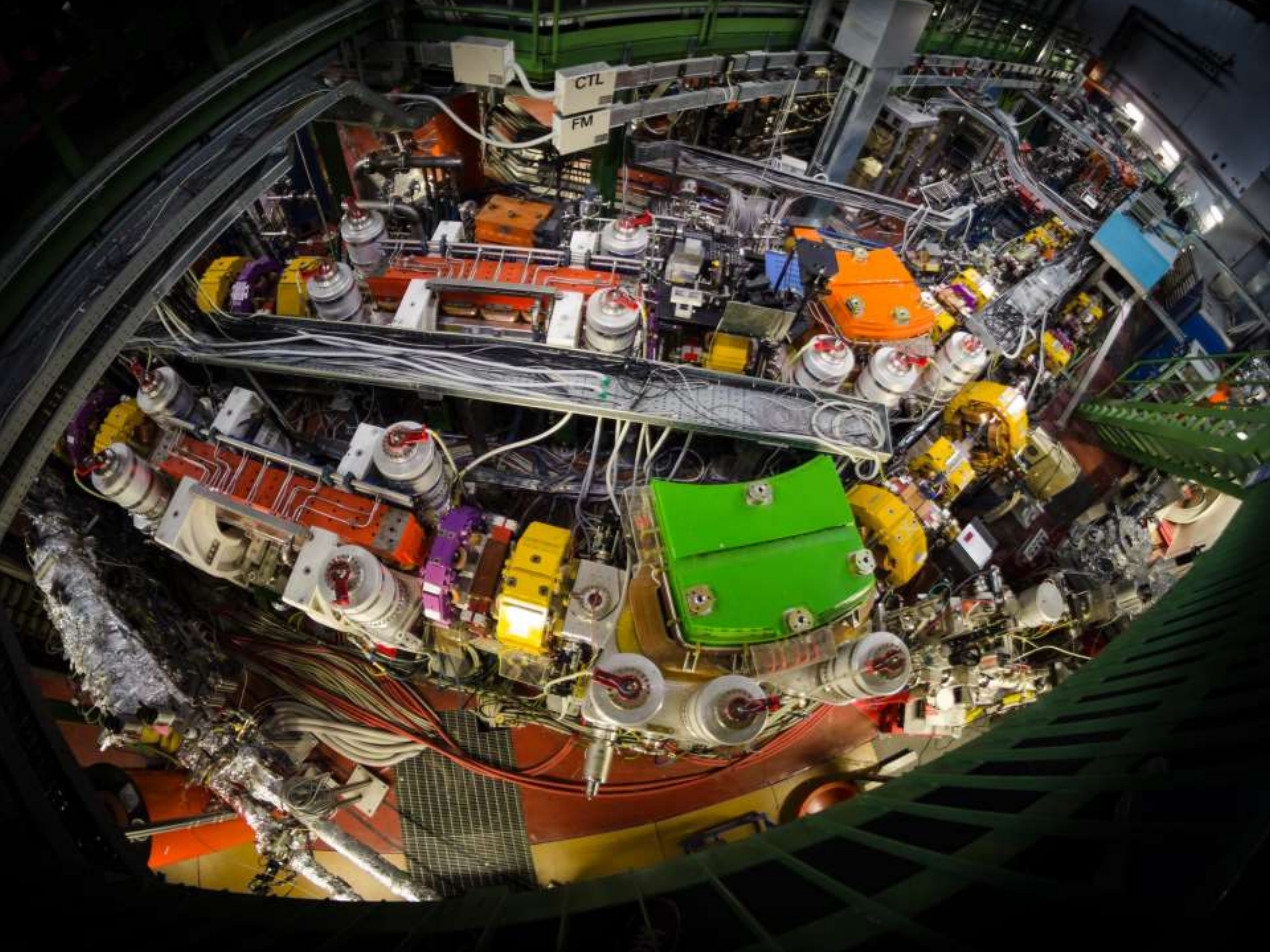
Challenging Quantum Mechanics Underground: Hunting Collapse Signals and Pauli Principle Violations

Catalina Curceanu, LNF-INFN, Frascati (Italy)
On behalf of the VIP Collaboration

Laws of Nature Autumn/Winter 25/26 Series, 12th January2026

My Institute: INFN-LNF

DAΦNE collider


CTL
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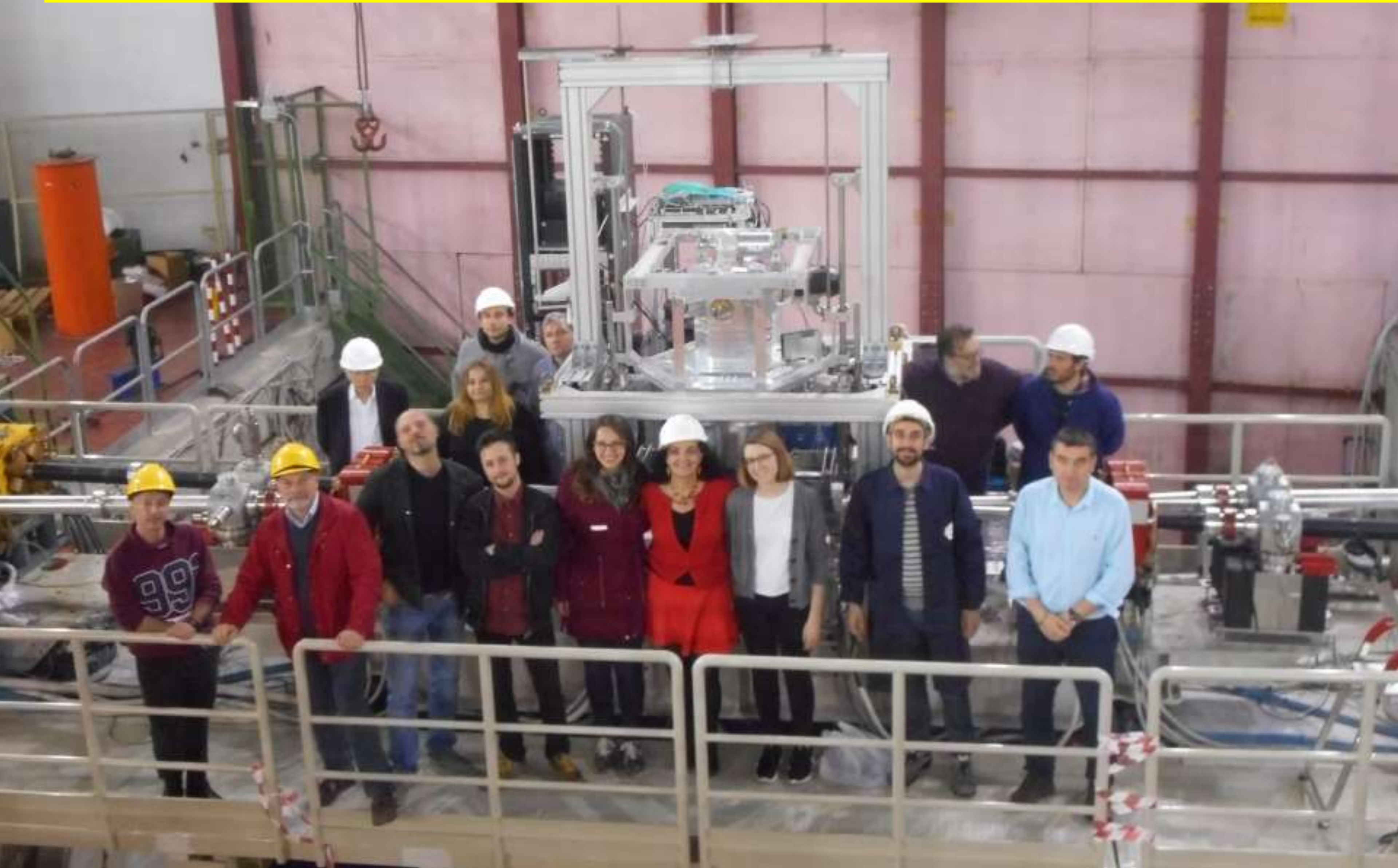
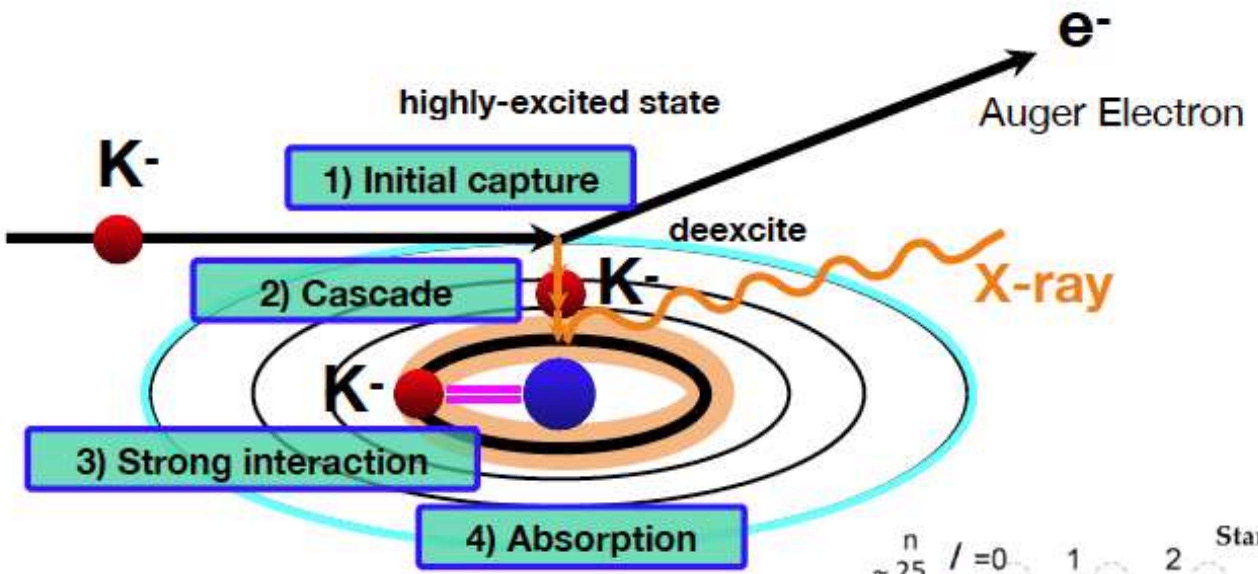
SIDDHARTA

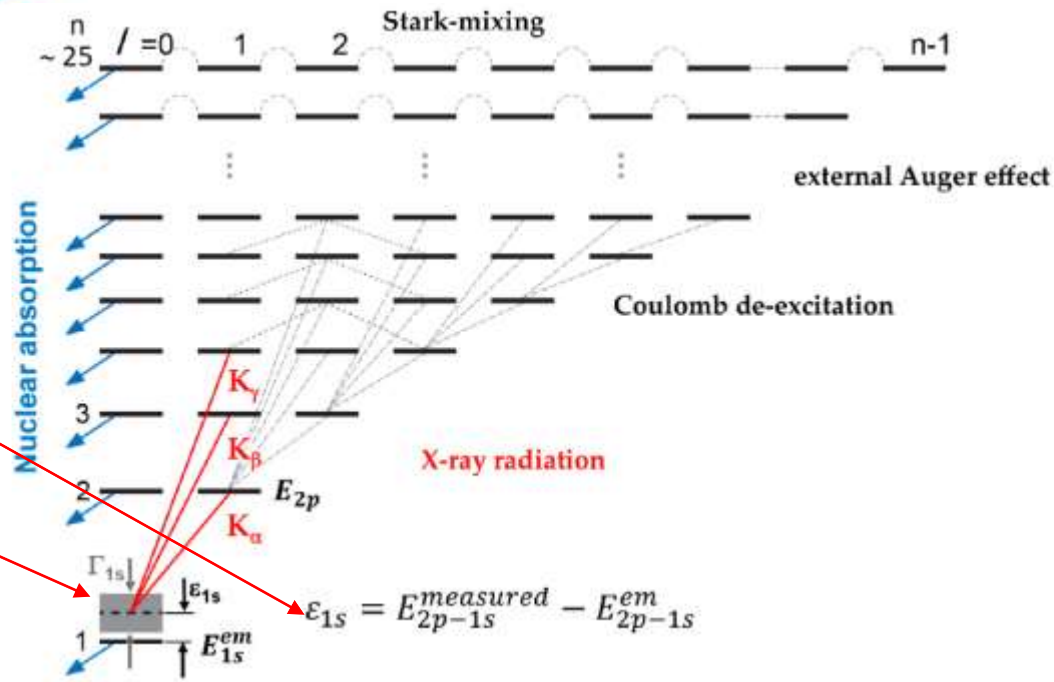
SIlicon Drift Detector for Hadronic Atom Research by Timing Application



