Search for Quantum Gravity

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PERSPECTIVES OF FUNDAMENTAL COSMOLOGY

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NORDITA

Vetenskapsrådet

OUTLINE

LECTURE I

(i) Fundamental Symmetries & Quantum Gravity:
Models & Local Effective field theory bounds

(ii) Microscopic Stringy Models of space-time foam with stochastically fluctuating D-brane defects (D(efect)-foam).

Phenomenological Predictions beyond Local Effective Field Theories:
(a) Quantum (String) Gravity (time-space) Uncertainties:
induced vacuum refraction –Astrophysical tests (delayed photon arrivals)
(b) Light-Cone fluctuations
(c) Quantum Decoherence of matter in Low Energy Worlds:
Ill-defined CPT operator ``Smoking Gun Evidence '' in Entangled Particle States (EPR- modification)– ω-effect : TESTS at DAΦNE-2 , B-factories

LECTURE II

(d) D(efect)-foam Cosmology : CPT Violation in Early Universe & Baryon Asymmetry through Leptogenesis
(e) D(efect)foam Cosmology : Modified Gravity & Enhanced Galactic Growth

Quantum Gravity (QG) Models

- **String Theories** – most consistent theories of QG to date, incorporation of Standard Model Physics at low energies , but LANDSCAPE vacuum ambiguities;

  towards background independence via AdS/CFT

- **Loop Quantum Gravity** (Canonical or Covariant Quantization), attempts to incorporate consistently Standard Model matter, progress is being made - background independence claimed, progress in **Loop Quantum Cosmology**….

- More phenomenological Models, such as **Deformed Special Relativities**: built out of necessity of maintaining Planck length invariant under (modified) Lorentz boosts – *quantization consistency? Locality? …open issues*

  κ - **deformed Poincare** models

- **Non-Commutative Field Theories / Geometries: Standard Model Higgs Physics, links to Cosmology → interesting models, still not completely understood , background independence?**

Symmetries of QG

- ***General Coordinate Invariance*** (may be broken , c.f. Horava-Lifshitz theories, where time is treated differently from space)

- ***Local Lorentz Invariance*** may be **violated (LIV)** by quantum gravity space-time fluctuations (e.g. black holes or in some string theories space-time defects)

- ***CPT symmetry*** (i.e. invariance of relativistic field theory Lagrangians under Charge conjugation, Time reveral and Parity (reflexion) operations, may **no longer characterize** QG models (CPT theorem is valid for flat, Lorentz invariant theories)

- If QG plays a role in cosmology, such violations **may be testable** in the Early Universe (Universe Energy budget & Dark Matter Relic modifications) or in high-energy astrophysics or in some particle physics ``interferometers'' (such as meson factories)

PART I

PHENOMENOLOGICAL TESTS OF LIV & QG

For Phenomenology it is important to deal with Low-energy Effective *Local Field Theories (EFT)*

Kostelecky, Russell, Mewes, Lehnert…(00-11)

Standard Model Extension (SME)

Phenomenological Lagrangian of Lorentz Invariant Violating and/or CPT Terms (LIV) with ***dimensionful*** coefficients to be constrained by (a plethora Expts

$$\mathcal{L}_{\rm SME} = \overline{\psi}\left(i\gamma^\mu D_\mu - M - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu - \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^\mu D^\nu + id_{\mu\nu}\gamma_5\gamma^\mu D^\nu\right)\psi$$

+ photon sector + …

a, b : LIV & CPTV
H, c, d LIV

Cosmic sources masers : $b < 10^{-27}$ **GeV**

Dimensional analysis
$a, b \approx E^2/M_{QG}$

Atomic Physics precision spectroscopy, looking for ***forbidden*** atomic transitions in H, anti-H molecules ν1S-2S (and even comparison):
For ***CERN expts*** such sensitivity would require spectra line resolution at **1 mHZ**

Neutral Kaon factories (q=quark flavour) $\Delta a_\mu \equiv a_\mu^{q_2} - a_\mu^{q_1}$
KTEV Expt: $\Delta a_{\chi,\Upsilon} < 9.\ 10^{-22}$ **GeV , DAΦNE(2)** $\Delta a_0 < 10^{-18}$ **GeV**

LEADING ORDER BOUNDS

EXPER.	SECTOR	PARAMS. (J=X,Y)	BOUND (GeV)
Penning Trap	electron	$\bar{b}_J^e$	5×10^{-25}
Hg-Cs clock comparison	electron	$\bar{b}_J^e$	10^{-27}
	proton	$\bar{b}_J^p$	10^{-27}
	neutron	$\bar{b}_J^n$	10^{-30}
H Maser	electron	$\bar{b}_J^e$	10^{-27}
	proton	$\bar{b}_J^p$	10^{-27}
spin polarized matter	electron	$\bar{b}_J^e / \bar{b}_Z^e$	$10^{-29} / 10^{-28}$
He-Xe Maser	neutron	$\bar{b}_J^n$	10^{-31}
Muonium	muon	$\bar{b}_J^\mu$	2×10^{-23}
Muon g-2	muon	$\bar{b}_J^\mu$	5×10^{-25} (estimated)

X,Y.Z celestial equatorial coordinates $\bar{b}_J = b_3 - m d_{30} - H_{12}$

(Bluhm, hep-ph/0111323)

For Phenomenology it is important to deal with Low-energy Effective ***Local Field Theories (EFT)***

I will also point out some cases where the latter are ***not*** completely ***well-defined*** . Characteristic (``smoking-gun'') predictions on:

(i) time-space quantum uncertainties in stringy QG
Astrophysical tests: ***delayed arrivals*** of more energetic photons & ***stochastic light cone flcts***

(ii) ill-defined effective field theory ***CPT operator*** & EPR modifications : neutral meson interferometers

Generic predictions (EFT & beyond):

Modified Dispersion relations if QG behaves as a medium

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

Expectation : higher the energy of probe the larger the disturbance of space-time, the bigger the effect , $n > 0$

Vacuum Refraction induced

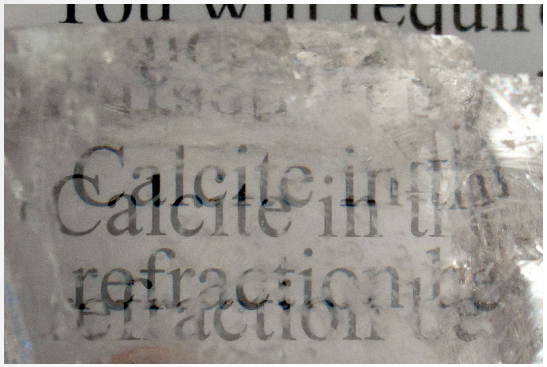
$$V_{\rm phase} = \frac{E}{|\vec{p}|} = \frac{1}{\eta}\ , \qquad V_{\rm group} = \frac{\partial E}{\partial |\vec{p}|}$$

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

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

Subluminal: More energetic components of a photon wavepacket will arrive later

STRONG CONSTRAINTS IF SUPERLUMINAL PROPAGATION



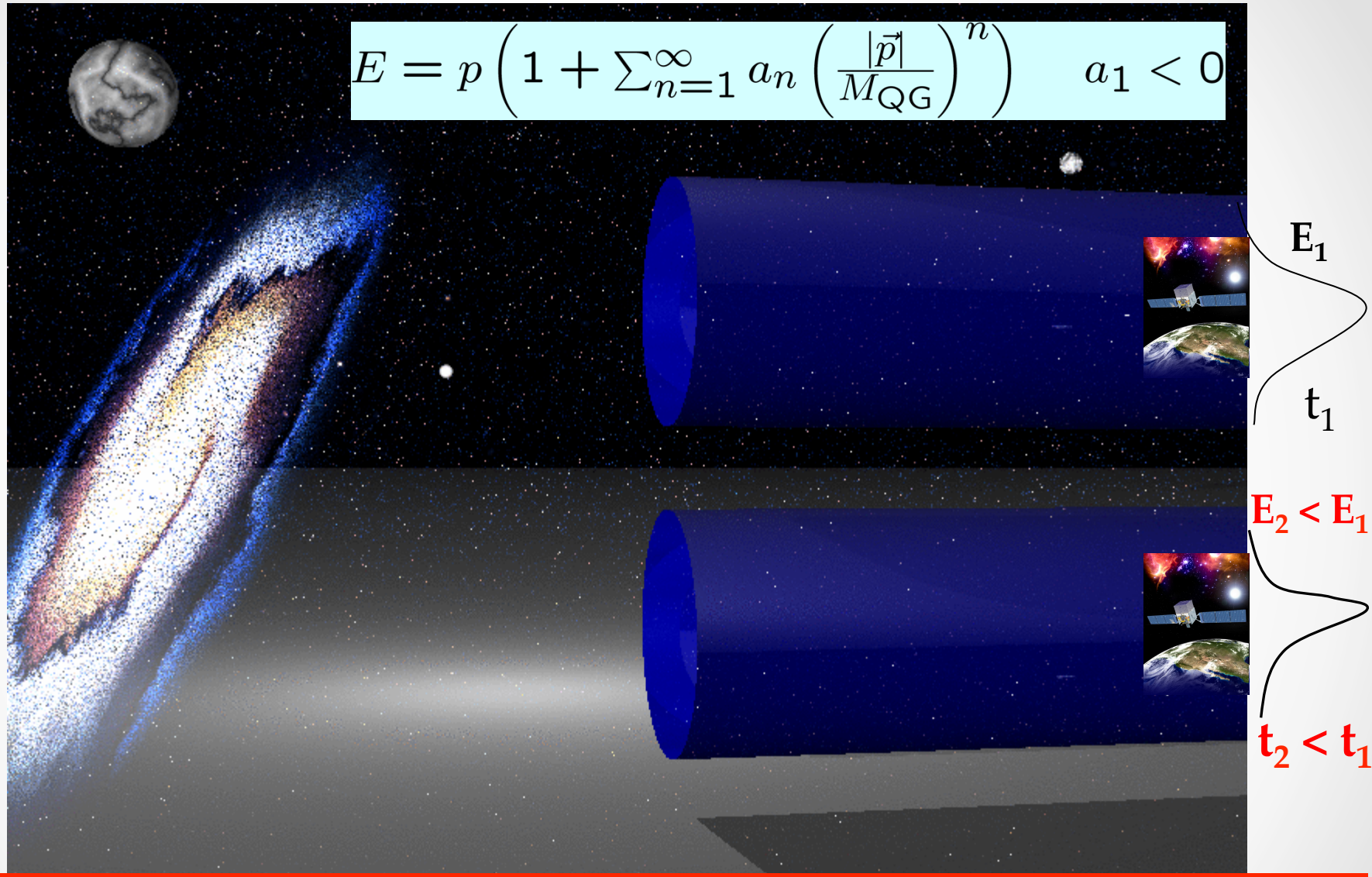
$$E = p\left[1 + \sum_{n=1}^{\infty} a_n \left(\frac{|\vec{p}|}{M_{\rm P}}\right)^n\right]$$

$M_{\rm P}$ = 1.2. 10^{19} GeV

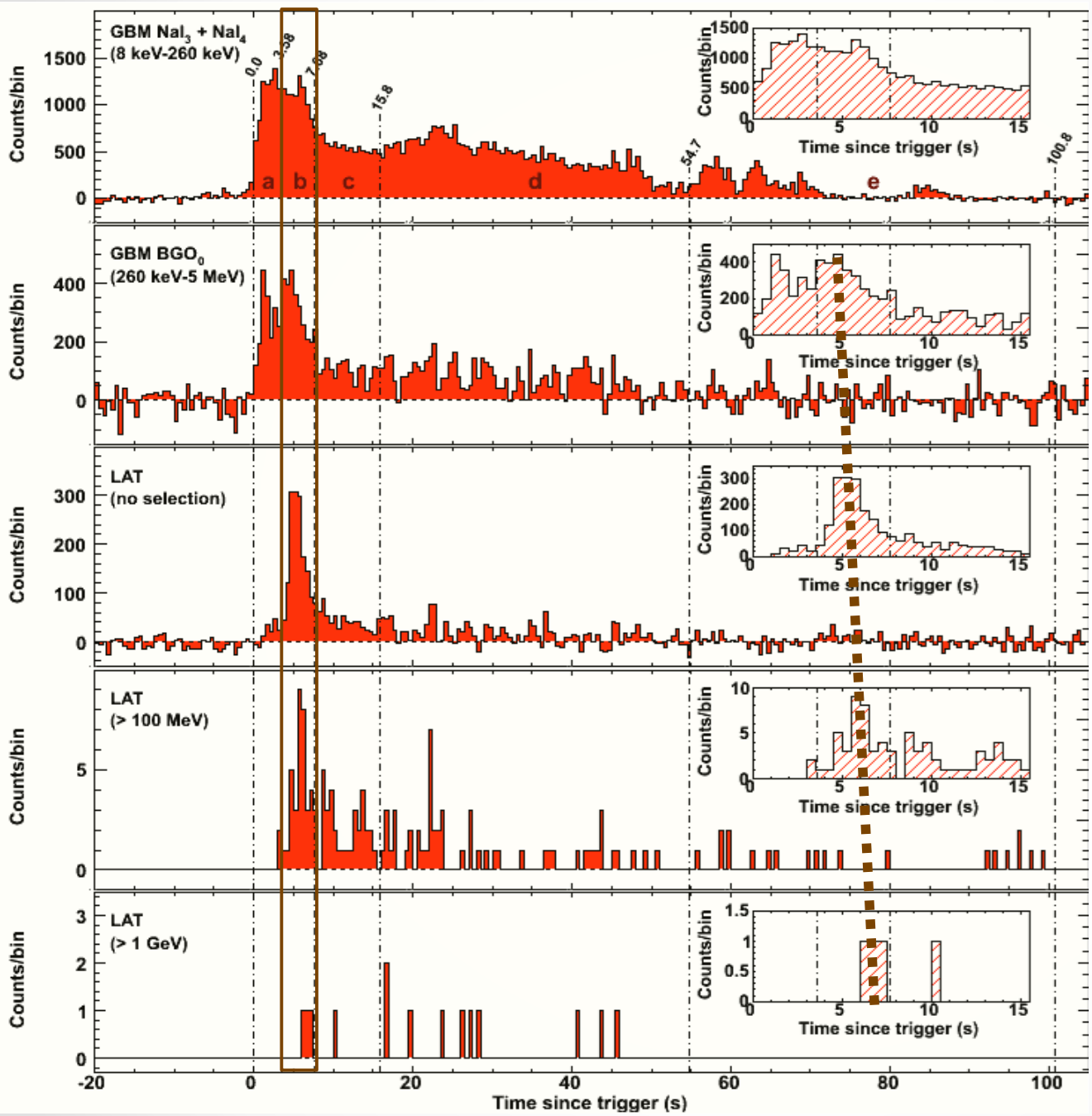
If Vacuum Refraction contains both sub- ($a_1 < 0$) and super- ($a_1 > 0$) luminal models, then there is ***BIREFRINGENCE***

In the case of Birefringent vacua, very strong constraints for ***n=1*** from extragalactic GRB and cosmic photon polarization

$a_1 < 10^{-10}$ ➡ 10^{-16} planned X-ray polarimeters observing galaxies at z = 1



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



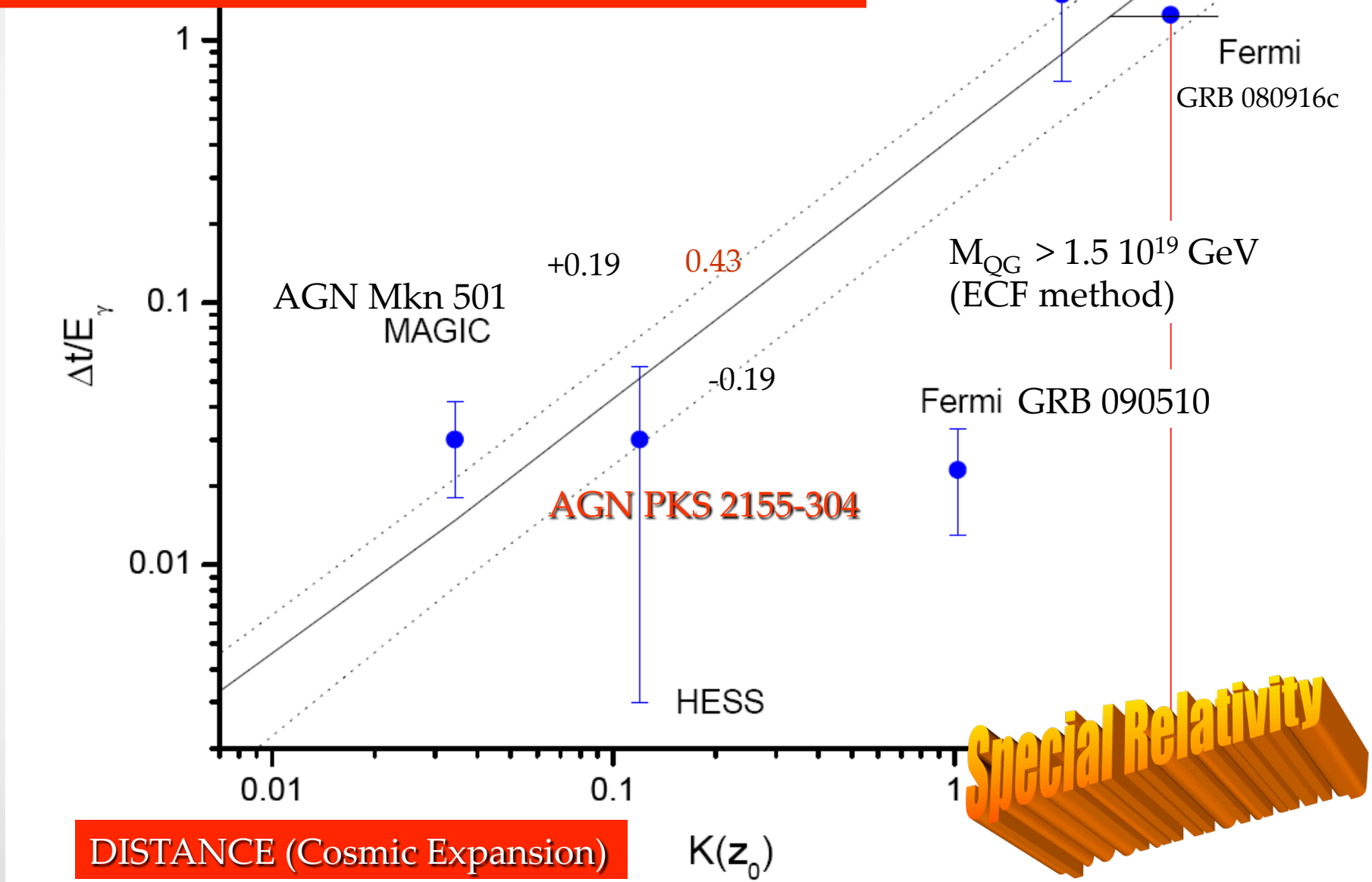
Fermi/LAT collab, Science, 323:1688,2009
GRB 080916c,
12.2 billion light yrs
Most powerful GRB observed todate

2nd peak is moving toward later times as the energy increases;
clear signature of spectral evolution;
16.5 sec delay of highest energy (GeV)photon
source effects to be understood

$$\Delta t \sim \frac{E^n - E_0^n}{E_{QG}^n} \frac{L}{c}$$

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

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



DISTANCE (Cosmic Expansion)

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

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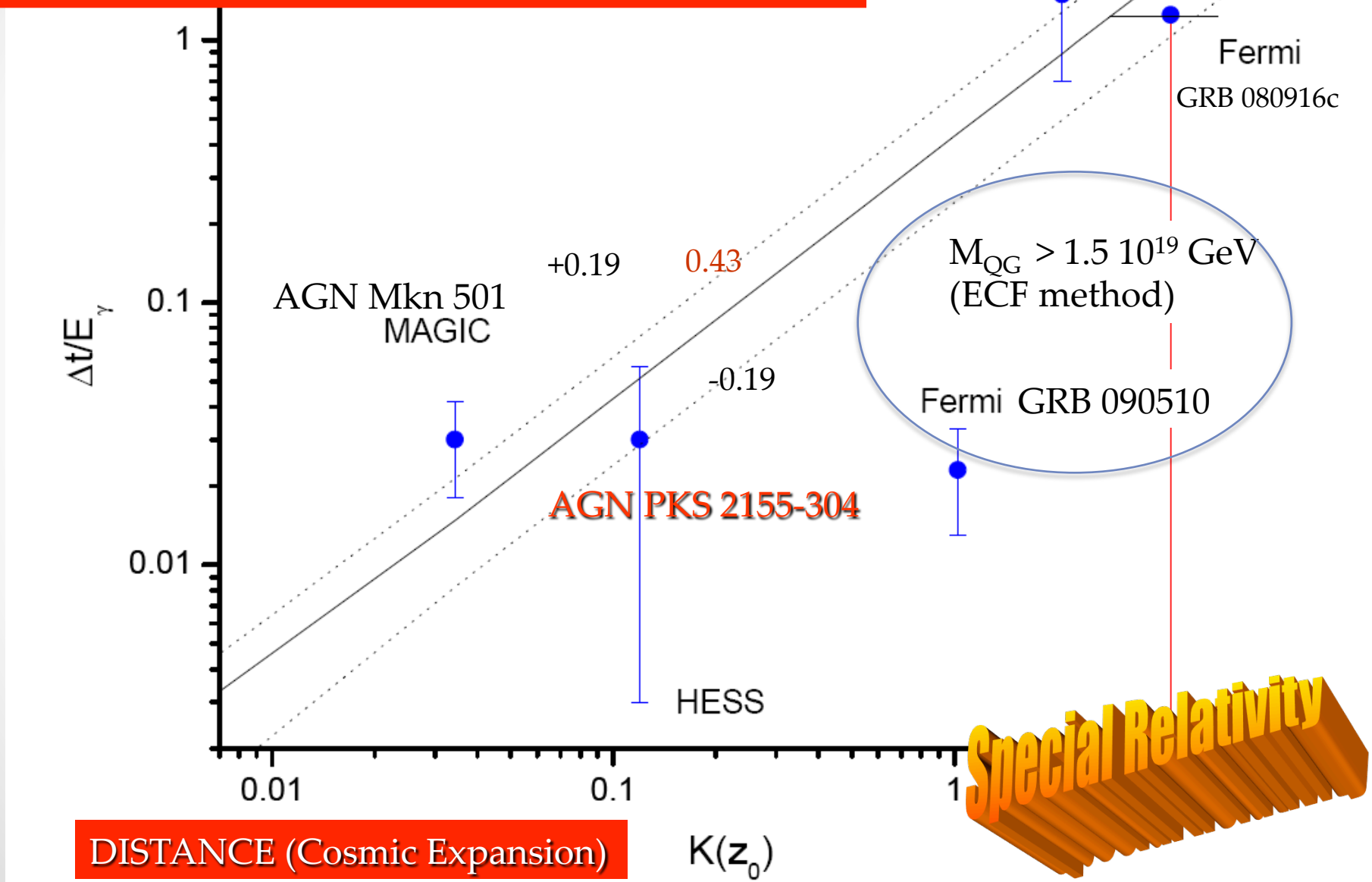


DISTANCE (Cosmic Expansion)

Need much more statistics to disentangle source from propagation effects

Hopefully with more Active Galactic Nuclei (AGN) & GRB observations by FERMI-LAT & CTAs we shall achieve this soon…

BUT …. WE SHALL ALSO ARGUE
THAT OBSERVED ***TIME DELAYS***
OF MORE ENERGETIC PHOTONS,
LINEAR IN ENERGIES,
CAN OCCUR
BEYOND EFFECTIVE FIELD THEORIES
DUE TO TIME-SPACE STRINGY QG UNCERTAINTIES
IN SOME
MODELS OF SPACE-TIME FOAM

DISTINGUISHING FEATURE :
OBSERVED IN PHOTONS BUT NOT
AFFECTING COSMIC RAY
ULTRA-HIGH-ENERGY SPECTRUM
…CAN ALSO FIT GRB090510 with rest

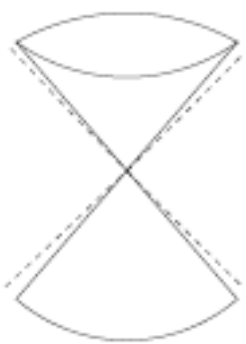
Another Effect :
Stochastic Light-Cone Fluctuations & Broadening of Photon peaks with energy

"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)

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

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

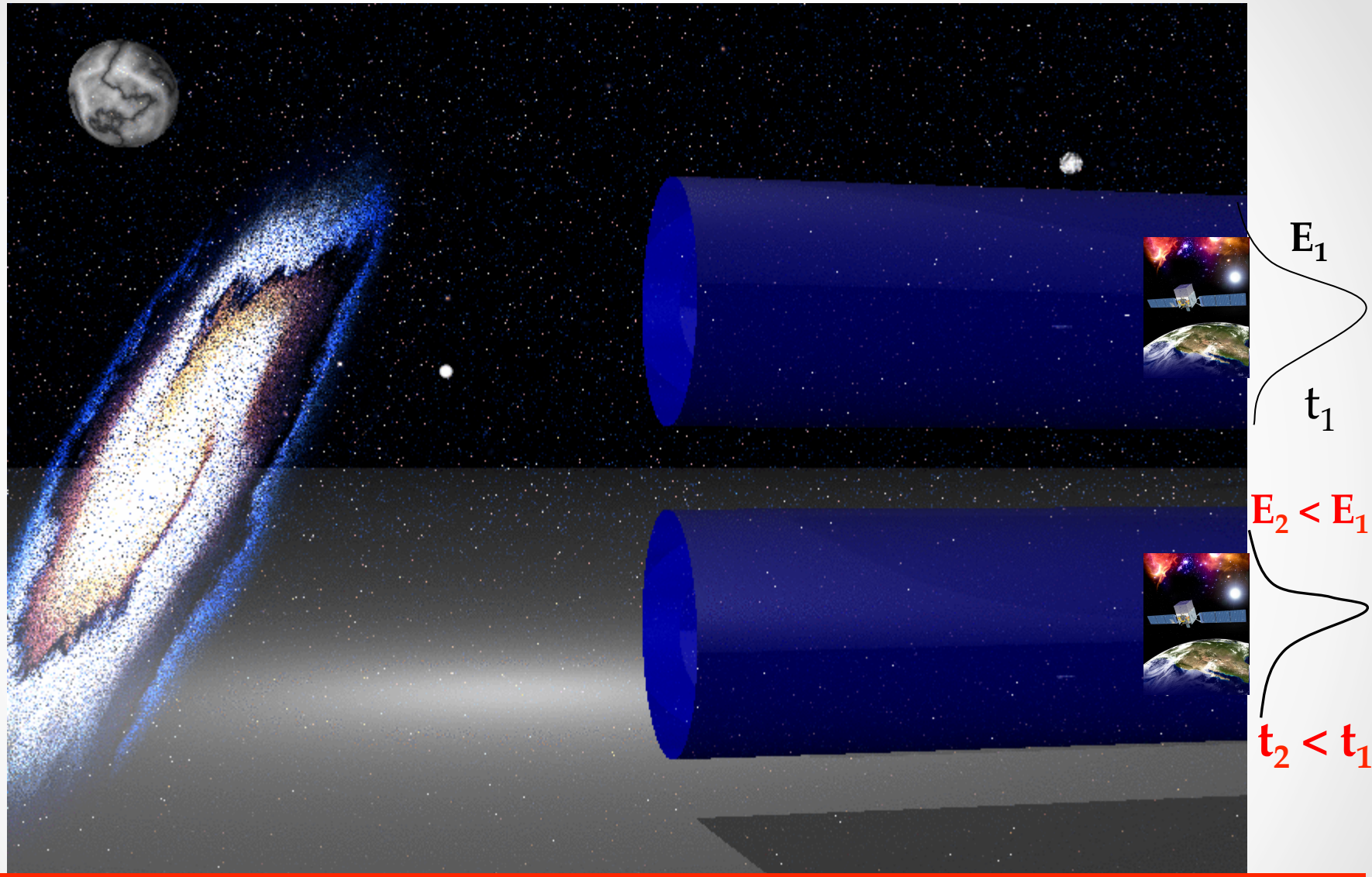


Light Cone Fluct.
(quantum)

$P_\mu P_\nu g^{\mu\nu} = -m^2$

$< g^{\mu\nu} g^{\rho\sigma} > =/= 0$ (non trivial)

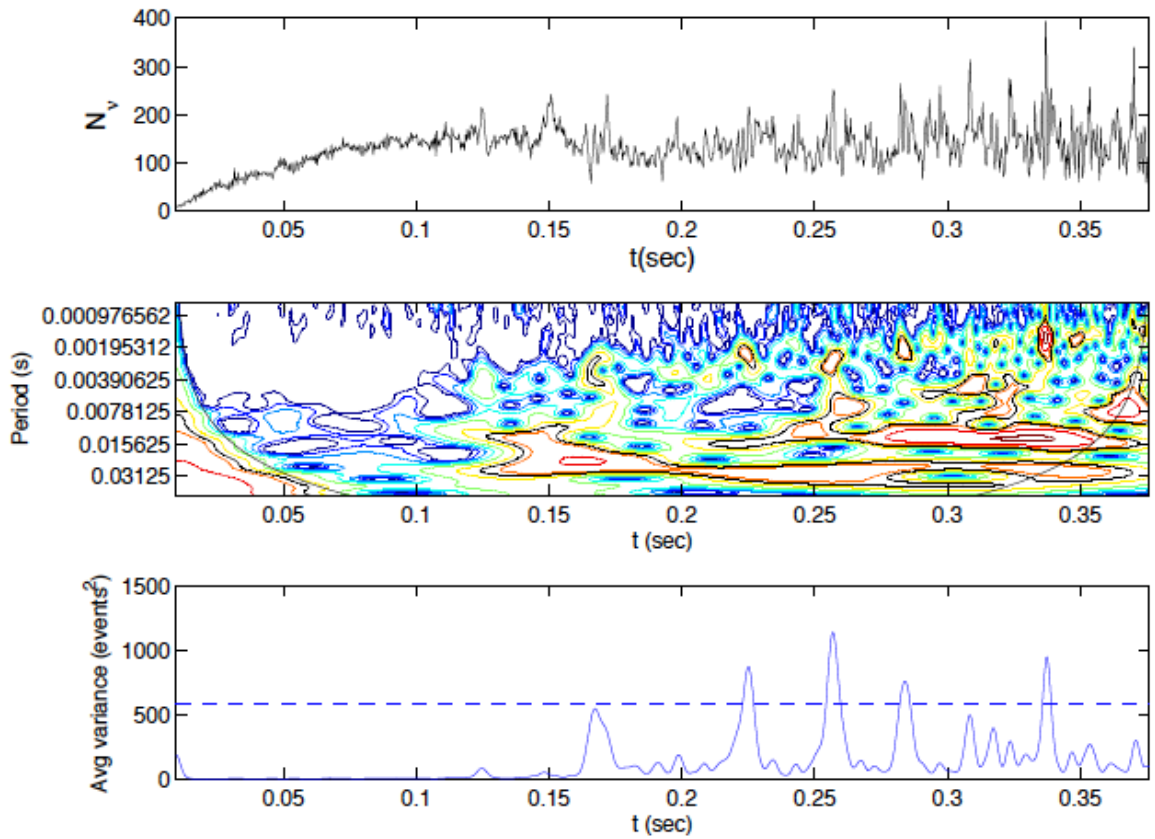
Observed Width of Photon Peaks increases at arrival with Energy



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)

Prospects for LIV Tests using Neutrino from Core-Collapse Supernovae

Ellis, Janka, NM, Sakharov, Sarkisyan (11)



Hypothesize SN explosion at 10 Kpc

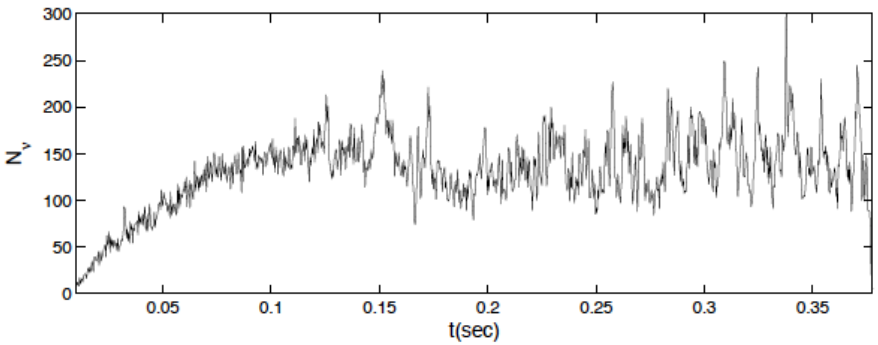
Red regions differ from white noise at 95% C.L.

