Quantum Gravity & Entangled Particle States

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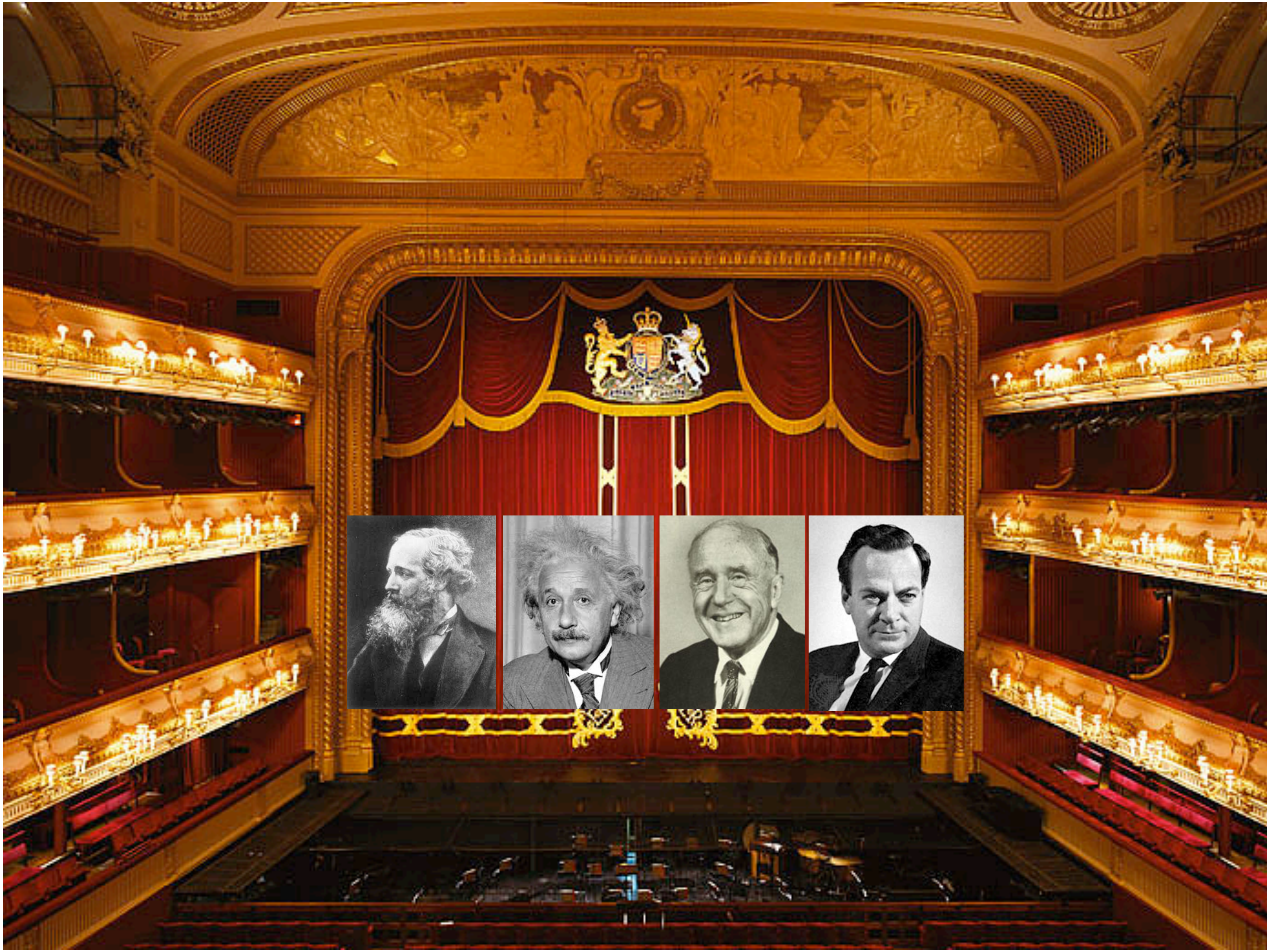



OUTLINE

A PRELUDE - **Experimental Surprises?:** MAGIC (2005) *et al*. & OPERA (2011)

Playing with Light: Quantum Field Theories in non-trivial Vacua & Light (superluminal) Refraction

Causality & Superluminality – not necessarily incompatible

ACT I **QUANTUM GRAVITY (QG**) as a non-trivial Vacuum (``Medium'')

CONCEPTS & MODELS

PHENOMENOLOGY OF QG FOAM VACUA (``FOAM-OLOGY''):

Some aspects

Non-trivial Optical properties (refractive index, birefringence(?))

ACT II ***A*** **STRINGY MODEL OF SPACE-TIME** ***D-*****(efect)** ***FOAM***

ENTR'ACTE

ACT III **QUANTUM GRAVITY, DECOHERENCE & ENTANGLED PARTICLE STATES:**

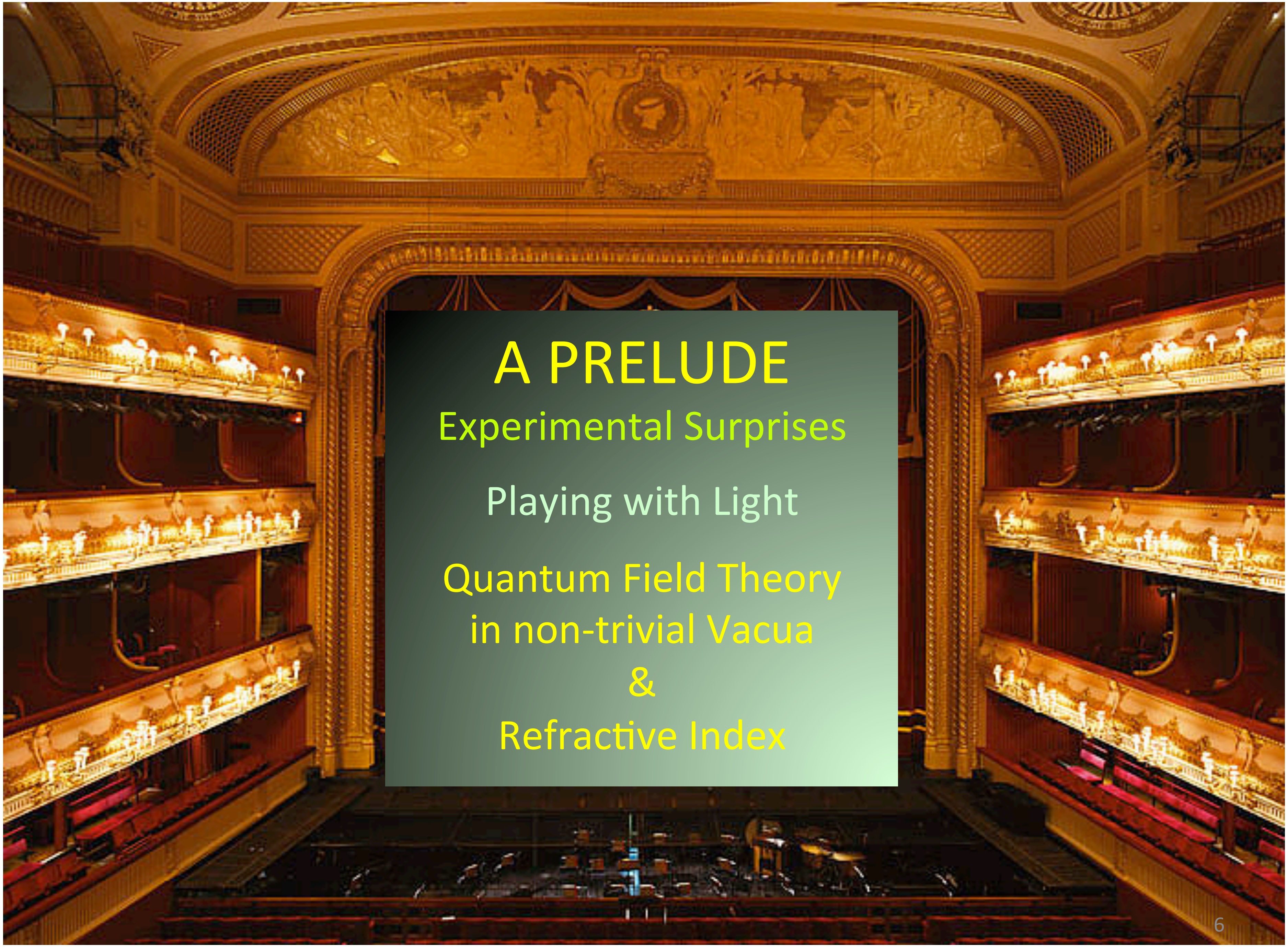
QG Decoherence & CPT Violation

ACT IV **PHENOMENOLOGY OF CPT VIOLATION**

(i) EPR Modifications – the ω-effect-
Order of Magnitute Estimates/Model dependence

(ii) Kaon vs B-systems and the ω-effect

EPILOGUE: **Reconciling MAGIC et al. with OPERA & DAΦNE-2**: ***D-FOAM,***
Further QG Tests?



A PRELUDE

Experimental Surprises

Playing with Light

Quantum Field Theory
in non-trivial Vacua
&
Refractive Index

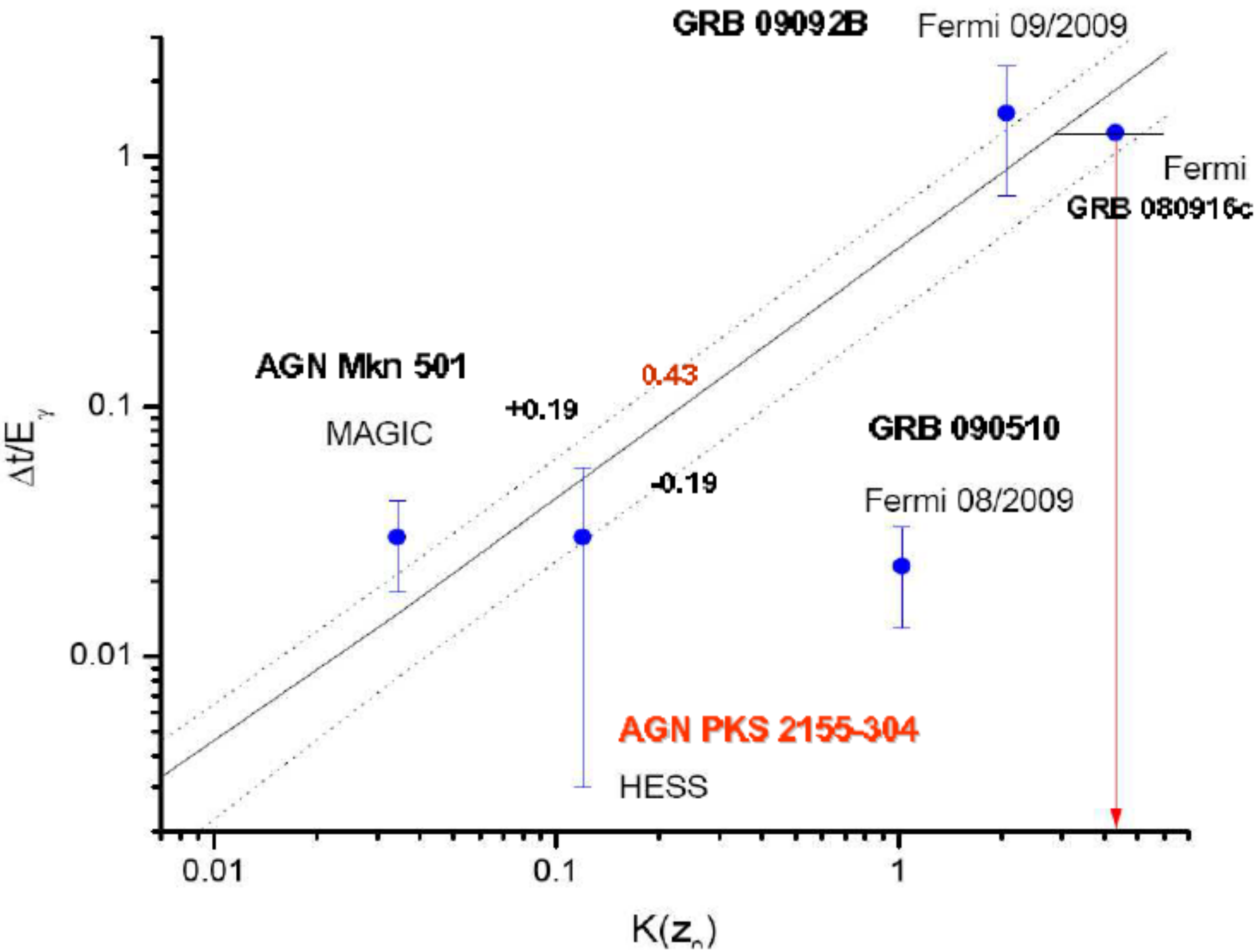
MAGIC results (2005)

TeV Photons from
Active Galactic Nucleus
(AGN) Mkn 501 at red-shift
z = 0.03

More energetic
photons (1.2 - 10 TeV)
delayed by O(1 min) compared
to E < 0.6 TeV

First Interesting result…
in conflIct with Conventional
Astrophysical acceleration
AGN Models (e.g. Crab Nebula)

Other Observed Photon Delays (H.E.S.S, FERMI)



OPERA RESULTS – Superluminal neutrinos ?

2011 : Another Surprise, more mysterious

NEUTRINOS IN OPERA have been argued to propagate with superluminal velocities

$$v/c - 1 = (\,2.48 \pm 0.28 \pm 0.30\,)\ 10^{-5}$$

(but independent of the energy, at least in the range of the experiment)

OPERA v2

$$(v\text{-}c)/c = (2.37 \pm 0.32\ (\mathrm{stat.})\ {}^{+0.34}_{-0.24}\ (\mathrm{sys.})) \times 10^{-5}$$

overall significance more 6.2 σ

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Can MAGIC *et al.* Photon events be reconciled with OPERA within a fundamental new physics framework?

GAMES WITH LIGHT

Lorentz Invariance → Speed of Light in Vacuo = c (Universal constant)

But in MATERIAL SYSTEMS light propagates with different speed, $v_{light} \neq c$

NON TRIVIAL REFRACTIVE INDEX

Phase velocity $$v_{\text{light}} = \frac{c}{\eta}$$

Group Velocity $$v_{\text{group}} = \frac{\partial \omega}{\partial k} \neq c$$

GAMES WITH LIGHT

NON TRIVIAL REFRACTIVE INDEX

~~Lorentz Invariance~~

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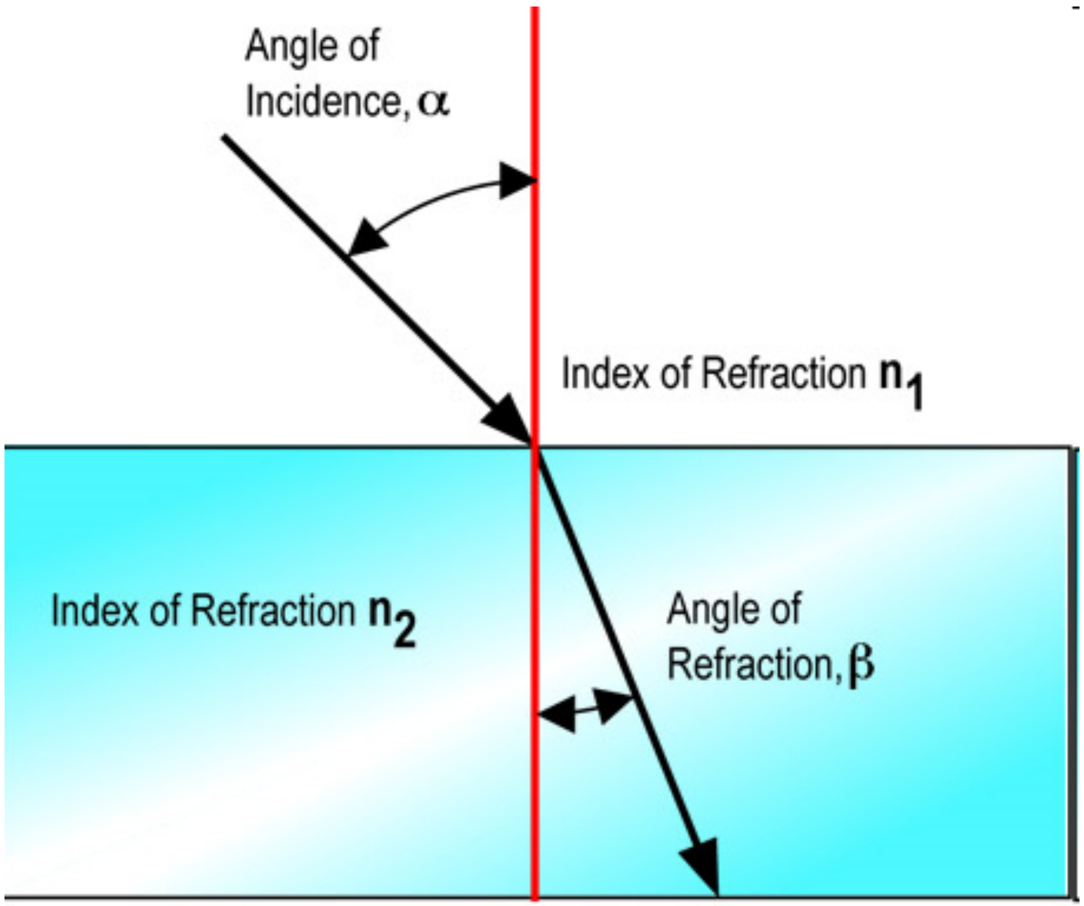


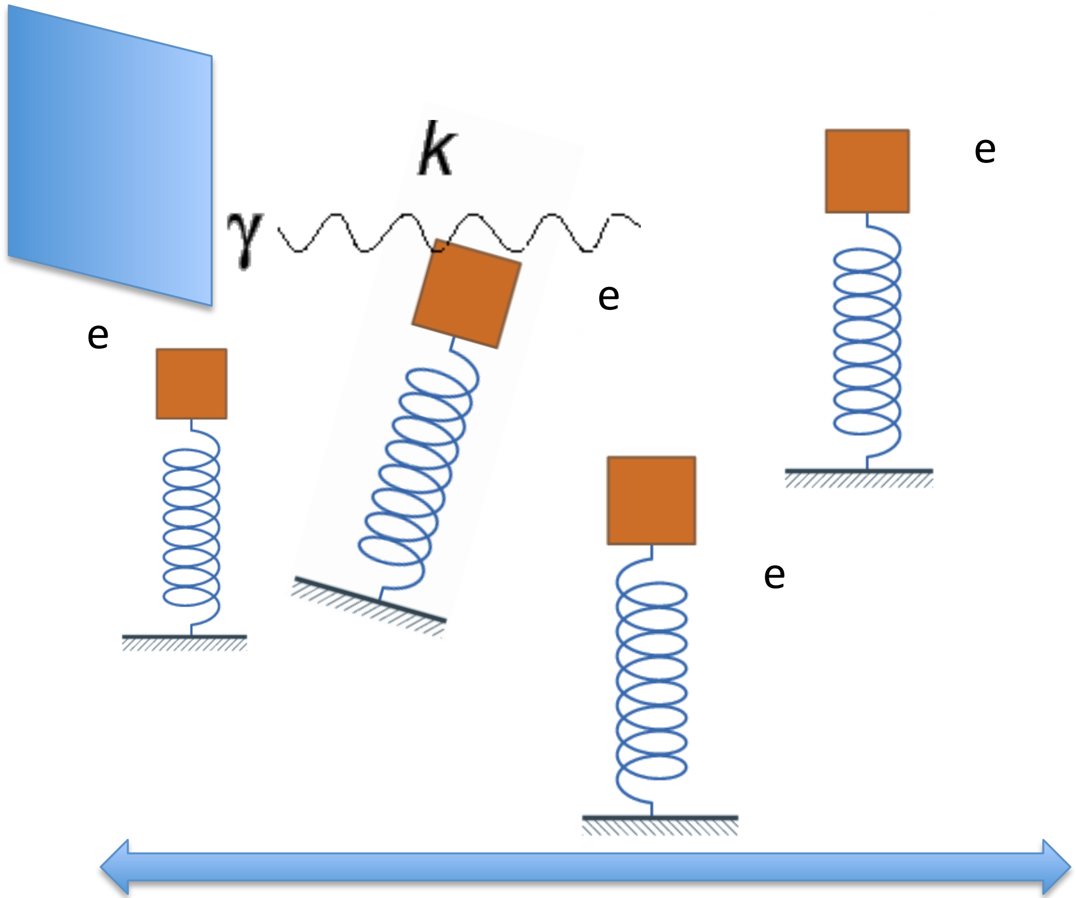
$$n_1 \text{ sine } \alpha = n_2 \text{ sine } \beta$$

QUANTUM MECHANICS & REFRACTIVE INDEX

electrons (mass m) of the medium as forced quantum oscillators, with force exerted by electromagnetc field photons interact with this background

Feynman

Electron area density $n_e = \rho_e \Delta z$ (ρ_e = volume density of electrons)



Distance Δz traversed by photons

$$m\left(\frac{d^2}{dt^2}x+\omega_0^2 x\right)=eE_0e^{i\omega t}$$

Excited-atoms produced electric field

$$E_a=-\frac{en_e}{\epsilon_0 c}i\frac{eE_0}{m(\omega^2-\omega_0^2)}e^{i\omega(t-z)},$$

Speed of photons in medium ***c/n*** suppressed by refractive index n causing ***delay Δt = (n-1)Δz /c***

$$(n-1)\Delta z=\frac{n_e e^2}{2\epsilon_0 m(\omega_0^2-\omega^2)}$$

$$\boxed{n=1+\frac{\rho_e e^2}{2\epsilon_0 m(\omega_0^2-\omega^2)}}$$

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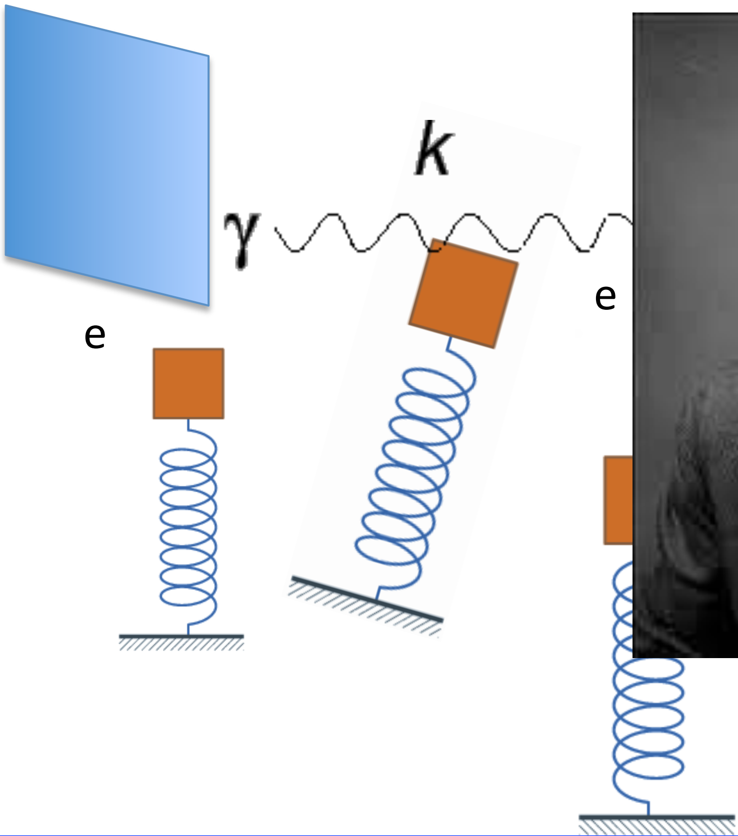

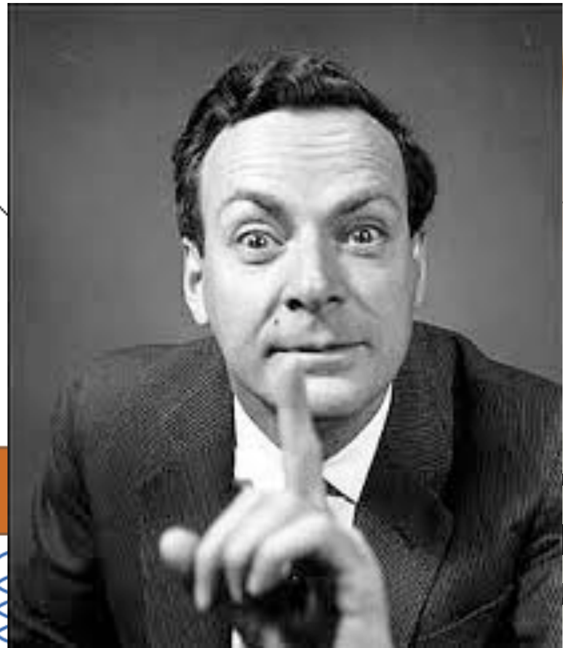

$$\left(\frac{d^2}{dt^2}x + \omega_0^2 x\right) = eE_0 e^{i\omega t}$$

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$$= -\frac{en_e}{\epsilon_0 c} i \frac{eE_0}{m(\omega^2 - \omega_0^2)} e^{i\omega(t-z)},$$

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$$(n-1)\Delta z = \frac{n_e e^2}{2\epsilon_0 m(\omega_0^2 - \omega^2)}$$

REFRACTIVE INEX INVERSELY PROPORTIONAL TO PHOTON ENERGIES (cf. MATTER EFFECTS)

$$\boxed{n = 1 + \frac{\rho_e e^2}{2\epsilon_0 m(\omega_0^2 - \omega^2)}}$$

GAMES WITH LIGHT

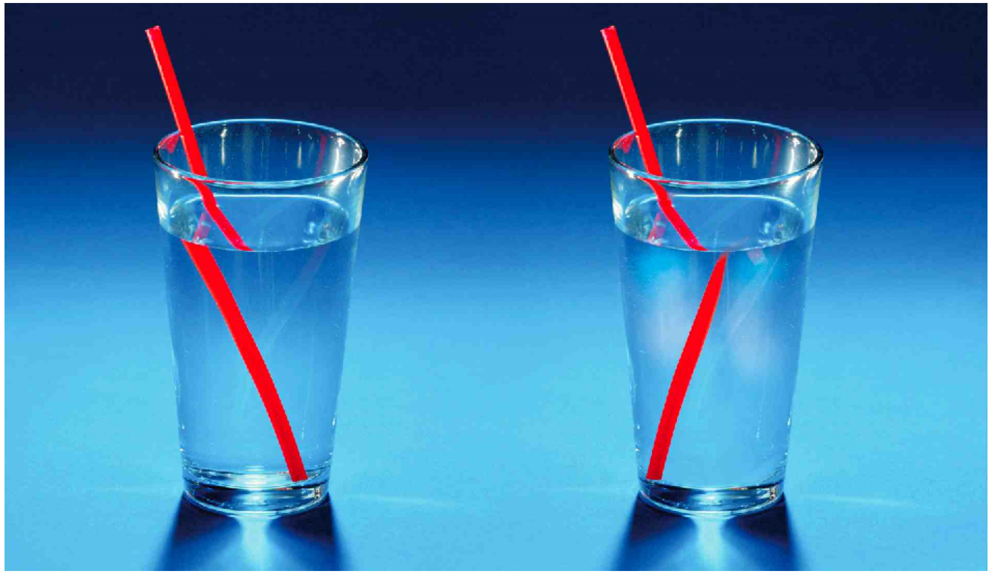
~~Lorentz Invariance~~

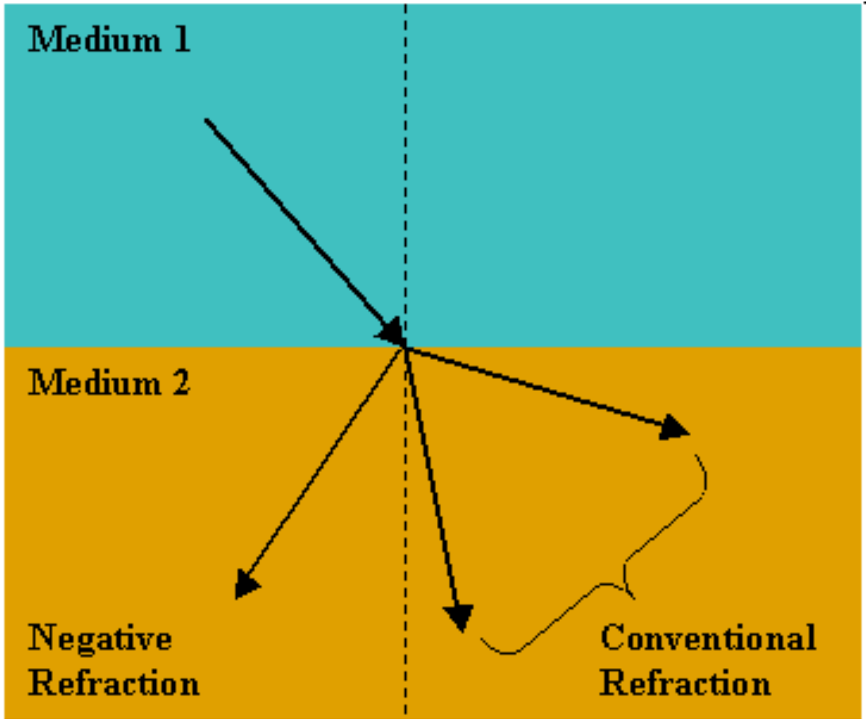
in MATERIAL SYSTEMS light propagates with different speed, $v_{light} \neq c$

Depending on Light Polarization

BIREFRINGENCE

NEGATIVE REFRACTIVE INDICES IN METAMATERIALS





Normal Refraction

Courtesy Univ. of Surrey

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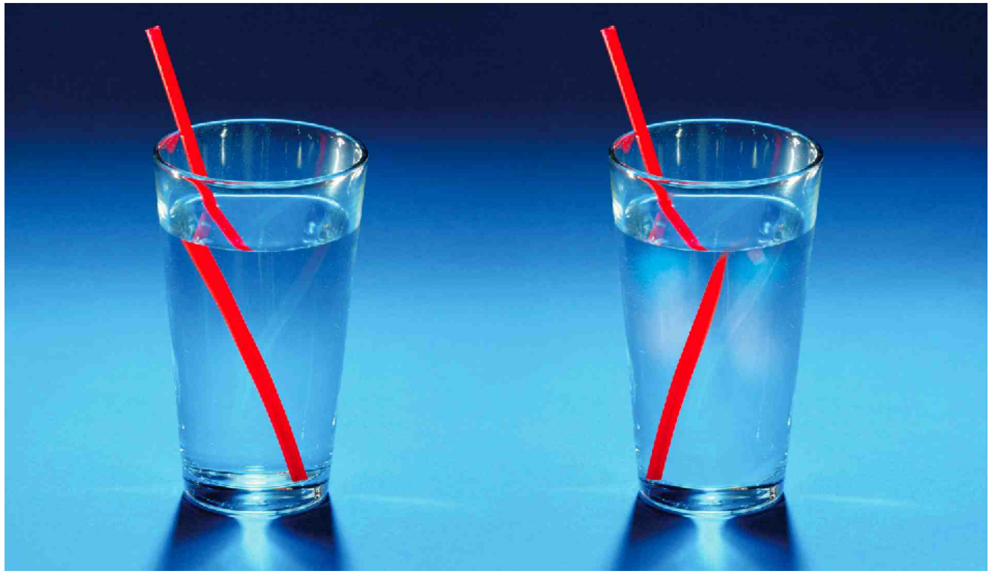
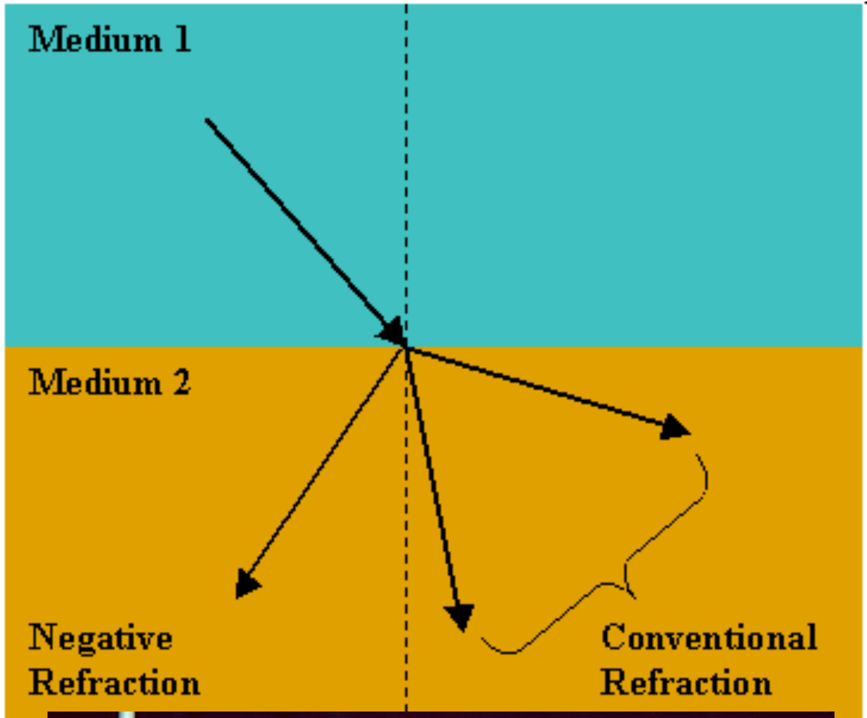
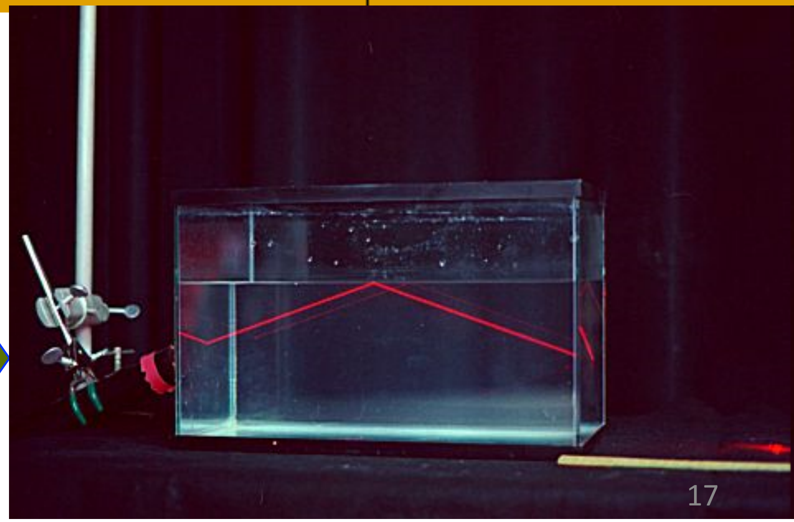




