Not only time delays. UHE photons as probes of Quantum Gravity

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SciNeGHE 2010, Trieste, 10.09.2010

QG and LV

Known theories of gravity rest on Einstein's equivalence principle → local Lorentz invariance

Principle of relativity — Implies the group structure

Isotropy — Implies reciprocity together with Principle of Relativity

Homogeneity — Implies linearity of coordinate transformations

Pre-causality — Implies a notion of past and future

Lorentz invariance

von Ignatowski (1910-1911)

Modified dispersion relations

Many QG of these models have led to modified dispersion relations

From a purely phenomenological point of view, the general form of Lorentz invariance violation (LIV) is encoded into the dispersion relations

$$E^2 = p^2 + m^2 + \Delta(p, M)$$

$M \equiv$ spacetime structure scale, generally assumed $\approx M_{\text{Planck}} = 10^{19}$ GeV

Assuming rotation invariance
we can expand this as

$$E^2 = p^2 + m^2 + M\eta^{(1)}|p| + \eta^{(2)}p^2 + \eta^{(3)}|p|^3/M \quad \ldots$$

Time of flight constraints

Constraint on photon LV by using the fact that different colors will travel at different speeds. Look at distant sources to see the cumulative effect.
Do a step back and consider simply modified dispersion relations $O(E/M_{Pl})$

$$v_\gamma = \frac{\partial E}{\partial p} = 1 + \xi \frac{E}{E_{Pl}}$$

$$\begin{aligned} \Delta t &= \Delta v T = \xi \frac{E_2 - E_1}{M} T \\ \Delta t &\approx 10\,\mathrm{msec}\, \xi\, d_{Gpc}\, E_{GeV} \end{aligned}$$

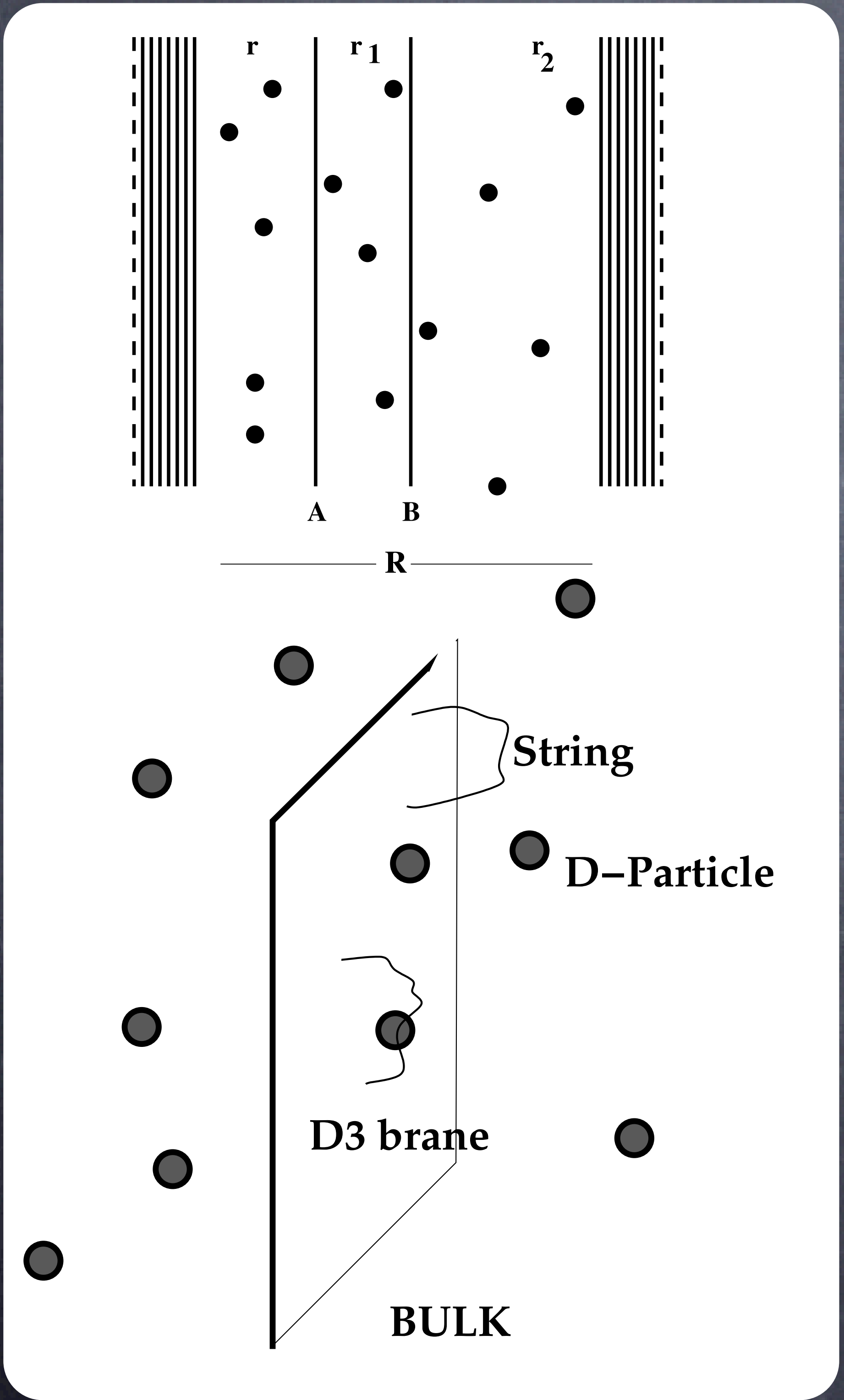
Caveat: in full EFT this description is not valid: $\xi_+ = -\xi_-$ and a non polarized photon beam will not show time delays, but only broadening (hard to detect)

With this technique lot of (poor) constraints

- GRB: Coburn et al. using GRB021206 , $|\xi|<55$ ($z\approx0.3$, very uncertain).
- Magic Coll+Ellis et al. (2007) using AGN, Markarian 501 flares, $z\approx0.034$, $|\xi| <47$, but possible best fit with $|\xi|\simeq O(1)$!?! ...
- HESS Coll (2008), using Mrk flares (PKS 2155, $z=0.116$ i.e. more far away than Mkn 501)
- FERMI Coll (Nature, 2009), using GRB 090510 ($z = 0.903$), observed up to 31 GeV, $\xi <0.8$

Amelino-Camelia et al, Nature 393 (1998)
Ellis et al, ApJ 535 (2000)
FERMI Coll, Science 323 (2009)
Amelino-Camelia and Smolin, PRD 80 (2009)

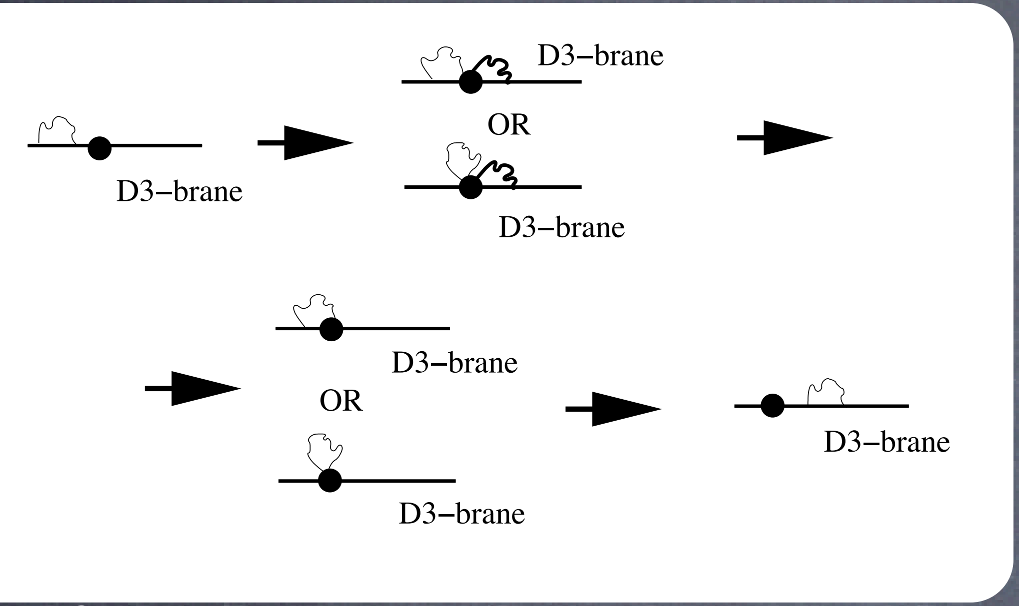
Space-time foam models



Ellis, Mavromatos, Nanopoulos, Phys. Lett. B, 293 (1992)
Amelino-Camelia et al., Int. J. Mod. Phys. 12, 3 (1997)
Ellis et al, Phys. Rev. D 63 (2001)
Ellis et al, Int. J. Mod. Phys. A 19 (2004)
Ellis et al, Phys. Lett. B 665 (2008)
Li et al, Phys. Lett. B 679 (2009)
Ellis et al, arXiv:0912.3428v1
Ellis et al, arXiv:1004.4167v1
and many other references I forgot...

