CPT and DECOHERENCE in QUANTUM GRAVITY

N. E. Mavromatos
King's College London
Physics Department

MRTN-CT-2006-035863

DISCRETE 08 SYMPOSIUM ON PROSPECTS IN THE PHYSICS OF DISCRETE SYMMETRIES
IFIC – Valencia (Spain), December 11-16 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

→ This talk

OUTLINE

- Theoretical motivation for CPT Violation (CPTV) :

(i) Lorentz violation (LV): microscopic & cosmological

Briefly

(ii) Quantum G
(Decohere

- Towards n
(non-critic

Order of mag
effects

- 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)

-time

s talk

ce
llation
h by

s talk

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:

    → 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.

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.

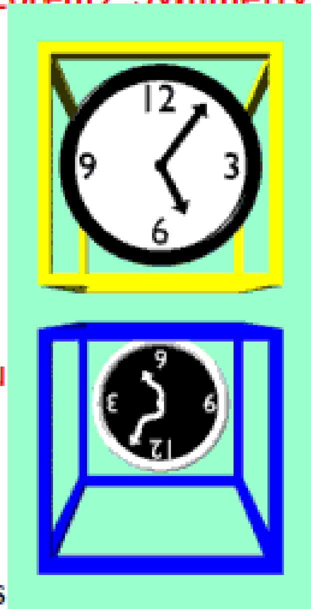
E.g.: LORENTZ-VIOLATING NON-TRIVIAL VACUA OF STRINGS, SPACE-TIME FOAMY SITUATIONS IN SOME QUANTUM GRAVITY MODELS.

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.

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

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



T... nd John Bell).

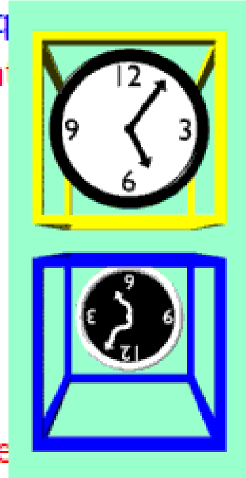
J... properties of Wightman's functions (i.e. quantu...
(... $< 0|\phi(x_1)\ldots\phi(x_n)|0 >$) under Lorentz group.

Theories with HIGHLY CURVED SPACE TIMES , with space time boundaries ... izon 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.

CPT THEOREM

C(harge) -P(arity=reflection) -T(ime reversal) INVARIANCE is a property of any q



theory in Flat space times which respects: (i) Locality, (ii) Unitarity and (iii) Loren

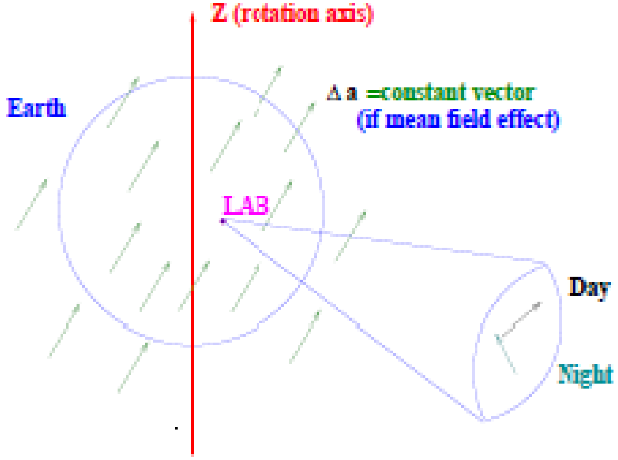
$$\Theta \mathcal{L}(x) \Theta^\dagger = \mathcal{L}(-x) \ ,$$

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

nd John Bell).

properties of Wightman's functions (i.e. quantum-fie

$0|\phi(x_1) \dots \phi(x_n)|0 >$) under Lorentz group (O. Greenberg



Theories with HIGHLY CURVED SPACE TIMES , with sp

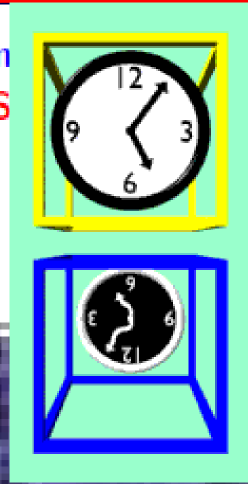
type, may violate (ii) & (iii) and hence CPT.

E.g.: LORENTZ-VIOLATING NON-TRIVIAL VACUA OF

SITUATIONS IN SOME QUANTUM GRAVITY MODELS

CPT THEOREM

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

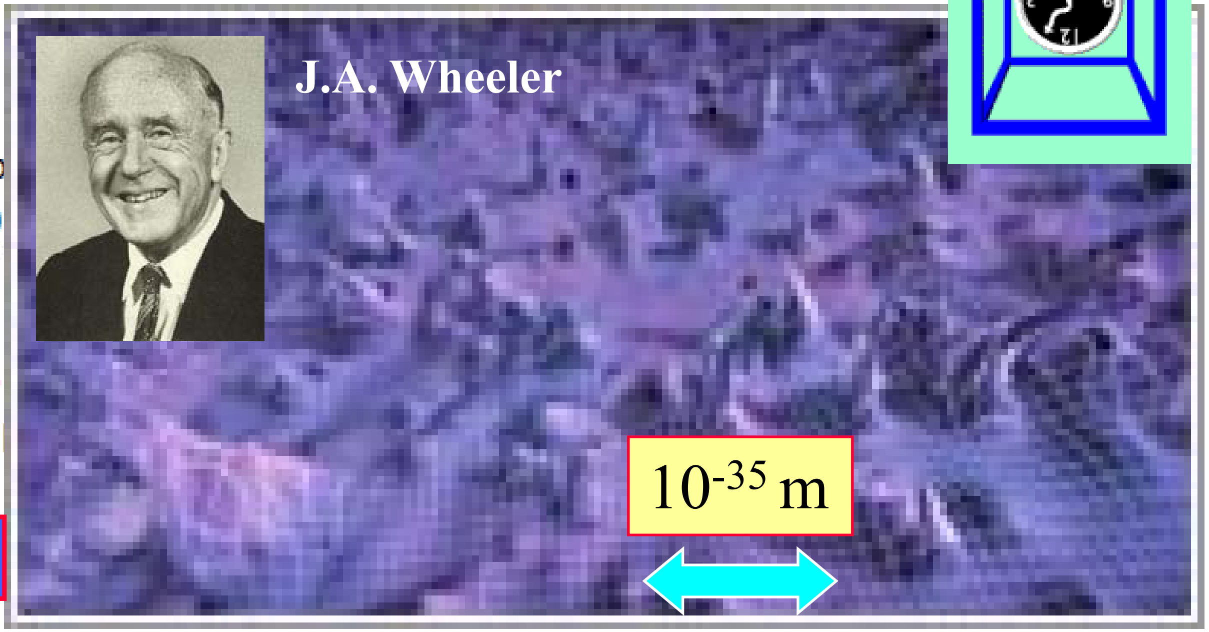


$$\Theta \mathcal{L}(x) \Theta^\dagger = \mathcal{L}(-x) \ ,$$

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

Theories with HIGHLY CURVED
type, may violate (ii) & (iii) and

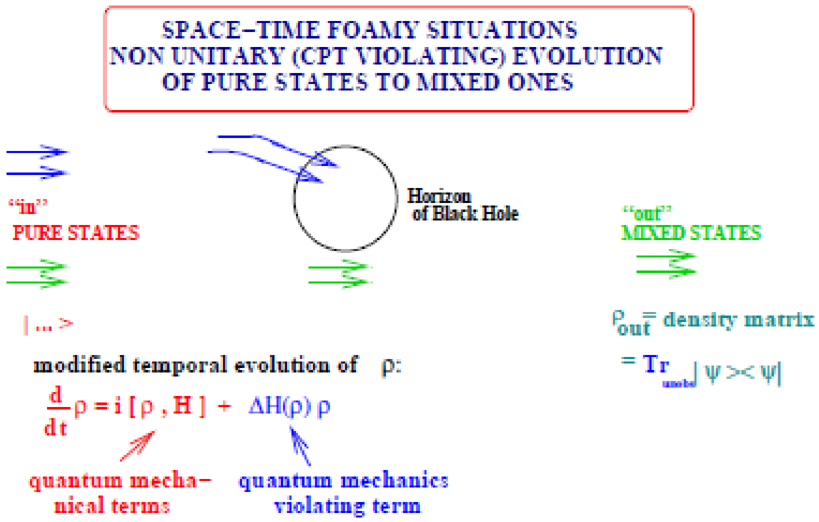
Space-time Foam



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 $\longrightarrow$ mixed



$\rho_{out} = \text{Tr}_{\text{unobs}}|out><out| = \$ \rho_{in}$, $\$ \neq SS^\dagger$, $S = e^{iHt}$ =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

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

SPACE-TIME FOAM AND UNITARITY VIOLATION

Arguments in favour of ho

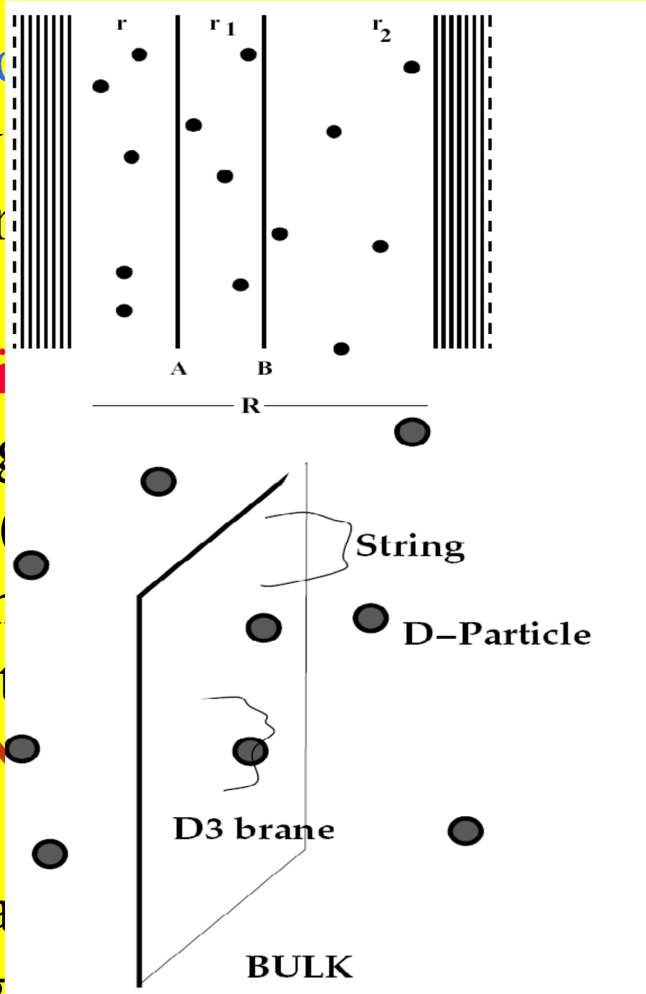
Path Integral over non-triv … s with time, leaving only trivial (unitar … s (**Maldacena, Hawking**)

Arguments against resoluti

(i) not rigorous proof thou … ure.

(ii) Entanglement entropy (… **ustein,Yarom**).

(iii) Also, Space-time foam … , e.g. due to stochastic space-time point … ane worlds (**D-particle foam**) **….(Ellis, N … r).**



Hence possible non-trivia … effective theories. Worth checking experimentally…. → CPTV issues

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.

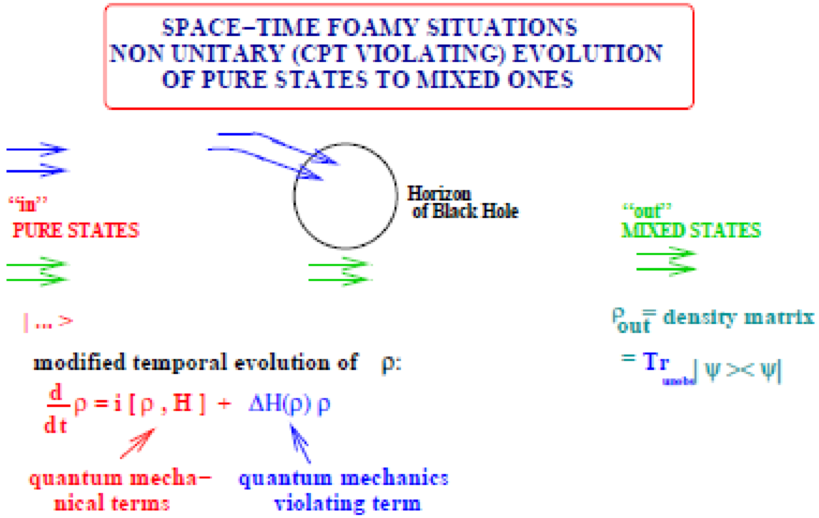
(ii) Entanglement entropy (**Srednicki**, **Einhorn, Brustein,Yarom**).

(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

SPACE-TIME FOAM AND UNITARITY VIOLATION

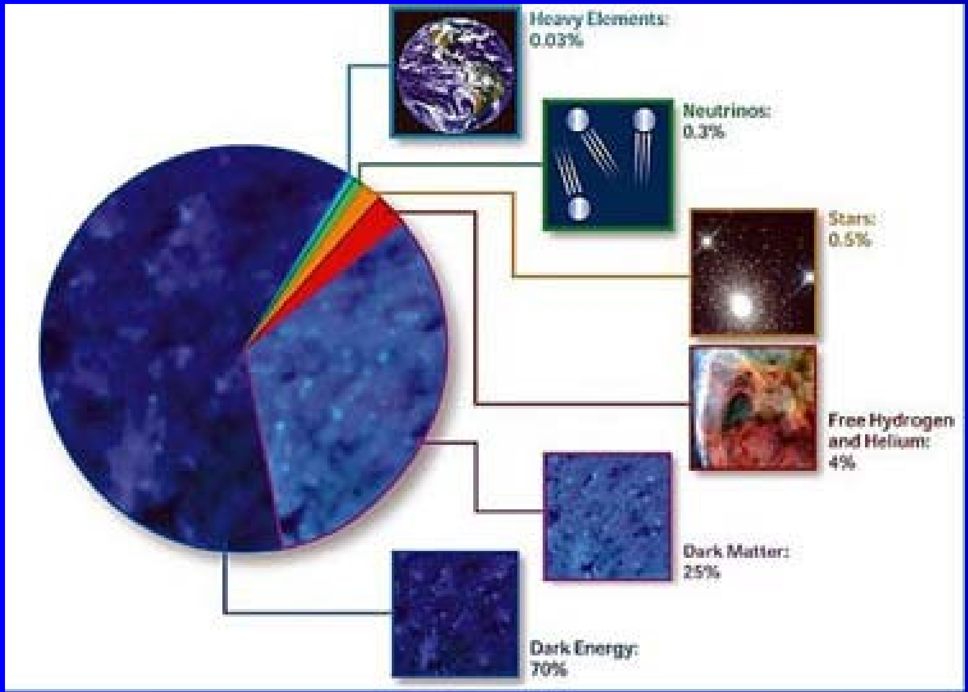
SPACE-TIME FOAM: Quantum Gravity SINGULAR Fluctuations (microscopic (Planck size) black holes etc) MAY imply: pure states $\longrightarrow$ mixed



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

$\rho_{out} = \mathrm{Tr}_{\mathrm{unobs}}|out><out| = \$\ \rho_{in}$, $\$ \neq SS^{\dagger}$, $S = e^{iHt}$ =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...

COSMOLOGICAL MOTIVATION FOR CPT VIOLATION?



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

Evidence for :

Dark Matter(23%)

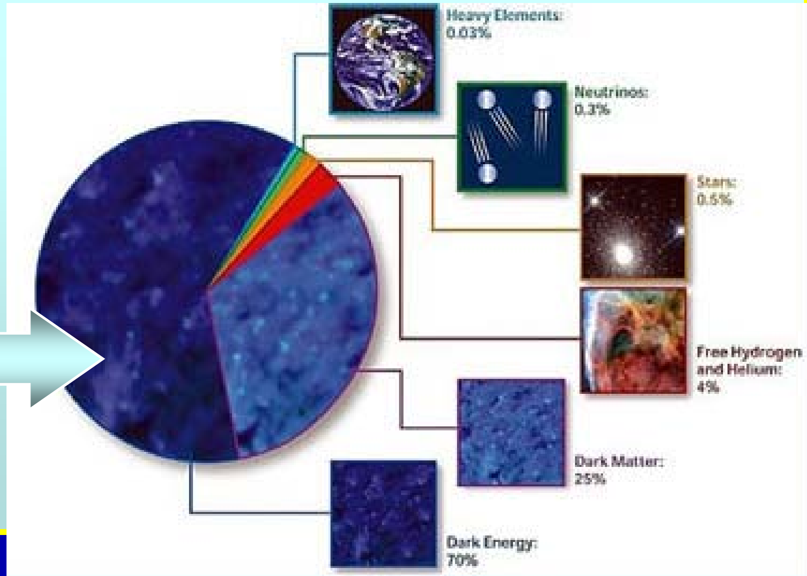
Dark Energy (73%)

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 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?



DARK ENERGY& Cosmological CPTV?

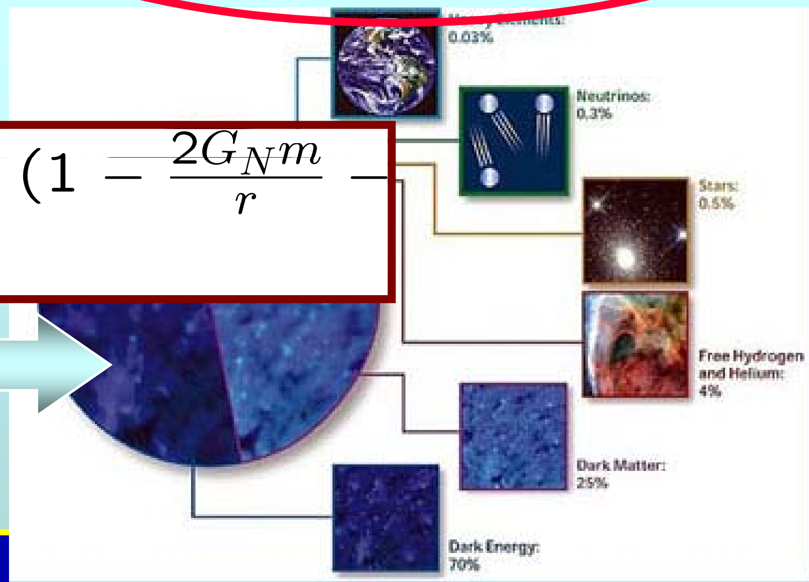
- KNOW VERY LITTLE ABOUT IT…
- EMBARASSING SITUATION 74% OF THE UNIVERSE BUDGET CONSISTS OF UNKNOWN SUBSTANCE

- **Could be:**
  - a Cosmological Constant

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

  - 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?



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

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

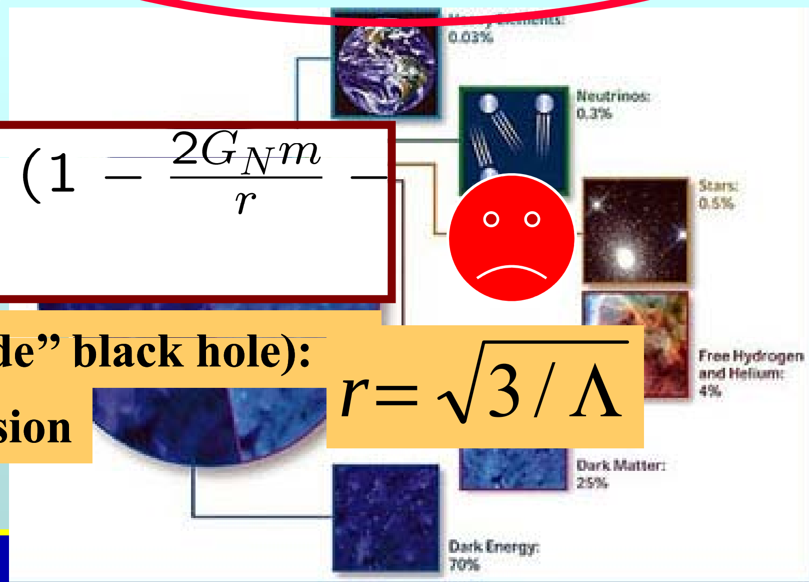
  - Something e… dimensions, … worlds *etc.*

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

Unstable, indicates expansion

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

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



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
  - $$ds^2_{FRW} = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$
    $$a(t) = e^{\sqrt{\frac{\Lambda}{3}}t}$$
  - Something else…Extra dimensions, colliding brane worlds *etc.*

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

Global (Cosmological FRW solution)

DARK ENERGY& Cosmological CPTV?

