QUANTUM PHYSICS OF BLACK HOLES
&
PHENOMENOLOGY OF QUANTUM GRAVITY:
DECOHERENCE & CPT VIOLATION

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QUANTUM GRAVITY ISSUES...

A Century after Einstein... Quantum Gravity is **still elusive**, despite progress in strings & canonical approach (loops):

- **Hawking Evaporation of Quantum Black Holes (BH), Microscopic (Planck size $10^{-35}\ m$) BH**
- **Is there information loss?** Superimpose (quantum) topologically different configurations: Black Hole (non trivial topology) & Flat space time. **Holography or evolution from pure to mixed states?**
- **Microscopic** BH and other topologically non-trivial space time fluctuations on the ground state of Quantum Gravity may lead to CPT Violation (Microscopic Time Irreversibility) & Decoherence of quantum matter, as it propagates through the "environment" of gravitational fluctuations **which are inaccessible to low energy observer.**
- Quantum Gravity may, in some cases, also lead to Violations of Lorentz symmetry in the Hamiltonian, e.g. through modified dispersion relations for matter probes in the foam, or spontaneous breaking of Lorentz symmetry $< A_{\mu\nu\ldots} > \neq 0$.
- Dark Energy and Its Origin? Quantisation ?

QUESTIONS

- **Are there theories which allow CPT breaking?** **(c.f. Quantum Black Holes)**
- **How (un)likely is it that somebody finds CPT violation, and why?**
- **What formalism? How can we be sure of observing CPT Violation ? our current phenomenology is based on CPT invariance...**
- **No single "figure of merit" for CPT tests: Complex Phenomenology**
- **How should we compare various "figures of merit" of CPT tests**: Direct mass measurement, K^0-$\overline{K}^0$ mass difference a la CPLEAR, electron g-2, **antimatter factories spectroscopy**, cyclotron frequency comparison, **decoherence effects**, **EPR-modifications**, **...**

OUTLINE

- **WHAT IS CPT SYMMETRY.**

- **WHY CPT VIOLATION ?**
  Theoretical models and ideas, and generic order of magnitude estimates of expected effects:
  Quantum Gravity Models violating Lorentz symmetry and/or quantum coherence:
  (i) space-time foam,
  (ii) (non supersymmetric) string-inspired standard model extension
  (iii) Loop Quantum Gravity/background independent formalism. Non-linear deformations of Lorentz symmetry ("Doubly Special Relativities")

OUTLINE

- **HOW CAN WE DETECT CPT VIOLATION?**

  (i) neutral mesons: KAONS, B-MESONS, entangled states in ϕ and B factories

  (ii) antihydrogen (precision spectroscopic tests on free and trapped molecules)

  (iii) Low energy atomic physics experiments.

  (iv) Ultra cold neutrons

  (v) Neutrino Physics

  (vi) Terrestrial & Extraterrestrial tests of Lorentz Invariance (modified dispersion relations of matter probes: GRB, AGN photons, Crab nebula synchrotron-radiation constraint on electrons ...)

CPT THEOREM

C(harge) -P(arity=reflection) -T(ime reversal) INVARIANCE is a property of any quantum field theory in Flat space times which respects:
(i) Locality, (ii) Unitarity and (iii) Lorentz Symmetry.

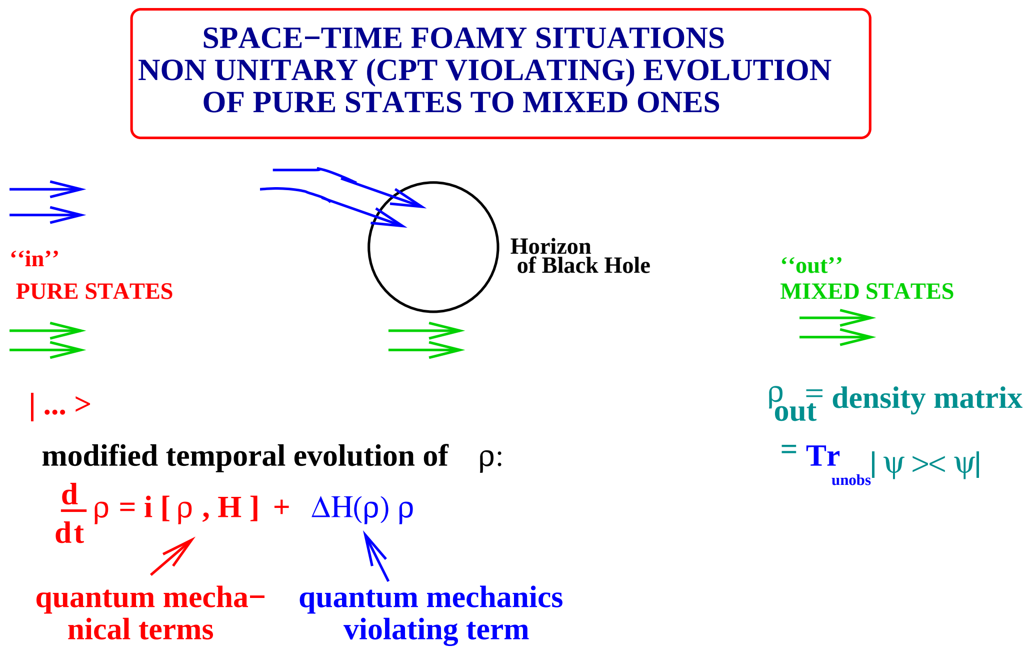
Theories with HIGHLY CURVED SPACE TIMES , of space time boundaries of black-hole horizon type, may violate (ii) &/or (iii), sometimes (i) and hence CPT.

e.g. SPONTANEOUS BREAKING OF LORENTZ SYMMETRY, OR
SPACE-TIME FOAMY SITUATIONS IN SOME QUANTUM GRAVITY MODELS INDUCING DECOHERENCE.

SPACE-TIME FOAM

FOAM AND UNITARITY VIOLATION

SPACE-TIME FOAM: Quantum Gravity SINGULAR Fluctuations (microscopic (Planck size) black holes etc) may imply "environment" → evolution of initially pure states to mixed ones:



$\rho_{out} = \mathrm{Tr}_{\mathrm{unobs}}|out >< out| = \$$
$\rho_{in}, \$ \neq SS^\dagger$, $S = e^{iHt}$ =scattering matrix \$ non invertible, unitarity lost in effective theory.

BUT...HOLOGRAPHY can change the picture

(Strings in anti-de-Sitter space times (Maldacena, Witten), Hawking 2003- superposition of space-time topologies (Quantum Gravity) (but in Euclidean space time) may solve info-problem?: not quite sure (in QG) if thew BH is there)

CPT VIOLATION AND $ $\neq SS^\dagger$

A THEOREM BY R. WALD (1980):

If $ $\neq S\ S^\dagger$, then CPT is violated, at least in its strong form.

PROOF:

Suppose CPT is conserved, then there exists unitary, invertible opearator Θ : $\Theta\overline{\rho}_{in} = \rho_{out}$

$$\rho_{out} = \$\ \rho_{in} \to \Theta\overline{\rho}_{in} = \$\ \Theta\overline{\rho}_{out} \to \overline{\rho}_{in} = \Theta^{-1}\$\ \Theta\overline{\rho}_{out}.$$

But $\overline{\rho}_{out} = \$\overline{\rho}_{in}$, hence :

$$\overline{\rho}_{in} = \Theta^{-1}\$\Theta\ \$\ \overline{\rho}_{in}$$

BUT THIS IMPLIES THAT $ HAS AN INVERSE-IMPOSSIBLE,hence CPT MUST BE VIOLATED (at least in its strong form):

Θ**: ill-defined quantum operator**, DISTINCT case from CPT Violation in Hamiltonian, i.e. $[\Theta, H] \neq 0$.

CPT SYMMETRY WITHOUT CPT SYMMETRY?

But....nature may be tricky: WEAK FORM OF CPT INVARIANCE might exist, such that the fundamental "arrow of time" does not show up in any experimental measurements (scattering experiments).

Probabilities for transition from ψ =initial pure state to ϕ =final state

$$P(\psi \to \phi) = P(\theta^{-1}\phi \to \theta\psi)$$

where θ: $\mathcal{H}_{\rm in} \to \mathcal{H}_{\rm out}$, $\mathcal{H}$= Hilbert state space,
$\Theta\rho = \theta\rho\theta^\dagger, \quad \theta^\dagger = -\theta^{-1} \ ({\rm anti-unitary})$.

In terms of superscattering matrix \$:

$$\$^\dagger = \Theta^{-1}\$\Theta^{-1}$$

Here, Θ is well defined on pure states, but \$ has no inverse, hence $\$^{\dagger} \ne \$^{-1}$ (full CPT invariance: $\$ = SS^\dagger$, $\$^\dagger = \$^{-1}$).

Supporting evidence for Weak CPT from Black-hole thermodynamics: *Although white holes do not exist (strong CPT violation), nevertheless the CPT reverse of the most probable way of forming a black hole is the most probable way a black hole will evaporate:* **the states resulting from black hole evaporation are precisely the CPT reverse of the initial states which collapse to form a black hole.**

COSMOLOGICAL CPTV?

(NM, hep-ph/0309221)

Recent Astrophysical Evidence for Dark Energy (acceleration of the Universe (SnIA), CMB anisotropies (WMAP...))

Best fit models of the Universe consistent with non-zero **cosmological constant** $\Lambda \neq 0$ (de Sitter)

Λ-universe will eternally accelerate, as it will enter in an inflationary phase again: $a(t) \sim e^{\sqrt{\Lambda/3}t}$, $t \to \infty$, there is **cosmological Horizon**.

Horizon implies incompatibility with S-matrix & decoherence: no proper definition of asymptotic state vectors, environment of d.o.f. crossing the horizon (c.f. dual picture of black hole, now observer is inside the horizon).

Theorem by Wald on $-matrix and CPTV: CPT is violated due to $\Lambda > 0$ induced decoherence:

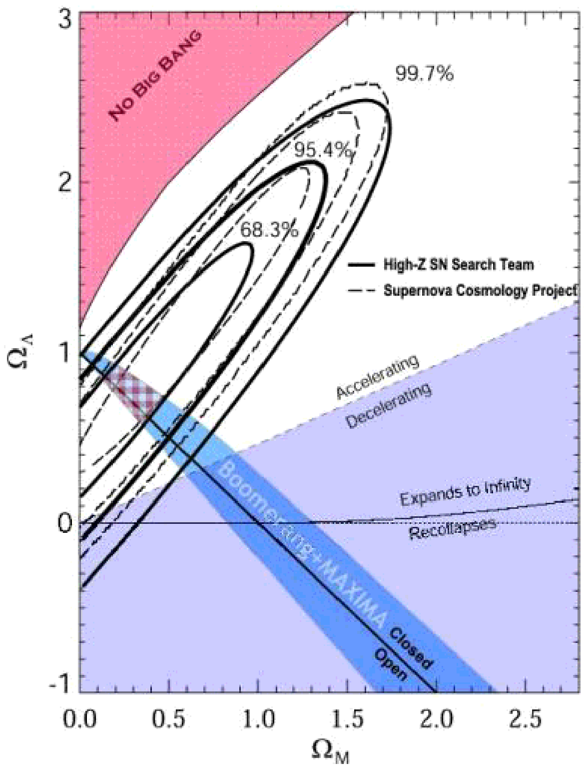
$$\partial_t \rho = i[\rho, H] + \frac{\Lambda}{M_P^3}[g_{\mu\nu}, [g^{\mu\nu}, \rho]]$$

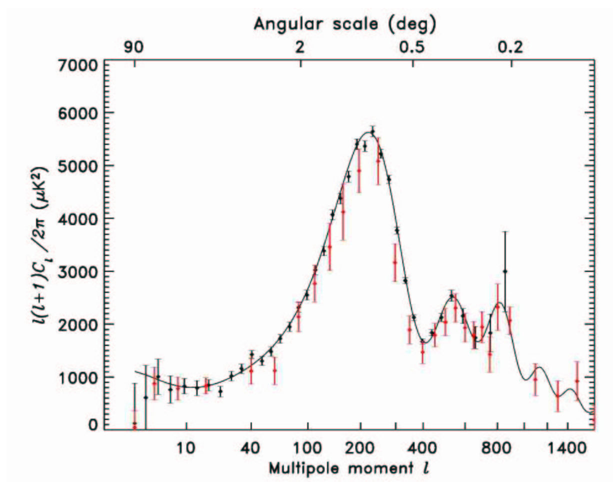
Tiny cosmological CPTV effects, but detected through Universe acceleration!

