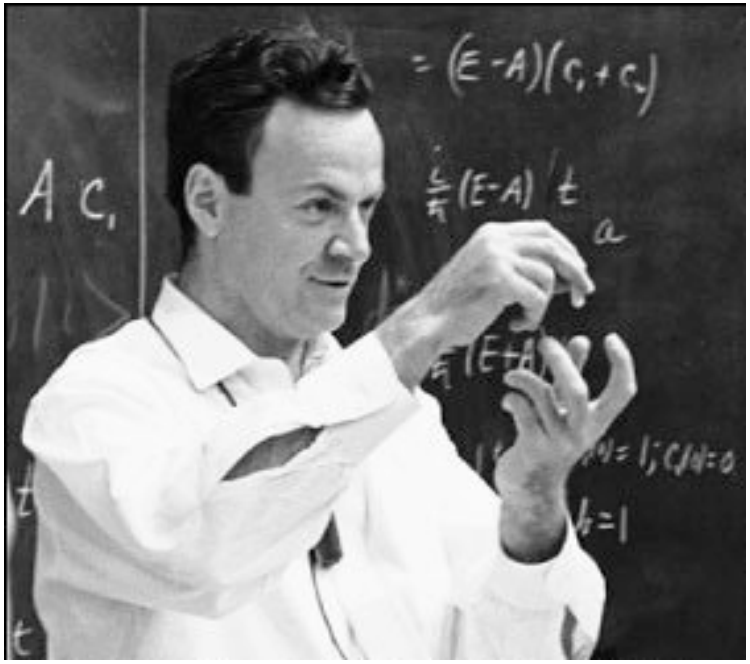
PACIFIC 2011 CONFERENCE, MO’OREA, FRENCH POLYNESIA

HIGH ENERGY ASTROPHYSICS TESTS OF LORENTZ INVARIANCE AND QUANTUM GRAVITY MODELS

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.”*



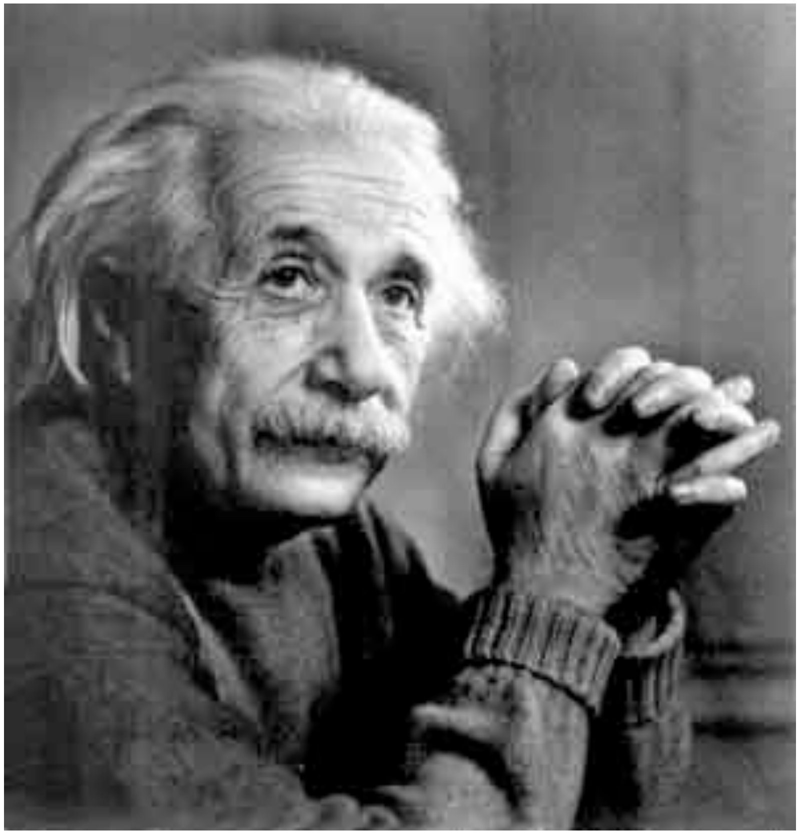
- Richard Feynman

(Feynman lectures in physics)

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

- Subramanian Chandrasekar

“You imagine that I look back on my life’s work with calm satisfaction. But from nearby it looks quite different. There is not a single concept of which I am not convinced that it will stand firm…”



- Albert Einstein

Why Modify Relativity?

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

- Effective Field Theory (EFT)
- “Deformed Special Relativity” (DSR)
- Stochastic space-time “foam”
- Loop Quantum Gravity (LQG)
- String inspired models (D-branes)

Why Use High Energy Astrophysical Observations?

- 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 for 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.
- Planck scale (10^{-35} m) physics such as quantum gravity may lead to the breaking or deformation of Lorentz invariance.

Astrophysical Tests of Lorentz Invariance Violation

- Time-of-flight of γ-rays from cosmologically distant sources
- Threshold for annihilation of γ-rays by e^+e^- production interactions with intergalactic low energy photons
- Vacuum birefringence
- Modification of the “GZK” spectrum of ultrahigh energy cosmic rays

Testing Lorentz Invariance with *Fermi*

Some classes of quantum gravity models postulate or imply a photon velocity dispersion relation with a pertubative term which may be linear with energy (e.g. , Amelino-Camelia et al. 1998; Ellis et al. 2008).

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

Using Fermi data for distant γ-ray bursts the difference in arrival times of γ-rays of different energies could be > 100 ms.

Time of flight constraint

arrival time delay

Constraints from blazar flares and GRB’s.

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

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

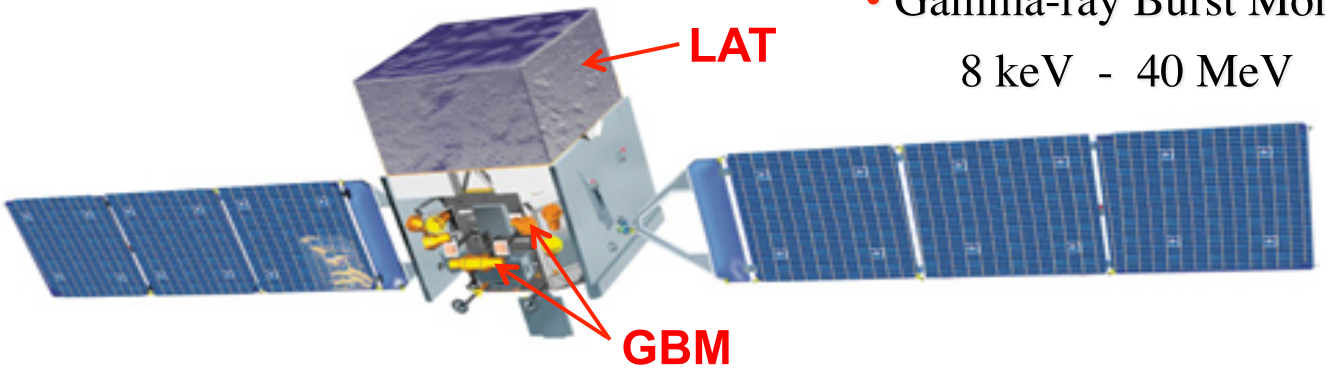
Longer distance and higher energy help, also intrinsically short bursts.

Fermi Launch: June 11, 2008

Fermi γ-ray Space Telescope:

Two *Fermi* instruments:

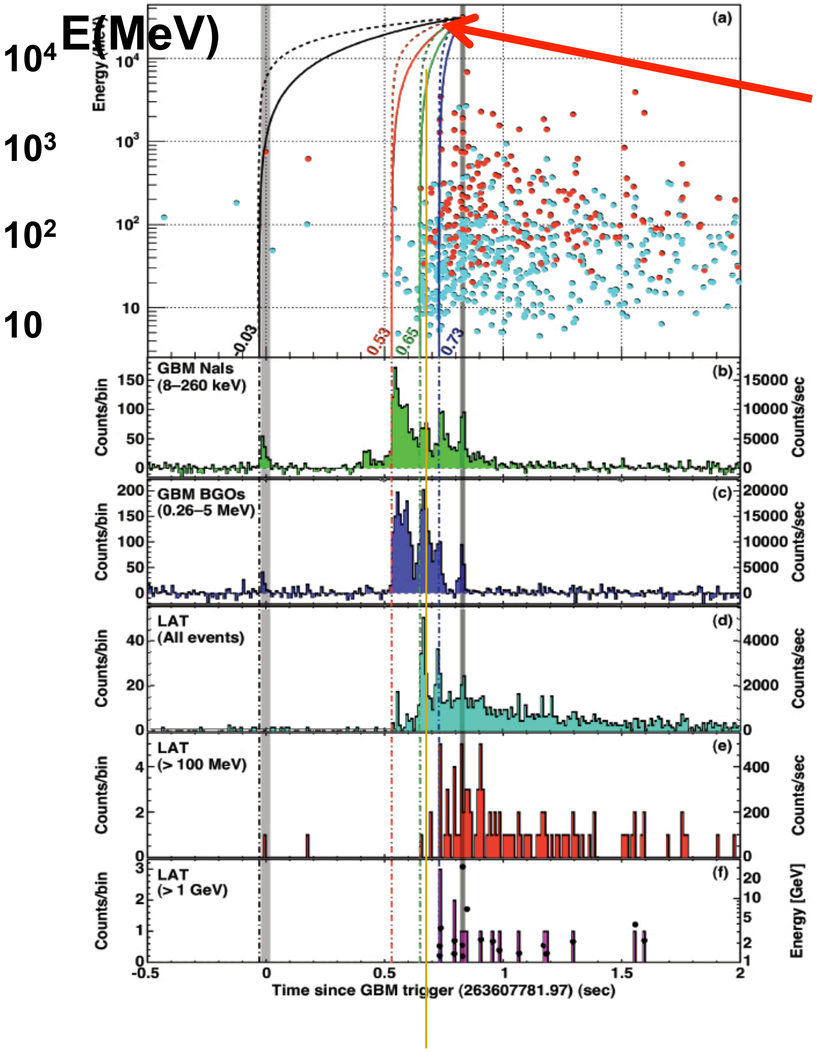
- Large Area Telescope (LAT)
  20 MeV - >300 GeV
- Gamma-ray Burst Monitor (GBM)
  8 keV - 40 MeV



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 : 0.83 s after the trigger

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)

New Results from *Fermi* Observations of GRBs: *Fermi* collaboration, *Nature* 462, 331(2009)

- GRB 080916C:

$M_{QG} > 0.1\ M_{Planck}$ (where $M_{Planck} \sim 10^{19}$ GeV)

- GRB 090510 (short-hard burst):

$M_{QG} > 1.2\ M_{Planck}$

(probably larger, depending on the assumed start of the burst)

- But we would expect *that* $M_{QG} \leq M_{Planck}$

Implied Constraints on Lorentz Invariance Violation (LIV) from Very High Energy γ-ray Observations of Nearby Blazars

THE "ALMOST STANDARD" RENORMALIZABLE MODEL

WITH LORENTZ INVARIANCE VIOLATION

General Free Particle Lagrangian with dimension four operators:

$$\mathcal{L} \;=\; \partial_\mu \Psi^* \mathbf{Z} \partial^\mu \Psi \;-\; \Psi^* \mathbf{M^2} \Psi$$

Add very small Lorentz invariance violating term:

$$\mathcal{L} \;\Rightarrow\; \mathcal{L} \;+\; \partial_i \Psi^* \epsilon \partial^i \Psi$$

where ϵ is dimensionless and $[\epsilon, \mathbf{M}] = 0$.

