Title: Planck-scale violations of relativistic symmetries in astrophysics and in quantum systems

Speakers: Giulia Gubitosi

Collection/Series: Emmy Noether Workshop: Quantum Space Time

Date: March 10, 2025 - 11:15 AM

URL: https://pirsa.org/25030057

Abstract:

The Planck scale is generally believed to mark the onset of quantum gravity effects. In this talk, I will illustrate some of the most relevant features of models where the Planck scale governs deformations of relativistic symmetries and discuss opportunities for experimental tests of such models arising in physical frameworks much below the Planck scale. This concerns astrophysical observations, sensitive to tiny residual signatures at low energies thanks to amplification mechanisms, and table-top experiments, whose extremely high-precision might soon allow us to test the interplay between (quantum) gravity and quantum systems at ultra-low energies.

Following different trails in a bottom-up journey to quantum gravity

A major advance in quantum gravity research in the past couple of decades has been marked by by efforts to **link quantum gravity to observations**, thanks to the identification of several physical frameworks where new physics effects related to QG could be observable, e.g. early-universe cosmology, astrophysics , gravity-wave astronomy, table-top experiments on quantum systems.

This allows us to complement purely theoretical investigations, aimed at developing models for quantum spacetime based on first principles, with a **bottom-up approach**, aimed at capturing **residual QG effects in an intermediate regime** between the classical spacetime/low energy regime of current theories and the full quantum spacetime/Planck-scale regime:

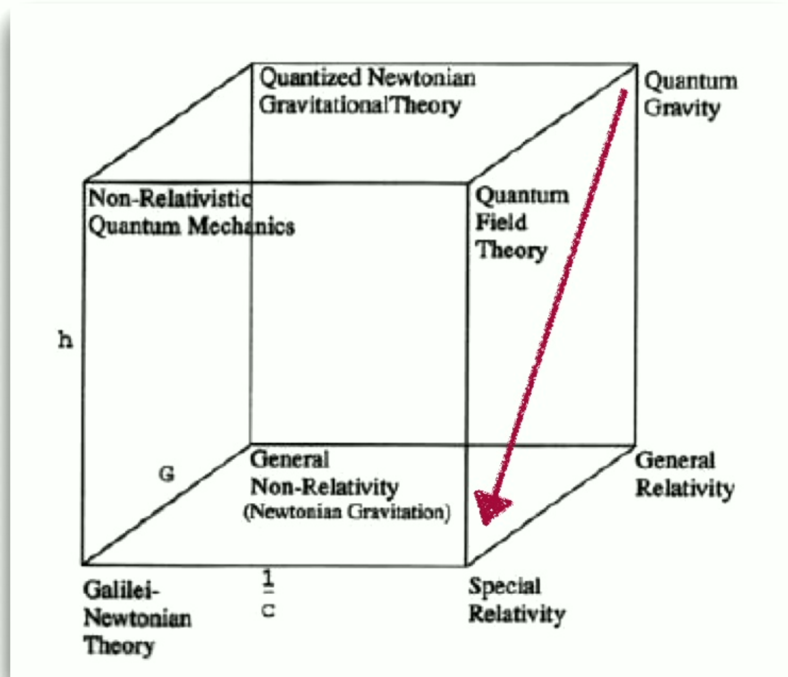
- construct ***effective models*** which are directly testable and try to relate them to features of a given QG theory

- derive ***semi-classical effects*** from QG theories, even if with heuristic arguments, and try to link them to phenomenological models

These methods identify several paths that explore different intermediate regions between the known phenomena and quantum gravity, all of which are relevant in the search for phenomenological constraints.

Following different trails in a bottom-up journey to quantum gravity

Effective models and "semiclassical" QG effects may concern different regions in the space of theories — different directions through which QG reduces to established physics



[Bronstein cube, picture from J. Stachel, 2001]

