POSSIBLE VIOLATIONS OF SPACE-TIME SYMMETRIES

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PLAN OF THE TALK

- STANDARD SPACETIME SYMMETRIES
- TESTING LORENTZ SYMMETRY: MOTIVATIONS
- MODEL FOR PROBING ACTIVE LORENTZ INVARIANCE VIOLATION (LIV)
- THE PHOTON SECTOR AND BOUNDS
- OVERVIEW OF ADDITIONAL THEORETICAL POSSIBILITIES
- EXAMPLES OF PREVIOUS AND RECENT RESEARCH
- FINAL COMMENTS
- REFERENCES

SYMMETRIES IN THE ACTION APPROACH

- Fundamental matter, their interactions and dynamics are described by fields and one functional of them: the ACTION S

$$S[A,\Psi] = \int dt\ d^3x\ L[A(t,\vec{x}),\Psi(t,\vec{x})]$$

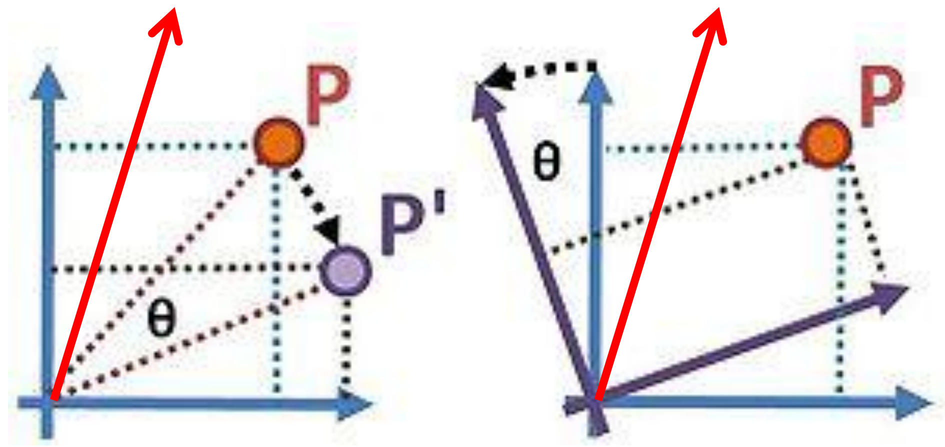
- Equations of motion (EM) are obtained extremizing S.
- Symmetries correspond to transformations

$$\delta A(t,\vec{x}) = \varepsilon^M F_M(A,\Psi), \qquad \delta\Psi(t,\vec{x}) = \mu^N G_N(A,\Psi)$$

that leave the action invariant.

- This guarantees that the EM are mixed among themselves by the symmetry.
- The action also provides the quantum version of the system.

ACTIVE AND PASSIVE TRANSFORMATIONS



- Left hand side: **ACTIVE** rotation (Fixed reference frame).
- Right hand side: **PASSIVE** rotation (Change of reference frame). Must respect freedom of observer.
- Violate **ACTIVE** symmetry with fixed non-dynamical object (Red arrow here).

- Fundamental theorem (E. Noether):

  GLOBAL SYMMETRIES IMPLY CONSERVED QUANTITIES

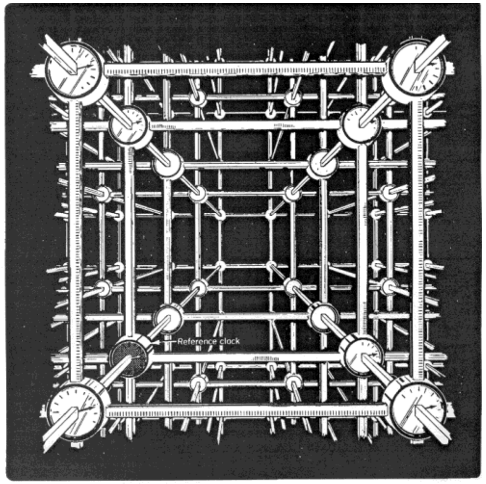
$$\partial_\mu Q^{\mu A} = 0$$

- The conserved charges are

$$Q^A(t) = \int d^3x \;\; Q^{0A}(t,\vec{x}), \qquad \frac{dQ^A}{dt} = 0$$

- In a Hamiltonian formulation they generate the Lie algebra of the corresponding symmetry group.

SPACETIME SYMMETRIES



- EVENT : recorded by coordinate system

$$(ct,\ \vec{x}) = (x^{\mu}), \quad \mu = 0,1,2,3$$

- Speed of light c is constant in inertial frames
- Laws of Physics have the same form in inertial frames:

$$T = 0, \quad T_{\alpha\beta\ldots}{}^{\mu\nu\ldots\ldots} = 0, \quad T'_{\alpha\beta\ldots}{}^{\mu\nu} = 0$$

- Transformations among inertial frames are such that

$$x'^{\mu} = \Lambda^{\mu}{}_{\nu} x^{\nu}, \quad c^2dt^2 - dx^2 - dy^2 - dz^2 = c^2dt'^2 - dx'^2 - dy'^2 - dz'^2$$

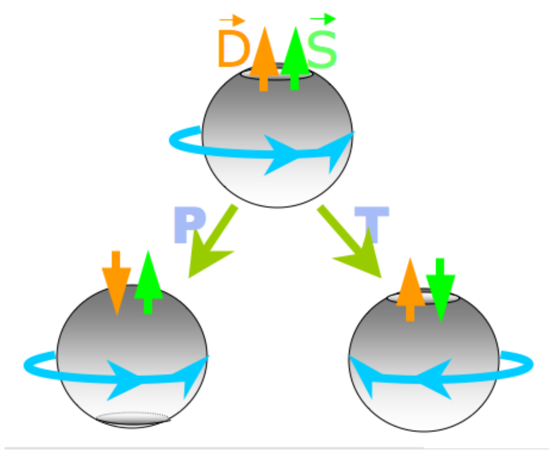
- This set of transformation defines the six parameter Lorentz group, which contains the rotation group.

- Invariance of the action under LT and T, via Noether's theorem provide conservations laws: energy and momentum P_ρ and angular momentum $M_{\mu\nu}$.
- These generators combine to produce the Poincare algebra

$$[P_\mu, P_\nu] = 0, \qquad [M_{\mu\nu}, P_\rho] = i\left(\eta_{\mu\rho}P_\nu - \eta_{\nu\rho}P_\mu\right)$$

$$[M_{\mu\nu}, M_{\rho\sigma}] = i\left(\eta_{\mu\rho}M_{\nu\sigma} - \eta_{\mu\sigma}M_{\nu\rho} - \eta_{\nu\rho}M_{\mu\sigma} + \eta_{\nu\sigma}M_{\mu\rho}\right)$$

- Discrete spacetime symmetries:



$$\text{Parity} \quad P: \quad \vec{x}\,' = -\vec{x},$$

$$\text{Time reversal} \quad T: \quad t' = -t$$

- Related symmetry:

$$\text{Charge conjugation} \quad C: \quad \text{particle} \leftrightarrow \text{antiparticle}$$

PARITY

- Violated in weak interactions only.
- 1956: Lee and Yang propose tests to probe it .
- 1957: C.S. Wu et al. Find violation in beta decay of Co^{60} [PR 105(1957)1413].
- 1957: Garwin, Ledermann and Weinrich separetely confirm violation [PR 105(1957)1415].

