QUANTUM GRAVITY DECOHERENCE & Intrinsic CPT Violation in entangled states

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Trieste (Italy), 21-25 October 2008

OUTLINE

- Theoretical motivation for CPT Violation (CPTV) :
- (i) Lorentz violation (LV): microscopic & cosmological

  → Briefly

(ii) Quantum Gravity Foam (QGF) (Decoherence)

  → This talk

- Towards microscopic models from (non-critical) strings &

  Order of magnitude estimates of expected effects

  → This talk

- TeV photon astrophysics LV tests
- Precision tests of QGF-CPTV of smoking-gun-evidence type:

  neutral mesons factories – entangled states: EPR correlations modified (ω-effect)

  Disentangling (i) from (ii)

  ω-effect as discriminant of space-time foam models

  → This talk

- Neutrino Tests of QG decoherence Damping factors in flavour Oscillation Probabilities – suppressed though by neutrino mass differences

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IMPORTANT : QUANTUM GRAVITY DECOHERENCE CURRENT BOUNDS &

MICROSCOPIC BLACK HOLES AT LHC

Details of microscopic model matter a lot before concusions are reached in excluding large extra dimensional models by such decoherence studies…

Generic Theory Issues

- **CPT SYMMETRY:**
  - (1) Lorentz Invariance, (2) Locality , (3) Unitarity
    - **Theorem proven for FLAT space times**

      (Jost, Luders, Pauli, Bell, Greenberg)
- **Why CPT Violation?**
  - Quantum Gravity (QG) Models violating Lorentz and/or Quantum Coherence:

(I) Space-time foam: QG as "Environment"

→ **Decoherence, CPT Ill defined (Wald 1979)**

(II) Standard Model Extension: Lorentz Violation in Hamiltonian H:

Non-commutative Field Theory

→ **CPT well defined but non-commuting with H**

(III) Loop QG/space-time background independent; Non-linearly Deformed Special Relativities : Quantum version not fully understood…

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.

$$\Theta \mathcal{L}(x) \Theta^\dagger = \mathcal{L}(-x) \; ,$$

$$\Theta = CPT \; , \; \mathcal{L} = \mathcal{L}^\dagger \; \text{(Lagrangian)}$$

Theorem due to: Jost, Pauli (and John Bell).

Jost proof uses covariance trnsf. properties of Wightman's functions (i.e. quantum-field-theoretic (off-shell) correlators of fields $< 0|\phi(x_1) \dots \phi(x_n)|0 >$) under Lorentz group. (O. Greenberg, hep-ph/0309309)

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

E.g.: LORENTZ-VIOLATING NON-TRIVIAL VACUA OF STRINGS, SPACE-TIME FOAMY SITUATIONS IN SOME QUANTUM GRAVITY MODELS.

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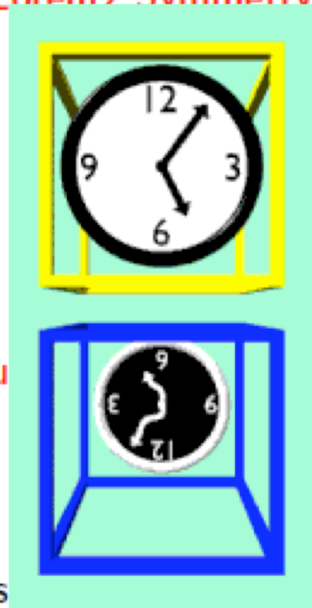

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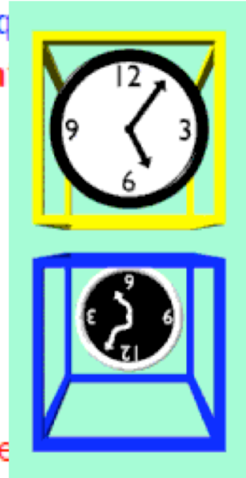

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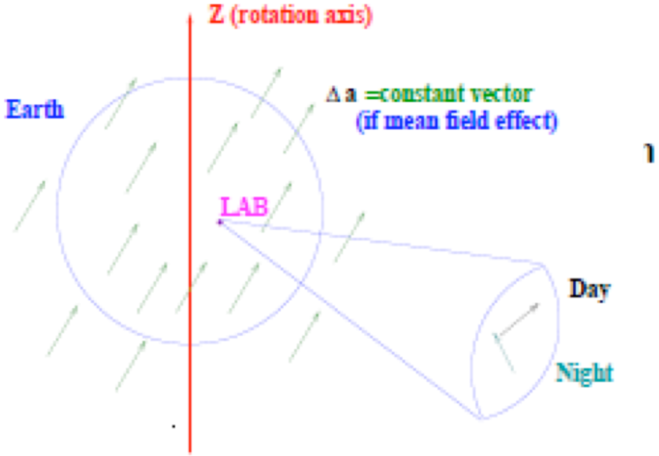

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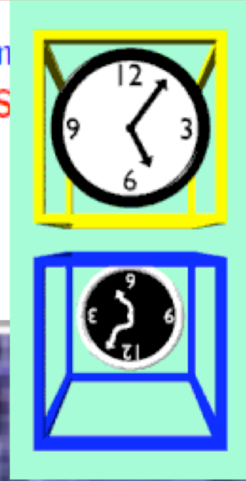

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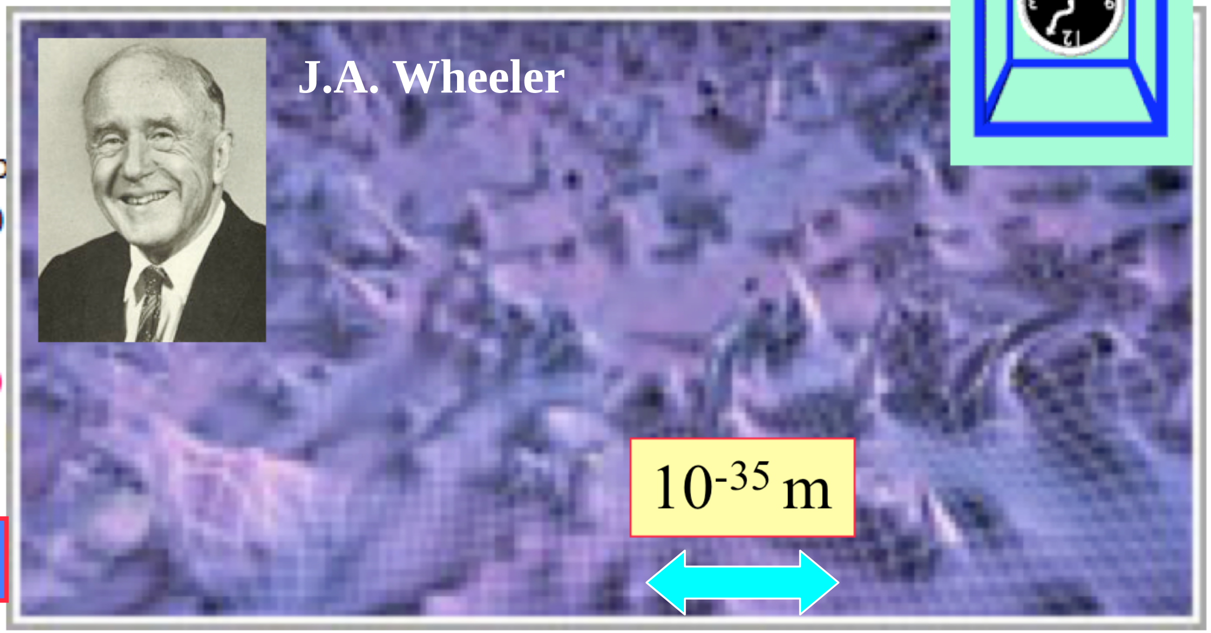

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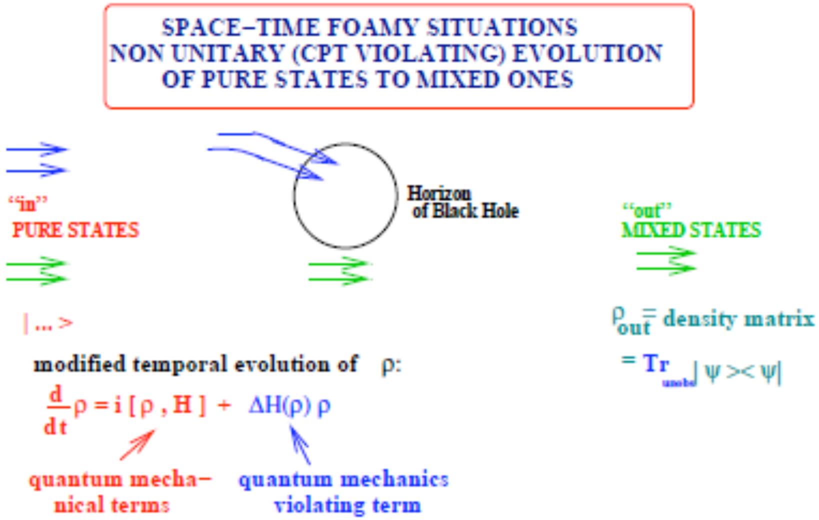
Space-time Foam

SITUATIONS IN SOME QUANTUM GRAVITY MODELS.

SPACE-TIME FOAM AND UNITARITY VIOLATION

SPACE-TIME FOAM: Quantum Gravity SINGULAR Fluctuations (microscopic (Planck size) black holes etc) MAY imply: pure states $\rightarrow$ mixed



$\rho_{out} = \mathrm{Tr}_{\mathrm{unobs}}|out><out| = \$ \, \rho_{in}$, $\$ \neq SS^{\dagger}$, $S = e^{iHt}$ =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- BUT NO PROOF AS YET... OPEN ISSUE...

SPACE-TIME FOAM AND UNITARITY VIOLATION

Arguments in favour of holographic picture :

Path Integral over non-trivial BH topologies decays with time, leaving only trivial (unitary) topology contributions (**Maldacena, Hawking**)

Arguments against resolution of issue:

(i) not rigorous proof though over space-time measure.

(ii) Entanglement entropy (**Srednicki**, **Einhorn, Brustein,Yarom**).

(iii) Also, Space-time foam may be of different type, e.g. due to stochastic space-time point-like defects crossing brane worlds (**D-particle foam**) **….(Ellis, NM, Nanopoulos, Sarkar).**

Hence possible non-trivial decoherence effects in effective theories. Worth checking experimentally…. → CPTV issues

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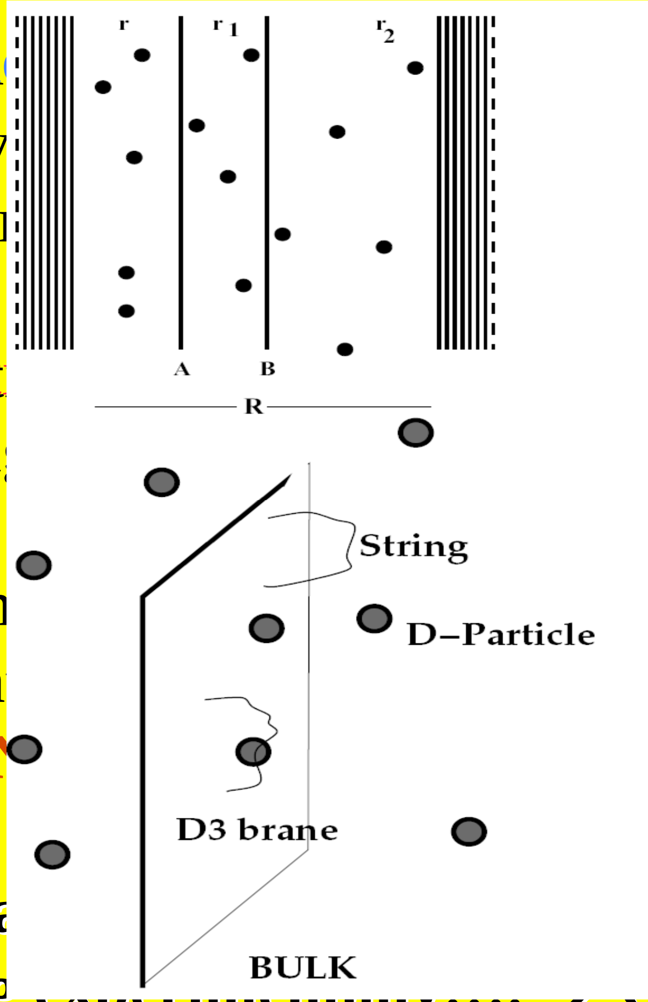

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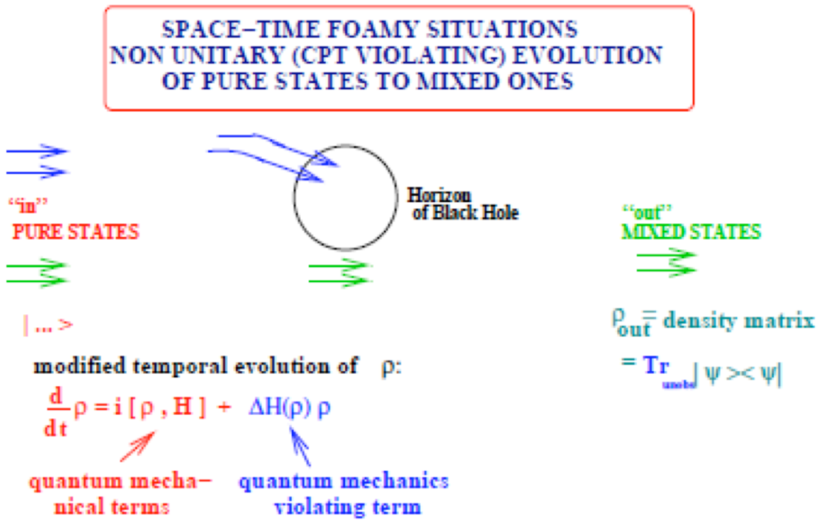

In general, in space-times with Horizons (e.g. De Sitter cosmology…)

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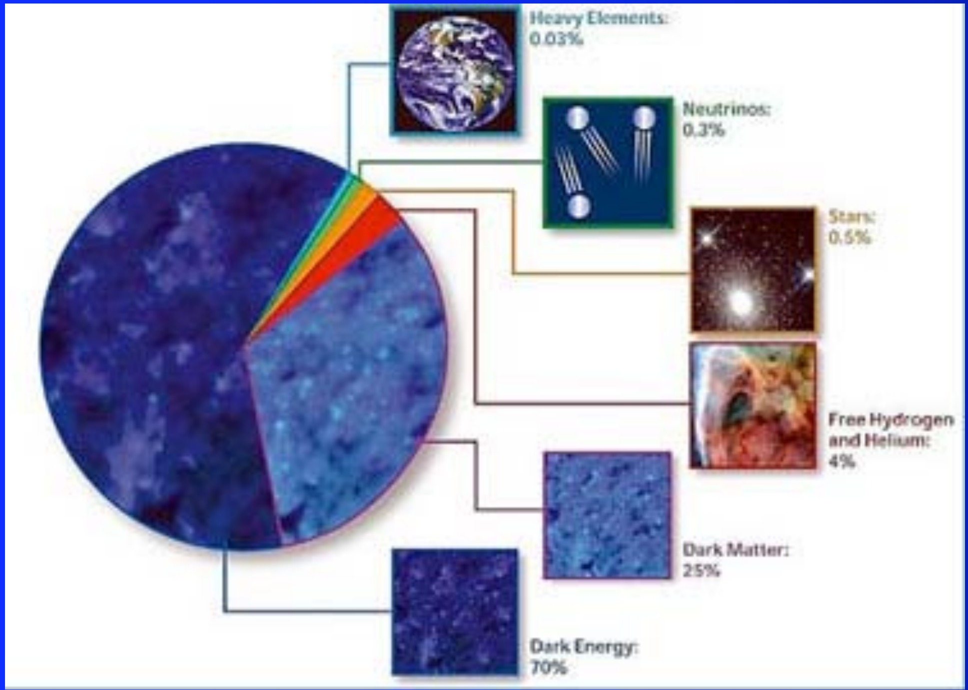
COSMOLOGICAL MOTIVATION FOR CPT VIOLATION?