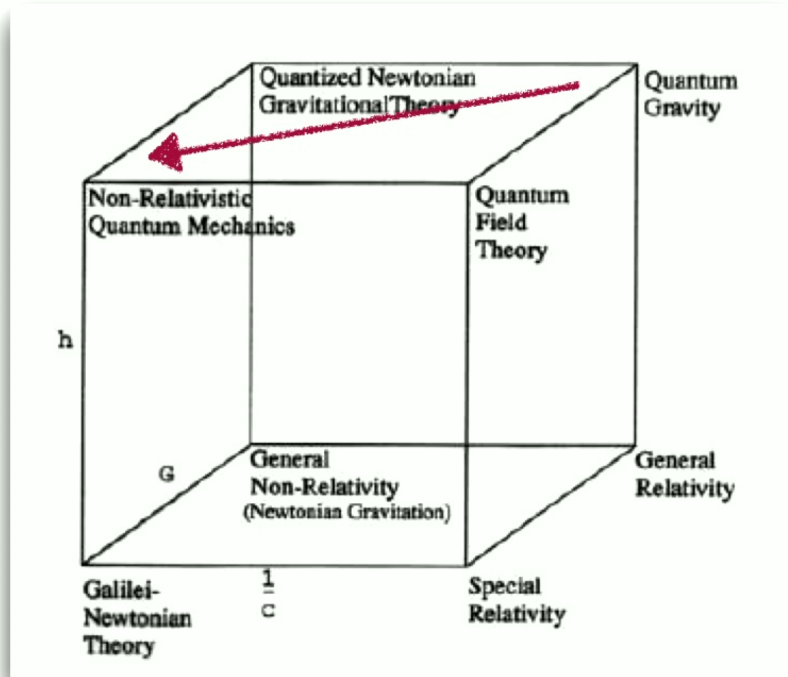
In this talk:

- Modified* relativistic kinematics

* not ANY deviation, but effects that are informed of possible Planck-scale physics

Following different trails in a bottom-up journey to quantum gravity

Effective models and "semiclassical" QG effects may concern different regions in the space of theories — different directions through which QG reduces to established physics



[Bronstein cube, picture from J. Stachel, 2001]

In this talk:

- Modified* relativistic kinematics
- Deviations* from Quantum Mechanics

* not ANY deviation, but effects that are informed of possible Planck-scale physics

Noncommutative spacetime

Spacetime noncommutativity was first proposed in the 1930s-1940s to cure divergences in QFT

Heisenberg, letter to Peierls, 1930
Snyder, Phys. Rev 1947

The idea was revived in the early 1990s to encode the fundamental limitations in the localisability of events that arise when taking both quantum and gravitational effects into account

Doplicher, Fredenhagen, Roberts, PLB 1994
Ahluwalia, PLB 1994

Spacetime noncommutativity also emerges as a possible effective description in several more fundamental approaches to quantum gravity: string theory with background fields, loop quantum gravity, and when considering matter coupled to 2+1 quantum gravity…

D. J. Gross and P. F. Mende, Nucl. Phys. B 1988
D. Amati, M. Ciafaloni, and G. Veneziano, PLB 1989
N. Seiberg, E. Witten, JHEP 1999
Freidel, Kowalski-Glikman, Smolin, PRD 2004
Freidel, Livine PRL 2006
Cianfrani, Kowaslki-Glikman, Pranzetti, Rosati, PRD 2016
Rosati, PRD 2017

Bojowald, Paily, PRD 2013
G. Amelino-Camelia, M. M. da Silva, M. Ronco, L.Cesarini, O. M. Lecian PRD 2017
Brahma, Ronco, PLB 2018
Mielczarek, Trzesniewski, PRD 2017

Noncommutative spacetime

Nontrivial commutators between spacetime coordinates formalise a fundamental uncertainty in the localisability of spacetime points in analogy to the quantization of phase space in quantum mechanics

$$[\hat{x}^\mu, \hat{x}^\nu] = \Theta^{\mu\nu}(\hat{x}) \quad \longrightarrow \quad \Delta\hat{x}^\mu \Delta\hat{x}^\nu \geq \frac{1}{2} |\langle \Theta^{\mu\nu} \rangle|$$

Most work on noncommutative spacetime explored models that can be generically described by

$$[\hat{x}^\mu, \hat{x}^\nu] = \ell_P^2 \theta^{\mu\nu} + \ell_P \gamma^{\mu\nu}_\beta \, \hat{x}^\beta$$

One of the most studied classes of noncommutative spacetime is the so-called κ-Minkowski spacetime, $\kappa^{-1} \sim \ell_P$

Lukierski, Nowicki, Ruegg, PLB 1992
Majid, Ruegg, PLB 1994
Kowalski-Glikman, Nowak 2002-2003

$$\left[x^0, x^i\right] = \frac{i}{\kappa} x^i, \quad \left[x^i, x^j\right] = 0$$

Relativistic symmetries need to be revised in order to leave these commutation relations invariant

Hopf-algebra symmetries of non commutative spacetime

Nontrivial commutation relations of spacetime coordinates are covariant under quantum deformations of the Poincaré symmetries, encoded Hopf algebra formalism.

