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Quantum Gravity phenomenology: achievements and challenges

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The quantum gravity problem

- **Why we need a theory of Quantum Gravity?**
  - Philosophy: reductionism in physics
  - Lack of predictability of current theories

  (e.g. Singularities, Time Machines, spacetime topology and signature…)

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

Problem!

QG phenomenology

Old "dogma": you shall not access any quantum gravity effect as this would require experiments at the Planck scale!

Quantum gravity phenomenology is a recently developed field aimed at testing, observationally or experimentally possible predictions of quantum gravity frameworks.

- Primordial gravitons from the vacuum
- Loss of quantum coherence or state collapse
- QG imprint on initial cosmological perturbations
- Cosmological variations of couplings
- Extra dimensions and low-scale QG (LHC BH) : $M_p^2 = R^n M_{p(4+n)}^{n+2}$
- Violation of global internal symmetries
- Violation of discrete symetries
- Violation of spacetime symmetries

We shall focus here on the last item.
More precisely on the possibility that Lorentz symmetry can be violated at high energies…

The LV dim Dark Ages

When violating Lorentz (symmetry) was an heresy...

- **Is there an Aether?** (Dirac, 1951)
- **LV & particle interactions?** (Blokhintsev, 1964?)
- **Dispersion & LV** (Pavlopoulos, 1967)
- **Vector-tensor gravity** (Nordvedt & Will, 1972)
- **Emergent LI in gauge theory?** (Nielsen & Picek, 1983)
- **LV modification of general relativity** (Gasperini, 1987)
- **Spontaneous LV in string theory** (Kostelecky & Samuel, 1988)
- **LV Chern-Simons in Electrodynamics** (Carroll, Field & Jackiw, 1990)
- **LV & BH trans-Planckian question** (Jacobson, 1990)
- **LV Dispersion & Hawking radiation** (Unruh, 1994, Brout-Massar-Parentani-Spindel 1995))
- **Possibilities of LV phenomenology** (Gonzalez-Mestres, 1995)

The turning LV tide

- **"Standard model extension" & lab. experimental limits** (Colladay & Kostelecky, 1997, & many experimenters)
- **High energy threshold phenomena: photon decay, vacuum Cerenkov, GZK cutoff** (Coleman & Glashow, 1997-8)
- **GRB photon dispersion limits** (Amelino-Camelia et al, 1997)
- **Trans-GZK events?** (AGASA collab. 1998), **TeV gamma ray crisis?** (Protheroe & Mayer 2000)

Lorentz violation: a first glimpse of QG?

Suggestions for Lorentz violation (at low or high energies) came from several tentative calculations in QG models:

- String theory tensor VEVs (Kostelecky-Samuel 1989)
- Cosmological varying moduli (Damour-Polyakov 1994)
- Spacetime foam scenarios (Amelino-Camelia et al. 1997-1998)
- Some semiclassical spin-network calculations in Loop QG (Gambini-Pullin 1999)
- Some non-commutative geometry calculations (Carroll et al. 2001)
- Some brane-world backgrounds (Burgess et al. 2002)
- Ghost condensate in EFT (Cheng, Luty, Mukohyama, Thaler 2006)

Warning: LIV can be a prediction of some QG/Emergent gravity models but it is not a general prediction due to Planck scale as minimal length (see e.g. Rovelli, Speziale 2002)

As well as from long standing problems in BH physics and QG:

- Transplanckian problem with Hawking Radiation → Condensed matter analogues of "emergent gravity" (Unruh 1981-95, Brout et al. 1995, Jacobson 1996). For more see Liv.Rev.Rel. Barceló, SL, Visser.
- Power counting renormalizability of canonical quantum gravity: Renormalization of LIV QFT (Anselmi 2007, Visser 2009), Horava-Lifshiftz (Horava 2009) ← Einstein-Aether theory (Jacobson-Mattingly 2000).

Anyway if you can test a seemingly fundamental symmetry of nature at unexplored energies, as a physicist you better do it! (Independently from what you believe!)

Modified dispersion relations

Many of the aforementioned QG models have been shown to lead to modified dispersion relations

Let's take a purely phenomenological point of view and encode the general form of Lorentz invariance violation (LIV) into the dispersion relations

$$E^2 = p^2 + m^2 + \Delta(p, M, \mu)$$

$\mu =$ some particle mass scale

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

Generally assumed rotational invariance

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

Then one can perform a momentum expansion…

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

Were $\eta^{(i)}$ are dimensionless coefficients possibly containing the small ratio $(\mu/M)^m$
The lowest order (p, p^2) terms encode a (better small!) low energy LI violation
The highest (p^3 and higher) encode high energy LIV

Picking up a framework...

Of course to efficiently cast constraints on LIV using these phenomena one needs more than just the kinematics information provided by the modified dispersion relations, one also often needs to compute reaction rates and decay times, I.e. one need a dynamical framework...

Lorentz symmetry violation

Deformed/Doubly SR paradigm

Non-critical Strings
Spacetime foam models

EFT+LV
Renormalizable, or higher dimension operators

Non-commutative spacetimes?
Finsler Geometries?
Measurement theory at E_{pl}?

Minimal Standard Model Extension
Renormalizable ops. (Low energy LIV)

E.g. QED, dim 3,4 operators

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

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

(Colladay-Kosteleky 1998)

EFT with LIV
Non-renormalizable ops, (HE LIV)

E.g. QED, dim 5 operators

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

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

(Myers-Pospelov 2003)

Why an Effective Field Theory?

Not because it *must* be true, but because

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

E.g. QED with LIV at *O(E/M)*

Let's consider all the Lorentz-violating dimension 5 terms that are quadratic in fields, gauge & rotation invariant, not reducible to lower order terms (Myers-Pospelov, 2003).