- ★ 10-D bulk space-time bounded by two 8-D orientifold planes.
- ★ The bulk space-time also contains two stacks of 8-D branes, and the entire structure is compactified to 3-D.
- ★ The bulk space is punctured by point-like D0-branes (D-particles).
- ★ Big-Bang cosmology: collision between two of the D-branes from the original stack. After the collision, the D-branes recoil. As a result of this motion, the population of D-particles in the bulk cross the D-brane worlds and interact with the stringy matter particles moving on them. To an observer on the D-brane, the space-time defects appear to be 'flashing' on and off.

Space-time foam models



QG medium as oscillators that absorb and emit photons
Oscillators are D-particles flashing in the space-time

Photon absorption and re-emission: D-particles and photons form a compound state that stretches in between D3-branes and D-particles, and eventually decays. The D-particle recoils
D-particles are neutral: charged particles do not feel their presence.

Consequences:

LV only for photons (and Majorana neutrinos)

$$\Delta t = \alpha' E$$

No birefringence
Photons are delayed and acquire an effective modified dispersion relation

$$E^2 = p^2 + \xi \frac{p^3}{M_{\rm Pl}}$$

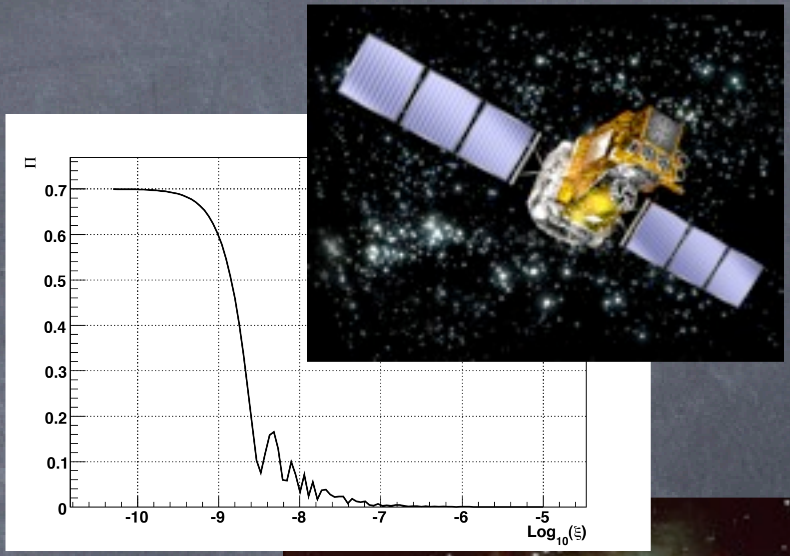
In case D-particles have a bulk recoiling motion, the background metric is modified and energy non-conservation during interaction is possible

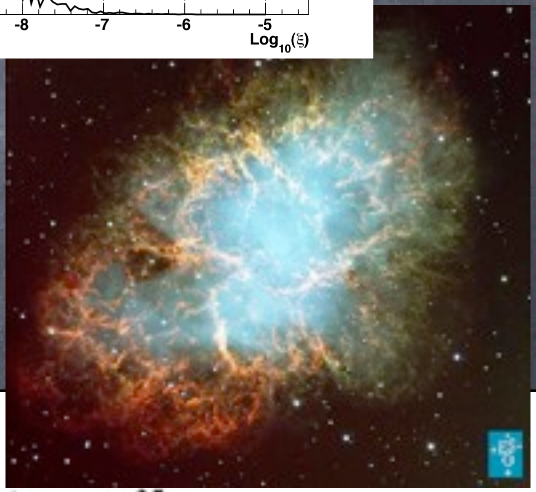
$$\xi_I$$

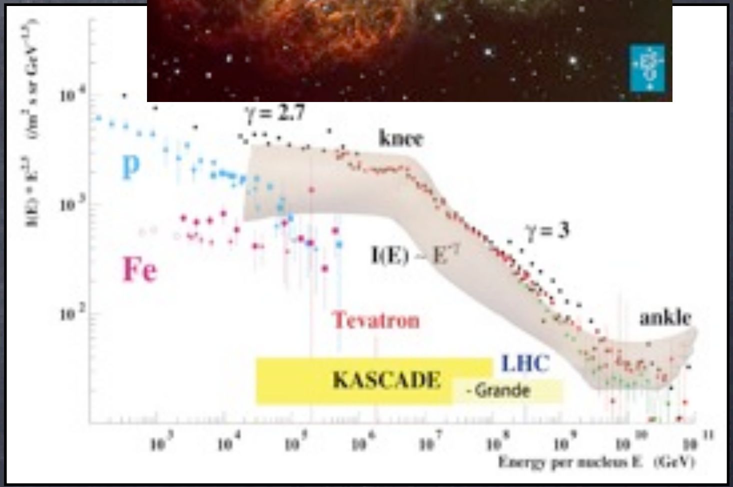
Effects proportional to the D-particle density

How to constrain the model?

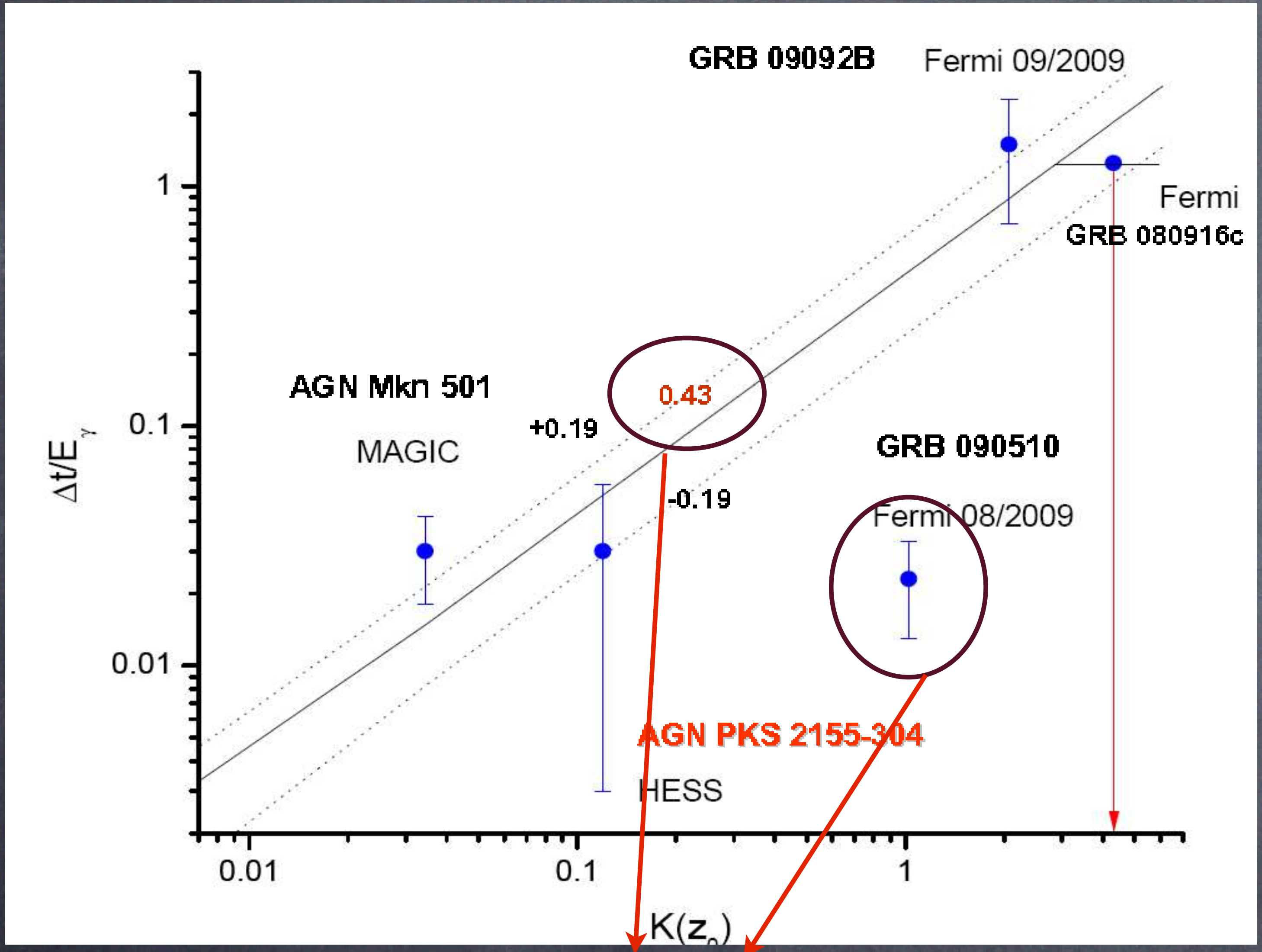
- Standard constraints are not viable
- Birefringence --> absent
- Synchrotron --> not enough affected
- Threshold reactions --> only photons are LV, hard to probe







