Lorentz Invariance Violation Constraints
Theory and (some) Tests

KING'S College LONDON

Nick E. Mavromatos

King's College London

QUANTUM · GRAVITY · MULTI · MESSENGER

CA18108 - Quantum gravity phenomenology in the multi-messenger approach

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Kick-off meeting, Barcelona 2-4 October 2019

The (classical) theory of General relativity is working well

Most recent detection of Gravitational Waves (LIGO/VIRGO)

Special Relativity works EXTREMELY WELL – PARTICLE PHYSICS is BASED ON IT

Quantum Field Theory / String Theory in standard backgrounds....:
assumed : LORENTZ → CPT INVARIANT

BUT:

Quantum Gravity (QG): still elusive
Some QG models may entail violation of Lorentz symmetry
(and quantum decoherence of particles in such QG
(``space-time foam") environments)

Early Universe Models might entail spontaneous breaking
of Lorentz symmetry (e.g. flux background fields in string theory)

→ CPT Violation → Matter-Antimatter asymmetry (novel ways)

The (classical) theory of General relativity is working well

Most recent detection of Gravitational Waves (LIGO/VIRGO)

Special Relativity works EXTREMELY WELL – PARTICLE PHYSICS is BASED ON IT

STANDARD MODEL EXTENSION (SME) (Kostelecky et al.)
AS AN EFFECTIVE FIELD THEORETIC (EFT) PARAMETRIZATION

BUT:

Quantum Gravity (QG): still elusive
Some QG models may entail violation of Lorentz symmetry
(and quantum decoherence of particles in such QG
(``space-time foam") environments)

Early Universe Models might entail spontaneous breaking
of Lorentz symmetry (e.g. flux background fields in string theory)

→ CPT Violation → Matter-Antimatter asymmetry (novel ways)

The (classical) theory of General r… working well

Most recent detection of G… (LIGO/VIRGO)

Special Relativity works E… …SED ON IT

STANDARD MOD…
AS AN EFFECT… …ATION

BUT:

S… … Lorentz symmetry
(an… …es in such QG
(``s… …nts)

Early Un… … entail spontaneous breaking
of Lorentz … flux background fields in string theory)

→ CPT Violat… …atter-Antimatter asymmetry (novel ways)

Can we test/falsify
such Models
and/or
probe Lorentz Violation
in a model independent way?
or even …
go beyond EFT?

OUTLINE

MOTIVATION-theory background

- Models of Quantum Gravity (QG) predicting LV, matter/antimatter asymmetry and/or Vacuum refraction

- Some things we should know on the induced refractive index **– highly model dependent** → **not easy to exclude even the simplest of models**

OUTLINE

MOTIVATION-theory background

- Models of Quantum Gravity (QG) predicting LV, matter/antimatter asymmetry and/or Vacuum refraction

- Some things we should know on the induced refractive index – **highly model dependent** → **not easy to exclude even the simplest of models**

Experimental Tests

- **LV Tests (SME): atomic transitions, tests @ LHC and Future colliders**
- **Very High Energy (cosmic) photon propagation :**

  extragalactic sources - MECHANISMS @ THE SOURCE:

  important knowledge still missing – should combine with propagation (QG induced, refractive) effects

- **Current Experimental Tests/sensitivities (> M_{Pl} in some cases)**
- **Cherenkov Telescope Arrays – bright future in QG searches…**

OUTLINE

MOTIVATION-theory background

- Models of Quantum Gravity (QG) predicting LV, matter/antimatter asymmetry and/or Vacuum refraction

- Some things we should know on the induced refractive index – **highly model dependent** → **not easy to exclude even the simplest of models**

Experimental Tests

- **LV Tests (SME): atomic transitions, tests @ LHC and Future colliders**
- **Very High Energy (cosmic) photon propagation :**
  extragalactic sources - MECHANISMS @ THE SOURCE:
  important knowledge still missing – should combine with propagation (QG induced, refractive) effects

what does this mean?

- **Current Experimental Tests/sensitivities (> M_{Pl} in some cases)**
- **Cherenkov Telescope Arrays – bright future in QG searches…**

OUTLINE

Further Experimental Tests

- Neutrino (ν) Telescopes: sringent limits for LV modified dispersion, QG decoherence (far exceeding M_{Pl} sensitivity)
- Truly multimessenger Tests: coincident observations of HE ν & γ-rays
- Quantum Gravity Decoherence induced CPT (& LV) Tests in
- Entangled Particle Physics systems (neutral meson factories)

  `smoking-gun' ω-effect beyond EFT?

- LV can affect CMB spectrum → complimentary constraints

  (not discussed here (time) → explore further in our COST)

Take home Messages:

What do such tests imply for models? > M_{Pl} sensitivities?

Interpretation of bounds, Microscopic Models ?

Theorists ←→ Experimentalists/Astrophysicists

OUTLIN…

Further Experimental …

- Neutrino (ν) Tel… …persion, QG decoherenc…
- Truly multimesse… …-rays
- Quantum Gravity …
- Entangled Particle … …es) `smoking-gun' ω-effe…
- LV can affect CMB sp… …ary constraints (not discussed here (tin… …urther in our COST)

See also:
Review Talks, e.g. by
Gubitosi,. Amelino-Camelia,
Bolmont, Tórtola, Sigl, di Matteo…
I will **focus here** on some **complementary issues** when covering some of the above topics, **omitting discussion** on topics **already covered there**

Take home Messages:

What do such tests imply for models? > M_{Pl} sensitivities?

Interpretation of bounds, Microscopic Models ?

Theorists ←→ Experimentalists/Astrophysicists

MOTIVATION –
PREDICTIONS FROM THEORY & CAUTIONARY REMARKS

Spontaneous Lorentz Violation in Early Universe,
Matter-Antimatter Asymmetry
&
Today's Tests:
STANDARD MODEL EXTENSION
Effective Field Theory Framework

STANDARD MODEL EXTENSION

Kostelecky *et al.*

$$\mathcal{L}_{\text{eff}} \ni \sum b_{\mu_1 \ldots \mu_n} \mathcal{O}^{\mu_1 \ldots \mu_n}(x)$$

constants in x
energy dependent

LV &/or CPTV
field operators

e.g. lowest derivative order Fermion sector

$$\mathcal{L} = \frac{1}{2} \mathrm{i} \bar{\psi} \Gamma^{\nu} \bar{\partial}_{\nu} \psi - \bar{\psi} M \psi,$$

$$M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \frac{1}{2} H^{\mu\nu}\sigma_{\mu\nu}$$

$$\Gamma^{\nu} \equiv \gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu} + \mathrm{e}^{\nu} + \mathrm{i} f^{\nu}\gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}\sigma_{\lambda\mu}$$

+ gauge + mixed (fermion+gauge) sectors + gravity

Parametrisation mostly,
Phenomenological study of effects of LV terms so far

Microscopic Origin of SME coefficients?

Several ``Geometry-induced'' examples:

Non-Commutative Geometries

Axisymmetric Background

Geometries of the Early Universe

Torsionful Geometries (including strings…)

Early Universe T-dependent effects:
large @ high T, low values today
for coefficients of SME

Microscopic Origin of SME coefficients?

Several ``Geometry-induced'' examples:

Non-Commutative Geometries

Axisymmetric Background

Geometries of the Early Universe

Torsionful Geometries (including strings…)

Early Universe T-dependent effects:
large @ high T, low values today
for coefficients of SME

STANDARD MODEL EXTENSION

Fermion sector

Kostelecky *et al.*

$$\mathcal{L} = \frac{1}{2} i \bar{\psi} \Gamma^{\nu} \overleftrightarrow{\partial}_{\nu} \psi - \bar{\psi} M \psi,$$

$$M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \frac{1}{2} H^{\mu\nu}\sigma_{\mu\nu}$$

LV & CPTV

$$\Gamma^{\nu} \equiv \gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu} + e^{\nu} + i f^{\nu}\gamma_5 + \frac{1}{2} g^{\lambda\mu\nu}\sigma_{\lambda\mu}$$

A non-trivial example: String Theories with LV Antisymmetric Tensor Backgrounds

Massless Gravitational multiplet of (closed) strings: **spin 0 scalar (dilaton)**
spin 2 traceless symmetric rank 2 tensor (graviton)
spin 1 antisymmetric rank 2 tensor

KALB-RAMOND FIELD $B_{\mu\nu} = -B_{\nu\mu}$

Effective field theories (low energy scale E << M_s) `` **gauge**'' invariant

$$B_{\mu\nu} \to B_{\mu\nu} + \partial_{[\mu}\theta(x)_{\nu]}$$

Depend only on field strength : $H_{\mu\nu\rho} = \partial_{[\mu}B_{\nu\rho]}$

Bianchi identity : $\partial_{[\sigma}H_{\mu\nu\rho]} = 0 \to d \star \mathbf{H} = 0$

ROLE OF H-FIELD AS TORSION

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

4-DIM PART

$$S^{(4)} = \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}\,H^{\mu\nu\rho}\Big)$$

$$= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R}\Big)$$

$\kappa^2 = 8\pi\, G$

$$\overline{R}(\overline{\Gamma})$$

generalised curvature

$$\overline{\Gamma}^{\mu}_{\nu\rho} = \Gamma^{\mu}_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^{\mu}_{\nu\rho} \neq \overline{\Gamma}^{\mu}_{\rho\nu}$$

Contorsion

ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

$$\sim \frac{1}{2}\partial^\mu b\,\partial_\mu b$$

4-DIM PART

$$S^{(4)} = \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}\,H^{\mu\nu\rho}\Big)$$

$$= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R}\ \Big)$$

$\kappa^2 = 8\pi\, G$

$$\overline{R}(\overline{\Gamma}) \qquad \overline{\Gamma}^\mu_{\nu\rho} = \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

IN 4-DIM DEFINE DUAL OF H AS :

$$-3\sqrt{2}\partial_\sigma b = \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}$$

b(x) **= Pseudoscalar (Kalb-Ramond (KR) axion)**

Fermions and (generic) Torsion

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$\gamma^a\gamma^b\gamma^c = \eta^{ab}\,\gamma^c + \eta^{bc}\,\gamma^a - \eta^{ac}\,\gamma^b - i\,\epsilon^{dabc}\,\gamma_d\,\gamma^5$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

$$g_{\mu\nu} = e^a_\mu\,\eta_{ab}\,e^b_\nu$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\gamma\mu}e^\gamma_c e^\mu_a\right).$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \tfrac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a\partial_a - m) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd}e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu}e^\alpha_c e^\mu_a\right)$$

If **torsion** then $\Gamma_{\mu\nu} \neq \Gamma_{\nu\mu}$ ***antisymmetric*** part is the contorsion tensor, contributes

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

$$S_\psi = \frac{i}{2}\int d^4x\sqrt{-g}\Big(\overline{\psi}\gamma^\mu \overline{\mathcal{D}}_\mu\psi - (\overline{\mathcal{D}}_\mu\overline{\psi})\gamma^\mu\psi\Big)$$

TORSIONFUL CONNECTION

$$S_\psi \ni \int d^4x B_a\, \overline{\psi}\gamma^a\gamma^5\psi$$

$$B^d \sim \epsilon^{abcd} H_{bca}$$

$$-3\sqrt{2}\partial_\sigma b \;=\; \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma} H^{\mu\nu\rho}$$

***b(x)* = KR (gravitational) axion**

Non-trivial contributions to ***B**$^\mu$*

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e_c^\lambda + \Gamma^\lambda_{\alpha\mu} e_c^\alpha e_a^\mu\right)$$

$$\overline{\Gamma}^\mu_{\nu\rho} \;=\; \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}} H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

$$S_\psi = \frac{i}{2}\int d^4x\sqrt{-g}\Big(\overline{\psi}\gamma^\mu \overline{\mathcal{D}}_\mu\psi - (\overline{\mathcal{D}}_\mu\overline{\psi})\gamma^\mu\psi\Big)$$

TORSIONFUL CONNECTION → AXION-LIKE CP-VIOLATING INTERACTION

$$S_\psi \ni \int d^4x B_a\,\overline{\psi}\gamma^a\gamma^5\psi \;\rightarrow\; -\int d^4x\sqrt{-g}\,\partial_\alpha b\,\big(\overline{\psi}\,\gamma^\alpha\,\gamma^5\,\psi\big)$$

Universal (gravitational) Coup[ling

$$B^d \sim \epsilon^{abcd}H_{bca} \;\rightarrow\; -3\sqrt{2}\partial_\sigma b \;=\; \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}$$

b(x) **= KR (gravitational) axion**

Non-trivial contributions to ***B***$^\mu$

$$B^d = \epsilon^{abcd}e_{b\lambda}\left(\partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu}e^\alpha_c e^\mu_a\right)$$

$$\overline{\Gamma}^\mu_{\nu\rho} \;=\; \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

When **db/dt = constant** → Torsion is constant

Covariant Torsion tensor

$$\overline{\Gamma}^{\lambda}_{\ \mu\nu} = \Gamma^{\lambda}_{\ \mu\nu} + e^{-2\Phi} H^{\lambda}_{\mu\nu} \equiv \Gamma^{\lambda}_{\ \mu\nu} + T^{\lambda}_{\ \mu\nu}$$

$$T_{ijk} \sim \epsilon_{ijk} \, \dot{b}$$

Constant

$$S_{\psi} \ni \int d^4x B_a \, \overline{\psi} \gamma^a \gamma^5 \psi$$

constant B^0 $\propto \dot{b}$

When **db/dt = constant** → Torsion is constant

Covariant Torsion tensor

$$\overline{\Gamma}^{\lambda}{}_{\mu\nu} = \Gamma^{\lambda}{}_{\mu\nu} + e^{-2\Phi} H^{\lambda}_{\mu\nu} \equiv \Gamma^{\lambda}{}_{\mu\nu} + T^{\lambda}{}_{\mu\nu}$$

$$T_{ijk} \sim \epsilon_{ijk}\, \dot{b}$$

Constant

$$S_{\psi} \ni \int d^4x B_a \overline{\psi} \gamma^a \gamma^5 \psi$$

constant $\boldsymbol{B^0}$ $\propto \dot{b}$

$$\mathcal{L} = \tfrac{1}{2} i \bar{\psi}\, \gamma^{\nu}\, \bar{\partial}_{\nu} \psi - \bar{\psi} M \psi, \qquad M \equiv m + b_{\mu}\, \gamma^5\, \gamma^{\mu}$$

LV & CPTV

Standard Model Extension type with CPT and Lorentz Violating background $b^0 = B^0$

Kostelecky et al.

Antoniadis, Bachas, Ellis, Nanopoulos (non-critical strings)

NEM + Sarkar
de Cesare
Bossingham

Basilakos, NEM, Sola (2019)

Gravitational Anomalies-induced condensates due to primordial GW

$$\langle R_{\mu\nu\rho\sigma}\, R^{\mu\nu\rho\sigma} \rangle = \partial_\mu\, K^\mu \neq 0$$

In string-theory (inspired) Cosmologies with such KR-b axions there are solutions with

b(t) = (constant) t = B_0 t , t = FLRW cosmic time

$$\partial^0 b \propto \mathcal{K}^0 = \text{const}$$

→ Spontaneously Broken Lorentz (& nCPT) Symmetry (SBL)

→ massless KR axion = Goldstone Boson of SBL

Antoniadis, Bachas, Ellis, Nanopoulos (non-critical strings)

NEM + Sarkar, de Cesare, Bossingham

Basilakos, NEM, Sola (2019)

Gravitational Anomalies-induced condensates due to primordial GW

$$\langle R_{\mu\nu\rho\sigma}\, R^{\mu\nu\rho\sigma}\rangle = \partial_\mu\, K^\mu \neq 0$$

In string-theory (inspired) Cosmologies with such KR-b axions there are solutions with

b(t) = (constant) t = B_0 t , t = FLRW cosmic time

$$\partial^0 b \propto \mathcal{K}^0 = \text{const}$$

→ Spontaneously Broken Lorentz (& nCPT) Symmetry (SBL)

→ massless KR axion = Goldstone Boson of SBL

Post Inflationary era

$$\partial_\mu\Big[\sqrt{-g}\,\Big(\sqrt{\frac{3}{8}}\frac{\alpha'}{\kappa}\,J^{5\mu} - \frac{\alpha'}{\kappa}\sqrt{\frac{2}{3}}\,\frac{1}{96}\,\mathcal{K}^\mu\Big)\Big] = \sqrt{\frac{3}{8}}\,\frac{\alpha'}{\kappa}\,\Big(\frac{\alpha_{\rm EM}}{2\pi}\,\sqrt{-g}\,F^{\mu\nu}\,\widetilde{F}_{\mu\nu} + \frac{\alpha_s}{8\pi}\,\sqrt{-g}\,G^a_{\mu\nu}\,\widetilde{G}^{a\mu\nu}\Big)$$

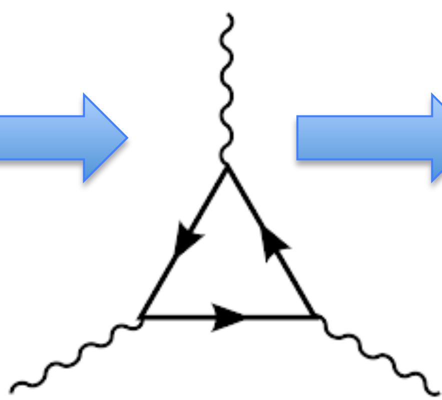
CPT VIOLATING LEPTOGENESIS & GRAVITATIONAL ANOMALIES IN THE EARLY UNIVERSE

S Basilakos, NEM, J Sola (2019)

Microscopic Mechanism For LV & CPTV H-Torsion Background

Inflationary (de Sitter) Phase

Primordial Gravitational Waves



Gravitational anomaly (GA)

$$\langle b(x) R_{\mu\nu\rho\sigma}\, R^{\mu\nu\rho\sigma} \rangle \neq 0$$

Undiluted constant (LV)
H-torsion
(B_0 = db/dt)
background
→ axion **b(t) = c t**
+ chiral matter generation
@ inflation exit

Radiation Era

Cancellation of GA (consitency of QFT)

$B_0 \propto T^3$

(slowly varying)

Leptogenesis
(decays of RHN)

NEM, Sarkar Bossnigham

NEM, Sarkar,
+ de Cesare, Bossingham

Early Universe
T >> T_{EW}

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{M}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

Heavy RHN interact with axial constant background

with only temporal component $B_0 \neq 0$

NEM, Sarkar,
+ de Cesare, Bossingham

Early Universe
$T \gg T_{EW}$

$$\mathcal{L} = i\overline{N}\not{\partial} N - \frac{M}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Heavy RHN interact with axial constant background

with only temporal component $B_0 \neq 0$

Lorentz &
CPT Violation

CPT Violation

de Cesare, NEM, Sarkar
Eur.Phys.J. C75, 514 (2015)

Early Universe
$T \gg T_{EW}$

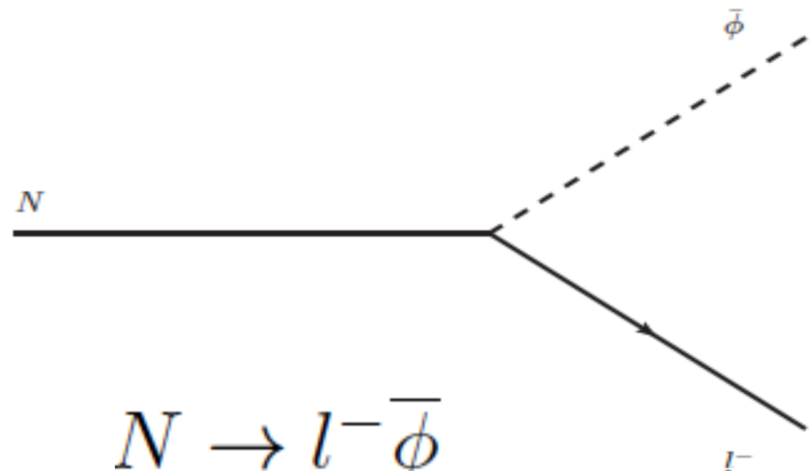
$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{M}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

Heavy RHN interact with axial constant background

with only temporal component $B_0 \neq 0$

Produce Lepton asymmetry

Lepton number & CP Violations
@ tree-level due to
Lorentz/CPTV Background



$$N \to l^+ \phi \qquad\qquad N \to l^- \overline{\phi}$$

$$\Gamma_1 = \sum_k \frac{|Y_k|^2}{32\pi^2} \frac{M^2}{\Omega} \frac{\Omega + B_0}{\Omega - B_0} \neq \Gamma_2 = \sum_k \frac{|Y_k|^2}{32\pi^2} \frac{M^2}{\Omega} \frac{\Omega - B_0}{\Omega + B_0}$$

$B_0 \neq 0$

CPV & LV

$$\Omega = \sqrt{B_0^2 + M^2}$$

$$\mathcal{L} = i\overline{N}\not{\partial} N - \frac{M}{2}(\overline{N^c}N \;{}^{m}\overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Constant B_0 Background

CPT Violation

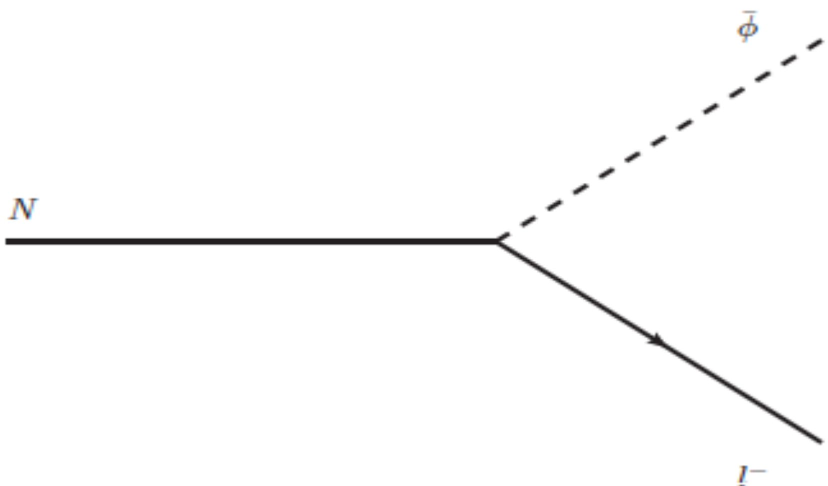
Early Universe

T > 10^5 GeV

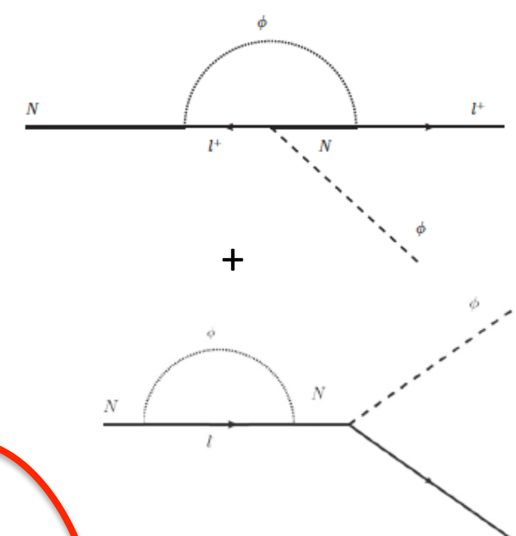
Lepton number & CP Violations @ tree-level
due to Lorentz/CPTV Background

$$N_I \to \overline{\phi}\,\ell\,,\;\phi\,\overline{\ell}$$

Produce Lepton asymmetry



Contrast with one-loop conventional CPV Leptogenesis (in absence of H-torsion)



Fukugita, Yanagida,

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
T > 10^5 GeV

CPT Violating Leptogenesis

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \to \overline{\phi}\,\ell\,,\ \phi\,\overline{\ell}$$

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Constant $B^0 \neq 0$ background

Early Universe
T > 10^5 GeV

CPT Violation

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \to \overline{\phi}\,\ell\,,\ \phi\,\overline{\ell}$$

Produce Lepton asymmetry

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
$T > 10^5$ GeV

CPT Violation

Constant $B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \rightarrow \overline{\phi}\,\ell\,,\;\; \phi\,\overline{\ell}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

*** Solving system of Boltzmann eqs**

Produce Lepton asymmetry

$$\left(N \rightarrow \ell^-\phi^+, \nu\;\phi^0\right) - \left(N \rightarrow \ell^+\phi^-, \overline{\nu}\;\phi^0\right)$$

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
T > 10^5 GeV

CPT Violation

Constant $B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \rightarrow \overline{\phi}\,\ell\,,\ \phi\,\overline{\ell}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

$$\frac{\Delta L^{TOT}}{s} \simeq \frac{g_N}{7\,e\,(2\pi)^{3/2}}\frac{B_0}{m_N} \simeq 0.007\,\frac{B_0}{m_N}$$

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
$T > 10^5$ GeV

CPT Violation

Constant $B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \to \overline{\phi}\,\ell\,,\;\phi\,\overline{\ell}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

$$\frac{\Delta L^{TOT}}{s} \simeq \frac{g_N}{7\,e\,(2\pi)^{3/2}}\frac{B_0}{m_N} \simeq 0.007\,\frac{B_0}{m_N}$$

$$Y_k \sim 10^{-5}$$

$$m \geq 100\text{TeV} \to$$

$$B^0 \sim 1\text{MeV}$$

$$T_D \simeq m \sim 100\ \text{TeV}$$

$$\mathcal{L} = i\overline{N}\partial\!\!\!/ N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}B\!\!\!/\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

Early Universe
T > 10^5 GeV

CPT Violation

Constant $B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \rightarrow \overline{\phi}\,\ell\,,\;\; \phi\,\overline{\ell}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

$$\frac{\Delta L^{TOT}}{s} \simeq \frac{g_N}{7\,e\,(2\pi)^{3/2}}\frac{B_0}{m_N} \simeq 0.007\,\frac{B_0}{m_N}$$

$$Y_k \sim 10^{-5}$$

$$m \geq 100\text{TeV} \rightarrow$$

$$B^0 \sim 1\text{MeV}$$

$$T_D \simeq m \sim 100 \text{ TeV}$$

Phenomenologically relevant regime for SM neutrino mass via, e.g., **seesaw mechanisms**

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k \overline{L}_k \tilde{\phi} N + h.c.$$

Early Universe
$T > 10^5$ GeV

CPT Violation

Constant $B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \to \overline{\phi}\,\ell\,,\ \phi\,\overline{\ell}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

$$\frac{\Delta L^{TOT}}{s} \simeq \frac{g_N}{7\,e\,(2\pi)^{3/2}} \frac{B_0}{m_N} \simeq 0.007\,\frac{B_0}{m_N}$$

$$Y_k \sim 10^{-5}$$

$$m \geq 100\text{TeV} \to$$

$$B^0 \sim 1\text{MeV}$$

$$T_D \simeq m \sim 100\ \text{TeV}$$

Similar order of magnitude estimates if $B^0 \sim T^3$ during Leptogenesis era

Bossingham, NEM, Sarkar

$$\mathcal{L} = i\overline{N}\not{\partial}N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

CPT Violation

Early Universe
$T > 10^5$ GeV

Constant $B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \rightarrow \overline{\phi}\,\ell\,,\ \phi\,\overline{\ell}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10}, \quad \rightarrow \quad \frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

Equilibrated electroweak
B+L violating sphaleron interactions

B-L conserved

Environmental Conditions Dependent

Observed Baryon Asymmetry In the Universe (BAU)

$$L = \frac{2}{M} l_L l_L \phi\phi + \mathrm{H.c.}$$

where

$$l_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

Fukugita, Yanagida,

$$\mathcal{L} = i\overline{N}\not\partial N - \frac{m}{2}(\overline{N^c}N + \overline{N}N^c) - \overline{N}\not{B}\gamma^5 N - Y_k\overline{L}_k\tilde{\phi}N + h.c.$$

Early Universe
$T > 10^5$ GeV

CPT Violation

Constant $B^0 \neq 0$ background

Lepton number & CP Violations @ tree-level due to Lorentz/CPTV Background

$$N_I \rightarrow \overline{\phi}\,\ell\,,\ \phi\,\overline{\ell}$$

$$\frac{\Delta L}{n_\gamma} \simeq 10^{-10},$$

$$\frac{B_0}{m} \simeq 10^{-8}$$

Produce Lepton asymmetry

$$Y_k \sim 10^{-5}$$

$$m \geq 100\text{TeV} \rightarrow$$

$$B^0 \sim 1\text{MeV}$$

$$T_D \simeq m \sim 100\ \text{TeV}$$

Equilibrated electroweak B+L violating sphaleron interactions

B-L conserved

Environmental Conditions Dependent

Observed Baryon Asymmetry In the Universe (BAU)

Estimate BAU by fixing CPTV background parameters
In some models this means fine tuning ….

B^0 : (string) model: cancellation of gravity anonaly @ exit from inflation implies

$$B^0 \sim \dot{\bar{b}} \sim 1/a^3(t) \sim T^3$$

i.e. scales @ leptogenesis era @ T ≈ $T_d = 10^5$ GeV,
from B^0 = const = 1 MeV **to** :

$$B_0 = c_0 T^3 \qquad c_0 = 10^{-42}\,\text{meV}^{-2}$$

(ii) **or B^0 small today but non zero**

$$B_{0\,\text{today}} = \mathcal{O}\left(10^{-44}\right)\ \text{meV}$$

Quite safe from stringent Experimental Bounds

$$|B^0| < 10^{-2}\,\text{eV}$$
$$B_i \equiv b_i < 10^{-31}\,\text{GeV}$$

B^0 : (string) model: cancellation of gravity anonaly @ exit from inflation implies

$$B^0 \sim \dot{\bar{b}} \sim 1/a^3(t) \sim T^3$$

i.e. scales @ leptogenesis era @ T ≈ T_d = 10^5 GeV, from B^0 = const = 1 MeV **to** :

Basilakos, NEM, Sola (2019),

$$B_0 = c_0\, T^3 \qquad c_0 = 10^{-42}\,\mathrm{meV}^{-2}$$

If chiral U(1) anomalies present

$$B^0 \sim T^2$$

(ii) **or B^0 small today but non zero**

$$B_{0\,\mathrm{today}} = \mathcal{O}\left(10^{-44}\right)\ \mathrm{meV}$$

$$B_0\Big|_{\mathrm{today}} \sim 2.435 \times 10^{-34}\,\mathrm{eV}$$

Quite safe from stringent Experimental Bounds

$$|B^0| < 10^{-2}\,\mathrm{eV}$$
$$B_i \equiv b_i < 10^{-31}\,\mathrm{GeV}$$

Take Home Message:

This is **only one class of models**

Reverse the logic:

use current Bounds,

and see if you can construct models

to yield acceptable

leptogenesis / Baryogenesis

(i.e. appropriate Temperature dependence as you go back in time)

Quite safe from stringent Experimental Bounds

$$|B^0| < 10^{-2}\,\mathrm{eV}$$
$$B_i \equiv b_i < 10^{-31}\,\mathrm{GeV}$$

Take Home Message:

This is **only one class of models**

Reverse the logic:

use current Bounds,

and see if you can construct models

to yield acceptable

leptogenesis / Baryogenesis

(i.e. appropriate Temperature dependence

as you go back in time)

Quite safe from stringent Experimental Bounds

$$|B^0| < 10^{-2}\,\mathrm{eV}$$
$$B_i \equiv b_i < 10^{-31}\,\mathrm{GeV}$$

Lorentz Violation & (Anti)-Hydrogen

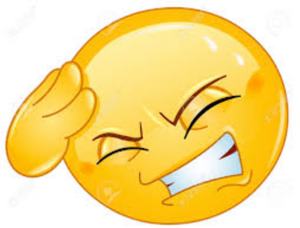
- **Trapped Molecules:**
  Forbidden transitions
  e.g. 1s → 2s

  NB: Sensitivity in b_3
  that rivals astrophysical or atomic-physics bounds can only be attained if spectral resolution of 1 mHz is achieved.
  Not feasible at present in anti-H factories

EXPER.	SECTOR	PARAMS. (J=X,Y)	BOUND (GeV)
Penning Trap	electron	$\bar{b}_J^e$	5×10^{-25}
Hg–Cs clock comparison	electron	$\bar{b}_J^e$	10^{-27}
	proton	$\bar{b}_J^p$	10^{-27}
	neutron	$\bar{b}_J^n$	10^{-30}
H Maser	electron	$\bar{b}_J^e$	10^{-27}
	proton	$\bar{b}_J^p$	10^{-27}
spin polarized matter	electron	$\bar{b}_J^e$ / $\bar{b}_Z^e$	10^{-29} / 10^{-28}
He–Xe Maser	neutron	$\bar{b}_J^n$	10^{-31}
Muonium	muon	$\bar{b}_J^\mu$	2×10^{-23}
Muon g–2	muon	$\bar{b}_J^\mu$	5×10^{-25} (estimated)

X,Y,Z celestial equatorial coordinates $\bar{b}_J = b_3 - m d_{30} - H_{12}$

(Bluhm, hep–ph/0111323)



NB $|B^0| < 10^{-2}\,\mathrm{eV}$

Lorentz Violation & (Anti)-Hydrogen

- **Trapped Molecules:**

  Forbidden transitions e.g. 1s → 2s

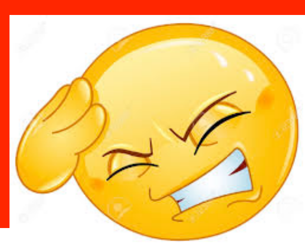
  NB: Sensitivity in b_3 **that rivals astrophysical or atomic-physics bounds can only be attained if spectral resolution of 1 mHz is achieved.**

  Not feasible at present in anti-H factories

EXPER.	SECTOR	PARAMS. (J=X,Y)	BOUND (GeV)
Penning Trap	electron	$\bar{b}_J^e$	5×10^{-25}
Hg–Cs clock comparison	electron	$\bar{b}_J^e$	10^{-27}
	proton	$\bar{b}_J^p$	10^{-27}
	neutron	$\bar{b}_J^n$	10^{-30}
H Maser	electron	$\bar{b}_J^e$	10^{-27}
	proton	$\bar{b}_J^p$	10^{-27}
spin polarized matter	electron	$\bar{b}_J^e$ / $\bar{b}_Z^e$	10^{-29} / 10^{-28}
He–Xe Maser	neutron	$\bar{b}_J^n$	10^{-31}
Muonium	muon	$\bar{b}_J^\mu$	2×10^{-23}
Muon g–2	muon	$\bar{b}_J^\mu$	5×10^{-25} (estimated)

X,Y.Z celestial equatorial coordinates $\bar{b}_J = b_3 - md_{30} - H_{12}$

(Bluhm, hep–ph/0111323)



NB $|B^0| < 10^{-2}\,\mathrm{eV}$

Probing CPT Violation via Atomic Dipole moments

Bolokhov, Pospelov, Romalis 0609.153

Non-relativistic Hamiltonian

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S} \ .$$

In the presence of Lorentz-violating background vector

$$\mathcal{L}_{\rm EDM} = \frac{-i}{2} d_{\rm CP} \overline{\psi} \sigma^{\mu\nu} F_{\mu\nu} \psi + d_{\rm CPT} \overline{\psi} \gamma_\mu \gamma_5 \psi F_{\mu\nu} n^\nu$$

$$d_{\rm CP} + d_{\rm CPT} = d.$$ Total atomic dipole moment

nil result of neutron EDM → constraint on combination

SME & Atomic Dipole moments

Bolokhov, Pospelov, Romalis 0609.153

a_μ , b_μ LV background

$$\mathcal{L}_3 = -\sum \bar{\psi}(a^\mu \gamma_\mu + b^\mu \gamma_\mu \gamma_5)\psi,$$

+

$$\mathcal{L}_5 = -\sum [c^\mu \overline{\psi} \gamma^\lambda F_{\lambda\mu} \psi \; + \; d^\mu \overline{\psi} \gamma^\lambda \gamma^5 F_{\lambda\mu} \psi \; + \; f^\mu \overline{\psi} \gamma^\lambda \gamma^5 \widetilde{F}_{\lambda\mu} \psi \; + \; g^\mu \overline{\psi} \gamma^\lambda \widetilde{F}_{\lambda\mu} \psi].$$

properties

Coefficient	Operator	C	P	T
a^0	$\overline{\psi}\gamma_0\psi$	$-$	$+$	$+$
b^0	$\overline{\psi}\gamma_0\gamma_5\psi$	$+$	$-$	$+$
c^0	$F_{\lambda 0}\overline{\psi}\gamma^\lambda\psi$	$+$	$+$	$-$
d^0	$F_{\lambda 0}\overline{\psi}\gamma^\lambda\gamma^5\psi$	$-$	$-$	$-$
f^0	$\widetilde{F}_{\lambda 0}\overline{\psi}\gamma^\lambda\gamma^5\psi$	$-$	$+$	$+$
g^0	$\widetilde{F}_{\lambda 0}\overline{\psi}\gamma^\lambda\psi$	$+$	$-$	$+$

CPT V @ low energies (1 GeV) in SU(2) x U(1)

Bolokhov, Pospelov, Romalis 0609.153

manipulating field identities

$$\mathcal{L}_{\rm CPT} = \sum_{i=u,d,s} d_i^{\mu} \bar{q}_i \gamma^{\lambda}\gamma^5 F_{\lambda\mu} q_i .$$

light quarks (u, d, s)
+ photons, gluons

Disentangle CP- from CPT-odd operators

CP-odd terms require helicity flip → dim 6 operators . suppressed by $1/\Lambda^2_{\rm CP}$
→ spin precession with magnetic field $[\mathbf{B}\times\mathbf{v}]$

CPT-odd terms do not require helicity flip → dim 5 operators in SU(2) X U(1)
→ no spin precession

$$\bar{q}_{R(L)}\gamma^{\lambda}\gamma^5 F_{\lambda\mu} q_{R(L)} \; ; \quad \bar{q}_L \gamma^{\lambda}\gamma^5 \tau^a F^a_{\lambda\mu} q_L$$

Current bounds → $\Lambda_{\rm CPT} \sim (10^{11} - 10^{12})$ GeV

EDM neutrons
diamagnetic atoms (Hg, Xe,…)
paramagnetic atoms (Tl, Cs,…)

EDM-induced CPT bounds

Bolokhov, Pospelov, Romalis 0609.153

Neutron

$$d_n \simeq 0.8 d_d^0 - 0.4 d_u^0 - 0.1 d_s^0.$$

$|d_n| \; < \; 3 \times 10^{-26} ecm$ (2002)

CPT-odd EDMs
limited @ $O(10^{-25} \text{ecm})$.