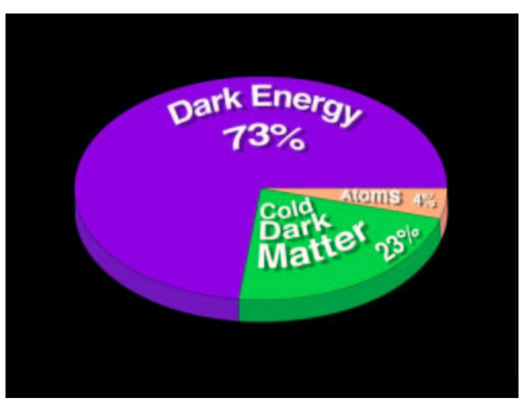
Issue: Quantize de Sitter space as an open system? or use Relaxation models for Dark Energy, where S-matrix is OK?.

Evidence for Dark Energy

WMAP improved results on CMB: $\Omega_{\rm total} = 1.02 \pm 0.02$, high precision measurement of secondary (two more) acoustic peaks (c.f. new determination of Ω_b). Agreement with SnIa Data. Best Fit : $\Omega_\Lambda = 0.73$, $\Omega_{\rm Matter} = 0.27$







FOAM DECOHERENCE: FORMALISM

Three Major approaches:

(i) Lindblad (linear) model-independent formalism (not specific to foam):

Requirements: (i) Energy conservation on average, (ii)(complete) positivity of ρ, (iii) monotonic entropy increase

Generic Decohering Evolution:

$$\frac{\partial \rho_\mu}{\partial t} \sum_{ij} h_i \rho_j f_{ij\mu} + \sum_\nu \mathcal{L}_{\mu\nu} \rho_\mu \ ,$$

$$\mu, \nu = 0, \ldots N^2 - 1, \quad i, j = 1, \ldots N^2 - 1 \qquad (1)$$

for N-level systems. For us $N = 3$, f_{ijk} structure constants of SU(3).

Entropy increase requirement:

$$\mathcal{L}_{0\mu} = \mathcal{L}_{\mu 0} = 0 \ ,$$

$$\mathcal{L}_{ij} = \frac{1}{2} \sum_{k,\ell,m} b_m^{(n)} b_k^{(n)} f_{imk} f_{\ell kj} \ ,$$

with the notation $b_j \equiv \sum_\mu b_\mu^{(j)} \mathcal{J}_\mu$, b_i Lindblad (entanglement) operators, $\mathcal{J}_\mu$, $\mu = 0, \ldots 8(3)$ be a set of SU(3) generators.

FOAM DECOHERENCE: FORMALISM

(ii) Non-critical Strings (possibly non-linear, specific to QG foam) (**Ellis, NM, Nanopoulos 1992)**:

$$\partial_t \rho = i[\rho, H] + : \beta^i < V_i V_j > [g^j, \rho] :,$$

where $> \dots >$ hides non linearirties, $g^i = g_{\mu\nu}, \dots$ string backgrounds, $\beta^i = \sum_n C^i_{i_1 \dots i_n} g^{i_1} \dots g^{i_n}$, describes deviation from conformal invariance on the world sheet (foam effect).

(iii) Fokker-Planck equation for probability density P distributions with diffusion $\mathcal{D}$,

$$\partial_t P = \mathcal{D} \nabla^2 P + \nabla \cdot \mathcal{J}$$

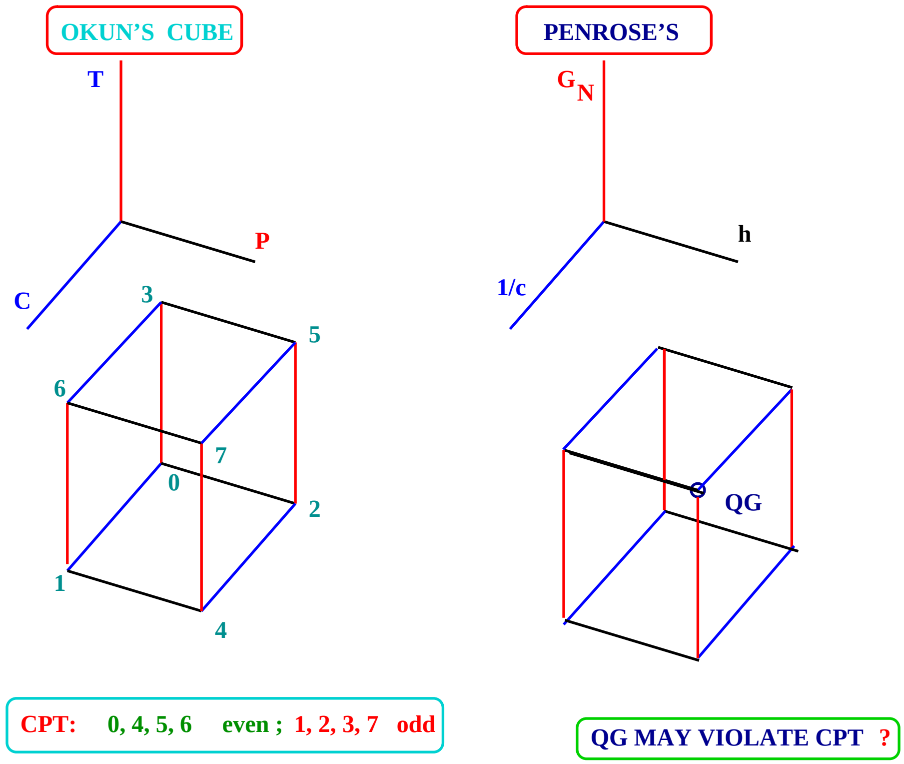
diffeomorphism invariant, leading to non-linear Schrödinger equation (Doebner-Goldin) for matter wavefunction ψ in gravitational environment (no use of density matrices):

$$i\hbar\partial_t \Psi = -\frac{\hbar^2}{2m}\nabla^2\Psi + i\mathcal{D}\hbar\left(\nabla^2\Psi + \frac{|\nabla\Psi|2}{|\Psi|^2}\Psi\right)$$

Not specific to foam, if foam: $\mathcal{D} = O\left((E/M_P)^n\right)$.
Non-critical non supersymmetric D0-branes interacting with closed strings **(NM & Szabo 2001)**.

COMPLEX PHENOMENOLOGY OF CPT VIOLATION

MNEMONIC CUBES



point 1: particle-antiparticle mass differences, non-vanishing sum of magnetic moments, $\mu_{e^+(\bar{p})} \neq -\mu_{e-(p)} \cdots$

Interference of points (3,5), & (2,0): CPTV term: $g\phi F_{\mu\nu}F_{\rho\sigma}\epsilon^{\mu\nu\rho\sigma}$, $h\phi F_{\mu\nu}F^{\mu\nu}$, ϕ pseudoscalar pion field, g, h complex $\rightarrow$ CPTV: **Complex** magnetic (complex g, real h) or electric (real g, complex h) **moments** for proton (through loop graphs), *etc.*

ORDER OF MAGNITUDE

Naively, Quantum Gravity (QG) has a dimensionful constant: $G_N \sim 1/M_P^2$, $M_P = 10^{19}$ GeV. Hence, CPT violating and decoherening effects may be expected to be suppressed at least by $\frac{E^3}{M_P^2}$, where E is a typical energy scale of the low-energy probe.

HOWEVER: RESUMMATION & OTHER EFFECTS in theoretical models may result in much larger effects of order: $\frac{E^2}{M_P}$.

(This happens, e.g., loop gravity, some stringy models of QG involving open string excitations)

SUCH LARGE $1/M_P$ EFFECTS ARE ACCESSIBLE BY CURRENT OR NEAR FUTURE EXPERIMENTS.

$1/M_P^2$ **EFFECTS MAY BE ACCESSIBLE IN FUTURE ASTROPHYSICS EXPTS (cosmic neutrinos etc.).**

LORENTZ & CPT VIOLATION IN THE HAMILTONIAN

LORENTZ INVARIANCE TESTS

Astrophysical - using Gamma Ray Bursts (GRB)

Lorentz Violation via Modified Dispersion

$$p_\mu p_\nu < g^{\mu\nu} >= -m^2$$

$< g^{\mu\nu} >\ne \eta_{\mu\nu}$ Energy (E) dependent, macroscopic effect of QG foam, $\rightarrow$ refractive index for photons $+$ light cone flucts (quantum).

$$c(E) = 1 - \mathcal{O}[(E/M_P)^\alpha]$$

Figure of Merit : Photon Arrival time Fluctuations

$$\Delta t = \frac{L}{c}\delta c = \frac{L}{c}\left(\frac{E}{M_P}\right)^\alpha$$

There are also stochastic fluctuations at the same energy channel $\Delta t_{\rm stoch} = g_s^\eta \frac{L}{c}\delta c = g_s^\eta \frac{L}{c}\left(\frac{E}{M_P}\right)^\alpha$, $\eta \ge 1$

Sensitivity in immediate future experiments ONLY if $\alpha = 1$

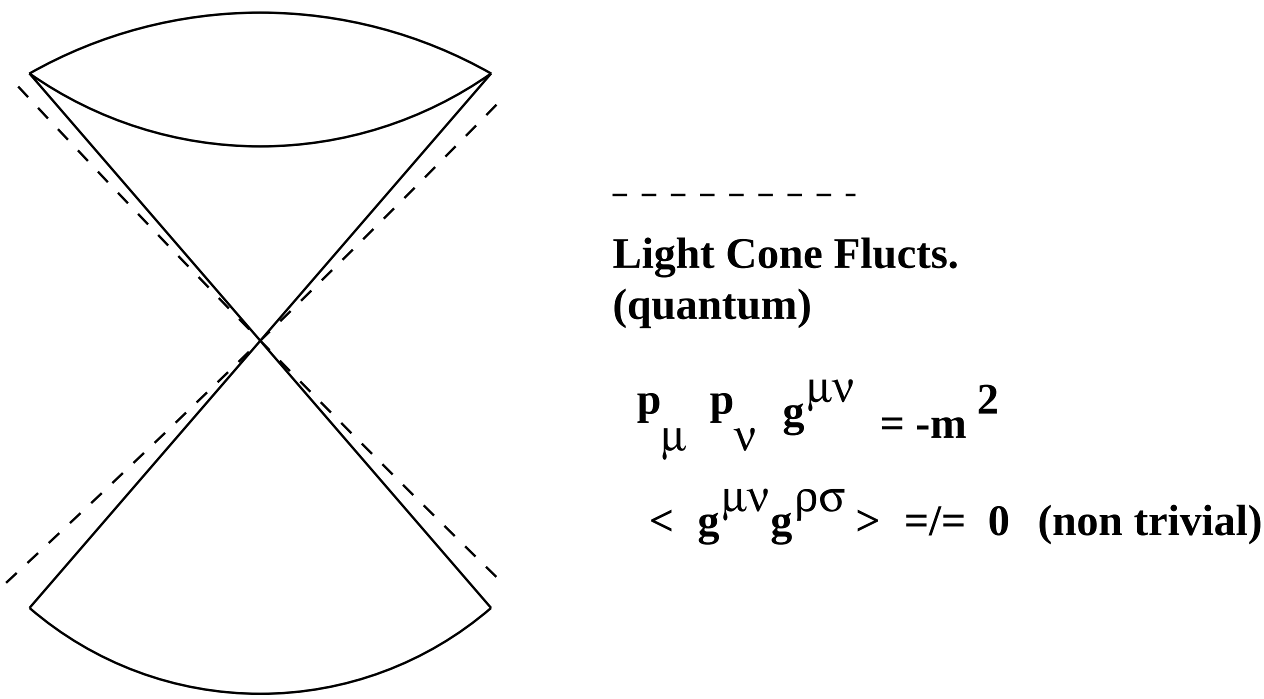
Why GRB? : pulses of light, enormous energy, various models about their origin, still puzzling.