Time of flight constraints?



Observed time-delays can be turned into estimates for LV effects (Another disclaimer: standard physical processes in the sources can explain the observed delays)

Ellis et al, arXiv:0912.3428

$$\Delta t \simeq \xi \frac{\Delta E}{M} \frac{1}{H_0} \int_0^{\bar{z}} dz \frac{1+z}{\sqrt{\Omega_\Lambda + (1+z)^3 \Omega_M}}$$

A part from the outlier at z~1, the other delays are all compatible with the same QG model! Hint of the presence of a D-void at z~1? Cosmological variation of the density of D-particles?

Are there other observables that can falsify the time delay interpretation? Maybe, they might come from threshold reactions

Key point: the effect of the non LI dispersion relations can be important at energies well below the fundamental scale

$$E^2 = c^2 p^2 \left(1 + \frac{m^2 c^2}{p^2} + \eta \frac{p^{n-2}}{M^{n-2}} \right)$$

Corrections start to be relevant when the last term is of the same order as the second.
If η is order unity, then

$$\frac{m^2}{p^2} \approx \frac{p^{n-2}}{M^{n-2}} \Rightarrow p_{crit} \approx \sqrt[n]{m^2 M^{n-2}}$$

n	p_{crit} for ν_e	p_{crit} for e^-	p_{crit} for p^+
2	$p \approx m_\nu$~1 eV	$p \approx m_e$=0.5 MeV	$p \approx m_p$=0.938 GeV
3	~1 GeV	~10 TeV	~1 PeV
4	~100 TeV	~100 PeV	~3 EeV

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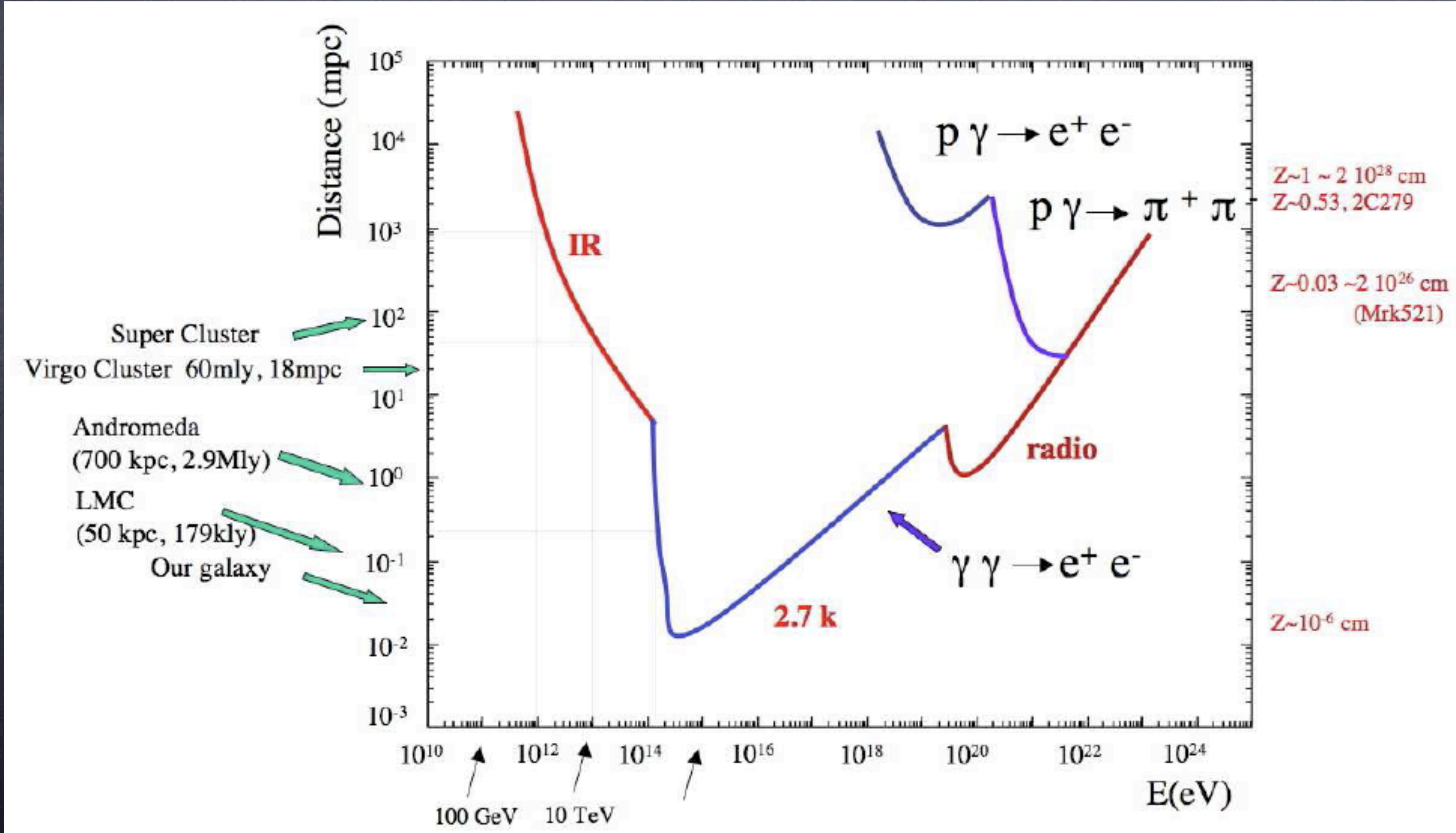
Need to look for reactions with photons in the initial state - they are the only ones affected by D-particles

$$\gamma\gamma \to e^+ e^-$$

GZK effect and secondary production

$$p + \gamma \rightarrow N + \pi \quad \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^\pm \rightarrow \mu\nu_\mu \rightarrow e\,\nu_\mu\bar{\nu}_\mu\nu_e \end{cases}$$



