



Universität Hamburg



Not only time delays. UHE photons as probes of QG scenarios

Luca Maccione (DESY)

in collaboration with S. Liberati and G. Sigl

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Brief outline

- Intro to LV
- Review of constraints
- Space-time foam and Lorentz violation, and why constraints do not work
- Constraint strategy (the working one!)

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- Disclaimer: I'm not an expert in string theory.

The problem of QG

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- Why do we need quantum gravity?
Philosophical intuition: reductio ad unum
Lack of predictability by GR (singularities, BH entropy)
- What do we need to understand quantum gravity?
Observe phenomena that "have to do" with QG
Extract testable predictions from the theory(ies)

Why 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

Challenging Lorentz invariance

Lorentz invariance relates, through homogeneity, **short to long distances**.

What happens if we have a minimum length scale?

$$l_{\text{Pl}} = \sqrt{\hbar G_N / c^3} \sim 1.6 \times 10^{-35} \text{ m}$$
$$M_{\text{Pl}} = \sqrt{\hbar c / G_N} \sim 1.22 \times 10^{19} \text{ GeV}$$

Homogeneity likely to be broken



Boost invariance likely to be broken

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 $\approx M_{\text{Planck}} = 10^{19} \text{ GeV}$

Assuming rotation invariance
we can expand this as

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

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

EFT+LV

Renormalizable, or higher dimension operators

Non-critical Strings

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.

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

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Warning:
CPT violated!

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$$\begin{array}{ll} \text{electrons} & E^2 = m^2 + p^2 + \eta_{\pm} (p^3/M_{Pl}) \\ \text{photons} & \omega^2 = k^2 \pm \xi (k^3/M_{Pl}) \end{array}$$

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

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?

Windows on Quantum Gravity

$$M_{\text{Pl}} \sim 10^{19} \text{ GeV} \sim 10^8 E_{\text{UHECR}}$$

At energies $\ll M_{\text{Pl}}$ only **tiny effects** are expected.

BUT there are **special situations** where these tiny corrections can be magnified to sizable effects

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BUT there are **special situations** where these tiny corrections can be magnified to sizable effects

Cumulative effects

(e.g. color dispersion & birefringence)

Anomalous threshold reactions

(e.g. forbidden if LI holds, e.g. gamma decay, Vacuum Cherenkov)

Shift of standard threshold reactions

(e.g. gamma absorption or GZK)

new threshold phenomenology

(asymmetric pair creation and upper thresholds)

LV induced decays not characterized by a threshold

(e.g. decay of particle from one helicity to the other or photon splitting)

Reactions affected by “speed limits”

(e.g. synchrotron radiation)

Astrophysical constraints: birefringence

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

Hence, **linear polarization is rotated as signal propagates**

Angle of rotation of
linear polarization

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

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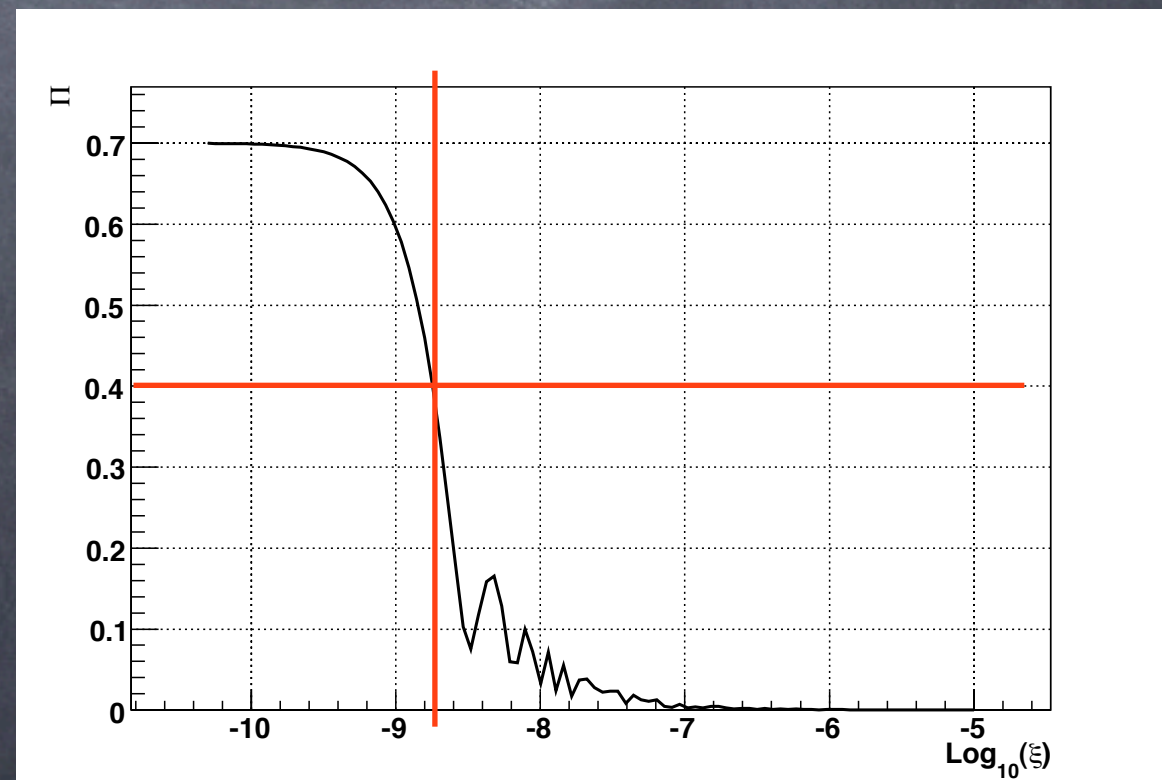
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For a photon beam $\mathcal{P}(E)$ the degree of linear polarization can be computed as

$$\Pi(\xi) = \Pi(0) \sqrt{\langle \cos(2\theta) \rangle_{\mathcal{P}}^2 + \langle \sin(2\theta) \rangle_{\mathcal{P}}^2}$$



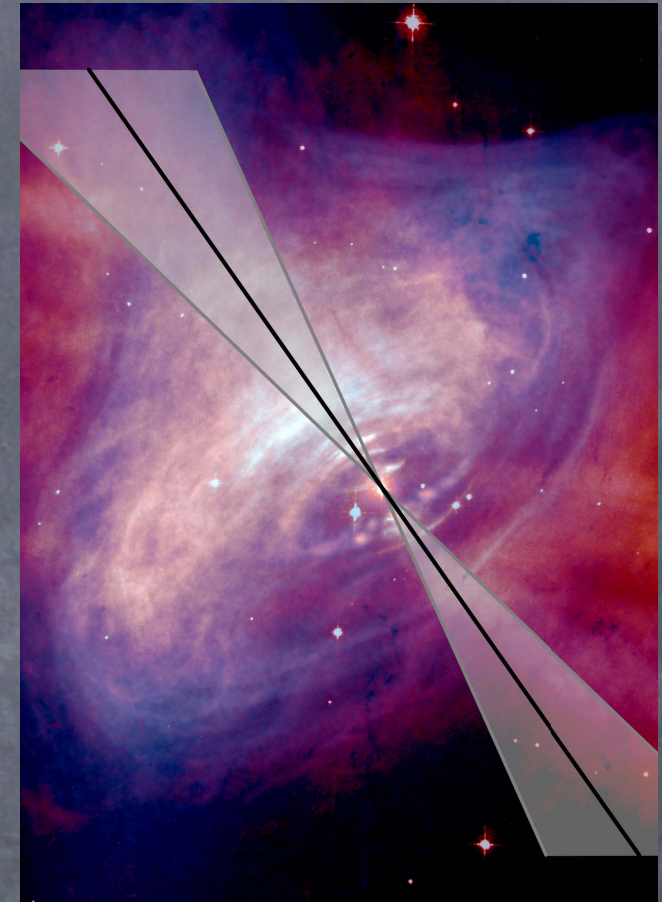
Improved constraints

- ★ There is compelling (theoretical and observational) evidence that the initial position angle of the linear polarization of the Crab emission is aligned with the pulsar spin axis ($\theta_{\text{theo}}=124^\circ$, see optical observations)
- ★ We can then cast a constraint by requiring that the overall (LV induced) position angle after propagation θ_f (with respect to the expected one), observed over the 150–300 keV range, is not larger than the difference between the observed and theoretical ones... From SPI we have

$$\theta_{\text{obs}} = (123 \pm 11)^\circ$$

$$\tan(2\theta_f) = \frac{\int \sin(2\theta(k)) \mathcal{P}(k) dk}{\int \cos(2\theta(k)) \mathcal{P}(k) dk}$$

This leads to the following limits



$$\theta_f < |\theta_{\text{obs}} - \theta_{\text{theo}}|$$

$$|\xi| < 9 \times 10^{-10} \quad (99\% \text{ CL})$$

$$|\xi| < 6 \times 10^{-10} \quad (95\% \text{ CL})$$

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

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

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Astrophysical constraints:

LV QED

Gamma decay

- Lorentz violation allows the conservation of energy-momentum.
- Well above threshold it is very fast as the decay rate goes like $\Gamma \gg E^2/M$.
- 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 polarization must travel on cosmological distances. I.e. they must be below threshold.
- If $|\xi| \ll |\eta|$ the constraint has the form

$$|\eta_{\pm}| \lesssim 6\sqrt{3}m^2 M/k_{\text{th}}^3$$

Vacuum Cherenkov (Helicity Decay)

- 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 .

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

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

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

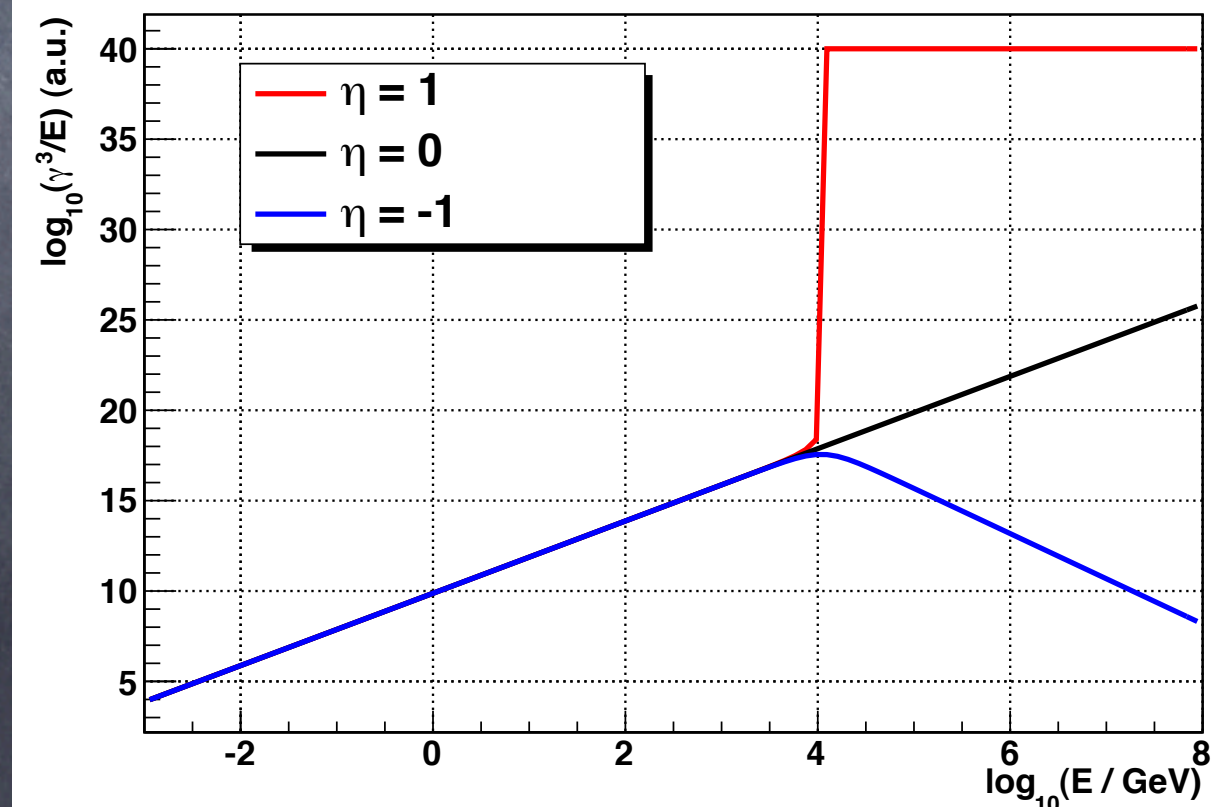
This leads to a modified formula for the peak frequency:

$$\omega_c^{LIV} = \frac{3}{2} \frac{eB}{E} \gamma^3$$

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

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

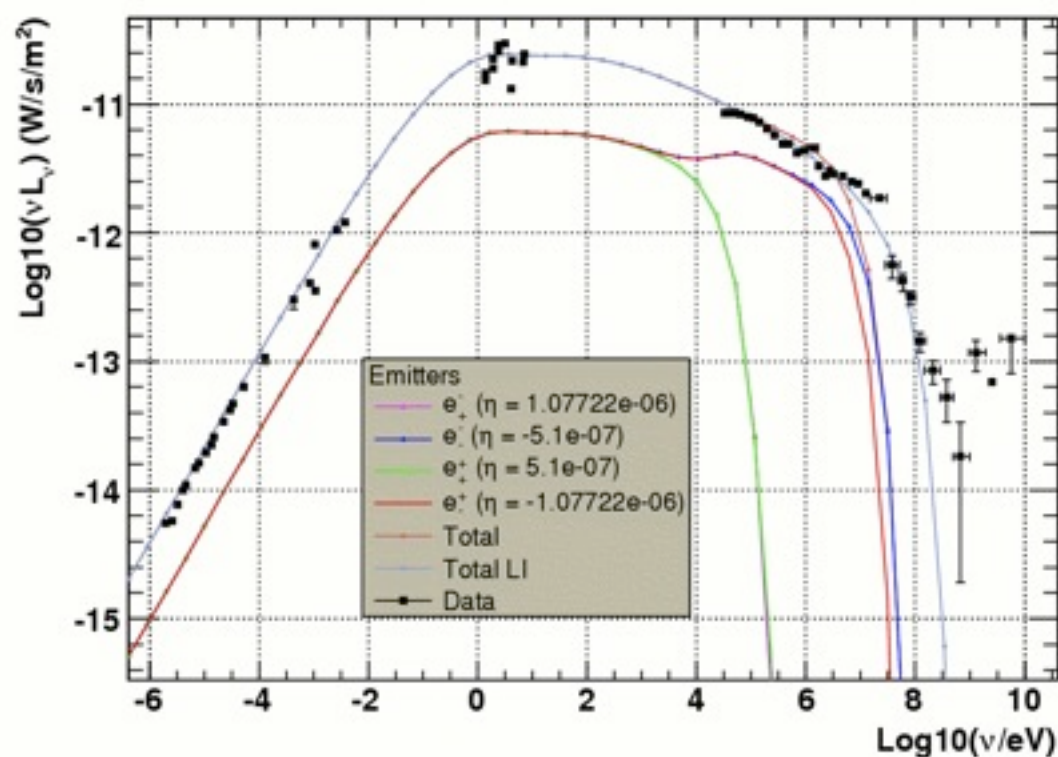
No immediate way to have
a constraint in this case



