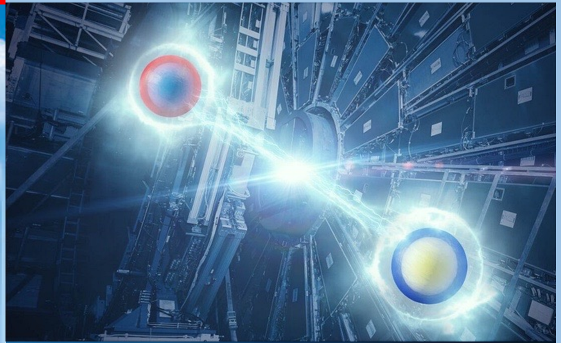
Quantum-Gravity-Induced Entanglement in High-Energy Physics & Gravitation

Nick E. Mavromatos

Natl. Tech. U. Athens &

King's College London

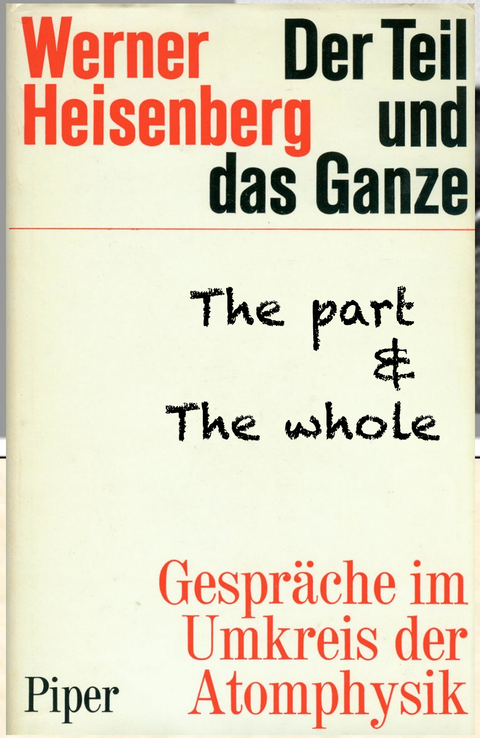


Happy
Anniversary
QM !
100 yrs
(1925-2025)

"There is a fundamental error in separating the parts from the whole, the mistake of atomizing what should not be atomized.

Unity and complementarity constitute reality"

Werner Karl Heisenberg
German Scientist & Nobel Prize
1901-1976



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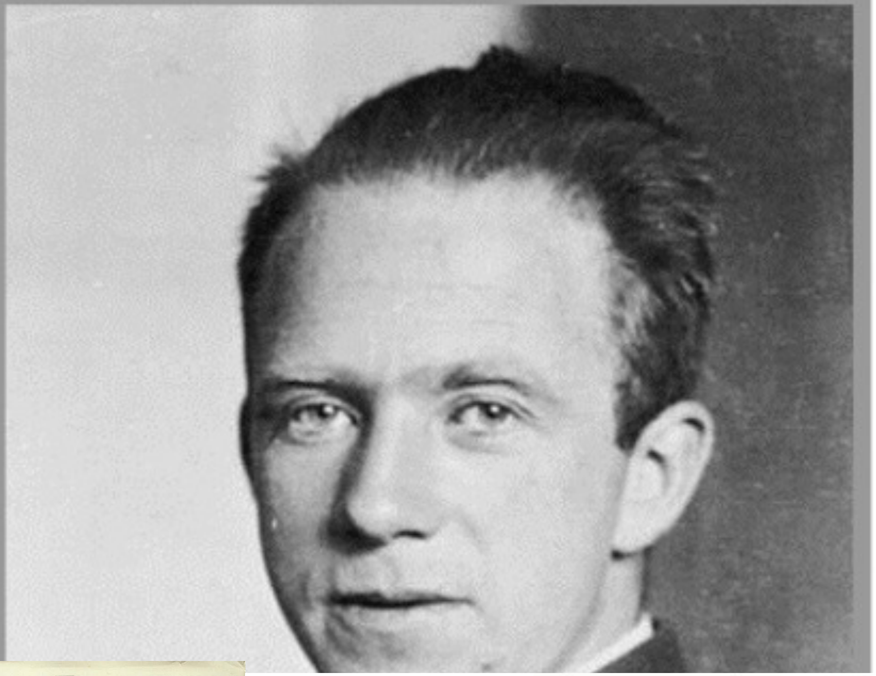
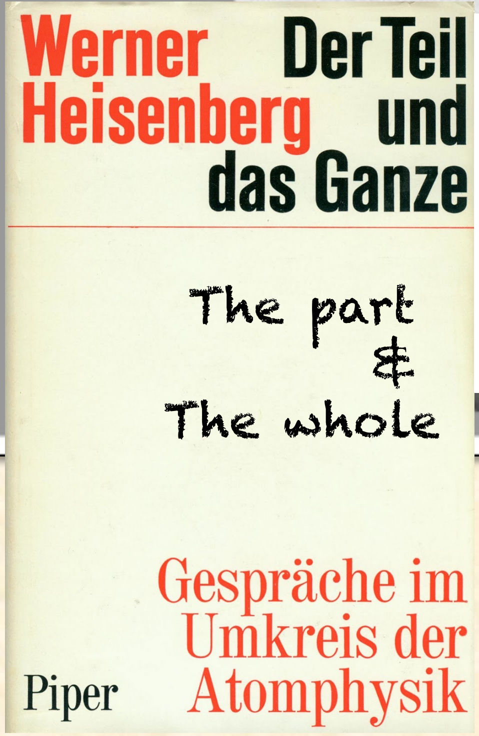
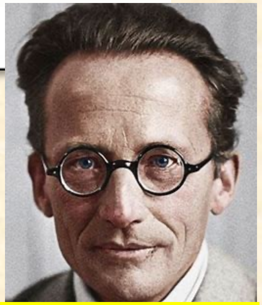




A. Einstein B. Podolsky N. Rosen

Quantum Entanglement (1935)



Schroedinger

Happy
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100 yrs
(1925-2025)
Recent
years:
Enormous
progress
in
Quantum
Information,
Quantum
Computation

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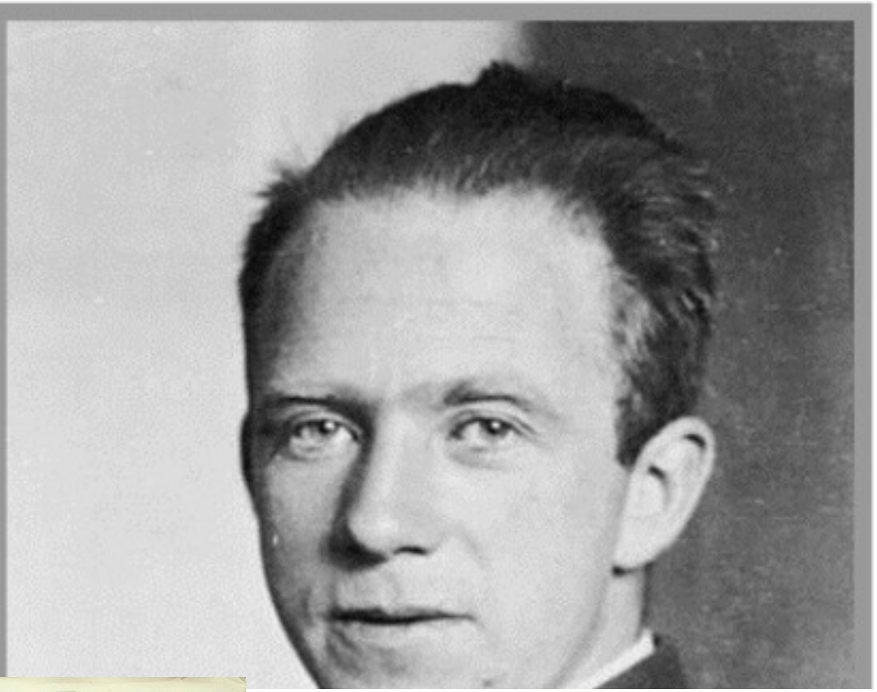

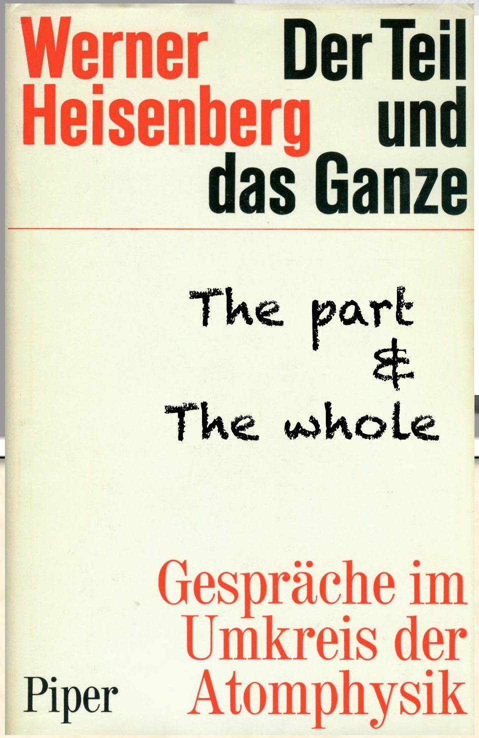

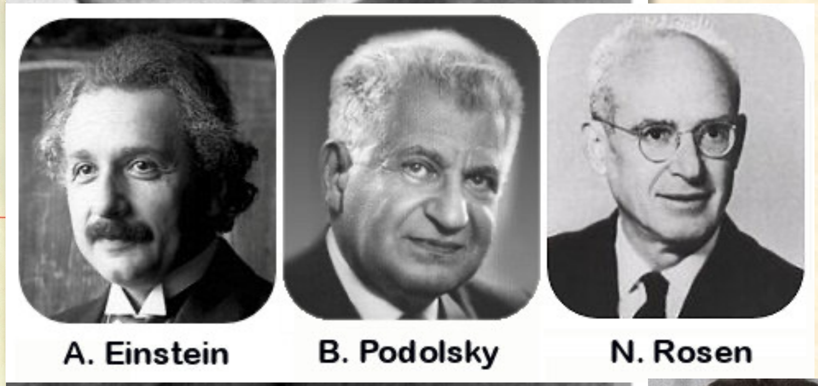

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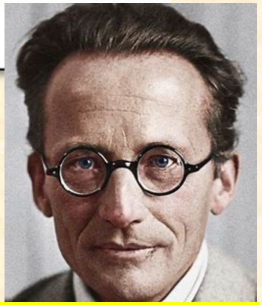

Schroedinger

“There is a fundamental
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parts
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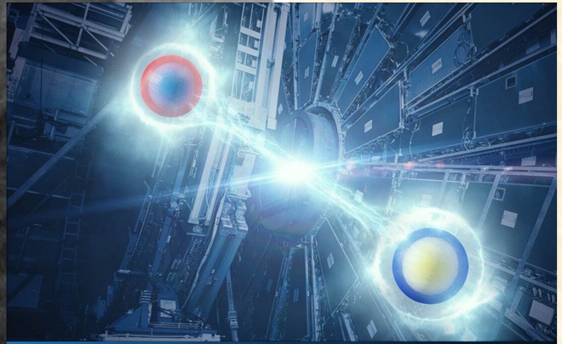
Our talk:
Quantum-Gravity
Effects (?)
on
Entanglement
in
HEP & Gravity



OUTLINE

Quantum Gravity ?

Effects in effective gravitational (low-energy) theories & beyond

Part I

Induced Decoherence & CPT operator ill-definition (intrinsic CPT Violation)

Intrinsic CPT Violation and Entangled Particle States (ω-εffect):

Neutral-Meson Factories modifications of Einstein-Podolsky-Rosen (EPR) correlations

Spin-system analogues of the ω-effect → connections to cryptography?
tomography?

Current sensitivities (KLOE (-2), B-systems (BaBar), BES III)

Part II (brief)

Superradiant-rotating-Black-Hole Axionic clouds & Quantum Graviton Squeezing ?

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Complement Yu Shi’ s analysis (c.f. his talk); role of ω-effect in Violation of Leggett inequality ?

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Complement Tao Han's analysis (c.f. his talk); role of ω-effect in HEP tomography ?

Bernabeu, NEM, Sarkar PR D 74 (2006) 045014

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Dorlis, NEM, Sarkar, Vlachos
arXive 2507.01689 [gr-qc]

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A way of detecting quantum gravitons...

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Neutral-Meson Factories m

Spin-system analogues of t

Current sensitivities (KLOE (-2), B-systems (BaBar), BES III)

For importance of Squeezed Quantum states, including those of Gravitational Waves → cf F. Wilczek's talk & related work

Our focus here will be different

Part II (brief)

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Superra… & Quantum Graviton Squeezing ?

A way … detecting quantum gravitons…

Role of Chern-Simons Gravitational Anomalies in inducing multimode graviton squeezing

Dorlis, NEM, Sarkar, Vlachos
arXive 2507.01689 [gr-qc]

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Current sensitivities (KLOE (-2), B-systems

Part I

Superra ... n Squeezing ?

A way ... gravitons...

Role of Chern-Simons Gravitational Anomalies
in inducing multimode graviton squeezing
But also affecting entangled-graviton correlations
(remote analogy with ω-effect)

Dorlis, NEM, Sarkar, Vlachos
arXive 2507.01689 [gr-qc]

Quantum Gravity: (QG) **(1)** Is gravity quantized like the rest of the fundamental interactions in Nature → there exist quantum gravitons (carrier quantum fields of gravitational interaction)

or

(2) is it an ``emergent" not-fundamental force, e.g (entropic) force associated (**E. Verlinde**) with the statistical behaviour of microscopic material degrees of freedom, specifically with information linked to positions of material bodies → no quantum gravitons. Gravity in this second approach is related to the tendency of the Universe to maximize entropy (Einstein's equations are reproduced this way! ←→ combined thermodynamics approach with `t Hooft holographic principle). Gravity in Verlinde's model emerges from quantum entanglement of ``small" bits of spacetime information.

In **(1)**: **weak QG** can be treated as a (non-renormalizable) quantum local effective field theory **(EFT)**

$$g_{\mu\nu} = \underbrace{g^{(0)}_{\mu\nu}}_{\text{background}} + \underbrace{\kappa\, h_{\mu\nu}}_{\text{quantum flct.}}\,, \qquad \kappa = M_{\rm Pl}^{-1} \quad (\text{units}\, \hbar = c = 1)$$

But non-perturbative formulation and background-independent formalism (dynamical generation of spacetime itself) still at large (loop quantum gravity, spin-foam models etc – string theory helps understanding (1) but is not background independent)

Nonetheless, there are successes in **(1)**: e.g. asymptotic safety → **shall use it in discussing graviton squeezing**

Important Questions: Is QG respecting Lorentz Symmetry as we know it?
or is QG associated with:
Spontaneous Lorentz-Invariance-Violation (LIV)
(e.g. in situations of space-time foam)

Ellis, NEM, Mavromatos

modified dispersion relations (MDR) of material probes

or:

Lorentz-symmetry **modification** (**Deformed Special Relativities**)
not necessarily MDR of material probes

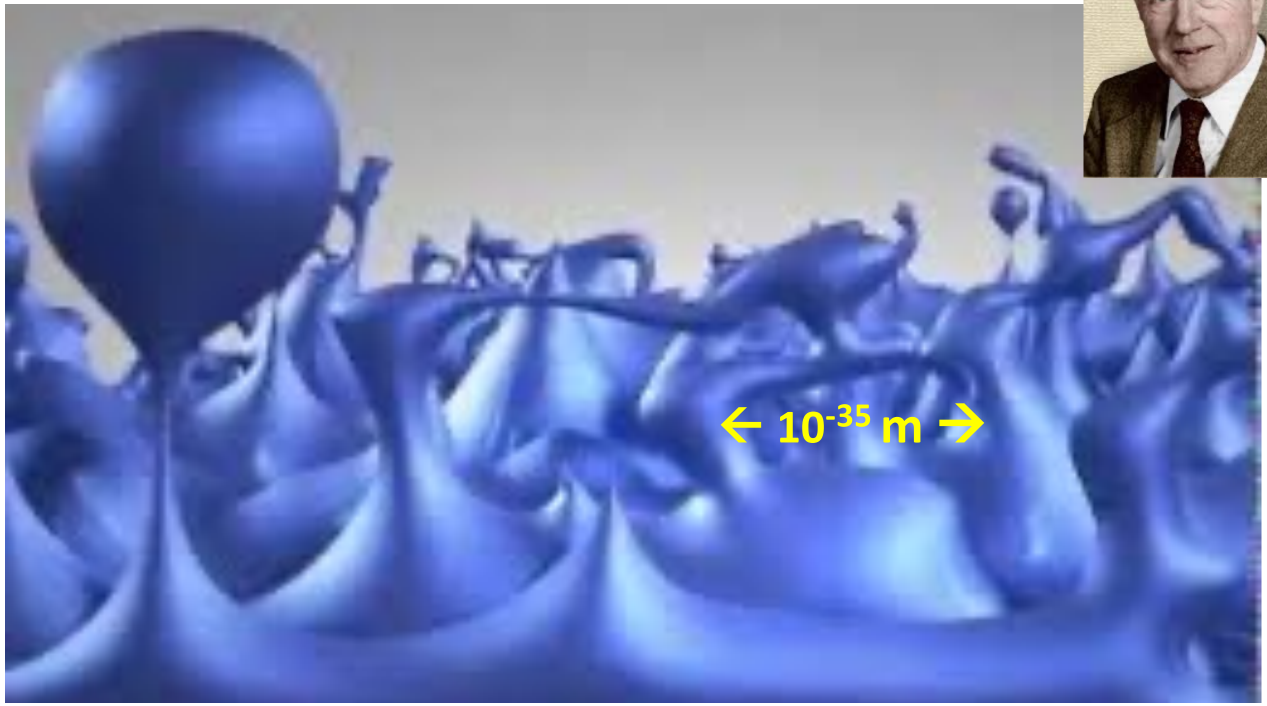
Amelino-Camelia
Magueijo, Smolin

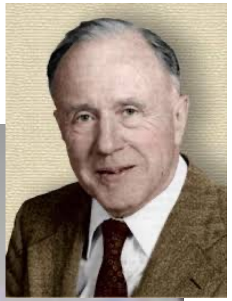
If MDR in QG due to LIV or DSR: Rich Astro-particle Phenomenology (mutlimessenger approach)
(scale of LIV-MDR or DSR-MDR M_{QG} a phenomenological parameter
in EFT approach to QG, not necessarily equal to Planck $M_{QG} \neq M_{Pl}$)

A. Addazi *et al.*,
Prog.Part.Nucl.Phys. 125 (2022) 103948
e-Print: 2111.05659 [hep-ph]

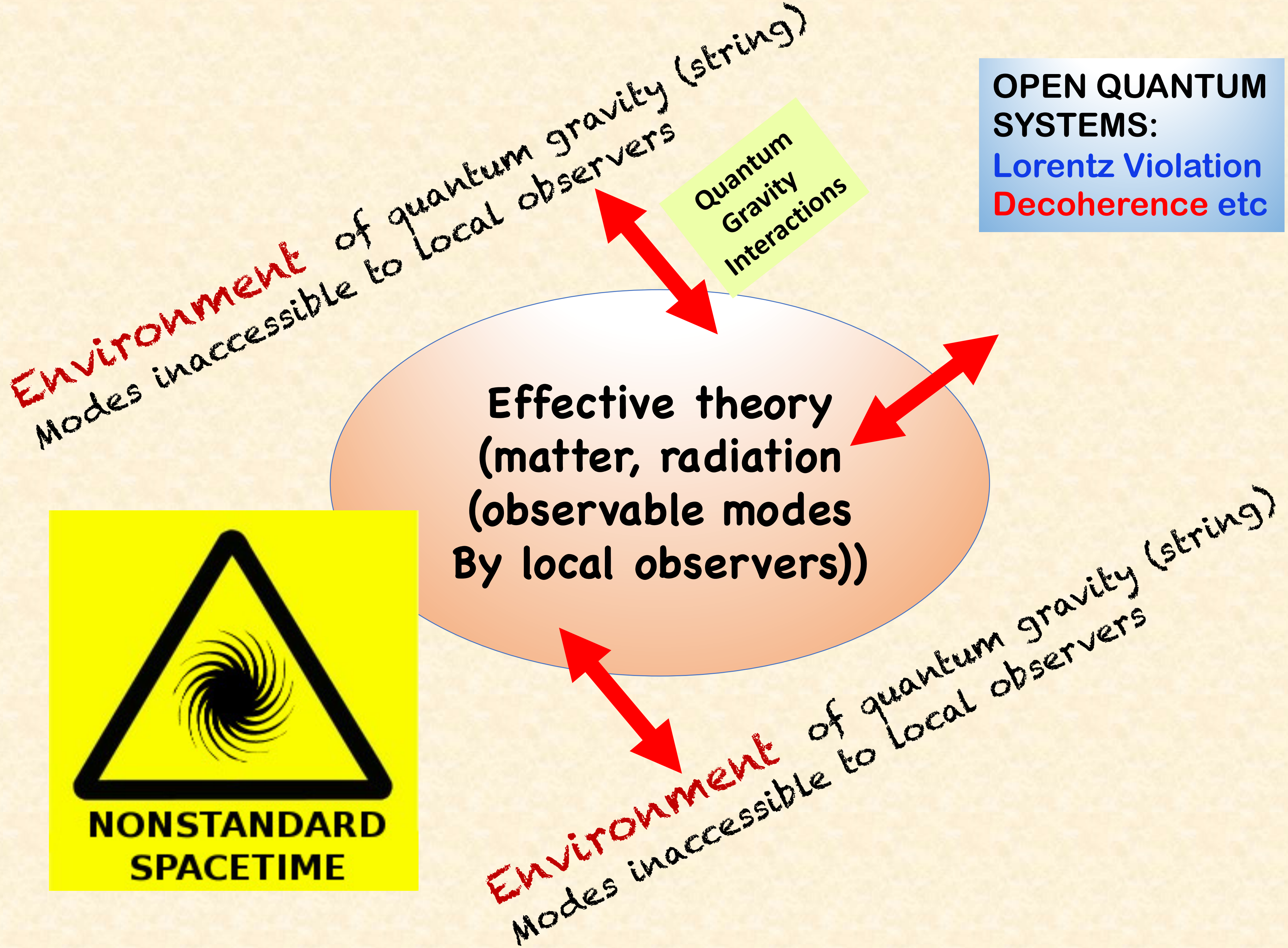
Beyond-EFT QG Effects

QG-induced Space-time foam and induced quantum decoherence of material probes





J.A. Wheeler



OPEN QUANTUM SYSTEMS:
Lorentz Violation
Decoherence etc
Environment of quantum gravity (string)
Modes inaccessible to local observers
Quantum Gravity Interactions
Effective theory (matter, radiation (observable modes By local observers))
Environment of quantum gravity (string)
Modes inaccessible to local observers
NONSTANDARD SPACETIME