Diamagnetic atoms

$$d_{\text{Hg}} \simeq -5 \times 10^{-4}(d_n + 0.1 d_p)$$
$$\simeq -5 \times 10^{-4}(0.74 d_d^0 - 0.32 d_u^0 - 0.11 d_s^0),$$

$d_{\text{Hg}}/d_n \sim -5 \times 10^{-4}$ → if $d_n \neq 0$ → CPTV

paramagnetic atoms

EDMs predicted to be extremely suppressed

higher-loop CPV corrections yields
imprecise estimates

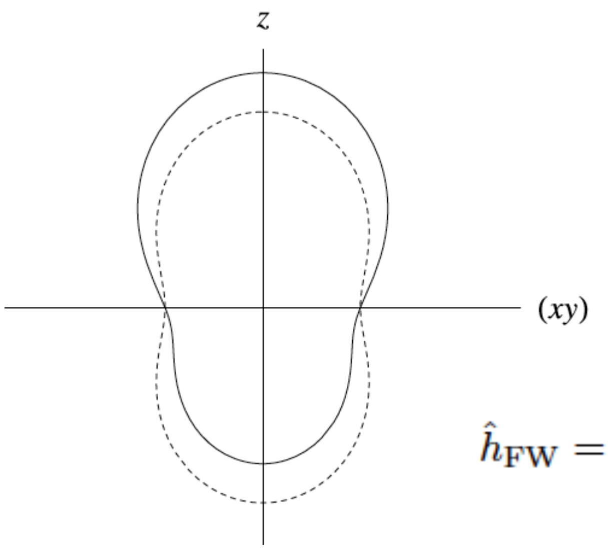
$$a^\mu, b^\mu \sim d^\mu (10^{-20} - 10^{-18}) \times \text{GeV}^2. < 10^{-31} \text{GeV}$$

$$d_\mu \leq O(10^{-12}) \text{GeV}^{-1}$$

Effects of b_μ on dipole moments in Hydrogen-like atoms

Angular distribution for spontaneous radiation for the transition

$$2p_{1/2,1/2} \to 1s_{1/2,-1/2}$$



Corrections to electromagnetic dipole moments of bound electrons calculated in 1/c expansion (Foldy-Wouthysen (FW) method) to second order in b_0 → contributions to **anapole moment** of the atomic orbital → **asymmetry of angular distribution of radiation** of, e.g. hydrogen atom

Kharlanov, Zhukovsky 0705.3306

$$\hat{h}_{\mathrm{FW}} = \frac{\hat{\boldsymbol{p}}^2}{2m_e} + \boldsymbol{\sigma b} - \frac{b_0}{m_e c}\boldsymbol{\sigma}\hat{\boldsymbol{p}} + \frac{\hat{p}_j \sigma_l}{2m_e^2 c^2}(b_j \hat{p}_l - b_l \hat{p}_j) + \frac{b_0}{2m_e^3 c^3}\hat{\boldsymbol{p}}^2(\boldsymbol{\sigma}\hat{\boldsymbol{p}}).$$

electric & magnetic dipole corrections

$$\hat{\boldsymbol{\mu}}_A = \frac{eb_0}{m_e}\gamma^0[\boldsymbol{\Sigma r}],$$

$$\hat{\boldsymbol{d}}_A = -i\gamma_5\hat{\boldsymbol{\mu}}_A = -\frac{ieb_0}{m_e}[\boldsymbol{\gamma r}].$$

LIV (SME) TESTS @ LHC & FUTURE COLLIDERS

SU(2) x U$_Y$(1) SME - gauge and fermion mixed sector

Gomes, Malta & Neves, **arXiv:1909.10398 [hep-ph].**

$$\mathcal{L}_{g\ell} = i\,\overline{\psi}_{\ell L}\,\gamma^\mu D_\mu \psi_{\ell L} + i\,\bar{\ell}_R\,\gamma^\mu D_\mu \ell_R$$

$$D_\mu = \partial_\mu - ig' Y\,B_\mu - ig\,W^a_\mu \frac{\sigma^a}{2} + \frac{i}{2}\xi^\nu\,B_{\mu\nu} + i\,\rho^\nu\,W^a_{\mu\nu}\frac{\sigma^a}{2}\,,$$

$$\mathcal{L}_{g\ell} = \mathcal{L}^{SM}_{g\ell} + \mathcal{L}^{LSV}_{g\ell}\,;$$

$$\begin{aligned}\mathcal{L}^{LSV}_{g\ell} &= \frac{1}{2}\xi^\mu\left(\bar{\psi}_{\ell L}\gamma^\nu\psi_{\ell L} + \bar{\ell}_R\gamma^\nu\ell_R\right)\left(\cos\theta_W F_{\mu\nu} - \sin\theta_W Z_{\mu\nu}\right)\\ &+\rho^\mu\,\overline{\psi}_{\ell L}\gamma^\nu\left(F^+_{\mu\nu}\frac{\sigma^+}{2} + F^-_{\mu\nu}\frac{\sigma^-}{2} + W^3_{\mu\nu}\frac{\sigma^3}{2}\right)\psi_{\ell L}\,,\end{aligned}$$

$$\sqrt{2}\,\sigma^\pm = \sigma^1 \pm i\,\sigma^2. \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \qquad Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu,$$

$$\begin{aligned}W^3_{\mu\nu} &= \cos\theta_W Z_{\mu\nu} + \sin\theta_W F_{\mu\nu} - ig\left(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu\right),\\ F^+_{\mu\nu} &= W^+_{\mu\nu} + ig\cos\theta_W\left(W^+_\mu Z_\nu - Z_\mu W^+_\nu\right) + ig\sin\theta_W\left(W^+_\mu A_\nu - W^+_\nu A_\mu\right)\end{aligned}$$

$SU(2) \times U_Y(1)$ SME - gauge and fermion mixed sector

Gomes, Malta & Neves, **arXiv:1909.10398 [hep-ph].**

$$\begin{aligned}
\mathcal{L}_{g\ell}^{\mathrm{LSV}} &= \bar{\ell}\left(c_1^{\mu}\gamma^{\nu} + c_2^{\mu}\gamma^{\nu}\gamma_5\right)\ell\, F_{\mu\nu} + \frac{1}{4}\, v_2^{\mu}\,\bar{\nu}_{\ell}\,\gamma^{\nu}\,(1-\gamma_5)\,\nu_{\ell}\, F_{\mu\nu} + \\
&+ \bar{\ell}\left(c_3^{\mu}\,\gamma^{\nu} + c_4^{\mu}\,\gamma^{\nu}\,\gamma_5\right)\ell\, Z_{\mu\nu} + \frac{1}{4}\, v_4^{\mu}\,\bar{\nu}_{\ell}\,\gamma^{\nu}\,(1-\gamma_5)\,\nu_{\ell}\, Z_{\mu\nu} + \\
&+ \frac{ig}{4}\,\rho^{\mu}\, W^{+}_{[\mu} W^{-}_{\nu]}\left[\bar{\ell}\,\gamma^{\nu}\,(1-\gamma_5)\,\ell - \bar{\nu}_{\ell}\,\gamma^{\nu}\,(1-\gamma_5)\,\nu_{\ell}\right] + \\
&+ \frac{1}{2\sqrt{2}}\,\rho^{\mu}\,\bar{\ell}\,\gamma^{\nu}\,(1-\gamma_5)\,\nu_{\ell}\left(W^{-}_{\mu\nu} - ieA_{[\mu}W^{-}_{\nu]} - ie\cot\theta_W\, Z_{[\mu}W^{-}_{\nu]}\right) + \mathrm{H.c.}
\end{aligned}$$

$$A_{[\mu}B_{\nu]} \equiv A_{\mu}B_{\nu} - B_{\mu}A_{\nu}$$

$$\begin{aligned}
v_{1\mu} &= \cos\theta_W\,\xi_{\mu} - \sin\theta_W\,\rho_{\mu}\ , \\
v_{2\mu} &= \cos\theta_W\,\xi_{\mu} + \sin\theta_W\,\rho_{\mu}\ , \\
v_{3\mu} &= -\sin\theta_W\,\xi_{\mu} - \cos\theta_W\,\rho_{\mu}\ , \\
v_{4\mu} &= -\sin\theta_W\,\xi_{\mu} + \cos\theta_W\,\rho_{\mu}\ .
\end{aligned}$$

$$\begin{aligned}
c_{1\mu} &= \frac{1}{2}\left(\cos\theta_W\,\xi_{\mu} - \frac{1}{2}\sin\theta_W\,\rho_{\mu}\right)\ , \quad c_{2\mu} = \frac{1}{4}\sin\theta_W\,\rho_{\mu}\ , \\
c_{3\mu} &= -\frac{1}{2}\left(\sin\theta_W\,\xi_{\mu} + \frac{1}{2}\cos\theta_W\,\rho_{\mu}\right)\ , \quad c_{4\mu} = \frac{1}{4}\cos\theta_W\,\rho_{\mu}
\end{aligned}$$

present in the SM		no SM counterpart	
interaction	vertex factor	interaction	vertex factor
$\gamma\,\ell\,\bar{\ell}$	$(c_1^{[\mu}\gamma^{\nu]} + c_2^{[\mu}\gamma^{\nu]}\gamma_5)q_\nu$	$\gamma\,\nu_\ell\,\bar{\nu}_\ell$	$\frac{1}{4}\,v_2^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)\,q_\nu$
$Z^0\,\ell\,\bar{\ell}$	$(c_3^{[\mu}\gamma^{\nu]} + c_4^{[\mu}\gamma^{\nu]}\gamma_5)q_\nu$	$W^-\,\gamma\,\ell\,\bar{\nu}_\ell$	$-\frac{ie}{2\sqrt{2}}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)$
$Z^0\,\nu_\ell\,\bar{\nu}_\ell$	$\frac{1}{4}\,v_4^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)\,q_\nu$	$W^-\,Z^0\,\ell\,\bar{\nu}_\ell$	$-\frac{ie\cot\theta_W}{2\sqrt{2}}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)$
$W^-\,\ell\,\bar{\nu}_\ell$	$\frac{1}{2\sqrt{2}}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)\,q_\nu$	$W^+\,W^-\,\ell\,\bar{\ell}$	$\frac{ig}{4}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)$
		$W^+\,W^-\,\nu_\ell\,\bar{\nu}_\ell$	$-\frac{ig}{4}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)$

present in the SM		no SM counterpart	
interaction	vertex factor	interaction	vertex factor
$\gamma\,\ell\,\bar{\ell}$	$(c_1^{[\mu}\gamma^{\nu]} + c_2^{[\mu}\gamma^{\nu]}\gamma_5)q_\nu$	$\gamma\,\nu_\ell\,\bar{\nu}_\ell$	$\frac{1}{4}\,v_2^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)\,q_\nu$
$Z^0\,\ell\,\bar{\ell}$	$(c_3^{[\mu}\gamma^{\nu]} + c_4^{[\mu}\gamma^{\nu]}\gamma_5)q_\nu$	$W^-\,\gamma\,\ell\,\bar{\nu}_\ell$	$-\frac{ie}{2\sqrt{2}}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)$
$Z^0\,\nu_\ell\,\bar{\nu}_\ell$	$\frac{1}{4}\,v_4^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)\,q_\nu$	$W^-\,Z^0\,\ell\,\bar{\nu}_\ell$	$-\frac{ie\cot\theta_W}{2\sqrt{2}}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)$
$W^-\,\ell\,\bar{\nu}_\ell$	$\frac{1}{2\sqrt{2}}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)\,q_\nu$	$W^+\,W^-\,\ell\,\bar{\ell}$	$\frac{ig}{4}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)$
		$W^+\,W^-\,\nu_\ell\,\bar{\nu}_\ell$	$-\frac{ig}{4}\,\rho^{[\nu}\gamma^{\mu]}\,(1-\gamma_5)$

SELECTED PROCESSES

I. W-decay width

$$\mathrm{BR}(W^- \to \ell \overline{\nu}_\ell) = \frac{G_F\, m_W^3}{6\sqrt{2}\pi\, \Gamma_W} \left(1 + \frac{\rho_0^2}{4\sqrt{2}\, G_F}\right)$$

$$G_F = \sqrt{2} g^2 / 8 m_W^2 ,$$

$$\mathrm{BR}(W^- \to \ell \overline{\nu}_\ell)_{\mathrm{exp}} = (10.86 \pm 0.09)\ \%$$

$\Rightarrow$

$$|\rho^0| \lesssim 8 \times 10^{-4}\, \mathrm{GeV}^{-1} .$$

II. Z-decay widths

$$\mathrm{BR}(Z \to \overline{\ell}\, \ell) = \frac{G_F\, m_Z^3\, (1 + g_V^2)}{24\sqrt{2}\pi\, \Gamma_Z} \left[1 + \frac{2\sqrt{2}}{1 + g_V^2} \left(\frac{c_{30}^2 + c_{40}^2}{G_F}\right)\right]$$

$$\mathrm{BR}(Z \to \overline{\ell}\, \ell)_{\mathrm{exp}} = (3.3658 \pm 0.0023)\ \% ,$$

$\Rightarrow$

$$\sqrt{c_{30}^2 + c_{40}^2} \lesssim 5 \times 10^{-5}\, \mathrm{GeV}^{-1} .$$

$$\mathrm{BR}(Z \to \overline{\nu}_\ell\, \nu_\ell) = \frac{G_F\, m_Z^3}{12\sqrt{2}\pi\, \Gamma_Z} \left(1 + \frac{v_{40}^2}{4\sqrt{2}\, G_F}\right)$$

$$\mathrm{BR}(Z \to \mathrm{invisible})_{\mathrm{exp}} = (20.000 \pm 0.055)\ \%$$

$\Rightarrow$

$$|v_{40}| \lesssim 4 \times 10^{-4}\, \mathrm{GeV}^{-1}$$

III. Muon decay

$$\Gamma(\mu^- \to \nu_\mu\, e^-\, \overline{\nu}_e) = \frac{G_F^2\, m_\mu^5}{192\pi^3} \left[1 + \frac{113\, m_\mu^2}{15360\, m_W^2\, G_F} \left(\rho_0^2 + \frac{55|\rho|^2}{226}\right)\right]$$

$$\tau_\mu = \Gamma_\mu^{-1} = (2.1969811 \pm 0.0000022) \times 10^{-6}\, \mathrm{s}$$

$\Rightarrow$

$$\sqrt{\rho_0^2 + \frac{55|\rho|^2}{226}} \lesssim 3 \times 10^{-2}\, \mathrm{GeV}^{-1}$$

SELECTED PROCESSES

I. W-decay width

$$\mathrm{BR}(W^- \to \ell\,\overline{\nu}_\ell) = \frac{G_F\, m_W^3}{6\sqrt{2}\pi\,\Gamma_W}\left(1 + \frac{\rho_0^2}{4\sqrt{2}\,G_F}\right)$$

$$\mathrm{BR}(W^- \to \ell\,\overline{\nu}_\ell)_{\mathrm{exp}} \;=\; (10.86 \pm 0.09)\ \%$$

$G_F = \sqrt{2}$ … m_W^2

II. Z-decay widths

$$\mathrm{BR}(Z \to \overline{\ell}\,\ell) = \frac{G_F\, m_Z^3\,(1+g_V^2)}{24\sqrt{2}\pi\,\Gamma_Z}\Big[\ldots$$

$\mathrm{BR}(Z \to \overline{\ell}\,\ell)_{\mathrm{exp}} =$ …

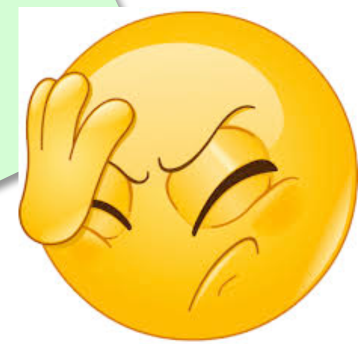
$$\sqrt{c_{30}^2 + c_{40}^2} \lesssim 5\times 10^{-5}\,\mathrm{GeV}^{-1}$$

BR(… $2 G_F$)

BR(Z … .000 ± 0.055) %

$$|v_{40}| \lesssim 4\times 10^{-4}\,\mathrm{GeV}^{-1}$$

BUT: ....Without Microscopic understanding of the various coefficients is not possible to appreciate the current bounds & collider sensitivities



III. Mu… decay

$$\Gamma(\mu^- \to \nu_\mu\, e^-\, \overline{\nu}_e) = \frac{G_F^2\, m_\mu^5}{192\pi^3}\left[1 + \frac{113\, m_\mu^2}{15360\, m_W^2 G_F}\left(\rho_0^2 + \frac{55|\rho|^2}{226}\right)\right]$$

$$\tau_\mu = \Gamma_\mu^{-1} = (2.1969811 \pm 0.0000022)\times 10^{-6}\,\mathrm{s}$$

$$\sqrt{\rho_0^2 + \frac{55|\rho|^2}{226}} \lesssim 3\times 10^{-2}\,\mathrm{GeV}^{-1}$$

Probing LV SME @ LHC and Future Colliders via top-quark studies

Carle, Chanon & Perries,
arXiv:1909.01990 & 1908.11734 [hep-ph].

e.g. CPT-even LV interactions

$$\mathcal{L} \supset \frac{1}{2} i (c_L)_{\mu\nu} \bar{Q}_t \gamma^\mu \overleftrightarrow{D}^\nu Q_t + \frac{1}{2} i (c_R)_{\mu\nu} \bar{U}_t \gamma^\mu \overleftrightarrow{D}^\nu U_t$$

Q_t is the third generation left-handed quark doublet

U_t is the right-handed charge-2/3 top singlet.

Top-pair production in SME

$$w = \frac{|\mathcal{M}_{SME}|^2}{|\mathcal{M}_{SM}|^2} = 1 + f(t)$$

$$f(t) = (c_{L,\mu\nu} + c_{R,\mu\nu}) R^\mu_\alpha(t) R^\nu_\beta(t) \left(\frac{\delta_p P}{P} + \frac{\delta_v P}{P} \right)^{\alpha\beta}$$
$$+ c_{L,\mu\nu} R^\mu_\alpha(t) R^\nu_\beta(t) \left(\frac{\delta F}{F} + \frac{\delta \bar{F}}{\bar{F}} \right)^{\alpha\beta}$$

Carle, Chanon & Perries, **arXiv:1909.01990 & 1908.11734 [hep-ph].**

$$p\bar{p} \rightarrow t\bar{t}$$

Tevatron: dominant process: $q\bar{q}$ annihilation

LHC: dominant process: gluon fusion

	D∅	LHC (Run II)	HL-LHC	HE-LHC	FCC
$\Delta c_{LXX}, \Delta c_{LXY}$	1×10^{-1}	7×10^{-4}	2×10^{-4}	2×10^{-5}	5×10^{-6}
$\Delta c_{LXZ}, \Delta c_{LYZ}$	8×10^{-2}	3×10^{-3}	5×10^{-4}	9×10^{-5}	2×10^{-5}
$\Delta c_{RXX}, \Delta c_{RXY}$	9×10^{-2}	3×10^{-3}	5×10^{-4}	8×10^{-5}	5×10^{-5}
$\Delta c_{RXZ}, \Delta c_{RYZ}$	7×10^{-2}	1×10^{-2}	2×10^{-3}	4×10^{-4}	8×10^{-5}
$\Delta c_{XX}, \Delta c_{XY}$	7×10^{-1}	1×10^{-3}	2×10^{-4}	3×10^{-5}	9×10^{-6}
$\Delta c_{XZ}, \Delta c_{YZ}$	6×10^{-1}	4×10^{-3}	7×10^{-4}	1×10^{-4}	3×10^{-5}
$\Delta d_{XX}, \Delta d_{XY}$	1×10^{-1}	6×10^{-4}	1×10^{-4}	2×10^{-5}	8×10^{-6}
$\Delta d_{XZ}, \Delta d_{YZ}$	7×10^{-2}	2×10^{-3}	4×10^{-4}	8×10^{-5}	2×10^{-5}

Studies of **single top production** can also be made within SME: Compare rates single top to single antitop production → ***b_μ LV & CPTV*** *coefficient bounds*

Berger, Kostelecky, Liu, **PRD 93, 036005 (2016)**.

Carle, Chanon & Perries, **arXiv:1909.01990 & 1908.11734 [hep-ph].**

$$p\bar{p} \to t\bar{t}$$

Tevatron: dominant process: $q\bar{q}$ annihilation

LHC: dominant process: gluon fusion

	D∅	LHC (Run II)	HL-LHC	HE-LHC	FCC
$\Delta c_{LXX}, \Delta c_{LXY}$	1×10^{-1}	7×10^{-4}	2×10^{-4}	2×10^{-5}	5×10^{-6}
$\Delta c_{LXZ}, \Delta c_{LYZ}$	8×10^{-2}	3×10^{-3}	5×10^{-4}	9×10^{-5}	2×10^{-5}
$\Delta c_{RXX}, \Delta c_{RXY}$	9×10^{-2}	3×10^{-3}	5×10^{-4}	8×10^{-5}	5×10^{-5}
$\Delta c_{RXZ}, \Delta c_{RYZ}$	7×10^{-2}	1×10^{-2}	2×10^{-3}	4×10^{-4}	8×10^{-5}
$\Delta c_{XX}, \Delta c_{XY}$	7×10^{-1}	1×10^{-3}	2×10^{-4}	3×10^{-5}	9×10^{-6}
$\Delta c_{XZ}, \Delta c_{YZ}$	6×10^{-1}	4×10^{-3}	7×10^{-4}	1×10^{-4}	3×10^{-5}
$\Delta d_{XX}, \Delta d_{XY}$	1×10^{-1}	6×10^{-4}	1×10^{-4}	2×10^{-5}	8×10^{-6}

$$\mathcal{L} = \tfrac{1}{2} i \bar{\psi} \Gamma^{\nu} \overleftrightarrow{\partial}_{\nu} \psi - \bar{\psi} M \psi,$$

$$M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \tfrac{1}{2} H^{\mu\nu}\sigma_{\mu\nu}$$

Studies of **single top production** can also be made within SME: Compare rates single top to single antitop production → ***b_μ LV & CPTV*** *coefficient bounds*

Berger, Kostelecky, Liu, **PRD 93, 036005 (2016)**.

Carle, Chanon & Perries, **arXiv:1909.01990 & 1908.11734 [hep-ph].**

$$p\bar{p} \rightarrow t\bar{t}$$

Tevatron: dominant process: $q\bar{q}$ annihilation

LHC: dominant process: gluon fusion

	D∅	LHC (Run II)	HL-LHC	HE-LHC	FCC
$\Delta c_{LXX}, \Delta c_{LXY}$	1×10^{-1}	7×10^{-4}	2×10^{-4}	2×10^{-5}	5×10^{-6}
$\Delta c_{LXZ}, \Delta c_{LYZ}$	8×10^{-2}	3×10^{-3}	5×10^{-4}	9×10^{-5}	[illegible]
$\Delta c_{RXX}, \Delta c_{RXY}$	9×10^{-2}	3×10^{-3}	[illegible]	[illegible]	[illegible]
$\Delta c_{RXZ}, \Delta c_{RYZ}$	7×10^{-2}	[illegible]	[illegible]	[illegible]	[illegible]
$\Delta c_{XX}, \Delta c_{XY}$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	8×10^{-6}
[illegible]	[illegible]	[illegible]	[illegible]	8×10^{-5}	2×10^{-5}

We discussed above

MICROSCOPIC STRING-INSPIRED MODELS

of **the b_μ coefficients** in connection

with **Lepto/Baryogenesis**

production can also be made within SME: Compare rates

top to single antitop production → ***b_μ LV & CPTV*** *coefficient bounds*

Berger, Kostelecky, Liu, **PRD 93, 036005 (2016)**.

OTHER COLLIDER SME TESTS :

A test of CPT violation through Bs oscillations at LHCb

B_0 and B_s neutral-meson oscillations

$$\mathcal{L} = \frac{1}{2} i \bar{\psi} \Gamma^{\nu} \bar{\partial}_{\nu} \psi - \bar{\psi} M \psi, \qquad M \equiv m + a_{\mu}\gamma^{\mu} + b_{\mu}\gamma_5\gamma^{\mu} + \frac{1}{2} H^{\mu\nu}\sigma_{\mu\nu}$$

The tiny **mass difference between the Bs and its antiparticle** is used to achieve excellent precision on the ***a_{μ}*** **SME coefficients for b quarks.** The analysis, performed as a function of sidereal time, achieved a precision of **10^{-14} GeV, a factor 102 improvement relative to previous measurements (@ 8 TeV data)**.

LHCb Coll. **PRL 116, 241601 (2016)**.

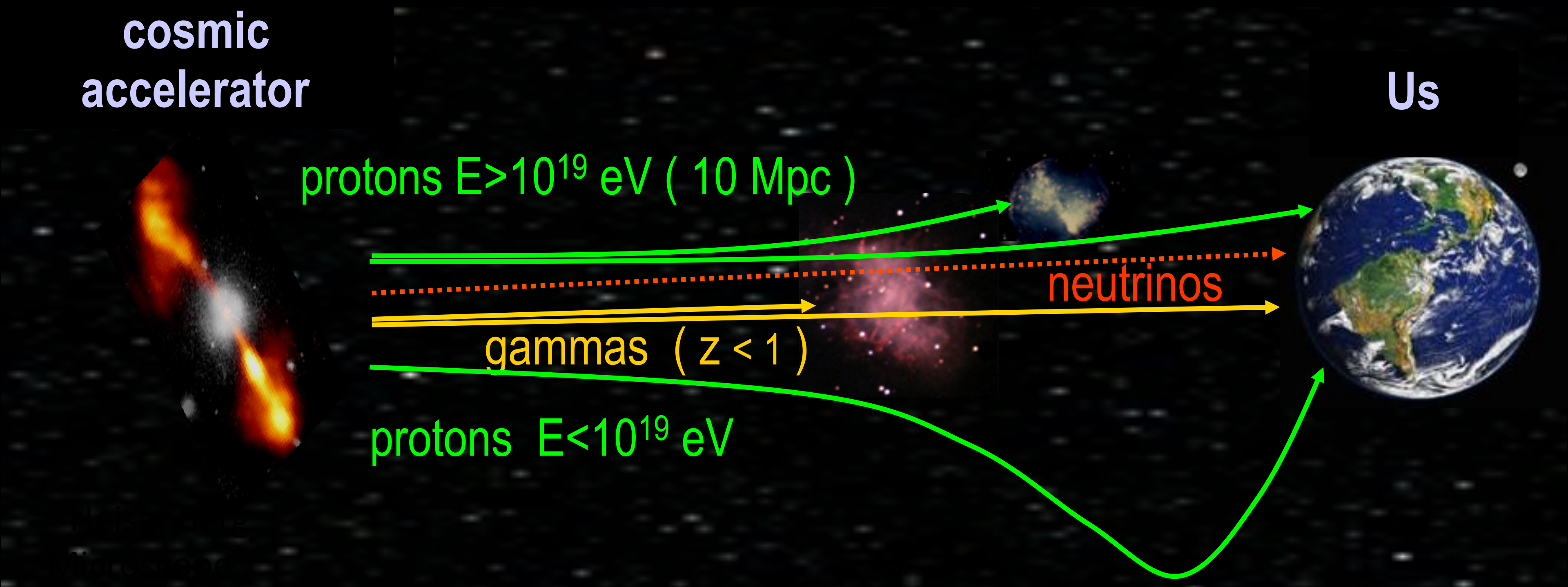
Improvement by a factor of 3 in c-quark SME coefficients through studies of decays $D^0 \to K^-\pi^+$

van Tilburg and van Veghel, **Phys. Lett. B742, 236 (2015)**

...and many others.....

COSMIC HIGH ENERGY PARTICLE PROBES OF LORENTZ INVARIANCE VIOLATION THROUGH MODIFIED DISPERSION RELATIONS: TESTS/CONSTRAINTS

Testing QG Modified Dispersion Effects



protons/nuclei: Deviated by magnetic fields,
Absorbed by radiation field (GZK)

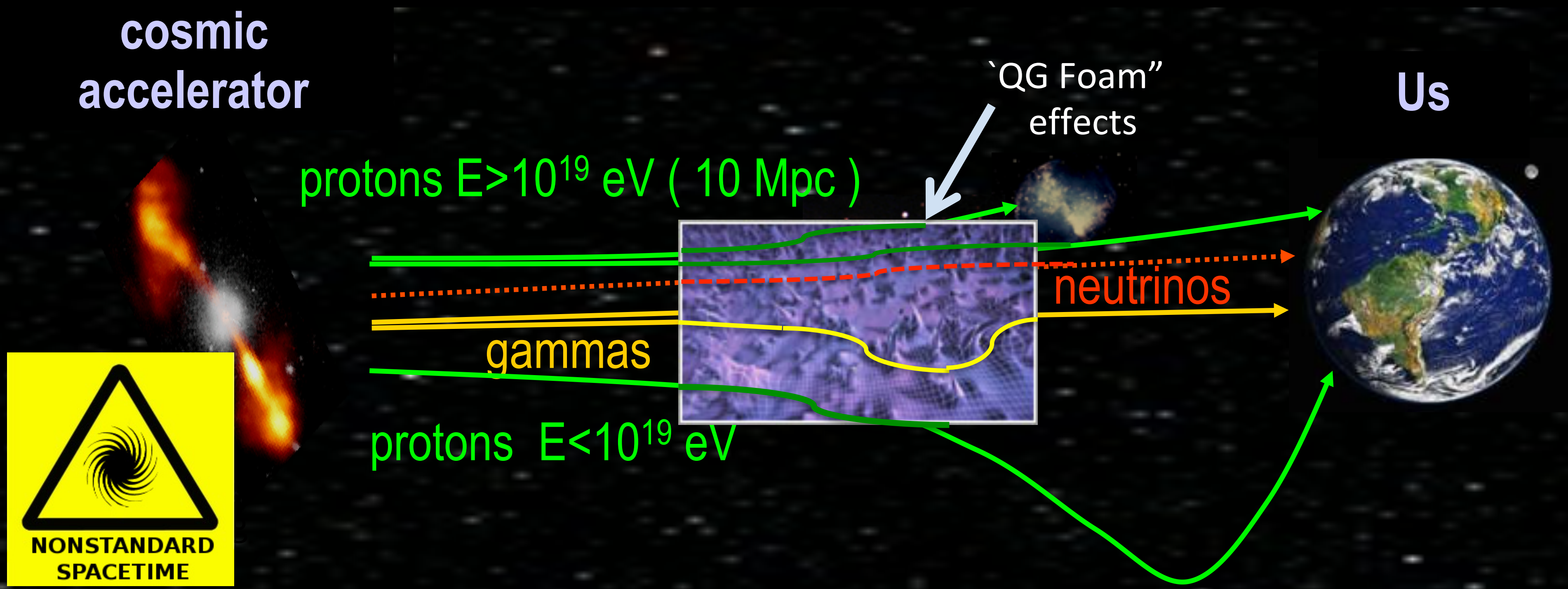
photons: Absorbed by dust & radiation field (CMB)

neutrinos: Difficult to detect

⇒ Three "astronomies" possible...

DeNaurois 2008

Testing QG Modified Dispersion Effects



protons/nuclei: QG effects may be suppressed

Absorbed by radiation field (GZK)

Jacobson,Liberati,Mattingly, Galaverni, Sigl ....

photons: QG effects Unsuppressed in certain theories

neutrinos: QG effects unsuppressed in certain theories

⇒ Three "astronomies" possible...

Amelino-Camelia, Ellis, NEM, Nanopoulos, Sarkar, Farakos, Mitsou, Sakharov, Sarkisyan ...

QG-induced Vacuum Refraction Theoretical Model Predictions

QG-Induced Modified Dispersion Relations for massive and massless particles

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^{2+\alpha}}{M_P^\alpha},$$

$$E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^{2+\alpha}}{M_P^\alpha}$$

QG-induced Vacuum Refraction Theoretical Model Predictions

QG-Induced Modified Dispersion Relations for massive and massless particles

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^{2+\alpha}}{M_P^\alpha},$$

$$E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^{2+\alpha}}{M_P^\alpha}$$

Two types:

Amelino-Camelia, Ellis, NEM, Nanopoulos (96) ...
first in non-critical strings

Induced momentum and coordinate dependent metrics (Finsler-type) due to interactions with QG-``medium''

Ellis, NEM, Nanopoulos (non-critical strings), Vacaru, Liberati, Aloisio, Blasi, Ghia,Grillo ...

Fundamental Modifications of the Lorentz Algebra (Deformed Special Relativities)

Amelino Camelia, Magueijo-Smolin

QG-induced Vacuum Refraction
Theoretical Model Predictions

QG-Induced Modified Dispersion Relations for massive and massless particles

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^{2+\alpha}}{M_P^\alpha},$$

$$E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^{2+\alpha}}{M_P^\alpha}$$

Two types:

Amelino-Camelia, Ellis, NEM, Nanopoulos (96) ...
first in non-critical strings

Induced momentum and coordinate dependent metrics (Finsler-type) due to interactions with QG-``medium''

Ellis, NEM, Nanopoulos (non-critical strings), Vacaru, Liberati, Aloisio, Blasi, Ghia,Grillo ...

Fundamental Modifications of the Lorentz Algebra (Deformed Special Relativities)

κ-Minkowski: Lukierski,Kowalski-Glikman

QG-induced Vacuum Refraction Theoretical Model Predictions

QG-Induced Modified Dispersion Relations for massive and massless particles

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^{2+\alpha}}{M_P^\alpha},$$

$$E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^{2+\alpha}}{M_P^\alpha}$$

Two types:

Amelino-Camelia, Ellis, NEM, Nanopoulos (96) ...
first in non-critical strings

Induced ... s
(Finsler ...

Important Distiinguishing Properties/open issues in DSR: multiparticle states, combination of momenta

Ellis, NEM, Nanopoulos (non-critical strings), Vacaru, Liberati, Aloisio, Blasi, Ghia,Grillo ...

Fundamental Modifications of the Lorentz Algebra (Deformed Special Relativities)

QG-induced Vacuum Refraction
Theoretical Model Predictions

QG-Induced Modified Dispersion Relations for massive and massless particles

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^{2+\alpha}}{M_P^\alpha},$$

$$E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^{2+\alpha}}{M_P^\alpha}$$

Two types:

Amelino-Camelia, Ellis, NEM, Nanopoulos (96) ...
first in non-critical strings

Induced momentum and coordinate dependent metrics (Finsler-type) due to interactions with QG-``medium''

Ellis, NEM, Nanopoulos (non-critical strings), Vacaru, Liberati, Aloisio, Blasi, Ghia,Grillo ...

Quantum-Gravity Induced Modified Dispersion for Photons

Finsler-type modified dispersion due to QG induced space-time (metric) distortions (c=1):

$$p^\mu p^\nu G_{\mu\nu}(\vec{p}, E) = 0 \ , \qquad p^\mu = (E, \vec{p})$$

$$E = p\left(1 + \sum_{n=1}^{\infty} a_n \left(\frac{|\vec{p}|}{M_{\rm QG}}\right)^n\right)$$

$$V_{\rm phase} = \frac{E}{|\vec{p}|} = \frac{1}{\eta} \ , \qquad V_{\rm group} = \frac{\partial E}{\partial |\vec{p}|}$$

$$\eta(|\vec{p}|) = \text{refractive index in vacuo}$$

$$\text{subluminal} : \ \eta > 1 \ , \ \text{superluminal} \ \eta < 1$$

Quantum-Gravity Induced Modified Dispersion for Photons

Finsler-type modified dispersion due to QG induced space-time (metric) distortions (c=1):

$$p^\mu p^\nu G_{\mu\nu}(\vec{p}, E) = 0 \ , \qquad p^\mu = (E, \vec{p})$$

In **non-critical strings**, describing propagation of photons in non-trivial Black-Hole backgrounds it is the **entire Finsler-type dispersion, including the ``infinity'' of higher order powers of momenta suppressed by the string scale $M_s = (\alpha')^{1/2} = M_{QG}$,** required **for world-sheet local scale (conformal)** invariance, i.e. the corresponding conformal dimension of the σ-model vertex operator describing the excitation of a photon in such a background is one (i.e. **no anomalous dimension**) only if these higher order operators are included.

Ellis, NEM, Nanopoulos (1992)
+ Amelino-Camelia (1996)

Quantum-Gravity Induced Modified Dispersion for massive particles

Finsler-type modified dispersion due to QG induced space-time (metric) distortions (c=1):

$$p^\mu p^\nu G_{\mu\nu}(\vec{p}, E) = m^2, \quad p^\mu = (E, \vec{p})$$

$$E = p\left(1 + \sum_{n=1}^{\infty} a_n \left(\frac{|\vec{p}|}{M_{\rm QG}}\right)^n\right)$$

$$V_{\rm phase} = \frac{E}{|\vec{p}|} = \frac{1}{\eta}\ , \qquad V_{\rm group} = \frac{\partial E}{\partial |\vec{p}|}$$

$\eta(|\vec{p}|) =$ refractive index in vacuo

subluminal : $\eta > 1$, superluminal $\eta < 1$

QG-induced Vacuum Refraction Theoretical Model Predictions

QG-Induced Modified Dispersion Relations for massive and massless (photons) particles

$$\omega^2(k) = k^2 + \xi_\gamma \frac{k^{2+\alpha}}{M_P^\alpha},$$

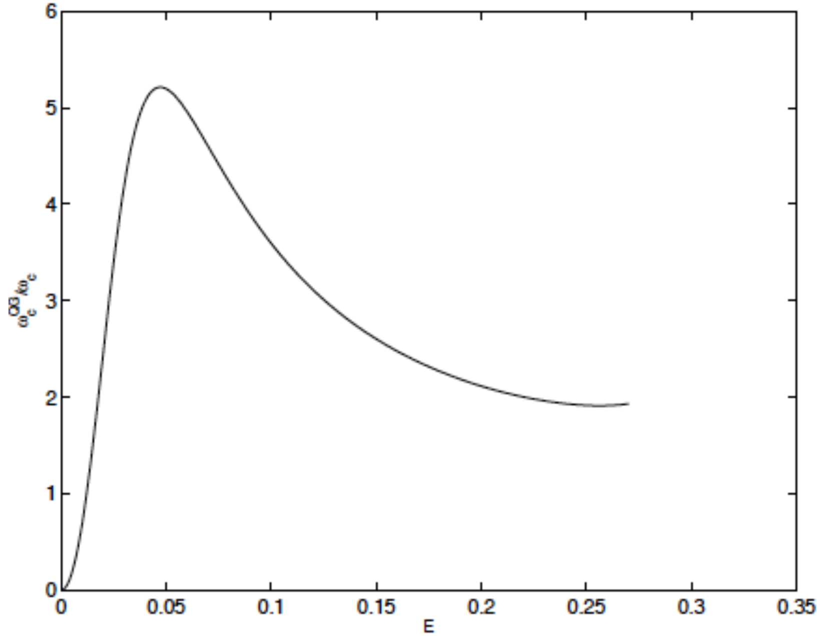
$$E^2(p) = m_0^2 + p^2 + \xi_e \frac{p^{2+\alpha}}{M_P^\alpha}$$

$\xi_\gamma \neq \xi_e$ in general, as this depends on the details of foam – QG effects **may be non universal**

Very stringent constraints for ξ_e on linearly ($\alpha = 1$) suppressed QG effects from Crab Nebula synchrotron radiation

Jacobson, Liberati, Mattingly

Synchrotron radiation constraint for LIV for electrons-Crab Nebula



$$\omega_c^{QG} \propto \omega_c^{LI} \frac{1}{(1+\sqrt{2-1/\eta^2})^{1/2}\left(\frac{m_0^2}{E^2}+(\alpha+1)\left(\frac{E}{\mathcal{M}}\right)^{\alpha}\right)}$$

$$\mathcal{M} \equiv M_P/|\xi_e|\ , \quad \eta \equiv 1-(E/\mathcal{M})^{\alpha}$$

$$160\times 10^{-6}\ \text{Gauss}\ <\ H\ <\ 260\times 10^{-6}\ \text{Gauss}$$

$$|\xi_e| \leq 1$$

$$\alpha \geq \alpha_c\ :\qquad 1.72 < \alpha_c < 1.74$$

Hence linear effects suppressed by terms of order of M_P for electrons excluded

Jacobson, Liberati, Mattingly

Ellis, NEM, Sakharov

QG-induced Vacuum Refraction Theoretical Model Predictions

QG-Induced Modified Dispersion Relations for particles (**photons for this talk**)

$$E^2 = p^2 \left(1 \pm |\xi|_\alpha \left[\frac{p}{M_{\rm QG}} \right]^\alpha + \ldots \right)$$

$$\alpha = 1 \quad \text{or} \quad 2,$$

QG-induced Vacuum Refraction Theoretical Model Predictions

QG-Induced Modified Dispersion Relations for particles (**photons for this talk**)

$$E^2 = p^2\Big(1 \pm |\xi|_\alpha \Big[\frac{p}{M_{\rm QG}}\Big]^\alpha + \ldots\Big)$$

$$\alpha = 1 \quad \text{or} \quad 2,$$

Birefringence (i.e. dependence on photon polarization in general → stringent limits:

$|\xi_1| < 2 \times 10^{-7}$

from GRB UV/optical polarization

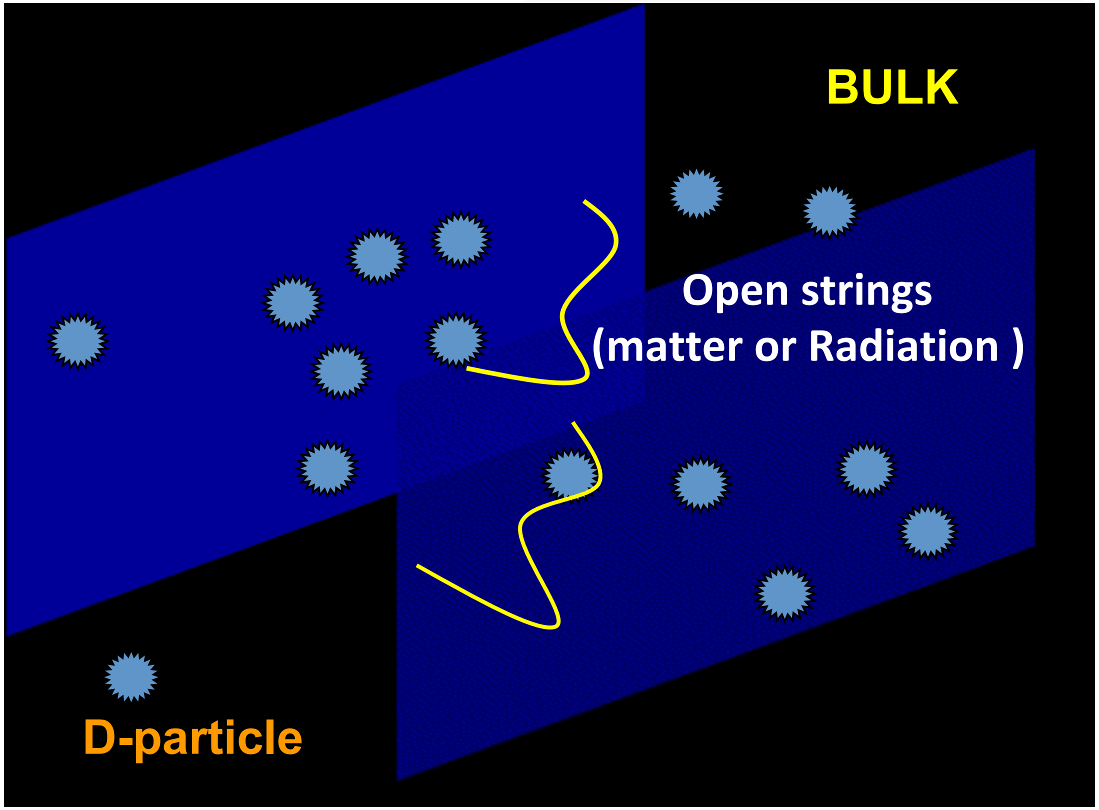
...But some stringy QG models have no Birefringence...