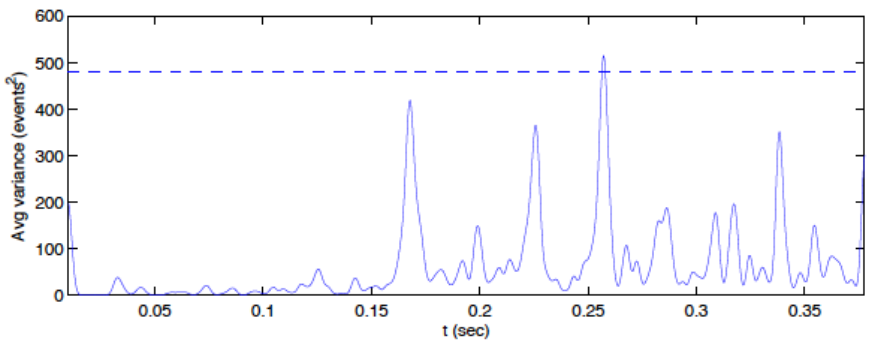
Thermal neutrino spectrum from core-collapse SN,
Wavelet analysis of peaks can distinguish
a white noise spike in the data from harmonic components

An O(10) ms fine structure in neutrino emission would improve previous bounds based on O(s) emissions 100 times

Neutrino from Supernova Tests of Lorentz Invariance

Ellis, Janka, NM,Skharov, Sarkisyan (11)





neutrino wavepacket

$$|f(x,t)|^2 = \frac{A^2}{(1+\frac{\alpha^2 t^2}{(\Delta x_0)^4})^{1/2}} \exp\left[-\frac{(x-v_g t)^2}{\left(2(\Delta x_0)^2[1+\frac{\alpha^2 t^2}{(\Delta x_0)^4}]\right)}\right]$$

Dispersion QG modified
& stochastic effects (tilde)

$$\alpha \equiv \frac{1}{2}\left(d^2\omega/d^2k\right)$$
$$= \frac{m^2}{k^3} - n\,(n+1)\frac{k^{n-1}}{M^n_{\nu\widetilde{QG}n}}$$

$$\begin{aligned} M_{\nu QG1} &> 2.68\times 10^{13}\ \text{GeV} \\ M_{\nu QG2} &> 0.97\times 10^{6}\ \text{GeV}, \\ M_{\nu\widetilde{QG}1} &> 4.78\times 10^{13}\ \text{GeV} \\ M_{\nu\widetilde{QG}2} &> 1.04\times 10^{6}\ \text{GeV}. \end{aligned}$$

Bounds much weaker than
photon data but promising

MDR for other matter probes

Massive Probes (e.g. electrons):

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

Constraints from Crab Nebula via Synchrotron Radiation

Jacobson, Liberatti, Mattingly,
Ellis, NM, Sakharov

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

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

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

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

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*:

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

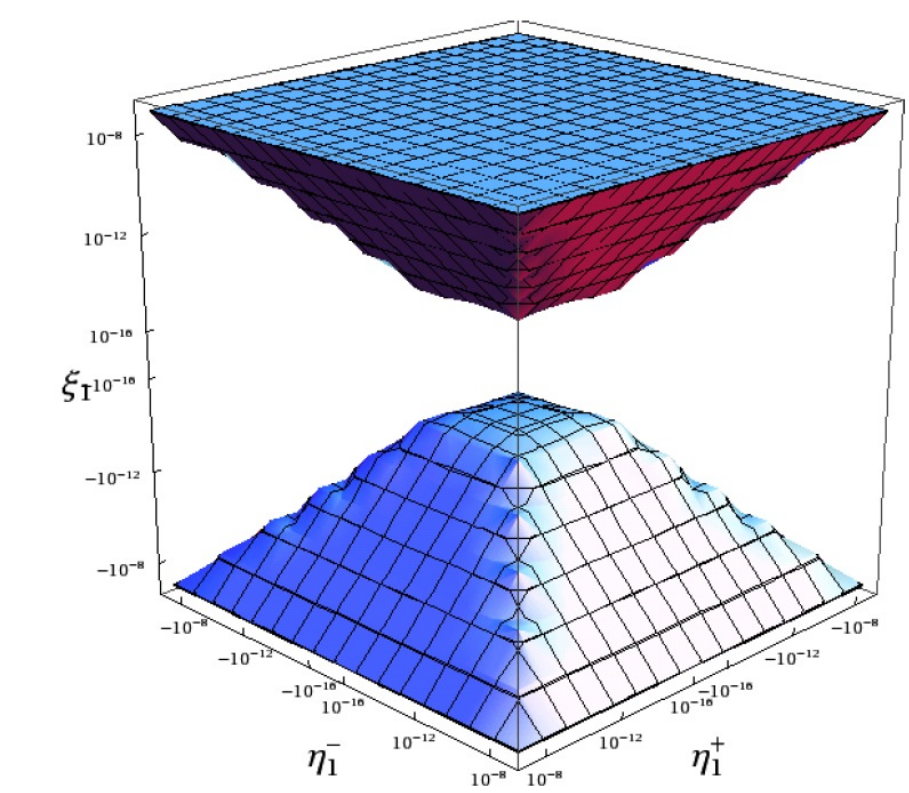
UV radiation from Galaxies: $\xi \lesssim 2\times 10^{-4}$.

For $M \sim M_{\rm Pl} \approx 1.22\times10^{19}$ GeV.

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

Ultra-high-energy photons

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



Galaverni & Sigl

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

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

(ii) Photon Decay

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

Allowed, above threshold if MDR

Other Effects of Foam

Stochastic space-time metric fluctuations (Foam):

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

$$\langle h_{\mu\nu} \rangle = 0$$

$$\langle h_{\mu\nu} h_{\rho\sigma} \rangle \neq 0$$

May induce **quantum decoherence** of propagating matter and **intrinsic CPT Violation** in the sense that the CPT operator Θ is **not well-defined**

Decoherence implies that asymptotic density matrix of low-energy matter :

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

$$\rho = {\rm Tr} |\psi\rangle\langle\psi|$$

$$\$ \neq S\, S^\dagger$$

$$S = e^{i \int H dt}$$

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

If Θ well-defined can show that $\$^{-1} = \Theta^{-1} \$ \Theta^{-1}$ exists !

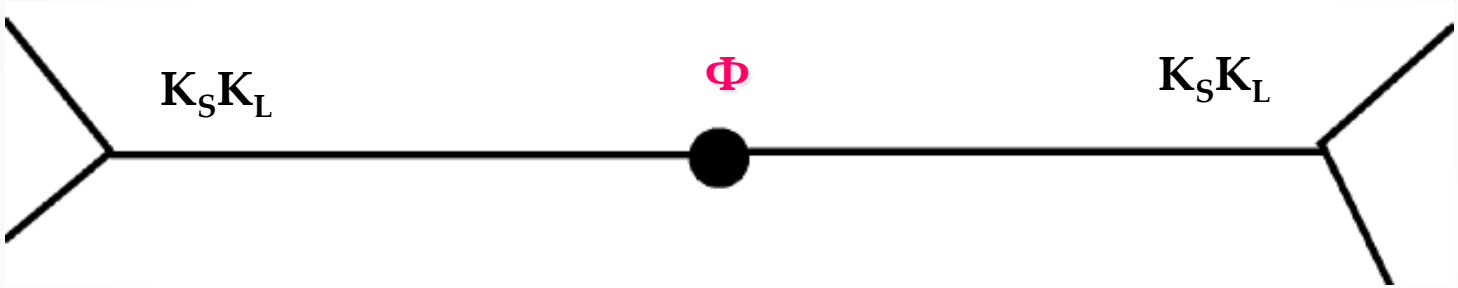
INCOMPATIBLE WITH DECOHERENCE

Wald (79)

Hence Θ ill-defined at low-energies in QG foam models

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

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



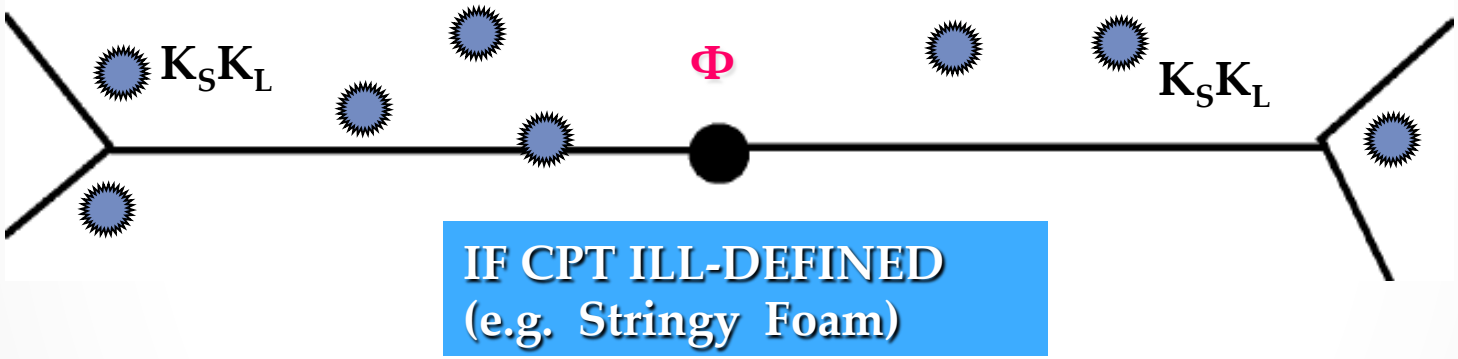
IF CPT Θ-operator WELL-DEFINED

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

Bernabeu, NM, Papavassiliou (04)

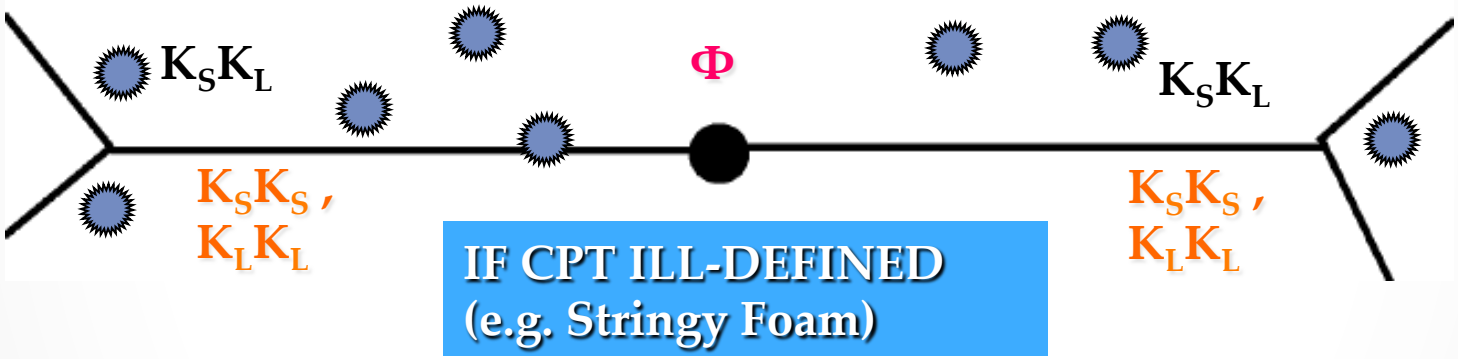


IF CPT ILL-DEFINED
(e.g. Stringy Foam)

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

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

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



ω – effect : can be distinguished from conventional background effects

Bernabeu, NM, Papavassiliou (04)

PART II

TOWARDS MORE MICROSCOPIC MODELS

STRING THEORY UNCERTAINTIES & TIME-SPACE NON COMMUTATIVITY?

STRINGY TIME,SPACE UNCERTAINTIES

Phase-Space Corrected (due to minimum length)

$$\Delta p\, \Delta x \geq 1 + \alpha' \quad (\Delta p)^2 + \ldots$$

Veneziano, Amati, Ciafalone

Time-Space (New compared to QM):

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

Yoneya

(α' = Regge slope = Square of minimum string length scale= ℓ_s^2)

STRINGY TIME,SPACE UNCERTAINTIES

Phase-Space Corrected [illegible] minimum length)

Δp [illegible] $)^2 + \ldots$

Time Space [illegible] QM):

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

(α' = Regge slope = Square of minimum string length scale= ℓ_s^2)

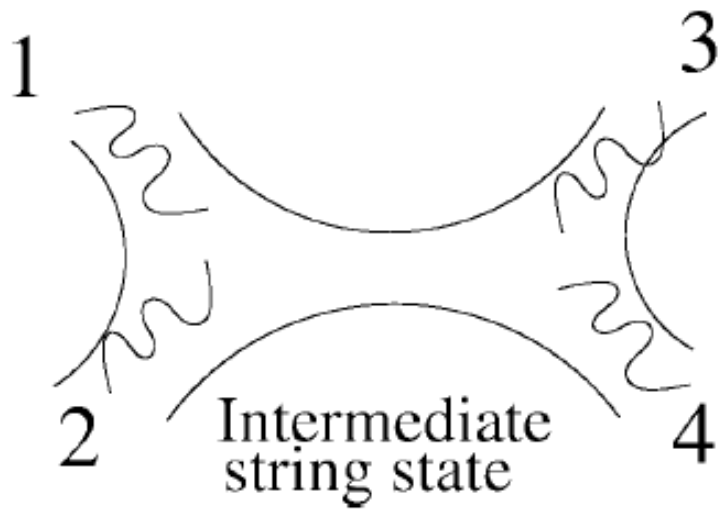
Does this imply Time, Space Non Commutativity

Ciafalone

Stringy Uncertainties, Non-Commutativity & Causality

Seiberg, Susskind, Toumbas

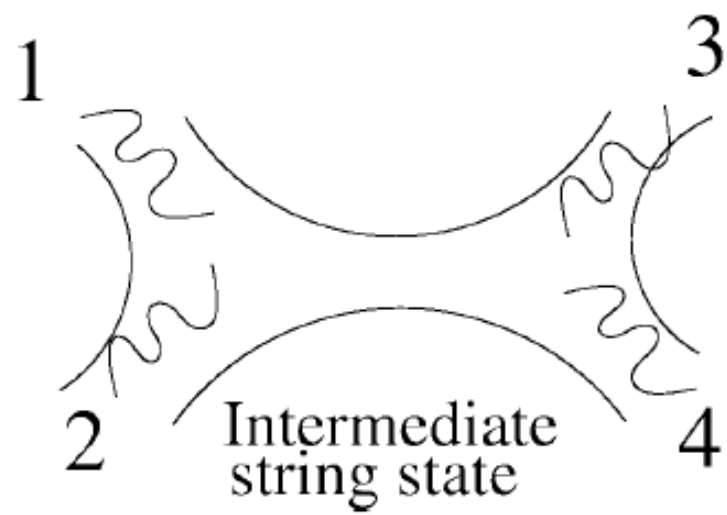
Veneziano amplitude for massless open string scattering



Stringy Uncertainties, Non-Commutativity & Causality

Seiberg, Susskind, Toumbas

Veneziano amplitude for massless open string scattering



Non Commutativity if electric
External field E considered,
Open string metric modified

$$\tilde{E} = E/E_{cr} \leq 1$$

$$E_{cr} = 1/2\pi l_s^2$$

$$[X^1, t] = 2\pi \ell_s^2 \frac{\tilde{E}}{1-\tilde{E}^2}$$

World-Sheet Formalism

Open strings in constant External Electric fields

spacetime lightcone coordinates $x^{\pm} = \frac{1}{\sqrt{2}}(x^0 \pm x^1)$

World-sheet Boundary Conditions

$$\left(\partial_\sigma x^{\pm} \mp \widetilde{E}\partial_\tau x^{\pm}\right)\Big|_{\sigma=0,\pi} = 0.$$

$$\widetilde{E} = \frac{2\pi\alpha' E}{g} = \frac{E}{E_{cr}}$$

$$x^{\pm}(\sigma,\tau) = x_0^{\pm} + \alpha' p^{\pm}(\tau \pm \widetilde{E}\sigma) - i(\alpha')^{\frac{1}{2}} \sum_{n\neq 0} \frac{a_n^{\pm}}{n}\left[\left(1 \pm \widetilde{E}\right) e^{in(\sigma+\tau)} + \left(1 \mp \widetilde{E}\right) e^{in(-\sigma+\tau)}\right]$$

$$= x_0^{\pm} + \frac{1}{2}\alpha' p^{\pm}\left[(\tau+\sigma)(1 \pm \widetilde{E}) + (\tau-\sigma)(1 \mp \widetilde{E})\right]$$

$$- i(\alpha')^{\frac{1}{2}} \sum_{n\neq 0} \frac{a_n^{\pm}}{n}\left[\left(1 \pm \widetilde{E}\right) e^{in(\sigma+\tau)} + \left(1 \mp \widetilde{E}\right) e^{in(-\sigma+\tau)}\right],$$

$$(a_n^{\pm})^* = a_{-n}^{\pm}$$

Open String 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 target-space metric ``seen'' by open string

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

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

and effective string coupling

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

World-Sheet Formalism

Centre of mass coordinates $\widetilde{x}_0^{\pm} = x_0^{\pm} \pm \frac{\pi}{2}\alpha' p^{\pm}\widetilde{E}$ **commute**

but:

$$[x_0^\mu, x_0^\nu] = i\theta^{\mu\nu},$$

$$[x_0^\mu, p^\nu] = i2G^{\mu\nu},$$

$$[a_n^\mu, a_m^\nu] = \frac{1}{2} n\delta_{n+m,0} G^{\mu\nu}$$

lack of commutativity due to the boundaries of the open string

open string metric

$$G_{\mu\nu} = G\begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}_{\mu\nu} \qquad \theta^{\mu\nu} = \theta\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}^{\mu\nu}$$

$$G = g(1-\widetilde{E}^2) \qquad \widetilde{E} = \frac{2\pi\alpha' E}{g} = \frac{E}{E_{cr}}$$

$$\theta = \frac{1}{E_{cr}} \frac{\widetilde{E}}{1-\widetilde{E}^2}$$

Effective string coupling

$$G_s = g_s\left(1-\widetilde{E}^2\right)^{\frac{1}{2}}$$

Stringy Uncertainties, Non-Commutativity & Causality

Seiberg, Susskind, Toumbas

Veneziano amplitude for massless open string scattering

$$
\begin{aligned}
A_4 \sim\ & G_s\left(K_{st}e^{i(p_1\wedge p_2+p_3\wedge p_4)}+K'_{st}e^{i(p_1\wedge p_4+p_3\wedge p_2)}\right)\frac{\Gamma(-2sl_s^2)\Gamma(-2tl_s^2)}{\Gamma(1+2ul_s^2)}\\
+\ & G_s\left(K_{su}e^{i(p_1\wedge p_2+p_4\wedge p_3)}+K'_{su}e^{i(p_1\wedge p_4+p_2\wedge p_3)}\right)\frac{\Gamma(-2sl_s^2)\Gamma(-2ul_s^2)}{\Gamma(1+2tl_s^2)}\\
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\end{aligned}
$$

$s = 2p_1p_2, \quad t = 2p_1p_4, \quad u = 2p_1p_3$ Mandelstam Variables

Non Commutativity if electric
External field E considered,
Open string metric modified

$\tilde{E} = E/E_{cr} \leq 1$

$E_{cr} = 1/2\pi l_s^2$

$$[X^1, t] = 2\pi\ell_s^2\frac{\tilde{E}}{1-\tilde{E}^2}$$

Seiberg, Susskind, Toumbas

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G_{\mu\nu} &= \delta_{\mu\nu}\ , \quad \mu\nu \neq 0,1 \\
\theta^{01} &= 2\pi l_s^2\frac{\tilde{E}}{1-\tilde{E}^2} \\
G_s &= g_s(1-\tilde{E}^2)^{\frac{1}{2}}.
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$$p\wedge k = \theta^{01}(p_0k_1 - k_0p_1).$$

Look at Backward Scattering, u=0

$$A_{st} \sim G_s \left(K_{st} e^{2\pi i \tilde{E} s l_s^2} + K'_{st} e^{-2\pi i \tilde{E} s l_s^2} \right) \Gamma(-2sl_s^2)\Gamma(2sl_s^2)$$

Using the identity $\quad y\Gamma(y)\Gamma(-y) = -\frac{\pi}{\sin(\pi y)},$

$$A_{st} \sim G_s s \left(a_1 e^{2\pi i \tilde{E} s l_s^2} + a_2 e^{-2\pi i \tilde{E} s l_s^2} \right) \frac{1}{\sin(2\pi s l_s^2)}$$

$$s \longrightarrow s + i\epsilon$$

$$\boxed{A_{st} \sim G_s s \sum_{n>0 \ \ odd} a_1 e^{2\pi i (n+\tilde{E}) s l_s^2} + a_2 e^{2\pi i (n-\tilde{E}) s l_s^2} + O(\epsilon)}$$

$$A_{st} \sim G_s s \sum_{n>0 \ \ odd} a_1 e^{2\pi i (n+\tilde{E}) s l_s^2} + a_2 e^{2\pi i (n-\tilde{E}) s l_s^2} + O(\epsilon)$$

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Causal Phases Only

OUTGOING WAVES ONLY RETARDED, NO ADVANCED WAVES
(CONTRAST WITH NON-COMMUTATIVE FIELD THEORY)

Outgoing waves have TIME DELAYS:

$$\Delta t = \frac{\alpha' p^0}{1-\tilde{E}^2}$$

p^0 = Total incident string energy

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p^0 = Total incident string energy

However, delays exist independently of external field, finite value if E switched off… So Space-Time String Uncertainties do not indicate (necessarily) space-time non commutativity …

Beyond Local Field Theory & Stringy Uncertainties

During Scattering: as two strings come together, an intermediate String 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. Ends of intermediate string move with speed of light in vacuo c=1 Hence TIME DELAY (causality) during scattering:

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

Compatible with Stringy Uncertainties

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

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Photon-Photon Scattering in Dense Galactic Regions?

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Can we Measure Such Delays?

Photon-Photon Scattering in Dense Galactic Regions?

Negilgible Time Delays within experimental errors

Photon-Photon Scattering

Open Strings can represent Photons in Modern Brane theories

Single Scattering outgoing-wave time delay

$$\Delta t = \frac{\alpha' p^0}{1-\tilde{E}^2}$$

Answer depends on energy of photons, and size of string length $\sqrt{\alpha'}$

Delay is causal, so additive effect, if there are multiple scatterings

Can multiple scatterings in intense Cosmic sources (Active Galactic Nuclei and Gamma Ray Bursts) produce measurable (at least msec) delays in arrival of more energetic photons compared to lower-energy ones!

Some numbers: **Optimistic case:** string scale is TeV , Photon energy is TeV

$$\Delta t_{\text{single scattering}} \sim \sqrt{\alpha'} \sim 10^{-27} \text{ sec}$$

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Need Unphysically High Concentrations of Photons...

Some numbers: **Optimistic case:** string

$$\Delta t_{\text{single scattering}} \sim \sqrt{\alpha'} \sim$$

Photon-Photon Scattering

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PART III

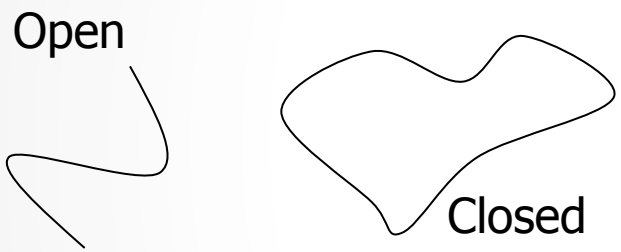
TOWARDS MORE MICROSCOPIC MODELS

STRING THEORY FOAM & INDUCED FINSLER METRICS

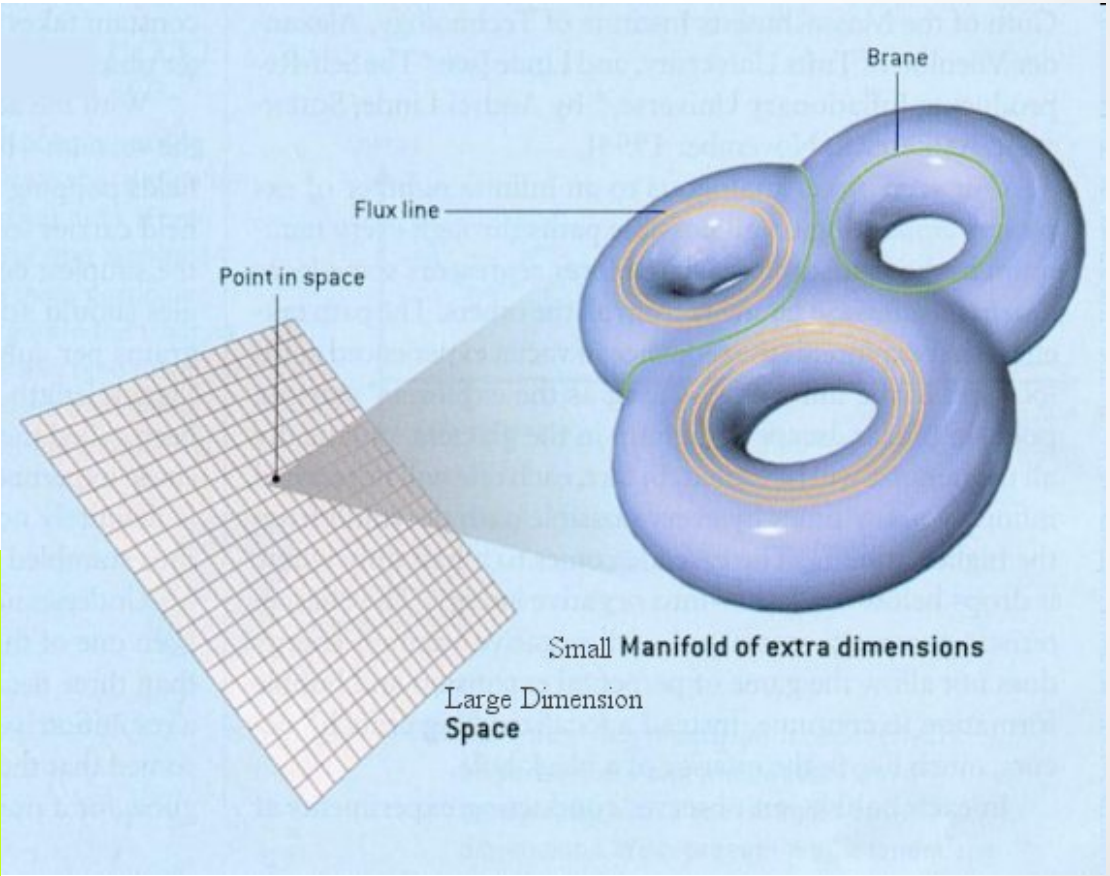
NM, J. Ellis, D. Nanopoulos (99)
+ Sarben Sarkar (05-11),

What is String Theory?

Fundamental Excitations are not point-like but one-dimensional (strings)



ONE VERSION :
Strings live in Large Four space-time dimensions but have extra dimensions ``Curled-up'' in small-size but of complicated Geometry spaces



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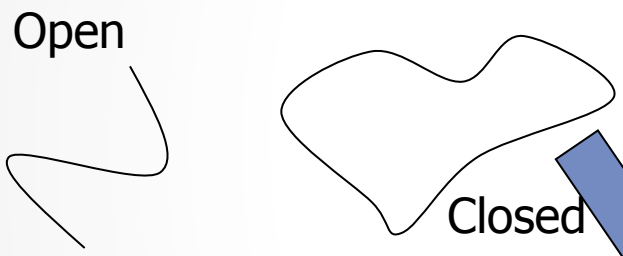

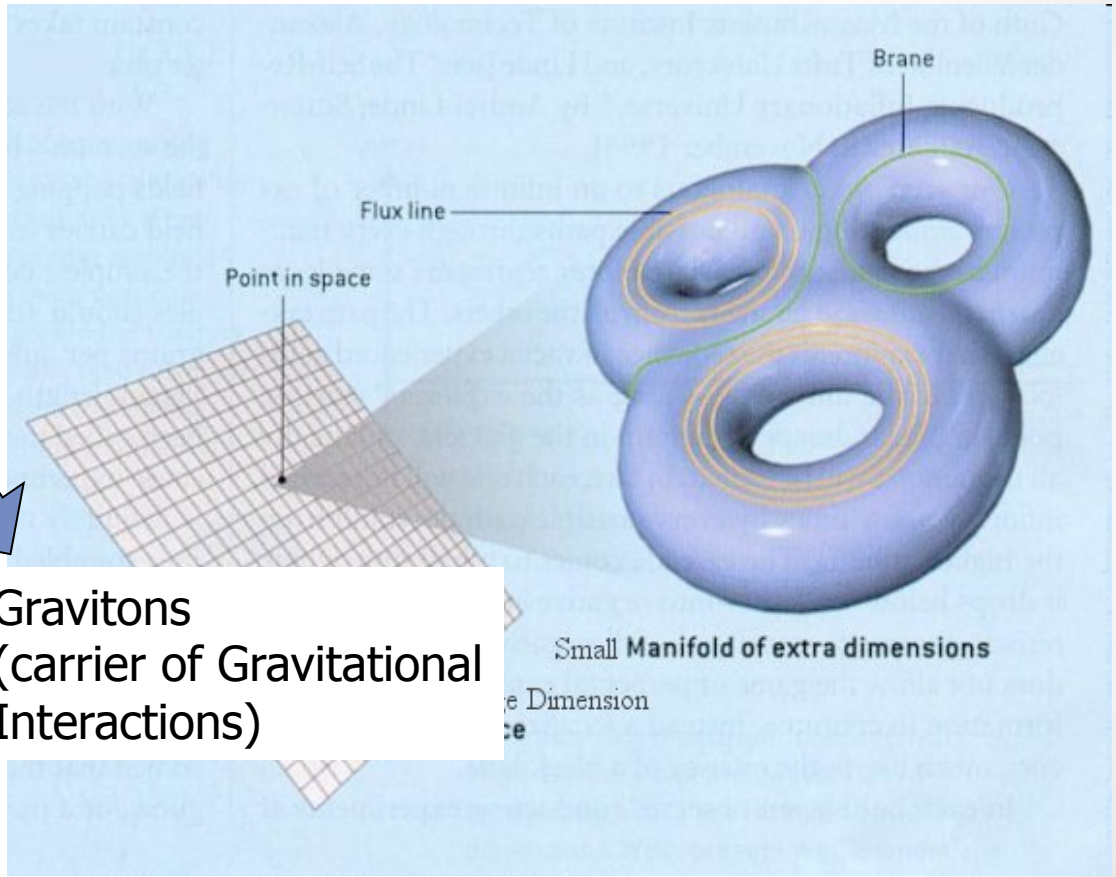

Gravitons
(carrier of Gravitational Interactions)

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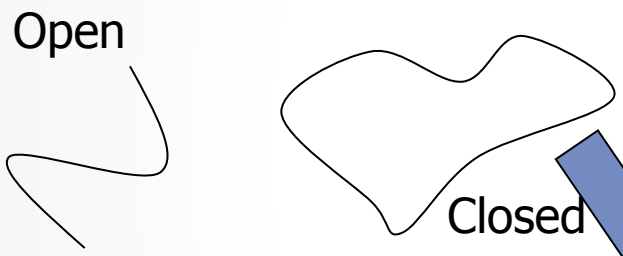

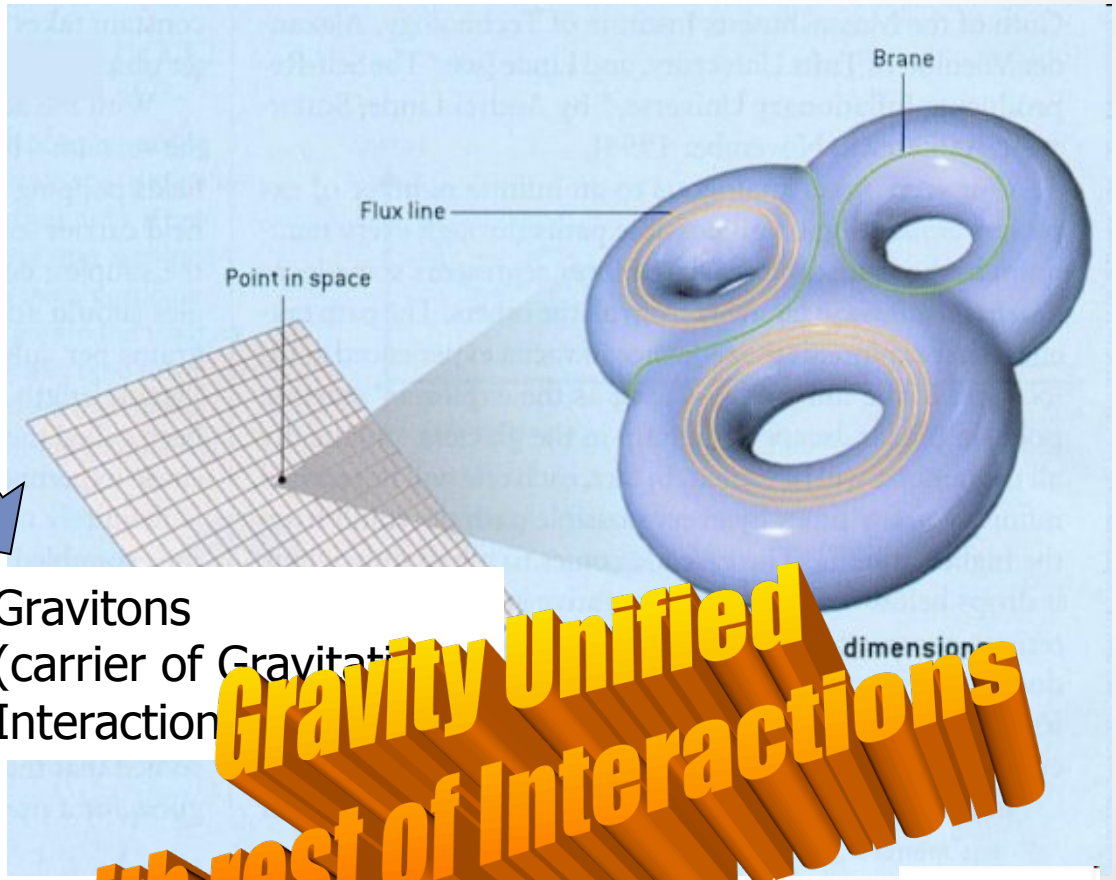

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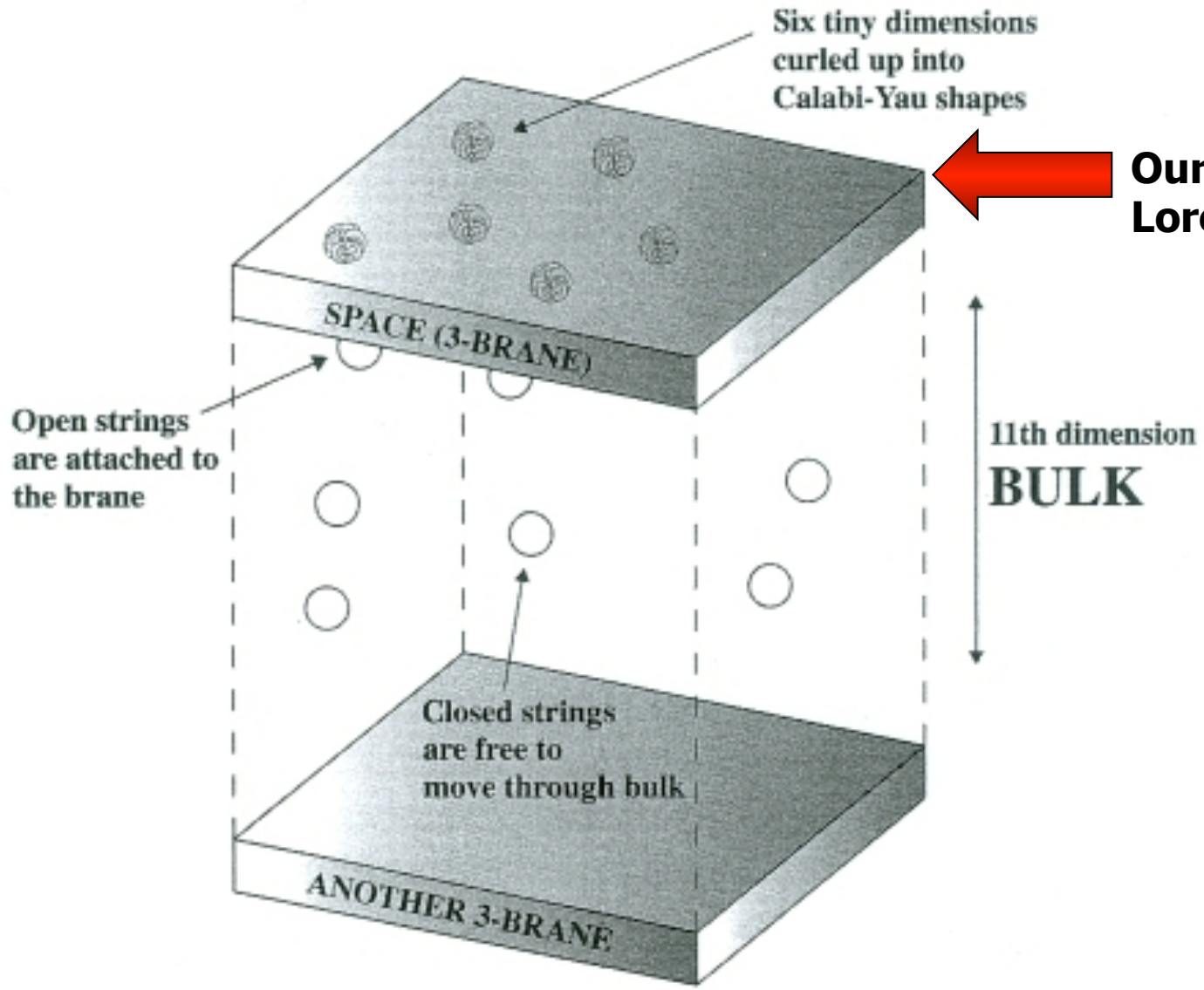
Gravitons
(carrier of Gravitati
Interaction

