Title: Quantum Gravity Phenomenology with Neutrinos and High Energy Photons

Date: Jul 22, 2013 11:00 AM

URL: http://pirsa.org/13070037

Abstract: <span>I review the main properties of the Gamma Ray Bursts (GRBs) as possible sources of high energy (E>TeV) neutrinos and confirmed sources of high energy (E>GeV) photons.<br>I discuss the possibility to use the data of neutrino telescopes, such as IceCube and the GeV-photon telescopes, such as Fermiâ€™s LAT, for precision tests of Einstein's Special Relativity as applied to neutrinos and photons. My focus is on possible departures from Special Relativity that can be motivated by models of quantum space-time. I observe that neutrinos which one would not associate to a GRB, when assuming a classical spacetime picture, may well be GRB neutrinos if the possibility that Lorentz invariance is broken at very high energies is taken into account. I outline how future analyses of neutrino data should be done in order to systematically test the Lorentz Invariance Violation possibility. In addition I consider the possibility that Lorentz Invariance Violation might be responsible for the spectral lags that characterize the GeV signal observed for the remarkable GRB130427A. <br>A comparison of these features for GRBs at different redshifts provides<br>some encouragement for a redshift dependence of the effects of the type expected for a quantum-spacetime interpretation, but other aspects of the analysis appear to invite the interpretation as intrinsic properties of GRBs.</span>

המכללה האקדמית להנדסה
אורט בראודה
ORT BRAUDE COLLEGE

# Lorentz Invariance Violation Phenomenology with Neutrinos and GeV photons

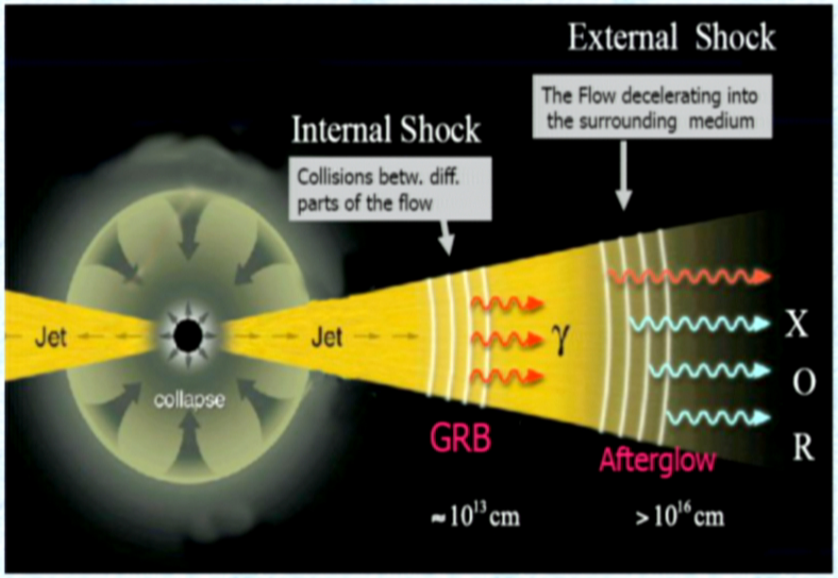
Dafne Guetta

# Outline of the Talk:

- What are GRBs
- Neutrino flux from GRBs in the fireball model
- Lorentz Invariance Violation (LIV) test with neutrinos
- LIV in the GeV signal of GRB 130427A
- Conclusions

# GRB Theoretical Framework:

- **Progenitors**:
  - Long: massive stars
  - Short: binary merger?
- **Acceleration**: fireball (electron, positron hadron? plasma or magnetic?)
- **Prompt γ-rays**: internal shocks? magnetic plasma?



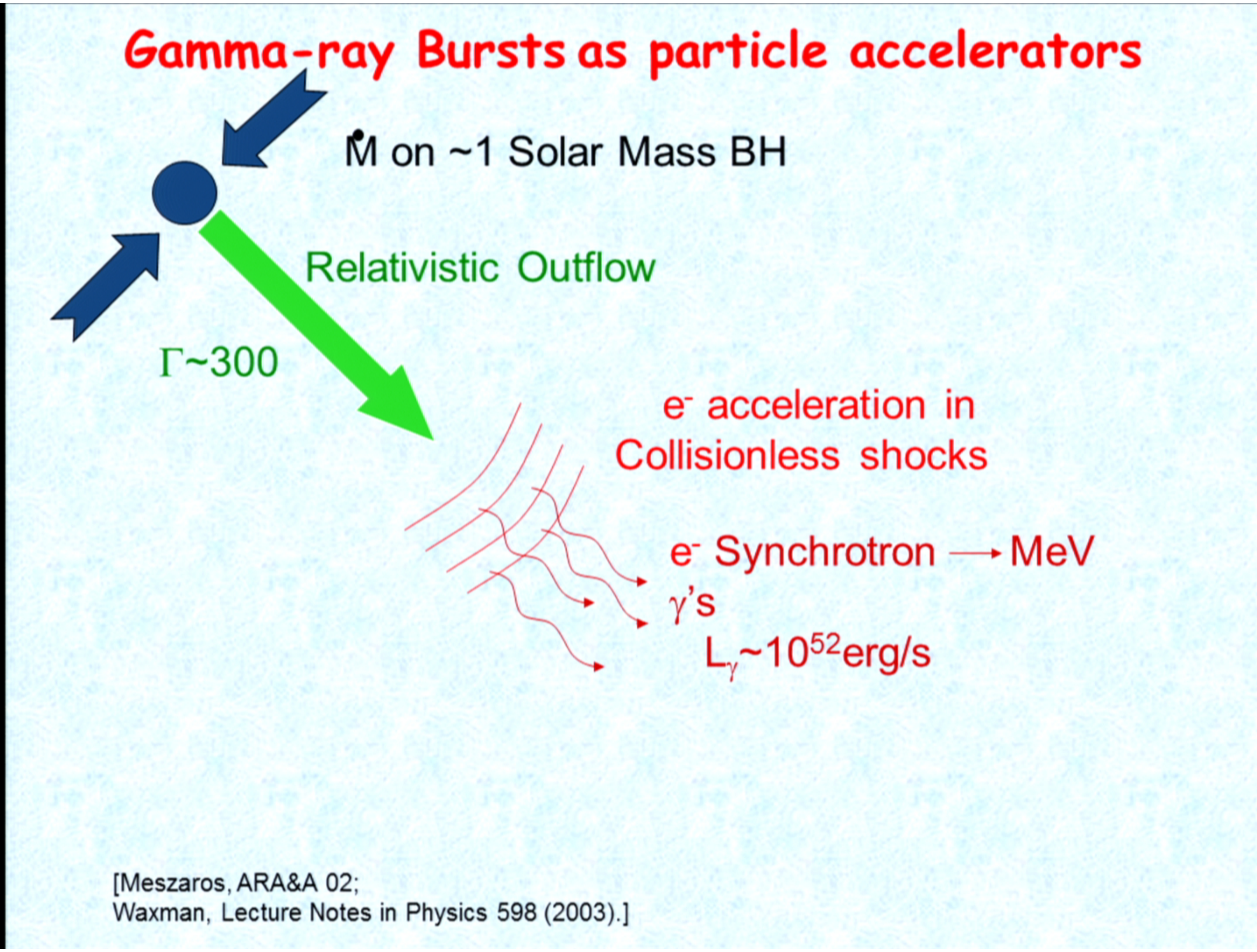

- **Deceleration**: the outflow decelerates as it sweeps-up the external medium
- **Afterglow**: from the long lived **forward** shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray → optical → radio

# GRBs most luminous objects in the Universe!!

- Sun Luminosity $L_{\odot}$~4 X$10^{33}$ erg/s
- Supernova L~$10^{51}$ erg/s
- Galaxies with nuclei L~$10^{48}$ erg/s
- **GRB luminosity L~$10^{52}$ erg/s**

# Known facts and open questions in GRBs

- We know that GRBs are at cosmological distance:Typical observed z>1
- Are GRBs the sources of UHECR?
- What is the composition of the jet, there are hadrons in the jet?
- What is the mechanism responsible of the high energy emission detected in GRBs


Gamma-ray Bursts as particle accelerators
Ṁ on ~1 Solar Mass BH
Relativistic Outflow
Γ~300
e⁻ acceleration in
Collisionless shocks
e⁻ Synchrotron → MeV
γ's
Lγ~10^52 erg/s
[Meszaros, ARA&A 02;
Waxman, Lecture Notes in Physics 598 (2003).]

# High Energy ν from GRBs

**In the fireball (FB) dissipation region:**

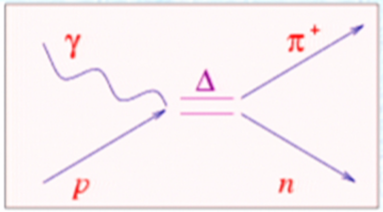
protons accelerated to ~ $10^{20}$eV

photo-meson interaction of HE p with the FB photons

**The main mechanism: photomeson interaction**

$$\gamma + p \rightarrow n + \pi^{+}\ ; \quad \pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \nu_{\mu} + \bar{\nu}_{\mu}$$