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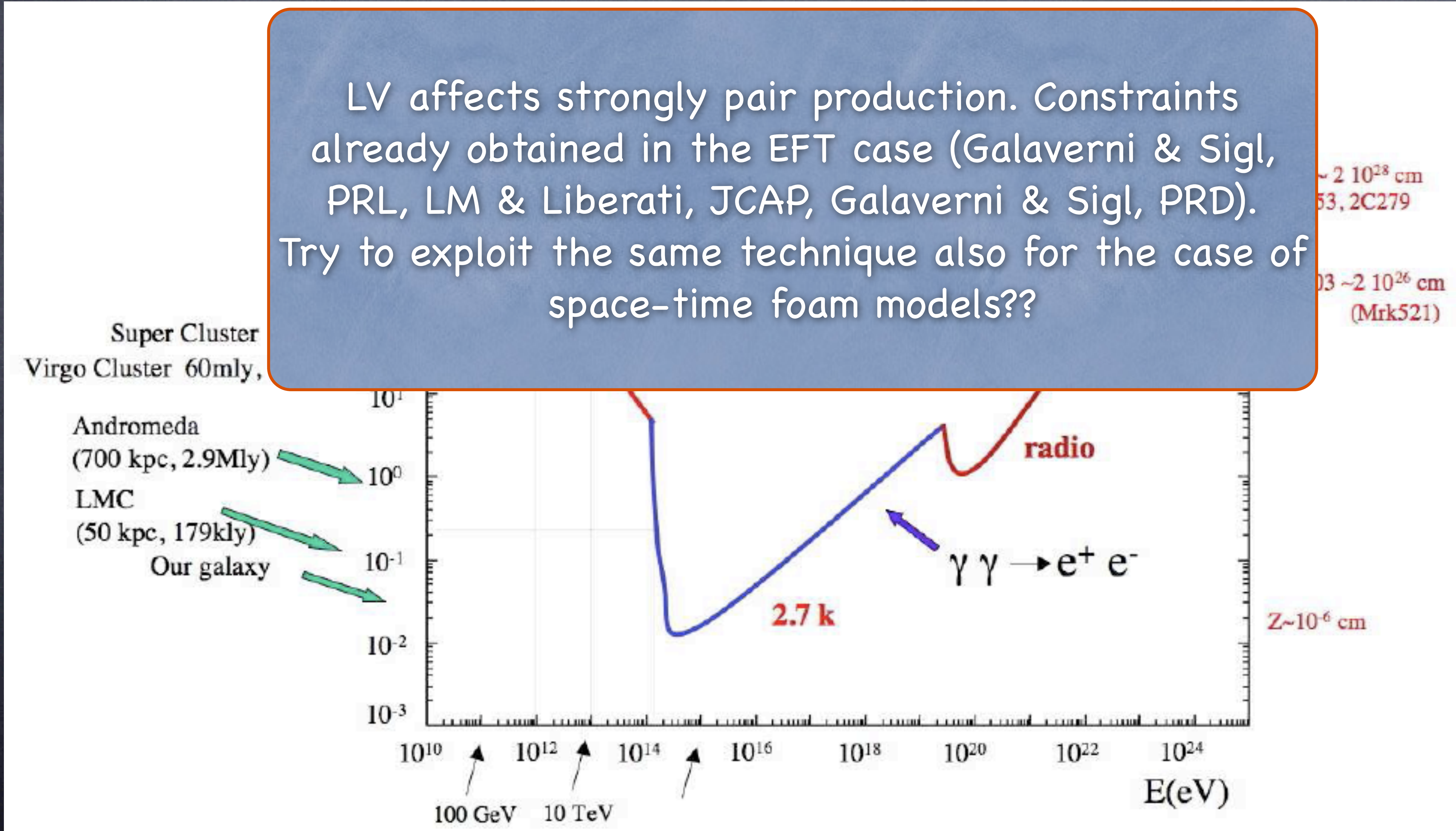
LV affects strongly pair production. Constraints already obtained in the EFT case (Galaverni & Sigl, PRL, LM & Liberati, JCAP, Galaverni & Sigl, PRD). Try to exploit the same technique also for the case of space-time foam models??



UHE photons and LV in space-time foam

LM, Liberati, Sigl, PRL 105, 021101 (2010)

- Pair production is modified by LV even in the case of space-time foam models (Ellis et al., PRD 63 (2001))

- In general, momentum is conserved, but energy is not. Effective description

$$\begin{aligned} E_1 + \omega &= E_2 + E_3 + \delta E_D \\ p_1 - \omega &= p_2 + p_3 \end{aligned}$$

$$-\frac{\xi_I + \xi/2}{2} x^3 + 2\frac{\omega}{M} x - 2\frac{m_e^2}{M^2} + \cdots = 0$$

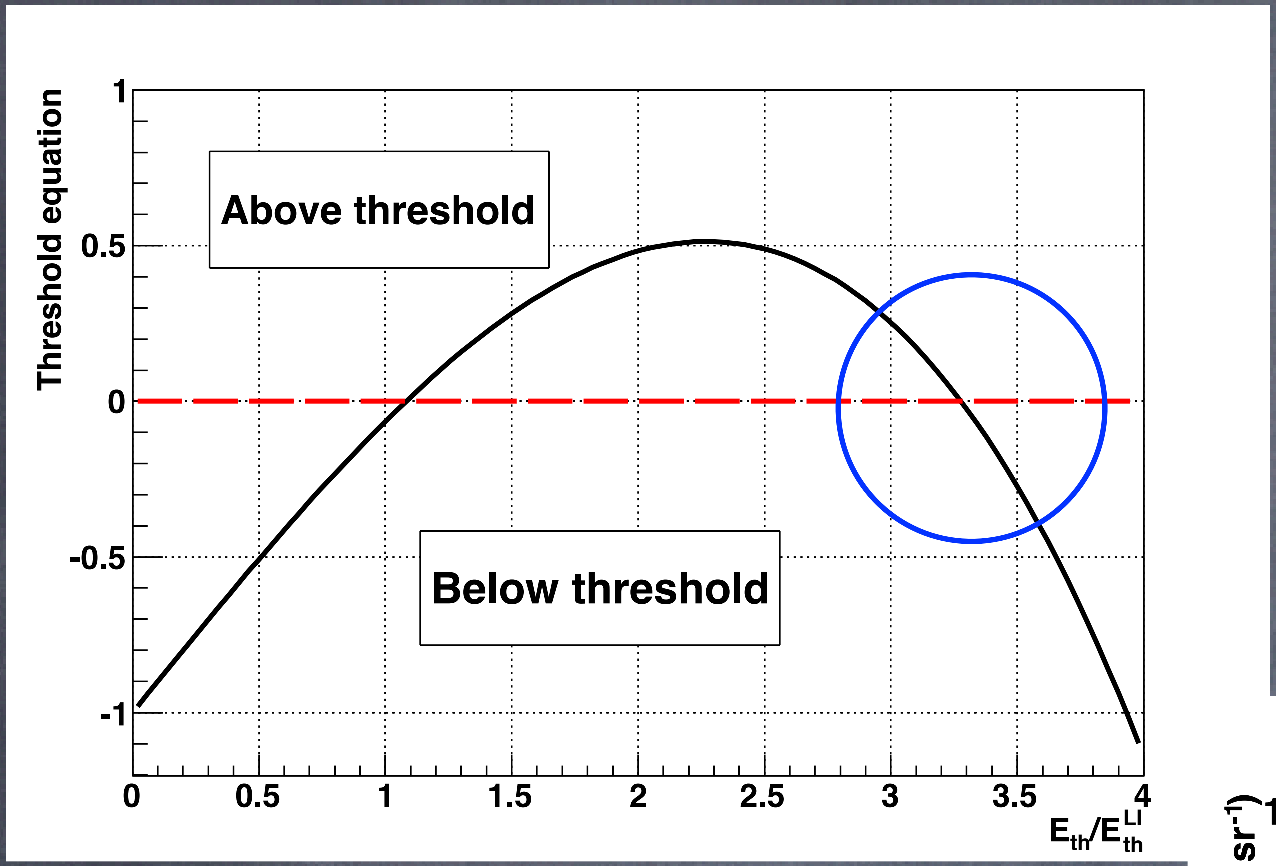
LV contribution

$$x \equiv \frac{E_{\rm th}}{M}$$

- ξ describes LV in propagation (the one probed by time delays)