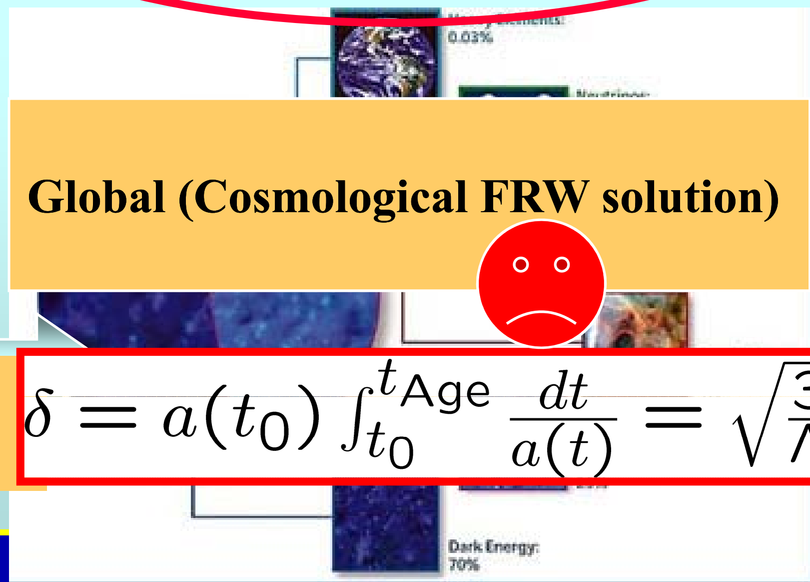
- KNOW VERY LITTLE ABOUT IT…
- EMBARASSING SITUATION 74% OF THE UNIVERSE BUDGET CONSISTS OF UNKNOWN SUBSTANCE
- **Could be:**
  - a Cosmological Constant
  - $ds^2_{FRW} = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$

    $a(t) = e^{\sqrt{\frac{\Lambda}{3}}t}$
  - Something else…Extra

Cosmological (global) deSitter horizon:

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

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



Global (Cosmological FRW solution)

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...)

CPT symmetry without CPT invariance ?

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

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

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

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

In terms of superscattering matrix \$:

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

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

CPT symmetry without CPT invariance ?

But....nature may be tricky: WEAK FORM OF CPT
INVARIANCE ...
of time ...
measu...
Probal...
ϕ =fin...

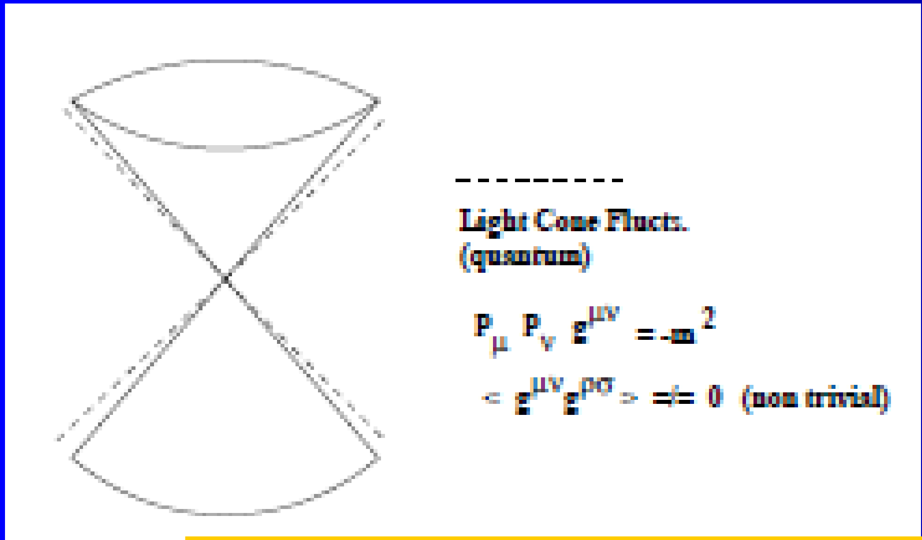
where ...
$\Theta\rho =$ ...
In term...

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.**

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

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

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)

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

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

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…)**

Caution on CPTV & Lorentz Violation

- **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…)**

- **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) $\longrightarrow$ 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

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

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

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

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

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

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

$$\widehat{\psi} = \psi - \tfrac{1}{2}\theta^{\alpha\beta} A_\alpha \partial_\beta \psi.$$

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

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

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)

Non-commutative effective field theories

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

Moyal $\star$ products

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

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

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

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

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

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

$$D_\mu \psi = \partial_\mu \psi - i q A_\mu \psi$$

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

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) $\longrightarrow$ 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: $i\partial_t \Psi = \mathcal{H}\Psi$

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

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

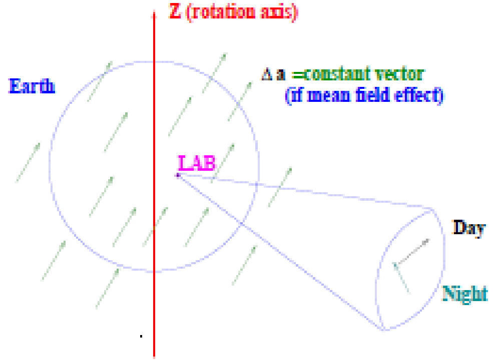
S=short-lived, L=long-lived, I=interference term, $\Delta m = m_L - m_S$, $\Delta\Gamma = \Gamma_S - \Gamma_L$,

$\hat{\phi} = \arctan(2\Delta m/\Delta\Gamma)$, $\Delta a_\mu \equiv a^{q_2}_\mu - a^{q_1}_\mu$, 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** $K^{\pm} \to \pi^{+}\pi^{-}\ell^{\pm}\nu_{\ell}(\overline{\nu}_{\ell})$
- **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.

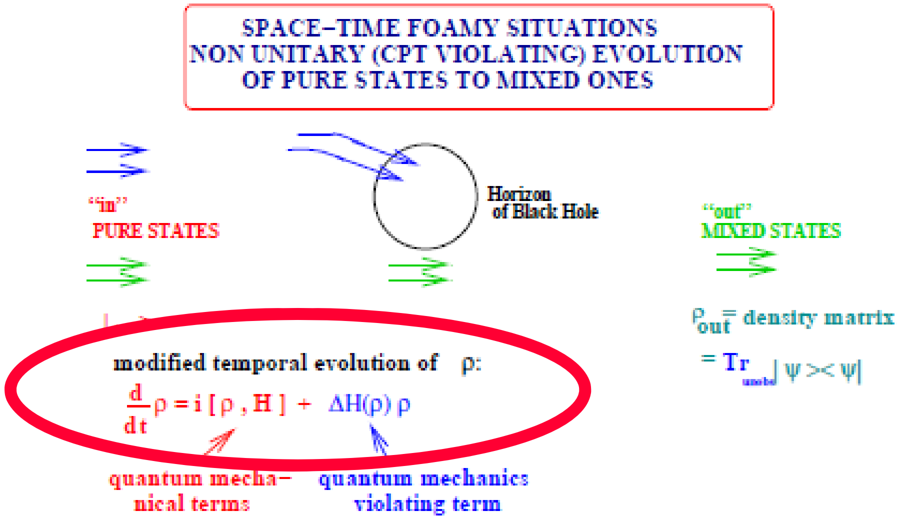
HOWEVER: RESUMMATION & OTHER EFFECTS in theoretical models may result in much larger effects of order: $\frac{E^2}{M_P}$.
(This happens, e.g., loop gravity, some stringy models of QG involving open string excitations)

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.).

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...

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

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 :

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

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

al t

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

t) $D = H$

$(\Delta m^2)^2/E^2M_P$

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

Adler-Horwitz decoherent evolution model

/st

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 :

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

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 :

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

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 :

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

Order of Magnitude Estimates

However there are models with i…

(i) Adler's Lindblad model for E… …n two level systems (hep-th/0005220): decohe… …ional to Hamiltonian

Deco… …D t) ,

Decoherence Pa… …$(\Delta m^2)^2/E^2 M_P$

(ii) Stochastic models of foam in … …recoil models (below)) Decoherence Parameters estima… …e.g. distribution of recoil velocities of populatio… …e time (Sarkar, NM) :

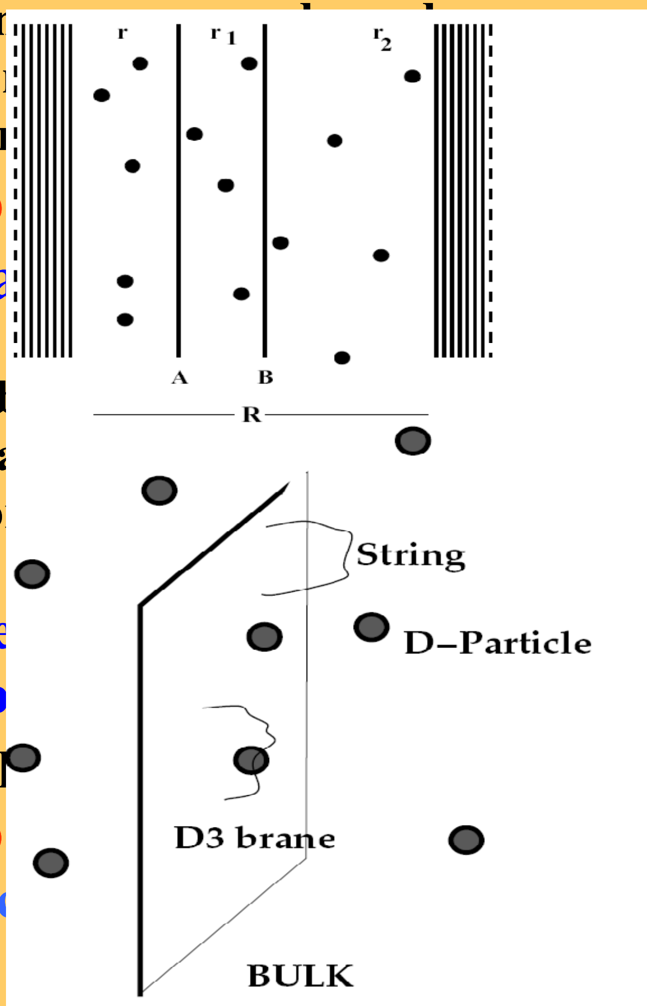
(a) Gaussian D-particle re… …read σ :

Decoherence damp… …-level systems :

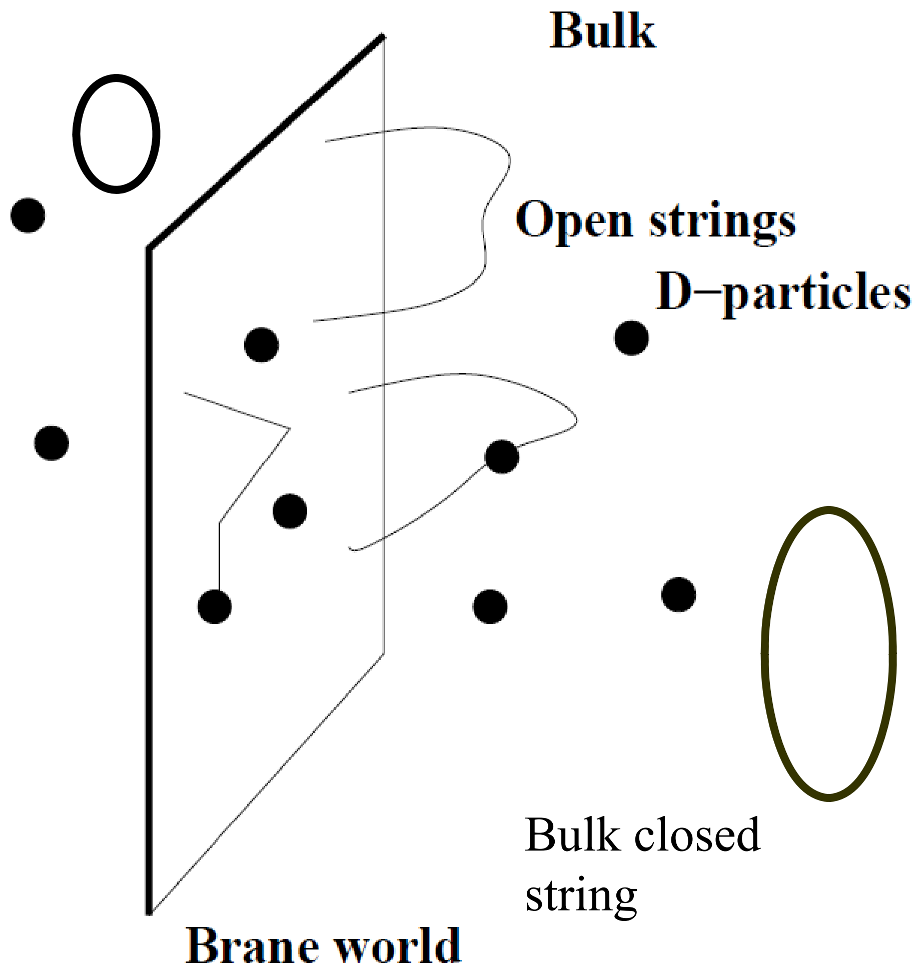
ex…

(b) Cauchy-Lorentz D-p… …ution, parameter γ :

Decoheren… γ $(\Delta m^2)/E$



D-particle Foam Models



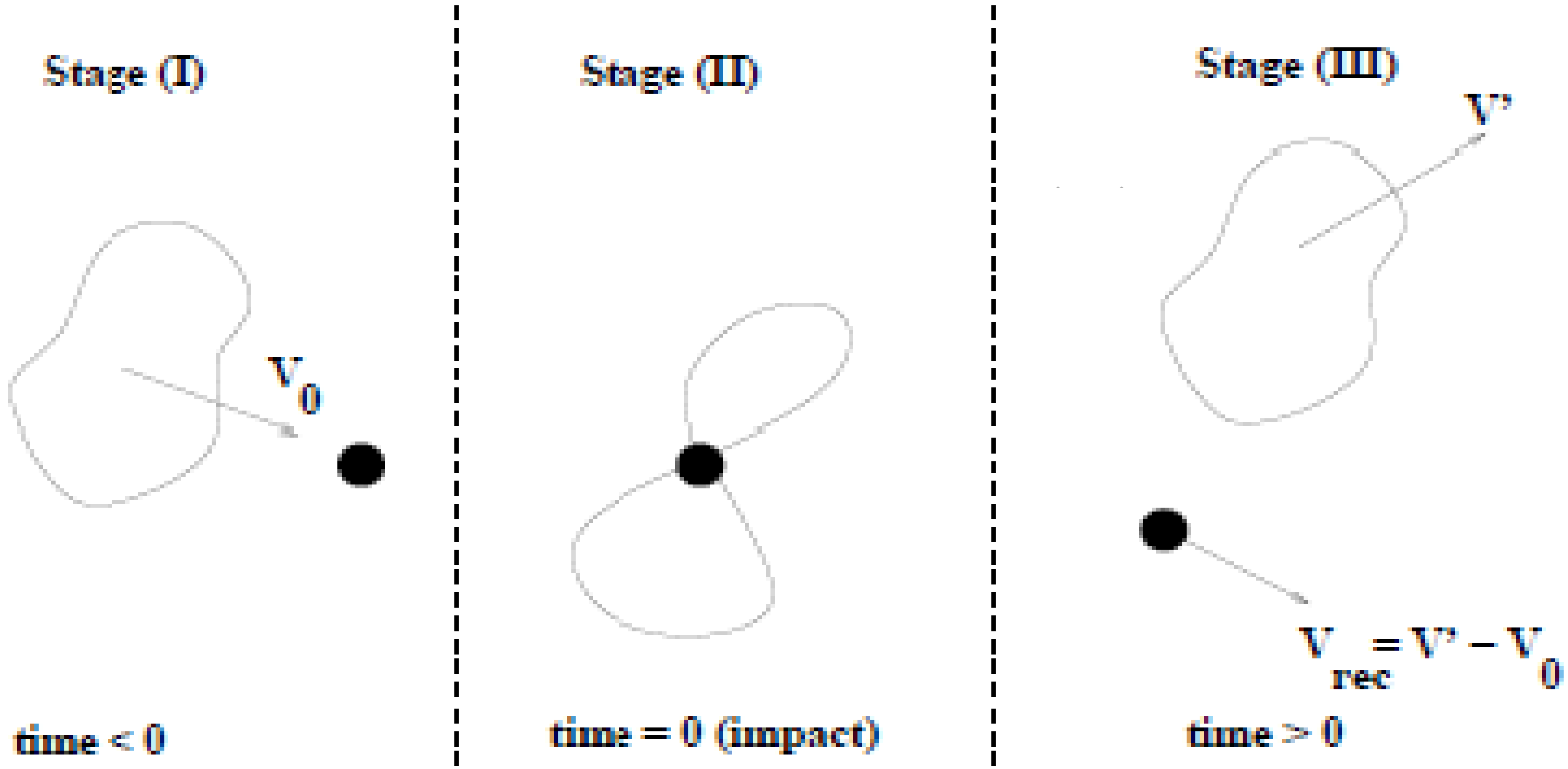
Consistent supersymmetric D−particle foam models can be constructed

