

VIP Status report

K. Piscicchia

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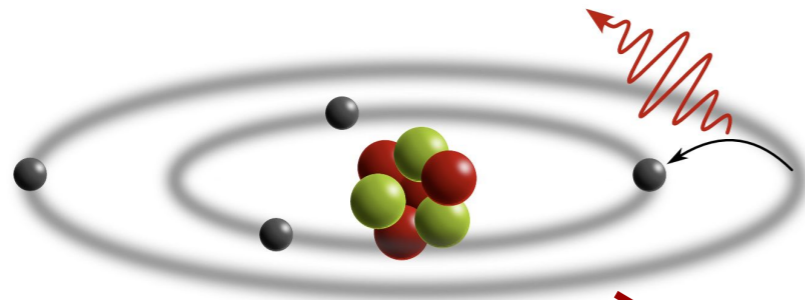
on behalf of the VIP collaboration

LXV meeting of the SC committee

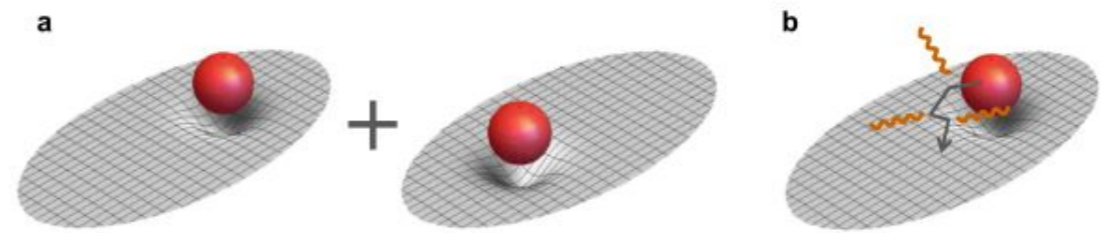
20-21 April 2026

What is VIP doing?

Pauli Principle Violation



Spontaneous w.f. collapse



Open systems
experiments
VIP-2 / VIP-3

Closed systems
experiments
HPGe / BEGe

To test
QUON / GUP

To test
NCQG

To test **CSL**,
Grav. Collapse ..

hinging on the quantum-gravity connection

What is VIP doing?

Overview of theoretical and experimental VIP activities (with discussion on competitors)

Kristian Piscicchia^{1,2} and Catalina Curceanu²

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“Enrico Fermi”, Italy

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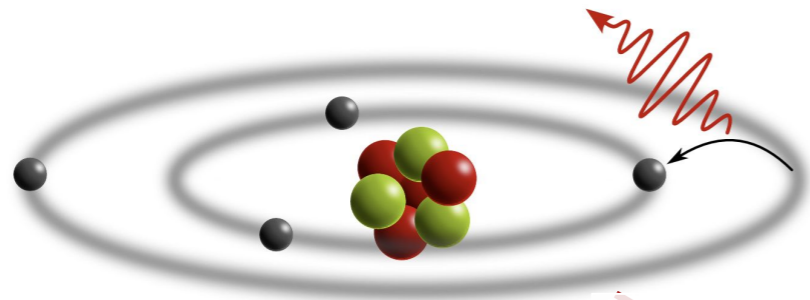
September 21, 2024

Abstract

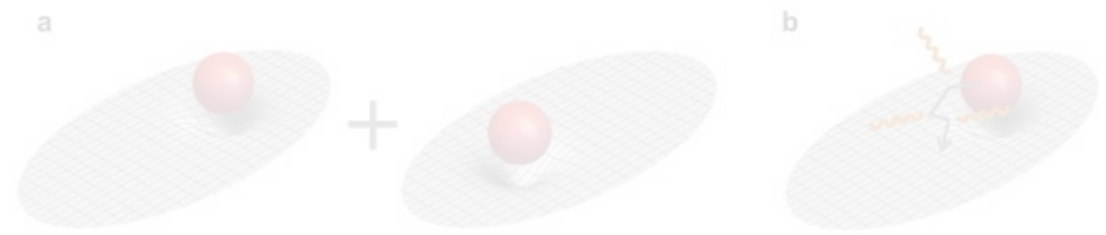
In this document an overview of the VIP collaboration's theoretical and experimental activities is presented. The introduction provides a discussion of the theoretical framework for the two main research lines, namely deformation (violations) of the spin-statistics and spontaneous wave function collapse, interconnections among them are also examined. In the following sections the VIP experimental setups are described, the phenomenological strategies, the data analyses frameworks and the main results are reviewed and compared with the other approaches/experiments which are available in the literature.

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Open systems - PEPV in Quon

Pauli Exclusion Principle (PEP) is a direct consequence of the **Spin-Statistics Th.**

which is fundamentally grounded on:

Poncaré, Locality, Microcausality i.e. **CPT symmetries**

PEP tests -> high sensitivity tests of the Standard Model pillars

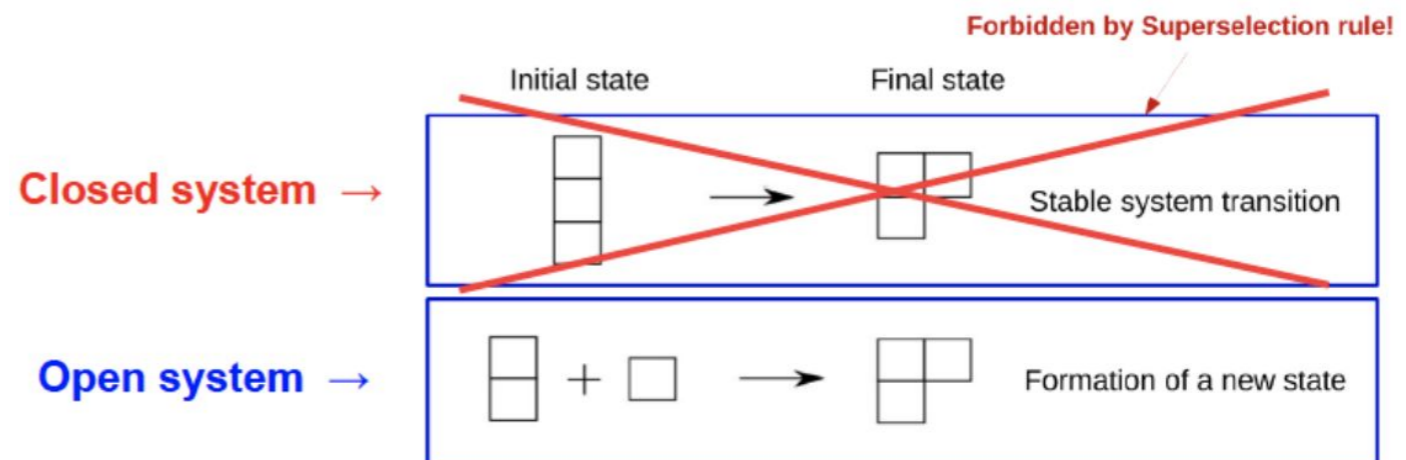
Non-Local QFT - Greenberg & Mohapatra (Quon Model), Ignatiev, Kuzmin, Rahal, Campa...

$$a_k a_l^\dagger - q a_l^\dagger a_k = \delta_{k,l}$$

are subjected to M-G superselection rule: transition probability between two symmetry states is zero



introduce new fermions (current) in a pre-existing identical fermion system and check for PEP-violating atomic transitions **VIP2/3 Open Systems**



Strongest bound on Quon in Nature Sci Rep

scientific reports

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Article | [Open access](#) | Published: 24 November 2025

Strongest constraint on the parastatistical Quon model with the VIP-2 measurements

Whole VIP-2 statistics analyzed
best constraint ever respecting MG

$$P_{\text{PEPV}} < 2.47 \times 10^{-43}$$

90% CL

more than 2 o.m. better than VIP

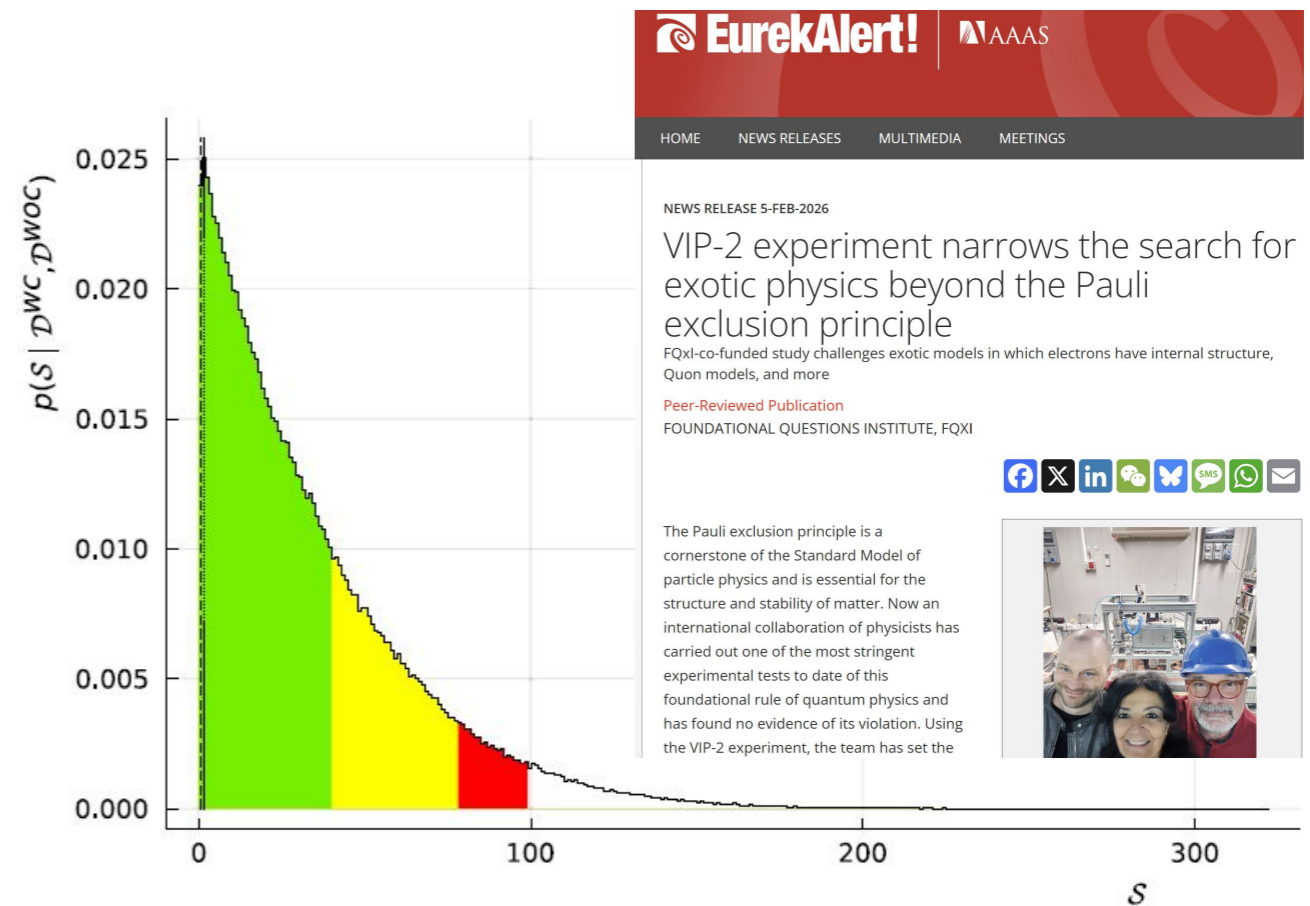
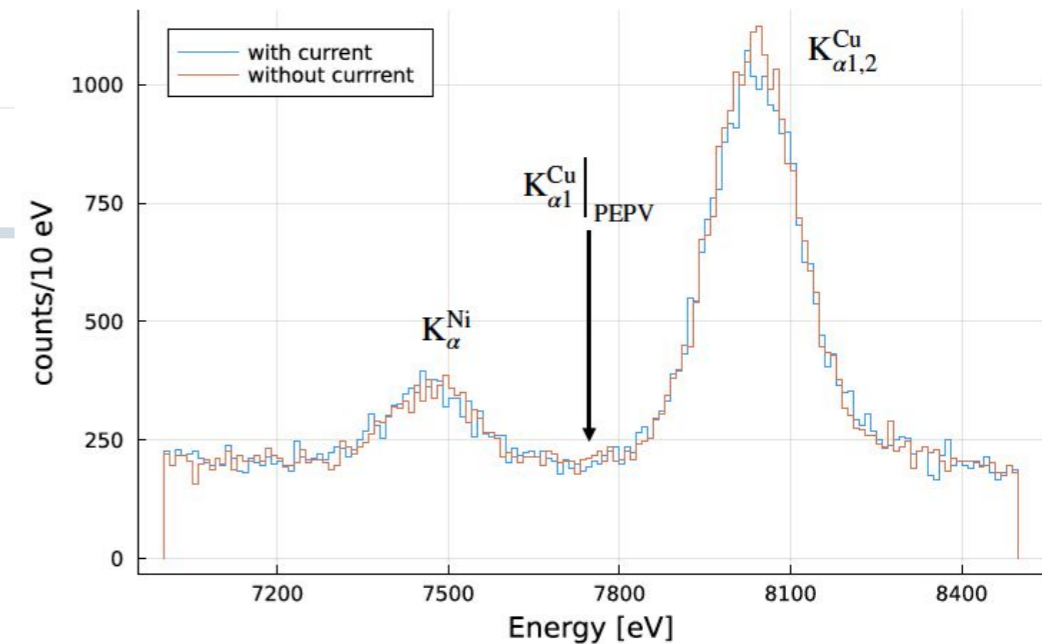


Fig. 5. The posterior distribution for the signal-strength S is derived via numerical Markov-Chain Monte Carlo integration and marginalization on the remaining parameters. Red, yellow, and green show the 95%, 90%, and 66% intervals of CL, respectively.

Open systems - PEPV in GUP

- In all QG scenarios the Heisenberg uncertainty relations (HUP) modify at sufficiently high energies, where the gravitational field plays a relevant role,
- **NON-LOCAL** nature of the fundamental degrees of freedom -> deformation of HUP -> minimal uncertainty in space -> **VIOLATION OF STATISTICS**

RECENT REVIEW Classical and Quantum Gravity 40 (2023) 195014.

- For a one-dimensional quantum system: $\Delta x \Delta p \geq \frac{\hbar}{2} (1 + \beta \Delta p^2)$

- **MINIMUM LENGTH** $\Delta x_{\min} : \hbar \sqrt{\beta}$. $\beta = \beta_0 \frac{\ell_p^2}{\hbar^2}$

- generalized commutation relations -> deformed quantum theory (Eur. Phys. J. C 81 (2021) 982, [2109.15259])

$$[c, c^\dagger] = \hbar \omega \left(\sqrt{1 + 2\beta m H} + \beta \frac{m \hbar \omega}{2} \right)$$

Consistent QUON LIKE quantum field theory with minimal length -> deformation of the canonical anticommutation relations for fermionic fields

PEPV probability depends on the TRANSITION ENERGY and the ATOMIC STRUCTURE

Strongest bound on Generalized Uncertainty Principle

Principle

Test data taking in current modulation regime (about five months) full statistics analyzed:

- with-without (wc-woc) current alternation was automatized with a fixed period of 100 s: 50 s of wc phase alternated to 50 s woc
- a **new data analysis framework** was developed [Eur. Phys. J. C (2024) 84: 214]: simultaneous spectral and discrete Fourier transform Bayesian analysis
- **result: 32% enhanced sensitivity**

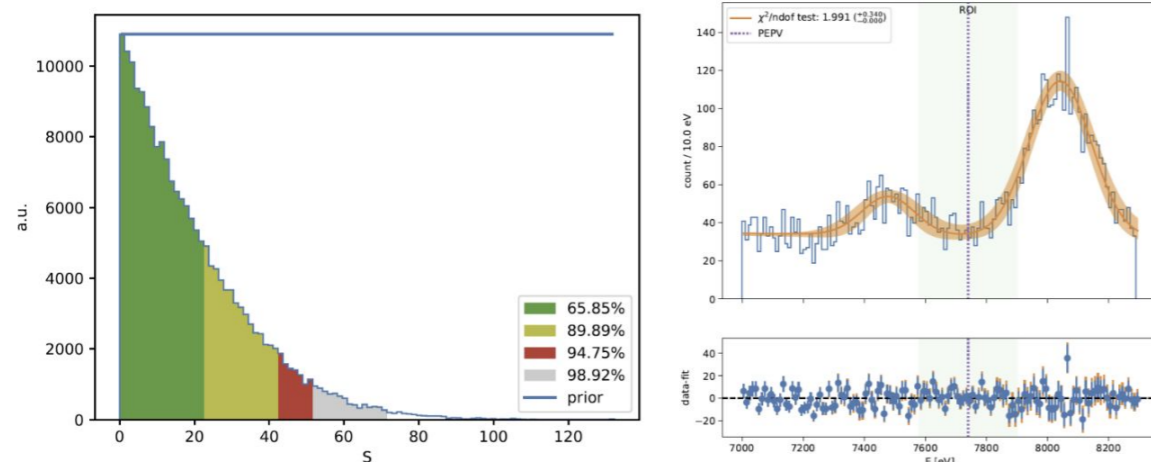


Figure 3: Left panel - marginalized posterior of the total expected number of signal counts, obtained from the analysis of the data collected in current modulated regime. Right panel - Corresponding fit of the new data set.

Strongest constraint on GUP:

$$\beta_0 < 1.73 \times 10^{-2}$$

90% CL

18 o.m. stronger than the result from time delay astrophysical measurement [Phys. Rev. D 108 (2023) 066008]

i.e. the minimal length in QG is constrained up to: $\Delta x_{\min} < 0.132 l_P$

Strongest bound on Generalized Uncertainty Principle

Ricerca di una possibile violazione del Principio di Esclusione di Pauli nell'ambito dell'esperimento VIP

Elaborato di tesi triennale

Candidato: Lorenzo Peppoloni (N85002120)

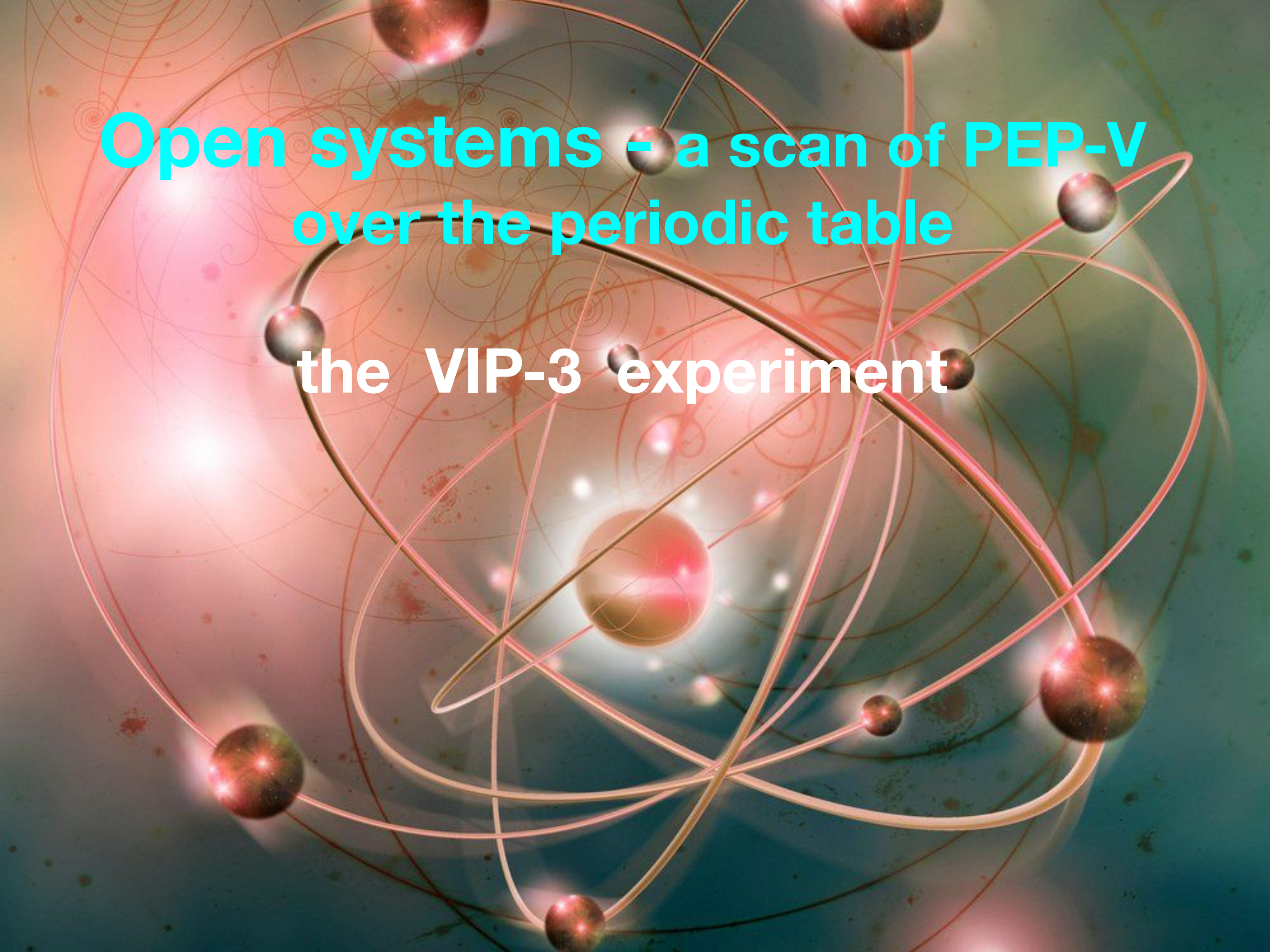
Relatore: prof. Luca Lista

Correlatori:

dott.ssa Catalina Curceanu, dott. Kristian Piscicchia,

dott. Alessio Porcelli, dott. Nicola Bortolotti

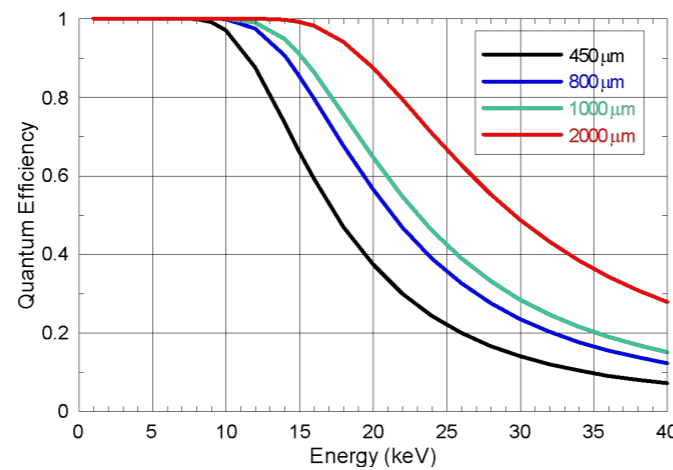
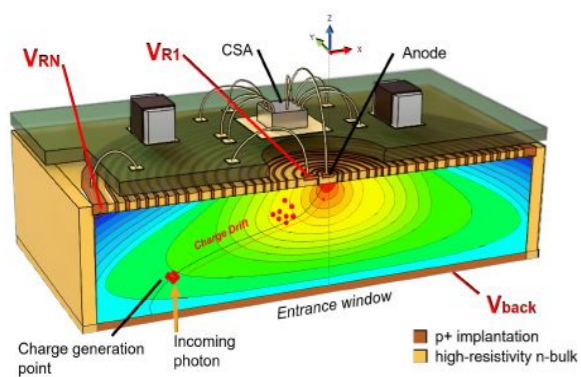




**Open systems – a scan of PEP-V
over the periodic table**

the VIP-3 experiment

VIP-3 scan the PEP violation probability as a function of Z (i.e. of Energy and atomic structure)



Okun, L.:

“it is specifically the fundamental nature of the Pauli principle which would make such tests, over the entire periodic table, of special interest”

Possible violation of the Pauli principle in atoms. JETP Lett.

