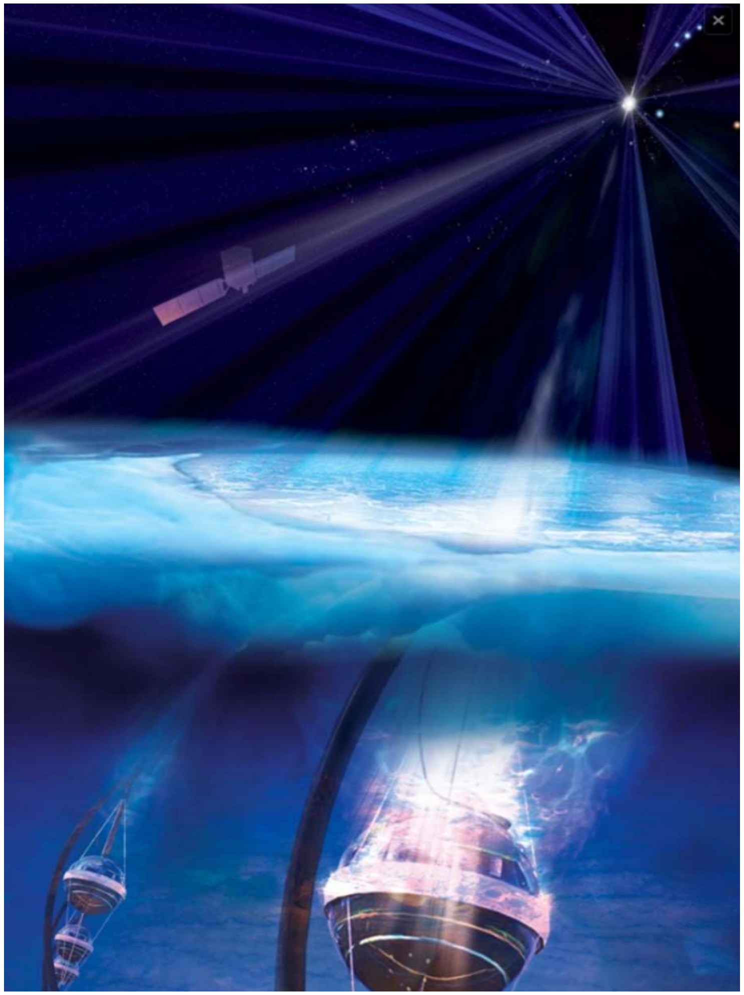
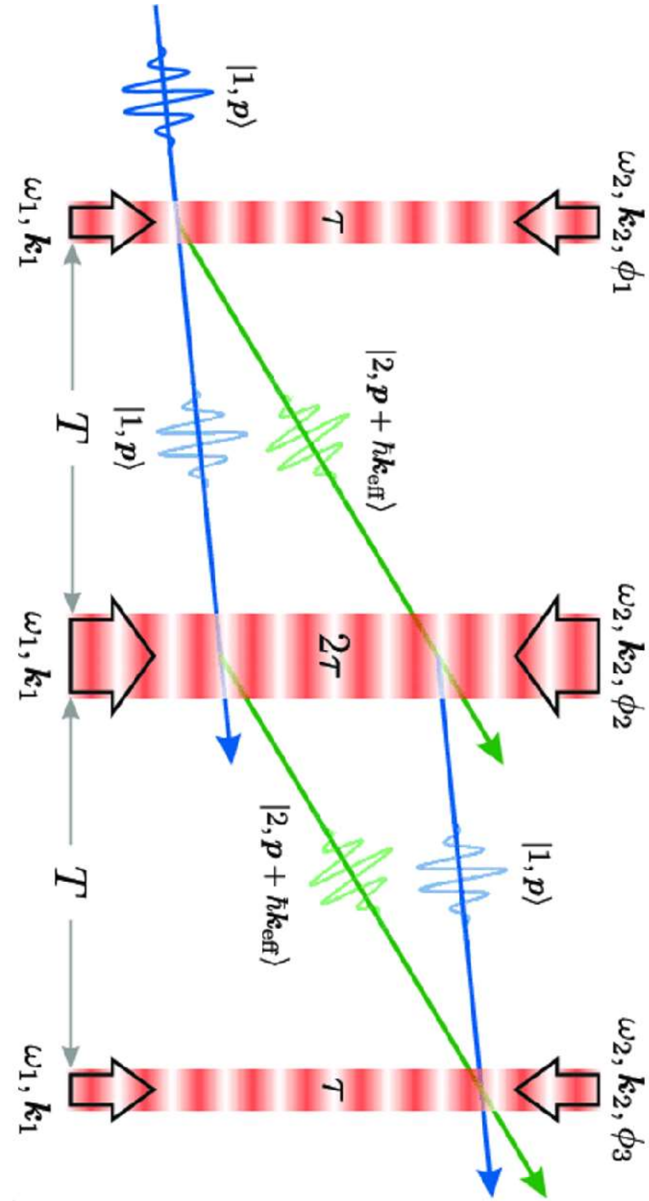
Giovanni Amelino-Camelia (working group 5)

Paris, 7 July 2025





goals of WG5 [FLAVIO+GIACOMO]

1. To **identify and investigate the questions** that lie at the interface between the two regimes, comparing the different approaches that the communities of high-energy QG and gravitational quantum physics have so far undertaken and developing inter-disciplinary methods to address them.
2. To analyze available experimental results from astrophysical and table-top experiments, to **establish the best constraints** on given models and identify the **features that are relevant for all regimes**.
3. To coordinate between all WGs the writing of a **living review** about the state of the art in research at the interface between QG at high energy and gravitational quantum physics. The review will be updated when new results stemming from the Action are available.
4. To coordinate between all WGs the preparation of an online document serving as a **vademecuum**, thoroughly explaining the key concepts from each field, with the goal of clarifying and unifying the languages of the different communities.