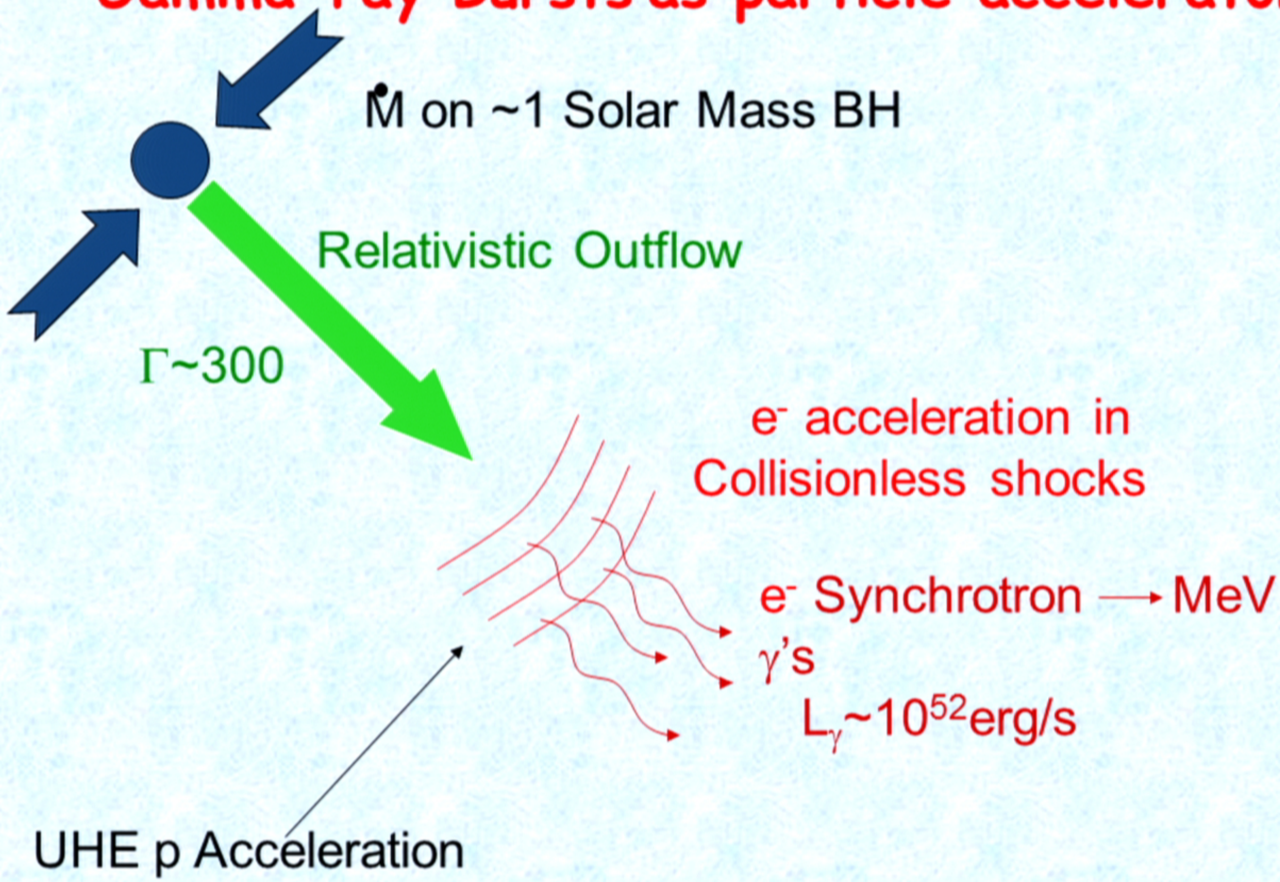
$$\left(\varepsilon_{p} / \Gamma\right)\left(\varepsilon_{\gamma} / \Gamma\right) \geq 0.3\ \mathrm{GeV}^{2}$$




[Waxman & Bahcall '97,'99, Guetta Spada & Waxman 2001]

In each collision: Eν ~ 0.05 $E_p$, Eγ~MeV, Ep ~ $10^{16}$eV therefore we expect ~ 100 TeV ν, coincident with GRBs

# Gamma-ray Bursts as particle accelerators

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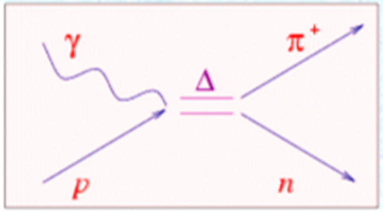


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## For a typical burst at z~1, E ~ $10^{53}$erg

Internal shocks ν: "effective" $f_\pi$~20% [Guetta Spada Waxman 2001]

$$\Rightarrow \quad \varepsilon^2 \Phi_\nu \approx 10^{-8} \frac{\text{GeV}}{\text{cm}^2\text{s sr}} \quad , \quad \varepsilon_\nu \geq 10^{14.5} \text{ eV}$$

$$J_{\nu \to \mu} \approx 20 / \text{km}^2\text{yr}$$

**Detection probability ~ 0.01 per burst in km-cube neutrino telescope** ⇒ Twenty 100 TeV events per yr correlated in **time** and direction with GRBs!

**In the collapsar:** Emission of ~ TeV ν from *p, photon* interactions occurring inside collapsar while the jet is burrowing its way out of the star [Meszaros & Waxman 2001,Schneider Guetta & Ferrara 2002]

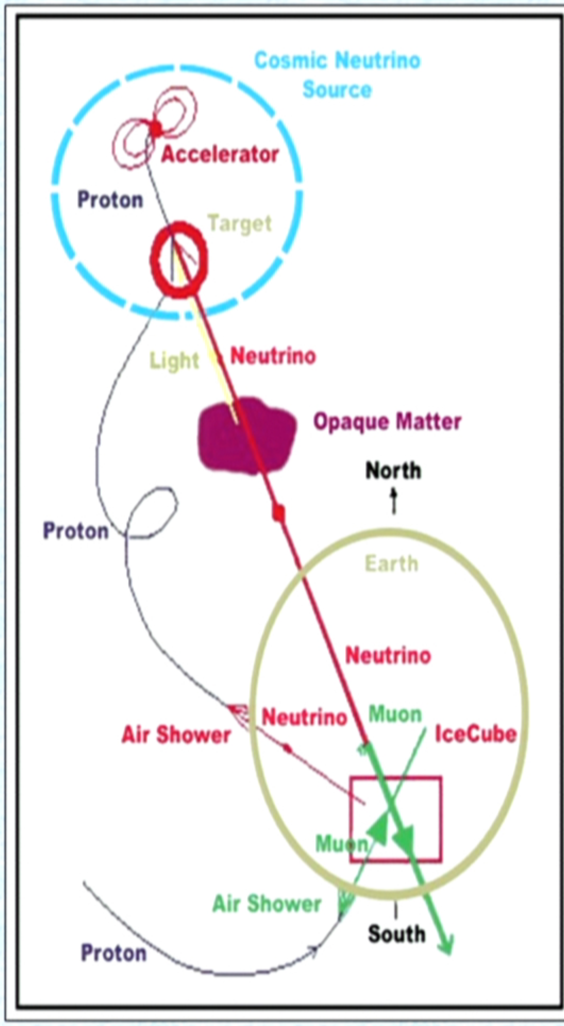
**<10 events expected anticipating the GRBs by few seconds**

# Why Neutrinos?

Neutrinos are ideal astrophysical messengers

- Travel in straight lines
- Very difficult to absorb

flight




IceCube Preliminary

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# Why neutrino is a "nice" particle

- Is neutral $\rightarrow$ trajectory not affected by magnetic fields (information on cosmic rays that are affected).
- Is stable $\rightarrow$ can reach us from cosmic distances (not like neutrons)
- Only weak interactions $\rightarrow$ can give us information on regions opaque to photons.
- Escape from deep within the sources Study the physics responsible for powering

# Astrophysical Implications of detecting neutrinos

**Help to resolve open questions in astrophysics:**

- **Baryonic component of the Jet: Composition of the jet is an open issue** $e^+e^-$ or $pe^-$ plasma? Still not clear
- What are the sources of UHECR

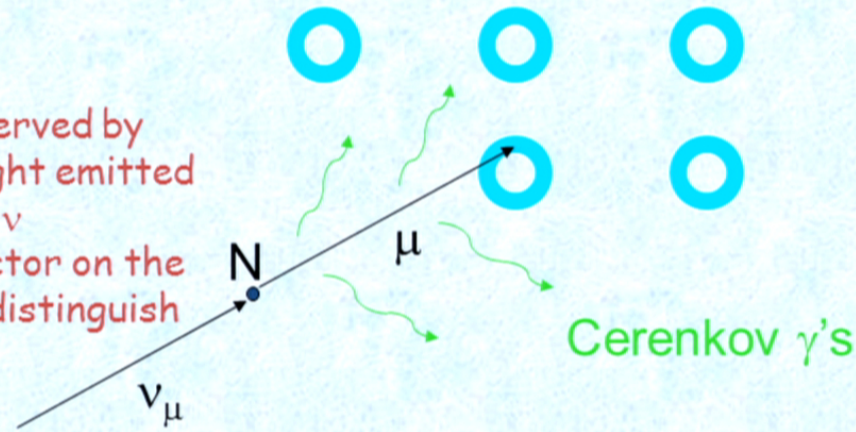
- But: Weak interaction Big detectors 10's of kilo-tons

Basic process: $\nu_\mu + N \rightarrow \mu + X$

The signals are upward $\mu$

# Detection

$\gamma$ detector




High energy $\mu$ may be observed by detecting the Cerenkov light emitted by HE muons produced by $\nu$ interactions below a detector on the surface of the Earth. To distinguish

From atmospheric muons

That come from above

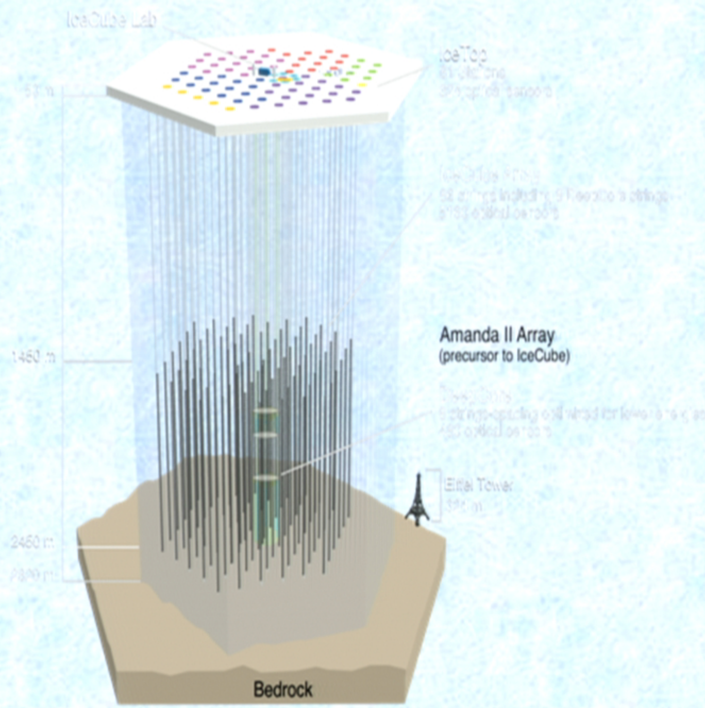
$\lambda_\mu > 1$ km for $\varepsilon_\mu > 0.3$ TeV