Supernova and CMB Data (2006)
Baryon oscillations, Large Galactic Surveys & other data (2008)

Evidence for :

Dark Matter(23%)

Dark Energy (73%)

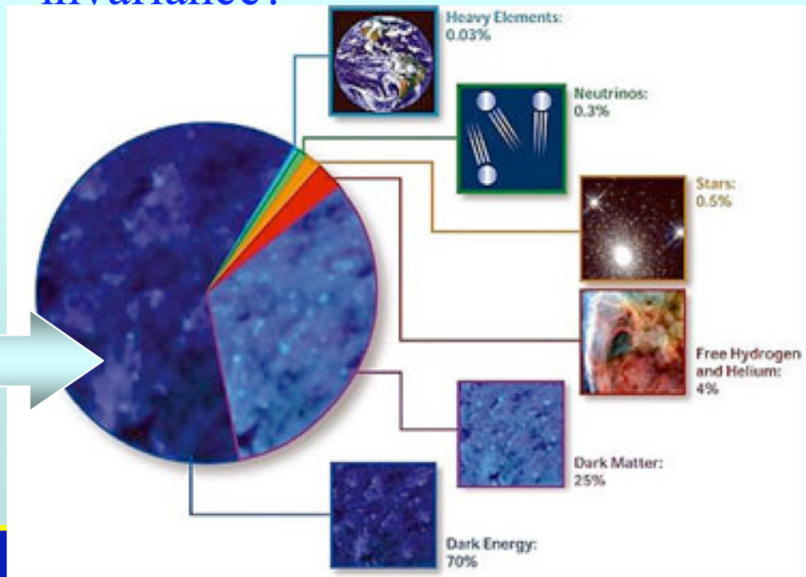
Ordinary matter (4%)

DARK ENERGY& Cosmological CPTV?

- KNOW VERY LITTLE ABOUT IT…
- EMBARASSING SITUATION 74% OF THE UNIVERSE BUDGET CONSISTS OF UNKNOWN SUBSTANCE

- **Could be:**
  - a Cosmological Constant
  - Quintessence (scalar field relaxing to minimum of its potential)
  - Something else…Extra dimensions, colliding bran worlds *etc.*

- Certainly of Quantum Gravitational origin
- If cosmological constant (de Sitter), then quantization of field theories not fully understood due to cosmic h CPT invariance?



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$$ds^2 = -(1 - \frac{2G_N m}{r} - \frac{\Lambda}{3}r^2)dt^2 + (1 - \frac{2G_N m}{r} - \frac{\Lambda}{3}r^2)^{-1}dr^2 + dr^2(d\theta^2 + \sin^2\theta d\phi^2)$$

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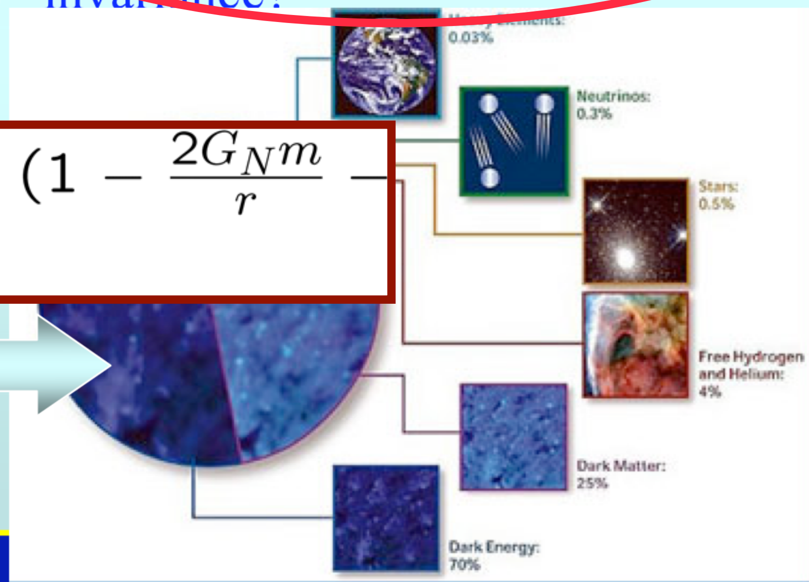

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Outer Horizon (live ``inside'' black hole):

Unstable, indicates expansion

$$r = \sqrt{3/\Lambda}$$

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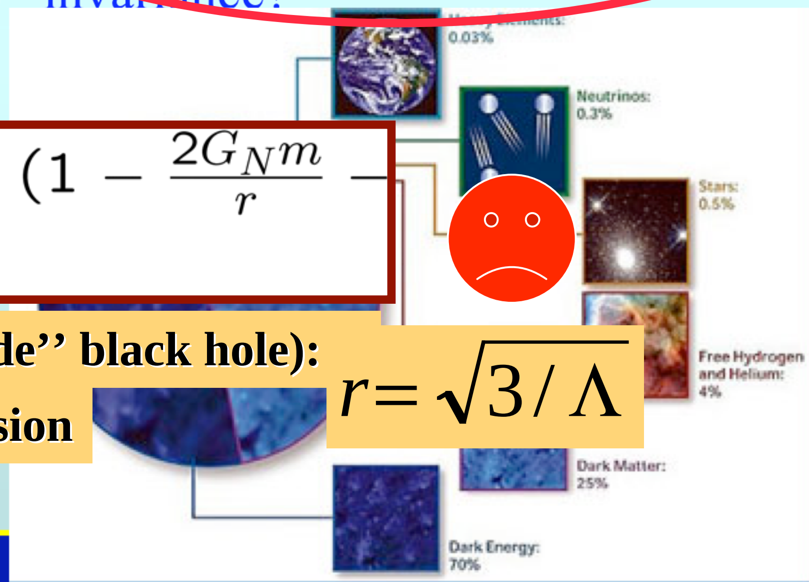

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$$ds^2_{FRW} = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

$$a(t) = e^{\sqrt{\frac{\Lambda}{3}}t}$$

  - Something else…Extra dimensions, colliding brane worlds *etc.*

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- If cosmological constant (de Sitter), then quantization of field theories not fully understood due to cosmic horizon → CPT invariance?

Global (Cosmological FRW solution)

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  - Something else…Extra

Cosmological (global) deSitter horizon: (Observer dependent, though…)

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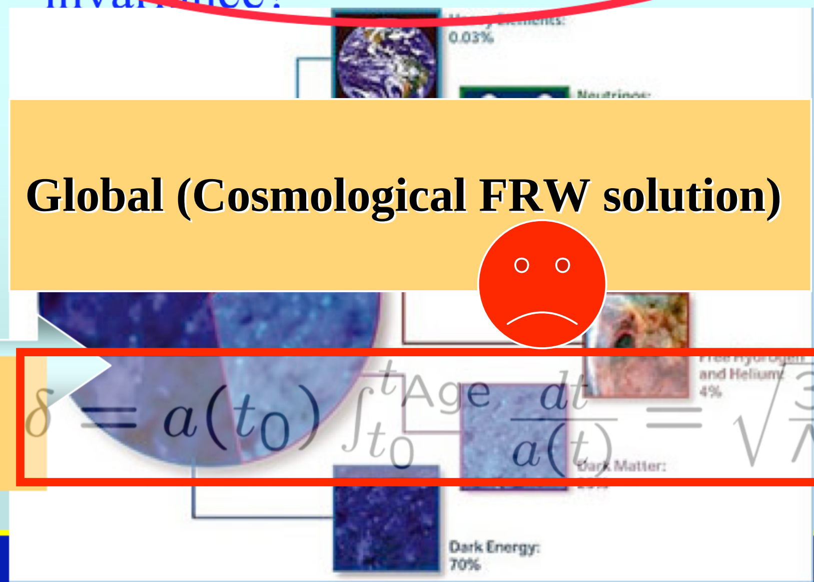
- If cosmological constant (de Sitter), then quantization of field theories not fully understood due to cosmic h… → CPT invariance?



Global (Cosmological FRW solution)

$$\delta = a(t_0)\int_{t_0}^{t_{Age}} \frac{dt}{a(t)} = \sqrt{\frac{3}{\Lambda}}$$

Space-Time Foam & Intrinsic CPT Violation

A THEOREM BY R. WALD (1979): **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 operator Θ : $\Theta\overline{\rho}_{in} = \rho_{out}$

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

But $\overline{\rho}_{out} = \$\overline{\rho}_{in}$, hence : $\overline{\rho}_{in} = \Theta^{-1}\$\Theta^{-1}\ \$\ \overline{\rho}_{in}$

BUT THIS IMPLIES THAT \$ HAS AN INVERSE- $\Theta^{-1}\$\Theta^{-1}$, IMPOSSIBLE (information loss), hence CPT MUST BE VIOLATED (at least in its strong form).

NB1: IT ALSO IMPLIES: $\Theta = \$\ \Theta^{-1}\ \$$ (fundamental relation for a full CPT invariance).

NB2: My preferred way of CPTV by Quantum Gravity Introduces fundamental arrow of time/microscopic time irreversibility...

NB3: Effective theories decoherence, i.e. (low-energy) experimenters do not have access to all d.o.f. of quantum gravity (e.g. back-reaction effects...)

CPT symmetry without CPT invariance ?

But....nature may be tricky: WEAK FORM OF CPT INVARIANCE might exist, such that the fundamental "arrov 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,
$\Theta\rho = \theta\rho\theta^\dagger, \quad \theta^\dagger = -\theta^{-1}$ (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: $\$ = SS^\dagger$, $\$^\dagger = \$^{-1}$).

CPT symmetry without CPT invariance ?

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Probab...

ϕ =fin...

where ...

$\Theta\rho =$ ...

In term...

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.**

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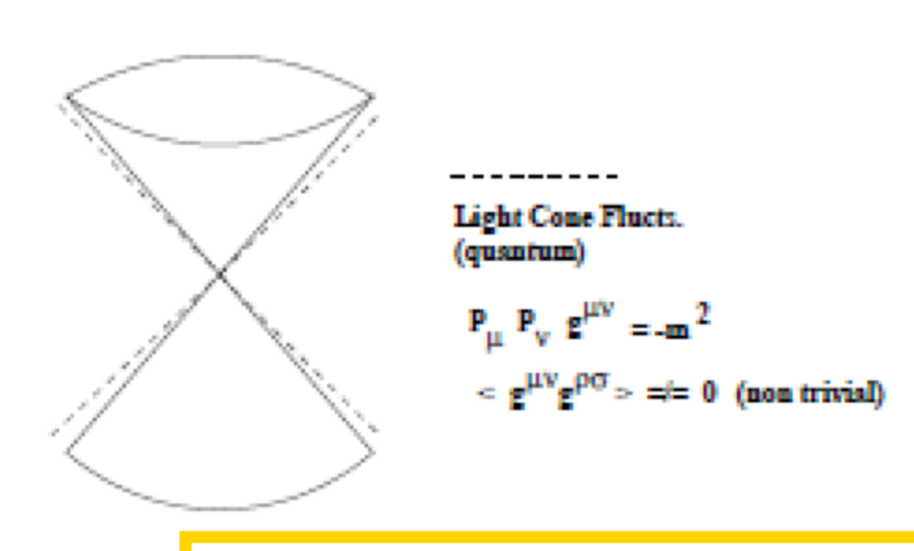
Stochastic Light-Cone Fluctuations



CPT may also be violated in such stochastic models

"Fuzzy" Space times may induce (Ford, Yu 1994, 2000): $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, $\langle g_{\mu\nu} \rangle = \eta_{\mu\nu}$ BUT $\langle h_{\mu\nu}(x) h_{\lambda\sigma}(x') \rangle \neq 0$, , i.e. Quantum light cone fluctuations BUT NOT mean-field effects on dispersion relations, that is, Lorentz symmetry is respected on average BUT not on individual measurements. Path of light: null geodesics $0 = ds^2 = g_{\mu\nu} dx^\mu dx^\nu$. Fluctuations: Geodesic deviations $\frac{D^2 n^\mu}{d\tau^2} = -R^\mu_{\alpha\nu\beta} u^\alpha n^\nu u^\beta$, quantum fluctuate.

Fluctuations in arrival time of photons at detector: ($|\phi\rangle$=state of gravitons, $|0\rangle$= vacuum state)

$$\Delta t^2_{obs} = |\Delta t^2_\phi - \Delta t^2_0| = \frac{|\langle \phi | \sigma_1^2 | \phi \rangle - \langle 0 | \sigma_1^2 | 0 \rangle|}{r^2} \equiv \frac{|\langle \sigma_1^2 \rangle_R|}{r} .$$

$$\langle \sigma_1^2 \rangle_R = \frac{1}{8} (\Delta r)^2 \int_{r_0}^{r_1} dr \int_{r_0}^{r_1} dr' \; n^\mu n^\nu n^\rho n^\sigma \; \langle \phi | h_{\mu\nu}(x) h_{\rho\sigma}(x') + h_{\mu\nu}(x') h_{\rho\sigma}(x) | \phi \rangle$$

Caution on CPTV & Lorentz Violation

- **CPT Operator well defined but NON-Commuting with Hamiltonian [H , Θ] $\neq$ 0**
  - Lorentz & CPT Violation in the Hamiltonian
    - **Neutral Mesons & Factories, Atomic Physics, Anti-matter factories, Neutrinos, …**
    - **Modified Dispersion Relations (GRB, neutrino oscillations, synchrotron radiation…)**

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- **CAUTION:**
  LV does not necessarily imply CPTV

e.g. Standard Model Extension,

Non-commutative Geometry field theories

STANDARD MODEL EXTENSION

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

In this case Lorentz symmetry is violated and hence CPT, but no quantum decoherence or unitarity loss. CPT well-defined operator, does not commute with Hamiltonian of the system.