But.... in Non-Critical String Induced Vacuum Refraction
(STRING UNCERTAINTIES)
THERE ARE NO BIREFRINGENCE EFFECTS

HENCE CAN IN PRINCIPLE DISTINGUISH / FALSIFY

Ellis, NEM, Nanopoulos

A STRINGY MODEL
OF ``QG MEDIUM''
D-BRANE UNIVERSE IN A
BULK PUNCTURED BY
COMPACTIFIED D-BRANES
(EFFECTIVELY POINT-LIKE)



Open strings can be ``captured'' by defects

Ellis, NEM, Westmucket

But.... in Non-Critical String Induced Vacuum Refraction (STRING UNCERTAINTIES)

THERE ARE NO BIREFRINGENCE EFFECTS

HENCE CAN IN PRINCIPLE DISTINGUISH / FALSIFY

Ellis, NEM, Nanopoulos

A STRINGY MODEL
OF ``QG MEDIUM''
D-BRANE UNIVERSE IN A
BULK PUNCTURED BY
COMPACTIFIED D-BRANES
(EFFECTIVELY POINT-LIKE)

Open strings can be ``captured'' by defects

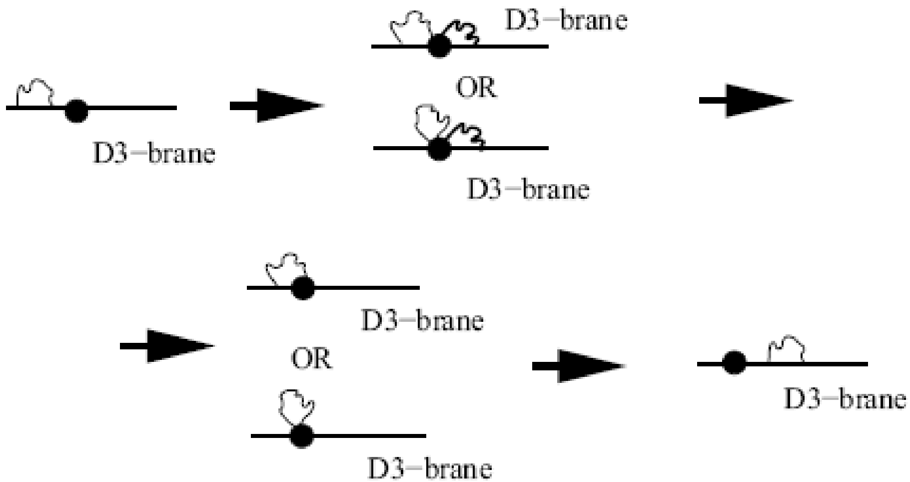
Ellis, NEM, Westmucket

Not true for **electrically charged** excitatIons – GAUGE SYMMETRY PROTECTED,

NON UNIVERSAL MODIFIED DISPERSION RELATION EFFECTS

Stringy Uncertainties & the Capture Process

Ellis, NEM, Nanopoulos, PLB 674 (2009) 83



During Capture: intermediate String stretching between D-particle and D3-brane is Created. It acquires N internal Oscillator excitations & Grows in size & oscillates from Zero to a maximum length by absorbing incident photon Energy p^0 :

$$p^0 = \frac{L}{\alpha'} + \frac{N}{L}.$$

Minimise right-hand-size w.r.t. L.
End of intermediate string on D3-brane
Moves with speed of light in vacuo c=1
Hence TIME DELAY (causality) during
Capture:

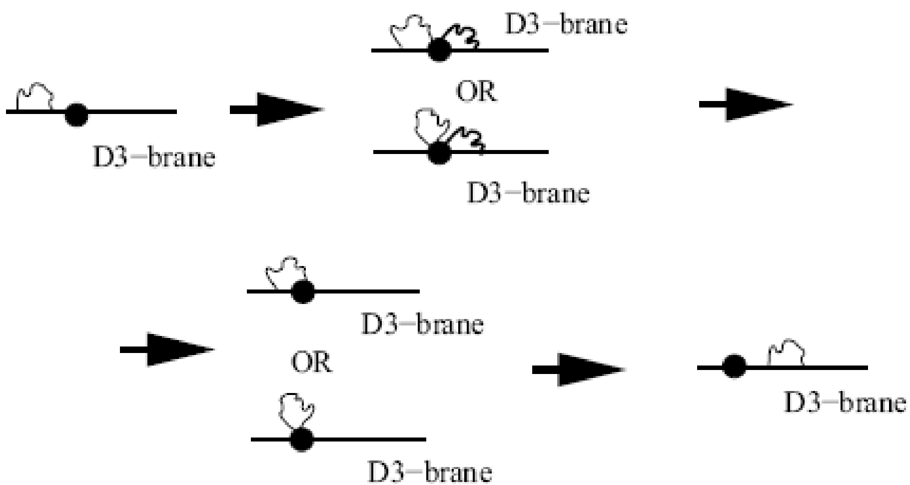
$$\Delta t \sim \alpha' p^0$$

$$p^0 \ll \frac{1}{\sqrt{\alpha'}} \equiv M_s$$

DELAY IS INDEPENDENT OF PHOTON POLARIZATION, HENCE **NO BIREFRINGENCE….**

Stringy Uncertainties & the Capture Process

Ellis, NEM, Nanopoulos, PLB 674 (2009) 83



During Capture: intermediate String stretching between D-particle and D3-brane is Created. It acquires N internal Oscillator excitations & Grows in size & oscillates from Zero to a maximum length by absorbing incident photon

Minimise right-hand-size w.r.t. L.
End of intermediate string on D3-brane
Moves with speed of light in vacuo c=1
Hence **TIME DELAY (causality)** during
Capture:

$$\Delta t \sim \alpha' p^0$$

$$p^0 \ll \frac{1}{\sqrt{\alpha'}} \equiv M_s$$

DELAY IS INDEPENDENT OF PHOTON POLARIZATION, HENCE **NO BIREFRINGENCE….**

Collective Effects of D-foam medium on Stringy Uncertainties

- D-foam: transparent to electrons – **avoid Cran Nebula constraints**
- D-foam captures photons & re-emits them
- Time Delay (Causal) in **each** Capture: $\Delta t \sim \alpha' p^0$ $\quad p^0 \ll M_s$
- Independent of photon polarization (**no Birefringence**)
- **Total Delay** from emission of photons till observation over **a distance D** (assume n^* defects per string length):

$$\Delta t_{\rm total} = \alpha' p^0 n^* \frac{D}{\sqrt{\alpha'}} = \frac{p^0}{M_s} n^* D$$

Effectively modified Dispersion relation for photons due to induced metric distortion $G_{0i} \sim p^0$

Collective Effects of D-foam medium on Stringy Uncertainties

- D-foam: transparent to electrons – **avoid Cran Nebula constraints**
- D-foam captures photons & re-emits them
- Time Delay (Causal) in **each** Capture: $\Delta t \sim \alpha' p^0$ $\quad p^0 \ll M_s$

COMPATIBLE WITH STRING UNCERTAINTY PRINCIPLES:

$$\Delta t\, \Delta x \geq \alpha' \,, \quad \Delta p\, \Delta x \geq 1 + \alpha' (\Delta p)^2 + \ldots$$

(α' = Regge slope = Square of minimum string length scale)

$$\Delta t_{\rm total} = \alpha' p^0 n^* \frac{D}{\sqrt{\alpha'}} = \frac{p^0}{M_s} n^* D$$

Effectively modified Dispersion relation for photons due to induced metric distortion $G_{0i} \sim p^0$

NB: **For VHE photons:**

$$\Delta t \sim \frac{\alpha' \, p^0}{1 - 2\pi\alpha' \, E^2}$$

But scattering amplitude of photons with D-particles in the foam

$$\mathcal{A} \propto g_s \, (1 - 2\pi\alpha' E^2)^{1/2} \times \text{kinematic factors}$$

i.e. goes to zero for $E \sim 1/\sqrt{\alpha' \, 2\pi} = M_s/\sqrt{2\pi}$

→ D-foam transparent to such VHE photons

Amplitude becomes imaginary (capture) for higher photon energies

$E = M_s/\sqrt{2}\,\pi$ plays the role of a characteristic **upper bound** for photon **energy** in such models

Ellis, NEM, Nanopoulos, B674 (2009) 83-86,
Int.J.Mod.Phys. A26 (2011) 2243-2262

Collective Effects of D-foam medium on Stringy Uncertainties

- D-foam: transparent to electrons
- D-foam captures photons & re-emits them
- Time Delay (Causal) in **each** Capture: $\Delta t \sim \alpha' p^0$ $\quad p^0 \ll M_s$
- Independent of photon polarization (**no Birefringence**)
- **Total Delay** from emission of photons till observation over **a distance D** (assume n^* defects per string length):

$$\Delta t_{\rm total} = \alpha' p^0 n^* \frac{D}{\sqrt{\alpha'}} = \frac{p^0}{M_s} n^* D$$

Collective Effects of D-foam medium on Stringy Uncertainties

- D-foam: transparent to electrons
- D-foam captures photons & re-emits them
- Time Delay (Causal) in **each** Capture: $\Delta t \sim \alpha' p^0$ $\quad p^0 \ll M_s$
- Independent of photon polarization (**no Birefringence**)
- **Total Delay** from emission of photons till observation over **a distance D** (assume n^* defects per string length):

M_{QG} Proportional to Density of Defects (details of model)

$$\Delta t_{\rm total} = \alpha' p^0 n^* \frac{D}{\sqrt{\alpha'}} = \frac{p^0}{M_s} n^* D$$

$$M_{\rm QG} = \frac{M_s}{n^\star} \neq M_{\rm Pl}$$

Astrophysical constraints on defect densities

Ellis, NEM, Sakharov, Sarkisyan
Jacob & Piran

Red-Shift Dependent QG Scale

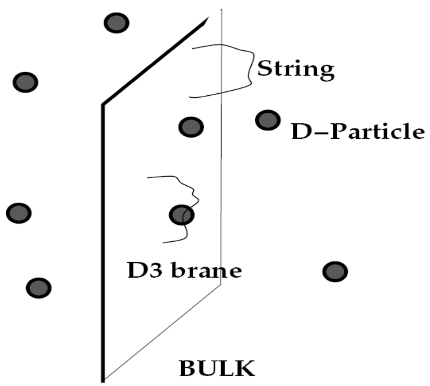
Universe Expansion may affect density of defects – n*(z) Red-shift Dependent

$$\Delta t_{\rm obs} = \int_0^z dz \frac{n(z)\, E_{\rm obs}}{M_s\, H_0} \frac{(1+z)}{\sqrt{\Omega_M\, (1+z)^3 + \Omega_\Lambda}}$$

Red-Shift Dependent QG Scale

Universe Expansion may affect density of defects – n*(z) Red-shift Dependent

$$\Delta t_{\rm obs} = \int_0^z dz \frac{n(z)\, E_{\rm obs}}{M_s\, H_0} \frac{(1+z)}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}$$



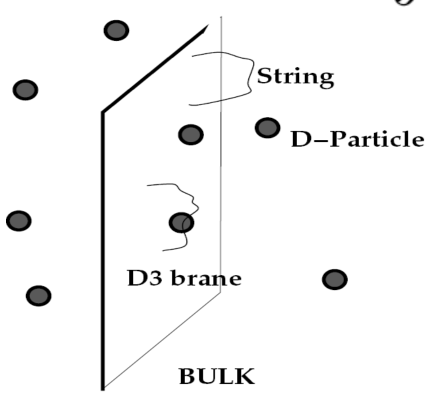
$$M_{\rm QG} = \frac{M_s}{n^\star(z)} \neq M_{\rm Pl}$$

n* (z) can depend on redshift z
If brane moves in inhomogeneous bulk

Red-Shift Dependent QG Scale

Universe Expansion may affect density of defects – n*(z) Red-shift Dependent

$$\Delta t_{\rm obs} = \int_0^z dz \frac{n(z)\, E_{\rm obs}}{M_s\, H_0} \frac{(1+z)}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}$$



$$M_{\rm QG} = \frac{M_s}{n^\star(z)} \neq M_{\rm Pl}$$

Can be >> M_{Pl}
in regions depleted
from defects

n* (z) can depend on redshift z
If brane moves in inhomogeneous bulk

Can explain FERMI/LAT measurement on GRB090510

Fits to astrophysical Measurements
Look for modified dispersion relation effects in high energy cosmic rays, extragalactic neutrinos, and
High Energy Photons...

Fits to astrophysical Measurements
Look for late arrivals of
high energy photons compared to
lower energy ones from
extragalactic intense sources
such as GRBs, AGNs plus
time variations of the width
of the photon pulses...

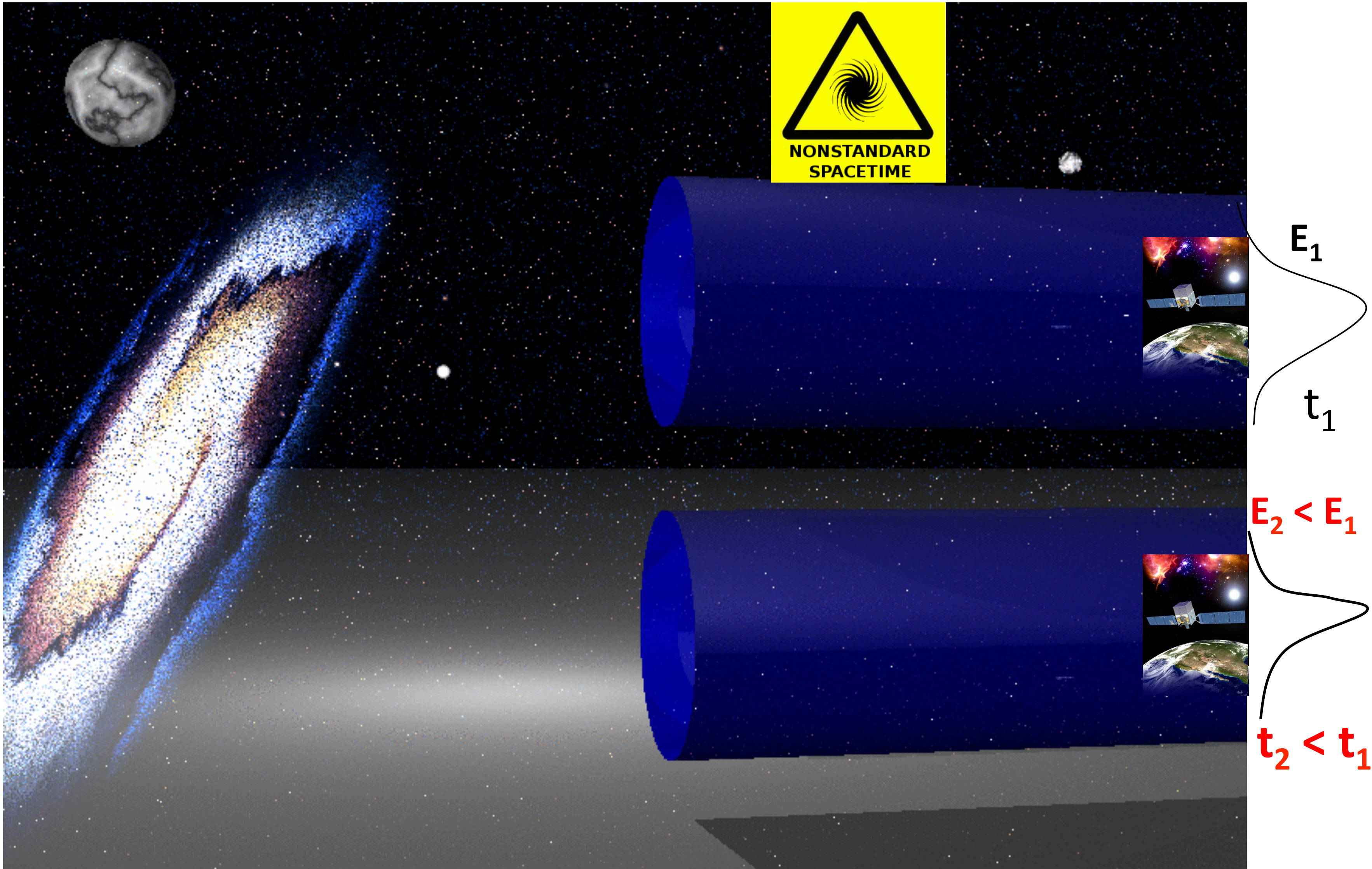
Amelino-Camelia, Ellis, NEM, Nanopoulos, Sarkar
Nature 393 (1998) 763-765

Ellis, Farakos, NEM, Mitsou, Nanopoulos,
Astrophys.J. 535 (2000) 139-151

+ Sakharov, Sarkisyan, Astropart.Phys. 25 (2006) 402-411, Astropart.Phys. 29 (2008) 158-159

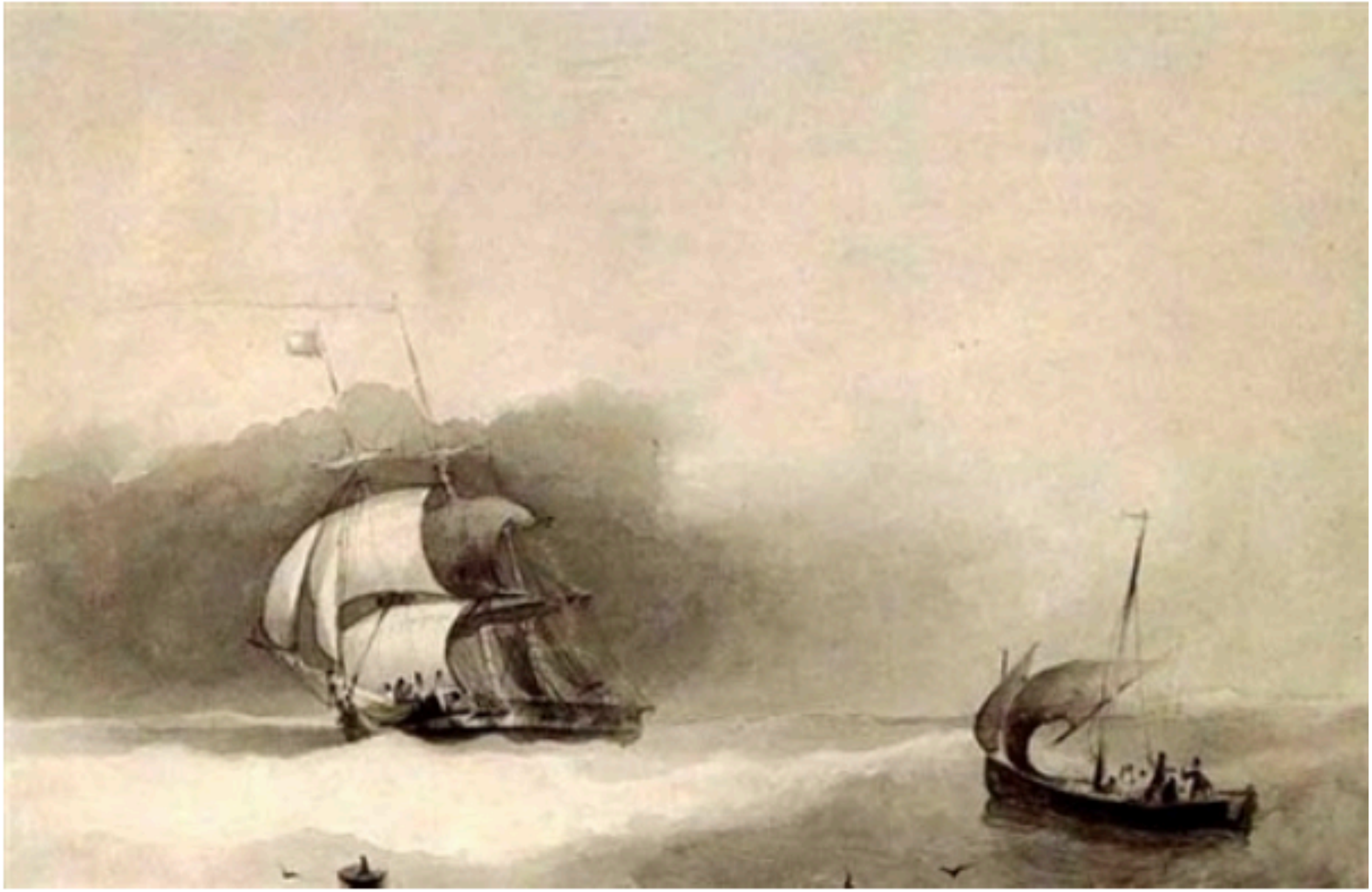
+ MAGIC Coll, Phys.Lett. B668 (2008) 253-257

.....



Subluminal QG-induced Refractive Index: Higher energy photons arrive later
Stochastic Light-Cone fluctuations: Energy dependent width of photon pulses
(e.g. D-particle (stringy) foam, width proportional to photon energy)

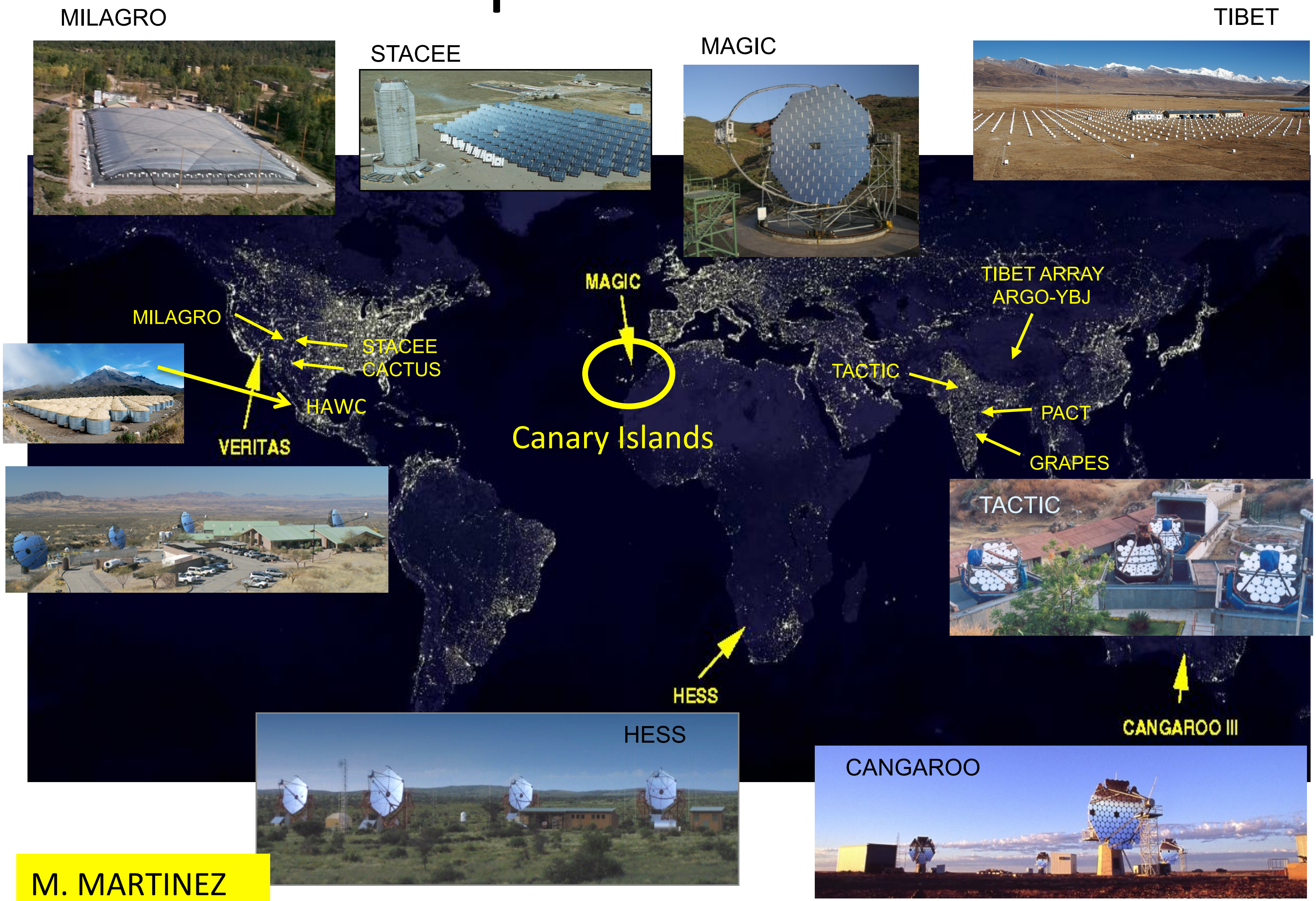
Artistic analogy



A ship and a small sailing boat on a rough sea

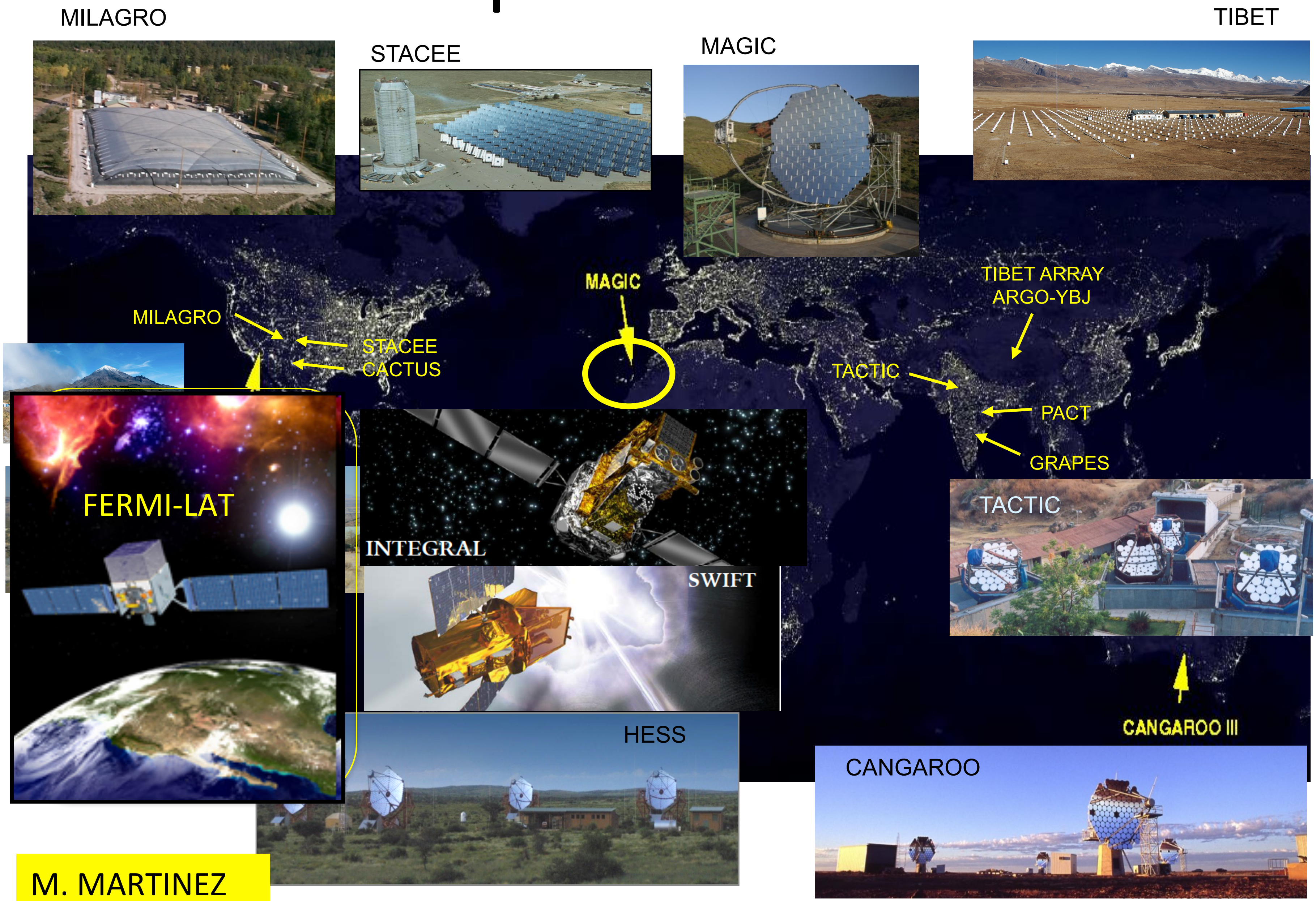
Charles Frederik Bartholomeus de Florimont (Dutch, 1802–1846)

VHE Experimental World



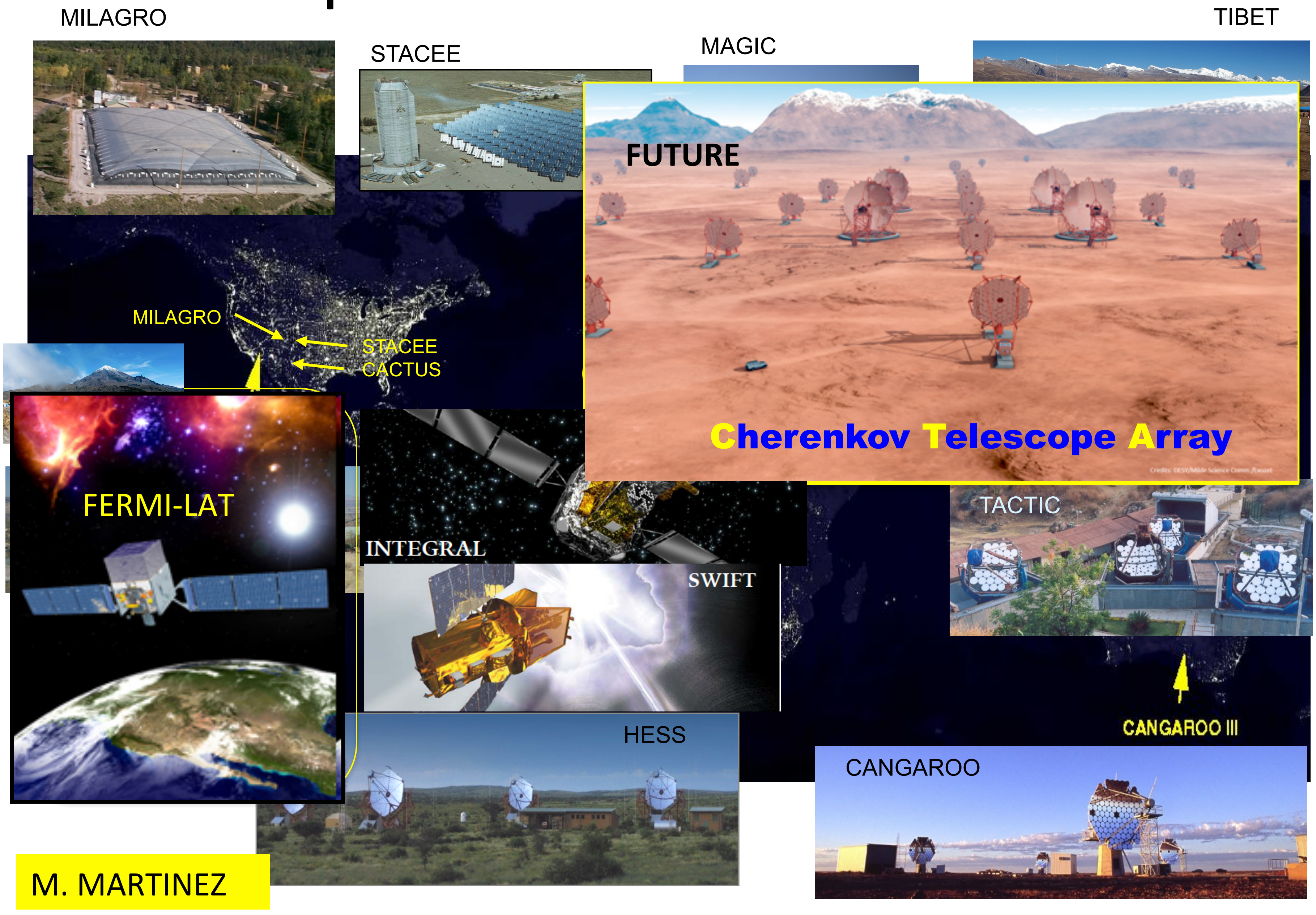
M. MARTINEZ

VHE Experimental World



M. MARTINEZ

VHE Experimental World-**the future**



Earlier Evidence of Delayed Arrivals of more energetic photons

MAGIC (AGN Mkn 501 , z=0.034), Highest Energy 1.2 TeV Photons

Observed Delays of O(4 min)

HESS (AGN PKS 2155-304 z=0.116), Highest Energy 10 TeV photons

Original claim no observed time lags

FERMI (GRB 090816C, z=4.35), Highest Energy Photon 13.2 GeV

4.5 s time-lag between E > 100 MeV and E < 100 KeV
Observed Time Delay 16.5 sec

FERMI (GRB 090510, z=0.9), Highest Energy Photon 31 GeV, several 1-10 GeV

Short, intense GRB, Observed Time Delays < 1 sec

FERMI (GRB 09092B, z=1.822), Highest Energy Photon 33.4 GeV

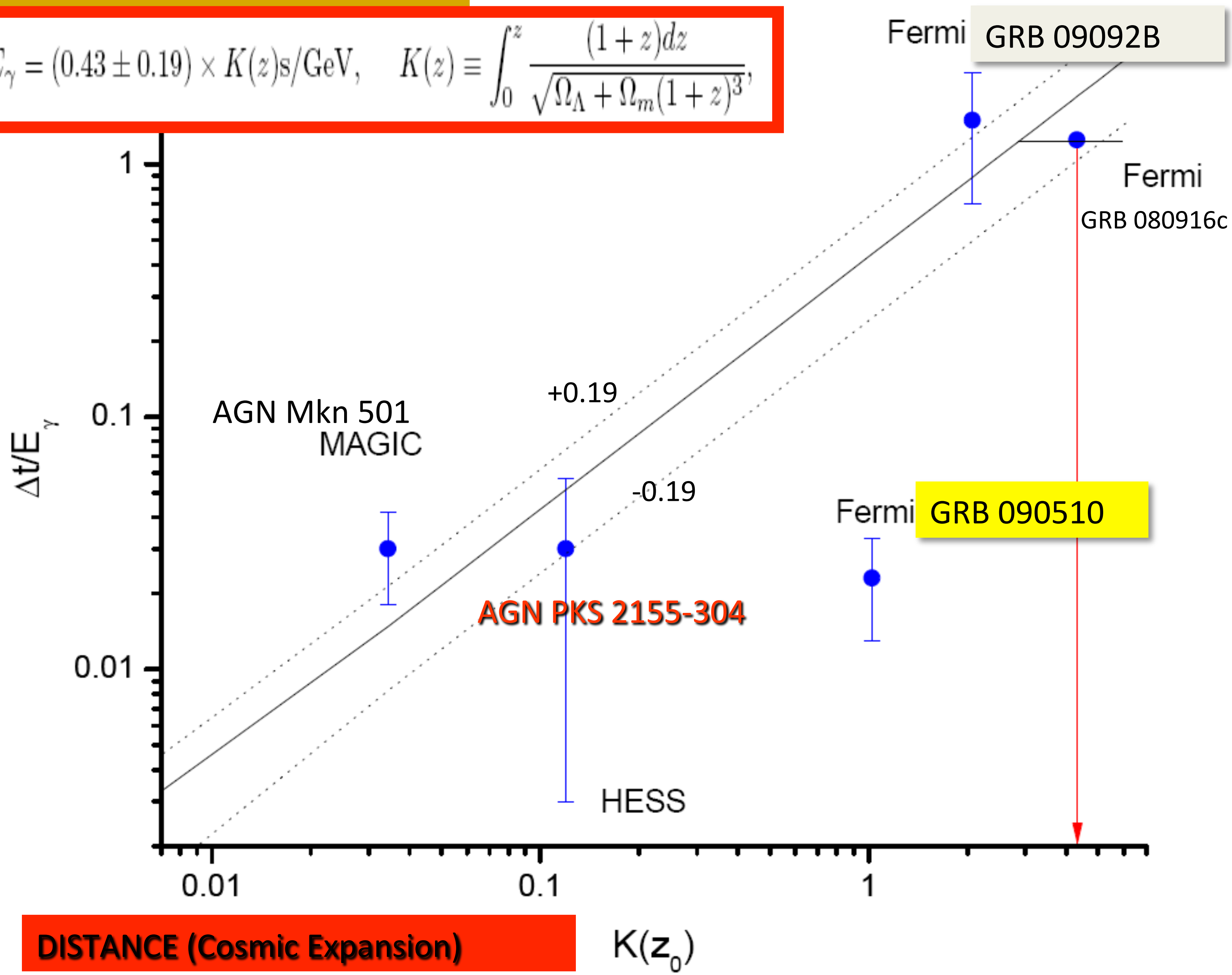
Observed Time Delay Δt: 82 sec after GMB trigger
50 sec after end of emission

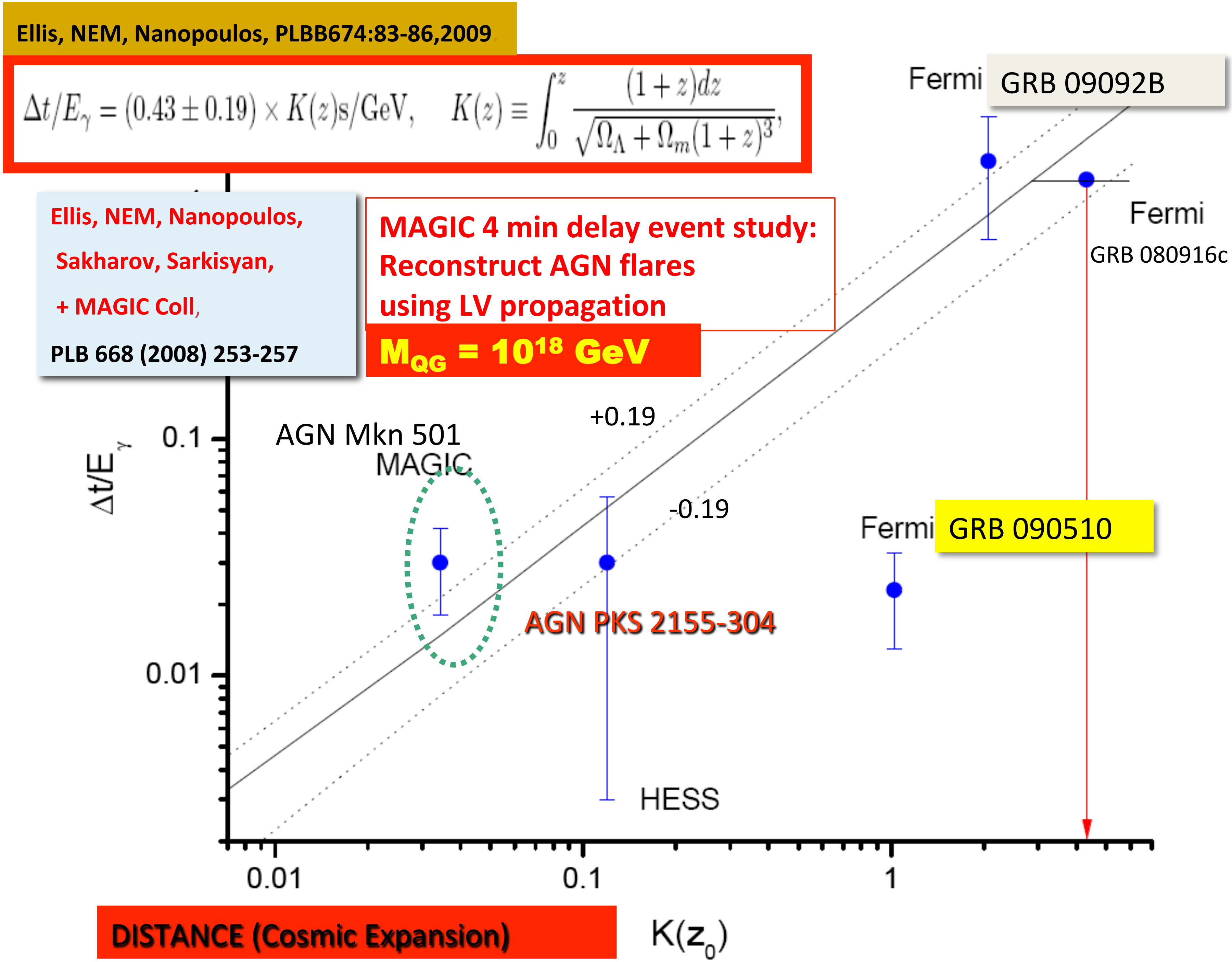
Naïve Fits assuming more or less simultaneous emission of various energy photons from the source

Assume: Dominant effect for late arrivals → QG/Lorentz Violation

Ellis, NEM, Nanopoulos, PLBB674:83-86,2009

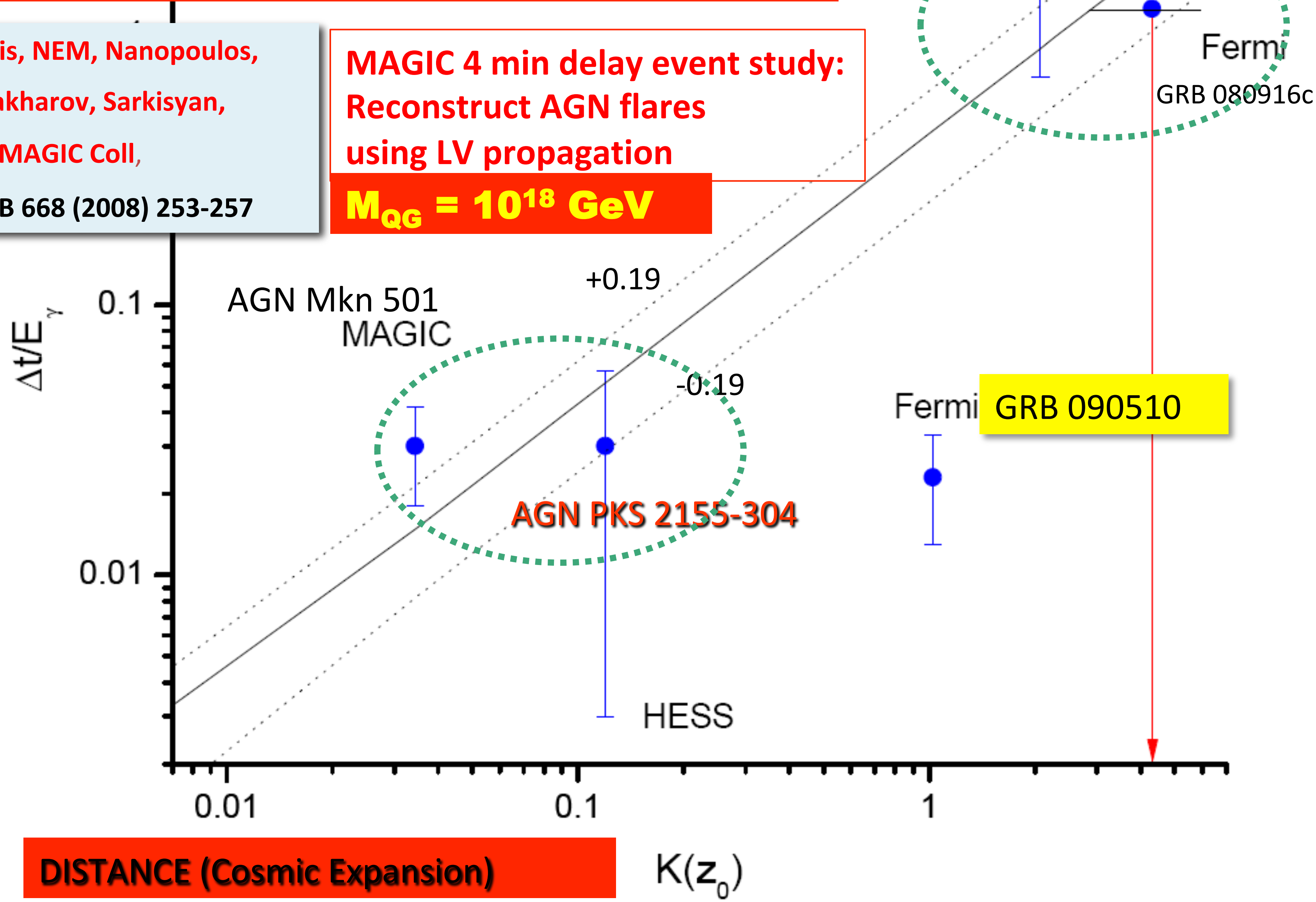
$$\Delta t/E_\gamma = (0.43 \pm 0.19) \times K(z)\mathrm{s/GeV}, \quad K(z) \equiv \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}},$$




Ellis, NEM, Nanopoulos, PLBB674:83-86,2009
$\Delta t/E_\gamma = (0.43 \pm 0.19) \times K(z)\mathrm{s/GeV}, \quad K(z) \equiv \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}},$
Ellis, NEM, Nanopoulos,
Sakharov, Sarkisyan,
+ MAGIC Coll,
PLB 668 (2008) 253-257
MAGIC 4 min delay event study:
Reconstruct AGN flares
using LV propagation
$M_{QG} = 10^{18}$ GeV
Fermi
GRB 09092B
Fermi
GRB 080916c
+0.19
-0.19
AGN Mkn 501
MAGIC
Fermi
GRB 090510
AGN PKS 2155-304
HESS
0.1
0.01
$\Delta t/E_\gamma$
0.01
0.1
1
$K(z_0)$
DISTANCE (Cosmic Expansion)