1km$^3$ feasible for transparent medium

# The IceCube Neutrino Observatory

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)

- 5160 PMTs
- 1 $km^3$ volume
- 86 strings
- 17 m PMT-PMT spacing per string
- 125 m string spacing
- Completed2010

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IceCube Preliminary

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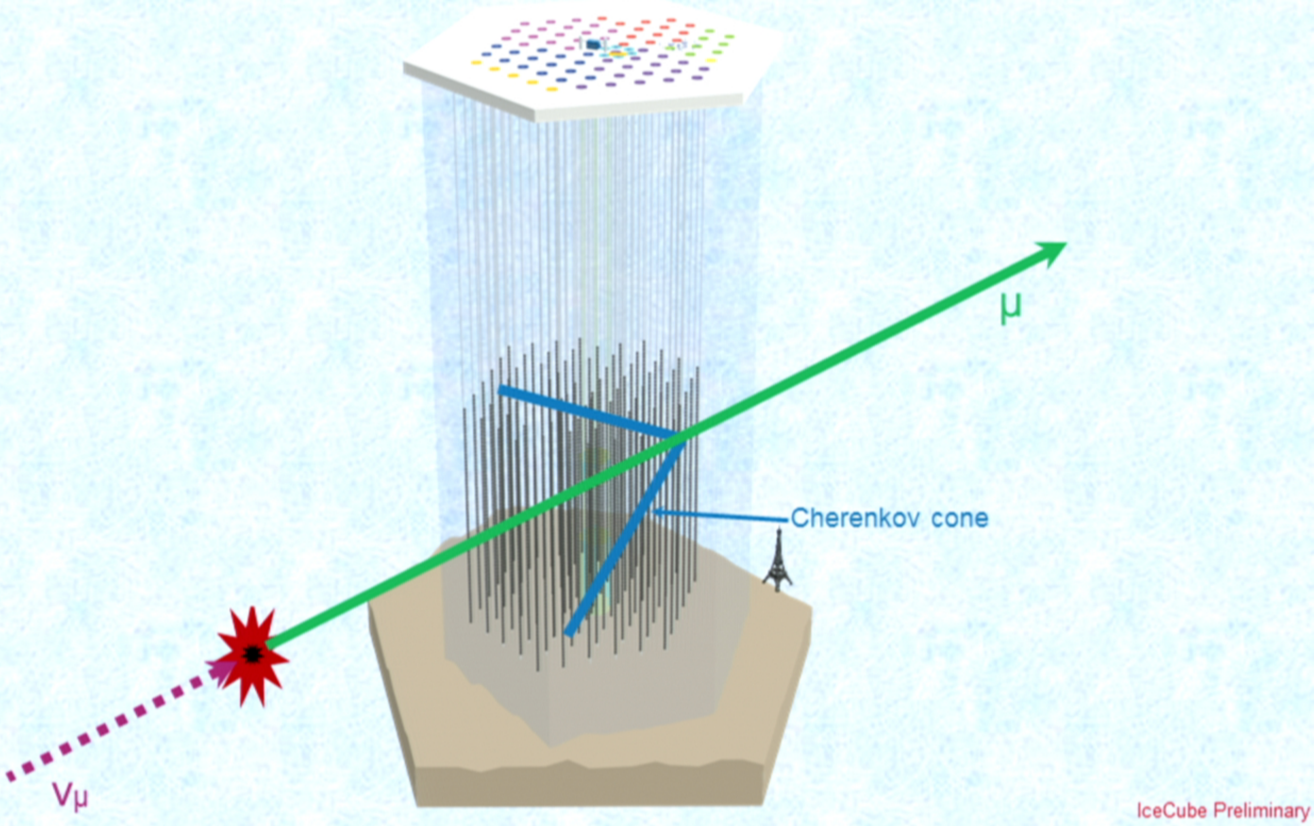


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# Results from IceCube: **No signal from GRBs!!!**

Abbasi et al, Nature 2012

- fireball model challanged by Icecube?
- No! Maybe $f_\pi$ (the fraction of energy that goes to pions) is smaller (Hummer et al. 2012) **If effects of particle physics are taken into account**
- No maybe the window time of IceCube is too short as neutrinos may arrive later or before the GRB signal if the Lorentz Invariance is Violated.

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# Constraints on Quantum Gravity Models

- Some Quantum Gravity models allows Lorentz symmetry violation (LV) (e.g., *Amelino-Camelia et al. 2001, Ellis et al. 2003; 2008*)
  - ➔ Speed of light becomes energy dependent $V_{ph}(E_{ph}) \neq c$
  - ➔ Time dispersion between low and high energy photons coming from the same source

Parametrized through a Taylor expansion of the LV terms In the dispersion relation

Photon dispersion relation

$$E^2 = k^2\left[1 + \xi_1 \frac{E}{M_{QG}} + \xi_2 \frac{E^2}{M_{QG}^2} + \dots\right]$$

QG mass scale

Photon propagation speed given by Photon group velocity

$$c_{LV}(E) \approx c\left[1 - \xi_1 \frac{E}{M_{QG}} - \xi_2 \frac{E^2}{M_{QG}^2}\right]$$

$\xi_1, \xi_2 \approx \pm 1$ expansion coefficients

$M_{QG} \sim M_{Pl} = 1.2\text{x}10^{19}$ GeV

Time dispersion over cosmological distance ➔

$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{QG,n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz'$$

**Light Travel Time (LTT) effect**

The most natural scale for LV is the Plank scale where quantum effects on the structure of space time are expected to be strong

$$l_{Planck} = (hG/c^3)^{1/2} \approx 1.62 \times 10^{-33}\ \text{cm or } E_{Planck} \cong M_{Planck}c^2 \cong 1.22 \times 10^{19}\ \text{GeV}$$

# LIV implications

Amelino Camelia + Guetta + Piran

arXiv.org > astro-ph > arXiv:1303.1826

If there is in-vacuo dispersion what you actually expect is to never have conclusive GRB-neutrino detections!!

you cannot expect the GRB-neutrino signal to coincide temporally
with the trigger of the (lower-energy) GRB-gamma-ray signal!!

Jacob+Piran, NaturePhys3 (2007) 87
GAC+Smolin, PhysRevD80 (2009) 084017

it will look like we have only background neutrinos
but with a "funny" temporal distribution with respect to the GRB triggers

especially if we tightly select using directional criteria

# LIV predictions

- High energy neutrinos may arrive at different time from the GRB with a time delay given by

$$t_{LIV} \propto -s_{\pm} \frac{E}{M_{LIV}} \frac{D(z)}{c}$$

Jacob & Piran (2008)

E is the neutrino energy and $s_{\pm} = \pm 1$

$$D(z) = \int_0^z dz' \frac{c}{H_0} \frac{(1+z')}{\sqrt{\Omega_\Lambda + (1+z')^3 \Omega_m}}$$

**Eq. 1**

The parameter s and $M_{LIV}$ determined experimentally, $M_{LIV}$ Should be close to the Plank scale constraint from GRBs $M_{LIV} > 0.1\text{-}1\ M_{Plank}$

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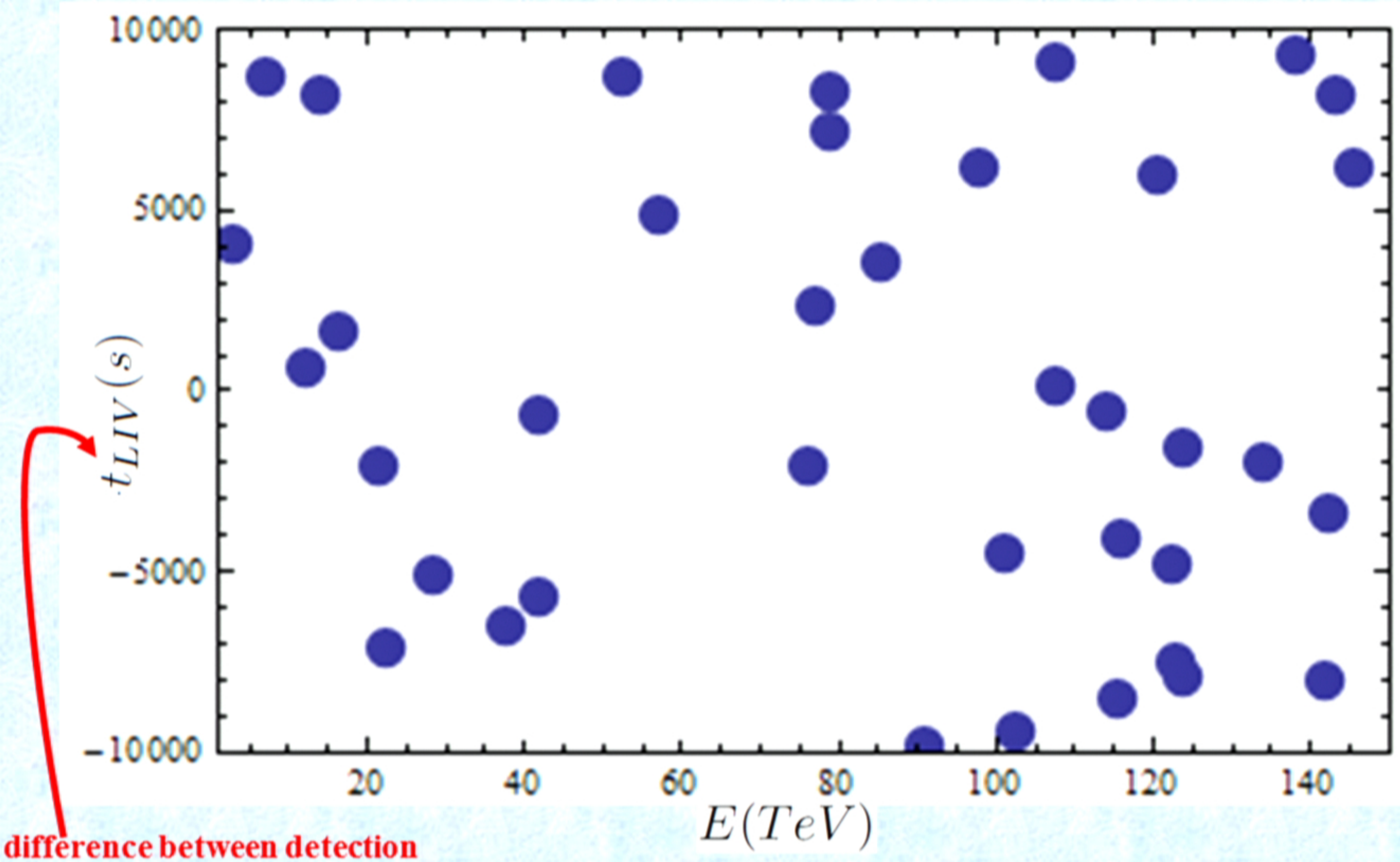
**Simulation: random GRB-neutrino-candidate events, if pure background**