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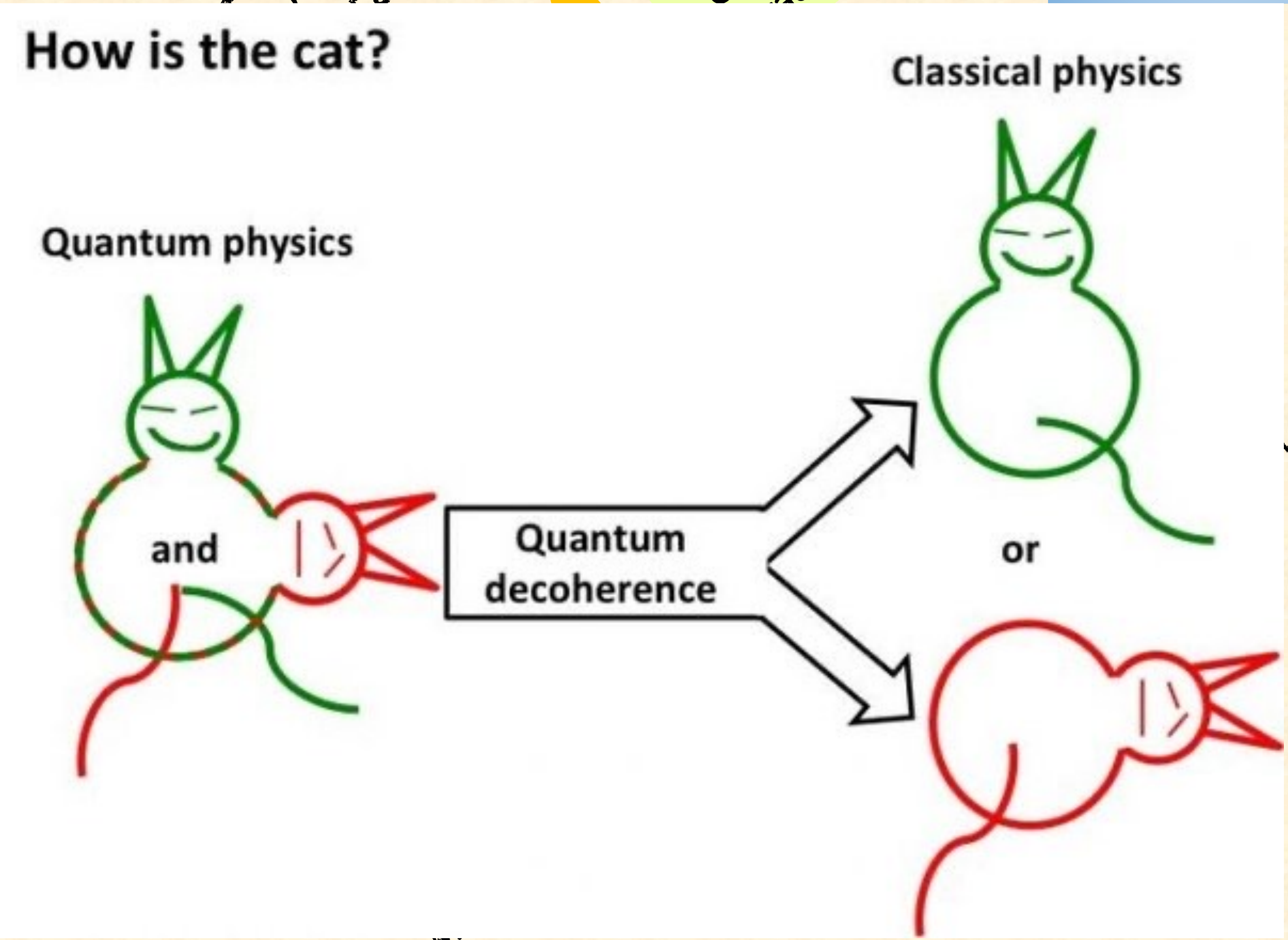
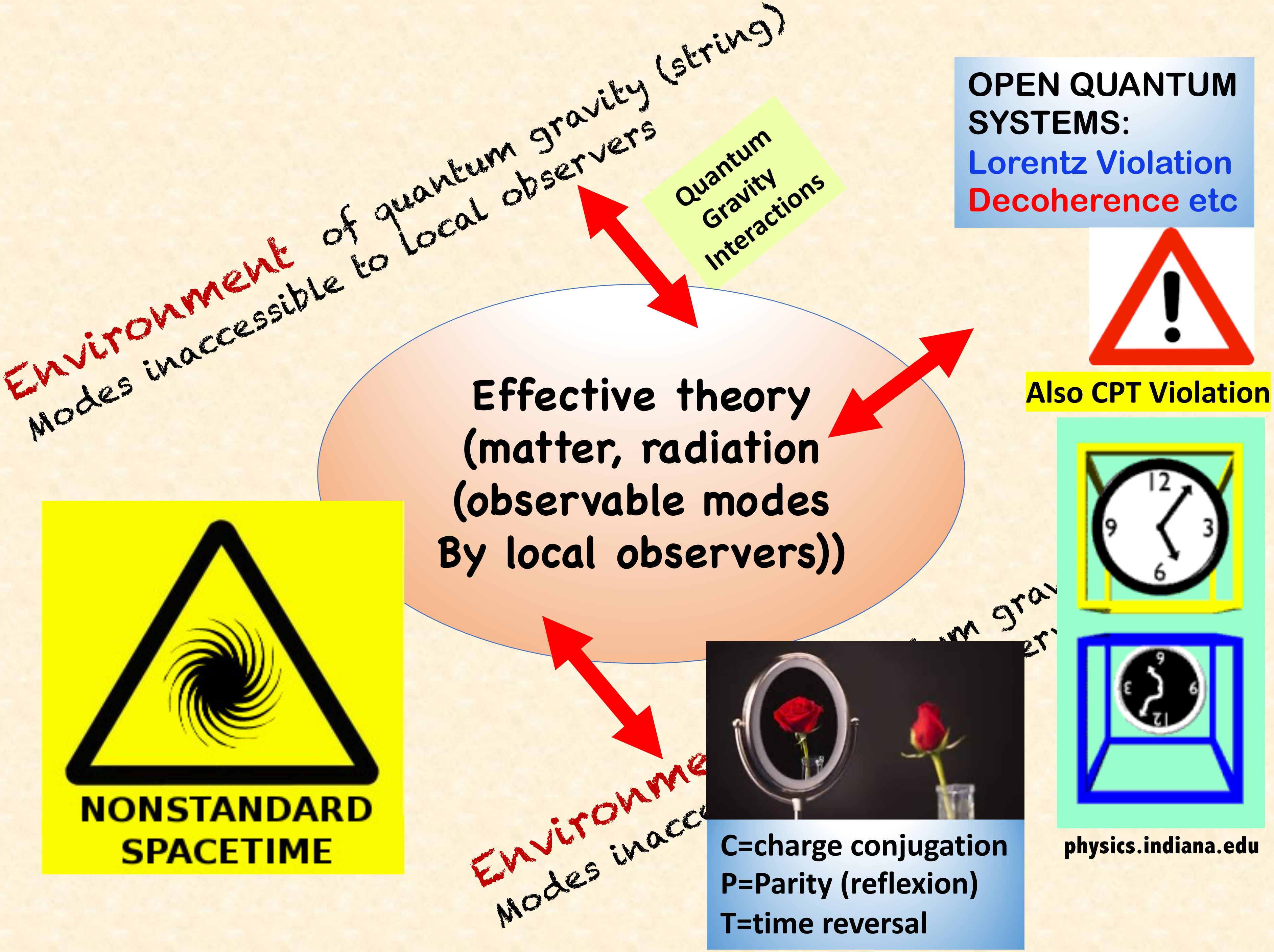


(string)



Environment of quantum gravity (string)
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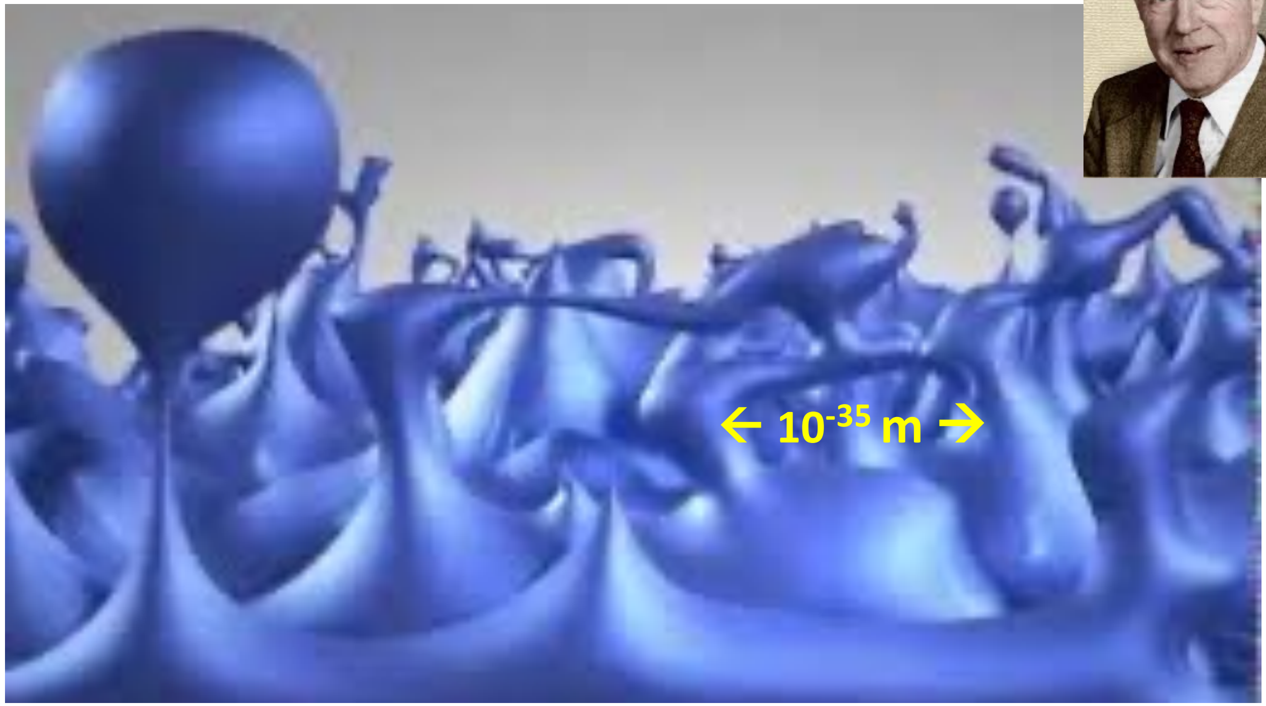
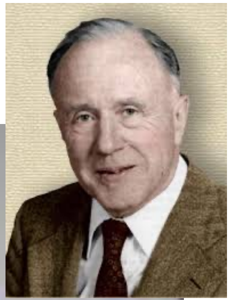
OPEN QUANTUM SYSTEMS:
Lorentz Violation
Decoherence etc
Also CPT Violation
Effective theory
(matter, radiation
(observable modes
By local observers))
NONSTANDARD SPACETIME
C=charge conjugation
P=Parity (reflexion)
T=time reversal
physics.indiana.edu

Beyond-EFT QG Effects

QG-induced Space-time foam and induced quantum **decoherence** of material probes





J.A. Wheeler

LIV

Spin-statistics may fail

CPT-operator may be ill-defined

Not necessarily occurring simultaneously

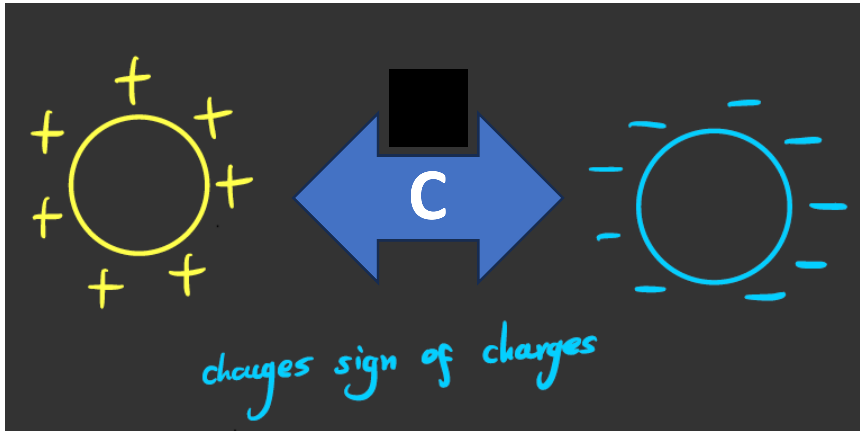
Part I

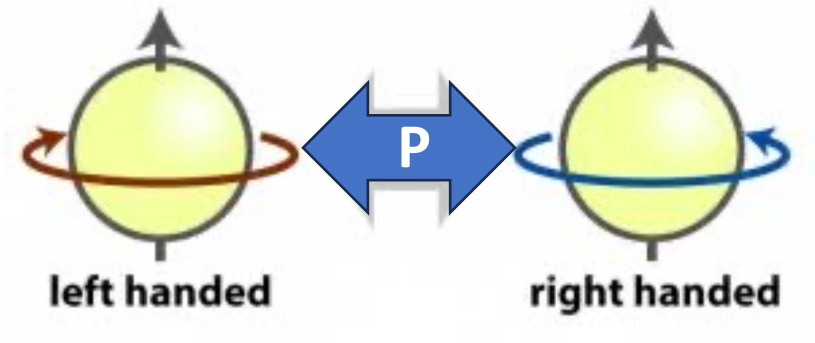
CPT Invariance : a theorem for flat relativistic quantum field theories

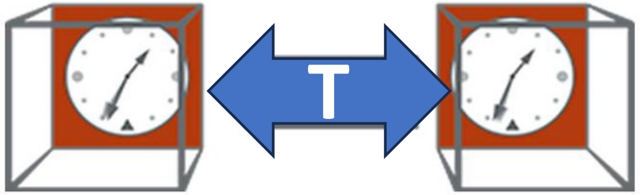
Bell. Jost, Luders, Pauli, Schwinger

Quantum Field theory with interactions **(i) Local (ii) Lorentz invariant** and **(ii) Unitary (probability conserved)**
In flat spacetime is described by lagrangian densities which are **invariant** under the combined discrete symmetries transformations (in any ordering**)** **CPT or PCT *etc***

C (charge conjugation) , **P (parity=spatial reflexion**)., **T (time reversal)**







CPT Invariance : a theorem for flat relativistic quantum field theories

Picaso

CP

T

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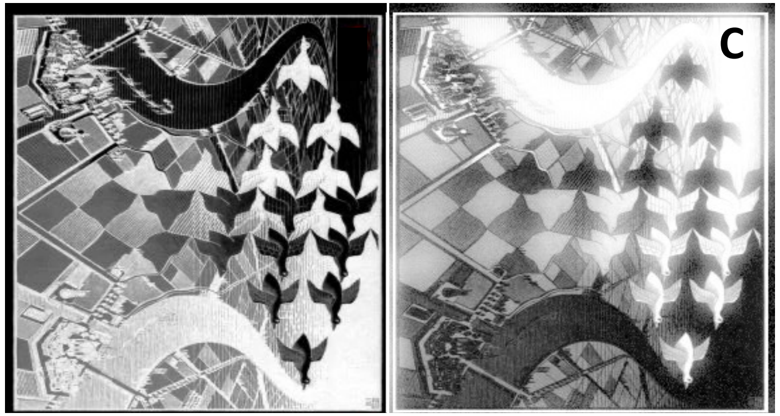

Escher

P Violation

T Violation

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CP ✗
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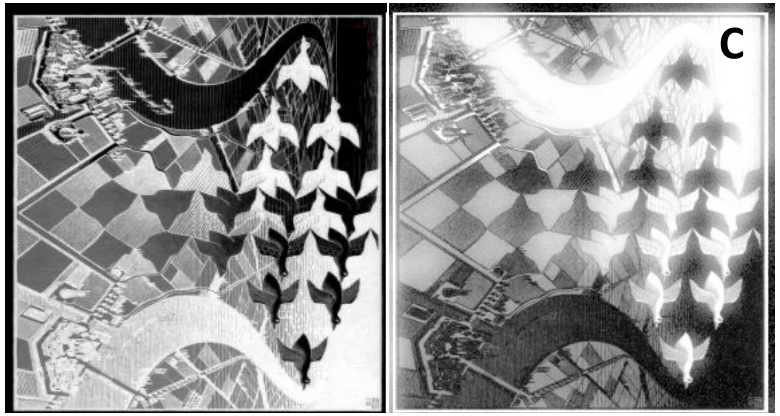

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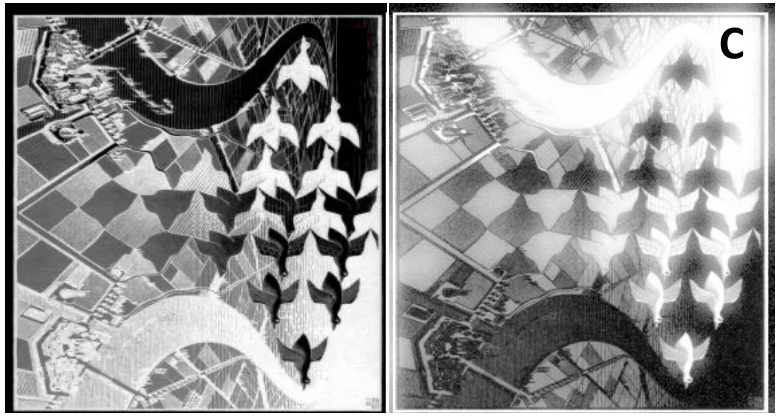

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O.W. Greenberg, *Phys.Rev.Lett.* 89 (2002) 231602

Bell. Jost, Luders, Pauli, Schwinger

CPT VIOLATION

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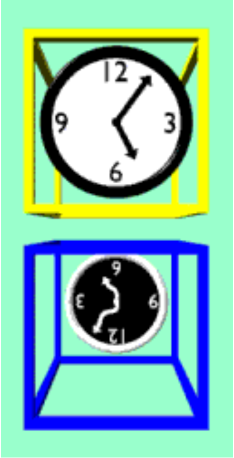

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either

CPT operator well-defined but not commuting with system's Hamiltonian: $[\widehat{\Theta}_{\rm CPT}\,,\,\widehat{\mathcal{H}}] \neq 0$

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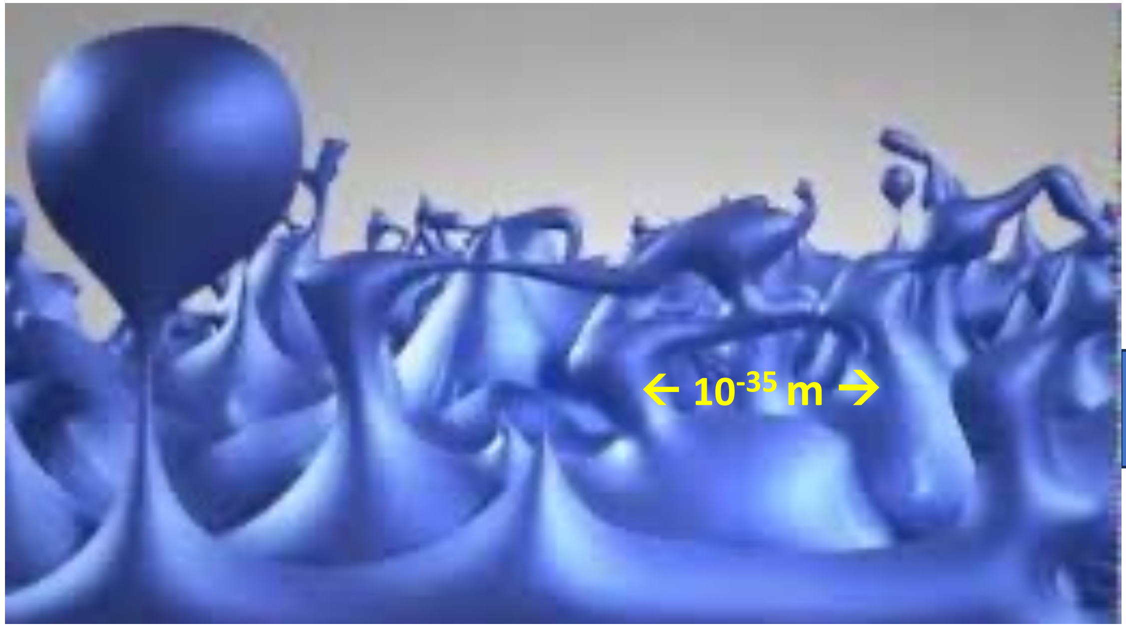

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CPT operator is not well-defined (e.g. decoherence situations in quantum gravity → Fundamental Time Arrow)

Wald

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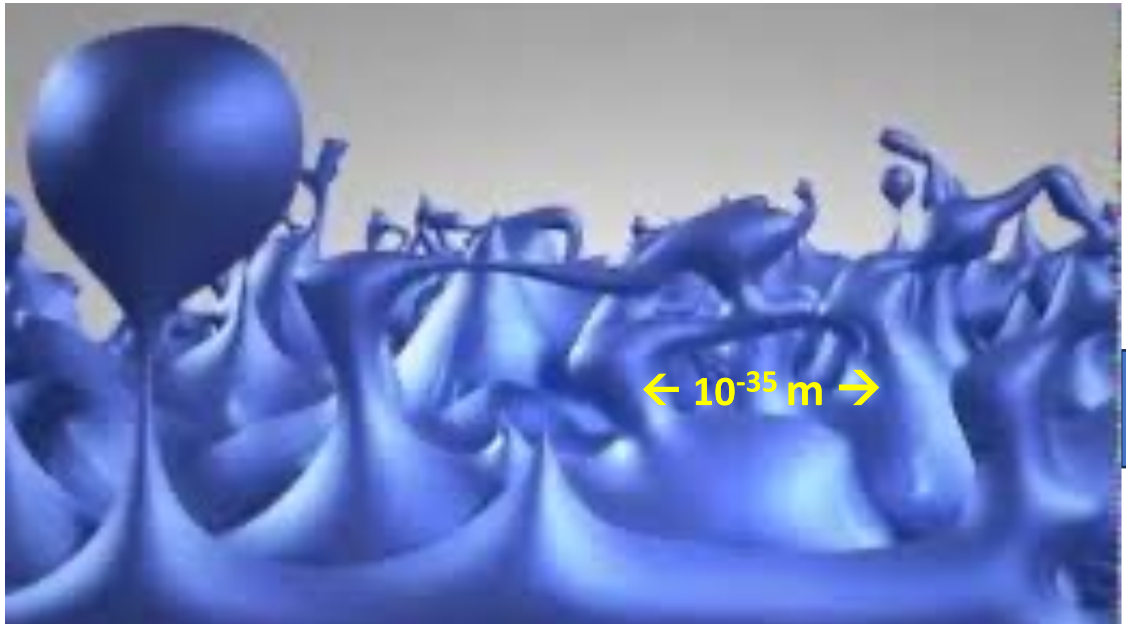

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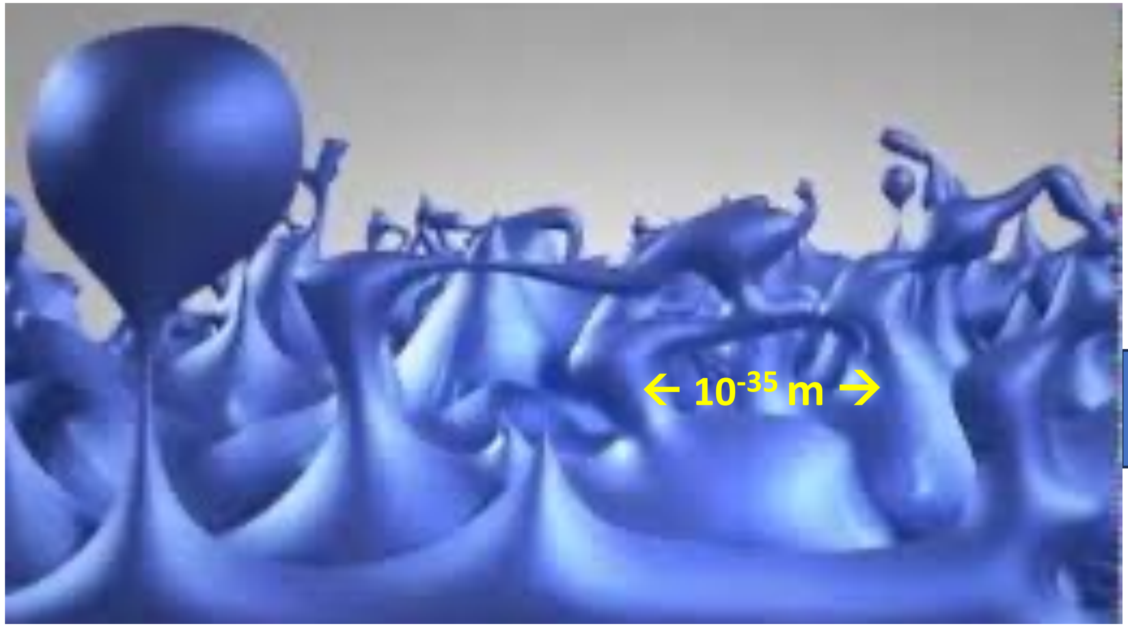

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Wald

NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$\rho_{\mathrm{out}} = \$\rho_{\mathrm{in}}$$

$$\$ \neq S\, S^{\dagger}$$

$$S = e^{i\int H dt}$$

May induce **quantum decoherence** of propagating matter and

intrinsic CPT Violation

in the sense that the CPT operator **Θ** is **not well-defined →**
beyond Local Effective Field theory

$$\Theta \rho_{\mathrm{in}} = \bar{\rho}_{\mathrm{out}}$$

If Θ well-defined can show that $\$^{-1} = \Theta^{-1}\$\Theta^{-1}$

exists !

