HARMONY: HAdron physics Research into Models of Nonunitary Dynamics and quantum gravity

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Town Meeting,

Hadron Physics in Horizon Europe

1-3 July 2025, Nantes, France

PROJECT AIM and POTENTIAL

HARMONY: a novel opportunity in hadron physics - testing Quantum Gravity (QG) from accelerator to underground experiments

HARMONY will build a global research network, connecting top-tier institutions across Europe, UK, America, and Asia to foster a synergistic theoretical and experimental investigation of QG:

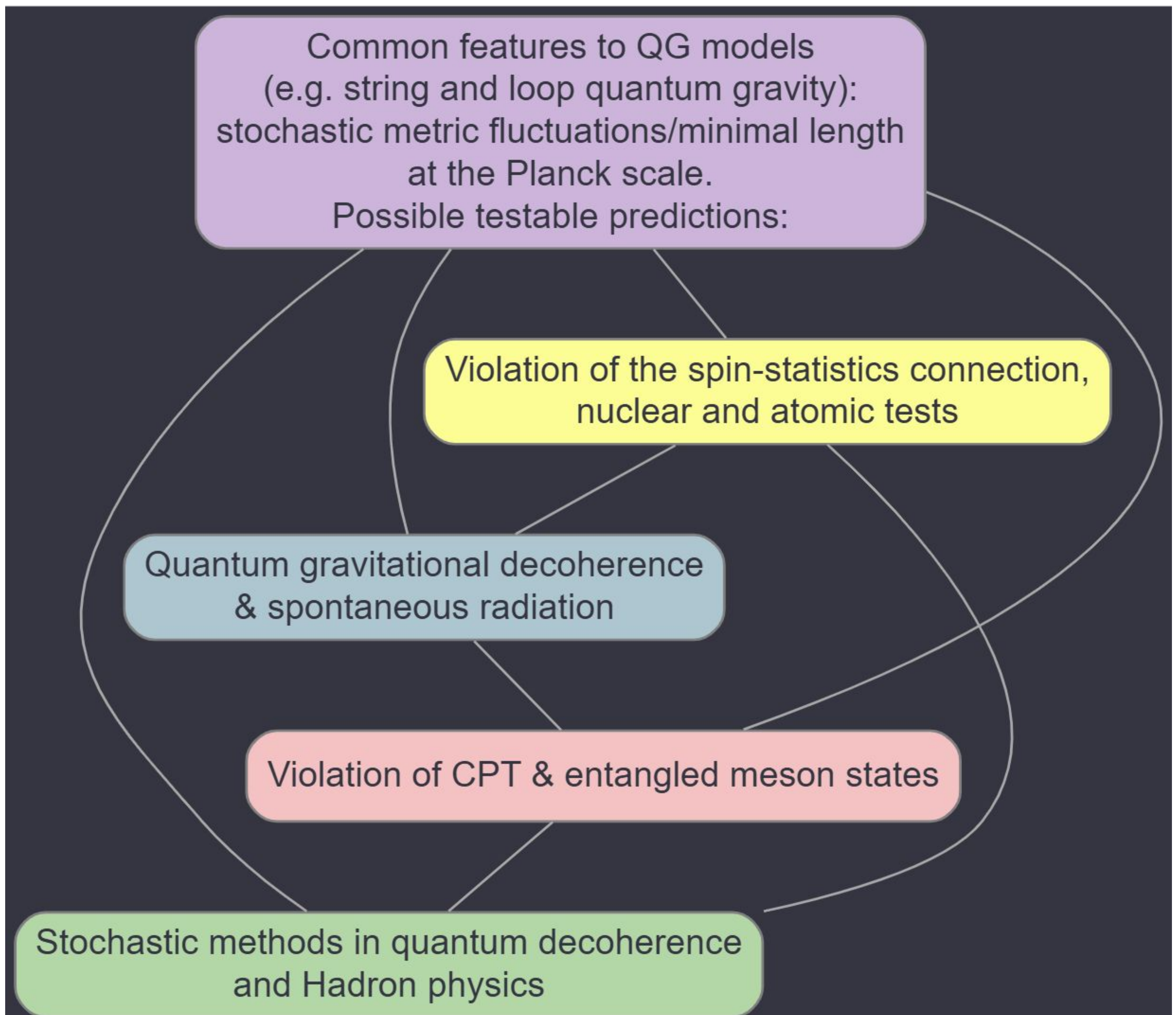
- New **phenomenological methods** will be developed by leveraging techniques from **hadron physics**, validated through data from **underground experiments**.
- The project aims to bring **Quantum Gravity into the realm of testable theories**, positioning HARMONY as an **Occam's razor** to discriminate between competing QG models — moving toward a unified theory.
- **Annual workshops** and **regular analysis meetings** to consolidate and expand the scientific community, while sharing results and refining methodologies.
- A strong focus will be placed on **dissemination and outreach**, ensuring broad visibility and engagement with the scientific community and the public.

PROJECT AIM and POTENTIAL

Questions HARMONY can answer

- **After one century Quantum Gravity (QG) remains the most elusive challenge in modern physics, some experts (e.g. Penrose) have even suggested that quantizing gravity may not be the correct approach.**

- **Prevailing paradigm: in the search for measurable evidence of QG effects - identifying commonalities across QG models to make robust, testable predictions**

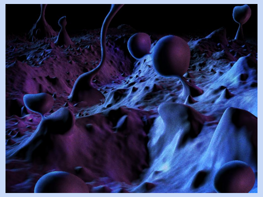


Shared features among QG models

Non-commutativity of S-T:

- in quantum mechanics (relatively large-scales/low-energies) phase space is a smooth manifold.
- On distances of the order of ℓ_P this breaks down, Heisenberg uncertainty + GR -> black hole formation -> the smooth manifold structure is lost.
- The notion of a point becomes meaningless and the simple commutation relation between space-time points is no longer expected to hold (first suggested by Snyder (1947) and Heisenberg (1954).

stochastic fluctuations of the metric



Minimal length

$$\delta x \simeq \frac{\hbar c}{2E} + \beta \ell_p^2 \frac{2E}{\hbar c},$$

Increased Heisenberg uncertainty (GUP)

$$\Delta x \, \Delta p \geq \frac{\hbar}{2}\left[1 + \beta\left(\frac{\Delta p}{m_p c}\right)^2\right].$$

Whose manifestation are testable!

1 - Pauli Exclusion Principle (PEP) Violation, 2 - spontaneous radiation from gravitational decoherence, 3 - CPT violation in entangled meson systems

QG tests through nuclear and atomic PEPV transitions

- **Why? Lorentz symmetry is a central assumption of the spin-statistics theorem, which is deformed in QG framework. Leading order PEPV probability:**

$$W_V = \frac{\beta}{m_p^2 c^2} m_e E_T W_S$$

  - **Upper bound ML: β < 10 (90% C.L.)**
    i.e. 1 o.m. sensitivity Planck scale

w.r. to Class.Quant.Grav. 40 (2023) 19, 195014 →

Experiment	Upper bound on β
Perihelion precession (Solar System, 1)	10^{34}
Time-of-flight measurements	10^{16}
Equivalence principle (pendula)	10^{73}
Gravitational bar detectors	10^{93}
Equivalence principle (atoms)	10^{45}
Low-mass stars	10^{48}
LIV in torsion pendulum	10^{51}
Perihelion precession (Solar System, 2)	10^{69}
Perihelion precession (pulsars)	10^{71}
Gravitational redshift	10^{76}
Black hole quasi normal modes	10^{77}
Light deflection	10^{78}
Time delay of light	10^{81}
Black hole shadow	10^{90}
Black hole shadow	10^{90}

OTHER QG MODELS PRL 129, 131301 (2022)
PRD 107, 026002 (2023)

- **k-Poincaré excluded in the A-M quantization (dispersion relations from AGN flares - sensitivity 0.1 Planck scales)**

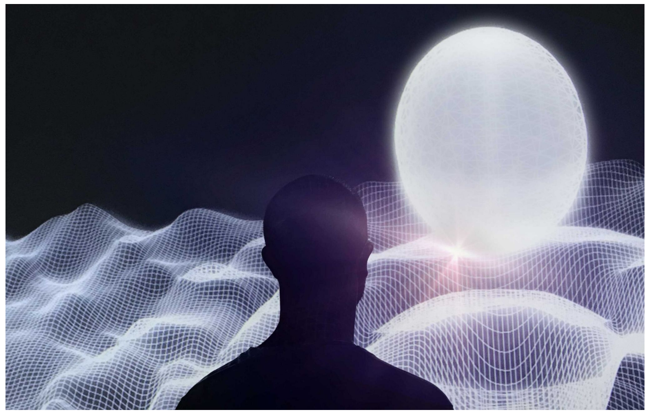
- **Hadronic sector - θ-Poincaré excluded (DAMA, BOREXINO and KAMIOKANDE)**

Not accessible with dispersion relations

- **Leptonic sector - θ-Poincaré excluded up to 0.1 Planck scales (90% C.L.)**

QG-decoherence tests through spontaneous radiation

- **Suppression of quantum coherence is one of the key features of QG.**

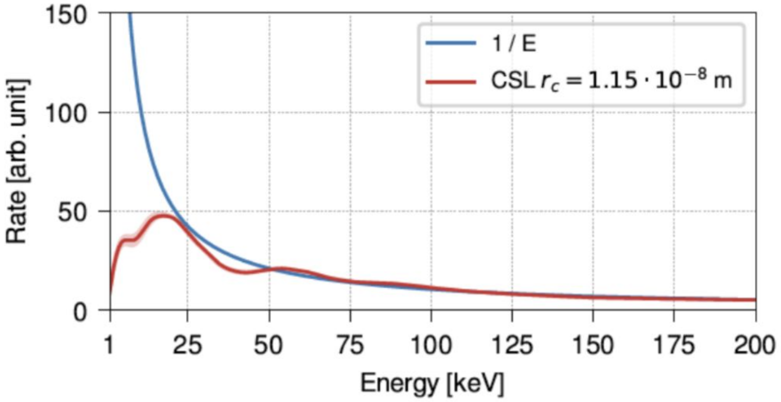


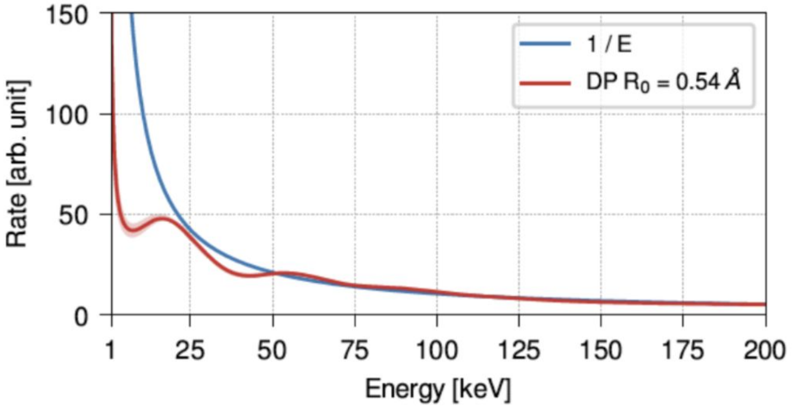
E.g. (Nat. Comm. 12, 4449 (2021)) **fluctuating ML due to the foamy structure of quantum space-time induces a universal gravitational decoherence.**

Benchmark is provided by X-ray and γ-ray measurements of *spontaneous radiation* (Nature Physics 17, 74 (2021), Phys. Rev. Lett. 130, 230202 (2023), Phys. Rev. Lett. 132, 250203, (2024)).

