OUTLINE

Quantum Gravity: Space-Time Foam "medium" & Fundamental Symmetries (Lorentz) – modified dispersion for matter and radiation, time delays of more energetic photons

String theory foam model (D-(brane) foam):
D(effect)-foam -induced Vacuum refraction
Breakdown of Local effective field theory
Stringy D-foam and the DARK SECTOR

Tests: HIGH-ENERGY GAMMA-RAY ASTRONOMY as a discriminant of space-time foam models. The string model survives stringy tests

Outlook

Corfu 2010

N.E. Mavromatos
Elusive theory for the Quantum structure of space-time at Microscopic scales (e.g. Planck, string length...) 

Several candidates: 
- Strings (phenomenologically more successful but higher dimensional), 
- Loop quantum Gravity, 
- Effective (Lorentz violating, non-commutative) field theories ...

\[ [X^\mu, X^\nu] = \theta^{\mu \nu} \neq 0 \]

Generic low-energy Predictions?

(i) QG as a “medium” over which matter propagates: Quantum Decoherence 

(ii) Lorentz violations (?) – modified dispersion relations (MDR) for matter/radiation 

(iii) CPT violation(?) 

(iv) Non-commutativity effects I at low-energies 

Cosmology: effects on Dark sector of Universe, origin of Dark energy
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Cosmology: effects on Dark sector of Universe, origin of Dark energy
Corfu 2010

QG as a medium: an old story...

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.
- Manifested through delays in arrival times of the the more energetic photons.

First Model non-critical String theory (Ellis, NM, Nanopoulos (1992), + Amelino-Camelia (1996))


Plethora of other approaches since then… Deformed Special Relativities, Loop QG(?) …
Modified dispersion due to QG induced space-time (metric) distortions (c=1 units):

\[ p^\mu p^\nu G_{\mu\nu}(\vec{p}, E) = 0 , \quad p^\mu = (E, \vec{p}) \]
Quantum-Gravity Induced Modified Dispersion for Photons

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Space-time Metric describing space-time Distortions induced by Interactions of Photons with space-time defects FINSLER type: depends on momentum (transfer)... Higher the energy, higher the distortion of space-time around the defect
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\[
E = p \left( 1 + \sum_{n=1}^{\infty} a_n \left( \frac{|\vec{p}|}{M_{\text{QG}}} \right)^n \right)
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\[
E = p \left( 1 + \sum_{n=1}^{\infty} a_n \left( \frac{|\vec{p}|}{M_{QG}} \right)^n \right)
\]

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

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

subluminal: \(\eta > 1\) , superluminal \(\eta < 1\)
Subluminal QG-induced Refractive Index: Higher energy photons arrive later

\[ E = p \left( 1 + \sum_{n=1}^{\infty} a_n \left( \frac{|p|}{M_{QG}} \right)^n \right) \quad a_1 < 0 \]

Courtesy: N. Doltsinis@kcl.ac.uk
Decoherence may be induced & CPT may also be violated in such stochastic models.

"Fuzzy" Space times may induce (Ford, Yu 1994, 2000): $g_{\mu\nu} = \eta_{\mu\nu} + \hbar_{\mu\nu}$, $\langle g_{\mu\nu} \rangle = \eta_{\mu\nu}$ BUT $\langle \hbar_{\mu\nu}(x)\hbar_{\lambda\sigma}(x') \rangle \neq 0$, i.e. Quantum light cone fluctuations BUT NOT mean-field effects on dispersion relations, that is, Lorentz symmetry is respected on average BUT not on individual measurements. Path of light: null geodesics $0 = ds^2 = g_{\mu\nu}dx^\mu dx^\nu$. Fluctuations: Geodesic deviations $\frac{D^2 n^\mu}{dt^2} = -R^\mu_{\alpha\nu\beta}u^\alpha n^\nu u^\beta$, quantum fluctuate.

Fluctuations in arrival time of photons at detector: $|\phi\rangle=\text{state of gravitons, } |0\rangle=\text{vacuum state}$)

\[
\Delta t_{obs}^2 = |\Delta t^2_{\phi} - \Delta t_0^2| = \frac{|\langle \phi | \sigma_1^2 | \phi \rangle - \langle 0 | \sigma_1^2 | 0 \rangle|}{r^2} \equiv \frac{|\langle \sigma_1^2 \rangle_R|}{r}
\]

\[
\langle \sigma_1^2 \rangle_R = \frac{1}{8} (\Delta r)^2 \int_0^{T_1} dr \int_0^{T_1} dr' \ n^\mu n^\nu n^\rho n^\sigma \langle \phi | h_{\mu\nu}(x) h_{\rho\sigma}(x') + h_{\mu\nu}(x') h_{\rho\sigma}(x) | \phi \rangle
\]
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)
TESTING THE MODELS

HIGH ENERGY ASTRONOMY
Multi-messenger observations of the Cosmos

**cosmic accelerator**

- protons $E > 10^{19}$ eV (10 Mpc)
- protons $E < 10^{19}$ eV

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

**photons:**
Absorbed by dust & radiation field (CMB)

**neutrinos:**
Difficult to detect

$\Rightarrow$ Three “astronomies” possible...