- They are pulse like
- They are cosmological in origin (large Distance L) (e.g. redshifts $1 < z < 5$ (z=1=3 $\times 10^9$ Mpc))
- Photons in Many energy chanels (from KeV up to MeV, or GeV and even TeV)

LORENTZ INVARIANCE TESTS

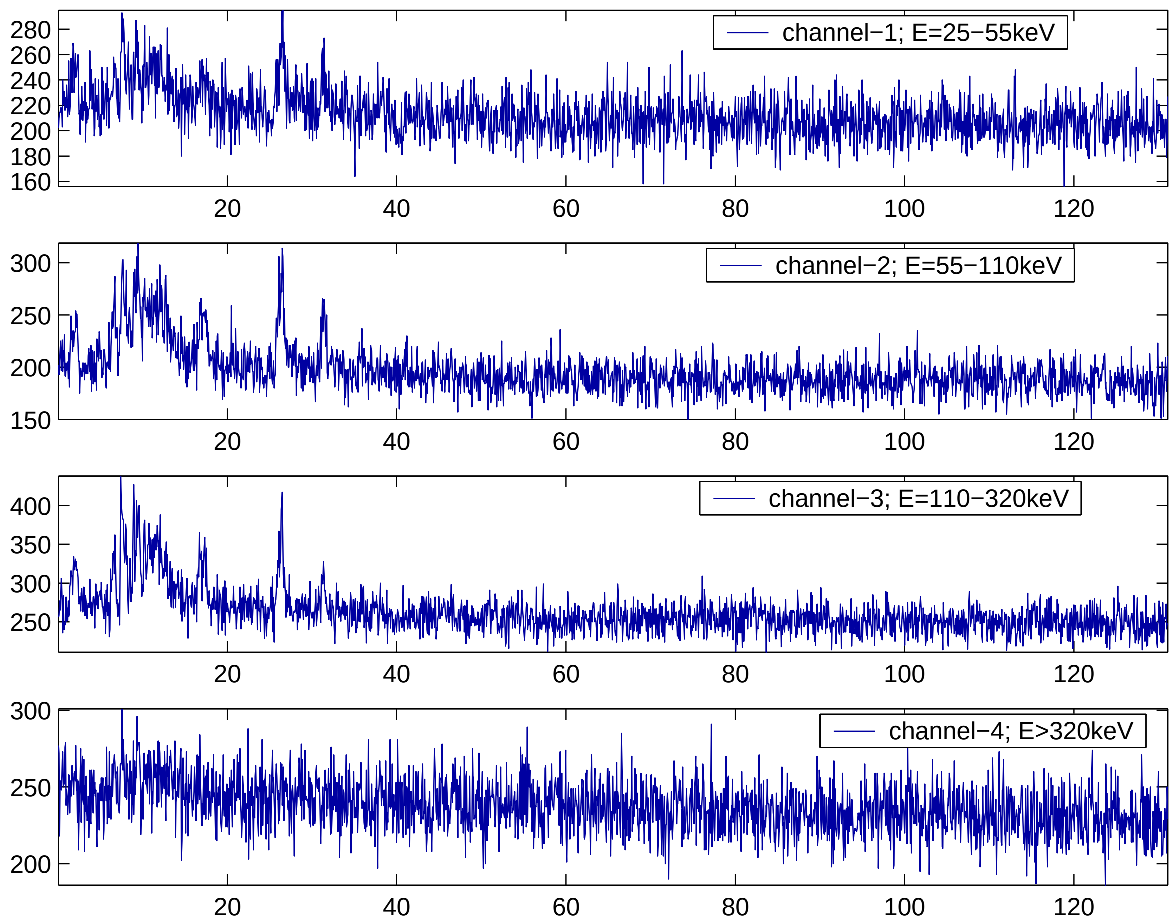
Light Cone fluctuations may be another effect of Quantum Gravity **(Ford,..., Ellis, NM, Nanopoulos)**

They induce stochastic fluctuations in arrival times of photons with the same energy.

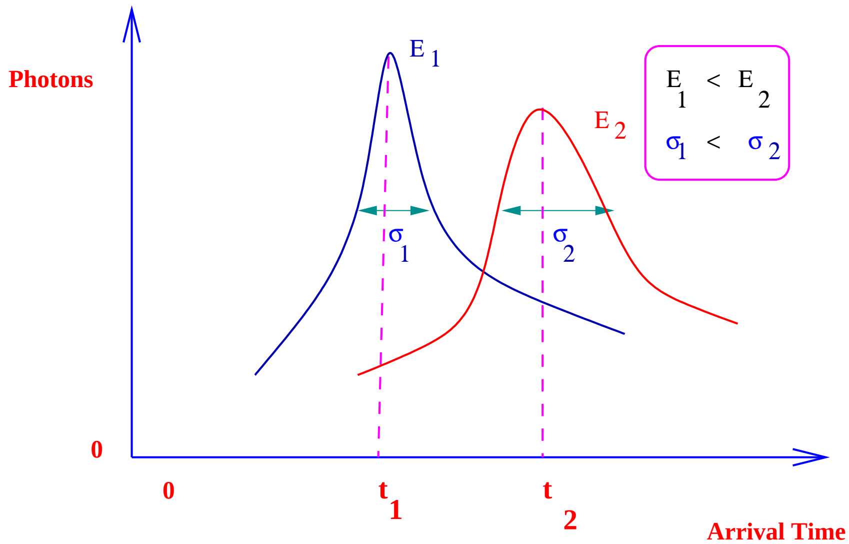


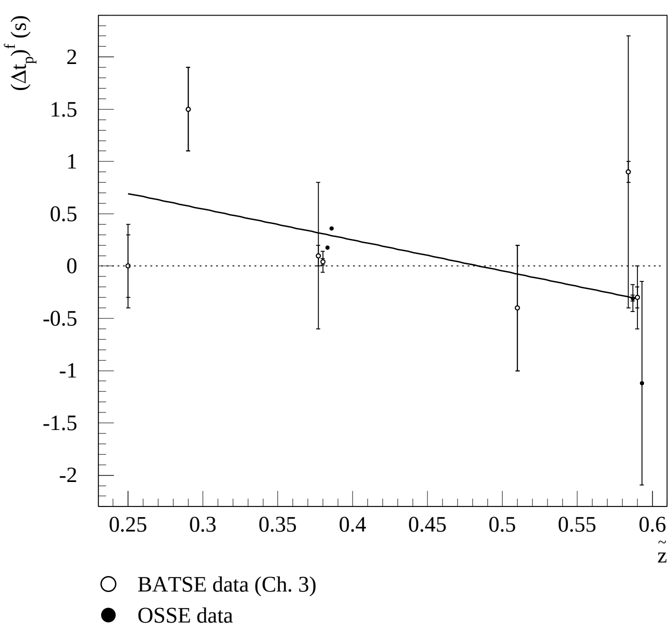
GRB TESTS of QG

Pulse-like and mutli-energy channel structure of GRB:



GRB TESTS of QG

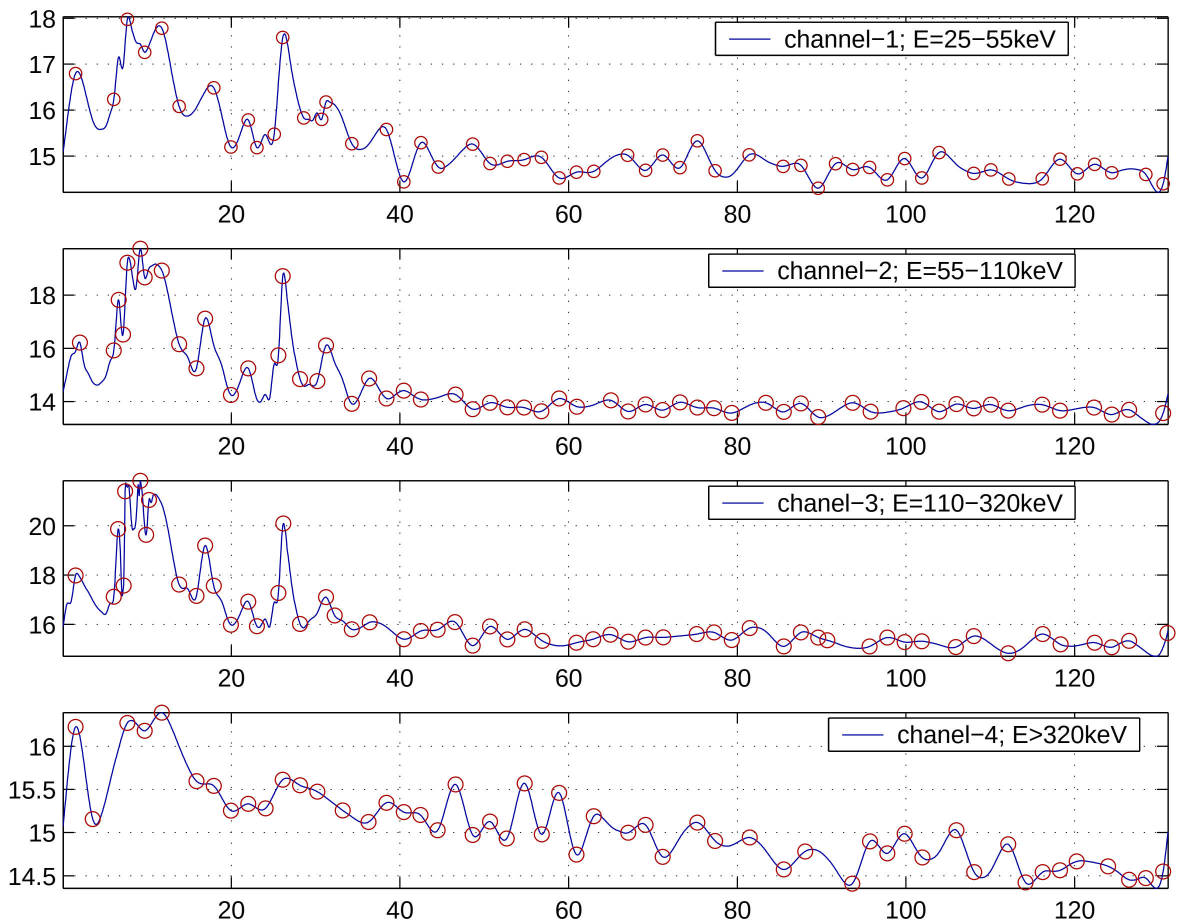




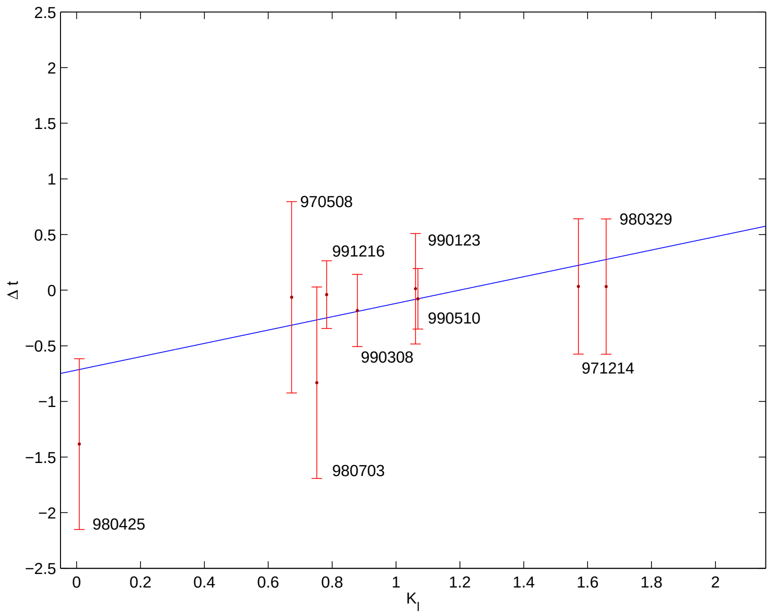
Measure linear regression of Δt with z (J. Ellis, K. Farakos, NM, V. Mitsou and D. Nanopoulos (1999))

