CPT & DECOHERENCE IN QUANTUM GRAVITY

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KAON '07 LN Frascati (Italy) , May 21 – 25 2007

OUTLINE

- Theoretical motivation for CPT Violation (CPTV) :
- (i) Lorentz violation: microscopic & cosmological
- (ii) Quantum Gravity Foam (Decoherence)
- Order of magnitude estimates of expected effects

- Precision tests of CPTV: atomic physics, antihydrogen, neutral mesons & factories – Disentangling (i) from (ii)
- Complementary tests of CP, T & CPT symmetry using charged Kaon decays: explore high statistics recently available in $K^{\pm}_{\ell 4}$ decays

Some Theory

- **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:

    → **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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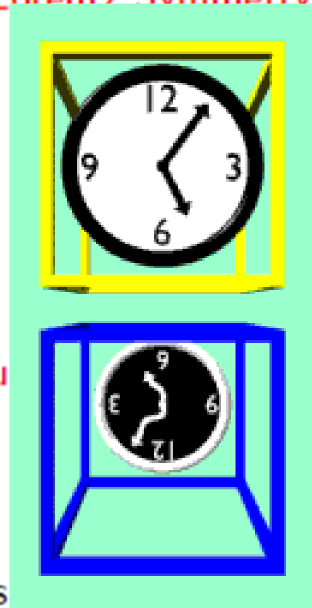

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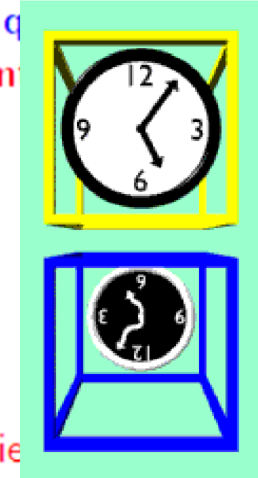

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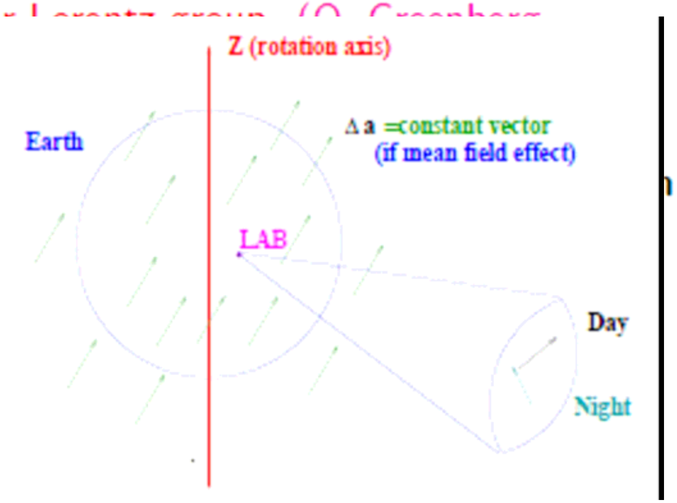

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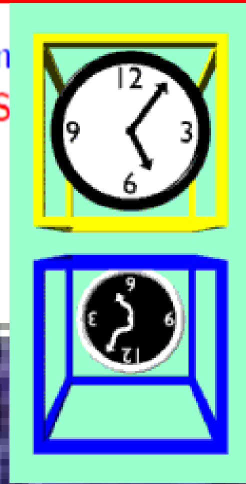

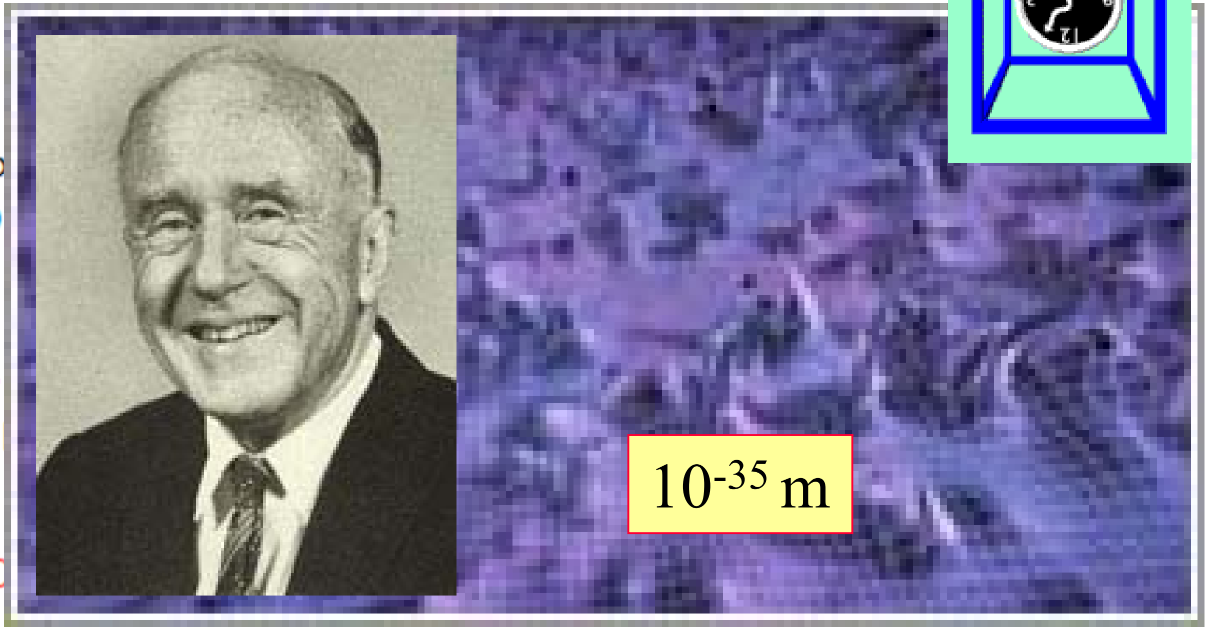

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LORENTZ VIOLATION AND ALTERNATIVE TO DARK MATTER MODELS

Cosmological Lorentz Violation?

DARK MATTER

Non luminous massive matter: matter of unknown composition that does not emit or reflect enough electromagnetic radiation to be observed directly, but whose presence can be inferred from gravitational effects on visible matter.

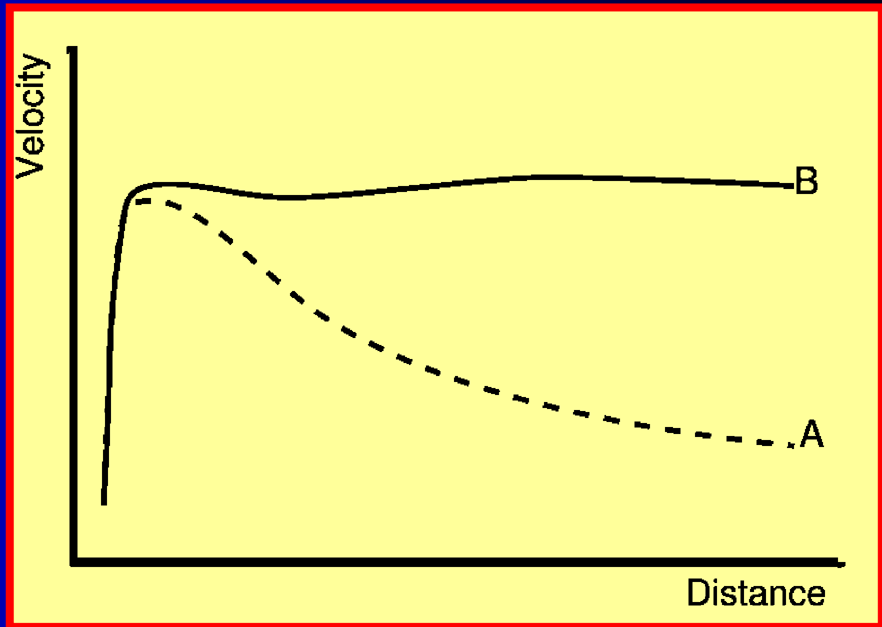
Observed phenomena consistent with existence of dark matter: (I) rotational speeds of galaxies and orbital velocities of galactic clusters,
(II) gravitational lensing of background objects by galaxy clusters such as the Bullet cluster, and
(III) the temperature distribution of hot gas in galaxies and clusters of galaxies.
(IV) Dark matter also plays a central role in structure formation and galaxy evolution, and has measurable effects on the anisotropy of the cosmic microwave background.

