allows only relatively nearby UHECRs to reach us at the highest energies, this leads to an apparent cutoff in the observed UHECR energy spectrum above ~10^{11} GeV – the GZK effect.

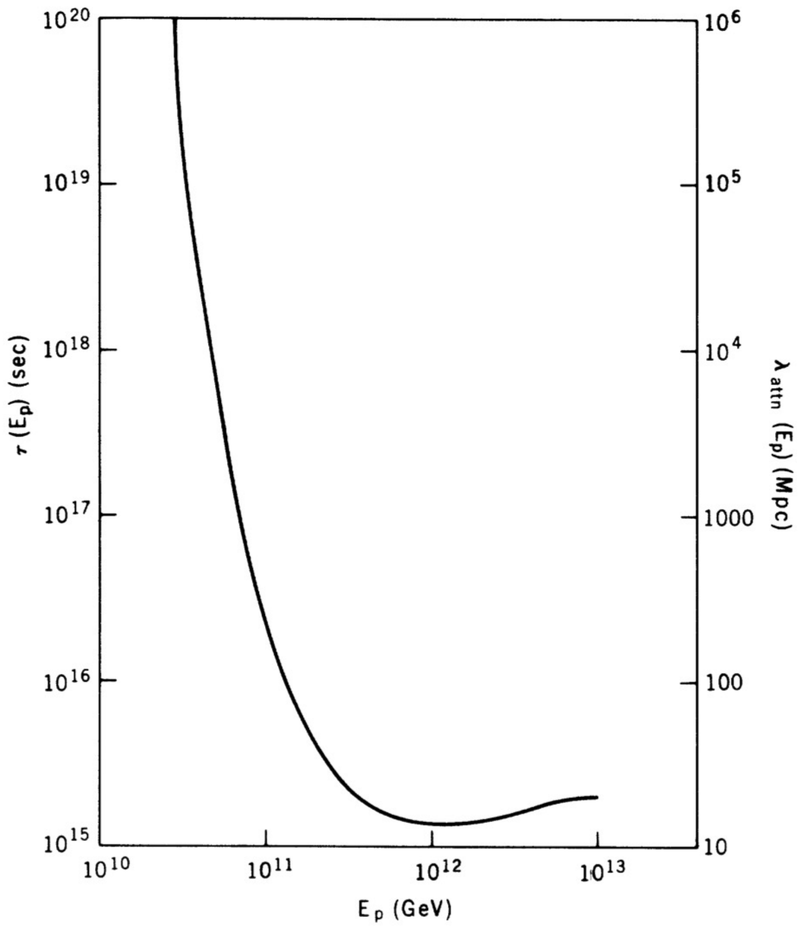


FIG. 2. Characteristic lifetime and attenuation mean free path for high-energy protons as a function of energy.

Modifying Photomeson Interactions with LIV

- With LIV, different particles, i, can have different maximum attainable velocities $\boldsymbol{c_i}$. (S. Coleman and S. Glashow 1999)

- The higher the value of δ, the higher threshold photon energy ω required for the interactions to occur.

- Since $\boldsymbol{s} \sim \omega E_p$, and there is a peak in the photomeson cross section at a fixed value of $\boldsymbol{s}$ 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 .

LIV Modified Interaction Threshold

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

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

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]

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

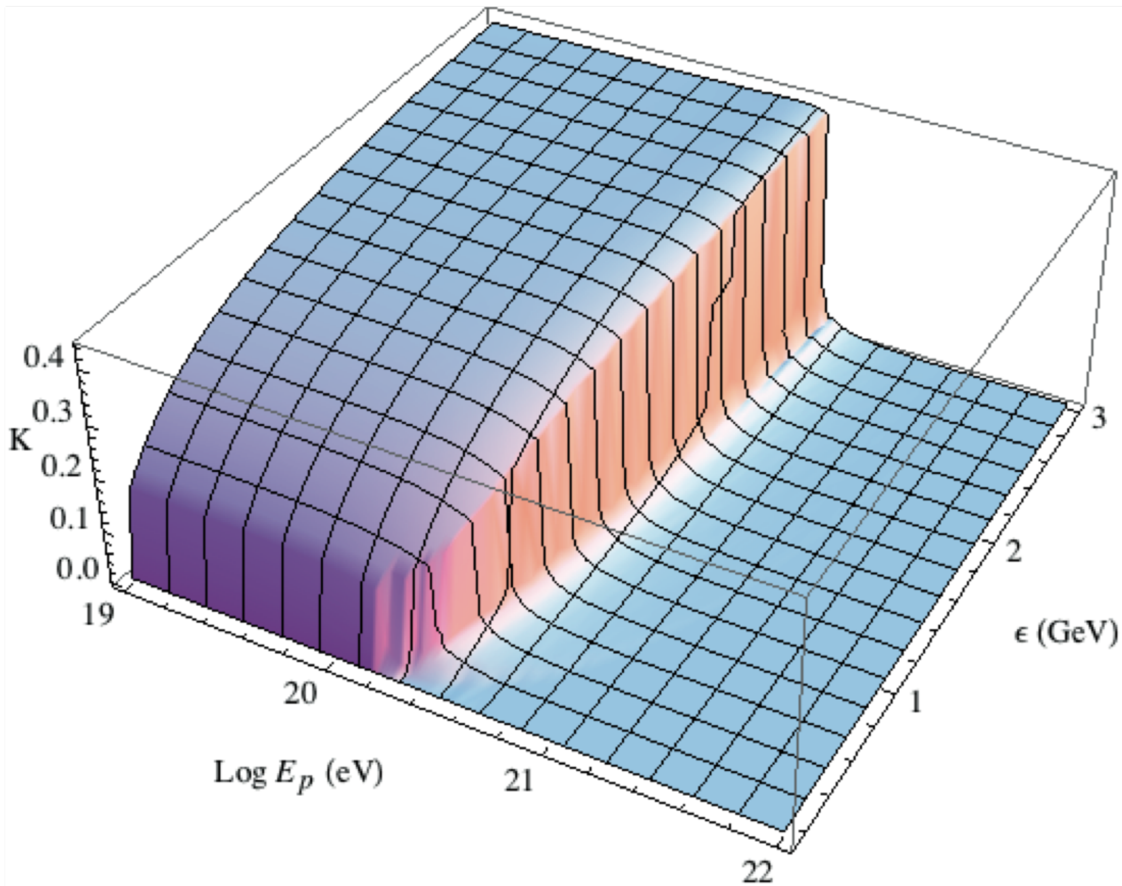
Equation (10) is a quadratic equation with real roots only under the condition