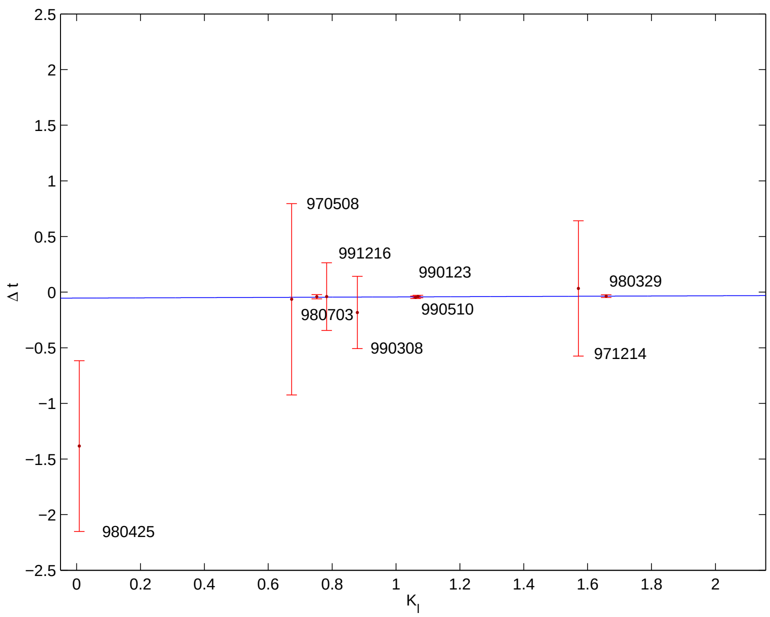
GRB TESTS of QG

Improved model-independent analysis of GRB using wavelets (J Ellis, NM, D. Nanopoulos, A Sakharov (2002))



GRB TESTS of QG





Bounds: $M_{QG} > 10^{16}$ **GeV**

Look into the future: AMS, GLAST (satellite experiments) At present GRB provide most stringent bounds on QG from photon physics

STANDARD MODEL EXTENSION (SME)

V.A. Kostelecký, R. Bluhm, D. Colladay, R. Potting, N. Russell

In this case Lorentz symmetry is violated and hence CPT, but no quantum decoherence or unitarity loss.

String theory (non supersymmetric) $\to$ Tachyonic instabilities, coupling with tensorial fields (gauge etc), $\to < A_\mu > \neq 0$, $< T_{\mu_1 \dots \mu_n} > \neq 0$,

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua

MODIFIED DIRAC EQUATION in SME: for FREE Hydrogen H (anti-hydrogen $\overline{H}$): spinor ψ reps. electron (positron) with charge $q = -|e| (q = |e|)$ around a proton (antiporoton) of charge $-q$:

$$(i\gamma^\mu D^\mu - M - a_\mu \gamma^\mu - b_\mu \gamma_5 \gamma^\mu -$$
$$-\frac{1}{2} H_{\mu\nu} \sigma^{\mu\nu} + ic_{\mu\nu} \gamma^\mu D^\nu + id_{\mu\nu} \gamma_5 \gamma^\mu D^\nu) \psi = 0$$

where $D_\mu = \partial_\mu - qA_\mu$, $A_\mu = (-q/4\pi r, 0)$ Coulomb potential. CPT & Lorentz violation: a_μ , b_μ .

Lorentz violation only: $c_{\mu\nu}$, $d_{\mu\nu}$, $H_{\mu\nu}$

FREE H, $\overline{H}$ CPT TESTS

In SME models there are energy shifts between states $|J, I; m_J, m_I>$, $J(I)$ electronic (nuclear) angular momentum (perturbation theory):

$$\Delta E^H(m_J, m_I) \simeq a_0^e + a_0^p - c_{00}^e m_e - c_{00}^p m_p + \\ (-b_3^e + d_{30}^e m_e + H_{12}^e)\frac{m_J}{|m_J|} + \\ (-b_3^p + d_{30}^p m_p + H_{12}^p)\frac{m_I}{|m_I|}$$

where e electron; p proton.

For $\overline{H}$: $a_\mu^{e,p} \to -a_\mu^{e,p}$,$b_\mu^{e,p} \to -b_\mu^{e,p}$, $d_{\mu\nu}^{e,p} \to d_{\mu\nu}^{e,p}$, $H_{\mu\nu}^{e,p} \to H_{\mu\nu}^{e,p}$. SPECTROSCOPY OF FORBIDDEN TRANSITIONS 1S-2S:

If CPT and Lorentz violating parameters are constant they drop out to leading order energy shifts in free H ($\overline{H}$). Subeading effects, suppressed by $\alpha^2 \sim 5 \times 10^{-5}$ (fine structure constant squared) :

$$\delta\nu_{1S-2S}^H \simeq -\frac{\alpha^2 b_3^e}{8\pi}$$

This is too small to be seen...but what about CONFINED H ($\overline{H}$) in magnetic traps?

TRAPPED H, $\overline{H}$ CPT TESTS

Magnetic fields induce hyperfine Zeeman splittings in 1S, 2S states. There are four spin states, mixed under the the magnetic field B ($|m_J, m_I>$ basis):

$$|d>_n = |\frac{1}{2}, \frac{1}{2}> \quad ,$$

$$|c>_n = \sin\theta_n | -\frac{1}{2}, \frac{1}{2}> + \cos\theta_n |\frac{1}{2}, -\frac{1}{2}> \quad ,$$

$$|b>_n = | -\frac{1}{2}, -\frac{1}{2}> \quad ,$$

$$|a>_n = \cos\theta_n | -\frac{1}{2}, \frac{1}{2}> - \sin\theta_n |\frac{1}{2}, -\frac{1}{2}> \quad .$$

where $\tan 2\theta_n = (51\mathrm{mT})/\mathrm{n}^3\mathrm{B}$.

$|c>_1 \rightarrow |c>_2$ transitions dominant effects for CPT:

$$\delta\nu_c^H \simeq -\frac{\kappa(b_3^e - b_3^p - d_{30}^e m_e + d_{30}^p m_p - H_{12}^e + H_{12}^p)}{2\pi}$$

$$\delta\nu_c^{\overline{H}} \simeq -\frac{\kappa(-b_3^e + b_3^p - d_{30}^e m_e - d_{30}^p m_p - H_{12}^e + H_{12}^p)}{2\pi}$$

$$\Delta\nu_{1S-2S,c} \equiv \delta\nu_c^H - \delta\nu_c^{\overline{H}} \simeq -\frac{\kappa(b_3^e - b_3^p)}{\pi} \quad ,$$

$\kappa = \cos 2\theta_2 - \cos 2\theta_1$, $\kappa \simeq 0.67$ for $B = 0.011$ T.

NB: $\Delta\nu_{c\rightarrow d} \simeq -2b_3^p/\pi$, $|b_3| \leq 10^{-27}\mathrm{GeV}$, if frequency resolution 1mHz attained.

A STRING-INSPIRED MODEL OF SME

E. Gravanis & N.M.

Interaction of string matter with space-time solitonic defects results in a model for space-time foam with a modified Dirac equation of SME type but with ONLY (boost sensitive) temporal components of (e.g. for protons)

$$a_0 \sim \xi \frac{E^3}{E - m_p} \frac{1}{M_P} ,$$

where ξ depends on string interaction coupling and is model dependent. The model also predicts modified Dispersion relations (Ellis, NM, Nanopoulos).

The energy dependence of a_0 implies that hyperfine Zeeman splittings due to external magnetic field B acquire shifts $\Delta E \sim a_0(E)$. Hence (say 1S level):

$$\delta\nu^H_{1S} - \mu_N B \sim \frac{\xi}{M_P} \frac{m_p^3}{\mathcal{E}^2_{1S}} \mu_N B \sim \xi 10^{-21} (\frac{B}{\mathrm{mT}}) \mathrm{GeV}$$

where $\mathcal{E}_{1S}$ is the energy level, μ_N nuclear magneton. H, $\overline{H}$ spectroscopic measurements may be devised to constrain the parameter ξ in a_0. **Also use relativistic beams of H, $\overline{H}$ for enhancement of effects.**

Neutrinos & SME

SME-LV+CPTV (phenomenological) model for ν

(Kostelecký & Mewes 20003)

$\mathcal{L}_{SME} \ni \frac{1}{2} i \overline{\psi}_{a,L} \gamma^\mu D_\mu \psi_{a,L} - (a_L)_{\mu ab} \overline{\psi}_{a,L} \gamma^\mu \psi_{b,L} + \frac{1}{2} i (c_L)_{\mu\nu ab} \overline{\psi}_{a,L} \gamma^\mu D^\nu \psi_{b,L}$

a, b flavour indices, No ν mass differences.

Presence of LV induces directional dependence (sidereal effects)!

Effective Hamiltonian:

$(H_{\rm eff})_{ab} = |\vec{p}|\delta_{ab} + \frac{1}{|\vec{p}|}((a_L)^\mu p_\mu - (c_L)^{\mu\nu} p_\mu p_\nu)_{ab}$

NB: ν Oscillations now are controlled by (dimensionless) $a_L L$ & $c_L L E$ (L=oscill. length). Contrast conventional case: $\Delta m^2 L/E$

Imporant SME feature: despite CPTV, oscillation probs $P_{\nu_x \to \nu_y} = P_{\bar{\nu}_x \to \bar{\nu}_y}$ (if no mass differences).

Bind LV+CPTV SME experimentally. E.g.: High energy long baseline expts: no evidence for $\nu_{e,\mu} \to \nu_\tau$ at $E \sim 100$ GeV , $L \sim 10^{-18}$ GeV^{-1} $\to a_L < 10^{-18}$ GeV, $c_L < 10^{-20}$.

For LSND anomaly: Mass-squared difference required: $\Delta m^2 = 10^{-19}$ GeV$^2 = 10^{-1}$ eV^2, $a_L \sim 10^{-18}$ GeV, $c_L \sim 10^{-17}$. Affect other expts. . No good for LSND.

