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UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

COULD QUANTUM GRAVITY SLOW DOWN NEUTRINOS?

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based on

G. Amelino-Camelia, M. G. Di Luca, G. Gubitosi, G. Rosati & G. D’Amico

Nature Astronomy 7, 996–1001 (2023)

TeVPA23 - Napoli

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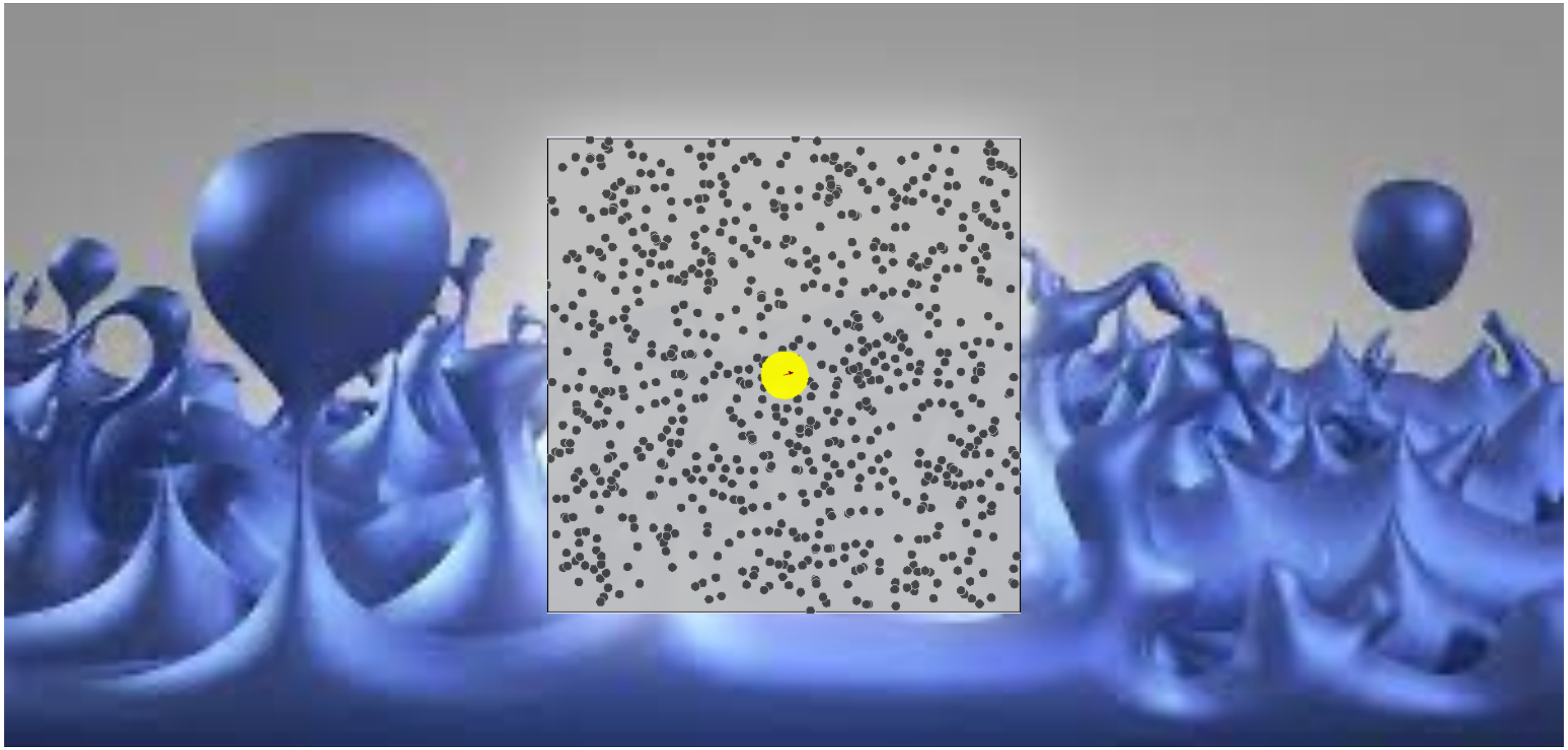
Propagation of particles in quantum spacetime

In quantum gravity research it is expected that spacetime shows quantum properties when tested at length scales of the order of the Planck length

$$L_P \sim 10^{-35}\mathrm{m}$$

When particles travel in such spacetime, anomalous propagation effects accumulate

