(Stringy) Space-Time Foam & Gamma Ray Astronomy

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Recent Developments in Gravity,
Ioannina (GR), June 8-11, 2010

OUTLINE

- Space-Time Foam & Fundamental Symmetries
- Terrestrial & Extraterrestrial Tests
- High-Energy γ-Ray Astronomy as a probe & Discriminant of space-time foam models
- Pushing the experimental sensitivity to Planck scales?? The case of GRB090510
- String theory foam model survives stringent astro-tests
- Outlook: Stringy foam and DARK MATTER – Collider constraints?

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- String theory foam model survives stringent astro-tests
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A rather Old Story…

Space-Time at Planck scales may have a ``foamy'' structure (J. A. Wheeler), with possible coordinate non-commutativity or Lorentz Violation at microscopic scales

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Quantum Gravity then may behave as a medium, with non-trivial ``optical'' properties:

Vacuum Refractive Index induced by QG !
Energy dependent speed of light, effects increase with energy of photon, due to increase in distortion of space time. Contrast with Matter-induced ordinary refractive indices.

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

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

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

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

Quantum-Gravity Induced Modified Dispersion for Photons

Ellis, NM, Nanopoulos

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

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

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Space-time Metric describing space-time Distortions induced by Interactions of Photons with space-time defects

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FINSLER type: depends on momentum (transfer)…

One type

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

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

Metric in a boosted frame of velocity u_i

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Space-time Metric describing space-time Distortions induced by Interactions of Photons with space-time defects
FINSLER type: depends on momentum (transfer)…

Another type : $g_{\mu\nu} = \eta_{\mu\nu}\left(1 - |\vec{u}|^2\right) , \qquad \mu, \nu = 0, 1$

(1 direction of $u_i = g_s \frac{\Delta k_i}{M_s}$)

$g_{\mu\nu} = \eta_{\mu\nu}, \qquad \mu, \nu \neq 0, 1$

Metric felt by open string in a background of a recoiling stringy point-like defect

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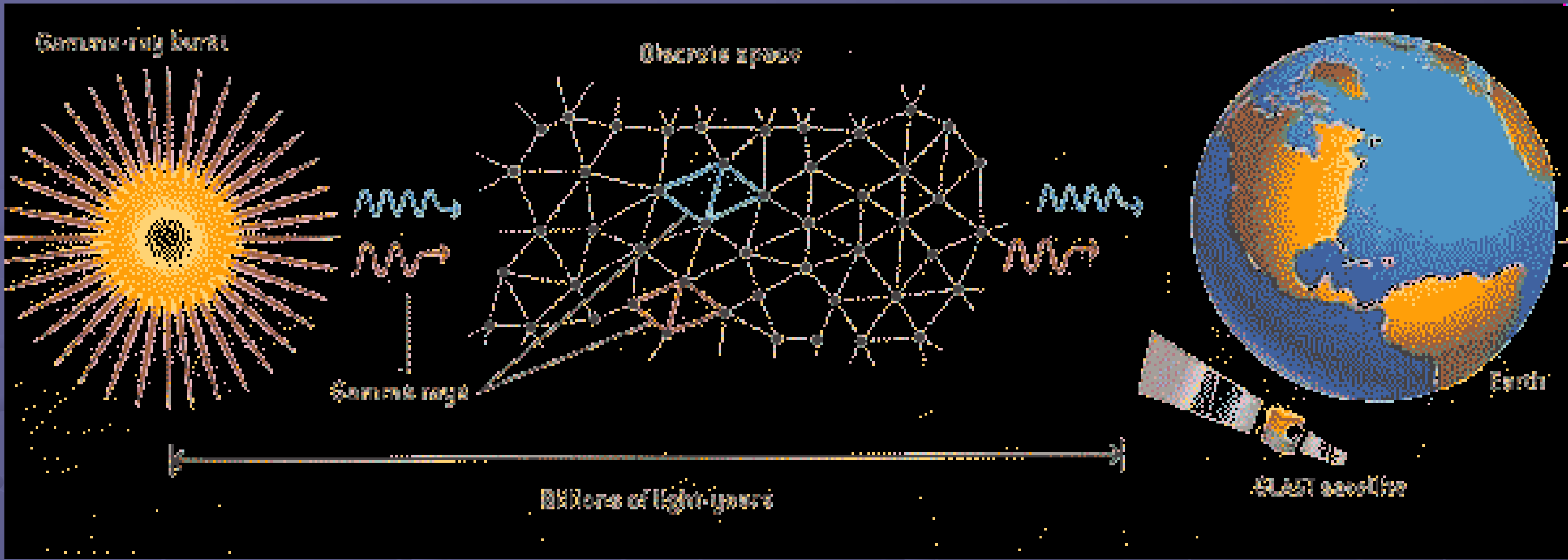
$$V_{\rm phase} = \frac{E}{|\vec{p}|} = \frac{1}{\eta} \ , \qquad V_{\rm group} = \frac{\partial E}{\partial |\vec{p}|}$$

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

$$\text{subluminal} : \ \eta > 1 \ , \ \text{superluminal} \ \eta < 1$$

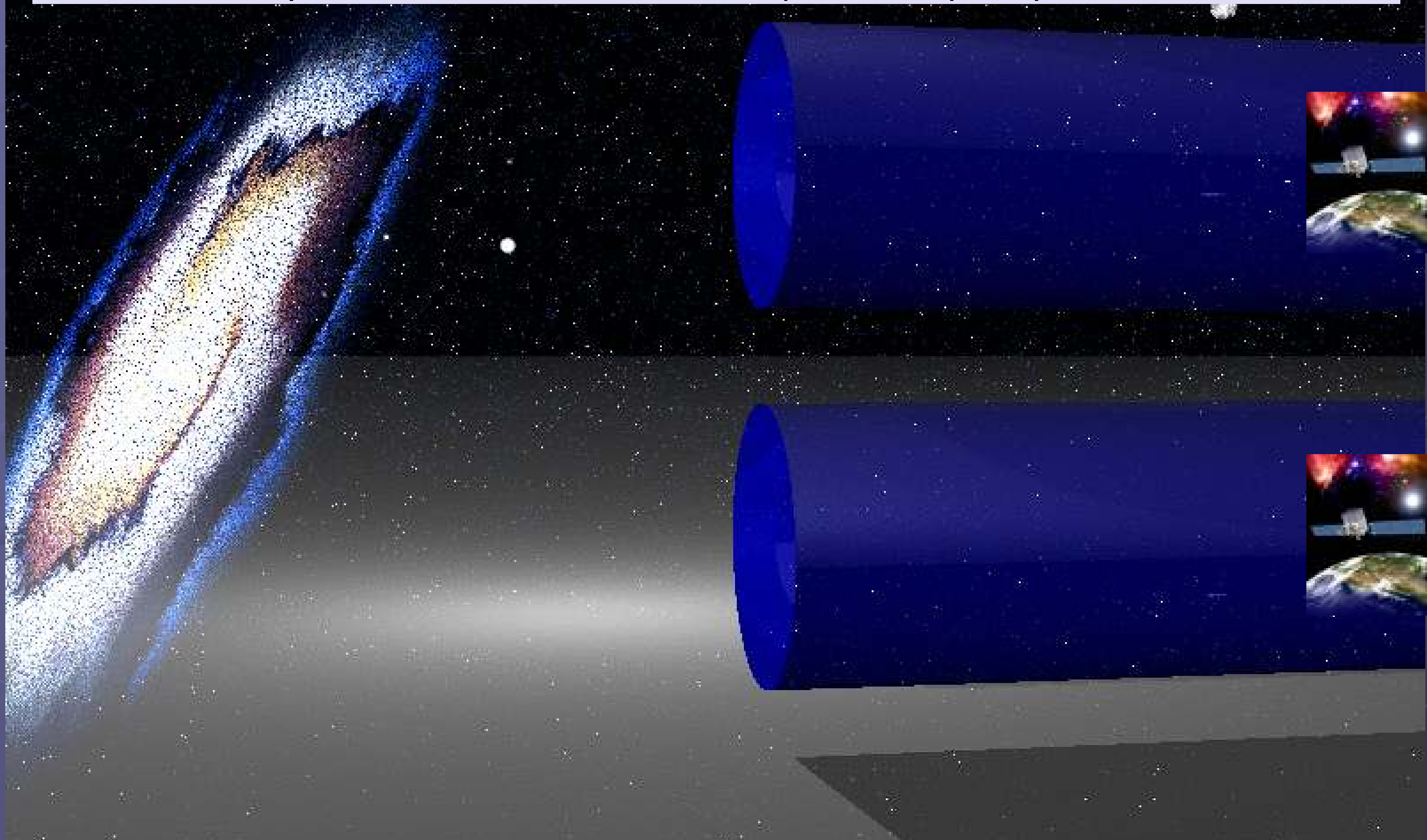


Non Commutative Discrete structure of Space-time at Microscopic (Planck) scales of order 10^{-35} meters

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

Courtesy: N. Doltsinis@kcl.ac.uk

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



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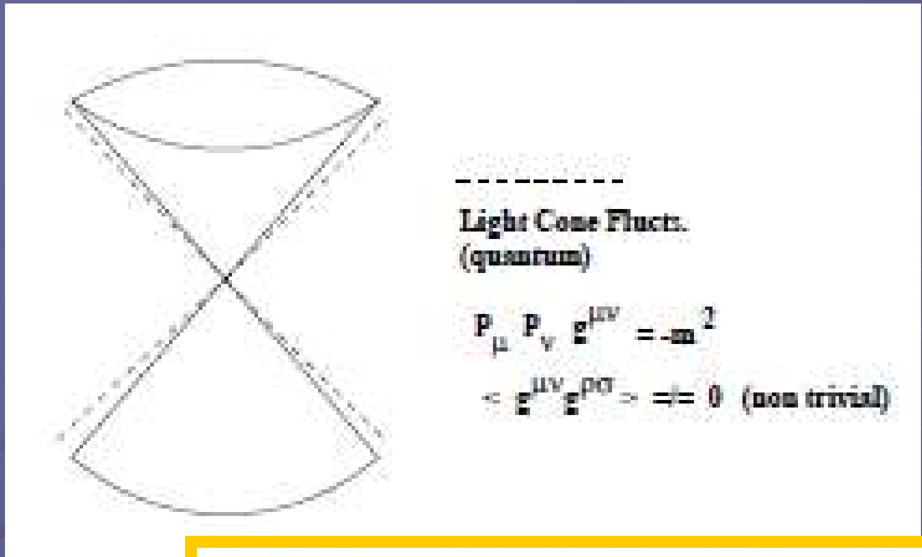
Stochastic Light-Cone Fluctuations



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

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

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

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

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

COSMIC PHOTON TESTS :

(i) Measuring Arrival times

(delays of more energetic γ s)

Uncertainties Emission Mechanism

Must accumulate statistically significant of ``events''

(ii) *Birefringence* (ONLY for some QG models) :

Measuring afterglow from distant GRBs

(iii) *Ultra-High Energy Cosmic Ray Spectrum* : LIV modifications of GZK cutoff

Constraints: Non observation of UHE γ s with E > 10^{20} eV

MASSIVE COSMIC PROBE TESTS: Charged Probes (electrons)

QG Modifications in Synchrotron radiation spectrum **– stringent constraints from CRAB NEBULA**

QG induced DECOHERENCE

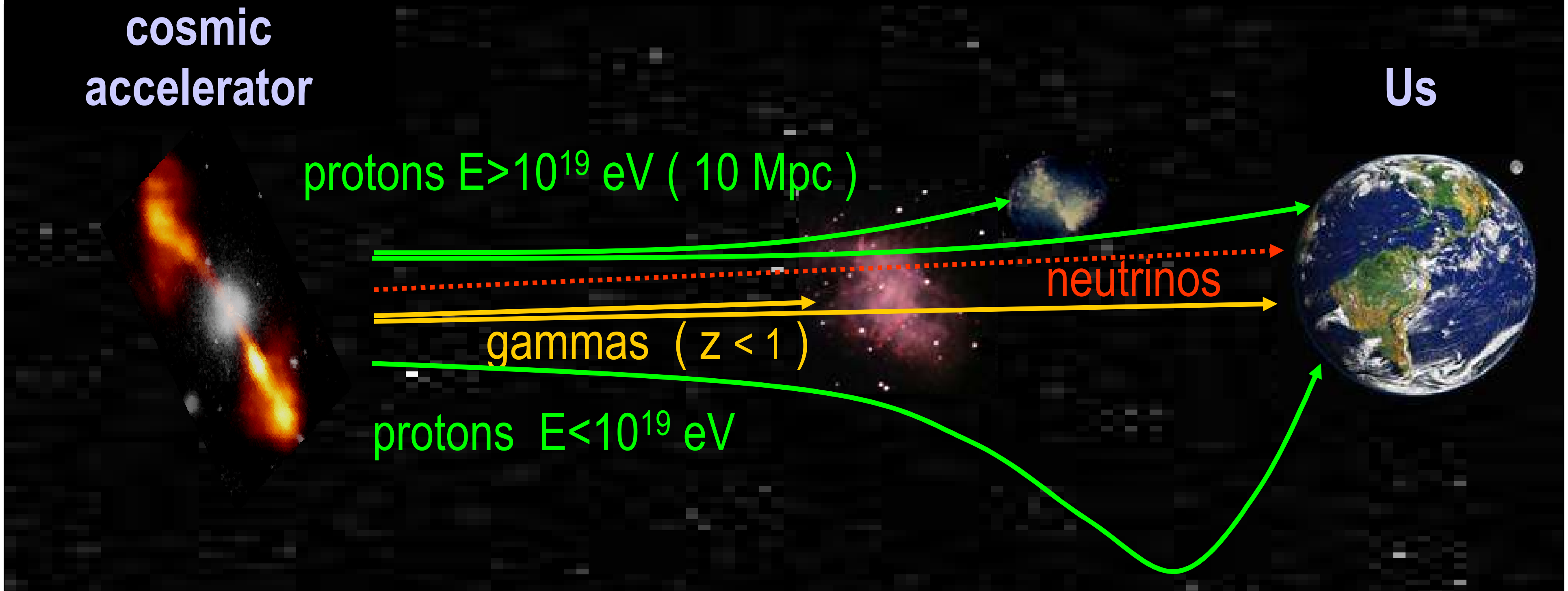
(i) Damped flavour oscillators Cosmic neutrinos

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

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

ω-effect (Bernabeu, NEM, Papavassiliou 04)

Multi-messenger observations of the Cosmos



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

photons: Absorbed by dust & radiation field (CMB)

neutrinos: Difficult to detect

⇒ Three "astronomies" possible...