QG models have distinctive spontaneous radiation E-spectra

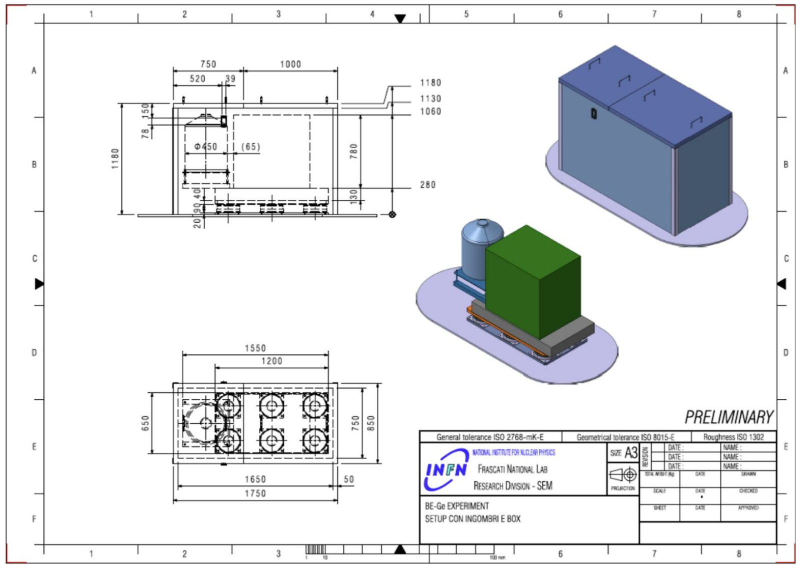
due to the intertwined nuclear and atomic spontaneous radiation





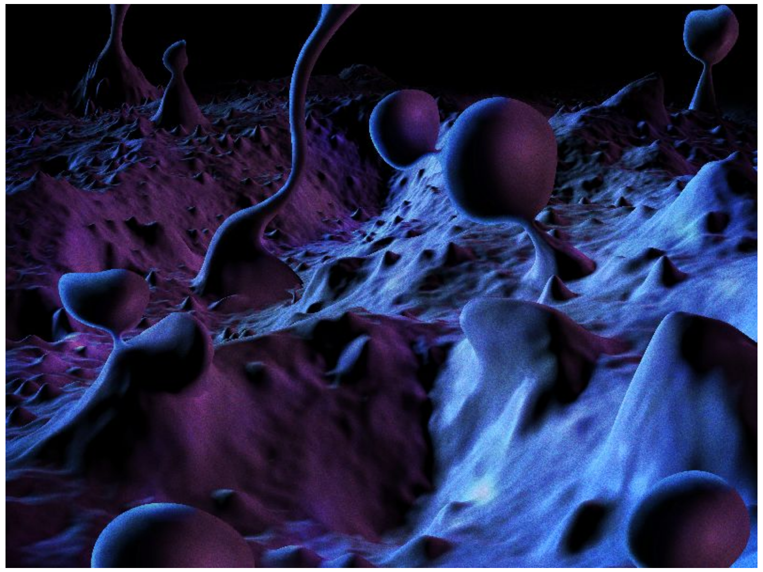
- **Prototype setup REGe-based is under finalization (&LNGS (INFN)): simultaneous test of spontaneous radiation & PEPV**
  expected improved sensitivity on β - factor 14

Condens. Matter 2024, *9*(2), 22



QG induced CPT violation with entangled meson experiments

- The CPT theorem is a consequence of Lorentz invariance, locality and unitarity



- Wheeler: ST has a foamy structure at the Planck scale, microscopic horizons of radius of the order of the Planck length induce in ST a fuzzy structure

- topological fluctuations of ST break the unitary evolution

  QG-DECOHERENCE

- Wald : entanglement of matter systems with gravitational fluctuations imply violation of CPT .

- If CPT QM operator is well defined, neutral meson pairs are produced in meson decays into a fully anti-symmetric entangled state with $J^{PC} = 1^{--}$:

$$|i> \;=\; \frac{1}{\sqrt{2}}\left(|K_0(\vec{k}), \overline{K}_0(-\vec{k}) > - |\overline{K}_0(\vec{k}), K_0(-\vec{k}) >\right)$$

$$= \;\Big[\mathcal{N}\left(|K_S(\vec{k}), K_L(-\vec{k}) > - |K_L(\vec{k}), K_S(-\vec{k}) >\right)$$

QG induced CPT violation with entangled meson experiments

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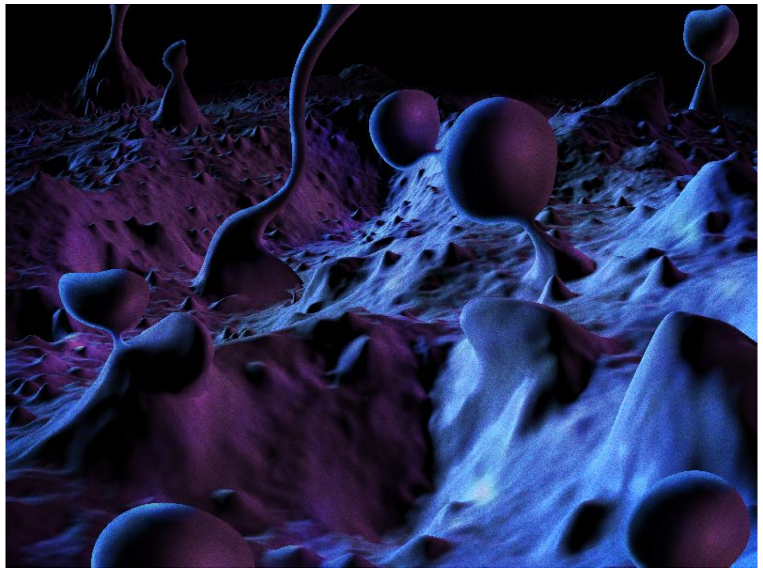


- Wheeler: ST has a foamy structure at the Planck scale, microscopic horizons of radius of the order of the Planck length induce in ST a fuzzy structure

- topological fluctuations of ST break the unitary evolution

QG-DECOHERENCE

- Wald : entanglement of matter systems with gravitational fluctuations imply violation of CPT .

- If CPT is ill defined:

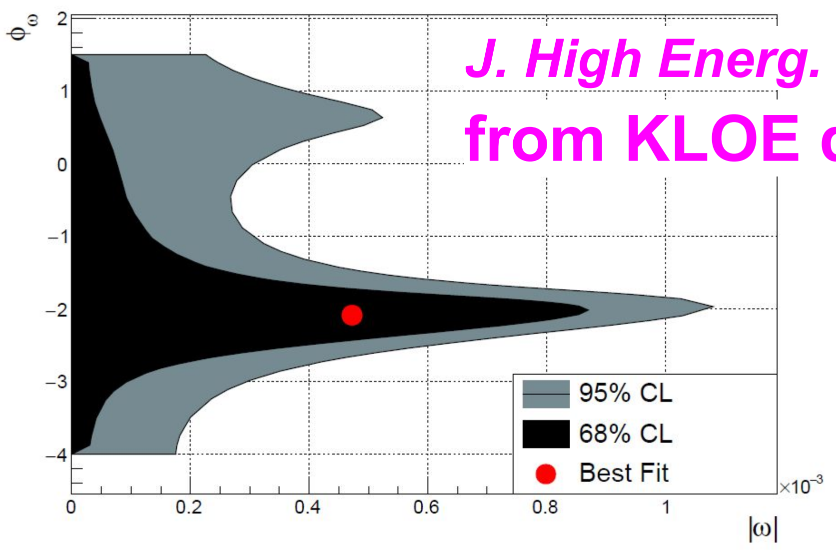
ALSO INDUCED BY Spin-Stat VIOLATION

$$
\begin{aligned}
|i> &= \frac{1}{\sqrt{2}}\left(|K_0(\vec{k}), \overline{K}_0(-\vec{k}) > - |\overline{K}_0(\vec{k}), K_0(-\vec{k}) >\right) \\
&+ \frac{\omega}{2}\left(|K_0(\vec{k}), \overline{K}_0(-\vec{k}) > + |\overline{K}_0(\vec{k}), K_0(-\vec{k}) >\right)\Big] \\
&= \Big[\mathcal{N}\left(|K_S(\vec{k}), K_L(-\vec{k}) > - |K_L(\vec{k}), K_S(-\vec{k}) >\right) \\
&+ \omega\left(|K_S(\vec{k}), K_S(-\vec{k}) > - |K_L(\vec{k}), K_L(-\vec{k}) >\right)\Big]
\end{aligned}
$$

Phys. Rev. Lett. 92, 131601 (2004)
Phys. Rev. D 74, 045014 (2006)
Eur. Phys. J. C 77, 865 (2017)

QG induced CPT violation with entangled meson experiments

Th. prediction $|\omega|^2 \sim \dfrac{\zeta^2 k^4}{M_P^2 (m_1 - m_2)^2}$



***J. High Energ. Phys.* 2022, 59 (2022)**

from KLOE data

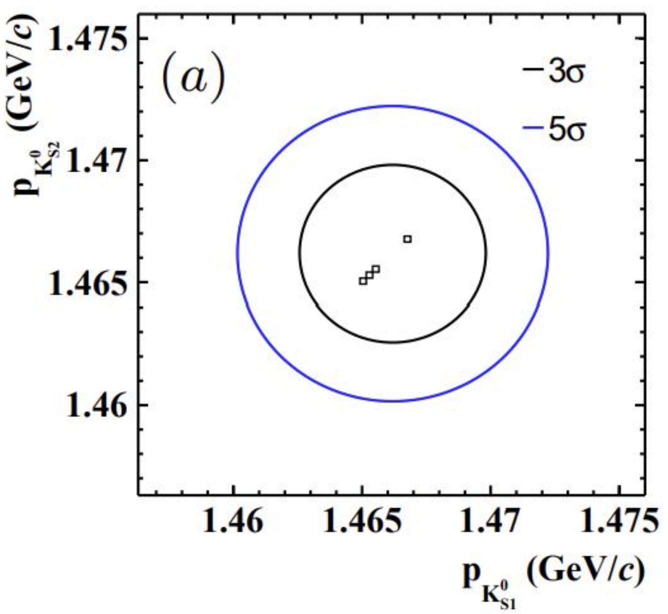
theory expectation ω ~ 10^{-6}

arXiv:2504.13771 [hep-ex] from BESIII data

$$J/\psi \to K_S^0 K_S^0$$

exp. result ω < 5 x10^{-3} 90% CL

theory expectation ω ~ 10^{-4}



LHCb data $D^0 \to K^-\pi^+$ and $\overline{D^0} \to K^+\pi^-$

is setting the strongest bounds on $\delta\Gamma_D$ **and** δm_D

Phys. Rev. D 104, 072010 (2021), Phys. Rev. D 110, 055021 (2024)

to be reinterpreted in terms of ω

Theory also ready for testing entangled B systems [*Eur.Phys.J.C* 77 (2017) 12, 865]

Stochastic methods bridging QG-induced decoherence and Hadron physics

Within the HARMONY, innovative stochastic methods will be developed and adapted from the domain of quantum gravity to address fundamental open problems in hadron physics:

Stochastic quantization (Parisi and Wu): quantum field theory as the equilibrium limit of a stochastic process.

CONNECTION WITH QG: Stochastic Ricci flow models the Planck scale fluctuations of ST by introducing random terms into the Ricci flow equation - quantum version of spacetime evolution. [arXiv:2307.10136[gr-qc]]

RESULT: general relativistic gravitational decoherence testeable in the low-energy regime through PEPV & CPTV

