

Testing Quantum Mechanics Underground: From Pauli Exclusion Principle Violations to Spontaneous Collapse

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On behalf of the VIP Collaboration

***Bridging high and low energies in search of quantum gravity Cost
Action CA23130 First Annual Conference
Paris, 7 – 11 July 2025***

Quantum Mechanics tests:

- Pauli Exclusion Principle Violation
- Collapse Models



Bridging QM and Gravity WG4 COST Action

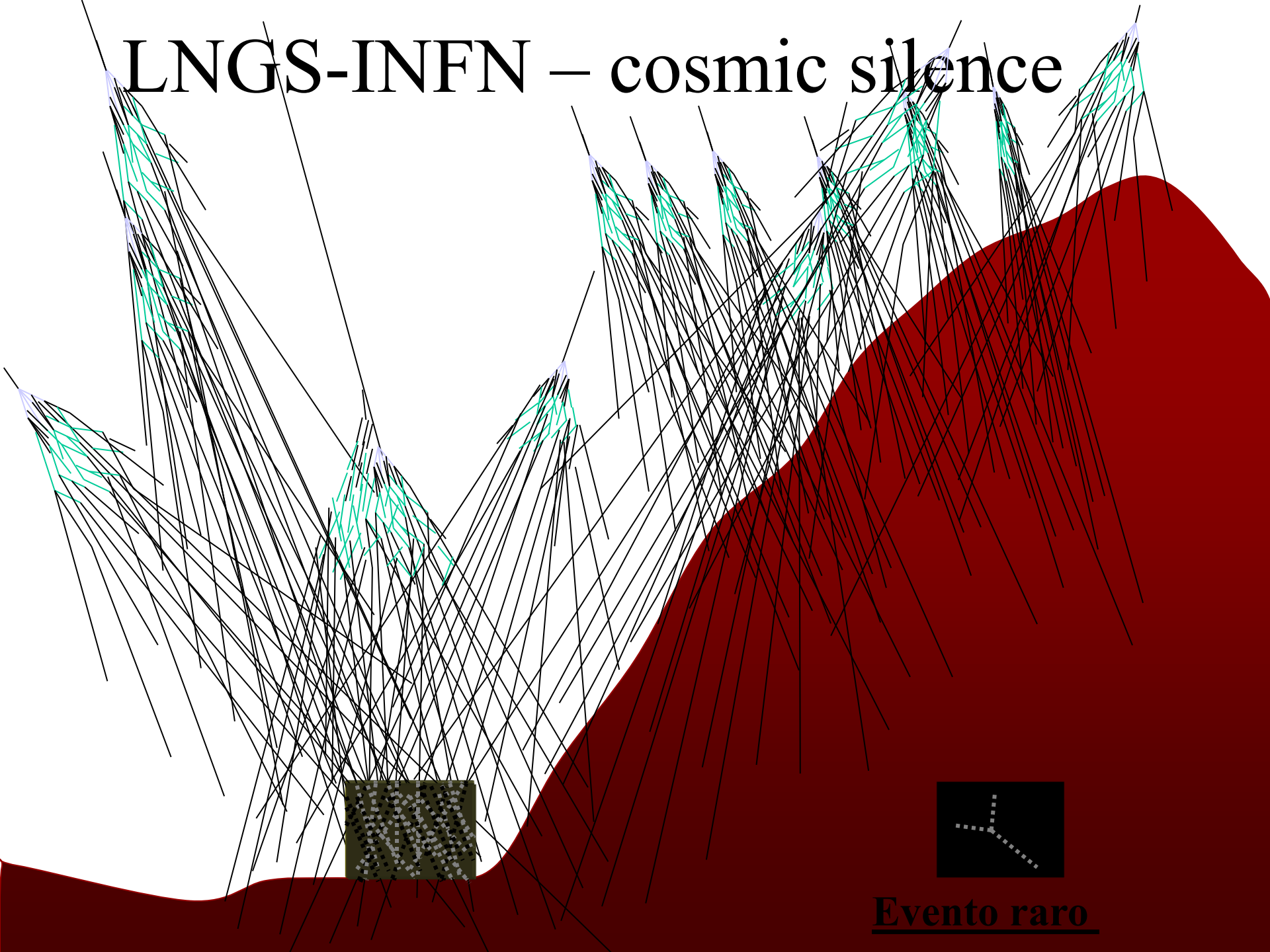
Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare



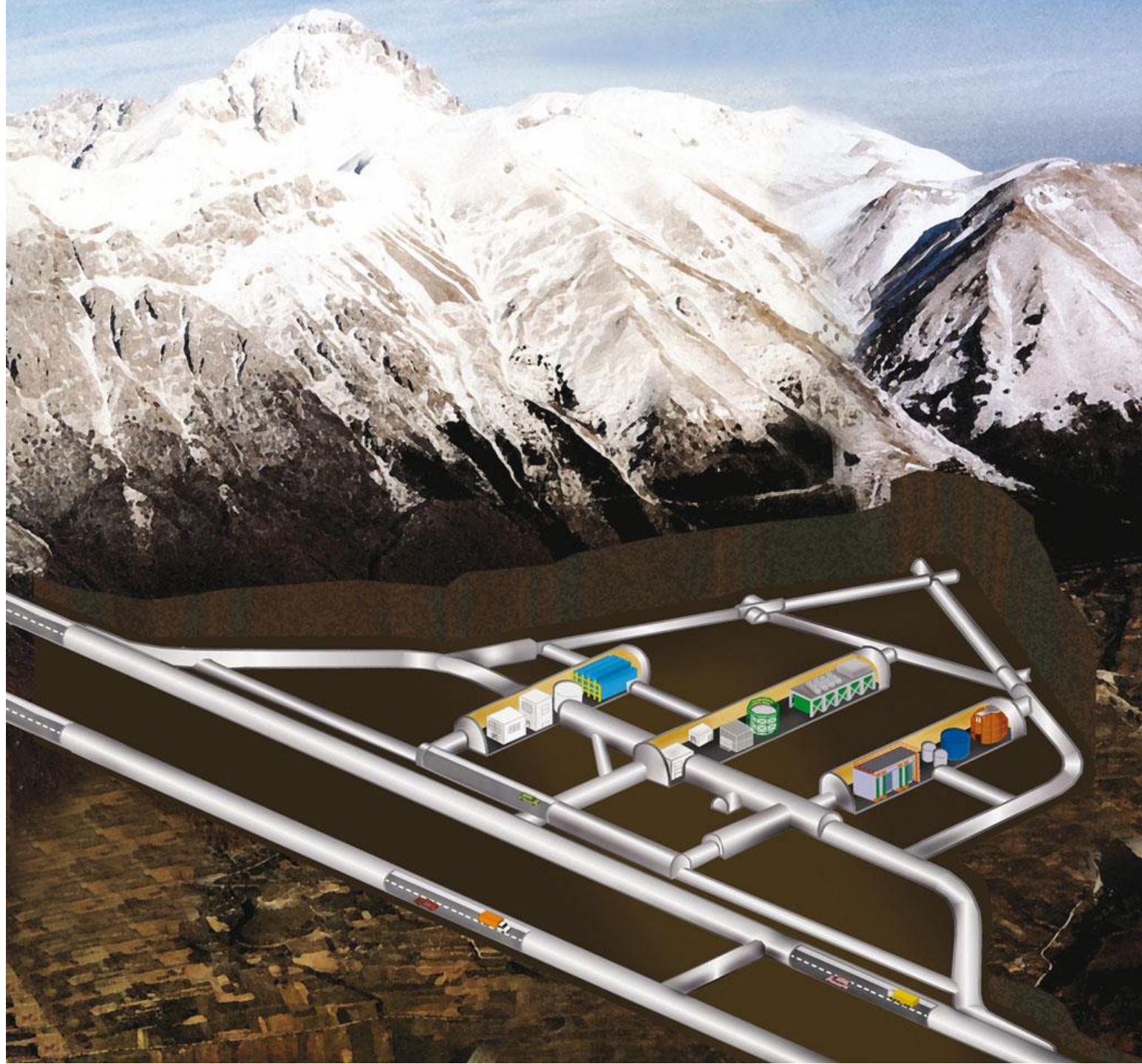
LNGS



LNGS-INFN – cosmic silence



Evento raro







We search for the *impossible atoms*

An experiment to test the Pauli Exclusion Principle (PEP) for electrons in a clean environment (LNGS) using *atomic physics methods* – *the VIP experiment*



The Pauli Exclusion Principle

In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers coincide. If an electron exists in an atom for which all of these numbers have definite values, then the state is occupied.