κ-Minkowski spacetime is covariant under the κ-Poincaré Hopf algebra [shown in 1+1D]:

- Non-linear deformation of commutators and Casimir

$$\begin{aligned}
[P_0, P_1] &= 0 \\
[N, P_0] &= P_1 \\
[N, P_1] &= \tfrac{\kappa}{2}\left(1 - e^{-2P_0/\kappa}\right) - \tfrac{1}{2\kappa} P_1^2
\end{aligned}$$

$$C = 4\kappa^2 \sinh^2\left(\frac{P_0}{2\kappa}\right) - (P_1)^2 e^{P_0/\kappa}$$

- Non-trivial action on products of functions (coproduct and antipode)

$$\begin{aligned}
\Delta(P_0) &= P_0 \otimes 1 + 1 \otimes P_0 \\
\Delta(P_1) &= P_1 \otimes 1 + e^{-P_0/\kappa} \otimes P_1 \\
\Delta(N) &= N \otimes 1 + e^{-P_0/\kappa} \otimes N
\end{aligned}$$

$$\begin{aligned}
S(P_0) &= -P_0 \\
S(P_1) &= -e^{P_0/\kappa} P_1 \\
S(N) &= -e^{P_0/\kappa} N
\end{aligned}$$

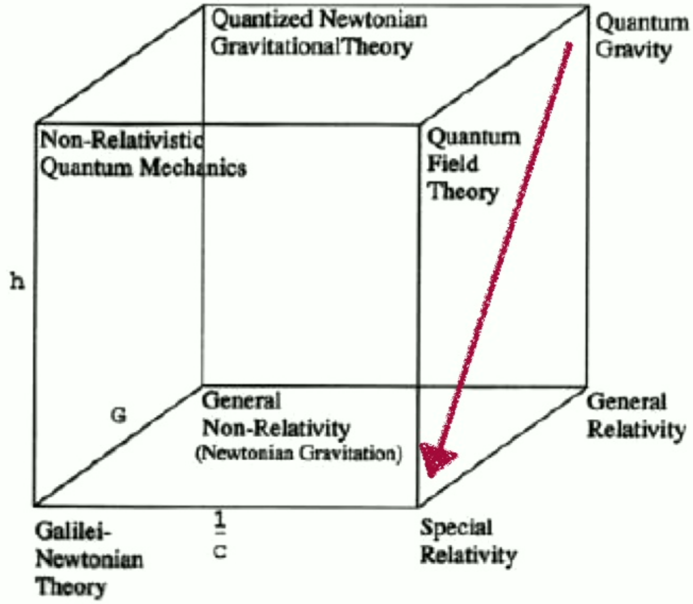
Lukierski, Ruegg, Nowicki, Tolstoi, PLB 1991
Lukierski, Nowicki, Ruegg, PLB 1992
Majid, Ruegg, PLB 1994
Kowalski-Glikman, Nowak 2002-2003

The deformed kinematics regime

In the $\hbar \to 0$ regime of quantum gravity, if we take the limit while keeping $\frac{\hbar}{G} = const$

we can construct an **energy scale**, but **not a length scale**

$$E_P = \sqrt{\frac{\hbar c^5}{G}} \to const \qquad \ell_P = \sqrt{\frac{\hbar G}{c^3}} \to 0$$



- it is natural to look at physics from the point of view of **momentum space rather than spacetime**

- We can construct **deformed special-relativistic symmetries (DSR)**, such that the energy scale is a second relativistic invariant besides the speed of light

Amelino-Camelia, IJMPD 2002, PLB 2001
Kowalski-Glikman, IJMPA 2001
Magueijo, Smolin, PRL 2002, PRD 2003

Hopf-algebra symmetries of non commutative spacetime

Nontrivial commutation relations of spacetime coordinates are covariant under quantum deformations of the Poincaré symmetries, encoded Hopf algebra formalism.

κ-Minkowski spacetime is covariant under the κ-Poincaré Hopf algebra [shown in 1+1D]:

- Non-linear deformation of commutators and Casimir

$$\begin{aligned} [P_0, P_1] &= 0 \\ [N, P_0] &= P_1 \\ [N, P_1] &= \tfrac{\kappa}{2}\left(1 - e^{-2P_0/\kappa}\right) - \tfrac{1}{2\kappa}P_1^2 \end{aligned}$$

$$C = 4\kappa^2 \sinh^2\left(\frac{P_0}{2\kappa}\right) - (P_1)^2 e^{P_0/\kappa}$$