INCOMPATIBLE WITH DECOHERENCE !

Hence Θ ill-defined at low-energies in QG foam models

Wald (79)

NB: Decoherence & CPTV

- **Quantum Gravity Decoherence induced CPT (& LV) Tests in Entangled Particle Physics systems (neutral meson factories):**

`smoking-gun' ω-effect beyond (local) Effective Field Theories ?

(Modifications of Einstein-Podolsky-Rosen correlations)

Bernabeu, NEM, Papavasssiliou (2004)

``Smoking-gun'' QG Decoherence **CPT Violating** (& LIV) Effects in Entangled Particle States ?

NB: Decoherence & CPTV

Decoherence implies that asymptotic density matrix of low-energy matter :

May induce **quantum decoherence** of propagating matter and
intrinsic CPT Violation
in the sense that the CPT operator **Θ** is **not well-defined →**
beyond Local Effective Field theory

$$\rho = \mathrm{Tr}|\psi\rangle\langle\psi|$$

$$\boxed{\begin{aligned}|i\rangle = \mathcal{N}\Big[&|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle - |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle \\ &+\omega\Big(|M_0(\vec{k})\rangle\,|\overline{M}_0(-\vec{k})\rangle + |\overline{M}_0(\vec{k})\rangle\,|M_0(-\vec{k})\rangle\Big)\Big]\end{aligned}}$$

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

May contaminate initially antisymmetric neutral meson *M* state by symmetric parts (ω-effect)

Hence Θ ill-defined at low-energies in QG foam models → may affect EPR

Wald (79)

Bernabeu, NEM, Papavassiliou (04),...

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Bernabeu, NEM, Papavassiliou (04),…

NB: Including conventional CPTV (θ) in the Hamiltonian

Bernabeu, Botella, NEM, Nebot

$$\mathbf{H}|B_H\rangle = \mu_H|B_H\rangle, \quad |B_H\rangle = p_H|B_d^0\rangle + q_H|\bar{B}_d^0\rangle,$$
$$\mathbf{H}|B_L\rangle = \mu_L|B_L\rangle, \quad |B_L\rangle = p_L|B_d^0\rangle - q_L|\bar{B}_d^0\rangle.$$

H (L) = (High (Low) mass states

$$|\Psi_0\rangle \propto |B_L\rangle|B_H\rangle - |B_H\rangle|B_L\rangle$$
$$+\,\omega\left\{\theta\left[|B_H\rangle|B_L\rangle + |B_L\rangle|B_H\rangle\right] + (1-\theta)\frac{p_L}{p_H}|B_H\rangle|B_H\rangle - (1+\theta)\frac{p_H}{p_L}|B_L\rangle|B_L\rangle\right\}$$

ω-effect

CPTV in Hamiltonian

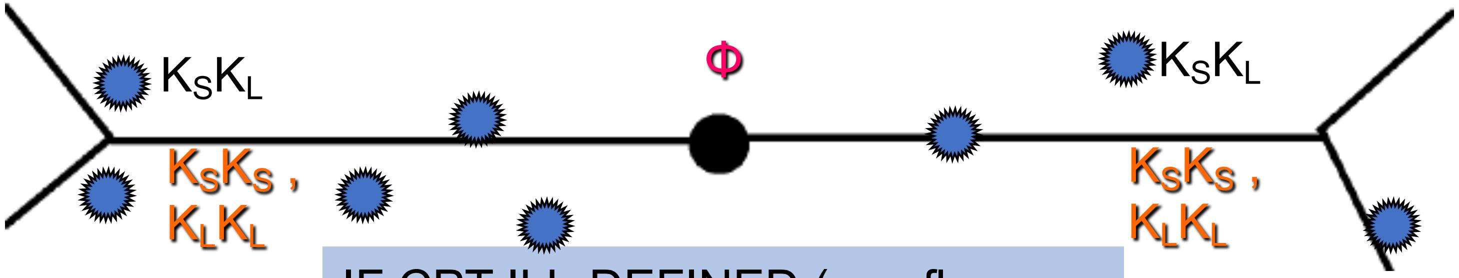
$$\theta = \frac{\mathbf{H}_{22}-\mathbf{H}_{11}}{\mu_H-\mu_L}$$

- Stringy **D-brane defects (D-) foam Models** : Neutral mesons **no** longer **indistinguishable** particles, initial entangled state:

Bernabeu, NEM, Sarkar

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

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



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

$m_L - m_S = O(10^{-15})$ GeV

$$|\omega|^2 \sim \frac{\zeta^2\, k^4}{M_{\rm QG}^2 (m_1 - m_2)^2}, \Delta k = \zeta\, k\, (\text{particle momentum transfer})$$

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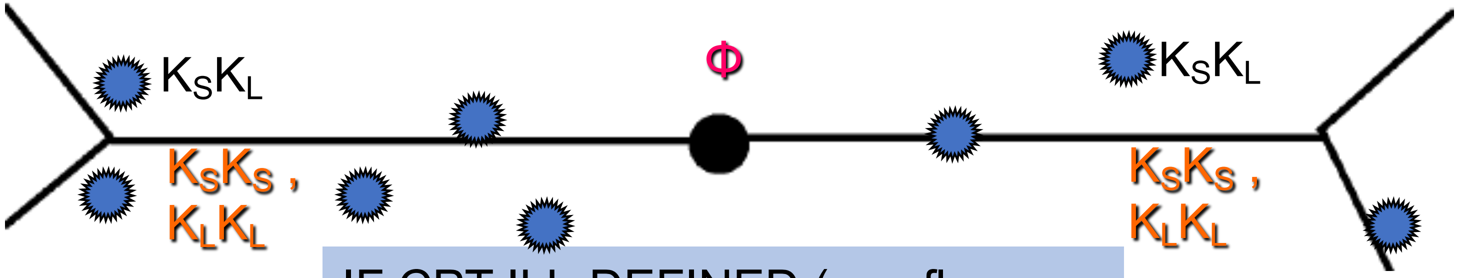

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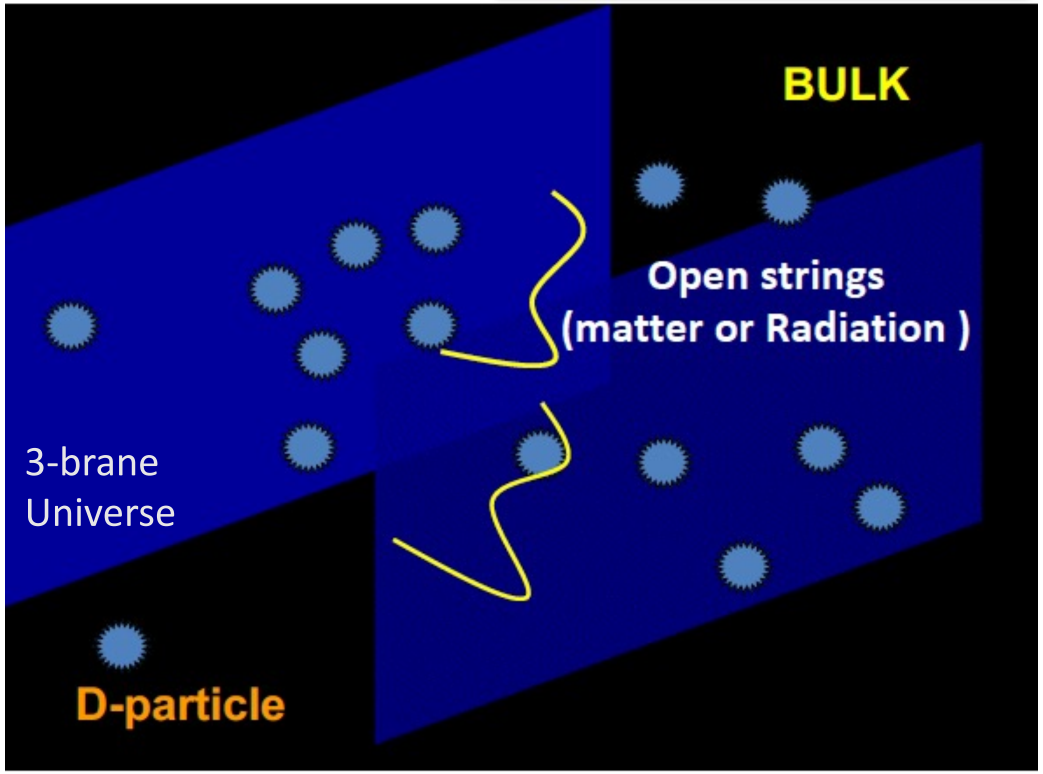
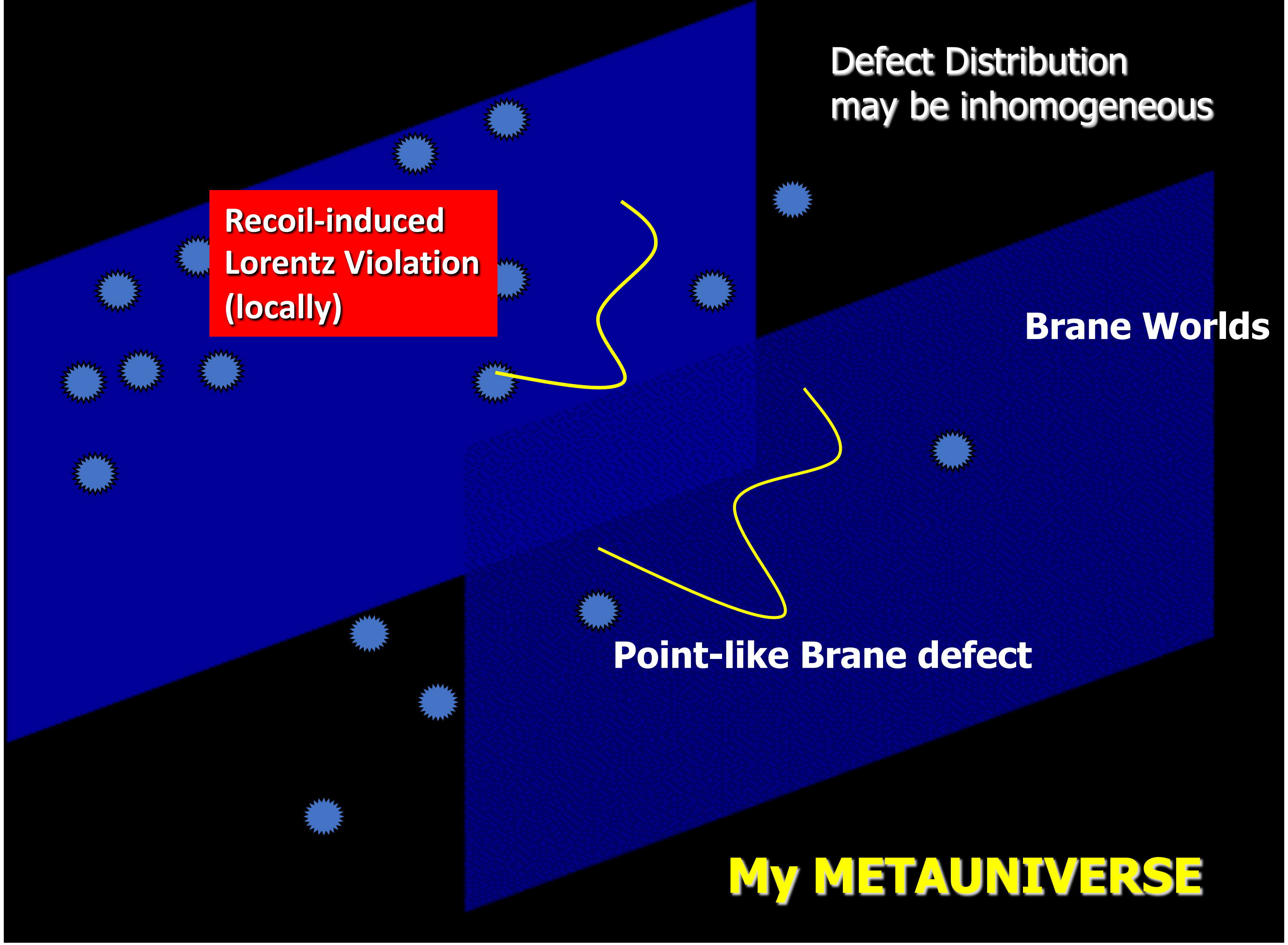
Proof

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

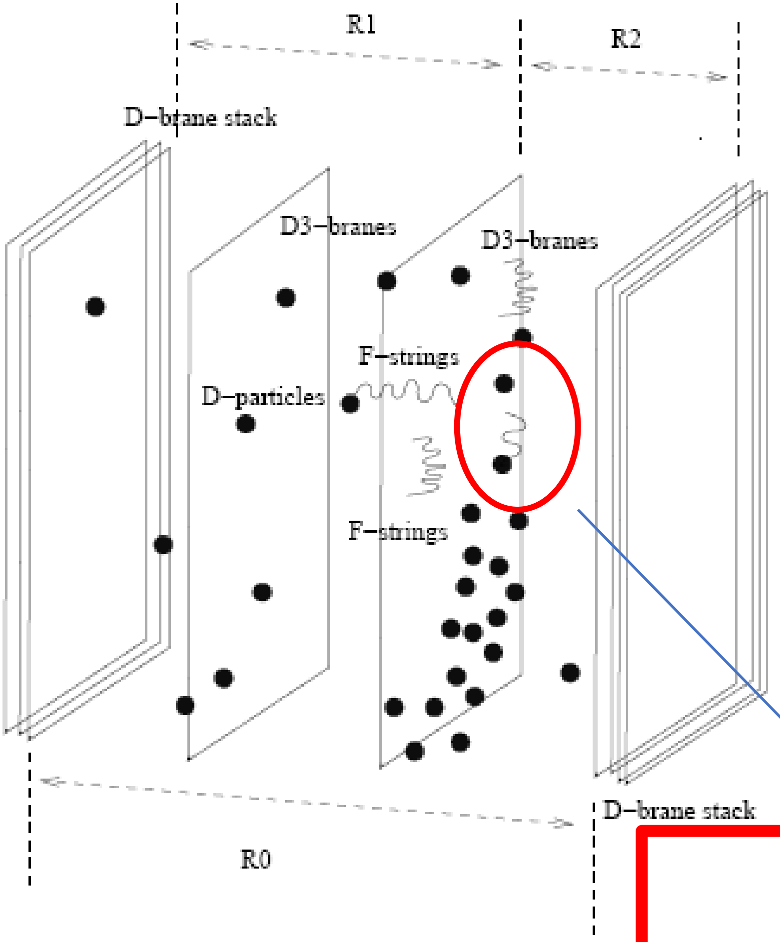
Ellis, NEM, Westmucket

Open strings can be ``captured'' by defects





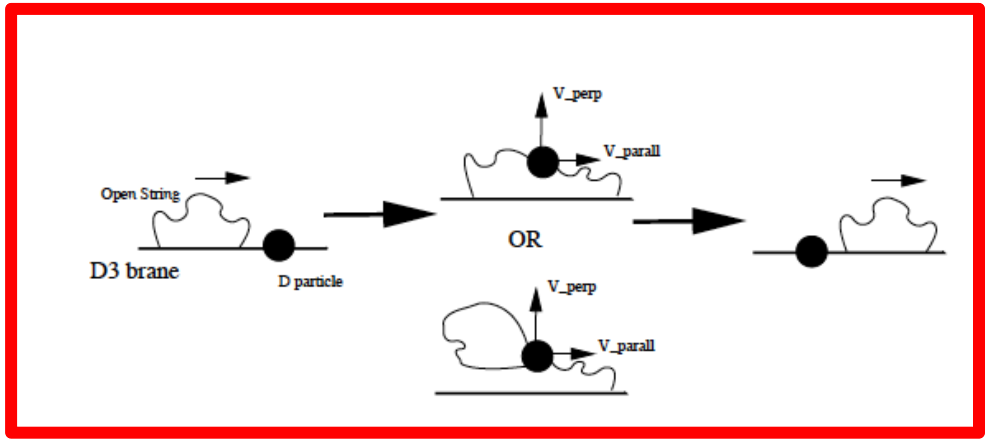
Colliding Brane world model of Space-Time with point-like space-time defects

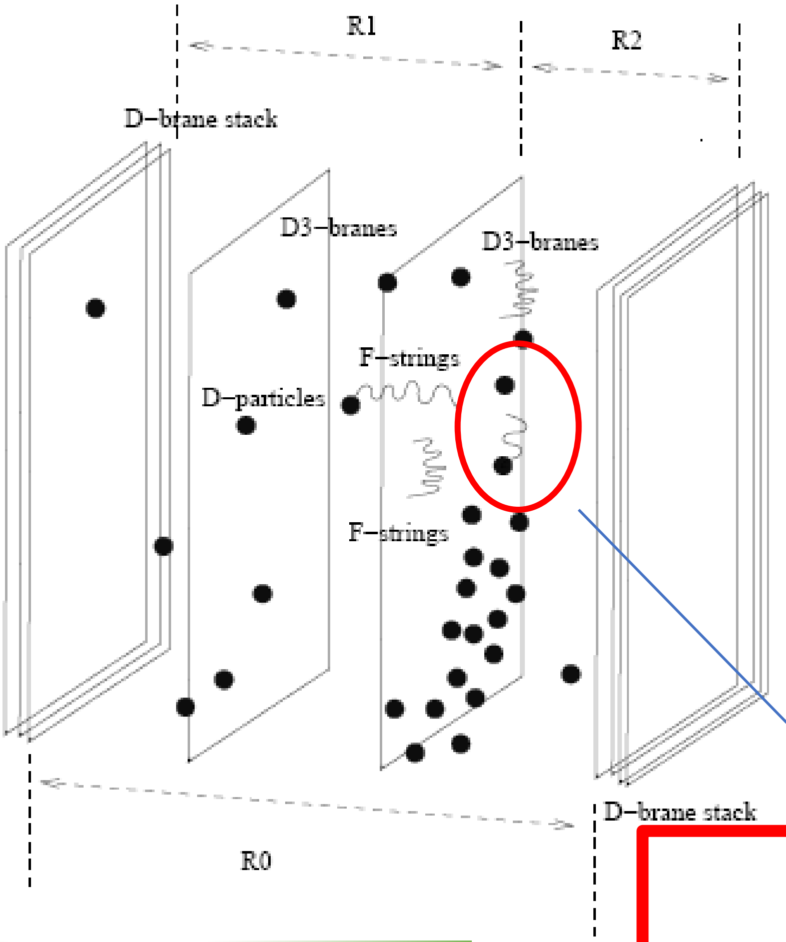


CHARGE CONSERVATION MUST BE RESPECTED DURING STRING SPLITTING, INTERNEDIATE CREATION AND STRETCHING:

ONLY ELECTRICALLY NEUTRAL EXCITATIONS INTERACT DOMINANTLY WITH FOAM

Type IIB strings: **Li, NEM, Nanopoulos, Xie** *Phys.Lett.B* 679 (2009) 407-413





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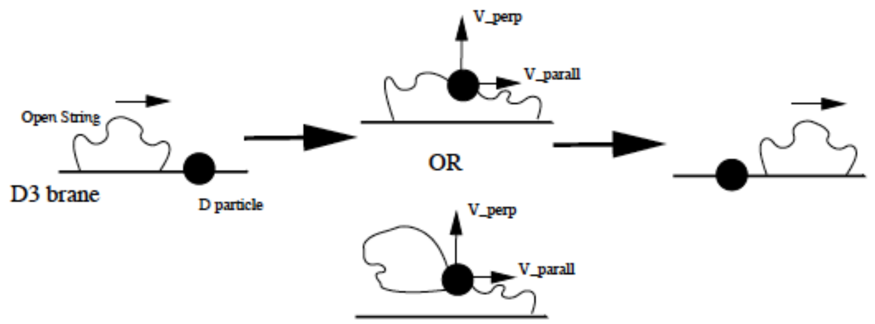


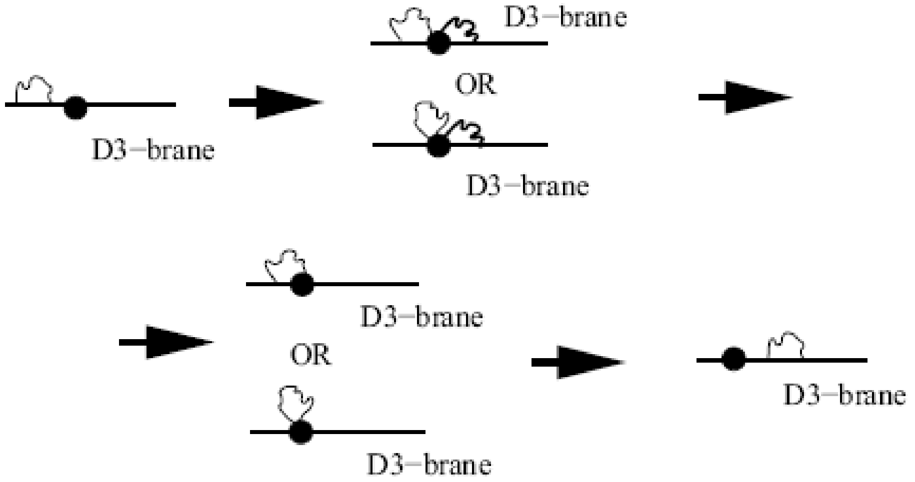
Open string Capture/recoil of brane defect is described by Logarithmic conformal theory in world-sheet of NON-CRITICAL strings (impulse RECOIL operators)

