DISCRETE 2014: Fourth Symposium on Prospects in the Physics of Discrete Symmetries

Lorentz breaking effective field theories: phenomenology and constraints

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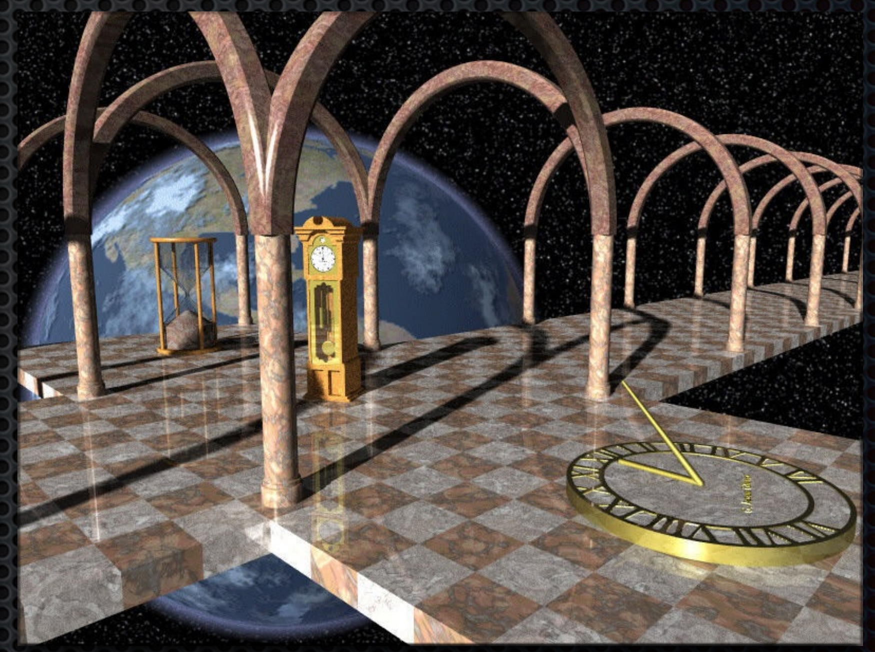
THE QUEST FOR QG PHENOMENOLOGY

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: $M_p^2 = R^n M_p(4+n)^{n+2}$**
- **Modified Uncertainty principle tests**
- **Planck scale spacetime fuzziness tests**
- **Violation of discrete symmetries tests**
- **Violation of spacetime symmetries tests**



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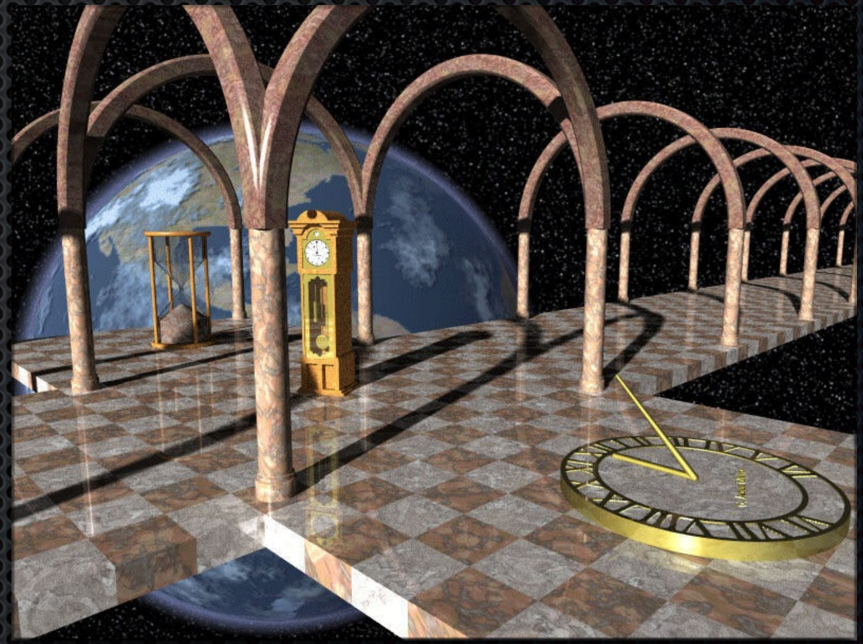

We shall focus here on the last item.
More precisely on tests of Local Lorentz invariance
Why?

- Lorentz invariance 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 tests 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

Giordano Bruno Monument - Rome

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)

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GRB photon dispersion limits at the Planck scale

Coleman-Glashow test theory

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, ...)

Which Breaking of 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=∞ → Galileo
C=clight → Lorentz
Experiments determine C!

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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.

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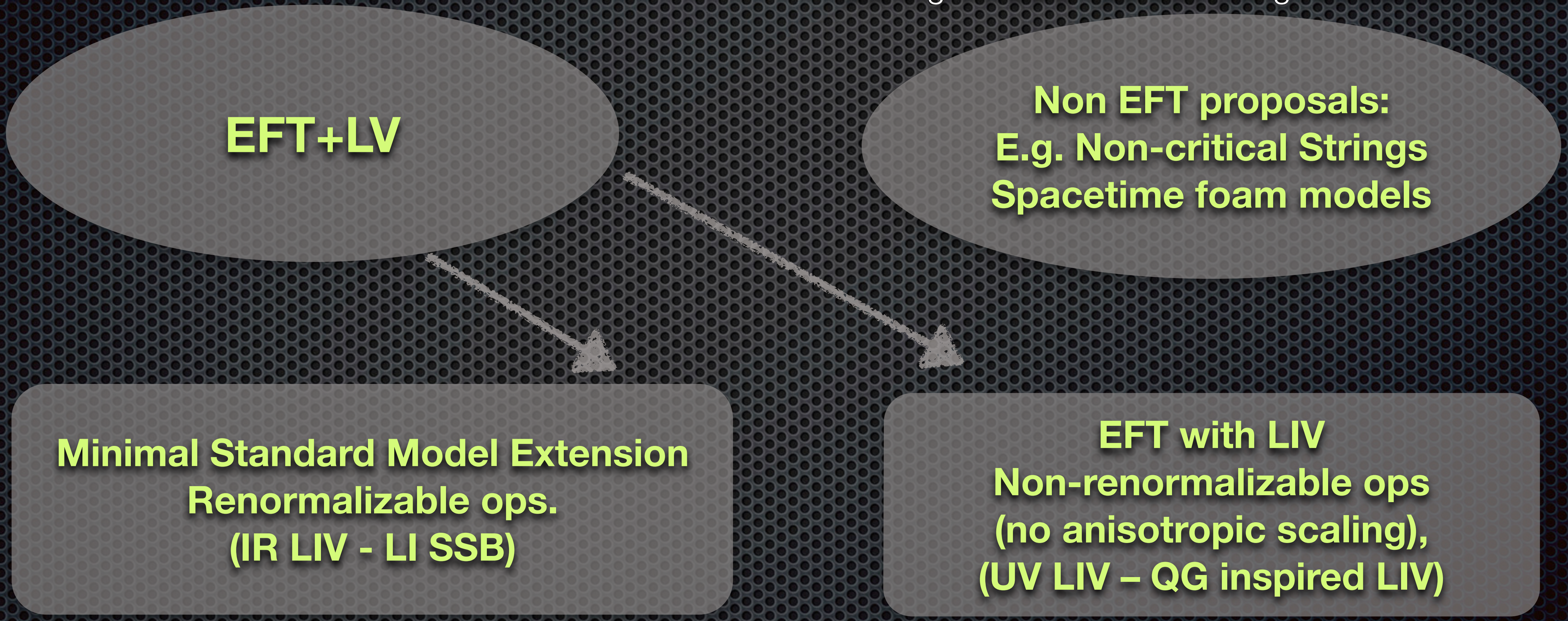
Let's start relaxing the Relativity Principle…

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

See e.g. Amelino-Camelia Living Reviews of Relativity



EFT+LV

Non EFT proposals:
E.g. Non-critical Strings
Spacetime foam models

Minimal Standard Model Extension
Renormalizable ops.
(IR LIV - LI SSB)

EFT with LIV
Non-renormalizable ops
(no anisotropic scaling),
(UV LIV – QG inspired LIV)

Generally preferred frame aligned with CMB

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.
SL, Class. Quant. Grav. 2013

LIV PHENOMENOLOGY IN MATTER: A TOOOLKIT

Terrestrial tests:

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

Furthermore generally assumed rotational invariance

- simpler and boost w.r.t. CMB frame small
- cutoff idea only implies boosts are broken, rotations maybe not
- boost violation constraints likely also boost + rotation violation constraints

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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

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

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

electron helicities have independent LIV coefficients

photon helicities have opposite LIV coefficients

Moreover electron and positron have 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 $M_{\rm pl}$ 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

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

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

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

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

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

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

Note: no birefringence
Favored 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!

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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.

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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

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Improved RG flow at HE

Models with strong coupling at high energies improving RG flow a la Nielsen

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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).

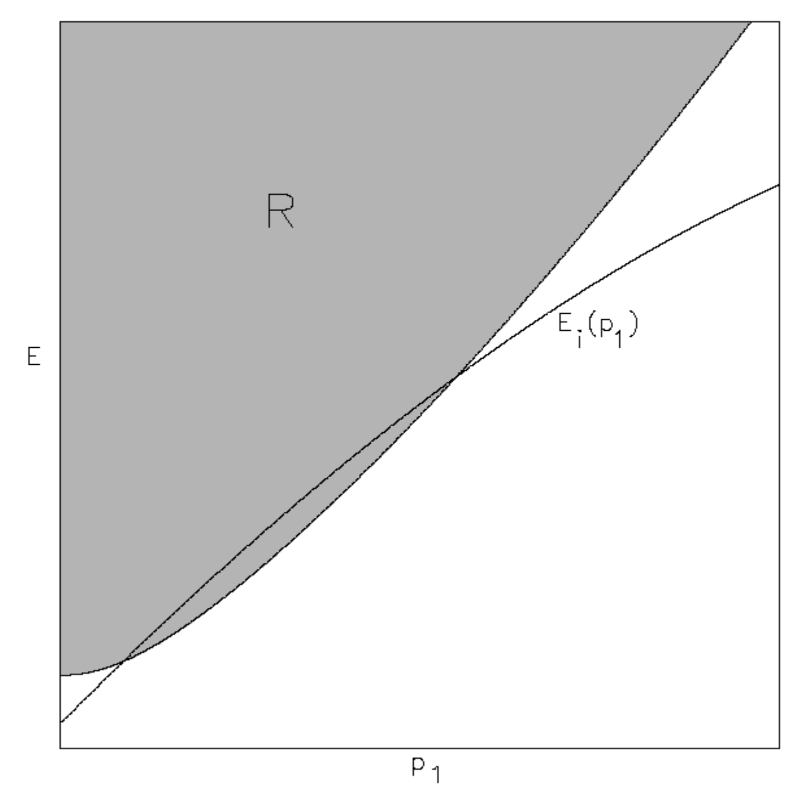
$$\theta(t) = [\omega_+ - \omega_-(k)]\, t/2 = \xi k^2 t/2M$$

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

- 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	$p \approx m_\nu \sim 1$ 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