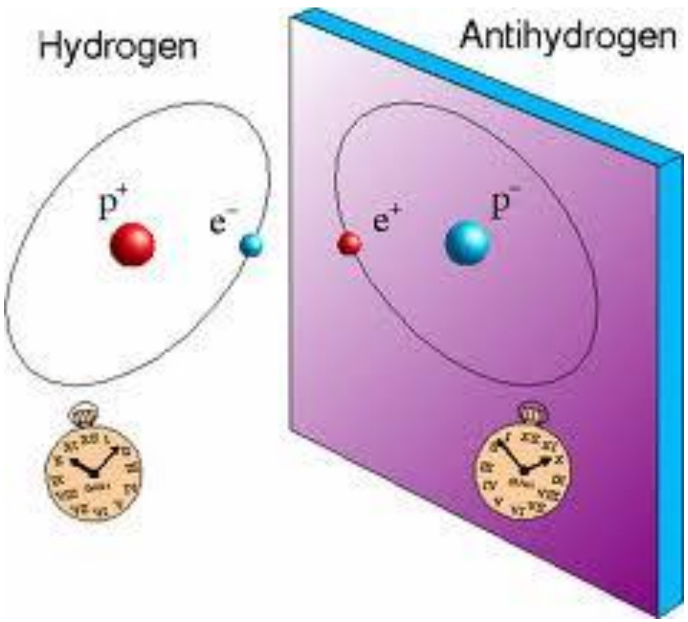
CP

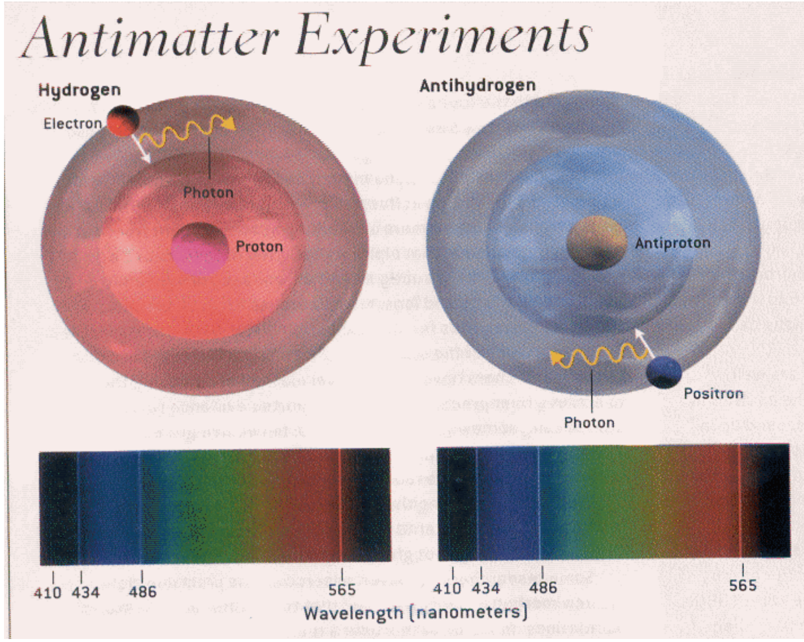
- Violated in weak interactions.
- 1964: J. Cronin and V. Fitch find violation in decays of the neutral Kaons.
- Strong CP problem: no experimental CP violations detected in strong interactions , even if theoretically allowed.

- CPT theorem:

Any quantum theory which is Lorentz invariant, local, with an hermitian Hamiltonian, must have CPT symmetry

[Schwinger, Luders-Pauli,……]



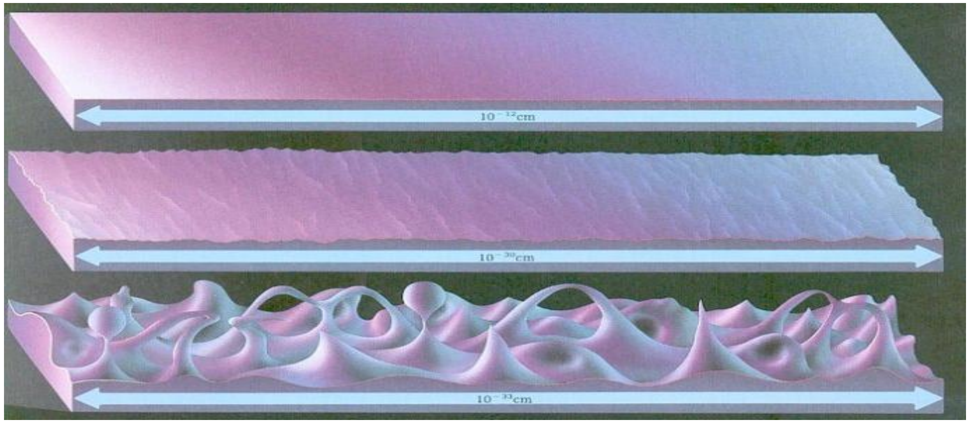


- Greenberg’s Theorem [O.W. Greenberg, PRL 89(2002)231602]

CPT violation implies Lorentz violation

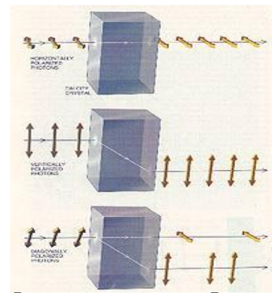
WHY TESTING LORENTZ SYMMETRY??

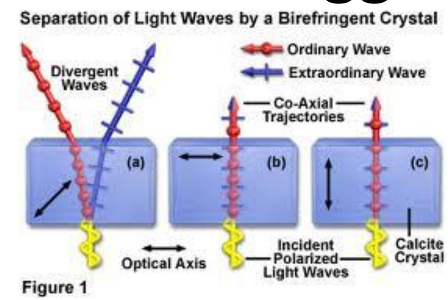
- Physics is an experimental science.
- For example, many experiments and observations in Atomics Physics have attained Planck scale sensitivities ⇨ they may serve as constraints for competing dynamical theories of spacetime.
- Most of them suggest that space has a granular, foamy, discrete structure at very short distances.
- Loop Quantum Gravity leads to discrete spectrum for area and volume operators.



- Big question arises: **does this structure modifies particle propagation at SM energies?**

- Propagation of photons in a crystal would suggest modifications do arise.

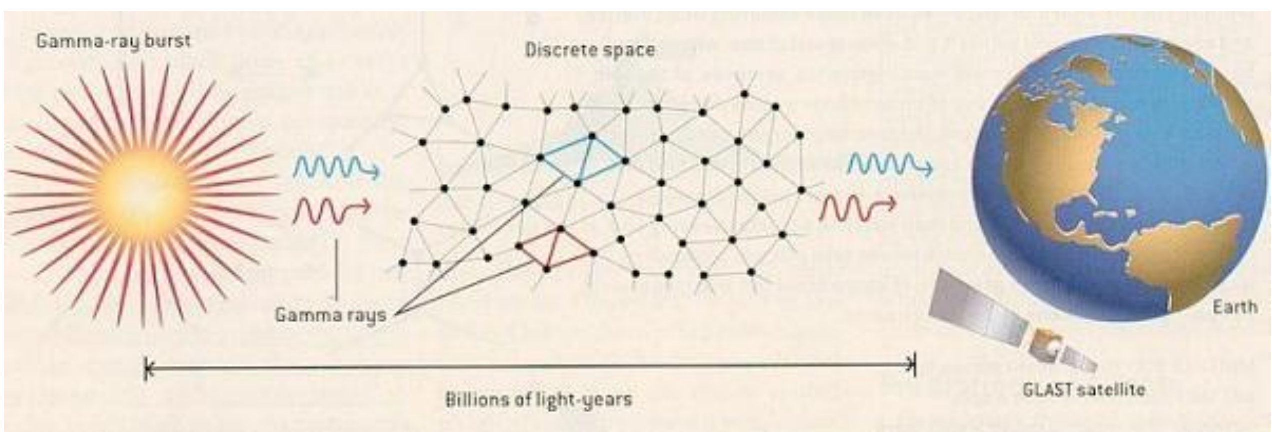




- **Nature of them???**

- Possibility of incorporating minute Lorentz invariance violations suppressed by quantum gravity scale **[G. Amelino-Camelia et al., Nature 393(1998) 763].**

$$E_{QG} \approx M_{Planck} = M_P \approx 10^{19}\ GeV \qquad L_{Planck} = \ell_P \approx 10^{-33}\ cm.$$



- Modified dispersion relation for photons:

$$c^2 \vec{k}^2 = E^2 \left(1 \pm \xi \frac{E}{E_{QG}} + \dots \right), \quad \Rightarrow \quad |\vec{v}| = |grad_{\vec{k}} E| = c \left(1 \mp \xi \frac{E}{E_{QG}} + \dots \right).$$

- Predicts time delays for photons with different energies emitted from a given source. A first approximation provides

$$\Delta t = \xi \frac{L}{c} \frac{\Delta E}{E_{QG}}.$$

- For example:

$$L \approx 10^{10} l.y. , \quad \Delta E \approx 20 \ MeV, \quad E_{QG} / \xi \approx 10^{19} GeV,$$

yields

$$\Delta t \approx 10^{-3} s$$

- Numerous observations have been made and set limits upon the quantum gravity scale

OBSERVATIONAL PERSPECTIVES

(1) PHOTONS

Some Gamma Ray Burst (GRB) originate at cosmological distances ($D > 10^{10}$ l.y., $z > 1$) with known red shifts.

