Quantum Gravity, Cosmology and High-Energy Gamma-Ray Astronomy

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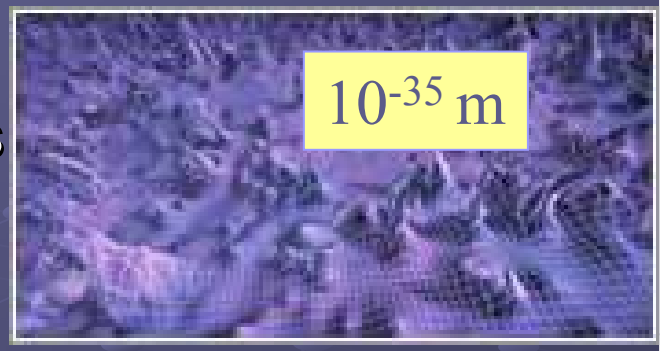
OUTLINE

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

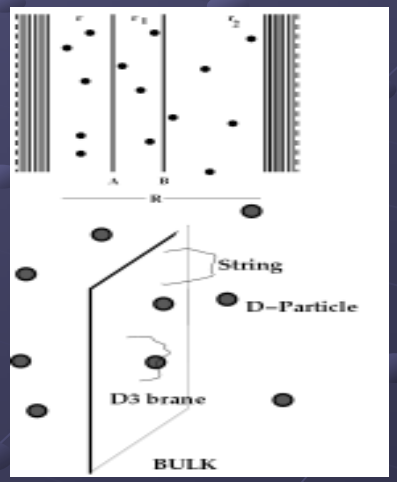


- String theory foam model (D-(brane) foam):

  D(efect)-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**

QUANTUM GRAVITY (QG)

- 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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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))

First Tests suggestion Using GRBs as probes: (Amelino-Camelia, Ellis, NM, Nanopoulos, Sarkar (1998)) Ellis, Farakos, NM, Mitsou, Nanopoulos (1999))

Plethora of other approaches since then… Deformed Special Relativities, Loop QG(?) …

Quantum-Gravity Induced Modified Dispersion for Photons

Ellis, NM, Nanopoulos

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

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

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

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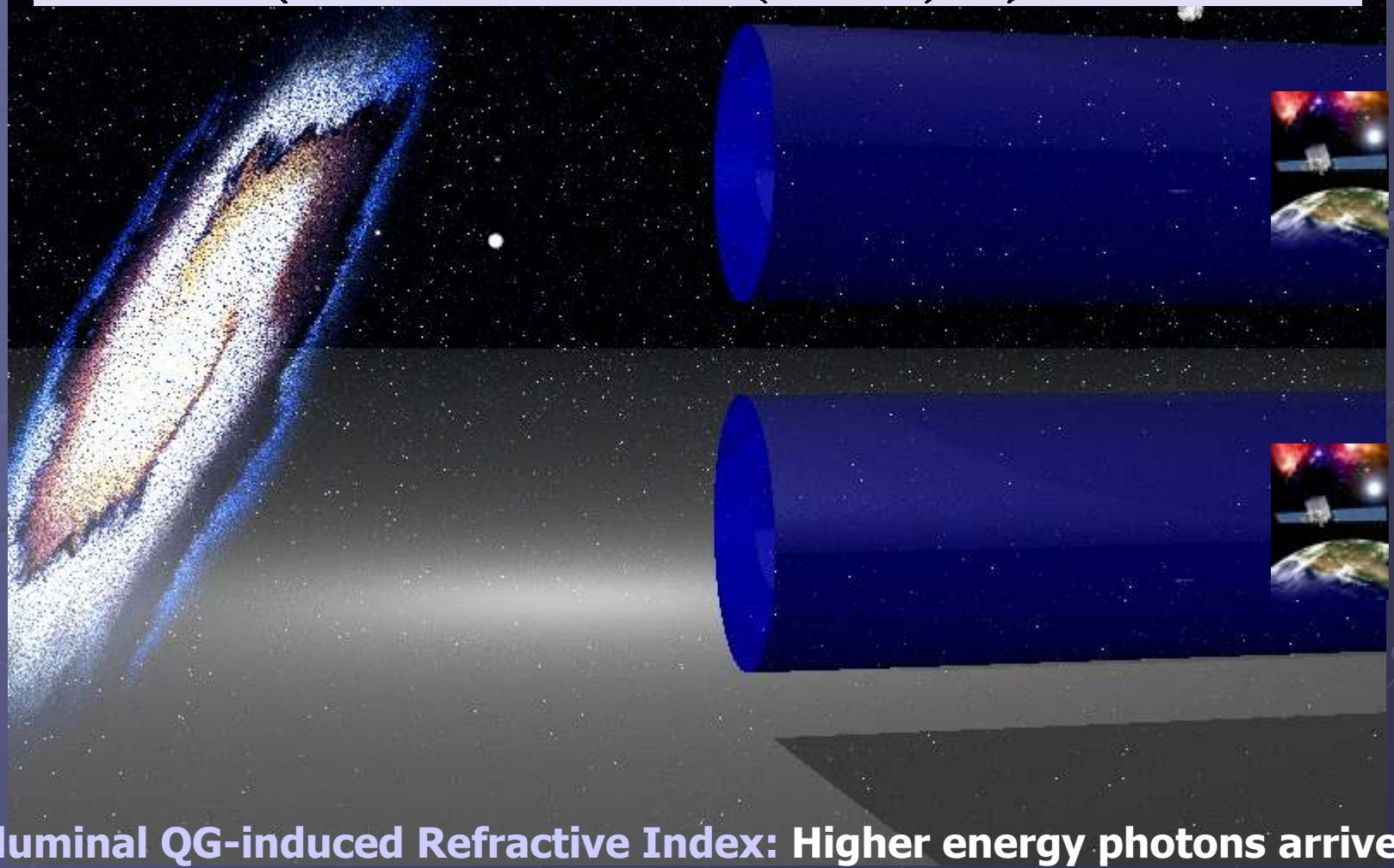
$$V_{\rm phase} = \frac{E}{|\vec{p}|} = \frac{1}{\eta} \ , \quad V_{\rm group} = \frac{\partial E}{\partial |\vec{p}|}$$

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

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

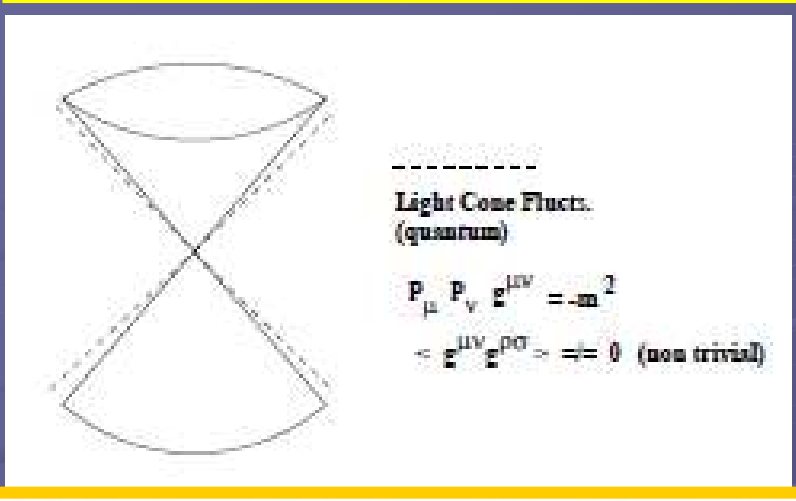
Courtesy: N. Doltsinis@kcl.ac.uk

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



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

Stochastic Light-Cone Fluctuations



Decoherence may be induced & CPT may also be violated in such stochastic models

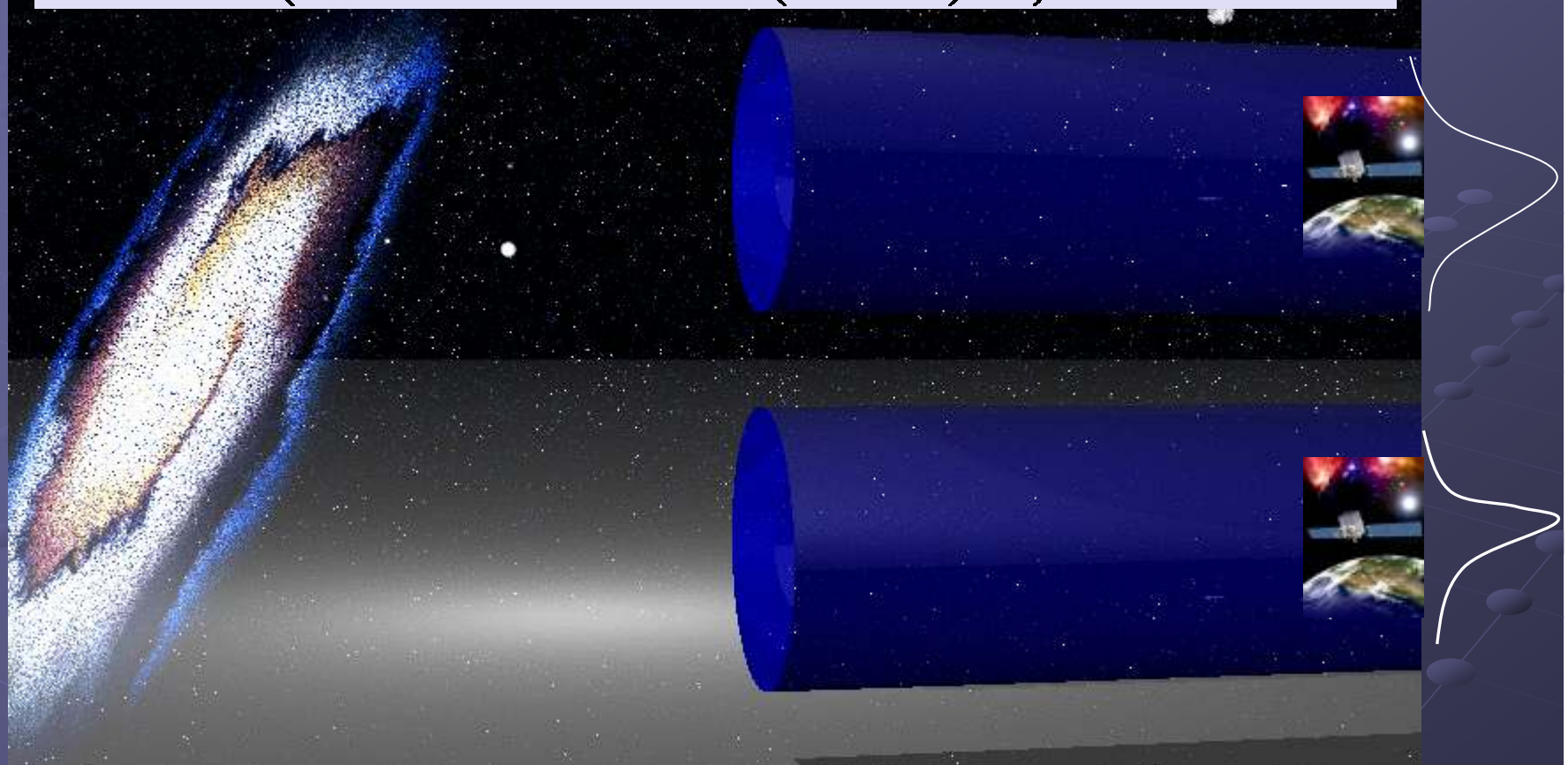
"Fuzzy" Space times may induce (Ford, Yu 1994, 2000): $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$, $\langle g_{\mu\nu} \rangle = \eta_{\mu\nu}$ BUT $\langle h_{\mu\nu}(x) h_{\lambda\sigma}(x') \rangle \neq 0$, , i.e. Quantum light cone fluctuations BUT NOT mean-field effects on dispersion relations, that 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 $\frac{D^2 n^\mu}{d\tau^2} = -R^\mu_{\alpha\nu\beta} u^\alpha n^\nu u^\beta$, quantum fluctuate.

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

$$\Delta t^2_{obs} = |\Delta t^2_\phi - \Delta t^2_0| = \frac{|\langle\phi|\sigma_1^2|\phi\rangle - \langle 0|\sigma_1^2|0\rangle|}{r^2} \equiv \frac{|\langle\sigma_1^2\rangle_R|}{r}.$$

$$\langle\sigma_1^2\rangle_R = \tfrac{1}{8}(\Delta r)^2 \int_{r_0}^{r_1} dr \int_{r_0}^{r_1} dr' \; n^\mu n^\nu n^\rho n^\sigma \; \langle\phi|h_{\mu\nu}(x) h_{\rho\sigma}(x') + h_{\mu\nu}(x') h_{\rho\sigma}(x)|\phi\rangle$$

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

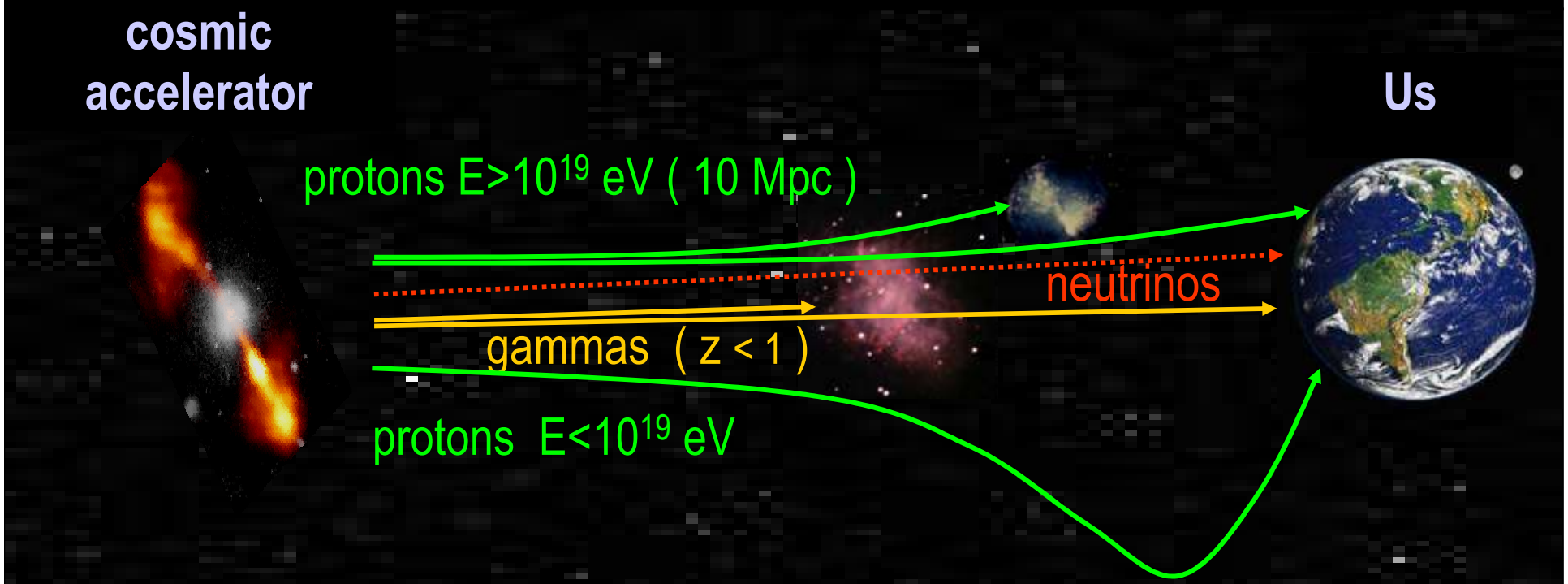


Subluminal QG-induced Refractive Index: **Higher energy photons arrive later**
Stochastic Light-Cone fluctuations: **Energy dependent width of photon pulses (e.g. D-particle (stringy) foam, width proportional to photon energy)**

TESTING THE MODELS

HIGH ENERGY ASTRONOMY

Multi-messenger observations of the Cosmos



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

COSMIC PHOTON TESTS :

(i) Measuring Arrival times

(delays of more energetic γ 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 γ 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

$$P_{\alpha\to\beta} \propto e^{-Dt}\sin\left(\frac{\Delta m^2_{12}}{E}t\right)$$

(ii) EPR Correlation modifications in meson factories (CPT operator ill-defined due to QG decoherence (Wald 79)

ω-effect (Bernabeu, NEM, Papavassiliou 04)

MDR for charged matter probes

Massive Probes (e.g. electrons):

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

Constraints from Crab Nebula via Synchrotron Radiation

Jacobson, Liberati, Mattingly, Ellis, NM, Sakharov

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

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

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

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

WHAT ABOUT PHOTONS ?

