Lorentz Invariance, Strings and High-Energy Gamma Ray Astronomy

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Effective Field Theory Approach to Quantum Gravity

A.V. Kostelecky and collaborators, other rich literature in the subject, Burgess, Myers-Pospelov, Urrutia, … Sudarsky,…

Represent effective Quantum Gravity (QG) effects as Lorentz and/or CPTV higher-dimension non-renormalizable operators in a flat space-time local effective Lagrangian (Standard-Model Extension (SME))

No idea what the order of their (dimensionful) coefficients is…unless Microscopic models become available….

Nevertheless obtain interesting limits experimentally on such effects… ``reaching or exceeding Planck Scale sensitivity'' (whatever that means in EFT context)…

SME Tests: Mainly from atomic Physics experiments, but also particle/nuclear physics systems, such as neutral kaons (KTeV, φ-factories), hydorgen/anti-hydrogen spectroscopies …

STANDARD MODEL EXTENSION

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

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

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

Spontaneous breaking of Lorentz symmetry by (exotic) string vacua MODIFIED DIRAC EQUATION in SME: for spinor ψ reps. electrons, quarks etc. with charge q

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

where $D_\mu = \partial_\mu - A^a_\mu T^a - q A_\mu$.

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

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

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

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CPT & Lorentz violation: a_μ , b_μ.

NB1: : mass differences between

KTeV: a_X, $a_Y < 10^{-21}$ GeV
Φ-factories: $a_0 < 10^{-18}$ GeV

Sidereal variations
H-Masers: $b_Z < 10^{-31}$ GeV

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

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But EFT may not always be an appropriate tool for QG... Beyond EFT ? Formalism? Experiments?

OUTLINE – PART I

N.E.M 0903.0318

- High-Energy Gamma Ray Astrophysics as a probe for New Physics

- **The MAGIC and Fermi results:** non-simultaneous arrival of high-energy photons from celestial objects: more energetic photons arrive later… **(Non(?)) Observation by H.E.S.S.** …

- Possible Interpretations:

  (i) Astro-Physics at source: hadronic mechanisms or synchrotron radiation + inverse Compton scattering produce delays at emission: Non conclusive …

  (ii) Exotic Interpretation: Quantum Gravity (QG) propagation effects (?): *QG as a medium with refractive index, Modified Dispersion Relations for matter probes with Linear QG scale suppression (LMDR)*

- **Check on other tests on (LMDR) modified dispersion relations: Electrons: Synchrotron Radiation from Crab Nebula**

  Photons: Birefringence constraints for LMDR

OUTLINE – PART II

N.E.M 0906.2712

- **Stringy Models of Space Time Foam (SMSTF) : Non-universal action of ``gravity foam'' on matter probes:**
  Electrons (and in general charged particles): foam transparent,
  Photons (and neutral particles) feel the foam medium effects

- **String Uncertainties, (Induced, Finsler-type) Non-commutative geometry at string scales: a uniquely stringy effect ?**
- **Beyond EFT?**
  …. Compatible with other tests constraining LMDR

- Other consequences of the SMSTF: **CPT Violation** (ill-definition) due to **decoherence** and unique effects (?) in **entangled states** of meson factories
- **Outlook: NEED TO CONFIRM MAGIC effect by H.E.S.S. and other experiments**, much more statistics needed (GRB's…)
  further tests using High-Energy Neutrino astrophysics

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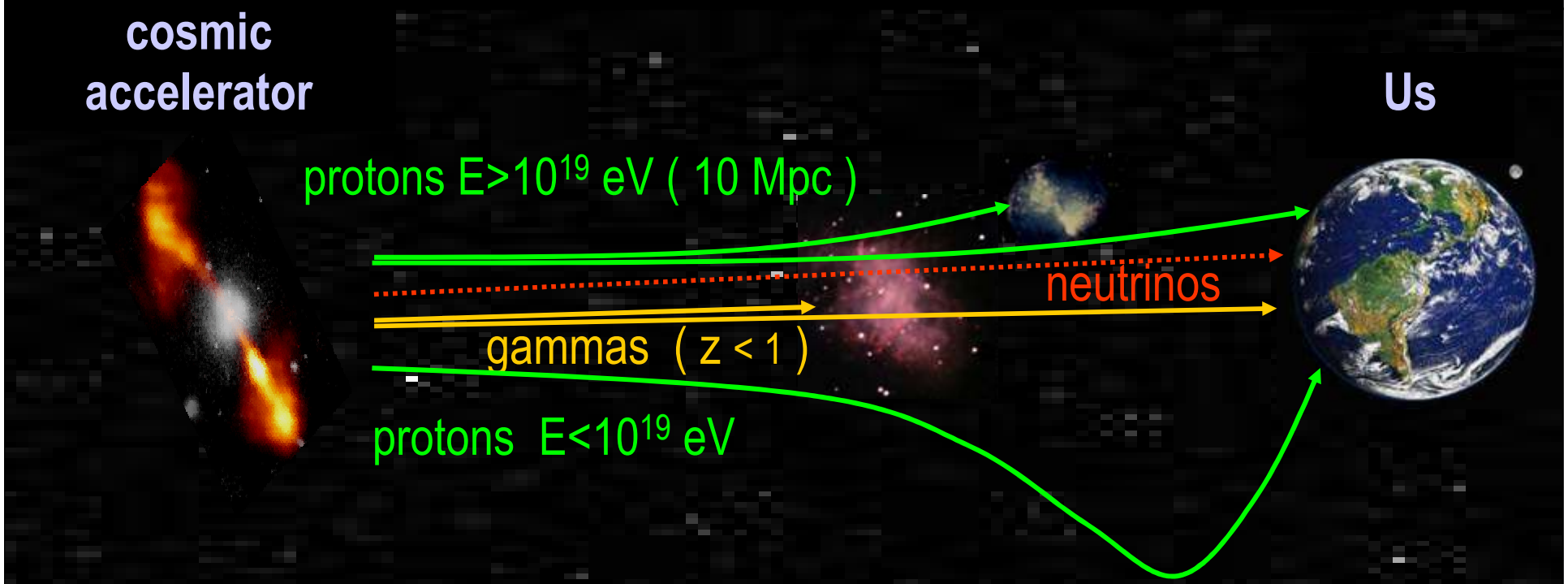
Multi-messenger observations of the Cosmos



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

photons: Absorbed by dust & radiation field (CMB)

neutrinos: Difficult to detect

⇒ **Three "astronomies" possible...**

DeNaurois 2008

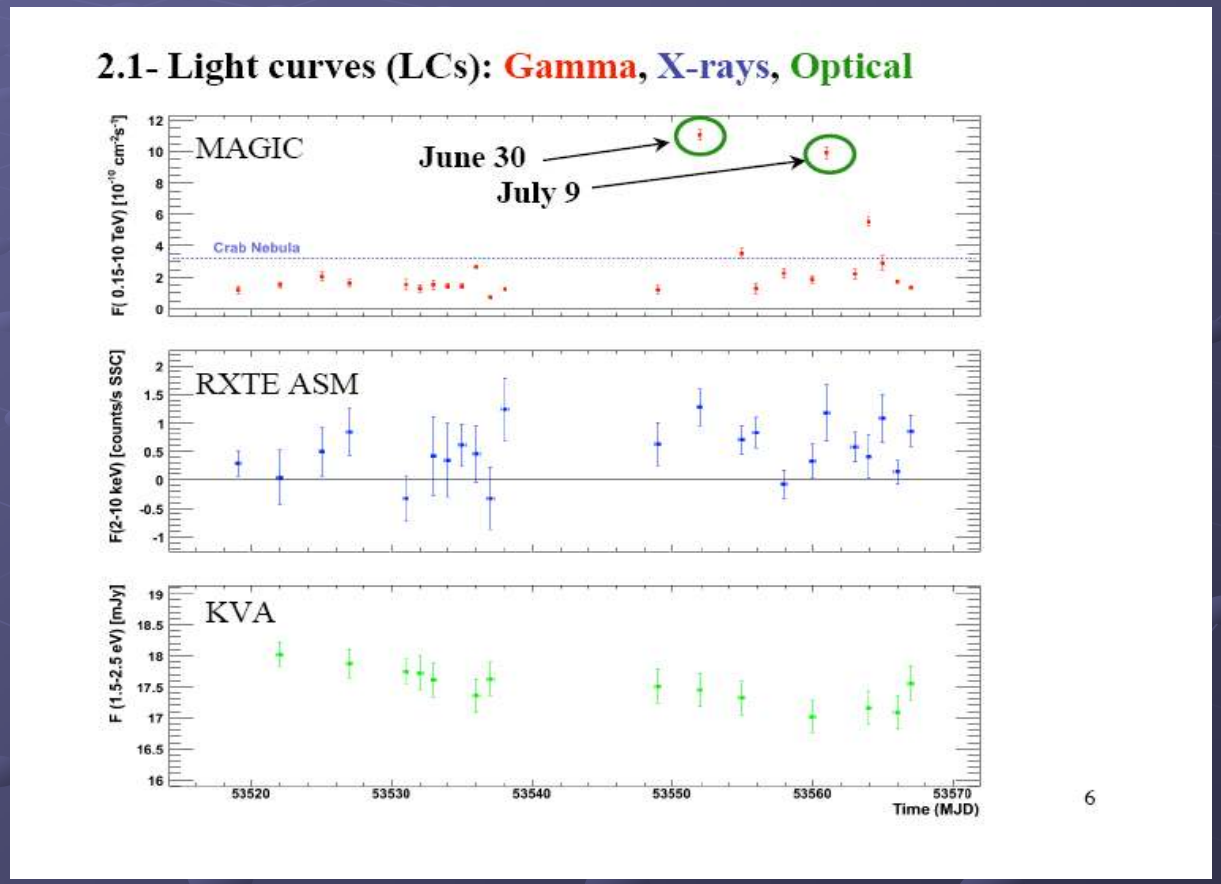
VHE Experimental World Today

M. MARTINEZ

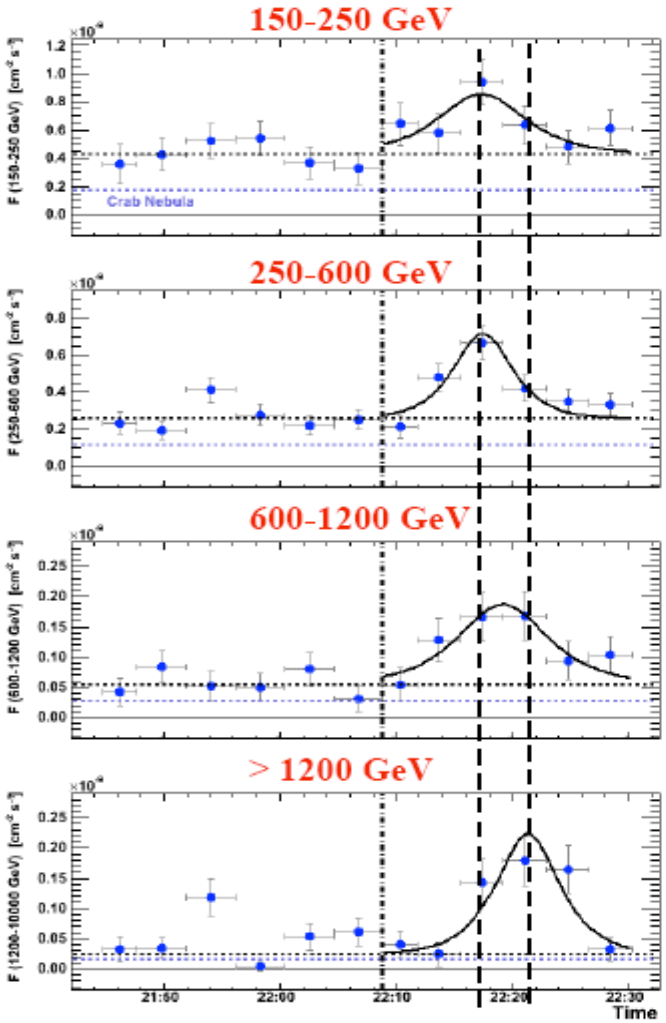
The MAGIC Collaboration (Major Atmospheric Gamma-ray Imaging Cherenkov Telescope)