1987, 46, 529532

Universe 2023, 9(7), 321

New avantgarde 1mm thick detectors in coll. with FBK (Trento) and PoliMi

- production new SDDs 1mm finalized,
- increment of a factor 2 in efficiency at ~ 20 keV with excellent resolution -> higher Z targets (Ag, Sn, Zr) ($Z \in 40-50$),
- in Ag $K\alpha_1$ tran. shift 482.70 eV with respect to the standard line (improved multiconfiguration Dirac-Fock and General Matrix Elements algorithm)
- double active area of about 41 cm²
- new target cooling system & SDDs-cold-finger thermal impedance improved -> higher current



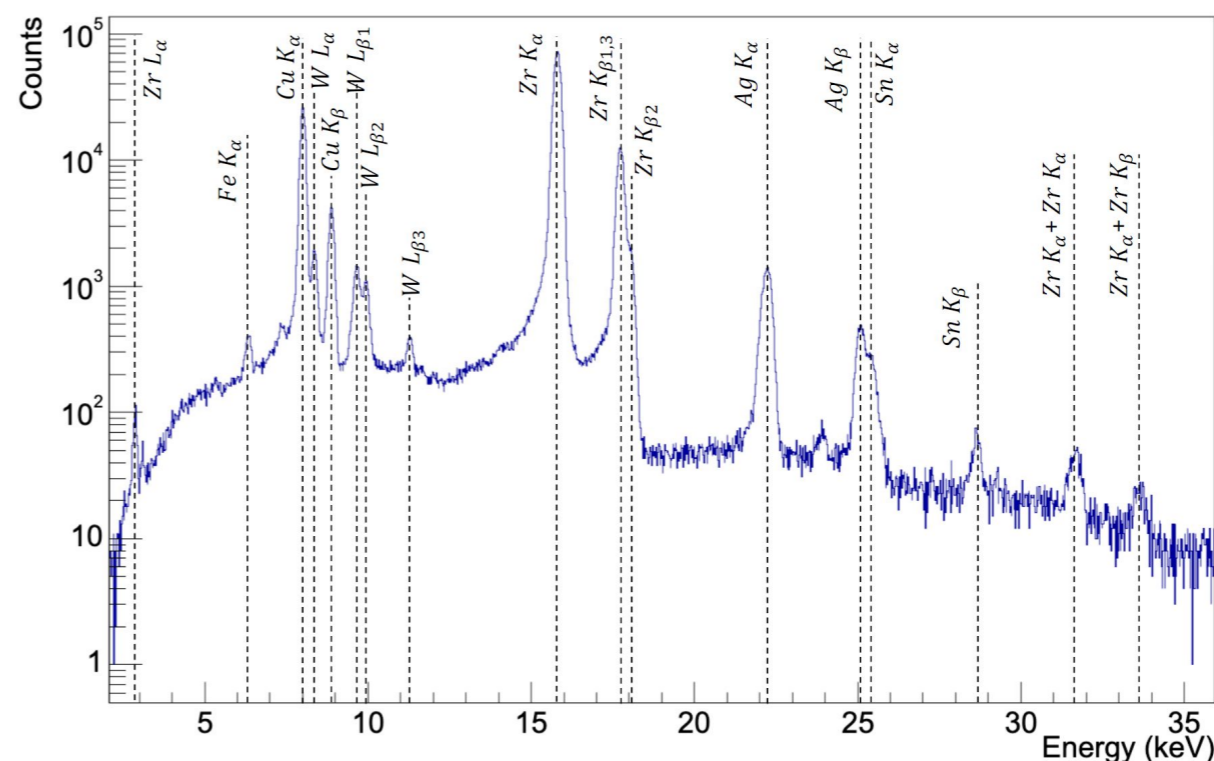
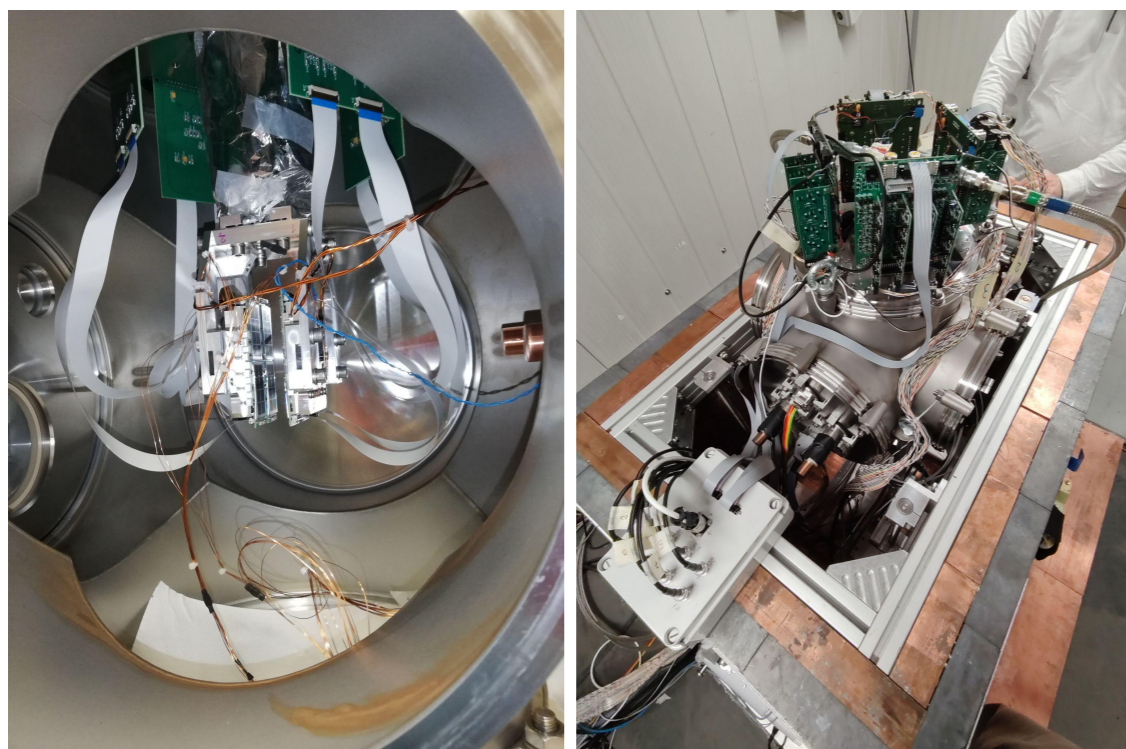
“Testing the PEP .. with the VIP-3 Experiment”, *Entropy* 26 (2024) 9, 752

“New 1mm thick Silicon Drift Detectors ... SUBMITTED”

VIP-3 the first experiment with 1mm SDDs

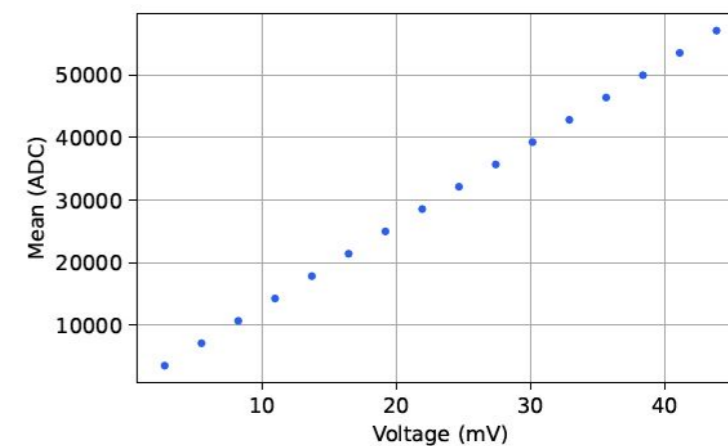
Activities on the setup October 2025-now

The [final VIP-3 setup](#) was [completed](#), [installed and tested](#) (within March 2026); presently is [in data taking](#):



Detailed characterization of the SDDs and of the front-end electronics:

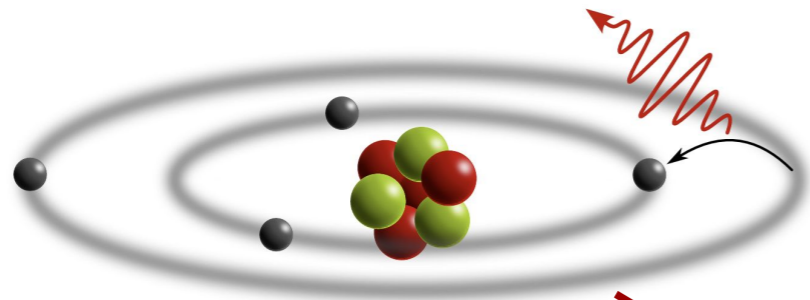
- [excellent linear performance](#) of the entire acquisition chain, deviation from linearity is approximately 0.02 mV, corresponding to an energy uncertainty of less than 1 eV,
- energy resolution of 168 ± 5 eV at 8 keV (Cu $K\alpha$) and 264 ± 7 eV at 22 keV (Ag $K\alpha$) across all readout channels. [More than 20 eV improvement in energy resolution w.r. to VIP-2.](#)



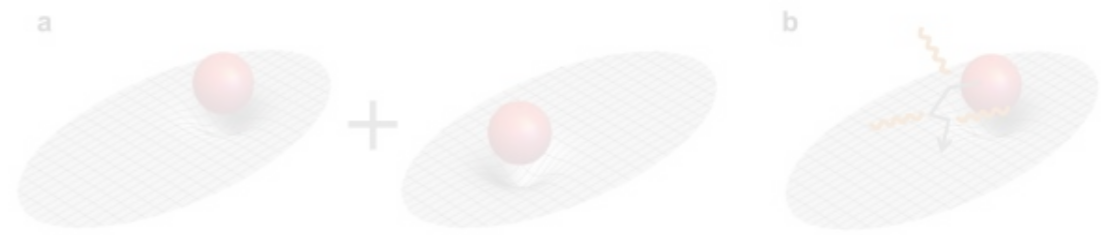
Correlation between the input pulse amplitude generated by the pulse generator (in mV) and the corresponding signal measured in ADC counts, by one channel.

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Closed Systems - PEPV in NCQG

Non-commutative QFT:

- in quantum mechanics (large-scales/low-energies) phase space is a smooth manifold.
- On distances of the order of λ_P this breaks down, Heisenberg uncertainty + GR prediction of black hole formation \rightarrow at small enough length scales the energy uncertainty enables black hole formation and the smooth manifold structure is lost.

The notion of a point becomes meaningless and the standard commutation relation between space-time points is no longer expected to hold (first suggested by Snyder (1947) and Heisenberg (1954)).

Space-time non-commutativity common prediction of QG models

Poincaré symmetry is deformed \rightarrow SST is violated \rightarrow PEPV (MG is violated)
(Marcianò, Addazzi, Balachandran, Mavromatos, Illuminati ...)

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. Marcianò *Int.J.Mod.Phys.A* 35 (2020) 32, 204200

arXiv:2603.25552 [hep-th]



CLOSED SYSTEMS

PEP violation in quantum gravity

non-commutativity of space-time (e.g. *k*-Poincarè, *θ*-Poincarè) is common to several quantum gravity frameworks (e.g. **the low-energy limit of string theory for magnetic like background B-fields**)



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

PEP violation is suppressed with $\delta^2(E, \Lambda)$

***E* is the characteristic transition energy, Λ is the ch. energy scale of QG.**

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. Marcianò *Int.J.Mod.Phys.A* 35 (2020) 32, 204200

[arXiv:2603.25552](https://arxiv.org/abs/2603.25552) [hep-th]



VIP-2 Closed Systems - High Purity Ge detectors, set of ultra-radiopure targets to check $\delta^2(E)$ with a systematic scan over Z.

Strongest QG limits in the lepton sector

- We demonstrated that experimental tests of PEP represent the strongest Occam razor for different models of QG.
- Our measurements provide a guideline for further development of specific theories:

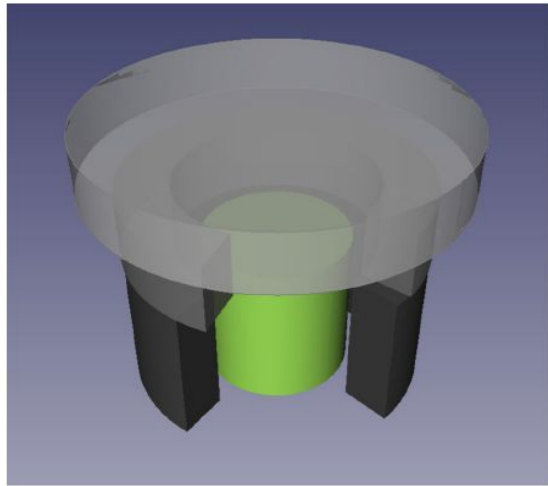


Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

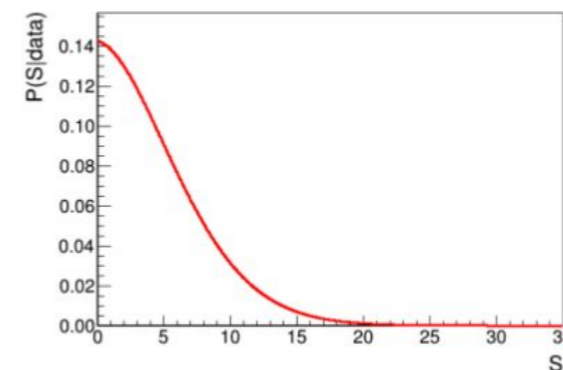
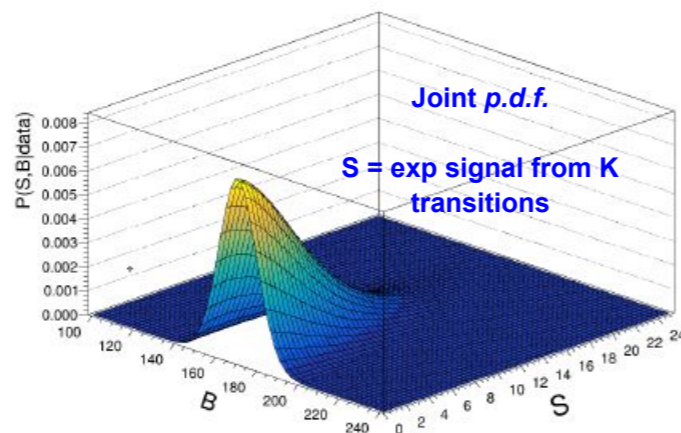
MAIN ACHIEVEMENTS -

- θ -Poincarè 90% Probability limits on the NC scale
BEST CONSTRAINT EVER

PRL 129, 131301 (2022)

PRD 107, 026002 (2023)

θ_{0i}	\bar{S}	lower limit on Λ (Planck scales)
$\theta_{0i} = 0$	13.2990	$6.9 \cdot 10^{-2}$
$\theta_{0i} \neq 0$	18.1515	$2.6 \cdot 10^2$



- “**triply special relativity**” model by Kowalski-Glikman–Smolin (KS):
First measurement ever, excluded up to $\Lambda > 5.6 \cdot 10^9$ 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.

Universe 2023, 9(7), 321

High Energy Physics - Theory*[Submitted on 26 Mar 2026]***When identical particles cease to be indistinguishable: violation of statistics in quantum spacetime**

Nicola Bortolotti, Catalina Curceanu, Antonino Marciano, Kristian Piscicchia

Quantum gravity may modify the fundamental symmetries that govern identical particles. In particular, noncommutative spacetime frameworks predict deformations of Bose and Fermi statistics. Here we develop a relativistic quantum field theory based on the most general oscillator algebra compatible with θ -deformed Poincaré symmetry. This construction generalizes twisted statistics to a class of quon-like deformations allowing non-involutive particle exchange. We show that the resulting theory is consistent at both the free and interacting levels and derive its implications for atomic systems. Purely twisted statistics predicts Pauli-forbidden atomic transitions at rates incompatible with experiments. By contrast, a class of quon deformations suppresses such processes by powers of the noncommutativity scale, but only if superselection rules between permutation-symmetry sectors are violated. This implies an effective breakdown of particle indistinguishability and provides theoretical motivation for high-precision experimental tests of the Pauli exclusion principle.

Subjects: **High Energy Physics - Theory (hep-th)**; High Energy Physics - Phenomenology (hep-ph)Cite as: [arXiv:2603.25552](https://arxiv.org/abs/2603.25552) [hep-th](or [arXiv:2603.25552v1](https://arxiv.org/abs/2603.25552v1) [hep-th] for this version)<https://doi.org/10.48550/arXiv.2603.25552> **Paper submitted:**

- **first analysis of the complete algebra for annihilation and creation operators compatible with deformed Poincaré symmetry: first relativistic generalization of the quon model.**



SAPIENZA
UNIVERSITÀ DI ROMA

Sapienza University of Rome

Department of Physics
PhD in Physics

On these subjects **Dr. Nicola Bortolotti obtained his PhD with the highest honors at Sapienza University.**

**Exploring the Quantum-Gravity Connection:
Theoretical Insights and Unprecedented
Experimental Constraints**

Abstract

This thesis investigates the quantum-gravity interface from both theoretical and experimental perspectives, focusing on two complementary approaches: violations of particle statistics and spontaneous radiation. These frameworks provide sensitive probes of possible departures from standard quantum mechanics and quantum field theory. Underground X-ray experiments offer an ideal environment to detect ultra-rare events, providing a unique window into Planck-scale physics, where direct measurements are impossible due to the prohibitive energy scales. The VIP collaboration has recently devoted considerable effort to bridging theory and experiment, achieving unprecedented precision in tests of fundamental quantum principles. Small violations of Bose and Fermi statistics are predicted by several low-energy effective quantum-gravity models, while spontaneous radiation constitutes a distinctive signature of spontaneous collapse models (SCMs). Although no predicted signals have been observed, several models have been experimentally constrained and even excluded.

