Underground tests of Quantum Mechanics - Collapse models and Pauli Exclusion Principle

Catalina Curceanu, LNF-INFN, Frascati (Italy)

Many thanks to: the VIP Collaboration; Kristian Piscicchia, Matthias Laubenstein; Angelo Bassi, Sandro Donadi, Lajos Diosi, Maaneli Derakhshani, Antonino Marciano, Andrea Addazi & LNGS

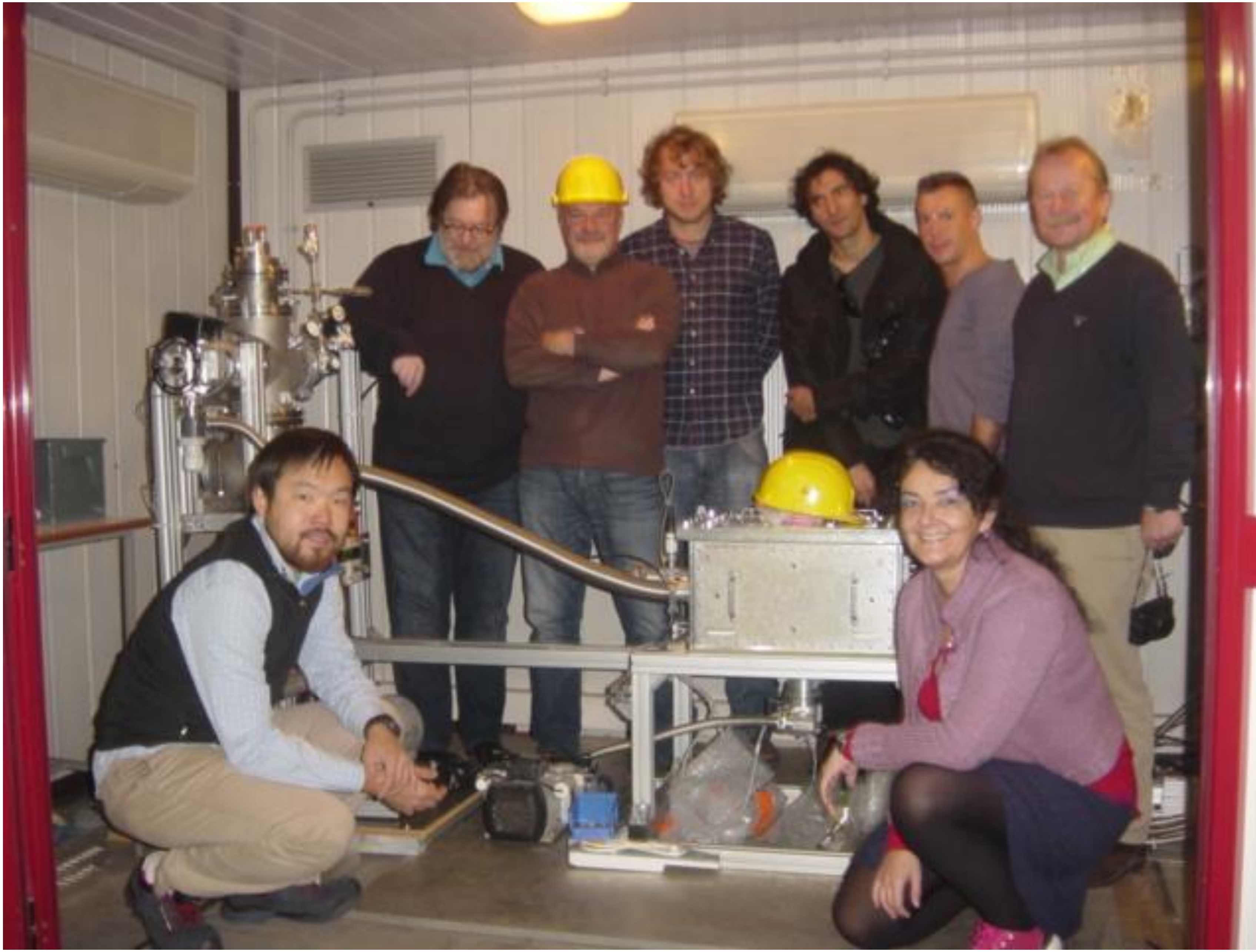
LNGS, 9-11 Maggio 2022

Quantum Mechanics tests:

- Collapse Models

- Pauli Exclusion Principle Violation

Relation between Quantum and Gravity




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

The measurement problem

Possible solutions:

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

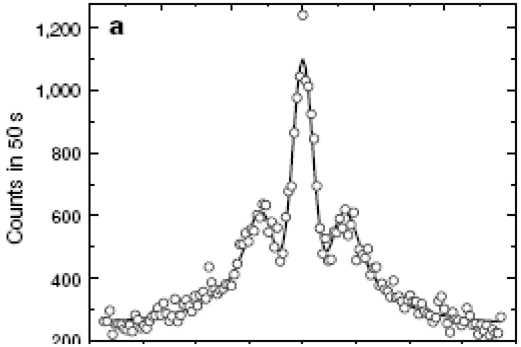
What are collapse models

1. **Collapse models = solution of the measurement problem**

   Paradox-free description of the quantum world

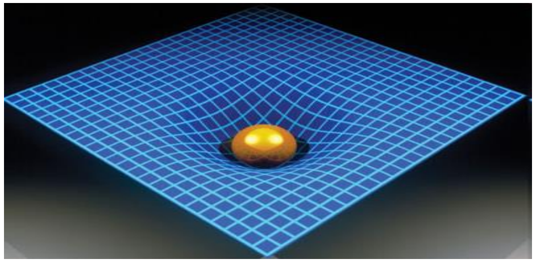
2. **Collapse models = rival theory of Quantum Mechanics**

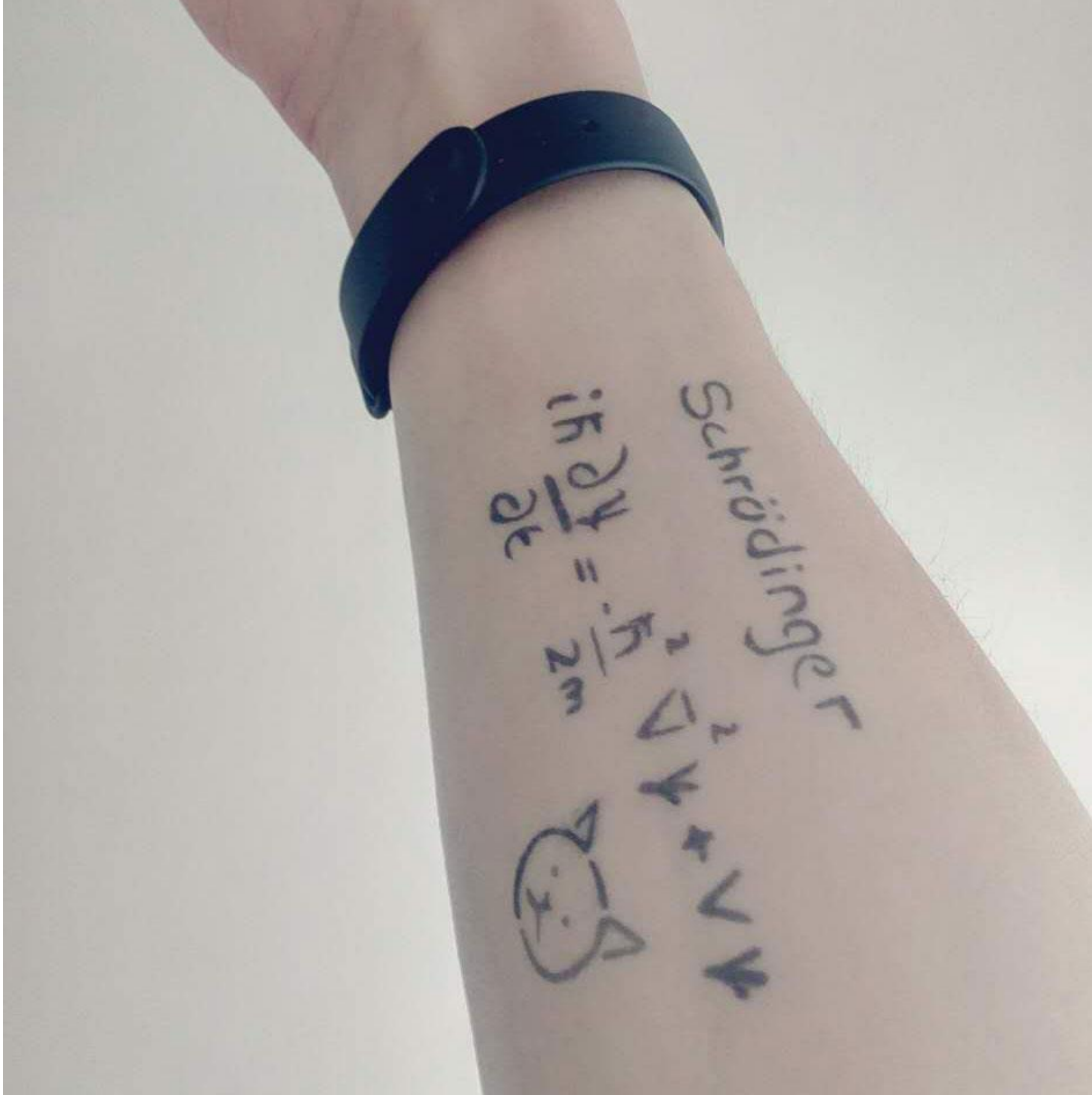
   They are related to experiments testing quantum linearity