- Non-trivial action on products of functions (coproduct and antipode)

$$\begin{aligned} \Delta(P_0) &= P_0 \otimes 1 + 1 \otimes P_0 \\ \Delta(P_1) &= P_1 \otimes 1 + e^{-P_0/\kappa} \otimes P_1 \\ \Delta(N) &= N \otimes 1 + e^{-P_0/\kappa} \otimes N \end{aligned}$$

$$\begin{aligned} S(P_0) &= -P_0 \\ S(P_1) &= -e^{P_0/\kappa}P_1 \\ S(N) &= -e^{P_0/\kappa}N \end{aligned}$$

Lukierski, Ruegg, Nowicki, Tolstoi, PLB 1991
Lukierski, Nowicki, Ruegg, PLB 1992
Majid, Ruegg, PLB 1994
Kowalski-Glikman, Nowak 2002-2003

Particle kinematics in κ-DSR

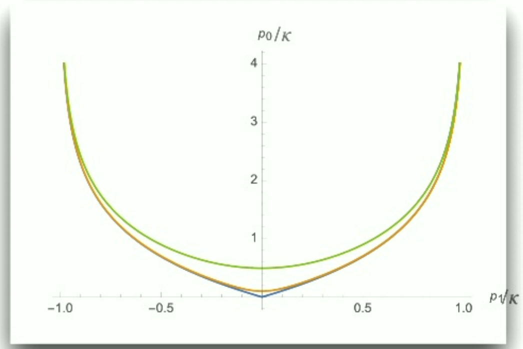
The Hopf-algebra generators encode properties of the energy and momentum

- From the Casimir of the algebra we derive a deformed free-particle **mass-shell** condition

$$\begin{aligned} m^2 &= 4\kappa^2 \sinh^2(E/2\kappa) - p_1^2 e^{E/\kappa} \\ &\simeq E^2 - p_1^2 - \frac{1}{\kappa} E p_1^2 \end{aligned}$$

for massless particles $p_1(p_0) = \kappa\left(1 - e^{-p_0/\kappa}\right)$

maximum value for spatial momentum: $p_1^{max} = \kappa$



- From the coproduct we derive deformed the **composition rule** of energy and momenta

$$\begin{aligned} E_p \oplus E_q &= E_p + E_q \\ p_1 \oplus q_1 &= p_1 + e^{-E_p/\kappa} q_1 \\ &\simeq p_1 + (1 - \frac{E_p}{\kappa}) q_1 \end{aligned}$$

Kowalski-Glikman PLB 2002
Gubitosi, Mercati CQG 2013
Gubitosi, Heefer PRD 2019

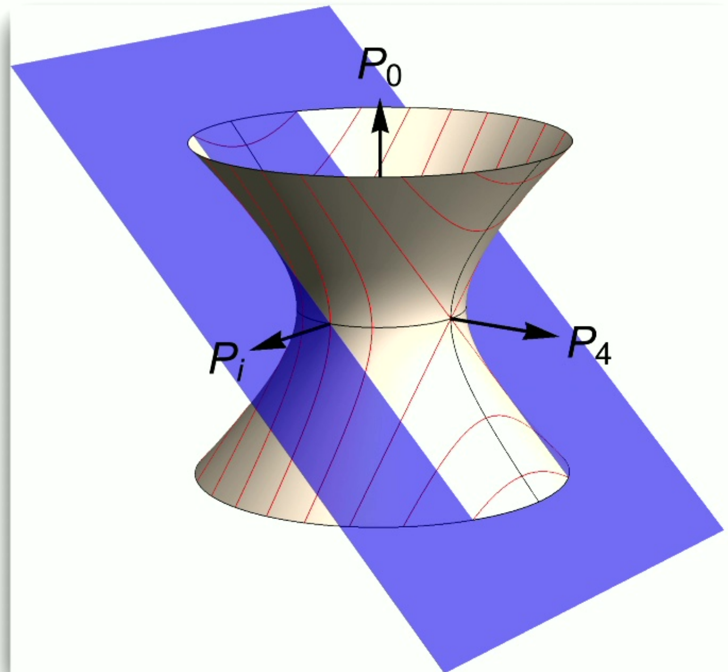
Particle kinematics in κ-DSR

The Hopf-algebra generators encode properties of the energy and momentum

- momenta live on (half of) a de Sitter manifold, the energy scale κ defines its radius of curvature

$$ds_p^2 = dp_0^2 - e^{2p_0/\kappa} dp_1^2$$

Kowalski-Glikman PLB 2002
Gubitosi, Mercati, CQG 2013
Amelino-Camelia, Arzano, Kowalski-Glikman, Rosati, Trevisan, CQG 2012



