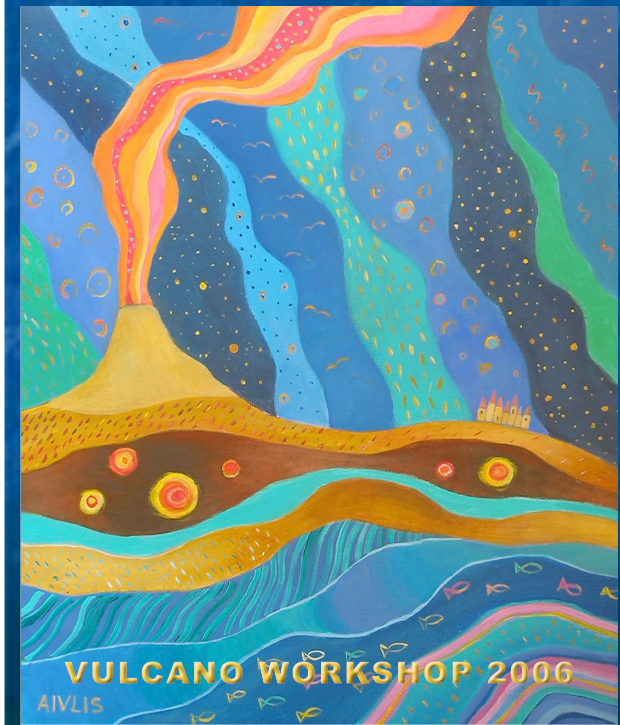
Quantum Gravity Phenomenology: a review



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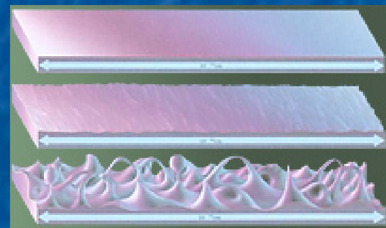
Talk @ Vulcano Workshop 2006



The Quantum gravity problem

- **To eventually understand QG, we will need to**
  - observe phenomena that depend on QG
  - extract reliable predictions from candidate theories & compare them with observations

Old "dogma" we cannot access any quantum gravity effect…

Motivated by tentative theories, partial calculations, potential symmetry violation, hunches, philosophy, we now have some ideas where to look for

- **Primordial gravitons from the vacuum**
- **Loss of quantum coherence or state collapse**
- **QG imprint on initial cosmological perturbations**
- **Scalar moduli or other new field(s)**
- **Extra dimensions and low-scale QG :** $M_p^2 = R^n M_{p(4+n)}^{n+2}$
  - dev. from Newton's law
  - collider black holes
- **Violation of global internal symmetries**
- **Violation of spacetime symmetries**

Lorentz violation: first evidence of QG?

Idea: LI linked to scale-free spacetime -> unbounded boosts expose ultra-short distances…

Suggestions for Lorentz violation come from:

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

Very different approaches but common prediction of modified dispersion relations for elementary particles

QG phenomenology via modified dispersion relations

Almost all of the above cited framework do lead to modified dispersion relations that can be cast in this form

$$\boxed{E^2 = p^2 + m^2 + f(p, M, \mu)}$$

μ = some particle mass scale

$M \equiv$ spacetime structure scale, generally assumed $\approx M_{\text{Planck}} = 10^{19}$ GeV

If we presume that any Lorentz violation is associated with quantum gravity and suppressed by at least one inverse power of the Planck scale *M* and we violate only boost symmetry
(<u>no violation of rotational symmetry</u>)

$$\boxed{E^2 = p^2 + m^2 + M\eta^{(1)}|p| + \eta^{(2)}p^2 + \eta^{(3)}|p|^3/M}$$

Were $\eta^{(i)}$ are dimensionless coefficients possibly of the kind
$(\mu/M)^m$

Theoretical Frameworks for LV

Real LIV with a preferred frame

Apparent LIV with an extended SR

(i.e. possibly a new special relativity with two invariant scales: c and l_p)

QFT+LV

Renormalizable, or higher dimension operators

Spacetime foam leading to stochastic Lorentz violations

Non-commutative spacetime

Extended Standard Model
Renormalizible ops.

E.g. QED, dim 3,4 operators

electrons $\quad E^2 = m^2 + p^2 + f_e^{(1)} p + f_e^{(2)} p^2$

photons $\quad \omega^2 = \left(1 + f_\gamma^{(2)}\right) k^2$

EFT, non-renormalizable ops,
(all op. of mass dimension> 4)

E.g. QED, dim 5 operators

electrons $\quad E^2 = m^2 + p^2 + \eta_\pm^{(3)} (E^3/M_{\rm Pl})$

photons $\quad \omega^2 = k^2 \pm \xi (\omega^3/M_{\rm Pl})$

Framework choice: EFT, all dimension ops, rotation inv., non-universal

- EFT
  - ✓ well-defined & simple
  - ✓ implies energy-momentum conservation (below the cutoff scale)
  - ✓ covers standard model, GR, condensed matter systems, string theory …

- All dimension ops: who knows?