Negative Refractive Index metamaterials



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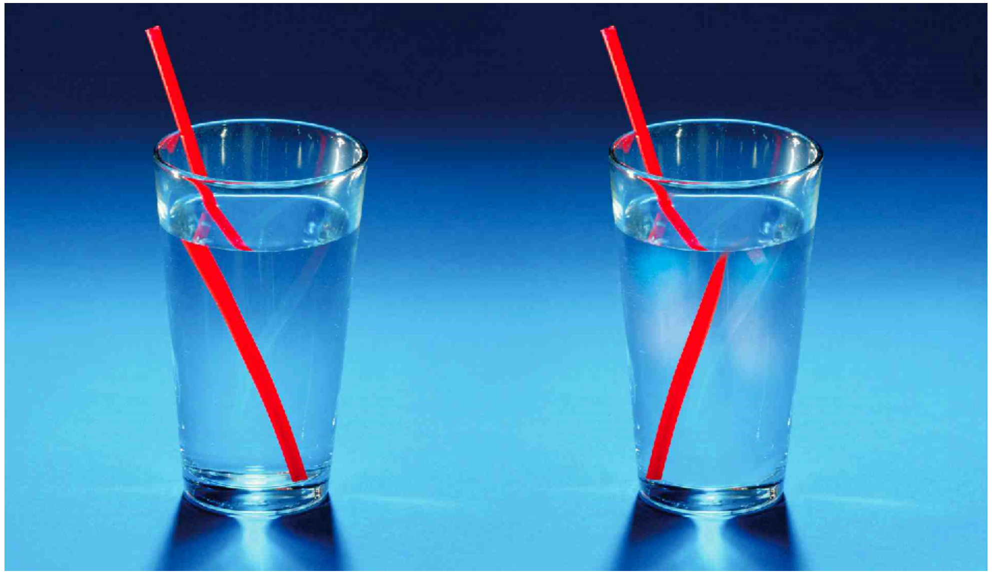
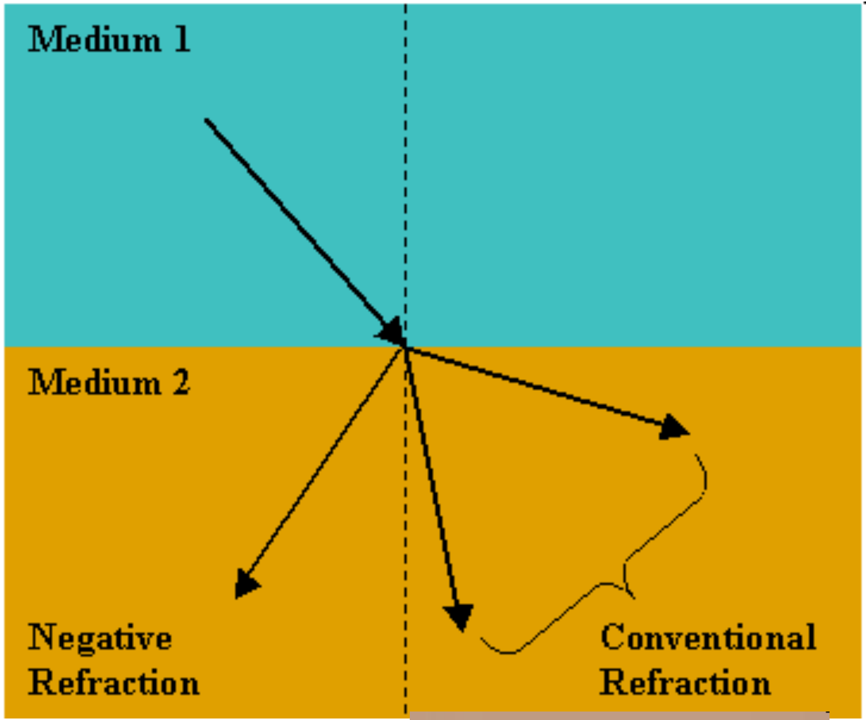
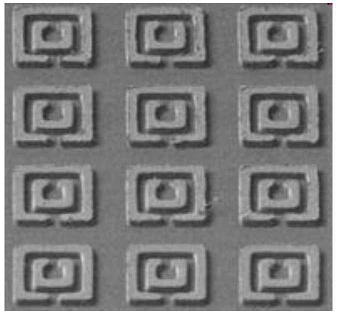
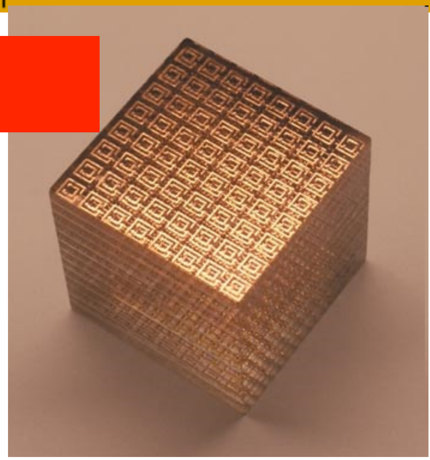




Normal Refraction

Typical Metamaterial





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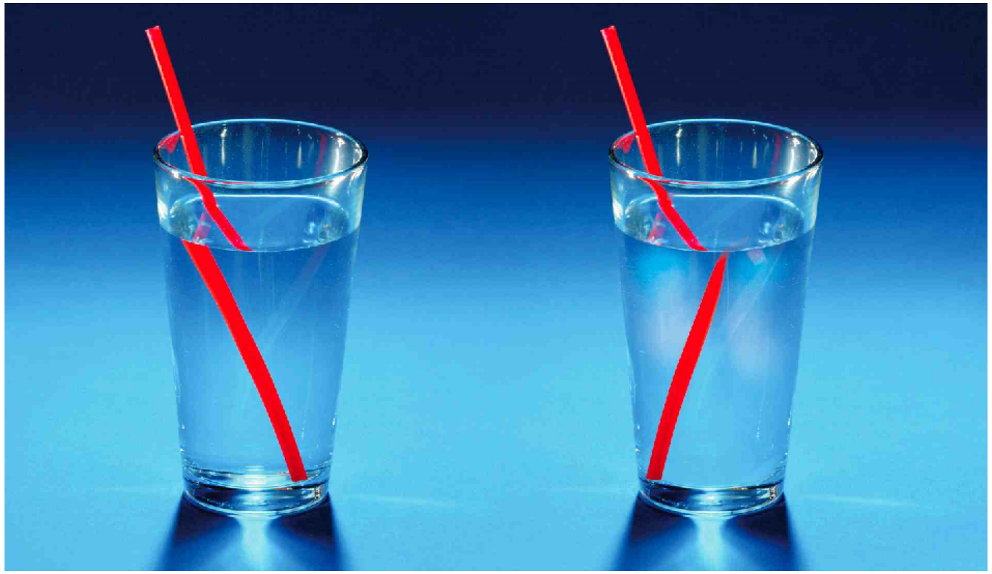
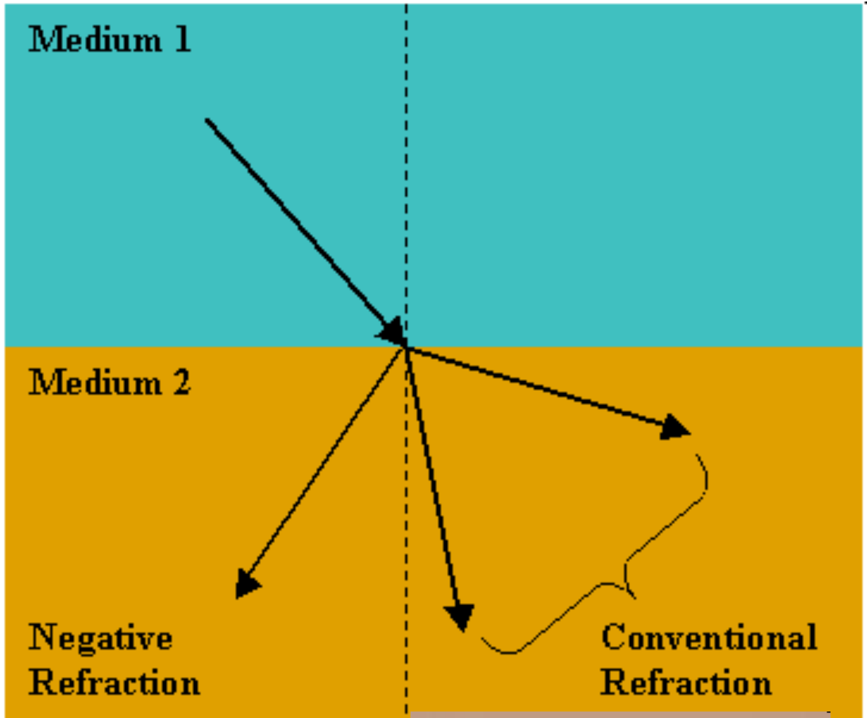
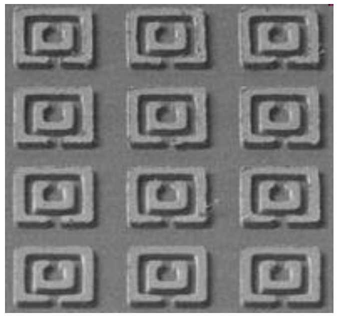


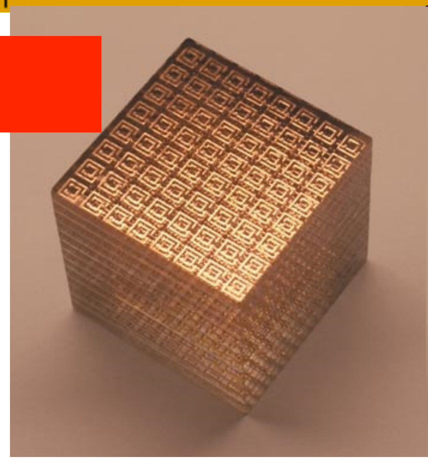


Normal Refraction

Typical Metamaterial

WEIRD GEOMETRIES & Boundary conditions





Courtesy Univ. of Surrey

Technology engineers all sorts of materials inside which Light has Strange properties ….

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The Vacuum (i.e. lowest energy state) of QUANTUM SYSTEMS may also be characterized by strange properties of light, e.g. Lorentz invariant Breaking ….

BOUNDARY CONDITIONS

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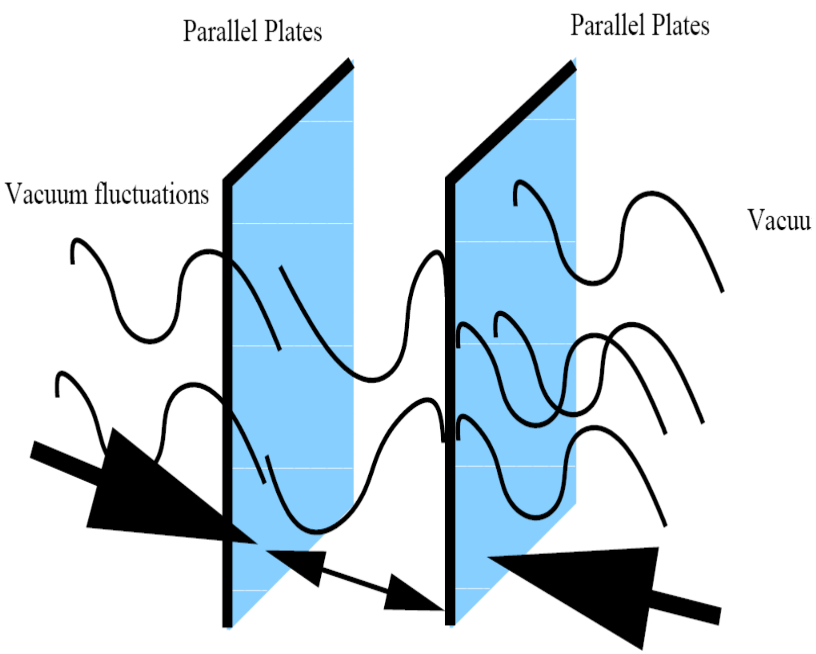

Distance L

CASIMIR VACUUM: Force due to Quantum fluctuations of Photons in space between neutral capacitor plates.

Quantum effects lead to ``vacuum polarization'' (emission of virtual electron-positron pairs as a photon propagates in this non-trivial vacuum Between the plates) and to a modified group Velocity of photons, larger than c:

$$\boxed{v_{\rm gr}^{\rm Casimir} = 1 + \frac{11\pi^2}{8100}\alpha^2 \frac{1}{L^4 m_{\rm e}^4} > 1}$$

Scharnhost (1990), Barton (1990)
Lattore, Pascual, Tarrach (1995)

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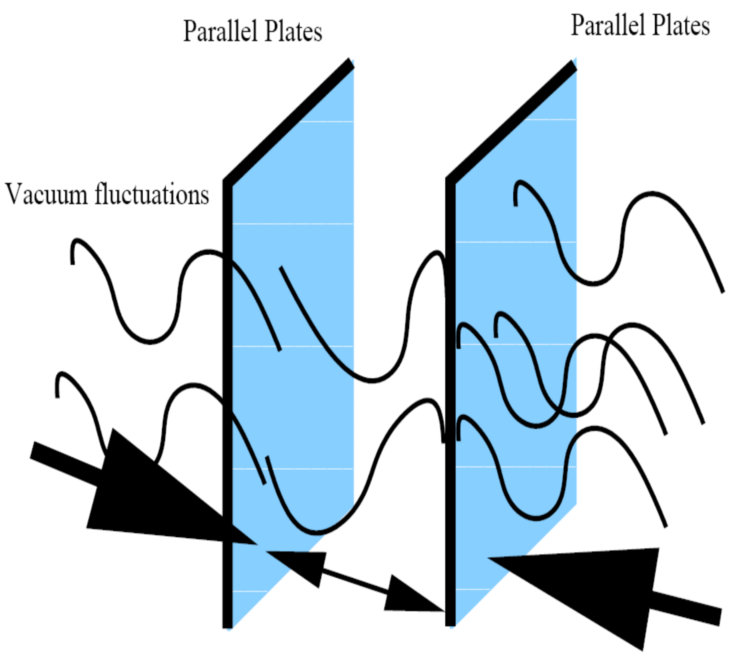

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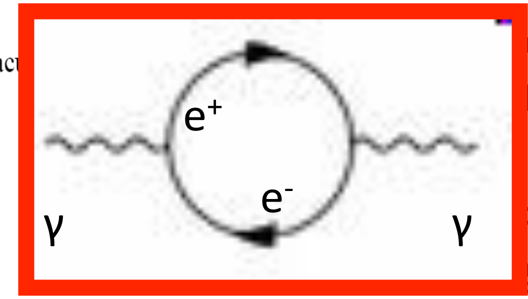

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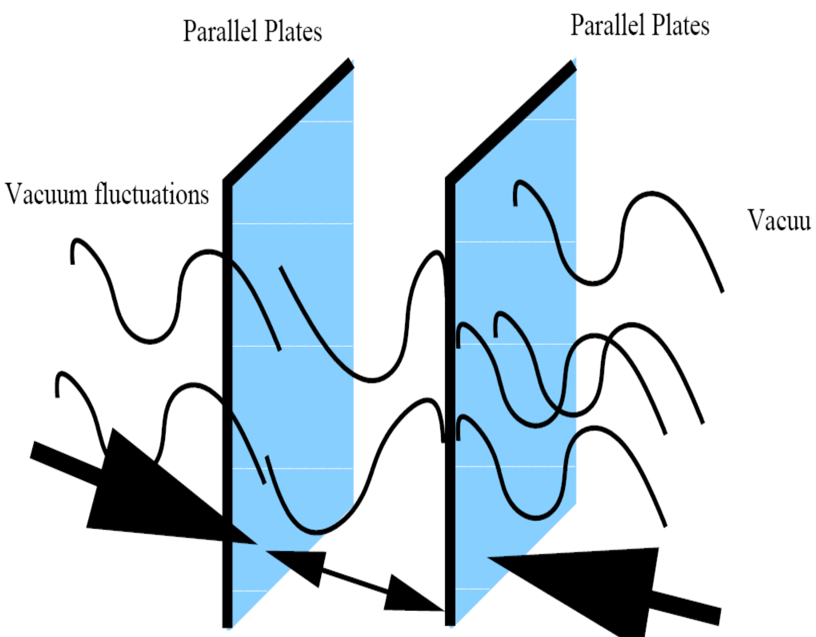

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α = $e^2 / 4\pi$ = Fine structure constant

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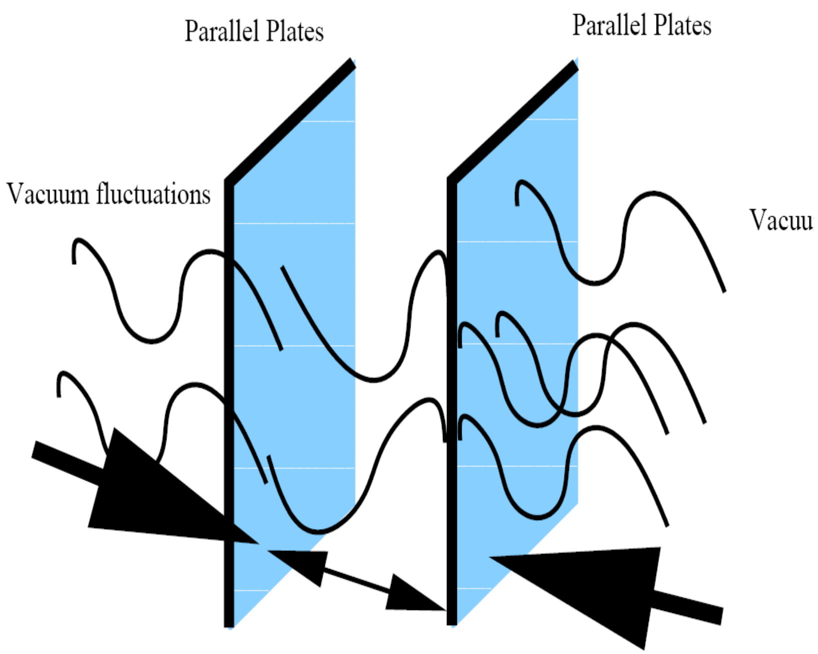

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Boundary Conditions Break Lorentz Symmetry in vacuo

FINITE TEMPERATURE

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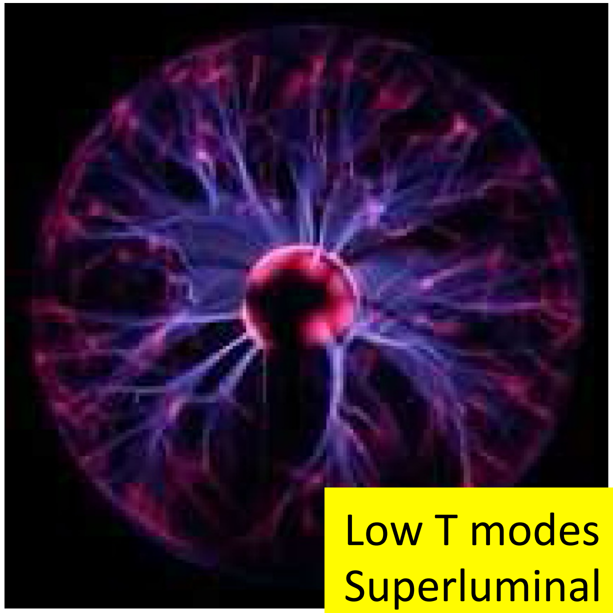

Low T modes Superluminal

PLASMA VACUUM:Plasma is a state of Matter at very high temperature where Matter is ionized.

Temperature T

Quantum effects related to vacuum polarization in this non-trivial vacuum lead to a modified Group Velocity for photons, larger than c

(low T: analogy with Casimir Vacuum: **L^{-1}** ⟺ **2T**)

$$v_{gr}(kT \ll m_e^2) = 1 + \frac{11\pi^2}{8100}\alpha^2\left(\frac{2T}{m_e}\right)^4 \;>\; 1$$

High T modes Subluminal

$$v_{gr}(kT \gg m_e^2) = 1 - \frac{\alpha^2}{6}\left(\frac{T}{k}\right)^2 \ln^2\left(\frac{kT}{m_e^2}\right) \;<\; 1$$

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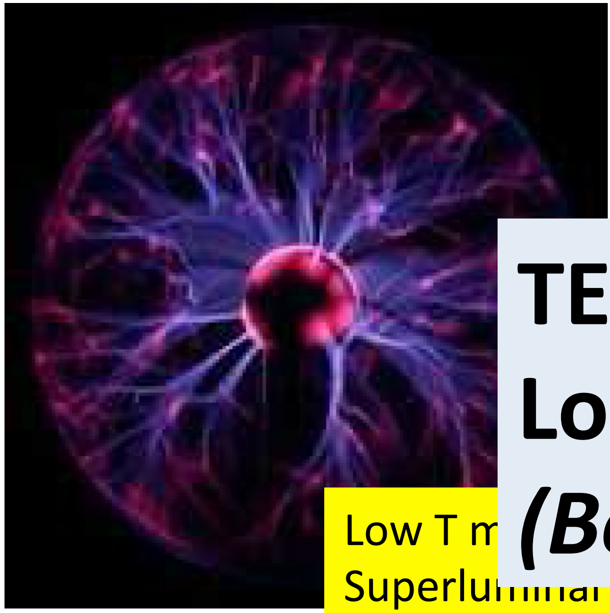

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Temperature T

TEMPERATURE breaks Lorentz Symmetry *in Vacuo (Boundary Conditions…)*

Low T m
Superluminal

$$v_{\rm gr}(kT \ll m_e) = 1 + \ldots \frac{\ldots}{8100}\alpha \ldots \left(\frac{\ldots}{m_e}\right) \ldots > 1$$

High T modes
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FINITE TEMPERATURE-NEUTRINOS

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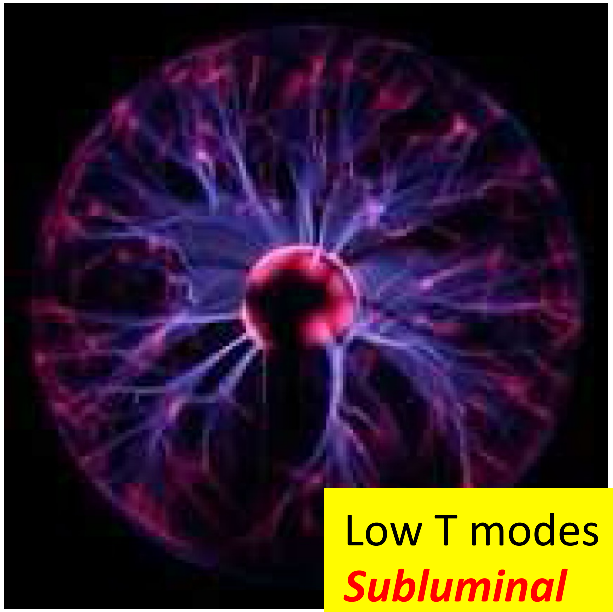

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(low T: analogy with Casimir Vacuum**: L^{-1}** $\Leftrightarrow$ **2T**)

Low T modes
Subluminal

$$\boxed{v(qT \ll M_z^2) = 1 - g_W^2 \frac{7\pi^2}{45}\left(\frac{T}{M_z}\right)^4 + \mathcal{O}\left(\frac{q^2T^6}{M_z^8}\right)}$$

High T modes
Subluminal

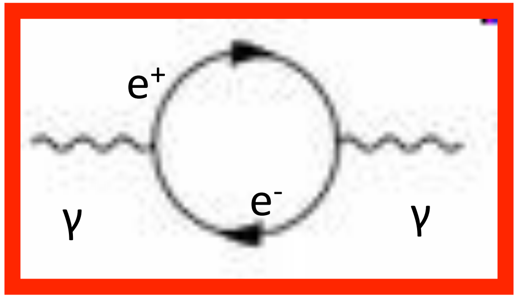
$$\boxed{v(qT \gg M_z^2) = 1 - g_W^2 \frac{1}{24}\left(\frac{T}{q}\right)^2 + \mathcal{O}\left(\frac{M_z^4}{q^4}\right) \quad , \quad T \leq q}$$

CURVED SPACE-TIME BACKGROUNDS

Drummond & Hathrell (1980)

VACUUM POLARIZATION EFFECTS IN QED IN CURVED BACKGROUNDS

EFFECTIVE HIGHER DERIVATIVE ACTION AFTER
ELECTRON FIELDS ARE INTEGRATED OUT IN A PATH INTEGRAL



$$S_{\rm eff} = \int d^4x \sqrt{-g}\left(-\frac{1}{4}F_{\mu\nu}\,F^{\mu\nu} + W_{1-{\rm loop}}\right)$$

$$W_{1-{\rm loop}} = \int d^4x\sqrt{-g}\;\left(aR\,F_{\mu\nu}\,F^{\mu\nu} + bR_{\mu\nu}\,F^{\mu\lambda}\,F^{\nu}_{\;\;\lambda} + cR_{\mu\nu\rho\lambda}F^{\mu\nu}\,F^{\rho\lambda} + dD_\mu F^{\mu\nu}D_\lambda F^{\lambda}\;\nu\right)$$

Consequence **: modified (by higher derivative terms) photon propagator & dispersion relations, Coefficients proportional to the product of Newton's constant with the fine structure constant $G_N\,\alpha$ & *inversely* proportional to electron mass squared m_e^2**

Example: **Photon group velocity in Expanding Friedman-Robertson-Walker (FRW) Backgrounds**

$$v = 1 + \frac{11}{45}\alpha G_N \frac{\rho + p}{m_e^2} \qquad > 1$$

Superluminal for ordinary matter, radiation fluids **ρ + p > 0**
Light like for Cosmological constant (Lorentz invariant) vacua **ρ + p =0**

CURVED SPACE-TIME BACKGROUNDS

Drummond & Hathrell (1980)

Shore, Hollowood

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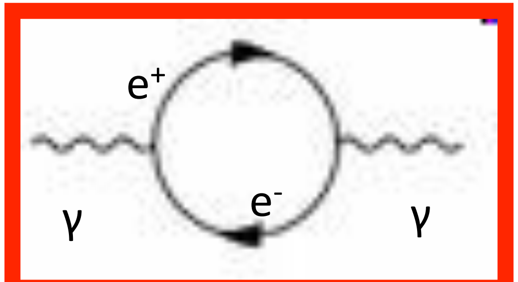

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Understanding these results

Latorre, Pascual, Tarrach

$$n = 1 + \frac{\rho_e e^2}{2\epsilon_0 m_e(\omega_0^2 - \omega^2)} = 1 + \frac{\tilde{\rho}_e e^2}{2\epsilon_0 m_e^2(\omega_0^2 - \omega^2)}$$

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energy density of ground state

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effective energy scale

energy density of ground state

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$$n = 1 + a\,\frac{\tilde{\rho}\,g^2}{m_e^4}$$

Energy density of non-trivial vacua may be lower w.r.t. normal

$$\tilde{\rho} < 0$$

e.g. FRW gravitational energy $\rho_G = -\tilde{\rho} < 0$

CAUSALITY & SUPERLUMINALITY

No problems with Causality if Superluminality is Observer dependent

Liberati, Sonego, Viser (2002)

i.e. Causality paradox arise
if signals travel with the
same speed V > c
in **two different** frames

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Liberati, Sonego, Viser (2002)

i.e. Causality paradox arise
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Previous examples are fine in this respect, the effects on photon dispersion relation can be represented by `` effective '' metrics ,

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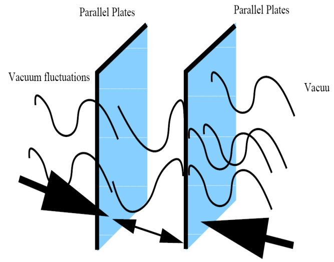

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$$g_{\mu\nu} = \eta_{\mu\nu} - \frac{\xi}{1+\xi} n_{\mu} n_{\nu} \qquad \xi = \frac{11\pi^2\alpha^2}{4050\, L^4\, m_e^2}$$

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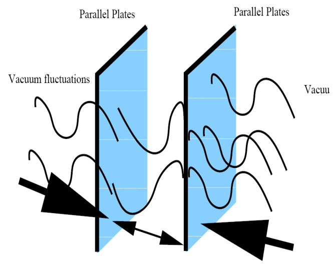

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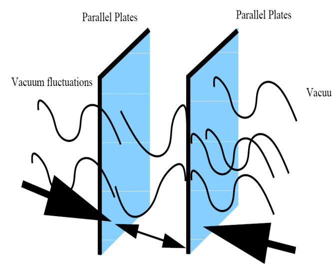

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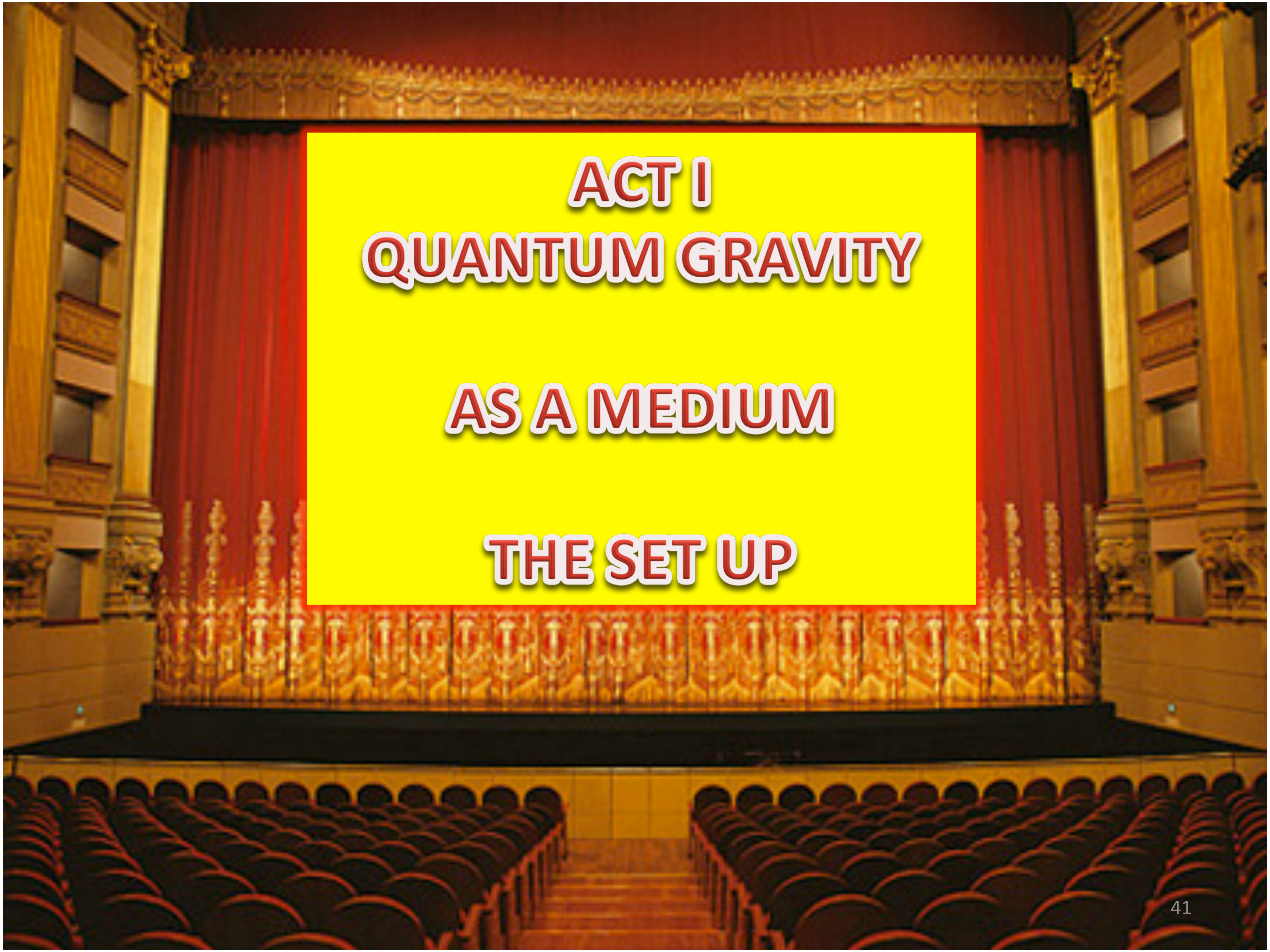
$$\boxed{\begin{array}{c} x^\mu \to x^\mu + \xi^\mu(x,u) \\ g_{\mu\nu} \to g_{\mu\nu} + \partial_{(\mu}\xi_{\nu)} \end{array}}$$

As such, speed of signal depends on *observer velocities u^μ* relative to system


ACT I
QUANTUM GRAVITY
AS A MEDIUM
THE SET UP

QUANTUM GRAVITY

- Quantum Gravity (QG) is a (quantum?) theory that describes the emergence as well as the dynamical structure of space-time at Microscopic scales.

Quantization of Gravitational Interaction is still a mystery

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Quantization of Gravitational Interaction is still a mystery

String theory is one approach to quantum gravity.
The theory predicts extra dimensions
But also two ``gravitational'' scales:
(i) one on our world, The Planck Mass scale, $M_P = 1.2 \times 10^{19}$ GeV
&
(ii) the bulk (extra dimensional) one, which is the *string mass scale* characterizing string theory itself, and may be as low *as a few TeV*

Towards Background independence via AdS/CFT

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Also : *Doubly* or *Deformed Special Relativities* might be effective theories of QG — their quantization still in progress

***cf*. Amelino – Camelia talk**

FEATURES OF QUANTUM GRAVITY

- QUANTUM FLUCTUATIONS OF SPACE TIME METRIC AT PLANCK SCALES MAY RESULT IN MICROSCOPIC ***FOAMY*** SPACE-TIME ***STRUCTURE***

$$\int Dg_{\mu\nu}(x)D(\dots)e^{-\frac{1}{\kappa}\int d^4xR(g)+\dots}$$

$$\kappa \propto G_N = M_P^{-2}$$
$$\ell_P = M_P^{-1} = 10^{-35}\ \mathrm{m}$$

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includes singular configurations

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QUANTUM GRAVITY AS A MEDIUM

Space-Time at Planck scales may have a ``foamy'' structure (J. A. Wheeler), with possible coordinate non-commutativity or Lorentz Violation at microscopic scales

Quantum Gravity then may behave as a medium, with non-trivial ``optical'' properties:

Vacuum Refractive Index induced by QG !
Energy dependent speed of light, effects increase with energy of photon, due to increase in distortion of space time. Contrast with Matter-induced ordinary refractive indices.

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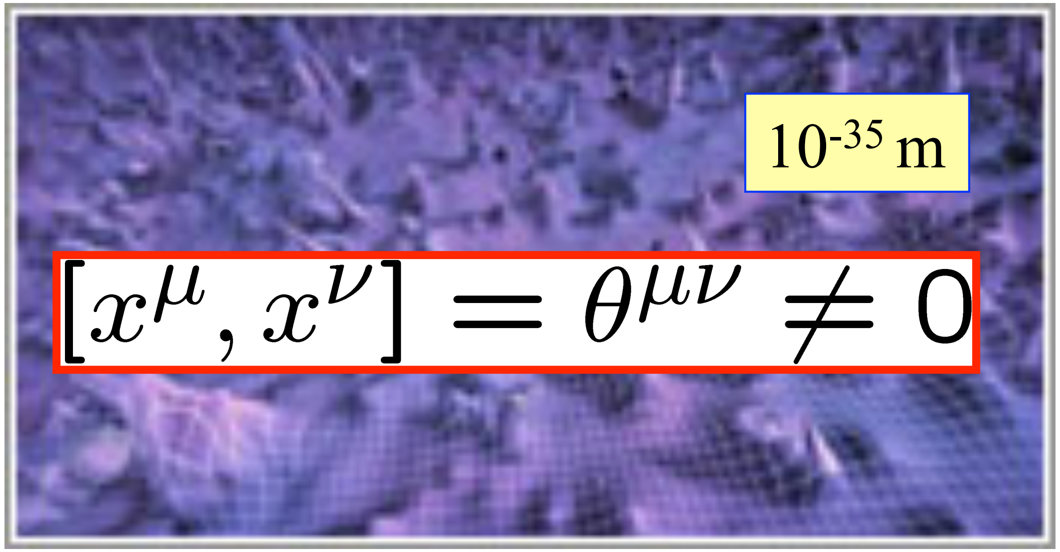

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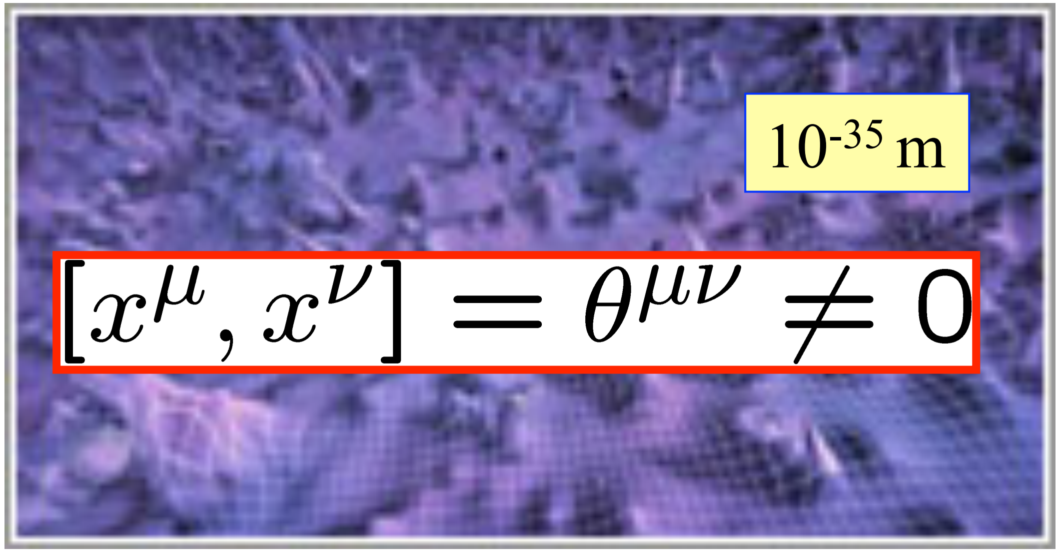

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ACT I
``FOAM'' OLOGY
PHENOMENOLOGY OF
QG FOAM VACUA
Some Aspects

Quantum-Gravity Induced Modified Dispersion for Photons

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

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

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Space-time Metric describing space-time Distortions induced by Interactions of Photons with space-time defects

NB: momentum dependent metric (Finsler)

GEOMETRY OF PHASE-SPACE IMPORTASNT IN QG?