i.e. contribute to (and coordinate) efforts aimed at building the bridge…

goals of WG5

5. To investigate theoretical scenarios with **infrared/ultraviolet mixing** and propose new experimental strategies to test them.
6. To explore the signatures of **LIV and DSR at low energy**, like modifications to relativistic kinematics that become relevant for low-energy or large-mass particles, deformations of Bose/Fermi statistics and violations of selection rules. Identify experimental setups to test those effects, for example, precision measurements of the energy-momentum of low-energy particles and their conservation laws, tests of CPT symmetries, violations of the Pauli exclusion principle.
7. To explore the possibility of developing new, **dedicated low-energy experimental setups** to investigate the properties of quantum reference frames.

Example 1:
classical gravity in quantum mechanics, e.g. testing equivalence principle

Deformed kinematics could also affect tests of quantum Einstein Equivalence Principle, that combines Weak Equivalence Principle, Local Lorentz Invariance and "Local Position Invariance":

$$\hat{H} \simeq \hat{M}_R c^2 + \frac{\hat{p}^2}{2\hat{M}_I} + \hat{M}_G \Phi(\hat{x})$$

$$\hat{M}_i = m_i \hat{\mathbb{1}}_{int} + \hat{H}_{int,i}/c^2 \qquad i = R, G, I$$

[Zych–Brukner, Nature Phys. 14 (2018)]

(Planck scale?) modifications to the kinematics or the dynamics of the constituents and their interaction vertex would change the eigenvalues and eigenstates of the internal (binding) energy. It could lead to observable effects

here I still do not see a path for QG to matter….

Example 2: decoherence (with or without classical gravity)

Generally described by a "master" equation describing the time evolution of the density operator of Lindblad type:

$$\partial_t \hat{\rho} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] + \lambda(\hat{L}\hat{\rho}\hat{L}^\dagger - \frac{1}{2}\{\hat{L}^\dagger \hat{L}, \hat{\rho}\})$$

Several models do not advocate for a departure from classical gravity, like *e.g.* collapse models Diosi–Penrose '86-'87 (modifying QM), or Anastopoulos–Hu–Blencowe model (2013), coupling GR to QFT.

Other proposals suggest a connection with QG, either as string-matter coupling (Ellis–Mavromatos–Nanopoulos PLB '92) or emergent nonlocality (Garay PRL '98) in spacetime foam, or as (Planck-scale) spacetime fluctuations (*e.g.* Gambini–Porto–Pullin PRL (2004)).

An equation of the same type has been derived in a model of Planck-scale noncommutative spacetime based on κ-Poincaré Hopf-algebra

$$\partial_t \hat{\rho} = -\frac{i}{\hbar}[\hat{P}_0, \hat{\rho}] - \frac{1}{2\kappa}(\hat{P}^2 \hat{\rho} + \hat{\rho}\hat{P}^2 - 2\hat{P}_i \hat{\rho}\hat{P}^i) \qquad \kappa \sim E_P$$

[Arzano–D'Esposito–Gubitosi, Commun.Phys. 6 (2023)]

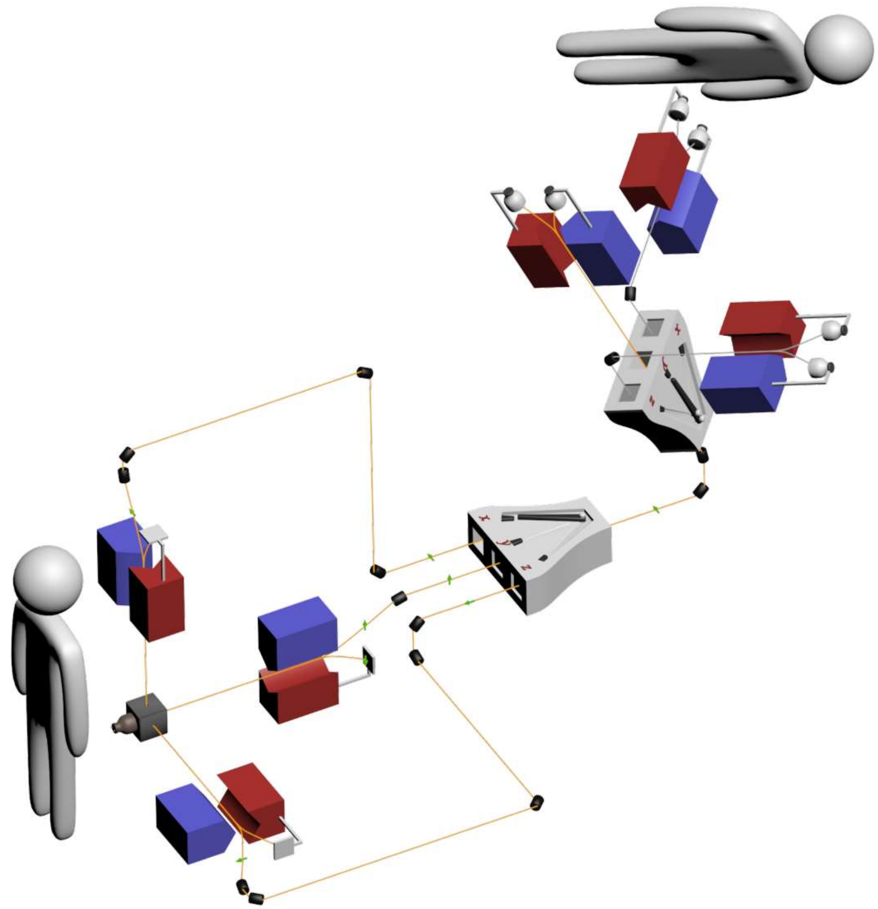
Quantum reference frames in quantum spacetime