W. Pauli, Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren, Zeitschrift für Physik 31 (1925) 765.



Pauli Archive, holding: fierz_0092-064

2
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

ZÜRICH 7,
Glockenstrasse 31 16. Okt. 1949

Lieber Herr Fierz,

Heute möchte ich Sie als Kenner von Leibniz ^{an}appellieren.
Herr Veyl hat mir vorhin eine engländer, ^{die} durch mehrere
offensichtliche beweisbare Ausprüche eines früheren Arztes
(Philosophie von Hakt. o. Thg.) im Handbuche der Philosophie (1927,
geschickt. Im Appendix B, p. 247 ^{bezieht sich} ~~findet sich~~ das
Ausschließungsprinzip mit Leibniz in Zusammenhang
und zwar mit dem "principium identitatis"
in der Metaphysik. Das liegt aber viel zu weit von der Physik.



Required for
bosons.

$$\psi = \psi_1(a)\psi_2(b) \pm \psi_1(b)\psi_2(a)$$

Probability amplitude that
both states "a" and "b" are
occupied by electrons 1 and
2 in either order.

Required for
fermions.



***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)

Theories of Violation of Statistics

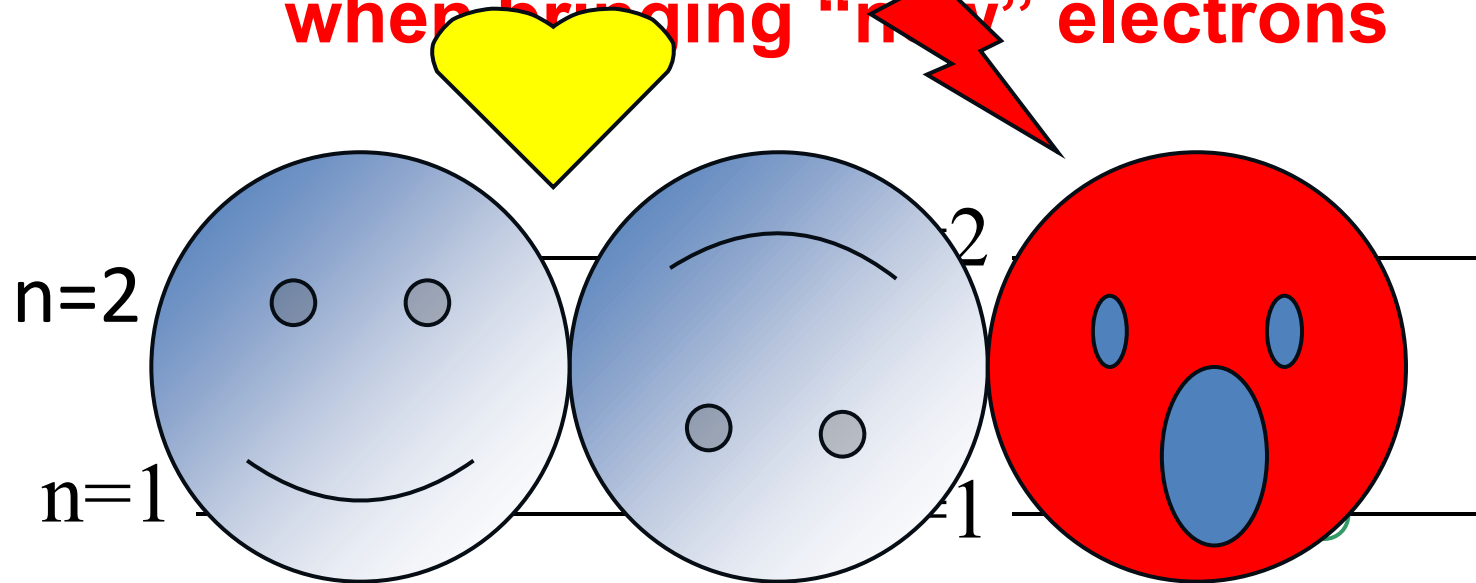
O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

“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.”

Experimental method:

**Search for anomalous X-ray transitions
when bringing “new” electrons**



Normal $2p \rightarrow 1s$
transition

Energy 8.04 keV

$2p \rightarrow 1s$ transition
violating

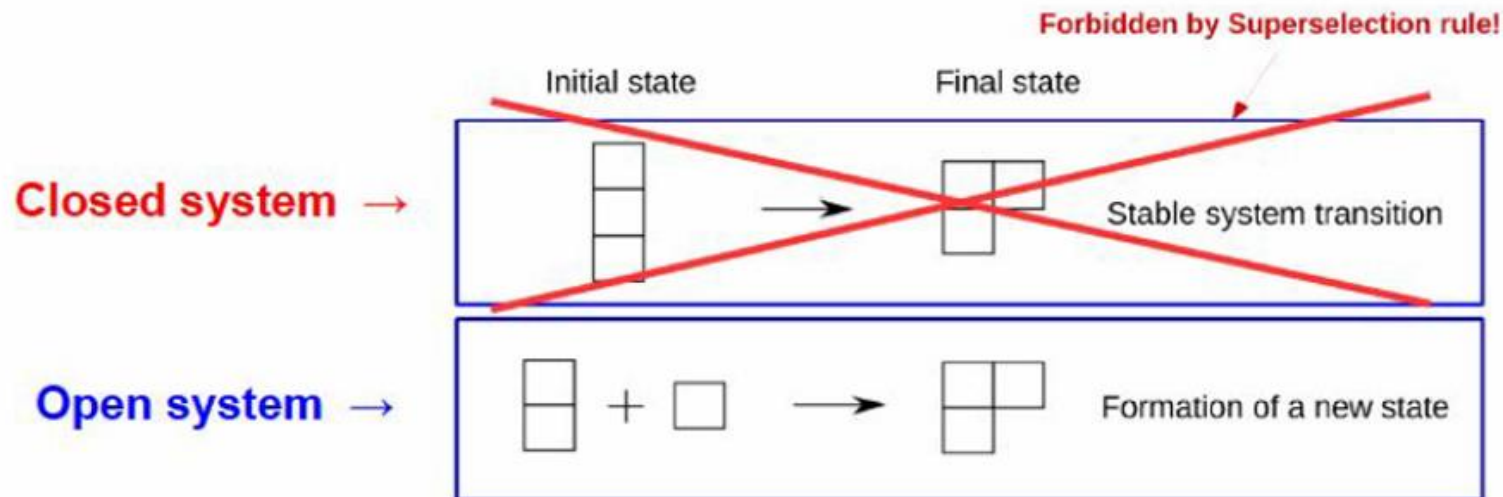
Pauli principle

Energy 7.7 keV

Messiah-Greenberg super-selection rule:

Superposition of states with different symmetry are not allowed →

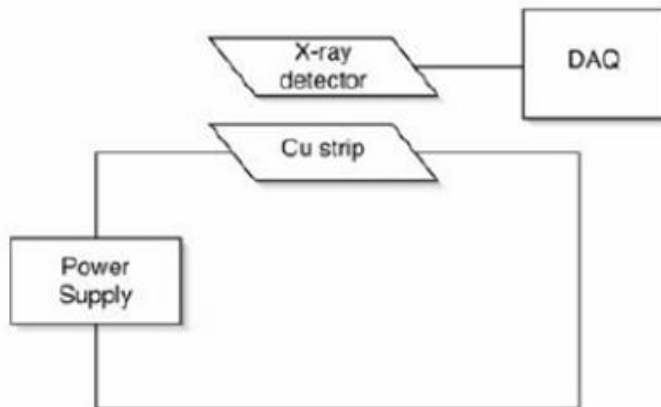
Transition probability between two symmetry states is ZERO



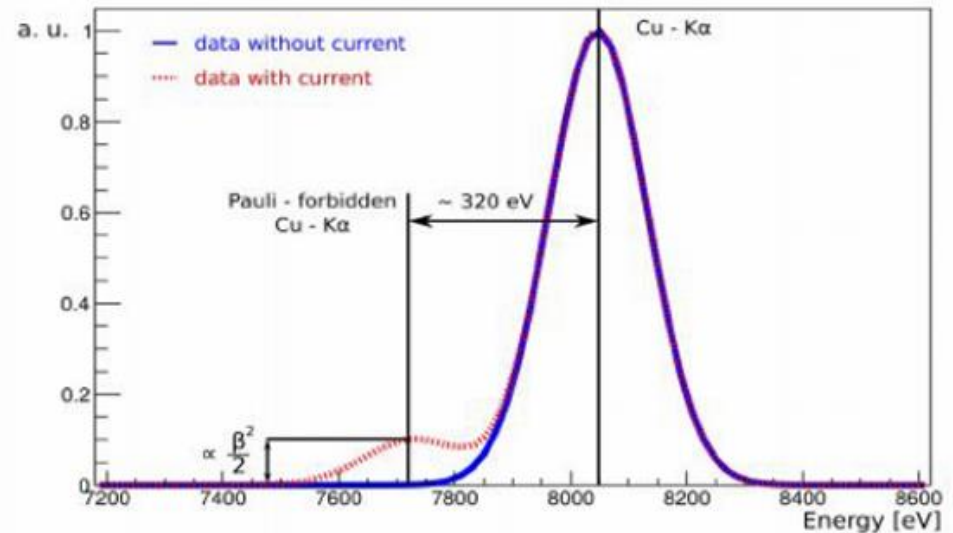
VIP-2 Experiment: best limits on PEP violation of an elementary particle respecting the Messiah-Greenberg super-selection rule