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

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

subluminal : $\eta > 1$, superluminal $\eta < 1$

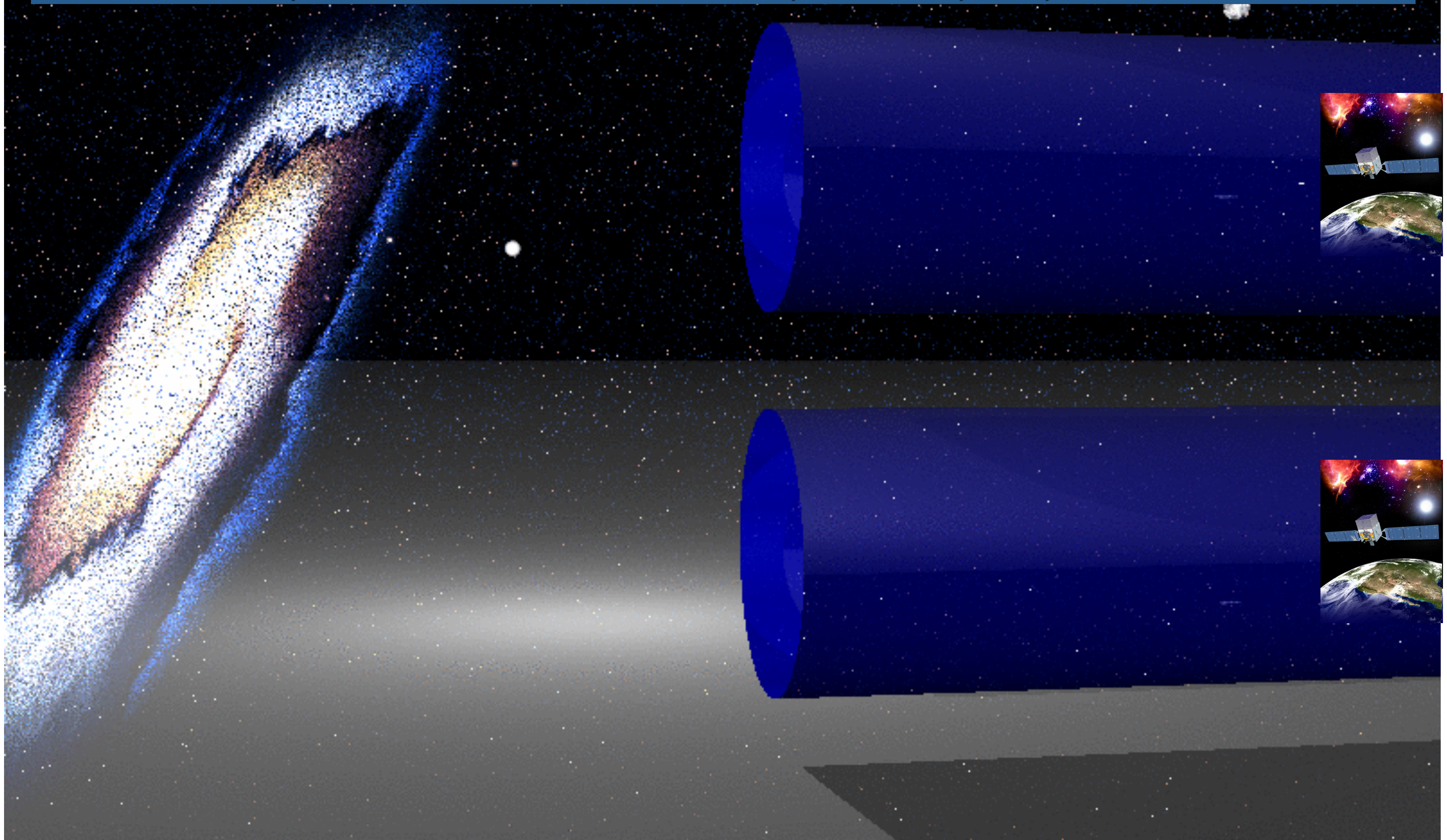
QUANTUM GRAVITY AS A MEDIUM

Quantum Gravity then may behave as a medium, with non-trivial ``optical'' properties:

If Vacuum Refractive Index induced by QG non trivial…

….then, it would be Manifested through delays (subluminal) or advances (superluminal) in arrival times of the the more energetic photons in a wave packet or in general a multi frequency group of ``simultaneously" emitted photons.

$$E = p\left(1 + \sum_{n=1}^{\infty} a_n \left(\frac{|\vec{p}|}{M_{\mathrm{QG}}}\right)^n\right) \qquad a_1 < 0$$



Subluminal QG-induced Refractive Index: Higher energy photons arrive later

Courtesy: N. Doltsinis@kcl.ac.uk

Early Theoretical Predictions

Time as a Renormalization Group
Irreversibly flowing scale in
(Liouville, non-critical) String Theory

Ellis, NEM, Nanopoulos (1992)

Time – Space different behaviour, different symmetries
Lorentz Violation natural consequence of this microscopic approach

``Environment'' of Quantum Gravity (QG) (stringy) d.o.f.
inaccessible to low-energy observer scattering experiment;
Induced Decoherence and hence Microscopic Time Arrow

Off-shell stringy matter excitations due to interaction with
the QG ``environment''

Induced Modified Dispersion Relations (c(E) refractive index)
for photon probes due to propagation in QG ``medium''

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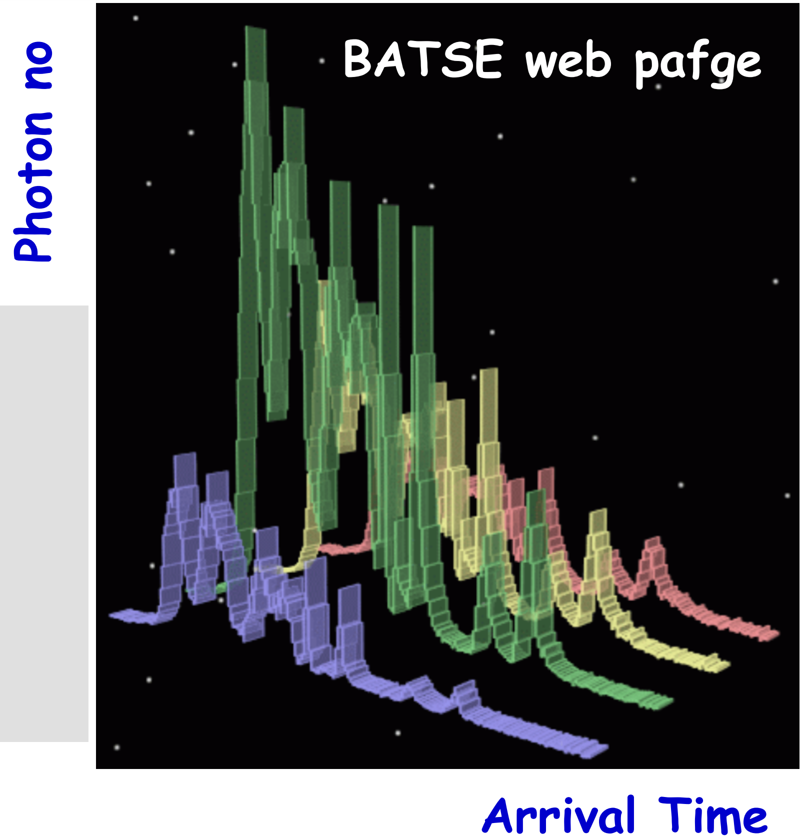
Early Suggested Tests

Gamma Ray Bursts (GRB)

GRB light curves: Fine structure
in sharp photon arrival peaks
at different energy channels

Red	25-50 keV
Yellow	50-100 keV
Green	100-300 keV
Blue	> 300 keV



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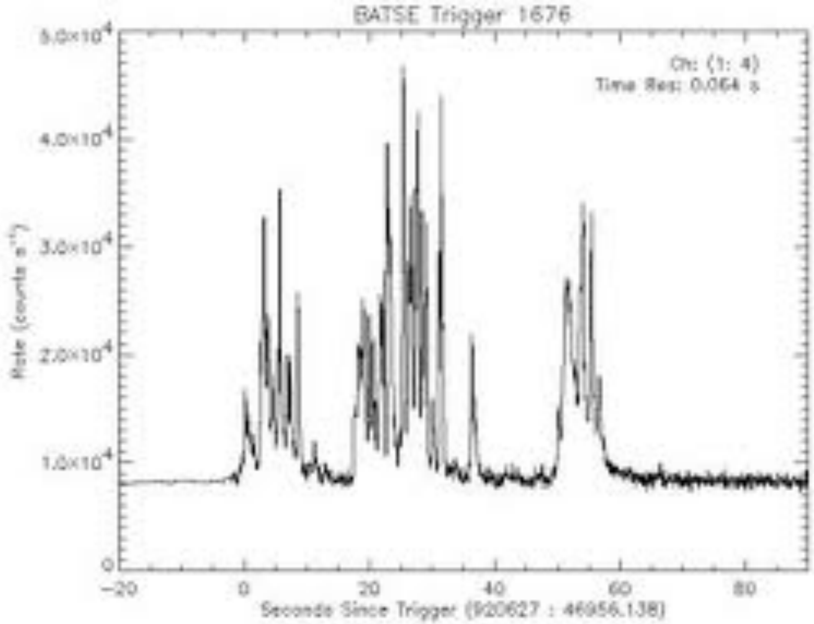


Use them to Test energy dependent speed of photons ….

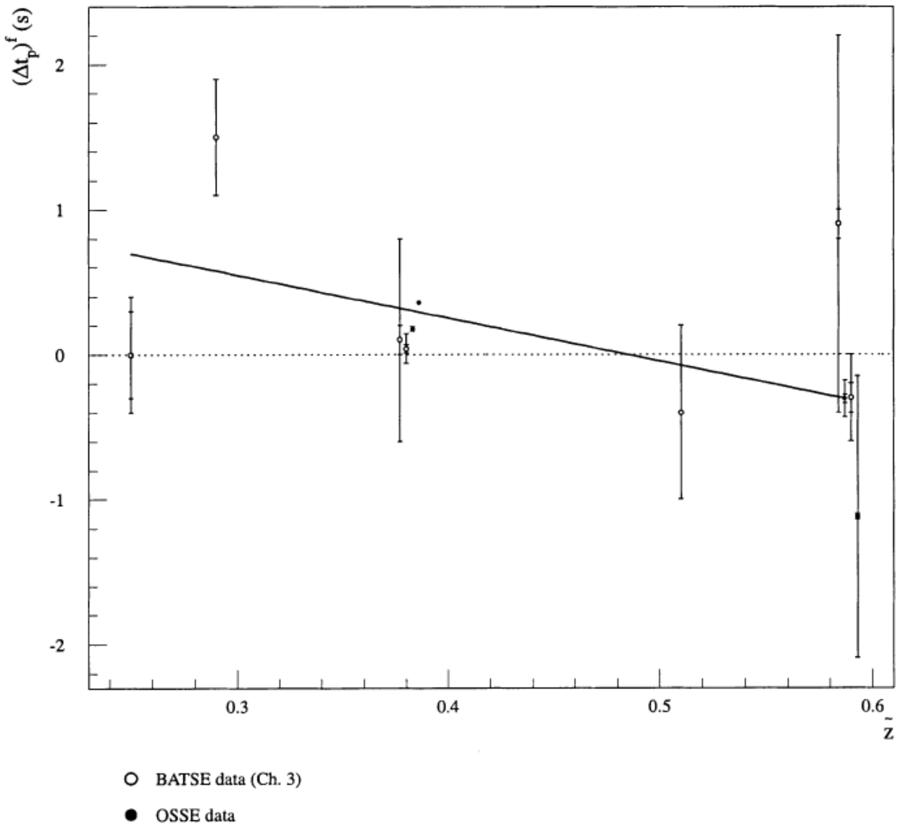
Amelino Camelia, Ellis, NEM, Nanopoulos, Sarkar (1997/12)
Ellis, Farakos, Mitsou, NEM, Nanopoulos (1999/07)
Ellis, NEM, Nanopoulos, Sakharov, Sarkisyan (2002- 2011)

Early Suggested Tests

Gamma Ray Bursts (GRB)

Arrival time
delays or advances

$$\Delta t = \frac{\Delta E^n}{M_{\rm QG}^n} \frac{``L"}{c}, \quad n \geq 1$$



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Early Suggested Tests

Gamma Ray Bursts (GRB)

Arrival time delays or advances

$$\Delta t = \frac{1+n}{2H_0} \int_0^z dz \frac{E^n}{M_{\rm QG}^n} \frac{(1+z)^n}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}} \, , n \geq 1$$

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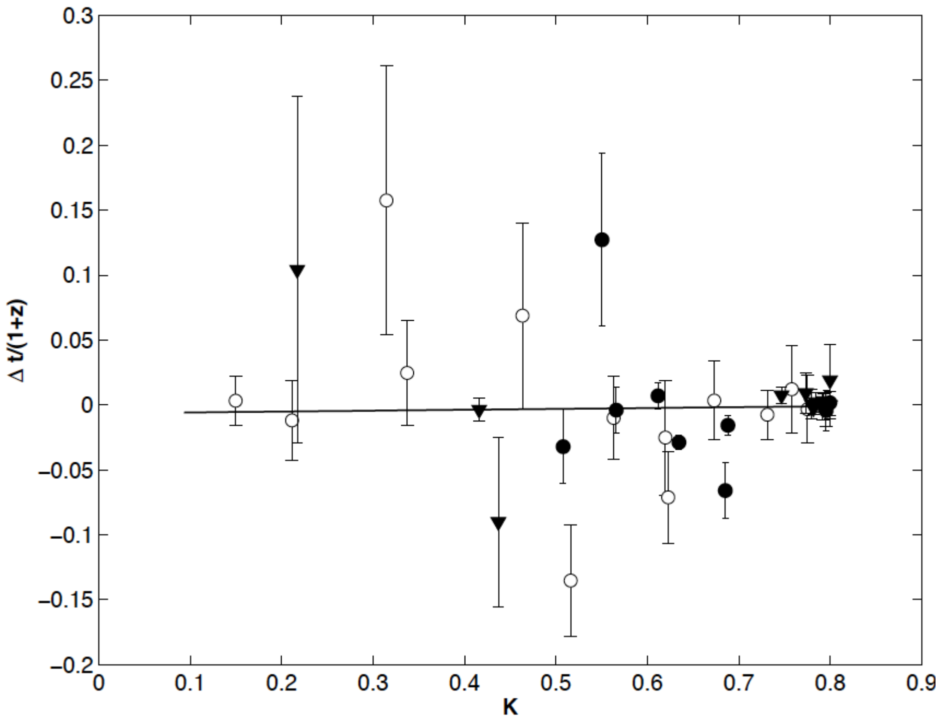


Ellis, NEM, Nanopoulos, Sakharov, Sarkisyan (2002-2007)
Jacob Piran (2007)

$M_{QG(1)} > 1.4 \times 10^{16}$ GeV

MAGIC results (2005)

TeV Photons from
Active Galactic Nucleus
(AGN) Mkn 501 at red-shift
z = 0.03

More energetic
photons (1.2 - 10 TeV)
delayed by O(1 min) compared
to E < 0.6 TeV

First Interesting result…
in conflIct with Conventional
Astrophysical acceleration
AGN Models (e.g. Crab Nebula)

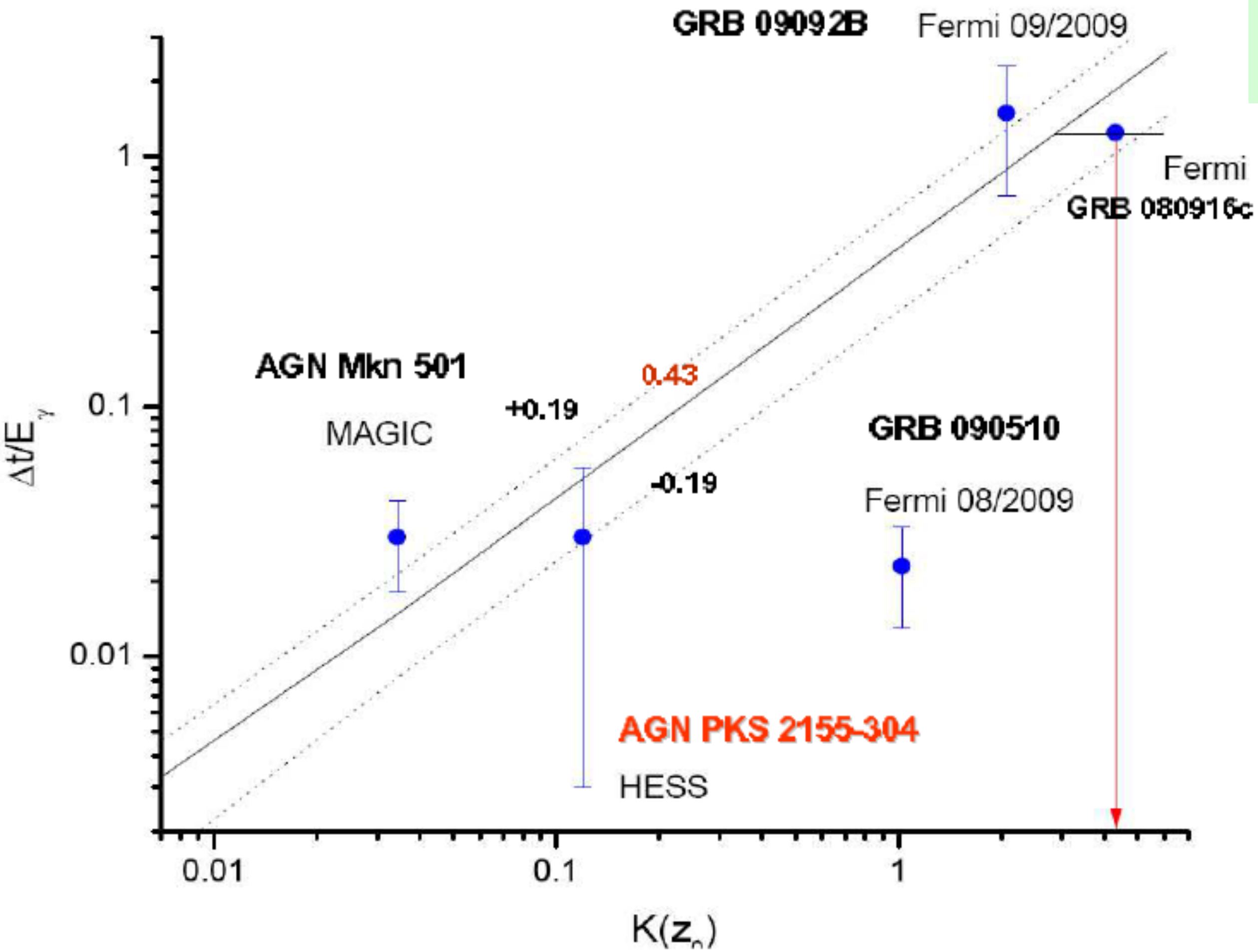
Interestingly can fit ***QG subluminal refractive index***
with ***linear*** M_{QG} suppression
with $M_{QG(1)} = 0.2 \times 10^{18}$ GeV

or, if astrophysics at source
taken into account

$$\mathbf{M_{QG(1)} > 0.2 \times 10^{18}\ GeV}$$

Other Observed Photon Delays (H.E.S.S, FERMI)

Ellis, NEM, Nanopoulos (2009, 2010)



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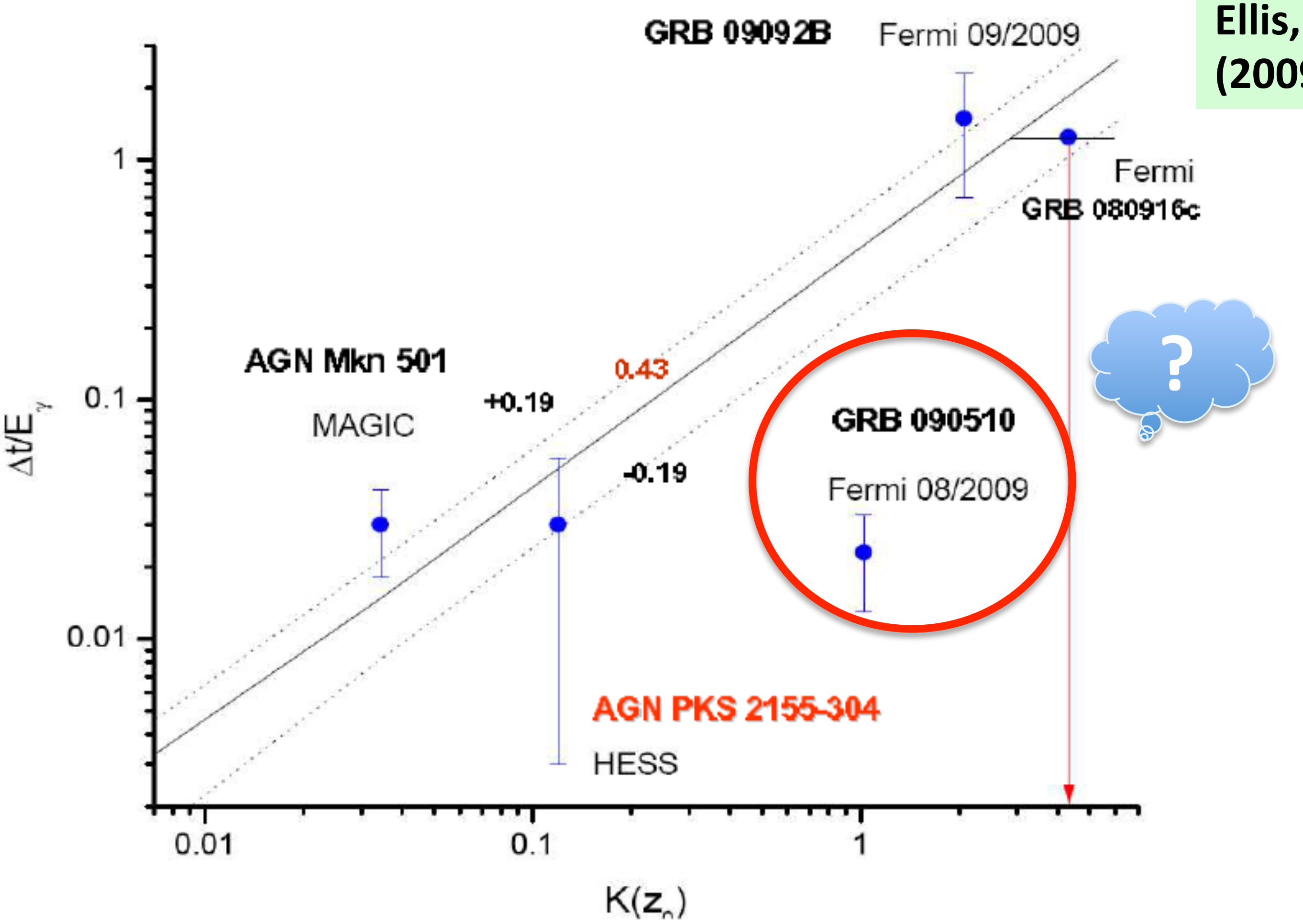

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OPERA RESULTS – Superluminal neutrinos

2011 : Another Surprise, more mysterious

NEUTRINOS IN OPERA have been argued to propagate with superluminal velocities

$v/c - 1 = (\, 2.48 \pm 0.28 \pm 0.30\,)\ 10^{-5}$

(but independent of the energy, at least in the range of the experiment)

OPERA v2

$$(v\text{-}c)/c = (2.37 \pm 0.32\ (\text{stat.})\ ^{+0.34}_{-0.24}\ (\text{sys.})) \times 10^{-5}$$

overall significance more 6.2 σ

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Can Subluminal Photons and Superluminal Neutrinos be consistent with Causality and models of Quantum Gravity?

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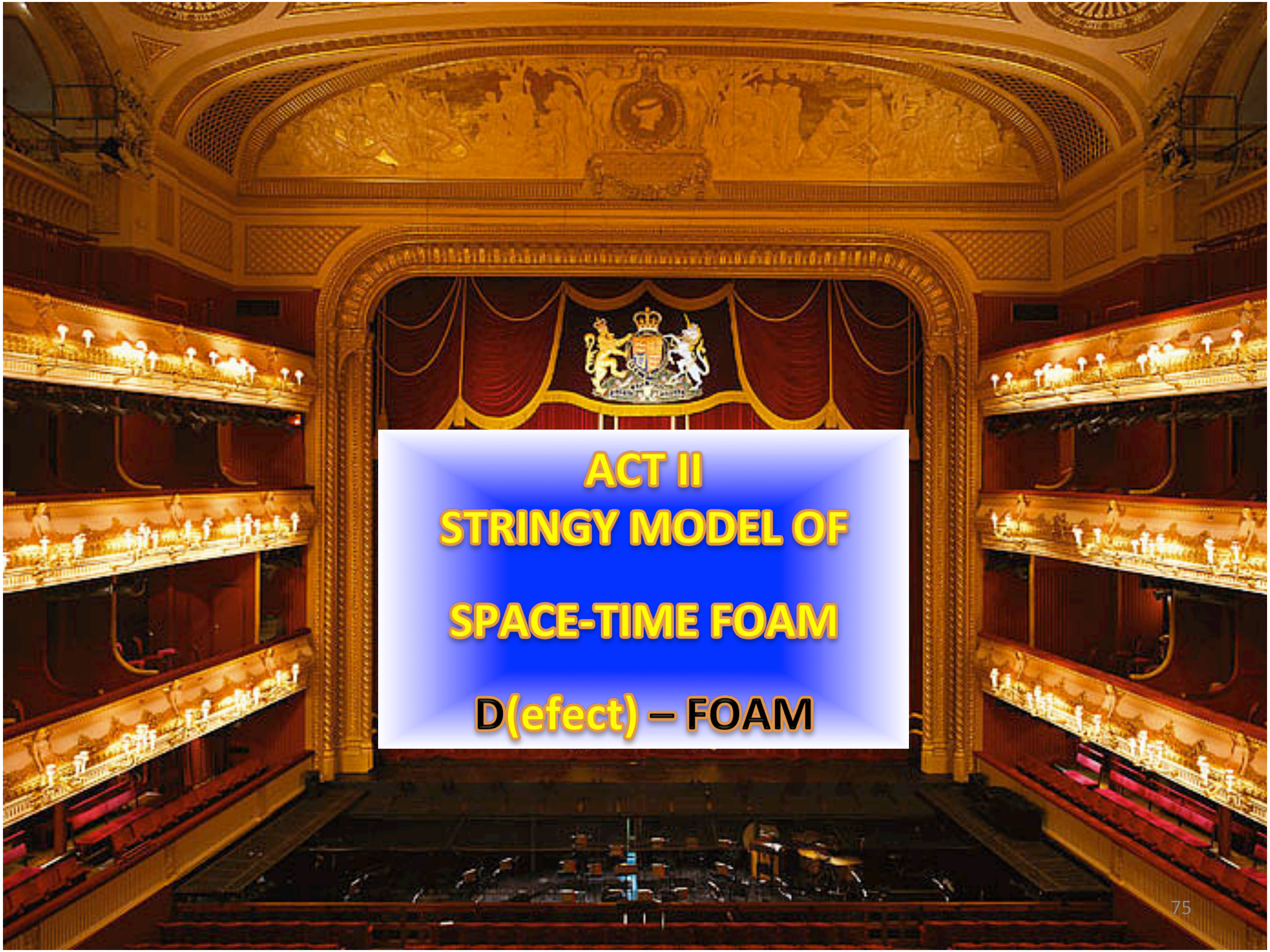
Can Subluminal Photons and Superluminal Neutrinos be consistent with Causality and models of Quantum Gravity?

YES ***e.g.*** **IN A SPACE-TIME FOAM MODEL INSPIRED FROM STRING THEORY**



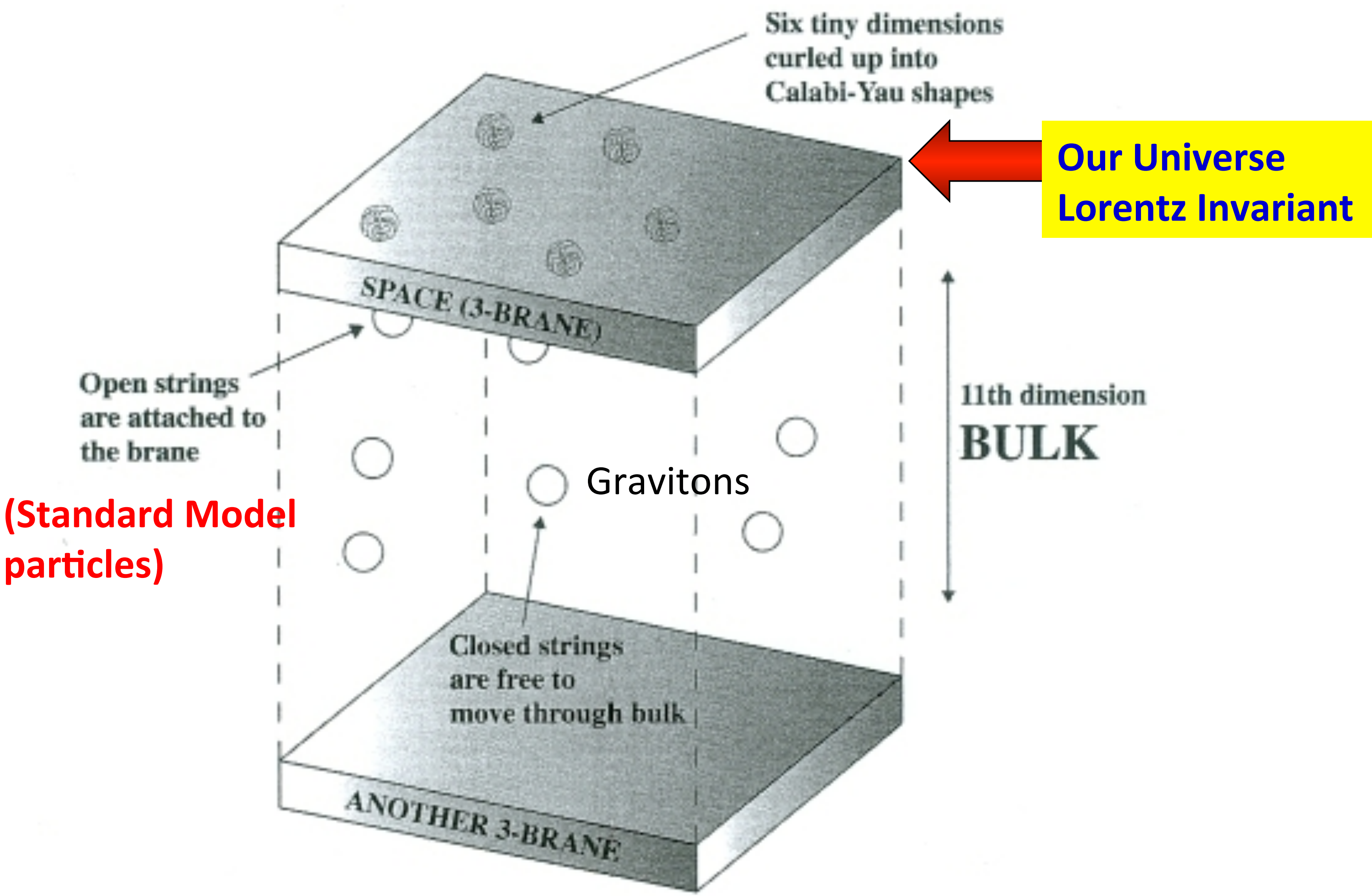
ACT II
STRINGY MODEL OF
SPACE-TIME FOAM
D(efect) – FOAM

``Foamy Structures'' in String Theory

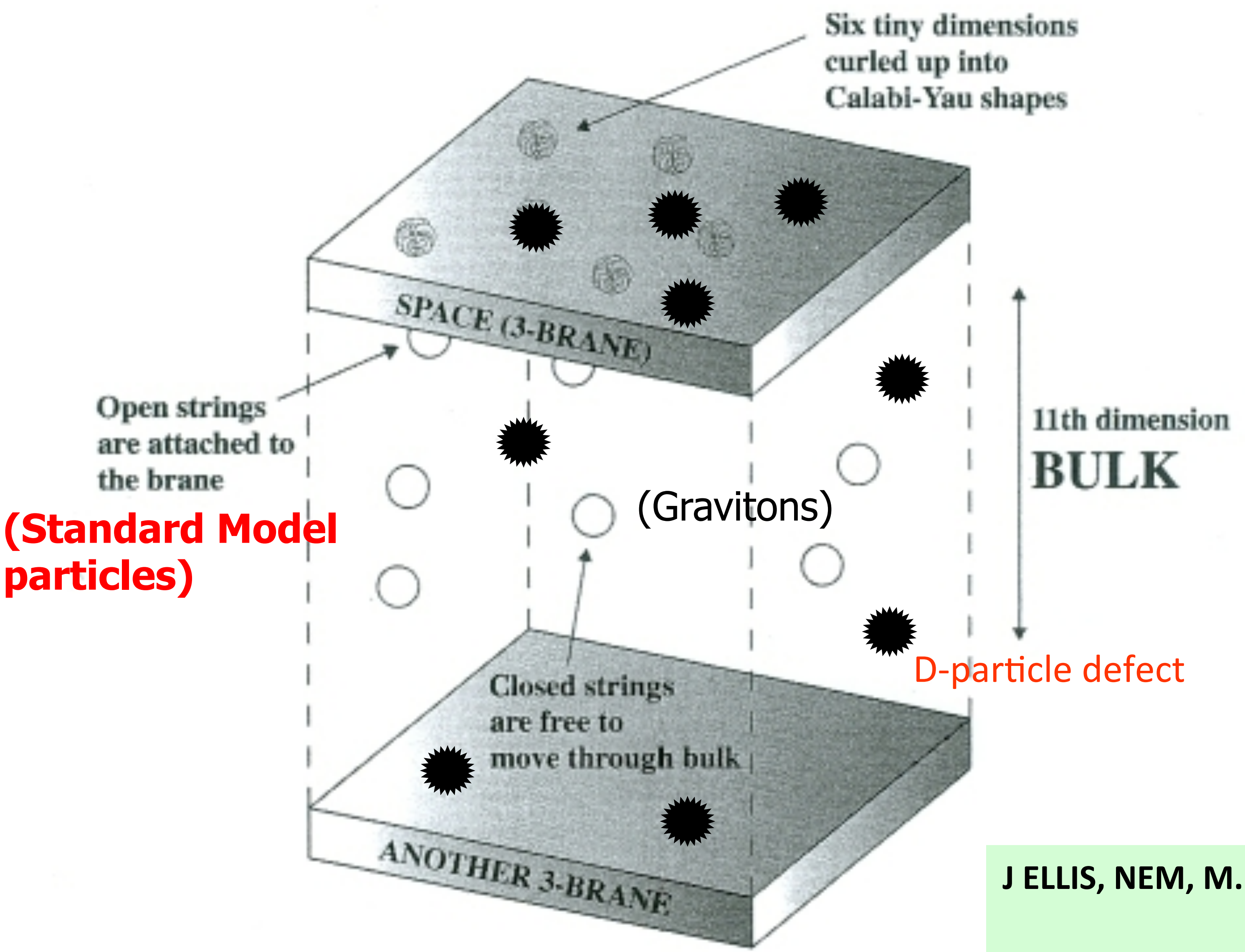
- Foamy space-time structures may also be provided by higher-dimensional space-time ``***real* D*efects***'' in the modern version of string theory involving ***branes*** (***D-Foam***)