- Rot. invariance
  - ✓ simpler
  - ✓ cutoff idea only implies boosts are broken, rotations maybe not
  - ✓ boost violation constraints likely also boost + rotation violation constraints

- Non-universal
  - ✓ EFT implies it for different polarizations & spins

An open problem: un-naturalness of small LV.

Renormalization group arguments might suggest that lower powers of momentum in

$$E^2 = p^2 + m^2 + M\eta^{(1)}|p| + \eta^{(2)}p^2 + \eta^{(3)}|p|^3/M$$

$$E^2 = p^2 + m^2 + \tilde{\eta}_1 \frac{\mu^2}{M^2} M p^1 + \tilde{\eta}_2 \frac{\mu}{M} p^2 + \tilde{\eta}_3 \frac{\mu}{M^2} p^3 + \tilde{\eta}_4 \frac{\mu}{M^3} p^4 + \ldots + \tilde{\eta}_n \frac{\mu}{M^{n-1}} p^n$$

Alternatively one can see that even if one postulates classically a dispersion relation with only terms $\eta^{(n)} p^n M^{n-2}$ with $n \geq 3$ and $\eta^{(n)} \sim O(1)$ then radiative (loop) corrections involving this term will generate terms of the form $\eta^{(n)} p^2 + \eta^{(n)} p\, M$ which are unacceptable observationally (Collins et al. 2004).

This need not be the case if a symmetry or other mechanism protects the lower dimensions operators from violations of Lorentz symmetry.

- SUSY protect dim<5 operators but SUSY is broken…
  (e.g. Bolokhov et al. hep-ph/0505029)
- Use analogue models of gravity to get hints
  (e.g. 2-BEC analogue model, Liberati et al. PRL.96: 151301,2006)

Terrestial tests of Lorentz violation

- Penning traps
- Clock comparison experiments
- Cavity experiments
- Spin polarized torsion balance
- Neutral mesons

All these experiments deal with low energies, as such they are well suited to study lowest order LIV and have been applied extensively to the Standard Model Extension (renormalizable EFT with LIV) which is nowadays very well constrained.

In order to constraint higher order LIV one needs high energy physics, nowadays really high energy physics is actually high energy astrophysics

Exception: Electron spin resonance in torsion balance experiments yields $|\square_L \,\square\, \square_R| \,\square\, 4$

Applications: QED with LIV at O(E/M)

Let's consider all the Lorentz-violating dimension 5 terms (n=3 LIV in dispersion relation) that are quadratic in fields, gauge & rotation invariant, not reducible to lower order terms (Myers-Pospelov, 2003). For E»m

Warning: All these LIV terms also violate CPT

$$-\frac{\xi}{2M}u^m F_{ma}(u\cdot\partial)(u_n\tilde{F}^{na}) + \frac{1}{2M}u^m\bar{\psi}\gamma_m(\zeta_1+\zeta_2\gamma_5)(u\cdot\partial)^2\psi$$

electrons $\quad E^2 = m^2 + p^2 + \eta_\pm(p^3/M_{\rm Pl})$

photons $\quad \omega^2 = k^2 \pm \xi(k^3/M_{\rm Pl})$

$$\eta_\pm = 2(\zeta_1 \pm \zeta_2)$$

electron helicities have independent LIV coefficients

photon helicities have opposite LIV coefficients

Moreover electron and positron have inverted and opposite positive and negatives helicities LIV coefficients (JLMS, 2003).

	Positive helicity	Negative helicity
Electron	η_+	η_-
Positron	$-\eta_-$	$-\eta_+$

Astrophysical tests of Lorentz violation

- **Cumulative effects**

(time of flight & birefringence)

- **Anomalous threshold reactions**

(I.e. forbidden if LI holds, e.g. gamma decay, Vacuum Cherekov)

- **Shift of standard thresholds reactions**

(e.g. gamma absorption or GZK) with

New phenomenology

(asymmetric pair creation and upper thresholds)

- **LV induced decays not characterized by a threshold**

(e.g. decay of particle from one helicity to the other or photon splitting)

- **Reactions affected by "speeds limits"**

(e.g. synchrotron radiation)

Time of flight

Constraint on the photon LIV coefficient □ by using the fact that different colors will travel at different speeds.

NOTE: independent on the dynamics

$$v_\gamma = \frac{\partial E}{\partial p} = 1 + \xi \frac{E}{E_{Pl}}$$

$$\begin{aligned} \Delta t &= \Delta v T = \xi \frac{E_2 - E_1}{M} T \\ \Delta t &\approx 10\,\mathrm{msec}\, \xi\, d_{Gpc}\, E_{GeV} \end{aligned}$$

Best constraint up to date Coburn et al. using GRB021206 use only sharp pulse from 10 MeV to 17 MeV over 15 msec, obtained |□|<55 (z≈0.3). However uncertainty on determination of z.