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

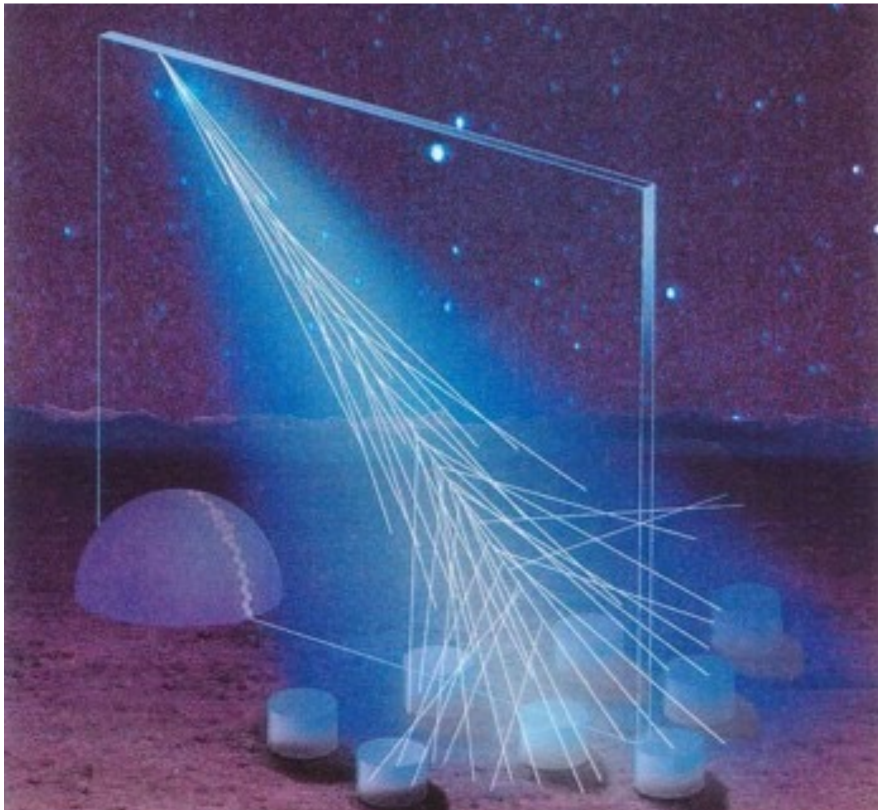
Defining $\omega_0 \equiv kT_{\mathrm{CBR}} = 2.35 \times 10^{-4}$ eV with $T_{\mathrm{CBR}} = 2.725 \pm 0.02$ K, equation (11) can be rewritten

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

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



Pierre Auger Observatory



On the Pampa Amarilla in western Argentina

Auger spectrum with curves for various amounts of LIV giving the limit $\delta_{\pi p} < 4.5 \times 10^{-23}$ (FWS & S. Scully 2009)

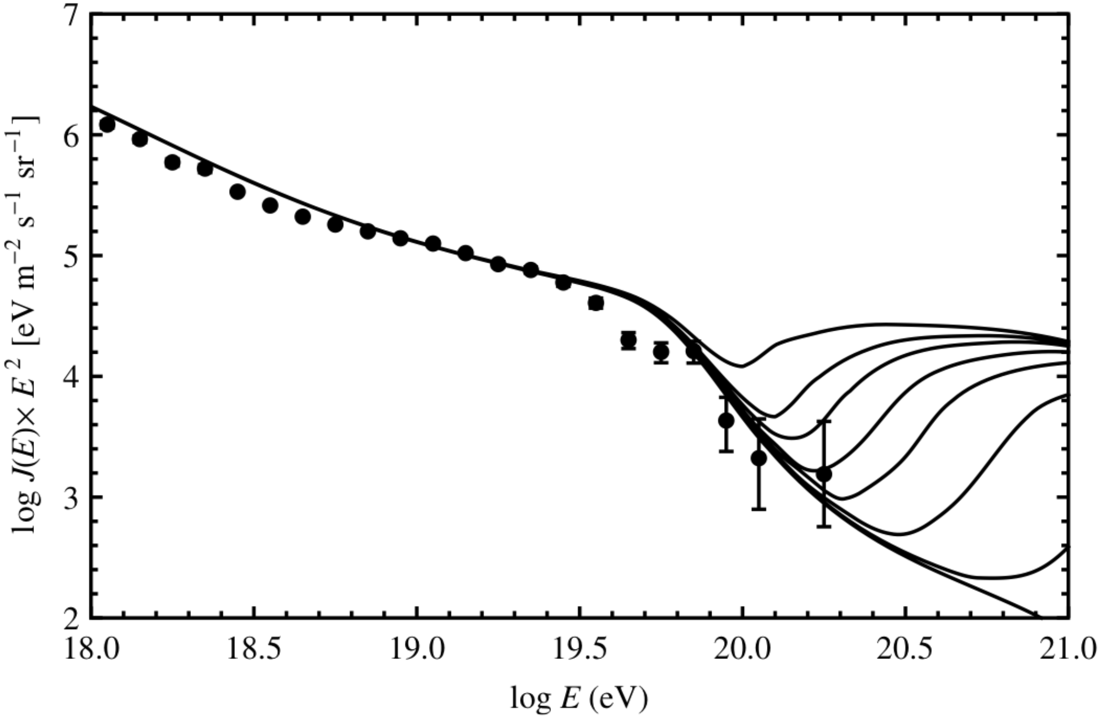
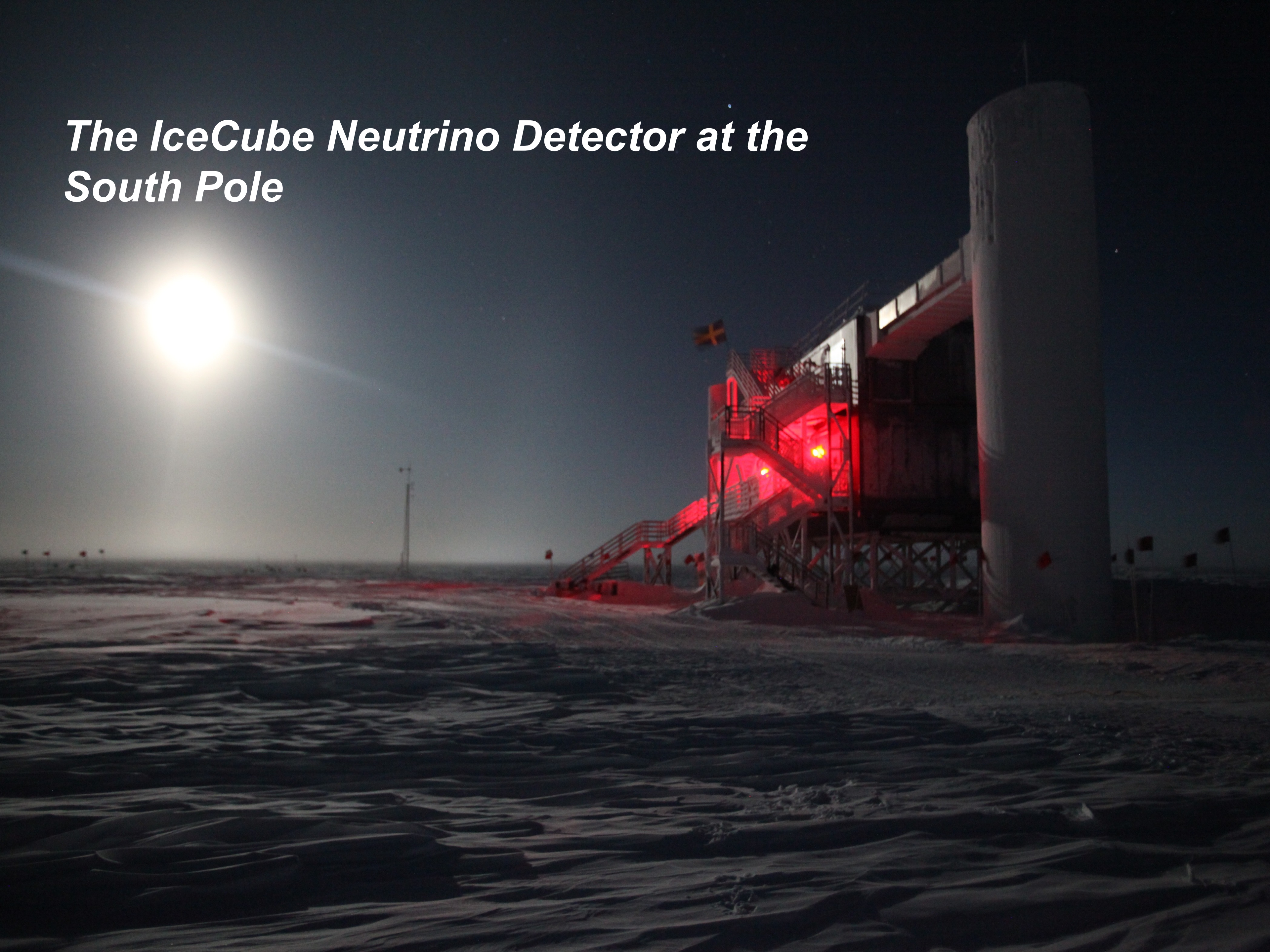


