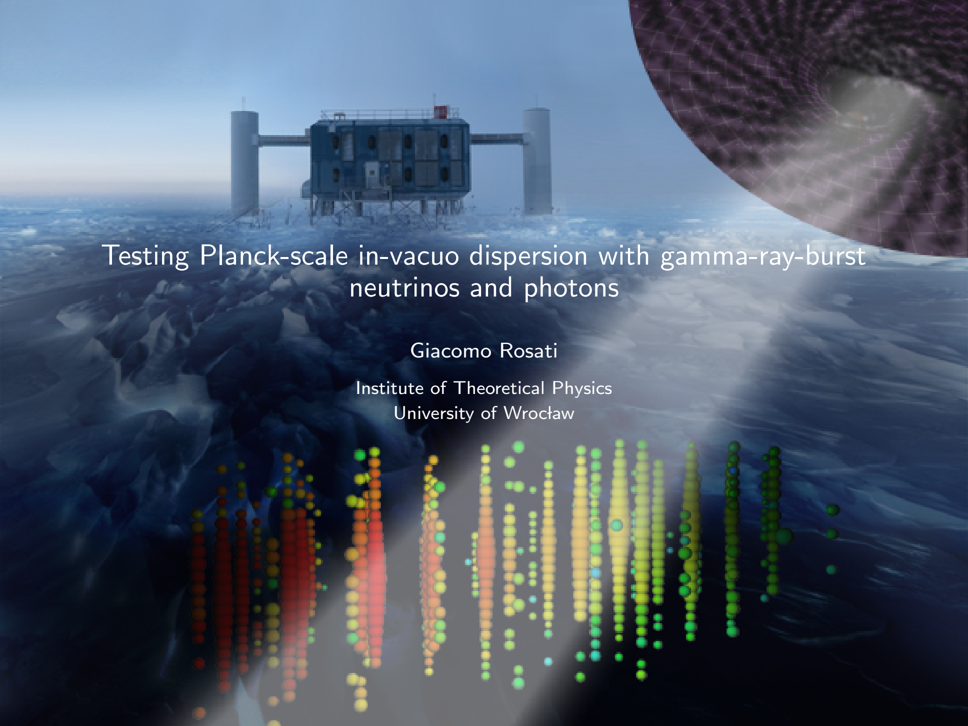
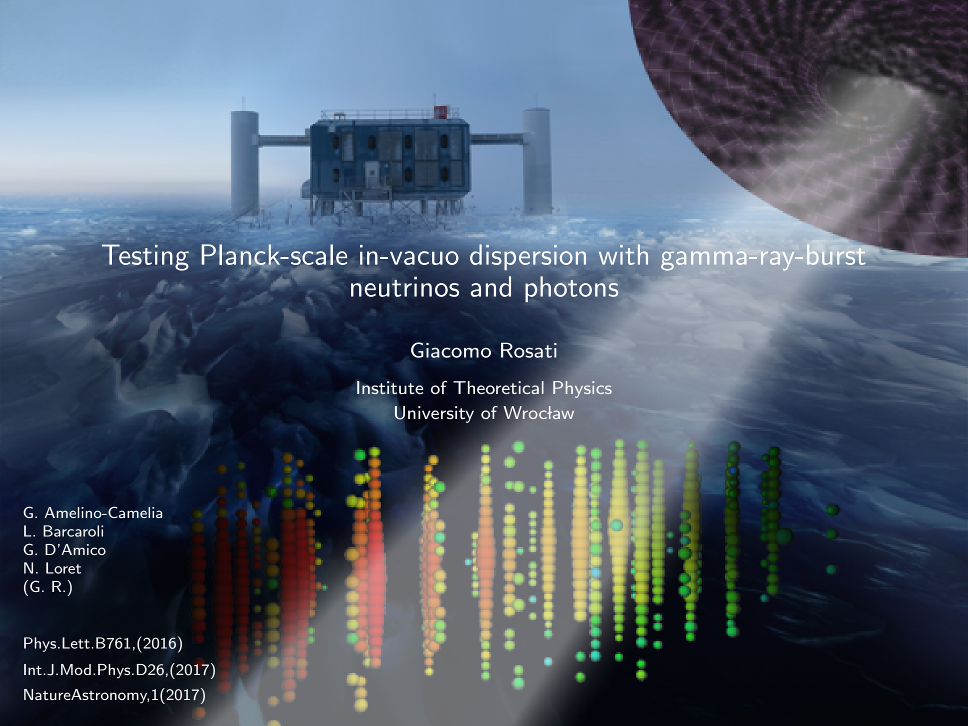