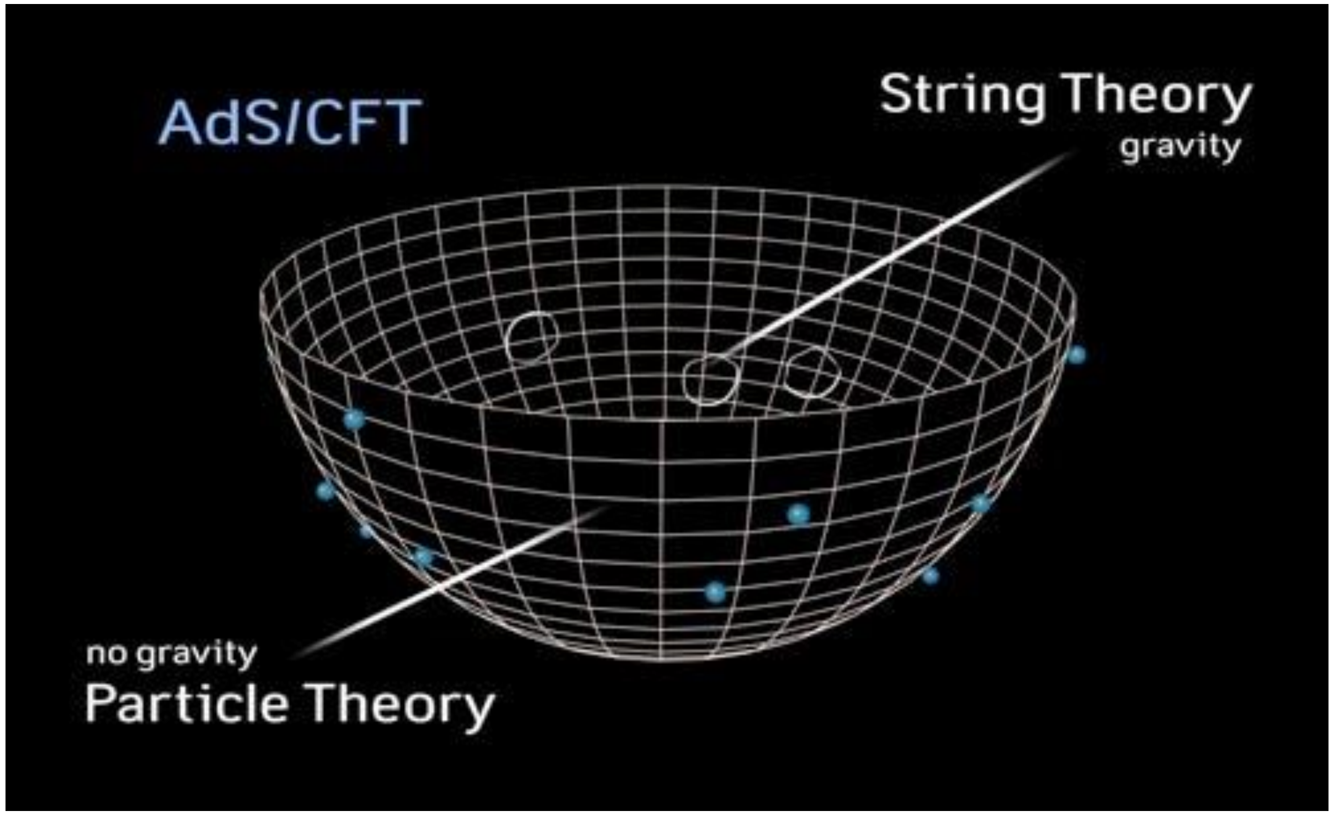
Applications to Hadron physics will be explored in the following frameworks:

Stochastic methods bridging QG-induced decoherence and Hadron physics

- QCD confinement, QCD phase transitions in extreme conditions and quark-gluon plasma (e.g. ALICE)

  phase transitions and critical phenomena can be related to the breakdown of the systems' symmetries out-of-equilibrium, and their restoration in the "infrared regime". [arXiv:2488.15986[hep-th]]

- AdS/QCD (holographic) approaches to hadron spectroscopy.



OUTCOMES

Within HARMONY we will perform:

- combined analysis of all available entangled mesons data. Calculation of analogous ω-effect CPTV for other entangled pairs of particle states in current or future experiments,
- Spin-statistics violation implications on the ω-effect, analysis of the relevant experimental data,
- calculation of the spontaneous radiation spectrum for the relevant QG models (ML, stochastic flow…),
- implementation of stochastc flow techniques to QCD confinement, phase transitions in QCD and AdS/QCD.

Outputs, at least: 20 publications and 2 public dissemination articles.
HARMONY will be promoted through: social media, website, dissemination in schools, universities, public events, and online activities.

HARMONY will strategically engage with key Transnational Access infrastructures to promote probing quantum gravity effects using hadronic systems (e.g. CERN, INFN-LNF, GSI/FAIR). ECT* could host focused theory–experiment workshops.
Connection with Virtual Access projects will be explored.

HARMONY - cross-site analysis, detector synergies, and optimized experimental design to push sensitivity to QG toward the Planck scale.

Financial requests

Budget request for a 4-year duration of the Project:

- Annual workshops and meetings (travel): €40,000/year,
- Outreach and administration: €20,000/year,
- Indirect costs: €15,000/year.

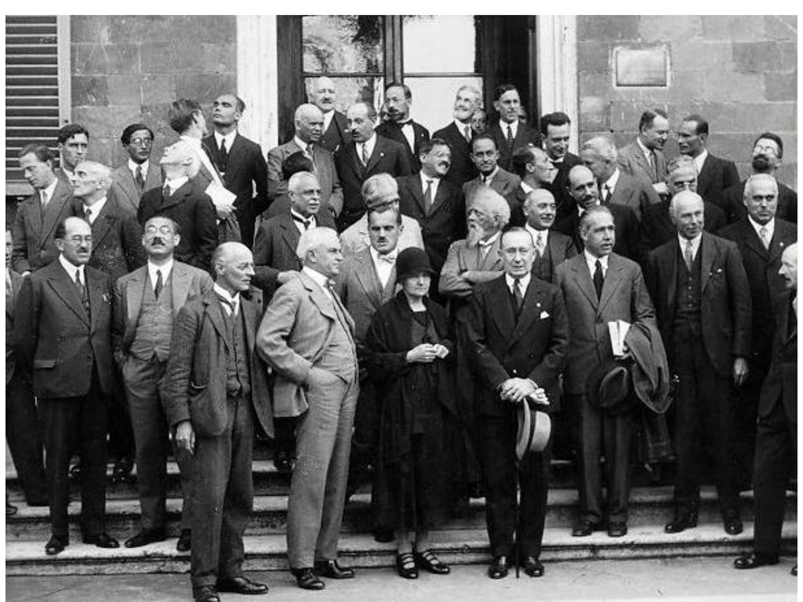
The total estimated cost is €300,000

Core group of involved institutions:

Enrico Fermi Research Center, Italian National Institute of Nuclear Physics (INFN), Salerno Univ., Italian National Research Council (CNR), Fudan Univ., Regensburg Uni., Lund Univ., Antofagasta Univ., Jagiellonian Univ., Zurich Univ., National Institute of Physics and Nuclear Engineering (Bucharest-Magurele), King's Coll. London, Natl. Tech. Univ. Athens, Mines Paris, Wigner Research Centre for Physics, Eötvös Loránd Univ., Univ. of Zagreb.

Enrico Fermi Research Center

the perfect environment to host workshops, meetings, dissemination activities



Thank you

Spare slides

PEP violation in quantum gravity

Quantum gravity models can embed PEP violating transitions

PEP is a consequence of the spin statistics theorem based on: Lorentz/Poincaré and CPT symmetries; locality; unitarity and causality. Deeply related to the very same nature of space and time

↓

non-commutativity of space-time operators is common to several quantum gravity frameworks (e.g. *k*-Poincarè, θ-Poincarè)

↓

non-commutativity induces a deformation of the Lorentz symmetry and of the locality → naturally encodes the violation of PEP <u>not constrained by MG</u>

PEP violation is suppressed with δ^2 (E, Λ)
***E* is the characteristic transition energy, *Λ* is the scale of the space-time non-commutativity emergence.**

A. P. Balachandran, G. Mangano, A. Pinzul and S. Vaidya, Int. J. Mod. Phys. A 21 (2006) 3111

A.P. Balachandran, T.R. Govindarajan, G. Mangano, A. Pinzul, B.A. Qureshi and S. Vaidya, Phys. Rev. D 75 (2007)

A. Addazi, A. Marciano, *Int.J.Mod.Phys.A* 35 (2020) 32, 2042003

Non-commutativity as effective description of QG

$$[x_i, x_j] \neq 0 \quad \text{implies} \quad \Delta x_i > 0$$

Foam-like structure of spacetime

String theory: NCG is a **necessary ingredient** for the stability of the theory and to recover the standard model of particle physics (*Seiberg and Witten*)

LQG: NCG possibly **emerges at mesoscopic scale** as a residual property of the discreteness of space at Planckian scales (*Camelia, Marcianò, Cianfrani…*)

The case of θ-Poincarè:

$$[\hat{x}^\mu, \hat{x}^\nu] = i\frac{C^{\mu\nu}}{\Lambda^2}$$

In the low energy regime ($E \ll \Lambda$) the PEP violation probability is highly suppressed:

Closed Systems experimental apparatus

High Purity Ge detector based setup:

- high purity co-axial p-type germanium detector (HPGe), diameter of 8.0 cm, length of 8.0 cm, surrounded by an inactive layer of lithium-doped germanium of 0.075 mm.
- The target material is composed of three cylindrical sections of radio-pure Roman lead, completely surrounding the detector.

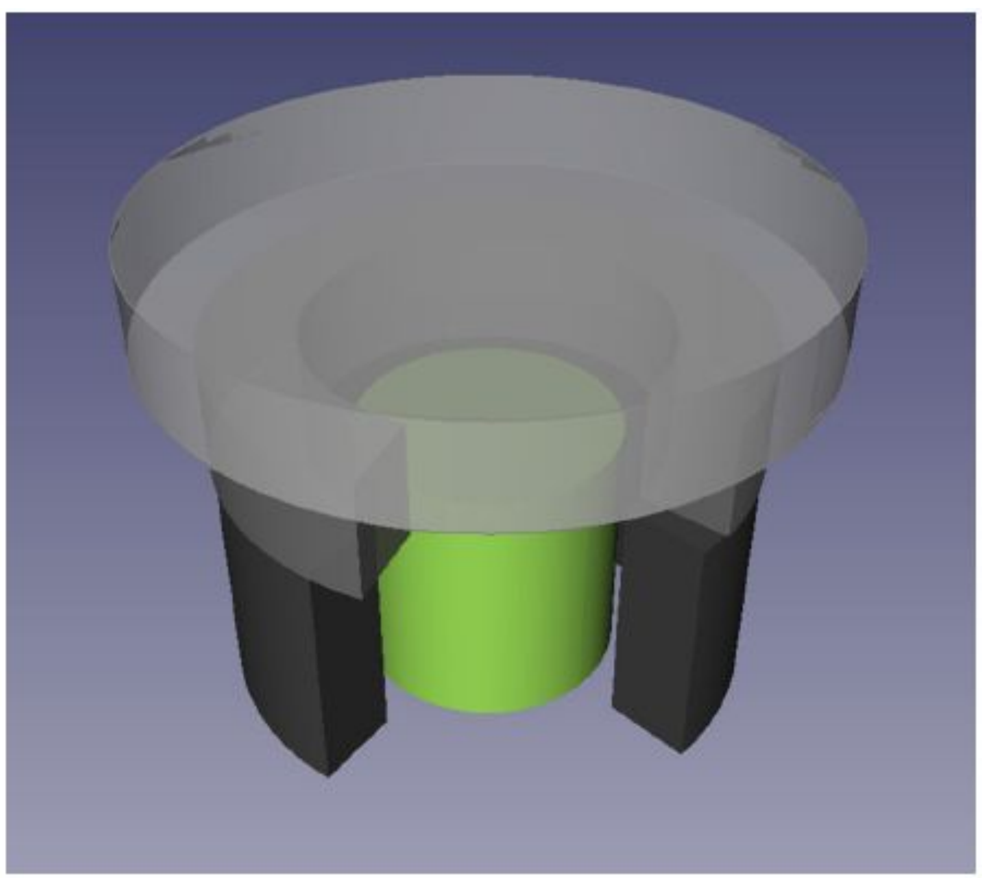


Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

- Passive shielding: inner - electrolytic copper, outer - lead

- 10B-polyethylene plates reduce the neutron flux towards the detector

- shield + cryostat enclosed in air tight steel housing flushed with nitrogen to avoid contact with external air (and thus radon).