In QM on a classical spacetime manifold, assuming a relational / perspective neutral framework, one finds surprising features: entanglement and superposition are frame-dependent, causal order can be in superposition, etc. (…rest frame of a microscopic/quantum particle…) [Giacomini–Castro-Ruiz–Brukner, NJP 18 (2016)] [Vanrietvelde–Hoehn–Giacomini–Castro-Ruiz, Quantum 4 (2020)].

What about a *quantum* spacetime? A relational framework can be built using **quantum groups** (Hopf algebras). Transformations between reference frames become noncommutative operators.(rest frame of macroscopic observer if spacetime is quantum…)
E.g., in $\mathrm{SU}_q(2)$ ($q \in \mathbb{C}$) the spin-1 representation of $\mathrm{SU}_q(2)$ gives a 3D rotation matrix whose component do not commute with each other:

$$[R_{xx}, R_{xy}] \neq 0\,, \quad [R_{zy}, R_{xy}] \neq 0\,, \ldots$$

Two rotated labs can exchange N electrons in eigenstates of σ_x, σ_y and σ_z in order to determine their relative orientation. In commutative spacetime, in the large-N limit, their relative Euler angles can be determined exactly. If spacetime is noncommutative, these angles are incompatible observables [Amelino-Camelia–D'Esposito–Fabiano–Frattulillo–Hoehn–Mercati, PTEP 2024 (2024)].



[D'Esposito–Fabiano–Frattulillo—Mercati, Quantum 9 (2025)]: to have a consistent framework, spinors describing spin-1/2 states need to live on a noncommutative generalization of $\mathbb{C}^2$: $x\,y = q\,y\,x$. Following this logic, probability of outcomes of Stern–Gerlach experiments, needs to be promoted to self-adjoint operator on Hilbert space, $P(\uparrow) \to \hat{P}(\uparrow)$.

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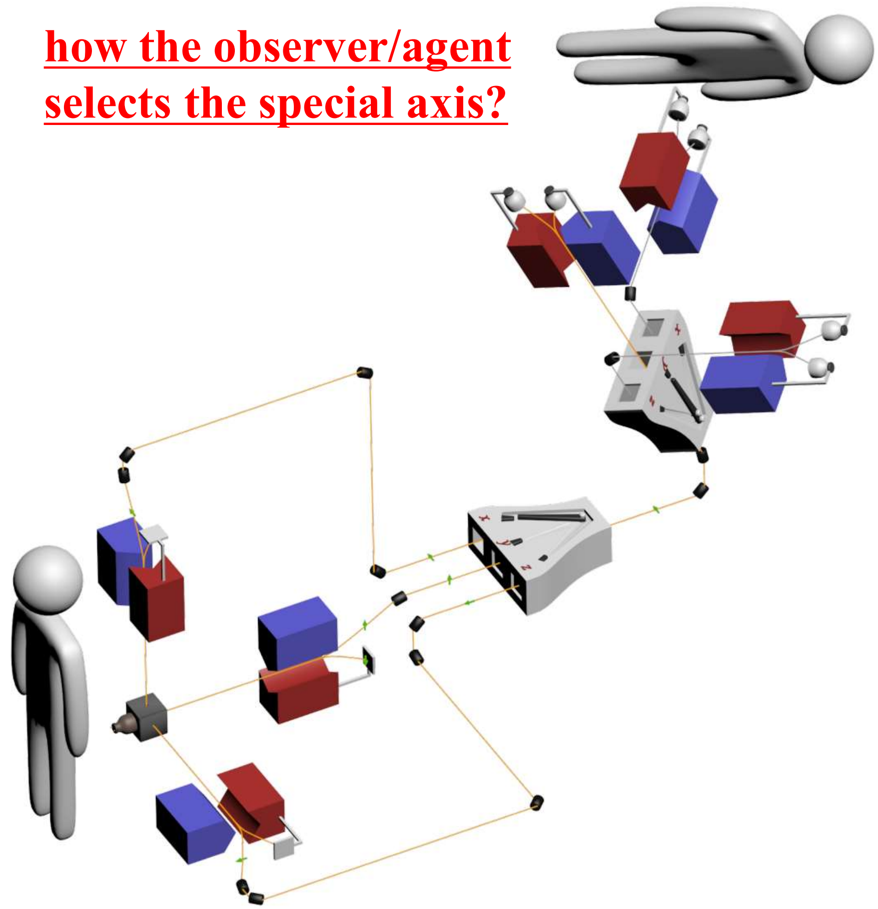

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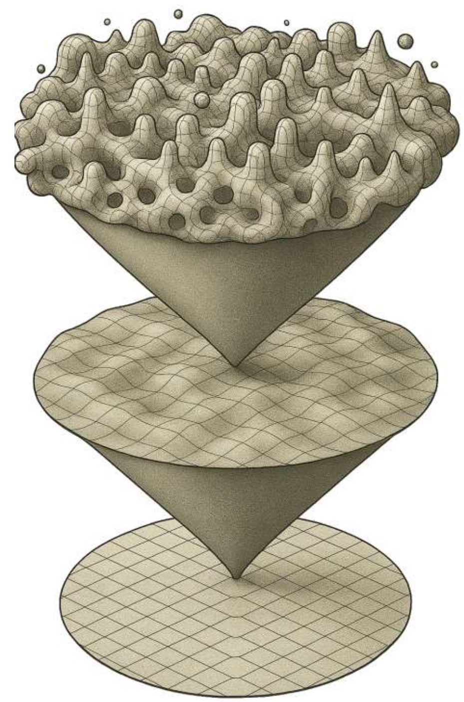
spacetime foam and strain noise for earth-bound (low-energy) interferometers (and IR/UV mixing!!!)