Testing Planck-scale in-vacuo dispersion with gamma-ray-burst neutrinos and photons

Giacomo Rosati

Institute of Theoretical Physics
University of Wrocław



Testing Planck-scale in-vacuo dispersion with gamma-ray-burst neutrinos and photons

Giacomo Rosati

Institute of Theoretical Physics
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G. Amelino-Camelia
L. Barcaroli
G. D'Amico
N. Loret
(G. R.)

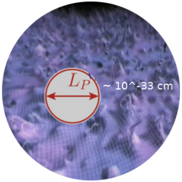
Phys.Lett.B761,(2016)

Int.J.Mod.Phys.D26,(2017)

NatureAstronomy,1(2017)

Motivations and hypothesis: phenomenology of Quantum Gravity

effective theory
quantum spacetime



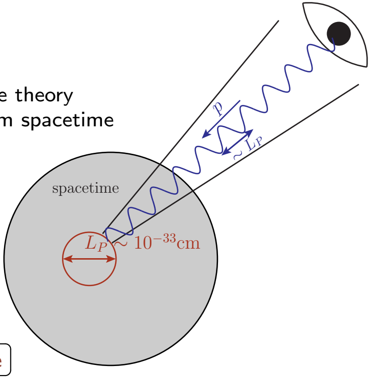
Planck scale

⇑

fundamental Quantum Gravity theories

Motivations and hypothesis: phenomenology of Quantum Gravity

Heisenberg microscope



effective theory
quantum spacetime

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

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

Planck scale

$\Uparrow$

fundamental Quantum Gravity theories

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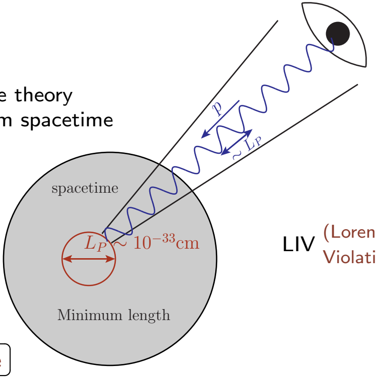

$$\max p \sim \frac{\hbar}{L_{Pl}} \sim \frac{E_{Pl}}{c} \sim \sqrt{\frac{\hbar c^3}{G}} \sim 10^{19}\,\frac{\text{Gev}}{c}$$

LIV (Lorentz Invariance Violation)

DSR (Deformed Special Relativity)

Planck scale

⇑

fundamental Quantum Gravity theories

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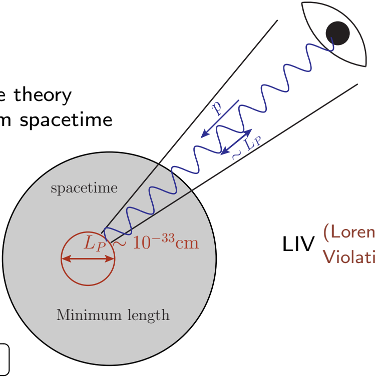

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LIV (Lorentz Invariance Violation) DSR (Deformed Special Relativity)

⇓

in-vacuo dispersion

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

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

Planck scale

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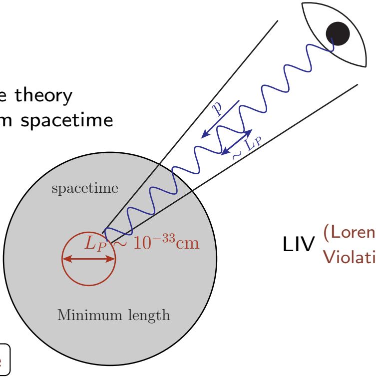

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(LIV scenario)

(Ellis,Mavromatos,Amelino-Camelia,Nanopulos,Sarkar,Jacob,Piran,...)

