Status report: VIP-2 experiment

LNGS - LXI meeting of the Scientific Committee

C. Curceanu, LNF (INFN)
K. Piscicchia, LNF (INFN), Centro Ricerche Enrico Fermi

on behalf of the VIP collaboration

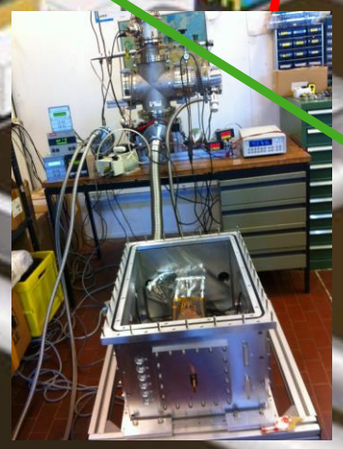
April 22-23, 2024, LNGS

VIP collaboration is performing:
Research in Foundational Quantum Mechanics

- Pauli Exclusion Principle Violation Searches

- Quantum Collapse Models investigations (impact in Quantu

Technologies)



Interplay between Quantum and Gravity

Contents:

1) Introduction: what we do

2) VIP Pauli Exclusion Principle violation

On the scientific case -> classes of tests and landscape of models

Highlights of the VIP-2 OPEN SYSTEMS activity

Update on the activity for the future VIP-3/4 experiment

Gator/VIP collaboration

VIP CLOSED SYSTEMS

3) Experimental tests of Quantum Collapse Models

Ganttchart

Contents:

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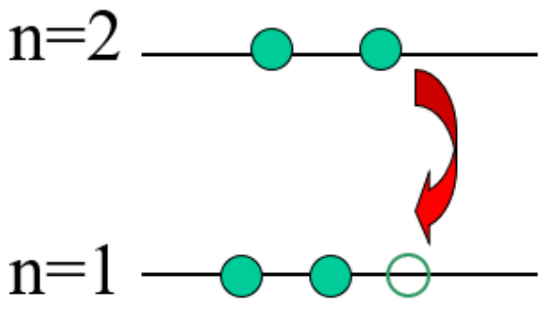
3) Experimental tests of Quantum Collapse Models

Ganttchart

What is VIP doing?

Testing (Foundations of) Quantum Mechanics
by applying atomic and nuclear physics techniques

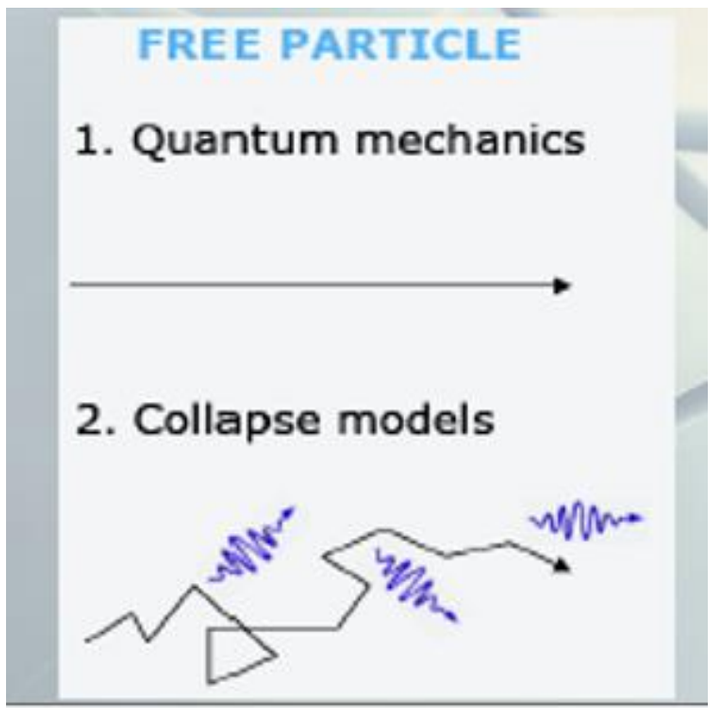
Searching for Pauli Exclusion Principle violation: in atomic transitions



2p –>1s atomic transition violating PEP in Copper
Energy 7.7 keV
(8.08 keV normal one)

Sets limits on the Probability of PEP violation (for e-)

Tests of Quantum Collapse Models: spontaneous radiation (continuous)



1/E continuous spectrum
in simplest white noise models

$$\frac{d\Gamma_k}{dk} = \frac{e^2\lambda\hbar}{2\pi^2\epsilon_0 m^2 c^3 k}$$

Sets limits on the Quantum Collapse Models

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Update on the activity for the future VIP-3/4 experiment and plans

Gator/VIP (Prof. Laura Baudis) collaboration spares

VIP CLOSED SYSTEMS

3) Experimental tests of Quantum Collapse Models

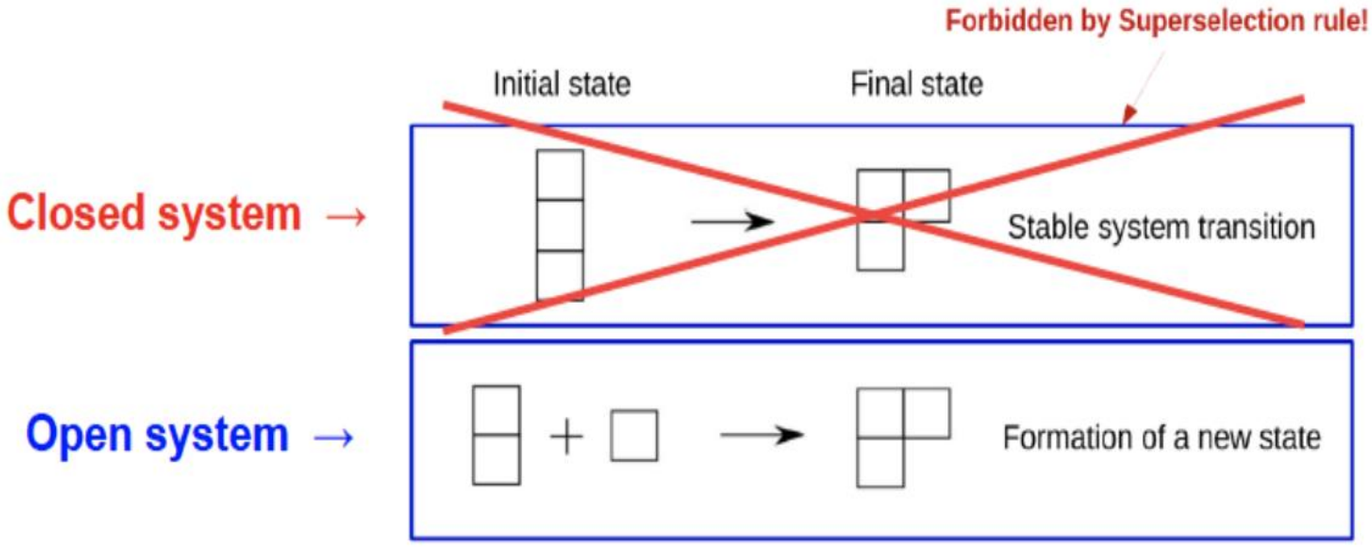
Ganttchart

Two classes of PEP violation models -> two classes of experiments

Local QFT - Greenberg & Mohapatra (Quon Model), Ignatiev, Kuzmin, Rahal, Campa … are subjected to Messiah-Greenberg superselection rule: transition probability between two symmetry states in a closed system is zero

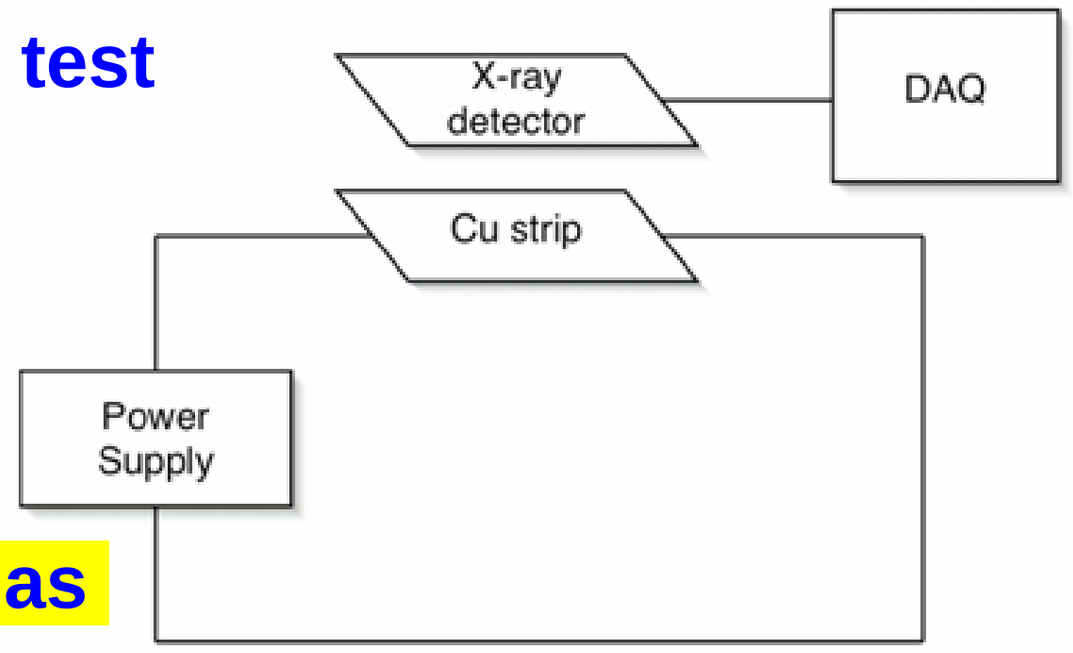
↓

introduce new fermions (current) in a pre-existing identical fermion system and search for PEP-violating atomic transitions:



VIP-2/3 Open Systems: cleanest method - UNIQUE - the only experiment capable to test these models for elementary particles (electrons) with high sensitivity!

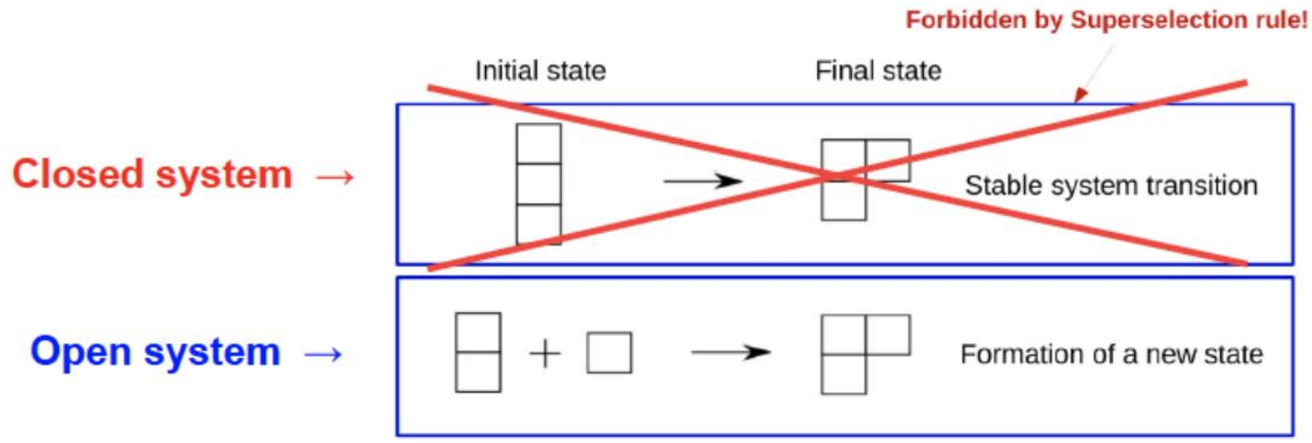
Our dedicated VIP-2 setup (OS).



NB: VIP Open Systems can be also used as Closed systems!

Two classes of PEP violation models -> two classes of experiments

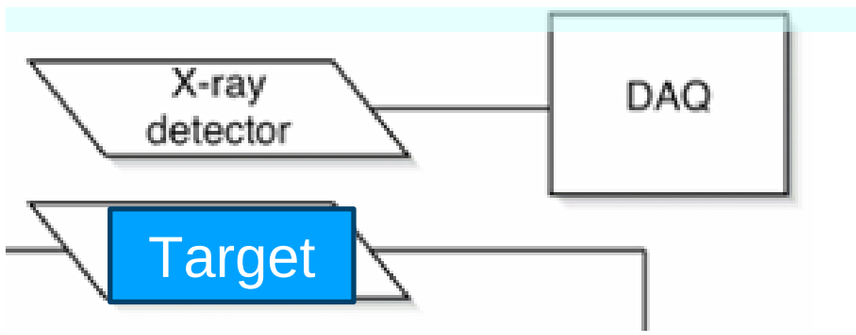
One can violate the Messiah-Greenberg superselection rule (classes of Quantum Gravity Models): Closed systems (CS)



↓

No new fermions (current) in a pre-existing identical fermion system and search for PEP-violating atomic transitions:

VIP-2 Closed Systems - High Purity Ge detectors, set of ultra-radiopure targets– based on collaboration with Low Radioactivity Lab (Laubenstein) for present.



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NB: VIP Closed Systems cannot be used as Open systems!

The VIP experiments - PEP

Theories of Violation of Statistics

O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

"Possible external motivations for violation of statistics include: (a) violation of CPT, (b) violation of locality, (c) violation of Lorentz invariance, (d) extra space dimensions, (e) discrete space and/or time and (f) noncommutative spacetime. Of these (a) seems unlikely because the quon theory which obeys CPT allows violations, (b) seems likely because if locality is satisfied we can prove the spin-statistics connection and there will be no violations, (c), (d), (e) and (f) seem possible……..

Hopefully either violation will be found experimentally or our theoretical efforts will lead to understanding of why only bose and fermi statistics occur in Nature."

Landscape of theories (50 articles)

OS

OS+CS

Quantum Gravity Non-Commutative

Generalized Uncertainty Principle (GUP)

Fundamental Symmetries (Lorentz, CPT)

Thermodynamics and cosmology

Experimentally:
limits on the probability PEP is violated (fundamental test of QM – spin-statistics theorem)

.....

Algebraic Quon-model, thermodynamics and cosmology

Quantum Gravity Non-Commutative

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 not constrained by MG

PEP violation is suppressed with $\delta^2(E, \Lambda)$
***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, P. Belli, R. Bernabei and A. Marciano, Chin. Phys. C 42 (2018) no.9

PHYSICAL REVIEW LETTERS **129,** 131301 (2022)

Strongest Atomic Physics Bounds on Noncommutative Quantum Gravity Models

Kristian Piscicchia,[2,3] Andrea Addazi,[1,3,*] Antonino Marcianò,[4,3,†] Massimiliano Bazzi,[3] Michael Cargnelli,[5,3] Alberto Clozza,[3] Luca De Paolis,[3] Raffaele Del Grande,[6,3] Carlo Guaraldo,[3] Mihail Antoniu Iliescu,[3] Matthias Laubenstein,[7] Johann Marton,[5,3] Marco Miliucci,[3] Fabrizio Napolitano,[3] Alessio Porcelli,[5,3] Alessandro Scordo,[3] Diana Laura Sirghi,[3,8] Florin Sirghi,[3,8] Oton Vazquez Doce,[3] Johann Zmeskal,[5,3] and Catalina Curceanu[3,8]

The analysis yields stringent bounds on the noncommutativity energy scale, which exclude θ-Poincaré up to 2.6×10^2 Planck scales when the "electriclike" components of the $\theta_{\mu\nu}$ tensor are different from zero, and up to 6.9×10^{-2} Planck scales if they vanish, thus providing the strongest (atomic-transitions) experimental test of the model.

