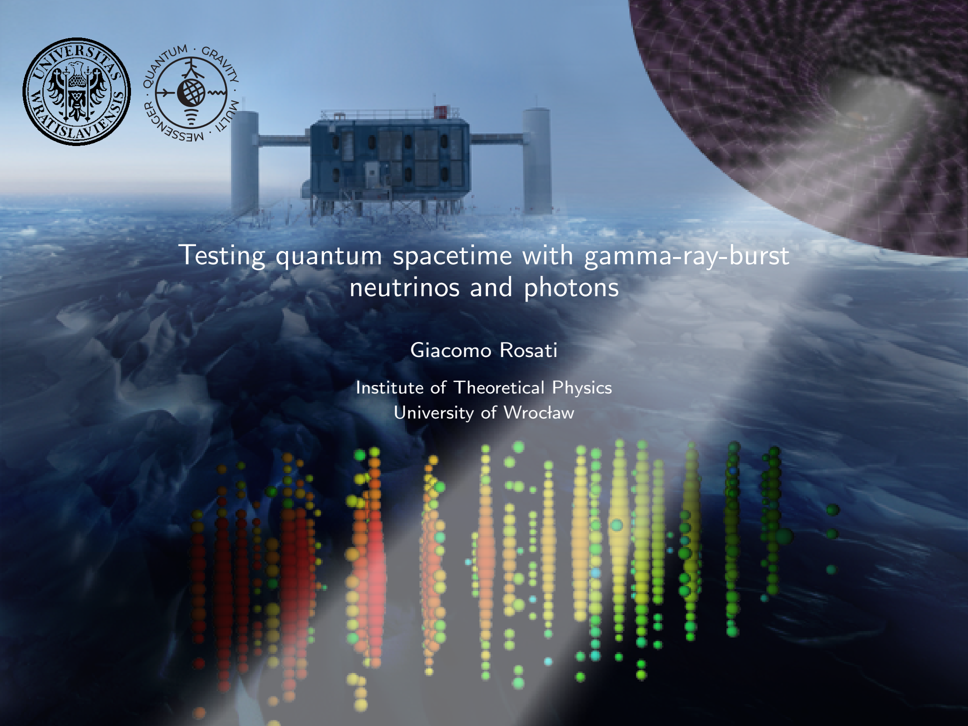

Testing quantum spacetime with gamma-ray-burst neutrinos and photons

Giacomo Rosati

Institute of Theoretical Physics
University of Wrocław

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(G. R.)

Phys.Lett.B761,(2016)

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NatureAstronomy,1(2017)

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G. Gubitosi
M.G.Di Luca
(G. R.)

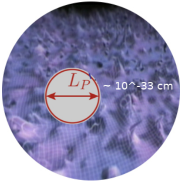
in progress

G. Amelino-Camelia
S. Bedić
(G. R.)

Phys.Lett.B 820, (2021)

Motivations and hypothesis: phenomenology of Quantum Gravity

effective theory
quantum spacetime



Planck scale

$\Uparrow$

fundamental Quantum Gravity theories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Heisenberg microscope

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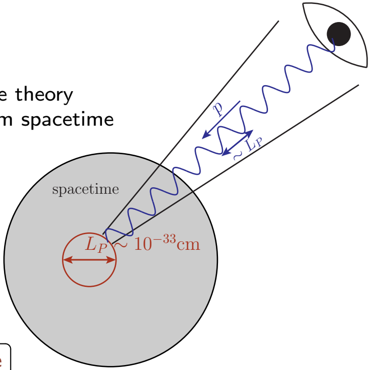

$$p \sim \frac{\hbar}{L_{Pl}} \sim \frac{E_{Pl}}{c}$$

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

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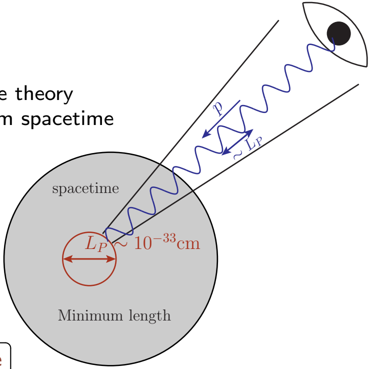