COSMOLOGICAL MOTIVATION FOR LORENTZ VIOLATION ?

Rotational Curves of Galaxies

Evidence for Dark Matter

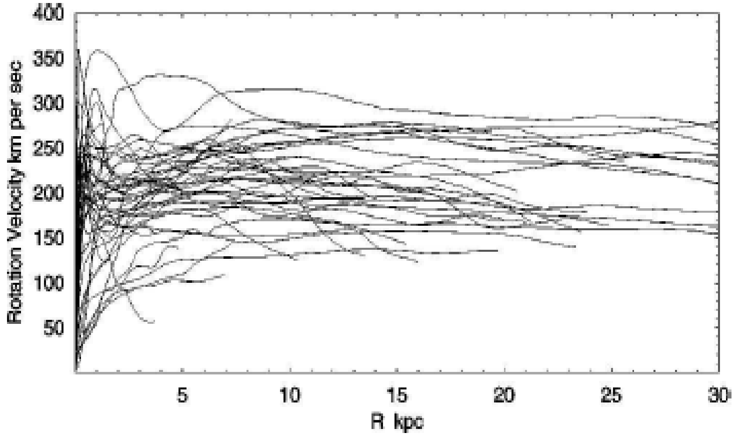
Bullet cluster: blue areas Dark Matter inferred by Gravitational Lensing Techniques



DARK MATTER

DARK MATTER (DM)

First Evidence from Rotational Curves (RC) of Galaxies. If all matter were luminous $v(r) \sim r^{-1/2}$ but observation show $v(r) \sim$ const .



Collage of RCs of nearby spiral galaxies obtained by combining Doppler data from CO molecular lines for the central regions, optical lines for the disks, and HI 21 cm line for the outer (gas) disks. The rotation velocity in units of km s^{-1} is plotted vs galactocentric radius R in kiloparsecs (kpc); 1 kpc $\approx$ 3000 light years. It is seen that the RCs are flat to well beyond the edges of the optical disks ($\sim$ 10 kpc). Graph from Ref.(Annual Review of Astronomy and Astrophysics, Volume 39 (c)2001)

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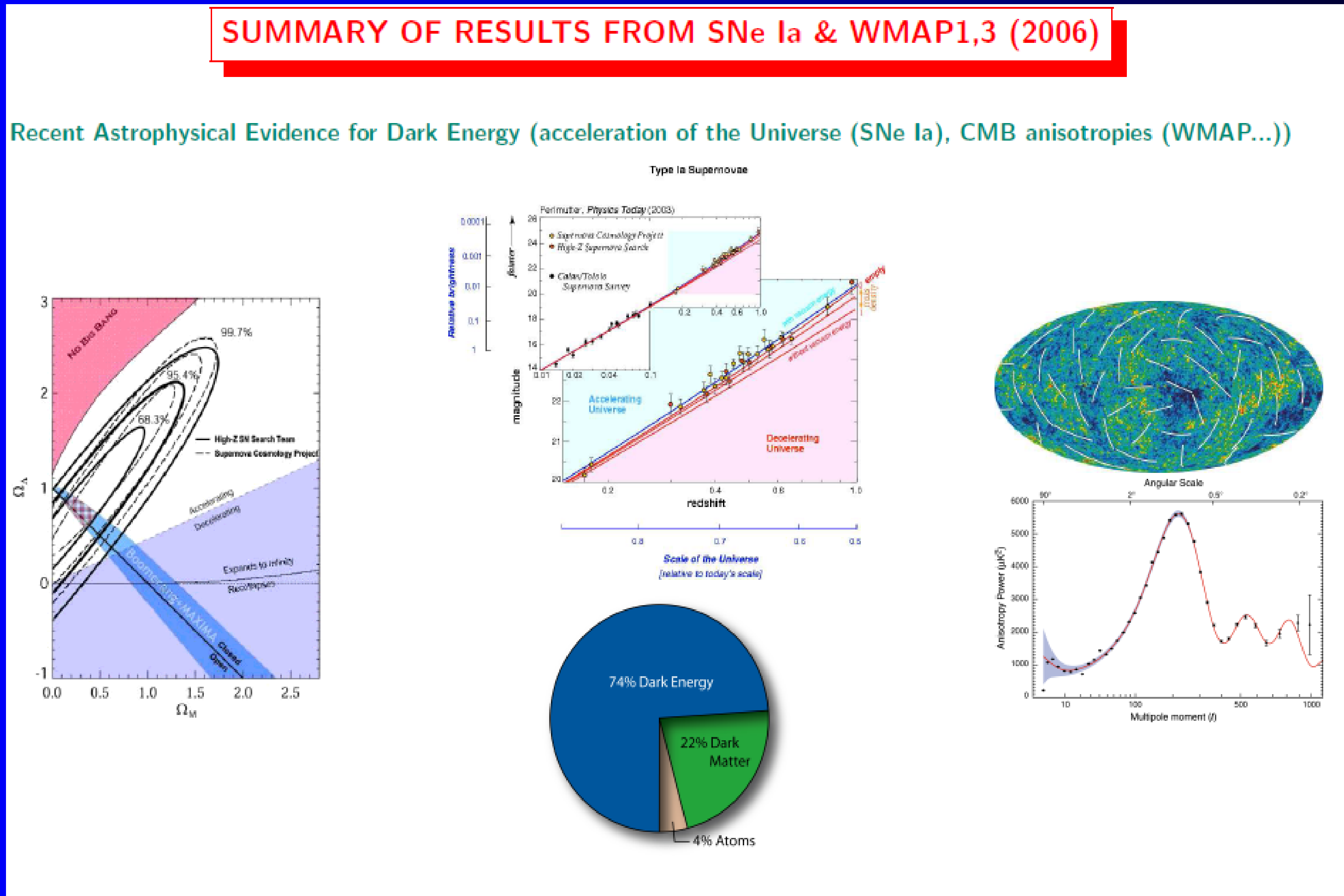
Supernova and CMB Data (2006)



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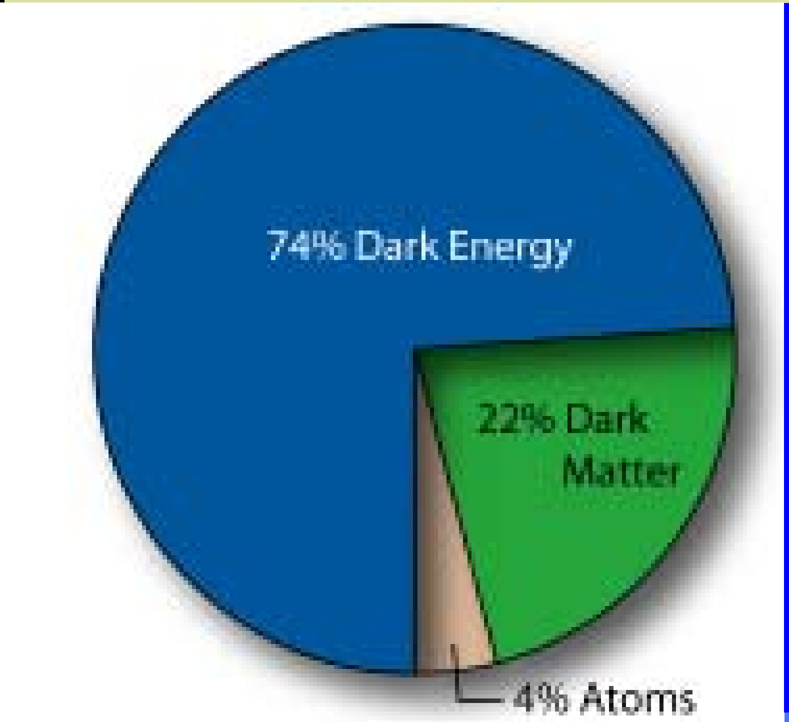