No recoil, no brane motion= zero vacuum energy, unbroken SUSY

recoil contributions to vacuum energy
Broken SUSY

ELLIS, NM, WESTMUCKETT

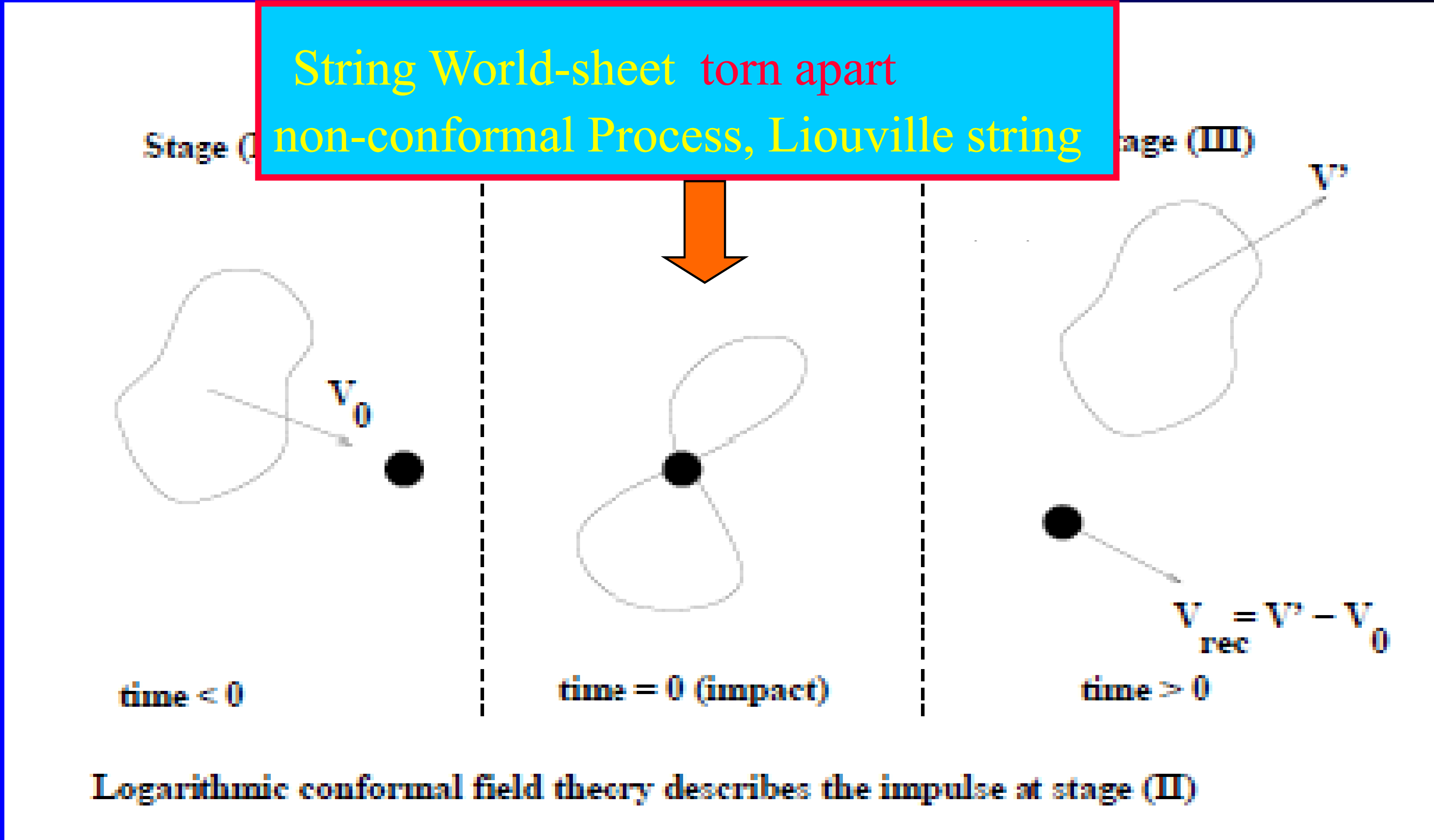
D-particle Recoil & LIV models



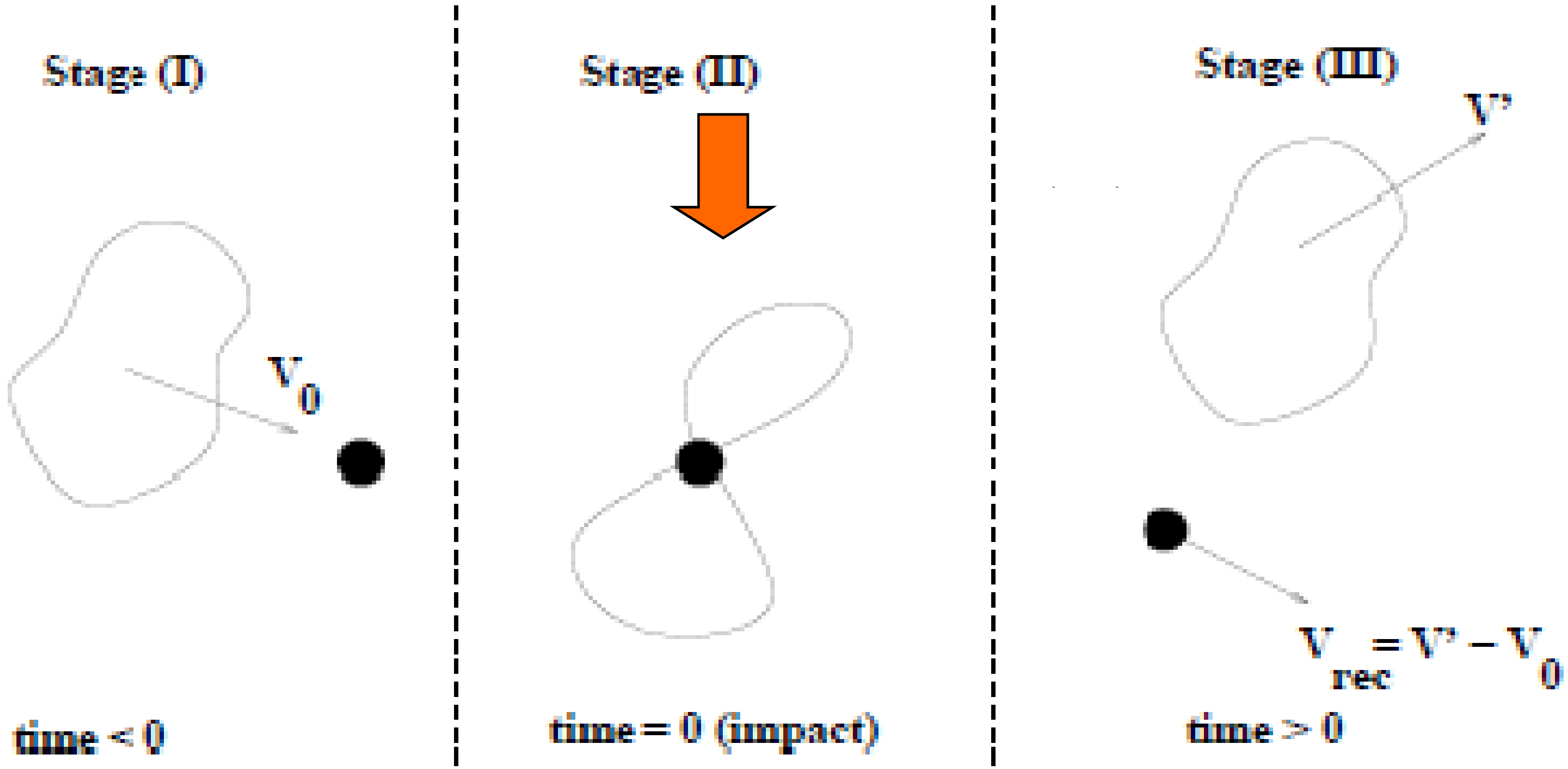
Logarithmic conformal field theory describes the impulse at stage (II)

D-particle Recoil & LIV models

String World-sheet torn apart
non-conformal Process, Liouville string



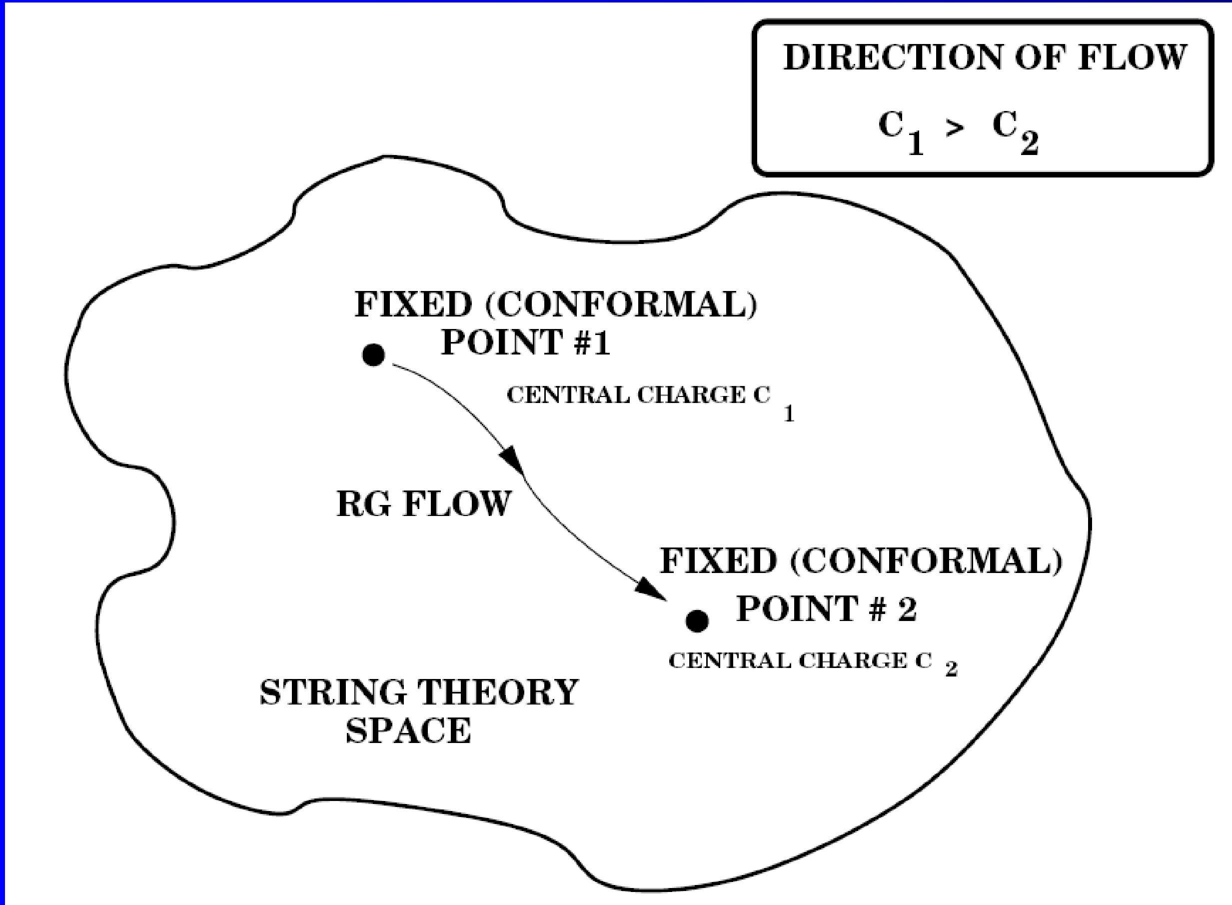
D-particle Recoil & LIV models



Logarithmic conformal field theory describes the impulse at stage (II)

A (non-critical) string theory time Arrow

Ellis, NM Nanopoulos



Non-equilibrium Strings (non-critical), due to e.g. cosmically catastrophic events in Early Universe, for instance brane worlds collisions:

World-sheet conformal Invariance is disturbed

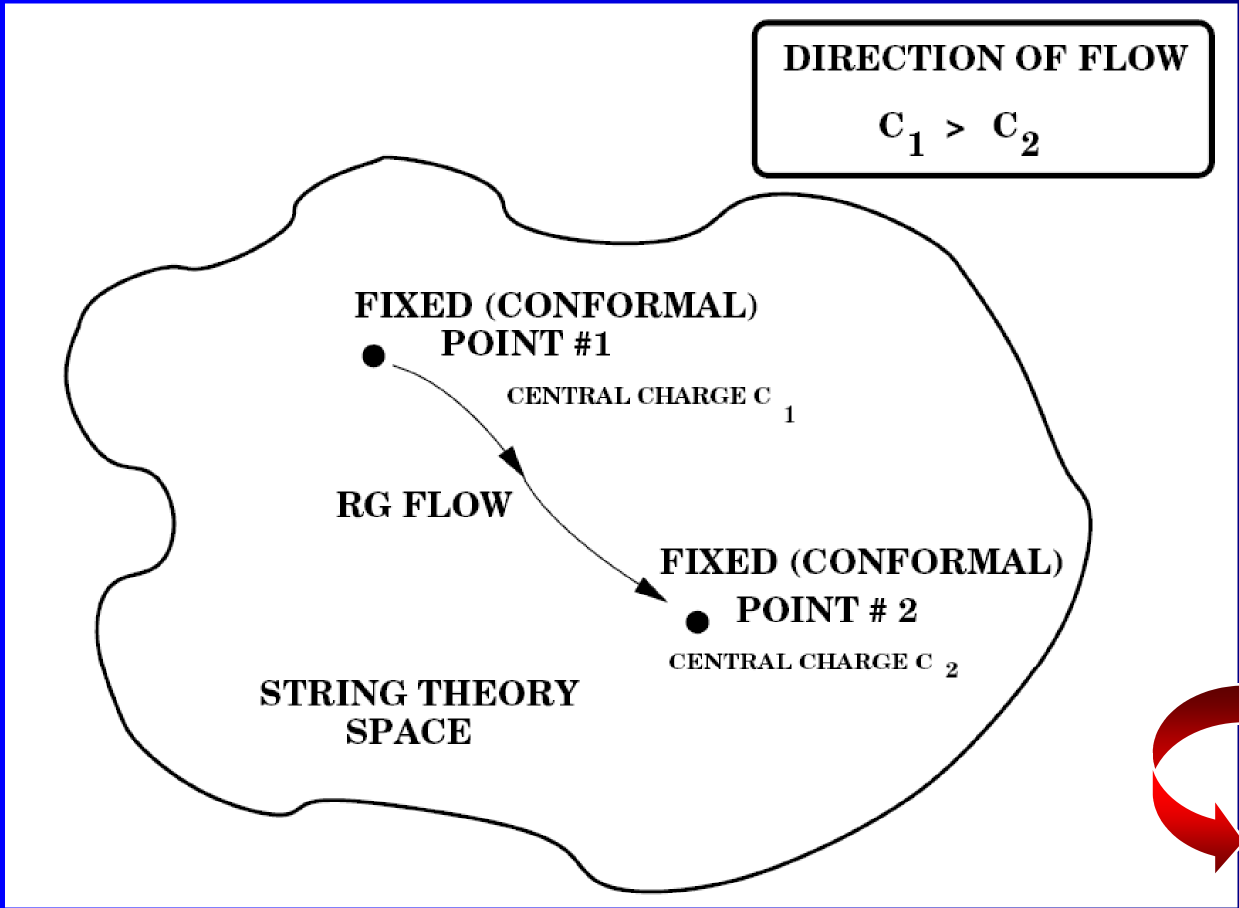
Central charge of world-Sheet theory ``runs" To a minimal value

Zamolodchikov's C-theorem An H-theorem for CFT

Change in degrees of Freedom (i.e. entropy)

A (non-critical) string theory time Arrow

Ellis, NM Nanopoulos



Non-equilibrium Strings (non-critical), due to e.g. cosmically catastrophic events in Early Universe, for instance brane worlds collisions:

World-sheet conformal Invariance is disturbed

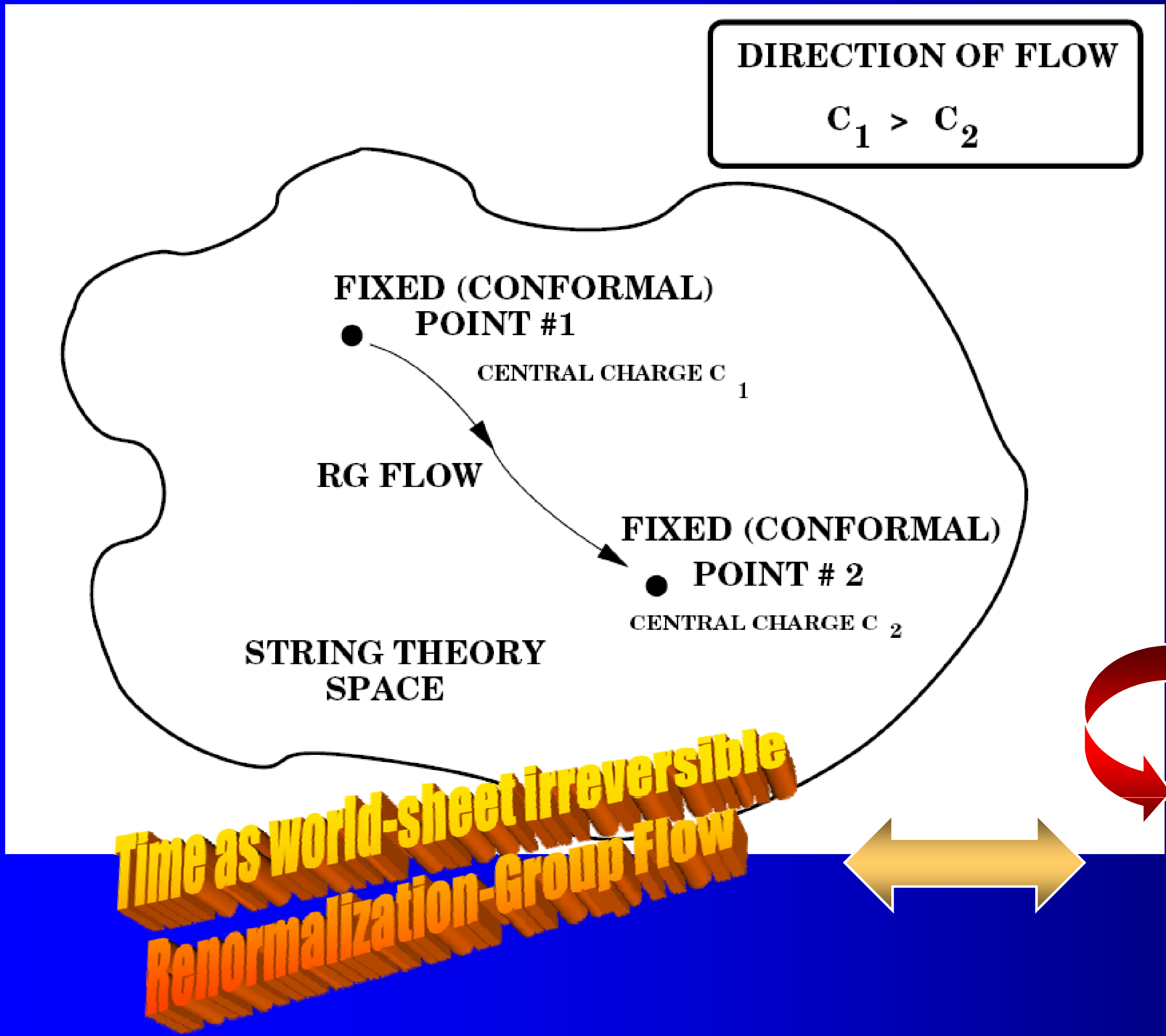
Central charge of world-Sheet theory ``runs" To a minimal value

Zamolodchikov's C-theorem
An H-theorem for CFT

Change in degrees of Freedom (i.e. entropy)

A (non-critical) string theory time Arrow

Ellis, NM Nanopoulos



Non-equilibrium Strings (non-critical), due to e.g. cosmically catastrophic events in Early Universe, for instance brane worlds collisions:

World-sheet conformal Invariance is disturbed

Central charge of world-Sheet theory ``runs" To a minimal value

Zamolodchikov's C-theorem An H-theorem for CFT

Change in degrees of Freedom (i.e. entropy)

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 :

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

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))

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

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

(a) Gaussian D-particle recoil velocity distrib

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

Decoherence damping in oscillations among two-level systems :

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

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 :

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

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 :

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

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 :

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

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 ... (below))
Decoherence ... on of
recoil vel ... r, NM) :

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

(a) Gaus
De ... ms :

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

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

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 :

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

Order of Magnitude Estimates

(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 :

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

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

Decoherence damping $\exp(-D\, t), \quad D = \gamma\ (\Delta m^2)/E$

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…)**

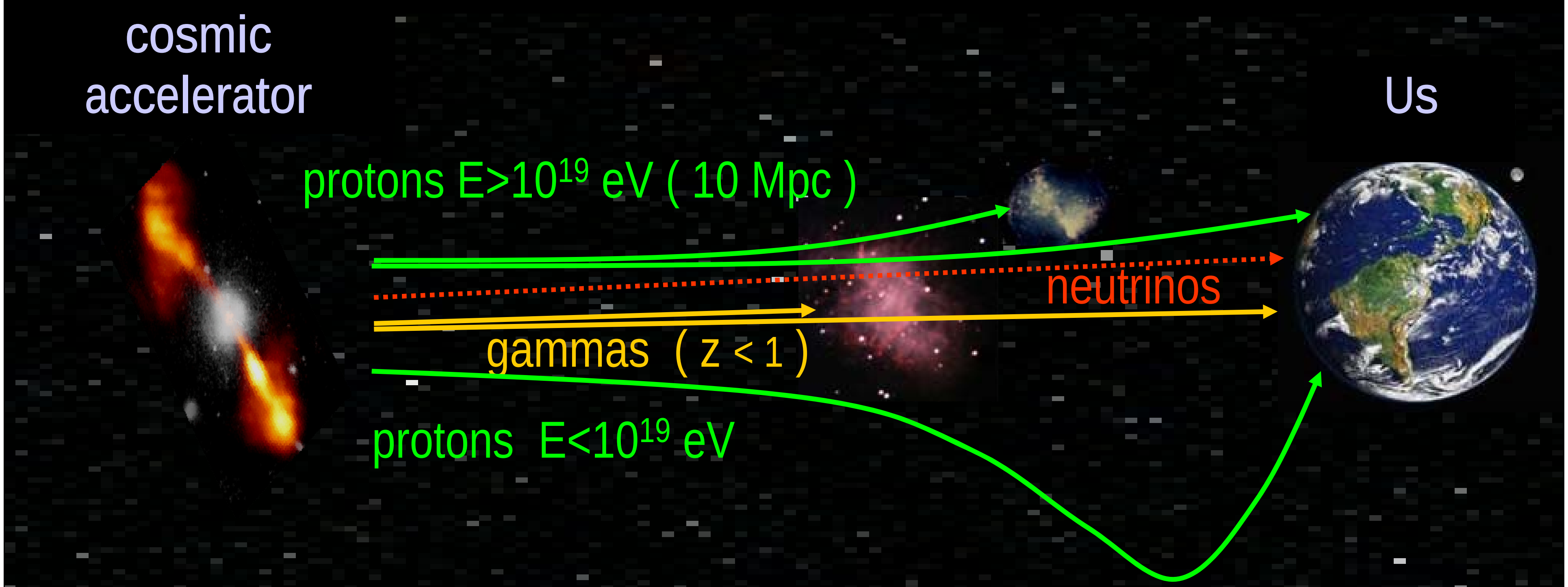
- CPT Operator **ill defined** (Wald), intrinsic violation, **modified** concept of **antiparticle**
  - **Decoherence CPTV Tests**
    - **Neutral Mesons:** K, B & factories (novel effects in entangled states :