- Acquisition time $\Delta t \approx 70\text{d} \approx 6.1\ 10^6\text{s}$

K. P. et al., Eur. Phys. J. C (2020) 80: 508
https://doi.org/10.1140/epjc/s10052-020-8040-5

Statistical model

- The *pdf* of the expected number of total signal counts *S* given the measured distribution is:

$$P(S|data) = \int_0^\infty \int_{\mathcal{D}_\mathbf{p}} P(S,B|data,\mathbf{p})\; d^m\mathbf{p}\; dB$$

$$P(S,B|data,\mathbf{p}) =$$

$$= \frac{P(data|S,B,\mathbf{p}) \cdot f(\mathbf{p}) \cdot P_0(S) \cdot P_0(B)}{\int P(data|S,B,\mathbf{p}) \cdot f(\mathbf{p}) \cdot P_0(S) \cdot P_0(B)\; d^m\mathbf{p}\; dS\; dB}$$

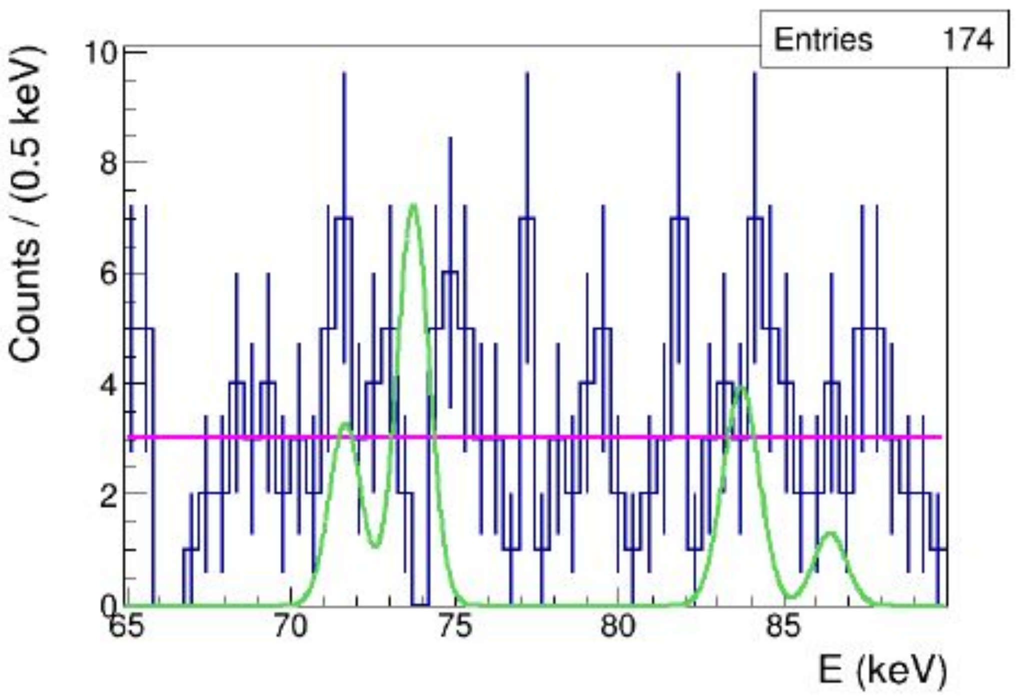


FIG. 1. The measured X-ray spectrum, in the region of the K_α and K_β standard and violating transitions in Pb, is shown in blue; the magenta line represents the fit of the background distribution. The green line corresponds to the shape of the expected signal distribution (with arbitrary normalization) for $\theta_{0_i} \neq 0$.

- the likelihood is weighted on the joint *pdf* of the experimental parameters

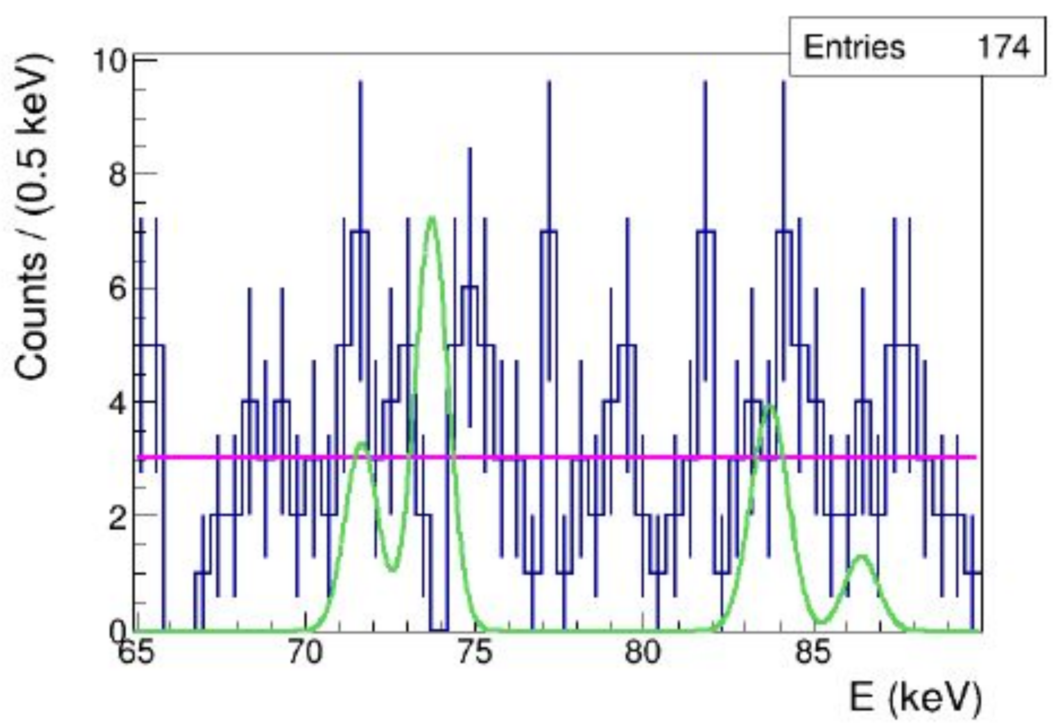
$$P(\mathrm{data}|S,B,\mathbf{p}) = \prod_{i=1}^{N} \frac{\lambda_i(S,B,\mathbf{p})^{n_i} e^{-\lambda_i(S,B,\mathbf{p})}}{n_i!}$$

$$\lambda_i(S,B) = B \cdot \int_{\Delta E_i} f_B(E,\boldsymbol{\alpha})\; dE \; + \\ + S \cdot \int_{\Delta E_i} f_S(E,\boldsymbol{\sigma})\; dE$$

The prior for S consistent with existing limits [Found. Phys. 42, 1015-1030 (2012)**].**

Statistical model

- First analysis which accounts for the predicted energy dependence **of the PEP violation probability. Expected rate of Kalpha1 transitions:**



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$$\Gamma_{K_{\alpha 1}} = \frac{\delta^2(E_{K_{\alpha 1}})}{\tau_{K_{\alpha 1}}} \cdot \frac{BR_{K_{\alpha 1}}}{BR_{K_{\alpha 1}} + BR_{K_{\alpha 2}}} \cdot 6 \cdot N_{atom} \cdot \epsilon(E_{K_{\alpha 1}}).$$

- probability to observe n transitions in the time t:

$$P(n;t) = \frac{(\Gamma_{K_{\alpha 1}}\, t)^n e^{-\Gamma_{K_{\alpha 1}}\, t}}{n!},$$

$$f_S(E,k) = \frac{1}{N} \cdot \sum_{K=1}^{N_K} \Gamma_K \frac{1}{\sqrt{2\pi\sigma_K^2}} \cdot e^{-\frac{(E-E_K)^2}{2\sigma_K^2}}$$

- upper limit on the non-commutativity scale:

$$\mu = \sum_{K=1}^{N_K} \mu_K = \frac{\aleph}{\Lambda^k} < \bar{S}$$

Generalized analysis

- Generalized analysis based on an analytic expansion of the PEP violation prob.

$$\delta^2(E) = c_k \left(\frac{E}{\Lambda_{NC}^{(k)}} \right)^{k} + \mathcal{O}\left(\frac{E}{\Lambda_{NC}^{(k)}} \right)^{k+1}$$

Diffenent ***k*** represent different models

- *k* = 1 corresponds to *k*-Poincaré. Different quantization procedures lead to different predictions:

- **Arzano-Marcianò procedure - PEP violation is suppressed with a probability proportional to $\delta^2 = E / \Lambda$**
- **Freidel-Kowalski-Glikman-Nowak procedure - PEP violation is missing.**

So experimental investigation of statistics violations provides important down-top indications on the “right" quantization procedure: the AM *k*-Poincaré field’s quantization model is ruled out.

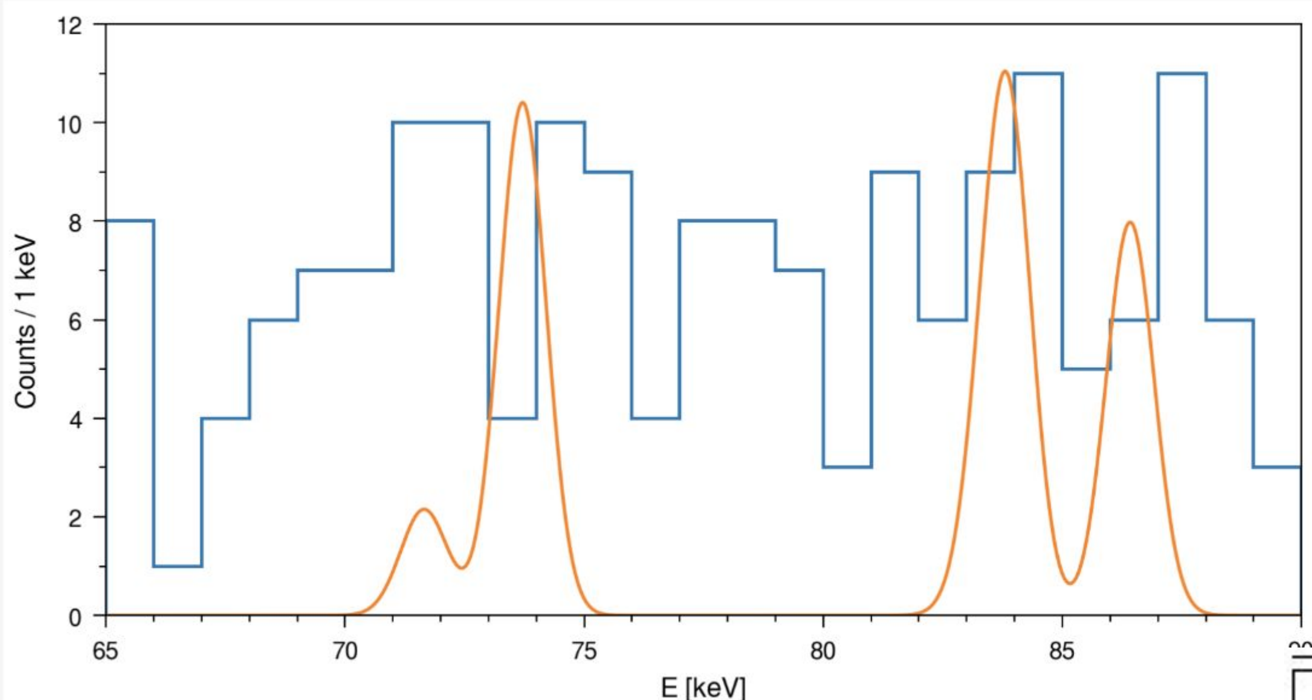
- *k* = 2 corresponds to *θ*-Poincaré: excluded up to $\Lambda > 1.6\ 10^{-1}$ Planck scales

- *k* = 3 corresponds to “triply special relativity” model by Kowalski-Glikman–Smolin (KS). First measurement ever, excluded up to $\Lambda > 5.6\ 10^{-9}$ Planck scales -> experimental guidance towards future developments of the model with two invariant energy scales accounting for the deformation of the (non-commutative) space-time symmetries.

Generalized analysis

- The normalised signal shape for the *M_3* parametrization:

Figure 1. The figure shows the measured X-ray spectrum corresponding to an acquisition time of $\Delta t \approx 6.1 \cdot 10^6$ s in the region of interest. For a comparison, the expected signal distribution (with arbitrary normalization) is also shown in orange for the A_3 analysis and the M_3 parametrization.



- The sensitivity on Λ increases with E -> the analysis is repeated by searching for PEP violation signal in Kα, Kβ and Kα + Kβ transitions.

A_i, M_k	$\bar{S}$	lower limit on Λ in unit of Planck scale
A_1, $k=1$	11.4913	$3.1 \cdot 10^{21}$
A_1, $k=2$	11.3776	$1.4 \cdot 10^{-1}$
A_1, $k=3$	11.2610	$4.9 \cdot 10^{-9}$
A_2, $k=1$	15.1408	$2.8 \cdot 10^{21}$
A_2, $k=2$	15.1640	$1.4 \cdot 10^{-1}$
A_2, $k=3$	15.1859	$5.1 \cdot 10^{-9}$
A_3, $k=1$	18.7270	$4.2 \cdot 10^{21}$
A_3, $k=2$	19.1847	$1.6 \cdot 10^{-1}$
A_3, $k=3$	19.5993	$5.6 \cdot 10^{-9}$

K. P. et al., PRL 129, 131301 (2022)

K. P. et al., PRD 107, 026002 (2023)

KP et al., Universe 2023, 9(7), 321

Preliminary analysis on PEPV in Generalized Uncertainty Principle models

Several QG candidates predict the existence of a **minimal length** on the order of the Planck scale -> deformation of the Heisenberg uncertainty principle: $\delta x\, \delta p \geq \frac{\hbar}{2}\left(1+\beta\, \delta p^2\right)$

E.g. GUP structure emerges from **string theory** in the high energy limit.