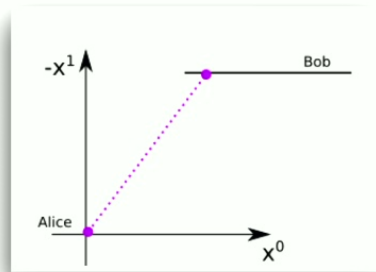
Dual redshift and relativity of locality

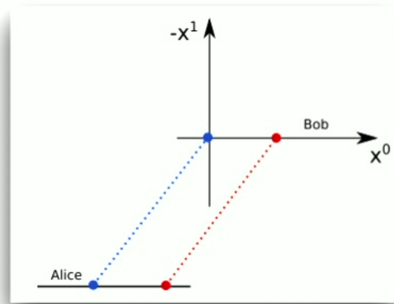
Curvature in momentum space causes effects which are "dual" to the ones induced by spacetime curvature.

Example: **dual redshift**

- When Alice emits two particles with different energies at the same time, Bob sees an energy-dependent shift in their time of arrival

worldlines seen by Alice (local at emission)





worldlines seen by Bob (local at detection)

$$\Delta x^0_B = a^0 \left(e^{\Delta p_0/\kappa} - 1\right) \xrightarrow{1/\kappa = \eta/E_P} \Delta t \simeq \eta \frac{\Delta E}{E_P}\frac{L}{c}$$

Amelino-Camelia, Loret, Rosati, PLB 2011
Amelino-Camelia, Barcaroli, Gubitosi, Loret, CQG 2013

Astrophysical tests of time-of-flight anomalies

Time-of-flight anomalies can be tested by looking at the **propagation of high energy particles** (photons, neutrinos) from astrophysical sources

In flat spacetime:

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

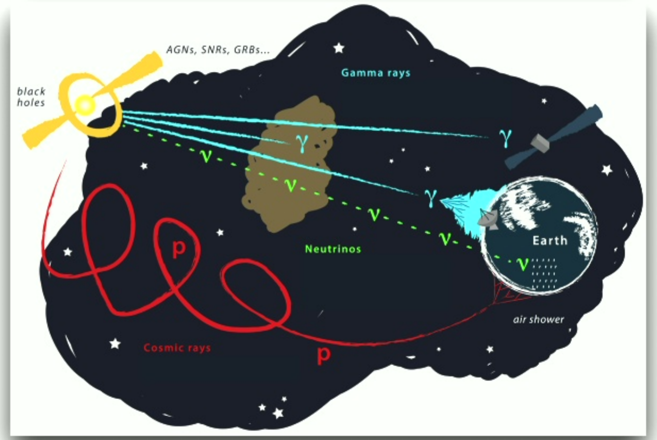
in FRW spacetime*:

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

Jacob, Piran, JCAP 2008

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

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



Credits: IceCube Collaboration

*Other forms of redshift dependence are possible, taking into account a more general dependence of energy redshift on the scale factor, compatibility with DSR symmetries, etc…

Astrophysical tests of time-of-flight anomalies

Time-of-flight anomalies can be tested by looking at the **propagation of high energy particles** (photons, neutrinos) from astrophysical sources

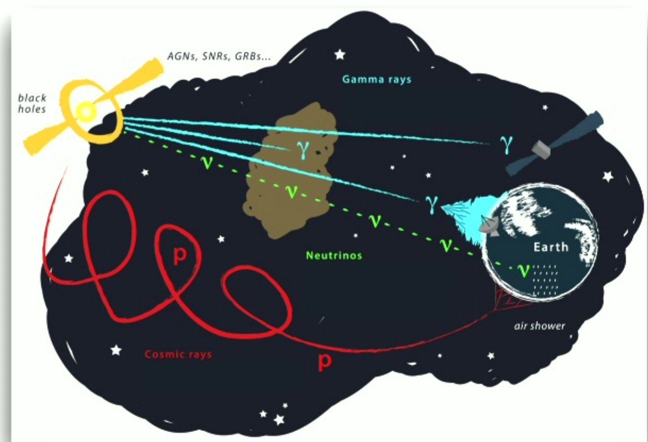
In flat spacetime: $$\Delta t = \eta L \frac{\Delta E}{M_P}$$

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

Jacob, Piran, JCAP 2008

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

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



Credits: IceCube Collaboration

Linear relation between Δt and $\mathcal{K}$

*Other forms of redshift dependence are possible, taking into account a more general dependence of energy redshift on the scale factor, compatibility with DSR symmetries, etc…