DeNaurois 2008
COSMIC PHOTON TESTS:
(i) *Measuring Arrival times* (delays of more energetic $\gamma$ s) Uncertainties Emission Mechanism Must accumulate statistically significant of ``events”

(ii) *Birefringence* (ONLY for some QG models): Measuring afterglow from distant GRBs

(iii) *Ultra-High Energy Cosmic Ray Spectrum*: LIV modifications of GZK cutoff Constraints: Non observation of UHE $\gamma$ s with $E > 10^{20}$ eV

MASSIVE COSMIC PROBE TESTS: Charged Probes (electrons)
*QG Modifications in Synchrotron radiation spectrum* – stringent constraints from CRAB NEBULA *exclude linearly* MDR for electrons

QG induced DECOHERENCE
(i) Damped flavour oscillators Cosmic neutrinos

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

(ii) EPR Correlation modifications in meson factories (CPT operator ill-defined due to QG decoherence (Wald 79) $\omega$-effect (Bernabeu, NEM, Papavassiliou 04)
MDR for charged 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:

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

- \( \omega_c \) = critical frequency
- \( R \) = 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 \( M_{QG} = M_{QG1\ (MAGIC)} \sim 10^{18} \text{ GeV} \) that \( \alpha > 1.74 \)

WHAT ABOUT PHOTONS?
VHE Experimental World Today

MILAGRO

STACEE

MAGIC

TIBET ARRAY

VERITAS

CACTUS

ARGO-YBJ

TACTIC

PACT

GRAPES

TACTIC

HENSS

CANGAROO

M. MARTINEZ

N.E. Mavromatos
VHE Experimental World Today

Corfu 2010

N.E. Mavromatos
Current Evidence of Delayed Photon Arrivals

MAGIC (AGN Mkn 501, z=0.034), Highest Energy 1.2 TeV Photons
Observed Delays of O(4 min)

HESS (AGN PKS 2155-304, z=0.116), Highest Energy 10 TeV photons
Originally claim no observed time lags

FERMI (GRB 090816C, z=4.35), Highest Energy Photon 13.2 GeV
4.5 s time-lag between E > 100 MeV and E < 100 KeV
Observed Time Delay 16.5 sec

FERMI (GRB 090510, z=0.9), Highest Energy Photon 31 GeV, several 1-10 GeV
Short, intense GRB, Observed Time Delays < 1 sec

FERMI (GRB 09092B, z=1.822), Highest Energy Photon 33.4 GeV
Observed Time Delay \( \Delta t \): 82 sec after GMB trigger
50 sec after end of emission

\( z=1 \rightarrow 10^{26} \text{ m} \)
Effective Field Theory Approach

Space-Time at Planck scales may have a \``foamy\'' structure (J. A. Wheeler), with possible coordinate non-commutativity or Lorentz Violation at microscopic scales. Parametrized at low-energies by local effective Field theories (EFT), e.g. Standard Model Extension with Lorentz and/or CPT Violating Extensions (Kostelecky, Lehnert ..., Myers, Pospelov...)

Add Local operators
In a field theory in flat Space-times that Represent LV or non Commutative effects

Several tests and bounds on relevant Parameters so far, from both Atomic (non-observations of forbidden atomic transitions) and Particle physics (neutral Kaons) as well as Astrophysics

\[ E = p \left( 1 + \sum_{n=1}^{\infty} a_n \left( \frac{|p|}{M_{\text{QG}}} \right)^n \right) \]
\[ a_1 < 0 \]
Birefringence Constraints on photons MDR

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

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

Maccione et al., arXive0707.2673

**Photons:**

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

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

**Electrons:**

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

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

UV radiation from Galaxies:

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

From GRB polarization:

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

**For**

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

Difference in polarization angle over cosmological distance \(d\):

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

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

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

\[
E^2 = p_e^2 + m_e^2 + \eta^{e} \pm p_e \left( \frac{p_e}{M_{\text{pl}}} \right)^n
\]

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: \( \xi < 10^{-12} \)

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

(ii) Photon Decay

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

Allowed, above threshold if MDR
Current Evidence of Delayed Photon Arrivals

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$z=1 \quad 10^{26} \text{ m}$
DELAYED ARRIVALS OR DELAYED EMISSION?

ASTROPHYSICAL MECHANISMS FOR COSMIC ACCELERATION
NO CONSENSUS AS YET.....
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
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DELAYED ARRIVALS OF MORE ENERGETIC PHOTONS:
FIT WITH A LINEARLY SUPPRESSED (BY THE QG SCALE) SUBLUMINAL DISPERSION RELATION?

\[ E = p \left(1 - \frac{p}{M_{\text{QG}}} \right) \]

\[ \text{Delay } \Delta t \propto E \text{ (plus cosmic expansion)} \]

BUT WHAT IS A NATURAL SIZE OF \( M_{\text{QG}} \)?
Is it Planck?
Is it the String Scale?
Is it Microscopic
Model Dependent?
\[
\Delta t/E_\gamma = (0.43 \pm 0.19) \times K(z)/\text{GeV}, \quad K(z) \equiv \int_0^2 \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}.
\]
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\[ M_{QG} > 1.5 \times 10^{19} \text{ GeV} = 1.22 \, M_p \text{ (ECF method)} \]

AGN Mkn 501
MAGIC

AGN PKS 2155-304
HESS

Fermi GRB 09092B
Fermi GRB 080916c

AGN PKS 2155-304
HESS

Fermi GRB 090510

+ Sakharov Sarkisyan

Special Relativity
Effective Field Theory Approach

Space-Time at Planck scales may have a `foamy’ structure (J. A. Wheeler), with possible coordinate non-commutativity or Lorentz Violation at microscopic scales. Parametrized at low-energies by local effective Field theories (EFT), e.g. Standard Model

\[ E = p \left( 1 + \sum_{n=1}^{\infty} a_n \left( \frac{|p|}{M_{\text{QG}}} \right)^n \right) \quad a_1 < 0 \]

\[ 10^{-35} \text{ m} \]

BUT WHAT IS A NATURAL SIZE OF \( M_{\text{QG}} \)?
Is it Planck?
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Is it Microscopic Model Dependent?