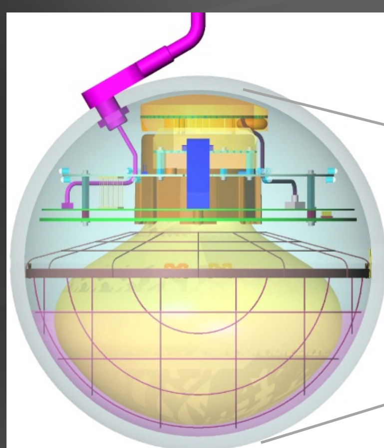
Figure 4. Comparison of the latest Auger data with calculated spectra for various values of $\delta_{\pi p}$, taking $\delta_p = 0$ (see text). From top to bottom, the curves give the predicted spectra for $\delta_{\pi p} = 1 \times 10^{-22}$, 6×10^{-23}, 4.5×10^{-23}, 3×10^{-23}, 2×10^{-23}, 1×10^{-23},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

LIV Test #5

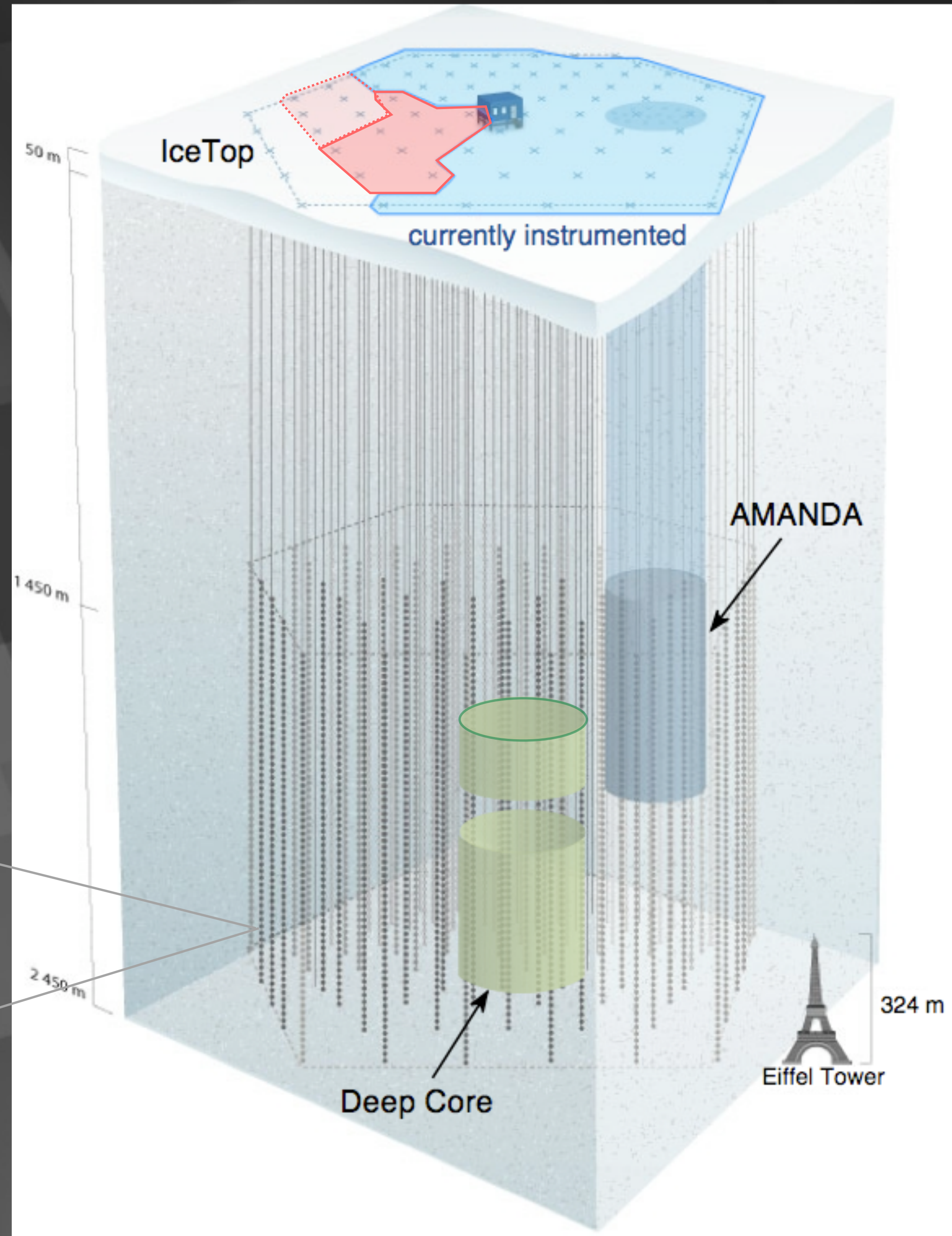
Pair production *in vacuo* by high energy superluminal neutrinos