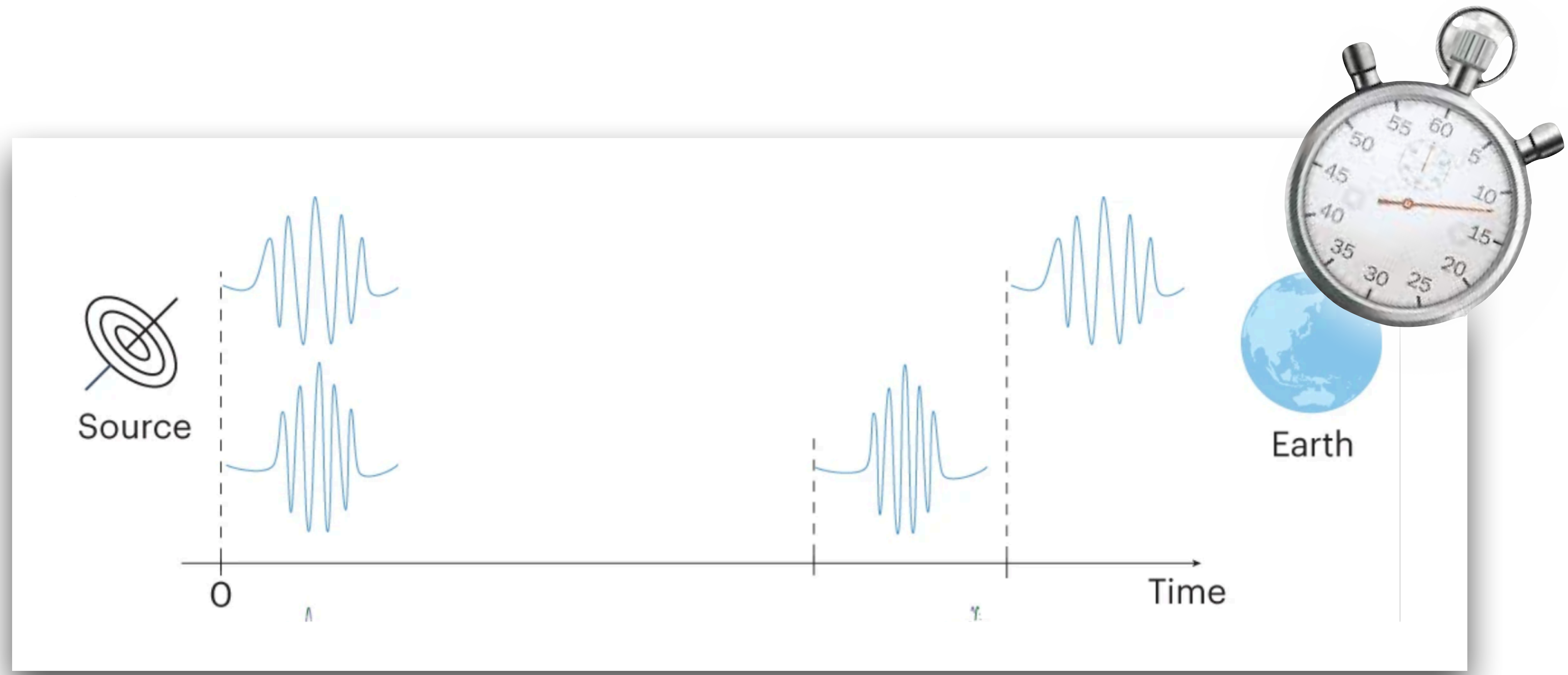


Propagation of particles in quantum spacetime - in vacuo dispersion

A possible anomalous propagation effect is in vacuo dispersion: the speed of ultra relativistic particles acquires an energy dependence

$$v(E) = \left(1 + \eta \frac{E}{E_P}\right)$$

(Showing only the leading-order term in powers of the particle's energy over the Planck energy $E_P \sim 10^{19}\text{GeV}$)



Propagation of particles in quantum spacetime - in vacuo dispersion

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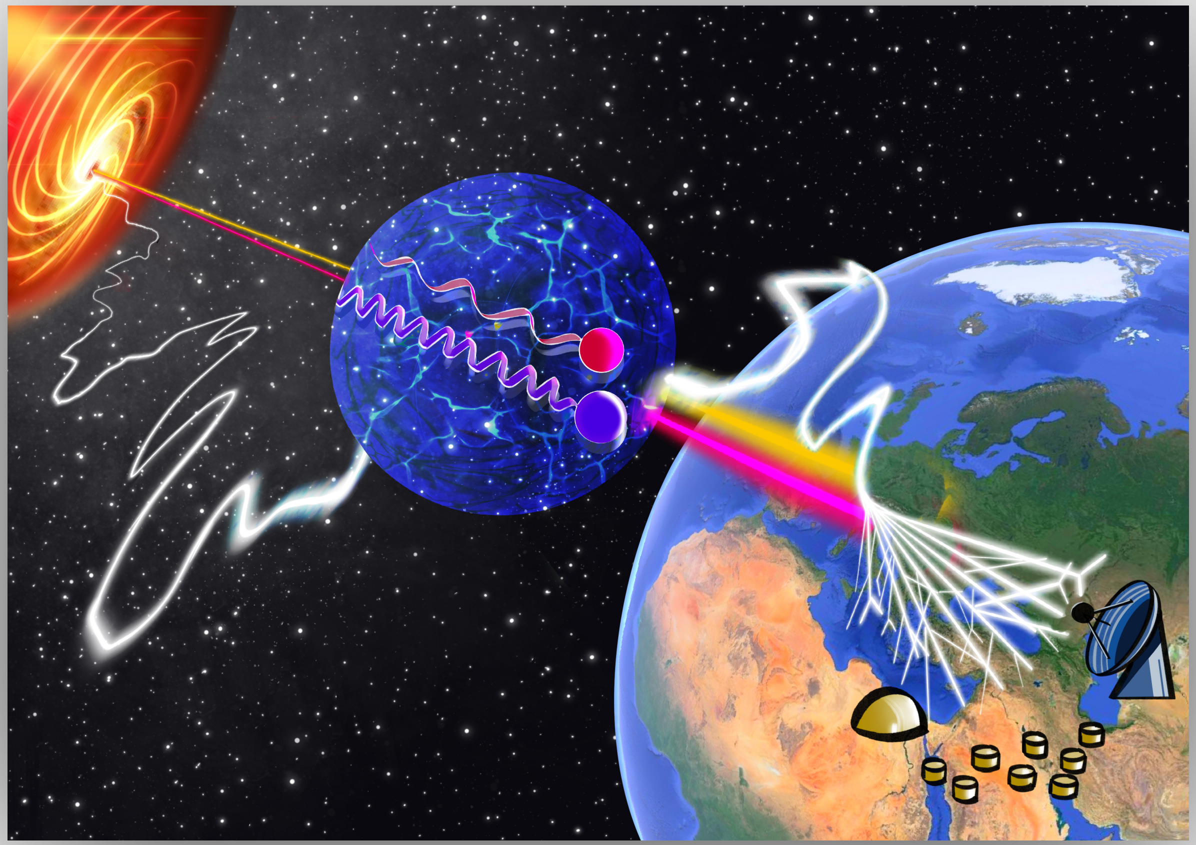
(Showing only the leading-order term in powers of the particle's energy over the Planck energy $E_P \sim 10^{19}\mathrm{GeV}$)