Safest best constraint is Biller (1998, Markarian 421, z≈0.03, 1-2 TeV over 280 sec. | □|<252).

Being sure both photon polarization are present in the pulse one could use the fact that opposite coefficients for photon helicities imply larger dispersion 2|□|p/M rather than that due to different energies □(p_2-p_1)/M.

The current best limits |□|<63 (from Biller 1998, AGN) or |□|<22 (from Boggs et al. 2003, GRB).

Problem: there is strong evidence that most GRB and AGN are not "good" objects for ToF constraints because of intrinsic time lags (different energies emitted at different times) not well understood.

Robust limits can be claimed only by a careful statistical analysis on large sample of sources

See recent ***Ellis et al., astro-ph/0510172***

Conservative limit | □|<10^3

Birefringence

The birefringence constraint arises from the fact that the LV parameters for left and right circular polarized photons are opposite. The phase velocity thus depends on both the wavevector and the helicity. NOTE: independent on the dynamics

Linear polarization is therefore rotated through an energy dependent angle as a signal propagates, which depolarizes an initially linearly polarized signal comprised of a range of wavevectors.

In more detail, with the dispersion relation from EFT with LIV at order E/M the direction of linear polarization is rotated through the angle

$$\theta(t) = [\omega_+ - \omega_-(k)]\, t/2 = \xi k^2 t/2M$$

for a plane wave with wave-vector k over a propagation time t. The difference in rotation angles for wave-vectors k_1 and k_2 is thus

$$\Delta\theta = \xi \left(k_2^2 - k_1^2\right) d/2M, \quad (\text{where } d = \text{distance source-detector})$$

Current safest constraint was obtained by Gleiser and Kozameh using observed 10% polarization UV light from distant, z=1.82, radio galaxy 3C 256 $|\xi| \leq 2 \times 10^{-4}$

The claim of strongly polarized MeV photons (Coburn-Boggs, 2003) in the prompt emission from the γ-ray burst GRB021206 (using the RHESSI detector) yields the constraint $|\xi| < 5.0 \times 10^{-15}/d_{0.5}$.

($d_{0.5}$ = the distance to the burst in units of 0.5 Gpc.)

Unfortunately new data analysis found no polarization...

Threshold reactions

Key point: the effect of the non LI dispersion relations can be important at energies well below the fundamental scale

$$E^2 = c^2 p^2 \left(1 + \frac{m^2 c^2}{p^2} + \eta \frac{p^{n-2}}{M^{n-2}}\right)$$

Corrections start to be relevant when the last term is of the same order as the second.

If η is order unity, then

$$\frac{m^2}{p^2} \approx \frac{p^{n-2}}{M^{n-2}} \Rightarrow \quad p_{crit} \approx \sqrt[n]{m^2 M^{n-2}}$$

n	p_{crit} for ν_e	p_{crit} for e^-	p_{crit} for p^+
2	$p \approx m_\nu \sim 1\ eV$	$p \approx m_e = 0.5\ MeV$	$p \approx m_e = 0.938\ GeV$
3	$\sim 1\ GeV$	$\sim 10\ TeV$	$\sim 1\ PeV$
4	$\sim 100\ TeV$	$\sim 100\ PeV$	$\sim 3\ EeV$

For n=3 and m=m$_{electron}$

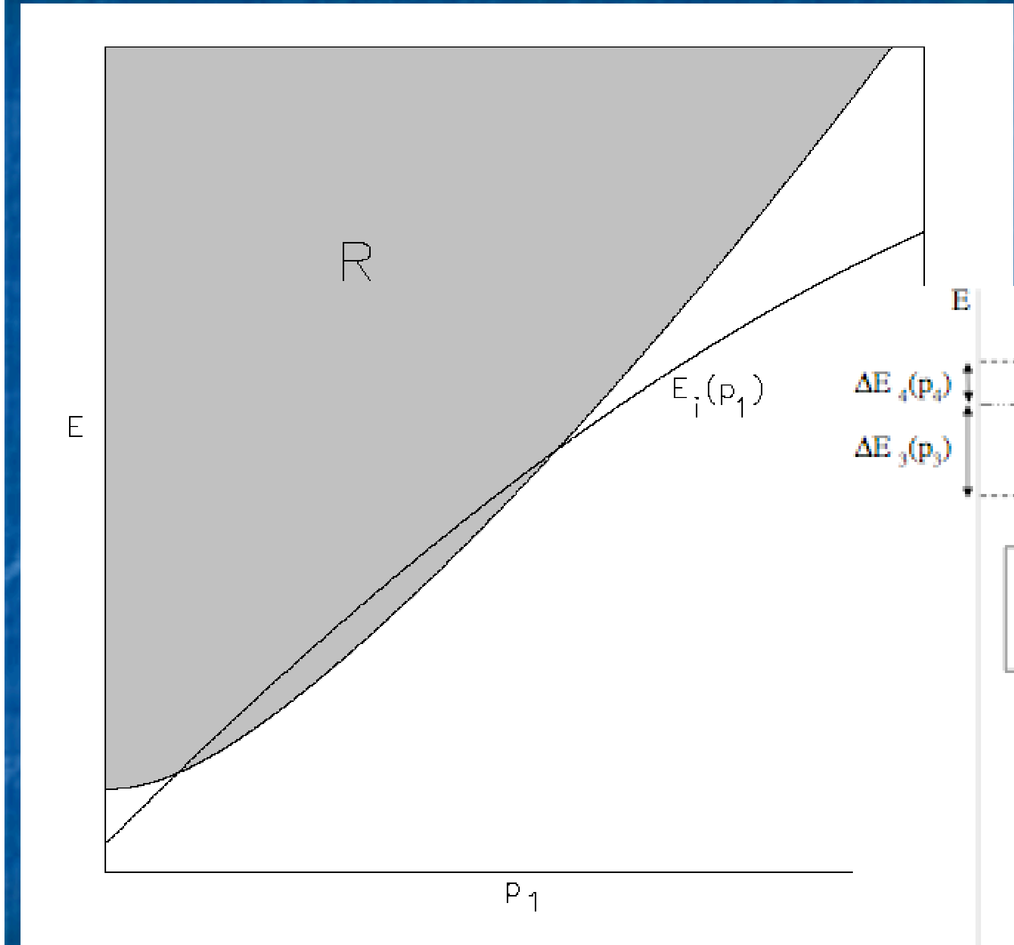
$$m^2 \approx \eta p^3 / M \Rightarrow \quad p \approx (m^2 M / \eta)^{1/3} \approx 10\,\mathrm{TeV}\,\eta^{-1/3}$$