The IceCube Neutrino Detector at the South Pole

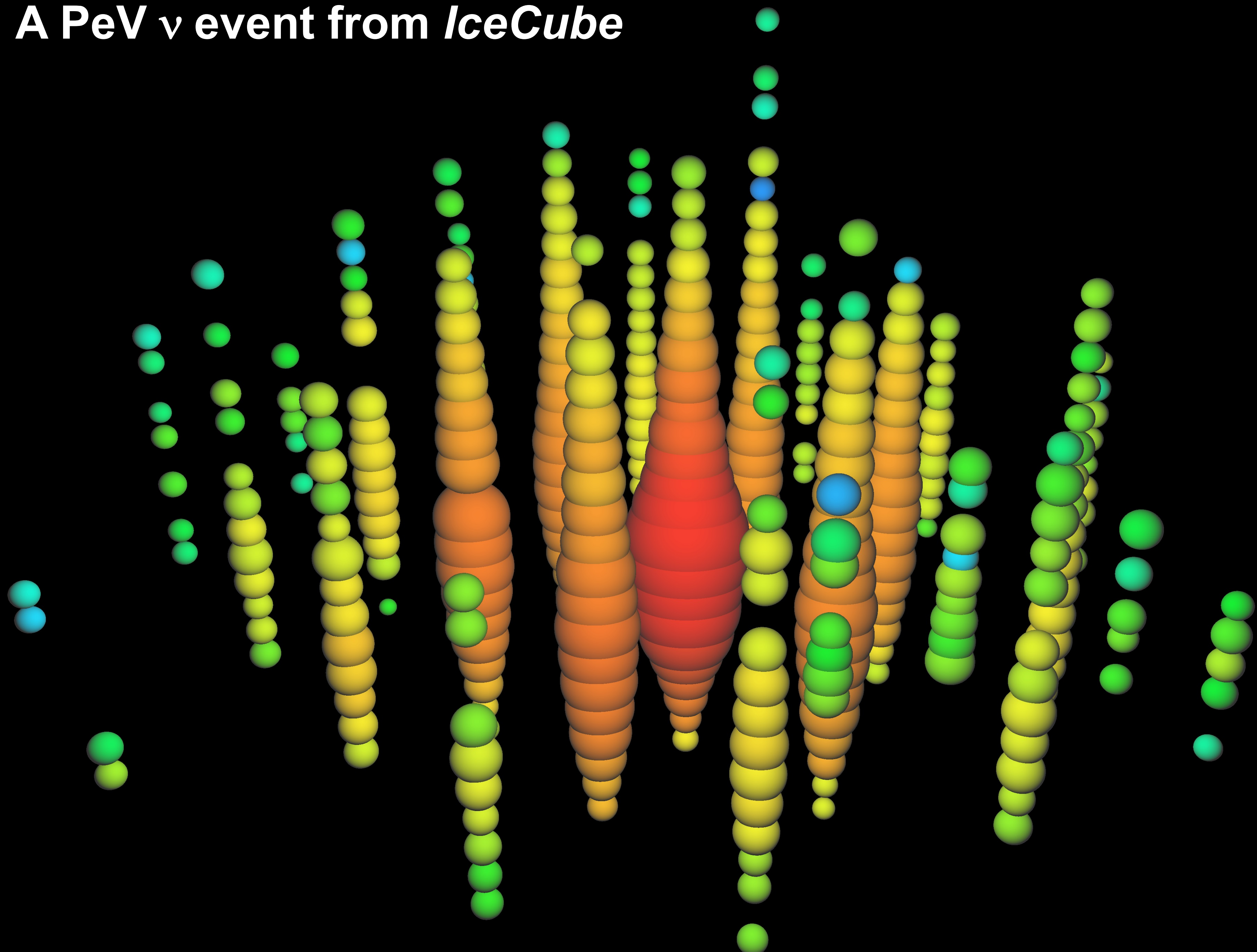
- *5160 optical sensors between 1.5 ~ 2.5 km*
- *detects > 200 neutrino-induced muons and ~ 2 x10^8 cosmic ray muons per day*



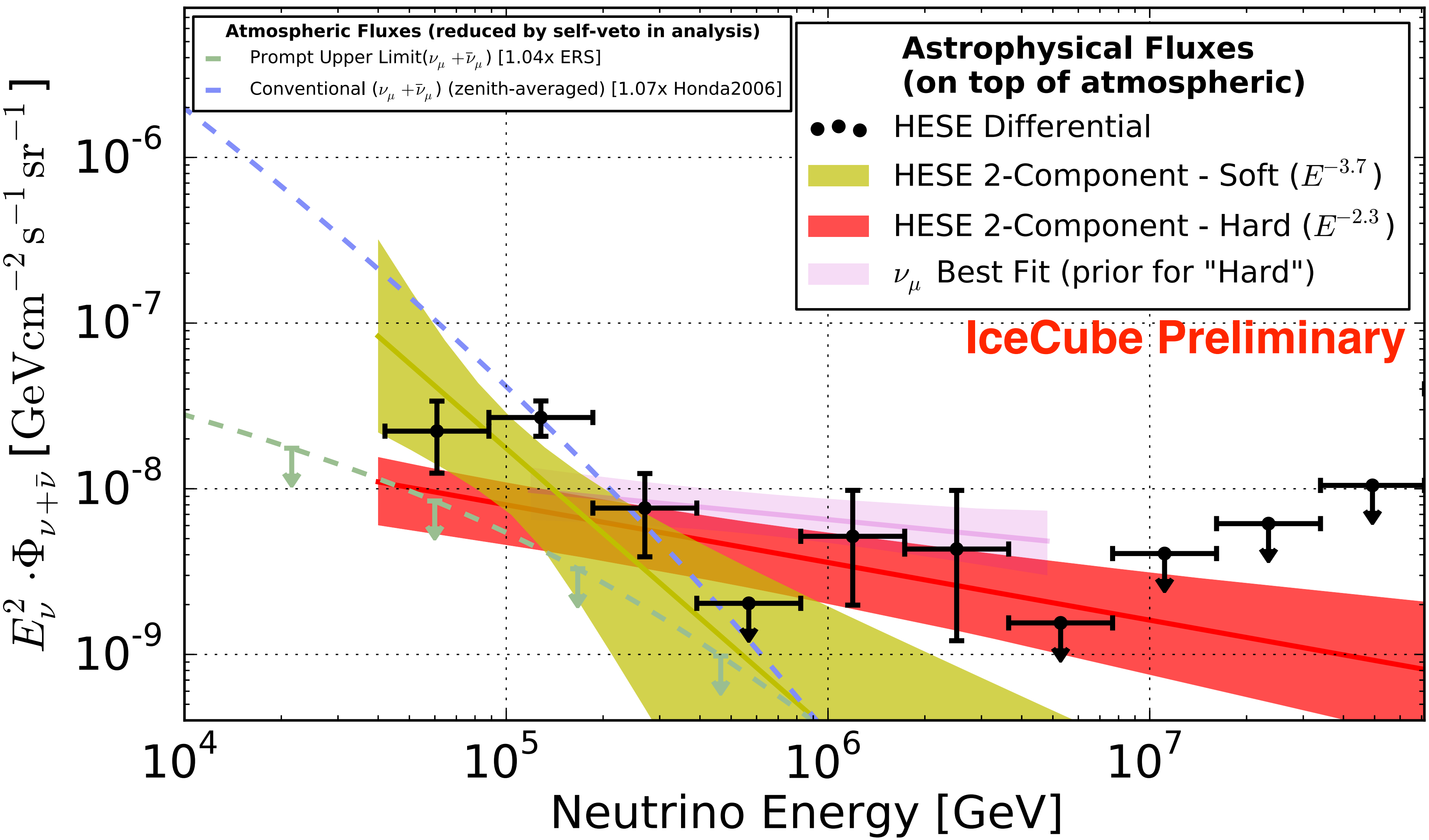
Digital Optical Module (DOM)