Advisors

**Dr. Kristian Piscicchia
Prof. Fabio Sciarrino**

Candidate

**Nicola Bortolotti
1761232**



BEGe based prototype activity

at the Stella Laboratory of LNGS

BEGe based prototype, motivation

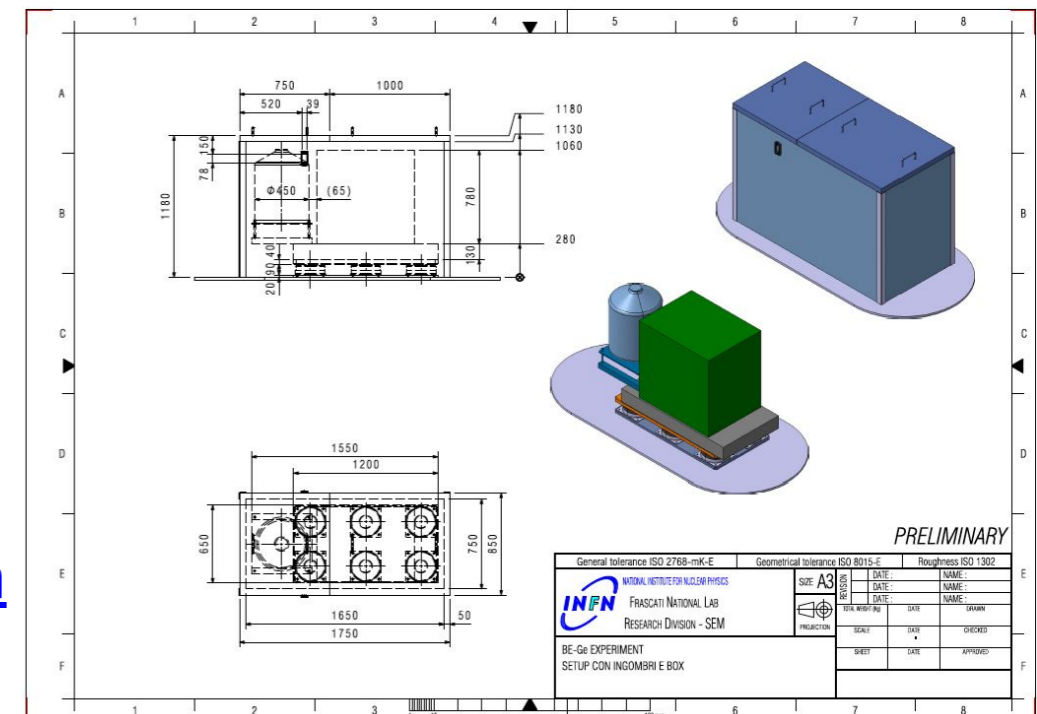
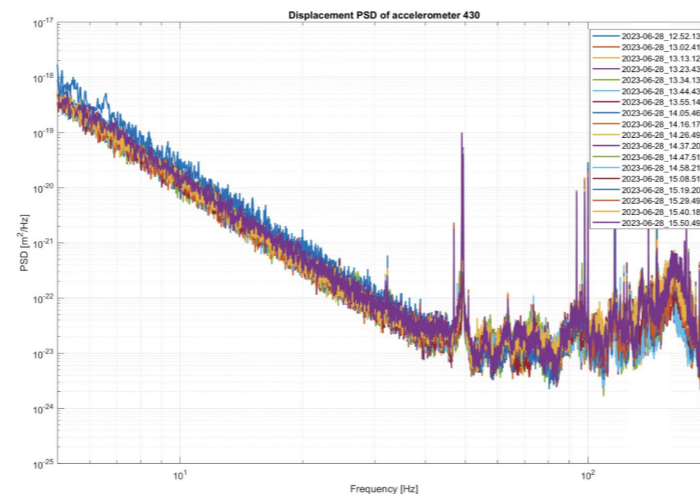
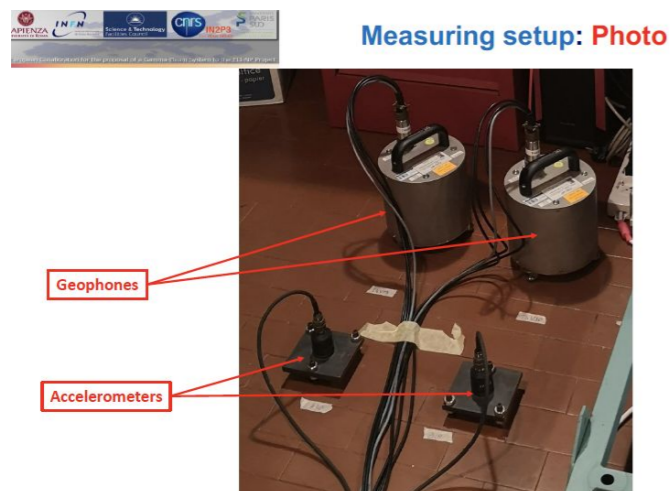
- In order to improve on QG limits → improve on efficiency → use Ge as active material. (Ge K α at 10 keV)
 - Difficulty: HPGe below 20 keV high background due to electronic noise,
 - solution BEGe + Pulse Shape analysis: rejection of electronic noise
- + proof of concept for a versatile detector to measure spontaneous w.f. collapse.

• Data taking Jan-March 2024

data sets (already passed for a dedicated offline filtering stage) were passed through events selection using the pulse shape discrimination algorithm, calibrated and analyzed.

below 13 keV prohibitive microphonic noise (due to flooring vibrations, sound...)

Dedicated measurement (in collaboration with Ing. Tomassini):



We designed a dedicated background mitigation system to mechanically isolate the germanium crystal

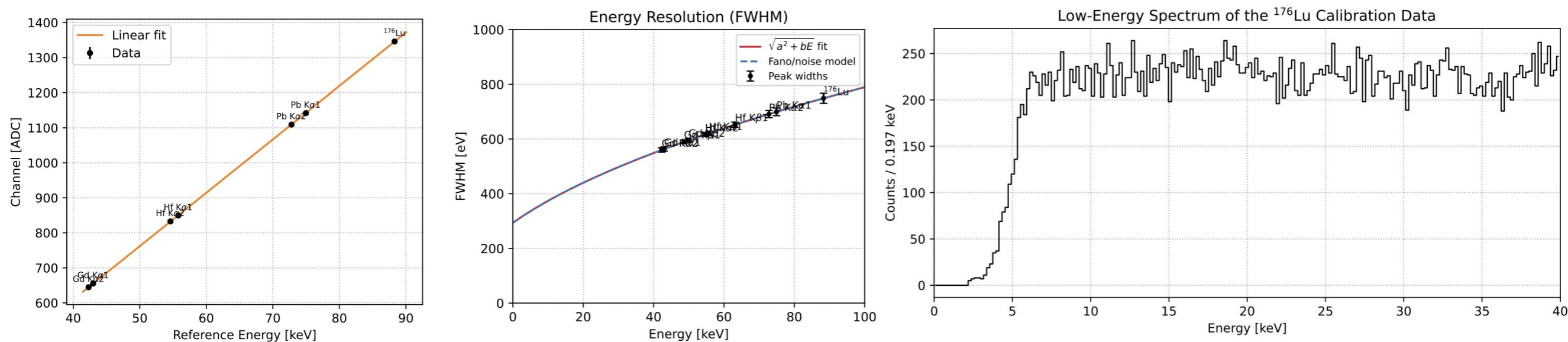
BEGe based prototype completed

Completion of the installation of the BEGe setup on the mechanical isolation system and the enclosure in the soundproof housing:



optimization of the electronic readout chain: **factor of 1.6 improvement in energy resolution**

December 2025 - calibration and characterization data acquisition run:

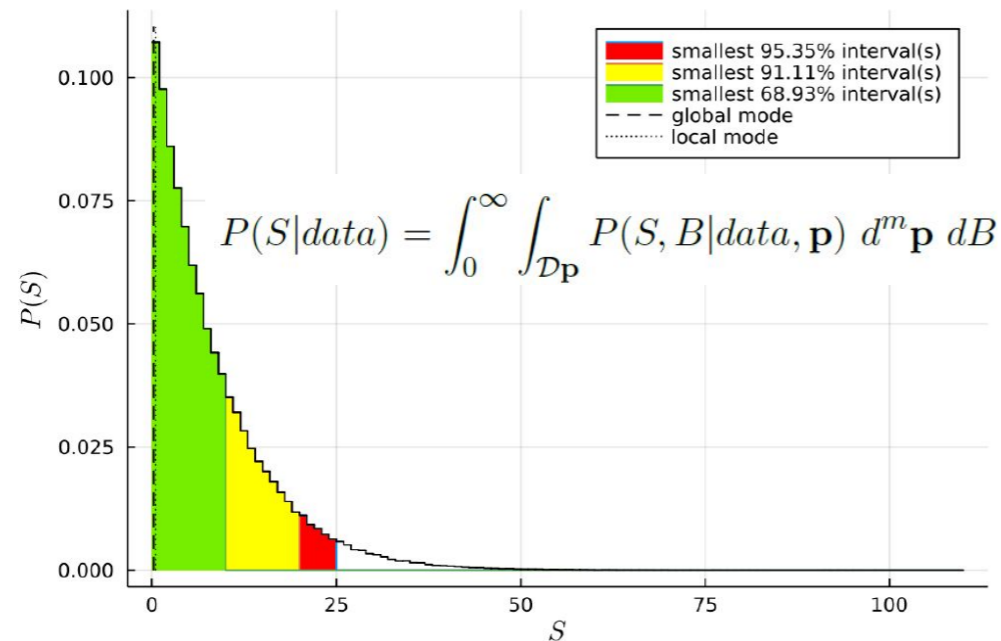


Energy resolution ~ 350 eV (FWHM) at 10 keV, low-energy threshold of 6 keV
full achievement of the intended goal

Exploratory data analysis

The calibration data set is used for an exploratory analysis:

The goal of the analysis is to determine the upper limit \bar{S} on the total number of signal counts expected from PEP-violating transitions in Ge. By comparing \bar{S} with the theoretically predicted photon yield from PEP-violating atomic transitions, a constraint on the characteristic energy scale Λ of the model can be derived.



A low-background measurement can reduce the background by approximately a factor of 100

+

data-taking period of about 3 months

=

would allow us to improve our world record in view of the realization of the dedicated setup.

8 days data taking w.r. to 80 days
HPGe data taking:

$\Lambda > 1.1 \times 10^{-2}$ Planck scales

90% C.L.

Formal request for a physics data taking run, with the prototype BEGe based setup.

Kristian Piscicchia, Catalina Curceanu, Nicola Bortolotti, Alberto Clozza, Chiara Ghiano, Matthias Laubenstein, Simone Manti, on behalf of the VIP Collaboration

April 2026

1 Introduction - theoretical motivation

The VIP collaboration is investigating possible violations of the spin-statistics relation (and its implications for violations of the Pauli Exclusion Principle (PEP)) within the framework of several Quantum Gravity (QG) models, as discussed in detail at previous Scientific Committee meetings and documented in October 2024. This work is carried out in collaboration with several leading theoretical groups in the field.

The PEP is a fundamental pillar of quantum mechanics and is responsible for the stability of atoms and matter. It forbids identical fermions from occupying the same quantum state and arises from the spin-statistics theorem [1], which relies on Lorentz invariance and the structure of relativistic quantum field theory.

This connection implies that any violation of the PEP would signal a modification of space-time symmetries at a fundamental level. In particular, several approaches to QG predict that space-time may become non-commutative at very high energies, leading to deformations of Poincaré symmetry.

PAPER • OPEN ACCESS

Machine-learning-enhanced event selection for BEGe detectors in the VIP experiment

S. Manti, S.H. Yip, M. Bazzi, N. Bortolotti, M. Bragadireanu, I. Carnevali, A. Clozza, L. De Paolis, R. Del Grande, C. Guaraldo [▼ Show full author list](#)

Published 26 January 2026 • © 2026 The Author(s)

[Journal of Instrumentation](#), [Volume 21](#), [January 2026](#)

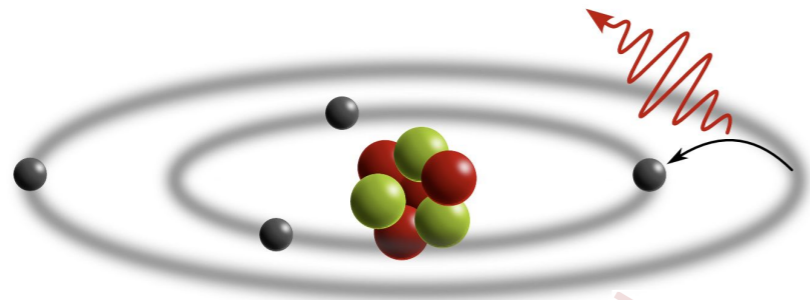
Citation S. Manti *et al* 2026 *JINST* 21 P01036

DOI 10.1088/1748-0221/21/01/P01036

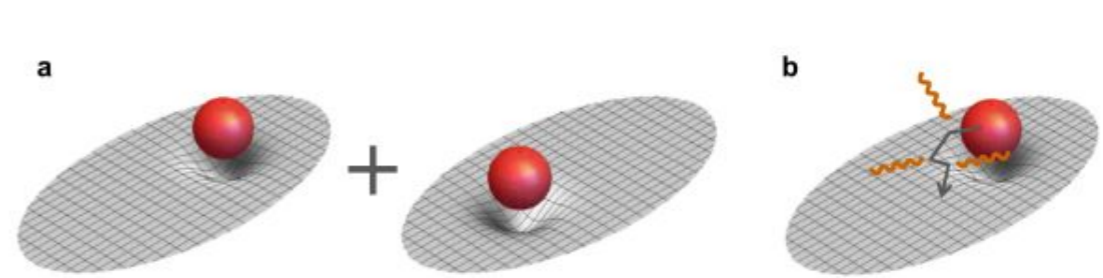
**DOE/INFN summer research project of S.
H. Yip (University of California, Berkeley)**

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Spontaneous w.f. collapse

- Why the quantum properties (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 (Ghirardi, Rimini, Weber, Penrose, Diosi, Pearle, Adler, Karojhazi, Lukacs, Milburn, Bassi ...) the most studied models:
GRW, Continuous Spontaneous Localization (CSL) & Diosi-Penrose (DP)

STRONG CONNECTION WITH QG:

Spontaneous decoherence induced by space-time uncertainty
&

Irreversibility in Quantum Gravity/Cosmology at the Planck scale

lead to the same structure of master equations

Wheeler, Ellis, ... Diosi (2023) J. Phys.: Conf. Ser. 2533 012005)

Physical Review X, 13(4):041040, 2023, J. Phys. A, 57:395303, 2024, Nat. Comm. 12, 4449 (2021)

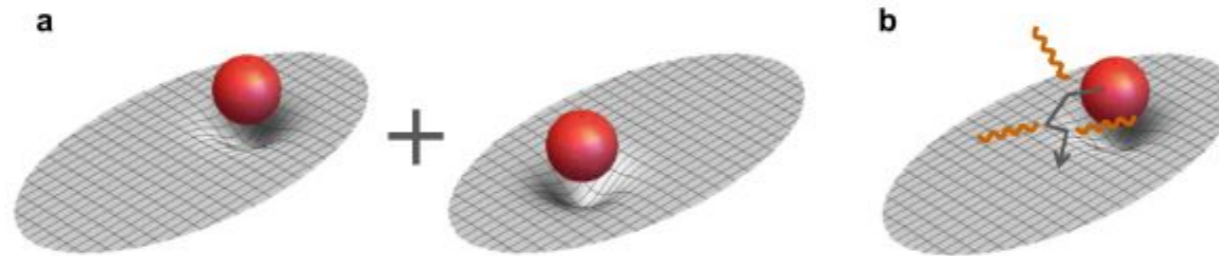
this spectacular connection points toward a potential reconciliation between quantum mechanics and gravity

can be potentially tested with VIP (ONGOING)

Radiation measurements to test the collapse

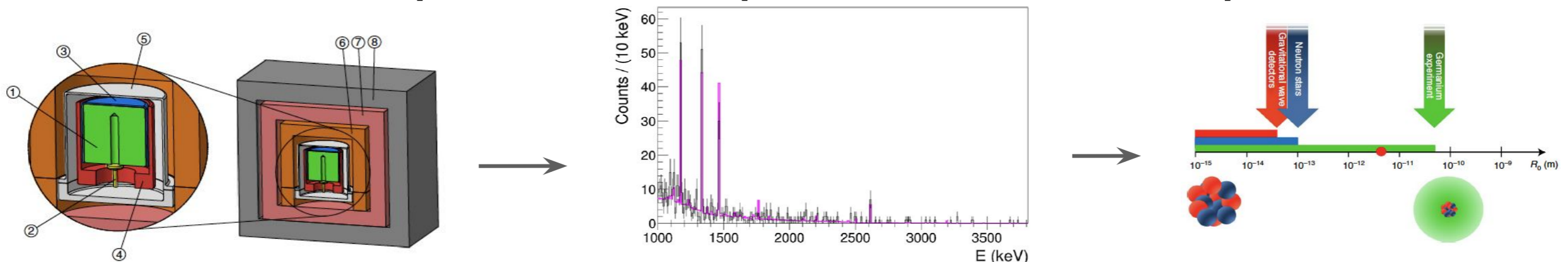
- Unavoidable side effect of the stochastic collapse dynamics:
Brownian-like diffusion of the system in space Phys. Rev. Lett. 130, 230202 (2023).

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

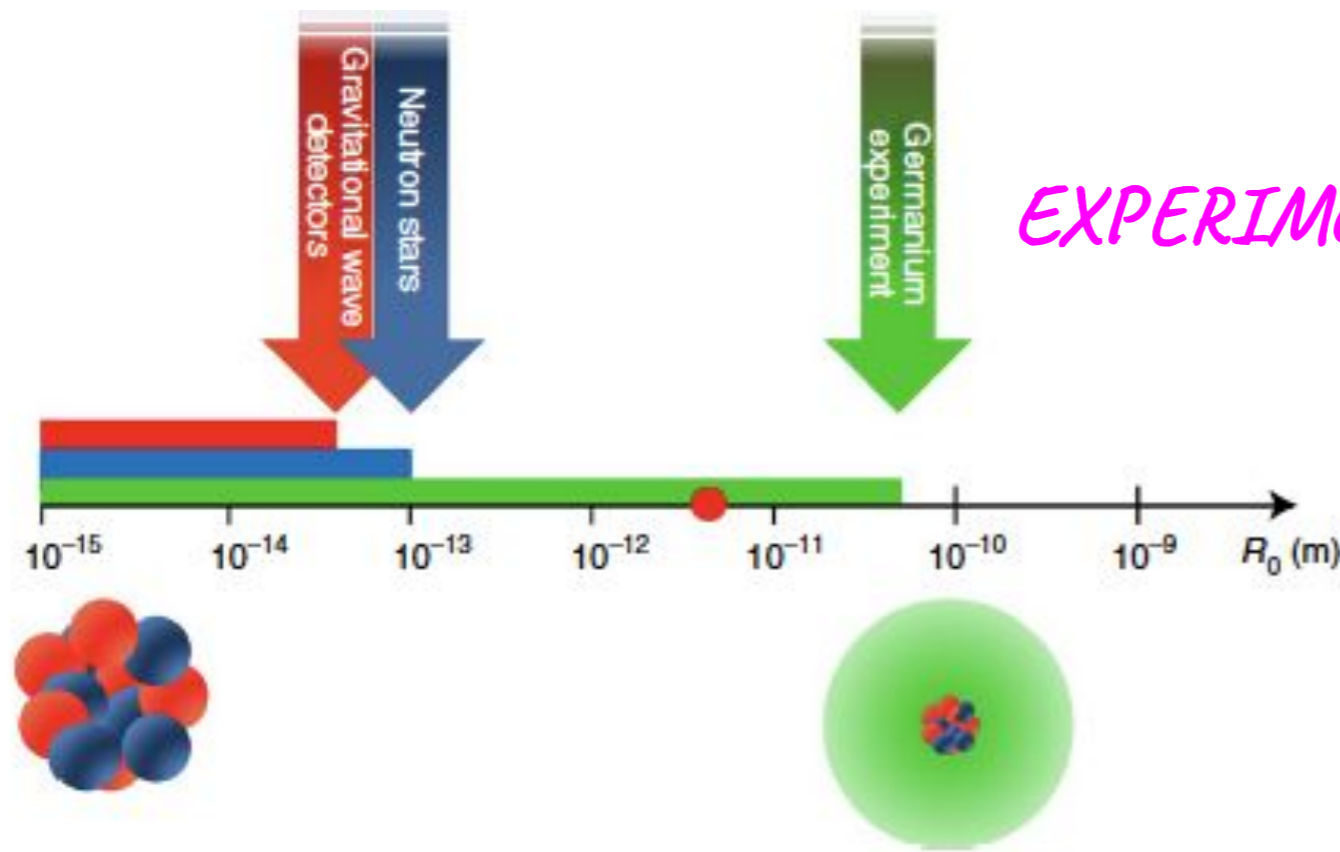


- Then charged particles emit spontaneous radiation. We search for spontaneous radiation emission from a germanium crystal and the surrounding materials in the experimental apparatus.

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



Markovian DP falsified



EXPERIMENTAL: $R_0 > 0.54 \cdot 10^{10} \text{ m}$

If R_0 is the size of the nucleus's wave function as suggested by Penrose, we have to compare the limit with the properties of nuclei in matter.

In a crystal $R^2_0 = \langle u^2 \rangle$ is the mean square displacement of a nucleus in the lattice, which, for the germanium crystal, cooled to liquid nitrogen temperature amounts to:

THEORETICAL EXPECTATION $R_0 = 0.05 \cdot 10^{10} \text{ m}$

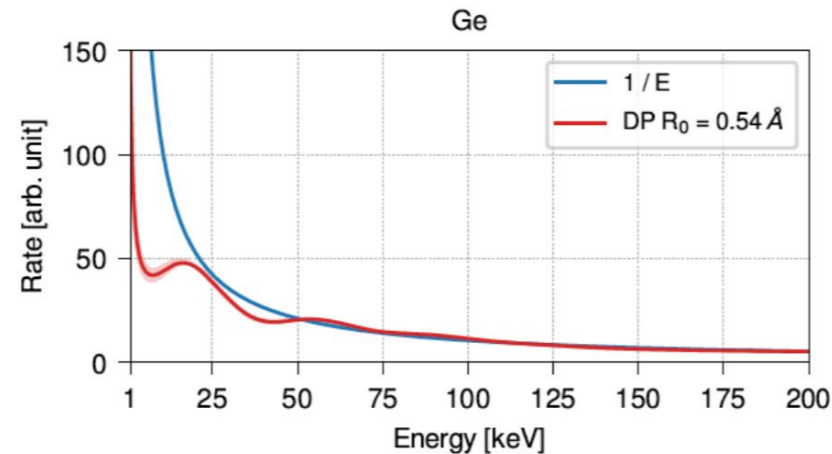
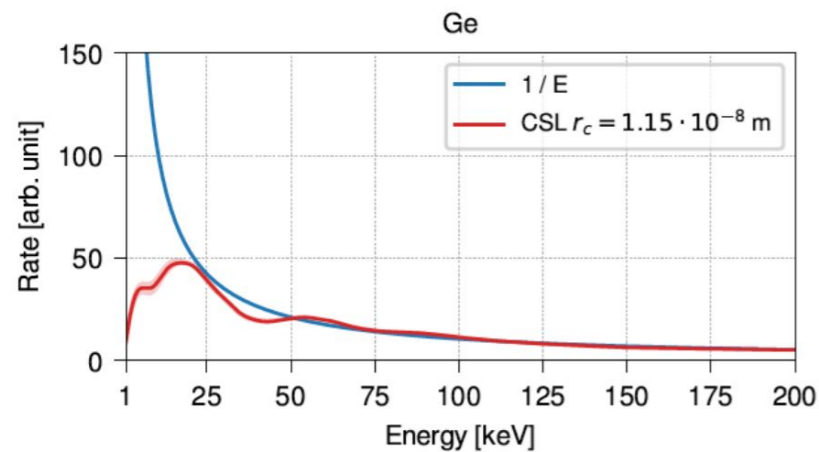
“Underground test of gravity-related wave function collapse”.