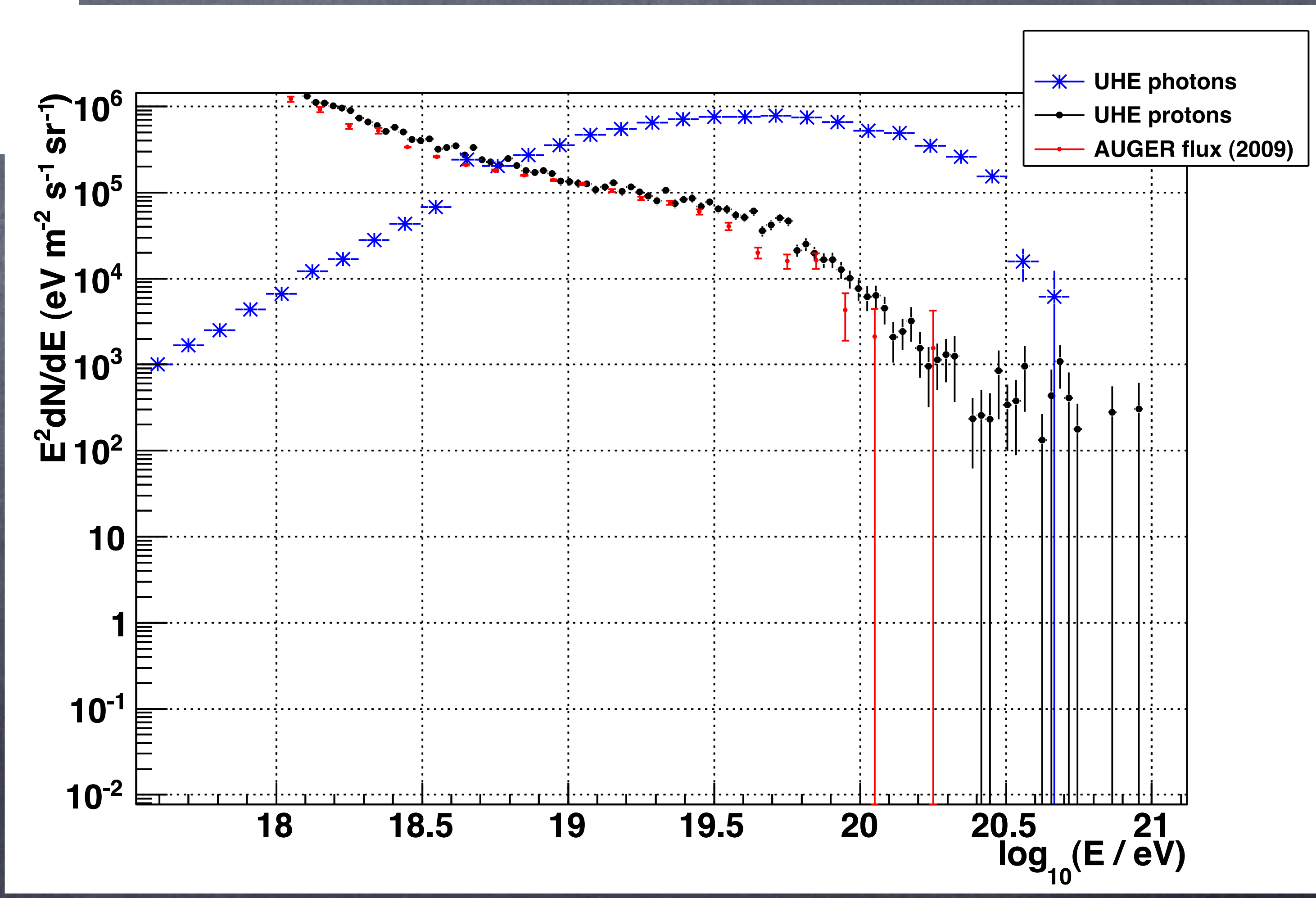
- ξ_I describes energy non-conservation in interactions

UHE photons and LV in space-time foam



$$\xi/2 + \xi_I = 10^{-5}$$

An upper threshold! Photons above this energy are no longer absorbed



Then the fraction of photons in UHECRs can be large. Experimental limits are less than 30% at 10^{20} eV --> constraint on the sum

$$\xi/2 + \xi_I \lesssim 10^{-12}$$

UHE photons and LV in space-time foam

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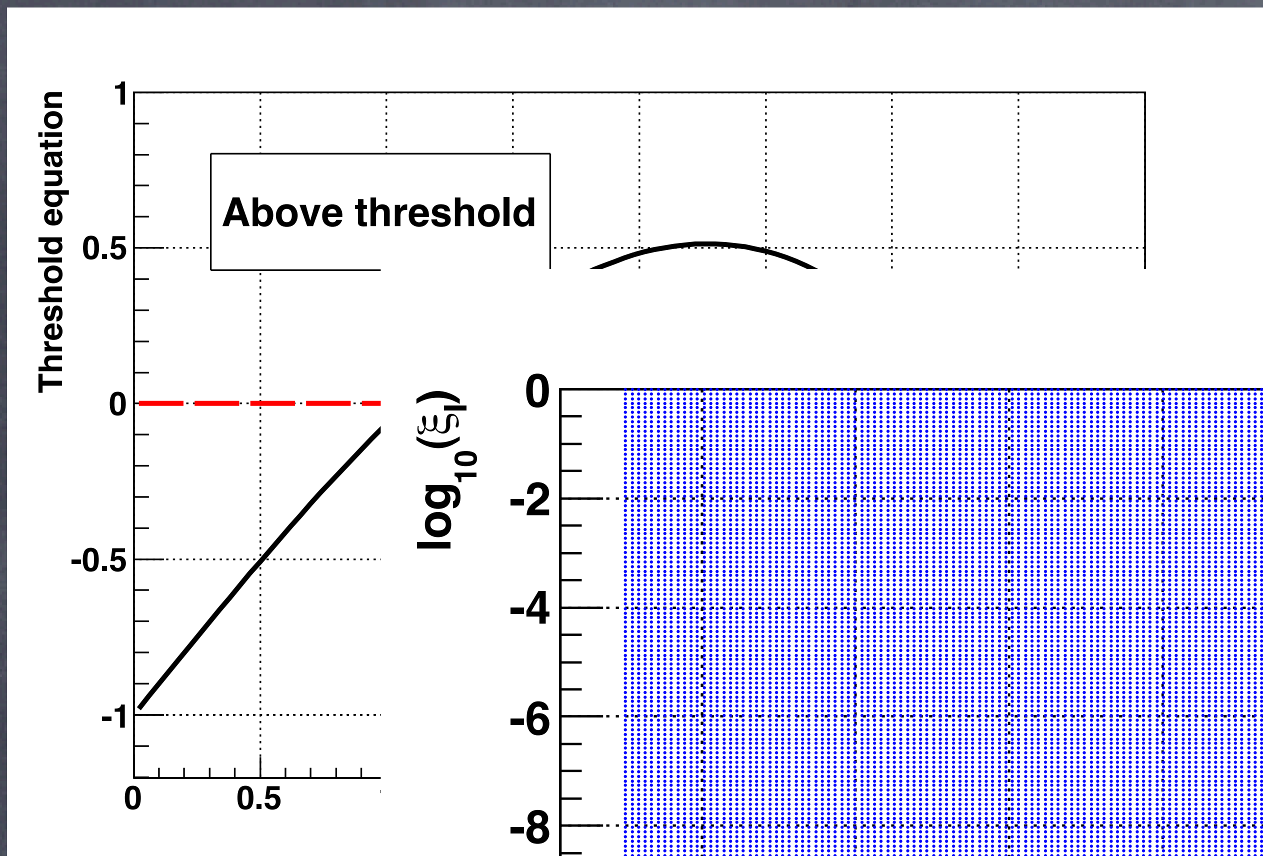
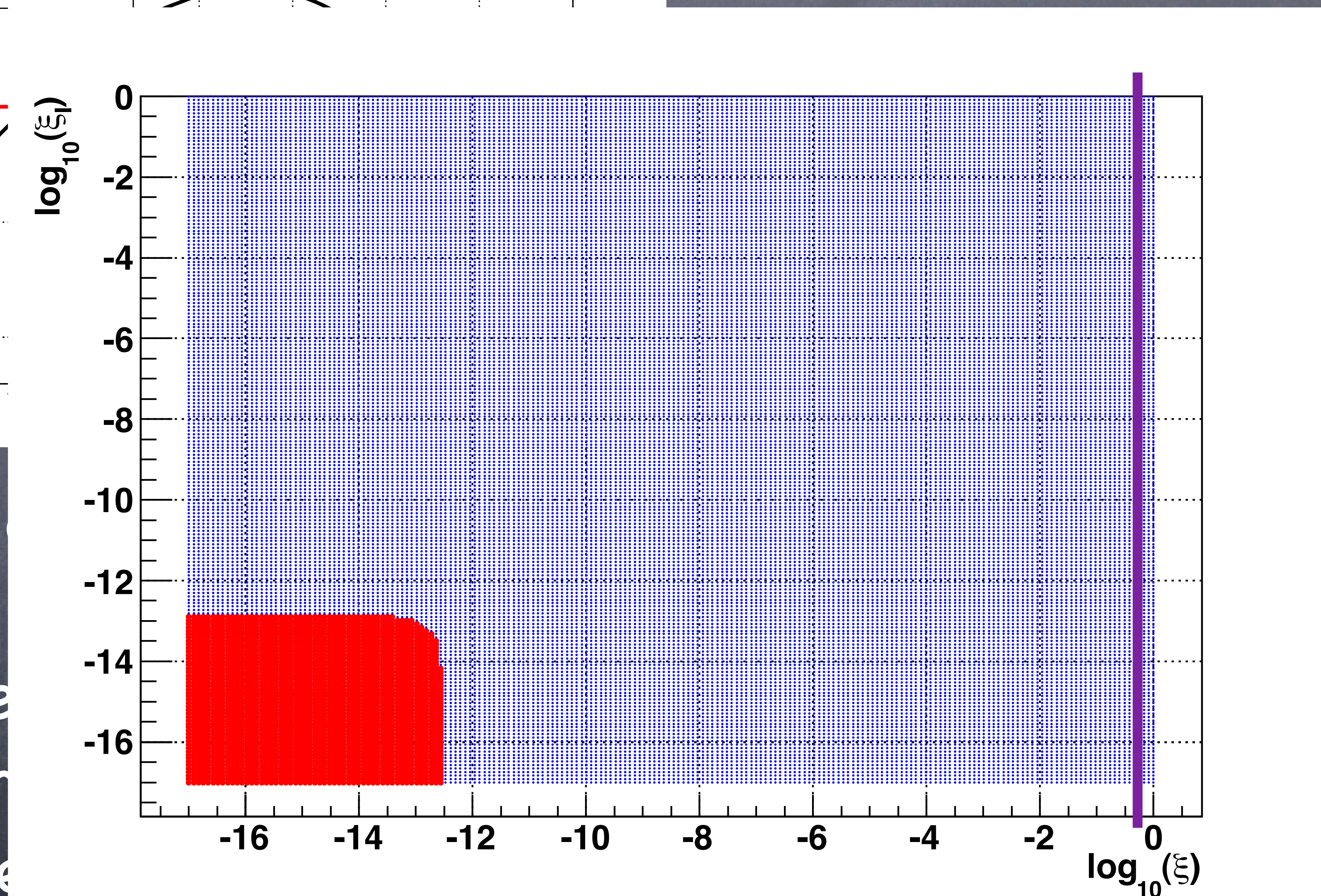
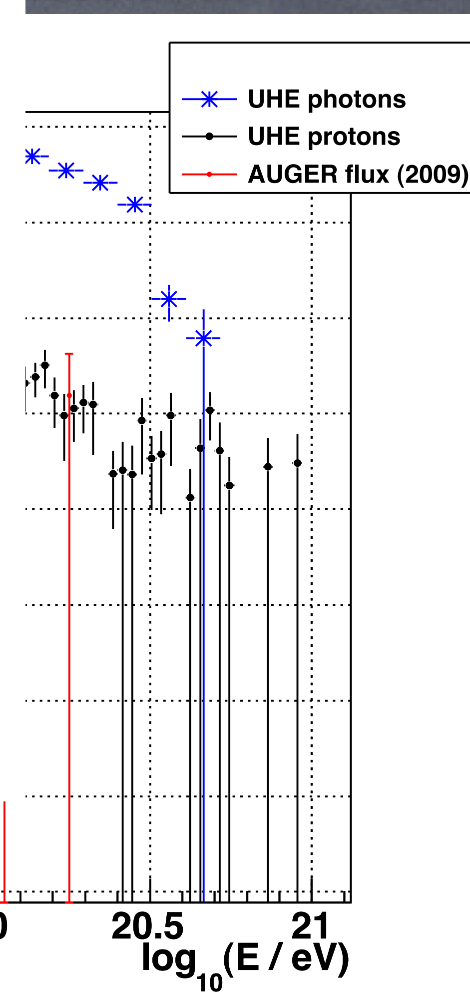
Photons