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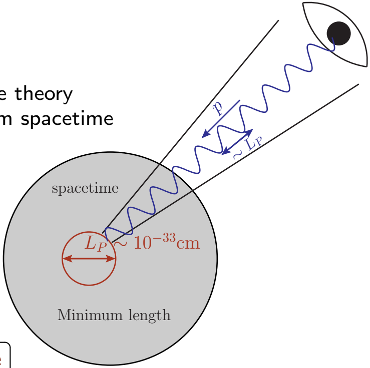

$$\max p \sim \frac{\hbar}{L_{Pl}} \sim \frac{E_{Pl}}{c}$$

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$\Downarrow$

in-vacuo dispersion

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

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

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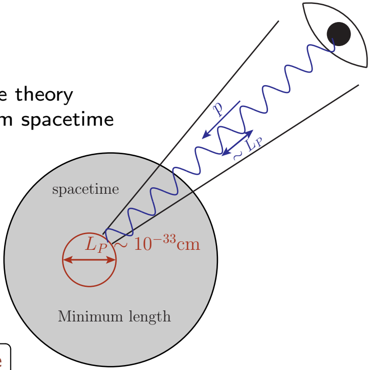

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⇑

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↙ ↘

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...)

LIV $vs.$ DSR scenarios

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Analogy with

transition from Galilean to Special Relativity
introduction of a maximum velocity scale in the laws of motion

$$mE_* - \frac{\mathbf{p}^2}{2} = 0 \qquad \longrightarrow \qquad E^2 - \mathbf{p}^2 c^2 - m^2 c^4 = 0$$

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spacetime "aether"
Galilean transformations

$$\mathbf{u} \oplus \mathbf{v} = \mathbf{u} + \mathbf{v}$$

special relativity
no preferred frame
Poincaré (Lorentz + translations)
transformations
($1/c$-deformation of Galilean transformations)

$$\mathbf{u} \oplus \mathbf{v} = \frac{1}{1 + \frac{\mathbf{u} \cdot \mathbf{v}}{c^2}} \left(\mathbf{u} + \frac{1}{\gamma_u} \mathbf{v} + \frac{1}{c^2} \frac{\gamma_u}{1 + \gamma_u} (\mathbf{u} \cdot \mathbf{v}) \mathbf{u} \right) \qquad v_{max} = c$$

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quantum spacetime: maximum energy(momentum) scale

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

LIV
"quantum gravity aether"
Poincaré transformations

DSR
no preferred frame
$1/\kappa = \eta / E_{Pl}$-deformation
of Poincaré transformations

$$\mathbf{p} \oplus \mathbf{q} = \mathbf{p} + e^{-\ell E(p)} \mathbf{q} \qquad p_{max} = \kappa$$

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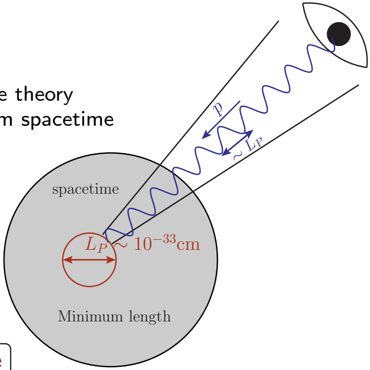

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In most of these scenarios the relevant effect can be characterized by a correlation between the energy and Δt (time delay) of the observed particles

Is it possible to experimentally observe quantum structure of spacetime?

How can we reach Planck-scale sensitivity?

Is it possible to experimentally observe quantum structure of spacetime?

How can we reach Planck-scale sensitivity?