*Nature Physics 17, pages 74–78 (2021) **CITIED BY 226***

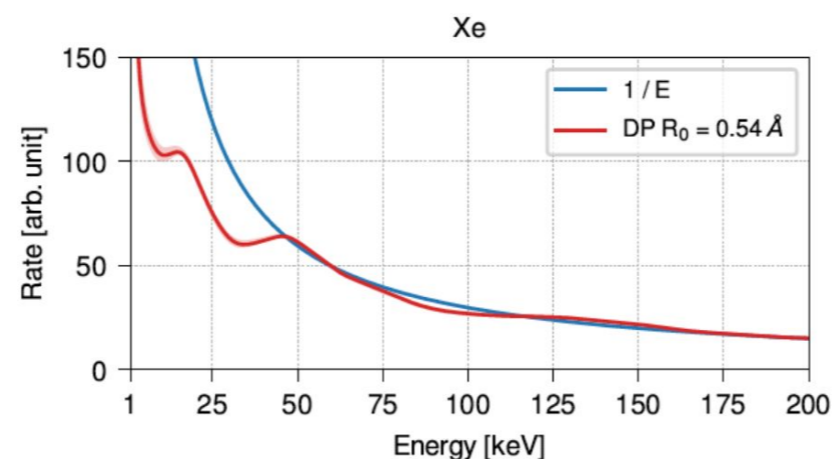
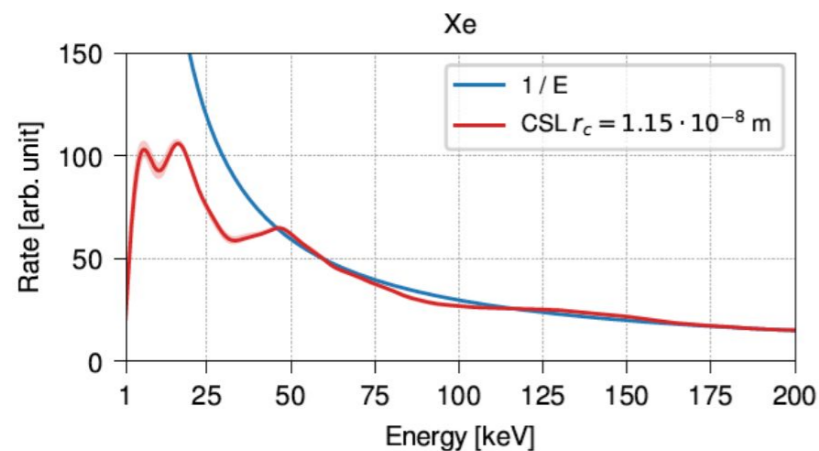
Spontaneous emission in the X-rays regime

First model which predicts a characteristic spontaneous E. M. radiation distinctive of the decoherence mechanism:

Phys. Rev. Lett. 132, 250203 (2024)



- The energy spectrum of this radiation is influenced by the atomic structure of the emitter.



- The spontaneous radiation rate, within the range of (1-15) keV, is unique to the specific decoherence mechanism.

Based on the success of the BEGe prototype activity

R&D of a specialized detector that features high resolution and high detection efficiency for photons emitted by optimized external targets in the 1-15 keV range

Activity October2025-now

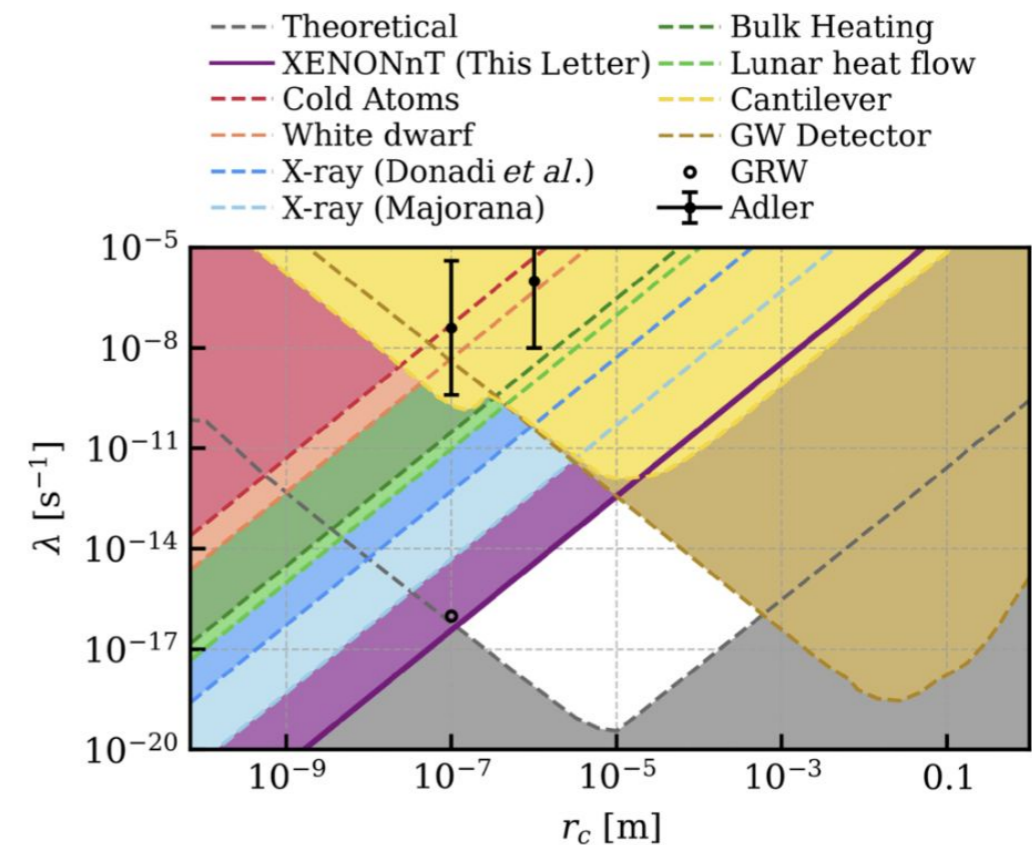
Our model [Phys. Rev. Lett. 132, 250203 (2024)] stimulated a joint analysis in collaboration with XENONnT:

- this analysis produced new world-leading limits on the free parameters of the Markovian CSL and DP models: improvement of two orders of magnitude and a factor of five, respectively,
- the original values proposed for the strength and correlation length of the CSL model have been experimentally excluded.

paper published:

Phys. Rev. Lett. 136, 120201 (2026)

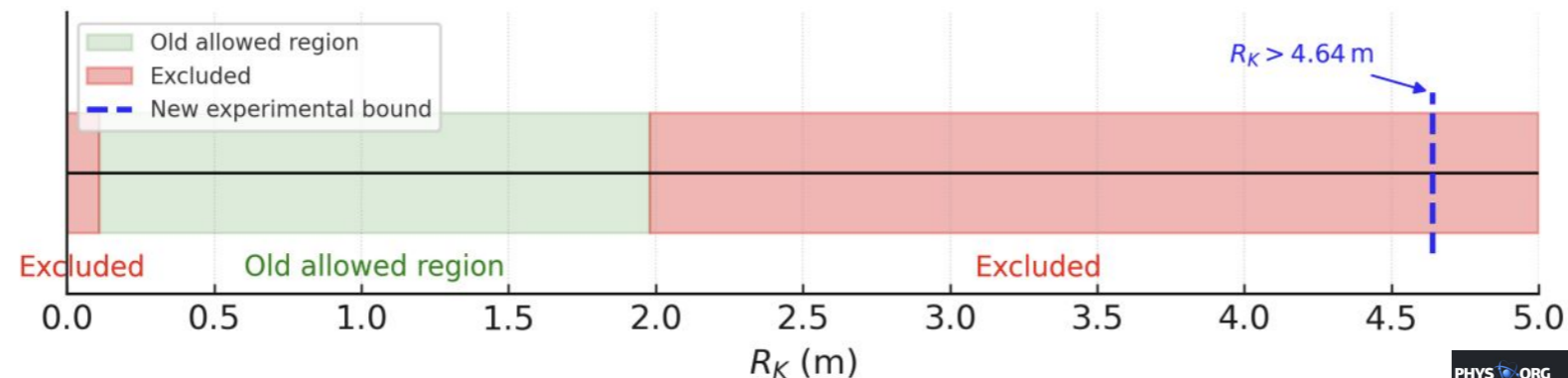
We finalized an improved model of the spontaneous radiation emission rate calculation incorporating intracule functions to calculate electron–electron distances within the atom: **paper under finalization**.



Activity October2025-now

The analysis of data collected with the HPGe detector, aimed at constraining the non-Markovian gravity-related Károlyházy collapse model, has also been completed:

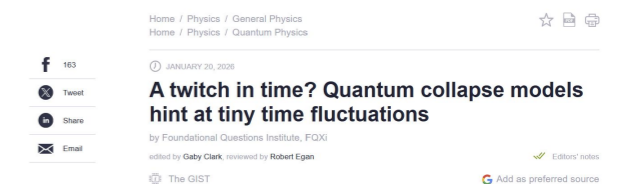
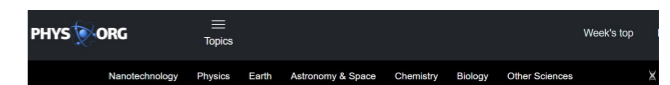
- improved lower bound on the spatial correlation length R_K characterizing metric fluctuations in the model **$R_K > 4.64 \text{ m}$ (95% C.L.) 1o.o.m. improvement on the previous experimental limit.**
 - combined with the theoretical upper bound $R_K < 1.98 \text{ m}$, **excludes the Károlyházy model.**
 - **Also excludes the associated non-Markovian formulation of the CSL.**
- e-Print: 2601.00651 PAPER SUBMITTED



Study of relativistic time fluctuations in the context of CSL and DP

published: **Phys. Rev. Res. 7 (2025) no.4, 043166**

STRONG media impact



Quantum collapse models hint at tiny time fluctuations. Credit: FQXi/Gabriel Fitzpatrick (2025)



Dissemination

Dissemination-publications October2025-now

Published:

- 1) **Phys. Rev. Research 7, 043166 (2025)**
- 2) **Sci Rep 15, 41544 (2025)**
- 3) **2026 JINST 21 P01036**
- 4) **Phys. Rev. Lett. 136, 120201 (2026)**

Submitted:

- 1) **Experimental exclusion of a generalized Károlyházy gravity-induced decoherence model, e-Print: 2601.00651**
- 2) **New 1mm thick Silicon Drift Detectors for future researches of Kaonic Atoms and the Pauli Exclusion principle**
- 3) **When identical particles cease to be indistinguishable: violation of statistics in quantum spacetime, arXiv:2603.25552 [hep-th]**

strong media impact

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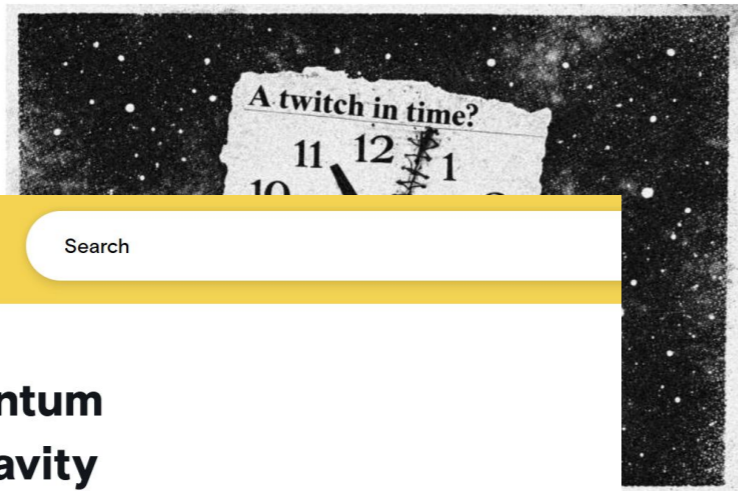
A twitch in time? Quantum collapse models hint at tiny time fluctuations

by Foundational Questions Institute, FQXi

edited by Gaby Clark, reviewed by Robert Egan

The GIST

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New research links quantum collapse to time and gravity

BRIGHTER

JOSHUA SHAVIT
Jan 26, 2026



Science 06 FEB 2026 3:20 AM AEDT

VIP-2 Experiment Tightens Exotic Physics Search

Foundational Questions Institute, FQXi

The Pauli exclusion principle is a cornerstone of the Standard Model of particle physics and is essential for the structure and stability of matter. Now an international collaboration of physicists has carried out one of the most stringent experimental tests to date of this foundational rule of quantum physics and has found no evidence of its violation. Using the VIP-2 experiment, the team has set the strongest limits so far for possible violations involving electrons in atomic systems, significantly constraining a range of speculative theories beyond the Standard Model, including those that suggest electrons have internal structure, and so-called 'Quon models.' Their experiment, which was partially supported by the Foundational Questions Institute, FQXi, was reported in Scientific Reports in November 2025.

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NEWS RELEASE 5-FEB-2026

VIP-2 experiment narrows the search for exotic physics beyond the Pauli exclusion principle

FQXi-co-funded study challenges exotic models in which electrons have internal structure, Quon models, and more

Peer-Reviewed Publication

FOUNDATIONAL QUESTIONS INSTITUTE, FQXI



The Pauli exclusion principle is a cornerstone of the Standard Model of particle physics and is essential for the structure and stability of matter. Now an international collaboration of physicists has carried out one of the most stringent experimental tests to date of this foundational rule of quantum physics and has found no evidence of its violation. Using the VIP-2 experiment, the team has set the



Dissemination-publications October2025-now

Organized workshops/conferences:

Testing Quantum Foundations in the 2025 Quantum Year, to be held at Frascati (INFN-LNF) in the days 2022 October 2025, <https://agenda.infn.it/event/47405/overview>.

Participation to workshops/conferences:

11 talks as colloquia, international workshops and conferences, and 7 for public/school dissemination were delivered.

Within VIP and Quantum Mechanics tests at LNGS we participate to the following projects:

- BridgeQG COST Action (WG4 Group leader)
- RQI COST Action
- ENRICH COST Action (WG3 Co-leader – Simone Manti)
- EU MCSE, NEXUS

C. Curceanu received the prize “Voci di Scienza, Voci di Donna 2026” from Radio Parlamentare e l’Intergruppo parlamentare per la Conoscenza e la Ricerca Scientifica



INFN LNF

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Home » In evidenza » A Catalina Curceanu il premio “Voci di Scienza, Voci di Donna 2026” di Radio Parlamentare e dell’Intergruppo parlamentare per la Conoscenza e la Ricerca Scientifica

A CATALINA CURCEANU IL PREMIO “VOCI DI SCIENZA, VOCI DI DONNA 2026” DI RADIO PARLAMENTARE E DELL’INTERGRUPPO PARLAMENTARE PER LA CONOSCENZA E LA RICERCA SCIENTIFICA

25 Marzo 2026 In evidenza, News

Oggi 25 marzo la nostra collega Catalina Curceanu, Dirigente di Ricerca presso i Laboratori Nazionali di Frascati dell’INFN, è stata insignita del premio “Voci di Scienza, Voci di Donna 2026” di Radio Parlamentare e dell’Intergruppo parlamentare per la Conoscenza e la Ricerca Scientifica, insieme ad altre otto esponenti del mondo scientifico.

Il premio “Voci di Scienza, Voci di Donna” intende conferire un riconoscimento al valore scientifico e culturale delle donne che, attraverso il proprio impegno nella ricerca, contribuiscono in modo significativo al progresso della conoscenza e alla crescita civile della nostra società. Esso valorizza la qualità della ricerca, la responsabilità intellettuale e la capacità di rappresentare con autorevolezza la presenza femminile nella scienza contemporanea, in qualunque fase del percorso professionale essa si esprima.

“Sono molto felice e profondamente onorata di ricevere il riconoscimento “Voci di Scienza, Voci di Donna”. Lo accollo con gratitudine e con un forte senso di responsabilità.” dichiara Catalina. “Dedico questo premio alla memoria dei miei genitori: anche se non sono più qui,



Future Plans in brief

Activity 2026

VIP-Open-Systems:

- **VIP-3 data taking with Ag target (2026-2027).**
- **VIP-3 data taking with other selected targets (e.g. tin and zirconium) in the period (2027-2029/30)**
- **After 2030 a new setup for testing PEP for targets with atomic numbers >60**
VIP

Closed-Systems:

- **Refinements on theoretical interpretations (quantum gravity models and CPT deformation).**
- **Dedicated data taking with the BEGe prototype detector (STELLA lab), with enhanced sensitivity 2026-2027 (3-months request).**

Spontaneous Collapse Models:

- **Refined phenomenological analyses.**
- **R&D for a dedicated system to search spontaneous radiation signals (based on our PRL paper) with various optimized targets.**



Thank You!

The VIP Collaboration acknowledges the excellent working conditions and the continuous and friendly support provided to the experiment by the LNGS staff and by the LNGS Director, Dr. Ezio Previtalli.

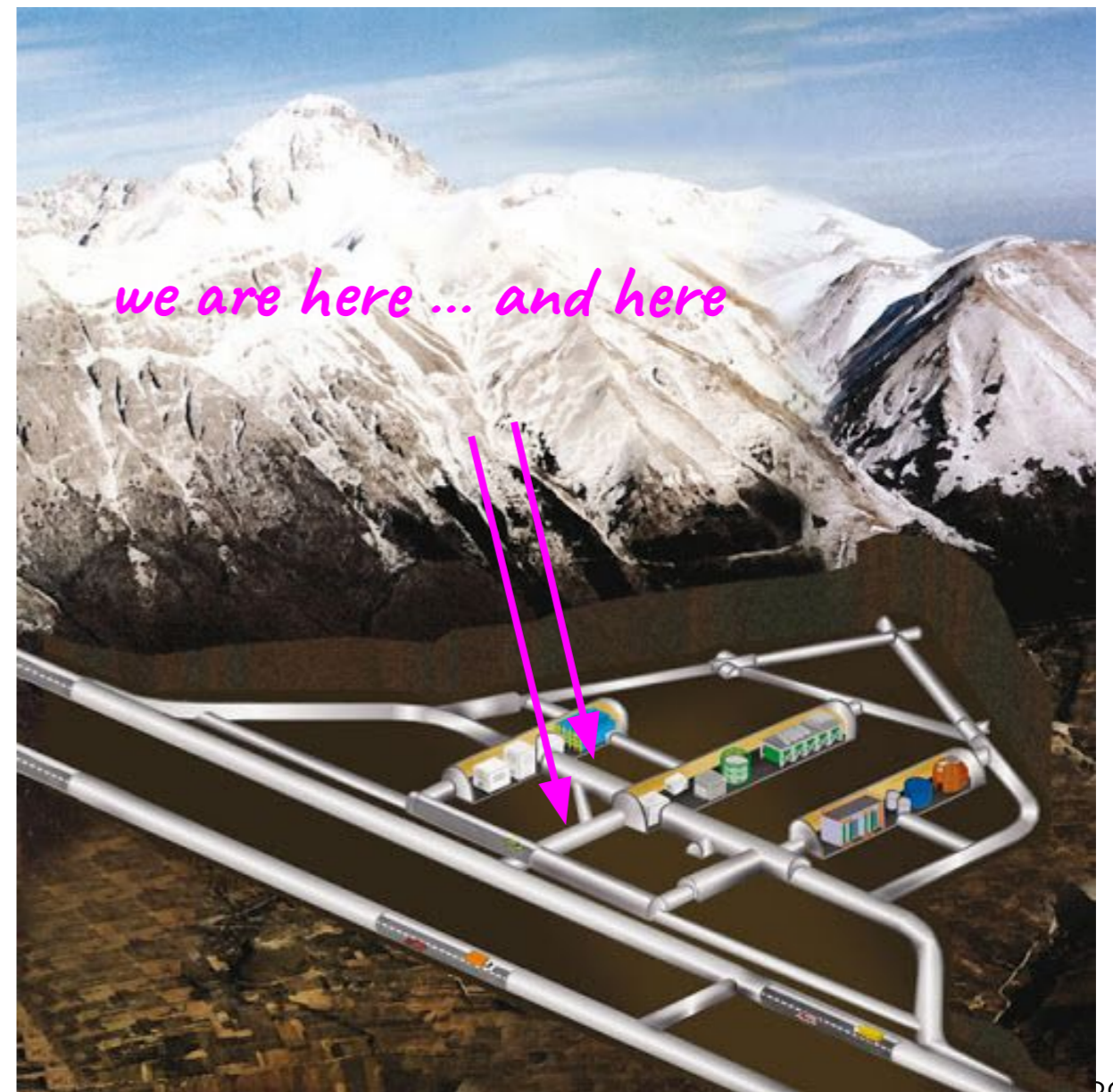


Spare Slides

Where? At The LNGS

The experiments are performed in the low-background environment of the underground *Gran Sasso National Laboratory of INFN*:

- overburden corresponding to a minimum thickness of 3100 m w.e.
- the muon flux is reduced by almost six orders of magnitude, to a flux of three oom.
- the main background source consists of γ -radiation produced by long-lived γ -emitting primordial isotopes and their decay products.