PHYSICAL REVIEW D **107,** 026002 (2023)

Experimental test of noncommutative quantum gravity by VIP-2 Lead

Kristian Piscicchia,[2,3] Andrea Addazi,[1,3,*] Antonino Marcianò,[4,3,†] Massimiliano Bazzi,[3] Michael Cargnelli,[5,3] Alberto Clozza,[3] Luca De Paolis,[3] Raffaele Del Grande,[6,3] Carlo Guaraldo,[3] Mihail Antoniu Iliescu,[3] Matthias Laubenstein,[7] Johann Marton,[5,3] Marco Miliucci,[3] Fabrizio Napolitano,[3] Alessio Porcelli,[5,3] Alessandro Scordo,[3] Diana Laura Sirghi,[3,8] Florin Sirghi,[3,8] Oton Vazquez Doce,[3] Johann Zmeskal,[5,3] and Catalina Curceanu[3]

First Experimental Survey of a Whole Class of
Non-Commutative Quantum Gravity Models in the VIP-2 Lead
Underground Experiment, *Universe 2023, 9, 32*

$$\delta^2 = c_k \left(\frac{E}{\Lambda'_k}\right)^k = \left(\frac{E}{\Lambda_k}\right)^k,$$

The case k = 3, introduces a deformation of the space-time and momentum algebra that is appropriate for the "triply special relativity" model and involves a third invariant scale (other than the velocity of light and the Planck energy), associated to the cosmological constant by the authors.

As a consequence, the measurement is very sensitive to high orders in the
power series expansion of the Pauli violation probability, which allows to set the first constraint to the "triply special relativity" model proposed by Kowalski-Glikman and Smolin.
The characteristic energy scale of the model is bound to Λ > 5.6 · 10**−9 Planck scales

Future plans: test other QG models

What is VIP doing?

Searching for Pauli Exclusion Principle violation: selected papers

- ***Phys.Rev.Lett.* 129 (2022) 13, 131301**
- **Phys. Rev. D 107, 026002 (2023)**
- ***Symmetry 2023, 15(2), 480***
- **Eur. Phys. J. C (2024) 84: 214**

  Strongest bound on quon-theor

  Strongest bounds on Non-Commutative Quantum Gravity

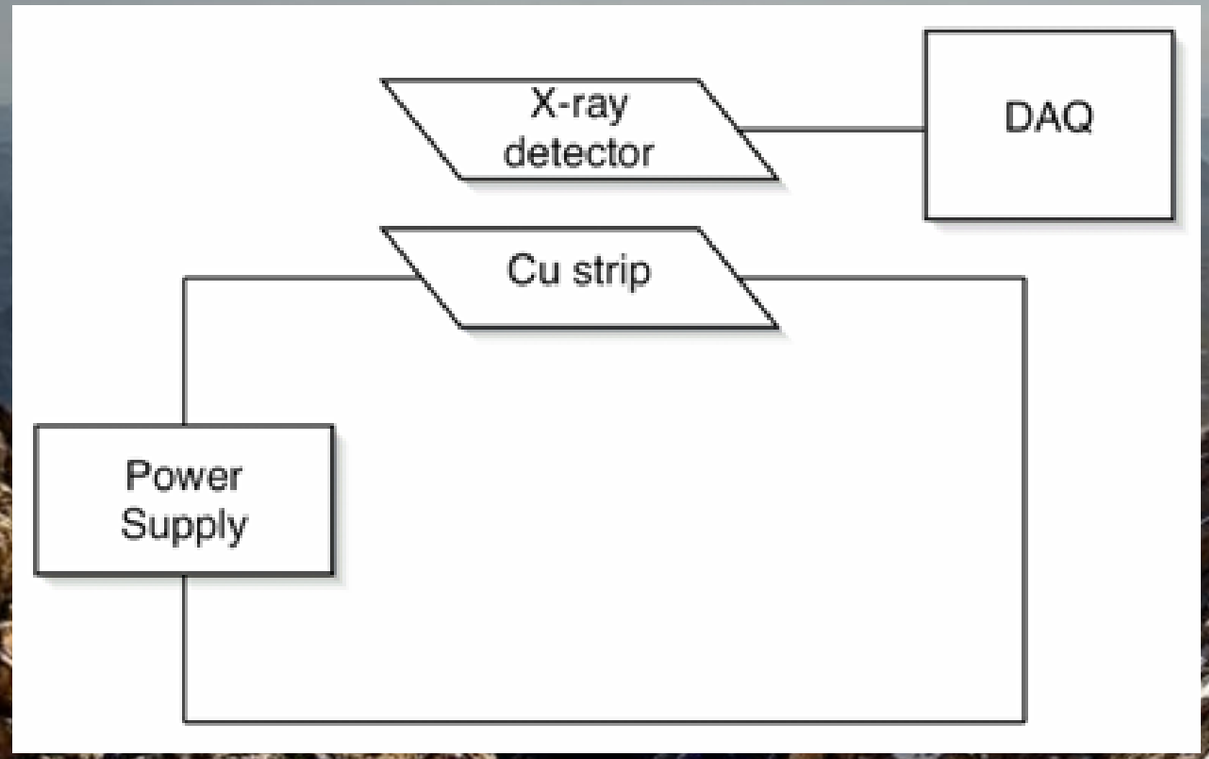
Tests of Quantum Collapse Models: selected papers

- **Nature Physics 17, 74-78 (2021)**
- **Eur.Phys.J.C 81 (2021) 8, 773**
- ***Entropy* 2023, *25*(2), 295**
- **Physics of Life Reviews, Volume 42, 2022, Pages 8-14**
- **X-ray emission from atomic systems… accepted in *Phys.Rev.Lett.***

  Diosi-Penrose model excluded if Markovian

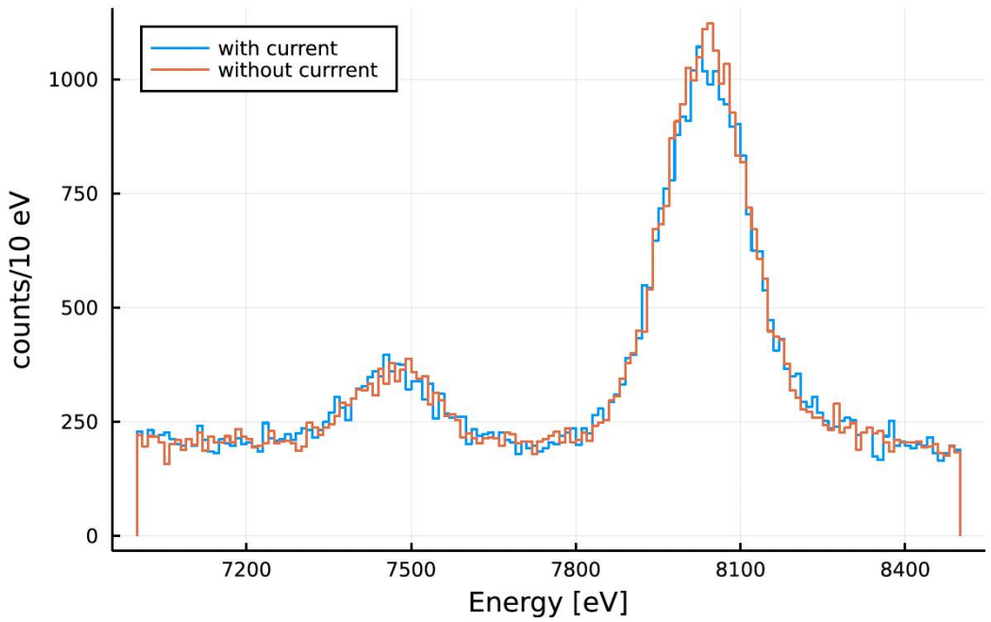
  Strongest bound on correlation length of CSL model

VIP-2 Open systems activities and plans (this is our main experimental involvement)



VIP-2 Open Systems - update on data analyses

Total acquired statistics before VIP-2 shack renovation analyzed (paper under submission):

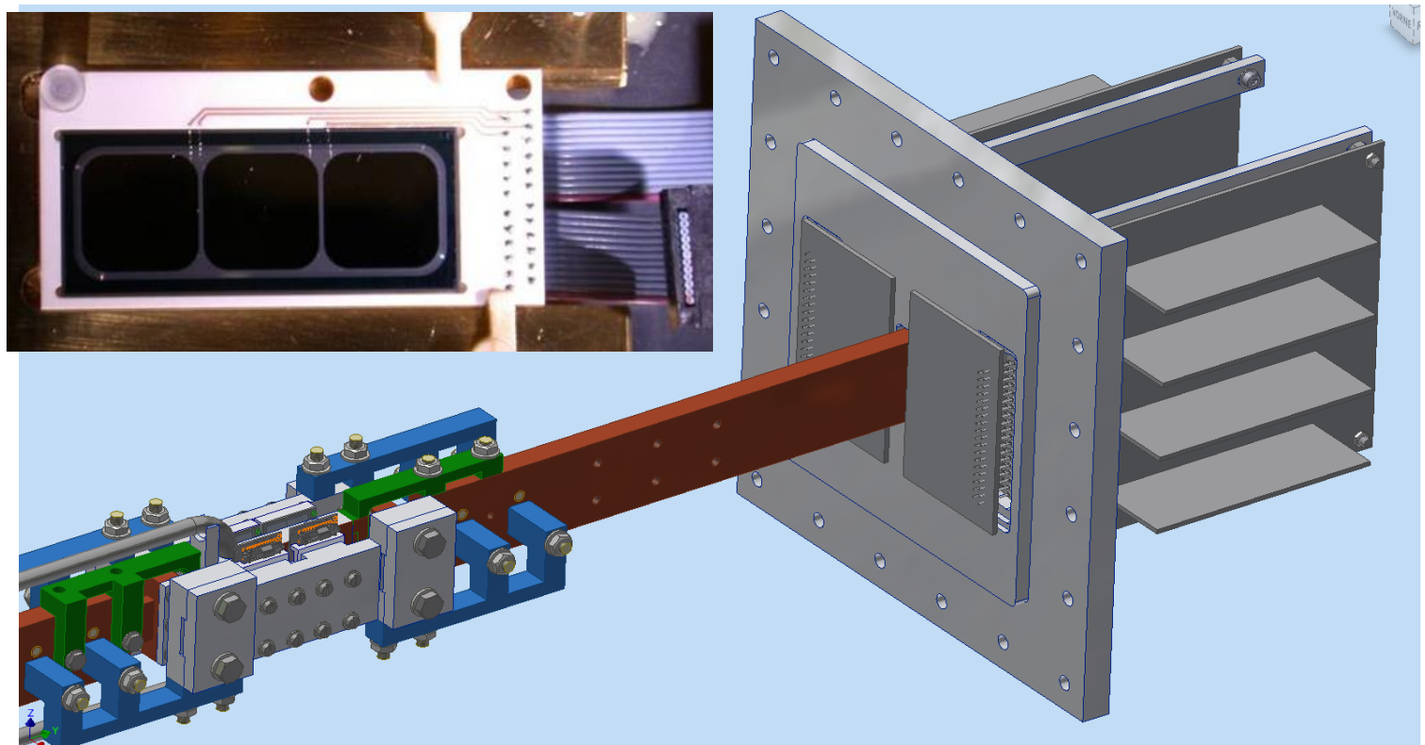


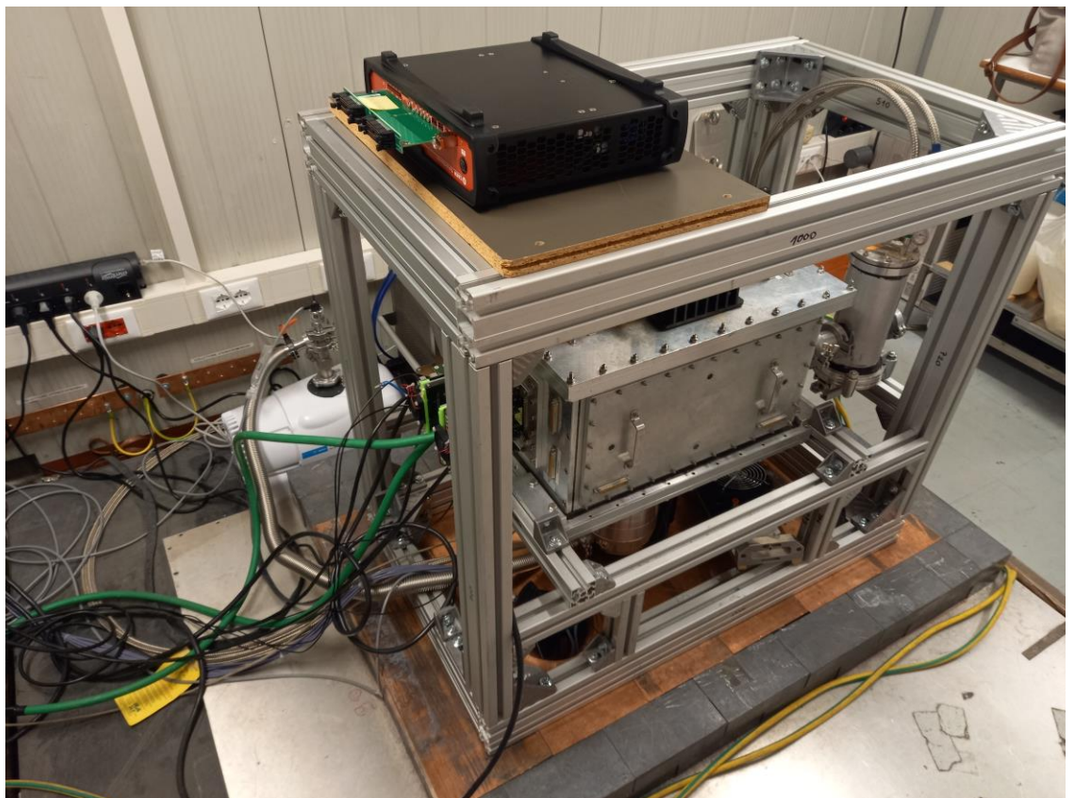
VIP-2 calibrated data in the region-of-interest 7000-8500 eV, of about two years of data taking (May 2019 to May 2021). The spectrum of the data acquired with a current circulating in the target is shown in blue. Data taken without current in the target, used as reference and control, shown in red. The copper and nickel K_α lines are visible in the spectra.

Bayesian analysis validated by means of frequentist CLs exclusion method, exploiting Neyman construction for a robust evaluation of the CLs.

Strongest limits in the PEP violation probability respecting MG:

$$\beta^2/2 < 2.4 \cdot 10^{-43}$$





Refined current modulation run analysis

Modulated current test run (68 days in 2021) the wc-woc alternation is automatized with a fixed period of 100 s: 50 s of wc phase, 50 s of woc.