GAC, Nature398(1999)216
GAC, PhysRevD62(2000)024015
GAC,Nature410(2001)1965

something I did before famous first results on IR/UV mixing from spacetime noncommutativity…
context is attempts to model phenomenologically spacetime foam as effectively causing any given distance L to be affected by minute stochastic fluctuations….

from that perspective assume that distance L experiences a fluctuation of Planck-length size occurring at the frequency of one for each Planck time:
How "fuzzy" would then be the distance L?
What type of strain noise would we then find in gravity-wave interferometers?

$$\rho_h(f) = \frac{cL_P}{L^2 f^2}$$



it's a form of IR/UV mixing:
the model introduces effects in the deep UV,
but some counterpart effects show up also in the far-infrared regime of very low frequencies…

is this testable?
effect is Planck-length suppressed,
but gets amplified at low frequencies…
modern gravity-wave interferometers are very sensitive and work at low frequencies

GAC, Nature398(1999)216
GAC, PhysRevD62(2000)024015
GAC,Nature410(2001)1965

when aliens arrive we should start by comparing our interferometers to theirs

all of physics contributes to strain noise in an interferometer:
classical mechanics (e.g. earthquakes, big cars driving close to interferometer…)
thermodynamics (thermal noise)
quantum mechanics (shot noise)
I am sure there is a quantum-gravity contribution to strain noise
but it's not

$$\rho_h(f) = \frac{cL_P}{L^2 f^2}$$

which is already ruled out!!!!

LIGO/VIRGO are at strain noise of about 10^{-46} Hz^{-1} for lengths of about 4 Km!!!
Alternative: if quantum-gravity noise was white we would have the natural estimate

$$\rho_h(f) = \frac{L_P}{c}$$

which is also ruled out

Next target is "holographic noise"

[Christiansen+Ng+VanDam,Phys.Rev.Lett. 96 (2006) 051301]

$$\rho_h(f) = \frac{c^{2/3} L_P^{4/3}}{L^2 f^{5/3}}$$

but perhaps assuming distances intrinsically fuzzy is too naïve….maybe spacetime foam really means that particle's trajectories have a quantum-gravity contribution to their fuzziness [Vasileiou + Granot + Piran+GAC, Nature Physics 11 (2015) 344]

IR/UV mixing appears to be "structural" to the quantum-gravity problem:
not only spacetime foam can motivate IR/UV mixing,
but also Bekenstein-Hawking entropy is a manifestation of IR/UV mixing
[Cohen+Kaplan+Nelson,PhysRevLett82(1999)4971]

however, IR/UV mixing became popular only when it was found in field theories formulated with canonical spacetime noncommutativity:
UV effects of noncommutativity require an adaptation of renormalization which in turn produces IR modifications of the onshell relation… from canonical noncommutativity one gets either "hard IR/UV mixing"

$$E \simeq m + \frac{p^2}{2m} + \frac{\Lambda_*}{\theta^{\mu}{}_{\nu}\theta^{\nu\rho}p_{\mu}p_{\rho}}$$

Minwalla+VanRaamsdonk+Seiberg,JHEP02(2000)020

or "soft IR/UV mixing"

$$E \simeq m + \frac{p^2}{2m} + \frac{M_\theta}{M_P}\vec{p}\cdot\vec{u}_\theta$$

Matusis+Susskind+Toumbas,JHEP12(2000)002

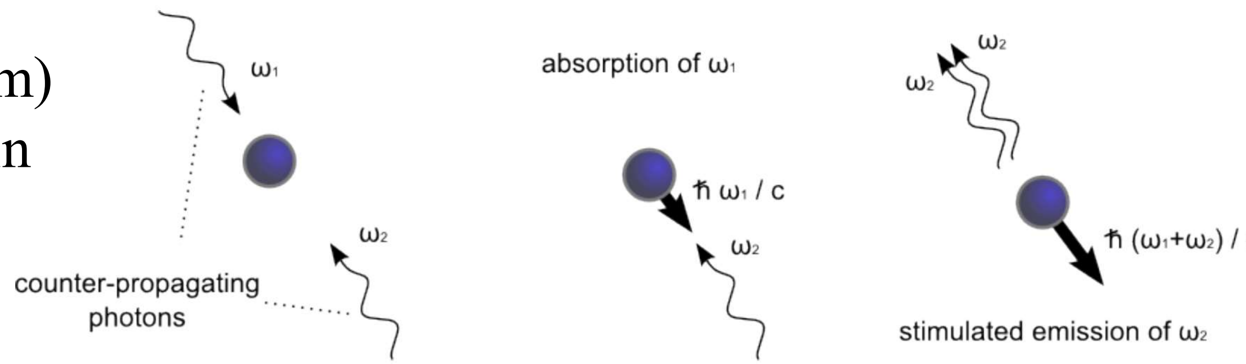
some discrete-spacetime pictures inspired by Loop Quantum Gravity also produce a form of "soft IR/UV mixing"

$$E \simeq m + \frac{p^2}{2m} + \frac{\xi}{M_P}mp$$

Alfaro+MoralesTecotl+Urrutia, PhysRevLett84(2000)2318

GAC +Laemmerzahl+Mercati+Tino, Phys.Rev.Lett.103(2009)171302
Mercati+Mazon+GAC+Carmona +Cortes+Indurain+Laemmerzahl+Tino, CQG27(2010)215003