Observation of Flares from AGN Mk 501

Red-shift: z=0.034



The MAGIC ``Effect”



LCs for different energy ranges (4 min bins)

July 9

Flare is seen in all energy ranges

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

13

SSC as explanation of the MAGIC Effect

- **Classical SSC model**: emission region moves along the jet with constant **Lorentz factors** . In other AGN (e.g.; Crab Nebula), such factors are of order **10 – 20** . However, to account for the **4 ± 1 minute delay observed** in **MAGIC** requires **Lorentz factors four orders of magnitude higher.**
- ***Modify SSC model :*** **(i) assume gradual acceleration of relativistic electrons inside blob (SSC I)**

  (ii) assume the blob captured in inner part of the jet during its acceleration phase (SSC II) : lower-energy part of flare close to base of the jet, lower Lorentz factor, higher-energy at larger distances from jet base, higher Lorentz factor.

  Time-delay in SSC II inversely proportional to γ-ray Energies

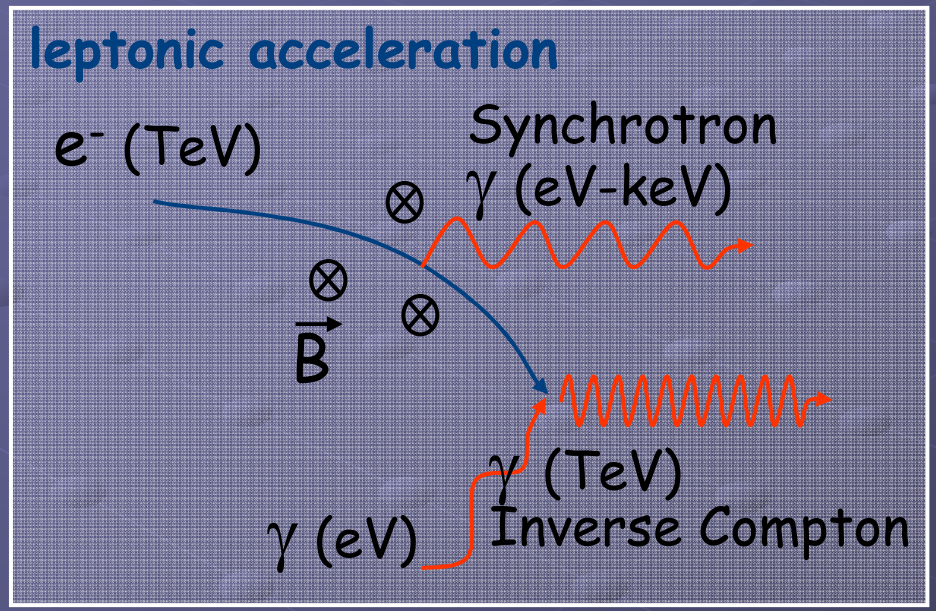
- **SITUATION NON CONCLUSIVE: DOES FLARE PHYSICS DEPEND ON INDIVIDUAL FLARES (SSC I) ? MATTER OF LUCK TO HAVE OBSERVED BLOB IN ITS ACCELERATION PHASE IN Mk501 (SSC II) ?**

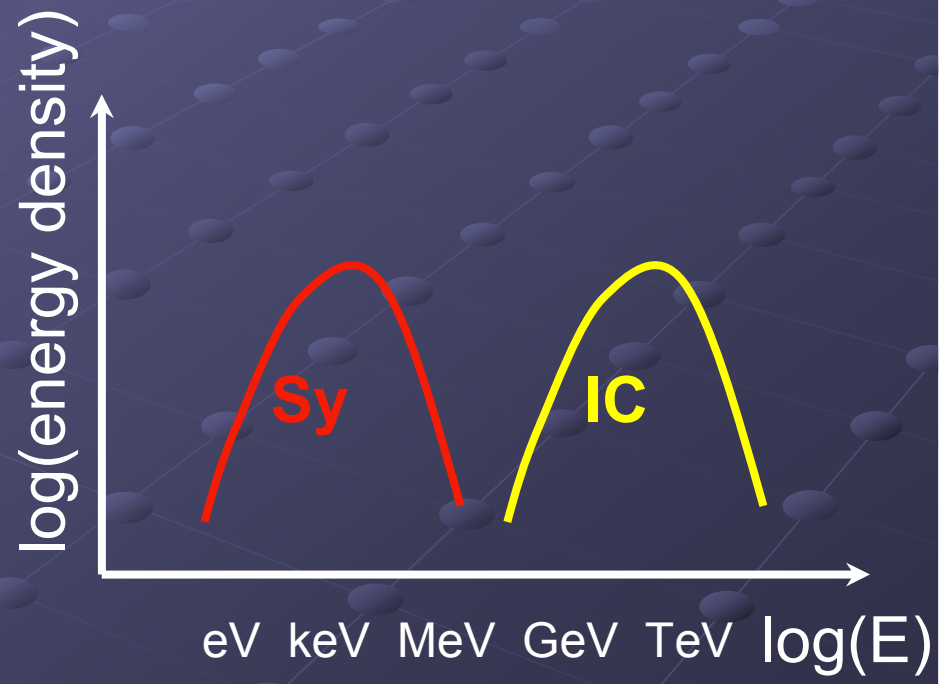
AGN High Energy Gamma Rays

- electron accelerators:

synchrotron: e B -> e gamma

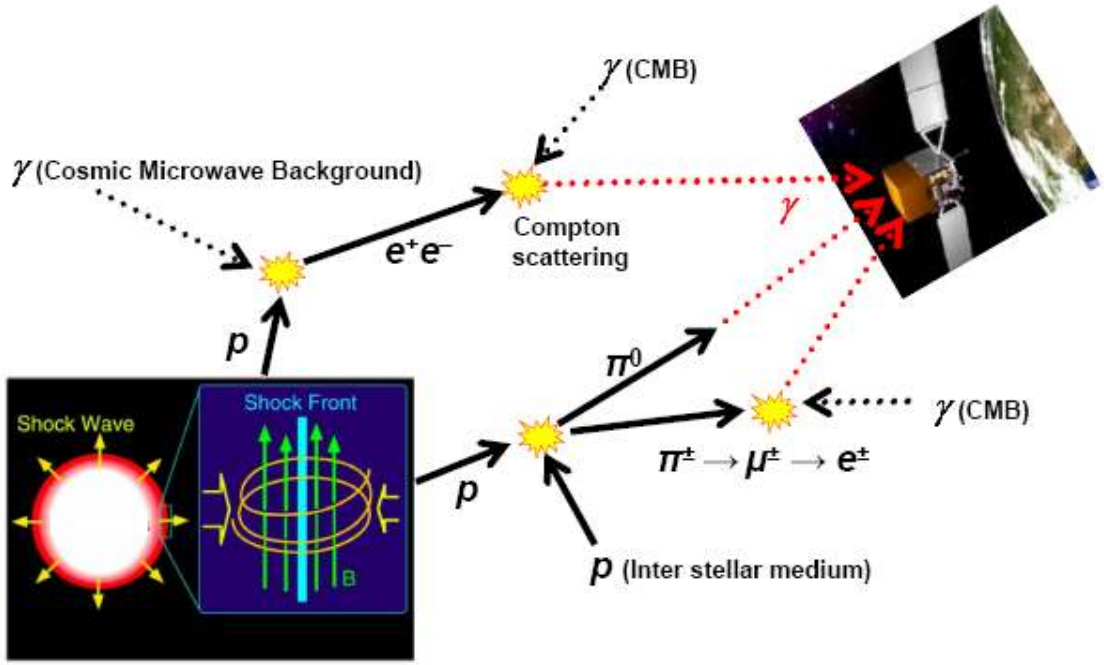
+ inverse Compton: e gamma -> gamma e



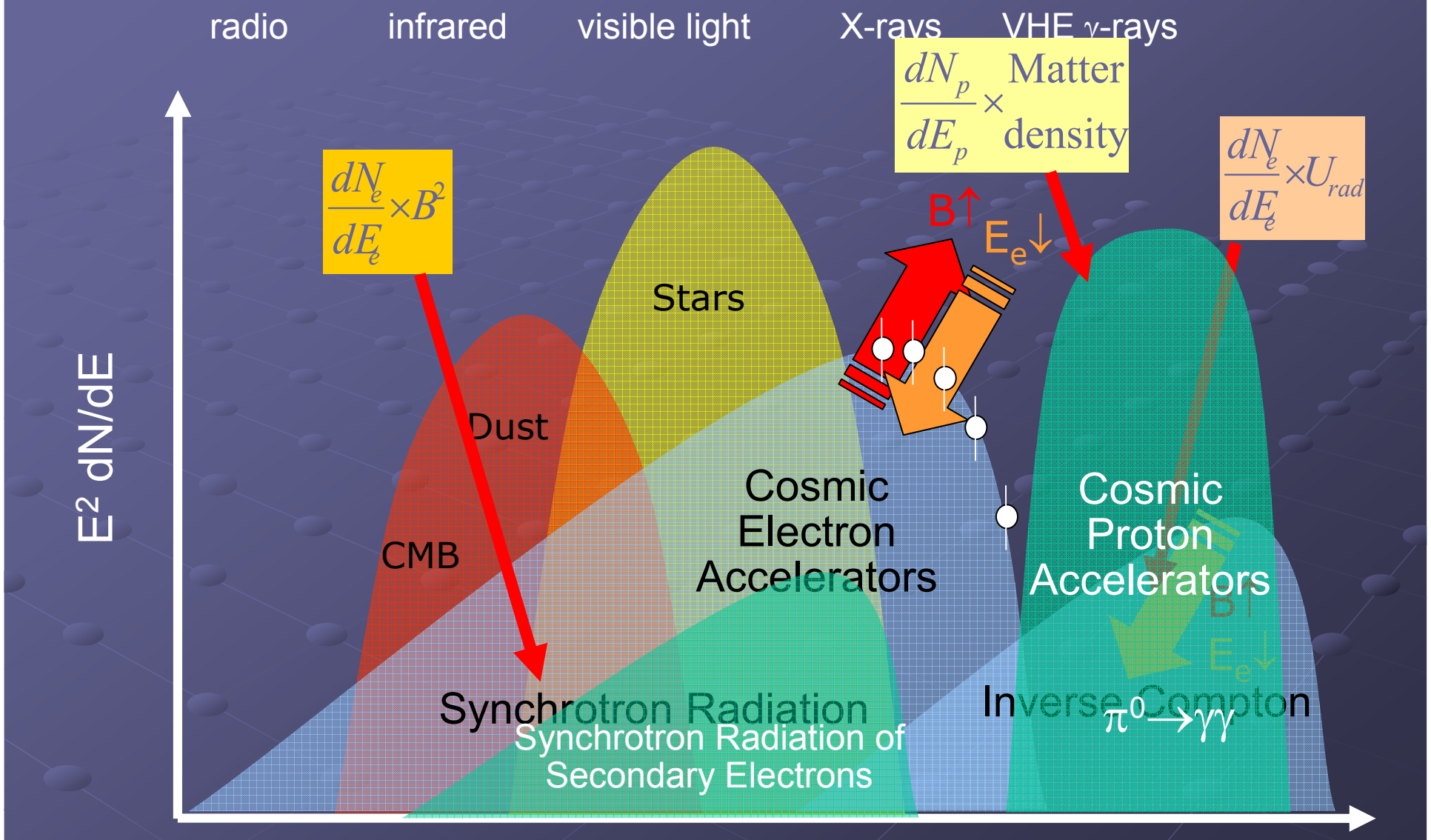


AGN HE γ: Hadronic acceleration

- Alternative models for explaining high energy Gamma Rays from AGN involve hadronic acceleration: $\pi^0 \rightarrow \gamma\gamma$



