Lorentz Invariance, Strings and High-Energy Gamma Ray Astronomy

Nick E. Mavromatos
King’s College London
Physics Department

XXV MAX BORN SYMPOSIUM, The Planck Scale,
WROCLAW ITP (POLAND), 29 June – 3 July 2009
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 ...
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 $\psi$ reps. electrons, quarks etc. with charge $q$

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

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

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

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

**NB2:** In general $a_\mu$, $b_\mu$... 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.
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) → Tachyonic instabilities, coupling with tensorial fields (gauge etc), \( \rightarrow < A_{\mu} > \neq 0, < T_{\mu_{1}...\mu_{n}} > \neq 0 \).

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

\[
(i\gamma^{\mu}D^{\mu} - M - a_{\mu}\gamma^{\mu} - b_{\mu}\gamma_{5}\gamma^{\mu} - \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^{\mu}D^{\nu} + id_{\mu\nu}\gamma_{5}\gamma^{\mu}D^{\nu})\psi = 0
\]

where \( D_{\mu} = \partial_{\mu} - A_{\mu}^{a}T_{a} - qA_{\mu} \).

CPT & Lorentz violation: \( a_{\mu}, b_{\mu} \).

NB1: mass differences between \( K_{\ell_{2}} \) and \( K_{\ell_{3}} \) (for \( \ell_{2} \rightarrow \ell_{3} \) via weak interactions). \( a_{\mu} \), \( b_{\mu} \).

NB2: In general \( a_{\mu}, b_{\mu} \) 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

KTeV: \( a_{x}, a_{\gamma} < 10^{-21} \text{GeV} \)

\( \Phi \)-factories: \( a_{0} < 10^{-18} \text{GeV} \)

Sidereal variations \( H \)-Masers: \( b_{z} < 10^{-31} \text{GeV} \)
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 coherence or unitarity loss. CPT well-defined operator, does not commute with Hamiltonian of system.

String theory (non supersymmetric), Virial theorem (non interacting), obtaining Virial fields (gauge etc), \( \rightarrow <A_\mu > \neq 0 , <T_{\mu \nu} > = 0 \).

Spontaneous breaking of Lorentz symmetry by SME: for spinor \( \psi \) reps., functions \( \tilde{\xi} \) of scalar \( \tilde{\xi} \). COEQUIV. DIRED. EQUATION in SME: for spinor \( \psi \) reps.: orbitals \( \tilde{\xi} \) of scalar \( \tilde{\xi} \). Vertical gauge \( \tilde{\xi} \), \( \tilde{\xi} \). Vertical gauge \( \tilde{\xi} \), \( \tilde{\xi} \).

\[
(i\gamma^\mu D^\mu - M - a_\mu)\psi + \frac{1}{2}m^2\psi = 0
\]

where \( D_\mu = \partial_\mu - A^a_\mu T^a_\mu \).

CPT & Lorentz violation: \( <a_\mu > <10^{-18} \) GeV

Sidereal variations H-Masers: \( b_z < 10^{-31} \) GeV

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

Formalism? Experiments?

NB1: mass differences between masses: \( a_0 < 10^{-18} \) GeV

NB2: In general energy dependent and NOT constants (c.f. Lorentz-Violation due to quantum 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.
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 delays at emission: Non conclusive ...

(ii) Exotic Interpretation: Quantum Gravity (QG) as a medium with refractive index, Modified Dispersion Relations for matter probes with Linear QG scale (LMDR) effects (?): QG as a medium with refractive index, Modified Dispersion Relations for matter probes with Linear QG scale (LMDR) ... (Non(?)) Observation by H.E.S.S. ...

Check on other tests on (LMDR) modified dispersion relations:

Electrons: Synchrotron Radiation from Crab Nebula

Photons: Birefringence constraints for LMDR

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

Sub-luminal Refractive index in vacuo, No Birefringence

String Uncertainties, (Induced, Finsler-type) Non-commutative geometry at string scales: a uniquely stringy effect?
Beyond EFT? Time Delays of Astrophysical photons...
.... 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
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

Sub-luminal Refractive index in vacuo, No Birefringence

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
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

Canary Islands

MILAGRO

STACEE

MAGIC

TIBET ARRAY

ARGO-YBJ

PACT

GRAPES

TACTIC

VERITAS

HESS

CANGAROO III

M. MARTINEZ
The MAGIC Collaboration

(Major Atmospheric Gamma-ray Imaging Cherenkov Telescope)