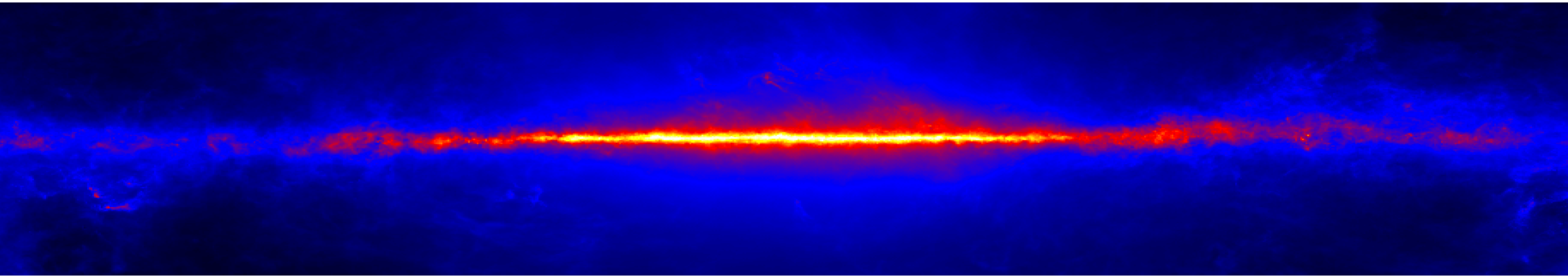
A PeV ν event from *IceCube*



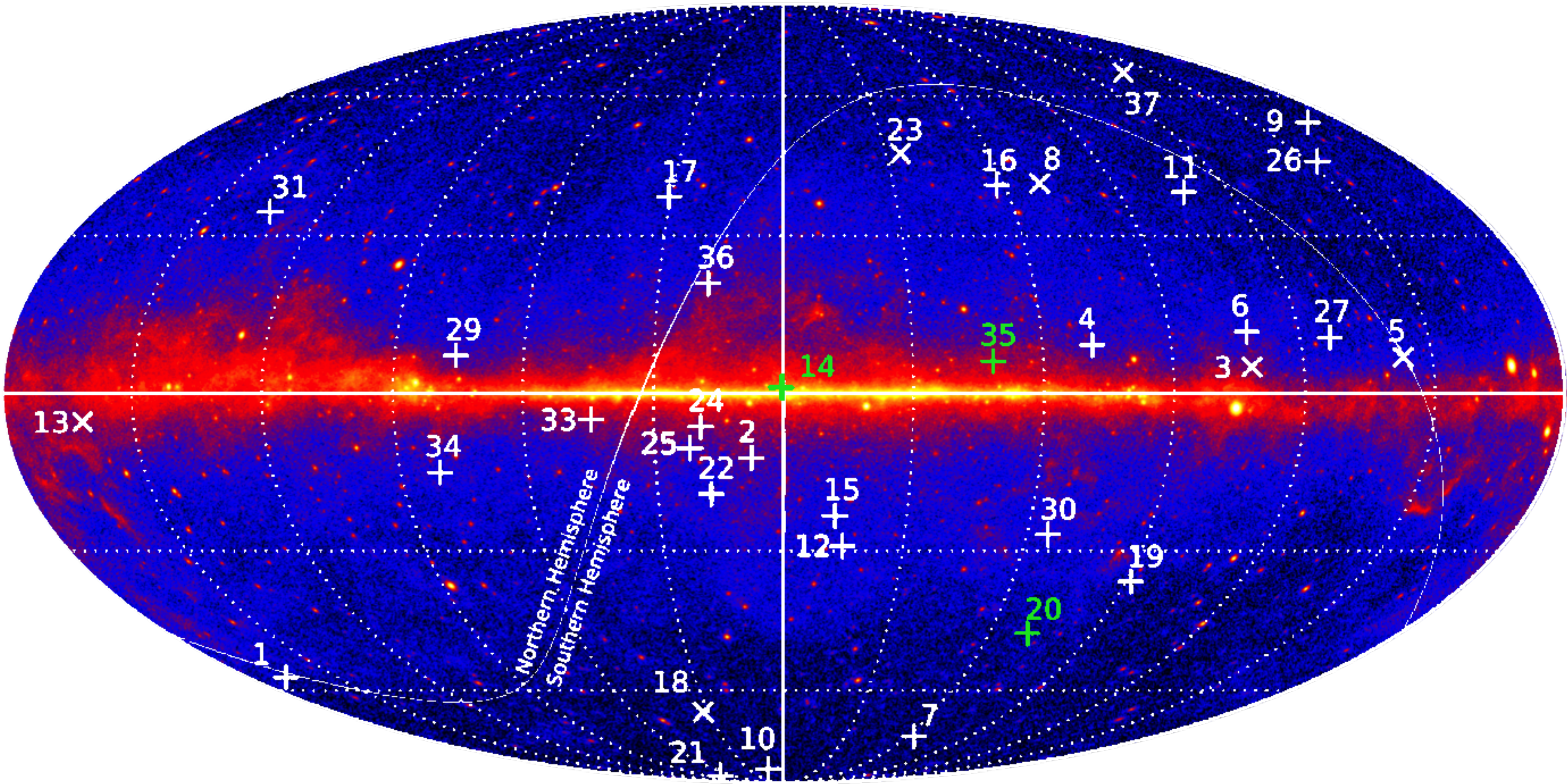
IceCube 6 yr. ν_μ Spectrum



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) .