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

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua MODIFIED DIRAC EQUATION in SME: for spinor ψ reps. electrons, quarks etc. with 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 $D_\mu = \partial_\mu - A^a_\mu T^a - qA_\mu$.

CPT & Lorentz violation: a_μ , b_μ. Lorentz violation only: $c_{\mu\nu}$, $d_{\mu\nu}$, $H_{\mu\nu}$.

NB1: : mass differences between particle/antiparticle not necessarily.

NB2: In general $a_\mu, b_\mu \dots$ might be energy dependent and NOT constants (c.f. Lorentz-Violation due to quantum space time foam, back reaction effects); ALSO in stochastic models of QG (c.f. below) $\langle a_\mu \, , b_\mu \rangle = 0$, $\langle a_\mu a_\nu \rangle \neq 0$, $\langle b_\mu a_\nu \rangle \neq 0$, $\langle b_\mu b_\nu \rangle \neq 0$, etc ... much more suppressed effects

Non-commutative effective field theories

$$[x^\mu, x^\nu] = i\theta^{\mu\nu}$$

Moyal $\star$ products

$$f \star g(x) \equiv \exp(\tfrac{1}{2} i\theta^{\mu\nu}\partial_{x^\mu}\partial_{y^\nu}) f(x) g(y)\big|_{x=y}$$

$$\mathcal{L} = \tfrac{1}{2} i \overline{\widehat{\psi}} \star \gamma^\mu \overset{\leftrightarrow}{\widehat{D}_\mu} \widehat{\psi} - m\overline{\widehat{\psi}} \star \widehat{\psi} - \frac{1}{4q^2}\widehat{F}_{\mu\nu} \star \widehat{F}^{\mu\nu}$$

$$\widehat{D}_\mu \widehat{\psi} = \partial_\mu \widehat{\psi} - i\widehat{A}_\mu \star \widehat{\psi}$$

$$\widehat{f} \star \overset{\leftrightarrow}{\widehat{D}_\mu} \widehat{g} \equiv \widehat{f} \star \widehat{D}_\mu \widehat{g} - \widehat{D}_\mu \widehat{f} \star \widehat{g}$$

$$\theta_{\mu\nu}\theta^{\mu\nu} > 0$$

$$\widehat{A}_\mu = A_\mu - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha(\partial_\beta A_\mu + F_{\beta\mu}),$$
$$\widehat{\psi} = \psi - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha \partial_\beta \psi.$$

$$D_\mu \psi = \partial_\mu \psi - iqA_\mu \psi$$

$$\begin{aligned}\mathcal{L} = {} & \tfrac{1}{2} i\overline{\psi}\gamma^\mu \overset{\leftrightarrow}{D_\mu} \psi - m\overline{\psi}\psi - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & -\tfrac{1}{8} iq\theta^{\alpha\beta}F_{\alpha\beta}\overline{\psi}\gamma^\mu \overset{\leftrightarrow}{D_\mu} \psi + \tfrac{1}{4} iq\theta^{\alpha\beta}F_{\alpha\mu}\overline{\psi}\gamma^\mu \overset{\leftrightarrow}{D_\beta} \psi \\ & +\tfrac{1}{4} mq\theta^{\alpha\beta}F_{\alpha\beta}\overline{\psi}\psi \\ & -\tfrac{1}{2} q\theta^{\alpha\beta}F_{\alpha\mu}F_{\beta\nu}F^{\mu\nu} + \tfrac{1}{8} q\theta^{\alpha\beta}F_{\alpha\beta}F_{\mu\nu}F^{\mu\nu}.\end{aligned}$$

CPT invariant SME type field theory (Q.E.D.) - only even number of indices appear in effective non-renormalisable terms. (Carroll et al. hep-th/0105082)

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Moyal $\star$ products

$$f \star g(x) \equiv \exp(\tfrac{1}{2} i\theta^{\mu\nu}\partial_{x^\mu}\partial_{y^\nu}) f(x) g(y)\big|_{x=y}$$

$$\mathcal{L} = \tfrac{1}{2} i\overline{\widehat{\psi}} \star \gamma^\mu \overleftrightarrow{\widehat{D}_\mu}\, \widehat{\psi} - m\overline{\widehat{\psi}} \star \widehat{\psi} - \frac{1}{4q^2}\widehat{F}_{\mu\nu} \star \widehat{F}^{\mu\nu}$$

$$\widehat{D}_\mu \widehat{\psi} = \partial_\mu \widehat{\psi} - i\widehat{A}_\mu \star \widehat{\psi}$$

$$\widehat{f} \star \overleftrightarrow{\widehat{D}_\mu}\, \widehat{g} \equiv \widehat{f} \star \widehat{D}_\mu \widehat{g} - \widehat{D}_\mu \widehat{f} \star \widehat{g}$$

$$\theta_{\mu\nu}\theta^{\mu\nu} > 0$$

$$\widehat{A}_\mu = A_\mu - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha(\partial_\beta A_\mu + F_{\beta\mu}),$$
$$\widehat{\psi} = \psi - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha \partial_\beta \psi.$$

$$D_\mu \psi = \partial_\mu \psi - iqA_\mu \psi$$

$$\begin{aligned}\mathcal{L} = {} & \tfrac{1}{2} i\overline{\psi}\gamma^\mu \overleftrightarrow{D_\mu}\, \psi - m\overline{\psi}\psi - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & -\tfrac{1}{8} iq\theta^{\alpha\beta} F_{\alpha\beta}\overline{\psi}\gamma^\mu \overleftrightarrow{D_\mu}\, \psi + \tfrac{1}{4} iq\theta^{\alpha\beta} F_{\alpha\mu}\overline{\psi}\gamma^\mu \overleftrightarrow{D_\beta}\, \psi \\ & +\tfrac{1}{4} mq\theta^{\alpha\beta} F_{\alpha\beta}\overline{\psi}\psi \\ & -\tfrac{1}{2} q\theta^{\alpha\beta} F_{\alpha\mu}F_{\beta\nu}F^{\mu\nu} + \tfrac{1}{8} q\theta^{\alpha\beta} F_{\alpha\beta}F_{\mu\nu}F^{\mu\nu}.\end{aligned}$$

CPT invariant SME type field theory (Q.E.D.) - only even number of indices appear in effective non-renormalisable terms. (Carroll et al. hep-th/0105082)

STANDARD MODEL EXTENSION

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

In this case Lorentz symmetry is violated and hence CPT, but no quantum decoherence or unitarity loss. CPT well-defined operator, does not commute with Hamiltonian of the system.

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

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua MODIFIED DIRAC EQUATION in SME: for spinor ψ reps. electrons, quarks etc. with 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 $D_\mu = \partial_\mu - A^a_\mu T^a - qA_\mu$.

CPT & Lorentz violation: a_μ , b_μ. Lorentz violation only: $c_{\mu\nu}$, $d_{\mu\nu}$, $H_{\mu\nu}$.

NB1: : mass differences between particle/antiparticle not necessarily.

NB2: In general $a_\mu, b_\mu \dots$ might be energy dependent and NOT constants (c.f. Lorentz-Violation due to quantum space time foam, back reaction effects); ALSO in stochastic models of QG (c.f. below) $\langle a_\mu \, , b_\mu \rangle = 0$, $\langle a_\mu a_\nu \rangle \neq 0$, $\langle b_\mu a_\nu \rangle \neq 0$, $\langle b_\mu b_\nu \rangle \neq 0$, etc ... much more suppressed effects

Lorentz Violation & Anti-Hydrogen

❖ **Trapped Molecules:**

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)

Tests of Lorentz Violation in Neutral Kaons

(A. Kostelecky, hep-ph/9809572 (PRL))

Wave-function of neutral Kaon: Ψ (two-component $K^0, \overline{K}^0$)

Evolution within quantum mechanics but Lorentz & CPT Violation: $i\partial_t \Psi = \mathcal{H}\Psi$

$\mathcal{H} \quad \ni$ CP-violation: $\epsilon_K \sim 10^{-3}$ & CPT-violation δ_K, $\delta_K \sim (\mathcal{H}_{11} - \mathcal{H}_{22})/2\Delta\lambda$, $\Delta\lambda$ eigenvalue difference.

NB: $\mathcal{H}_{11} - \mathcal{H}_{22}$ is flavour diagonal. Parameter δ_K must be C violating but P,T preserving (c.f. strong interaction properties in neutral meson evolution):

Hence look for terms in SME that are flavour diagonal, violate C but preserve T, P. δ_K sensitive ONLY to $-a^q_\mu \overline{q}\gamma_\mu q$ terms in SME (q quark fields, meson composition: $M = q_1\overline{q}_2$):

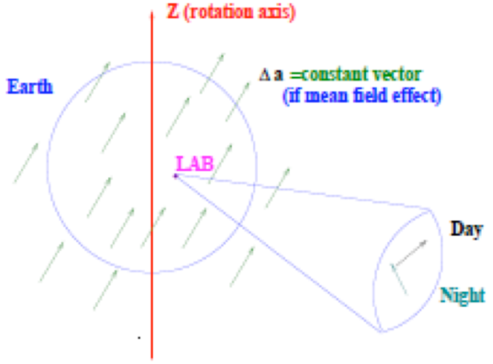
$$\delta_K \simeq i \sin\widehat{\phi} \exp(i\widehat{\phi})\gamma \left(\Delta a_0 - \vec{\beta}_K \cdot \Delta\vec{a}\right) /\Delta m,$$

S=short-lived, L=long-lived, I=interference term, $\Delta m = m_L - m_S$, $\Delta\Gamma = \Gamma_S - \Gamma_L$,

$\widehat{\phi} = \arctan(2\Delta m/\Delta\Gamma)$, $\quad \Delta a_\mu \equiv a^{q_2}_\mu - a^{q_1}_\mu$, and $\beta^\mu_K = \gamma(1, \vec{\beta}_K)$ is the 4-velocity of boosted kaon.

EXPERIMENTAL BOUNDS

Experimental bounds on a_μ: Look for sidereal variations of δ_K (day-night effects):



From KTeV: $\Delta a_X, \Delta a_Y < 9.2 \times 10^{-22}$ GeV.

From ϕ factories: (NB: additional polar (θ) and azimuthal (ϕ) angle dependence of δ_K):

$$\delta_K^\phi(|\vec{p}|, \theta, t) = \frac{1}{\pi}\int_0^{2\pi} d\phi \delta_K(\vec{p}, t) \simeq i \sin\widehat{\phi} \exp(i\widehat{\phi})(\gamma/\Delta m)\left(\Delta a_0 + \beta_K \Delta a_Z \cos\chi\cos\theta + \beta_K \Delta a_X \sin\chi\cos\theta\cos(\Omega t) + \beta_K \Delta a_Y \sin\chi\cos\theta\sin(\Omega t)\right)$$

(Ω: Earth's sidereal frequency, χ: angle between Z-lab axis and Earth's axis.)

KLOE (at DAΦNE) is sensitive to a_Z (actually limits on $\delta(\Delta a_Z)$ from forward-backward asymmetry $A_L = 2\mathrm{Re}\epsilon_K - 2\mathrm{Re}\delta_K$). For KLOE-2 at DaΦNE-2 (if approved): expected sensitivity $\Delta a_\mu = \mathcal{O}(10^{-18})$ GeV, not competitive with KTeV for $a_{X,Y}$ limits (c.f. Experimental Talk (M. Testa)). Similar tests for other mesons (B-mesons, *etc.*...). Are QG LV effects Universal?

DETECTING CPT VIOLATION (CPTV)

Complex Phenomenology
No single figure of merit

- **Neutral Mesons: K, B, (unique (?) QG induced decoherence tests) meson-factories entangled states**
- **$K^{\ell 4}_{\pm}$ charged-meson decays** $K^{\pm} \rightarrow \pi^{+}\pi^{-}\ell^{\pm}\nu_{\ell}(\overline{\nu}_{\ell})$
- **Antihydrogen (precision spectroscopic tests on free & trapped molecules - search for forbidden transitions)**

- **Low-energy atomic Physics Experiments**
- **Ultra – Cold Neutrons**
- **Neutrino Physics**
- **Terrestrial & Extraterrestrial tests of Lorentz Invariance - search for modified dispersion relations of matter probes: GRB, AGN photons, Crab nebula synchrotron radiation, Flares….**

Order of Magnitude Estimates

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 (ultra-high-energy cosmic neutrinos, synchrotron radiation from astro sources etc.).

Order of Magnitude Estimates

However there are models with inverse energy dependence, e.g.