DeNaurois 2008

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VHE Experimental World Today

M. MARTINEZ

VHE Experimental World Today

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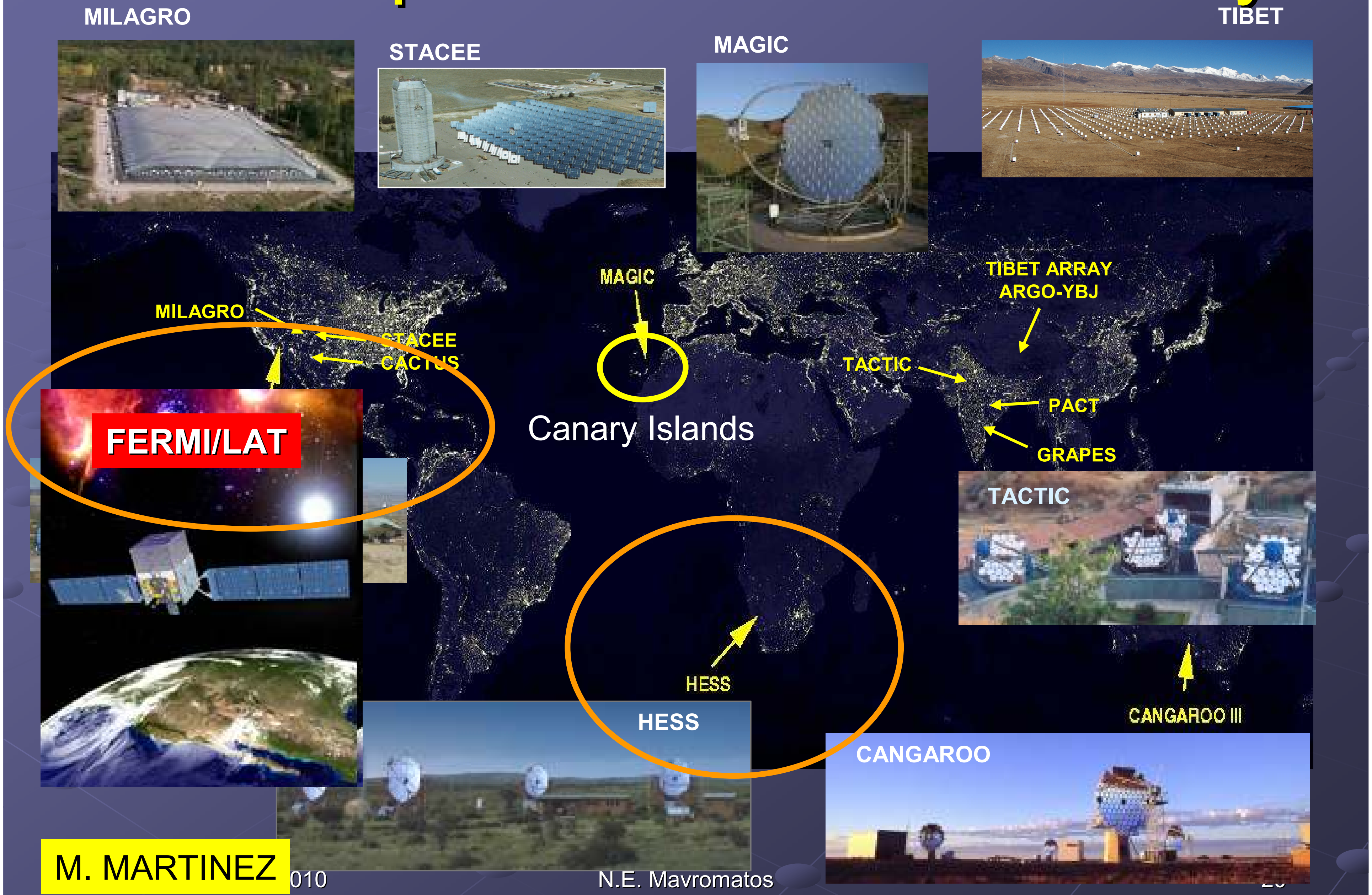

Gamma Ray Astronomy & LIV

Review N.E.M 0903.0318

- High-Energy Gamma Ray Astrophysics as a probe for New Physics
- **The MAGIC and Fermi results**: non-simultaneous arrival of high-energy photons from celestial objects: more energetic photons arrive later… **(Non(?)) Observation by H.E.S.S. …**
- Possible Interpretations:

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

  (ii) Exotic Interpretation: Quantum Gravity (QG) propagation effects (?): *QG as a medium with refractive index, Modified Dispersion Relations for matter probes with Linear QG scale suppression (LMDR)*
- **Check on other tests on (LMDR) modified dispersion relations:**
  Electrons: Synchrotron Radiation from Crab Nebula
  Photons: Birefringence constraints for LMDR

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Fundamental Physics

Link ?

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

  Photons: Birefringence constraints for LMDR

Current Evidence of Delayed Photon Arrivals

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

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

?

FERMI (GRB 090816C, z=4.35), Highest Energy Photon 13.2 GeV

4.5 s time-lag between E > 100 MeV and E < 100 KeV
Observed Time Delay 16.5 sec

FERMI (GRB 090510, z=0.9), Highest Energy Photon 31 GeV, several 1-10 GeV

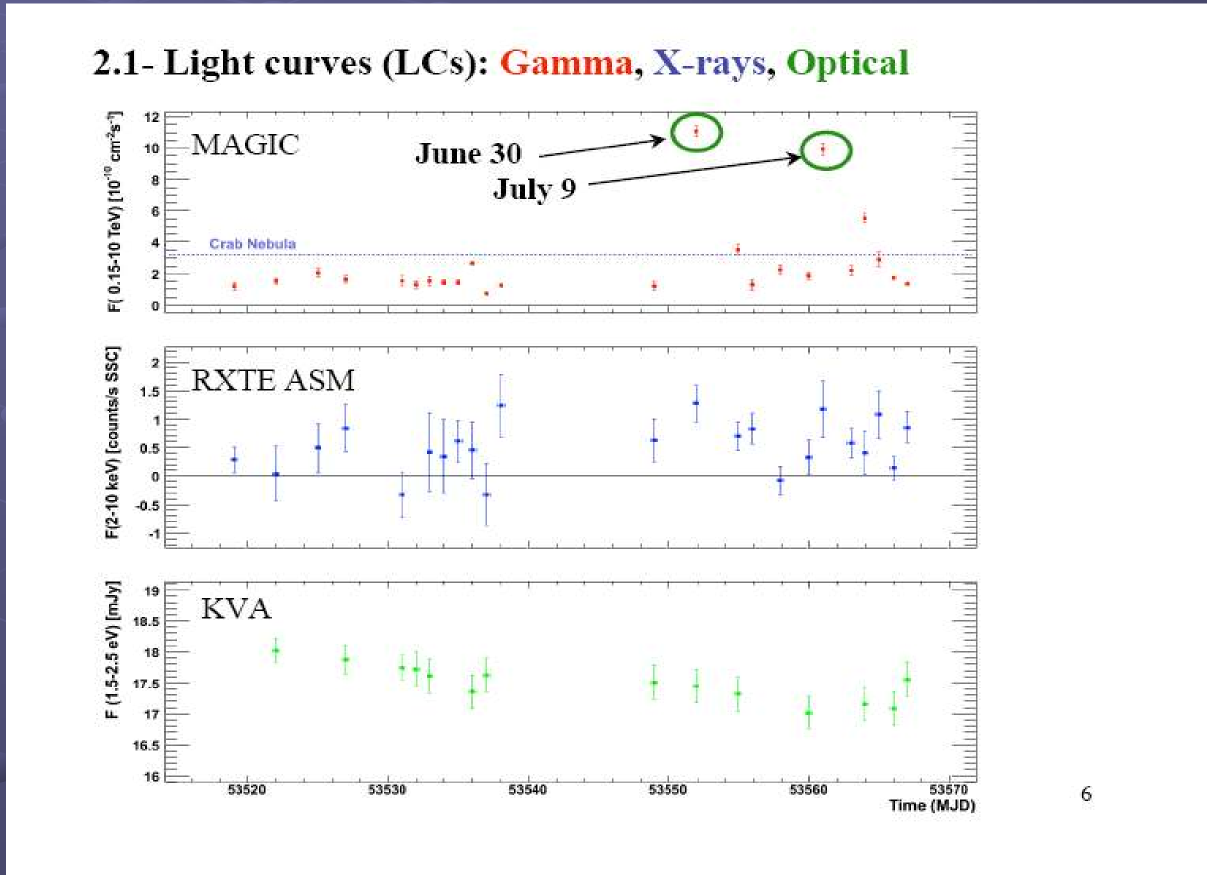
Short, intense GRB, Observed Time Delays < 1 sec

FERMI (GRB 09092B, z=1.822), Highest Energy Photon 33.4 GeV

Observed Time Delay Δt: 82 sec after GMB trigger
50 sec after end of emission

z=1 → 10^{26} m

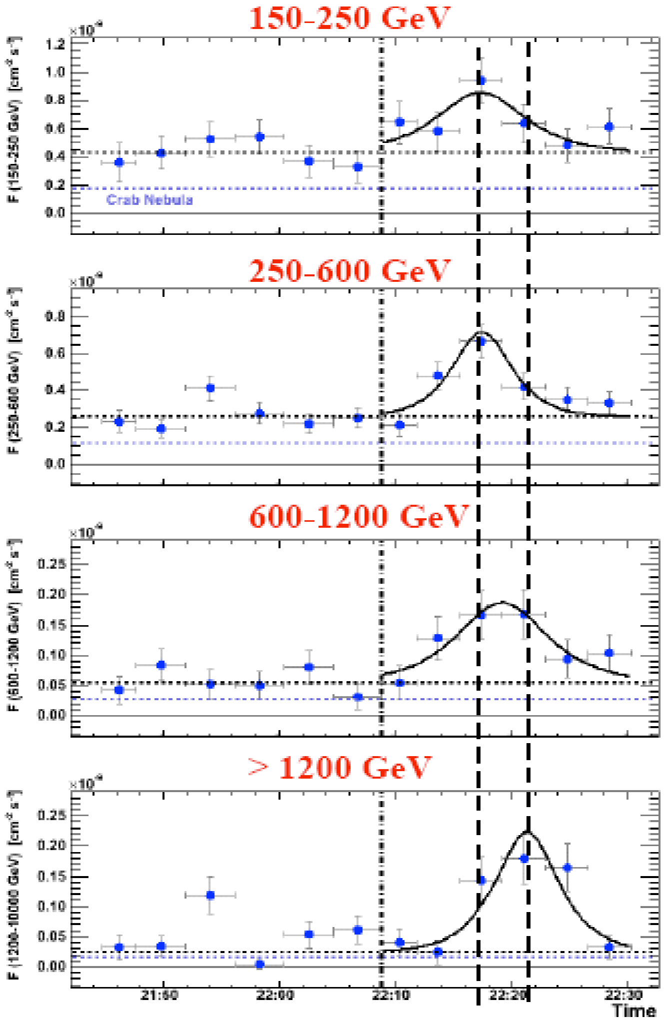
The MAGIC Collaboration (Major Atmospheric Gamma-ray Imaging Cherenkov Telescope)



Observation of Flares from AGN Mk 501

Red-shift: z=0.034

The MAGIC ``Effect''



LCs for different energy ranges (4 min bins)

July 9

Flare is seen in all energy ranges

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

13

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$z=1 \longrightarrow 10^{26}$ m

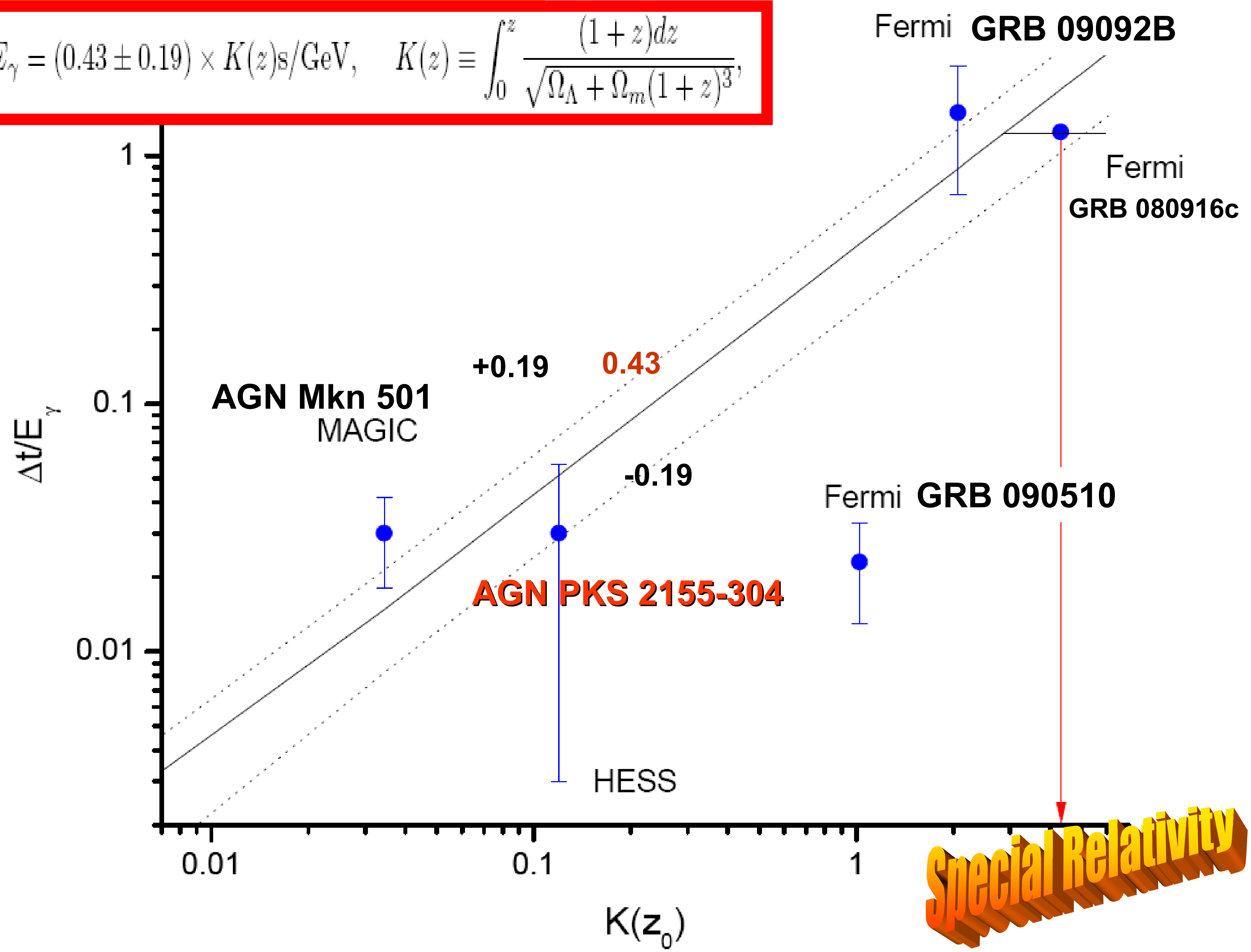
DELAYED ARRIVALS OF MORE ENERGETIC PHOTONS:
FIT WITH A LINEARLY SUPPRESSED (BY THE QG SCALE) SUBLUMINAL DISPERSION RELATION ?