Kogan, NEM, Wheater

NB:

Stringy Uncertainties & the Capture Process

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



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

$$\boxed{\Delta t \sim \alpha' p^0}$$

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

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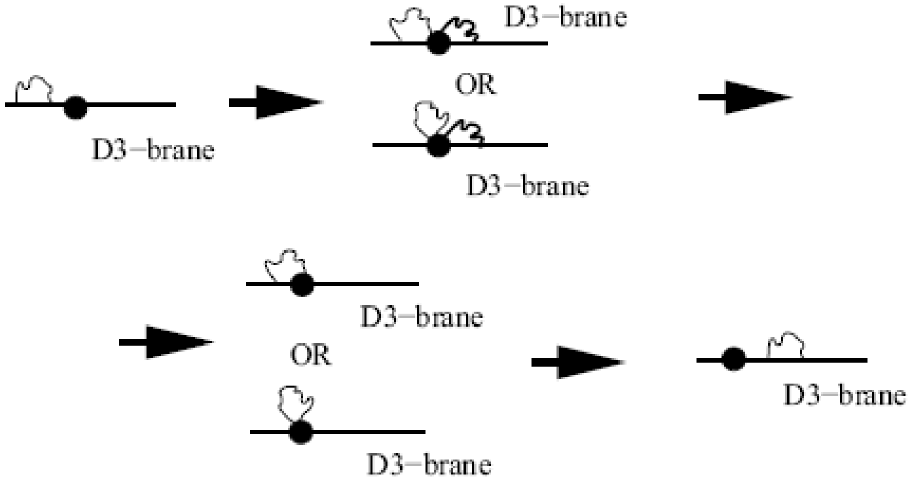

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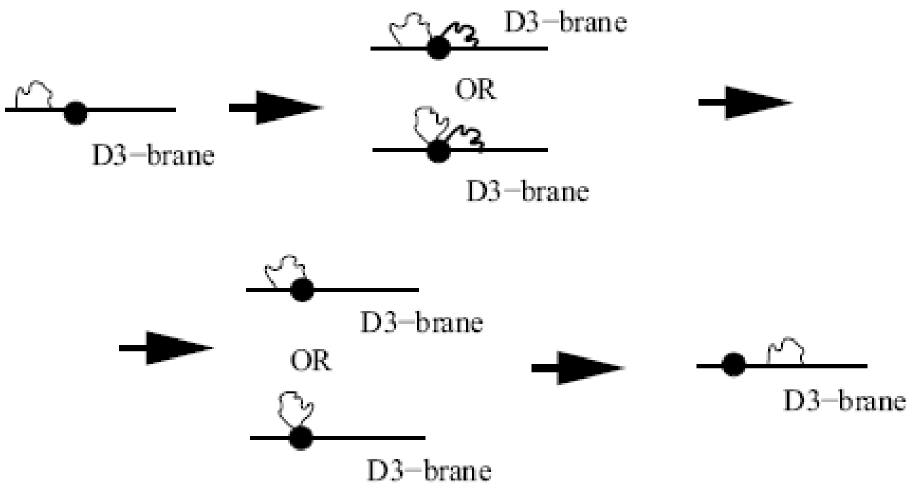

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For Very High Energy *E* Photons:

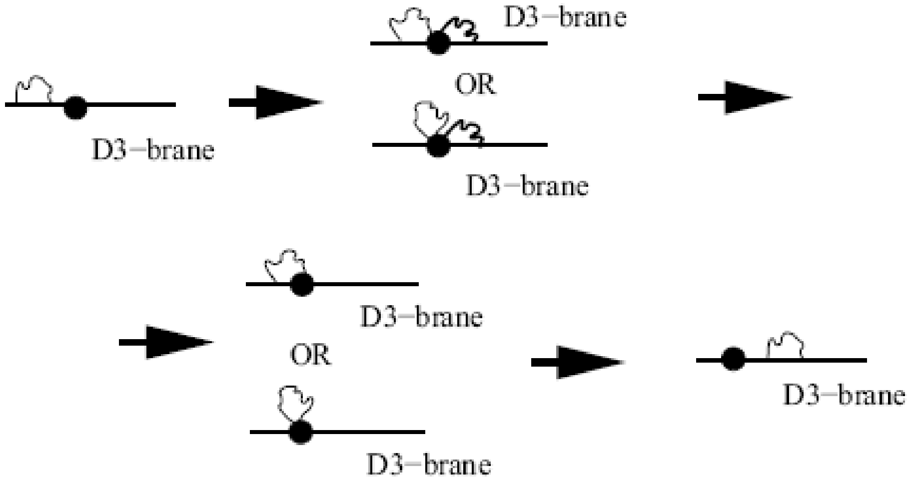
$$\Delta t \sim \frac{\alpha' \, p^0}{1 - 2\pi\alpha' \, E^2}$$

⚠

NB:

Stringy Uncertainties & the Capture Process

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



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

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

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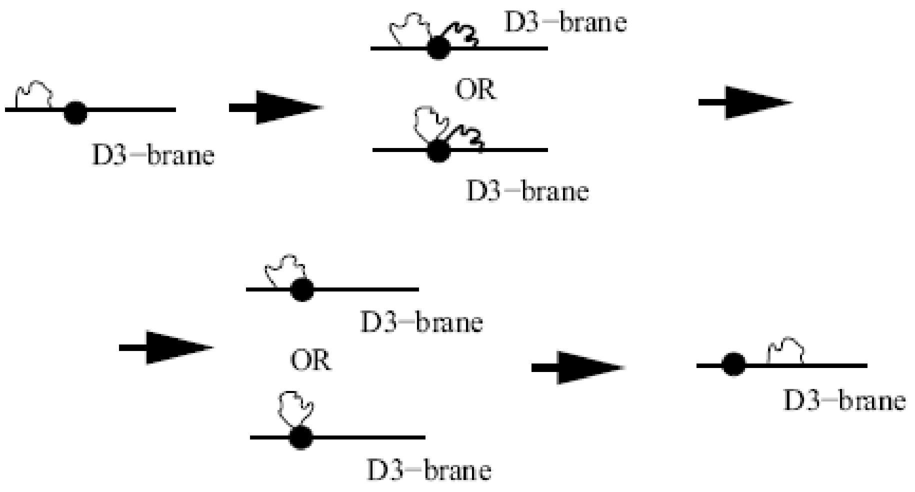

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Multimessenger Astroparticle tests of string-induced LIV

NB:

Collective Effects of D-foam medium on Stringy Uncertainties

- Time Delay (Causal) in **each** Capture: $\boxed{\Delta t \sim \alpha' p^0}$ $\quad p^0 \ll M_s$

- Independent of photon polarization (**no Birefringence**)
- **Total Delay** from emission of photons till observation over **a distance D** (assume n^* defects per string length):

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

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

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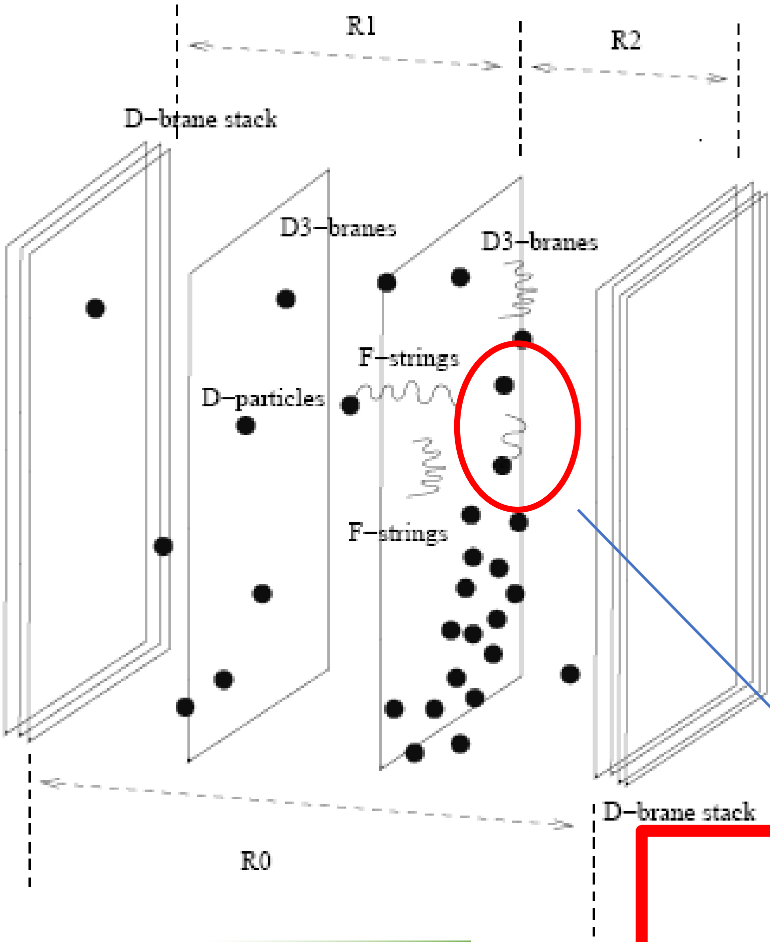
***M_{QG} inversely* Proportional to Density of Defects (details of model)**

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

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

Astrophysical constraints on defect densities



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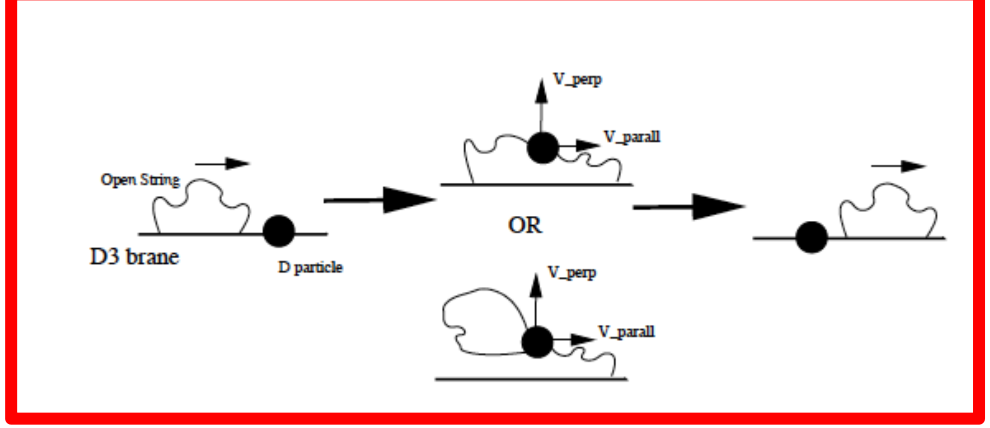


Open string Capture/recoil of brane defect is described by Logarithmic conformal theory in world-sheet of NON-CRITICAL strings (impulse RECOIL operators)

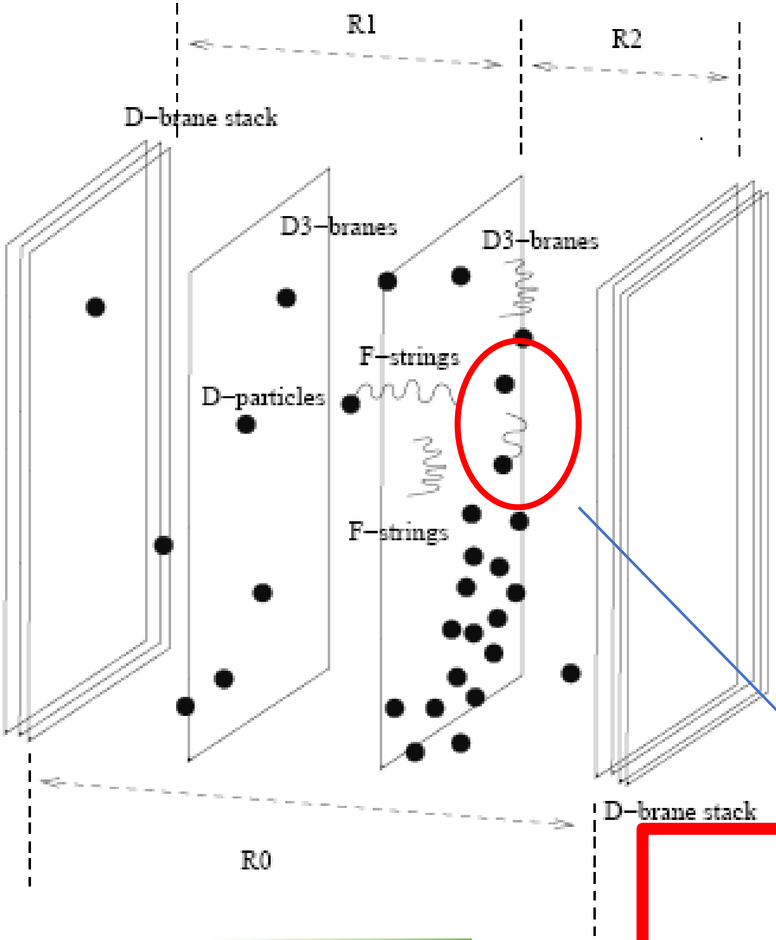
Kogan, NEM, Wheater

$\Delta\, p_i$ = momentum transfer of probe

$$h_{0i} \propto \frac{\Delta p_i}{M_s}$$

Recoil of massive quantum flct. defect distorts spacetime

$$g^{(0)}_{\mu\nu} \rightarrow g^{(0)}_{\mu\nu} + h_{\mu\nu}$$



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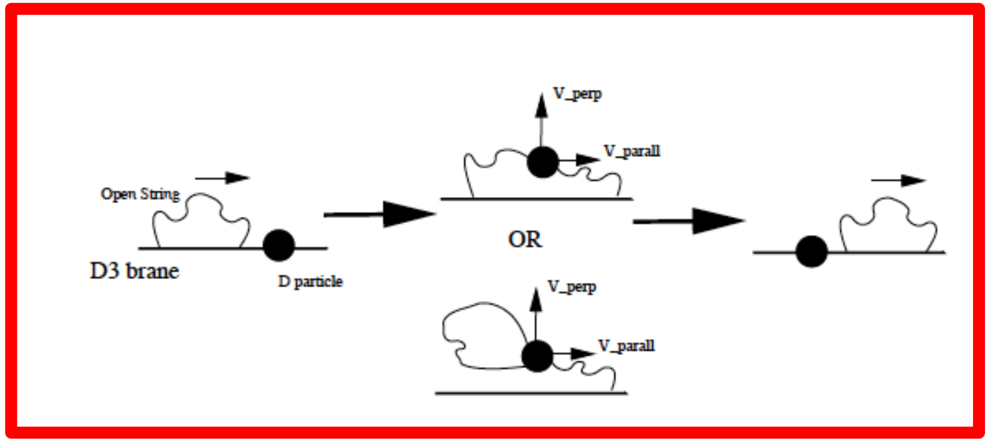

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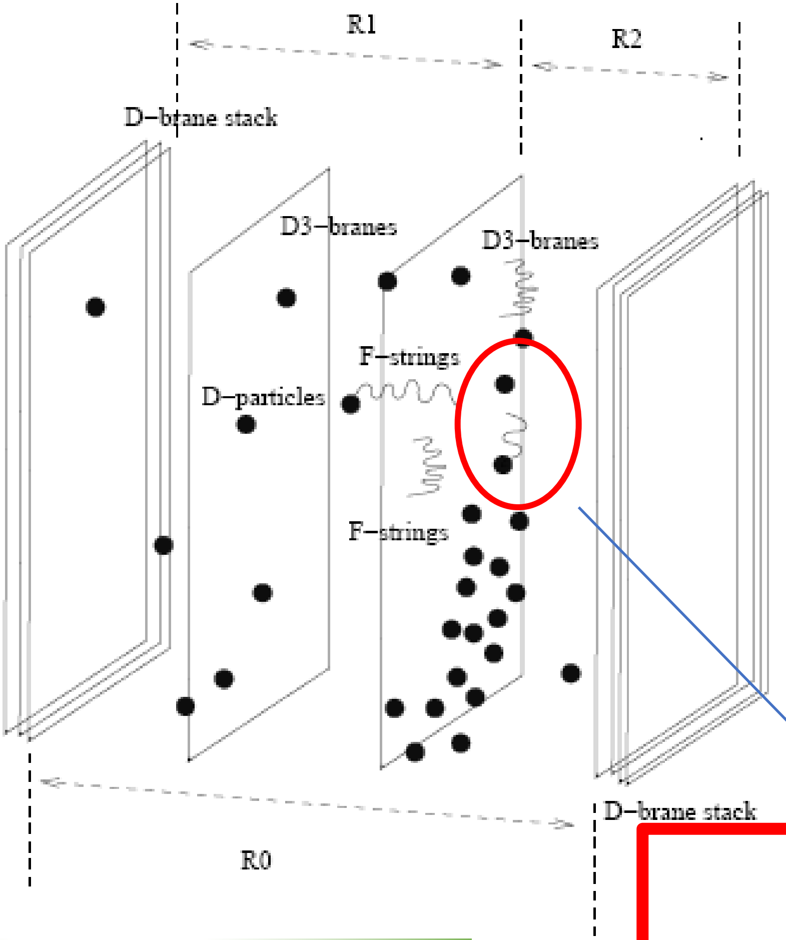
Kogan, NEM, Wheater

Recoil Allows ``flavour''flip

Recoil of massive quantum flct. defect distorts spacetime
$g^{(0)}{}_{\mu\nu} \to g^{(0)}{}_{\mu\nu} + h_{\mu\nu}$



CHARGE CONSERVATION MUST BE RESPECTED DURING STRING SPLITTING, INTERNEDIATE CREATION AND STRETCHING:

Apply to two-``flavour'' Meson systems

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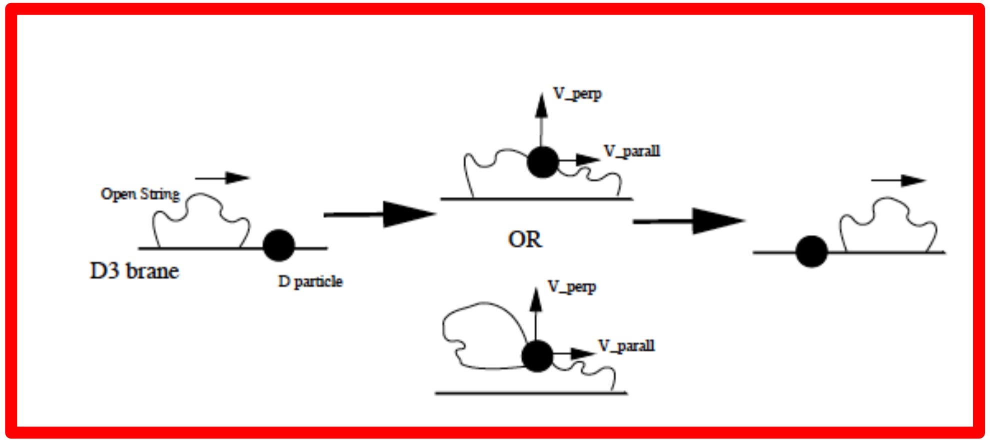

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Kogan, NEM, Wheater

Gravitating-Spin-system analogue of ω-effect

Bernaneu, NEM, Sarkar
Phys.Rev.D 74 (2006) 045014

Recoil-induced metric fluctuation during propagation (along direction 1, say) of 2-state (``**flavour**'') Boson

$$\Phi = \begin{pmatrix} \phi^{\uparrow} \\ \phi^{\downarrow} \end{pmatrix}$$

(`` Qubit '')

in interactions with a point-like space-time defect (D0-brane –particle (inspired from brane/string) theory), Involving spin-flip

$$g^{00} = (-1 + r_4)\,\mathbf{1}$$
$$g^{01} = g^{10} = r_0 \mathbf{1} + r_1\sigma_1 + r_2\sigma_2 + r_3\sigma_3$$
$$g^{11} = (1 + r_5)\,\mathbf{1}$$

r_μ, μ =0,2,…,5 stochastic variables ,

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

σ_i are the Pauli matrices

Klein-Gordon in the above **metric flct.** backrround $(g^{\alpha\beta} D_\alpha D_\beta - m^2)\Phi = 0$

$$\left(g^{00}\partial_0^2 + 2g^{01}\partial_0\partial_1 + g^{11}\partial_1^2\right)\Phi - m^2\Phi = 0$$

Initial (generic) two-boson state state (e.g. neutral meson states)

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

$\overrightarrow{k}$ to have only a non-zero component k in the x-direction

Evolution of state is governed by interaction Hamiltonian (inducing spin-flip)

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

Simplification: Dominant features of ω-εffect encapsulated in this single-particle interaction Hamiltonian

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

Perturbation theory in **Quantum Mechanics** of the states $|\psi>$

This interacting states are identified with the **``(quantum) gravitationally dressed states''**

Bernaneu, NEM, Sarkar
Phys.Rev.D 74 (2006) 045014

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

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

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

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Hence a **totally antisymmetric gravitationally dressed *initial state*** can be expressed in terms of **unperturbed single-particle states** as :

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

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\end{aligned}$$

Comparison with standard ω-effect ?

Bernabeu, NEM, Papavasssiliou (2004)

Comparison with standard ω-effect

Bernabeu, NEM, Papavasssiliou (2004)

$$|i\rangle = \mathcal{C}\left\{ \begin{array}{c} \left(\left|K_L\left(\vec{k}\right)\right\rangle \left|K_S\left(-\vec{k}\right)\right\rangle - \left|K_S\left(\vec{k}\right)\right\rangle \left|K_L\left(-\vec{k}\right)\right\rangle\right) + \\ \omega\left(\left|K_S\left(\vec{k}\right)\right\rangle \left|K_S\left(-\vec{k}\right)\right\rangle - \left|K_L\left(\vec{k}\right)\right\rangle \left|K_L\left(-\vec{k}\right)\right\rangle\right) \end{array} \right\}$$

ω- effect corresponds to $r_i \propto \delta_{i2}$ (and the generation of $\xi = -\xi'$) since $\alpha^{(i)} = \beta^{(i)}$

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

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

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ω- effect corresponds to $r_i \propto \delta_{i2}$ (and the generation of $\xi = -\xi'$) since $\alpha^{(i)} = \beta^{(i)}$

On averaging the relevant density matrix Tr (|ψ>$_{QG\,QG}$<ψ|) over the random variables r_i → only terms of order |ω|^2

$$|\omega|^2 = \mathcal{O}\left(\frac{1}{(E_1 - E_2)}(\langle\downarrow, k|H_I|k,\uparrow\rangle)^2\right) = \mathcal{O}\left(\frac{\Delta_2 k^2}{(E_1 - E_2)^2}\right) \sim \frac{\Delta_2 k^2}{(m_1 - m_2)^2}$$

$$\Delta_2 = \zeta^2 k^2 / M_P^2$$

ζ is at present a phenomenological parameter

Momentum transfer during interaction with the ``d-particle'' foam

tomography?