Greenberg, O. W. & Mohapatra, R. N., Phys Rev Lett 59, (1987).
E. Ramberg and G. A. Snow, Phys Lett B 238, 438-441(1990)

Search for anomalous electronic transitions in Cu
induced by a circulating current
introduced electrons interact with the valence electrons
search transition from 2p to 1s already filled by 2 electrons
alternated to X-ray background measurements without current

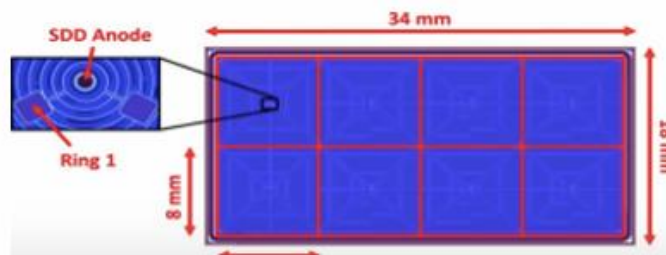
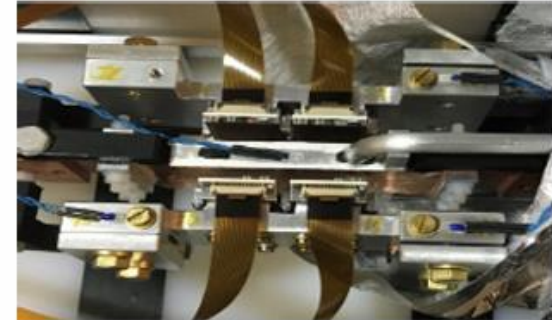
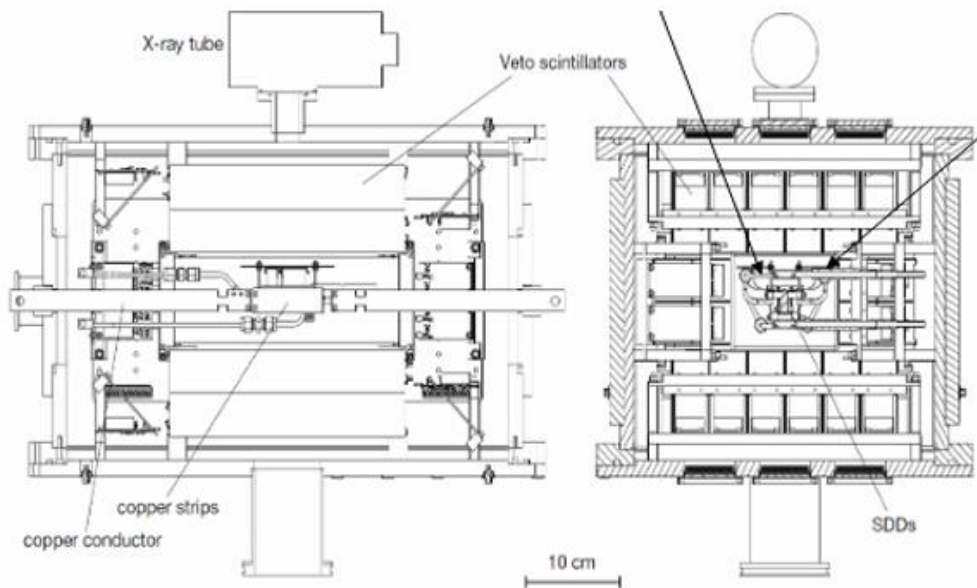


PEP Violation Signal:



The VIP-2 Experiment

Silicon Drift Detectors (SDDs) higher resolution (190 eV FWHM at 8.0 \rightarrow keV), faster (triggerable) detectors. 4 arrays of 2 x 4 SDDs 8mm x 8mm each, liquid argon closed circuit cooling 170 °C



The VIP-2 Experiment

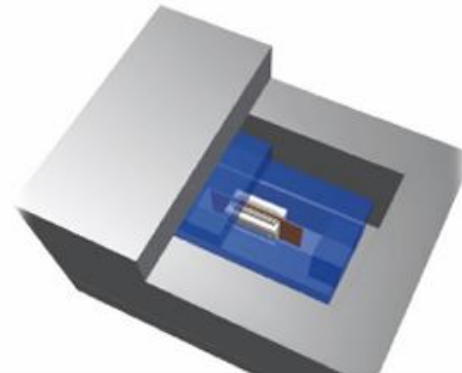
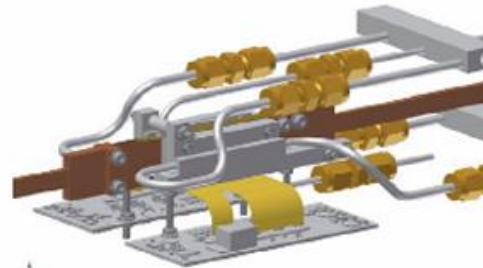
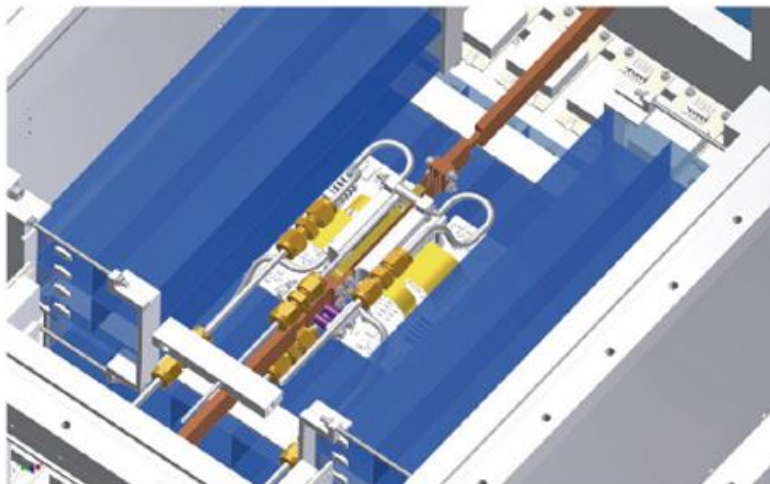
*2 strip shaped Cu targets (25 μm x 7 cm x 2 cm) more compact target \rightarrow higher acceptance, thinner \rightarrow **higher efficiency***

DC current supply to Cu bars

*Cu strips cooled by a closed Fryka chiller circuit \rightarrow **higher current***

(100 A) @ 20 °C of Cu target implies 1 °K heating in SDDs










































Sketch of the VIP2 Setup:





Net Phys (2020)

VIP-2 —High-Sensitivity Tests on the Pauli Exclusion Principle for Electrons

by  Kristian Piscicchia ^{1,2} ,  Johann Marton ^{2,3,*} ,  Sergio Bartalucci ² ,  Massimiliano Bazzi ² ,
 Sergio Bertolucci ⁴ ,  Mario Bragadireanu ^{2,5} ,  Michael Cargnelli ³ ,  Alberto Clozza ²  
 Raffaele Del Grande ^{1,2,6,*} ,  Luca De Paolis ² ,  Carlo Fiorini ⁷ ,  Carlo Guaraldo ²  
 Mihail Iliescu ² ,  Matthias Laubenstein ⁸  ,  Marco Miliucci ²  ,  Edoardo Milotti ⁹ ,
 Fabrizio Napolitano ² ,  Andreas Pichler ³ ,  Alessandro Scordo ² ,  Hexi Shi ³ , + Show full author list

Entropy **2020**, *22*(11), 1195;
<https://doi.org/10.3390/e22111195>

Entropy **2020**, *22*, 1195

$$\frac{\beta^2}{2} \leq \frac{\bar{\lambda}_s}{N_{\text{int}} N_{\text{new}} \epsilon} \leq 4.5 \times 10^{-42},$$