Electron or Hadron Accelerator?



DeNaurois 2008

VHE Experimental World Today

M. MARTINEZ

H.E.S.S. (non) Observations of time-lags

PRL 101,170402 (2008)

No appreciable Time-Lag claimed for Photons from AGN PKS 2155-304 At red-shifts z=0.116

H.E.S.S. Telescopes array (Namibia)

1ST TELESCOPE (2002)

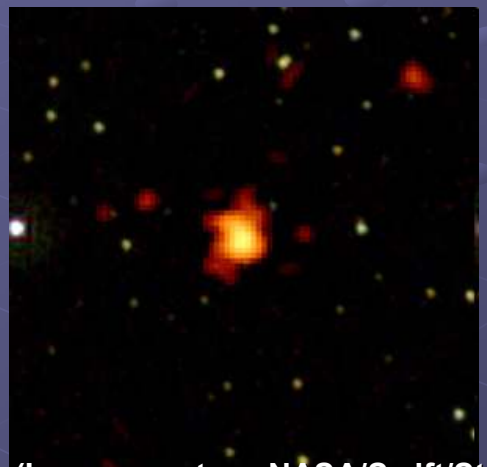
FERMI/GLAST Observations

GRB 080916c (September 2008)

Highest energy Emission:

$$E = 13.2^{+0.70}_{-1.54}\ \mathrm{GeV}$$

4.5 s time-lag between E > 100 MeV and E < 100 KeV



(Image courtesy NASA/Swift/Stefan Immler)

Time-Lag (Delay) Measured for high-energy Photons of 13 GeV:

Δt = 16.5 s

Most Extreme GRB ever !!

FERMI/GLAST Observations

GRB 080916c (September 2008)

Measured Red-Shift by GROND Collaboration

Z = 4.2 ± 0.3

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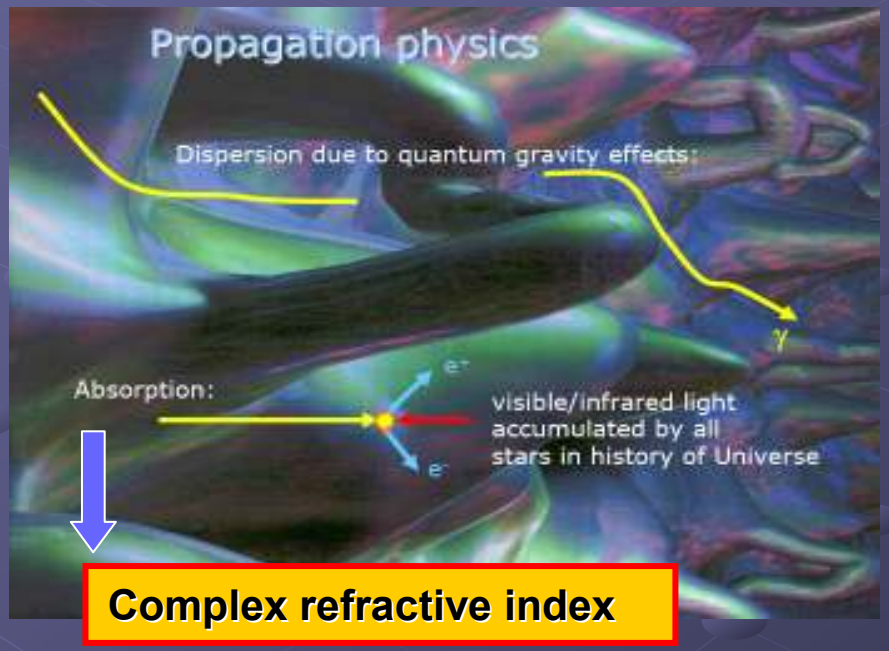
New fundamental Physics Interpretation

- Quantum Gravity as a dispersive medium (space-time foam) , modified dispersion relations **(MDR)** for matter, radiation



- **Phenomenological Models of MDR**
  Gonzalez-Mestres, Amelino-Camelia, Ellis, NM, Nanopoulos, Sarkar
- **Stochastically fluctuating space time backgrounds**
  Ford, Yu , Sarben Sarkar, NM…
- **String & Brane-inspired Models**
  Ellis, NM, Nanopoulos, Szabo, Sakharov, Farakos, Mitsou, …
- **Loop Quantum Gravity (?)**
  Gambini, Pullin, Urrutia, …
- **Deformed Special Relativity Models (unclear if there is a consistent quantum version)**
  Amelino-Camelia, Magueijo, Smolin, Kowalski- Glikman …

Quantum-Gravity Induced Modified Dispersion for Photons

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

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

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

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

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

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

MAGIC QG scale Bounds (individual photon study, reproduction of flare peak)

Linear

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

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

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

Quadratic

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

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

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

95% CL

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

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

Ellis, NM, Nanopoulos

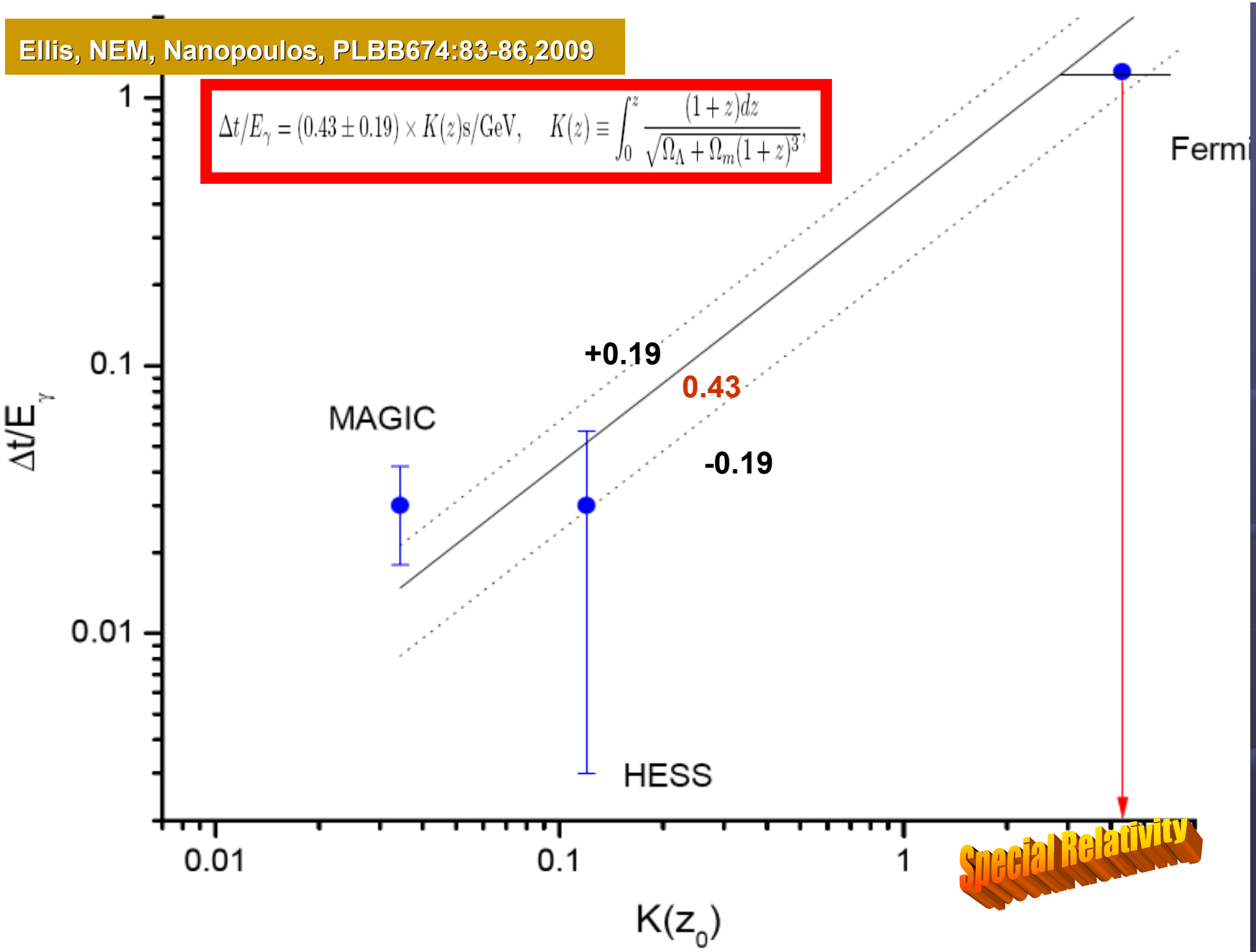
ALL THREE CASES (or 2.5!) (MAGIC, FERMI and(?) HESS) COMPATIBLE WITH LINEARLY SUPPRESSED MDR FOR PHOTONS BUT NOT QUADRATIC...

n=1

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

Ellis, NEM, Nanopoulos, PLBB674:83-86,2009

$$\Delta t/E_\gamma = (0.43 \pm 0.19) \times K(z)\mathrm{s/GeV}, \quad K(z) \equiv \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}},$$



MDR for other matter probes

Massive Probes (e.g. electrons):

$$E^2 = p^2\left(1 - \left(\frac{p}{M_{QG}}\right)^{\alpha}\right) + m^2 \ , \ p \equiv |\vec{p}|$$

Constraints from Crab Nebula via Synchrotron Radiation

Jacobson, Liberatti, Mattingly, Ellis, NM, Sakharov

Electron moving in magnetic field H emits discrete frequency spectrum with a maximum at critical frequency:

$$\omega_c = \frac{3}{4}\frac{1}{R\delta(E)}\frac{1}{c(\omega_c) - v(E)}$$

R=orbit radius, $c(\omega_c)$=photon group velocity, v(E)=electron group velocity
δ(E) = angle for forward radiation pattern

Experimental measurement of ω_c (Crab Nebula) yields For $M_{QG} = M_{QG1\ (MAGIC)} \sim 10^{18}$ GeV that $\alpha > 1.74$

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WHAT ABOUT PHOTONS & THE MAGIC RESULT?