Observation of Flares from AGN Mk 501

Red-shift: z=0.034

2.1 - Light curves (LCs): Gamma, X-rays, Optical

- MAGIC
  - June 30
  - July 9

- RXTE ASM

- KVA
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
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) ?
- electron accelerators:
  synchrotron: \( e \to e \gamma \)
  + inverse Compton: \( e \gamma \to \gamma e \)

leptonic acceleration

\[ e^- \text{ (TeV)} \]

\[ \gamma \text{ (eV-keV)} \]

\[ \gamma \text{ (TeV)} \]

\[ \text{Inverse Compton} \]

\[ \text{Synchrotron} \]

\[ \log(E) \]

\[ \log(\text{energy density}) \]

\[ \text{eV keV MeV GeV TeV} \]

XXV Max Born Symposium
Wroclaw ITP (Poland) 2009

N.E. Mavromatos
Alternative models for explaining high energy Gamma Rays from AGN involve hadronic acceleration: $\pi^0 \rightarrow \gamma \gamma$
Electron or Hadron Accelerator?

\[ \frac{dN_e}{dE_e} \times B^2 \]

Stars

Cosmic Electron Accelerators

\[ \frac{dN_p}{dE_p} \times \text{Matter density} \]

Cosmic Proton Accelerators

Synchrotron Radiation

Synchrotron Radiation of Secondary Electrons

\[ \pi^0 \rightarrow \gamma \gamma \]

DeNaurois 2008
H.E.S.S. (non) Observations of time-lags

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)

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

PRL 101,170402 (2008)
FERMI/GLAST Observations

GRB 080916c
(September 2008)

Highest energy Emission:

\[ E = 13.2^{+0.70}_{-1.54} \text{ GeV} \]

4.5 s time-lag between \( E > 100 \text{ MeV} \)
and \( E < 100 \text{ KeV} \)

Time-Lag (Delay) Measured for high-energy Photons of 13 GeV:
\[ \Delta t = 16.5 \text{ s} \]

Most Extreme GRB ever!!

(Image courtesy NASA/Swift/Stefan Immler)
FERMI/GLAST Observations

GRB 080916c
(September 2008)

Highest energy Emission:

\[ E = 13.2^{+0.70}_{-1.54} \text{ GeV} \]

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

Time-Lag (Delay) Measured for high-energy Photons of 13 GeV:
\[ \Delta t = 16.5 \text{ s} \]

Measured Red-Shift
by GROND Collaboration

\[ Z = 4.2 \pm 0.3 \]
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 ...

XXV Max Born Symposium
Wroclaw ITP (Poland) 2009
N.E. Mavromatos
Quantum-Gravity Induced Modified Dispersion for Photons

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

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

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

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

\[ \eta(|\vec{p}|) = \text{refractive index in vacuo} \]

subluminal: \( \eta > 1 \) , superluminal \( \eta < 1 \)
MAGIC QG scale Bounds (individual photon study, reproduction of flare peak)

**Linear**

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

\[ M_{QG1} = 1.398 \times 10^{16} \left( 1 \text{ s/}\tau_l \right) \]

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

**Quadratic**

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

\[ M_{QG2} = 1.182 \times 10^{8} \left( 1 \text{ s/}\tau_q \right)^{1/2} \]

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

95% CL

\[ M_{QG1} > 0.26 \times 10^{18} \text{ GeV} \]

\[ M_{QG2} > 0.27 \times 10^{11} \text{ GeV} \]
ALL THREE CASES (or 2.5!) (MAGIC, FERMI and (?) HESS) COMPATIBLE WITH LINEARLY SUPPRESSED MDR FOR PHOTONS BUT NOT QUADRATIC...

\[ E = p \left( 1 + \sum_{n=1}^{\infty} a_n \left( \frac{|p|}{M_{QG}} \right)^n \right) \]
\[ \Delta t/E_\gamma = (0.43 \pm 0.19) \times K(z)s/GeV, \quad K(z) \equiv \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}} \]
MDR for other matter probes

Massive Probes (e.g. electrons):

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

Constraints from Crab Nebula via Synchrotron Radiation

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
\( \delta(E) = \) angle for forward radiation pattern

Experimental measurement of \( \omega_c \) (Crab Nebula) yields

For \( M_{QG} = M_{QG1(MAGIC)} \sim 10^{18} \) GeV that \( \alpha > 1.74 \).
MDR for other matter probes

Massive Probes (e.g. electrons):

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

Constraints from Crab Nebula via Synchrotron Radiation

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

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

\( \delta(E) \) = angle for forward radiation pattern

\( v(E) \) = electron group velocity

Experimental measurement of \( \omega_c \) (Crab Nebula) yields

\[ \omega_c = \frac{3}{4} \frac{1}{R \delta(E)} \frac{1}{c(\omega_c) - v(E)} > 1.74 \]