Indirect observation: through some source of amplification

Hope: we can at least falsify (put constraints on) some class of models

crucial for the progress of Quantum Gravity research

COST action CA18108:
"Quantum Gravity Phenomenology In The Multi-Messenger Approach"

(First attempt to join the efforts of experimental and theoretical community in Quantum Gravity)

"Quantum gravity phenomenology at the dawn of the multi-messenger era – A review'
arXiv:2111.05659 [hep-ph]

https://qg-mm.unizar.es

Testing in-vacuo dispersion

Transient ultra-high energy astrophysical sources could provide the suitable setting

Expected time delay for two simultaneously emitted photons:

$$\Delta t = \eta \frac{\Delta E}{E_{Pl}} T$$

(short) Gamma Ray Bursts:

The time of flight is the amplifier: $T \gtrsim 10^{17} s$

Energies, and thus $\Delta E = E - E_0$, up to $10 - 100 GeV$

$$\Rightarrow \qquad \boxed{\Delta t \simeq \eta \; 10^{-2} s}$$

Duration of microbursts $\sim 10^{-3} - 10^{-4} s$

(thus, if we observe for instance $\Delta t \lesssim 0.1 s$, we constrain $\eta \lesssim 10$)

(Amelino-Camelia+Ellis+Mavromatos+Nanopoulos+Sarkar,Nature393(1998))

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We need a formula that includes universe curvature/expansion

$T \longrightarrow D(z)$ (where z is the redshift)

Phenomenological model

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

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
(G.R.+Amelino-Camelia +Marciano +Matassa)
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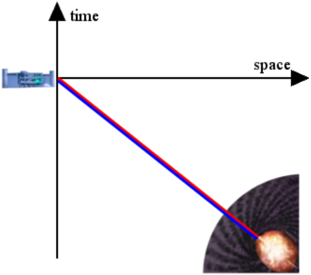

$\eta = 0$, $\delta = 0$

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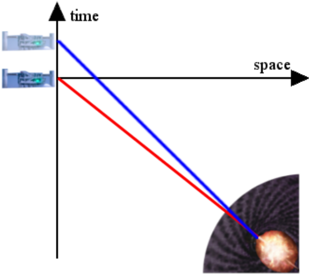

$\eta \neq 0$, $\delta = 0$

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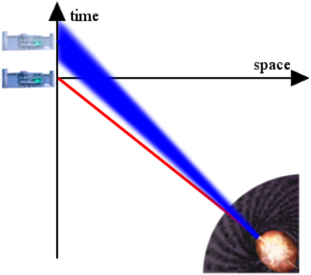

$\eta \neq 0$, $\delta \neq 0$

A model for in-vacuo dispersion stemming from non-commutative spacetime

Minimal length / maximum energy as an observer invariant scale

"Heisenberg principle for spacetime" (κ-Minkowski: $\kappa = \eta/E_p = \eta L_p/\hbar$)

$$[\hat{t}, \hat{\mathbf{x}}] = i\eta L_p \hat{\mathbf{x}}, \qquad [\hat{x}^j, \hat{x}^k] = 0$$

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In order for this relation to hold for all inertial observers (translated, boosted, rotated), the symmetry group describing transformations between their coordinates must be "deformed"

κ-Poincaré (Hopf) algebra of relativistic symmetry generators

$$[p_\mu, p_\nu] = 0\ , \quad [R_j, R_k] = \epsilon_{jkl} R_l\ , \quad [N_j, N_k] = -\epsilon_{jkl} R_l\ , \quad [R_j, p_0] = 0\ , \quad [R_j, p_k] = \epsilon_{jkl} p_l\ ,$$

$$[N_j, p_0] = p_j\ , \quad [N_j, p_k] = \delta_{jk} \left(\frac{\kappa}{2} \left(e^{2p_0/\kappa} - 1 \right) - \frac{\mathbf{p}^2}{2\kappa} \right) + \frac{1}{\kappa} p_j p_k\ .$$

$$\mathcal{C}_\kappa = (2\kappa)^2 \sinh^2\left(\frac{p_0}{2\kappa}\right) - e^{-p_0/\kappa}\mathbf{p}^2$$

(Lukierski,Nowicki,Tolstoy,Ruegg,Majid,...90')