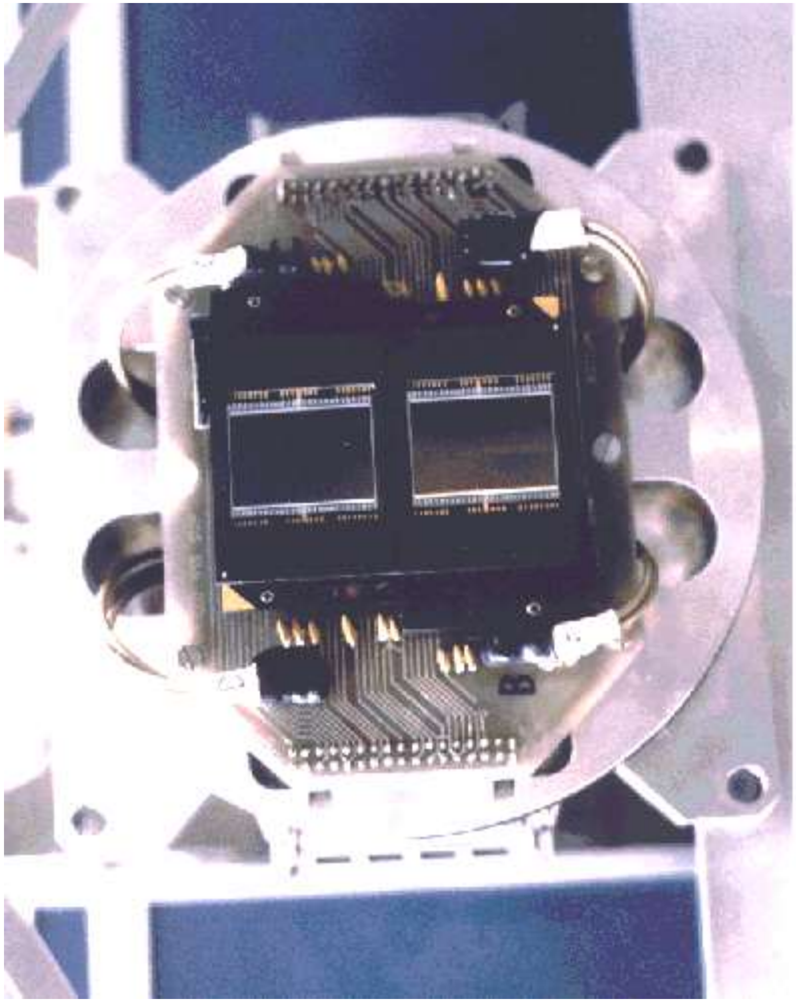
Kaonic atom Formation

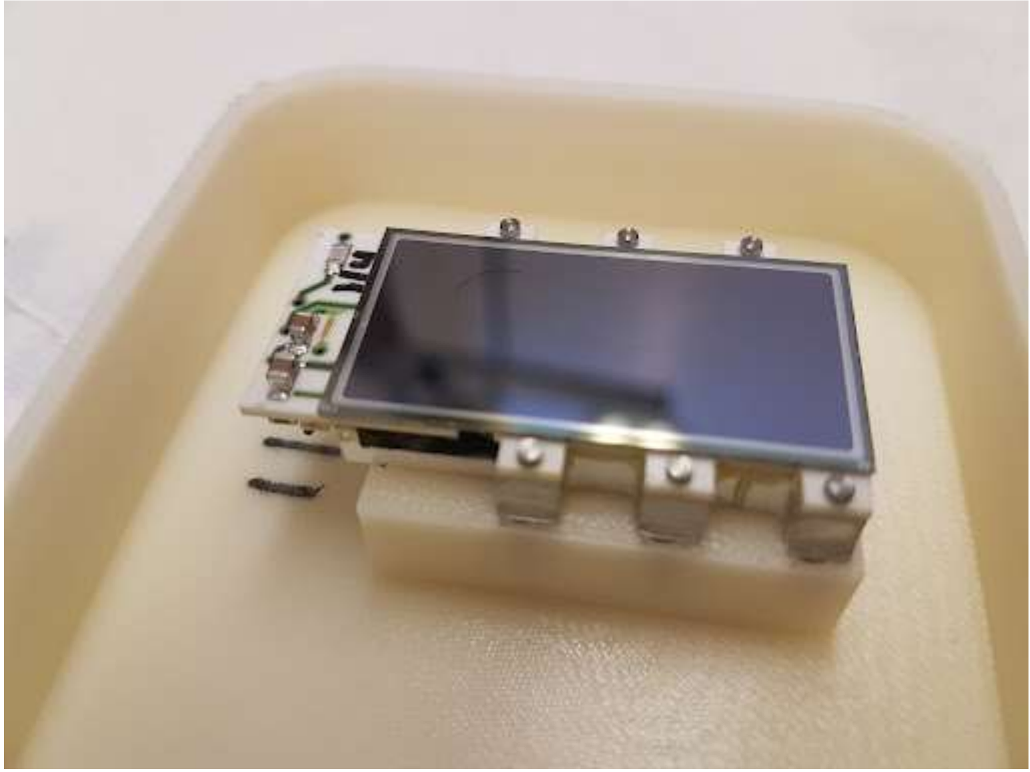


Width Γ and shift ε obtained by measuring the X-rays emitted



X-ray detectors (CCD, SDD)





Quantum Mechanics tests:

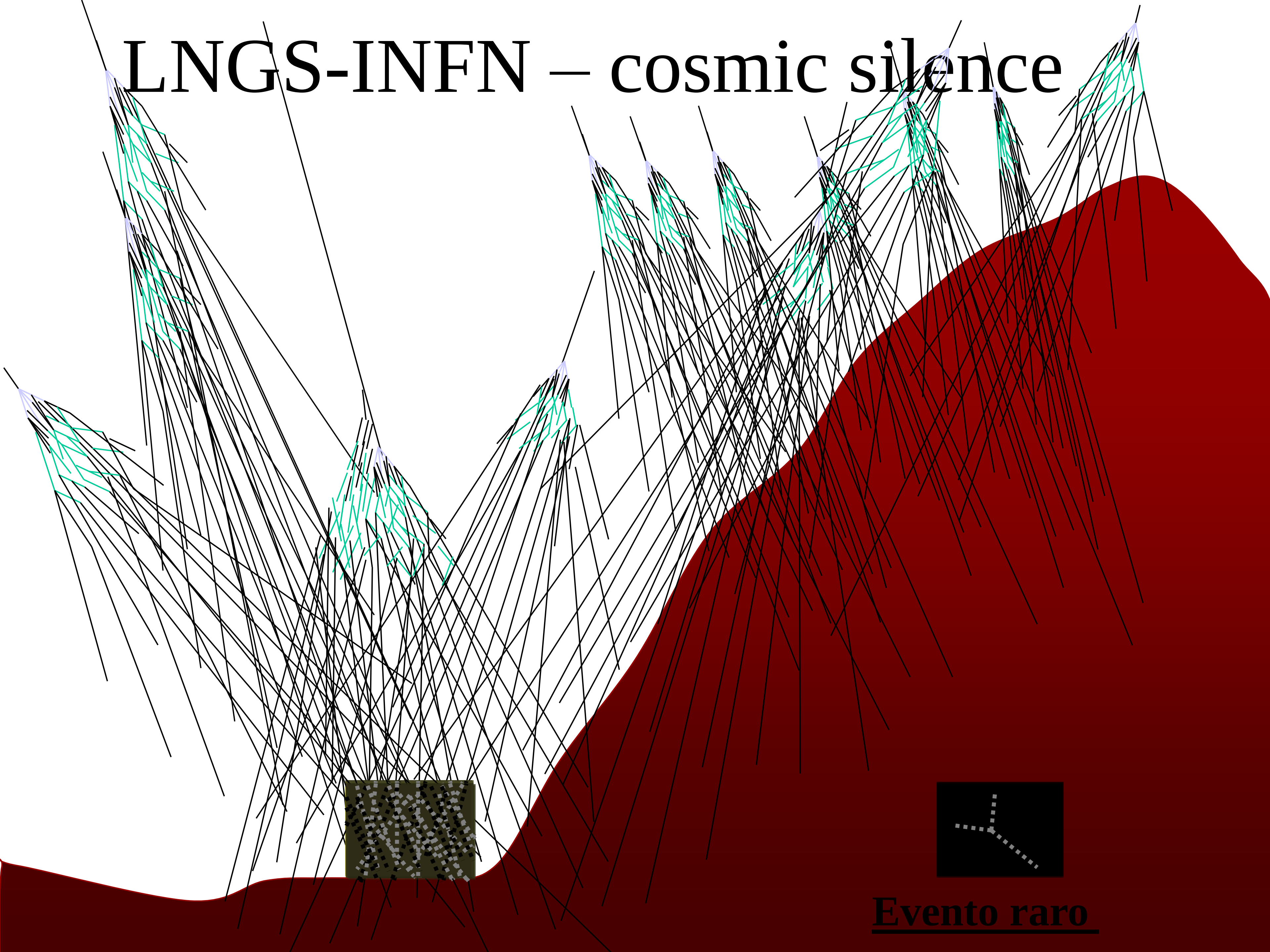
- Pauli Exclusion Principle Violation
- Collapse Models