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



Neutrino Energy Loss Processes for LIV with $\delta_\nu > 0$ ([d]=4 assumed) (A. Cohen & S.L. Glashow 2011)

- $\nu \longrightarrow \nu + \nu + \nu$

Not relevant even for different flavors because oscillation data show that any difference in ν flavor velocities < *10^-20*

- $\nu \longrightarrow \nu + e^+ + e^-$

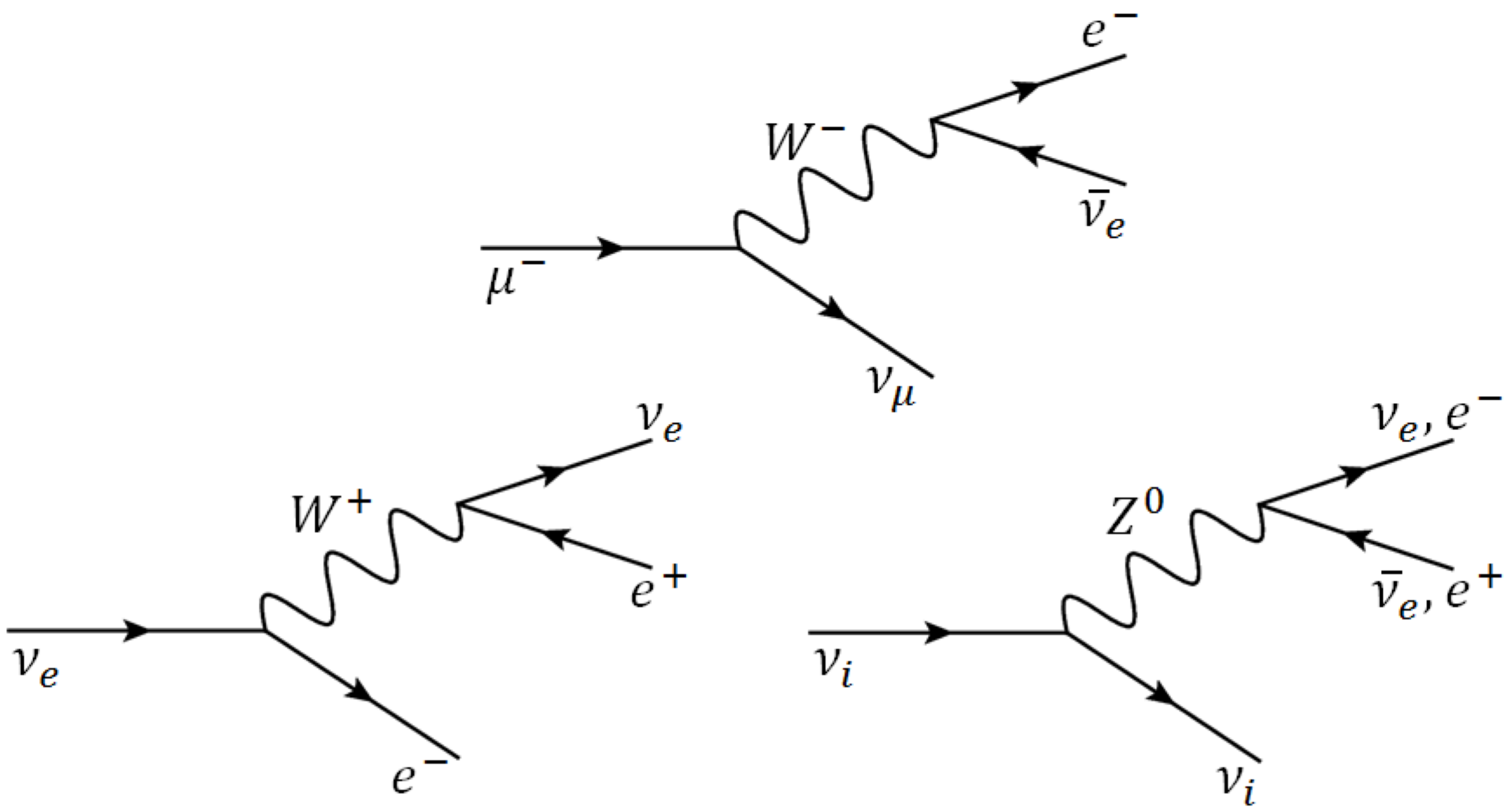
Pair emission (Most Important Loss Process)

- $\nu \longrightarrow \nu + \gamma$

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

Remember: The extra energy allowing for the decay comes from the $2\delta E^2$ term!

Vacuum Pair Emission (VPE) by Superluminal Neutrinos*



*A weak interaction version of Cherenkov radiation

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 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

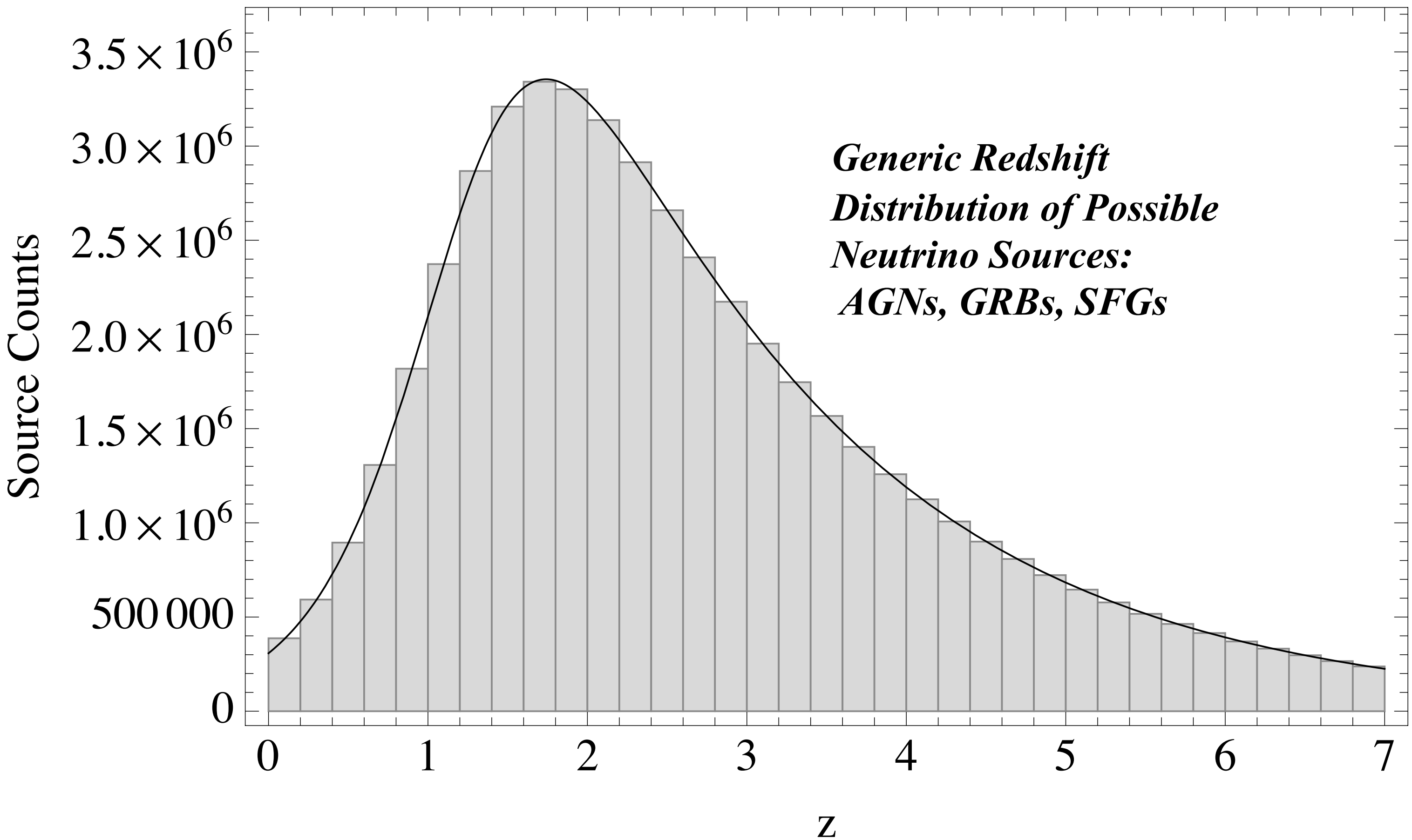
$$E_\nu > m_e\,[2/(\delta_\nu - \delta_e)]^{1/2}\,,$$