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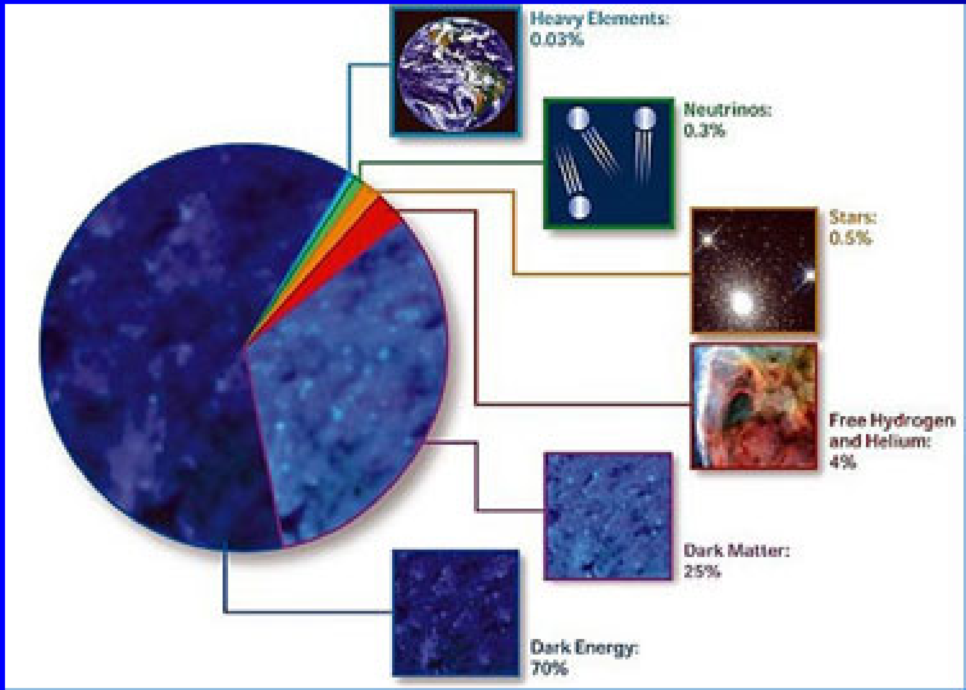

Evidence for :

Dark Matter(23%)

Dark Energy (73%)

Ordinary matter (4%)

COSMOLOGICAL MOTIVATION FOR LORENTZ VIOLATION?

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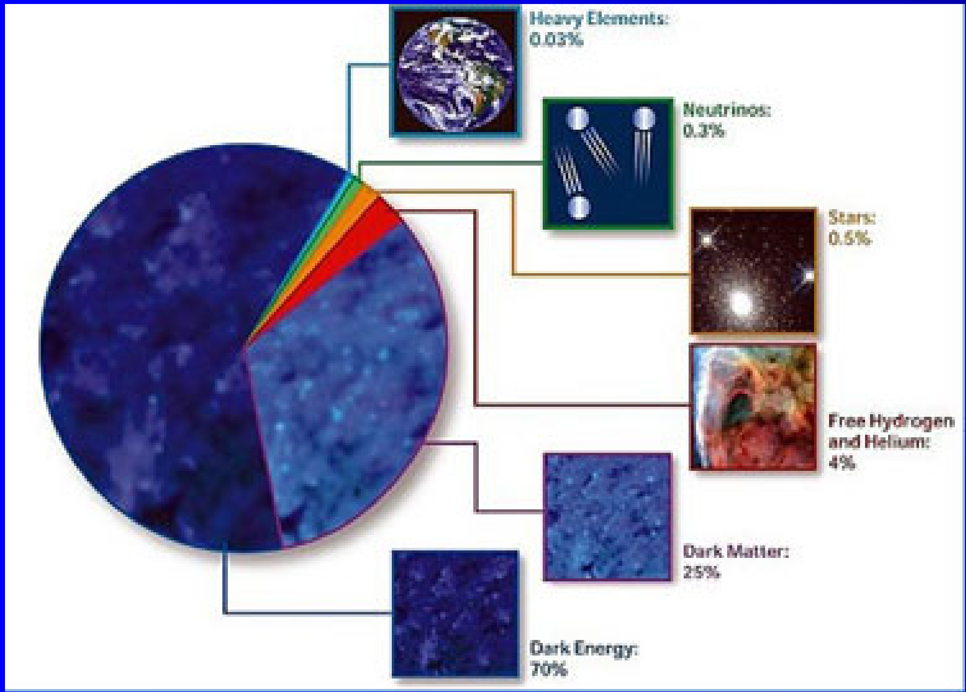

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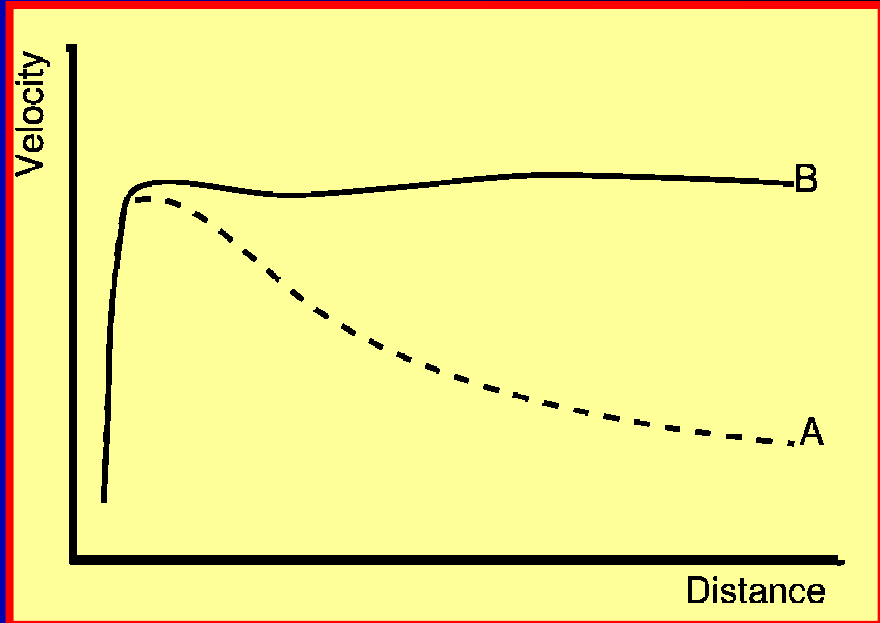
Or is it NOT?

COSMOLOGICAL LV MOTIVATION ?

Or is it not?
Modified Newtonian Law in Galactic Dynamics? (MOND)
(Milgrom 1983)

Rotational Curves of Galaxies reproduced WITHOUT Dark Matter



COSMOLOGICAL LV MOTIVATION ?

Make MOND derivable from a (classical…) field theory:
Introduce two metrics in space time, one for space-time dynamics, the other "felt" by matter fields with **Preferred frame** for the latter

$$G_{\mu\nu}^{\text{matter}} = G_{\mu\nu}^{\text{spacetime}} + (e^{-2\varphi} - e^{2\varphi})\, u_\mu u_\nu$$

(Bekenstein 2004: TeVeS theory)

Important feature of TeVeS: existence of a Lorentz violating vector field $u_\mu u^\mu = -1$, $u_\mu = (u_0, 0, 0, 0)$ (isotropy of Universe).