Analogue spin-system for ω-effect → potential role in Cryptography?
(due to modified EPR correlations)

Comparison with standard ω-effect

Bernabeu, NEM, Papavasssiliou (2004)

$$|i\rangle = \mathcal{C}\left\{ \begin{array}{l} \left(\left|K_L\left(\vec{k}\right)\right\rangle\left|K_S\left(-\vec{k}\right)\right\rangle - \left|K_S\left(\vec{k}\right)\right\rangle\left|K_L\left(-\vec{k}\right)\right\rangle\right) + \\ \omega\left(\left|K_S\left(\vec{k}\right)\right\rangle\left|K_S\left(-\vec{k}\right)\right\rangle - \left|K_L\left(\vec{k}\right)\right\rangle\left|K_L\left(-\vec{k}\right)\right\rangle\right) \end{array}\right\}$$

ω- effect corresponds to $r_i \propto \delta_{i2}$ (and the generation of $\xi = -\xi'$) since $\alpha^{(i)} = \beta^{(i)}$

On averaging the relevant density matrix Tr ($|\psi\rangle_{QG}\,{}_{QG}\langle\psi|$) over the random variables r_i

→ only terms of order $|\omega|^2$

$$|\omega|^2 = \mathcal{O}\left(\frac{1}{(E_1 - \ldots}\right) \sim \frac{\Delta_2 k^2}{(m_1 - m_2)^2}$$

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

$$\Delta_2 = \zeta^2 k^2 / M_P^2$$

ζ is at present a phenomenological parameter

Momentum transfer during interaction with the ``d-particle'' foam

tomography?

Analogue spin-system for ω-effect → potential role in Cryptography?

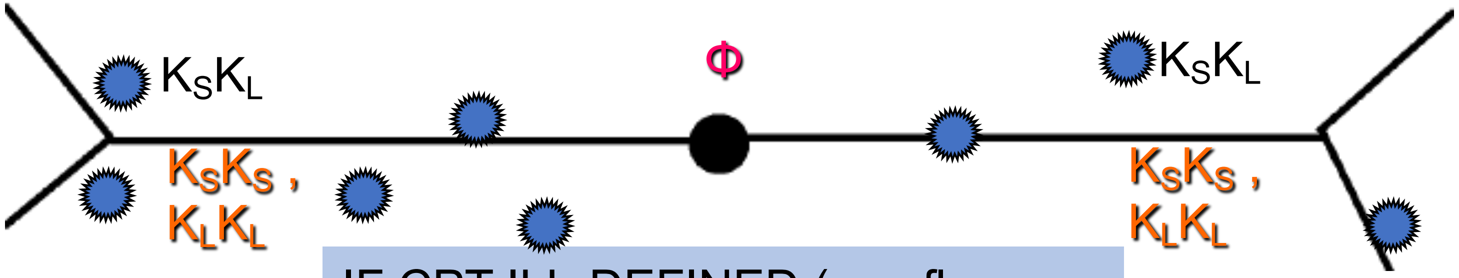
(due to modified EPR correlations)

- Stringy **D-brane defects (D-) foam Models** : Neutral mesons **no** longer **indistinguishable** particles, initial entangled state:

Bernabeu, NEM, Sarkar

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

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



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

$m_L - m_S = O(10^{-15})$ GeV

$$|\omega|^2 \sim \frac{\zeta^2 k^4}{M_{\rm QG}^2 (m_1 - m_2)^2}, \Delta k = \zeta\, k \,(\text{particle momentum transfer})$$

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

Not far from sensitivity of upgraded meson factories (e.g. **KLOE2**, **BESIII**)

Generation of the ω-terms during time evolution

Bernaneu, NEM, Sarkar
Phys.Rev.D 74 (2006) 045014

2-particle state **2-particle state**

$$|\psi(t)\rangle = \exp\left[-i\left(\widehat{H}^{(1)} + \widehat{H}^{(2)}\right)\frac{t}{\hbar}\right]|\psi\rangle$$

$$\boxed{\begin{aligned} e^{-i\widehat{H}^{(1)}t}\,|k,\uparrow\rangle^{(1)} &= e^{-i\widehat{\lambda}_0^{(1)}t}\left(\widehat{f}^{(1)}(t)\,|k,\uparrow\rangle^{(1)} - i\widehat{g}^{(1)}(t)\,|k,\downarrow\rangle^{(1)}\right) \\ e^{-i\widehat{H}^{(1)}t}\,|k,\downarrow\rangle^{(1)} &= e^{-i\widehat{\lambda}_0^{(1)}t}\left(\widehat{f}^{(1)*}(t)\,|k,\uparrow\rangle^{(1)} - i\widehat{g}^{(1)}(t)\,|k,\downarrow\rangle^{(1)}\right)\end{aligned}}$$

(hold also for states (2) upon *k* → *-k*)

$$\widehat{f}^{(j)}(t) = \cos\left(\left|\widehat{\lambda}^{(j)}\right|t\right) - i\sin\left(\left|\widehat{\lambda}^{(j)}\right|t\right)\left|\widehat{\lambda}^{(j)}\right|^{-1}\widehat{\lambda}_3^{(j)}$$

$$\widehat{g}^{(j)}(t) = \left(\widehat{\lambda}_1^{(j)} + i\widehat{\lambda}_2^{(j)}\right)\left|\widehat{\lambda}^{(j)}\right|^{-1}\sin\left(\left|\widehat{\lambda}^{(j)}\right|t\right).$$

Generation of the ω-terms during time evolution

2-particle state

2-particle state

$$|\psi(t)\rangle = \exp\left[-i\left(\widehat{H}^{(1)} + \widehat{H}^{(2)}\right)\frac{t}{\hbar}\right]|\psi\rangle$$

$$\boxed{|\psi(t)\rangle = e^{-i\left(\lambda_0^{(1)}+\lambda_0^{(2)}\right)t}\left\{\begin{array}{l} \hat{a}_{\uparrow\downarrow}(t)\,|k,\uparrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)} + \hat{a}_{\uparrow\uparrow}(t)\,|k,\uparrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} \\ +\hat{a}_{\downarrow\downarrow}(t)\,|k,\downarrow\rangle^{(1)}|-k,\downarrow\rangle^{(2)} + \hat{a}_{\downarrow\uparrow}(t)\,|k,\downarrow\rangle^{(1)}|-k,\uparrow\rangle^{(2)} \end{array}\right\}}$$

$$\hat{a}_{\uparrow\downarrow}(t) = \hat{f}^{(1)}(t)\,\hat{f}^{(2)}(t)^* + \hat{g}^{(1)}(t)^*\,\hat{g}^{(2)}(t) - i\xi_1\hat{f}^{(1)}(t)\,\hat{g}^{(2)}(t) - i\xi_2\hat{g}^{(1)}(t)^*\,\hat{f}^{(2)}(t)^*$$

$$\hat{a}_{\uparrow\uparrow}(t) = -i\hat{f}^{(1)}(t)\,\hat{g}^{(2)}(t)^* + i\hat{g}^{(1)}(t)^*\,\hat{f}^{(2)}(t) + \xi_1\hat{f}^{(1)}(t)\,\hat{f}^{(2)}(t) - \xi_2\hat{g}^{(1)}(t)^*\,\hat{g}^{(2)}(t)^*$$

$$\hat{a}_{\downarrow\downarrow}(t) = -i\hat{g}^{(1)}(t)\,\hat{f}^{(2)}(t)^* + i\hat{f}^{(1)}(t)^*\,\hat{g}^{(2)}(t) - \xi_1\hat{g}^{(1)}(t)\,\hat{g}^{(2)}(t) + \xi_2\hat{f}^{(1)}(t)^*\,\hat{f}^{(2)}(t)^*$$

$$\hat{a}_{\downarrow\uparrow}(t) = -\hat{g}^{(1)}(t)\,\hat{g}^{(2)}(t)^* - \hat{f}^{(1)}(t)^*\,\hat{f}^{(2)}(t) - i\xi_1\hat{g}^{(1)}(t)\,\hat{f}^{(2)}(t) - i\xi_2\hat{f}^{(1)}(t)^*\,\hat{g}^{(2)}(t)^*$$

Generation of the ω-terms during time evolution

2-particle state

$$|\psi(t)\rangle = \exp\left[-i\left(\widehat{H}^{(1)}+\widehat{H}^{(2)}\right)\frac{t}{\hbar}\right]|\psi\rangle$$

2-particle state

$$|\psi(t)\rangle = e^{-i\left(\lambda_0^{(1)}+\lambda_0^{(2)}\right)t}\left\{\begin{array}{l}\hat{a}_{\uparrow\downarrow}(t)\,|k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}+\hat{a}_{\uparrow\uparrow}(t)\,|k,\uparrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)}\\ +\hat{a}_{\downarrow\downarrow}(t)\,|k,\downarrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}+\hat{a}_{\downarrow\uparrow}(t)\,|k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)}\end{array}\right\}$$

Define $\varpi(t) = i\left(f^{(2)}(t)\,g^{(1)*}(t)-f^{(1)}(t)\,g^{(2)*}(t)\right)$ **&** $\varpi'(t) = i\left(f^{(1)*}(t)\,g^{(2)}(t)-g^{(1)}(t)\,f^{(2)*}(t)\right)$

From

$$\left.\begin{array}{l}\widehat{f}^{(j)}(t) = \cos\left(\left|\widehat{\lambda}^{(j)}\right|t\right)-i\sin\left(\left|\widehat{\lambda}^{(j)}\right|t\right)\left|\widehat{\lambda}^{(j)}\right|^{-1}\widehat{\lambda}_3^{(j)}\\ \widehat{g}^{(j)}(t) = \left(\widehat{\lambda}_1^{(j)}+i\widehat{\lambda}_2^{(j)}\right)\left|\widehat{\lambda}^{(j)}\right|^{-1}\sin\left(\left|\widehat{\lambda}^{(j)}\right|t\right).\end{array}\right\}\Rightarrow$$

$$\Rightarrow \varpi(t) = i\left[\left(\cos\left(\left|\lambda^{(2)}\right|t\right)-i\sin\left(\left|\lambda^{(2)}\right|t\right)\frac{\lambda_3^{(2)}}{\left|\lambda^{(2)}\right|}\right)\sin\left(\left|\lambda^{(1)}\right|t\right)\frac{\lambda_1^{(1)}-i\lambda_2^{(1)}}{\left|\lambda^{(1)}\right|}-(1\leftrightarrow 2)\right],\quad \varpi'(t)=\varpi(t)^*$$

Generation of the ω-terms during time evolution

2-particle state **2-particle state**

$$|\psi(t)\rangle = \exp\left[-i\left(\widehat{H}^{(1)} + \widehat{H}^{(2)}\right)\frac{t}{\hbar}\right]|\psi\rangle$$

$$|\psi(t)\rangle = e^{-i\left(\lambda_0^{(1)}+\lambda_0^{(2)}\right)t}\left\{\begin{array}{l} \hat{a}_{\uparrow\downarrow}(t)\,|k,\uparrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)} + \hat{a}_{\uparrow\uparrow}(t)\,|k,\uparrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} \\ +\hat{a}_{\downarrow\downarrow}(t)\,|k,\downarrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)} + \hat{a}_{\downarrow\uparrow}(t)\,|k,\downarrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} \end{array}\right\}$$

To lowest order in (weak) metric fluctuations, when $r_2 = 0$, $r_1 \neq 0$: $\mathrm{Im}\left(\varpi(t)\right) \gg \mathrm{Re}\left(\varpi(t)\right)$

$$\Rightarrow \quad \varpi(t) \sim i\cos\left(\left|\lambda^{(2)}\right|t\right)\sin\left(\left|\lambda^{(1)}\right|t\right)\left[\frac{\lambda_1^{(1)}}{\left|\lambda^{(1)}\right|} - \frac{\lambda_1^{(2)}}{\left|\lambda^{(2)}\right|}\right]$$

$$\Rightarrow \quad |\psi(t)\rangle \sim e^{-i\left(\lambda_0^{(1)}+\lambda_0^{(2)}\right)t}\varpi(t)\left\{|k,\uparrow\rangle^{(1)}\,|-k,\uparrow\rangle^{(2)} - |k,\downarrow\rangle^{(1)}\,|-k,\downarrow\rangle^{(2)}\right\}$$

$$O(\varpi) \simeq \frac{\lambda_1^{(1)}-\lambda_1^{(2)}}{\left|\lambda^{(1)}\right|} \sim 2\left(1+\Delta_4^{\frac{1}{2}}\right)\frac{\Delta_1^{\frac{1}{2}}k}{\left|\lambda^{(1)}\right|}\,, \quad \left|\lambda^{(1)}\right| \sim \left(1+\Delta_4^{\frac{1}{2}}\right)\sqrt{\chi_1^2+\chi_3^2}\,, \; \chi_3 \sim \left(k^2+m_1^2\right)^{\frac{1}{2}} - \left(k^2+m_2^2\right)^{\frac{1}{2}}$$

Generation of the ω-terms during time evolution

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$$\boxed{O(\varpi) \simeq \frac{2\Delta_1^{\frac{1}{2}}k}{(k^2+m_1^2)^{\frac{1}{2}} - (k^2+m_2^2)^{\frac{1}{2}}}\cos\left(\left|\lambda^{(1)}\right|t\right)\sin\left(\left|\lambda^{(1)}\right|t\right) = \varpi_0 \sin\left(2\left|\lambda^{(1)}\right|t\right)}$$

$$\varpi_0 \equiv \frac{\Delta_1^{\frac{1}{2}}k}{\left(k^2+m_1^2\right)^{\frac{1}{2}} - \left(k^2+m_2^2\right)^{\frac{1}{2}}}$$

Generation of the ω-terms during time evolution

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Sinusoidal time dependence of ω-effect induced by temporal evolution of the system.

Generation of the ω-terms during time evolution

2-particle state

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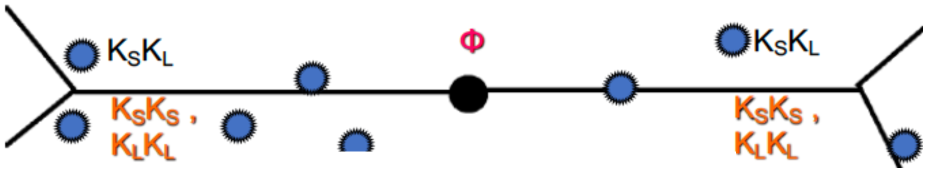
$$\Rightarrow \quad \boxed{O(\varpi) \simeq \frac{2\Delta_1^{\frac{1}{2}}k}{(k^2+m_1^2)^{\frac{1}{2}} - (k^2+m_2^2)^{\frac{1}{2}}}\cos\left(\left|\lambda^{(1)}\right|t\right)\sin\left(\left|\lambda^{(1)}\right|t\right) = \varpi_0 \sin\left(2\left|\lambda^{(1)}\right|t\right)}$$

$$\varpi_0 \equiv \frac{\Delta_1^{\frac{1}{2}}k}{\left(k^2+m_1^2\right)^{\frac{1}{2}} - \left(k^2+m_2^2\right)^{\frac{1}{2}}}$$



In D-foam models, $\Delta_1^{1/2} \sim |\zeta|\,|k|\,/\,M_{QG}$

Recapitulate: ω-effect analogue in spin sytems

- Inspired by D-particle foam models (interaction of particle probes with space-time defects)

- Perturb Hamiltonian of 2-flavour states with flavour-flip interactions of a certain type, depending on momentum transfer as a result of defect recoil, which spacetime-induced metric flcutuations

- Apply Quantum Mechanical perturbation to consider ``dressed'' interacting states
  Starting from a totally antisymmetric dressed state → ω-effect follows when express the state in terms of unperturbed states, after taking into account stochastic quantum fluctuations of recoil-induced metric

- **Two types of ω-effect: (i) in the initial state of the two entangled particles,**
  (ii) generated by time evolution, due to aforementioned Hamiltonian interactions.

NOTE : If we consider the particle states embedded in a **Thermal Bath** → **NO ω-type entangling effects** arise
(proved via use of thermal master equations)

Bernaneu, NEM, Sarkar
Phys.Rev.D 74 (2006) 045014

NB: Heat is known to destroy quantum entanglement in any case,
since thermal flcts. affect the delicate quantum correlations required
→ recent breakthrough algorithms were constructed proving ``sudden death'' of entanglement by heat
https://www.quantamagazine.org/computer-scientists-prove-that-heat-destroys-entanglement-20240828/

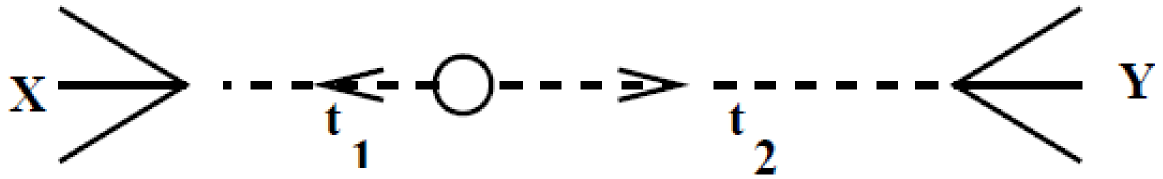
ω-effect observables/current bounds

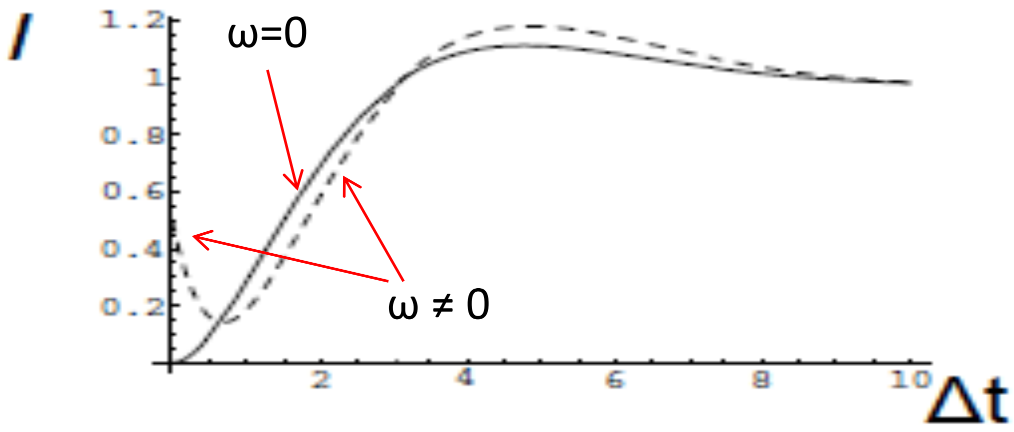
ω-effect observables/current bounds

Bernabeu, NEM, Papavassiliou (04),...

ϕ Decays and the ω Effect

Consider the ϕ decay amplitude: final state X at t_1 and Y at time t_2 ($t = 0$ at the moment of ϕ decay)





I(Δt=0) ≠ 0
if ω-effect present

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

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

ω-Effect & Intensities

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

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

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

enhancement factor due to CP violation compared with, eg, B-mesons

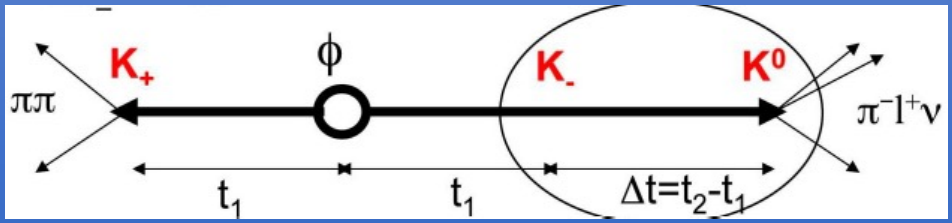
$$I_{12}(\Delta t) = -\frac{4}{4(\Delta M)^2 + (3\Gamma_S + \Gamma_L)^2}\frac{|\omega|}{|\eta_{+-}|} \times$$
$$\Big[2\Delta M \Big(e^{-\Gamma_S \Delta t}\sin(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\sin(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)$$
$$-(3\Gamma_S + \Gamma_L)\Big(e^{-\Gamma_S \Delta t}\cos(\phi_{+-} - \Omega) - e^{-(\Gamma_S+\Gamma_L)\Delta t/2}\cos(\phi_{+-} - \Omega + \Delta M \Delta t)\Big)\Big]$$

$\Delta M = M_S - M_L$ and $\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}}$.

NB: sensitivities up to $|\omega| \sim 10^{-6}$ in ϕ factories, due to enhancement by $|\eta_{+-}| \sim 10^{-3}$ factor.

Bernabeu, NEM, Papavassiliou (04),...