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

where $\tilde{F}$ is the dual of F and ξ, $\zeta_{1,2}$ are dimensionless parameters.

Warning: All these dim 5 LIV terms also violate CPT

NOTE: CPT violation implies Lorentz violation but LV does not imply CPT violation. "Anti-CPT" theorem (Greenberg 2002).

For E»m this ansatz leads to the following dispersion relations

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

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

electron helicities have independent LIV coefficients

photon helicities have opposite LIV coefficients

Moreover electron and positron have exchanged and opposite positive and negatives helicities LIV coefficients (Jacobson,SL,Mattingly,Stecker. 2003).

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

Note: RG studies show that the running of LV coefficients is only logarithmic: so if LIV is O(1) at $M_{\rm Pl}$ we expect it to remain so at TeV scales (Bolokhov & Pospelov, hep-ph/0703291)

"Windows" on quantum gravity

Terrestrial tests (low energy): mainly constraints on renormalizable LIV operators

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

Astrophysical tests (low energy): constraints on non-renormalizable LIV operators

- Cosmological variation of couplings
(e.g. varying fine structure constant)
- Cumulative effects in astrophysics
(e.g. color dispersion & birefringence)
- Anomalous threshold reactions
(e.g. forbidden if LI holds, e.g. gamma decay, Vacuum Cherekov)
- Shift of standard thresholds reactions (e.g. gamma absorption or GZK) with new threshold phenomenology
(e.g. 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)

For extensive review see D. Mattingly, Living Rev. Rel. 8:5,2005.

Astrophysical constraints: Time of flight

Constraint on the photon LIV coefficient ξ by using the fact that different colors will travel at different speeds. Given current data can cast constrains only on O(E/M) LIV...

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

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

Actually for cosmological distances this generalizes to: $$\Delta t \simeq \xi \frac{\Delta E}{M} \frac{1}{H_0} \int_0^z dz \frac{1+z}{\sqrt{\Omega_\Lambda + (1+z)^3 \Omega_M}}$$

Constraints of O(1) on O(E/M) LIV have been cast using time of arrival measurements on beams of light from distant sources like GRBs and AGN (FERMI,MAGIC,HESS).
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.
Ellis et al (2005): careful statistical analysis on large sample of sources of the delay-redshift correlation leads to conservative limit $|\xi|<10^3$

The EFT tackle

We have seen that QED with O(E/M) LIV has birefringence photons.
In this case unpolarized light beams will have both helicities and the net effect of slow and fast modes can cancel the above TOF effect. Indeed one gets only a bean intensity LV induced modulation (SL, Maccione. 2009)

However, being sure both photon polarization are present in the pulse, one could use the fact that opposite coefficients for photon helicities imply larger dispersion $2|\xi|p/M$ at the same energy rather than that due to different energies $\xi(p_2-p_1)/M$.
This would remove problem of source delays and roughly cut in half the current constraints but implies separate detection of opposite helicities and no spurious helicity dependent mechanism.

Astrophysical constraints: Birefringence

The birefringence constraint arises from the fact that the LV parameters for left and right circular polarized photons are opposite.

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. For a monochromatic plane wave with wave-vector k over a propagation time t

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

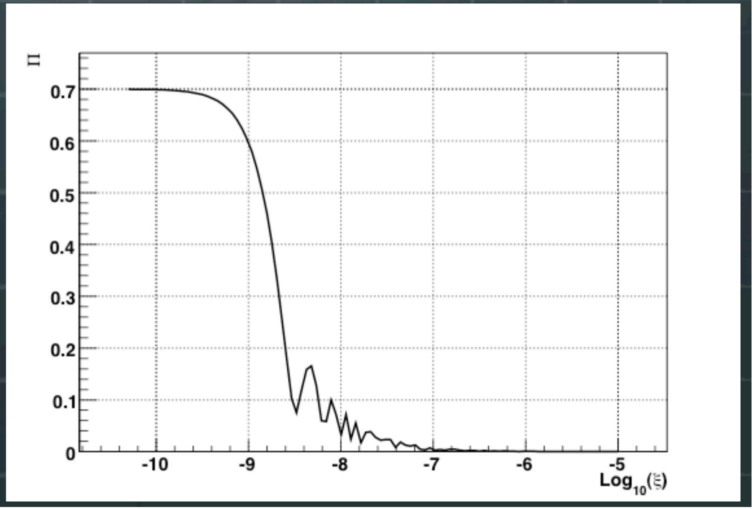
The difference in rotation angles for wave-vectors k_1 and k_2 is thus

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

The polarization is strongly reduced if this angle becomes $\Delta\theta_{12} \lesssim \pi/2$ and this condition can be used to cast a constraint.

Alternatively a more accurate way is to match the theoretical polarization Π(ξ) (Stokes parameters) to the observed one.

$$\Pi(\xi) = \sqrt{\langle \cos(2\theta) \rangle^2_{\mathcal{P}} + \langle \sin(2\theta) \rangle^2_{\mathcal{P}}},$$



Astrophysical constraints: 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

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

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	$\sim 100\ TeV$	$\sim 100\ PeV$	$\sim 3\ EeV$

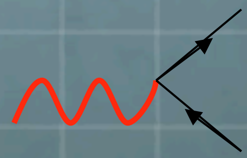
E.g. for n=3 and $m = m_{electron}$

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

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

Some LIV QED threshold reactions

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



Vacuum Cherenkov and helicity decay $e^{\pm} \rightarrow \gamma + e^{\pm}$

- The reaction can preserve or not the helicity of the lepton.
- First case called Vacuum Cherenkov, second case called helicity decay.