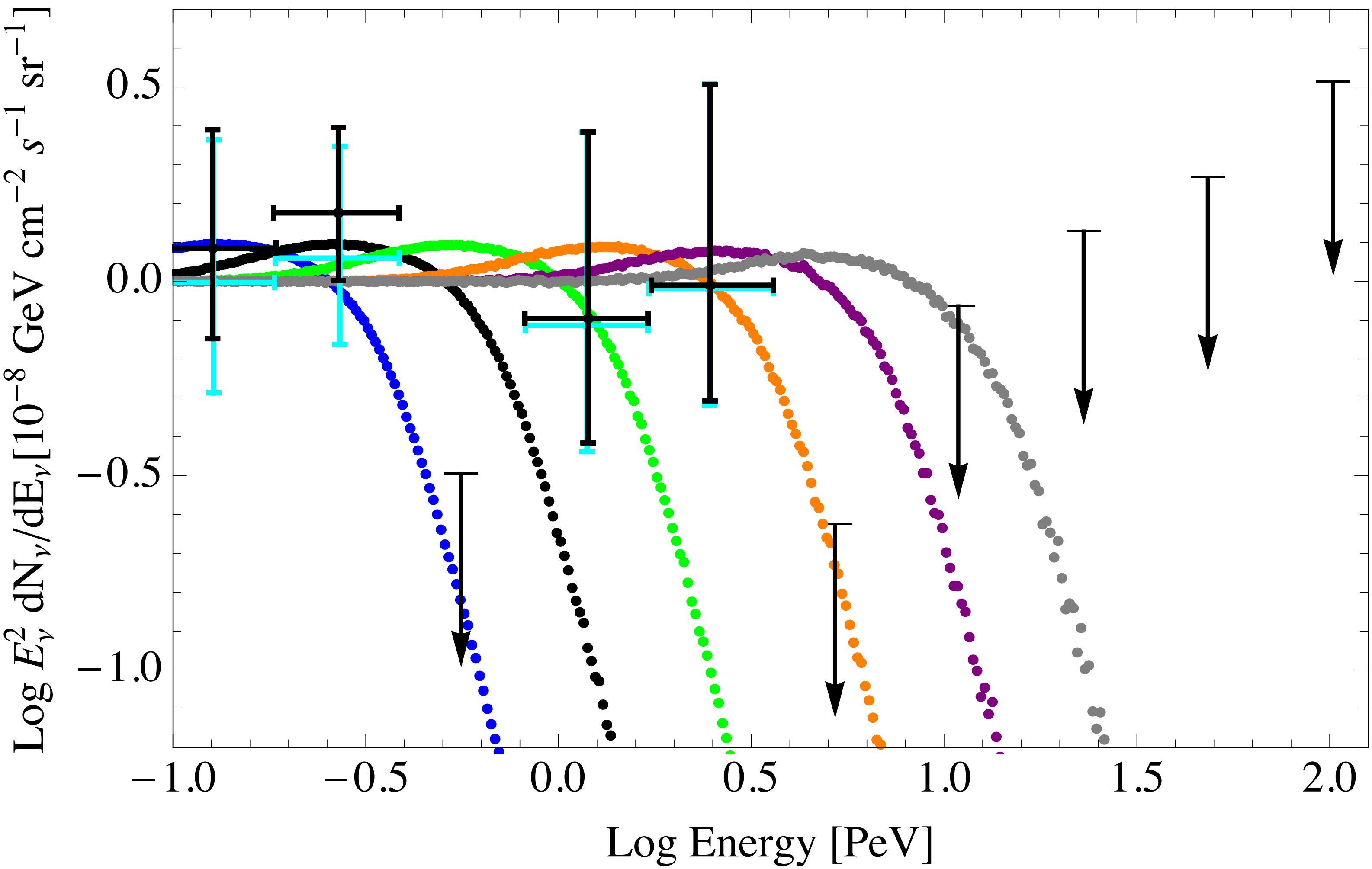
with $v_{\nu,e} = c_\gamma(1 + \delta_{\nu,e})$