A bit of history: VIP selected publications

Selection of recent publications:

- ***Phys.Rev.Lett.* 129 (2022) 13, 131301**
- **Phys. Rev. D 107, 026002 (2023)**
- ***Eur.Phys.J.C* 84 (2024) 11, 1137**
- ***Eur.Phys.J.C* 84 (2024) 3, 214**
- ***Sci Rep* 15, 41544 (2025)**

Strongest bounds on Non-Commutative Quantum Gravity

Strongest bound on Quon-theory

- **Nature Physics 17, 74-78 (2021)**
- ***Eur.Phys.J.C* 81 (2021) 8, 773**
- **Phys. Rev. Lett. 132, 250203 (2024)**
- **Phys. Rev. Research 7, 043166 (2025)**
- **Phys. Rev. Lett. 136, 120201 (2026)**

Diosi-Penrose model excluded if Markovian

Strongest bound on correlation length of CSL model

Spin-statistics

What we learned at school:

Nature only allows for fermions and bosons !

i.e. quantum states only transform under two (one-dim) irreducible representations of the symmetric group S_N :

(a) Totally symmetric representation

$$U(\pi)\psi = +\psi \quad \forall \pi \in S_N$$

→ Bosons

(b) Totally antisymmetric representation

$$U(\pi)\psi = \text{sgn}(\pi) \psi$$

→ Fermions



superselection rules (SSRs) forbidding transitions between sectors of different permutation symmetry.

Spin-statistics

SSRs:

in standard QM, for identical particles H has to be invariant under particle exchange, i.e. it commutes with all permutation operators

$$[H, U(\pi)] = 0 \quad \forall \pi \in S_N$$

If the Hilbert space decomposes following irreducible representations of S_N

$$\mathcal{H} = \bigoplus_{\alpha} \mathcal{H}_{\alpha}$$

the H will be block-diagonal in this decomposition and:

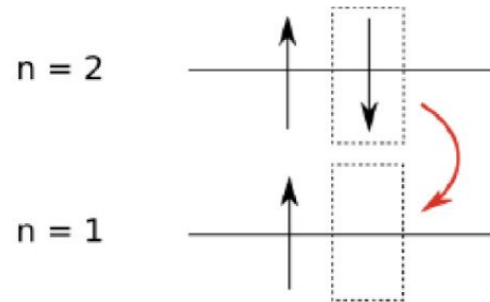
$$\langle \psi_{\alpha} | H | \psi_{\beta} \rangle = 0 \quad \text{for } \alpha \neq \beta$$

So interactions preserve permutation symmetry sectors !

Experimental signature of a PEPV transition

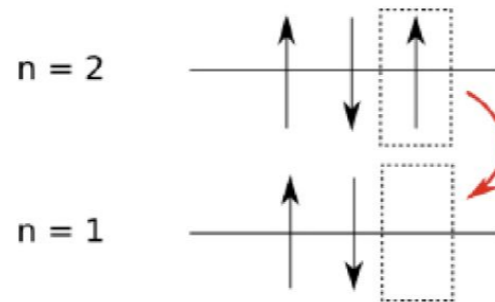
In both **VIP Open & Closed Systems** we search for electrons transitions to the fundamental level, already filled by 2 electrons, e.g. in **Cu target**:

Allowed transition
 $2p \rightarrow 1s$ ($K\alpha$)

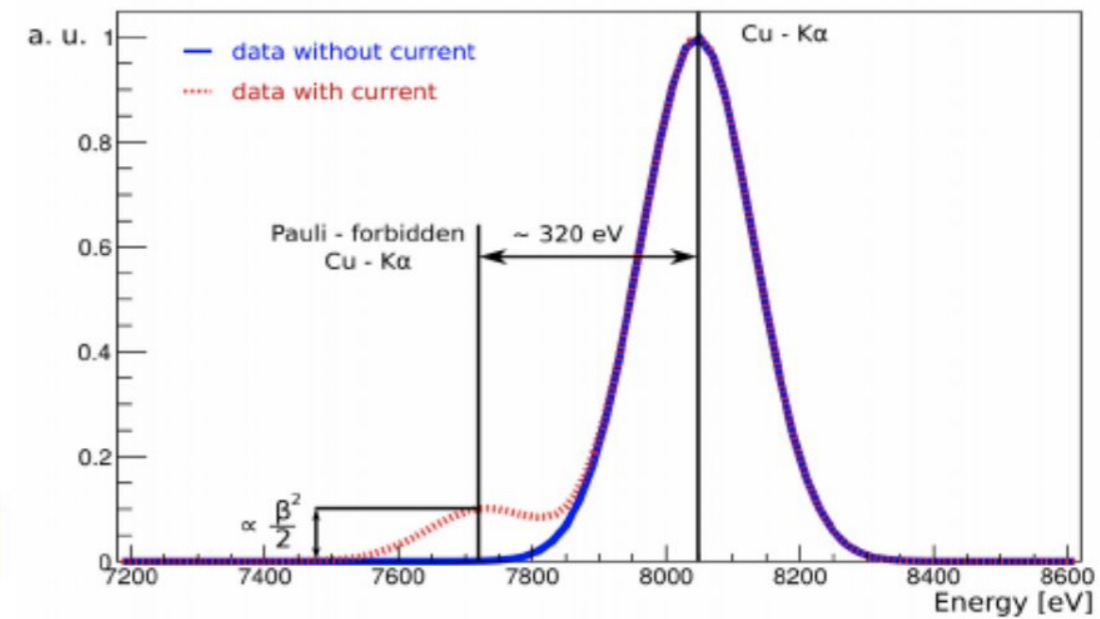


~ 8.05 keV in Cu

Pauli-forbidden transition
 $2p \rightarrow 1s$ ($K\alpha$)



~ 7.7 keV in Cu

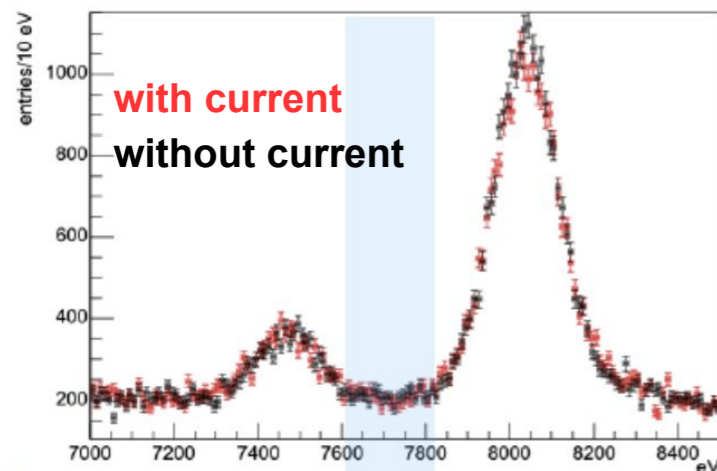


Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

Multiconfiguration Dirac-Fock approach

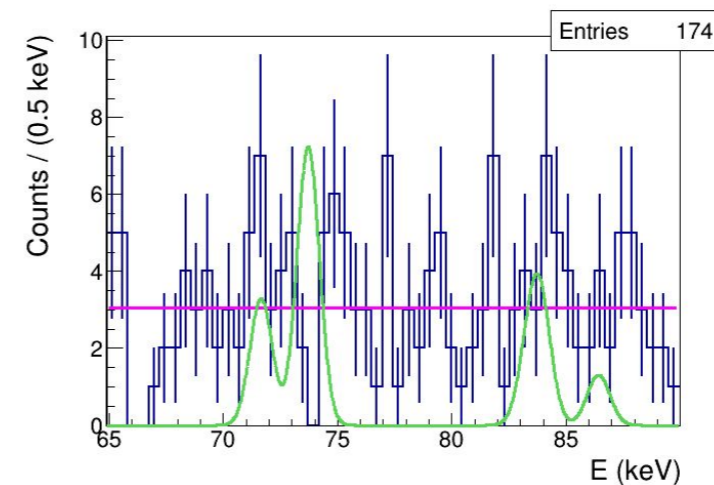
Accounts for the shielding of the two inner electrons

Background in **VIP-2 Open Systems** :
provided by data acquisition without current



$t^{wc} = 27110263$ s = 314 days
 $t^{woc} = 26916404$ s = 311 days

Background in **VIP-2 Closed Systems** :
accurate characterization of the detector



acquisition time
 6.1×10^6 s 70 ~ d

From theory to Open Systems experiments

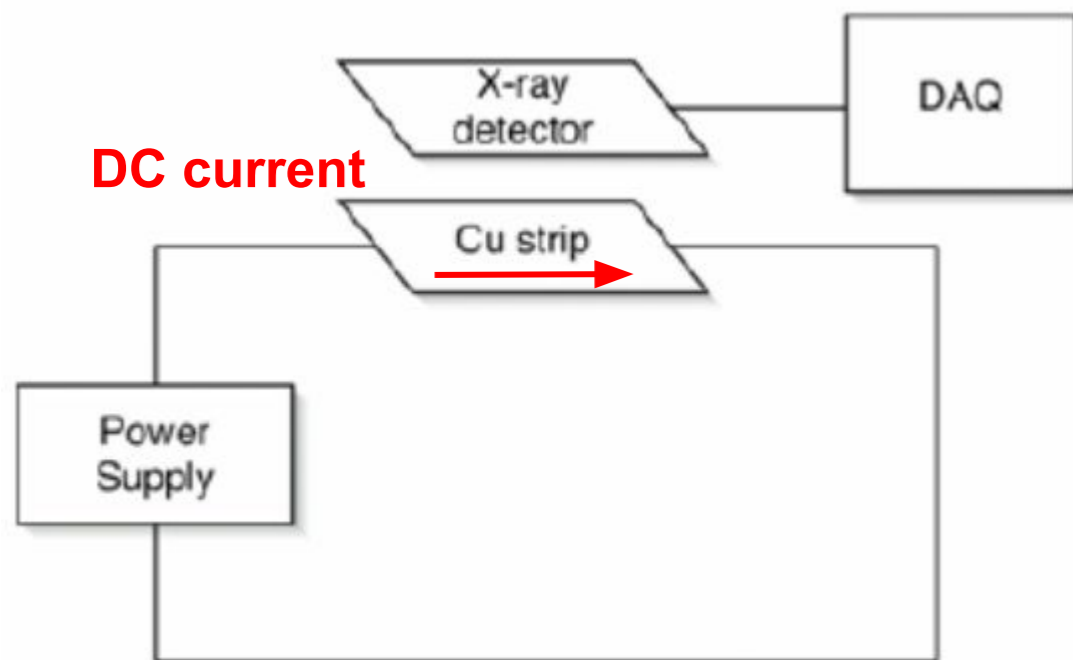
The PEP violation probability P_{PEPV} is related to the q parameter by

$$P_{PEPV} = 2 + 2q$$

such probability is the anomalous component of the two-identical fermions density matrix

$$\rho_2 = (1 - 2P_{PEPV})\rho_a + 2P_{PEPV} \rho_s$$

a **high sensitivity test** of P_{PEPV} consists in (Ramberg E. and Snow G. A. 1990 Phys. Lett. B 238 438)



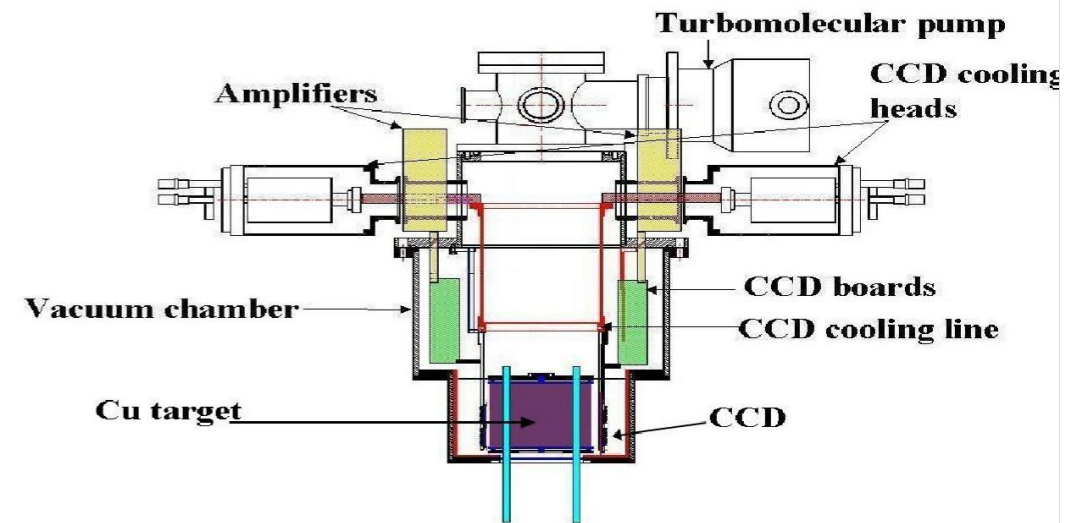
If the symmetry state formed by a *new current* electron with the electrons of the target is such that the K shell of an atom accommodates two equal spin electrons:



Then the X-ray detector will measure (with a certain efficiency)

From VIP to VIP-2

- a) copper ultrapure cylindrical foil
- b) surrounded by 16 Charge Coupled Devices (CCD) res. at 8 keV 320 eV (FWHM)
- c) inside a vacuum chamber: CCDs cooled to 168K by a cryogenic system
- d) amplifiers + read out ADC boards.

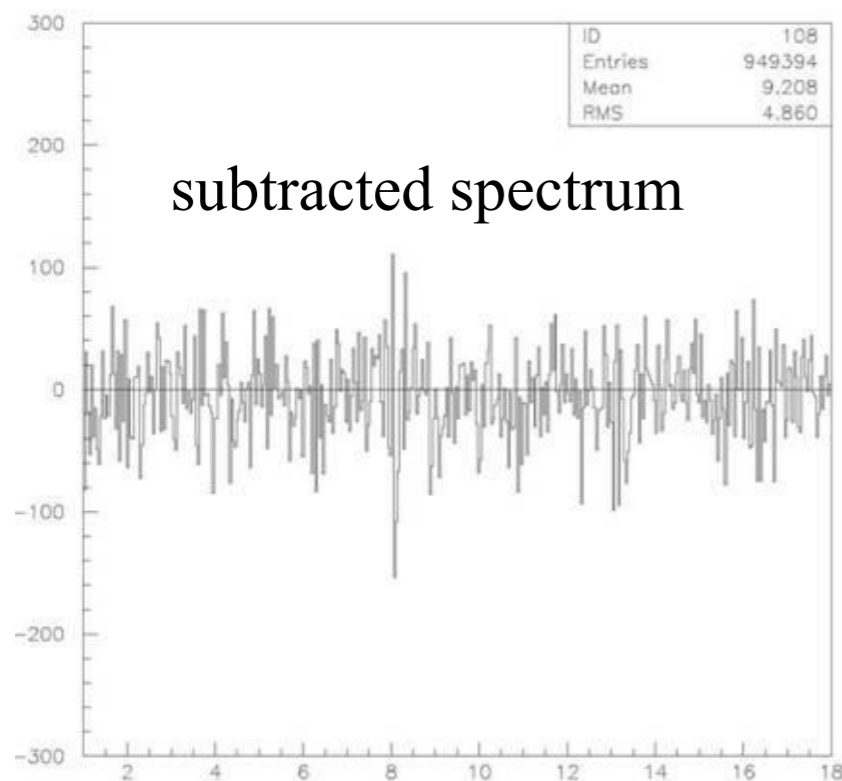


*improved the limit obtained by Ramberg & Snow
by a factor ~ 400*

(Foundation of Physics 41 (2011) 282+ other papers)

VIP-2 GOAL:

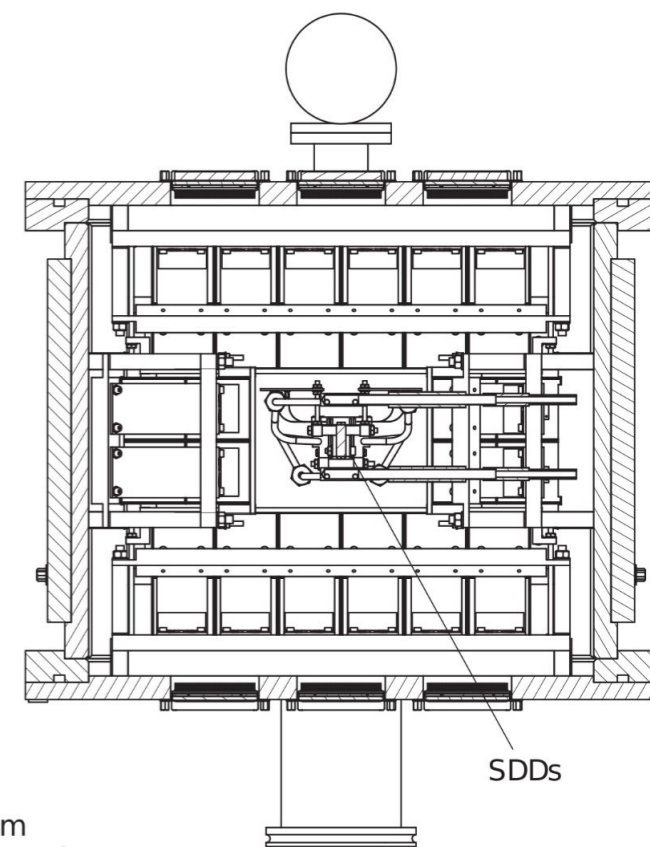
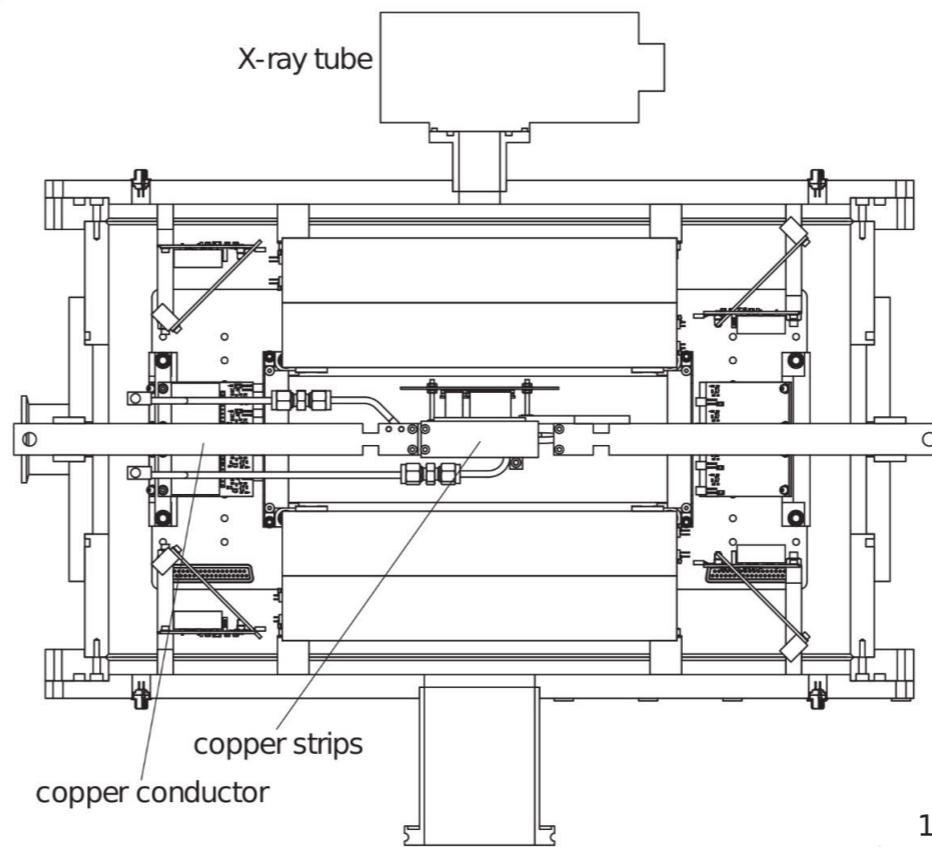
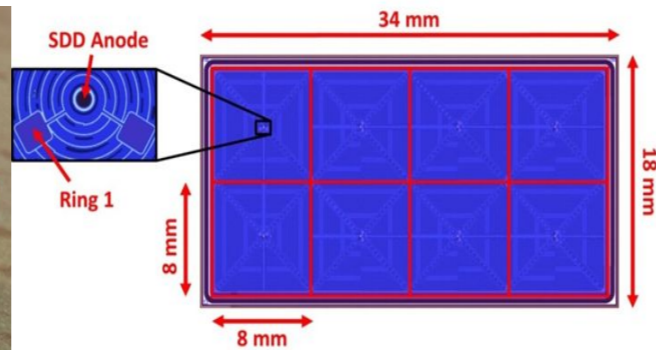
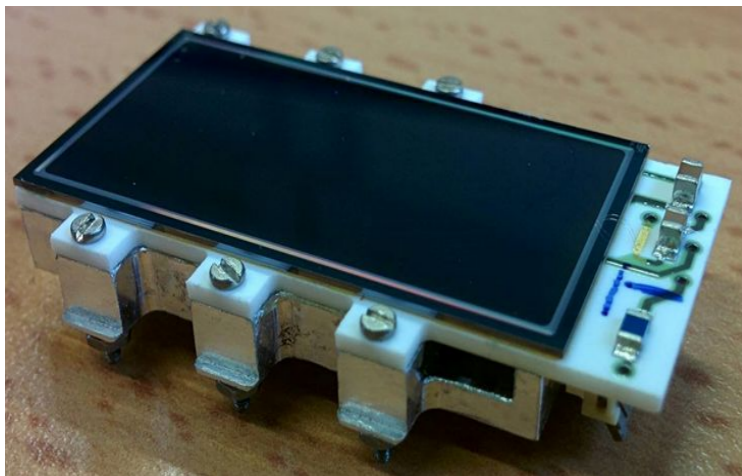
further improvement of 2 o.m.