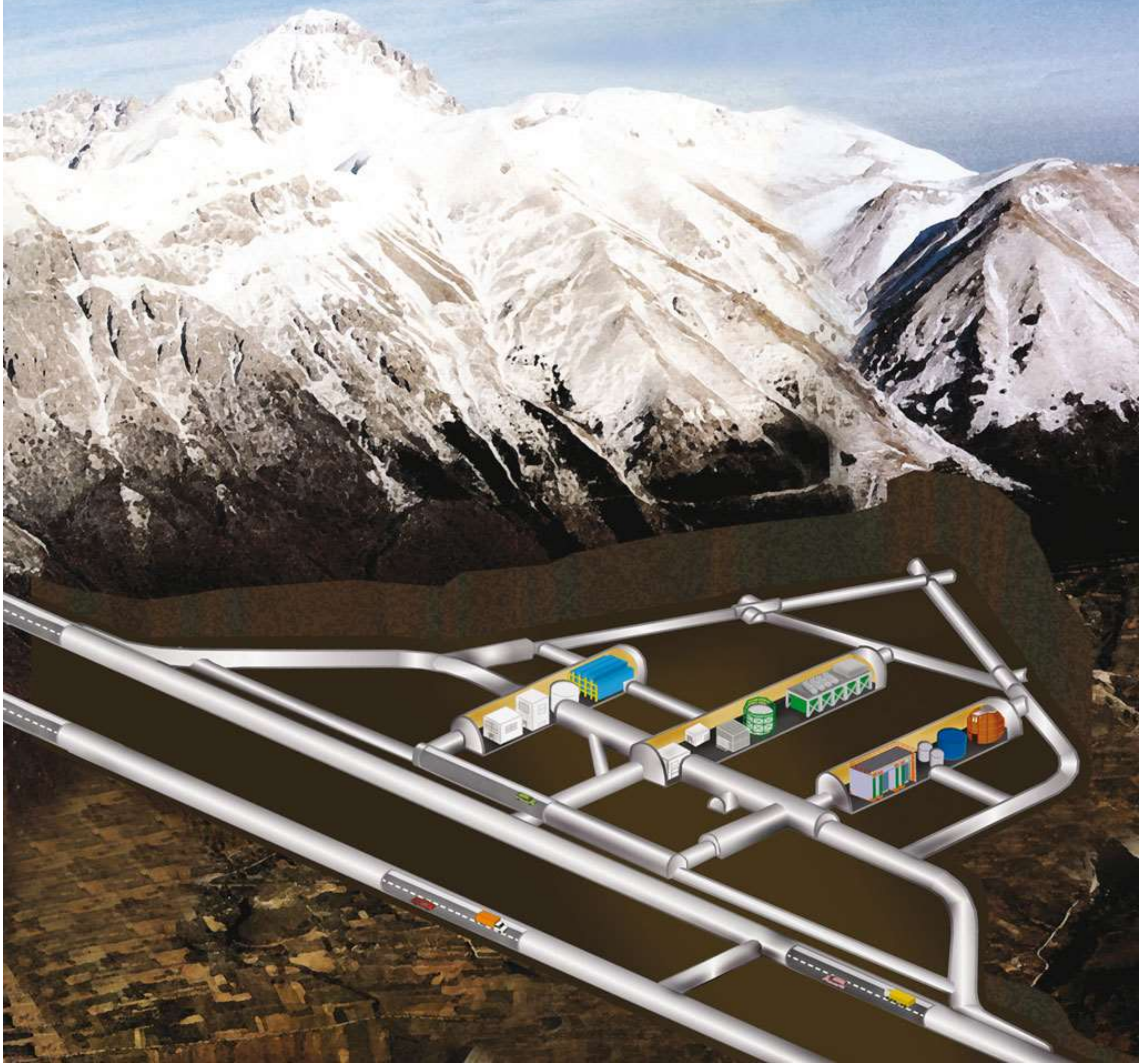
Relation between Quantum and Gravity

Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare

LNGS

LNGS-INFN – cosmic silence






I.N.F.N.
solo autorizzati
STOP
STO


INFN-LABORATORI
NAZIONALI
DEL GRAN SASSO
DAMA

We search for the impossible atoms

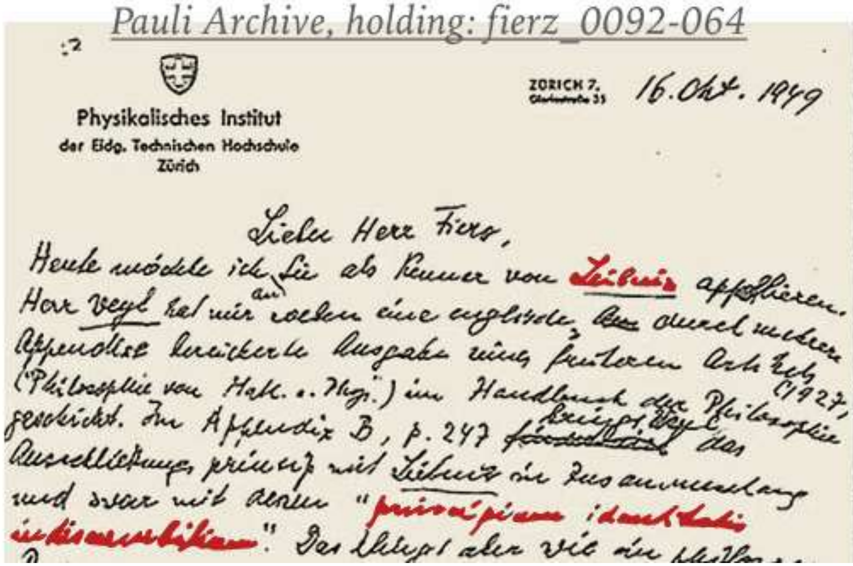
An experiment to test the Pauli Exclusion Principle (PEP) for electrons in a clean environment (LNGS) using atomic physics methods – the VIP experiment

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



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

ZÜRICH 7, Gloriastrasse 35 — 16. Okt. 1949

Lieber Herr Fierz,
Heute möchte ich Sie als Kenner von Leibniz apostrophieren.
Herr Weyl hat mir eben eine englische, um durch mehrere
Appendices bereicherte Ausgabe eines früheren Artikels (1927)
("Philosophie von Math. u. Nat.") im Handbuch der Philosophie
geschickt. Im Appendix B, p. 247 bringt Weyl das
Ausschließungsprinzip mit Leibniz in Zusammenhang
und zwar mit dessen "principium identitatis
indiscernibilium". Das ...

Required for bosons.

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

Required for fermions.

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

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)

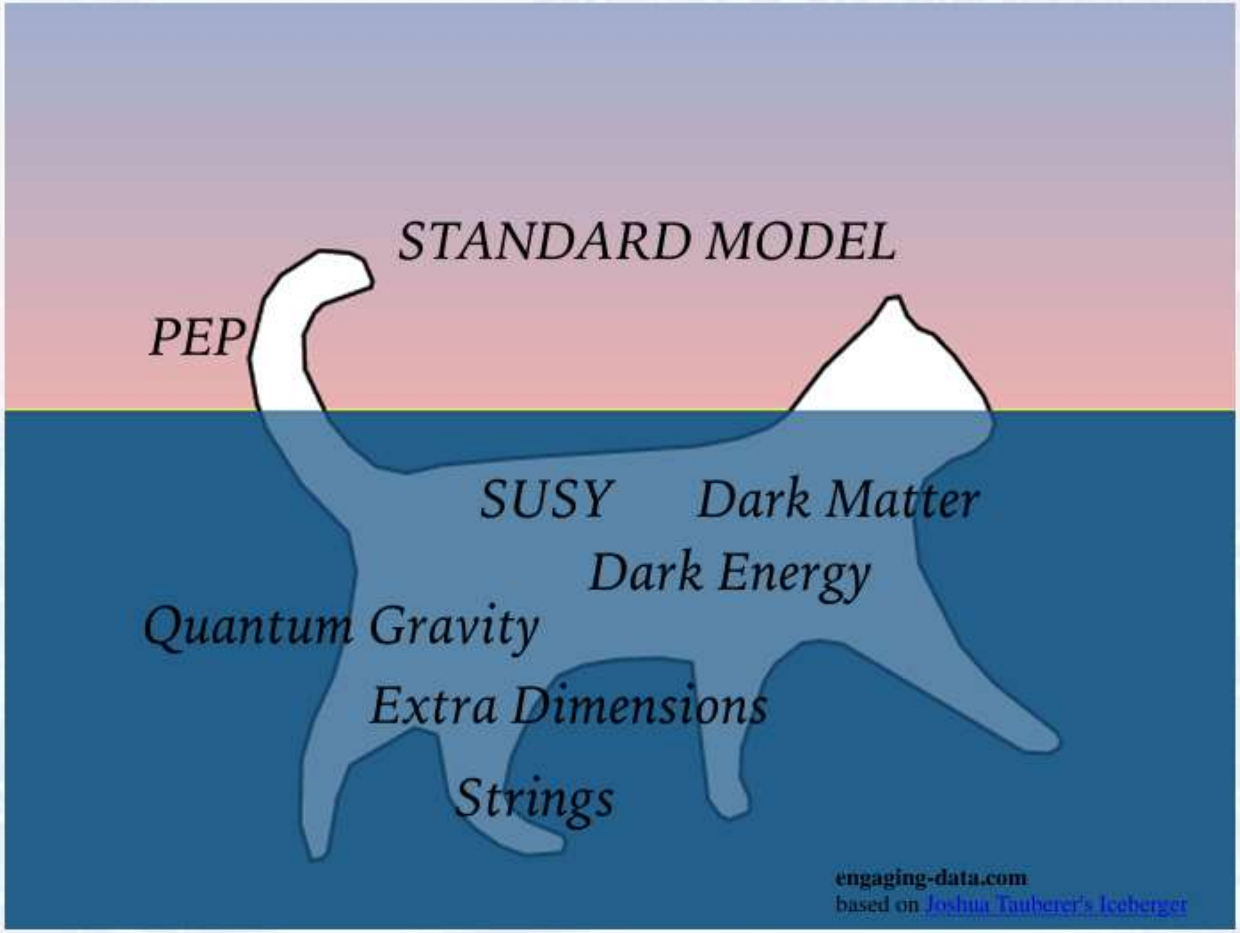
Theories of Violation of Statistics

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."

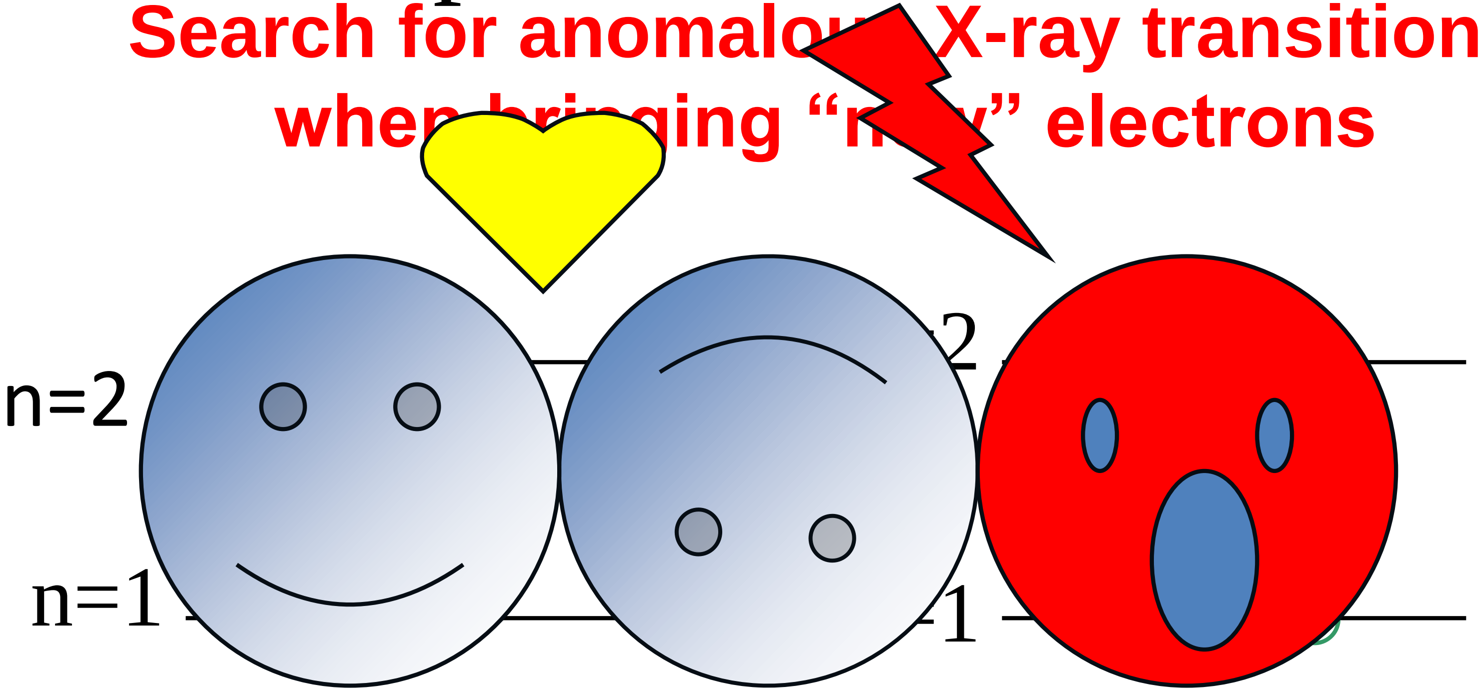
The Pauli Exclusion Principle (PEP)



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

Experimental method:

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



Normal 2p –>1s transition

Energy 8.04 keV

2p –>1s transition violating Pauli principle

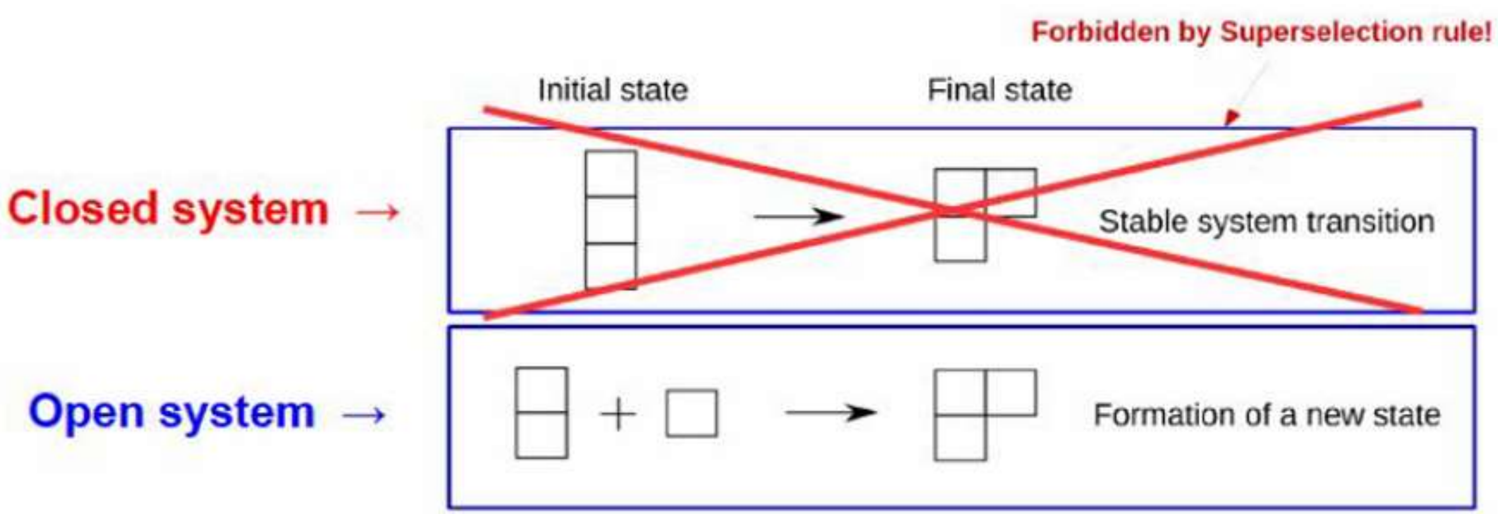
Energy 7.7 keV

Messiah Greenberg superselection rule

Messiah-Greenberg super-selection rule:

Superposition of states with different symmetry are not allowed →

<u>Transition probability between two symmetry states is ZERO</u>



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

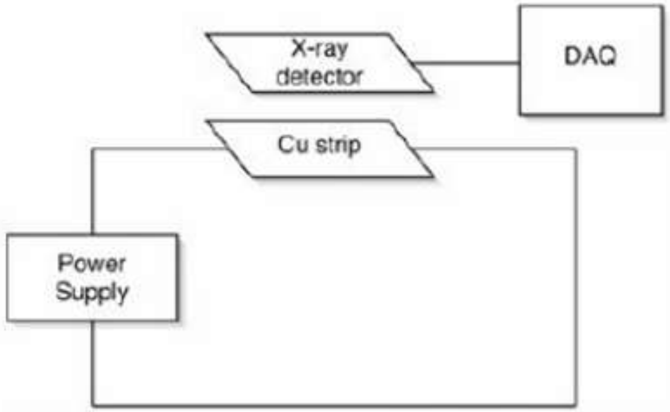
Greenberg, O. W. & Mohapatra, R. N., Phys Rev Lett 59, (1987).
E. Ramberg and G. A. Snow, Phys Lett B 238, 438–441(1990)

Search for anomalous electronic transitions in Cu induced by a circulating current

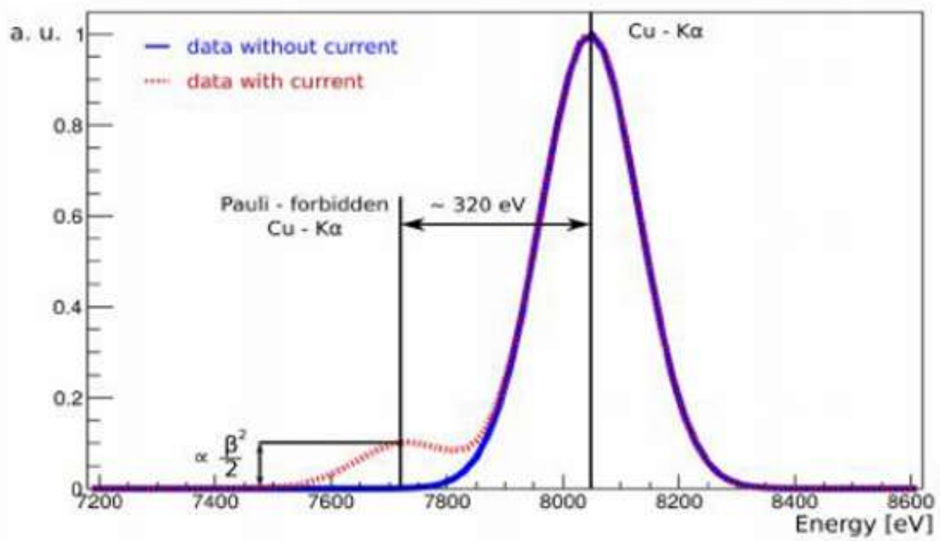
introduced electrons interact with the valence electrons

search transition from 2p to 1s already filled by 2 electrons

alternated to X-ray background measurements without current

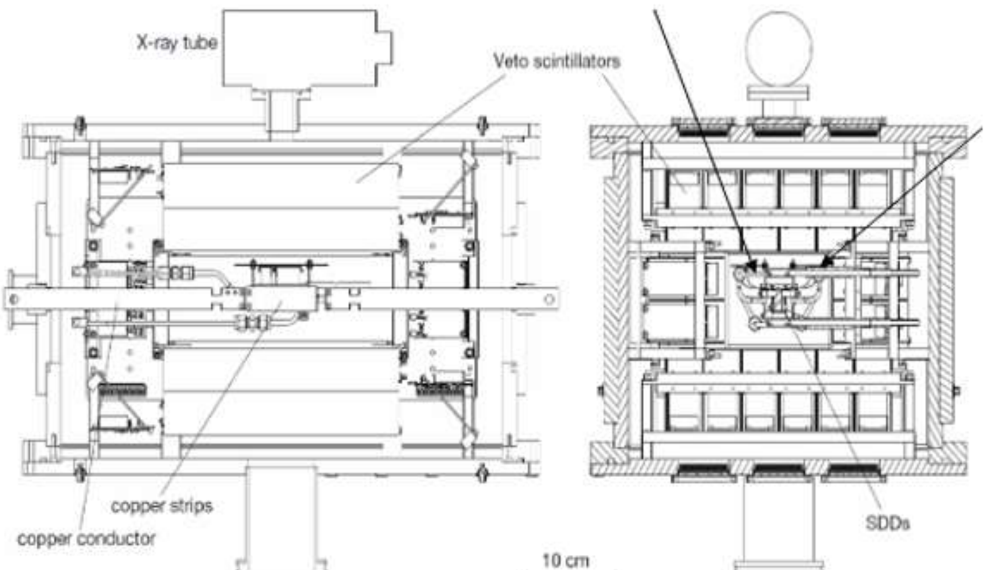


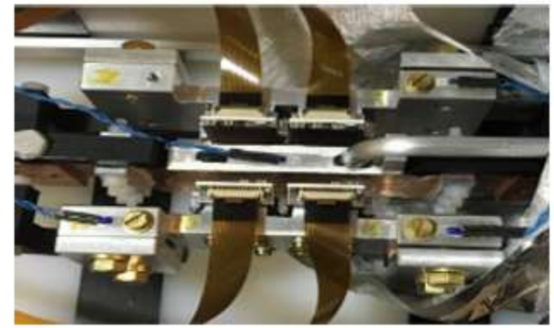
PEP Violation Signal:

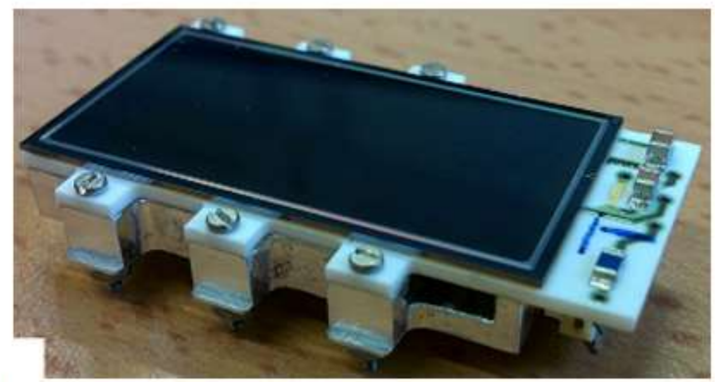


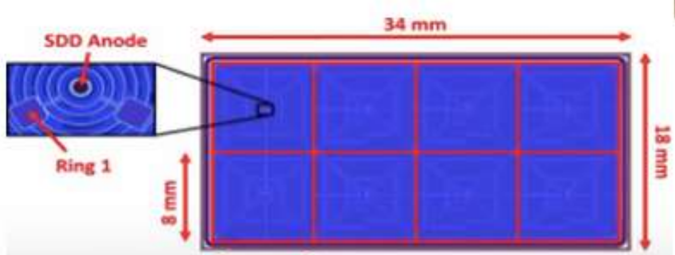
The VIP-2 Experiment

Silicon Drift Detectors (**SDDs**) higher resolution (190 eV FWHM at 8.0 →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

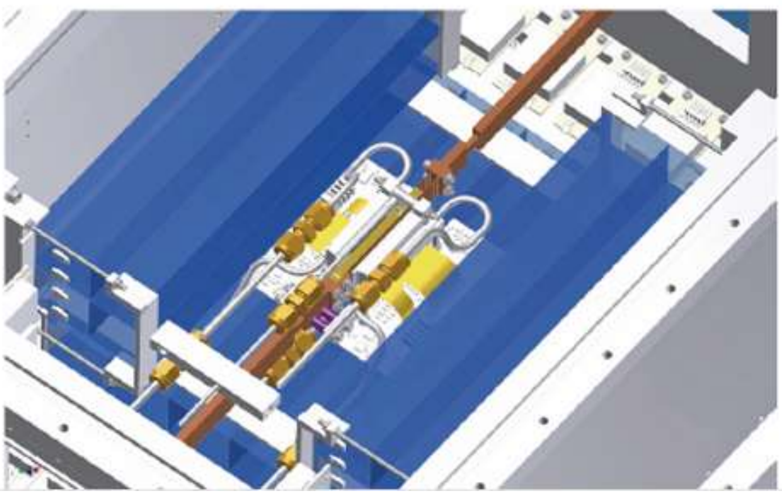
*2 strip shaped Cu targets (25 um x 7 cm x 2 cm) more compact target → higher acceptance, thinner → **higher efficiency***

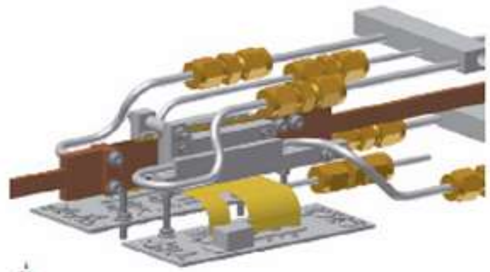
DC current supply to Cu bars

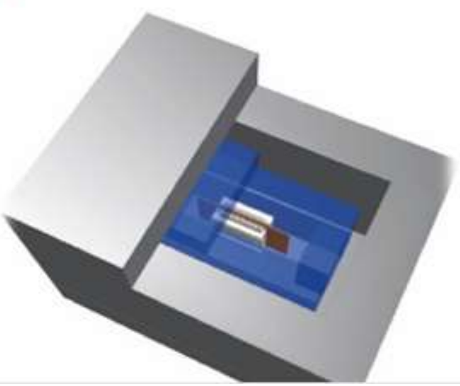
*Cu strips cooled by a closed Fryka chiller circuit →**higher current***

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

Sketch of the VIP2 Setup:







Nat. Phys. (2020)

Open Access Feature Paper Article

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

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

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

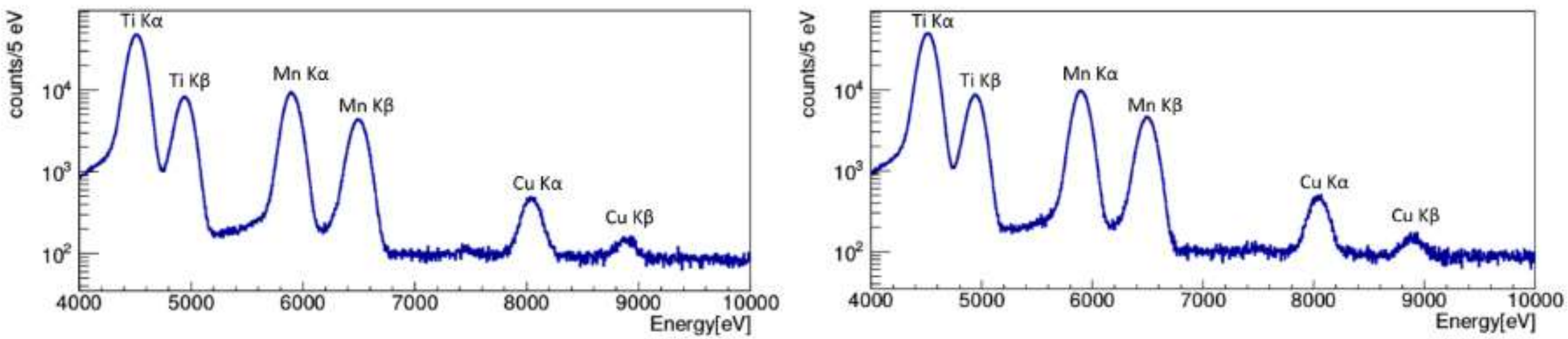


Figure 3. Energy calibrated spectra corresponding to about 42 days of data taking (during 2018) collected with current on (left), the spectrum collected with current off (right), which is normalized to the time of data taking with current on.