Old Measurements Status of ω-effect



KLOE result: PLB 642(2006) 315
Found. Phys. 40 (2010) 852

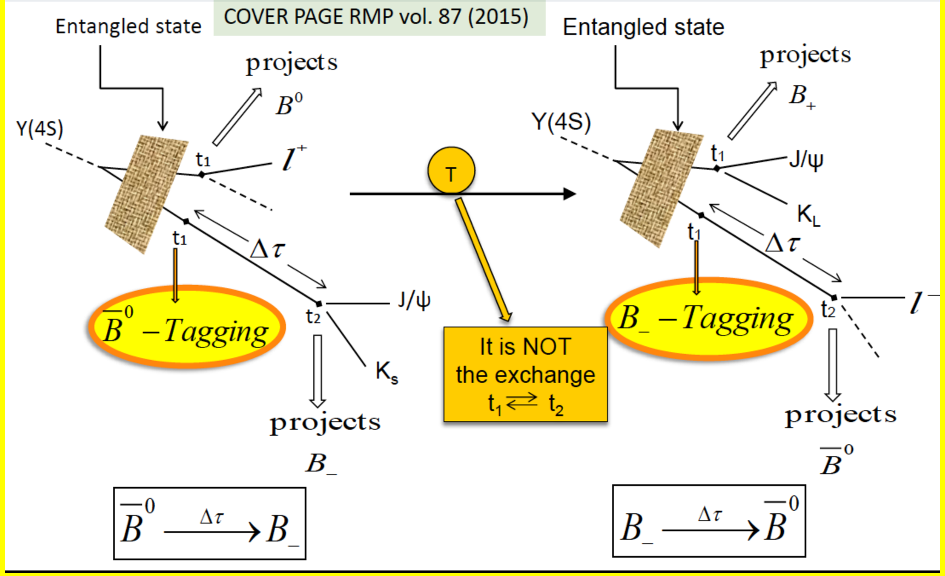
$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right)\times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right)\times 10^{-4}$$

$$|\omega| < 1.0\times 10^{-3} \quad \text{at } 95\%\ \text{C.L.}$$

Neutral Kaons

COVER PAGE RMP vol. 87 (2015)



Nautral B-mesons

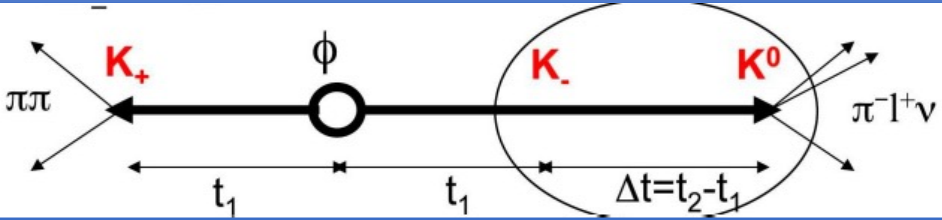
Equal Sign Dilepton Asymmetry
(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 087)

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

Novel signal from (f,g) ←→ (g,f)
(Bernabeu, Botella, NEM, Nebot,
EPJC 77 (2017) 865)

$\mathrm{Im}\,(\theta)$	$(0.99 \pm 1.98)10^{-2}$
$\mathrm{Im}\,(\omega)$	$\pm(6.40 \pm 2.80)10^{-2}$

Old Measurements Status of ω-effect



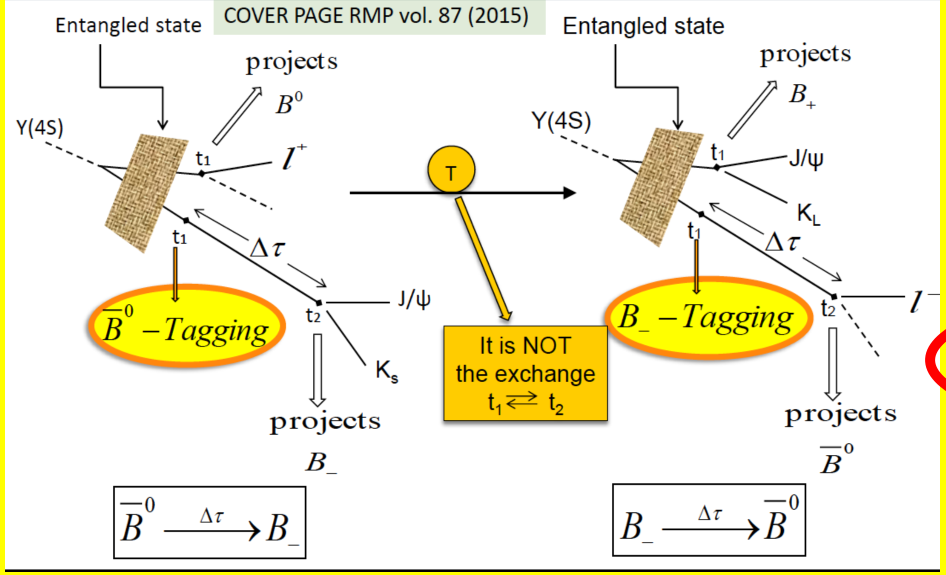
KLOE result: PLB 642(2006) 315
Found. Phys. 40 (2010) 852

$$\Re\omega = \left(-1.6^{+3.0}_{-2.1\,STAT} \pm 0.4_{SYST}\right) \times 10^{-4}$$

$$\Im\omega = \left(-1.7^{+3.3}_{-3.0\,STAT} \pm 1.2_{SYST}\right) \times 10^{-4}$$

$$|\omega| < 1.0 \times 10^{-3} \quad \text{at } 95\% \text{ C.L.}$$

Neutral Kaons



Nautral B-mesons

Equal Sign Dilepton Asymmetry
(Alvarez, Bernabeu, Nebot, JHEP 0611 (2006) 087)

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

Novel signal from (f,g) ←→ (g,f)
(Bernabeu, Botella, NEM, Nebot,
EPJC 77 (2017) 865)

$\text{Im}\,(\theta)$	$(0.99 \pm 1.98)10^{-2}$
$\text{Im}\,(\omega)$	$\pm(6.40 \pm 2.80)10^{-2}$

Bernabeu, Botella, NEM, Nebot, EPJC 77 (2017) 865)

Double Decay rate **(Approximation $\Delta\Gamma = 0$,)**

$$I(f,g;t) = \int_0^\infty \mathrm{d}t_0 \,|\langle f, t_0; g, t+t_0|T|\Psi_0\rangle|^2$$

$$I(f,g;t) = \frac{\langle\Gamma_f\rangle\langle\Gamma_g\rangle}{\Gamma} e^{-\Gamma t}\{\mathscr{C}_h^\omega[f,g] + \mathscr{C}_c^\omega[f,g]\cos(\Delta M t) + \mathscr{S}_c^\omega[f,g]\sin(\Delta M t)\}$$

$$\langle f|T|\bar{B}_d^0\rangle \equiv \bar{A}_f \qquad \langle f|T|B_d^0\rangle \equiv A_f$$

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}, \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad R_f = \frac{2\mathrm{Re}\,(\lambda_f)}{1+|\lambda_f|^2},$$

$$S_f = \frac{2\mathrm{Im}\,(\lambda_f)}{1+|\lambda_f|^2},$$

$$N_{[f,g]} = \frac{1-\delta^2}{(1+|\omega|^2)(1-\delta C_f)(1-\delta C_g)},$$

& corresponding f --> g quantities)

$$\begin{aligned}\mathscr{C}_h^\omega[f,g] = N_{[f,g]}\Big[&1 - R_f R_g + \mathrm{Re}\,(\theta)\,(C_g R_f + C_f R_g) \\ &- \mathrm{Im}\,(\theta)\,(S_f + S_g) \\ &+ \frac{1}{1+(x/2)^2}\{(2C_f + xS_f)\mathrm{Re}\,(\omega) \\ &+ (xC_f - 2S_f)R_g \mathrm{Im}\,(\omega)\}\Big],\end{aligned} \qquad (15)$$

$$\begin{aligned}\mathscr{C}_c^\omega[f,g] = N_{[f,g]}\Big[&-(C_f C_g + S_f S_g) \\ &- \mathrm{Re}\,(\theta)\,(C_g R_f + C_f R_g) \\ &+ \mathrm{Im}\,(\theta)\,(S_f + S_g) \\ &+ \frac{1}{1+(x/2)^2}\{-(2C_g + xS_g)\mathrm{Re}\,(\omega) \\ &+ (-xC_g + 2S_g)R_f \mathrm{Im}\,(\omega)\}\Big],\end{aligned}$$

$$\begin{aligned}\mathscr{S}_c^\omega[f,g] = N_{[f,g]}\Big[&(C_g S_f - C_f S_g) \\ &+ \mathrm{Re}\,(\theta)\,(R_g S_f - R_f S_g) \\ &+ \mathrm{Im}\,(\theta)\,(C_f - C_g) \\ &+ \frac{1}{1+(x/2)^2}\{(xC_g - 2S_g)\mathrm{Re}\,(\omega) \\ &- (2C_g + xS_g)R_f \mathrm{Im}\,(\omega)\}\Big],\end{aligned}$$

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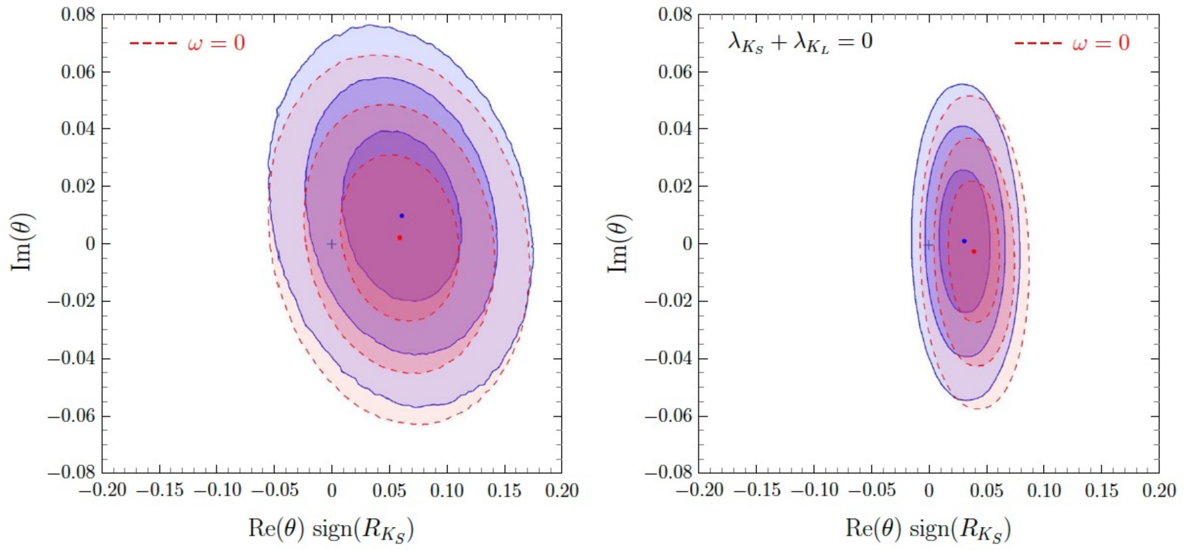
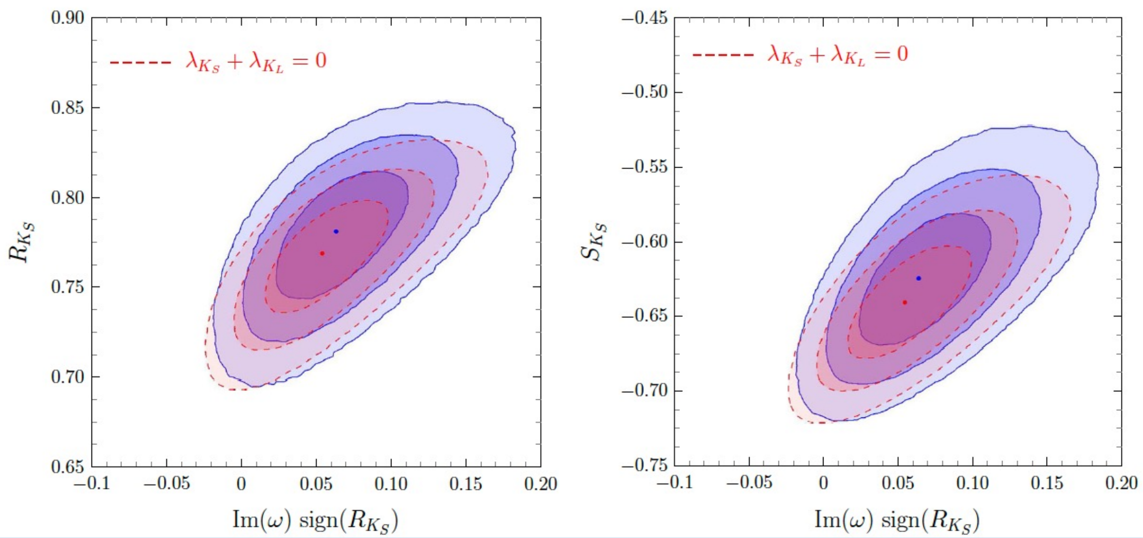
& corresponding f --> g quantities)

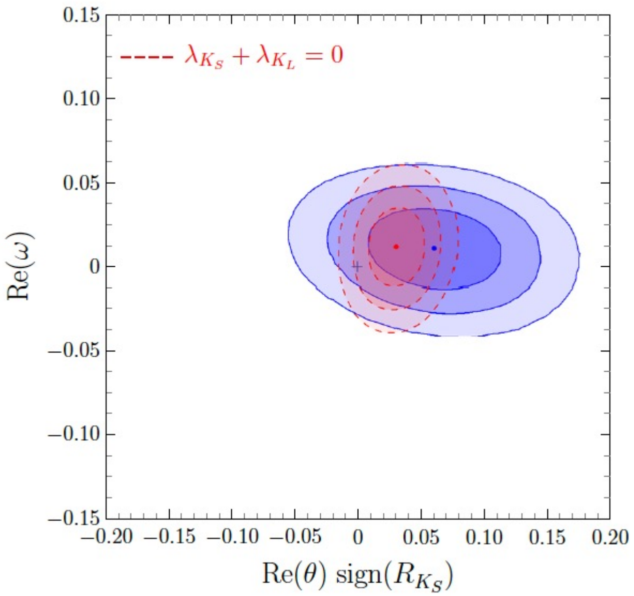
$$\langle f, t_0; g, t+t_0 | T | \Psi_0 \rangle \propto \mathrm{e}^{(-iM - \Gamma/2)(2t_0 + t)} \begin{pmatrix} [\mathrm{e}^{-i\Delta\mu t/2} A_f^L A_g^H - \mathrm{e}^{i\Delta\mu t/2} A_f^H A_g^L] \\ +\omega\theta [\mathrm{e}^{-i\Delta\mu t/2} A_f^L A_g^H + \mathrm{e}^{i\Delta\mu t/2} A_f^H A_g^L] \\ +\omega(1-\theta) \frac{p_L}{p_H} \mathrm{e}^{-i\Delta\mu (t_0 + t/2)} A_f^H A_g^H \\ -\omega(1+\theta) \frac{p_H}{p_L} \mathrm{e}^{i\Delta\mu (t_0 + t/2)} A_f^L A_g^L \end{pmatrix}.$$

Bernabeu, Botella, NEM, Nebot,
EPJC 77 (2017) 865)

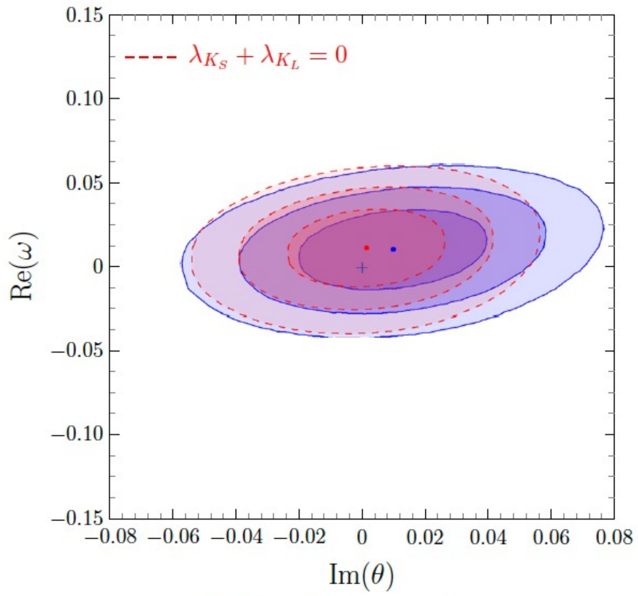


(a) Complete fit. **(b)** Restricted.

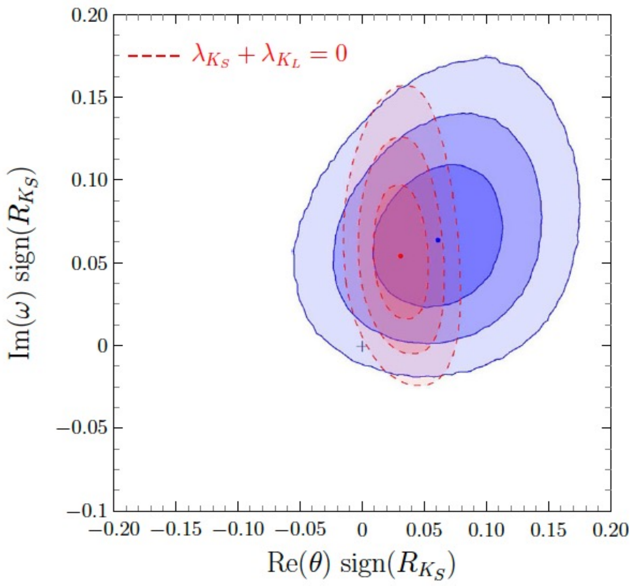




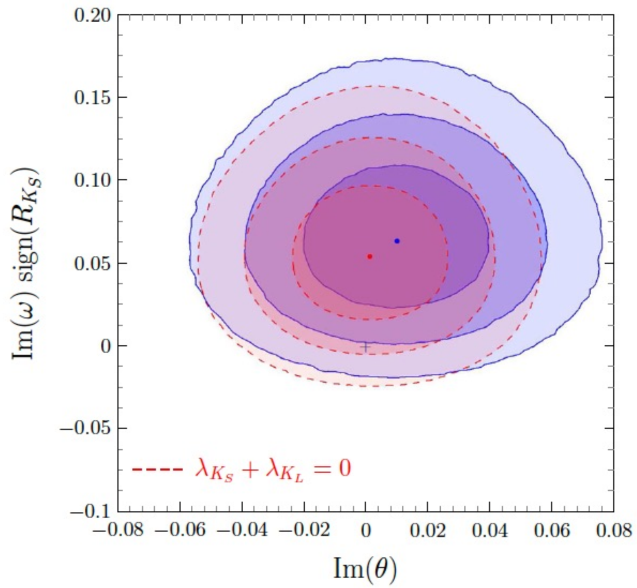
(a) $\mathrm{Re}(\omega)$ vs. $\mathrm{Re}(\theta)$.



(b) $\mathrm{Re}(\omega)$ vs. $\mathrm{Im}(\theta)$.

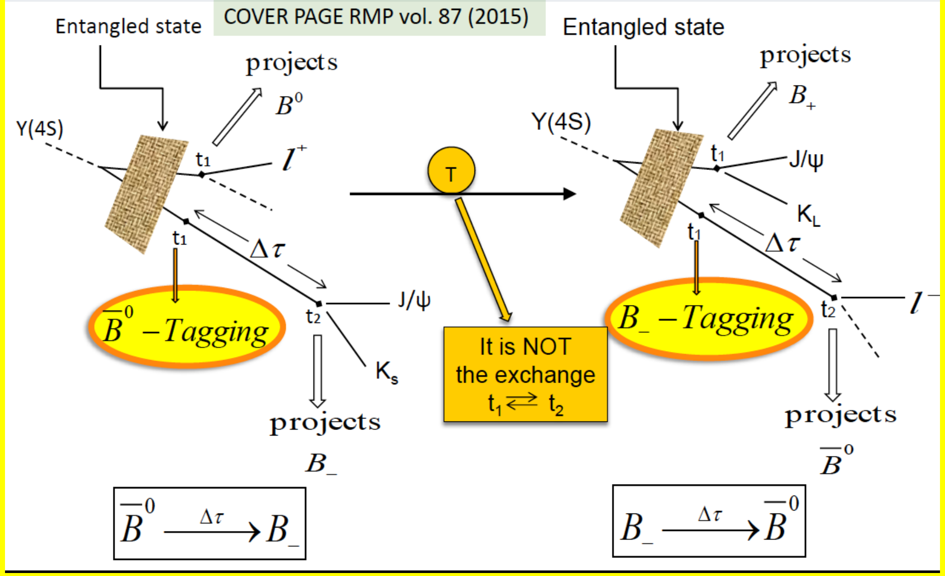


(c) $\mathrm{Im}(\omega)$ vs. $\mathrm{Re}(\theta)$.



(d) $\mathrm{Im}(\omega)$ vs. $\mathrm{Im}(\theta)$.

Old Measurements Status of ω-effect



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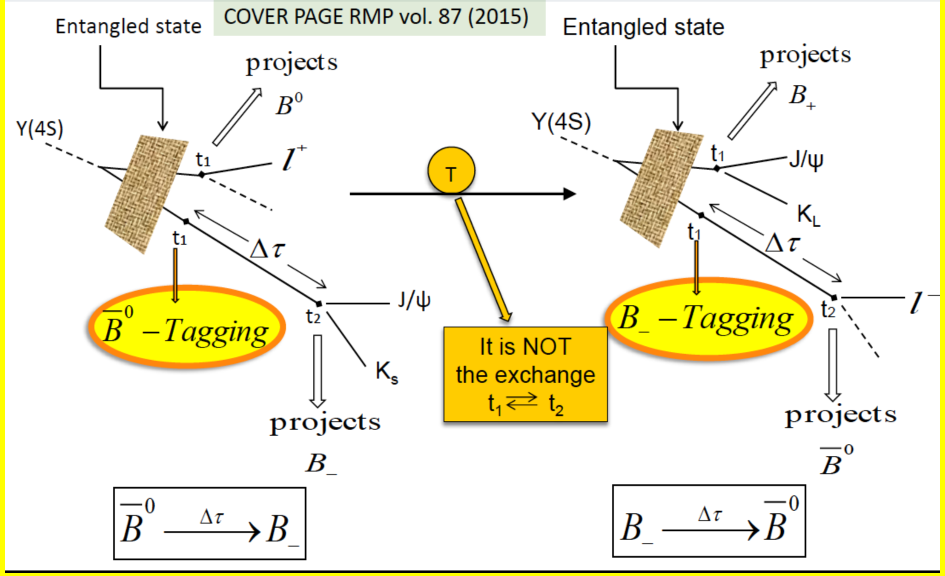

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(Bernabeu, Botella, NEM, Nebot,

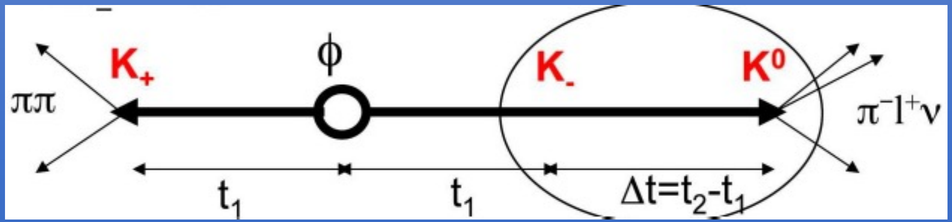
EPJC 77 (201[illegible])

$\mathrm{Im}\,(\theta)$	[illegible]$.99 \pm 1.98)10^{-2}$
$\mathrm{Im}\,(\omega$[illegible]	$\pm(6.40 \pm 2.80)10^{-2}$

Quality of data issue

Current Measurements Status of ω-effect

cf. A. Di Domenico 's talk



Neutral Kaons

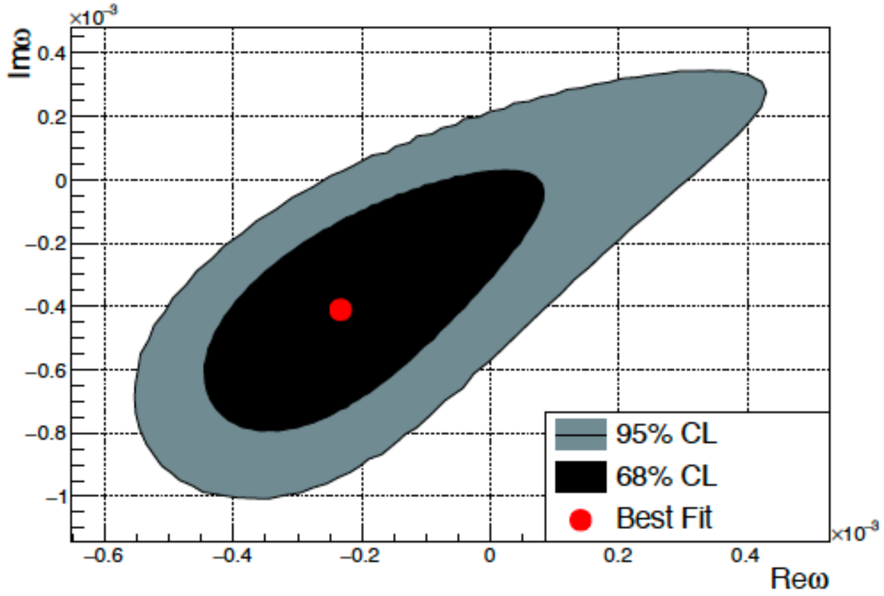
KLOE 2 result

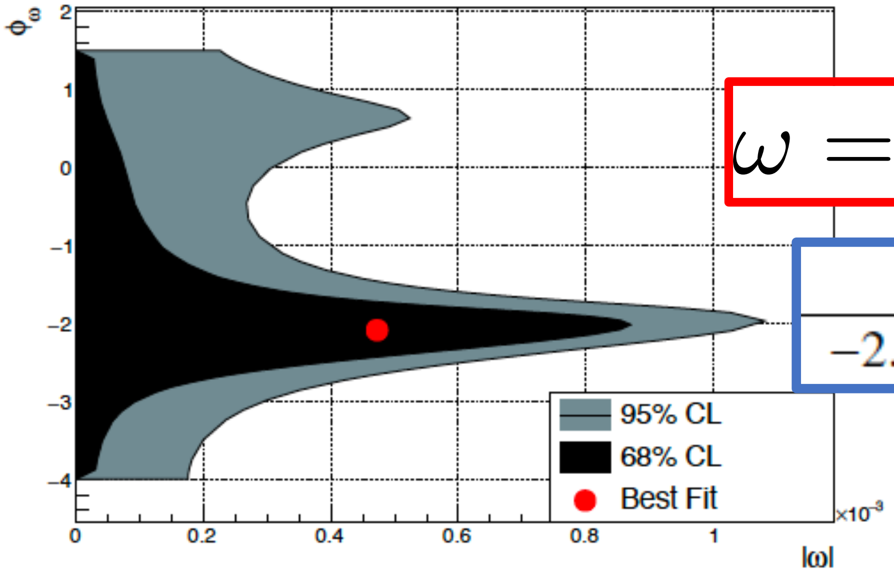
PoS DISCRETE2022(2024) 066
JHEP04 (2022) 169

$$\Re\omega = \left(-2.3^{+1.9}_{-1.5} \pm 0.7\right)\times 10^{-4}$$

$$\Im\omega = \left(-4.1^{+2.8}_{-2.6} \pm 4.9\right)\times 10^{-4}$$

$$|\omega| < (4.7 \pm 2.9 \pm 1.0)\times 10^{-4} \;@\, 95\%\ \mathrm{C.L.}$$





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

ϕ_ω (rad)
$-2.1 \pm 0.2 \pm 0.1$

Current Measurements Status of ω-effect

M. Ablikim *et al.* [BESIII], [arXiv:2504.13771 [hep-ex]].

Search for $J/\psi \to K_S^0 K_S^0$ and $\psi(3686) \to K_S^0 K_S^0$ (CP Violating decays)
BESIII detector.