$$E = p\,(\,1\ - p^2/M_{QG}\,)$$

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

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

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



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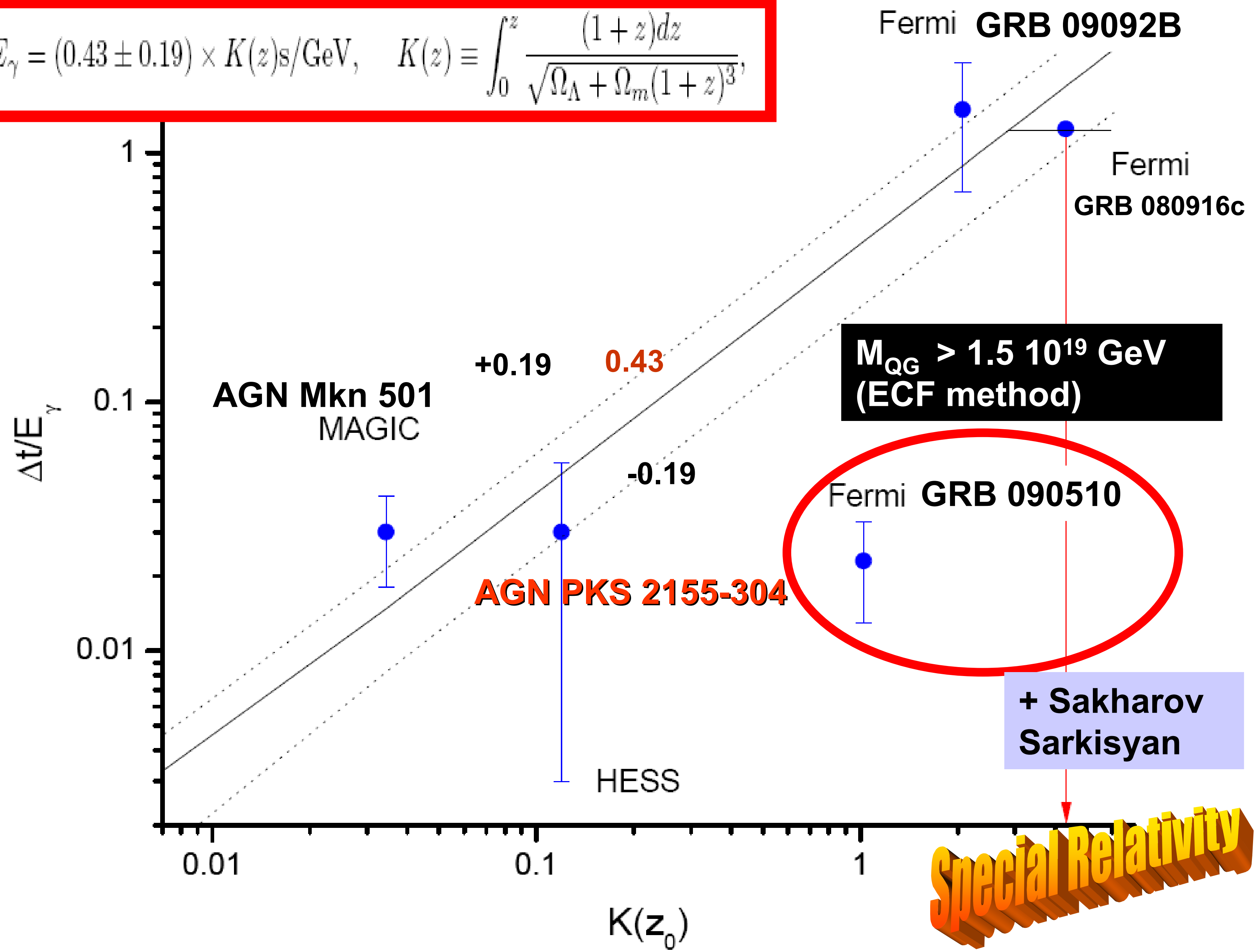
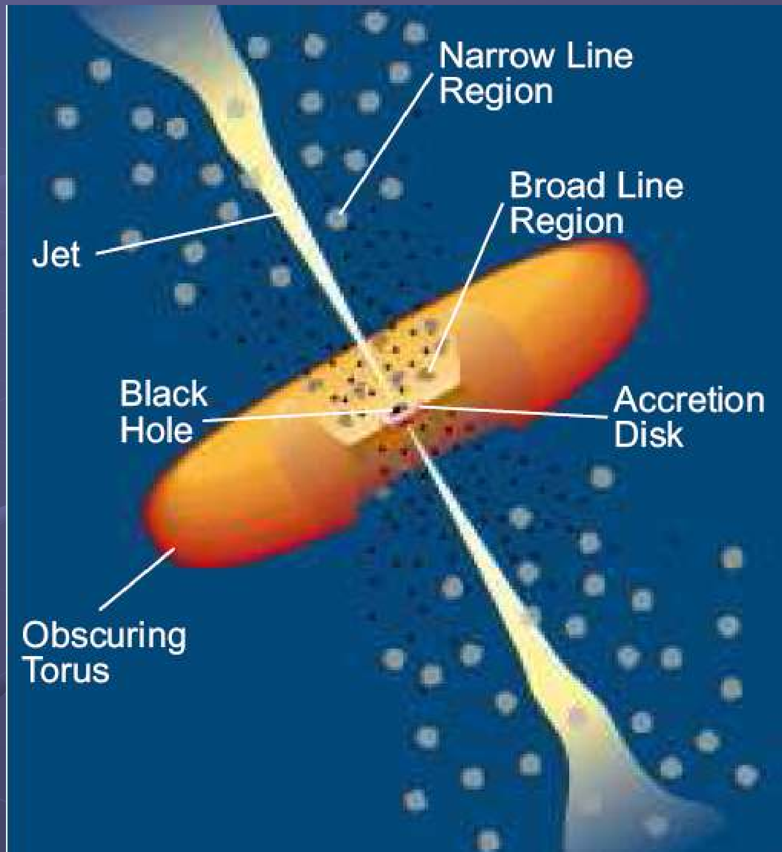


DELAYED ARRIVALS
OR DELAYED EMISSION?

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

AGN High Energy Gamma Rays

High-Energy Photons from Gravitational Energy Conversion, released by collapses towards a central massive object (black hole); angular momentum implies accretion disk, and jets outflowing the accretion plane…



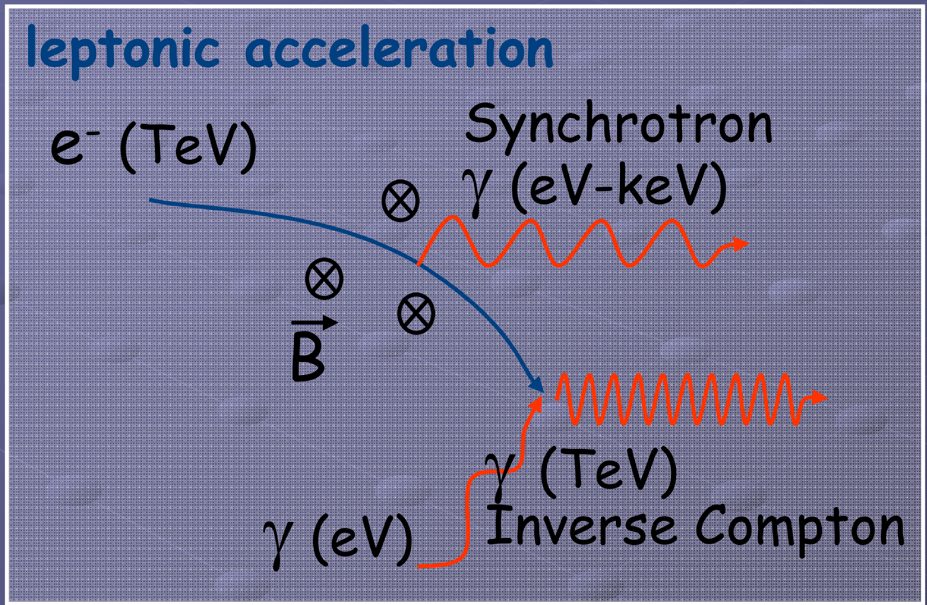
Most popular Interpretation is Self-Synchrotron-Compton (SSC):
Time-varying populations of Ultrarelativistic electrons accelerated in strong magnetic fields → Synchrotron Radiation generating Inverse Compton Emission (100 MeV-100 GeV) from soft photons scattered off energetic electrons.
Compton components peak at TeV energies.

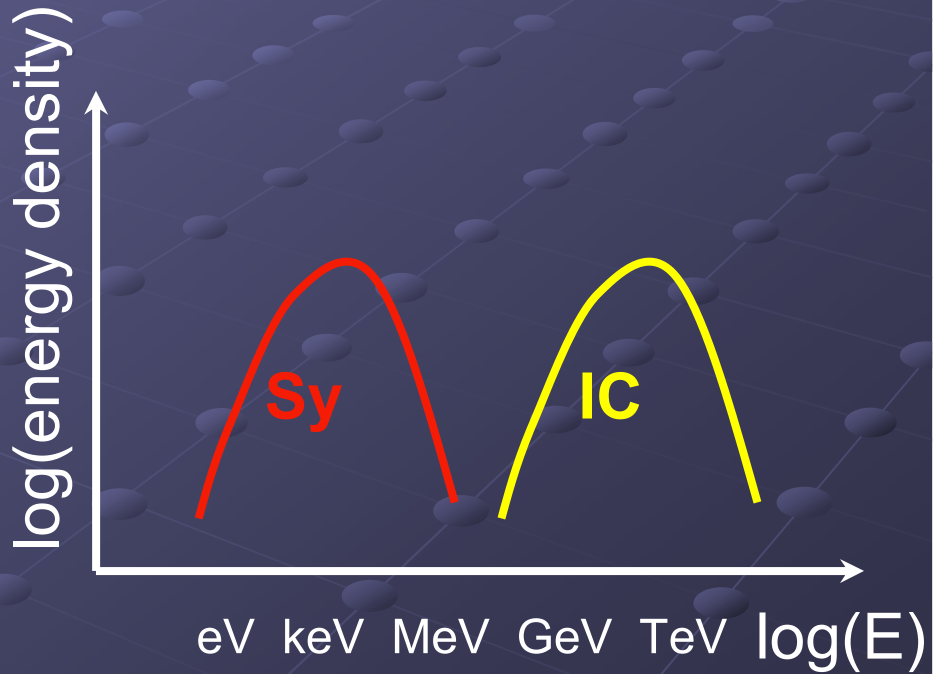
AGN High Energy Gamma Rays

- electron accelerators:

synchrotron: e B -> e gamma

+ inverse Compton: e gamma -> gamma e





SSC as explanation of the MAGIC Effect

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

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

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

  Bednarek, Wagner

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

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Plasma Source Effects & Refractive Index

Latorre, Pascual, Tarrach (1994)

Moreover, Photons at the source region find themselves in a non-trivial Vacuum of Quantum Electrodynamics (QED) due to Plasma Conditions

Vacuum Polarization Effects of QED induced (group velocity) Refractive Index: For Plasma magnetic fields B and temperature T >> m_e , q = photon momentum

2-loop effects

$$v(qT \gg m_e^2) = 1 - \frac{\alpha^2}{6}\left(\frac{T}{q}\right)^2 \ln^2 \frac{qT}{m_e^2} \quad , \quad T \leq q$$

Subluminal refractive index, at high energies, but decreasing with photon momentum and hence the effect cannot account for the MAGIC delays. Moreover, the magnitude of the correction to reproduce the required magnitude of the MAGIC effect, would require unrealistically high values of T .

$$\Delta t = D(\alpha^2 T^2 / 6q^2)\ln^2(qT/m_e^2)$$

D = Plasma size ~ 10^9 Km
T = 10^{-2} MeV

MAGIC Coll + Ellis, NM, Nanopoulos Sakharov, Sarkisyan (2007)

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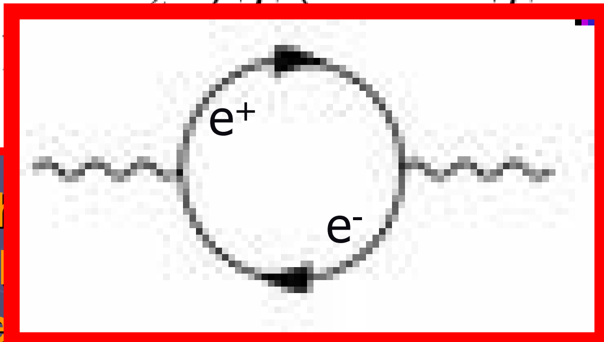

