Lorentz breaking effective field theories: phenomenology and constraints

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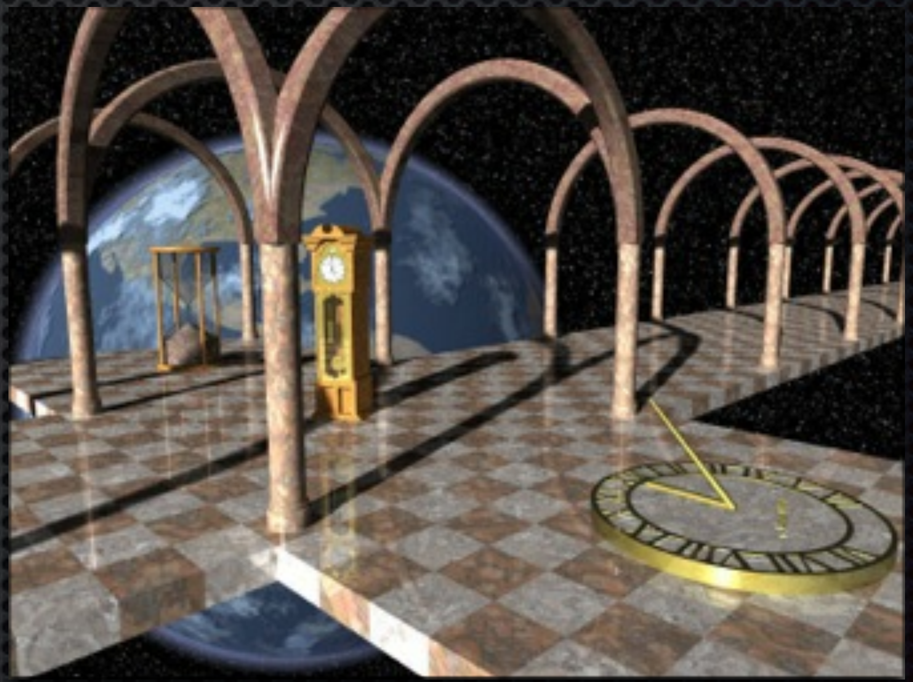
The quest for QG phenomenology

Old "dogma": you shall not access any quantum gravity effect as this would require experiments at the Planck scale!
This has changed in the last decade, e.g.

- Loss of quantum coherence or state collapse
- QG imprints on initial cosmological perturbations - BICEP2!
- Extra dimensions and low-scale QG (LHC BH) : Mp
- Modified Uncertainty principle tests
- Planck scale spacetime fuzziness tests
- Violation of discrete symmetries tests
- Violation of spacetime symmetries tests



We shall focus here on the last item.
More precisely on tests of Local Lorentz invariance
Why?

- Lorentz invariance is assumed to be a fundamental symmetry of nature. It is rooted via the equivalence principle in GR and it is a fundamental pillar of the SM.
- The more fundamental is an ingredient of your theory the more needs to be tested observationally.
- This is one of the few cases in which our sensitivity can constraints new physics at the Planck scale, so test of Lorentz invariance can be used to rule out QG models: Lorentz violations tests are so far the best example of QG phenomenology.

History of a heresy

Is there an Aether? (Dirac, 1951)

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)

Non-critical string spacetime foam models (Ellis, Mavromatos & Nanopoulos, 1992)

LV Dispersion & Hawking radiation (Unruh, 1994, Brout-Massar-Parentani-Spindel 1995)

Possibilities of LV phenomenology (Gonzalez-Mestres, 1995)

"Minimal Standard model extension" & experimental limits (Colladay & Kostelecky, 1997 & many experimenters)

GRB photon dispersion limits at the Planck scale (Amelino-Camelia et al, 1997)

Coleman-Glashow test theory (manageable subcase of SME) (Coleman & Glashow, 1997-8)

Trans-GZK events? (AGASA collab. 1998). Many investigations (Aloisio et al 2000, Amelino-Camelia et al 2002-3, ...)

TeV gamma ray crisis? (Protheroe & Mayer 2000)

Einstein-Aether gravity (Jacobson-Mattingly 2000)

Doubly/Deformed Special Relativity (Amelino-Camelia 2002)

"Standard Model Extensions" beyond renorm. Ops. (Myers-Pospelov 2003, JLM 2003-4).

Horava-Lifshiftz Gravity (Horava 2009, ...)

Giordano Bruno Monument - Rome

Breaking Local Lorentz Invariance?

W. von Ignatowsky theorem (1911):
Principle of relativity ➔ group structure
Homogeneity ➔ linearity of the transformations
Isotropy ➔ rotational invariance and Riemannian structure
Precausality ➔ observer independence of co-local time ordering

Lorentz transformations with unfixed limit speed C
$C=\infty$ ➔ Galileo
$C=c_{light}$ ➔ Lorentz
Experiments determine C!

Breaking Bad (please one breaking at a time)

Break Precausality ➔ Hell breaks loose, better not!

Break Principle of relativity ➔ Preferred frame, Modified dispersion relations

Break kinematical Isotropy ➔ Finsler geometries. True geometry on the phase space.
E.g. Very Special Relativity (Glashow, Gibbons et al.). Possible link with Relative Locality?

Break Homogeneity ➔ tantamount to give up operative meaning of coordinates. Breaking the underlying assumption of euclidean space locally used to start posing von Ingnatovski theorem.

Let's start relaxing the Relativity Principle…

Picking up a framework...