(i) Adler's Lindblad model for Energy-driven QG Decoherence in two level systems (hep-th/0005220): decoherence Lindblad operator propotional to Hamiltonian

Decoherence damping $\exp(-D\,t)$,

Decoherence Parameter estimate: $D = (\Delta m^2)^2/E^2 M_P$

(ii) Stochastic models of foam in brane/string theory (D-particle recoil models (below)) Decoherence Parameters estimates depend on details of foam, e.g. distribution of recoil velocities of populations of D-parfticle defects in space time (Sarkar, NM) :

(a) Gaussian D-particle recoil velocity distribution, spread σ :

Decoherence damping in oscillations among two-level systems :

$\exp(-D\,t^2)$, $D = \sigma^2(\Delta m^2)^2/E^2$

(b) Cauchy-Lorentz D-particle recoil velocity distribution, parameter γ :

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$$d\rho = -i[H,\rho]dt - \frac{1}{8}\sigma^2[D,[D,\rho]]dt + \frac{1}{2}\sigma[\rho,[\rho,D]]dW_t$$

al t … n t) $D = H$

…meter estimate: D ~ $(\Delta m^2)^2/E^2M_P$

$$dW_t^2 = dt \ , \quad dtdW_t = 0$$

Adler-Horwitz decoherent evolution model

…e/string theory (D-particle recoil models (below))

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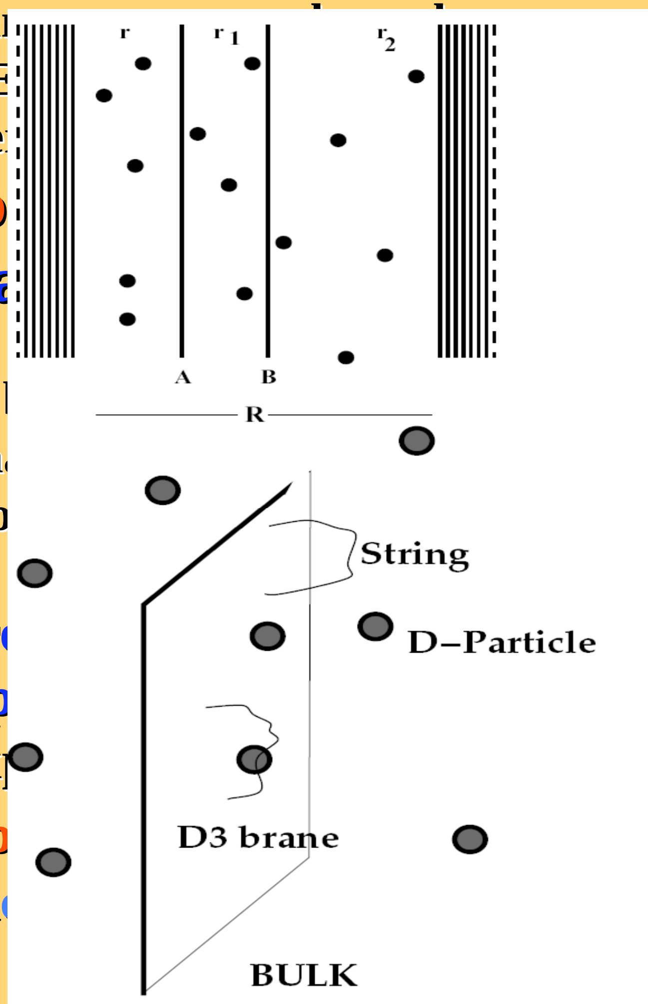

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Decoherence damp… o-level systems :
ex

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$$\partial_t \rho_{Matter} = i\left[\rho_{Matter}, H\right] - \Omega\left[\overline{u}_\ell, \left[\overline{u}^\ell, \rho_{Matter}\right]\right]$$

e.g. distribution of ... ce

$$\overline{u_x} \to \frac{r}{M_P}\widehat{p}$$

(a) Gaussian D-particle recoil velocity distril

$$\langle r \rangle = 0 \, , \quad \text{and} \quad \langle r^2 \rangle = \sigma^2 \, .$$

Decoherence damping in oscillations among two-level systems :

$$i\frac{\partial}{\partial t}\rho = \frac{1}{2m}\left[\widehat{p}^2, \rho\right] - i\Lambda\left[\widehat{x}, \left[\widehat{x}, \rho\right]\right] + \frac{\gamma}{2}\left[\widehat{x}, \{\widehat{p}, \rho\}\right] - i\Omega r^2\left[\widehat{p}, \left[\widehat{p}, \rho\right]\right]$$

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Decoherenc ... on of
recoil vel ... r, NM) :

(a) Gaus
De ... ms :

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The parameters σ and γ depend on microscopic model and are suppressed by (powers of) the string scale M_{String}

Complex Phenomenology of CPTV

- **CPT Operator well defined but NON-Commuting with Hamiltonian $[H, \Theta] \neq 0$**
  - Lorentz & CPT Violation in the Hamiltonian
    - **Neutral Mesons & Factories, Atomic Physics, Anti-matter factories, Neutrinos, …**
    - **Modified Dispersion Relations (GRB, neutrino oscillations, synchrotron radiation, TeV AGN…)**

- CPT Operator **ill defined** (Wald), intrinsic violation, **modified** concept of **antiparticle**
  - **Decoherence CPTV Tests**
    - **Neutral Mesons:** K, B & factories (novel effects in entangled states :

      (perturbatively) modified EPR correlations)
    - **Ultracold Neutrons**
    - **Neutrinos** (highest sensitivity)
    - **Light-Cone fluctuations** (GRB, Gravity-Wave Interferometers, neutrino oscillations)

Complex Phenomenology of CPTV

- **CPT Operator well defined but NON-Commuting with Hamiltonian [H , Θ] $\neq$ 0**
  - Lorentz & CPT Violation in the Hamiltonian
    - **Neutral Mesons & Factories, Atomic Physics, Anti-matter factories, Neutrinos, …**
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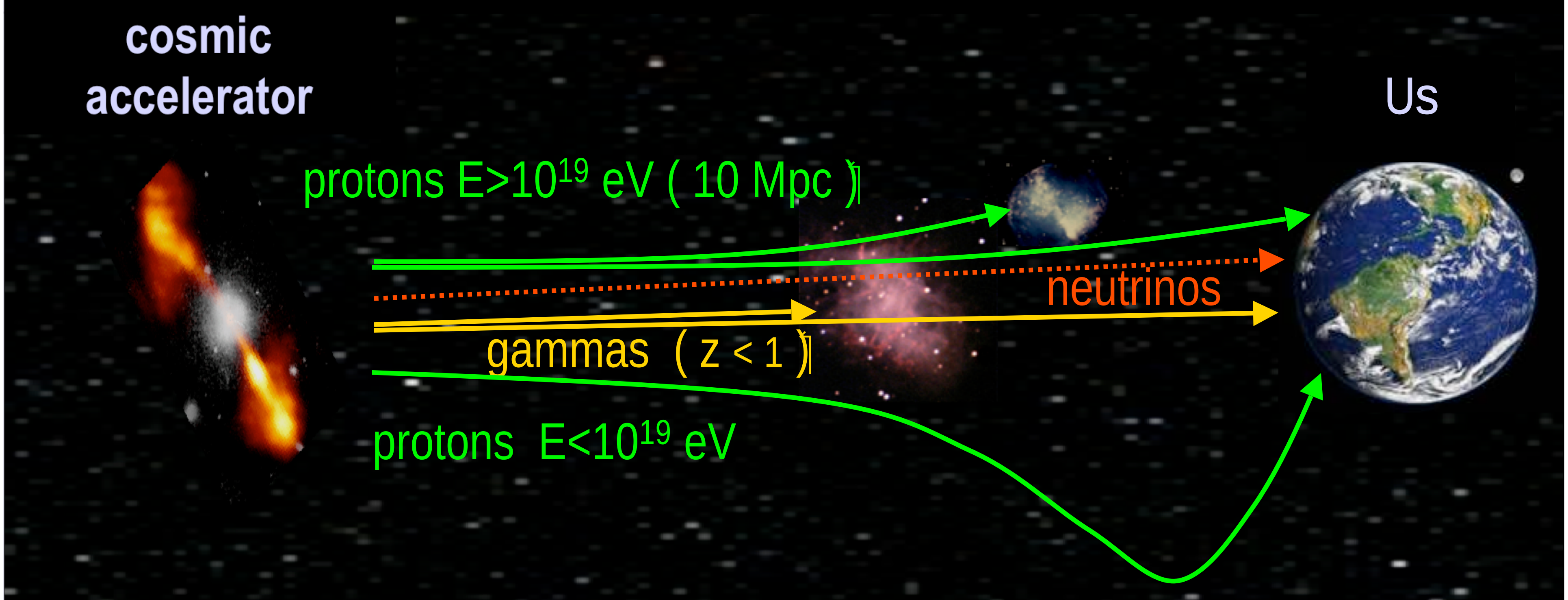
Multi-messenger observations of the Cosmos



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

photons: Absorbed by dust & radiation field (CMB)

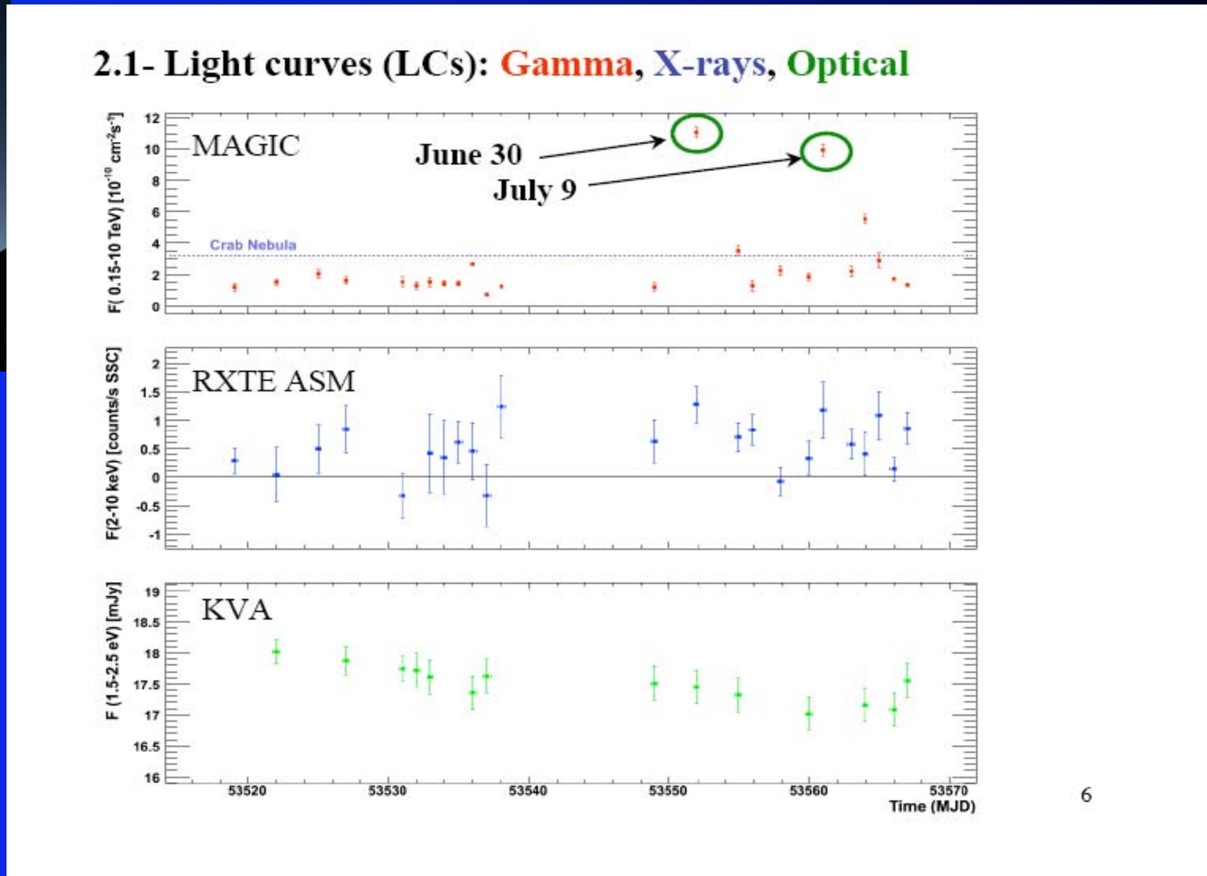
neutrinos: Difficult to detect

⇒ Three "astronomies" possible...

DeNaurois 2008


VHE Experimental World Today
MILAGRO
STACEE
MAGIC
TIBET
MAGIC
MILAGRO
STACEE
CACTUS
VERITAS
Canary Islands
TIBET ARRAY
ARGO-YBJ
TACTIC
PACT
GRAPES
TACTIC
HESS
HESS
CANGAROO III
CANGAROO
M. MARTINEZ

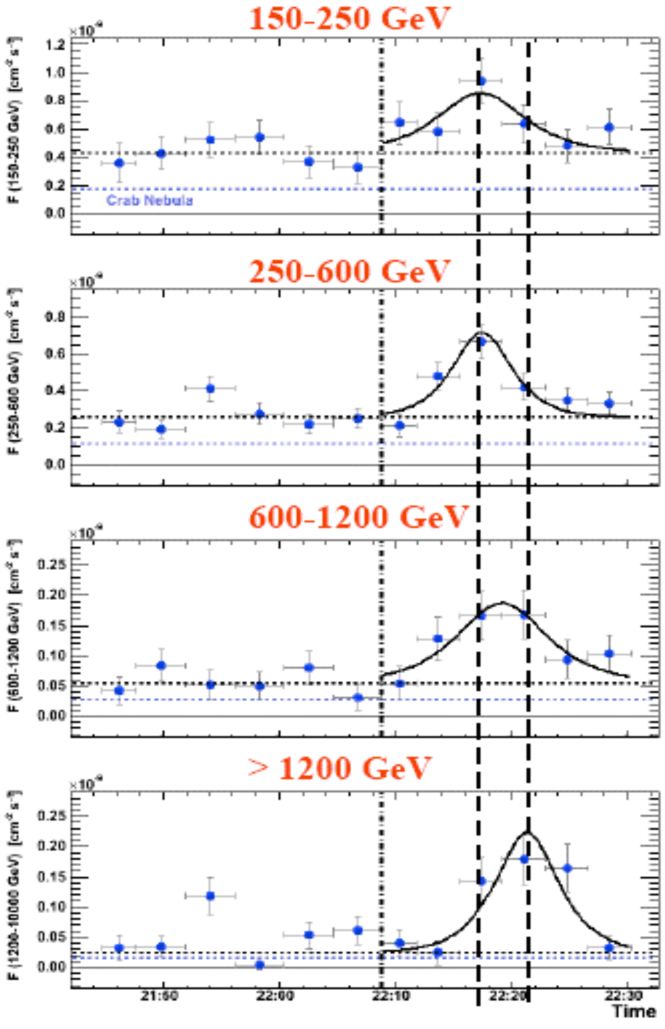
The MAGIC Collaboration (Major Atmospheric Gamma-ray Imaging Cherenkov Telescope)



Observation of Flares from AGN Mk 501

Red-shift: z=0.034

The MAGIC ``Effect''



LCs for different energy ranges (4 min bins)

July 9

Flare is seen in all energy ranges

Time delay of 4 +/- 1 minute between highest and lowest energy ranges

13

Quantum-Gravity Induced Modified Dispersion for Photons

Modified dispersion due to QG induced space-time (metric) distortions (c=1 units):

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

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

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

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

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

MAGIC Results (ECF Method):