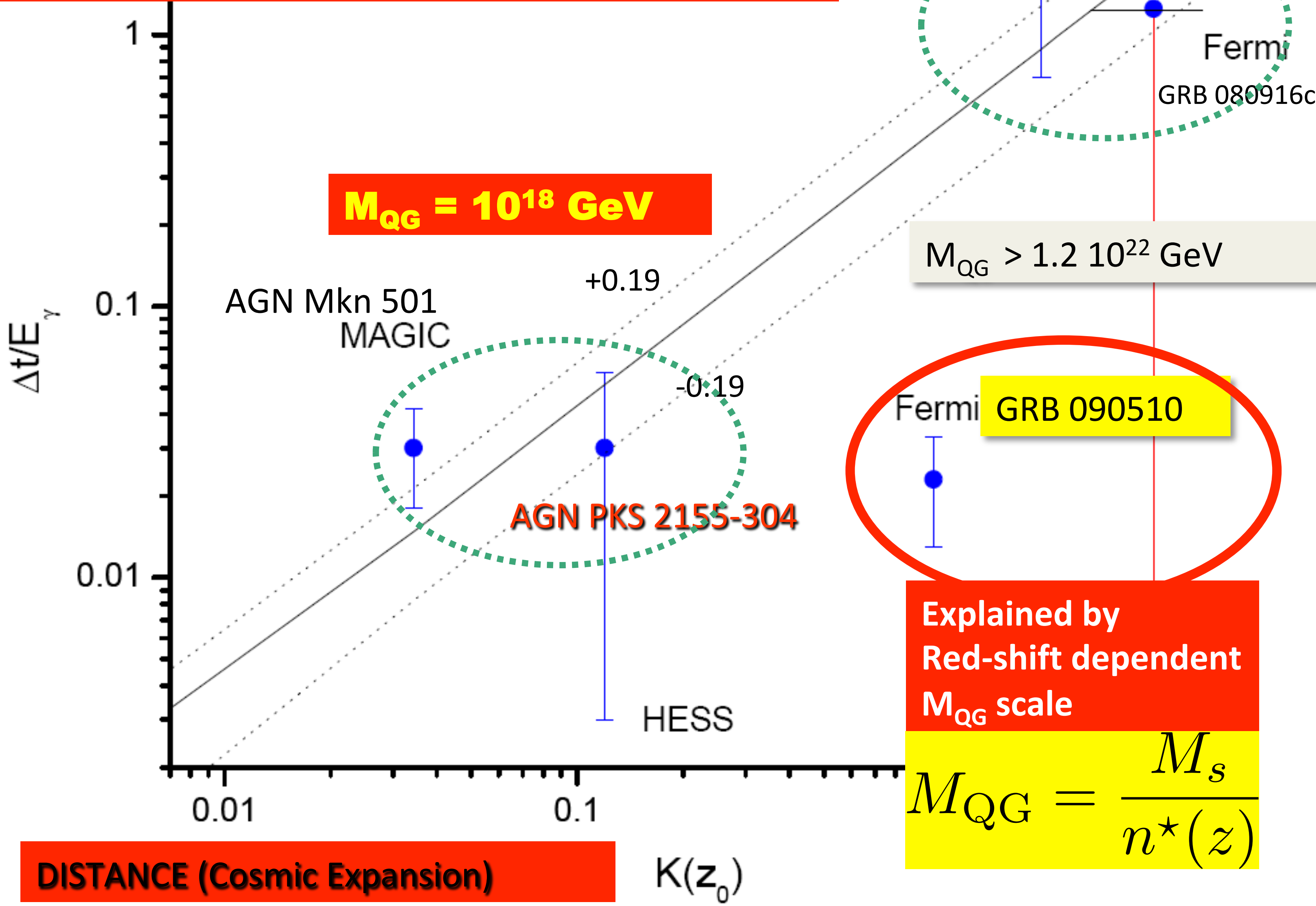
Ellis, NEM, Nanopoulos, PLBB674:83-86,2009

$$\Delta t/E_\gamma = (0.43 \pm 0.19) \times K(z)\mathrm{s/GeV}, \quad K(z) \equiv \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}},$$



Ellis, NEM, Nanopoulos, PLBB674:83-86,2009

$$\Delta t/E_\gamma = (0.43 \pm 0.19) \times K(z)\mathrm{s/GeV}, \quad K(z) = \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}},$$



Explained by Red-shift dependent M_{QG} scale

$$M_{\mathrm{QG}} = \frac{M_s}{n^\star(z)}$$

Caution: mechanisms for high energy emission @ the source still not confirmed

- **High-Energy Gamma Ray Astrophysics as a probe for New Physics**

Astro-Physics at source: hadronic mechanisms or synchrotron radiation + inverse Compton scattering produce **delays at emission: Non conclusive …**

Combine: models for emission @ the source with QG-induced Vacuum refraction during propagation

e.g Shao. Xiao, Ma, Astroparticle Physics 33 (2010) 312
Chang, Jiang, Lin, Astroparticle Physics 36 (2012), 47

Caution: mechanisms for high energy emission @ the source still not confirmed

- **High-Energy Gamma Ray Astrophysics as a probe for New Physics**

Astro-Physics at source: hadronic mechanisms or synchrotron radiation + inverse Compton scattering produce **delays at emission: Non conclusive ...**

Combine: models for emission @ the source with QG-induced Vacuum refraction during propagation

e.g Shao. Xiao, Ma, Astroparticle Physics 33 (2010) 312
Chang, Jiang, Lin, Astroparticle Physics 36 (2012), 47

Combine source & propagation effects → recalculating the QG scale

$$v(E) = c_0\left(1 - \xi\frac{E}{E_P} - \zeta\frac{E^2}{E_P^2}\right),$$

photon energy in QG medium

$$\Delta t_{LV} = \frac{1+n}{2H_0}\left(\frac{E_h^n - E_l^n}{E_{QG}^n}\right)\int_0^z \frac{(1+z')^n dz'}{h(z')},$$

$$E_{QG,L} = |\xi|^{-1} E_P$$

$$E_{QG,Q} = |\zeta|^{-1/2} E_P$$

$$H_0 \simeq 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$$h(z) = \sqrt{\Omega_\Lambda + \Omega_M(1+z)^3}$$

$$\Omega_\Lambda \simeq 0.73 \quad \Omega_M \simeq 0.27$$

$$\Delta t_{obs} = \Delta t_{LV} + \Delta t_{in}(1+z).$$

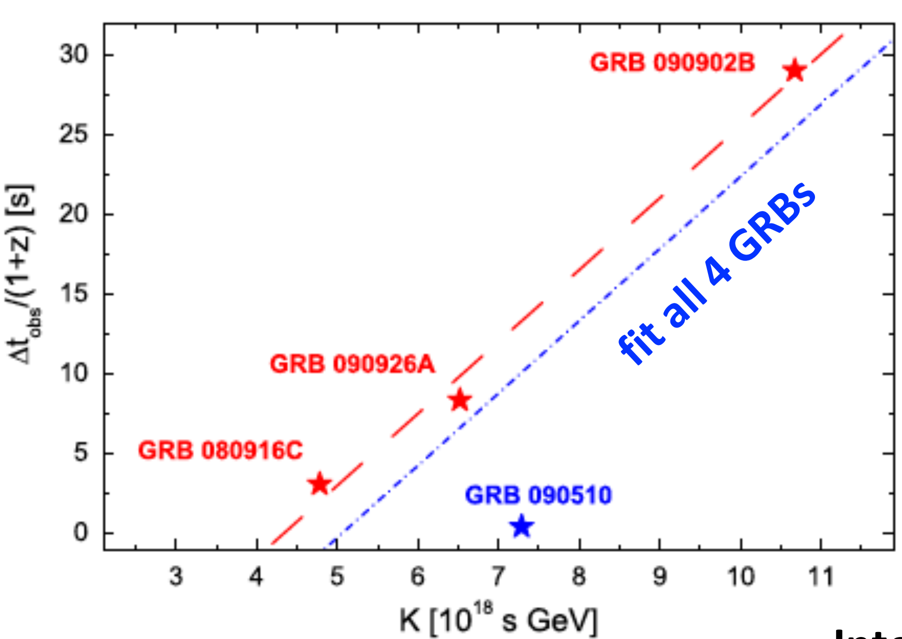
independent of source – propagation but $E^n_{QG}(z)$

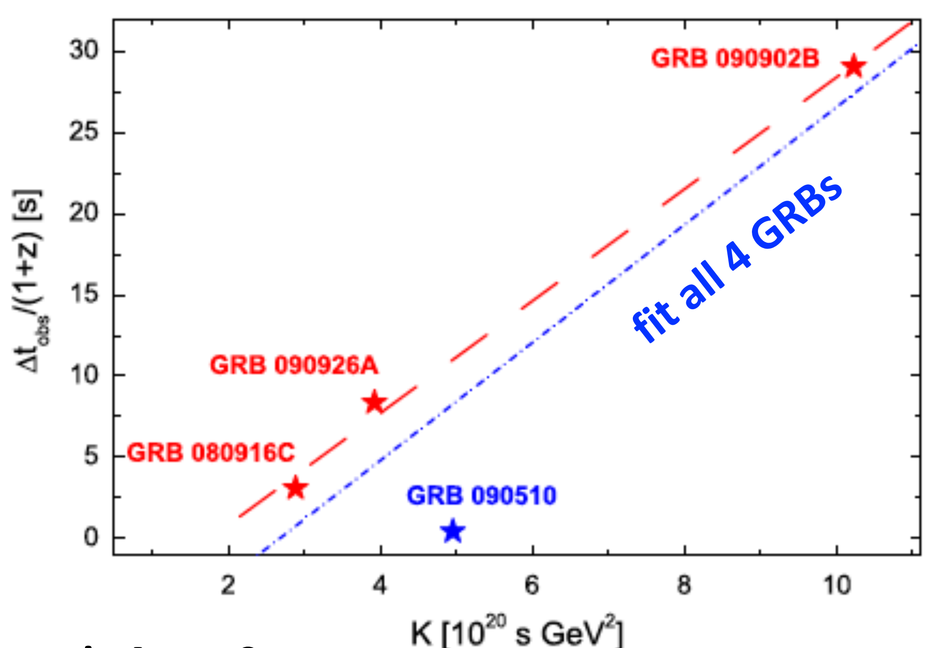
Intrinsic Time Lag
z independent
constant for objects in a particular class

Combine source & propagation effects → Model-agnostic source effects

Shao. Xiao, Ma, Astroparticle Physics 33 (2010) 312

GRBs	z	E (GeV)	Δt_{obs} (s)	$E_{QG,L}$ (GeV)	$E_{QG,Q}$ (GeV)
080916C [30]	4.35 [32]	13.22	16.54	1.5×10^{18}	9.7×10^{9}
090510 [31]	0.903 [33]	31	0.829	1.7×10^{19}	3.4×10^{10}
090902B [34]	1.822 [35]	33.4	82	3.7×10^{17}	5.9×10^{9}
090926A [36]	2.1062 [37]	19.6	26	7.8×10^{17}	6.8×10^{9}



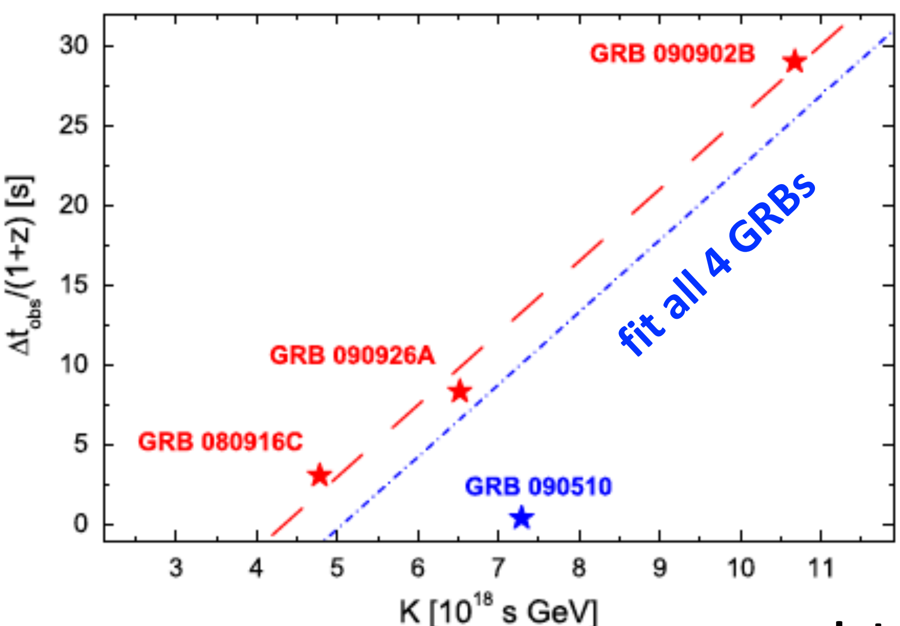


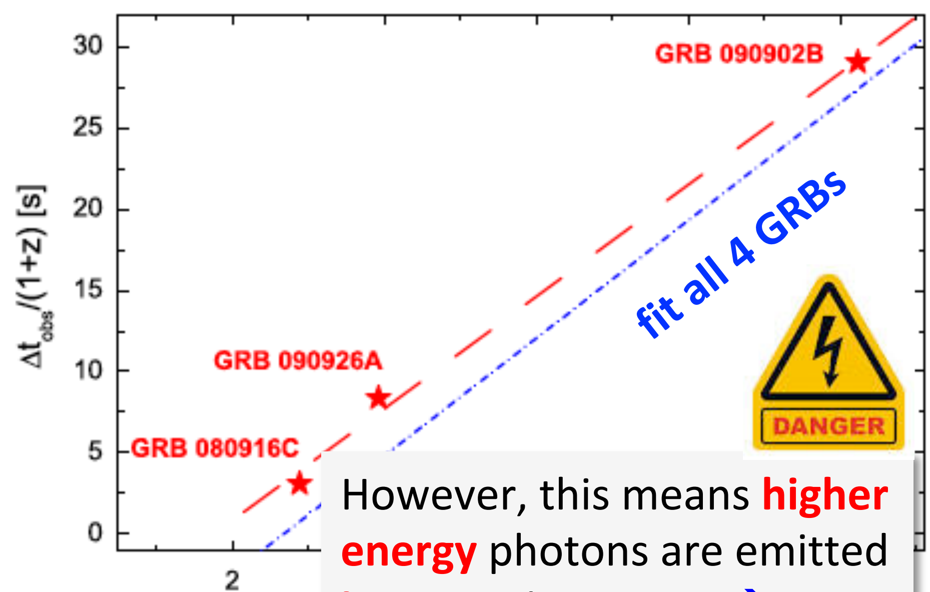
Intercept is $\Delta t_{in} < 0$

Combine source & propagation effects→ Model-agnostic source effects

Shao. Xiao, Ma, Astroparticle Physics 33 (2010) 312

GRBs	z	E (GeV)	Δt_{obs} (s)	$E_{QG,L}$ (GeV)	$E_{QG,Q}$ (GeV)
080916C [30]	4.35 [32]	13.22	16.54	1.5×10^{18}	9.7×10^{9}
090510 [31]	0.903 [33]	31	0.829	1.7×10^{19}	3.4×10^{10}
090902B [34]	1.822 [35]	33.4	82	3.7×10^{17}	5.9×10^{9}
090926A [36]	2.1062 [37]	19.6	26	7.8×10^{17}	6.8×10^{9}





Intercept is $\Delta t_{in} < 0$!

However, this means **higher energy** photons are emitted **later** @ the source → **non standard GRB models?**

Concrete Models for Intrinsic time Lag:
Magnetic Jet flow as an example

Bošnjak, Kumar MNRAS (2012)

In the magnetic jet model, photons with energy less than 10 MeV can escape when the jet radius is beyond the Thomson photosphere radius, i.e., the optical depth for low energy photons is $\tau_T \approx 1$. However, **GeV photons** will be converted to electron–positron pairs at this radius, and can **escape later** when the pair-production optical depth $\tau_{\gamma\gamma} < 1$.

The bulk Lorentz factor of an expanding spherical fireball increases with the radius roughly as $\Gamma \propto r$, until reaching a saturate radius r_s where the Lorentz factor is saturated.

$$\Gamma(r) \approx \begin{cases} (r/r_0)^{1/3} & \text{for } r_0 \lesssim r \lesssim r_s, \\ \eta & \text{for } r \gtrsim r_s, \end{cases}$$

$r_0 \approx 10^7$ cm base of the outflow

$$\Delta t_{\rm in} = \frac{3r_0(1+z)}{2c}\left[\left(\frac{r_{\gamma\gamma}(E_0)}{r_0}\right)^{1/3} - \left(\frac{r_p}{r_0}\right)^{1/3}\right]$$

$$\frac{r_p}{r_0} \approx 1.36\times 10^5 L_{52}^{3/5}\sigma_{0,3}^{-3/5} r_{0,7}^{-3/5},$$

$L_{52} \equiv L/10^{52}\ \mathrm{erg\cdot s^{-1}}$, $\sigma_{0,3} \equiv \sigma_0/10^3$, and $r_{0,7} \equiv r_0/10^7$ cm.

$$\frac{r_{\gamma\gamma}(E_0)}{r_0} \approx 4.13\times 10^6 L_{>p,52}^{0.41} E_{p,-6}^{0.08} E_{0,-4}^{0.49} r_{0,7}^{-0.41}(1+z)^{0.57},$$

$E_{p,-6} = E_p/\mathrm{MeV}$, and $E_{0,-4} = E_0/100\ \mathrm{MeV}$.

Combine source & propagation effects in Magnetic Jet Model

Chang, Jiang, Lin, Astroparticle Physics 36 (2012), 47

$$\Delta t_{LIV} = \frac{1+n}{2c}\left(\frac{\Delta E}{M_n c^2}\right)^n D_n;$$

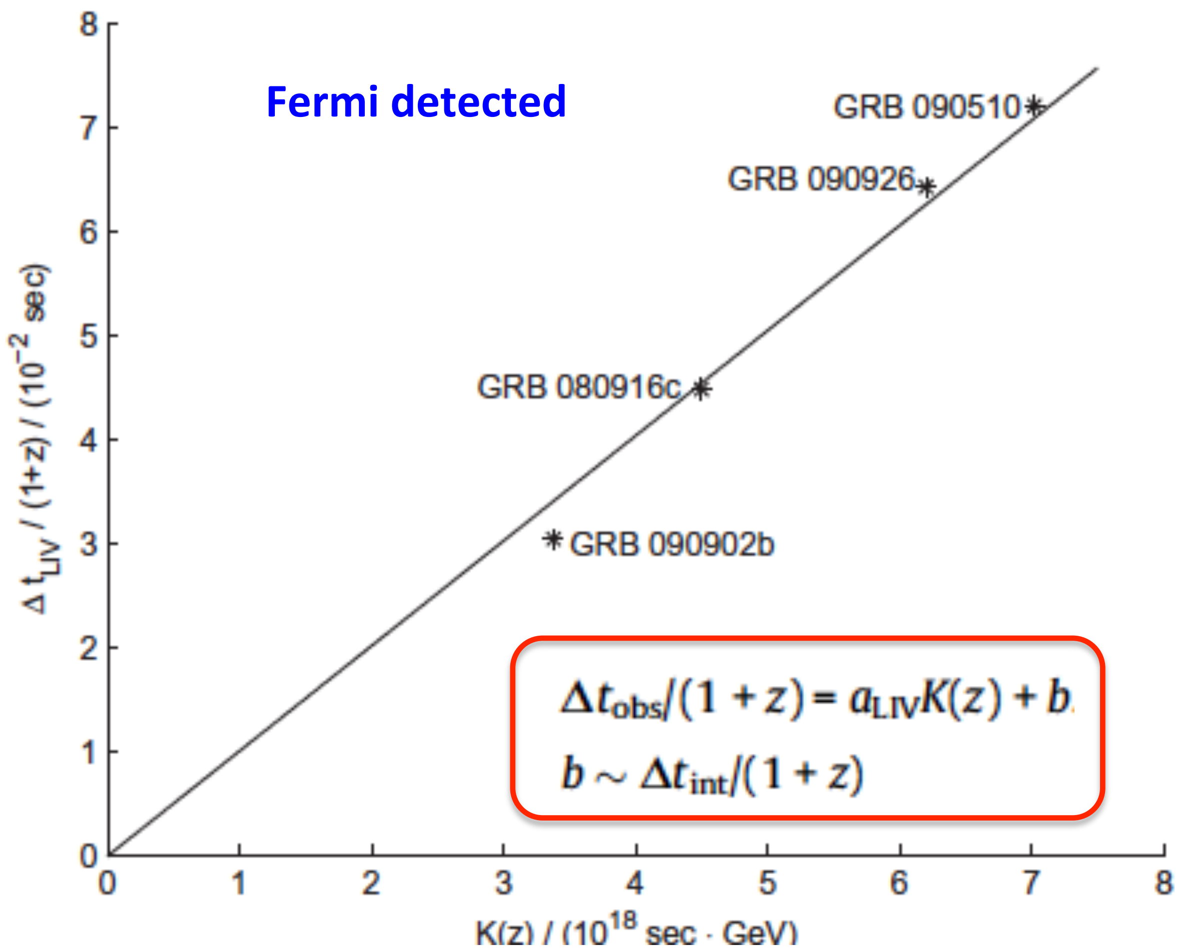
$$D_n \equiv \frac{c}{H_0}\int_0^z \frac{(1+z')^n dz'}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda}},$$

linear effects

$$M_1 c^2 = \frac{\Delta E D_1}{c \Delta t_{LIV}}.$$

$$K(z) \equiv \frac{\Delta E}{(1+z)}\frac{D_1}{c}.$$

careful selection of high energy photon events



$$\Delta t_{obs}/(1+z) = a_{LIV} K(z) + b$$

$$b \sim \Delta t_{int}/(1+z)$$

Estimate Δt_{in} using Magnetic Jet model

$$b \simeq 0.08 r_{0.7}^{0.86} L_{>p,52}^{0.14} E_{p,-6}^{0.03} E_{0,-4}^{0.16} (1+z)^{0.19};$$

$$\Delta t_{int} \simeq 0.06 \text{ s for GRB 090510}$$

$$r_0 = 10^6 \text{ cm}$$

r_0 must be < 10^7 cm to **avoid superluminal** HE photons

Combine source & propagation effects in Magnetic Jet Model

Chang, Jiang, Lin, Astroparticle Physics 36 (2012), 47

$$\Delta t_{\rm obs}/(1+z) = a_{\rm LIV} K(z) + b$$

$$b \sim \Delta t_{\rm int}/(1+z)$$

$$b \simeq 0.08 r_{0.7}^{0.86} L_{>p,52}^{0.14} E_{p,-6}^{0.03} E_{0,-4}^{0.16} (1+z)^{0.19}$$

GRB	$E_{\rm low}$ (MeV)	$E_{\rm high}$ (GeV)	$\Delta t_{\rm obs}$ (s)	$\Delta t_{\rm LIV}$ (s)	$K(z)$ s · GeV	M_1c^2 (GeV)
080916c	100	13.22	12.94	0.24	4.50×10^{18}	10.02×10^{19}
090510	100	31	0.20	0.14	7.02×10^{18}	9.73×10^{19}
090902b	100	11.16	9.5	0.10	3.38×10^{18}	9.94×10^{19}
090926	100	19.6	21.5	0.20	6.20×10^{18}	9.59×10^{19}

for magnetic jet model parameters: $\sigma_{0,3} \sim 1$ $r_{0.7} = 16.7,\ 0.1,\ 28.7$ and 55.0

GRB 080916c, GRB 090510, GRB 090902b, GRB 090926,

$$M_1c^2 \sim 1.0 \times 10^{20}\ {\rm GeV}$$

BUT take into account....

$$M_{\rm QG} = \frac{M_s}{n^\star(z)}$$

Caution: mechanisms for high energy emission @ the source still not confirmed

- **High-Energy Gamma Ray Astrophysics as a probe for New Physics**

Astro-Physics at source: hadronic mechanisms or synchrotron radiation + inverse Compton scattering produce **delays at emission: Non conclusive ...**

Combine: models for emission @ the source with QG-induced Vacuum refraction during propagation

Be careful when selecting events

e.g Shao. Xiao, Ma, Astroparticle Physics 33 (2010) 312
Chang, Jiang, Lin, Astroparticle Physics 36 (2012), 47

- **Check on other tests on QG modified dispersion relations:** (recall: QG vacuum refraction may not be universal)

Electrons: Synchrotron Radiation from Crab Nebula

Photons: Birefringence constraints for QG modified dispersion very stringent

$$M_{\rm QG} = \frac{M_s}{n^\star(z)}$$

Summary of Constraints on Modified Dispersion Relations for both charged particles (electrons,protons) and photons from non observation of high-energy photons

Galaverni & Sigl,
Phys.Rev.Lett. 100 (2008) 021102
Phys.Rev. D78 (2008) 063003

LIV modified dispersion for HE particle:

$$\omega_{\pm}^2 = k^2 + \xi_n^{\pm} k^2 \left(\frac{k}{M_{\rm pl}}\right)^n,$$

$$\omega_{\rm b}^2 = k_{\rm b}^2, \quad \text{IR background photon}$$

$$E_{{\rm e},\pm}^2 = p_{\rm e}^2 + m_{\rm e}^2 + \eta_n^{{\rm e},\pm} p_{\rm e}^2 \left(\frac{p_{\rm e}}{M_{\rm pl}}\right)^n;$$

$$E_{{\rm p},\pm}^2 = p_{\rm p}^2 + m_{\rm e}^2 + (-1)^n \eta_n^{{\rm e},\mp} p_{\rm p}^2 \left(\frac{p_{\rm p}}{M_{\rm pl}}\right)^n.$$

$n = 1$ and $n = 2$

using Effective Field Theory

Processes affected by LIV

Pair production ($\gamma\gamma_{\rm b} \rightarrow e^- e^+$) (PP)

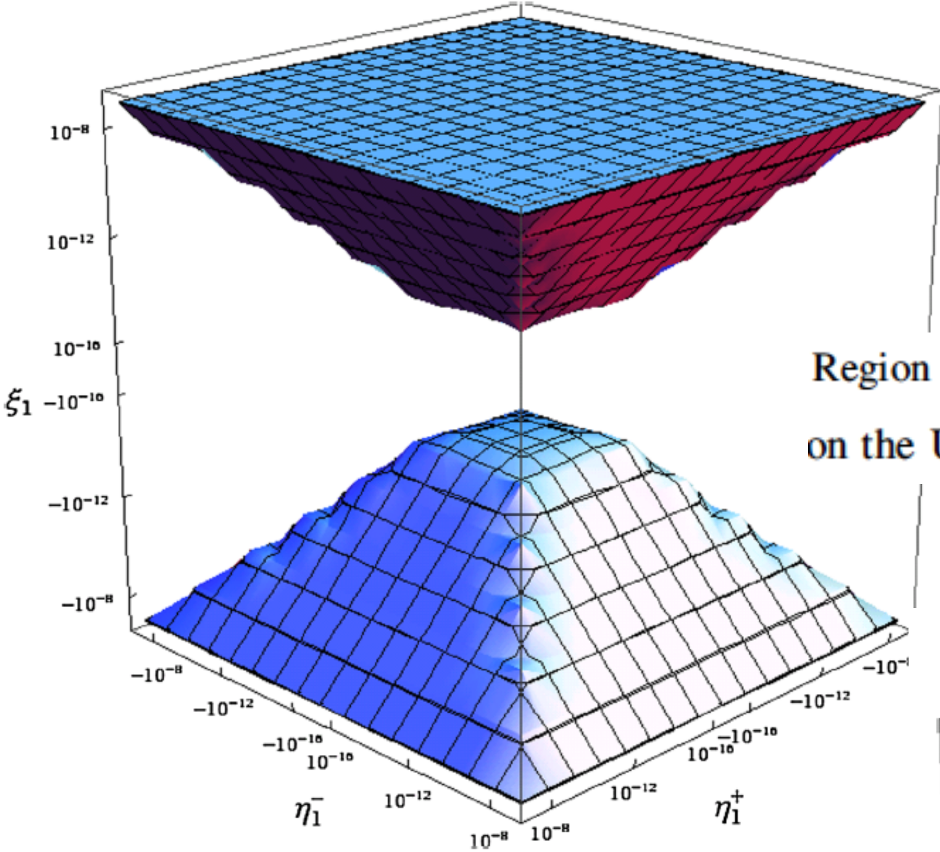
Allowed, if LIV modified dispersion present

Photon decay ($\gamma \rightarrow e^- e^+$) (PD)

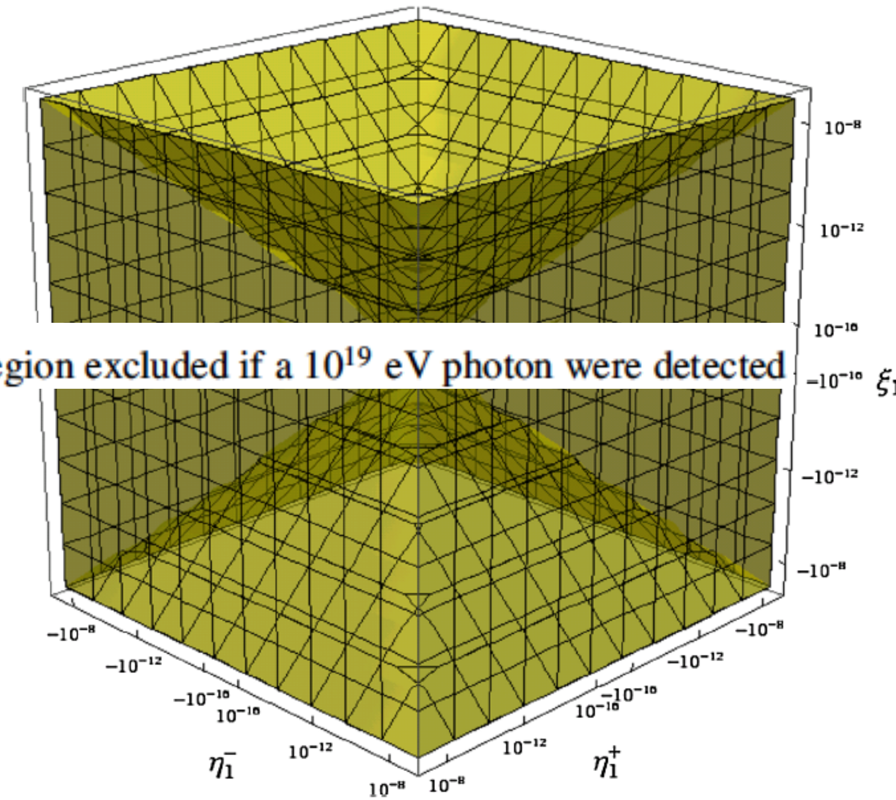
Galaverni & Sigl, Phys.Rev. D78 (2008) 063003

	UHE γ	e^-	e^+	(ξ, η_e, η_p)	Number of LIV param.	s-wave allowed for PP	s-wave allowed for PD
1	$+$	$+$	$+$	$(\xi_n, \eta_n^+, (-1)^n \eta_n^-)$	3	No	Yes
2	$+$	$+$	$-$	$(\xi_n, \eta_n^+, (-1)^n \eta_n^+)$	2	Yes	No
3	$+$	$-$	$+$	$(\xi_n, \eta_n^-, (-1)^n \eta_n^-)$	2	Yes	No
4	$+$	$-$	$-$	$(\xi_n, \eta_n^-, (-1)^n \eta_n^+)$	3	No	Yes
5	$-$	$+$	$+$	$((-1)^n \xi_n, \eta_n^+, (-1)^n \eta_n^-)$	3	No	Yes
6	$-$	$+$	$-$	$((-1)^n \xi_n, \eta_n^+, (-1)^n \eta_n^+)$	2	Yes	No
7	$-$	$-$	$+$	$((-1)^n \xi_n, \eta_n^-, (-1)^n \eta_n^-)$	2	Yes	No
8	$-$	$-$	$-$	$((-1)^n \xi_n, \eta_n^-, (-1)^n \eta_n^+)$	3	No	Yes

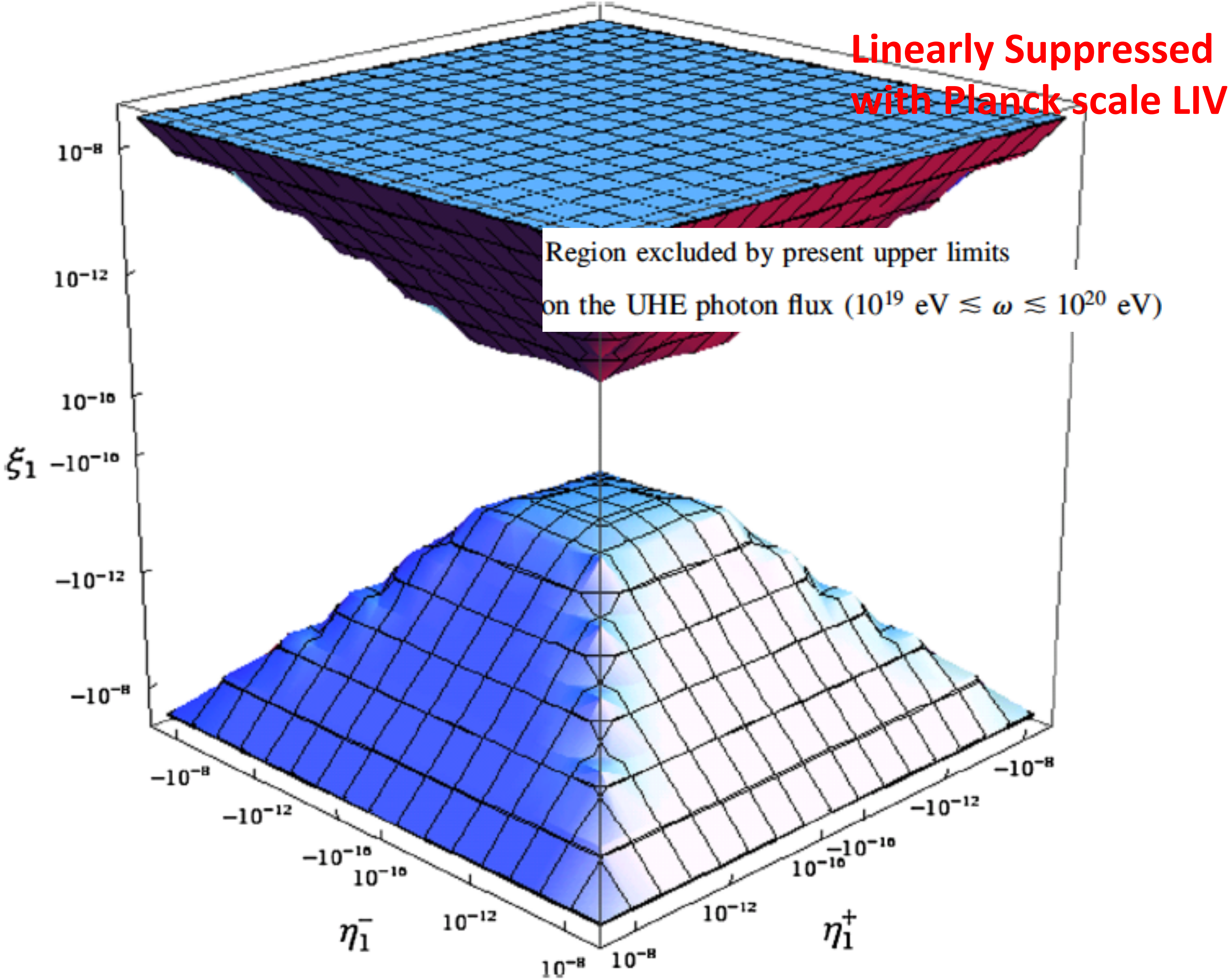
Linearly Suppressed with Planck scale LIV



Region excluded by present upper limits on the UHE photon flux (10^{19} eV $\lesssim \omega \lesssim 10^{20}$ eV)

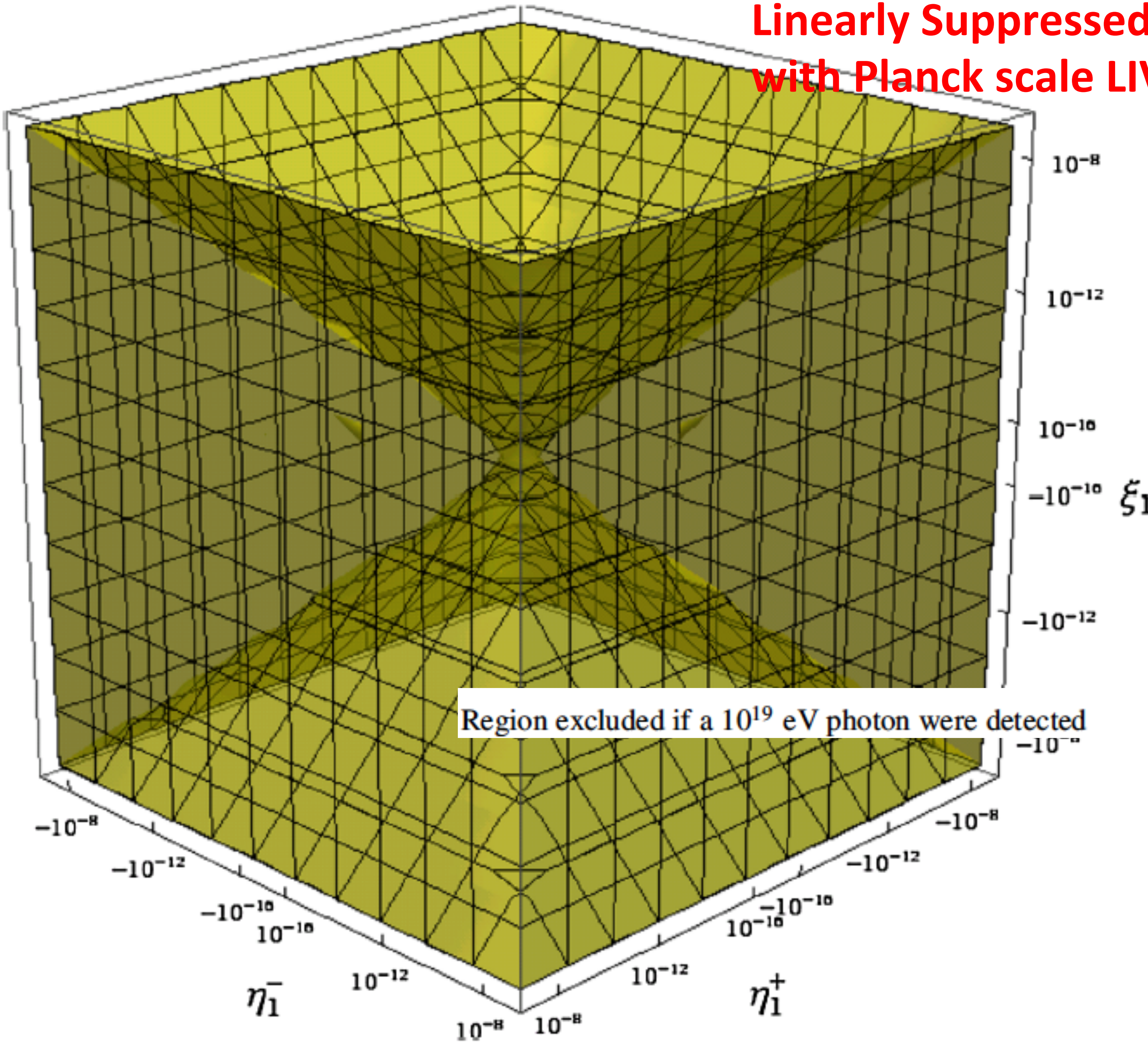


Region excluded if a 10^{19} eV photon were detected

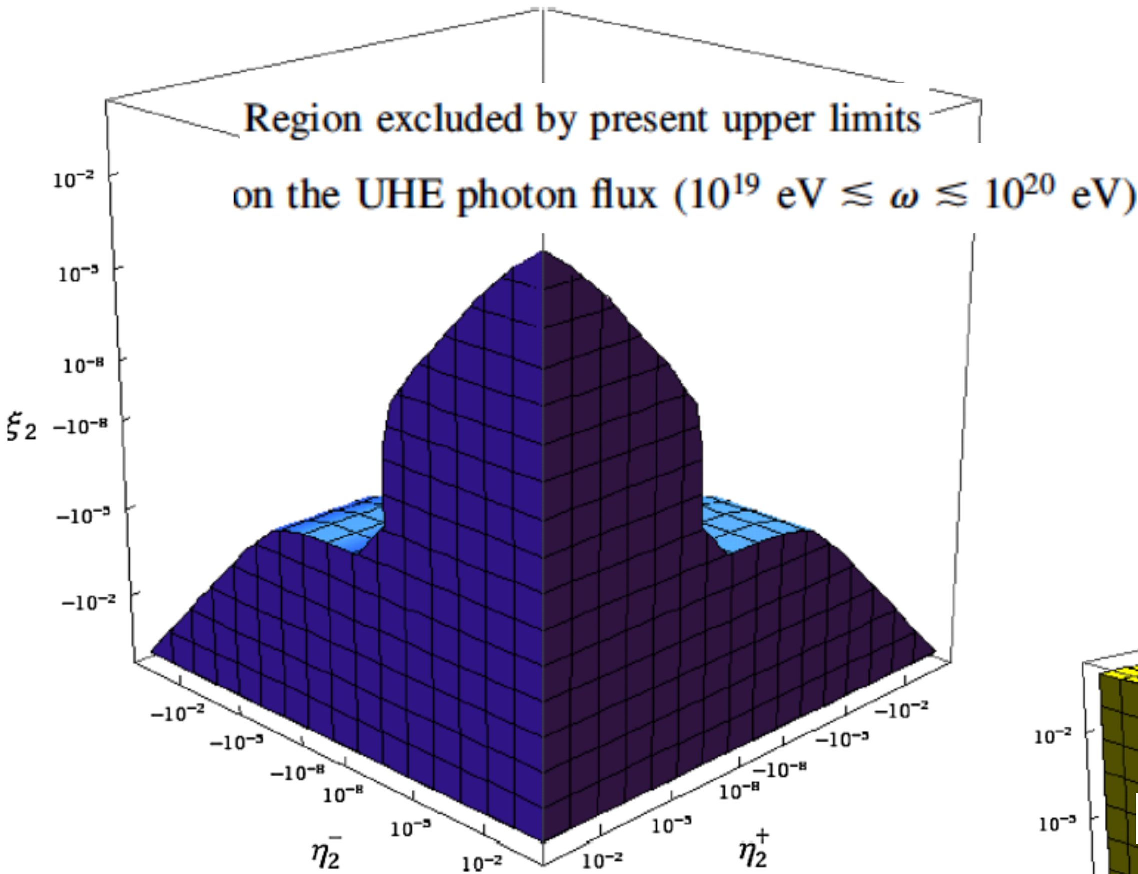


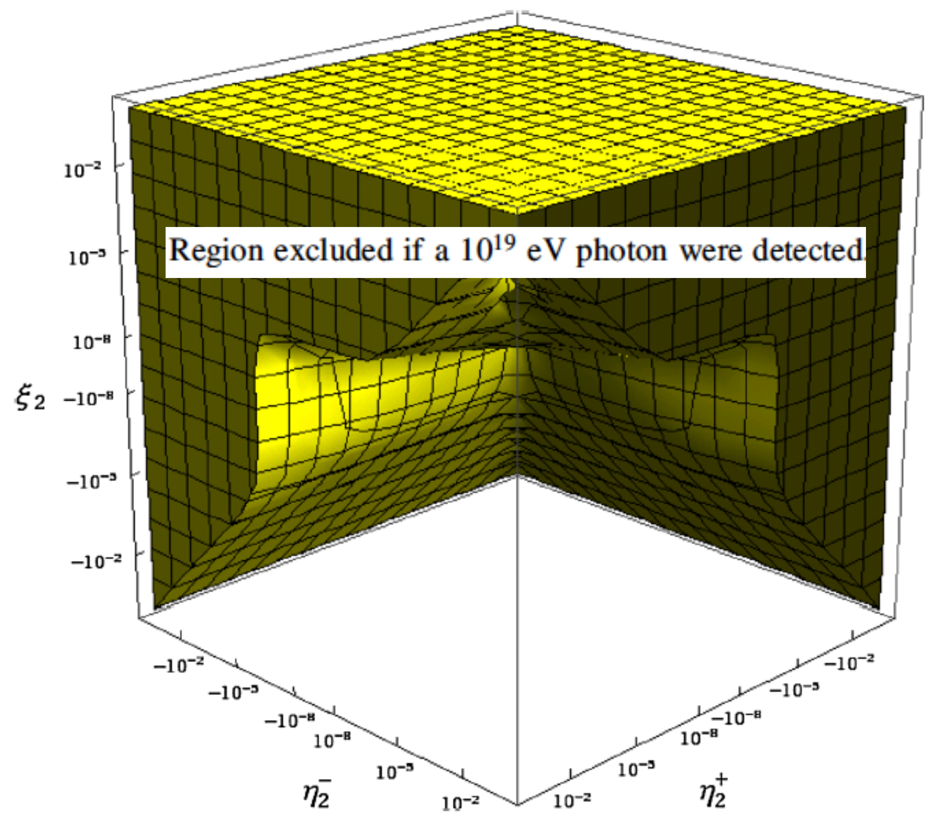
Linearly Suppressed
with Planck scale LIV
Region excluded by present upper limits
on the UHE photon flux (10^{19} eV $\lesssim \omega \lesssim 10^{20}$ eV)
ξ_1
10^{-8}
10^{-12}
10^{-16}
-10^{-16}
-10^{-12}
-10^{-8}
η_1^-
η_1^+