      (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 $[H , \Theta] \neq 0$**
  - 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…)**

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

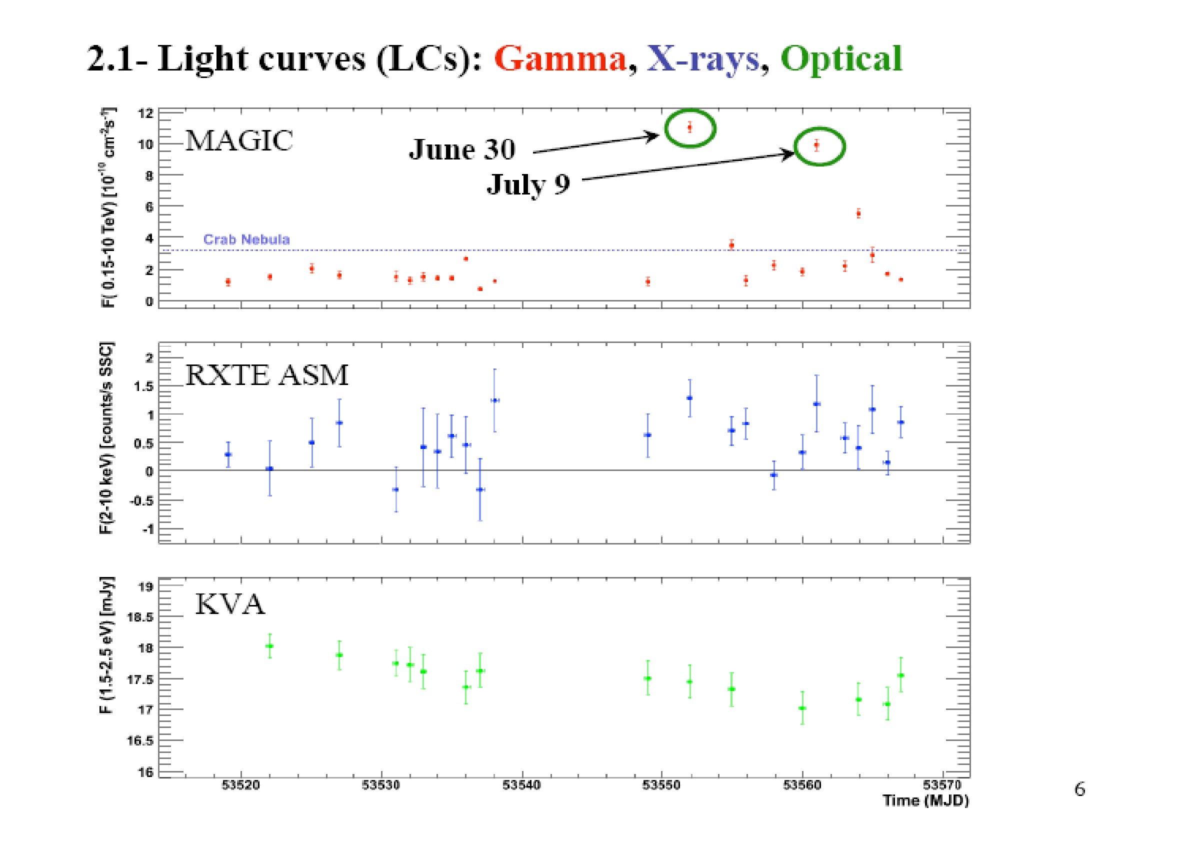
⇒ Three "astronomies" possible...

DeNaurois 2008

VHE Experimental World Today

M. MARTINEZ

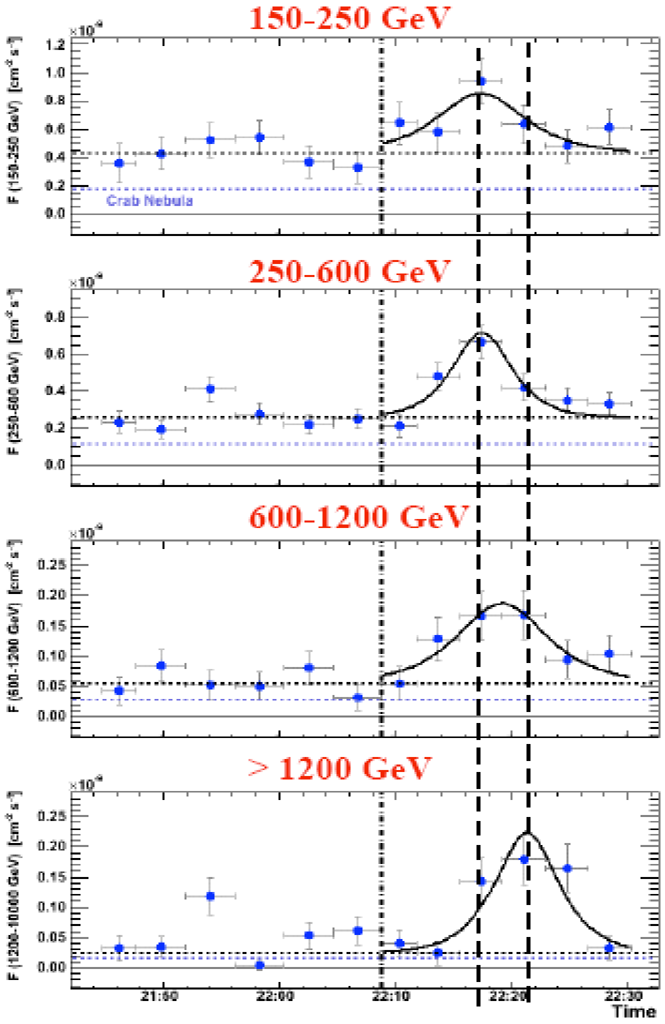
The MAGIC Collaboration (Major Atmospheric Gamma-ray Imaging Cherenkov Telescope)



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

Possible Interpetations

- Delays of more energetic photons are a result of AGN **source** Physics (SSC mechanism)

MAGIC Coll. ApJ 669, 862 (2007) : SSC I
Bednarek & Wagner arXive:0804.0619 : SSCII

- **Delays of more energetic photons occur in propagation due to new fundamental Physics (e.g. refractive index** *in vacuo* **due to Quantum Gravity space-time Foam Effects…)**

MAGIC Coll & Ellis, NM, Nanopoulos, Sakharov, Sarkisyan [arXive:0708.2889] (individual photon analysis – reconstruct peak of flare by assuming modified dispersion relations for photons, linearly or quadratically suppressed by the QG scale)

SOURCE MECHANISM BIGGEST THEORETICAL UNCERTAINTY AT PRESENT….

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

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

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

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

Quadratic

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

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

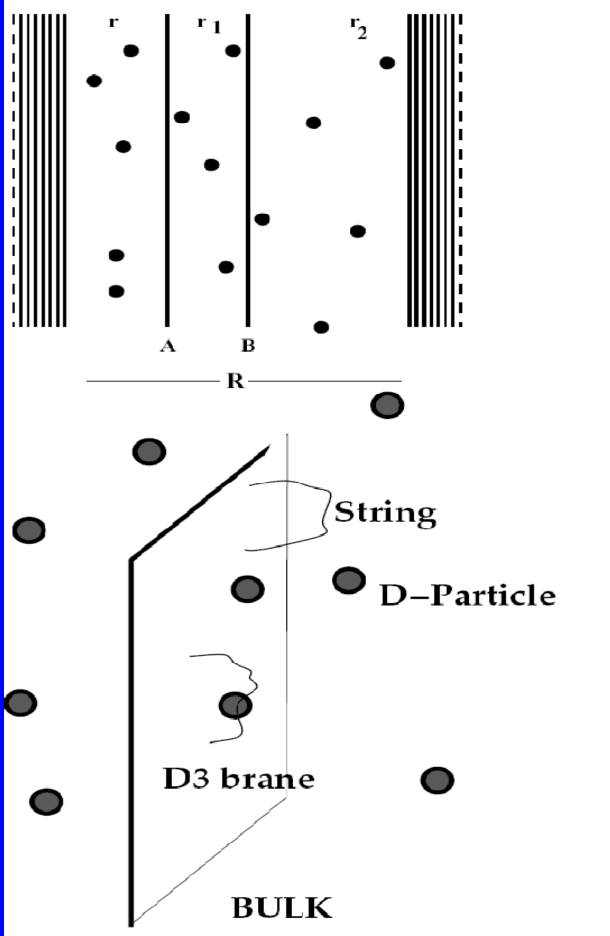
$$M_{\rm QG2} = (0.61^{+0.49}_{-0.14}) \times 10^{11} \ \text{GeV}$$

95% CL

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

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

A Stringy Model of Space -Time Foam



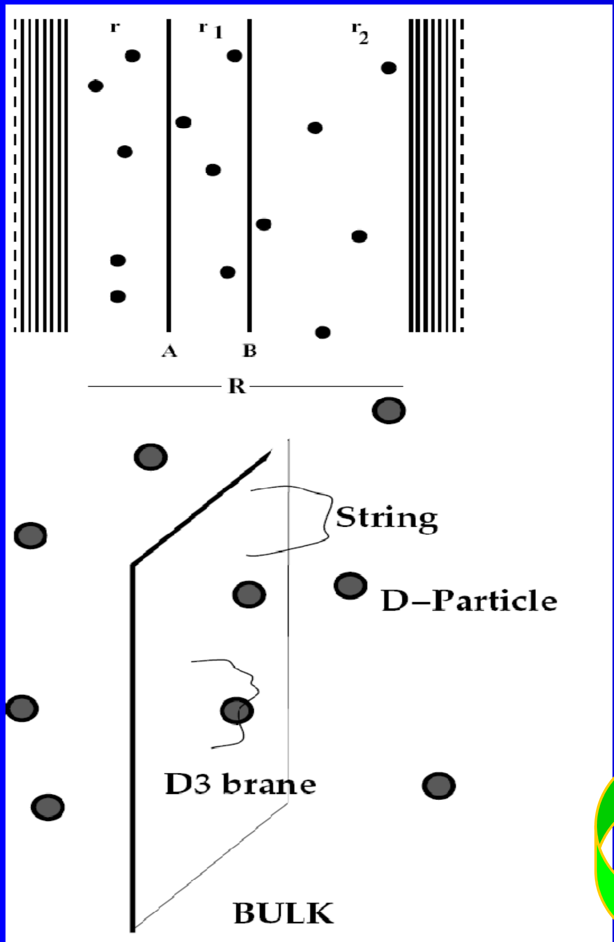
Ellis, NM, Nanopoulos

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

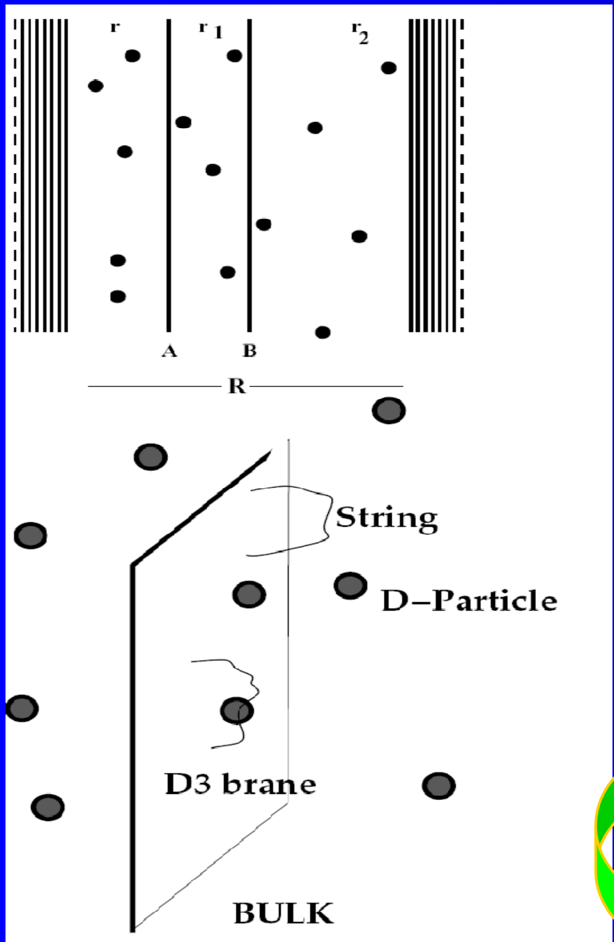
Open strings on D3-brane world represent electrically neutral matter or radiation, interacting via splitting/capture with D-particles (electric charge conservation) .

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



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) .

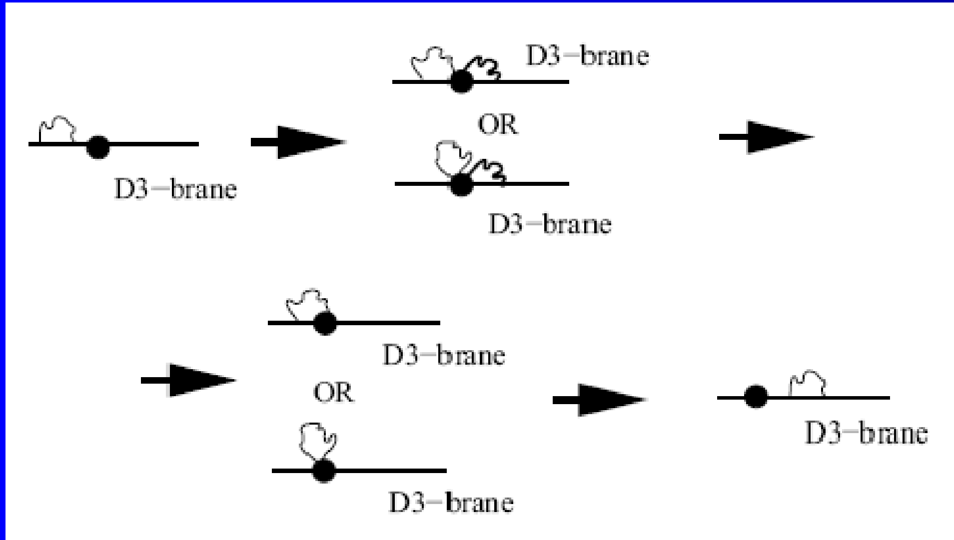
D-particle foam medium transparent to (charged) Electrons ⇒ no modified dispersion for them

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

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……

Stringy Uncertainties & the MAGIC Effect

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

  ti

  p

COMPATIBLE WITH STRING UNCERTAINTY PRINCIPLES:

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

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

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

...lified ...tion 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……

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**
    - **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 $[H, \Theta] \neq 0$**
  - 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**
    - **Ultracold Neutrons**
    - **Neutrinos** (highest sensitivity)
    - **Light-Cone fluctuations** (GRB, Gravity-Wave Interferometers, neutrino oscillations)

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):

$$\partial_t \rho = i[\rho, H] + \delta H\!\!\!/ \rho$$

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

$$\delta H\!\!\!/_{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -2\alpha & -2\beta \\ 0 & 0 & -2\beta & -2\gamma \end{pmatrix}$$

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

α, β, γ violate CPT (Wald : decoherence) & CP: $CP = \sigma_3 \cos\theta + \sigma_2 \sin\theta, \qquad [\delta H\!\!\!/_{\alpha\beta}, CP] \neq 0$

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.]

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"):

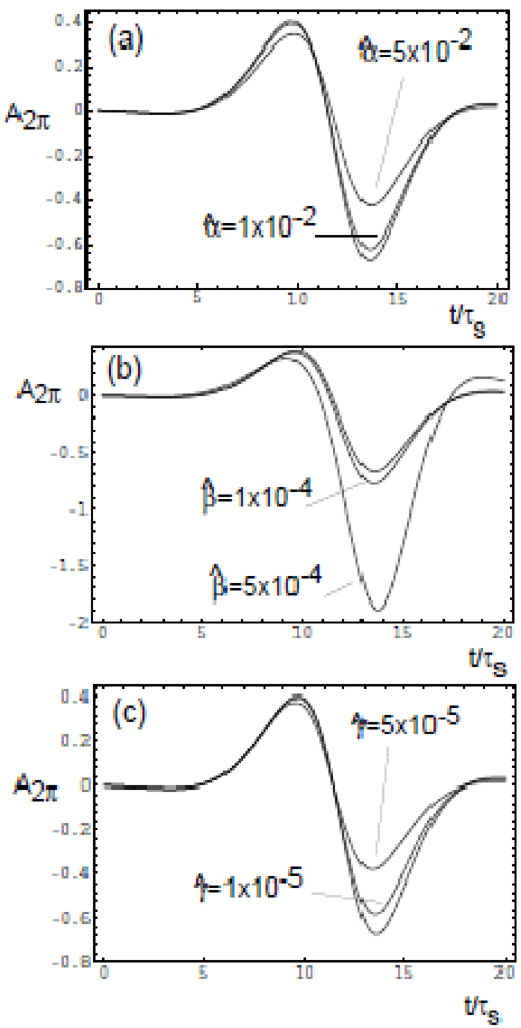
$$\zeta \rightarrow \frac{\widehat{\gamma}}{2|\epsilon^2|} - 2\frac{\widehat{\beta}}{|\epsilon|}\sin\phi$$

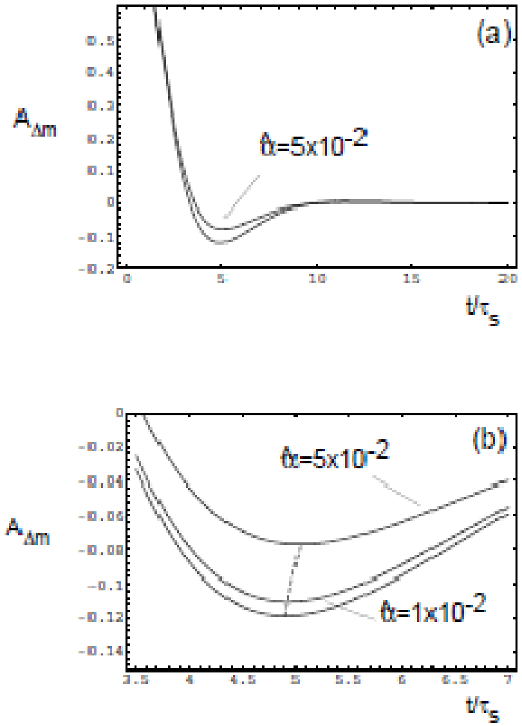
(for meson-factories, complete positivity $\widehat{\beta} = 0$).