[N.B.: in the simulations I assume for simplicity that all GRB candidates are at the same redshift]

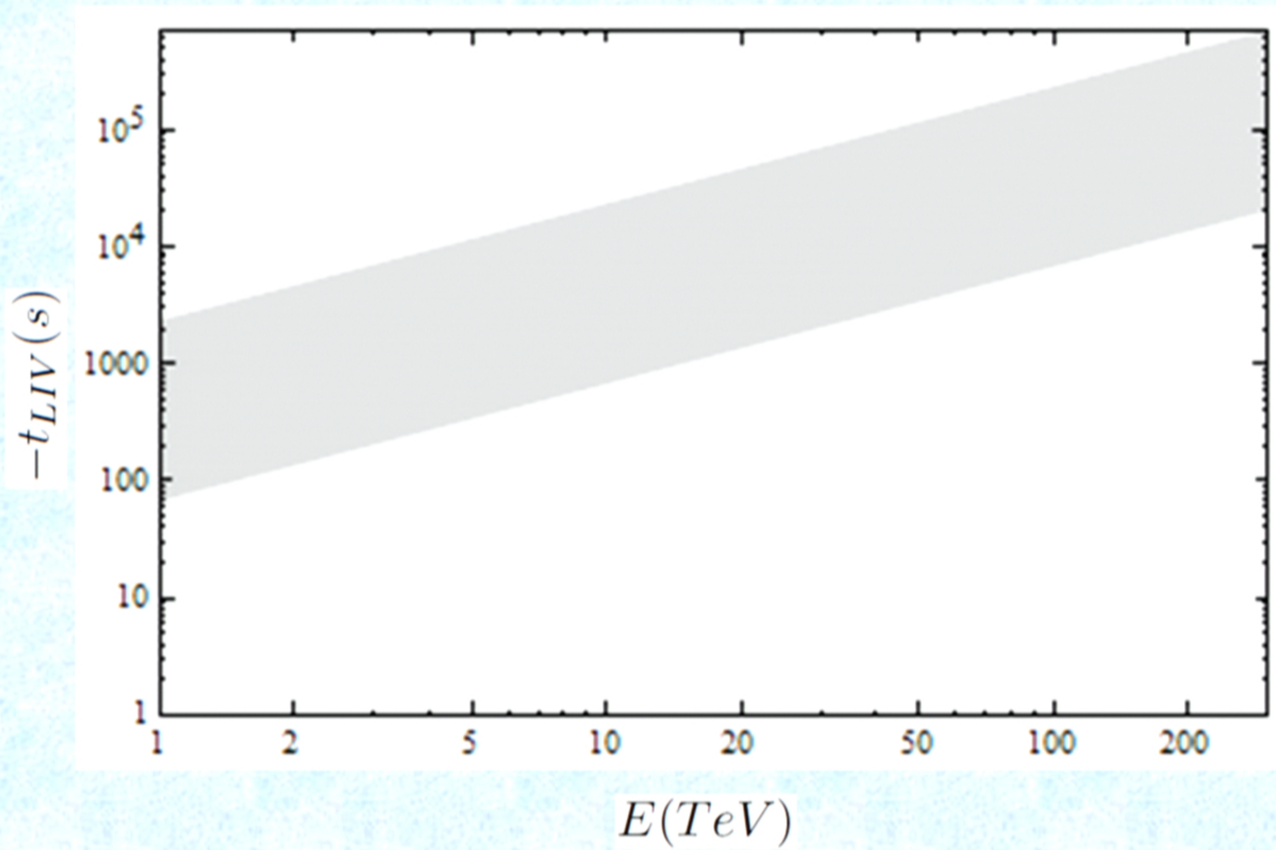



**difference between detection time for the neutrino and trigger of the candidate GRB source**

# LIV effects on neutrinos

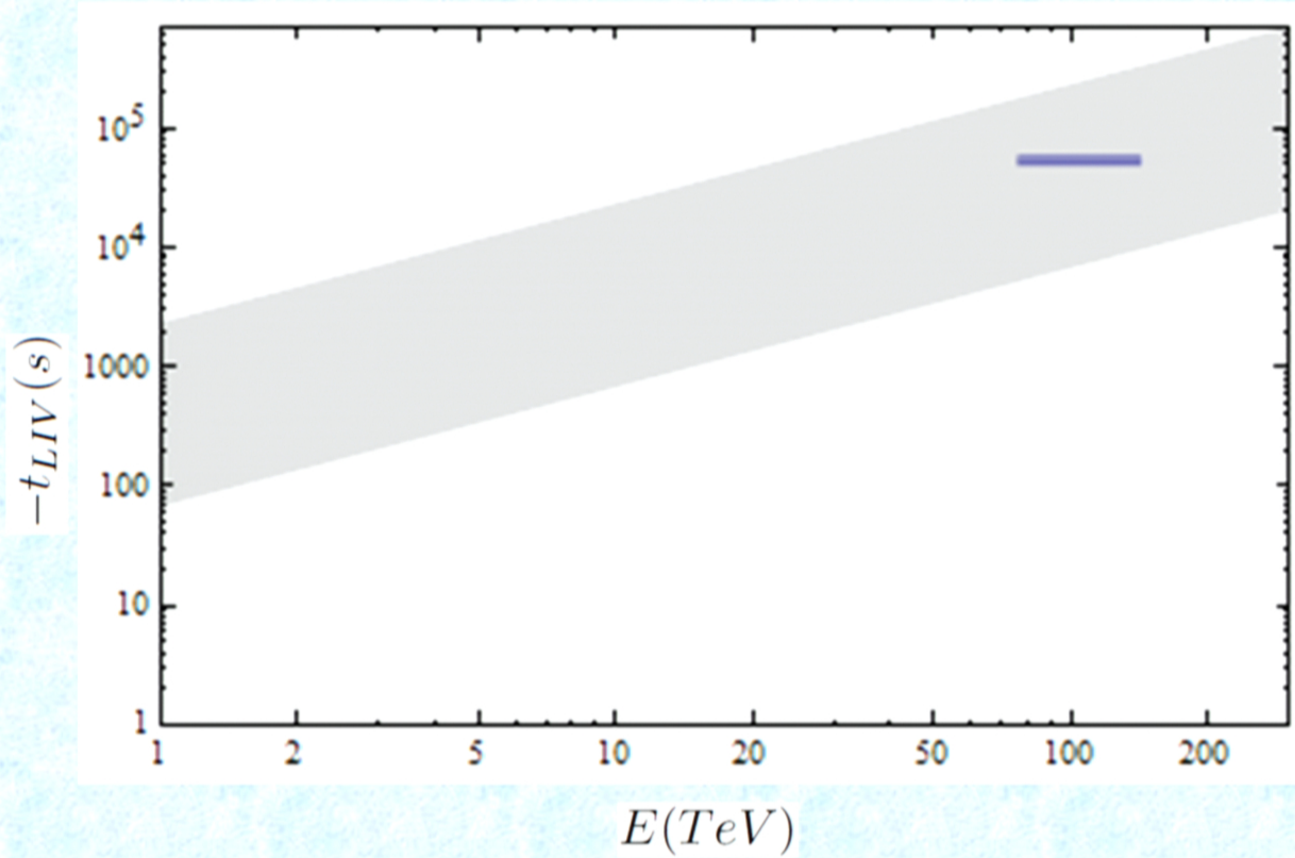
Let us now prepare for looking at real data. We assume $M_{LIV}$=0.1 $M_{Planck}$ and a fixed sign of the in-vacuo dispersion (and s=1) so we look only at one sign of $t_{LIV}$

[N.B.: with real data the redshift of GRB candidates will often not be known]