Linearly Suppressed with Planck scale LIV

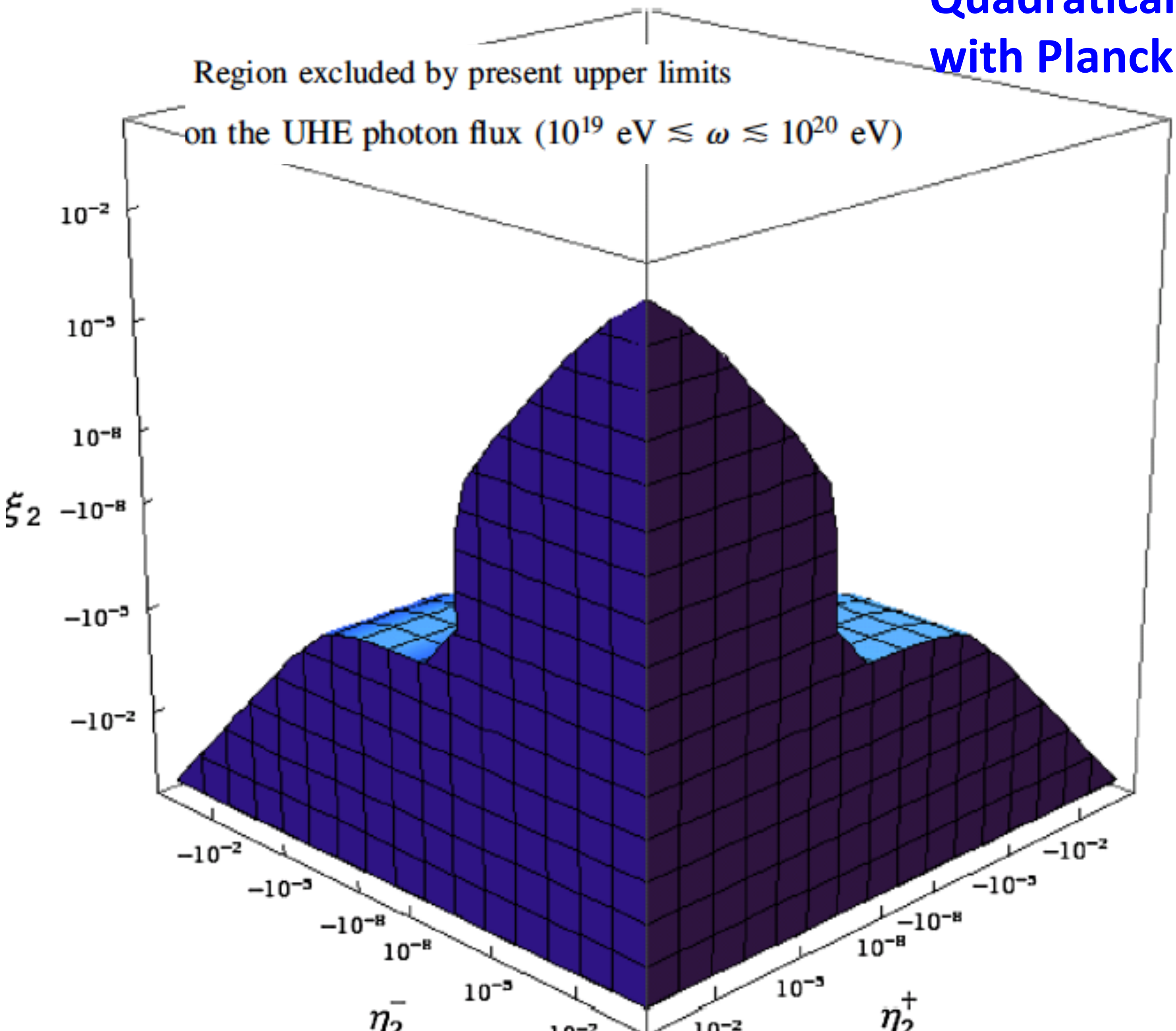


Quadratically Suppressed with Planck scale LIV

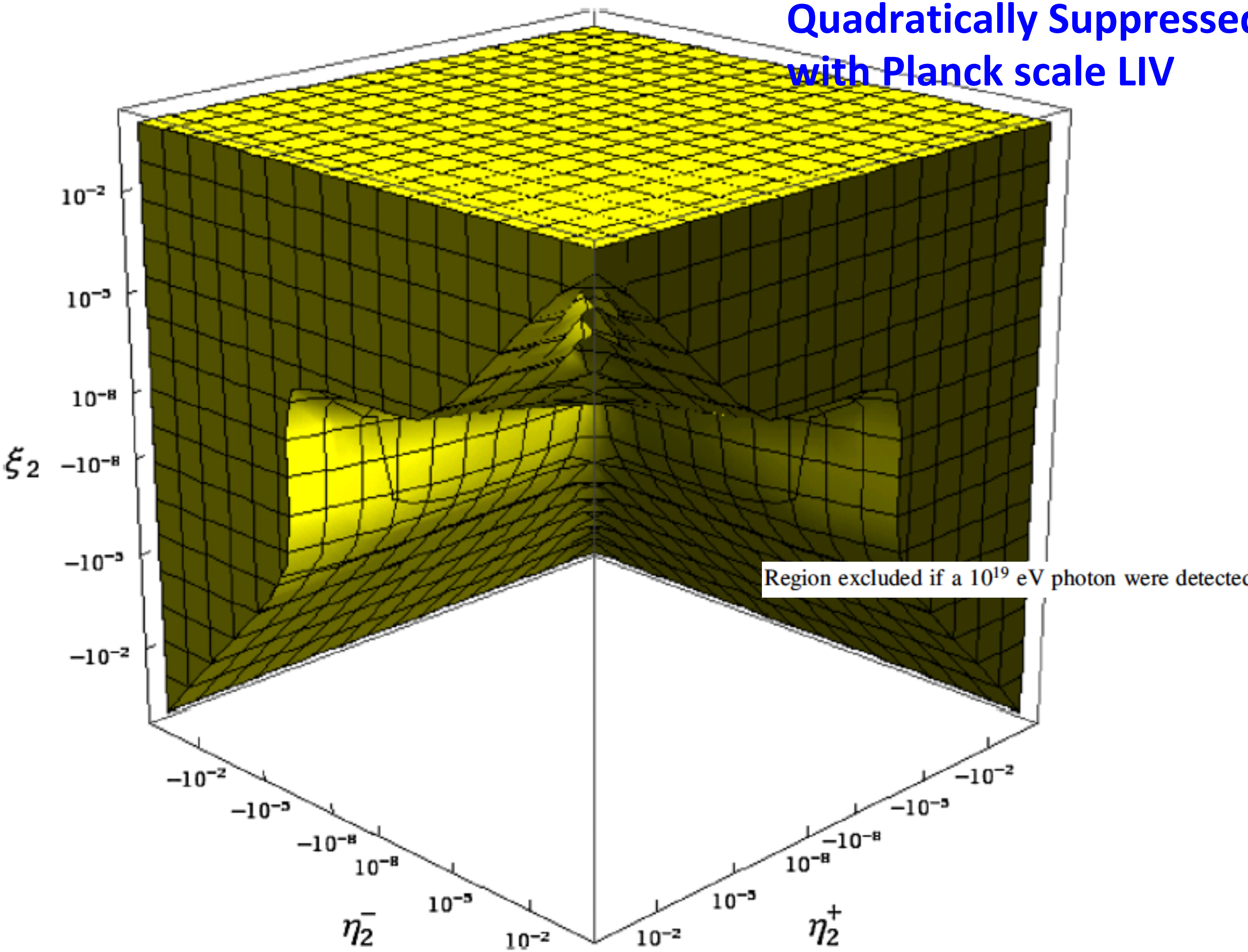




Quadratically Suppressed with Planck scale LIV



Quadratically Suppressed with Planck scale LIV



HIGH ALTITUDE WATER CHERENKOV (HAWC) & LIV SENSITIVITY

Martínez-Huerta, Marinelli, Linnemann & Lundeen for the HAWC Collaboration, **arXiv: 1908.09614**

Superluminal LIV enables the decay of photons at high energy over relatively short distances, giving astrophysical spectra which have a hard cutoff above this energy. **HAWC** can make detailed measurements of **gamma-ray energies above 100 TeV**. With these observations, HAWC can limit **the LIV energy scale greater than 10^{31} eV**, over 800 times the Planck energy scale. This limit on LIV is over **60 times more constraining than the best previous value for linear LIV : $E^{(1)}_{LIV}$.**

$$E_a^2 - p_a^2 = m_a^2 \pm |\alpha_{a,n}| A_a^{n+2}$$

A = E or momentum p

LIV coefficients (*M* scale of new Physics)

$$\alpha_{a,n} = \varepsilon^{(n)}/M$$

Some models Predict *superluminal* photon propagation → ***Vacuum Cherenkov radiation***

Hard cutoff for high energy E_γ photons

$$\alpha_n \geq \frac{4m_e^2}{E_\gamma^n (E_\gamma^2 - 4m_e^2)}$$

electron mass

$E_{Pl} \approx 1.22 \times 10^{28}$ eV

HAWC Coll: arXiv: 1908.09614

Source	E_c TeV	$\lvert\alpha_0\rvert$ 10^{-17}	$\lvert\alpha_1\rvert$ $10^{-31}eV^{-1}$	$\lvert\alpha_2\rvert$ $10^{-45}eV^{-2}$	$E_{LIV}^{(1)}$ $10^{30}eV$	$E_{LIV}^{(2)}$ $10^{22}eV$	p value
2HWC J1825-134	253	1.63	0.64	0.26	15.5	6.26	1
2HWC J1908+063	213	2.30	1.08	0.51	9.25	4.44	0.99
Crab (HAWC)	152	4.52	2.97	1.96	3.4	2.26	1
2HWC J2031+415	144	5.04	3.5	2.43	2.9	2.02	0.714
2HWC J2019+367	121	7.13	5.6	4.87	1.7	1.43	0.828
J1839-057	79	16.74	21.1	26.8	0.47	0.61	0.357
2HWC J1844-032	77	17.62	22.9	29.7	0.44	0.58	0.294

Table 1: The HAWC Sources used in this analysis and the derived 95% CL lower limits on E_c and its different LIV coefficients (Prel.).

Source	E_γ TeV	$\lvert\alpha_0\rvert$ 10^{-17}	$\lvert\alpha_1\rvert$ $10^{-31}eV^{-1}$	$\lvert\alpha_2\rvert$ $10^{-45}eV^{-2}$	$E_{LIV}^{(1)}$ $10^{30}eV$	$E_{LIV}^{(2)}$ $10^{22}eV$	Ref.
Crab (HEGRA) 2017	~ 56	-	66.7	128	0.15	0.28	[4]
Tevatron 2016	0.442	6×10^5	-	-	-	-	[5]
RX J1713.7–3946 (HESS) 2008	30	180	-	-	-	-	[7]
Coleman & Glashow (1997)	20	100	-	-	-	-	[6]
GRB09510 (*Fermi*) 2013 $v > c$	-	-	-	-	0.134	0.009	[8]
GRB09510 (*Fermi*) 2013 $v < c$	-	-	-	-	0.093	0.013	[8]
Crab (HEGRA) 2019	75	-	-	0.059	-	13	[9]

Table 2: Previous strong constraints to LIV photon decay are shown as well as the best limits based on energy-dependent time delay and superluminal photon splitting at bottom.

$E_{Pl} \approx 1.22 \times 10^{28}$ eV

HAWC Coll: arXiv: 1908.09614

Source	E_c TeV	$\lvert\alpha_0\rvert$ 10^{-17}	$\lvert\alpha_1\rvert$ $10^{-31}\mathrm{eV}^{-1}$	$\lvert\alpha_2\rvert$ $10^{-45}\mathrm{eV}^{-2}$	$E^{(1)}_{LIV}$ 10^{30}eV	$E^{(2)}_{LIV}$ 10^{22}eV	p value
2HWC J1825-134	253	1.63	0.64	0.26	15.5	6.26	1
2HWC J1908+063	213	2.30	1.08	0.51	9.25	4.44	0.99
Crab (HAWC)	152	4.52	2.97	1.96	3.4	2.26	1
2HWC J2031+415	144	5.04	3.5	2.43	2.9	2.02	0.714
2HWC J2019+367	121	7.13	5.6	4.87	1.7	1.43	0.828
J1839-057	79	16.74	21.1	26.8	0.47	0.61	0.357
2HWC J1844-032	77	17.62	22.9	29.7	0.44	0.58	0.294

Table 1: The HAWC Sources used in this analysis and the derived 95% CL lower limits on E_c and its different LIV coefficients (Prel.).

Source	E_γ TeV	$\lvert\alpha_0\rvert$ 10^{-17}	$\lvert\alpha_1\rvert$ $10^{-31}\mathrm{eV}^{-1}$	$\lvert\alpha_2\rvert$ $10^{-45}\mathrm{eV}^{-2}$	$E^{(1)}_{LIV}$ 10^{30}eV	$E^{(2)}_{LIV}$ 10^{22}eV	Ref.
Crab (HEGRA) 2017	~ 56	-	66.7	128	0.15	0.28	[4]
Tevatron 2016	0.442	6×10^5	-	-	-	-	[5]
RX J1713.7–3946 (HESS) 2008	30	180	-	-	-	-	[7]
Coleman & Glashow (1997)	20	100	-	-	-	-	[6]
GRB09510 (*Fermi*) 2013 $v > c$	-	-	-	-	0.134	0.009	[8]
GRB09510 (*Fermi*) 2013 $v < c$	-	-	-	-	0.093	0.013	[8]
Crab (HEGRA) 2019	75	-	-	0.059	-	13	[9]

Table 2: Previous strong constraints to LIV photon decay are shown as well as the best limits based on energy-dependent time delay and superluminal photon splitting at bottom.

$E_{Pl} \approx 1.22 \times 10^{28}$ eV

HAWC Coll: arXiv: 1908.09614

Source	E_c TeV	$\lvert\alpha_0\rvert$ 10^{-17}	$\lvert\alpha_1\rvert$ $10^{-31}eV^{-1}$	$\lvert\alpha_2\rvert$ $10^{-45}eV^{-2}$	$E_{LIV}^{(1)}$ $10^{30}eV$	$E_{LIV}^{(2)}$ $10^{22}eV$	p value
2HWC J1825-134	253	1.63	0.64	0.26	15.5		
2HWC J1908+063	213	2.30	1.08	0.51	9.25		
Crab (HAWC)	152	4.52	2.97	1.96	3.4		
2HWC J2031+415	144	5.04	3.5	2.43	2.9		
2HWC J2019+367	121	7.13	5.6	4.87	1.7		
J1839-057	79	16.74	21.1	26.8	0.47		
2HWC J1844-032	77	17.62	22.9	29.7	0.44		

Tempting to Explain by Red-shift dependent M_{QG} scale in, e.g., string models

$$M_{QG} = \frac{M_s}{n^\star(z)}$$

Table 1: The HAWC Sources used in this analysis and the derived 95% CL lower l
its different LIV coefficients (Prel.).

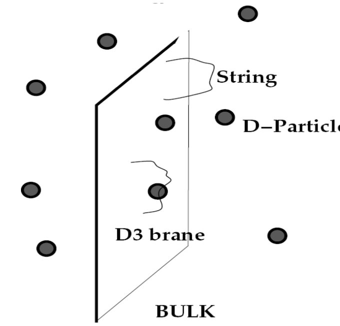
Source	E_γ TeV	$\lvert\alpha_0\rvert$ 10^{-17}	$\lvert\alpha_1\rvert$ $10^{-31}eV^{-1}$	$\lvert\alpha_2\rvert$ $10^{-45}eV^{-2}$	$E_{LIV}^{(1)}$ $10^{30}eV$	$E_{LIV}^{(2)}$ $10^{22}eV$	Ref.
Crab (HEGRA) 2017	~ 56	-	66.7	128	0.15	0.28	[4]
Tevatron 2016	0.442	6×10^5	-	-	-	-	[5]
RX J1713.7–3946 (HESS) 2008	30	180	-	-	-	-	[7]
Coleman & Glashow (1997)	20	100	-	-	-	-	[6]
GRB09510 (*Fermi*) 2013 $v > c$	-	-	-	-	0.134	0.009	[8]
GRB09510 (*Fermi*) 2013 $v < c$	-	-	-	-	0.093	0.013	[8]
Crab (HEGRA) 2019	75	-	-	0.059	-	13	[9]

Table 2: Previous strong constraints to LIV photon decay are shown as well as the best limits based on energy-dependent time delay and superluminal photon splitting at bottom.

STRINGY D(efect) -foam Model HAS VHE cutoff:

NB: For VHE photons:

$$\Delta t \sim \frac{\alpha' \, p^0}{1 - 2\pi\alpha' \, E^2}$$



But scattering amplitude of photons with D-particles in the foam

$$\mathcal{A} \propto g_s \, (1 - 2\pi\alpha' E^2)^{1/2} \times \text{kinematic factors}$$

i.e. goes to zero for $E \sim 1/\sqrt{\alpha' \, 2\pi} = M_s/\sqrt{2\pi}$

→ D-foam transparent to such VHE photons

Amplitude becomes imaginary (capture) for higher photon energies

$E = M_s/\sqrt{2}\,\pi$ plays the role of a characteristic **upper bound** for photon **energy** in such models

BUT ALWAYS SUBLUMINAL PHOTONS
→ NO VACUUM CHERENKOV

Ellis, NEM, Nanopoulos, B674 (2009) 83-86,
Int.J.Mod.Phys. A26 (2011) 2243-2262

FURTHER PRECISION TESTS OF STOCHASTIC QG FLUCTUATIONS EFFECTS (LIKE THOSE PREDICTED IN THE D-foam MODEL)

Ellis, Farakos, NEM, Mitsou & Nanopoulos
Astrophys.J. 535 (2000) 139-151

Ellis, Konoplich, NEM, Nguyen, Sakharov & Sarkisyan-Grinbaum,
Phys.Rev. D99 (2019) no.8, 083009

The Shape of the photon pulse matters

Wave packet propagation in a **QG dispersive medium**

$$u(x,t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} A(k) e^{ikx - i\omega(k)t} dk \longrightarrow A(k) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} u(x,0) e^{-ikx} dx$$

Assume Gaussian foam

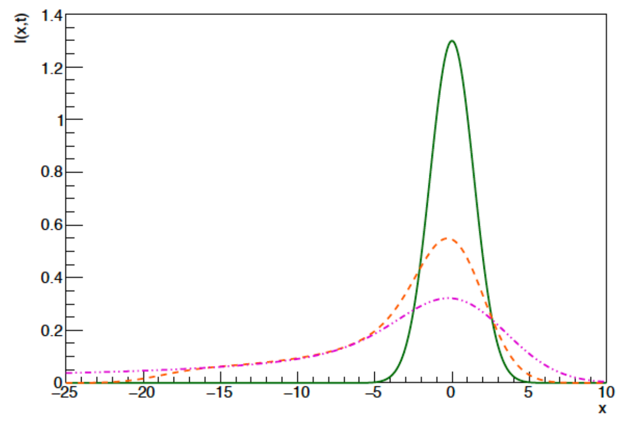
$$u(x,0) = \frac{1}{a\sqrt{2\pi}} e^{-\frac{x^2}{2a^2}}$$

group velocity

$$v_g = \frac{d\omega}{dk}\Big|_{k_0} \qquad \omega^2 = k^2(1 + 2\beta_n k^n)$$

e.g.
for n=1

$$u(x,t) = \frac{1}{2\sqrt{\pi}} \frac{e^{i(xk_0 - t\omega_0)}}{\left(\frac{a^2}{2} + i\beta_1 t\right)^{1/2}} \exp\left[-\frac{(x - v_g t)^2}{4\left(\frac{a^2}{2} + i\beta_1 t\right)}\right]$$



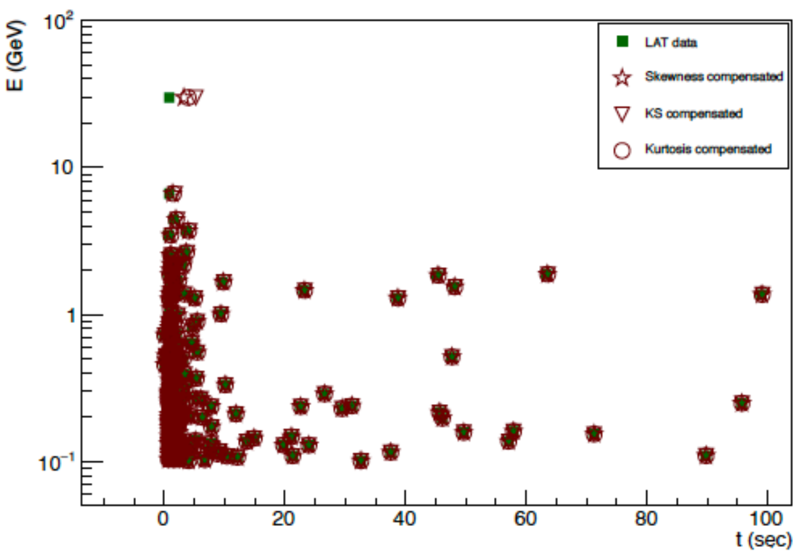
Fermi-LAT data

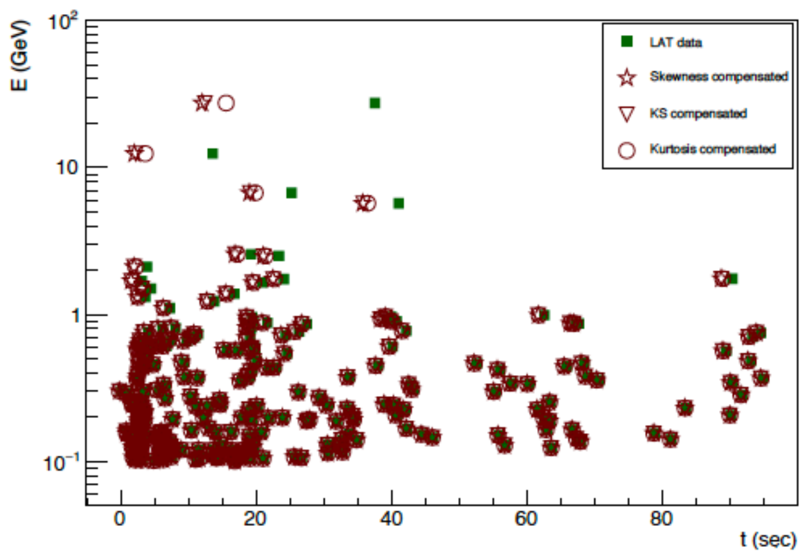
Ellis, Konoplich, NEM, Nguyen, Sakharov & Sarkisyan-Grinbaum, **Phys.Rev. D99 (2019) no.8, 083009**

Most energetic γ arrival time | Energy

GRB	z_{src}	N	T^{γ}_{HE} [s]	E^{γ}_{HE} [GeV]	$\tau \pm \sigma_\tau$ [s·GeV^{-1}]	σ_τ (Bias corr.) [s·GeV^{-1}]
080916C	4.350	220	16.5	13.2	0.892 ± 0.053	0.096
090510A	0.903	222	0.8	31.3	-0.099 ± 0.014	0.023
090902B	1.822	329	81.8	33.4	1.655 ± 0.088	0.139
090926A	2.1062	310	24.8	19.6	0.534 ± 0.054	0.104
110731A	2.830	80	5.0	3.2	4.54 ± 1.12	1.692
130427A	0.34	584	243.0	95	0.652 ± 0.107	0.618
160509A	1.60	33	77.0	52	0.946 ± 0.054	0.122
170214A	2.53	298	105	7.8	-3.68 ± 1.16	3.084

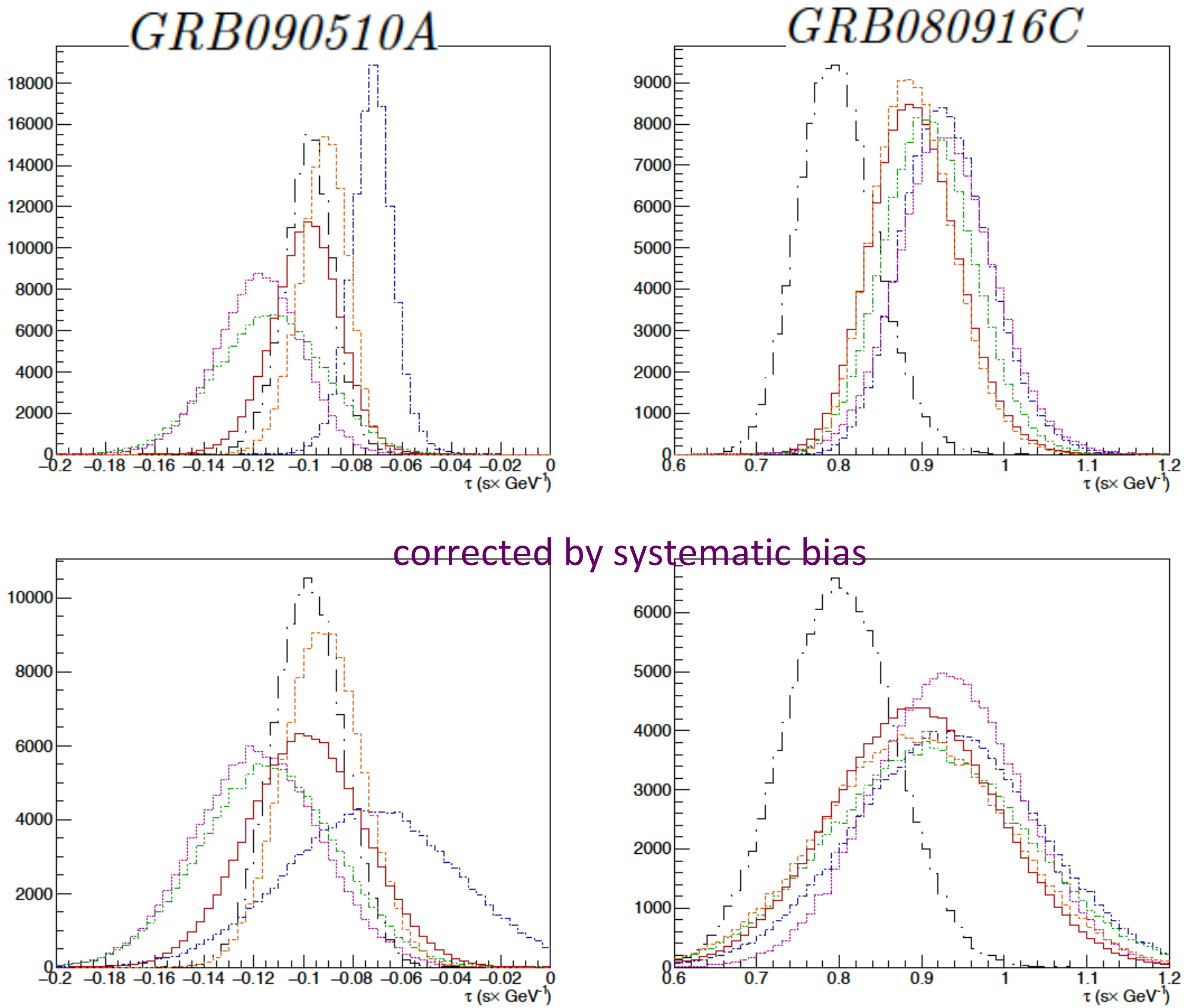
Various Estimators used in analysis
IRREGULARITY
KURTOSIS
SKEWNESS
plus their uncertainties





Ellis, Konoplich, NEM, Nguyen, Sakharov & Sarkisyan-Grinbaum, **Phys.Rev. D99 (2019) no.8, 083009**

Fermi-LAT data



Various Estimators used in analysis

IRREGULARITY

KURTOSIS

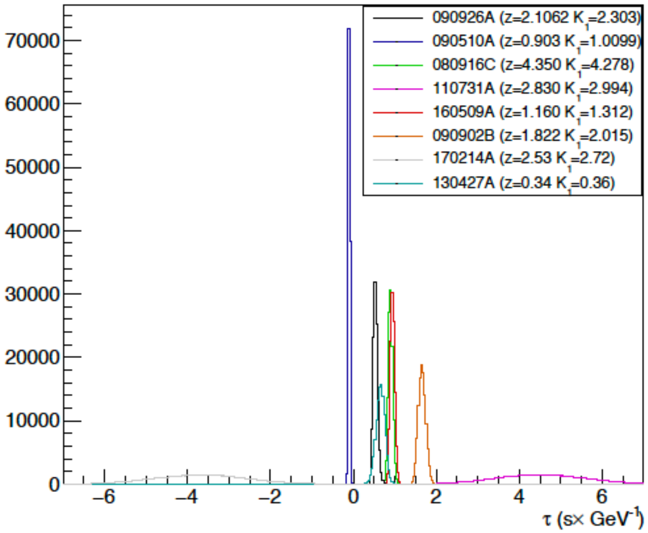
SKEWNESS

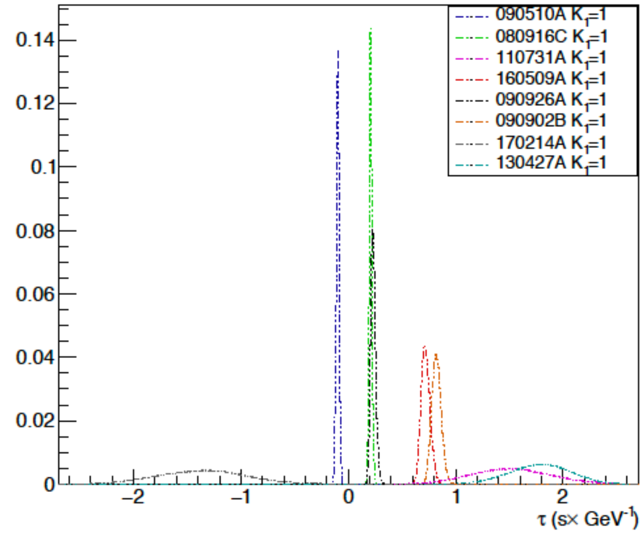
plus their uncertainties

Final distributions: Red Solid Lines

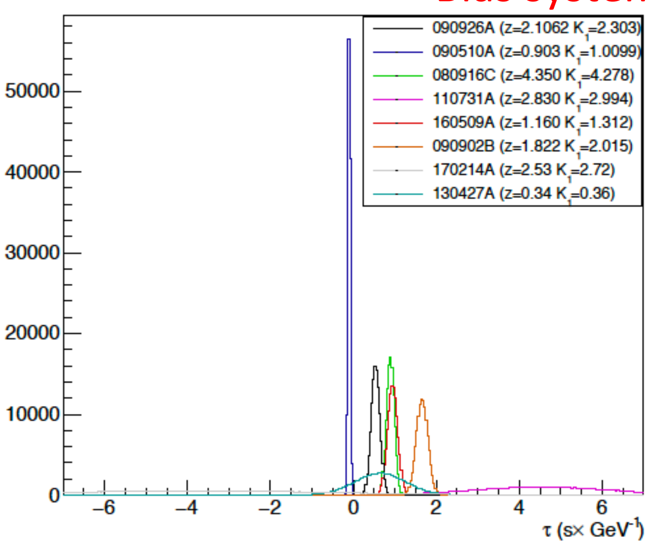
Ellis, Konoplich, NEM, Nguyen, Sakharov & Sarkisyan-Grinbaum,
Phys.Rev. D99 (2019) no.8, 083009

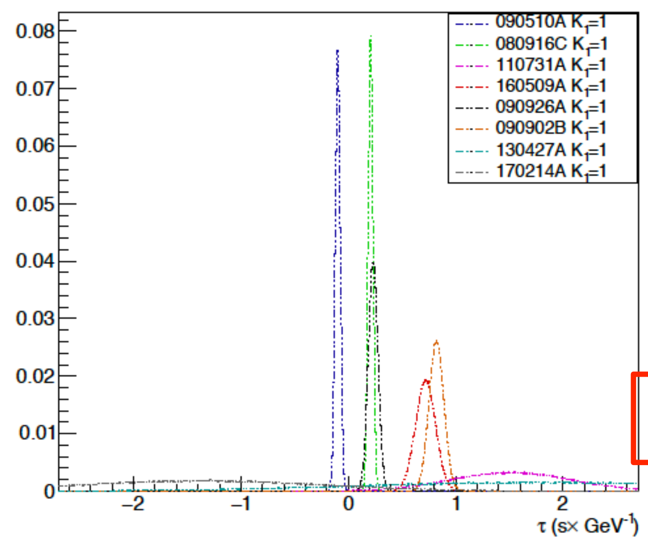
Fermi-LAT data





Bias systematic corrected





Various Estimators used in analysis
IRREGULARITY
KURTOSIS
SKEWNESS
plus their uncertainties

Depending on method of consolidating the results (estimating **unknown source effects**)
→ Robust LIV limit (linear energy dependence)

$M_1 \sim (8.4 \text{ or } 2.4) \times 10^{17}$ GeV

The Future: Cerenkov Telescope Array

The large collection area and acceptance of CTA will provide it with unique prospects for gathering data on astrophysical sources of energetic γ-rays → new opportunities **for probing Lorentz violation**.

Much more detailed studies on AGNs: Mk421, Mk501 & PKS 2155-304 potential observation of **higher energy photons from other objects at similar redshifts and more statistics** → improve LIV test sensitivities.

CTA able to observe structures with smaller amplitudes than those accessible to previous γ-ray telescopes. **Such small-amplitude structures** might be associated with emissions from smaller regions of the AGNs, that therefore could exhibit **shorter time-scales** and provide **improved sensitivity** to Lorentz violation.

Extend γ-ray observations **to larger families of less-luminous AGNs**, some with similar intrinsic luminosities as known AGNs but **at larger redshifts** → **improve LIV tests sensitivities, separate source from propagation effects** (important for QG vacuum refraction tests)

The Future: Cerenkov Te… …pe Array

The large collection area and acceptance o… …prospects for gathering data on astrophysical sources … new opportunities **for probing Loren…**

Much more detailed studies o… …-304 potential observation of **hig…** …**jects at similar redshifts and more statistics** → i…

CTA able to obs… …udes than those accessible to previous γ-ray telesc… …**res** might be associated with emissions from sma… …efore could exhibit **shorter time-scales** and provide… …violation.

Extend γ-ray … …**families of less-luminous AGNs**, some with similar intrinsic lumino… …AGNs but **at larger redshifts** → **improve LIV tests sensitivities, sepa… …e from propagation effects** (important for QG vacuum refraction tests)

CTA advantages for increased LIV tests sensitivity :

Higher Energies, Larger Redshifts & Finer Time Structures

An example of improved sensitivity

$$\text{typical spectral index } \Gamma : dN/dE_\gamma \sim (E_\gamma/E_0)^{-\Gamma} \text{ for AGN}$$

$\Gamma \sim 2$ → to extend the observations of H.E.S.S. on PKS 2155-304 to γ-rays with **< E> = O(10) TeV** , a collecting power **100 times stronger** is required → assuming the observation of a transient emission of similar time scale is achieved → linearly suppressed LIV scale

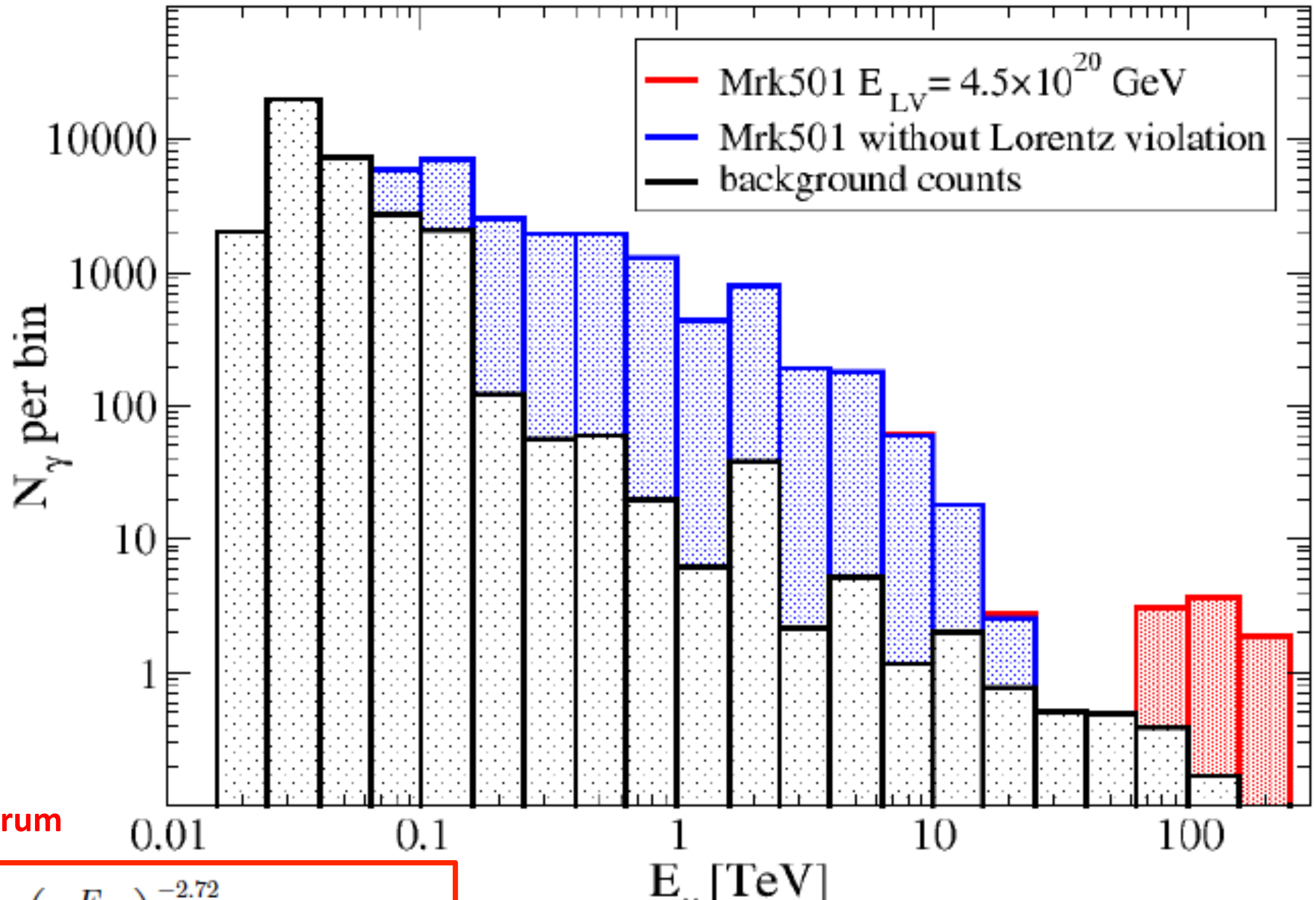
$$M_1 \sim 10^{19} \text{ GeV}$$

i.e. close to Planck

J. Ellis, NEM. Astropart.Phys. 43 (2013) 50-55

The CTA Sensitivity to Lorentz-Violating Effects on the Gamma-Ray Horizon

Fairbairn, Nilsson, Ellis, Hinton, White JCAP 1406 (2014) 005



Power-law spectrum

$$\frac{dN_{501}}{dE} = 5.78 \cdot 10^{-12} \left(\frac{E}{1\ \text{TeV}}\right)^{-2.72} \text{cm}^{-2}\,\text{s}^{-1}\,\text{TeV}^{-1}$$

assume exponential cutoffs at 10 or 20 TeV

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.*

Limitations

- Stochastic properties of γ-ray emissions
- Interactions (hence energy loss) with CMB and Infrared Background

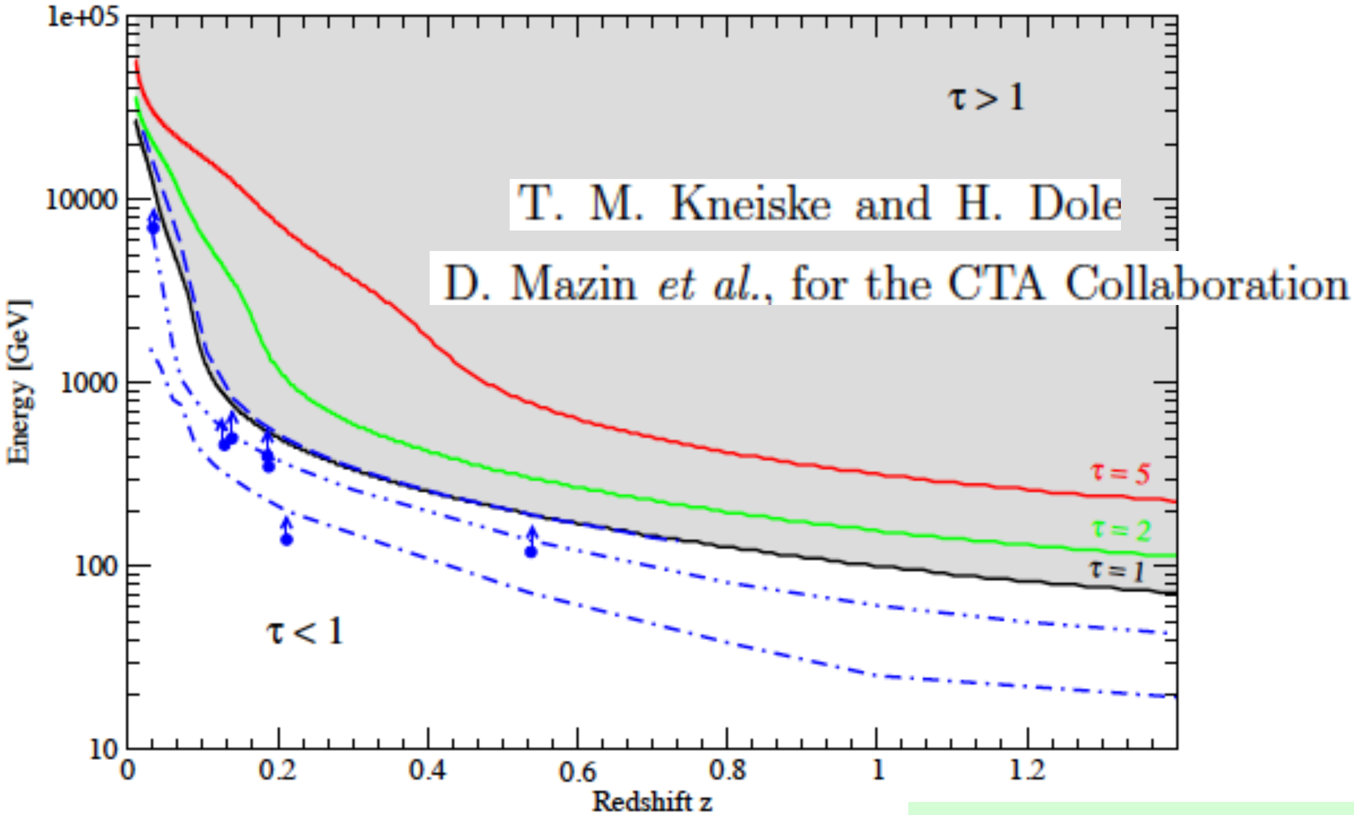
$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

→ mean-free-path limitations on high energies of photons that can be observed: e.g. **CMB-HE-γ-rays interactions** → **no observations of photons with E_γ > 100 TeV from sources at a few Mpc away**

J. Ellis, NEM. Astropart.Phys. 43 (2013) 50-55

Limitations

- Interactions (hence energy loss) with Infrared Background → most likely no observations of photons with $E_\gamma > 1$ TeV from AGNs @ distances > Mk 421, Mk501 and PKS 2155-304.