Jacobson, Liberatti, Mattingly, Ellis, NM, Sakharov

Massive QG mass, \( M_{QG} \)
MDR for other matter probes

Massive Probes (e.g. electrons):

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

Constraints from Crab Nebula via Synchrotron Radiation

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
\(\delta(E) = \text{angle for forward radiation pattern}\)

Experimental measurement of $\omega_c$ (Crab Nebula) yields

For $M_{QG} = M_{QG1 \text{ (MAGIC)}} \sim 10^{18}$ GeV that $\alpha > 1.74$
MDR for other matter probes

Massive Probes (e.g. electrons):

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

Constraints from Crab Nebula via Synchrotron Radiation

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, \(\delta(E) = \)angle for forward radiation pattern

Experimental measurement of \(\omega_c\) (Crab Nebula) yields

For \(M_{QG} = M_{QG1\ (MAGIC)} \sim 10^{18}\) GeV that \(\alpha > 1.74\)

WHAT ABOUT PHOTONS & THE MAGIC RESULT?
Birefringence Constraints on photons MDR

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

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

Photons:

\[ \omega_\pm^2 = k^2 \pm \frac{\xi}{M} k^3 \]

Electrons:

\[ E_\pm^2 = p^2 + m^2 + \eta_\pm \frac{p^3}{M} \]

\[ \eta_\pm = 2(\zeta_1 \pm \zeta_2) \]

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

\[ \xi \lesssim 2 \times 10^{-4} \]

\[ |\xi| \lesssim 2 \times 10^{-7} \]

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

UV radiation from Galaxies:

\[ M \sim M_{Pl} \approx 1.22 \times 10^{19} \text{ GeV} \]

From GRB polarization

Myers-Pospelov QED

Myers et al., arXive0707.2673
Birefringence Constraints on photons MDR

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

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

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

\[
\omega^2 = k^2 \pm \frac{\xi}{M} k^3
\]

Electrons:

\[
E^2_\pm = p^2 + m^2 + \eta \pm \frac{p^3}{M}
\]

\[
\eta_\pm = 2(\zeta_1 \pm \zeta_2)
\]

\[
\Delta \theta = \xi (k^2_2 - k^2_1) d / 2M
\]

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

UV radiation from Galaxies: From GRB polarization

\[
\xi \lesssim 2 \times 10^{-4}
\]

\[
|\xi| \lesssim 2 \times 10^{-7}
\]

For \( M \sim M_{Pl} \approx 1.22 \times 10^{19} \text{ GeV} \)

MAGIC EFFECT due to QG ruled out?

Myers-Pospelov

QED

Maccione et al., arXive0707.2673

XXV Max Born Symposium
Wroclaw ITP (Poland) 2009

N.E. Mavromatos

32
If MDR for probes stem from Local Effective Lagrangians (LEL): arXive0707.2673

\[ E_{\pm}^2 = p^2 + m^2 + \eta \frac{p^3}{M} \]
\[ \eta = 2(\zeta_1 \pm \zeta_2) \]

Difference in polarization angle of foam and...

\[ \epsilon = \xi (k_2^2 - k_1^2) d / 2M \]

\[ M \sim M_{Pl} \approx 1.22 \times 10^{19} \text{ GeV} \]

MAGIC EFFECT due to QG ruled out?
Ultra-high-energy photons

\[ \omega_{\pm}^2 = k^2 + \xi_m k^2 \left( \frac{k}{M_{\text{pl}}} \right)^n, \]

\[ \omega_{b}^2 = k_{b}^2, \]

\[ E_{e, \pm}^2 = p_{e}^2 + m_e^2 + \eta_{m, +} p_{e}^2 \left( \frac{p_{e}}{M_{\text{pl}}} \right)^n. \]

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:

\[ \gamma_{\text{UHE}} + \gamma_{\text{background}} \rightarrow e^+ e^- \]

(ii) Photon Decay

\[ \gamma_{\text{UHE}} \rightarrow e^+ e^- \]

Allowed, above threshold if MDR
Avoid MDR but still have Time Delays?