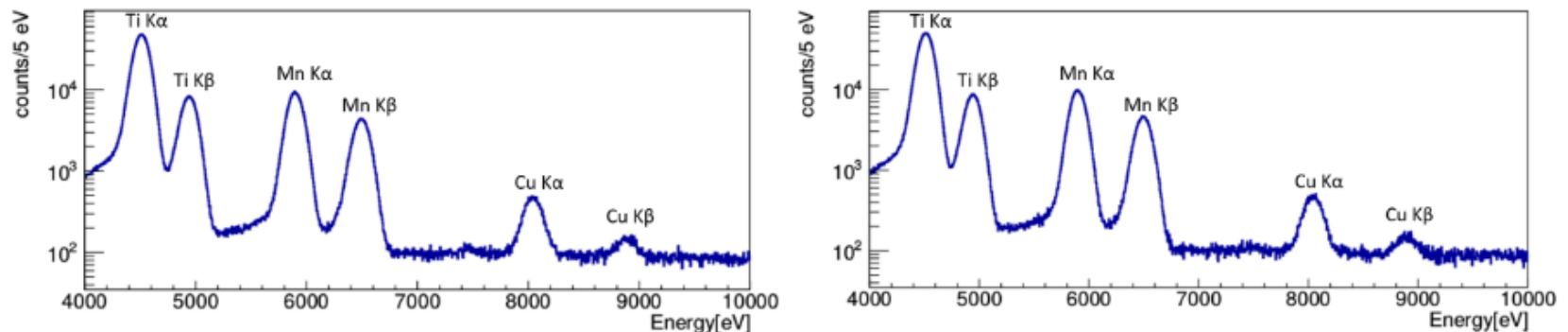
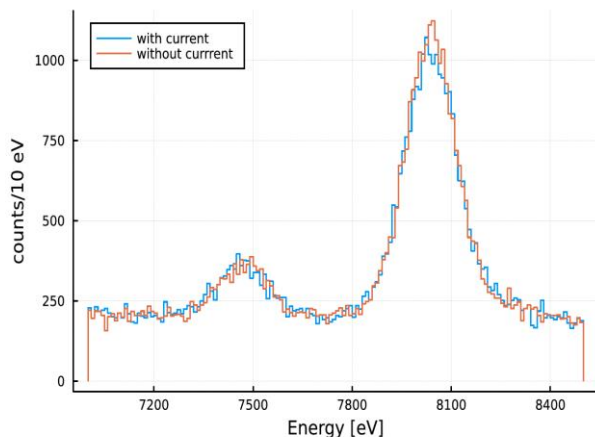


Figure 3. Energy calibrated spectra corresponding to about 42 days of data taking (during 2018) collected with current on (left), the spectrum collected with current off (right), which is normalized to the time of data taking with current on.




Open Access

Feature Paper

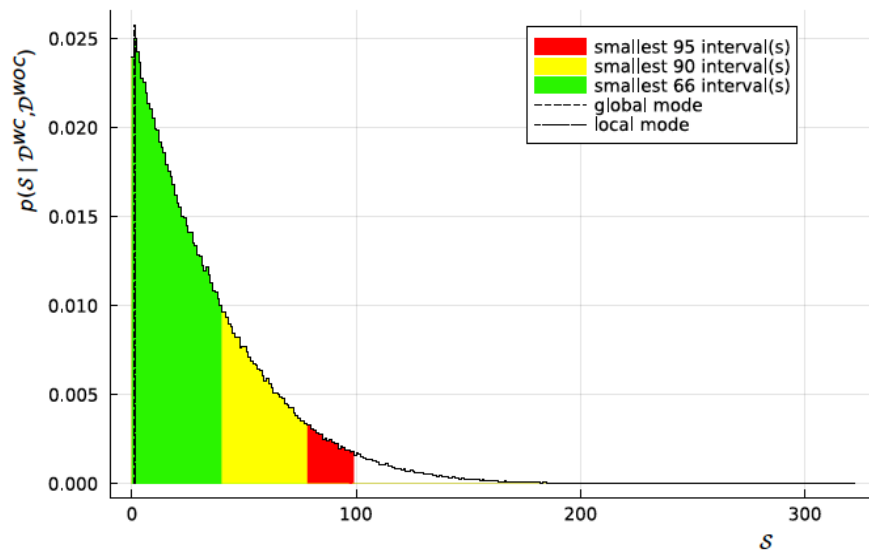
Article

Testing the Pauli Exclusion Principle with the VIP-2 Experiment

by Fabrizio Napolitano ^{1,*} , Sergio Bartalucci ¹ , Sergio Bertolucci ² , Massimiliano Bazzi ¹ , Mario Bragadireanu ^{1,3} , Cesidio Capoccia ¹ , Michael Cargnelli ⁴ , Alberto Clozza ¹ , Luca De Paolis ¹ , Raffaele Del Grande ^{1,5,6} , Carlo Fiorini ⁷ , Carlo Guaraldo ¹ , Mihail Iliescu ¹ , Matthias Laubenstein ⁸ , Johann Marton ^{1,4} , Marco Miliucci ¹ , Edoardo Milotti ⁹ , Federico Nola ¹⁰ , Kristian Piscicchia ^{1,5} , Alessio Porcelli ^{1,4} , + Show full author list

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 result: [strongest limits on PEPV probability for electrons:](#)



$$\theta^{2/2} < 6.8 \cdot 10^{-43}$$

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 is common to several quantum gravity frameworks (e.g. k -Poincaré, θ -Poincaré)



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

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 Clozza³, Luca De Paolis,³ Raffaele Del Grande,^{6,3} Carlo Guaraldo,³ Mihail Antoniu Iliescu,³
 Matthias Laubenstein⁷, Johann Marton^{5,3}, Marco Miliucci,³ Fabrizio Napolitano³, Alessio Porcelli^{5,3},
 Alessandro Scordo,³ Diana Laura Sirghi,^{3,8} Florin Sirghi^{3,8}, Oton Vazquez Doce³,
 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.

Accepted Paper

Experimental test of noncommutative quantum gravity by VIP-2 Lead

Phys. Rev. D

Kristian Piscicchia, Andrea Addazi, Antonino Marcianò, Massimiliano Bazzi, Michael Cargnelli, Alberto Clozza, Luca De Paolis, Raffaele Del Grande, Carlo Guaraldo, Mihail Antoniu Iliescu, Matthias Laubenstein, Johann Marton, Marco Miliucci, Fabrizio Napolitano, Alessio Porcelli, Alessandro Scordo, Diana Laura Sirghi, Florin Sirghi, Oton Vazquez Doce, Johann Zmeskal, and Catalina Curceanu

Accepted 7 December 2022

Future plans: test other QG models – with directionality (magnetic field) – interest in exp. Australia and Canada (MSCA NEXUS)!

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.

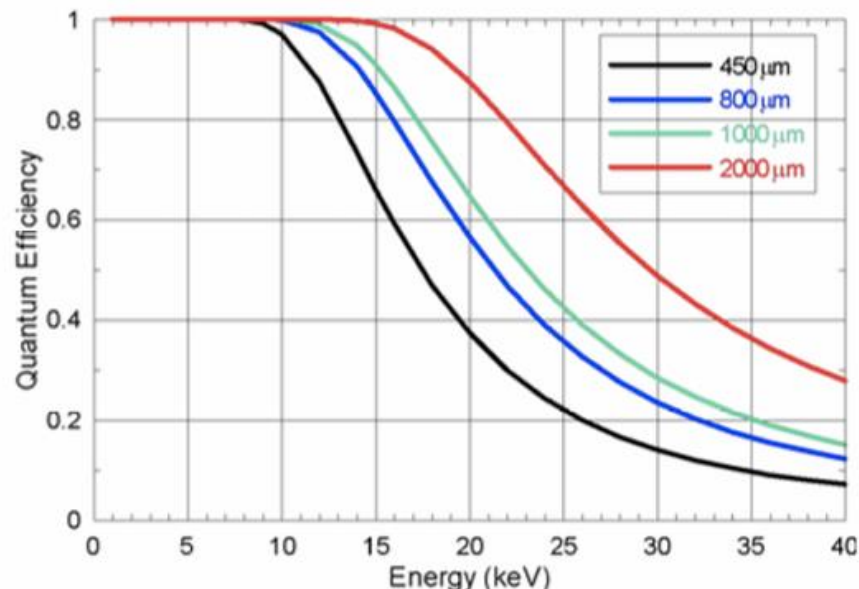
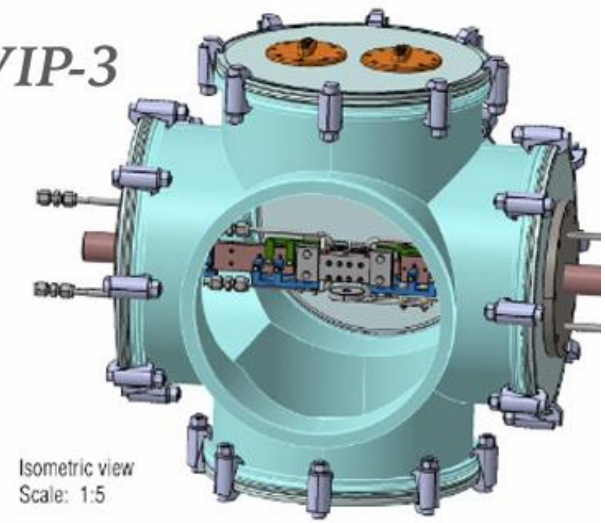
As a consequence, the measurement is very sensitive to high orders in the power series expansion of the Pauli violation probability, which allows to set the first constraint to the “triply special relativity” model proposed by Kowalski-Glikman and Smolin.