A simultaneous spectral and Discrete Fourier Transform Bayesian analysis is performed: improvement by about 30% in limits to PEP violation probability

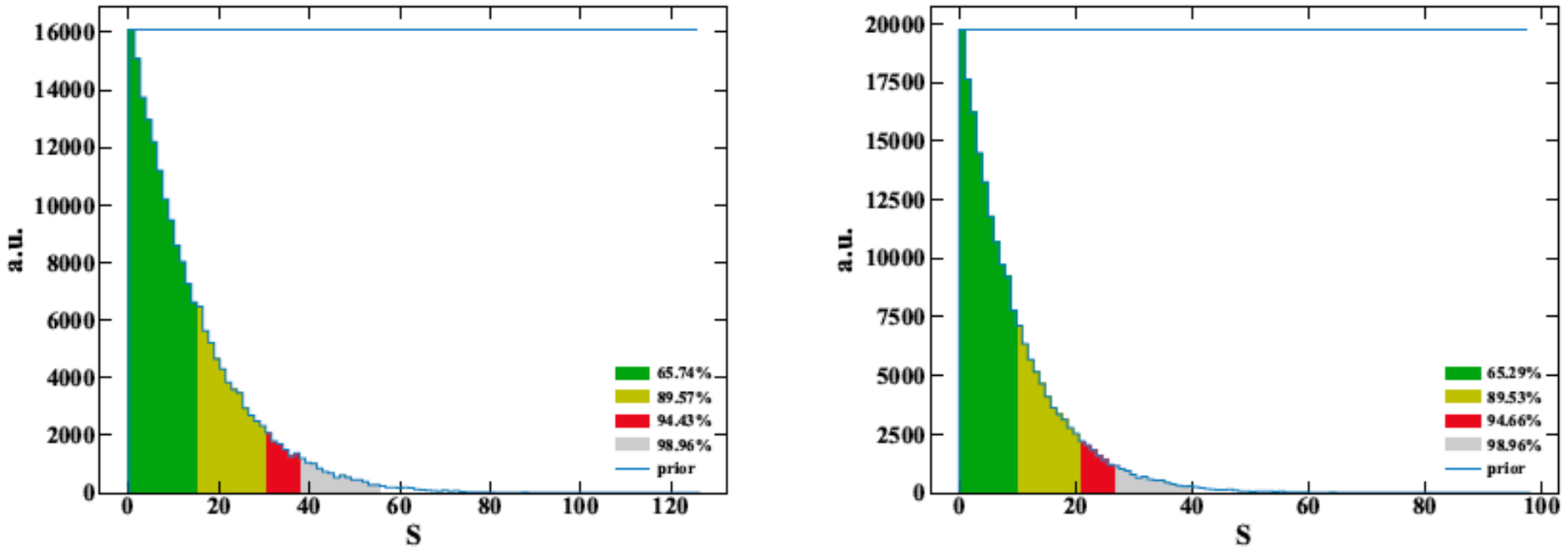


Fig. 6 Marginalized posterior distribution of S using only the spectral analysis as per Section 3 (left) and spectral+modulated combined as per Section 5 (right). Colored regions represent the distribution areas; the blue lines represent the prior representation.

$$\left|\frac{\beta^2}{2}\right|_{\text{comb}} < 6.74 \cdot 10^{-43} \quad \text{(close encounters)}$$

Paper published:
Eur. Phys. J. C (2024) 84: 214

Paper published
Meas. Sci. Technol. 35 (2024) 025501

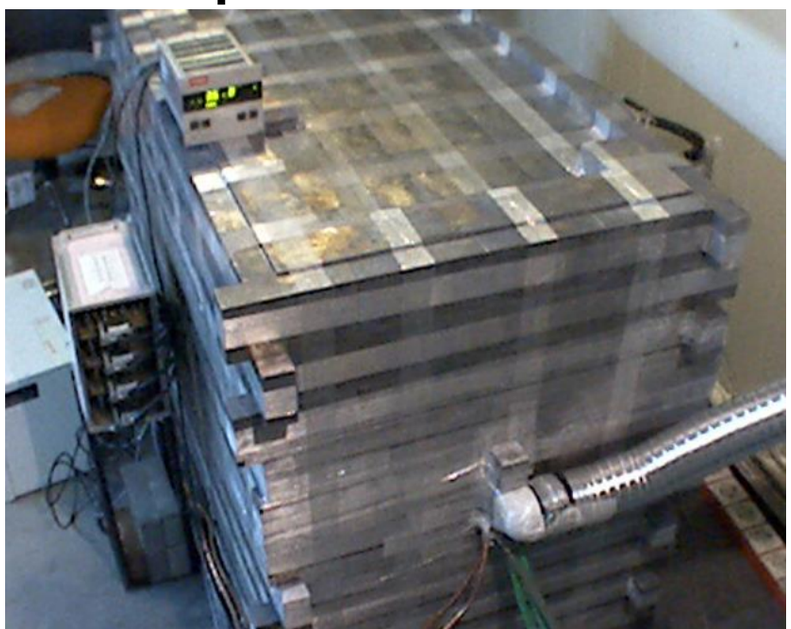
Novel Machine Learning and Differentiable Programming Techniques applied to the VIP-2 Underground Experiment

Abstract. In this work, we present novel Machine Learning and Differentiable Programming enhanced calibration techniques used to improve the energy resolution of the Silicon Drift Detectors (SDDs) of the VIP-2 underground experiment at the Gran Sasso National Laboratory (LNGS). We achieve for the first time a Full Width at Half Maximum (FWHM) in VIP-2 below 180 eV at 8 keV, improving around 10 eV on the previous state-of-the-art. SDDs energy resolution is a key parameter in the VIP-2 experiment, which is dedicated to searches for physics beyond the standard quantum theory, targeting Pauli Exclusion Principle (PEP) violating atomic transitions. Additionally, we show that this method can correct for potential miscalibrations, requiring less fine-tuning with respect to standard methods.

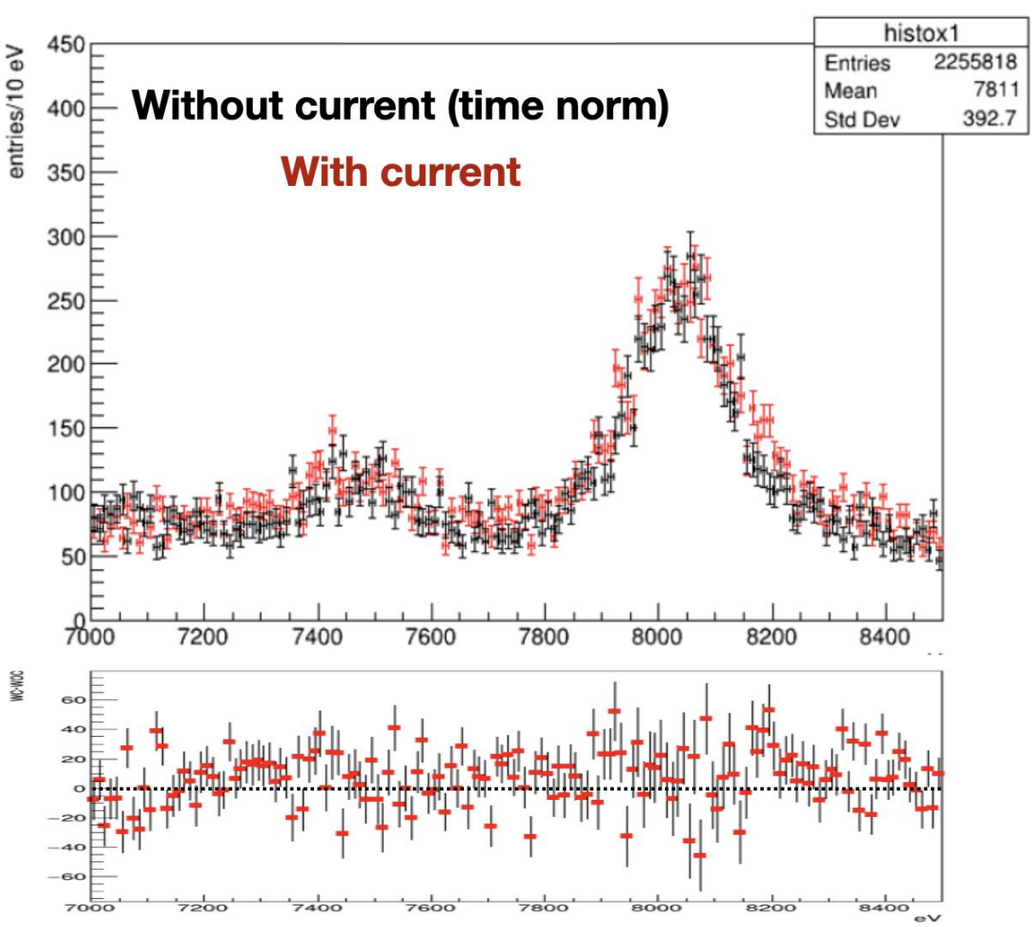
VIP-2 Open systems ongoing data taking and plan

- **In September 2023, after completion of a complex renovation of the setup (target cooling system and feedthrough system replacements, vacuum chamber maintenance and substitution of some damaged SDDs):**
- **the data taking was resumed (currently ongoing), alternating periods with DC current on (signal) and off (background) circulating in the target;**
- **based on our recent findings we are presently taking data in current modulated regime.**
- **The VIP-2 data taking will go on till end 2024 (early 2025), compatible with the VIP-3 setup preparation.**
- **Aiming probability down to 10^{-44}**

Meanwhile investigate theoretical impact – at least one paper: QG θ0i=0 towards Planck scale; GUP – under study; Record quon-models

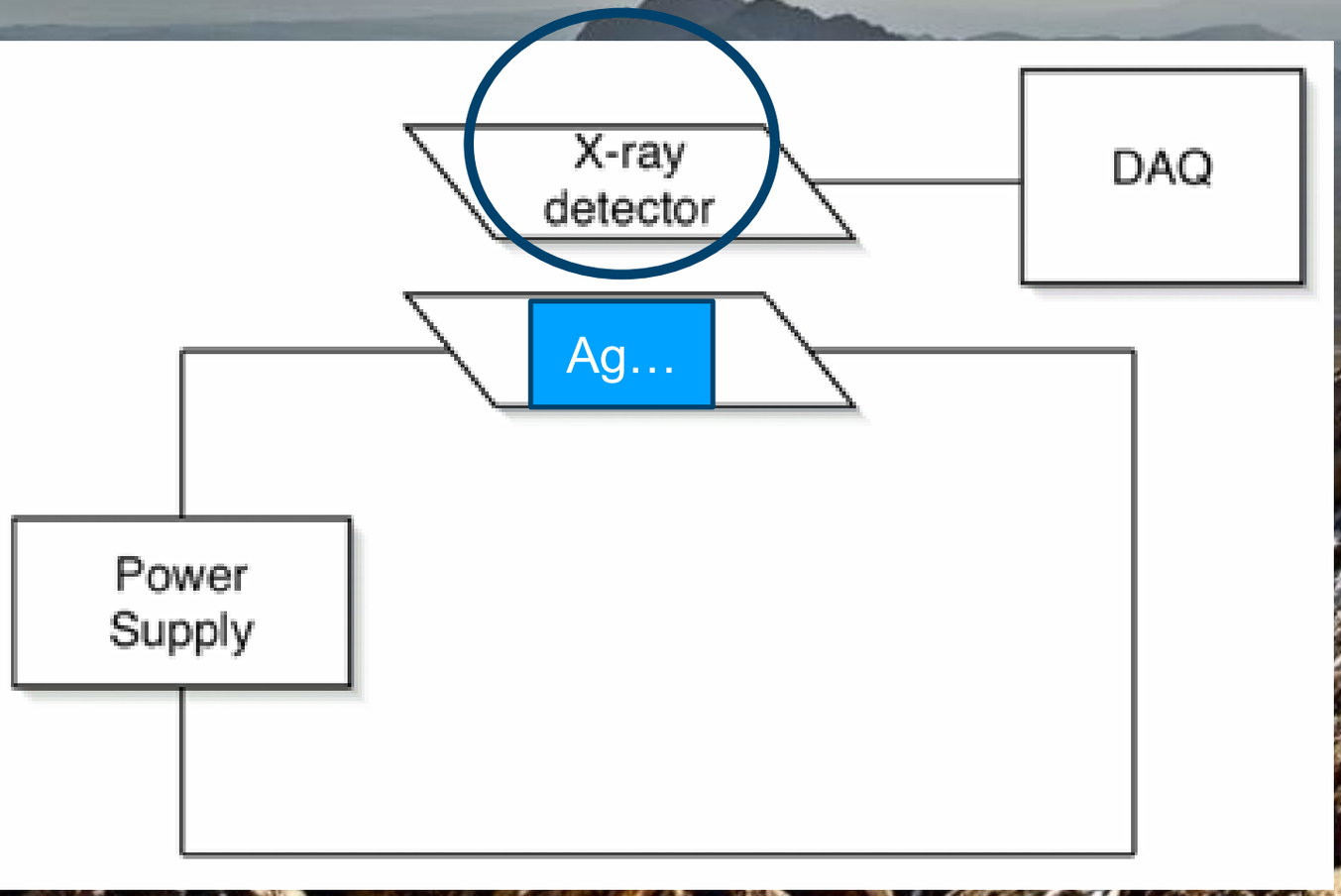


Preliminary calibrated and normalized spectra from the 2023/2024 data taking runs:



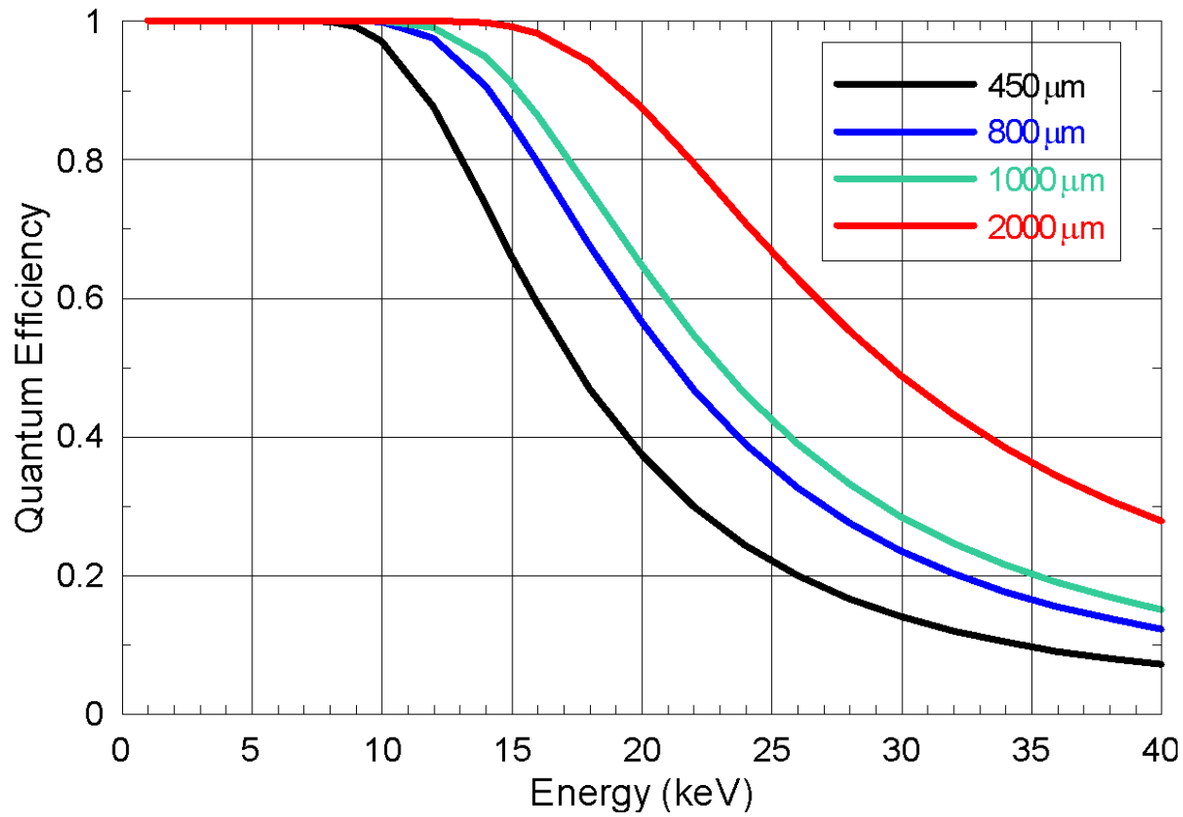
Plans for future VIP-3/4 experiment

Scan of the PEP violation probability for intermediate atomic numbers Z ~ 60



VIP-3 activity: new SDD detectors (1 mm)

Scan the PEP violation probability as a function of Z (i.e. of Energy)
Limits on PEP violation similar to Cu (VIP-2) on other elements



Okun, L.:

“The special place enjoyed by the Pauli principle in modern theoretical physics does not mean that this principle does not require further and exhaustive experimental tests. On the contrary, it is specifically the fundamental nature of the Pauli principle which would make such tests, over the entire periodic table, of special interest” JETP Lett. 1987, 46, 529532

Quantum Gravity Models:

& dependence on Z vastly discussed in our recent papers e.g. *Universe* 2023, *9*(7), 321