LV model for the Crab Nebula



Total spectrum obtained by integrating
in a spherical region of radius 1.8 pc

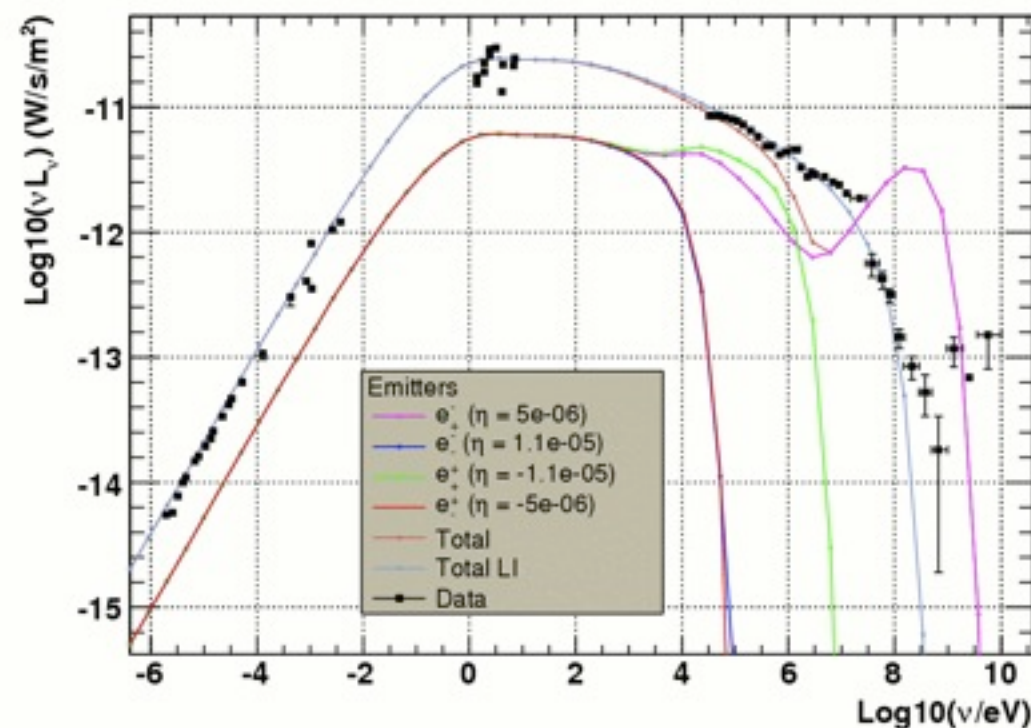


Case A: $\eta_+ > 0, \eta_- < 0$

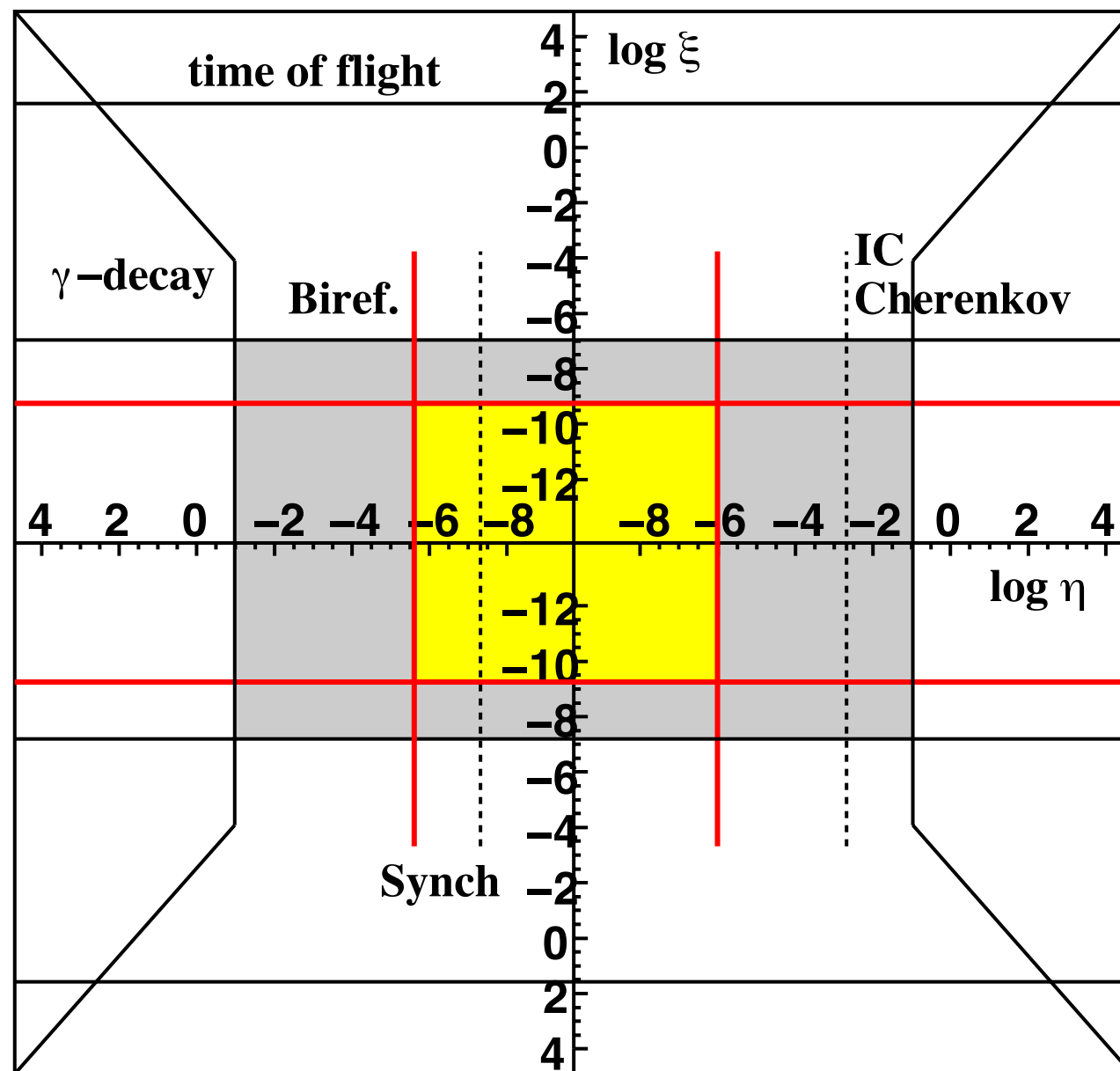
HD : only particles with negative
coefficients survive

Case B: $\eta_+ > 0, \eta_- > 0$

high energy features, due to the divergence
of the synchrotron critical frequency.

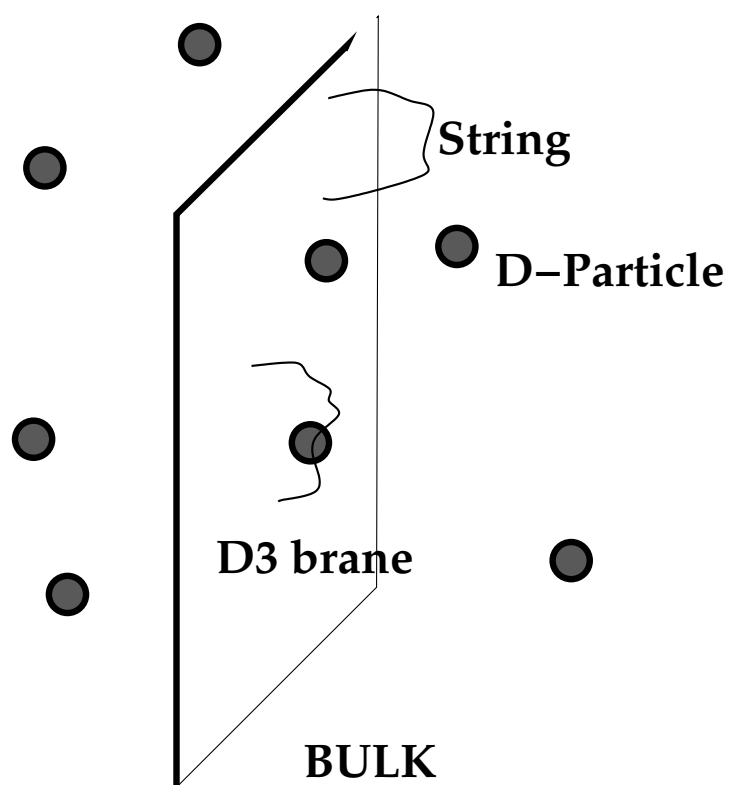
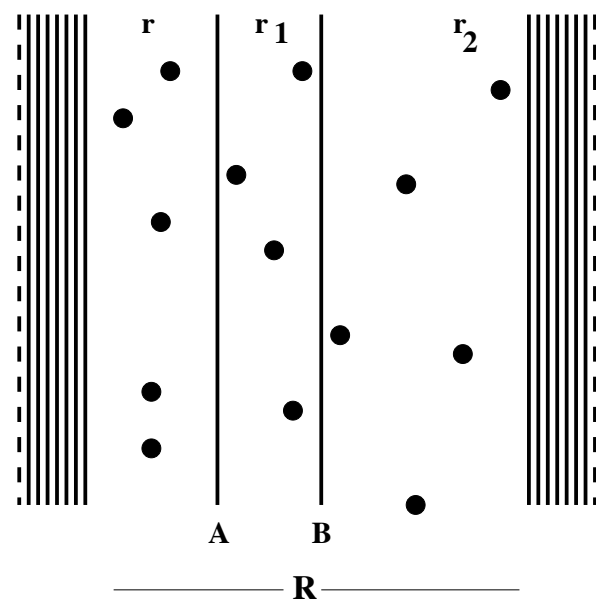


Resume



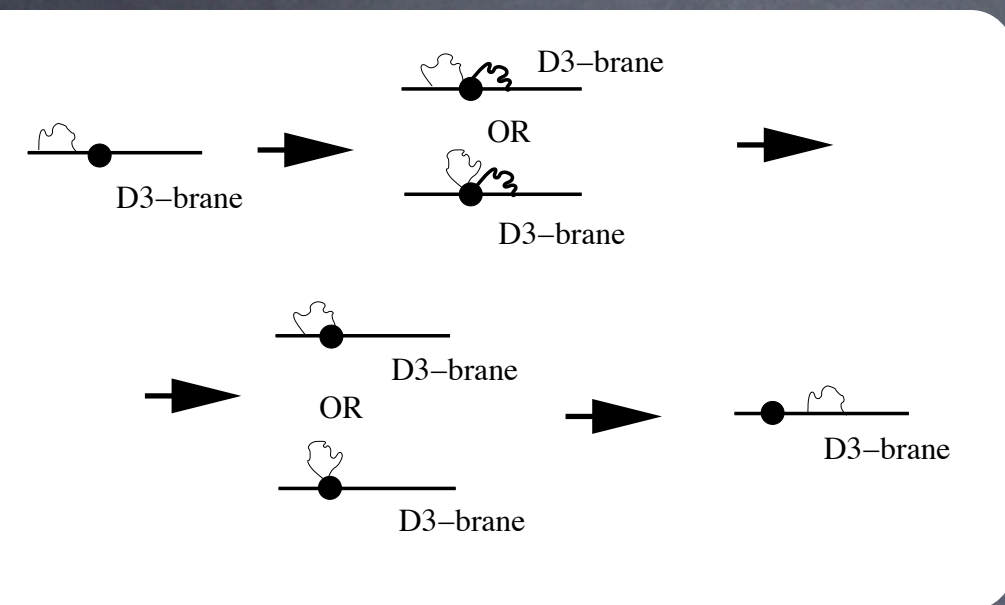
Space-time foam models

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)

No birefringence

Photons are delayed and acquire an effective modified dispersion relation

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

ξ

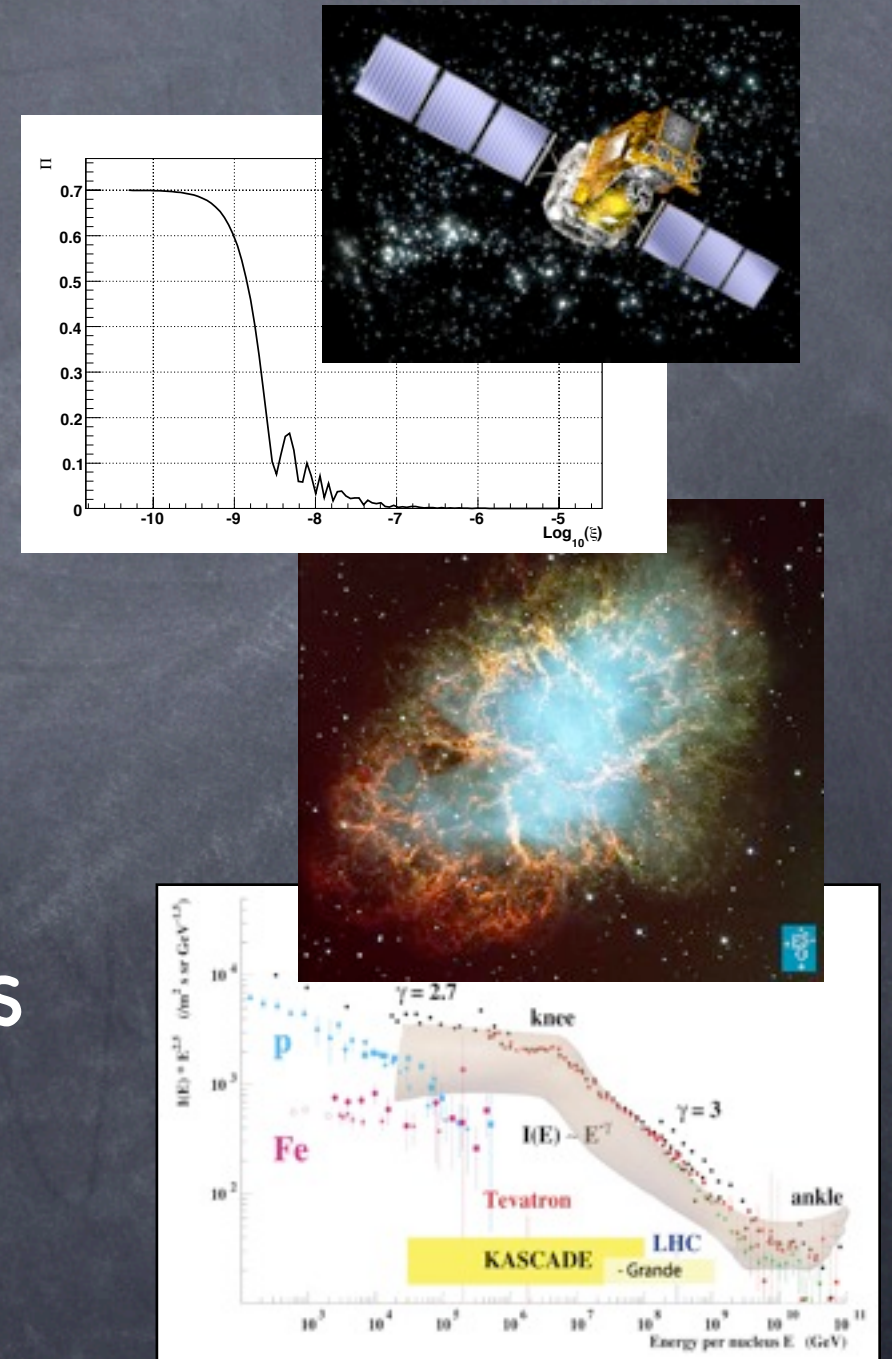
In case D-particles have a bulk recoiling motion, the background metric is modified and energy non-conservation during interaction is possible

ξ_I

Effects proportional to the D-particle density

How to constrain the model?