Particles with energy difference ΔE emitted simultaneously arrive at the detector with a time difference (in flat spacetime)

$$\Delta t = \eta L \frac{\Delta E}{E_P}$$

Implications for astrophysical messengers

This kind of effect can be tested best by looking at high energy particles (photons, neutrinos) from astrophysical sources (so that the very long travel time can amplify even tiny propagation effects to a detectable level)



flat spacetime: $$\Delta t = \eta \, L \, \frac{\Delta E}{E_P}$$

FRW spacetime: $$\boxed{\Delta t = \eta \, D(1) \, \frac{\mathcal{K}(E,z)}{E_P}}$$

Jacob, Piran, JCAP 2008

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

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

→ Search for correlation between energy, distance of the source and arrival time

Implications for astrophysical messengers

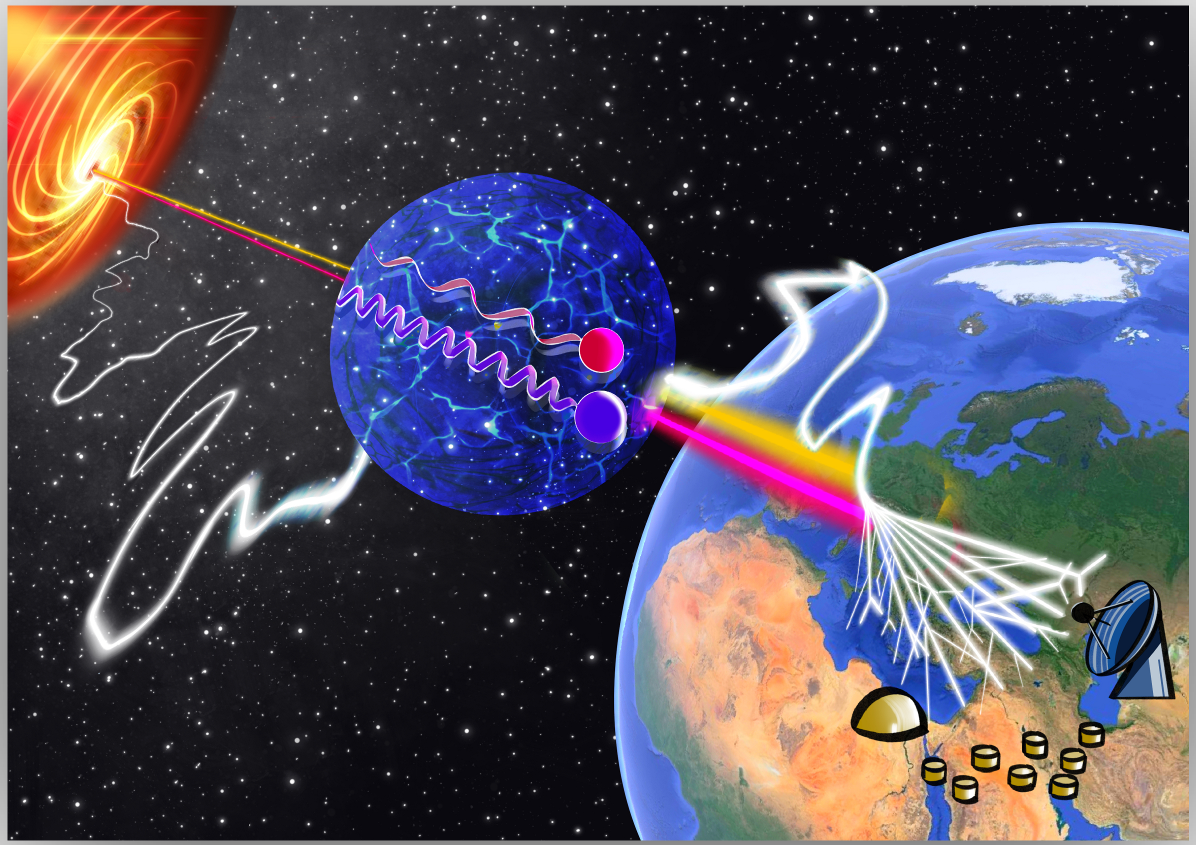
Using the FRW formula for time delays, assuming $\eta = 1$ and a source at redshift $z = 1$