VHE Experimental World Today

M. MARTINEZ

VHE Experimental World Today

MILAGRO

STACEE
CACTUS

MAGIC

Canary Islands

TIBET ARRAY
ARGO-YBJ

TACTIC

PACT

GRAPES

VERITAS

HESS

CANGAROO III

M. MARTINEZ

VHE Experimental World Today

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 Δt: 82 sec after GMB trigger

50 sec after end of emission

z=1 → 10^{26} 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.g. Photons

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

Birefringence Constraints on photons MDR

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

Maccione et al., arXive0707.2673

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

Myers-Pospelov QED

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

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

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

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

Difference in polarization angle over cosmological distance *d*:

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

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

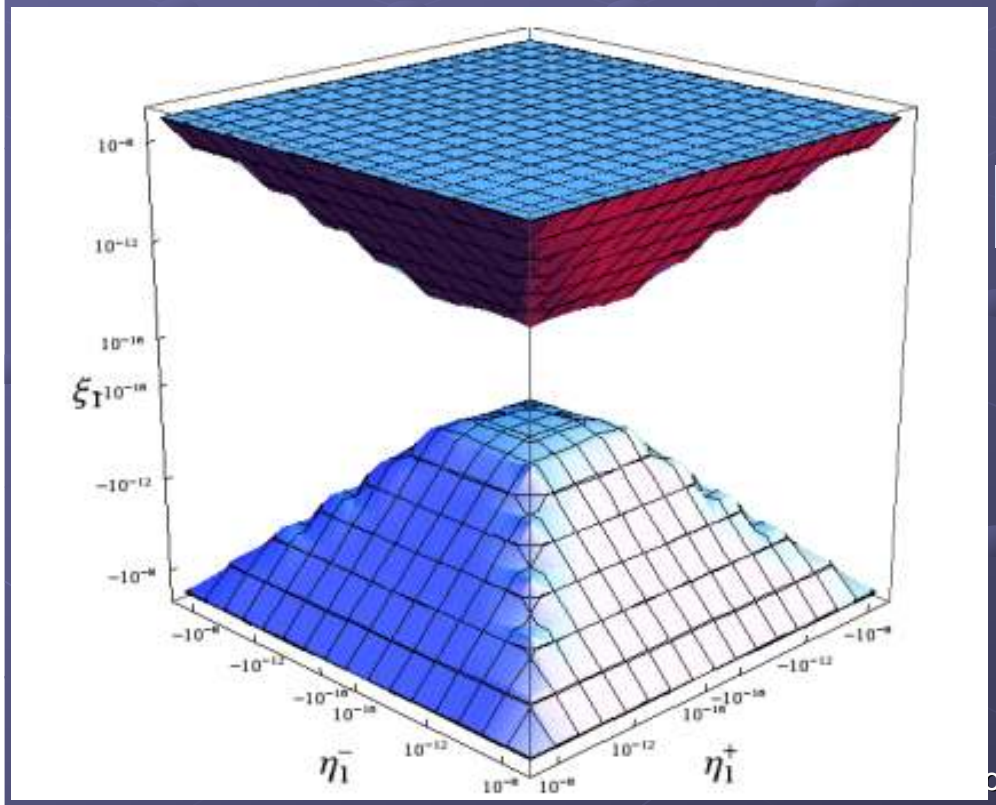
For $M \sim M_{\rm Pl} \approx 1.22\times 10^{19}$ GeV

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

Ultra-high-energy photons

Galaverni & Sigl
+ Liberati. Maccione

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



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: $\xi < 10^{-12}$

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

(ii) Photon Decay

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

Allowed, above threshold if MDR

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DELAYED ARRIVALS OR DELAYED EMISSION?

ASTROPHYSICAL MECHANISMS FOR COSMIC ACCELERATION NO CONSENSUS AS YET…..

Gamma Ray Astronomy & LIV

Review N.E.M 0903.0318

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

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

- Possible Interpretations:

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

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

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

  Photons: Birefringence constraints for LMDR

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DELAYED ARRIVALS OF MORE ENERGETIC PHOTONS:
FIT WITH A LINEARLY SUPPRESSED (BY THE QG SCALE) SUBLUMINAL DISPERSION RELATION ?

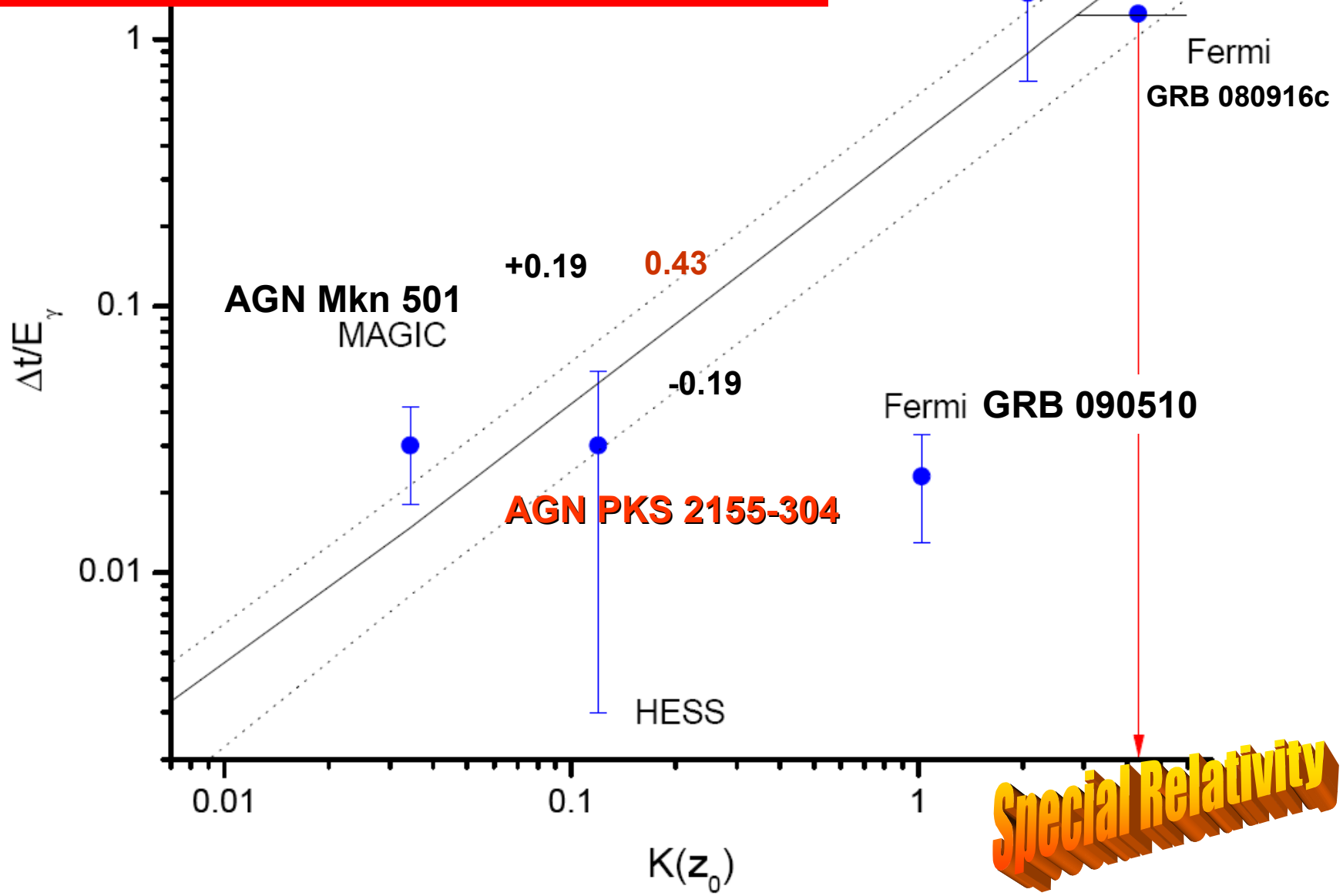
$$E = p\,(1 - p/M_{QG})$$

Delay $\Delta t \propto E$ (plus cosmic expansion)

BUT WHAT IS A NATURAL SIZE OF M_{QG} ?
Is it Planck?
Is it the String Scale?
Is it Microscopic Model Dependent?

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

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



Special Relativity

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

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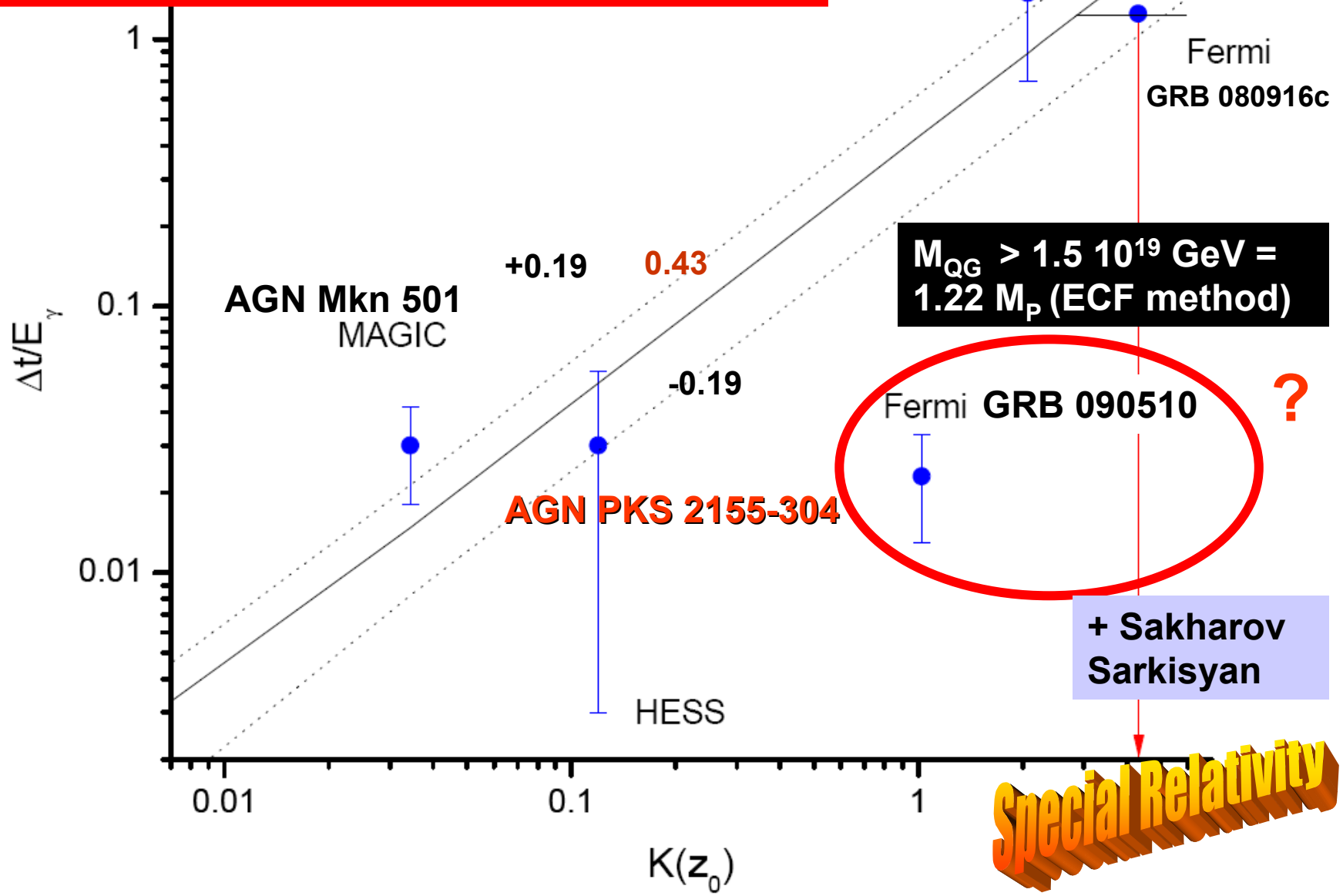

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Time Delays due to QG foam

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

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

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

Induced Time delay for photons e.g. for n=1

$$\Delta t = \frac{a_1 \Delta E}{M_{\rm QG}} \frac{L}{c}$$

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 ….

EFFECTIVE FIELD THEORY MAY BREAK DOWN FOR QG

A CLASS OF MODELS WITH SUCH PROPERTIES AS...

