Uniwersytet Wrocławski

Testing Planck-scale in-vacuo dispersion with GRB neutrinos

Giacomo Rosati

Institute of Theoretical Physics
University of Wrocław

G. Amelino-Camelia
L. Barcaroli
G. D'Amico
N. Loret
(G. R.)

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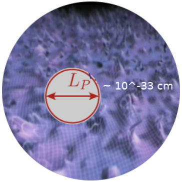
G. Amelino-Camelia
G. D'Amico
G. Gubitosi
M.G.Di Luca
(G. R.)

NatureAstronomy 7 (2023) 996

Motivations and hypothesis: phenomenology of Quantum Gravity

effective theory
quantum spacetime



Planck scale

$\Uparrow$

fundamental Quantum Gravity theories

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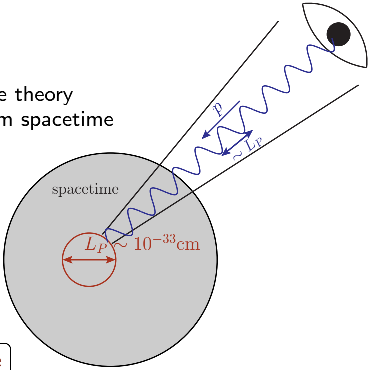

$$p \sim \frac{\hbar}{L_{Pl}} \sim \frac{E_{Pl}}{c}$$

$$\sim \sqrt{\frac{\hbar c^3}{G}} \sim 10^{19}\,\frac{\text{Gev}}{c}$$

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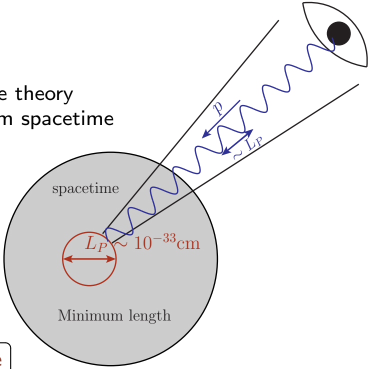

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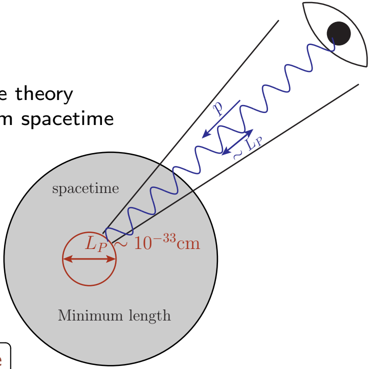

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$$\Downarrow$$

in-vacuo dispersion

$$m^2 c^4 \simeq E^2 - p^2 c^2 + \eta \frac{E p^2 c^2}{E_{Pl}}$$

$$v_{m\sim 0} \sim \frac{dE}{d|p|} \sim c\left(1 - \eta \frac{E}{E_{Pl}}\right)$$

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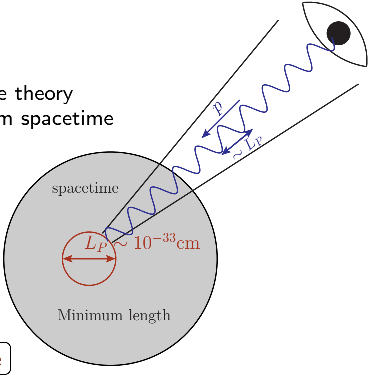

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$\boxed{\text{Planck scale}}$

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fundamental Quantum Gravity theories

$\swarrow$ $\searrow$

LIV (Lorentz Invariance Violation)

(Ellis, Mavromatos, Amelino-Camelia, Nanopoulos, Sarkar, Mattingly, Szabo, Kostelecký, Jacob, Piran, ...)

DSR (Deformed Special Relativity)
(κ-Poincaré / κ-Minkowski non-commutative spacetime)

(Lukierski, Ruegg, Majid, Borowiec, ... Amelino-Camelia, Kowalski-Glikman, Smolin, Magueijo, Arzano, Mercati, Gubitosi, Loret, G.R...)