For particles of energy ~10 GeV, one might expect a time difference w.r.t. low energy particles

$$\Delta t \sim 10^{-1} s$$

For particles of energy ~100 TeV, one might expect a time difference w.r.t. to low energy particles

$$\Delta t \sim 1\,\text{day}$$



Challenges: intrinsic emission mechanisms at the source; identification of the source and its redshift; energy resolution

Searching for energy-dependent time delays with astrophysical messengers

QUANTUM · GRAVITY · MULTI · MESSENGER ·

See the review "*Quantum gravity phenomenology in the multi-messenger approach*" by the COST Action CA18108, Prog. Part. Nucl. Phys. 125 (2022) 103948 arXiv: 2111.05659 [hep-ph]

letters to nature

Tests of quantum gravity from observations of γ-ray bursts

G. Amelino-Camelia, John Ellis, N. E. Mavromatos, D. V. Nanopoulos & Subir Sarkar

Nature **393**, 763–765 (1998)

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Bounds on Lorentz Invariance Violation from MAGIC Observation of GRB 190114C

V. A. Acciari *et al.* (MAGIC Collaboration)
Phys. Rev. Lett. **125**, 021301 – Published 9 July 2020

nature astronomy

***In vacuo* dispersion features for gamma-ray-burst neutrinos and photons**

Giovanni Amelino-Camelia[1,2*], Giacomo D'Amico[1,2], Giacomo Rosati[3] and Niccoló Loret[4]

nature astronomy

Article https://doi.org/10.1038/s41550-023-01993-z

Could quantum gravity slow down neutrinos?

Received: 29 September 2022
Accepted: 3 April 2023

Giovanni Amelino-Camelia[1,2], Maria Grazia Di Luca[1,2,3], Giulia Gubitosi[1,2], Giacomo Rosati[4] & Giacomo D'Amico[5]

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A. A. Abdo, M. Ackermann, [...] M. Ziegler

Nature **462**, 331–334 (2009) | Cite this article

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Limits on an Energy Dependence of the Speed of Light from a Flare of the Active Galaxy PKS 2155-304

F. Aharonian *et al.* (H.E.S.S. Collaboration)
Phys. Rev. Lett. **101**, 170402 – Published 22 October 2008

Search for energy-dependent time delays in GRB-neutrinos

Search for a correlation between the time of arrival of GRB neutrino candidates and the corresponding GRB signal (which is relatively low energy)

Jacob, Piran, Nature Physics 2007; Amelino-Camelia, Guetta, Piran, ApJ 2015; Amelino-Camelia, D'Amico, Rosati, Loret, Nature Astronomy 2017

Selection criteria of GRB neutrino candidates:

- 4y sample of ICECUBE 'cascade' events (good energy resolution, $\sim 10\,\%$, poor angular resolution, $\sim 15°$), from the catalogue in Abbasi, R. et al. [IceCube collaboration] Phys. Rev. D 104, 022002 (2021)
- Neutrino energy $60\,\mathrm{TeV} < E_\nu < 500\,\mathrm{TeV}$
- GRB catalogue from icecube.wisc.edu/~grbweb_public/Summary_table.html
- Neutrino signal observed in a 3-day window w.r.t. the GRB and in spatial coincidence with the GRB (within a 3σ sigma region, $\sigma = \sqrt{\sigma_{GRB}^2 + \sigma_\nu^2}$)

Redshift of the source is assigned based on the GRB redshift. For GRBs with unknown redshift this is estimated from GRBs with known redshift that find a neutrino match

Search for energy-dependent time delays in GRB-neutrinos

We consider separately the hypotheses $\eta < 0$ (early GRB neutrino signal) and $\eta > 0$ (late GRB neutrino signal)