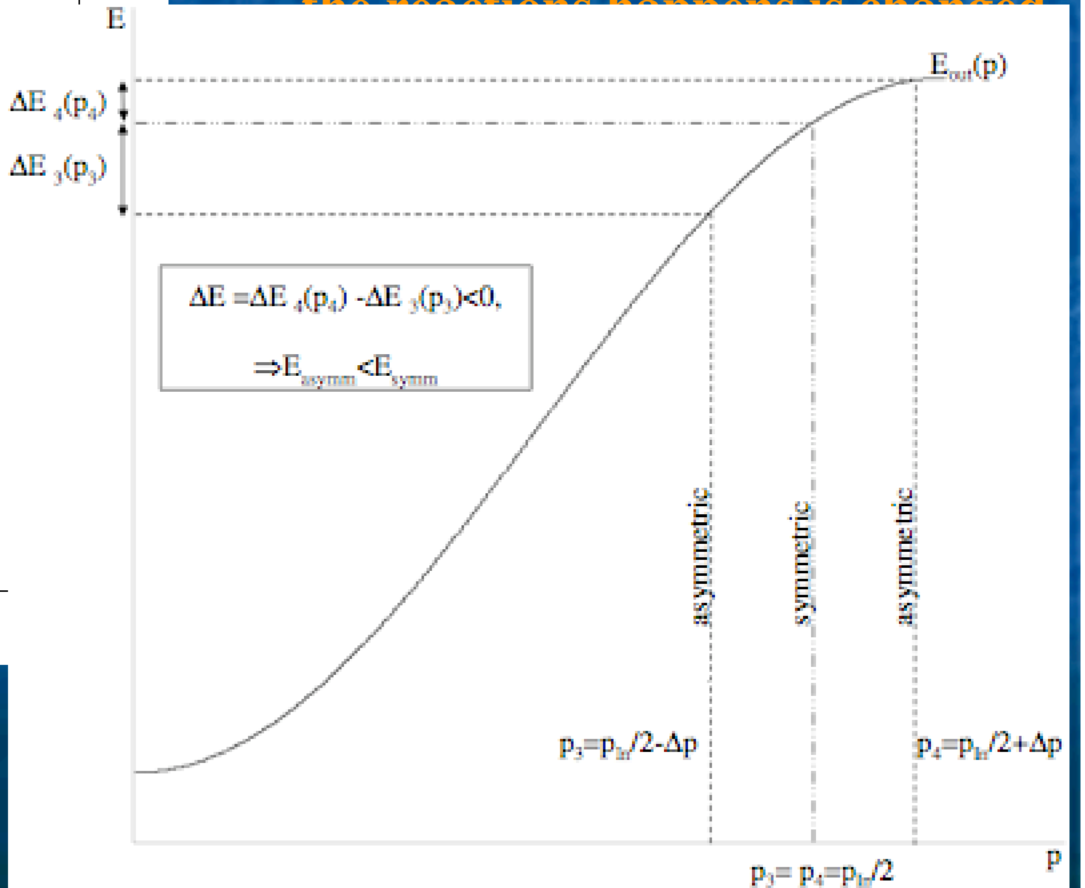
$$\eta \text{ constraint} \propto \frac{1}{p^3_{\max}}$$

Novelties in threshold reactions: why

❖ **Upper thresholds**:

The range of available energies of the incoming particles for which the reactions happens is changed





QED anomalous threshold reactions

□□ $e^+ + e^-$

Gamma decay

- Lorentz violation allows the conservation of energy-momentum.
- To obtain constraints on just two parameters, but consistent with EFT, we can focus on processes in which only either $\square_+$ or $\square_-$ is involved, namely reactions in which the positron has opposite helicity to the electron.
- Threshold at about 10 TeV.
- Once the reaction can happens it is very fast as the decay rate goes like $\square\square E^2/M$. 10 TeV photons would decay in approximately 10^{-5} seconds.
- If we see very high energy gamma rays from distant sources at least one photon polarization must travel on cosmological distances. I.e. they must be above threshold.