Missing a definitive QG candidate able to provide definitive sub-Planckian predictions different general dynamical framework have been proposed
Many of the aforementioned QG models have been shown to lead to modified dispersion relations but we need also a dynamical framework

Frameworks for preferred frame effects

EFT+LV

Non EFT proposals:
Non-critical Strings
Spacetime foam models

Minimal Standard Model Extension
Dim 3-4 ops.
(IR LIV - LI SSB)

EFT with LIV
Dim 5-6, ops.
(UV LIV – QG inspired LIV)

E.g. QED, rot. Inv. 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)

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)

For extensive review see D. Mattingly, Living Rev. Rel. 8:5,2005.
S. Liberati. Topic Review CQG (2013)

LIV phenomenology in Matter: A Tooolkit

Terrestrial tests:

Penning traps
Clock comparison experiments
Cavity experiments
Spin polarized torsion balance
Neutral mesons
Anti-Hydrogen
Slow atoms recoils

Astrophysical tests:

Cosmological variation of couplings, CMB
Cumulative effects in astrophysics
Anomalous threshold reactions
Shift of standard thresholds reactions with new threshold phenomenology
LV induced decays not characterized by a threshold
Reactions affected by "speeds limits"

This wealth of tests already severely constraints the Minimal Standard Model extension (dim 3,4 ops, boost and rot breaking):

QED: up to O(10^{-22}) on dim 4,
Hadronic sector : up to O(10^{-46}) on dim 3, O(10^{-27}) on dim 4.
Neutrinos: up to O(10^{-28}) on dim 4 from neutrino oscillations

Hence we shall in what follow consider the higher order LIV operators mass dimension 5 and 6 and hence mainly Astrophysical/Cosmological constraints…

Mass Dimension 5, CPT odd LIV QED

NOTE: CPT violation implies Lorentz violation but LV does not imply CPT violation.
"Anti-CPT" theorem (Greenberg 2002).
So one can catalogue LIV by behaviour under CPT
NOTE 2: The above statement is true only for local EFT (Chaichian et al. 2012)

Let's consider all the Lorentz-violating dimension 5 CPT odd 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.

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

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

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

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	-η-	-η+

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

Mass Dimension 5-6, CPT even LIV QED

Lets' look then at QED with dim 5-6 CPT even Lorentz violating Operators

$$-\frac{1}{2M_{\rm Pl}^2}\beta_\gamma^{(6)}F^{\mu\nu}u_\mu u^\sigma(u\cdot\partial)F_{\sigma\nu}$$

$$-\frac{1}{M_{\rm Pl}}\overline{\psi}(u\cdot D)^2(\alpha_L^{(5)}P_L+\alpha_R^{(5)}P_R)\psi-\frac{i}{M_{\rm Pl}^2}\overline{\psi}(u\cdot D)^3(u\cdot\gamma)(\alpha_L^{(6)}P_L+\alpha_R^{(6)}P_R)\psi-\frac{i}{M_{\rm Pl}^2}\overline{\psi}(u\cdot D)\Box(u\cdot\gamma)(\tilde{\alpha}_L^{(6)}P_L+\tilde{\alpha}_R^{(6)}P_R)\psi$$

$$E^2-p^2-m^2=\frac{\alpha_R^{(6)}E^3}{M_{\rm Planck}^2}(E+sp)+\frac{\alpha_L^{(6)}E^3}{M_{\rm Pl}^2}(E-sp)+\frac{m}{M_{\rm Pl}}(\alpha_R^{(5)}+\alpha_L^{(5)})p^2+\alpha_R^{(5)}\alpha_L^{(5)}\frac{p^4}{M_{\rm Pl}^2}$$

$$\omega^2-k^2=\beta^{(6)}\frac{k^4}{M_{\rm Pl}^2}\,,$$

For E»m this ansatz leads to the following dispersion relations. Note that there is a naturally suppressed p^2 coefficient…

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

Note: no birefringence Favoured theoretically if one requires QG CPT even

Again electron and positron have exchanged and opposite positive and negatives helicities LIV coefficients but without minus sign.

	Positive helicity	Negative helicity
Electron	η+	η-
Positron	η-	η+

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

[Collins et al. PRL93 (2004), Lifshitz theories (anisotropic scaling): Iengo, Russo, Serone (2009)]

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 $n \geq 3$ 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 ($\eta^{(1)} p M_{Pl}, \eta^{(2)} p^2$) which are unacceptable observationally if $\eta^{(1,2)} \approx O(1)$.

This is THE main problem with UV Lorentz breaking!

Three main Ways out

Gravitational confinement

Assume only gravity LIV with $M_{LIV} \ll M_{PL}$, then percolation into the (constrained) matter sector is suppressed by smallness of coupling constant GN.

E.g. Horava gravity coupled to LI Standard Model: Pospelov & Shang arXiv.org/1010.5249v2

Custodial symmetry

One needs another scale other from E_{LIV} (which we have so far assumed $O(M_{Pl})$.
So far main candidate SUSY but needs ESUSY not too high.

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). See also Pujolas-Sibiryakov (arXiv:1109.4495) for SUSY Einstein-Aether gravity.

Improved RG flow at HE

Models with strong coupling at high energies improving RG flow a la Nielsen [G.Bednik, O.Pujolàs, S.Sibiryakov, JHEP 1311 (2013) 064]

But let's see what we can say "order by order" for the moment…

Main constraint routes from HE Astrophysics

- Time of Flight constraints.

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

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

- Birefringence (only for CPT odd EM-LIV like dim 5 ops).