Linear

$$\tau_l = (0.030 \pm 0.012)\ \mathrm{s/GeV}$$

$$M_{\rm QG1} = 1.398 \times 10^{16} (1\ \mathrm{s}/\tau_l)$$

$$M_{\rm QG1} = (0.47^{+0.31}_{-0.13}) \times 10^{18}\ \mathrm{GeV}$$

Quadratic

$$\tau_q = (3.71 \pm 2.57) \times 10^{-6}\ \mathrm{s/GeV^2}$$

$$M_{\rm QG2} = 1.182 \times 10^{8} (1\ \mathrm{s}/\tau_q)^{1/2}$$

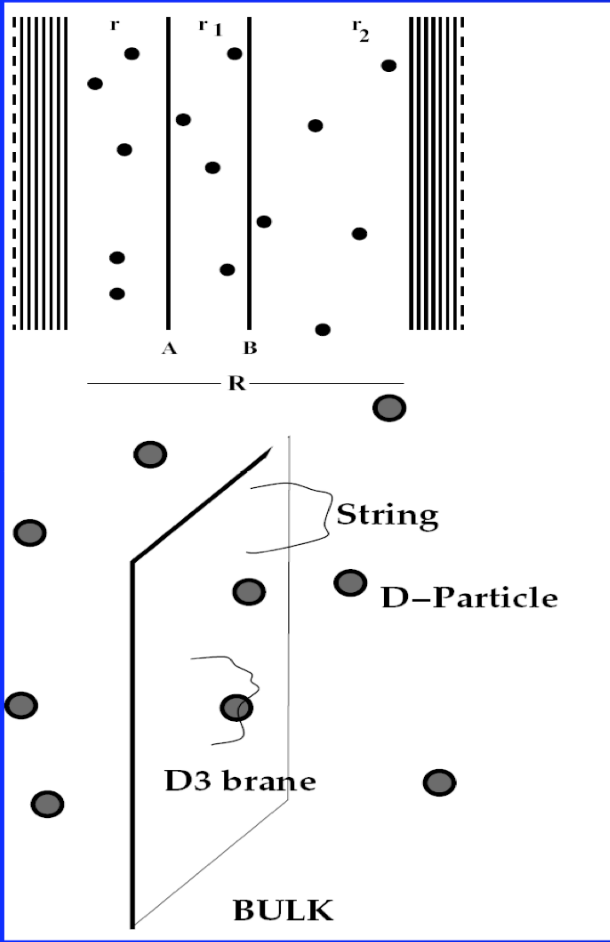
$$M_{\rm QG2} = (0.61^{+0.49}_{-0.14}) \times 10^{11}\ \mathrm{GeV}$$

95% CL

$$M_{\rm QG1} > 0.26 \times 10^{18}\ \mathrm{GeV}$$

$$M_{\rm QG2} > 0.27 \times 10^{11}\ \mathrm{GeV}$$

A Stringy Model of Space -Time Foam



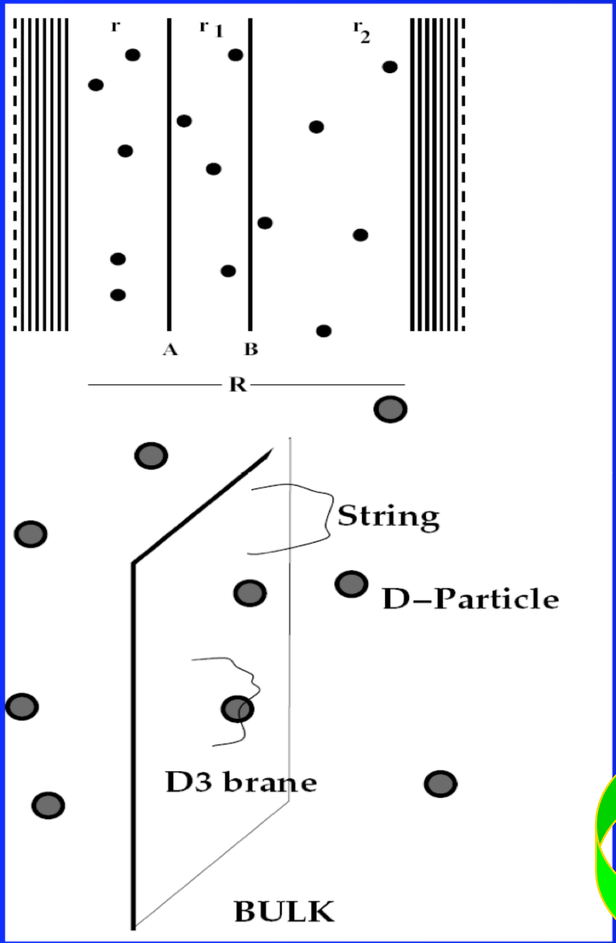
Ellis, NM, Nanopoulos

Open strings on D3-brane world represent **electrically neutral** matter or radiation, interacting via splitting/capture with D-particles **(electric charge conservation)** .

D-particle foam medium **transparent** to (charged) **Electrons** ⇒ **no modified dispersion for them**

Photons or electrically neutral probes feel the effects of D-particle foam ⇒
Modified Dispersion for them….

A Stringy Model of Space -Time Foam



Ellis, NM, Nanopoulos

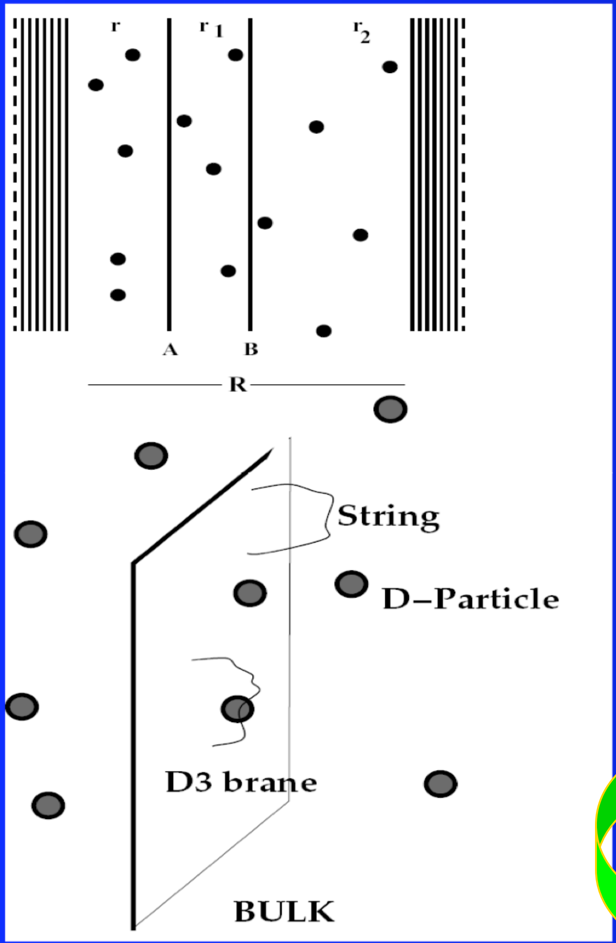
Open strings on D3-brane world represent electrically neutral matter or radiation, interacting via splitting/capture with D-particles (electric charge conservation) .

D-particle foam medium transparent to (charged) Electrons ⇒ no modified dispersion for them

Photons or electrically neutral probes feel the effects of D-particle foam ⇒ Modified Dispersion for them….

NON-UNIVERSAL ACTION OF D-PARTICLE FOAM ON MATTER & RADIATION

A Stringy Model of Space -Time Foam



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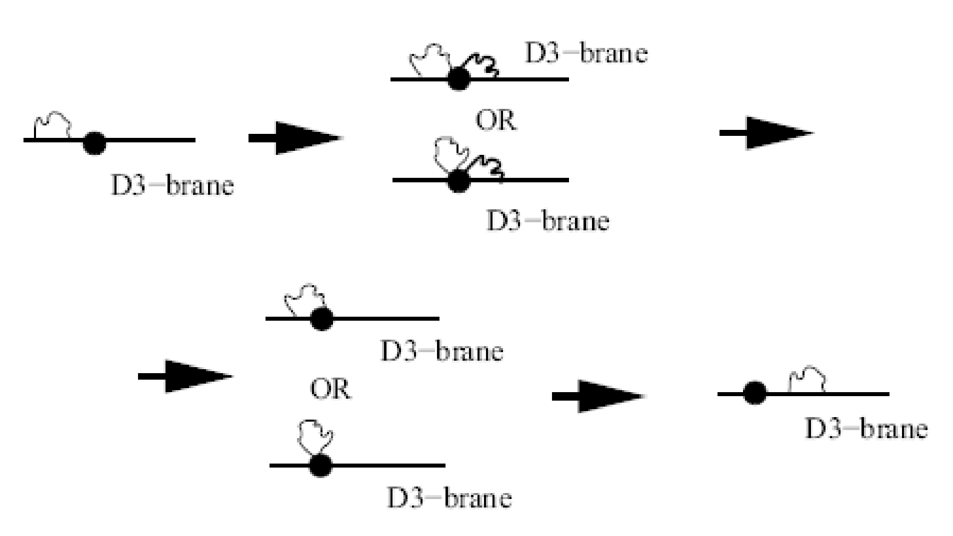
Stringy Uncertainties & the Capture Process

Ellis, NM, Nanopoulos arXiv:0804.3566



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:

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

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

Stringy Uncertainties & the MAGIC Effect

- D-foam: transparent to electrons
- D-foam captures photons & re-emits them
- Time Delay (Causal) in each Capture: $\Delta t \sim \alpha' p^0$
- 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 $G_{0i} \sim p^0$

REPRODUCE 4±1 MINUTE DELAY OF MAGIC from Mk501 (redshift z=0.034) For n^* =O(1) & $M_s \sim 10^{18}$ GeV, consistently with Crab Nebula & other Astrophysical constraints on modified dispersion relations……

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- D-foam captures photons & re-emits them
- Time Delay (Causal) in each Capture: $\Delta t \sim \alpha' p^0$
- I…
- T…
  ti…
  p…

COMPATIBLE WITH STRING UNCERTAINTY PRINCIPLES:

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

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

$$\Delta t_{\rm total} = \alpha' p\, n \ldots \frac{\ldots}{\sqrt{\alpha'}} = \frac{\ldots}{M_s} n\, D$$

…lified
…tion
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Complex Phenomenology of CPTV

- **CPT Operator well defined but NON-Commuting with Hamiltonian $[H, \Theta] \neq 0$**
  - Lorentz & CPT Violation in the Hamiltonian
    - **Neutral Mesons & Factories, Atomic Physics, Anti-matter factories, Neutrinos, …**
    - **Modified Dispersion Relations (GRB, neutrino oscillations, synchrotron radiation…)**

- CPT Operator **ill defined** (Wald), intrinsic violation, **modified** concept of **antiparticle**
  - **Decoherence CPTV Tests**
    - **Neutral Mesons:** K, B & factories (novel effects in entangled states :

      (perturbatively) modified EPR correlations) ⇒ **this talk**
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QUANTUM GRAVITY DECOHERENCE & CPTV

NEUTRAL MESON PHENOMENOLOGY

QG DECOHERENCE IN NEUTRAL KAONS: SINGLE STATES

Quantum Gravity (QG) may induce decoherence and oscillations $K^0 \to \overline{K}^0$ $\Rightarrow$ **could use Lindblad-type approach (one example)** (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.

(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 $K^0, \overline{K}^0$:

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

$R(K^0 \to f) \equiv \mathrm{Tr}\,[O_f \rho(t)]$ =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 QG-induced Lindblad decoherence scenario (QG plays rôle of "medium"):

$$\zeta \to \frac{\widehat{\gamma}}{2|\epsilon^2|} - 2\frac{\widehat{\beta}}{|\epsilon|}\sin\phi$$

(for meson-factories, complete positivity $\widehat{\beta} = 0$).

[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.]

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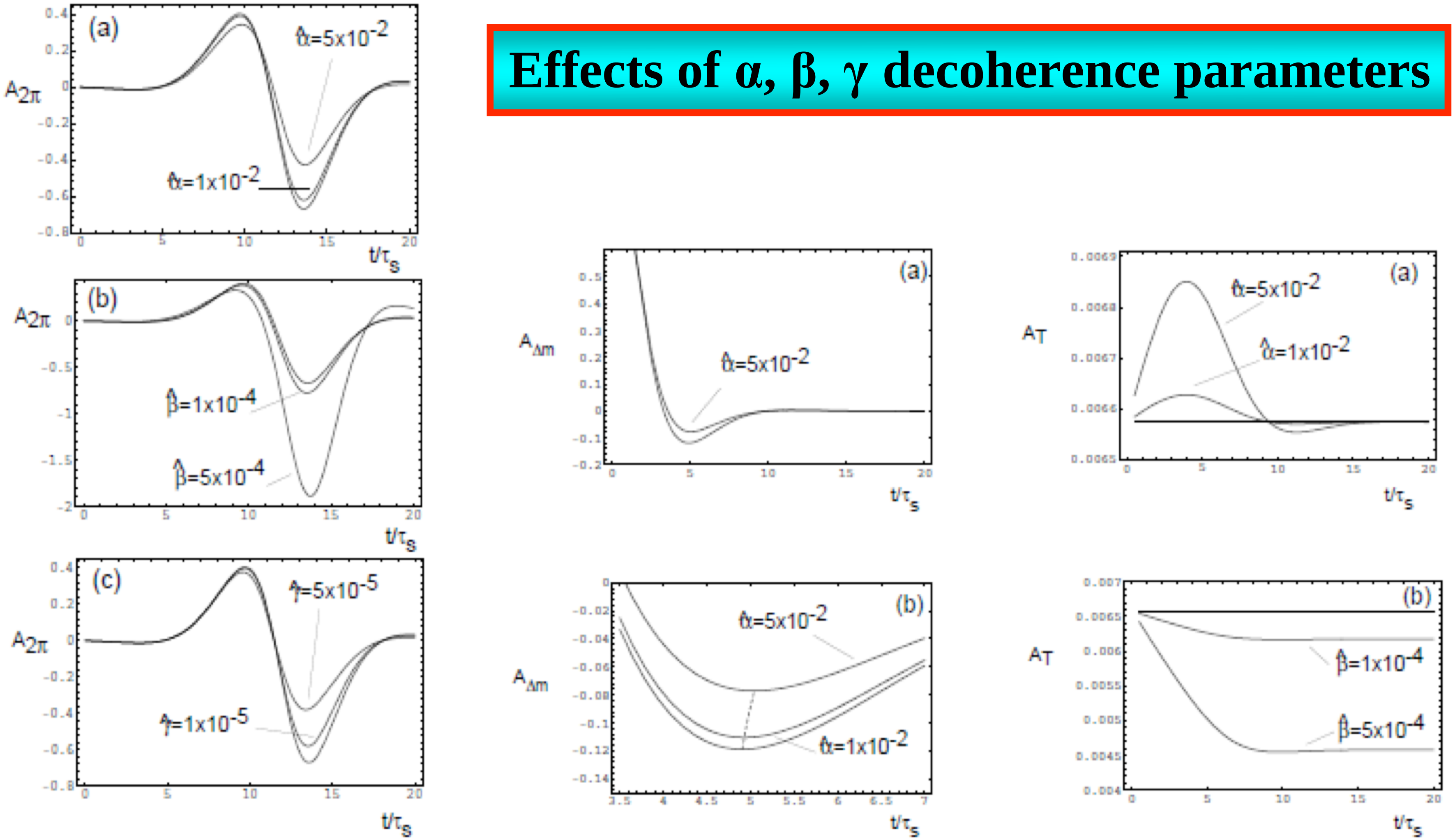
Neutral Kaon Asymmetries

Effects of α, β, γ decoherence parameters



Decoherence vs QM effects

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

Table 1: 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	$\neq$	$=$

Indicative Bounds

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

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 (some models) α , β , $\gamma = \mathcal{O}(\xi \frac{E^2}{M_P})$.