QED anomalous threshold reactions

Vacuum Cherenkov and helicity decay

$e^{\pm}$□ □$+e^{\pm}$

- Lorentz violation allows the conservation of energy-momentum.
- The reaction can preserve or not the helicity of the lepton.
- First case called Vacuum Cherenkov, second case called helicity decay.

Vacuum Cherenkov

- Threshold at about 10 TeV.
- Depending on parameters one can have emission of soft or hard photon.
- Once the reaction can happens it is very fast as the rate of energy loss goes like

dE/dt□*E*^{3}*/M* □ *10* TeV electron would loose most of its energy in □10^{-9} seconds.

- The observation of the propagation of some high energy given electrons implies that at least one helicity state cannot decay in *either* of the photon helicities.
- Hence the constraint can be worked out for one of the □$_{\pm}$ and □and then the excluded region can be obtained by just flipping around the □axis.

Helicity decay

- It can happen if there are unequal □$_{\pm}$. There is no threshold energy
- There is an "effective threshold" due to small reaction rate below energy comparable to Cherenkov threshold.
- Above "effective threshold" the reaction is very fast, electron would loose most of its energy in □10^{-9} seconds.

From observation of propagating leptons comes the constraint

Other examples of QED reactions

Fermion pair emission

e^-□ $e^- e^- e^+$

• Lorentz violation allows the conservation of energy-momentum.

• Similar to vacuum Cherenkov both in threshold energy and rate.

• Similar to Cherenkov strength of constraint (slightly weaker)

Photon splitting

□□ n□

• Allowed by Lorentz violation (in standard QED amplitudes vanish).

• Requires □>0. No threshold but small amplitude.

• Using Euler-Hisember Lagrangian was found sufficiently rapid rate for constraint □<10^{-3} for observed 50 TeV photons.

• However the analysis did not take into account LIV dependence on helucities in QED. Needs better analysis.

Photon absorption

□□$_0$□ $e^- e^+$

• Well know reaction in HE astrophysics. Absorption of TeV gamma rays (from AGN) on IR and CMB background.

• LIV shift threshold and creates possibility for upper threshold

• Qualitative analysis done for helicity independent dispersion relations. Big uncertainties from IR background and primary spectrum of AGN

• Constraint of order 10^{-2} on both coefficients from 20 TeV Mrk 501.

Synchrotron radiation

Jacobson, SL, Mattingly: Nature 424, 1019 (2003)
R. Montemayor, L.F. Urrutia: Phys.Lett.B606:86-94 (2005)

LI synchrotron critical frequency: $$\omega_c^{LI} = \frac{3}{2}\frac{eB\gamma^2}{m}$$

e - electron charge

m - electron mass

B - magnetic field

The key point is that for negative η, γ is now a bounded function of E! There is now a maximum achievable synchrotron frequency ω^{max} for ALL electrons!

$$\gamma = (1-\mathrm{v}^2)^{-1/2} \simeq \left(\frac{m^2}{E^2} - 2\eta\frac{E}{M_{QG}}\right)^{-1/2}$$

So one gets a constraints from asking $\omega^{max} \geq (\omega^{max})_{observed}$

However in order to get a real constraint one needs a detailed re-derivation of the synchrotron effect with LIV based on EFT.

This leads to a modified formula for the peak frequency: $$\omega_c^{LIV} = \frac{3}{2}\frac{eB}{E}\gamma^3$$

We can now maximize the synchrotron frequency with respect to the electron energy ($\eta<0$)
One gets that the maximal peak frequency achievable is