The construction of field theories in this context implies **deformations of the statistics:**
Theory already developed by Bosso, Petruzziello, Illuminati

PEP atomic tests suitable to investigate GUP models. **FIRST STUDY EVER!**

Violation of the PEP depends on the energy and on Λ_{GUP} as $\boxed{\delta^2(E,\beta) = \frac{m\,\Delta E}{\Lambda_{GUP}^2}}$

Preliminary result!

$\Lambda_{GUP} > 0.52$ Planck scales

QG tests through nuclear and atomic PEPV transitions

- **Why? Lorentz symmetry is a central assumption of the spin-statistics theorem, which is deformed in QG framework.**

- **Leading order PEPV probability:** $$W_V = \frac{\beta}{m_p^2 c^2} m_e E_T W_S$$

ADVANTAGE - the PEPV transition energies are not model dependent. E.g. in atomic transitions they are determined by the nuclear shielding provided by the fully occupied 1s state.

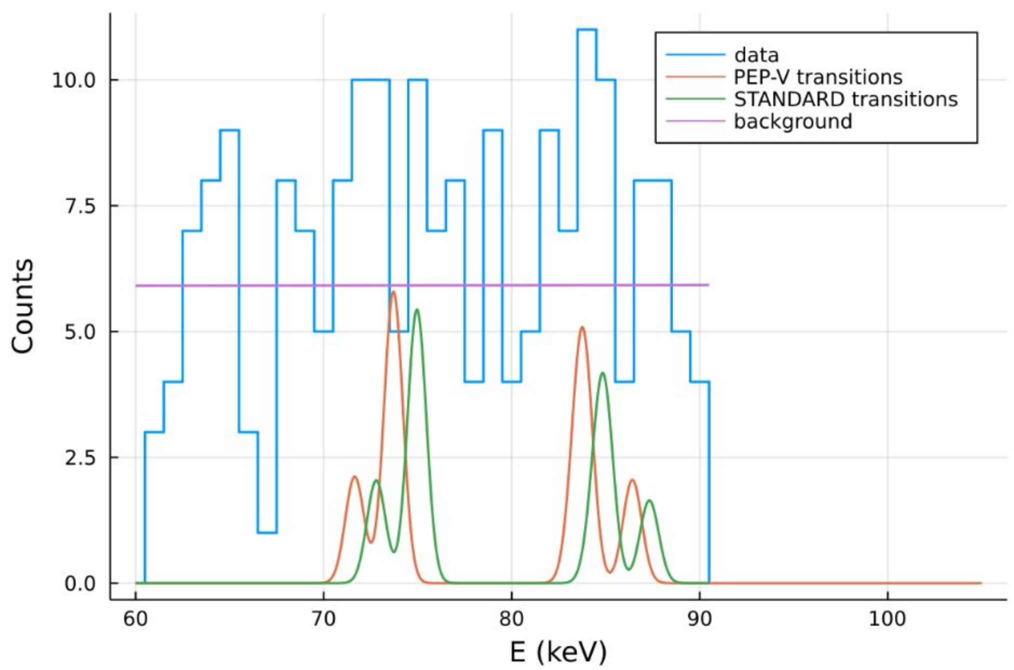
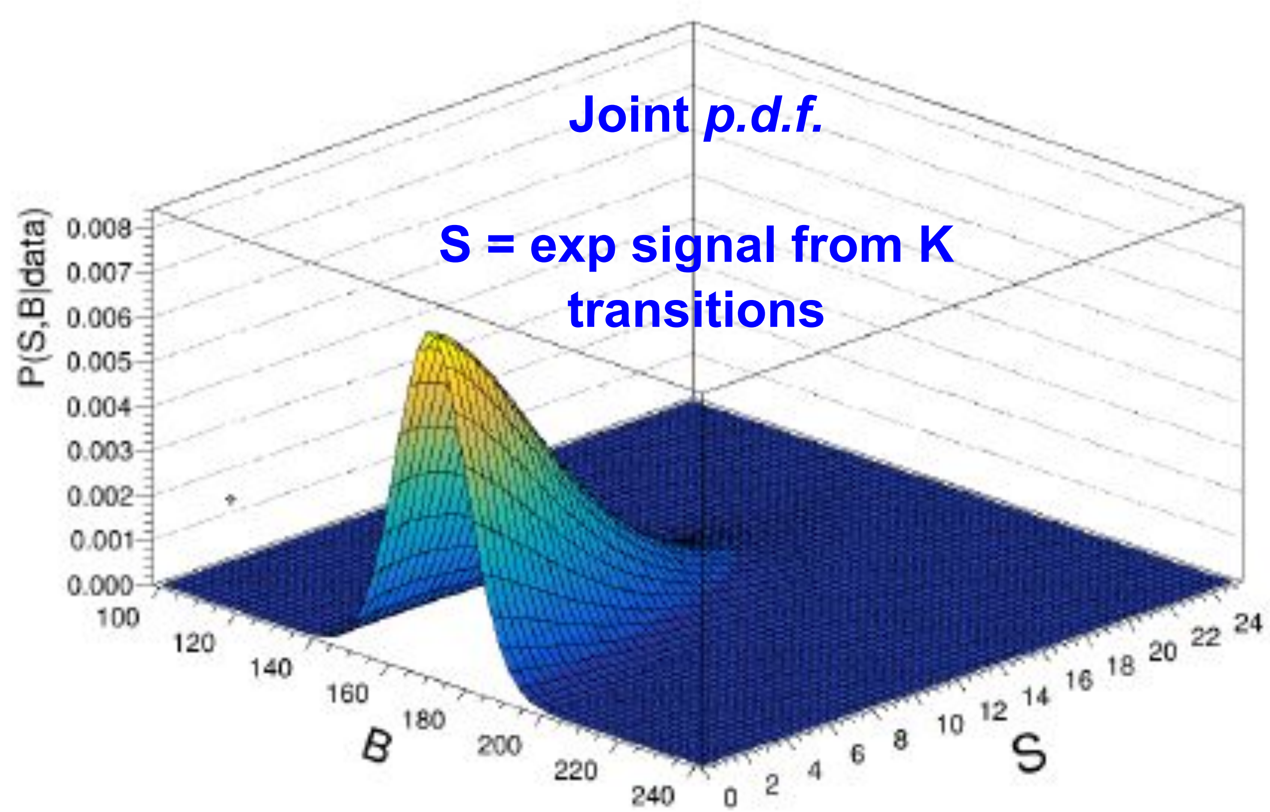


Figure 1 - The results of a Bayesian fit are shown of the data collected in Ref. [12]. The blue distribution corresponds to data, the background is shown in purple. The green curve corresponds to the contribution of the standard K atomic transitions in the Roman Pb target. The orange distribution corresponds to the 90% C.L. on the PEP-violating K atomic transitions.



QG tests through nuclear and atomic PEPV transitions

- **Upper bound ML: β < 10 (90% C.L.)**
  i.e. 1 o.m. sensitivity to exclude the ML model up to Planck scale

With respect to cosmological / astrophysical bounds

Experiment	Upper bound on β
Perihelion precession (Solar System, 1)	10^{34}
Time-of-flight measurements	10^{16}
Equivalence principle (pendula)	10^{73}
Gravitational bar detectors	10^{93}
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BOUNDS ON OTHER QG MODELS:

- **k-Poincaré excluded in the A-M quantization scheme (dispersion relations bound from AGN flares - sensitivity 0.1 Planck scales)**

- **Hadronic sector - θ-Poincaré excluded (DAMA, BOREXINO and KAMIOKANDE)**

- **Leptonic sector - θ-Poincaré excluded up to 0.16 Planck scales (90% C.L.)**

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  i.e. 1 o.m. sensitivity to exclude the ML model up to Planck scale

Experiment	Upper bound on β
Perihelion precession (Solar System, 1)	10^{34}
Time-of-flight measurements	10^{16}
Equivalence principle (pendula)	10^{73}
Gravitational bar detectors	10^{93}
Equivalence principle (atoms)	10^{45}
Low-mass stars	10^{48}
LIV in torsion pendulum	10^{51}
Perihelion precession (Solar System, 2)	10^{69}
Perihelion precession (pulsars)	10^{71}
Gravitational redshift	10^{76}
Black hole quasi normal modes	10^{77}
Light deflection	10^{78}
Time delay of light	10^{81}
Black hole shadow	10^{90}
Black hole shadow	10^{90}

Class.Quant.Grav. 40 (2023) 19, 195014

PRL 129, 131301 (2022)

PRD 107, 026002 (2023)

Universe 2023, 9(7), 321

- **k-Poincaré excluded in the A-M quantization scheme (dispersion relations bound from AGN flares - sensitivity 0.1 Planck scales)**

- **Hadronic sector - θ-Poincaré excluded (DAMA, BOREXINO and KAMIOKANDE)**

Not accessible with dispersion relations

- **Leptonic sector - θ-Poincaré excluded up to 0.1 Planck scales (90% C.L.)**

Quantum and Gravity

DYNAMICAL COLLAPSE MODELS:

- **Why the quantum properties (e.g. superposition) do not carry over to the macro-world?**

- **Stochastic and non-linear modifications of the Schroedinger dynamics -> spontaneous collapse, progressive reduction of the superposition, proportional to the increase of the mass of the system**

"**<u>spontaneous universal collapse in massive degrees of freedom, assuming a fundamental gravity-related irreversibility, may have perspectives for quantum cosmology as well</u>**"
L. Diósi (2023) J. Phys.: Conf. Ser. 2533 012005)

Spontaneous decoherence induced by space-time indeterminacy

&

Irreversibility in Quantum Gravity/Cosmology at the Planck scale

lead to the same structure of master equations

<u>this spectacular connection can be experimentally tested</u> !

Global time uncertainty and decoherence

Diosi, L. (2005), Braz. J. Phys. 35, 260, Diosi, L., and B. Lukacs (1987), Annalen der Physik 44, 488, Diosi, L. (1987), Physics Letters A 120, 377, A. Bassi et al.,Rev. Mod. Phys. 85,471

Initial state of a quantum system is a superposition of two eigenstates of total Hamiltonian

$$|\psi\rangle = c_1|\varphi_1\rangle + c_2|\varphi_2\rangle$$

time evolution

$$|\psi(t)\rangle = c_1 \exp(-i\hbar^{-1}E_1 t)|\varphi_1\rangle + c_2 \exp(i\hbar^{-1}E_2 t)|\varphi_2\rangle$$

Let us add an uncertainty to the time $t \to t + \delta t$

and assume that is distributed Gaussian, with zero mean, and dispersion which is proportional to the mean time, $\mathbf{M}[(\delta t)^2] = \tau t$ then the density matrix evolves as:

$$\begin{aligned}
& \rho(t) \equiv \mathbf{M}\left[|\psi(t)\rangle\langle\psi(t)|\right] = \\
= \; & |c_1|^2|\varphi_1\rangle\langle\varphi_1| + |c_2|^2|\varphi_2\rangle\langle\varphi_2| + \\
+ \; & \{c_1^\star c_2 \exp(i\hbar^{-1}\Delta E t)\mathbf{M}\left[\exp(i\hbar^{-1}\Delta E \delta t)\right]|\varphi_2\rangle\langle\varphi_1| + \\
+ \; & \quad \text{h.c.} \quad \} \, .
\end{aligned}$$

Global time uncertainty and decoherence

Diosi, L. (2005), Braz. J. Phys. 35, 260, Diosi, L., and B. Lukacs (1987), Annalen der Physik 44, 488, Diosi, L. (1987), Physics Letters A 120, 377, A. Bassi et al.,Rev. Mod. Phys. 85,471