NB(2): $m_{K^0} - m_{\overline{K}^0} \sim 2|\beta|$

(at present $(m_{K^0} - m_{\overline{K}^0})/m_{K^0} < 7.5 \times 10^{-19}$)

Neutral Kaon Entangled States

- **Complete Positivity Decoherence matrix** ⟹ **Different parametrization of (Benatti-Floreanini)**

(in α, β, γ framework: $\alpha = \gamma,\ \beta = 0$)

FROM DAΦNE :

KLOE preliminary (A. Di Domenico Home Page, (c.f. Experimental Talk (M. Testa)).)
http://www.roma1.infn.it/people/didomenico/roadmap/kaoninterferometry.html

$$\alpha = \left(-10^{+41}_{-31 \mathrm{stat}} \pm 9_{\mathrm{syst}}\right) \times 10^{-17}\ \mathrm{GeV}\ ,$$

$$\beta = \left(3.7^{+6.9}_{-9.2 \mathrm{stat}} \pm 1.8_{\mathrm{syst}}\right) \times 10^{-19}\ \mathrm{GeV}\ ,$$

$$\gamma = \left(-0.4^{+5.8}_{-5.1 \mathrm{stat}} \pm 1.2_{\mathrm{syst}}\right) \times 10^{-21}\ \mathrm{GeV}\ ,$$

NB: For entangled states, **Complete Positivity** requires (Benatti, FLoreanini) $\alpha = \gamma, \beta = 0$, **one independent parameter** (which has the greatest experimental sensitivity by the way) γ !

with $L = 2.5\ fb^{-1}$: $\gamma \to \pm 2.2_{stat} \times 10^{-21}\ \mathrm{GeV}$,

Perspectives with KLOE-2 at DAΦNE-2 :

$\gamma \to \pm 0.2. \times 10^{-21}\ \mathrm{GeV}$

(present best measurement: $\gamma = (1.1 \pm 2.5) \times 10^{-21}\ \mathrm{GeV}$**)**

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Entangled States:CPT & EPR correlations

- **Novel (genuine) two body effects:**
  - If CPT not-well defined ⇒

    modification of EPR correlations (ω-effect)

    (Bernabéu, Papavassiliou, NM, Alvarez, Nebot, Sarkar, Waldron)

Unique effect in Entangled states of mesons !!
Characteristic of ill-defined nature of intrinsic CPT
Violation (e.g. due to decoherence)

EPR correlated states and particle physics

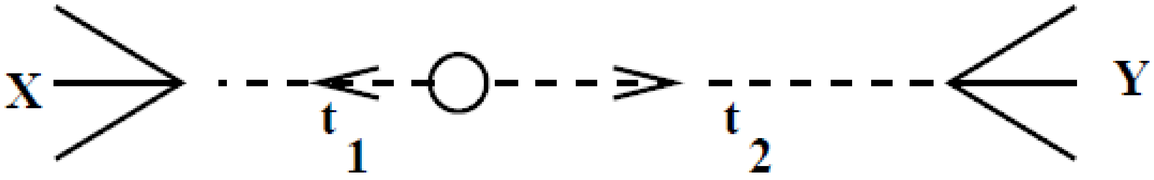
What are EPR correlations?

Einstein-Podolsky-Rosen (EPR) effect proposed originally as a **PARADOX** testing foundations of Quantum Theory.

Correlations between spatially separated events, instant transport of information? contradicts relativity?

NO, NO PARADOX

EPR has been confirmed EXPERIMENTALLY:
(i) pair of particles can be created in a definite quantum state,
(ii) move apart,
(iii) decay when they are widely separated (spatially).



EPR CORRELATIONS between different decay modes should be taken into account, when interpreting any experiment. (Lipkin (1968))

EPR and ϕ Factories

(Dunietz, Hauser, Rosner (1987), Bernabeu, Botella, Roldan (1988), Lipkin (1989))

Was claimed that due to EPR correlations, irrespective of CP, CPT violation, FINAL STATE in ϕ decays: $e^+e^- \Rightarrow \phi \Rightarrow K_S K_L$ WHY? *Entangled* meson states: *Bose statistics* for the state $K^0\overline{K}^0$, to which ϕ decays, implies that the physical neutral meson-antimeson state must be *symmetric* under $C\mathcal{P}$, with C the charge conjugation and $\mathcal{P}$ the operator that permutes the spatial coordinates.

Assuming *conservation* of angular momentum, and a proper existence of the *antiparticle state* (denoted by a bar), one observes that: for $K^0\overline{K}^0$ states which are C-conjugates with $C = (-1)^\ell$ (with ℓ the angular momentum quantum number), the system has to be an eigenstate of $\mathcal{P}$ with eigenvalue $(-1)^\ell$. Hence, for $\ell = 1$: $C = - \rightarrow \mathcal{P} = -$. Bose statistics ensures that for $\ell = 1$ the state of two identical bosons is forbidden. Hence initial entangled state:

$$|i> = \frac{1}{\sqrt{2}}\left(|K^0(\vec{k}), \overline{K}^0(-\vec{k}) > - |\overline{K}^0(\vec{k}), K^0(-\vec{k}) >\right) =$$
$$\mathcal{N}\left(|K_S(\vec{k}), K_L(-\vec{k}) > - |K_L(\vec{k}), K_S(-\vec{k}) >\right)$$

with $\mathcal{N} = \frac{\sqrt{(1+|\epsilon_1|^2)(1+|\epsilon_2|^2)}}{\sqrt{2}(1-\epsilon_1\epsilon_2)} \simeq \frac{1+|\epsilon^2|}{\sqrt{2}(1-\epsilon^2)}$, and $K_S = \frac{1}{\sqrt{1+|\epsilon_1^2|}}(|K_+ > +\epsilon_1|K_- >)$, $K_L = \frac{1}{\sqrt{1+|\epsilon_2^2|}}(|K_- > +\epsilon_2|K_+ >)$, where ϵ_1, ϵ_2 are complex parameters, such that, $\delta \equiv \epsilon_1 - \epsilon_2$ parametrizes the CPT violation within quantum mechanics.

BUT, if CPT is intrinsically violated...The concept of antiparticle may be MODIFIED (perturbatively)!

CPTV & EPR-correlations modification

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

If CPT is broken via Quantum Gravity (QG) decoherence 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. $\Rightarrow$ initial Entangled State in ϕ (B) factories $|i>$ (in terms of mass eigenstates):

$$|i> \;=\; \mathcal{N}\Big[\Big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\Big) + \omega\Big(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\Big)\Big]$$

$$\omega = |\omega| e^{i\Omega}$$

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 $\longrightarrow$ demise of flavour tagging (Alvarez et al. (PLB607))

NB1: Disentangle ω C-even background effects ($e^+e^- \Rightarrow 2\gamma \Rightarrow K^0\overline{K}^0$): terms of the type $K_S K_S$ (which dominate over $K_L K_L$) coming from the ϕ-resonance as a result of ω-CPTV can be distinguished from those coming from the $C = +$ background because they interfere differently with the regular $C = -$ resonant contribution with $\omega = 0$.

NB2: Also disentangle ω from non-unitary evolution ($\alpha = \gamma$ ...) effects (different structures) (Bernabéu, NM, Papavassiliou, Waldron NP B744:180-206,2006)

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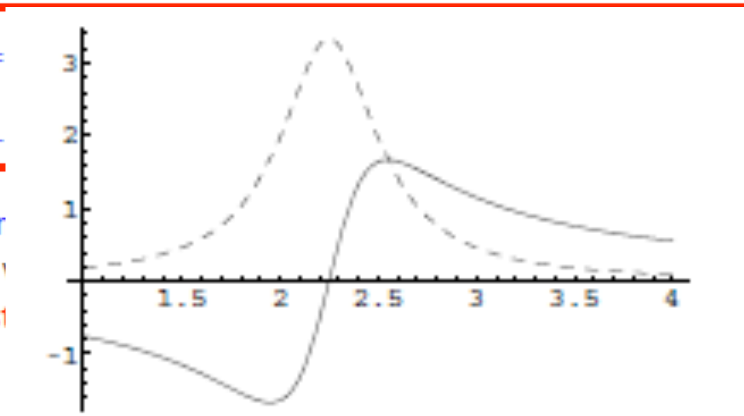

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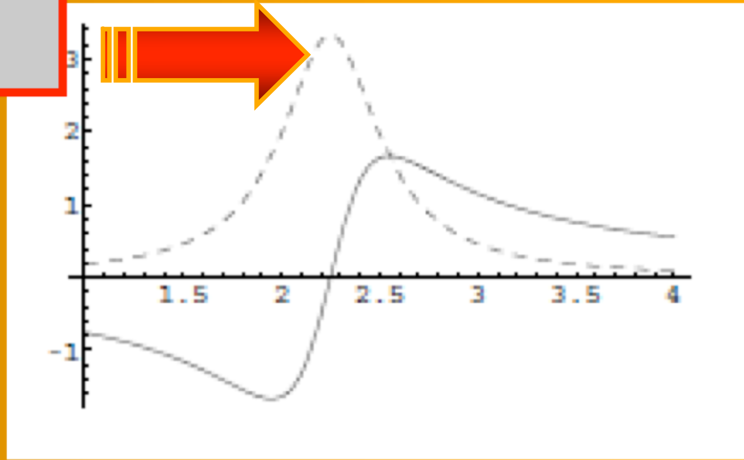
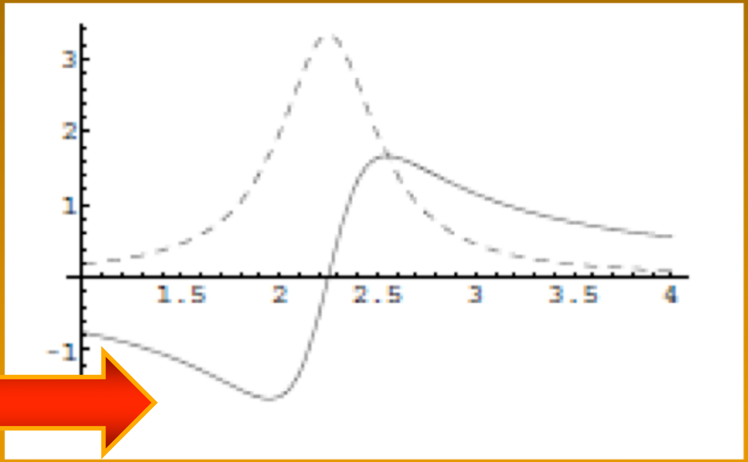
CPTV & EPR-correlations modification

CPTV $K_L K_L$, $\omega K_S K_S$ terms originate from Φ-particle , hence same dependence on centre-of-mass energy s. Interference proportional to real part of amplitude, exhibits peak at the resonance….



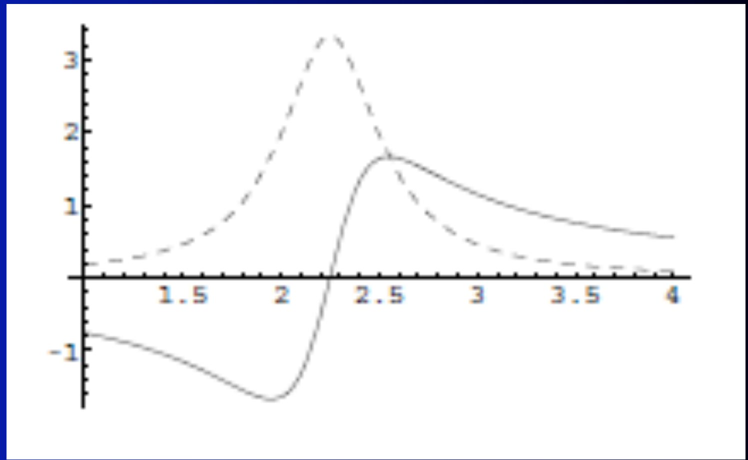
CPTV & EPR-correlations modification

$K_S K_S$ terms from C=+ background
no dependence on centre-of-mass energy s.
Real part of Breit-Wigner amplitude
Vanishes at top of resonance, Interference
of C=+ with C=-- background, vanishes
at top of the resonance, opposite signature
on either side…..



CPTV & EPR-correlations modification

CLEAR EXPERIMENTAL DISTINCTION BETWEEN THE TWO CASES



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

$$\omega = |\omega| e^{i\Omega}$$

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.

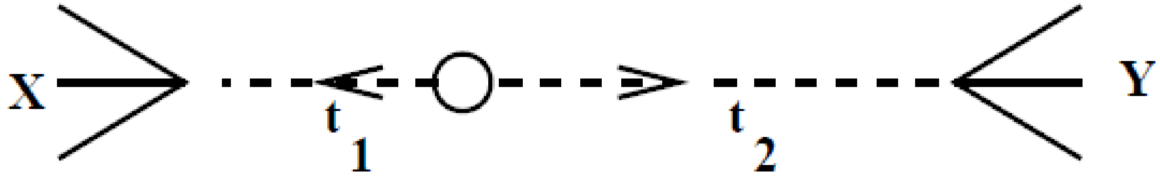
Experimental Tests of ω-Effect in ϕ, B factories... in B-factories: ω-effect $\longrightarrow$ demise of flavour tagging (Alvarez et al. (PLB607))

NB1: Disentangle ω C-even background effects ($e^+e^- \Rightarrow 2\gamma \Rightarrow K^0\overline{K}^0$): terms of the type $K_S K_S$ (which dominate over $K_L K_L$) coming from the ϕ-resonance as a result of ω-CPTV can be distinguished from those coming from the $C = +$ background because they interfere differently with the regular $C = -$ resonant contribution with $\omega = 0$.