Several tests and bounds on relevant Parameters so far, from both Atomic (non-observations of forbidden atomic transitions) and Particle physics (neutral Kaons) as well as Astrophysics.
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BUT WHAT IS A NATURAL SIZE OF \( M_{QG} \)? Is it Planck? Is it the String Scale? Is it Microscopic Model Dependent?

Corfu 2010
If QG-induced modified dispersion relations occur, due to Finsler-type metric distortions, then time delays of more energetic photons may occur.

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

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

Induced Time delay for photons e.g. for \( n=1 \)

\[ \Delta t = \frac{a_1 \Delta E L}{M_{\text{QG}} c} \]
Time Delays due to QG foam

But are these time delays necessarily linked to modified dispersion?

NOT NECESSARILY, BEST EXAMPLE STRINGY SPACE-TIME FOAM DUE TO BRANE DEFECTS ....
(1) Time Delays proportional to E dominant for photons
(2) Stable Photons
(3) No birefringence
(4) Beyond EFT
(5) Possibly z-dependent effective QG scale (inversely proportional to density of defects in the foam)
(1) Time Delays proportional to $E$
dominant for photons

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(inversely proportional
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Linear Time Delays related to stringy uncertainties, hence disentangled from Modified Dispersion Relations that may be quadratically suppressed (or higher-order) by the \( M_{\text{QG}} \) ...
Colliding Brane world model of Space-Time with point-like space-time defects
DEFECT-STRING CAPTURE
### String Theory Types and p-Branes

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

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**Compactify to** 3 + 1 Large Dim.
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Heterotic Strings admit no p-branes

**Compactify to**

3 + 1 Large Dim

**Wrap up along**

Three cycles ("D-particles")

Li, NM, Nanopoulos, Xie

---

Corfu 2010  
N.E. Mavromatos  
44
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
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)

\[
\frac{1}{g_{37}^2} = \frac{V_{A3}R'}{(1.55l_s)^4 \frac{l_s^4}{g_i^2}} = \frac{V_{A3}R'}{(1.55)^4 \frac{1}{g_i^2}}
\]

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 \(l_s\)

Capture process: Backward Scattering \(u=0\) (Mandelstam)
Time delays arise by considering Backward scattering \( u=0 \).

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

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

\[
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\]

Seiberg, Susskind
Toumbas
Time delays arise by considering 
Backward scattering \( u = 0 \). 
For massless particles \( u + t + s = 0 \) ...

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

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

To define the poles we use the correct \( \epsilon \) prescription replacing \( s \rightarrow s + i\epsilon \), 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)
A Stringy (type IIA) 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.

TYPE IIA string models: D-foam transparent to charged probes

TYPE IIB string models electrically charged probes have suppressed foam effects compared to neutral probes by several orders of magnitude.
Backward scattering $u=0$ implies

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

JUST POLE TERMS...
NO TIME DELAY AT LEADING ORDER in $\eta$

T.Li, NM, Nanopoulos, D. Xie
At order $\eta$, there are time delays...

\[
A(1_{j_1 I_1} 2_{j_2 I_2} 3_{j_3 I_3} 4_{j_4 I_4}) =
\]
\[-g_s l_s^2 \int_0^1 dx \; x^{-1-s l_s^2} (1 - x)^{-1-t l_s^2} \frac{1}{[F'(x)]^2} \times
\]
\[
\left[ \bar{u}^{(1)} \gamma_\mu u^{(2)} \bar{u}^{(4)} \gamma_\mu u^{(3)} (1 - x) + \bar{u}^{(1)} \gamma_\mu u^{(4)} \bar{u}^{(2)} \gamma_\mu u^{(3)} x \right]
\]
\[
\times \{ \eta \delta_{I_1, \bar{I}_2} \delta_{I_3, \bar{I}_4} \delta_{\bar{j}_1, j_4} \delta_{j_2, \bar{j}_3} \sum_{m \in \mathbb{Z}} e^{-\pi \tau m^2 \ell_s^2/R'^2}
\]
\[
+ \delta_{j_1, \bar{j}_2} \delta_{j_3, \bar{j}_4} \delta_{\bar{I}_1, I_4} \delta_{I_2, \bar{I}_3} \sum_{n \in \mathbb{Z}} e^{-\pi \tau n^2 R'^2 / \ell_s^2} \}
\]

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

\[
\eta = \frac{(1.55 \ell_s)^4}{V_A 3 R'}.
\]
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 Capture Process

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Stringy Uncertainties & the MAGIC Effect

- D-foam: transparent to electrons
- D-foam captures photons & re-emits them
- Time Delay (Causal) in each Capture:

\[ \Delta t \sim \alpha' p^0 \]

THESE TIME DELAYS ARE ASSOCIATED WITH STRING UNCERTAINTY PRINCIPLES:

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

(\( \alpha' = \) 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……
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- 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 

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Red-Shift Dependent QG Scale

Universe Expansion may affect density of defects – $n^\ast(z)$ Red-shift Dependent

\[
\Delta t_{\text{obs}} = \int_0^z \frac{n(z) E_{\text{obs}}}{M_s H_0} \frac{(1+z)}{\sqrt{\Omega_M (1+z)^3 + \Omega_\Lambda}}
\]
Red-Shift Dependent QG Scale