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

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

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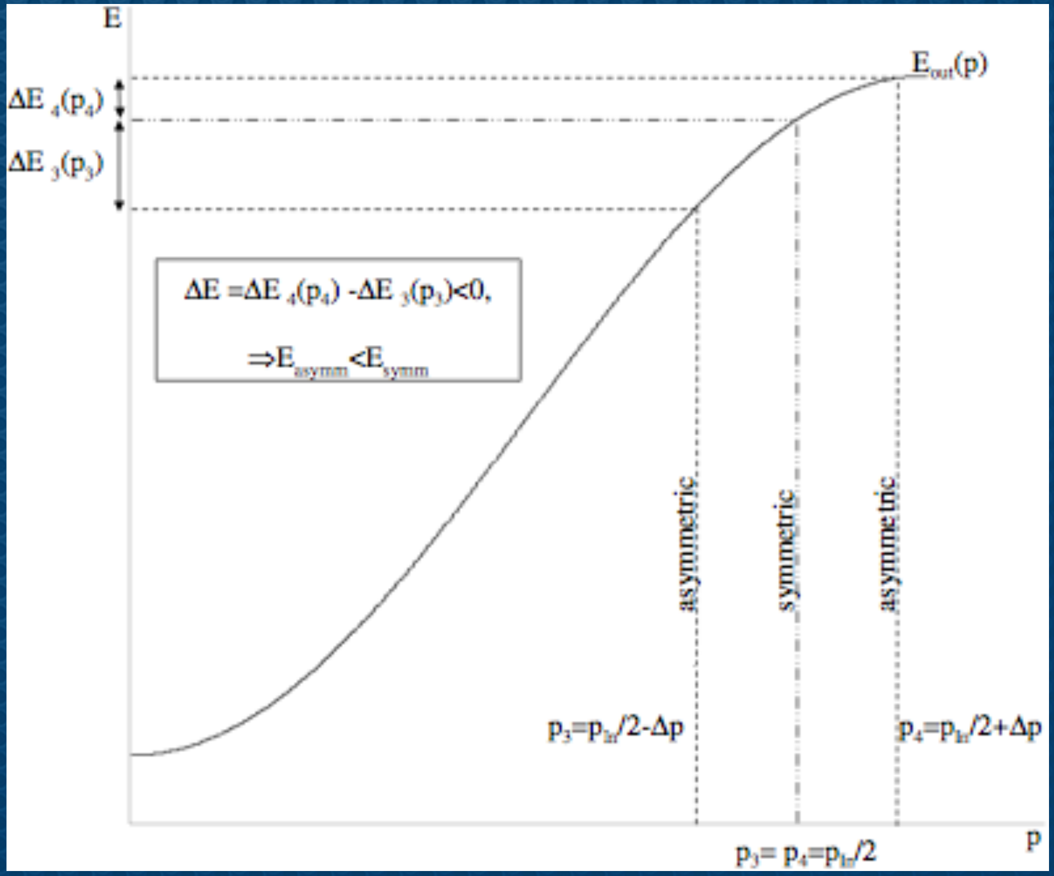
3	~1 GeV	~10 TeV	~1 PeV
4	~100 TeV	~100 PeV	~3 EeV

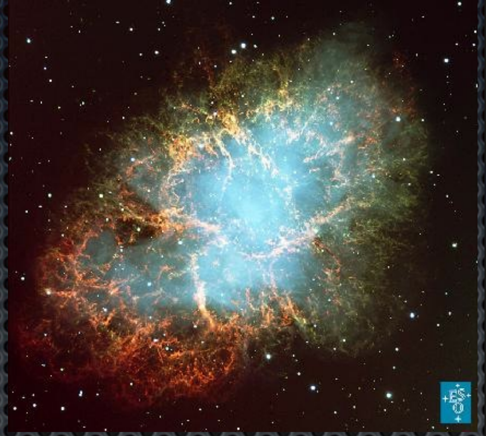


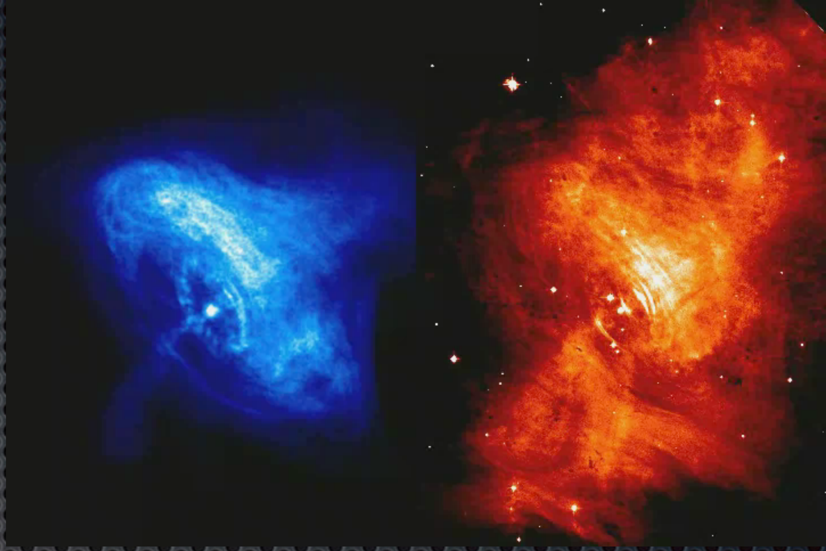
- Synchrotron

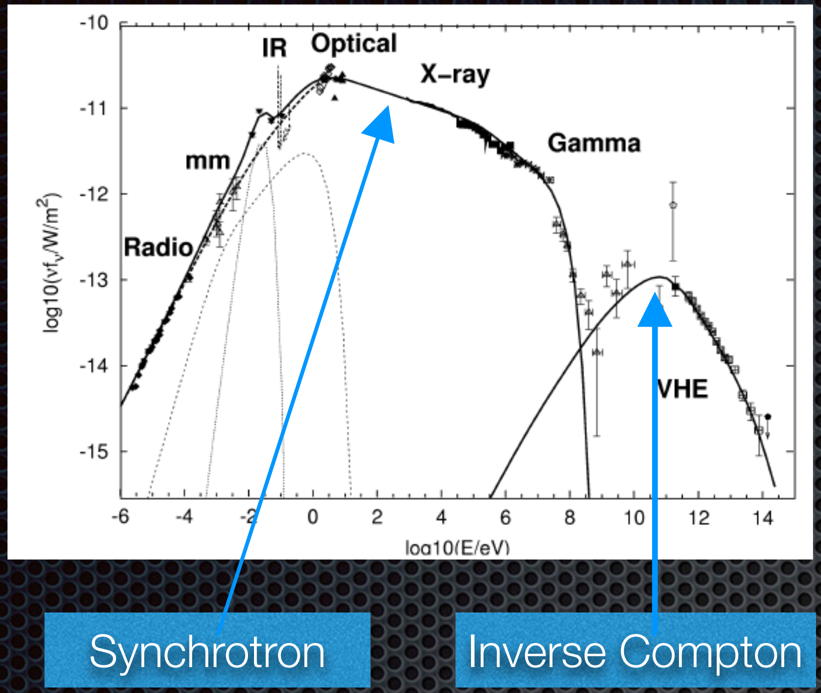
$$\omega_c^{LIV} = \frac{3}{2} \frac{eB}{E} \gamma^3$$

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

CONSTRAINTS ON QED
DIM 5 CPT ODD QED EXTENSION







Synchrotron

Inverse Compton

L.Maccione, SL, A.Celotti and J.G.Kirk: JCAP 0710 013 (2007)
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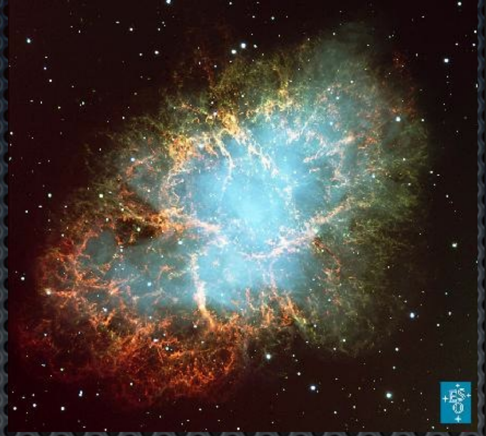

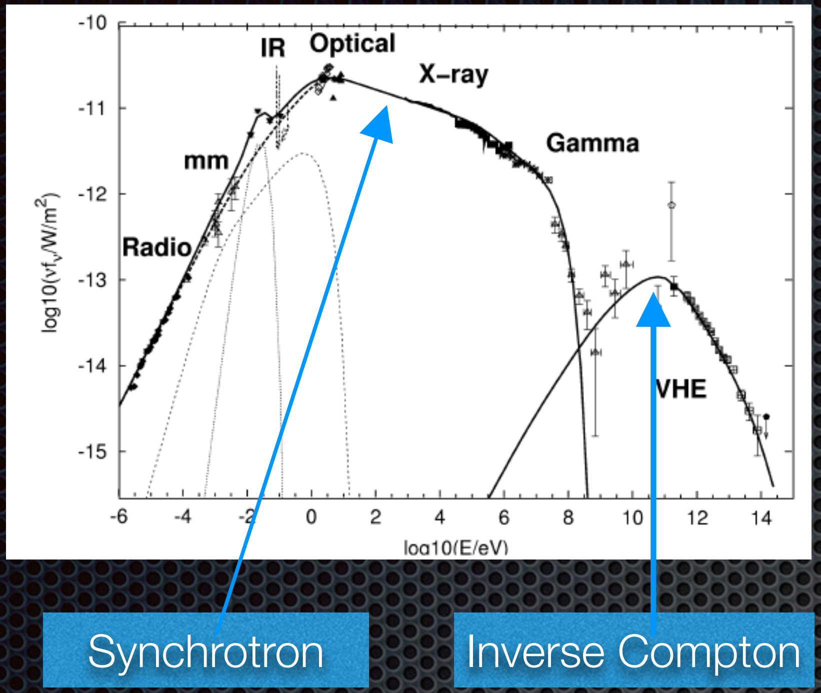

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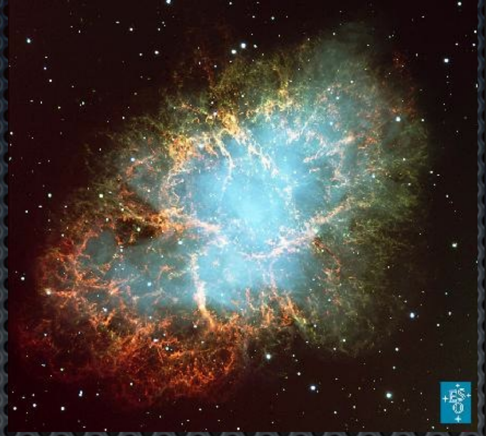