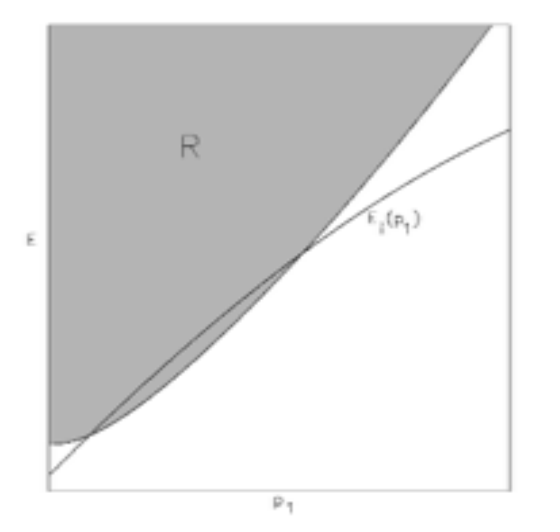
$$\theta(t) = [\omega_+ - \omega_-(k)]\, t/2 = \xi k^2 t/2M$$

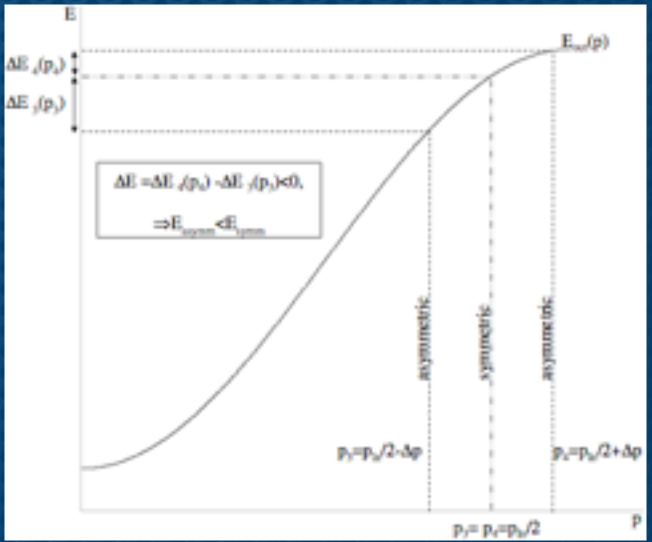
$$\Delta\theta = \xi \left(k_2^2 - k_1^2\right) d/2M, \quad \text{(where } d = \text{distance source-detector)}$$