- Standard constraints are not viable
- Birefringence $\rightarrow$ absent
- Synchrotron $\rightarrow$ not affected
- Threshold reactions $\rightarrow$ only photons are LV, hard to probe



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 $O(E/M_{Pl})$

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

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

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 , $|\xi| < 55$ ($z \approx 0.3$, very uncertain).
- Magic Coll+Ellis et al. (2007) using AGN, Markarian 501 flares, $z \approx 0.034$, $|\xi| < 47$, but possible best fit with $|\xi| \approx O(1)!$?! ...
- 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, $\xi < 0.8$

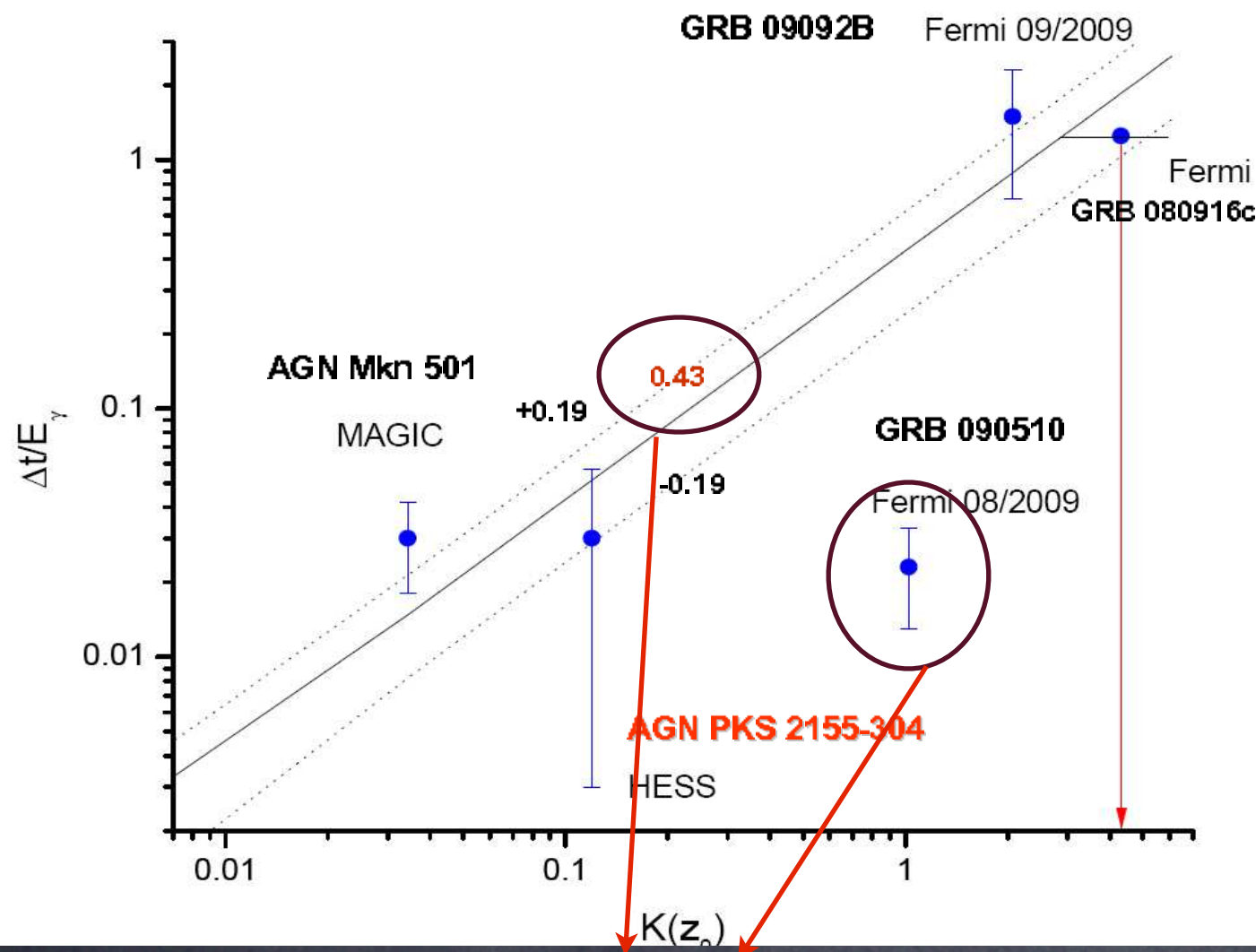
Amelino-Camelia et al, Nature 393 (1998)

Ellis et al, ApJ 535 (2000)

FERMI Coll, Science 323 (2009)

Amelino-Camelia and Smolin, PRD 80 (2009)

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 $z \sim 1$, the other delays are all compatible with the same QG model! Hint of the presence of a D-void at $z \sim 1$?
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

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

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

UHECRs phenomenology

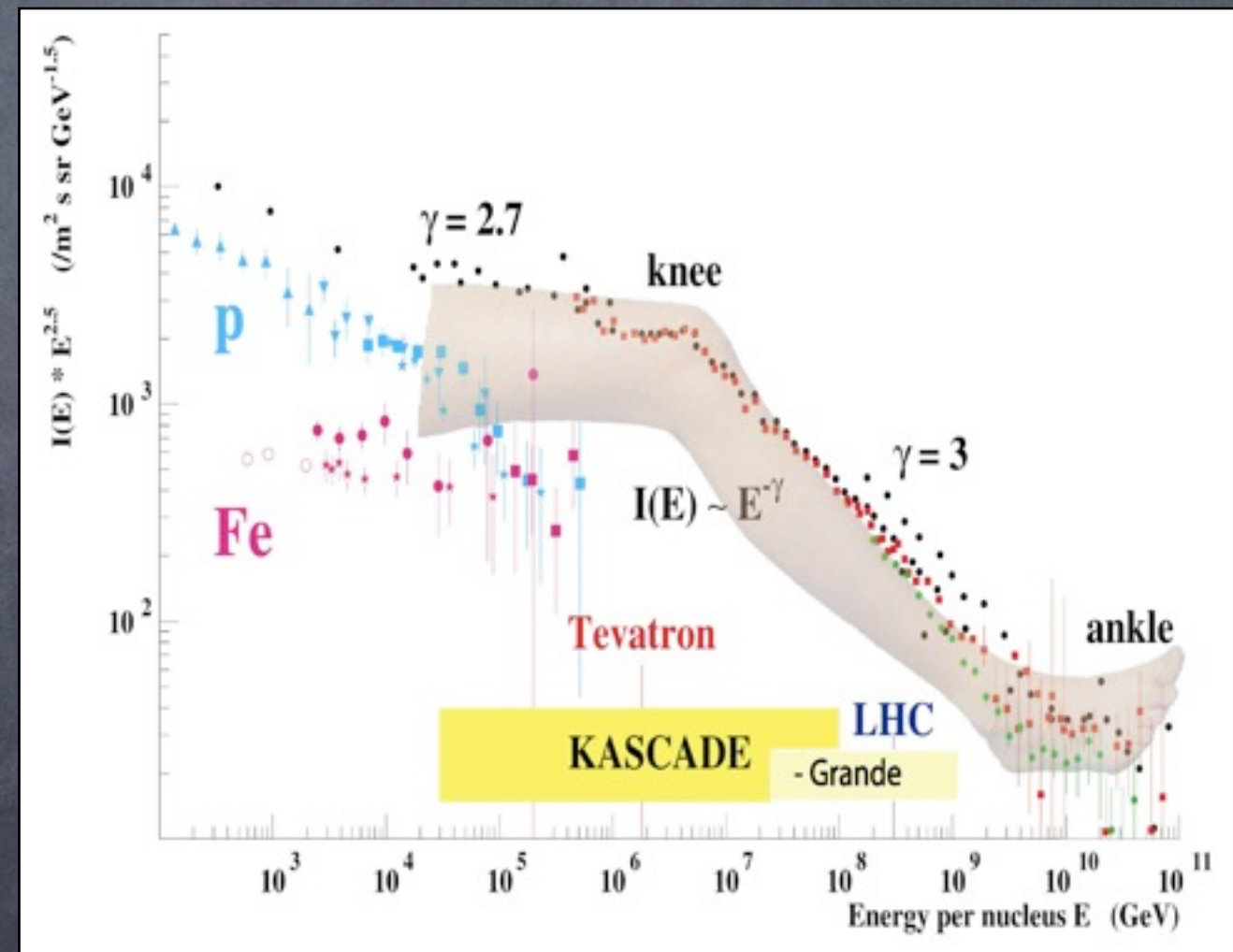
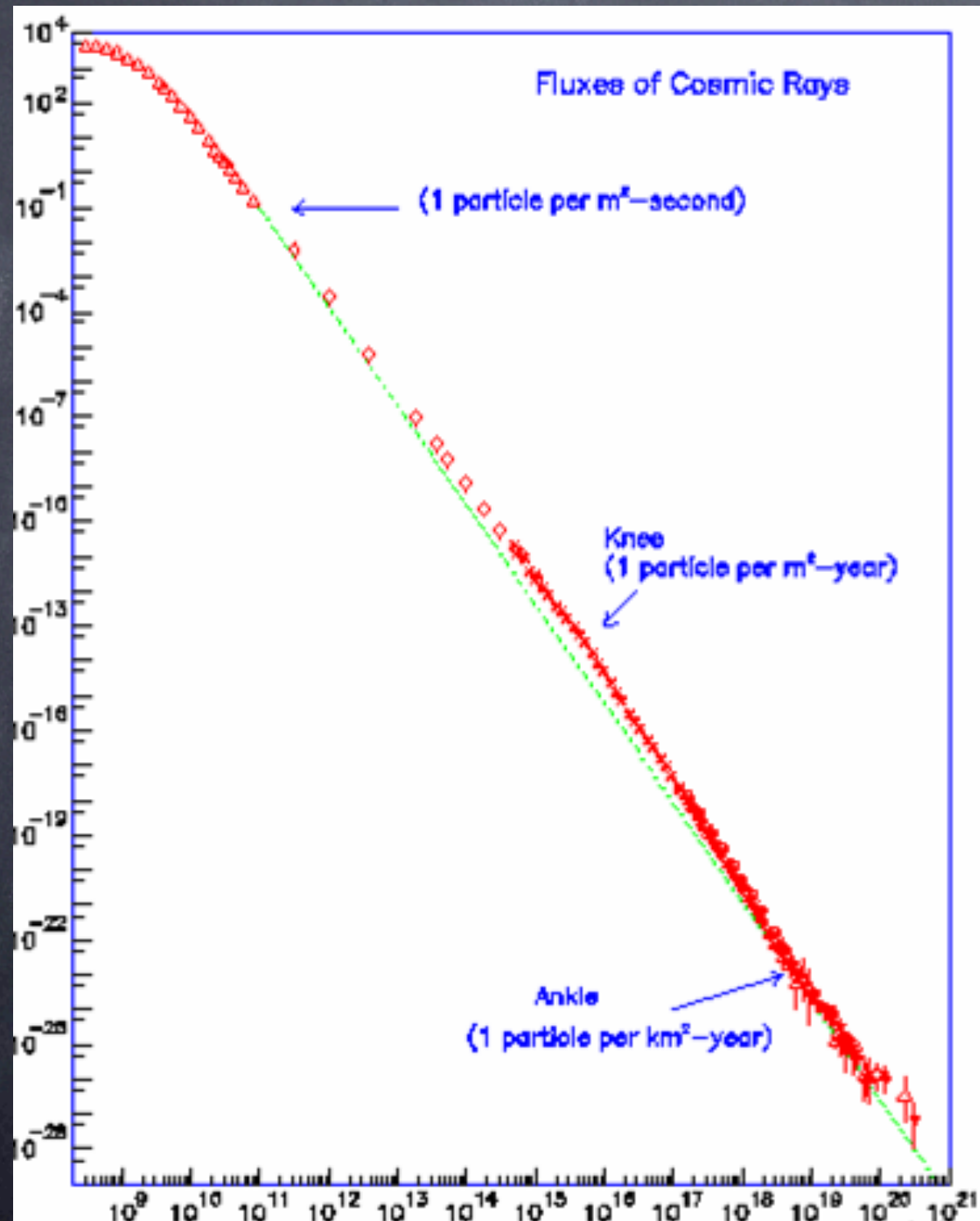
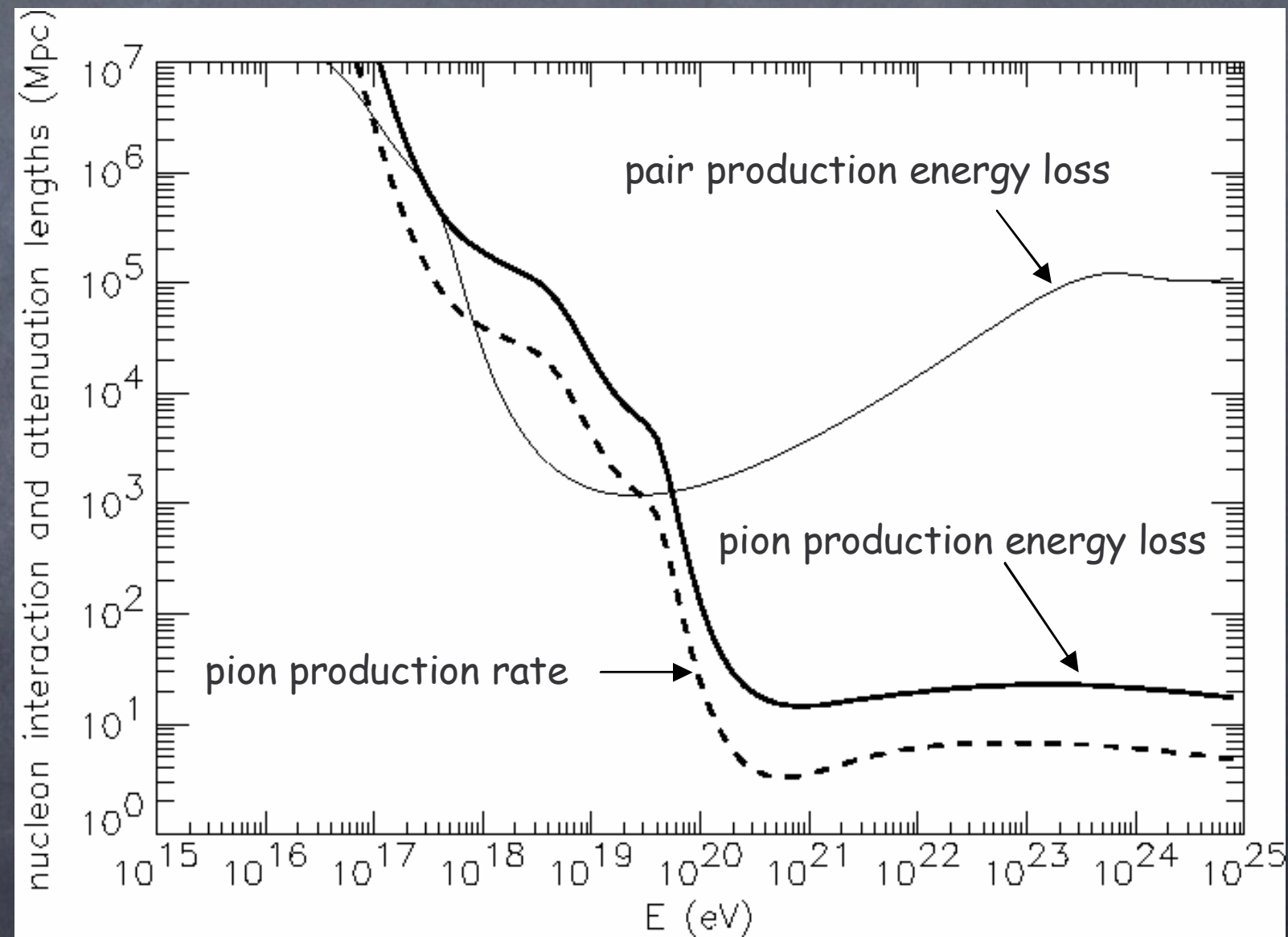
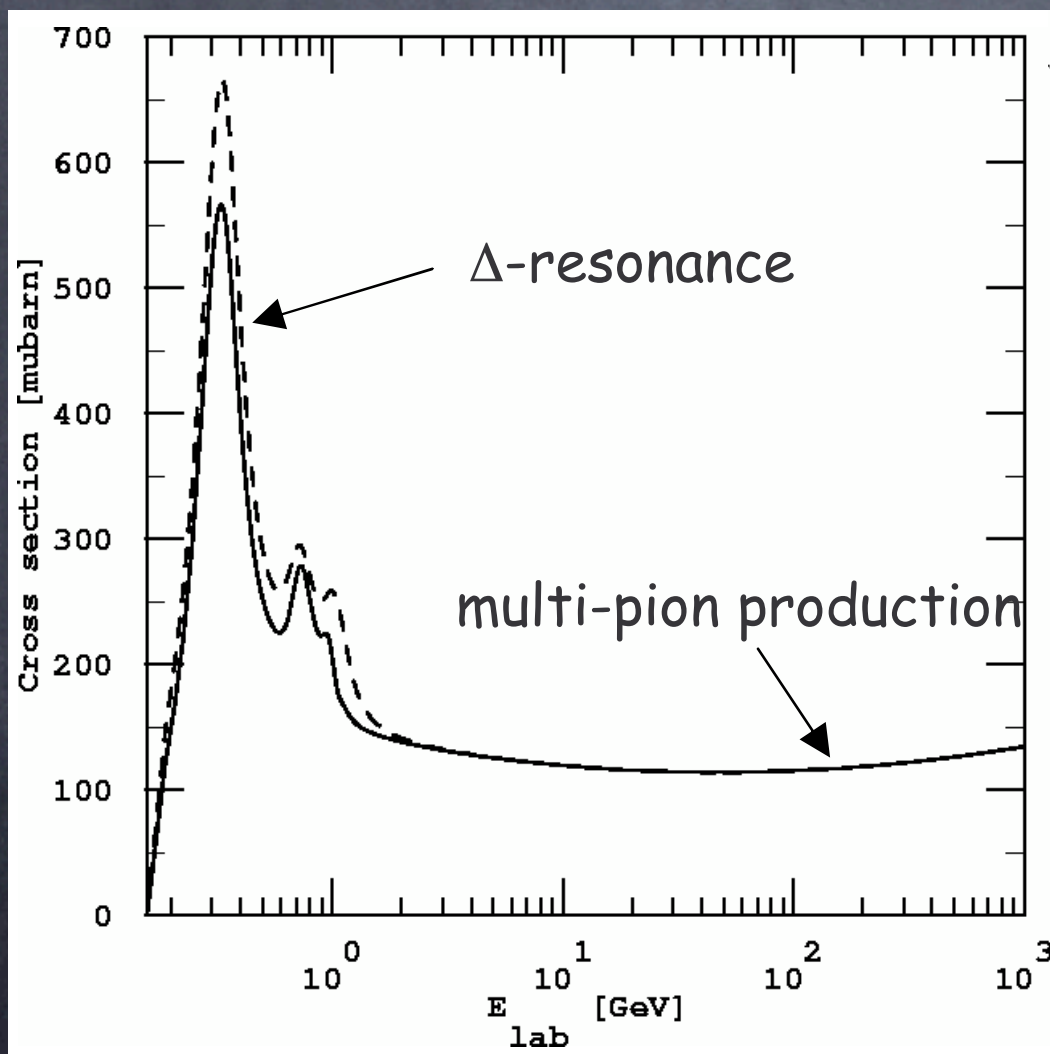