Vacuum Cherenkov

Requires: $v_e > c$
Threshold energy

Helicity decay

Requires unequal $\eta_{\pm}$.
No threshold energy but "effective threshold" due to small reaction rate below energy comparable to Cherenkov threshold

Photon absorption $\gamma\gamma_0 \rightarrow e^{+} + e^{-}$

- Well know reaction in HE astrophysics.
- LIV shift threshold and creates possibility for upper threshold
- Big uncertainties from IR background and primary spectrum of AGN.
- Much stronger constraints obtained from UHECR physics…

Astrophysical constraints: Synchrotron radiation

Jacobson, SL, Mattingly: Nature 424, 1019 (2003)
Ellis et al. Astropart.Phys.20:669-682,(2004)
R. Montemayor, L.F. Urrutia: Phys.Lett.B606:86-94 (2005)
Maccione,SL, Celotti, Kirk. JCAP 10, 013 (2007)

LI synchrotron critical frequency:

$$\omega_c^{LI} = \frac{3}{2}\frac{eB\gamma^2}{m}$$

e - electron charge
m - electron mass
B - magnetic field

However a proper analysis requires a detailed re-derivation of the synchrotron effect with LIV based on EFT. Let's take QED with O(E/M) LIV.

This leads to a modified formula for the peak frequency:

$$\omega_c^{LIV} = \frac{3}{2}\frac{eB}{E}\gamma^3$$

While the rate of energy loss differs from the LV one only nearby the VC threshold...

Now:

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

η<0

γ is a bounded function of E. There is now a maximum achievable synchrotron frequency ω^{max} for ALL electrons!

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

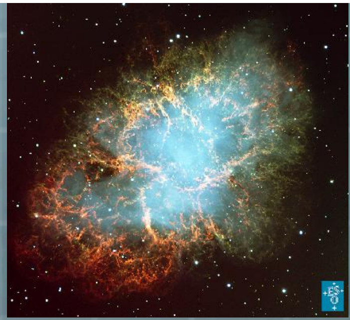
η>0

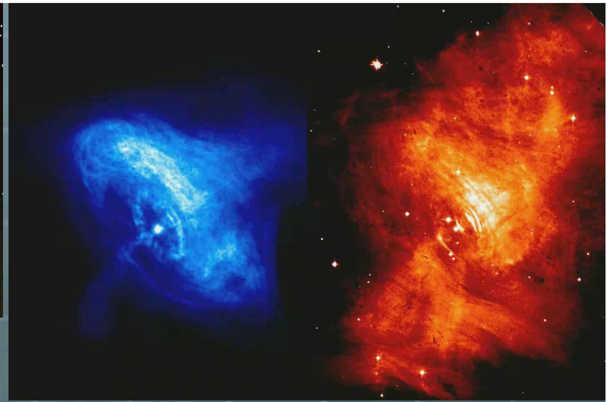
γ diverges as p_{th} is approached. This is unphysical as also the energy loss rates diverges in this limit, however signifies a rapid decay of the electron energy and a violent phase of synchrotron radiation wich becomes vacuum Cherenkov.

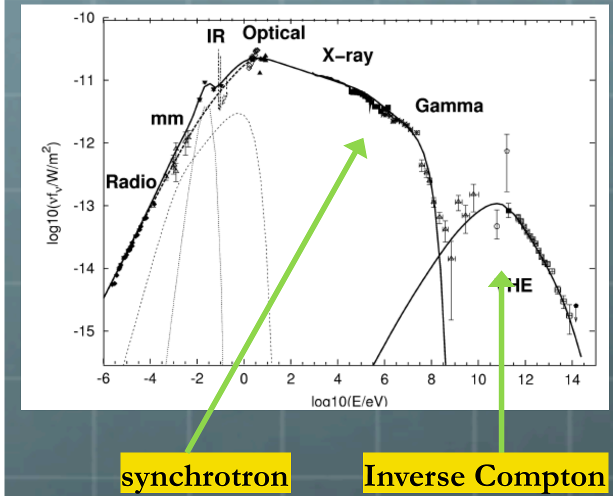
What is then the best studied synching astrophysical object?

Constraints on QED with LIV O(E/M)

L.Maccione, SL, A.Celotti and J.G.Kirk: JCAP 0710 013 (2007)
L.Maccione, SL, A.Celotti and J.G.Kirk, P. Ubertini:Phys.Rev.D78:103003 (2008)







The Crab nebula a supernova remnant (1054 A.D.) distance ~1.9 kpc from Earth.

Spectrum (and other SNR) well explained by synchrotron self-Compton (SSC) model

1. Electrons are accelerated to very high energies at pulsar: in LI QED $\gamma_e \approx 10^9 \div 10^{10}$
2. High energy electrons emit synchrotron radiation
3. Synchrotron photons undergo inverse Compton with the high energy electrons

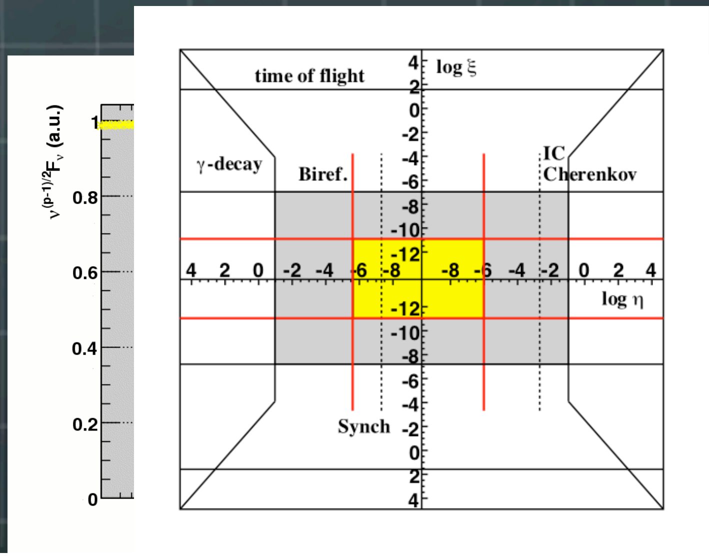
The Crab nebula alone has provided so far the best constraints on dim 5 LIV in QED. Currently the best two test come from: the measurement of the spectrum and polarization of Crab synchrotron emission.