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$$\Delta p_j = p_j \otimes \mathbb{1} + e^{\ell p_0} \otimes p_j \ , \qquad \Delta p_0 = p_0 \otimes \mathbb{1} + \mathbb{1} \otimes p_0 \ ,$$

$$\Delta N_j = N_j \otimes \mathbb{1} + e^{\ell p_0} \otimes N_j - \ell \epsilon_{jkl} p_k \otimes R_l \ , \qquad \Delta R_j = R_j \otimes \mathbb{1} + \mathbb{1} \otimes R_j \ ,$$

$$S(p_0) = -p_0 \ , \quad S(p_j) = -e^{-\ell p_0} p_j \ , \quad S(N_j) = -e^{-\ell p_0} N_j - \ell \epsilon_{jkl} e^{-\ell p_0} p_k R_l \ , \quad S(R_j) = -R_j \ ,$$

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$$\mathcal{C}_\kappa = (2\kappa)^2 \sinh^2 \left(\frac{p_0}{2\kappa} \right) - e^{-p_0/\kappa} \mathbf{p}^2$$

Several works seem to indicate that symmetries of this type would emerge from quantization of gravity at an effective theory level (The results are quite solid for 3D quantum gravity)

Amelino-Camelia+Smolin+Starodubtsev2004,Freidel+Livine2006,G.R.2017

The field theory invariant under κ-Poincaré symmetries is a non-commutative field theory characterized by an associated $\star$-product structure

$$\phi(\hat{x}) \cdot \psi(\hat{x}) = \Omega\left(\phi(x) \star \psi(x)\right)$$

where Ω is the Weyl map $\phi(\hat{x}) = \Omega(\phi(x))$, a notion of integration

$$\widehat{\int} \phi(\hat{x}) \equiv \int d^4x \; \Omega^{-1}(\phi(\hat{x})) = \int d^4x \; \phi(x)$$

and a non-commutative Fourier transform

$$\phi(\hat{x}) = \int d\mu(p) \;\; : e^{ip_\mu \hat{x}^\mu} : \tilde{\phi}(p)$$

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the action is

$$\mathcal{S} = \int d^4x \; \frac{1}{2}\phi(x) \star \Box_\kappa \phi(x) - \frac{1}{2}\mu^2 \; \phi(x) \star \phi(x) + \text{interactions}$$

where $\Box_\kappa \phi(x) = \mathcal{C}_\kappa \triangleright \phi(x)$, so that the on-shell relation is deformed

$$\mu^2 = (2\kappa)^2 \sinh^2\left(\frac{m}{2\kappa}\right) = (2\kappa)^2 \sinh^2\left(\frac{p_0}{2\kappa}\right) - e^{-p_0/\kappa}\mathbf{p}^2$$

This action is invariant under κ-Poincaré symmetries

In-vacuo dispersion from κ-deformed on-shellness

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for $m = 0 \qquad p_0(\mathbf{p}) = \ln\left(1 + |\mathbf{p}|/\kappa\right)$

it thus follows that for a photon

$$|\mathbf{v}| = \frac{\partial E}{\partial |\mathbf{p}|} = \frac{c}{1 + |\mathbf{p}|/\kappa} \simeq c(1 - \frac{1}{\kappa}E)$$

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Generalization to expanding spacetimes rely on the inclusion of cosmological constant (G.R.+Amelino-Camelia+Marciano+Matassa,PRD92(2015))

this is related to non-commutative spacetime/ deformed (Hopf algebra) symmetries of the so-called q-de Sitter type (Lukierski,Ruegg,Ballesteros,Gubitosi,. . .)