The energy loss rate is given by

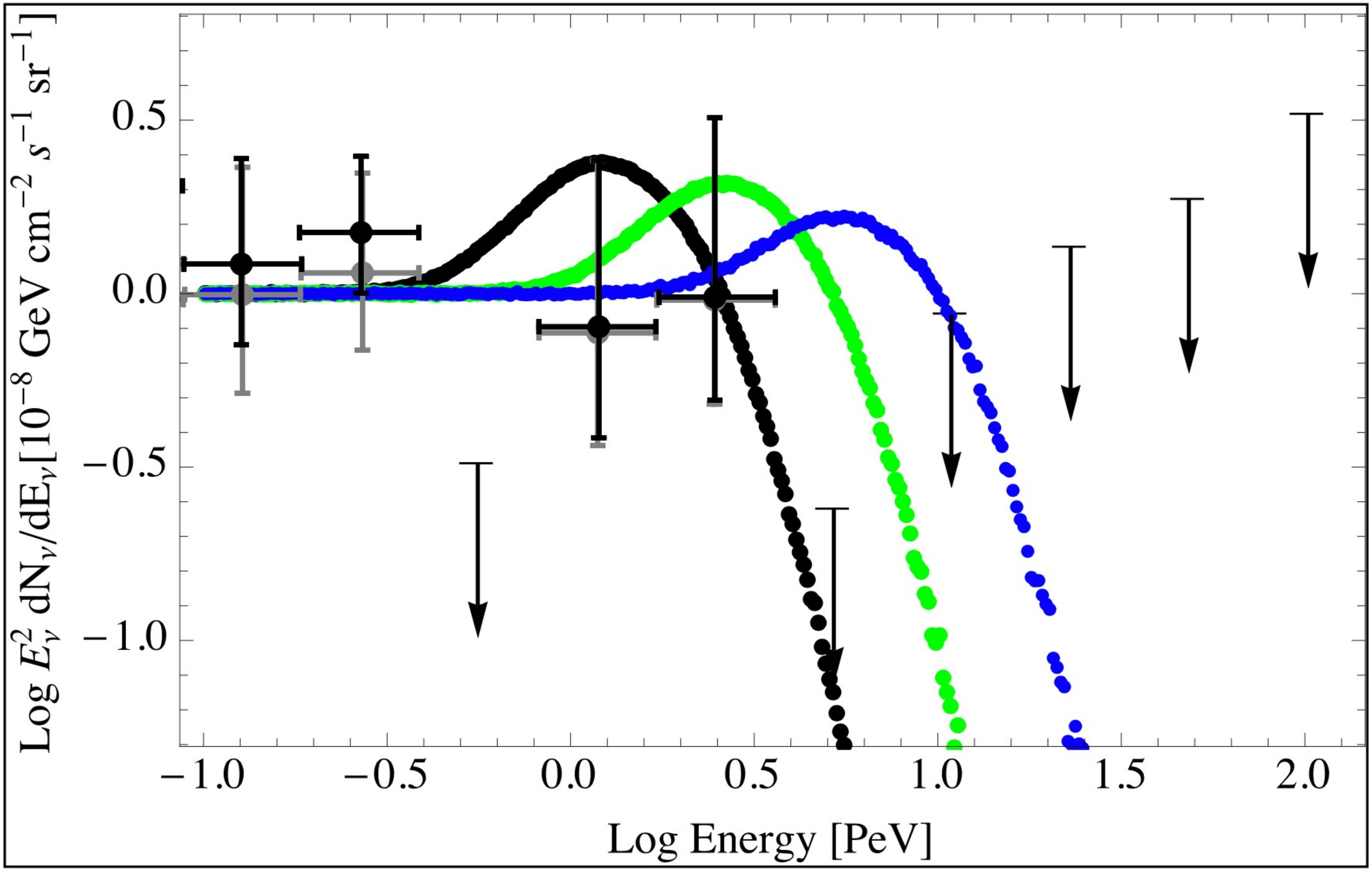
$$\frac{dE}{dx} = -k\,\frac{G_F^2}{192\pi^3}\,E^6\,\delta^3$$

Possible Extragalactic Neutrino Sources





[d] = 4 case: Orange curve: $\delta = 10^{-20}$



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, FWS et al. 2016)

- *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.*

- *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 (requires better data).*

- *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 the gamma-ray burst 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 $M_{QG} > M_{Planck}$.

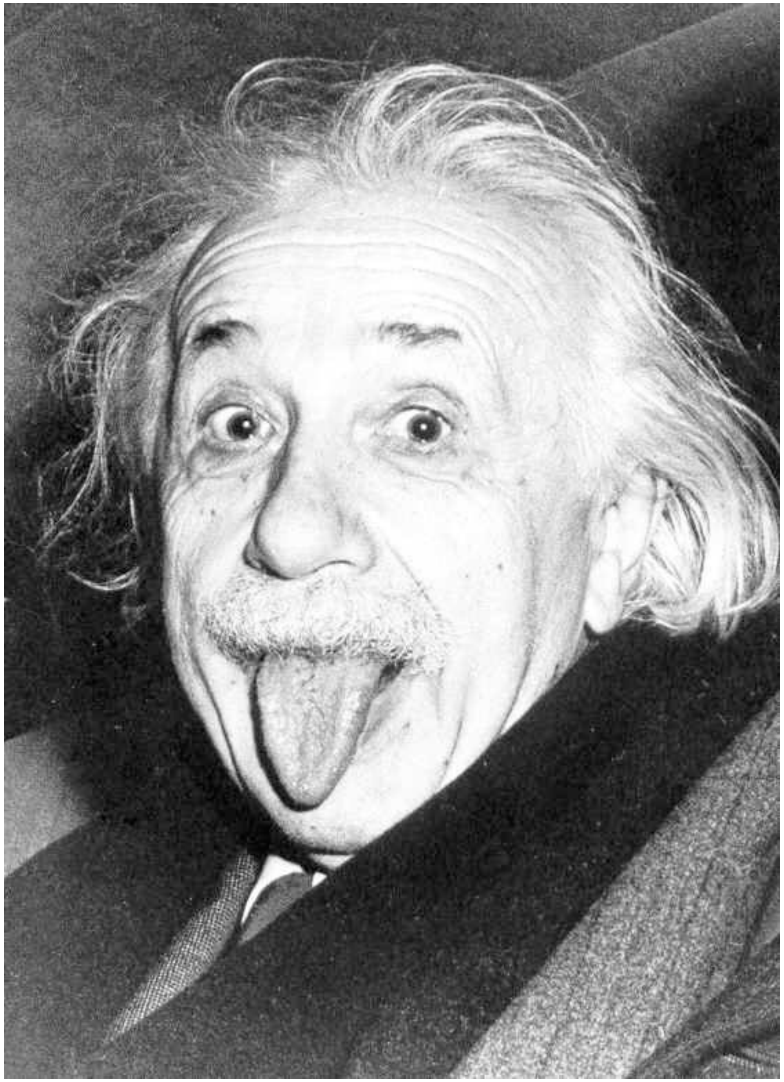
- More indirect results from γ-ray birefringence limits, the non-decay of 50 TeV γ–rays from the Crab Nebula, and the TeV spectra of nearby AGNs place severe limits on EFT LIV with [d] = 5 dominance.

- 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.

The Bottom Line!

Presently, we have no conclusive evidence for modifying special relativity at even the highest energies observed.



No Big Bang Theory Series Finale!

We are still in the dark regarding Planck scale physics and quantum gravity.

The search goes on --

Tune in for the next exciting episode!

Thank you!

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 (2017), arXiv:1708.05672