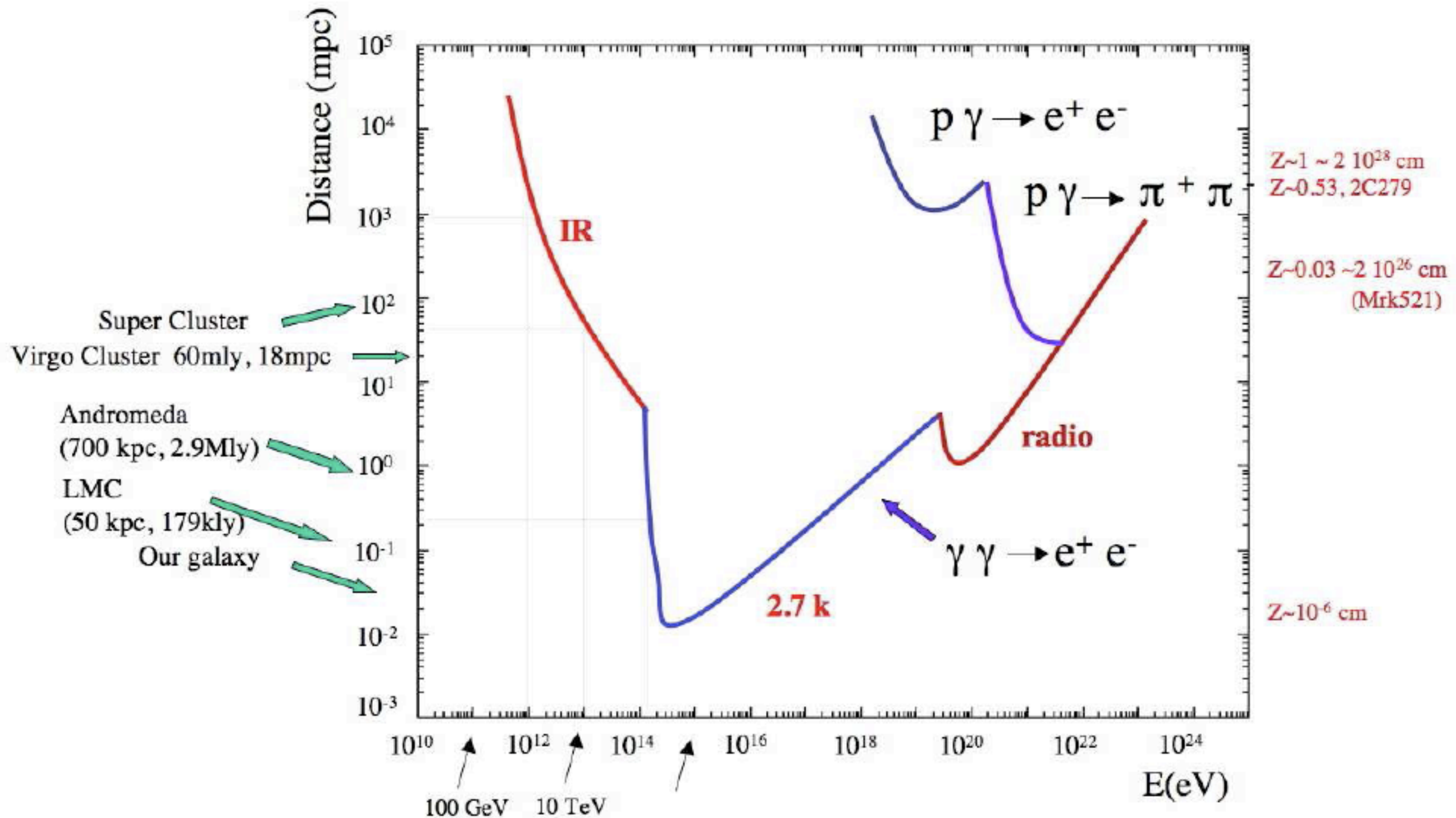
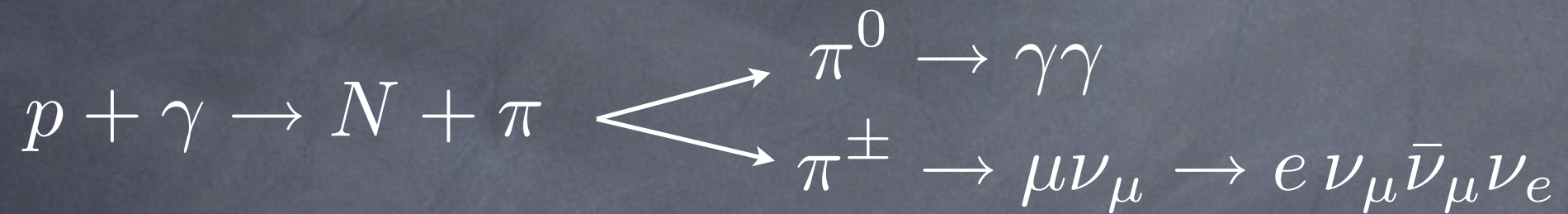
Photo pion production

The Greisen-Zatsepin-Kuzmin effect

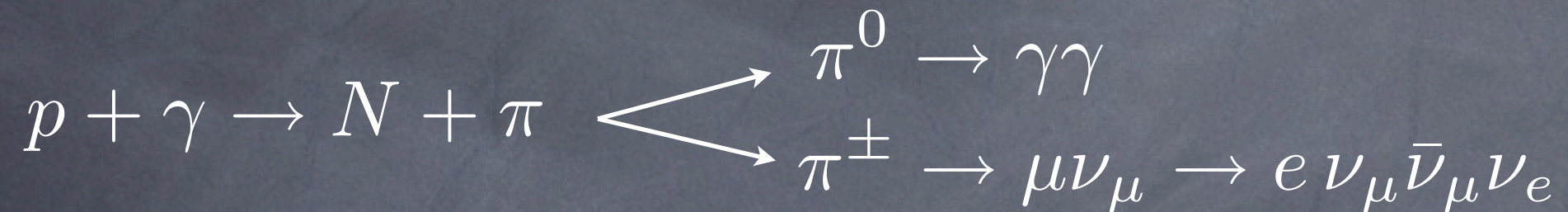
$$p + \gamma \rightarrow N + \pi \quad E_{\text{th}} = \frac{2m_p m_\pi + m_\pi^2}{4\epsilon} \sim 4 \cdot 10^{19} \text{ eV on CMB}$$



GZK effect and secondary production



GZK effect and secondary production



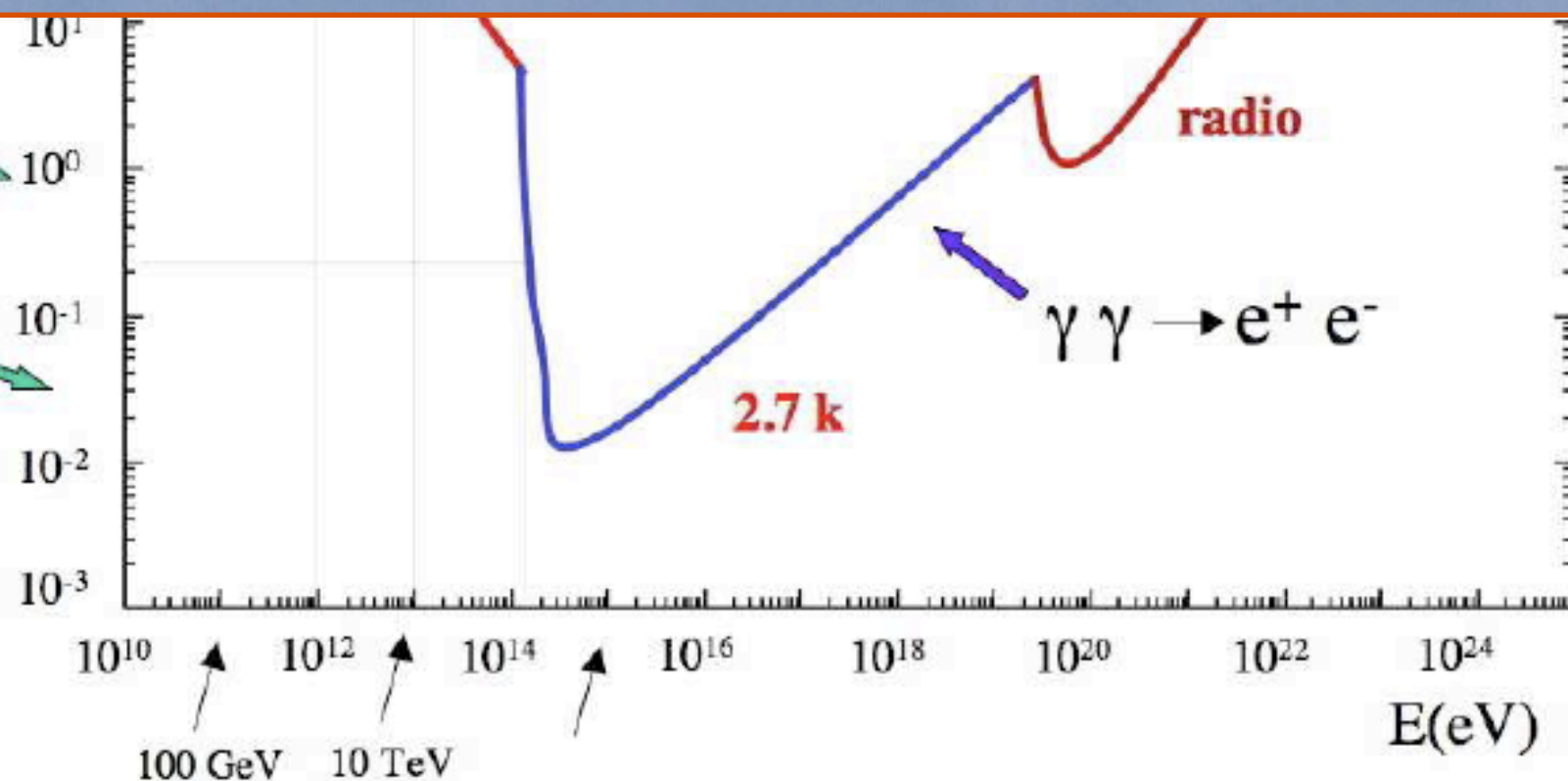
LV affects strongly pair production. Constraints already obtained in the EFT case (Galaverni & Sigl, PRL, LM & Liberati, JCAP, Galaverni & Sigl, PRD). Try to exploit the same technique also for the case of space-time foam models??