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

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

MAGIC EFFECT due to QG ruled out?
(1) Time Delays proportional to $E$
(2) Stable Photons
(3) No birefringence
(4) Beyond EFT

STRING THEORY & VACUUM REFRACTIVE INDICES
### String Theory Type

<table>
<thead>
<tr>
<th>String Theory Type</th>
<th>p-brane types allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>type-I</td>
<td>$p = 1, 5, 9$</td>
</tr>
<tr>
<td>type-IIA</td>
<td>$p = 0, 2, 4, 6, 8$</td>
</tr>
<tr>
<td>type-IIB</td>
<td>$p = -1, 1, 3, 5, 7, (9)$</td>
</tr>
</tbody>
</table>

**Heterotic Strings admit no p-branes**
# STRING/D-BRANE BASICS

<table>
<thead>
<tr>
<th>String theory type</th>
<th>p-brane types allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>type-IIA</td>
<td>$p = 0, 2, 4, 6, 8$</td>
</tr>
<tr>
<td>type-IIB</td>
<td>$p = -1, 1, 3, 5, 7, 9$</td>
</tr>
<tr>
<td>type-I</td>
<td>$p = 1, 5, 9$</td>
</tr>
</tbody>
</table>

**Heterotic Strings admit no p-branes**
## STRING/D-BRANE BASICS

### String Theory Types and p-brane Types Allowed

<table>
<thead>
<tr>
<th>String Theory Type</th>
<th>p-brane Types Allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>type-IIA</td>
<td>( p = 0, 2, 4, 6, 8 )</td>
</tr>
<tr>
<td>type-IIB</td>
<td>( p = -1, 1, 3, 5, 7, 9 )</td>
</tr>
<tr>
<td>type-I</td>
<td>( p = 1, 5, 9 )</td>
</tr>
</tbody>
</table>

- **Heterotic Strings admit no p-branes**

- **Compactify to 3 + 1 Large Dim**
### STRING/D-BRANE BASICS

<table>
<thead>
<tr>
<th>String theory type</th>
<th>p-brane types allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>type-IIA</td>
<td>$p = 0, 2, 4, 6, 8$</td>
</tr>
<tr>
<td>type-IIB</td>
<td>$p = -1, 1, 3, 5, 7, 9$</td>
</tr>
<tr>
<td>type-I</td>
<td>$p =$</td>
</tr>
</tbody>
</table>

Heterotic Strings admit no p-branes

- Compactify to 3 + 1 Large Dim
- Wrap up along Three cycles (``D-particles'')

For our models of Foam...
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

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

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

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

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

Ellis, NM, Westmuckett

Orientifold planes, stacks of D8 branes

XXV Max Born Symposium
Wroclaw ITP (Poland) 2009

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

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

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

NON-UNIVERSAL ACTION OF D-PARTICLE FOAM ON MATTER & RADIATION
Stringy Uncertainties & the Capture Process

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....

XXV Max Born Symposium
Wroclaw ITP (Poland) 2009

Ellis, NM, Nanopoulos arXiv:0804.3566
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 \textbf{(no Birefringence)}
- \textbf{Total Delay} from emission of photons
  till observation over a distance \textbf{D} (assume \( n^* \) defects per string length):
  \[ \Delta t_{\text{total}} = \alpha' p^0 n^* \frac{D}{\sqrt{\alpha'}} = \frac{p^0}{M_s} n^* D \]

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

**REPRODUCE 4\pm1 MINUTE DELAY OF MAGIC from Mk501 (redshift } z = 0.034)\**
For \( n^* = O(1) \) & \( M_s \sim 10^{18} \text{ GeV} \), 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:**

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

\( (\alpha' = \text{Regge slope} = \text{Square of minimum string length scale}) \)

**REPRODUCE 4±1 MINUTE DELAY OF MAGIC from Mk501 (redshift z=0.034)**

For \( n^* = O(1) \) & \( M_s \sim 10^{18} \text{ GeV} \), consistently with Crab Nebula & other Astrophysical constraints on modified dispersion relations......
Induced (Finsler-type) Non-Commutativity

D-particle recoil $\sigma$-model deformation

$$\nu_{D}^{imp} = \frac{1}{2\pi \alpha'} \sum_{i=1}^{d} \int_{D} d\tau \ u_i X^0 \Theta \left( X^0 \right) \partial_{n} X^i \ .$$

Written as world-sheet Bulk operator
(Stokes theorem)

$$\nu_{D}^{imp} = \frac{1}{2\pi \alpha'} \int_{D} d^{2}z \ \epsilon_{\alpha \beta} \partial^{\beta} \left[ u_i X^0 \right] \Theta \left( X^0 \right) \partial^{\alpha} X^i =$$

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

Open strings in "electric" field background, provided here by recoil velocity $u_i$

Statistically averaged $\langle u_i \rangle$ over D-particle populations, might lead to Uniform `electric field’ backgrounds

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

XXV Max Born Symposium
Wroclaw ITP (Poland) 2009

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

**Mixed Boundary Conditions**

\[ g_{\mu\nu} \partial_{\mu} X^\nu + B_{\mu\nu} \partial_{\tau} X^\nu \big|_{\partial D} = 0 \]