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$$\begin{aligned} &\rho(t) \equiv \mathbf{M}\left[|\psi(t)\rangle\langle\psi(t)|\right] = \\ = \ &|c_1|^2|\varphi_1\rangle\langle\varphi_1| + |c_2|^2|\varphi_2\rangle\langle\varphi_2| + \\ + \ &\cancel{\{c_1^\star c_2 \exp(i\hbar^{-1}\Delta E t)\mathbf{M}\left[\exp(i\hbar^{-1}\Delta E\delta t)\right]|\varphi_2\rangle\langle\varphi_1| +} \\ + \ &\cancel{\quad \text{h.c.} \quad \}} \ . \end{aligned}$$

$$\mathbf{M}\left[\exp(i\hbar^{-1}\Delta E\delta t)\right] = e^{-t/t_D}$$

$$t_D = \frac{\hbar^2}{\tau}\frac{1}{(\Delta E)^2}$$

Global time uncertainty and decoherence

The time evolution for the density matrix

$$\hat{\rho}(t+\tau)=\exp\left[\frac{-i\hat{H}\tau}{\hbar}\right]\hat{\rho}(t)\exp\left[\frac{i\hat{H}\tau}{\hbar}\right]$$

Described by the von Neumann equation $\frac{d\rho}{dt}=-i\hbar^{-1}[H,\rho]$

turns to $$\frac{d\rho}{dt}=-i\hbar^{-1}[H,\rho]-\frac{1}{2}\tau\hbar^{-2}[H,[H,\rho]]$$

G. J. Milburn Prys. Rev. A 44 5401 (1991)

Local time uncertainty and decoherence

To generalize the concept for a local time $t_{\mathbf{r}} \to t + \delta t_{\mathbf{r}}$

one defines the correlation $\mathbf{M}[\delta t_{\mathbf{r}} \delta t_{\mathbf{r}'}] = \tau_{\mathbf{r}\mathbf{r}'} t$

Galileo invariant spatial correlation function

If the total Hamiltonian is decomposed in the sum of the local ones

$$\frac{d\rho}{dt} = -i\hbar^{-1}[H, \rho] - \frac{1}{2}\hbar^{-2} \sum_{\mathbf{r},\mathbf{r}'} \tau_{\mathbf{r}\mathbf{r}'} [H_{\mathbf{r}}, [H_{\mathbf{r}'}, \rho]]$$

The master equation suppresses superpositions of eigenstates of local energy

$$[\tau_d(X, X')]^{-1} = \frac{G}{2\hbar} \int \int d^3r \, d^3r' \times \frac{[f(\mathbf{r}|X) - f(\mathbf{r}|X')][f(\mathbf{r}'|X) - f(\mathbf{r}'|X')]}{|\mathbf{r} - \mathbf{r}'|}$$

Self-gravitational energy of the difference between the mass distributions of two states |X> and |X'> in superposition.

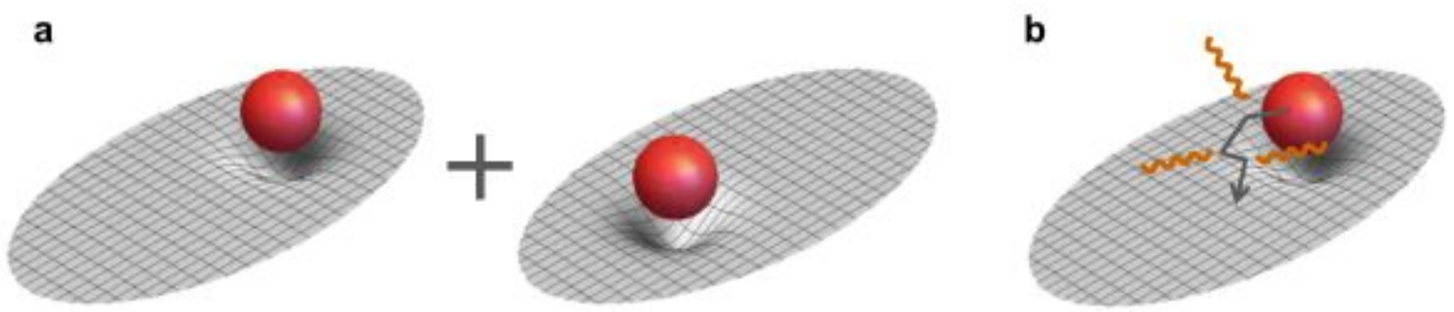
Diverges for point-like particles -> a short-length cutoff R_0 is introduced to regularize the theory.

Radiation measurements to test the collapse

- Unavoidable side effect of the stochastic collapse dynamics:

a Brownian-like diffusion of the system in space Phys. Rev. Lett. 130, 230202 (2023).

Collapse probability is Poissonian in t -> Lindblad dynamics for the statistical operator -> free particle average square momentum increases in time.



- Then charged particles emit spontaneous radiation. We search for spontaneous radiation emission from a germanium crystal and the surrounding materials in the experimental apparatus.

Strategy: simulate the background from all the known emission processes -> perform a Bayesian comparison of the residual spectrum with the theoretical prediction -> extract the pdf of the model parameters -> bound the parameters.

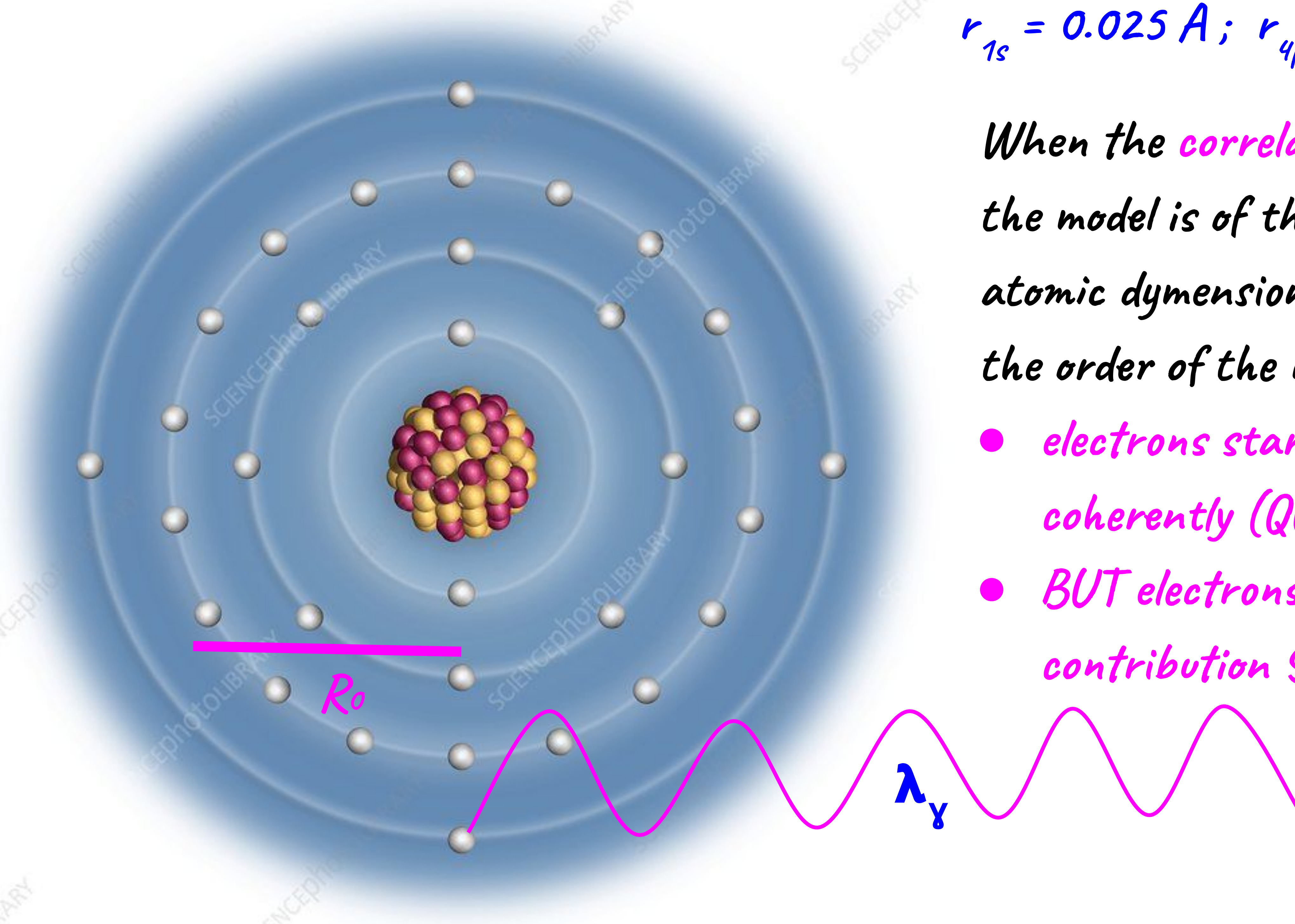
Spontaneous emission

in the X-rays

In the low-energy regime, the photon w.l. is comparable to the atomic orbits dimensions

e.g. $\lambda_{dB}(E = 15\ keV) = 0.8\ A$

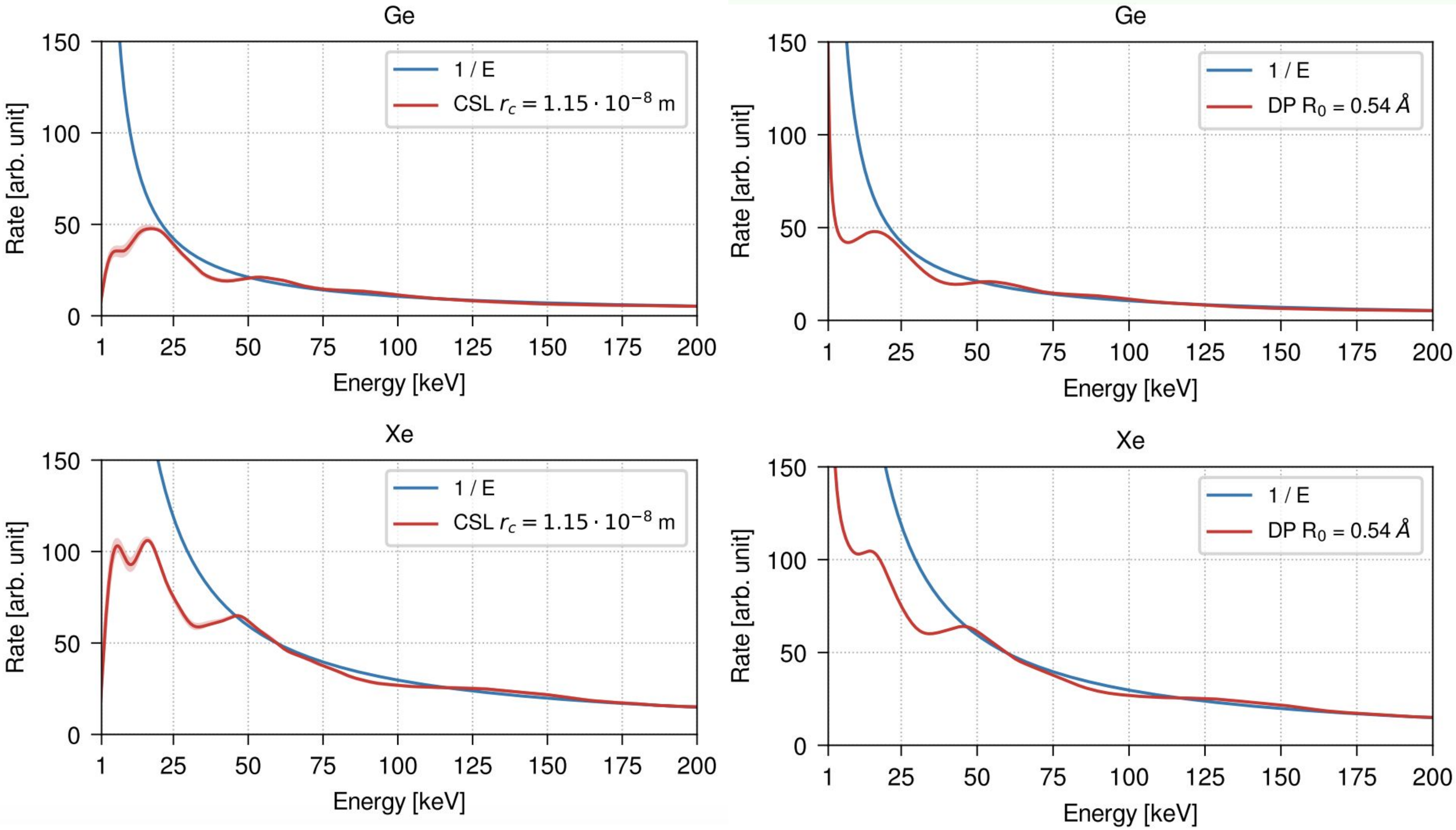
$r_{1s} = 0.025\ A\ ;\ r_{4p} = 1.5\ A$



When the correlation length (R_0) of the model is of the order of the atomic dymension, and also λ_γ is of the order of the mean atomic radii:

- electrons start to emit coherently (QUADRATICALLY)
- BUT electrons-protons contribution START TO CANCEL

Spontaneous emission in the X-rays regime



- at each energy the atomic structure influences the expected S.E. spectrum shape
- the S.E. spectrum shape is different for different collapse mechanisms.