Gravity Unified with rest of Interactions

SECOND VERSION OF STRING THEORY (BRANE-THEORY):



Our Universe
Lorentz Invariant

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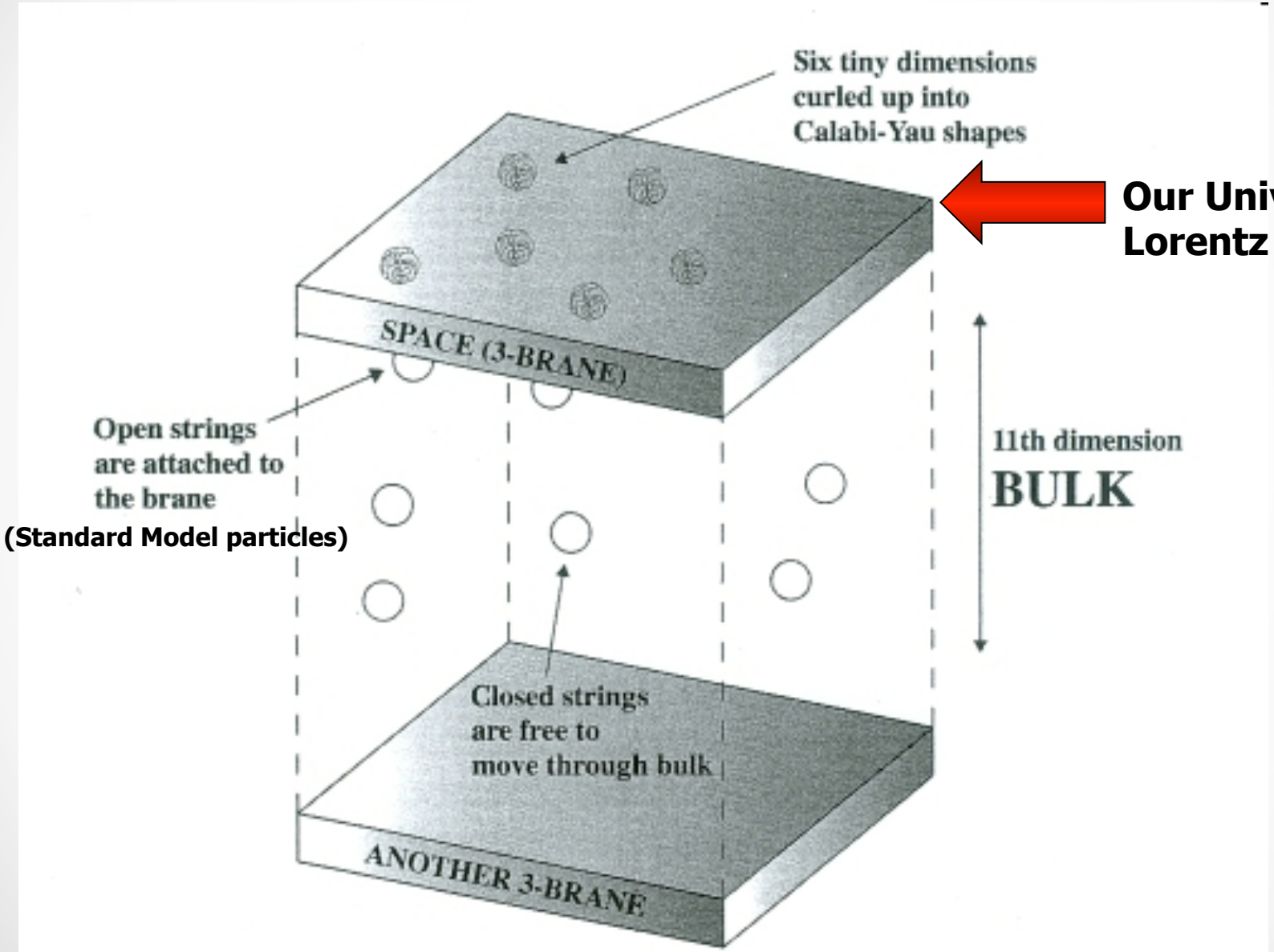

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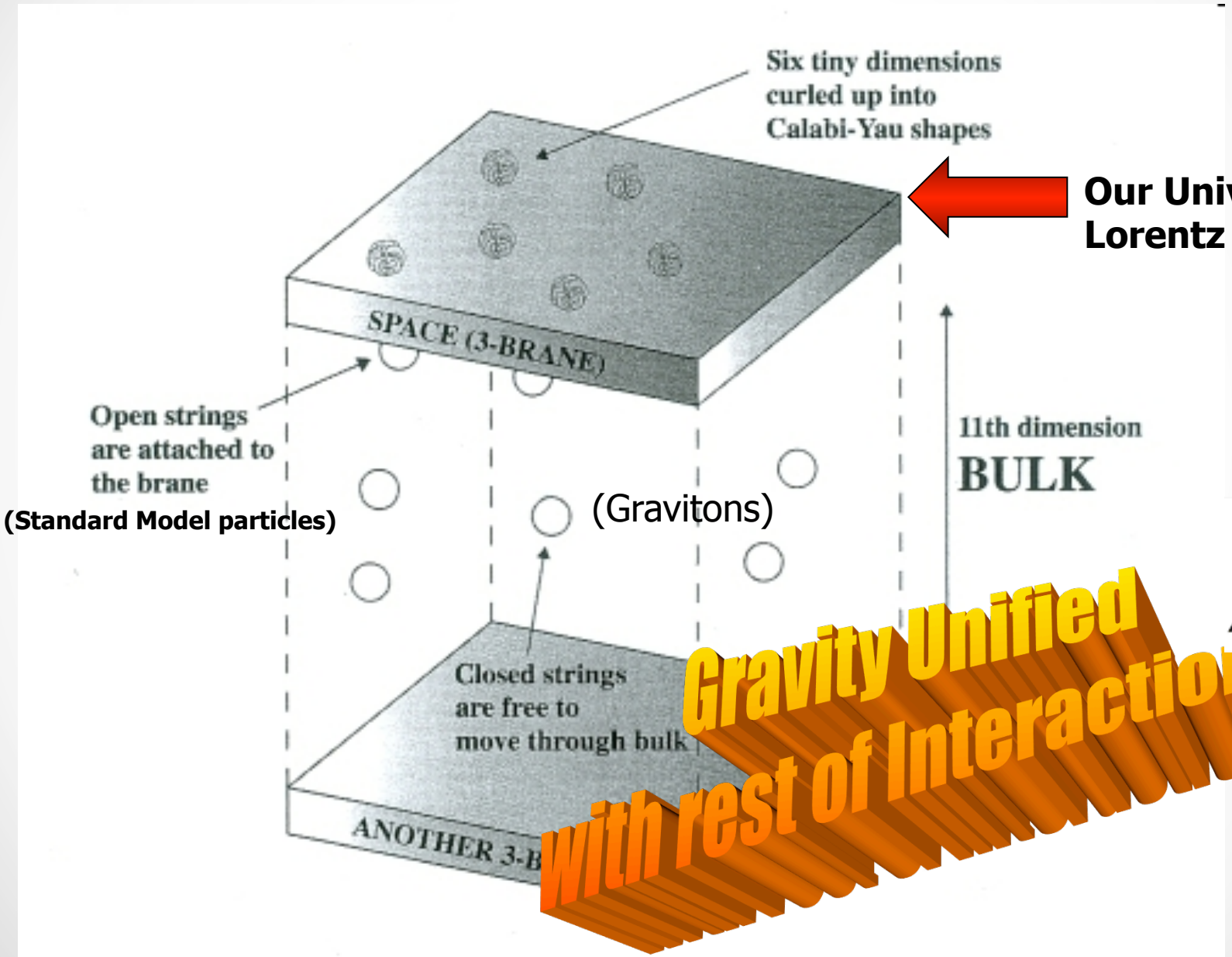
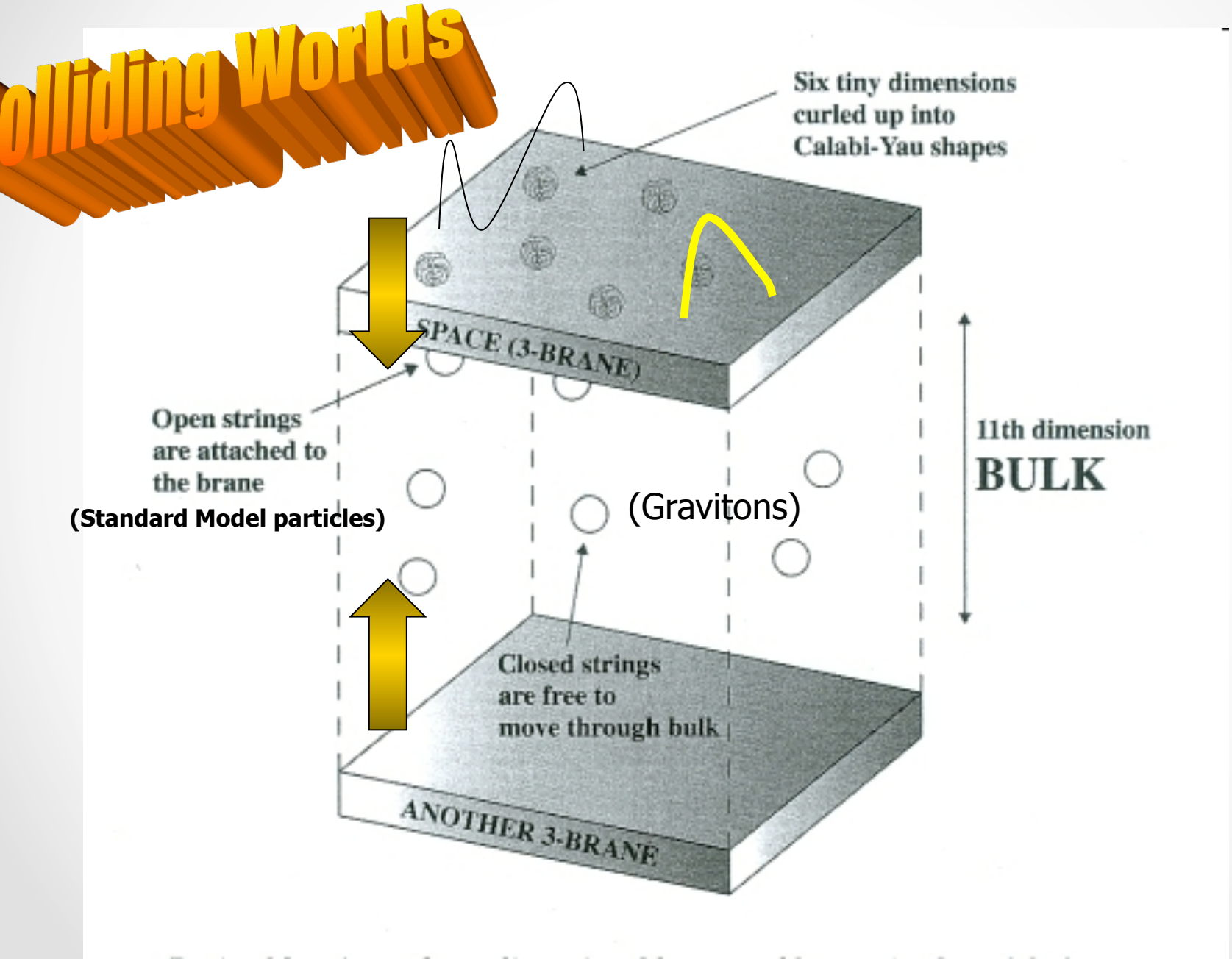
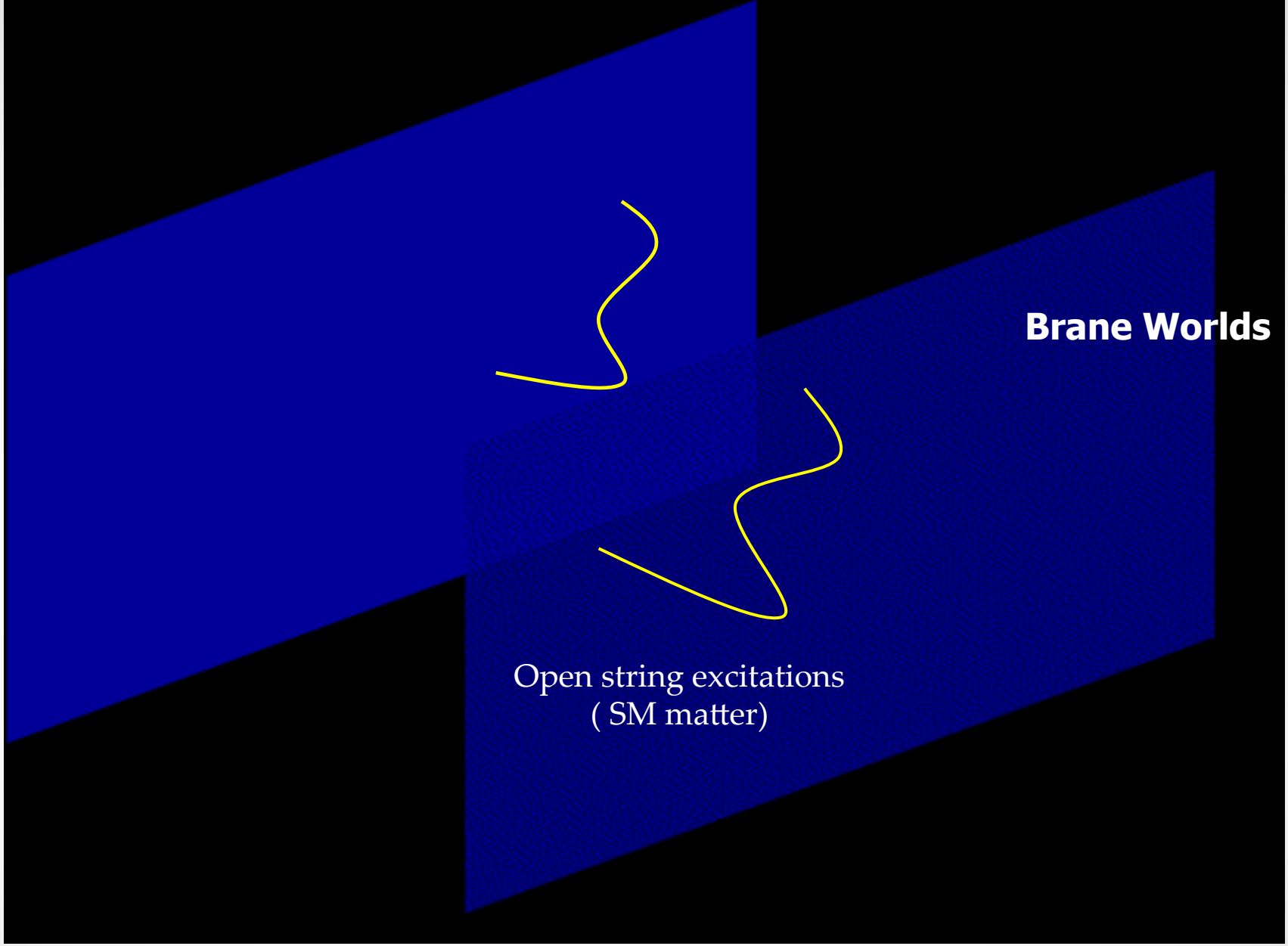


Gravity Unified with rest of Interactions

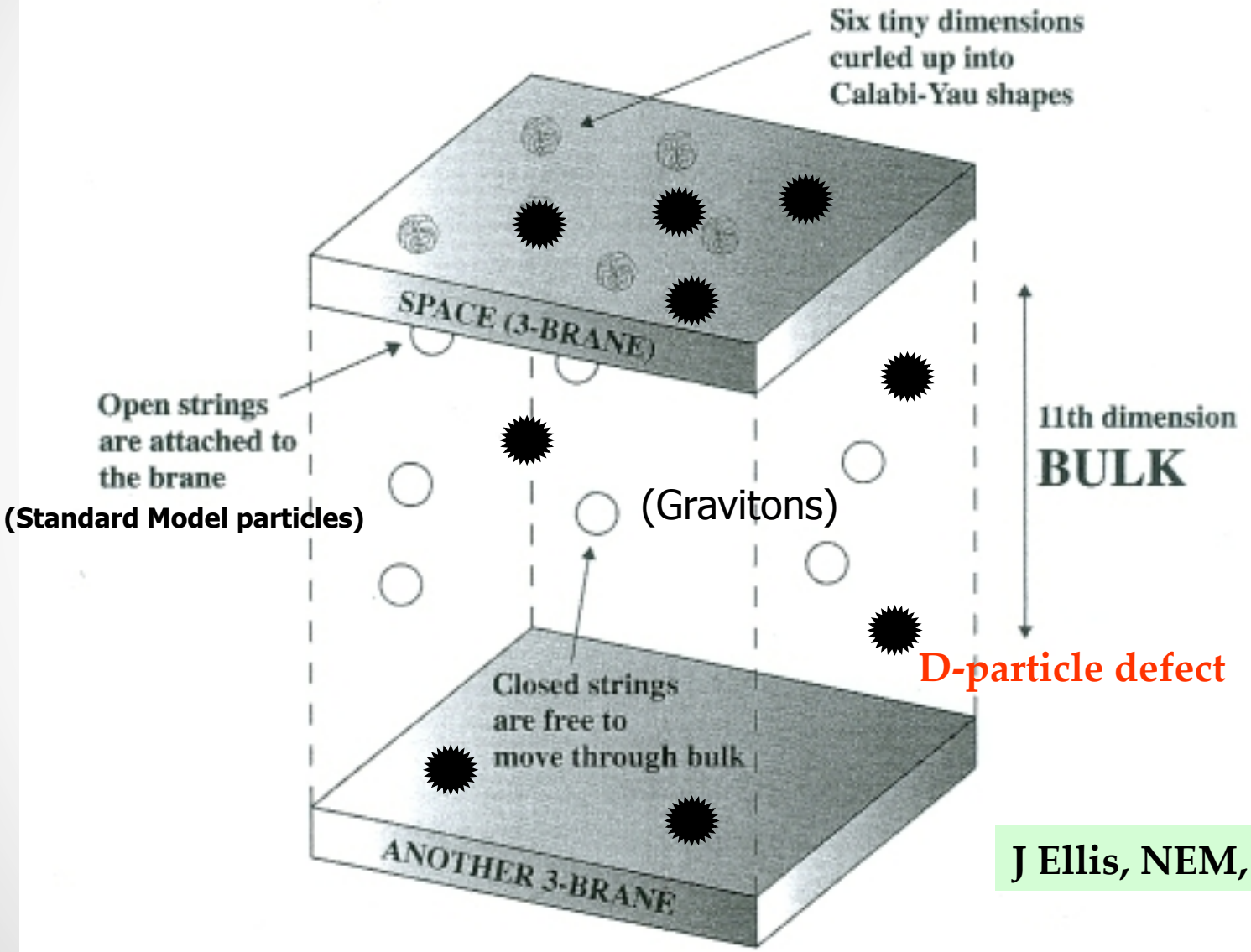
ANTOHER VERSION: COLLIDING BRANE WORLDS :





Colliding & Bouncing Brane world Cosmology

ANTOHER VERSION of BRANE WORLDS with D-PARTICLE (POINT-LIKE BRANE) DEFECTS :



J Ellis, NEM, M Westmucket

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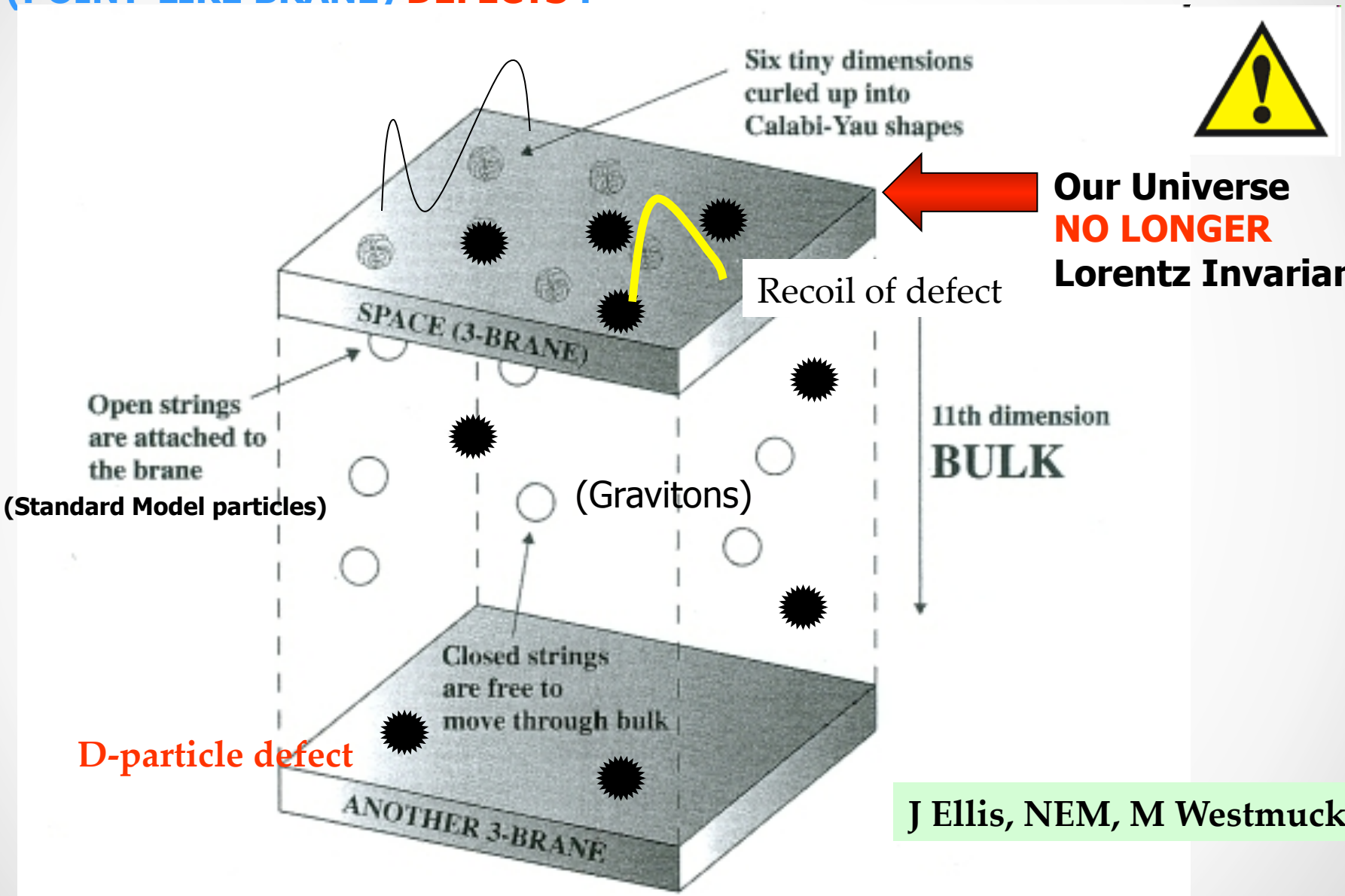

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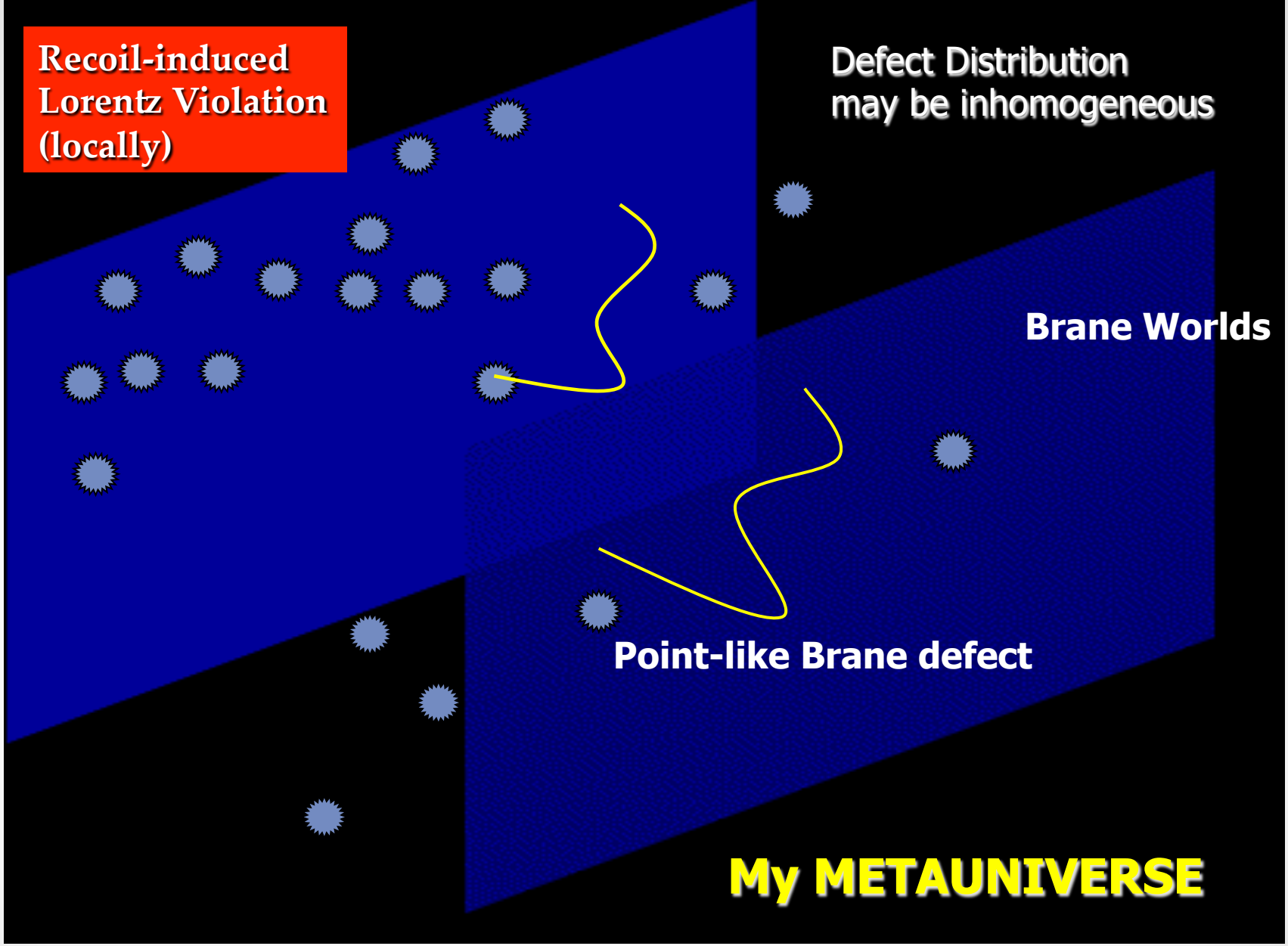
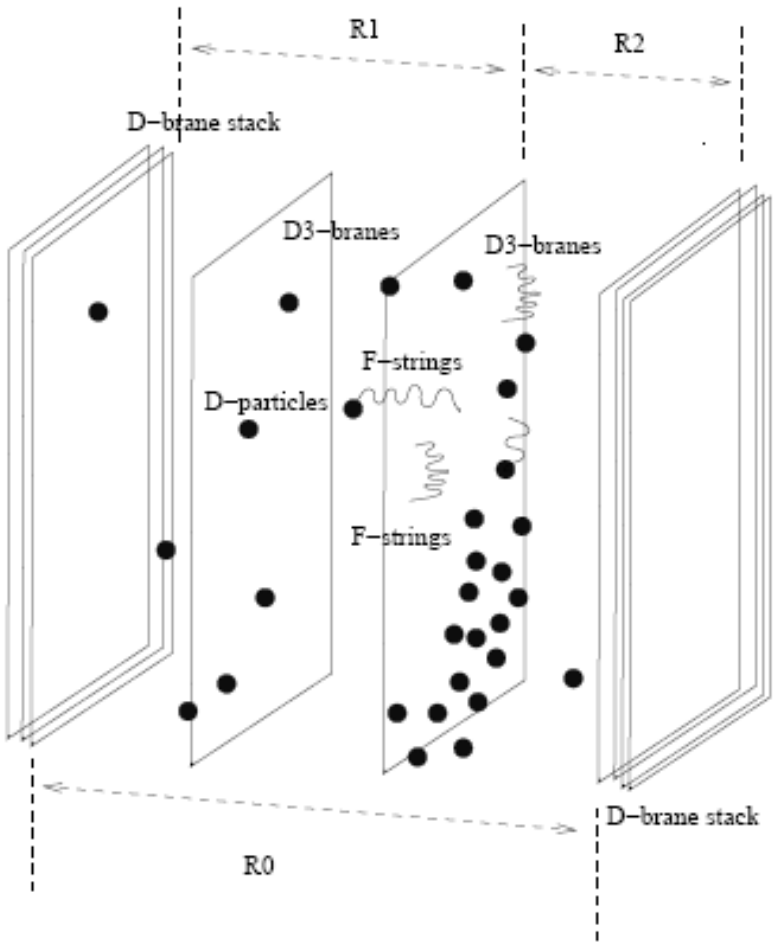
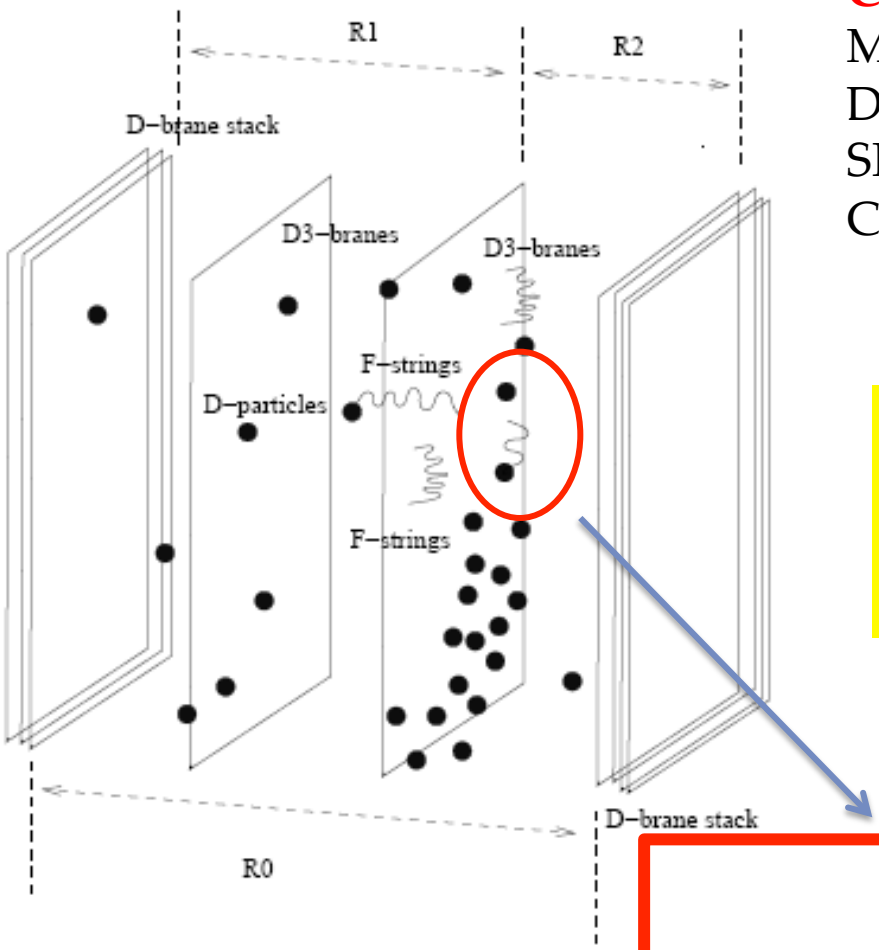


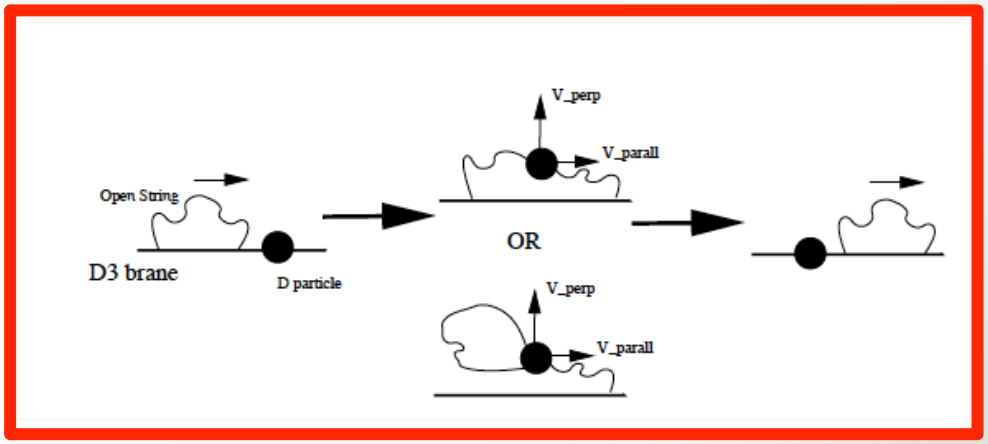
Colliding Brane world model of Space-Time with point-like space-time defects