Neumann \quad Dirichlet

**World-sheet 1\textsuperscript{st} quantization leads to N.C. (induced by recoil here)**

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

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

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

\[ u_i = g_s \frac{(\Delta \tilde{k})_i}{M_s} \]

Seiberg-Witten

Seiberg, Susskind, Toumbas

NEM, arXive:0906.2712
Non-commutative effective field theories & CPT

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

\[ \theta_{\mu\nu}\theta^{\mu\nu} > 0 \]

\[ \hat{A}_\mu = A_\mu - \frac{1}{2} \theta^{\alpha\beta} A_\alpha (\theta_\beta A_\mu + F_{\beta\mu}), \]

\[ \hat{\psi} = \psi - \frac{1}{2} \theta^{\alpha\beta} A_\alpha \partial_\beta \psi. \]

\[ D_\mu \psi = \partial_\mu \psi - iq A_\mu \psi \]

Moyal * products

\[ f \ast g(x) = \exp(\frac{1}{2} i\theta^{\mu\nu} \partial_{x^\mu} \partial_{y^\nu}) f(x) g(y) \bigg|_{x=y} \]

\[
\mathcal{L} = \frac{1}{2} i \hat{\bar{\psi}} \ast \gamma^\mu \hat{D}_\mu \hat{\psi} - m \hat{\bar{\psi}} \ast \hat{\psi} - \frac{1}{4q^2} \hat{F}_{\mu\nu} \ast \hat{F}^{\mu\nu} \\
\hat{D}_\mu \hat{\psi} = \partial_\mu \hat{\psi} - i \hat{A}_\mu \ast \hat{\psi} \quad \hat{f} \ast \hat{D}_\mu \hat{g} \equiv \hat{f} \ast \hat{D}_\mu \hat{g} - \hat{D}_\mu \hat{f} \ast \hat{g} \\
\mathcal{L} = \frac{1}{2} i \bar{\psi} \gamma^\mu \hat{D}_\mu \psi - m \bar{\psi} \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
-\frac{1}{8} i q \theta^{\alpha\beta} F_{\alpha\beta} \bar{\psi} \gamma^\mu \hat{D}_\mu \psi + \frac{1}{4} i q \theta^{\alpha\beta} F_{\alpha\mu} \bar{\psi} \gamma^\mu \hat{D}_\beta \psi \\
+ \frac{1}{4} m q \theta^{\alpha\beta} F_{\alpha\beta} \bar{\psi} \psi \\
- \frac{1}{2} q \theta^{\alpha\beta} F_{\alpha\mu} F_{\beta\nu} F^{\mu\nu} + \frac{1}{8} q \theta^{\alpha\beta} F_{\alpha\beta} F_{\mu\nu} F^{\mu\nu}. \]

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

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

Implies Finsler-type target-space metric

\[
g_{\text{open, electric}}^{\mu\nu} = \begin{cases} 
(1 - \tilde{u}_i^2) \eta_{\mu\nu} , & \mu, \nu = 0, 1 \\
\eta_{\mu\nu} , & \mu, \nu = \text{all other values ,}
\end{cases}
\]

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

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

\[ p_\mu p_\nu g_{\mu\nu}^{\text{open,electric}} = 0 \]

Implies Finsler-type target-space metric

\[
g_{\mu\nu}^{\text{open,electric}} = (1 - \tilde{u}_i^2) \eta_{\mu\nu}, \quad \mu, \nu = \text{all}
\]

and effective string coupling

\[
g_s^{\text{electric}} = (1 - \tilde{u}^2)^{1/2}
\]

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

\[ \Delta t > \alpha' p^0 x \geq 1 \text{ (minimum string length scale)} \]

\( \alpha' = \text{Regge slope} \)

**REPRODUCE 4±1 MINUTE DELAY OF MAGIC from Mk501 (redshift \( z=0.034 \))**

For \( n^* = \mathcal{O}(1) \) & \( M_s \sim 10^{18} \text{ GeV} \), consistently with Crab Nebula & other

Astrophysical constraints on modified dispersion relations......