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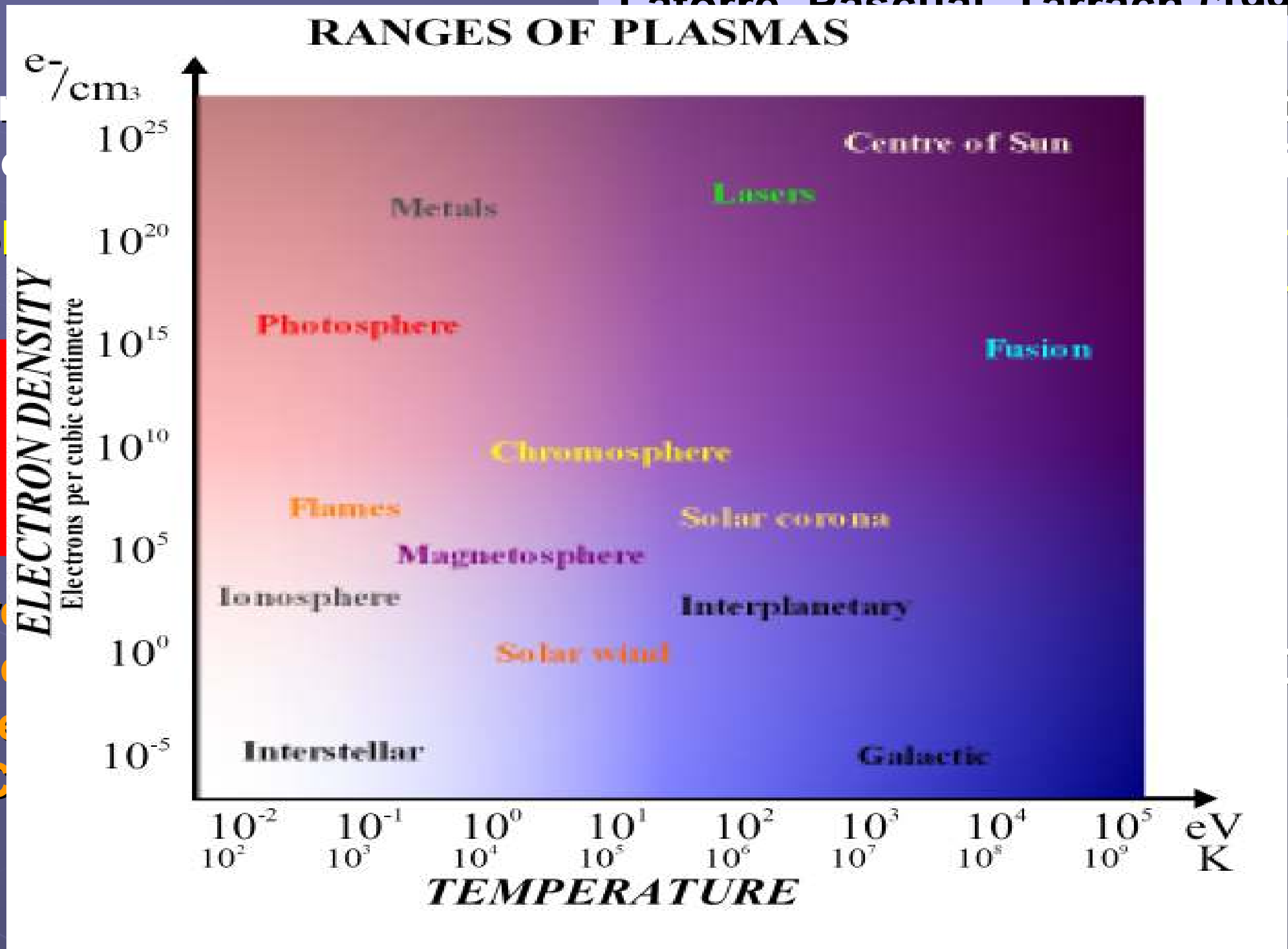

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RULED OUT

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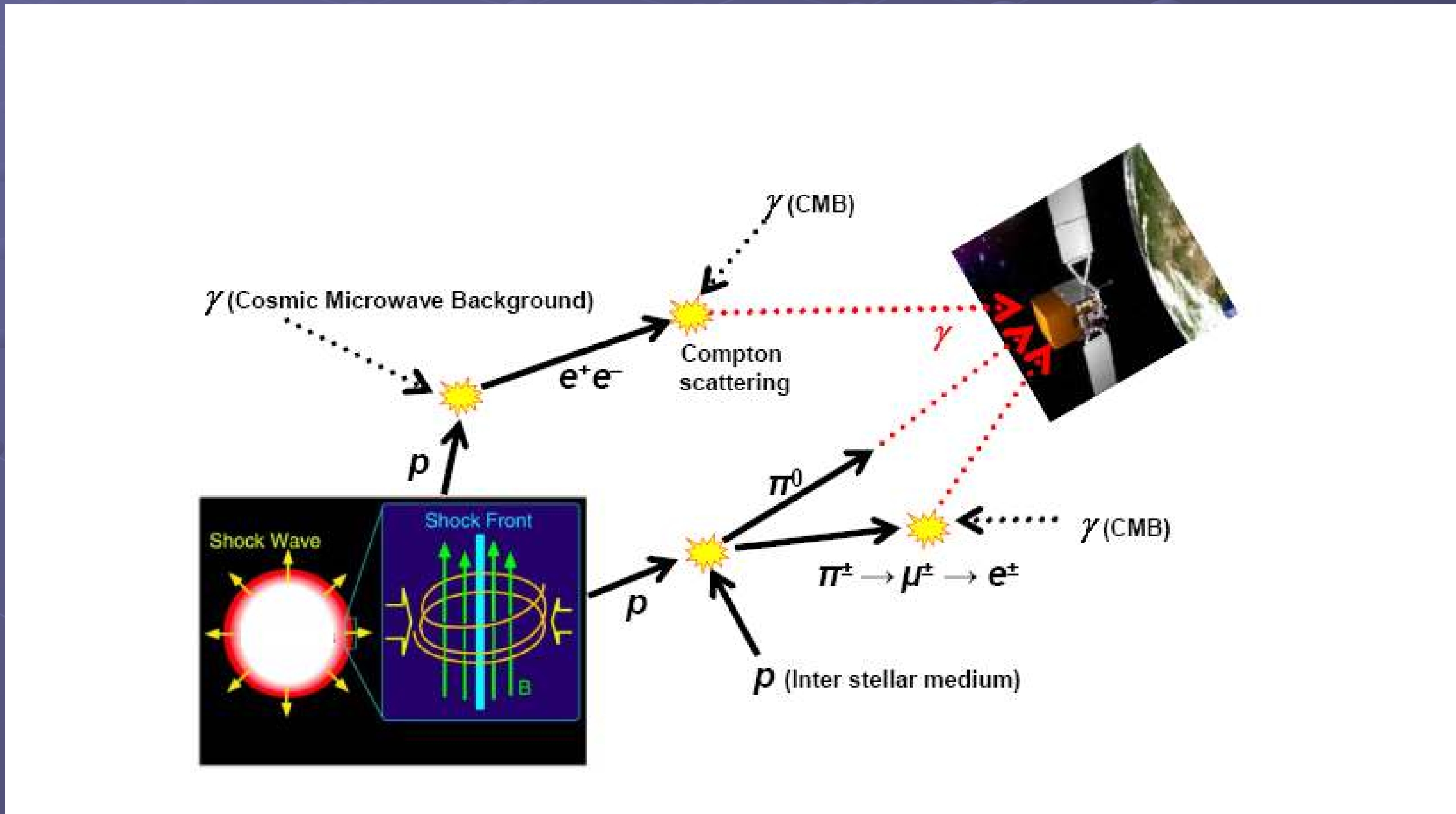
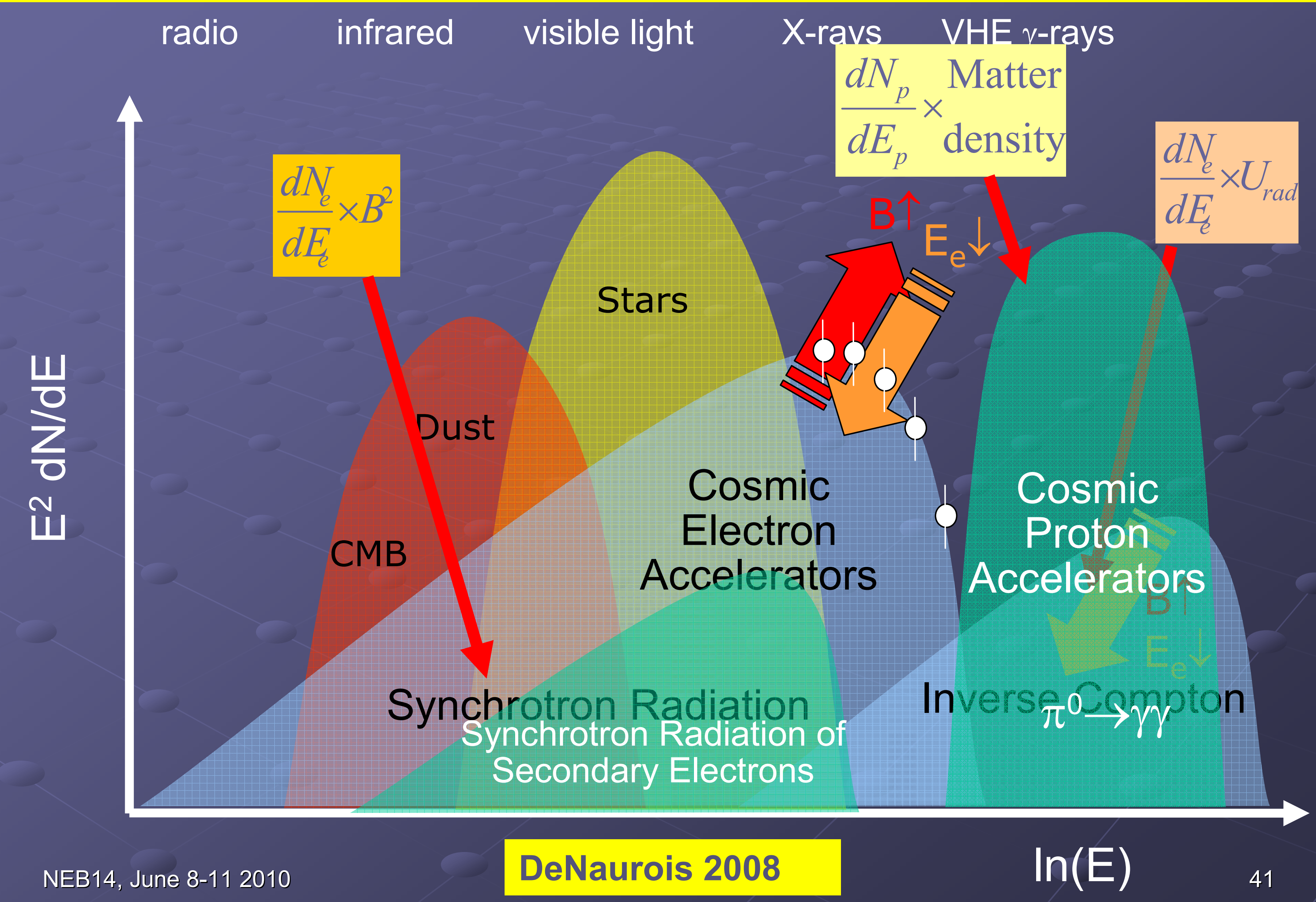
AGN HE γ: Hadronic acceleration

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



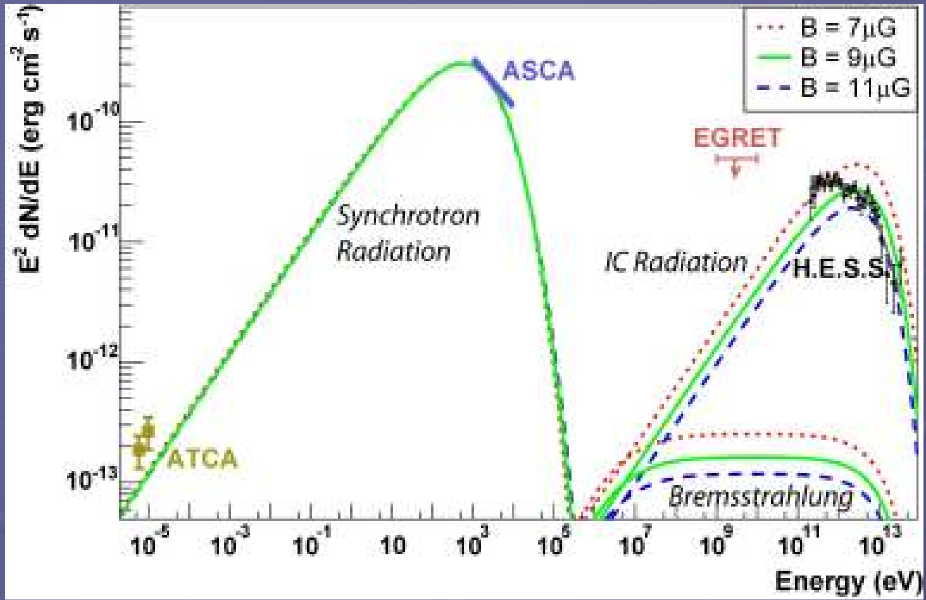
Electron or Hadron Accelerator?

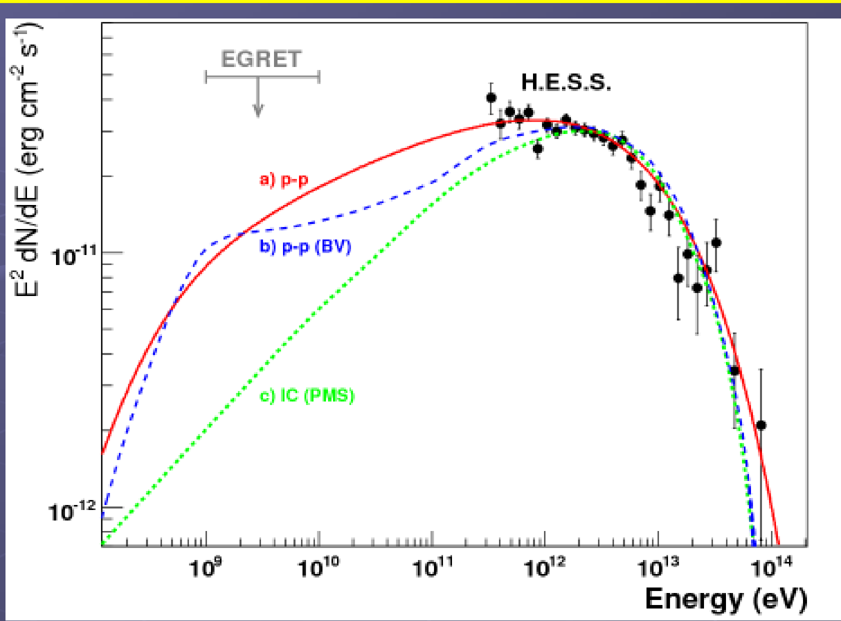


Hadronic or Leptonic acceleration?