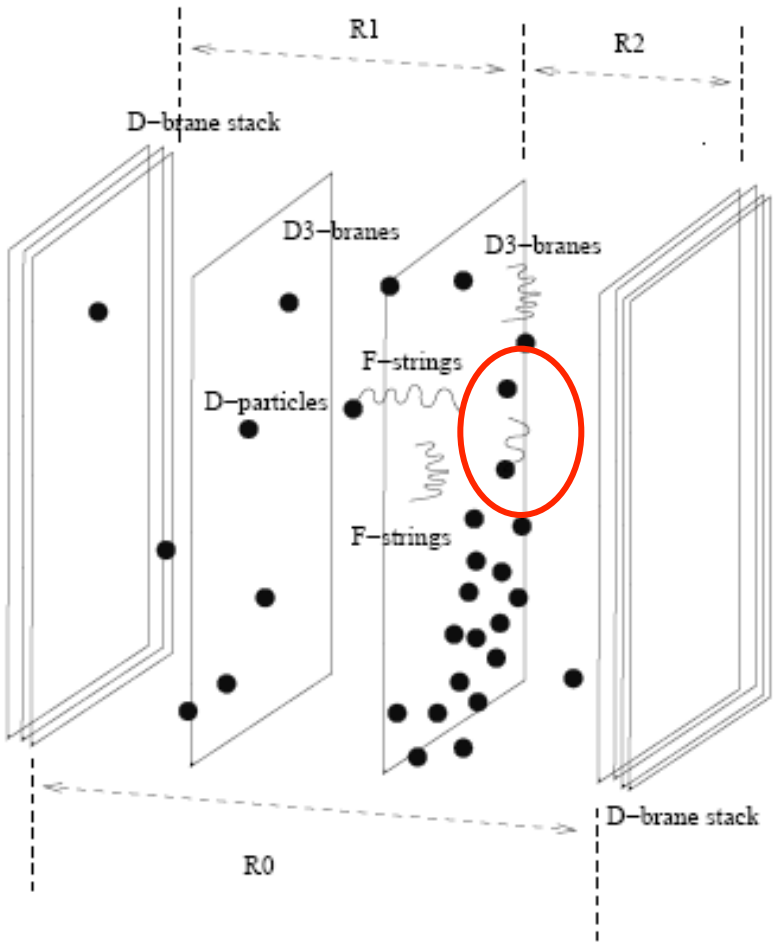

R1
R2
D−brane stack
D3−branes
D3−branes
F−strings
D−particles
F−strings
D−brane stack
R0



CHARGE CONSERVATION MUST BE RESPECTED DURING STRING SPLITTING, INTERNEDIATE CREATION AND STRETCHING:

ONLY ELECTRICALLY NEUTRAL EXCITATIONS INTERACT DOMINANTLY WITH FOAM

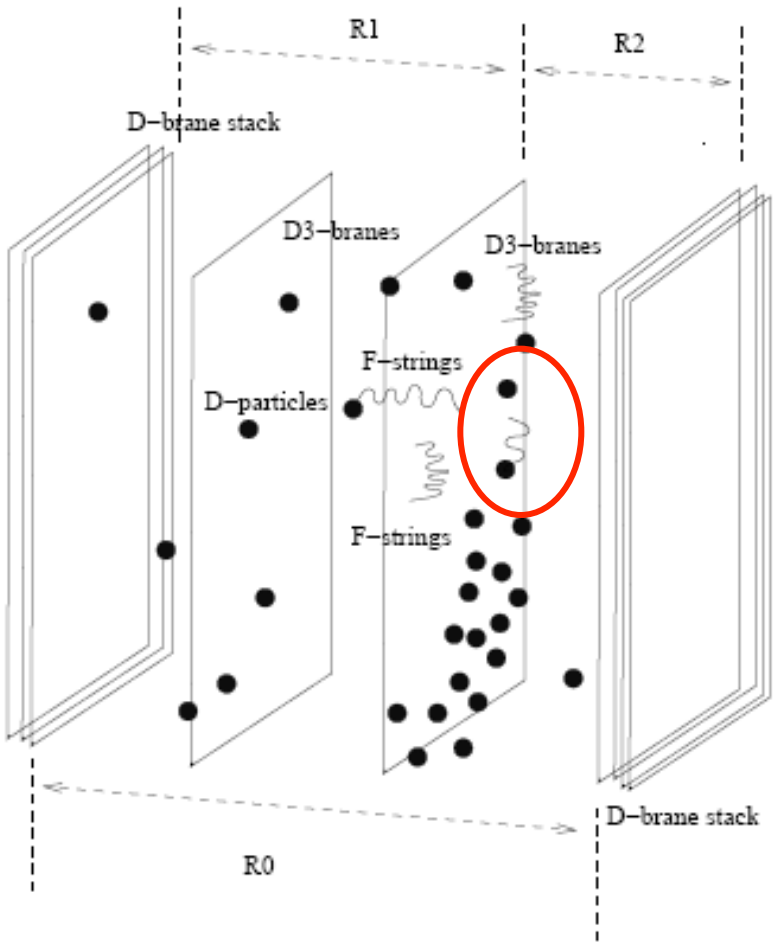




Problem Equivalent to
Strings propagating
in Local ``electric field''
backgrounds
Time-Space non-commutativity

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

But electric field is on
phase space



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Time-Space non-commutativity

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But electric field is on phase space

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

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

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

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

Local Lorentz Violation due to direction of Defect recoil velocities

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

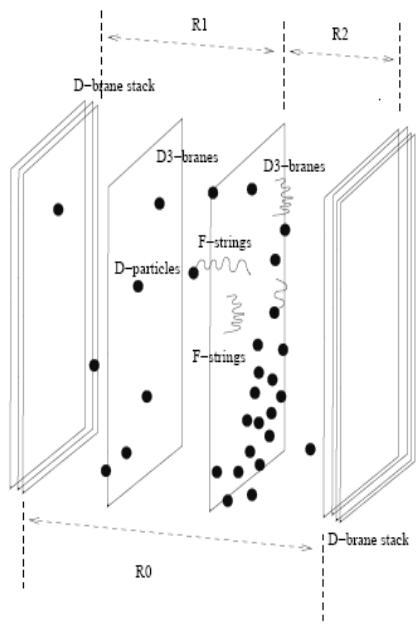
Isotropic
& homogeneous foam:

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

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

Lorentz Invariance on Average

Violated in flcts



c.f. Stochastic Foam, through coherent graviton states

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

$$\langle h_{\mu\nu} \rangle = 0$$

$$\langle h_{\mu\nu} h_{\rho\sigma} \rangle \neq 0$$

leading to light cone fluctuations

Ford (95)

NM, Ellis, Nanopoulos, Li, Xie

Dispersion Relations OF NEUTRAL PARTICLES (e.g. photons) may be modified *but quadratically suppressed by M_s / g_s*

$$k_\mu k_\nu g^{\mu\nu}(x,k) = -m^2$$

(m = 0 for photons)

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

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

$$\langle r_i \rangle = 0$$

$$\langle r_i r_j \rangle \neq 0$$

Inverse induced metric, depends on $\langle u_i u^i \rangle \neq 0$

$$g^{\mu\nu} = \begin{pmatrix} -\frac{1}{1+B} & \frac{r_1 k_1}{1+B} & \frac{r_2 k_2}{1+B} & \frac{r_3 k_3}{1+B} \\ \frac{r_1 k_1}{1+B} & 1 - \frac{r_1^2 k_1^2}{1+B} & -\frac{r_1 r_2 k_1 k_2}{1+B} & -\frac{r_1 r_3 k_1 k_3}{1+B} \\ \frac{r_2 k_2}{1+B} & -\frac{r_1 r_2 k_1 k_2}{1+B} & 1 - \frac{r_2^2 k_2^2}{1+B} & -\frac{r_2 r_3 k_2 k_3}{1+B} \\ \frac{r_3 k_3}{1+B} & -\frac{r_1 r_3 k_1 k_3}{1+B} & -\frac{r_2 r_3 k_2 k_3}{1+B} & 1 - \frac{r_3^2 k_3^2}{1+B} \end{pmatrix},$$

$$u_i = r_i k_i \quad \text{no sum i}$$

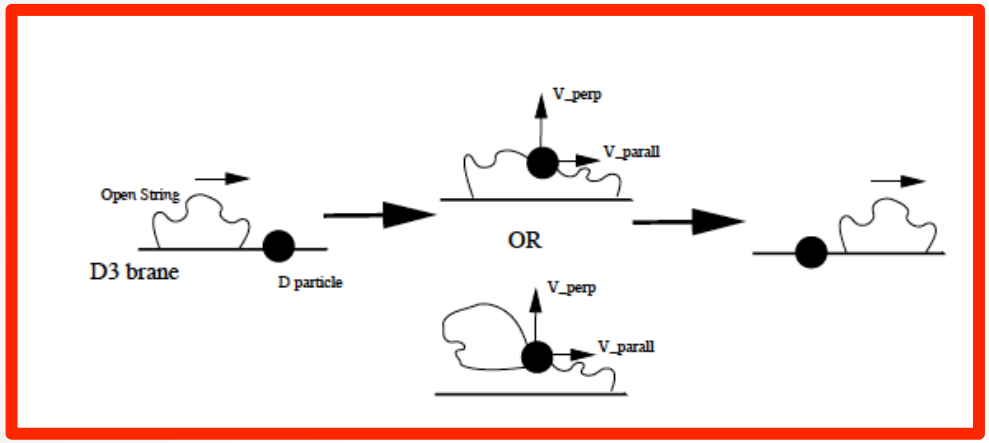
$$B = \sum_{i=1}^{3} r_i^2 k_i^2$$

NM, Ellis, Nanopoulos, Li, Xie

Dispersion Relations OF NEUTRAL PARTICLES (e.g. photons) may be modified ***but quadratically suppressed by M_s / g_s***

$$k_\mu k_\nu g^{\mu\nu}(x,k) = -m^2$$

(m = 0 for photons)



Stringy foam:
Prediction of ***Linearly*** modified ***vacuum refraction*** due to ***Time-Space uncertainties***
(c.f. time-space non commutativity confirmed by amplitude calculations)

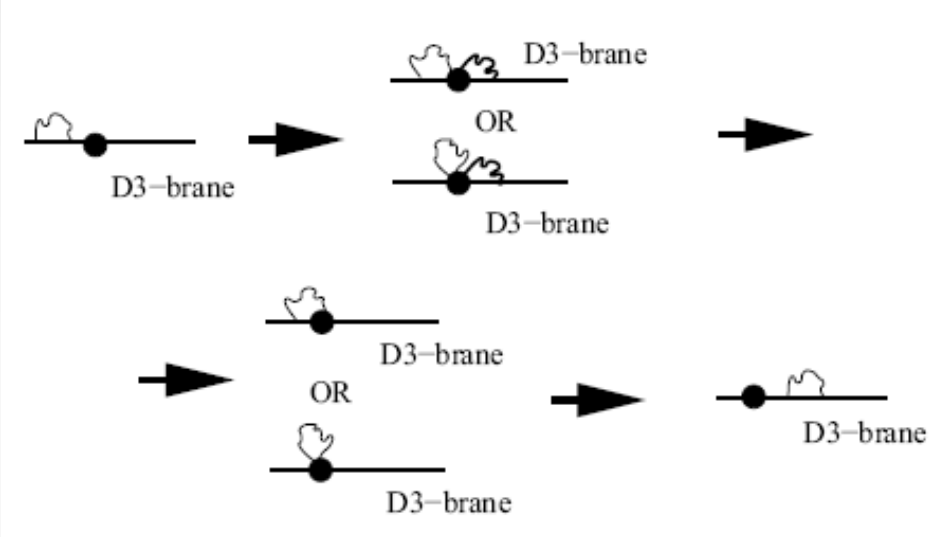
$$\Delta t \sim \sqrt{\alpha'} p^0$$

Time Delays of more energetic neutral matter proportional to Energy

Beyond Local Effective Field Theories – intermediate string state oscillating growth

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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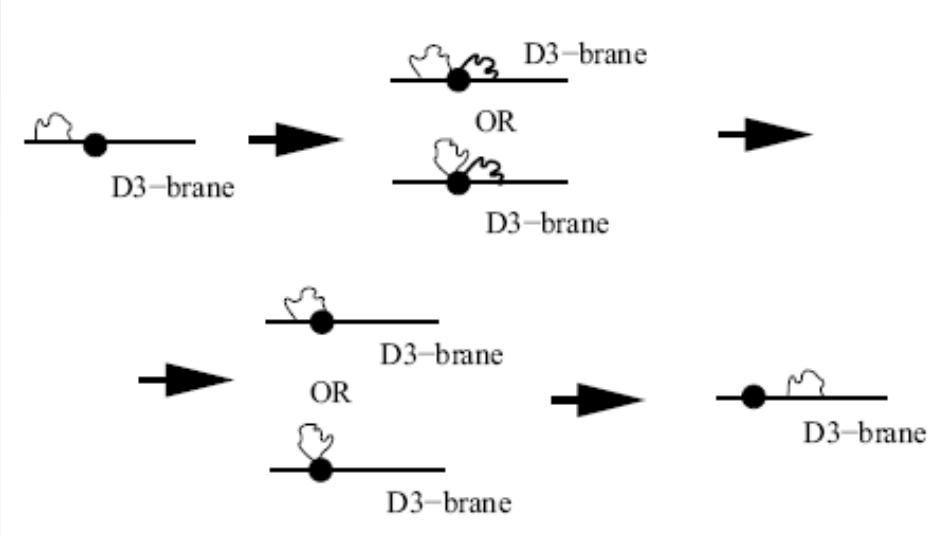

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Stringy Uncertainties & the D-Foam

- 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):

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

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COMPATIBLE WITH STRING UNCERTAINTY PRINCIPLES:

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

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

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

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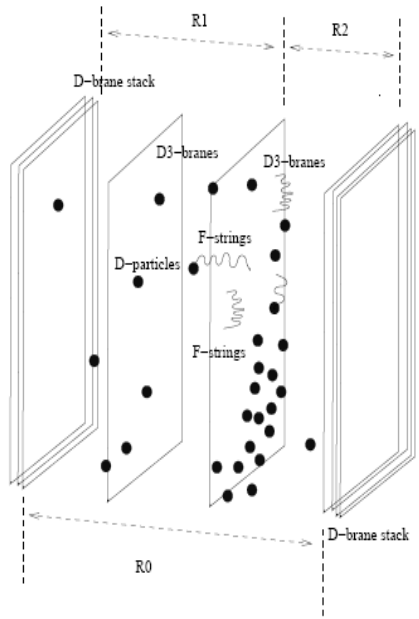
Effective QG Scale depending on density of D-foam

Space time Foam Universes

Total delay (of more energetic photons) proportional to density of foam (affected by cosmic expansion, z=redshift) :



$$(\Delta t)_{\rm obs} = \frac{\Delta E}{M_{\rm QG1}} {\rm H}_0^{-1} \int_0^z \frac{(1+z)dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}},$$

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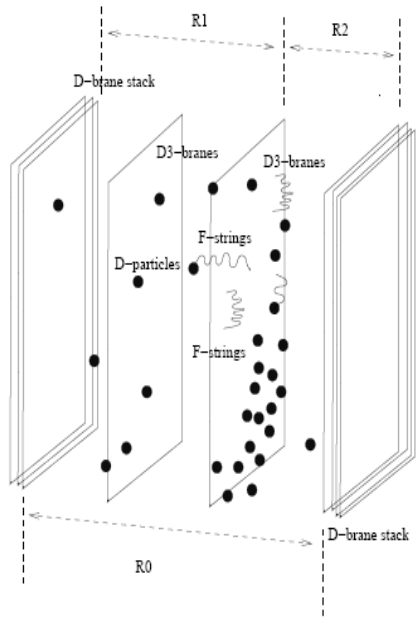

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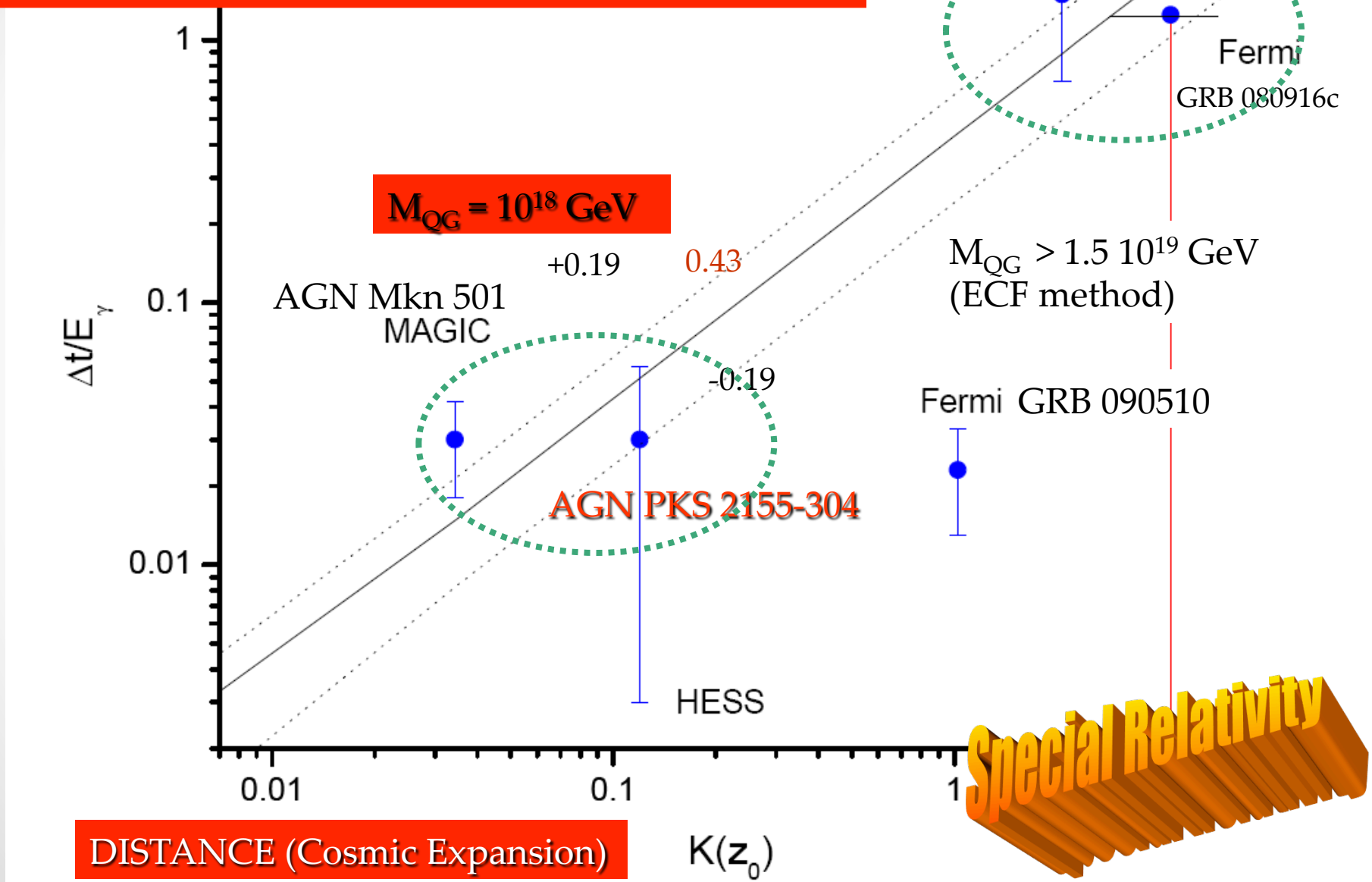
$$M_{\rm QG1} = \frac{M_s}{\eta(z) g_s (1 - \frac{g_s^2 |\vec{\Delta k}|^2}{M_s})}$$

$\eta(z)$ = linear density of foam defects, in general red-shift dependent

Isotropic & (in)homogeneous foam:

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

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



DISTANCE (Cosmic Expansion)

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

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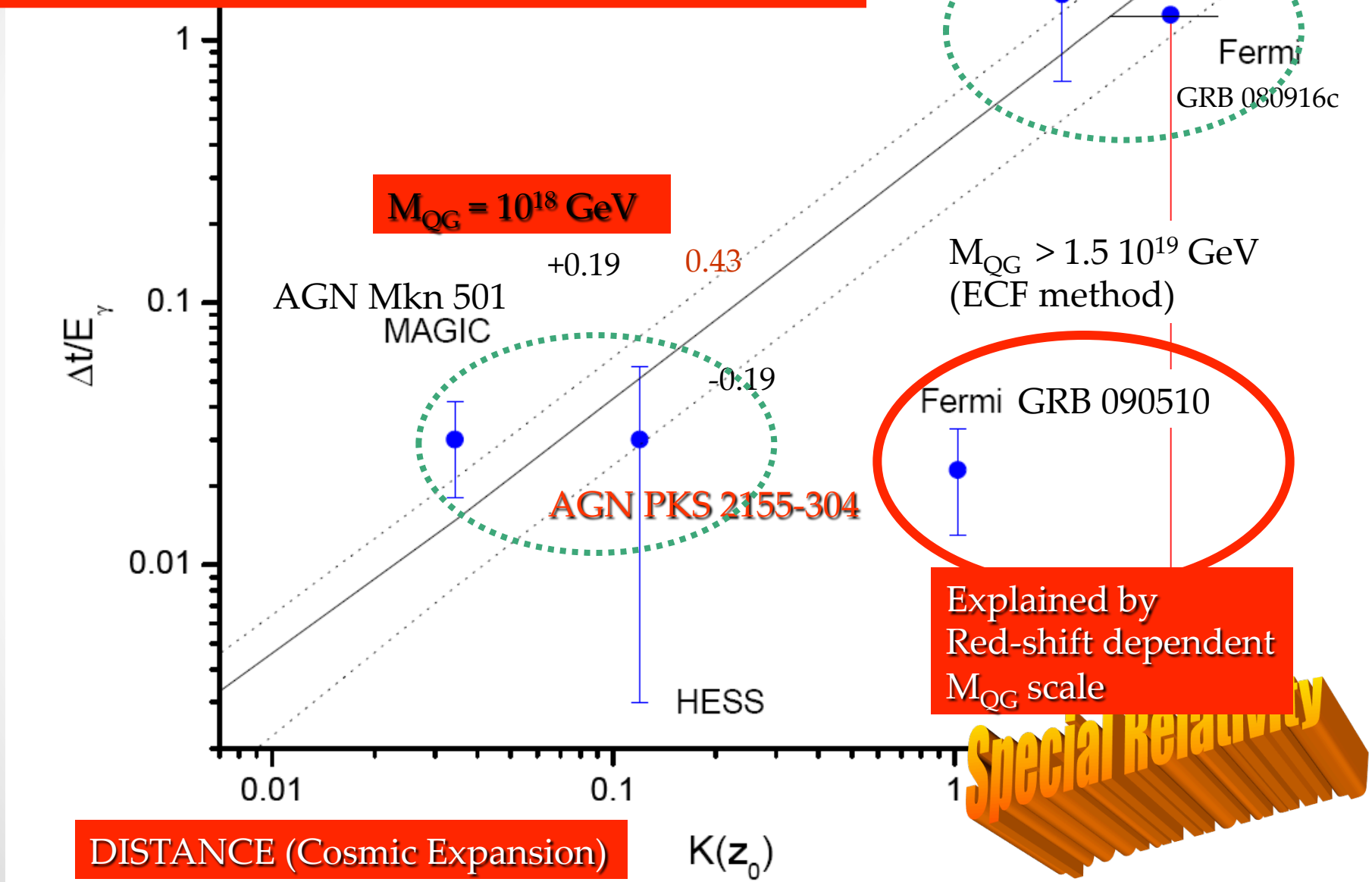

DISTANCE (Cosmic Expansion)

Need much more statistics *at various red-shifts* to disentangle source from propagation effects

Hopefully with more Active Galactic Nuclei (AGN) & GRB observations by FERMI-LAT & CTAs we shall achieve this soon…

WHY BEYOND LOCAL EFT?

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

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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…
Cannot represent the effect by local field operators (higher-derivatives) in a flat space-time lagrangian…

D-particle Recoil Formalism

σ-Model 1st Quantized Formalism

Recoil Velocity u_i as Constant Electric Field Background

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

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

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

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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 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)

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Space, Time Uncertainties...

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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

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

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Implies Finsler-type target-sp

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

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Induced (Finsler) Space-Time Metric

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

Implies Finsler-type target-space metric

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.

and effective string coupling

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BEYOND LOCAL EFFECTIVE FIELD THEORY

Implies Fi

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Effects of Recoil on Time Delays

$$\Delta t_{\text{recoil}} = \frac{\alpha' E}{1 - |\vec{u}|^2}$$

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

effective string coupling

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effective string coupling

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

Suppressed Relativistic Recoil Effects in Scattering Amplitudes

$$\mathcal{A}(1,2,3,4) \to (1 - |\vec{\tilde{u}}|^2)^{1/2} \mathcal{A}(1,2,3,4)$$

INCLUDE D-PARTICLE RECOIL

And thus string scattering amplitudes

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

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

$$\mathcal{A}(1,2,3,4) \to (1 - |\vec{\tilde{u}}|^2)^{1/2} \mathcal{A}(1,2,3,4)$$

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

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

RECAP: PROPERTIES OF D-particle FOAM

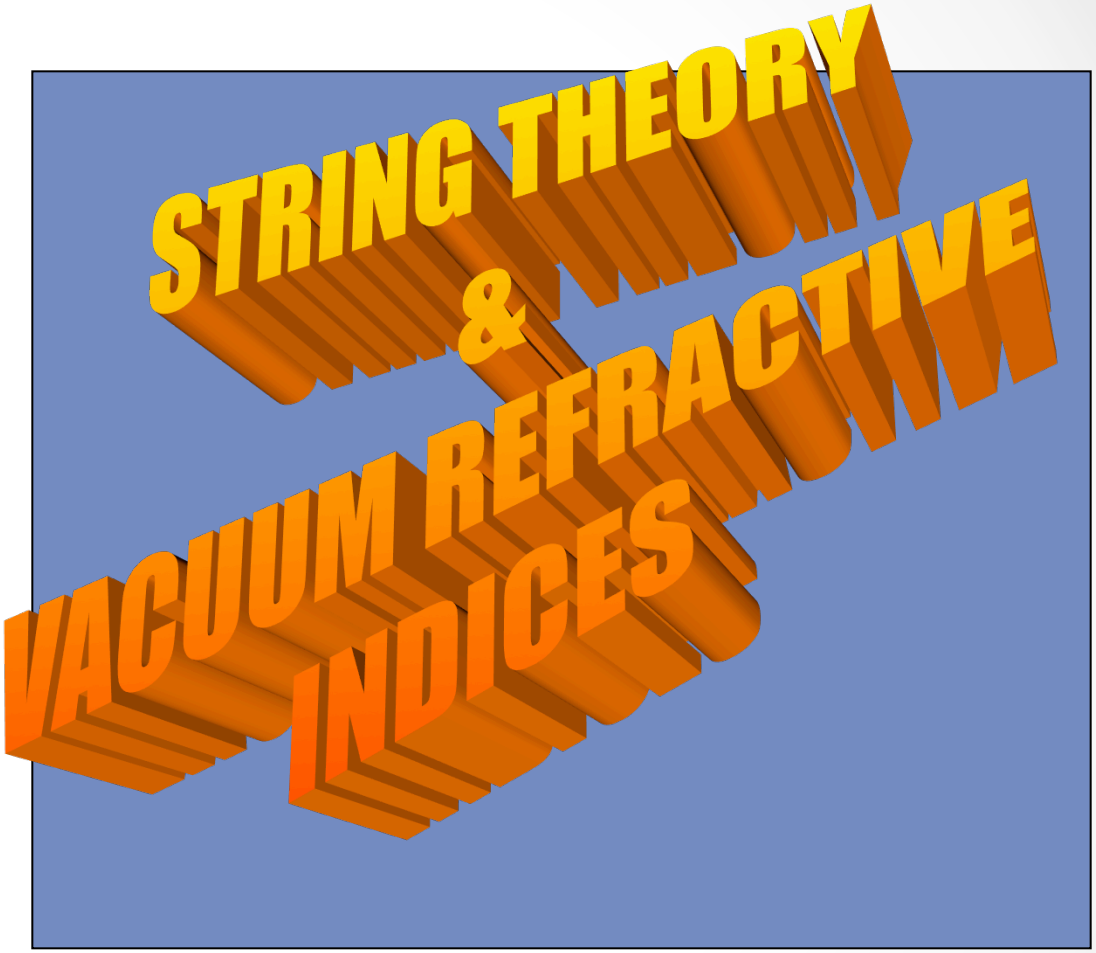
(1) Time Delays proportional to E dominant for photons

(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)



Model avoids constraints from:

Crab nebula synchrotron radiation –

Jacobson, Liberaty,Matingly (03)

electrons are charged, interact subdominantly with the foam , ***no appreciable*** maximum synchrotron radiation ***frequency shift***

Ellis, NM, Sakharov (04)

Birefringence :

No birefringence, superluminal propagation is excluded (underlying string theory, no superluminal propagation)

Model Avoids stringent constraints from ultra-high energy (> 10^{20} eV) cosmic rays

Galaverni, Liberati, Maccione,Sigl (08-10)

For very high energy delays vanish due to form of effective QG scale

$$M_{\mathrm{QG1}} = \frac{M_s}{\eta(z) g_s (1 - \frac{g_s^2 |\vec{\Delta k}|^2}{M_s})}$$

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$$\frac{g_s^2 |\vec{\Delta k}|^2}{M_s} \sim 1 \quad \Rightarrow \quad M_{\mathrm{QG1}} \to \infty$$

$$\Delta k_i \sim k_i > 10^{20} \mathrm{eV}$$

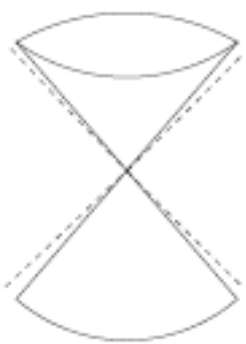
Another Effect :
Stochastic Light-Cone Fluctuations & Broadening of Photon peaks with energy

"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)

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

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



Light Cone Fluct.
(quantum)

$P_\mu P_\nu g^{\mu\nu} = -m^2$

$< g^{\mu\nu} g^{\rho\sigma} > =/= 0$ (non trivial)

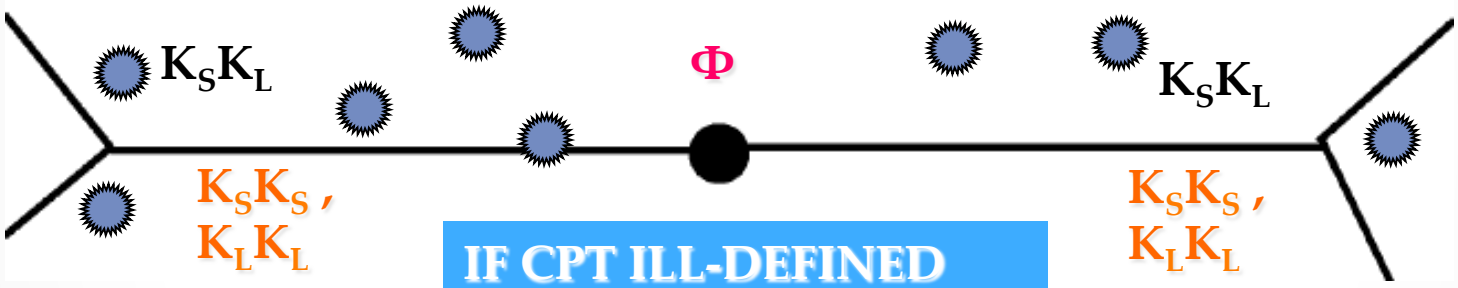
Observed Width of Photon Peaks increases at arrival with Energy

ω-effect

- 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)

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

Bernabeu, NM, Sarkar

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)

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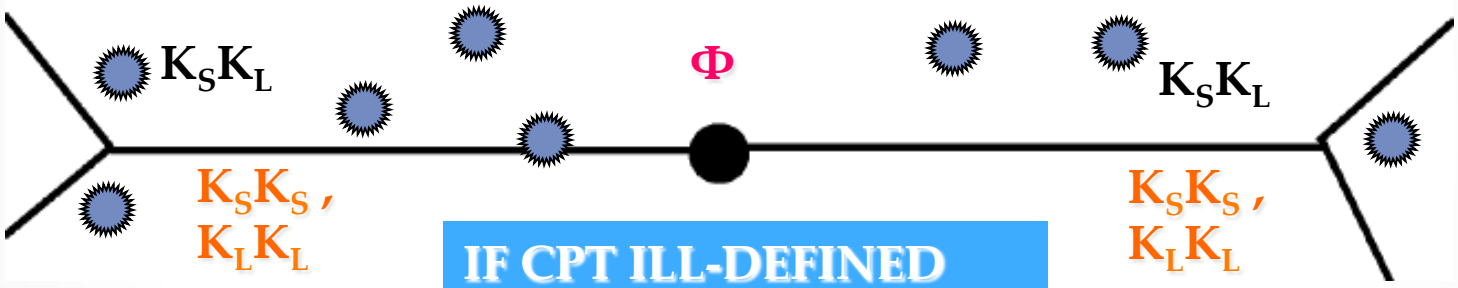

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Amplification due to mass degeneracy

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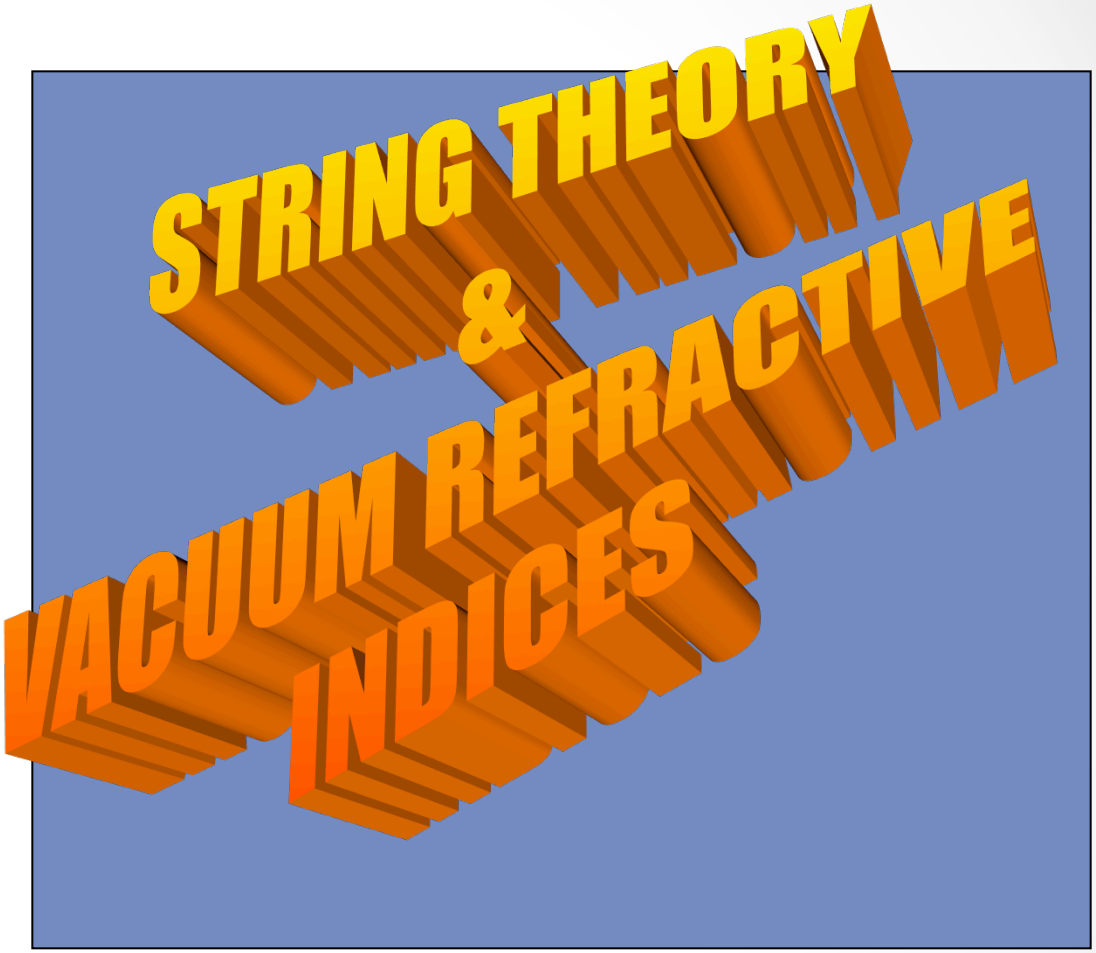


CONSISTENCY WITH CURRENT ASTROPHYSICAL AND COSMOLOGICAL TESTS

CONCLUSIONS-LECTURE I

Quantum Gravity may violate spontaneously (or explicitly) fundamental space-time symmetries, such as Lorentz and/or CPT

Concrete models from string theory do exist with such violations.