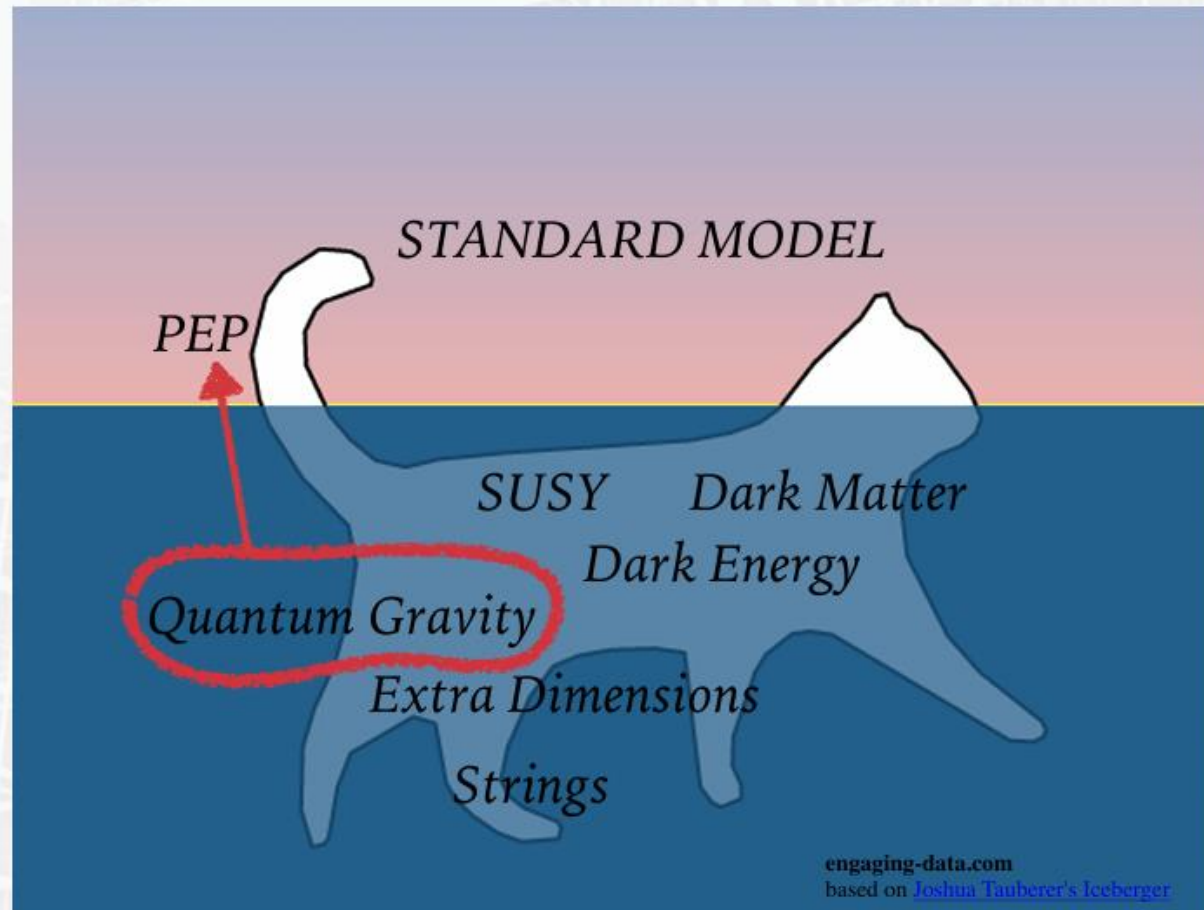
The characteristic energy scale of the model is bound to $\Lambda > 5.6 \cdot 10^{*-9}$ Planck scales

Future plans: test other QG models – with directionality (magnetic field) – interaction with theoreticians BridgeQG

VIP-2 experimental upgrade: VIP-3

- *new vacuum chamber, increase the number of SDD detectors, increase the geometrical efficiency, higher current up to 400 A*
- *New thermal contact between cold finger and SDDs*
- *New target cooling system*
- *Higher quantum efficiency needed for the SDDs at higher Z: use 1 mm thick SDDs, allowing to scan e.g. Ag, Sn and Pd*





BSM theories embedding extra dimensions, non commutative and/or discrete spacetime could have effect on PEP

Putting the Pauli exclusion principle on trial

The exclusion principle is part of the bedrock of physics, but that hasn't stopped experimentalists from devising cunning ways to test it.

If we tightly grasp a stone in our hands, we neither expect it to vanish nor leak through our flesh and bones. Our experience is that stone and, more generally, solid matter is stable and impenetrable. Last year marked the 50th anniversary of the demonstration by Freeman Dyson and Andrew Lenard that the stability of matter derives from the Pauli exclusion principle. This principle, for which Wolfgang Pauli received the 1945 Nobel Prize in Physics, is based on ideas so prevalent in fundamental physics that their underpinnings are rarely questioned. Here, we celebrate and reflect on the Pauli principle, and survey the latest experimental efforts to test it.

The exclusion principle (EP), which states that no two fermions can occupy the same quantum state, has been with us for almost a century. In his Nobel lecture, Pauli provided a deep and broad-ranging account of its discovery and its connections to unsolved problems of the newly born quantum theory. In the early 1920s, before Schrödinger's equation and Heisenberg's matrix algebra had come along, a young Pauli performed an extraordinary feat when he postulated both the EP and what he called "classically non-describable two-valuedness" – an early hint of the existence of electron spin – to explain the structure of atomic spectra.



PAULI-ARCHIVE-PRIO-011-1

Portrait of a young Pauli at Svein Rosseland's institute in Oslo in the early 1920s, when he was thinking deeply on the applications of quantum mechanics to atomic physics.



GIFsBOOM
.net



$$\psi_{\text{kitty}} = \frac{1}{\sqrt{2}} \psi_{\text{alive}} + \frac{1}{\sqrt{2}} \psi_{\text{dead}}$$

The measurement problem

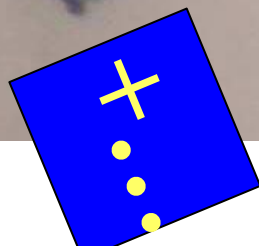
Possible solutions:

- De Broglie - Bohm
- Many-World Interpretations
- Collapse of the w.f.

-

Schrödinger

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V\psi$$



What are collapse models

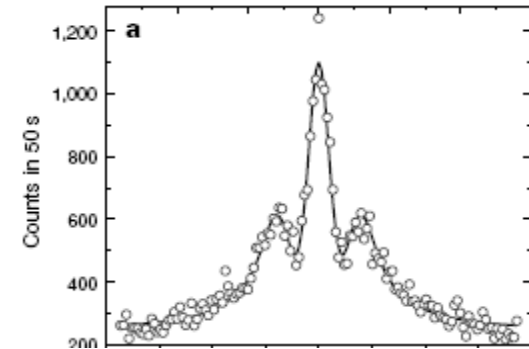
1. Collapse models = solution of the measurement problem

Paradox-free description of the quantum world



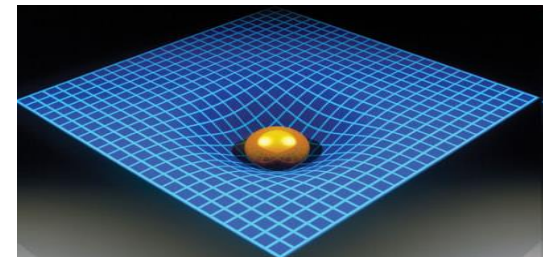
2. Collapse models = rival theory of Quantum Mechanics

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:

$$d|\psi_t\rangle = \left[\underbrace{-\frac{i}{\hbar}H dt}_{\text{System's Hamiltonian}} + \underbrace{\sqrt{\lambda} \int d^3x (N(\mathbf{x}) - \langle N(\mathbf{x}) \rangle_t) dW_t(\mathbf{x}) - \frac{\lambda}{2} \int d^3x (N(\mathbf{x}) - \langle N(\mathbf{x}) \rangle_t)^2 dt}_{\text{NEW COLLAPSE TERMS}} \right] |\psi_t\rangle$$

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

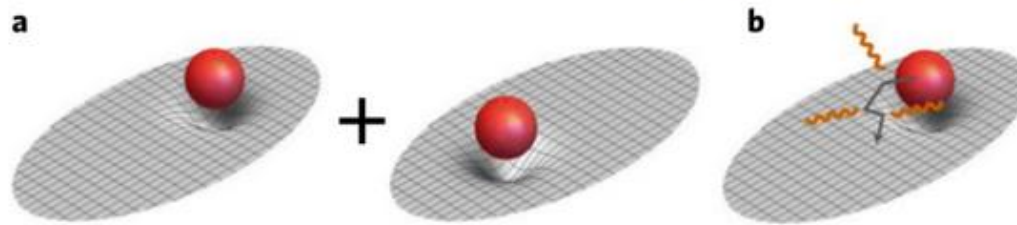
- Diosi – Penrose – gravity related collapse model ...