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

$$\Delta t_{\text{obs}} = \int_{0}^{z} dz \frac{n(z) E_{\text{obs}}}{M_s H_0} \frac{(1 + z)}{\sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda}}$$

$$M_{\text{QG}}^{\text{Eff}} = \frac{M_s}{n^*(z)}$$
Universe Expansion may affect density of defects – \( n^*(z) \) Red-shift Dependent

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\Delta t_{\text{obs}} = \int_{0}^{z} dz \frac{n(z) E_{\text{obs}}}{M_s H_0} \frac{(1 + z)}{\sqrt{\Omega_M (1 + z)^3 + \Omega_\Lambda}}
\]

\[
M_{QG}^{\text{Eff}} = \frac{M_s}{n^*(z)}
\]

\( n^*(z) \) = effective density of defects
Interacting with propagating photon
Universe Expansion may affect density of defects – $n^*(z)$ Red-shift Dependent

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

$n^*(z)$ can increase with $z$

If brane moves in inhomogeneous bulk
Red-Shift Dependent QG Scale

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

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

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

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 Source Delayed Emission

D-void around $z = 1$ ?

Accounts for Deceleration/ Acceleration transition in Brane Universe

$n^*(z)$ can increase with $z$

If brane moves in inhomogeneous bulk
Stringy Uncertainties & the MAGIC Effect

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- Time Delay (Causal) in each Capture:

\[ \Delta t \sim \alpha' p^0 \]

**THESE TIME DELAYS ARE ASSOCIATED WITH STRING UNCERTAINTY DUE TO ENERGETIC SUSCEPTIBILITY**

\[ \Delta \alpha \propto \Delta \alpha' \propto \Delta x \geq 1 \text{ (mm, micron, etc.)} \]

(\( \alpha' = \text{Regge slope} \), \( \Delta x \) = minimum string length scale)

**REPRODUCE 4\pm1 MINUTE DELAY OF MAGIC from Mk501 (redshift } z = 0.034\)**

For } n^* \approx O(1) \& M_s \approx 10^{18} \text{ GeV, consistently with Crab Nebula & other Astrophysical constraints on modified dispersion relations} ...
WHY BEYOND LOCAL EFT?
Recoil of the D-particle Defects during scattering
Distortion of the neighbouring space-time, with a Metric (Finsler type) which depends on both position and momentum transfer of incident string...
Recoil of the D-particle Defects during scattering
Distortion of the neighbouring space-time, with a Metric (Finsler type) which depends on both position and momentum transfer of incident string…
Cannot represent the effect by local field operators (higher-derivatives) in a flat space-time lagrangian…
Induced (Finsler) Space-Time Metric

D-particle Recoil velocity as "electric field" string background

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

Implies Finsler-type target-space metric

\[ g^{\text{open,electric}}_{\mu \nu} = (1 - \tilde{u}_i^2) \eta_{\mu \nu}, \quad \mu, \nu = 0, 1 \]

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

Notice that corrections to MDR due to metric are Quadratically suppressed by the string mass scale \( M_s \) in contrast to time delays due to stringy uncertainties which are linear.

\[ \Delta t \sim \alpha' p^0 \]

Stringy Uncertainties... Beyond Local EFT!
NEW TYPE OF ``GZK'' CUTOFF, From Lorentz Invariance of underlying string theory: recoil velocity must be

\[ \frac{u}{c} = \frac{\Delta p}{M_{QG}} < 1 \]

\[ (M_{QG} = M_s / g_s) \]

\[ g_{\mu\nu}^{\text{open,electric}} = \left(1 - \tilde{u}_i^2\right) \eta_{\mu\nu} , \quad \mu, \nu = 0, 1 \]
\[ g_{\mu\nu}^{\text{open,electric}} = \eta_{\mu\nu} , \mu, \nu = \text{all other values} , \]

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

\[ M_s / g_s \text{ free parameter in string theory…} \]

\[ \text{Avoid constraints on UHECR altogether?} \]
Ultra-high-energy photons

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

\[ \omega_b^2 = k_b^2, \]

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

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:

\[ \gamma_{\text{UHE}} + \gamma_{\text{background}} \not\rightarrow e^+ e^- \]

(ii) Photon Decay

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

Allowed, above threshold if MDR

NB: MDR are quadratically suppressed by the QG scale
Ultra-high-energy photons

\[ \omega_\pm^2 = k^2 + \xi_n^\pm k^2 \left( \frac{k}{M_{\text{pl}}} \right)^n, \]
\[ \omega_b^2 = k_b^2, \]
\[ E_{e, \pm}^2 = p_e^2 + m_e^2 + \eta_{\pm}^e \pm p_e^2 \left( \frac{p_e}{M_{\text{pl}}} \right)^n. \]

Severe constraints on LIV Parameters from absence of:

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D-FOAM & THE UNIVERSE DARK SECTOR
Uses 8-Brane stacks to account for appropriate supersymmetries if no motion + Orientifold 8-Planes to compactify bulk 9th space dim.
Interaction of D-particles with Brane Worlds via stretched Strings due to relative motion perpendicularly to branes only
D-FOAM & THE DARK SECTOR

Interaction of D-particles with Brane Worlds via stretched Strings due to relative motion perpendicularly to branes only

Contributions to Brane potentials (additional contrib. to Dark Energy)
Interaction of D-particles with Brane Worlds via stretched Strings due to relative motion perpendicularly to branes only

Contributions to Brane potentials (additional contrib. to Dark Energy)