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

Scientific Reports volume 15, Article number: 41544 (2025)

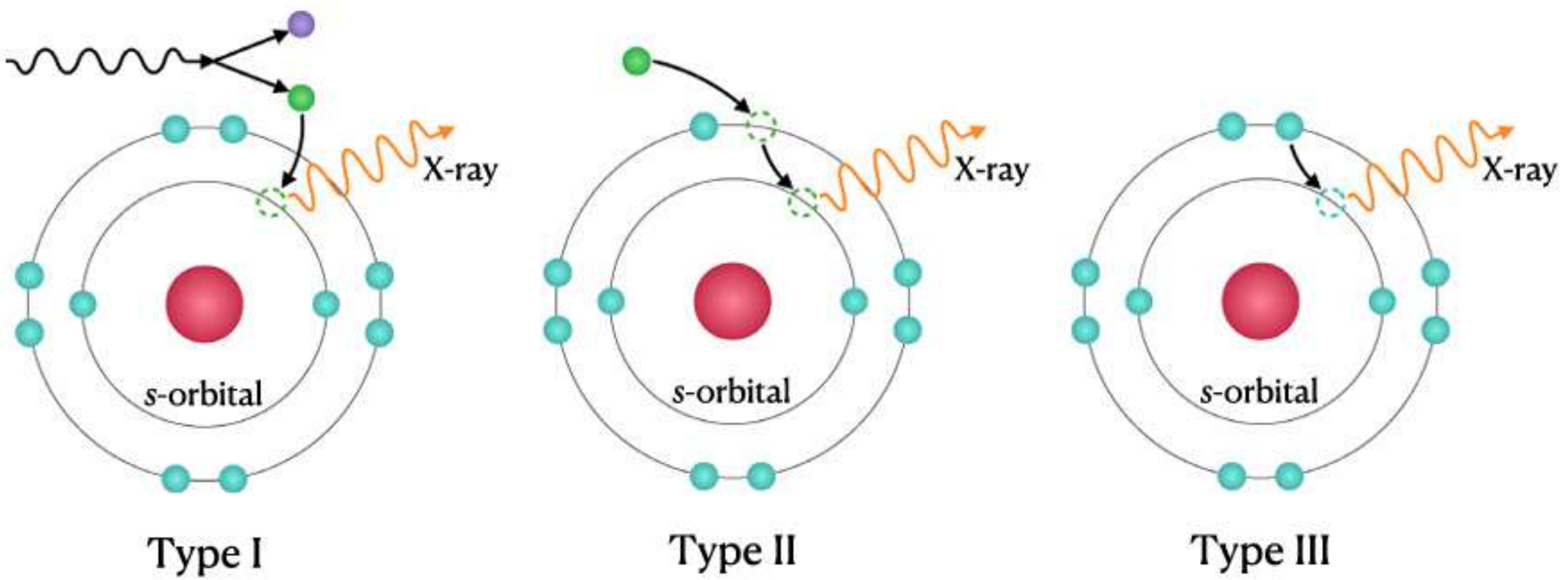


Fig. 1. Scheme of the Type I, II, and III transition processes and signature emission (see Sect. 1.1). In the atom depiction, nuclei are in red, electrons of the system in cyan, newly introduced electrons in green, positrons in purple, and emitted X-rays in yellow. For simplicity, we depicted the atomic levels of interest for this work involved in the K_α transition with the *s*-orbital of the ground state represented by an inner circle with two electrons (fully occupied) and the non-ground states simplified as an external circle with an electron octet.

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

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

Scientific Reports volume 15, Article number: 41544 (2025)

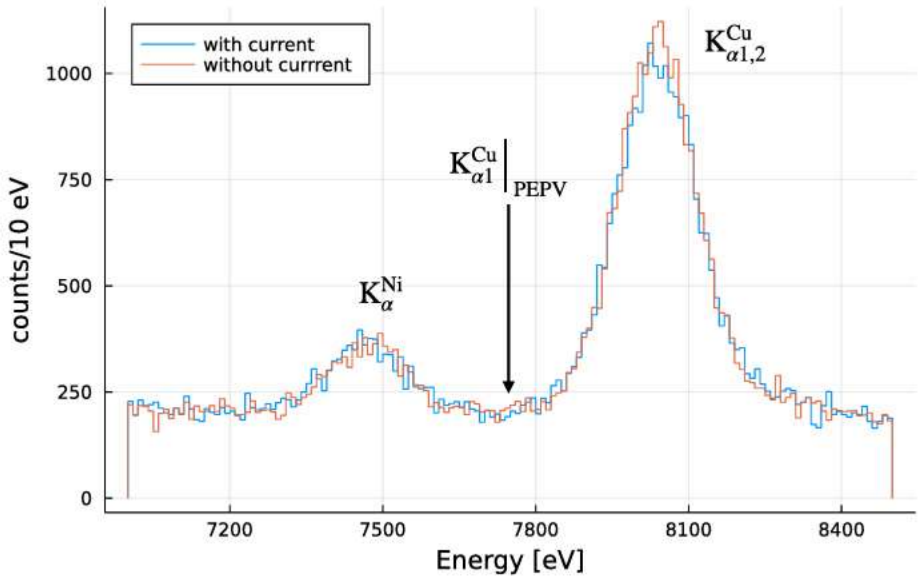


Fig. 4. VIP-2 calibrated data in the region-of-interest 7000-8500 eV, of about two years of data taking (May 2019 to May 2021). The spectrum of the data acquired with a current circulating in the target is shown in blue. Data taken without current in the target, used as reference and control, shown in red. The copper and nickel K_α lines are visible in the spectra.

$$\beta^2/2 < 2.47 \times 10^{-43} \text{ @ } 90\% \text{ CL},$$

$$1 + q < 4.94 \times 10^{-43} \text{ @ } 90\% \text{ CL},$$

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

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

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

A. Addazi, 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.

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

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 – with directionality (magnetic field) – minimal length, holography… IDEAS?

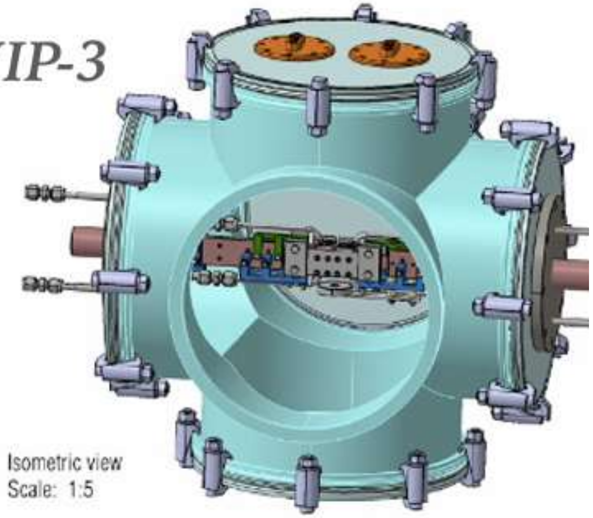
Lev Okun' wrote in his 1987 paper (JETP Lett. 1987 46:11, 529–532) that

"***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***"

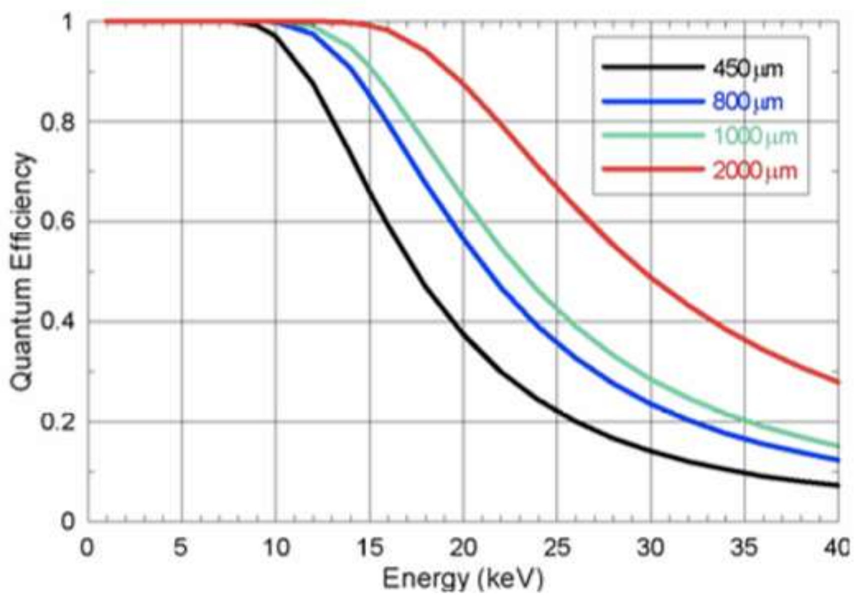
New setup: VIP3 – new SDDs
In preparation
Study PEP violation
Along the periodic table

VIP-2 experimental upgrade: VIP-3

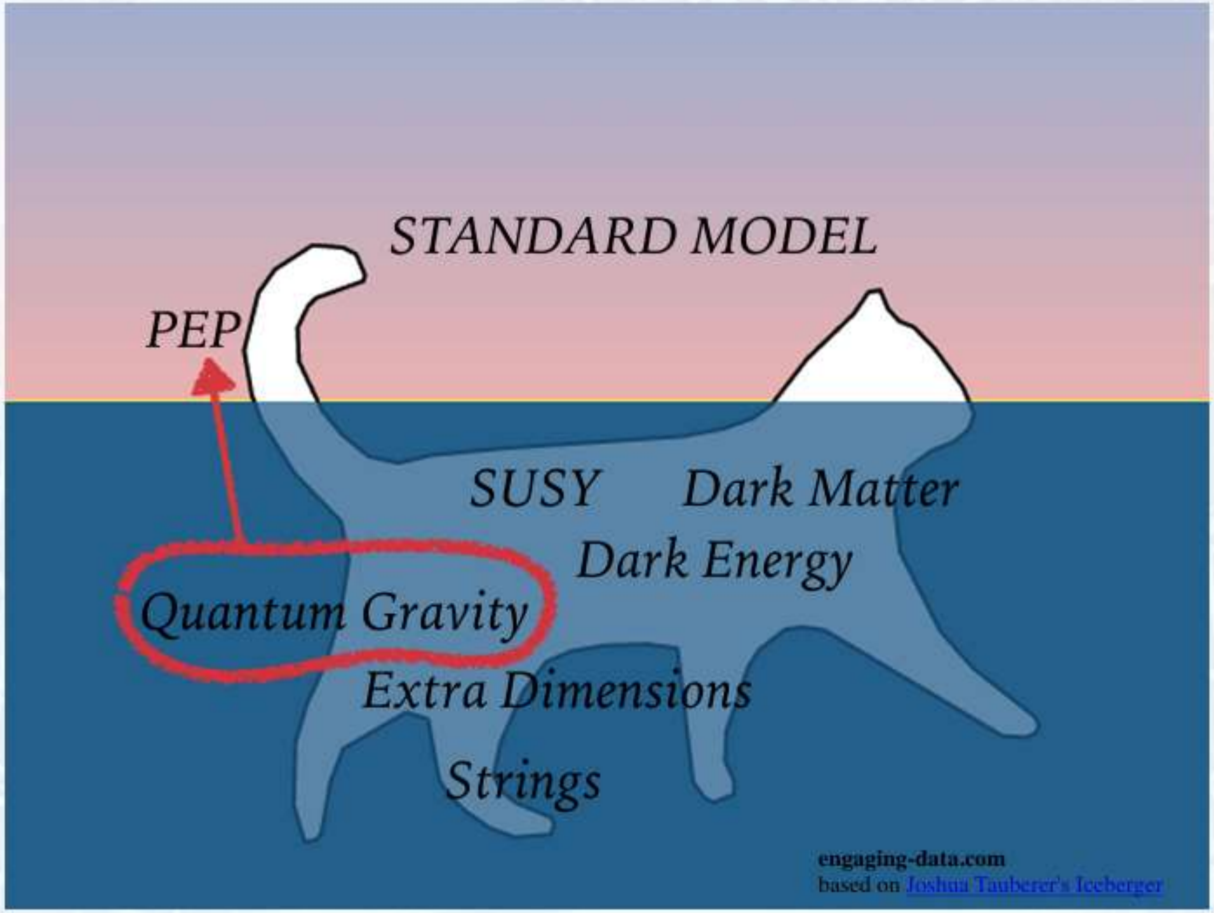
- ***new vacuum chamber,*** *increase the number of SDD detectors, increase the geometrical efficiency, higher current up to* ***400 A***
- *New thermal contact between cold finger and SDDs*
- *New target cooling system*



- ***Higher quantum efficiency needed for the SDDs at higher Z: use 1 mm thick SDDs, allowing to scan e.g. Ag, Sn and Pd***



Testing the Pauli Exclusion Principle across the Periodic Table with the VIP-3 Experiment
Entropy 26 (2024) 9, 752



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-PHO-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.


Foto: Andrei Paul, Primaria Brasov

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

The measurement problem

Possible solutions:

-De Broglie – Bohm

- Many-World Interpretations

The measurement problem

Possible solutions:

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


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

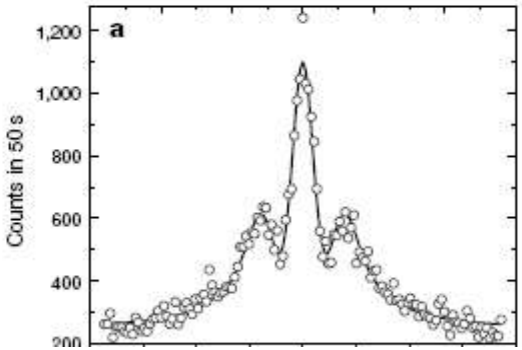
What are collapse models

1. **Collapse models = <u>solution of the measurement problem</u>**

   Paradox-free description of the quantum world

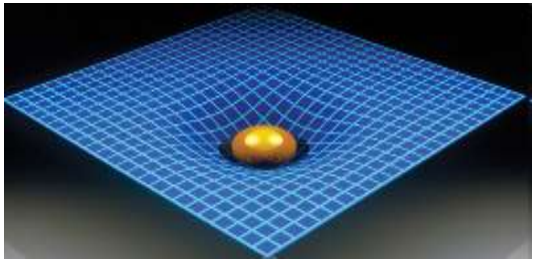
2. **Collapse models = <u>rival theory of Quantum Mechanics</u>**

   They are related to experiments testing quantum linearity



3. **Collapse models as <u>phenomenological models of an underlying pre-quantum theory</u>**

   Can gravity causes the collapse?