Experimental Sensitivities for ν's

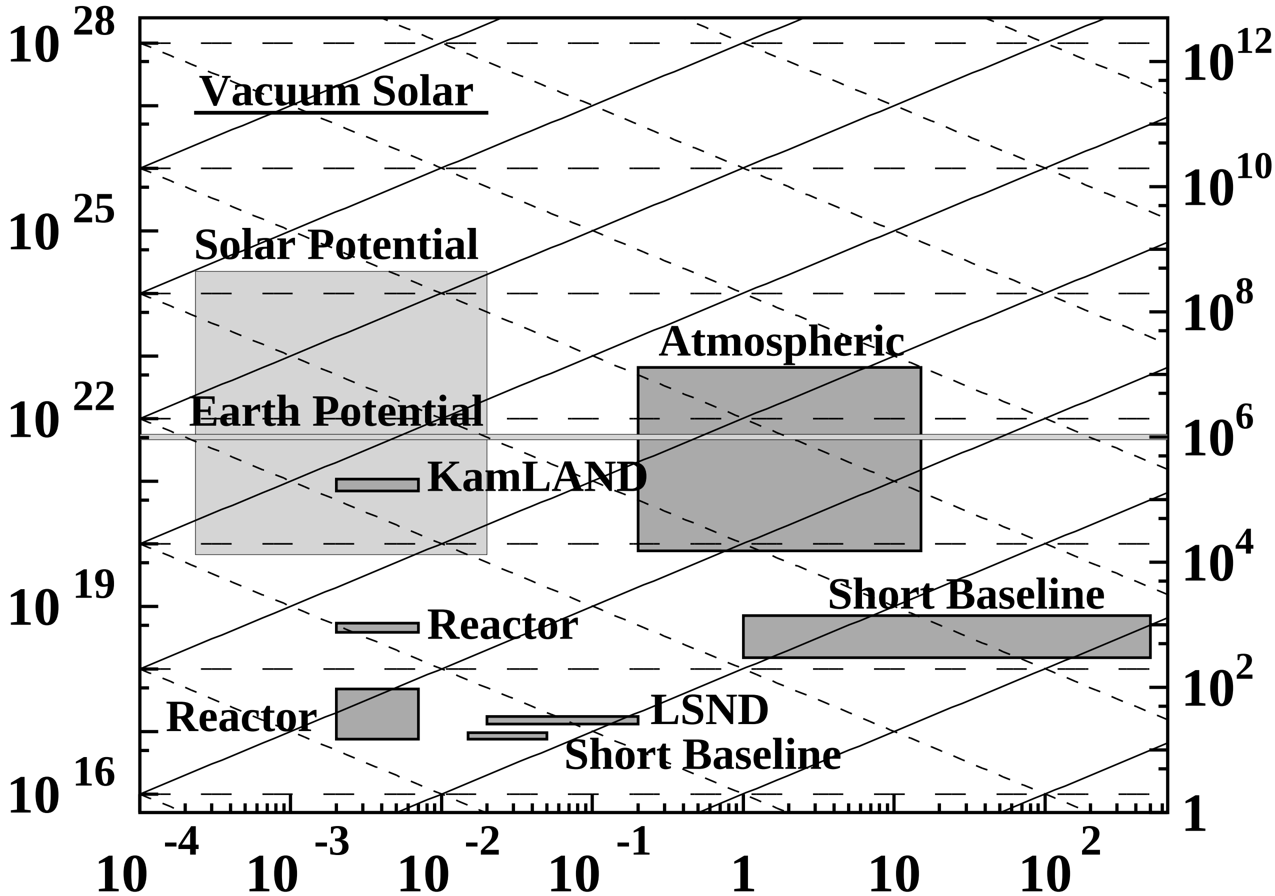


Figure 1: Approximate experimental sensitivities. Lines of constant L/E (solid), L (dashed), and LE (dotted) are shown, which give sensitivities to Δm^2, a_L, and c_L, respectively. (Kostelecky & Mews hep-ph/0308300)

FRAME DEPENDENCE

If Lorentz symmetry is violated (LV) then the effects should be frame dependent.

$\Delta\nu_c^H$ depends on spatial components of LV couplings $\rightarrow$ sidereal variations due to earth rotation (clock comparison experiments using H alone).

There is a preferred frame, which might be taken to be the cosmic microwave background frame with velocity $w \sim 10^{-3}c$.

High precision tests possible if modified dispersion relations for matter probes exist, via quadrupole moment measurements: sensitivity higher than $10^{23}\text{GeV} > M_P = 10^{19}$ GeV .

Severe constraints also from astrophysics (Crab Nebula magnetic field measurements implies sensitivity of some quantum gravity effects up to scales 10^{27} GeV $>> M_P = 10^{19} GeV$!).

PLANCK SCALE EFFECTS BOUNDS

LOW-ENERGY ATOMIC PHYSICS EXPERIMENTS:

LEADING ORDER BOUNDS

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)

QG-DECOHERENCE & CPT:

NEUTRAL MESONS

QG Decoherence in neutral Kaons

Quantum Gravity (QG) may induce decoherence and oscillations $K^0 \to \overline{K}^0$ (Ellis, Hagelin, Nanopoulos, Srednicki, Lopez+NM).

$$\partial_t \rho = i[\rho, H] + \delta \not{H} \rho$$

where

$$H_{\alpha\beta} = \begin{pmatrix} -\Gamma & -\frac{1}{2}\delta\Gamma & -\mathrm{Im}\Gamma_{12} & -\mathrm{Re}\Gamma_{12} \\ -\frac{1}{2}\delta\Gamma & -\Gamma & -2\mathrm{Re}M_{12} & -2\mathrm{Im}M_{12} \\ -\mathrm{Im}\Gamma_{12} & 2\mathrm{Re}M_{12} & -\Gamma & -\delta M \\ -\mathrm{Re}\Gamma_{12} & -2\mathrm{Im}M_{12} & \delta M & -\Gamma \end{pmatrix}$$

and

$$\delta \not{H}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix}$$

positivity of ρ requires: $\alpha, \gamma > 0, \qquad \alpha\gamma > \beta^2$.

α, β, γ violate CPT (Wald : decoherence) & CP:

$CP = \sigma_3 \cos\theta + \sigma_2 \sin\theta, \qquad [\delta \not{H}_{\alpha\beta}, CP] \neq 0$

DECOHERENCE vs. CPTV IN QM

Should distinguish two types of CPT Violation (CPTV):

(i) CPTV within Quantum Mechanics:
$\delta M = m_{K^0} - m_{\overline{K}^0}$, $\delta\Gamma = \ldots$. This could be due to (spontaneous) Lorentz violation (c.f. below).

(ii) CPTV through decoherence α, β, γ (entanglement with QG 'environment').

Experimentally two types can be disentangled !

RELEVANT OBSERVABLES: $\langle O_i \rangle = \mathrm{Tr}\,[O_i \rho]$

LOOK AT DECAY ASYMMETRIES for $K^0, \overline{K}^0$:

$$A(t) = \frac{R(\bar{K}^0_{t=0} \to \bar{f}) - R(K^0_{t=0} \to f)}{R(\bar{K}^0_{t=0} \to \bar{f}) + R(K^0_{t=0} \to f)}\,, \qquad (2)$$

$R(K^0 \to f) \equiv \mathrm{Tr}\,[O_f \rho(t)]$ =decay rate into the final state f (pure K^0 at $t = 0$).

NEUTRAL KAON ASYMMETRIES: identical final states $f = \bar{f} = 2\pi$: $A_{2\pi}$, $A_{3\pi}$,
semileptonic: A_T (final states $f = \pi^+ l^- \bar{\nu} \;\neq\; \bar{f} = \pi^- l^+ \nu$), A_{CPT} ($\overline{f} = \pi^+ l^- \bar{\nu},\; f = \pi^- l^+ \nu$), $A_{\Delta m}$.

NEUTRAL KAON ASYMMETRIES

Typically

$$R_{2\pi}(t) = c_S\, e^{-\Gamma_S t} + c_L\, e^{-\Gamma_L t} + 2c_I\, e^{-\Gamma t} \cos(\Delta m t - \phi)\ ,$$

S=short-lived, L=long-lived, I=interference term,
$\Delta m = m_L - m_S$, $\Gamma = \frac{1}{2}(\Gamma_S + \Gamma_L)$.

Decoherence Parameter

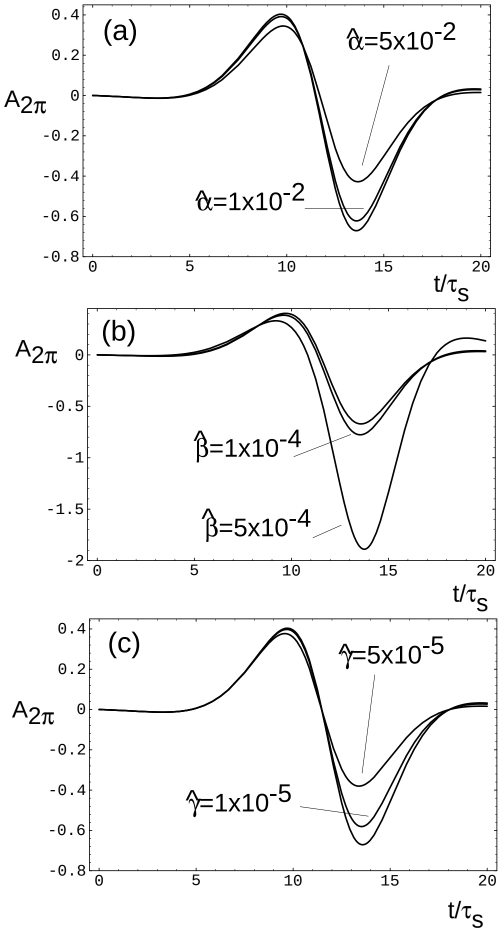
$$\zeta = 1 - \frac{c_I}{\sqrt{c_S c_L}}\ .$$

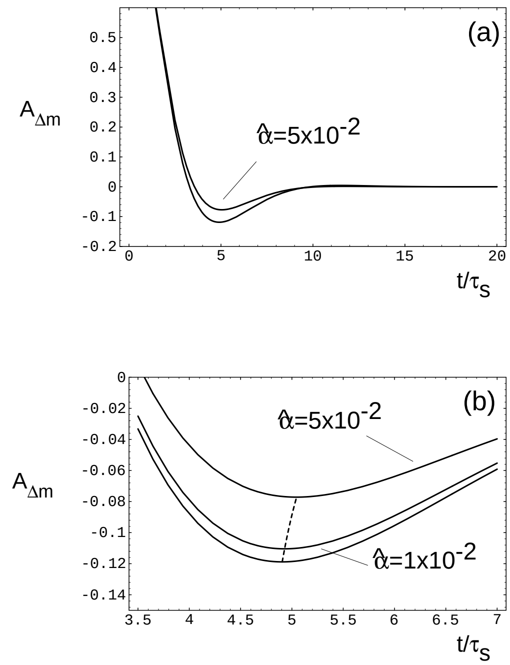
Can Look at this parameter also in the presence of a regenerator. In our decoherence scenario depends mainly on β.

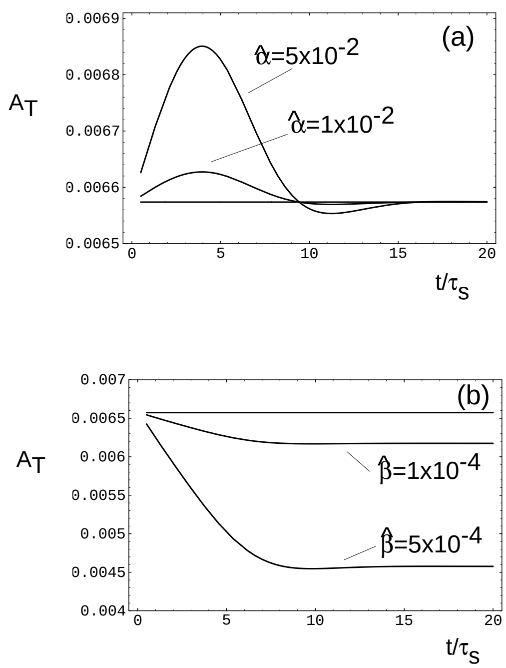
Convenient parametrization:
$\widehat{a},\ \widehat{\beta},\ \widehat{\gamma} \equiv \frac{\alpha,\ \beta,\ \gamma}{\Delta\Gamma}$, $\Delta\Gamma = \Gamma_S - \Gamma_L$.

For Kaons: $\Delta\Gamma \sim 10^{-15}$ GeV.

NEUTRAL KAON ASYMMETRIES







INDICATIVE BOUNDS

Table 1: Compilation of indicative bounds on CPT-violating parameters and their source.

Source	Indicative bound
$R_{2\pi}, A_{2\pi}$	$\widehat{\alpha} < 5.0 \times 10^{-3}$
$R_{2\pi}, A_{2\pi}$	$\widehat{\beta} = (2.0 \pm 2.2) \times 10^{-5}$
$\vert m_{K^0} - m_{\bar{K}^0}\vert$	$\widehat{\beta} < 2.6 \times 10^{-5}$
$R_{2\pi}$	$\widehat{\gamma} \lesssim 5 \times 10^{-7}$
ζ	$\frac{\widehat{\gamma}}{2\vert\epsilon\vert^2} - \frac{2\widehat{\beta}}{\vert\epsilon\vert} \sin\phi = 0.03 \pm 0.02$
Positivity	$\widehat{\alpha} > \widehat{\beta}^2/\widehat{\gamma}_{\rm max} \sim (10^3\widehat{\beta})^2$

FROM CPLEAR MEASUREMENTS (PLB364 (1995) 239): $\alpha < 4.0 \times 10^{-17}$ GeV , $|\beta| < 2.3. \times 10^{-19}$ GeV , $\gamma < 3.7 \times 10^{-21}$ GeV

NB(1): Theoretically expected values $\alpha \ , \beta \ , \gamma = \mathcal{O}(\xi \frac{E^2}{M_P})$.