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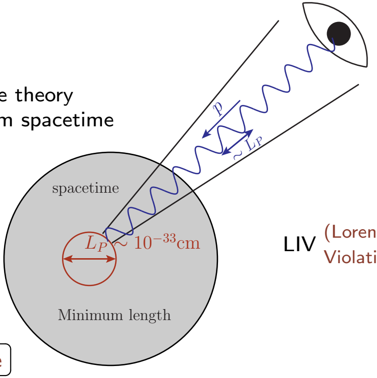

Planck scale

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$\swarrow$ $\searrow$

LIV (Lorentz Invariance Violation) DSR (Deformed Special Relativity)

$\Downarrow$

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

(κ-Poincaré / DSR)
non-commutative spacetime

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

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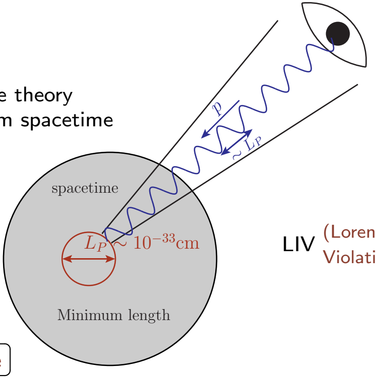

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In most of these scenarios the relevant effect can be characterized by a correlation between the energy of the observed GRB/neutrino (or HE photon) and Δt

Phenomenological model

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

Jacob&Piran
(JCAP0801,031(2008))
heursitic formula

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

interplay between
spacetime curvature
and Planck scale effects
(Amelino-Camelia+Marciano
+Matassa+G.R.)
(PRD92(2015))

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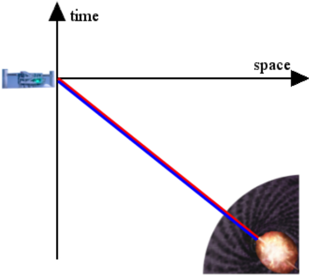

$\eta = 0$, $\delta = 0$

Phenomenological model

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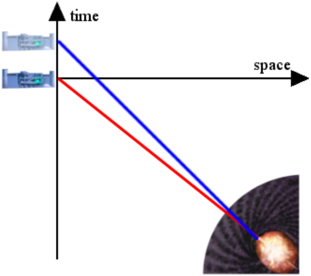

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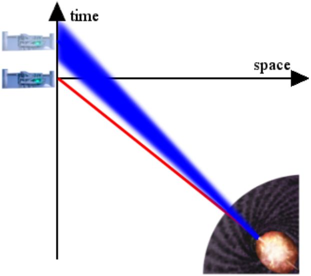

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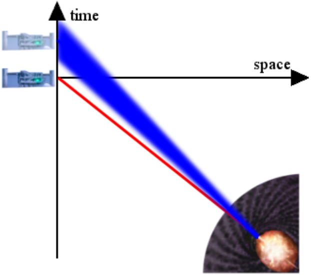

$\eta \neq 0$, $\delta \neq 0$

Different values of η, δ for different particles

helicity: $\eta_+,\ \eta_-,\ \delta+,\ \delta_-$

(Jacobson+Liberati+Mattingly2005)

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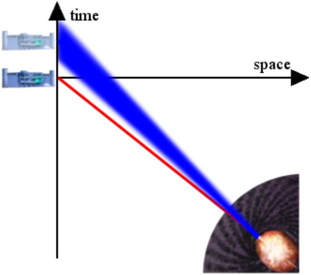

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Different values of η, δ for different particles

$\boxed{\text{helicity: } \eta_+,\ \eta_-,\ \delta+,\ \delta_-}$

(Jacobson+Liberati+Mattingly2005)

Present upper bounds:

photons $|\eta_\gamma| \lesssim 1,\ \delta_\gamma \lesssim 1$
(FERMI:GRB090510,Amelino-Camelia,...)

neutrinos several order less constraining
(Supernova 1987A, MINOS, OPERA)

Phenomenological model

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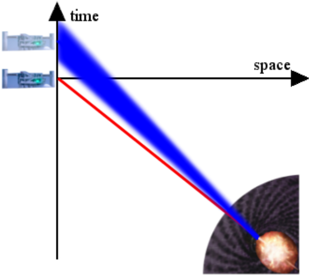