- **The situation (hadronic vs electronic acceleration) is still inconclusive …**

To this end: Energy Spectrum

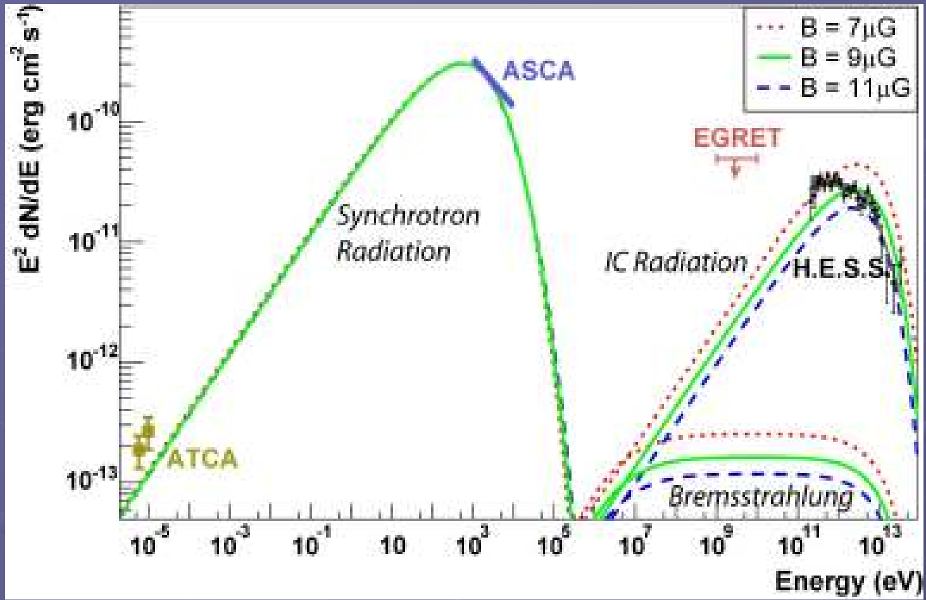


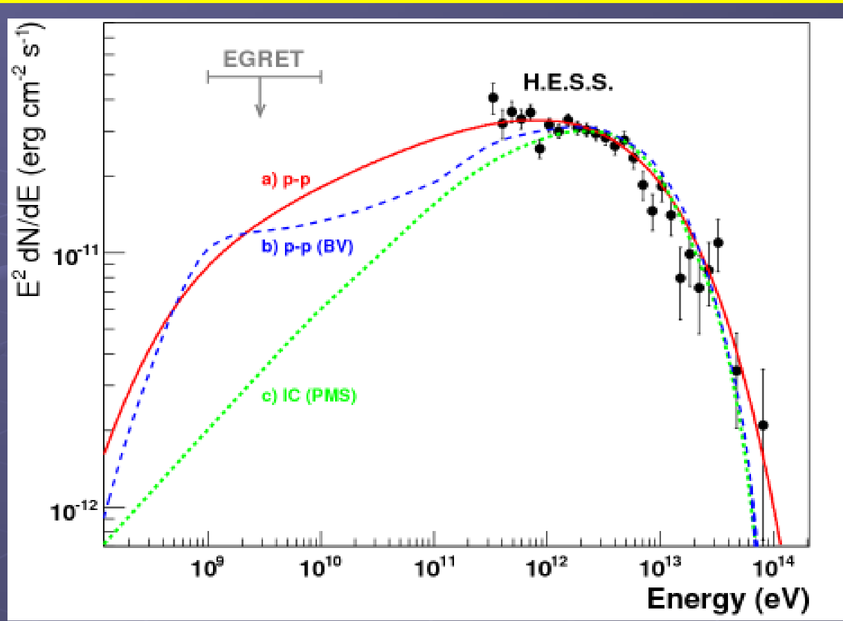


- Close correlation with X-rays [+electrons]
- Spectral shape [+protons]
- IC interpretation implies (too) low B-field [+protons]
- No correlation with molecular material [+electrons]
- Not yet clear…
  - Need data at lower energies to be sure, e.g. FERMI/*GLAST*

DeNaurois 2008

To this end: Energy Spectrum



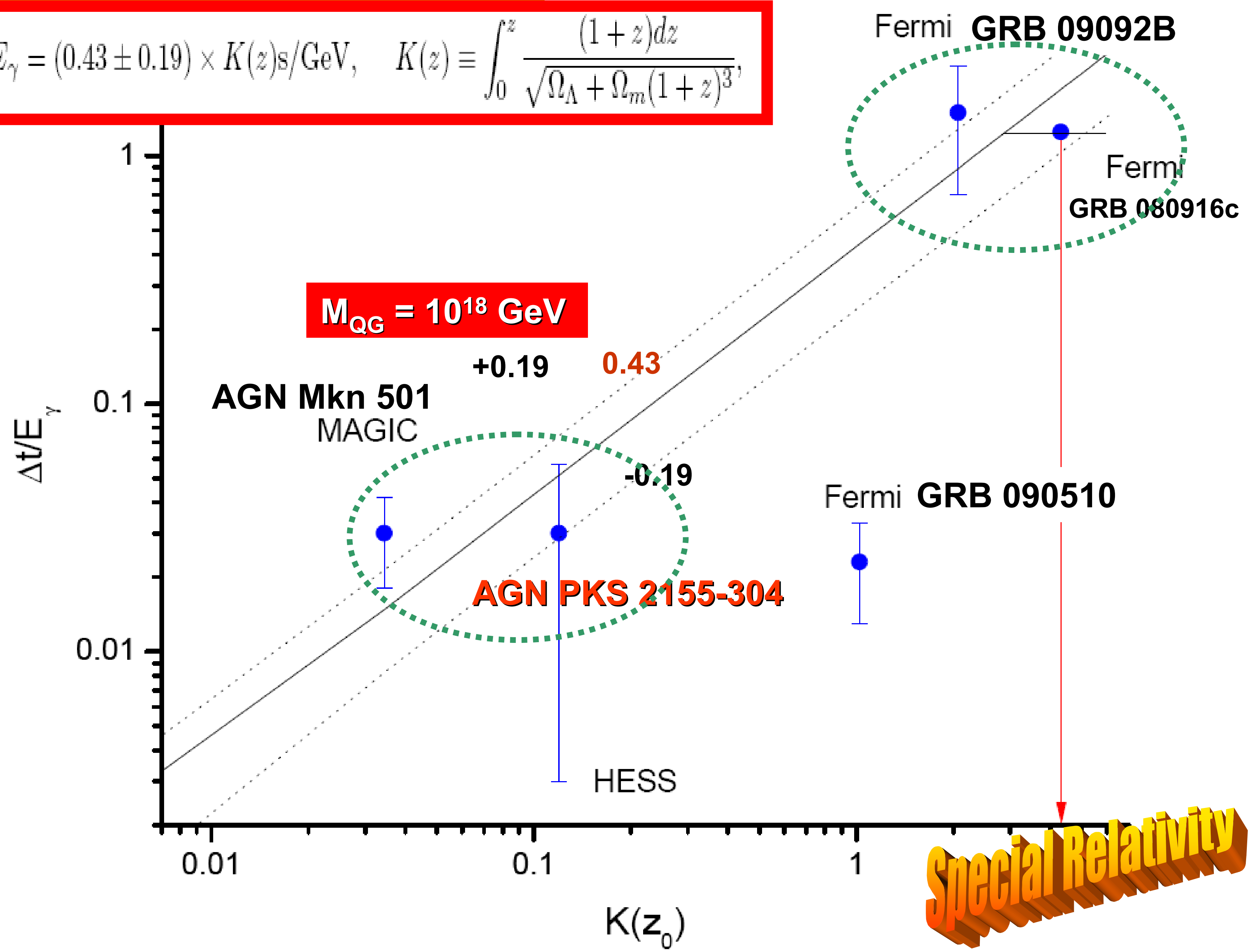


- Close correlation with X-rays [+electrons]
- Spectral shape [+protons]
- IC interpretation implies (too) low B-field [+protons]
- No correlation with molecular material [+electrons]
- Not yet clear...
  - Need data at lower energies to be sure, e.g. FERMI/*GLAST*

DeNaurois 2008

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

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



BUT EVEN IF SUCH FITS SUCCEED FOR PHOTONS ARE THEY SENSIBLE FROM THE VIEW POINT OF OTHER ASTROPHYSICAL (OR TERRESTRIAL) TESTS OF LORENTZ INVARIANCE ?

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

NO BIREFRINGENCE

Effective Field Theory Approach

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

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e.g. higher order QG induced terms in QED :

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

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

MDR for other matter probes

Massive Probes (e.g. electrons):

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

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 $\alpha > 1.74$

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δ(E) = ar ... n

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WHAT ABOUT PHOTONS & THE MAGIC RESULT?

Birefringence Constraints on photons MDR

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

Maccione et al., arXive0707.2673

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

Myers-Pospelov QED

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

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

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

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

Difference in polarization angle over cosmological distance *d*:

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

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

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

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

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MAGIC EFFECT due to QG ruled out ?

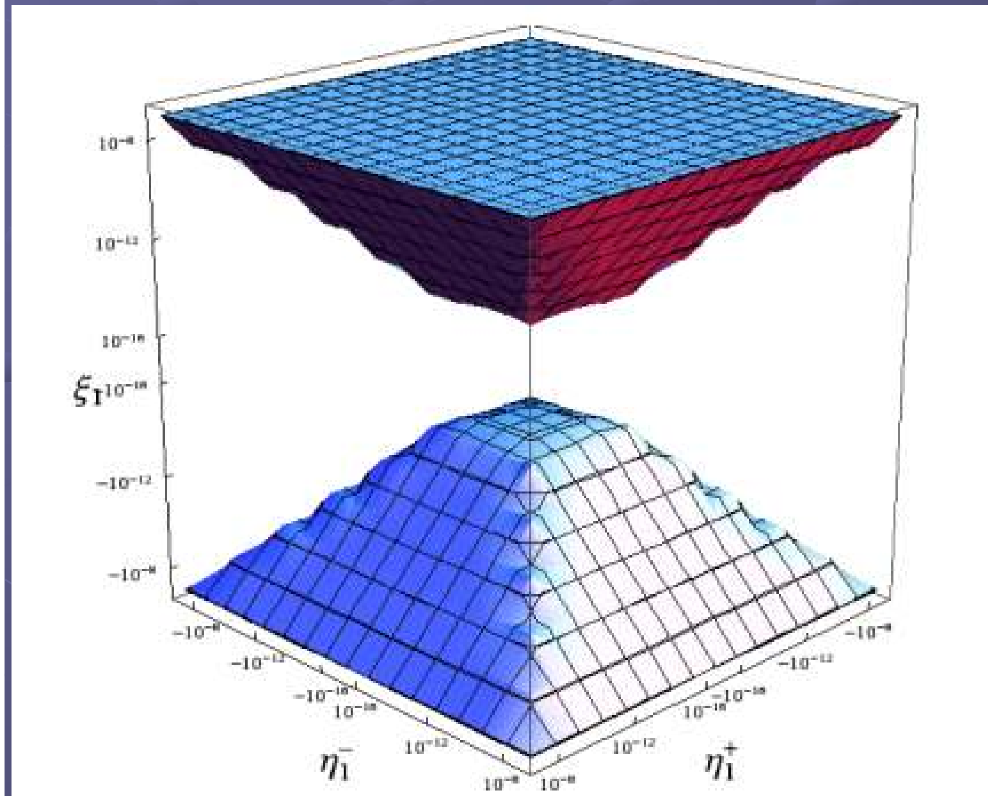
Ultra-high-energy photons

Galaverni & Sigl
+ Liberati. Maccione

$$\omega_{\pm}^2 = k^2 + \xi_n^{\pm} k^2 \left(\frac{k}{M_{\rm pl}}\right)^n ,$$

$$\omega_{\rm b}^2 = k_{\rm b}^2 ,$$

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



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

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

(ii) Photon Decay

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

Allowed, above threshold if MDR

Questions…

Can we have a red-shift z-dependent Effective QG Scale?

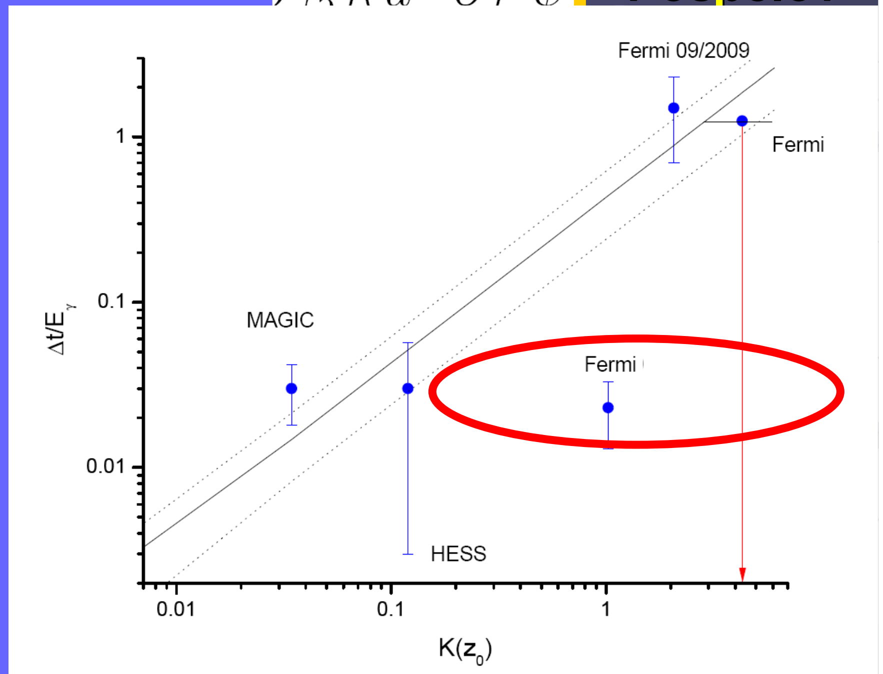
Such that time delays of MAGIC, HESS & GRB090510 are due to linear QG & rest due to both Source and QG effects?

grangians (LEL):

arXive0707.2673

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

Myers-Pospelov



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MAGIC EFFECT due to QG ruled out ?