Velocity-independent terms cancelled by Orientifold O8 contributions

\begin{align*}
\mathcal{V}_{D0-D8}^{\text{short}} &= -\frac{r}{4\pi\alpha'} - \frac{\pi\alpha' v^2}{12 r^3} \\
r &\ll \sqrt{\alpha'}, \quad v \ll 1
\end{align*}

\begin{align*}
\mathcal{V}_{D0-D8}^{\text{long}} &= -\frac{r}{4\pi\alpha'} + \frac{r v^2}{8\pi\alpha'} \\
r &\gg \sqrt{\alpha'}, \quad v \ll 1
\end{align*}
Interaction of D-particles with Brane Worlds via stretched Strings due to relative motion perpendicularly to branes only

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Sign of velocity-dependent terms in potential depends on D-particle/D-brane distance. May cancel out over long periods

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\mathcal{V}_{D0-D8}^{\text{short}} = -\frac{r}{4\pi\alpha'} - \frac{\pi\alpha' v^2}{12} r^3
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\[ V_{short}^{D0-D8} = -\frac{r}{4\pi \alpha'} - \frac{\pi \alpha' v^2}{12 r^3} \]
\[ V_{long}^{D0-D8} = -\frac{r}{4\pi \alpha'} + \frac{r v^2}{8\pi \alpha'} \]

\[ r \ll \sqrt{\alpha'} , \quad v \ll 1 \]

\[ r \gg \sqrt{\alpha'} , \quad v \ll 1 \]
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Velocity-independent terms cancelled by Orientifold O8 contributions

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\[ V_{short}^{D0-D8} = -\frac{r}{4\pi\alpha'} - \frac{\alpha'}{12} \frac{v^2}{r^3} \]

\[ r \ll \sqrt{\alpha'}, \quad v \ll 1 \]

\[ V_{long}^{D0-D8} = -\frac{r}{4\pi\alpha'} + \frac{r}{8\pi\alpha'} \frac{v^2}{r^3} \]

\[ r \gg \sqrt{\alpha'}, \quad v \ll 1 \]
D-FOAM EFFECTS ON DARK MATTER (THERMAL) RELICS
Interaction of D-particles with Open strings attached to the Brane world (Standard Model Excitations)
CORFU 2010

D-contribution to dark-energy

NOT DARK MATTER PER SE.

D-PARTICLES VIEWED AS BACKGROUND DEFECTS.

Ellis, NEM, Nanopoulos
D-PARTICLES VIEWED AS BACKGROUND DEFECTS, NOT DARK MATTER PER SE...

D-particle fluctuations Induce metric distortions which affect Dark Sector

Sarben Sarkar, Vergou, NEM
D-foam Induced Finsler metric modifications in thermal Dark Matter Relic Abundances – Modification in Botlzmann equation

\[ g_{\mu\nu} = \begin{pmatrix} -1 & a^2(t)r_1 p_1 & a(t)^2 r_2 p_2 & a^2(t) r_3 p_3 \\ a^2(t)r_1 p_1 & a^2(t) & 0 & 0 \\ a^2(t)r_2 p_2 & 0 & a^2(t) & 0 \\ a^2(t)r_3 p_3 & 0 & 0 & a^2(t) \end{pmatrix}. \]

Sarben Sarkar, NEM, Vergou

\[ v_i = g_s \frac{\Delta p_i}{M_s} \equiv r_i p_i \]

Stochastic foam fluctuations

\[ \langle r_i \rangle = 0, \quad \langle r_i r_j \rangle = \sigma_i^2 \delta_{ij} \]

Metric in a boosted frame of velocity \( u_i \) embedded in a FRW expanding Universe

D-particle recoil velocity
BOLTZMAN EQ. MODIFICATION

\[ f(x^\mu, \bar{p}^\mu, ; t) \]

\[ \hat{L}[f] = C[f] \]

\[ \hat{L}[f] = p^\mu \frac{\partial f}{\partial x^\mu} + m \sum_i \frac{\partial f}{\partial \bar{p}^i} \frac{d\bar{p}^i}{d\tau}. \]

\[ \bar{p}^i \equiv a(t)p^i, \quad i = 1, 2, 3 \]

\[ C[f] = -\langle \bar{\sigma} v \rangle (n^2 - n_{eq}^2) \]
BOLTZMAN EQ. MODIFICATION

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\[ C[f] = -\langle \bar{\sigma} v \rangle (n^2 - n_{eq}^2) \]

\[ \hat{L}[f] = p^\mu \frac{\partial f}{\partial x^\mu} + m \sum_i \frac{\partial f}{\partial \overline{p}^i} \frac{d\overline{p}^i}{d\tau} \]

GEODESIC EQUATION (DEFINING THE FORCE) IS MODIFIED AS WELL

\[
\begin{align*}
\frac{\hat{L}[f]}{\overline{p}^0} &= \frac{\partial f}{\partial t} - H \sum_i \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} - 2H a^2(t) \overline{p}^0 \sum_i r_i \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} + 8H a^4(t) \sum_i r_i^2 (\overline{p}^i)^3 \frac{\partial f}{\partial \overline{p}^i} \\
&+ \frac{2}{\overline{p}^0} H a^2(t) \sum_j (\overline{p}^j)^2 \sum_i r_i \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} + 4H a^4(t) (\overline{p}^0)^2 \sum_i r_i^2 \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} - 4a^4(t)H \sum_i (\overline{p}^i)^2 \sum_i r_i^2 \overline{p}^i \frac{\partial f}{\partial \overline{p}^i}
\end{align*}
\]
BOLTZMAN EQ. MODIFICATION