Super Cluster
Virgo Cluster 60mly,

Andromeda
(700 kpc, 2.9Mly)

LMC
(50 kpc, 179kly)

Our galaxy



$\sim 2 \cdot 10^{28}$ cm
53, 2C279

03 $\sim 2 \cdot 10^{26}$ cm
(Mrk521)

$Z \sim 10^{-6}$ cm

UHE photons and LV: general case

Galaverni, Sigl, LM, Liberati

- Consider a toy model in which we have LV in photons, electrons and positrons

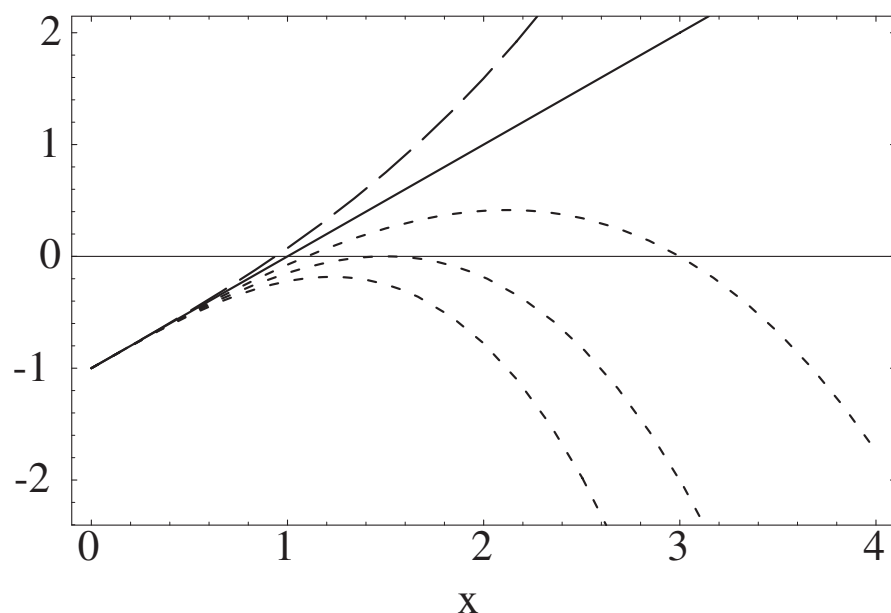
$$E^2 = m^2 + p^2 + \eta \frac{p^n}{M_{\text{Pl}}^{n-2}}$$

- Energy-momentum conservation prescribes the following threshold equation

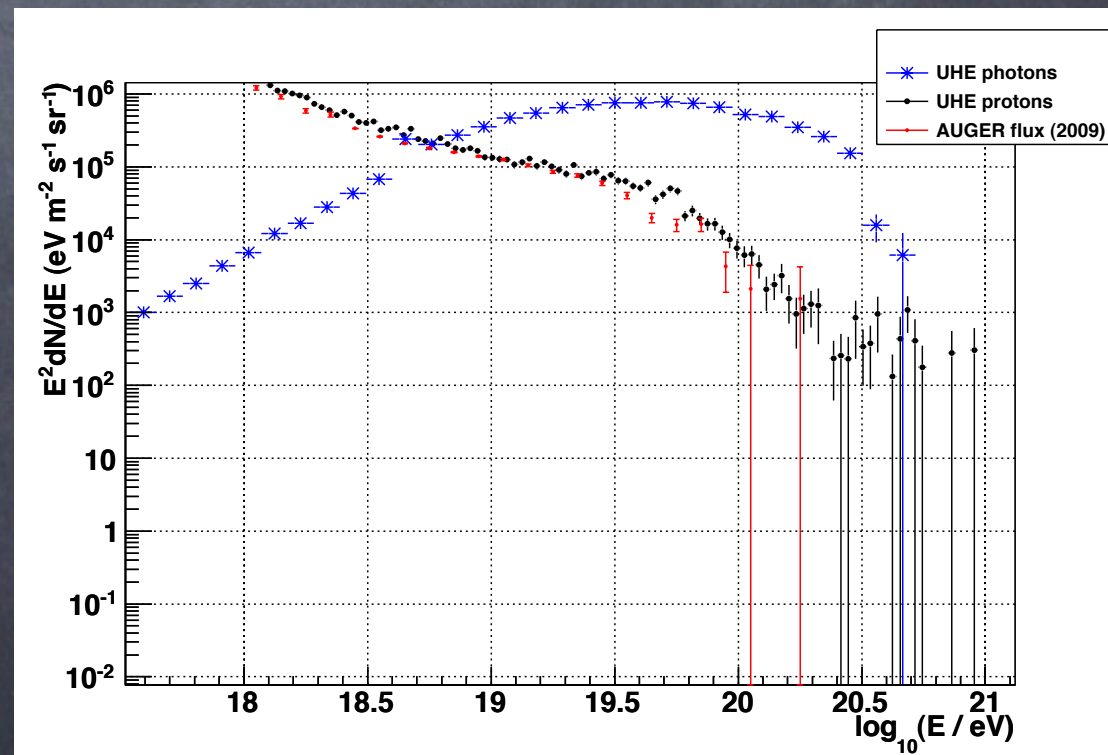
$$x^n \left[\xi - \eta_1 y^{n-1} - \eta_2 (1-y)^{n-1} \right] + 4 \frac{\omega_b}{M} x = \frac{m_e^2}{M^2 y(1-y)}$$

LV contribution

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



Galaverni, Sigl, PRL 100(2008)021102



UHECR constraints: pair production

Galaverni, Sigl, PRL 100(2008)021102
LM, S. Liberati, JCAP 08(2008)027
Galaverni & Sigl, PRD 78(2008)063003