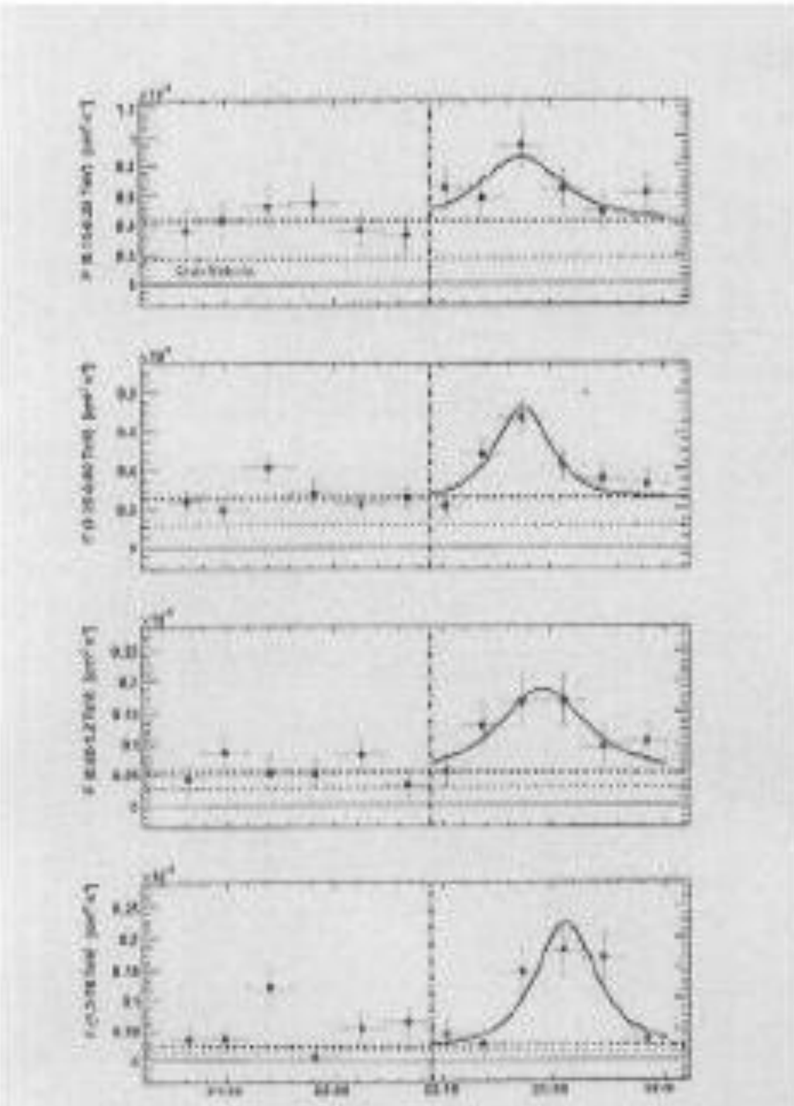
EXPERIMENT	GRB/YEAR	*PHOTON ENERGY*	δt (s)
AMS	25	$E_\gamma > 100$ GeV	10^{-3}
RHESSI		$3\,\mathrm{KeV} < E_\gamma < 17\,\mathrm{MeV}$	10^{-6}
GLAST	25	$E_\gamma > 10$ GeV	10^{-7}

(2) NEUTRINOS

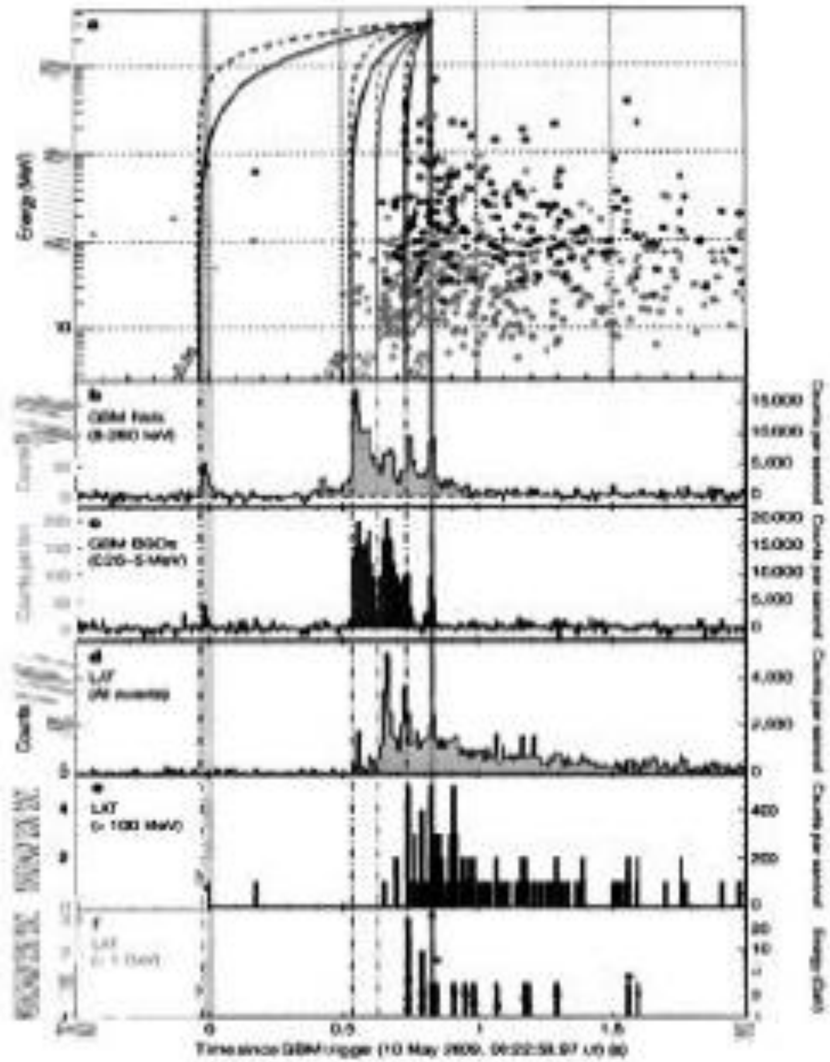
The fireball model of GRB's predicts also the generation of $10^{14} - 10^{19}$ eV Neutrino Bursts (NB).

EXPERIMENT	EVENTS/YEAR	*PARTICLE ENERGY*	TYPE OF EVENTS
NUBE	20	$E_\nu > 10^4$ GeV	ν in coindicence with γ
OWL	100	$E_\nu > 10^8$ GeV	ν in coindicence with γ
EUSO	$300 - 1000$	$10^{13} < E < 10^{15}$ GeV	UHECR + ν

Light curve of AGN Markarian 501, MAGIC collaboration



Light curve of GRB090510 [FERMI collaboration]



FOR LINEAR DISPERSION RELATIONS

OBSERVATION			Lower Bound for E_{QG} / ξ
Kaaret et al.	99	(Pulsar)	$1.8 \; x \; 10^{15} \; GeV$
Ellis et al.	06	(GRB)	$0.9 \; x \; 10^{16} \; GeV$
Biller et al.	98	(AGN)	$4.0 \; x \; 10^{16} \; GeV$
Boggs et al.	04	(GRB)	$1.8 \; x \; 10^{17} \; GeV$
Albert et al.	08	(AGN)	$0.2 \; x \; 10^{18} \; GeV$
Abdo et al.	09	(GRB1)	$1.3 \; x \; 10^{18} \; GeV$
Abdo el al.	09	(GRB2)	$(1.4-122) \; x \; 10^{19} \; GeV$

$$M_{Planck} = 1.2 \; x \; 10^{19} \; GeV$$

MODEL FOR PROBING ACTIVE LIV

- In atomics physics sensitivities up to

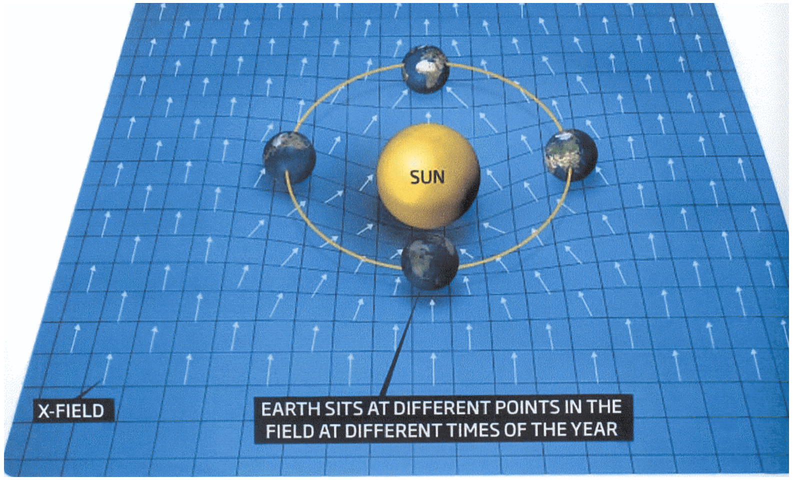
$$\Delta\nu \approx 1\,\mathrm{mHz} \quad \Rightarrow \quad \Delta\mathrm{E} \approx 4 \times 10^{-27}\,\mathrm{GeV}$$