Astrophysical tests of time-of-flight anomalies

Time-of-flight anomalies can be tested by looking at the **propagation of high energy particles** (photons, neutrinos) from astrophysical sources

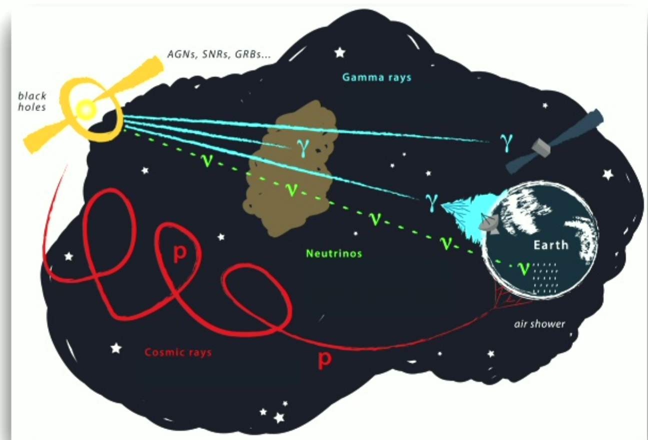
Using the FRW Jacob+Piran formula for time delays, assuming $\eta = 1$ and a source at redshift $z = 1$

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

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



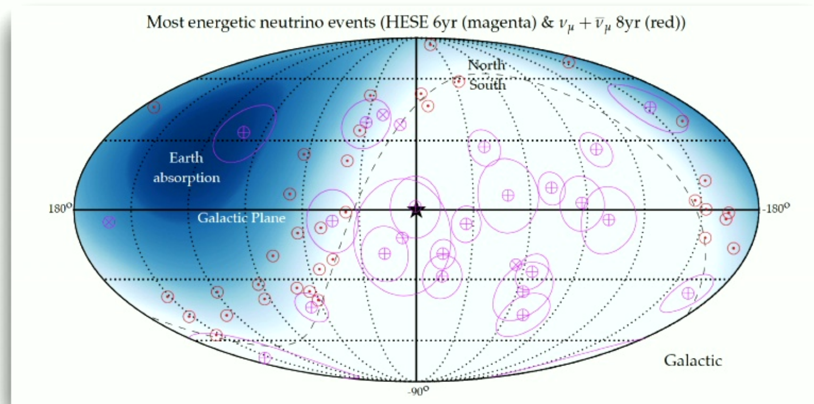
Credits: IceCube Collaboration

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

Search for neutrino energy-dependent time-of-flight anomalies

IDEA: **Combine data from GRBs catalogues** (Fermi, Swift, INTEGRAL, HESS, MAGIC…), **with data from the ICECUBE neutrino detector**, identifying events with directional compatibility
Search for a correlation between the time of arrival of GRB-neutrino candidates and the corresponding low-energy GRB signal

Jacob, Piran, Nature Physics 2007
Amelino-Camelia, Guetta, Piran, ApJ 2015
Amelino-Camelia, D'Amico, Rosati, Loret, Nat. Astr. 2017



Credits: IceCube Collaboration

- Neutrinos from distant sources can have higher energy than photons (the universe is transparent to neutrinos while being opaque for HE photons)
- Neutrinos are not affected by astrophysical propagation effects (interaction with background, with extragalactic magnetic fields, etc.)
- Given the higher energy and thus larger possible time delay, neutrinos are less sensitive to source-intrinsic time lags

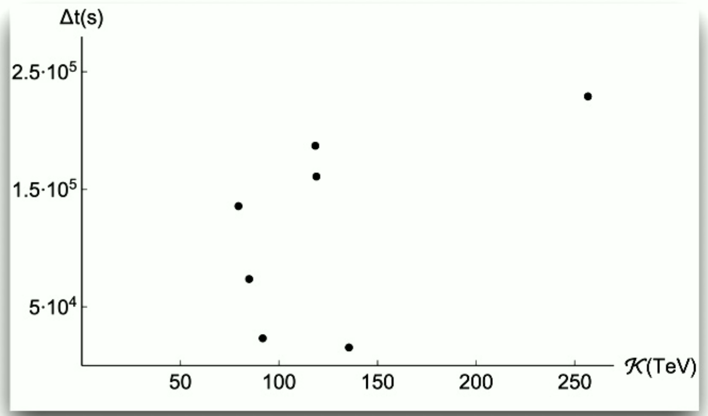
No neutrino has been observed in coincidence with a GRB so far, despite astrophysical models predict they should be emitted in the same events… however typical searches for GRB neutrino search within ~100 seconds.