Ellis, NEM, Nanopoulos, Sarben Sarkar, Szabo, Westmuckett…

BRANE/STRING -THEORY



BRANE-WORLDS with D-PARTICLE (POINT-LIKE BRANE) DEFECTS



J ELLIS, NEM, M. WESTMUCKETT

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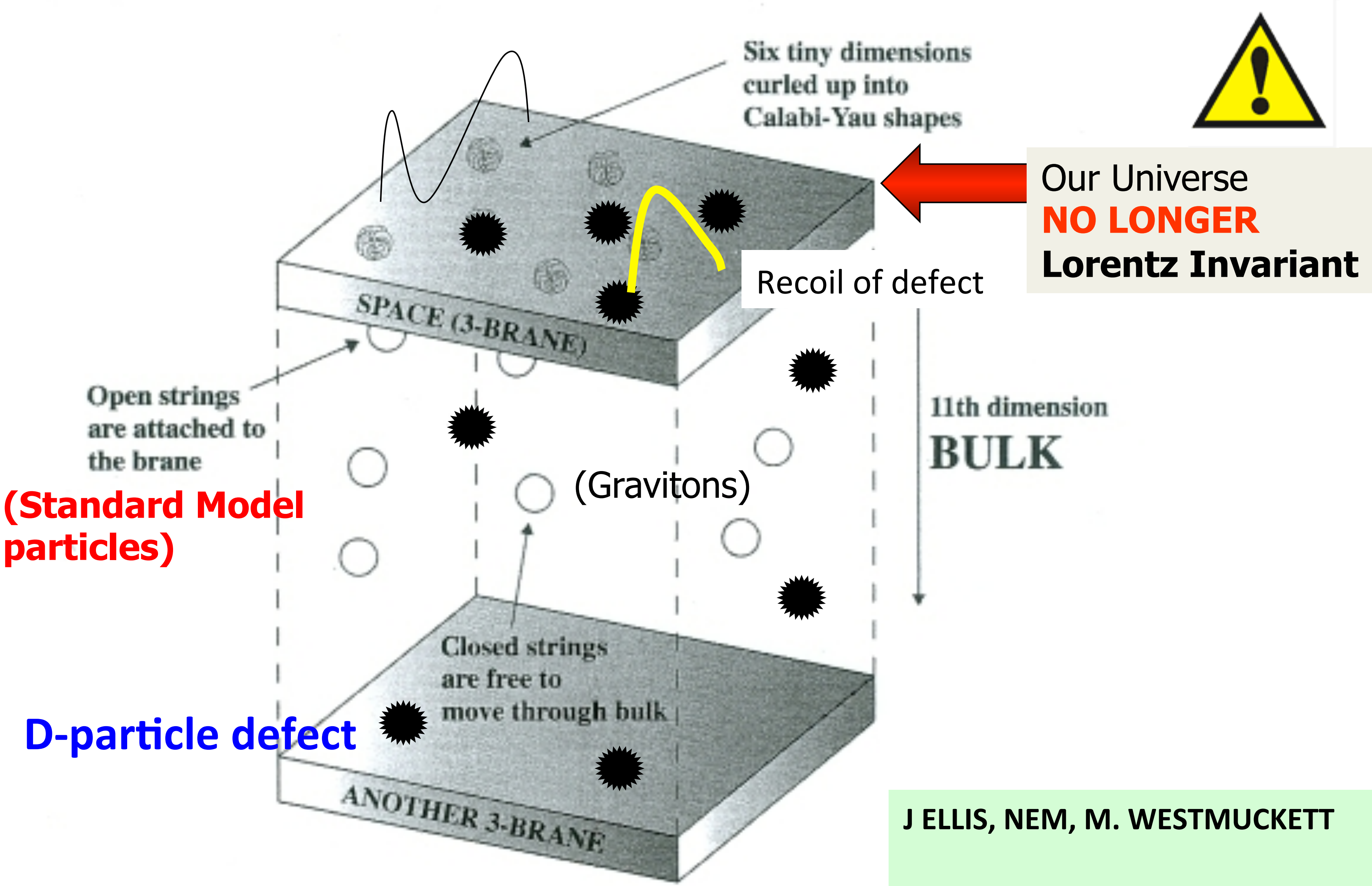

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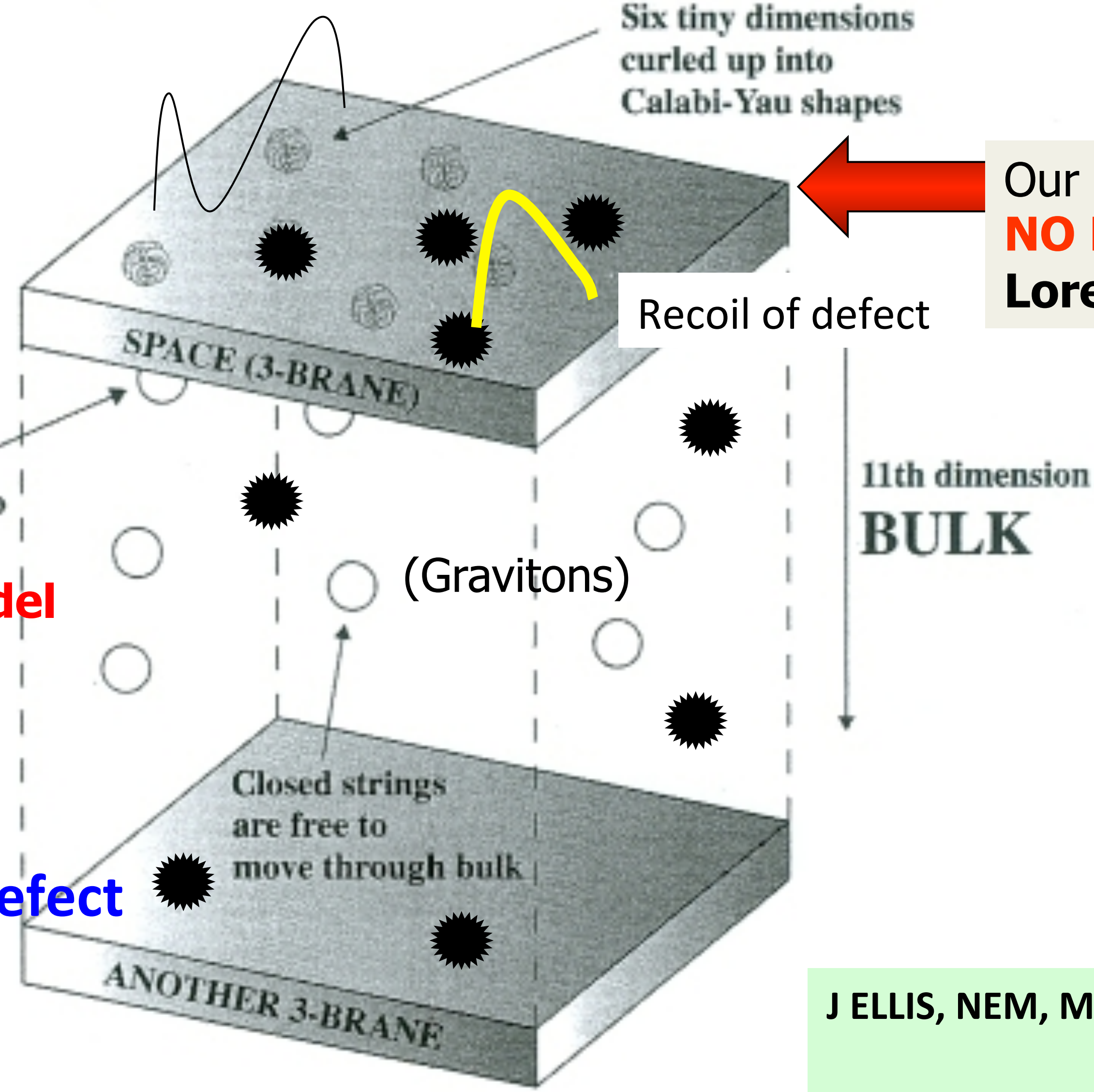
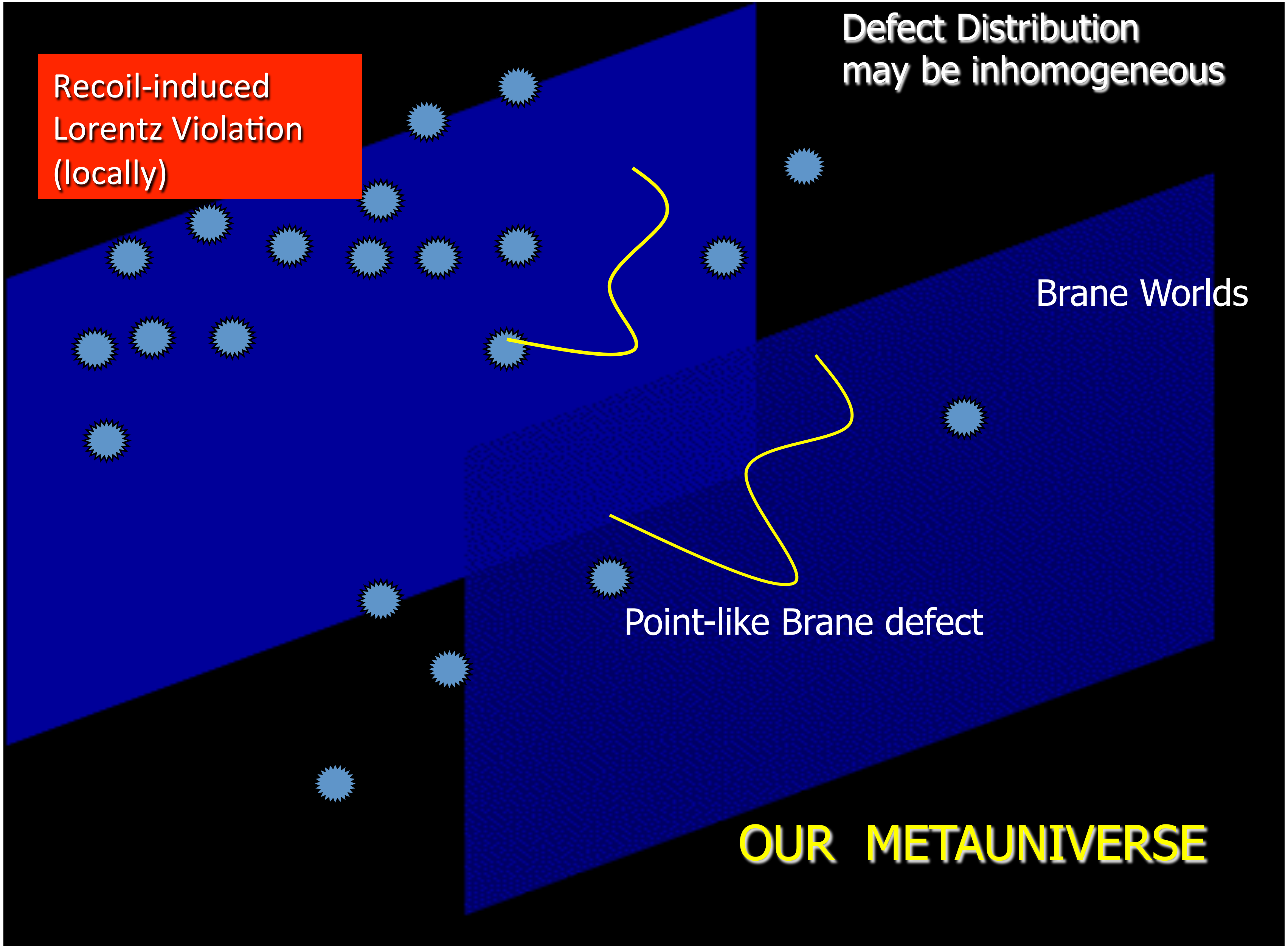


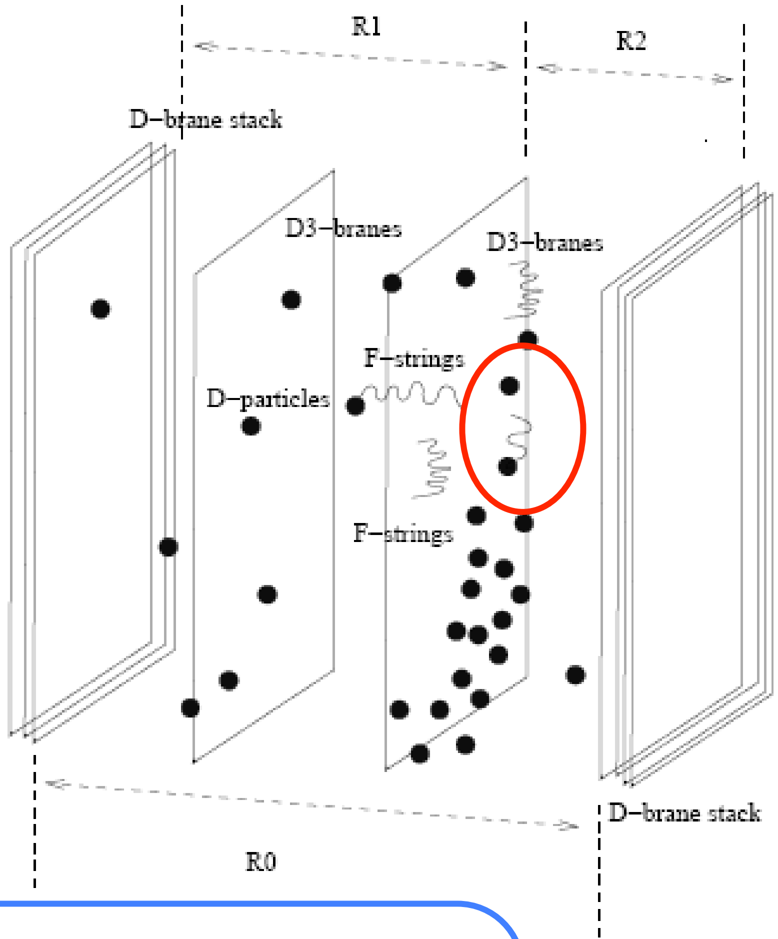
Our Universe
NO LONGER
Lorentz Invariant

J ELLIS, NEM, M. WESTMUCKETT

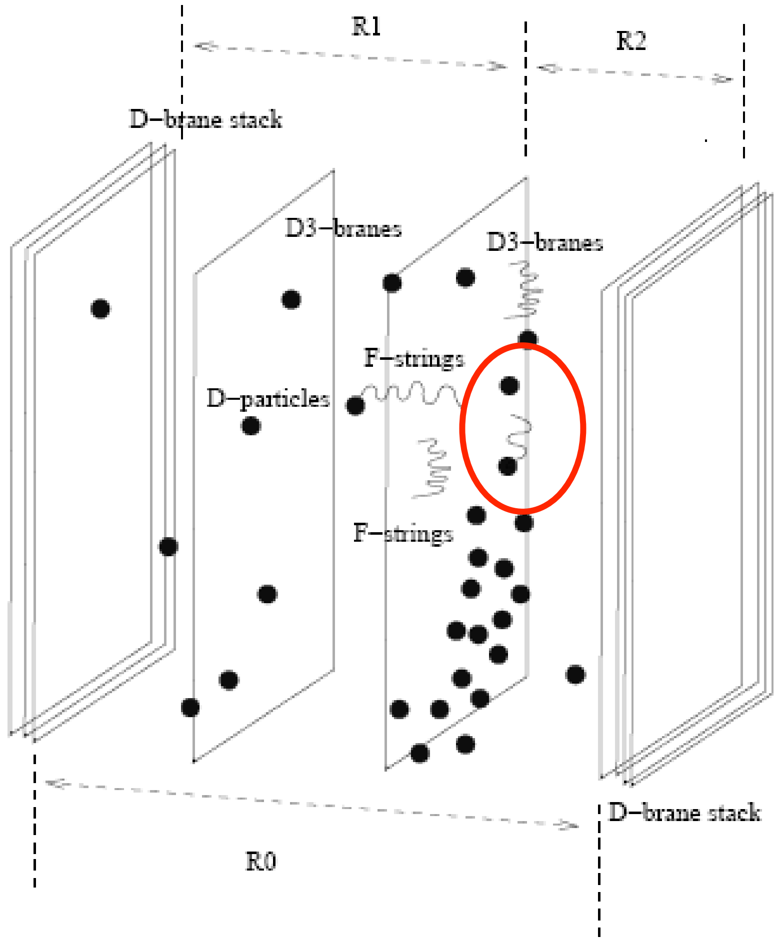


Colliding Brane world model of Space-Time with point-like space-time defects

Two kinds of Interactions



Involve ``spontaneous'' ***change*** of world-sheet ***boundary conditions*** for the open string



Two kinds of Interactions

(I) Just RECOIL of massive defect distortion of surrounding space time

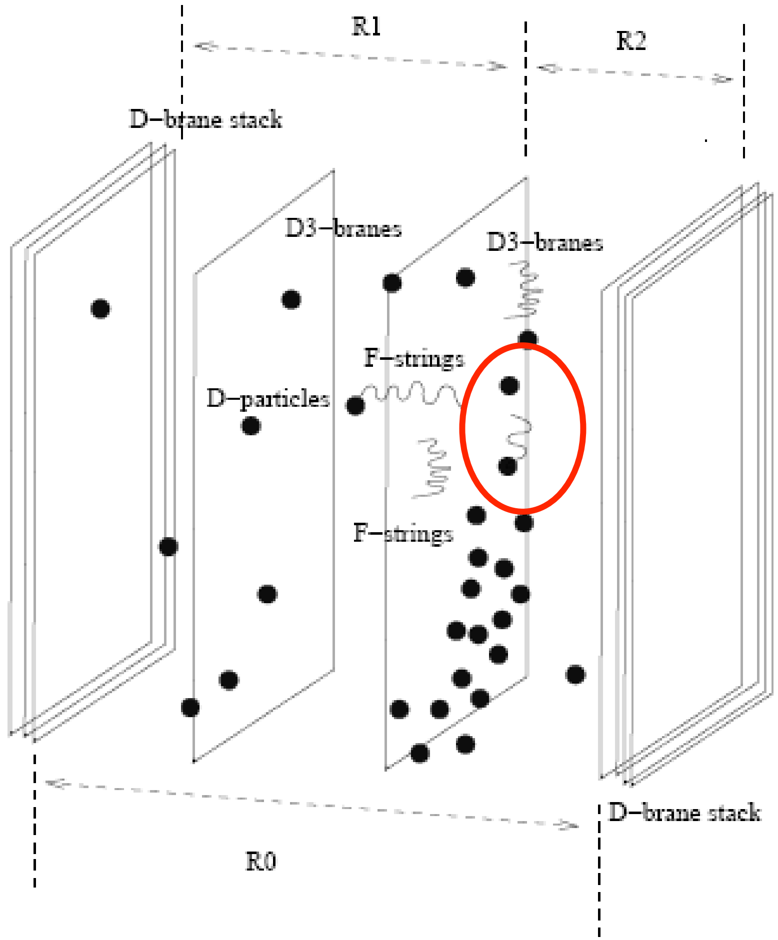
Problem Equivalent to Strings propagating in Local ``electric field'' backgrounds Time-Space non-commutativity

$$[X^i, t] \propto F^{0i}(k,x) \equiv u^i(k,x)$$

But electric field is on phase space

$$u^i(k,x) = g_s \frac{\Delta k_i}{M_s}$$

D-particle's recoil velocity depends on momentum transfer Δk_i



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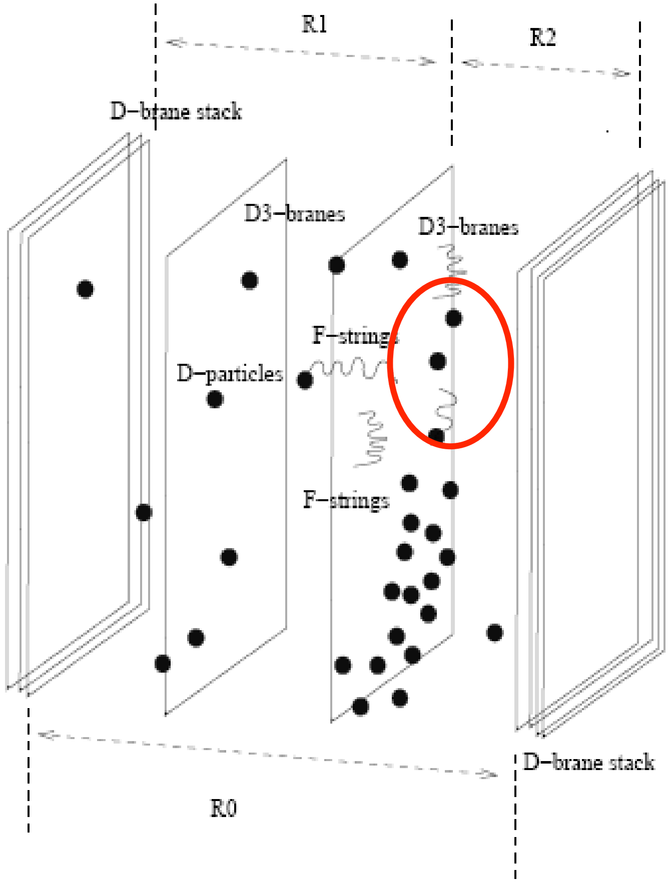
M_s / g_s arbitrary D-particle mass (bulk string scale M_s not determined, can be as low as a few TeV, $g_s < 1$).



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***Induced metric* depends on momenta as well as coordinates (Finsler type) : e.g. u || X_1**

$$h_{00} = -h_{11} = |u_1|^2$$

$$h_{01} = g_s \frac{\Delta k_i}{M_s} \equiv u_1$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Explicit local breaking of SO(3,1) down to SO(2,1) rotation and boosts in transverse directions

Local Lorentz Violation due to direction of Defect recoil velocities

Locally induced metric distortions seen by ``open strings''

$$\boxed{\begin{aligned} ds^2 &= g_{\mu\nu} dx^\mu \, dx^\nu = \\ &-(1-|\vec{u}|^2)dt^2 + (1-|\vec{u}|^2)dx_1^2 + dx_2^2 + dx_3^2 + 2\vec{u}\cdot d\vec{x}\, dt \end{aligned}}$$

Modified photon dispersion relations due to locally induced metric

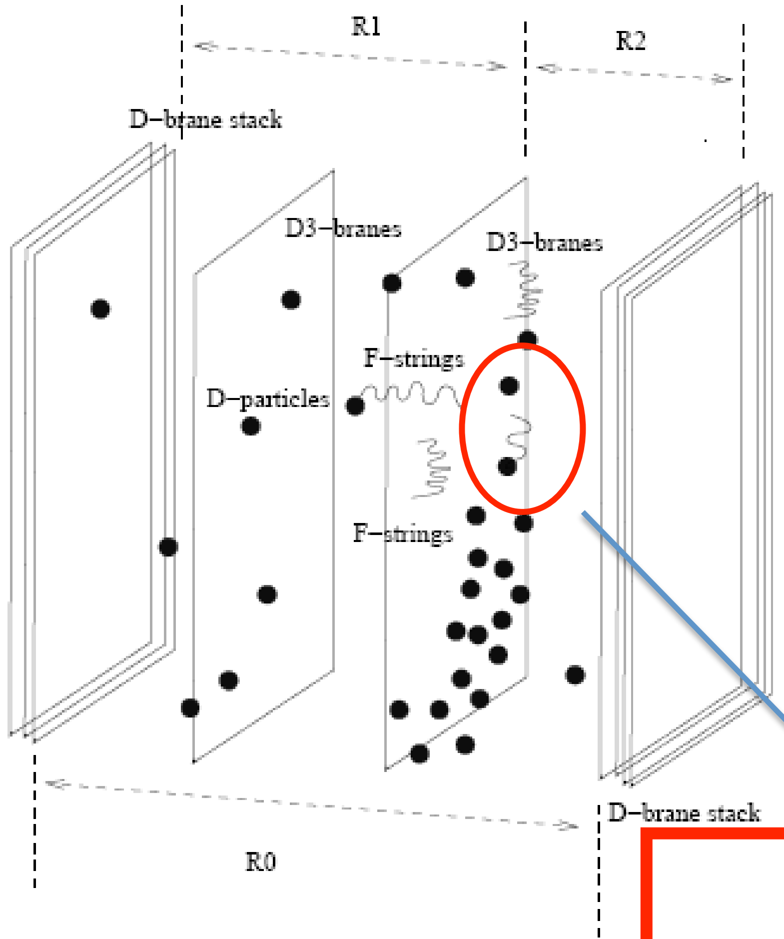
$$p^\mu p^\nu g_{\mu\nu} = 0$$

$$p^\mu = (E, \vec{p}) \Rightarrow \; 0 < E = -\vec{p}\cdot\vec{u} + p\left(1 + \frac{1}{2}|\vec{u}|^2 + O(|\vec{u}|^3)\right)$$

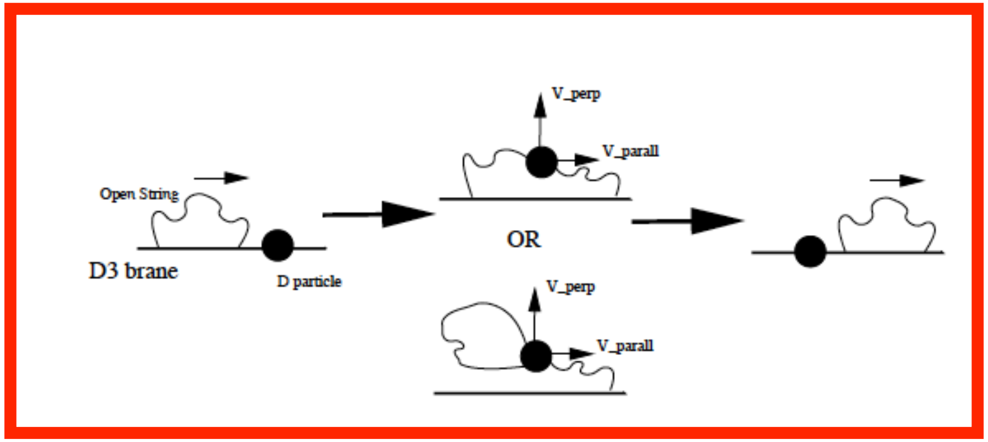
(Sub)Superluminal Group photon velocities, depending on relative directions u, p

$$v_g = \frac{\partial E}{\partial p} = 1 - |\vec{u}|\cos\vartheta + \frac{1}{2}|\vec{u}|^2 + \mathrm{O}(|\vec{u}|^3)$$

Two kinds of Interactions



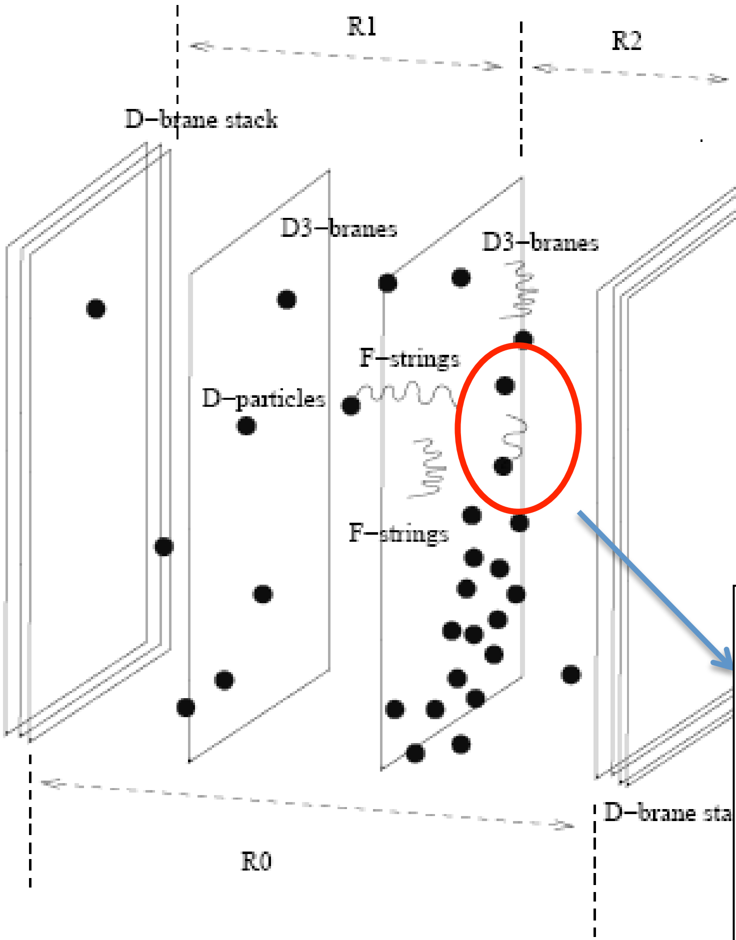
(II) String ***Splitting*** & (``momentary'') **Capture** by the defects

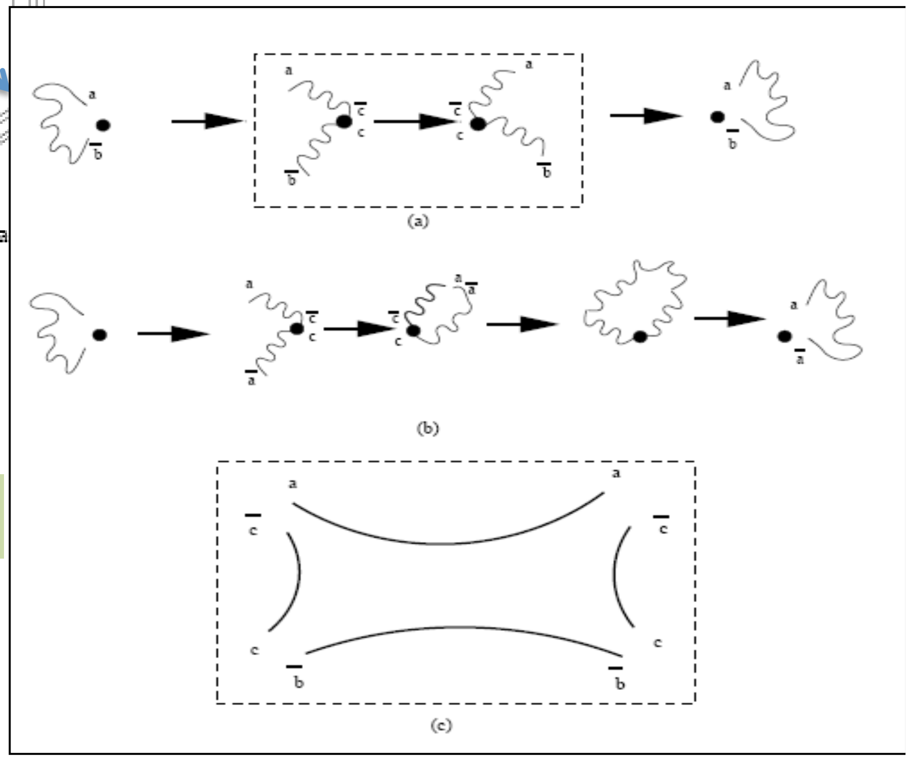


INTEMEDIATE STRING CREATION/EXCHANGE
PURELY NON-LOCAL EFFECT

Two kinds of Interactions

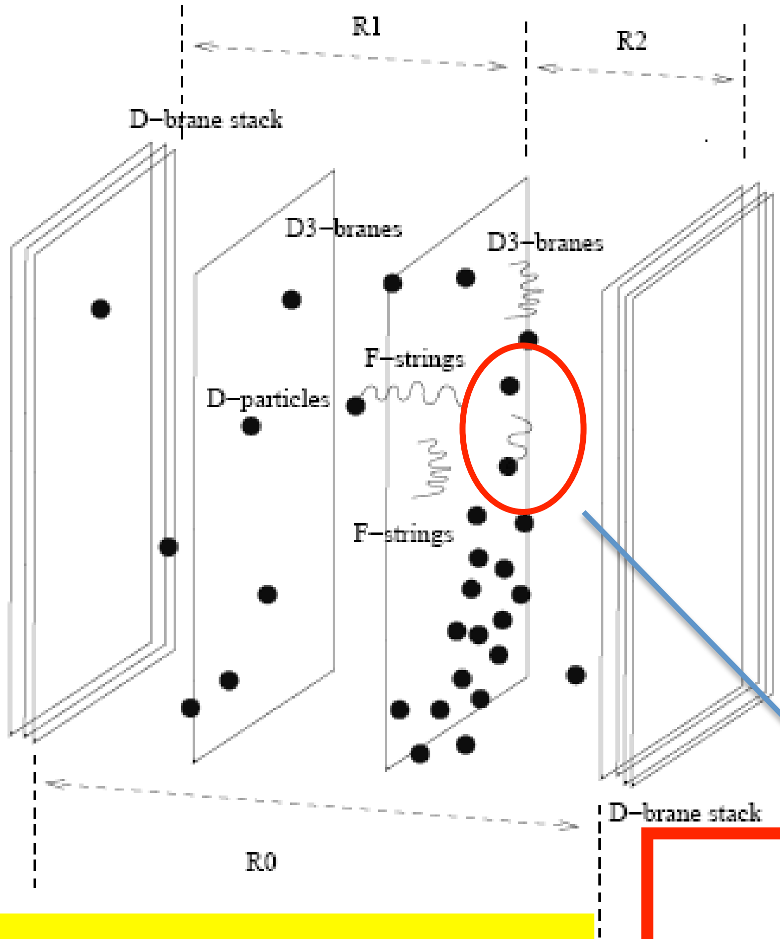
(II) String ***Splitting*** & (``momentary'') **Capture** by the defects