Phenomenological model

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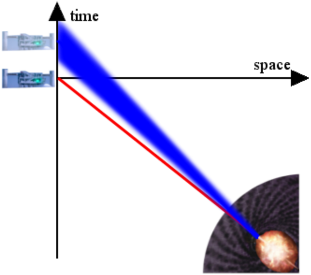


$\eta \neq 0,\ \delta \neq 0$

Different values of η, δ for different particles

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

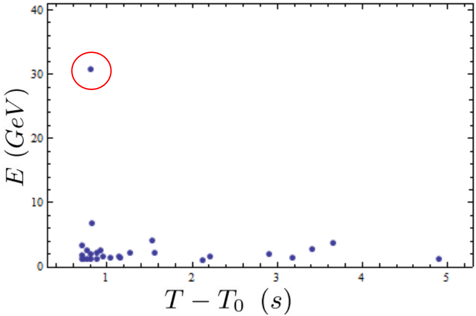
(Jacobson+Liberati+Mattingly2005)

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)

Testing Jacob-Piran formula

The tightest bound comes from GRB090510 which constrained $\eta = E_P/E_{QG} \lesssim 1.2$ a test with accuracy of about one part in 10^{20}!!! (Fermi,Nature462(2009))



this Planck-scale sensitivity is illustrative of how we have learned that there are ways for achieving in some cases sensitivity to Planck-scale-suppressed effects, something that was thought to be impossible up to the mid 1990s

Quantum-Gravity Phenomenology exists!!!

still makes sense to test in-vacuo dispersion statistically

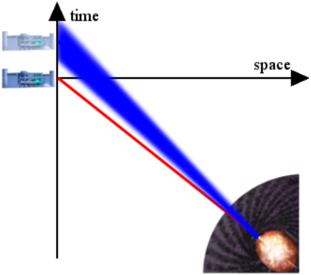
Phenomenological model

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
+Marciano +Matassa)
(PRD92(2015))



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

We can reabsorb 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

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

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 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 ($\sim$2008-) IceCube, besides the detection of a significant number of high-energy candidate astrophysical neutrinos, still reports 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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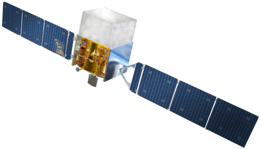
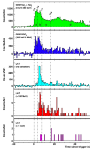
  This suggests to open the time window in which one should look for GRB/neutrino candidates (Amelino-Camelia,Guetta,Piran2015)

analysis of GRB-neutrinos time-delays

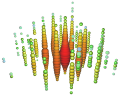
Combining the data from the GRBs catalogue (Fermi, Swift, INTEGRAL, HESS, MAGIC...)





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 studying the correlation between arrival time-delays (with respect to the low-energy photon peak of the GRB) and energy of 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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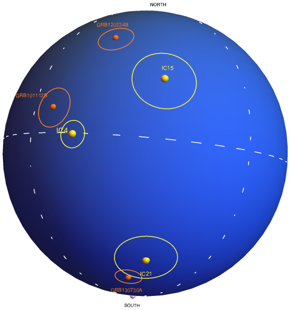
- As directional criteria for the selection of GRB/neutrino candidates we asked the pair composed by the neutrino and the GRB to be at angular distance compatible within a 2 σ region.



Strategy of analysis

"Distance rescaled time-delay"

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

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

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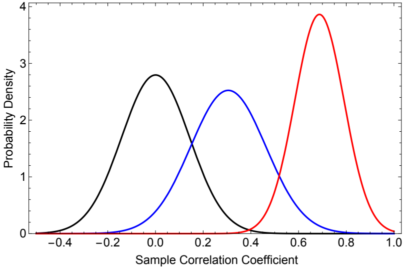
correlation between $|\Delta t^*|$ and E



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:

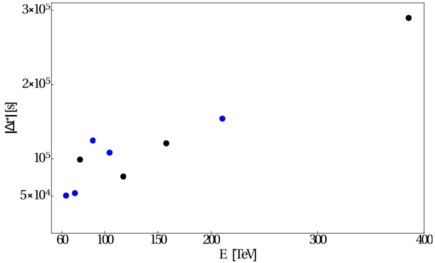
- Four years of operation of IceCube, from June 2010 to May 2014
- Only IceCube " shower events"

- 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 $\Rightarrow$ multiple candidates $\rightarrow$ 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