Dynamical Reduction Models:

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

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

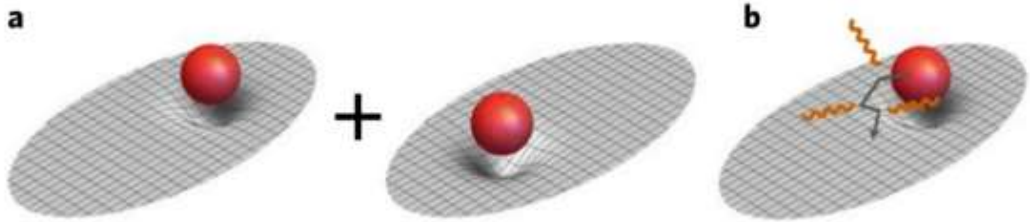
- **Diosi – Penrose – gravity related collapse model …**

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

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 R0

Penrose – no radiation (but not yet dynamics?)

Which values for λ and r_c?

Microscopic world
(few particles)

$\lambda \sim 10^{-8\pm2}\mathrm{s}^{-1}$

QUANTUM – CLASSICAL
TRANSITION
(Adler - 2007)

Mesoscopic world
Latent image formation
+
perception in the eye
(~ 10^4 - 10^5 particles)

S.L. Adler, JPA 40, 2935 (2007)

A. Bassi, D.A. Deckert & L. Ferialdi, EPL 92, 50006 (2010)

$\lambda \sim 10^{-17}\mathrm{s}^{-1}$

QUANTUM – CLASSICAL
TRANSITION
(GRW - 1986)

Macroscopic world
(> 10^{13} particles)

G.C. Ghirardi, A. Rimini and T. Weber, PRD 34, 470 (1986)

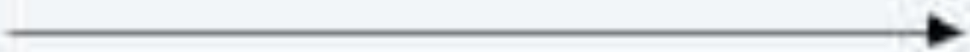
$r_C = 1/\sqrt{\alpha} \sim 10^{-5}\mathrm{cm}$

Increasing size of the system

PREDICTIONS of collapse models are **different from standard quantum mechanical predictions** … they can be tested experimentally! …

FREE PARTICLE

1. Quantum mechanics



2. Collapse models

nature physics

Article | Published: 07 September 2020

Underground test of gravity-related wav
function collapse

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

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

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-non-covid-19-edition

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

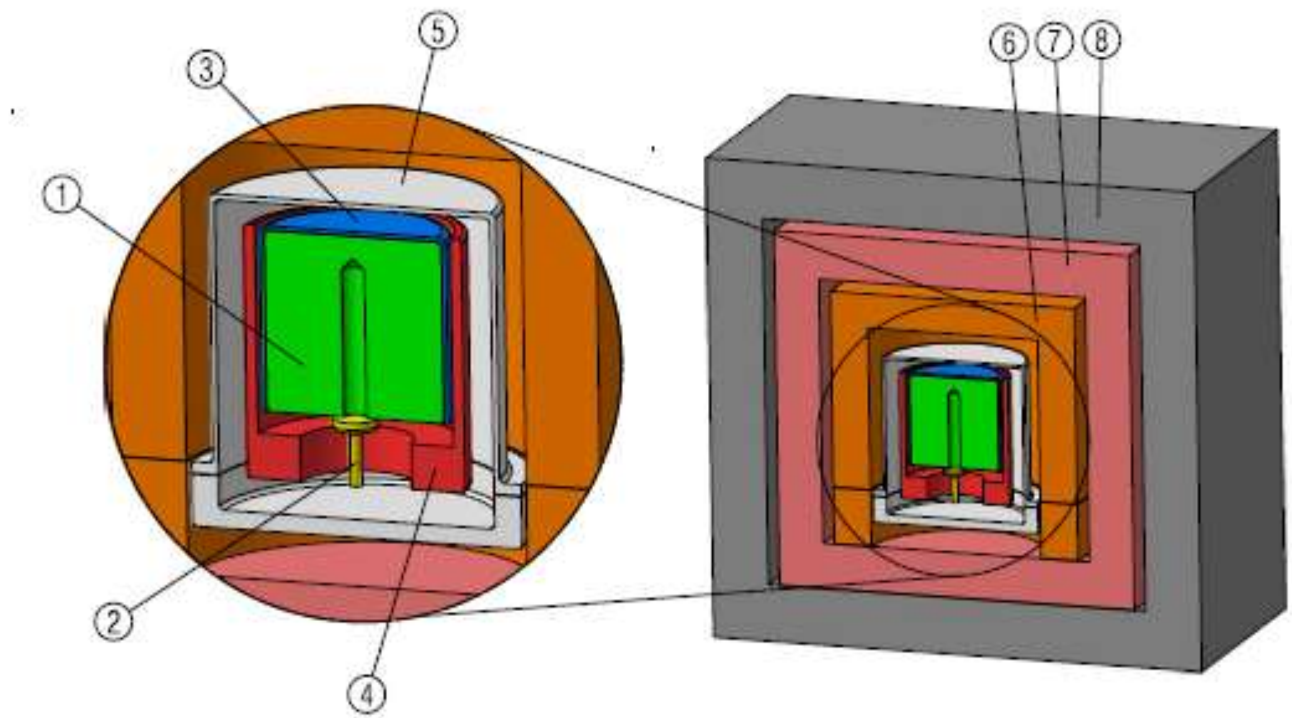


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

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:

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

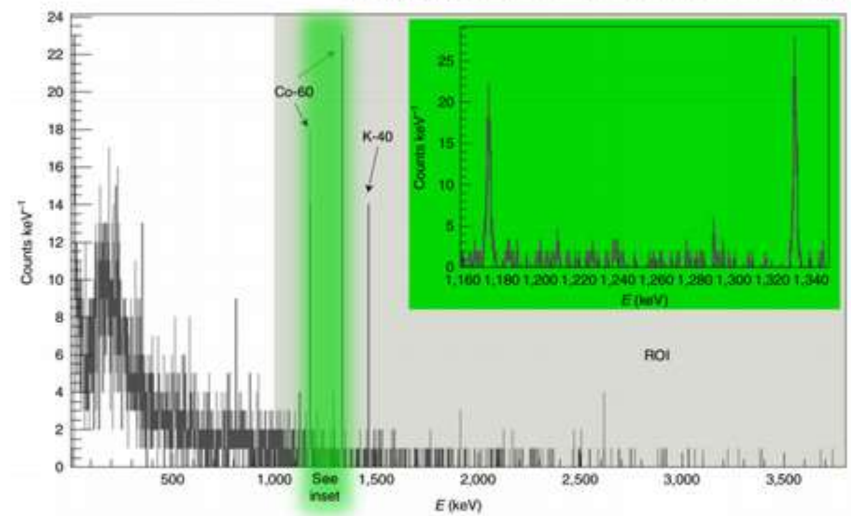
$R_0 > 0.54 \times 10^{-10}$ m **95% C. L.**

→ Diosi-Penrose excluded

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

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

Region Of Interest ΔE=(1000 – 3800)keV compatible with theretical constrains



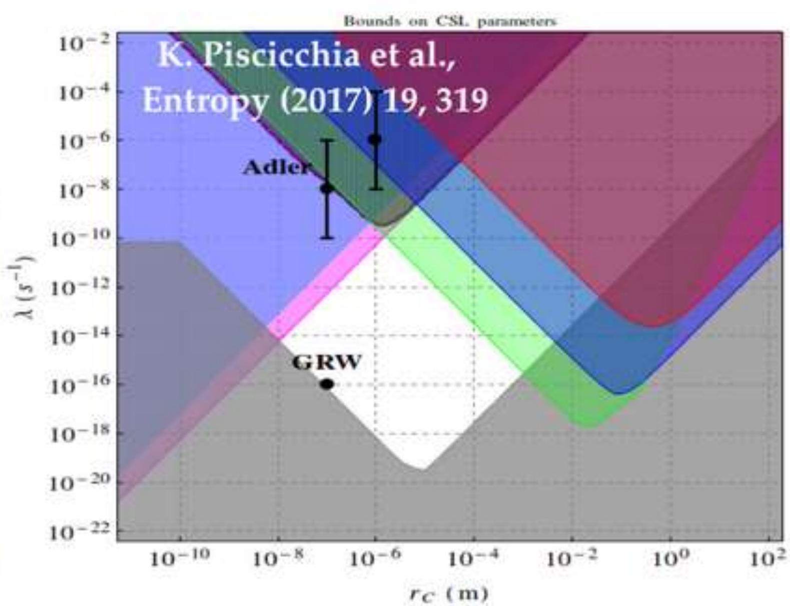
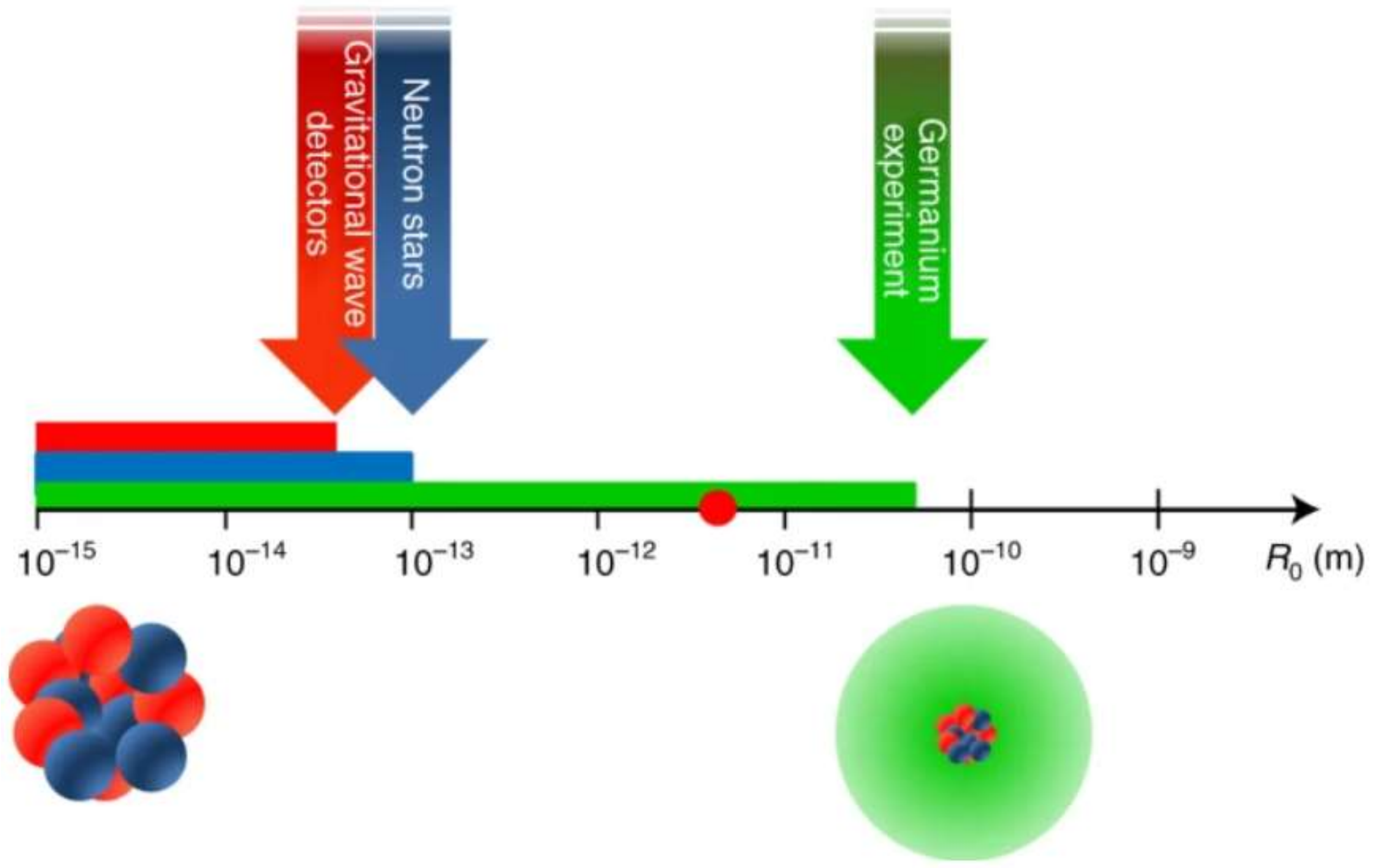


Fig. 5: Lower bounds on the spatial cutoff R_0 of the DP model.