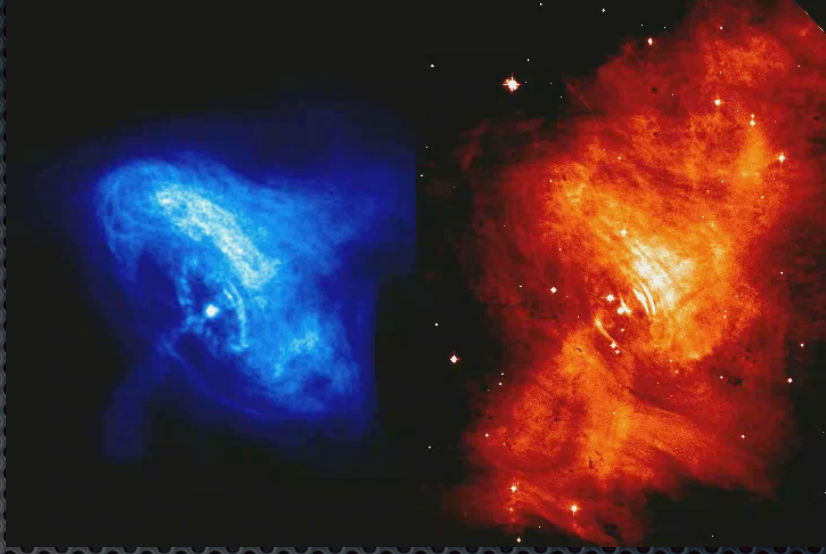

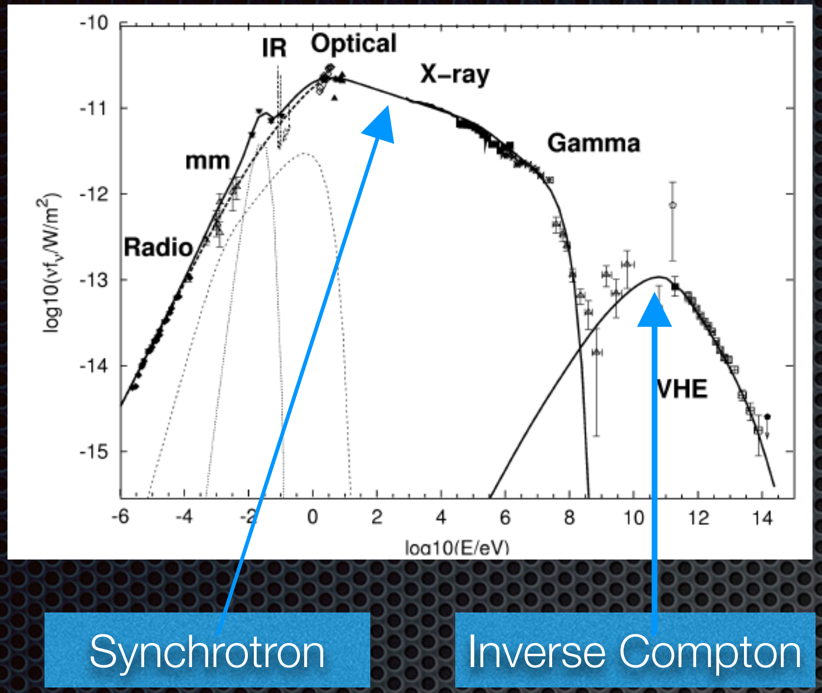

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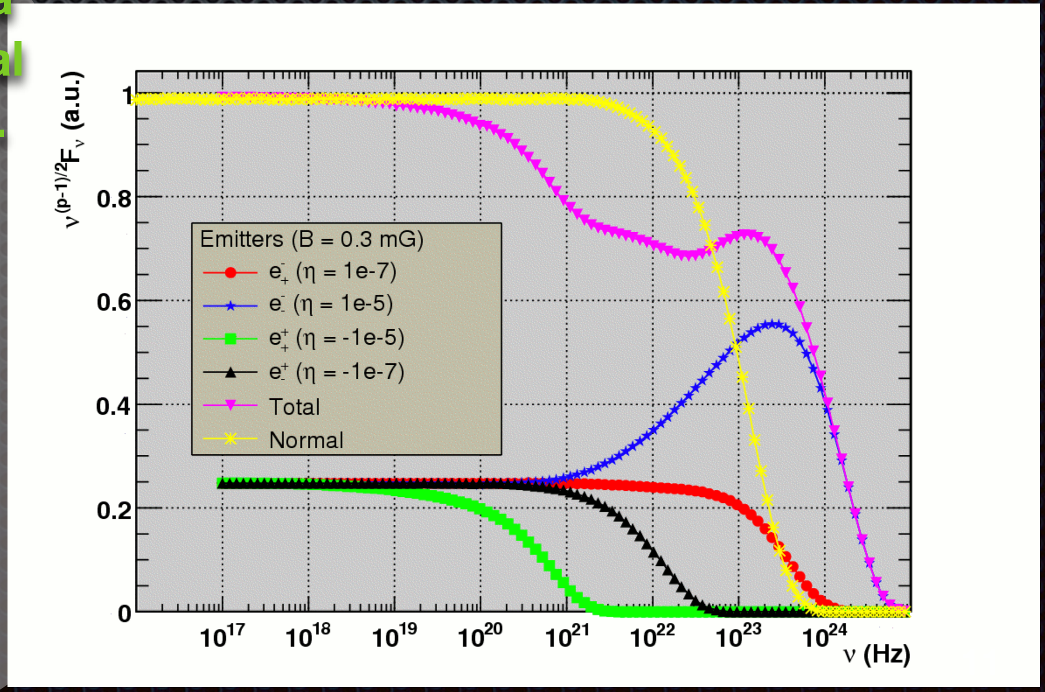

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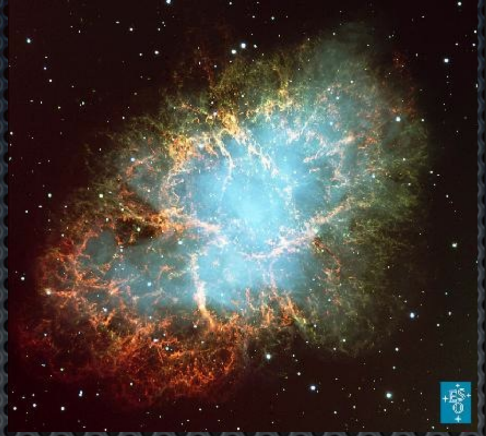

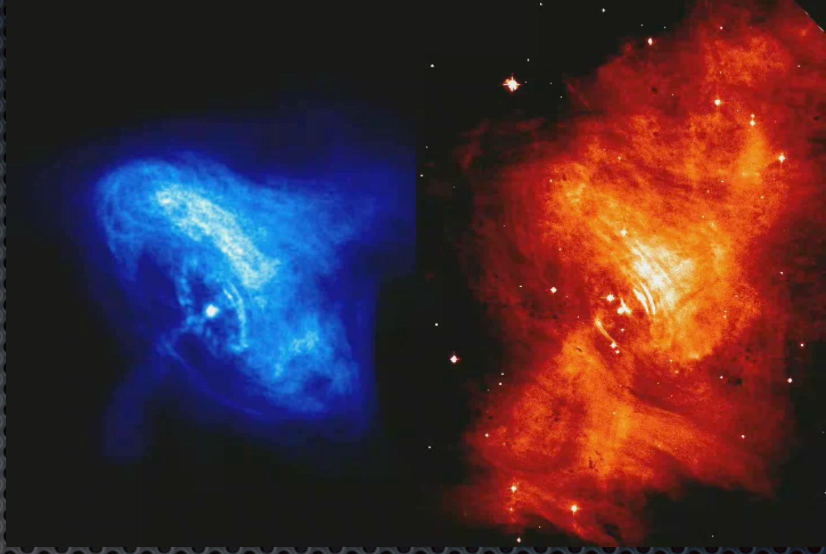

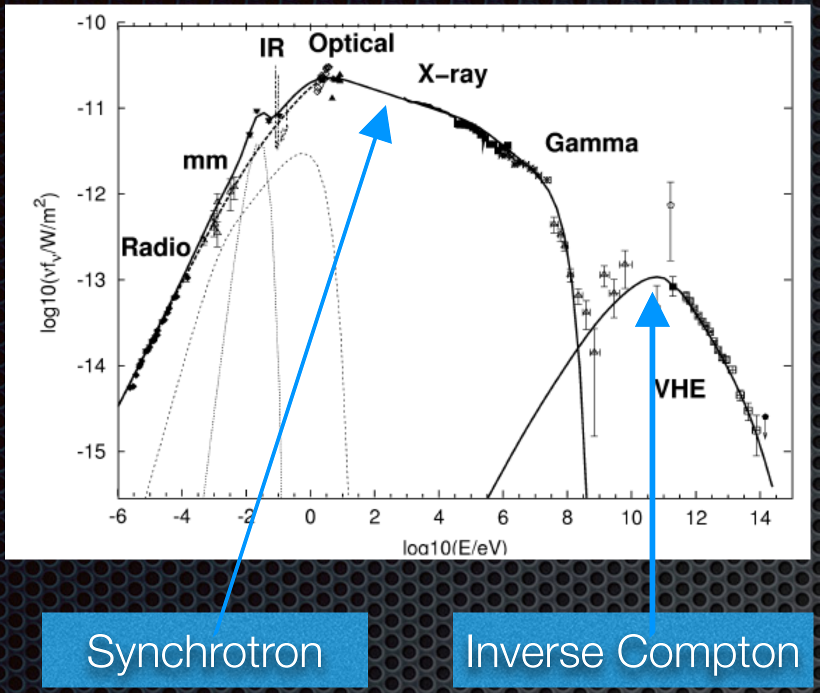

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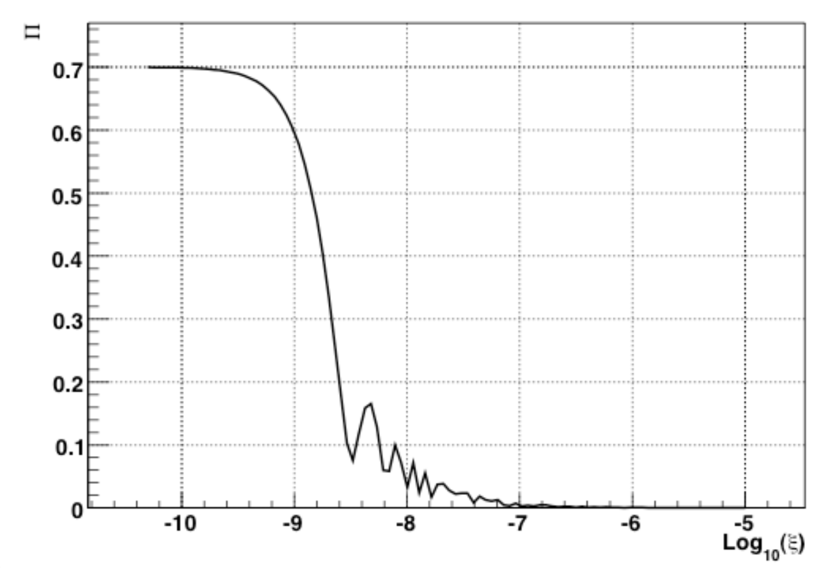
$$\Delta\theta = \xi\left(k_2^2 - k_1^2\right) d/2M, \quad (\text{where } d = \text{distance source-detector})$$

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



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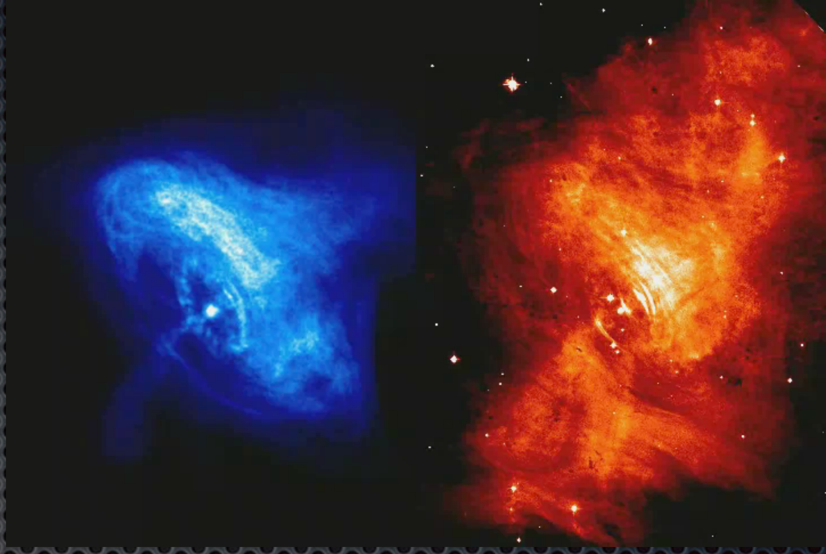