Consistency of those Models with Cosmology remains to be seen but at present are sufficiently instructive to make concrete predictions with ``smoking gun '' evidence for such violations, unique to those models, beyond Local Effective Field Theories

(i) Time delays of more energetic cosmic photons proportional to Energy

(ii) Modifications of EPR correlators of entangled particle states

Such predictions can be disentangled from those of other local field theory models with Lorentz Violation and may be falsifiable in the near future

LECTURE II

D-FOAM COSMOLOGY:
CPT VIOLATION

MODIFIED GRAVITY
GALACTIC GROWTH
MODIFIED
DARK-MATTER & ENERGY BUDGET

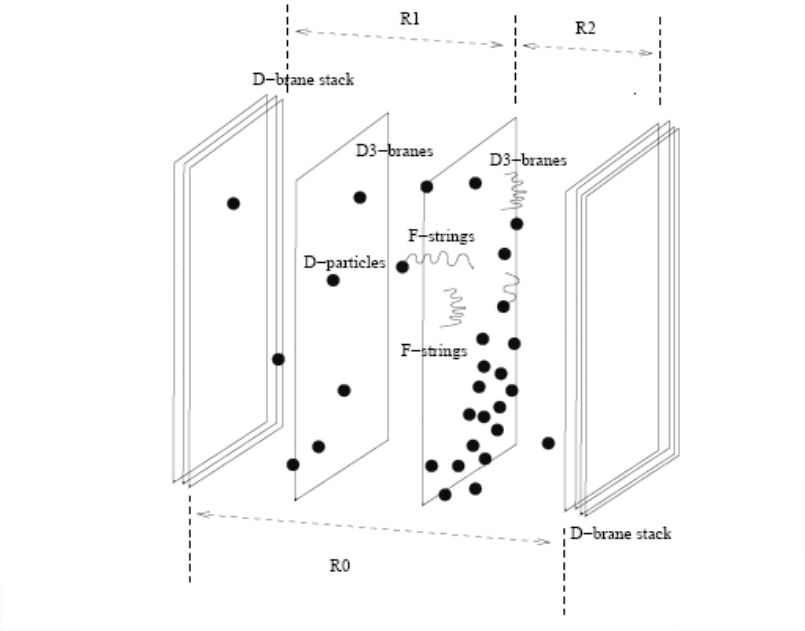
COSMOLOGICAL EFFECTS OF D-FOAM

PRESENCE OF D-PARTICLES AFFECTS:

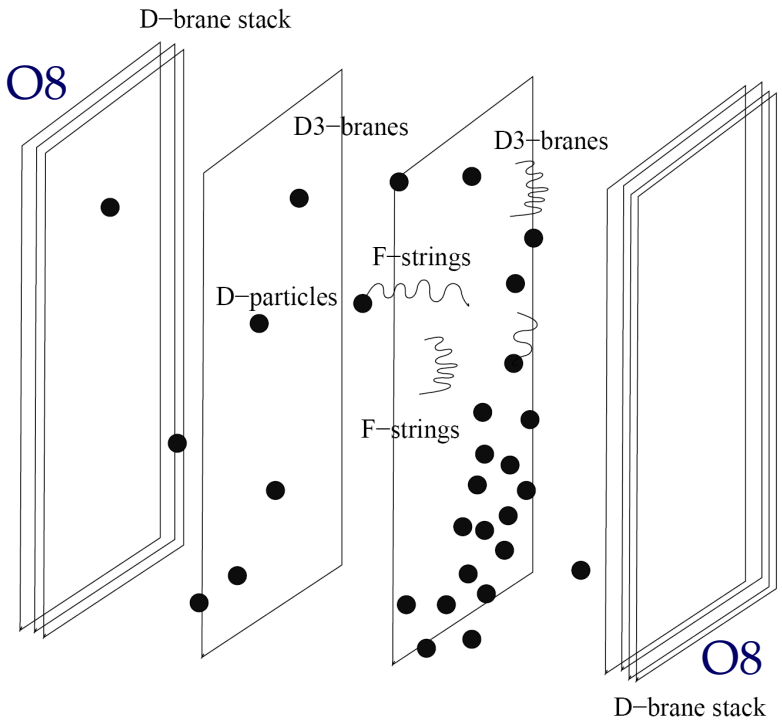
PARTICLE/ANTIPARTICLE DISPERSION RELATIONS

HUBBLE EXPANSION

DARK ENERGY & MATTER BUDGET



D-FOAM & THE DARK SECTOR

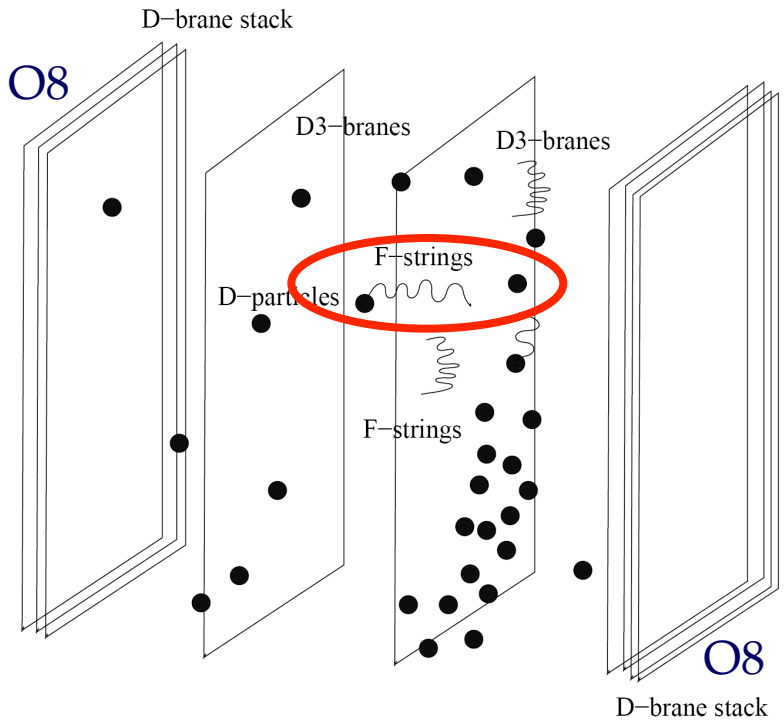


Ellis, NM, Westmuckett

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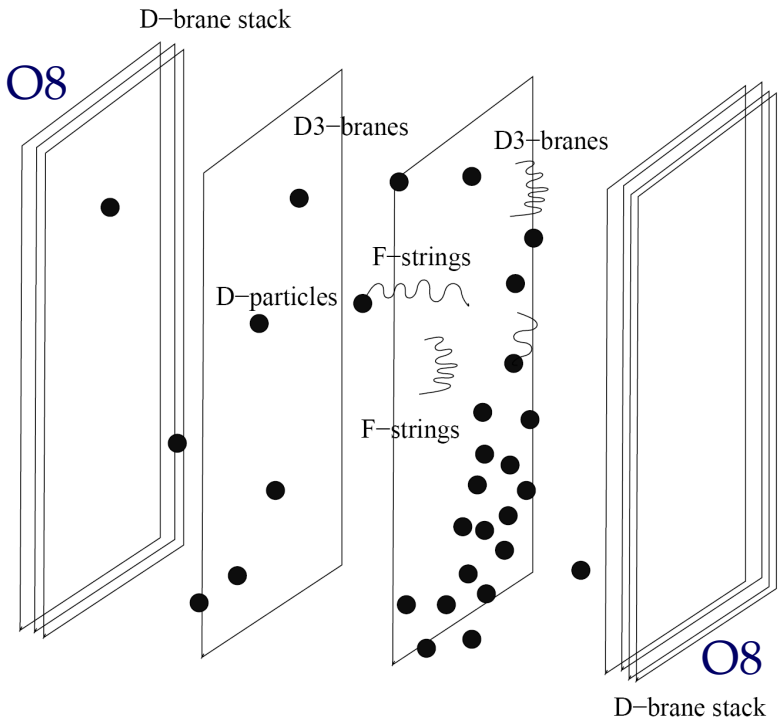
Contributions to Brane potentials (additional contrib. to Dark Energy)



D-FOAM & THE DARK SECTOR

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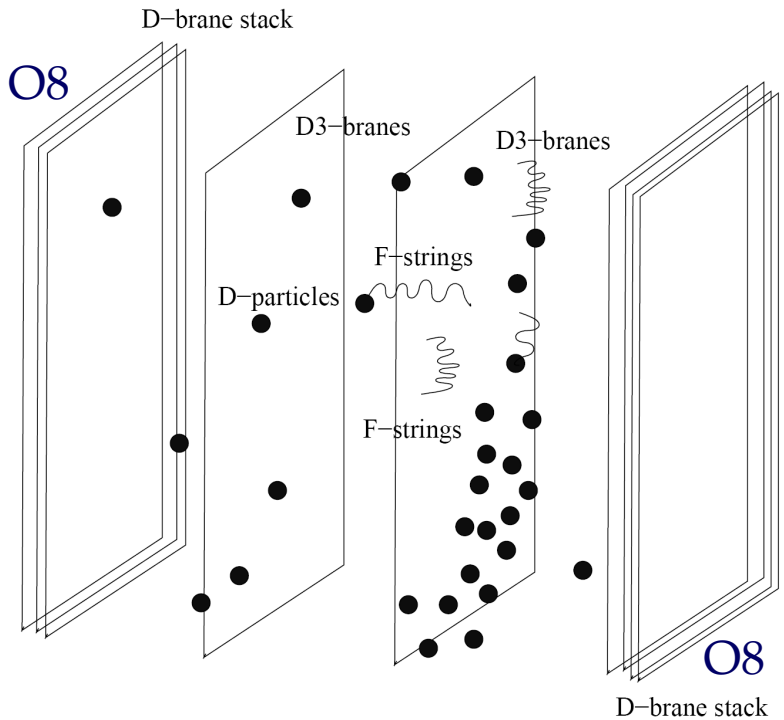
Contributions to Brane potentials (additional contrib. to Dark Energy)

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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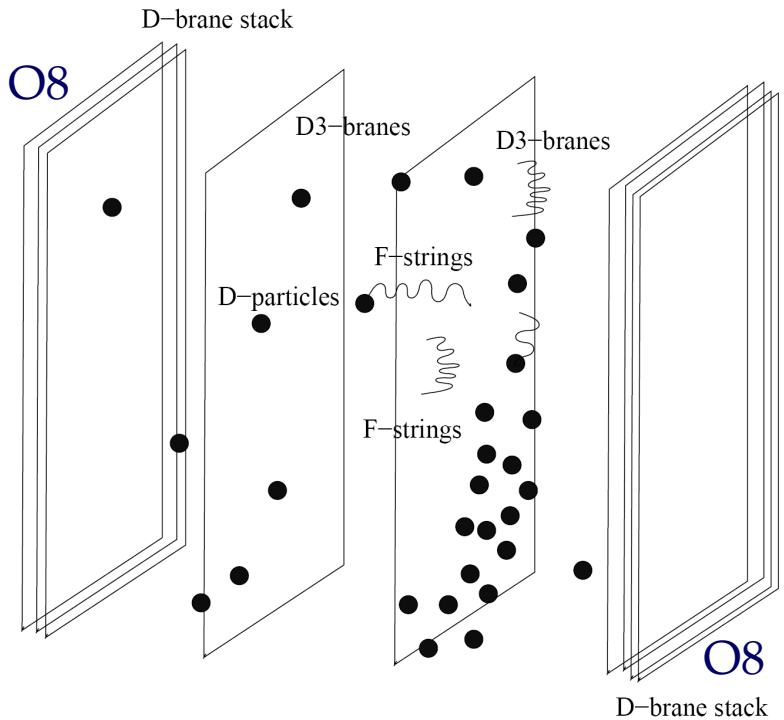

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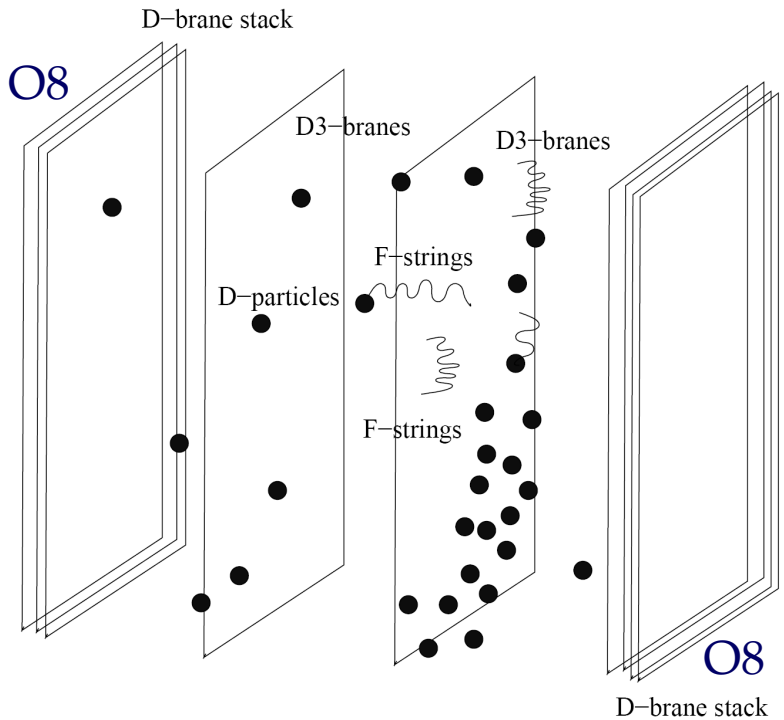
Sign of velocity-dependent terms in potential depends on D-particle/D-brane distance. May cancel out over long periods



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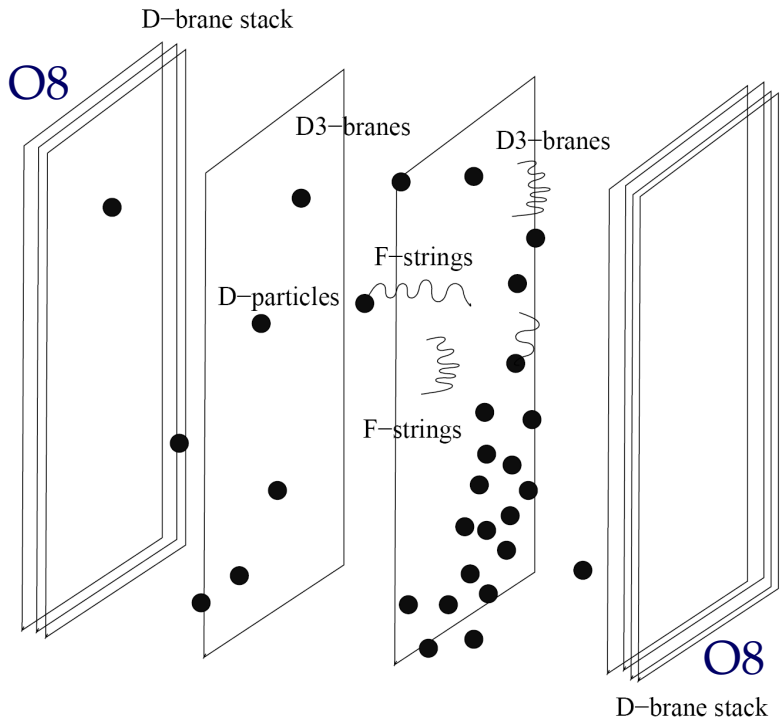

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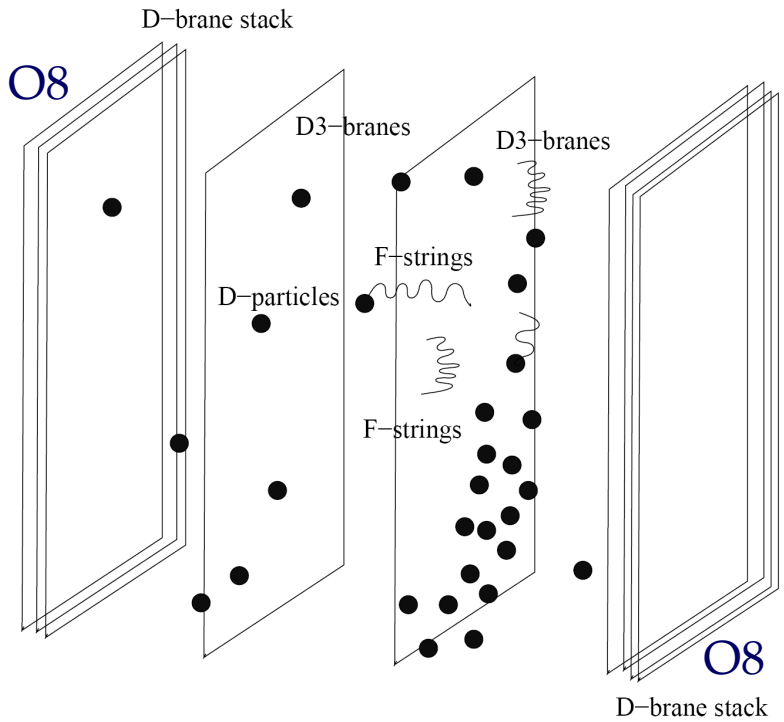

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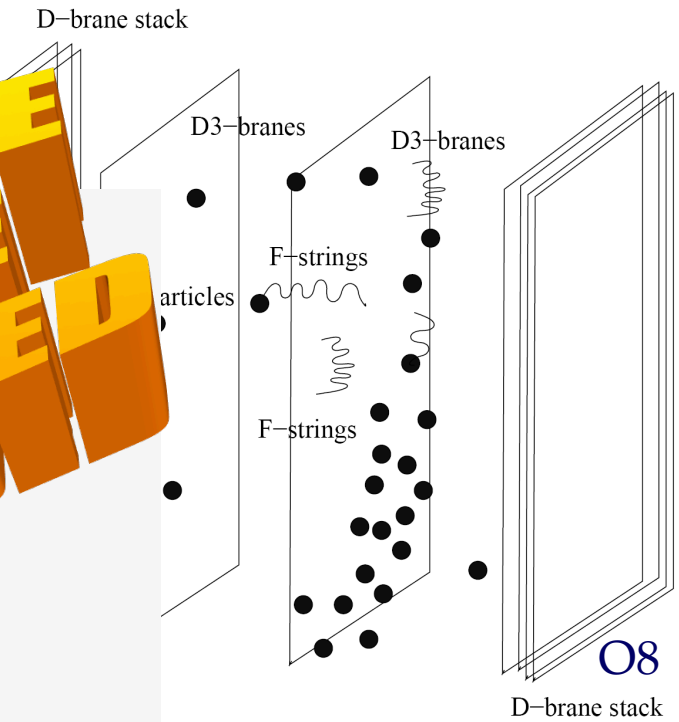

OVERCLOSURE OF UNIVERSE MAY BE AVOIDED IN D-FOAM

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

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

THUS WE CAN CONSIDER **SUFFICIENTLY LARGE D-PARTICLE DENSITIES** IN BULK AND ON THE BRANE AT EARLY EPOCHS OF THE UNIVERSE, NOT NECESSARILY IN PRESENT ERA, MUCH LARGER THAN RADIATION & MATTER DENSITIES

THIS HAS THE ADVBANTAGE OF DISCUSSING PROPAGATION OF MATTER & RADIATION IN ``**MEDIA**'' OF **D-PARTICLES**

EFFECTS: **(I) INDUCED *CPT VIOLATION* AMONG NEUTRINOS @ EARLY EPOCHS → COMMUNICATED TO BARYON SECTOR VIA B(aryon)-L(epton) NUMBER PRESERVING PROCESSES → baryogenesis from leptogenesis**

Sarben Sarkar & NEM arXiv:1211.0968

(II) *ENHANCED GALACTIC GROWTH* due to D(EFECT) -FOAM → role of Defects as Dark Matter

NEM, Sakellariadou & Yusaf arXiv:1211.1726

(III) *MODIFIED DARK MATTER RELIC ABUNDANCES*

NM, Mitsou, Vergou, Sarkar 2010

Generic Concepts

- ***Leptogenesis***: physical ***out of thermal equilibrium*** processes in the (***expanding)*** Early Universe that produce an asymmetry between leptons & antileptons

- ***Baryogenesis***: The corresponding processes that produce an asymmetry between baryons and antibaryons

- ***Ultimate question: why is the Universe made only of matter?***

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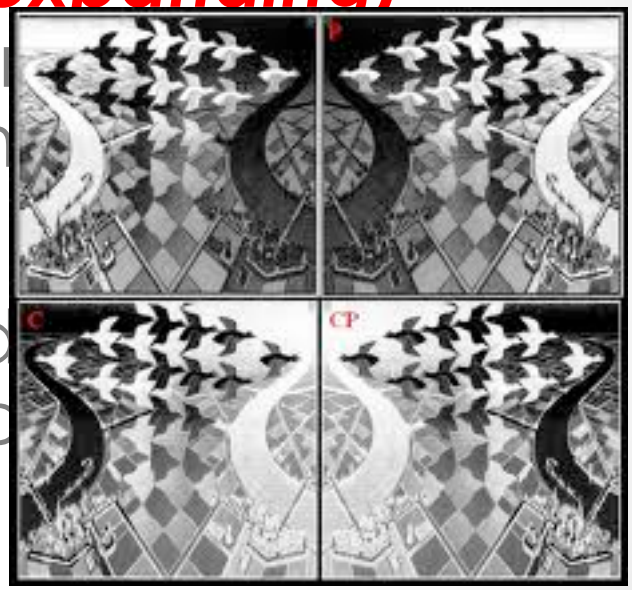

escher

- ***Ultimate question: why is the Universe made only of matter?***

NEUTRINOS & LEPTOGENESIS

- Matter-Antimatter asymmetry in the Universe ➡ Violation of Baryon # (B), C & CP
- Tiny CP violation (O(10^{-3})) in Labs: e.g. $K^0 \overline{K}^0$
- But Universe consists only of matter

$$\frac{n_B - \overline{n}_B}{n_B + \overline{n}_B} \sim \frac{n_B - \overline{n}_B}{s} = (8.4. - 8.9) \times 10^{-11}$$

T > 1 GeV

Sakharov : Non-equilibrium physics of early Universe, **B, C, CP violation**

➡ $n_B - \bar{n}_B$ but **not quantitatively in SM**, still a mystery

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Assume CPT

Beyond SM sources of CPViolation?

- Several Ideas to go beyond the SM (e.g. GUT models, Supersymmetry, extra dimensional models etc.)
- Massive ν are **simplest** extension of SM
- Right-handed supermassive ν may provide extensions of SM with:

extra CP Violation and thus Origin of Universe's **matter-antimatter asymmetry** due to neutrino masses, **Dark Matter**

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…**BUT** ***MAY NOT BE NECESSARY IF CPT VIOLATION IN EARLY UNIVERSE***

CPT VIOLATION IN THE EARLY UNIVERSE

GENERATE Baryon and/or Lepton ASYMMETRY without Heavy Sterile Neutrinos?

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CPT Invariance Theorem :

(i) Flat space-times
(ii) Lorentz invariance
(iii) Locality
(iv) Unitarity

Schwinger, Pauli, Luders, Jost, Bell
revisited by:
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Kostelecky , Mewes, Diaz ….
Standard Model Extension (SME)
PHENOMENOLOGICAL 3-LV parameter (texture) model for neutrino oscillations fitting also LSND, MINOS

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Barenboim, Borissov, Lykken PHENOMENOLOGICAL models with non-local mass parameters

(ii)-(iv) Independent reasons for violation

$$\mathbf{S} = \int d^4x\, \bar{\psi}(x) i\partial\!\!\!/ \psi(x) + \frac{im}{\pi} \int d^3x \int dt dt'\, \bar{\psi}(t, \mathbf{x}) \frac{1}{t - t'} \psi(t', \mathbf{x}).$$

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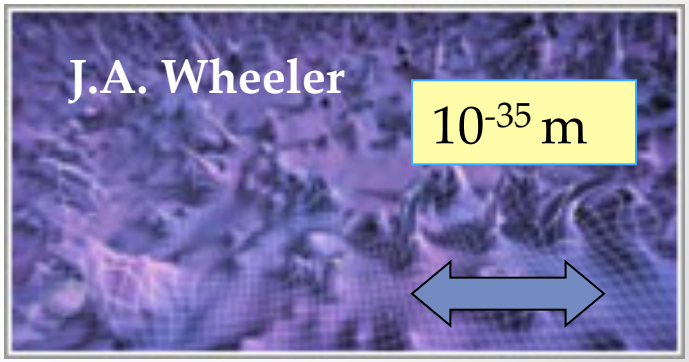
e.g. ***QUANTUM SPACE-TIME FOAM AT PLANCK SCALES***



CPT VIOLATION IN THE EARLY UNIVERSE

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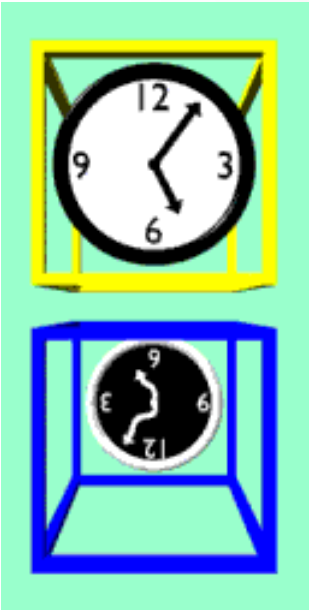
Assume CPT Violation.
e.g. due to ***Quantum Gravity*** fluctuations, ***strong*** in the Early Universe



physics.indiana.edu

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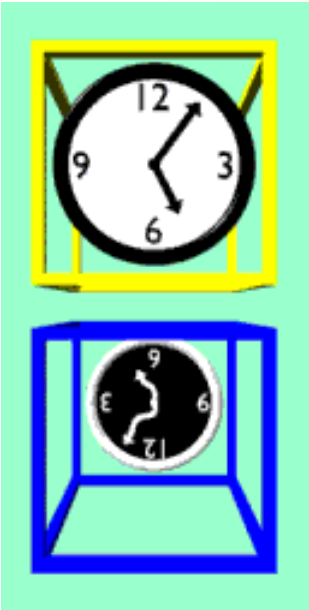

ONE POSSIBILITY:

particle-antiparticle mass differences

$$m \neq \overline{m}$$

physics.indiana.edu

Equilibrium Distributions different between particle-antiparticles

Can these create the observed matter-antimatter asymmetry?

$$f(E,\mu) = \frac{1}{\exp[(E-\mu)/T] \pm 1}$$

$$m \neq \overline{m}$$

$$\delta m = m - \overline{m}$$

$$\delta n \equiv n - \bar{n} = g_{df} \int \frac{d^3p}{(2\pi)^3} \left[f(E,\mu) - f(\bar{E},\bar{\mu})\right]$$

$$E = \sqrt{p^2 + m^2},\ \bar{E} = \sqrt{p^2 + \bar{m}^2}$$

Dolgov, Zeldovich
Dolgov (2009)

Assume dominant contributions to Baryon asymmetry from quarks-antiquarks

$$m(T) \sim gT$$

High-T quark mass >> Lepton mass

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Assuming dominant contributions to Baryon asymmetry from quarks-antiquarks

$$\boxed{\beta_T = \frac{n_B}{n_\gamma} = -8.4 \cdot 10^{-3} \left(18 m_u \delta m_u + 15 m_d \delta m_d\right) / T^2}$$

Dolgov, Zeldovich
Dolgov (2009)

$n_\gamma = 0.24 T^3$ photon equilibrium density at temperature T

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$$n_\gamma = 0.24 T^3$$

Dolgov (2009)

Current bound for protons

$$\delta m_p < 2 \cdot 10^{-9} \text{ GeV}$$

Reasonable to take: $\delta m_q \sim \delta m_p$ → ***Too small*** $\beta^{T=0}$

NB: To reproduce the observed $\beta^{(T=0)} = 6 \cdot 10^{-10}$ need

$$\delta m_q (T = 100 \text{ GeV}) \sim 10^{-5} - 10^{-6} \text{ GeV} >> \delta m_p$$

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CPT Violating quark-antiquark Mass difference alone CANNOT REPRODUCE observed BAU

OTHER INTERESTING IDEAS FOR GENERATING CPT VIOLATING EFFECTS (PARTICLE-ANTIPARTICLE DIFFERENCES IN DISPERSION RELATIONS) IN THE EARLY UNVIERSE

CPTV Effects of different Space-Time-Curvature/Spin couplings between ν, $\bar{\nu}$

B. Mukhopadhyay, U. Debnath, N. Dadhich, M. Sinha

Curvature Coupling to **fermion spin** may lead to different dispersion relations between neutrinos and antineutrinos in the Early Universe in **non-spherically symmetric** (e.g. axisymmetric, Bianchi type) geometries in the Early Universe.

$$ds^2 = -dt^2 + S(t)^2\, dx^2 + R(t)^2\, [dy^2 + f(y)^2\, dz^2] - S(t)^2\, h(y)\, [2dx - h(y)\, dz]\, dz$$

Bianchi II, VIII and IX models, respectively $f(y)$ and $h(y)$ are given as

$$f(y) = \{y, \sinh y, \sin y\}, \qquad h(y) = \{-y^2/2, -\cosh y, \cos y\}.$$

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

$$D_a = \left(\partial_a - \frac{i}{4}\omega_{bca}\sigma^{bc}\right),$$

Gravitational covariant derivative including spin connection

$$\sigma^{ab} = \frac{i}{2}\left[\gamma^a, \gamma^b\right]$$

$$\omega_{bca} = e_{b\lambda}\left(\partial_a e^{\lambda}_{c} + \Gamma^{\lambda}_{\gamma\mu} e^{\gamma}_{c} e^{\mu}_{a}\right).$$

$$e^{\mu}{}_{a} e^{\nu}{}_{b} \eta^{a\,b} = g^{\mu\nu}$$

vielbeins (tetrads)

Christoffel Symbol

$$\Gamma^{\lambda}_{\mu\nu} = \frac{1}{2}\, g^{\lambda\rho}\left(g_{\rho\mu,\nu} + g_{\rho\nu,\mu} - g_{\mu\nu,\rho}\right)$$

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$$\omega_{bca} = e_{b\lambda}\left(\partial_a e_c^\lambda + \Gamma^\lambda_{\gamma\mu} e_c^\gamma e_a^\mu\right).$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[\left(i\gamma^a\partial_a - m\right) + \gamma^a\gamma^5 B_a\right]\psi,$$

$$B^d = \epsilon^{abcd} e_{b\lambda}\left(\partial_a e_c^\lambda + \Gamma^\lambda_{\alpha\mu} e_c^\alpha e_a^\mu\right)$$

Can be constant in a given local frame in Early Universe axisymmetric cosmologies or near rotating Black holes

Dirac Lagrangian (for concreteness, it can be extended to Majorana neutrinos)

$$\mathcal{L} = \sqrt{-g}\left(i\,\bar{\psi}\,\gamma^a D_a \psi - m\,\bar{\psi}\psi\right)$$

for the Majorana neutrinos, above $\mathcal{L}_I$ turns out explicitly as

$$\mathcal{L}_I = \psi_L^\dagger \gamma^a \psi_L B_a, \qquad \mathcal{L}_I = -\psi_L^{c\,\dagger} \gamma^a \psi_L^c B_a$$

$$\mathcal{L} = \mathcal{L}_f + \mathcal{L}_I = \sqrt{-g}\bar{\psi}\left[(i\gamma^a \partial_a - m) + \gamma^a \gamma^5 B_a\right]\psi,$$

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Can be constant in a given local frame in Early Universe axisymmetric cosmologies or near rotating Black holes

DISPERSION RELATIONS OF NEUTRINOS ARE *DIFFERENT* FROM THOSE OF ANTINEUTRINOS IN *SUCH* GEOMETRIES

$(p_a \pm B_a)^2 = m^2,$ ± refers to chiral fields (here neutrino/antineutrino)

CPTV Dispersion relations

$$E = \sqrt{(\vec{p} - \vec{B})^2 + m^2} + B_0 \ , \quad \bar{E} = \sqrt{(\vec{p} + \vec{B})^2 + m^2} - B_0$$

but masses are equal between particle/anti-particle sectors

Abundances of neutrinos in Early Universe, then, ***different*** from those of antineutrinos if $\mathbf{B_0}$ is ***non-trivial***.

Abundances of neutrinos in Early Universe *different* from those of antineutrinos if $B_0 \neq 0$

$$\Delta n = \frac{g}{(2\pi)^3} \int d^3\mathbf{p} \left[\frac{1}{1+\exp(E_\nu/T)} - \frac{1}{1+\exp(E_{\bar{\nu}}/T)} \right]$$

$$\Delta n = \frac{g}{(2\pi)^2} T^3 \int_0^\infty \int_0^\pi \left[\frac{1}{1+e^u\, e^{B_0/T}} - \frac{1}{1+e^u\, e^{-B_0/T}} \right] u^2\, d\theta\, du$$

$$u = |\vec{p}|/T$$

$$\Delta n_\nu \equiv n_\nu - n_{\bar{\nu}} \sim g^\star\, T^3 \left(\frac{B_0}{T} \right)$$

with $g^\star$ the number of degrees of freedom for the (relativistic) neutrino.