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

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

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

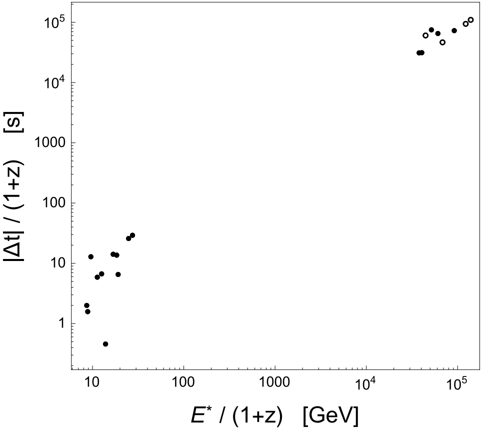
	$z_{long} = \bar{z}$	$z_{long} = 2$
$z_{short} = 0.5$	0.844	0.869
$z_{short} = 0.6$	0.803	0.849
$z_{short} = 0.7$	0.751	0.822

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

Statistical test of in-vacuo dispersion for 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)

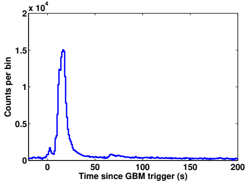
$$\frac{\Delta t}{1+z} = t_{\text{off}} + \eta_\gamma D(1) \frac{E^*}{E_{Pl}(1+z)}$$

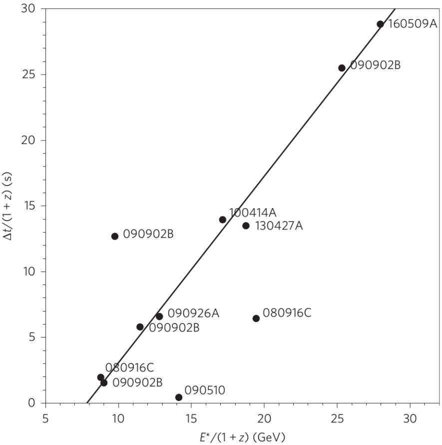
criteria:

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

- 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 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

False-alarm probability estimated to $\sim 0.1 - 1\%$

All these studies have been based on scenarios where quantum-gravity effects are present even in absence of spacetime curvature

Theoretical considerations however suggest that it may likely that quantum gravity effects are triggered by curvature

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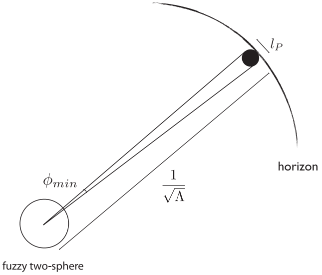
particularly intriguing considering the interplay between cosmological constant Λ (cosmological horizon) and Planck scale ℓ_p (minimum length/quantum gravity)

(see for instance (Rovelli+Bianchi,PRD84(2011)) for a suggestive conceptual interpretation)



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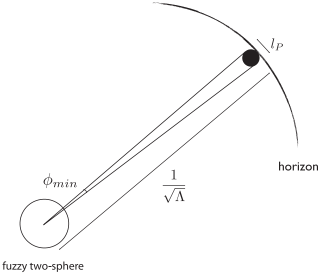
$$q = \exp(i\ell_P^2\Lambda)$$

(3+1)D quantum gravity: deformation typical of q-de Sitter noncommutative models

(Hopf algebras/quantum groups)



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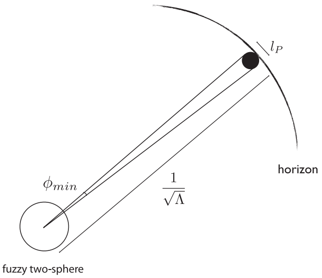

To disentangle quantum-gravity effects from curvature seems to require some sizeable fine tuning (Amelino-Camelia+Smolin+Starodubtsev,Class.QuantumGrav.21(2004)): in (3+1)D contraction requires some "renormalization" of generators, $\Lambda \to 0$ seems to lead to standard Poincaré symmetries unless some fine tuning of renormalization parameters is applied.