Avoid MDR but still have Time Delays?

grangians (LEL):

, arXive0707.2673

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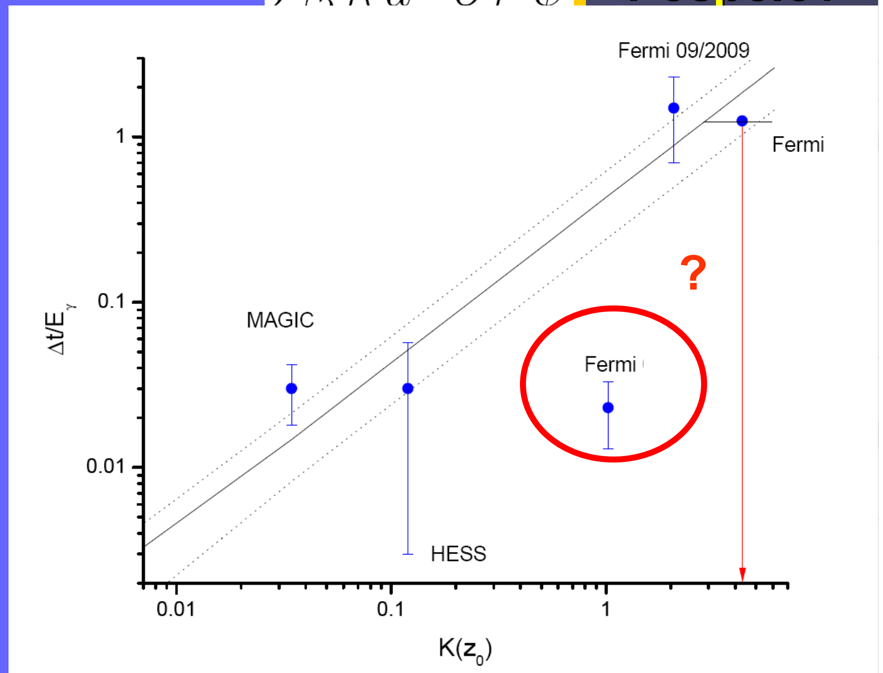
Myers-Pospelov

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



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MAGIC EFFECT
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A CLASS OF MODELS WITH SUCH PROPERTIES…

(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
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STRING THEORY & VACUUM REFRACTIVE INDICES

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STRING THEORY & VACUUM REFRACTIVE INDICES

Stringy Space-Time Foam

Ellis, NM, Nanopoulos, Review: N.E.M 0906.2712

- **Stringy Models of Space Time Foam (SMSTF) : Non-universal action of ``gravity foam'' on matter probes:**

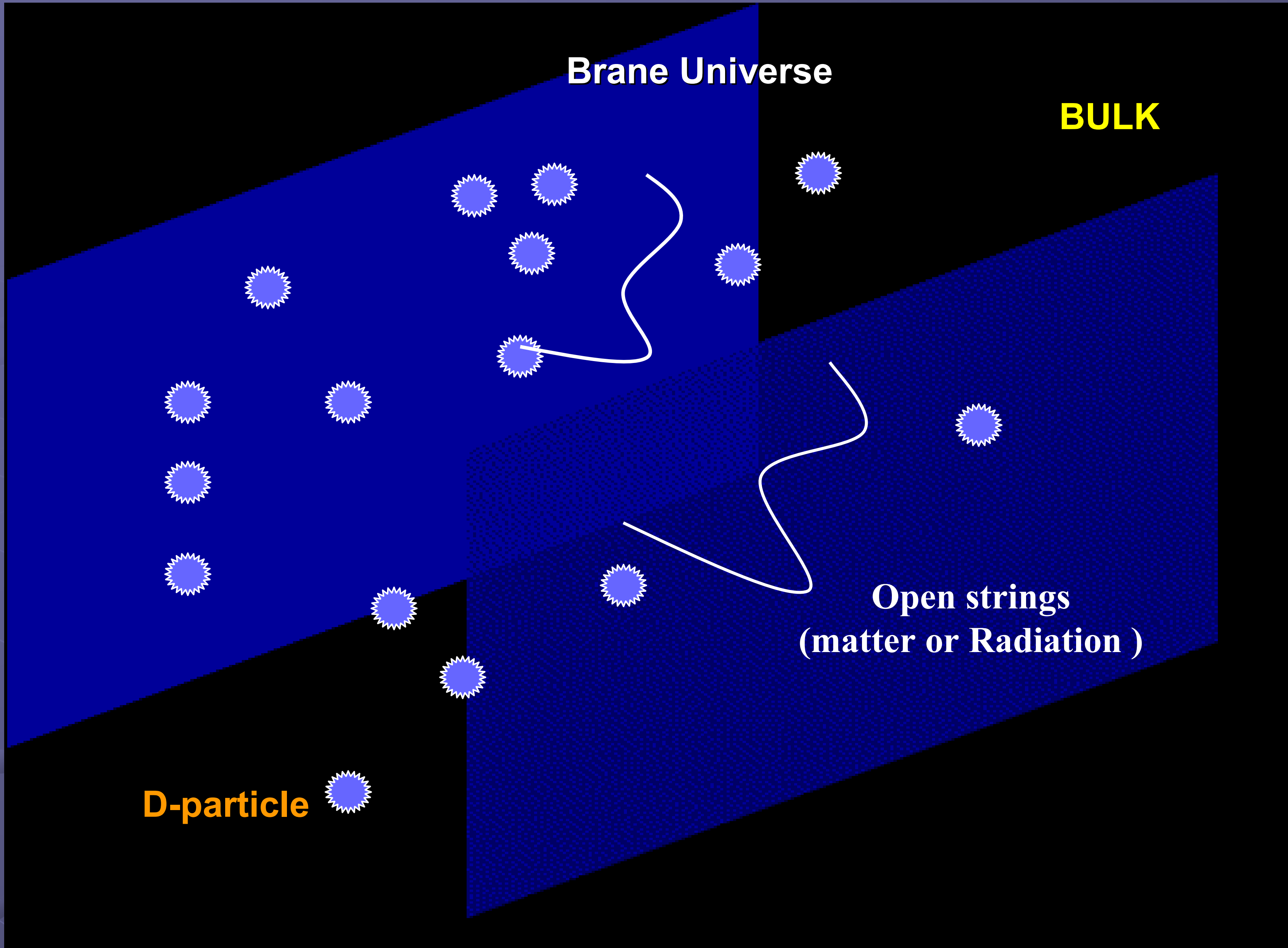
  Electrons (and in general charged particles): foam transparent,

  Photons (and neutral particles) feel the foam medium effects

- **String Uncertainties, (Induced, Finsler-type) Non-commutative geometry at string scales: a uniquely stringy effect ?**
- **Beyond EFT?**

  …. Compatible with other tests constraining LMDR

- Other consequences of the SMSTF: **CPT Violation** (ill-definition) due to **decoherence** and unique effects (?) in **entangled states** of meson factories



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

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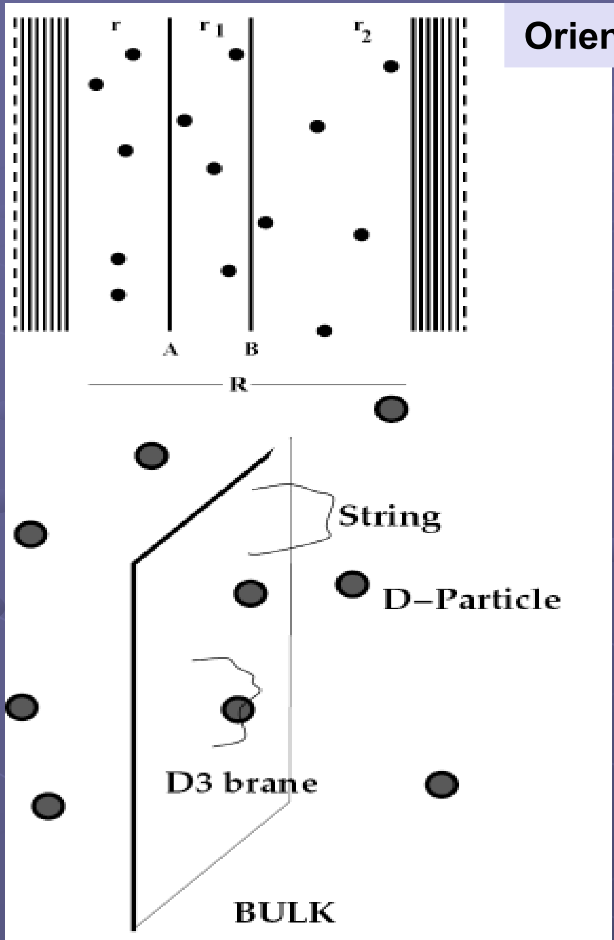
A Stringy (type IIA) Model of Space -Time Foam



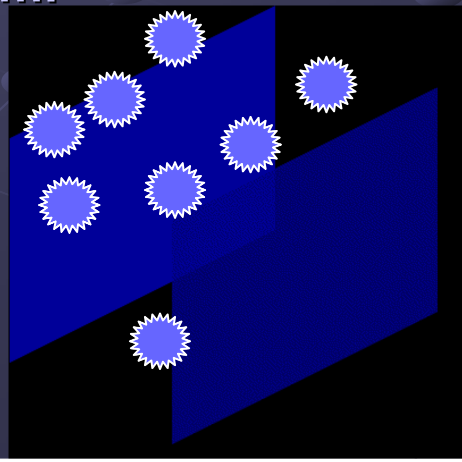
Orientifold planes, stacks of D8 branes

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….**



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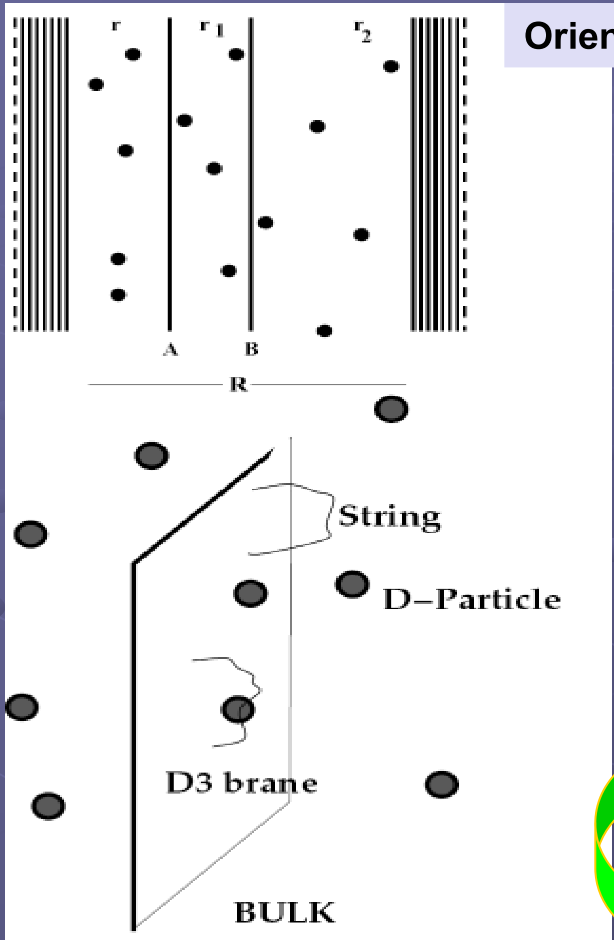

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NON-UNIVERSAL ACTION OF D-PARTICLE FOAM ON MATTER & RADIATION

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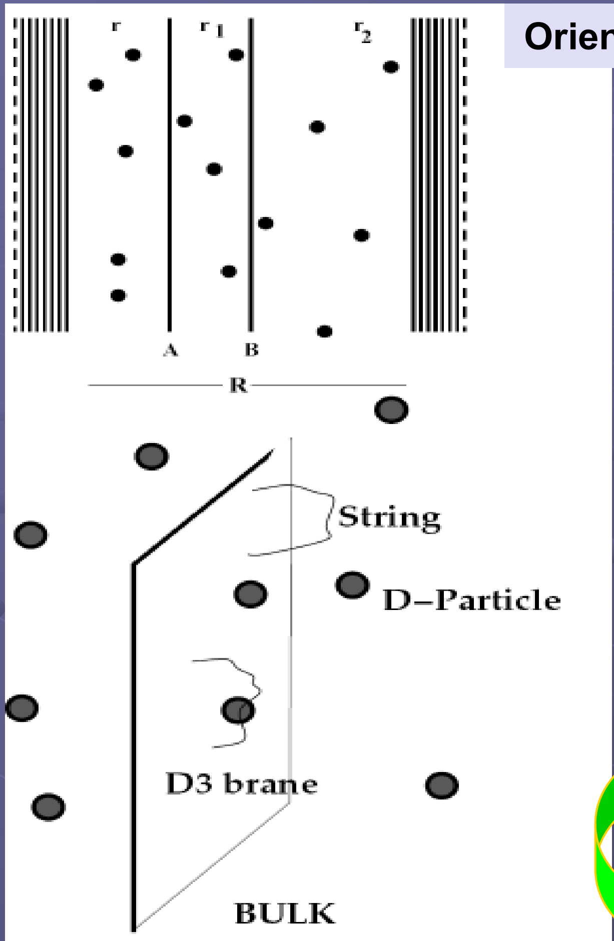

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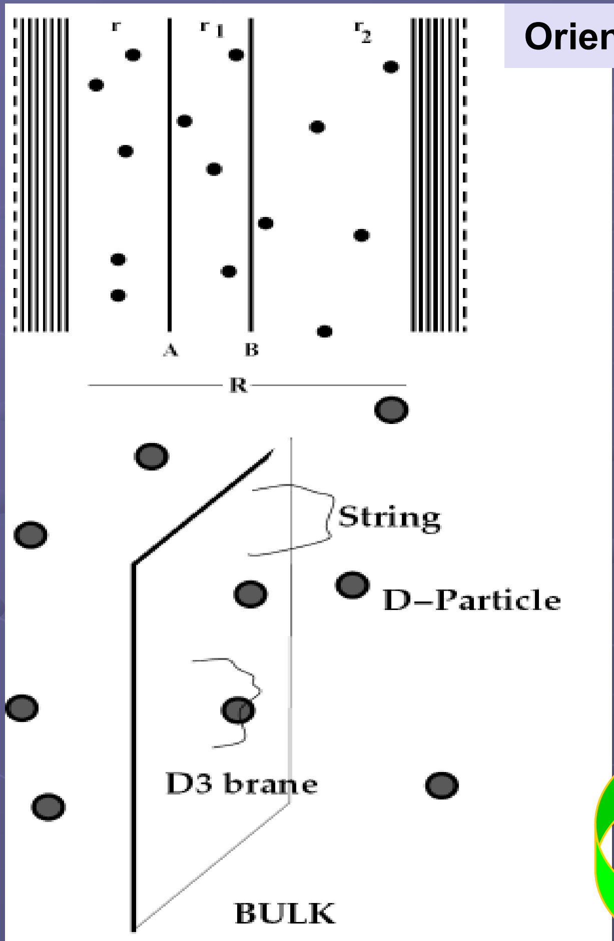