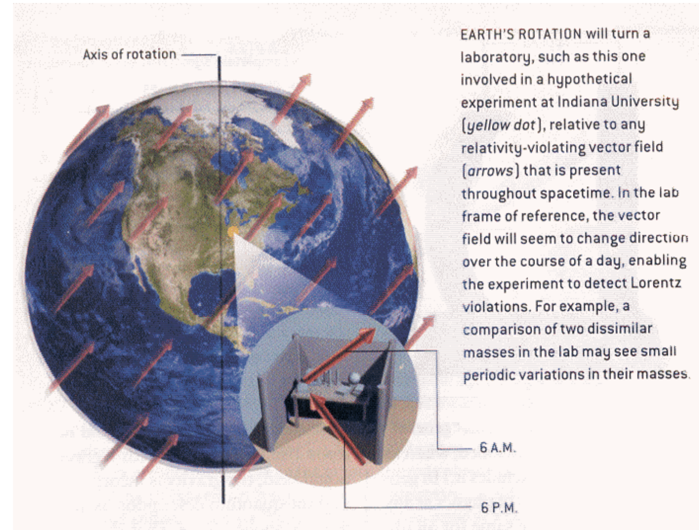
$$\left(\frac{\mathrm{m_p}}{\mathrm{M_P}}\right)\mathrm{m_p} \approx 10^{-19}\,\mathrm{GeV}, \qquad \left(\frac{\mathrm{m_e}}{\mathrm{M_P}}\right)\mathrm{m_e} \approx 10^{-26}\,\mathrm{GeV}$$

- Introduce phenomenological actions that violate LIV via some parameters. Design experiments that probe these parameters: either find a signal or bound them.
- **The Standard Model Extension: SME** **[Colladay and Kostelecky, PRD55(1997)6760; PRD58(1998)116002; Kostelecky, PRD69(2004)105009 + … +…+………]**
- **SME**: (1) All possible dim 3 and 4 LIV operators consistent with particle content and interactions of SM. Extended to gravity and higher order operators.

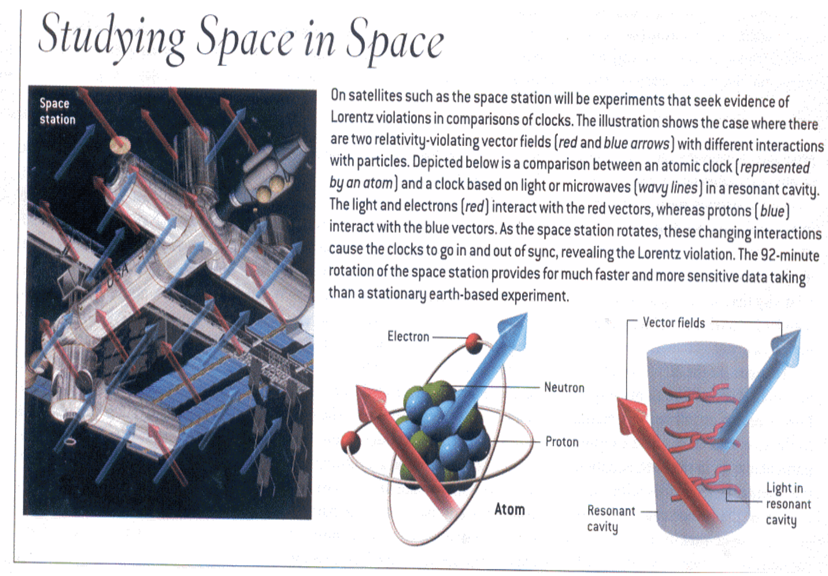
  (2) LIV non-dynamical fields arising from spontaneous symmetry breaking in a more fundamental theory

- The picture that emerges





- Most experiments look for sidereal or daily variations of signals produced by the coupling of matter and gauge fields to the VEV's



THE PHOTON SECTOR OF THE SME

(Talk by P. Wolf et al., Paris, june 2010)

$$L = -\frac{1}{4} f_{\mu\nu} f^{\mu\nu} - \frac{1}{4} (k_F)^{\kappa\lambda\mu\nu} f_{\kappa\lambda} f_{\mu\nu}, \qquad (k_F)^{\kappa\lambda\mu\nu} : 19 \text{ components}$$

$$\begin{pmatrix} \vec{D} \\ \vec{H} \end{pmatrix} = \begin{pmatrix} \varepsilon_0 (\boldsymbol{\varepsilon}_r + \boldsymbol{\kappa}_{DE}) & \sqrt{\varepsilon_0/\mu_0}\, \boldsymbol{\kappa}_{DB} \\ \sqrt{\varepsilon_0/\mu_0}\, \boldsymbol{\kappa}_{HE} & \mu_0^{-1} (\boldsymbol{\mu}_r^{-1} + \boldsymbol{\kappa}_{HB}) \end{pmatrix} \begin{pmatrix} \vec{E} \\ \vec{B} \end{pmatrix}$$

10 components: limited by astrophysical tests to $\leq 10^{-32}$

$$(\tilde{\kappa}_{e+})^{jk} = \tfrac{1}{2}(\kappa_{DE} + \kappa_{HB})^{jk}; \qquad (\tilde{\kappa}_{o-})^{jk} = \tfrac{1}{2}(\kappa_{DB} - \kappa_{HE})^{jk}$$

$$(\tilde{\kappa}_{e-})^{jk} = \tfrac{1}{2}(\kappa_{DE} - \kappa_{HB})^{jk} - \tfrac{1}{3}\delta^{kj}(\kappa_{DE})^{ll}; \quad (\tilde{\kappa}_{o+})^{jk} = \tfrac{1}{2}(\kappa_{DB} + \kappa_{HE})^{jk},$$

$$\tilde{\kappa}_{tr} = \tfrac{1}{3}(\kappa_{DE})^{ll}.$$

1 component: limited by IS exp. at $\approx 10^{-7}$

5 components: limited by resonator tests at $\approx 10^{-17}$

3 components: limited by resonator tests at $\approx 10^{-13}$

LIST OF EXPERIMENTS AND BOUNDS

arXiv: 0801.0287v8: Rev. Mod. Phys.83(2011)11-31

IUHET 538, January 2010

Data Tables for Lorentz and CPT Violation

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(Dated: January 2010 edition)

This work tabulates measured and derived values of coefficients for Lorentz and CPT violation in the Standard-Model Extension. Summary tables are extracted listing maximal attained sensitivities in the matter, photon, and gravity sectors. Tables presenting definitions and properties are also compiled.

TABLE VIII: Photon sector (continued)

Combination	Result	System	Ref.
$(\tilde{\kappa}_{e-})^{XX} - (\tilde{\kappa}_{e-})^{YY}$	$(0.80 \pm 1.27) \times 10^{-17}$	Rotating optical resonators	[46]
"	$(0.8 \pm 2.0 \pm 0.3) \times 10^{-17}$	"	[47]
"	$(-2.0 \pm 1.7) \times 10^{-17}$	"	[48]
"	$(-12 \pm 16) \times 10^{-16}$	Optical, microwave resonators	[27]*
"	$(-5.0 \pm 4.7) \times 10^{-16}$	Rotating microwave resonators	[49]
"	$(5.4 \pm 4.8) \times 10^{-16}$	Rotating optical resonators	[50]
"	$(-1.3 \pm 0.9) \times 10^{-15}$	Rotating microwave resonators	[51]
"	$(2.8 \pm 3.3) \times 10^{-15}$	Optical, microwave resonators	[28]*
"	$(-3.2 \pm 4.6) \times 10^{-15}$	Microwave resonator, maser	[52]
"	$(8.9 \pm 4.9) \times 10^{-15}$	Optical resonators	[53]
"	$(-1.0 \pm 2.1) \times 10^{-13}$	Microwave resonators	[54]