\[ \frac{\dot{L}[f]}{p^0} = \frac{\partial f}{\partial t} - H \sum_i \vec{p}^i \frac{\partial f}{\partial \vec{p}^i} - 2H a^2(t) \vec{p}^0 \sum_i r_i \vec{p}^i \frac{\partial f}{\partial \vec{p}^i} + 8H a^4(t) \sum_i r_i^2 (\vec{p}^i)^3 \frac{\partial f}{\partial \vec{p}^i} \\
+ \frac{2}{p^0} H a^2(t) \sum_j (\vec{p}^j)^2 \sum_i r_i \vec{p}^i \frac{\partial f}{\partial \vec{p}^i} + 4H a^4(t) (\vec{p}^0)^2 \sum_i r_i^2 \vec{p}^i \frac{\partial f}{\partial \vec{p}^i} - 4a^4(t) H \sum_i (\vec{p}^i)^2 \sum_i r_i^2 \vec{p}^i \frac{\partial f}{\partial \vec{p}^i} \]

\[ \hat{L}[f] = C[f] \]

Number density of particles

\[ n(t) \equiv \frac{g}{(2\pi)^3} \int d^3\vec{p} \ f(t, \vec{p}^i) \]

Average temperature

\[ \frac{g}{(2\pi)^3} \int d^3\vec{p} (\vec{p}^i)^2 f \equiv T mn \]
D-foam Induced Finsler metric modifications in thermal Dark Matter
Relic Abundances – \textbf{Modification in Botlzmann equation}

\[
\frac{dn}{dt} + 3H n = \Gamma(t) n + \frac{g}{(2\pi)^3} \int d^3p \frac{C[f]}{E}
\]

\[
C[f] = -\langle \tilde{\sigma} \nu \rangle \left(n^2 - n_{eq}^2\right)
\]

Number density of DM particles

Thermal equilibrium density

\[
\Gamma(t) = H a^4(t) \left( \sum_i \sigma_i^2 \right) \left[ 18Tm + 4m^2 \right]
\]

Heavy DM $m \gg T$

Also modified by the Foam

Due to modified dispersion Relations

Corfu 2010

N.E. Mavromatos
D-foam Induced Finsler metric modifications in thermal Dark Matter Relic Abundances – Modification in Botlzmann equation

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\Gamma(t) = H a^4(t) \left( \sum_i \sigma_i^2 \right) \left[ 18Tm + 4m^2 \right]
\]

Heavy DM m >> T

Thermal equilibrium density

\[
C[f] = -\langle \tilde{\sigma} \nu \rangle \left( n^2 - n_{eq}^2 \right)
\]

Also modified by the Foam

Due to modified dispersion Relations

Source terms in Boltzmann, related to particle production features of D-foam
\[ \overline{p}^0 = a^2(t) \sum_i \left( \overline{p}^i \right)^2 r_i + \sqrt{\sum_i \left( \overline{p}^i \right)^2 + m^2} \left[ 1 + \frac{a^4(t) \left( \sum_i \left( \overline{p}^i \right)^2 r_i \right)^2}{\sum_i \left( \overline{p}^i \right)^2 + m^2} \right]^{1/2} \]

\[ \ll r_i \gg = 0 \] , \[ \ll r_i r_j \gg = \sigma_i^2 \delta_{ij} \]  

Quadratically suppressed by QG scale after stochastic averaging
D-foam Induced Finsler metric modifications in thermal Dark Matter

Relic Abundances – Modification in Boltzmann equation

\[
\frac{dn}{dt} + 3Hn = \Gamma(t)n + \frac{g}{(2\pi)^3} \int d^3p \frac{C[f]}{E}
\]

\[
C[f] = -\langle \tilde{\sigma} \nu \rangle (n^2 - n_{eq}^2)
\]

Due to modified dispersion Relations

\[
n_{eq} = g \left( \frac{m}{2\pi^3} \right)^{\frac{3}{2}} e^{-(m-\mu)\beta} \times \left[ 1 + \frac{\sqrt{2}}{5\pi^{3/2}} \left( m^2 (2\pi)^{3/2} \right) \sigma_0^2 \left( \frac{15}{2} - \frac{45}{16\sqrt{2}} \xi e^{-(m-\mu)\beta} + \frac{15}{27\sqrt{3}} \xi^2 e^{-2(m-\mu)\beta} \right) \right. \\
- \left. \frac{1}{12\pi^{3/2}} \left( \beta^{-2} + m^2 \right) \sigma_0^2 (2\pi)^{3/2} \left( 3 - \frac{3}{4\sqrt{2}} \xi e^{-(m-\mu)\beta} \right) \right]
\]

\[
= n_{st} \times \left[ 1 + \frac{\sqrt{2}}{5\pi^{3/2}} \left( m^2 (2\pi)^{3/2} \right) \sigma_0^2 \left( \frac{15}{2} - \frac{45}{16\sqrt{2}} \xi e^{-(m-\mu)\beta} + \frac{15}{27\sqrt{3}} \xi^2 e^{-2(m-\mu)\beta} \right) \right. \\
- \left. \frac{1}{12\pi^{3/2}} \left( \beta^{-2} + m^2 \right) \sigma_0^2 (2\pi)^{3/2} \left( 3 - \frac{3}{4\sqrt{2}} \xi e^{-(m-\mu)\beta} \right) \right]
\]

\[
\sigma_0^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2
\]
D-foam Induced Finsler metric modifications in thermal Dark Matter
Relic Abundances – Modification in Botlzmann equation