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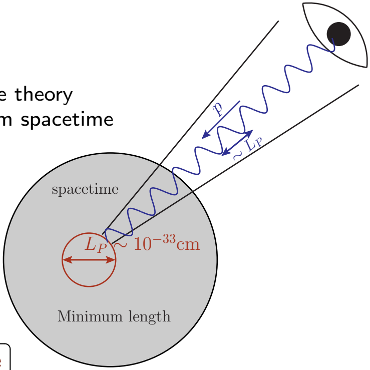

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fundamental Quantum Gravity theories

LIV (Lorentz Invariance Violation)

DSR (Deformed Special Relativity)

In most of these scenarios the relevant effect can be characterized by a correlation between the energy and Δt (time delay) of the observed particles

preliminaries on GRB-neutrinos

- The prediction of a neutrino emission associated with Gamma Ray Bursts is generic within the most widely accepted astrophysical models

  Fireball model (Piran1999): GRBs should produce neutrinos with energy $\gtrsim$100 TeV through the interaction of high-energy protons with radiation (Guetta,Spada,Waxman2001;Mészáros,Waxman2001)

  produced (& detected) in close $\boxed{\text{temporal coincidence}}$ with the associated γ rays

  with a rate (assuming UHECR/GRBs creation) of about 5 GRB/neutrinos per year (Waxman,Bachall1997;Rachen,Mészáros1998;Guetta et al.2004; Ahlers et al.2011)

  After some years of operation ($\sim$2008-) IceCube, besides the detection of a significant number of high-energy candidate astrophysical neutrinos, still reports $\boxed{\text{no detection of GRB/neutrinos}}$

  The IceCube results appear to rule out GRBs as the main sources of UHECRs or to imply that the efficiency of neutrino production is much lower than estimated (Baerwald et al.2011;Hummer et al.2012;Zang,Kumar2012)

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  After some years of operation ($\sim$2008-) IceCube, besides the detection of a significant number of high-energy candidate astrophysical neutrinos, still reports $\boxed{\text{no detection of GRB/neutrinos}}$

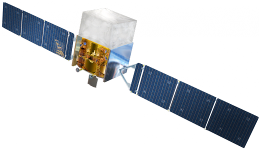
- However:

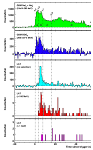
  A $\boxed{\text{sizeable mismatch } (\Delta t)}$ between GRB/neutrino detection time and trigger time for the GRB is expected in several much-studied models of neutrino propagation in a quantum-gravity/quantum-spacetime

  This suggests to $\boxed{\text{open the time window}}$ in which one should look for GRB/neutrino candidates (Jacob+PiranNaturePhys2007,Amelino-Camelia+Guetta+PiranAstrophysJ2015)

analysis of GRB-neutrinos time-delays

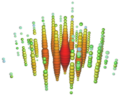
Combining the data from the GRBs catalogue (Fermi, Swift, INTEGRAL, HESS, MAGIC...)





Name	RA	Decl	ERR	T100	T90	Epeak	Fluence	emin	emax	z
070721B	33.128	− 2.198	0.0122	40.4	40.4	200	0.0000036	0.015	0.15	2.15
070724 A	27.824	− 18.61	0.0233	0.4	0.4	1000	0.00000003	0.015	0.15	0.457
070724B	17.629	57.673	0.2027	57	41	82	0.000018	0.01	10	2.15

with the ones from the IceCube neutrino observatory



#ID	Deposited Energy (TeV)		Time (MJD)	Declination(deg.)	RA(deg.)	Med. Ang. Resolution(deg.)	Topology
2	117.0	(−14.6 +15.4)	55351.4659661	−28.0	282.6	25.4	Shower
4	165.4	(−14.9 +19.8)	55477.3930984	−51.2	169.5	7.1	Shower
9	63.2	(−8.0 +7.1)	55685.6629713	33.6	151.3	16.5	Shower

we can estimate the model's parameters by studying the correlation between arrival time-delays (with respect to the low-energy photon peak of the GRB) and energy of the neutrinos.