The synchrotron spectrum is strongly affected by LIV: maximum gamma factor for subliminal leptons and vacuum Cherekov limit for superluminal ones (there are both electrons and positrons and they have opposite η).
Spectrum very well know via EGRET, now AGILE+FERMI

The polarization of the synchrotron spectrum is strongly affected by LIV: there is a rotation of the angle of linear polarization with different rates at different energies. Strong, LIV induced, depolarization effect.

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

Polarization recently accurately measured by INTEGRAL mission: 40±3% linear polarization in the 100 keV - 1 MeV band + angle θ_{obs}= (123±1.5)° from the North



An open problem: un-naturalness of small LV in EFT

Dim 3,4 operators are tightly constrained: $O(10^{-46})$, $O(10^{-27})$. This is why much attention was focused on dim 5 and higher operators (which are already Planck suppressed).

However

- if one postulates classically a dispersion relation with only naively (no anisotropic scaling) non-renormalizable operators (i.e. terms $\eta^{(n)}p^n/M_{Pl}^{n-2}$ with $n\geq3$ and $\eta^{(n)}\approx O(1)$ in disp.rel.)
- then radiative (loop) corrections involve integration up to the natural cutoff M_{Pl} will generate the terms associated to renormalizable operators ($\eta^{(1)}pM_{Pl}$,$\eta^{(2)}p^2$) which are unacceptable observationally if $\eta^{(1,2)}\approx O(1)$.
- Roughly the generated coefficients $\eta^{(1)}$, $\eta^{(2)}$ are of order one because the M_{Pl}^{n-2} suppression is cancelled by the integration cutoff which is again M_{Pl}

[Collins et al. PRL93 (2004)]

NOTE: this is common to all QG models with LV which do admit a low energy EFT description!
(e.g. Horava gravity. Iengo,Russo, Serone 2009)
This is THE problem with UV Lorentz breaking

As usual, this need not be the case if a custodial symmetry or other mechanism protects the lower dimensions operators from violations of Lorentz symmetry: you need another scale other from E_{LIV} (which we have so far assumed $O(M_{Pl})$)

E.g. SUSY protect dim<5 operators but when SUSY broken leads to too large renormalizable ops.
However CPT+SUSY push allowed operators to dim 6... when SUSY broken $\eta^{(4)}\approx O(E_{SUSY}/M)^2$
E.g. gr-qc/0402028 (Myers-Pospelov) or hep-ph/0404271 (Nibblink-Pospelov) or gr-qc/0504019 (Jain-Ralston),
SUSY QED:hep-ph/0505029 (Bolokhov, Nibblink-Pospelov)

It is also possible to study a 2BEC analogue model of gravity: in this case calculation from microphysics shows suppression of the lowest order $\eta^{(2)}$ induced LIV coefficient due to a similar mechanism.
Something else to learn from Analogue Models?
[SL, Visser, Weinfurtner. PRL96 (2006)]

Constraints on dim 6 LV QED in EFT O(E²/M²)

Galaverni, Sigl, arXiv:0708.1737. PRL
Maccione, SL, arXiv:0805.2548. JCAP

Lets' look then at QED with dim 6 Lorentz violating Operators

$$\begin{aligned} \omega^2 &= k^2 + \xi\, k^4/M_{\rm Pl}^2 \\ E_\pm^2 &= p^2 + m_e^2 + \eta_\pm\, p^4/M_{\rm Pl}^2 \\ \text{where} \quad \pm &= \text{opposite helicity states} \end{aligned}$$

In this case we need ultra high energies: p_{crit} for e^-~100 PeV

Cosmic Rays Photo pion production:
The Greisen-Zatsepin-Kuzmin effect

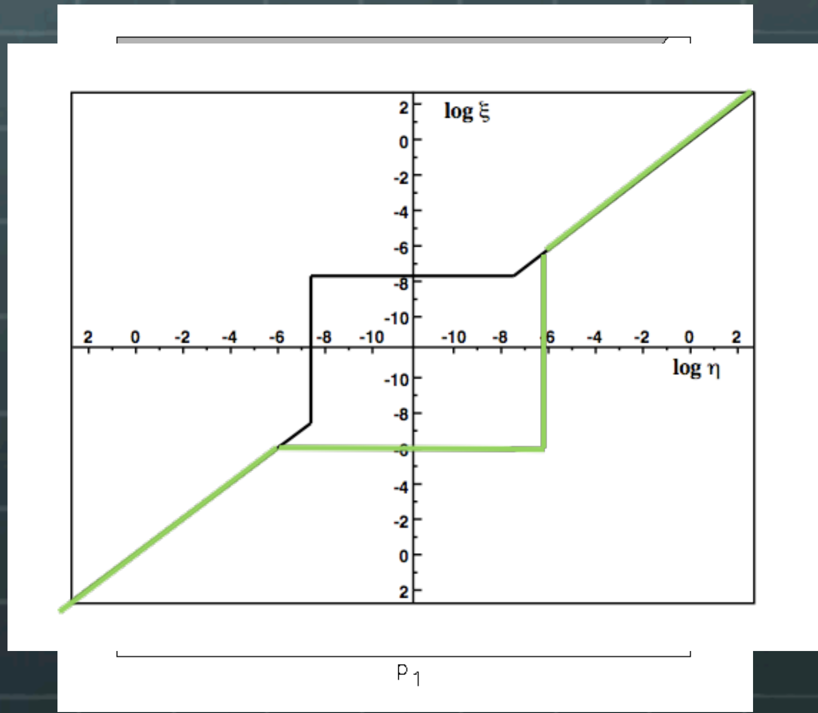
$$p + \gamma \to p + \pi^0 (n + \pi^+) \quad E_{\rm th} = \frac{2 m_p m_\pi + m_\pi^2}{4\epsilon} \sim 4 \cdot 10^{19}\ {\rm eV}$$