Birefringence Constraints on photons MDR

- If MDR for probes stem from Local Effective Lagrangians (LEL):

Maccione et al., arXive0707.2673

$$-\frac{\xi}{2M}u^m F_{ma}(u\cdot\partial)(u_n\tilde{F}^{na}) + \frac{1}{2M}u^m\bar{\psi}\gamma_m(\zeta_1+\zeta_2\gamma_5)(u\cdot\partial)^2\psi$$

Myers-Pospelov QED

Photons : $\omega_\pm^2 = k^2 \pm \frac{\xi}{M}k^3$

Electrons: $E_\pm^2 = p^2 + m^2 + \eta_\pm \frac{p^3}{M}$

$\eta_\pm = 2(\zeta_1 \pm \zeta_2)$

± signs indicate left/right movers and for Circularly polarized photons imply rotation of linear polarization angle (BIREFRINGENCE).

Difference in polarization angle over cosmological distance *d*:

$$\Delta\theta = \xi(k_2^2 - k_1^2)d/2M$$

UV radiation from Galaxies: $\xi \lesssim 2\times 10^{-4}$

For $M \sim M_{\rm Pl} \approx 1.22\times 10^{19}$ GeV

From GRB polarization $|\xi| \lesssim 2\times 10^{-7}$

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MAGIC EFFECT due to QG ruled out ?

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arXive0707.2673

$\gamma_5)(u \cdot \partial)^2 \psi$

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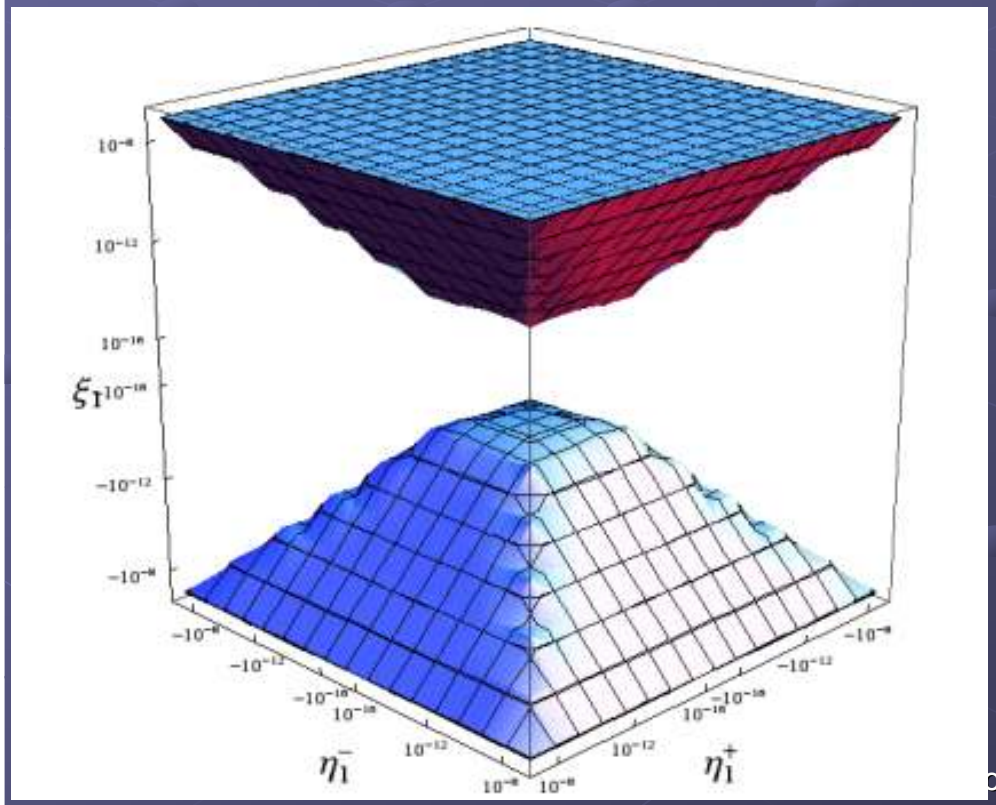
MAGIC EFFECT due to QG ruled out ?

NO ! ... PROVIDED ONLY PHOTONS ARE SUBJECT TO EFFECTS OF FOAM AND... NO BIREFRINGENCE

Ultra-high-energy photons

$$\omega_\pm^2 = k^2 + \xi_n^\pm k^2 \left(\frac{k}{M_{\rm pl}}\right)^n ,$$
$$\omega_{\rm b}^2 = k_{\rm b}^2 ,$$
$$E_{{\rm e},\pm}^2 = p_{\rm e}^2 + m_{\rm e}^2 + \eta_n^{{\rm e},\pm} p_{\rm e}^2 \left(\frac{p_{\rm e}}{M_{\rm pl}}\right)^n$$



Galaverni & Sigl

Severe constraints on LIV Parameters from absence of:
(i) Observations on UHE photons, which would evade pair production due to threshold modifications if MDR hold:

$$\gamma_{UHE} + \gamma_{background} \not\rightarrow e^+ e^-$$

(ii) Photon Decay

$$\gamma_{UHE} \rightarrow e^+ e^-$$

Allowed, above threshold if MDR

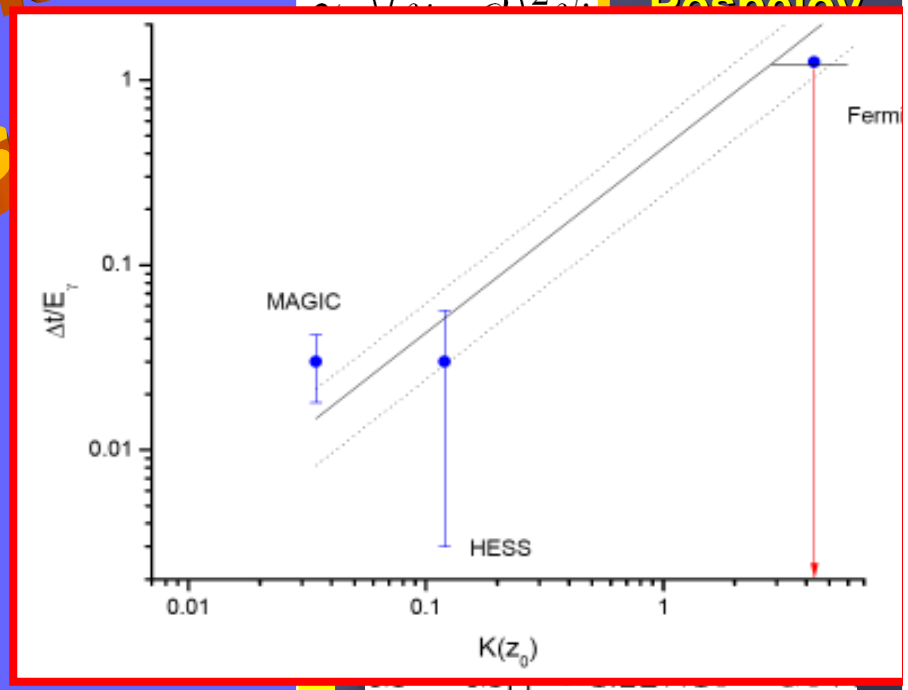
Avoid MDR but still have Time Delays?

grangians (LEL):

arXive0707.2673

Myers-

Moreover...
Time Delays may be not due to modified dispersion...
but effects BEYOND Local Effective Theories



$$\Delta t/E_\gamma = (0.43 \pm 0.19) \times K(z)\mathrm{s/GeV}, \quad K(z) \equiv \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}},$$

MAGIC EFFECT due to QG ruled out ?

A CLASS OF MODELS WITH SUCH PROPERTIES...

(1) Time Delays proportional to E

(2) Stable Photons

(3) No birefringence

(4) Beyond EFT

STRING THEORY & VACUUM REFRACTIVE INDICES

STRING/D-BRANE BASICS

String theory type	p-brane types allowed
type-IIA	$p = 0, 2, 4, 6, 8$
type-IIB	$p = -1, 1, 3, 5, 7, (9)$
type-I	$p = 1, 5, 9$

Heterotic Strings admit no p-branes

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For our models of Foam...

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Compactify to 3 + 1 Large Dim

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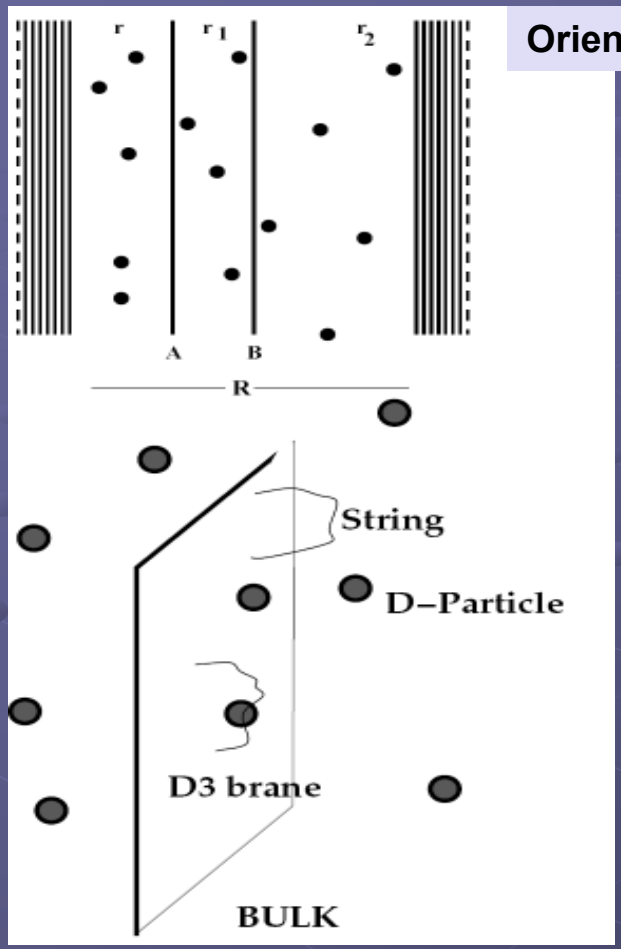
type-I	$p =$

Compactify to 3 + 1 Large Dim

Wrap up along Three cycles (``D-particles'')