Search for neutrino energy-dependent time-of-flight anomalies - 2023 results

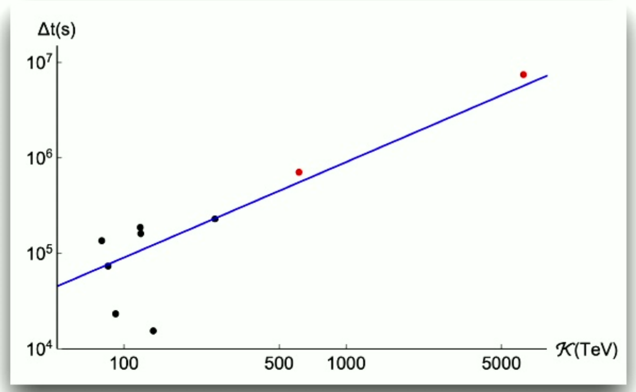
4 years of ICECUBE "cascade events" (10% energy resolution, poor angular resolution, $\sim 15^{\circ}$)

- Neutrino energies: $60\,\text{TeV} < E_\nu < 500\,\text{TeV}$
  3-day time window search
  statistical assignment of GRB redshift*

- We used the range $\eta = 21.7 \pm 9$ estimated from TeV neutrinos to search for GRB-PeV neutrino association in the time window $|\Delta t - \eta \cdot \mathcal{K}(E,z)| < 2\,\delta\eta\,\mathcal{K}(E,z)$



Correlation of the data points is 0.56, p-value 0.007



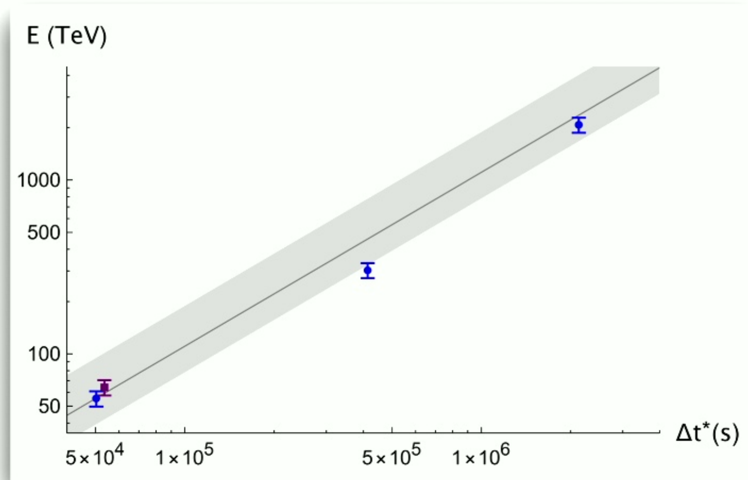
Blue line corresponds to $\eta = 21.7$
Correlation 0.9997, p-value 0.00005

Amelino-Camelia, Di Luca, Gubitosi, Rosati, D'Amico, Nat. Astr. 2023

Search for neutrino energy-dependent time-of-flight anomalies - 2025 results

12 years of ICECUBE "cascade events" (10% energy resolution, poor angular resolution, $\sim 15°$), just use **GRBs with known redshift** (10% of all known GRBs)

- We used the range $\eta = 21.7 \pm 9$ estimated from our previous study to search for GRB-neutrino association in the time window $|\Delta t - \eta \cdot \mathcal{K}(E,z)| < 2\,\delta\eta\,\mathcal{K}(E,z)$



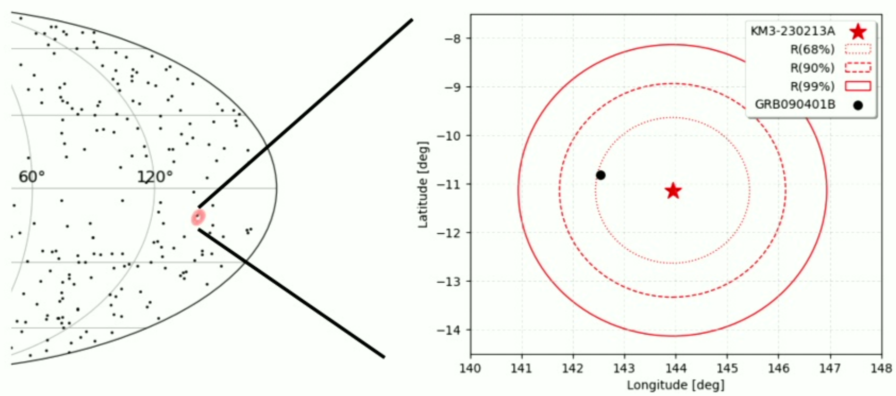
Gray band is the search window. Correlation 0.9985, p-value 0.006