NB(2): $m_{K^0} - m_{\overline{K}^0} \sim 2|\beta|$ (present bound on $(m_{K^0} - m_{\overline{K}^0})/m_{K^0} < 7.5 \times 10^{-19}$)

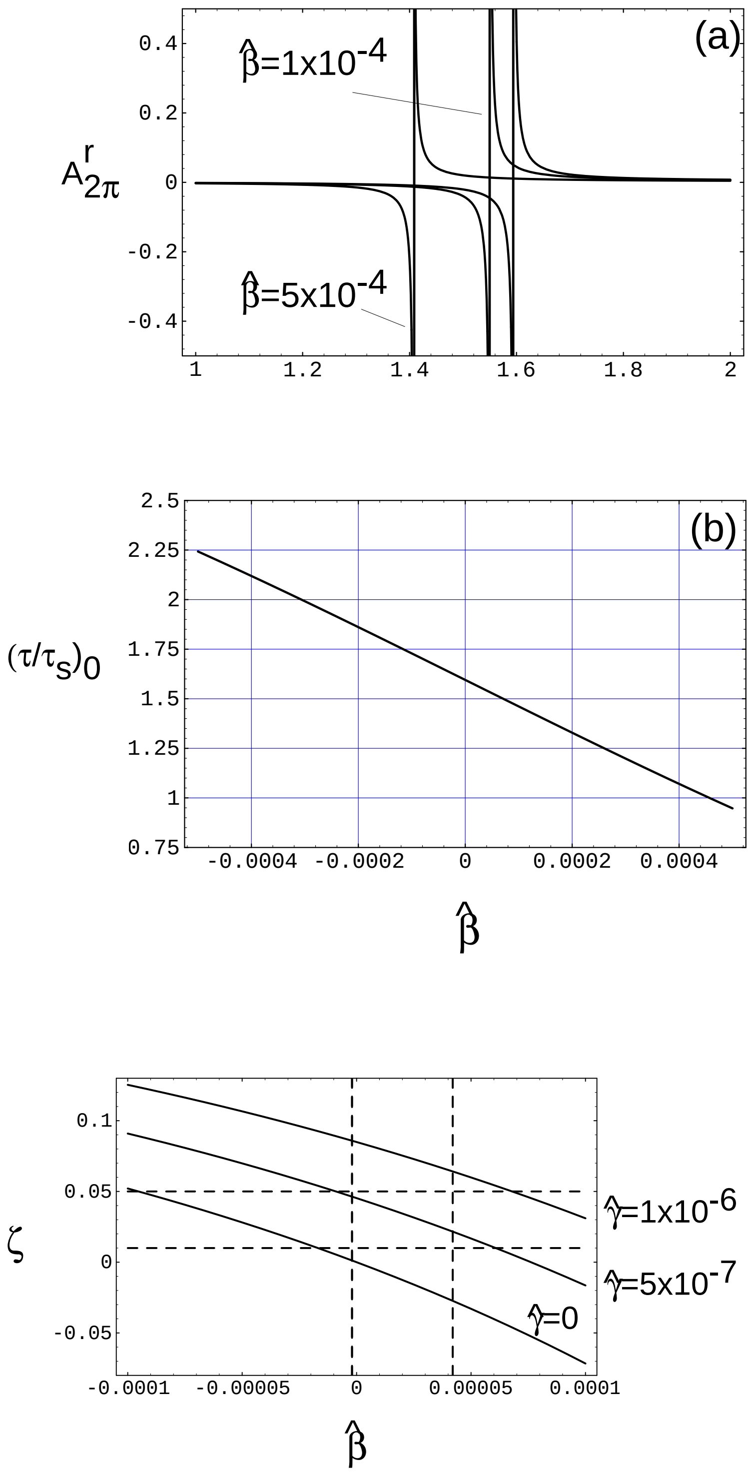
QMV vs. QM effects

(Ellis, Lopez, NM and Nanopoulos, hep-ph/9505340 (PRD))

Table 2: Qualitative comparison of predictions for various observables in CPT-violating theories beyond (QMV) and within (QM) quantum mechanics. Predictions either differ ($\neq$) or agree ($=$) with the results obtained in conventional quantum-mechanical CP violation. Note that these frameworks can be qualitatively distinguished via their predictions for $A_{\rm T}$, $A_{\rm CPT}$, $A_{\Delta m}$, and ζ.

Process	QMV	QM
$A_{2\pi}$	$\neq$	$\neq$
$A_{3\pi}$	$\neq$	$\neq$
$A_{\rm T}$	$\neq$	$=$
$A_{\rm CPT}$	$=$	$\neq$
$A_{\Delta m}$	$\neq$	$=$
ζ	$\neq$	$=$

NEUTRAL KAONS IN REGENERATOR



CPTV and EPR-correlations modification

(Bernabeu, NM and Papavassiliou, hep-ph/0310180 (PRL 92))

If CPT is broken, e.g. via Quantum Gravity (QG) effects on $\$ \neq SS^\dagger$, then: CPT operator Θ is ILL defined $\Rightarrow$ Antiparticle Hilbert Space INDEPENDENT OF particle Hilbert space.

Neutral mesons K^0 and $\overline{K}^0$ SHOULD NO LONGER be treated as IDENTICAL PARTICLES. This implies that the initial Entangled State in ϕ (B) factories $|i>$ can now be written (in terms of mass eigenstates):

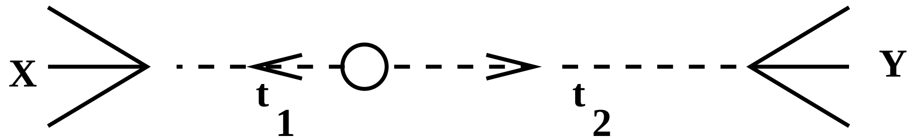
$$\begin{aligned} |i> &= C\Big[\Big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\Big) \\ &+ \omega\Big(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\Big)\Big] \end{aligned}$$

NB! $K_S K_S$ or $K_L - K_L$ combinations, due to CPTV ω, important in decay channels. There is contamination of C(odd) state with C(even). Complex ω controls the amount of contamination by the "wrong" (C(even)) symmetry state.

Experimental Tests of ω-Effect in ϕ, B factories... in B-factories: ω-effect $\rightarrow$ demise of flavour tagging (Alvarez et al. (PLB607)) **Disentangle ω from non-unitary evolution and background effects**.

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)



Amplitudes:

$$A(X, Y) = \langle X|K_S\rangle\langle Y|K_S\rangle\, C\, (A_1 + A_2)$$

with

$$\begin{aligned} A_1 &= e^{-i(\lambda_L+\lambda_S)t/2}[\eta_X e^{-i\Delta\lambda\Delta t/2} - \eta_Y e^{i\Delta\lambda\Delta t/2}] \\ A_2 &= \omega[e^{-i\lambda_S t} - \eta_X \eta_Y e^{-i\lambda_L t}] \end{aligned}$$

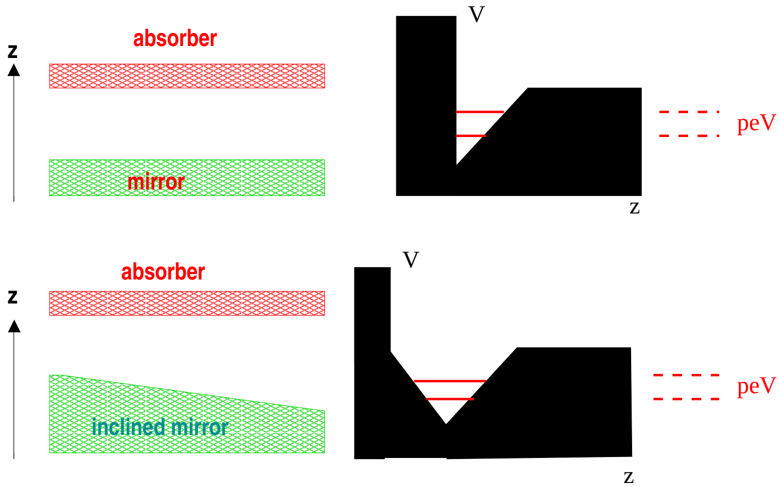
the CPT-allowed and CPT-violating parameters respectively, and $\eta_X = \langle X|K_L\rangle/\langle X|K_S\rangle$ and $\eta_Y = \langle Y|K_L\rangle/\langle Y|K_S\rangle$.

The "intensity" $I(\Delta t)$: ($\Delta t = t_1 - t_2$)

$$I(\Delta t) \equiv \frac{1}{2}\int_{|\Delta t|}^{\infty} dt\, |A(X, Y)|^2$$

NB: sensitivities up to $|\omega| \sim 10^{-6}$ in ϕ factories.

ULTRACOLD NEUTRONS



Inclined mirror ensures Parity invariance of QG modifications and hence formalism similar to neutral kaons. A few (two here) energy states (peV energy differences between levels) are inside the Earth' s potential well. Probability of finding neutrons in either state is:

$$\mathrm{Tr}(\rho' \varrho_{1,2}) = \frac{1}{2} \pm \frac{1}{2} e^{-\frac{\alpha+\gamma}{2}t} \sin(\Delta E t) \ , \qquad \delta E \simeq \mathrm{peV}$$

If Lorentz invariance is violated $\alpha, \gamma \simeq \frac{E_{\rm kin}^2}{M_P}$; if NOT, $\alpha, \gamma \simeq \frac{m_n^2}{M_P}$. $t \sim \mathrm{msec}$ Second case effect is much larger. However, at present no significant sensitivity.

QG-DECOHERENCE & NEUTRINOS

QG Decoherence and neutrino mixing

Quantum Gravity (QG) may induce oscillations between neutrino flavours independently of masses (Liu et al., 1997, Chang et al., 1998, Lisi et al., Benatti & Floreanini 2000).

$$\partial_t \rho = i[\rho, H] + \delta \not{H} \rho$$

where (Ellis, Hagelin, Nanopoulos, Srednicki 1984)

$$\delta \not{H}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & -2\alpha & -2\beta & 0 \\ 0 & -2\beta & -2\gamma & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

for energy and lepton number conservation. and

$$\delta \not{H}_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix}$$

if energy and lepton number violated, but flavour conserved (σ_1 Pauli matrix). Positivity of ρ requires: $\alpha, \gamma > 0, \qquad \alpha\gamma > \beta^2$. α, β, γ **violate CPT** (Ellis, NM, Nanopoulos 1992, Lopez + EMN 1995). **Decoherence affects (damps) OSCILLATION PROBABILITIES**

QG Decoherence and neutrino mixing

In some models of QG Decoherence, with complete positivity in ideal Markov environments

$\alpha = \beta = 0, \gamma > 0.$

Theoretical Models Predictions vs. Experiment: **Optimistic: (Ellis, NM, Nanopoulos, ...)** $\gamma \sim \gamma_0 (\frac{E}{\mathrm{GeV}})^n, n = 0, 2, -1,$ $n = 2$ stringy QG, $n = -1$ ordinary matter effects.

Pessimistic: (Adler 2000) $\gamma \sim \frac{(\Delta m^2)^2}{E^2 M_{qg}}$**,** **(**$M_{qg} \sim M_P \sim 10^{19}$ **GeV).**

with E the neutrino energy.