- For $\eta < 0$ we find 3 candidate GRB neutrino out of 27 neutrino events

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

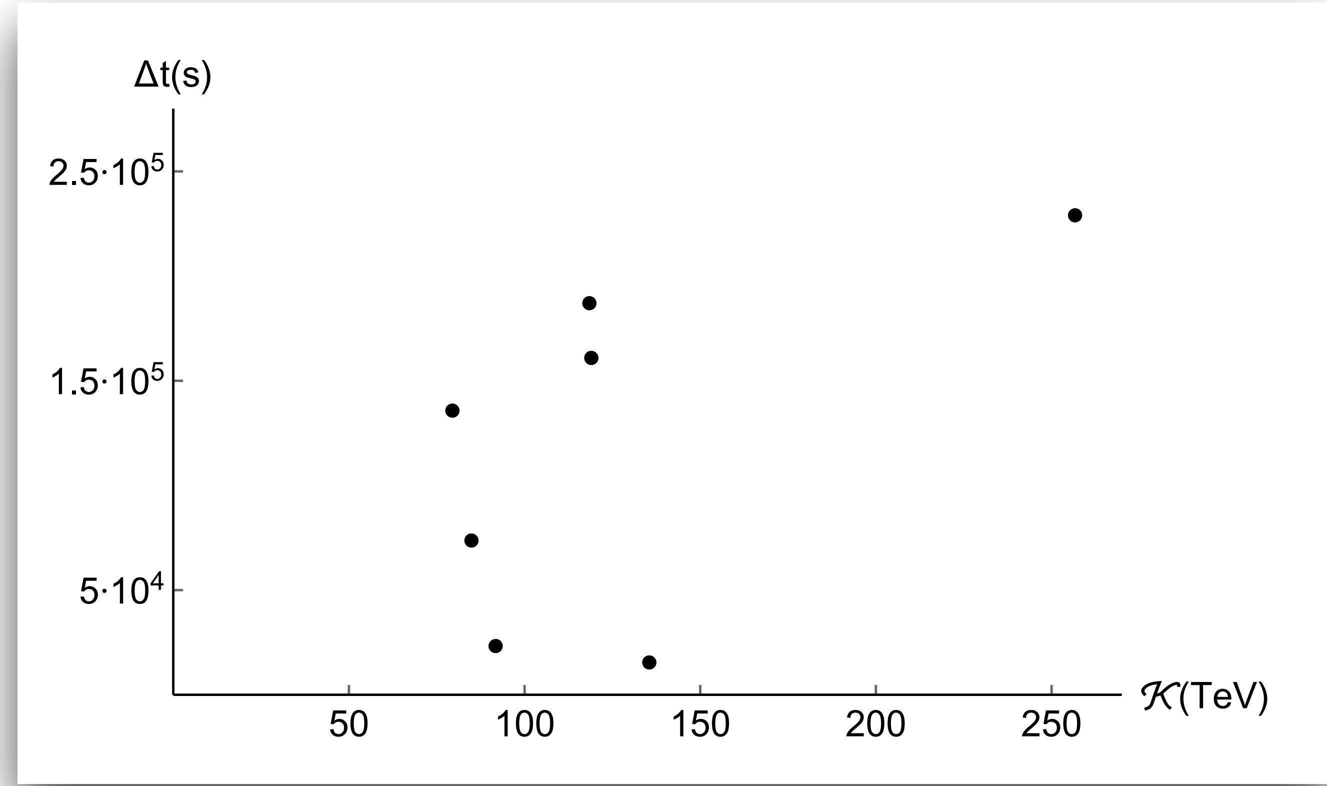
Probability of accidentally finding at least 3 such associations is 81% (using 10^5 simulations of the 27 neutrino events and the same selection criteria as for the real dataset), therefore we exclude this possibility

- For $\eta > 0$ we find 7 candidate GRB neutrino out of 27 neutrino events

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

Probability of accidentally finding at least 7 such associations is 5% (using 10^5 simulations of the 27 neutrino events and the same selection criteria as for the real dataset), therefore we investigate this possibility

Characterisation of candidate late GRB-neutrino events



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

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

- When more than one GRB-neutrino association is found, we select the GRB that gives the highest correlation

- We estimate the background (i.e. number of neutrinos that accidentally find a GRB association) to be at least 1 with 83% probability, at least 2 with 39% probability and at least 3 with 18% probability

- Correlation of the data points is 0.56

- Probability of accidentally finding at least 7 GRB neutrino candidates (out of 27 neutrinos in the catalogue) with correlation at least 0.56 is 0.7% (using 10^5 simulations of the 27 neutrino events and the same selection criteria as for the real dataset)

Search for energy-dependent time delays in GRB-neutrino — including PeV neutrino

In order to extend the energy range of the analysis to PeV neutrino one would need to open the time window too much (tens of days), causing trouble in handling too many multiple GRB associations.