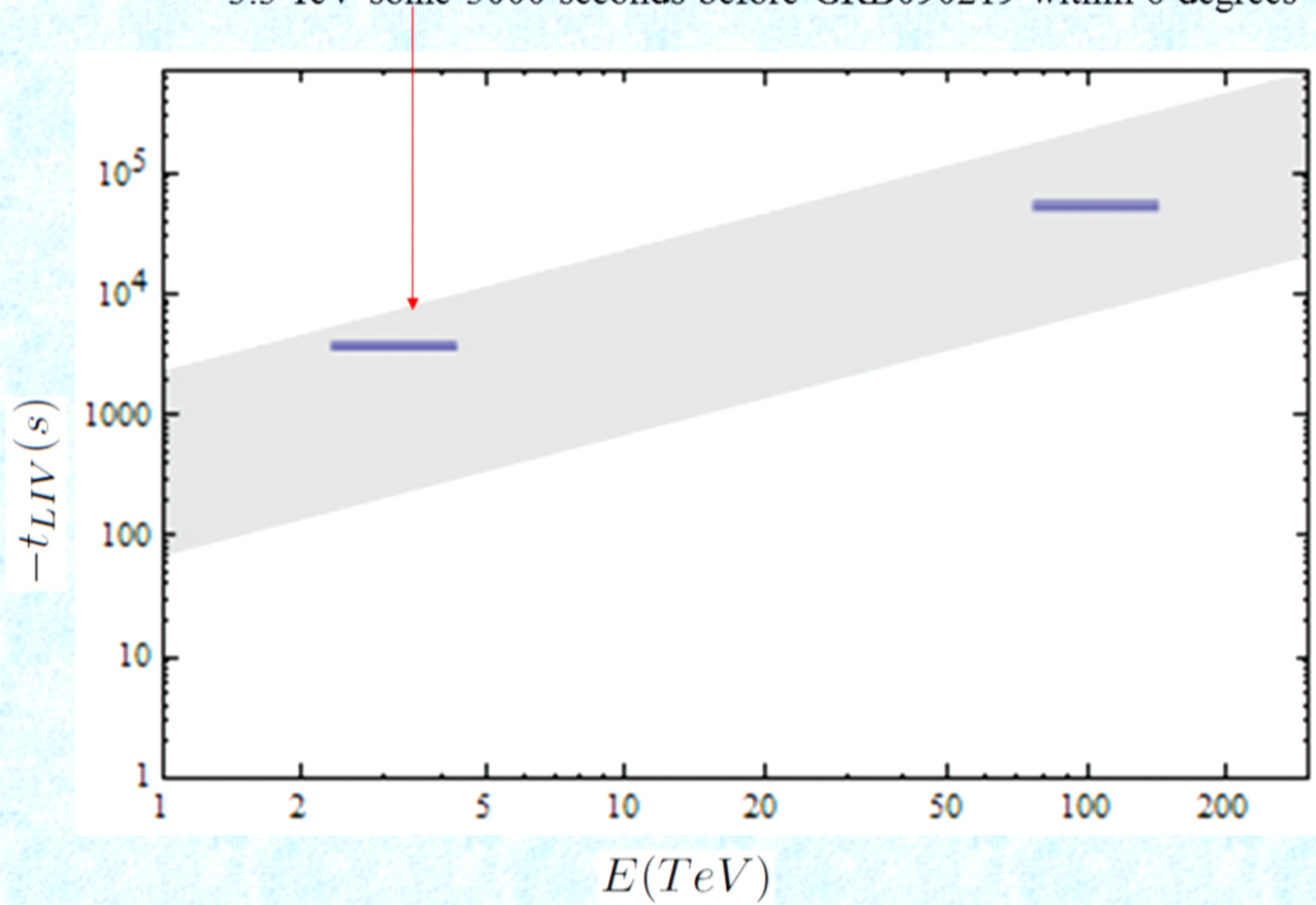


109 TeV some 14 hours before GRB091230A within 0.2 degrees

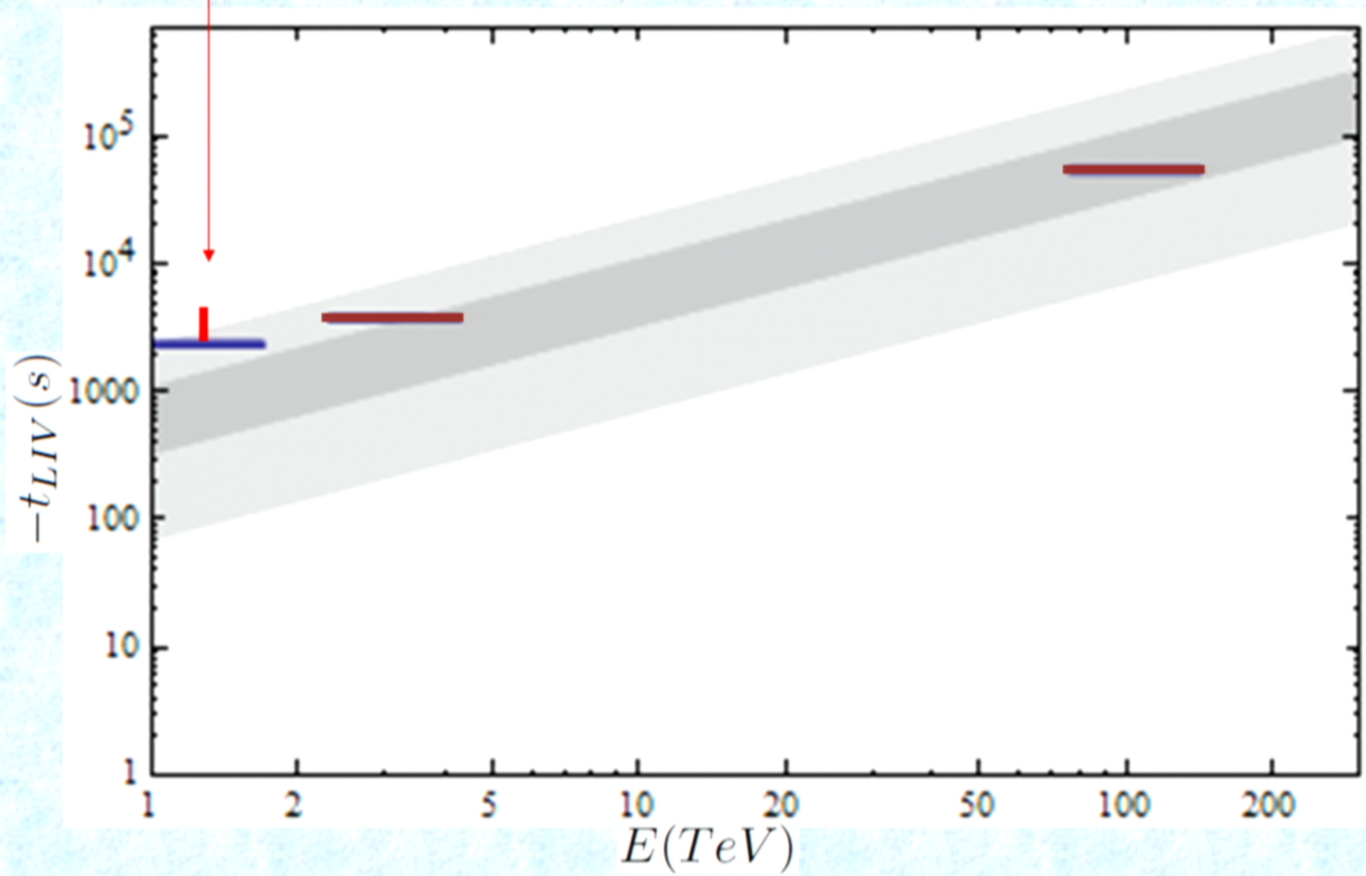
[appears amazing without look-elsewhere, still noteworthy when factoring in look-elsewhere effect]



3.3 TeV some 3000 seconds before GRB090219 within 6 degrees



1.3 TeV some 2000 seconds before the ultralong GRB090417B within 2 degrees



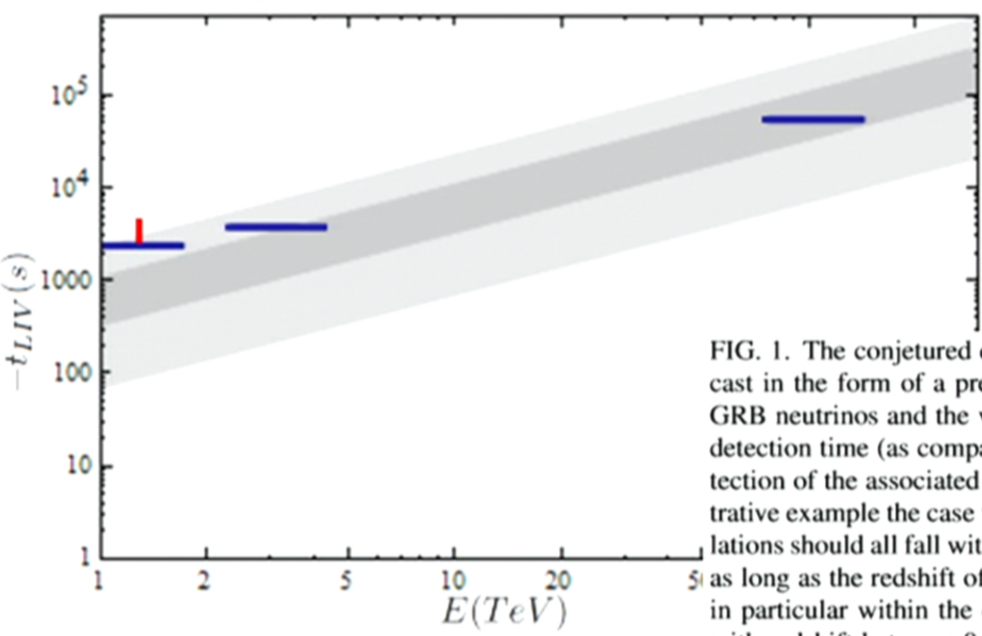
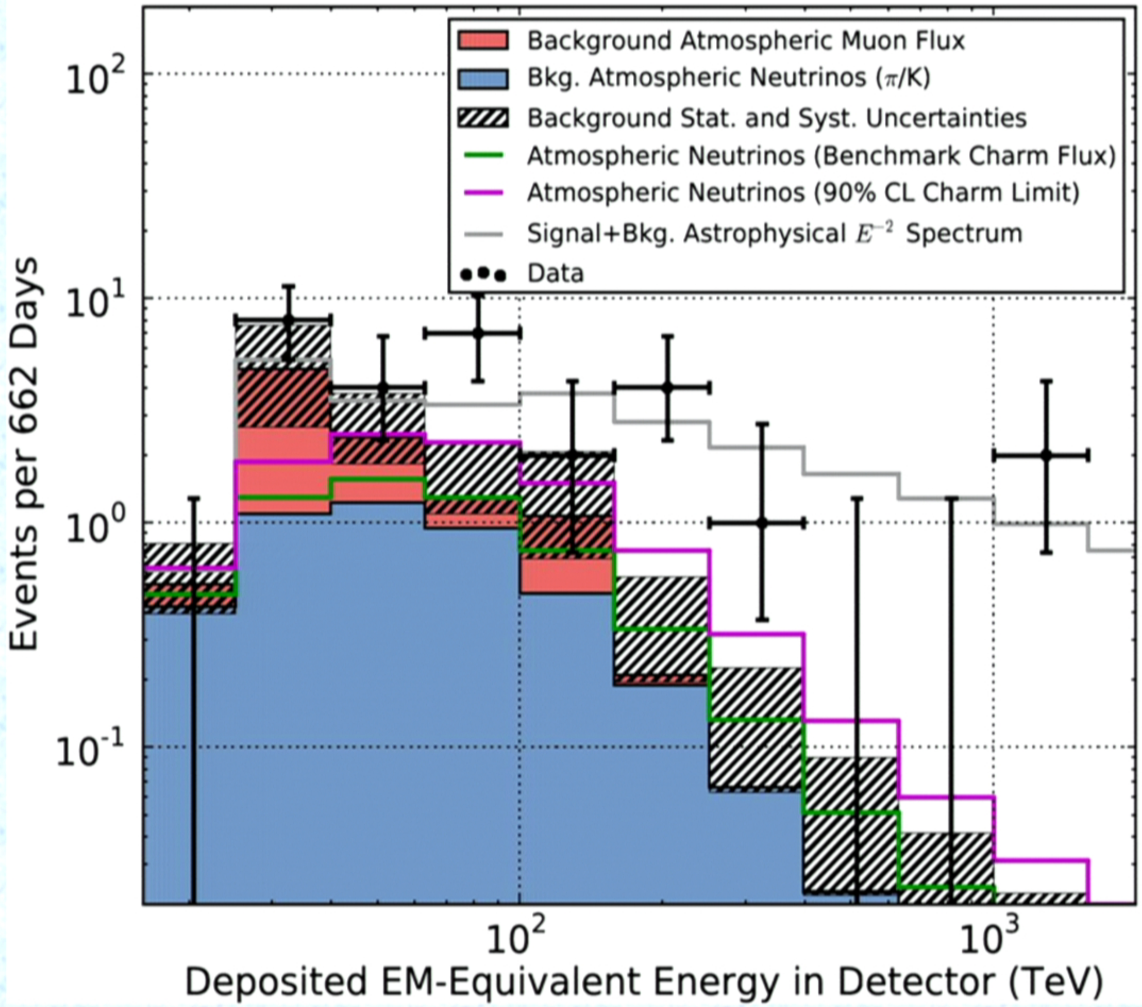