- Threshold reactions

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

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



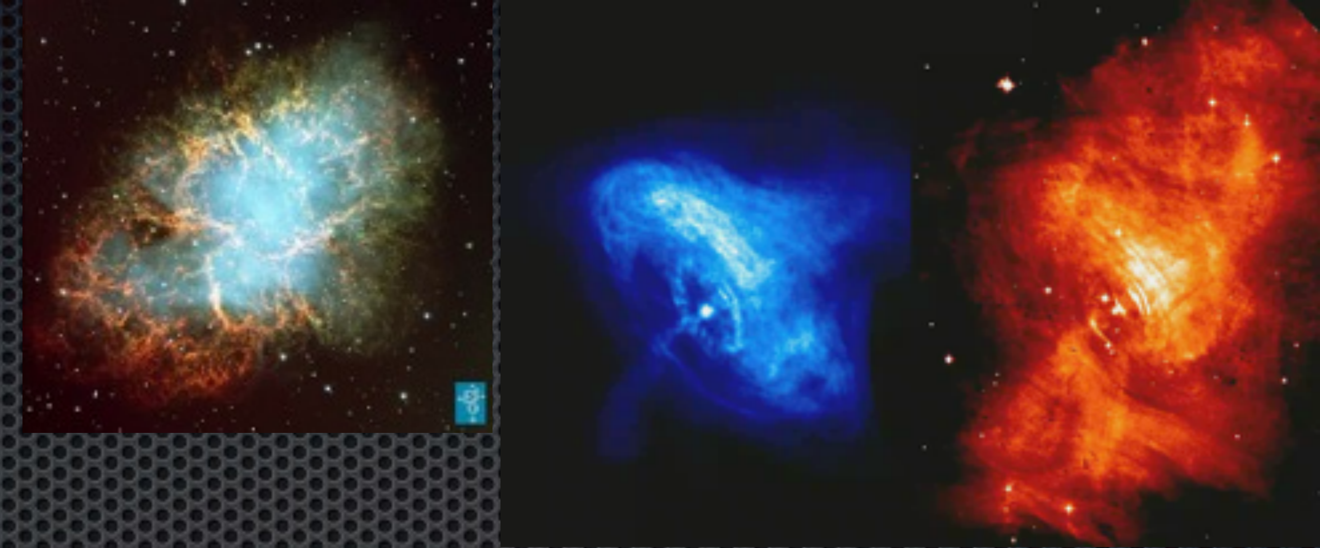


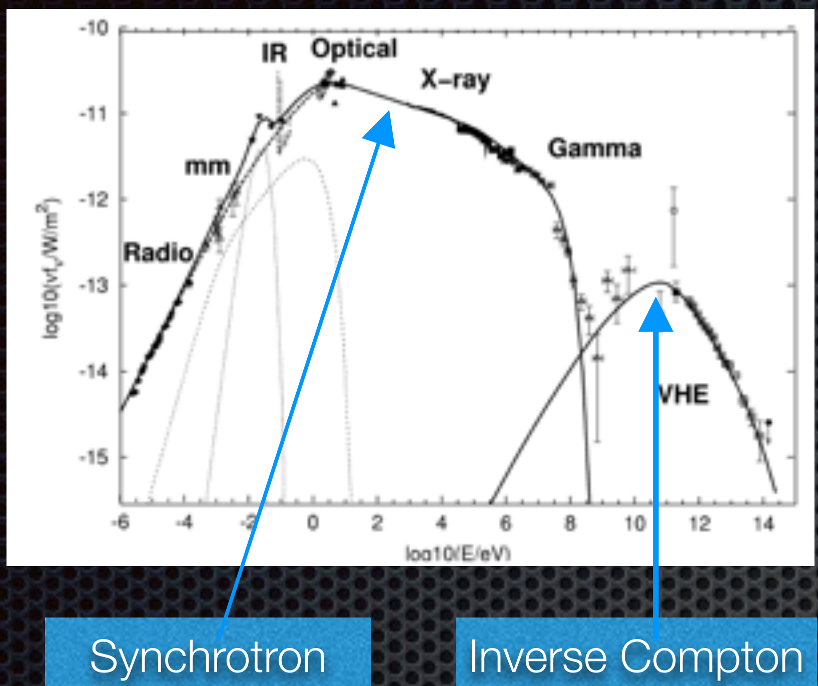
- Synchrotron

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

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

Constraints on QED
dim 5 CPT Odd QED extension





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)
Electrons are accelerated to very high energies at pulsar: in LI QED γe≈109÷1010
High energy electrons emit synchrotron radiation
Synchrotron photons undergo inverse Compton with the high energy electrons

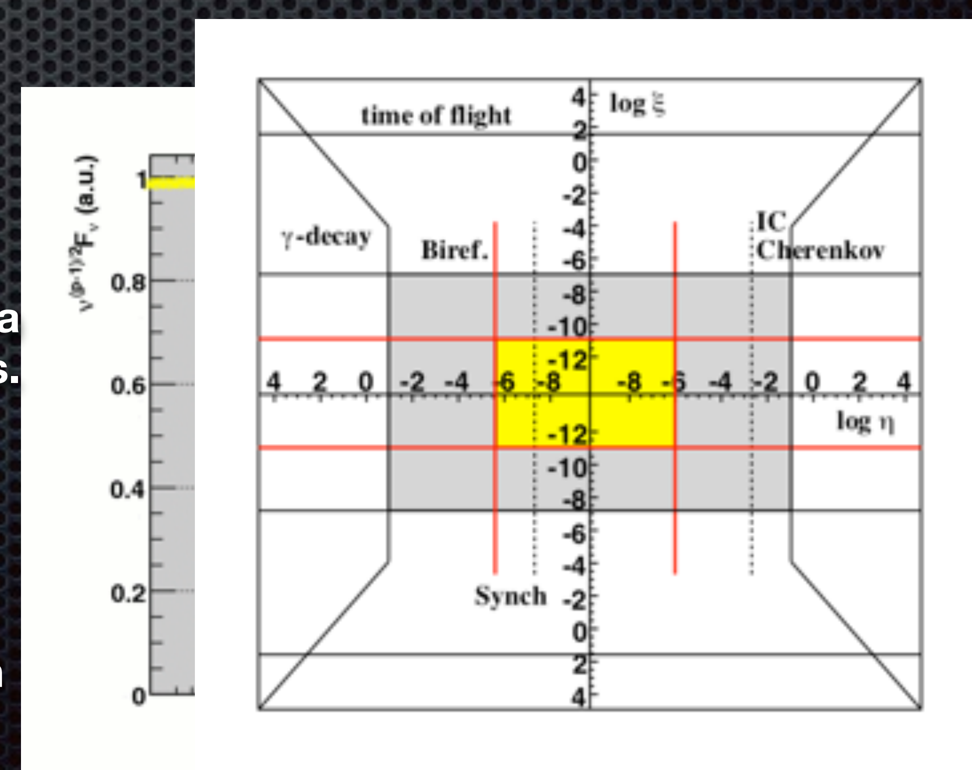
Currently the best two test come from the measurement of the spectrum and polarization of Crab synchrotron emission.

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 θobs= $(123\pm1.5)^\circ$ from the North



Constraints on dim 5-6 CPT even LV QED

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

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

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

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

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

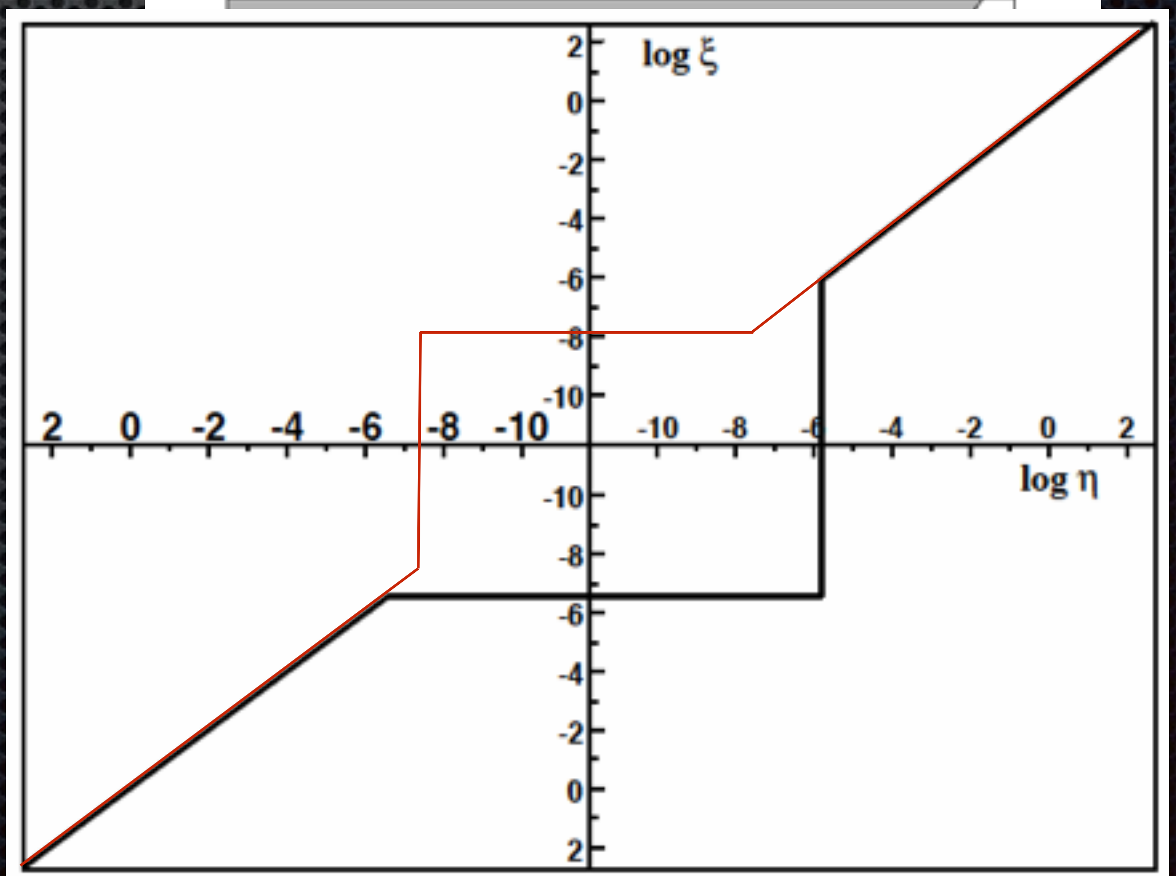
GZK photons are pair produced by decay of π_0 produced in GZK process