Amelino-Camelia, D'Amico, Fabiano, Frattulillo, Gubitosi, Moia, Rosati, arXiv:2501.13840 [gr-qc]

Search for neutrino energy-dependent time-of-flight anomalies - 2025 results

On February 12, 2025, the KM3-NET collaboration announce the detection of the **highest-energy neutrino ever observed**, a “track" event (precise directional information) with median estimated energy 220PeV

- Searching within the known-redshift GRB catalogue we find that **GRB090401B has very good directional compatibility with the neutrino** (even considering the full GRB catalogue this is the only GRB found with such a good directional agreement)

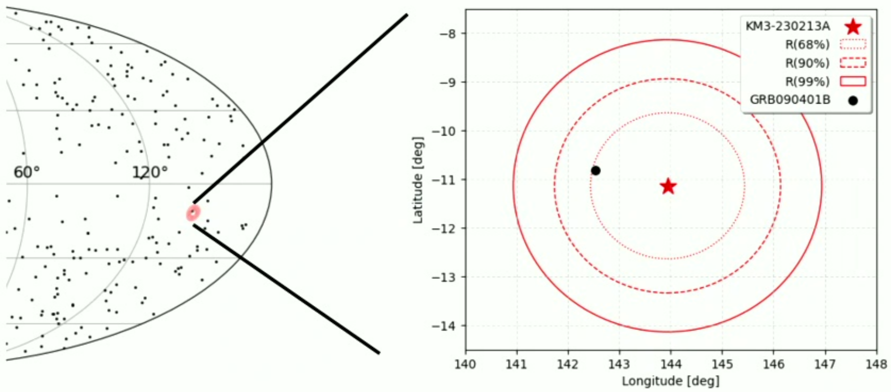


Amelino-Camelia, D’Amico, Fabiano, Frattulillo, Gubitosi, Moia, Rosati, arXiv: 2502.13093 [astro-ph.HE]

Search for neutrino energy-dependent time-of-flight anomalies - 2025 results

On February 12, 2025, the KM3-NET collaboration announce the detection of the **highest-energy neutrino ever observed**, a “track" event (precise directional information) with median estimated energy 220PeV

- Searching within the known-redshift GRB catalogue we find that **GRB090401B has very good directional compatibility with the neutrino** (even considering the full GRB catalogue this is the only GRB found with such a good directional agreement)

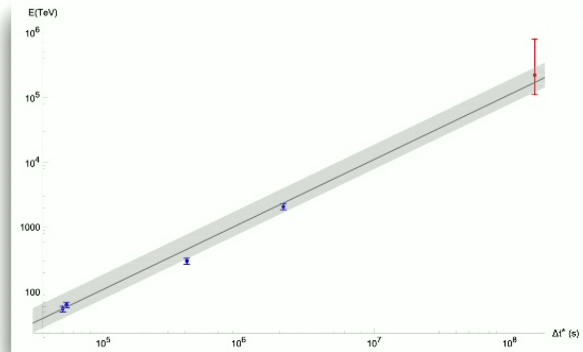


Amelino-Camelia, D’Amico, Fabiano, Frattulillo, Gubitosi, Moia, Rosati, arXiv: 2502.13093 [astro-ph.HE]

Search for neutrino energy-dependent time-of-flight anomalies - 2025 results

On February 12, 2025, the KM3-NET collaboration announce the detection of the highest-energy neutrino ever observed, a “track" event (precise directional information) with median estimated energy 220PeV

- Searching within the known-redshift GRB catalogue we find that **GRB090401B has very good directional compatibility with the neutrino** (even considering the full GRB catalogue this is the only GRB found with such a good directional agreement)
- Using the measured values of Δt (~14 years!) and $z = 3.1$, the range $\eta = 21.7 \pm 9$ estimated from 2023 study is converted in a neutrino energy range by using $\Delta t = \eta D(1) \frac{\mathscr{K}(E,z)}{M_P}$
- These levels of directional and energy compatibility result in a p-value 0.015 (i.e. they have a 1.5% probability of being due to chance, in the no-time-of-flight anomaly scenario)
- Putting this data point together with GRB-neutrino associations found in previous work



Amelino-Camelia, D’Amico, Fabiano, Frattulillo, Gubitosi, Moia, Rosati, arXiv: 2502.13093 [astro-ph.HE]