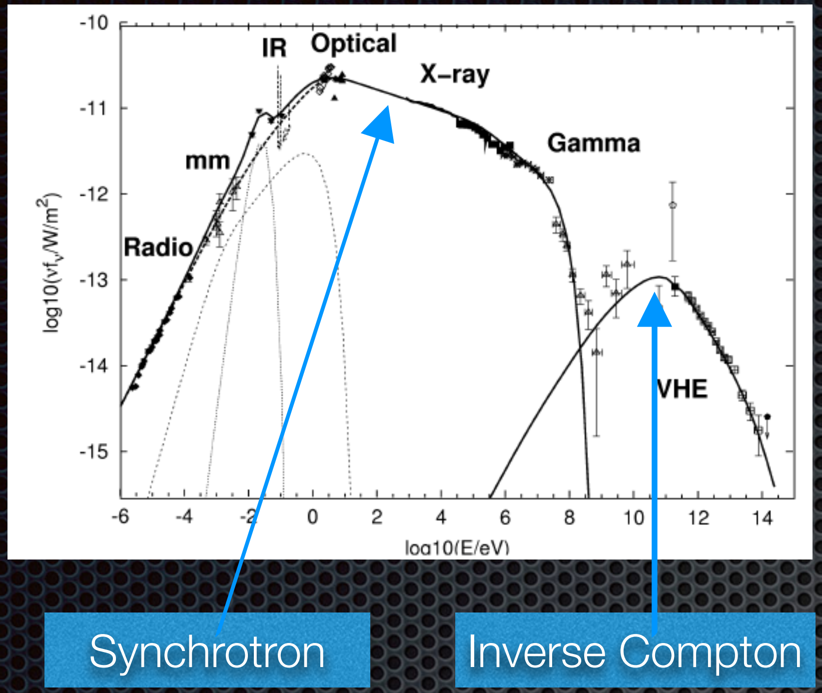

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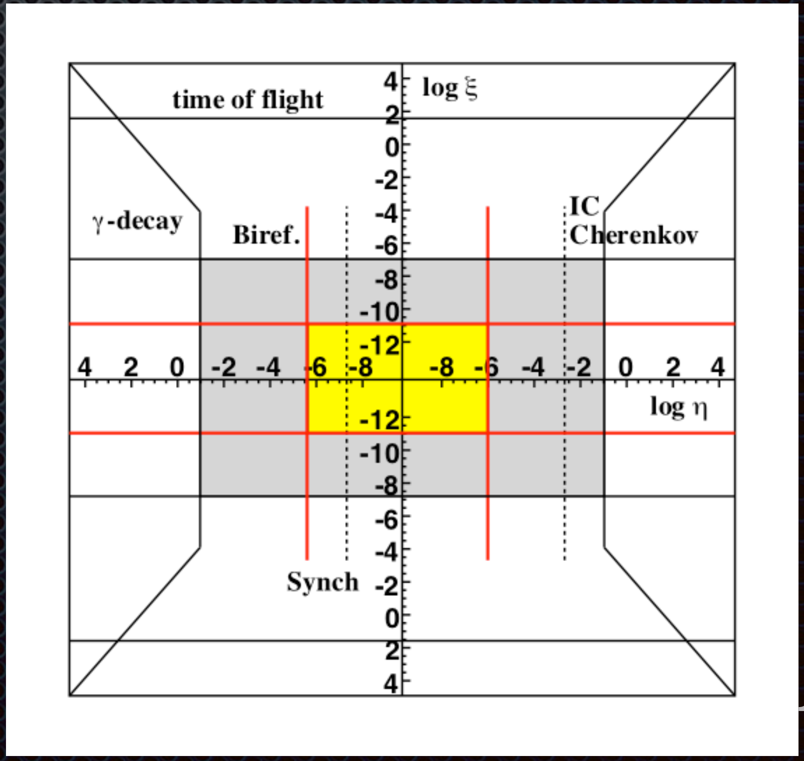
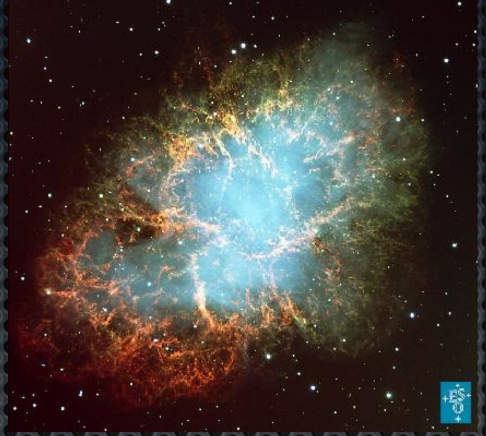
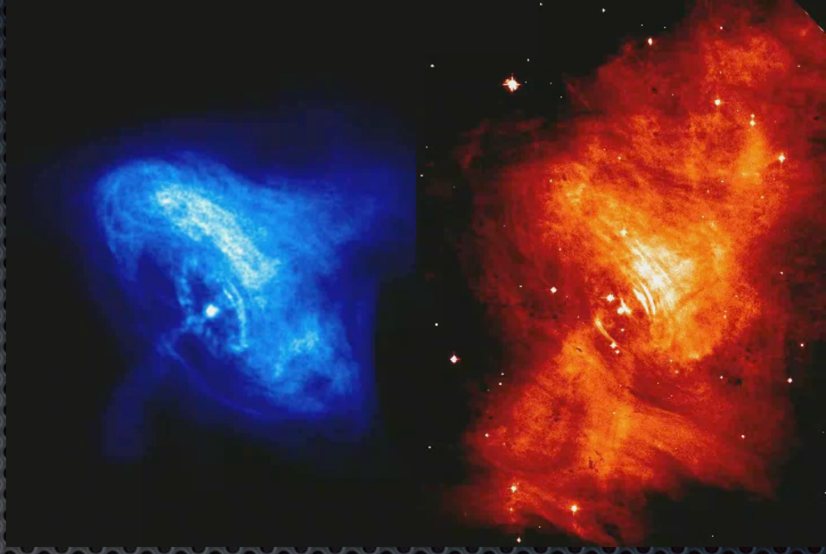
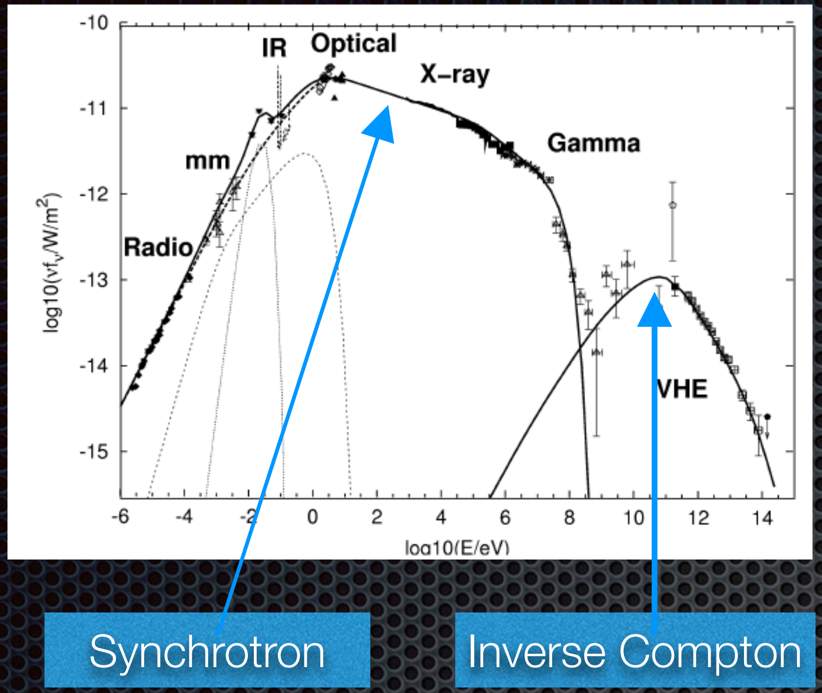


Constraints on QED dim 5 CPT Odd QED extension







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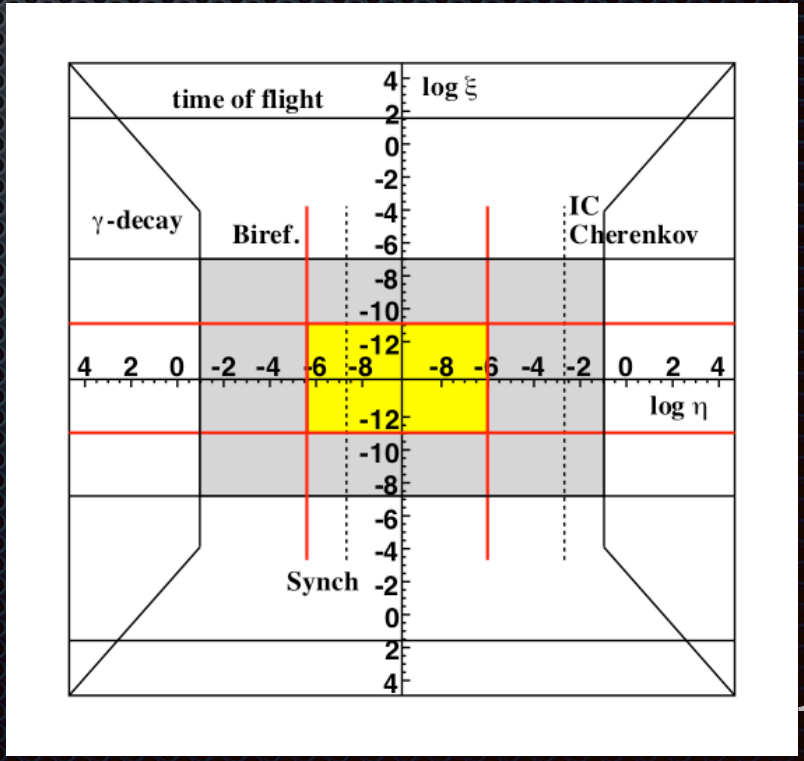

Constraints on dim 5-6 CPT even LV QED

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

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

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

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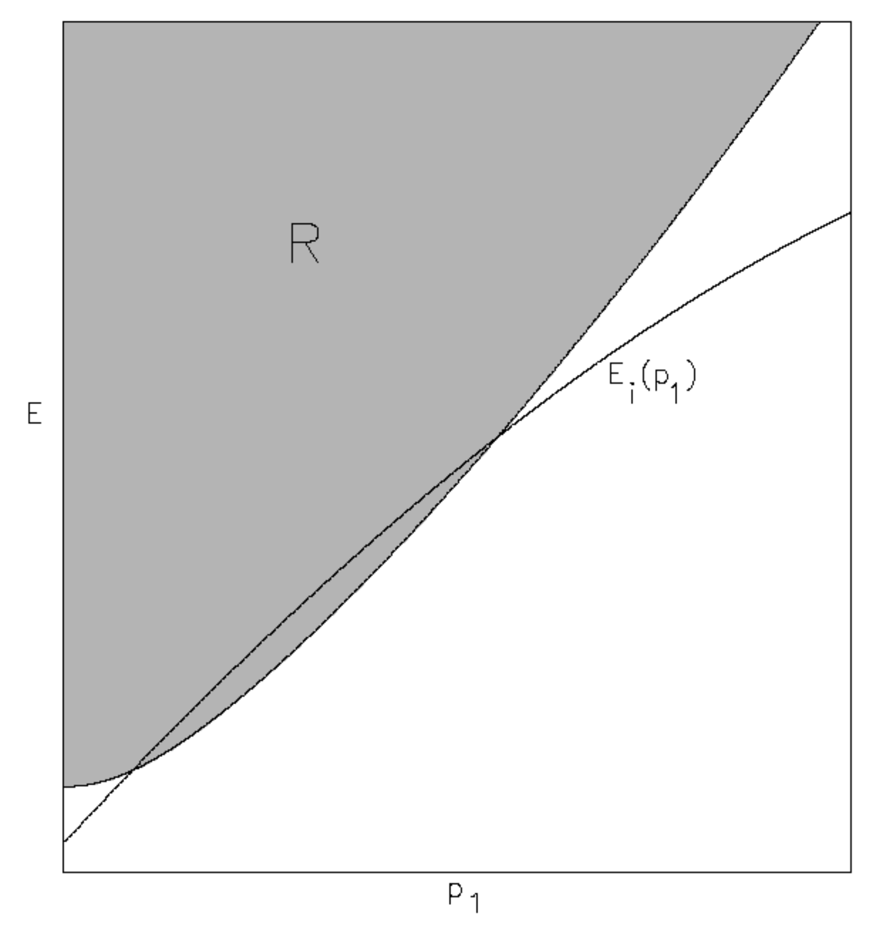

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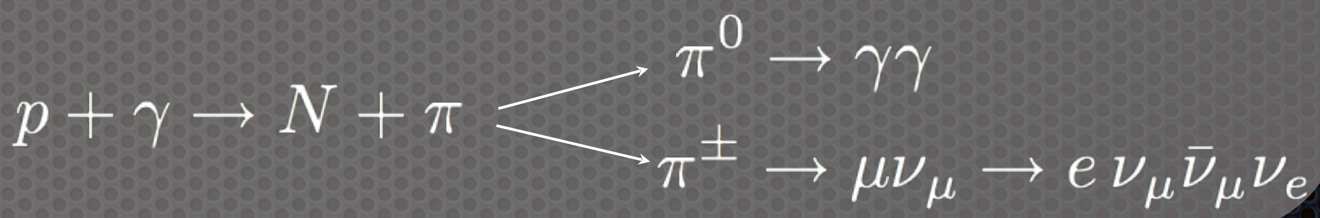