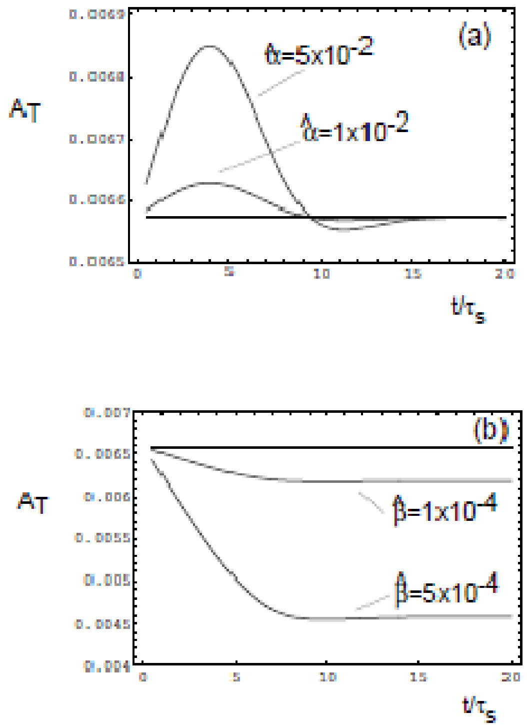
[Convenient parametrization: $\widehat{a},\ \widehat{\beta},\ \widehat{\gamma} \equiv \frac{\alpha,\ \beta,\ \gamma}{\Delta\Gamma}$, $\Delta\Gamma = \Gamma_S - \Gamma_L$. For Kaons: $\Delta\Gamma \sim 10^{-15}$ GeV.]

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 $A_{\rm T}$, $A_{\rm CPT}$, $A_{\Delta m}$, 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
$R_{2\pi}, A_{2\pi}$	$\widehat{\alpha} < 5.0 \times 10^{-3}$
$R_{2\pi}, A_{2\pi}$	$\widehat{\beta} = (2.0 \pm 2.2) \times 10^{-5}$
$\lvert m_{K^0} - m_{\overline{K}^0} \rvert$	$\widehat{\beta} < 2.6 \times 10^{-5}$
$R_{2\pi}$	$\widehat{\gamma} \lesssim 5 \times 10^{-7}$
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) $\alpha\ , \beta\ , \gamma = \mathcal{O}(\xi \frac{E^2}{M_P})$.

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)

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

But recall...

...r of Magnitude Estimates

H... ...are models with inverse energy dependence, e.g.

(i... ...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 :

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

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

Decoherence damping $\exp(-D\,t), \quad D = \gamma\,(\Delta m^2)/E$

But recall...

...r of Magnitude Estimates

H... ...re models with inverse energy dependence, e.g.

(i... ...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 :

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

But recall...

...er of Magnitude Estimates

H... ...re models with inverse energy dependence, e.g.

(i... ...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 :

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

But recall... Order of Magnitude Estimates

H... are models with inverse energy dependence, e.g.
(i) ...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 :

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

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**
    - **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 $[H, \Theta] \neq 0$**
  - 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**
    - **Ultracold Neutrons**
    - **Neutrinos** (highest sensitivity)
    - **Light-Cone fluctuations** (GRB, Gravity-Wave Interferometers, neutrino oscillations)

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

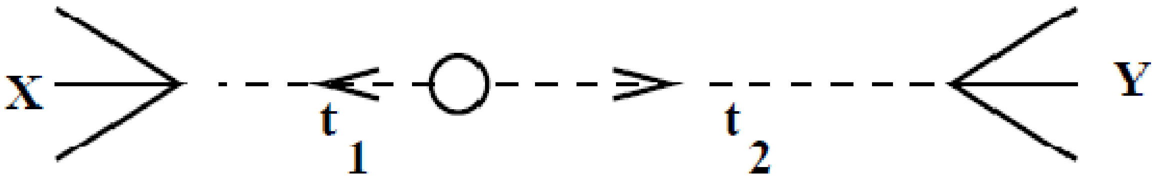
What are EPR correlations?

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:

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

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):

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

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

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

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

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)

CPTV & EPR-correlations modification

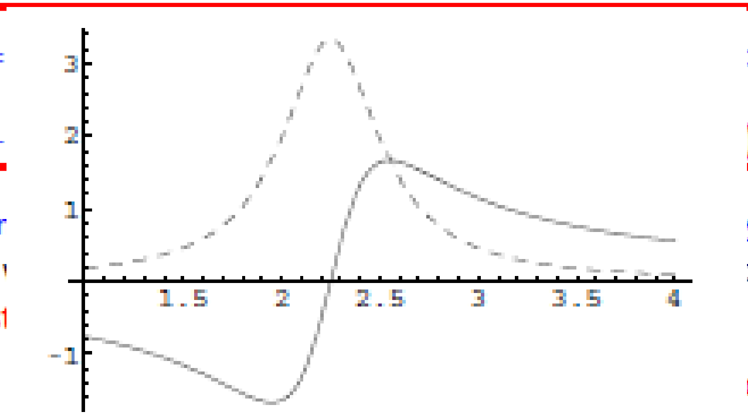
(Bernabeu, NM and Papavassiliou, hep-ph/0310180 (PRL 92))

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):

$|i> \quad =$ … $>)$

$+$ … $)]$



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

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

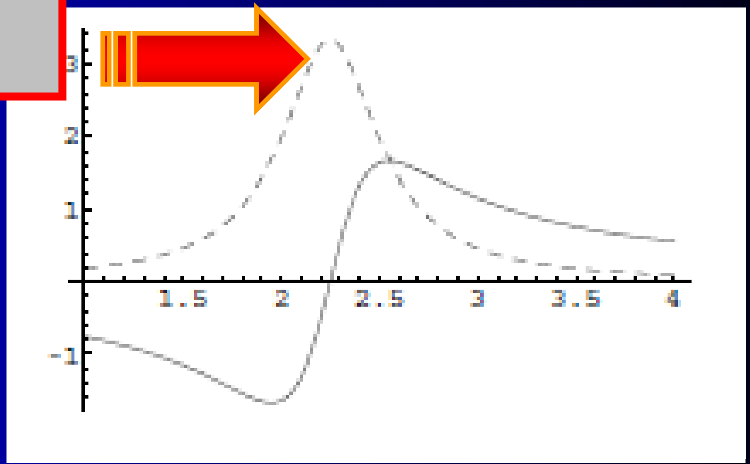
Experimental Tests of ω-Effect … demise of flavour tagging (Alvarez et al. (PLB607))

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)

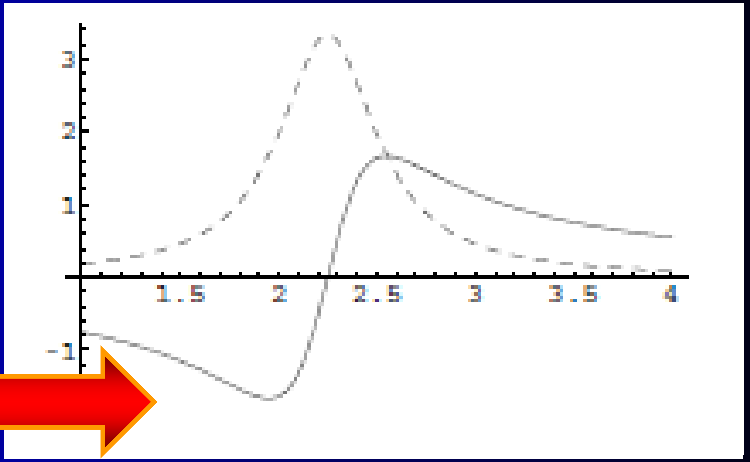
CPTV & EPR-correlations modification

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

(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):

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

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

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

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

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)

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

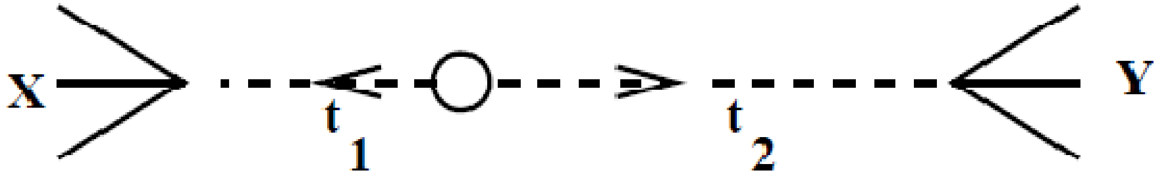
Experimental Tests of ω-Effect in ϕ, B factories... in B-factories: ω-effect $\rightarrow$ demise of flavour tagging (Alvarez et al. (PLB607))

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

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

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

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

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

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

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

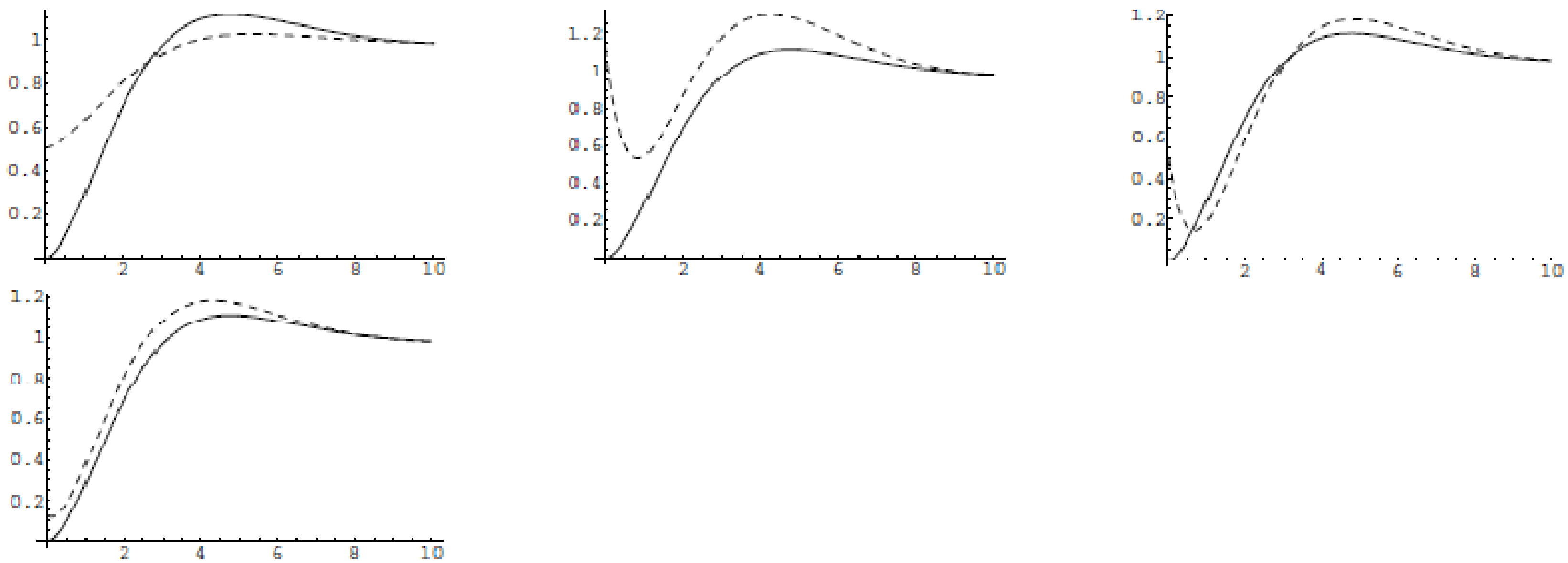
$$\Big[2\Delta M \Big(e^{-\Gamma_S \Delta t}\sin(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\sin(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)$$

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

$\Delta M = M_S - M_L$ 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

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

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

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

$$\Delta M = M_1 - M_2$$

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

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

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

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

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

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

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

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

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

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

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, $B \to X'\ell^{\pm}$

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

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, $B \to X'\ell^{\pm}$

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

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

EquaL-Sign di-lepton charge asymmetry Δt dependence

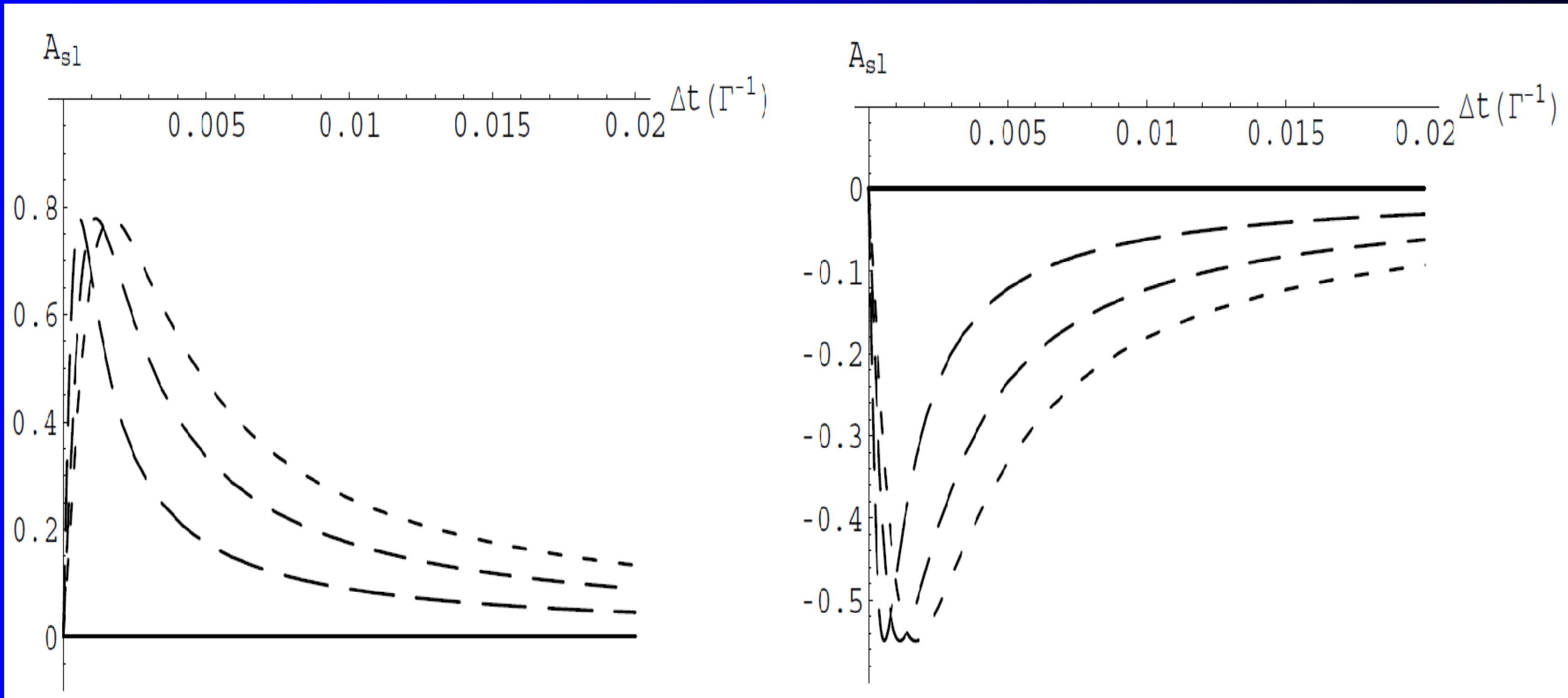
ALVAREZ, BERNABEU, NEBOT

- **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, $B \to X'\ell^{\pm}$

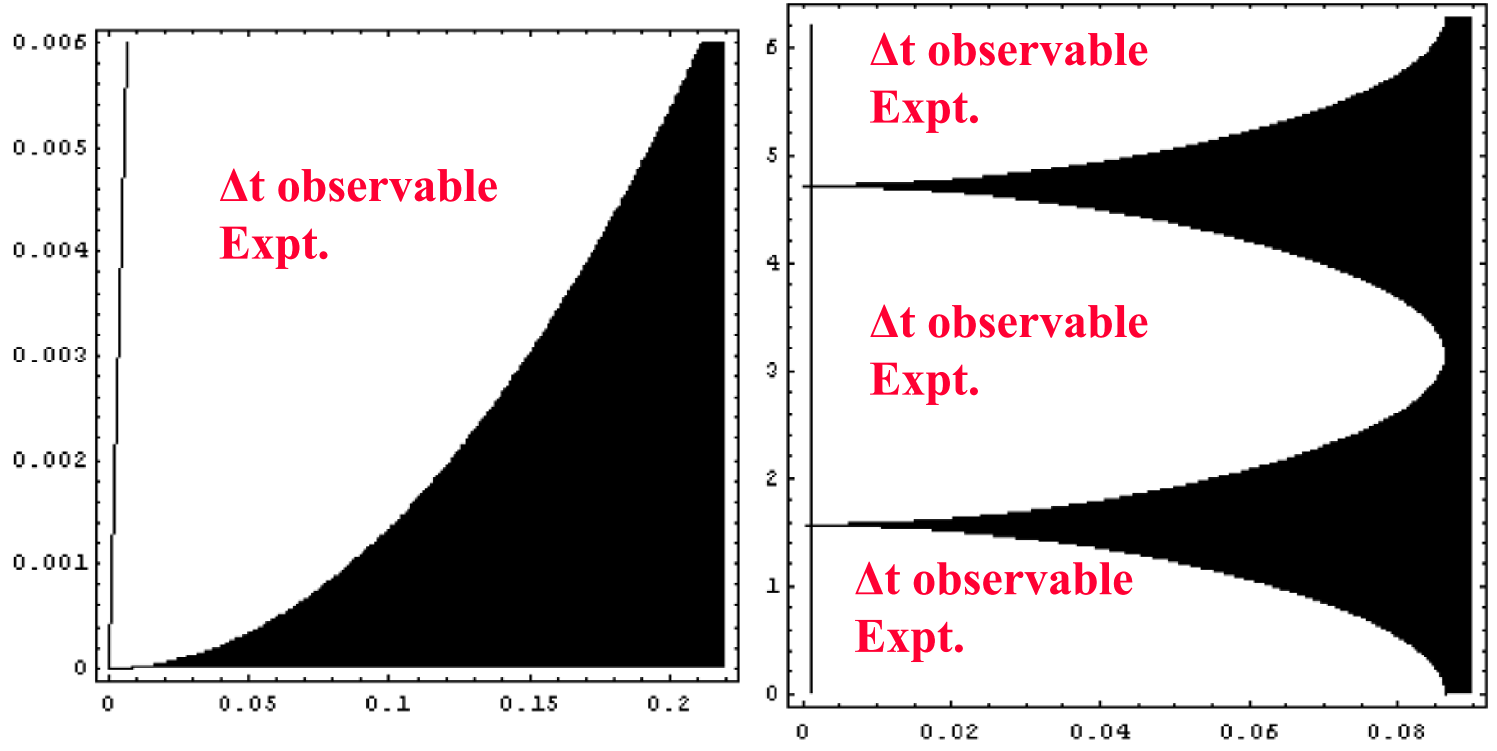
$$A_{sl} = \left.\frac{I(\ell^+,\ell^+,\Delta t) - I(\ell^-,\ell^-,\Delta t)}{I(\ell^+,\ell^+,\Delta t) + I(\ell^-,\ell^-,\Delta t)}\right|_{\omega=0} = 4\frac{Re(\varepsilon)}{1+|\varepsilon|^2} + \mathcal{O}((Re\,\varepsilon)^2)$$

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



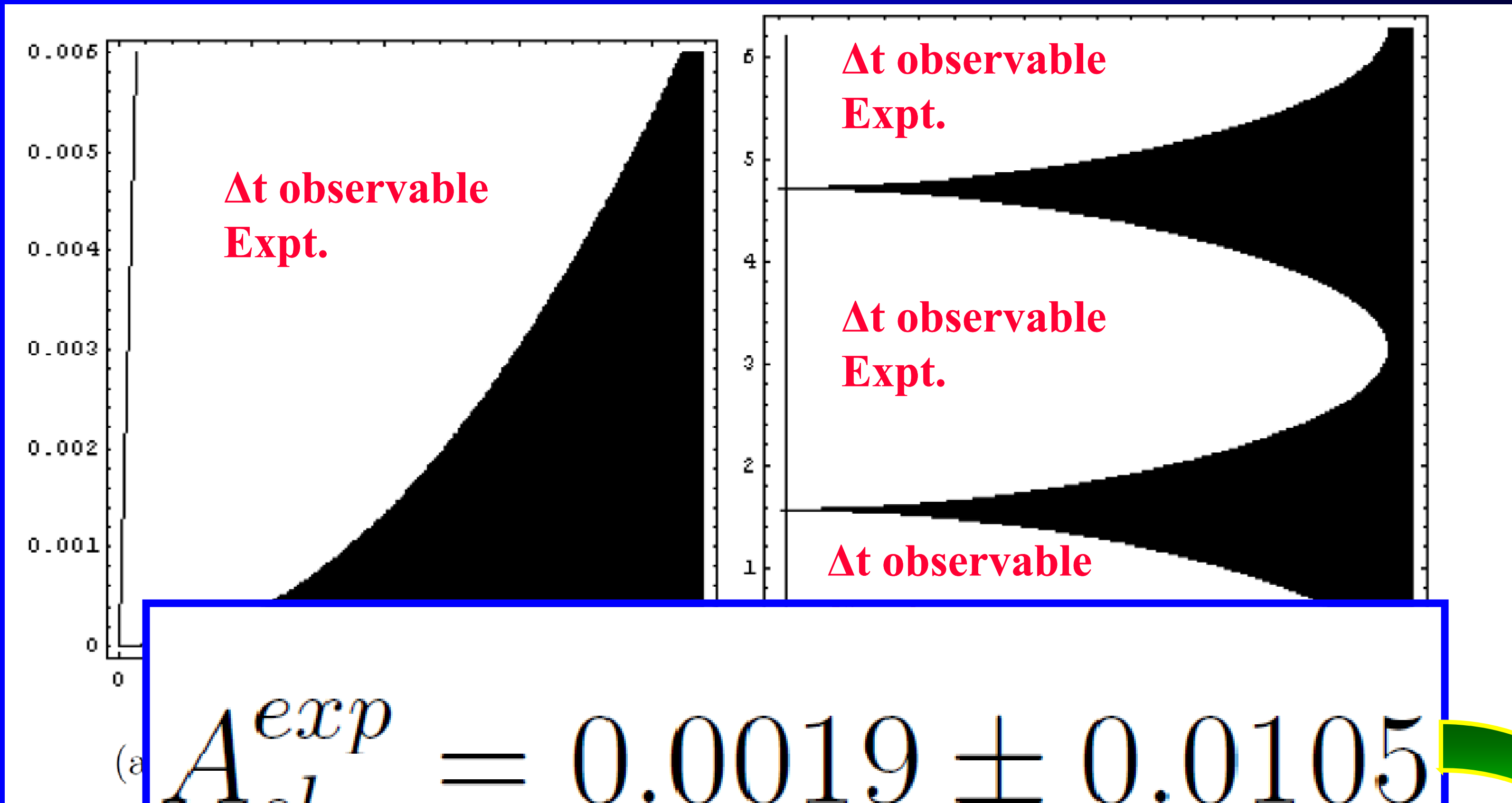
(a) $\Omega = 0$ (b) $\Omega = \frac{3}{2}\pi$

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



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

CURRENT EXPERIMENTAL LIMITS



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

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

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.