The Greisen-Zatsepin-Kuzmin effect:
secondary production

$$p + \gamma \to N + \pi \quad \begin{cases} \pi^0 \to \gamma\gamma \\ \pi^\pm \to \mu\nu_\mu \to e\,\nu_\mu\bar{\nu}_\mu\nu_e \end{cases}$$

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 1020 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...

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

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

Maccione , Taylor, Mattingly, ,SL: JCAP 0904 (2009) 022

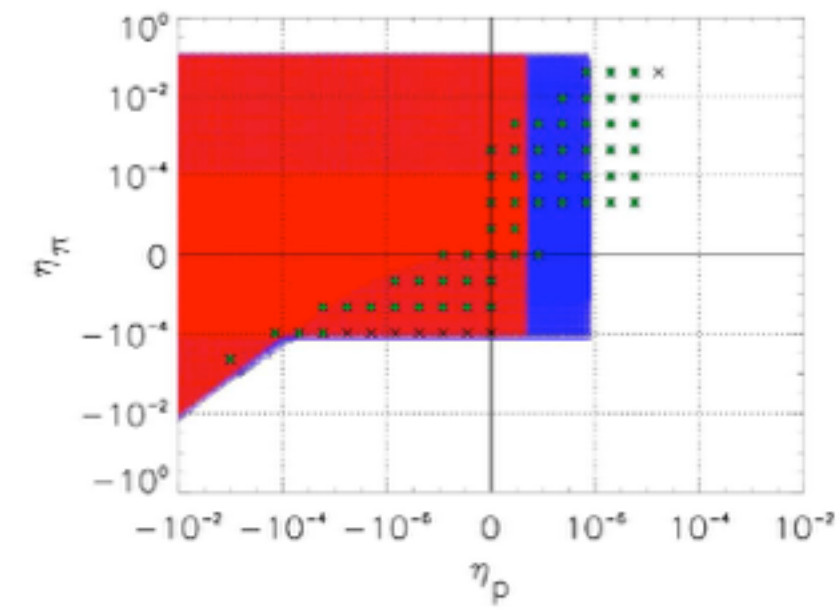


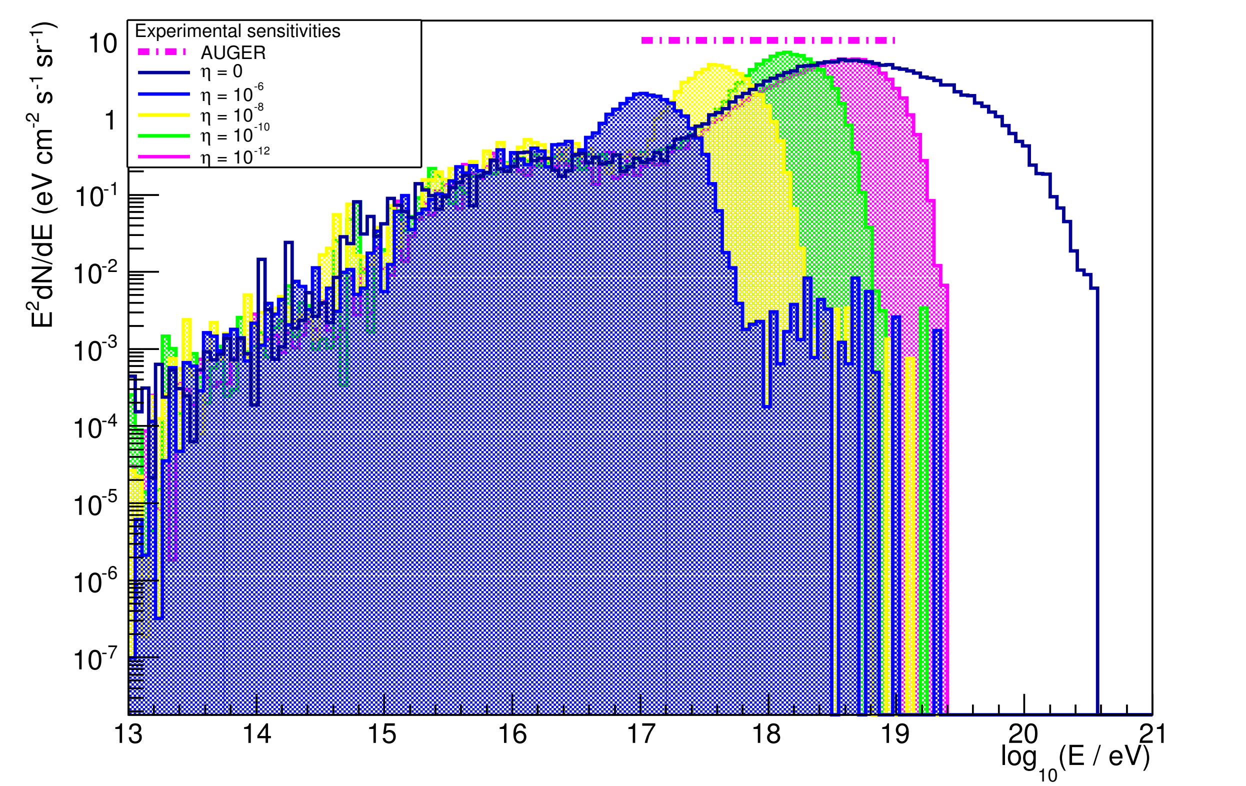
Figure 4. This plot shows the (η_p, η_π) parameter space allowed by different UHECR observations. The red and blue shaded regions corresponds to the portion of parameter space for which the energy threshold for VC emission is higher than, respectively, $10^{20.25}$ eV and $10^{19.95}$ eV, so that it 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