BARYOGENESIS VIA LEPTOGENESIS

$$\Delta n_\nu \equiv n_\nu - n_{\overline{\nu}} \sim g^\star T^3 \left(\frac{B_0}{T}\right)$$

@ T = T_d (decoupling Temp. of Lepton number (L) Violating processes) there is a ***constant ratio*** of net neutrino/antineutrino asymmetry (ΔL) to entropy density (~T^3)

$$\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} \sim \frac{B_0}{T_d}$$

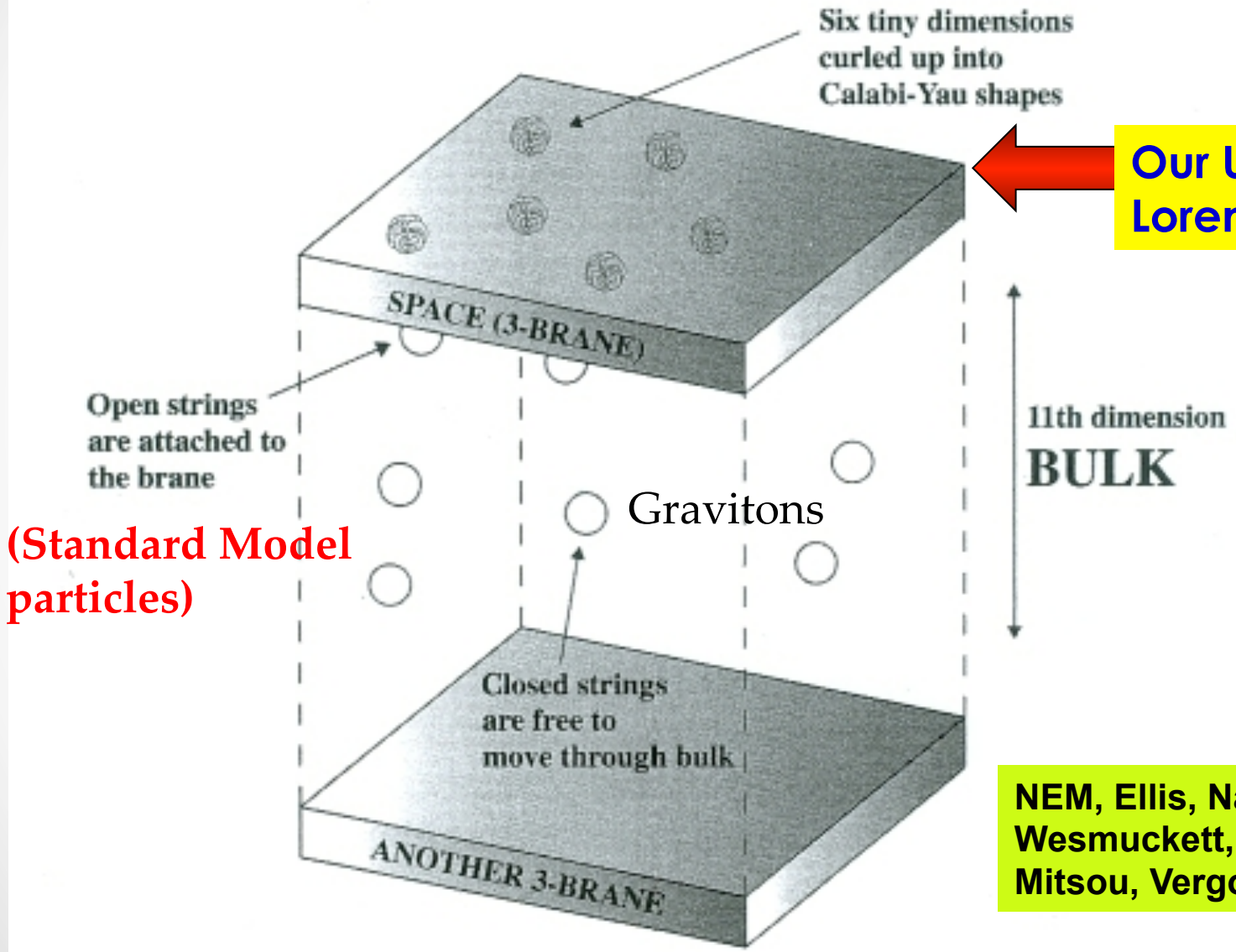
for $T_d \sim 10^{15}$ GeV and $B_0 \sim 10^5$ GeV

$\Delta L \sim 10^{-10}$, in agreement with observations (***Leptogenesis***)

Communicated to Baryon sector, and thus generates BAU either via a B-L conserving symmetry as in GUT models or via B + L conserving sphaleron processe → ***BARYOGENESIS***

BACK TO OUR D-FOAM

A MICROSCOPIC MODEL OF SPACE-TIME FOAM IN THE EARLY UNIVERSE WITH THIS TYPE OF CPTV MODIFIED DISPERSION

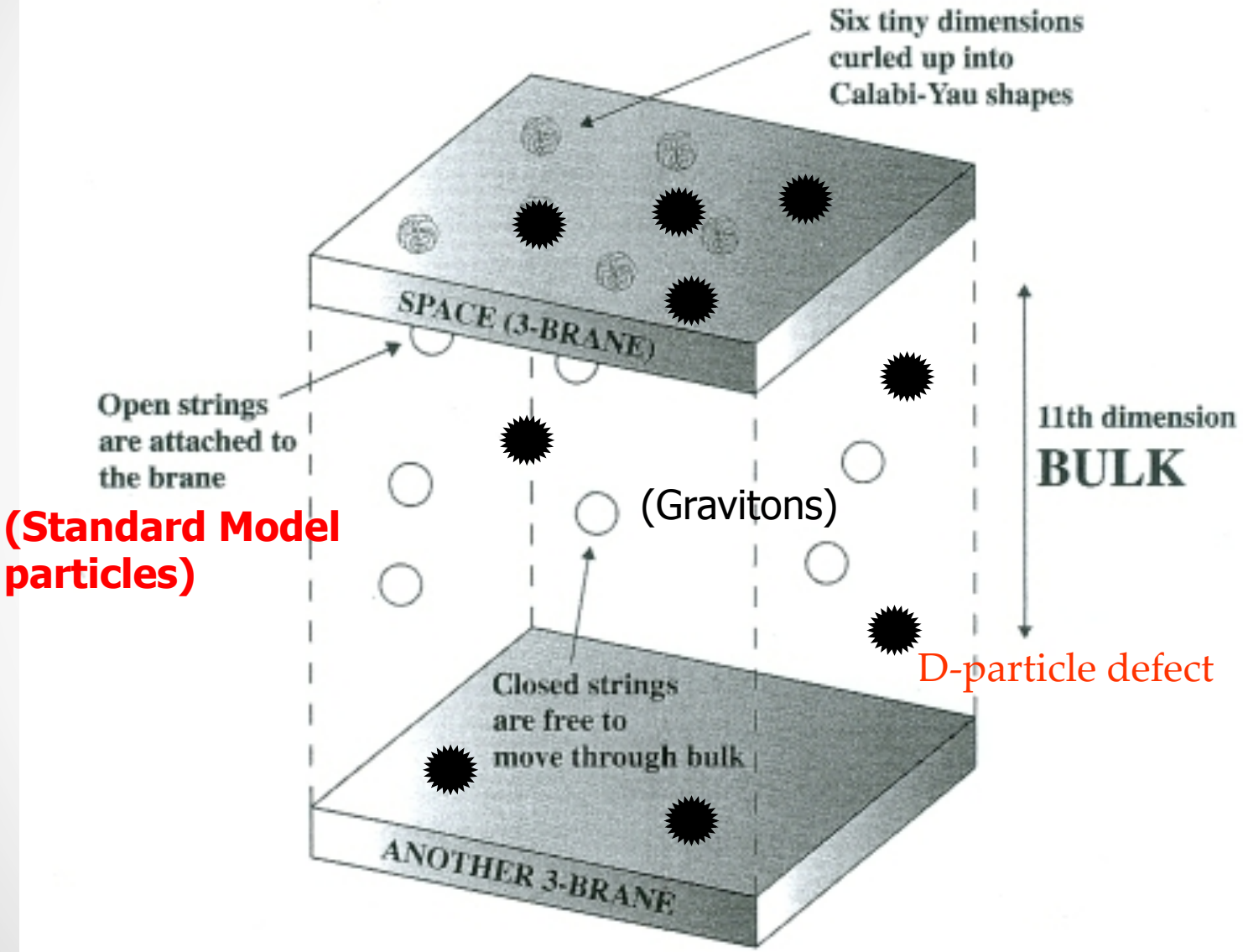


Our Universe Lorentz Invariant

(Standard Model particles)

NEM, Ellis, Nanopoulos Wesmuckett, Sarben Sarkar, Mitsou, Vergou

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



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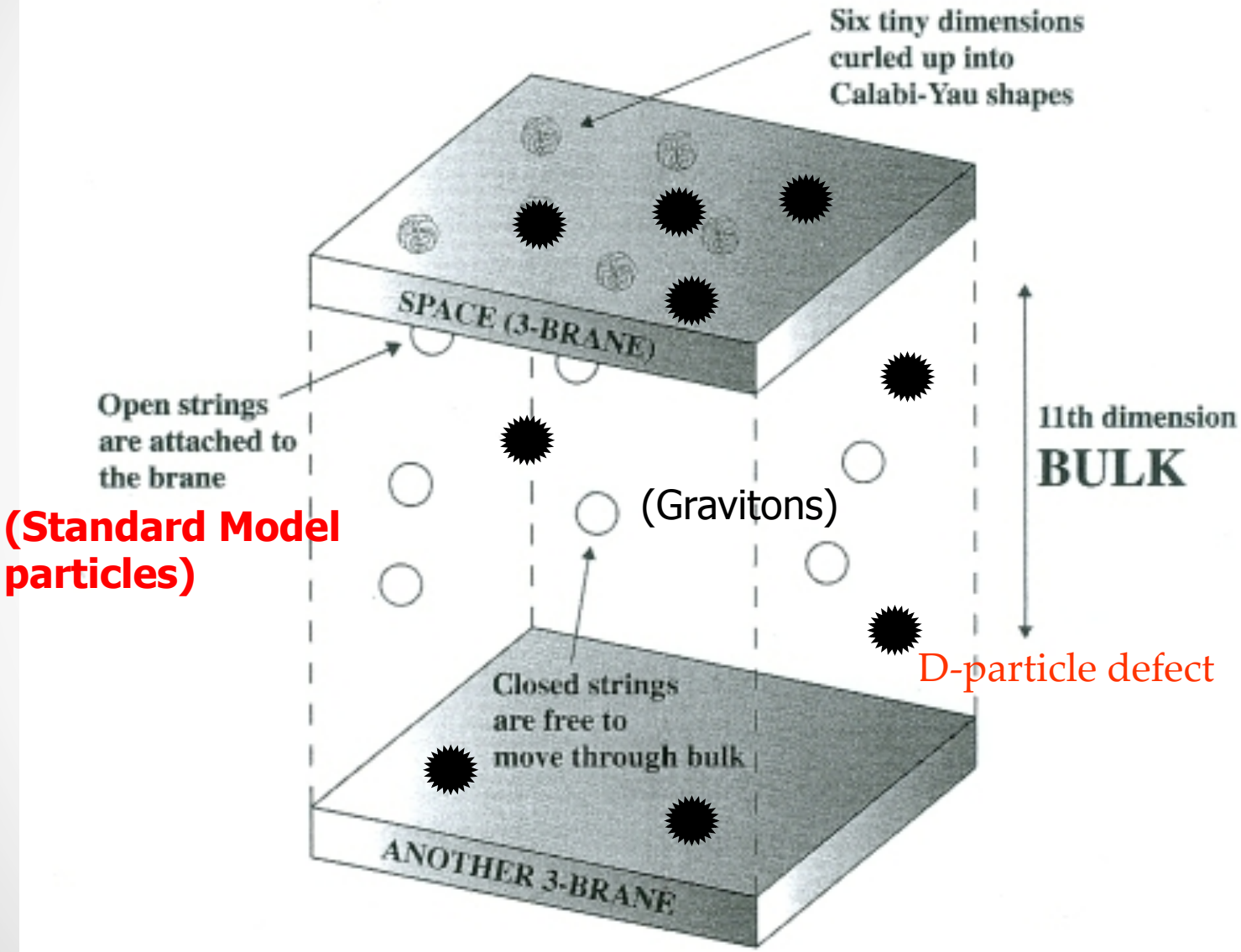

``Effectively point-like": p-branes wrapped around p-cycles

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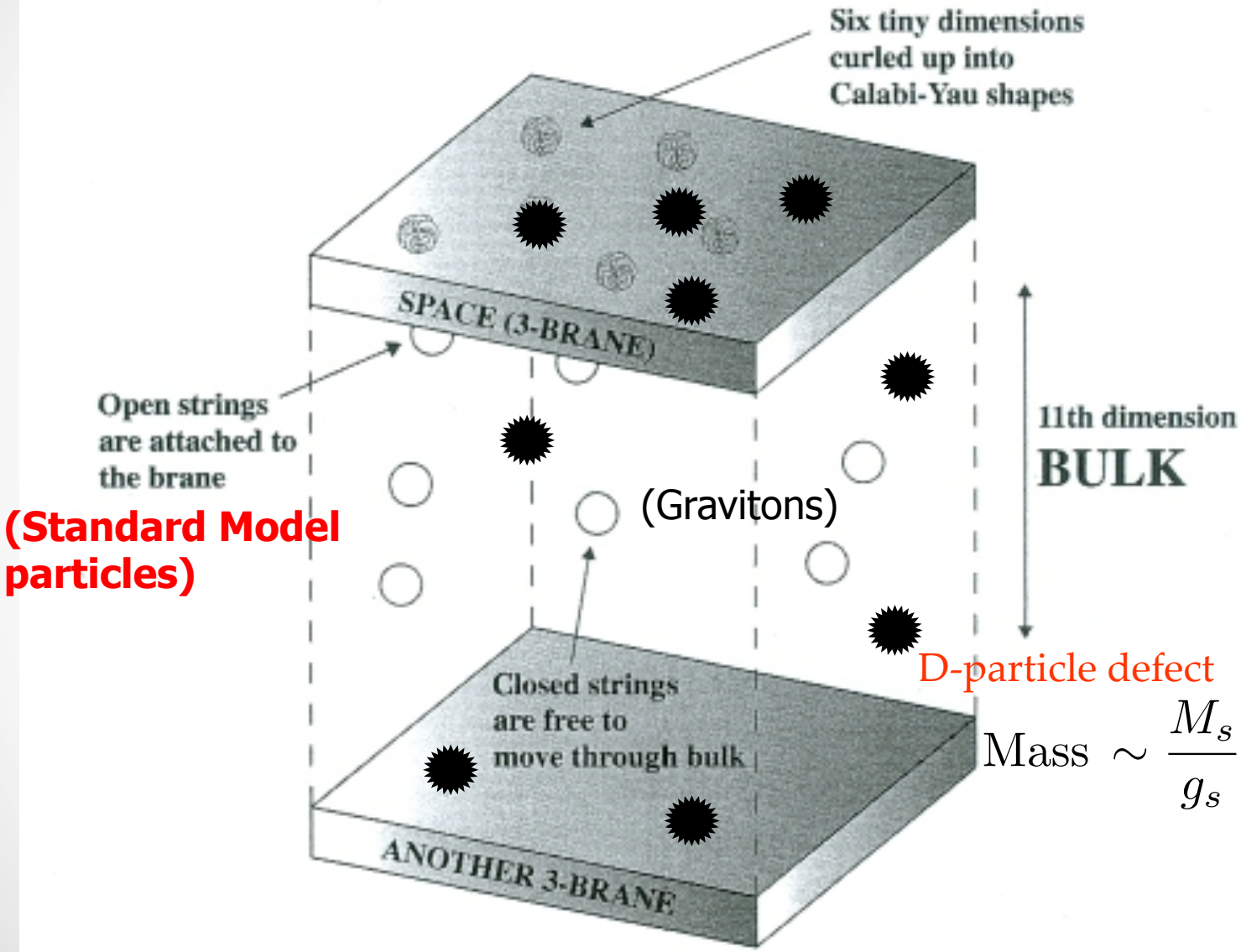

$$\text{Mass} \sim \frac{M_s}{g_s}$$

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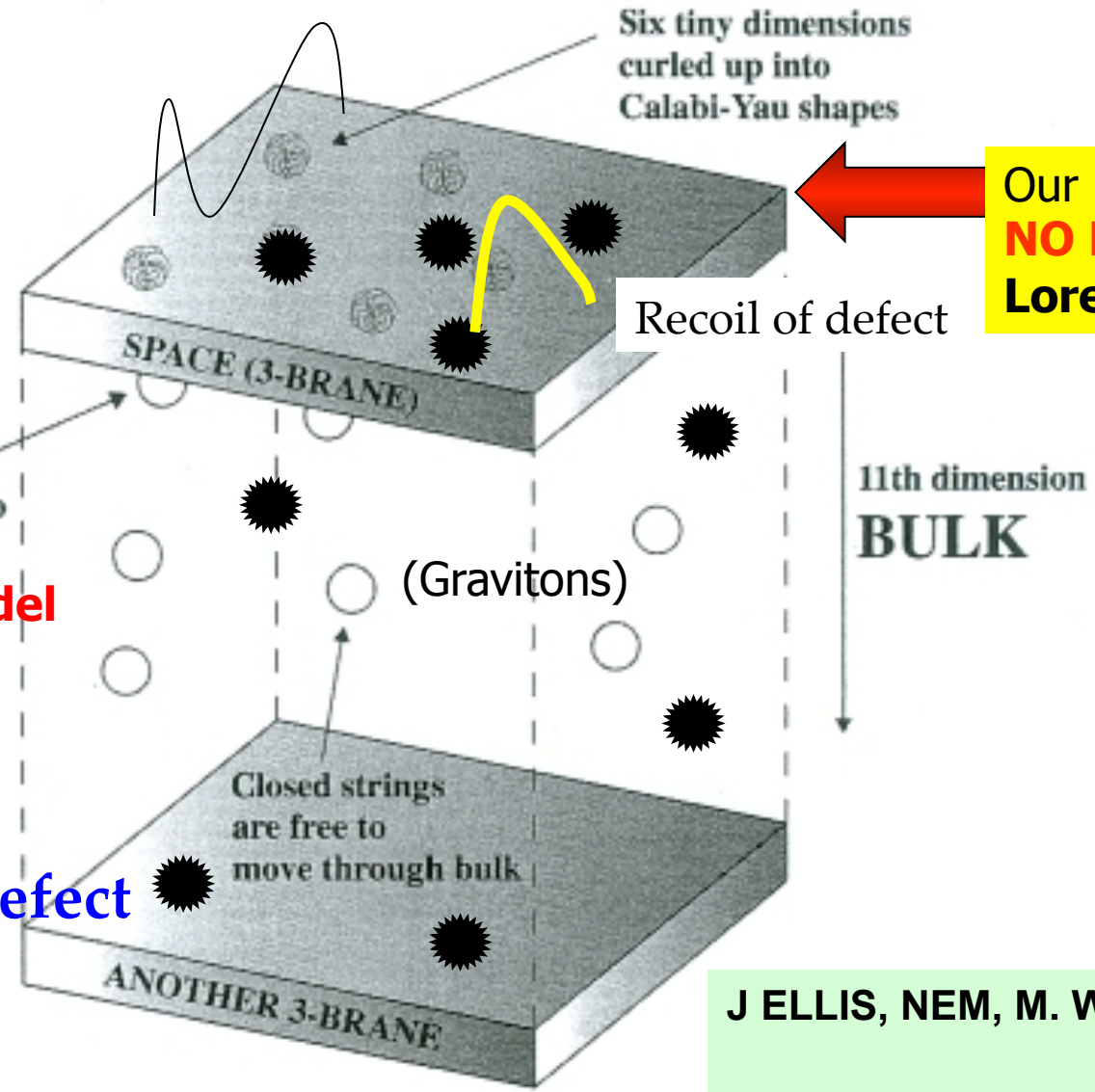


Recoil of defect

Our Universe
NO LONGER
Lorentz Invariant

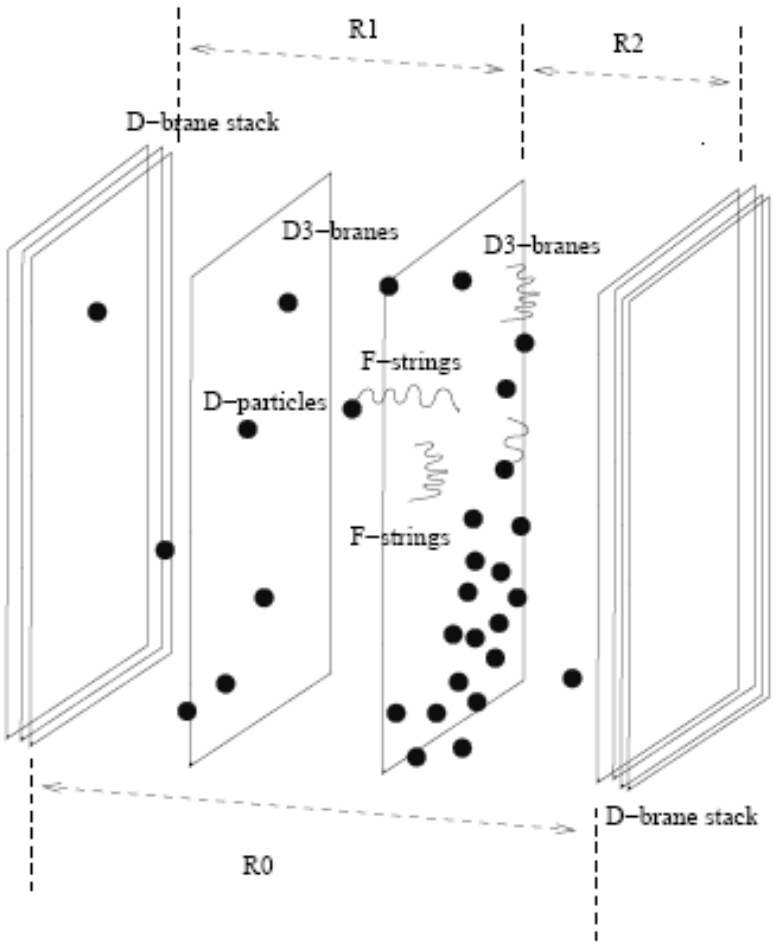
(Standard Model particles)

D-particle defect

$$\text{Mass} \sim \frac{M_s}{g_s}$$

J ELLIS, NEM, M. WESTMUCKETT

Matter/D-foam Interactions



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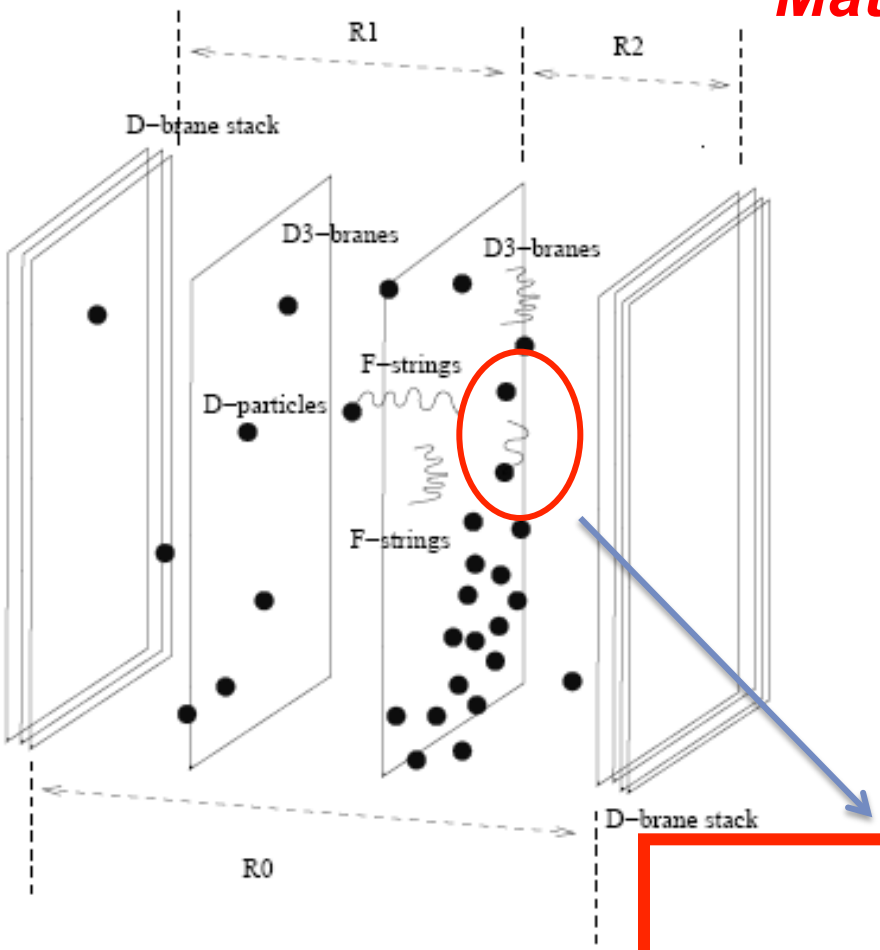
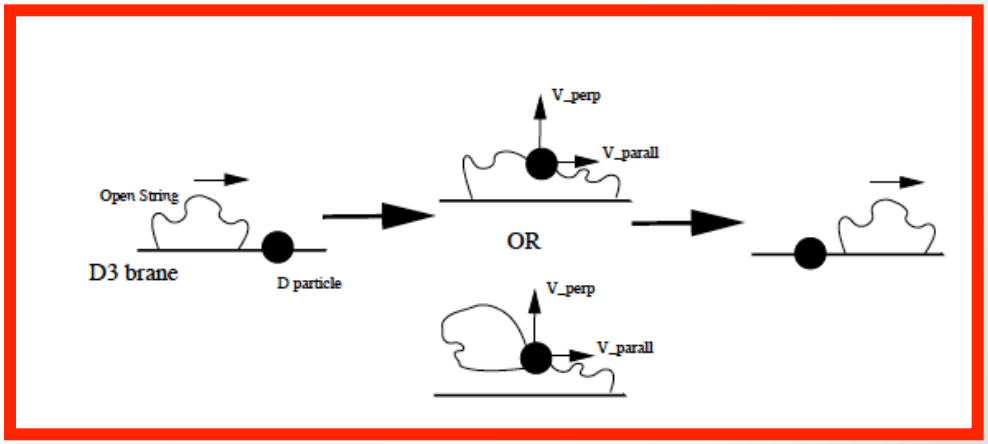
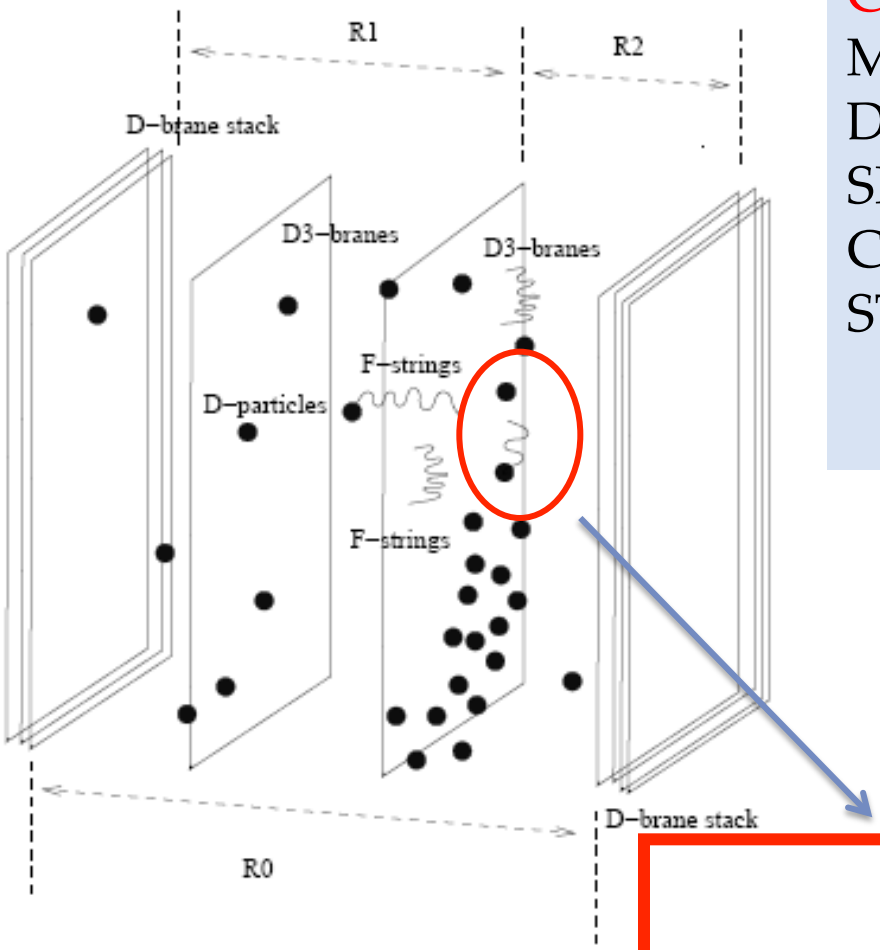


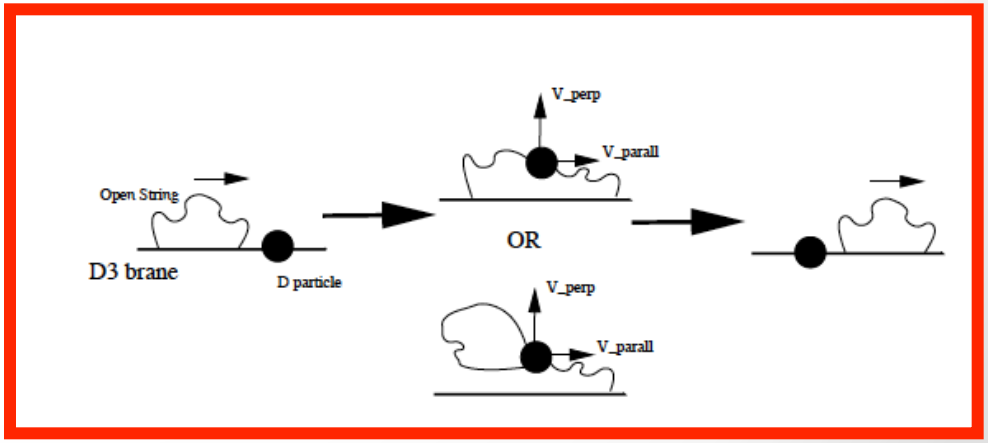
String ***Splitting*** &
(``momentary'')
Capture by the defects

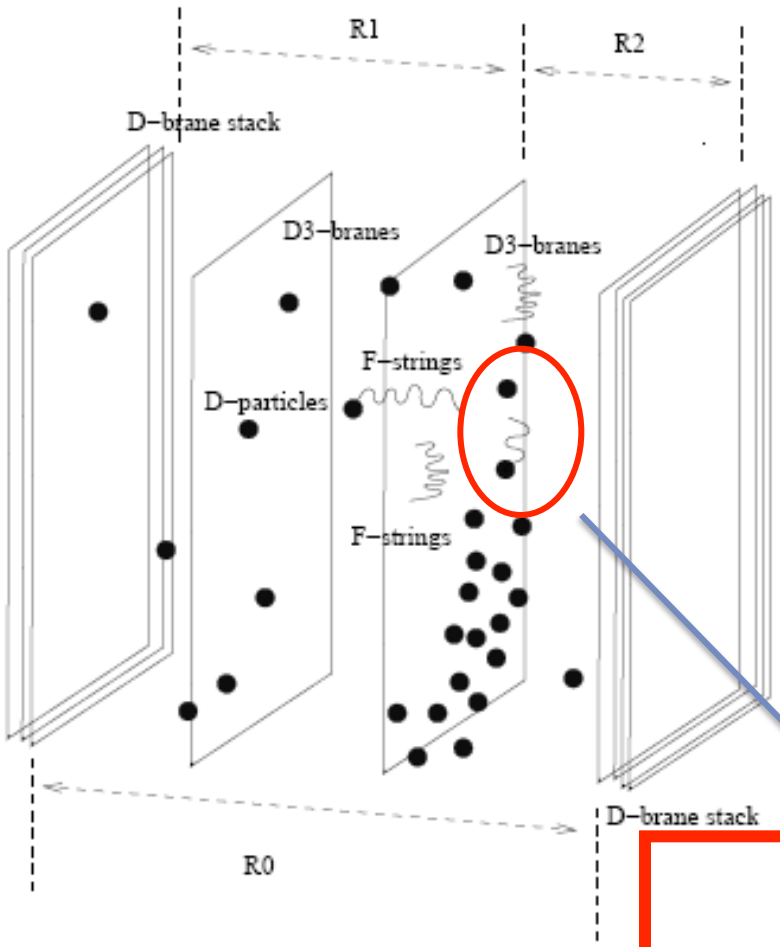
INTEMEDIATE STRING
CREATION/EXCHANGE
PURELY NON-LOCAL EFFECT



CHARGE CONSERVATION MUST BE RESPECTED DURING STRING SPLITTING, INTERNEDIATE CREATION AND STRETCHING:

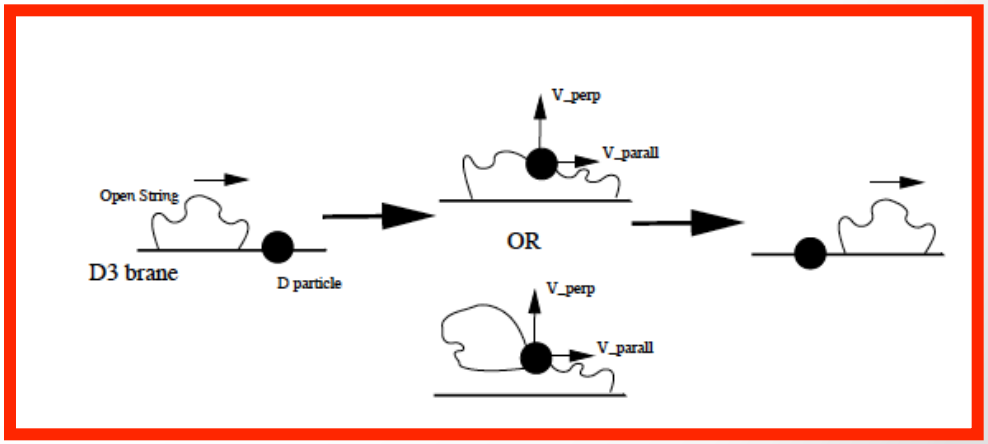




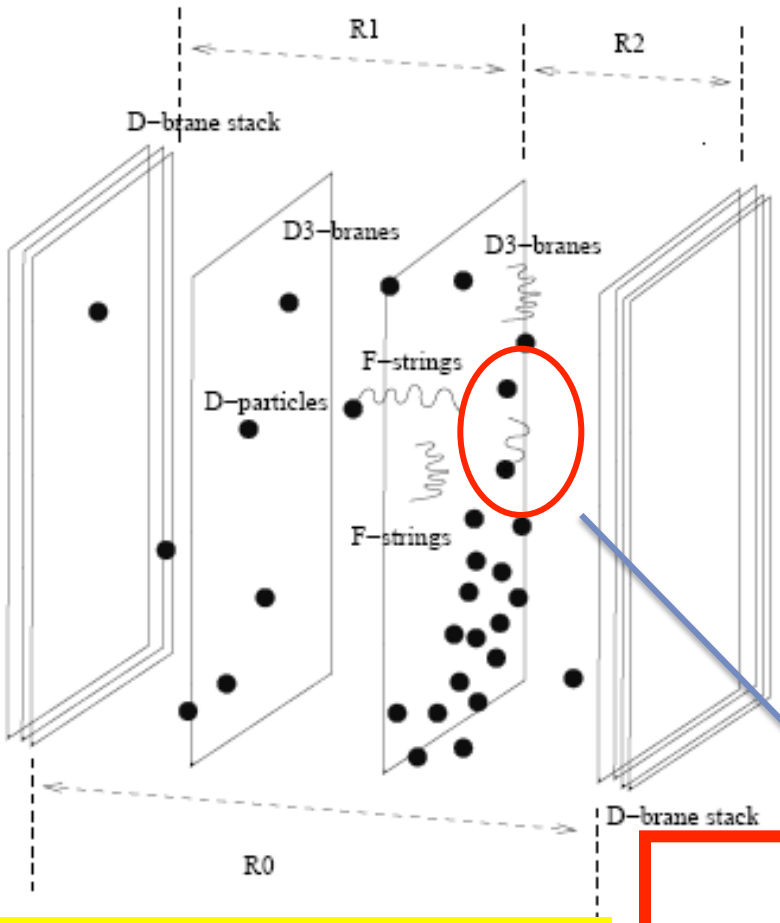


CHARGE CONSERVATION MUST BE RESPECTED DURING STRING SPLITTING, INTERNEDIATE CREATION AND STRETCHING:

ONLY ELECTRICALLY NEUTRAL EXCITATIONS (e.g. Photons, Neutrinos) INTERACT VIA CAPTURE DOMINANTLY WITH FOAM



ELLIS, NEM, SAKHAROV, NANOPOULOS



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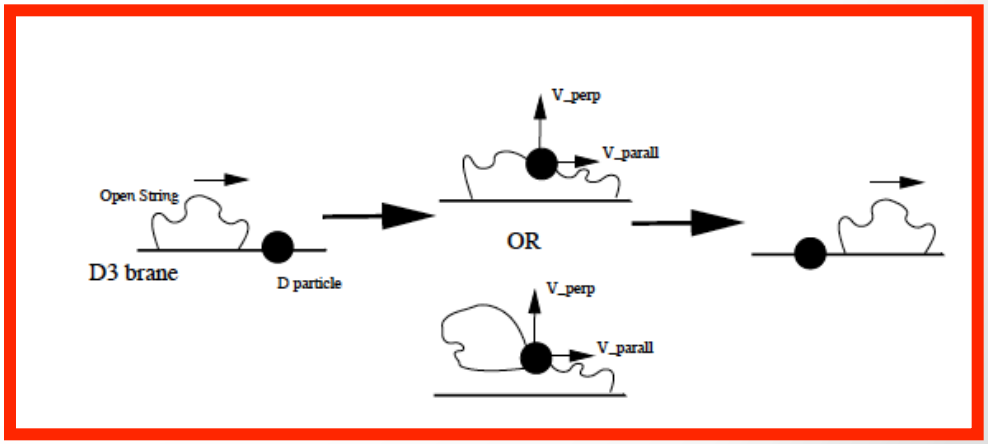
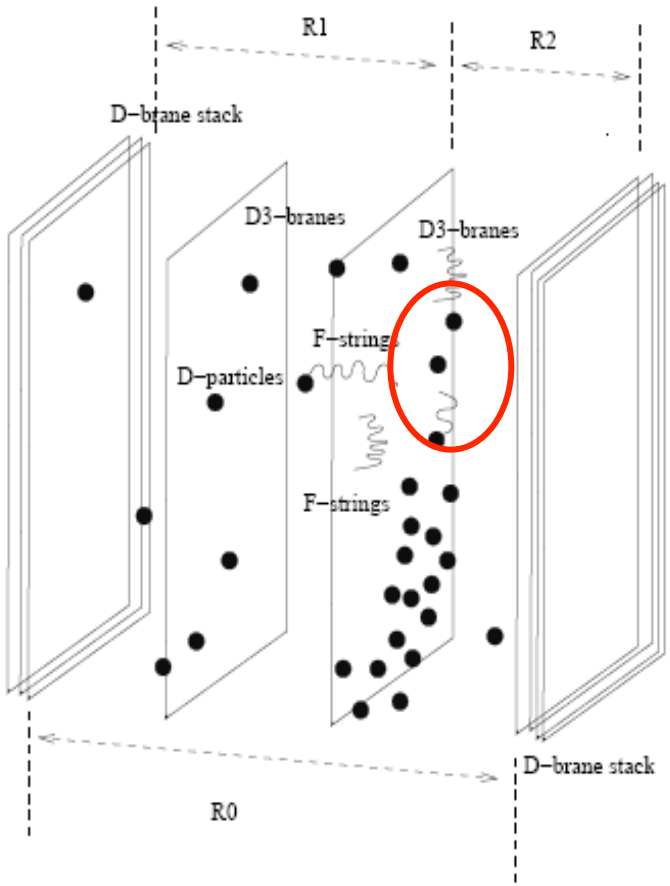


Time Delays due to Intermediate String Creation & Oscillations – ***Subluminal Vacuum Refractive Index***

J ELLIS, NEM, NANOPOULOS



***Local Lorentz Violation* due to direction of Defect recoil velocities**

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

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

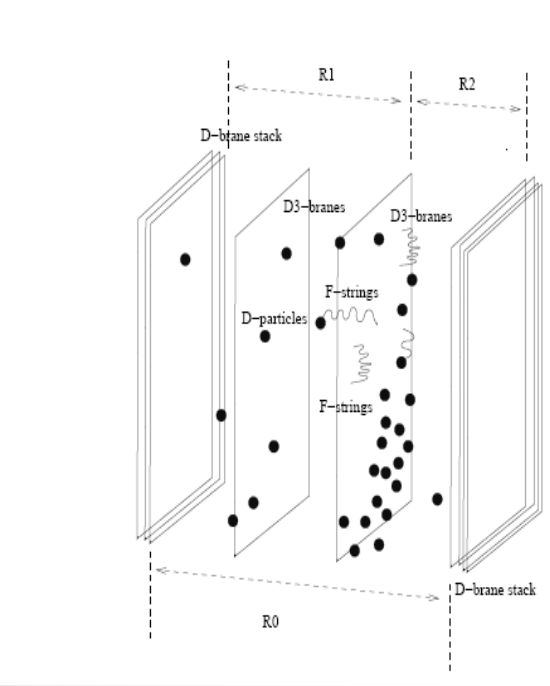
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

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

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

Isotropic & (in)homogeneous foam

for a brane observer:



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

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

Lorentz Invariance on Average

Violated in flcts

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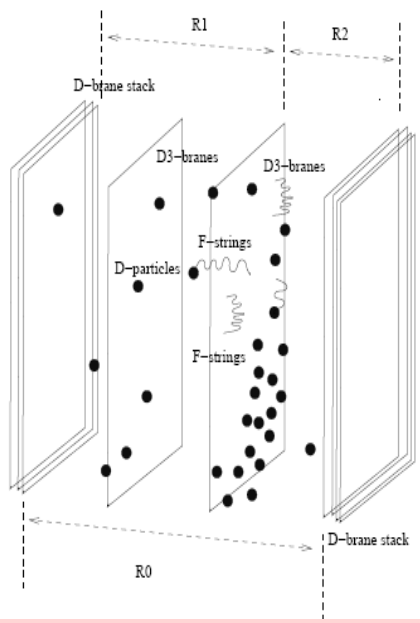

c.f. Stochastic Foam, through coherent graviton states

leading to light cone fluctuations

Ford (95)

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

Modified Neutrino dispersion relations due to locally induced metric

$$p^\mu p^\nu g_{\mu\nu} = -m^2 \Rightarrow \qquad E = \vec{p}\cdot\vec{u} \pm \sqrt{p^2 + m^2 + (\vec{p}\cdot\vec{u})^2}$$

Interpret (Dirac) negative energies as corresponding to anti-particles

$$\ll E \gg = \ll \vec{p}\cdot\vec{u} \gg \pm \ll \sqrt{p^2 + m^2 + (\vec{p}\cdot\vec{u})^2} \gg$$

$$\ll E \gg \simeq \pm\sqrt{p^2 + m^2}\left(1 + \frac{1}{2}\sigma^2\right), \qquad p \gg m$$

Momentum-Energy conservation during ν scattering with D-particles

$$\ll \vec{p}_1 + \vec{p}_2 \gg = \frac{M_s}{g_s} \ll \vec{u} \gg = 0$$

$$\ll E_1 \gg = \ll E_2 \gg + \frac{1}{2}\frac{M_s}{g_s} \ll u^2 \gg \qquad \Rightarrow$$

$$\ll E_2 \gg = \pm\sqrt{p^2 + m^2}\left(1 + \frac{1}{2}\sigma^2\right) - \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

NEM, Sarkar, Tarantino
Phys.Rev. D84 (2011) 044050

D-foam Induced CPTV for Neutrinos

$$\ll E_\nu \gg = \sqrt{p^2 + m_\nu^2}\left(1 + \frac{1}{2}\sigma^2\right) - \frac{1}{2}\frac{M_s}{g_s}\sigma^2$$

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One can thus generate a Lepton asymmetry and, then through B-L conserving processes in the Early Universe a Baryon asymmetry.

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$\pm B_0$

$$\Delta n = \frac{g}{(2\pi)^3}\int d^3\mathbf{p}\left[\frac{1}{1+\exp(E_\nu/T)} - \frac{1}{1+\exp(E_{\bar{\nu}}/T)}\right]$$

$$\Delta n_\nu \equiv n_\nu - n_{\overline{\nu}} \sim g^\star T^3\left(\frac{B_0}{T}\right)$$

BARYOGENESIS VIA LEPTOGENESIS

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@ T = T_d (decoupling Temp. of Lepton number (L) Violating processes) there is a ***constant ratio*** of net neutrino/antineutrino asymmetry (ΔL) to entropy density (~T^3)

$$\Delta L(T < T_d) = \frac{\Delta n_\nu}{s} \sim \frac{B_0}{T_d}$$

for $T_d \sim 10^{15}$ GeV and $B_0 \sim 10^5$ GeV

$\Delta L \sim 10^{-10}$, in agreement with observations (***Leptogenesis***)

Communicated to Baryon sector, and thus generates BAU either via a B-L conserving symmetry as in GUT models or via B - L conserving sphaleron processes → ***BARYOGENESIS***

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The correct value (observed) for BAU is reproduced for

$$\boxed{\frac{1}{2}\frac{M_s}{g_s}\sigma^2 \sim 10^5\ \mathrm{GeV}}$$

for D-foam at $T_d \sim 10^{15}$ GeV

implying that in these scenarios, for $\sigma^2 < 1$, one must have $M_s/g_s > 200$ TeV

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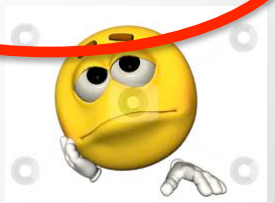

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PHENOMENOLOGY OF EARLY UNIVERSE NEEDS TO BE CHECKED FOR COMPATIBILITY…. IN PROGRESS

IS THIS CPTV ROUTE WORTH FOLLOWING? ….

CPT Violation

Construct Microscopic Quantum Gravity models with strong CPT Violation in Early Universe (dominant in (anti)neutrino sector?), but weak today… Fit with all data… Estimate in this way matter-antimatter asymmetry in Universe.

D-FOAM, MODIFIED EFFECTIVE GRAVITY THEORIES & ENHANVED GALACTIC GROWTH DUE TO DEFECTS

D-FOAM, MODIFIED EFFECTIVE GRAVITY THEORIES & ENHANVED GALACTIC GROWTH DUE TO DEFECTS

THESE ASPECTS (unlike Vacuum Refraction)
CAN BE STUDIED WITHIN
A LOCAL EFFECTIVE FIELD THEORY APPROACH

NEM, Sakellariadou, Yusaf, arXiv:1211.1726

Basic observation: Recoil of a D-particle during capture by electrically neutral matter is represented by a vector field , proportional to recoil velocity u_μ of the space-time D-particle defect

$$A_\mu = -a^2(t) u_\mu = -a(t)\, u_\mu^{\rm phys}$$

4-Velocity obeys constraint

$$u_\mu^{(\rm phys)} u_\nu^{(\rm phys)}\, \eta^{\mu\nu} = -|{\rm constant}| = -\frac{|{\rm T}_3|}{{\rm g}_{s0}} 2\pi\alpha' {\rm e}^{-\phi_0} < 0$$

$$\boxed{A_\mu A_\nu g^{\mu\nu} = -\frac{|T_3|}{g_{s0}} 2\pi\alpha' e^{-\phi_0} < 0}$$

Implemented via lagrange multiplier in low energy effective field theory path integral → *crucial for the existence of an enhanced growth*

LOW-ENERGY EFFECTIVE ACTION OBTAINED BY COMPATIBILITY WITH STRING AMPLITUDES

$$S_{\text{eff 4dim}} = \int d^4x \left[-\frac{T_3}{g_{s0}} e^{-\phi} \sqrt{-\det\left(g + 2\pi\alpha' F\right)} \left(1 - \alpha R(g)\right) - \sqrt{-g}\, e^{-2\phi} \frac{1}{\kappa_0} \tilde{\Lambda} + \frac{1}{\kappa_0} \sqrt{-g}\, e^{-2\phi} R(g) + \mathcal{O}((\partial\phi)^2) \right]$$

$$\alpha = \alpha' \zeta(2) = \alpha' \pi^2/6$$

LOW-ENERGY EFFECTIVE ACTION OBTAINED BY COMPATIBILITY WITH STRING AMPLITUDES

brane tension

$$S_{\text{eff 4dim}} = \int d^4x \left[-\frac{T_3}{g_{s0}} e^{-\phi} \sqrt{-\det\left(g + 2\pi\alpha' F\right)} \Big(1 - \alpha R(g) \Big) \right.$$
$$\left. - \sqrt{-g}\, e^{-2\phi} \frac{1}{\kappa_0} \tilde{\Lambda} + \frac{1}{\kappa_0} \sqrt{-g}\, e^{-2\phi} R(g) + \mathcal{O}((\partial\phi)^2) \right]$$

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DILATONS assumed **constant ϕ_0** during era of galaxy formation

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Born-Infeld Action for the Vector field

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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Constraint

$$S_{\text{eff}-\text{Lagrange}} = \int d^4x \sqrt{-g}\, \lambda(x) \left(A_\mu A^\mu + \frac{|T_3|}{g_{s0}} 2\pi\alpha' e^{-\phi_0} \right)$$

For late epochs, suffices to restrict ourselves to quartic derivative order

Pass onto Einstein frame
(canonically normalised Einstein term) :

$$g_{\mu\nu} \to \tilde{g}_{\mu\nu} = e^{-2\phi} g_{\mu\nu}$$

$$\begin{aligned} S_{\text{eff 4dim}} = \int d^4x \sqrt{-g} \Bigg[& -\frac{T_3}{g_{s0}} e^{-\phi} - e^{-2\phi} \frac{1}{\kappa_0} \tilde{\Lambda} \\ & - \frac{T_3}{4g_{s0}} 2\pi\alpha' e^{-\phi} F^{\mu\nu} F_{\mu\nu} + \alpha \frac{T_3}{4g_{s0}} 2\pi\alpha' e^{-\phi} F^{\mu\nu} F_{\mu\nu} R(g) \\ & + \left(\alpha \frac{T_3}{g_{s0}} e^{-\phi} + \frac{1}{\kappa_0} e^{-2\phi} \right) R(g) + \mathcal{O}\left((\partial\phi)^2 \right) \Bigg] . \end{aligned}$$

Effective gravitational constant

$$\frac{1}{\kappa} \equiv \frac{1}{\kappa_0} + \alpha \frac{T_3}{g_{s0}} e^{\phi}$$

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Friedmann-Robertson-Walker Background

$$\phi = \phi_0 = \text{const} \ , \quad g_{00} = -1 + 2\sinh(\phi_0)u_0^2 \ , \quad g_{ij} = a^2(t)(\delta_{ij} + 2\sinh(\phi_0)u_i u_j)$$

$\phi_0 = \mathcal{O}(1)$ (required by phenomenology, since $g_s = \exp(\phi_0)$)

Consider D-foam situation, average over populations of D-particles with

$$\ll u_i \gg = 0 \quad \text{and} \quad \ll u_i u_j \gg = \sigma_0^2 \delta_{ij}$$

$$\sigma_0^2(t) = \frac{\beta}{a^3(t)} \frac{2\pi\alpha' |T_3| e^{-\phi_0}}{g_{s0}} \ , \quad \beta = \text{constant} > 0 \ .$$

NB: ***no force (``dust-like'')*** condition (up to one loop) among D-particles due to underlying supersymmetries in string theory (like BPS states)

EQUATIONS OF MOTION

$$\left[F_{\nu\mu}\left(1-\alpha e^{-2\phi_0}R\right)\right]^{;\nu}+2\lambda(x)A_\mu \;=0\;,$$

$$\left[\frac{1}{4}F^{\alpha\beta}F_{\alpha\beta}+\frac{\tilde{\Lambda}\,e^{2\phi_0}}{\kappa_0}+\frac{T_3e^{3\phi_0}}{g_{s0}}-\lambda(x)(A_\alpha A^\alpha+\frac{|T_3|}{g_{s0}}2\pi\alpha'\,e^{-\phi_0})\right]\frac{g_{\mu\nu}}{2}$$
$$+\left(R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R\right)\left[\frac{1}{\kappa_0}+\alpha\frac{T_3}{g_{s0}}e^{\phi_0}+\frac{\alpha e^{-2\phi_0}}{4}F^{\alpha\beta}F_{\alpha\beta}\right]-\frac{1}{2}g^{\sigma\lambda}F_{\mu\lambda}F_{\nu\sigma}(1-\alpha e^{-2\phi_0}R)$$
$$+\frac{\alpha e^{-2\phi_0}}{4}\left\{g_{\mu\nu}\nabla^2\left[F^{\alpha\beta}F_{\alpha\beta}\right]-\nabla_\mu\nabla_\nu\left[F^{\alpha\beta}F_{\alpha\beta}\right]\right\}=T^{\mathrm{m}}_{\mu\nu}-\lambda(x)A_\mu A_\nu\;,$$

$$-\frac{3}{2}\alpha\,e^{2\phi_0}\nabla^2(F_{\alpha\beta}F^{\alpha\beta})+3\frac{T_3}{g_{s0}}e^{3\phi_0}+2\frac{\tilde{\Lambda}}{\kappa_0}e^{2\phi_0}-\alpha\left(\frac{T_3}{g_{s0}}e^{\phi_0}-\frac{1}{2}F_{\mu\nu}F^{\mu\nu}e^{-2\phi_0}\right)R(g)=0$$

The Background Solution

$$
\begin{aligned}
g_{00} &= -1 \ , \\
g_{ij} &= a^2(t)\delta_{ij} \ , \\
A_0 &= \left[\frac{2\pi\alpha'|T_3|e^{-\phi_0}}{g_{s0}} + u^2 a^2(t)\right]^{1/2} \\
A_i &= -a^2(t)u_i \ .
\end{aligned}
$$

$$
\begin{aligned}
T^{\mathrm{m}0}{}_0 &= -\rho \ , \\
T^{\mathrm{m}i}{}_j &= P\delta^i{}_j
\end{aligned}
$$

$$
\lambda(x)\frac{2\pi\alpha'|T_3|e^{-\phi_0}}{g_{s0}} = -\frac{A^\mu}{2}\left[F_{\nu\mu}(1-\alpha e^{-2\phi_0}R)\right]^{;\nu}
$$

Approximate solutions for late eras of the Universe

The Perturbed Solution

$$g_{00} = -1 + 2\Psi \ , \quad g_{ij} = a^2(t)\,(1 + 2\Phi)\,\delta_{ij}$$

$$A_\mu = a(t)\left(-a(t)u_\mu + \tilde{A}_\mu\right) \qquad \tilde{A}_\mu = -\Xi t_\mu + \overline{q}^\nu{}_\mu \overline{\nabla}_\nu \zeta + \beta_\mu$$

$$\Xi = -\Psi \ , \quad \beta_\mu = 0 \qquad \overline{\nabla}^2 \zeta = \vec{\overline{\nabla}} \cdot \vec{\tilde{A}} \ .$$

$$\tilde{A}_\mu = \left[\frac{|T_3| e^{-\phi_0}}{g_{s0}} 2\pi\alpha'\right]^{1/2} \left(\Psi, \vec{\tilde{A}}\right)$$

Eqs of motion for perturbed solution yield

$$\Psi - \Phi = 0 \qquad \ddot{\zeta} + b_1 \dot{\zeta} + b_2 \zeta = S[\Phi, C]$$

Growing Modes of Vector fields

$$\ddot{\zeta} + b_1\dot{\zeta} + b_2\zeta = S[\Phi, C]$$

$$\begin{aligned}
S[\Phi, C] &= \frac{\dot{\Phi}}{a} + \frac{\Phi}{a}\left(H + \frac{6\alpha e^{-2\phi_0}\left[2H^3 - \frac{\ddot{a}H}{a} - \frac{\dddot{a}}{a}\right]}{1 - 6\alpha e^{-2\phi_0}\left(H^2 + \frac{\ddot{a}}{a}\right)}\right) , \\
b_1 &= 3H + \frac{6\alpha e^{-2\phi_0}\left[2H^3 - \frac{\ddot{a}H}{a} - \frac{\dddot{a}}{a}\right]}{1 - 6\alpha e^{-2\phi_0}\left(H^2 + \frac{\ddot{a}}{a}\right)} , \\
b_2 &= \frac{\ddot{a}}{a} + H^2 + \frac{6\alpha e^{-2\phi_0} H\left[2H^3 - \frac{\ddot{a}H}{a} - \frac{\dddot{a}}{a}\right] - 2\langle\lambda(x)\rangle}{1 - 6\alpha e^{-2\phi_0}\left(H^2 + \frac{\ddot{a}}{a}\right)} .
\end{aligned}$$

Growing mode if $b_2 < 0$

$\phi_0 = \mathcal{O}(1)$ $\langle\lambda(x)\rangle > 0.$ for late eras (radiation & matter dominated)

proportional to reoil velocity foam flucts σ_0

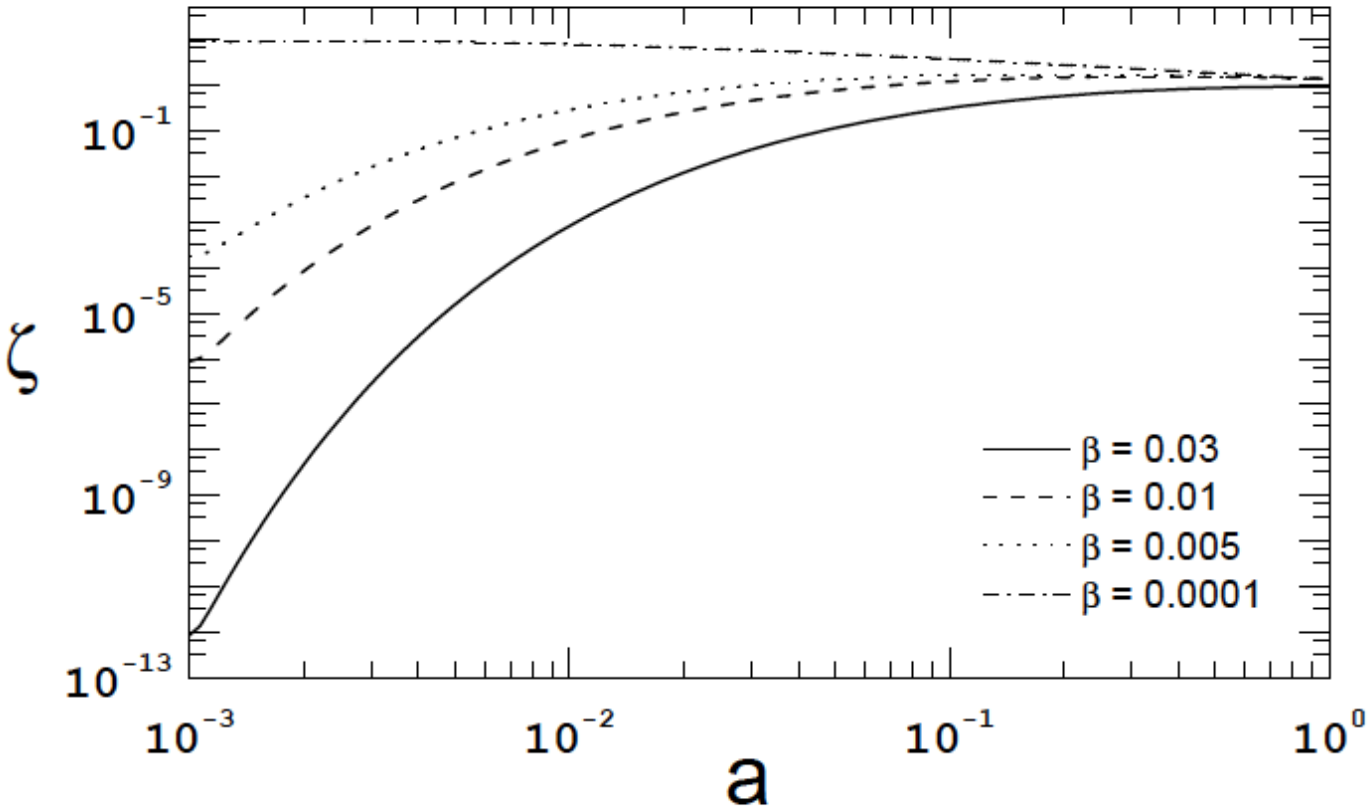


FIG. 2: Vector perturbation ζ as a function of the scale factor $a(t)$ in the matter-dominated era, for different values of the D-particle recoil velocity variance $\sigma_0^2 \propto \beta/a^3$. The string mass M_s is assumed to be 10 TeV, $\phi_0 = 1$ and $k = 0.5$ Mpc^{-1}.

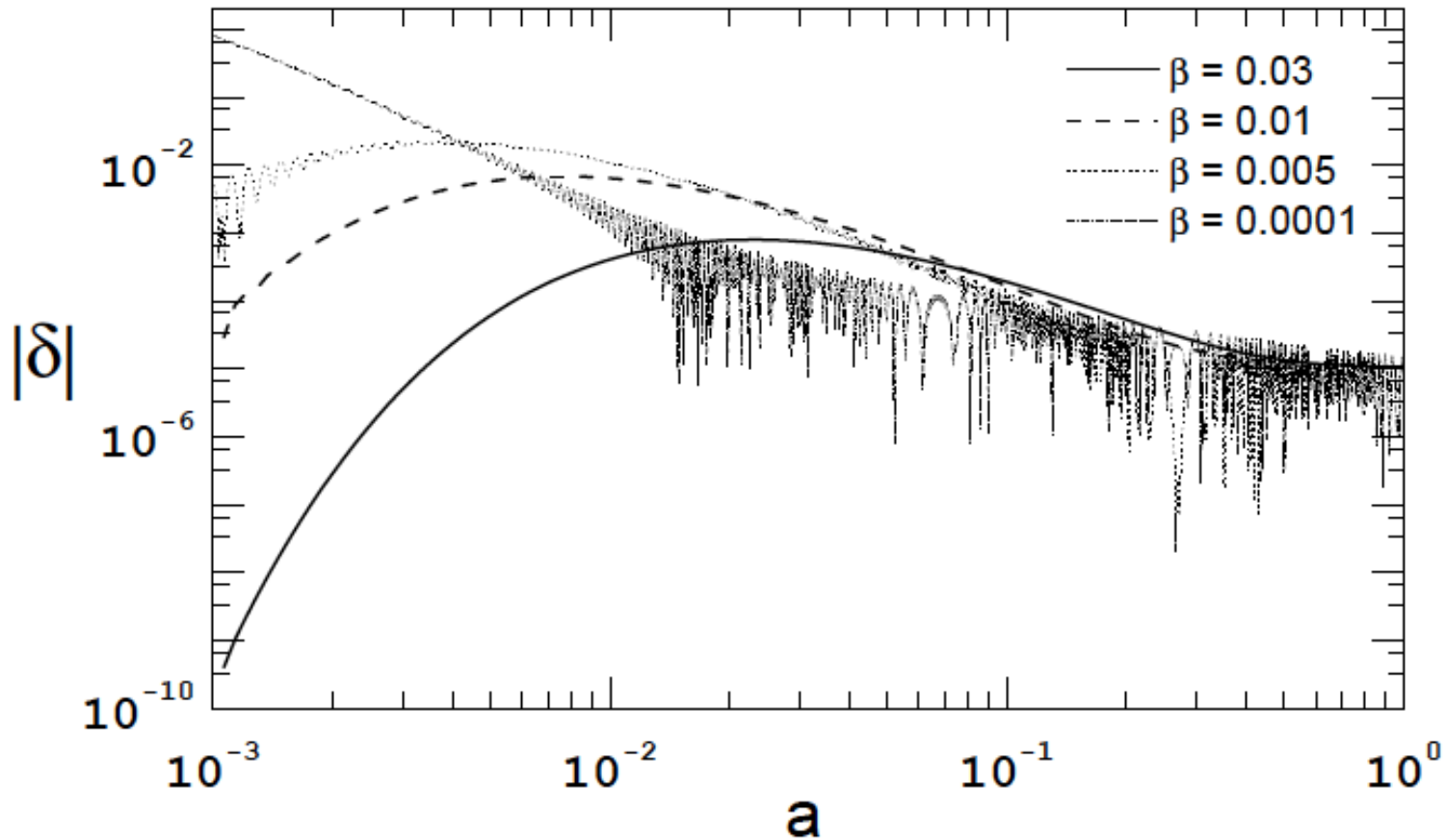


FIG. 3: Over-density parameter $|\delta| = \delta\rho/\rho$ as a function of the scale factor $a(t)$ in the matter-dominated era, for different values of the D-particle recoil velocity variance $\sigma_0^2 \propto \beta/a^3$. The string mass M_s is assumed to be 10 TeV, $\phi_0 = 1$ and $k = 0.5$ Mpc^{-1}. $|\delta|$ is taken to be 10^{-5} today.