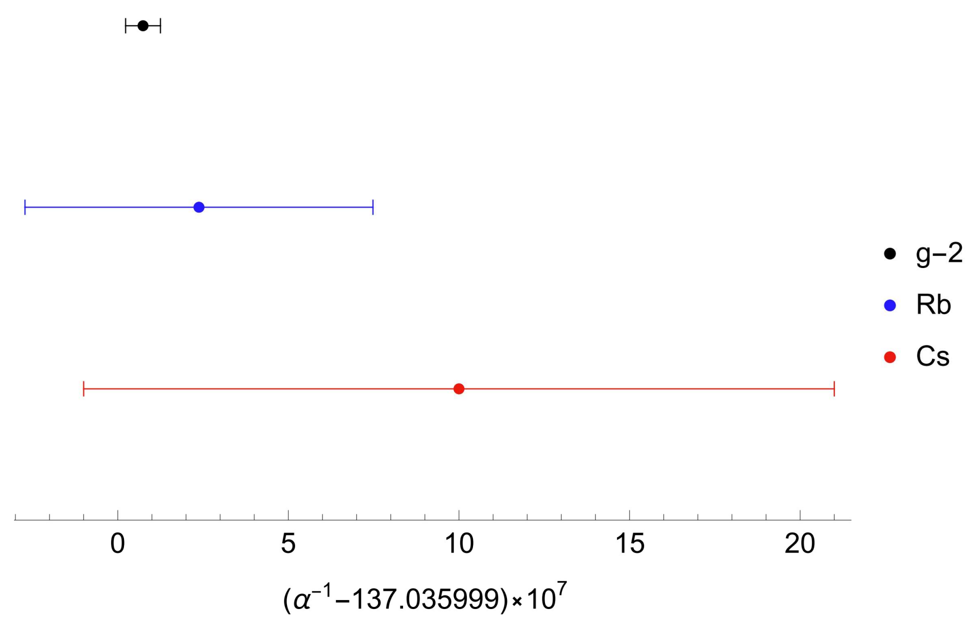
phenomenology of soft IR/UV mixing based on measurements
of the fine structure constant
(electron g-2….Cesium….Rubidium)
A cold-atom interferometer works in
an infrared regime where p<m



there was no discrepancy among measurements of the fine structure constant
in 2009 and this allowed us to set a bound on ξ

$$\xi = -1.8 \pm 2.1$$

$$E \simeq m + \frac{p^2}{2m} + \frac{\xi}{M_P} mp$$



N.B.: cancellation for Rb setup

GAC +Fabiano+Frattulillo+Mercati, arXiv:2507.XXXXX

latest measurements of the fine structure constant: there is a discrepancy!!

once again effect cancels out for the Rb interfeometer

In order to remove the discrepancy between Rb and g-2 measurements and the measurement by the Cs interferometer one gest ξ of order unity!!

$$\xi = 0.60 \pm 0.12$$

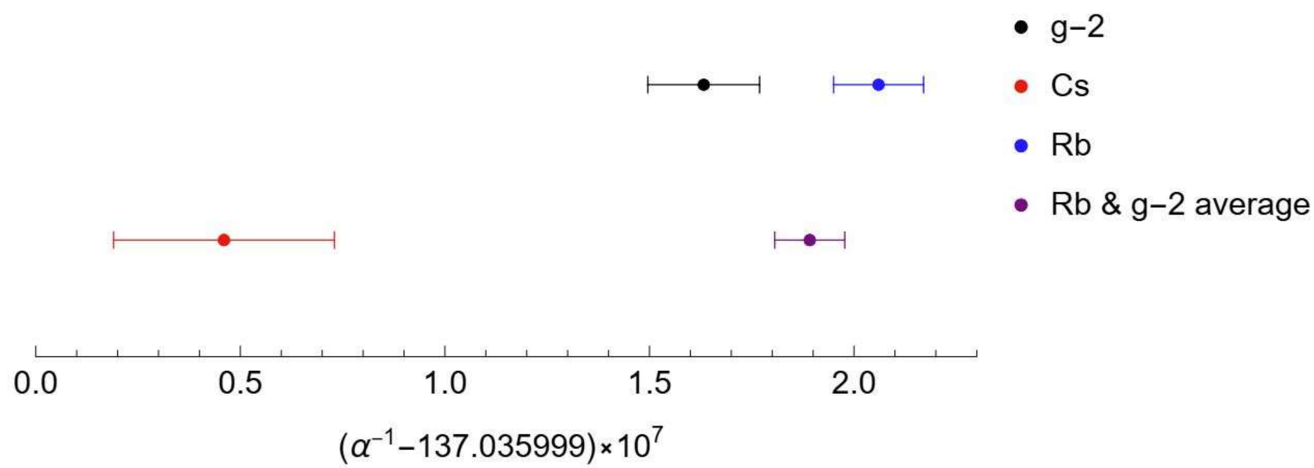


FIG. 1. The black data point is for the present status of α measurements using the electron g-2 [14, 15]($\alpha^{-1}_{g-2} = 137.035999163(14)$). The red and blue data points are for the latest atom-interferometry measurements of α using, respectively, Cesium [15, 16] ($\alpha^{-1}_{Cs} = 137.035999046(27)$) and Rubidium [15, 17] ($\alpha^{-1}_{Rb} = 137.035999206(11)$). The weighted average of the g-2 and Rubidium measurements is in violet.