(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)

STRING THEORY & VACUUM REFRACTIVE INDICES

Ellis, NM, Westmuckett

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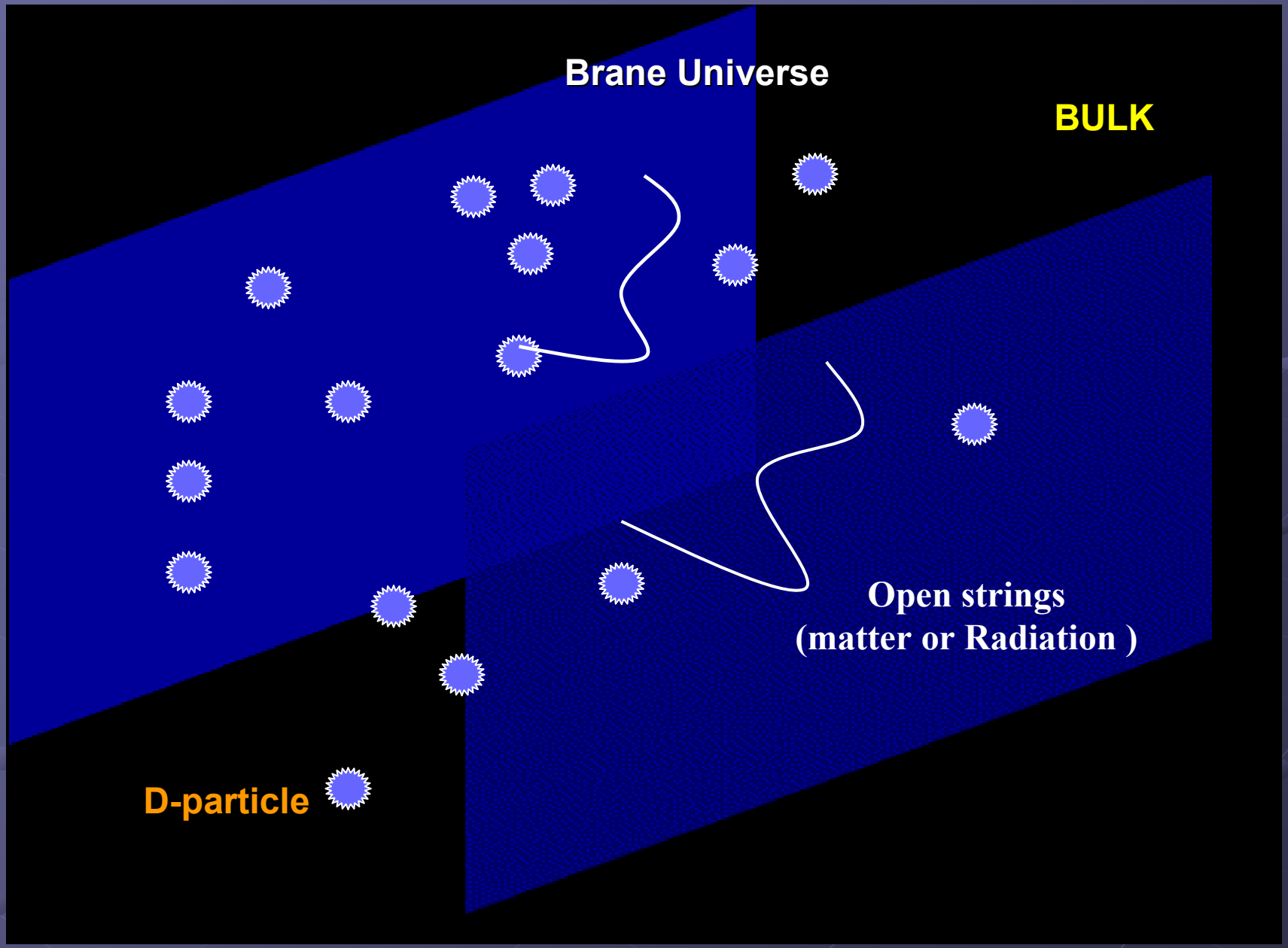
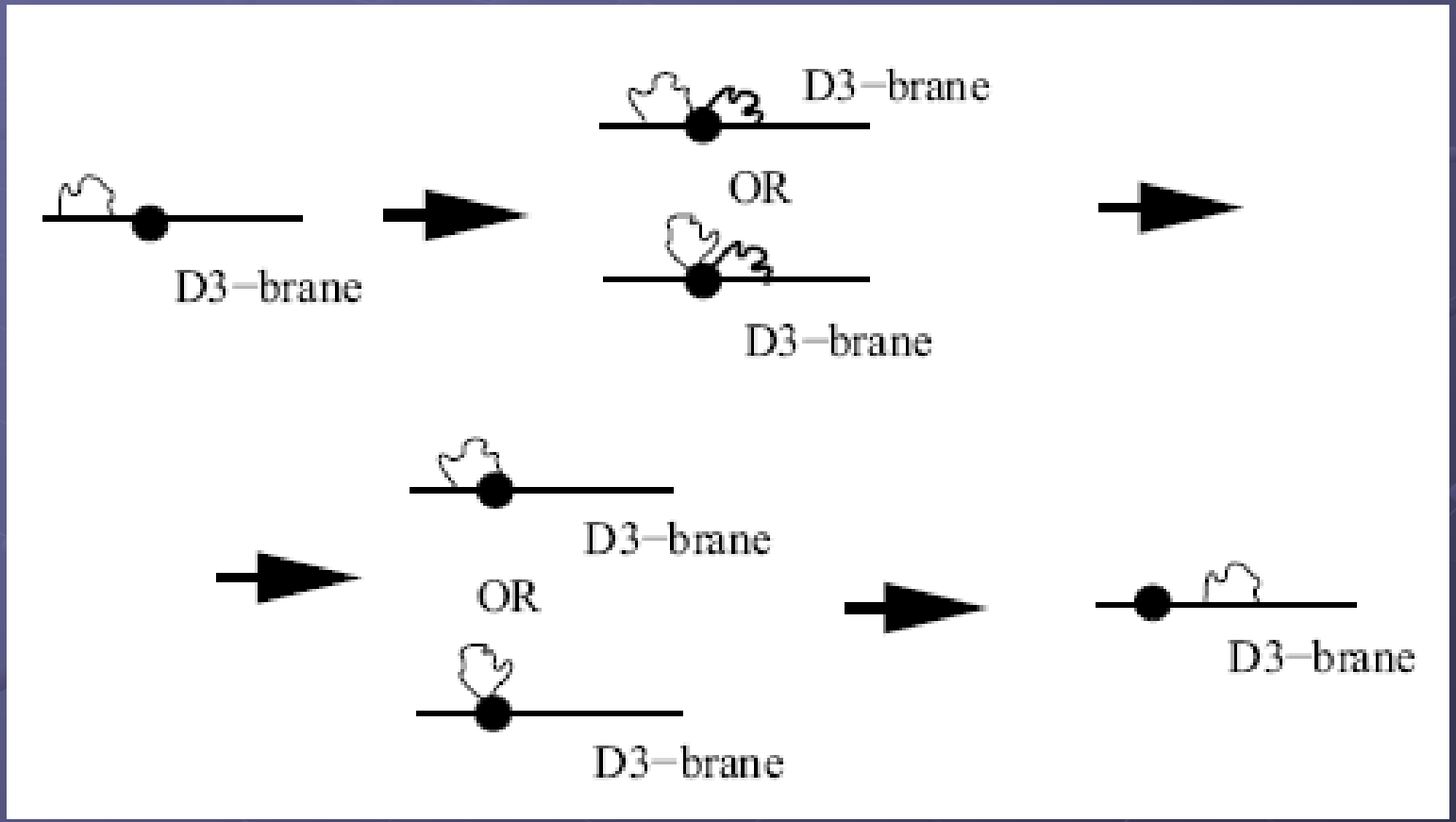
STRING THEORY & VACUUM REFRACTIVE INDICES

Linear Time Delays related to stringy uncertainties, hence disentangled from Modified Dispersion Relations that may be quadratically suppressed (or higher-order) by the M_{QG} …



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

DEFECT-STRING CAPTURE



STRING/D-BRANE BASICS

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

Heterotic Strings admit no p-branes

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For our models of Foam...

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Compactify to 3 + 1 Large Dim

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type-I	$p =$

Heterotic Strings admit no p-branes

Compactify to

3 + 1 Large Dim

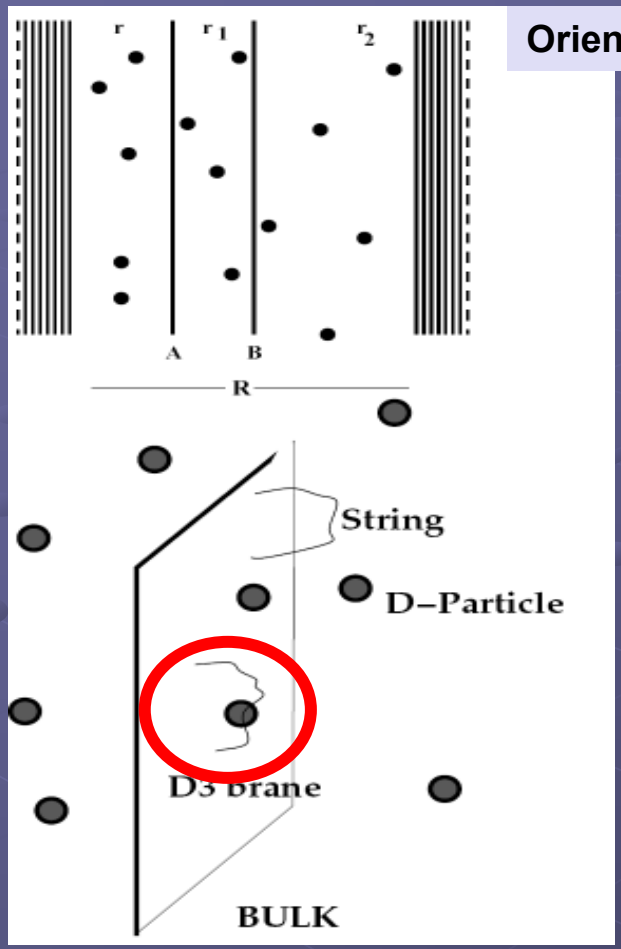
Wrap up along

Three cycles

(``D-particles'')

Li, NM, Nanopoulos, Xie

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



Orientifold planes, stacks of D8 branes

Ellis, NM, Westmuckett

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

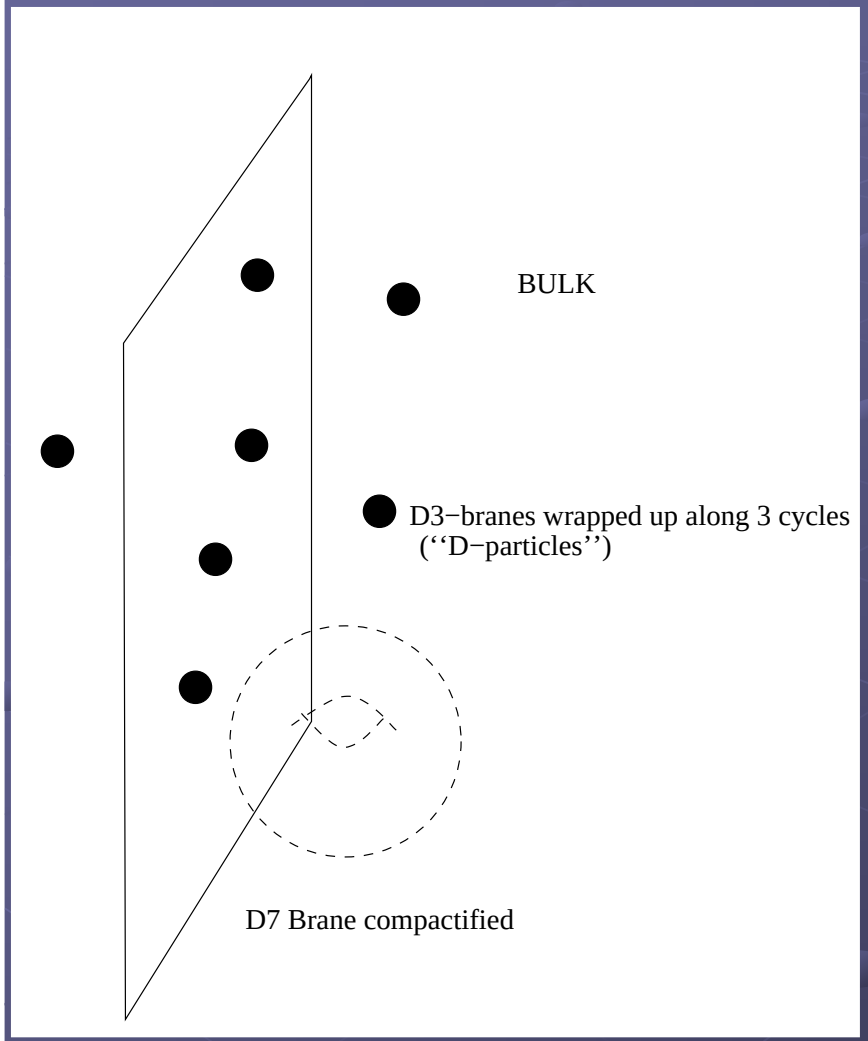
D-particle foam medium transparent to (charged) Electrons ⇒ no modified dispersion for them

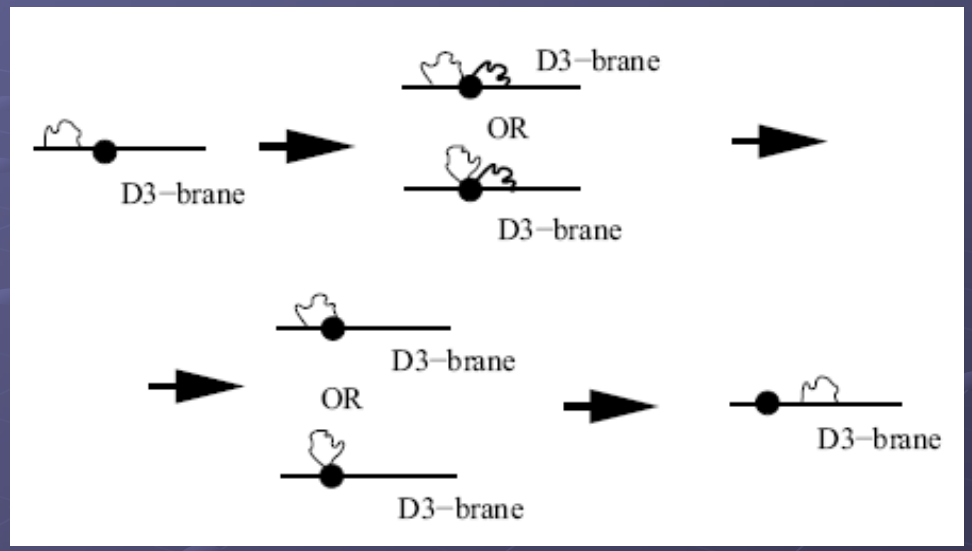
Photons or electrically neutral probes feel the effects of D-particle foam ⇒ Modified Dispersion for them….