FIG. 1. The conjetured quantum-spacetime effects of Eq.(1) can be cast in the form of a prediction for correlations between energy of GRB neutrinos and the value of $t_{LIV}$ that can be inferred from their detection time (as compared to the trigger in gamma rays of the detection of the associated GRB). According to (1), assuming as illustrative example the case with $s_{\pm} = 1$ and $M_{LIV} = 0.1 M_P$, such correlations should all fall within the shaded region for all GRB neutrinos, as long as the redshift of the GRB source is between 0.2 and 8 (and in particular within the darker part of the shaded region for GRBs with redshift between 0.9 and 3). The 3 IceCube events are shown with the horizontal segments reflecting a 30% uncertainty in their energy. The vertical red segment reflects our estimate of $\Delta t_{GRB}$, which is appreciable for the lowest-energy event, tentatively associated to an unusually long burst.

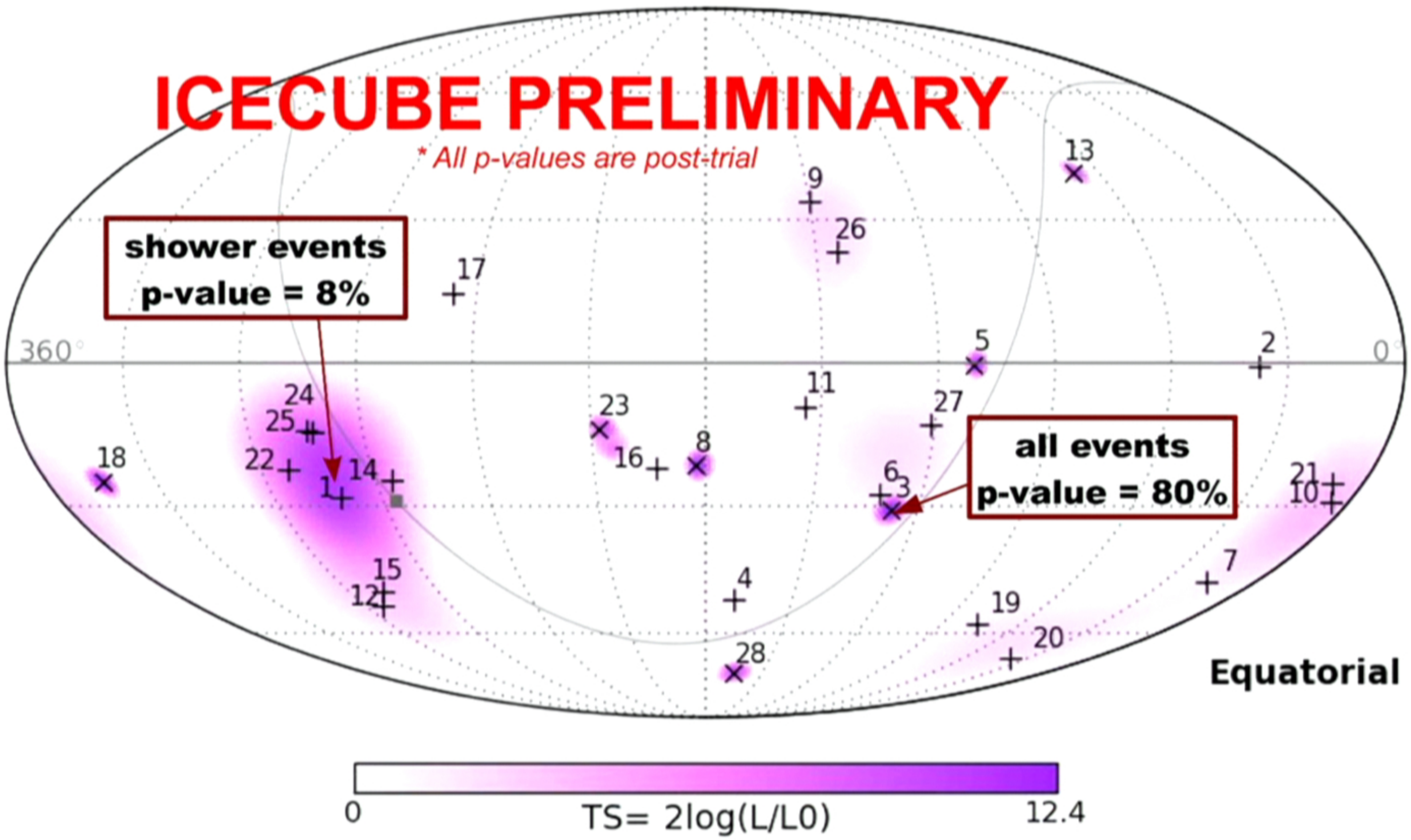
The slope that fits these events seems to imply $M_{LIV}$~$M_{plank}$/25 which which is consistent with what found by Amelino Camelia and Smolin (2009) from the Fermi results on GRB080916C. Here we have advanced effects while the Fermi results on delayed effects imply $M_{LIV}$>$M_{plank:}$ stronger bounds on the delayed effects.

**LIV effect different between photons and neutrinos?**

- Harder than atmospheric ν



Skymap no significant clustering



# New Results From IceCube

26 more events in the 2 years of IceCube data (2010/2011 season: "IC79"&"IC86")

- 28 events observed!
- Check possible angular correlation with GRBs open the window time. For a given data set that will include neutrino candidates from GRBs with and without redshift one should then estimate the probability of association of neutrinos to GRBs according to the standard old prior (simultaneity in time) but also using this new one (delay time between photons and neutrinos). In principle a significant fit with this new prior could point towards Lorentz invariance violation and enable us to estimate $M_{LIV}$ . The analysis is not easy as it will need long computing time BUT EXITING results will be available SOON!!!

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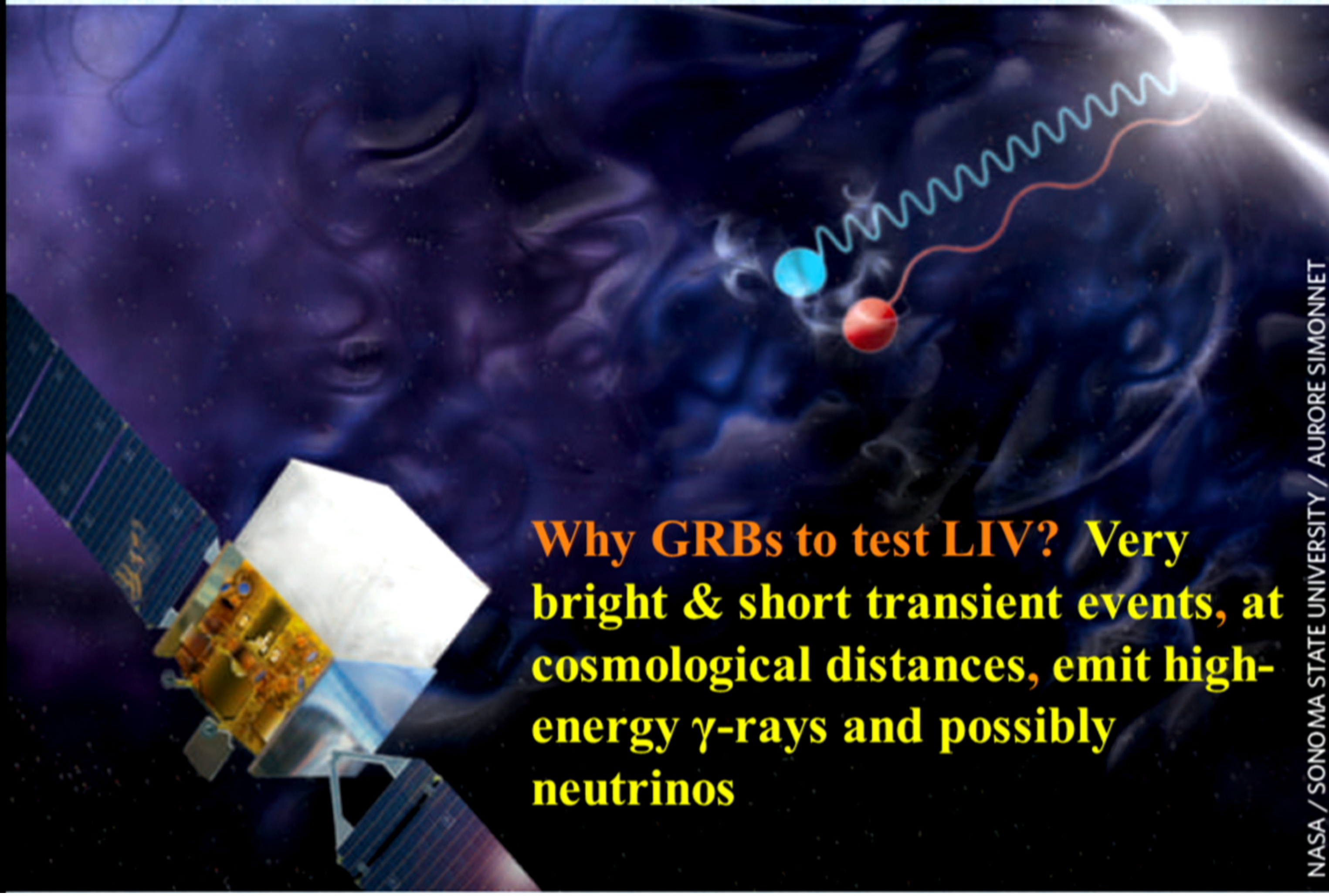
IceCube Preliminary