K. P. et al., Phys. Rev. Lett. 132, 250203 (2024)

Spontaneous emission in the X-rays regime

K. P. et al., Phys. Rev. Lett. 132, 250203 (2024)

$$\left.\frac{d\Gamma}{dE}\right|_t^{DP} = \frac{Ge^2}{12\pi^{5/2}\epsilon_0 c^3 R_0^3 E}\left\{N_p^2 + N_e + 2\sum_{o\,o'\ \text{pairs}} N_o\,N_{o'}\,\frac{\sin\left[\frac{\beta|\rho_o-\rho_{o'}|\,E}{\hbar\,c}\right]}{\left[\frac{\beta|\rho_o-\rho_{o'}|\,E}{\hbar\,c}\right]}e^{-\frac{\beta^2(\rho_o-\rho_{o'})^2}{4R_0^2}} + \right.$$

$$\left. + \sum_o N_o\,(N_o-1)\,e^{-\frac{(\alpha\,\rho_o)^2}{4R_0^2}}\cdot\frac{\sin\left(\frac{\alpha\,\rho_o\,E}{\hbar\,c}\right)}{\left(\frac{\alpha\,\rho_o\,E}{\hbar\,c}\right)} - 2N_p\sum_o N_o\,\frac{\sin\left(\frac{\rho_o\,E}{\hbar\,c}\right)}{\left(\frac{\rho_o\,E}{\hbar\,c}\right)}\cdot e^{-\frac{\rho_o^2}{4R_0^2}}\right\}$$

first prediction of a distinctive experimental signature in the radiation produced by different decoherence mechanisms!

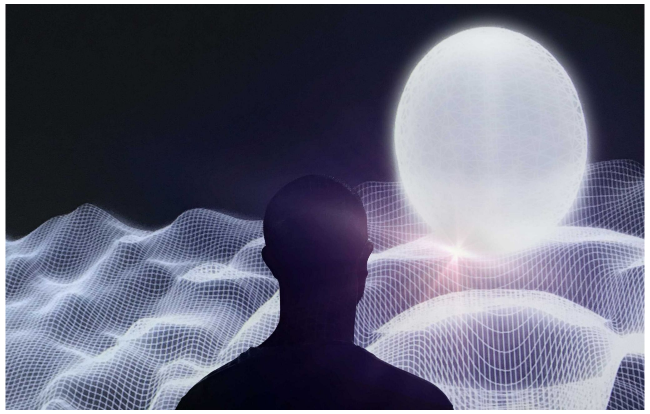
Opens up a world of new experimental challenges, to test established and new models linking gravitation to quantum mechanics.

R&D of a dedicated experiment ongoing.

QG-decoherence tests through spontaneous radiation measurements

- **Suppression of quantum coherence is one of the features of QG.**

E.g. (Nat. Comm. 12, 4449 (2021)) **fluctuating ML due to the foamy structure of quantum space-time induces a universal gravitational decoherence.**

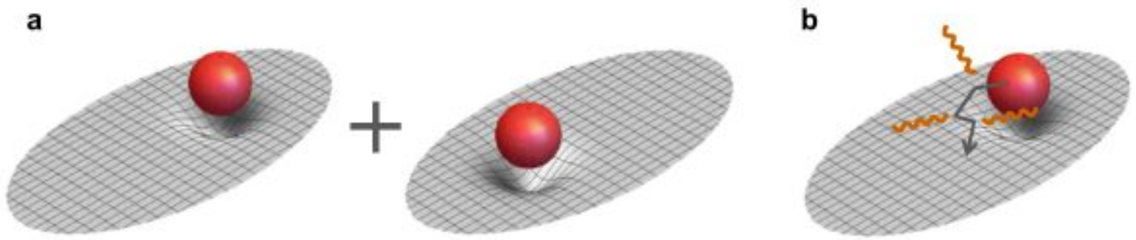


In the vast scenario of experimental techniques applied to investigating spontaneous decoherence: interferometric experiments, cold atoms, optomechanical setups, phonon excitations in crystals, gravitational wave detectors ..

the best sensitivity is provided by X-ray and γ-ray measurements of *spontaneous radiation* (Nature Physics 17, 74 (2021), Phys. Rev. Lett. 129, 080401 (2022)).

Stochastic fluctuations of the gravitational field induce diffusion

charged particles emit radiation (Phys. Rev. Lett. 130, 230202 (2023))



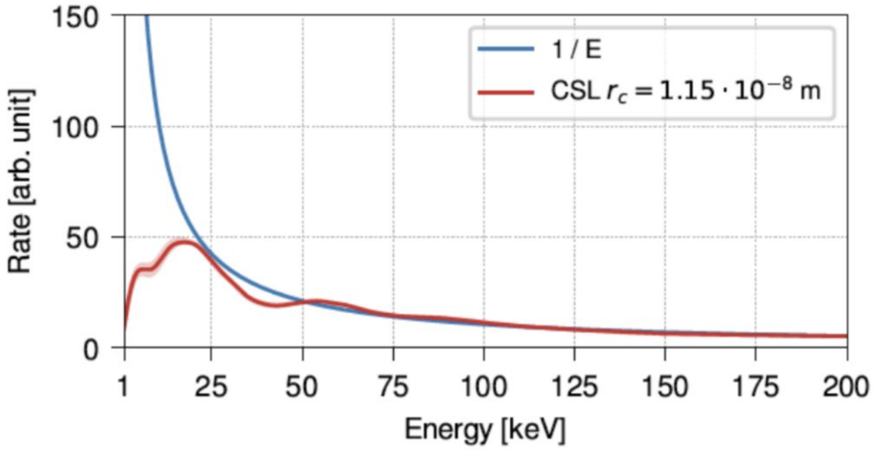
QG-decoherence tests through spontaneous radiation measurements

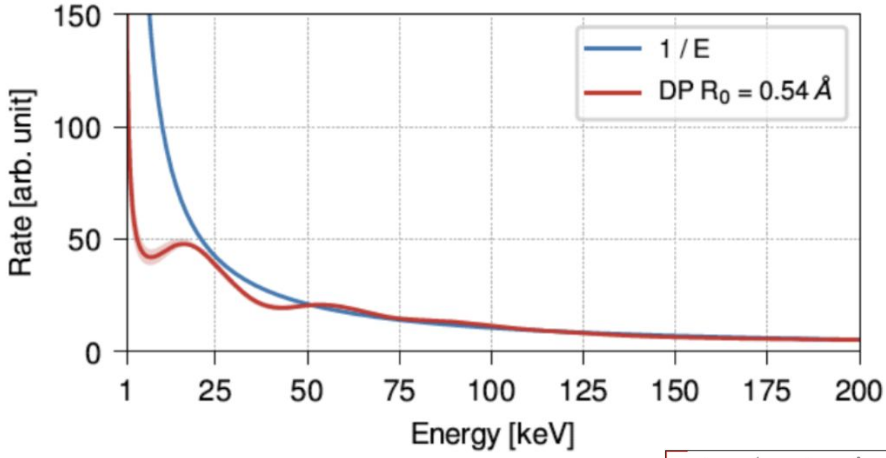
- **We have recently shown (Phys. Rev. Lett. 132, 250203, (2024)) that:**

the spontaneous radiation signature in the energy range of few keV is sensitive to the decoherence mechanism

QG models would produce distinctive spontaneous radiation E-spectra

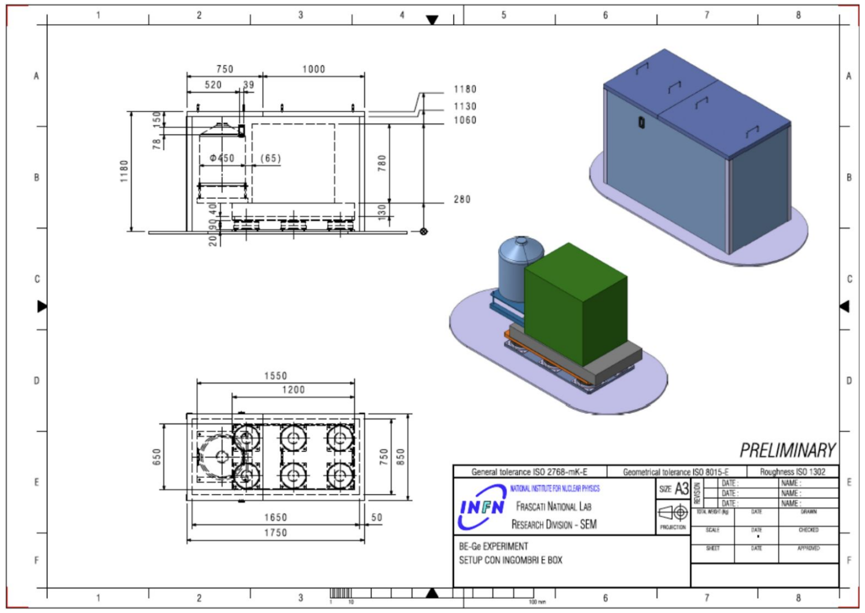
due to the intertwined nuclear and atomic spontaneous radiation





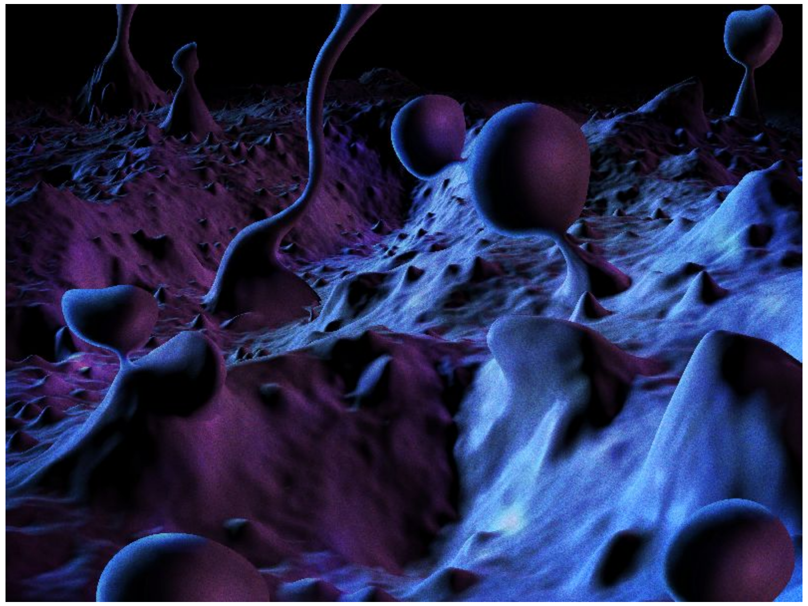
- **A prototype setup for a REGe-based detector is under finalization (&LNGS (INFN)) to test simultaneously this effect, and PEPV transitions in several targets:**
  expected improved sensitivity on β - factor 14

Condens. Matter 2024, *9*(2), 22



QG induced CPT violation with entangled meson experiments

- The CPT theorem is a consequence of Lorentz invariance, locality and unitarity



- Wheeler: ST has a foamy structure at the Planck scale, microscopic horizons of radius of the order of the Planck length induce in ST a fuzzy structure

- topological fluctuations of ST break the unitary evolution

- von Neumann turns to Lindblad equation for the density matrix

- Wald : entanglement of matter systems with gravitational fluctuations imply violation of CPT .