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

Type IIB String Model of D-particle Foam

T.Li, NM, Nanopoulos, D. Xie

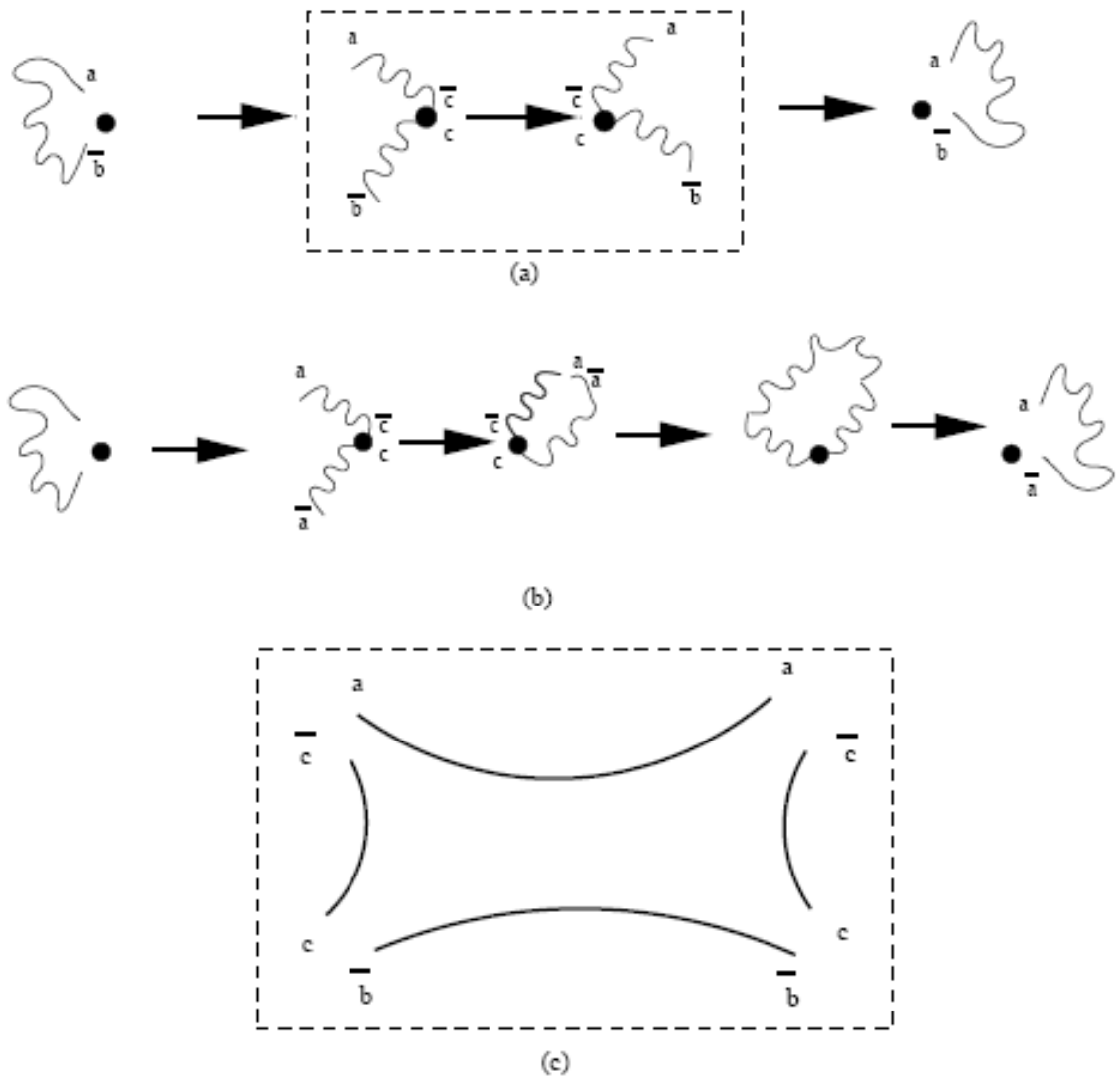




Consider Four-point Veneziano Amplitude for scattering of two open string states to two open string states in the D-particle/D3-branes backgrounds

Antoniadis, Benakli, Laugier

Type IIB String Model of D-particle Foam



T.Li, NM, Nanopoulos, D. Xie

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

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

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

Avoid tachyon condensation: D3 branes have widths 1.55 ℓ_s

Capture process: Backward Scattering u=0 (Mandelstam)

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

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

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Seiberg,Susskind

Toumbas

Time delays arise by considering Backward scattering u=0.

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

Photons or Cartan subalgerba of Gauge Group Gauginos

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

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

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

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

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

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

$$e^{iEt + i\vec{k}\cdot\vec{x} + i\pi E^2 \ell_s} ,$$

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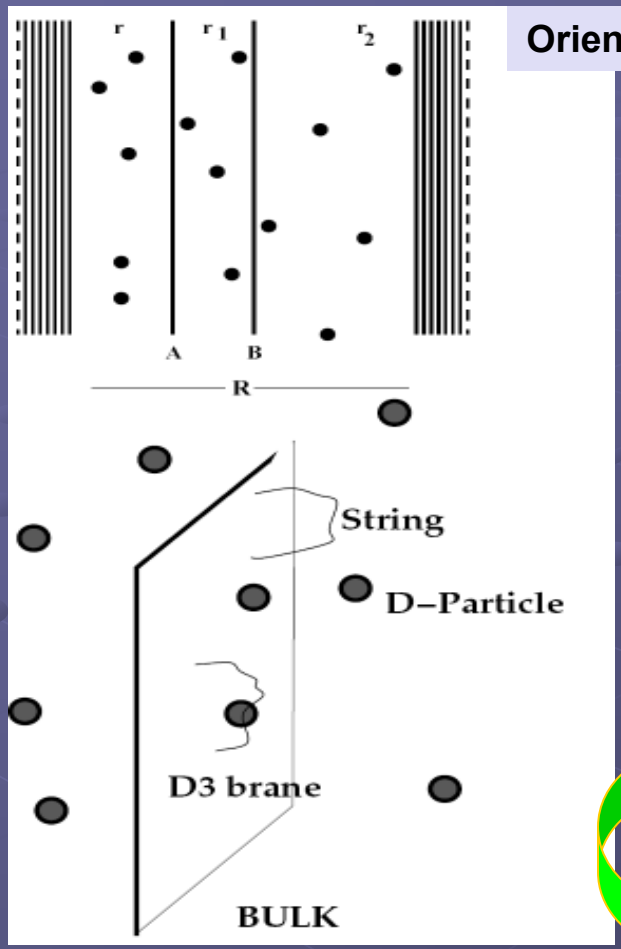

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TYPE IIA string models: D-foam transparent to charged probes

TYPE IIB string models electrically charged probes have suppressed foam effects compared to neutral probes by several orders of magnitude

OTHER PARTICLES

$j_1 \neq j_2$

Backward scattering u=0 implies

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

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

T.Li, NM, Nanopoulos, D. Xie

At order η, there are time delays…

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

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

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

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

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

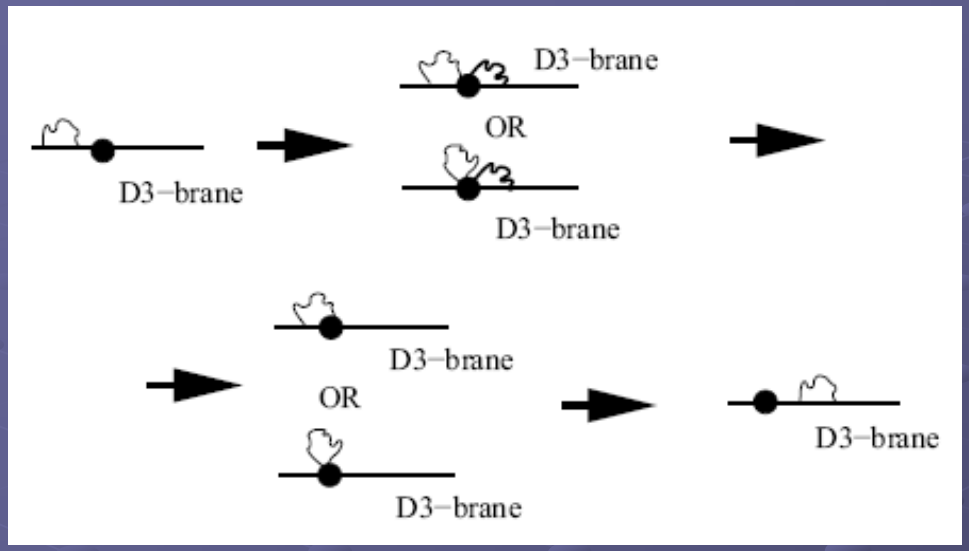
where j_i and I_i with $i = 1,\ 2,\ 3,\ 4$ are indices on the D7-branes and D3-branes, repsectively. And η is

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

Suppressed compared to Photons or neutral particles

Stringy Uncertainties & the Capture Process

Ellis, NM, Nanopoulos arXiv:0804.3566



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

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

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

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

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

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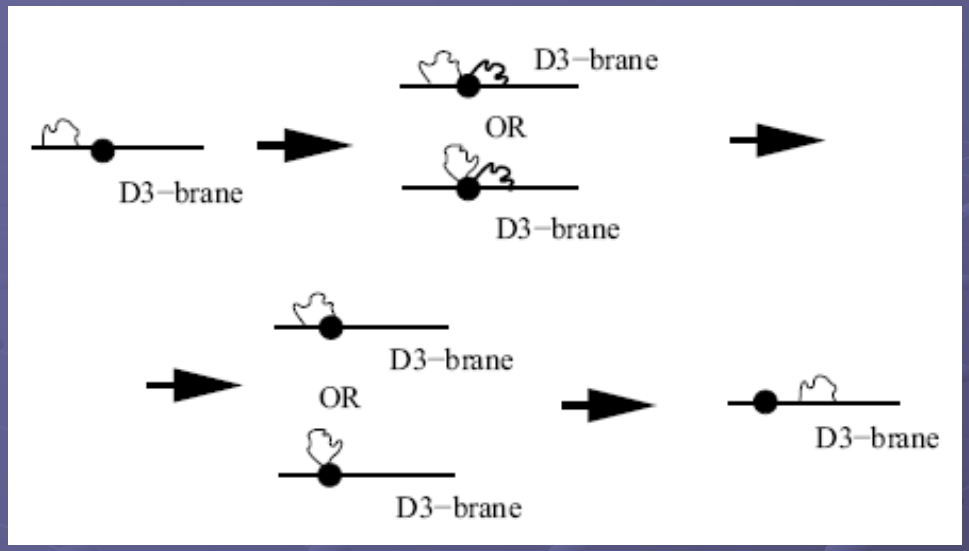

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Stringy Uncertainties & the MAGIC Effect

- 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:

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

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

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

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- 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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- Time Delay (Causal) in effective [illegible] $\sim \alpha' p^0$

- Independent of photon [illegible] (non-) [illegible]ingence)
- **Total Delay** from em[illegible] of [illegible]
  till observation over a [illegible] D (assume [illegible] defects per string length)

Effective QG Scale Dependending on density of D(efect)-foam

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Red-Shift Dependent QG Scale

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

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

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n* (z) = effective density of defects Interacting with propagating photon

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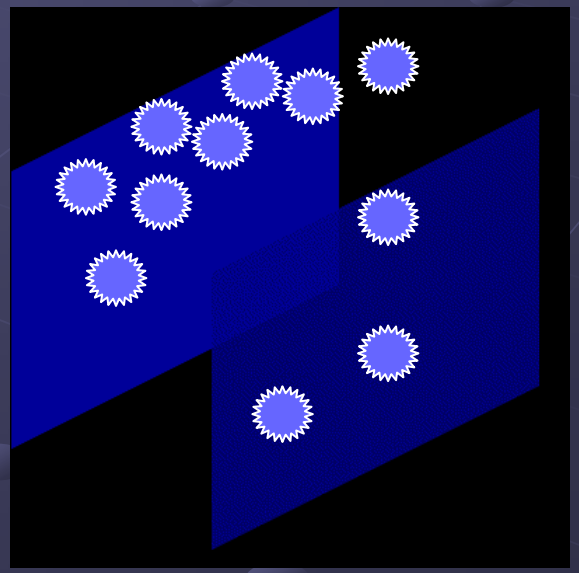

n* (z) can increase with z
If brane moves in inhomogeneous bulk

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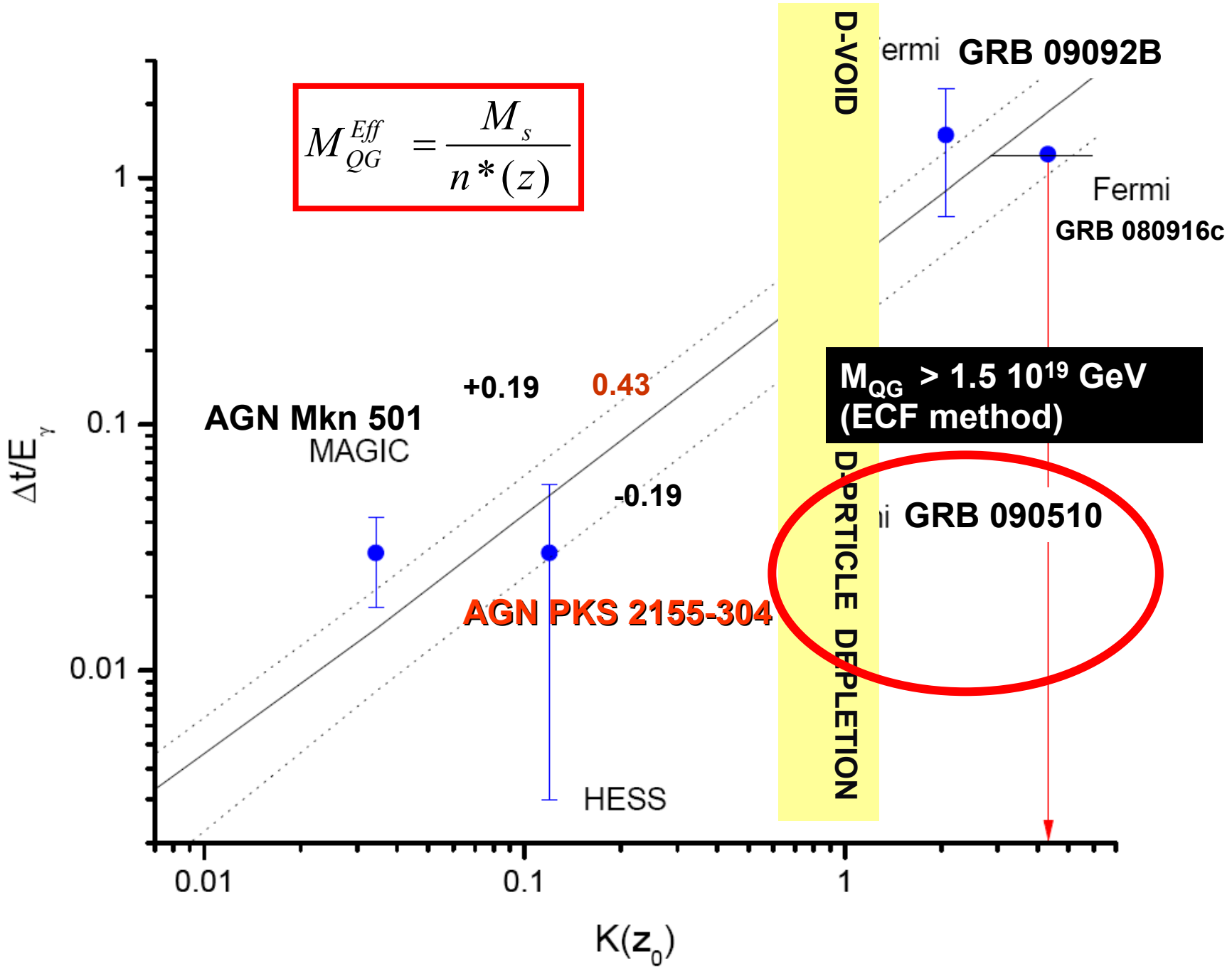
n* (z) can increase with z
If brane moves in inhomogeneous bulk