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...

ω-Effect order of magnitude estimates

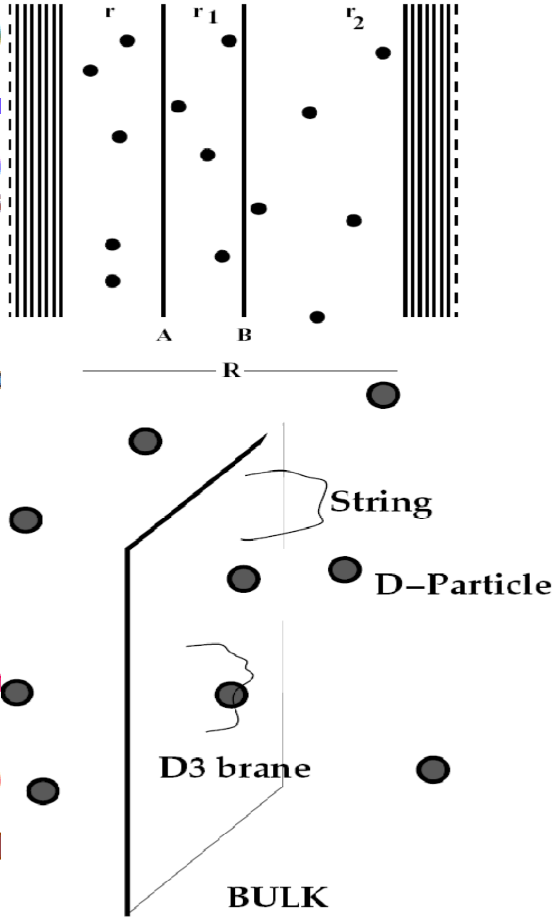
(Bernabéu, Sarben Sarkar, NM

Theoretical models using inte : space-time defects (e.g.
D-particles, inspired by string, ation theory to describe
gravitationally dressed 2-mes $\Rightarrow$ initial state:

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

NB: $\xi = -\xi'$: strangeness c $\zeta_S\rangle = |\downarrow\rangle$.).

In recoil D-particle stochastic ζp_i, $\langle\Delta p_i\rangle = 0$, $\langle\Delta p_i \Delta p_j\rangle \neq 0$)



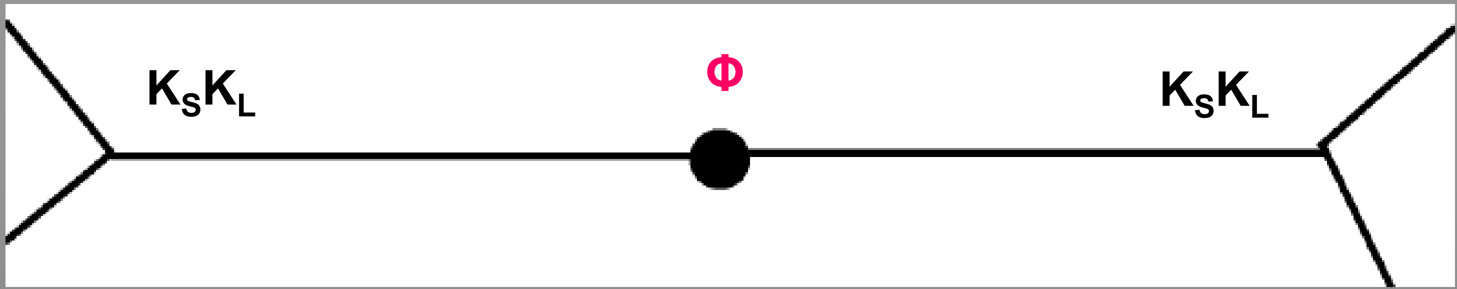
NB: For neutral kaons, with n ies $|\omega| \sim 10^{-4}|\zeta|$. For
$1 > \zeta \geq 10^{-2}$ not far below h as DAΦNE (c.f. Experimental
Talk (M. Testa)). Constrain

Perspectives for KLOE-2 at I ge) :
$\mathrm{Re}(\omega),\ \mathrm{Im}(\omega) \longrightarrow 2 \times 10$

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...

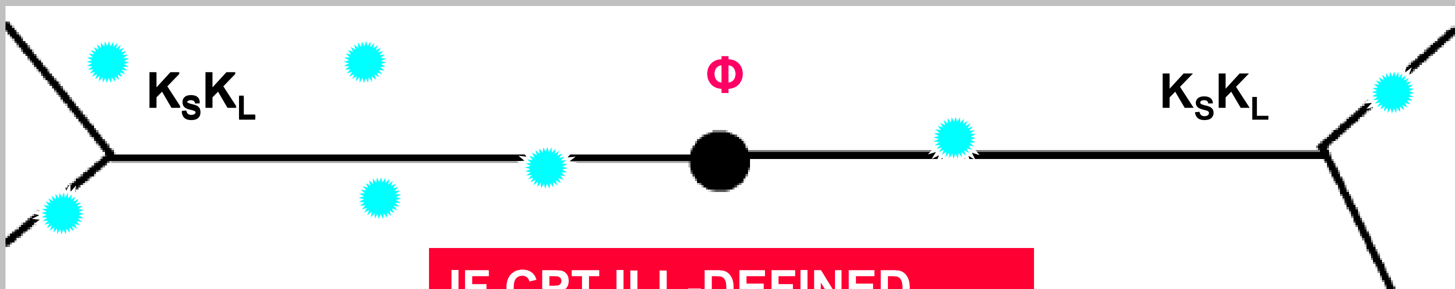
D-particle Foam & Entangled States

- If CPT Operator well-defined as operator, **even if CPT is broken** in the Hamiltonian… (e.g. Lorentz violating models)



EPR Modifications & D-particle Foam

- If CPT Operator **ill-defined, unique** consequences in **modifications of EPR** correlations of entangled states of neutral mesons in meson factories (Φ-, B-factories) Bernabeu, NM, Papavassiliou,Nebot, Alvarez, Sarben Sarkar

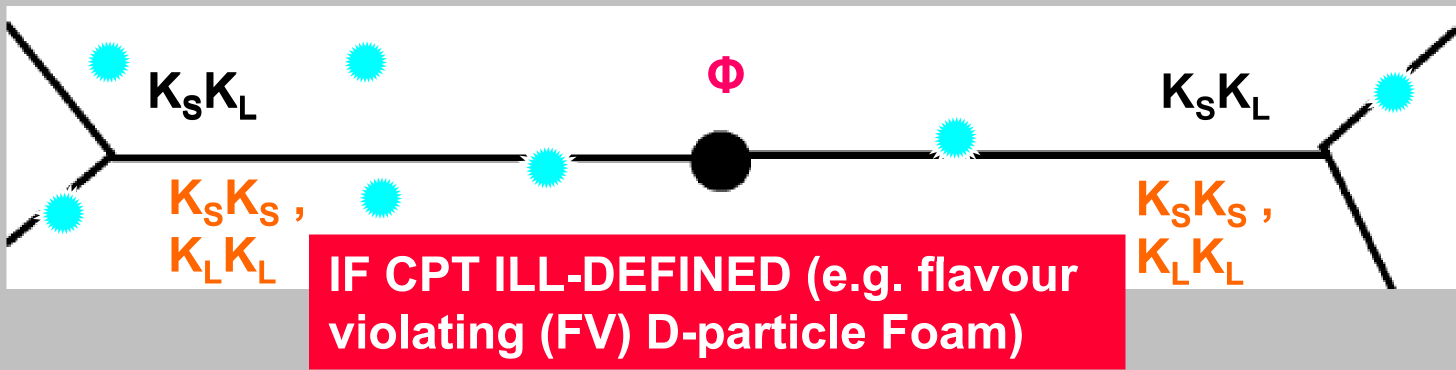


IF CPT ILL-DEFINED (e.g. D-particle Foam)

Induced metric due to capture/recoil, stochastic fluctuations, Decoherence

EPR Modifications & D-particle Foam

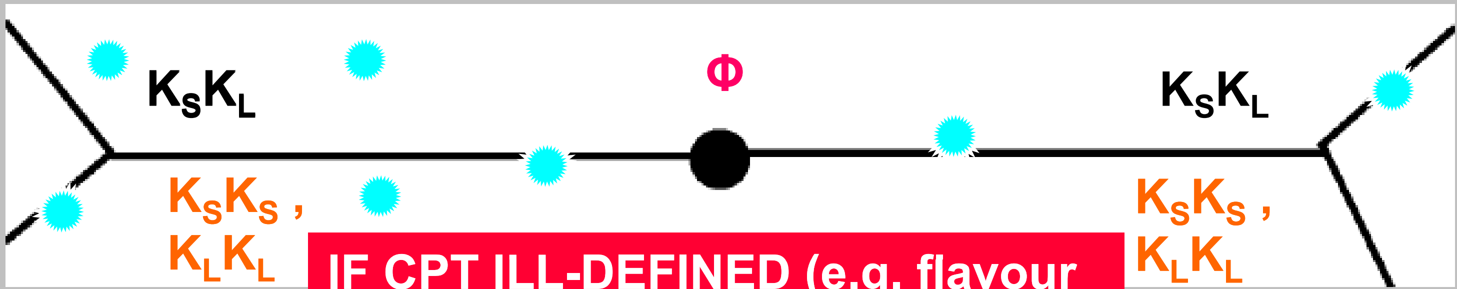
- **CPT Operator ill-defined, unique consequences in modifications of EPR correlations of entangled states of neutral mesons in meson factories (Φ-, B-factories)** Bernabeu, NM, Papavassiliou,Nebot, Alvarez, Sarben Sarkar



Induced metric due to capture/recoil, stochastic fluctuations, Decoherence
Estimates of such D-particle foam effects in neutral mesons complicated due to strong QCD effects present in such composite neutral particles

EPR Modifications & D-particle Foam

- **CPT Operator ill-defined, unique consequences in modifications of EPR correlations of entangled states of neutral mesons in meson factories (Φ-, B-factories)** Bernabeu, NM, Papavassiliou,Nebot, Alvarez, Sarben Sarkar



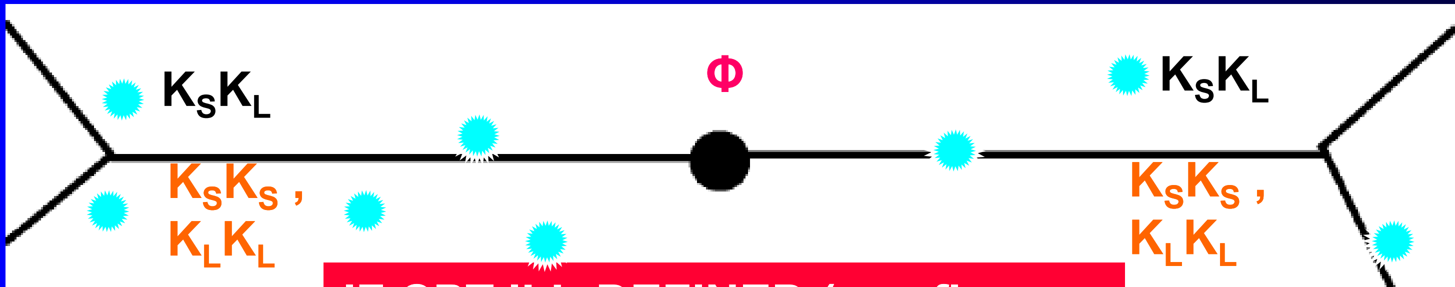
IF CPT ILL-DEFINED (e.g. flavour violating (FV) D-particle Foam)

Induced metric due to capture/recoil, stochastic fluctuations, Decoherence
Estimates of such D-particle foam effects in neutral mesons complicated due to strong QCD effects present in such composite neutral particles

- Neutral mesons no longer indistinguishable particles, initial entangled state:

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

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



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

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

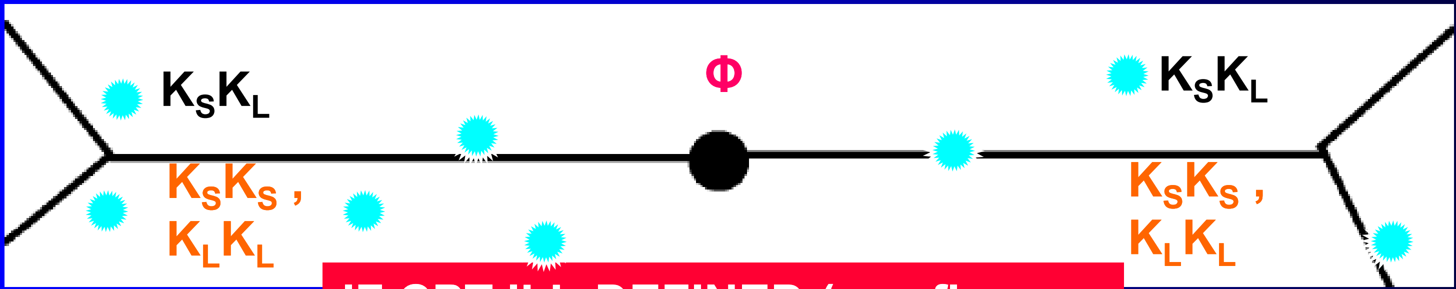
If QCD effects, sub-structure in neutral mesons ignored, and D-foam acts as if they were structureless particles, then for $M_{QG} \sim 10^{18}$ GeV (MAGIC) the estimate for ω: $|\omega| \sim 10^{-4}\ |\zeta|$, for $1 > |\zeta| > 10^{-2}$ (natural)

Not far from sensitivity of upgraded meson factories (e.g. DAFNE2)

- **Neutral mesons no longer indistinguishable particles, initial entangled state:**

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

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



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

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

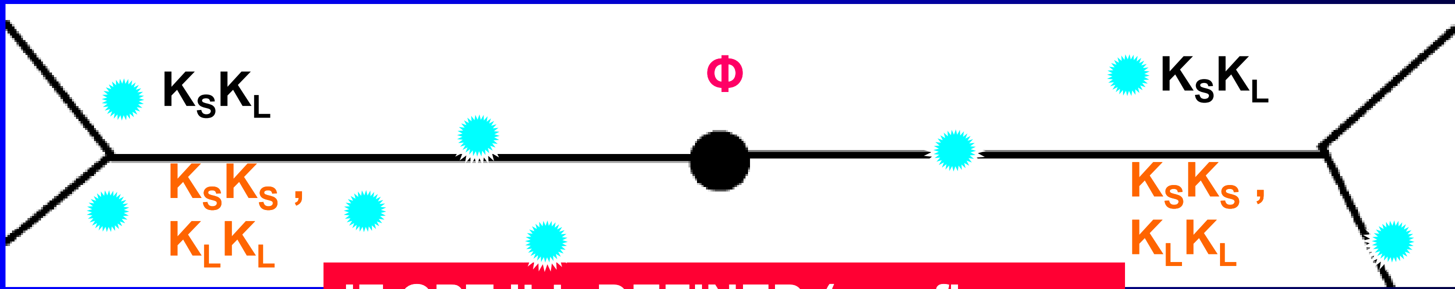
If QCD effects, sub-structure in neutral mesons ignored, and D-foam acts as if they were structureless particles, then for $M_{QG} \sim 10^{18}$ GeV (MAGIC) the estimate for ω: $|\omega| \sim 10^{-4} \; |\zeta|$, for $1 > |\zeta| > 10^{-2}$ (natural)

Not far from sensitivity of upgraded meson factories (e.g. DAFNE2)

- **Neutral mesons no longer indistinguishable particles, initial entangled state:**

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

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



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

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

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)

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 ($|K_L\rangle = |\uparrow\rangle$, $|K_S\rangle = |\downarrow\rangle$.).

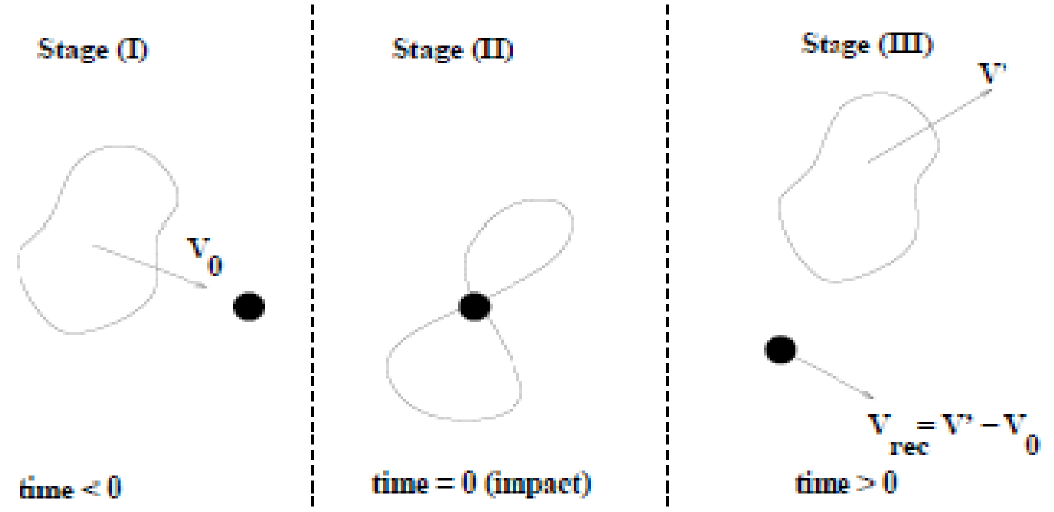
In recoil D-particle stochastic model: (momentum transfer: $\Delta p_i \sim \zeta p_i$, $\langle \Delta p_i \rangle = 0$, $\langle \Delta p_i \Delta p_j \rangle \neq 0$)

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

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...