- If CPT QM operator is well defined, neutral meson pairs are produced in meson decays into a fully anti-symmetric entangled state with $J^{PC} = 1^{--}$:

$$|i\rangle = \frac{1}{\sqrt{2}}\left(\left|\overline{M_0}\left(\vec{k}\right)\right\rangle\left|M_0\left(-\vec{k}\right)\right\rangle - \left|M_0\left(\vec{k}\right)\right\rangle\left|\overline{M_0}\left(-\vec{k}\right)\right\rangle\right)$$

BUT …

QG induced CPT violation with entangled meson experiments

- **If CPT is ill-defined the initial entangled state can be parametrized as:**

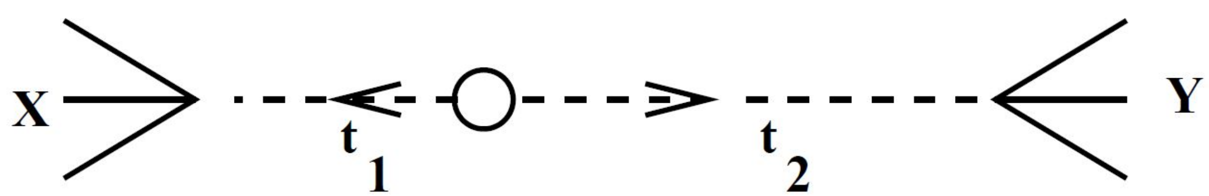
$$|i\rangle = \frac{1}{\sqrt{2}}\left(\left|\overline{M_0}\left(\vec{k}\right)\right\rangle\left|M_0\left(-\vec{k}\right)\right\rangle - \left|M_0\left(\vec{k}\right)\right\rangle\left|\overline{M_0}\left(-\vec{k}\right)\right\rangle\right)$$
$$+ \frac{\omega}{\sqrt{2}}\left(\left|\overline{M_0}\left(\vec{k}\right)\right\rangle\left|M_0\left(-\vec{k}\right)\right\rangle + \left|M_0\left(\vec{k}\right)\right\rangle\left|\overline{M_0}\left(-\vec{k}\right)\right\rangle\right)$$

with ω the complex CPTV parameter. E.g. for kaons, in terms of the mass eigenstates:

$$\begin{aligned} |i> \; &= \; C\Big[\Big(|K_S(\vec{k}), K_L(-\vec{k}) > - |K_L(\vec{k}), K_S(-\vec{k}) >\Big) \\ &+ \; \omega\Big(|K_S(\vec{k}), K_S(-\vec{k}) > - |K_L(\vec{k}), K_L(-\vec{k}) >\Big)\Big] \end{aligned}$$

Phys. Rev. Lett. 92, 131601 (2004)
Phys. Rev. D 74, 045014 (2006)
Eur. Phys. J. C 77, 865 (2017)

EXPERIMENTAL STRATEGY: The amplitude for the final state:



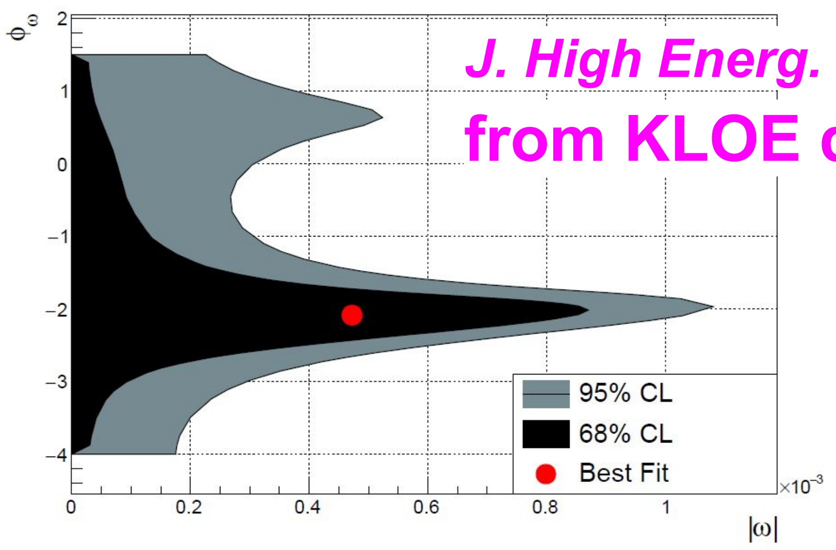
$$I(\Delta t) \equiv \frac{1}{2}\int_{|\Delta t|}^{\infty} dt\, |A(X,Y)|^2 \qquad \Delta t = t_2 - t_1$$

is used to fit the experimental distribution.

Best channel: $X \; = \; Y \; = \; \pi^+\pi^-$

QG induced CPT violation with entangled meson experiments

Th. prediction $$|\omega|^2 \sim \frac{\zeta^2 k^4}{M_P^2 (m_1 - m_2)^2}$$



J. High Energ. Phys. **2022, 59 (2022)**

from KLOE data

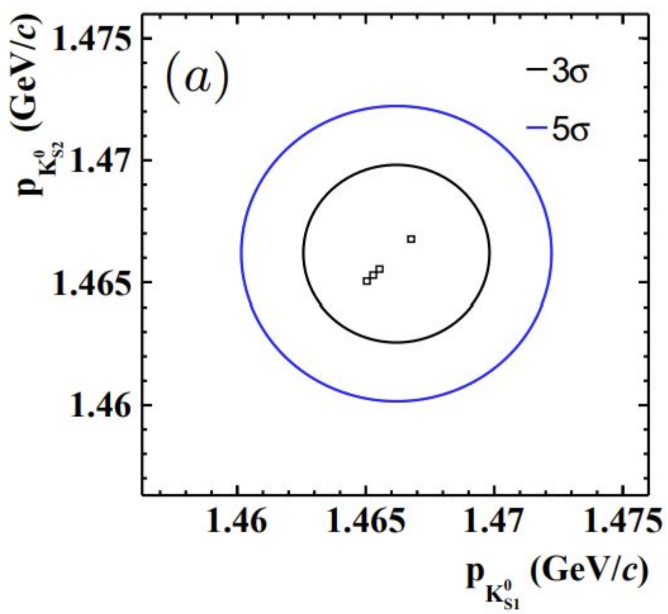
theory expectation ω ~ 10^{-6}

arXiv:2504.13771 [hep-ex] from BESIII data

$$J/\psi \to K_S^0 K_S^0$$

exp. result ω < 5 x10^{-3} 90% CL

theory expectation ω ~ 5 x 10^{-4}



LHCb data $D^0 \to K^- \pi^+$ and $\overline{D^0} \to K^+ \pi^-$

is setting the strongest bounds on $\delta\Gamma_D$ **and** δm_D

Phys. Rev. D 104, 072010 (2021), Phys. Rev. D 110, 055021 (2024)

to be reinterpreted in terms of ω

Theory also ready for testing the decays in a B factory [*Eur.Phys.J.C* 77 (2017) 12, 865]

Entangled mesons - data fit

- The fit is performed over the measured Delta t distribution. The fit-function in the j-th bin is:

$$I(\mathbf{q})_j^{\mathrm{th}} = \int_{(j-1)\overline{\Delta t}}^{j\overline{\Delta t}} d(\Delta t) \int_{\Delta t}^{\infty} I(t_1, t_2|\mathbf{q})\ d(t_1 + t_2)$$

- This is then corrected by efficiency, the smearing on the time resolution, and the regeneration, the estimated bkg is subtracted from the measured events:

$$\chi^2 = \sum_i \left(\frac{N_i^{\mathrm{data}} - N(\mathbf{q})_i^{\mathrm{th}}}{\sigma_i} \right)^2$$

- fit result in polar coordinates:

$$|\omega| = (4.7 \pm 2.9_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}) \cdot 10^{-4},$$

$$\phi_\omega = -2.1 \pm 0.2_{\mathrm{stat}} \pm 0.1_{\mathrm{syst}}\ (\mathrm{rad}) \quad \text{with } \chi^2/\mathrm{dof} = 9.2/9$$

Stochastic methods bridging QG-induced decoherence and Hadron physics

Stochastic quantization method developed by Parisi and Wu (Sci. Sin. 24, 483 (1981)):

quantum field theory as the equilibrium limit of a stochastic process.

CONNECTION WITH QG:

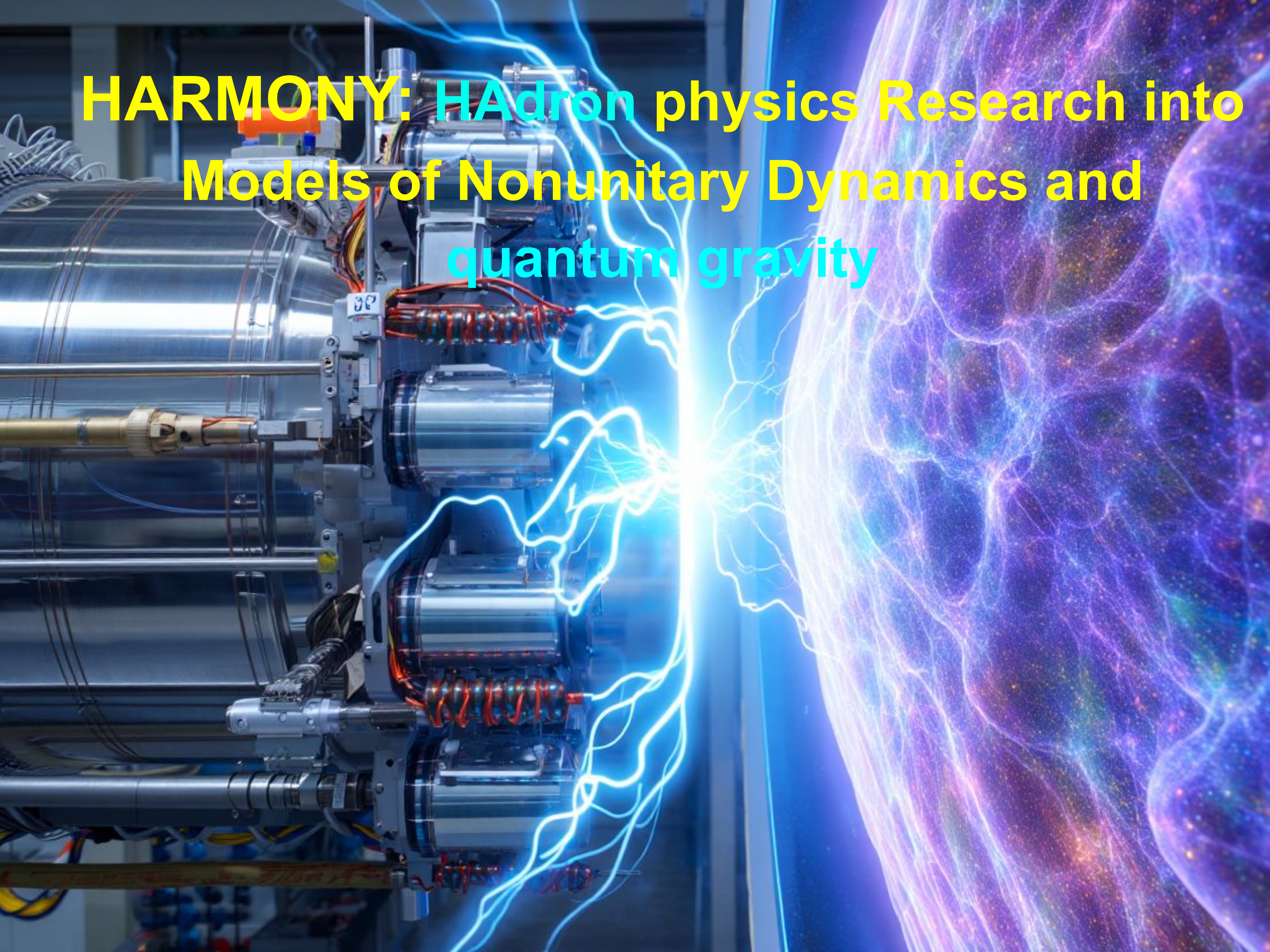
Ricci flow describes how the metrics evolves in time according to the curvature

$$\frac{\partial g_{ij}}{\partial t} = -2\, R_{ij}$$

In quantum gravity, spacetime is expected to fluctuate at the Planck scale.

Stochastic Ricci flow models these fluctuations by introducing random terms into the Ricci flow equation, creating a quantum version of spacetime evolution.

RESULT: the Diosi-Penrose decoherence is retrieved in the non-relativistic limit of QG $\longrightarrow$ this feature of QG is testeable in the low-energy regime through PEPV & CPTV


HARMONY: HAdron physics Research into Models of Nonunitary Dynamics and quantum gravity