GZK photons are pair produced by the decay of π⁰s produced in GZK process

The Greisen-Zatsepin-Kuzmin effect: secondary production $p + \gamma \to N + \pi$, with $\pi^0 \to \gamma\gamma$ and $\pi^\pm \to \mu\nu_\mu \to e\,\nu_\mu\bar{\nu}_\mu\nu_e$

- In LI theory UHE gamma rays are attenuated mainly by pair production: $\gamma\gamma_0 \to e^+e^-$ onto CMB and URB (Universal radio Background) leading to a theoretically expected photon fraction < 1% at 10^{19} eV and < 10% at 10^{20} eV.
- Present limits on photon fraction: 2.0%, 5.1%, 31%, 36% (95% CL) at 10, 20, 40, 100 EeV from AUGER

- LIV strongly affects the threshold of this process: *lower and also upper thresholds.*
- *If $k_{up} < 10^{20}$ eV then photon fraction in UHECR much larger than present upper limits*
- *LIV also introduces competitive processes: γ-decay*
- *If photons above 10^{19} eV are detected then γ-decay threshold > 10^{19} eV*



Going further…

Hadronic sector dim 6 LIV (CPT even) ops constraints using UHECR

Theoretical reconstruction of Ultra High Energy Cosmic Rays spectrum in a EFT with dim 6 operators and confront with data

$$
\begin{aligned}
-10^{-3} &\lesssim \eta_p \lesssim 10^{-6} \\
-10^{-3} &\lesssim \eta_\pi \lesssim 10^{-1} \qquad (\eta_p > 0) \\
&\lesssim 10^{-6} \qquad (\eta_p < 0)\ .
\end{aligned}
$$

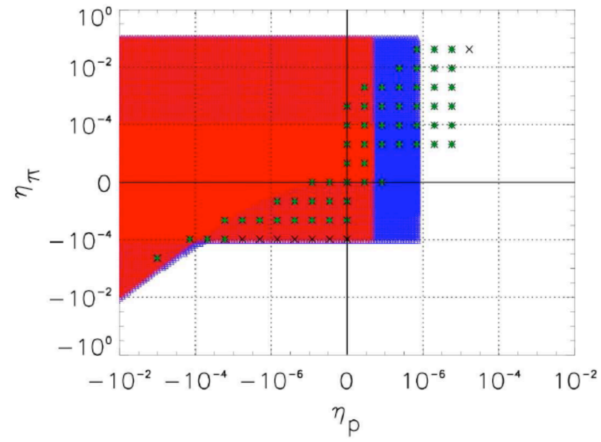


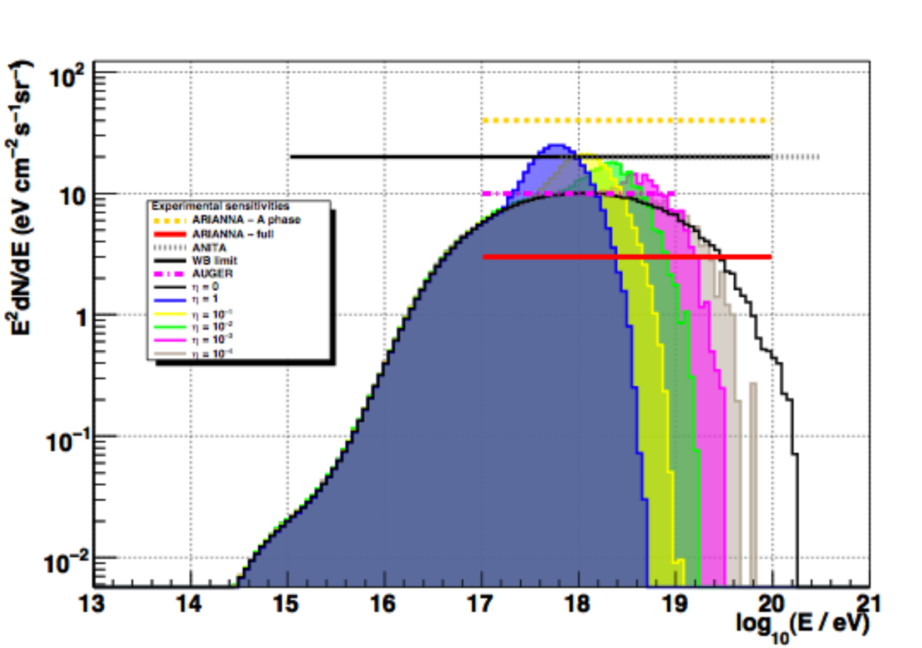
Figure 4. This plot shows the (η_p,η_π) parameter space allowed by different UHECR observations. The red and blue shaded regions corresponds to the portion of parameter space for which the energy threshold for VC emission is higher than, respectively, $10^{20.25}$ eV and $10^{19.95}$ eV, so that it does not conflict with PAO observations. The green circles and black crosses corresponds respectively to points in the parameter space for which LV effects in the UHECR spectrum are still in agreement with experimental data. They correspond respectively to an agreement with data within 2σ and 3σ CL.

Neutrinos dim 6 LIV ops constraints using cosmogenic neutrinos

ν-splitting : $\nu \to \nu\nu\bar{\nu}$.