This gives a new propagator

$$-iD^{-1} \;=\; (p^2_{(4)} \;-\; m^2) \;+\; \epsilon p^2.$$

so that

$$p^2_{(4)} \;=\; E^2 \;-\; p^2 \;\Rightarrow\; m^2 \;+\; \epsilon p^2.$$

which can be rewritten in the "conventional" form:

$$E^2 \;=\; p^2 \;+\; m^2$$

where

$$m \;\Rightarrow\; \frac{m}{(1+\epsilon)^2} \;\simeq\; m(1-2\epsilon),$$

and

$$c^2 \;\Rightarrow\; 1+\epsilon$$

Thus, the maximum photon velocity ($c = 1$) has changed by $\epsilon/2$.

Other effects become important when $p^2 \;\simeq\; m^2/\epsilon$.

γ-Ray Astrophysics Limit on LIV from Blazar Absorption Features

Let us characterize Lorentz invariance violation by the parameter δ = ε/2 such that

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

(Coleman & Glashow 1999).

If δ > 0, the γ-ray photon propagator in the case of pair production

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

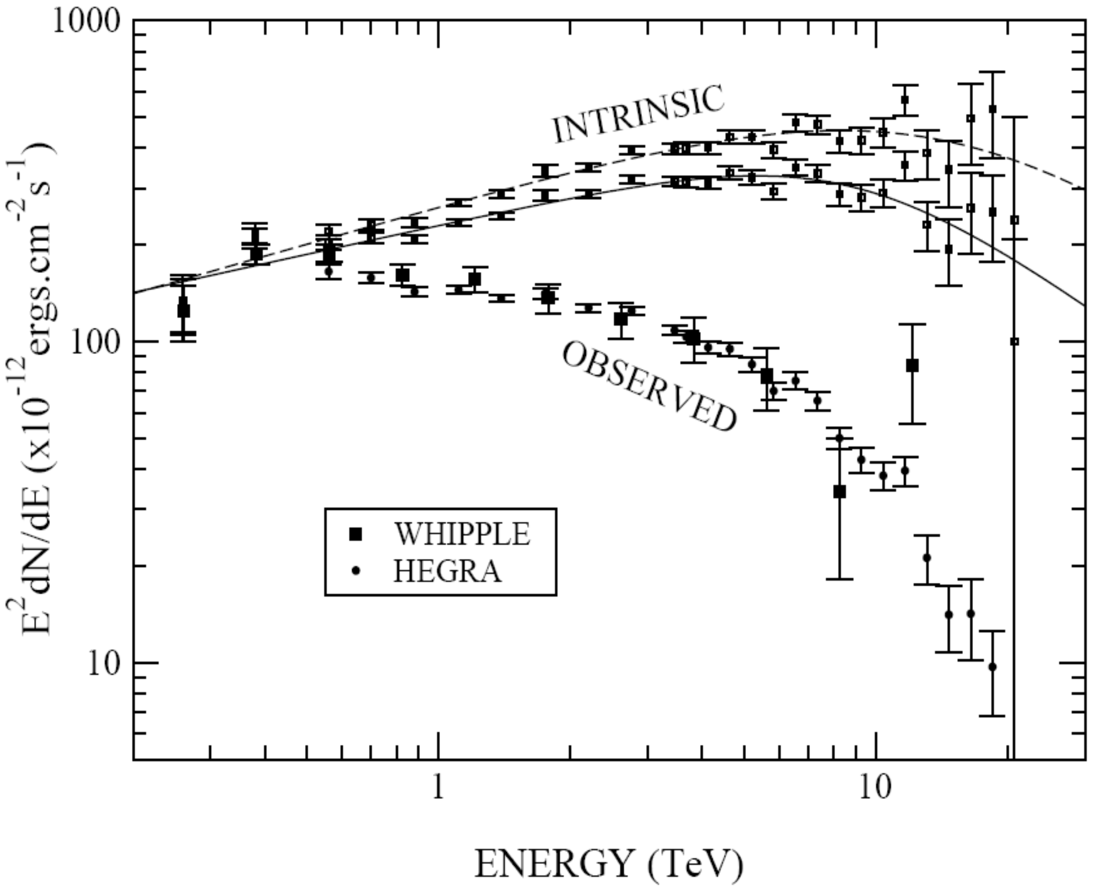
is changed by the quantity $\varepsilon p_\gamma^2 = -2E_\gamma^2 \delta$

And the threshold energy condition is given by

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

Flaring Spectrum of Mrk 501:

(Derived Intrinsic Spectrum fits standard SSC model.)



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

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

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

(Stecker & Glashow 2001).

Limit on the Quantum Gravity Scale

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 Stecker and Glashow (2001)

$$\frac{E_\gamma^2 \delta}{2} \leq \frac{m^2}{E_\gamma}$$

reduces to

$$M_{QG} \geq \frac{E_\gamma^3}{8m^2}$$

Limit on the Quantum Gravity Scale
(Stecker 2003):

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

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

Arguing against some TeV scale quantum gravity models involving extra dimensions!

EFT of LIV suppressed by E/M_P

(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 π/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 $k_{1,2}(z') = (1+z') \cdot k_{1,2}(z'=0)$ 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

$$\mathcal{D} = \frac{c}{H_0} \int\limits_0^z dz' \frac{(1+z')}{\sqrt{\Omega_\Lambda + (1+z')^3\Omega_m}} \tag{7}$$

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

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

Weighted Birefringence Distance

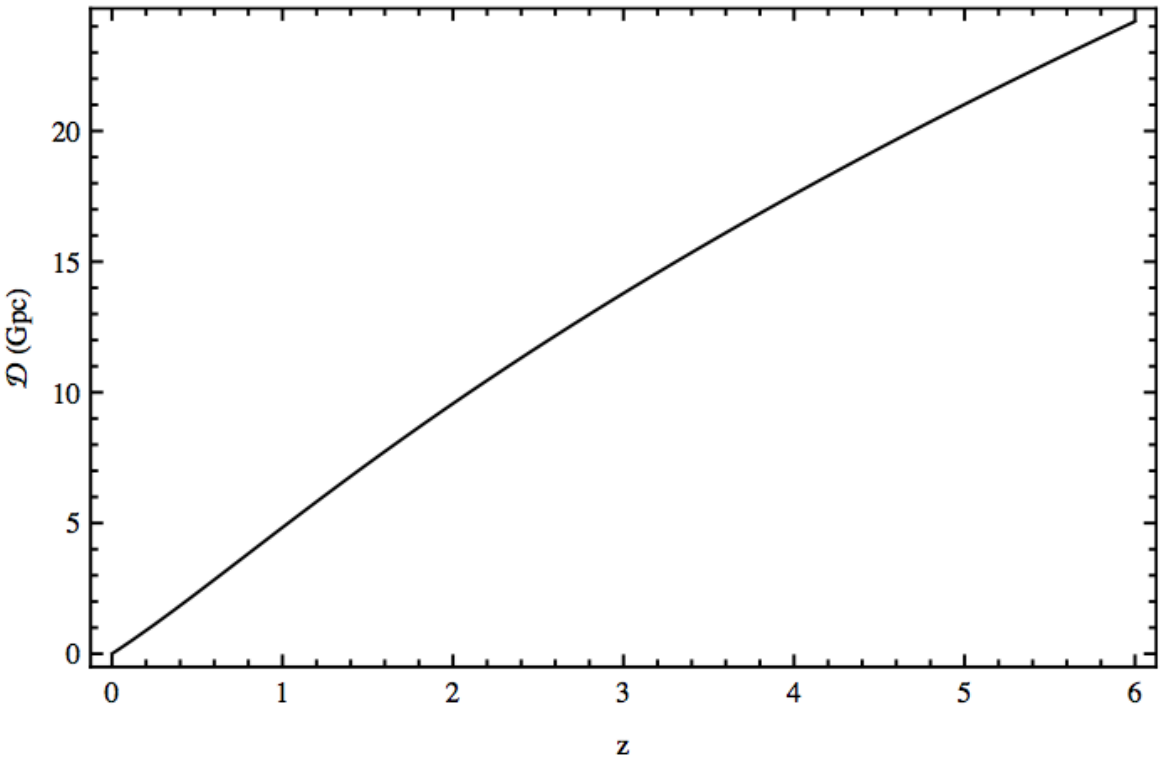


Figure 1: A linear plot of the integral $\mathcal{D}$ as defined in Equation (7), given as a function of redshift, z.