TABLE XII: Electroweak sector

Combination	Result	System	Ref.
$\lvert(k^A_{\phi\phi})_{\mu\nu}\rvert$	$< 3 \times 10^{-16}$	Cosmological birefringence	[91]*
$\lvert(k_{\phi B})_{\mu\nu}\rvert$	$< 0.9 \times 10^{-16}$	"	[91]*
$\lvert(k_{\phi W})_{\mu\nu}\rvert$	$< 1.7 \times 10^{-16}$	"	[91]*
$\lvert(k^S_{\phi\phi})_{XX}\rvert, \lvert(k^S_{\phi\phi})_{YY}\rvert, \lvert(k^S_{\phi\phi})_{ZZ}\rvert$	$< 10^{-27}$	Clock comparisons	[91]*
$\lvert(k^S_{\phi\phi})_{XY}\rvert$	$< 10^{-27}$	"	[91]*
$\lvert(k^S_{\phi\phi})_{XZ}\rvert, \lvert(k^S_{\phi\phi})_{YZ}\rvert$	$< 10^{-25}$	"	[91]*
$\lvert(k^S_{\phi\phi})_{TT}\rvert$	$< 4 \times 10^{-13}$	H^- ion, $\bar{p}$ comparison	[91]*
$\lvert(k_\phi)_X\rvert, \lvert(k_\phi)_Y\rvert$	$< 10^{-31}$	Xe-He maser	[91]*
$\lvert(k_\phi)_Z\rvert, \lvert(k_\phi)_T\rvert$	$< 2.8 \times 10^{-27}$	"	[91]*
$\lvert k_W\rvert$	$< 10^{-5}$	Astrophysics	[32]*

TABLE VI: Proton sector

Combination	Result	System	Ref.
$\tilde{b}_X$	$(6.0 \pm 1.3) \times 10^{-31}$ GeV	K/He magnetometer	[21]
$\tilde{b}_Y$	$(1.5 \pm 1.2) \times 10^{-31}$ GeV	"	[21]
$\sqrt{(\tilde{b}^e_X + \tilde{b}^p_X)^2 + (\tilde{b}^e_Y + \tilde{b}^p_Y)^2}$	$(3 \pm 2) \times 10^{-27}$ GeV	H maser	[35]
$\lvert\tilde{b}_J\rvert$ $(J = X, Y)$	$< 2 \times 10^{-27}$ GeV	"	[36]
$\lvert\tilde{b}_J\rvert$ $(J = X, Y)$	$< 10^{-27}$ GeV	Hg/Cs comparison	[25]*
$\tilde{c}_Q$	$(-0.3 \pm 2.2) \times 10^{-22}$ GeV	Cs fountain	[37]

EXAMPLES OF SOME EFFECTS IN LIV

- Modified dispersion relations and dynamical modifications to cross sections, decay rates, etc. [Amelino-Camelia et al., Nature 1998, Amelino-Camelia, Nature 2000.].
- Modifications in reaction thresholds [Coleman and Glashow, PRD 1999; Lehnert PRD 2003].
- Vacuum Cerenkov radiation [Lehnert and Potting, PRL 2004].
- Modifications in GZK cutoff [Coleman and Glashow, PLB 1997 ; Alfaro and Palma, PRD 2002, 2003].
- Modifications in synchrotron radiation properties [Jacobson et al., Nature 2003 , Montemayor and LFU, PLB 2005, PRD 2005].
- Photon decay [Jacobson et al., PRD 2002].
- Novel signals in neutrino oscillations [J. Diaz et al., PRD 2009].

ADDITIONAL THEORETICAL POSSIBILITIES

- Extended relativity principle. (DSR: Extended, Deformed (Double) Special Relativity): No preferred reference frame. Needs to incorporate interactions. **[Review: Amelino-Camelia, Symmetry 2010.]**
- Space foam model from non-critical string theory. Only zero charged particles receive corrections. **[J. Ellis, N. Mavromatos, D.V. Nanopoulos, et. al.: Int. J. Mod. 1997; Gen. Rel. Grav. 2000, Astrophys. J. 2000, Gen. Rel. Grav. 2000), Mavromatos PoS QG-PH:027, 2007].**
- Minimal length scenarios **[S. Hossenfelder, Liv. Rev. Rel. 16 (2013) 2].**
- Photon and Graviton as Goldstone bosons arising from SSB of Lorentz symmetry. **[Y. Nambu, 1968; J. D. Bjorken, 1963; Azatov and Chkareulli , 2006 ; Bluhm and Kostelecky, 2005; Kostelecky and Potting, 2009; Chekareuli et al. 2007,2008,2009,2001; C. Escobar and LFU, 2015].**
- Finsler Geometry. **[F. Girelli et al.,PRD 2007, Rund: The differential geometry of Finsler spaces, Springer, 1969].**
- Horava-Lifshitz gravity. **[Horava, PRD 2009].**

Makes contact with the area called Quantum Gravity Phenomenology **[Amelino-Camelia], Liv. Rev. Rel 16(2013)5.**

FIRST MODELS INVOLVING QG INSPIRED CORRECTIONS TO ELECTRODYNAMICS

- Loop Quantum Gravity inspired [R. Gambini and J. Pullin, Phys. Rev. D59(1999)124021]

$$\nabla \cdot \vec{E} = 0, \quad \partial_t \vec{E} = -\nabla \times \vec{B} + 2\,\xi\,\ell_P\,\nabla^2\,\vec{B},$$

$$\nabla \cdot \vec{B} = 0, \quad \partial_t \vec{B} = +\nabla \times \vec{E} - 2\,\xi\,\ell_P\,\nabla^2\,\vec{E}$$

$$\Rightarrow \omega_\pm(\vec{k}) = |\vec{k}|\left(1 \mp 2\,\xi\,\ell_P\,|\vec{k}|\right).$$

- String Theory inspired [J. Ellis et al., Gen. Relativ. Gravit. 32(2000)127; J. Ellis et al., Astrophys. J. 535(2000)139.]

$$\nabla \cdot \vec{E} + \vec{U} \cdot \partial_t \vec{E} = 0, \quad \nabla \times \vec{E} + \partial_t \vec{B} = 0,$$

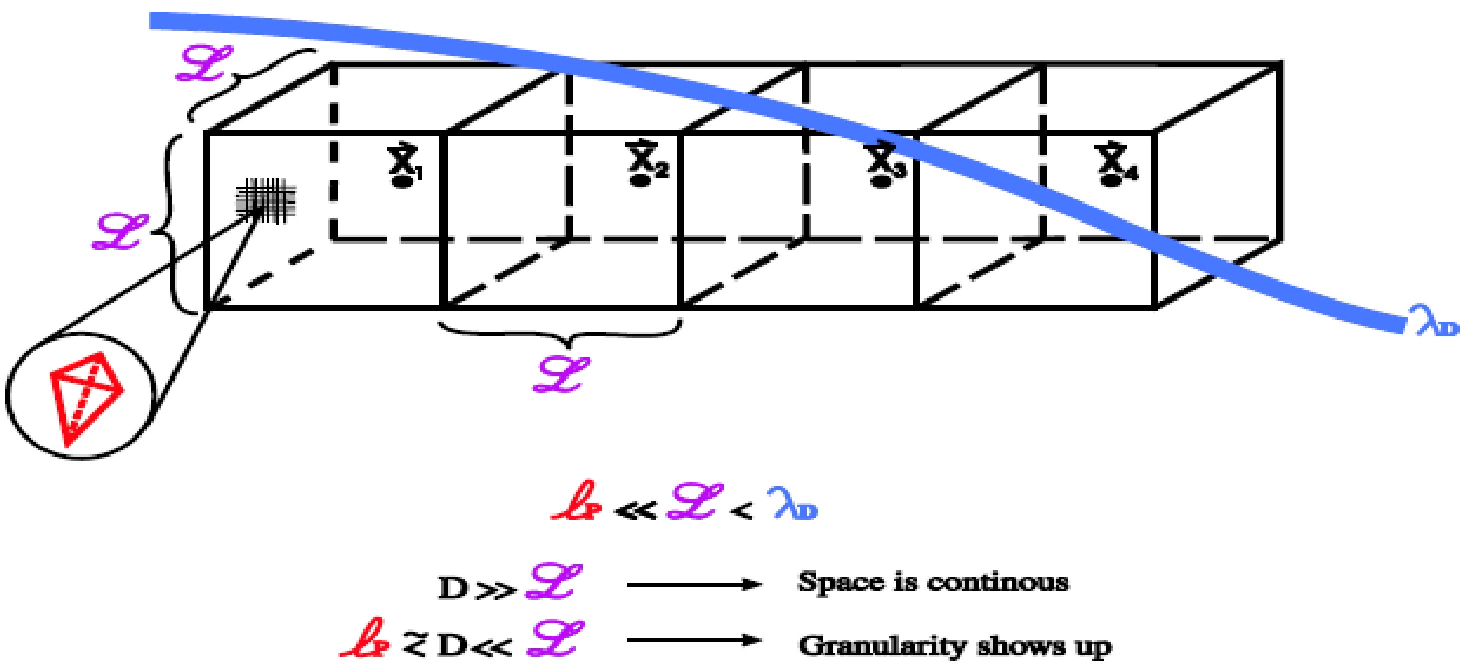
$$\nabla \cdot \vec{B} = 0, \quad \nabla \times \vec{B} - (1 - |\vec{U}|^2)\partial_t \vec{E} + \vec{U} \times \partial_t \vec{B} + (\vec{U} \cdot \nabla)\vec{E} = 0,$$

$$\Rightarrow \omega(|\vec{k}|) = |\vec{k}|\left(1 - |\vec{k}|\,\xi\,\ell_P\right), \quad |\vec{U}| = O\left(|\vec{k}|\,\xi\,\ell_P\right).$$