From Atmosperic ν data $\rightarrow$ Bounds:

$n = 0$, $\gamma_0 < 3.5 \times 10^{-23}$ GeV

$n = 2$, $\gamma_0 < 0.9 \times 10^{-27}$ GeV (c.f. CPLEAR bound for Kaons: $\gamma < 10^{-21}$ GeV (PLB364 (1995) 239))

$n = -1$, $\gamma_0 < 2 \times 10^{-21}$ GeV.

NB: Tests on ν-mixing from Decoherence exhibit much greater sensitivity than neutral mesons. Very stringent limits from neutrinos from exaglactic sources (Supernovae, AGN), if QG induces lepton number violation and/or flavour oscillations:From SN1987a, using the observed constraint on the oscillation probability $P_{\nu_e \rightarrow \nu_{\mu,\tau}} < 0.2$: $\gamma < 10^{-40}$ GeV.

QG Decoherence and neutrino mixing

FITTING THE DATA (Lisi et al. PRL 85 (2000), 1166)

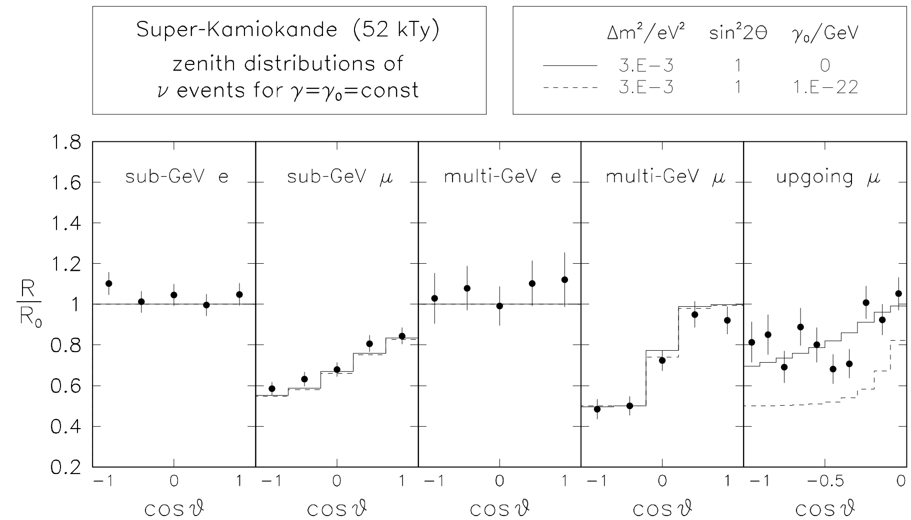


Figure 2: Effects of decoherence $(\gamma = \gamma_0 = \mathrm{const} \neq 0)$ on the distributions of lepton events as a function of the zenith angle ϑ

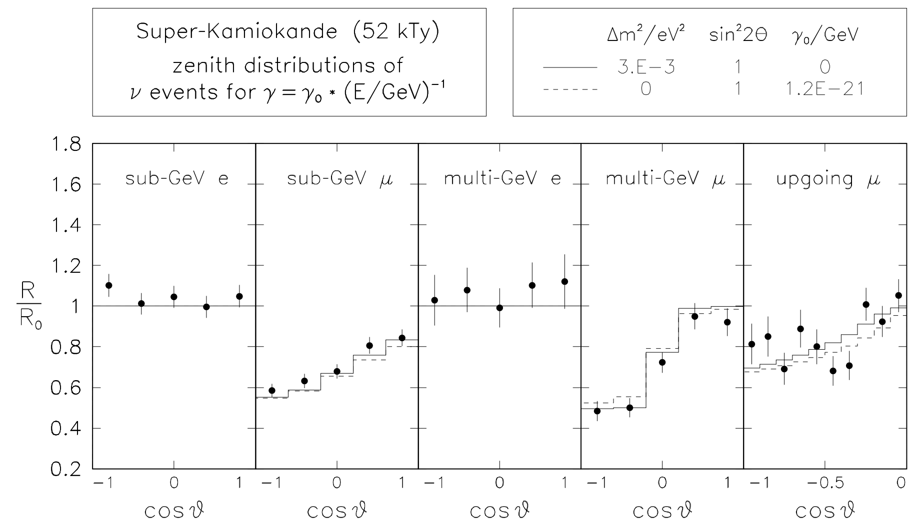


Figure 3: Best-fit scenarios for pure oscillations $(\gamma = 0)$ (solid line) and for pure decoherence with $\gamma \propto 1/E$ (dashed line).

Three ν Generations, Decoherence and LSND

G. Barenboim & NM, JHEP & PRD70 (2004)

Parameters of model: At least eight, if decoherence matrix assumed

$$\delta \not{H} = \mathrm{Diag}(\gamma_1, \gamma_2, \ldots, \gamma_8)$$

for three generations of ν. **Oscillations:** $\nu_\alpha \to \nu_\alpha$**, or** $\overline{\nu}_\alpha \to \overline{\nu}_\beta$ **Assume decoherence parameters different between** ν **and** $\overline{\nu}$ **sectors:** $\gamma_i \neq \overline{\gamma}_i$, (e.g. may be $\gamma_i \ll \overline{\gamma}_i$).

CPT violation is driven by, and restricted to, the decoherence parameters, masses and mixing angles are the same in both sectors, and selected to be the standard ones

$$\Delta m_{12}^2 = \Delta \overline{m_{12}}^2 = 7 \cdot 10^{-5} \text{ eV}^2,$$

$$\Delta m_{23}^2 = \Delta \overline{m_{23}}^2 = 2.5 \cdot 10^{-3} \text{ eV}^2,$$

$$\theta_{23} = \overline{\theta_{23}} = \pi/4,\ \theta_{12} = \overline{\theta_{12}} = .45,\ \theta_{13} = \overline{\theta_{13}} = .05,$$

Decoherence parameters to account for LSND & All data

BUT: KamLand spectral distortions ? (E=energy of $\bar{\nu}$)

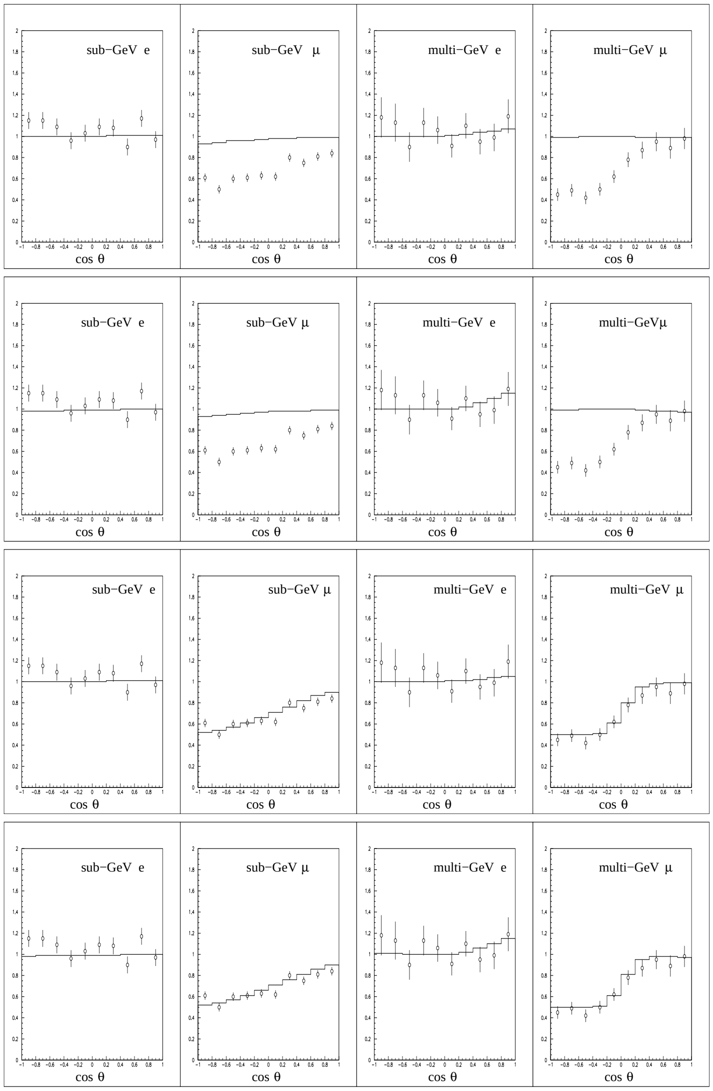
$$\overline{\gamma_{1=2=4=5}} = 2 \cdot 10^{-18} \cdot E \quad \text{QG effect},$$

$$\overline{\gamma_{3=6=7=8}} = 1 \cdot 10^{-24} / E \quad \text{ordinary} - \text{matter effect},$$

NB: mixed E dependence, disentangle QG from fake matter effects, linear decoherence only in a regime of energies (expts OK) for positivity of probabilities.

Relevance to Baryon-Asymmetry in Early Universe?

The FIT: Barenboim & NM (JHEP 0501034)



Top to bottom: (a) pure decoherence in antineutrino sector, (b) pure decoherence in both sectors, (c) mixing plus decoherence in the antineutrino sector only, (d) mixing plus decoherence in both sectors. The dots correspond to SK.

BUT recent KamLand spectral distortions not fitted this way: decoherence damping unable to fit KamLand; only oscillations OK; LSND definitely wrong? Matter effect?

GENUINE (QG) vs. MATTER-INDUCED CPT VIOLATION

Genuine vs "Fake" CPTV & Decoherence Effects

Important to distinguish: Intrinsic (genuine, due to QG) from Extrinsic ("fake") CPTV effects due to matter influences.

Matter vs QG Effects: Disentangle mainly due to Energy E dependence: QG effects increase with E, matter effects decrease with E

EXTRINSIC CPTV:

- (i) Neutral mesons: e.g. K^0, $\overline{K}^0$ in regenerator
- (ii) in neutrinos: ν, $\overline{\nu}$ in matter media.

(i) Matter regenerator scatters K^0 differently from $\overline{K}^0$, this implies. e.g. ASYMMETRY:

$$A^r_{CPT} = 2\Delta T e^{-\frac{1}{2}(\Gamma_S - \Gamma_L)t_r} \sin(\Delta m t_r)$$

NB: no dependance (to second order) on α, β, γ decoherence parameters, CAN DISENTANGLE from genuine QG (!)

[Notation: $\Delta T = \int dt(T - \overline{T})$;, $T = \frac{2\pi\mathcal{N}}{m_K}\mathcal{M}$, $\overline{T} = \frac{2\pi\mathcal{N}}{m_K}\overline{\mathcal{M}}$, $\mathcal{M} \equiv \langle K^0|A|K^0\rangle$, A =forward scatt. amplitude, N =nuclear regenerator density. $T \neq \overline{T}$]

Genuine vs "Fake" CPTV & Decoherence Effects

(ii) Passage of neutrinos through media with or without stochastically fluctuating matter density (e.g. sun, nuclear matter, atmosphere ...) causes (a) Modified oscillations (MSW effect) (b) "Fake" CPT Violation:

$\Delta P_{\alpha\beta}^{\mathrm{CPT,fake}} = P_{\alpha\beta} - P_{\overline{\beta}\overline{\alpha}} \neq 0$

L/E dependence of ΔP^{CPT} due to matter would distinguish it from QG effects, where one might have enhancement with ν energy E .

FORMALLY: if ONLY Fake CPTV effects are present:

$$\Delta P_{\alpha\beta}^{\mathrm{CPT}} = -\Delta P_{\overline{\beta}\overline{\alpha}}^{\mathrm{CPT}}$$

i.e. probability difference for $\overline{\nu}$ do not give further information. CONTRAST WITH GENUINE CPTV where $\Delta P_{\alpha\beta}^{\mathrm{CPT}} \neq \Delta P_{\overline{\beta}\overline{\alpha}}^{\mathrm{CPT}}$ due to different decoherence parameters between ν and $\overline{\nu}$ sectors.