Vacuum birefringence constraint

$$\Delta\theta = \xi\,(E_2^2 - E_1^2)\,d/2M_P$$

relative polarization rotation

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

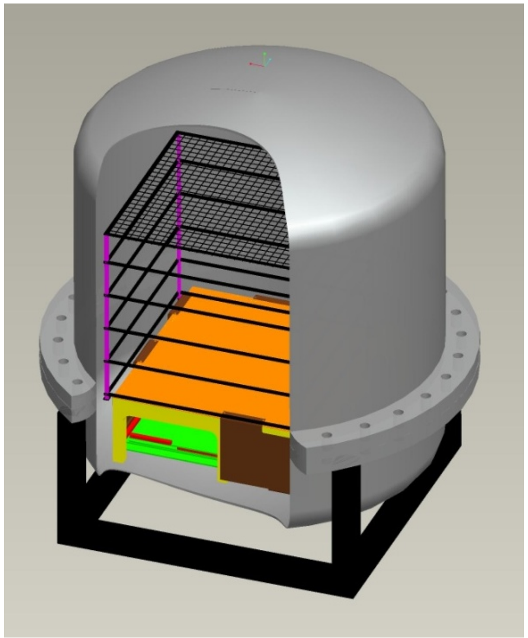
$$|\xi| =< 9 \text{ x } 10^{-10}$$ Maccione et al. 2008

Polarized X-rays from GRB 041219a yields

$$|\xi| < 2.4 \text{ x } 10^{-15}$$ Stecker 2011

Medium Energy γ-ray Detector with Polarization Capability

-Stanley Hunter, NASA/GSFC



- Argon Filled (1.5 atm) to reduce energy threshold and Coulomb scattering so polarization can be measured.
- Wire grids to establish E-field.
- γ-rays convert to e^+e^- and leptons then ionize gas.
- Timing at bottom detector gives 3-D construction of tracks.
- Lepton energies measured at bottom detector also.
- Energy Range ~5 to ~200 MeV*

  **Sensitivity to LIV Vacuum Birefringence goes like E^2*

- Large field of view, ~2π sr
- Uniform sensitivity (homogenous detector)
- Minimize instrument background
- Maximize angular resolution & polarization sensitivity

Photomeson Production by Ultrahigh Energy Cosmic Rays off the Cosmic Microwave Background Radiation

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

Produces "GZK Cutoff" Effect

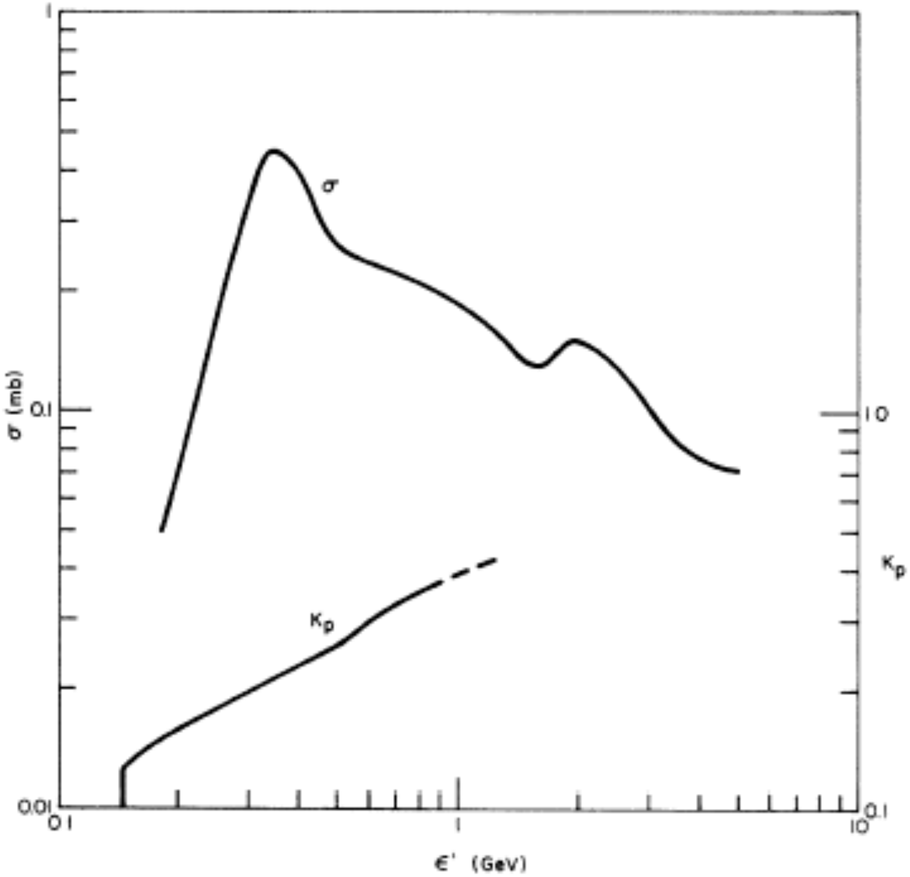


FIG. 1. Total photomeson production cross section and inelasticity as a function of gamma-ray energy in the proton rest system.

UHECR Attenuation (Stecker 1968)

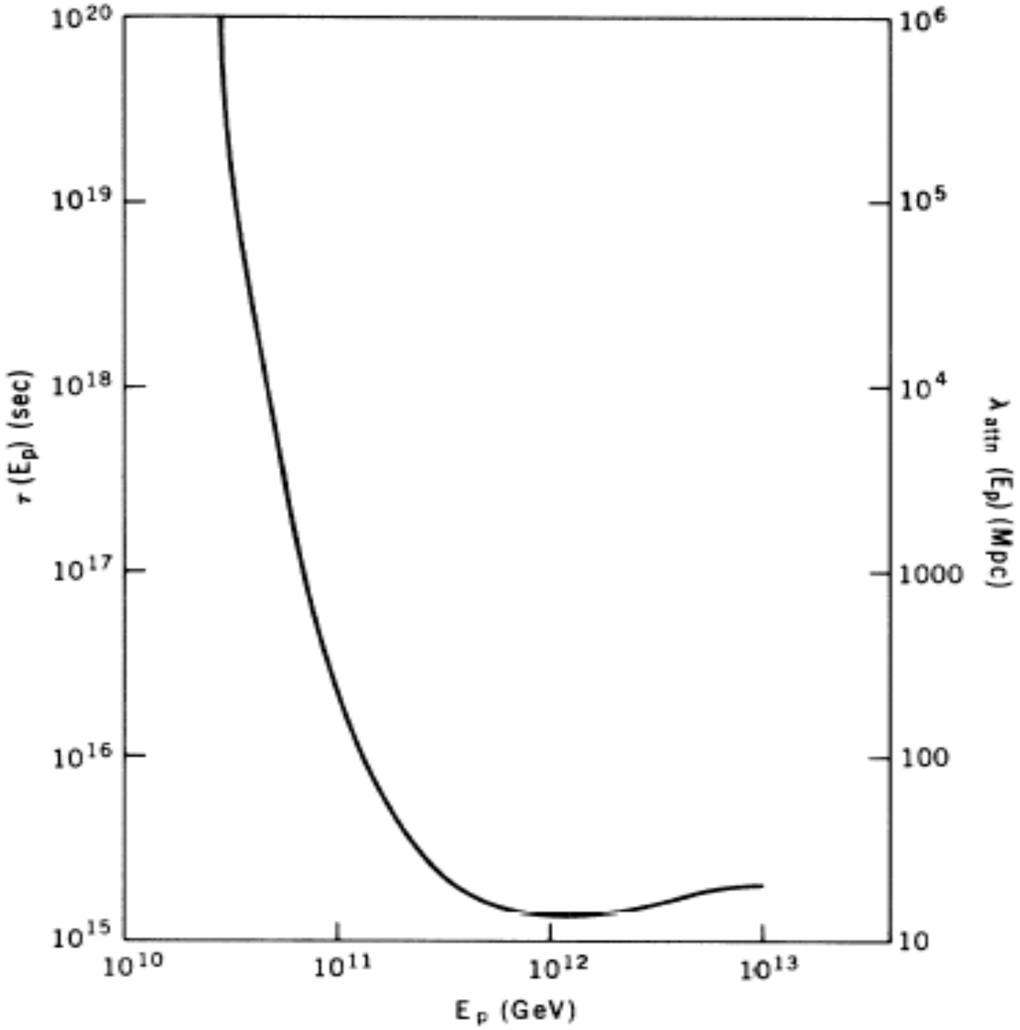
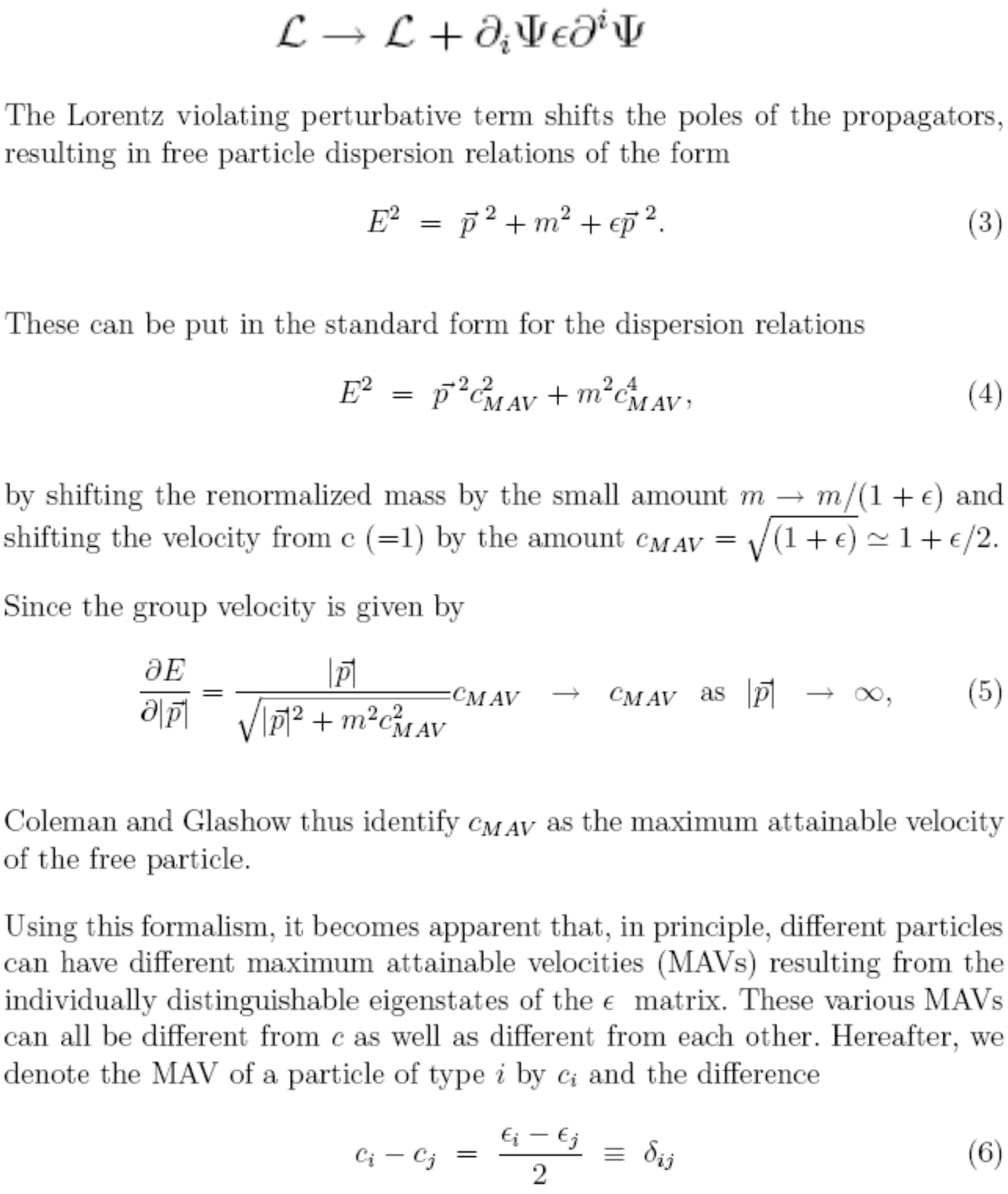


FIG. 2. Characteristic lifetime and attenuation mean free path for high-energy protons as a function of energy.