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

both models induce a diffusion motion for the wave packet :

each time a collapse occurs the center of mass is shifted towards the localized wave function position. Since the process is random this results in a diffusion process



spontaneous emission (A. Bassi & S. Donadi)

- CSL – s. e. photons rate:

$$\frac{d\Gamma'}{dE} = \{ (N_p^2 + N_e) \cdot (N_a T) \} \frac{\lambda \hbar e^2}{4\pi^2 \varepsilon_0 c^3 m_0^2 r_C^2 E}$$

Gravity-related

photons rate:

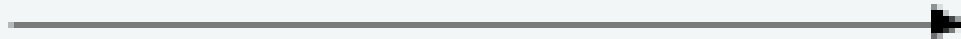
$$\frac{d\Gamma_t}{d\omega} = \frac{2}{3} \frac{G e^2 N^2 N_a}{\pi^{3/2} \varepsilon_0 c^3 R_0^3 \omega},$$

the size of the particle's mass density R_0

Penrose – no radiation (but not yet dynamics?)

FREE PARTICLE

1. Quantum mechanics



2. Collapse models



**Spontaneous emission including nuclear protons –
data taking at LNGS (ultrapure Ge; Matthias Laubenstein)!**



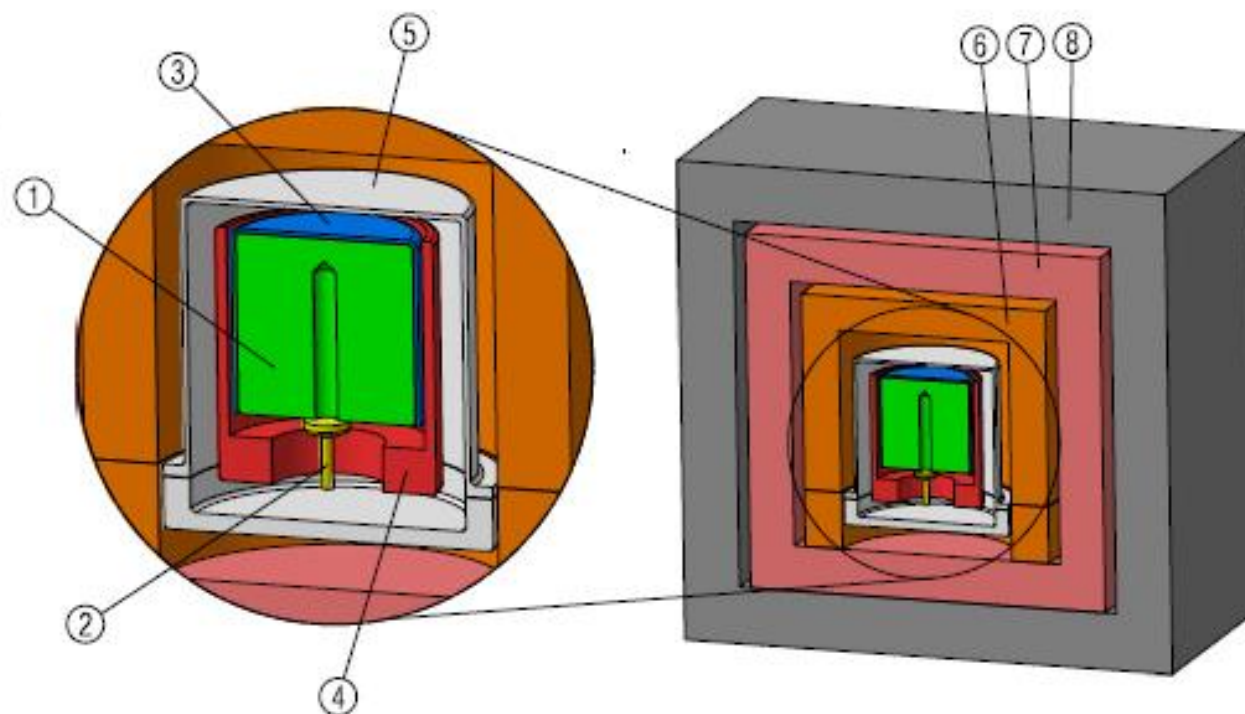


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

HPGe detector based experiment @ LNGS

three months data taking with
2kg Germanium active mass



the pdf of the models parameters is
obtained within a Bayesian model:

$$\tilde{p}(\Lambda_c(R_0)) = \frac{\Lambda_c^{z_c} e^{-\Lambda_c} \theta(\Lambda_c^{\max} - \Lambda_c)}{\int_0^{\Lambda_c^{\max}} \Lambda_c^{z_c} e^{-\Lambda_c} d\Lambda_c}$$

$$R_0 > 0.54 \times 10^{-10} \text{ m} \quad 95\% \text{ C. L.}$$

→ Diosi-Penrose excluded

$$\lambda < 5.2 \cdot 10^{-13} \quad 95\% \text{ C. L.}$$

cosmic rays, bremsstrahlung
from ^{210}Pb & daughters

Region Of Interest $\Delta E = (1000 - 3800) \text{ keV}$
compatible with theoretical constraints

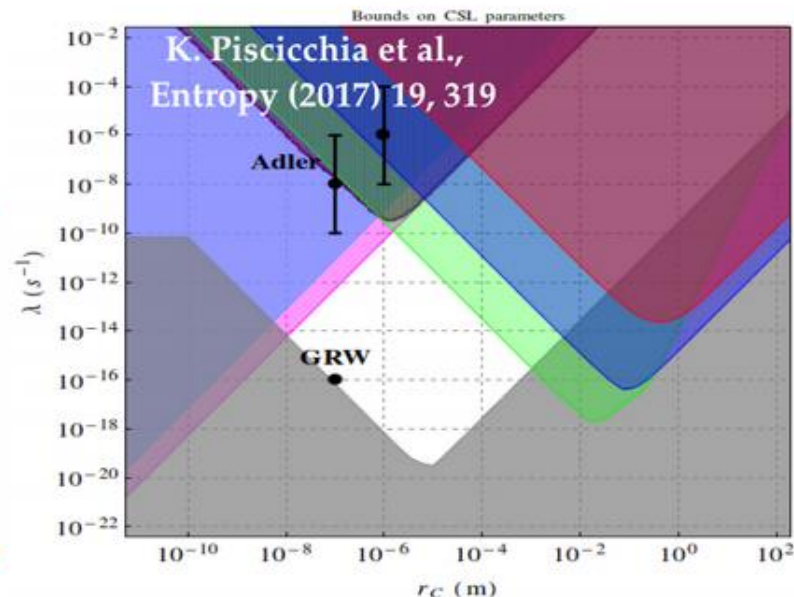
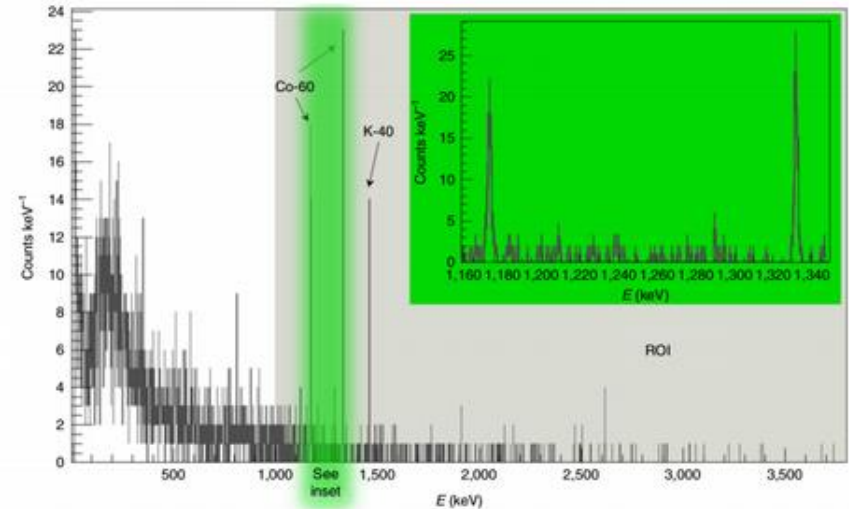
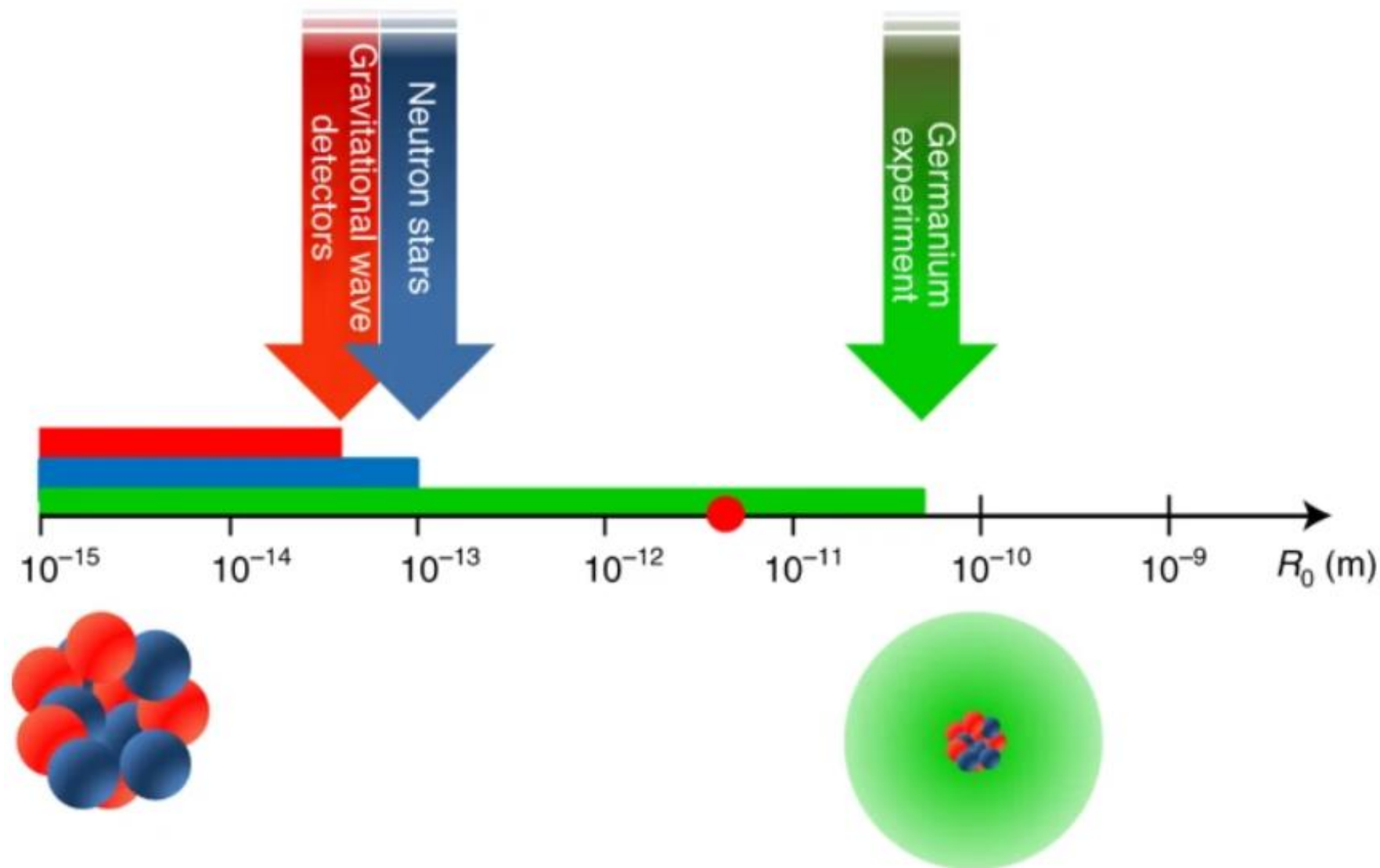