Heterotic Strings admit no p-branes

A Stringy (type IA) Model of Space -Time Foam



Orientifold planes, stacks of D8 branes

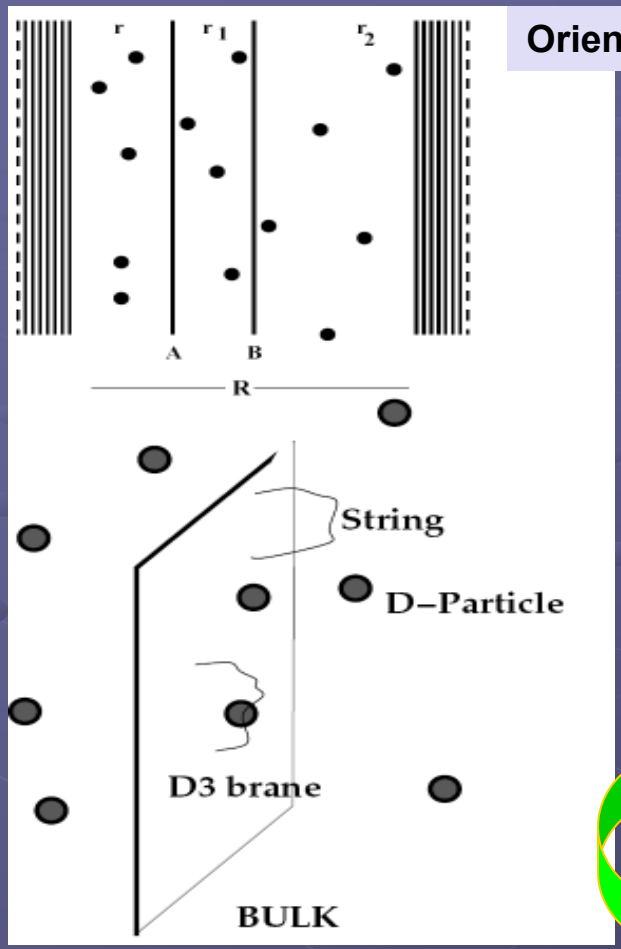
Ellis, NM, Westmuckett

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

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

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

A Stringy (type IA) Model of Space -Time Foam



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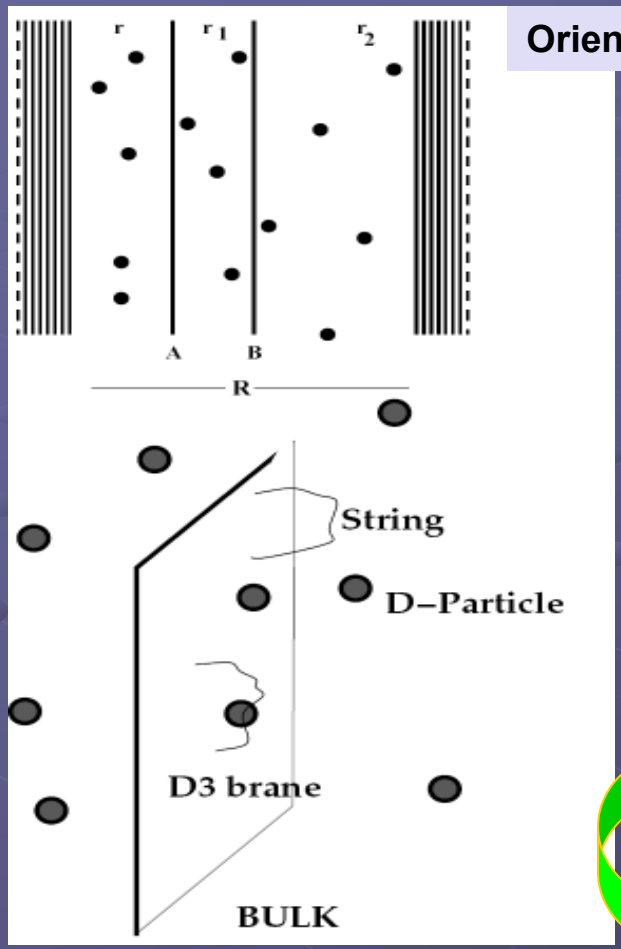
NON-UNIVERSAL ACTION OF D-PARTICLE FOAM ON MATTER & RADIATION

A Stringy (type IA) Model of Space -Time Foam



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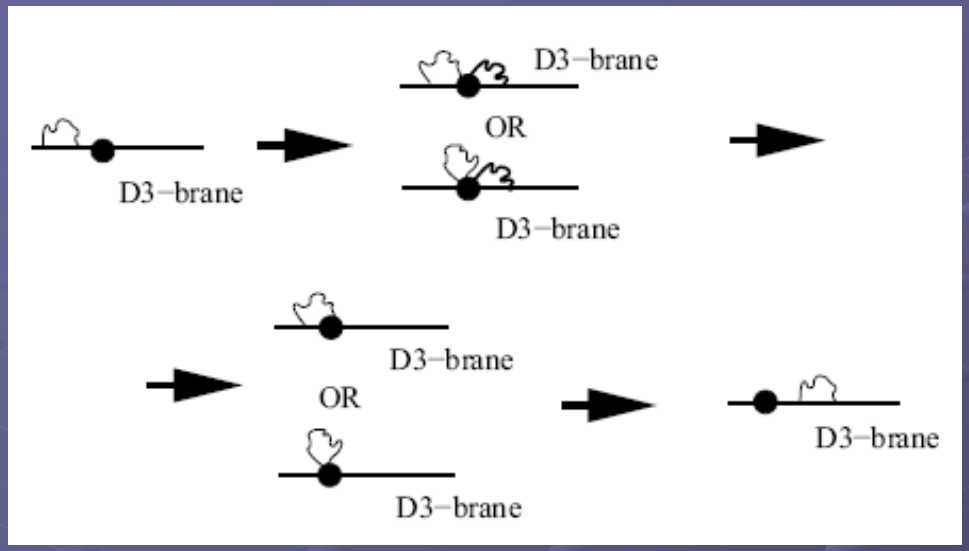
NON-UNIVERSAL ACTION OF D-PARTICLE FOAM ON MATTER & RADIATION

Stringy Uncertainties & the Capture Process

Ellis, NM, Nanopoulos arXiv:0804.3566



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

$$p^0 = \frac{L}{\alpha'} + \frac{N}{L}.$$

Minimise right-hand-size w.r.t. L.
End of intermediate string on D3-brane
Moves with speed of light in vacuo c=1
Hence TIME DELAY (causality) during Capture:

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

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

Stringy Uncertainties & the MAGIC Effect

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

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

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

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

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

Stringy Uncertainties & the MAGIC Effect

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

COMPATIBLE WITH STRING UNCERTAINTY PRINCIPLES:

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

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

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

Induced (Finsler-type) Non-Commutativity

NEM, arXive:0906.2712

D-particle recoil σ-model deformation

$$\mathcal{V}_{\mathrm{D}}^{imp} = \frac{1}{2\pi\alpha'} \sum_{i=1}^{d} \int_{\partial D} d\tau \, u_i X^0 \Theta\left(X^0\right) \partial_n X^i .$$

Written as world-sheet Bulk operator (Stokes theorem)

$$\mathcal{V}_{\mathrm{D}}^{imp} = \frac{1}{2\pi\alpha'} \int_D d^2z \, \epsilon_{\alpha\beta} \partial^\beta \left(\left[u_i X^0 \right] \Theta\left(X^0\right) \partial^\alpha X^i \right) =$$

$$\frac{1}{4\pi\alpha'} \int_D d^2z \, (2u_i) \, \epsilon_{\alpha\beta} \partial^\beta X^0 \left[\Theta_\varepsilon\left(X^0\right) + X^0 \delta_\varepsilon\left(X^0\right) \right] \partial^\alpha X^i$$

Open strings in ``electric'' field background , provided here by recoil velocity u_i

$$B_{0i} \sim u_i \ , \qquad B_{ij} = 0$$

Statistically averaged << u_i >> over D-particle populations, might lead to Uniform `electric field' backgrounds

Induced (Finsler-type) Non-Commutativity (N.C.)

NEM, arXive:0906.2712

Mixed Boundary Conditions

$$g_{\mu\nu}\partial_n X^\nu + B_{\mu\nu}\partial_\tau X^\nu|_{\partial\mathcal{D}} = 0$$

Seiberg-Witten
Seiberg, Susskind, Toumbas

Neumann **Dirichlet**

World-sheet 1st quantization leads to N.C. (induced by recoil here)

$$[X^1, t] = i\theta^{10}\ , \qquad \theta^{01}(= -\theta^{10}) \equiv \theta = \frac{1}{u_c}\frac{\tilde{u}}{1-\tilde{u}^2}$$

$$\tilde{u}_i \equiv \frac{u_i}{u_c} \text{ and } u_c = \frac{1}{2\pi\alpha'}$$

But of Finsler type
(i.e. momentum dependent)

$$u_i = g_s\frac{(\Delta\vec{k})_i}{M_s}$$

Non-commutative effective field theories & CPT

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

Moyal $\star$ products

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

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

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

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

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

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

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

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

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

Induced (Finsler) Space-Time Metric

World-Sheet Propagator in the presence of recoil background

$$\langle X^\mu(\tau) X^\nu(0) \rangle = -\alpha' g^{\mu\nu}_{\text{open, electric}} \ln \tau^2 + i \frac{\theta^{\mu\nu}}{2} \epsilon(\tau)$$

Implies Finsler-type target-space metric

$$g^{\text{open,electric}}_{\mu\nu} = \left(1 - \tilde{u}_i^2\right) \eta_{\mu\nu} \ , \qquad \mu, \nu = 0, 1$$

$$g^{\text{open,electric}}_{\mu\nu} = \eta_{\mu\nu} \ , \mu, \nu = \text{all other values} \ ,$$

and effective string coupling

$$g_s^{\text{eff}} = g_s \left(1 - \tilde{u}^2\right)^{1/2}$$

Induced (Finsler) Space-Time Metric

World-Sheet Propagator in the presence of recoil background

$$\langle X^\mu(\tau) X^\nu(0) \rangle = -\alpha' g^{\mu\nu} \ldots \ln \tau^2 + i \frac{\theta^{\mu\nu}}{\ldots} \epsilon(\tau)$$

$$p_\mu p_\nu g^{\mu\nu}_{\text{open,electric}} = 0$$

Implies Finsler-type target-space metric

$$g^{\text{open,electric}}_{\mu\nu} = \left(1 - \tilde{u}_i^2\right) \eta_{\mu\nu} \ ,$$

$$g^{\text{open,electric}}_{\mu\nu} = \eta_{\mu\nu} \ , \mu, \nu = \text{all} \ldots$$

and effective string coupling

$$g_s^{\text{e}} \ldots \left(1 - \tilde{u}^2\right)^{1/2}$$

Notice corrections to dispersion relations due to metric are quadratic in string scale

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- D-foam: transparent to electrons
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- Time Delay (Causal) in **each** Capture: $\Delta t \sim \alpha' p^0$

COMPATIBLE WITH STRING UNCERTAINTY PRINCIPLES:

$\Delta p\, \Delta x \geq 1$ ...

(α' = Regge slope ... mum string length scale)

Beyon Local Effective Field Theories though...