XXV Max Born Symposium
Wrocław ITP (Poland) 2009

N.E. Mavromatos
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

<table>
<thead>
<tr>
<th>String theory type</th>
<th>p-brane types allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>type-I A</td>
<td>$p = 0, 2, 4, 6, 8$</td>
</tr>
<tr>
<td>type-I B</td>
<td>$p = -1, 1, 3, 5, 7, (9)$</td>
</tr>
<tr>
<td>type-I</td>
<td>$p$</td>
</tr>
</tbody>
</table>

**Compactify to**

3 + 1 Large Dim

**Wrap up along**

Three cycles

(“D-particles”)

---

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 strings stretched between D3 and D7 branes (Capture process)

\[
\frac{1}{g_3^2} = \frac{V_{A3} R'}{(1.55 l_s)^4 \frac{l_s^4}{g_t^2}} = \frac{V_{A3} R'}{(1.55)^4 \frac{l_s^2}{g_t^2}}
\]

D-Foam: Uniform Distribution of D-particles in space with

\[V_{A3} = \text{their average 3D-volume,} \]

\[R' = \text{radius of forth space dim transverse to D3 branes.} \]

Avoid tachyon condensation: D3 branes have widths 1.55 \[l_s\]
CAUSAL TIME DELAYS

\[ A_{total} \equiv A(1, 2, 3, 4) + A(1, 3, 2, 4) + A(1, 2, 4, 3) \]

\[ A(1, 2, 3, 4) \equiv A(1, 2, 3, 4) + A(4, 3, 2, 1) \]

\[
(2\pi)^4 \delta^{(4)} \left( \sum_a k_a \right) A(1, 2, 3, 4) = \frac{-i}{g_s l_s^4} \int_0^1 dx \left\langle \mathcal{V}^{(1)}(0, k_1) \mathcal{V}^{(2)}(x, k_2) \mathcal{V}^{(3)}(1, k_3) \mathcal{V}^{(4)}(\infty, k_4) \right\rangle
\]

First approx: ignore D-particle recoil

Vertex operator for fermionic or Bosonic open string state

XXV Max Born Symposium
Wroclaw ITP (Poland) 2009

N.E. Mavromatos
\[ A(1_{j_1I_1}, 2_{j_2I_2}, 3_{j_3I_3}, 4_{j_4I_4}) = 
\]

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

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

\[ \times \left\{ \eta \delta_{I_1, \bar{I}_2} \delta_{I_3, \bar{I}_4} \delta_{j_1, \bar{j}_2} \delta_{j_3, \bar{j}_4} \sum_{m \in \mathbb{Z}} e^{-\pi \tau} m^2 \ell_s^2 / R'^2 \right. \]

\[ + \delta_{j_1, \bar{j}_2} \delta_{j_3, \bar{j}_4} \delta_{I_1, \bar{I}_2} \delta_{I_4, \bar{I}_3} \sum_{n \in \mathbb{Z}} e^{-\pi \tau} n^2 R'^2 / \ell_s^2 \left\} \right. \]

\[ (6) \]

where \( j_i \) and \( I_i \) with \( i = 1, 2, 3, 4 \) are indices on the D7-branes and D3-branes, respectively. And \( \eta \) is

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

\[ (7) \]

\( s = -(k_1 + k_2)^2 \), \( t = -(k_2 + k_3)^2 \) and \( u = -(k_1 + k_3)^2 \), for which \( s + t + u = 0 \) for massless particles.

Mandelstam variables
Time delays arise by considering Backward scattering $u=0$. 

XXV Max Born Symposium
Wroclaw ITP (Poland) 2009

N.E. Mavromatos
Time delays arise by considering backward scattering \( u=0 \). For massless particles \( u + t + s = 0 \)

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

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

To define the poles we use the correct \( \epsilon \) 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

\[
y = e^{i\pi s\ell_s^2 - \epsilon}.
\]

(10)

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

\[
\Delta t = E\ell_s^2.
\]

(11)
Time delays arise by considering Backward scattering $u=0$. For massless particles $u + t + s = 0$,

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

It has poles at $s = \frac{n}{\ell_s^2}$, 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.

To define the poles we use the correct $\epsilon$ prescription replacing $s \rightarrow s + i \epsilon$, which shift the poles off the real axis. Note that $s = \frac{n}{\ell_s^2}$ is of order

\[ \Delta t = E \ell_s^2 . \]  \hspace{1cm} (11)
\[ j_1 \neq j_2 \]

Backward scattering \( u=0 \) implies

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

JUST POLE TERMS...
NO TIME DELAY AT LEADING ORDER in \( \eta \)
At order $\eta$, there are time delays...