are no







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Conclusions

- Strong constraint placed on stringy space-time foam models of QG and LV
- QG explanations of time delays in the GeV-TeV range are incompatible with UHE photon data
- There are indeed alternatives to TOF for investigating LV
- Escape with refining the model: Ellis et al, arXiv:1004.4167 and future papers
- This was the last unconstrained model of LV. What's next then?

Backup

QG phenomenology

"You shall not access any quantum gravity effect as this would require experiments at the Planck scale!"

Quantum gravity phenomenology is a recently developed field aimed at testing, observationally or experimentally possible predictions of quantum gravity frameworks.

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Quantum decoherence
QG imprint on initial cosmological perturbations
Cosmological variations of couplings
Extra dimensions and low-scale QG (LHC BH)
Violation of discrete symmetries
Violation of space-time symmetries

Lorentz violation: a first glimpse of QG?

Suggestions for Lorentz violation (at low or high energies) came from several tentative calculations in QG models:

For extensive review see D. Mattingly, Living Rev. Rel. 8:5,2005.

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Suggestions for Lorentz violation (at low or high energies) came from several tentative calculations in QG models:

- string theory tensor VEVs (Kostelecky-Samuel 1989)
- space-time foam scenarios (Amelino-Camelia et al. 1997-1998, Ellis et al.)
- semiclassical spin-network calculations in Loop QG (Gambini-Pullin 1999)
- non-commutative geometry (Carroll et al. 2001)
- some brane-world backgrounds (Burgess et al. 2002)
- condensed matter analogues of "emergent gravity" (Unruh 1981)

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Theoretical frameworks

Of course to cast constraints on LIV using these phenomena one needs more than just the kinematics information provided by the modified dispersion relations, one also often needs to compute reaction rates and decay times, i.e. a dynamical framework…

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Explicit Lorentz symmetry violation

Deformed/Doubly SR paradigm

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Explicit Lorentz symmetry violation

Deformed/Doubly SR paradigm

Non-critical Strings

EFT+LV

Renormalizable, or higher dimension operators

Non-commutative spacetime
Finsler geometry

Standard Model Extension
Renormalizable ops. (Low energy LIV)
(Colladay & Kostelecki, 1998)

EFT with LIV
Non-renormalizable ops. (HE LIV)
(Myers & Pospelov, 2003)

Applications: QED with LV at O (E/M)

Dimension 5 Standard Model Extension: include dimension 5 LV operators in the SM preserving gauge and rotation invariance and quadratic in the fields
Myers & Pospelov, 2003

Contribution at order p^3/M to the MDR.

$$L = L_{QED} - \frac{\xi}{2M} u^m F_{ma} (u \cdot \partial)(u_n \tilde{F}^{na}) + \frac{1}{2M} u^m \overline{\psi} \gamma_m (\varsigma_1 + \varsigma_2 \gamma_5)(u \cdot \partial)^2 \psi$$

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$$\text{electrons} \quad E^2 = m^2 + p^2 + \eta_\pm (p^3/M_{\rm Pl})$$
$$\text{photons} \quad \omega^2 = k^2 \pm \xi (k^3/M_{\rm Pl})$$

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

electron helicities have independent LIV coefficients

photon helicities have opposite LIV coefficients

	Positive helicity	Negative helicity
Electron	η_+	η_-
Positron	$-\eta_-$	$-\eta_+$

correspondence relation between LV coeff
for electrons and positrons

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Well, this is our theory, how to test it?

Astrophysical constraints: birefringence

The birefringence constraint arises from the fact that the LV parameters for left and right circular polarised photons are opposite.