Logarithmic conformal field theory describes the impulse at stage (II)

NB: direction of recoil dependence **LIV** ….+ Stochastically flct. Environment Decoherence, **CPTV ill defined**…

In statistical populations of D-particles, one might … **with** $\langle\langle u_i \rangle\rangle = 0$, **but stochastically fluctuating** $\langle\langle u_i u^i \rangle\rangle \neq 0$.

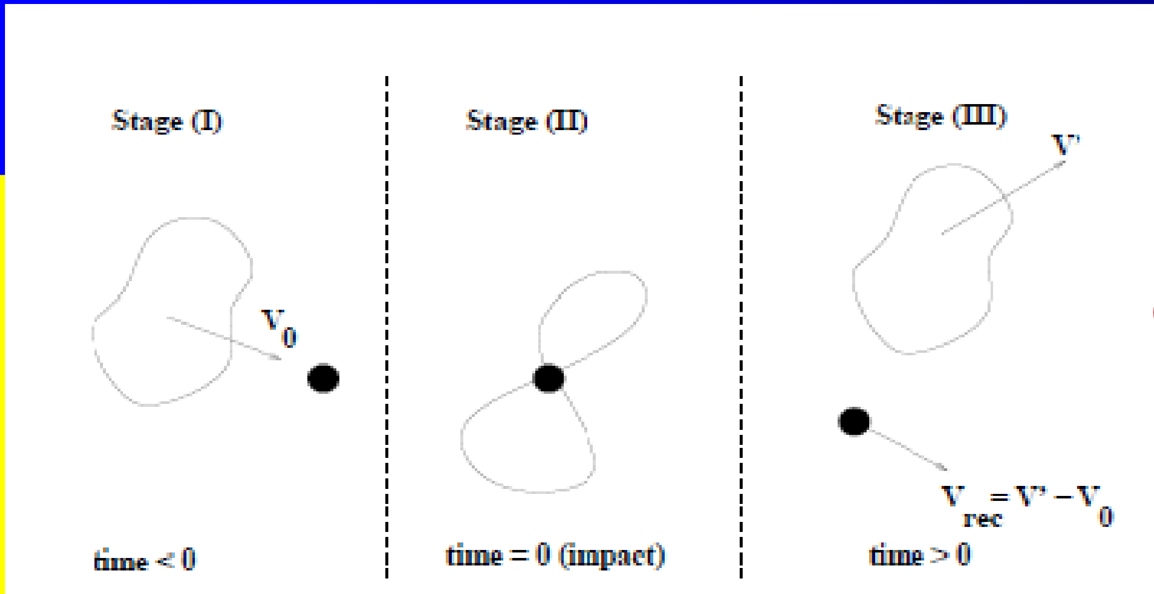
For slow recoiling heavy D-particles the resulting Hamiltonian, expressing interactions of neutrinos (or "flavoured" particles, including oscillating neutral mesons), reads:

$$\widehat{H} = g^{01}\left(g^{00}\right)^{-1}\widehat{k} - \left(g^{00}\right)^{-1}\sqrt{\left(g^{01}\right)^2 k^2 - g^{00}\left(g^{11}k^2 + m^2\right)}$$

$$g^{01} = g^{10} = r_0 1 + r_1\sigma_1 + r_2\sigma_2 \quad \Rightarrow \quad \widehat{H_I} = -\left(r_1\sigma_1 + r_2\sigma_2\right)\widehat{k}$$

$$\langle r_\mu \rangle = 0, \ \langle r_\mu r_\nu \rangle = \Delta_\mu \delta_{\mu\nu}$$

$$\Delta_\mu \sim O\left(\frac{E^2}{M_P^2}\right)$$



Logarithmic conformal field theory describes the impulse at stage (II)

NB: direction of recoil dependence **LIV** ….+ Stochastically flct. Environment Decoherence, **CPTV ill defined**…

In statistical populations of D-particles, one might … **with** $\langle\langle u_i \rangle\rangle = 0$, **but stochastically fluctuating** $\langle\langle u_i u^i \rangle\rangle \neq 0$.

For slow recoiling heavy D-particles the resulting Hamiltonian, expressing interactions of neutrinos (or "flavoured" particles, including oscillating neutral mesons), reads:

$$\widehat{H} = g^{01}\left(g^{00}\right)^{-1}\widehat{k} - \left(g^{00}\right)^{-1}\sqrt{\left(g^{01}\right)^2 k^2 - g^{00}\left(g^{11}k^2 + m^2\right)}$$

$$g^{01} = g^{10} = r_0 1 + r_1\sigma_1 + r_2\sigma_2 \quad \Rightarrow \quad \widehat{H_I} = -\left(r_1\sigma_1 + r_2\sigma_2\right)\widehat{k}$$

$$\langle r_\mu \rangle = 0, \ \langle r_\mu r_\nu \rangle = \Delta_\mu \delta_{\mu\nu}$$

$$\Delta_\mu \sim O\left(\frac{E^2}{M_P^2}\right)$$

D-particle recoil and entangled Meson States

- **Apply non-degenerate perturbation theory to construct "gravitationally dressed'' states from** $|k, \uparrow\rangle^{(i)}, \; |k, \downarrow\rangle^{(i)}, \; i = 1, 2$

D-particle recoil and entangled Meson States

- **Apply non-degenerate perturbation theory to construct "gravitationally dressed'' states from** $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

$$\left|k^{(i)},\downarrow\right\rangle_{QG}^{(i)} = \left|k^{(i)},\downarrow\right\rangle^{(i)} + \left|k^{(i)},\uparrow\right\rangle^{(i)}\alpha^{(i)}$$

D-particle recoil and entangled Meson States

- **Apply non-degenerate perturbation theory to construct "gravitationally dressed'' states from** $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

$$\left|k^{(i)},\downarrow\right\rangle_{QG}^{(i)} = \left|k^{(i)},\downarrow\right\rangle^{(i)} + \left|k^{(i)},\uparrow\right\rangle^{(i)} \alpha^{(i)}$$

$$\alpha^{(i)} = \frac{{}^{(i)}\left\langle \uparrow, k^{(i)}\right| \widehat{H_I} \left|k^{(i)},\downarrow\right\rangle^{(i)}}{E_2 - E_1}$$

D-particle recoil and entangled Meson States

- **Apply non-degenerate perturbation theory to construct "gravitationally dressed'' states from** $|k,\uparrow\rangle^{(i)}, \; |k,\downarrow\rangle^{(i)}, \; i = 1,2$

$$\left|k^{(i)},\downarrow\right\rangle_{QG}^{(i)} = \left|k^{(i)},\downarrow\right\rangle^{(i)} + \left|k^{(i)},\uparrow\right\rangle^{(i)} \alpha^{(i)}$$

$$\alpha^{(i)} = \frac{{}^{(i)}\langle\uparrow, k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\downarrow\rangle^{(i)}}{E_2 - E_1}$$

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

$$\langle r_\mu\rangle = 0, \; \langle r_\mu r_\nu\rangle = \Delta_\mu \delta_{\mu\nu}$$

D-particle recoil and entangled Meson States

- **Apply non-degenerate perturbation theory to construct "gravitationally dressed'' states from** $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

$$\left|k^{(i)},\downarrow\right\rangle_{QG}^{(i)} = \left|k^{(i)},\downarrow\right\rangle^{(i)} + \left|k^{(i)},\uparrow\right\rangle^{(i)} \alpha^{(i)}$$

$$\alpha^{(i)} = \frac{{}^{(i)}\langle\uparrow,k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\downarrow\rangle^{(i)}}{E_2-E_1}$$

Similarly for $|k^{(i)},\uparrow\rangle^{(i)}$ the dressed state is obtained by $|\downarrow\rangle \leftrightarrow |\uparrow\rangle$ and $\alpha \to \beta$

$$\beta^{(i)} = \frac{{}^{(i)}\langle\downarrow,k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\uparrow\rangle^{(i)}}{E_1-E_2}$$

D-particle recoil and entangled Meson States

- **Apply non-degenerate perturbation theory to construct "gravitationally dressed" states from** $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

$$\left|k^{(i)},\downarrow\right\rangle^{(i)}_{QG} = \left|k^{(i)},\downarrow\right\rangle^{(i)} + \left|k^{(i)},\uparrow\right\rangle^{(i)}\alpha^{(i)}$$

$$\alpha^{(i)} = \frac{{}^{(i)}\langle\uparrow, k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\downarrow\rangle^{(i)}}{E_2 - E_1}$$

Similarly for $|k^{(i)},\uparrow\rangle^{(i)}$ the dressed state is obtained by $|\downarrow\rangle \leftrightarrow |\uparrow\rangle$ and $\alpha \rightarrow \beta$

$$\beta^{(i)} = \frac{{}^{(i)}\langle\downarrow, k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\uparrow\rangle^{(i)}}{E_1 - E_2}$$

$$\begin{aligned}
&|k,\uparrow\rangle^{(1)}_{QG}\,|-k,\downarrow\rangle^{(2)}_{QG} - |k,\downarrow\rangle^{(1)}_{QG}\,|-k,\uparrow\rangle^{(2)}_{QG} = \\
&|k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} \\
&+|k,\downarrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}\left(\beta^{(1)}-\beta^{(2)}\right) + |k,\uparrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)}\left(\alpha^{(2)}-\alpha^{(1)}\right) \\
&+\beta^{(1)}\alpha^{(2)}\,|k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} - \alpha^{(1)}\beta^{(2)}\,|k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}
\end{aligned}$$

D-particle recoil and entangled Meson States

- **Apply non-degenerate perturbation theory to construct "gravitationally dressed" states from** $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

$$\left|k^{(i)},\downarrow\right\rangle_{QG}^{(i)} = \left|k^{(i)},\downarrow\right\rangle^{(i)} + \left|k^{(i)},\uparrow\right\rangle^{(i)}\alpha^{(i)}$$

$$\alpha^{(i)} = \frac{{}^{(i)}\langle\uparrow,k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\downarrow\rangle^{(i)}}{E_2-E_1}$$

Similarly for $|k^{(i)},\uparrow\rangle^{(i)}$ the dressed state is obtained by $|\downarrow\rangle\leftrightarrow|\uparrow\rangle$ and $\alpha\to\beta$

$$\beta^{(i)} = \frac{{}^{(i)}\langle\downarrow,k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\uparrow\rangle^{(i)}}{E_1-E_2}$$

$$\begin{aligned}
&|k,\uparrow\rangle_{QG}^{(1)}|-k,\downarrow\rangle_{QG}^{(2)} - |k,\downarrow\rangle_{QG}^{(1)}|-k,\uparrow\rangle_{QG}^{(2)} = \\
&|k,\uparrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} \\
&+|k,\downarrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)}\left(\beta^{(1)}-\beta^{(2)}\right) + |k,\uparrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)}\left(\alpha^{(2)}-\alpha^{(1)}\right) \\
&+\beta^{(1)}\alpha^{(2)}|k,\downarrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} - \alpha^{(1)}\beta^{(2)}|k,\uparrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)}
\end{aligned}$$

D-particle recoil and entangled Meson States

- **Apply non-degenerate perturbation theory to construct "gravitationally dressed" states from** $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

$$\left|k^{(i)},\downarrow\right\rangle_{QG}^{(i)} = \left|k^{(i)},\downarrow\right\rangle^{(i)} + \left|k^{(i)},\uparrow\right\rangle^{(i)} \alpha^{(i)}$$

$$\alpha^{(i)} = \frac{{}^{(i)}\langle\uparrow,k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\downarrow\rangle^{(i)}}{E_2-E_1}$$

Similarly for $|k^{(i)},\uparrow\rangle^{(i)}$ the dressed state is obtained by $|\downarrow\rangle\leftrightarrow|\uparrow\rangle$ and $\alpha\to\beta$

$$\beta^{(i)} = \frac{{}^{(i)}\langle\downarrow,k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\uparrow\rangle^{(i)}}{E_1-E_2}$$

$$\begin{aligned}
&|k,\uparrow\rangle_{QG}^{(1)}\,|-k,\downarrow\rangle_{QG}^{(2)} - |k,\downarrow\rangle_{QG}^{(1)}\,|-k,\uparrow\rangle_{QG}^{(2)} = \\
&|k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} \\
&+|k,\downarrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}\left(\beta^{(1)}-\beta^{(2)}\right) + |k,\uparrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)}\left(\alpha^{(2)}-\alpha^{(1)}\right) \\
&+\beta^{(1)}\alpha^{(2)}\,|k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} - \alpha^{(1)}\beta^{(2)}\,|k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}
\end{aligned}$$

D-particle recoil and entangled Meson States

- **Apply non-degenerate perturbation theory to construct "gravitationally dressed'' states from** $|k,\uparrow\rangle^{(i)},\ |k,\downarrow\rangle^{(i)},\ i=1,2$

$$|k^{(i)},\downarrow\rangle^{(i)}_{QG} = |k^{(i)},\downarrow\rangle^{(i)} + |k^{(i)},\uparrow\rangle^{(i)}\alpha^{(i)}$$

$$\alpha^{(i)} = \frac{{}^{(i)}\langle\uparrow,k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\downarrow\rangle^{(i)}}{E_2-E_1}$$

Similarly for $|k^{(i)},\uparrow\rangle^{(i)}$ the dressed state is obtained by $|\downarrow\rangle \leftrightarrow |\uparrow\rangle$ and $\alpha \rightarrow \beta$

$$\beta^{(i)} = \frac{{}^{(i)}\langle\downarrow,k^{(i)}|\,\widehat{H_I}\,|k^{(i)},\uparrow\rangle^{(i)}}{E_1-E_2}$$

$$\begin{aligned}
&|k,\uparrow\rangle^{(1)}_{QG}|-k,\downarrow\rangle^{(2)}_{QG} - |k,\downarrow\rangle^{(1)}_{QG}|-k,\uparrow\rangle^{(2)}_{QG} = \\
&|k,\uparrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} \\
&+|k,\downarrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)}\left(\beta^{(1)}-\beta^{(2)}\right) + |k,\uparrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)}\left(\alpha^{(2)}-\alpha^{(1)}\right) \\
&+\beta^{(1)}\alpha^{(2)}|k,\downarrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} - \alpha^{(1)}\beta^{(2)}|k,\uparrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)}
\end{aligned}$$

Prediction of ω-like effects in entangled states ….(Bernabeu, NM, Papavassiliou)

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...

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...

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...

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

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: $\widehat{H_I} = -(r_1\sigma_1 + r_2\sigma_2)\,\widehat{k}$

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 (Ω)

"atom" (matter) frequency (ν)

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 (Ω)

"atom" (matter) frequency (ν)

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: $\widehat{H_I} = -(r_1\sigma_1 + r_2\sigma_2)\,\widehat{k}$

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

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:

$e^{i\xi} A = \langle \pi^+\pi^- | \ell = 0, m = 0\rangle \langle \ell = 0, m = 0 | S_z + ivS_4 | K^+\rangle m_K^{5/2} (\omega_+\omega_-)^{1/2}$

$e^{i\xi + i\eta_0} B_0 \cos\theta = \langle \pi^+\pi^- | \ell = 1, m = 0\rangle \langle \ell = 1, m = 0 | S_z + ivS_4 | K^+\rangle m_K^{5/2} (\omega_+\omega_-)^{1/2}$

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

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:

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

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

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):

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

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

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

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

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.

QG DECOHERENCE & NEUTRINOS

QG Decoherence & Neutrinos

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

- **Quantum Gravitational MSW effect**

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

QG Decoherence & Neutrinos

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

$$P_{\alpha\rightarrow\beta} \propto e^{-Dt} \sin(\frac{\Delta m_{12}^2}{E} t)$$

- **Quantum Gravitational MSW effect**

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

QG Decoherence & Neutrinos

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

$$P_{\alpha\to\beta} \propto e^{-Dt} \sin\left(\frac{\Delta m_{12}^2}{E} t\right)$$

- **Quantum Gravitational MSW effect**

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

Stochastic QG metric fluctuations

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

$$\langle h_{\mu\nu} \rangle = 0$$
$\langle h_{\mu\nu} h_{\rho\sigma} \rangle$ are non trivial

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

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

$$M = \begin{pmatrix} m_e & m_{e\mu} \\ m_{e\mu} & m_\mu \end{pmatrix}$$

$$\begin{pmatrix} \psi_e \\ \psi_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

Flavour states $\qquad$ **Mass eigenstates**

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

Oscillation Probability

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

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

Stochastic QG metric fluctuations

Oscillation Probability

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

Two kinds of foam examined:

(i) Gaussian distributions

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

NM, Sarkar , Alexandre, Farakos, Pasipoularides

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

(ii) Cauchy-Lorentz

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

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

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

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

NB: damping suppressed by neutrino mass differences

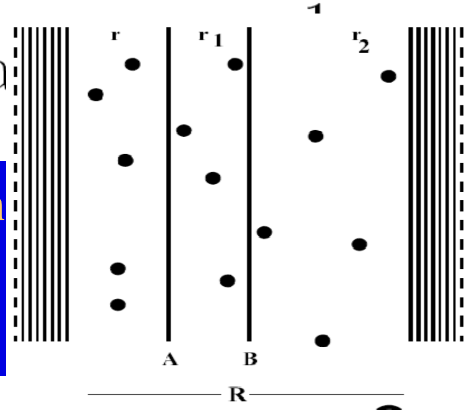
Stochastic QG metric fluctuations

Oscillation Probability

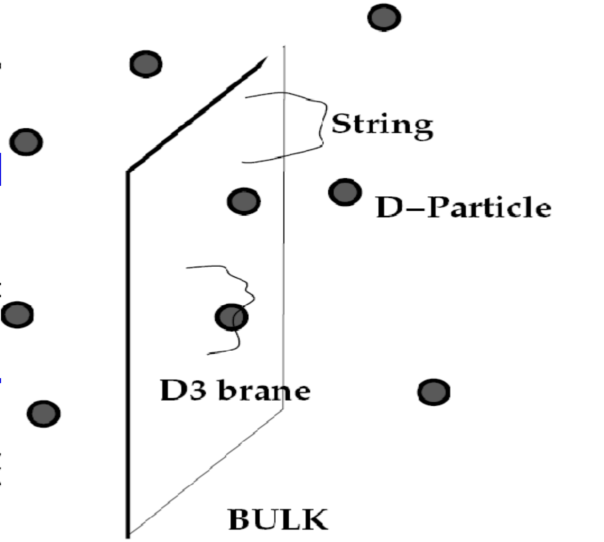
$\langle \mathrm{Prob}(\alpha$ ... $1 - e^{-\chi(t)} \cos(at) \big)$

Two kinds of foam examin

(i) Gaussian distributions



$\langle e^{i(\omega_1 - \omega_2)t} \rangle \simeq \exp$ ... $\Big\} \exp \Big\{ -\frac{\sigma^2 (kt)^2}{8} \Delta^2 \Big\}$



(ii) Cauchy-Lorentz

$f(x)$ ...

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

$\langle e^{i(\omega_1 - \omega_2)t} \rangle \simeq$ ... $\Big\}$

In D-particle foam model, h_{oi} n= u_i involves recoil velocity distribution of D-particle populations .