\[ A(1_{j_1 I_1}, 2_{j_2 I_2}, 3_{j_3 I_3}, 4_{j_4 I_4}) = \]
\[-g_s l_s^2 \int_0^1 dx \ x^{-1-s l_s^2} (1-x)^{-1-t l_s^2} \frac{1}{[F(x)]^2} \times \]
\[ \left[ \bar{u}^{(1)} \gamma_\mu u^{(2)} \bar{u}^{(4)} \gamma_\mu u^{(3)} (1-x) + \bar{u}^{(1)} \gamma_\mu u^{(4)} \bar{u}^{(2)} \gamma_\mu u^{(3)} x \right] \]
\[ \times \{ \eta \delta_{I_1, \bar{I}_2} \delta_{I_3, \bar{I}_4} \delta_{j_1, \bar{j}_2} \delta_{j_3, \bar{j}_4} \sum_{m \in \mathbb{Z}} e^{-\pi \tau \ m^2 \ell_s^2/R'2} \}
\]
\[ + \delta_{j_1, \bar{j}_2} \delta_{j_3, \bar{j}_4} \delta_{I_1, \bar{I}_2} \delta_{I_3, \bar{I}_4} \sum_{n \in \mathbb{Z}} e^{-\pi \tau \ n^2 \ R'^2/\ell_s^2} \} , \quad (6) \]

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

\[ \eta = \frac{(1.55 \ell_s)^4}{V_{A3} R'} . \quad (7) \]
At order $\eta$, there are time delays...

\[
A(1_{j_1 I_1}, 2_{j_2 I_2}, 3_{j_3 I_3}, 4_{j_4 I_4}) = \\
- g_s l_s^2 \int_0^1 dx x^{-1 - s l_s^2} x^{l_s^2} \frac{1}{[F(x)]^2} \times \\
\left[ \bar{u}^{(1)} \gamma_\mu u^{(4)} \gamma_\mu u^{(2)} \gamma_\mu u^{(3)} x \right] \\
\times \{\eta \delta_{j_1 j_2} \delta_{I_1 I_2} \delta_{I_3 I_4} - \sum \text{e}^{-\pi \tau m^2 \ell_s^2/R'^2} \}
\]

\[E^2 = p^2 + m_e^2 - \eta p^3 / M_{St} \] (6)

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

\[\eta = \frac{\left(1.55 \ell_s\right)^4}{V_{A3} R'} . \] (7)
At order $\eta$, there are time delays...

\[ A(1_{j_1 I_1}, 2_{j_2 I_2}, 3_{j_3 I_3}, 4_{j_4 I_4}) = 
\]
\[ -g_s l_s^2 \int_0^1 dx \ x^{-1-s l_s^2} (1-x)^{-1-s l_s^2} \]
\[ \left[ \bar{u}^{(1)}(1) \gamma_\mu u^{(2)}(2) \bar{u}^{(4)}(4) \gamma_\mu u^{(3)}(3) (1-x) \right] \]
\[ \times \{ \eta \delta_{I_1 I_2} \delta_{j_1 j_2} + \delta_{j_1, j_2} \} \]
\[ + \frac{E^2}{p^2 + m_e^2 - \eta p^3/M_{St}}, \]

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

\[ \eta = \frac{(1.55 l_s)^4}{V_{A3} R'}, \]

where $\eta \leq 10^{-6}$.
At order $\eta$, there are time delays...

\[
A(1_{j_1 I_1}, 2_{j_2 I_2}, 3_{j_3 I_3}, 4_{j_4 I_4}) =
- g_s l_s^2 \int_0^1 dx \ x^{-1-s} l_s^2 (1-x)^{-1-s} \left[ \bar{u}^{(1)} \gamma_\mu u^{(2)} \bar{u}^{(4)} \gamma_\mu u^{(3)} (1-x) \right] 
\times \{ \eta \delta L_s + \text{finite terms} \}
\]

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

where D7-branes and D3-branes, respectively. An example of a constraint is

\[
\eta \leq 10^{-6}
\]

with

\[
\eta = \frac{(1.55 \ell_s)^4}{V_{A3} R'}.
\]
Inclusion of D-particle recoil, leads to an effective "electric" field background,

Affects Time delays as follows:

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

But also replaces string coupling

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

And thus string scattering amplitudes

\[ A(1, 2, 3, 4) \rightarrow (1 - |\vec{u}|^2)^{1/2} A(1, 2, 3, 4) \]
Inclusion of D-particle recoil, leads to an effective "electric" field background,

Affects Time delays as follows:

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

But also replaces string coupling

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

And thus string scattering amplitudes

\[ A(1, 2, 3, 4) \rightarrow (1 - |\vec{u}|^2)^{1/2} A(1, 2, 3, 4) \]

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
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...

Also high energy Neutrino Astrophysics may provide complementary test of such fundamentally new physics...
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...