Hence, linear polarisation is rotated as signal propagates

$$\theta(t) = [\omega_+ - \omega_-(k)]\, t/2 = \xi k^2 t/2M$$

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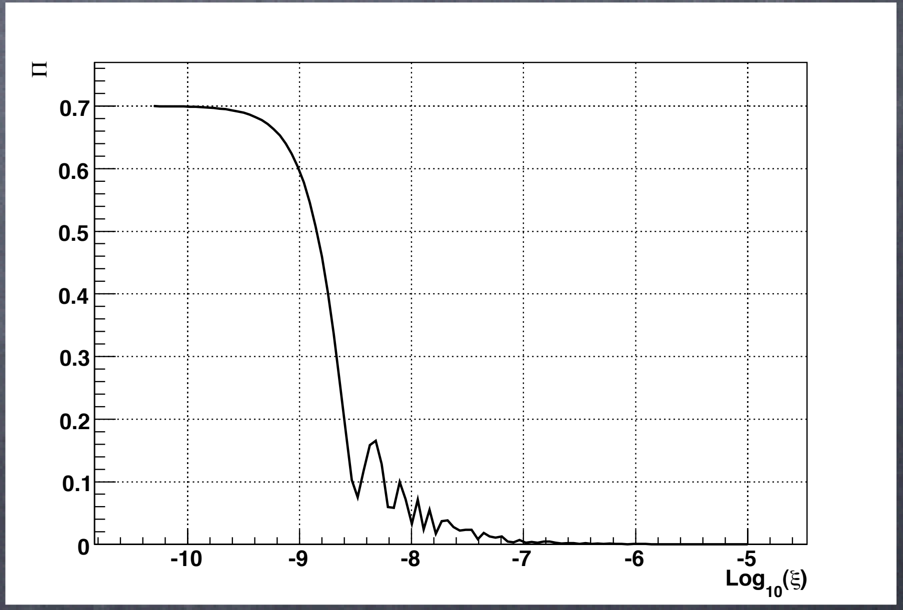
For a photon beam $\mathcal{P}$(E) the degree of linear polarisation can be computed as

$$\Pi(\xi) = \sqrt{\langle \cos(2\theta) \rangle^2_{\mathcal{P}} + \langle \sin(2\theta) \rangle^2_{\mathcal{P}}},$$

The constraint is obtained by imposing $\Pi(\xi) > \Pi_{obs}$



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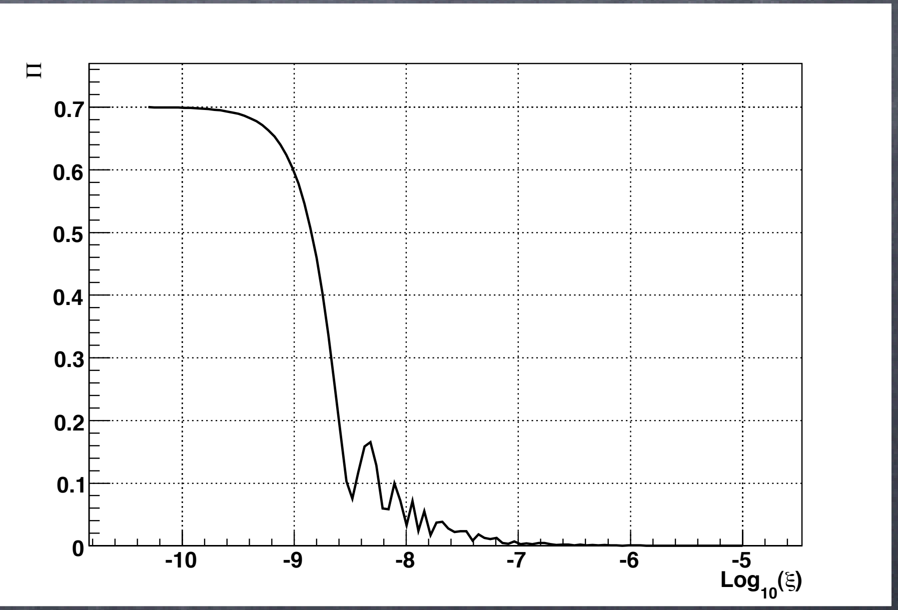

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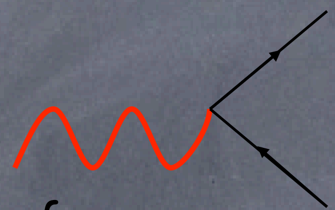
Good constraint $|\xi| \lesssim 10^{-7}$ (Fan et al) looking at polarised optical/UV light from distant GRBs

Astrophysical constraints: LV QED

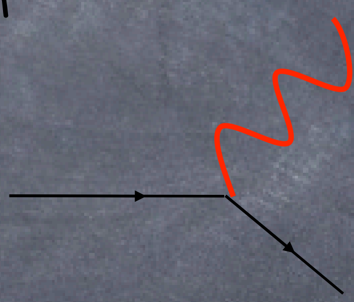
Gamma decay $\gamma \rightarrow e^+ + e^-$



- Lorentz violation allows the conservation of energy-momentum.
- Well above threshold it is very fast as the decay rate goes like Γ»E^2/M.
- 10 TeV photons would decay in approximately 10^{-8} seconds.
- If we see very high energy gamma rays from distant sources at least one photon polarisation must travel on cosmological distances. I.e. they must be below threshold.
- If $|\xi|$«$|\eta|$ the constraint has the form

$$|\eta_{\pm}| \lesssim 6\sqrt{3}m^2 M/k^3_{\rm th}$$

Vacuum Cherenkov (Helicity Decay) $e^{\pm} \rightarrow e^{\pm} + \gamma$



- Depending on parameters one can have emission of soft or hard photon.
- Once the reaction can happen it is very fast as the rate of energy loss goes like $dE/dt \approx E^3/M \Rightarrow$ 10 TeV electron would lose most of its energy in $\approx 10^{-9}$ seconds.
- The observation of the propagation of some high energy electrons implies that at least one helicity state cannot decay in either of the photon helicities.
- Hence the constraint can be worked out for one of the $\pm\eta_{\pm}$ and ξ.

$$p_{\rm th} = \left(m^2 M/2\eta\right)^{1/3}$$

Astrophysical constraints: synchrotron radiation

Jacobson, Liberati, Mattingly: Nature 424, 1019 (2003)
Ellis et al. Astropart.Phys.20:669-682,(2004)
R. Montemayor, L.F. Urrutia: Phys.Lett.B606:86-94 (2005)
LM,Liberati, Celotti, Kirk. JCAP 10, 013 (2007)

LI synchrotron critical frequency: $$\omega_c^{LI} = \frac{3}{2}\frac{eB\gamma^2}{m}$$

e - electron charge
m - electron mass
B - magnetic field

However in order to get a real constraint one needs a detailed re-derivation of the synchrotron effect with LIV based on EFT.

This leads to a modified formula for the peak frequency: $$\omega_c^{LIV} = \frac{3}{2}\frac{eB}{E}\gamma^3$$

$$\gamma = (1-\mathrm{v}^2)^{-1/2} \approx \left(\frac{m^2}{E^2} - 2\eta\frac{E}{M_{QG}}\right)^{-1/2}$$

η<0

γ is a bounded function of E.
There is a maximum achievable synchrotron frequency ω^{max} for ALL electrons!

So one gets a constraint by asking $\omega^{max} \geq (\omega^{max})_{observed}$

η>0

γ diverges as p_{th} is approached. This is unphysical as also the energy loss rates diverges in this limit, however means a rapid decay of the electron energy and a violent phase of synchrotron radiation.

No immediate way to have a constraint in this case

UHECR propagation: energy losses

- red-shift
- $p + \gamma \to p + \mathrm{hadrons}$
- $p + \gamma \to p + e^+ + e^-$

(also photo-disintegration for heavy nuclei)

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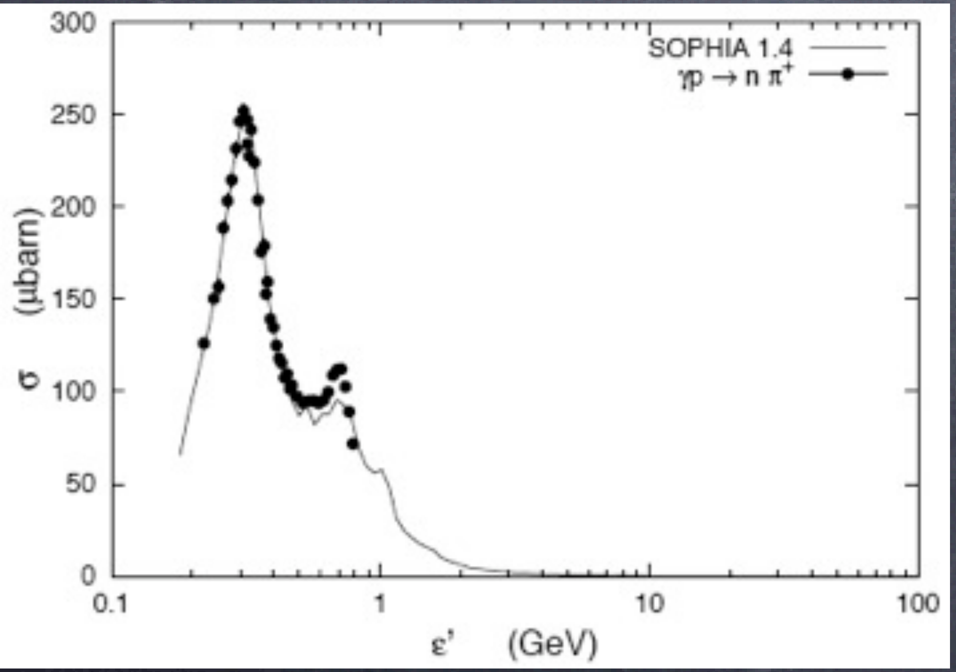
The Greisen-Zatsepin-Kuzmin (GZK) effect:

attenuation of proton spectrum due to resonant photo-pion-production $p + \gamma \rightarrow p + \pi^0 (n + \pi^+)$ mainly through the interaction with the CMB