**Modified Thermal Relic abundances of heavy DM due to Finsler geometry**

\[
\frac{\Omega'_{\chi} h^2}{(\Omega_{\chi} h^2)^{no\, source}} = \left(1 + \int_{x_f}^{x_0} \frac{\Gamma(x)}{H x} \, dx - \frac{1}{J} \int_{x_f}^{x_0} J(s) \left( \int_{x_f}^{s} \frac{\Gamma(x)}{H x} \, dx \right) \, ds \right) \times \left( \frac{g'_{eff,f}}{g_{eff,f}} \right)^{\frac{1}{2}}
\]

\[
J \equiv \int_{x_0}^{x_f} \langle v\tilde{\sigma} \rangle' \, dx, \quad J(x) \equiv \frac{\langle v\tilde{\sigma} \rangle'}{x^2}
\]

\(x_f = m/T_f\), freezeout, typically \(x_f \approx 20\) (neutralino DM)
\(x_0 = m/T_0\), \(T_0 =\) today (CMB, 2.7 K)
Modification in effective d.o.f. $g'_{\text{eff}}$ due to modified equilibrium distributions

$$
\rho = \frac{g}{(2\pi)^3} \int \ll n\omega_r \gg d^3\vec{p}
$$

$$
\begin{align*}
\ll n\omega_r \gg &\equiv \prod_j \frac{1}{\sigma_j \sqrt{2\pi}} \int_{-\infty}^{\infty} dr_j \ll n\omega \gg_r \exp\left(-\frac{r_j^2}{2\sigma_j^2}\right), \\
\ll n\omega \gg_r &= \frac{\omega_r}{\exp(\beta(\omega_r - \mu)) + \xi}
\end{align*}
$$

$\omega_r = \text{energy in the presence of foam}$

$$
\begin{align*}
g'_{\text{eff}} &= g_{\text{eff}} + \frac{30}{\pi^2\sigma^2} \left( \frac{2\pi^4}{189} \sum_i g_{i,b} \left(\frac{T_{i,b}}{T}\right)^4 T_{i,b}^2 + \frac{793.92}{\pi^2} \sum_j g_{j,f} \left(\frac{T_{j,f}}{T}\right)^4 T_{j,f}^2 \right)
\end{align*}
$$

$$
\begin{align*}
g_{\text{eff}} &= \sum_i g_{i,b} \left(\frac{T_{i,b}}{T}\right)^4 + \frac{7}{8} \sum_j g_{j,f} \left(\frac{T_{j,f}}{T}\right)^4
\end{align*}
$$
Modification in effective d.o.f. $g'_{\text{eff}}$ due to modified equilibrium distributions

$$
g'_{\text{eff}} = g_{\text{eff}} + \frac{30}{\pi^2} \sigma^2 \left( \frac{2\pi^4}{189} \sum_i g_{i,b} \left( \frac{T_{i,b}}{T} \right)^4 T_{i,b}^2 + \frac{793.92}{\pi^2} \sum_j g_{j,f} \left( \frac{T_{j,f}}{T} \right)^4 T_{j,f}^2 \right)
$$

$$
\frac{\Omega' h_0^2}{(\Omega h_0^2)_{\text{no source}}} \approx \left[ 1 + 207.38 g_s^2 \frac{m_s^2}{M_s^2} x_f^{-2} \left( \sum_{i=1}^3 \Delta_i^2 \right) \right]^{1/2} \left[ 1 + g_s^2 \frac{m_s^2}{M_s^2} x_f^{-2} \left( \sum_{i=1}^3 \Delta_i^2 \right) \left( 1 + 6 x_0^{-1} \right) \right]
$$

$x_f = T_f / m$, freezeout, typically $x_f \approx 0.05$

$x_0 = T_0 / m$, $T_0 = \text{today (CMB, 2.7 K)}$

$\Delta^2 = g_s^2 \sigma^2 / M_s^2$
Modification in effective d.o.f. $g'_{\text{eff}}$ due to modified equilibrium distributions

$$g'_{\text{eff}} = g_{\text{eff}} + \frac{30}{\pi^2} \sigma^2 \left( \frac{2\pi^4}{189} \sum_i g_{i,b} \left( \frac{T_{i,b}}{T} \right)^4 T_{i,b}^2 + \frac{793.92}{\pi^2} \sum_j g_{j,f} \left( \frac{T_{j,f}}{T} \right)^4 T_{j,f}^2 \right)$$

\[
\frac{\Omega'_{\chi} h_0^2}{(\Omega_{\chi} h_0^2)_{\text{no source}}} \approx \left[ 1 + 207.38 g_s^2 \frac{m^2}{M_s^2} x_f^{-2} \left( \sum_{i=1}^{3} \Delta_i^2 \right) \right]^{1/2} \left[ 1 + g_s^2 \frac{m^2}{M_s^2} \left( \sum_{i=1}^{3} \Delta_i^2 \right) (1 + 6 x_0^{-1}) \right]
\]

$x_f = T_f / m$, freezeout, typically $x_f \approx 0.05$

$x_0 = T_0 / m$, $T_0 =$ today (CMB, 2.7 K)

$\Delta^2 = g_s^2 \pi^2 / M_s^2$

Significant ($\sim 10^{-3}$) for TeV scale $M_s$ and $m$, can be constrained from WMAP data...