# Constraining LIV Using GeV from GRBs

(first suggested by Amelino-Camelia et al. 1998)



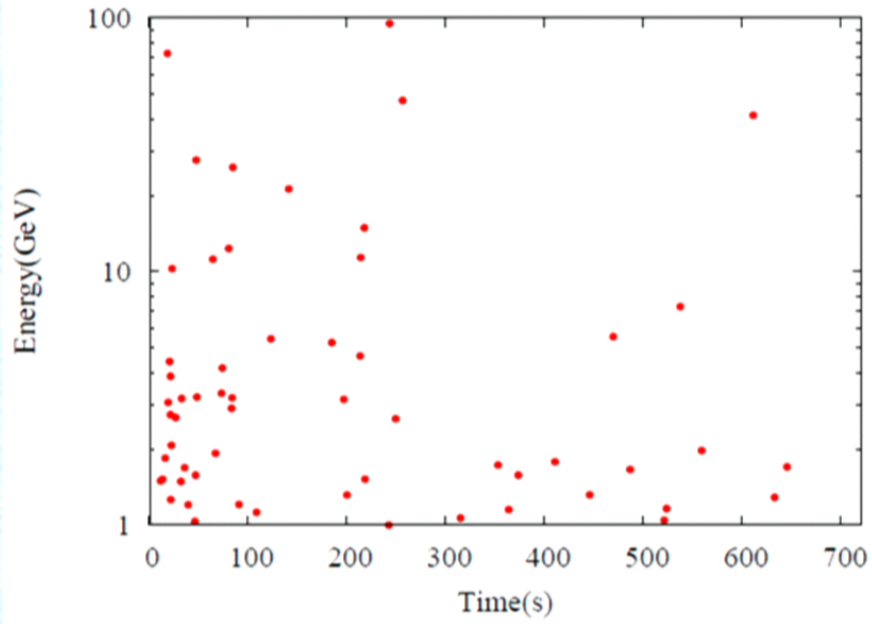

**Why GRBs to test LIV? Very bright & short transient events, at cosmological distances, emit high-energy γ-rays and possibly neutrinos**

# Quantum-spacetime scenarios and soft spectral lags of the remarkable GRB130427A

Amelino Camelia+ Fiore + Guetta + Puccetti

arXiv.org > astro-ph > arXiv:1305.2626

**the remarkable GRB130427A, seen above 1 GeV:**




Detection time (after subtraction of a conventional trigger time) and the energy detection of each event above 1 GeV

## Quantum-spacetime scenarios and soft spectral lags of the remarkable GRB130427A

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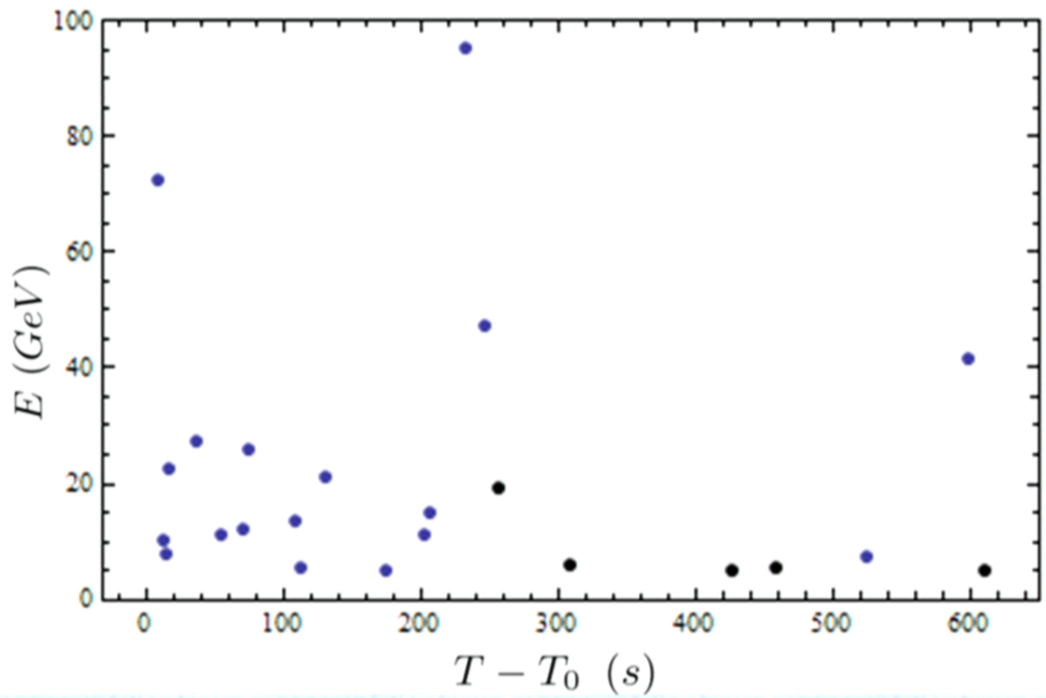
the remarkable GRB130427A, seen above 5 GeV:



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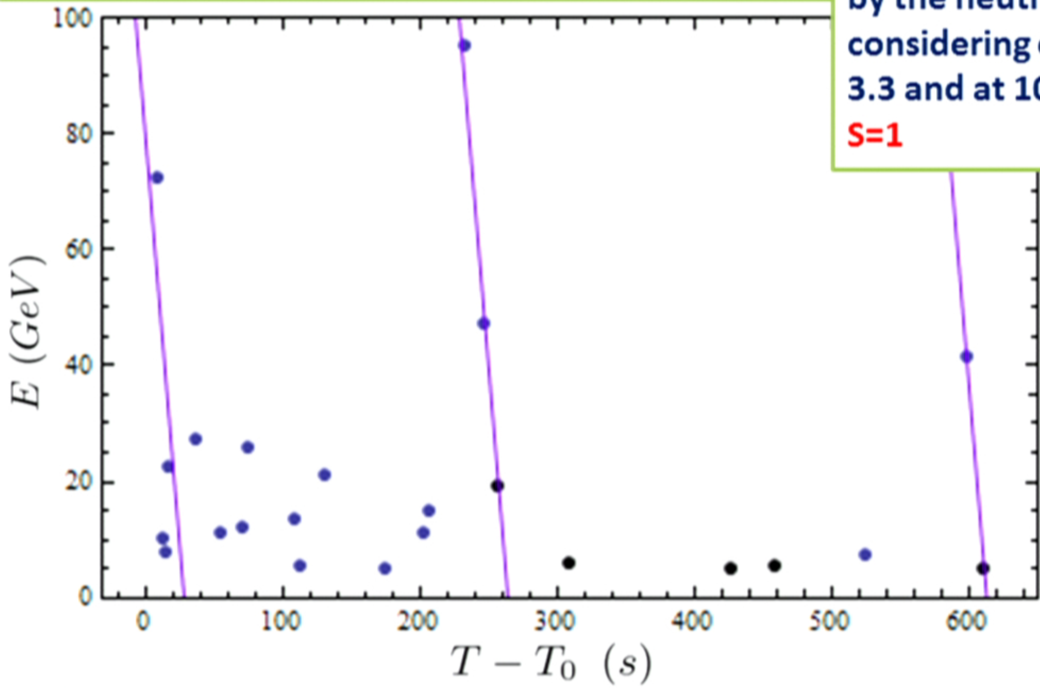
## Evidence of spectral lags

the remarkable GRB130427A, seen above 5 GeV:




let us see what happens drawing lines with the slope determined by the neutrino speculation considering only the neutrinos at 3.3 and at 109 TeV $M_{LIV}$~$M_{plank}$/25 S=1

Minibursts inside the GRB. In each miniburst the first photon is the highest energy one