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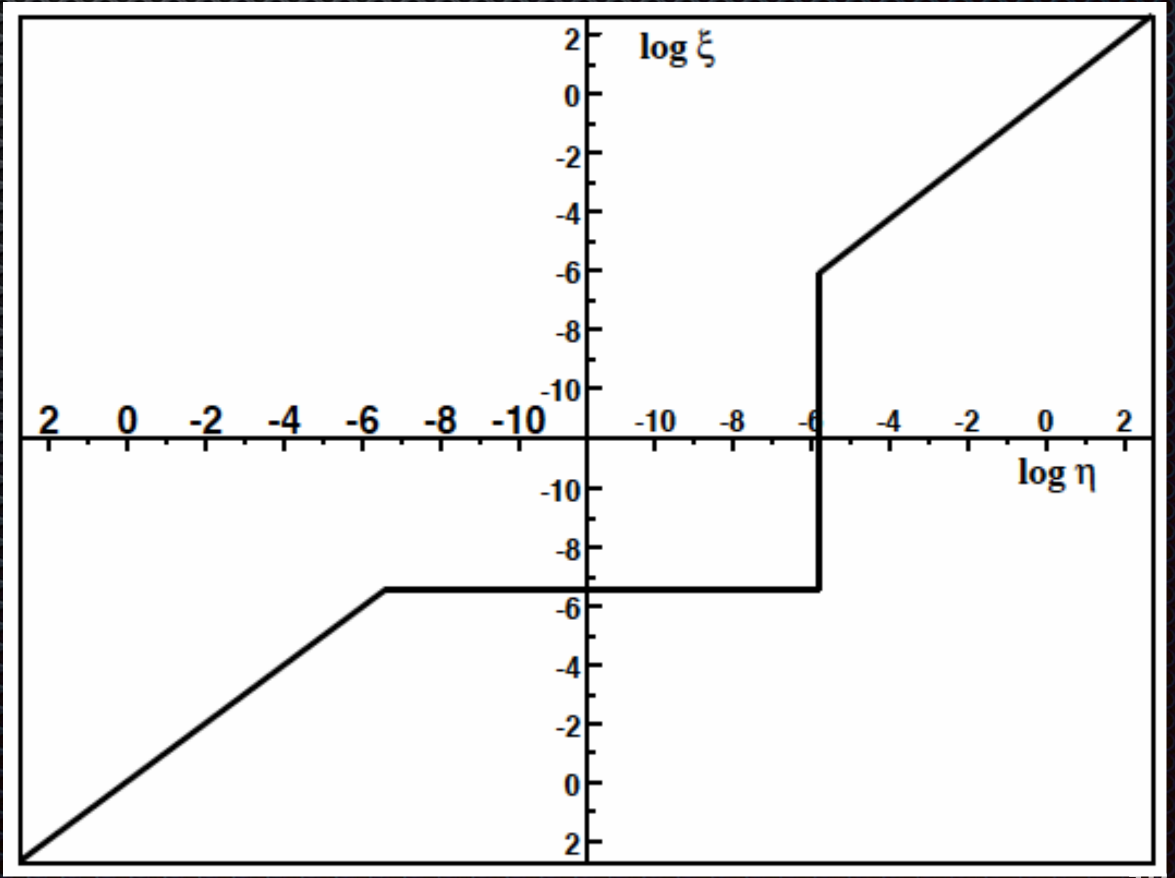
If $k_{up} < 10^{20}$ eV then photon fraction in UHECR much larger than present upper limits



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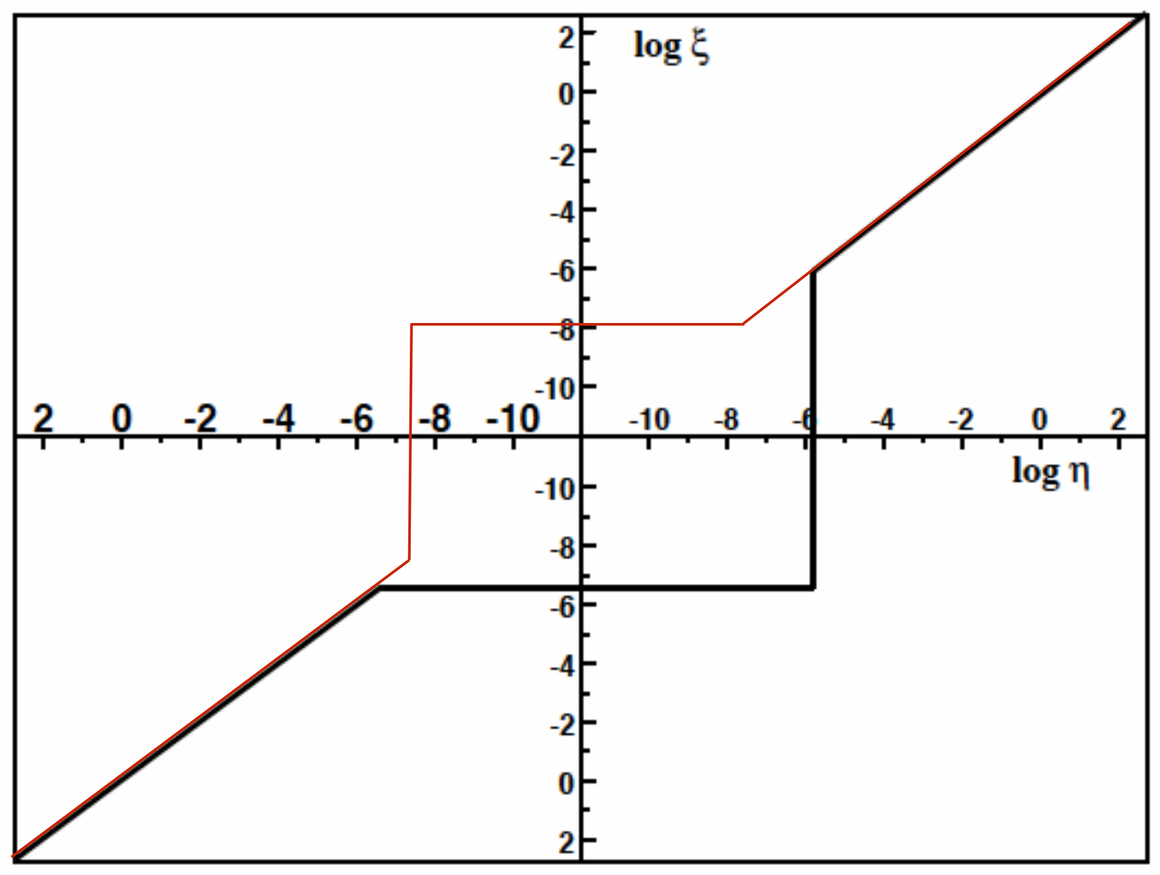
LIV also introduces competitive processes: γ-decay
If photons above 10^{19} eV are detected then γ-decay threshold > 10^{19} eV



Beyond QED …

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

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

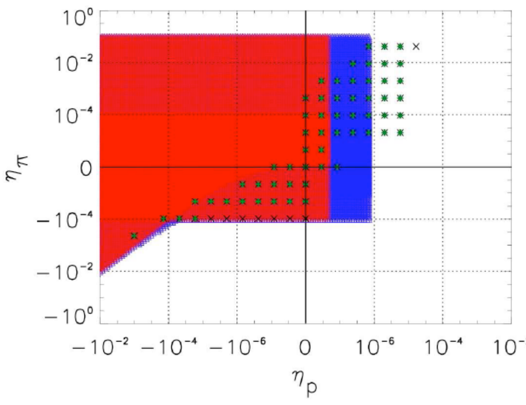


Figure 4. This plot shows the (η_p,η_π) parameter space allowed by different UHECR observations. The red and blue shaded regions corresponds to the portion of parameter space for which the energy threshold for VC emission is higher than, respectively, $10^{20.25}$ eV and $10^{19.95}$ eV, so that it does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

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

Constraints on Flavour-Dependent LIV from Neutrino Oscillations: “LIV must be flavour blind”

Neutrino flavor oscillations yield constraints on LIV differences within the neutrino sector. Neutrino oscillations depend on the differences in E–p between different neutrino eigenstates.
In standard neutrino oscillations, this difference is governed by the squared mass differences between the energy eigenstates. With LV oscillations are governed by the differences in the effective mass squared,

$$N_i^2 = m_i^2 + \xi_i p^n / M_i^{n-2}$$

The transition probability between two flavors I,J is then ruled by the factor

$$\delta N_{ij}^2 = \Delta m_{ij}^2 + p^2 \left(\frac{\Delta c}{c}\right)_{ij}^{LIV} \qquad \text{where now} \qquad \left(\frac{\Delta c}{c}\right)_{ij}^{LIV} = \xi_i \left(\frac{p}{M_i}\right)^{n-2} - \xi_j \left(\frac{p}{M_j}\right)^{n-2}$$

The best constraint to date comes from survival of atmospheric muon neutrinos observed by the former IceCube detector AMANDA-II in the energy range 100 GeV ÷ 10 TeV, and reads $(\Delta c/c)_{\nu_\mu\nu_\tau} \leq 2.8 \times 10^{-27}$ at 90% CL. Given that IceCube does not distinguish neutrinos from antineutrinos, the same constraint applies to the corresponding antiparticles.

NEUTRINOS THRESHOLD REACTIONS

Vacuum Cherenkov: ν->νγ

Too suppressed (extra α factor w.r.t reactions below): relevant only above ~10^{19} eV

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

Neutrino splitting: ν_I->$\nu_I\nu_J\nu_J$

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

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

$$\tau_{\nu-\mathrm{splitting}} \simeq \frac{64\pi^3}{3G_F^2 E^5}\xi_n^{-3}\left(\frac{\mathrm{Mpl}}{E}\right)^{3(n-2)}$$

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

Neutrino decay by pair creation: ν_l->$\nu_l e^+ e^-$

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

Neglect electron-positron LIV (much more constrained) then

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

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

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 (2012)

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

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

Here E is the energy on a neutrino starting with energy E_0 after propagation over the distance L and Eref is the energy at which we normalize the parameter ξ_ν

The "termination" energy E_T corresponds to the energy that a neutrino would approach after sufficient propagation

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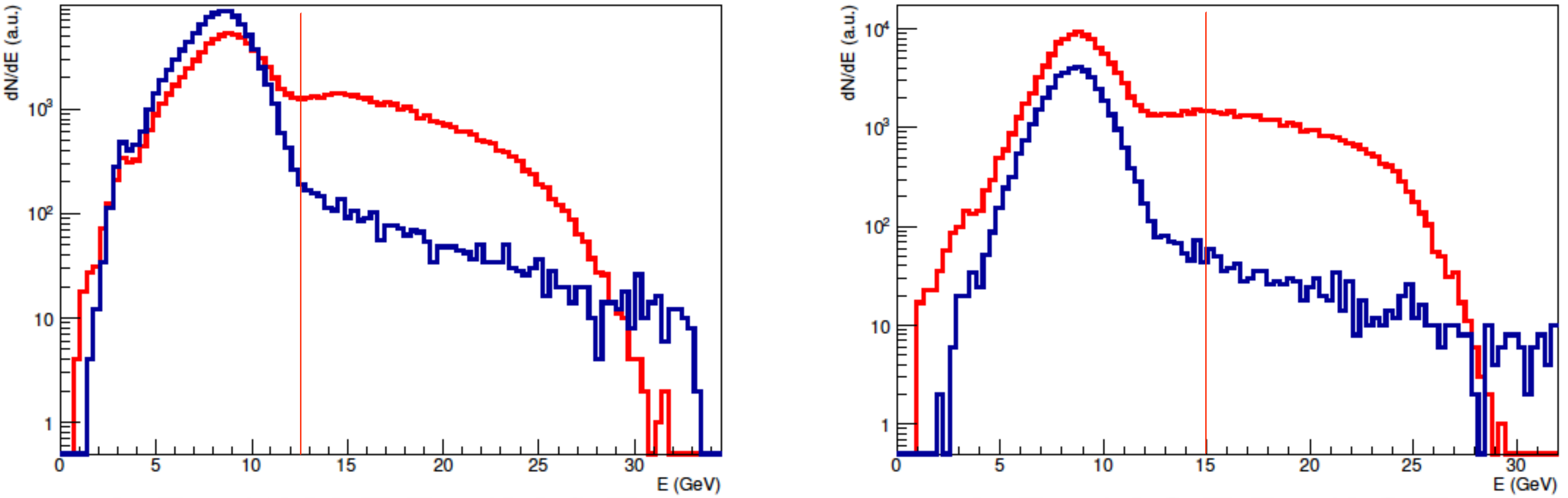

n=2 E_{th}~140 MeV, E_T~12.5 GeV

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 $n = 3$.