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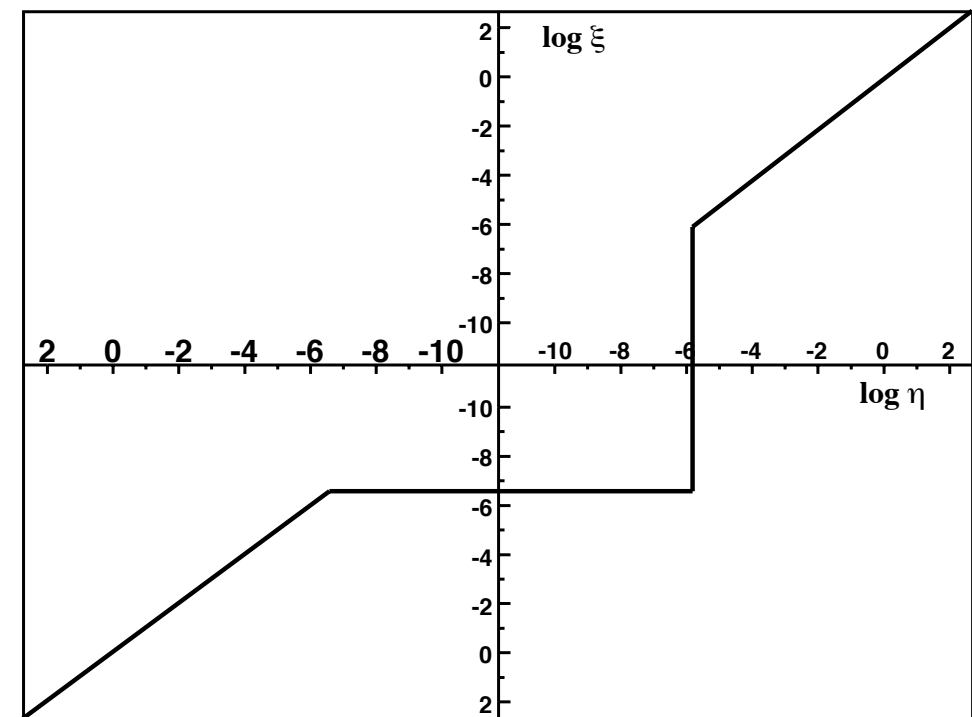
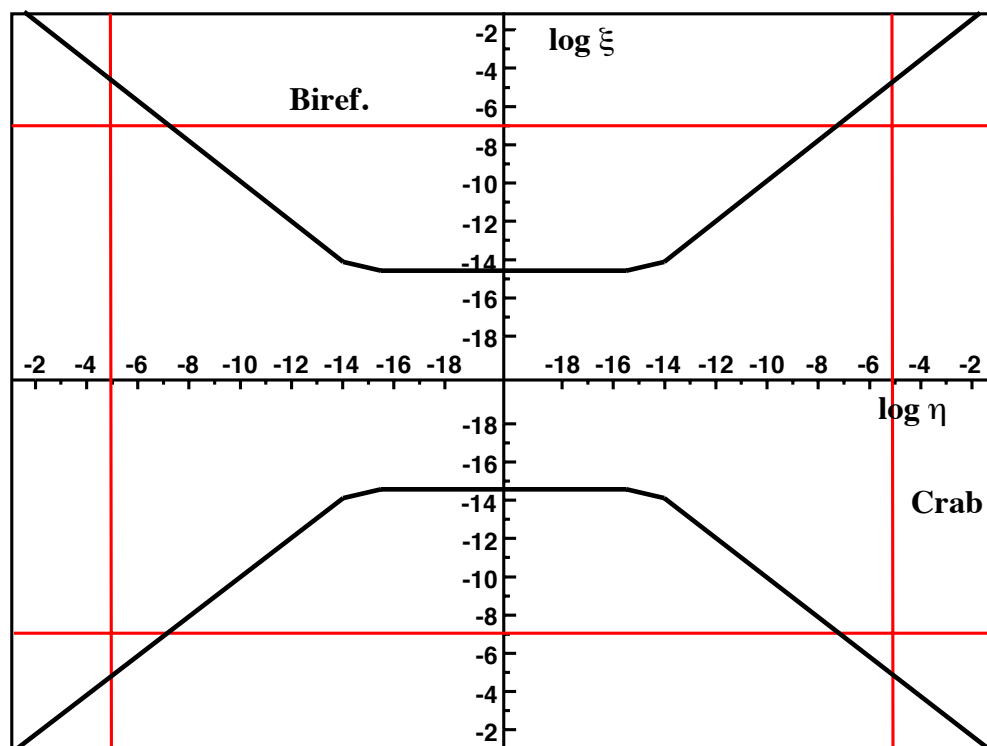
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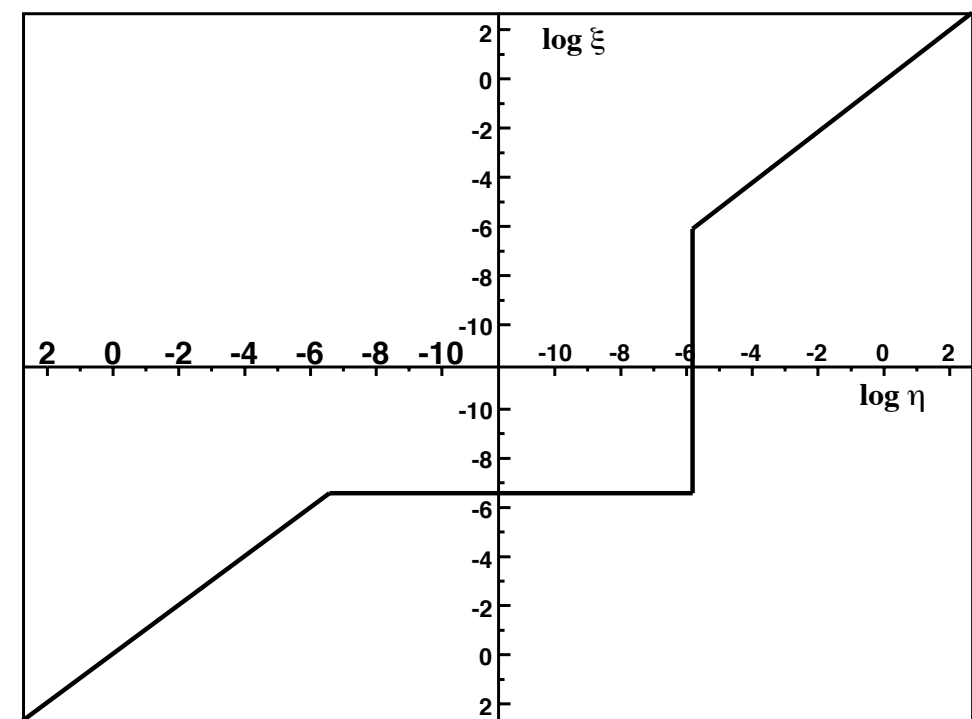
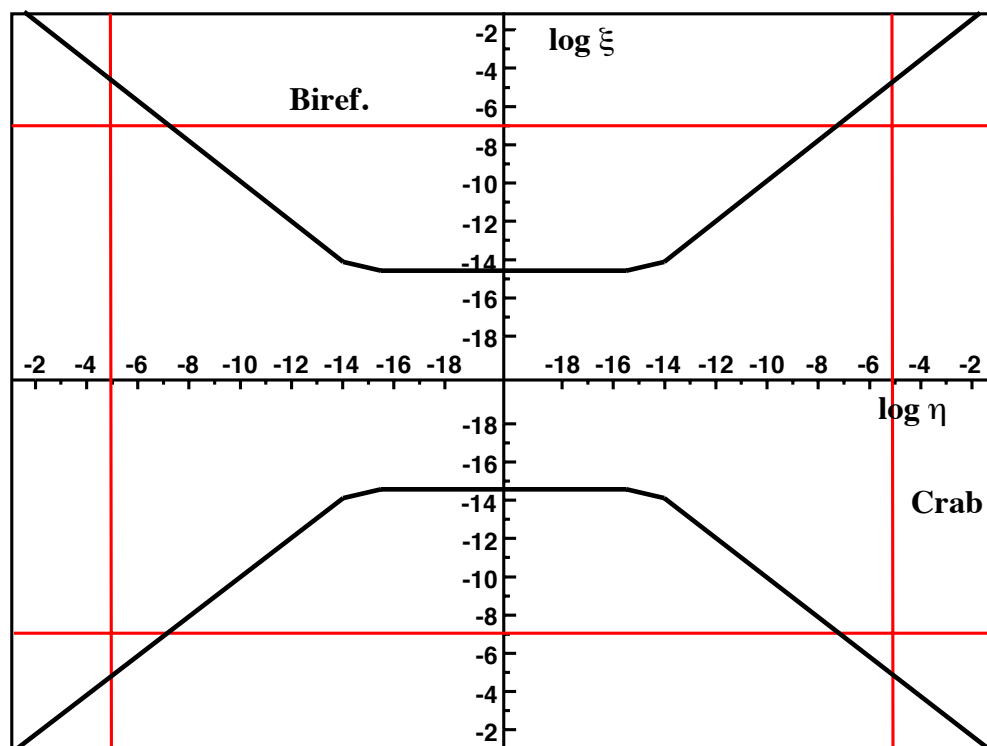
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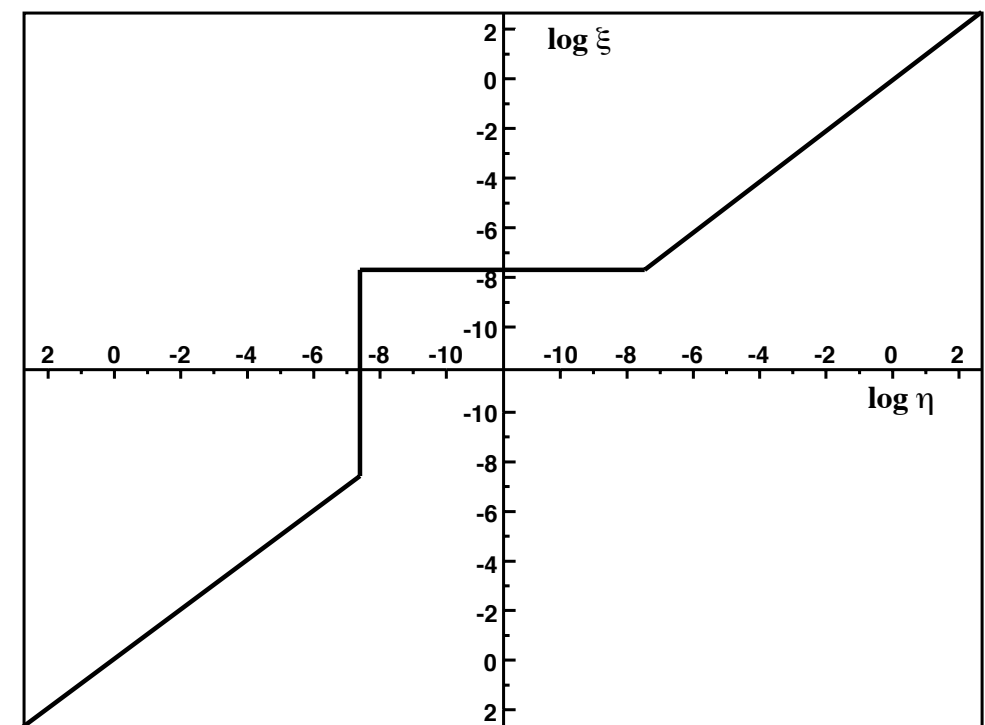
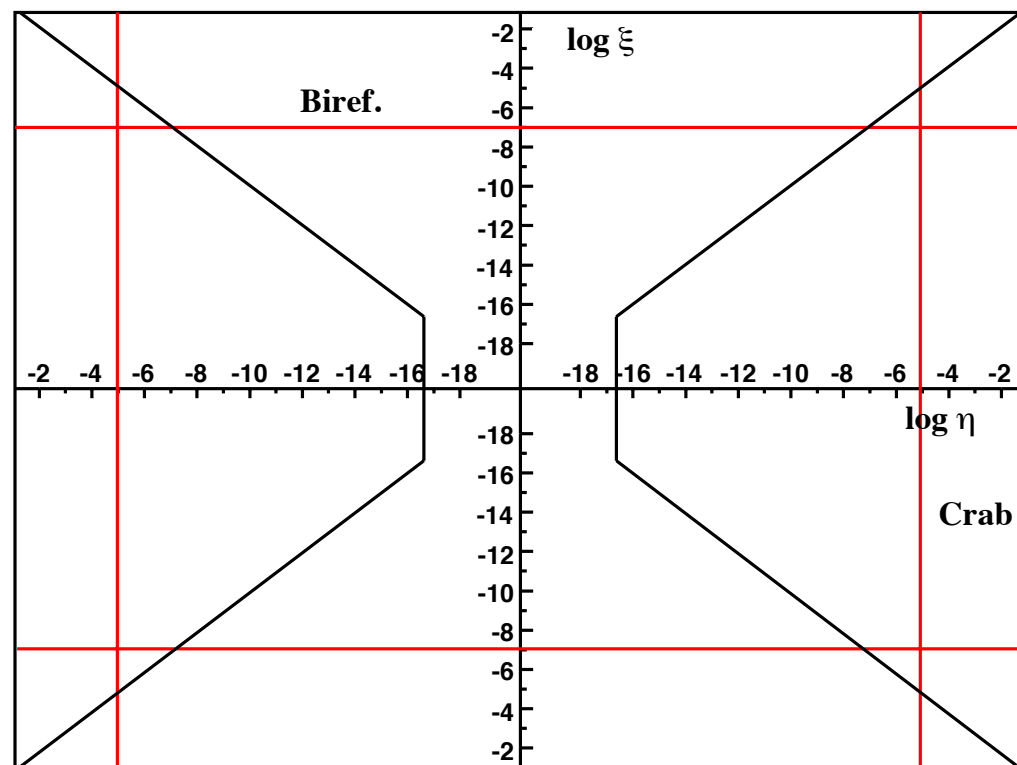
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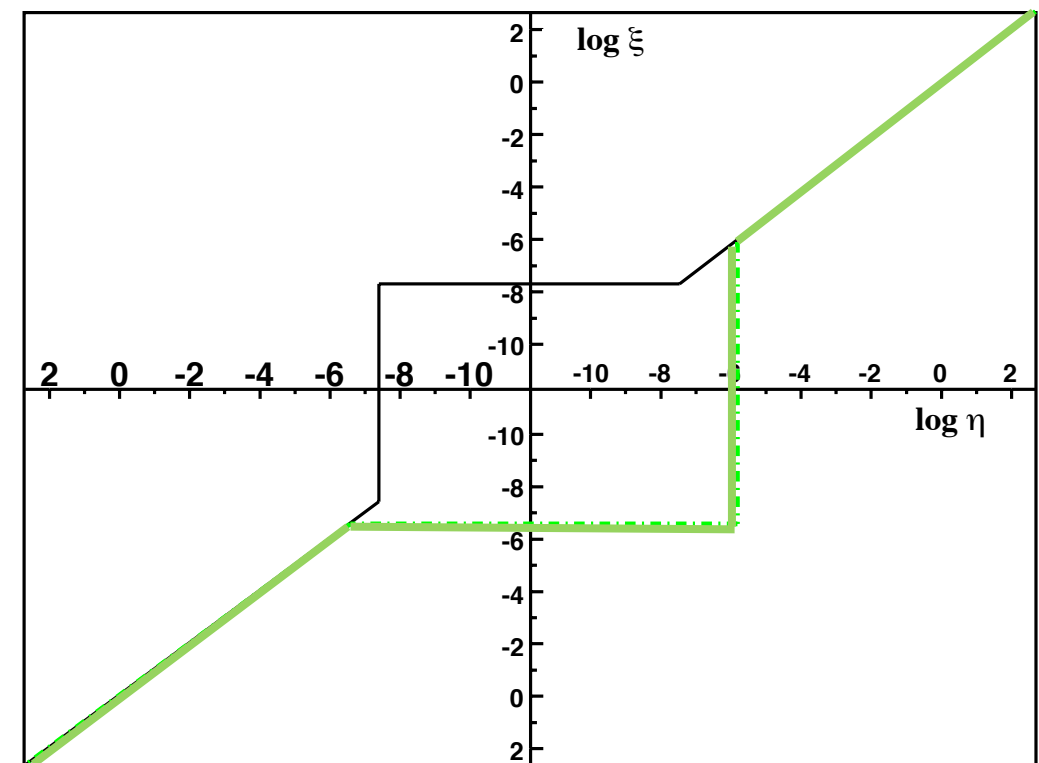
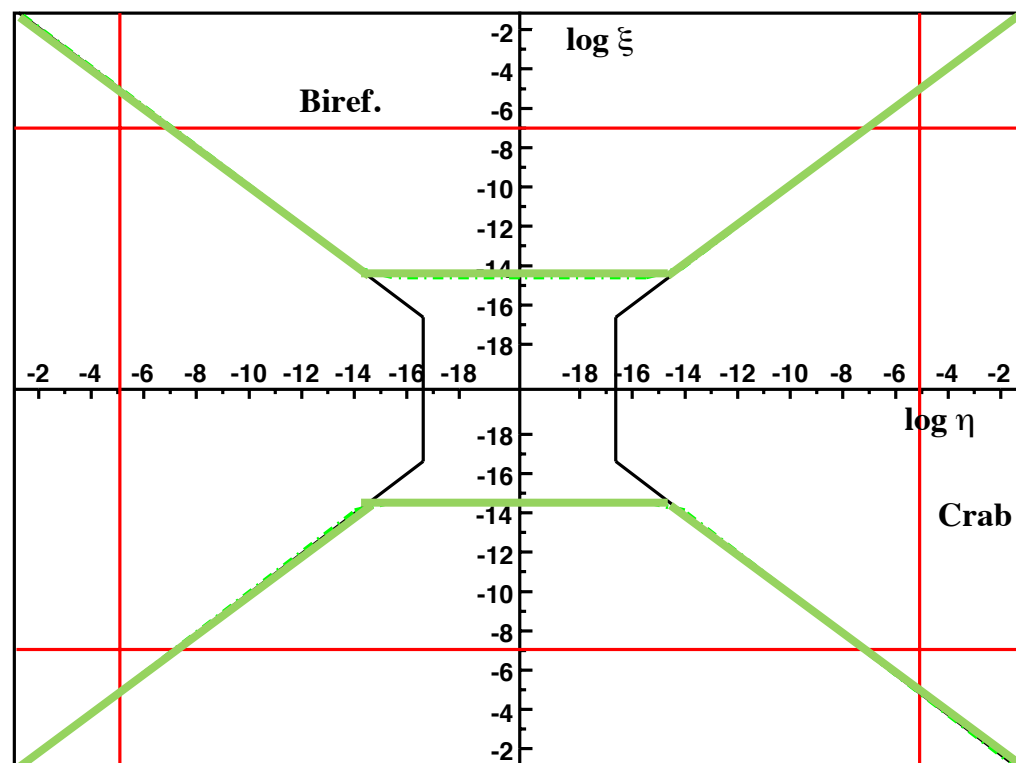
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UHE photons and LV in space-time foam

LM, Liberati, Sigl, arXiv:1003.5468, to appear in PRL

- 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

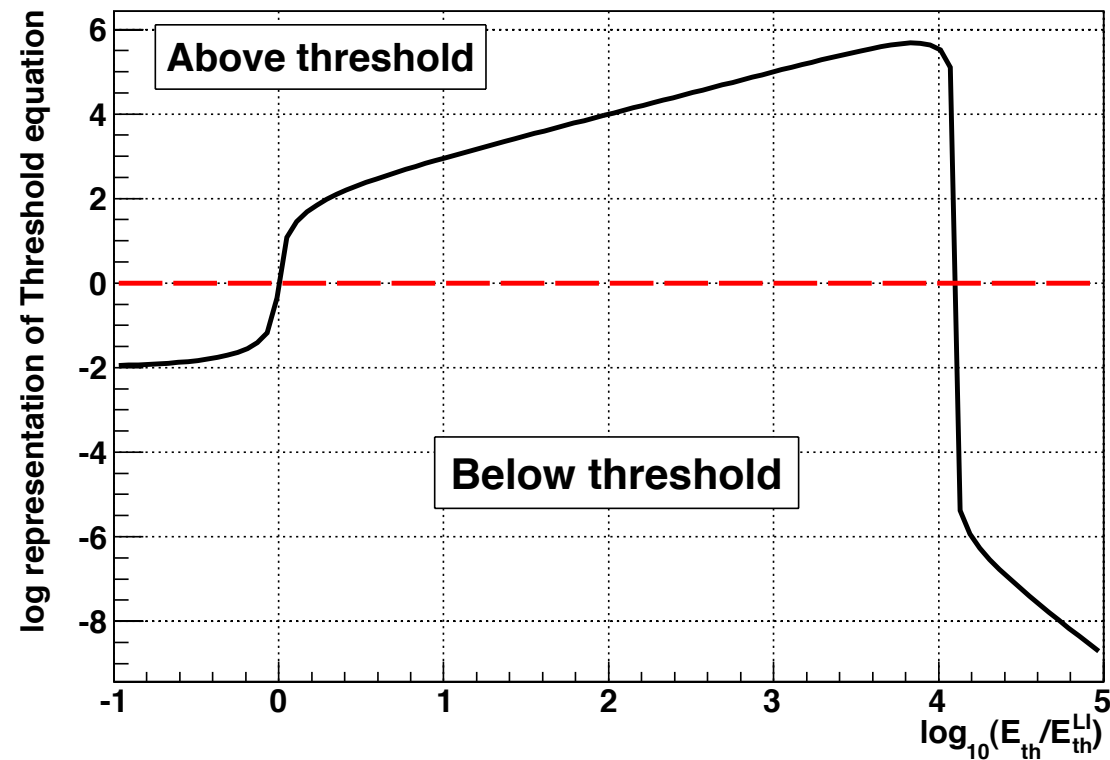
$$\begin{aligned} E_1 + \omega &= E_2 + E_3 + \delta E_D \\ p_1 - \omega &= p_2 + p_3 \end{aligned} \quad \left(-\frac{\xi_I + \xi/2}{2} x^3 + 2\frac{\omega}{M} x - 2\frac{m_e^2}{M^2} + \dots = 0 \right)$$