VIP-2

VIP-2 Open Systems -

- SDD detectors (high resolution 190 eV FWHM at 8 keV) [ML/DP analysis improvement of 10 eV \(Meas. Sci. Technol. 35 \(2024\) 025501\)](#)
- 4 arrays of 2x4 SDDs, cryocooler closed circuit cooling
- 2 strip shaped Cu targets (cooled by closed chiller circuit -> with (peak) 200A circulating current ~1 °K heating in the SDDs)




Statistical model

The statistical model accounts for uncertainties on the parameters of the signal and background shapes, and scale factor of the current on/off spectra:

- the two spectra are simultaneously analysed by constructing the joint likelihood:

$$\mathcal{L} = \text{Pois}(Data^{wc} | f^{wc}(\theta)) \times \text{Pois}(Data^{woc} | f^{woc}(\theta) \times \text{SCALE})$$


$$f^{wc}(\theta) = yield_{Ni} * Ni(\theta_{1,2}) + yield_{Cu} * Cu(\theta_{3,4}) + yield_{pol1} * pol_1(\theta_5) + yield_{PEPV} * PEPV(\theta_4)$$

$$f^{woc}(\theta) = (yield_{Ni} * Ni(\theta_{1,2}) + yield_{Cu} * Cu(\theta_{3,4}) + yield_{pol1} * pol_1(\theta_5))$$

where θ is the vector of parameters of the signal and bkg shapes

- The posterior *pdf* is obtained based on the Bayes theorem:

$$P(S, B, s, \theta_S, \theta_B | data_{wc}, data_{woc}) = \frac{\mathcal{L}}{N} P_0(S) \cdot P_0(B) \cdot P_0(s) \cdot P_0(\theta_S) \cdot P_0(\theta_B)$$

SCALE has a gaussian prior at t_{wc} / t_{woc}

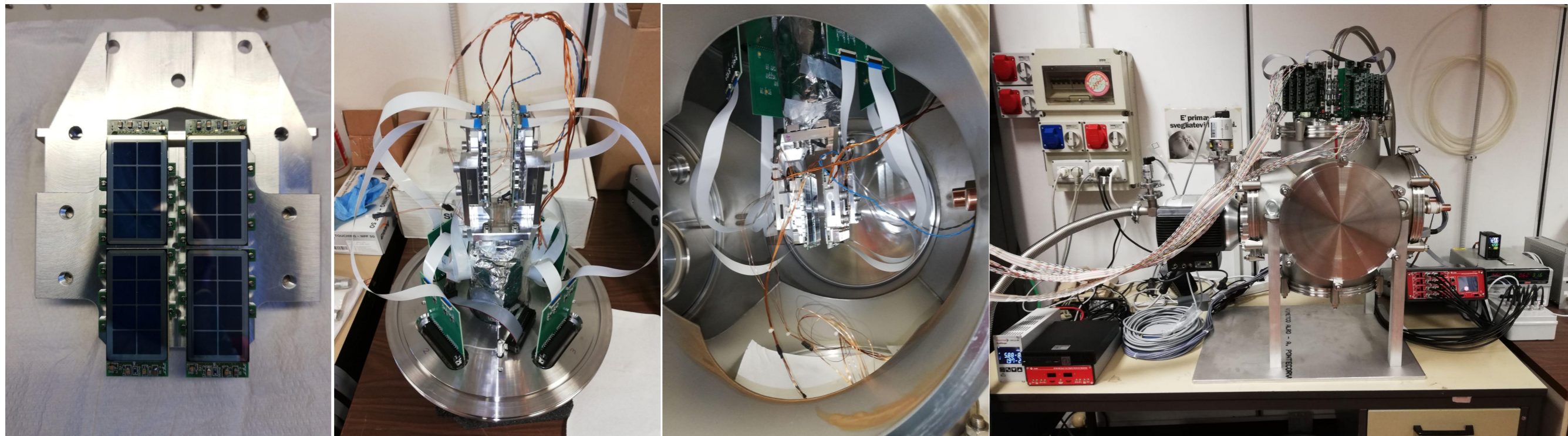
SHAPE par. - have flat priors, except gaussians for transitions positions and *B*

Activities on the setup 2025-now

- The **full set of new (1 mm thick) SDDs was completed and characterized.**

The **VIP-3 electronics was finalized.** The SDD signal processing is currently based on the conversion of the preamplified front-end signal (CUBE integrated into the SDD array) into an exponentially shaped signal through shaping, ensuring compatibility with the digitizer:

- design and development of a low-noise, low-power buffering stage for the front-end signal.
- Design and development of a signal interface board and bias voltage distribution system with integrated SDD reset functionality.
- Design and development of a low-noise exponential shaping stage with integrated differential driver.
- Review and update of the power supply modules.
- Full refurbishment of the power supply and signal cabling.
- Testing and commissioning.



Characterization of the SDDs and front-end electronics

SDDs and front-end electronics were carefully characterized:

- the [linearity of the entire acquisition chain was evaluated](#) starting from the front-end electronics, using a pulse generator to simulate the signal produced by an SDD detector.
- Pulses with amplitudes ranging from 2 mV to 46 mV were produced at regular intervals in order to cover the full dynamic range of the front-end electronics.
- Linearity curve is shown in Fig. 1. The residuals demonstrate that the response of the electronics is highly linear across the entire dynamic range.
- The observed deviation from linearity is approximately 0.02 mV, corresponding to an energy uncertainty of less than 1 eV ->
- [excellent linear performance of the readout electronics.](#)

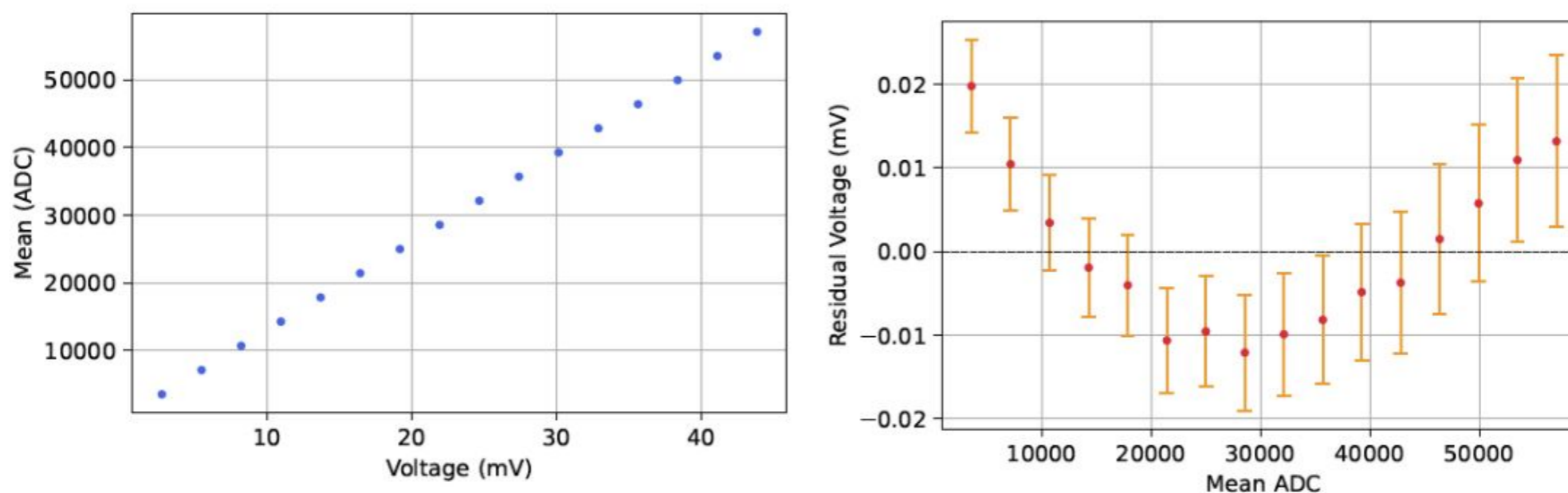


Figure 1 Linearity test of the acquisition chain. **Left:** correlation between the input pulse amplitude generated by the pulse generator (in mV) and the corresponding signal measured in ADC counts by one channel of the readout system. **Right:** residuals of the data points with respect to the linear fit performed on the distribution shown in the left panel.

Characterization of the SDDs and front-end electronics

The energy resolution of the detector system was characterized at 8.0 keV and 22 keV:

- Fluorescence from copper and silver targets was induced using an ^{241}Am source, spectra from one detector channel are shown in Fig. 2.
- The silver spectrum was fitted with two Gaussians components to account for the $K\alpha_1$ and $K\alpha_2$ transitions, combined with a linear function to model the background.
- In copper $K\alpha_1$ and $K\alpha_2$ lines are separated by ~ 20 eV (less than the detector resolution) a single Gaussian was sufficient to describe the main peak + linear background.
- Peak centroids and Gaussian widths are used for energy calibration and to quantify the energy resolution.

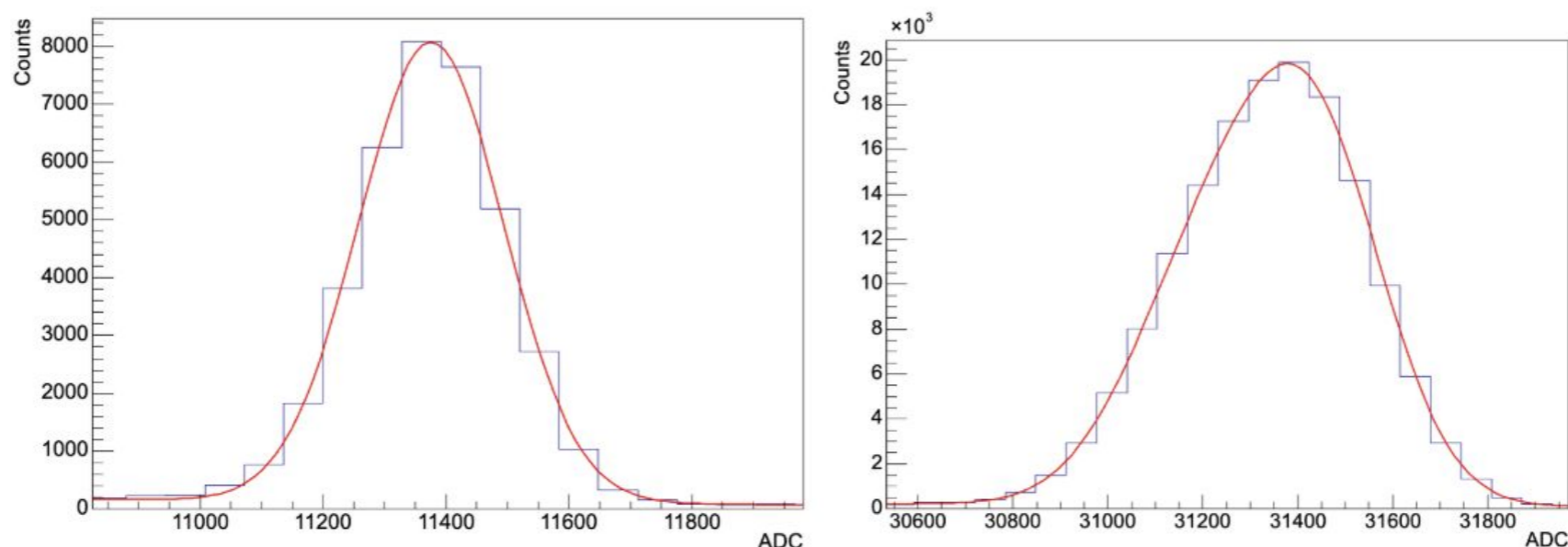


Figure 2. Example of fluorescence spectra from a single SDD. **Left:** Cu K_α spectrum fitted with a single Gaussian and linear background. **Right:** Ag K_α spectrum, where the peak asymmetry arises from the two components (K_{α_1} and K_{α_2}) separated by ~ 170 eV, fitted with two Gaussians and a linear background.

RESULT: resolution = 168 ± 5 eV at 8 keV (Cu K_α) and 264 ± 7 eV at 22 keV (Ag K_α) across all readout channels.

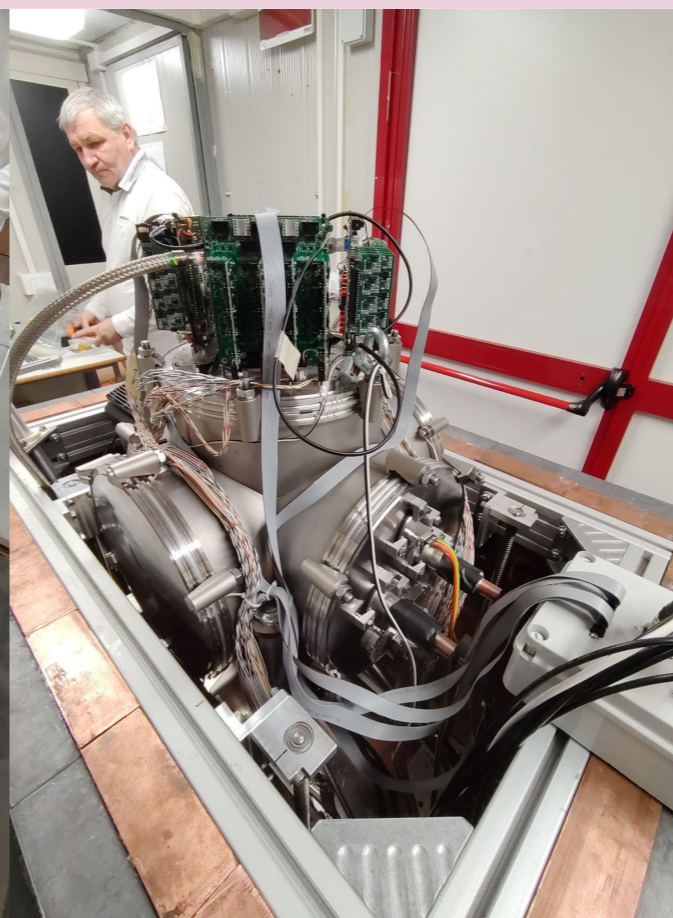
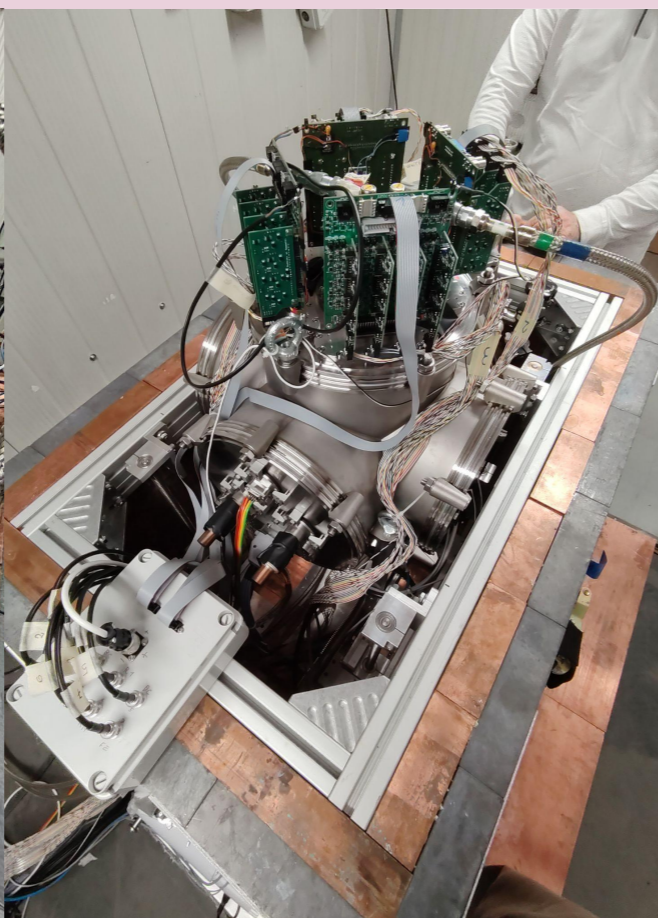
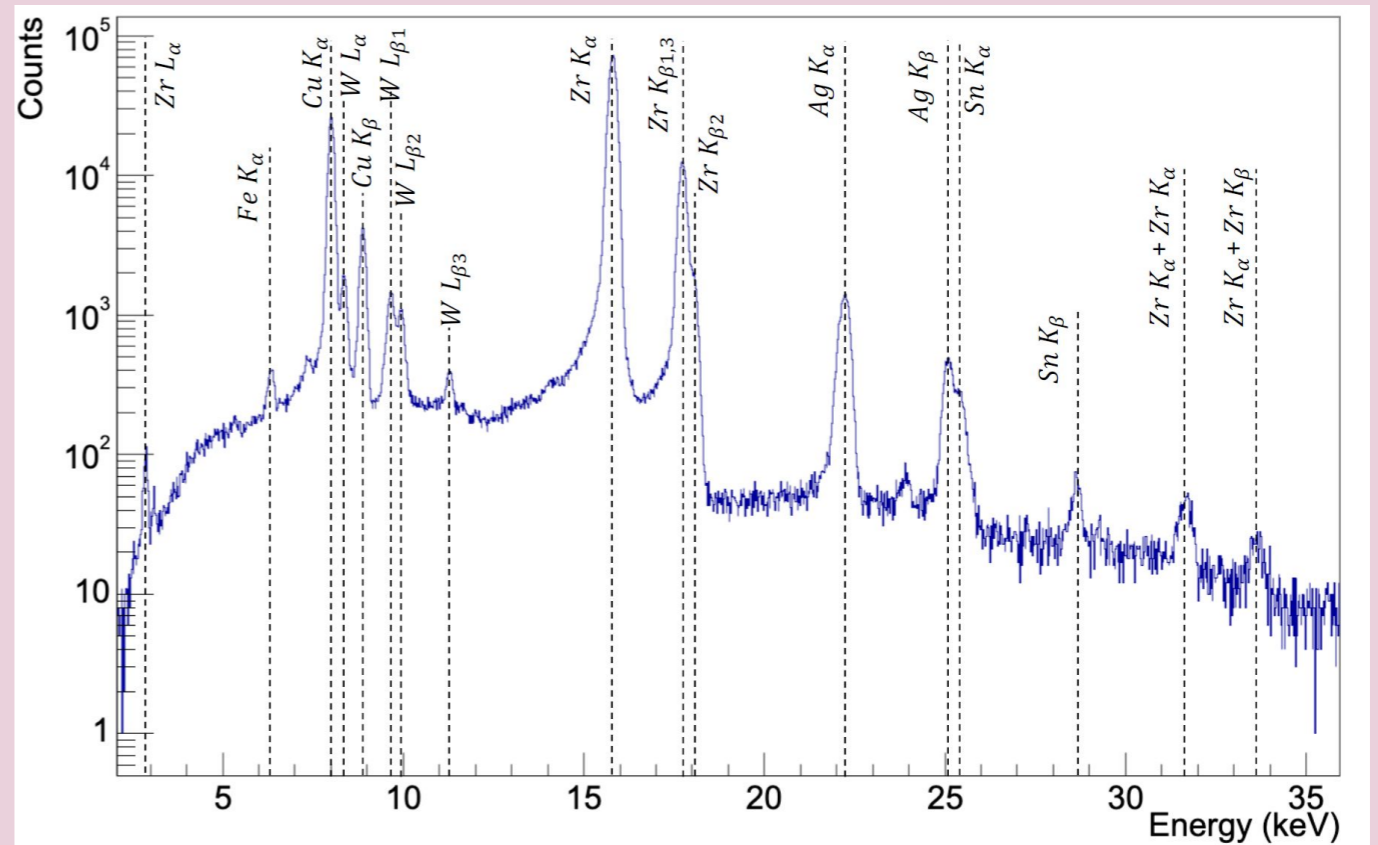
Improvement of more than 20 eV with respect to VIP-2. Reflects the improved design of the SDDs and front-end electronics for VIP-3.

VIP-3 at LNGS

The VIP-3 setup was transported
and mounted at LNGS

data taking started

Milestone fulfilled



PEP-V in GUP

Search for GUP induced PEP violation

- It is widely believed that the Heisenberg uncertainty relations (HUP) modify at sufficiently high energies, where the gravitational field plays a relevant role,
- nonlocal nature of the fundamental degrees of freedom -> deformation of HUP -> minimal uncertainty in space.

RECENT REVIEW Classical and Quantum Gravity 40 (2023) 195014.

- For a one-dimensional quantum system: $\Delta x \Delta p \geq \frac{\hbar}{2} (1 + \beta \Delta p^2)$
- minimum position uncertainty: $\hbar \sqrt{\beta}$. with $\beta = \beta_0 \frac{\ell_p^2}{\hbar^2}$

strongest available bound F. Wagner, et al., Phys. Rev. D 108 (2023) 066008, [2306.05205]

- From the generalized commutation relations one can build a deformed quantum theory (Eur. Phys. J. C 81 (2021) 982, [2109.15259])

$$[c, c^\dagger] = \hbar \omega \left(\sqrt{1 + 2\beta m H} + \beta \frac{m \hbar \omega}{2} \right)$$

Search for GUP induced PEP violation

- extended to a consistent quantum field theory incorporating a minimal length ->
- deformation of the canonical anticommutation relations for fermionic fields ->
- **violation of PEP**
- **Fundamental motivation** : PEP follows from the spin-statistics theorem, the connection between spin and statistics depends on locality and Poincaré covariance. The introduction of a **minimal length breaks locality**.
- **QUON**: interpolates continuously between Bose and Fermi statistics, consistent quantum theory with **violations of locality and statistics confined below arbitrarily small scales**. GUP PEP-violation is similar and forbids transitions between states with different permutation symmetry.
- Fraction of states with wrong symmetry (i.e., not fully antisymmetric) is suppressed by:

$$\mathcal{P}_s = \beta \frac{m^5}{\Delta_{(\chi)}^3} \sum_i BR_i I_{\varphi_i}$$

where m is the electron mass, $\Delta_{(\chi)}$ is the momentum spread of wave packets in the conduction band, I_{φ_i} is the overlap of these wave packets with the orbital φ_i , and BR_i are the

branching ratios for the transitions from the conduction band to the lower energy levels, with $\sum_i BR_i = 1$.