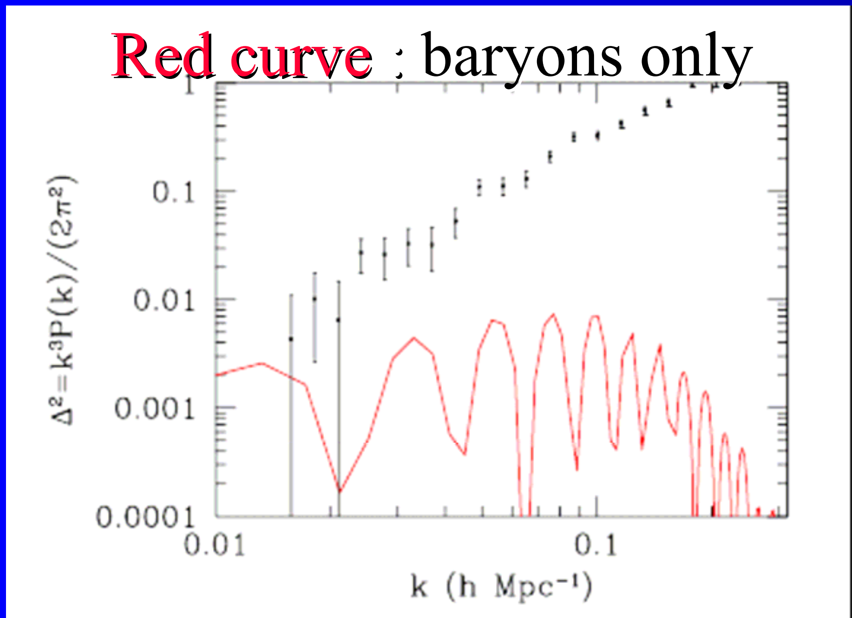
In an expanding FRW Universe:

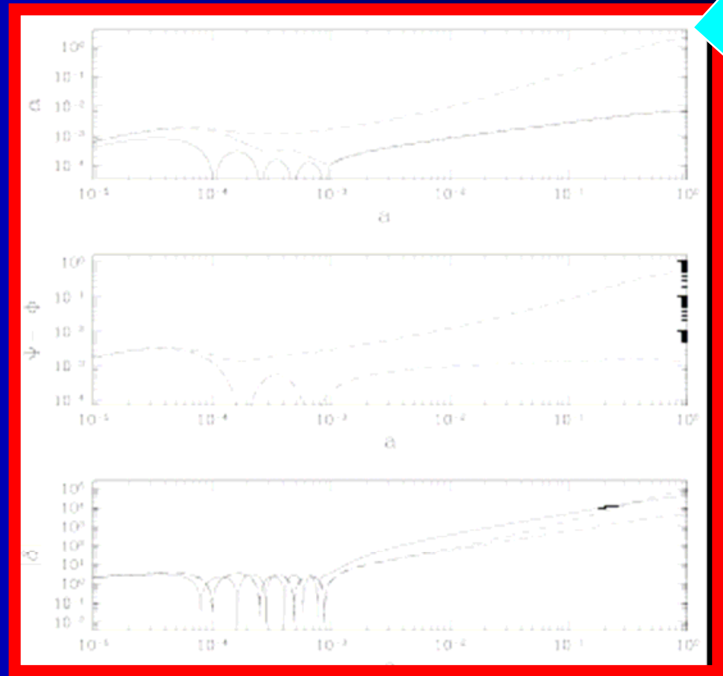
$$u_0\,(z) = a_0\, \boldsymbol{a}\,(z)\, e^{-\varphi}$$

(z=redshift , $\boldsymbol{a}$ (z) =scale factor, φ=scalar field of TeVeS)

COSMOLOGICAL LV MOTIVATION ?

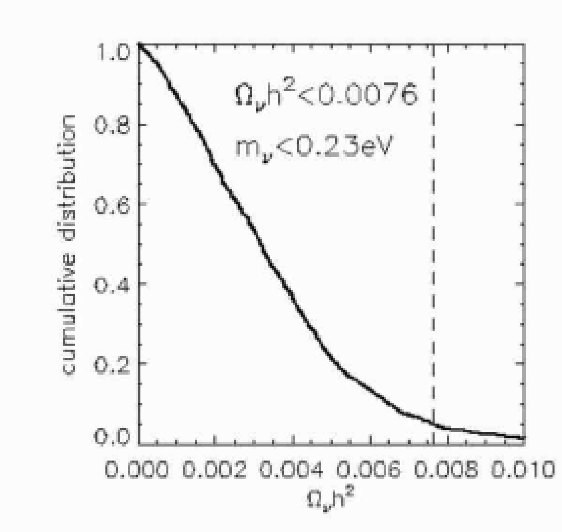
Rotational Curves of Galaxies reproduced in MOND/TeVeS, but also enhanced growth of cosmic perturbations observed in galaxies explained by means of vector field u_μ instabilities **(Dodelson-Liguori 2006)**





WMAP excludes HOT Dark Matter

Caution:
FRW- Comology &
local Lorentz
invariance **assumed.**
If Lorentz violated (TeVeS)
ν of 2 eV mass could have
Ω_ν ~ 0.15 to reproduce
CMB spectrum
(Dodelson-Liguori 2006)



Contribution of neutrinos to energy density of Universe: $\Omega_\nu h^2 = \frac{\sum_i m_i}{94.0\ \mathrm{eV}}$
(sum over light neutrino species (decouple while still relativistic)).
WMAP and other experiments (the Lyman α data etc) $\Omega_\nu h^2 < 0.0076 \Rightarrow < m_\nu >_e < 0.23$ eV :
Excludes HOT DM.

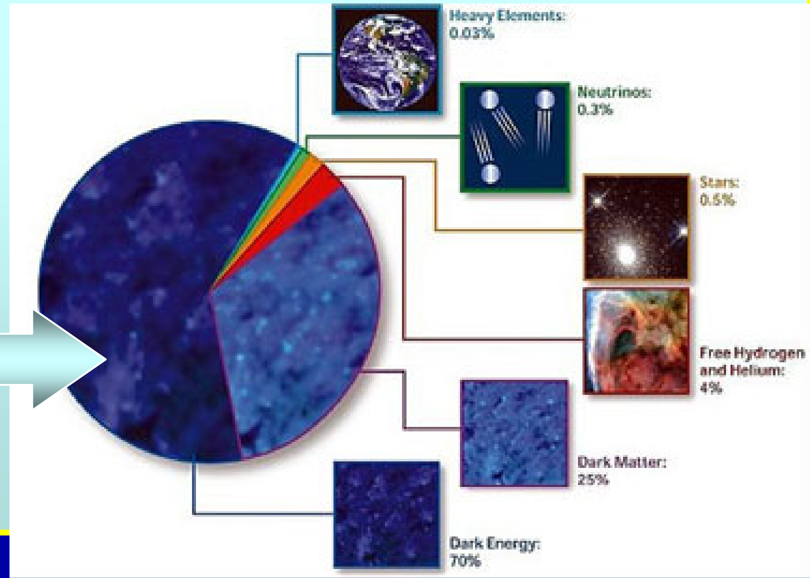
NB: WMAP still consistent with Majorana neutrinos, and also marginally with $\beta\beta$-decay
(Heidelberg-Moscow Coll.).