VIP-3 activity: the SDD 1 mm detector

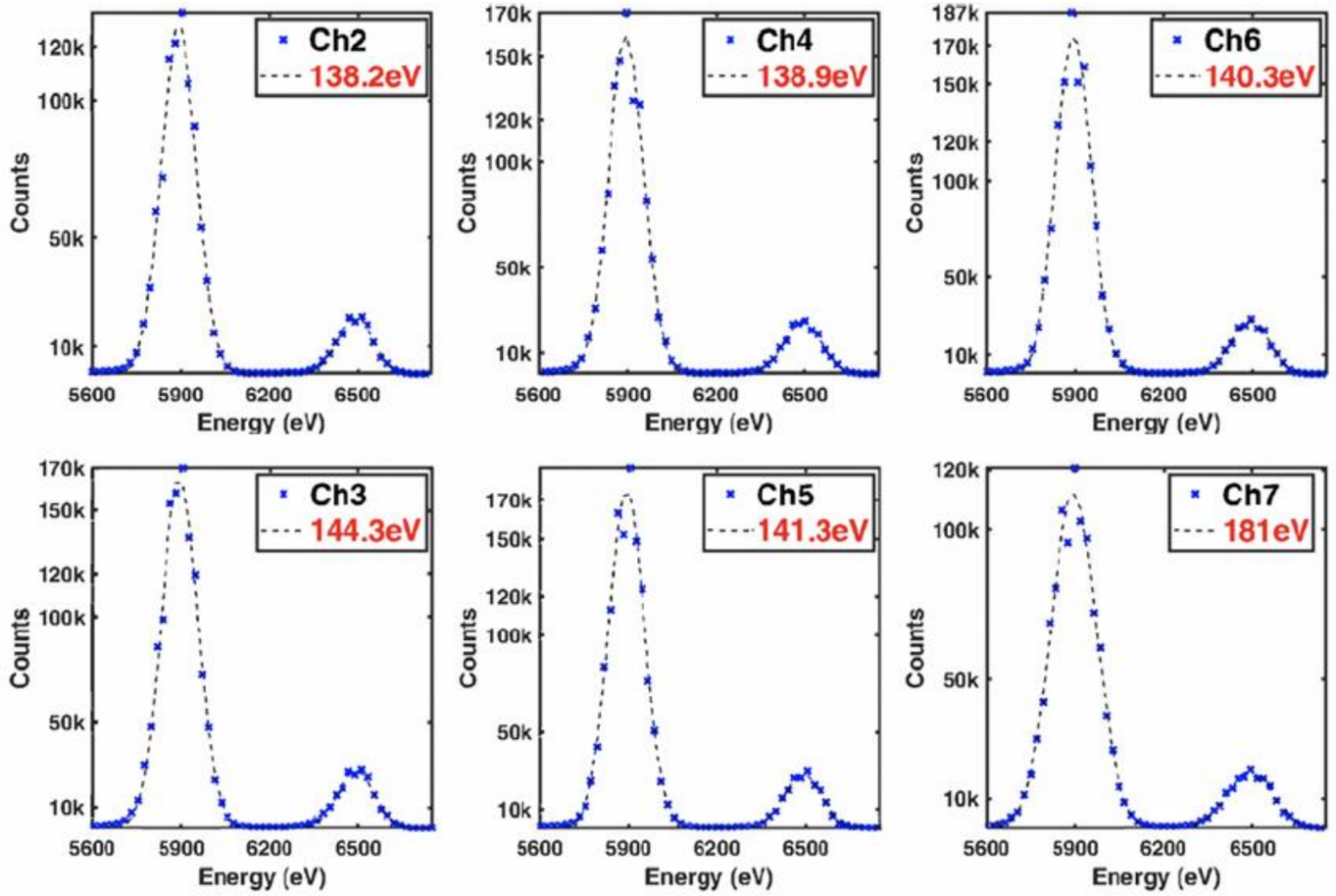
- **prototypes of the 1 mm thick SDDs bonded and successfully characterized :**

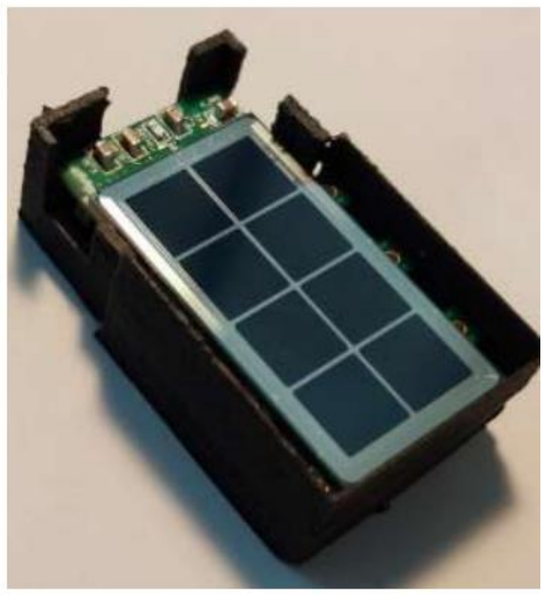
- **Optimization of the operational parameters of the new SDD, including the voltage of the focusing electrode;**

- **Good spectroscopic performance of the new 1-mm-thick SDDs.**

Spectroscopic measurements with a first prototype with partially working channels:

- irradiation with an ^{55}**Fe** X-ray source;
- detector temperature: -30° C;
- spectra acquired with **SFERA APP**, shaping time 6 μs;
- best **energy resolution** @5.9keV (Mn-Kα peak): **138.2 eV**, (channel 2).



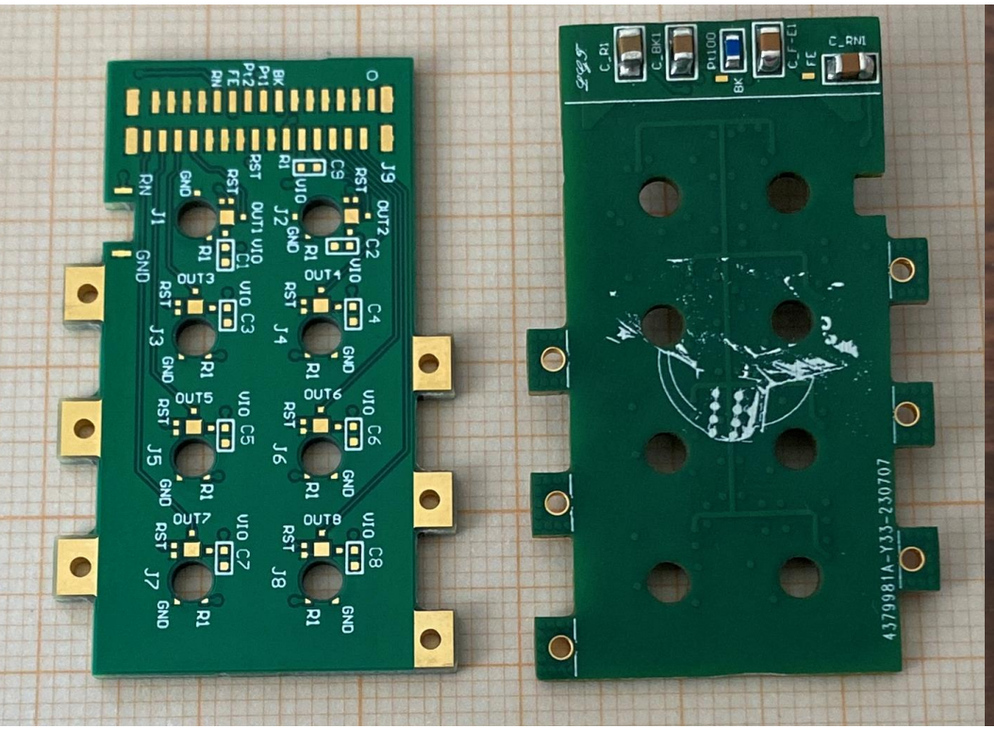


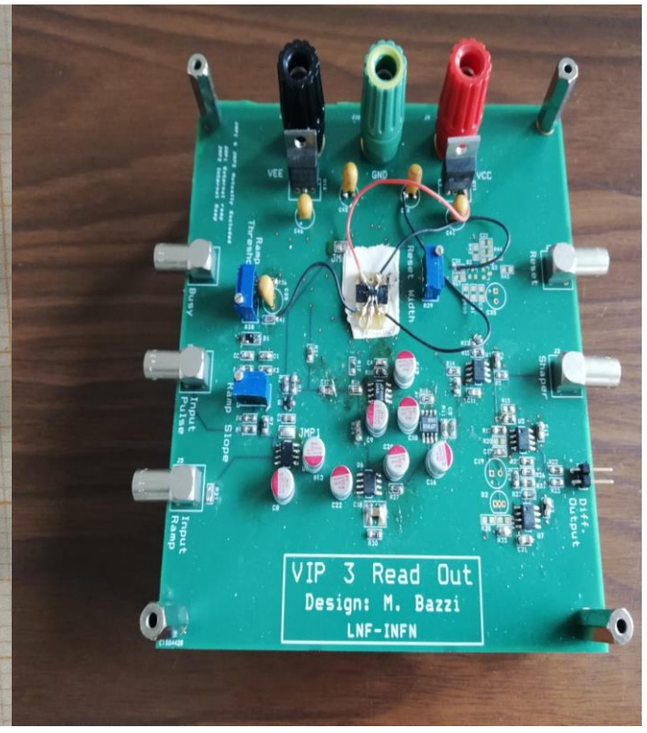
VIP-3 activity: main elements in brief

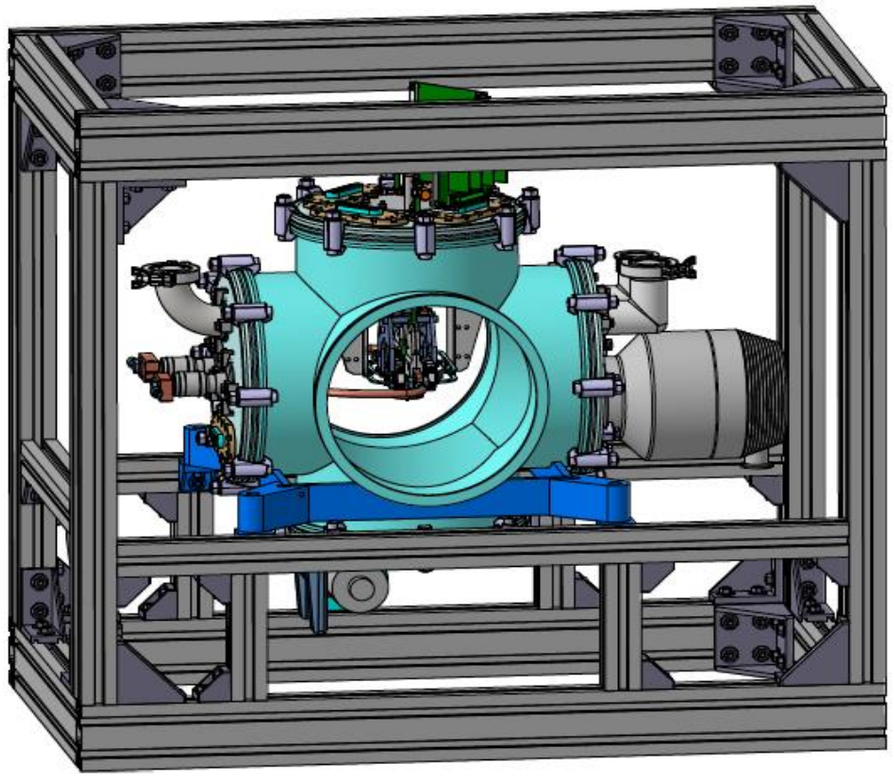
Design of the PCB support prototype finalized, prototype realized for testing

Finalization of the new SDDs readout electronics

Realization of the new vacuum chamber and target – under finalization







NEXT STEPS:

- **thermal cycles in the cryostat with the new modules to verify their mechanical robustness**
- **PCB production (setting final geometry)**
- **PCB bonding**
- **Readout finalized**
- **Setup assembly and test**

Plans VIP-3/4

VIP-3 - exploit enhanced quantum efficiency of the 1mm thick SDDs to perform a scan of $\beta^2/2$ with comparable sensitivity to VIP-2 for silver, tin, zirconium 2025 - 2028/9

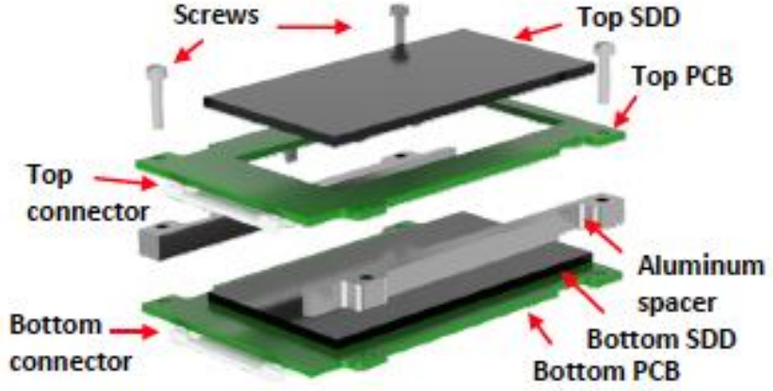
After VIP-3:

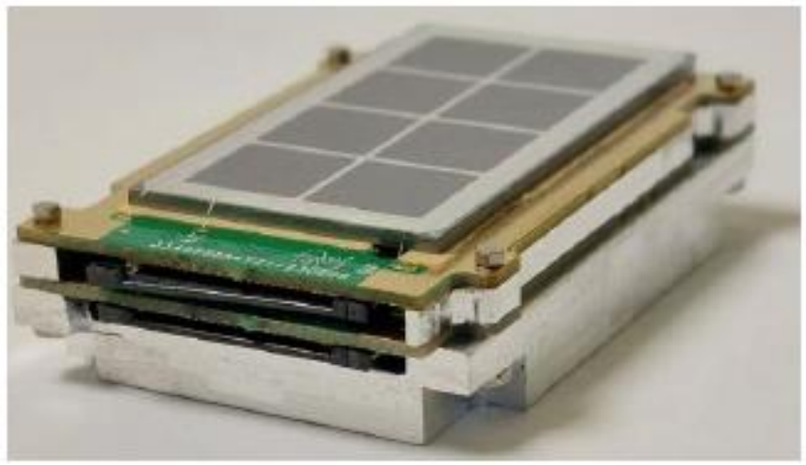
VIP-4 - further increase of quantum efficiency, layered structures of 1mm thick SDDs to perform a scan of $\beta^2/2$ with comparable sensitivity to VIP-2/3 tfor Z > 60:

- **R&D ongoing,**
- **installation 2028/9**
- **data taking 2029 - 2033**

Stacked-detector assembly:

- two identical PCB carriers, at a distance of 2mm;
- Aluminum spacers on the sides for mechanical support and thermal conduction;
- Four screws to hold the system together and provide additional thermal conductivity.





A first stacked detection module has been assembled and tested:

- readout performed with the SFERA ASIC, a 16-channel analog pulse processor designed for both X and γ-ray detectors;

VIP-2 Closed systems

Based on the collaboration with Low Radioactivity lab (M. Laubenstein); use Ge - detectors

First analysis of PEPV in GUP (New!)

Generally related to the existence of a minimal length - as predicted by several QG models - E.g. GUP structure emerges from string theory in the high energy limit.