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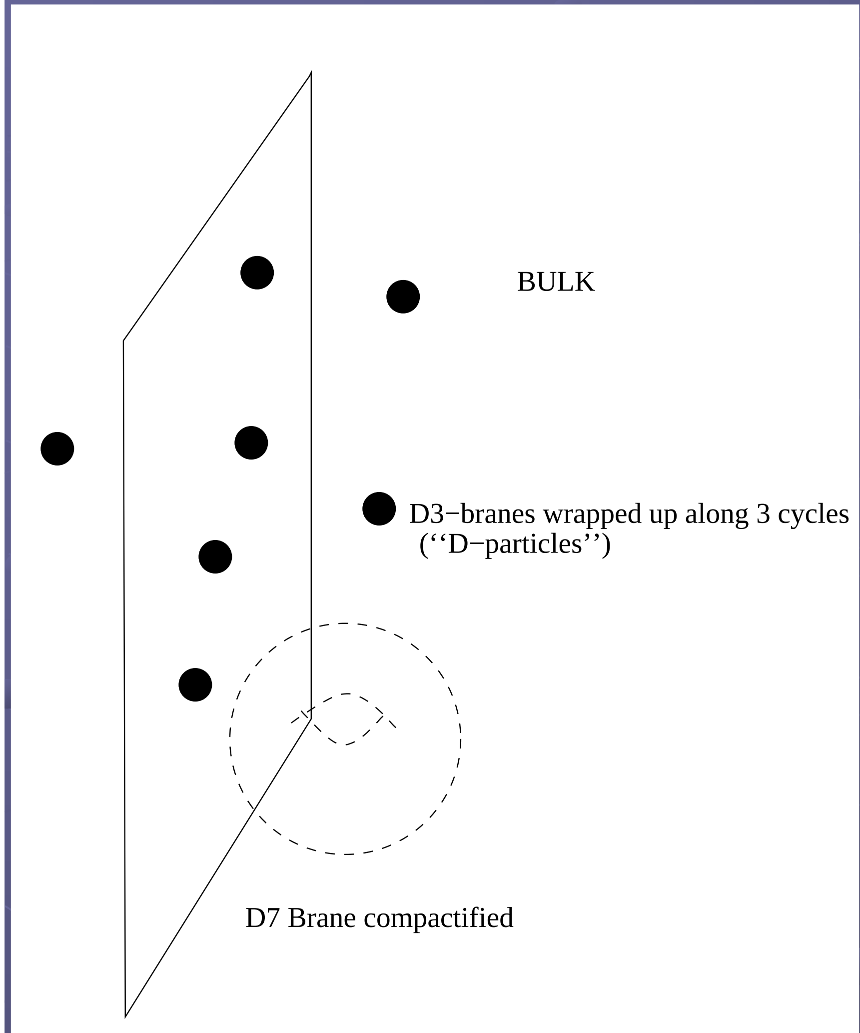
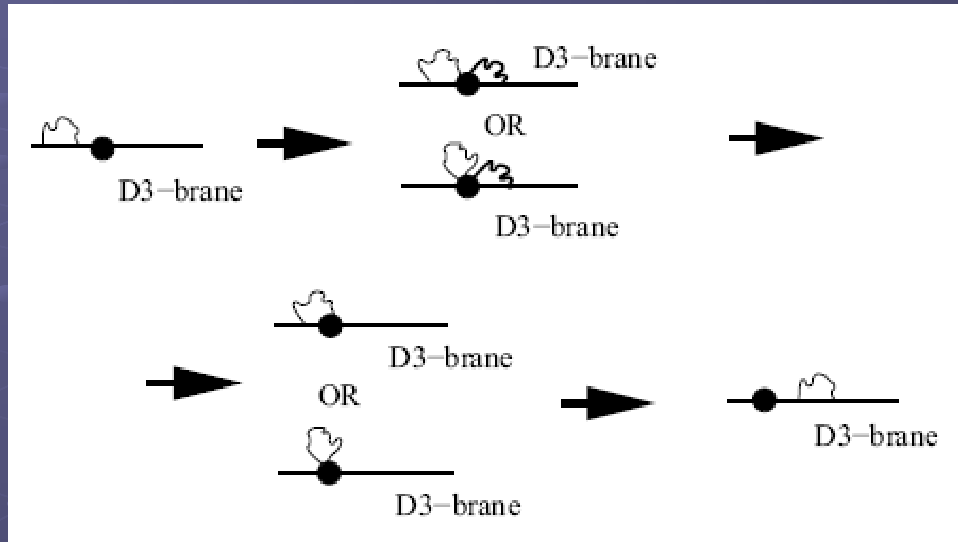
TYPE IA string models: D-foam transparent to charged probes

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

Type IIB String Model of D-particle Foam

T.Li, NM, Nanopoulos, D. Xie

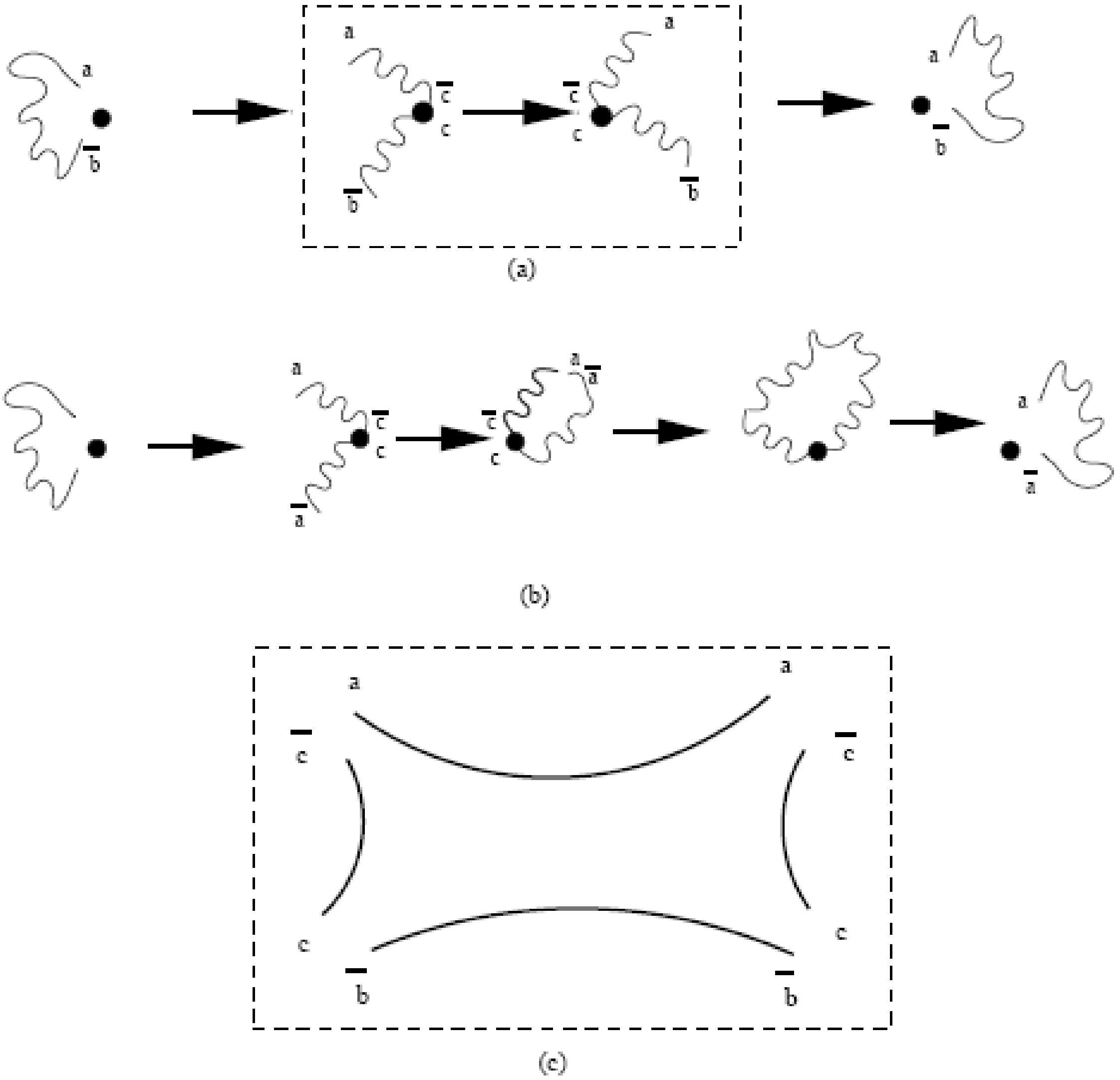




Consider Four-point Veneziano Amplitude for scattering of two open string states to two open string states in the D-particle/D3-branes backgrounds

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)

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

D-Foam: **Uniform Distribution of D-particles in space with V_{A3} = their average 3D-volume, R' = radius of forth space dim transverse to D3 branes.**
Avoid tachyon condensation: D3 branes have widths 1.55 ℓ_s

Capture process: Backward Scattering u=0 (Mandelstam)

Type IIB: For charged probes, suppressed time delays…

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

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

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

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

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

Effecitve Low-Energy Modified Dispersion

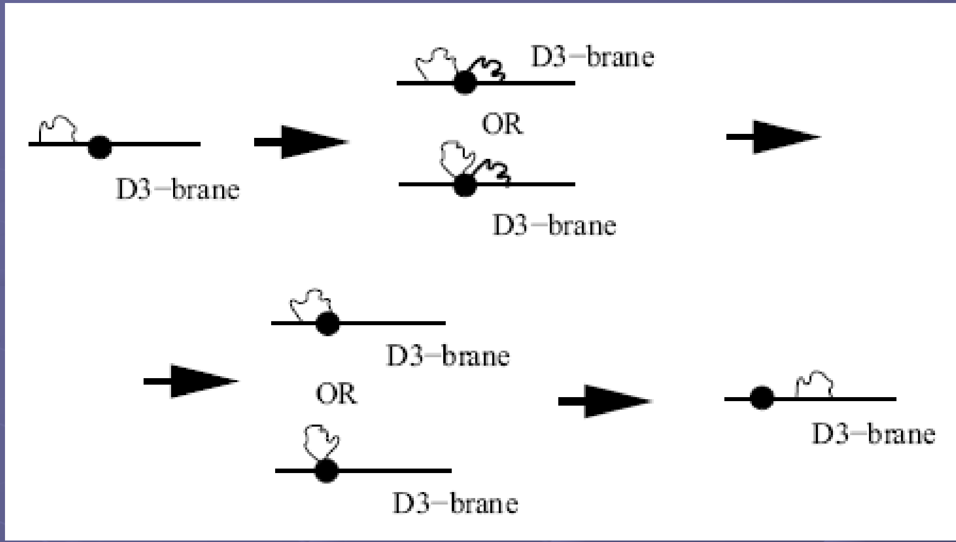
$$\boxed{E^2 = p^2 + m_e^2 - \eta p^3 / M_{\text{St}} \;,} \qquad (6)$$

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

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

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

Stringy Uncertainties & the Capture Process



Ellis, NM, Nanopoulos arXiv:0804.3566

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

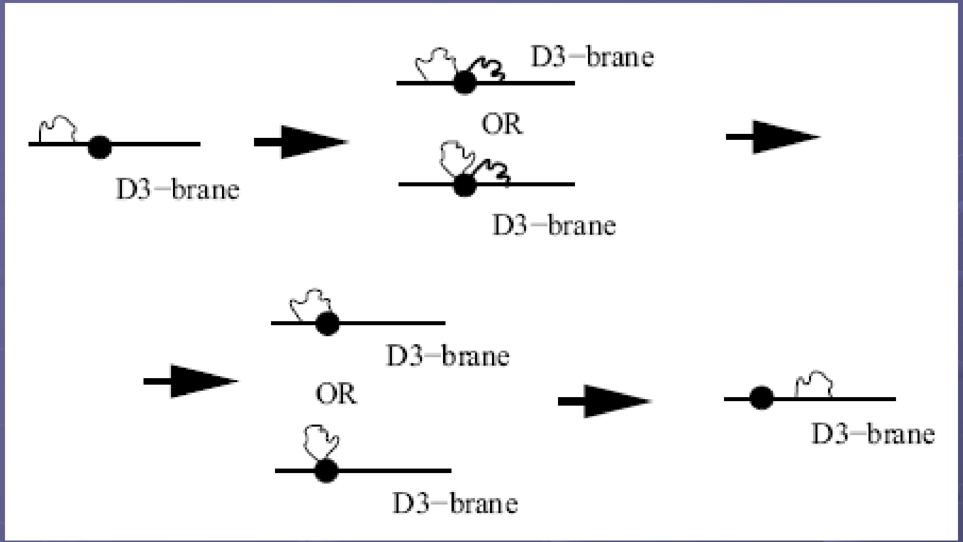
$$p^0 = \frac{L}{\alpha'} + \frac{N}{L}.$$

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

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

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

Stringy Uncertainties & the Capture Process



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Stringy Uncertainties & the MAGIC Effect

- D-foam: transparent to electrons
- D-foam captures photons & re-emits them
- Time Delay (Causal) in **each** Capture: $\Delta t \sim \alpha' p^0$
- Independent of photon polarization (**no Birefringence**)
- **Total Delay** from emission of photons till observation over **a distance D** (assume n^* defects per string length):

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

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

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

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

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

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

Stringy Uncertainties & the MAGIC Effect

- D-foam: transparent to electrons
- D-foam captures photons & re-emits them
- Time Delay (Causal) in each ... $\sim \alpha' p^0$
- Independent of photo... ...ngence)
- **Total Delay** from em... ...s till observation over a ... D (assume ... defects per string length

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

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Red-Shift Dependent QG Scale