Systematic Computations: Jacobson-Ohlsson, hep-ph/0305064

"Fake" CPTV & neutrinos

Experiment	CPT probability differences	
	Quantities	Numerical value
BNL NWG	$\Delta P_{\mu e}^{\rm CPT}$	0.010
BNL NWG	$\Delta P_{\mu e}^{\rm CPT}$	0.032
BooNE	$\Delta P_{\mu e}^{\rm CPT}$	$6.6 \cdot 10^{-13}$
MiniBooNE	$\Delta P_{\mu e}^{\rm CPT}$	$4.1 \cdot 10^{-14}$
CHOOZ	$\Delta P_{ee}^{\rm CPT}$	$-3.6 \cdot 10^{-5}$
ICARUS	$\Delta P_{\mu e}^{\rm CPT}$	$4.0 \cdot 10^{-5}$
	$\Delta P_{\mu \tau}^{\rm CPT}$	$-3.8 \cdot 10^{-5}$
JHF-Kamioka	$\Delta P_{\mu e}^{\rm CPT}$	$3.8 \cdot 10^{-3}$
	$\Delta P_{\mu \mu}^{\rm CPT}$	$-1.3 \cdot 10^{-4}$
K2K	$\Delta P_{\mu e}^{\rm CPT}$	$1.0 \cdot 10^{-3}$
	$\Delta P_{\mu \mu}^{\rm CPT}$	$-5.3 \cdot 10^{-5}$

Experiment	CPT probability differences	
	Quantities	Numerical value
KamLAND	$\Delta P_{ee}^{\rm CPT}$	-0.033
LSND	$\Delta P_{\mu e}^{\rm CPT}$	$4.8 \cdot 10^{-15}$
MINOS	$\Delta P_{\mu e}^{\rm CPT}$	$1.9 \cdot 10^{-4}$
	$\Delta P_{\mu \mu}^{\rm CPT}$	$-1.1 \cdot 10^{-5}$
NuMI I	$\Delta P_{\mu e}^{\rm CPT}$	0.026
NuMI II	$\Delta P_{\mu e}^{\rm CPT}$	$2.6 \cdot 10^{-3}$
NuTeV	$\Delta P_{\mu e}^{\rm CPT}$	$1.6 \cdot 10^{-18}$
NuTeV	$\Delta P_{\mu e}^{\rm CPT}$	$8.2 \cdot 10^{-20}$
OPERA	$\Delta P_{\mu \tau}^{\rm CPT}$	$-3.8 \cdot 10^{-5}$
Palo Verde	$\Delta P_{ee}^{\rm CPT}$	$-1.2 \cdot 10^{-5}$
Palo Verde	$\Delta P_{ee}^{\rm CPT}$	$-2.2 \cdot 10^{-5}$

Table 3: Extrinsic CPT pds for some past, present, and fututre long-baseline experiments (Jacobson-Ohlsson, hep-ph/0305064).

NB: Extrinsic CPTV negligible for future ν factories ($\sim 10^{-5}$), sensitive to genuine CPTV? (study for 2 cases: $L \sim 3000\ Km, 7000\ Km, hep-ph/0305064$)

"Fake" Decoherence & Neutrinos

Another "Fake" Effect: Gaussian Averaged ν-oscillations can produced Damping (a lá Decoherence) (T. Ohlsson, hep-ph/0012272)

Recall scillation formula:

$$P_{\alpha\beta} = P_{\alpha\beta}(L, E) =$$

$$\delta_{\alpha\beta} - 4\sum_{a=1}^{n}\sum_{\beta=1, a<b}^{n} \mathrm{Re}\left(U^*_{\alpha a} U_{\beta a} U_{\alpha b} U^*_{\beta b}\right) \sin^2\left(\frac{\Delta m^2_{ab} L}{4E}\right)$$

$$-2\sum_{a=1}^{n}\sum_{b=1, a<b}^{n} \mathrm{Im}\left(U^*_{\alpha a} U_{\beta a} U_{\alpha b} U^*_{\beta b}\right) \sin\left(\frac{\Delta m^2_{ab} L}{2E}\right)$$

where $\alpha, \beta = e, \mu, \tau, ..., \; a, b = 1, 2, ...n,$
$\Delta m^2_{ab} = m^2_a - m^2_b$

BUT...UNCERTAINTIES for E IN PRODUCTION OF ν-WAVE; Also: NOT WELL-DEFINED PROPAGATION LENGTH L :

$$\Delta E \neq 0, \qquad \Delta L \neq 0$$

Hence, have to AVERAGE Oscillation Probabilitty P over L/E Dependance.

“Fake” Decoherence & Neutrinos

GAUSSIAN AVERAGE: Approximate $\langle L/E \rangle \simeq \langle L \rangle / \langle E \rangle$

$$\langle P \rangle = \int_{-\infty}^{\infty} \mathrm{d}x \; P(x) \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\ell)^2}{2\sigma^2}}$$

$\ell \equiv \langle x \rangle$, $\sigma = \sqrt{\langle (x - \langle x \rangle)^2}$, $x = L/4E$.

AVERAGE $\langle P_{\alpha\beta} \rangle$:

$$\langle P_{\alpha\beta} \rangle = \delta_{\alpha\beta} - 2\sum_{a=1}^{n}\sum_{\beta=1,a<b}^{n} \mathrm{Re}\left(U^*_{\alpha a} U_{\beta a} U_{\alpha b} U^*_{\beta b}\right)\left(1 - \cos(2\ell\Delta m^2_{ab}) e^{-2\sigma^2(\Delta m^2_{ab})^2}\right) - 2\sum_{a=1}^{n}\sum_{b=1,a<b}^{n} \mathrm{Im}\left(U^*_{\alpha a} U_{\beta a} U_{\alpha b} U^*_{\beta b}\right) \sin(2\ell\Delta m^2_{ab}) e^{-2\sigma^2(\Delta m^2_{ab})^2}$$

NB: Damping factors due to σ (!)

“Fake” Decoherence & Neutrinos

EXAMPLE: TWO FLAVOURS

$$\langle P_{\alpha\beta}\rangle = \frac{1}{2}\sin^2 2\theta\left(1 - e^{-2\sigma^2(\Delta m^2)^2}\cos(2\ell\Delta m^2)\right), \; \ell = \frac{\langle L\rangle}{4\langle E\rangle}$$

Bounds on σ (T. Ohlsson)

- Pessimistic: $\sigma \simeq \Delta x \simeq \Delta\frac{L}{4E} \leq \frac{\langle L\rangle}{4\langle E\rangle}\left(\frac{\Delta L}{\langle L\rangle} + \frac{\Delta E}{\langle E\rangle}\right)$
- Optimistic: $\sigma \leq \frac{\langle L\rangle}{4\langle E\rangle}\left([\frac{\Delta L}{\langle L\rangle}]^2 + [\frac{\Delta E}{\langle E\rangle}]^2\right)^{1/2}$

“Fake” Decoherence & Neutrinos

Equivalence with Lindblad decoherence:

$\dot{\rho} = i[\rho, H] + \mathcal{D}[\rho]$, $\mathcal{D}[\rho] = \sum_{i=1}^{n}[D_i, [D_i, \rho]]$

(if $D_i^\dagger = D_i$, energy is conserved on average, and the ρ is a completely positive map) (Adler 2000)

Example: TWO FLAVOURS: One Decoherence Coefficient γ ($L = t$, $c = 1$):

$$P_{e\mu}(L, E) = \frac{1}{2}\sin^2 2\theta \left(1 - e^{-\gamma L}\cos(\frac{\Delta m^2 L}{2E})\right)$$

COMPARE WITH “FAKE” GAUSSIAN AVERAGE:

$2\sigma^2(\Delta m^2)^2 = \gamma L \quad \rightarrow \quad \gamma = \frac{(\Delta m^2)^2}{8E^2} L r^2$

with $\sigma = (L/4E)r$, $r = \frac{\Delta L}{L} + \frac{\Delta E}{E}$ (pessimistic), or $r = \sqrt{(\frac{\Delta L}{L})^2 + (\frac{\Delta E}{E})^2}$ (optimistic).

For atmospheric ν: $\sigma_{\rm atm} \sim 1.5 \times 10^3$ eV^2 (for $L \sim 12000\ Km$), $r \sim \mathcal{O}(1)$, hence

$$\gamma_{\rm atm,fake} < 10^{-24}\ {\rm GeV}$$

COMPARE WITH QG: (i) optimistic (Ellis, NM, Nanopoulos) : $\gamma_{QG} \sim E^2/M_{QG}$, (ii) pessimistic: (Adler) $\gamma_{QG} \sim \frac{(\Delta m^2)^2}{E^2 M_{QG}}$.

NB: In QG NO L Dependence, but $1/M_{QG}$ (in 4-dim $M_{QG} \sim M_P \sim 10^{19}$ GeV) CAN DISENTANGLE (!)

“Fake” Decoherence & Neutrinos

NB: GAUSSIAN AVERAGE ALSO DUE TO QUANTUM-GRAVITY UNCERTAINTIES:

If Δ/L is due to “Fuzzyness” of space time due to quantum fluctuations, then (Van Dam, Ng, Ellis, NM, Nanopoulos)

$$\frac{\Delta L}{L}, \quad \frac{\Delta E}{E} \sim \beta \left(\frac{E}{M_{QG}}\right)^{\alpha},$$

α some positive integer, $\alpha \geq 1$, β some coefficient. In this case $r \sim \beta \left(\frac{E}{M_{QG}}\right)^{\alpha}$.

Then, from Gaussian Average we get for Decoherence:

$$\gamma \sim \frac{(\Delta m^2)^2}{8E^2}\beta \left(\frac{E}{M_{QG}}\right)^{\alpha} L$$

NB: modified E-dependence, but still $\propto L$.

INTERESTING TO EXPLORE FURTHER...

HOWEVER, IN GENERAL SUCH EFFECTS CAN BE DISENTANGLED FROM OTHER α, β, γ COEFFICIENTS OR STOCHASTIC-MEDIUM EFFECTS BY THEIR L DEPENDENCE...

Decoherence, ν-mass differences and Dark Energy ?

Barenboim & NM (PRD70:093015,2004)

Some amusing speculations, irrespective of LSND fit...

Field Theories with Mixing: Canonical Fock Space quantisation? (Blasone & Vitiello 1995):

Quantum field theory (QFT) requires infinite volume limit. In contrast to quantum mechanical treatment of fixed volume (Pontecorvo), the neutrino *flavour* states are *orthogonal* to the *energy* eigenstates. They define two inequivalent vacua related by a *non unitary* transformation.

Modified Oscillation Formulae.

Flavour vacuum $|0\rangle$, correct one, conserves probability (Blasone, Henning, Vitiello 1999).

Flavour-vacuum average of Energy-momentum tensor T_{00} of (a Dirac) fermion field in the Robertson-Walker space-time background **is non zero**:

$$_f\langle 0|T_{00}|0\rangle_f = 8\pi \sin^2\theta (\Delta m^2)^2$$

correct order phenomenologically for Dark Energy.

NB: Δm^2 might be due to decoherence if quantum gravity operates as a CPTV medium (c.f. MSW effect?). CPTV and Cosmological constant linked (c.f. above).

CONCLUDING QUESTIONS

Various ways for Quantum Gravity (QG)-induced CPT breaking, in principle independent, e.g. decoherence and Lorentz Violation are independent effects. One may have Lorentz invariant decoherence in QG (Millburn).

Neutrino Physics may provide most stringent (to date) constraints on QG CPT Violation.

Interesting theoretical issues on QG decoherence, neutrino mass differences and dark Energy.

There are plenty of low energy nuclear and atomic physics experiments which yield stringent bounds in QG models with Lorentz (LV) and CPT violation. Frame dependence of LV effects crucial.

Antimatter factories very useful in placing stringent bounds on some of these LV & CPTV parameters via spectroscopic measurements, provided frequency resolution improves.But what about QG decoherence effects sensitivity of antimatter factories?

Neutral meson factories (B, ϕ), EPR modifications due to decoherence-CPTV, novel effects with future?

What about Equivalence principle and QG?: are QG effects universal among particle species? ...

A Century after *annus mirabilis*, still a long way to go...