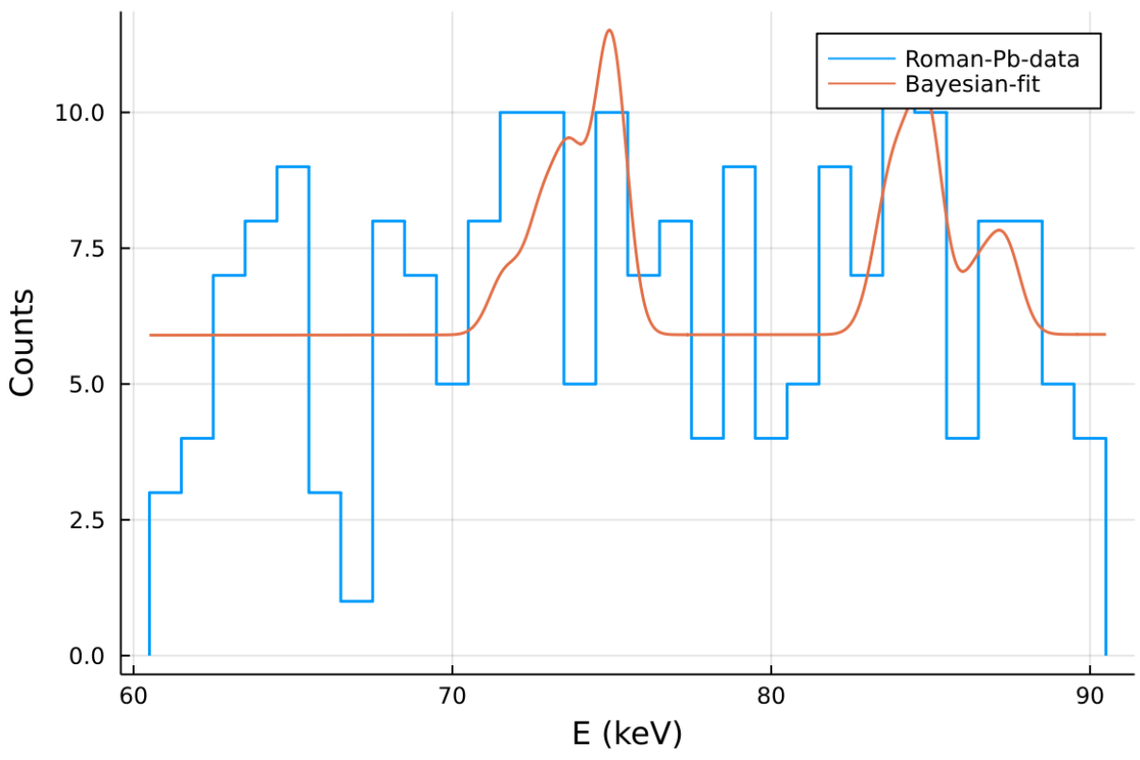
The construction of field theories in this context may involve deformations of the statistics:

Theory already developed in collaboration with Illuminati, Bosso and Luciano

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

Violation of the PEP depends on the energy and on Λ_{GUP} as

$$\delta^2(E,\beta) = \frac{m\,\Delta E}{\Lambda_{GUP}^2}$$



We are analyzing the data collected (collaboration M. Laubenstein) with the HPGe detector and an ultra-radio pure Ta target (as test measurement), to set first limits on ΛGUP from Spin-Statistics deformation, towards a publication

Preliminary result!

$\Lambda_{GUP} > 0.52$ Planck scales

Continue collaboration with Low Radioactivity Lab and use as much as possible data coming from different materials eventually with dedicated runs

while considering the development of a dedicated setup in the coming years

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VIP CLOSED SYSTEMS

3) (On the)Experimental tests of Quantum Collapse Models

Ganttchart

Experimental test of the Dynamical Collapse Models (>20 articles)

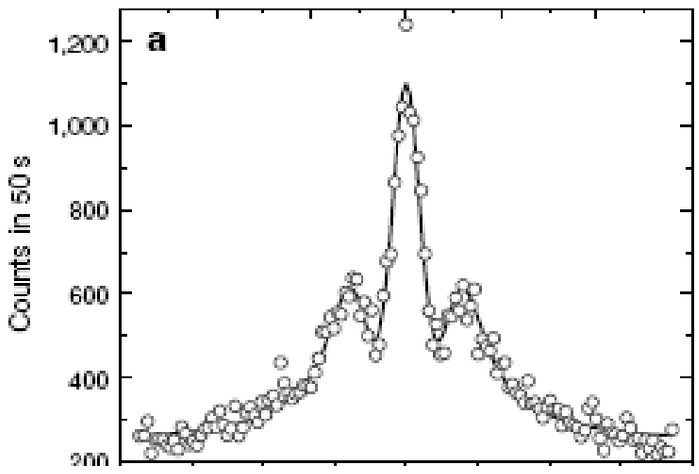
What are collapse models

1. Collapse models = solution of the measurement problem

   Paradox-free description of the quantum world

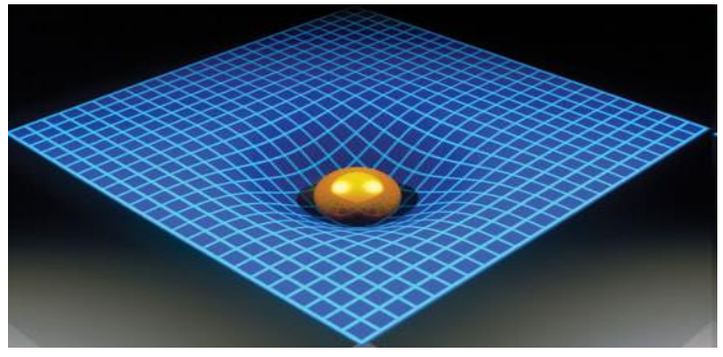
2. Collapse models = rival theory of Quantum Mechanics

   They are related to experiments testing quantum linearity



3. Collapse models as phenomenological models of an underlying pre-quantum theory

   Can gravity causes the collapse?



Dynamical Reduction Models:

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar}Hdt + \sqrt{\lambda}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)dW_t(\mathbf{x}) - \frac{\lambda}{2}\int d^3x(N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)^2 dt\right]|\psi_t\rangle$$

System's Hamiltonian — NEW COLLAPSE TERMS → New Physics

- **CSL – non-linear and stochastic modification of the Schrödinger equation …**

λ - collapse strength

measures the strength of the collapse

strongly debated, see e. g. S. L. Adler, JPA 40, (2007) 2935
Adler, S.L.; Bassi, A.; Donadi, S., JPA 46, (2013) 245304.

$r_c \sim 10^{-7}$ m – correlation length

- **Diosi – Penrose – gravity related collapse model …**

system is in a quantum superposition of two different positions →
superposition of two different space-times is generated →
the more massive the superposition, the faster it is suppressed.

The model characteristic parameter R_0

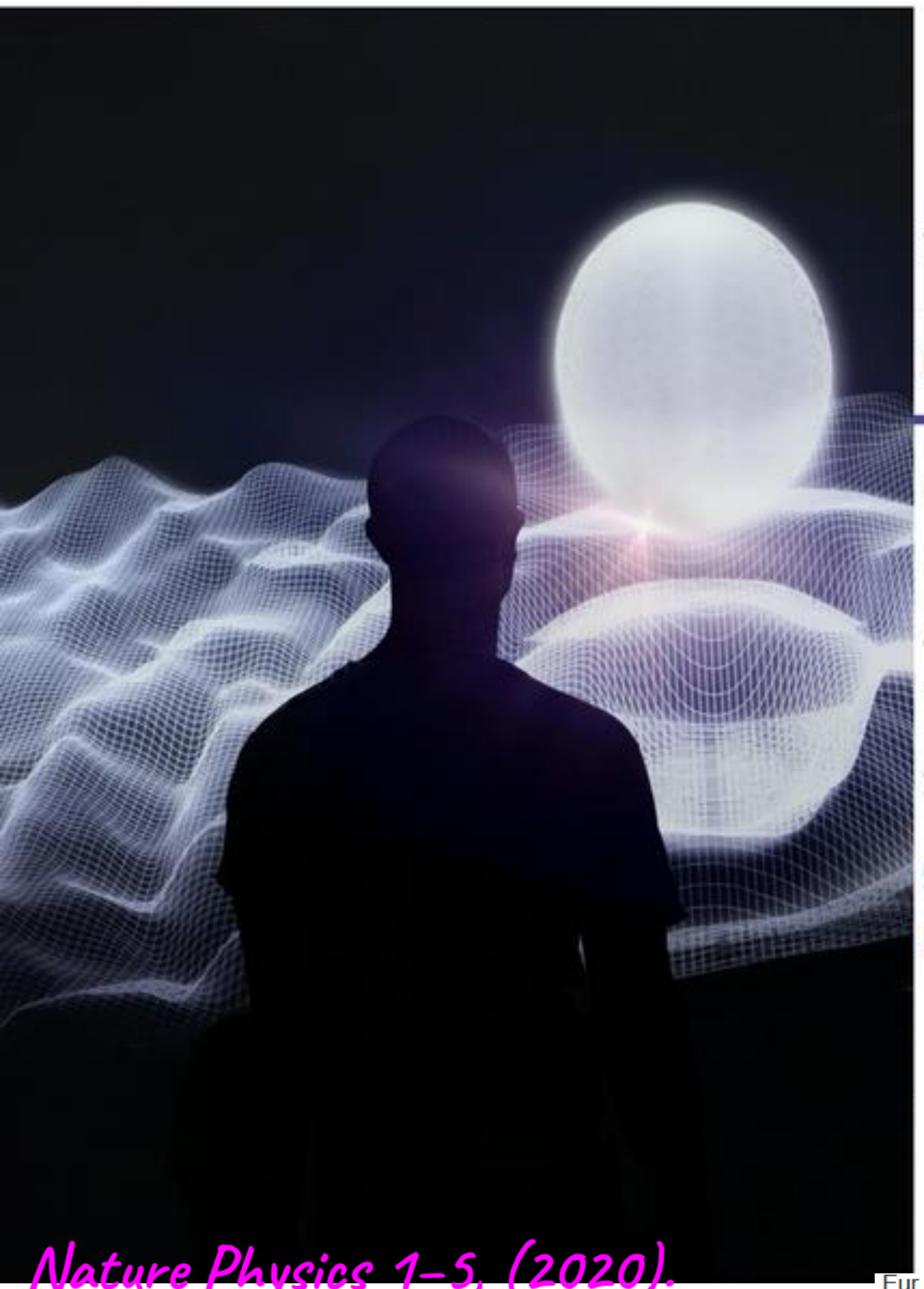
What is VIP doing?

Searching for Pauli Exclusion Principle violation: selected papers

- ***Phys.Rev.Lett.* 129 (2022) 13, 131301**
- **Phys. Rev. D 107, 026002 (2023)**
- ***Symmetry 2023, 15(2), 480***
- **Eur. Phys. J. C (2024) 84: 214**
  Strongest bound on quon-theor
  Strongest bounds on Non-Commutative Quantum Gravity

Tests of Quantum Collapse Models: selected papers

- **Nature Physics 17, 74-78 (2021)**
- **Eur.Phys.J.C 81 (2021) 8, 773**
- ***Entropy* 2023, *25*(2), 295**
- **Physics of Life Reviews, Volume 42, 2022, Pages 8-14**
- **X-ray emission from atomic systems… accepted in *Phys.Rev.Lett.***
  Diosi-Penrose model excluded if Markovian
  Strongest bound on correlation length of CSL model



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Article | Published: 07 September 2020

Underground test of gravity-related wave function collapse

Sandro Donadi ✉, Kristian Piscicchia ✉, Catalina Curceanu, Lajos Diósi, Matthias Laubenstein & Angelo Bassi ✉

Nature Physics **17**, 74–78(2021) | Cite this article

Nature Physics 1–5, (2020).

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Eur. Phys. J. C (2021) **81**: 773
https://doi.org/10.1140/epjc/s10052-021-09556-0
Regular Article - Theoretical Physics

Novel CSL bounds from the noise-induced radiation emission from atoms

Sandro Donadi[1], Kristian Piscicchia[2,3], Raffaele Del Grande[4], Catalina Curceanu[3d], Matthias Laubenstein[5] an Angelo Bassi[1,6]

Phys.Rev.Lett. 129 (2022) 8, 080401, Phys.Rev.Lett. 130 (2023) 23, 239902 (erratum)
A Search for Spontaneous Radiation from Wavefunction Collapse in the Majorana Demonstrator (< 100 keV)
Cancellation effects?

A Novel Approach to Parameter Determination of the Continuous Spontaneous Localization Collapse Model
Entropy 25 (2023) 2, 295

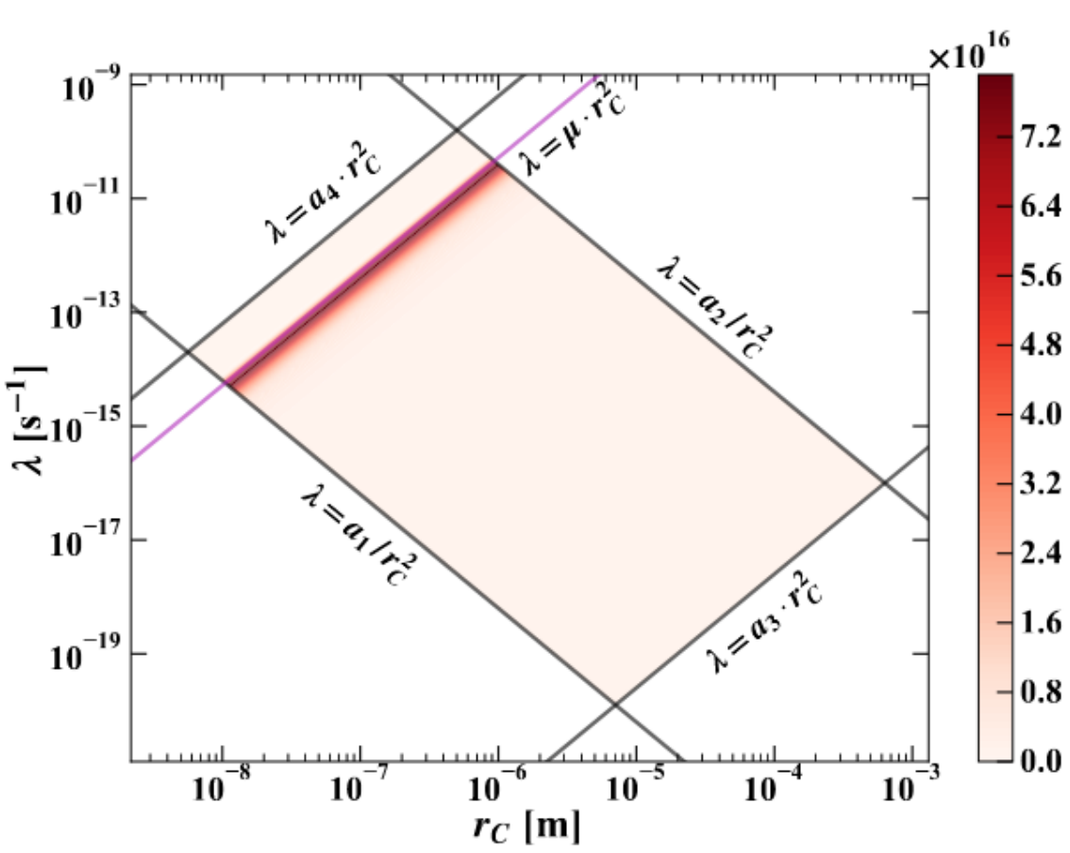

Figure 2. The joint *pdf* $\tilde{p}(\lambda, r_C)$ is shown in the figure.