Account for MAGIC (& HESS) events for low z and ALSO for GRB 090510 (short burst) at high z =1
Higher z GRBs delays partly due to D-foam, partly due to Sourcce Delayed Emission
D-void around z=1 ?
Accounts for Deceleration/ Acceleration transition in Brane Universe


$M_{QG}^{Eff} = \frac{M_s}{n^*(z)}$
D-VOID
ermi GRB 09092B
Fermi
GRB 080916c
M_{QG} > 1.5 10^{19} GeV
(ECF method)
ni GRB 090510
D-PARTICLE DEPLETION
+0.19
0.43
-0.19
AGN Mkn 501
MAGIC
AGN PKS 2155-304
HESS
1
0.1
0.01
$\Delta t/E_\gamma$
0.01
0.1
1
$K(z_0)$

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Beyon Local Effective Field Theories though...

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WHY BEYOND LOCAL EFT?

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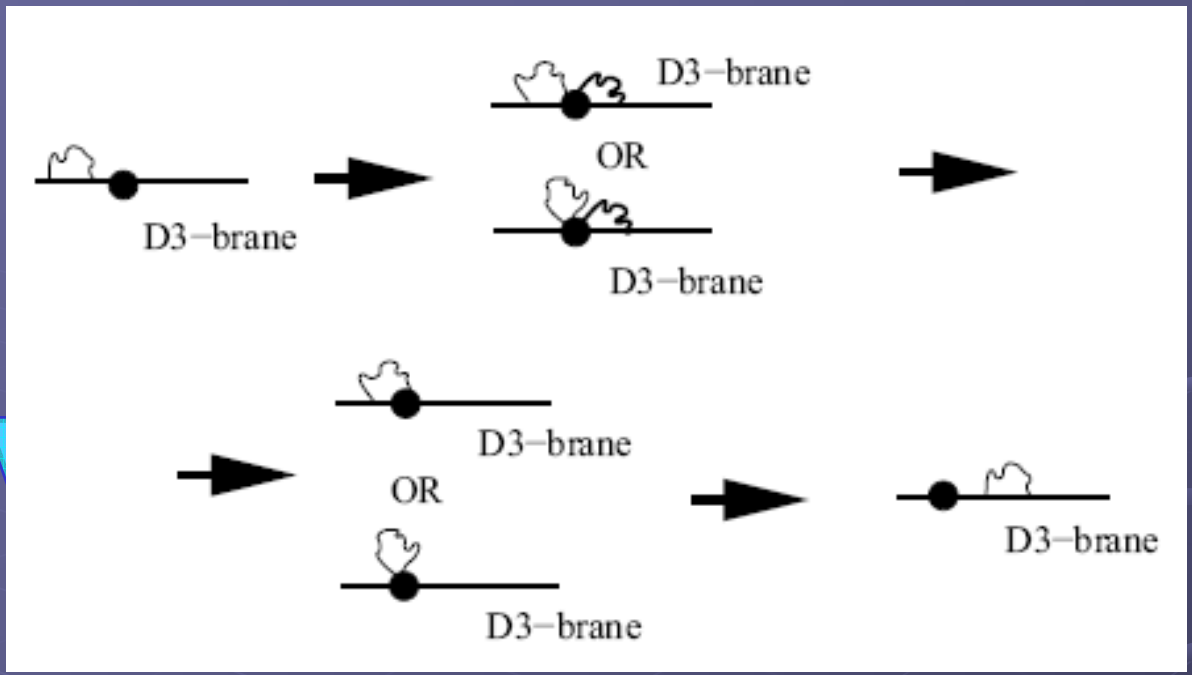


Recoil of the D-particle Defects during scattering
Distortion of the neighbouring space-time, with a Metric (Finsler type) which depends on both position and momentum transfer of incident string…

$$k^\mu k^\nu G_{\mu\nu}(\Delta k, \vec{X}, t) = -m^2$$

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

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

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

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 !

Ultra-High-Energy Cosmic Rays…

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

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

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

NEW TYPE OF ``GZK'' CUTOFF, From Lorentz Invariance of underlying string theory: recoil velocity must be

$$u/c = \Delta p / M_{QG} < 1$$

$$(M_{QG} = M_s/g_s)$$

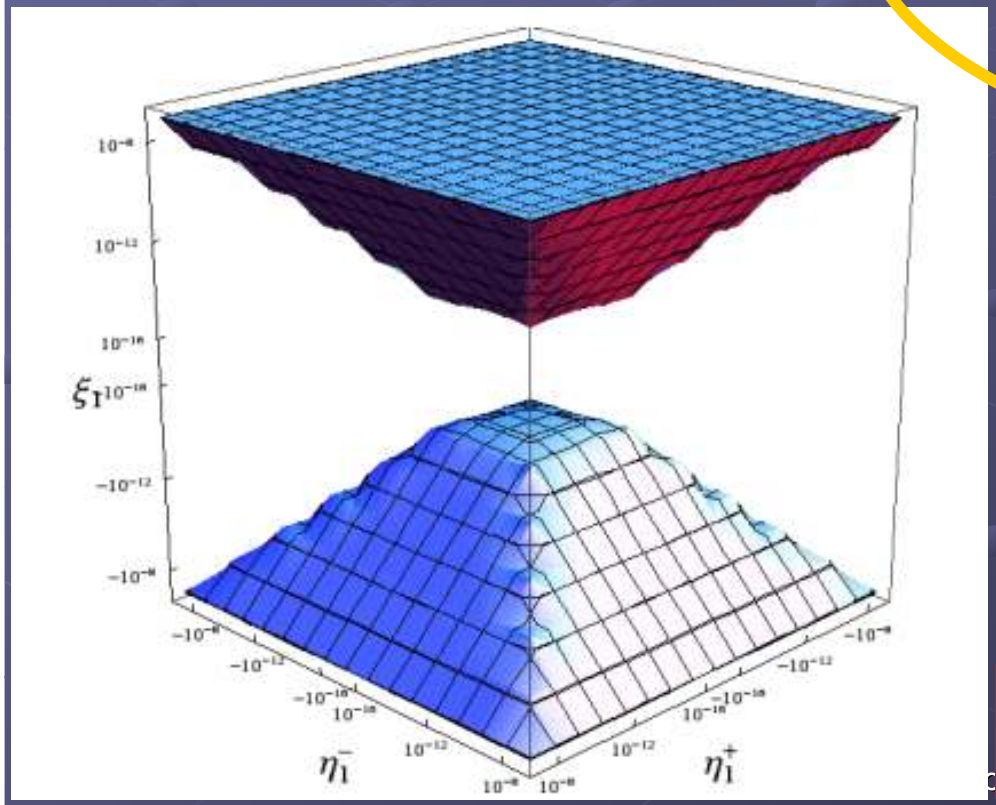
M_s/g_s free parameter in string theory…

Avoid constraints on UHECR altogether?

Ultra-high-energy photons

Galaverni & Sigl
+ Liberati. Maccione

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



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

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

(ii) Photon Decay

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

Allowed, above threshold if MDR

NB: MDR are quadratically suppressed by the QG scale

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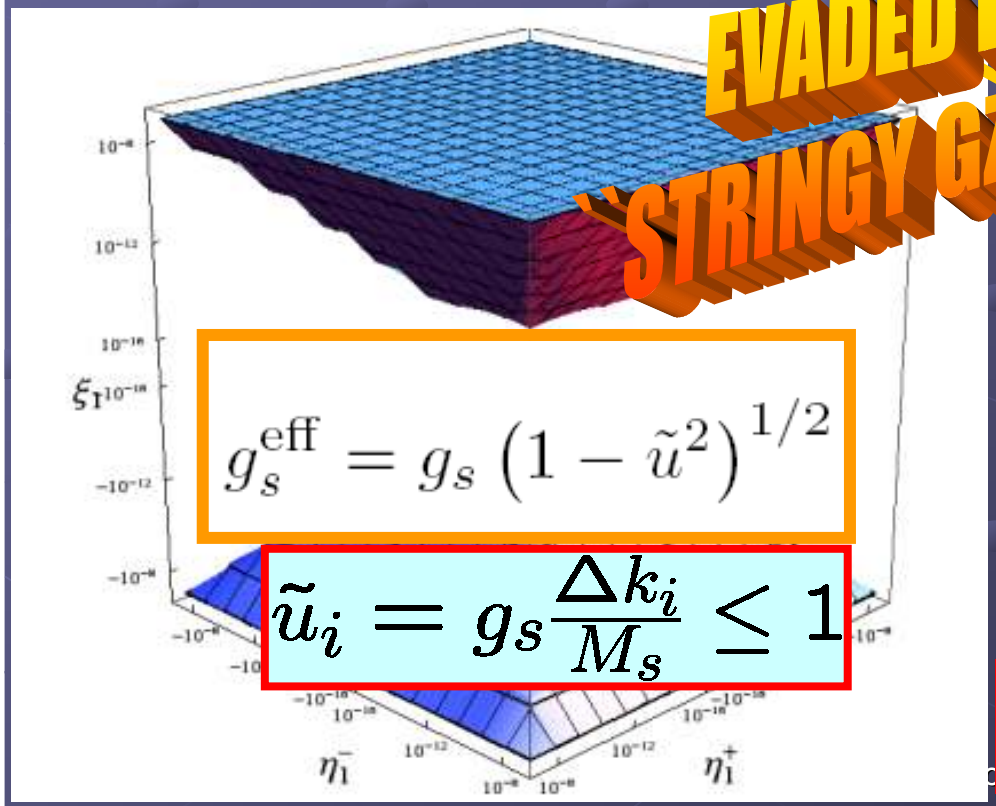
EVADED DUE TO "STRINGY GZK CUTOFF"

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



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

$$\tilde{u}_i = g_s \frac{\Delta k_i}{M_s} \leq 1$$

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D-FOAM & THE UNIVERSE DARK SECTOR

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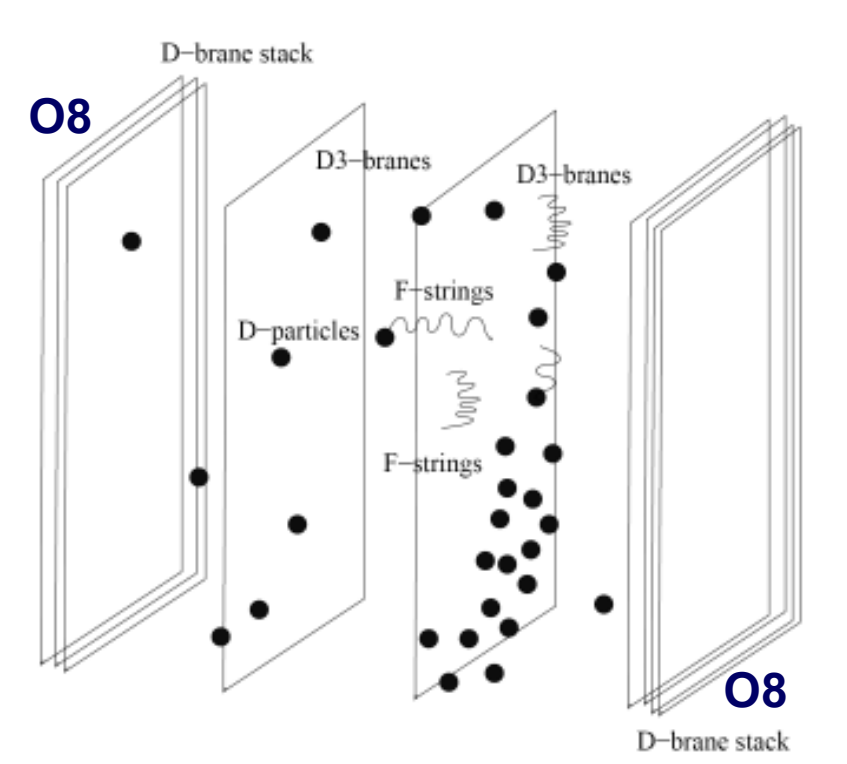
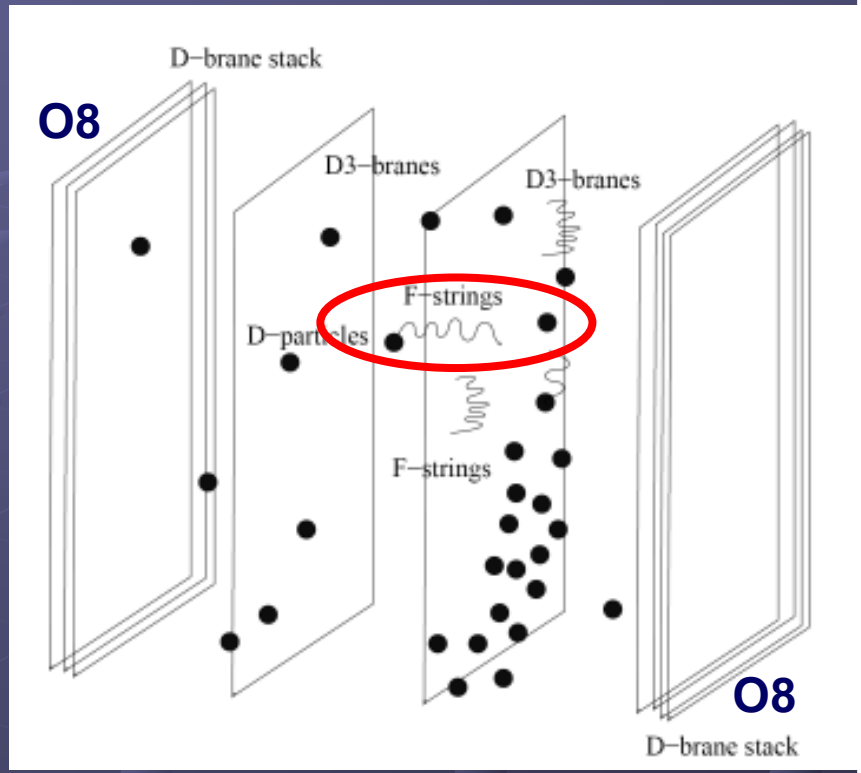


Ellis, NM, Westmuckett

Uses 8-Brane stacks to account For appropriate supersymemtries if no motion + Orientifold 8-Planes to compactify bulk 9th space dim.