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

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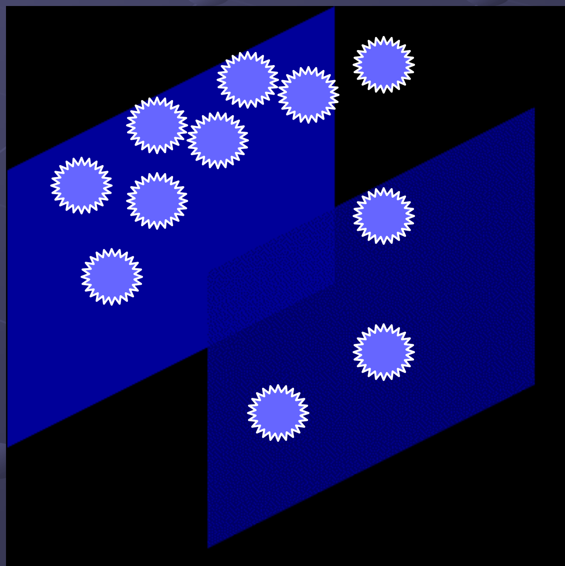

n* (z) can increase with z
If brane moves in inhomogeneous bulk

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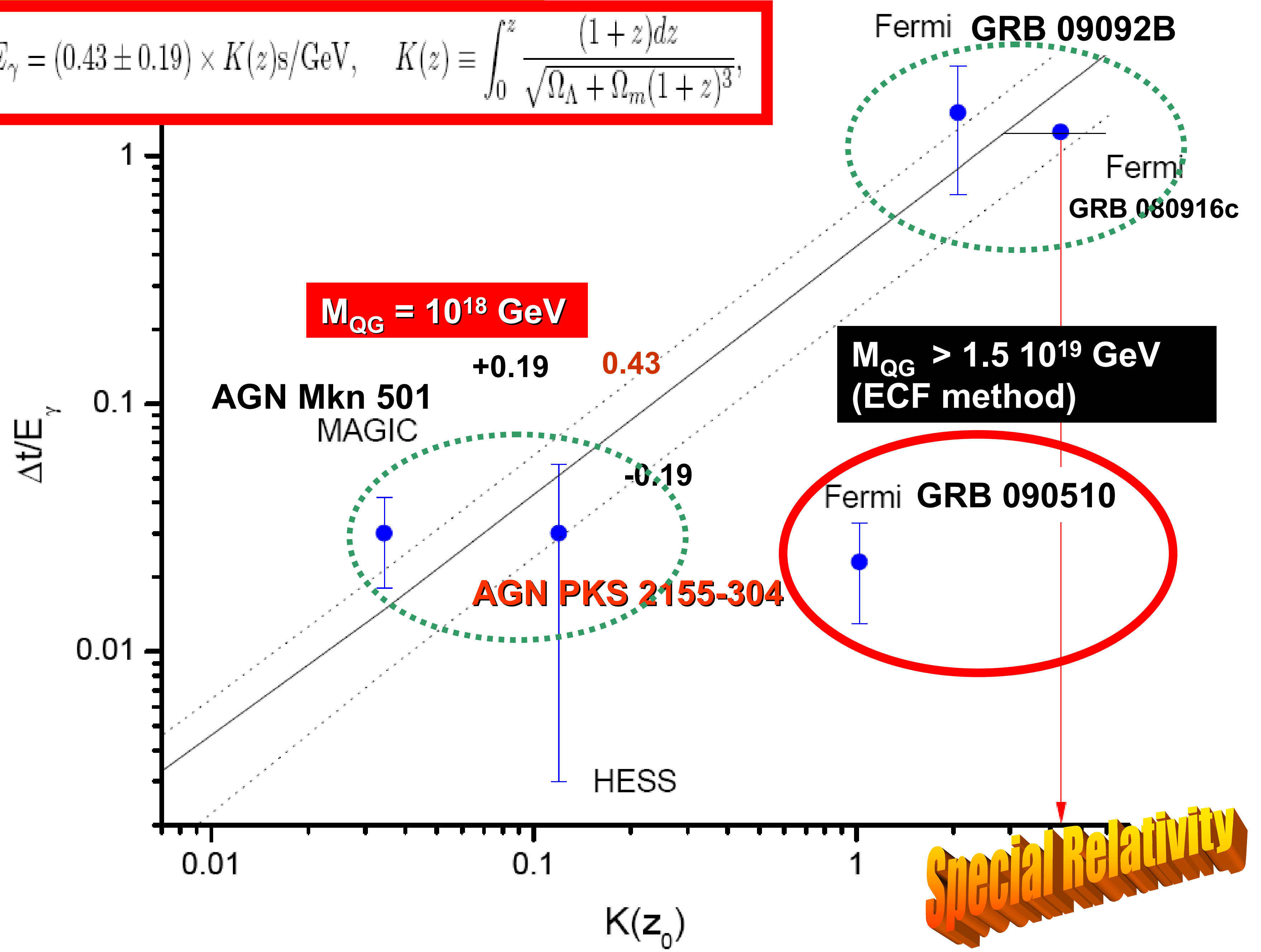
Account for MAGIC (& HESS) events for low z and ALSO for GRB 090510 (short burst) at high z =1 Higher z GRBs delays partly due to D-foam, partly due to Sourcce Delayed Emission

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

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



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COMPATIBLE WITH STRING UNCERTAINTY PRINCIPLES:

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

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

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Δ ... Δp Δx ≥ 1 ... ...

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

Beyon Local Effective Field Theories though...

REPRODUCE 4±1 MINUTE DELAY OF MAGIC from Mk501 (redshift z=0.034)
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WHY BEYOND LOCAL EFT?

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

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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…

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)

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

Induced (Finsler) Space-Time Metric

World-Sheet Propagator in the presence of recoil background

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

Implies Finsler-type target-space metric

$$\begin{aligned} g^{\text{open,electric}}_{\mu\nu} &= \left(1-\tilde{u}_i^2\right)\eta_{\mu\nu} \ , \qquad \mu,\nu = 0,1 \\ g^{\text{open,electric}}_{\mu\nu} &= \eta_{\mu\nu} \ , \mu,\nu = \text{all other values} \ , \end{aligned}$$

and effective string coupling

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

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

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

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

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

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

Induced (Finsler) Space-Time Metric

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

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

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

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

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

M_s/g_s free parameter in string theory…

Avoid constraints on UHECR altogether?

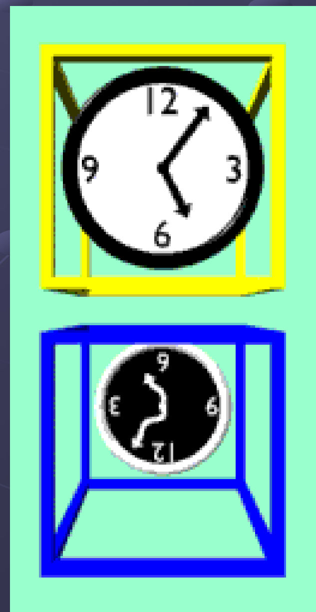
OTHER EFFECTS OF D-FOAM

Other Effects of Foam

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

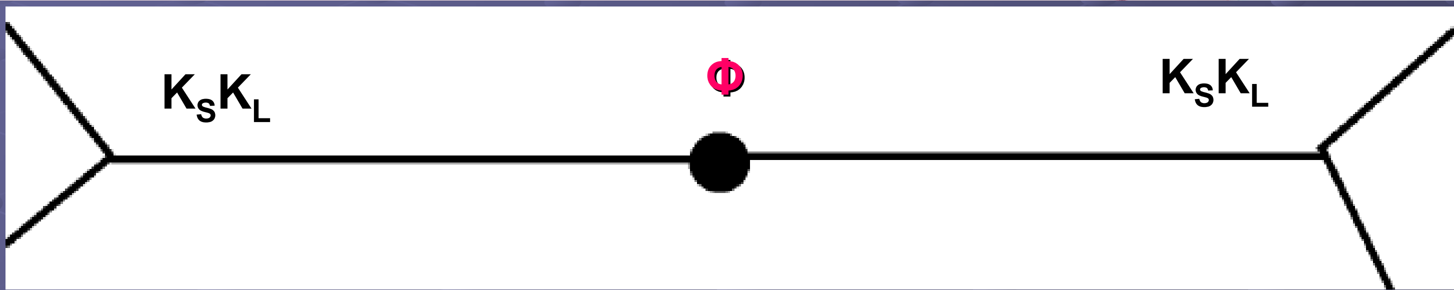
CPT may be Violated in D-particle Foam models but only through Target-space effective (low-energy) Decoherence, induced by stochastic quantum metric fluctuations …

Tests in Particle Interferometers…



- Consequences for Neutral mesons EPR – correlators

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

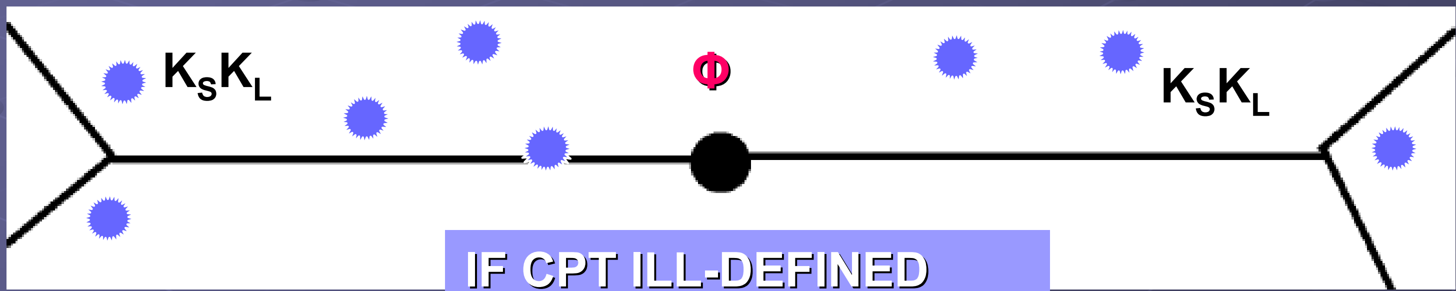


IF CPT Θ-operator WELL-DEFINED

Even if [Θ , H] ≠ 0

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

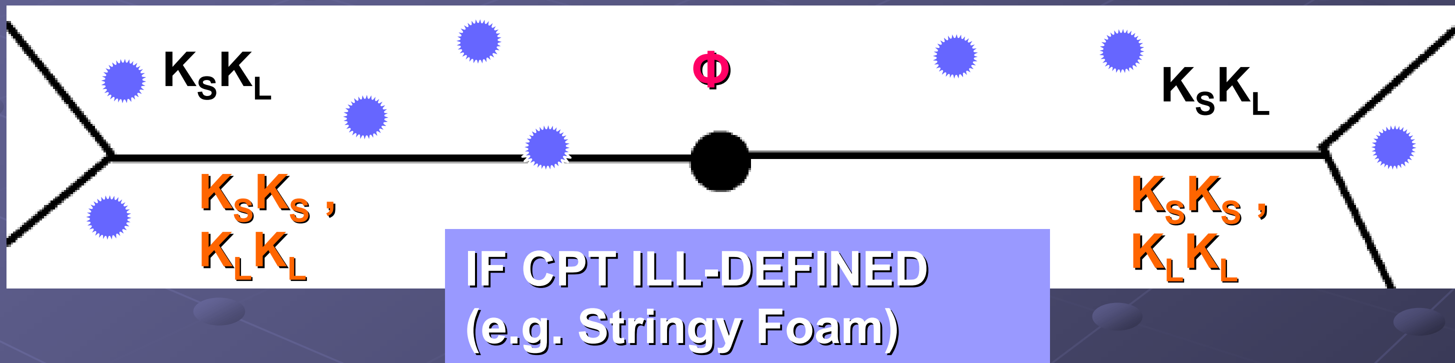
- If foam, concept of anti-particle may be perturbatively modified, Neutral mesons no longer indistinguishable



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

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

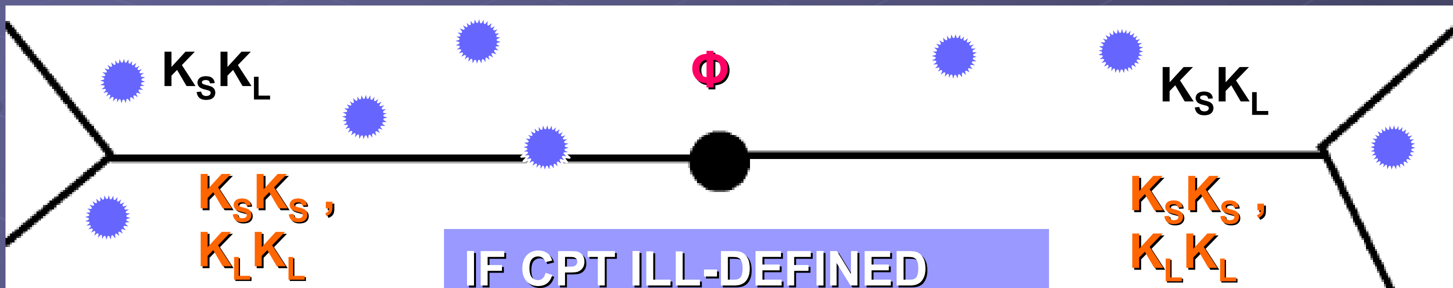
$$
\begin{aligned}
|i> &= \mathcal{N}\Big[\big(|K_S(\vec{k}), K_L(-\vec{k})> - |K_L(\vec{k}), K_S(-\vec{k})>\big) \\
&+ \omega\big(|K_S(\vec{k}), K_S(-\vec{k})> - |K_L(\vec{k}), K_L(-\vec{k})>\big)\Big]
\end{aligned}
\qquad \omega = |\omega| e^{i\Omega}
$$



- 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)

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

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

Conclusions

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

Outlook…

- On the Theoretical Side: Develop Foam Models to incorporate realistic standard model phenomenology and get agreement with current cosmology: intersecting brane models to get Standard Model Group, calculate and analyse effects of foam on CMB, Universe Dark Sector…
- On the experimental side: increase statistics of observations, luckily one should observe short GRBs at various red-shifts , which will allow falsification of models for $n^*(z)$ density of foam.
- Exciting Times for Astro-Particle Physics expected ?

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

Sarben Sarkar, NEM, Vergou 10

$$g_{\mu\nu} = \begin{pmatrix} -1 & a^2(t)r_1p_1 & a(t)^2 r_2p_2 & a^2(t)r_3p_3 \\ a^2(t)r_1p_1 & a^2(t) & 0 & 0 \\ a^2(t)r_2p_2 & 0 & a^2(t) & 0 \\ a^2(t)r_3p_3 & 0 & 0 & a^2(t) \end{pmatrix} .$$

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

D-particle recoil velocity

Stochastic foam fluctuations

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

Modified Boltzman

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

Heavy DM m >> T

$$\Gamma(t) = 2\left(\sigma_1^2 + \sigma_2^2 + \sigma_3^2\right) H \left[Tm + 6m^2a^2(t)\right]$$

Modified Thermal Relic abundances of heavy DM due to Finsler geometry

$$\frac{\Omega'_\chi h_0^2}{(\Omega_\chi h_0^2)_{\rm no\ source}} = \left(1 + \int_{x_0}^{x_f} \frac{\Gamma H^{-1}}{\psi(x)} dx\right) * \left(\frac{g'_{eff}}{g_{eff}}\right)^{\frac{1}{2}}$$

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

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

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

Bosons

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

fermions

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

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

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

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

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

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

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

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