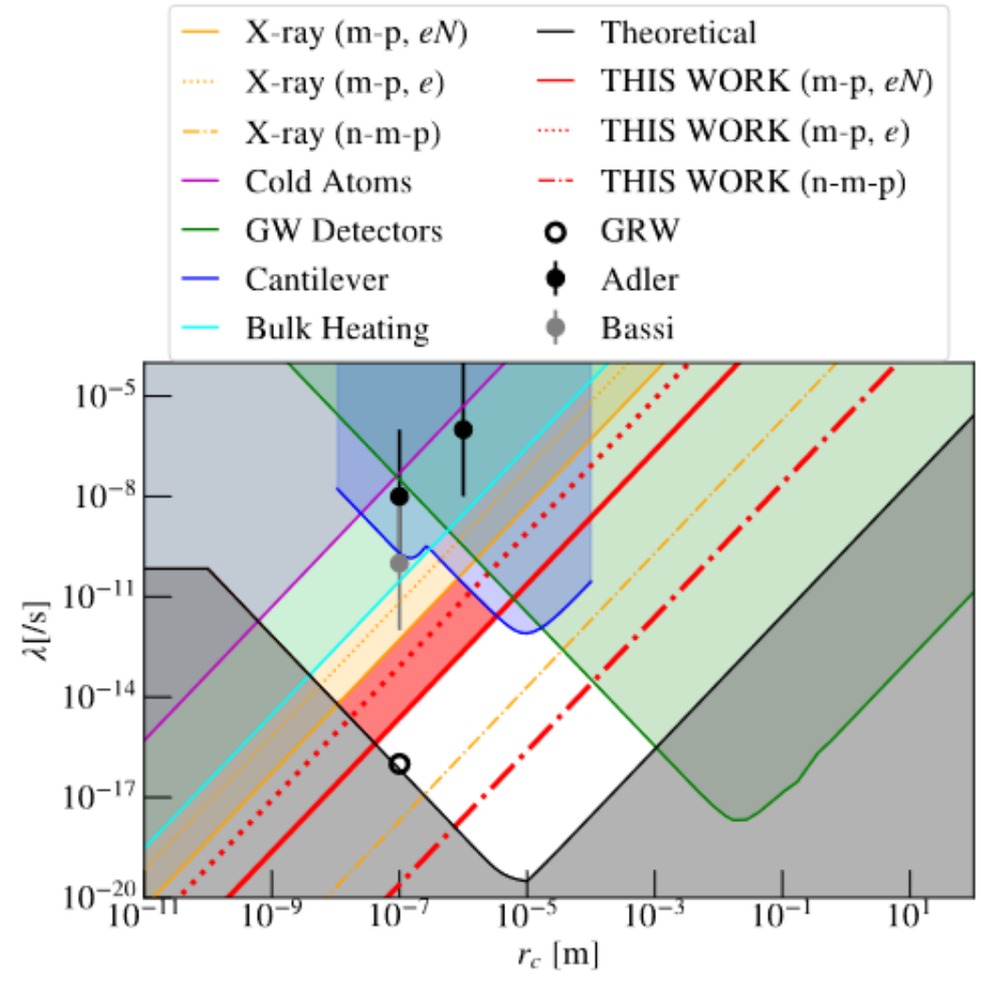

FIG. 2. Upper limits on the wavefunction collapse parameters compared to existing upper limits from other experiments.

Collapse Models: novelty

- Spontaneous emission rate for both white and generalized (non-Markovian) versions of the CSL and DP models ACCEPTED in *Phys.Rev.Lett*:

1. effect of the correlated electrons/protons emission in the X-rays range.

2. First prediction of a model-dependent emission in the range (1-100) keV – all other groups who did research in this field (Majorana) did not include this effect

PHYSICAL REVIEW LETTERS

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Accepted Paper

x-ray emission from atomic systems can distinguish between prevailing dynamical wave-function collapse models

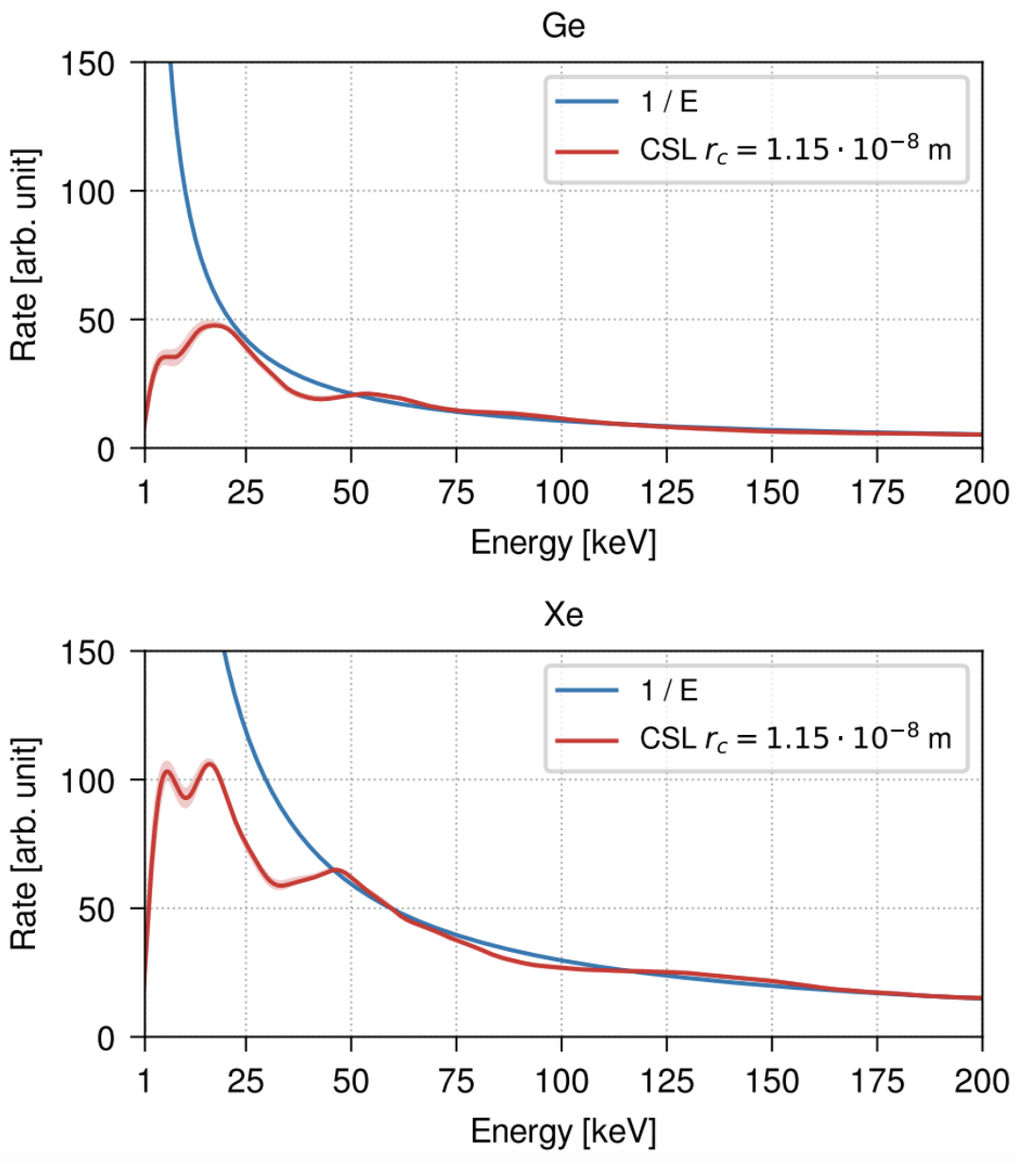
Phys. Rev. Lett.

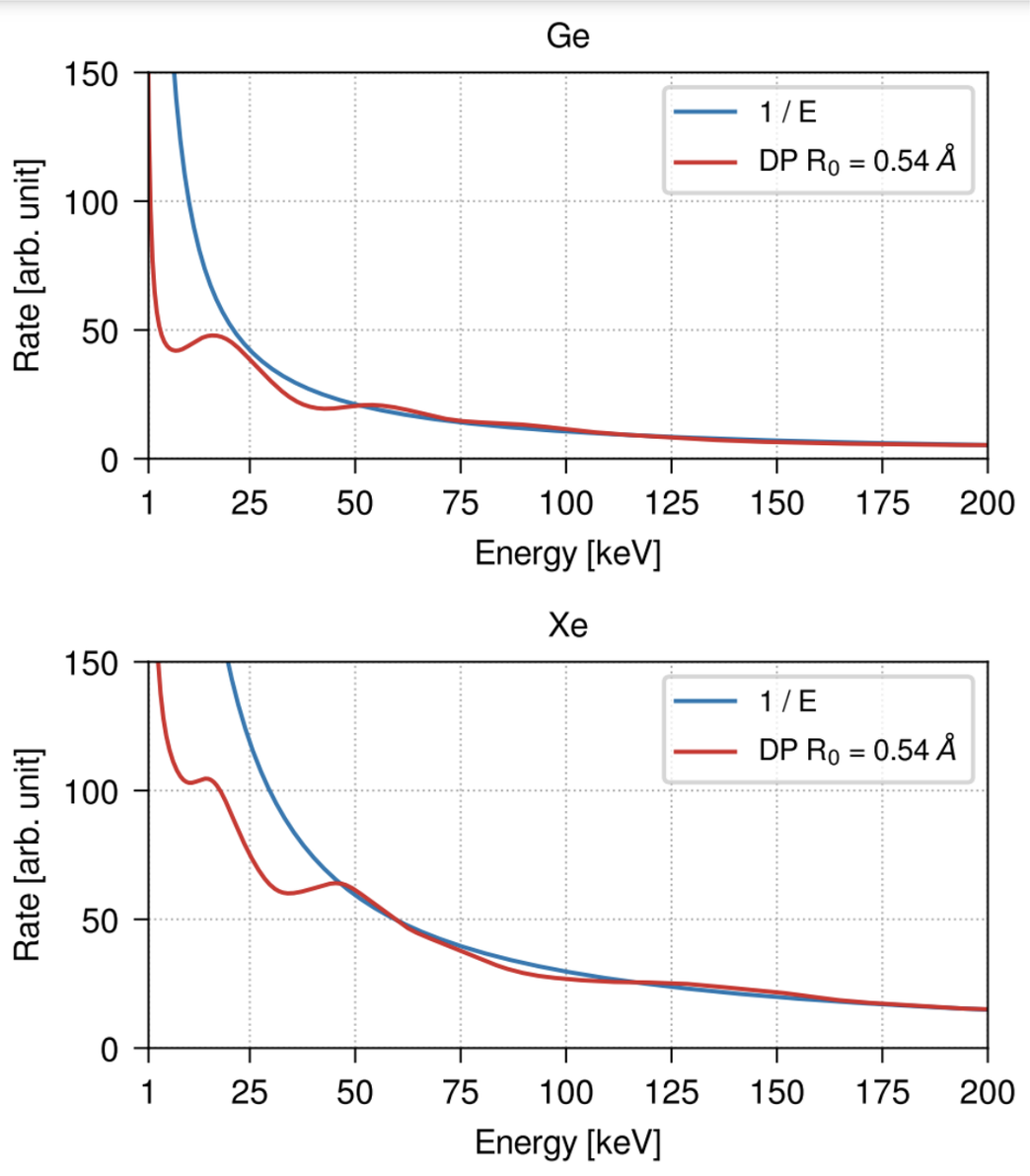
Kristian Piscicchia, Sandro Donadi, Simone Manti, Angelo Bassi, Maaneli Derakhshani, Lajos Diósi, and Catalina Curceanu

Accepted 17 April 2024

X-rays spontaneous radiation, atomic structure matters!

Change of paradigm





- at each energy the atomic structure influences the expected S.E. spectrum shape
- accurate shape analyses should allow to set much stronger bounds
- the S.E. spectrum shape is different for different collapse models.

The future of collapse models

- **a reanalysis of the data presented in [Phys. Rev. Lett. 129, 080401 (2022)], where the strongest bounds on the models were obtained, in the range (19-100) keV, is mandatory, in the view of our recent findings (points 1. & 2.)**

- **development of a dedicated experimental setup capable of investigating the predicted, new features of the spontaneous emission rate. GOAL - identify for the first time the process which induces the w.f. collapse.**

TIMELINE:

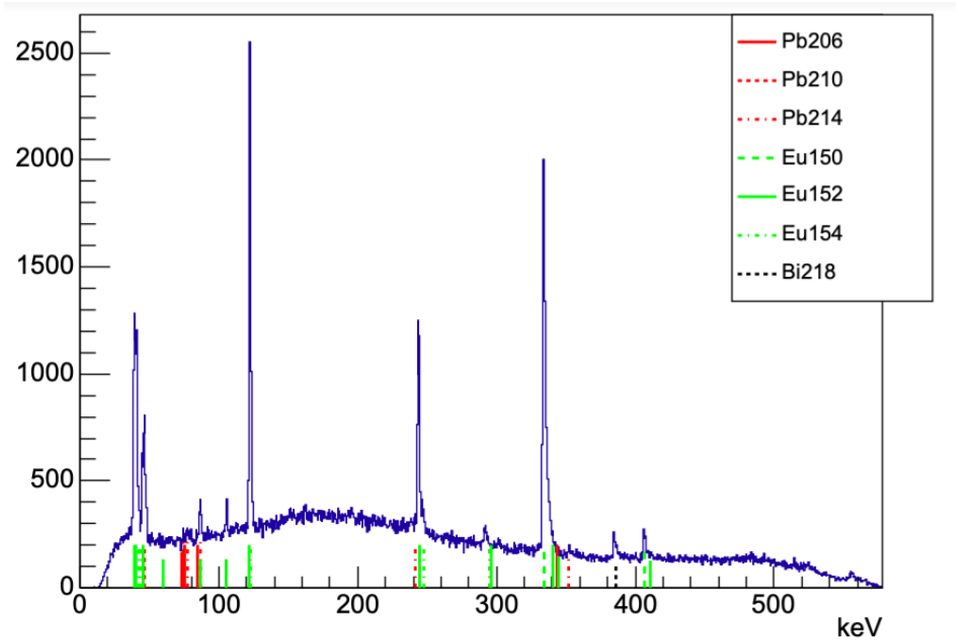
- **2025-2026, based on the results obtained with a prototype BEGe test setup a plan for preparing a setup based on BEGe detectors will be put forward.**

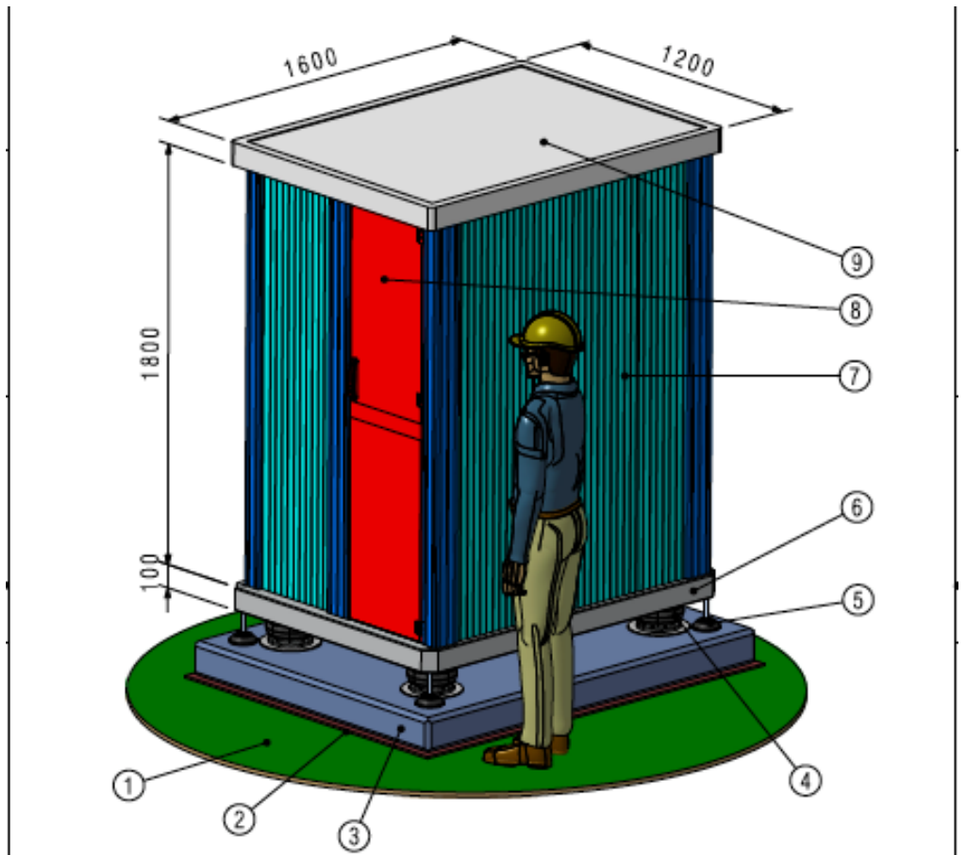
MAIN FEATURE:

- **to exploit spectral shape dependence on the atomic number, one needs to carry out a data taking campaign with different targets. -> Potentiality to strongly constrain the dissipative and non-Markovian DP and CLS collapse models & the mechanism responsible for the collapse**

BEGe detector activity

- **The data taking and the analysis of the collected data are ongoing:**





9	COPERTURA CON PANNELLI INSONORIZZATI	01
8	PORTA DI ACCESSO INSONORIZZATA	01
7	PARETI INSONORIZZATE (PANNELLI AUTOPORTANTI O PANNELLI E TELAIO IN ALLUMINIO)	04
6	BASE IN ALLUMINIO 1600x1200x100	01
5	PIEDINO DI STABILIZZAZIONE DURANTE GLI INTERVENTI SUL SETUP INTERNO	4-6
4	MOLLA PNEUMATICA CON PRESSIONE TARABILE PER LIVELLAMENTO	4-6
3	BASE IN CALCESTRUZZO PREFABBRICATA	01
2	GUAINA DI PROTEZIONE IMPERMEABILIZZAZIONE	01
1	PAVIMENTO ESISTENTE IMPERMEABILIZZATO	..