$\eta \neq 0$, $\delta \neq 0$

We can reabsorve the redshift dependence rescaling the energy

$$E^* = E \frac{D(z)}{D(1)}$$

so that we can analyze data in terms of a linear dependence

$$\Delta t = \eta \frac{E^*}{E_{Pl}} D(1) \pm \delta \frac{E^*}{E_{Pl}} D(1)$$

Statistical test of in-vacuo dispersion for photons

Zhang+Ma,Astropart.Phys.61(2014)
Xu+Ma,Astropart.Phys.82(2015)
Xu+Ma,Astropart.PhysLettB760(2016)

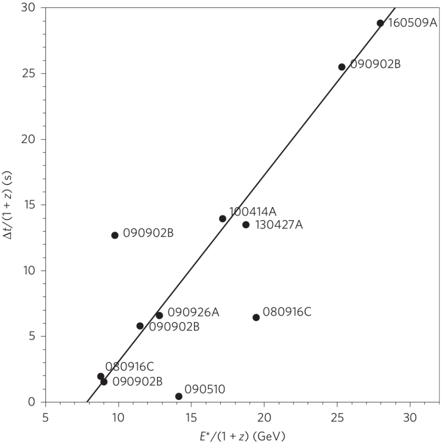
Amelino-Camelia+D'Amico+Loret+G.R.
NatureAstronomy1(2017),arXiv:1612.02765

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

criteria:

- 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 (mostly low-energy) signal



8 of our 11 photons are all compatible with the same value of η_γ (34 ± 1) and t_{off} $(-11s \pm 1s)$, with a very high correlation of 0.9959.

We ask how often such high correlation between Δt and E^* would occur if the pairing of values of Δt and E^* was just random: overall having such high correlation would happen in less than 0.1 % of cases, and correlation as high as seen for the best 8 out of 11 in 0.0013 % of cases.

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)

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- After a few years of operation (~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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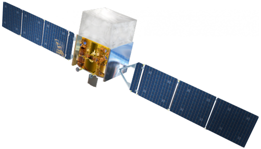
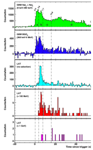
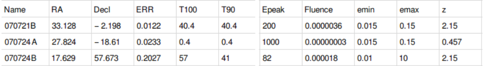
  This suggests to open the time window in which one should look for GRB/neutrino candidates (Amelino-Camelia,Guetta,Piran2015)

analysis of GRB-neutrinos time-delays

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

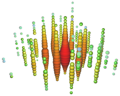


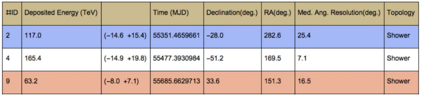




Name	RA	Decl	ERR	T100	T90	Epeak	Fluence	emin	emax	z
070721B	33.128	− 2.198	0.0122	40.4	40.4	200	0.0000036	0.015	0.15	2.15
070724 A	27.824	− 18.61	0.0233	0.4	0.4	1000	0.00000003	0.015	0.15	0.457
070724B	17.629	57.673	0.2027	57	41	82	0.000018	0.01	10	2.15

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 studyng the correlation between arrival time-delays (with respect to the low-energy photon peak of the GRB) and energy ot the neutrinos.

Criteria for selecting GRB/neutrino candidates

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

- Considering the rate of GRB observations of about 1 per day, we opt for focusing on neutrinos with energies between 60 TeV and 500 TeV, allowing for a temporal window of 3 days.

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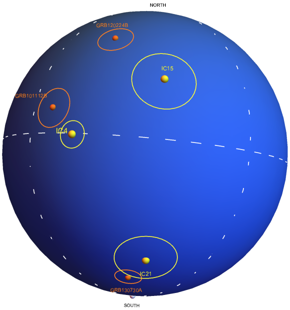
- As directional criteria for the selection of GRB/neutrino candidates we asked the pair composed by the neutrino and the GRB to be at angular distance compatible within a 2 σ region.