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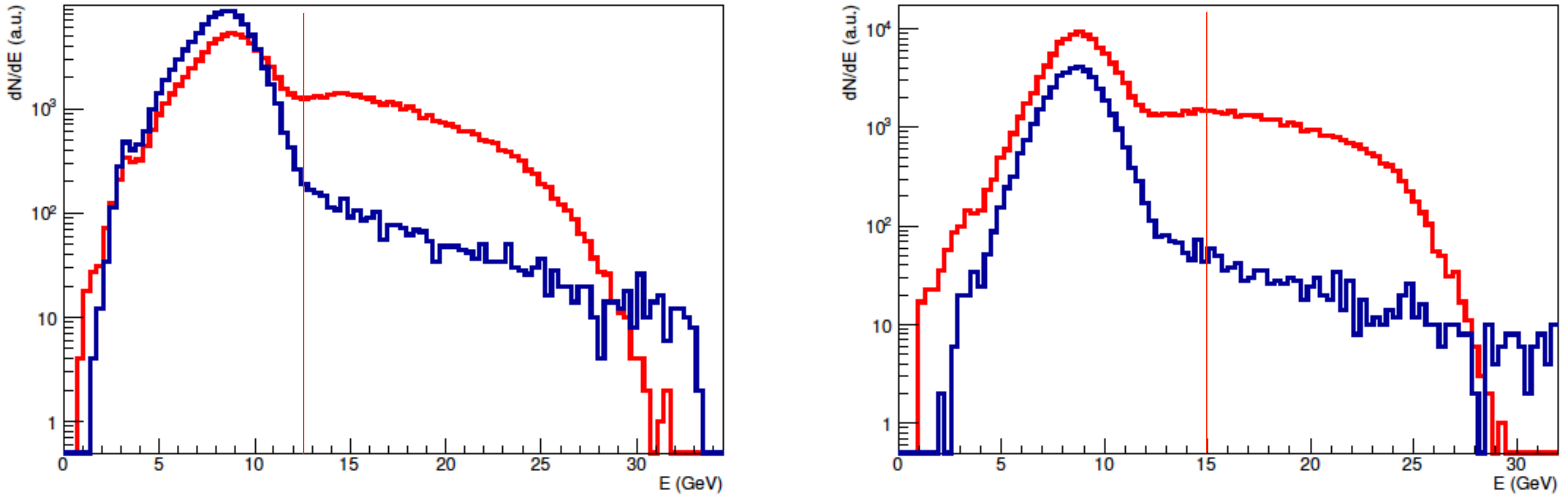

n=2 $E_{th}\sim$140 MeV, $E_T\sim$12.5 GeV　**n=3 $E_{th}\sim$1.5 GeV, $E_T\sim$15 GeV**

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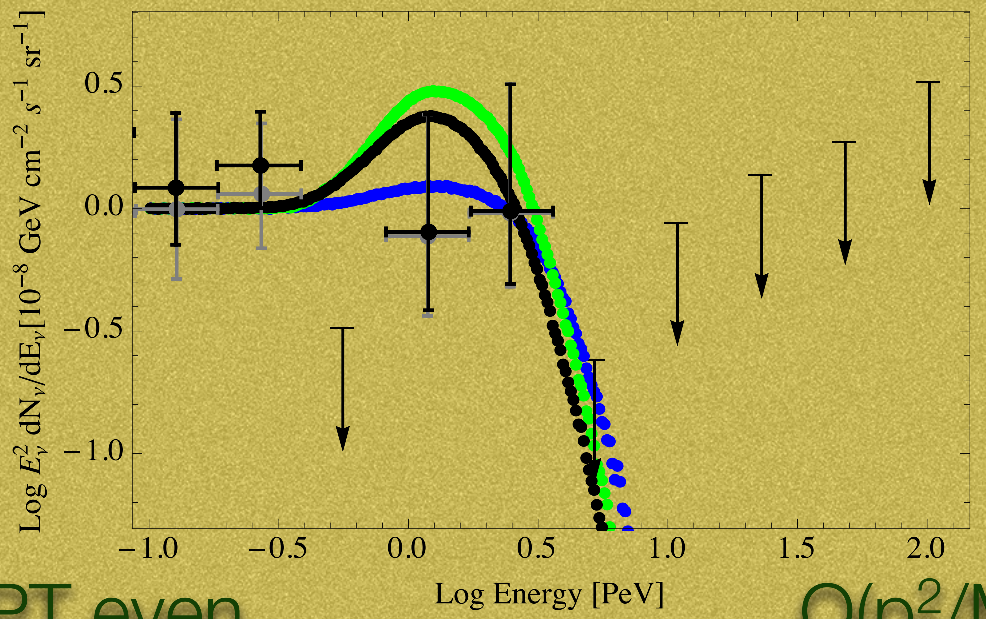
The argument was formally correct but did not worry about adjusting for the finite size of the baseline: a finite baseline can be of the same order as the energy loss length of neutrinos undergoing pair production.
This allows for some neutrinos to undergo only one or a few Cherenkov emissions within 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 ET.
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.

HE NEUTRINOS CUT-OFF FROM LIV?

F.W. Stecker, S.T. Scully, SL, D. Mattingly. arXiv:1411.5889

Assume a conservative scenario for the redshift distribution of extragalactic neutrino sources (tracing star formation rate) and employ Monte Carlo techniques to describe superluminal neutrino propagation, treating kinematically allowed energy losses of superluminal neutrinos caused by both vacuum pair emission (VPE) and neutrino splitting and redshift



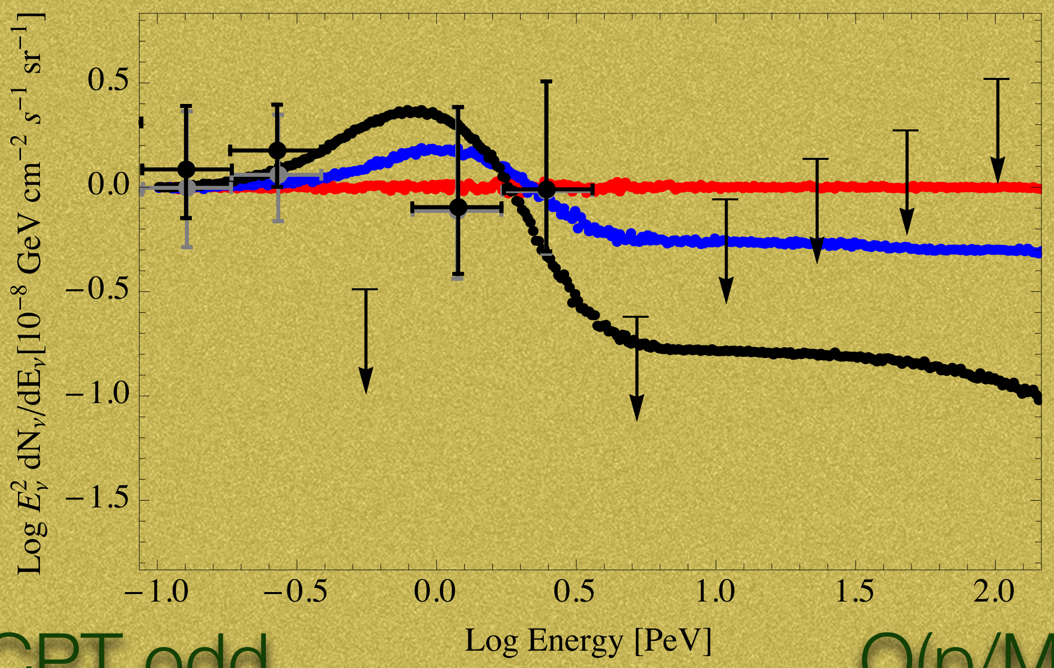
CPT even $O(p^2/M^2)$

FIG. 1: Separately calculated n = 2 neutrino spectra with the VPE case shown in blue and the neutrino splitting case shown in green. The black spectrum takes account of all three processes (redshifting, splitting, and VPE) occurring simultaneously. The rates for all cases are fixed by setting the rest frame threshold energy for VPE at 10 PeV. The neutrino spectra are normalized to the IceCube data both with (gray) and without (black) an estimated flux of prompt atmospheric neutrinos subtracted. [6].

$$\delta_{IJ} \equiv \kappa_{IJ,n}\left(\frac{E}{M_{Pl}}\right)^n$$

For CPT even

Spectra matched for $\delta_n = 5.2\times10^{-21}$ at 10 PeV which implies $\varkappa_2$ of 7.78×10^3



CPT odd $O(p/M)$

FIG. 5: Calculated n = 1 neutrino spectra assuming 100% (black), 50% (blue) and 0% (red) initial superluminal neutrinos (antineutrinos). The neutrino spectra are normalized to the IceCube data [6].

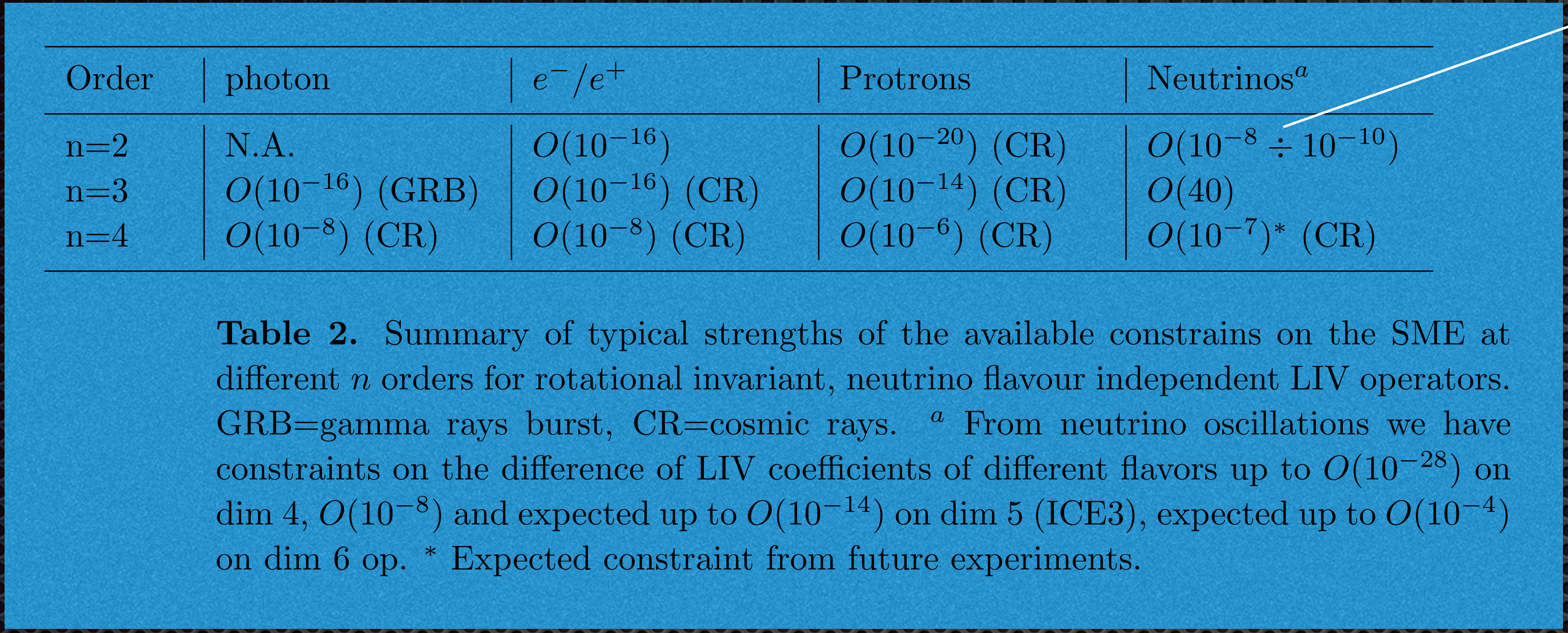
If the drop off in the neutrino flux above ~ 2 PeV is caused by Planck scale physics, rather than by a limiting energy in the source emission, a potentially significant pileup effect would be produced just below the drop off energy in the case of CPT-even operator dominance. However, such a clear drop off effect would not be observed if the CPT -odd, CPT -violating term dominates.