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

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 $\eta(4)_\nu < 10^{-7}$ on the neutrino LV parameter, depending on how LV is distributed among neutrino mass states.



Mattingly, Maccione , Galaverni,SL, Sigl: JCAP 1002 (2010) 007

Liberati, Maccione, Mattingly, (2012)

Neutrinos threshold reactions

Vacuum Cherenkov: ν->νγ

Too suppressed: relevant only above ~10^{19} eV

$$\tau_{\nu\gamma} \simeq \xi_n^{-2} \left(\frac{E}{1 \text{ PeV}} \right)^{-(2n+1)} \quad 10^{26n-86} \text{ s}$$

Neutrino splitting: $\nu_I \to \nu_I \nu_J \bar{\nu}_J$

For flavor blind LIV it is kinematically allowed only for $n > 2$

$$E_{th} = (m_\nu^2 \xi_n^{-1} M^{n-2})^{1/n}$$

$$\tau_{\nu-\text{splitting}} \simeq \frac{m_Z^4 \cos^2\theta_w}{g^4 E^5} \left(\frac{M}{E} \right)^{4(n-2)}$$

Where we used $\xi_{\bar{\nu}} = (-1)^n \xi_\nu$

Neutrino decay by pair creation: $\nu_I \to \nu_I e^+ e^-$

(Idea and n=2 worked out in Cohen-Glashow 2011)

Neglect electron-positron LIV (much more constrained) then

$$E_{th,(n)}^2 = \frac{4m_e^2}{\xi_n} \left(\frac{\mathrm{M_{pl}}}{E_{th}} \right)^{n-2}$$

$$\tau_{\nu-\text{pair}} \simeq G_F^{-2} E^{-5} \xi_n^{-3} \left(\frac{\mathrm{M_{pl}}}{E} \right)^{3(n-2)}$$

See also constraints from pion decay
Hep-ph/1109.6667, 1206.0713

$$\pi^+ \to \nu_\mu + \mu^+$$

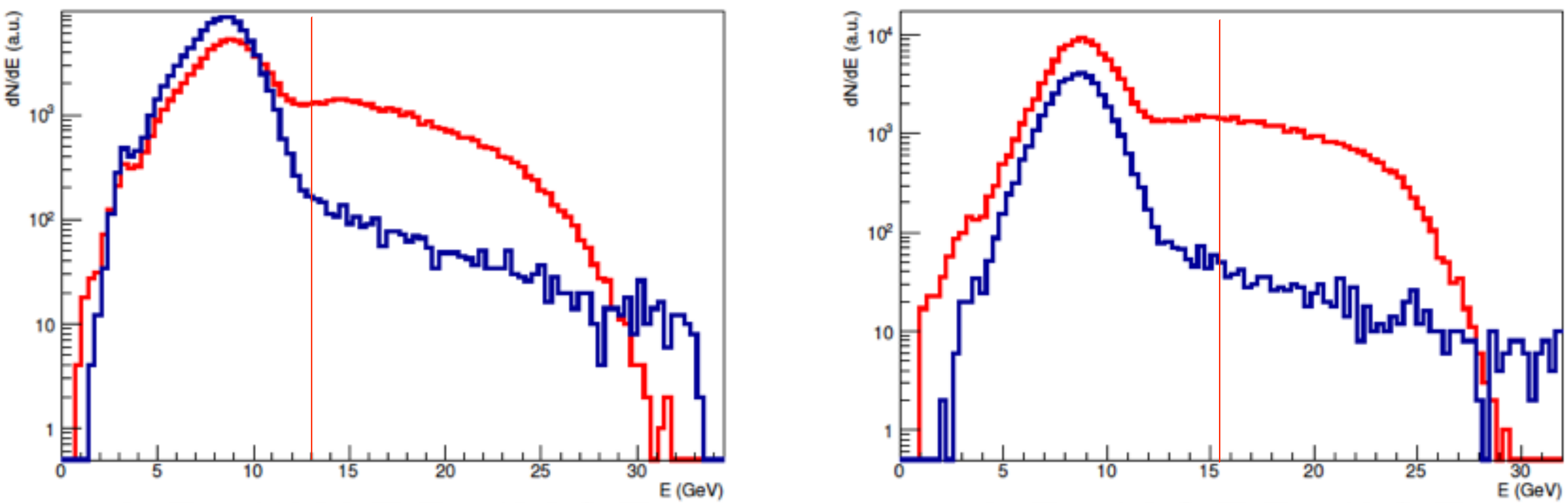
Used to “disprove” OPERA claim of superluminal neutrino