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

Coleman-Glashow Formalism Revisited:



$$\mathcal{L} \rightarrow \mathcal{L} + \partial_i \Psi \epsilon \partial^i \Psi$$

The Lorentz violating perturbative term shifts the poles of the propagators, resulting in free particle dispersion relations of the form

$$E^2 = \vec{p}^{\,2} + m^2 + \epsilon \vec{p}^{\,2}. \tag{3}$$

These can be put in the standard form for the dispersion relations

$$E^2 = \vec{p}^{\,2} c_{MAV}^2 + m^2 c_{MAV}^4, \tag{4}$$

by shifting the renormalized mass by the small amount $m \rightarrow m/(1+\epsilon)$ and shifting the velocity from c (=1) by the amount $c_{MAV} = \sqrt{(1+\epsilon)} \simeq 1 + \epsilon/2$.

Since the group velocity is given by

$$\frac{\partial E}{\partial |\vec{p}|} = \frac{|\vec{p}|}{\sqrt{|\vec{p}|^2 + m^2 c_{MAV}^2}} c_{MAV} \quad \rightarrow \quad c_{MAV} \quad \text{as} \quad |\vec{p}| \quad \rightarrow \quad \infty, \tag{5}$$

Coleman and Glashow thus identify c_{MAV} as the maximum attainable velocity of the free particle.

Using this formalism, it becomes apparent that, in principle, different particles can have different maximum attainable velocities (MAVs) resulting from the individually distinguishable eigenstates of the ϵ matrix. These various MAVs can all be different from c as well as different from each other. Hereafter, we denote the MAV of a particle of type i by c_i and the difference

$$c_i - c_j = \frac{\epsilon_i - \epsilon_j}{2} \equiv \delta_{ij} \tag{6}$$

LIV Modified Interaction Threshold

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. In terms of the pion energy for single pion production at threshold

$$4\omega E_\pi = \frac{m^2(2M+m)}{M+m}, \tag{8}$$

where M is the rest mass of the proton and m is the rest mass of the pion [4].

If LI is broken so that $c_\pi > c_p$, it follows from equation (3) that the threshold energy for photomeson production is altered because the square of the four-momentum is shifted from its LI form so that the threshold condition becomes

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

Equation (9) is a quadratic equation with real roots only under the condition

$$\delta_{\pi p} \leq \frac{2\omega^2(M+m)}{m^2(2M+m)} \simeq \omega^2/m^2. \tag{10}$$

Defining $\omega_0 \equiv kT = 2.35 \times 10^{-4}$ eV, equation (10) can be rewritten

$$\delta_{\pi p} \leq 3.23 \times 10^{-24}(\omega/\omega_0)^2. \tag{11}$$

Modifying Photomeson Interactions with LIV

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

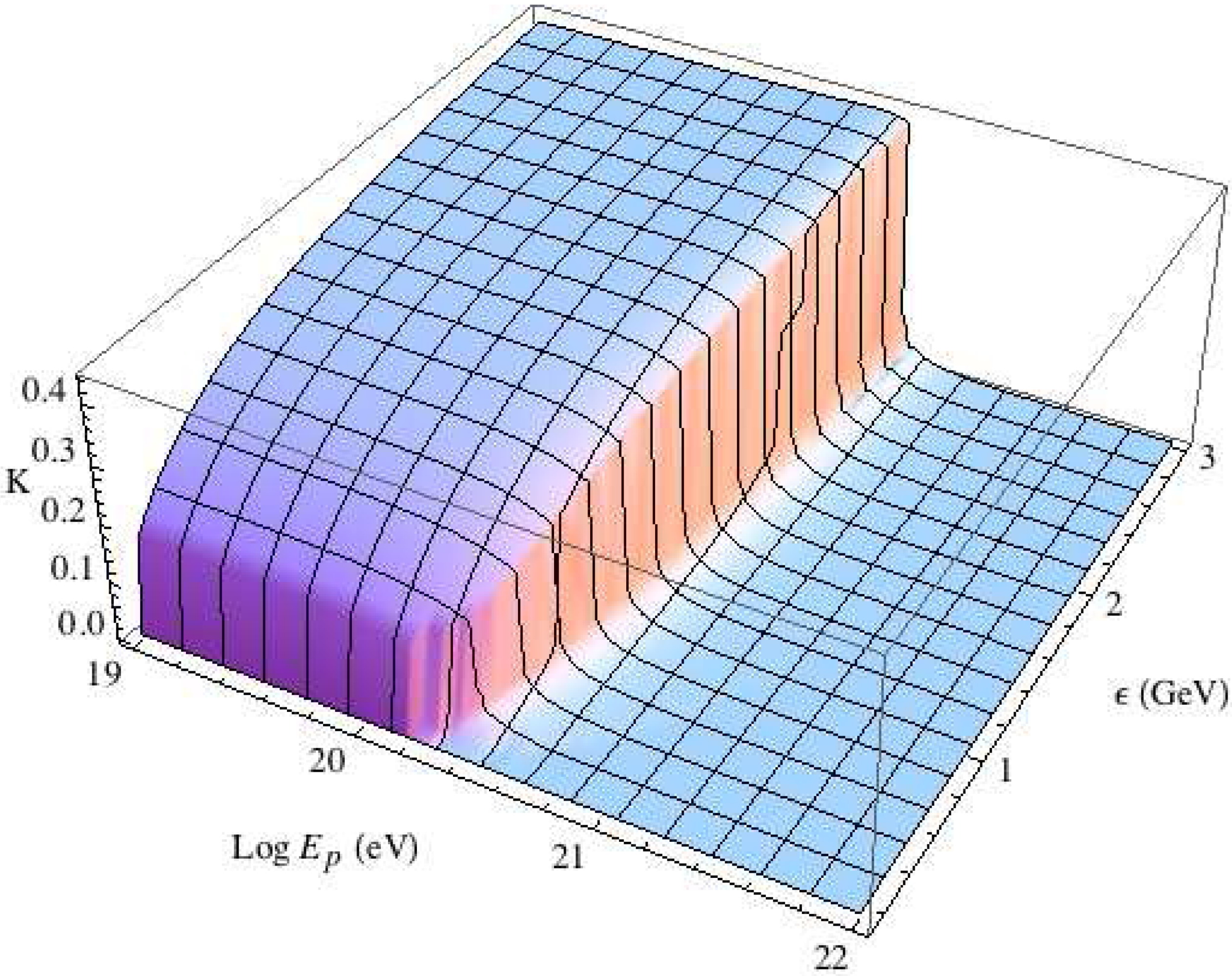
- Photomeson production interactions of ultrahigh energy cosmic rays are disallowed if

$$\delta_{\pi p} = c_\pi - c_p > 3.23\times10^{-24}(\omega/T_{CBR})^2$$

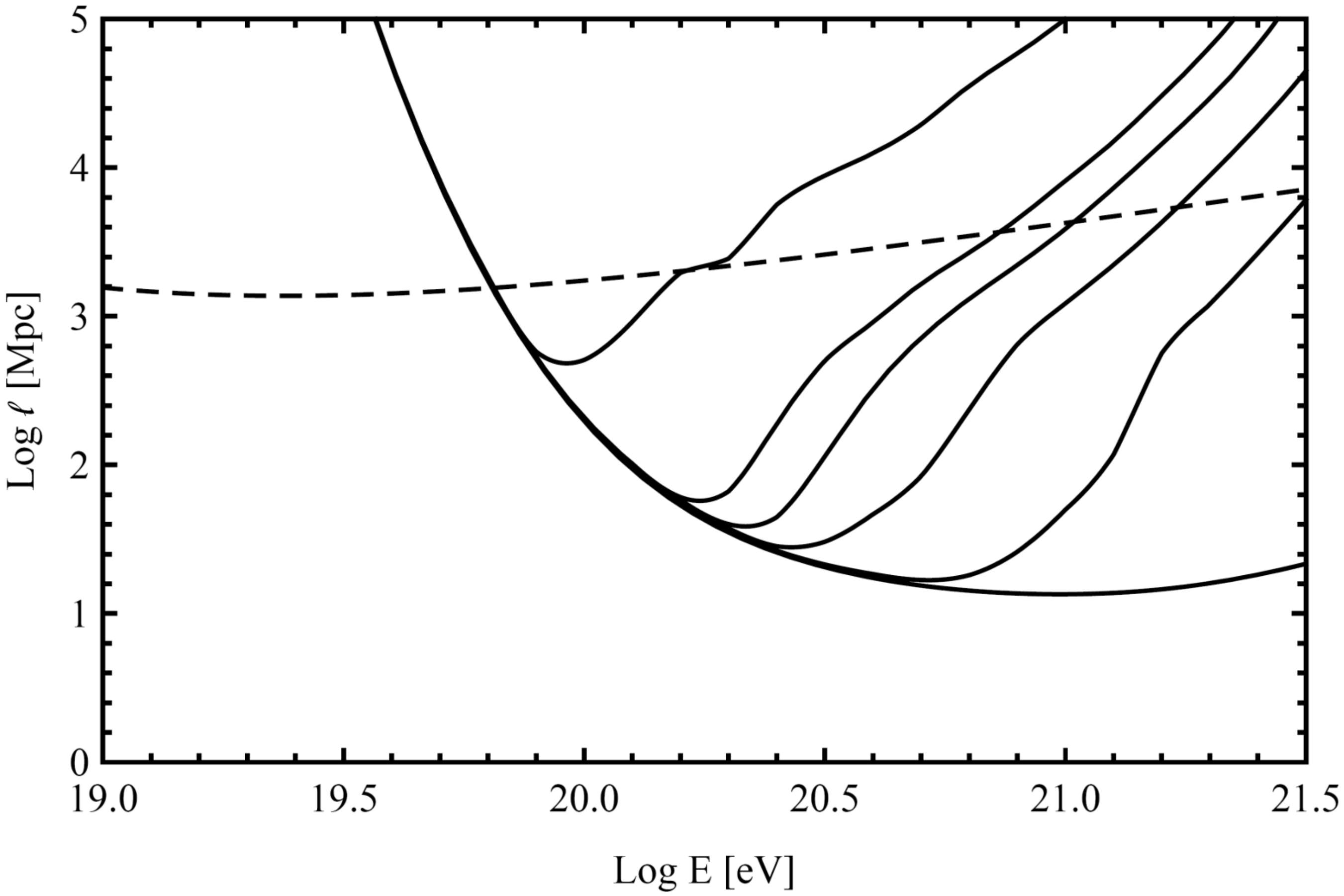
- The higher the value of δ, the higher the photon energy ω required for the interactions to occur.