NB2: Also disentangle ω from non-unitary evolution ($\alpha = \gamma$ ...) effects (different structures) (Bernabéu, NM, Papavassiliou, Waldron NP B744:180-206,2006)

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:

$$A(X,Y) = \langle X|K_S\rangle\langle Y|K_S\rangle \mathcal{N}\ (A_1 + A_2)$$

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" $I(\Delta t)$: ($\Delta t = t_1 - t_2$) is an observable

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

ω-Effect & Intensities

$$I(\Delta t) \equiv \frac{1}{2}\int_{|\Delta t|}^{\infty} dt\, |A(\pi^+\pi^-, \pi^+\pi^-)|^2 = |\langle\pi^+\pi^-|K_S\rangle|^4 |\mathcal{N}|^2 |\eta_{+-}|^2 \Big[I_1 + I_2 + I_{12}\Big]$$

$$I_1(\Delta t) = \frac{e^{-\Gamma_S \Delta t} + e^{-\Gamma_L \Delta t} - 2e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\Delta M \Delta t)}{\Gamma_L + \Gamma_S}$$

$$I_2(\Delta t) = \frac{|\omega|^2}{|\eta_{+-}|^2}\frac{e^{-\Gamma_S \Delta t}}{2\Gamma_S}$$

$$I_{12}(\Delta t) = -\frac{4}{4(\Delta M)^2 + (3\Gamma_S + \Gamma_L)^2}\frac{|\omega|}{|\eta_{+-}|} \times$$

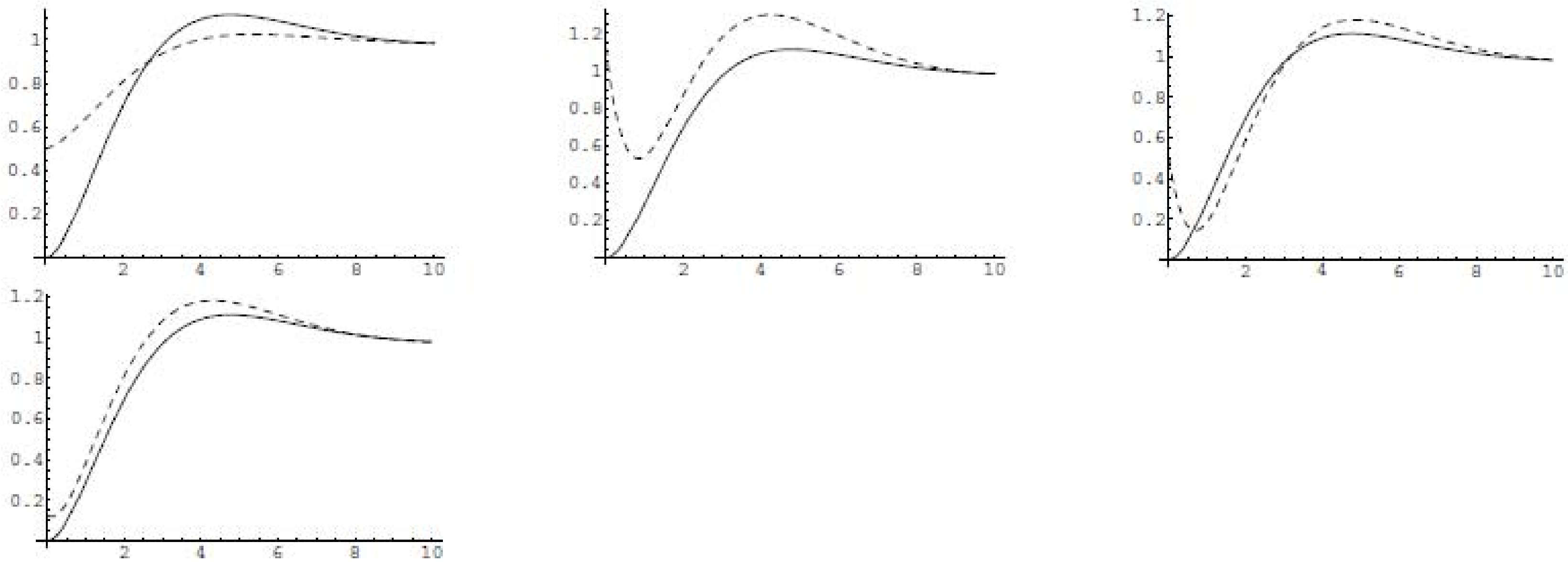
$$\Big[2\Delta M\Big(e^{-\Gamma_S\Delta t}\sin(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\sin(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)$$

$$-(3\Gamma_S + \Gamma_L)\Big(e^{-\Gamma_S\Delta t}\cos(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)\Big]$$

$\Delta M = M_S - M_L$ 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.

ω-Effect & Intensities



Characteristic cases of the intensity $I(\Delta t)$, with $|\omega| = 0$ (solid line) vs $I(\Delta t)$ (dashed line) with (from top left to right): (i) $|\omega| = |\eta_{+-}|$, $\Omega = \phi_{+-} - 0.16\pi$, (ii) $|\omega| = |\eta_{+-}|$, $\Omega = \phi_{+-} + 0.95\pi$, (iii) $|\omega| = 0.5|\eta_{+-}|$, $\Omega = \phi_{+-} + 0.16\pi$, (iv) $|\omega| = 1.5|\eta_{+-}|$, $\Omega = \phi_{+-}$. Δt is measured in units of τ_S (the mean life-time of K_S) and $I(\Delta t)$ in units of $|C|^2 |\eta_{+-}|^2 |\langle \pi^+ \pi^- | K_S \rangle|^4 \tau_S$.

B-systems, ω-effect & demise of flavour-tagging

Alvarez, Bernabeu NM, Nebot, Papavassiliou

- Kaon systems have increased sensitivity to ω-effects due to the decay channel $\pi^+\pi^-$.
- B-systems do not have such a "good'' channel but have the *advantage of statistics* →Interesting limits of ω-effects there
- Flavour tagging: Knowledge that one of the two-mesons in a meson factory *decays at a given time* through *flavour-specific* "channel''

Unambiguously *determine* the *flavour* of the other meson at the *same time* .

Not True if intrinsic CPTV – ω-effect present : Theoretical limitation ("demise'') of flavour tagging

B-systems, ω-effect & demise of flavour-tagging

$$|\psi(0)\rangle = \frac{1}{\sqrt{2\left(1+|\omega|^2\right)}}\left\{|B^0\overline{B}^0\rangle - |\overline{B}^0 B^0\rangle + \omega\left[|B^0\overline{B}^0\rangle + |\overline{B}^0 B^0\rangle\right]\right\}$$

$$|B_1\rangle = \frac{1}{\sqrt{2\left(1+|\epsilon_1|^2\right)}}\left((1+\epsilon_1)|B^0\rangle + (1-\epsilon_1)|\overline{B}^0\rangle\right)$$

$$|B_2\rangle = \frac{1}{\sqrt{2\left(1+|\epsilon_2|^2\right)}}\left((1+\epsilon_2)|B^0\rangle - (1-\epsilon_2)|\overline{B}^0\rangle\right)$$

$$\Delta M = M_1 - M_2$$

$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$

$$\Gamma = (\Gamma_1 + \Gamma_2)/2$$

$$|B_1(0)\rangle \mapsto e^{-iMt-\frac{\Gamma}{2}t}e^{-i\frac{\Delta M}{2}t-\frac{\Delta\Gamma}{4}t}|B_1(0)\rangle\,, \quad |B_2(0)\rangle \mapsto e^{-iMt-\frac{\Gamma}{2}t}e^{+i\frac{\Delta M}{2}t+\frac{\Delta\Gamma}{4}t}|B_2(0)\rangle$$

$$I_{ab}(t) = |\langle X_{ab}|\psi(t)\rangle|^2$$

$$I_{ab}(t) = |\langle Y_a|B^a\rangle|^2\,|\langle Z_b|B^b\rangle|^2\,\frac{e^{-\Gamma t}}{2(1+|\omega|^2)}\,|C_{ab}(t)|^2$$

In terms of intensities, $\omega \neq 0$ allows

$$I_{00}(t) \neq 0 \quad ; \quad I_{\bar{0}\bar{0}}(t) \neq 0\,.$$

B-systems, ω-effect & demise of flavour-tagging

CP-type asymmetry of the form

$$A_{CP}(t) = \frac{I_{00}(t) - I_{\bar{0}\bar{0}}(t)}{I_{00}(t) + I_{\bar{0}\bar{0}}(t)} \quad ; \quad \mathcal{A}_{CP} = \frac{\mathcal{I}_{00} - \mathcal{I}_{\bar{0}\bar{0}}}{\mathcal{I}_{00} + \mathcal{I}_{\bar{0}\bar{0}}} \; .$$

$$\mathcal{I}_{ab} = \int_0^\infty dt \; I_{ab}(t)$$

$$A(t) = \frac{2\Re e\left(\omega f(t)\right)}{1 + |\omega f(t)|^2}$$

$$f(t) = \frac{1}{\left(1 - \epsilon^2 + \frac{\delta^2}{4}\right)^2}\left[\delta^2 + \frac{1}{2}\left((1+\epsilon)^2 - \frac{\delta^2}{4}\right)\left((1-\epsilon)^2 - \frac{\delta^2}{4}\right)\left(e^{\alpha t} + e^{-\alpha t}\right)\right]$$

CP parameter

$\epsilon = (\epsilon_1 + \epsilon_2)/2,$

CPTV parameter (QM)

$\delta = \epsilon_1 - \epsilon_2$

$\alpha \equiv i\Delta M/2 + \Delta\Gamma/4$

EquaL-Sign di-lepton charge asymmetry Δt dependence

ALVAREZ, BERNABEU, NEBOT

- **Interesting tests of the ω-effect can be performed by looking at the equal-sign di-lepton decay channels**

a first decay $B \to X\ell^{\pm}$ and a second decay, Δt later, $B \to X'\ell^{\pm}$

$$A_{sl} = \left.\frac{I(\ell^+,\ell^+,\Delta t) - I(\ell^-,\ell^-,\Delta t)}{I(\ell^+,\ell^+,\Delta t) + I(\ell^-,\ell^-,\Delta t)}\right|_{\omega=0} = 4\frac{Re(\varepsilon)}{1+|\varepsilon|^2} + \mathscr{O}((Re\,\varepsilon)^2)$$

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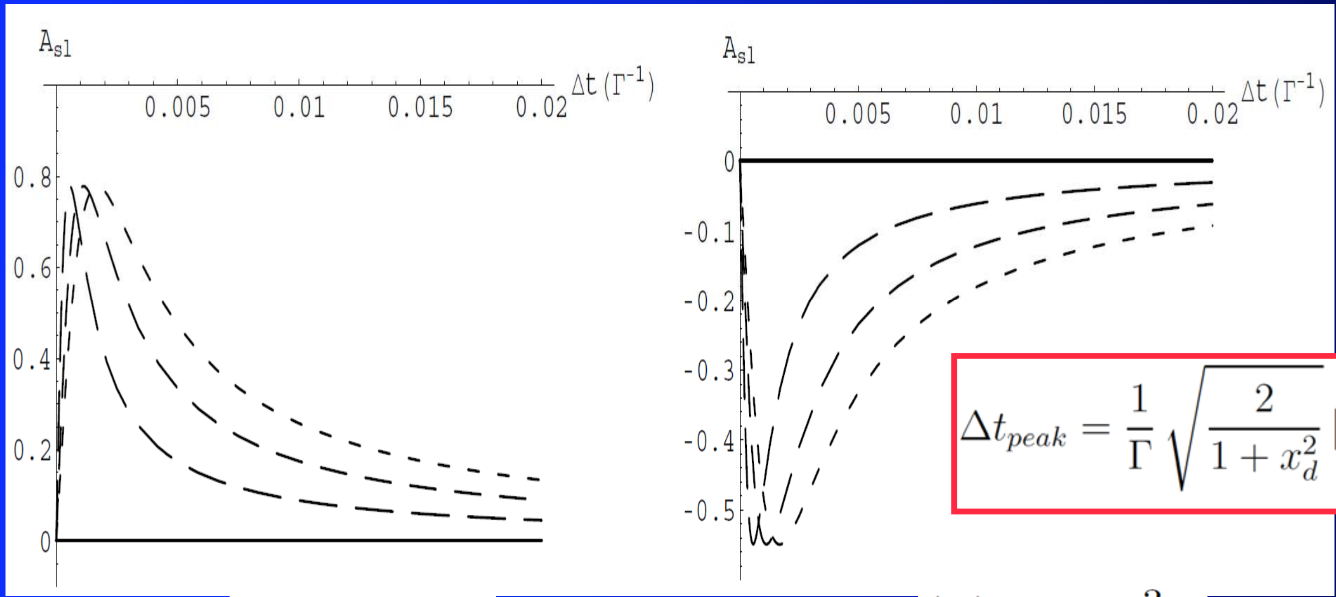
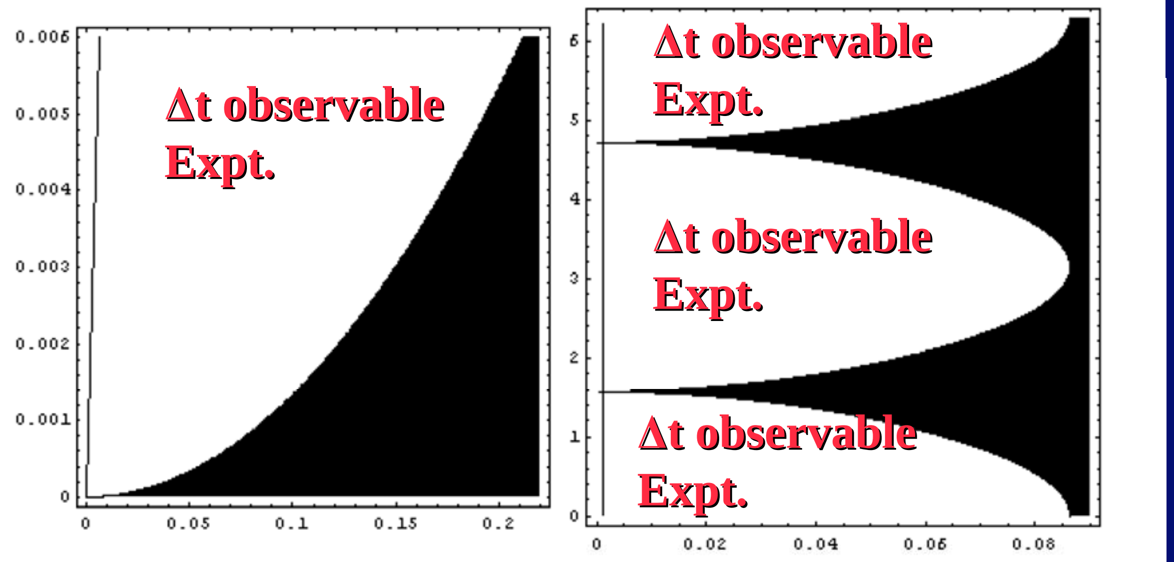
$$\omega = |\omega| e^{i\Omega} \quad \Rightarrow \quad I(\ell^{\pm},\ell^{\pm},\Delta t = 0) \sim |\omega|^2$$