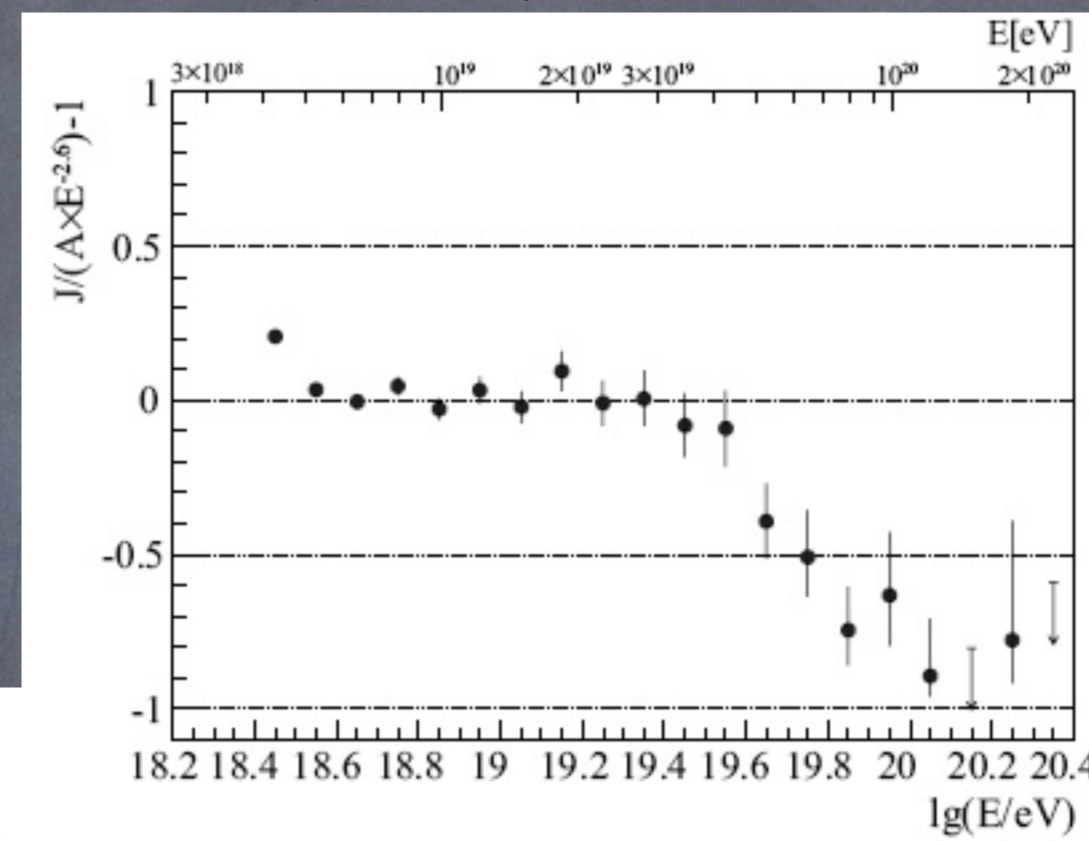
Attenuation length of ~100 Mpc above threshold.

Sources must lie in the GZK horizon. Only LIV at large boosts could evade this conclusion.

GZK feature: found!

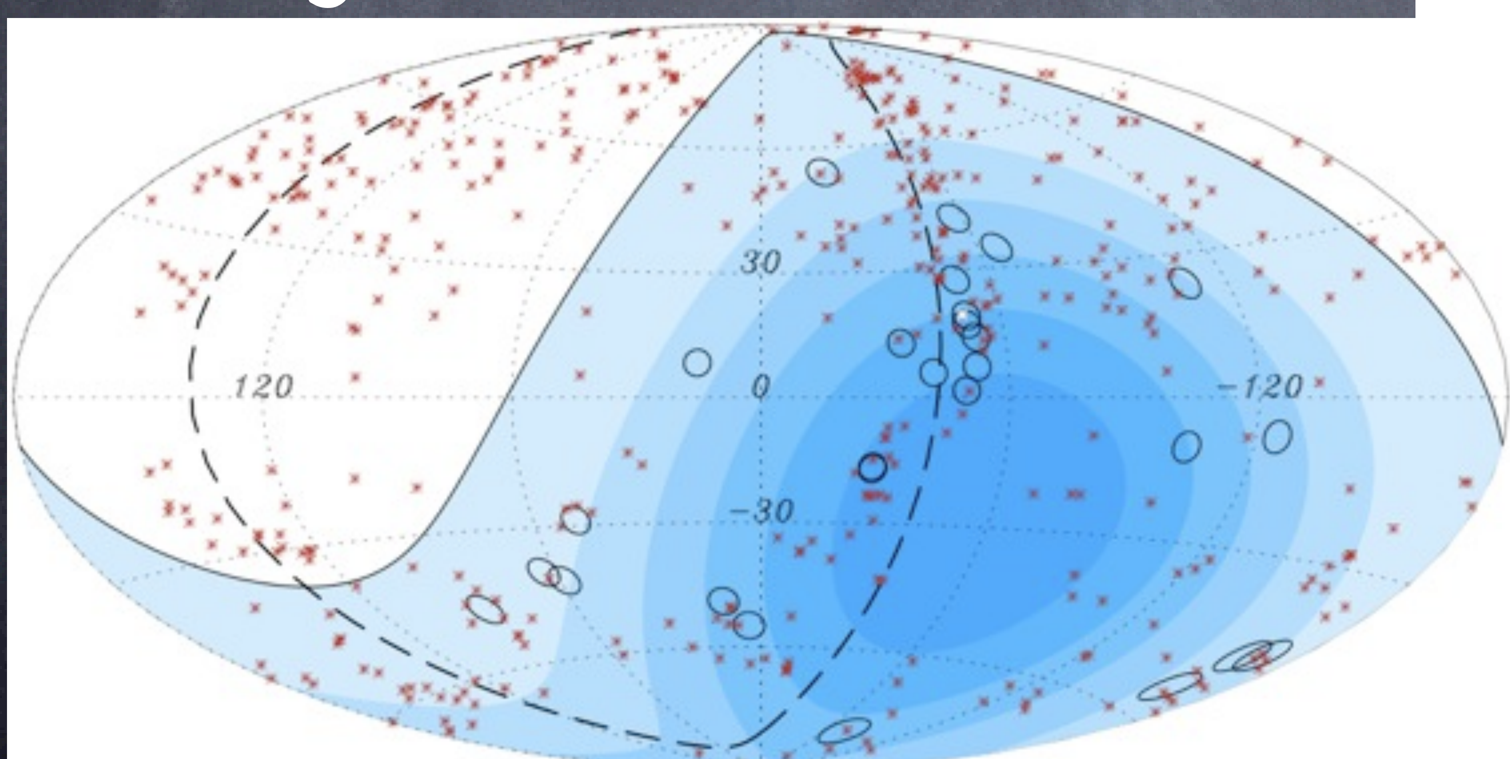
Early claim by HiReS

Abbasi R. *et al* (HiRes Collaboration), 2007 *Preprint* astro-ph/0703099



Confirmed by AUGER data

Further confirmation: found **correlation** between UHECR arrival directions and some extragalactic source



Best correlation parameters:

z_{max} ~0.017 (D_{max} ~ 71 Mpc)

E > 57 EeV

ψ = 3.2° (aperture angle)