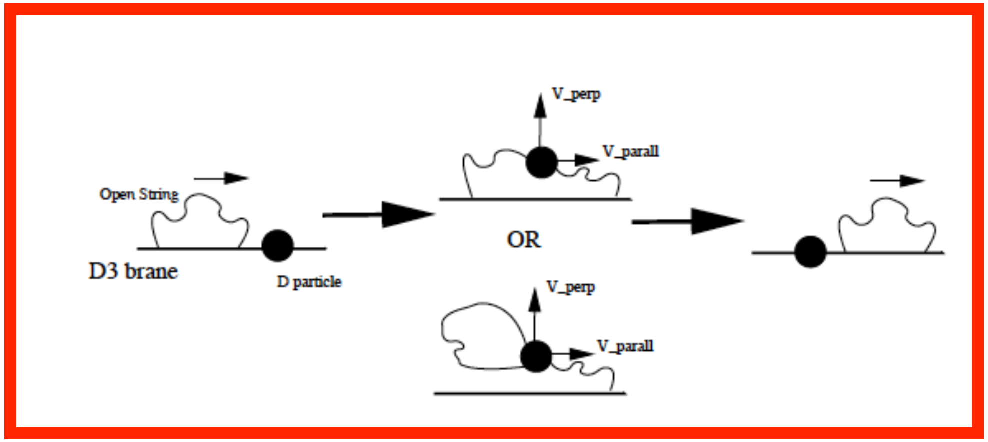
INTEMEDIATE STRING CREATION/EXCHANGE
PURELY NON-LOCAL EFFECT

string graphs



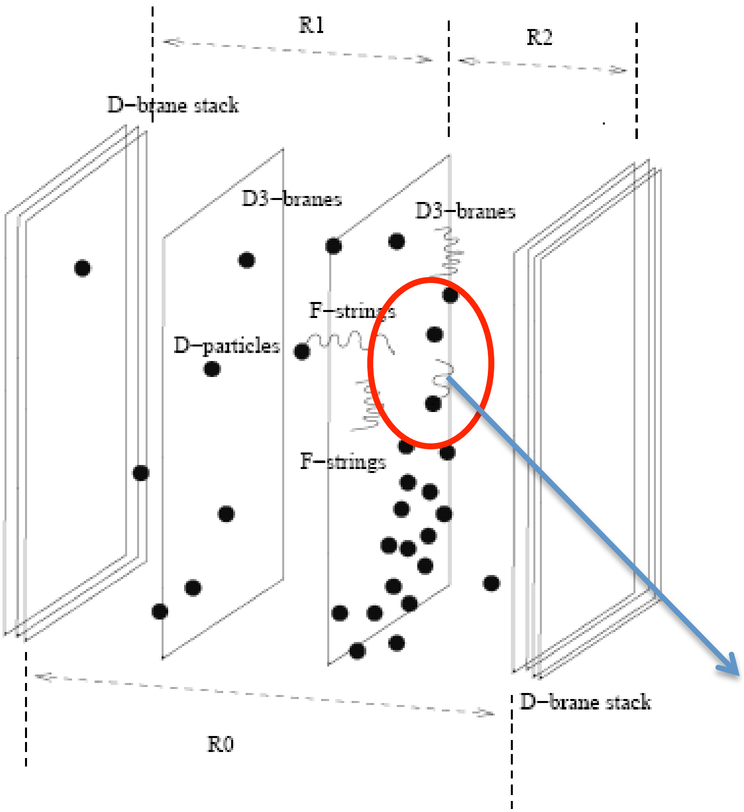
CHARGE CONSERVATION MUST BE RESPECTED DURING CAPTURE (***STRING SPLITTING***, INTERMEDIATE STRING CREATION & STRETCHING):

ONLY ELECTRICALLY NEUTRAL EXCITATIONS INTERACT VIA CAPTURE DOMINANTLY WITH FOAM DEFECT RECOIL OCCURS



Time Delays due to Intermediate String Creation & Oscillations

J ELLIS, NEM, NANOPOULOS



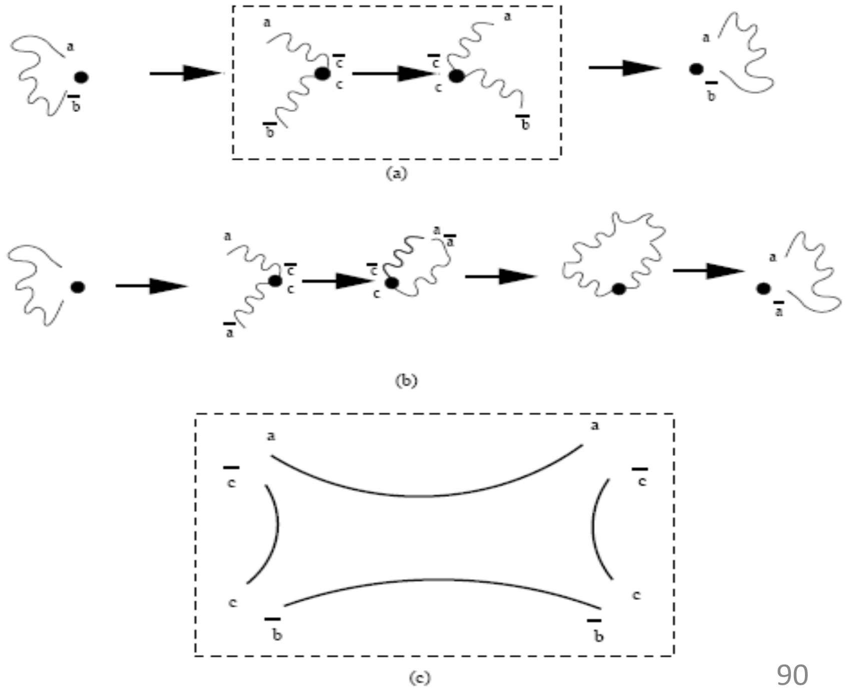
Veneziano Amplitude is proportional to

$$\frac{\pi}{\sin(\pi\, s\alpha')} \rightarrow e^{i\pi s\alpha' - \epsilon}$$

Poles at s = n/α ‘ (α ‘ = Regge slope)

Shift pole prescription s → s + iε

Delay: $\boxed{\Delta t \sim \alpha' E}$



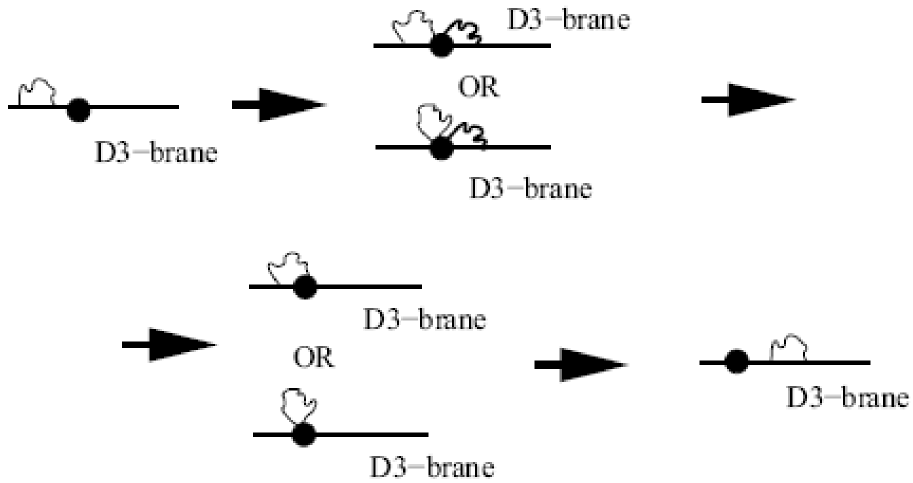
Time Delays due to
Intermediate String Creation
& Oscillations
Amplitude Pole Analysis

ELLIS, NEM, NANOPOULOS,
…+ LI, XIE

J ELLIS, NEM, DV NANOPOULOS

DELAYS COMPATIBLE WITH STRINGY UNCERTAINTIES

Time Delays due to Intermediate String Creation, growth up to length L & N Oscillations →



$$E = \frac{L}{\alpha'} + \frac{N}{L}$$

Compatible with the Stringy Uncertainties

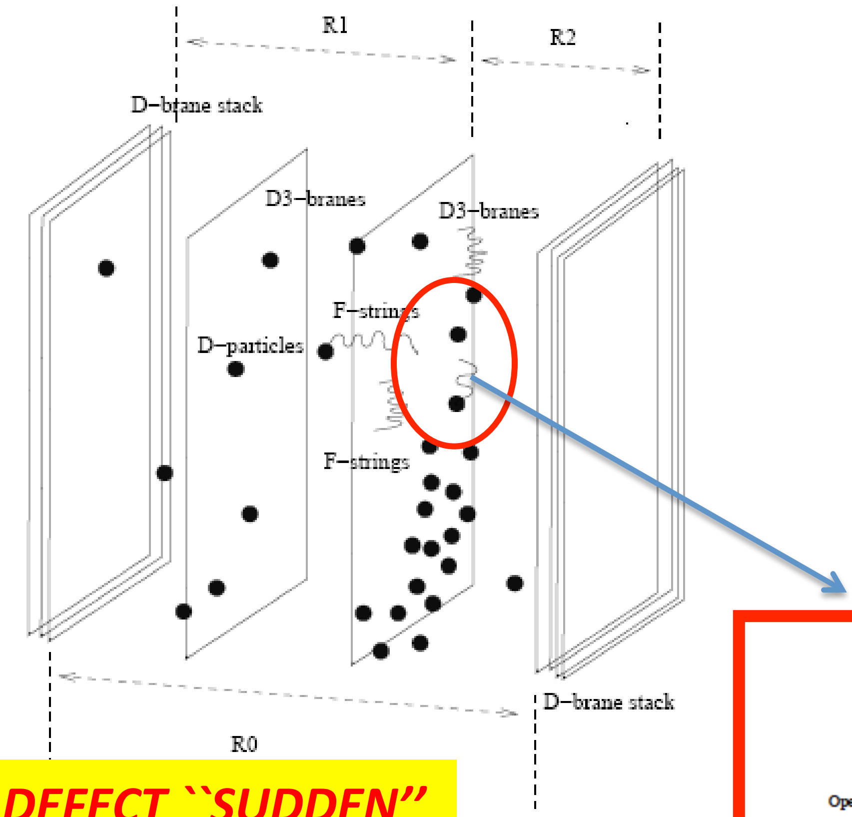
$$\Delta t \, \Delta x \geq \alpha'$$

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

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.

$$\Delta t \sim \alpha' E$$

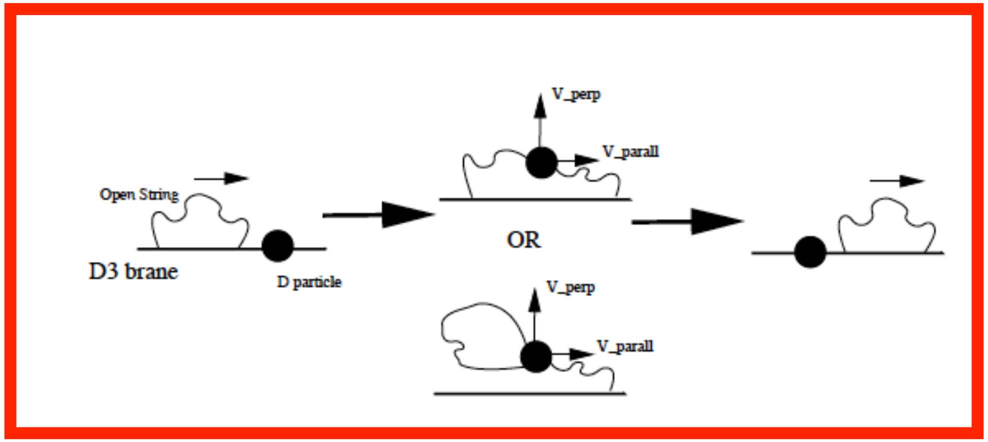
J ELLIS, NEM, NANOPOULOS



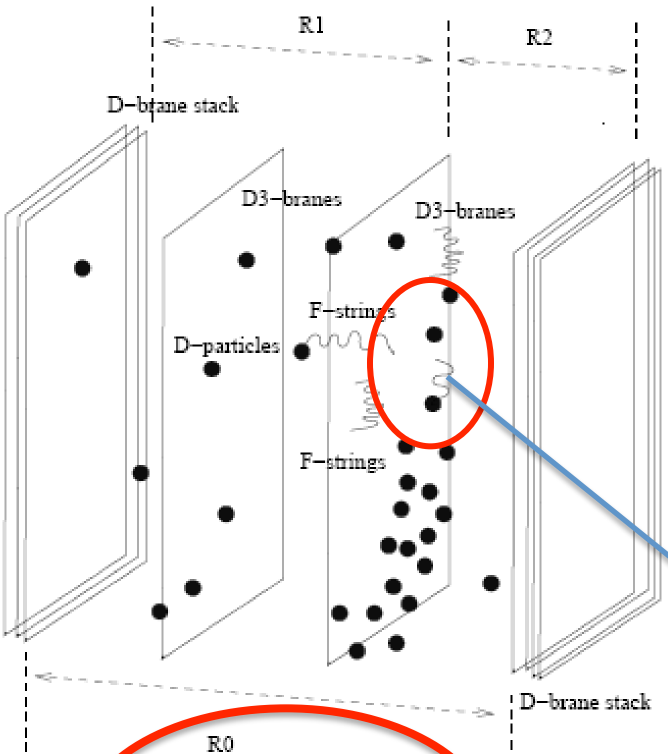
RECOILING DEFECT
``**DRAGS THE FRAME**''
NON-INERTIAL
ACCELERATION

DEFECT ``SUDDEN'' RECOIL OCCURS

$$u^i\Theta(t) = g_s \frac{\Delta k^i}{M_s} \equiv r^i k^i \Theta(t)$$



J ELLIS, NEM, DV NANOPOULOS

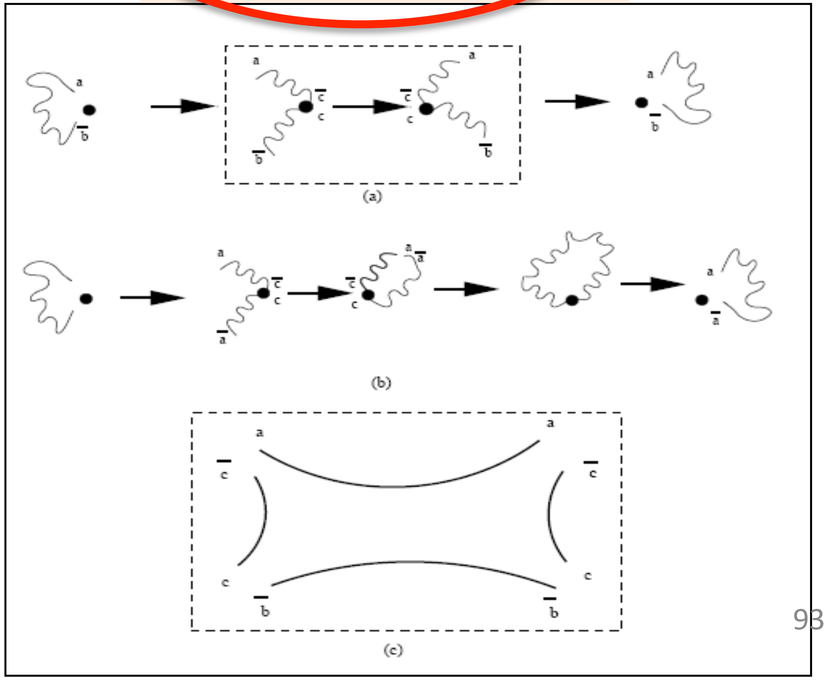


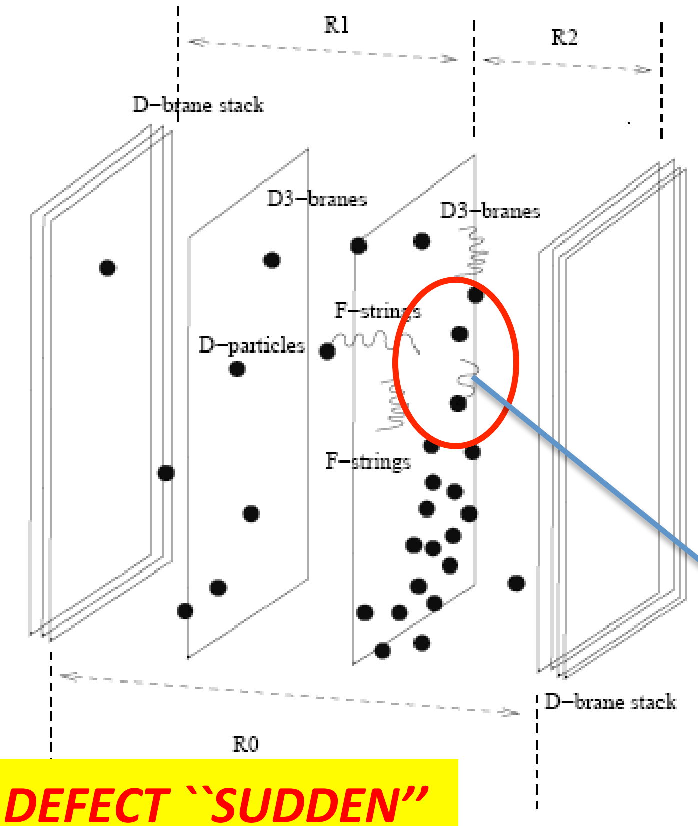
RECOILING DEFECT
``**DRAGS THE FRAME**''
NON-INERTIAL
ACCELERATION

NON-CRITICAL STRING in time-dependent recoil ``Electric'' field backgrounds

DEFECT ``SUDDEN'' RECOIL OCCURS

$$u^i\Theta(t) = g_s \frac{\Delta k^i}{M_s} \equiv r^i k^i \Theta(t)$$



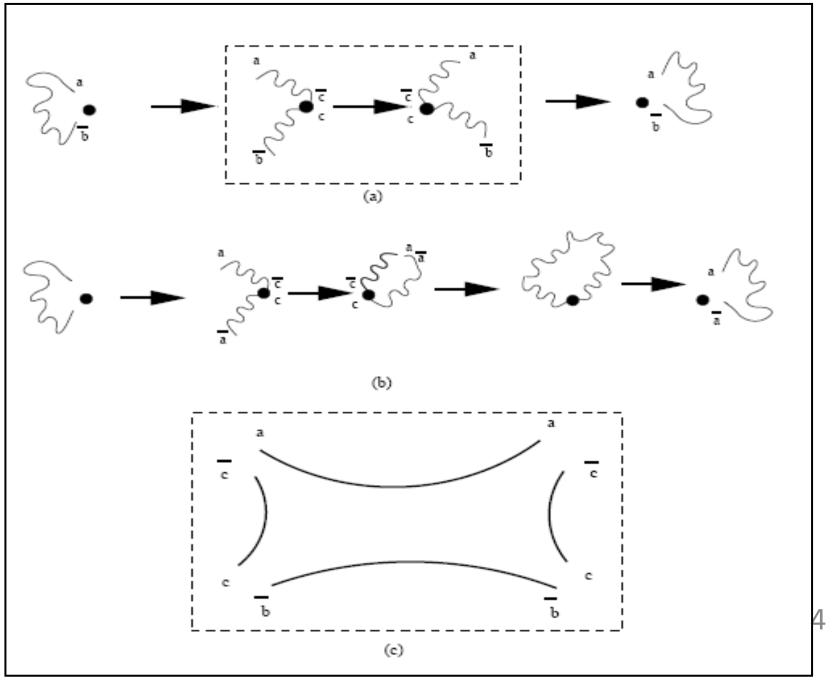


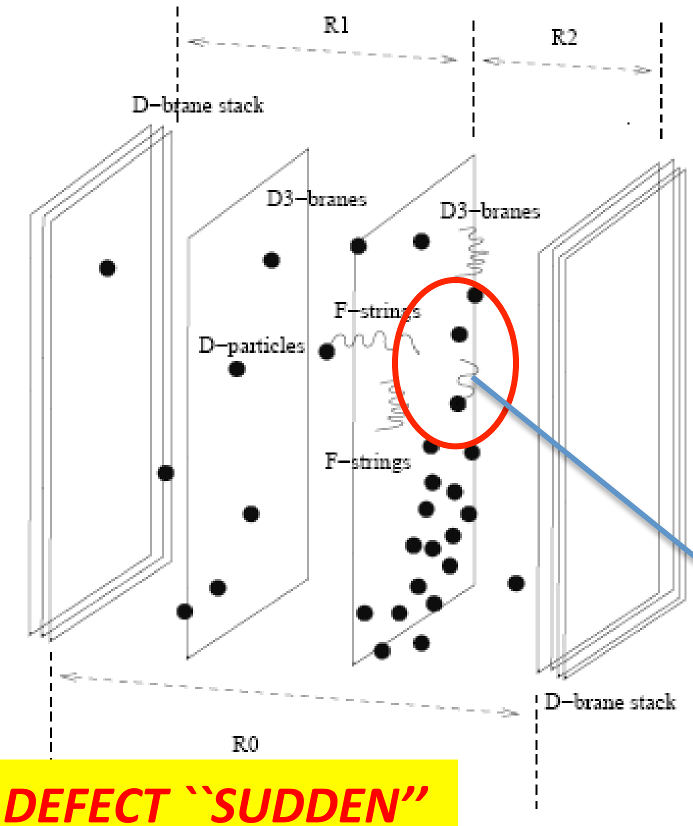
Time Delays due to Intermediate String Creation & Oscillations **increase** due to recoil

$$\Delta t \sim \frac{\alpha' E}{1 - |\vec{u}|^2}$$

DEFECT ``SUDDEN'' RECOIL OCCURS

$$u^i \Theta(t) = g_s \frac{\Delta k^i}{M_s} \equiv r^i k^i \Theta(t)$$





Time Delays due to
Intermediate String Creation &
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$$\Delta t \sim \frac{\alpha' E}{1 - |\vec{u}|^2}$$

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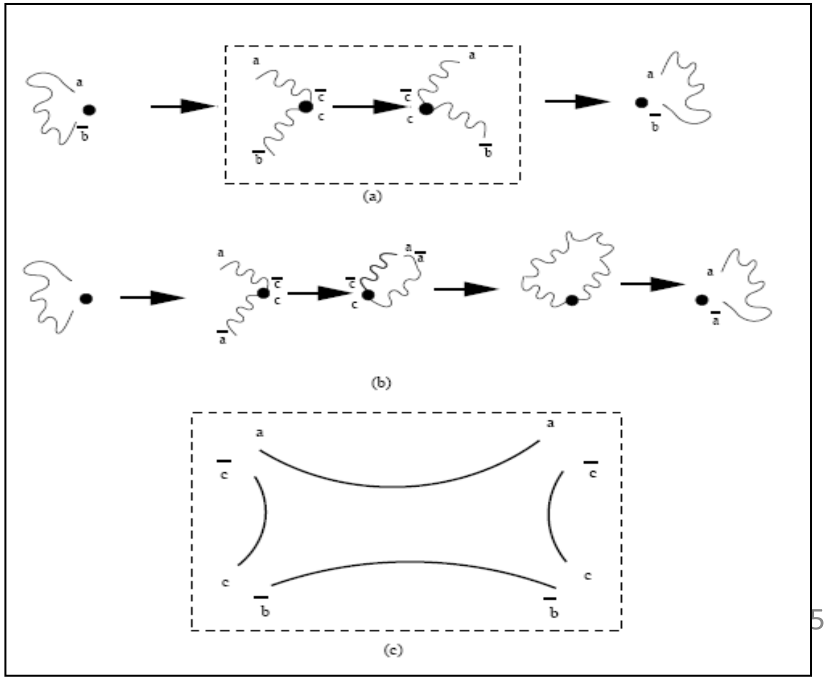

Time Delays due to
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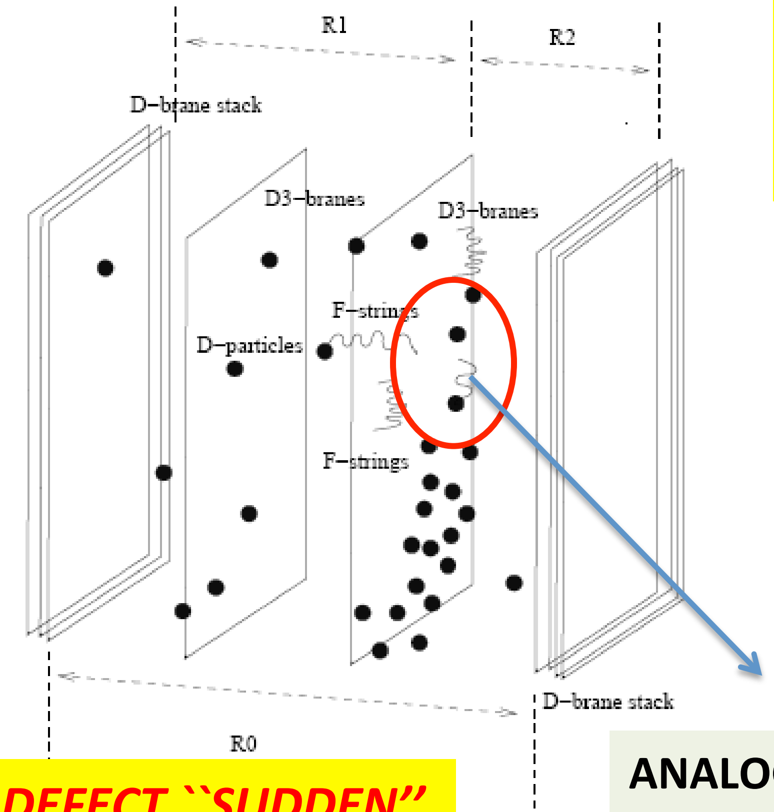
$$\boxed{\Delta t \sim \frac{\alpha' E}{1 - |\vec{u}|^2}}$$



DEFECT ``SUDDEN'' RECOIL OCCURS

$$\boxed{\begin{aligned} u^i\Theta(t) &= g_s \frac{\Delta k^i}{M_s} \\ &\equiv r^i k^i \Theta(t) \end{aligned}}$$

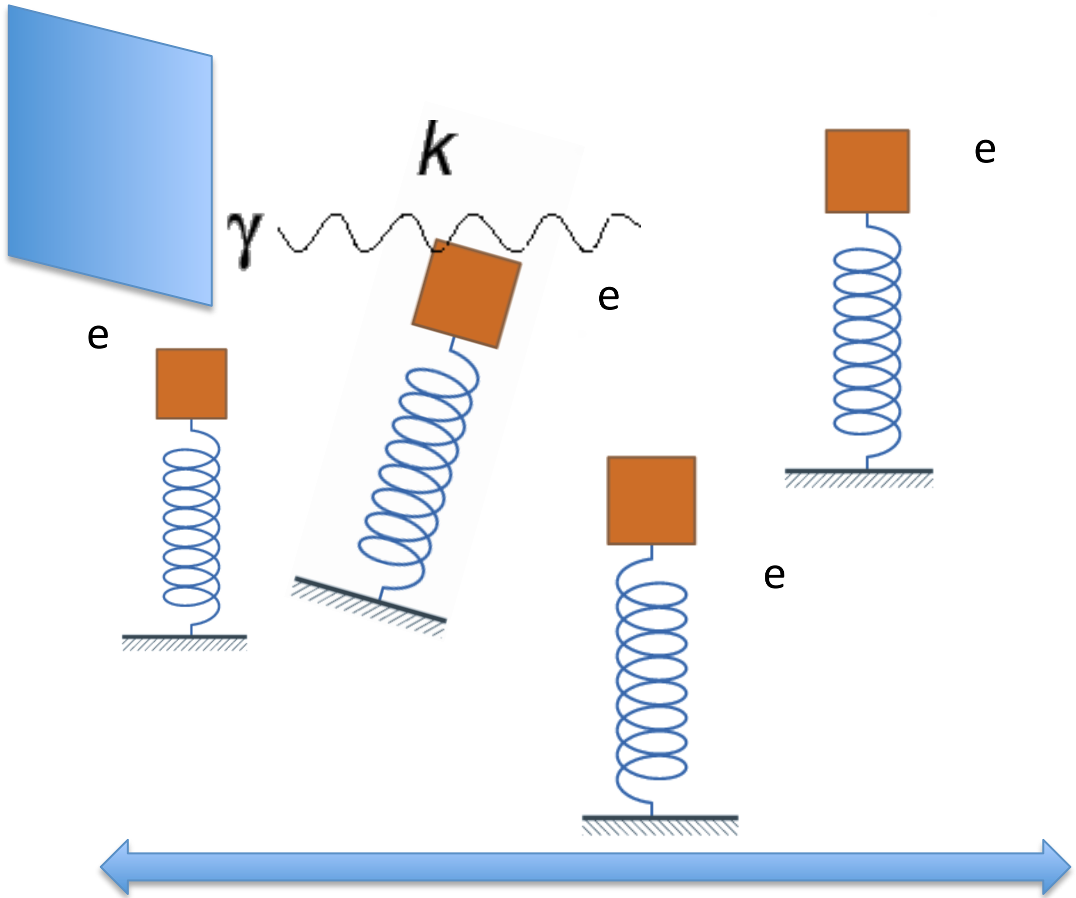
ANALOGY WITH FEYNMAN MODEL
D-PARTICLE DEFECTS PLAY ROLE OF ELECTRON OSCILLATIONS, BUT ENERGY DEPENDENCE OF DELAYS DIFFERENT FROM THAT IN MATTER

QUANTUM MECHANICS & REFRACTIVE INDEX

electrons (mass m) of the medium as forced quantum oscillators, with force exerted by electromagnetc field photons interact with this background

Feynman

Electron area density $n_e = \rho_e \Delta z$ (ρ_e = volume density of electrons)



Distance Δz traversed by photons

$$m\left(\frac{d^2}{dt^2}x + \omega_0^2 x\right) = eE_0 e^{i\omega t}$$

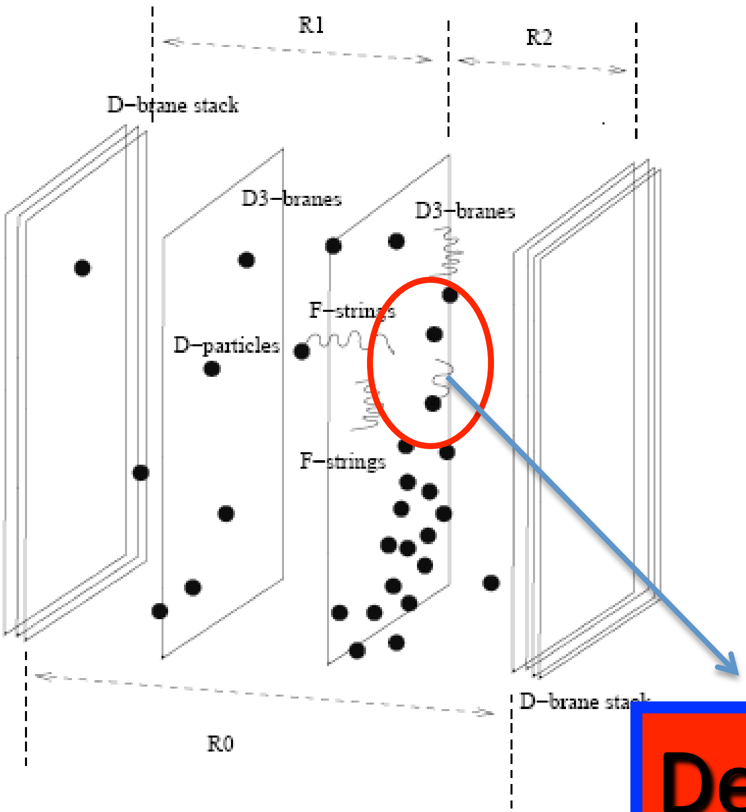
Excited-atoms produced electric field

$$E_a = -\frac{en_e}{\epsilon_0 c} i \frac{eE_0}{m(\omega^2 - \omega_0^2)} e^{i\omega(t-z)},$$

Speed of photons in medium ***c/n*** suppressed by refractive index n causing ***delay Δt = (n-1)Δz /c***

$$(n-1)\Delta z = \frac{n_e e^2}{2\epsilon_0 m(\omega_0^2 - \omega^2)}$$

$$\boxed{n = 1 + \frac{\rho_e e^2}{2\epsilon_0 m(\omega_0^2 - \omega^2)}}$$



Time Delays due to
Intermediate String Creation &
Oscillations increase due to recoil

$$\boxed{\Delta t \sim \frac{\alpha' E}{1 - |\vec{u}|^2}}$$

Delays are Independent of photon polarization NO BIREFRINGENCE

Stringy Uncertainties & D-Foam

- D-foam: populations of defects encountered by probe
- D-foam captures neutral probes & re-emits them
- Time Delay (Causal) in **each** Capture: $\boxed{\Delta t \sim \alpha' p^0}$ $\quad$ *$p^0 = E$*
- Independent of photon polarization **(no Birefringence**)
- **Total Delay** from emission of photons till observation over **a distance D** (assume n^* defects per string length):

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

COSMOLOGICAL D-FOAM

Universe Expansion may affect density of defects – n*(z) Red-shift Dependent

$$\Delta t_{\rm obs} = \int_0^z dz \frac{n(z)\, E_{\rm obs}}{M_s\, H_0} \frac{(1+z)}{\sqrt{\Omega_M\,(1+z)^3 + \Omega_\Lambda}}$$

COSMOLOGICAL D-FOAM

Universe Expansion may affect density of defects –
n*(z) Red-shift Dependent

$$\Delta t_{\rm obs} = \int_0^z dz \frac{n(z)\, E_{\rm obs}}{M_s\, H_0} \frac{(1+z)}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}$$

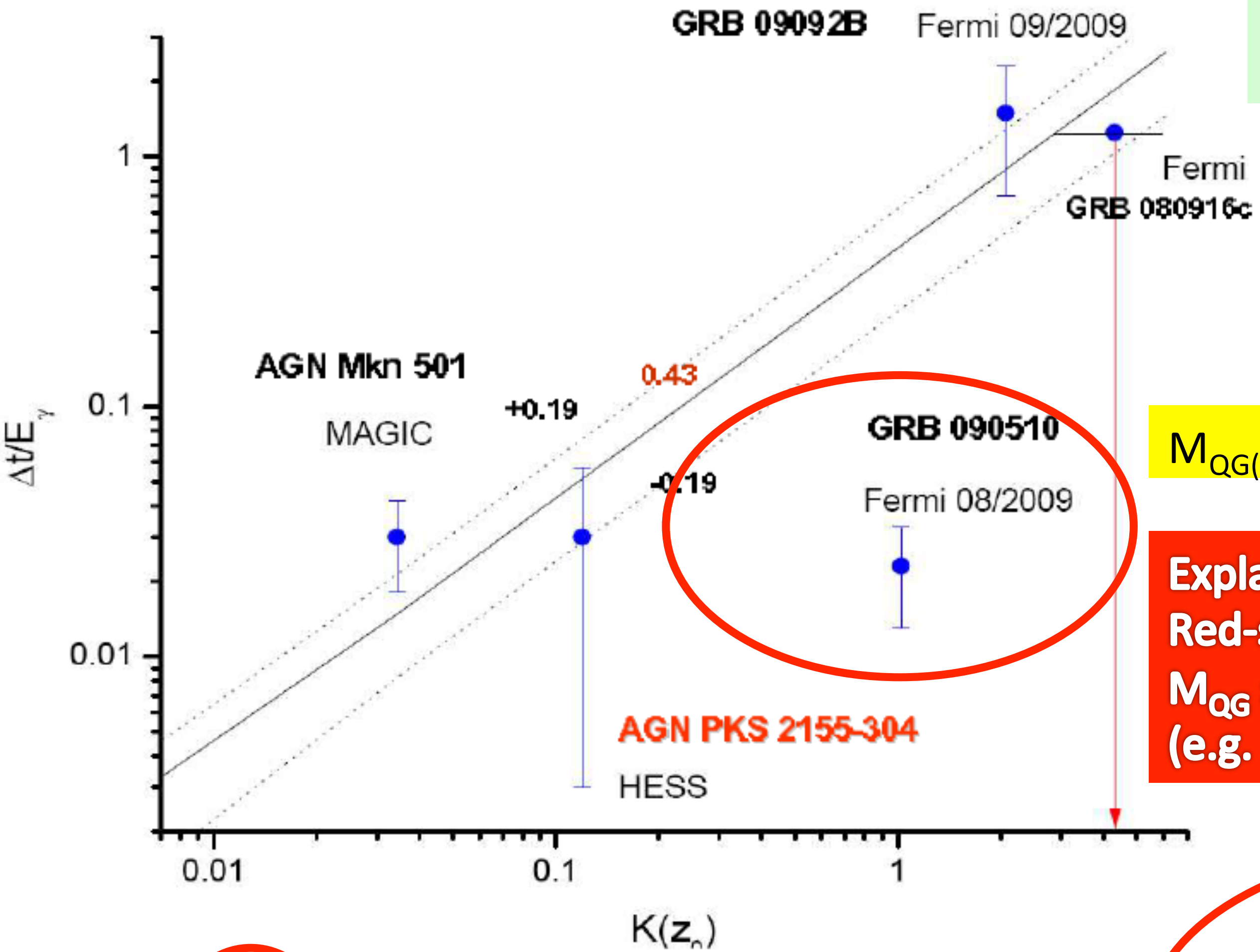
$$M_{\rm QG}^{\rm Eff} = \frac{M_s}{n^\star(z)}$$

n* (z) can increase with z
If brane moves in inhomogeneous bulk

Account for MAGIC
(& HESS) events for low z
and ALSO for GRB 090510
(short burst) at high z =1
Higher z GRBs delays partly
due to D-foam, partly due to
Sourcce Delayed Emission