A small comment about Cohen-Glashow disproof of OPERA (flawed) claim

Liberati, Maccione, Mattingly, JCAP (2013)

Cohen and Glashow used the fact that superluminal neutrinos should emit electron-positron pairs to argue that the OPERA results were not even self-consistent

$$E^{-3n+1} - E_0^{-3n+1} = (3n-1)\delta^3_{E_{\rm ref}} E_{\rm ref}^{-3(n-2)} k \frac{G_F^2}{192\pi^3} L \equiv E_T^{-3n+1}$$



n=2 E_{th}~140 MeV, E_T~12.5 GeV **n=3 E_{th}~1.5 GeV, E_T~15 GeV**

FIG. 1. Neutrino and pair spectra for propagation over a baseline of 730 km. In red we show the propagated neutrino spectrum, in blue the produced electron/positron spectrum. The left-hand panel refers to the case $n = 2$, while the right-hand panel to the case $n = 3$.

The argument was formally correct but did not worry about adjusting for the finite size of the baseline: a finite baseline can be of the same order as the energy loss length of neutrinos undergoing pair production.

This allows for some neutrinos to undergo only one or a few Cherenkov emissions within their time of flight. Therefore the most energetic neutrinos of the injection beam can still reach the end of the baseline with an energy larger than E_T.

It is then necessary, in order to cast a robust constraint, to run a full Monte Carlo simulation of the propagation of neutrinos aimed at computing the neutrino spectrum on arrival in the presence of this energy loss process.

Testing Lorentz violations: end of the story?

Order	photon	e^-/e^+	Protrons	Neutrinos[a]
n=2	N.A.	$O(10^{-16})$	$O(10^{-20})$ (CR)	$O(10^{-8} \div 10^{-10})$
n=3	$O(10^{-16})$ (GRB)	$O(10^{-16})$ (CR)	$O(10^{-14})$ (CR)	$O(40)$
n=4	$O(10^{-8})$ (CR)	$O(10^{-8})$ (CR)	$O(10^{-6})$ (CR)	$O(10^{-7})^*$ (CR)

Table 2. Summary of typical strengths of the available constrains on the SME at different n orders for rotational invariant, neutrino flavour independent LIV operators. GRB=gamma rays burst, CR=cosmic rays. [a] From neutrino oscillations we have constraints on the difference of LIV coefficients of different flavors up to $O(10^{-28})$ on dim 4, $O(10^{-8})$ and expected up to $O(10^{-14})$ on dim 5 (ICE3), expected up to $O(10^{-4})$ on dim 6 op. * Expected constraint from future experiments.

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.
Chances are high that improving observations in HE astrophysics will strengthen these constraints in a near future…
If there is Lorentz violation, and it is described by the same modified dispersion relation at all energies then 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…

Caveat: A potential problem with the UHECR data?

- With increased statistics the composition of UHECR beyond 1019 eV seems more and more dominated by iron ions rather than protons at AUGER. But Telescope Array (TA) in Utah is instead Ok with purely proton composition. Are we seeing the GZK?
- With improved statistic the correlated AUGER UHECR-AGN events have decreased from 70% to 40%: large deflections? i.e. heavy (high Z) ions?
- Also no evidence at the TA for AGN correlation. But some hint of correlation with LLS for E>57 EeV
- 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.
- Shaky n=4 constraints?

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?

Astro-ph [HE]:1101.2903, A. Saveliev, L. Maccione, G. Sigl

Assuming UHECR are heavy nucley and they are not loosing energy by LV spontaneous decay and vacuum Cherenkov the get the following tentative constraints

η= generic LIV coefficient of dim 6 ops for single nucleon

	$E_{max} = 10^{19.6}$ eV	$E_{max} = 10^{20}$ eV
^{4}He	$-3\times10^{-3} \lesssim \eta \lesssim 4\times10^{-3}$	$-7\times10^{-5} \lesssim \eta \lesssim 1\times10^{-4}$
^{16}O	$-7\times10^{-2} \lesssim \eta \lesssim 1$	$-2\times10^{-3} \lesssim \eta \lesssim 3\times10^{-2}$
^{56}Fe	$-1 \lesssim \eta \lesssim 200$	$-3\times10^{-2} \lesssim \eta \lesssim 4$

Beyond Dispersion, Dissipative effects

While dispersive effects have been thoroughly investigated, almost no attention has been devoted to dissipative effects (see however Parentani 2007).
Note that response theory and causality predicts they should come together (Kramers-Kronig relations)

Normally dissipative effects can be analysed in a unitary, causality preserving theory by considering a system and an environment (or heavy and light particles) and by tracing on the environment so to get a dissipative system. Unfortunately this generally leads to complicate calculations and non generic toy models

Let's then adopt here a different approach based on hydrodynamics that we might take as a large scale, EFT, limit of any discrete/quantum spacetime scenario.
Consider than an irrotational fluid at rest with some kinematic viscosity ν
The equation for the perturbations of the velocity potential reads $v^\mu = \nabla^\mu \psi$

$$\partial_t^2 \psi_1 = c^2 \nabla^2 \psi_1 + \frac{4}{3} \nu \, \partial_t \nabla^2 \psi_1$$