- Heuristic calculations inspired in loop quantum gravity produced LIV Maxwell and Dirac Lagrangians. [Gambini and Pullin, PRD59(1999)124021; Alfaro, Morales-Tecotl, Urrutia, PRL 84(2000)2318; PRD65(2002)103509; PRD66(2002)124006]

$$L_D = \frac{1}{2}\bar{\Psi}\gamma^{\mu} i\partial_{\mu}\Psi - \frac{1}{2}M\bar{\Psi}\Psi + \frac{1}{2}\Theta_1 M \ell_P \bar{\Psi}\gamma^k i\partial_k \Psi$$

$$-\frac{1}{2}\Theta_2 \ell_P M \bar{\Psi}\Sigma^k i\partial_k \Psi - \frac{1}{4}\Theta_4 M^2 \ell_P \bar{\Psi}\gamma_5\gamma^0\Psi + \text{h.c.}.$$



EFFECTIVE FERMION HAMILTONIAN

$$
\begin{aligned}
\mathrm{H^F} = \int \mathrm{d^3x} \Big[\mathrm{i}\, \pi(\vec{\mathrm{x}}) \; \Bigg(1 + \kappa_1 \left(\frac{\ell_\mathrm{P}}{\mathcal{L}}\right)^{1+\Upsilon} + \kappa_2 \left(\frac{\ell_\mathrm{P}}{\mathcal{L}}\right)^{2+2\Upsilon} + \\
+ \frac{\kappa_3}{2}\, \ell_\mathrm{P}^2\, \nabla^2 \Bigg) \tau^\mathrm{d} \partial_\mathrm{d}\, \xi(\vec{\mathrm{x}}) \\
+ \frac{\mathrm{i}}{4} \frac{1}{\mathcal{L}}\, \pi(\vec{\mathrm{x}}) \left(\kappa_4 \left(\frac{\ell_\mathrm{P}}{\mathcal{L}}\right)^{\Upsilon} + \kappa_5 \left(\frac{\ell_\mathrm{P}}{\mathcal{L}}\right)^{1+2\Upsilon} + \ldots + \frac{\kappa_7}{2} \ell_\mathrm{P}^2 \nabla^2 \right) \xi(\vec{\mathrm{x}}) \\
+ \frac{\mathrm{m}}{2} \xi^\mathrm{T}(\vec{\mathrm{x}})\; (\mathrm{i}\sigma^2) \left(1 + \kappa_8 \left(\frac{\ell_\mathrm{P}}{\mathcal{L}}\right)^{1+\Upsilon} + \Big(\kappa_9 \ell_\mathrm{P} + \ldots \Big) \tau^\mathrm{a} \partial_\mathrm{a} \right) \xi(\vec{\mathrm{x}}) + c.c. \Big]
\end{aligned}
$$

COMMENTS WITH RESPECT TO THE PROCEDURE

- Does not incorporate the dynamics (Hamiltonian constraint).

- Gives an order of magnitude estimate of each contribution with regard to the scales $\ell_{\rm P}, \mathcal{L}$. One might hope that the effect of the dynamics would be just to select the by now arbitrary dimensionless coefficients of each contribution.

- The calculation is made in a given reference frame. The use of the physical states should induce the correct transformation properties of the result.

- Results allow some motivation for phenomenological theories exploring such modifications and showing that either experiments or astrophysical observations can set rather stringent bounds upon the correction parameters

- Certainly an improved semiclassical approximation is required. A definition of the semiclassical states to correctly incorporate the dynamics is still an open problem. [Thiemann et. al., 2001]

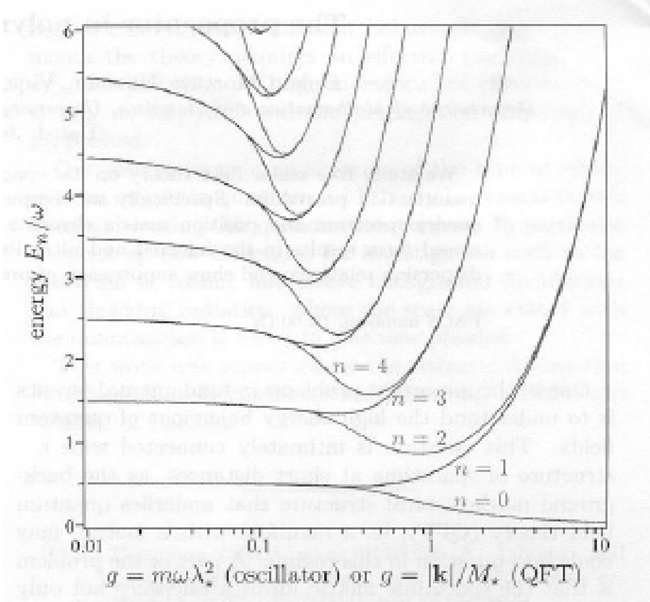
- Recent calculations are made using **polymer quantization**, a method that mimics the proposed modifications to quantization in loop quantum gravity.
- G.M. Hossain et al. calculate the scalar field propagator, without including gravitation, in this way and obtain

  [PRD, 2010].

- Modified Dispersion relations (LIV)

$$E = |\vec{k}|\left(1 - \frac{|\vec{k}|}{2M_*} + \quad \ldots\right), \qquad \frac{|\vec{k}|}{M_*} << 1$$

$$E = \frac{2|\vec{k}|^2}{M_*} + \quad \ldots, \qquad \frac{|\vec{k}|}{M_*} >> 1$$



- The continuous limit of any quantum gravity proposal is still an open question, to determine the nature of the possible corrections (if any) at SM energies, arising from the notion of space granularity. IN THE MEANTIME……….

RADIATIVE CORRECTIONS

[J.C. Collins, A. Pérez, D. Sudarsky, LU and H. Vucetich, PRL 93(2004)191301.]

- So far the corrections to the dynamics arise from the non-interacting theory, modified by $(E/M_P)^\Upsilon$ factors. They are relevant only at energies $E \geq M_P$

- An alternative way of probing high energies is through the calculation of radiative corrections (particle's self energies): the internal momentum is integrated up to the maximum allowed in a preferred frame associated to the space granularity.

- Standard folklore: any new physics entering at high scales (here Planck scale) has negligible effect on the leading-order low-energy physics (here free particle corrections).

- In such preferred frame we introduce a physical cut-off modelling the space granularity

$$\mathrm{f}(|\vec{\mathrm{k}}|/\Lambda), \quad \mathrm{f}(0) = 1, \quad \mathrm{f}(\infty) = 0, \quad \Lambda \approx \mathrm{M_P}$$

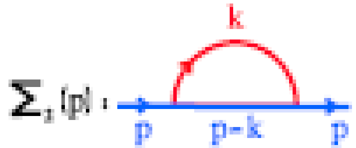
THE CASE OF A YUKAWA MODEL

- The Lagrangian is

$$L = \frac{1}{2}(\partial\phi)^2 + \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi + g\phi\bar{\psi}\psi + \ldots - i\xi_B\,\bar{\psi}\gamma_\mu W^\mu W^\nu\,\partial_\nu\,\psi$$

- The fermion self-energy $\Sigma_2(E,\vec{p})$ is defined by the full fermion propagator $S(E,\vec{p})$

$$S(E,\vec{p}) = \frac{i}{p^\mu\gamma_\mu - m - \Sigma_2(p)}\,,$$



- The one-loop calculation for $\Sigma_2(E,\vec{p})$ is

$$\Sigma_2(p) = ig^2\int\frac{d^4k}{(2\pi)^4}\,\frac{f(|\vec{k}|/\Lambda)}{k^2+i\epsilon}\,\frac{\gamma_\rho(p+k)^\rho + m}{(p+k)^2 - m^2 + i\epsilon}.$$

which can be conveniently presented as

$$\begin{aligned}\Sigma_2(E,\vec{p}) \quad &= \quad Am + p^\mu\gamma_\mu C - i\xi_{RC}\,\bar{\psi}\gamma_\mu W^\mu W^\nu\,\partial_\nu\,\psi \\ &\quad + \hat{\Sigma}^{LI}(p^2) + O(p/\Lambda, m/\Lambda).\end{aligned}$$

- The LIV coefficient gives a finite Λ-independent result

$$\xi_{\rm RC} = \frac{\rm g^2}{48\,\pi^2} \approx 10^{-3} - 10^{-1},$$

according to current estimates of the standard model.