Observed Photon Delays (H.E.S.S, FERMI)

Ellis, NEM, Nanopoulos (2009, 2010)



$M_{QG(1)} > 1.5\ 10^{19}$ GeV

Explained by Red-shift dependent M_{QG} scale (e.g. D-foam voids at z=0.9)

$$\Delta t = \frac{E}{M_{\rm QG}} H_0^{-1} \int_0^z dz \frac{(1+z)}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}$$

$$M_{\rm QG}^{\rm Eff} = \frac{M_s}{n^\star(z)}$$

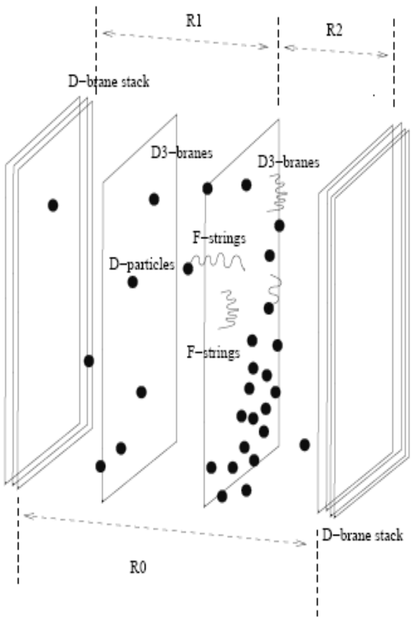
Space time Foam **situations –**
Average over both populations of defects & quantum fluctuations

Isotropic & (in)homogeneous foam

for a brane observer:

$$\boxed{\langle u_i \rangle \equiv \frac{g_s}{M_s} \langle \Delta k_i \rangle = 0}$$

Lorentz Invariance on Average



$$\boxed{\frac{g_s^2}{M_s^2} \langle \Delta k_i \Delta k_j \rangle = \sigma^2 \delta_{ij}}$$

Violated in flcts

$$v_g = 1 + \frac{1}{2}\langle |\vec{u}|^2 \rangle + \mathrm{O}(|\vec{u}|^3) = 1 + \frac{1}{2}\sigma^2 > 1$$

Superluminal propagation
IF NOT CAPTURE

$$\left(\text{cf. locally } v_g = \frac{\partial E}{\partial p} = 1 - |\vec{u}| \cos\vartheta + \frac{1}{2}|\vec{u}|^2 + \mathrm{O}(|\vec{u}|^3)\right)$$

***Space time Foam* situations –**
Average over both populations of defects & quantum fluctuations

Isotropic & (in)homogeneous foam

for a brane observer:

$$\boxed{\langle u_i \rangle \equiv \frac{g_s}{M_s} \langle \Delta k_i \rangle = 0}$$

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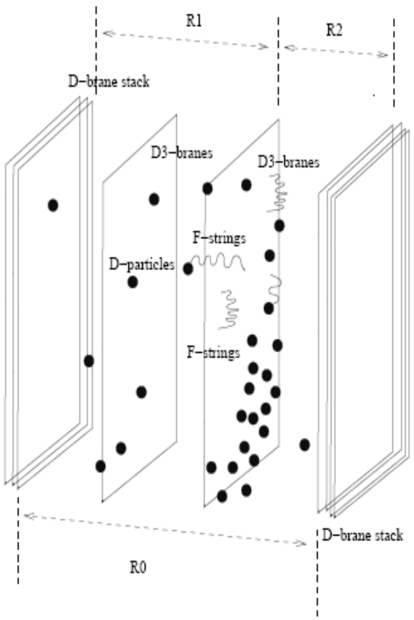
Violated in flcts

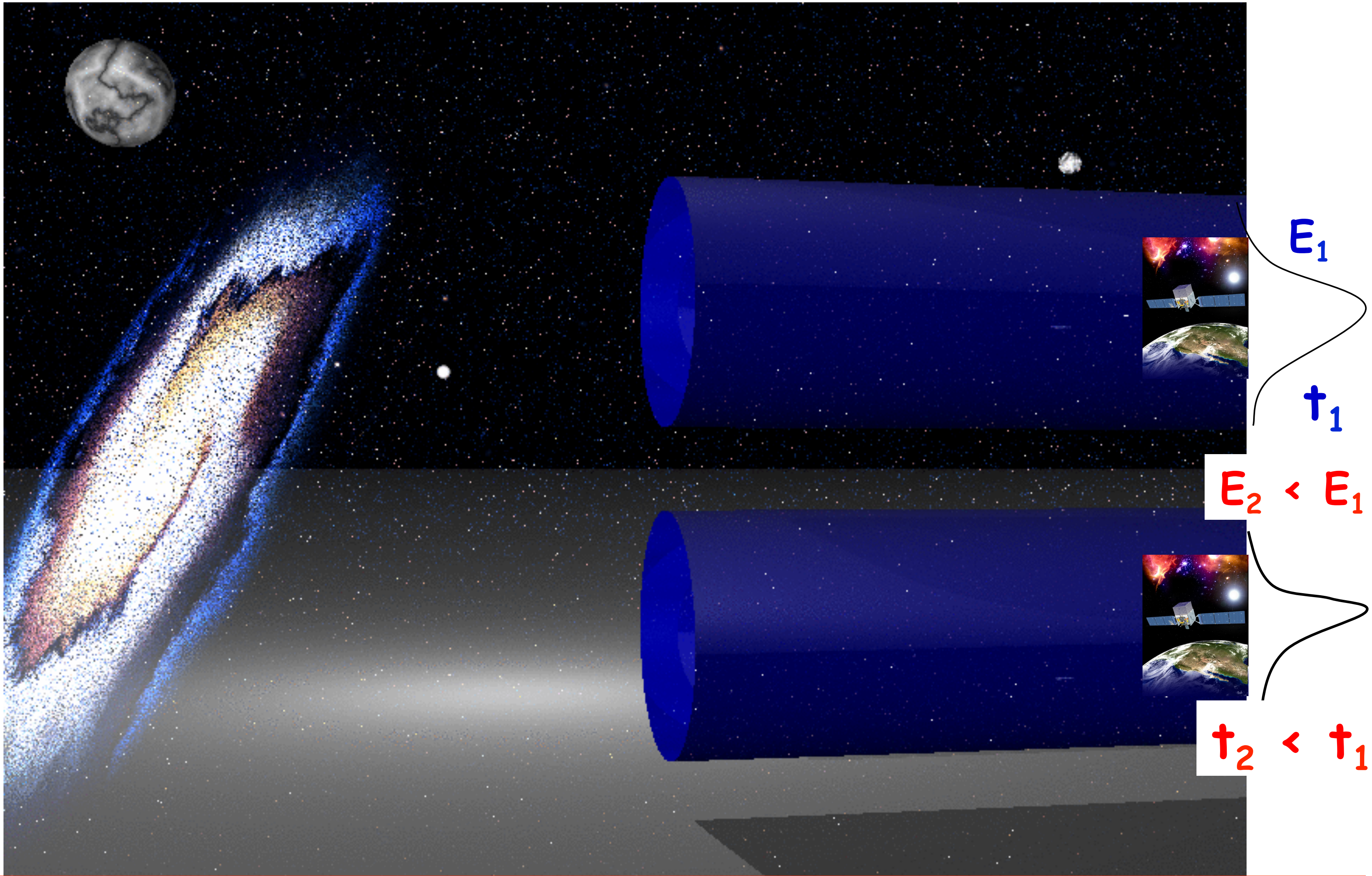


c.f. Stochastic Foam, through coherent graviton states

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$
$$\langle h_{\mu\nu} \rangle = 0$$
$$\langle h_{\mu\nu} h_{\rho\sigma} \rangle \neq 0$$

leading to light cone fluctuations energy-dependent photon pulse broadening

Ford (95) ….



Subluminal QG-induced Refractive Index: Higher energy photons arrive later
Stochastic Light-Cone fluctuations: Energy dependent width of photon pulses
(e.g. D-particle (stringy) foam, width proportional to photon energy)

Space time Foam situations –
Average over both populations of defects & quantum fluctuations

Isotropic & (in)homogeneous foam

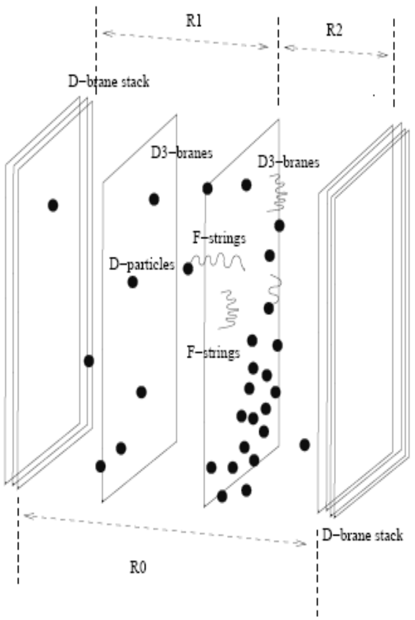
for a brane observer:

$$\boxed{\langle u_i \rangle \equiv \frac{g_s}{M_s} \langle \Delta k_i \rangle = 0}$$

Lorentz Invariance on Average

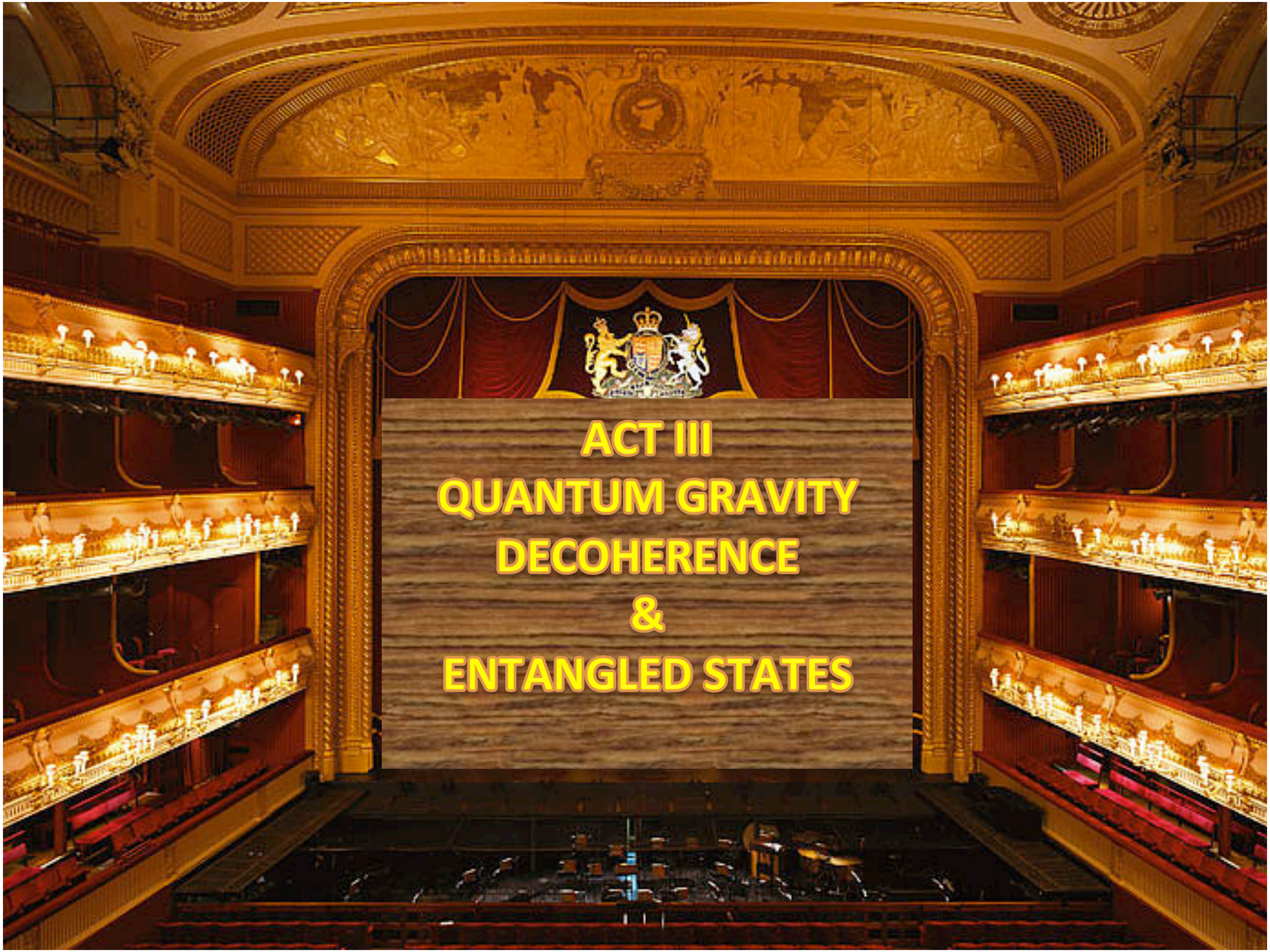
$$\boxed{\frac{g_s^2}{M_s^2} \langle \Delta k_i \Delta k_j \rangle = \sigma^2 \delta_{ij}}$$

Violated in flcts



STOCHASTIC FLUCTUATIONS ALSO INDUCE ***QUANTUM DECOHERENCE*** **FOR LOW-ENERGY MATTER**


ENTR' ACTE


ACT III
QUANTUM GRAVITY
DECOHERENCE
&
ENTANGLED STATES

FOAM & QUANTUM DECOHERENCE

- SPACE-TIME FOAM d.o.f. (metric fluctuations, defect recoil etc.) ***cannot*** be detected by a ***low-energy observer*** performing only scattering experiments.

- This implies an ``***environment***'' for low-energy matter (***open system***) propagating in a ***Quantum Gravity*** (QG) foamy background.

- ***INDUCED (LOW-ENERGY) DECOHERENCE***

- ***Coupling*** of matter system to environment is expected to be generically ``***weak***'' due to the weakness of quantum graviational interactions.

- ***Perturbative*** treatment of related ***QG effects***

MATTER EVOLUTION MASTER EQUATIONS

Time evolution of matter density matrix $\rho = |\psi\rangle\langle\psi|$

Highly dependent on details of the microscopic model

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

Basic phenomenological assumption*: LINDBLAD* form

(i) Linear evolution $\partial_t \rho = i[\rho, H] + \delta\!\!\!/ H \rho$

(ii) total probability conservation $Tr(\rho) = 1$

(iii) complete positivity of ρ eigenvalues ≥ 0

(iv) entropy increase $S=-Tr(\rho \ln(\rho))$, $dS/dt \geq 0$

(v) energy conservation (on the average)

LINDBLAD EVOLUTION

$$\rho = \mathrm{Tr}_{\mathcal{M}} |\Psi >< \Psi|$$

ENVIRONMENT OPERATORS $\mathbf{B_m}$, $\mathbf{B^+{}_m}$

$$\boxed{\dot{\rho} \equiv \partial_t \rho = i[\rho, H] - \sum_m \{B_m^\dagger B_m, \rho\}_+ + 2 \sum_m B_m \rho B_m^\dagger}$$

In terms of state vectors |ψ> :

$$|d\Psi >= -\frac{i}{\hbar} H |\Psi > + \sum_m (< B_m^\dagger >_\Psi B_m - \frac{1}{2} B_m^\dagger B_m -$$

$$\frac{1}{2} < B_m^\dagger >_\Psi < B_m >_\Psi) \, |\Psi > dt + \sum_m (B_m - < B_m >_\Psi) \, |\Psi > d\xi_m$$

LINDBLAD EVOLUTION

$$\rho = \mathrm{Tr}_{\mathcal{M}} |\Psi >< \Psi|$$

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$$\frac{1}{2} < B_m^\dagger >_\Psi < B_m >_\Psi) \, |\Psi > dt + \sum_m (B_m - < B_m >_\Psi) \, |\Psi > d\xi_m$$

stochastic	$d\xi_i \, d\xi_j = 0$
Wiener	
white noise	$d\xi_i^* \, d\xi_j = \delta_{ij} \, dt$

LINDBLAD EVOLUTION

$$\boxed{\dot{\rho} \equiv \partial_t \rho = i[\rho, H] - \sum_m \{B_m^\dagger B_m, \rho\}_+ + 2\sum_m B_m \rho B_m^\dagger}$$

(i) *Linear* evolution

(ii) total probability conservation : $\mathrm{Tr}(\rho) = 1$

but evolution of pure to mixed states: $\mathrm{Tr}(\rho^2) \neq 1$

(iii) complete positivity of $\rho(t)$: Eigenvalues of $\rho(t) \geq 0$

(iv) monotonic (Von Neumann) entropy increase: $S=-\mathrm{Tr}(\rho \,\mathrm{Ln}\, \rho)$, $dS/dt \geq 0$

(v) energy conservation (on the average) (?)

LINDBLAD EVOLUTION

$$\boxed{\dot{\rho} \equiv \partial_t \rho = i[\rho, H] - \sum_m \{B_m^\dagger B_m, \rho\}_+ + 2\sum_m B_m \rho B_m^\dagger}$$

(i) *Linear* evolution

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but evolution of pure to mixed states: Tr(ρ²) ≠ 1

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(iv) monotonic (Von Neumann) entropy increase: S=-Tr(ρ Ln ρ), dS/dt ≥0

(v) energy conservation (on the average) (?)

If (iv) & (v) $\Rightarrow$ $B_j^\dagger = B_j\,, \quad [B_j, H] = 0$ $\Rightarrow$

self-adjointness

LINDBLAD EVOLUTION

Adler & Horwitz

$$\dot{\rho} = i[\rho, H] + \mathcal{D}[\rho]$$

$$\mathcal{D}[\rho] = \sum_j [B_j, [B_j, \rho]]$$

$$B_j^\dagger = B_j, \quad [B_j, H] = 0$$

So *Double commutator form* for Lindblad term in master equation if:

(iv) monotonic (Von Neumann) entropy increase: $S=-\mathrm{Tr}(\rho \,\mathrm{Ln}\, \rho)$, $dS/dt \geq 0$

and

(v) energy conservation (on the average)

State Vector Diffusion & Localization

Gisin & Percival

Assumption: Hamiltonian : block diagonal form in channels independent of ``measurement''

$$H = \begin{pmatrix} H_1 \ldots\ldots \\ \ldots H_2 \ldots \\ \ldots\ldots\ldots \\ \ldots\ldots H_k \end{pmatrix}$$

Channel k projection operator: P_k $\Rightarrow$ **$[P_k, H] = 0$**

Localisation (``collapse'') is quantified by *rate of decrease* of *Quantum Dispersion Entropy*

$$\frac{d}{dt}(\mathcal{M}\mathcal{K}) = -\sum_j \frac{1-\langle P_k\rangle_\psi}{\langle P_k\rangle_\psi} \sum_m |\langle P_j B_m P_j\rangle_\psi|^2 \leq 0$$

State Vector Diffusion & Localization

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$\Downarrow$

Mean over classical noises

State Vector Diffusion & Localization

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Mean over classical noises

effective interaction rate depend on microscopic environmental details

State Vector Diffusion & Localization

Gisin & Percival

Assumption: Hamiltonian : block diagonal form in channels independent of ``measurement''

$$H = \begin{pmatrix} H_1 \ldots\ldots \\ \ldots H_2 \ldots \\ \ldots\ldots\ldots \\ \ldots\ldots H_k \end{pmatrix}$$

Channel k projection operator: P_k $\Rightarrow$ $[P_k, H] = 0$

Localisation (``collapse'') is quantified by *rate of decrease* of *Quantum Dispersion Entropy*

$$\frac{d}{dt}(\mathcal{MK}) = -\sum_j \frac{1-\langle P_k\rangle_\psi}{\langle P_k\rangle_\psi} \sum_m |\langle P_j B_m P_j\rangle_\psi|^2 \leq 0$$

Some times: Localization may stop before it is copmplete:
Pointer state from decoherence

Zurek

Master Equations-Order of Magnitude Estimates

Adler & Horwitz

Energy driven Lindblad decoherence $\boxed{D = H}$

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

$$\boxed{dW_t^2 = dt \ , \quad dtdW_t = 0}$$

(white noise conditions)

Decoherence damping : $e^{-\mathcal{D}t}$

Order of magnitude estimates: $\mathcal{D} = \dfrac{\left(\Delta m^2\right)^2}{E^2 M_{\rm QG}}$

Master Equations-Order of Magnitude Estimates

Adler & Horwitz

Energy driven Lindblad decpoherence

$$\boxed{D = H}$$

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

$$\boxed{dW_t^2 = dt \ , \quad dtdW_t = 0}$$

(white noise conditions)

Decoherence damping : $e^{-\mathcal{D}t}$

Order of magnitude estimates:

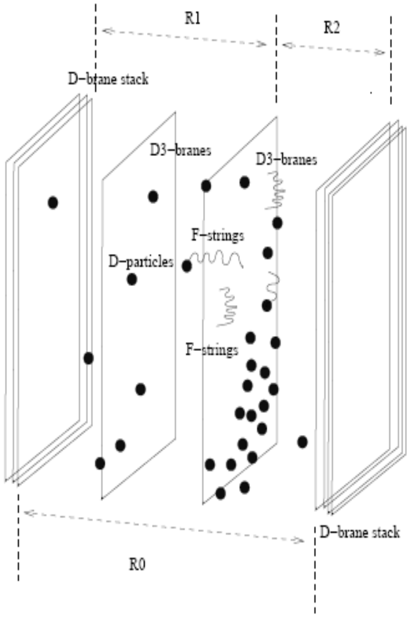
$$\mathcal{D} = \frac{\left(\Delta m^2\right)^2}{E^2 M_{\rm QG}}$$

Suppressed compared to naïve dimensional estimates of D= E^2/M_{QG}

Master Equations-Order of Magnitude Estimates

NEM, Sarkar

D-particle (stringy) Foam:



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

$$\overline{u}_x \to g_s \frac{r}{M_s}\widehat{p}$$

Generalization Including damping γ :

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

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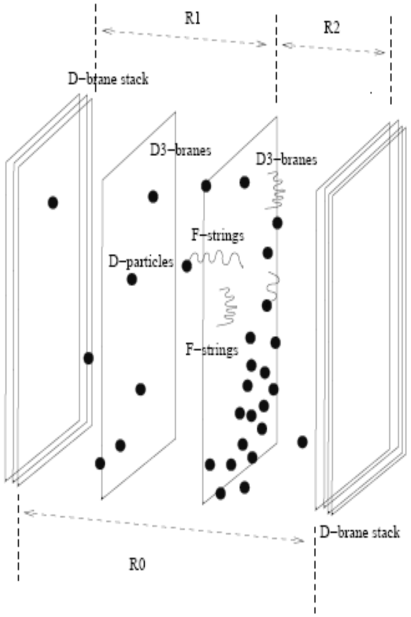

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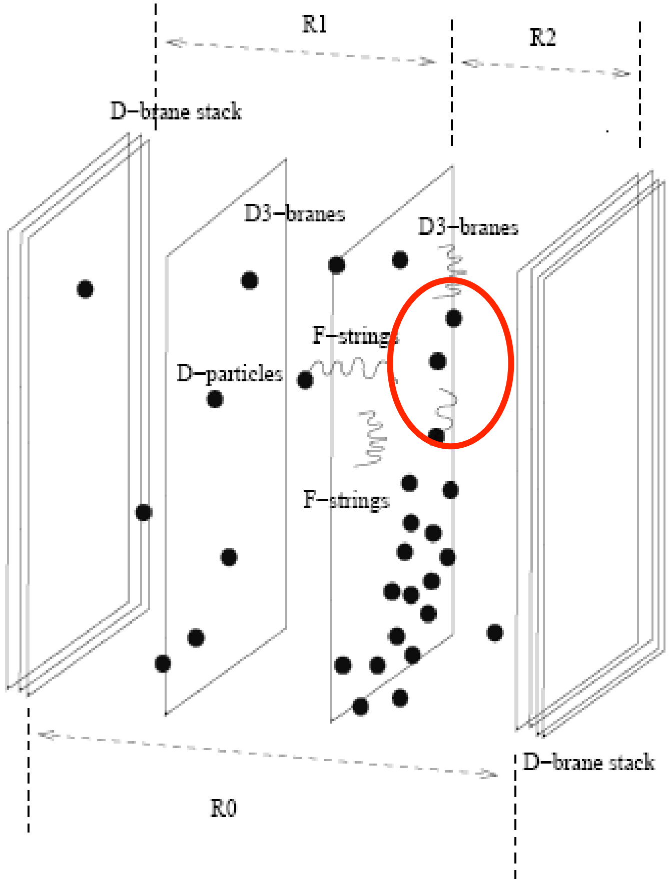


Problem Equivalent to
Strings propagating
in Local ``electric field"
backgrounds
Time-Space non-commutativity

$$\boxed{[X^i, t] \propto F^{0i}(k, x) \equiv u^i(k, x)}$$

Induced metric depends
on momenta as well as coordinates
(Finsler type)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$h_{0i} = g_s \frac{\Delta k_i}{M_s} \equiv u_i$$

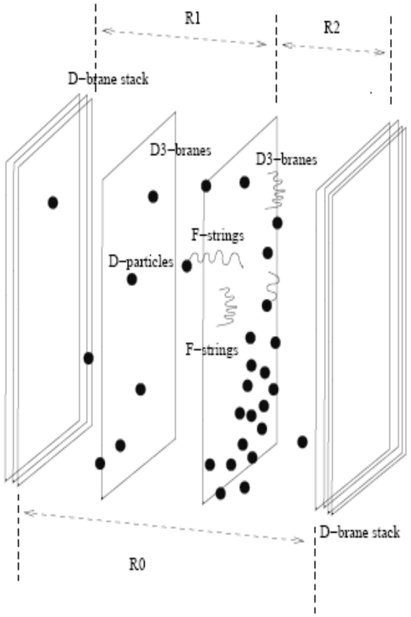
Explicit local breaking of SO(3,1) down to SO(2,1) rotation and boosts in transverse directions

Local Lorentz Violation due to direction of Defect recoil velocities

Master Equations-Order of Magnitude Estimates

NEM, Sarkar

D-particle (stringy) Gaussian Foam:



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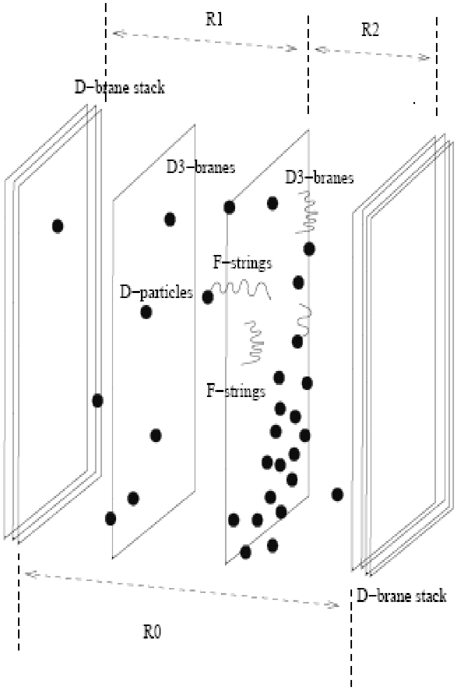
Decoherence damping in two-level systems: $e^{-\mathcal{D}t}$, $\mathcal{D} = \sigma^2 g_s \frac{\left(\Delta m^2\right)^2}{E^2 M_s}$

Master Equations-Order of Magnitude Estimates

NEM, Alexandre, Farakos...

D-particle Foam: ***Cauchy-Lorentz D-particle recoil velocities distribution***



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

$$\langle\langle \ldots \rangle\rangle_{\rm CL} = \int_{-\infty}^{\infty} dx\, f(x) \ldots$$

Decoherence damping in two-level systems: $e^{-\mathcal{D}t}$

$$\mathcal{D} = \gamma \frac{(\Delta m^2)}{E}$$


CPT INVARIANCE
&
QG-INDUCED
DECOHERENCE

CPT INVARIANCE & DECOHERENCE

Jost, Pauli, Bell, Schwinger

- ***CPT Theorem***: Invariance of the Lagrangian of a (relativistic) field theory under the action (generated byθ) of: **C**(harge conjugation),**P**(arity=reflexion) ,**T**(ime reversal) in any order

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

θ is anti-unitary in view of T-reversal

- It is proven for Relativistic field theories, ***in FLAT space-times***, upon the assumptions of:

(i) Lorentz invariance

(ii) Locality of interactions

(iii) Unitarity

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GREENBERG
Assumed: Covariant T-ordered product, well-defined S-matrix

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Local CPTViolating (CPTV) but LORENTZ INVARTIANT models explicitly constructed but with non covariant T-ordered product and not well defined S-matrix
Chaichian et al. PLB669, 177 (2011)

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May not be valid in highly-curved space-times

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May not be valid in highly-curved space-times of QG, e.g. space-time foam

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Decoherence

Ill-defined CPT operator
Wald 1979

CPT INTRINSIC VIOLATION & DECOHERENCE

Wald (1979)

Theorem*: If there is quantum *decoherence*, then there is a strong form of CPT Violation, in the sense that the *quantum generator* of *CPT* symmetry is *ill-defined

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Proof: **If Θ acting on density matrices is well-defined then Θ is a *unitary operator* (*θ* acting on sate vectors is anti-unitary)**

$$\Theta \sim \theta\theta^\dagger \qquad \Theta\rho \sim \theta\rho\theta^\dagger$$

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

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Hawking

super-scattering operator (linear)

If decoherence, $\$ \neq S\, S^+$ ($S = e^{iHt}$) has *NO INVERSE*

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$$\rho_{\rm in} = \Theta^{-1}\$\Theta^{-1}\$\rho_{\rm in}$$

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DETAILED PROOF

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

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

$$\overline{\rho}_{\mathrm{out}} = \$\overline{\rho}_{\mathrm{in}}$$

Bar denotes anti-particle states

WELL-DEFINED

unitary CPT generator $\Theta^{-1} = \Theta^{+}$

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

$$\$\Theta^{-1}\rho_{\mathrm{out}} = \$\Theta^{-1}\$\rho_{\mathrm{in}} \Rightarrow$$

$$\rho_{\mathrm{in}} = \Theta^{-1}\$\Theta^{-1}\$\rho_{\mathrm{in}}$$

Inverse of \$!

Also would imply:

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

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$\not\Leftrightarrow$ well-defined ! INCOMPATIBLE

CPT symmetry without CPT invariance ? Wald (79)

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,
$\Theta\rho = \theta\rho\theta^\dagger, \quad \theta^\dagger = -\theta^{-1}$ (anti – unitary).

In terms of superscattering matrix \$:

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

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

Weak CPT invariance in Black-Holes?

Wald (79)

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.**

EXPERIMENT CAN TELL…

IF CPT IS ILL-DEFINED (INTRINSIC VIOLATION)
QUITE DIFFERENT PHENOMENOLOGY
FROM ORDINARY LORENTZ- AND CPT-VIOLATION CASES
WHERE Θ IS WELL DEFINED BUT $[\Theta, H] \neq 0$

Kostelecky et al. Standard Model extension

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SMOKING-GUN EVIDENCE OF INTRINSIC CPT VIOLATION
MODIFICATIONS IN EINSTEIN-PODOLSKY-ROSEN (EPR)
CORRELATIONS IN ENTANGLED MESON STATES ***(ω – effect)***

Bernabeu, NEM, Papavassiliou

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In principle…
depends on the order of magnitude of the effect

Highly microscopic model dependent…


ACT IV
PHENOMENOLOGY
OF
CPT VIOLATION

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…)

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- 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)

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NEUTRAL KAON BASICS

$$|K^0\rangle = |d\,\overline{s}\rangle$$

$$|\overline{K}^0\rangle = |\overline{d}\,s\rangle$$

Physical (observable) states are the ``weak'' (or CP) eigenstates (having definite life times under weak interaction decays):

$$|K_L\rangle \;\propto\; (1+\epsilon-\delta)\left|K^0\right\rangle - (1-\epsilon+\delta)\left|\bar{K}^0\right\rangle \qquad \text{CP=+1}$$

$$|K_S\rangle \;\propto\; (1+\epsilon+\delta)\left|K^0\right\rangle + (1-\epsilon-\delta)\left|\bar{K}^0\right\rangle \qquad \text{CP=-1}$$

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CP-violation ($|\varepsilon| \approx 10^{-3}$)

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CP-violation ($|\varepsilon| \approx 10^{-3}$)

CPT violation in the Hamiltonian
e.g. due to Lorentz Violation

NEUTRAL KAON BASICS

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masses:

$$m_{K^0} = 497.614 \pm 0.024 \text{ MeV}$$

Bounds on CPTV :

$$\frac{m_{K^0} - m_{\overline{K}^0}}{m_{K^0}} < 8 \times 10^{-19}$$

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mean life: K_S: $(0.8958 \pm 0.0005) \times 10^{-10}$ s

K_L : $(5.116 \pm 0.020) \times 10^{-8}$ s

mass difference: $m_{K_L} - m_{K_S} = (3.483 \pm 0.006) \times 10^{-15}\,\text{GeV}$

QG DECOHERENCE IN NEUTRAL KAONS: SINGLE STATES

Quantum Gravity (QG) may induce decoherence and oscillations $K^0 \to \overline{K}^0$ $\Rightarrow$ **could use Lindblad-type approach (one example)** (Ellis, Hagelin, Nanopoulos, Srednicki, Lopez, NM):

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

where

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

and

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

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

α, β, γ violate CPT (Wald : decoherence) & CP: $CP = \sigma_3 \cos\theta + \sigma_2 \sin\theta, \qquad [\delta\not{H}_{\alpha\beta}, CP] \neq 0$

Neutral Kaon Entangled States

- Complete Positivity $\Rightarrow$ Different parametrization of Decoherence matrix (Benatti-Floreanini)

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

Current Experimental Bounds:

$\alpha \approx 10^{-17}$ GeV

$\gamma \approx 10^{-21}$ GeV

$\beta \approx 10^{-19}$ GeV

Can test complete positivity experimentally (in principle!)