Which at high momenta corresponds to the dispersion relation

$$\omega^2 \simeq c^2 k^2 \left[1 - i \frac{4}{3} \frac{\nu k}{c} - \frac{8}{9} \left(\frac{\nu k}{c} \right)^2 + i \frac{8}{27} \left(\frac{\nu k}{c} \right)^3 \right]$$

Generalising

$$\partial_t^2 \psi_1 = c^2 \nabla^2 \psi_1 + \sum_{n=2}^{\infty} \frac{4}{3} \nu_n \, \partial_t \nabla^n \psi_1$$

$$\omega^2 = c^2 k^2 - i \frac{4}{3} \nu_2 c k^3 + \sum_{j=1}^{\infty} (-)^{j+1} \mathcal{L}_{6j-3}^{3j-1} k^{6j-2} + i \sum_{j=1}^{\infty} (-)^{j+1} B_{2j}^{6j-2} k^{6j-1} +$$
$$\sum_{j=1}^{\infty} (-)^j \mathcal{L}_{6j-1}^{3j} k^{6j} + i \sum_{j=1}^{\infty} (-)^j A_{6j} k^{6j+1} + \sum_{j=1}^{\infty} (-)^{j+1} \mathcal{M}_{6j+1,2j+1}^{3j+1} k^{6j+2} + i \sum_{j=1}^{\infty} (-)^{j+1} A_{6j+2} k^{6j+3}$$

$$A_i = 4/3 \nu_i c, \; B_i^j = 8/27 \nu_i / c + 4/3 \nu_j c, \; \mathcal{L}_i^j = 4/3 \nu_i c - 8/9 \nu_j^2,$$
$$\mathcal{M}_{i,j}^k = 4/3 \nu_i c + 8/27 \nu_j^3 / c - 8/9 \nu_k^2$$

Constraints on dissipation

Let's then take the lowest order and rescale quantities using the Planck scale as the natural scale of the new physics and so define a dimensionless coefficient $\sigma=(4\nu M_{Pl})/3c$

$$\omega^2 = c^2k^2 - i\sigma c^2 \frac{k^3}{M_{\mathrm{Pl}}}$$

The energy loss rate Γ can be computed a la Breit-Wigner $\sigma c^2 \frac{k^3}{M_{\mathrm{Pl}}} \equiv 2\omega\Gamma$

For an ultra-relativistic particle with momentum k traveling over a long distance D, a constraint is obtained by requiring its lifetime τ to be larger than the propagation time D/c, that is $\tau>D/c$ or $c\hbar/\Gamma>D$.

Let us consider the observed 80 TeV photons from the Crab nebula, $D_{Crab} \approx 1.9$ kpc. We get

$$\sigma \leq \frac{2c\hbar}{D_{\mathrm{Crab}}(80\ \mathrm{TeV})^2} M_{\mathrm{Pl}} \approx 1.3 \times 10^{-26}$$

Similar considerations leads to

Electron/positron $\sigma< 10^{-23}$ (From Crab and 1 pc traveled)

Neutrinos $\sigma< 10^{-27}$ (detection of a bunch of extraterrestrial neutrinos with energies between 30 and 250 TeV by Ice-Cube)

Gravitational waves could in principle provide constraints in case of detection. Unfortunately, current experiments are sensitive to waves which are far too low energy (below 1 Hz) for providing meaningful constraints.

Next order would be

$$\omega^2 = c^2k^2 \pm i|\sigma_4|c^2k^5/M_{\mathrm{pl}}^3\ , \qquad \text{where} \qquad \sigma_4 \equiv (4\nu_4 M_{\mathrm{pl}}^3)/3c$$

Noticeably one cannot get constraints better than O(1). But if indeed spacetime would behave like a superfluid phase of fundamental constituents this would be the first non-zero terms. Worth keep looking…

What next?

Improving tests of Lorentz Violations

- We need better data from UHECR and Cosmogenic Neutrinos to constraint $O(k^4)$. Constraint k^5 dissipation.
- The LIV gravity sector needs more exploration…

Other mesoscopic physics without Lorentz violation?

- One might try to relax other principles rather than the relativity one… but nothing seems to work…

Break Precausality ➔ Hell breaks loose, better not!

Break Principle of relativity ➔ Preferred frame, Modified dispersion relations

Break kinematical Isotropy ➔ Finsler geometries. True geometry on the phase space.
E.g. Very Special Relativity (Glashow, Gibbons et al.) but reduced symmetry group… already very constrained.
Break Homogeneity ➔ tantamount to give up operative meaning of coordinates. Breaking the underlying assumption of euclidean space locally used to start posing von Ingnatovski theorem.

- Nonetheless we do have concrete QG models of emergent gravity like Causal Sets which predict exact Lorentz invariance below the Planck scale in spite of discreteness. The key point is that spacetime comes from a statistical averaging over many microscopic configurations. This produces Lorentz invariance physics which however has non-locality (EFT with infinite series of higher order derivatives).

$$\Box_\rho \approx \Box + \frac{\alpha}{\sqrt{\rho}}\Box^2 + \frac{\beta}{\sqrt{\rho}}\Box^2 \ln\left(\frac{\gamma}{\rho}\Box^2\right) + \ldots$$

- Similarly integrating out transplanckian d.o.f in Loop Quantum gravity gives non-Local EFT. Also Deformed Special Relativity attempt led to Non-Locality (Relative Locality).
- **Conjecture: Discreetness + Lorentz Invariance = Non-Locality. Can we test this kind of EFT?**
- **More soon…**