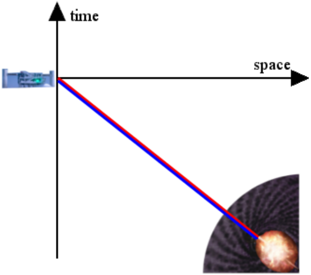
Phenomenological model

Ellis+Mavromatos
+Nanopoulos+Sakharov
Astron.Astrophys,402(2003)
Jacob+Piran
JCAP0801,031(2008)
heursitic formula

$$\Delta t = \eta \frac{\Delta E}{E_{Pl}} D(z) \pm \delta \frac{\Delta E}{E_{Pl}} D(z)$$

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

interplay between
spacetime curvature
and Planck scale effects
G.R.+Amelino-Camelia
+Marcianò +Matassa
PRD92(2015)
Amelino-Camelia+Frattulillo
+Gubitosi+G.R.
arXiv:2307.05428



$\eta = 0$, $\delta = 0$

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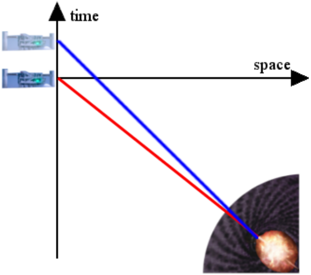

$\eta \neq 0$, $\delta = 0$

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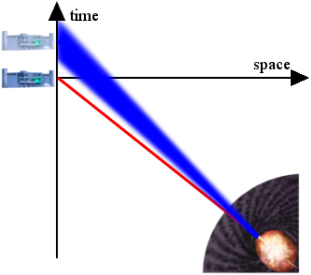

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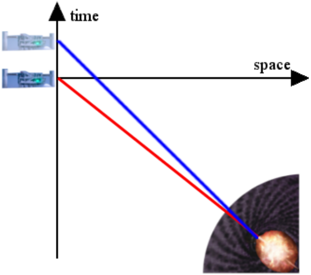


$\eta \neq 0$, $\delta = 0$

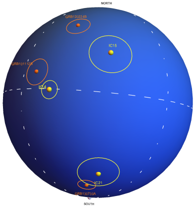
We focus on systematic in-vacuo dispersion ($\delta = 0$)

in most LIV or DSR scenarios, same value of η for different particles. In some models however, in principle possible to have different values of η for different particles, and in some cases (e.g. LIV Standard Model Extension), even for different polarization states.

$$\Delta t = \eta D(1) \frac{\mathcal{K}(E,z)}{M_P} \qquad \mathcal{K}(E,z) = E \frac{D(z)}{D(1)}$$

The first task is to find $\boxed{\text{GRB-neutrino candidates}}$: neutrinos whose direction is compatible with a GRB direction and whose energy and time of observation render them compatible with the time of observation of the GRB

- only "shower/cascade" neutrinos: Their energy is contained completely in the "instrumented volume", so that the energy reconstruction is very accurate ($\sim 10\%$ uncertainty)
- focus on neutrinos with energies between 60 and 500 TeV
- times that differ by no more than 3 days
- angular distance within a 3σ region, where $\sigma = \sqrt{\sigma^2_{GRB} + \sigma^2_{\nu}}$



Early GRB-neutrinos $(\eta < 0)$

we find only three GRB-neutrino candidates (out of 27)

GRB	E_ν (TeV)	Δt (s)	z	GRB length
100605A	98.5	−113,050	–	L
120224B	186.6	−175,141	–	L
140219B	66.7	−234,884	–	L

by generating 10^5 simulated datasets, randomizing the time of observation (of the whole 27 neurino dataset), while keeping their energy and direction fixed, counting how many times there were at least three early neutrinos

we estimated the probability of accidentally finding at least three early neutrinos in our data sample is 81%

$\Rightarrow$ most likely pure background

Late GRB-neutrinos $(\eta > 0)$

we find seven GRB-neutrino candidates (out of 27)