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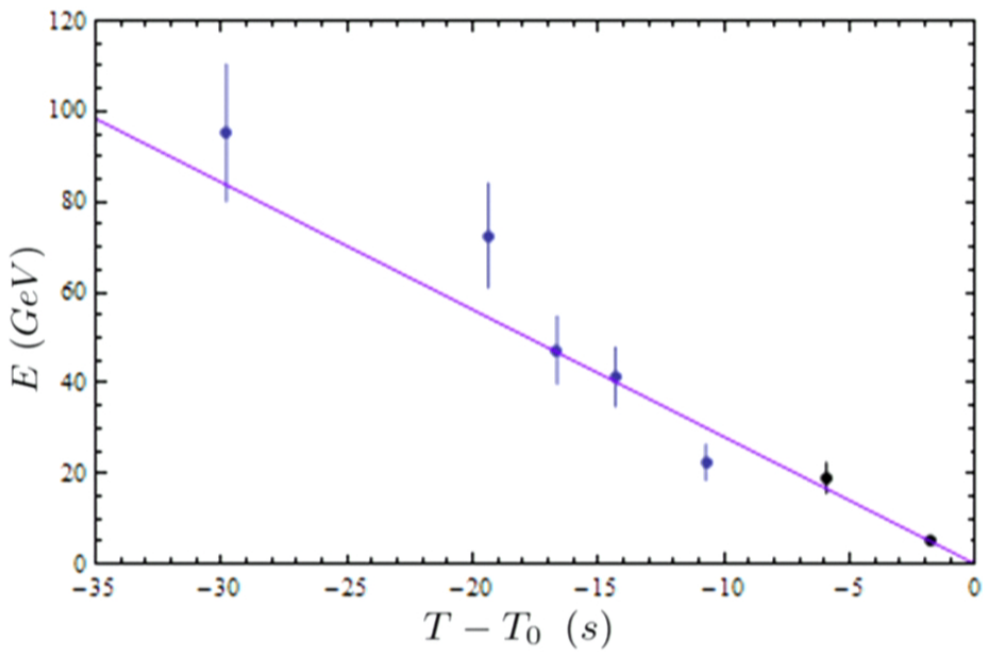
arXiv.org > astro-ph > arXiv:1305.2626

the remarkable GRB130427A, seen above 5 GeV:

superposing by rigid translation
the 3 lines from previous slide



# Our results in comparison to previous constraints

In this analysis we used the hypothesis that **$M_{LIV}$~$M_{plank}$/25** which interestingly is consistent with what found by Amelino Camelia and Smolin (2009) from Fermi results on GRBs for the case of advanced effects (s=1).
They confined the analysis to the most conservative bound-setting criteria and found that stronger bounds could placed on the case of delayed effect (s=-1) but for the advanced effect only a bound of about $M_{LIV}$~$M_{plank}$/25 could be set.

More recently GRB analyses by Fermi and AGN analyses by Hess have produced more stringent bounds, in light of which the quantum-spacetime interpretation of the feature we uncovered should be strongly disfavored.
It is worth mentioning that those more recent analyses by Fermi and Hess used slightly less conservative criteria, though apparently still robust.

## Redshift dependence

**if you want to compare to other GRBs and want to assume quantum-spacetime origin (<u>simpler hypothesis still is astrophysical origin</u>, but….) then keep in mind that you must take into account the difference in redshift**

**Eq. (1)**

$$t_{QG} = -s_{\pm} \frac{E}{M_{QG}} \frac{c}{H_0} \int_0^z d\zeta \frac{(1+\zeta)}{\sqrt{\Omega_\Lambda + (1+\zeta)^3 \Omega_m}}$$

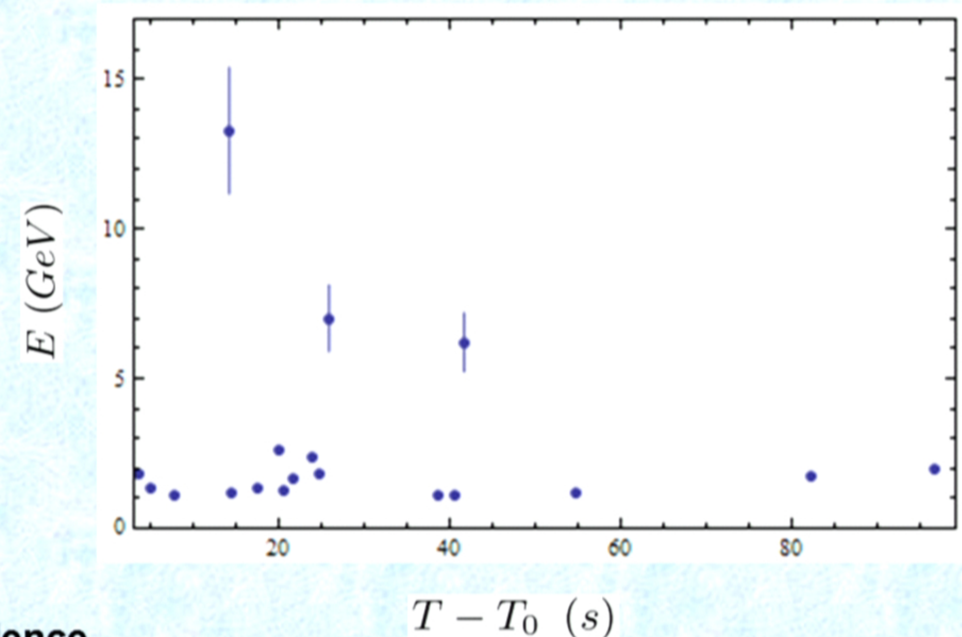
We may check if the GRB130427A features are present in other GRBs and in this case we should assume how this feature depends on the redshift and Can use the above equation to parameterize the redshift dependence.

## Quantum-spacetime scenarios and soft spectral lags of the remarkable GRB130427A

Amelino Camelia + Fiore + Guetta + Puccetti

arXiv.org > astro-ph > arXiv:1305.2626

GRB130427A was like seeing GRB080916C in high resolution
let us look back then as GRB080916C, above 1GeV




**GRB080916c is the best suited to study the dependence on the redshift as it is the farthest GRB**

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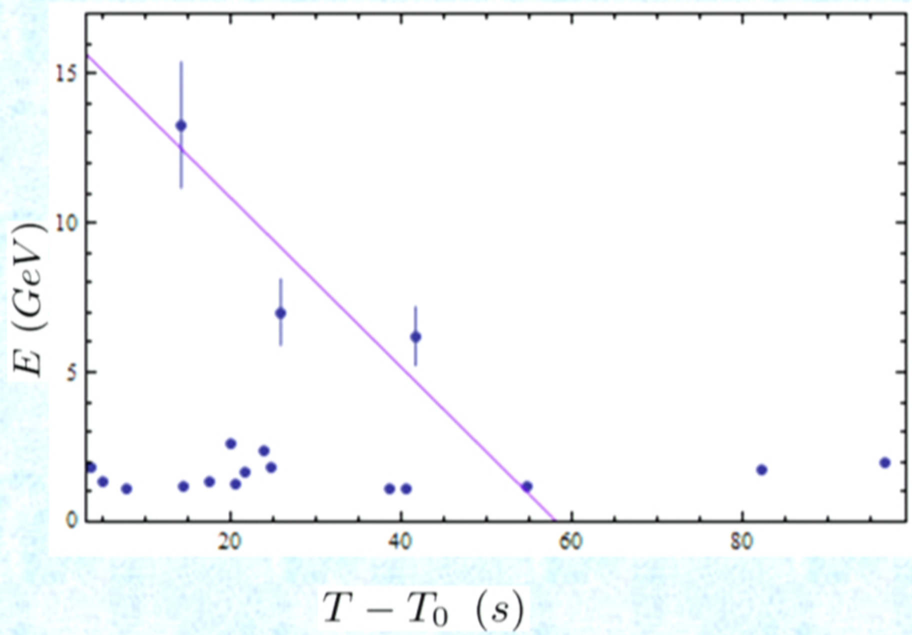
let us look back then as GRB080916C, above 1GeV

The slope is obtained by rescaling the slope obtained with the neutrino data and GRB130427A considering the redshift dependence given in Eq. 1

We do not find a significative result but it is intriguing that the 3 photons of maximum energy fit well the line



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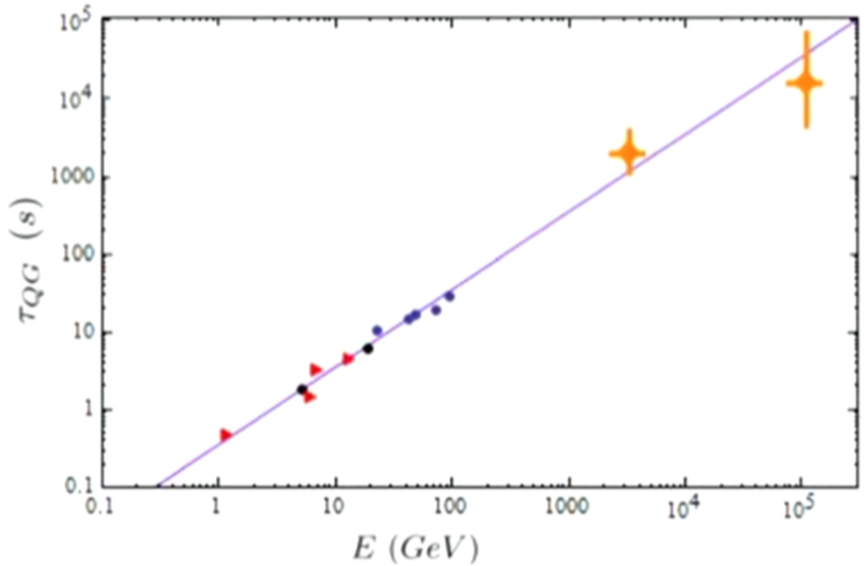
How good is the agreement between our earlier neutrinos, and what we now find for GRB130427A and GRB080916C ? Excluded the 1.3 TeV neutrino that is most likely background

$$E = \frac{cM_{QG}}{D(0.34)}\tau_{QG}(z)$$

$$\tau_{QG}(z) = -\frac{D(0.34)}{D(z)}t_{QG}$$



# Conclusions

We feel it is likely that there is some genuine insight hiding behind our neutrino and/or GRB130427A data analysis

This insight will most likely be relevant for astrophysics (which would be significant in itself) but some aspects of the analysis encourage us to keep an open eye on a possible quantum-spacetime interpretation

Even if our findings are "only" relevant for astrophysics they are indirectly relevant for the quantum-spacetime studies: one cannot look for tiny quantum spacetime effects without a good understanding of larger astrophysical effects of the same type

Bring-home point: with the announcement in May 2013 by IceCube the cosmological-neutrino window on astrophysics and spacetime structure is now truly open

Bring-home point: the april 2013 observation by Fermi of GRB130427A (which we see as the first "high-resolution GRB observation") allows us to positively reassess the potential reach of gamma-ray Telescopes in the physics of GRBs and as tools for the study of space-time structure