Upper limits experimental results:

$\mathcal{B}(J/\psi \to K_S^0 K_S^0) < 4.7 \times 10^{-9}$ $\quad |\omega| < (4.91 \pm 0.14) \times 10^{-3}$

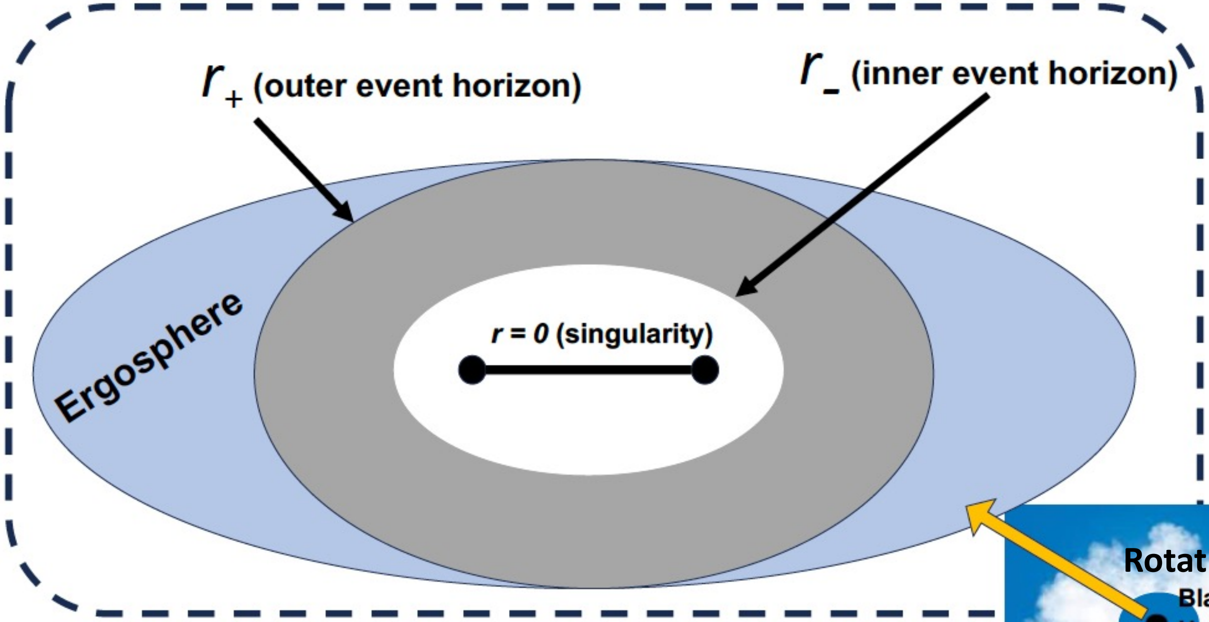
$\mathcal{B}(\psi(3686) \to K_S^0 K_S^0) < 1.1 \times 10^{-8}$ $\Rightarrow$ $|\omega| < (1.44 \pm 0.04) \times 10^{-2}$

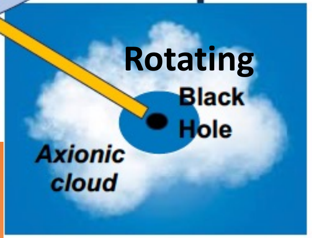
Compilation of such measurements can be used to restrict the ω-effect , and, through this, the parameters of the (stringy) D-foam Models $M_{QG} = M_s/n^*$, ζ *etc*, and combination with constraints on these parameters from multimessenger astroparticle measurements can provide complementary information

Part II

A way of detecting (squeezed) Quantum Gravitons

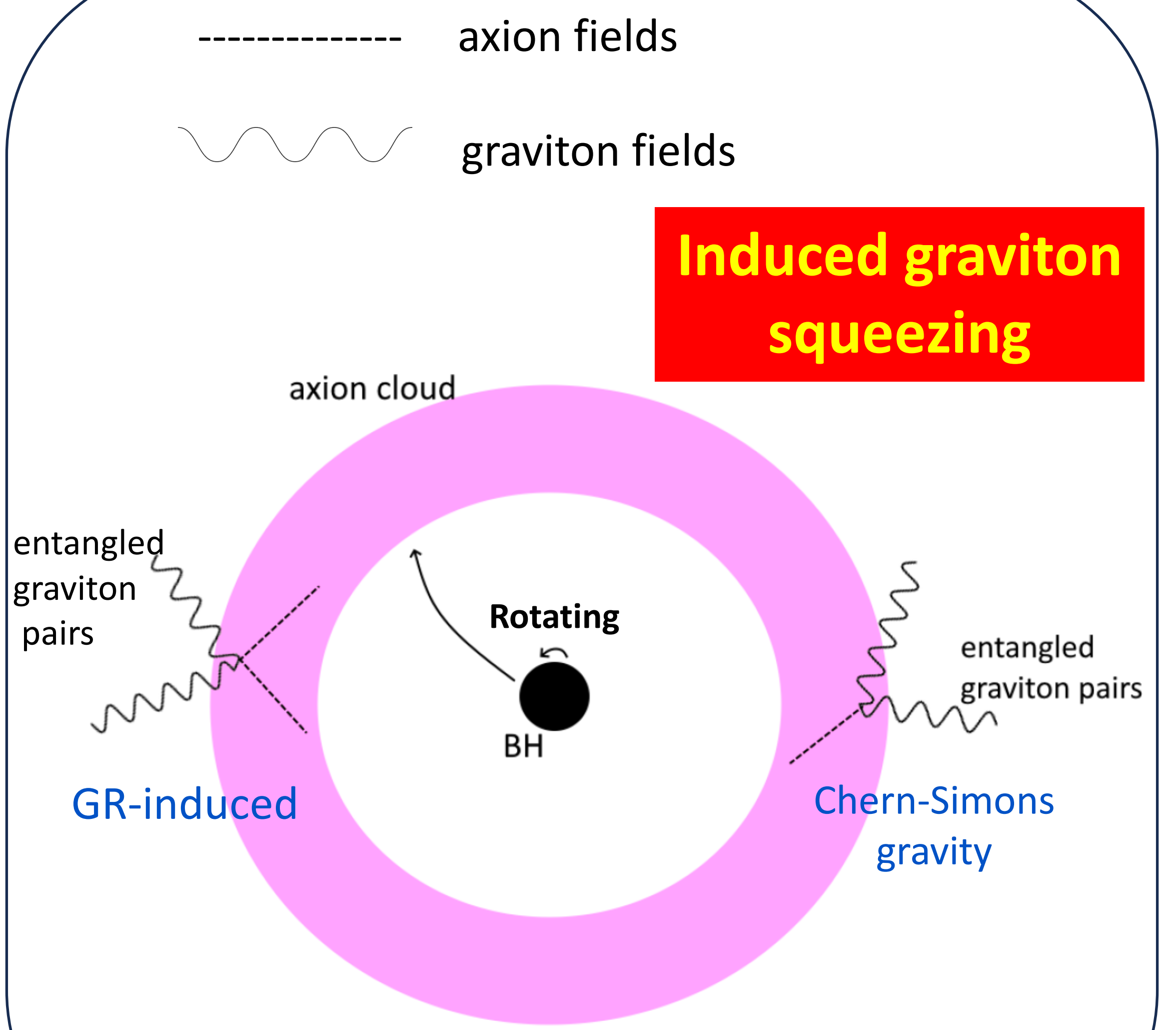
Entangled states of gravitons in axionic clouds of rotating Black Holes





Superradiant instability of rotating black holes (BH) → amplifies incoming waves, extracting energy & angular momentum from the BH → formation of massive-axion (condensate-like) clouds

Review: Brito, Cardoso, Pani
Lect. Notes. Phys. 906, 1 (2015)



Induced graviton squeezing

Dorlis, NEM, Sarkar, Vlachos
arXive [2507.01689](https://arxiv.org/abs/2507.01689) [gr-qc]

Axions ($b(x)$) exist in string theory: model independent axions, but also compactification axions

Non-trivial Chern-Simons (CS) gravitational anomalies in Rotating-Black-Holes background

$$S_{CS} = -\frac{A}{4}\int d^4x\sqrt{-g}\;\; b\;\; \underbrace{R_{\mu\nu\rho\sigma}\widetilde{R}^{\nu\mu\rho\sigma}}_{R_{CS}}$$

Campbell, Duncan, Kaloper, Olive
Phys. Lett. B 251 (1990), 34;
Nucl. Phys. B351 (1991), 778,

Jackiw, Pi

Phys.Rev.D 68 (2003) 104012

Svrcek, Witten,
JHEP 06 (2006) 051
hep-th/0605206 [hep-th]

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Cf. analogy with Chiral Gauge (e.g. U(1)) Anomalies

$$S_{b-A} = \frac{1}{f_b}\int d^4x\sqrt{-g}\, b(x)\, F_{\mu\nu}(A)\, \widetilde{F}^{\mu\nu}(A)$$

$$\Rightarrow\; \frac{2}{f_b}\int d^4x\sqrt{-g}\, b(x)\, \vec{E}\cdot\vec{B}$$

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Adding this coupling to GR-axion-b action

$$S = \int d^4x\,\sqrt{-g}\,\left[\frac{R}{2\kappa^2} - \frac{1}{2}(\partial_\mu b)(\partial^\mu b) - \frac{1}{2}\mu_b^2\; b^2 - A\,b\,R_{CS}\right]$$

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Massive Axions

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Non-conservation of b stress-energy tensor !

$$\nabla^\mu T^b_{\mu\nu} \propto A R_{CS}\,(\partial_\nu b) \neq 0$$

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Exchange of energy between axion and Gravitational Anomaly terms →
Diffeomorphism invariance of theory is OK !

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Axion-Cloud regions far away from BH Horizons → Minkowski spacetime approximation

$$\eta_{\mu\nu} \to \eta_{\mu\nu} + \kappa h_{\mu\nu},\; \kappa h_{\mu\nu} \ll 1$$

$$\left.\begin{aligned} S^{(1)} &= \frac{\kappa}{2}\int d^4x\; h_{ij}T^{ij}\;, \\ S^{(2)} &= -\frac{\kappa^2}{2}\int d^4x\; h_{im}h^m_{\;\;j}\;\partial^i b\,\partial^j b\;, \end{aligned}\right\}\text{GR terms}$$

$$S^{(2)}_{CS} = -A\kappa^2\int d^4x\; b(x)\epsilon_{ijk}\left(\partial_l\partial^k h^j_{\;m}\partial^m \dot{h}^{li} + \ddot{h}^{li}\partial^k \dot{h}^j_{\;l} - \partial_m\partial^k h^j_{\;l}\partial^m \dot{h}^{li}\right)$$

CS anomaly terms

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Weak Quantum Graviton formalism

$$\hat{h}_{ij}(t,\vec{x}) = M_{\rm Pl} \sum_{\vec{k},\lambda} f_k \left[e^{(\lambda)}_{ij}(\vec{k}) \hat{\alpha}^\dagger_{\lambda,\vec{k}}\ e^{-ik\cdot x} + h.c.\right]$$

$$[\hat{\alpha}_{\lambda,\vec{k}}, \hat{\alpha}^\dagger_{\lambda',\vec{k}'}] = \delta_{\lambda\lambda'}\delta_{\vec{k}\vec{k}'} \qquad e^{*(\lambda)}_{ij} e^{ij}_{(\lambda')} = 2\delta_{\lambda\lambda'}$$

$$\lambda = L, R$$

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Coherent gravitons

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$\Big\}$ GR terms

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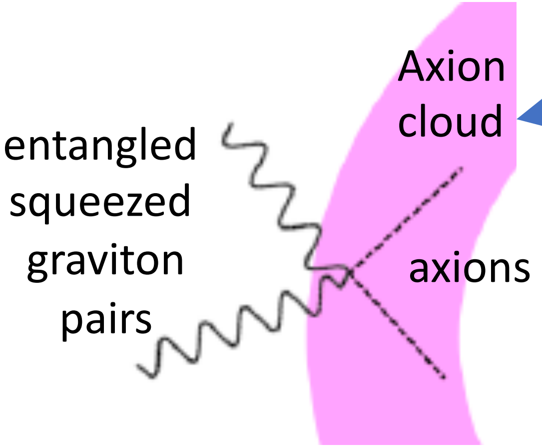
CS anomaly terms

Quantum Optics Analogue: Spontaneous Four-wave Mising (SFWM)



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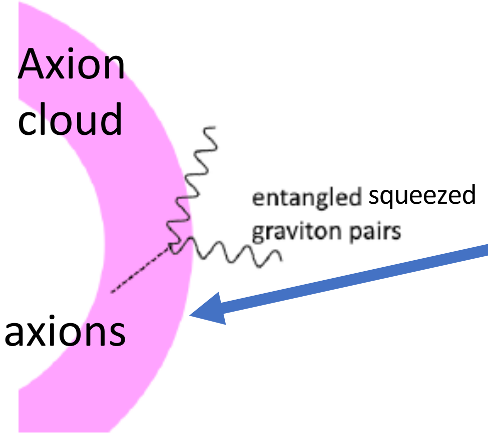
CS anomaly terms



Quantum Optics Analogue:
Spontaneous Parametric Down-Conversion (SPDC)

Multimode Squeezed graviton States

Dorlis, NEM, Sarkar, Vlachos
arXive 2507.01689 [gr-qc]

Evolution operator has the form of multimode squeezed operator

$$\hat{S} = \exp\left[\frac{1}{2}\sum_{I,J}\mathcal{G}_{IJ}\ \hat{\alpha}^\dagger_I\hat{\alpha}^\dagger_J - h.c.\right]$$

$$J, I = (\lambda, \vec{k})$$

Graviton states

$$\mathcal{G}_{IJ} = -2\ i\ \mathcal{F}_{IJ}\ T\ \mathrm{sinc}\left[(\Omega_k + \Omega_{k'} - E)\,\frac{T}{2}\right]$$

T = life time of cloud

$$T\mathrm{sinc}\left[(\Omega_k + \Omega_{k'} - E)\,(T/2)\right] \overset{T\to\infty}{=} \delta\,(\Omega_k + \Omega_{k'} - E)$$

Hence,

$$\hat{S}^\dagger\hat{\alpha}_I\hat{S} = \sum_J(\mu_{IJ}\hat{\alpha}_J + \nu_{IJ}\hat{\alpha}^\dagger_J)\ ,$$

$$\mu_{IJ} = \delta_{IJ} + \frac{1}{2!}\sum_M \mathcal{G}_{IM}\mathcal{G}^\star_{MJ}\ +\ \ldots\ ,$$

$$\nu_{IJ} = \mathcal{G}_{IJ} + \frac{1}{3!}\sum_{M,L}\mathcal{G}_{IM}\mathcal{G}^\star_{ML}\mathcal{G}_{LJ}\ +\ \ldots\ .$$

Number of squeezed graviton states

$$\boxed{\langle N_{gr}\rangle = \sum_{I,J}\left|\nu_{IJ}\right|^2 \lesssim \sum_{I,J}\left(\left|\mathcal{G}_{IJ}\right|^2\ +\ \ldots\right)}$$

Graviton-Squeezing GR terms

$$\frac{d^2}{d\Omega d\Omega'}\sum_{I,J}\left|(\mathcal{G}^{(GR)}_{IJ})\right|^2 = \frac{1}{128\pi^3}\left(\frac{\mu_b}{M_{\rm Pl}}\right)^4 N_{2p}^2\, T\mu_b$$

$$\times \sum_{\lambda,\lambda'}\int d\tilde{k}d\tilde{k}'\ \tilde{k}\tilde{k}'\delta\left(\tilde{k}+\tilde{k}'-2\right)\left|\widetilde{\mathcal{I}}^{(GR)}_{(\lambda,\vec{k})(\lambda',\vec{k}')}\right|^2 ,$$

$\tilde{k}^{(\prime)} = k^{(\prime)}/\mu_b$ and $\mathcal{I} = \widetilde{\mathcal{I}}/\mu_b^2$ **Axion mass: μ_b**

$$\boxed{\sum_{I,J}|\mathcal{G}^{(GR)}_{IJ}|^2 \lesssim 2.5\times 10^{-15}\, T\mu_b}$$

NB: Entangled 2-graviton state

$$\boxed{|\Psi_{GR}\rangle = \frac{1}{2}\left(\mathcal{G}^{(GR)}_{(R,\vec{k})(L,\vec{k}')}|RL\rangle + \mathcal{G}^{(GR)}_{(L,\vec{k})(R,\vec{k}')}|LR\rangle + \mathcal{G}^{(GR)}_{(L,\vec{k})(L,\vec{k}')}|LL\rangle + \mathcal{G}^{(GR)}_{(R,\vec{k})(R,\vec{k}')}|RR\rangle\right)}$$

with $\mathcal{G}^{(GR)}_{(R,\vec{k})(L,\vec{k}')}, \mathcal{G}^{(GR)}_{(L,\vec{k})(R,\vec{k}')} \gg \mathcal{G}^{(GR)}_{(L,\vec{k})(L,\vec{k}')}, \mathcal{G}^{(GR)}_{(R,\vec{k})(R,\vec{k}')}$

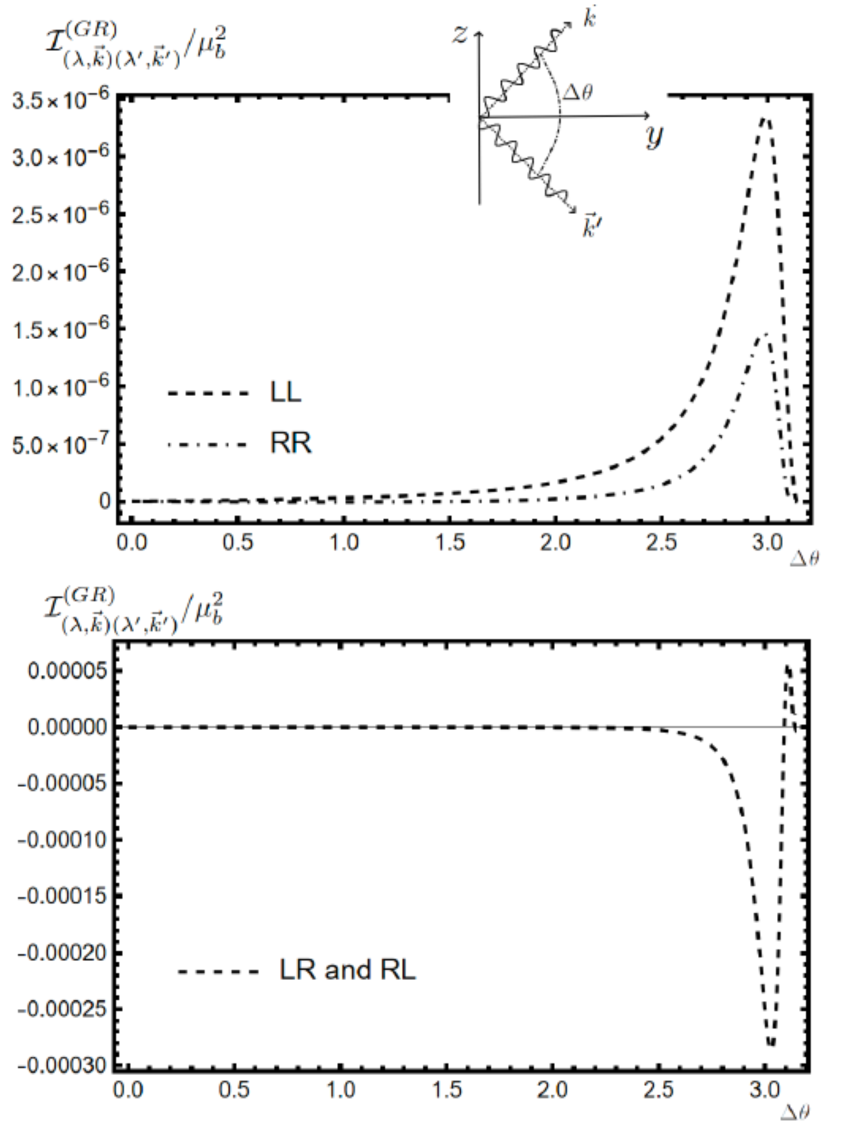


FIG. 2. Angular and polarization correlations for the G interaction. The 2p-state results in the asymmetry betwee the LL and RR pairs. The plot corresponds to $a_\mu = 0.1$.