Fig. 5: Lower bounds on the spatial cutoff R_0 of the DP model.





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

Sandro Donadi¹, Kristian Piscicchia^{2,3}, Raffaele Del Grande⁴, Catalina Curceanu^{3d}, Matthias Laubenstein⁵ and Angelo Bassi^{1,6}

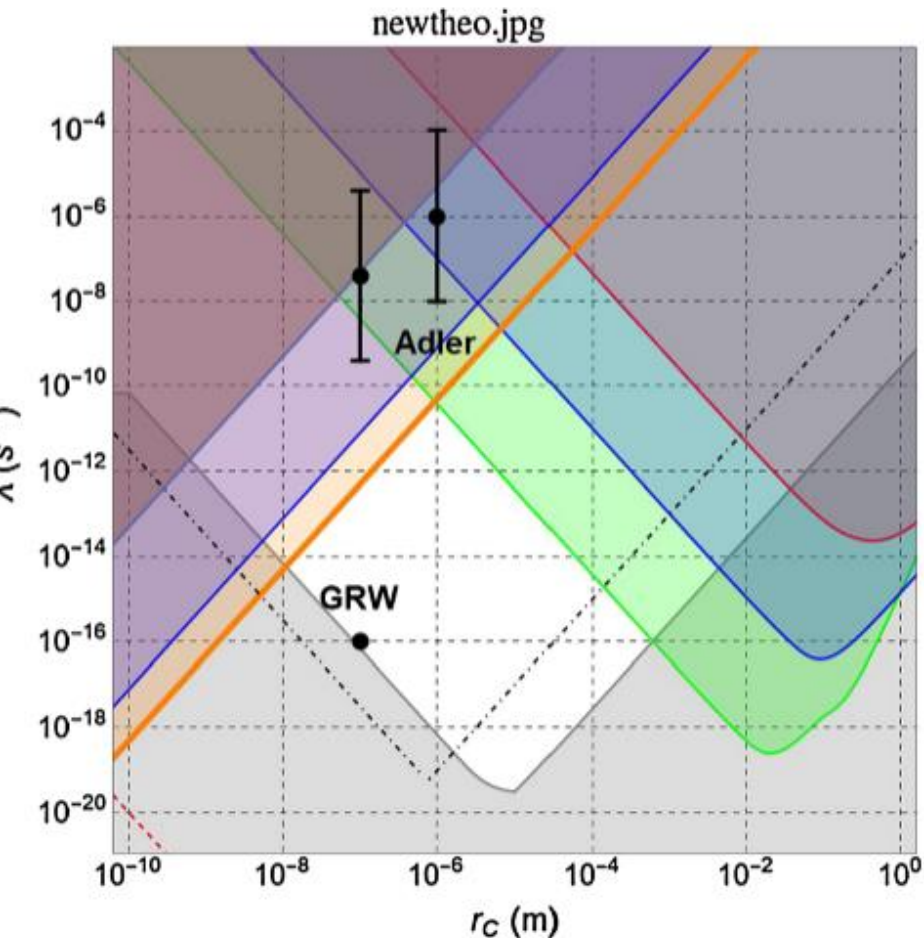


Fig. 4 Mapping of the $\lambda - r_C$ CSL parameters: the proposed theoretical values (GRW [6], Adler [24,25]) are shown as black points. The region excluded by theoretical requirements is represented in gray, and it is obtained by imposing that a graphene disk with the radius of $10 \mu\text{m}$ (about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

We obtain the upper limit on λ

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

X-Ray Emission from Atomic Systems Can Distinguish between Prevailing Dynamical Wave-Function Collapse Models

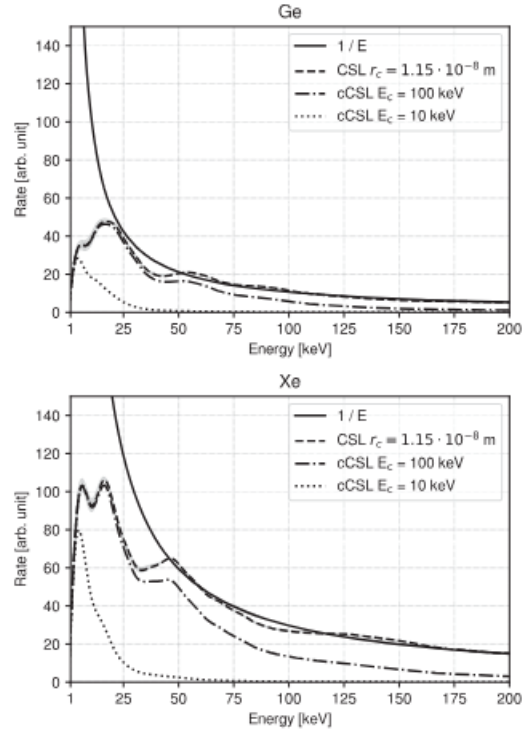


FIG. 1. The top panel of the figure shows (solid line) the $1/E$ dependence Eq. (4), for the spontaneous radiation rate of a Markovian CSL model, which is valid only in the high-energy domain. This is compared to the general rate in Eq. (3) (dashed line) for a prior value of the correlation length $r_c = 1.15 \times 10^{-8}$ m. The distributions are calculated for a germanium atom and normalized to the common constant prefactors. The bottom panel of the figure shows the shapes of the same rates, calculated for a xenon atom. The dotted and dash-dotted curves in the top and bottom panels, represent the