- On the other hand, the observational limit previously obtained for this type of correctional tells that

$$\xi_{\rm OBS} < 10^{-24}.$$

- In this way any attempt to renormalize

$$\xi_{\rm B} + \frac{\rm g^2}{48\,\pi^2} = \xi_{\rm OBS},$$

would require an extremely undesirable fine-tuning.

- Thus new physics at the Planck scale is not suppressed by factors of E/E_P, but only at the percent level, in preferred frames associated to space granularity

LQG INDUCED CORRECTIONS QUADRATIC IN ℓ_P

[J. Alfaro and G. Palma, PRD 65(2002)103516; PRD 67(2003)083003]

- GZK cutoff in cosmic rays: particles with $E > 4 \times 10^{10}$GeV should not be seen due to

$$p + \gamma_{cmb} \to p + e^{+} + e^{-}, \quad p + \gamma_{cmb} \to p + \pi^{0}.$$

Nevertheless, there are confirmed events of this type (UHECR)!!!!

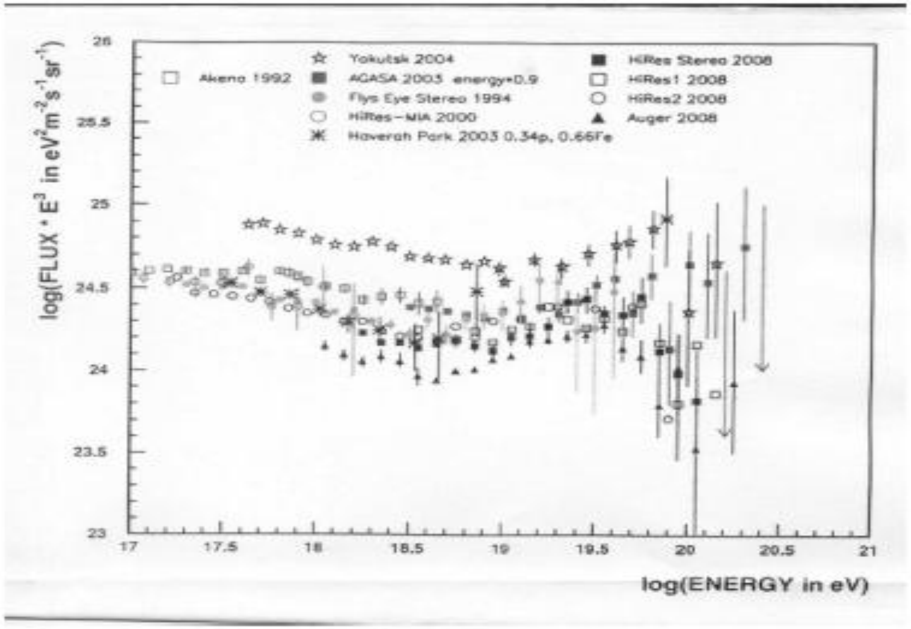
- A & P use the following modified dispersion relation for the fermions

$$E^2 = \vec{p}^{\,2} + \kappa \left(\frac{\ell_P}{\mathcal{L}}\right)^2 \vec{p}^{\,2} + m^2$$

$$\kappa \approx 1, \qquad 3 \times 10^{-9}\,\mathrm{GeV}^{-1} < \mathcal{L} < 5 \times 10^{-8}\,\mathrm{GeV}^{-1}$$

- A & P are able to adjust the flux of UHECR, according to present data, without disturbing the fit for the low energy sector ($E < 4 \times 10^{10}$GeV).

SUMMARY OF RESULTS



THE CASE OF THE GZK CUTOFF

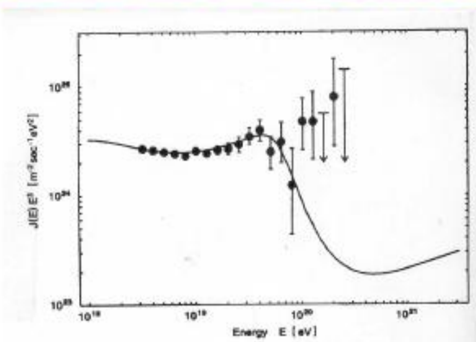


FIG. 1: UHECR spectrum and AGASA observations. The figure shows the UHECR spectrum $J(E)$ multiplied by E^3, for uniform distributed sources, without evolution, and with a maximum generation energy $E_{\max} = \infty$. Also shown are the AGASA observed events. The best fit for the low energy sector ($E < 4 \times 10^{19}$ eV) corresponds to $\gamma_g = 2.7$.

- [J. Alfaro and G. Palma, PRD 65(2002)103516.]

LORENTZ VIOLATION INCLUDED

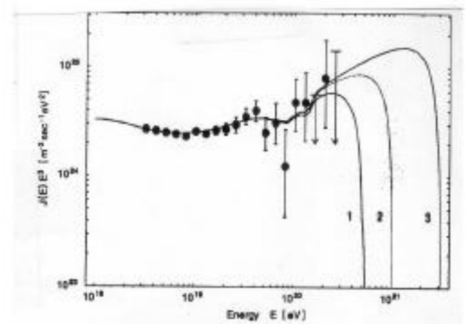


FIG. 3: Modified UHECR spectrum and AGASA observations. The figure shows the modified spectrum $J(E)$ multiplied by E^3, for uniform distributed sources and without evolution, for the case $\alpha_m = 1.5 \times 10^{-22}$ ($\mathcal{L} \simeq 6.7 \times 10^{-18}$ eV^{-1}). Three different maximum generation energies $E_{\max}$ are shown; these are, curve 1: 5×10^{20} eV; curve 2: 1×10^{21} eV; and curve 3: 3×10^{21} eV.

- [J. Alfaro and G. Palma, PRD 65(2002)103516.]

HIGH ENERGY GAMMA RAYS

33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

Sensitivity of the HAWC Detector to Violations of Lorentz Invariance

LUKAS NELLEN[1] FOR THE HAWC COLLABORATION.

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Abstract: Lorentz invariance is believed to be a fundamental symmetry of the universe. Many theories of quantum gravity, however, break Lorentz invariance at small scales and high energies explicitly. It is, therefore, of great interest to be able to place limits on some model and, if possible, even to observe this effect. The observation of a violation of Lorentz invariance would revolutionize our view of the universe and probe physics at energy scales not attainable with earthbound accelerators. Gamma-ray bursts provide an ideal laboratory to search for such phenomena. The combination of extreme distance (billions of light years), high energy emission (up to at least 30GeV), and short duration (burst durations of less than one-second have been observed), allows one to measure the relative speed of different energy photons to a part in 10^{16}. In this paper we will discuss current limits and the prospect for HAWC to improve upon these limits.

Keywords: HAWC, gamma rays, Lorentz Invariance Violation

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

The CTA sensitivity to Lorentz-violating effects on the gamma-ray horizon

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Abstract. The arrival of TeV-energy photons from distant galaxies is expected to be affected by their QED interaction with intergalactic radiation fields through electron-positron pair production. In theories where high-energy photons violate Lorentz symmetry, the kinematics of the process $\gamma + \gamma \to e^+ + e^-$ is altered and the cross section suppressed. Consequently, one would expect more of the highest-energy photons to arrive if QED is modified by Lorentz violation than if it is not. We estimate the sensitivity of Cherenkov Telescope Array (CTA) to changes in the gamma-ray horizon of the Universe due to Lorentz violation, and find that it should be competitive with other leading constraints.

Keywords: gamma ray theory, gamma ray experiments, absorption and radiation processes, quantum gravity phenomenology

ArXiv ePrint: 1401.8178

doi:10.1088/1475-7516/2014/06/005

JCAP06(2014)005

- High Altitude Water Cerenkov (HAWC) Sierra Negra, Mexico, 4.100 m .