GRB	E_ν (TeV)	Δt (s)	z	GRB length
100604A*	98.5	15,446	–	L
110625B*	86.5	160,909	–	L
111229A*	61.7	73,690	1.38	L
120121C	86.1	200,349	–	L
120121B	86.1	213,239	–	L
120121A*	86.1	187,050	–	L
120219A*	186.6	229,039	–	L
140129C*	134.2	135,731	–	S
140216A*	66.7	23,286	–	L

the probability of accidentally finding at least seven late neutrinos in our data sample is only 5% (as before, 10^5 simulations, randomizing only times)

estimate of the background:
we randomize the times of observation of the neutrinos that were not selected $(N - L)$
ask how frequently in such randomizations one finds the accidental appearance of late GRB-neutrino candidates (fraction ζ)
estimate M (true GRB-neutrinos) through $M + \zeta(N - M) = L$

probability of 83% at least one background, 39% at least two, 18% at lease three

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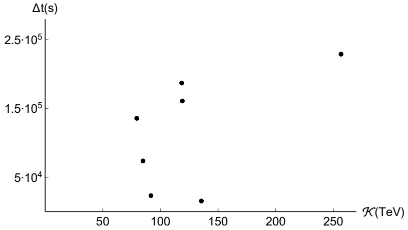


correlation of 0.56

false-alarm probability

we asked how likely it would be for our data sample to accidentally produce (without any intervening quantum-gravity effects) at least seven late GRB-neutrino candidates with a correlation of at least 0.56

10^5 randomizations of the times of detection (of the whole 27 neurino dataset)

For each of these randomizations we redid the analysis just as if they were real data

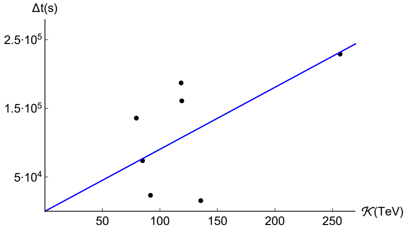
it happens only in about 1% of cases

Extending the energy range above 500 TeV

size of the time window of more than 10 days, handling multiple GRB "partners"

proposed strategy:

use the neutrinos with energy between 60 and 500 TeV to estimate a value η and then look for candidate GRB neutrinos with energies higher than 500 TeV that are compatible $|\Delta t - \eta \mathcal{K}(E,z)| \leq 2\delta\eta\mathcal{K}(E,z)$



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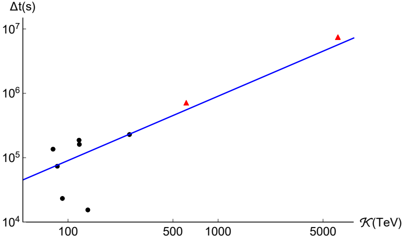
we find two late GRB-neutrino candidates
(out of 4 PeV neutrinos)

	E_ν (TeV)	Δt (s)	z	GRB length
110801B*	1,035.5	706,895	–	S
110730A	1,035.5	907,892	–	L
110725A	1,035.5	1,320,217	–	L
120909A	1,800	7,435,884	3.93	L



overall correlation 0.9997

false-alarm-probability:

how likely it would be for the available neutrinos with energies greater than 500 TeV to accidentally produce late GRB-neutrino candidates leading to this high value of correlation

10^5 randomizations (of the whole 4 (PeV-)neurino dataset), false alarm probability $\lesssim 1$

Outlook

- Main message: the proposed methodology can be applied to test new data, that are going to be available soon. Most likely, the effect will disappear. On the contrary, if the feature survives, one should address the question if it is of astrophysical origin or due to genuine quantum spacetime properties. In either case, a relevant result for quantum gravity phenomenology

- angular resolution of shower events is going to increase thanks to machine learning techniques

- challenge: is it possible to include track neutrinos in the analysis? The reconstructed energy is just a lower bound on the neutrino energy

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Giacomo Rosati

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Thanks!