TESTING LORENTZ VIOLATIONS: END OF THE STORY?

SN1987a time of flight Constraint

$$\left(\frac{\Delta c}{c}\right)_{\gamma,\bar{\nu}_e} \lesssim 10^{-8} \div 10^{-10}$$

E~10 MeV
L~150000 Ly



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…

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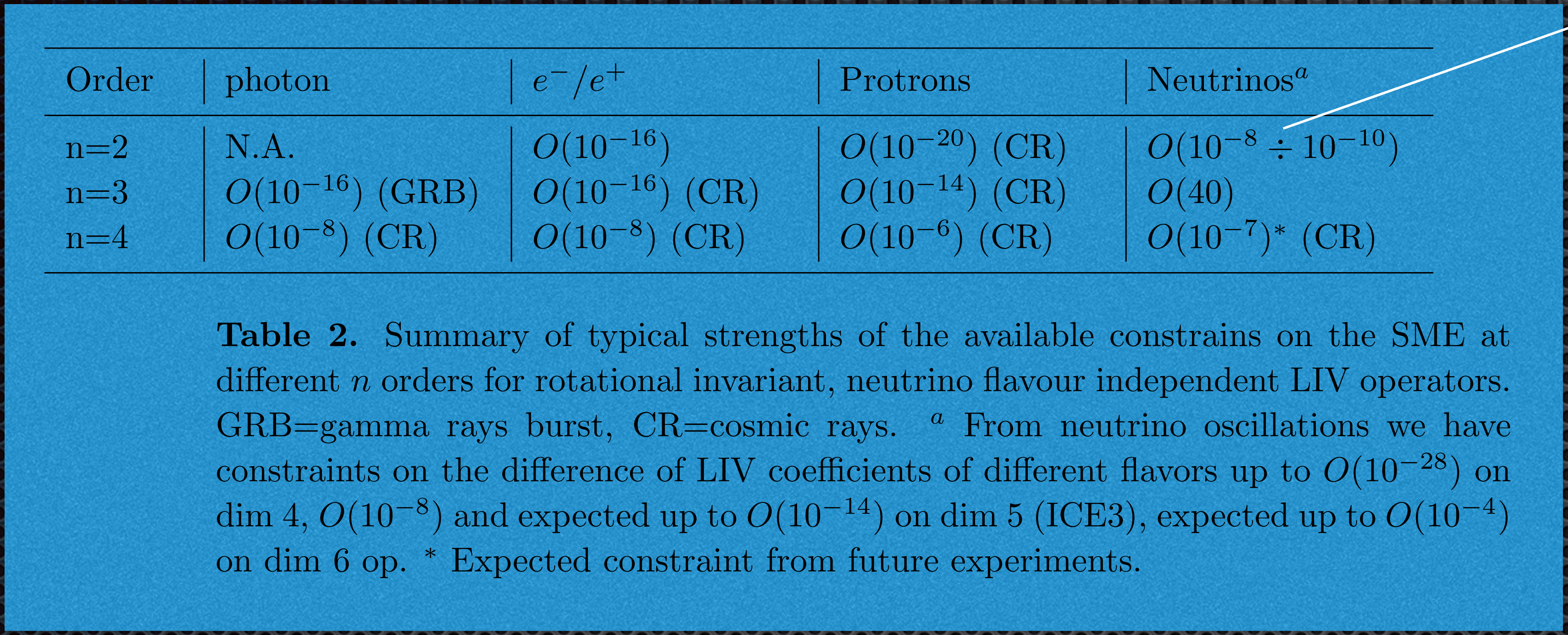

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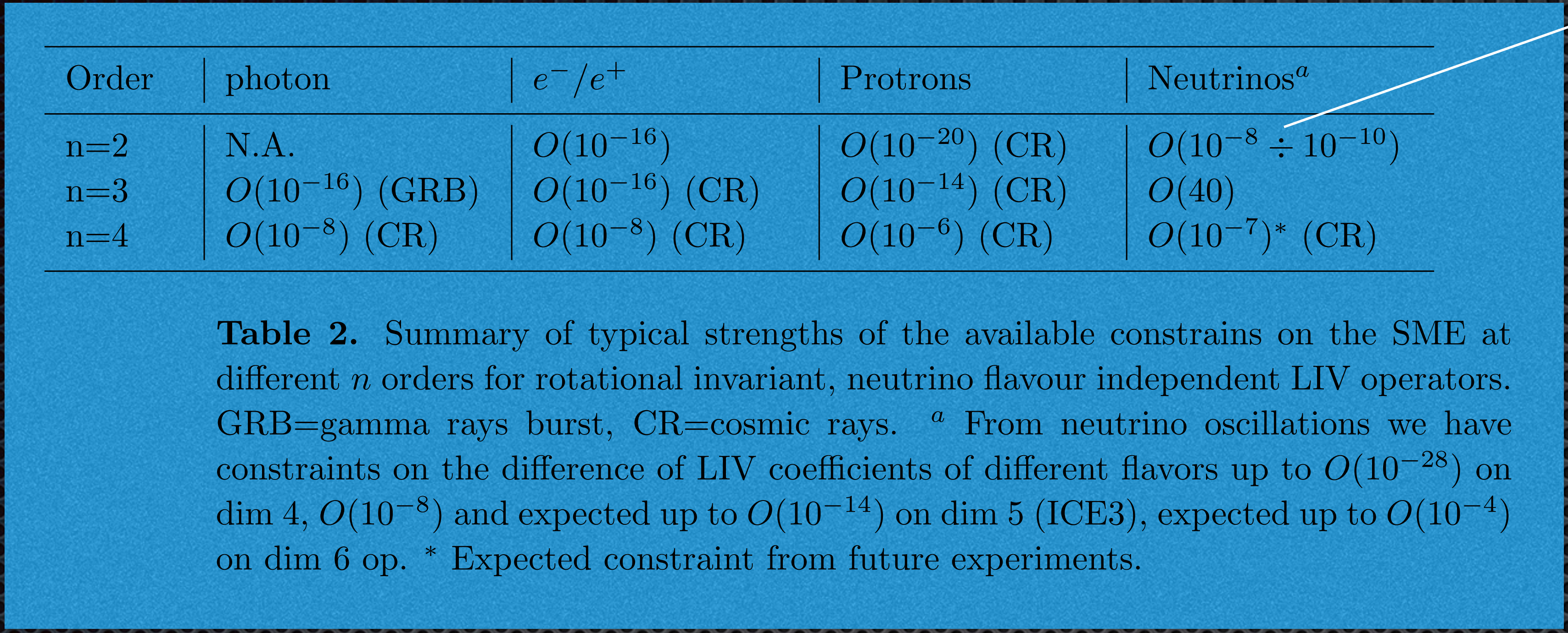

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Not quite…

CAVEAT: A POTENTIAL PROBLEM WITH THE UHECR DATA?

- With increased statistics the composition of UHECR beyond 10^{19} 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 really 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? See e.g. arXiv:1408.5213

Caveat: A potential problem with the UHECR data?

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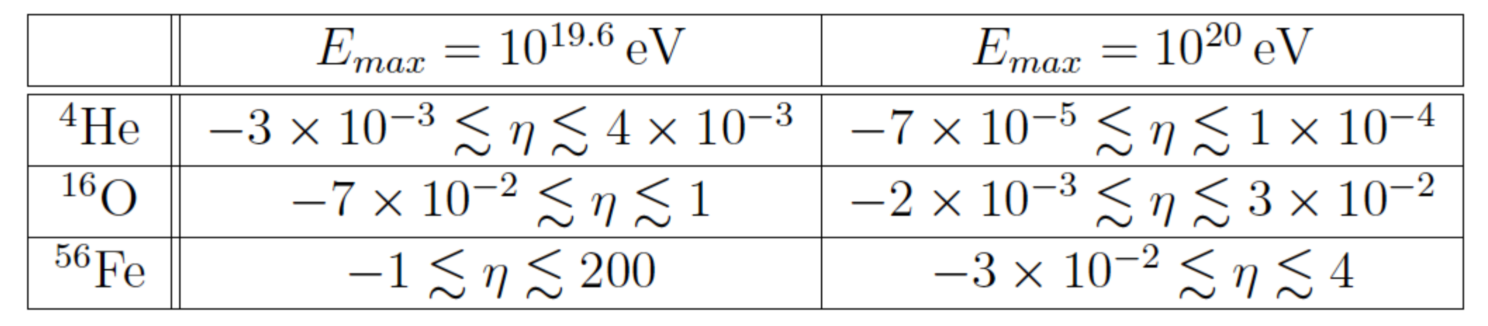
However…

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	$-3 \times 10^{-3} \lesssim \eta \lesssim 4 \times 10^{-3}$	$-7 \times 10^{-5} \lesssim \eta \lesssim 1 \times 10^{-4}$
^{16}O	$-7 \times 10^{-2} \lesssim \eta \lesssim 1$	$-2 \times 10^{-3} \lesssim \eta \lesssim 3 \times 10^{-2}$
^{56}Fe	$-1 \lesssim \eta \lesssim 200$	$-3 \times 10^{-2} \lesssim \eta \lesssim 4$

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 $v^\mu = \nabla^\mu \psi$ reads

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

Which at high momenta corresponds to the dispersion relation

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

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 $\sigma=(4\nu M_{Pl})/3c$

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

The energy loss rate Γcan 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 τto be larger than the propagation time D/c, that is τ>D/c or cħ/Γ>D.

Let us consider the observed 80 TeV photons from the Crab nebula, DCrab ≈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.

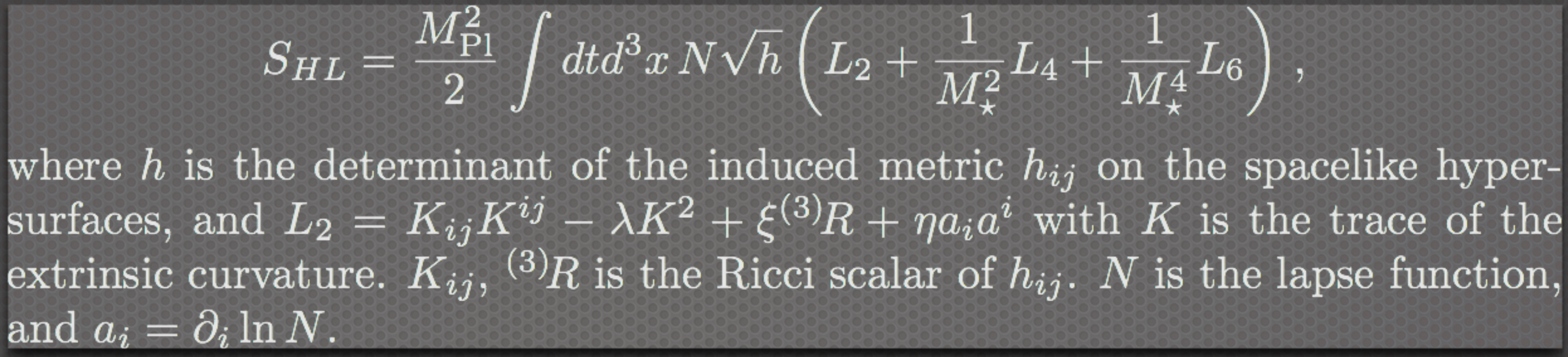
Next order would be

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

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…

UV Lorentz breaking Gravity with a preferred foliation: Horava gravity

Horava-Lifshitz Idea: achieve power-counting renormalizability by modifying the graviton propagator in the UV by adding to the action terms containing higher order spatial derivatives of the metric, but not higher order time derivatives, so to preserve unitarity (anistotropic scaling). This procedure naturally leads to a space-time foliation into spacelike surfaces, labeled by the t coordinate and with x_i being the coordinates on each surface.



$$S_{HL} = \frac{M_{\rm Pl}^2}{2}\int dt d^3x\, N\sqrt{h}\left(L_2 + \frac{1}{M_\star^2}L_4 + \frac{1}{M_\star^4}L_6\right),$$

where h is the determinant of the induced metric h_{ij} on the spacelike hypersurfaces, and $L_2 = K_{ij}K^{ij} - \lambda K^2 + \xi {}^{(3)}R + \eta a_i a^i$ with K is the trace of the extrinsic curvature. K_{ij}, ${}^{(3)}R$ is the Ricci scalar of h_{ij}. N is the lapse function, and $a_i = \partial_i \ln N$.