Penrose Penrose – no radiation (but which dynamics?)

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]

newtheo.jpg

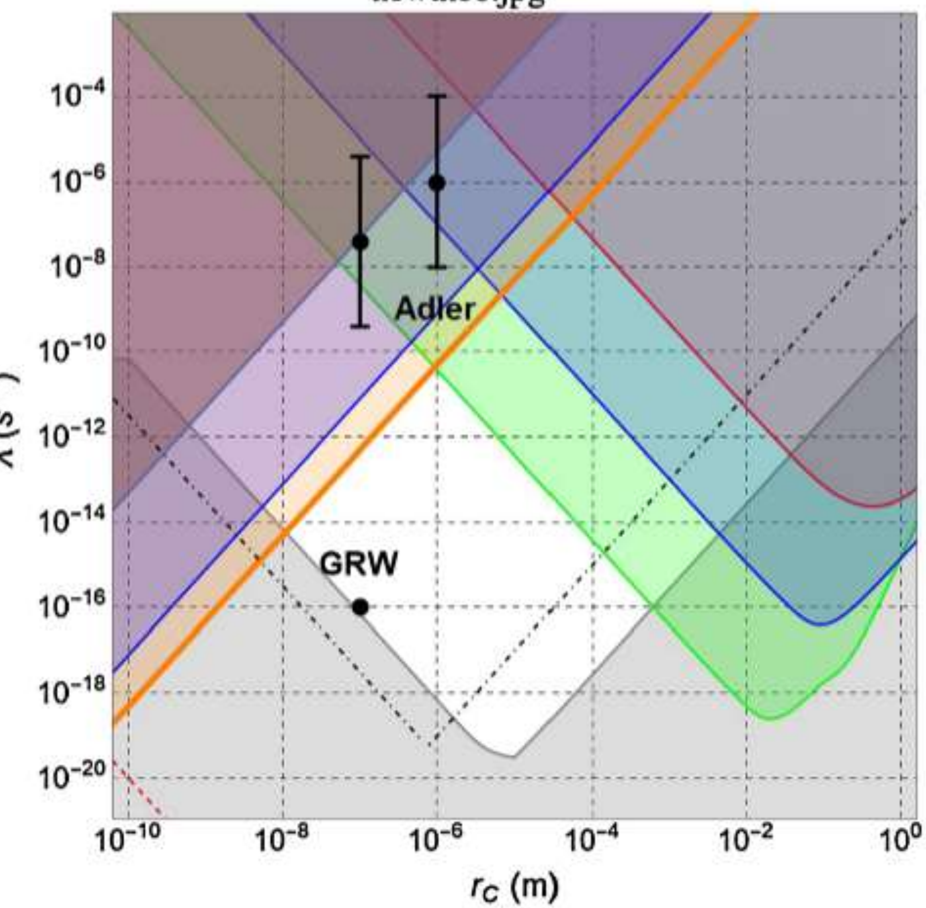


Fig. 4 Mapping of the $\lambda - r_C$ CSL parameters: the proposed theoretical values (GRW [6], Adler [24,25]) are shown as black points. The region excluded by theoretical requirements is represented in gray, and it is obtained by imposing that a graphene disk with the radius of 10 μm (about the smallest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

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

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

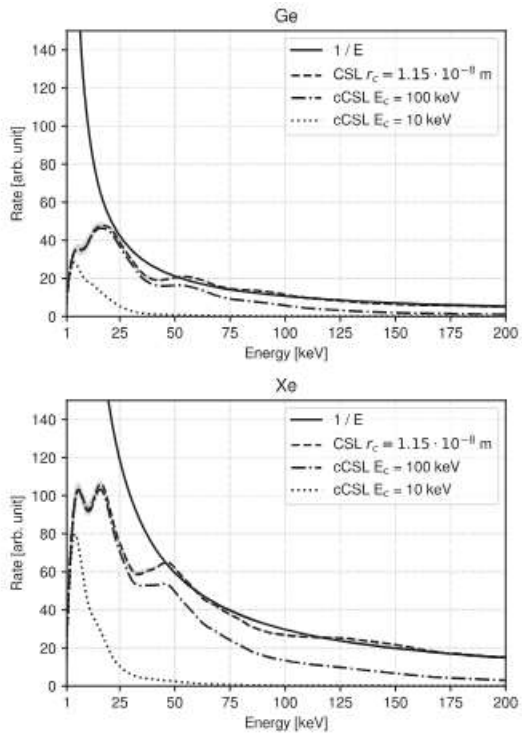


FIG. 1. The top panel of the figure shows (solid line) the $1/E$ dependence Eq. (4), for the spontaneous radiation rate of a Markovian CSL model, which is valid only in the high-energy domain. This is compared to the general rate in Eq. (3) (dashed line) for a prior value of the correlation length $r_C = 1.15 \times 10^{-8}$ 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

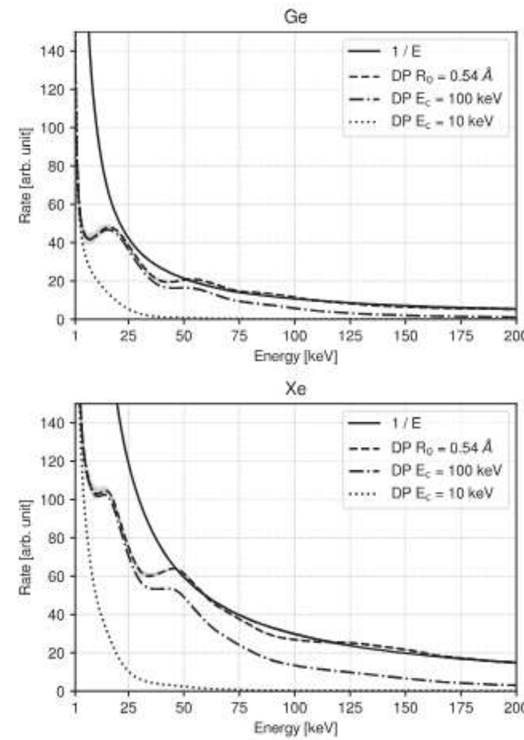


FIG. 2. Top panel of the figure shows (solid line) the $1/E$ dependence Eq. (7), for the spontaneous radiation rate of the Markovian DP model, which is valid only in the high-energy domain. This is compared to the general rate Eq. (10) (dashed line) for a prior value of the correlation length $R_0 = 0.54$ 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

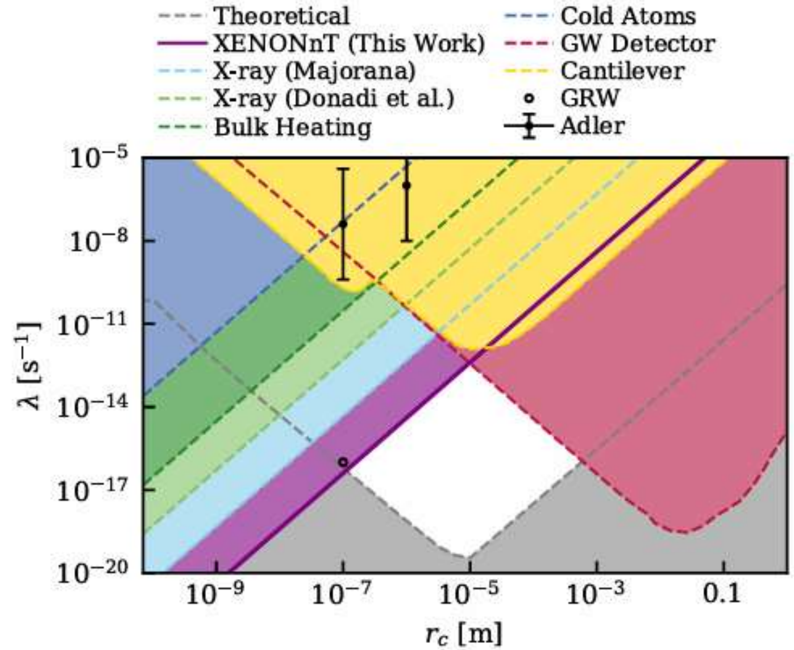


FIG. 2. XENONnT 95 % C.L. upper bound on the CSL model parameters, compared to exclusion limits from other non-interferometric experiments and theoretical propositions, with the shaded areas marking the excluded regions of the parameter space. Results from the LISA Pathfinder gravitational wave detector [10, 11], microcantilever measurements [5], cold atoms experiments [4], and estimates from the bulk heating rate in the CUORE experiment [38] are given. The two previous best limits from X-ray emission searches by Donadi et al. [14] and the MAJORANA DEMONSTRATOR [12] are shown as well. A commonly adopted lower theoretical bound can be introduced by requiring a maximum collapse time of ~10 ms, i.e., the perception time of the human eye, for a superposition of a single-layered graphene disk of a barely visible radius of ~10 µm [39]. The black markers indicate theoretical suggestions by Adler [40] and Ghirardi, Rimini, and

Image: LNGS, e-Print: 2506.05507 [hep-ex]

Challenging Spontaneous Quantum Collapse with XENONnT

PHYSICAL REVIEW A
covering atomic, molecular, and optical physics and quantum information

Accepted Paper

Linear-friction many-body equation for dissipative spontaneous wave-function collapse

Phys. Rev. A

Giovanni Di Bartolomeo, Matteo Carlesso, Kristian Piscicchia, Catalina Curceanu, Maaneli Derakhshani, and Lajos Diósi

Accepted 18 May 2023

PHYSICAL REVIEW RESEARCH **7**, 043166 (2025)

Fundamental limits on clock precision from spacetime uncertainty in quantum collapse models

Nicola Bortolotti,[1,2,3,*] Catalina Curceanu,[3,4,†] Lajos Diósi,[5,6] Simone Manti,[3] and Kristian Piscicchia[1,3]

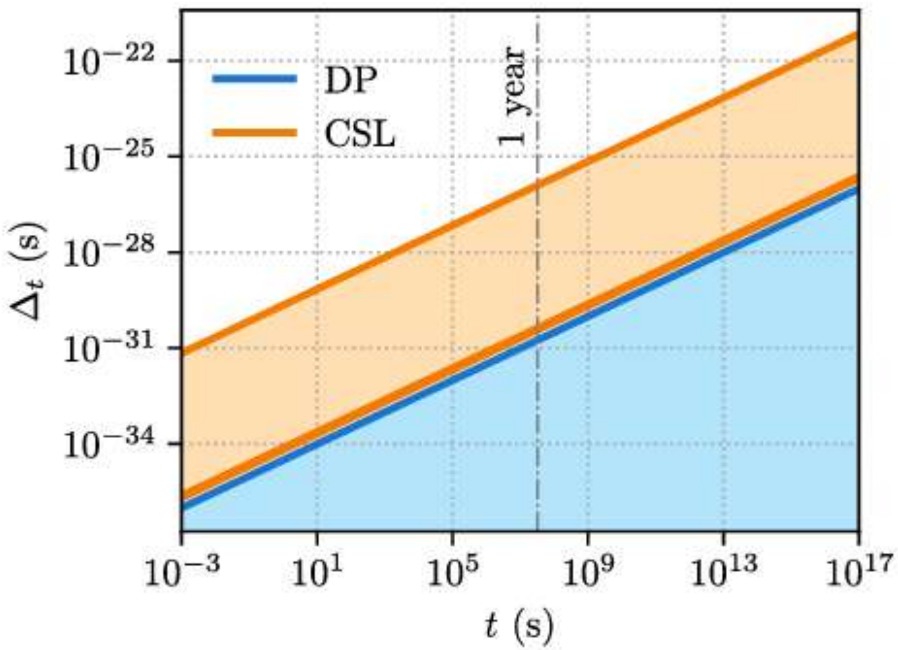


FIG. 2. Time uncertainty for optimal clocks as a function of time, extending up to the age of the universe. The colored areas correspond to the experimentally allowed regions. The blue region encompasses all allowed values constrained by the lower bound on the DP smearing length, $\sigma_{\rm DP} = 4.94 \times 10^{-10}$ m. The orange region corresponds to the range permitted by experimental bounds on the CSL collapse rate, 10^{-20} s^{-1} $< \lambda <$ 10^{-11} s^{-1}. The upper edges of both regions represent the maximum time uncertainty predicted by the DP and CSL models.