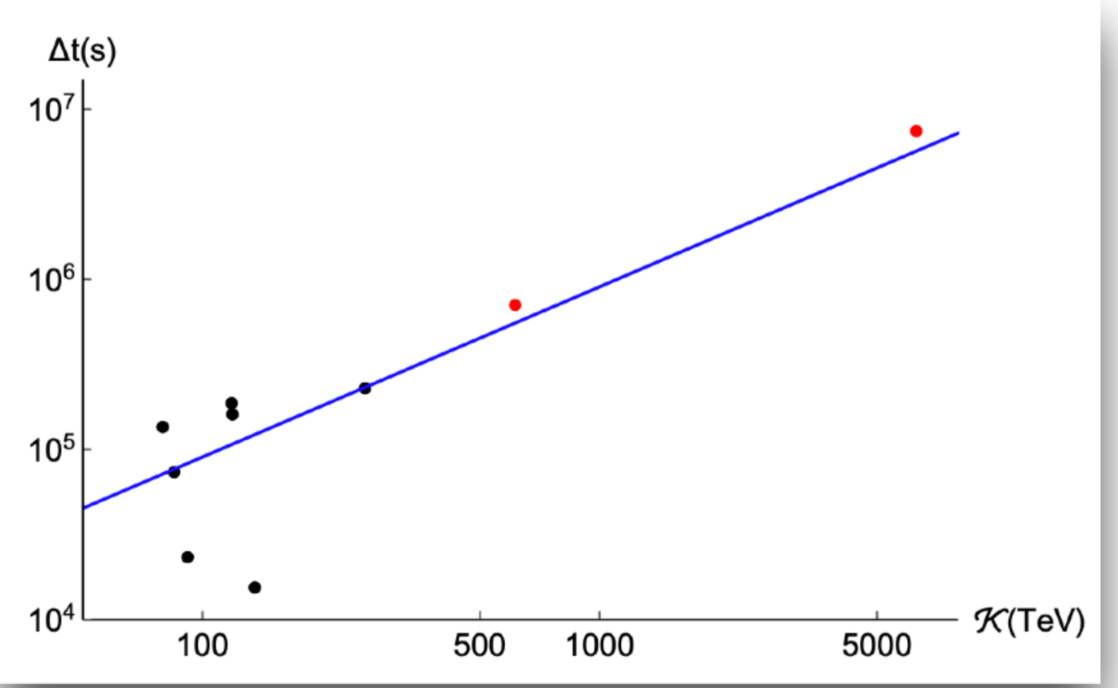
Instead, we use the 60 TeV - 500 TeV neutrinos to estimate $\eta = 21.7 \pm 9$ and use this information to search for candidate GRB neutrino in the PeV range in a restricted time window, asking that

$$|\,\Delta t - \eta \cdot \mathcal{K}(E,z)\,| < 2\,\delta\eta\,\mathcal{K}(E,z)$$

Of the 3 PeV neutrinos in our sample, we find 2 with a GRB association

	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	1,800.0	7,435,884	3.93	L

Characterisation of candidate late GRB-neutrino events — including PeV neutrinos



Blue line corresponds to $\eta = 21.7$

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

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

- When more than one GRB-neutrino association is found, we select the GRB that gives the highest correlation
- Overall correlation of the data points is 0.9997
- Probability of accidentally finding at least 2 PeV GRB neutrino candidates (out of the 3 PeV neutrinos in the sample) within the time window specified by the lower-energy GRB neutrino candidates and with correlation at least 0.9997 is 0.005%

Conclusions and outlook

- This work was aimed at establishing a methodology to search for anomalous propagation effects that are expected in some quantum gravity models.
- Applying this methodology to a sample of IceCube astrophysical neutrino cascade events, we found a correlation between the energy of GRB neutrino candidates and their time of arrival w.r.t the GRB counterparts.
- The significance of the result is currently limited by the small sample size, but the established methodology will be able to confirm or disprove the presence of such correlation as the neutrino data sample grows
- Improvement in the angular resolution of IceCube cascade events and improved energy reconstruction for IceCube track events would also improve the analysis


THANK YOU

Background estimation

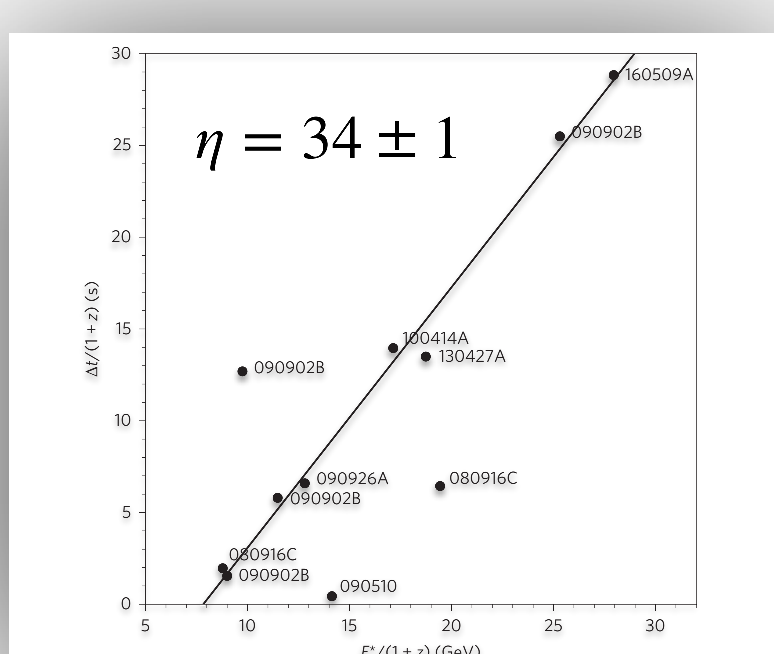
- L neutrinos that find a GRB association (in our case L=7)
- randomize the times of observation of the neutrinos that were not selected $(N - L)$ (in our case (27-7=20))
- count how frequently in such randomizations one finds the accidental appearance of late GRB-neutrino candidates (fraction ζ)
- estimate M (true GRB-neutrinos) through $M + \zeta(N - M) = L$