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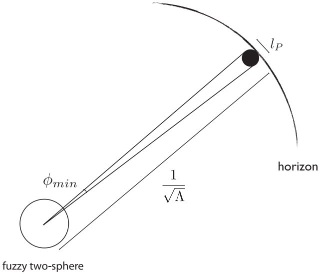

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see also the recent (Aschieri+Borowiec+Pachoł,JCAP04(2021),arXiv:2009.01051): noncommutative differential geometry approach based on Drinfeld twist deformation, κ-Minkowski in FLRW.

This encourages to consider **“curvature-induced” scenarios**:

in-vacuo dispersion is not present in the flat (even non-commutative) limit, but only when spacetime curvature is significant.

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However, it turns out that curvature appears in the formulas always multiplied by the distance traveled by the particle.

For the relevant phenomenology the distance is cosmological, (typical redshifts between 0.5 and 4) and compensates the spacetime curvature suppression.

Jacob-Piran dispersion relation (LIV) (Jacob+Piran,JCAP01(2008))

$$E = \frac{p}{a\left(t\right)}\left(1 - \frac{\lambda}{2}\frac{p}{a\left(t\right)}\right) \quad \longrightarrow \quad \Delta t = \lambda \Delta p \int_0^{z_{em}} \frac{dz}{H\left(z\right)}\left(1+z\right)$$

$$H\left(z\right) = H_0 \sqrt{\Omega_m \left(1+z\right)^3 + \Omega_\Lambda}$$

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alternative possibilities were considered (G.R.+Amelino-Camelia+Marciano+Matassa,PRD92(2015), "Planck-scale-modified dispersion relations in FRW spacetime")

$$\Delta t = p_h \int_0^z \frac{d\bar{z}}{H(\bar{z})}\left[\frac{\lambda'}{(1+\bar{z})} + \lambda'' + \lambda(1+\bar{z}) + \lambda'''(1+\bar{z})^2\right] \qquad \text{LIV}$$

$$\begin{aligned}\Delta t = \ell p_h \Bigg(&(\beta+\gamma)\int_0^z \frac{d\bar{z}\,(1+\bar{z})}{H(\bar{z})} \\ &+(\alpha-\gamma)\int_0^z \frac{d\bar{z}}{(1+\bar{z})H(\bar{z})}\left(1+\bar{z}-H(\bar{z})\int_0^{\bar{z}(t)}\frac{d\bar{z}'}{H(\bar{z}')}\right)^2\Bigg)\end{aligned} \qquad \text{DSR}$$

(see also (Rodriguez Martinez+Piran,JCAP04(2006)) and (Pfeifer,PLB780(2018)))

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Amelino-Camelia+G.R+Bedić, PLB 820(2021)136595, arXiv:2012.07790

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particle velocity
$\left(z = \frac{1}{a(t)} - 1, \quad a(0) = 1\right)$

$$v(z) = 1 + z - \left(\lambda + \lambda' + 2\lambda z\left(1 + \frac{1}{2}z\right)\right) p$$

for small t $\quad \simeq 1 - H_0 t - \left(\left(\lambda + \lambda'\right) - 2\lambda H_0 t\right) p$

for $\lambda' = -\lambda$ it is a pure "curvature-induced" correction

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time delay

$$\Delta t = \Delta p \int_0^{zem} \frac{dz}{H\left(z\right)}\left(\lambda\left(1+z\right) + \frac{\lambda'}{\left(1+z\right)}\right)$$

$$\Delta t\big|_{\lambda' = -\lambda} = 2\lambda \Delta p \int_0^{zem} \frac{dz}{H\left(z\right)} \frac{z + z^2/2}{1+z}$$

Amelino-Camelia+G.R+Bedić, PLB 820(2021)136595, arXiv:2012.07790

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

Amelino-Camelia+D'Amico+Loret+G.R.,Nat.Astr.1(2017)

GRB photons

event	z	E_{obs} [GeV]	Δt [s]
130427A	0.34	77.1	18.10
090510	0.90	29.9	0.86
160509A	1.17	51.9	62.59
100414A	1.37	29.8	33.08
090902Ba	1.82	14.2	4.40
090902Bb	1.82	15.4	35.84
090902Bc	1.82	18.1	16.40
090902Bd	1.82	39.9	71.98
090926A	2.11	19.5	20.51
080916Ca	4.35	12.4	10.56
080916Cb	4.35	27.4	34.53

selection criteria:
(energy at emission) $E_{em} > 40$ GeV
(intrinsic time lag) $t_{off} < 20$ s
assumptions: high-energy photons emitted in coincidence with the first low-energy peak