D-FOAM & THE DARK SECTOR

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



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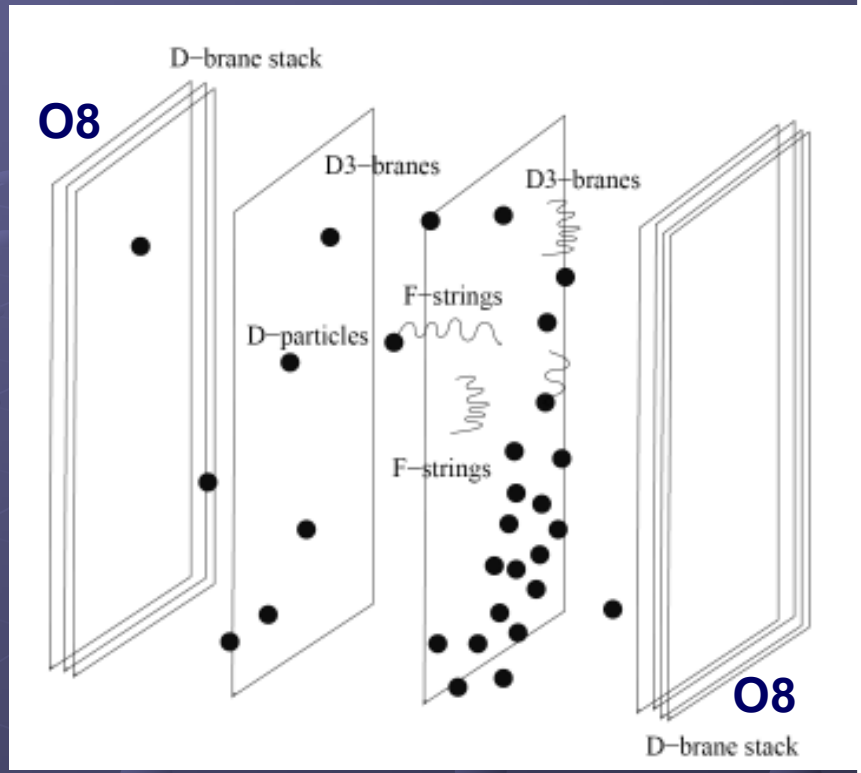
Contributions to Brane potentials (additional contrib. to Dark Energy)



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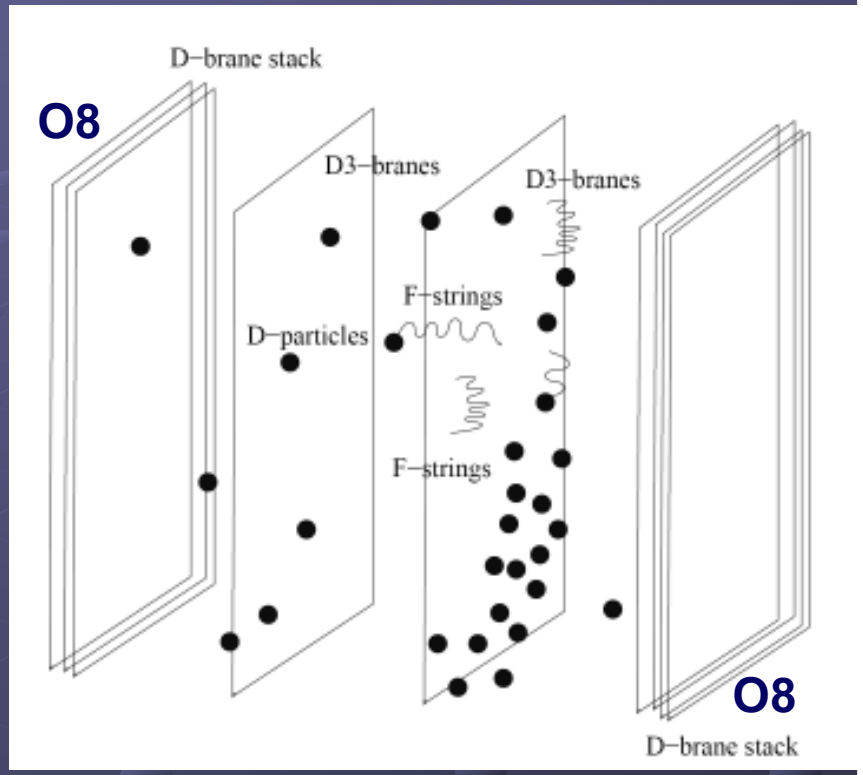
Velocity-independent terms cancelled by Orientifold O8 contributions



$$\mathcal{V}^{short}_{D0-D8} = -\frac{r}{4\pi\alpha'} - \frac{\pi\alpha'}{12}\frac{v^2}{r^3}$$

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

$$\mathcal{V}^{long}_{D0-D8} = -\frac{r}{4\pi\alpha'} + \frac{r\,v^2}{8\,\pi\,\alpha'}$$

$$r \gg \sqrt{\alpha'}\,, \quad v \ll 1$$

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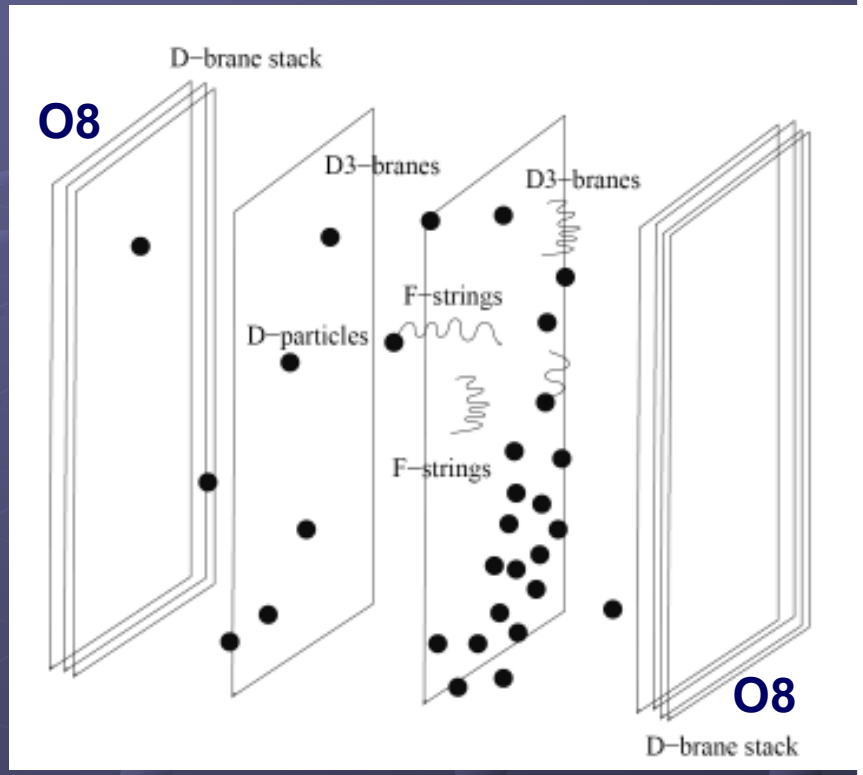

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$$r \gg \sqrt{\alpha'}\,, \quad v \ll 1$$

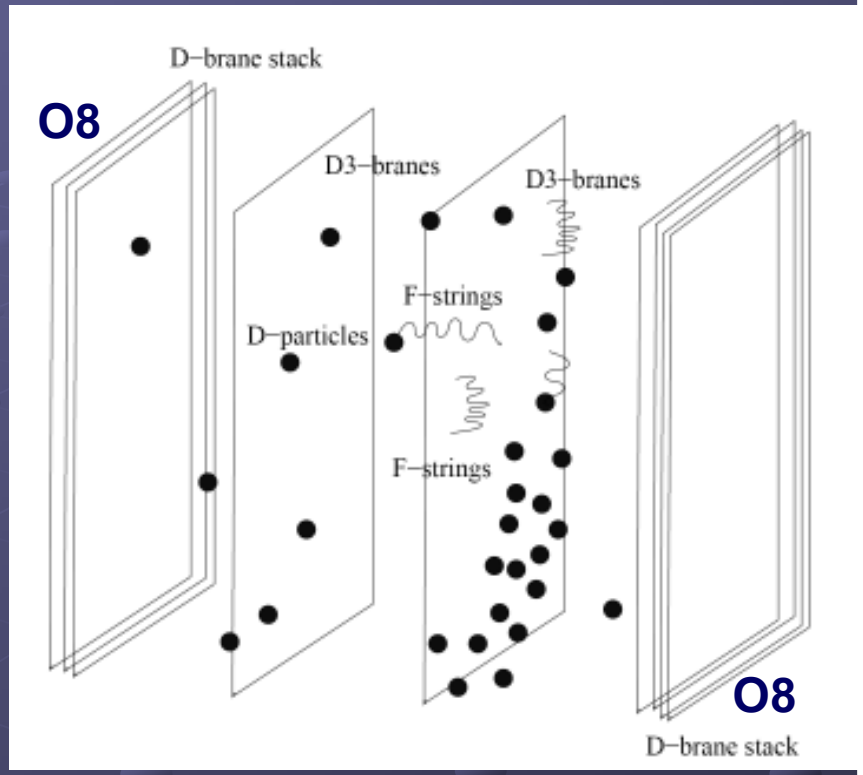
D-FOAM & THE DARK SECTOR

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)

Velocity-independent terms cancelled by Orientifold O8 contributions

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



$$\mathcal{V}^{short}_{D0-D8} = -\frac{r}{4\pi\alpha'} - \frac{\pi\alpha'}{12}\frac{v^2}{r^3}$$

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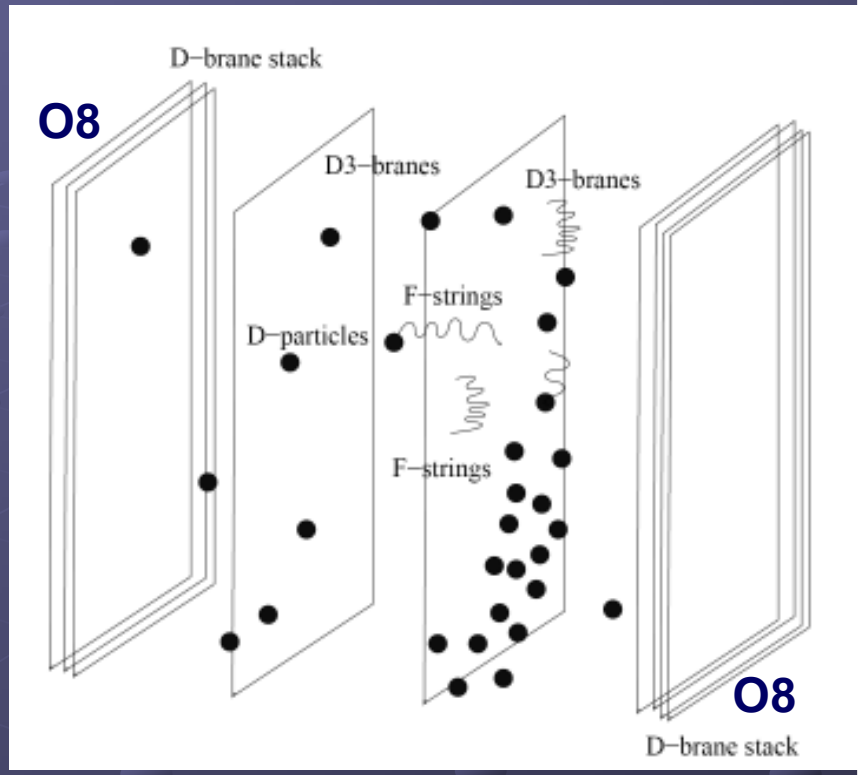

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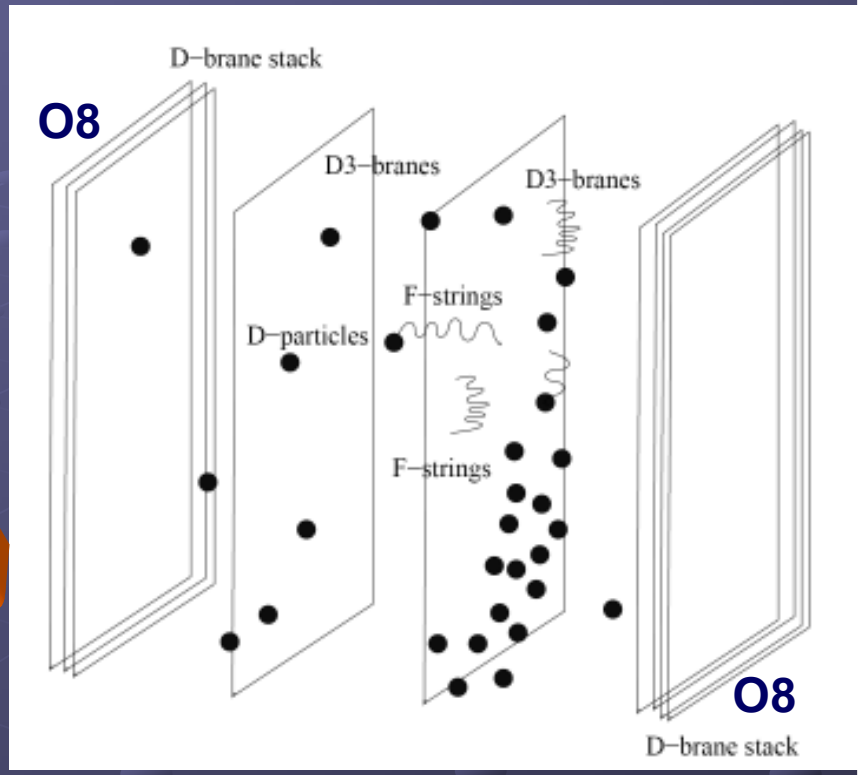
Interaction of D-particles with Brane Worlds via stretched Strings due to relative motion perpendicularly to branes only