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 Δ-resonance energy, interactions occur for lower values of E_p near the GZK "cutoff" energy but are suppressed at higher values of E_p

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



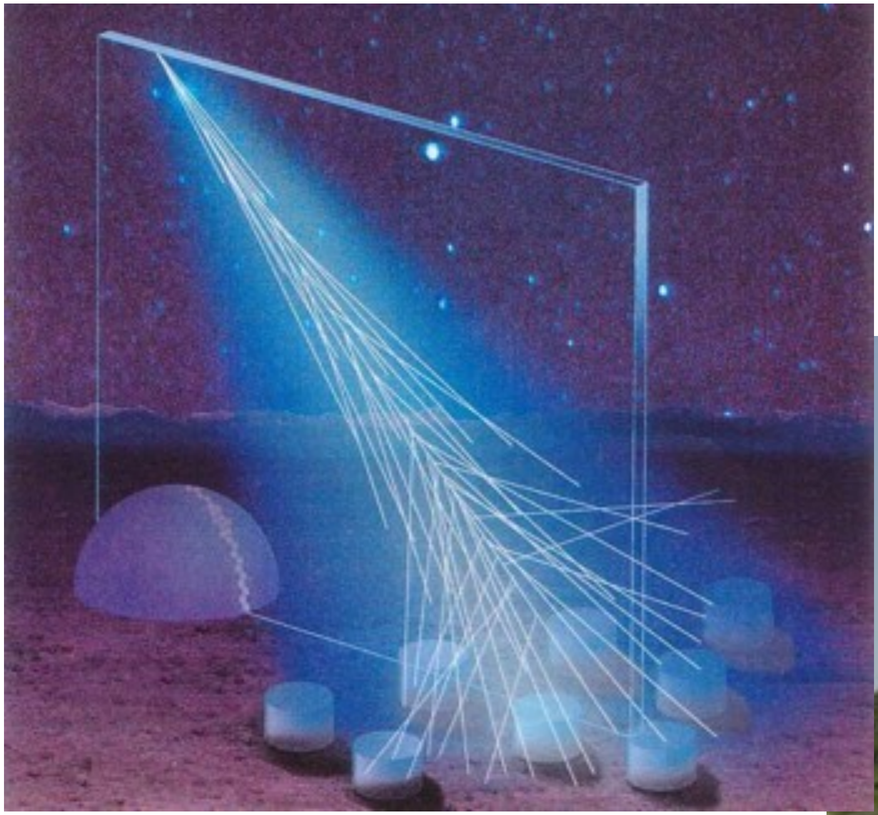
LIV Modified Proton Attenuation Lengths



IMPORTANT RESULT:

You can have (and indeed expect to have) *both* GZK suppression just above ~70 EeV *and* LIV that can be manifested as a "recovery" in the spectrum at higher energies caused by the suppression of the GZK (photomeson interaction) suppression!

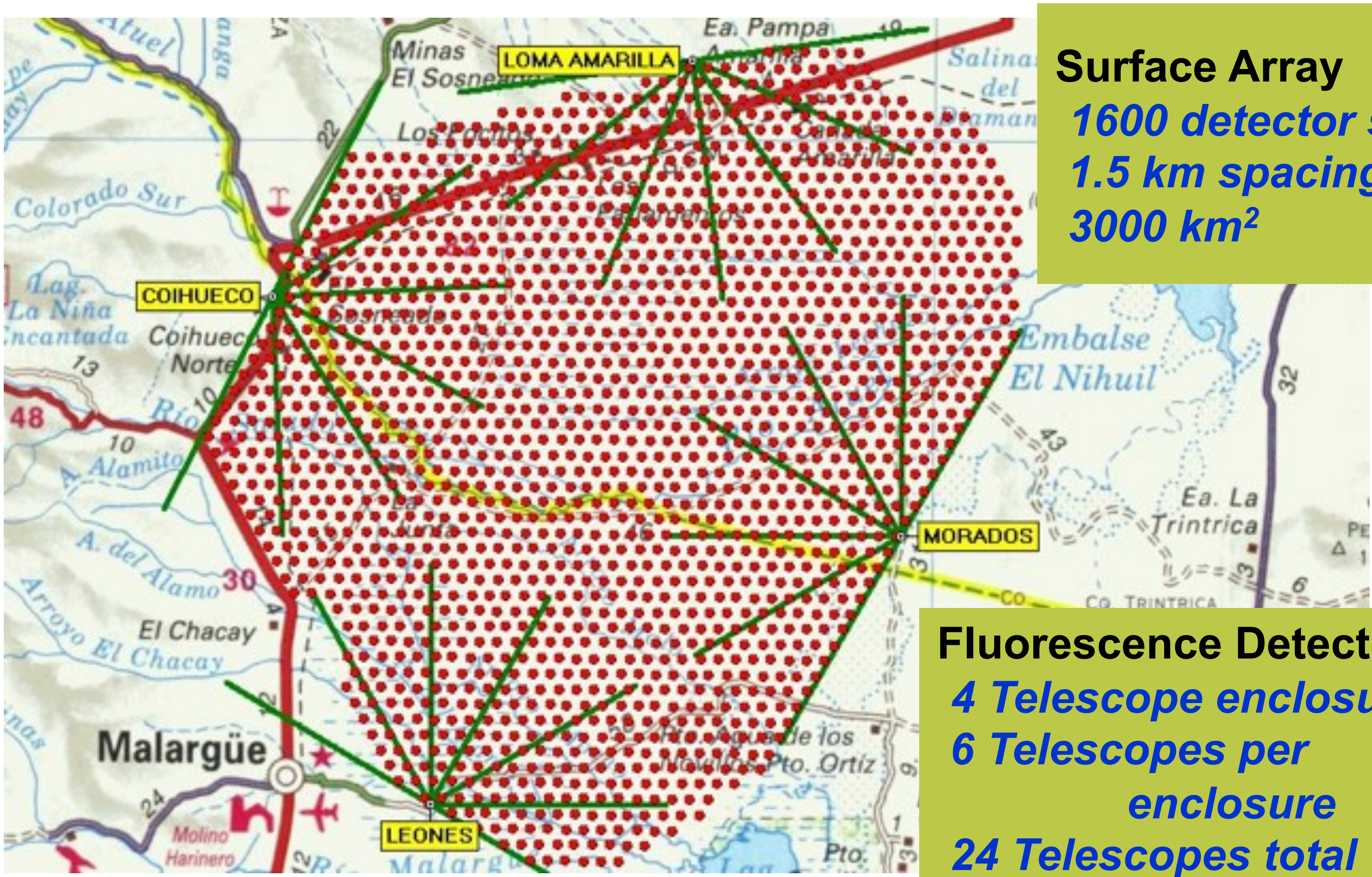
Pierre Auger Observatory



On the Pampa Amarilla in western Argentina

Slides from presentation of
Paul Mantsch, *Auger Project Manger*
www.auger.org

The Observatory Plan



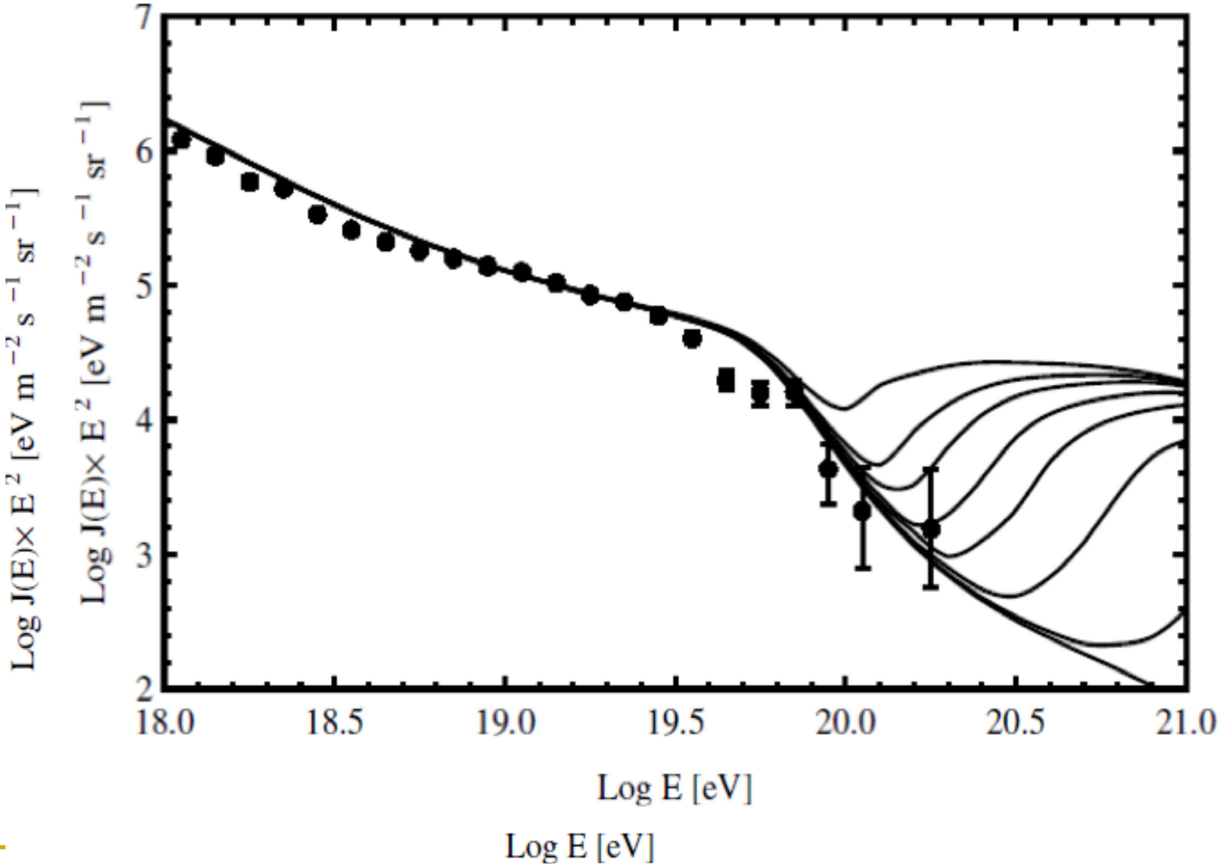
Surface Array

- *1600 detector stations*
- *1.5 km spacing*
- *3000 km^2*

Fluorescence Detectors

- *4 Telescope enclosures*
- *6 Telescopes per enclosure*
- *24 Telescopes total*