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NatureAstronomy 7 (2023) 996

Statistical tests of in-vacuo dispersion for GRB photons

Zhang+Ma,Astropart.Phys.61(2014)
Xu+Ma,Astropart.Phys.82(2015)
Xu+Ma,Phys.Lett.B760(2016)

Amelino-Camelia+D'Amico+Loret+G.R.
NatureAstronomy1(2017)

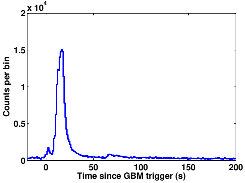
$$\frac{\Delta t}{1+z} = t_{\text{off}} + \eta_\gamma D(1) \frac{\mathcal{K}(E,z)}{E_{Pl}(1+z)}$$

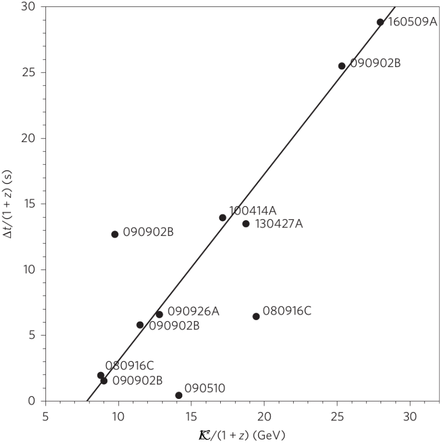
$$\mathcal{K}(E,z) = \frac{D(z)}{D(1)} \Delta E$$

analyze data in terms of a linear dependence

- focus on photons whose energy at emission was greater than 40 GeV

-take as Δt the time-of-observation difference between such high-energy photons and the first peak of the signal

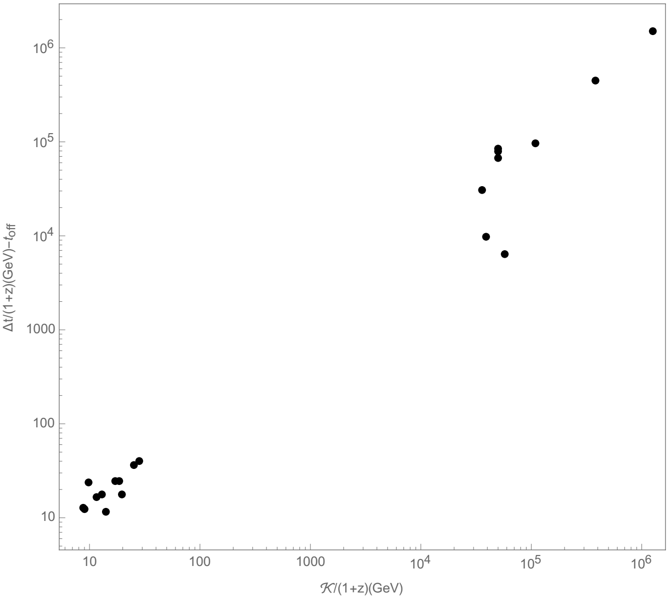




8 of our 11 photons compatible with the same value of η_γ (34 ± 3) and t_{off} $(-11 \pm 3$ s), with a very high correlation of 0.9959

Estimate significancy: simulate background by randomizing dataset (e.g. times or directions); on 10^5 randomizations, such a high correlation is achieved only on $\sim 1\%$ of cases.

"false alarm probability"



10^6
10^5
10^4
1000
100
10
$\Delta t/(1+z)(\text{GeV})-t_{\text{off}}$
10
100
1000
10^4
10^5
10^6
$\mathcal{K}/(1+z)(\text{GeV})$

Dependence on the redshift

We propose to estimate the unknown redshifts by inferring a redshift distribution for GRBs observed in neutrinos from the data themselves

a powerful tool when a large data sample becomes available

How much our key results depend on the redshift?

we redid the calculation of the false-alarm probability, but now for simulated data we estimated the redshift of GRBs whose redshift was unknown by choosing the value that produced the highest correlation (thus giving an "unfair advantage" to the simulated data)

still, we allowed for only a single free parameter (same redshift to all GRBs with unknown redshift)

the false-alarm probability doesn't raise much (still $\sim$ 1-2%)