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

Velocity-independent terms cancelled by Orientifold O8 contributions

Statistically

Sign of velocity-depend potential depends on D- /D-brane distance. May cancel out over long periods



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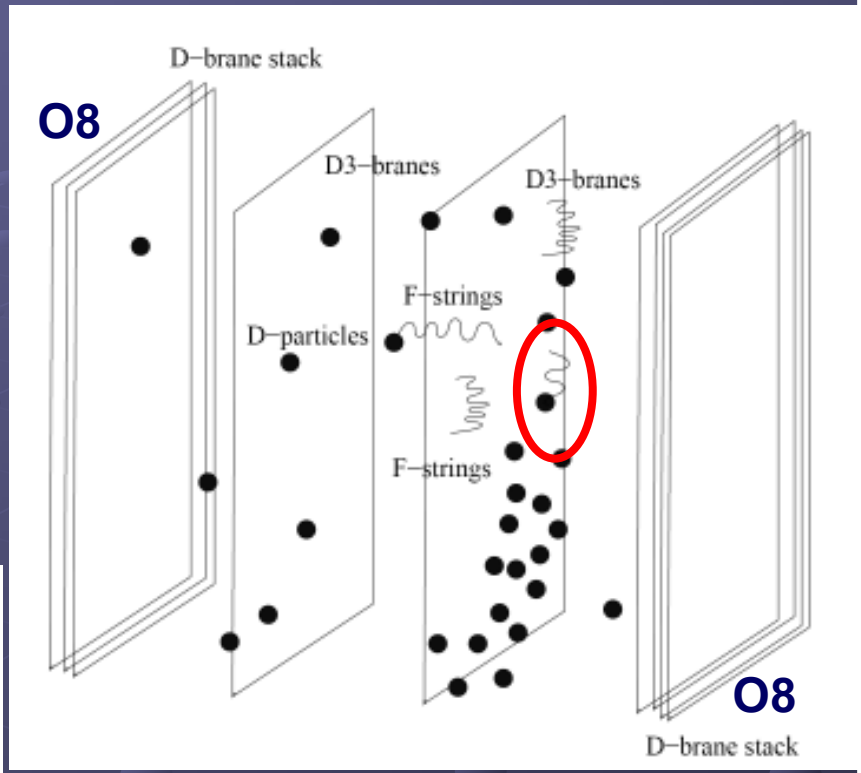
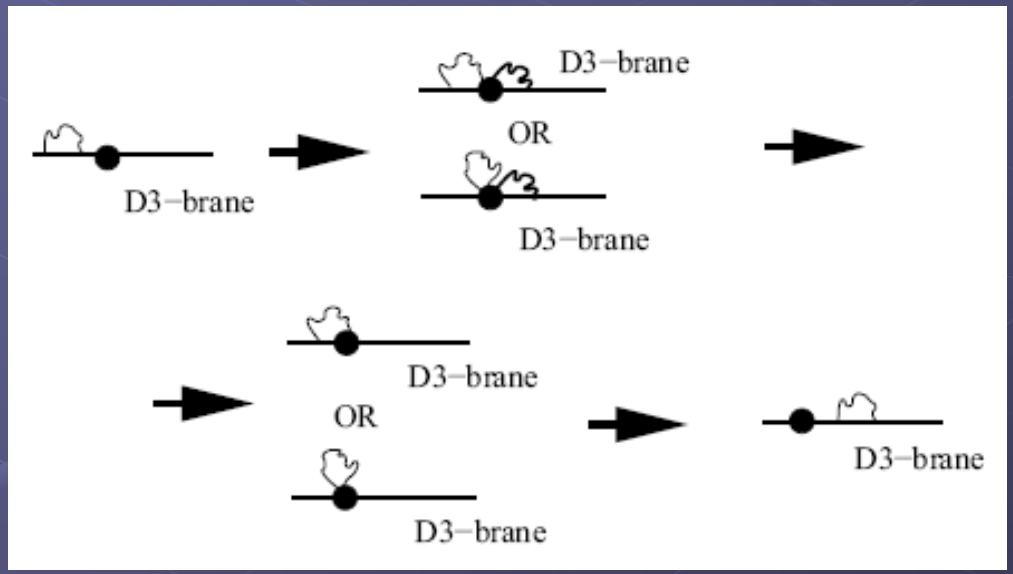
D-FOAM EFFECTS ON DARK MATTER (THERMAL) RELICS

D-FOAM & THE DARK SECTOR

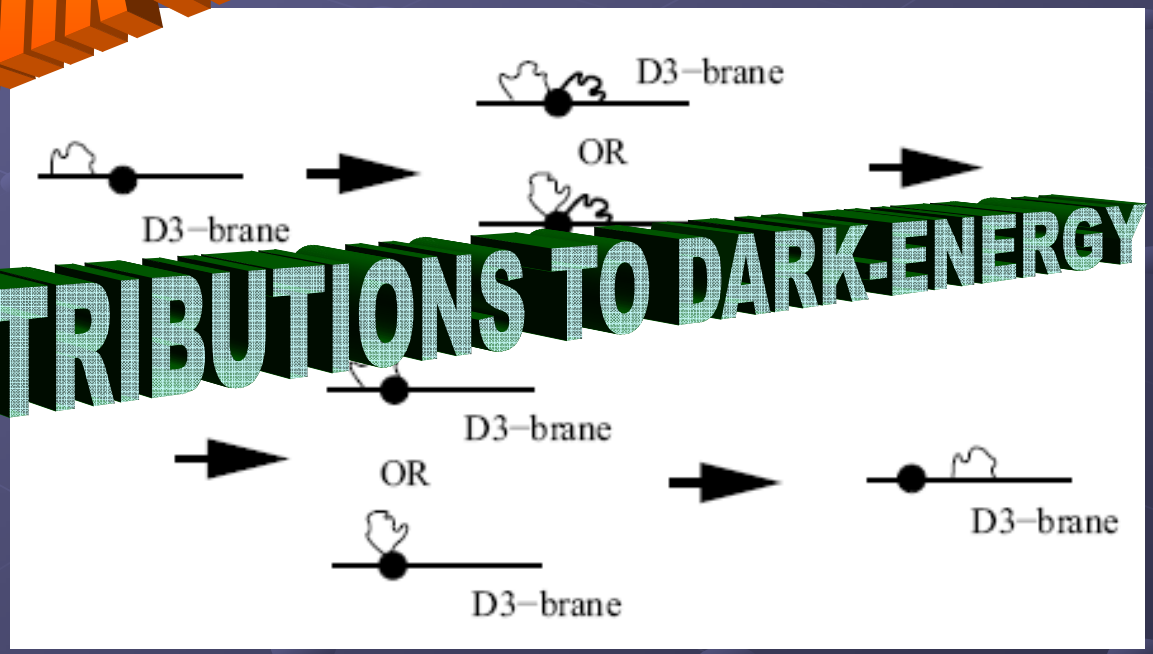
Interaction of D-particles with Open strings attached to the Brane world (Standard Model Excitations)





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

Ellis, NEM, Nanopoulos

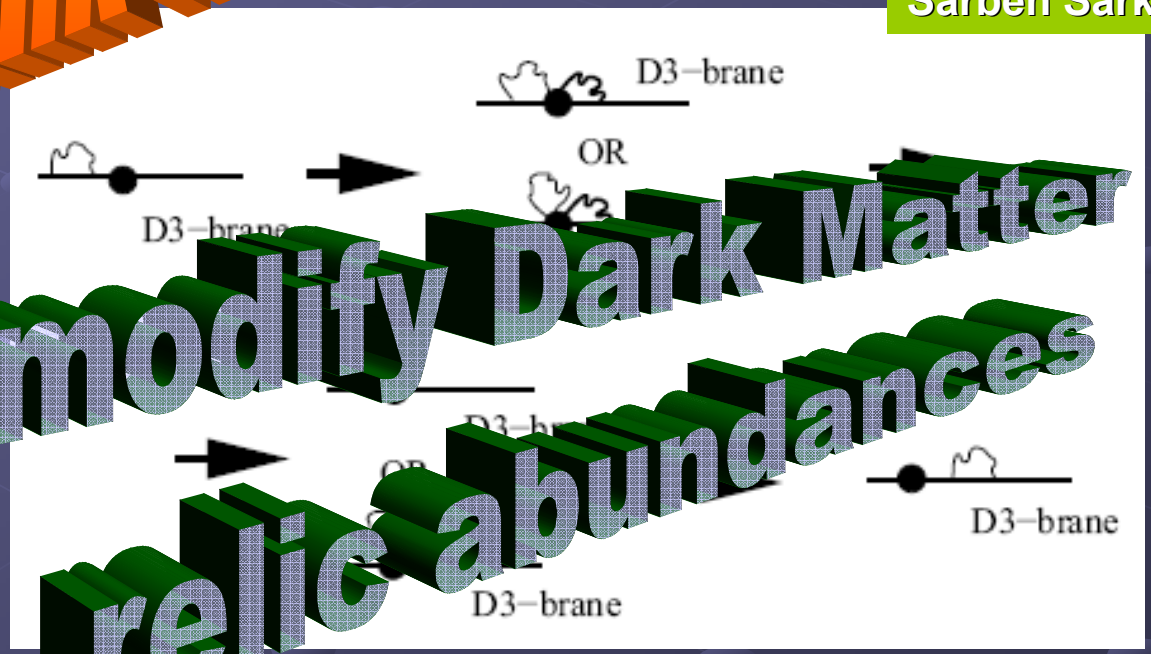


CONTRIBUTIONS TO DARK-ENERGY

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



modify Dark Matter relic abundances

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

Sarben Sarkar, NEM, Vergou

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

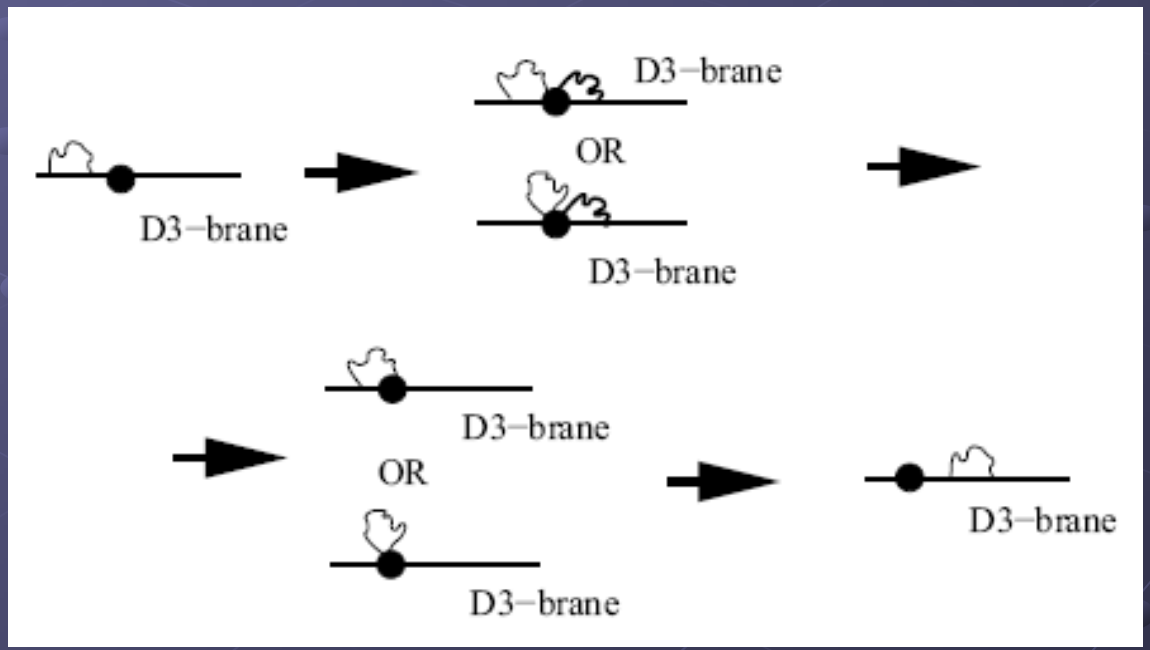
$$v_i = g_s \frac{\Delta p_i}{M_s} \equiv r_i p_i$$

D-particle recoil velocity

Stochastic foam fluctuations

$$\ll r_i \gg = 0 \ , \qquad \ll r_i r_j \gg = \sigma_i^2 \delta_{ij}$$

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



BOLTZMAN EQ. MODIFICATION

$$f(x^\mu, \overline{p}^\mu, ; t)$$

$$\overline{p}^i \equiv a(t) p^i \ , \qquad i = 1, 2, 3$$

$$\widehat{L}[f] = C[f]$$

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

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

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GEODESIC EQUATION (DEFINING THE FORCE) IS MODIFIED AS WELL

$$\frac{\hat{L}[f]}{\overline{p}^0} = \frac{\partial f}{\partial t} - H \sum_i \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} - 2Ha^2(t)\overline{p}^0 \sum_i r_i \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} + 8Ha^4(t) \sum_i r_i^2 \left(\overline{p}^i\right)^3 \frac{\partial f}{\partial \overline{p}^i}$$

$$+ \frac{2}{\overline{p}^0} H a^2(t) \sum_j \left(\overline{p}^j\right)^2 \sum_i r_i \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} + 4Ha^4(t) \left(\overline{p}^0\right)^2 \sum_i r_i^2 \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} - 4a^4(t) H \sum_j \left(\overline{p}^j\right)^2 \sum_i r_i^2 \overline{p}^i \frac{\partial f}{\partial \overline{p}^i}$$