Search for GUP induced PEP violation

PHENOMENOLOGICAL STRATEGY

- conduction-band electrons require finite time to interact with all atoms in the target
- average time between two electron–atom close encounters leading to electron capture is $\tau = 2.5 \times 10^{-17} \text{ s}$
- If the conductor was formed from multiple original pieces, electrons from one fragment can interact with atoms belonging to other fragments, probing a new ensemble of electron-pairs
- A statistical model is developed to describe the depletion of the reservoir of test electrons over time, requires a non-trivial normalization of the measured upper bound on the signal events S :

$$\mathcal{P}_s < \frac{\bar{S}}{N_{\text{int}} \varepsilon \sum_{i=1}^V N_{\text{free}}^i e^{-\frac{n}{n-1} \frac{T_i}{N_i \tau}}}$$

- We search for PEPV K complex in Ultra-radio-pure Pb target SHIFT ~ 1.2 keV

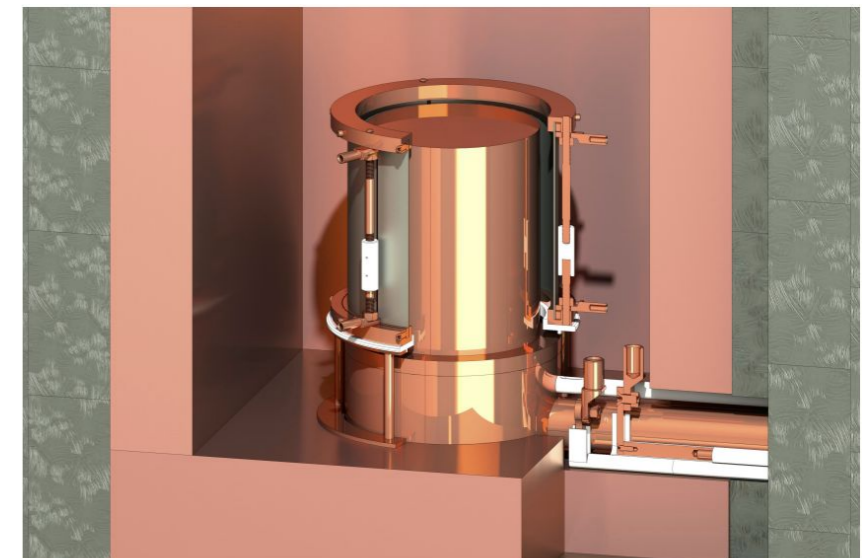


Fig. 2 Schematic view of the inner part of the setup, the Pb target is shown in gray.

search for GUP induced PEP violation

STATISTICAL Bayesian MODEL

$$\mathcal{F}(\boldsymbol{\theta}, \mathbf{y}, \mathcal{S}) = \frac{1}{N_{PEP}} \sum_{i=1}^5 y_1 BR_i \varepsilon(E_i) PEP_i(\boldsymbol{\theta}) +$$
$$+ \frac{1}{N_{PEPV}} \sum_{j=1}^5 \mathcal{S} BR_j \varepsilon(E_j) PEPV_j(\boldsymbol{\theta}) + y_2 \text{Pol}(\boldsymbol{\theta})$$

search for *GUP* induced *PEP* violation

STATISTICAL Bayesian MODEL

standard transitions

$$\mathcal{F}(\boldsymbol{\theta}, \mathbf{y}, \mathcal{S}) = \frac{1}{N_{PEP}} \sum_{i=1}^5 y_1 BR_i \varepsilon(E_i) PEP_i(\boldsymbol{\theta}) +$$
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search for *GUP* induced *PEP* violation

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PEPV transitions

search for *GUP* induced *PEP* violation

STATISTICAL Bayesian MODEL

standard transitions

$$\mathcal{F}(\boldsymbol{\theta}, \mathbf{y}, \mathcal{S}) = \frac{1}{N_{PEP}} \sum_{i=1}^5 y_1 BR_i \varepsilon(E_i) PEP_i(\boldsymbol{\theta}) +$$

$$+ \frac{1}{N_{PEPV}} \sum_{j=1}^5 \mathcal{S} BR_j \varepsilon(E_j) PEPV_j(\boldsymbol{\theta}) + y_2 \text{Pol}(\boldsymbol{\theta})$$

PEPV transitions

background

search for GUP induced PEP violation

STATISTICAL Bayesian MODEL

standard transitions

$$\mathcal{F}(\boldsymbol{\theta}, \mathbf{y}, \mathcal{S}) = \frac{1}{N_{PEP}} \sum_{i=1}^5 y_1 BR_i \varepsilon(E_i) PEP_i(\boldsymbol{\theta}) +$$

$$+ \frac{1}{N_{PEPV}} \sum_{j=1}^5 \mathcal{S} BR_j \varepsilon(E_j) PEPV_j(\boldsymbol{\theta}) + y_2 \text{Pol}(\boldsymbol{\theta})$$

PEPV transitions

background

Normalization:

$$N_{PEP} = \sum_{i=1}^5 BR_i \varepsilon(E_i)$$

and

$$N_{PEPV} = \sum_{j=1}^5 BR_j \varepsilon(E_j)$$

Requires the yields: \mathcal{S} and y_1
to be expected number of events

- The likelihood is Poissonian $\mathcal{L}(\mathcal{D}|\boldsymbol{\theta}, \mathbf{y}, \mathcal{S}) = \text{Pois}(\mathcal{D}|\mathcal{F}(\boldsymbol{\theta}, \mathbf{y}, \mathcal{S}))$
- The shape parameters $\boldsymbol{\theta}$, \mathcal{S} and \mathbf{y} are constrained by prior distributions,
- The posteriors are obtained via MCMC marginalization.

search for GUP induced PEP violation

RESULTS:

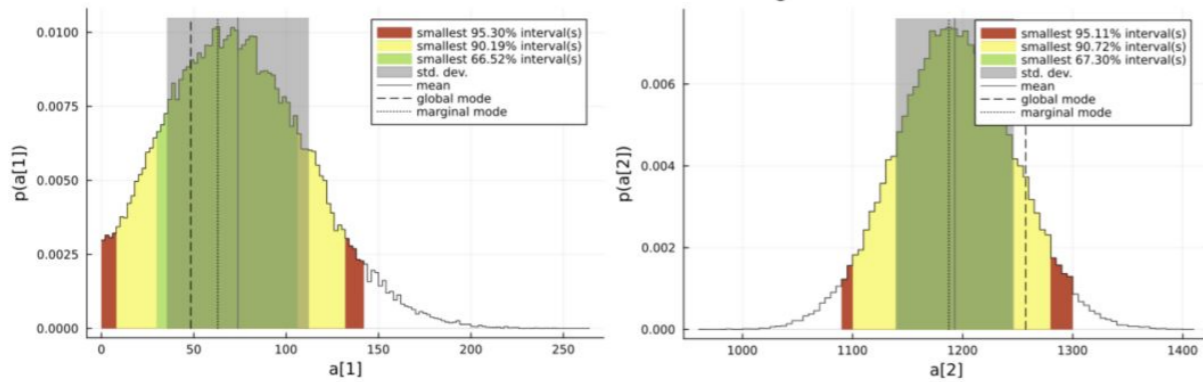


Fig. 4 Left panel: marginalized posterior distribution of the parameter of interest. The 90 % upper limit is indicated by the yellow band. Right panel: marginalized posterior for the expected total number of standard K_α and K_β transitions.

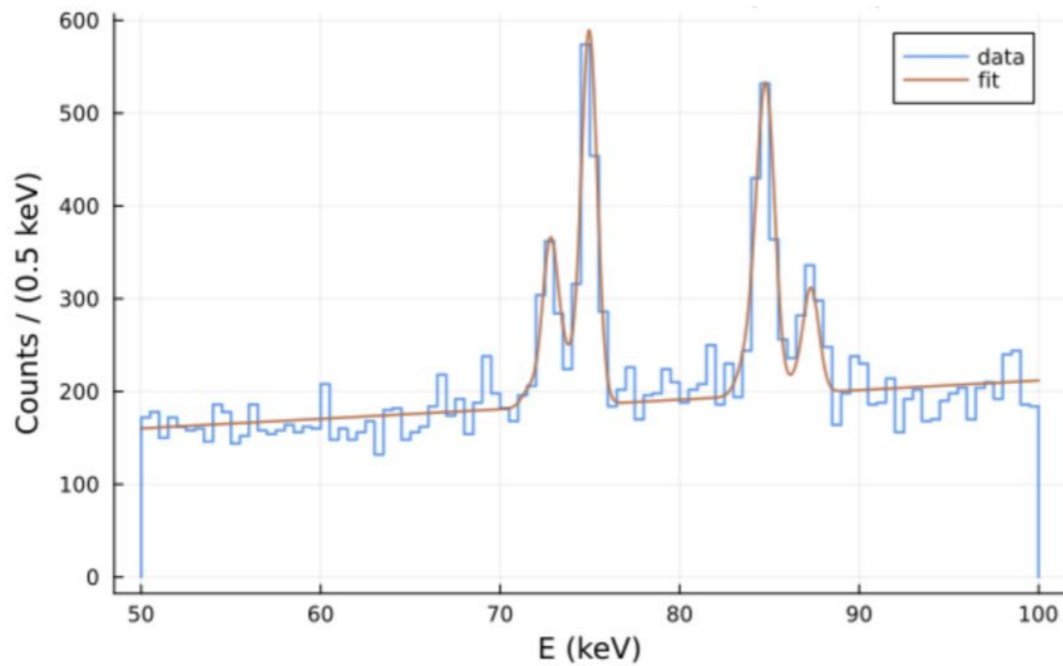


Fig. 3 The data set acquired by the Gator HPGe detector between April and August 2023 is shown as a blue distribution, in the energy region of interest 65-90 keV. The result of the Bayesian analysis is shown as an orange curve.

$$\mathcal{P}_s < \frac{\bar{S}}{N_{\text{int}} \epsilon \sum_{i=1}^V N_{\text{free}}^i e^{-\frac{n}{n-1} \frac{T_i}{N_i \tau}}} \longrightarrow \mathcal{P}_s = \beta \frac{m^5}{\Delta_{(\chi)}^3} \sum_i BR_i I_{\phi_i}$$

90% C.L. upper bound

$$\beta_0 < 98.4.$$

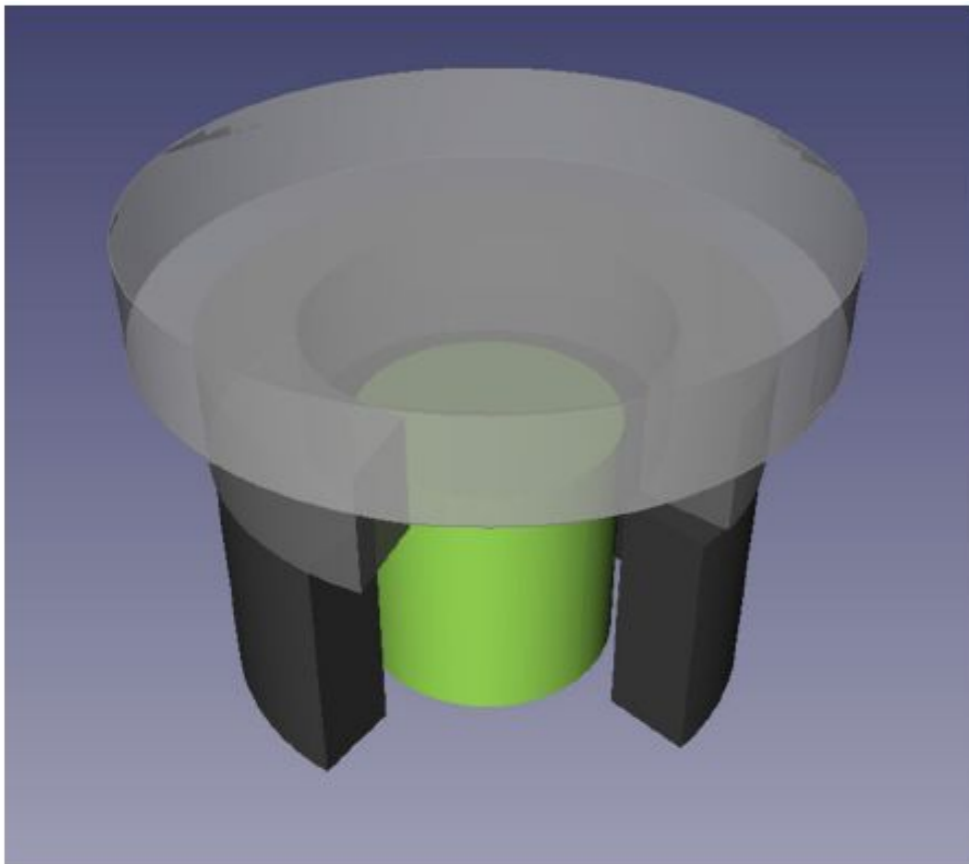
which corresponds to

$$\Delta x_{\text{min}} < 9.92 \text{ } l_P$$

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.



- 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 $\Delta t \approx 70d \approx 6.1 \cdot 10^6s$

K. P. et al., Eur. Phys. J. C (2020) 80: 508

<https://doi.org/10.1140/epjc/s10052-020-8040-5>

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

Statistical model

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

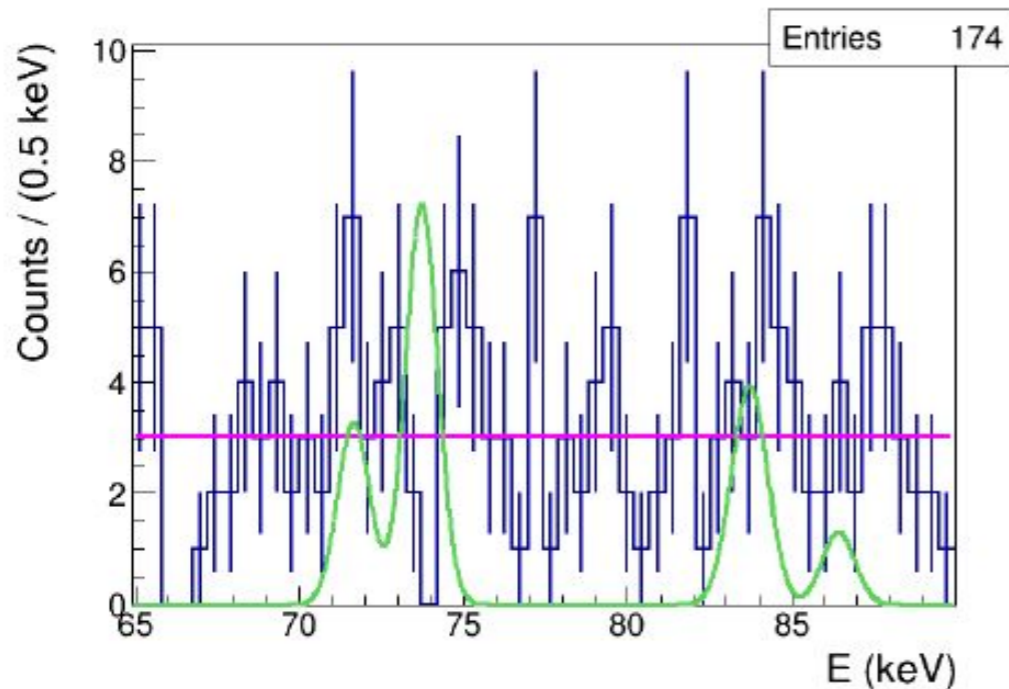


FIG. 1. The measured X-ray spectrum, in the region of the K_α and K_β standard and violating transitions in Pb, is shown in blue; the magenta line represents the fit of the background distribution. The green line corresponds to the shape of the expected signal distribution (with arbitrary normalization)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

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



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

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

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

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

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

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

Statistical model

- First analysis which accounts for the predicted energy dependence of the PEP violation probability. Expected rate of $K\alpha_1$ transitions:

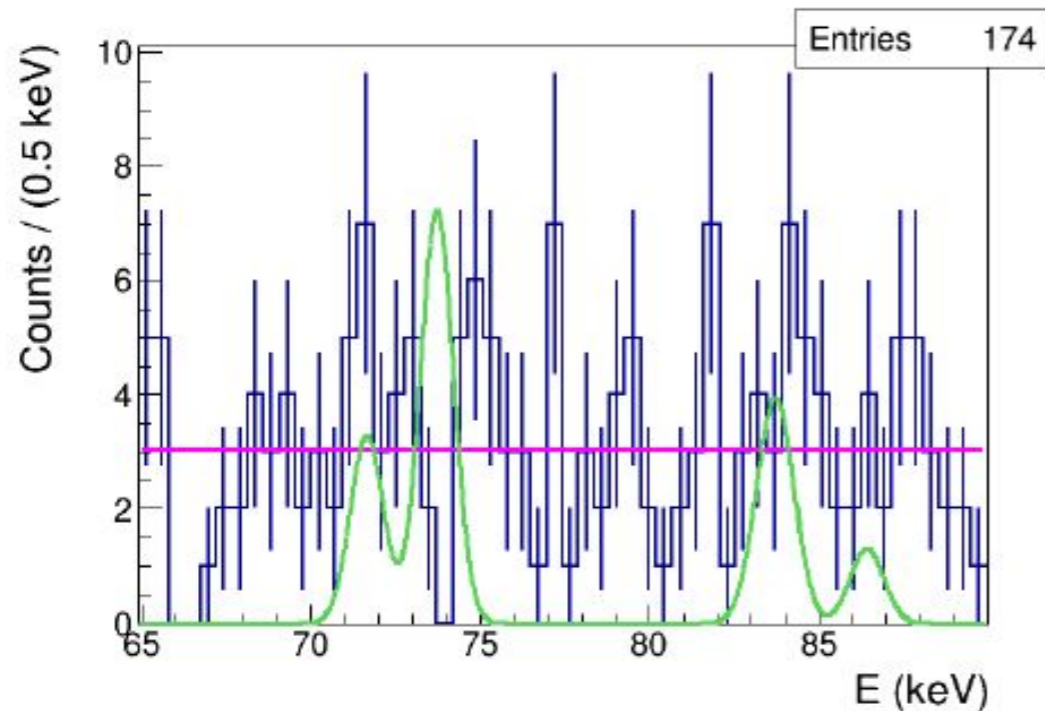


FIG. 1. The measured X-ray spectrum, in the region of the K_α and K_β standard and violating transitions in Pb, is shown in blue; the magenta line represents the fit of the background distribution. The green line corresponds to the shape of the expected signal distribution (with arbitrary normalization)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

$$\Gamma_{K\alpha_1} = \frac{\delta^2(E_{K\alpha_1})}{\tau_{K\alpha_1}} \cdot \frac{BR_{K\alpha_1}}{BR_{K\alpha_1} + BR_{K\alpha_2}} \cdot 6 \cdot N_{atom} \cdot \epsilon(E_{K\alpha_1}).$$

- 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:

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

Theoretical framework finalized

Motivations:

Spin-statistics theorem requires **locality** and **Poincaré symmetry**

In QG there is no sharp notion of locality and deformations of Poincaré are expected

Quon model may capture low-energy effects of QG

Effective low-energy QG models:

Introduce a **minimal length**:

QFT on **noncommutative coordinates**:

$$[x^\mu, x^\nu] \neq 0$$

QM with **Generalized uncertainty principle**:

$$[x, p] = if(p)$$

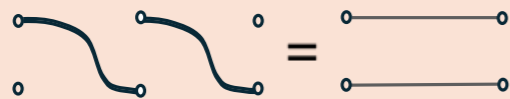
String theory induces both noncommutativity and GUP and predicts **deformation of statistics**

Noncommutative spacetime

$$[x^\mu, x^\nu] = i\theta^{\mu\nu} + a_p a_q^\dagger - \eta(p, q) e^{ip\theta q} a_q^\dagger a_p = \delta_{pq}$$

$\eta = \pm 1$: twisted Bose and Fermi statistics

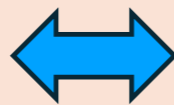
$$\psi(\mathbf{p}, \mathbf{q}) = \pm e^{ip\theta q} \psi(\mathbf{q}, \mathbf{p})$$



Large violations of PEP: **ruled out**

PEP-violating rates

$$\Gamma_{PV} = \delta(1/\Lambda_\theta) \Gamma_0$$



$\kappa = 1, 3$: linear suppression

$\kappa = 2$: quadratic suppression

$\kappa \geq 4$: no suppression

} Test with closed system experiments

$-1 < \eta < 1$: **quon deformation**. At low energies $|\eta(p, q)| - 1 \sim \frac{1}{\Lambda_\theta^\kappa}$

Expected to provide UV-complete QFT

The twist $e^{ip\theta q}$ induces **violation of SSRs**

Breakdown of particle indistinguishability: $\psi(\mathbf{p}, \mathbf{q}) \neq \psi(\mathbf{q}, \mathbf{p})$

Generalized uncertainty principle

$$[x, p] = i(1 + \beta p^2) + a_p a_q^\dagger - (-1 + \beta m E_p^4 \delta_{pq}) a_q^\dagger a_p = \delta_{pq}$$

$\sqrt{\beta}$ expected of order the Planck length

SSRs preserved: Test with open system experiments

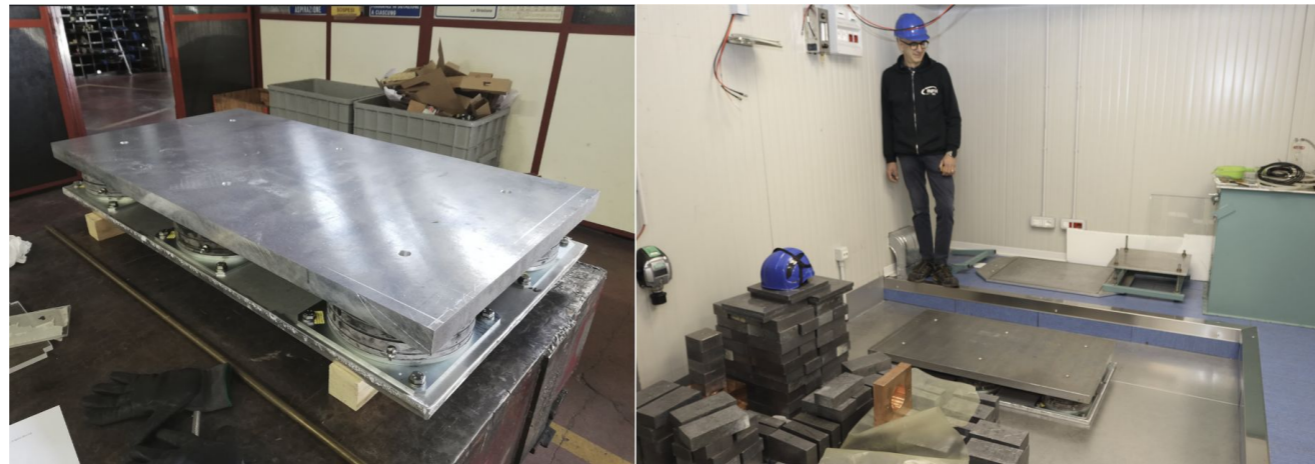
PEP-violating rates

Linear suppression with β

BEGe based prototype activity 2025-now

The project was approved by the review committee and funded by CSN3, and we successfully finalized the realization:

- January–February 2025 - the mechanical suspension system was constructed (lower aluminum sheet (20 mm thick), pneumatic suspensions mounted on top, second aluminum sheet supports the 3.5 ton weight of the setup)
- March 2025 - transportation and installation in the Stella Laboratory



- April 2025 the whole BEGe setup was installed on top of the mechanical suspension system
- late spring to summer 2025 - upgrade and testing of the electronics and data acquisition system:

factor 1.6 gain in resolution, DPP for pulse-height analysis of the signals, elimination of all ground loops

- November 2025 - the soundproof enclosure surrounding the entire experimental setup was installed.