DARK ENERGY

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

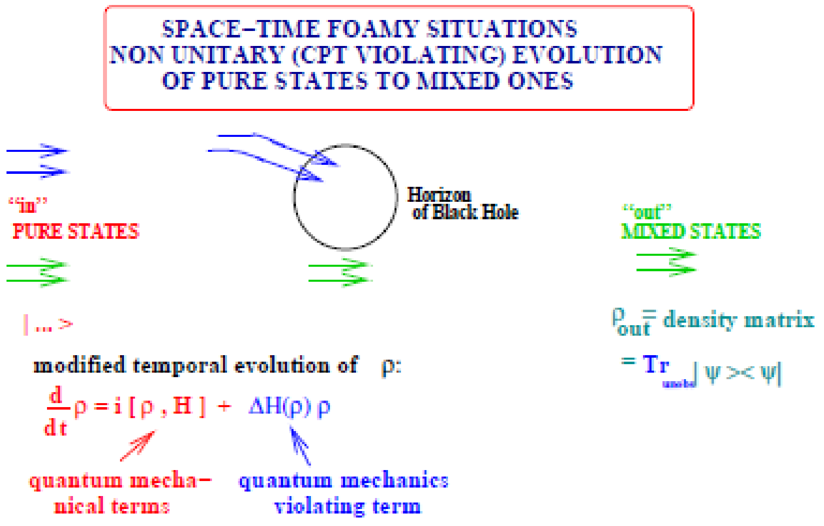
- **Could be:**
  - a Cosmological Constant
  - Quintessence (scalar field relaxing to minimum of its potential)
  - Something else…Extra dimensions, colliding brane worlds *etc.*

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



SPACE-TIME FOAM AND UNITARITY VIOLATION

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

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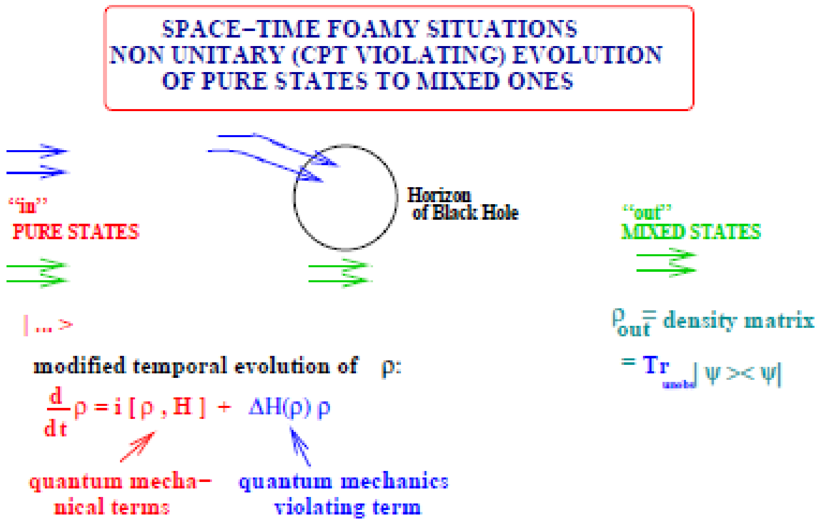

In general, in space-times with Horizons (e.g. De Sitter cosmology…)

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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 : $\Theta \overline{\rho}_{in} = \rho_{out}$

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

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

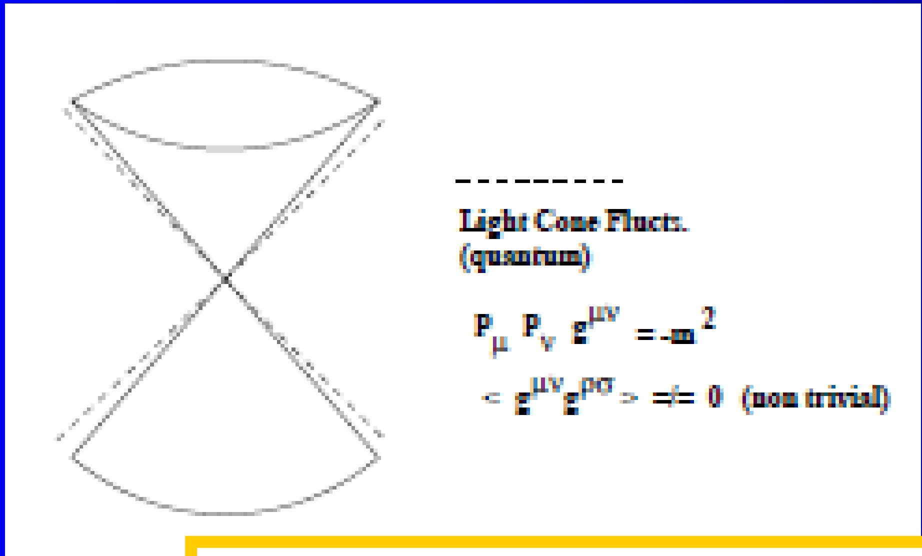
BUT THIS IMPLIES THAT \$ HAS AN INVERSE- $\Theta^{-1} \$ \Theta^{-1}$, IMPOSSIBLE (information loss), hence CPT MUST BE VIOLATED (at least in its strong form).

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...)

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)

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

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

DETECTING CPT VIOLATION (CPTV)

Complex Phenomenology
No single figure of merit

- **Neutral Mesons: K, B, (unique tests) meson-factories entangled states**
- **$K^{\pm}_{\ell 4}$ charged-meson decays** $K^{\pm} \to \pi^{+}\pi^{-}\ell^{\pm}\nu_{\ell}(\overline{\nu}_{\ell})$
- **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.).

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

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    - **Ultracold Neutrons**

INDIRECT TESTS: astrophysical evidence for dark Energy

- Relaxation off-equilibrium models of dark Energy and fundamental time irreversibility. If cosmological constant (de Sitter) then due to cosmic horizon CPT may be not well defined (NM, Wald).

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

- **Free Molecules: States (J(I) electronic (nuclear) angular momentum):** $|J, I; m_J, m_I>$
  - Energy-shifts between states (perturbation theory):

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

(e=electron, p=proton)

- **For Anti-Hydrogen:**

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?

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

Lorentz Violation & Anti-Hydrogen

- **Free Molecules: States (J(I) electronic (nuclear) angular momentum):** $|J, I; m_J, m_I>$
  - Energy-shifts between states (perturbation theory):

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

(e=electron, p=proton)

- **For Anti-Hydrogen:**

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?

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

Lorentz Violation & Anti-Hydrogen

❖ **Trapped Molecules:**

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):

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

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

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

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

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

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

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

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

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

$\kappa = \cos 2\theta_2 - \cos 2\theta_1$, $\kappa \simeq 0.67$ 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.

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: $M = q_1\overline{q}_2$):

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

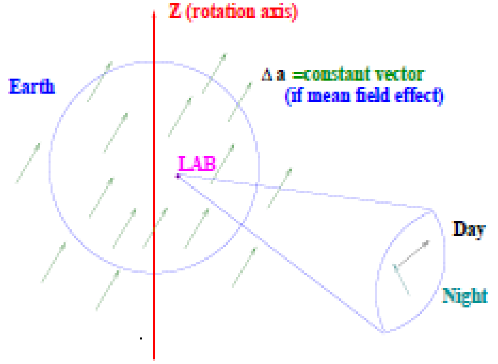
S=short-lived, L=long-lived, I=interference term, $\Delta m = m_L - m_S$, $\Delta\Gamma = \Gamma_S - \Gamma_L$,

$\widehat{\phi} = \arctan(2\Delta m/\Delta\Gamma)$, $\quad \Delta a_\mu \equiv a^{q_2}_\mu - a^{q_1}_\mu$, 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?

EXPERIMENTAL BOUNDS

- **BUT RECALL:**

COSMOLOGICAL

LORENTZ VIOLATION MIGHT

IMPLY ONLY A NON-TRIVIAL a_0

EXPERIMENTAL BOUNDS

❖ **BUT REC**

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

LORI

IMPLY ONLY A NON-TRIVIAL a_0

IN ATOMIC PHYSICS: Place atoms in external magnetic fields, of varying Strength, B, measure energy shifts, plot them vs. B and extrapolate to B = 0.

EXPERIMENTAL BOUNDS

- **BUT RECALL:**

COSMOLOGICAL

LORENTZ VIOLATION MIGHT

IMPLY ONLY A NON-TRIVIAL a_0

CAN PARTICLE PHYSICS (e.g. KAON EXPTS.)

PROVIDE STRINGENT BOUNDS ON IT?