WOMEN
BE
sextra

Machine Learning Optimization of BEGe Detector Event Selection in the VIP Experiment

Simone Manti (Frascati), Jason Yip (UC, Berkeley), Massimiliano Bazzi (Frascati), Nicola Bortolotti (Frascati and Enrico Fermi Ctr., Rome), Mario Bragadireanu (Bucharest, IFIN-HH) Show All(23)

Dec 10, 2025

e-Print: 2512.09777 [physics.ins-det]

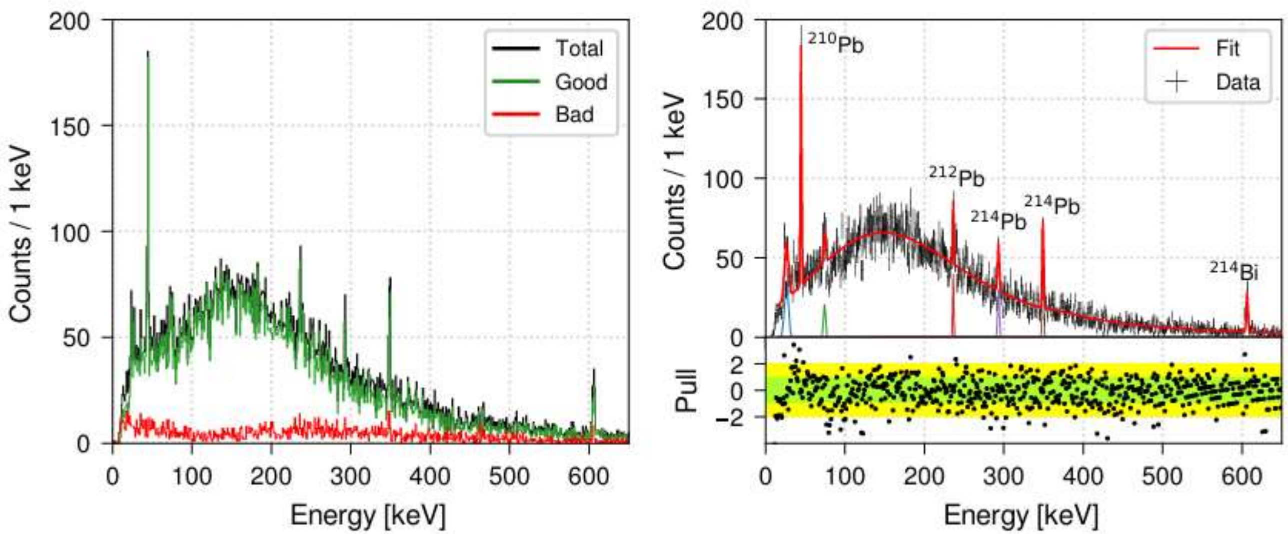


Figure 6. Left: measured spectra after ML-based event selection, showing normal (green), anomalous (red), and total (black) events. Right: fitted spectrum (red) with individual Gaussian components (coloured) and pull distribution below.

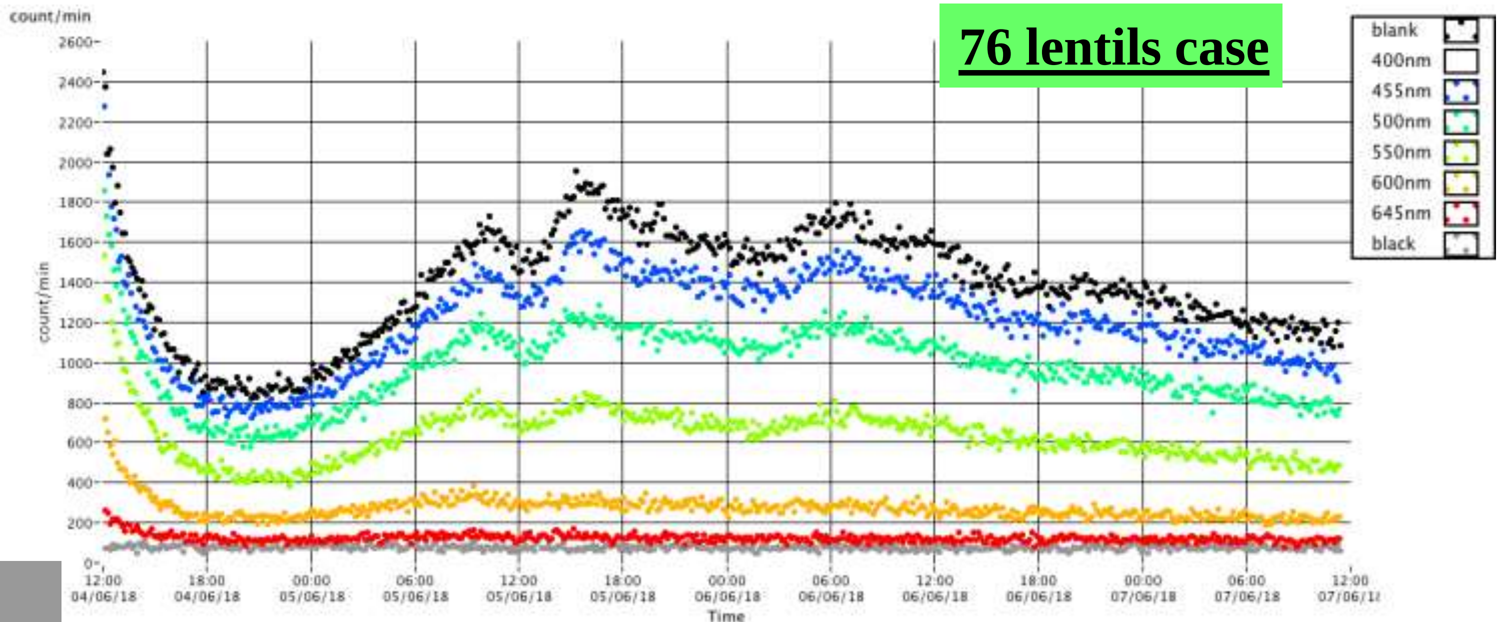
Accepted for publication in JINST

Biophotons germinating seeds

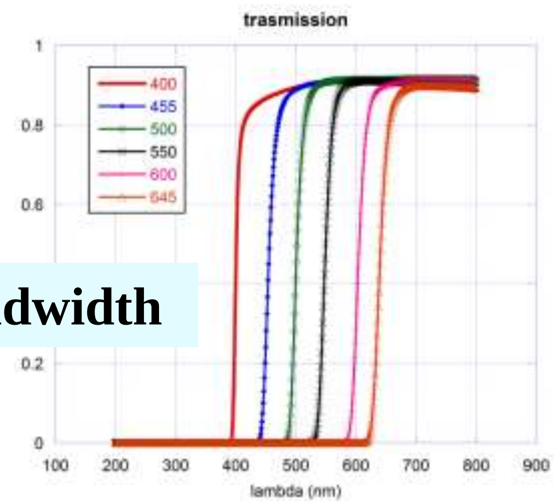
Experiment

time dependence of the different spectral components

76 lentils case



Time :
hours
days



Filters bandwidth

entropy

MDPI

Article

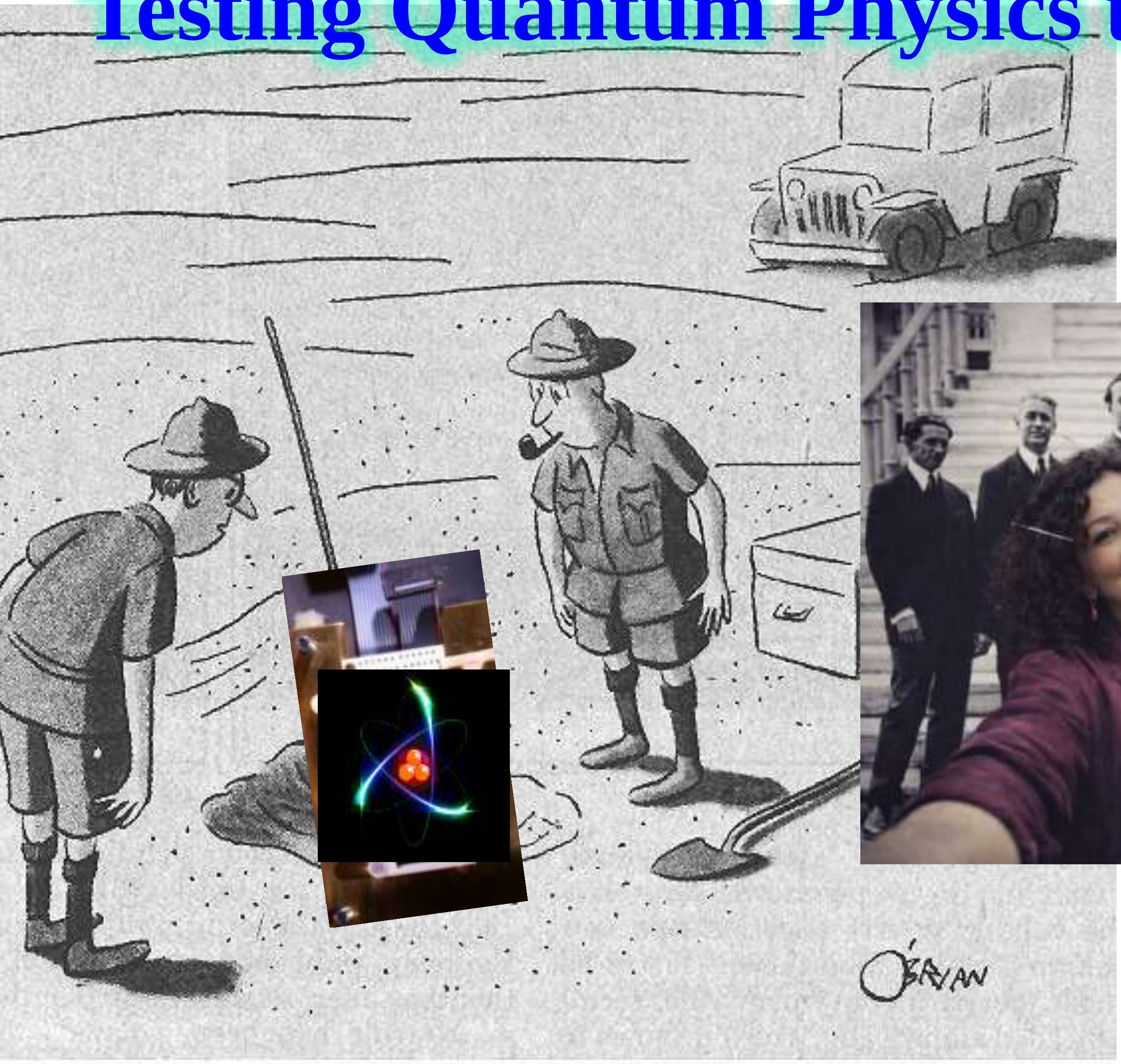
Biophotons and Emergence of Quantum Coherence—A Diffusion Entropy Analysis

Maurizio Benfatto [1,*], Elisabetta Pace [1], Catalina Curceanu [1], Alessandro Scordo [1], Alberto Clozza [1], Ivan Davoli [2], Massimiliano Lucci [2], Roberto Francini [3], Fabio De Matteis [3], Maurizio Grandi [4], Rohisha Tuladhar [5] and Paolo Grigolini [6,*]

We have seen the presence of crucial events in the biophoton emission using the Diffusion Entropy Analysis (DEA) method

M. Benfatto et al. Entropy 23, 554 (2021)

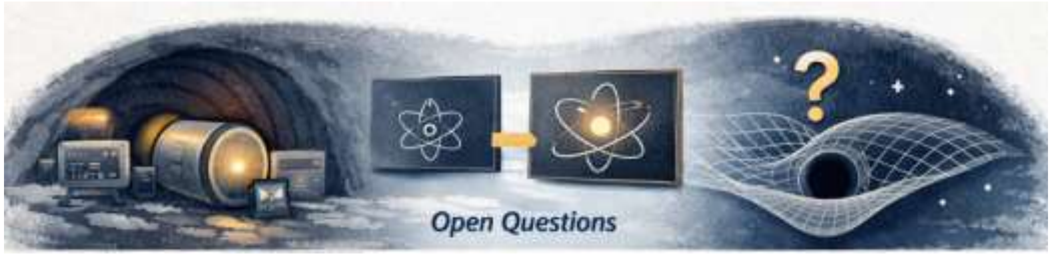
Testing Quantum Physics underground



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

Looking Ahead & Collaborations

Open Questions



- Which refined models for collapse-induced radiation observed underground?
- Pauli Exclusion Principle links to quantum gravity; which other thoories?

Next Steps

- Improved CSL & PEP tests/limits
- Cross-platform synergies: underground labs, resonators, quantum sensors

Collaboration Opportunities

- Theory: collapse models, PEP violation frameworks
- Experiment: ultra-low background detectors, fast X-ray, cryogenics
- Interfaces: foundations ↔ quantum gravity

Let's Discuss Ideas & Joint Projects!

CA23130 - Bridging high and low energies in search of quantum gravity (BridgeQG)

Workshop at Gran Sasso:
17 – 20 September 2026

Acknowledgements

STRONG 2020

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Istituto Nazionale di Fisica Nucleare

FQXi
Foundational Questions Institute