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NB: decoherence Damping of oscillations $e^{-\mathcal{D}t}$,

$$\mathcal{D} \sim \alpha + \gamma$$

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α ≈ 10^{-17} GeV

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$\Delta m \sim 3.5 \times 10^{-15}$ GeV

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$$e^{-\mathcal{D}t},$$

$$\mathcal{D} \sim \alpha + \gamma$$

e.g. Gaussian D – foam

$$\mathcal{D} \sim g_s \sigma^2 \frac{(\Delta m^2)^2}{E^2 M_s}$$

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$\mathrm{e.g.\ Cauchy-Lorentz}$

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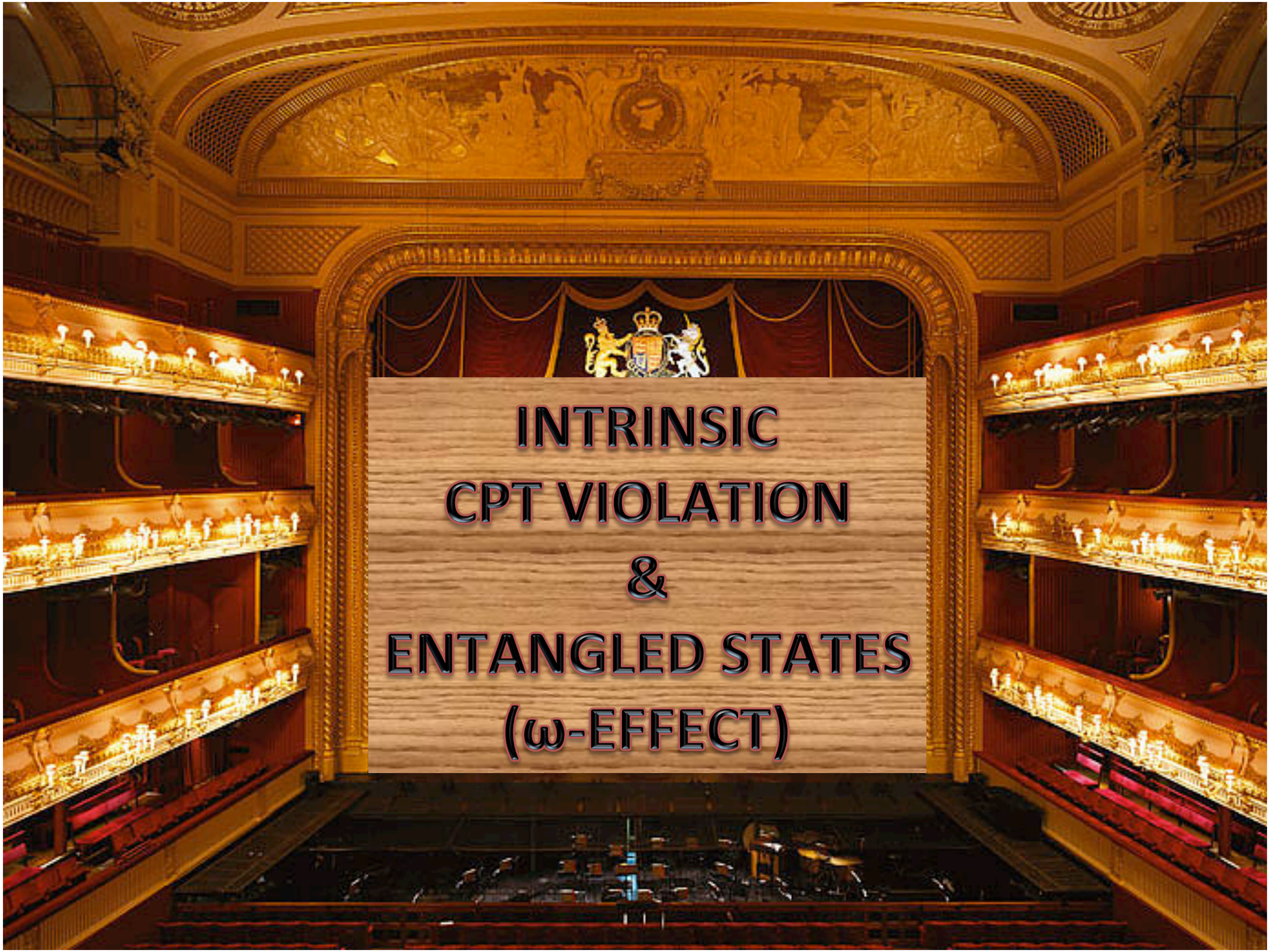
- CPT Operator well defined but NON-Commuting with Hamiltonian $[H , \Theta] \neq 0$
  - Lorentz & CPT Violation in the Hamiltonian
    - Neutral Mesons & Factories, Atomic Physics, Anti-matter factories, Neutrinos, …
    - Modified Dispersion Relations (GRB, neutrino oscillations, synchrotron radiation…)

- 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)
    - Ultracold Neutrons
    - Neutrinos (highest sensitivity)
    - Light-Cone fluctuations (GRB, Gravity-Wave Interferometers, neutrino oscillations)


INTRINSIC
CPT VIOLATION
&
ENTANGLED STATES
(ω-EFFECT)

EPR correlated states and particle physics

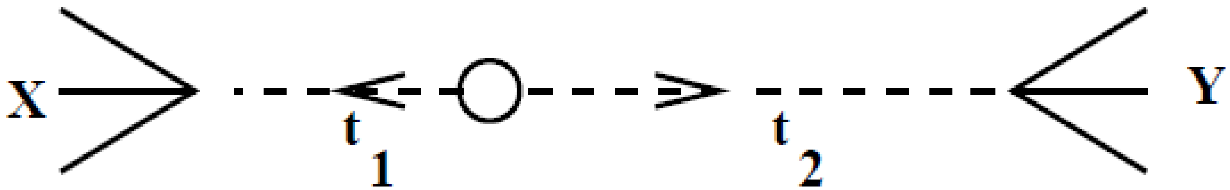
What are EPR correlations?

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?

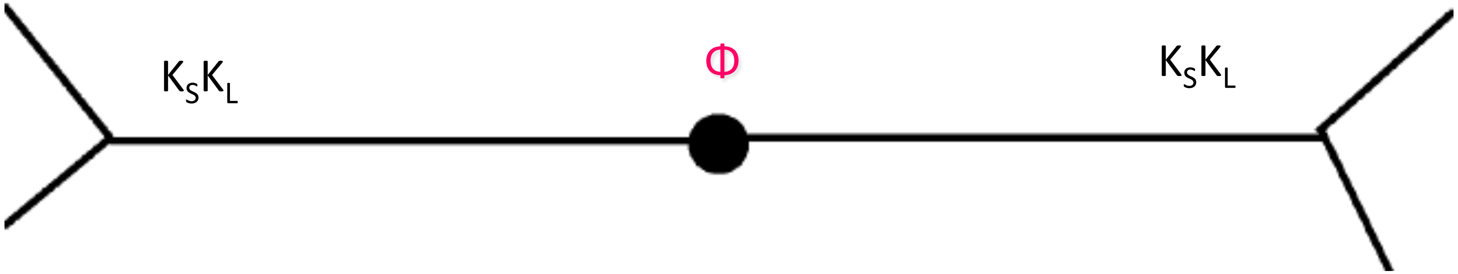
NO, NO PARADOX

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))

- CPT Violation Consequences for Neutral mesons
- Einstein Podolsky Rosen (EPR) – correlators



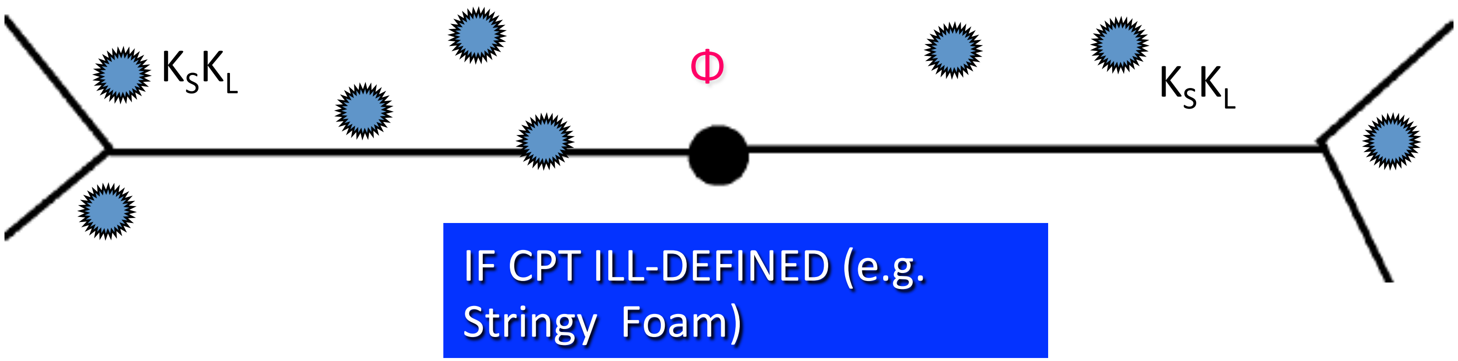
IF CPT Θ-operator WELL-DEFINED

Even if $[\Theta, H] \neq 0$

Neutral Kaon, anti-Kaon mesons treated as indistinguishable particles, Bose-statistics applies

- If foam, concept of anti-particle may be perturbatively modified, Neutral mesons ***no*** longer ***indistinguishable***

Bernabeu, NEM, Papavassiliou (04)



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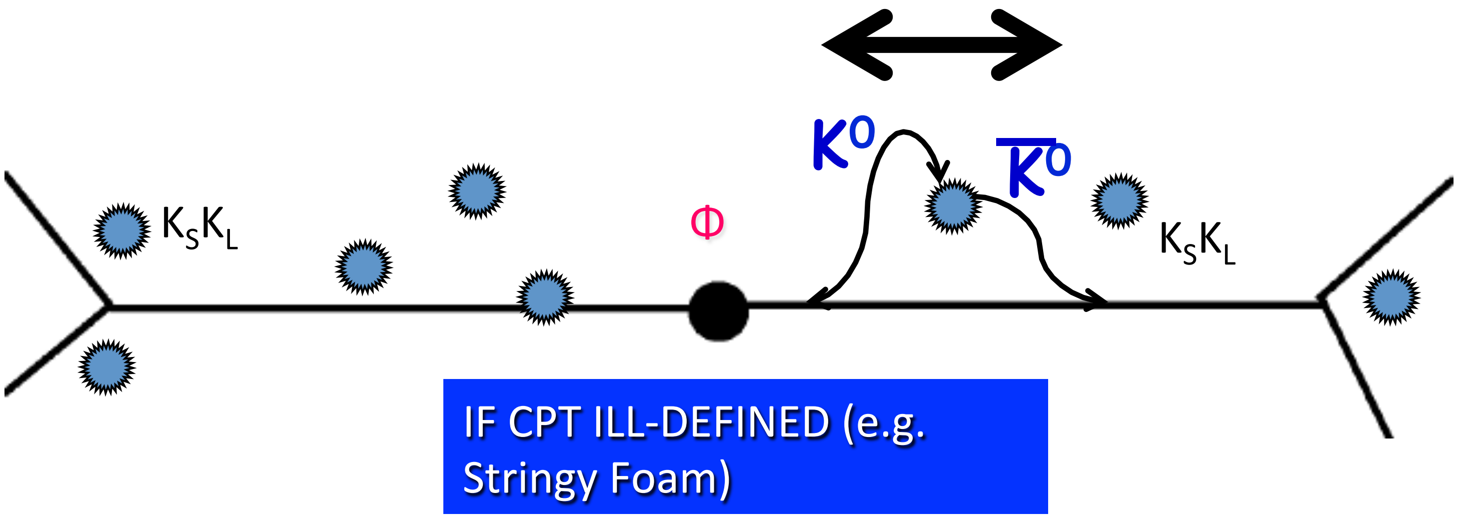
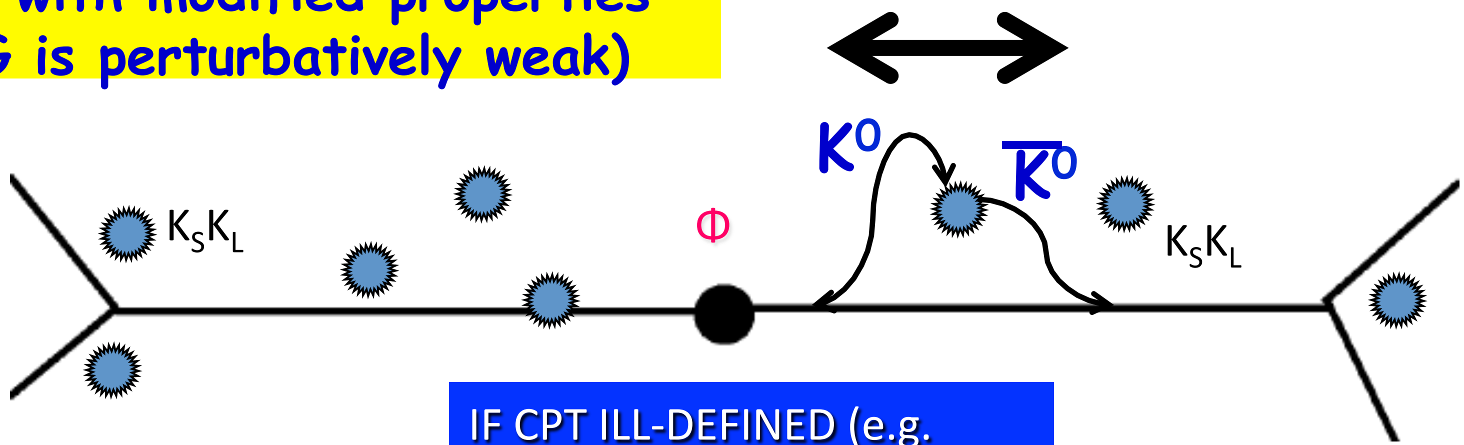


- If foam, concept of anti-particle may be perturbatively modified, Neutral mesons ***no*** longer ***indistinguishable***

Anti-particle exists
but with modified properties
(QG is perturbatively weak)

Bernabeu, NEM, Papavassiliou (04)



IF CPT ILL-DEFINED (e.g. Stringy Foam)

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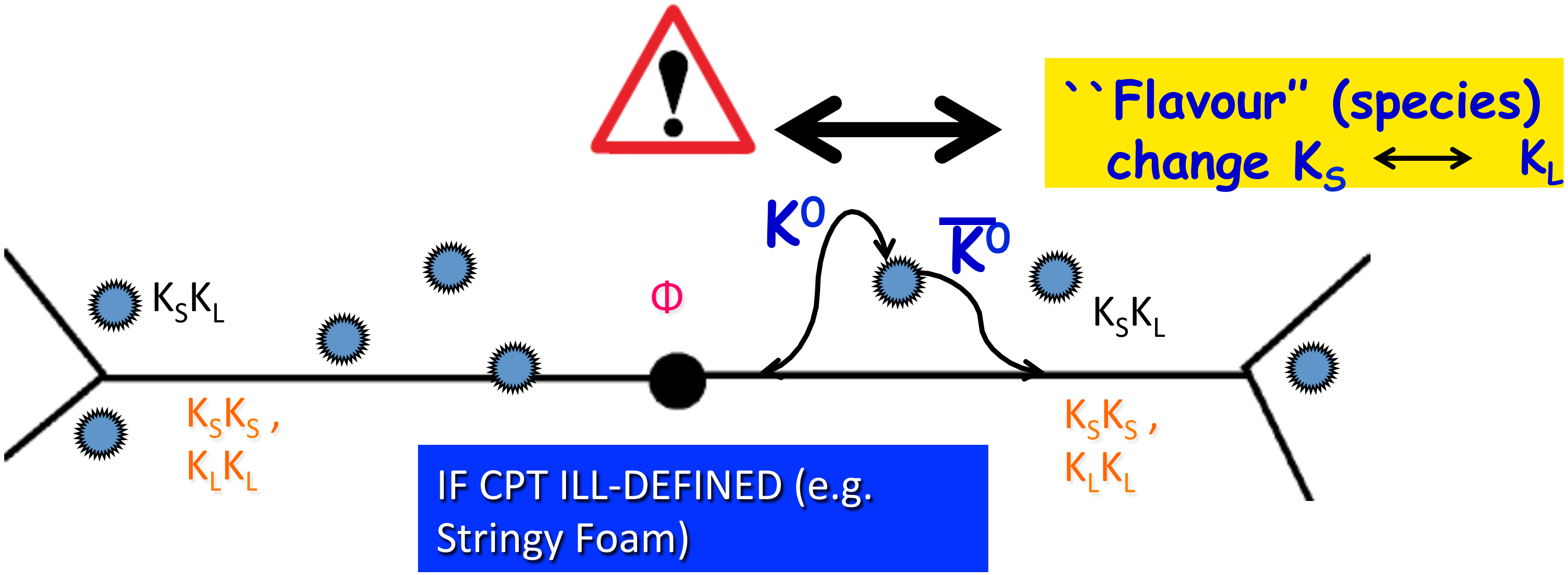
Bernabeu, NEM, Papavassiliou (04)



$$|K_L\rangle \propto (1+\epsilon-\delta)\left|K^0\right\rangle-(1-\epsilon+\delta)\left|\bar{K}^0\right\rangle$$
$$|K_S\rangle \propto (1+\epsilon+\delta)\left|K^0\right\rangle+(1-\epsilon-\delta)\left|\bar{K}^0\right\rangle$$

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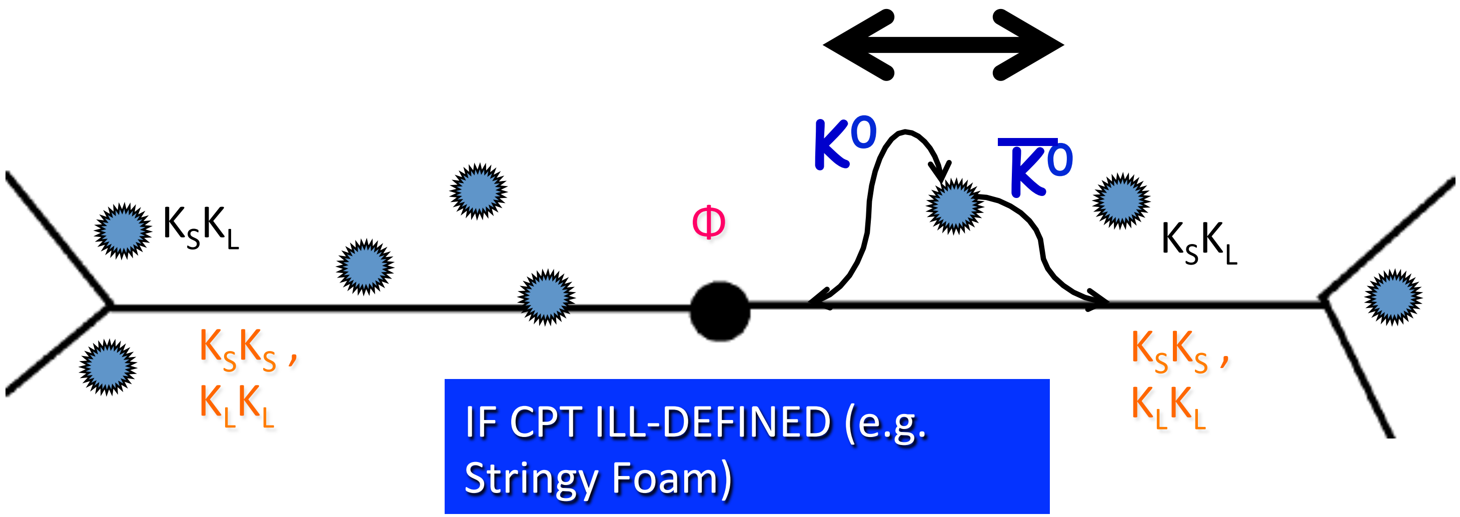
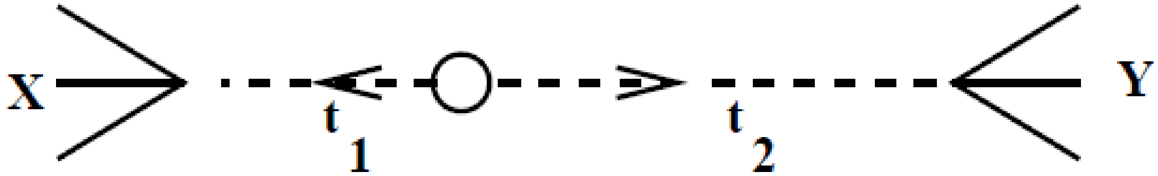


$$\boxed{\begin{aligned} |i> \quad &= \quad \mathcal{N}\Big[\Big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\Big) \\ &+ \quad \omega\Big(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\Big)\Big] \end{aligned}}$$

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

ϕ Decays and the ω Effect

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



Amplitudes:

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

with

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

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

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

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

ω-Effect & Intensities

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

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

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

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

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

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

$\Delta M = M_S - M_L$ 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.

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

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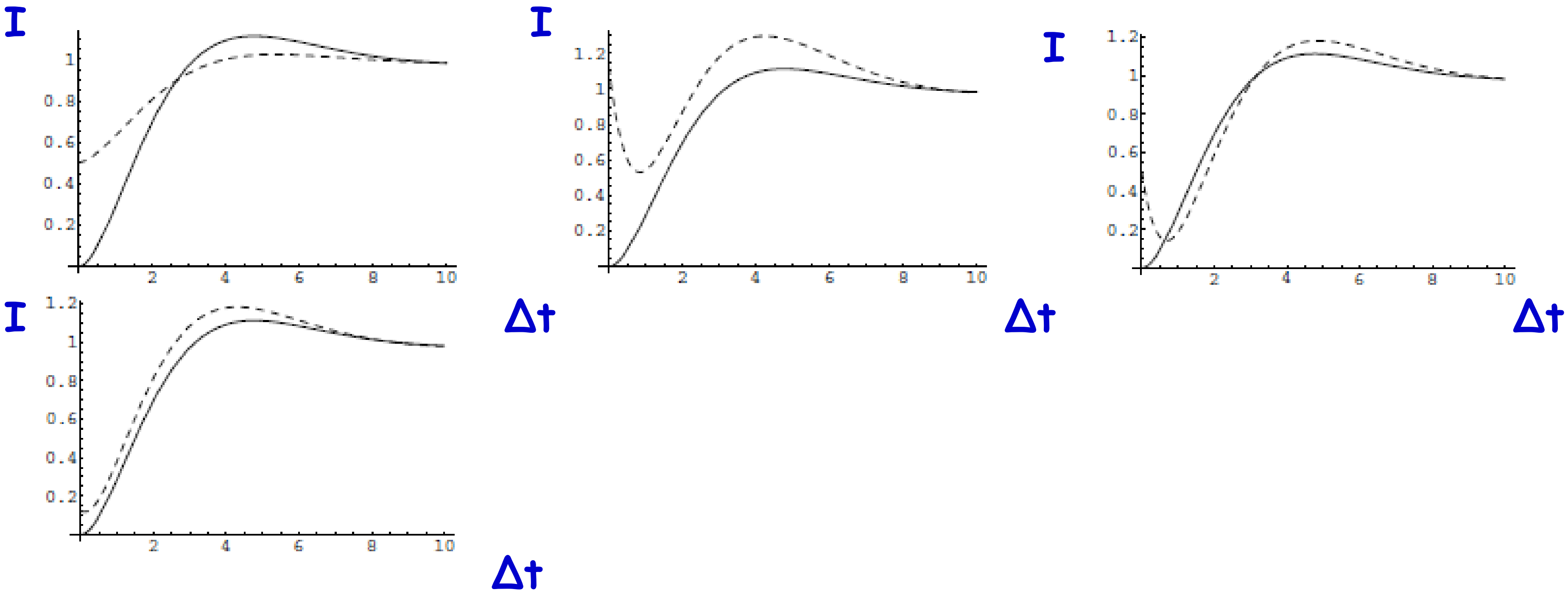
ω-Effect & Intensities



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 $|C|^2|\eta_{+-}|^2|\langle\pi^+\pi^-|K_S\rangle|^4\tau_S$.

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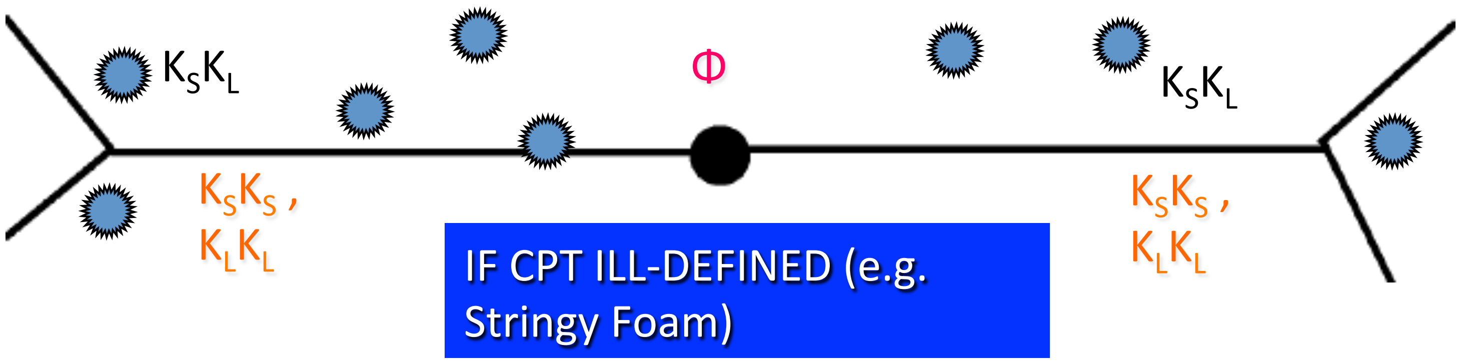

ω - effect : can be distinguished from conventional C-even background effects

$$e^+ e^- \to 2\gamma \to K^0 \overline{K}^0$$

Different interference effects

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.

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

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

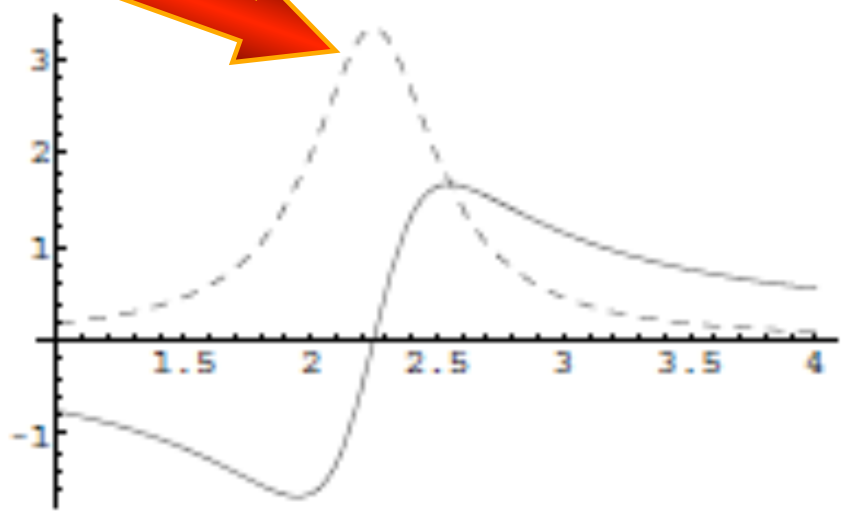
Experimental Tests of ω-Effect in ϕ, B factories... in B factories: ω-effect $\rightarrow$ demise of flavour tagging (Alvarez et al. (PLB607))

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)

Disentangling ω-effects from Background

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….**



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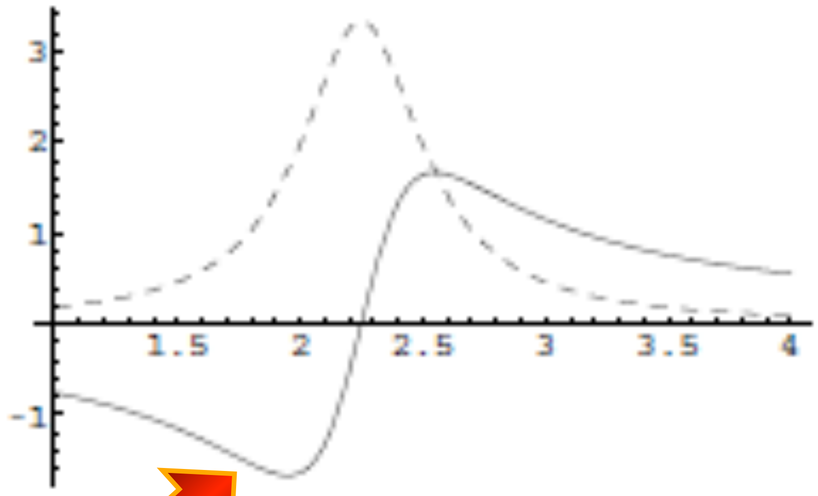

K_SK_S terms from C=+ background
no dependence on centre-of-mass energy s.
Real part of Breit-Wigner amplitude
Vanishes at top of resonance, Interference of
C=+ with C=- background, vanishes
at top of the resonance, opposite signature
on either side.....

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

Alvarez, Bernabeu NEM, 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*

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EquaL-Sign di-lepton charge asymmetry Δt dependence

ALVAREZ, BERNABEU, NEBOT

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

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

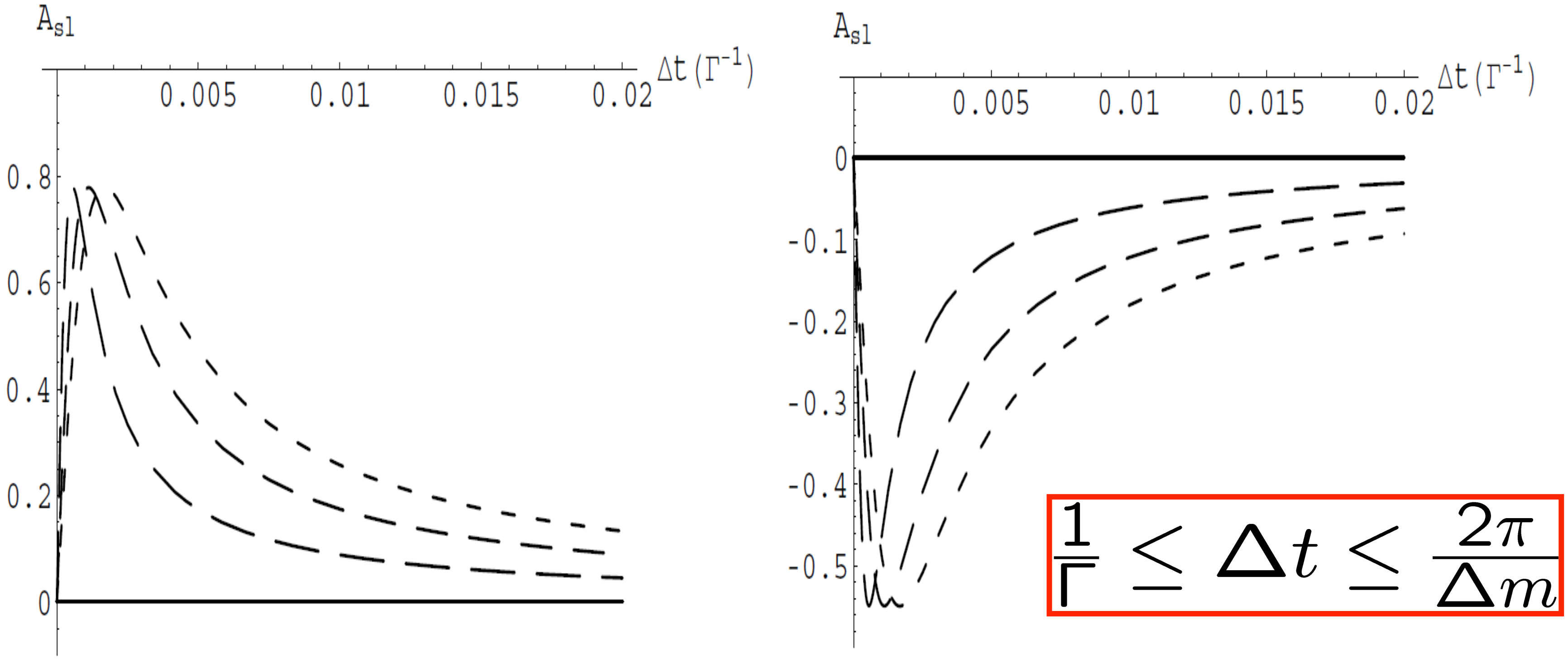
$$A_{sl} = \left. \frac{I(\ell^+,\ell^+,\Delta t) - I(\ell^-,\ell^-,\Delta t)}{I(\ell^+,\ell^+,\Delta t) + I(\ell^-,\ell^-,\Delta t)} \right|_{\omega=0} = 4\frac{Re(\varepsilon)}{1+|\varepsilon|^2} + \mathcal{O}((Re\,\varepsilon)^2)$$

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

EquaL-Sign di-lepton charge asymmetry Δt dependence

$$I(X\ell^{\pm},X'\ell^{\pm},\Delta t)=\int_0^{\infty}\left|\langle X\ell^{\pm},X'\ell^{\pm}|U(t_1)\otimes U(t_1+\Delta t)|\psi(0)\rangle\right|^2 dt_1$$

$$\begin{aligned}I(X\ell^{\pm},X'\ell^{\pm},\Delta t)=\frac{1}{8}e^{-\Gamma\Delta t}\,|A_X|^2|A_{X'}|^2\left|\frac{(1+s_\epsilon\,\epsilon)^2-\delta^2/4}{1-\epsilon^2+\delta^2/4}\right|^2\\
\left\{\left[\tfrac{1}{\Gamma}+a_\omega\tfrac{8\Gamma}{4\Gamma^2+\Delta m^2}Re(\omega)+\tfrac{1}{\Gamma}|\omega|^2\right]\cosh\left(\tfrac{\Delta\Gamma\Delta t}{2}\right)+\right.\\
\left[-\tfrac{1}{\Gamma}+b_\omega\tfrac{8\Gamma}{4\Gamma^2+\Delta m^2}Re(\omega)-\tfrac{\Gamma}{\Gamma^2+\Delta m^2}|\omega|^2\right]\cos(\Delta m\Delta t)+\\
\left.\left[d_\omega\tfrac{4\Delta m}{4\Gamma^2+\Delta m^2}Re(\omega)+\tfrac{\Delta m}{\Gamma^2+\Delta m^2}|\omega|^2\right]\sin(\Delta m\Delta t)\right\},\end{aligned}$$