Experimental searches for energy-dependent time shifts - current status

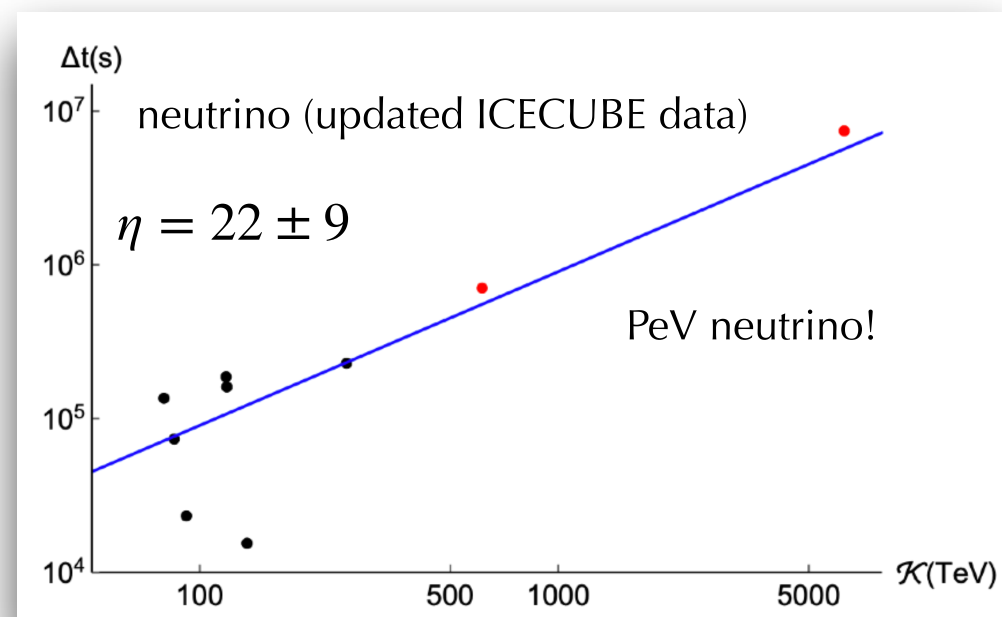
✦ When looking at **individual sources** (e.g. comparing arrival times of low energy and high energy photons within a single GRB), Planck-scale constraints have been set - but beware of intrinsic source effects

$$\Delta t \simeq \eta \frac{\Delta E}{E_P}\frac{L}{c} \qquad \longrightarrow \qquad \eta \lesssim 1$$

✦ When comparing arrival differences from **different sources** there is a different indication - but statistical significance is currently limited by the scarcity of data



[Amelino-Camelia, D'Amico, Rosati, Loret. Nature Astronomy 2017]



[Amelino-Camelia, Di Luca, Gubitosi, Rosati, D'Amico, Nature Astronomy 2023]

Experimental searches for energy-dependent time shifts - current status

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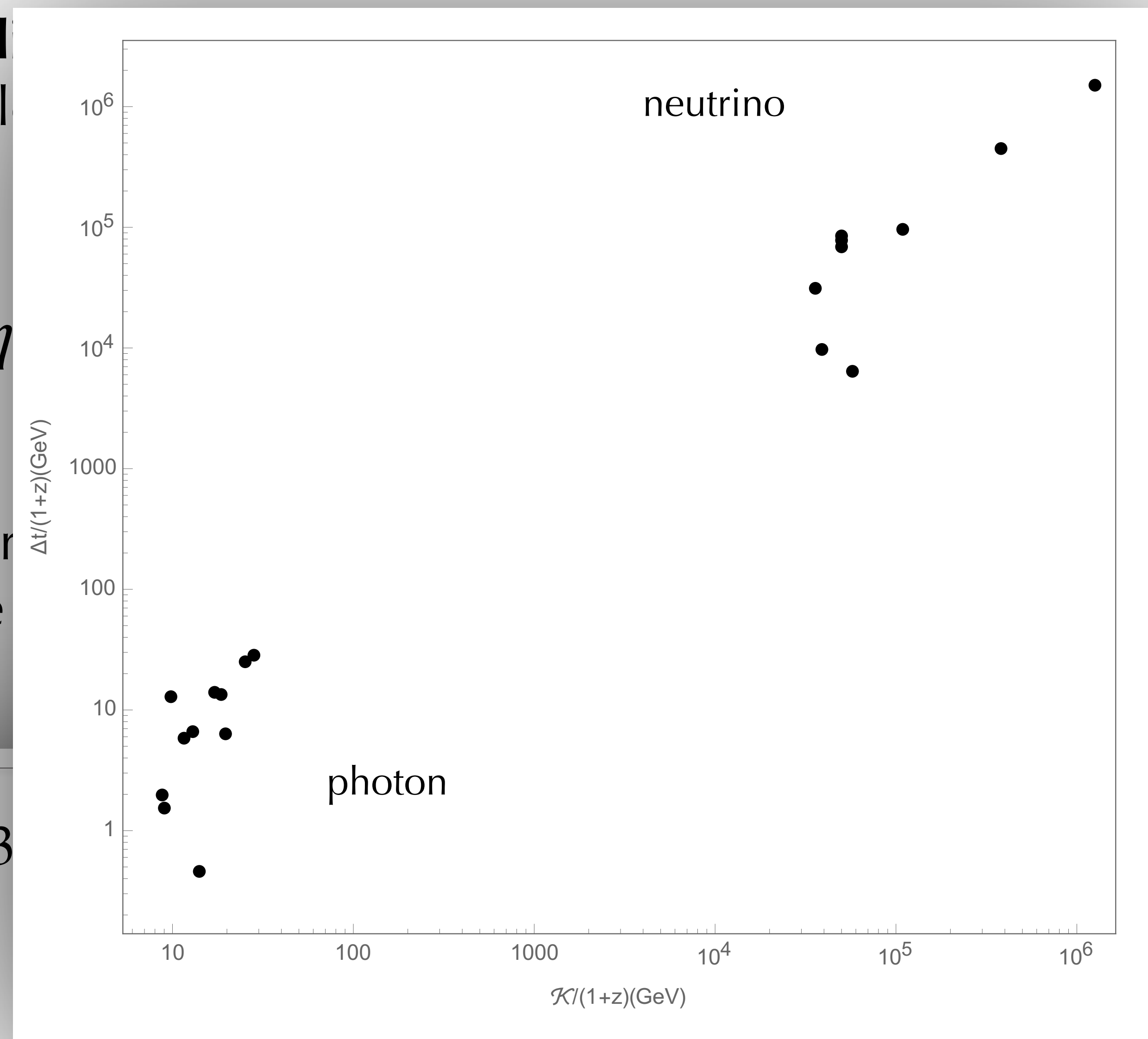