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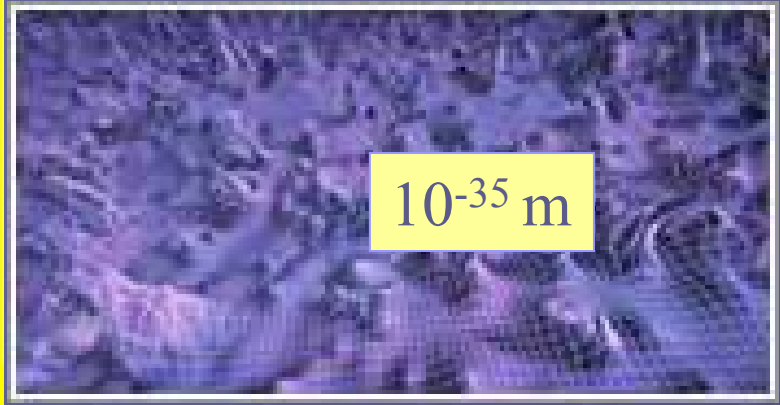
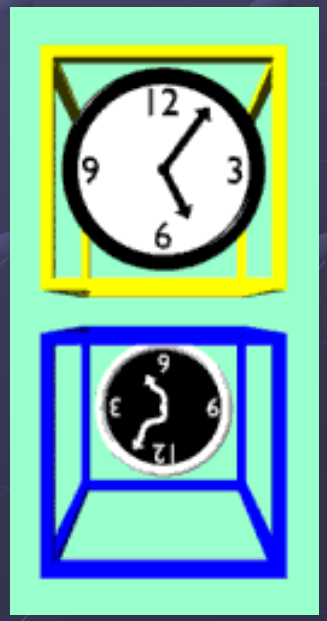


Decoherence-induced Ill-defined (Effective) CPT Operator (Wald 1979)

CPT may be Violated in D-particle Foam models but only through Target-space effective (low-energy) Decoherence, induced by quantum fluctuations of recoil velocity, and hence of induced metric and N.C.



Type IIB String Model of D-particle Foam

T.Li, NM, Nanopoulos, D. Xie

String theory type	p-brane types allowed
type-IIA	$p = 0, 2, 4, 6, 8$
type-IIB	$p = -1, 1, 3, 5, 7, (9)$
type-I	p [illegible]

Compactify to

3 + 1 Large Dim

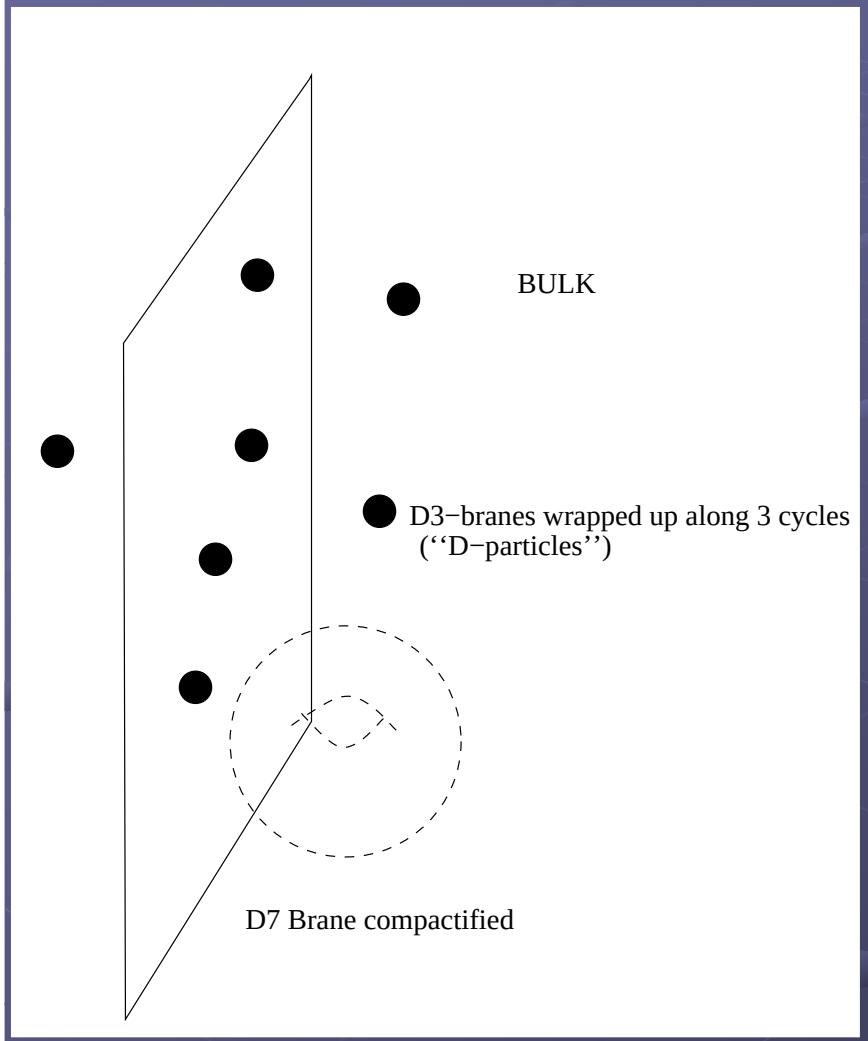
Wrap up along

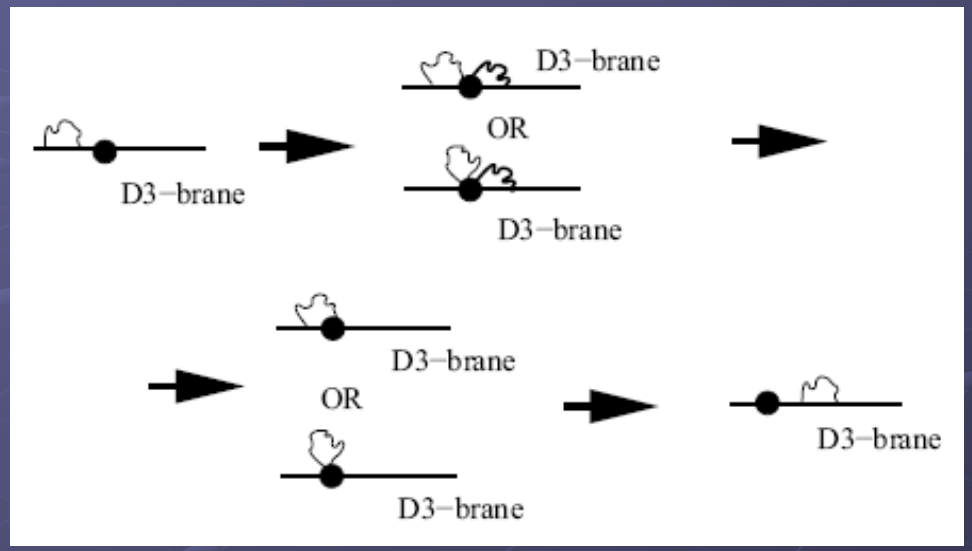
Three cycles

(``D-particles'')

Type IIB String Model of D-particle Foam

T.Li, NM, Nanopoulos, D. Xie

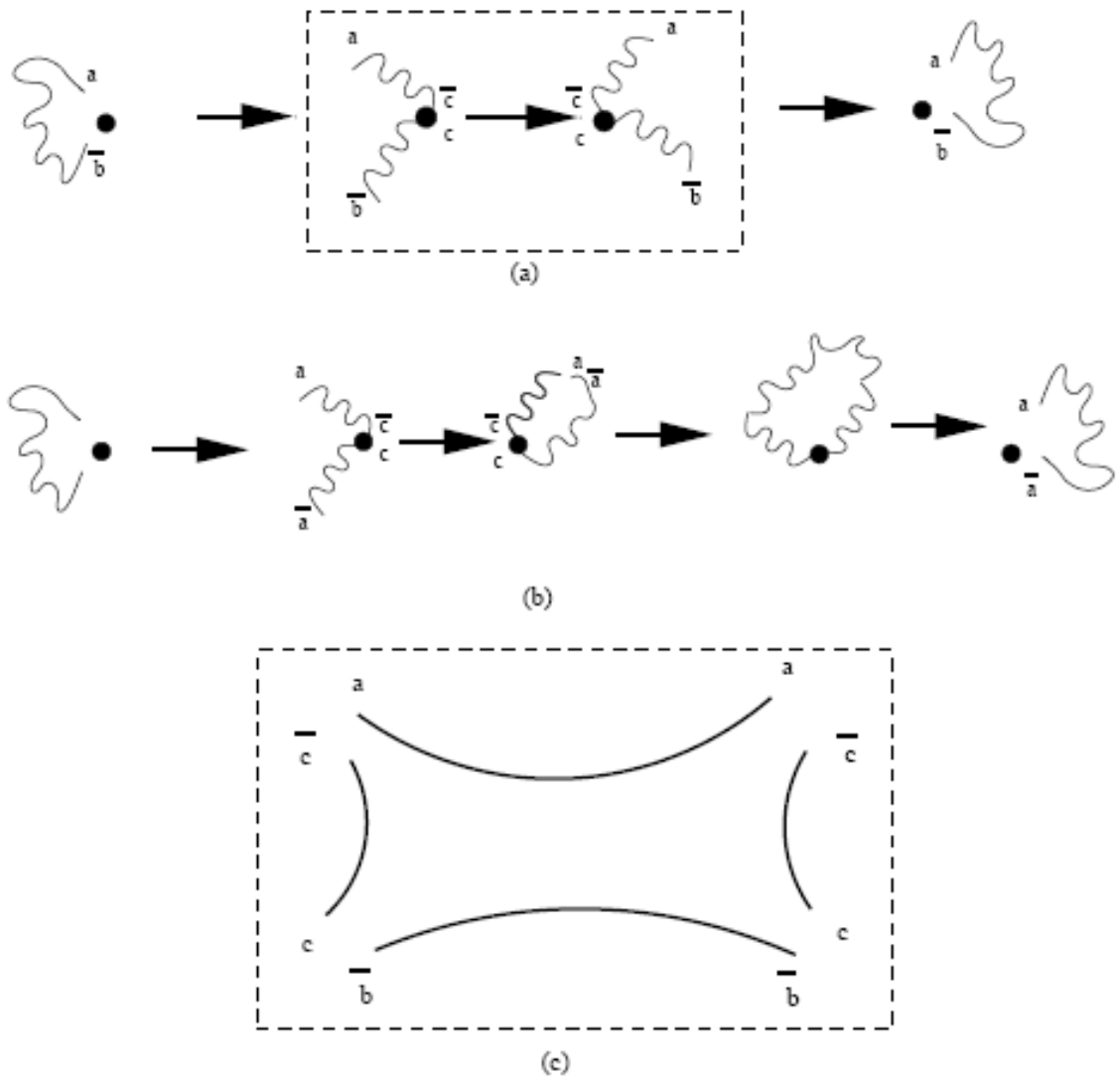




Consider Four-point Veneziano Amplitude for scattering of two open string states to two open string states in the D-particle/D3-branes backgrounds

Antoniadis, Benakli, Laugier

Type IIB String Model of D-particle Foam



T.Li, NM, Nanopoulos, D. Xie

Couplings of ND stringsStretched between D3 and D7 branes (Capture process)

$$\frac{1}{g_{37}^2} = \frac{V_{A3}R'}{(1.55 l_s)^4}\frac{l_s^4}{g_7^2} = \frac{V_{A3}R'}{(1.55)^4}\frac{1}{g_7^2}$$

D-Foam: Uniform Distribution of D-particles in space with V_{A3} = their average 3D-volume, R' = radius of forth space dim transverse to D3 branes.