but of course we must wait for other measurements… relevant Cs setup might be affected by unknown systematics…

dispersion relations which were of interest for the previous COST Action (for their UV properties) can also host a form of IR/UV mixing!!!!

$$E^2 = m^2 + p^2 + \frac{\alpha}{M_P} E p^2 + \frac{\beta}{M_P} E^3 + \frac{\gamma}{M_P} E^2 p$$

UV

$$E \simeq p + \frac{m^2}{2p} + \frac{\alpha + \beta + \gamma}{2M_P} p^3$$

IR

$$E \simeq m + \frac{p^2}{2m} + \frac{\beta}{2M_P} m^2 + \frac{\gamma}{2M_P} mp$$

$$\xi \equiv \frac{\gamma}{2}$$

Back to the UV: what about in-vacuo dispersion for neutrinos???

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

according to pre-IceCube predictions, IceCube should have seen a few GRB neutrinos in each year of operation but it has reported no GRB neutrinos!

of course it would not be too surprising if pre-IceCube models of neutrino production by GRBs were incorrect, but invacuo dispersion offers an alternative explanation:
IceCube looks for GRB neutrinos within a window of about 100 seconds of the GRB trigger, but even just with "Planckian" in-vacuo-dispersion you might need a much bigger time window

test in-vacuo dispersion statistically:

if the time window is large it's inevitable to select (also) some "accidental GRB-neutrino pairs", neutrinos unrelated to a GRB which just happens to be within the chosen large time window and directionally compatible with the GRB

in order to best setup the statistical analysis it is convenient to notice that in-vacuo dispersion amounts to linear relationship between the energy E and a certain ratio between the observation-time difference Δt and the redshift-dependent function D(z)

$$\Delta t = \eta \frac{E}{M_P} D(z) \qquad \textbf{with} \qquad D(z) = \int_0^z d\zeta \frac{(1+\zeta)}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}$$

Jacob+Piran [JCAP0801,031(2008)]

we can absorb the redshift dependence into an "accordingly rescaled Δt", which we call Δt^*

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

This then affords us the luxury of analysing data in terms of a linear relationship between E and Δt^*

$$\Delta t^* = \eta \frac{E}{M_P}$$

GAC+D'Amico+Rosati +Loret, arXiv1612.02765, NatureAstronomy1,0139
GAC+Barcaroli+D'Amico+Loret+Rosati, arXiv1605.00496,PhysicsLettersB761(2016)318
GAC +D'Amico+DiLuca+Gubitosi+Rosati, arXiv2209.13726, NatureAstronomy7,99
GAC+ D'Amico+ D'Esposito+ Fabiano+Frattulillo+Gubitosi +Moia +Guetta+Rosati, arXiv2501.13840

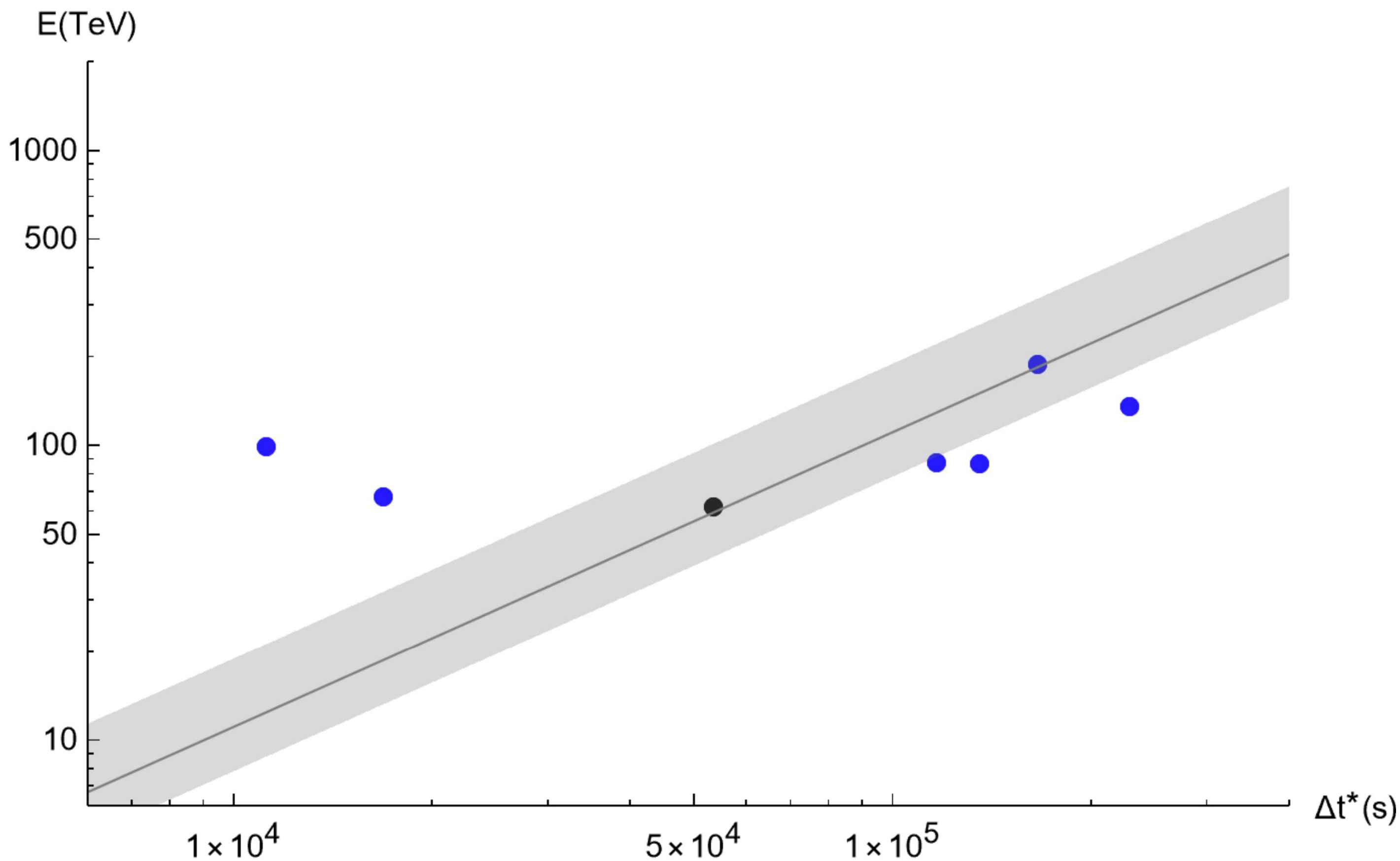
our first results (discussed within previous COST action)