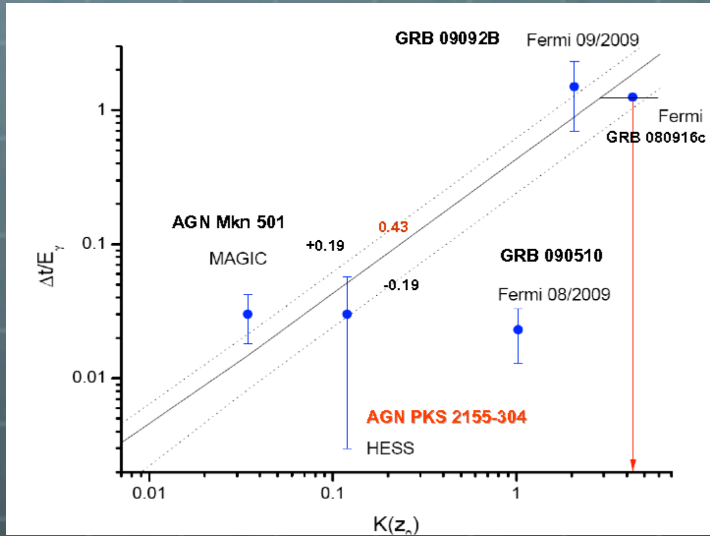
For positive O(1) coefficients no neutrino will survive above 10^{19} eV. The existence of this cutoff generates a bump in the neutrino spectrum at energies of 10^{17} eV and depression at UHE.

Experiments in construction or being planned have the potential to cast limits as strong as $\eta<10^{-4}$ on the neutrino LV parameter, depending on how LV is distributed among neutrino mass states.



UHE photons and LV in space-time foam

Currents status of Time of Flight Constraints:
Coburn et al. using GRB021206: $|\xi|<55$ ($z\approx 0.3$).
Magic Coll+Ellis et al. (2007) using Markarian 501 flares, $z\approx 0.034$, $\xi<47$.
HESS has also observed at another AGN flares (PKS 2155, z=0.116)
FERMI Collaboration GRB080916C and GRB 090510: $\xi<0.8$



Intriguing suggestion:
Observed time-delays can be explained by LV effects with $\xi\approx 0.4$!!!
(Disclaimer: standard physical processes in the sources can explain the observed delays. Furthermore, FERMI GRB 090510 seems to require hypothesis of redshift dependence of the LIV effect.
Ellis et al, arXiv:0912.3428, but see also Amelino-Camelia and Smolin, PRD 80 (2009)

However we have already seen that within EFT we have already much tighter constraints from birefringence: $|\xi|\leq O(10^{-10})$!!!
Is there an alternative model of LV which escapes these tight bounds?

Spacetime foam models

QG medium as oscillators that absorb and emit photons. Oscillators are D-particles flashing in the space-time
Photon absorption and re-emission: The D-particle recoils. D-particles are neutral: charged particles do not feel their presence.

Ellis, Mavromatos, Nanopoulos, Phys. Lett. B, 293 (1992),Amelino-Camelia et al., Int. J. Mod. Phys. 12, 3 (1997)
Ellis et al, Phys. Rev. D 63 (2001), Ellis et al, Int. J. Mod. Phys. A 19 (2004),Ellis et al, Phys. Lett. B 665 (2008)
Li et al, Phys. Lett. B 679 (2009),Ellis et al, arXiv:0912.3428v1, Ellis et al, arXiv:1004.4167v1

Consequences:
LV only for on-shell photons (and Majorana neutrinos)
Photons are delayed and acquire an effective modified dispersion relation
Note: no birefringence, no gamma decay…

$$E_\gamma^2 = p^2 - \xi\frac{p^3}{M} \qquad \text{with } \xi > 0$$

Constraining Space-time foam models

Can we test spacetime foam models in some other way different from TOF observations?

Yes. Via UHE gamma rays pair production!

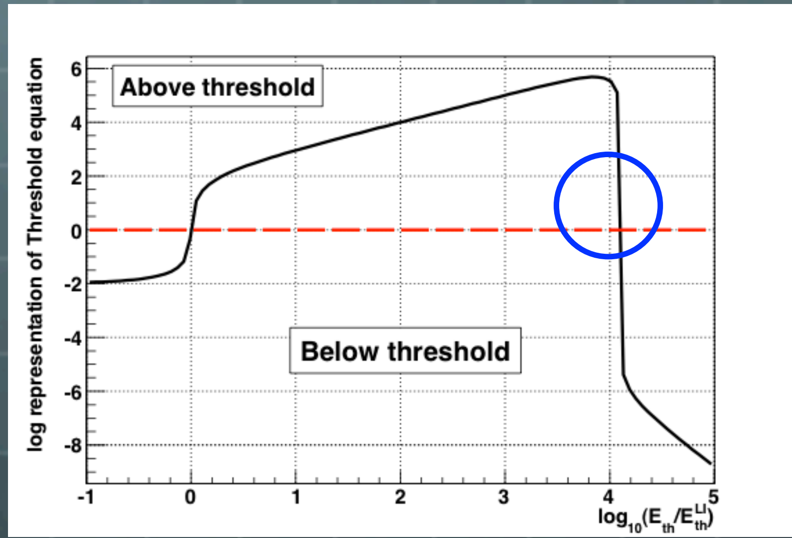
Maccione, SL, Sigl, Phys. Rev. Lett. 105, 2010

In case D-particles have a bulk recoiling motion which does not average to zero, the background metric is modified and energy non-conservation during interaction is possible: one can effectively "encode" this by introducing a new parameter ξ_I associated to deviation from exact energy conservation in an interaction.