Auger spectrum with curves for various amounts of LIV (the lowest curve is for no LIV)



UPPER LIMIT ON THE AMOUNT OF LORENTZ INVARIANCE VIOLATION FROM AUGER DATA

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

Implies LIV suppression by $\mathcal{O}(10^{-6})\, M_{Planck}^{\;-2}$

(Maccione et al. 2009; Stecker & Scully 2009)

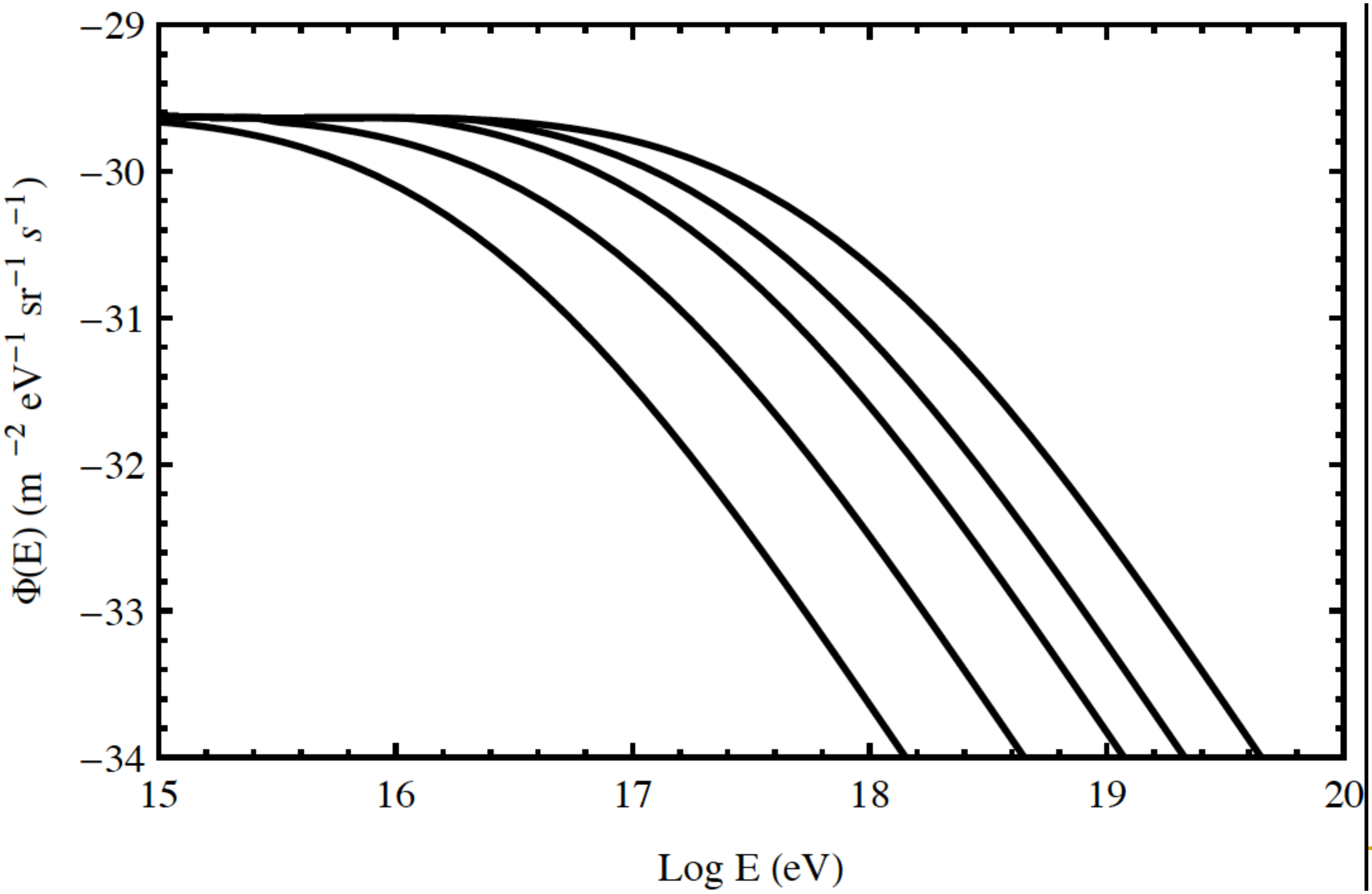
FURTHER EXPLORATION OF LIV

In order to further search for LIV, one must:

- obtain spectral data on ultrahigh energy cosmic rays above the GZK "cutoff" energy, *i.e.*, in the energy range between ~0.3 and ~1 ZeV or

- measure the spectrum of the neutrinos from the GZK process in the energy range between 0.1 and 10 EeV – If there are fewer photomeson production interactions at the higher energies, the resulting neutrino spectrum will be reduced at the high energy end.

Cosmogenic Neutrino Spectra with LIV for $\delta_{\pi p}$ between 0 (highest) and 10^{-22} (Scully & Stecker 2011)



ARIANNA Radio Array (Barwick 2009)

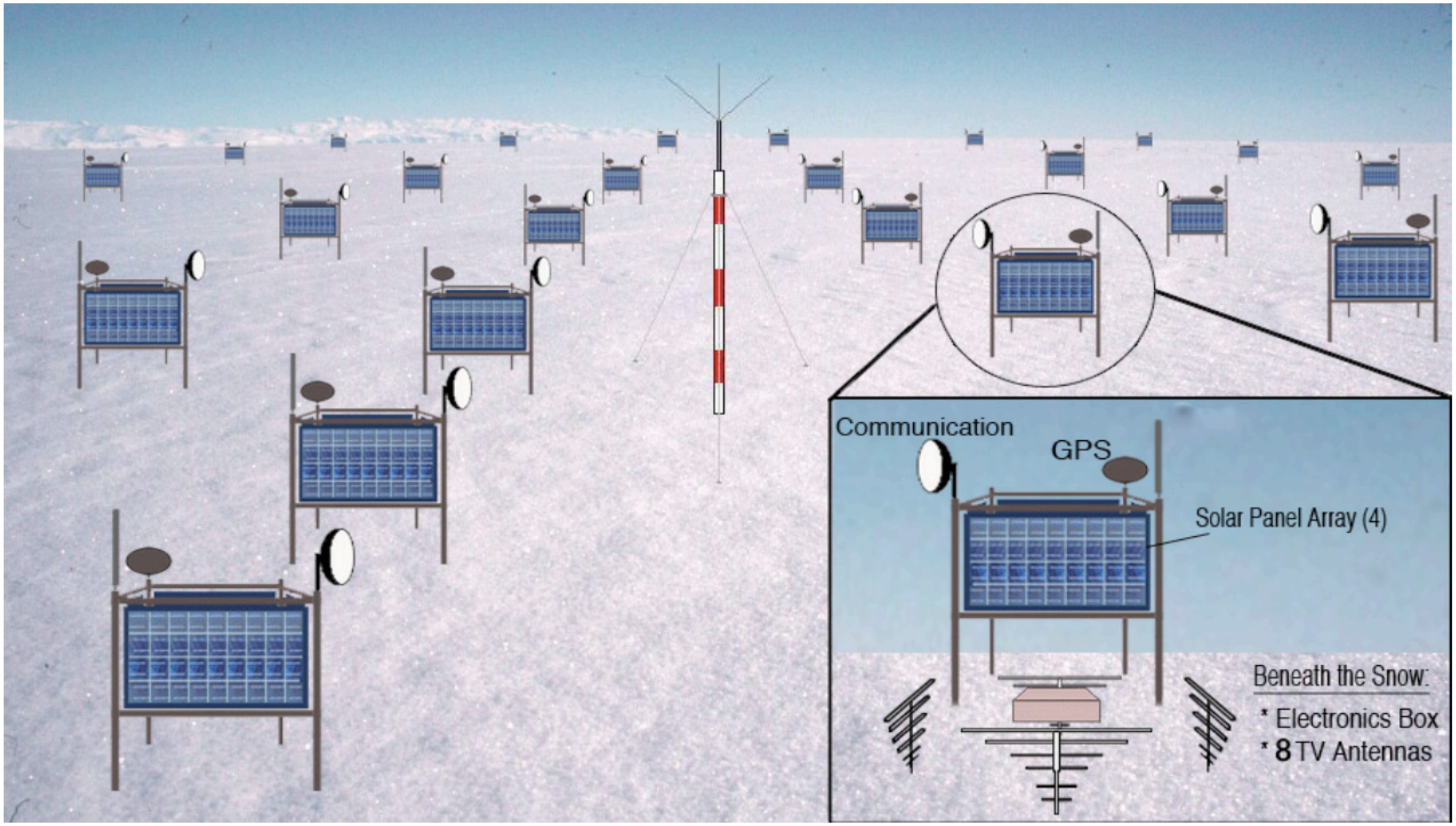
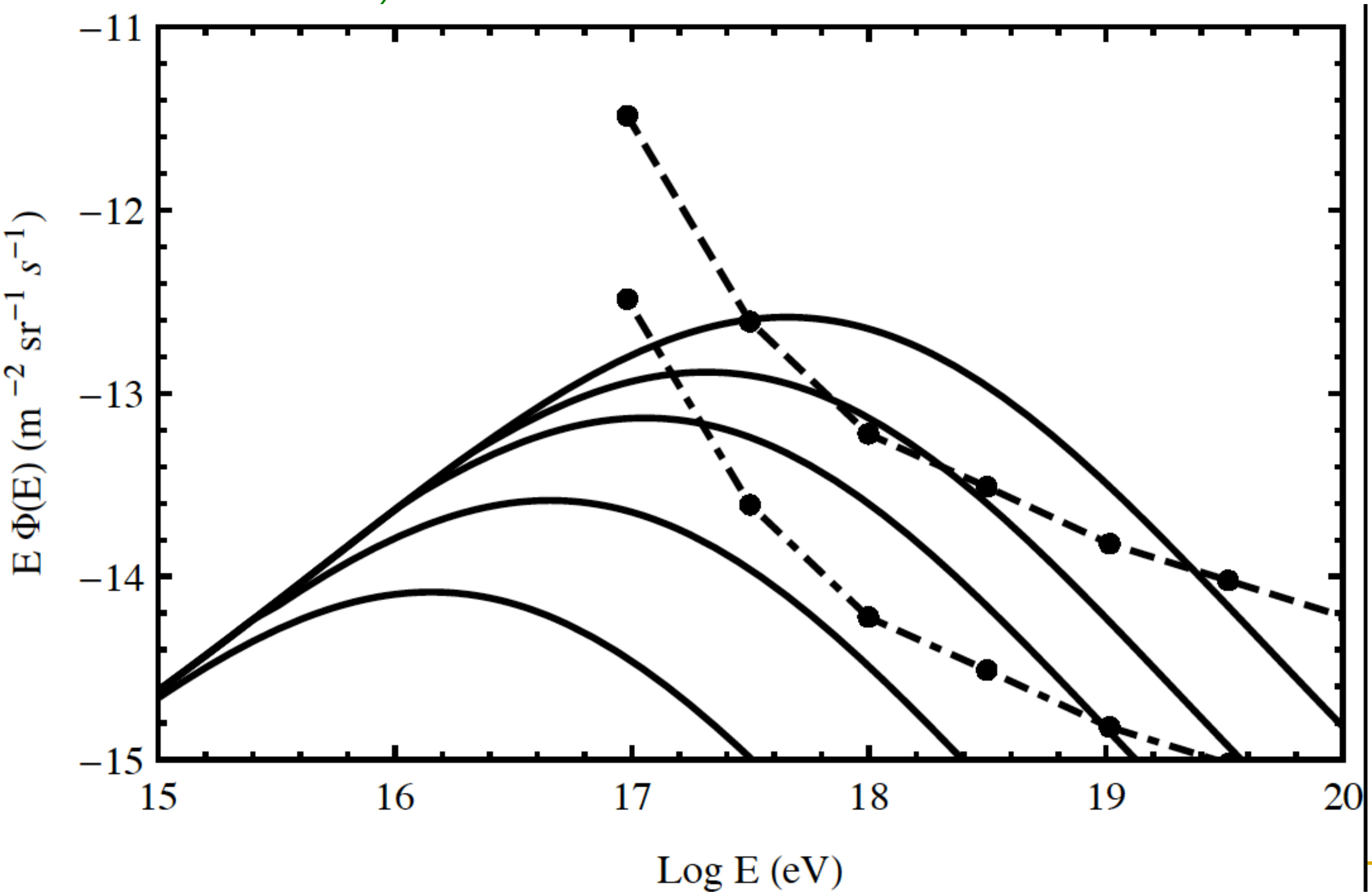