LV contribution

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

- 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

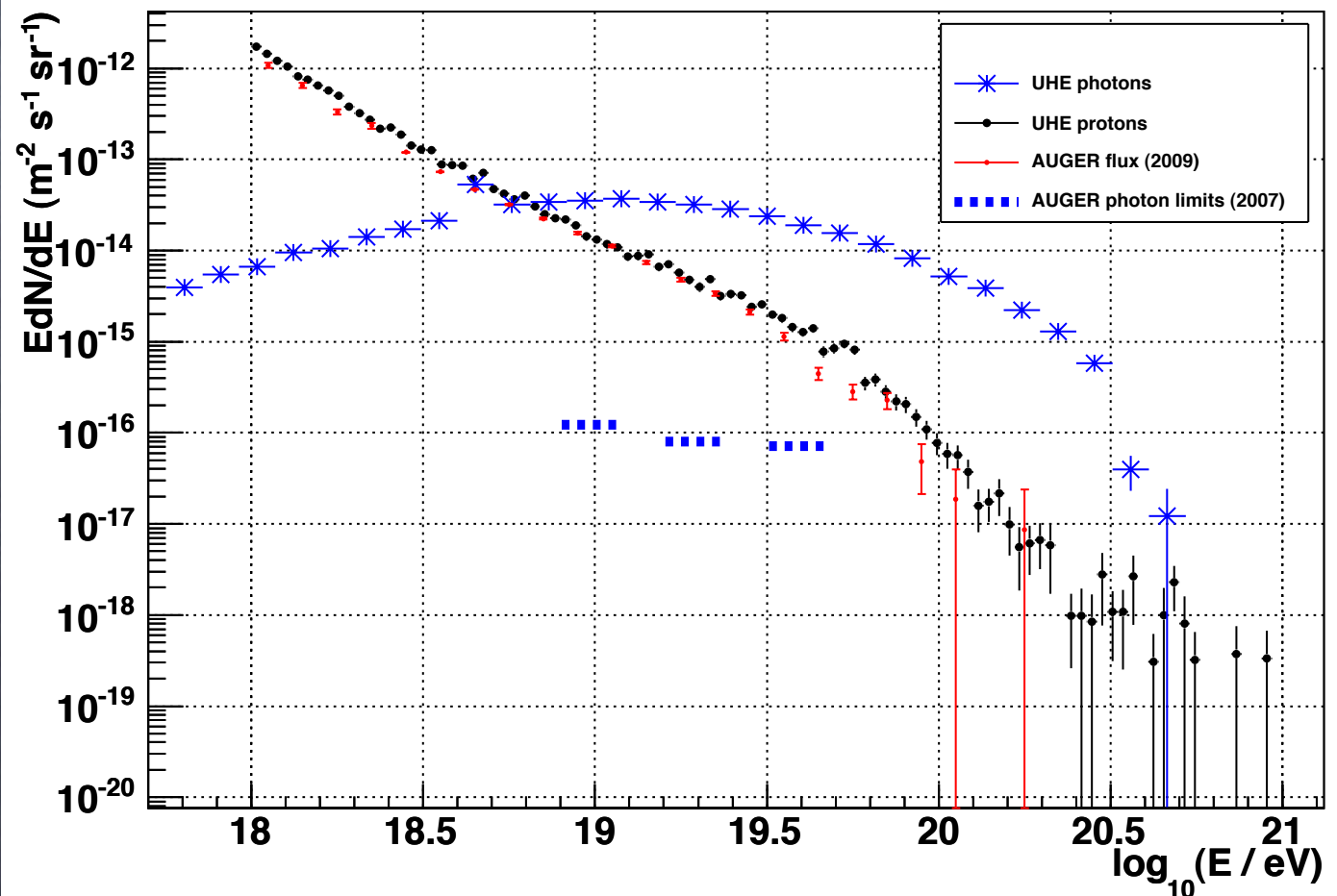


$$\xi/2 + \xi_I = 10^{-12}$$

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 $\rightarrow$ constraint on the sum

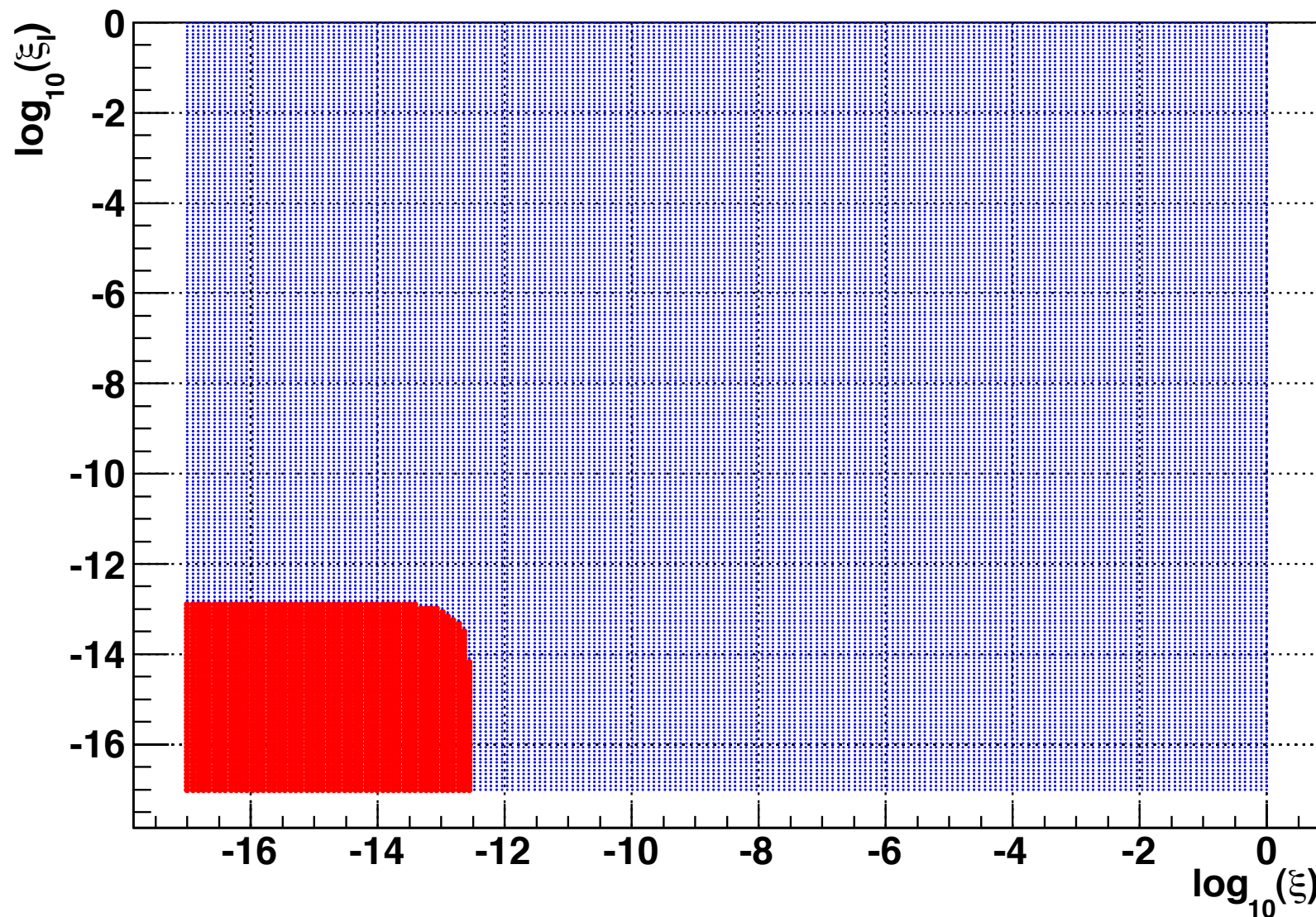
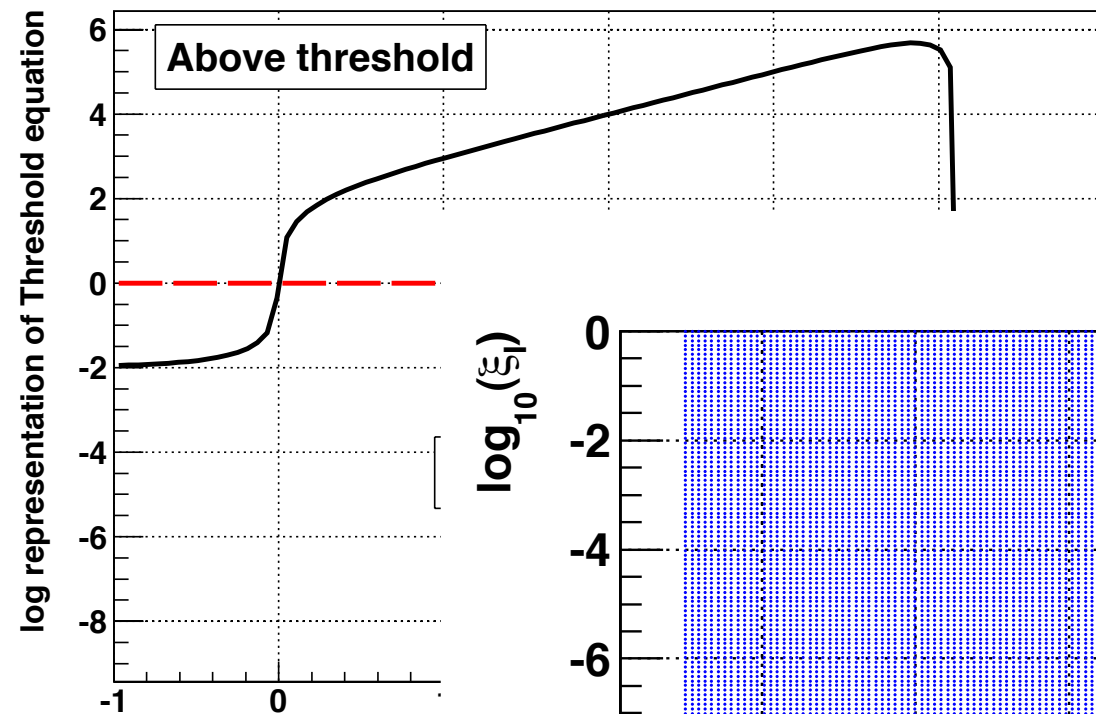
$$\xi/2 + \xi_I \lesssim 10^{-12}$$



UHE photons and LV in space-time foam

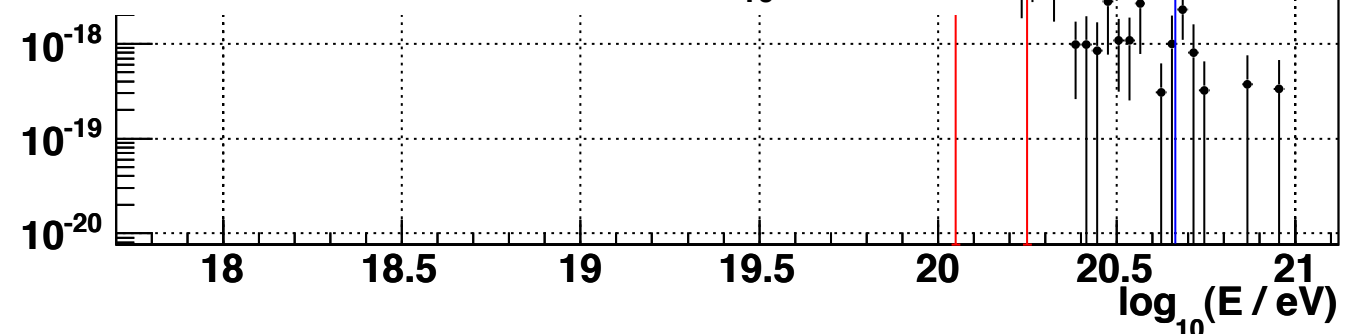
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Photons
are no



Then the
photons
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Conclusions

- Strong constraint placed on stringy space-time foam models of QG and LV
- Time delays in the GeV–TeV range are incompatible with UHE photon data
- No way out with redshift-dependent assumptions
- 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.

Lorentz violation: a first glimpse of QG?

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)

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

UHECR propagation: energy losses

- red-shift

- $p + \gamma \rightarrow p + \text{hadrons}$

- $p + \gamma \rightarrow p + e^+ + e^-$

(also photo-disintegration for heavy nuclei)

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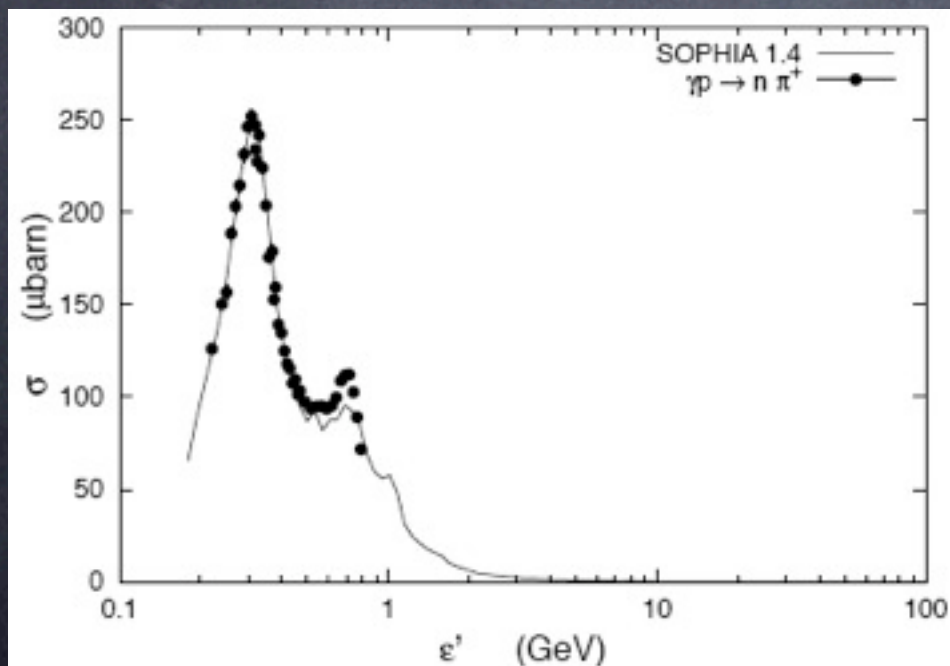
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The Greisen-Zatsepin-Kuzmin (GZK) effect:

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.