$$E_1 + \omega = E_2 + E_3 + \delta E_D \qquad x \equiv \frac{E_{\rm th}}{M}$$

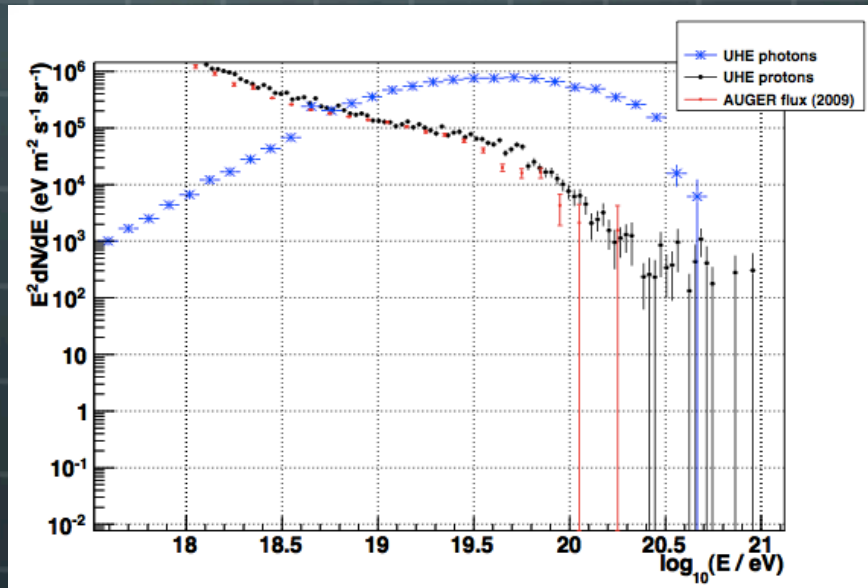
$$p_1 - \omega = p_2 + p_3$$

$$-\frac{\xi_I + \xi/2}{2} x^3 + 2\frac{\omega}{M}x - 2\frac{m_e^2}{M^2} + \cdots = 0$$



Hence pair production is modified by LV even in the case of space time foam models (including redshift dependence of D-particles) and we can again cast a constraint by the absence of an upper threshold…

$$\xi/2 + \xi_I \lesssim 10^{-12}$$



Note however that this constraint can be evaded by alternative spacetime foam models, See Ellis et al, arXiv:1004.4167

Caveat: A potential problem with the UHECR data?

- With improved statistic the correlated UHECR-AGN events have decreased from 70% to 40%: large deflections?
- With increased statistics the composition of UHECR beyond 10^{19} eV seems more and more dominated by iron ions rather than protons.
- Ions do photodisintegration rather than the GZK reaction, this may generate much less protons which are able to create pions via GZK and hence UHE photons.

Gist: This might reopen in a near future the games for the p^4/M^2 LIV!

However…

Astro-ph [HE]:1007.1306, D. Hooper, A. Taylor, S.Sarkar

They find the flux of UHE-photons is just suppressed by one order of magnitude.

LIV effects would increase the flux by about four orders… perhaps we are safe.

Further data/study needed…

Testing Lorentz violations: end of the story?

- QG phenomenology of Lorentz and CPT violations is a a success story in physics. We have gone in few years (1997->2010) from almost no tests to tight, robust constraints on EFT models and some spacetime foam models.
- In summary for EFT with LIV:
  - QED: up to $O(10^{-22})$ on dim 4, up to $O(10^{-11})$ on dim 5 op and up to $O(10^{-7})$ on dim 6 op
  - Hadronic sector : up to $O(10^{-46})$ on dim 3, $O(10^{-27})$ on dim 4, $O(10^{-14})$ on dim 5, up to $O(10^{-6})$ on dim 6 op
  - Neutrinos: up to $O(10^{-28})$ on dim 4, $O(10^{-14})$ on dim 5, expected up to $O(10^{-4})$ on dim 6 op
- Chances are high that improving observations in HE astrophysics will strengthen these constraints in a near future...
- If there is Lorentz violation its scales seems required to be well beyond the Planck scale....

Should we conclude that we have deviations from Special Relativity enough?
Mission Accomplished?

Not quite...

Local Lorentz Invariance in emergent/quantum Spacetimes

Lorentz violation vs Relativity Violation

Lorentz breaking is not one to one with relativity breaking.

W. von Ignatowsky theorem (1911):
- Principle of relativity => group structure
- Homogeneity => linearity of the transformations
- Isotropy => Riemannian structure (no Finsler)
- Precausality => time ordering

→ Lorentz transformations with unfixed limit speed C

$C=\infty$ \ Galileo

$C=c_{light}$ \ Lorentz

Can we preserve the relativity principle but give up some of the other postulates?

- **Isotropy:** in 1+1 it is possible to give up kinematical isotropy (opposite direction boosts are not equivalent) and still get a relativity group with same number of generators but Finslerian invariant line element (Sonego-Pin 2008). In 3+1 one does not have same number of generators but still exists subgroup with Finslerian line element -> Very Special Relativity (Bogoslovsky (1999), Cohen-Glashow (2006), Gibbons et al. (2007)).
- **Precausality:** too messy to give it up!
- **Homogeneity:** implies both linearity of transformations but also the directly related to affine structure → Differentiability.

What it might be a manifold that locally is not differentiable? Fractal/stochastic structure at the Planck scale? NC geometries?

A possible alternative?

Let's imagine that zooming on a small patch of spacetime with discrete underlying structure: one would progressively give up
- Homogeneity? → Non-linear transformations?
- Translation invariance? → Non-trivial composition of momenta?

Alternatively (Rovelli 2008)

$h \to 0$ $G_N \to 0$ but $M_P^2 = h/G_N$ = constant. Is this regime described by standard Special Relativity?

Perhaps it depends if there are physical phenomena sensitive to the h/G_N ratio

→ DSR?