NB: damping suppressed by neutrino mass differences

Quantum Gravitational MSW Effect

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

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

n^c_{bh} Black Hole density in foam

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

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

Neutrino density matrix evolution is of Lindblad decoherence type:

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

Barenboim, NM, Sarkar, Waldron-Lauda

Quantum Gravitational MSW Effect

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

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

n^c_{bh} Black Hole density in foam

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

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

Neutrino density matrix evolution is of Lindblad decoherence type:

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

CPT Violating (time irreversible, CP symmetric)

Quantum Gravitational MSW Effect

OSCILLATION PROBABILITY:

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

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

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

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

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

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

Damping suppressed by neutrino-flavour MSW-coupling differences

Quantum Gravitational MSW Effect

OSCILLATION PROBABILITY:

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

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

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

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

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

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

Damping suppressed by neutrino-flavour MSW-coupling differences

Quantum Gravitational MSW Effect

OSCILLATION PROBABILITY:

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

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

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

Damping suppressed by neutrino-flavour MSW-coupling differences

Quantum Gravitational MSW Effect

OSCILLATION PROBABILITY:

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

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

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

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

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

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

Damping suppressed by neutrino-flavour MSW-coupling differences

Current Experimental Bounds

Lindblad-type decoherence Damping:

Fogli, Lisi, Marrone, Montanino, Palazzo

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

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

$$\gamma_{\rm Lnb} < 0.4 \times 10^{-22} \ {\rm GeV} \ , \quad n = 0$$
$$\gamma_{\rm Lnb} < 0.9 \times 10^{-27} \ {\rm GeV} \ , \quad n = 2$$
$$\gamma_{\rm Lnb} < 0.7 \times 10^{-21} \ {\rm GeV} \ , \quad n = -1$$

Including LSND & KamLand Data:

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

Beyond Lindblad: stochastic metric Fluctuations damping: $e^{-\mathcal{D}L^2}$

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

Barenboim, NM, Sarkar, Waldron-Lauda

Current Experimental Bounds

Lindblad-type decoherence Damping:

Fogli, Lisi, Marrone, Montanino, Palazzo

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

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

$$\gamma_{\rm Lnb} < 0.4 \times 10^{-22}\ {\rm GeV}\ , \quad n = 0$$
$$\gamma_{\rm Lnb} < 0.9 \times 10^{-27}\ {\rm GeV}\ , \quad n = 2$$
$$\gamma_{\rm Lnb} < 0.7 \times 10^{-21}\ {\rm GeV}\ , \quad n = -1$$

Including LSND & KamLand Data: $\gamma L \sim 1.5. \cdot 10^{-2}$ **Best fits**

Beyond Lindblad: stochastic metric Fluctuations damping: $e^{-\mathcal{D}L^2}$ $\quad \mathcal{D}L^2 \sim 1.5. \cdot 10^{-2}$

Barenboim, NM, Sarkar, Waldron-Lauda

SOME EXPONENTS NON ZERO, NOT ALL…

Current Experimental Bounds

Barenboim, NM, Sarkar, Waldron-Lauda

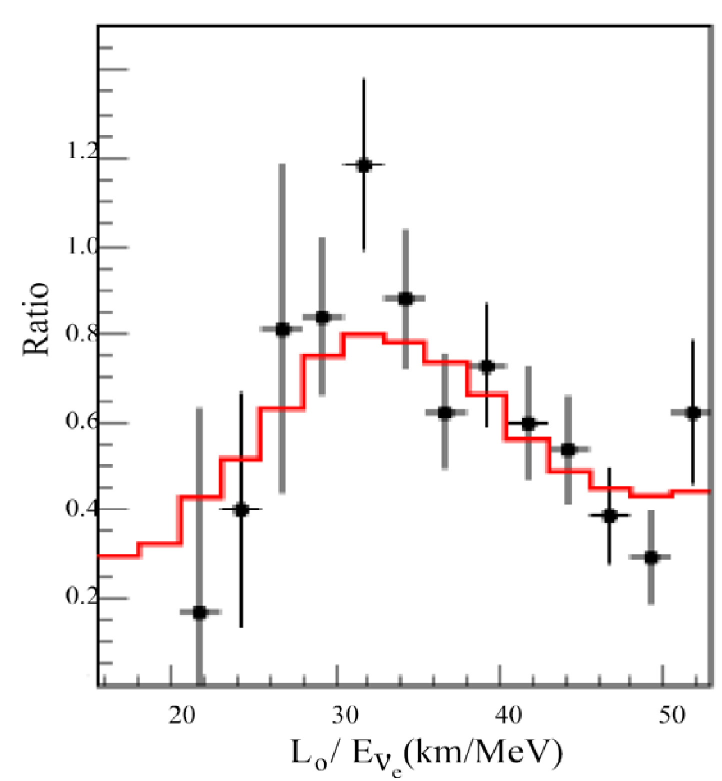
Including LSND & KamLand Data:

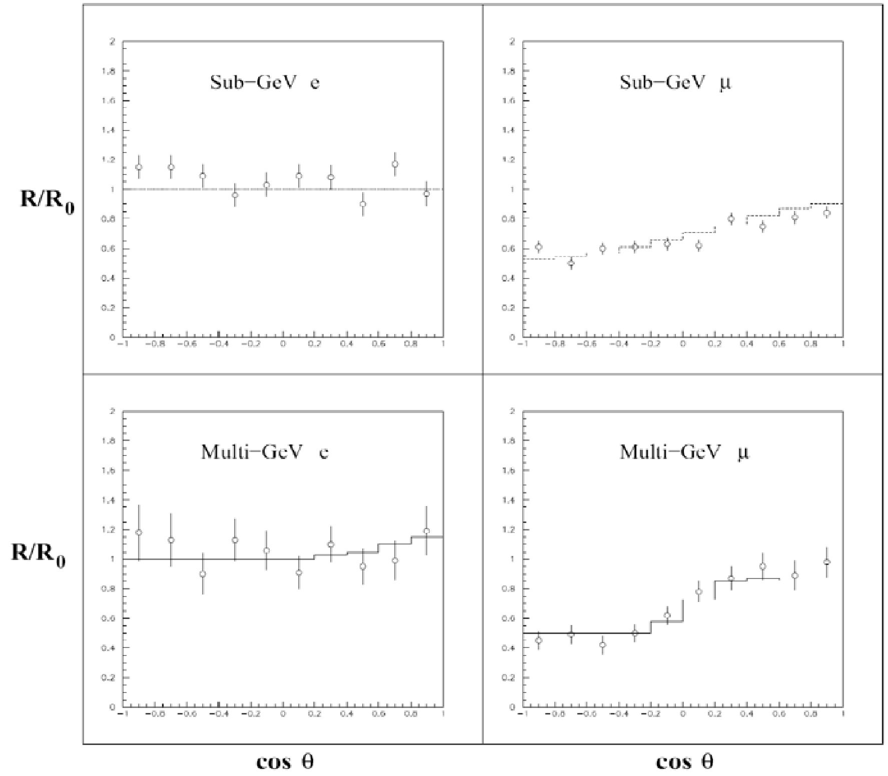
t = L (Oscillation length, (c=1)

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

Beyond Lindblad: stochastic metric Fluctuations damping (Best Fits):

$$e^{-\mathcal{D}L^2} \qquad \mathcal{D}L^2 \sim 1.5. \cdot 10^{-2}$$





Current Experimental Bounds

Including LSND & KamLand Data: **Barenboim, NM, Sarkar, Waldron-Lauda**

Lindblad type Decoherence $e^{-\gamma t}$ $\gamma L \sim 1.5. \cdot 10^{-2}$

Beyond Lindblad: stochastic metric Fluctuations damping (Best Fits): $e^{-\mathcal{D}L^2}$ $\mathcal{D}L^2 \sim 1.5. \cdot 10^{-2}$

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

$$t = L \sim \frac{2k}{(m_1^2 - m_2^2)}$$

$$\mathcal{D} = \sigma^2 \frac{(m_1^2 - m_1^2)^2}{2k^2}$$

$$\sigma^2 = \mathcal{O}(10^{-2})$$

Probably too Large to be QG Effect….

NB: Lindblad-type damping Also induced by uncertainties in energy of neutrino beams

Ohlsson, Jacobson

LSND+ KamLand $\frac{\Delta E}{E} \sim 1.6 \cdot 10^{-1}$

Current Experimental Bounds

Including LSND & KamLand Data:

Barenboim, NM, Sarkar, Waldron-Lauda

Lindblad type Decoherence $e^{-\gamma t}$ $\gamma L \sim 1.5. \cdot 10^{-2}$

Beyond Lindblad: stochastic metric Fluctuations damping (Best Fits): $e^{-\mathcal{D}L^2}$ $\mathcal{D}L^2 \sim 1.5. \cdot 10^{-2}$

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

$$t = L \sim \frac{2k}{(m_1^2 - m_2^2)}$$

$$\mathcal{D} = \sigma^2 \frac{(m_1^2 - m_1^2)^2}{2k^2}$$

$$\sigma^2 = \mathcal{O}(10^{-2})$$

Probably too Large to be QG Effect….

NB: Lindblad-type damping Also induced by uncertainties in energy of neutrino beams

Ohlsson, Jacobson

LSND+ KamLand $\frac{\Delta E}{E} \sim 1.6 \cdot 10^{-1}$

But in that case all exponents must be non zero Hence….still unresolved

Look into the future: Potential of J-PARC, CNGS

NM, Sakharov, Meregaglia, Rubbia, Sarkar

JPARC

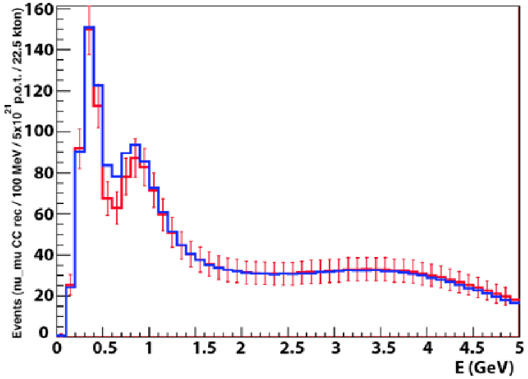


FIG. 3: The number of reconstructed ν_μ CC events in as a function of the neutrino energy w
(blue line) and without (red line with error bars) QG decoherence effect included in case of invers
proportional dependence on neutrino energy. 3σ difference between the expected and QG disturl
spectra is shown.

$$\langle P_{\alpha\beta}\rangle = \delta_{\alpha\beta} -$$

$$2\sum_{a=1}^{n}\sum_{b=1,a<b}^{n} \mathrm{Re}\left(U^*_{\alpha a}U_{\beta a}U_{\alpha b}U^*_{\beta b}\right)\left(1-\cos(2\ell\Delta m^2_{ab})e^{-q_1 L - q_2 L^2}\right)$$

$$-2\sum_{a=1}^{n}\sum_{b=1,a<b}^{n} \mathrm{Im}\left(U^*_{\alpha a}U_{\beta a}U_{\alpha b}U^*_{\beta b}\right)\sin(2\ell\Delta m^2_{ab})e^{-q_1 L - q_2 L^2}$$

$$\text{with} \qquad \ell \equiv \frac{L}{4E}$$

CNGS

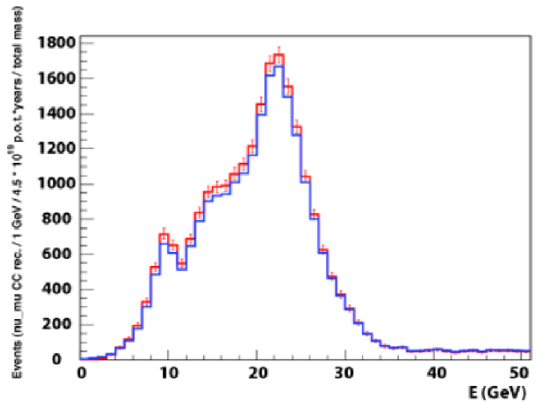


FIG. 2: The number of reconstructed ν_μ CC events in OPERA as a function of the neutrino energy with (blue line) and without (red line with error bars) QG decoherence effect included in case of inversely proportional dependence on neutrino energy. 3σ difference between the expected and QG disturbed spectra is shown.

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

Look into the future: Potential of J-PARC, CNGS

Lindblad-type mapping operators	CNGS	T2K	T2KK
γ_0 [eV] ; ([GeV])	2×10^{-13} ; (2×10^{-22})	2.4×10^{-14} ; (2.4×10^{-23})	1.7×10^{-14} ; (1.7×10^{-23})
γ_{-1}^2 [eV^2] ; ([GeV^2])	9.7×10^{-4} ; (9.7×10^{-22})	3.1×10^{-5} ; (3.1×10^{-23})	6.5×10^{-5} ; (6.5×10^{-23})
γ_2 [eV^{-1}] ; ([GeV^{-1}])	4.3×10^{-35} ; (4.3×10^{-26})	1.7×10^{-32} ; (1.7×10^{-23})	3.5×10^{-33} ; (3.5×10^{-24})
Gravitational MSW (stochastic) effects	**CNGS**	**T2K**	**T2KK**
α^2	4.3×10^{-13} eV	4.6×10^{-14} eV	3.5×10^{-14} eV
α_1^2	1.1×10^{-25} eV^2	3.2×10^{-26} eV^2	6.7×10^{-27} eV^2
β^2	3.6×10^{-24}	5.6×10^{-23}	1.7×10^{-23}
β_2^2	9.8×10^{-37} eV	4×10^{-35} eV	3.1×10^{-36} eV
β_1^2	8.8×10^{-35} eV^{-1}	3.5×10^{-32} eV^{-1}	7.2×10^{-33} eV^{-1}

TABLE I: Expected sensitivity limits at CNGS, T2K and T2KK to one parametric neutrino decoherence for Lindblad type and gravitational MSW (stochastic metric fluctuation) like operators.

Look into the future: High Energy Neutrinos

Morgan, Winstanley, Anchordoqui, Goldberg, Hooper, Subir Sarkar, Weiler, Halzen…

Much higher sensitivities from high energy neutrinos

AMANDA, ICE CUBE,
ASTROPHYSICAL/COSMOLOGICAL NEUTRINOS
(e.g. if neutrinos with energies close to 10^{20} eV from GRB
At redshifts $z > 1$ are observed …)

Look into the future: High Energy Neutrinos

Morgan, Winstanley, Anchordoqui, Goldberg, Hooper, Subir Sarkar, Weiler, Halzen…

Much higher sensitivities from high energy neutrinos

AMANDA, ICE CUBE,
ASTROPHYSICAL/COSMOLOGICAL NEUTRINOS
(e.g. if neutrinos with energies close to 10^{20} eV from GRB
At redshifts z > 1 are observed …)

Recently: Interesting scenarios of Lindblad decoherence with SOME damping exponents having energy dependence E^{-4} proposed for reconciling LSND (anti-ν) & MINIBOONE

$$\gamma \sim 2.5 \frac{\mu^2}{0.2\ \mathrm{eV}^2} \left(\frac{4\ \mathrm{MeV}}{E_\nu}\right)^4 \mathrm{cm}^{-1}$$

Farzan, Smirnov, Schwetz,

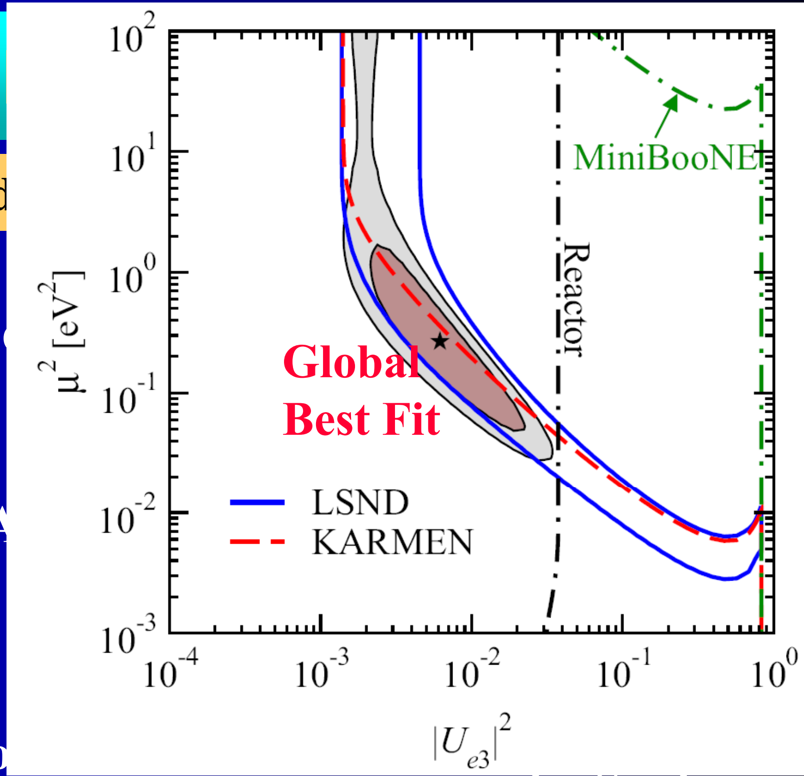
Damping $e^{-\gamma t}$

Look into the future: Hig

Morgan, Winstanley, Anchordoqui, Gold

Much higher sensitivities from high en

AMANDA, ICE CUBE,
ASTROPHYSICAL/COSMOLOGICA
(e.g. if neutrinos with energies close to
At redshifts z > 1 are observed …)



Recently: Interesting scenarios of Lindblad deco … **ts having energy dependence E^{-4} proposed for reconciling LSND (anti-ν) & MINIBOONE**

$$\gamma \sim 2.5 \frac{\mu^2}{0.2 \text{ eV}^2} \left(\frac{4 \text{ MeV}}{E_\nu} \right)^4 \text{ cm}^{-1}$$

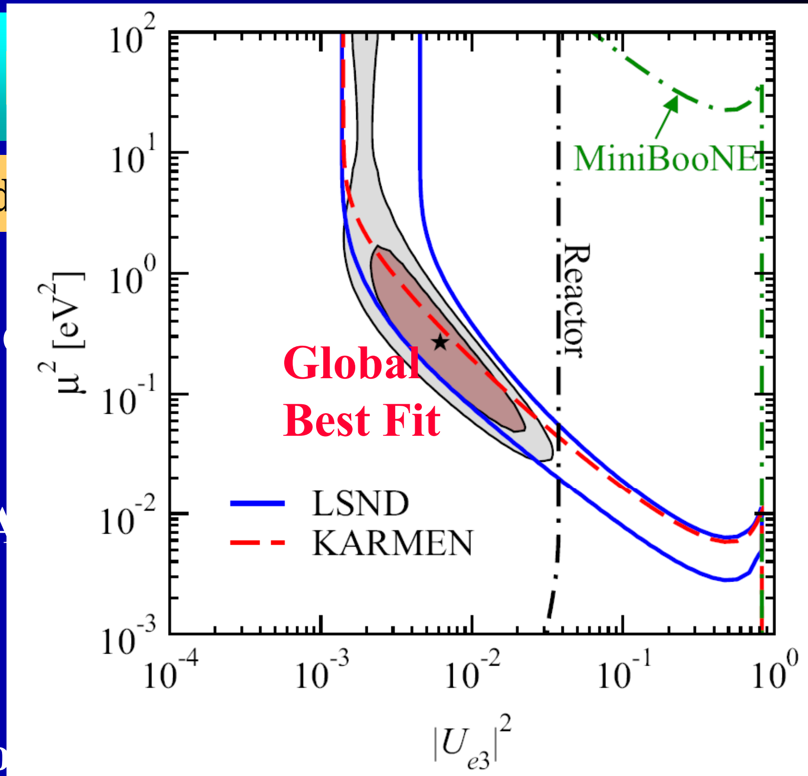
Farzan, Smirnov, Schwetz,

$$|U_{e3}|^2 = 6.1 \times 10^{-3}, \qquad \sin^2 \theta_{23} = 0.5, \; \mu^2 = 0.27 \, \text{eV}^2$$

Microscopic QG models ?

Look into the future: Hig

Morgan, Winstanley, Anchordoqui, Gold



Much higher sensitivities from high en

AMANDA, ICE CUBE,
ASTROPHYSICAL/COSMOLOGICA
(e.g. if neutrinos with energies close to
At redshifts z > 1 are observed …)

Recently: Interesting scenarios of Lindblad deco … ts having energy dependence E^{-4} proposed for reconciling LSND (anti-ν) & MINIBOONE

$$\gamma \sim 2.5 \frac{\mu^2}{0.2\ \mathrm{eV}^2} \left(\frac{4\ \mathrm{MeV}}{E_\nu}\right)^4 \mathrm{cm}^{-1}$$

Farzan, Smirnov, Schwetz,

$$|U_{e3}|^2 = 6.1 \times 10^{-3}, \qquad \sin^2\theta_{23} = 0.5\,, \ \mu^2 = 0.27\,\mathrm{eV}^2$$

Microscopic QG models ? **e.g. in our stochastic fluctuating metric models E^{-4} scaling is obtained in Gaussian model with $\sigma^2 \sim k^{-2}$**

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…**

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… Microscopic Time Irreversibility….**
- **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…**

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… Microscopic Time Irreversibility….**

- **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…**

Further 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...

Further 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…