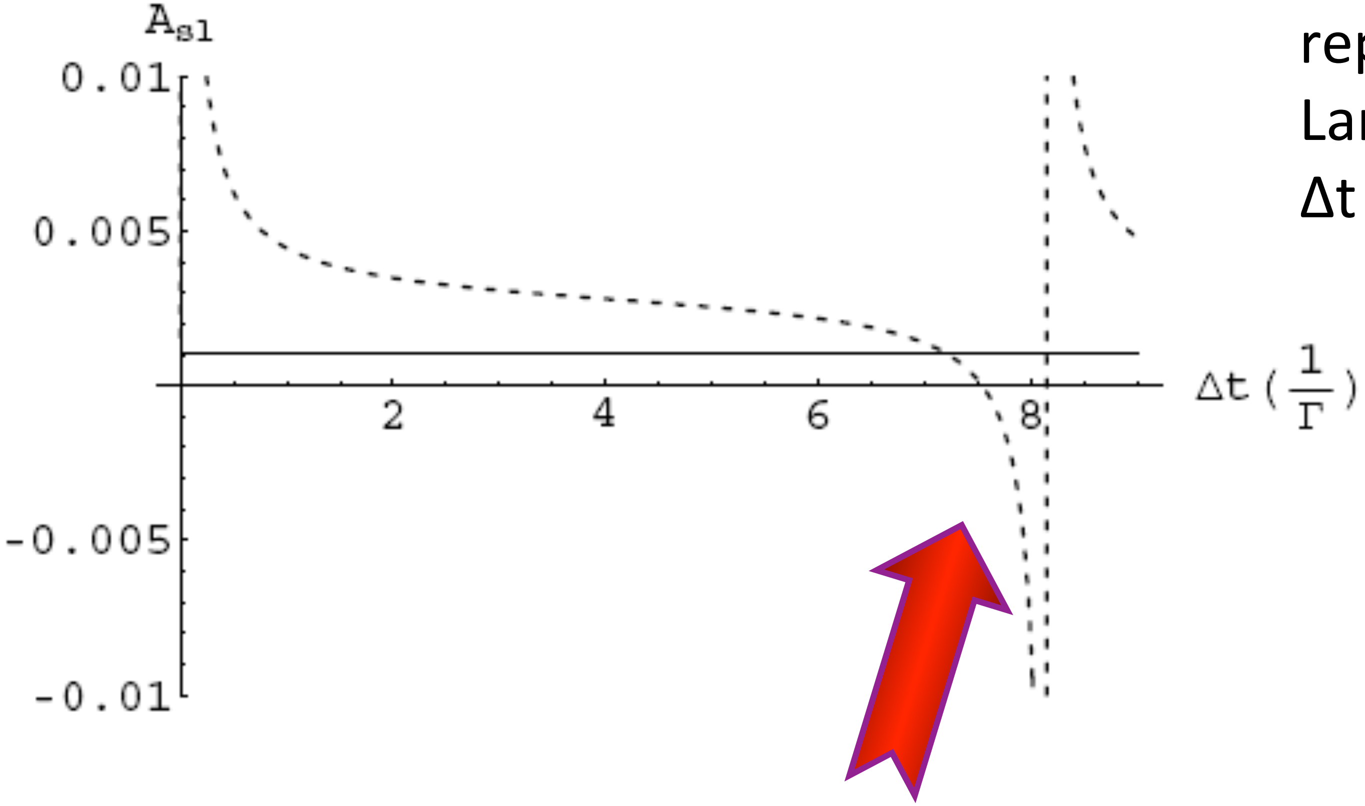
$$\frac{1}{\Gamma} \leq \Delta t \leq \frac{2\pi}{\Delta m}$$

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

$$A_{sl}(\Delta t_{peak}) = 0.77 \cos(\Omega)$$

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

EquaL-Sign di-lepton charge asymmetry



Peak structure repeats itself at Larger times
$\Delta t\ \Delta m = 2\pi$

$$\Delta t \Delta m \simeq 2\pi \simeq 8.2.\Gamma^{-1}\Delta m$$

Approximate Periodicity of A_{sl} in $\Delta t\ \Delta m$:
terms $\cosh(\Delta\Gamma\Delta t)$ almost constant for small $\Delta\Gamma$

EquaL-Sign di-lepton charge asymmetry Δt dependence

$$I(X\ell^{\pm}, X'\ell^{\pm}, \Delta t) = \int_0^{\infty} \left|\langle X\ell^{\pm}, X'\ell^{\pm}|U(t_1) \otimes U(t_1 + \Delta t)|\psi(0)\rangle\right|^2 dt_1$$

$$\begin{aligned} I(X\ell^{\pm}, X'\ell^{\pm}, \Delta t) = \frac{1}{8} e^{-\Gamma\Delta t} \, |A_X|^2 |A_{X'}|^2 \left| \frac{(1 + s_\epsilon\, \epsilon)^2 - \delta^2/4}{1 - \epsilon^2 + \delta^2/4} \right|^2 \\ \left\{ \left[\tfrac{1}{\Gamma} + a_\omega \tfrac{8\Gamma}{4\Gamma^2 + \Delta m^2} Re(\omega) + \tfrac{1}{\Gamma} |\omega|^2 \right] \boxed{\cosh\left(\tfrac{\Delta\Gamma\Delta t}{2}\right)} + \right. \\ \left[-\tfrac{1}{\Gamma} + b_\omega \tfrac{8\Gamma}{4\Gamma^2 + \Delta m^2} Re(\omega) - \tfrac{\Gamma}{\Gamma^2 + \Delta m^2} |\omega|^2 \right] \cos(\Delta m \Delta t) + \\ \left. \left[d_\omega \tfrac{4\Delta m}{4\Gamma^2 + \Delta m^2} Re(\omega) + \tfrac{\Delta m}{\Gamma^2 + \Delta m^2} |\omega|^2 \right] \sin(\Delta m \Delta t) \right\}, \end{aligned}$$

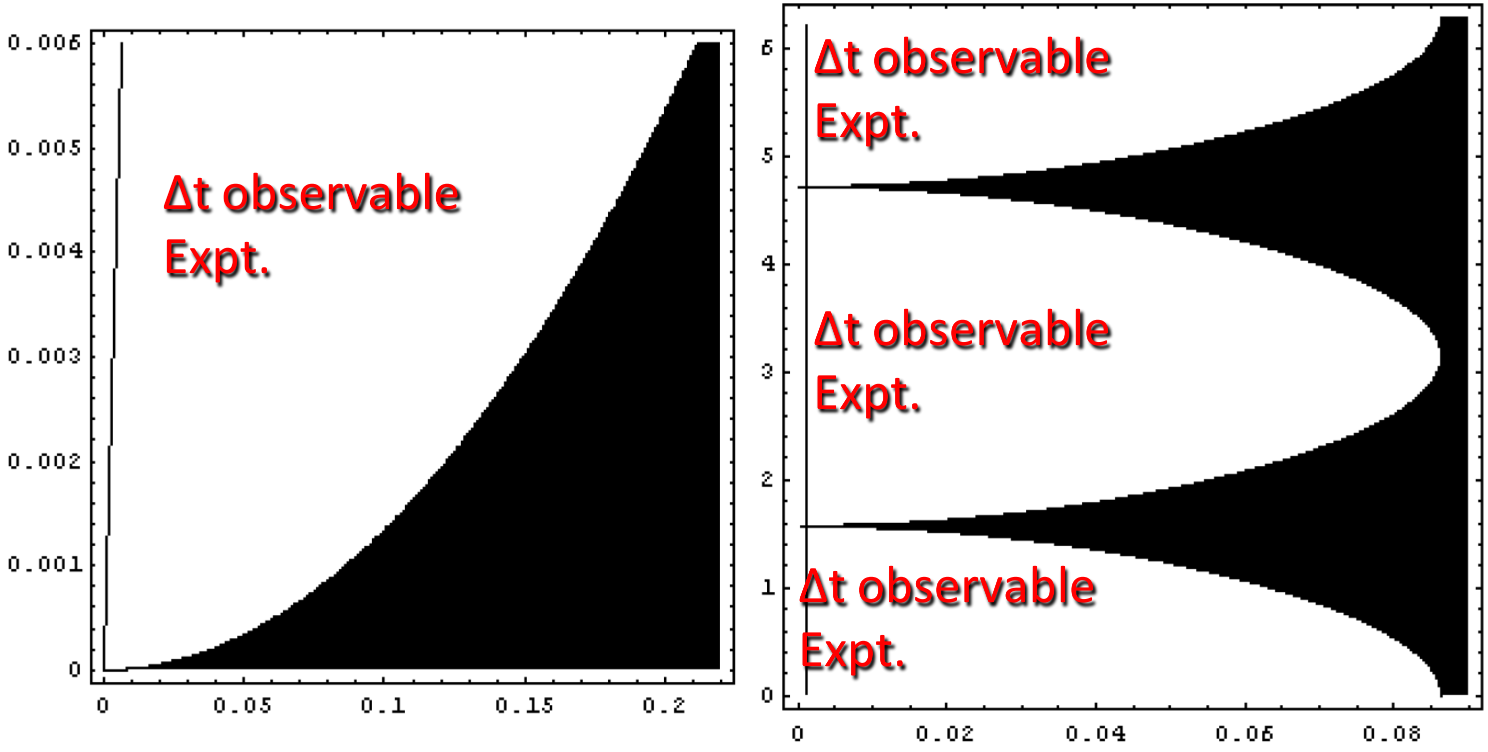
EquaL-Sign di-lepton charge asymmetry Δt dependence

Current Experimental measurements of A_{sl} have been performed for

$$0.8\,\Gamma^{-1} \leq \Delta t \leq 10\,\Gamma^{-1}$$

(BaBar, Belle Collaborations)

Current Experimental Limits



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

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

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

EquaL-Sign di-lepton charge asymmetry Δt dependence

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$$0.8\,\Gamma^{-1} \leq \Delta t \leq 10\,\Gamma^{-1}$$

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At large times region, where peak repeats itself, the amount of events is suppressed by:

$$e^{-8.2} \sim 10^{-4}$$

Future super B experiments could exhibit sensitivity in such regions (?)

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:

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

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

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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

Constrain ζ significantly in upgraded facilities.

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

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

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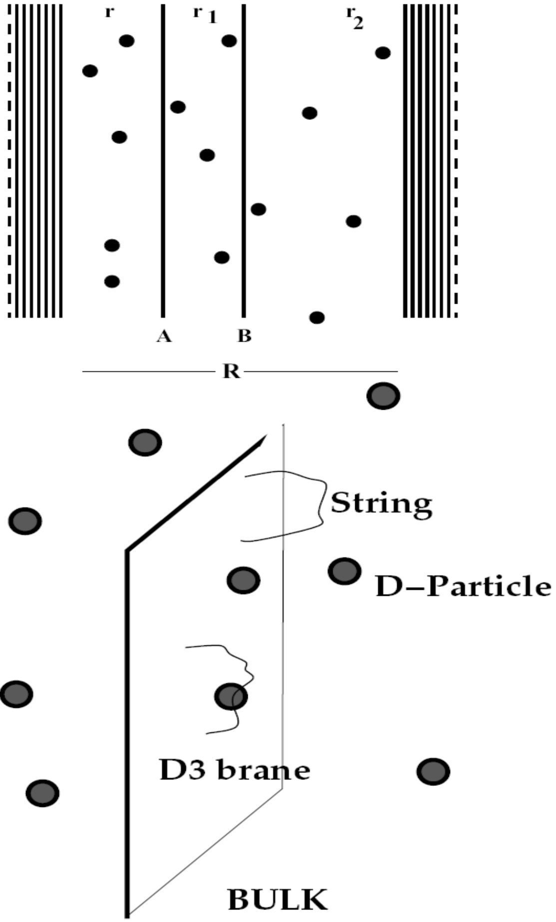

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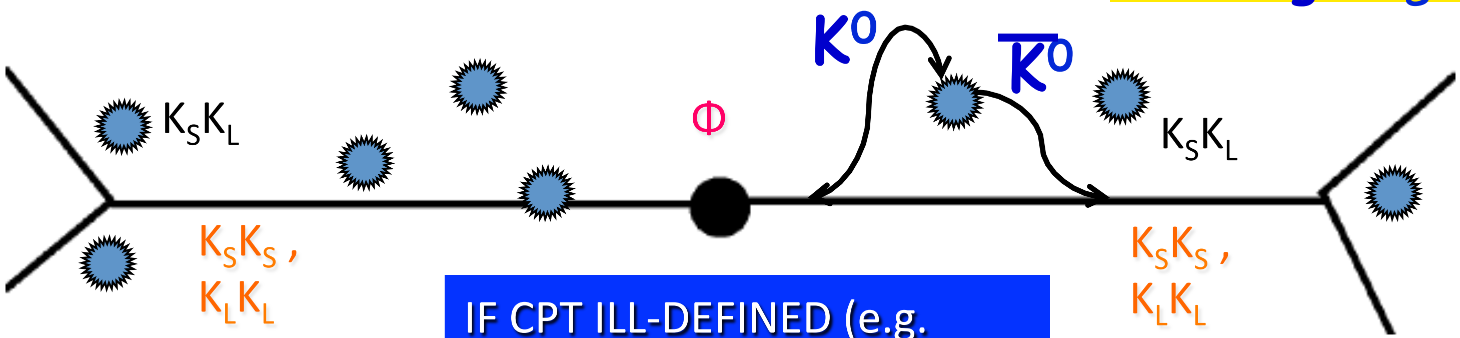
- If foam, ``flavour'' changes

Bernabeu, NEM, Sarkar

$$
\begin{aligned}
|K_L\rangle &\propto (1+\epsilon-\delta)\left|K^0\right\rangle - (1-\epsilon+\delta)\left|\bar{K}^0\right\rangle \\
|K_S\rangle &\propto (1+\epsilon+\delta)\left|K^0\right\rangle + (1-\epsilon-\delta)\left|\bar{K}^0\right\rangle
\end{aligned}
$$

$\Longleftrightarrow$ **``Flavour'' (species) change $K_S \longleftrightarrow K_L$**



IF CPT ILL-DEFINED (e.g. Stringy Foam)

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

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

ω-Effect estimates in D-particle Foam

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

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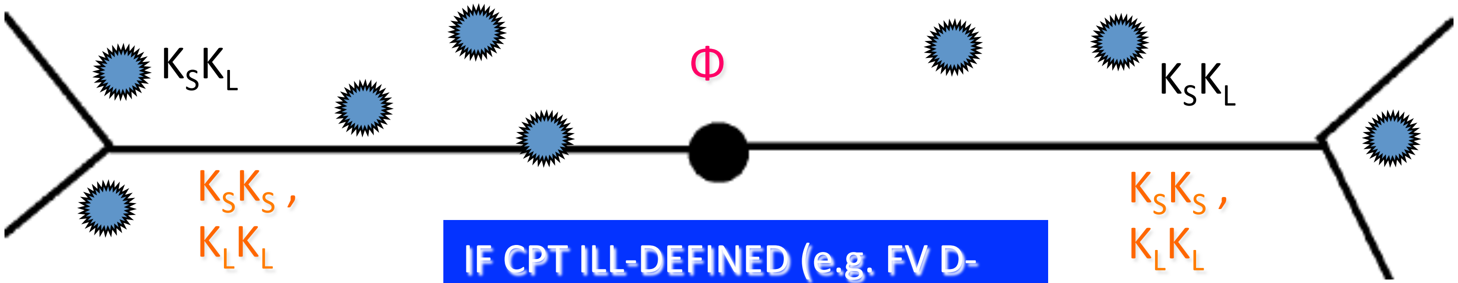

IF CPT ILL-DEFINED (e.g. FV D-particle Foam)

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

$M_{QG} = 2.\ 10^{19}$ GeV

$\Delta m \sim 3.5 \times 10^{-15}$ GeV

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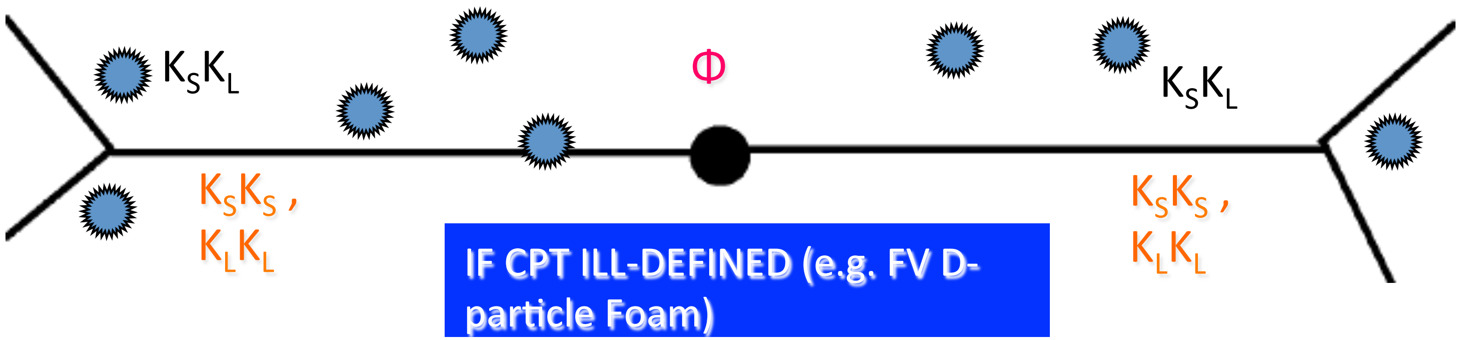

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$$\zeta^2 \sim \sigma^2$$

Stochastic Foam recoil fluctuations

ω-Effect Order of Magnitude Estimates

In above estimates:

QCD effects & sub-structure
in neutral mesons ignored, and D-foam acts
as if they were structureless particles,
then for $M_{QG} \sim 10^{19}$ 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. DAFNE2)

Re(ω), Im (ω) = $O(10^{-5})$

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In D-foam: quarks (charged) do not directly interact with D-particles
only *gluons* inside the Kaons *do*, suppressed effects?
QCD details matter? *need to estimate*

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ω-effect as discriminant of foam models

Bernabeu, NEM, Sarben Sarkar

- ***ω-effect not generic*, *depends on details* of *foam***
- (I) D-foam: $$\widehat{H_I} = -\left(r_1\sigma_1 + r_2\sigma_2\right)\widehat{k}$$

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

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

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

Garay

Bath frequency

"atom'' (matter) frequency

no ω-effect


EPILOGUE

OPERA & MAGIC RESULTS CAN BE RECONCILED : e.g. IN D-FOAM

TO RECAP: (I) RECOIL OF MASSIVE DEFECTS DISTORS SPACE TIME , MODIFIES DISPERSION RELATIONS FOR MATTER PROBES

(II) CAPTURE OF MATTER BY DEFECT LEAD TO EXTRA TIME DELAYS DUE TO STRINGY NATURE/MINIMUM LENGTH OF STRINGS, WHICH ARE ENHNACED BY RECOIL

$$\boxed{\Delta t \sim \alpha' E}$$

FOR CHARGE CONSERVATION REASONS CAPTURE (HENCE DELAYS) UNDERGO ONLY ELECTRICALLY NEUTRAL PARTICLES (PHOTONS…)

NEUTRINOS IN STRING THEORIES MAY HAVE ADDITIONAL ``CHARGES''/FLUXES DUE TO EXTRA U(1)' GROUP. IN SUCH A CASE NEUTRINOS WILL ALSO AVOID CAPTURE AND WILL THUS BE SUBJECTED ONLY TO (superluminal) GRAVITATIONAL D-foam RECOIL EFFECTS

$$v_g = 1 + \frac{1}{2}\langle|\vec{u}|^2\rangle + \mathrm{O}(|\vec{u}|^3) = 1 + \frac{1}{2}\sigma^2 > 1$$

MAGIC results (2005)

TeV Photons from
Active Galactic Nucleus
(AGN) Mkn 501 at red-shift
z = 0.03

More energetic
photons (1.2 - 10 TeV)
delayed by O(1 min) compared
to E < 0.6 TeV

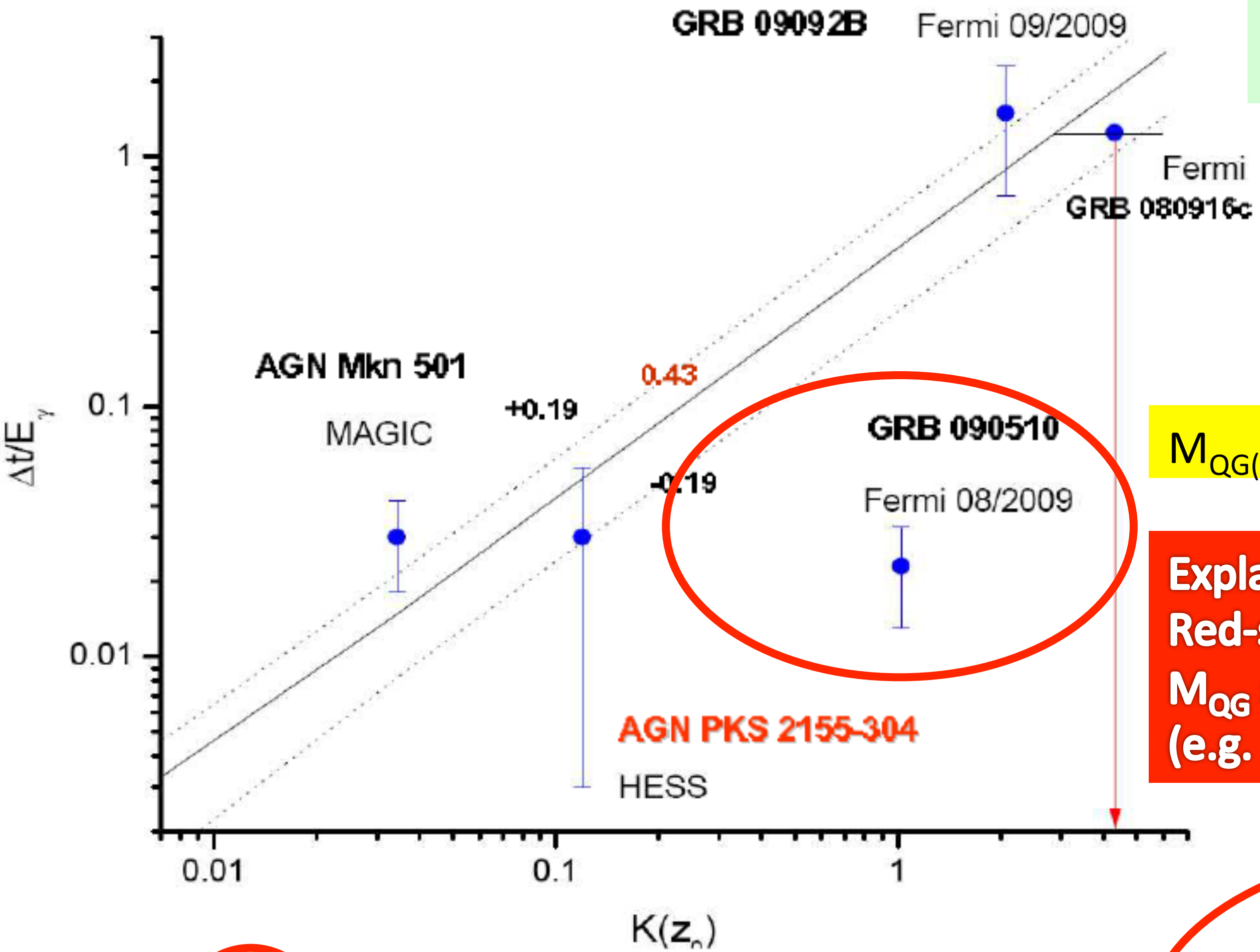
First Interesting result…
in conflIct with Conventional
Astrophysical acceleration
AGN Models (e.g. Crab Nebula)

Interestingly can fit QG
subluminal refractive index
with linear M_{QG} suppression
with $M_{QG(1)} = 0.2 \times 10^{18}$ GeV

or, if astrophysics at source
taken into account
$M_{QG(1)} > 0.2 \times 10^{18}$ GeV

Observed Photon Delays (H.E.S.S, FERMI)

Ellis, NEM, Nanopoulos (2009, 2010)



$M_{QG(1)} > 1.5\ 10^{19}$ GeV

Explained by
Red-shift dependent
M_{QG} scale
(e.g. D-foam voids at z=0.9)

$$\Delta t = \frac{E}{M_{\rm QG}} H_0^{-1} \int_0^z dz \frac{(1+z)}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}$$

$$M_{\rm QG}^{\rm Eff} = \frac{M_s}{n^\star(z)}$$

TWO PROCESSES IN D-FOAM/MATTER STRING INTERACTIONS

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Space time Foam situations –
Average over both populations of defects & quantum fluctuations

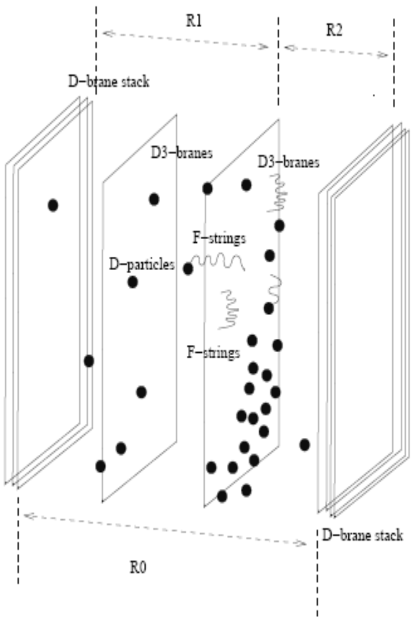
Isotropic & (in)homogeneous foam for a brane observer:

$$\boxed{\langle u_i \rangle \equiv \frac{g_s}{M_s} \langle \Delta k_i \rangle = 0}$$

$$\boxed{\frac{g_s^2}{M_s^2} \langle \Delta k_i \Delta k_j \rangle = \sigma^2 \delta_{ij}}$$

Lorentz Invariance on Average

Violated in flcts



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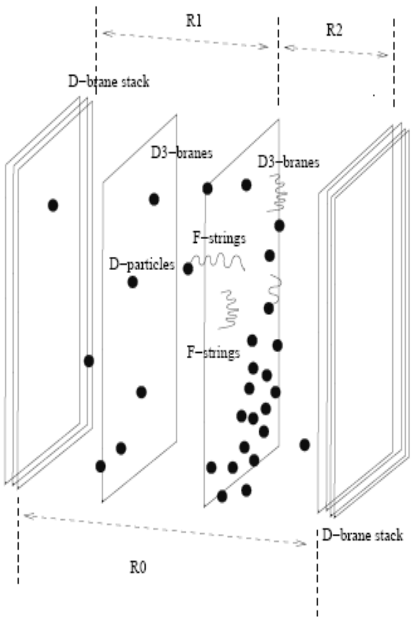

$$v_g = 1 + \frac{1}{2} \langle |\vec{u}|^2 \rangle + \mathrm{O}(|\vec{u}|^3) = 1 + \frac{1}{2} \sigma^2 > 1$$

Superluminal propagation
IF NOT CAPTURE

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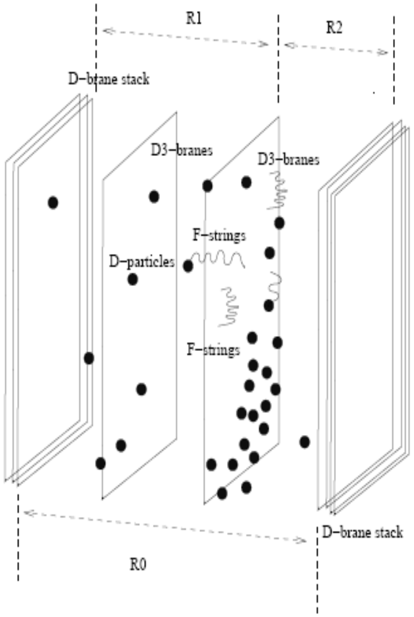

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Superluminal propagation
IF NOT CAPTURE

$$\left(\text{cf. locally } v_g = \frac{\partial E}{\partial p} = 1 - |\vec{u}|\cos\vartheta + \frac{1}{2}|\vec{u}|^2 + \mathrm{O}(|\vec{u}|^3)\right)$$

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POSSIBLE TO RECONCILE

OPERA ``ADVANCES''

DUE TO RECOIL-INDUCED SPACE-TIME DISTORTION FOR NEUTRINOS, NO CAPTURE BY FOAM POSSIBLY DUE TO U'(1) GAUGE SYMMETRIES

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NO PROBLEMS WITH CAUSALITY

CAUSALITY & SUPERLUMINALITY

No problems with Causality if Superluminality is Observer dependent

Liberati, Sonego, Viser (2002)

i.e. Causality paradox arise if signals travel with the **same** speed V > c in **two different** frames

Previous examples are fine in this respect, the effects on photon dispersion relation can be represented by `` effective " metrics ,

$$p^\mu p^\nu g_{\mu\nu} = 0$$

e.g. in Casimir photons in a cavity (n^μ unit space-like vector orthogonal to plates)

$$x^\mu \to x^\mu + \xi^\mu(x,u)$$

$$g_{\mu\nu} \to g_{\mu\nu} + \partial_{(\mu}\xi_{\nu)}$$

As such, speed of signal depends on *observer velocities u^μ* relative to system

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NO NEUTRINO CHERENKOV Radiation
(No Cohen-Glashow pair-production effect)

Alexandre, Ellis, NEM (2011)

NO NEUTRINO CHERENKOV Radiation in D-foam (No Cohen-Glashow pair-production effect)

$$\nu_\tau \to \nu_\tau + e^+ + e^-$$

Kinematically allowed if neutrino speed is faster than c=1 in vacuo and there is a preferred frame

But in D-foam there is general coordinate invariance built in (underlying string theory).
moreover superluminality is an ``effective'' phenomenon induced in given frame by the distorted geometry due to recoil
The latter is observer dependent,

$$p^\mu p^\nu g_{\mu\nu} = 0$$

$$\boxed{\begin{aligned} x^\mu &\to x^\mu + \xi^\mu(x,u) \\ g_{\mu\nu} &\to g_{\mu\nu} + \partial_{(\mu}\xi_{\nu)} \end{aligned}}$$

However Cherenkov radiation (decay) is observer independent
one can go (within string theory) to the rest frame of neutrino,
where such a Cherenkov process is not allowed kinematically.

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WITH ``MAGIC'' PHOTON ``DELAYS``

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OTHER EXPLANATIONS (including weird effective geometries & boundary conditions in the conditions of OPERA experiment) POSSIBLE OF COURSE……

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… & WITH EPR MODIFICATIONS IN ENTANGLED PARTICLE STATE (ω-effect)

DUE TO CAPTURE BY D-FOAM

$$\boxed{|\omega|^2 \sim \frac{\sigma^2 |\vec{k}|^4}{M_{\mathrm{QG}}^2 (m_1 - m_2)^2}}$$

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$$\boxed{\sigma^2 \sim O(10^{-5})}$$

DAΦNE-2?

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CONCLUSIONS & OUTLOOK

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- Quantum Gravity may affect the matter quantum mechanical behaviour by ``opening up'' the matter subsystem in certain models of space-time foam
- Low-energy experimentalists do not have access to QG d.o.f. , hence effective ***decoherence*** , affects Quantum Mechanical time ***evolution*** of matter
- This may induce ***an ill-defined CPT operator*** (perturbatively, anti-particle exists) for the low-energy matter subsystem with ``smoking-gun'' evidence in entangled particle states experiment – ***Modified EPR correlations …model dependent***

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Outlook

- Plethora of tests if Lorentz invariance is violated – but not so many if conserved on average but violated in quantum fluctuations
- Decoherence may be compatible with Lorentz Invariance on average – in such a case ω-effect may be a smoking gun, but for next generation facilities to have ***sensitivity*** one needs **densities of defects** at present as ***one per string volume***
- Such a situation ***affects early Universe cosmology***
- Could also lead to observable ***vacuum refraction*** Astrophysical & Terrestrial tests of the latter from cosmic photons and/or neutrinos…(Energy dependent) Arrival-time delays/advances…

Outlook

- Plethora of tests if Lorentz invariance is violated – but not so many if conserved on average but violated in quantum fluctuations
- Decoherence may be compatible with Lorentz Invariance on average – in such a case ω-effect may be a smoking gun, but for next generation facilities to have ***sensitivity*** one needs **densities of defects** at present as ***one per string volume***
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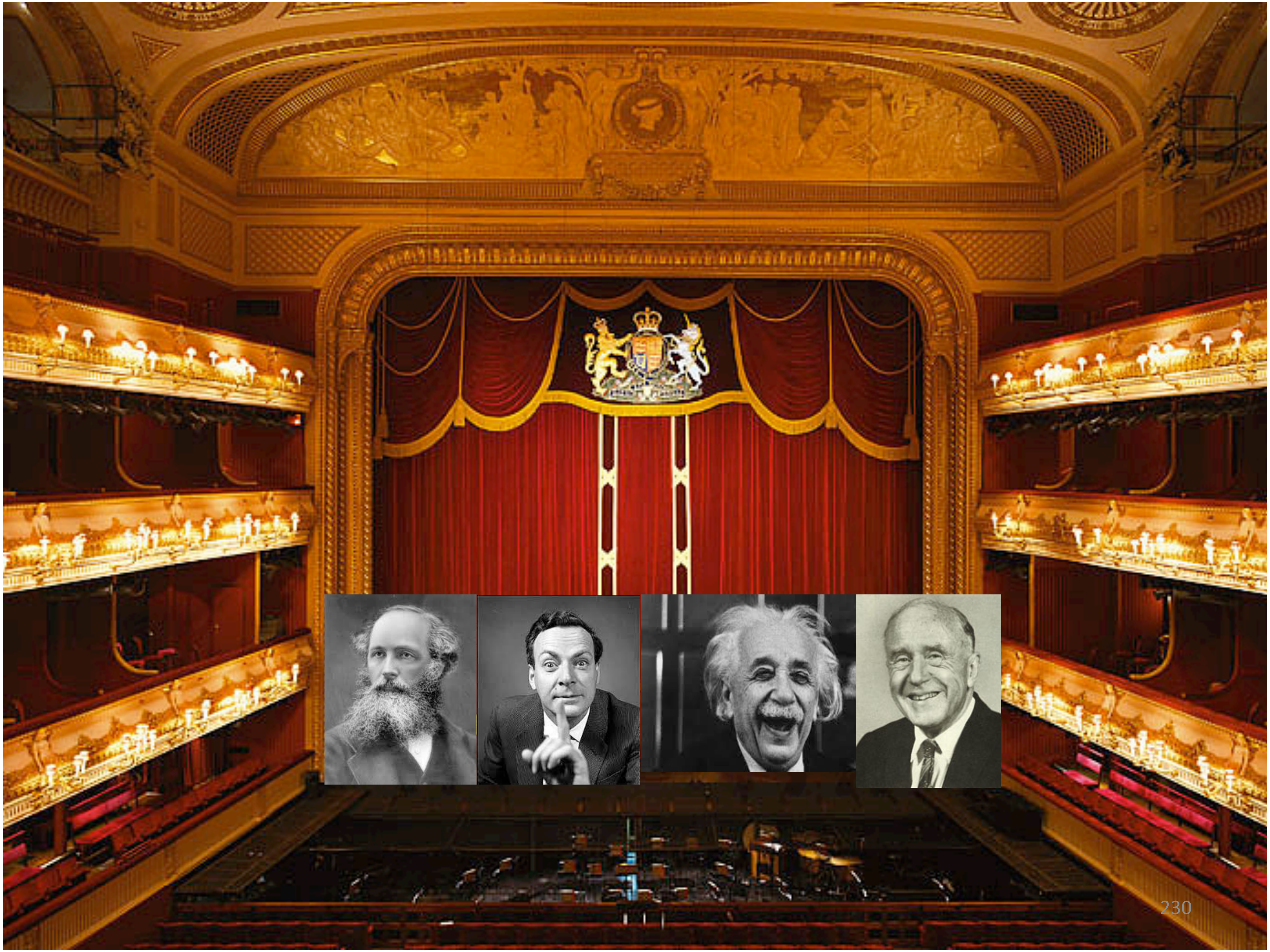
- ***CALCULATE EFFECTS IN DETAILED MODELS…***
  KEEP SEARCHING….


The End




OPERA
KLOE


SPARES

D-particle Recoil & the "Flavour" Problem

Not all particle **species** interact the **same way with D-particles**
e.g. electric charge symmetries should be preserved, hence electrically-charged excitations cannot split and attach to neutral D-particles….

Neutrinos (or neutral mesons) are good candidates…

But there may be flavour oscillations during the capture/recoil process, i.e. wave-function of recoiling string might differ by a phase from incident one….

In statistical populations of D-particles, one might have isotropic situations, 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:

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

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

$$\langle r_\mu \rangle = 0, \ \langle r_\mu r_\nu \rangle = \Delta_\mu \delta_{\mu\nu} \qquad \Delta_\mu \sim O\left(\frac{E^2}{M_P^2}\right)$$

D-particle Recoil & the "Flavou

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

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D-particle recoil and entangled Meson States

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

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

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

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Similarly for $\left|k^{(i)},\uparrow\right\rangle^{(i)}$ **dressed state** $|\downarrow\rangle \leftrightarrow |\uparrow\rangle$ and $\alpha \to \beta$

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

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&|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)}
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