Deformed/Doubly Special Relativity

Can we preserve the relativity principle but introduce a new invariant (ie. Obs independent) scale? (Amelino-Camelia, 2000)

To do so one does not change at all the Lorentz group $[L_i, L_j] = \mathrm{i}\,\epsilon_{ijk}\, L_k\,; \qquad [L_i, B_j] = \mathrm{i}\,\epsilon_{ijk}\, B_k\,; \qquad [B_i, B_j] = -\mathrm{i}\,\epsilon_{ijk}\, L_k$

L=rotations generators B=Boosts generators

but conjectures a non-trivial action on the momenta induce by energy scale κ

These commutation relations are given in terms of three unspecified, dimensionless structure functions f_1,f_2 and f_3, and are sufficiently general to include all known DSR proposals. For $f_1,f_2 \to 1$ and $f_3 \to$ finite for $\kappa \to +\infty$ one recovers standard SR. In order to preserve rotational invariance it is generally assumed that $f_i\left(\frac{P}{\kappa}\right) \to f_i\left(\frac{P_0}{\kappa}, \frac{\sum_{i=1}^{3} P_i^2}{\kappa^2}\right)$

$$[L_i, P_0] = 0\,; \qquad [L_i, P_j] = \mathrm{i}\,\epsilon_{ijk}\, P_k\,;$$

$$[B_i, P_0] = \mathrm{i}\, f_1\left(\frac{P}{\kappa}\right) P_i\,;$$

$$[B_i, P_j] = \mathrm{i}\left[\delta_{ij}\, f_2\left(\frac{P}{\kappa}\right) P_0 + f_3\left(\frac{P}{\kappa}\right)\frac{P_i\, P_j}{\kappa}\right].$$

$$[P_i, P_j] = 0\,.$$

Noticeably something like this can be recover in some specific model (Lie-type) of non-commutative geometry. Namely κ-Minkowski (see Kowalski-Glikman 2004 for review) $[X_0, X_i] = -\frac{i}{\kappa} X_i$

In all the DSR theories the physical energy and momentum can be expressed as nonlinear function of some (fictitious?) one-form π_μ whose components transform linearly under the action of the Lorentz group. The mapping saturates at the Planck scale κ as π_0 and/or π_1 go to infinity.

E.g. In DSR2, the specific DSR model developed by Magueijo and Smolin (2002): $E = \frac{-\pi_0}{1-\pi_0/\kappa} \qquad p_i = \frac{\pi_i}{1-\pi_0/\kappa}$

$\pi_0^2 - \boldsymbol{\pi}^2 = \mu_0^2$ ⇒ $\left(1 - \mu_0^2/\kappa^2\right) E^2 + 2\,\kappa^{-1}\,\mu_0^2\, E - \boldsymbol{p}^2 = \mu_0^2$ New Casimir if algebra as before with $f_1=(1-P_0/\kappa)$, $f_2=1$, $f_3=1$

Open issues:

- Still miss coordinate space formulation so far. No DSR QFT.
- In momentum space, the so called "soccer ball problem": saturation of E or p at the Planck scale
- Heated debate on possibly large non-locality if DSR lead to energy dependent speed of light (Hossenfelder, Amelino-Camelia, Smolin 2010)

A special relation: Emergent gravity and Lorentz Violation

"No spin 2 particle can be emergent if you have Lorentz invariance (you live in Minkowski) and Gauge invariant currents or conserved SET"

Hence possible ways out are:

1. Emerge everything at once (possibly 2d→4d?)
2. Emerge manifold with flat metric and primitive fields first then gravity

Conjecture: in case 2 Lorentz invariance has most probably to be emergent as well like in analogue models.
However this does not imply necessarily Galiean physics in the UV.
Lorentz→Lorentz (different limit speed) or Lorentz→Euclidean Poincarè?
Examples form Analogue models: See e.g. relativistic BEC.
S.Fagnocchi, S. Finazzi, SL, M. Kormos, A. Trombettoni: To appear in New. J. Phys.
Emergent Lorentzian signature and Nordstrom gravity+matter: Girelli, SL, Sindoni PRD 2008.

What else should emerge?

Metric theories of gravity rest on two funding principles

- Einstein equivalence principle: i.e. WEP+LLI+LPI
- Diffeomorphism invariance

What about diffeo invariance?

Emergent diffeomorphism invariance ? A pro argument

Diffeo Inv →Noether Charge → Horizon Entropy (Wald)→ Thermodynamical behaviour again?
If fundamental theory is Diffeo invariance (a' la GR, i.e. background independence) then isn't it another gravity theory?

Conjecture: if a pseudo-Riemannian manifold (M,g) is emergent then Lorentz and Diffeomorphism invariance have most probably to be both emergent at the same time

Shouldn't we then start looking systematically for phenomenological constraints of diffeo breaking?

E.g. Donoghue et al (gr-qc:0911.4123)

Conclusions

◈ It is indeed possible to constrain QG models predicting LIV with high energy astrophysics observations.

◈ Tight constraints have been cast on both (naively) renormalizable and non-renormalizable LIV operators in EFT (which includes some NC geometry proposals)

◈ The LIV Naturalness problem is a crucial open issue, custodial symmetry? Microphysics (beyond EFT) explanation?

◈ Eventual detection of TOF delays (FERMI) would signify that QG LIV does not admit an EFT description at low energies! Crucial insight?
Most probably there is an astrophysical explanation. Furthermore some spacetime foam models are already constrained…

◈ Basically no constraints have be cast so far on DSR models given their premature stage of development…

◈ It is perhaps time to be more specific about the models we are trying to constrain: e.g. emergent gravity proposals seems to have generic signatures which go beyond LV breaking at high energy… this is an appeal to anybody doing QG/EG theories…

Measure what is measurable, and make measurable what is not so.
Galileo Galilei