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"):

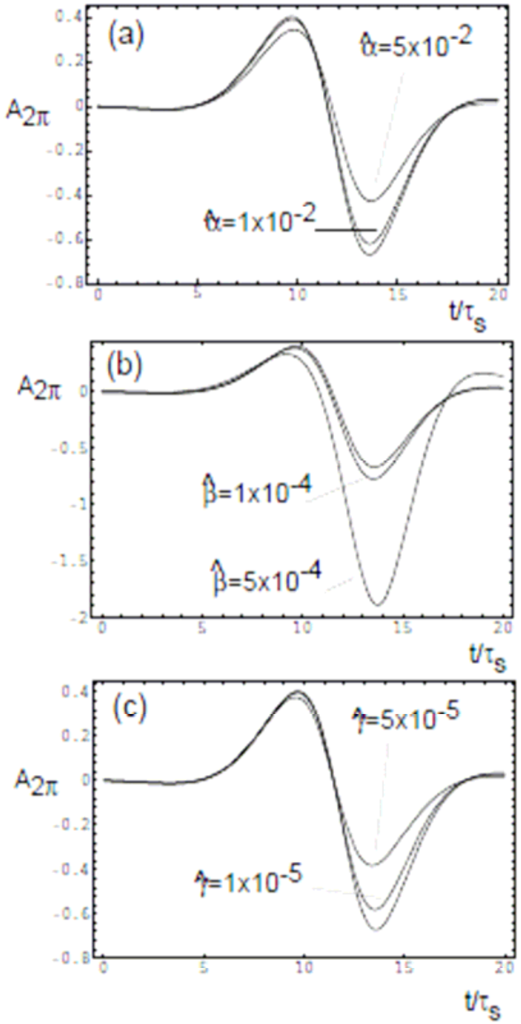
$$\zeta \rightarrow \frac{\widehat{\gamma}}{2|\epsilon^2|} - 2\frac{\widehat{\beta}}{|\epsilon|}\sin\phi$$

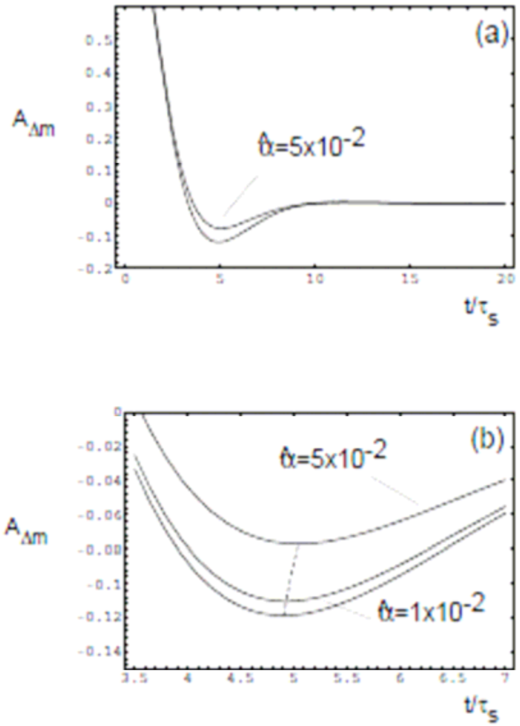
(for meson-factories, complete positivity $\widehat{\beta} = 0$).

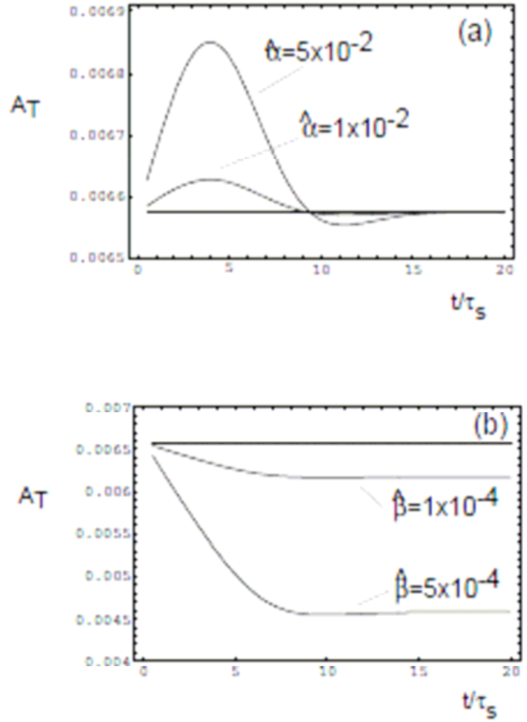
[Convenient parametrization: $\widehat{a}$, $\widehat{\beta}$, $\widehat{\gamma} \equiv \frac{\alpha,\ \beta,\ \gamma}{\Delta\Gamma}$, $\Delta\Gamma = \Gamma_S - \Gamma_L$. For Kaons: $\Delta\Gamma \sim 10^{-15}$ GeV.]

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_{T}, A_{CPT}, $A_{\Delta m}$, and ζ.

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

Indicative Bounds

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

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 (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

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

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

$\gamma = \left(-0.4^{+5.8}_{-5.1\,stat} \pm 1.2_{syst}\right) \times 10^{-21}$ 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 $L = 2.5\ fb^{-1}$: $\gamma \to \pm 2.2_{stat} \times 10^{-21}$ GeV ,

Perspectives with KLOE-2 at DAΦNE-2 :

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

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

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

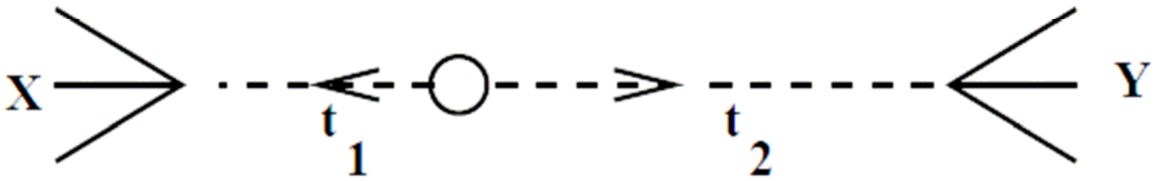
What are EPR correlations?

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):

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

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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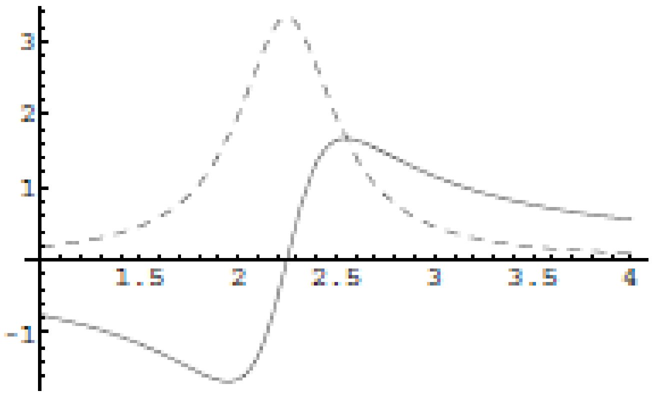
$|i> \quad =$ … $>)$

$+$ … $)]$



NB! K_SK_S or $K_L - K_L$ cor… y channels. There is contamination of C(odd) state … of contamination by the "wrong" (C(even)) symmetry st…

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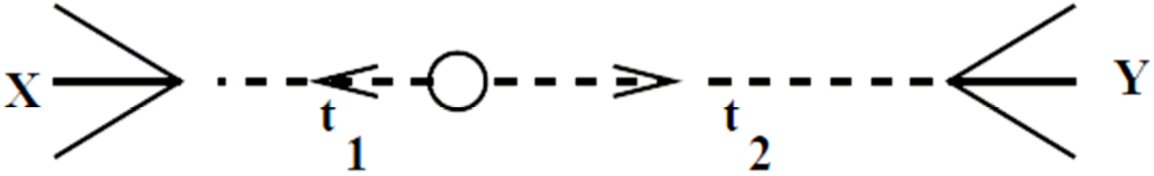
ϕ Decays and the ω Effect