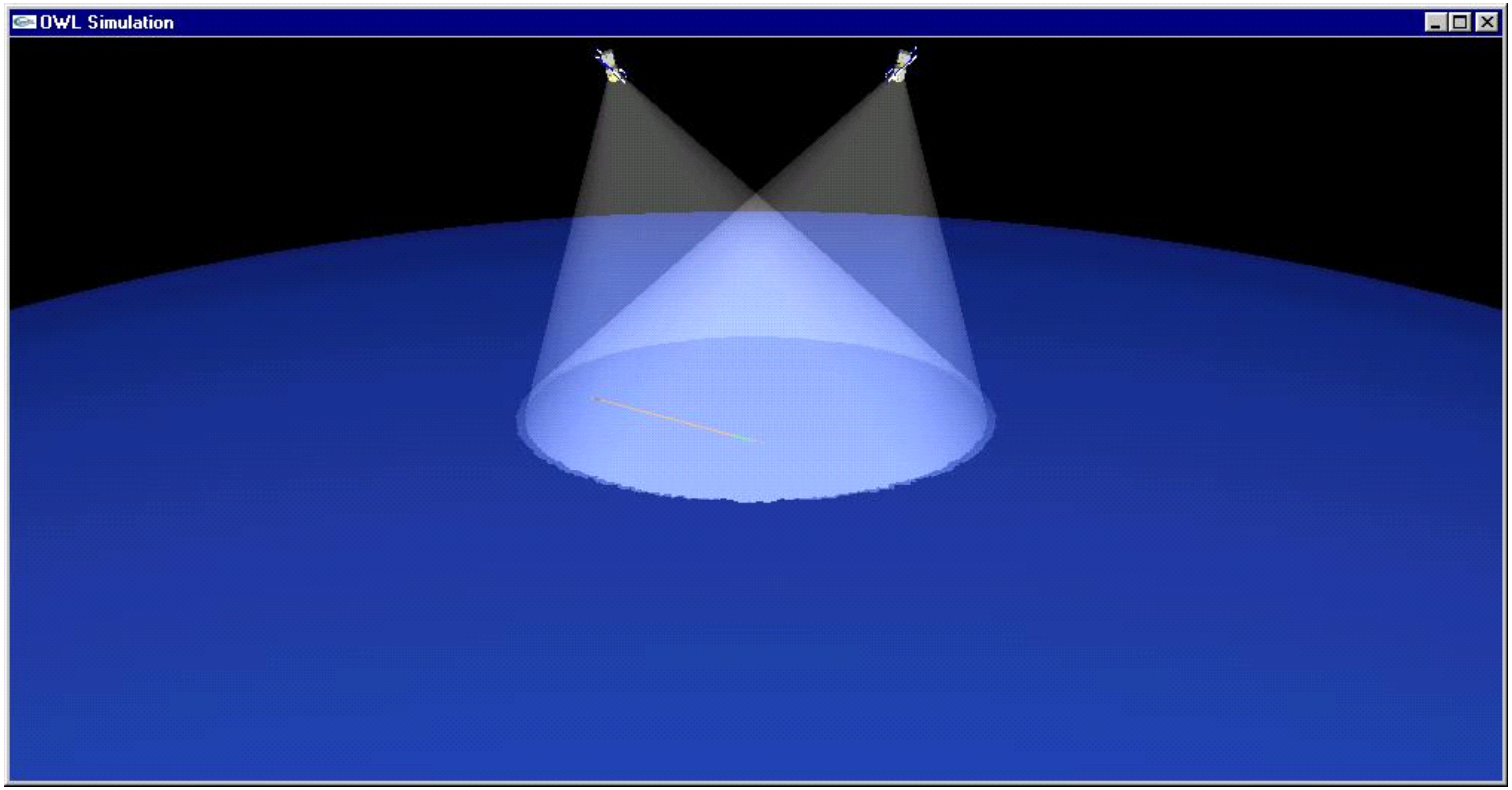
Fig. 1: Concept of ARIANNA array on Ross Ice Shelf, Antarctica. Each station, separated by 300 meters on a square grid, is comprised of 8 log-periodic dipole antennas that point down. Note that the stations are **not** drawn to scale. The striped pole in the center schematically represents the central hub for collection and data archiving. All stations communicate by wireless network protocols to other local stations and the central hub.

Neutrino Spectra for $0 < \delta_{\pi p} < 10^{-22}$ (Scully & Stecker 2011) with 0.5 and 5 yr sensitivities for *ARIANNA* (Barwick 2009) (also can use ARA)

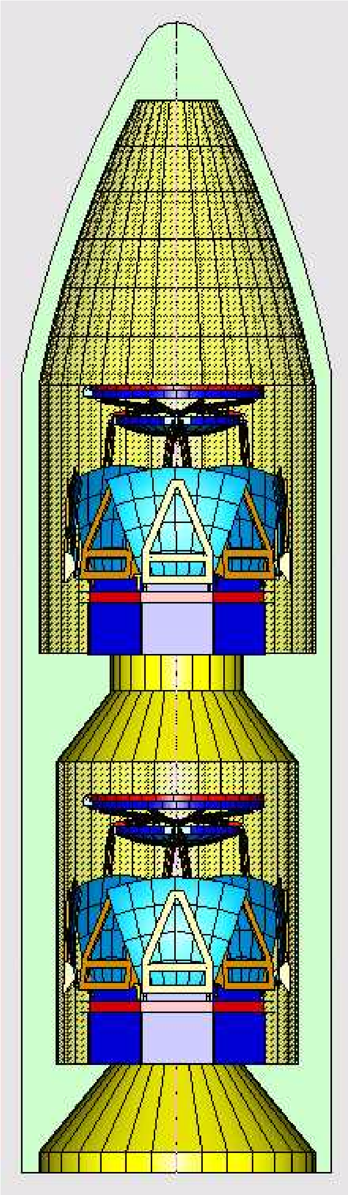


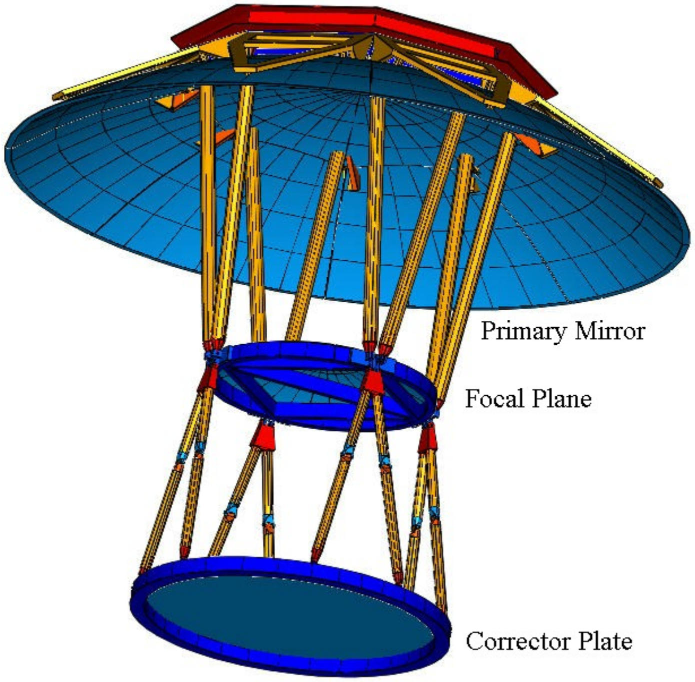
The Search for Higher Energy Cosmic Rays and Neutrinos with Orbiting Telescopes to Use the Earth's Atmosphere as a Detection Medium