Jacob-Piran

$$\Delta t\big|_{\lambda'=0} = \lambda \Delta p \int_0^{z_{em}} \frac{dz}{H(z)} (1+z)$$

curvature-induced

$$\Delta t\big|_{\lambda'=-\lambda} = 2\lambda \Delta p \int_0^{z_{em}} \frac{dz}{H(z)} \frac{z + z^2/2}{1+z}$$

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3 out of 11 photons do not fit the model

- 090902Bb larger delay (later peak)
- 080916Cb smaller delay, but large uncertainties
- 090510 ? smaller delay, and small uncertainties

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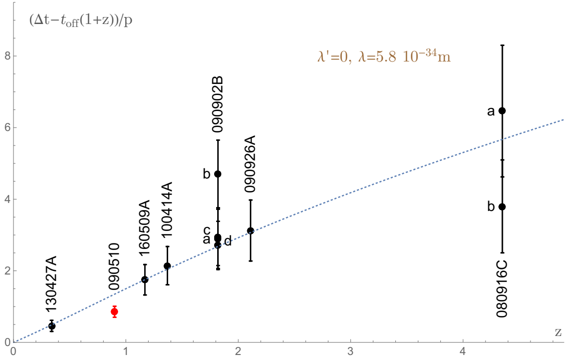

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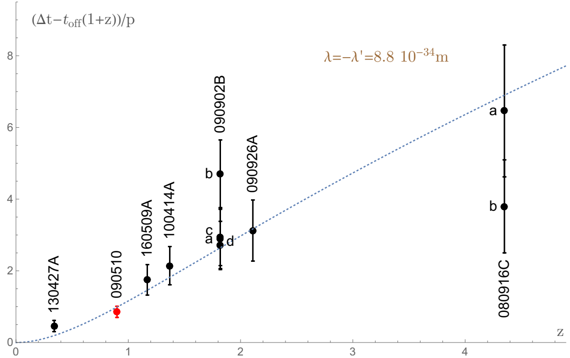

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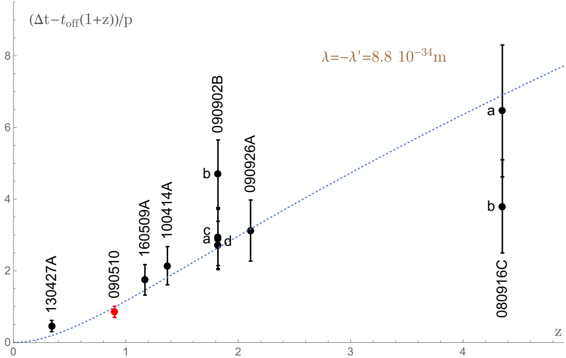

- no overall suppression of the effects due to curvature
- much weaker in-vacuo dispersion effects only for small redshifts
- handles well 090510!

Amelino-Camelia+G.R+Bedić, PLB 820(2021)136595, arXiv:2012.07790

Summary and Outlook

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- Nevertheless, comparing the statistical analysis for GRB photons 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

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- new data are going to be available soon, while old data have been reviewed from IceCube collaboration (recalibration of energy and angular analysis).

  (G. Amelino-Camelia + G. D'Amico + G. Gubitosi + M.G.Di Luca + (G. R.) *in progress*)

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- we have shown that phenomenology of curvature (& quantum-gravity) -induced in-vacuo dispersion is viable.

- We introduced this $\lambda' = -\lambda$ scenario just as a toy model. Nevertheless, we expect that some features, like the slow onset of effects at small redshifts, will characterize other scenarios for curvature-triggered quantum gravity effects.

Thanks!

Testing quantum spacetime with gamma-ray-burst neutrinos and photons

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Phys.Lett.B761,(2016)

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

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