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

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

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

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

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

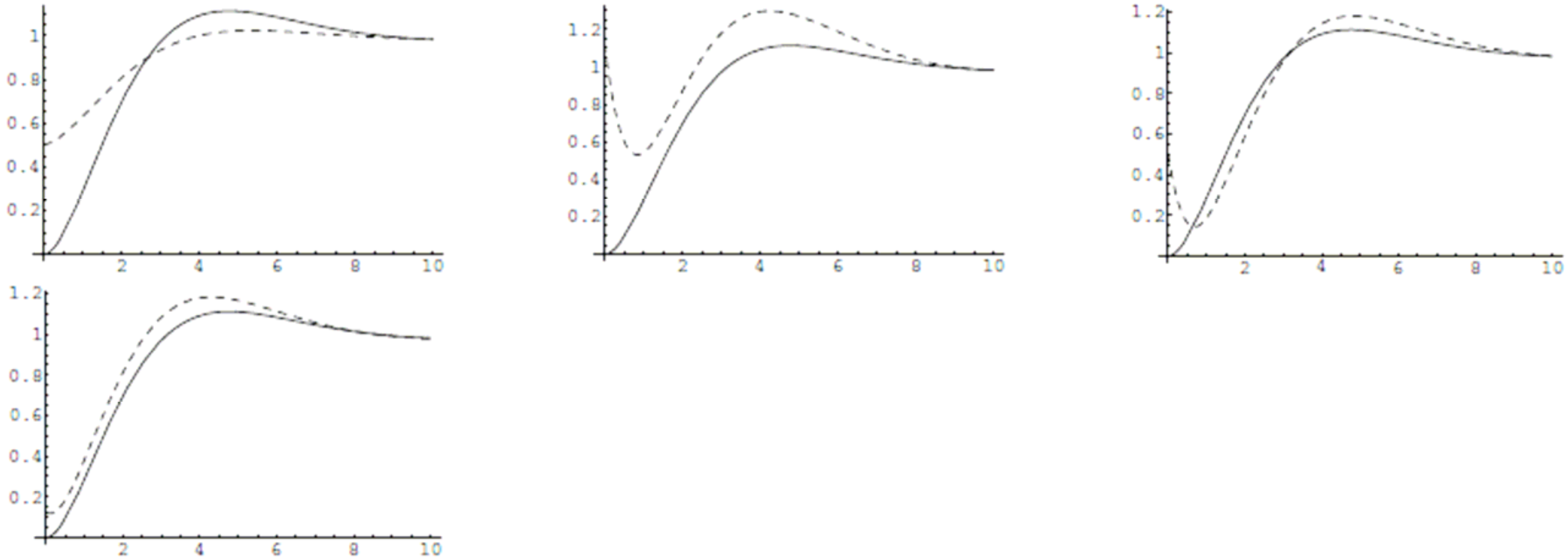
$$\Big[2\Delta M\Big(e^{-\Gamma_S\Delta t}\sin(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\sin(\phi_{+-} - \Omega + \Delta M\Delta t)\Big)$$

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

$\Delta M = M_S - M_L$ 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 $|C|^2|\eta_{+-}|^2|\langle\pi^+\pi^-|K_S\rangle|^4\tau_S$.

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.

Perspectives for KLOE-2 at DAΦNE-2 (A. Di Domenico home page) :
$\mathrm{Re}(\omega),\ \mathrm{Im}(\omega) \longrightarrow 2 \times 10^{-5}$.

NB: ω-Effect also generated by propagation through the medium, but with time-dependent (sinusoidal) $\omega(t)$-terms, can be (in principle) disentangled from initial-state ones...

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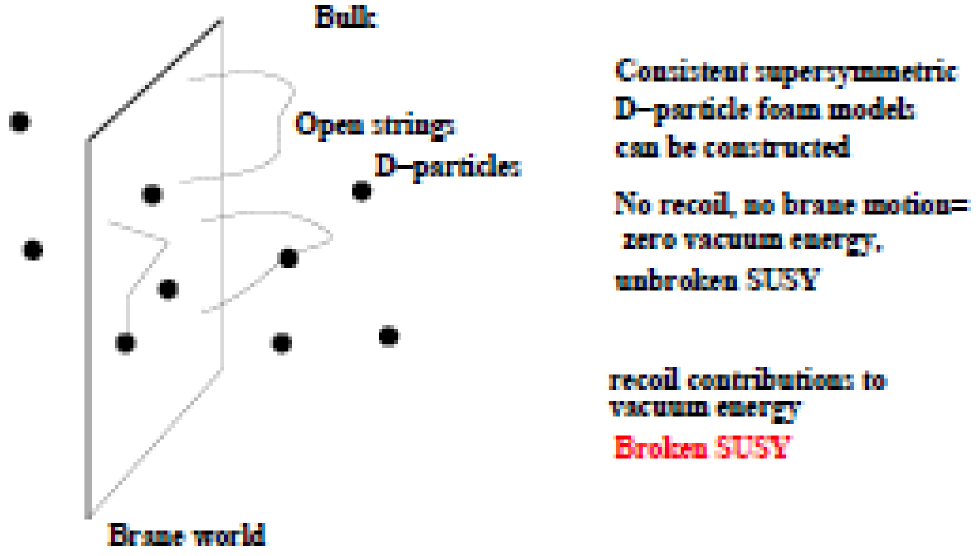

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PRECISION T, CP & CPT TESTS WITH CHARGED KAONS

$$K^{\pm} \to \pi^{+} + \pi^{-} + \ell^{\pm} + \nu_{\ell}(\overline{\nu}_{\ell})$$

Lee & Wu (Ann. Rev. Nucl. Sci. 16, 471 (1966), Pais & Treiman, Phys. Rev. D (1968))

If CPT well defined but not commuting with Hamiltonian:

$|K^{+}\rangle = \widehat{CPT}|K^{-}\rangle$

$|\pi^{+}\rangle = \widehat{CPT}|\pi^{-}\rangle, \qquad |\pi^{0}\rangle = \widehat{CPT}|\pi^{0}\rangle$

If CPT does not commute with Hamiltonian, then differences between particle antiparticle masses ...BUT this is not the end of the story.... In fact it is not even true in certain models of Lorentz and/or unitarity violating quantum gravity (QG).

If CPT ILL defined (e.g. QG decoherence) $\Longrightarrow$ (perturbative) ambiguities , antiparticle state still defined but modified, e.g. Bose-Statistics effects modified... Interesting novel effects on two particle states, e.g. two pion final states in $K^{\pm}_{\ell 4}$

In specific models of space time foam, there are induced imaginary (dissipative) terms as a result of space-time foam (Bernabeu, NM, Sarkar)

Interactions of particles with the foam MAY be DIFFERENT from those of antiparticles, $\Longrightarrow$ difference in decay widths, say between $K^{+}_{\ell 4}$ and $K^{-}_{\overline{\ell} 4}$ decays...

$K^{\pm}_{e4}$ tests of T, CP & CPT Invariance

Mainly QG models imply microscopic Time Reversal (T) Violation.

Use $K^{\pm}_{\ell 4}$ for precision tests of T, CP, CPT (Lee, Wu, Pais, Treiman)

Check on $\Delta S = \Delta Q$ rule (QG could violate this as well)

e.g. look for $\Delta S = -\Delta Q$ reaction: $K^+ \to \pi^+ + \pi^+ + e + \nu$

(i) assume $|\Delta I| = 1/2$ isospin rule (can check on that expt)