L_4 and L_6 denote a collection of 4th and 6th order operators respectively and M^* is the scale that suppresses these operators.

These Infrared (IR) Lorentz violations are controlled by three dimensionless parameters that take the values $\lambda=1$, $\xi=1$, $\eta=0$ in General Relativity (GR). L_2 coincides with Einstein-Aether gravity in the limit of hypersurface orthogonal aether. Constrained but not ruled out.

Unfortunately L_4 and L_6 contain a very large number of operators ($\sim 10^2$) and so have been proposed several restrictions to the theory to limit them. In particular

Projectability; $N=N(t)$ | Detailed balance

There is still debate about these constraints, we shall not deal with them here

CONSTRAINTS ON HORAVA-LIFSHITZ GRAVITY

How much can be M*? **It is indeed bounded from below and above**

$$M_{\rm obs} < M_\star < 10^{16}\ \mathrm{GeV} \qquad M_{\rm obs} \approx \text{few meV} \quad \text{(from sub mm tests)}$$

Due to the reduced symmetry with respect to GR, the theory propagates an extra scalar mode. If one chooses to restore diffeomorphism invariance, then this mode manifests as a foliation-defining scalar.

Blas,Pujolas,Sibiryakov,
Phys. Lett. B 688, 350 (2010).

The condition M*<10^{16} GeV
is a consequence of the need to protect perturbative renormalizability by assuring that the mass scale of the Horava scalar mode Msc>M* (ie. strong coupling only when UV terms become non negligible)
Plus Solar System constraints on L_2 that generically imply Msc<10^{16} GeV.

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However we have already seen that LIV cannot be confined to gravity!

Higher order operators will always induce lower order ones by radiative corrections!
The symmetries of the LIV operators in Hořava-Lifshitz action naturally leads to the expectation for matter MDR
(we assume no LIV at three level in matter and that CPT, P even nature of LIV in gravity sector is maintained in the LIV terms induced in matter)

$$E^2 = m^2 + p^2 + \eta \frac{p^4}{M_{\rm LV}^2} + O\left(\frac{p^6}{M_{\rm LV}^4}\right) .$$

Using time delay from GRB one can infer $M_{LV}>10^{11}$ GeV. Can we improve this without using UHECR?

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So is $M_{\rm LIV}$~M* or $M_{\rm LIV} \gg$M* ?

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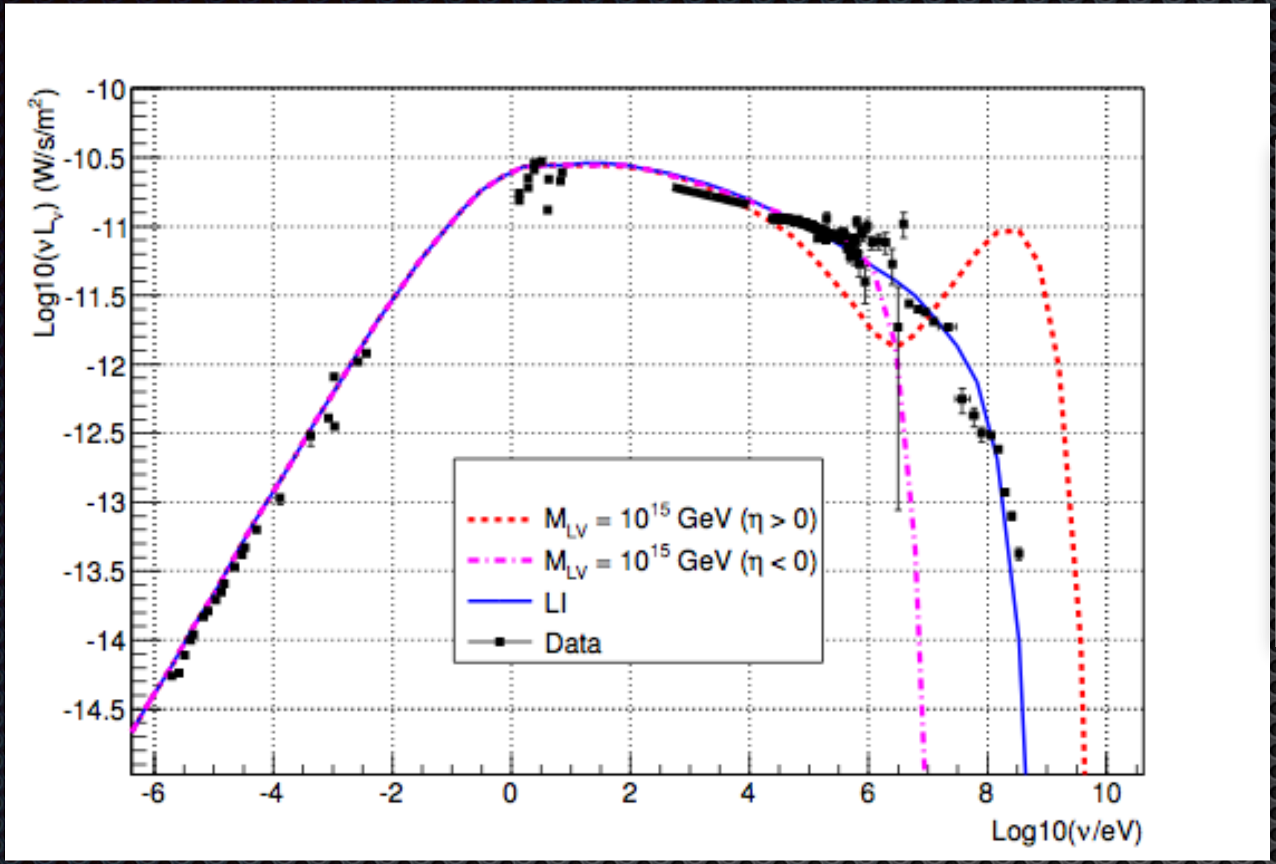
Synchrotron radiation constraint for Horava-Lifshitz Gravity



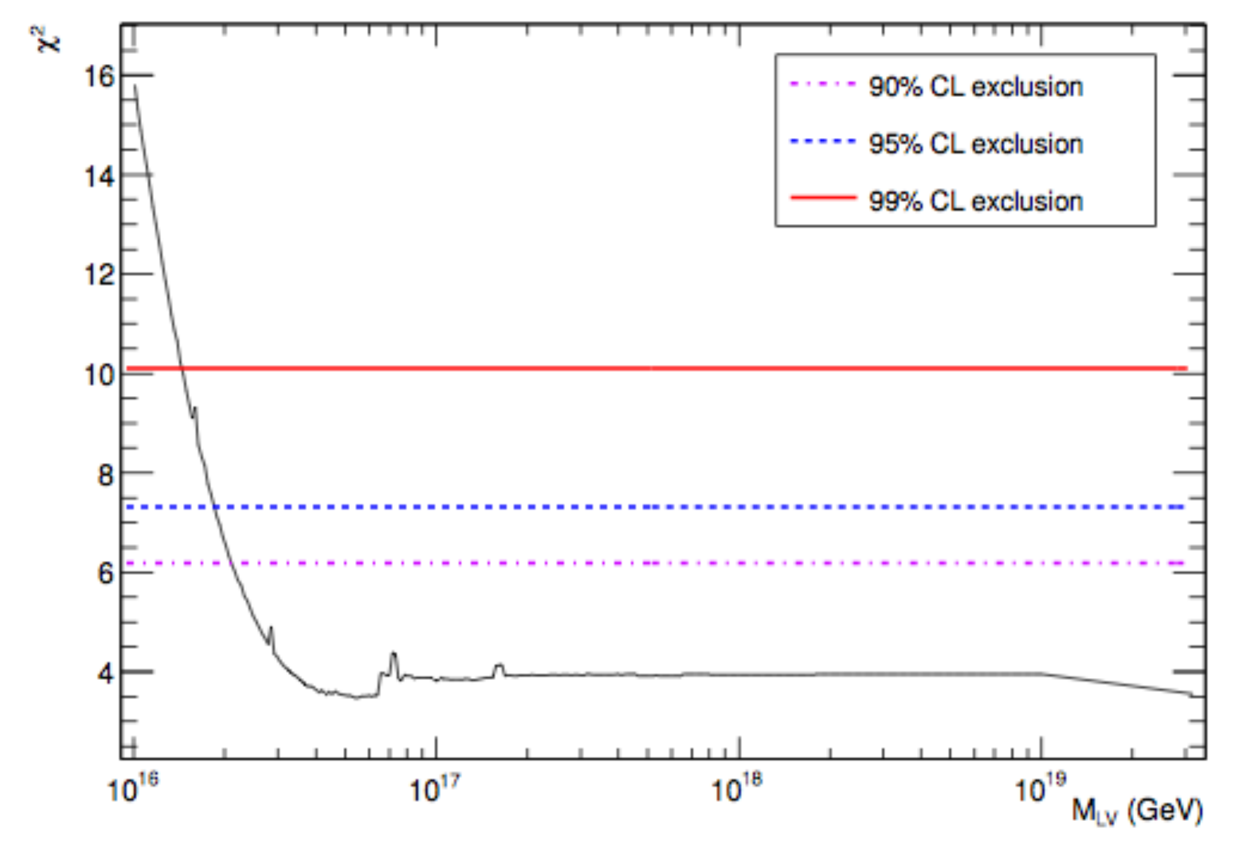
SL, Maccione, Sotiriou. Phys.Rev.Lett. 109 (2012) 151602

Crab Nebula spectrum for the LI case (blue, solid curve), for the LV case n=4, with $M_{LV} = 10^{15}$ GeV and $\eta>0$ (red, dashed curve), and for the case with same parameters but $\eta<0$ (magenta, dot-dashed curve). While, as discussed, the $\eta<0$ case would lead to premature fall off of the synchrotron spectrum, we see here that for $\eta>0$ there is a sudden surge of emission at high frequencies, followed by a dramatic drop due to the onset of vacuum Čerenkov emission at the characteristic threshold energy $E_{th}\cong[mM_{LV}]^{1/2}/\eta^{1/4}$.

Dependence of the reduced χ^2 on MLV.
By considering the offset from the minimum of the reduced χ^2 we set exclusion limits at 90%, 95% and 99% Confidence Level (CL).

Mass scales $M_{LV}\cong 2 \times 10^{16}$ GeV are excluded at 95% CL. The window for M_{LV}~M* is closed.

Therefore a mechanism, suppressing the percolation of LV in the matter sector, must be present in HL models, and such mechanism should not only protect lower order operators.



WHAT NEXT?

Tests of Lorentz Violations

- We need better data from UHECR and Cosmogenic Neutrinos to constraint O(k^4)
- The gravity sector needs more exploration: apparently consistent models need sub-Planck LIV scale, can we test it directly or indirectly?

Other mesoscopic physics without Lorentz violation?

- One might try to relax other principles rather than the relativity one… but nothing seems to work…
- 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). Also Deformed Special Relativity attempt led to Non-Locality (Relative Locality).
- Conjecture: Discreetness + Lorentz Invariance = Non-Locality

See e.g.
Belenchia, Benincasa and SL,
arXiv:1411.6513

Is this the new phenomenology we have to seek for?

More Soon…

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Break Precausality ➔ Hell breaks loose, better not!

Break Principle of relativity ➔ Preferred frame, Modified dispersion relations

Break kinematical Isotropy ➔ Finsler geometries.
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. Can this lead to Finsler again? True geometry on the phase space?

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