Strategy of analysis

"Distance rescaled time-delay"

$$\Delta t^* \equiv \Delta t \frac{D(1)}{D(z)}$$

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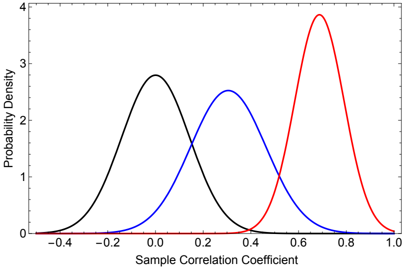
correlation between $|\Delta t^*|$ and E



Expectations for the correlation for:

- background neutrinos (black)
- 10% background while 90% GRB/neutrinos with $\eta_+ = \eta_- = 0$, $\delta_+ = \delta_- = 5$ (blue)
- 10% background while 90% are GRB/neutrinos with $|\eta_+| = |\eta_-| = 15$, $\delta_+ = \delta_- = 5$ (red)

whenever η_+, η_-, δ_+, δ_- do not vanish one should expect a correlation between the $|\Delta t^*|$ and the energy of the candidate GRB/neutrinos

Results

data set:

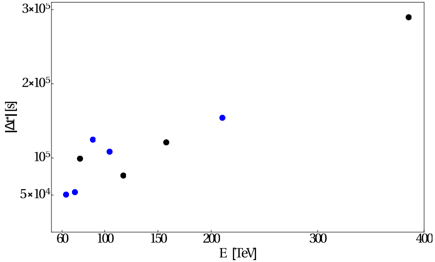
- Four years of operation of IceCube, from June 2010 to May 2014
- Only IceCube " shower events"

- 21 such events within our 60-500 TeV energy window
- 9 of them fit the requirements for candidate GRB/neutrinos

	E[TeV]	GRB	z	Δt^* [s]	
IC9	63.2	110503A	1.613	50227	*
IC19	71.5	111229A	1.3805	53512	*
IC42	76.3	131117A	4.042	5620	
		131118A	1.497 *	-98694	*
		131119A	?	-146475	
IC11	88.4	110531A	1.497 *	124338	*
IC12	104.1	110625B	1.497 *	108061	*
IC2	117.0	100604A	?	10372	
		100605A	1.497 *	-75921	*
		100606A	?	-135456	
IC40	157.3	130730A	1.497 *	-120641	*
IC26	210.0	120219A	1.497 *	153815	*
		120224B	?	-117619	
IC33	384.7	121023A	0.6 *	-289371	*

- 18 alternative descriptions of our 9 ⇒ <u>multiple candidates</u> → highest correlation
- redshift: short GRB z=0.6, long GRBs $\bar{z}$ = average of known z

Results



Blue points: "late neutrinos" ($\Delta t^* > 0$)
Black points: "early neutrinos" ($\Delta t^* < 0$)

we estimate

$$|\eta_\nu| = 22 \pm 2 \qquad \delta_+ = 6 \pm 2 \qquad \text{for } \eta_+ = -\eta_-,\ \delta_+ = \delta_-$$

$$|\eta_\nu| = 19 \pm 4 \qquad \text{for } \eta_+ = -\eta_-,\ \delta_+ = \delta_- = 0$$

maximum and minimum correlation

	$z_{long} = \bar{z}$	$z_{long} = 2$
$z_{short} = 0.5$	0.958	0.953
$z_{short} = 0.6$	0.951	0.960
$z_{short} = 0.7$	0.941	0.964

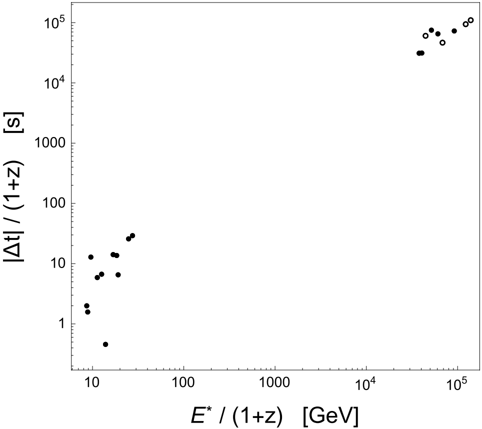
	$z_{long} = \bar{z}$	$z_{long} = 2$
$z_{short} = 0.5$	0.844	0.869
$z_{short} = 0.6$	0.803	0.849
$z_{short} = 0.7$	0.751	0.822

False alarm probability

How often a sample composed exclusively of background neutrinos would produce accidentally 9 or more GRB/neutrino candidates with correlation comparable to (or greater than) the correlation we found in data