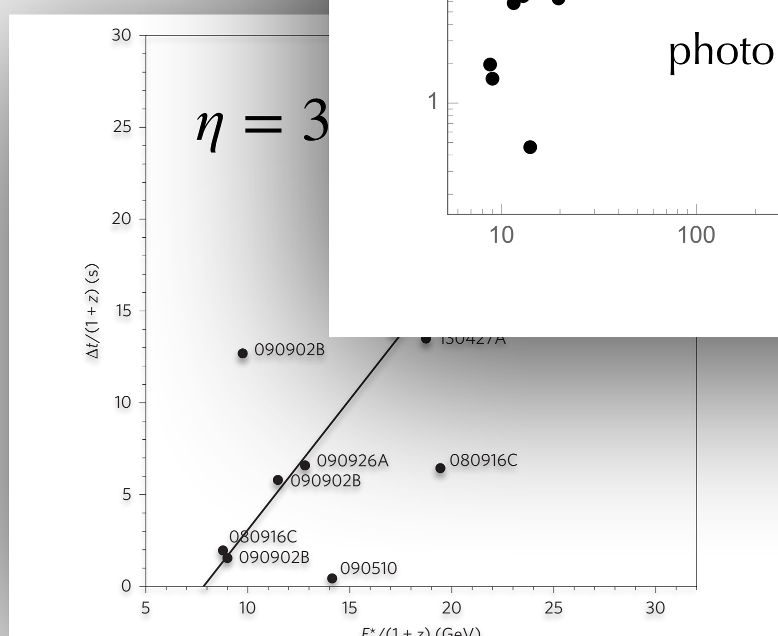

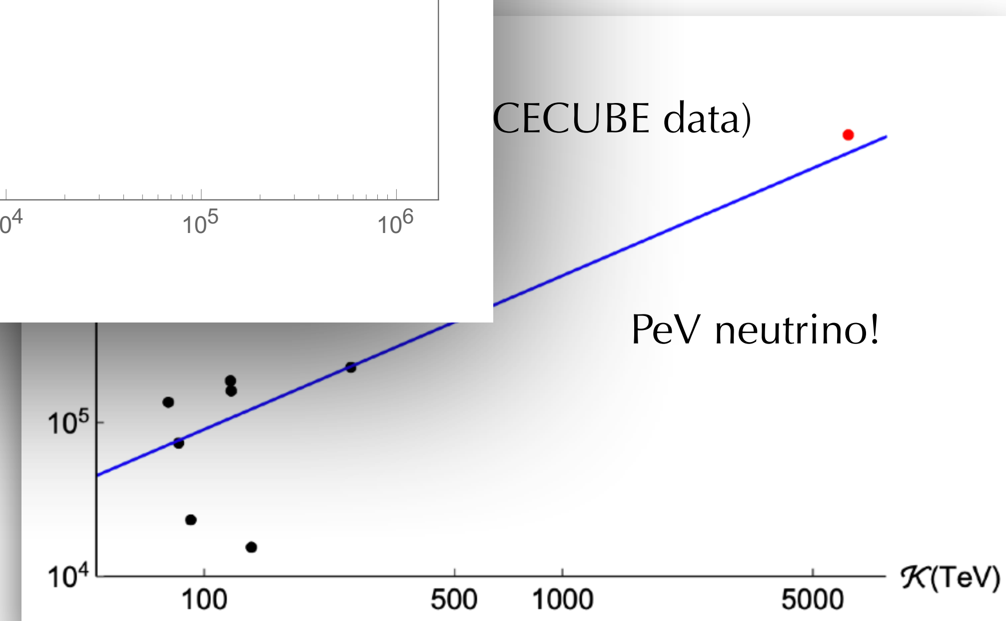

[Amelino-Camelia, D'Amico, Rosati, Loret. Nature Astronomy 2017]

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