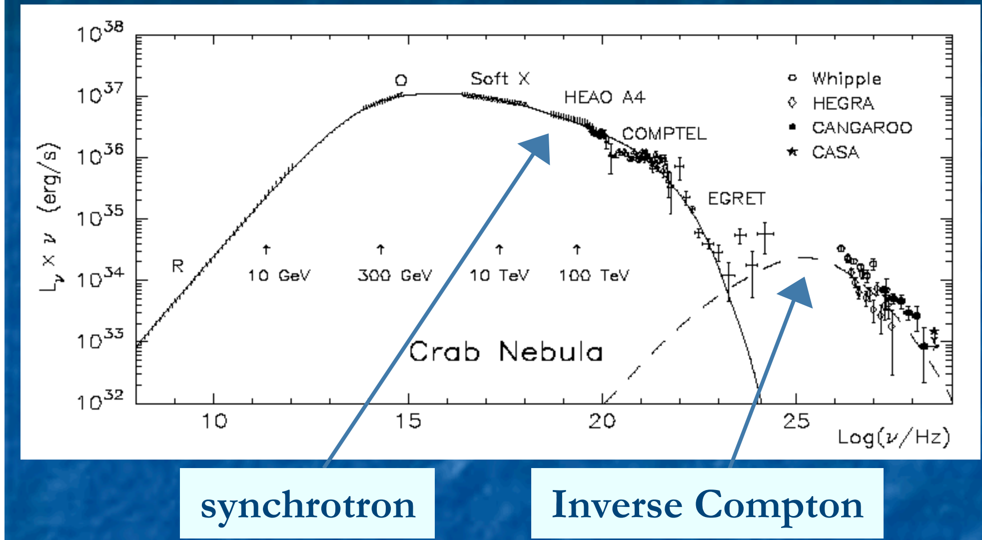
$$\omega_c^{\max} = 0.34\,\frac{eB}{m}(-\eta m/M)^{-2/3}$$

Then if one observes some max frequency ω_{obs} the LIV parameter must be such to allow it

$$\eta > -\frac{M}{m}\left(\frac{0.34\,eB}{m\,\omega_{\rm obs}}\right)^{3/2}$$

Stronger constraint for smaller $B/\omega_{observed}$
Best case is Crab nebula...

The EM spectrum of the Crab nebula



From Aharonian and Atoyan, astro-ph/9803091

Crab nebula (and other SNR) well explained by synchrotron self-Compton (SSC) model:

1. Electrons are accelerated to very high energies at pulsar
2. High energy electrons emit synchrotron radiation
3. High energy electrons undergo inverse Compton (mainly with synchrotron ambient photons)

We shall assume SSC correct and use Crab observation to constrain LV.

Crab alone provides three of the best constraints. We use:

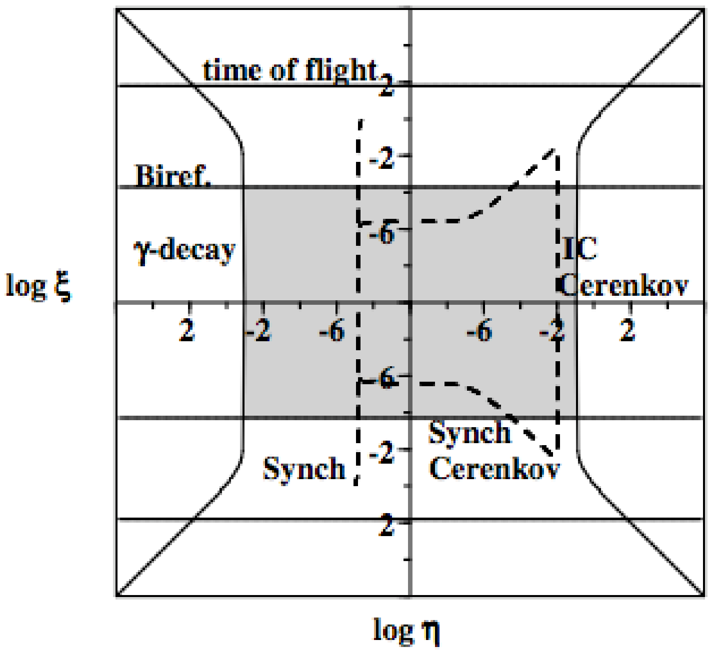
- Gamma rays up to 50 TeV reach us from Crab: no photon annihilation up to 50 TeV.
- By energy conservation during the IC process we can infer that electrons of at least 50 TeV propagate in the nebula: no vacuum Cherenkov up to 50 TeV
- The synchrotron emission extends up to 100 MeV (corresponding to ~1500 teV electrons if LI is preserved): LIV for electrons (with negative □) should allow an E^{max}□100 MeV. B at most 0.6 mG

Constraints for EFT with O(E/M) LIV

T. Jacobson, SL, D. Mattingly: PRD 66, 081302 (2002); PRD 67, 124011-12 (2003)
T. Jacobson, SL, D. Mattingly: Nature 424, 1019 (2003)
T. Jacobson, SL, D. Mattingly, F. Stecker: PRL 93 (2004) 021101
T. Jacobson, SL, D. Mattingly: Annals of Phys. 321 (2006) 150

electrons $\quad E^2 = m^2 + p^2 + \eta_{\pm} p^3/M$

photons $\quad \omega^2 = k^2 \pm \xi p^3/M$



TOF: $|\xi| \lesssim$ 0(100) from MeV emission GRB
(*Boggs et al 2004, but see also Ellis et al., astro-ph/0510172*)

Birefringence: $|\xi| \lesssim 10^{-4}$ from UV light of radio galaxies (*Gleiser and Kozameh, 2002*)

Using the Crab nebula we infer:

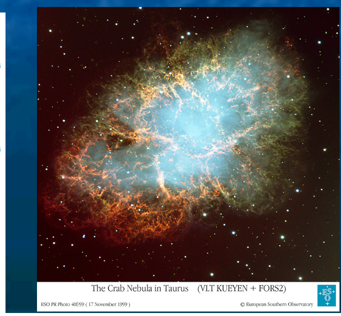
γ-decay: for $|\xi| \lesssim 10^{-4}$ implies $|\eta_{\pm}| \lesssim 0.2$ from 50 TeV gamma rays from Crab nebula

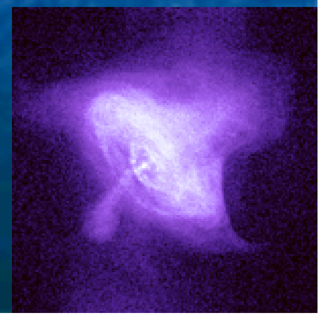
Inverse Compton Cherenkov: at least one of $\pm\eta_{\pm} \lesssim 10^{-2}$ from inferred presence of 50 TeV electrons

Synchrotron: at least one of $\pm\eta_{\pm} \geq -10^{-8}$

Synch-Cherenkov: for any particle with η satisfying synchrotron bound the energy should not be so high to radiate vacuum Cherenkov

Fig. 1. Constraints on LV in QED at $O(E/M)$ on a log-log plot. For negative parameters minus the logarithm of the absolute value is plotted, and region of width 10^{-10} is excised around each axis. The constraints in solid lines apply to ξ and both $\eta_{\pm}$, and are symmetric about both the ξ and the η axis. At least one of the two pairs $(\eta_{\pm}, \xi)$ must lie within the union of the dashed bell-shaped region and its reflection about the ξ axis. The IC and synchrotron Čerenkov lines are truncated where they cross.





Applications beyond QED: the GZK cut-off

Since the sixties it is well-known that the universe is opaque to protons (and other nuclei) on cosmological distances via the interactions

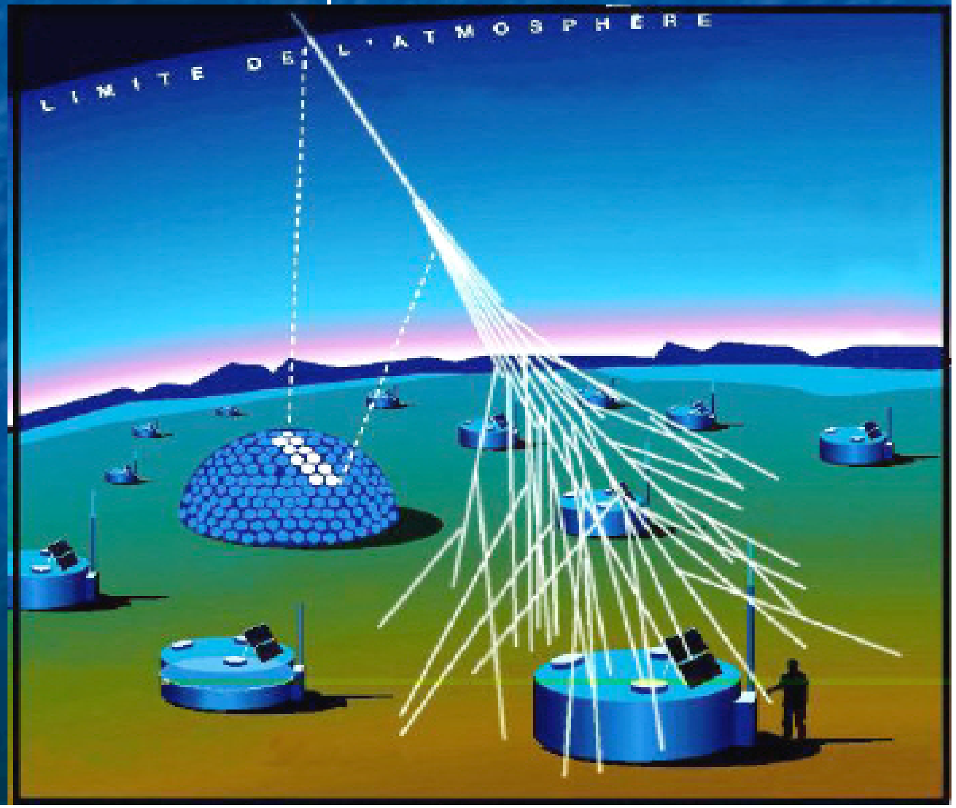
$$p + \gamma_{CMB} \to p + \pi$$
$$p + \gamma_{CMB} \to \Delta^* + 2\pi$$

In this way, the initial proton energy is degraded with an attenuation length of about 50 Mpc. Since plausible astrophysical sources for UHE particles (like AGNs) are located at distances larger than 50-100 Mpc, one expects the so-called Greisen-Zatsepin-Kuzmin (GZK) cutoff in the cosmic ray flux at the energy given by

$$E_{GZK} \approx 5 \times 10^{19}\ \mathrm{eV}$$

- HiRes collaboration claim that they see the expected event reduction
- A recent reevaluation of AGASA data seems to confirm the violation of the GZK cutoff.
- Everybody is waiting for the Auger experiment to give a definitive answers (but first data not yet enough statistics)