	$z_{long} = \bar{z}$	$z_{long} = 2$
$z_{short} = 0.5$	0.03 %	0.04 %
$z_{short} = 0.6$	0.03 %	0.02 %
$z_{short} = 0.7$	0.04 %	0.01 %

	$z_{long} = \bar{z}$	$z_{long} = 2$
$z_{short} = 0.5$	0.7 %	0.6 %
$z_{short} = 0.6$	1.0 %	0.6 %
$z_{short} = 0.7$	1.5 %	0.8 %



Comparing the analysis for GRB photons ($E \sim O(10\text{GeV})$) to the one for neutrinos, the two features are roughly compatible with a description such that the same effects apply over four orders of magnitude in energy.

We estimate $\boxed{\eta_\gamma = 34 \pm 1,\ |\eta_\nu| = 19 \pm 4}$

G. Amelino-Camelia, G. D'Amico, N. Loret, G. R.
Nature Astronomy 1 (2017) 0139, arXiv:1612.02765

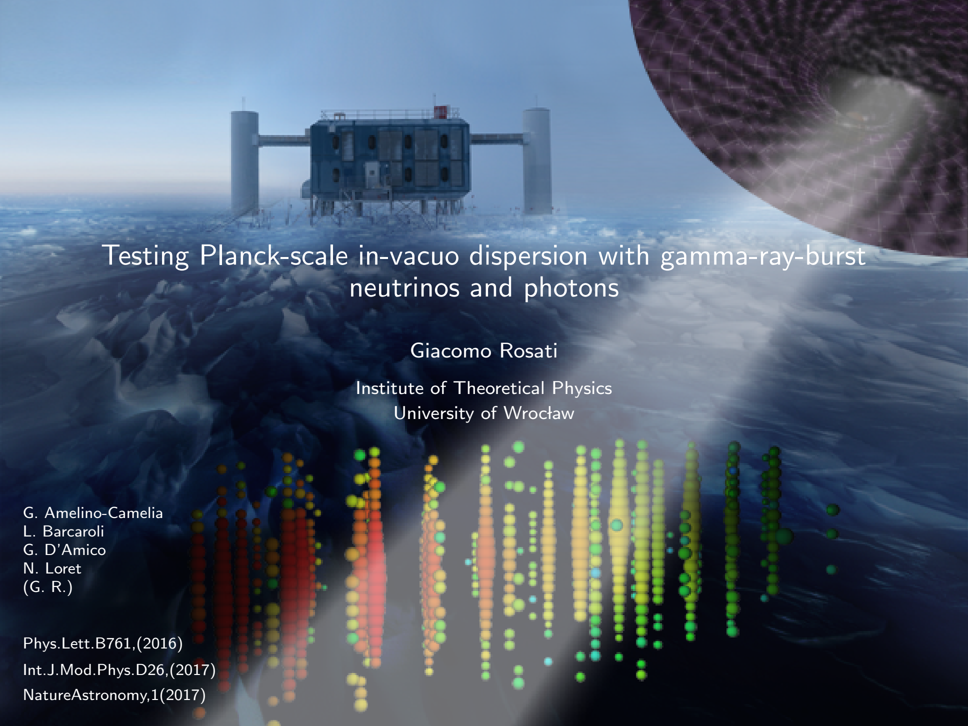
Summary and Outlook

- We looked within IceCube data from June 2010 to May 2014 which present a very strong feature characterized by a false alarm probability which we estimated fairly at 0.03% and conservatively at 1%. We feel this should suffice to motivate a vigorous program of further investigation of the scenarios here analyzed.

- The main ingredient of novelty is the central role played by the correlation between the energy of a neutrino and the difference between the time of observation of that neutrino and the trigger time of a GRB. The advantage of focusing on this correlation is that it is expected in a rather broad class of phenomenological models of particle propagation in a quantum spacetime.

- Challanges for the interpretation of data: Handling background neutrinos. We expect about 20 % to 30 % of data to be background. Statistic must be improved.

- In a following work Huang & Ma considered also 4 neutrinos with energy of PeV range, finding some candidate GRB-neutrinos that seem to be compatible with the estimated effect.



Testing Planck-scale in-vacuo dispersion with gamma-ray-burst neutrinos and photons

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