OWL : ORBITING WIDE-ANGLE LIGHT COLLECTORS



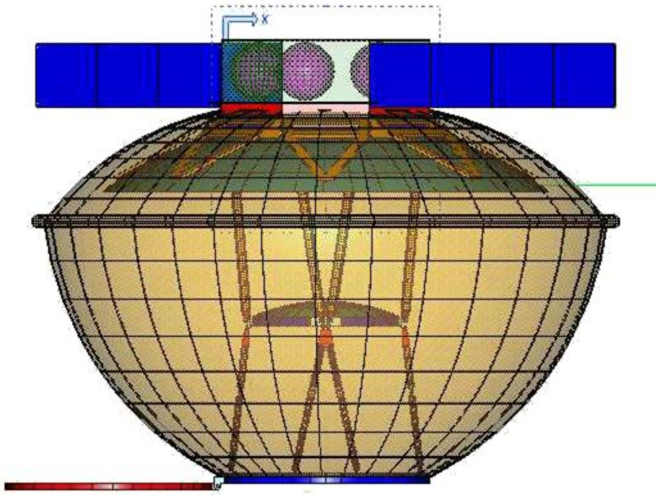
OWL Deployment





Schmidt Optics

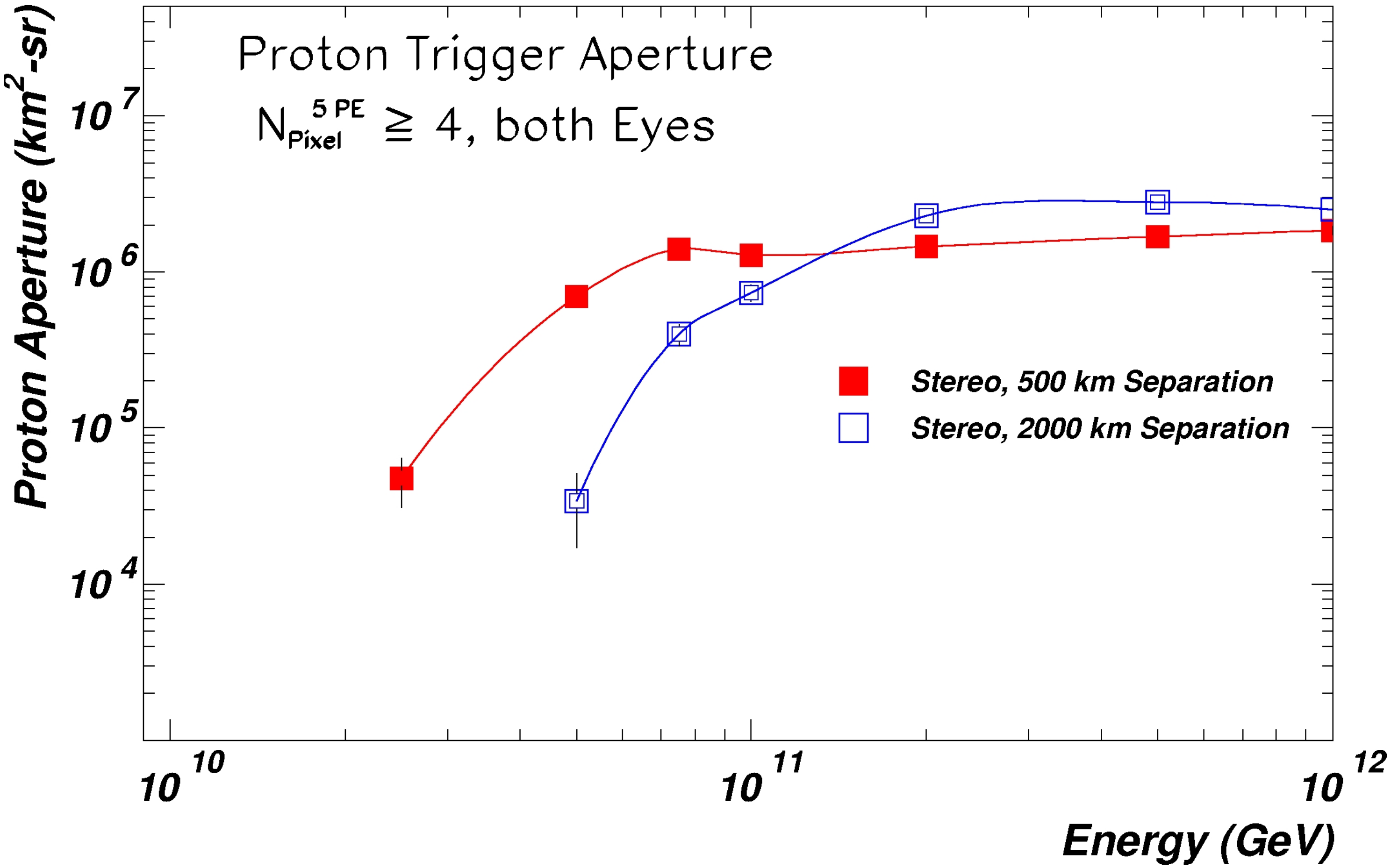
Mechanical Configuration



“Jiffy-Pop” Light Shield

OWL Instantaneous Proton Aperture

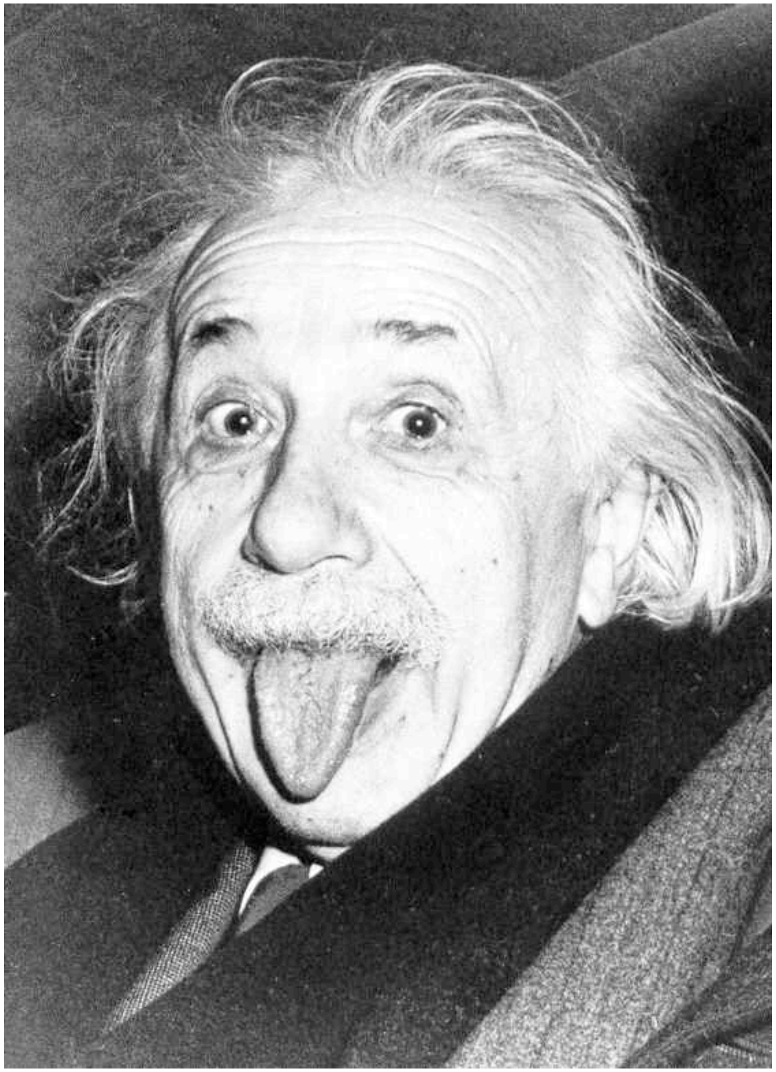
Schmidt Optics, 1000 km Orbits



Results:

- The Fermi timing observations of GRB090510 rule out 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 violations of special relativity (LIV).
- Observations of ultrahigh energy cosmic-rays provide extremely severe constraints on LIV.

The Bottom Line!



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

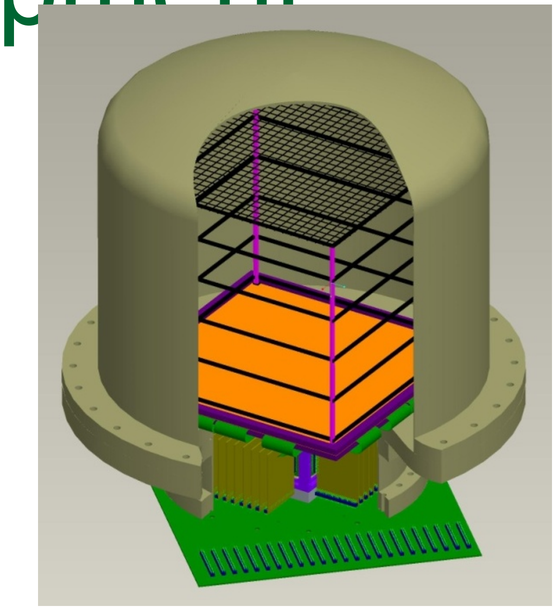
Theoretical models of Planck scale physics and quantum gravity need to meet all of the present observational constraints.

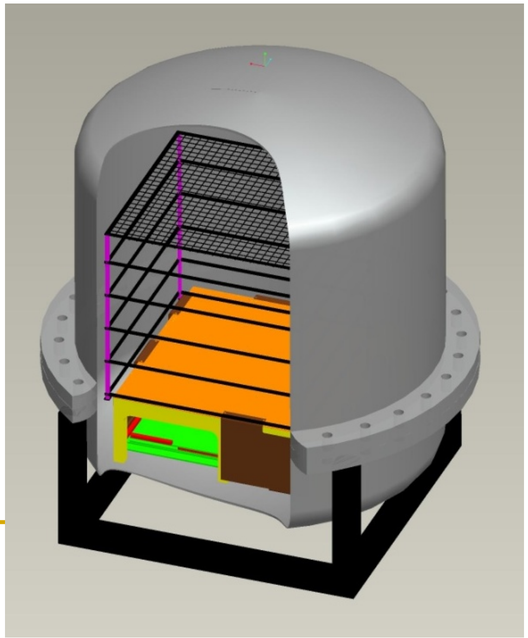
Thanks!

- *Thanks to Alex for inviting me.*
- *Mauru'uru, Hinano, Val et al. for all their help.*

Supplemental Slides

3-DTI Prototype Development





- 30 cm MWD with 10 cm electronics
  - 1/3 resolution readout (512 channels)
    - Gang 3 electrodes to one FEE channel
  - Snapshot and semi-streaming data mode
- 30 cm MWD with 30 cm electronics
  - 1/2 resolution readout (768 channels)
    - Every other electrode read out, limited by number of ASICs
  - Streaming data mode, mid-2012
    - Essentially zero dead-time
- Full resolution readout (1536 channels)
  - Additional ASICs, late-2012