Avoid tachyon condensation: D3 branes have widths 1.55 ℓ_s

CAUSAL TIME DELAYS

$$\mathcal{A}_{\text{total}} \equiv \mathcal{A}(1,2,3,4) + \mathcal{A}(1,3,2,4) + \mathcal{A}(1,2,4,3)$$

$$\mathcal{A}(1,2,3,4) \equiv A(1,2,3,4) + A(4,3,2,1)$$

$$(2\pi)^4\delta^{(4)}(\sum_a k_a)A(1,2,3,4) = \frac{-i}{g_s l_s^4}\int_0^1 dx$$

$$\left\langle \mathcal{V}^{(1)}(0,k_1)\mathcal{V}^{(2)}(x,k_2)\mathcal{V}^{(3)}(1,k_3)\mathcal{V}^{(4)}(\infty,k_4)\right\rangle$$

Vertex operator for fermionic or Bosonic open string state

First approx: ignore D-particle recoil

$$\mathcal{A}(1_{j_1 I_1}, 2_{j_2 I_2}, 3_{j_3 I_3}, 4_{j_4 I_4}) =$$

$$-g_s l_s^2 \int_0^1 dx\; x^{-1-s\, l_s^2}\; (1-x)^{-1-t\, l_s^2}\; \frac{1}{[F(x)]^2} \times$$

$$\left[\bar{u}^{(1)}\gamma_\mu u^{(2)}\bar{u}^{(4)}\gamma^\mu u^{(3)}(1-x) + \bar{u}^{(1)}\gamma_\mu u^{(4)}\bar{u}^{(2)}\gamma^\mu u^{(3)} x\right]$$

$$\times\{\eta\delta_{I_1,\bar{I}_2}\delta_{I_3,\bar{I}_4}\delta_{\bar{j}_1,j_4}\delta_{j_2,\bar{j}_3}\sum_{m\in\mathbf{Z}} e^{-\pi\tau\, m^2\, \ell_s^2/R'^2}$$

$$+\delta_{j_1,\bar{j}_2}\delta_{j_3,\bar{j}_4}\delta_{\bar{I}_1,I_4}\delta_{I_2,\bar{I}_3}\sum_{n\in\mathbf{Z}} e^{-\pi\tau n^2\, R'^2/\ell_s^2}\}\ , \qquad (6)$$

where j_i and I_i with $i = 1,\ 2,\ 3,\ 4$ are indices on the D7-branes and D3-branes, repsectively. And η is

$$\eta = \frac{(1.55\ell_s)^4}{V_{A3}R'}\ . \qquad (7)$$

$s = -(k_1+k_2)^2$, $t = -(k_2+k_3)^2$ and $u = -(k_1+k_3)^2$, for which $s+t+u = 0$ for massless particles **Mandelstam variables**

$$\mathcal{A}(1,2,3,4) \propto g_s \ell_s^2 \left(t\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(2)} \overline{u}^{(4)} \gamma^\mu u^{(3)} + s\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(4)} \overline{u}^{(2)} \gamma^\mu u^{(3)} \right) \times \frac{\Gamma(-s\ell_s^2)\Gamma(-t\ell_s^2)}{\Gamma(1+u\ell_s^2)} ,$$

$$\mathcal{A}(1,3,2,4) \propto g_s \ell_s^2 \left(t\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(3)} \overline{u}^{(4)} \gamma^\mu u^{(2)} + u\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(4)} \overline{u}^{(3)} \gamma^\mu u^{(2)} \right) \times \frac{\Gamma(-u\ell_s^2)\Gamma(-t\ell_s^2)}{\Gamma(1+s\ell_s^2)} ,$$

$$\mathcal{A}(1,2,4,3) \propto g_s \ell_s^2 \left(u\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(2)} \overline{u}^{(3)} \gamma^\mu u^{(4)} + s\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(3)} \overline{u}^{(2)} \gamma^\mu u^{(4)} \right) \times \frac{\Gamma(-s\ell_s^2)\Gamma(-u\ell_s^2)}{\Gamma(1+t\ell_s^2)}$$

Seiberg,Susskind

Toumbas

Time delays arise by considering Backward scattering u=0.

Time delays arise by considering Backward scattering u=0. For massless particles u + t + s =0

Photons or Cartan subalgerba of Gauge Group Gauginos

$$t\ell_s^2\Gamma(-s\ell_s^2)\Gamma(-t\ell_s^2) = -s\ell_s^2\Gamma(-s\ell_s^2)\Gamma(s\ell_s^2) = \frac{\pi}{\sin(\pi s\ell_s^2)} .$$

It has poles at $s = n/\ell_s^2$.

To define the poles we use the correct ϵ prescription replacing $s \to s + i\epsilon$, which shift the poles off the real axis. Thus, the functions $1/\sin(\pi s\ell_s^2)$ can be expanded as a power series in y which is

$$y = e^{i\pi s\ell_s^2 - \epsilon} . \tag{10}$$

Note that $s = E^2$, we obtain the time delay at the lowest order

$$\Delta t = E\ell_s^2 . \tag{11}$$

Time delays arise by considering
Backward scattering u=0.
For massless particles
u + t + s =0

Photons or Cartan subalgerba of Gauge Group Gauginos

$$t\ell_s^2\Gamma(-s\ell_s^2)\Gamma(-t\ell_s^2) = -s\ell_s^2\Gamma(-s\ell_s^2)\Gamma(s\ell_s^2) = \frac{\pi}{\sin(\pi s\ell_s^2)} .$$

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power series

Note that $s =$
order

Independent of photon polarization NO BIREFRINGENCE

$$\Delta t = E\ell_s^2 . \qquad (11)$$

OTHER PARTICLES

$j_1 \neq j_2$

Backward scattering u=0 implies

$$\mathcal{A}(1,3,2,4) \propto g_s \ell_s^2 \left(\frac{1}{u\ell_s^2} \overline{u}^{(1)} \gamma_\mu u^{(3)} \overline{u}^{(4)} \gamma^\mu u^{(2)} - \frac{1}{s\ell_s^2} u\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(4)} \overline{u}^{(3)} \gamma^\mu u^{(2)} \right)$$

JUST POLE TERMS…
NO TIME DELAY AT LEADING ORDER in η

At order η, there are time delays…

$$\mathcal{A}(1_{j_1 I_1}, 2_{j_2 I_2}, 3_{j_3 I_3}, 4_{j_4 I_4}) =$$

$$-g_s l_s^2 \int_0^1 dx\; x^{-1-s\, l_s^2}\; (1-x)^{-1-t\, l_s^2}\; \frac{1}{[F(x)]^2} \times$$

$$\left[\bar{u}^{(1)}\gamma_\mu u^{(2)}\bar{u}^{(4)}\gamma^\mu u^{(3)}(1-x) + \bar{u}^{(1)}\gamma_\mu u^{(4)}\bar{u}^{(2)}\gamma^\mu u^{(3)} x\right]$$

$$\times\{\eta\delta_{I_1,\bar{I}_2}\delta_{I_3,\bar{I}_4}\delta_{\bar{j}_1,j_4}\delta_{j_2,\bar{j}_3}\sum_{m\in\mathbf{Z}} e^{-\pi\tau\, m^2\, \ell_s^2/R'^2}$$

$$+\delta_{j_1,\bar{j}_2}\delta_{j_3,\bar{j}_4}\delta_{\bar{I}_1,I_4}\delta_{I_2,\bar{I}_3}\sum_{n\in\mathbf{Z}} e^{-\pi\tau n^2\, R'^2/\ell_s^2}\}\;, \qquad (6)$$

where j_i and I_i with $i = 1,\ 2,\ 3,\ 4$ are indices on the D7-branes and D3-branes, repsectively. And η is

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$$-g_s l_s^2 \int^1 dx\, x^{-1-s\, l_s^2} \qquad l_s^2 \quad \frac{1}{[F(x)]^2} \times$$

$$\left[\bar{u}^{(1)} \qquad x) + \bar{u}^{(1)} \gamma_\mu u^{(4)} \bar{u}^{(2)} \gamma^\mu u^{(3)} x\right]$$

$$\times \{\eta\delta \qquad \sum \qquad e^{-\pi\tau\, m^2\, \ell_s^2 / R'^2}$$

$$+\delta_{j_1, \bar{j}_2} \qquad E^2 = p^2 + m_e^2 - \eta p^3 / M_{\rm St} \qquad (6)$$

Effecitve Low-Energy Modified Dispersion

String Scale

where j_i and I_i with $i = 1, 2, 3, 4$ are indices on the D7-branes and D3-branes, repsectively. And η is

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At order η, there are time delays…

$$\mathcal{A}(1_{j_1 I_1}, 2_{j_2 I_2}, 3_{j_3 I_3}, 4_{j_4 I_4}) =$$

$$-g_s l_s^2 \int_0^1 dx\, x^{-1-s\, l_s^2}\, (1-x)^{-1-}$$

$$\left[\bar{u}^{(1)} \gamma_\mu u^{(2)} \bar{u}^{(4)} \gamma^\mu u^{(3)} (1-x) \right.$$

$$\times \{\eta \delta_{I_1}$$

$$+\delta_{j_1, \bar{j}_2}$$

$$E^2 = p^2 + m_e^2 - \eta p^3 / M_{\rm St} \ ,$$

where j_i and I_i with $i = 1, 2, 3, 4$ are
D7-branes and D3-branes, respectively. Ar

$$\eta = \frac{(1.55 \ell_s)^4}{V_{A3} R'} \ .$$

From Synchrotron Radiation Observations of Crab Nebula

$$\eta \leq 10^{-6}$$

At order η, there are time delays…

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$$+ \delta_{I} \; \mathrm{Tr}\; \; + m_2^2 - m p^3 / M_{\mathrm{St}} \; ,$$

$$V_{A3} \sim (10 \ell_s)^3 \; , \quad R' \sim 338 \ell_s \; .$$

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$$\eta = \frac{(1.55 \ell_s)^4}{V_{A3} R'} \; .$$

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easily satisfied

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INCLUDE D-PARTICLE RECOIL

- Inclusion of D-particle recoil, leads to an effective ``electric'' field background,
- Affects Time delays as follows:

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

- But also replaces string coupling

$$g_s \Rightarrow g_{\text{eff}} = g_s(1-|\vec{\tilde{u}}|^2)^{1/2}$$

$$\vec{u} = g_s \frac{\Delta \vec{k}}{M_s}$$

- And thus string scattering amplitudes

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Thus D-particle/string scattering suppressed for relativistic situations where D-particle recoil velocity approaches 1, i.e. momentum transfer approaches M_s/g_s

Important for discriminating Low (TeV) from High-string scale Phenomenology via such D-foam models, using UHE cosmic photons

Conclusions so far…

- MAGIC, FERMI … (?) observations indicate that high energy photons arrive later than lower-energy ones… H.E.S.S . compatible
- Source Effect or Propagation in Quantum Gravity Medium?
- There is a (unique?) string model of D-particle space-time foam reproducing the effect, using **time delays proportional to photon energy** (or MDR with linear QG scale suppression), consistent with all other tests of Lorentz invariance. No birefringence,
- Effect Beyond Local EFT! (stringy uncertainties, intermediate string)
- Very important: Improve on statistics … Find other flares, GRBs and check the energy dependence of photon arrival times: **Very High Energy γ-ray Astronomy very exciting prospects for the near future…**
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BACK-UP SLIDES