If DM is neutralino in SUSY models can be constrained by collider tests (LHC...)
Modification in effective d.o.f. $g'_{eff}$ due to modified equilibrium distributions

\[
g'_{eff} = g_{eff} + \frac{30}{\pi^2} \bar{\sigma}^2 \left( \frac{2\pi^4}{189} \sum_i g_{i,b} \left( \frac{T_{i,b}}{T} \right)^4 T_{i,b}^2 + \frac{793.92}{\pi^2} \sum_j g_{j,f} \left( \frac{T_{j,f}}{T} \right)^4 T_{j,f}^2 \right)
\]

\[
\frac{\Omega' \chi h_0^2}{(\Omega \chi h_0^2)_{\text{no source}}} \simeq \left[ 1 + 207.38 g_s^2 \frac{m^2}{M_s^2} x_f^{-2} \left( \sum_{i=1}^{3} \Delta_i^2 \right) \right]^{1/2} \left[ 1 + g_s^2 \frac{m^2}{M_s^2} \left( \sum_{i=1}^{3} \Delta_i^2 \right) (1 + 6 x_0^{-1}) \right]
\]

$\Delta_i^2 = g_s^2 \frac{m_i^2}{M_s^2}$

$x_f = T_f / m$, freezeout, typically $x_f \approx 0.05$

$x_0 = T_0 / m$, $T_0$ today ($\sim$ CMB, 2.7 K)

Significant ($\sim 10^{-3}$) for TeV scale $M_s$ and $m$, can be constrained from WMAP data...

If DM is neutralino in SUSY models can be constrained by collider tests (LHC...)

Corfu 2010

N.E. Mavromatos
OTHER EFFECTS OF D-FOAM
CPT may be Violated in D-particle Foam models but only through Target-space effective (low-energy) Decoherence, induced by stochastic quantum metric fluctuations ...

Tests in Particle Interferometers: EPR correlation modifications...
Conclusions

- 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? Or both?

- 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…

- Beyond Local EFT!? (stringy uncertainties, intermediate string formation)

- 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… UHE Cosmic Rays, cosmic neutrinos

- Foam effects in Dark Sector: Dark Energy contributions, Dark Matter abundancies modification

- Also Particle Interferometry (Neutral Meson factories) may provide complementary test of such fundamentally new physics…(CPTV)
Outlook…

On the Theoretical Side: Develop Foam Models to incorporate realistic standard model phenomenology and get agreement with current cosmology: intersecting brane models to get Standard Model Group, calculate and analyse effects of foam on CMB, Universe Dark Sector…

On the experimental side: increase statistics of observations, luckily one should observe short GRBs at various red-shifts, which will allow falsification of models for $n^*(z)$ density of foam.

Exciting Times for Astro-Particle Physics fundamental symmetries tests expected?
D-particle Recoil Formalism

σ-Model 1st Quantized Formalism

Recoil Velocity $u_i$ as Constant Electric Field Background

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

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

$$u_i = g_s \frac{(\Delta \vec{k})_i}{M_g}$$
D-particle Recoil Formalism

σ-Model 1\textsuperscript{st} Quantized Formalism

Recoil Velocity $u_i$ as Constant Electric Field Background

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

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

B-field deformation, $B_{0i} = u_i$

$$
\nu_i = g_s \frac{(\Delta \vec{k})_i}{M_s}
$$
Induced (Finsler-type) Non-Commutativity (N.C.)

Mixed world-sheet Boundary Conditions

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

Neumann  Dirichlet, $B_{0i} \sim u_i$ (D-particle recoil velocity)

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

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

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

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
Induced (Finsler) Space-Time Metric

World-Sheet Propagator in the presence of recoil background

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

Implies Finsler-type target-space metric

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

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

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

Implies Finsler-type target-space metric

\[ g_{\mu\nu}^{\text{open, electric}} = \left(1 - \tilde{u}_i^2\right) \eta_{\mu\nu}, \quad \mu, \nu = 0, 1 \]
\[ g_{\mu\nu}^{\text{open, electric}} = \eta_{\mu\nu}, \quad \mu, \nu = \text{all other values} \]

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

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

Implies Finsler-type target-space metric

Depends on Momentum Transfer due to momentum Conservation in D-particle Recoil

\[ u_i = g_s \Delta k_i / M_s \]

and effective string coupling

\[ g_s^{\text{eff}} = g_s \left( 1 - \tilde{u}^2 \right)^{1/2} \]
Induced (Finsler) Space-Time Metric

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

Implies Finsler-type target-space metric

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

Notice that corrections to MDR due to metric are \textbf{Quadratically} suppressed by the string mass scale \( M_s \) in contrast to \textbf{time delays} due to stringy uncertainties which are \textbf{linear}.

\[ \Delta t \sim \alpha' p^0 \]
Consequences for Neutral mesons EPR – correlators

\[ |\psi > = \mathcal{N}\left( |K_S(k), K_L(-k) > - |K_L(k), K_S(-k) > \right) \]

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

IF CPT $\Theta$-operator WELL-DEFINED

Even if $[\Theta, H] \neq 0$
If foam, concept of anti-particle may be perturbatively modified, Neutral mesons no longer indistinguishable.
If foam, concept of anti-particle may be perturbatively modified, Neutral mesons no longer indistinguishable

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

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

IF CPT ILL-DEFINED (e.g. Stringy Foam)
If foam, concept of anti-particle may be perturbatively modified, Neutral mesons no longer indistinguishable particles, initial entangled state:

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

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

\[
|\omega|^2 \sim \frac{\zeta^2 k^4}{M_{QG}^2 (m_1 - m_2)^2}, \Delta p \sim \zeta \rho \text{ (kaon momentum transfer)}
\]

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 \( \omega \):

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

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