(a) $\Omega = 0$ (b) $\Omega = \frac{3}{2}\pi$

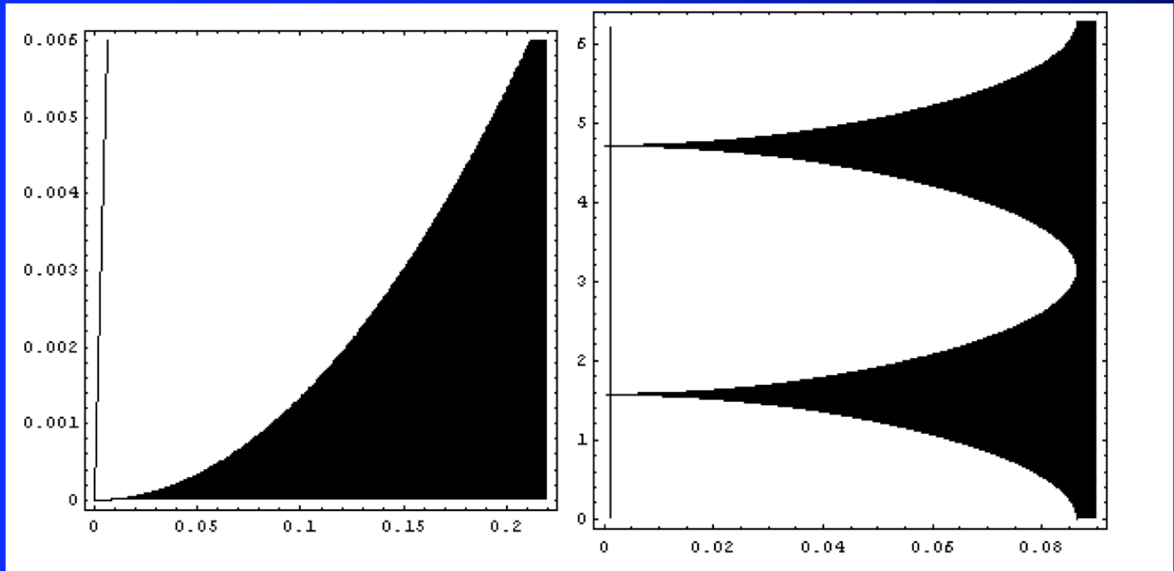
$$\Delta t_{peak} = \frac{1}{\Gamma}\sqrt{\frac{2}{1+x_d^2}}\,|\omega| + \mathcal{O}(\omega^2) \approx \frac{1}{\Gamma}\,1.12\,|\omega|$$

Figure 2: Equal-sign dilepton charge asymmetry for different values of ω; $|\omega| = 0$ (solid line), $|\omega| = 0.0005$ (long-dashed), $|\omega| = 0.001$ (medium-dashed), $|\omega| = 0.0015$ (short-dashed). When $\omega \neq 0$ a peak of height $A_{sl}(peak) = 0.77\cos(\Omega)$ appears at $\Delta t(peak) = 1.12\,|\omega|\,\frac{1}{\Gamma}$, producing a drastic difference with the $\omega = 0$ case, in particular in its time dependence. Observe that the peak, independently of the value of $|\omega|$, can reach enhancements up to 10^3 times the value of the asymmetry when $\omega = 0$.



(a) $|\omega|$ *vs.* $\Delta t(\Gamma^{-1})$; for $\Omega = 0$ (b) Ω *vs.* $\Delta t(\Gamma^{-1})$; for $|\omega| = 0.001$

Figure 4: Contour curves for $\frac{1}{\Gamma}|dA_{sl}/d\Delta t| = 0.1$, the white area represents the points where $\frac{1}{\Gamma}|dA_{sl}/d\Delta t| > 0.1$, and hence the time variation would be (expected to be) experimentally detectable. Notice the tiny dark line on the left of each graph which represents the first peak of the asymmetry, where of course the derivative also goes to zero. Fig. (a) plots $|\omega|$ *vs.* Δt for a fixed $\Omega = 0$, observe that although to see the peak in A_{sl} a very high Δt-resolution is required, the region where the time variation is detectable might be more accessible experimentally. Fig. (b) plots the phase Ω *vs.* Δt for a fixed value of $|\omega| = 0.001$, note that disregarding the values of the phase around $\pi/2$ and $3\pi/2$, the measurable region (white) is quite favoured in Δt.



(a) $|\omega|$ *vs.* $\Delta t(\Gamma^{-1})$; for $\Omega = 0$ (b) Ω *vs.* $\Delta t(\Gamma^{-1})$; for $|\omega| = 0.001$

Figure 4: Conto … te area represents the points where $\frac{1}{\Gamma}|dA_{sl}/d\Delta t| > 0.1$, and hence the time variation would be (exp … n the left c … ere of cours … fix $\Omega =$ … ution is rec … more acces … val of $|\omega$ … $\pi/2$ and …

CURRENT EXPERIMENTAL LIMITS

$$A_{sl}^{exp} = 0.0019 \pm 0.0105$$

$$-0.0084 \leq Re(\omega) \leq 0.0100 \qquad 95\%\mathrm{C.L}$$

ω-Effect order of magnitude estimates

(Bernabéu, Sarben Sarkar, NM, hep-th/0606137)

Theoretical models using interactions of particle-probes with specific space-time defects (e.g. D-particles, inspired by string/brane theory); Use stationary perturbation theory to describe gravitationally dressed 2-meson state - medium effects like MSW $\Rightarrow$ initial state:

$$|\psi\rangle = |k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} + \xi\,|k,\uparrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} + \xi'\,|k,\downarrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}$$

NB: $\xi = -\xi'$: strangeness conserving ω-effect ($|K_L\rangle = |\uparrow\rangle$, $|K_S\rangle = |\downarrow\rangle$.).

In recoil D-particle stochastic model: (momentum transfer: $\Delta p_i \sim \zeta p_i$, $\langle \Delta p_i \rangle = 0$, $\langle \Delta p_i \Delta p_j \rangle \neq 0$)

$$|\omega|^2 \sim \frac{\zeta^2 k^4}{M_P^2 (m_1 - m_2)^2}$$

NB: For neutral kaons, with momenta of the order of the rest energies $|\omega| \sim 10^{-4}|\zeta|$. For $1 > \zeta \geq 10^{-2}$ not far below the sensitivity of current facilities, such as DAΦNE (c.f. Experimental Talk (M. Testa)). Constrain ζ significantly in upgraded facilities.

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$\mathrm{Re}(\omega),\ \mathrm{Im}(\omega) \longrightarrow 2 \times 10^{-5}$.

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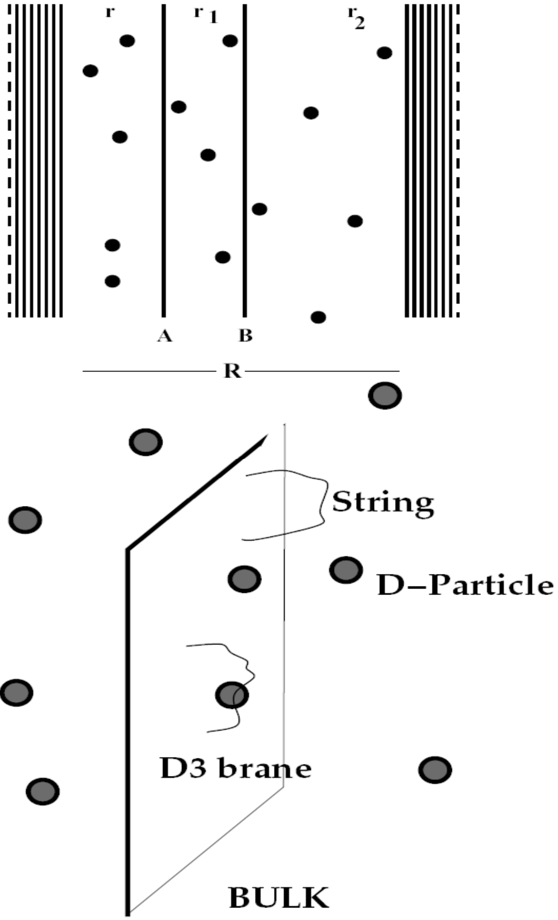

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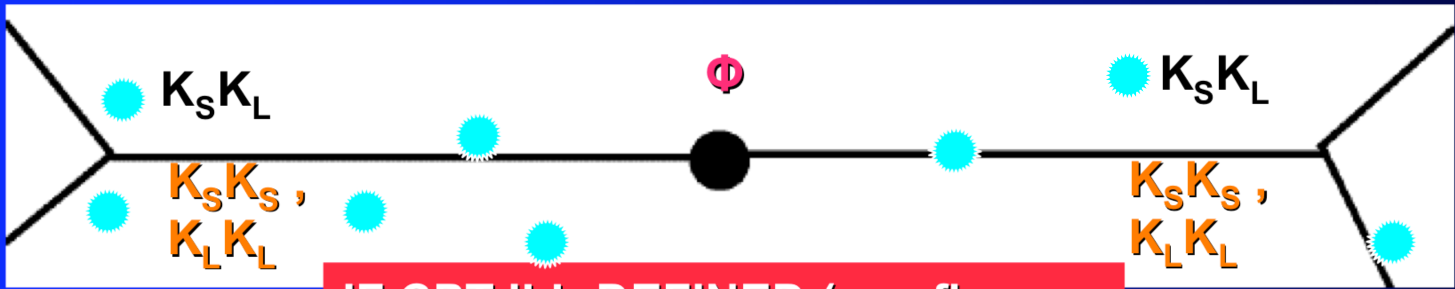

IF CPT ILL-DEFINED (e.g. flavour violating (FV) D-particle Foam)

$$|\omega|^2 \sim \frac{\zeta^2 k^2}{M_{QG}^2 (m_1 - m_2)^2} \; , \; \Delta p \sim \zeta p \text{ (kaon momentum transfer)}$$

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 (MAGIC) 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. DAFNE2)

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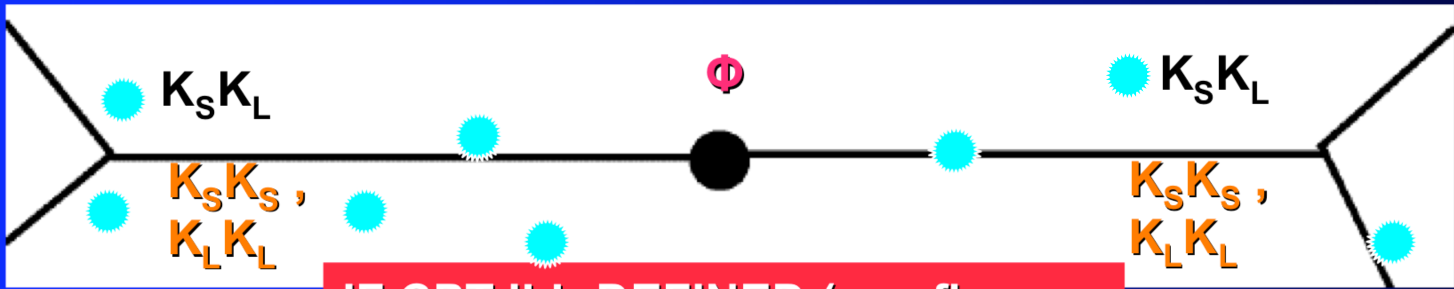

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ω-effect as discriminant of space-time foam models

Bernabeu, NM, Sarben Sarkar

- **ω-effect *not generic*, depends on *details* of *foam***

  Initially dressed states ⇒ depend on form of interaction Hamiltonian H_I ⇒ (non-degenerate) perturbation theory ⇒ determine existence of ω-effects

(I) D-foam: $\widehat{H_I} = -\left(r_1\sigma_1 + r_2\sigma_2\right)\widehat{k}$

features: *direction of k violates Lorentz symmetry, flavour non conservation* ⇒ **non-trivial ω-effect**

(II) Quantum Gravity Foam as "thermal Bath'' (Garay)

$$\mathcal{H} = \nu a^\dagger a + \frac{1}{2}\Omega\sigma_3^{(1)} + \frac{1}{2}\Omega\sigma_3^{(2)} + \gamma\sum_{i=1}^{2}\left(a\sigma_+^{(i)} + a^\dagger\sigma_-^{(i)}\right)$$

⇒ **no ω-effect**

Bath frequency

"atom'' (matter) frequency

QG Decoherence & LHC Black Holes

- **In string theory or extra-dimensional models (in general) QG mass scale may not be Planck scale but much smaller : $M_{QG} << M_{Planck}$**
- **Theoretically M_{QG} could be as low as a few TeV. In such a case, collision of energetic particles at LHC could produce microscopic Black Holes at LHC, which will evaporate quickly.**
- **If there is decoherence in such models, then, can the above tests determine the magnitude of M_{QG} beforehand?**
- **Highly model dependent issue…**

QG Decoherence & LHC Black Holes

- **Models of Decoherence:**

(i) Parameters = $O(E^2/M_{QG})$ (e.g. D-particle recoil LV foam)
current bounds: Kaons $M_{QG} > 10^{19}$ GeV
Photons $M_{QG} > 10^{18}$ GeV, Neutrinos $M_{QG} > 10^{26}$ GeV

No low M_{QG} mass scale allowed…

(ii) Parameters = $O((\Delta m^2)^2/E^2 M_{QG})$ (e.g. Adler's model of decoherence, stochastic D-particle LI models…)

Low MQG mass models (even TeV) allowed by current measurements of decoherence… compatible with LHC BH observations….

CONCLUSIONS

- **We know very little about QG so experimental searches & tests of various theoretical models will definitely help in putting us on the right course …**
- **(Intrinsic) CPT &/or Lorentz Violation & decoherence might characterise QG models…**
- **There may be `smoking-gun' experiments for intrinsic CPTV & QG Decoherence , unique in entangled states of mesons** (ω-effect best signature, if present though…. However, not generic effect, depends on model of QG foam…)
- **The magnitude of such effects is highly model dependent, may not be far from sensitivity of immediate-future facilities.**
- **QG Decoherence effects in neutrino oscillations yield damping signatures, but those are suppressed by (powers of) neutrino mass differences. Difficult to detect … Nevertheless future (high energy neutrinos) looks promising…**