BOLTZMAN EQ. MODIFICATION

$$\frac{\hat{L}[f]}{\overline{p}^0} = \frac{\partial f}{\partial t} - H\sum_i \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} - 2Ha^2(t)\overline{p}^0 \sum_i r_i \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} + 8Ha^4(t)\sum_i r_i^2 \left(\overline{p}^i\right)^3 \frac{\partial f}{\partial \overline{p}^i}$$

$$+\frac{2}{\overline{p}^0} Ha^2(t)\sum_j \left(\overline{p}^j\right)^2 \sum_i r_i \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} + 4Ha^4(t)\left(\overline{p}^0\right)^2 \sum_i r_i^2 \overline{p}^i \frac{\partial f}{\partial \overline{p}^i} - 4a^4(t)H\sum_j \left(\overline{p}^j\right)^2 \sum_i r_i^2 \overline{p}^i \frac{\partial f}{\partial \overline{p}^i}$$

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

$$n(t) \equiv \frac{g}{(2\pi)^3}\int d^3\overline{p}\, f\left(t, \overline{p}^i\right)$$

Number density of particles

$$\frac{g}{(2\pi)^3}\int d^3\overline{p}\, \left(\overline{p}^i\right)^2 f \equiv Tmn$$

Average tempterature

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

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

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

Number density of DM particles

Thermal equilibrium density

Heavy DM m >> T

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

Also modified by the Foam

Due to modified dispersion Relations

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Also modified by the Foam

Due to modified dispersion Relations

Source terms in Boltzmann, related to particle production features of D-foam

D-FOAM MODIFIED DISPERSION

$$\overline{p}^0 = a^2(t)\sum_i \left(\overline{p}^i\right)^2 r_i + \sqrt{\sum_i \left(\overline{p}^i\right)^2 + m^2}\left[1 + \frac{a^4(t)\left(\sum_i \left(\overline{p}^i\right)^2 r_i\right)^2}{\sum_i \left(\overline{p}^i\right)^2 + m^2}\right]^{\frac{1}{2}}$$

$$\ll r_i \gg = 0 \ , \qquad \ll r_i r_j \gg = \sigma_i^2 \delta_{ij}$$

Quadratically suppressed by QG scale after stochastic averaging

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

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

Due to modified dispersion Relations

$$\mathbf{n}_{\overline{\mathbf{eq}}} = g\left(\frac{m}{2\pi\beta}\right)^{\frac{3}{2}} e^{-(m-\mu)\beta} \times$$

$$\left[1 + \frac{\sqrt{2}}{5\pi^{3/2}}\left(m^2\,(2\pi)^{3/2}\right)\bar{\sigma}_0^2\left(\frac{15}{2} - \frac{45}{16\sqrt{2}}\xi e^{-(m-\mu)\beta} + \frac{15}{27\sqrt{3}}\xi^2 e^{-2(m-\mu)\beta}\right)\right.$$

$$\left. - \frac{1}{12\pi^{3/2}}\left(\beta^{-2} + m^2\right)\bar{\sigma}_0^2\,(2\pi)^{3/2}\left(3 - \frac{3}{4\sqrt{2}}\xi e^{-(m-\mu)\beta}\right)\right]$$

$$= n_{st} \times \left[1 + \frac{\sqrt{2}}{5\pi^{3/2}}\left(m^2\,(2\pi)^{3/2}\right)\bar{\sigma}_0^2\left(\frac{15}{2} - \frac{45}{16\sqrt{2}}\xi e^{-(m-\mu)\beta} + \frac{15}{27\sqrt{3}}\xi^2 e^{-2(m-\mu)\beta}\right)\right.$$

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$$\sigma_0^2 = \sigma_1^2 + \sigma_2^2 + \sigma_3^2$$

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

$$\frac{\Omega'_\chi h_0^2}{(\Omega_\chi h_0^2)_{\text{no source}}} = \left(1 + \int_{x_f}^{x_0} \frac{\Gamma(x)}{Hx} dx - \frac{1}{J} \int_{x_f}^{x_0} J(s) \left(\int_{x_f}^{s} \frac{\Gamma(x)}{Hx} dx \right) ds \right) * \left(\frac{g'_{eff,f}}{g_{eff,f}} \right)^{\frac{1}{2}}$$

$$J \equiv \int_{x_0}^{x_f} \langle \upsilon \tilde{\sigma} \rangle' \, dx, \; J(x) \equiv \frac{\langle \upsilon \tilde{\sigma} \rangle'}{x^2}$$

$x_f = m/T_f$, 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'_{eff} due to modified equilibrium distributions

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

$$\overline{p}^i \equiv a(t)p^i$$

$$\ll n\omega_r \gg \equiv \prod_j \frac{1}{\sigma_j\sqrt{2\pi}} \int_{-\infty}^{\infty} dr_j < n\omega >_r \exp(-\frac{r_j^2}{2\sigma_j^2}) \ , \qquad < n\omega >_r = \frac{\omega_r}{\exp(\beta(\omega_r - \mu)) + \xi}$$

Bosons

$$\xi = +1\,(-1)$$

fermions

ω_r = energy in the presence of foam

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

$$g_{eff} = \sum_i g_{i,b} \left(\frac{T_{i,b}}{T}\right)^4 + \frac{7}{8} \sum_j g_{j,f} \left(\frac{T_{j,f}}{T}\right)^4$$

Modification in effective d.o.f. g'_{eff} due to modified equilibrium distributions

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

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

$x_f = T_f / m$, freezeout, typically $x_f \approx 0.05$
$x_0 = T_0/m$, T_0 = today (CMB, 2.7 K)

$\Delta^2 = g_s^2\, \sigma^2/M_s^2$

Modification in effective d.o.f. g'_{eff} due to modified equilibrium distributions

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

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$x_f = T_f / m$, freezeout, typically $x_f \approx 0.05$
$x_0 = T_0/m$, T_0 = today (CMB, 2.7 K)

$\Delta^2 = g_s$ [illegible] $^2/M_s^2$

Significant (~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

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

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

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

$x_0 = T_0/m$, T

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

Less Room for SUSY

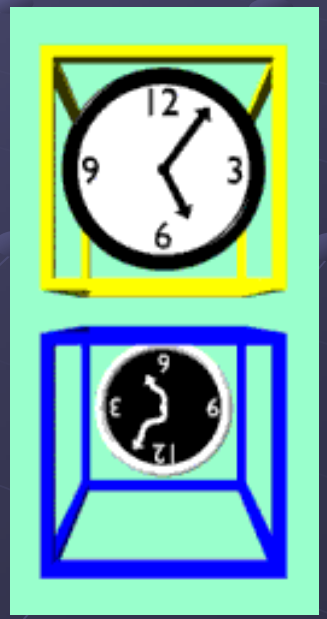
Significant (~10^{-3}) for TeV scale M_s and m, can be constrained from WMAP data…
If DM is neutralino in SUSY models can be constrained by collider tests (LHC…)

OTHER EFFECTS OF D-FOAM

Other Effects of Foam

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

CPT may be Violated in D-particle Foam models but only through Target-space effective (low-energy) Decoherence, induced by 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 ?

SPARES

D-particle Recoil Formalism

σ-Model 1st Quantized Formalism

Recoil Velocity u_i as Constant Electric Field Background

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

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

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

D-particle Recoil Formalism

σ-Model 1st Quantized Formalism

Recoil Velocity u_i as Constant Electric Field Background

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

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

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

NEM, arXive:0906.2712

Mixed world-sheet Boundary Conditions

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

Seiberg-Witten
Seiberg, Susskind, Toumbas

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

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

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

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

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

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

Induced (Finsler) Space-Time Metric

World-Sheet Propagator in the presence of recoil background

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

Implies Finsler-type target-space metric

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

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

and effective string coupling

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

Induced (Finsler) Space-Time Metric

World-Sheet Propagator in the presence of recoil background

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

Induced (Finsler) Space-Time Metric

World-Sheet Propagator in the presence of recoil background

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

Implies Finsler-type target-

Depends on Momentum Tranfer due to momentum Conservation in D-particle Recoil $u_i = g_s \Delta k_i / M_s$

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

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

and effective string coupling

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

Induced (Finsler) Space-Time Metric

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

Implies Finsler-type target-space metric $u_i = g_s \frac{(\Delta \vec{k})_i}{M_s}$

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

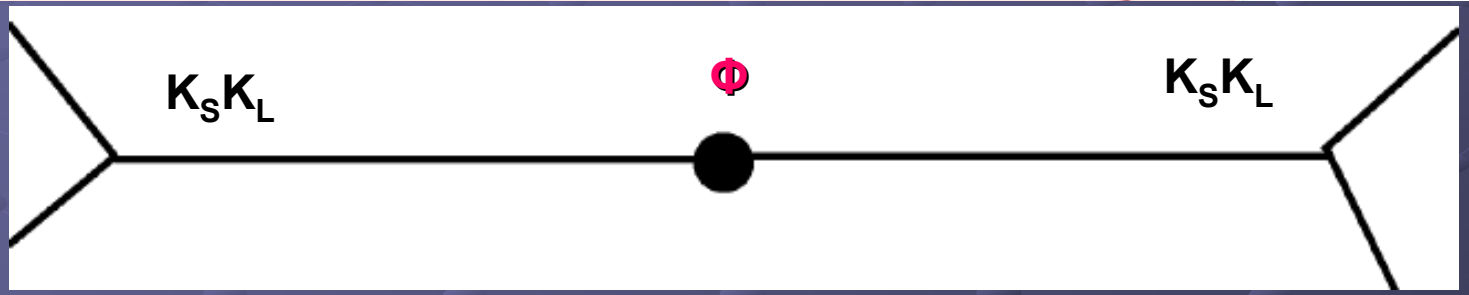
$$g^{\text{open,electric}}_{\mu\nu} = \eta_{\mu\nu} \ , \mu, \nu = \text{all other values} \ ,$$

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.

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

Consequences for Neutral mesons EPR – correlators

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

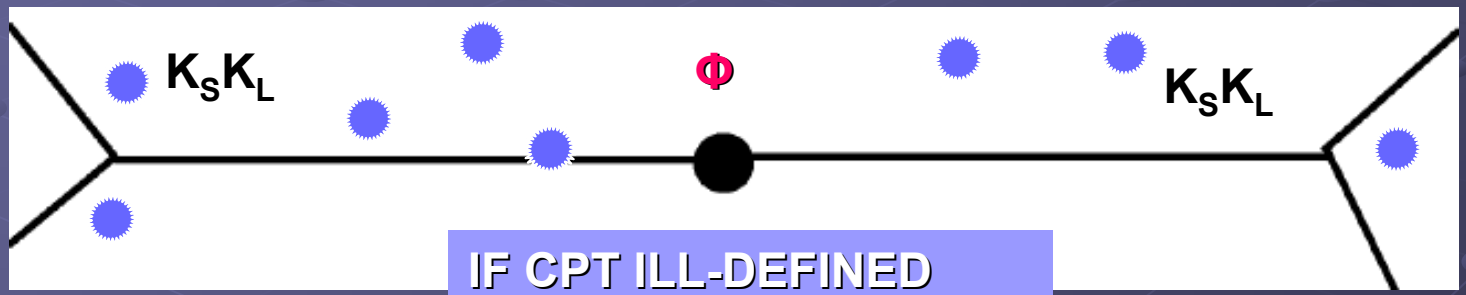


IF CPT Θ-operator WELL-DEFINED

Even if [Θ , H] ≠ 0

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

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

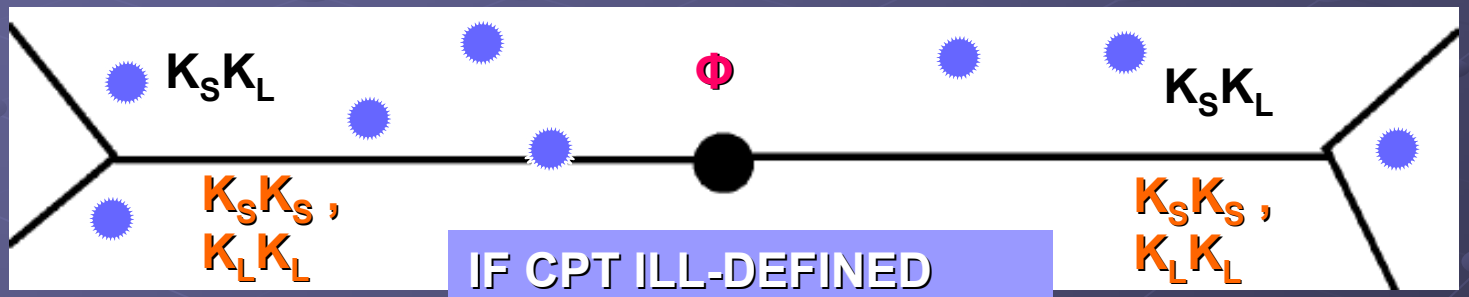


IF CPT ILL-DEFINED
(e.g. Stringy Foam)

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

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

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

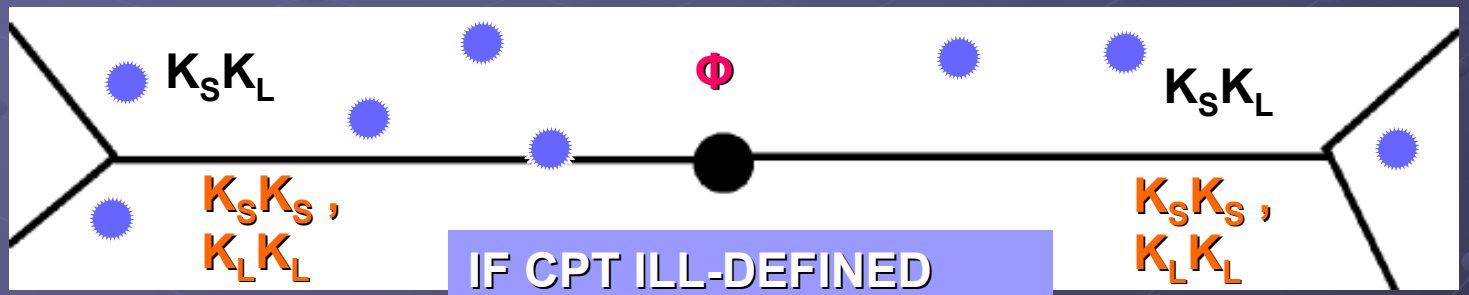


IF CPT ILL-DEFINED
(e.g. Stringy Foam)

- If foam, concept of anti-particle may be perturbatively modified, Neutral mesons no longer indistinguishable particles, initial entangled state:

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

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



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

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

If QCD effects, sub-structure in neutral mesons ignored, and D-foam acts as if they were structureless particles, then for $M_{QG} \sim 10^{18}$ GeV (MAGIC) the estimate for ω: $|\omega| \sim 10^{-4}\ |\zeta|$, for $1 > |\zeta| > 10^{-2}$ (natural)
Not far from sensitivity of upgraded meson factories (e.g. DAFNE2)