Solid lines: horizons of HE photons interacting with cosmic IR & CMB backgrounds

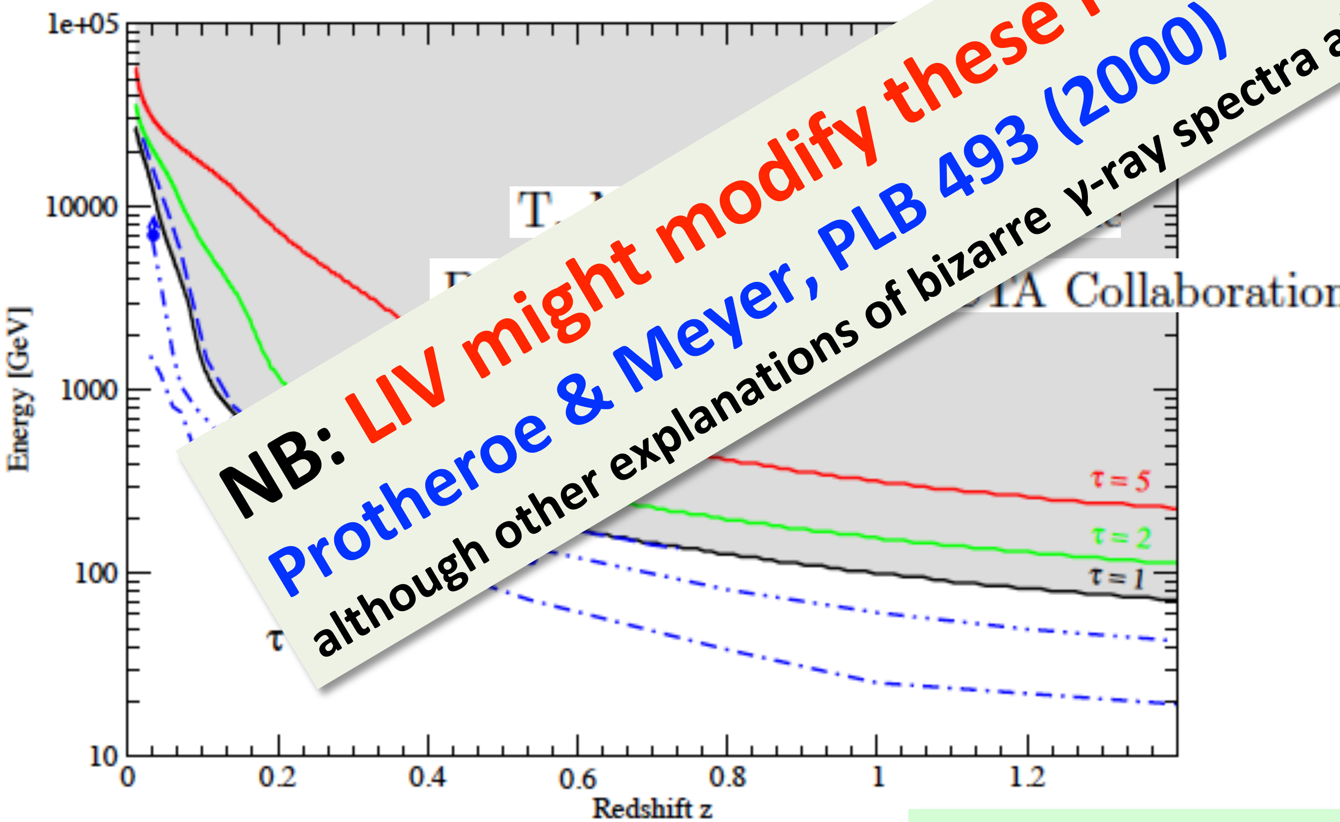
τ = optical depth

Dashed & dot-dashed curves → alternative models of extragalactic background light

J. Ellis, NEM. Astropart.Phys. 43 (2013) 50-55

Limitations

- Interactions (hence energy loss) with Infrared Ba… nd → most likely no observations of photons with … om AGNs @ distances > Mk 421, Mk501 a…



NB: LIV might modify these results
Protheroe & Meyer, PLB 493 (2000)
although other explanations of bizarre γ-ray spectra also possible

Solid lines: horizons of HE photons interacting with cosmic IR & CMB backgrounds

τ = optical depth

Dashed & dot-dashed curves → alternative models of extragalactic background light

J. Ellis, NEM. Astropart.Phys. 43 (2013) 50-55

Mean Free Path for HE γ-ray/IR background ineractions

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

$\sigma(s)$ is the total cross section $\quad s = m_\gamma^2 c^4 + 2\varepsilon E_\gamma (1 - \beta_\gamma \cos\theta)$

angle between energetic (γ-ray) and soft photon

$$s_{\min} = (2m_e c^2)^2 \qquad \varepsilon_{\min} = (s_{\min} - m_\gamma^2 c^4)/[2E_\gamma(1+\beta_\gamma)]$$

$$s_{\max}(\varepsilon, E_\gamma) = m_\gamma^2 c^4 + 2\varepsilon E_\gamma (1+\beta_\gamma)$$

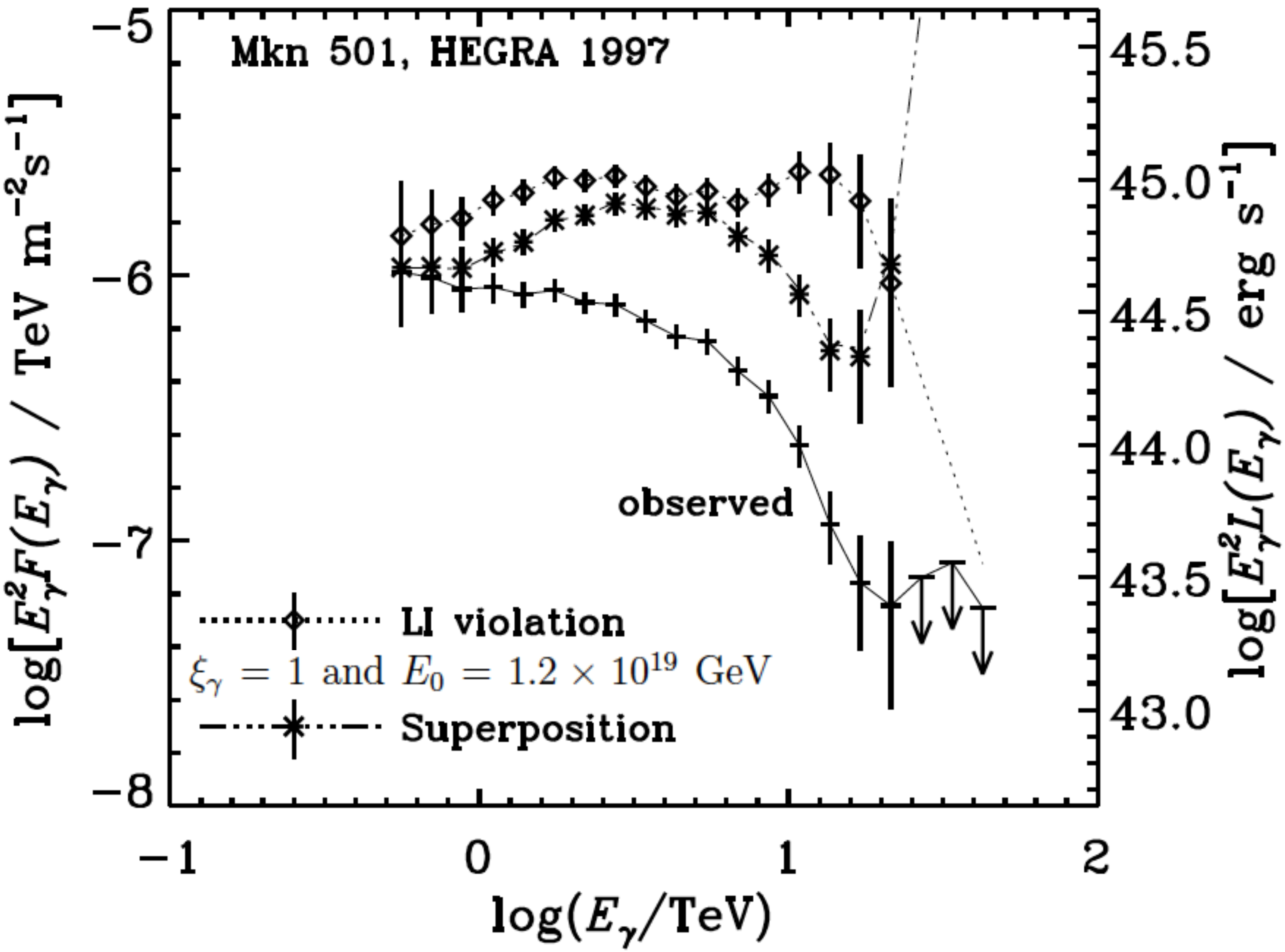
although s assumed Lorentz Invariant, nevertheless one can get a feeling of the effects of LV if:

$$\beta_\gamma c = (1 - \xi_\gamma E_\gamma / E_0) c \qquad p^2 c^2 = (E^2 + \xi_\gamma E_\gamma^3 / E_0)$$

→ LIV = ``effective mass of photons''

$$m_\gamma^2 c^4 = -\xi_\gamma E_\gamma^3 / E_0$$

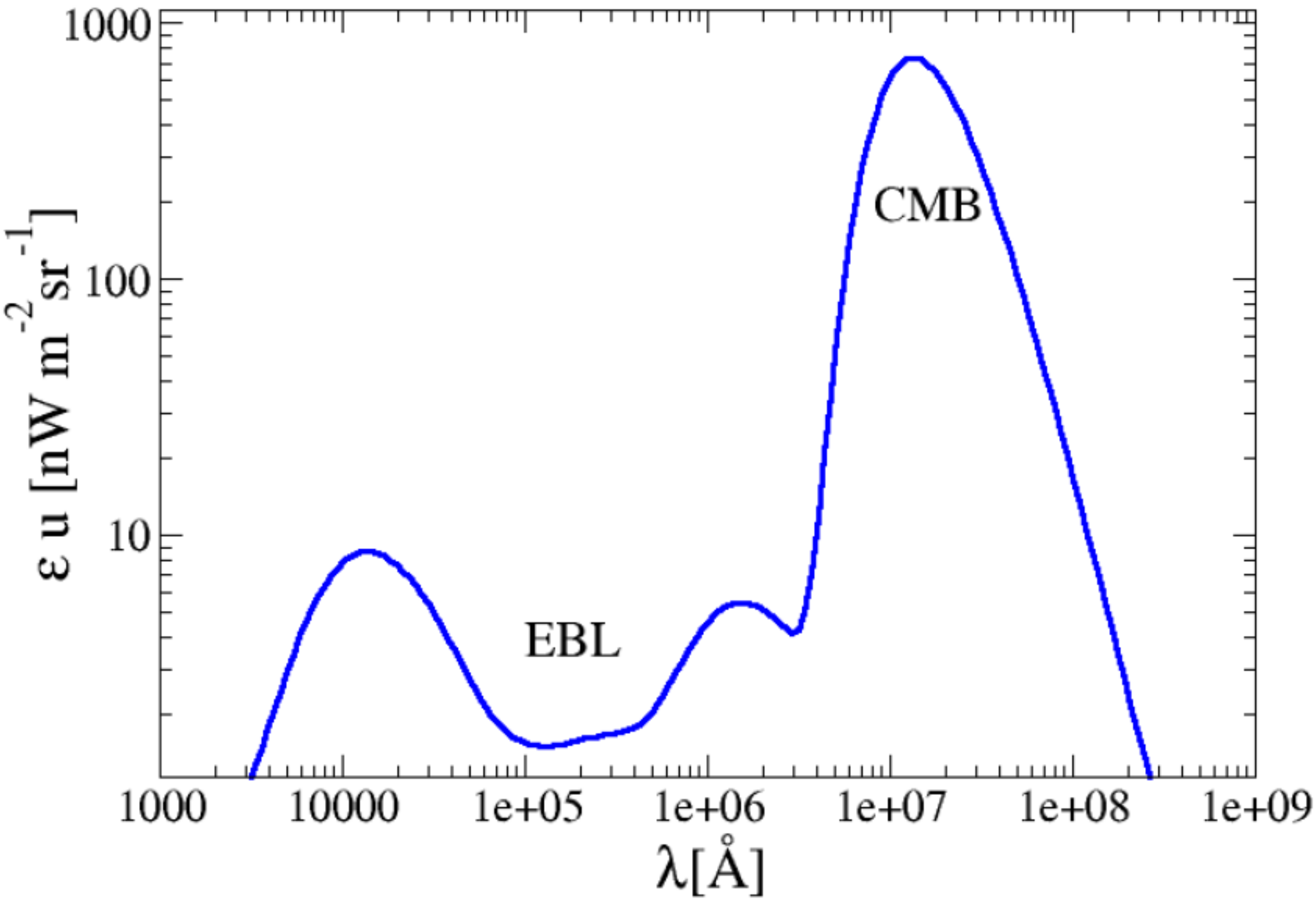
NB: Use here models including redshift dependent **E_0 (z)** , e.g. D-foam models



Protheroe & Meyer (2000) old result for linear LIV effects →

can be modified if one uses E_0 (z) z-dependent QG scale (eg in D-brane models)

The CTA Sensitivity to Lorentz-Violating Effects on the Gamma-Ray Horizon



Spectrum of the extragalactic background light (EBL) and the cosmic microwave background

calculated in **Fairbairn, Nilsson, Ellis, Hinton, White JCAP 1406 (2014) 005**

The CTA Sensitivity to Lorentz-Violating Effects on the Gamma-Ray Horizon

Fairbairn, Nilsson, Ellis, Hinton, White
JCAP 1406 (2014) 005

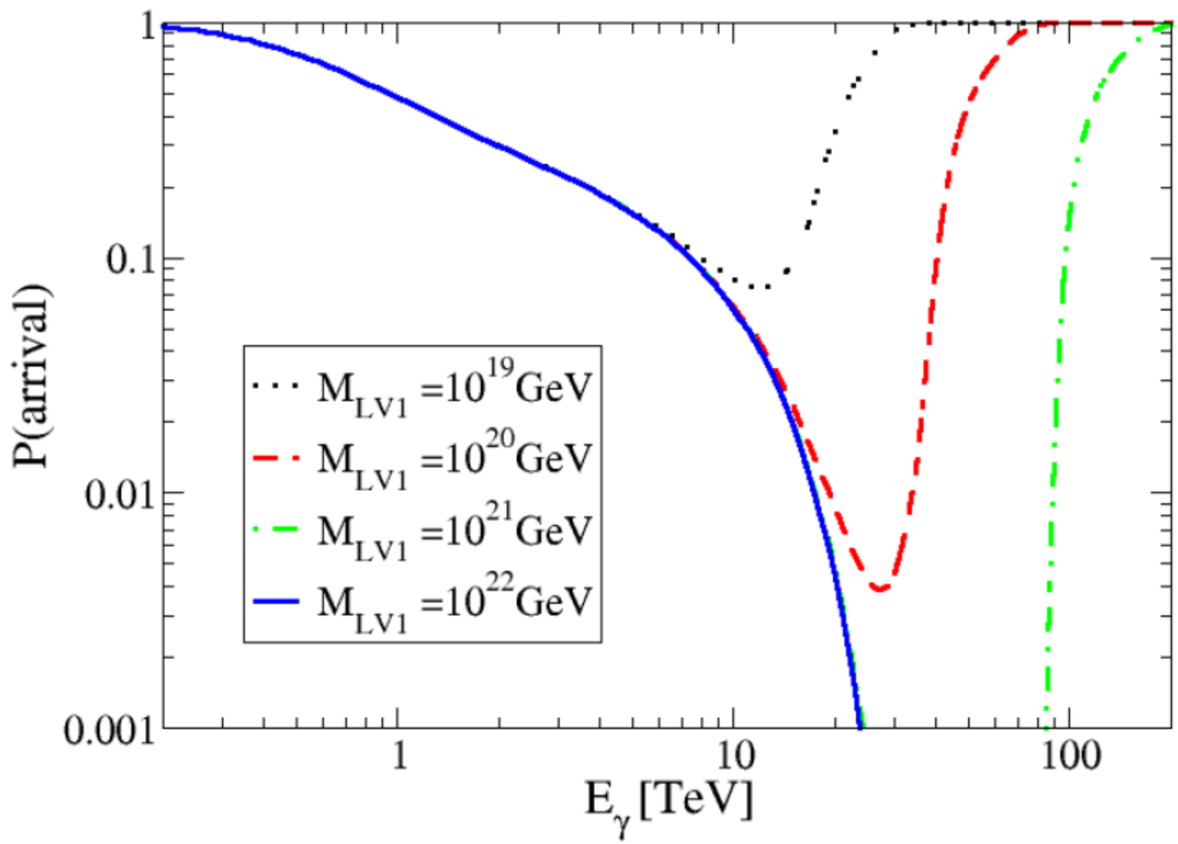
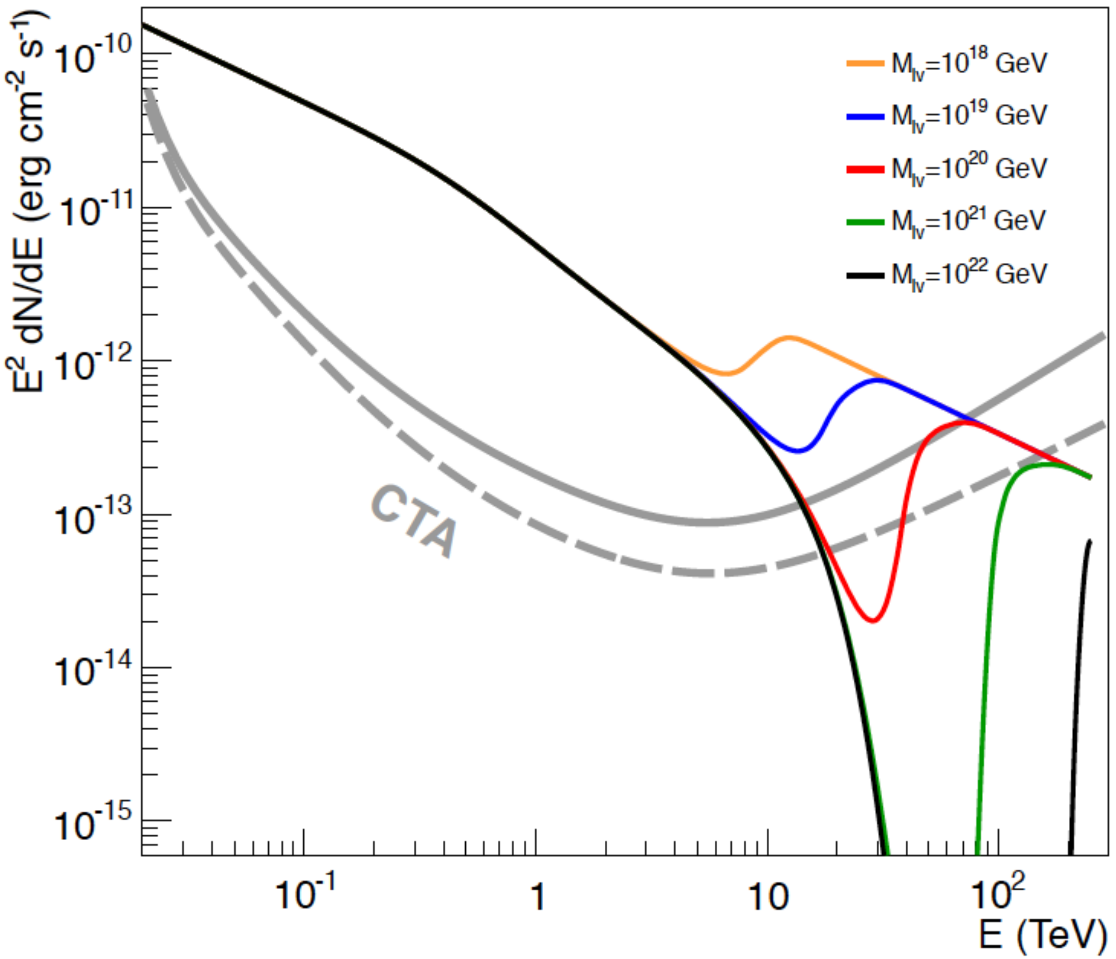


Figure 2. *The arrival probability of a photon emitted from a hypothetical source at redshift* $z = 0.05$ *as a function of energy. The different curves represent different values of the Lorentz-violating scale* M_{LV1}. *VHE photons with energies* $\gtrsim 100$ *TeV can travel through the CMB effectively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

The CTA Sensitivity to Lorentz-Violating Effects on the Gamma-Ray Horizon

Fairbairn, Nilsson, Ellis, Hinton, White
JCAP 1406 (2014) 005



Expected spectrum of Mk501 for different values of M_{LV1} vs CTA sensitivity

Upper solid curve: presented in Bernlöhr *et al. arXiv:1210.3503*

Dashed curve: *uses wider bins & remove requirement of 10 photons per bin*

The CTA Sensitivity to Lorentz-Violating Effects on the Gamma-Ray Horizon

Results: very competitive sensitivity of CTA in LIV effects

Fairbairn, Nilsson, Ellis, Hinton, White
JCAP 1406 (2014) 005

LIV refraction

$$\beta_\gamma^2 = 1 - \left(\frac{E_\gamma}{M_{LVn}}\right)^n \quad ; \quad m_\gamma^2 = \frac{E_\gamma^{2+n}}{M_{LVn}^n},$$

	Power-law flux 5σ (3σ) [GeV]	20-TeV cut-off 5σ (3σ) [GeV]	10-TeV cut-off 5σ (3σ) [GeV]
$n = 1$	4.5×10^{20} (1.4×10^{21})	1.8×10^{19} (3.2×10^{19})	4.1×10^{18} (9.1×10^{18})
$n = 2$	5.9×10^{12} (1.2×10^{13})	5.1×10^{11} (9.8×10^{11})	2.7×10^{11} (4.2×10^{11})

Table 1. *The 5-σ (3-σ) sensitivities to M_{LVn} for the cases $n = 1$ and $n = 2$ estimated by combining the likelihoods in high-energy , assuming 50 hours of observations of the AGN Markarian 501. In each row, the leftmost entry is obtained assuming a power-law extrapolation of the emitted flux from low-energy data, and the centre and rightmost entries assume exponential cut-offs at 20 and 10 TeV, respectively.*

Limitations

- The same issue (on **non observation of high energy photons**) arises in considering the potential for observing emissions from larger redshifts.
  For example, assuming conventional Lorentz-invariant kinematics, can be shown that only photons with **$E < 300$ GeV** are likely to be observable in emissions from **redshifts $z \sim 1$.** Nevertheless, if one assumes that a structure similar to that observed by H.E.S.S. in emissions from PKS 2155-304 were to be observed in **TeV-scale** emissions from an **AGN with $z \sim 1$**, which might be possible with the collecting power of CTA, this would also give sensitivity to linear LIV effects of order : **$M_1 \sim 10^{19}$ GeV**.

- Simlar sensitivities are to be expected if one observes (with CTA) transient emissions with shorter time scales than then ones observed so far, associated with AGNs with smaller cores (less luminous), or from 'hotspots' of accretion corresponding to small portions of the overall emission region**. If the larger statistics obtainable with CTA were to reveal structures with time-scales an order of magnitude shorter than that observed from PKS 2155-304, but with similar energies and from similar redshifts, sensitivity to $M_1 \sim 10^{19}$ GeV might again be attained.**

J. Ellis, NEM. Astropart.Phys. 43 (2013) 50-55

Complementarity of CTA with other experiments

- Principal competitors for LIV: GRBs observations (e.g. Fermi GRB 090510, $M_1 > M_P$)- **but single photon sensitivity (E_γ = 31 GeV)**

- **Large redshift GRBs (eg GRB 090423, z = 8.2)**

However, refractive index $\eta = E_\gamma / M_1$ → time delays highly non linear at high redshifts, no significant advantages for high redshift GRB measurements of LIV, rather robust limits on LIV effects would require high statistics (obtained from both GRBs and AGNs, hence complementarity of CTA)

- **CTA probes higher values of quadratic LIV effects: ability to measure photons with much higher energies than in GRB emissions**

- **Redshift dependent QG scale M_{QG} (z) (eg D-foam): probed by statistically-significant measurements at various redshifts, both AGNs and GRBs**

  e.g. at z=O(0.1) : AGNs sensitivity to LIV > GRBs sensitivity to LIV

Complementarity of CTA with other experiments

- **Also prospects for increasing sensitivity to LIV effects in long-base-line neutrino experiments (such as OPERA):**

  e.g. improve timing measurement in CNGS to 1 ns → improve sensitivity to

  $M_1^{\nu} > 5 \times 10^7$ GeV, $M_2^{\nu} > 4 \times 10^4$ GeV

J. R. Ellis, N. Harries, A. Meregaglia, A. Rubbia, A. Sakharov, Phys. Rev. D78 (2008) 033013.

- **NB: SN1987a supernova (subluminal) neutrino observations:**

  $M_1^{\nu} > 2.7 \times 10^{10}$ GeV, $M_2^{\nu} > 4.6 \times 10^4$ GeV

  If a galactic supernova at 10kpc observed would have sensitivity

  $M_1^{\nu} > 2 \times 10^{11}$ GeV, $M_2^{\nu} > 4 \times 10^5$ GeV

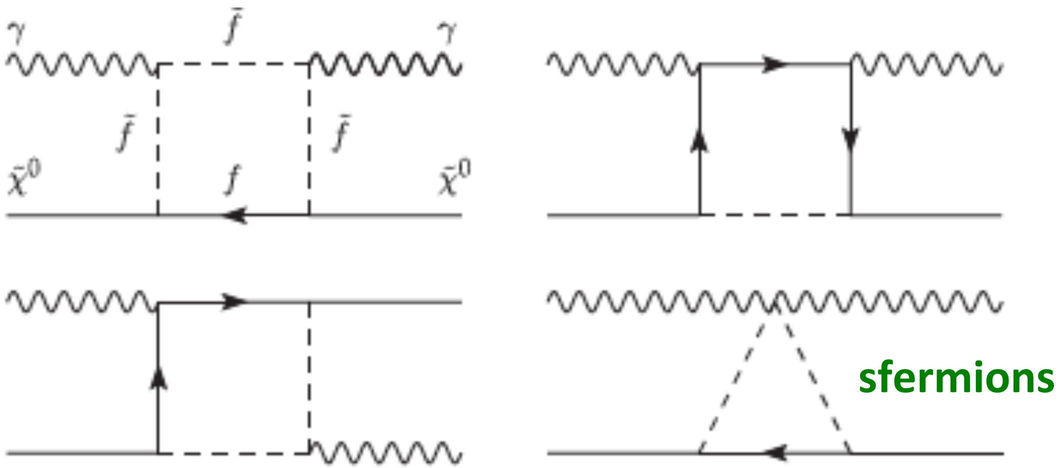
...still less sensitive than HE photons

NB: Refractive Index & Dark Matter

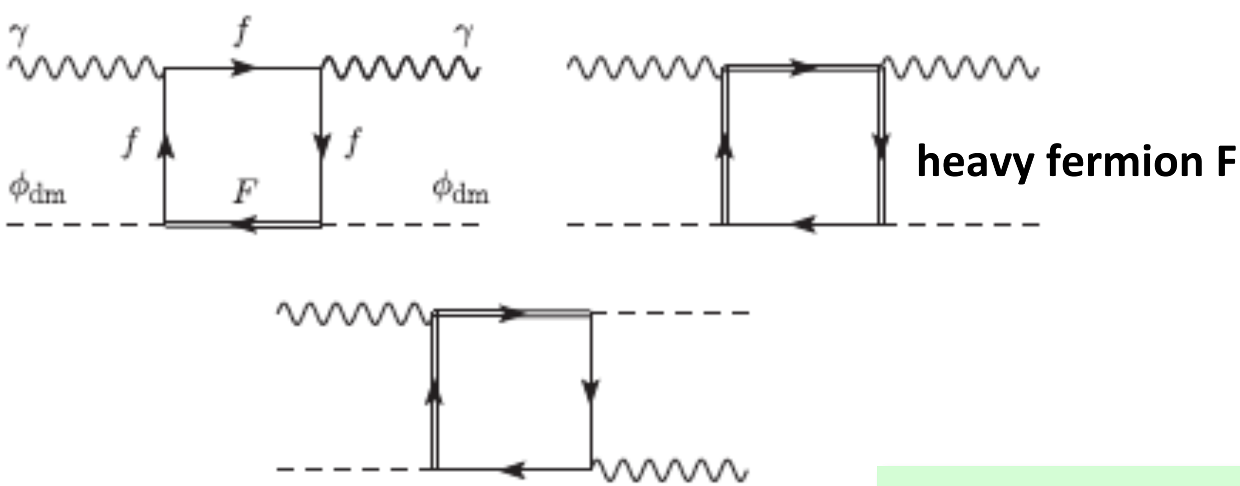
Latimer, PRD88, 063517 (2013)

- Exotic (milicharged or not) **DM may interact with photons** in theories BSM and produce **refractive-index-like** effects, with anomalous terms scaling like ω^2 for neutral DM, or ω^{-2} for charged DM, and ω if parity is violated

e.g. Photon-neutralino interactions



e.g. Photon-scalar-DM interactions (in models with heavy fermions F)



Latimer, PRD88, 063517 (2013)

NB: Refractive Index & Dark Matter

Latimer, PRD88, 063517 (2013)

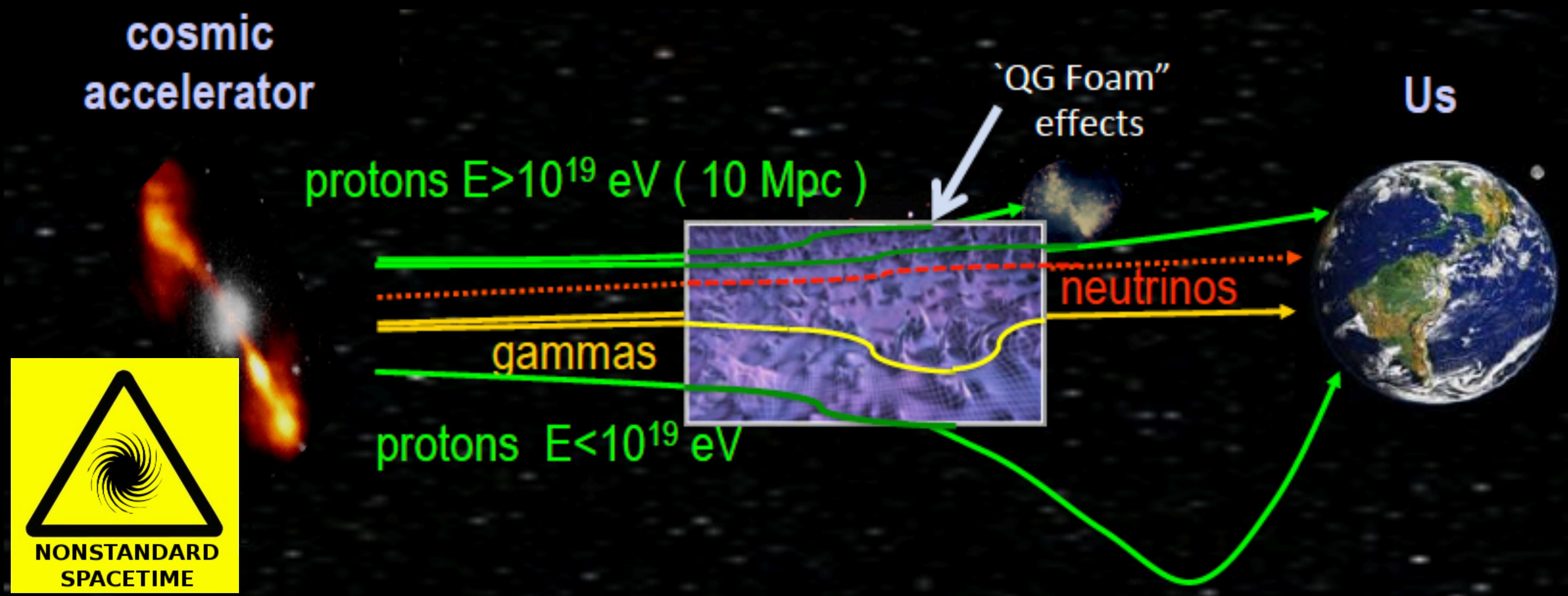
- Exotic (milicharged or not) **DM may interact with photons** in theories BSM and produce **refractive-index-like** effects, with anomalous terms scaling like ω^2 for neutral DM, or ω^{-2} for charged DM, and ω if parity is violated

- Matter effects can **compete with LIV effects scaling like ω^2** for neutral scalar DM models for UHE photons with **$\omega \geq 10^{29}$ GeV** (i.e. well above the GZK cutoff)

- DM effects scaling like ω are highly model dependent and result in **circular birefringence**

Thus linear DM-induced refractive effects can be disentangled from LIV stringy D-foam effects with no Birefringence ...

Testing QG Modified Dispersion Effects



protons/nuclei: QG effects may be suppressed

Absorbed by radiation field (GZK)

photons: QG effects Unsuppressed in certain theories

neutrinos: QG effects unsuppressed in certain theories-Less sensitivity to LIV than photons currently

except Quantum Gravity decoherence

Neutrino Telescopes
&
LV Modified Dispersion Relations

Some personal Selection of Topics

SME LV & Neutrinos

Diaz, **Symmetry 8, no. 10, 105 (2016)**

$$\mathcal{L} = \frac{1}{2}\overline{\Psi}(i\gamma^\alpha\partial_\alpha - M + \hat{\mathcal{Q}})\Psi + \text{h.c.} \qquad \Psi = (\nu_e, \nu_\mu, \nu_\tau, \nu_e^C, \nu_\mu^C, \nu_\tau^C)^T$$

LV

$$\hat{\mathcal{Q}} = \hat{\mathcal{S}} + i\hat{\mathcal{P}}\gamma_5 + \hat{\mathcal{V}}^\alpha\gamma_\alpha + \hat{\mathcal{A}}^\alpha\gamma_5\gamma_\alpha + \frac{1}{2}\hat{\mathcal{T}}^{\alpha\beta}\sigma_{\alpha\beta}$$

Deviation of ν velocity from speed of light

$$v_\nu - 1 = \frac{|\mathrm{m}|^2}{2|\boldsymbol{p}|^2} + \sum_{djm}(d-3)|\boldsymbol{p}|^{d-4}\, e^{im\omega_\oplus T_\oplus}\, {}_0\mathcal{N}_{jm}(\hat{\boldsymbol{p}})\big((a_{\text{of}}^{(d)})_{jm} - (c_{\text{of}}^{(d)})_{jm}\big)$$

Oscillations are affected

$$P_{\nu_b\to\nu_a} \simeq L^2\left|(a_L)^\alpha_{ab}\hat{p}_\alpha - (c_L)^{\alpha\beta}_{ab}\hat{p}_\alpha\hat{p}_\beta E\right|^2, \quad a \neq b,$$

Antineutrinos

$$(a_L)^\alpha_{ab} \to -(a_L)^{\alpha *}_{ab} \text{ and } (c_L)^{\alpha\beta}_{ab} \to (c_L)^{\alpha\beta *}_{ab}$$

Superluminal ν → lose energy in the form of Cherenkov radiation

SME LV & Neutrinos: EFT wth CPT-odd & CPT-even terms

Stecker, Scully, Liberati and D. Mattingly,
Phys.Rev. D91 (2015) no.4, 045009

$$\begin{aligned}\Delta\mathcal{L}_f &= -Mb\bar{\psi}\gamma_5(u\cdot\gamma)\psi \\ &-i\bar{\psi}(u\cdot\gamma)(d_L P_L + d_R P_R)(u\cdot D)\psi \\ &+M^{-1}\bar{\psi}(e_L P_L + e_R P_R)(u\cdot\gamma)(u\cdot D)^2\psi \\ &-M^{-1}\bar{\psi}(u\cdot D)^2(f_L P_L + f_R P_R)\psi \\ &-iM^{-2}\bar{\psi}(u\cdot D)^3(u\cdot\gamma)(g_L P_L + g_R P_R)\psi.\end{aligned}$$

→

$$\begin{aligned}E^2 - p^2 = m^2 &+ (1-s)\left(d_L p^2 + e_L\frac{p^3}{M_{Pl}} + g_L\frac{p^4}{M_{Pl}^2}\right) \\ &+(1+s)\left(d_R p^2 + e_R\frac{p^3}{M_{Pl}} + g_R\frac{p^4}{M_{Pl}^2}\right) \\ &+\frac{m}{M_{Pl}}(f_L + f_R)p^2 + f_L f_R\frac{p^4}{M_{Pl}}.\end{aligned}$$

↓

$$\tilde{m}^2(E) = m^2 + 2\delta_I E^2,$$

←

$$\delta_{IJ} \equiv \delta_I - \delta_J$$

I, J-particles

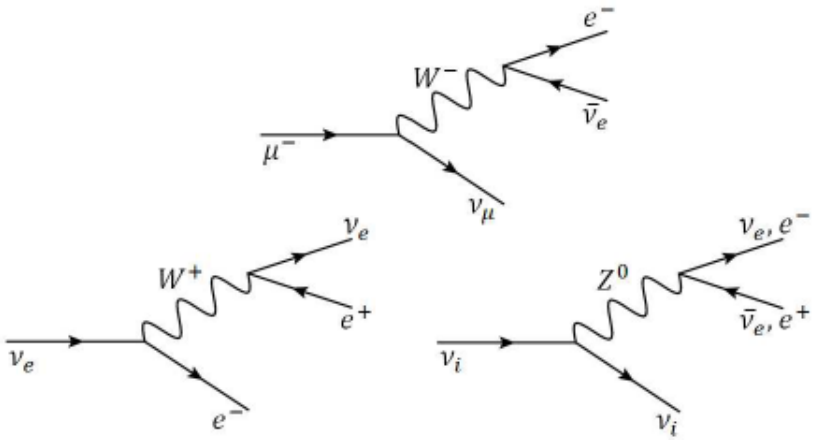
$$\delta_{IJ} \equiv \kappa_{IJ,n}\left(\frac{E}{M_{Pl}}\right)^n$$

n=1 → CPT-odd (CPTV)

n=2 → CPT - even (CPT Conserved)

SME LV & Neutrinos: EFT wth CPT-odd & CPT-even terms

Stecker, Scully, Liberati and D. Mattingly,
Phys.Rev. D91 (2015) no.4, 045009



$$\delta_{IJ} \equiv \delta_{\bar{I}} - \delta_{\bar{J}}$$

I, J-particles

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

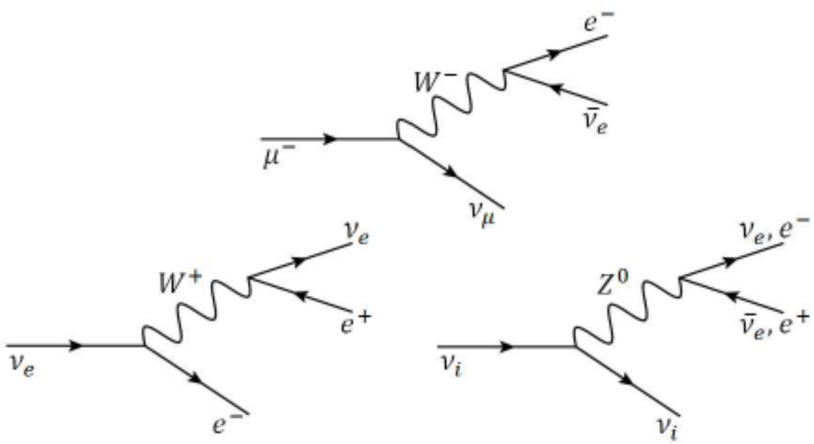
← $\tilde{m}^2(E) = m^2 + 2\delta_I E^2$,

n=1 → CPT-odd (CPTV) → not clear drop-off of high energy ν flux

n=2 → CPT - even (CPT Conserved) → Drop-off in ~ 2 PeV high energy neutrino flux (see ICE CUBE obs. → **could be due to source effects of course**)

SME LV & Neutrinos:
EFT wth CPT-odd & CPT-even terms

Stecker, Scully, Liberati and D. Mattingly,
Phys.Rev. D91 (2015) no.4, 045009



[d] = 5 CPT Violating Operator Dominance

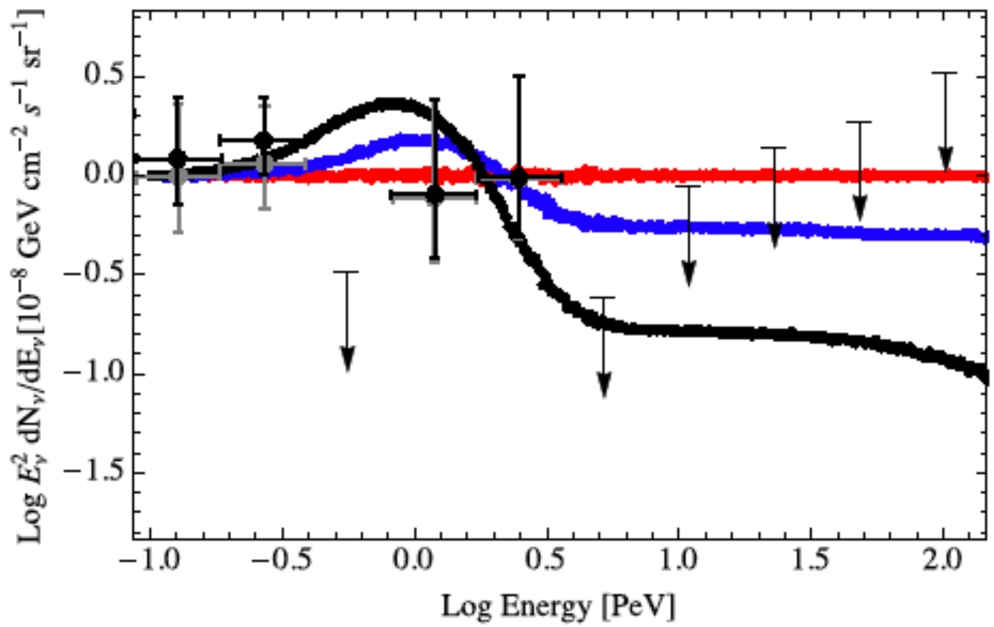


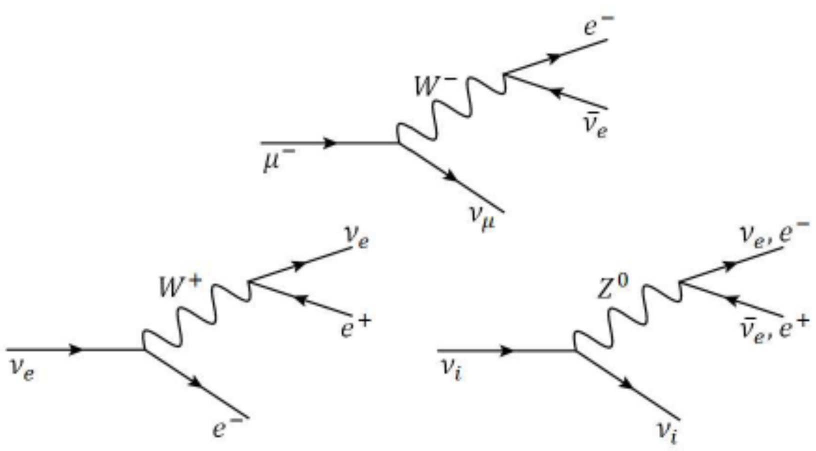
FIG. 6: Calculated n = 1 neutrino spectra assuming 100% (black), 50% (blue) and 0% (red) initial superluminal neutrinos (antineutrinos). The neutrino spectra are normalized to the IceCube data [6].