only "shower events" (our approach requires sharp energy estimate)

very few neutrinos

very wide search window

include GRBs of unknown redshift (only black point is of known redshift)



nonetheless actually provides a rather high-significance indication in favor of the range of in-vacuo-dispersion scales corresponding to the gray band

GAC+D'Amico+Rosati +Loret, arXiv1612.02765, NatureAstronomy1,0139
GAC+Barcaroli+D'Amico+Loret+Rosati, arXiv1605.00496,PhysicsLettersB761(2016)318
GAC +D'Amico+DiLuca+Gubitosi+Rosati, arXiv2209.13726, NatureAstronomy7,996
GAC +D'Amico +Fabiano+Frattulillo+Gubitosi +Moia+Rosati, arXiv2501.13840

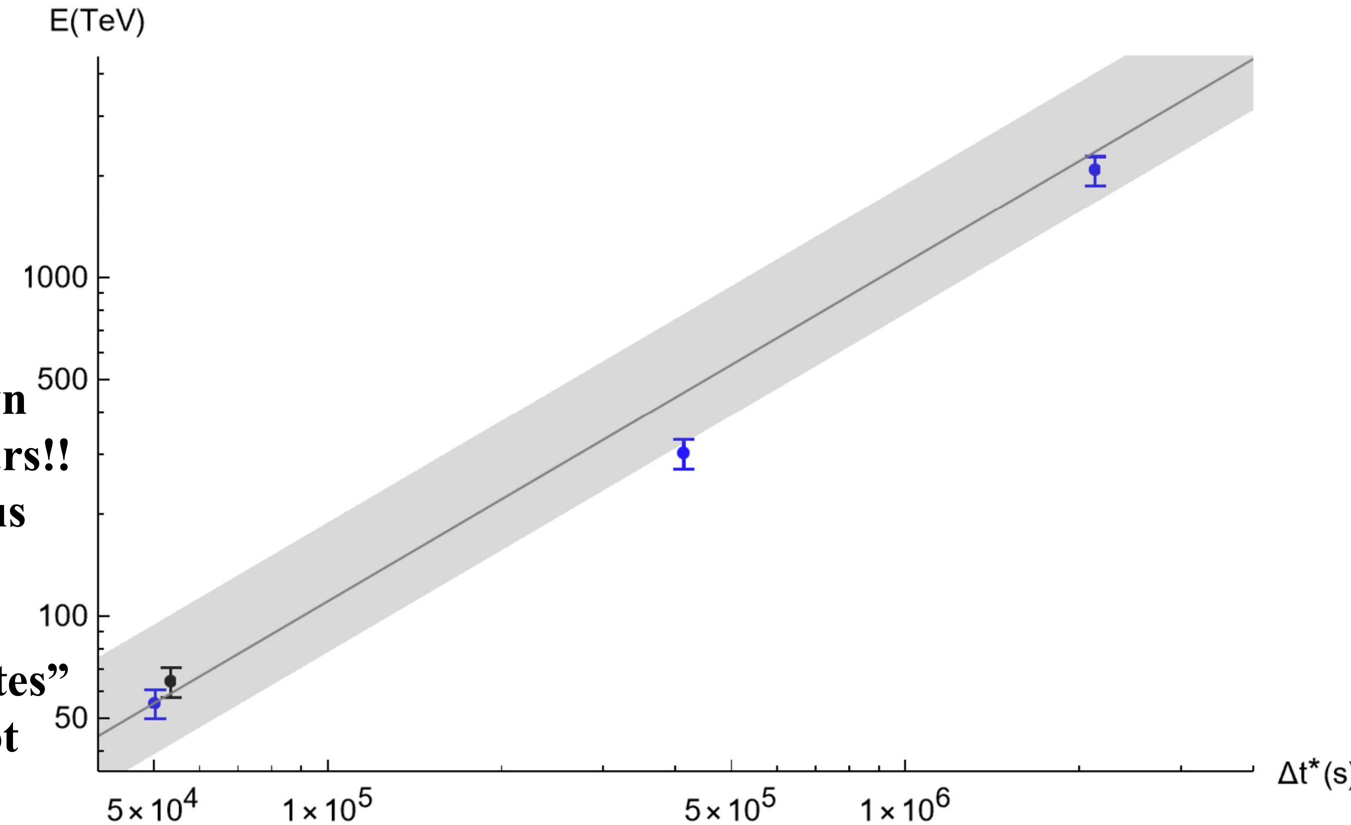
our very recent results

more neutrinos

still only include "shower events"