AMPLITUDES:

$$e^{i\xi} A = \langle \pi^+ \pi^- | \ell = 0, m = 0 \rangle \langle \ell = 0, m = 0 | S_z + iv S_4 | K^+ \rangle m_K^{5/2} (\omega_+ \omega_-)^{1/2}$$

$$e^{i\xi + i\eta_0} B_0 \cos\theta = \langle \pi^+ \pi^- | \ell = 1, m = 0 \rangle \langle \ell = 1, m = 0 | S_z + iv S_4 | K^+ \rangle m_K^{5/2} (\omega_+ \omega_-)^{1/2}$$

$$e^{i\xi + i\eta_\pm} B_\pm \sin\theta e^{\pm i\phi} = \langle \pi^+ \pi^- | \ell = 1, m = \pm 1 \rangle \langle \ell = 1, m = \pm 1 | \frac{1}{\sqrt{2}} (S_x + i S_y) | K^+ \rangle m_K^{5/2} (\omega_+ \omega_-)^{1/2}$$

phase conventions: $A, B_0, B_\pm$ real & positive, polar angles θ, ϕ pertain to di-pion center-of-mass system $\Sigma_{2\pi}$, xyz are Cartesian coordinates in Lab system $\Sigma_{\rm Lab}$. There is also angle α in dilepton center-of-mass system $\Sigma_{\ell \nu_\ell}$. The $\omega_\pm$ denote laboratory energies of $\pi^\pm$, $v = -[m_K - (\vec{P}^2 + M^2)^{1/2}]^{-1} |\vec{P}|$, is the velocity of Lorentz trnsf. connecting $\Sigma_{\ell\nu_\ell}$ to $\Sigma_{\rm Lab}$ frames, with $\vec{P}$ the total momentum of two pions in $\Sigma_{\rm Lab}$.

under CPT: Barred quantities: $\overline{(\dots)}$ $\quad K^+ \to K^-$, $\quad \pi^+(\vec{k}_1)\pi^-(\vec{k}_2) \to \pi^-(\vec{k}_1)\pi^+(\vec{k}_2)$, plus appropriate complex conjugates...

$K^{\pm}_{e4}$ tests of T, CP & CPT Invariance

CPT Invariance:

$A = \overline{A}, \quad B_0 = \overline{B}_0, \quad B_{\pm} = \overline{B}_{\mp}$

$\eta_+ + \overline{\eta}_- = \eta_- + \overline{\eta}_+ = \eta_0 + \overline{\eta}_0 = 2\,(\delta_p - \delta_s)$

independent of T invariance, with $\delta_p(\delta_s)$ the strong-interaction $\pi - \pi$ scattering phase shifts for the states $I = 1, \ell = 1 (I = 0, \ell = 0)$.

CPT Invariance independently of $|\Delta I| = 1/2$ rule, implies:

$\mathrm{rate}(K^+ \to \pi^+\pi^- e^+\nu_e) + \mathrm{rate}(K^+ \to \pi^0\pi^0 e^+\nu_e) = \mathrm{rate}(K^- \to \pi^+\pi^- e^-\overline{\nu}_e) + \mathrm{rate}(K^- \to \pi^0\pi^0 e^-\overline{\nu}_e)$

Under the assumption of $|\Delta I| = 1/2$ rule, CPT invariance implies for differential rates d^5N:

$\int d\phi d\cos\theta \quad d^5N(K^+ \to \pi^+\pi^- e^+\nu_e) = \int d\phi d\cos\theta \quad d^5N(K^- \to \pi^+\pi^- e^-\overline{\nu}_e)$

T invariance (independent of CP, CPT):

$\eta_\sigma = \delta_p - \delta_s \text{ (modulo } \pi) \,, \qquad \sigma = 0, \pm$

CP Invariance: (independent of T, CPT): angles $\theta, \phi, \alpha \to \theta, -\phi, \alpha$

$A = \overline{A}, \quad B_0 = \overline{B}_0, \quad B_{\pm} = \overline{B}_{\mp}, \quad \eta_0 = \overline{\eta}_0, \quad \eta_{\pm} = \overline{\eta}_{\mp}$

$[d^5N(K^+)]_{\alpha,\theta,\phi} = [d^5N(K^-)]_{\alpha,\theta,-\phi}$

implying also $\int d\phi d\cos\theta \quad d^5N(K^+ \to \pi^+\pi^- e^+\nu_e) = \int d\phi d\cos\theta \quad d^5N(K^- \to \pi^+\pi^- e^-\overline{\nu}_e)$ but without the assumption about $|\Delta I| = 1/2$ rule.

NOTE: Exotic $\Delta S = 1$ CP VIOLATION IN $K^{\pm}_{\ell 4}$

In Standard Model (SM) Physics direct CP violation or CP violation of pure $\Delta S = 1$ in origin or, equivalently (due to CPT symmetry) T-odd correlators are very suppressed in non-leptonic decays ($K^{\pm} \to (3\pi)^{\pm}$) ($10^{-5} - 10^{-6}$) and negligible in $K_{\ell 4}$. (D'Ambrosio- Isidori (1998))

Evidence for such violations in $K_{\ell 4}$ charged Kaon decays will therefore be taken as evidence for Physics beyond the Standard Model.

$$\mathcal{H}_{\rm eff} = 2\sqrt{2} G_F V^*_{us} \sum_i C_i \mathcal{O}_i + h.c.$$

$\mathcal{O}_i$ dimension six four-fermion operators involving left handed neutrinos (e.g. $\mathcal{O}^V_L = \overline{s}_L \gamma^\mu u_L \overline{\nu}_L \gamma_\mu \ell_L$, $\mathcal{O}^S_L = \overline{s}_R u_L \overline{\nu}_L \ell_R$, $\mathcal{O}^T_L = \overline{s}_R \sigma^{\mu\nu} u_L \overline{\nu}_L \sigma_{\mu\nu} \ell_R$, etc ($\mathcal{O}^i_R : s_R \to s_L,\ u_L \to u_R$)). In SM only $C^V_L = 1$, others are negligible.

Revelant matrix elements for $K_{\ell 4}$: within SM $\langle \pi^+ \pi^- | \overline{s} \gamma^\mu u | K^+ \rangle$, $\langle \pi^+ \pi^- | \overline{s} \gamma^\mu \gamma_5 u | K^+ \rangle$,

Beyond SM, e.g. $\langle \pi^+ \pi^- | \overline{s} \gamma_5 u | K^+ \rangle$, $\langle \pi^+ \pi^- | \overline{s} \sigma^{\mu\nu} \gamma_5 u | K^+ \rangle$,

Combined studies of T-odd correlators in $K_{\ell 4}$ decays, $\vec{p}_\ell \cdot (\vec{p}_{\pi_1} \times \vec{p}_{\pi_2})$ by analyzing (appropriate combinations of) BOTH K^+ and K^- modes, lead to new CP violating observables, free from strong final state interaction phases, sensitive to non standard $\Delta S = 1$ interactions , without the need for measurement of lepton polarization (A. Retico, hep-ph/0203044 for $\ell = \mu$ case, results complementary & of comparable accuracy to transverse muon polarization in $K_{\mu 3}$).

High Statistics of $K^{\pm}_{\ell 4}$: new constraints on exotic (beyond the standard model) scenarios, such as R-parity breaking in supersymmetry etc complementary to those obtained through $K_{\ell 3}$ decays.

Concluding Questions…

- Experimentally Testing Quantum Gravity (QG) may not be an oxymoron scheme....
  CPT Violation may not be an academic issue, but a real feature of QG.
- Various ways for CPT breaking, in principle independent, e.g. decoherence and Lorentz Violation (LV) are independent effects. One may have Lorentz invariant decoherence in Quantum Gravity (Millburn), frame dependence of LV effects (e.g. day-night measurement differences etc disentangle LV from LI CPTV, e.g. meson factories).
- Precision experiments in meson factories, will provide sensitive probes of QG-induced decoherence & CPT Violation, including NOVEL effects (ω-effect) exclusive to ENTANGLED states: modified EPR correlations, Theoretical (intrinsic) limitations on flavour tagging...Lorentz invariance would imply effects similar in ϕ and B-meson factories-: ϕ-meson produced at rest, Υ- state boosted...in contrast LV would lead to differences/frame dependence...
- Are there any effects of intrinsic (QG decoherence) CPT Violation on viewing entangled (neutral) mesons as Quantum Erasers & Markers ?
- What about Equivalence principle and QG?: are QG effects universal among particle species?
- Are QG-decoherence effects of the same strength between particles & antiparticles ? tests in antimatter factories ? neutrinos ?

- Precision experiments in charged Kaons: with improved statistics one can perform high precision tests of T, CPT & CP invariance using $K_{\ell 4}$ decays.

Worthy of investing effort...

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