- **Refined measurements of the microphonic background in the hosting lab performed in March 2024 (analysis ongoing). We are working towards the realization of the isolation system (financed)**

Optimization of a BEGe Detector Setup for Testing Quantum Foundations in the Underground LNGS Laboratory

by **Kristian Piscicchia, Alberto Clozza, Diana Laura Sirghi, Massimiliano Bazzi, Nicola Bortolotti, Mario Bragadireanu, Michael Cargnelli, Luca De Paolis, Raffaele Del Grande, Carlo Guaraldo, Mihail Iliescu, Matthias Laubenstein, Simone Manti, Johann Marton, Marco Miliucci, Fabrizio Napolitano, Alessio Porcelli, Alessandro Scordo, Francesco Sgaramella, Florin Sirghi,** + Show full author list

Condens. Matter **2024**, *9*(2), 22; **https://doi.org/10.3390/condmat9020022** - 11 Apr 2024

Abstract In this work, we report on tests performed with an experimental apparatus

Gantt chart of the future experimental activity

Planning	2024	2025	2026	2027	2028	2029	2030	
Open Systems								
VIP-2	data taking	data taking						
VIP-3	realization	installation	data taking	data taking	data taking			
VIP-4				test	realization	installation	data taking	data t
Closed Systems (tentative)								
HPGe QG	simulations	use data	use data	update on the possibility to realize a dedicated setip				
Clapse Models								
BeGe scan over Z	BeGe upgr.	upgr/test	data taking	data taking	data taking	explore further possibilities		

[Snowmass 2021 Topical Report on Synergies in Research at Underground Facilities]

VIP-2 publications/dissemination October 2023-now

Papers since last SC meeting:

1) Nuclear Physics Mid Term Plan at LNGS, *Eur.Phys.J.Plus 139* (2024) 3, 224
2) Novel machine learning and differentiable programming techniques applied to the VIP-2 underground experiment, *Meas. Sci. Technol*. 35 (2024) 025501
3) VIP-2 with modulated current: pathfinder for enhanced Pauli exclusion…., *Eur. Phys. J. C* (2024) 84: 214
4) PANTHEON: Towards High-precision Tests of the Pauli Exclusion Principle in Nuclear Reaction as a Testbed of Theories Beyond the Standard Model, *Acta Phys.Polon.Supp. 17* (2024) 1, 1-A6
5) x-ray emission from atomic systems can distinguish between prevailing dynamical wave-function collapse models, *accepted in Phys. Rev. Lett*. (17 April)
6) Stochastic Ricci Flow dynamics, arXiv:2307.10136, to be submitted for publication
7) Strongest constraints on the Pauli Exclusion Principle violation probability by VIP-2, under submission
8) Investigation of relativistic time fluctuations, in the context of both CSL and DP models, paper in preparation.
9) A Pauli Exclusion Principle Violation Search with Gator/VIP, paper in preparation

A MODERN ODYSSEY: QUANTUM GRAVITY MEETS QUANTUM COLLAPSE AT ATOMIC AND NUCLEAR PHYSICS ENERGY SCALES IN THE COSMIC SILENCE

03 June 2024 — 07 June 2024

Organizers

Catalina Oana Curceanu (INFN-LNF)
catalina.curceanu@lnf.infn.it
Angelo Bassi (Univ. and INFN Trieste)
abassi@units.it
Laura Baudis (Physics Department at the University of Zurich)
laura.baudis@physik.uzh.ch
Antonino Marciano (Fudan University China and INFN-LNF)
marciano@fudan.edu.cn
Kristian Piscicchia (CREF - CENTRO RICERCHE ENRICO FERMI)
kristian.piscicchia@cref.it
Lajos Diosi (Wigner Research Centre for Physics Budapest Eötvös Loránd University Budapest)

The VIP2 Collaboration acknowledges the excellent working conditions and the continuous and friendly support provided to the experiment by the LNGS staff.

Spares

Gator - VIP collaboration (Prof. Laura Baudis)

an Open Systems test of PEP violation in very high Z materials

Gator/VIP collaboration

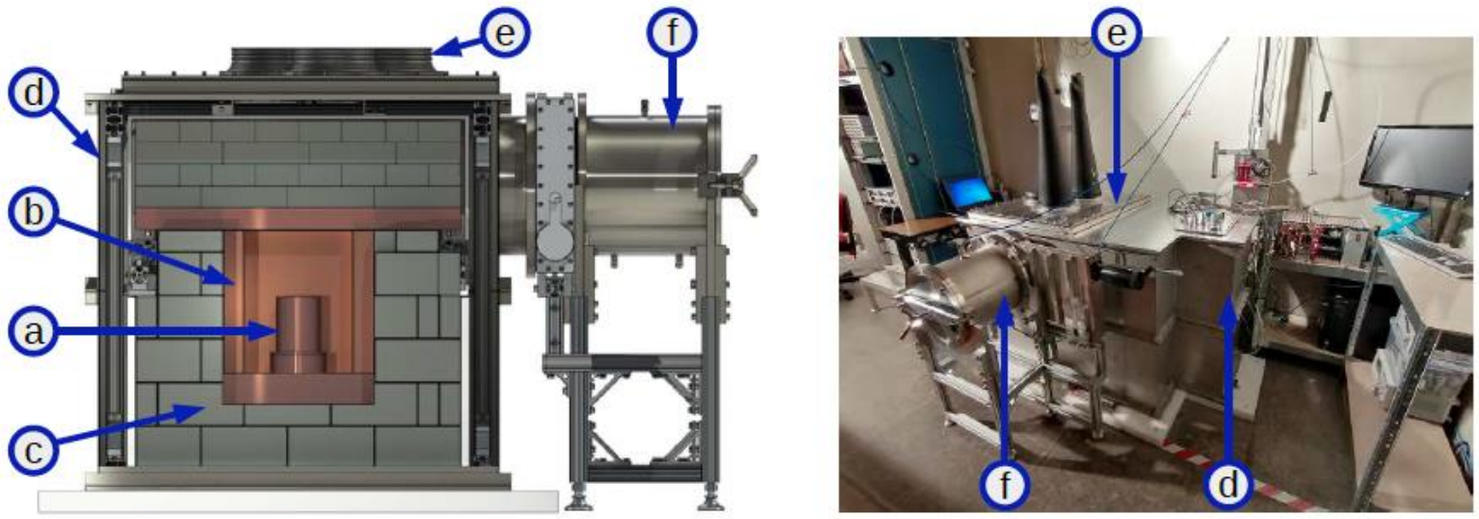
THE GOAL:
measurement of $\beta^2/2$ in Pb (Z = 82)
respecting MG superselection, at energies not accessible with SDD detectors:

Transitions in Pb	allow. (keV)	forb. (keV)
1s - $2p_{3/2}$ $K_{\alpha 1}$	74.961	73.713
1s - $2p_{1/2}$ $K_{\alpha 2}$	72.798	71.652
1s - $3p_{3/2}$ $K_{\beta 1}$	84.939	83.856
1s - $4p_{1/2(3/2)}$ $K_{\beta 2}$	87.320	86.418
1s - $3p_{1/2}$ $K_{\beta 3}$	84.450	83.385

- **using the Gator facility: high-performance low-background germanium spectrometer,**

- **with the implementation of a dedicated target system (high radio-purity Pb) fed by a DC power supply**

The Gator Detector



(a) HPGe detector inside Cu-OFE cryostat (cooled with LN_2 via copper coldfinger), **(b)** OFHC Cu cavity, **(c)** lead shield, polyethylene sheet, **(d)** airtight stainless steel enclosure (purged with GN_2), **(e)** glove ports, **(f)** sample load lock

Test measurement data analysis finalized

The analysis of the data collected during 2023 (41 days with a circulating current of 40 A and 56 days without current) was finalized:

using the electron diffusion model:

$\beta^2/2 < 4.8 \cdot 10^{-29}$ **Bayesian**

$\beta^2/2 < 5.7 \cdot 10^{-29}$ **Frequentist**

with probability 0.9

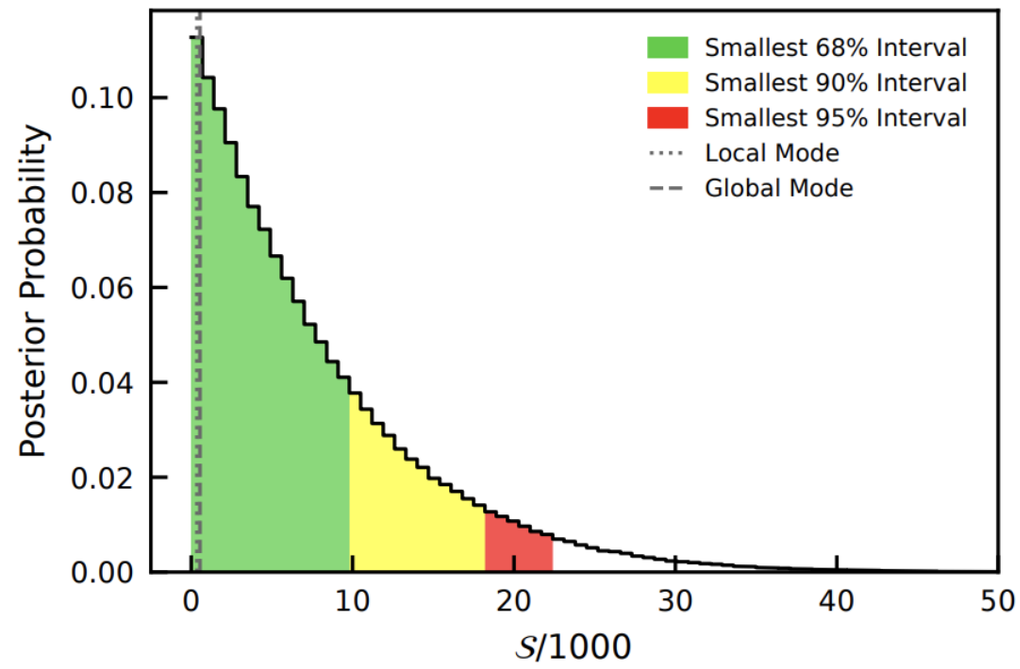


Fig. 5 Marginalized posterior distribution of the parameter of interest $\mathcal{S}/1000$, obtained from the Bayesian analysis. The 90 % upper limit is indicated by the yellow band.

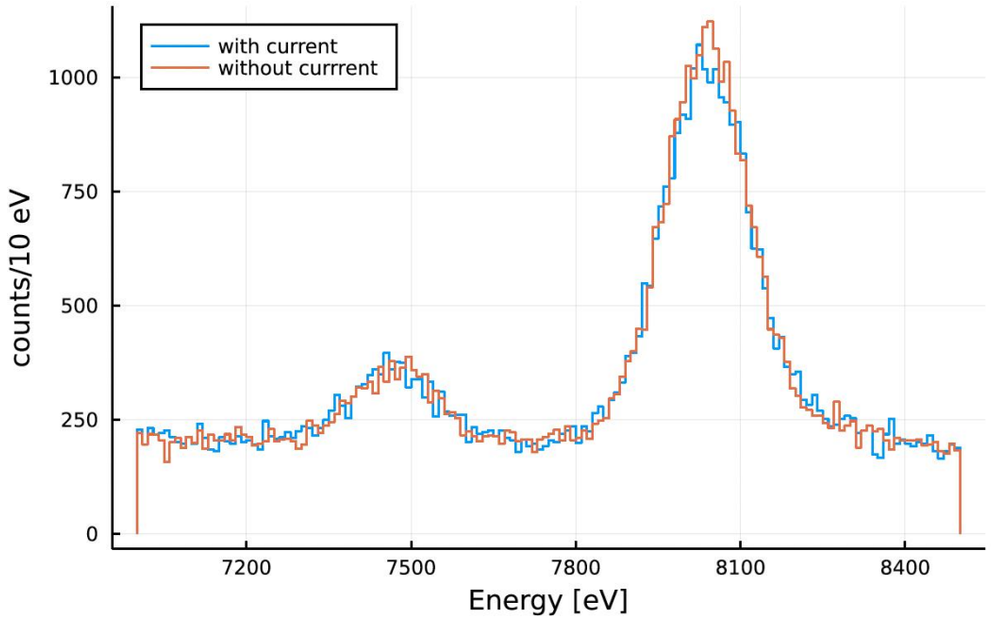
more than one order of magnitude improvement with respect to (*Found.Phys.* 42 (2012) 1015-1030)

PAPER UNDER FINALIZATION

Future plans are under discussion: higher current; new features…

VIP-2 Open Systems - present status and results

Total acquired statistics before VIP-2 shack renovation analyzed (paper under submission):

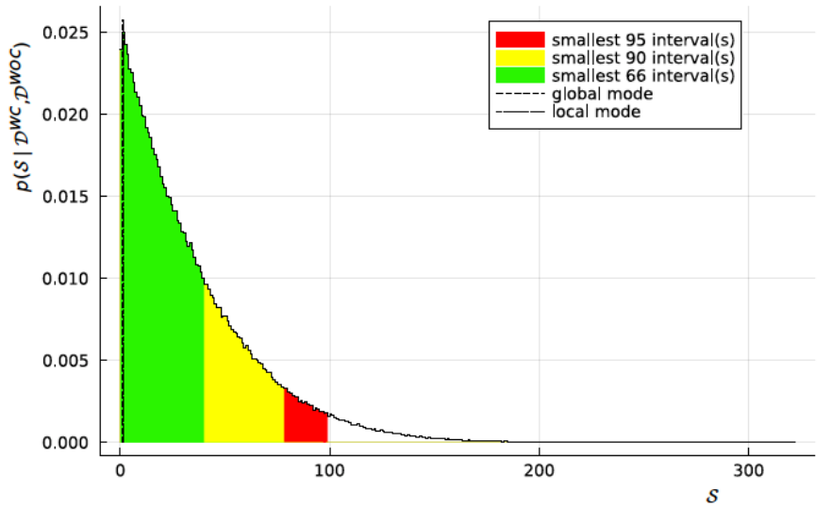


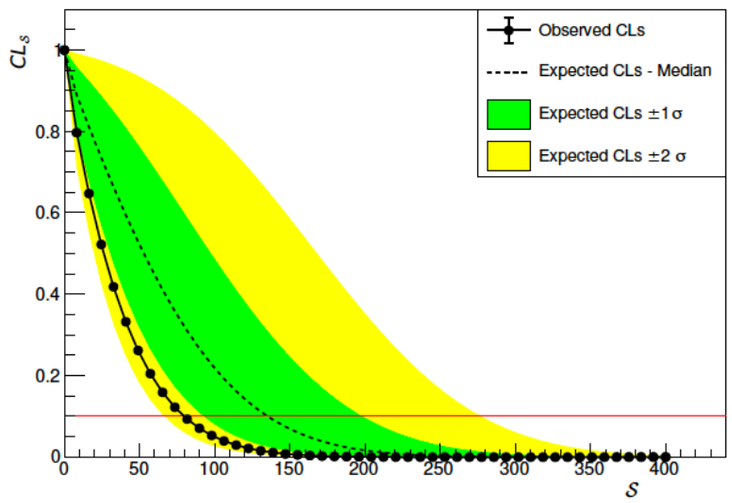
VIP-2 calibrated data in the region-of-interest 7000-8500 eV, of about two years of data taking (May 2019 to May 2021). The spectrum of the data acquired with a current circulating in the target is shown in blue. Data taken without current in the target, used as reference and control, shown in red. The copper and nickel K_α lines are visible in the spectra.