Other Consequences of D-particle Foam

- **Low-energy CPT Violation & Decoherence** from stochastic fluctuations of D-particle defects: Capture/re-emission process for neutral probes implies recoil of D-particle defect, **momentum-direction-dependent induced metrics** $G_{0i} \sim \Delta k_i \sim k_i \sim p^0$
  (Logarithmic Conformal Field Theory of recoil/capture on world-sheet of string model)
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Estimates of such D-particle foam effects in neutral mesons complicated due to strong QCD effects present in such composite neutral particles

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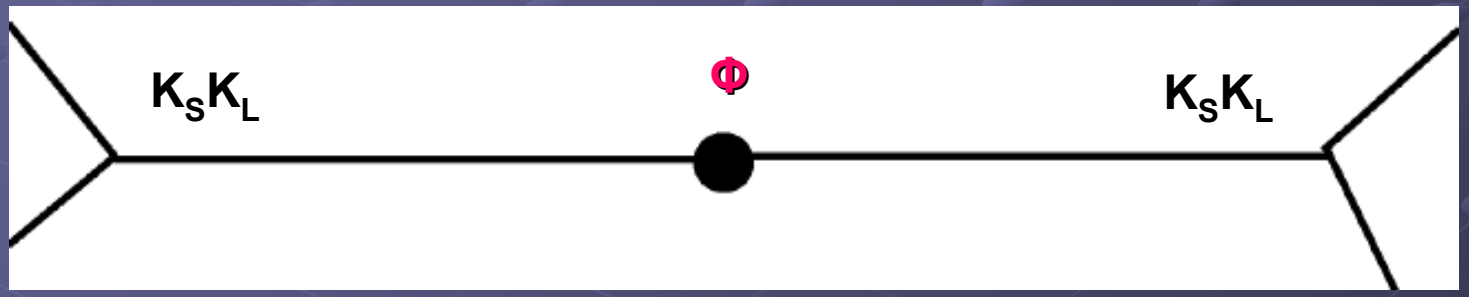
- If CPT Operator **well-defined as operator**, even if CPT is broken in the Hamiltonian… (e.g. Lorentz violating models)



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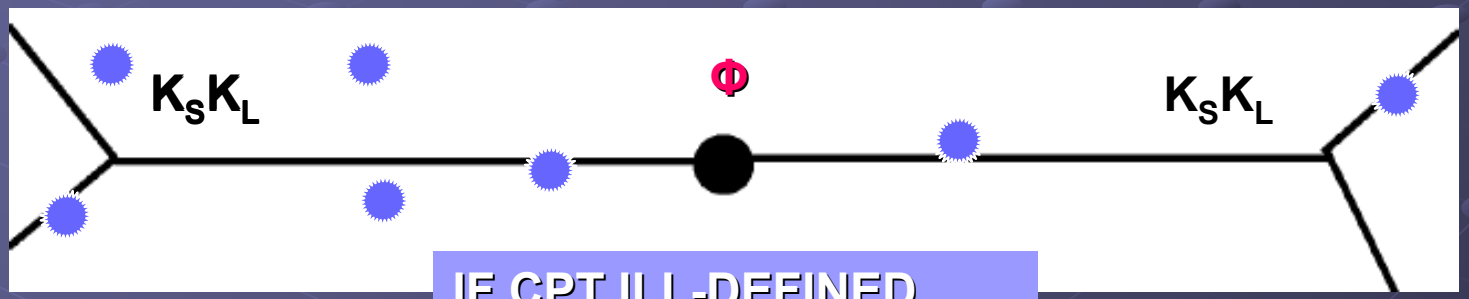

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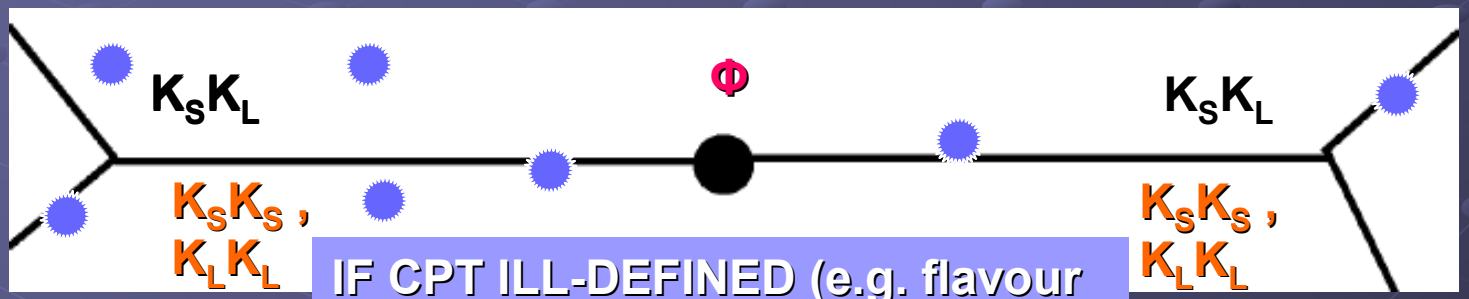

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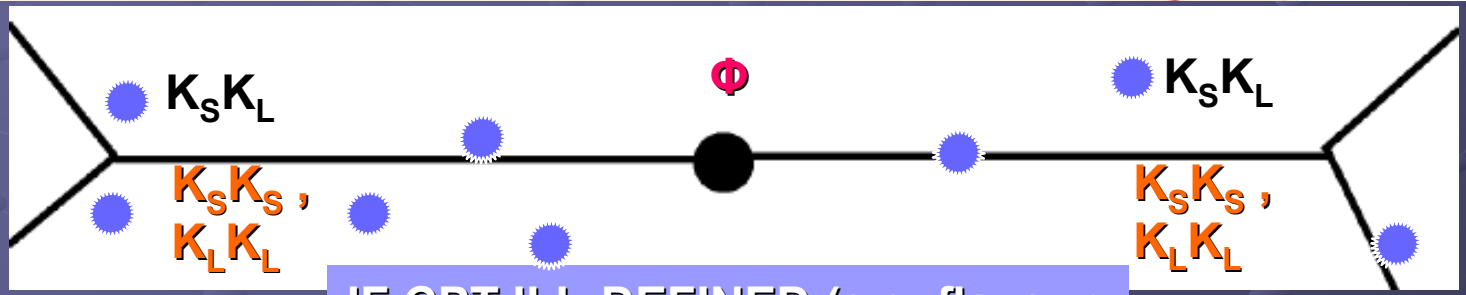
- Neutral mesons no longer indistinguishable particles, initial entangled state:

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

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



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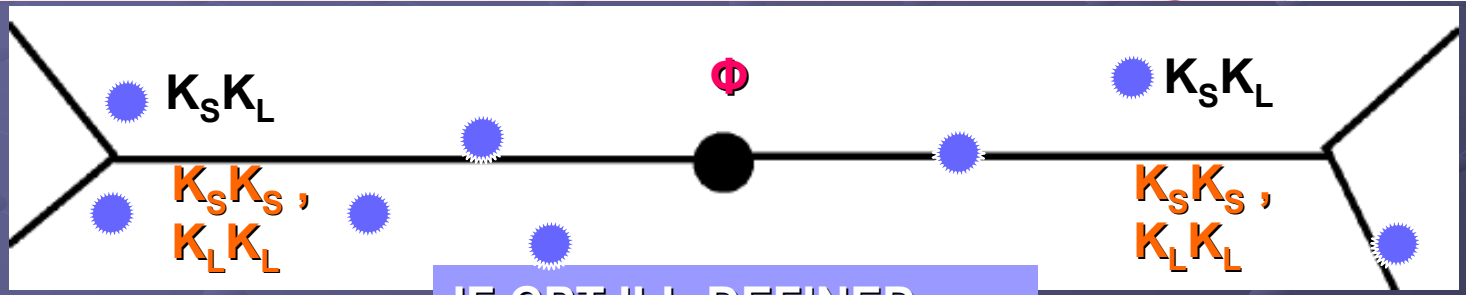

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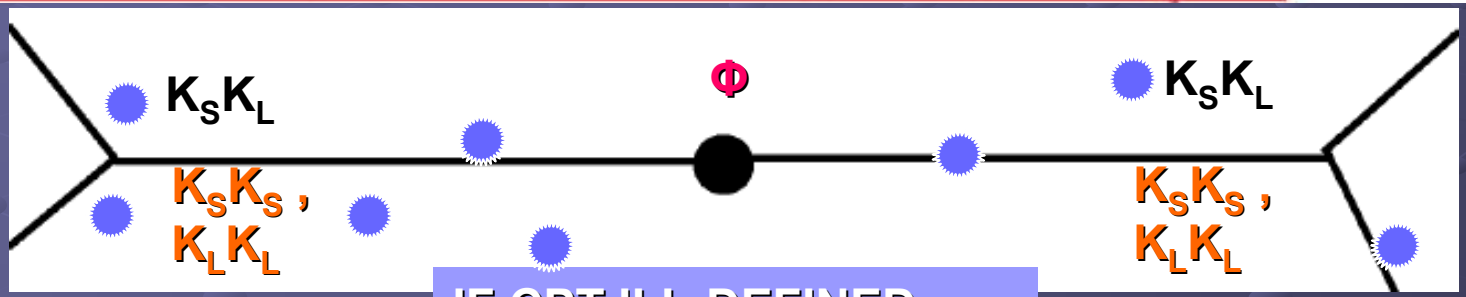

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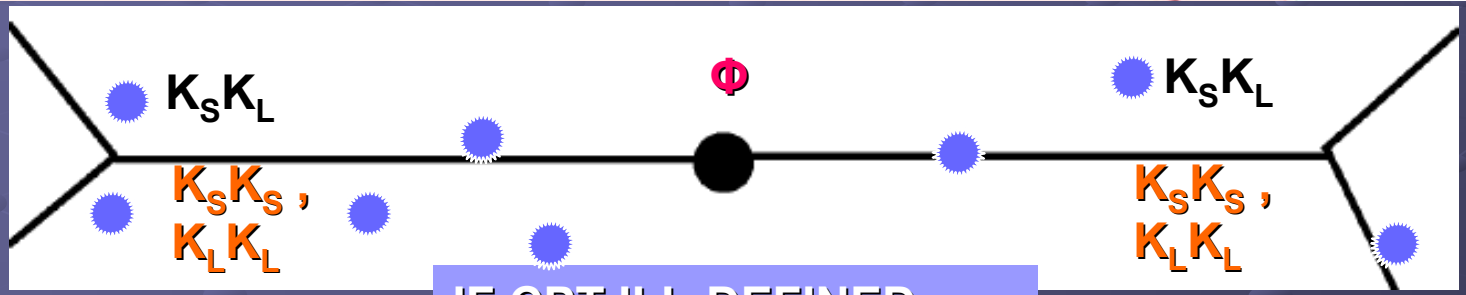

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