NEW: only include GRBs of known redshift (now points have error bars!! black point was already in previous analysis)

finding 4 "GRB-neutrino candidates" lined up as nicely as in figure is not very likely
(should happen accidentally with a probability of only 0.7%)



intriguing…but once again we must wait for more data…

GAC +D’Amico +Fabiano+Frattulillo+Gubitosi +Moia +Rosati, arXiv2502.13093

first chance of testing the “predictive power” of this picture:
on 12 February 2025 the KM3NeT collaboration reported the observation of the KM3-230213A neutrino, a truly remarkable neutrino, with energy of ~220PeV (~100 times bigger than previous record)

and KM3-230213A cannot be cosmogenic or atmospheric and also a blazar origin is not plausible…
it would make perfect sense if KM3-230213A was a GRB neutrino, but there is no GRB in good temporal and directional coincidence with KM3-230213A

there is only one GRB directionally compatible with KM3-230213A but it was observed much earlier (see talk by Frattulillo)

GAC +D'Amico +Fabiano+Frattulillo+Gubitosi +Moia +Rosati, arXiv2502.13093

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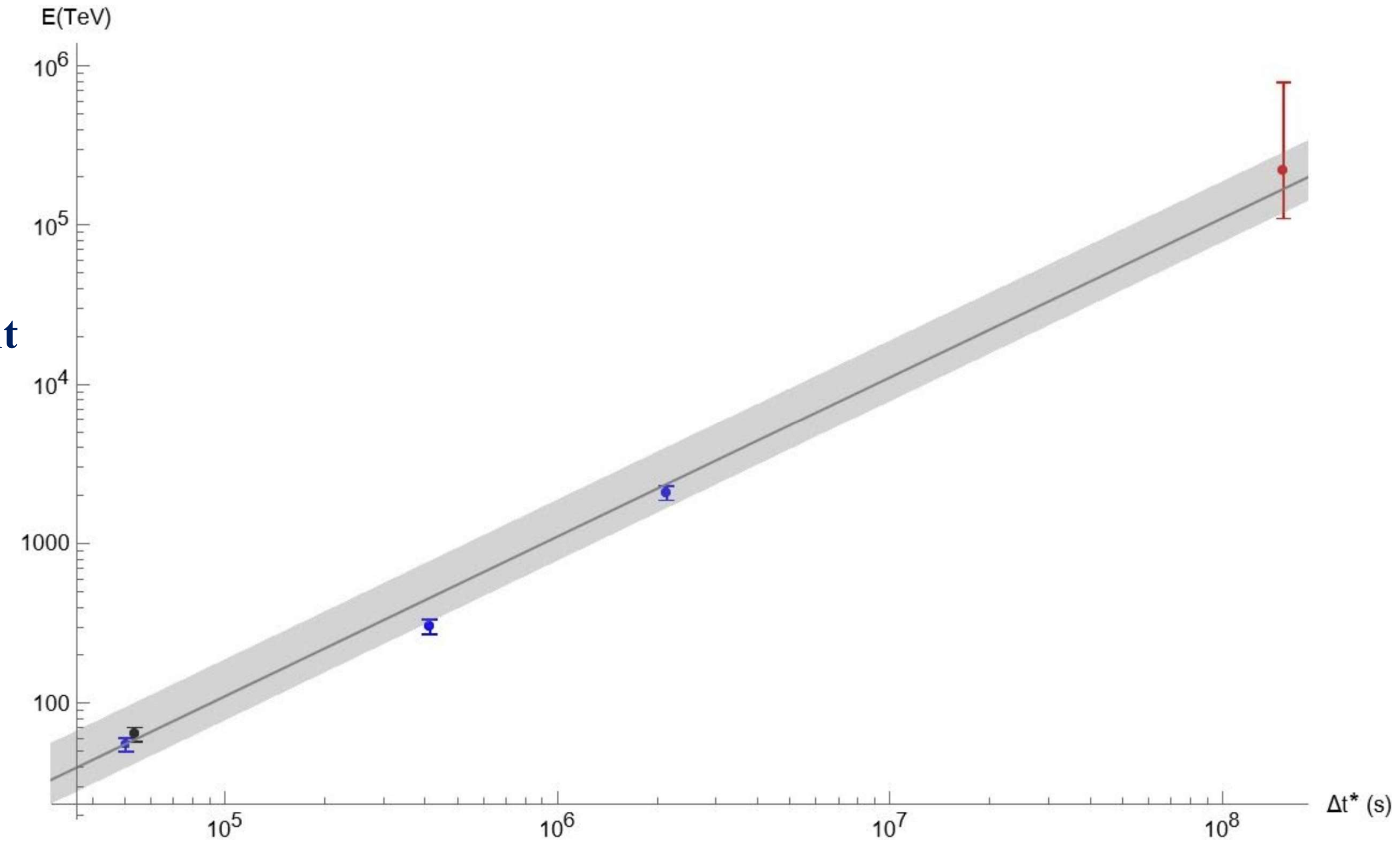

N.B.:
KM3-230213A is a track event