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Axion mass: μ_b

$$\boxed{\sum_{I,J} |\mathcal{G}_{IJ}^{(GR)}|^2 \lesssim 2.5 \times 10^{-15} \, T \mu_b}$$

$$\boxed{\tau_s = \frac{1}{\omega_I(2p)} = 24 \, \mu_b^{-1} \left(\frac{\alpha}{G\mathcal{M}}\right)^{-1} a_\mu^{-8}}$$

Life time of cloud can be sufficiently long compared to the characteristic scale τ_s superradiance is effective,

eg $T > 10^7 \tau_s$ → significant multimode squeezing

$$\alpha/(G\mathcal{M}) \sim \mathcal{O}(1)$$

$\mathcal{M}$ = **Rotating Black Hole Mass**

$$a_\mu \equiv G\mathcal{M}\mu_b = 0.1$$

$$\boxed{\sum_{I,J} |\mathcal{G}_{IJ}^{(GR)}|^2 \sim \mathcal{O}(10)} \Rightarrow \boxed{\langle N_{gr} \rangle \gg 1}$$

Graviton-Squeezing CS terms

String-inspired models for string-model independent axion (assuming it gets a mass μ_b via some mechanism

$$S_{CS} = -\frac{A}{4}\int d^4x\sqrt{-g}\;\; b\;\; R_{\mu\nu\rho\sigma}\widetilde{R}^{\nu\mu\rho\sigma}$$

$$A \sim 10^{-2} M_{\rm Pl}/M_s^2$$

$$\boxed{\sum_{I,J}\left|(\mathcal{G}^{(CS)}_{IJ})\right|^2 \lesssim 10^{-10}\left(\frac{\mu_b}{M_s}\right)^4 \mu_b T}$$

NB: Maximally entangled 2-graviton state (Bell type)

$$\boxed{|\Psi_{CS}\rangle = \frac{1}{2}\mathcal{G}^{(CS)}_{(R,\vec{k})(L,\vec{k}')}\left(|LR\rangle - |RL\rangle\right)}$$

since $\mathcal{G}^{(CS)}_{(R,\vec{k})(L,\vec{k}')} = -\mathcal{G}^{(CS)}_{(L,\vec{k})(R,\vec{k}')}$

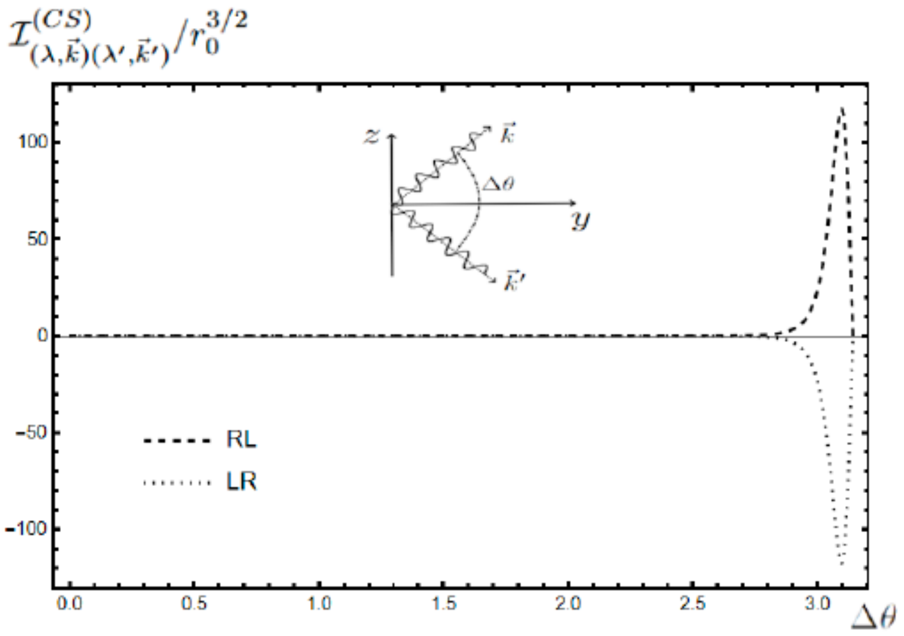

FIG. 3. Angular and polarization correlations for the CS interaction. Only pairs of opposite polarizations are produced; Maximal entanglement occurs between the L and R polarizations. The plot corresponds to $a_\mu = 0.1$.

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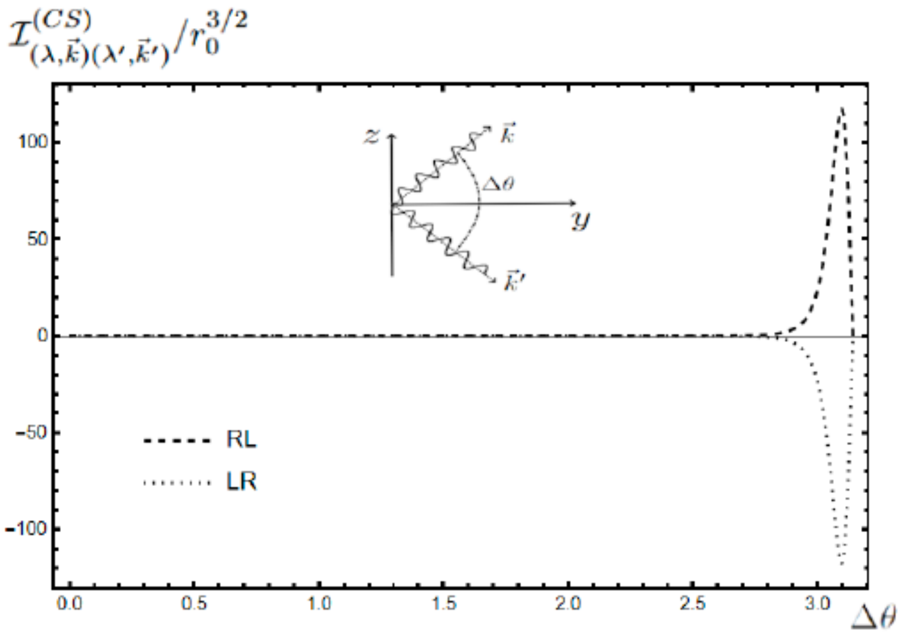
$$\boxed{\sum_{I,J}\left|\left(\mathcal{G}^{(CS)}_{IJ}\right)\right|^2 \lesssim 10^{-10}\left(\frac{\mu_b}{M_s}\right)^4 \mu_b T}$$

Significant suppression factor , especially for high string scales M_s



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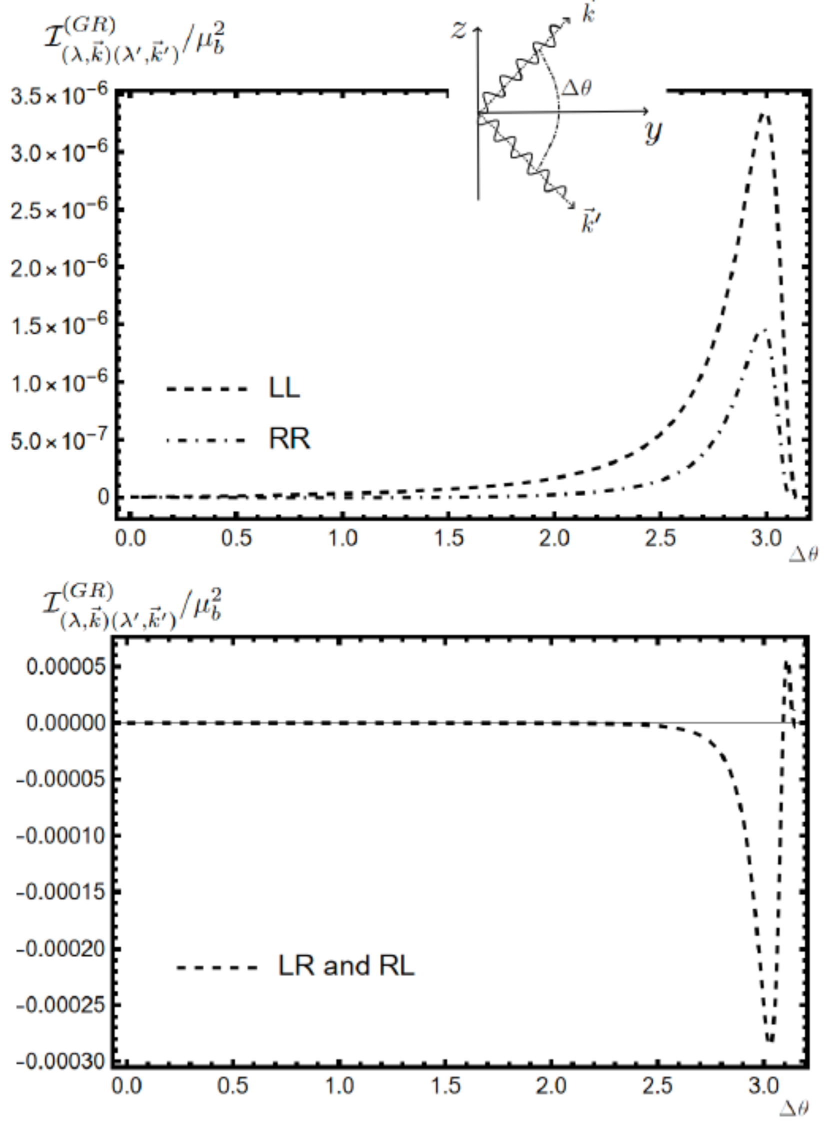
Hence, even for long-lived clouds CS-induced graviton squeezing will be suppressed compared to GR-induced one

$$\boxed{\langle N_{gr}\rangle^{\rm CS} << \langle N_{gr}\rangle^{\rm GR}}$$

NB:

GR correlations in absence of anomalies



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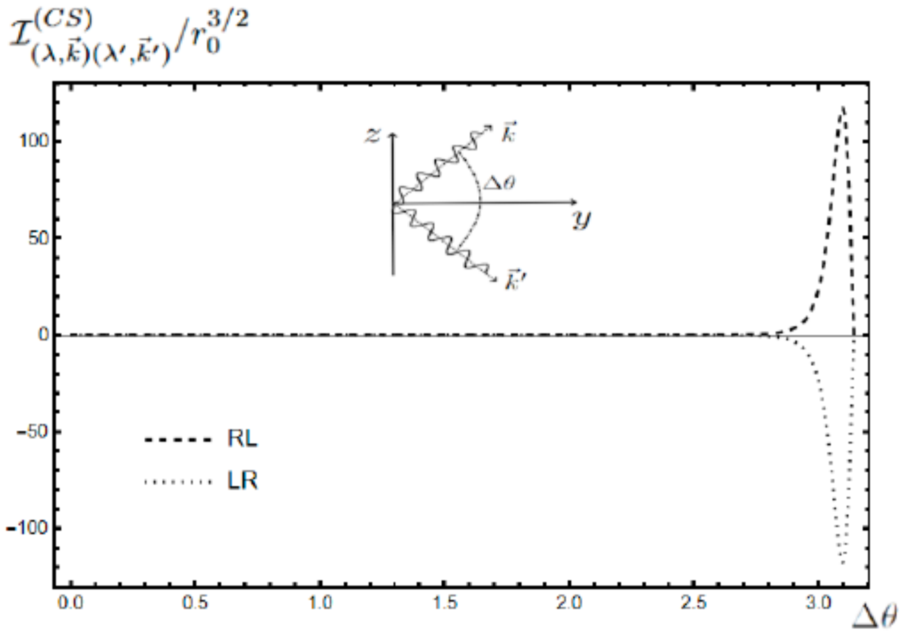
Contributions of CS gravitational Anomaly in EPR entangled graviton correlations



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Presence of gravitational anomaly affects the EPR correlations of the entangled gravitons (remote analogy with ω-effect)

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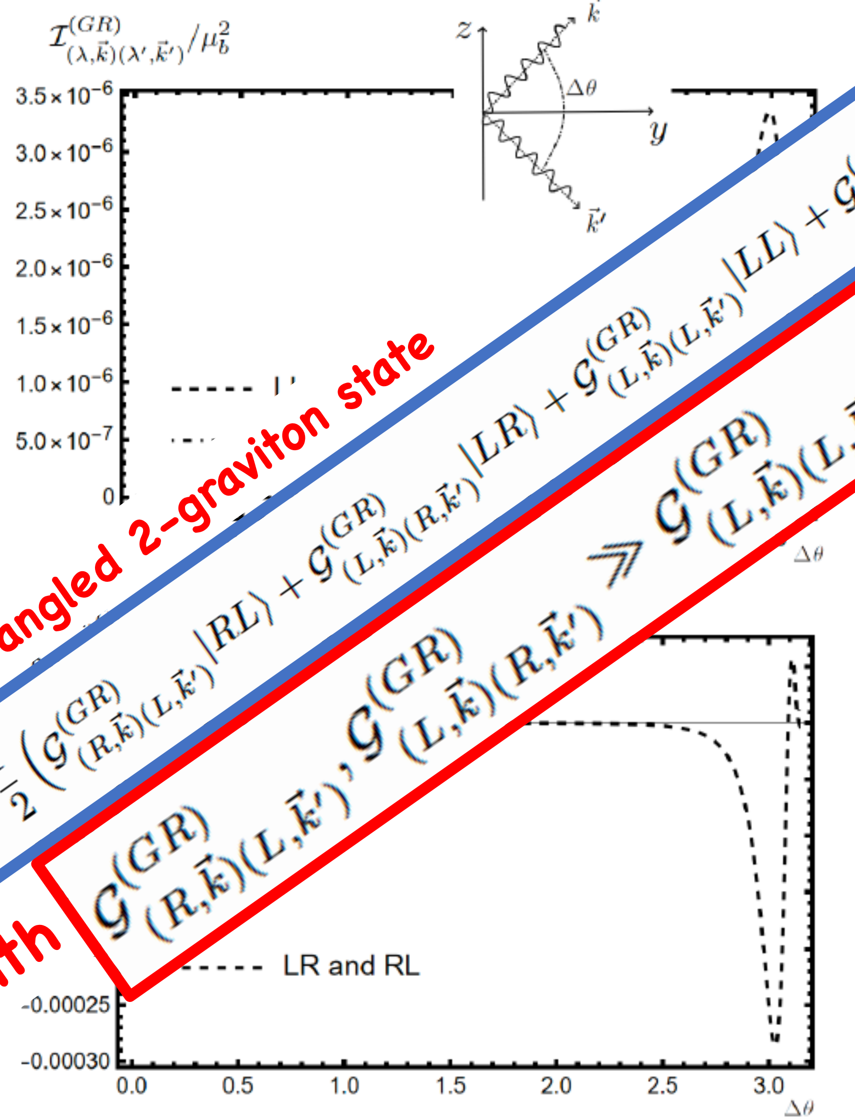

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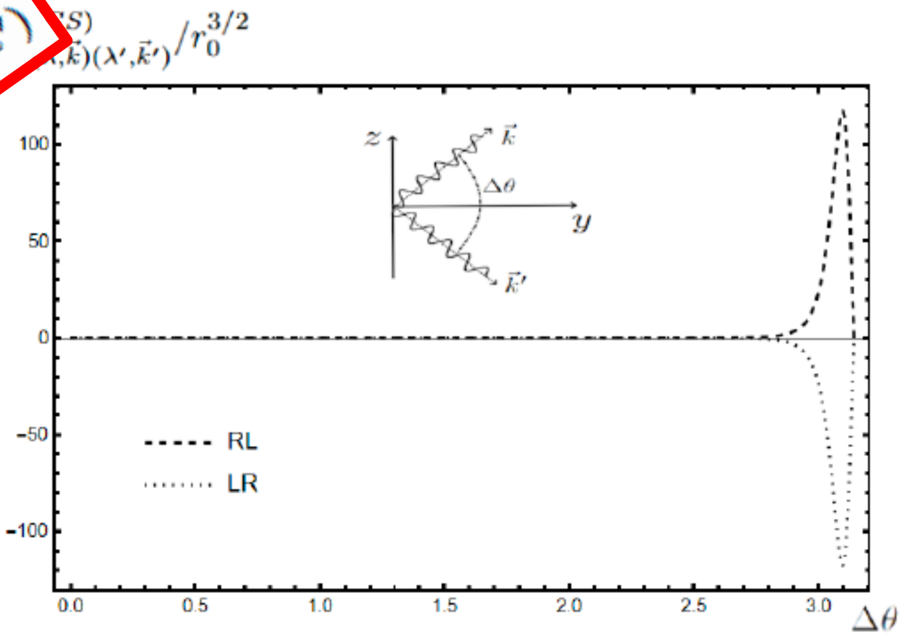

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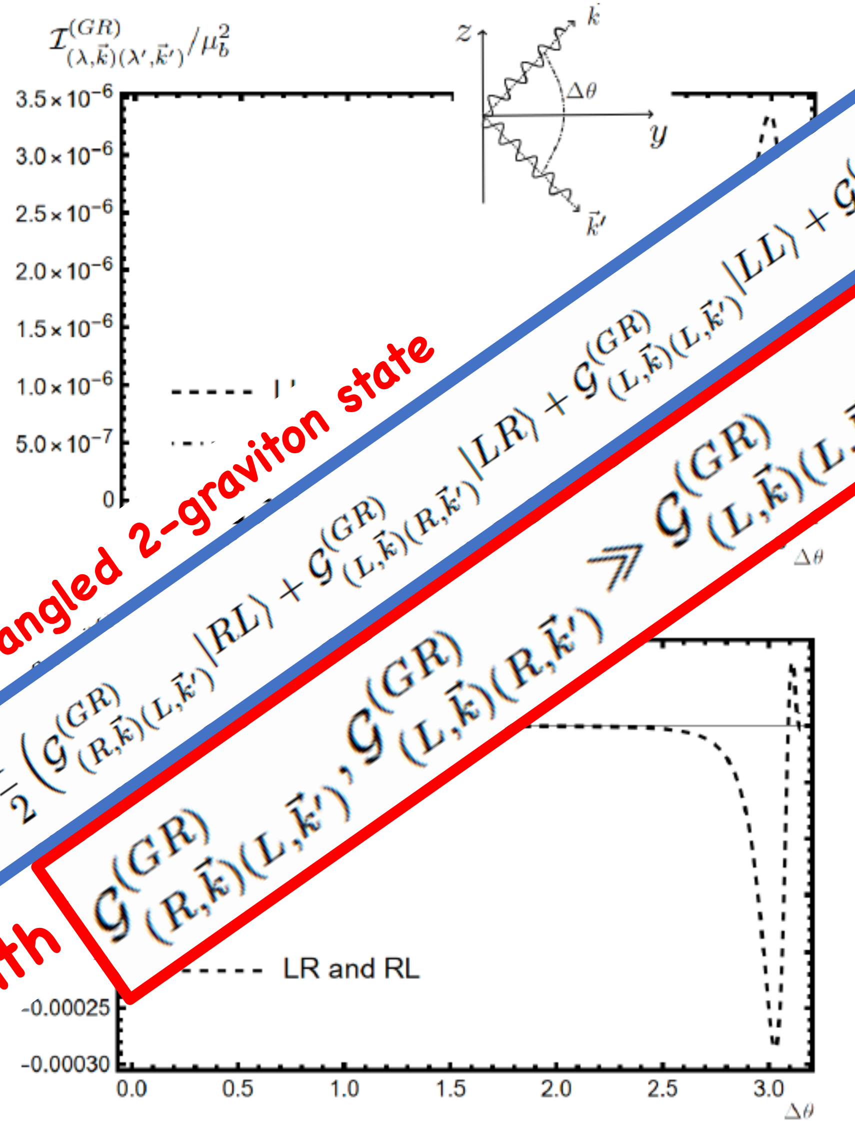

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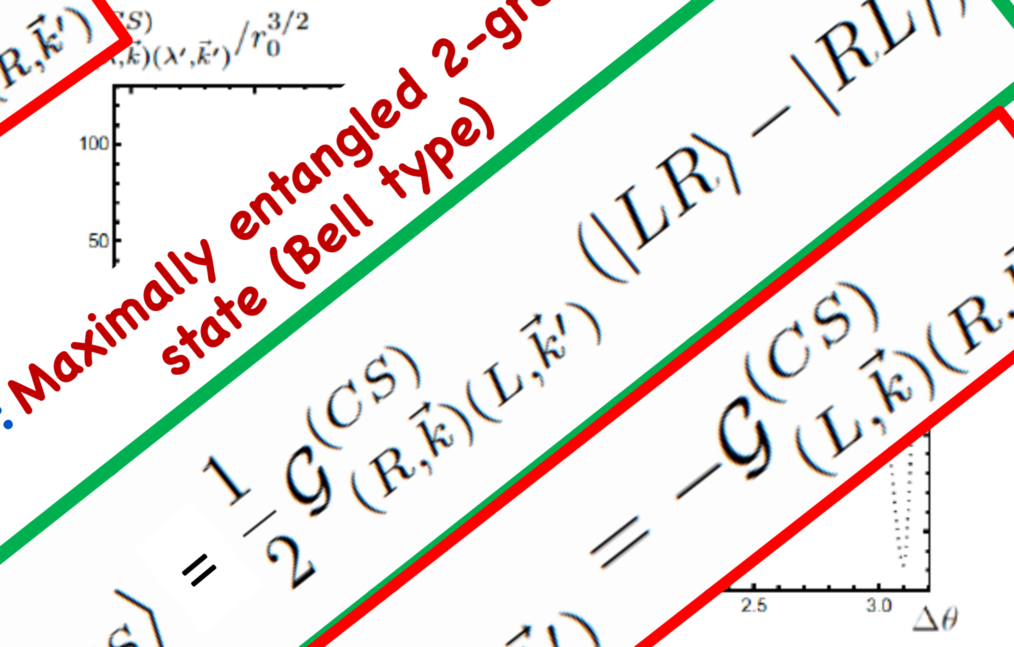

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Summary

Quantum Gravity (QG, if it exists) may manifests itself in various ways, some of which may be entirely unconventional (as compared to the other fundamental interactions in Nature.

One of them is through a space-time ``environment'' of QG fluctuating degrees of freedom whose dynamical description may require going beyond the EFT approach . The environment induces decoherence of quantum matter propagating in it.

One potential effect of such a decoherence is an ill-defined nature of the generator of the CPT transformations, which in flat spacetimes is a sacrosanct symmetry of Unitary, Lorentz invariant quantum field theories with Local interactions.

This ``intrinsic CPT Violation'' can be parametrized in terms of the ω-effect in Entangled neutral-meson states, modifying the EPR correlations. Current bounds in various facilities have been given.

The phenomenon can find interesting analogues in spin systems → uses in particle cryptography ??

Another potential effect of QG that we examined briefly, this time within the EFT approach to weak QG, is the production of multimode squeezed gravitons in axionic clouds of superradiant rotating black holes. The presence of Gravitational CS Anomalies affects the EPR correlations of the entangled gravitons produced in the process (remote analogy with ω-effect).

The GR effect, associated with the production of entangled graviton pairs from a pair of fusing axions in the cloud can lead to significant squeezing, for sufficiently long-lived axion clouds. CS-anomaly induced squeezing is suppressed compared to GR effect. Future detection of such gravitons using combinations of interferometers is foreseen.

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Thank you !