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

n=1 → CPT - odd

SME LV & Neutrinos: EFT wth CPT-odd & CPT-even terms

Stecker, Scully, Liberati and D. Mattingly,
Phys.Rev. D91 (2015) no.4, 045009



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

n=2 → CPT - even

$$\delta_{\nu e} = 5.2 \times 10^{-21}$$

ICE-CUBE data
10 PeV
threshold energy

SME dim 6 coefficient

$$\mathring{c}^{(6)} = -\kappa_2/M_{Pl}^2 \geq -5.2 \times 10^{-35} \ \mathrm{GeV}^{-2}$$

[d] = 6 $\mathcal{CPT}$ Conserving Operator Dominance

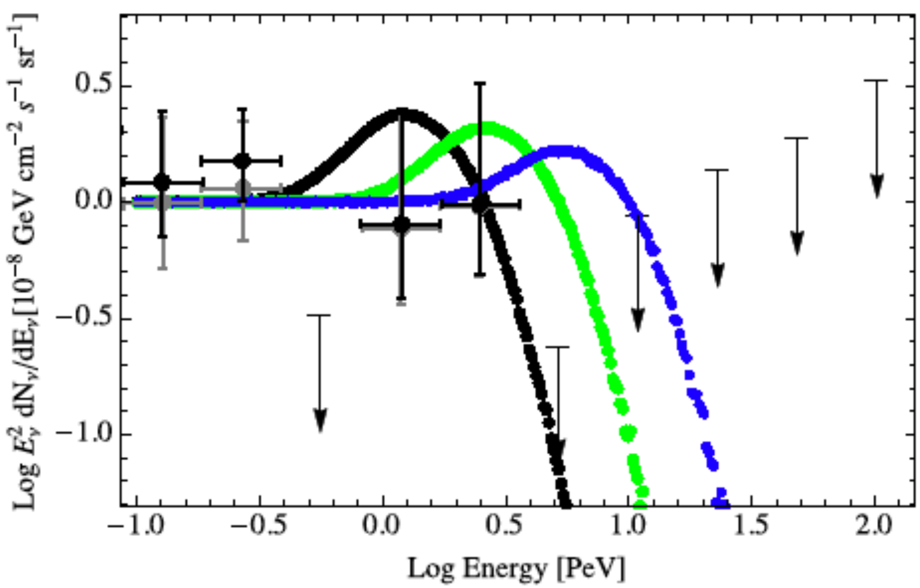


FIG. 5: Calculated n = 2 spectra taking into account of all three processes (redshifting, neutrino splitting, and VPE) occurring simultaneously for rest frame VPE threshold energies of 10 PeV (black, as in Figure 2), 20 PeV (green), and 40 PeV (blue). The IceCube data are as in Figure 2 [6].

LV & CPTV Tests with GRB Neutrinos ???

Zhang & B.Q. Ma, **Phys. .Rev. D99 (2019) no.4, 043013**

$$E(p) = |p| + \sum_{djm} |p|^{d-3} Y_{jm}(\hat{p})[(a_{\text{of}}^{(d)})_{jm} - (c_{\text{of}}^{(d)})_{jm}],$$

$$v_\nu = 1 + \sum_{djm} (d-3)|p|^{d-4} Y_{jm}(\hat{p})[(a_{\text{of}}^{(d)})_{jm} - (c_{\text{of}}^{(d)})_{jm}],$$

$$v_{\bar{\nu}} = 1 - \sum_{djm} (d-3)|p|^{d-4} Y_{jm}(\hat{p})[(a_{\text{of}}^{(d)})_{jm} + (c_{\text{of}}^{(d)})_{jm}].$$

Look @ ICE-CUBE events

$$E^2 \simeq p^2c^2 + m^2c^4 - s_n E^2 \left(\frac{E}{E_{\text{LV},n}}\right)^n \qquad s_n = \pm 1$$

$$\Delta t_{\text{obs}} = t_{\text{h}} - t_{\text{l}} = \Delta t_{\text{LV}} + (1+z)\Delta t_{\text{in}}. \qquad \Delta t_{\text{LV}} = s_n \frac{1+n}{2H_0} \frac{E_{\text{h}}^n - E_{\text{l}}^n}{E_{\text{LV},n}} \int_0^z \frac{(1+z')^n \mathrm{d}z'}{\sqrt{\Omega_{\text{m}}(1+z')^3 + \Omega_\Lambda}},$$

$$\frac{\Delta t_{\text{obs}}}{1+z} = \Delta t_{\text{in}} + s\frac{K}{E_{\text{LV}}}$$

ICE CUBE data studied in Zhang & B.Q. Ma, **Communications Physics 1 (2018) 62, Phys. .Rev. D99 (2019) no.4, 043013**

Table 1. The GRB candidates for the TeV neutrino events.

event	GRB	z	Δt_{obs} (10^3 s)	E (TeV)
#2	100605A	1.497*	-113.051	117.0
#9	110503A	1.613	80.335	63.2
#11	110531A	1.497*	185.146	88.4
#12	110625B	1.497*	160.909	104.1
#19	111229A	1.3805	73.960	71.5
#26	120219A	1.497*	229.039	210.0
#33	121023A	0.6*	-171.072	384.7
#40	130730A	1.497*	-179.641	157.3
#42	131118A	1.497*	-146.960	76.3

Table 2. GRB candidates for the four events of PeV neutrinos.

event	E (PeV)	GRB	z	Δt_{obs} (10^3 s)
#14	1.04	110725A†	2.15*	1320.217
		110730A	2.15*	907.885
		110731A	2.83	782.096
		110808B	0.5*	74.303
		110905A	2.15*	-2309.121
#20	1.14	111229A	1.3805	384.970
		120119C†	2.15*	-1940.176
		120210A	0.5*	-3304.901
#35	2.0	120919A	2.15*	6539.722
		121229A	2.707	-2091.621
		130121A†	2.15*	-4046.519
ATel #7856	2.6	140427A†	2.15*	3827.439
		140516B	2.15*	2185.942

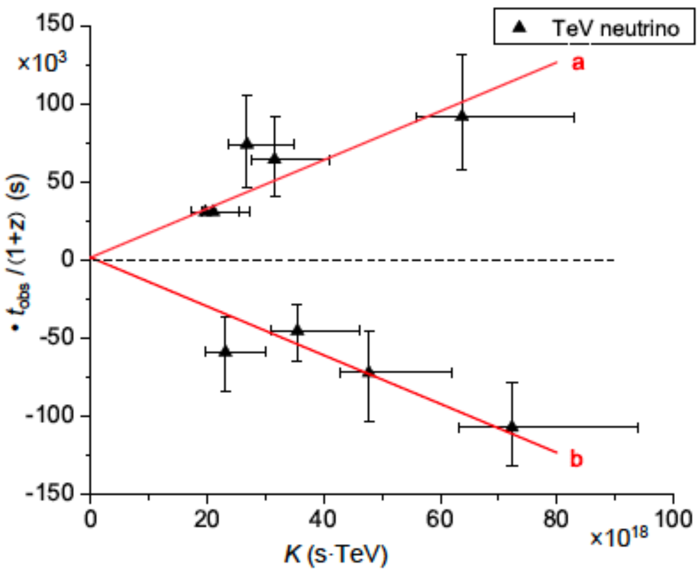
Selection/interpretation of events ?

Leads to "observed LV & CPTV" with scale

$$E_{LV} = (6.5 \pm 0.4) \times 10^{17}\ \text{GeV}$$

BUT...

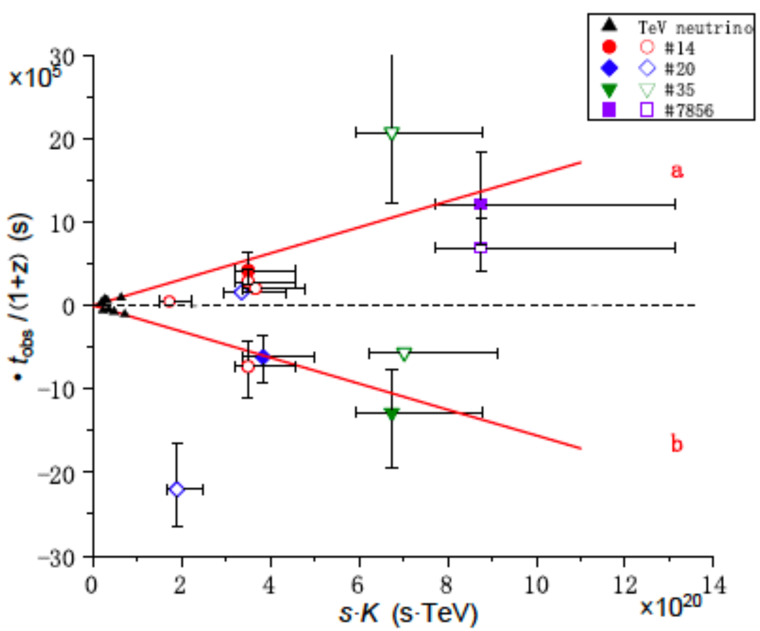
Zhang & B.Q. Ma, **Communications Physics 1 (2018) 62**



TeV events

Different signs of slopes may be the result of intrinsic distinction between neutrino & antineutrino

?



PeV events

BUT SUCH AN INTERPRETATION IS **NOT CONFIRMED BY EXPERIMENT**

CRUCIAL FOR THE CLAIM HENCE **ISSUE WIDE OPEN**

A different technique for probing Neutrino LIV Modified Dispersion Relations

$$v_g/c = 1 \pm (E/M_{\nu \mathrm{LV} l})^l \ , \quad l = 1 \text{ or } 2$$

Probing them from Core-Collapse Supernovae (SN)

Ellis, Harries, Meregaglia, Andre Rubbia, Sakharov
Phys.Rev. D78 (2008) 033013

Ellis, Janka, N.E.M, Sakharov, Sarkisyan
Phys.Rev. D85 (2012) 045032

Limits on $M_{\nu LVl}$ can be imposed by **demanding** that narrow peaks in neutrino emission from SN **not be broadened** significantly

ESSENTIAL IN THE ANALYSIS: Use (2D) simulations of SN explosion
Marek, Janka, Muller, **Astron. & Astrophys. 496, 475 (2009)**
Lund, Marek, Lunardini, Janka and Raffelt, **Phys. Rev. D 82 (2010) 063007**

Dispersion of a wave packet

$$|f(x,t)|^2 = \frac{A^2}{\sqrt{1+\frac{\alpha^2 t^2}{(\Delta x_0)^4}}} \exp\left\{-\frac{(x-v_g t)^2}{2(\Delta x_0)^2\left[1+\frac{\alpha^2 t^2}{(\Delta x_0)^4}\right]}\right\}$$

Parametrise for massive neutrinos of small mass *m* *with* ***LIV Modified Dispersion***

$$\alpha = \frac{m^2}{\kappa^3} - l\,(l+1)\frac{\kappa^{\,l-1}}{M^l_{\nu \mathrm{LV}\, l}}$$

Another effect (non-critical string space-time foam): **Stochastic quantum fluctuations of light cone**

Neutrino wave-packet

$$\mathcal{P}(t) \sim e^{-\frac{(t-t_0)^2}{2\sigma^2}}$$

$$\sigma^2 = \sigma_0^2 + c_1^2 \frac{E^{\,l}}{M^{\,l}_{\nu\,\widetilde{\mathrm{LV}l}}}\,, \quad l = 0 \text{ or } 1$$

Use Wavelet analysis techniques to analyse the neutrino time series genersated by the simulated SN neutrino explosion → time variation a few miliseconds

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2}$$

Wavelet trasnsform

$$W_n(s) = \Sigma_{n'=0}^{N-1} x_{n'} \psi^* \left[\frac{(n'-n)\delta t}{s} \right]$$

wavelet scale

$$\psi\left[\frac{(n'-n)\delta t}{s}\right] = \sqrt{\frac{\delta t}{s}}\ \psi_0\left[\frac{(n'-n)\,\delta t}{s}\right]$$

Wavelet power spectrum

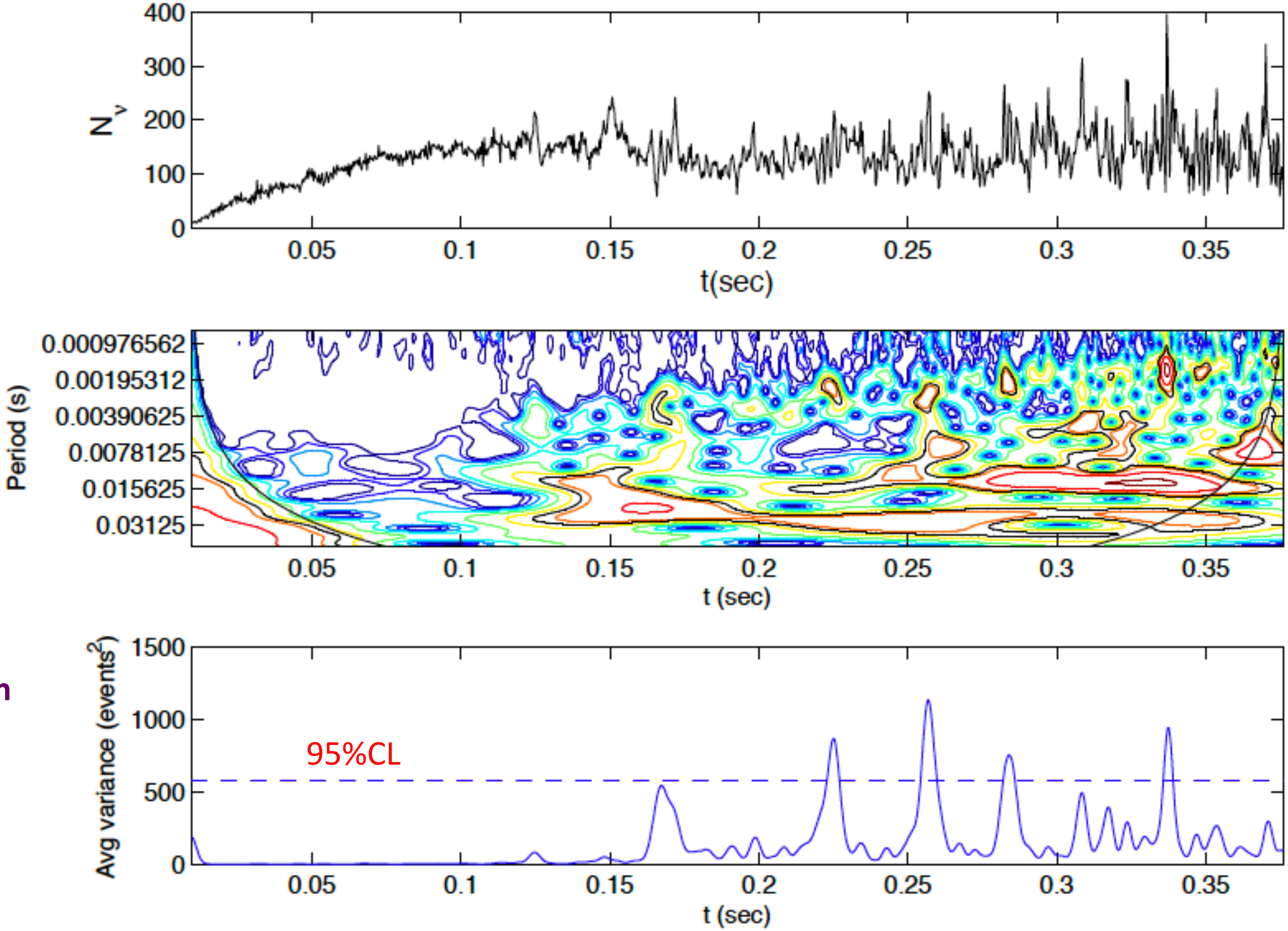
$$|W_n(s)|^2.$$

white noise $|W_n(s)|^2 = \sigma^2$

2D simulated ν time series

Local wavelet power spectrum normalised by $1/\sigma^2$

Average power in a 0.002-0.003 s band

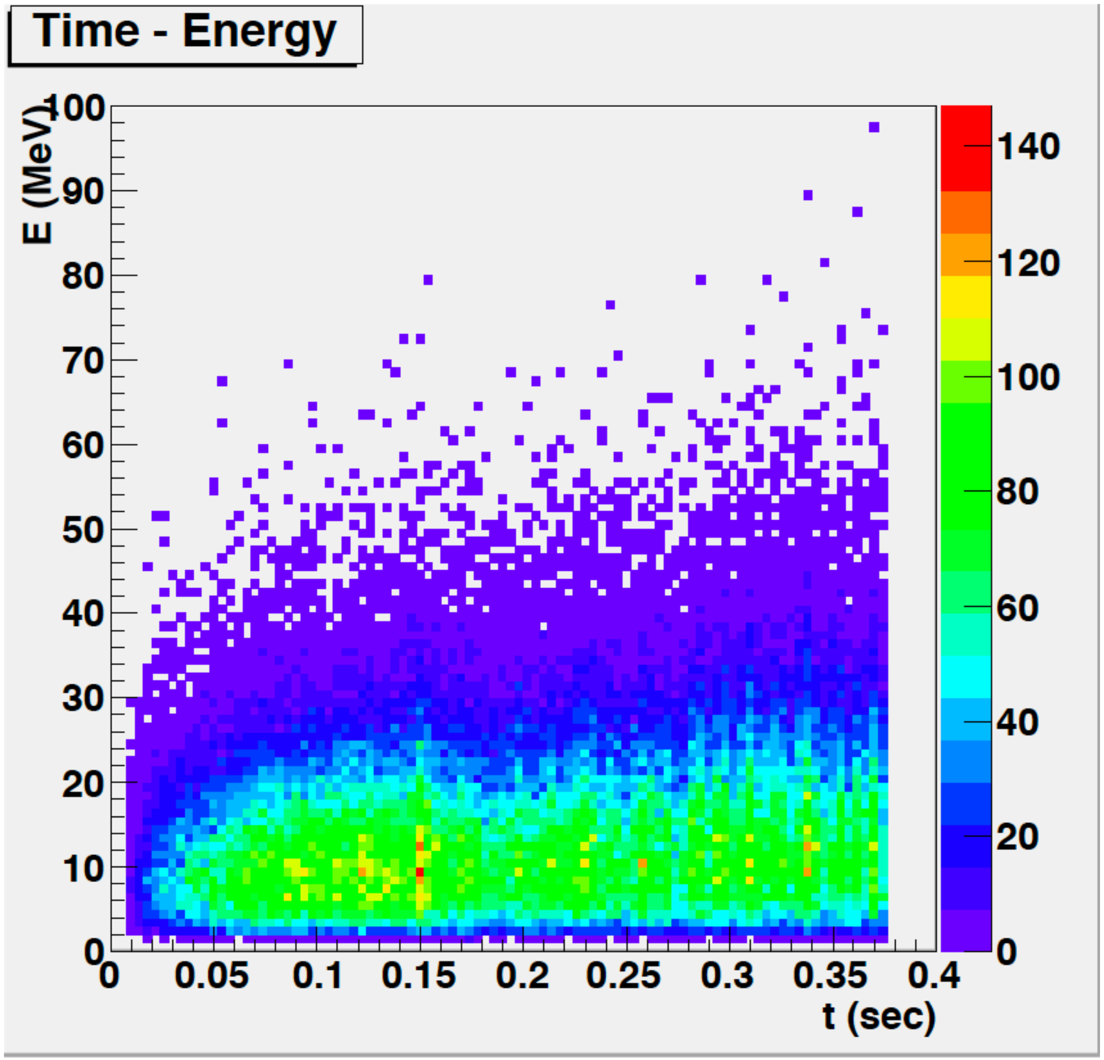


time of ν emission

Ellis, Janka, NEM, Sakharov,Sarkisyan
Phys.Rev. D85 (2012) 045032

2D simulated SN explosion

Distribution of
Energies and times assigned
to individual neutrinos in one
statistical realisation of the
thermal spectra found in
the simulation



Marek, Janka, Muller, **Astron. & Astrophys. 496, 475 (2009)**
Lund, Marek, Lunardini, Janka and Raffelt, **Phys. Rev. D 82 (2010) 063007**

Strength of time-scale averaged between 0.002-0.003 s **after adding**, e.g. a linear energy dependent **time shift**

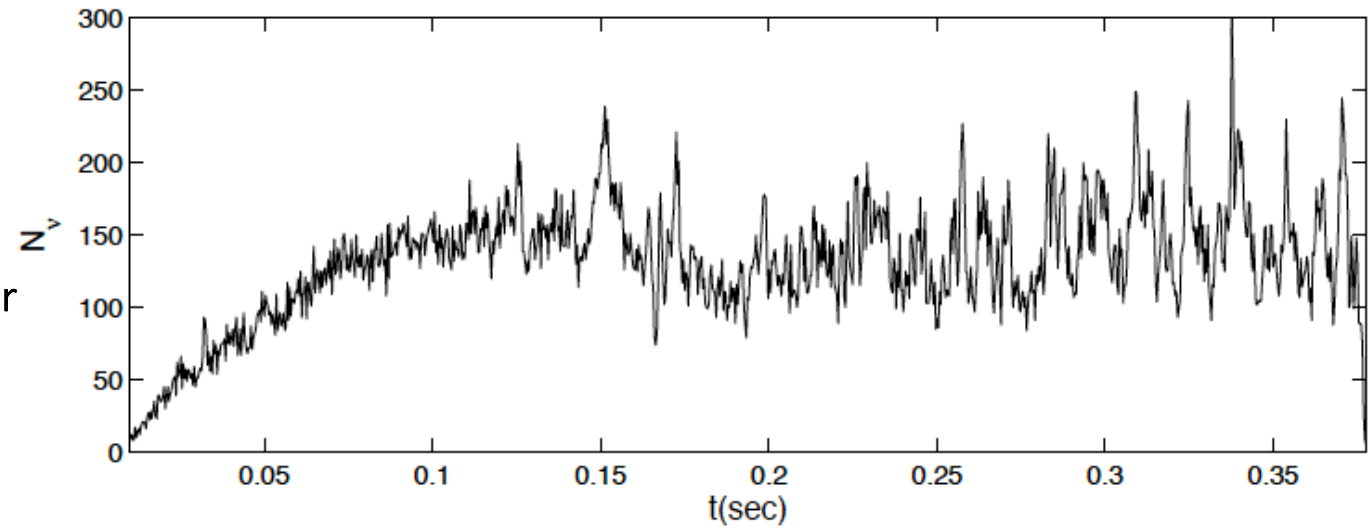
$$\Delta t = \tau_l E^l, \qquad l=1$$

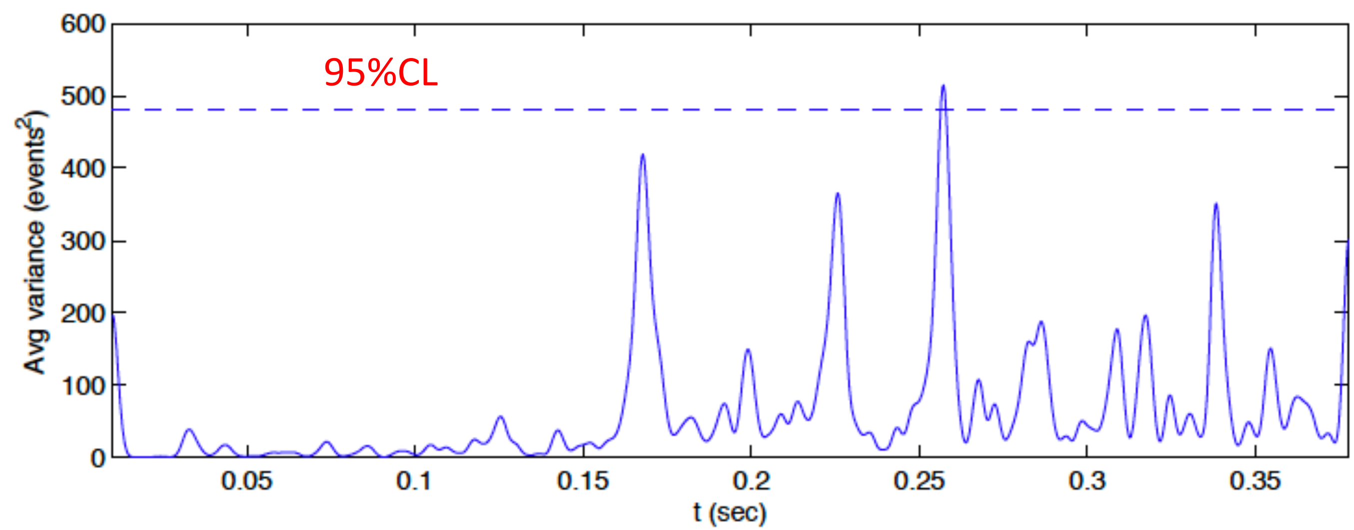
$$\tau_l = \frac{L}{c M^l_{\nu LVl}},$$

$$\tau_1 = 4.2 \times 10^{-5}\ (s/MeV)$$

It **disappears** below 95% C.L. of singificance

→ lower bound on $M^1_{\nu LV1}$ *scale*





Results – simulated SN explosion @ 10 kpc

$$\frac{v_{g\nu}}{c} = 1 \pm \left(\frac{E}{M_{\nu \mathrm{LV}\frac{1}{2}}}\right)^{1/2} \longrightarrow M_{\nu \mathrm{LV}\frac{1}{2}} > 1.11\,[1.07] \times 10^{22}\ \mathrm{GeV}$$

$$\frac{v_{g\nu}}{c} = 1 \pm \frac{E}{M_{\nu \mathrm{LV}1}}, \longrightarrow M_{\nu \mathrm{LV}1} > 2.68\,[2.61] \times 10^{13}\ \mathrm{GeV}$$

$$\frac{v_{g\nu}}{c} = 1 \pm \left(\frac{E}{M_{\nu \mathrm{LV}2}}\right)^{2}. \longrightarrow M_{\nu \mathrm{LV}2} > 0.97\,[0.96] \times 10^{6}\ \mathrm{GeV}$$

Applied to each neutrino event a time shift $\Delta t = \tau_l E^l, \quad \tau_l = \frac{L}{c M^l_{\nu \mathrm{LV}l}}, \quad l = \frac{1}{2}, 1, 2.$

$$\mathcal{P}(t^{\mathrm{stoch}}) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(t^{\mathrm{stoch}} - t)^2}{2\sigma^2}\right] \longrightarrow \begin{array}{l} M_{\nu \widetilde{\mathrm{LV}1}} > 4.78 \times 10^{13}\ \mathrm{GeV} \\ M_{\nu \widetilde{\mathrm{LV}2}} > 1.04 \times 10^{6}\ \mathrm{GeV} \end{array}$$

$$\sigma = \gamma_l E^l \qquad l = 0, 1, \text{ and } 2.$$

Exploit the **short time variations the SN core-collapse simulations** indicate to **probe NEUTRINO MASSES**

Ellis, Janka, NEM, Sakharov,Sarkisyan
Phys.Rev. D85 (2012) 105028

$$\frac{v_\nu}{c} = 1 - \left(\frac{E}{m_\nu}\right)^2$$

Use again Wavelet transforms

apply to each neutrino event a time shift

$$\Delta t = \frac{\tau_m}{E^2}, \qquad \tau_m = \frac{L m_\nu^2}{c}$$

If time structures as the ones in the simulation were to be seen **by ICE CUBE or water Cherenkov low-energy detector** then $m_\nu \; < \; 0.14 \text{ eV}.$

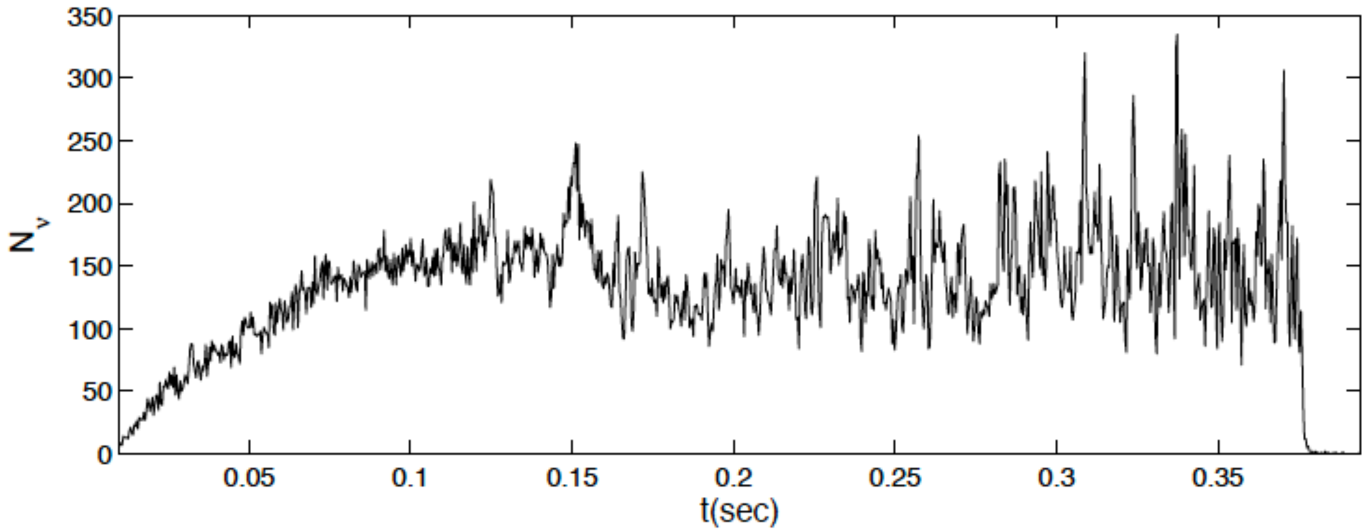
Strength of time-scale averaged between 0.002-0.003 s **after adding**, e.g. a linear energy dependent **time shift**

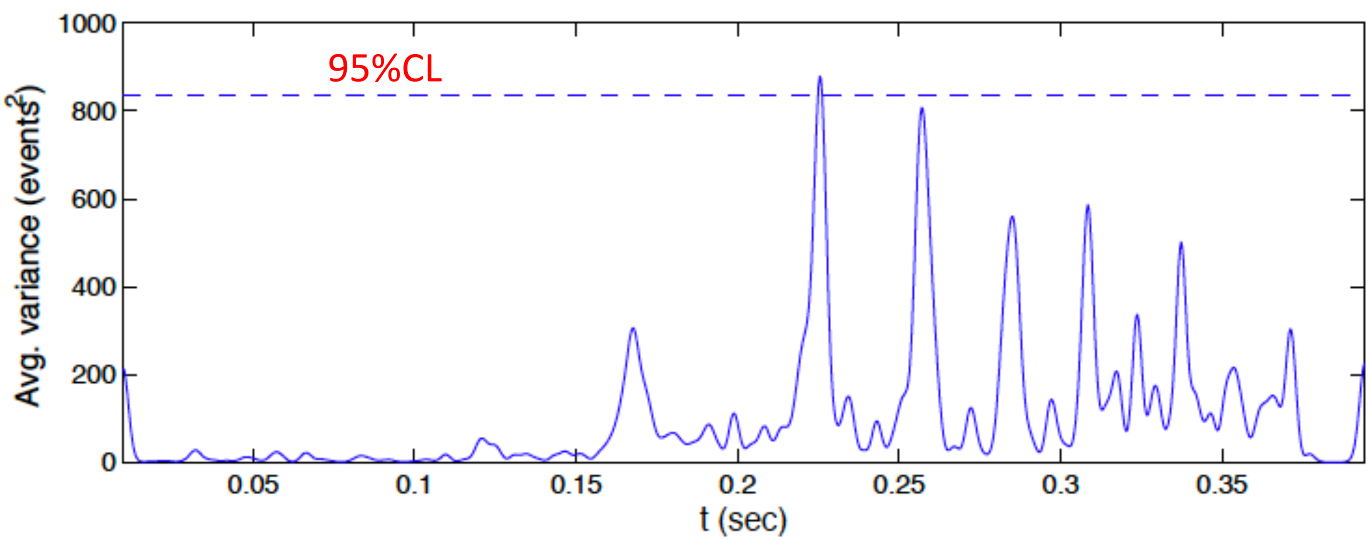
$$\Delta t = \frac{\tau_m}{E^2}, \quad \tau_m = \frac{L m_\nu^2}{c}$$

τ_m = 0.019 s MeV^2

It **disappears** below 95% C.L. of singificance

→ bound on neutrino mass





Ellis, Janka, NEM, Sakharov,Sarkisyan
Phys.Rev. D85 (2012) 105028

Exploit the **short time variations the SN core-collapse simulations** indicate to **probe NEUTRINO MASSES**

Ellis, Janka, NEM, Sakharov,Sarkisyan
Phys.Rev. D85 (2012) 105028

$$\frac{v_\nu}{c} = 1 - \left(\frac{E}{m_\nu}\right)^2$$

Use again Wavelet transforms

apply to each neutrino event a time shift

$$\Delta t = \frac{\tau_m}{E^2}, \qquad \tau_m = \frac{L m_\nu^2}{c}$$

If time structures as the ones in the simulation were to be seen **by ICE CUBE or water Cherenkov low-energy detector** then $m_\nu < 0.14 \text{ eV}.$

If **not** then $m_\nu \gtrsim 0.14 \text{ eV}$

(still consistent with earlier (< Plnack 2018) cosmological limit $m_\nu < 0.23 \text{ eV}$)

BUT Planck 2018 results combined with BAO imply $\sum_\nu m_\nu < 0.12\text{eV}$

assuming base-ΛCDM cosmology

QG Decoherence & Neutrinos

- Stochastic (quantum) metric fluctuations in Dirac or Majorana Hamiltonian for neutrinos affect oscillation probabilities by **damping exponential factors** – characteristic of **decoherence**

- **Quantum Gravitational MSW effect**

- Precise form of neutrino energy dependence of damping factors linked to specific model of foam

Stochastic QG metric fluctuations

$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

$\langle h_{\mu\nu} \rangle = 0$

$\langle h_{\mu\nu} h_{\rho\sigma} \rangle$ are non trivial

Consider Dirac or Majorana (two-flavour) Hamiltonian with mixing , in such a metric background, with equation of motion

$$(i\gamma^\alpha \mathcal{D}_\alpha - M)\,\Psi = 0$$

$$M = \begin{pmatrix} m_e & m_{e\mu} \\ m_{e\mu} & m_\mu \end{pmatrix} \qquad \begin{pmatrix} \psi_e \\ \psi_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

Flavour states

$$\tan(2\theta) = \frac{2m_{e\mu}}{m_\mu - m_e}$$

Mass eigenstates

$$|\psi_\alpha\rangle = \sum_i U_{\alpha i} |\psi_i\rangle$$

Oscillation Probability

$$\langle \mathrm{Prob}(\alpha \to \beta) \rangle = \sum_{i,j} U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j} \langle e^{i(\omega_i - \omega_j)t} \rangle$$

Stochastic QG metric fluctuations

Oscillation Probability

$$\langle \text{Prob}(\alpha \to \beta) \rangle = \frac{1}{2}\sin^2(2\theta)\left(1 - e^{-\chi(t)}\cos(at)\right)$$

Two kinds of foam examined:

NEM, Sarkar , Alexandre, Farakos, Pasipoularides

(i) Gaussian distributions

$$f(x) = \frac{e^{-x^2/\sigma^2}}{\sqrt{\pi\sigma^2}}$$

$$\langle e^{i(\omega_1-\omega_2)t} \rangle \simeq \exp\left\{ikt\Delta\left(1 - \frac{m_1^2+m_2^2}{4k^2}\right)\right\}\exp\left\{-\frac{\sigma^2(kt)^2}{8}\Delta^2\right\}$$

(ii) Cauchy-Lorentz

$$f(x) = \frac{1}{\pi}\frac{\gamma}{x^2+\gamma^2}$$

$$\Delta = \frac{m_1^2 - m_2^2}{2k^2} << 1$$

$$\langle e^{i(\omega_1-\omega_2)t} \rangle \simeq \exp\left\{ikt\Delta - \gamma kt|\Delta|\right\}$$

NB: damping suppressed by neutrino mass differences

Stochastic QG metric fluctuations

Oscillation Probability

$$\langle \mathrm{Prob}(\alpha \to \beta) \rangle = \frac{1}{2}\sin^2(2\theta)\left(1 - e^{-\chi(t)}\cos(at)\right)$$

Two kinds of foam examined:

NEM, Sarkar , Alexandre, Farakos, Pasipoularides

(i) Gaussian distributions

$$f(x) = \frac{e^{-x^2/\sigma^2}}{\sqrt{\pi\sigma^2}}$$

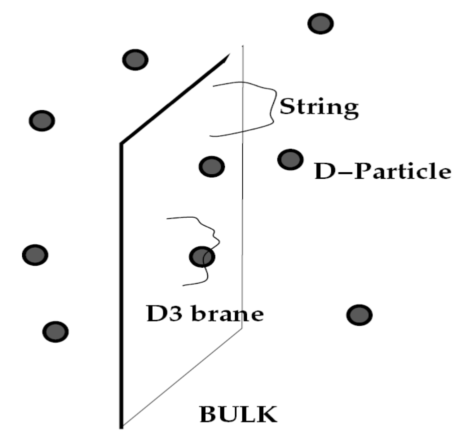
$$\langle e^{i(\omega_1 - \omega_2)t} \rangle \simeq \exp\left\{ikt\Delta\left(1 - \frac{m_1^2 + m_2^2}{4k^2}\right)\right\}\exp\left\{-\frac{\sigma^2 (kt)^2}{8}\Delta^2\right\}$$

(ii) Cauchy-Lorentz

$$f(x) = \frac{1}{\pi}\frac{\gamma}{x^2 + \gamma^2}$$

$$\Delta = \frac{m_1^2 - m_2^2}{2k^2} << 1$$

$$\langle e^{i(\omega_1 - \omega_2)t} \rangle \simeq \exp\left\{ikt\Delta - \gamma kt|\Delta|\right\}$$



NB: In D-particle foam model, $h_{0i}\, n = u_i$ involves recoil velocity distribution of D-particle populations .