- Also high energy Neutrino Astrophysics may provide complementary test of such fundamentally new physics...
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)
  Kogan, NM, Wheater, Szabo, Ellis, Nanopoulos

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

Estimates of such D-particle foam effects in neutral mesons complicated
due to strong QCD effects present in such composite neutral particles
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)
  - Kogan, NM, Wheeler, Szabo, Ellis, Nanopoulos

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

Estimates of such D-particle foam effects in neutral mesons complicated due to strong QCD effects present in such composite neutral particles
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)

  Kogan, NM, Wheater, Szabo, Ellis, Nanopoulos

- **CPT Operator ill-defined**, unique consequences in *modifications of EPR correlations of entangled states of neutral mesons in meson factories* ($\Phi$, B-factories)

  Bernabeu, NM, Papavassiliou, Nebot, Alvarez, Sarben, Sarkar

Estimates of such D-particle foam effects in neutral mesons complicated due to strong QCD effects present in such composite neutral particles
If CPT Operator well-defined as operator, even if CPT is broken in the Hamiltonian... (e.g. Lorentz violating models)
If CPT Operator \textit{ill-defined}, unique consequences in modifications of EPR correlations of entangled states of neutral mesons in meson factories (\(\Phi\)-, B-factories) \(\text{Bernabeu, NM, Papavassiliou, Nebot, Alvarez, Sarben Sarkar}\)

\(\text{Induced metric due to capture/recoil, stochastic fluctuations, Decoherence}\)
CPT Operator **ill-defined**, unique consequences in modifications of EPR correlations of entangled states of neutral mesons in meson factories (Φ-, B-factories) Bernabeu, NM, Papavassiliou, Nebot, Alvarez, Sarben Sarkar

Induced metric due to capture/recoil, stochastic fluctuations, Decoherence Estimates of such D-particle foam effects in neutral mesons complicated due to strong QCD effects present in such composite neutral particles
Neutral mesons no longer indistinguishable particles, initial entangled state:

\[
|\psi\rangle = \mathcal{N}\left[\left( |K_S(\bar{K}), K_L(-\bar{K})\rangle - |K_L(\bar{K}), K_S(-\bar{K})\rangle \right)
+ \omega \left( |K_S(\bar{K}), K_S(-\bar{K})\rangle - |K_L(\bar{K}), K_L(-\bar{K})\rangle \right)\right]
\]

\[
|\omega| \sim \frac{\xi^2 q^2}{M_{QG}^2 (m_1 - m_2)^2}, \Delta p \sim \xi p \text{ (kaon momentum transfer)}
\]

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

Not far from sensitivity of upgraded meson factories (e.g. DAFNE2)
Neutral mesons no longer indistinguishable particles, initial entangled state:

\[ |i\rangle = N \left[ (|K_S(\bar{K})\rangle, K_L(-\bar{K})\rangle - |K_L(\bar{K})\rangle, K_S(-\bar{K})\rangle \right] \]

\[ \omega = |\omega|e^{i\Omega} \]

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

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

\[ |\omega| \sim 10^{-4} |\zeta|, \text{ for } 1 > |\zeta| > 10^{-2} \] (natural)

Not far from sensitivity of upgraded meson factories (e.g. DAFNE2)
Neutral mesons no longer indistinguishable particles, initial entangled state:

\[ |i> = \mathcal{N} \left[ (|K_S(\bar{K})\rangle, K_L(-\bar{K})\rangle - |K_L(\bar{K})\rangle, K_S(-\bar{K})\rangle \right] + \omega \left( |K_S(\bar{K})\rangle, K_S(-\bar{K})\rangle - |K_L(\bar{K})\rangle, K_L(-\bar{K})\rangle \right) \]

\[ \omega = |\omega|e^{i\Omega} \]

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

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

\[ |\omega| \sim 10^{-4} |\zeta|, \text{ for } 1 > |\zeta| > 10^{-2} \] (natural)

Not far from sensitivity of upgraded meson factories (e.g. DAFNE2)
Neutral mesons no longer indistinguishable particles, initial entangled state:

\[
|\psi\rangle = N \left[ (|K_S(\bar{K})\rangle, K_L(-\bar{K})\rangle - |K_L(\bar{K})\rangle, K_S(-\bar{K})\rangle \right] + \omega (|K_S(\bar{K})\rangle, K_S(-\bar{K})\rangle - |K_L(\bar{K})\rangle, K_L(-\bar{K})\rangle)
\]

\[
\omega = |\omega| e^{i\Omega}
\]

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

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

\[
|\omega| \sim 10^{-4} |\zeta|, \quad \text{for} \quad 1 > |\zeta| > 10^{-2} \text{ (natural)}
\]

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