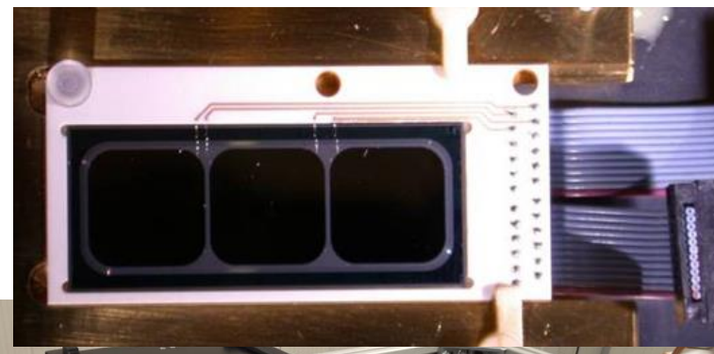
Bayesian analysis validated by means of frequentist CLs exclusion method, exploiting Neyman construction for a robust evaluation of the CLs.

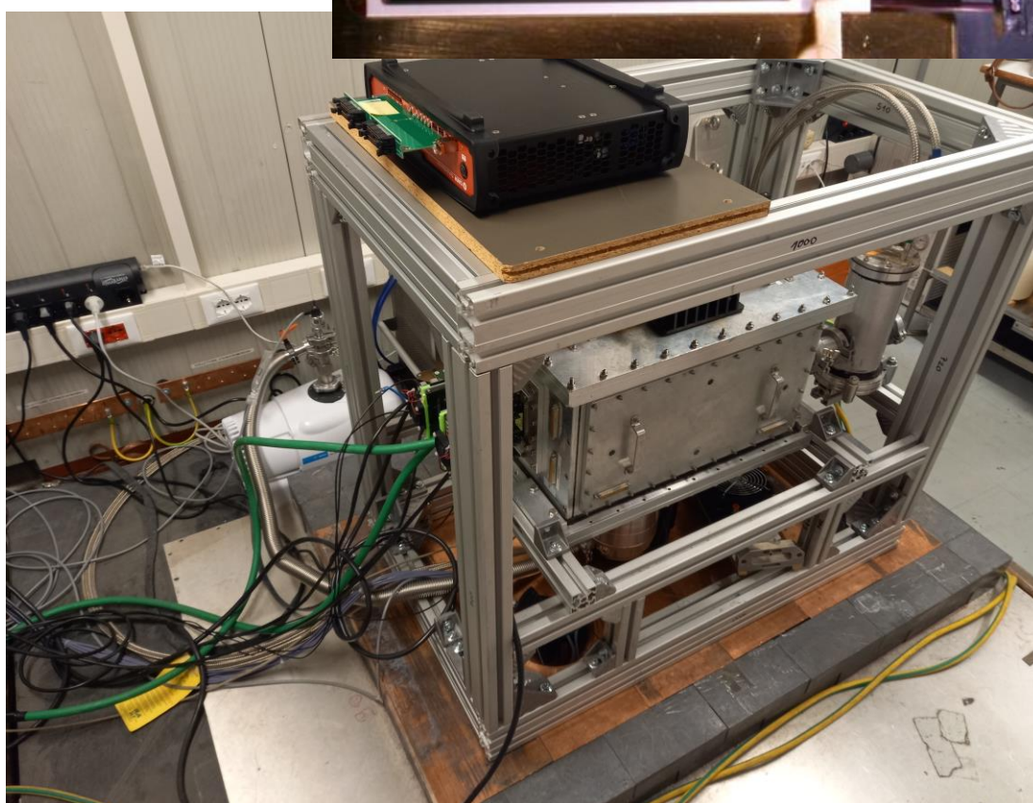
Strongest limits in the PEP violation probability respecting MG:

$$\beta^2/2 < 2.4 \cdot 10^{-43}$$









Theory: PEP violation in beyond SM

We enlarged our fruitful collaboration with leading theoretical groups

(Prof. Marcianò Fudan Univ., Prof. Mavromatos King's College, Prof. Illuminati Salerno Univ., Prof. Finster Regensburg Univ., Prof. Addazzi Sichuan Univ.)

to explore <u>specific theories</u> beyond SM bringing to PEP violation

1. **<u>Non-Commutative Quantum Gravity</u> (we already excluded the θ-Poincaré noncommutative quantum gravity models far above the Planck scale for nonvanishing θμν electriclike components, and up to 6.9×10−2 Planck scales if θ0i=0); presently first phenomelogical investigation of angular dependence of the PEPV emission -> crucial information on the commutation rules of the space coordinates, and therefore on the background field underlying non-commutativity (e.g. the B-field in String Theory). OS+CS**
2. **<u>Generalized Uncertainty Principle theories</u> (GUP): first calculation (in collaboration with the group led by Prof. Illuminati) of the PEP violation OS+CS**
3. **<u>CPT violations bringing to PEP violation</u>: N. Mavromatos – towards connecting PEP violation probability to CTP violation OS**
4. **<u>Quon-model, thermodynamics and cosmology</u> (Greenberg, Rahal, Campa,…) OS**

First analysis of PEPV in GUP (New!)

Generally related to the existence of a minimal length - as predicted by several QG models - E.g. GUP structure emerges from string theory in the high energy limit.

The construction of field theories in this context may involve deformations of the statistics:

Theory being developed in collaboration with Illuminati, Bosso and Luciano

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

Violation of the PEP depends on the energy and on Λ_{GUP} as

$$\delta^2(E,\beta) = \frac{m\,\Delta E}{\Lambda_{GUP}^2}$$

Why? PEP lacks a clear, intuitive explanation

... Already in my original paper I stressed the circumstance that I was unable to give a logical reason for the exclusion principle or to deduce it from more general assumptions.

I had always the feeling and I still have it today, that this is a deficiency.

... *The impression that the shadow of some incompleteness [falls] here on the bright light of success of the new quantum mechanics seems to me unavoidable.*

W. Pauli, Nobel lecture 1945

Why? PEP lacks a clear, intuitive explanation

W. Pauli, Nobel lecture 1945

At the root of the Exclusion Principle:
proof of spin-statistics theorem by Lüders and Zumino

Postulates:

I. **The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)**
II. **Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality - microcausality)**
III. **The vacuum is the state of lowest energy**
IV. **The metric of the Hilbert space is positive definite**
V. **The vacuum is not identically annihilated by a field**

From these postulates it follows that (pseudo)scalar fields commute and spinor fields anticommute.

(G. Lüders and B. Zumino, Phys. Rev. 110 (1958) 1450)

Eur. Phys. J. C (2021) **81**: 773
https://doi.org/10.1140/epjc/s10052-021-09556-0
Regular Article - Theoretical Physics

Novel CSL bounds from the noise-induced radiation emission from atoms

Sandro Donadi[1], Kristian Piscicchia[2,3], Raffaele Del Grande[4], Catalina Curceanu[3d], Matthias Laubenstein[5] and Angelo Bassi[1,6]

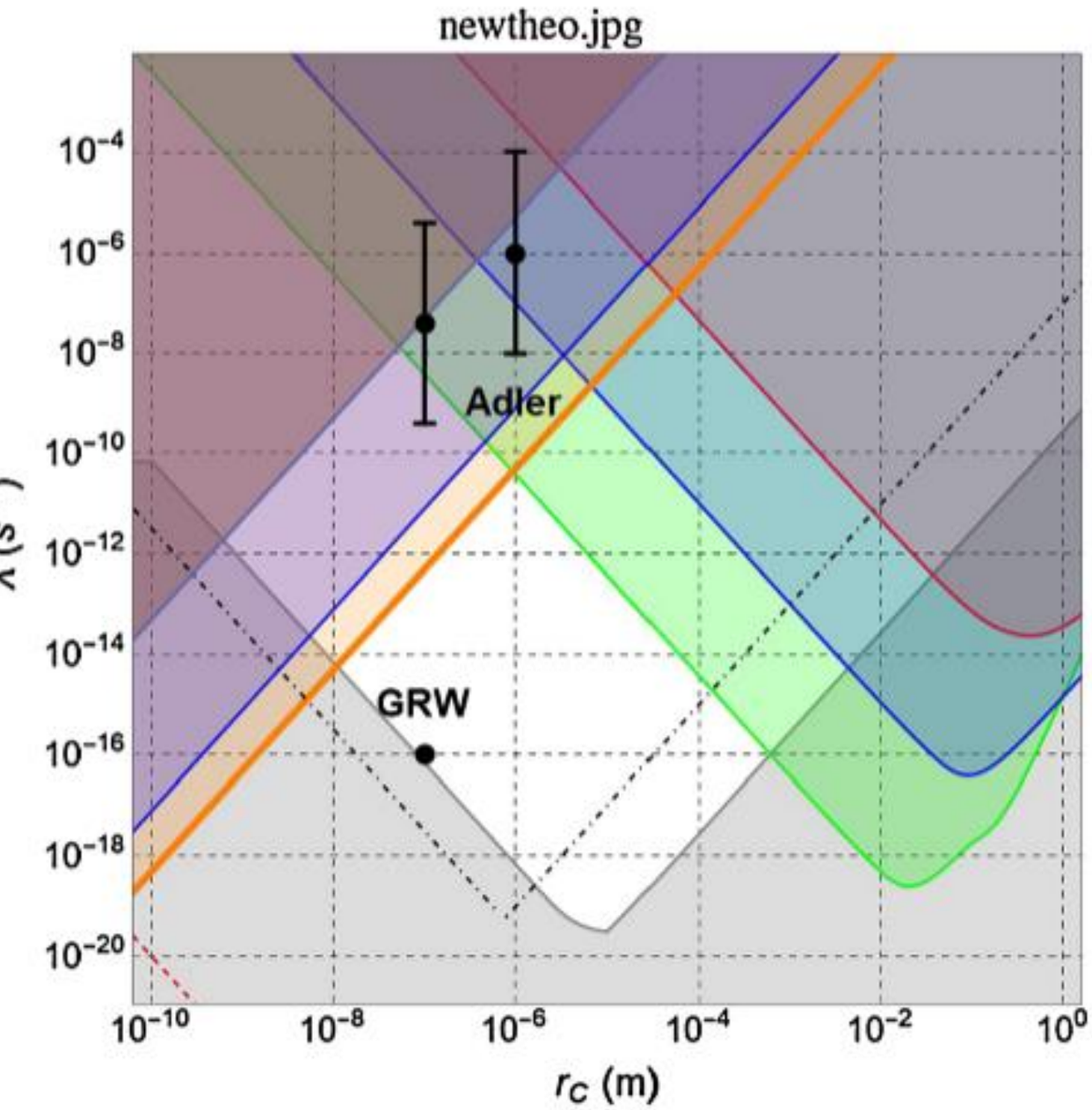


Fig. 4 Mapping of the $\lambda - r_C$ CSL parameters: the proposed theoretical values (GRW [6], Adler [24,25]) are shown as black points. The region excluded by theoretical requirements is represented in gray, and it is obtained by imposing that a graphene disk with the radius of 10 μm (about the smallest 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 Å 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

We obtain the upper limit on λ

$$\lambda < 5.2 \cdot 10^{-13}\ \mathrm{s}^{-1}$$

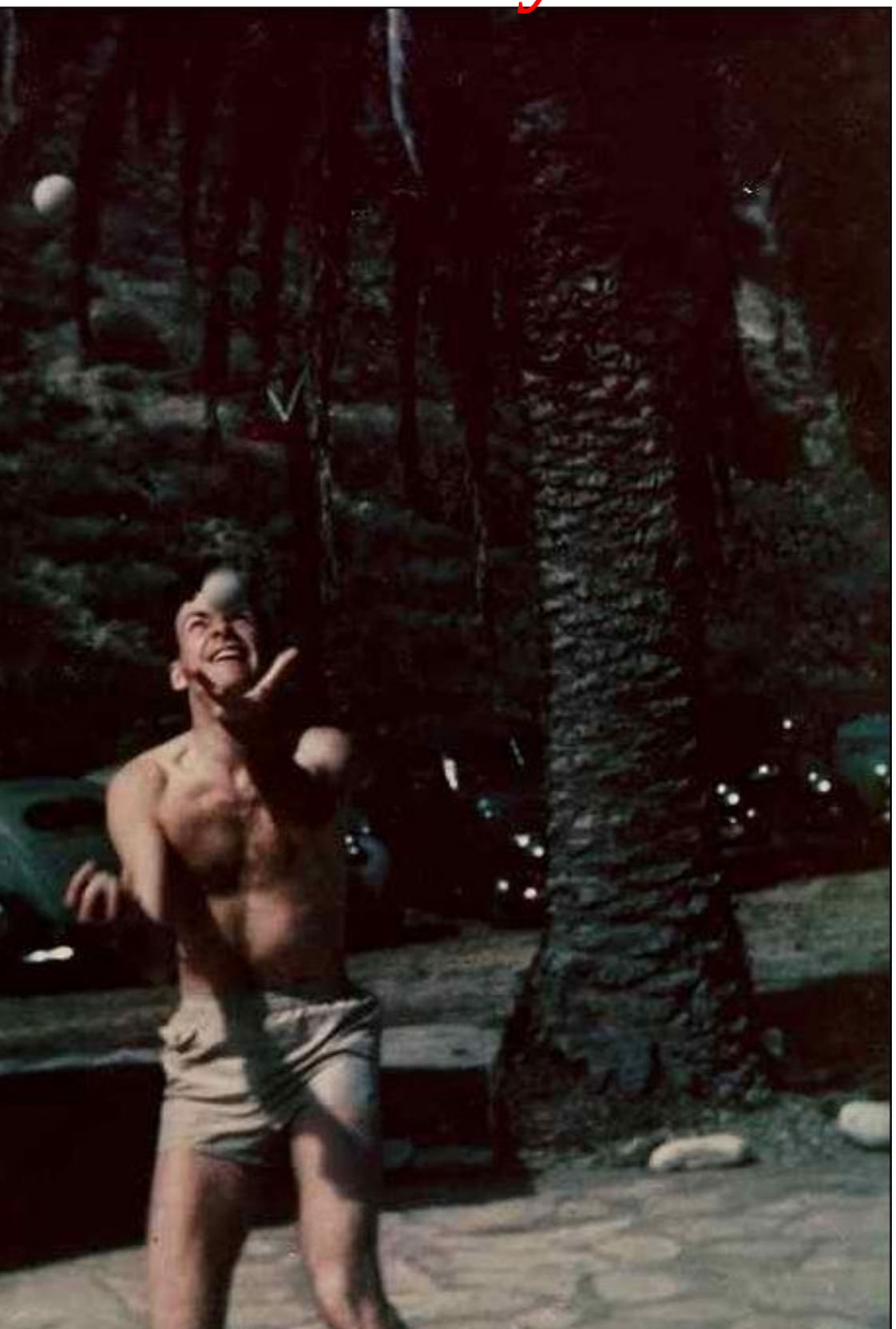
BEGe detector activity

We are working on a prototype of a setup based on BEGe detectors (M. Laubenstein) and PSA dedicated analysis tools capable to reach a lower energy threshold of few keV, with a double aim:

1. **PEP: to improve the sensitivity on the non-commutativity scale of the θ-Poincaré model, for $\theta_{0i} = 0$ (see PRL 129, 131301 (2022), PRD 107, 026002 (2023))**

2. to develop a versatile detector, which can measure the spontaneous radiation emitted by several targets in the range (1-15) keV to test recent, new predictions, on collapse models.

Feynman Lectures on Physics



This brings up an interesting question: Why is it that particles with half-integral spin are Fermi particles (...) whereas particles with integral spin are Bose particles (...)?

We apologize for the fact that we can not give you an elementary explanation.

An explanation has been worked out by Pauli from complicated arguments from quantum field theory and relativity. He has shown that the two must necessarily go together, but we have not been able to find a way to reproduce his arguments on an elementary level. It appears to be one of the few places in physics where there is a rule which can be stated very simply, but for which no one has found a simple and easy explanation. (...)

This probably means that we do not have a complete understanding of the fundamental principle involved. For the moment, you will just have to take it as one of the rules of the world