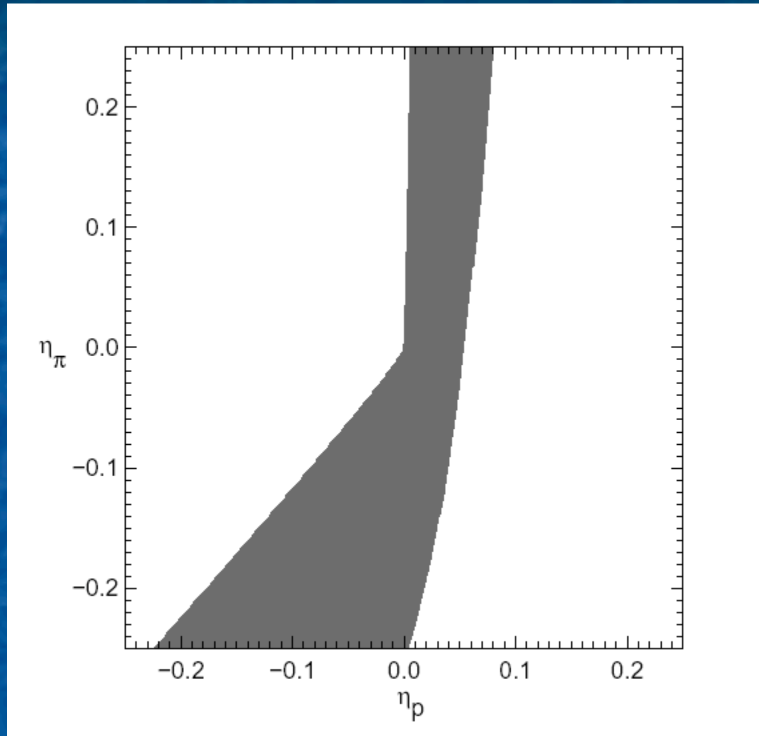
Several explanations proposed (e.g. Z-burst, Wimpzillas), remarkably LIV appears as possibly one of the less exotic…



Possible constraints from GZK

Constraint from photon-pion production
$p^+ \gamma_{CMB} \to p^+ \pi^0$ **(if GZK confirmed)**

The range of η_p, η_π for $n = 3$ dispersion modifications where the GZK cutoff is between $2\cdot10^{19}$ eV and $7\cdot10^{19}$ eV . →



η_p and η_π are in multiples of 10^{-10}

(Jacobson, SL, Mattingly: PRD 2003)

Constraint from absence of proton vacuum Cherenkov $p^+ \to p^+ \gamma$

If one presumes p pointlike the constraint has the same shape as for electrons but much stronger

$$
\begin{aligned}
\eta_p - \xi &< O(10^{-22}) \quad \text{for} \quad n = 2 \\
\eta_p - \xi &< O(10^{-14}) \quad \text{for} \quad n = 3 \\
\eta_p - \xi &< O(10^{-5}) \quad \text{for} \quad n = 4
\end{aligned}
$$

In 2004 Gagnon and Moore performed analysis taking into account the partonic structure founding same orders of magnitude for the constraints…

The future?

- **Definitively rule out n=3 LV, O(E/M), EFT including chirality effects**
  - Strengthen the n=3 bounds. E.g. via possible role of positrons in Crab nebula emission. (better observations with GLAST?)
  - naturalness problem: hints from analogue models. Emergent symmetries?
- **Constraint on n=4 (favored if CPT also for QG):**
- **From UHECR (Auger, EUSO, OWL)**
  - No GZK protons Cherenkov: □≤10^{-5}
  - If GZK cutoff seen: $□_{p=□}$≈≥□10^{-2}

$$m^2 \sim □\, p^4/M^2 \; □ \; p \sim \sqrt{mM}\, □^{□1/4}$$
$$p \sim 100 \text{ TeV (neutrino)},$$
$$3□10^{18} \text{ eV (proton)}, \; 100 \text{ PeV (electron)}$$

- **From Neutrinos (Amanda, IceCube, EUSO, OWL, NEST**
  - Neutrinos: 100 TeV neutrinos give order unity constraint by absence of vacuum Cherenkov but rate of energy loss too low. Recent calculations shows one need 10^{15}- 10^{20} eV UHE cosmological neutrinos. Possibly to be seen via EUSO and/or OWL satellites
- **From AGILE or GLAST we shall hardly get constraints in n=4.**
  For GRB we need anyway
  - better measures of energy, timing, polarization from distant □-ray sources.

  O(1) birefringence constraint on |□| requires polarization detection at 100 MeV
  - AGILE/GLAST could see TOF n=3 LIV, unfortunately no polarization