Quantum Gravitational MSW Effect

$$H_{\text{eff}} = H + n^{\text{c}}_{\text{bh}}(r) H_I$$

n^c_{bh} Black Hole density in foam

$$H_I = \begin{pmatrix} a_{\nu_\mu} & 0 \\ 0 & a_{\nu_\tau} \end{pmatrix}$$

$$\langle n^c_{\text{bh}}(t) \rangle = n_0$$

$$\langle n^c_{bh}(t) n^c_{bh}(t') \rangle \sim \Omega^2 n_0^2 \delta(t - t')$$

Neutrino density matrix evolution is of Lindblad decoherence type:

$$\frac{\partial}{\partial t}\langle \rho \rangle = -i[H + n_0 H_I, \langle \rho \rangle] - \Omega^2 n_0^2 [H_I, [H_I, \langle \rho \rangle]]$$

Barenboim, NM, Sarkar, Waldron-Lauda

Quantum Gravitational MSW Effect

$$H_{\rm eff} = H + n^{\rm c}_{\rm bh}(r) H_I$$

n^c_{bh} Black Hole density in foam

$$H_I = \begin{pmatrix} a_{\nu_\mu} & 0 \\ 0 & a_{\nu_\tau} \end{pmatrix}$$

$$\langle n^c_{\rm bh}(t) \rangle = n_0$$

$$\langle n^c_{bh}(t) n^c_{bh}(t') \rangle \sim \Omega^2 n_0^2 \delta(t - t')$$

Neutrino density matrix evolution is of Lindblad decoherence type:

$$\frac{\partial}{\partial t}\langle \rho \rangle = -i[H + n_0 H_I, \langle \rho \rangle] - \Omega^2 n_0^2 [H_I, [H_I, \langle \rho \rangle]]$$

CPT Violating (time irreversible, CP symmetric) + **LIV**

Barenboim, NEM, Sarkar, Waldron-Lauda

Quantum Gravitational MSW Effect

OSCILLATION PROBABILITY:

$$P_{\nu_\mu \to \nu_\tau} =$$

$$\frac{1}{2} + e^{-\Delta a_{\mu\tau}^2 \Omega^2 t \left(1 + \frac{\Delta_{12}^2}{4\Gamma}(\cos(4\theta)-1)\right)} \sin(t\sqrt{\Gamma}) \sin^2(2\theta) \Delta a_{\mu\tau}^2 \Omega^2 \Delta_{12}^2 \left(\frac{3\sin^2(2\theta)\Delta_{12}^2}{4\Gamma^{5/2}} - \frac{1}{\Gamma^{3/2}} \right)$$

$$- e^{-\Delta a_{\mu\tau}^2 \Omega^2 t \left(1 + \frac{\Delta_{12}^2}{4\Gamma}(\cos(4\theta)-1)\right)} \cos(t\sqrt{\Gamma}) \sin^2(2\theta) \frac{\Delta_{12}^2}{2\Gamma}$$

$$- e^{-\frac{\Delta a_{\mu\tau}^2 \Omega^2 t \Delta_{12}^2 \sin^2(2\theta)}{\Gamma}} \frac{(\Delta a_{\mu\tau} + \cos(2\theta)\Delta_{12})^2}{2\Gamma}$$

$$\Gamma = (\Delta a_{\mu\tau}\cos(2\theta) + \Delta_{12})^2 + \Delta a_{\mu\tau}^2 \sin^2(2\theta) \;,\; \Delta_{12} = \frac{\Delta m_{12}^2}{2k} \text{ and } \Delta a_{\mu\tau} \equiv a_{\nu_\mu} - a_{\nu_\tau}$$

$$\text{exponent} \sim -\Delta a_{\mu\tau}^2 \Omega^2 t f(\theta) \;;\; f(\theta) = 1 + \frac{\Delta_{12}^2}{4\Gamma}(\cos(4\theta) - 1) \;,\; \text{or } \frac{\Delta_{12}^2 \sin^2(2\theta)}{\Gamma}$$

Quantum Gravitational MSW Effect

OSCILLATION PROBABILITY:

$$P_{\nu_\mu \to \nu_\tau} =$$

$$\frac{1}{2} + e^{-\Delta a_{\mu\tau}^2 \Omega^2 t (1 + \frac{\Delta_{12}^2}{4\Gamma}(\cos(4\theta)-1))} \sin(t\sqrt{\Gamma}) \sin^2(2\theta) \Delta a_{\mu\tau}^2 \Omega^2 \Delta_{12}^2 \left(\frac{3\sin^2(2\theta)\Delta_{12}^2}{4\Gamma^{5/2}} - \frac{1}{\Gamma^{3/2}} \right)$$

$$+ e^{-\Delta a_{\mu\tau}^2 \Omega^2 t (1 + \frac{\Delta_{12}^2}{4\Gamma}(\cos(4\theta)-1))} \cos(t\sqrt{\Gamma}) \sin^2(2\theta) \frac{\Delta_{12}^2}{2\Gamma}$$

$$- e^{-\frac{\Delta a_{\mu\tau}^2 \Omega^2 t \Delta_{12}^2 \sin^2(2\theta)}{\Gamma}} \frac{(\Delta a_{\mu\tau} + \cos(2\theta)\Delta_{12})^2}{2\Gamma}$$

$$\Gamma = (\Delta a_{\mu\tau} \cos(2\theta) + \Delta_{12})^2 + \Delta a_{\mu\tau}^2 \sin^2(2\theta) \ , \ \Delta_{12} = \frac{\Delta m_{12}^2}{2k} \text{ and } \Delta a_{\mu\tau} \equiv a_{\nu_\mu} - a_{\nu_\tau}$$

$$\text{exponent} \sim -\Delta a_{\mu\tau}^2 \Omega^2 t f(\theta) \ ; \ f(\theta) = 1 + \frac{\Delta_{12}^2}{4\Gamma}(\cos(4\theta) - 1) \ , \ \text{or} \ \frac{\Delta_{12}^2 \sin^2(2\theta)}{\Gamma}$$

Damping suppressed by neutrino-flavour MSW-coupling differences

Quantum Gravitational MSW Effect

Experimental Bounds

Lindblad-type decoherence Damping:

Fogli, Lisi, Marrone, Montanino, Palazzo

$$e^{-\gamma t} \quad \gamma = \gamma_{\rm Lnb} \left(\frac{E}{\rm GeV}\right)^n$$

t = L (Oscillation length, (c=1)

$$\gamma_{\rm Lnb} < 0.4 \times 10^{-22}\ {\rm GeV}\ , \quad n = 0$$

$$\gamma_{\rm Lnb} < 0.9 \times 10^{-27}\ {\rm GeV}\ , \quad n = 2$$

$$\gamma_{\rm Lnb} < 0.7 \times 10^{-21}\ {\rm GeV}\ , \quad n = -1$$

Including LSND & KamLand Data:

$$\gamma L \sim 1.5. \cdot 10^{-2}$$

Best fits

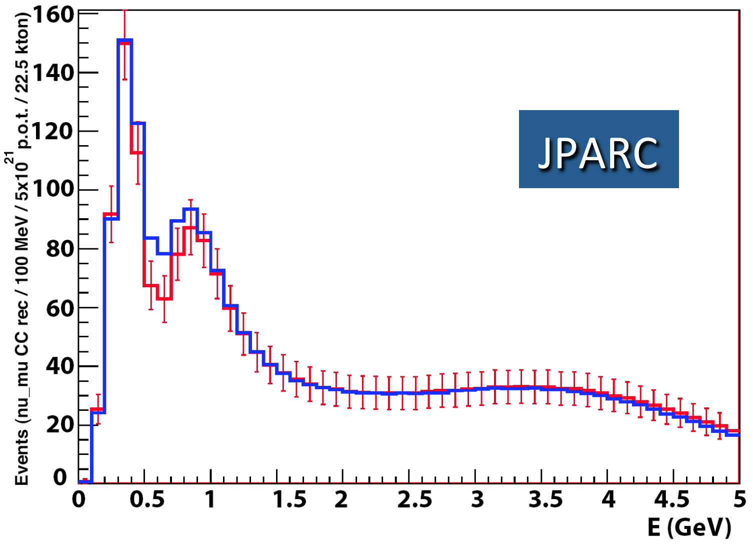
Beyond Lindblad: stochastic metric Fluctuations damping: $e^{-\mathcal{D}L^2}$

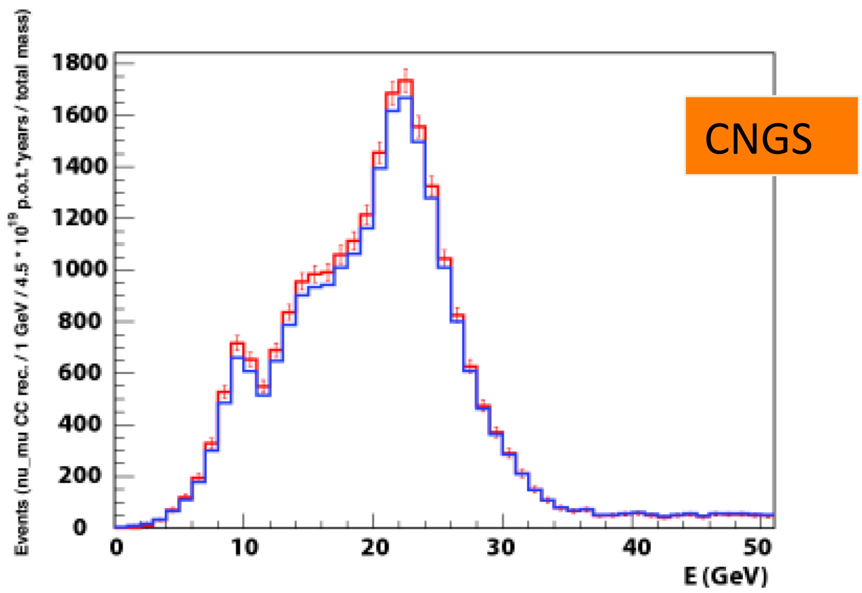
$$\mathcal{D}L^2 \sim 1.5. \cdot 10^{-2}$$

Barenboim, NM, Sarkar, Waldron-Lauda

Potential of J-PARC, CNGS

NEM, Sakharov, Meregaglia, Rubbia, Sarkar





$$\langle P_{\alpha\beta}\rangle = \delta_{\alpha\beta} -$$

$$2\sum_{a=1}^{n}\sum_{b=1,a<b}^{n} \mathrm{Re}\left(U^*_{\alpha a}U_{\beta a}U_{\alpha b}U^*_{\beta b}\right)\left(1-\cos(2\ell\Delta m^2_{ab})e^{-q_1 L - q_2 L^2}\right)$$

$$-\,2\sum_{a=1}^{n}\sum_{b=1,a<b}^{n} \mathrm{Im}\left(U^*_{\alpha a}U_{\beta a}U_{\alpha b}U^*_{\beta b}\right)\sin(2\ell\Delta m^2_{ab})e^{-q_1 L - q_2 L^2}$$

$$\text{with} \qquad \ell \equiv \frac{L}{4E}$$

Potential of J-PARC, CNGS

Lindblad-type mapping operators	CNGS	T2K	T2KK
γ_0 [eV] ; ([GeV])	2×10^{-13} ; (2×10^{-22})	2.4×10^{-14} ; (2.4×10^{-23})	1.7×10^{-14} ; (1.7×10^{-23})
γ_{-1}^2 [eV^2] ; ([GeV^2])	9.7×10^{-4} ; (9.7×10^{-22})	3.1×10^{-5} ; (3.1×10^{-23})	6.5×10^{-5} ; (6.5×10^{-23})
γ_2 [eV^{-1}] ; ([GeV^{-1}])	4.3×10^{-35} ; (4.3×10^{-26})	1.7×10^{-32} ; (1.7×10^{-23})	3.5×10^{-33} ; (3.5×10^{-24})
Gravitational MSW (stochastic) effects	**CNGS**	**T2K**	**T2KK**
α^2	4.3×10^{-13} eV	4.6×10^{-14} eV	3.5×10^{-14} eV
α_1^2	1.1×10^{-25} eV^2	3.2×10^{-26} eV^2	6.7×10^{-27} eV^2
β^2	3.6×10^{-24}	5.6×10^{-23}	1.7×10^{-23}
β_2^2	9.8×10^{-37} eV	4×10^{-35} eV	3.1×10^{-36} eV
β_1^2	8.8×10^{-35} eV^{-1}	3.5×10^{-32} eV^{-1}	7.2×10^{-33} eV^{-1}

TABLE I: Expected sensitivity limits at CNGS, T2K and T2KK to one parametric neutrino decoherence for Lindblad type and gravitational MSW (stochastic metric fluctuation) like operators.

`Truly multimessenger LV Tests:
Coincident observations of
High energy cosmic neutrinos & photons

IceCube and Fermi-LAT and MAGIC and AGILE and ASAS-SN and HAWC and H.E.S.S. and INTEGRAL and Kanata and Kiso and Kapteyn and Liverpool Telescope and Subaru and Swift NuSTAR and VERITAS and VLA/17B-403 Collaborations],
[arXiv:1807.08816 [astro-ph.HE]].

ICE CUBE Collaboration has reported the observation of an ***ultra- high-energy single neutrino beam*** **with energy 290 TeV (90% CL lower limit 183 TeV)/*IceCube-170922A*** from the direction of the **blazar TXS 0506+056**, ***at a distance 4 x 10^9 ly*** (redshift z = 0. 3365± 0.0010).

Together with a number of other groups, most notably the **MAGIC Collaboration**, have reported an enhanced level of activity in **γ-ray and photon emission** from ***this source***.
TXS 0506+056 was in a period of **flaring state** for about **Δt_{flare} ~ 10 days**

→ **if ν & γ emitted simultaneously** → $\Delta v_{\nu\gamma}/c \sim 10 \text{ days}/4\times 10^9 \text{ years} \sim 10^{-11}$

Rough estimates ignoring Universe expansion effects

vacuum speed diff. between
ν & γ assumed energy independent
(e.g. **Coleman-Glashow models**)

NB: from neutron star merger $\Delta v_{GW\gamma} \lesssim 10^{-17}$

IceCube and Fermi-LAT and MAGIC and AGILE and ASAS-SN and HAWC and H.E.S.S. and INTEGRAL and Kanata and Kiso and Kapteyn and Liverpool Telescope and Subaru and Swift NuSTAR and VERITAS and VLA/17B-403 Collaborations],
[arXiv: 1807.08816 [astro-ph.HE].

ICE CUBE Collaboration has reported the observation of an ***ultra- high-energy single neutrino beam*** **with energy 290 TeV (90% CL lower limit 183 TeV)/*IceCube-170922A*** from the direction of the **blazar TXS 0506+056**, ***at a distance 4 x 10^9 ly*** (redshift z = 0. 3365± 0.0010).

Together with a number of other groups, most notably the **MAGIC Collaboration**, have reported an enhanced level of activity in **γ-ray and photon emission** from ***this source***.
TXS 0506+056 was in a period of **flaring state** for about **Δt_{flare} ~ 10 days**

→ BUT IF **DISPERSION RELATIONS modified linearly** due to QG foam,
then scale of modifications might be different for ν & γ → $\Delta v_{\nu\gamma} = -E/M_1$
M_1 the lowest scale, e.g. in stringy models of D-foam $M_{1,\nu} \gg M_{1,\gamma}$

If ν & γ emitted simultaneously → sensitivity

$$M_1 \gtrsim \frac{H_0^{-1}}{\Delta t} E \int_0^{z_{\rm src}} \frac{(1+z)}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \approx 3 \times 10^{16}\ {\rm GeV}$$

weaker (by an order of mag) than $M_{1\gamma}$ photons from GRBs hence if true would refers directly to ν

IceCube and Fermi-LAT and MAGIC and AGILE and
ASAS-SN and HAWC and H.E.S.S. and INTEGRAL and Kanata and Kiso and
Kapteyn and Liverpool Telescope and Subaru and Swift NuSTAR and VERITAS
and VLA/17B-403 Collaborations],
[arXiv:1807.08816 [astro-ph.HE].

ICE CUBE Collaboration has reported the observation of an ***ultra- high-energy single neutrino beam*** **with energy 290 TeV (90% CL lower limit 183 TeV)/*IceCube-170922A*** from the direction of the **blazar TXS 0506+056**, ***at a distance 4 x 10^9 ly*** (redshift $z = 0.3365 \pm 0.0010$).

Together with a number of other groups, most notably the **MAGIC Collaboration**, have reported an enhanced level of activity in **γ-ray and photon emission** from ***this source***.
TXS 0506+056 was in a period of **flaring state** for about **Δt_{flare} ~ 10 days**

→ BUT IF **DISPERSION RELATIONS modified quadratically** due to QG foam:

If ν & γ emitted simultaneously → sensitivity

$$M_2 \gtrsim \left[\frac{3}{2} \frac{H_0^{-1}}{\Delta t} E^2 \int_0^{z_{src}} \frac{(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \right]^{1/2} \approx 10^{11} \text{ GeV}$$

stronger (by 7 orders of mag) than $M_{2\nu}$ from SN1987A and > 5 orders from potential sensitivity of future galactic SN events

Other important multimessenger observations :

Using Gravitational Waves to constrain Lorentz violation in graviton propagation, and, say, coincident transient photon sources to constrain

$$c_{GW} - c_{\gamma}$$

Ellis, NEM, Nanopoulos
MPLA31 (2016) no.26, 1675001

e.g. using GW150914 signal and apparently coincident flash of photons with energies > 50 keV observed
0.4 s later by FERMI-LAT (but signal is questioned)
and ignoring source mechanisms (which might be impotant) we get an upper bound for propagation speeds (c = light speed in vacuo)

$$c_{GW} - c_{\gamma} \lesssim 10^{-17}\, c$$

Non observaton of gravitational Cherenkov radiation from high energy cosmic rays (CR) implies:

Moore & Nelson
JHEP 0109, 023 (2001)

$$c_{\gamma} - c_{GW} \lesssim 2 \times 10^{-19}\, c_{\gamma} \quad \text{(Extragalactic origin CR)}$$
$$2 \times 10^{-15}\, c_{\gamma} \quad \text{(Galactic origin CR)}$$

LV Modified Dispersion in GW do not yield strong limits
Using LIGO massive graviton sensitivity for linear DR modification

$$\Delta v|_{LV1} = -\left(\frac{\omega}{M_1}\right) \simeq \Delta v|_{m_g} = -\left(\frac{m_g^2}{2\omega^2}\right)$$

yields M_1 > 100 keV far less than the photon one (~ 10^{19} GeV)

``Smoking-gun'' QG Decoherence

CPT Violating (& LIV) Effects in Entangled Particle States ?

CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell
revisited by:
Greenberg, Chaichian, Dolgov, Novikov, Tureanu…

(ii)-(iv) Independent reasons for violation

CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell **revisited by:** Greenberg, Chaichian, Dolgov, Novikov, Tureanu. .

(ii)-(iv) Independent reasons for violation

CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

(i) Flat space-times

(ii) Lorentz invariance

(iii) Locality

(iv) Unitarity

(ii)-(iii) CPT V well-defined as Operator Θ does not commute with Hamiltonian

$[\Theta, H] \neq 0$

CPT VIOLATION

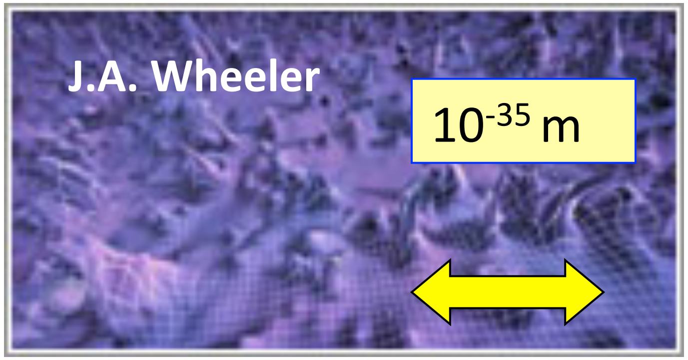
Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

(ii)-(iv) Independent reasons for violation

e.g. ***QUANTUM SPACE-TIME FOAM AT PLANCK SCALES***



CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

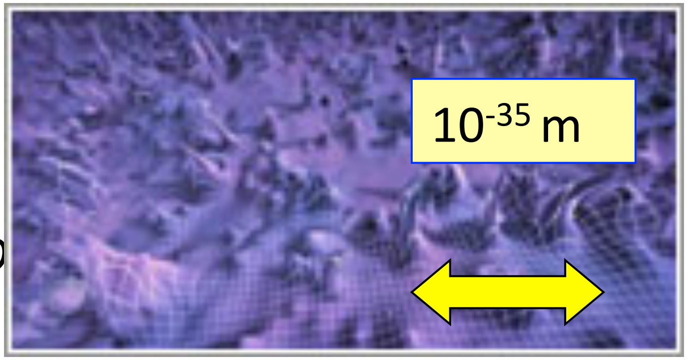
Hawking,
Ellis, Hagelin, Nanopoulos
Srednicki,
Banks, Peskin, Strominger,
Lopez, NEM, Barenboim…

(ii)-(iv) Independent reasons for violation

QUANTUM GRAVITY INDUCED DECOHERENCE
EVOLUTION OF PURE QM STATES TO MIXED
AT LOW ENERGIES

*LOW ENERGY **CPT** OPERATOR **NOT** WELL DEFINED*

cf. ω-effect in EPR entanglement



CPT VIOLATION

Conditions for the Validity of CPT Theorem

CPT Invariance Theorem :
(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

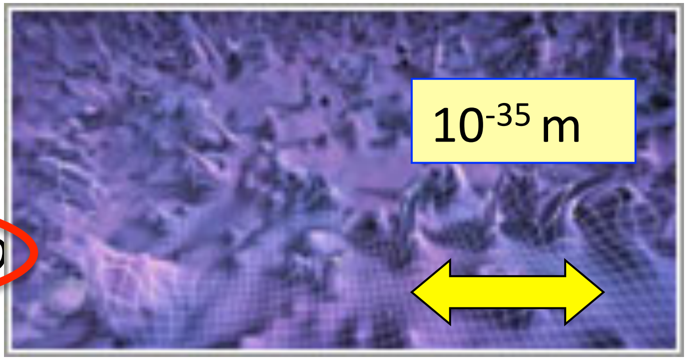
Hawking,
Ellis, Hagelin, Nanopoulos
Srednicki,
Banks, Peskin, Strominger,
Lopez, NEM, Barenboim…

(ii)-(iv) Independent reasons for violation

QUANTUM GRAVITY INDUCED DECOHERENCE
EVOLUTION OF PURE QM STATES TO MIXED
AT LOW ENERGIES

*LOW ENERGY **CPT** OPERATOR **NOT** WELL DEFINED*

cf. ω-effect in EPR entanglement



NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$\rho_{\rm out} = \$\rho_{\rm in}$$

$$\$ \neq S\, S^\dagger$$

$$S = e^{i\int H dt}$$

May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator **Θ** is **not well-defined → beyond Local Effective Field theory**

$$\Theta\rho_{\rm in} = \overline{\rho}_{\rm out}$$

If Θ well-defined can show that $\$^{-1} = \Theta^{-1}\$\Theta^{-1}$ exists !

INCOMPATIBLE WITH DECOHERENCE !

Hence Θ ill-defined at low-energies in QG foam models

Wald (79)

NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

May induce **quantum decoherence** of propagating matter and

intrinsic CPT Violation

in the sense that the CPT operator **Θ** is **not well-defined → beyond Local Effective Field theory**

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$|i\rangle = \mathcal{N}\Big[|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle - |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle + \omega\Big(|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle + |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle\Big)\Big]$$

$$\omega = |\omega|e^{i\vartheta}$$

May contaminate initially antisymmetric neutral meson *M* state by symmetric parts (ω-effect)

Bernabeu, NEM, Papavassiliou (04),…

Hence Θ ill-defined at low-energies in QG foam models → may affect EPR

Wald (79)

NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator **Θ** is **not well-defined →** **beyond Local Effective Field theory**

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$|i\rangle = \mathcal{N}\Big[|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle - |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle + \omega\Big(|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle + |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle\Big)\Big]$$

$$\omega = |\omega| e^{i\vartheta}$$

May contaminate initially antisymmetric neutral meson M state by symmetric parts (ω-effect)

Hence Θ ill-defined at low-energies in QG foam models → may affect EPR

Wald (79)

Bernabeu, NEM, Papavassiliou (04),…

NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

May induce **quantum decoherence** of propagating matter and

intrinsic CP… iolation

in the … CPT … defined → … ield theory

$\rho = \mathrm{Tr}|\psi\rangle\langle$ …

$|i\rangle = $ … $\rangle\, |M_0(-\vec{k})\rangle$

$+\omega\Big(|M$ … $|\bar{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle\Big)\Big]$

$\omega = |\omega| e^{i\vartheta}$

BEYOND LOCAL EFT?

|ω| can be estimated in some string-inspired foam models

…y contaminate initially antisymmetric neutral meson M state by symmetric parts (ω-effect)

Bernabeu, NEM, Papavassiliou (04),…

Hence Θ ill-defined at low-energies in QG foam models → may affect EPR

Wald (79)

NB: Including conventional CPTV (ϑ) in the Hamiltonian

Bernabeu, Botella, NEM, Nebot

$$\mathbf{H}|B_H\rangle = \mu_H|B_H\rangle, \quad |B_H\rangle = p_H|B_d^0\rangle + q_H|\bar{B}_d^0\rangle,$$
$$\mathbf{H}|B_L\rangle = \mu_L|B_L\rangle, \quad |B_L\rangle = p_L|B_d^0\rangle - q_L|\bar{B}_d^0\rangle.$$

H (L) = (High (Low) mass states

$$|\Psi_0\rangle \propto |B_L\rangle|B_H\rangle - |B_H\rangle|B_L\rangle$$
$$+\,\omega\left\{\theta\left[|B_H\rangle|B_L\rangle + |B_L\rangle|B_H\rangle\right] + (1-\theta)\frac{p_L}{p_H}|B_H\rangle|B_H\rangle - (1+\theta)\frac{p_H}{p_L}|B_L\rangle|B_L\rangle\right\}$$

ω-effect

CPTV in Hamiltonian

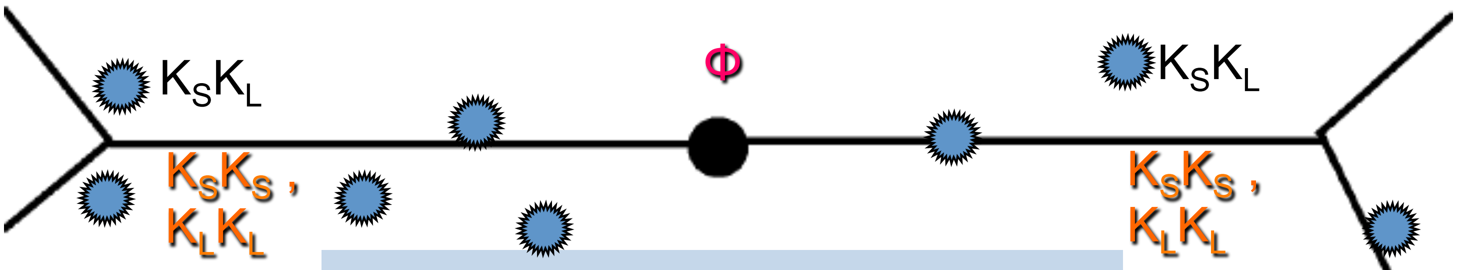
$$\theta = \frac{\mathrm{H}_{22} - \mathrm{H}_{11}}{\mu_H - \mu_L}$$

- Stringy **D-brane defects (D-) foam Models** : Neutral mesons **no** longer **indistinguishable** particles, initial entangled state:

Bernabeu, NEM, Sarkar

$$|i> \;=\; \mathcal{N}\Big[\big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\big) + \omega\big(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\big)\Big]$$

$$\omega = |\omega| e^{i\Omega}$$



IF CPT ILL-DEFINED (e.g. flavour violating (FV) D-particle Foam)

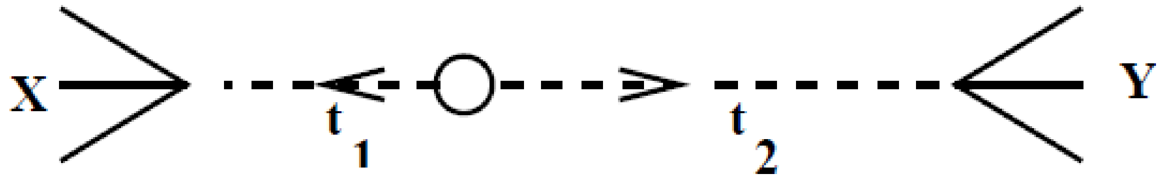
$$|\omega|^2 \sim \frac{\zeta^2\, k^4}{M_{\rm QG}^2 (m_1 - m_2)^2}, \Delta k = \zeta\, k \,(\text{particle momentum transfer})$$

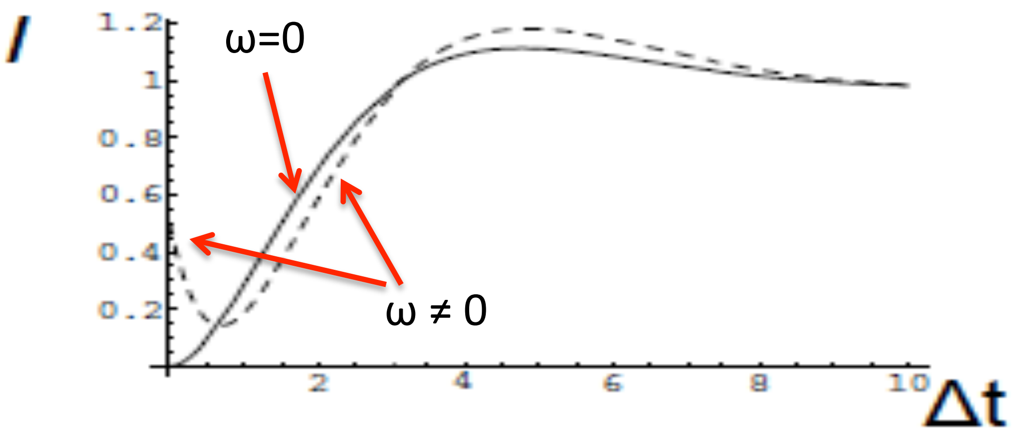
If QCD effects, sub-structure in neutral mesons ignored, and D-foam acts as if they were structureless particles, then for **$M_{QG} \sim 10^{18}$ GeV**
the estimate for ω: **$|\,\omega\,| \sim 10^{-4}\ |\zeta|$,** for $1 > |\zeta| > 10^{-2}$ (natural)
Not far from sensitivity of upgraded meson factories (e.g. **KLOE2**)

ω-effect observables/current bounds

ϕ Decays and the ω Effect

Consider the ϕ decay amplitude: final state X at t_1 and Y at time t_2 ($t = 0$ at the moment of ϕ decay)





I(Δt=0) ≠ 0
if ω-effect present

The "intensity" $I(\Delta t)$: ($\Delta t = t_1 - t_2$) is an observable

$$I(\Delta t) \equiv \frac{1}{2} \int_{|\Delta t|}^{\infty} dt \, |A(X,Y)|^2$$

ω-Effect & Intensities

$$I(\Delta t) \equiv \frac{1}{2}\int_{|\Delta t|}^{\infty} dt\, |A(\pi^+\pi^-,\pi^+\pi^-)|^2 = |\langle\pi^+\pi^-|K_S\rangle|^4 |\mathcal{N}|^2 |\eta_{+-}|^2 \Big[I_1 + I_2 + I_{12}\Big]$$

$$I_1(\Delta t) = \frac{e^{-\Gamma_S \Delta t} + e^{-\Gamma_L \Delta t} - 2e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\Delta M \Delta t)}{\Gamma_L + \Gamma_S}$$

$$I_2(\Delta t) = \frac{|\omega|^2}{|\eta_{+-}|^2}\,\frac{e^{-\Gamma_S \Delta t}}{2\Gamma_S}$$

enhancement factor due to CP violation compared with, eg, B-mesons

$$I_{12}(\Delta t) = -\frac{4}{4(\Delta M)^2 + (3\Gamma_S + \Gamma_L)^2}\,\frac{|\omega|}{|\eta_{+-}|} \times$$

$$\Big[2\Delta M\Big(e^{-\Gamma_S \Delta t}\sin(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\sin(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)$$

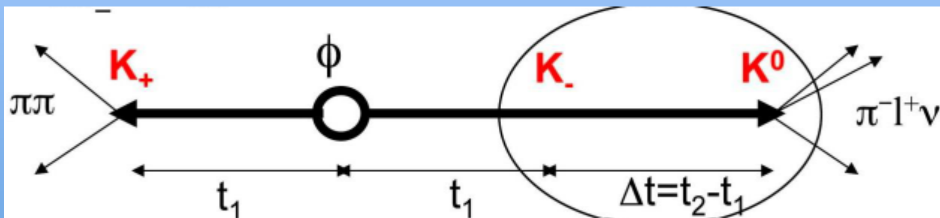
$$-(3\Gamma_S + \Gamma_L)\Big(e^{-\Gamma_S \Delta t}\cos(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)\Big]$$

$\Delta M = M_S - M_L$ and $\eta_{+-} = |\eta_{+-}|e^{i\phi_{+-}}$.

NB: sensitivities up to $|\omega| \sim 10^{-6}$ in ϕ factories, due to enhancement by $|\eta_{+-}| \sim 10^{-3}$ factor.

Bernabeu, NEM, Papavassiliou (04),…

Current Measurement Status of ω-effect
Bernabeu, Nebot, Di Domenico talks



KLOE result: PLB 642(2006) 315 Found. Phys. 40 (2010) 852

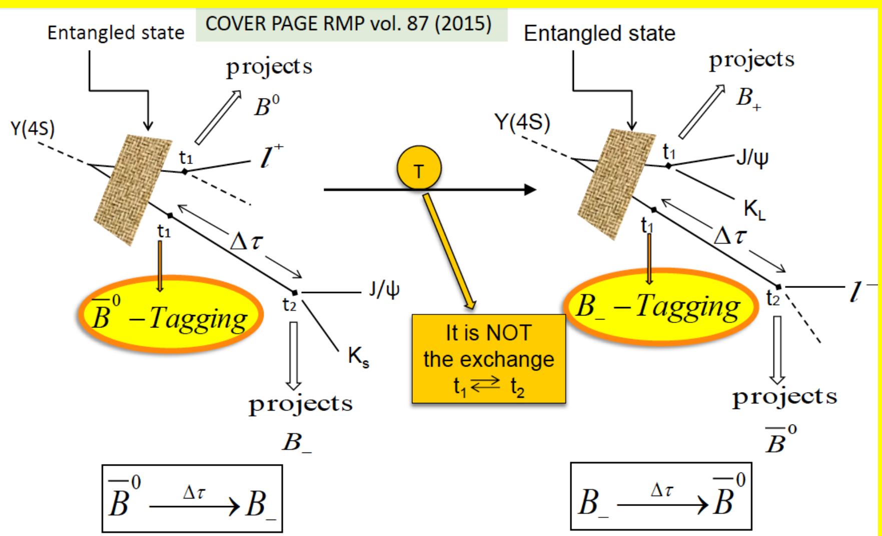
$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

$$|\omega| < 1.0\times 10^{-3} \quad \text{at } 95\%\ \text{C.L.}$$

Neutral Kaons

Prospects KLOE-2 Re(ω), Im(ω) → 2 x 10^{-5}



Nautral B-mesons

Equal Sign Dilepton Asymmetry

(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 087)

$$-0.0084 \le Re(\omega) \le 0.0100 \qquad 95\%\text{C.L}$$

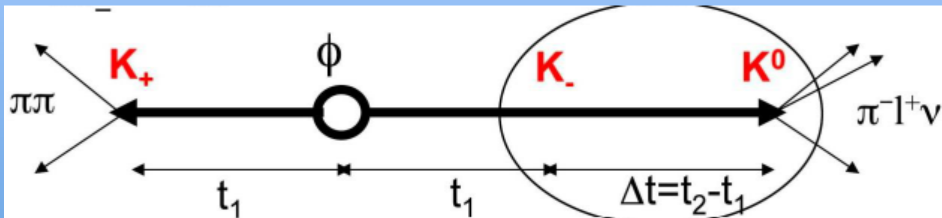
Novel signal from (f,g) ←→ (g,f)

(Bernabeu, Botella, NEM, Nebot,
EPJC 77 (2017) 865)

Im (θ)	$(0.99 \pm 1.98)10^{-2}$
Im (ω)	$\pm(6.40 \pm 2.80)10^{-2}$

Current Measurement Status of ω-effect

Bernabeu, Nebot, Di Domenico talks



KLOE result: PLB 642(2006) 315
Found. Phys. 40 (2010) 852

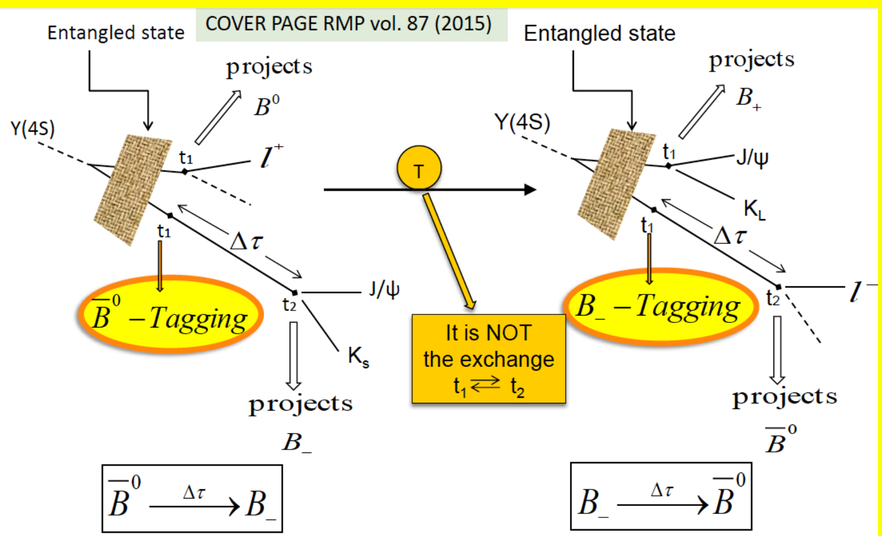
$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right) \times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right) \times 10^{-4}$$

$$|\omega| < 1.0 \times 10^{-3} \quad \text{at } 95\% \text{ C.L.}$$

Neutral Kaons

Prospects KLOE-2 Re(ω), Im(ω) → 2 x 10^{-5}



Nautral B-mesons

Equal Sign Dilepton Asymmetry

(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 087)

$$-0.0084 \le Re(\omega) \le 0.0100 \qquad 95\% C.L$$

Novel signal from (f,g) ←→ (g,f)

(Bernabeu, Botella, NEM, Nebot,

EPJC 77 (201[illegible]5)

Im (θ)	[illegible].99 ± 1.98)10^{-2}
Im (ω)	±(6.40 ± 2.80)10^{-2}

Quality of data issue

Conclusions - Outlook

- **Bright future** (with CTA) on tests of Lorentz-invariance violation with **very high energy γ-rays**

- **Separation of source from propagation effects important** → better understanding of acceleration mechanisms at the source needed – combine with QG-medium effects on propagation (refraction)

- Perform tests at various redshifts (in view of potential **redshift dependent QG scale**), increase statistics by observing both GRBs and AGNs

Conclusions - Outlook

- Probes using accelerator and astrophysical neutrinos are **much less sensitive**, and the very strong limits on Lorentz violation obtained using electrons do **not** have immediate implications for photons – **moreover can be avoided in certain string-inspired models of D-particle defect foam where the latter is more or less transparent to electrons and in general charged particles**

- **But ν Models with QG decoherence can surpass Planck Mass scale sensitivity significantly for some of the coefficients ($\sim$ E^2) : AMANDA , ICE CUBE**

- CTA will have a **unique scientific opportunity** to probe Lorentz violation using astrophysical photons, in particular **multi- TeV rays from AGNs**. The sensitivity that can be attained by CTA probes is subject to the unknown vagaries of energetic astrophysical sources, and is restricted by the horizon for absorption of energetic rays by extragalactic background light. However, these **restrictions can be evaded by observing emissions with short transient time-scales**, ...

- SME EFT LV tests also @ COLLIDERS...but we need to have microscopic undrstanding of their magnitude to understand the experimental bounds

Conclusions - Outlook

- ALSO LV effects can affect the CMB spectrum → interesting complementary constraints
  (not discussed here due to lack of time ....
  very interesting to explore further in our COST)

Gubitosi, Lim, Carroll, Field, Jackiw, Casana, Fereira, Rodrigues, ...

Important (personal) Comment/take home messages

- Classify LIV constraints : cosmic sources or LAB
- **Understand** the **parametrisations** carefully vs models
- **If SME**, understand constraints from sensitive terrestrial & extraterrestrial precision measurements → embed SME coefficients in microscopic models / **get a feeling of their magnitude**, e.g. by their effects on, say, **early Universe physics** *etc*
- **LIV & Vacuum Refraction**: Have **statistically significant populations of sources with known distances** at hand (AGN, GBR, cosmic rays (charged particles),...)
- Identify **astrophysical source mechanisms** for particle acceleration in such sources
- **Look for the unexpected** in particle propagation and apply LIV modified dispersion (or other effects) to get an estimate of the scale of the modification...
- **Look for effects beyond EFT** (e.g. Quantum Gravity -induced quantum decoherence in entangled particle states (ω-effect) *etc* ...)

Conclusions - Outlook

- ALSO LV … an affect the CMB spectrum … sting compl… y constrai…
  (not di…
  very … T)

Important (personal) Comment/take home messages

Until you have a microscopic understanding of a given LV constraint/bound, an underlying **model cannot be simply dismissed** based on ``**naturalness grounds**'', e.g. if **Planck scale sensitivity** of a given dimensionful parameter **is surpassed** by a measurement

Experimentalists/Astrophysicists ←→ Theorists

…ckiw, …ourigues, ….

Conclusions - Ou

- ALSO LV ... an affect th... spectrun... sting comp... constrai... (not di... very

Important (personal) Comment/take hom
Until you have a microscopic understanding of a given LV constraint/bound, an underlying **model cannot be simply dismis**... based on ``**naturalness grounds**'', e.g. if **Planck scale sensitivity** of a given dimension... parameter **is surpassed** by a measurement

...urgues, ...

Experimentalists/Astrophysicists <--> Theorists

Route might be painful & complicated but, I believe, it worths the effort !

Conclusions - Outlook

SPARES