D-FOAM & MODIFIED DARK MATTER (THERMAL) RELIC ABUNDANCE

RELIC ABUNDANCE BOTZMANN EQUATION FOR HEAVY DM SPECIES, m >> k

NM, Mitsou, Vergou, Sarkar 2010

Finsler form of distorted metric due to Defect recoil
when embedded to Cosmology affects DM relic abundances

$$h_{0i} \sim a^2(t) g_s \frac{\Delta k_i}{M_s}$$

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

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

phase-space
particle density

$$\boxed{\frac{dn}{dt} + 3Hn = \Gamma(t) n + \frac{g}{(2\pi)^3} \int d^3\overline{k} \frac{C[f]}{\overline{k}_0}}$$

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

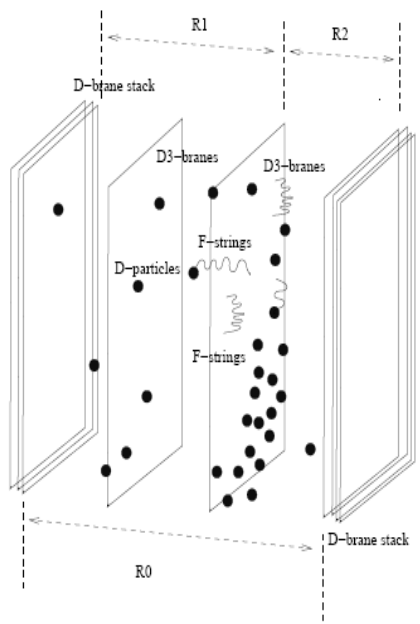
Isotropic
& homogeneous foam:

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

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

Lorentz Invariance on Average

Violated in flcts



c.f. Stochastic Foam, through coherent graviton states

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

$$\langle h_{\mu\nu} \rangle = 0$$

$$\langle h_{\mu\nu} h_{\rho\sigma} \rangle \neq 0$$

leading to light cone fluctuations

Ford (95)

RELIC ABUNDANCE BOTZMANN EQUATION FOR HEAVY DM SPECIES, m >> k

NM, Mitsou, Vergou, Sarkar 2010

Finsler form of distorted metric due to Defect recoil when embedded to Cosmology affects DM relic abundances

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phase-space particle density

$$\frac{dn}{dt} + 3Hn = \Gamma(t) n + \frac{g}{(2\pi)^3} \int d^3\overline{k} \frac{C[f]}{\overline{k}_0}$$

$$\Gamma(t) = 2H a^4(t) m \left(\sigma_{01}^2 + \sigma_{02}^2 + \sigma_{03}^2\right) [9T + 2m]$$

Foam leads to vacuum Particle production (non-trivial vacuum fluctuations)

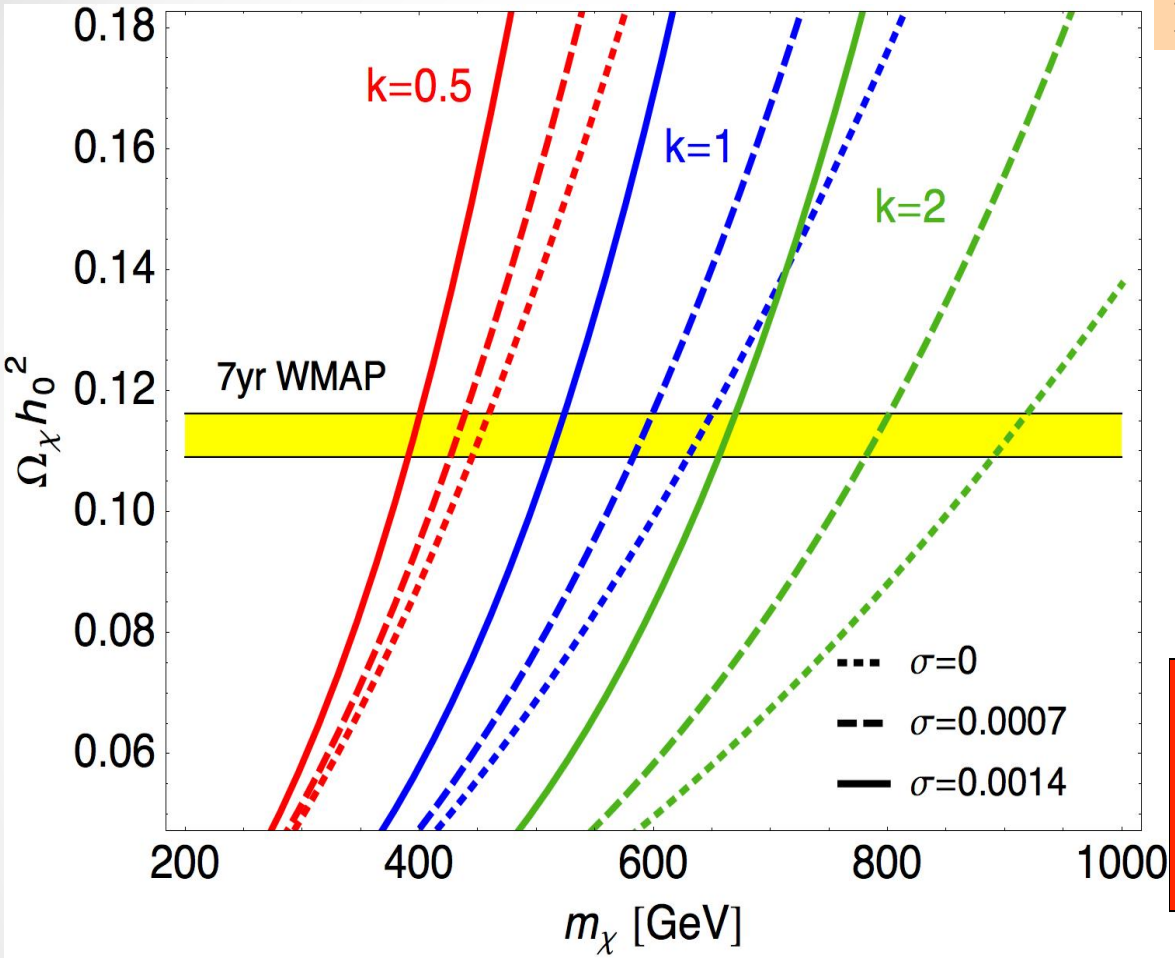
Weakly Interacting Dark Matter Phenomenology and Space-time Foam

NM, Mitsou, Vergou, Sarkar 2010

$$\frac{\Omega_\chi h_0^2}{(\Omega_\chi h_0^2)_{\text{no source}}} = 1 + \sigma^2 m_\chi^2 \ ,$$

$$\sigma^2 \equiv 1.259 \frac{g_s^2}{M_s^2} \sum_{i=1}^{3} \Delta_i^2 \ , \qquad (\Omega_\chi h_0^2)_{\text{no source}} = (2.6 \times 10^{-10}\ \text{GeV}^{-2}) \frac{16\pi^2 m_\chi^2}{k\, g_{\text{weak}}^4},$$

Weakly Interacting Dark Matter Phenomenology and Space-time Foam



NM, Mitsou, Vergou, Sarkar 2010

Foam fluctuations of order:

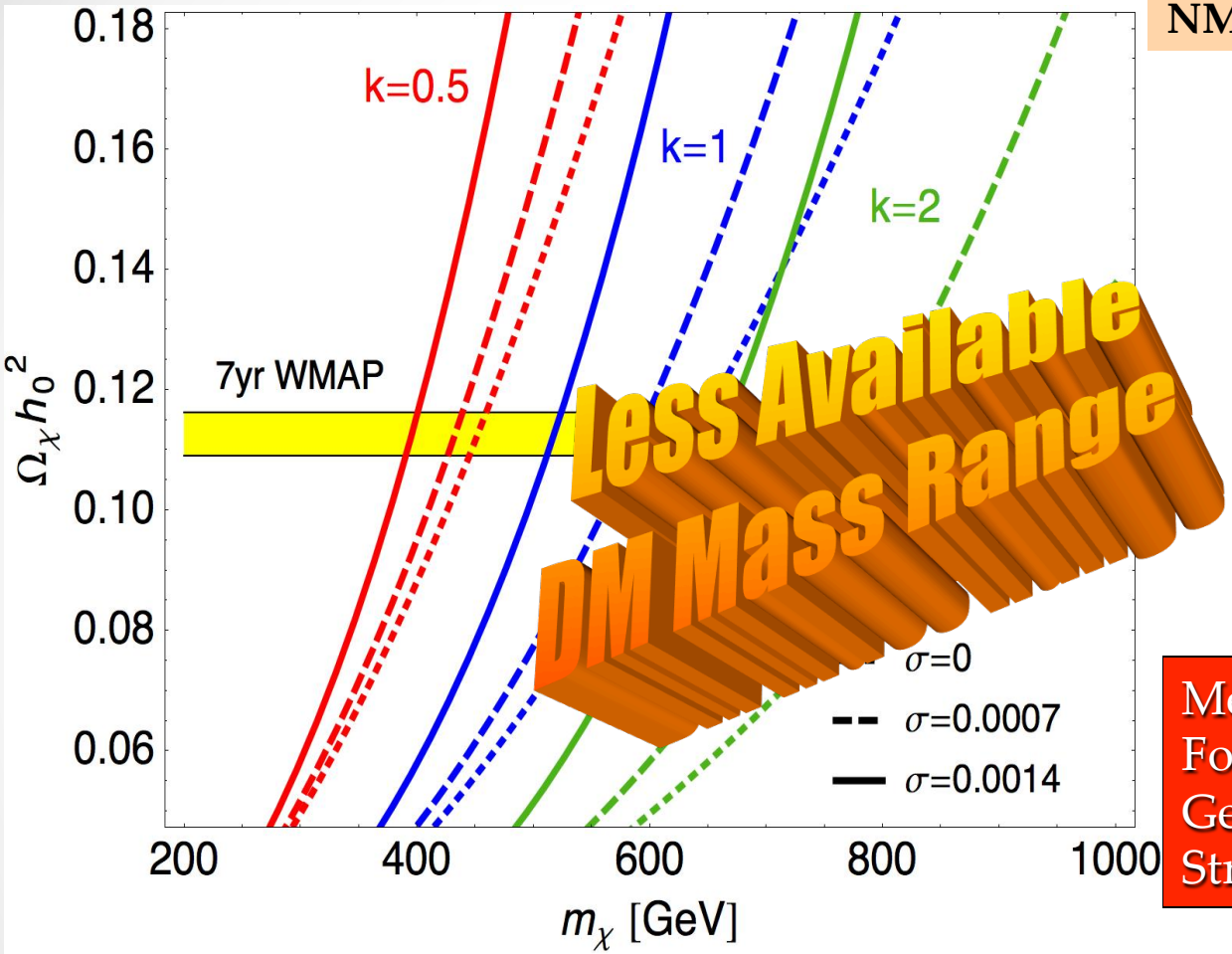
$$\sigma^2 = g_s^2 \frac{\Delta^2}{M_s^2}$$

$\Delta = O(1)$ dimensionless

Measurable effects For current or next Generation expts only if Low String scale O(1-10 TeV)

Cosmologically (WMAP_CMB) allowed regions for WIMP Dark Matter

Weakly Interacting Dark Matter Phenomenology and Space-time Foam



NM, Mitsou, Vergou, Sarkar 2010

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Cosmologically (WMAP_CMB) allowed regions for WIMP Dark Matter

CONCLUSIONS

In Lecture II, we have examined Cosmological properties of D-foam model and found possibility for consistency with realistic features, such as enhanced galactic growth during matter dominated eras.

We have also discussed the possibility that the D-foam induces CPT Violating dispersion relations between neutrinos which are different from those of antineutrinos, thereby leading to Leptogenesis and through B-L conserving processes of Baryogenesis

Although toy, such models demonstrate therefore the non-trivial role of space time defects in cosmology and in phenomenology of quantum gravity

EXTRAS

DETAILED DERIVATION OF TIME DELAYS IN STRINGY D-FOAM MODEL

A MODEL OF D-BRANE FOAM IN STRING THEORY

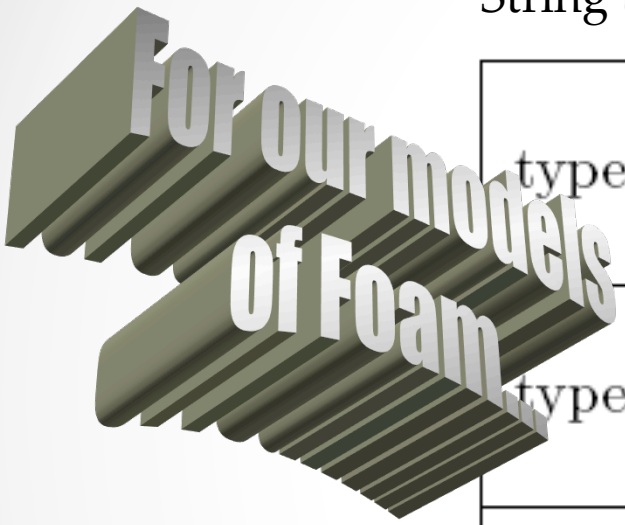
An Amplifier of Stringy Uncertainties

STRING/D-BRANE BASICS

String theory	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

STRING/D-BRANE BASICS



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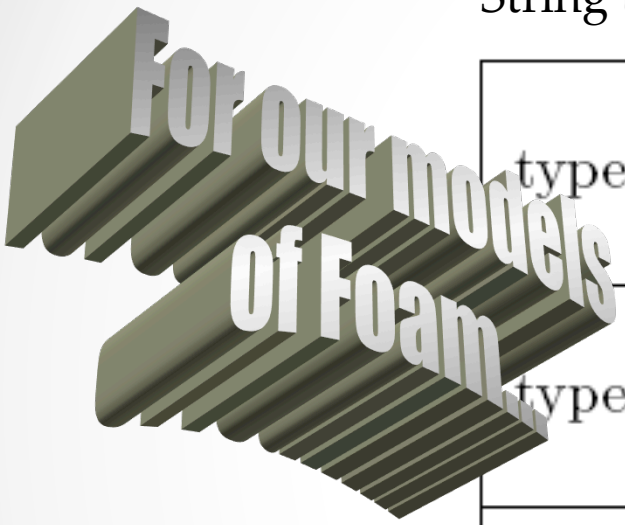

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Compactify to

3 + 1 Large Dim

Heterotic Strings admit no p-branes

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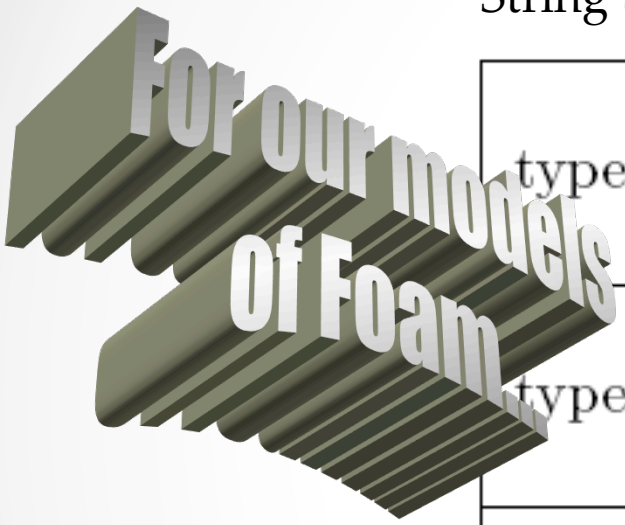


String theory	p-brane types allowed
type-IIA	$p = 0, 2, 4, 6, 8$
type-IIB	$p = -1, 1, 3, 5, 7, (9)$
type-I	$p =$

Compactify to

3 + 1 Large Dim

Wrap up along

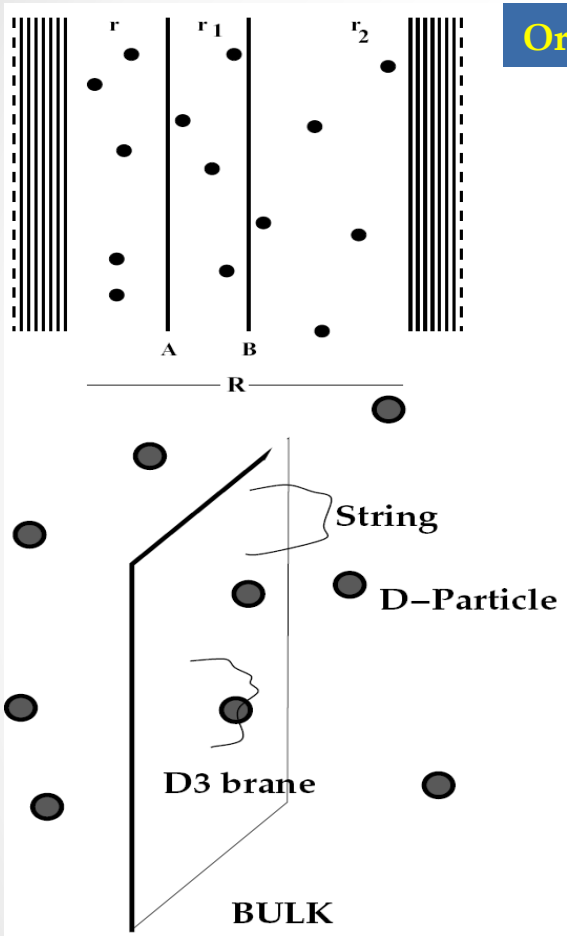
Three cycles

(``D-particles'')

Heterotic Strings admit no p-branes

Li, NM, Nanopoulos, Xie

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



Orientifold planes, stacks of D8 branes

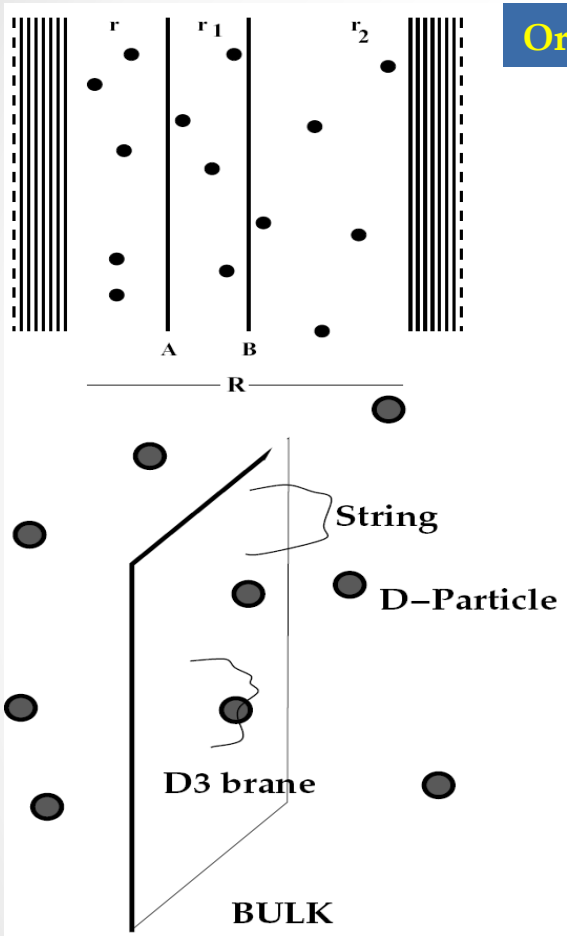
Ellis, NM, Westmuckett

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….

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



Orientifold planes, stacks of D8 branes

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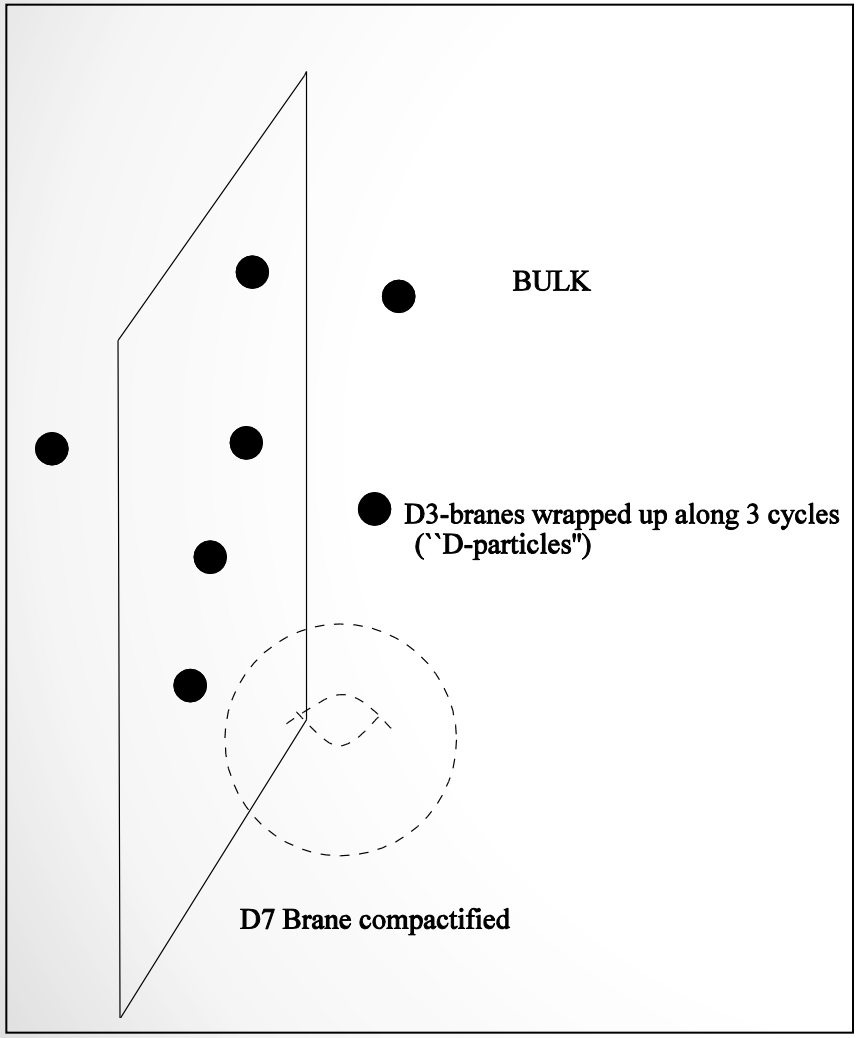
D-particle foam medium transparent to (charged)
Electrons ⇒ **no modified dispersion for them**

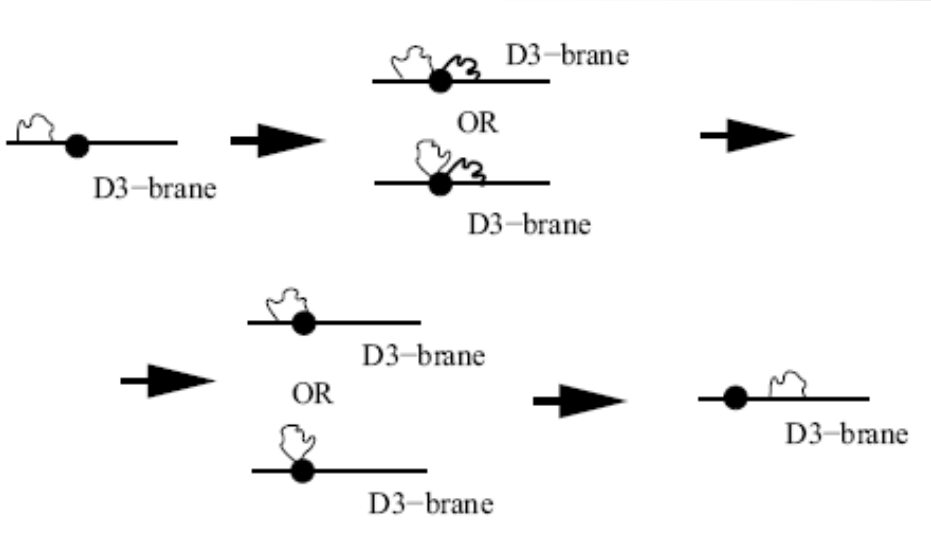
Photons or electrically neutral probes feel the effects of D-particle foam ⇒
Modified Dispersion for them….

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

Type IIB String Model of D-particle Foam

T.Li, NM, Nanopoulos, D. Xie

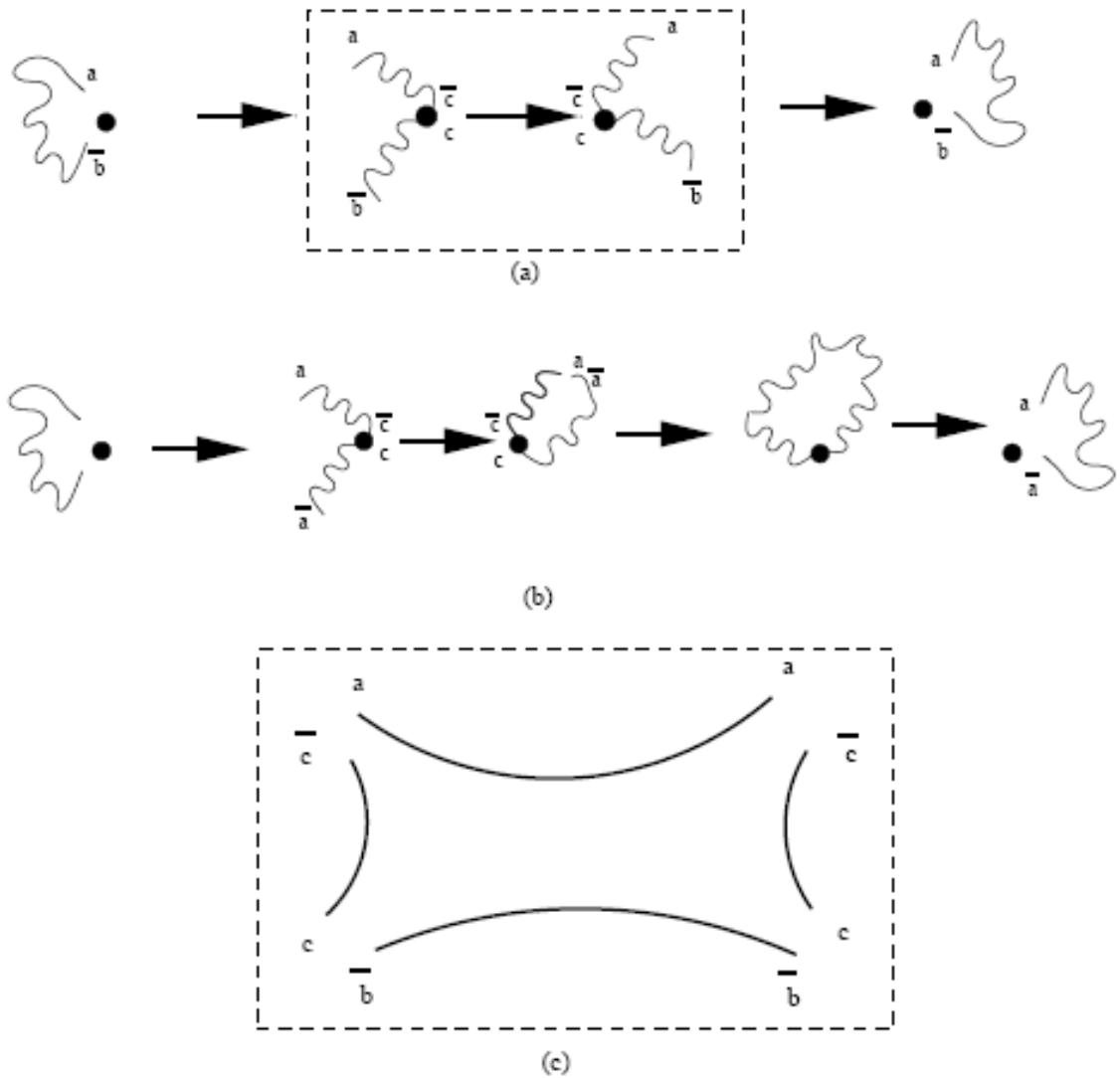




Consider Four-point Veneziano Amplitude for scattering of two open string states to two open string states in the D-particle/D3-branes backgrounds

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:

Capture process: Backward Scattering u=0 (Mandelstam)

CASUSAL TIME DELAYS

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

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

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

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

Vertex operator for fermionic or Bosonic open string state

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

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

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

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

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

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

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

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

$$\mathcal{A}(1,2,3,4) \propto g_s \ell_s^2 \Big(t\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(2)} \overline{u}^{(4)} \gamma^\mu u^{(3)}$$

$$+ s\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(4)} \overline{u}^{(2)} \gamma^\mu u^{(3)} \Big) \times \frac{\Gamma(-s\ell_s^2)\Gamma(-t\ell_s^2)}{\Gamma(1+u\ell_s^2)} \ ,$$

$$\mathcal{A}(1,3,2,4) \propto g_s \ell_s^2 \Big(t\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(3)} \overline{u}^{(4)} \gamma^\mu u^{(2)}$$

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$$\mathcal{A}(1,3,4,2) \propto g_s \ell_s^2 \Big(t\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(3)} \overline{u}^{(4)} \gamma^\mu u^{(2)}$$

$$+ u\ell_s^2 \overline{u}^{(1)} \gamma_\mu u^{(4)} \overline{u}^{(3)} \gamma^\mu u^{(2)} \Big) \times \frac{\Gamma(-u\ell_s^2)\Gamma(-t\ell_s^2)}{\Gamma(1+s\ell_s^2)} \,,$$

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Kaluza Klein excitations

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

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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 pa ti
u + t + s =

Photons or
rtan subalgerba
f Gauge Group
Gauginos

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

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

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

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

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

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

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

Photons or
rtan subalgerba
of Gauge Group
Gauginos

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Independent
of photon polarization
NO BIREFRINGENCE

Note that $s =$
order

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

OTHER PARTICLES

$j_1 \neq j_2$,

Backward scattering u=0 implies

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

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

At order η, there are time delays…

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

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

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

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

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

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

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

Type IIB: For charged probes, suppressed time delays…

Effecitve Low-Energy Modified Dispersion

$$\mathcal{A}(1, \ldots$$

$$-g \ldots l_s^2 \; \frac{1}{[F(x)]^2} \times$$

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

$$\times \{ \eta \delta_{I_1} \ldots \sum \ldots e^{-\pi \tau m^2 \ell_s^2 / R'^2}$$

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

$$E^2 = p^2 + m_e^2 - \eta p^3 / M_{\rm St} \; , \qquad (6)$$

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Naturally $\eta < O(10^{-6})$

At order η, there are time delays…

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From Synchrotron Radiation Observations of Crab Nebula

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

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$$+\delta$$

$$E^2 = v^2 + m_-^2 - mv^3/M_{\rm St}\ ,$$

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

wher

D7-branes and D3-branes, respectively. Ar

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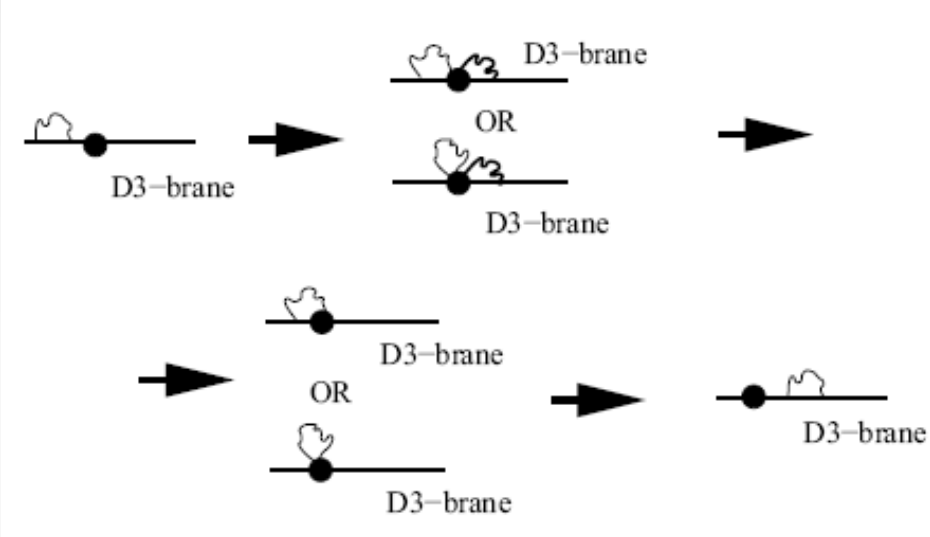
From Synchrotron Radiation Observations of Crab Nebula

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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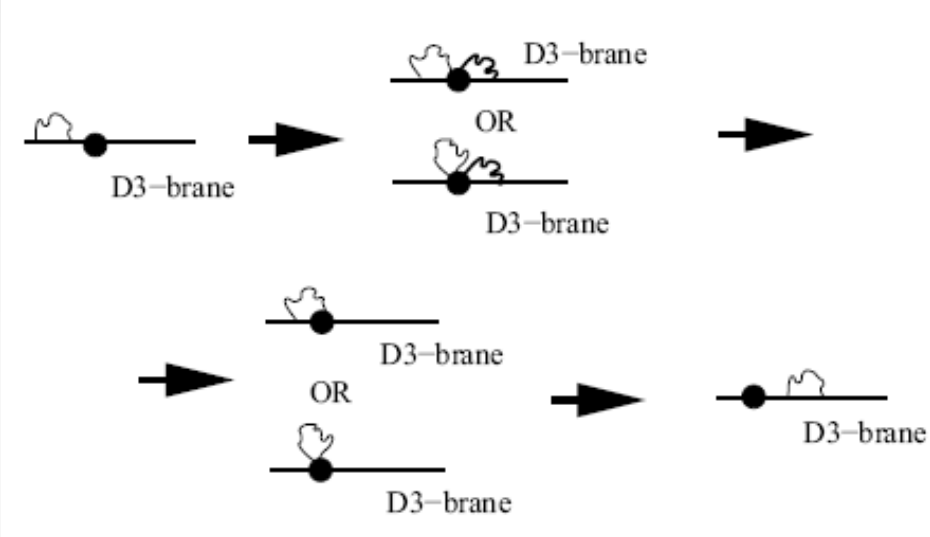

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Stringy Uncertainties & the D-Foam

- 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):

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

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COMPATIBLE WITH STRING UNCERTAINTY PRINCIPLES:

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

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

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

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Effective QG Scale depending on density of D-foam

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) can increase with z
If brane moves in inhomogeneous bulk

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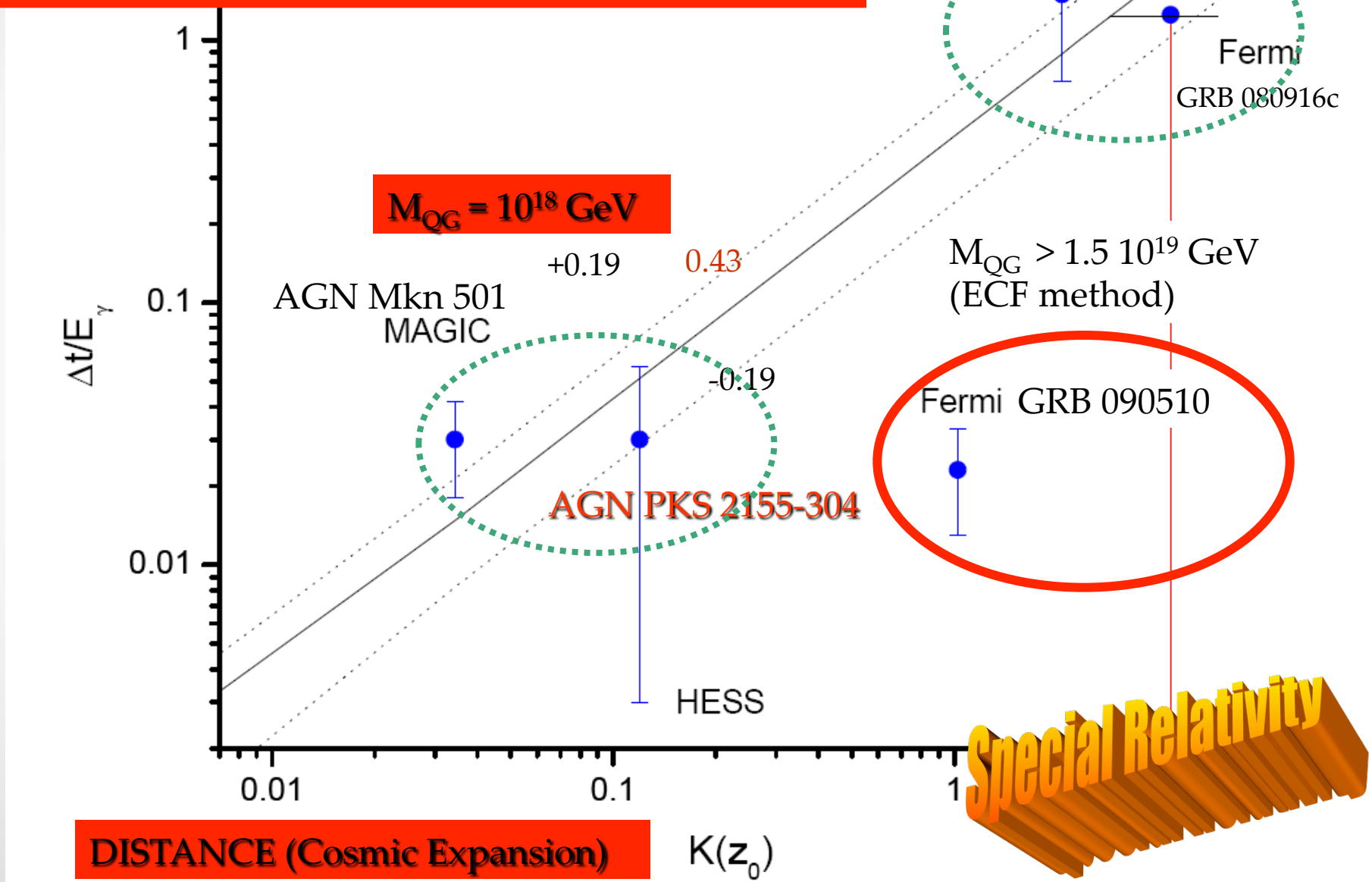
Account for MAGIC (& HESS) events for low z and ALSO for GRB 090510 (short burst) at high z =1
Higher z GRBs delays partly due to D-foam, partly due to Sourcce Delayed Emission

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

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



DISTANCE (Cosmic Expansion)

Ellis, NEM, Nanopoulos, PLBB674:83-86,2009, NEM 0909.2319

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