- Array of water tanks with photomulti- pliers, covering area of 150 m x150 m =22.500 m^2. Will be sensitive to 100 Gev < E_γ < 100 TeV.
- Detection of gamma rays with E_γ larger than 10 TeV is hard to explain in terms of the sources.
- The main ingredient is the reaction $\gamma + \gamma = e^+ + e^-$ together with the reciprocal of the mean free path for collisions:

$$x_{\gamma\gamma}(E_\gamma)^{-1} = \frac{1}{8E_\gamma{}^2\beta_\gamma}\int_{\varepsilon_{\min}}^{\infty} d\varepsilon \frac{n(\varepsilon)}{\varepsilon^2}\int_{s_{\min}}^{s_{\max}(\varepsilon,E_\gamma)} ds\,(s - m_\gamma^2(E_\gamma)c^4)\sigma(s),$$

- The Cerenkov Telescope Array (CTA), under design, will be comprised of telescopes of multiple different designs, to optimize the sensitivity and to provide the widest possible coverage in energy .
- Impact of the LIV scale upon arrival of UHE photons is studied in Ref. **Fairbairn, M et al. JCAP, 2914,** for CTA.
- Kinematical corrections supresses the cross section yielding more photons at high energy. Incorporate dynamics (**L. Nellen, J.D. Vergara and LFU+2 stud.)**

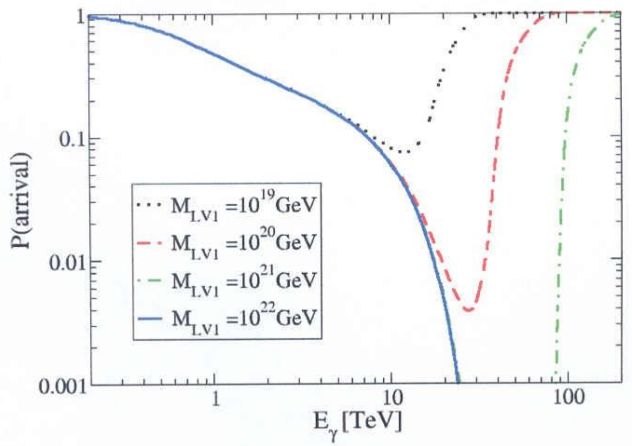

Figure 2. *The arrival probability of a photon emitted from a hypothetical source at redshift $z = 0.05$ as a function of energy. The different curves represent different values of the Lorentz-violating scale M_{LV1}. VHE photons with energies $\gtrsim 100$ TeV can travel through the CMB effectively unimpeded.*

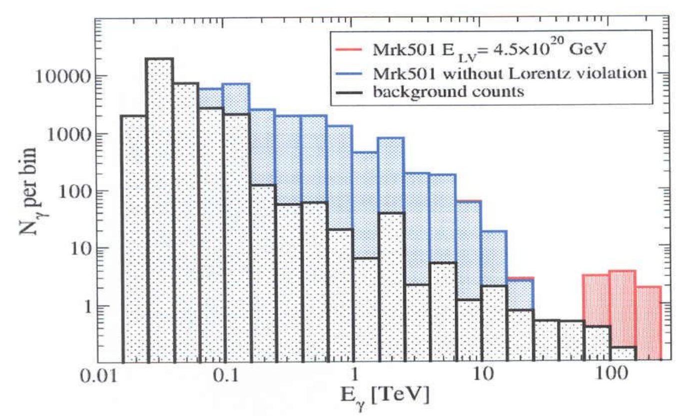

Figure 3. *The expected number of signal events (blue and red columns) compared with the expected number of background events alone (black columns), calculated for 50 hours of observation of the AGN Markarian 501, assuming the power-law spectrum (3.3). The red columns represent the expected flux assuming a Lorentz-violating energy scale $M_{LV1} = 4.5 \times 10^{20}$ GeV, whereas the blue columns denote the flux expected in the absence of Lorentz violation, and are identical to the red columns below 15 TeV.*

SOME ADDITIONAL WORKS IN MEXICO

- *Effects of Lorentz violation through the* $\gamma e \rightarrow W \nu_e$ *process in the Standard Model Extension*; J.I. Aranda, F. Ramirez-Zabaleta, D. A. Rosete, F. J. Tlachino, J. J. Toscano and E.S. Tututi; **J. Phys. G41(2014) 055003.**

- *Gauge invariant electromagnetic properties of fermions induced by CPT violation in the Standard Model Extension*; A. Moyotl, H. Novales-Sanchez, J. J. Toscano and E.S. Tututi; **Int. J. Mod. Phts. A29(2014)8, 1450039.**

- *Lorentz violating effects on pair production of W bosons in photon collisions;* J.I. Aranda, F. Ramirez-Zabaleta, F. J. Tlachino, J. J. Toscano and E.S. Tututi; **Int. J. Mod. Phys. A29(2014)31, 1450180.**

- *Implications of Lorentz violations on Higgs-mediated lepton flavor violation ; M. A. Lopez-Osorio, E. Martinez Pascual and J. J. Toscano;* ***arXiv:1408.3307****.*

- *Search for violations of CPT and Lorentz invariance in* B_s^0 *meson oscillations, The D0 Collaboration (includes nine participants from CINVESTAV) ;* ***arXiv:1506.04123.***

ACTIVITY IN THE FIELD

- The basic theoretical works are:

  (a) **Kostelecky and Potting, PRD 51(1995)3923** (372 citas)

  (b) **Coleman and Glashow, PLB 405(1997)249** (406 citas)

  (c) **Colladay and Kostelecky, PRD 55 (1997)6760** (1060 citas)

  (d) **Colladay and Kostelecky, PRD 58(1998)116002** (989 citas)

  (e) **Coleman and Glashow, PRD 59(1999)116008** (1318 citas)

- More than 100 experimental and phenomenological works to set bounds upon LIV parameters (Australia,UK, France, Germany, Italy, USA, …), also in big experimental collaborations (KLOE, FOCUS, BaBar, Belle, …).

- Theoretical interest also in Brasil, Chile and México .

SOME NAMES AT BIG INSTITUTIONS

- **Berkeley**: Petr Horava (T) ; Holger Müller (E),
- **CalTech** : Sean Carroll, Mark Wise (T),
- **Cambridge**: Malcolm Perry (T),
- **CERN**: John Ellis (T) ; Collaborations in antihydrogen spectroscopy (E).
- **Chicago**: Jeff Harvey (T)
- **Harvard**: **Sheldon Glashow**, Sidney Coleman (T) ; Gerry Gabrielse, Chris Stubbs, Ron Walsworth (E)
- **Maryland**: Wally Greenberg, Ted Jacobson (T).
- **MIT**: Roman Jackiw (T).
- **Oxford**: Subir Sarkar (T).
- **Princeton**: Nima Arkani-Hamed (T) ; Mike Romalis (E).
- **Stanford**: **Steve Chu** (E).
- **Washington**: Eric Adelberger, **Hans Dehmelt** (E) .
- **Yale**: Vernon Hughes, Virgilio Beltrán (E).

FINAL COMMENTS

- Planck scale sensitivities are already attained with present technologies and they are in the process of been improved.
- Large number of related experiments and observations in many different areas.
- This should provide experimental guidance to quantum gravity theories, thus demystifying lack of observational input.
- **SO FAR, NO SIGNAL OF EITHER LIV OR CPT BREAKING.**
- On one hand, studies of Lorentz and CPT violations should provide a firm observational basis for the range of validity of these symmetries.
- On the other hand, there is the possibility of finding new physics in case minute violations are detected.

GRACIAS POR SU ATENCION !!!!!!!

REVIEWS ON THE SUBJECT

- D. Mattingly, *Modern test of Lorentz invariance*, **Liv. Rev. Rel. 8 (2005).**
- G. Amelino-Camelia, J. Kowalski-Glikman (Eds.), *Planck scale effects in astrophysics and cosmology*, **Lecture Notes in Physics 669(2005), Springer Verlag.**
- T. Jacobson, S. Liberati and D. Mattingly, *Lorentz violation at high energy: Concepts, phenomena and astrophysical constraints,* **Annals Phys. (NY) 321(2006)150.**
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- H.A. Morales-Tecotl and L. F. Urrutia, *Quantum Gravity Phenome-nology*, **AIP Conference Proceedings 857(2006).**
- G. Amelino-Camelia, *Quantum Spacetime Phenomenology,* ***Liv. Rev. Rel. 16(2013) 5.***