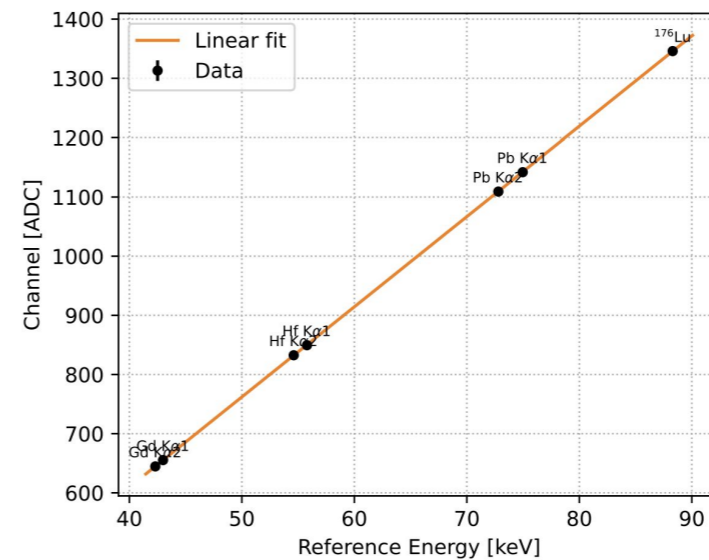
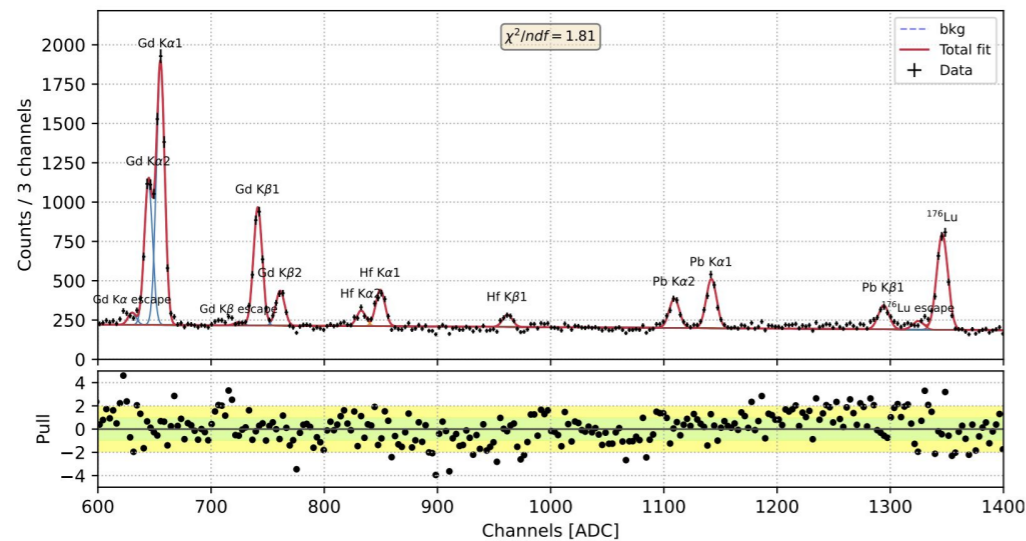


December 2025 - calibration and characterization data acquisition run:

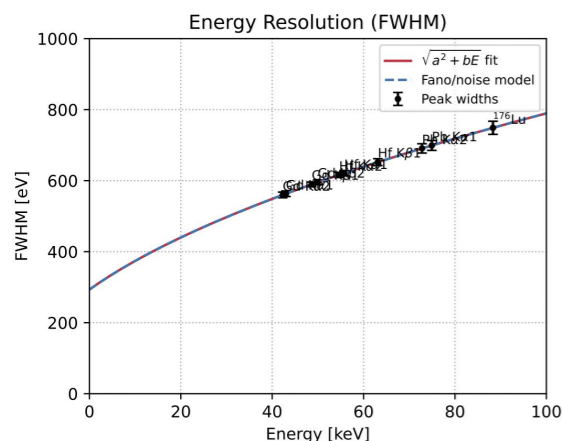
BEGe based prototype activity 2025-now

Calibration and characterization data acquisition run with lutetium calibration source:

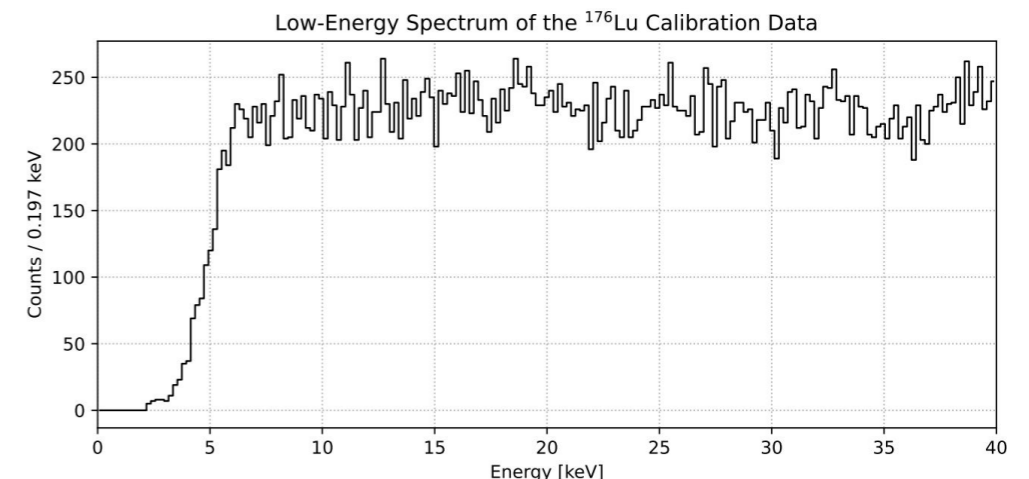
- **spectrum fit and calibration**: the raw spectrum was fit with a quadratic background plus Gaussian peaks for the Gd, Hf, Pb, and ^{176}Lu lines. the $K\alpha$ reference lines of Gd, Hf, and Pb together with the ^{176}Lu line are used for the linear calibration



- After calibration, the spectrum was refit in energy using a quadratic background and Gaussian peaks. The Gaussian widths from the calibrated-energy fit were converted to FWHM and fitted with the standard form $\text{FWHM}(E) = \sqrt{a^2 + bE}$



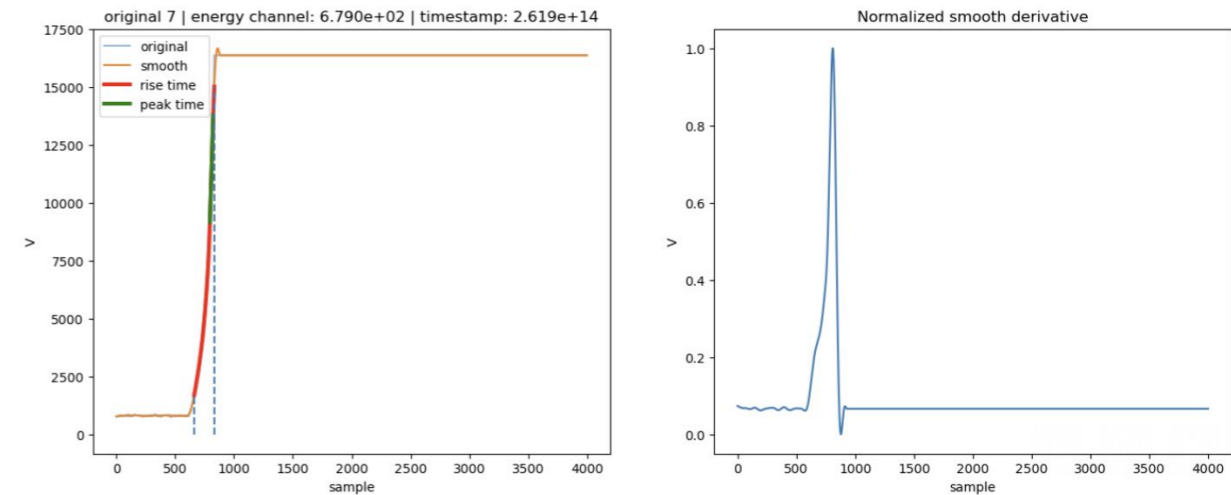
- A low-energy threshold of 6 keV was obtained, which fully achieves the intended goal



Dedicated ML pulse shape algorithm

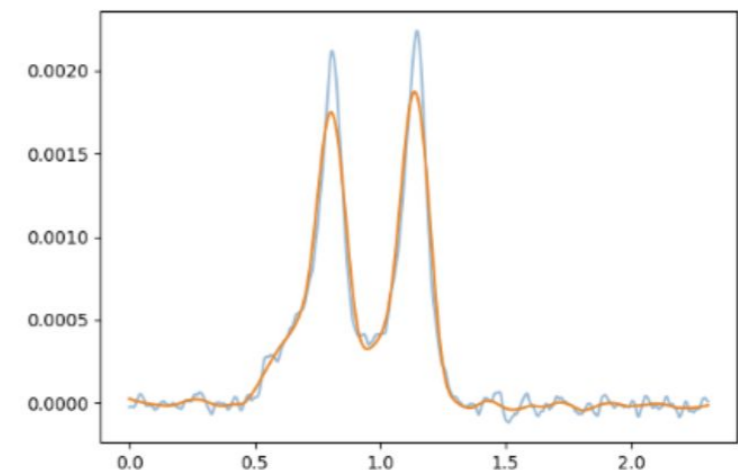
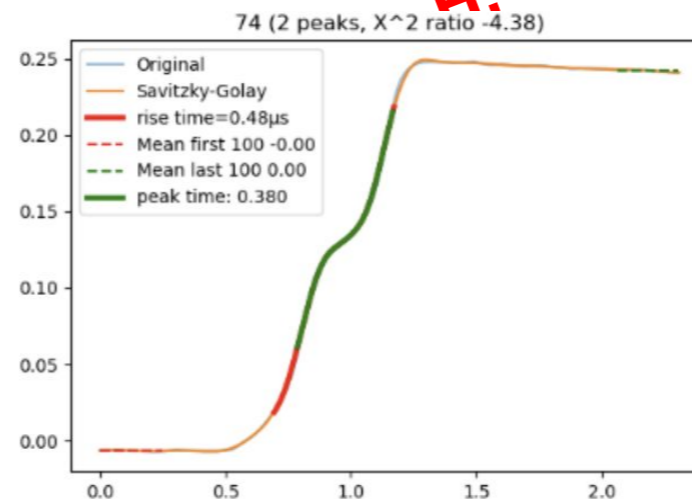
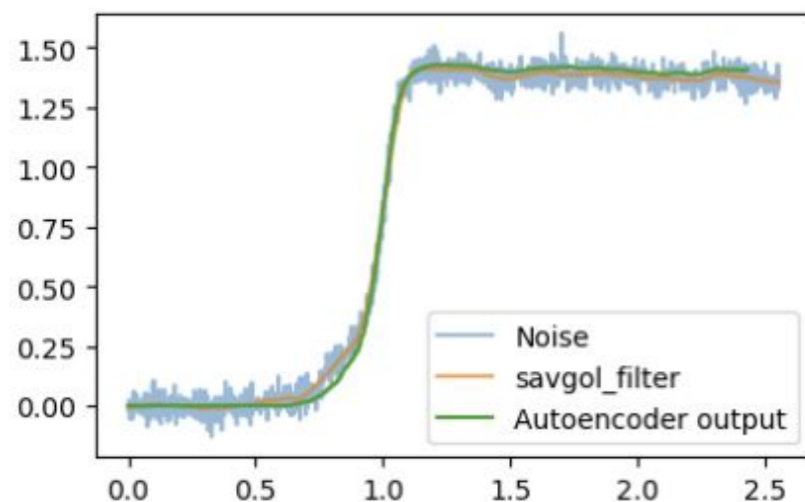
We finalized the development of an [improved ML-based pulse-shape discrimination algorithm](#):

- to improve energy resolution and enhance the signal-to-background ratio
- particularly effective in noisy conditions, where noise can lead to signal rejection and inaccurate feature extraction.
- the algorithm employs a denoising autoencoder, for reliable feature extraction even at low energies, followed by a CNN to reject background events.



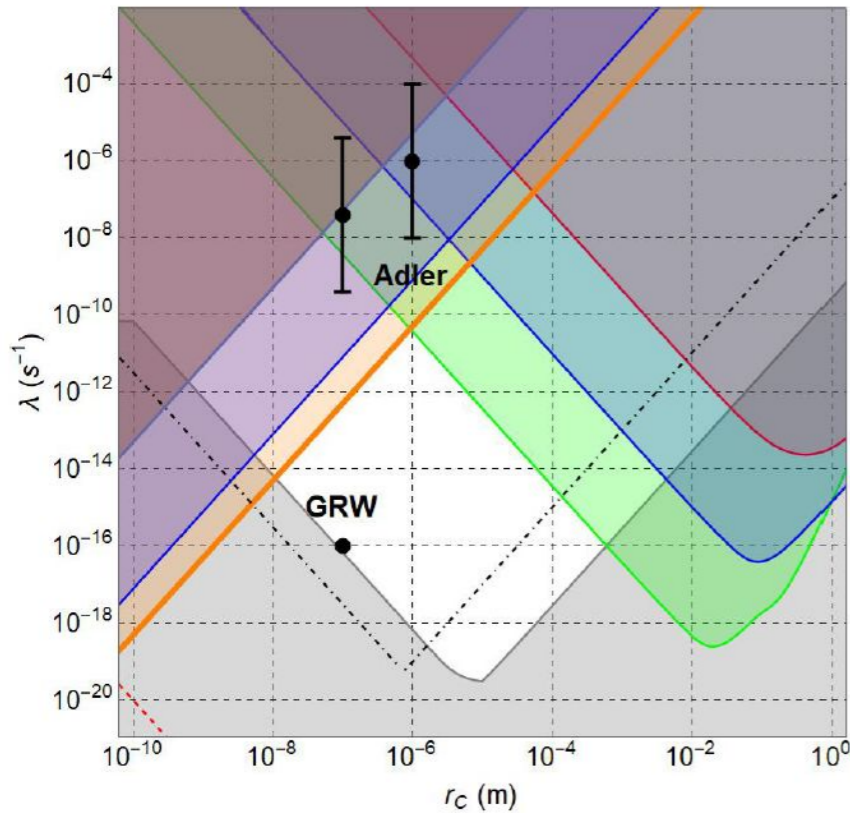
- **Focus on recovering low energy pulses** with denoising autoencoder
- Features extraction after denoising
- Machine learning on pulse discrimination with reconstructed pulses

Published:
S. Manti et al 2026 JINST 21 P01036
DOE/INFN summer research project of S.
H. Yip (University of California, Berkeley)



Constraints on the CSL

Bounds on the strength and correlation length of the CSL
(Eur. Phys. J. C (2021) 81: 773)

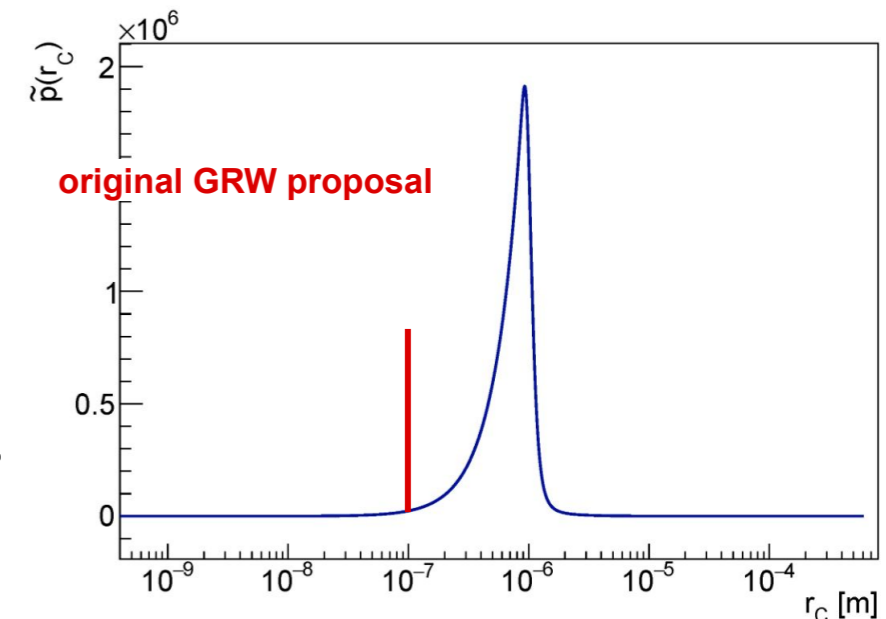


$$\lambda/r_c^2 < 52 \text{ m}^{-2} \text{ s}^{-1}$$

Fig. 4 Mapping of the $\lambda - r_c$ CSL parameters: the proposed theoretical values (GRW [6], Adler [24,25]) are shown as black points. The region excluded by theoretical requirements is represented in gray, and it is obtained by imposing that a graphene disk with the radius of $10 \mu\text{m}$ (about the smallest possible size detectable by human eye) collapses in less than 0.01 s (about the time resolution of human eye) [31]. Contrary to the bounds set by experiments, the theoretical bound has a subjective component, since it depends on which systems are considered as “macroscopic”. For example, it was previously suggested that the collapse should be strong enough to guarantee that a carbon sphere with the diameter of 4000 \AA should collapse in less than 0.01 s , in which case the theoretical bound is given by the dash-dotted black line [36]. A much weaker theoretical bound was proposed by Feldmann and Tumulka, by requiring the ink molecules corresponding to a digit in a printout to collapse in less than 0.5 s (red line in the bottom left part of the exclusion plot, the rest of the bound is not visible as it involves much smaller values of λ than those plotted here) [37]. The right part of the parameter space is excluded by the bounds coming from the study of gravitational waves detectors: Auriga (red), Ligo (Blue) and Lisa-Pathfinder (Green) [30]. On the left part of the parameter space there is the bound from the study of the expansion of a Bose-Einstein condensate (red) [28] and the most recent from the study of radiation emission from Germanium (purple) [22]. This bound is improved by a factor 13 by this analysis performed here, with a confidence level of 0.95, and it is shown in orange

strongest bound on r_c :

- Combined information from th. and other exp. \rightarrow exclusion of sectors of the $(\lambda - r_c)$ plane characterized by a different functional relation between λ and r_c .
- Including this rich prior information in the statistical analysis permits to disentangle the posterior of r_c



General Structure of the Collapse Dynamics

- Spontaneous w.f. collapse - quantum measurements occur continuously and everywhere,
- universal irreversibility breaks unitarity of the dynamics:
- **DP** - spontaneous measurement of the **MASS DENSITY** due to a fundamental uncertainty of the Newton field
- **CSL (GRW)** - each particle experience spontaneous localizations, independent one another, random in time ... **the collapse rate becomes mass proportional, but the stochastic field is unknown**

Standard QM : evolution [linear (superposition) & deterministic]

measurement [non-linear & stochastic]

SCM - non-linear and stochastic modifications of the Schödinger dynamics

General Structure of the Collapse Dynamics

Lindblad master equation

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{1}{2\hbar^2} \int d^3x d^3y \mathcal{D}(\mathbf{x} - \mathbf{y}) [\hat{\mu}(\mathbf{x}), [\hat{\mu}(\mathbf{y}), \hat{\rho}]]$$

statistical operator ← $\hat{\rho}$
← $\mathcal{D}(\mathbf{x} - \mathbf{y})$ ← **correlation function of spontaneous μ measurements at different locations**
← $[\hat{\mu}(\mathbf{x}), [\hat{\mu}(\mathbf{y}), \hat{\rho}]]$ ← **MASS DENSITY collapse operator**

The correlation function needs to be smeared: $\sigma =$ (spacial resolution of the μ measurement)

The master equation can be derived from the Stoch. Schödinger Eq. (SSE) :

$$\frac{d}{dt} |\psi_t\rangle = -\frac{i}{\hbar} \left[\hat{H} + \int d^3x \hat{\mu}(\mathbf{x}) \phi(\mathbf{x}, t) \right] |\psi_t\rangle$$

Schödinger Eq. in presence of a stoch. gravitational field

ϕ is a Gaussian noise field which can be chosen white in time

$$\mathbb{E}[\phi(\mathbf{x}, t)\phi(\mathbf{y}, t')] = \mathcal{D}(\mathbf{x} - \mathbf{y})\delta(t - t') \quad DP \text{ corr. func.} \quad D_{DP}(\mathbf{x} - \mathbf{y}) = \frac{\hbar G}{|\mathbf{x} - \mathbf{y}|}$$