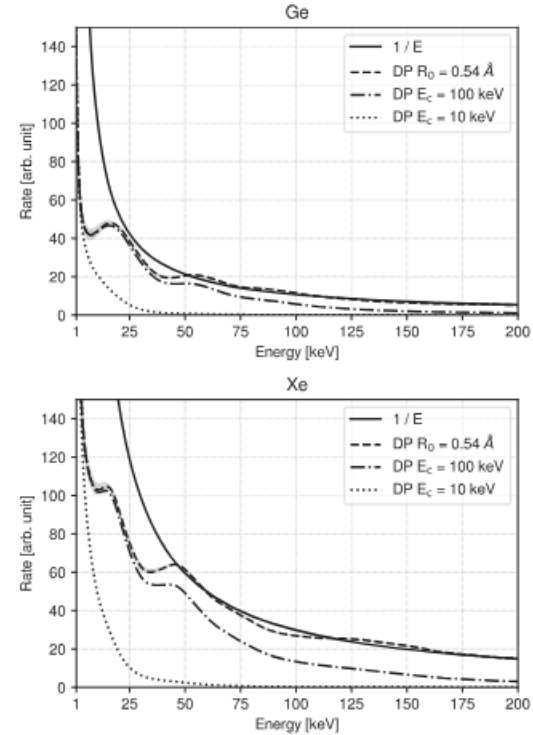


FIG. 2. Top panel of the figure shows (solid line) the $1/E$ dependence Eq. (7), for the spontaneous radiation rate of the Markovian DP model, which is valid only in the high-energy domain. This is compared to the general rate Eq. (10) (dashed line) for a prior value of the correlation length $R_0 = 0.54$ Å. The distributions are calculated for a germanium atom and normalized to the common constant prefactors. The bottom panel of the figure shows the shapes of the same rates, calculated for a xenon atom. The dotted and dash-dotted curves in the top and bottom

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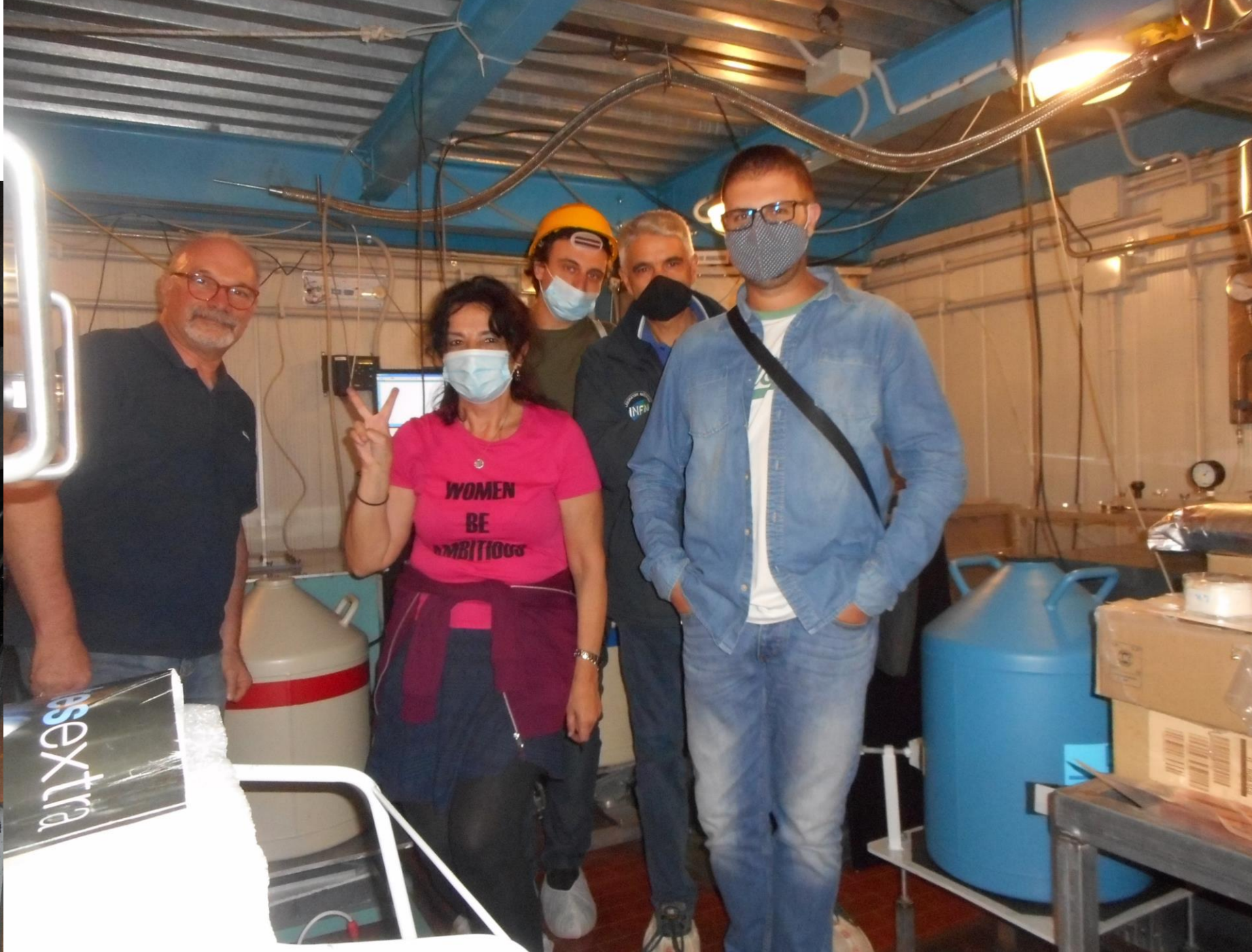
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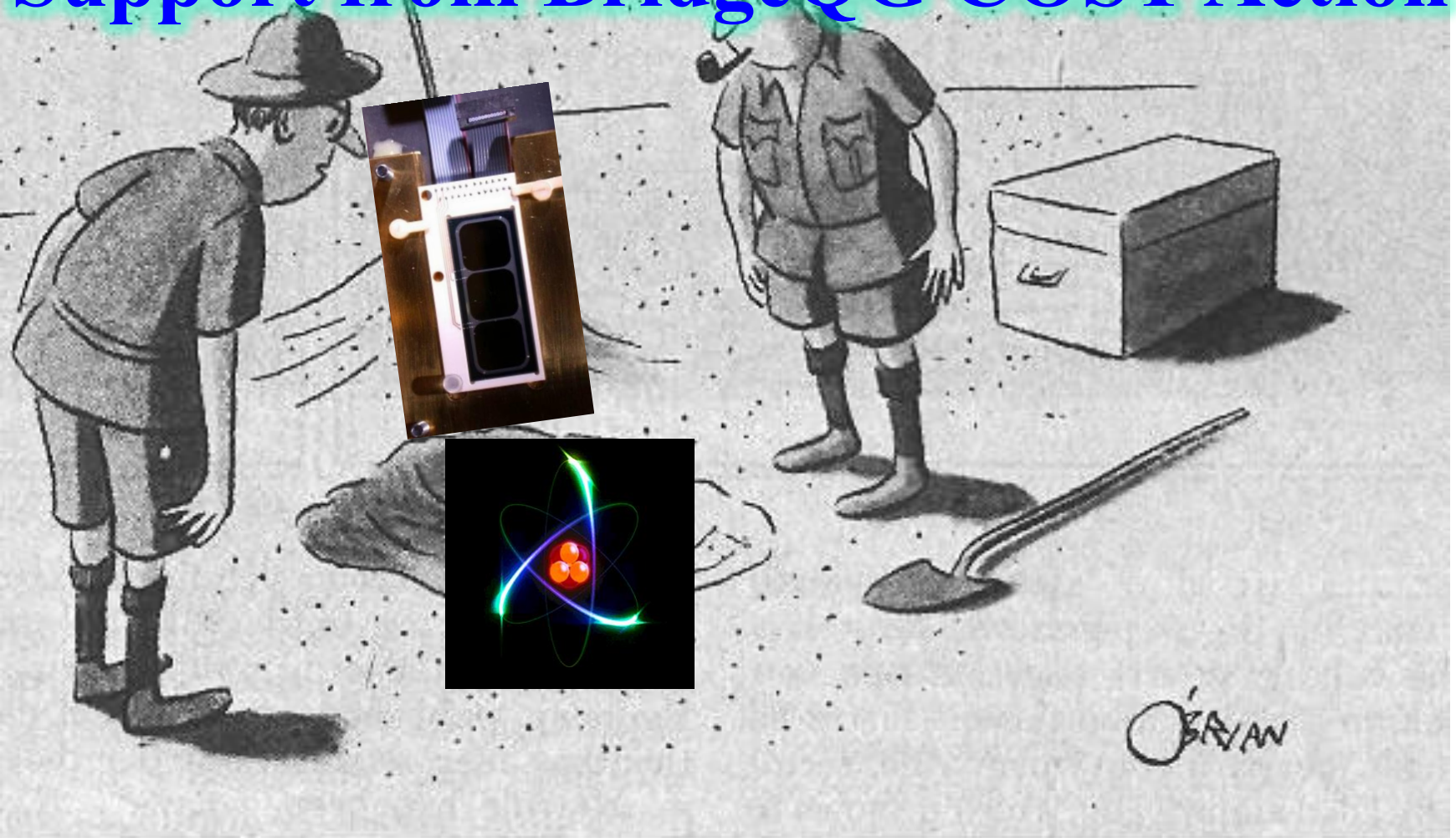
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“This could be the discovery of the century. Depending, of course, on how far down it goes.”

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