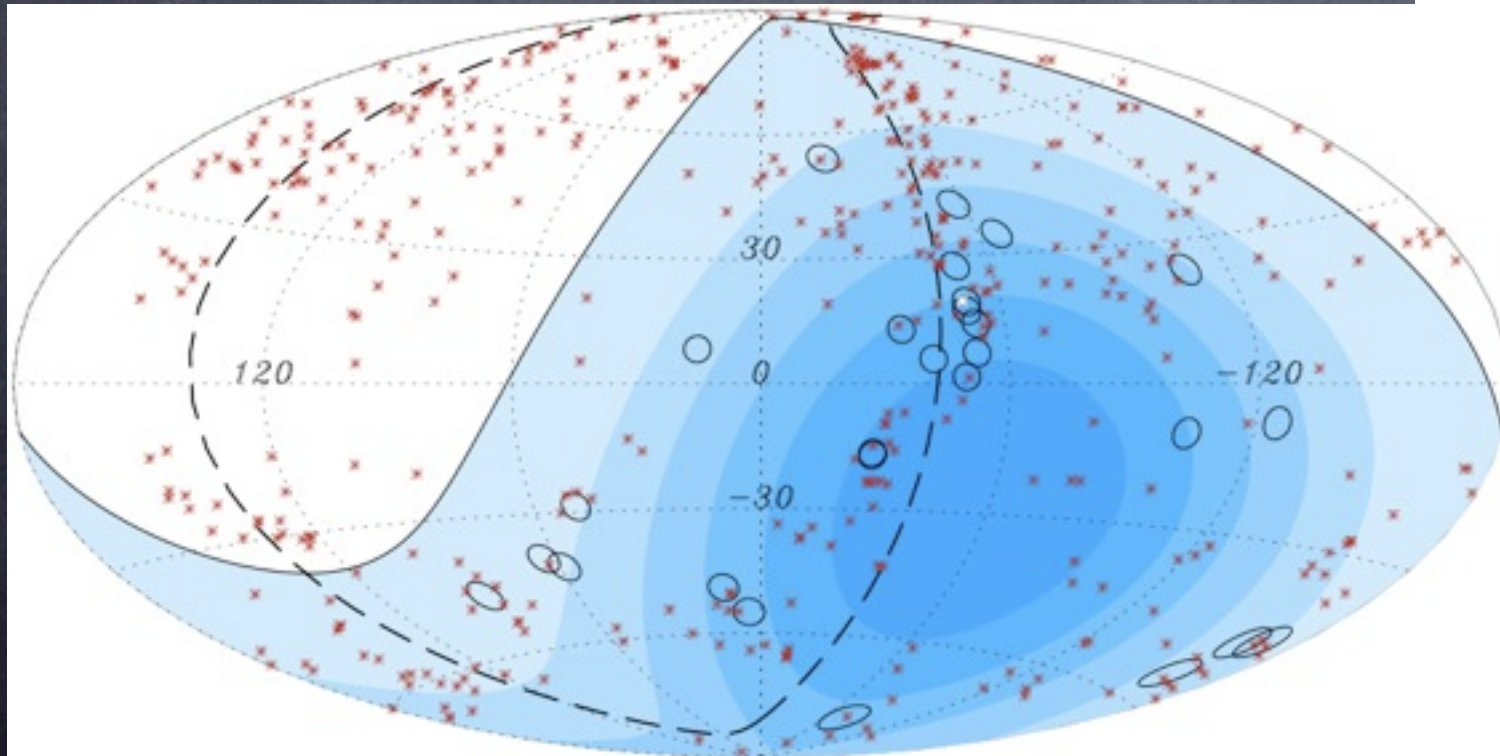
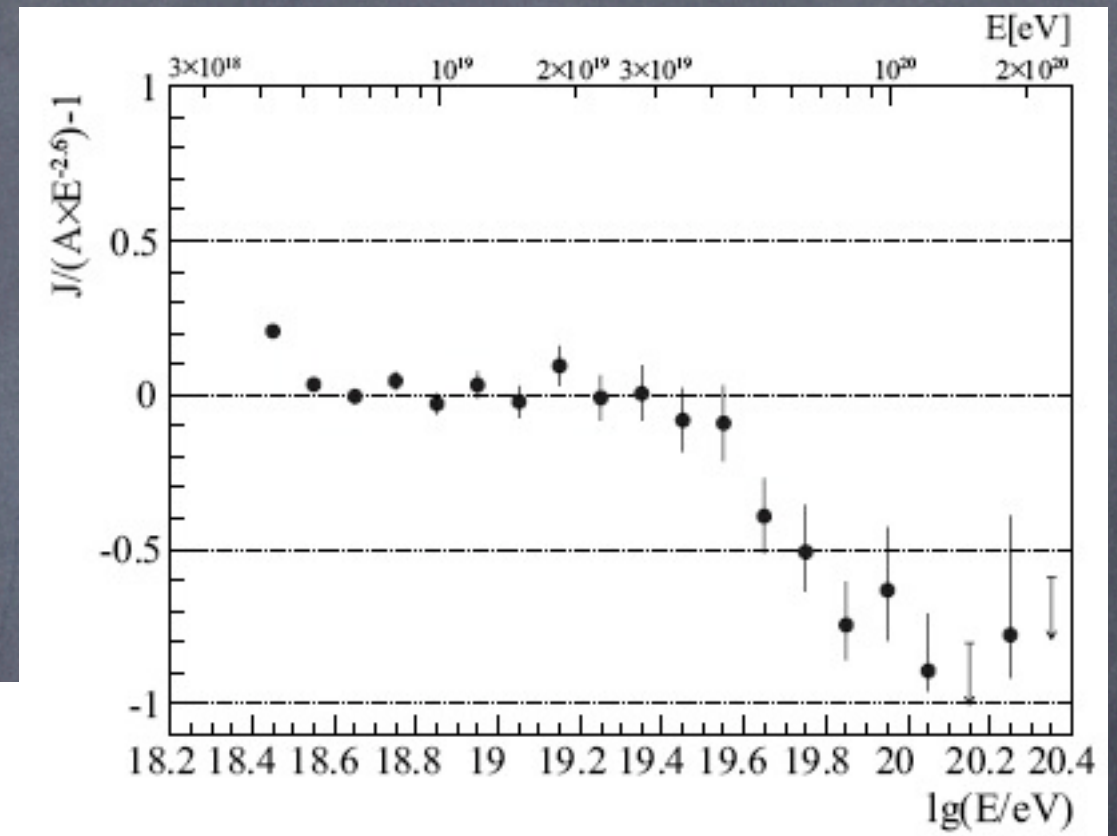
GZK feature: found!

Early claim by HiRes

Abbasi R. *et al* (HiRes Collaboration), 2007 Preprint [astro-ph/0703099](https://arxiv.org/abs/astro-ph/0703099)

Confirmed by AUGER data

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



Best correlation parameters:
 $z_{\text{max}} \sim 0.017$ ($D_{\text{max}} \sim 71 \text{ Mpc}$)
 $E > 57 \text{ EeV}$
 $\psi = 3.2^\circ$ (aperture angle)

Astrophysical constraints: time of flight

Constraint on the photon LIV coefficient ξ by using the fact that different colors will travel at different speeds.

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

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

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GRB: Coburn et al. using GRB021206

use only sharp pulse from 10 MeV to 17 MeV over 15 msec, obtained $|\xi| < 55$ ($z \approx 0.3$).

However uncertainty on determination of z .

Best constraint up to date from single source is MAGIC Coll+Ellis et al. (2007)

using AGN, Markarian 501 flares, $z \approx 0.034$, $|\xi| < 47$,
but possible best fit with $|\xi| \approx O(1)!!!$...

Also HESS has also observed at another Mrk flares (PKS 2155, $z = 0.116$ i.e. more far away than Mrk 501)
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Problem: there is strong evidence that most GRB and AGN are not “good” objects for TOF constraints because of intrinsic time lags (different energies emitted at different times) not well understood.

Robust limits can be claimed only by a careful statistical analysis on large sample of sources:
delay-redshift correlation

Ellis et al., astro-ph/0510172: Conservative limit $|\xi| < 10^3$

An open problem: is small LV
natural?

[Collins et al. PRL93 (2004)]

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Low energy, dim 3,4 operators are tightly constrained: $O(10^{-46}), O(10^{-27})$ while we would expect them $O(1)$.
Then attention focused on dim 5 and higher,
non-renormalizable operators

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Then attention focused on dim 5 and higher, **non-renormalizable operators**

However, in this case **radiative (loop) corrections** involving integrals up to the natural cutoff M will generate the terms associated to low energy operators which are unacceptable observationally if
 $\eta^{(NR)} \approx O(1)$.

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To make low energy LV small seems hard...

This need not be the case if a custodial symmetry or other mechanism protects the low energy operators from violations of Lorentz symmetry.

E.g. **SUSY** protects **dim<5** operators

BUT dim 5 theory not viable: SUSY breaking leads to not enough suppressed dim 3 operators

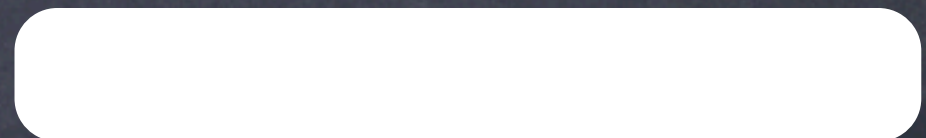
However **CPT+SUSY** push allowed operators to dim 6... when SUSY broken
 $\eta^{(2)} \approx O(E_{\text{SUSY}}/M)^2$ (LHC?)

E.g. gr-qc/0402028 (Myers-Pospelov) or hep-ph/0404271 (Nibbelink-Pospelov)
or gr-qc/0504019 (Jain-Ralston)...

LV model for the Crab Nebula

LM, Liberati, Celotti, Kirk, JCAP 10 (2007), 13

Emitters spectrum: *1st order Fermi mechanism.*



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Since it is essentially a kinematic mechanism, we can safely deduce the power-law spectrum to be in γ rather than in energy (see paper for further discussion). The presence of an intrinsic maximal energy that can be produced by this mechanism is implemented via an exponential cutoff

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Effect of the Helicity Decay:

- The helicity decay has no threshold.
- This has to compete with the **spin-rotation** (which mixes helicities) induced by the magnetic field. This reaction conserves the electron energy and does not interfere with the HD.

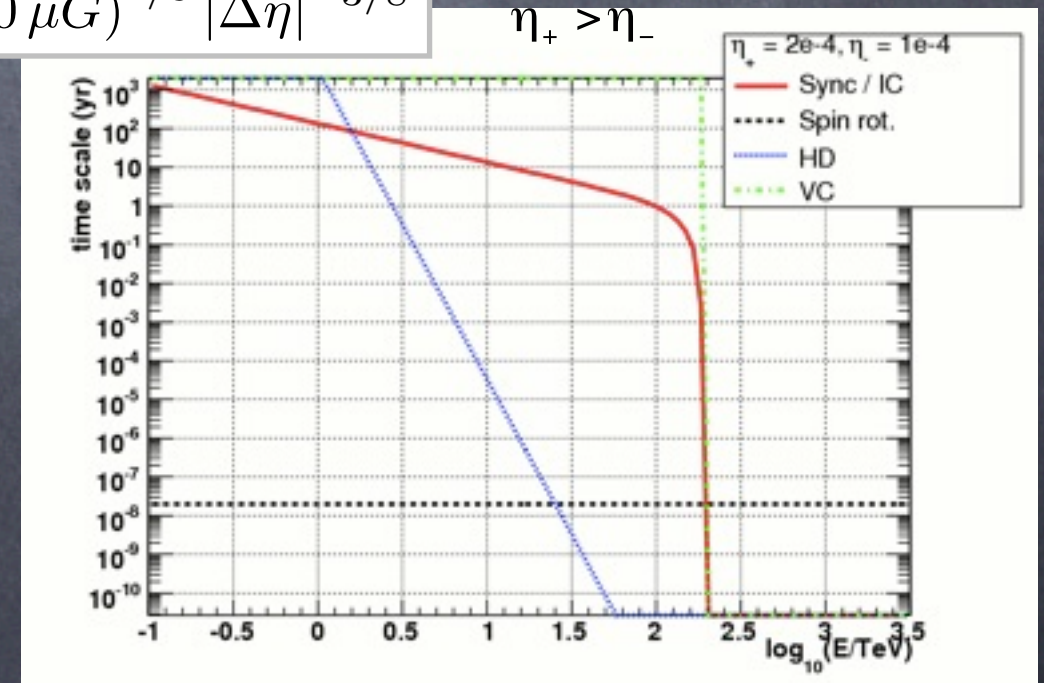
- The helicity decay becomes effective when $p_{\text{HD}}^{(\text{eff})} \geq 930 \text{ GeV} (B/300 \mu\text{G})^{1/8} |\Delta\eta|^{-3/8}$

$$\eta_+ > \eta_-$$

Populations:

charge	low energy ($E < \text{few TeV}$)	high energy ($E > 10 \text{ TeV}$)	
e_+^-	1/4	0	↻
e_-^-	1/4	1/2	
e_+^+	1/4	0	↻
e_-^+	1/4	1/2	

"helicity" state



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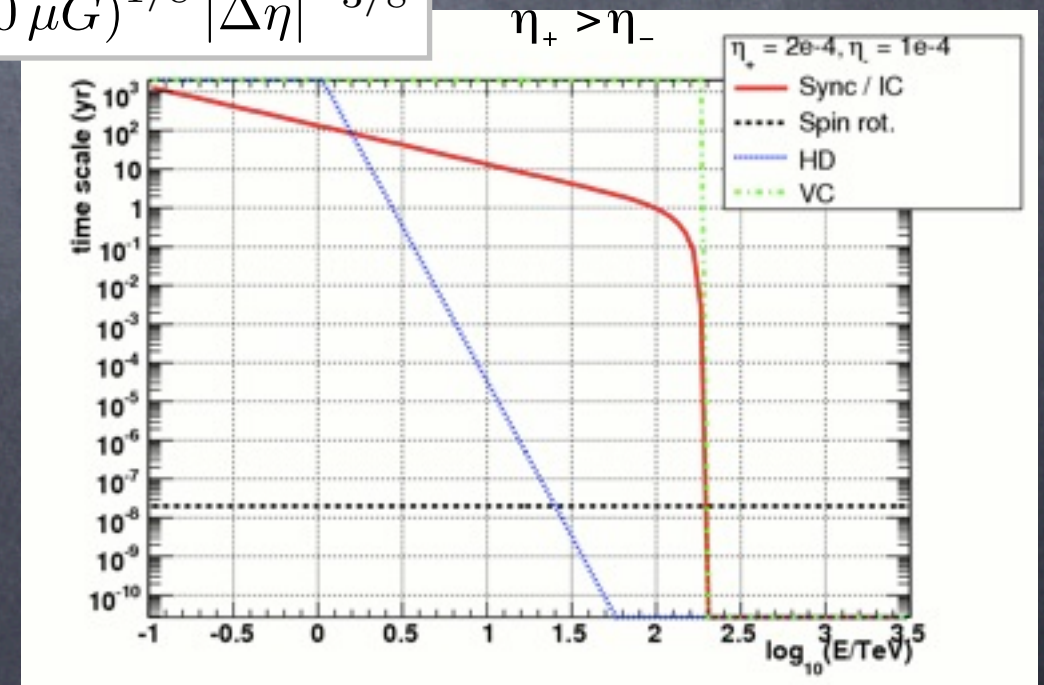
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"helicity" state



High energy cut-off: set by Vacuum Cherenkov

$$E_{\text{VC}} = \left(m^2 M / 2\eta \right)^{1/3} \approx 10 \text{ TeV} \eta^{-1/3}$$