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

   Can gravity causes the collapse?




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

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 …**

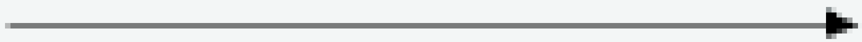
system is in a quantum superposition of two different positions →
superposition of two different space-times is generated →
the more massive the superposition, the faster it is suppressed.

The model characteristic parameter R_0

The collapse depends on the effective size of the mass density of particles in the superposition, and is random: this randomness shows up as a diffusion of the particles' motion, resulting, if charged, in the emission of radiation. We computed the radiation emission rate, which is faint but detectable

FREE PARTICLE

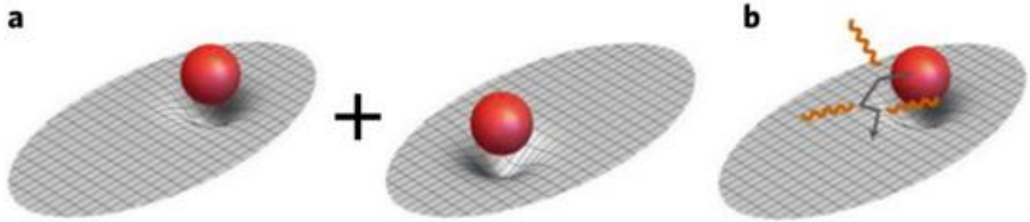
1. Quantum mechanics



2. Collapse models

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:

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

- Diosi – Penrose – s. e. photons rate:

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

We then performed a dedicated experiment at the Gran Sasso underground laboratory to measure this radiation emission rate. **Our result sets a lower bound on the effective size of the mass density of nuclei, which is about three orders of magnitude larger than previous bounds. This rules out the natural parameter-free version of the Diósi–Penrose model.**

Nature Physics 1–5, (2020).

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https://www.sciencemag.org/news/2020/12/our-favorite-science-news-stories-2020

-non-covid-19-edition

nature physics

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

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

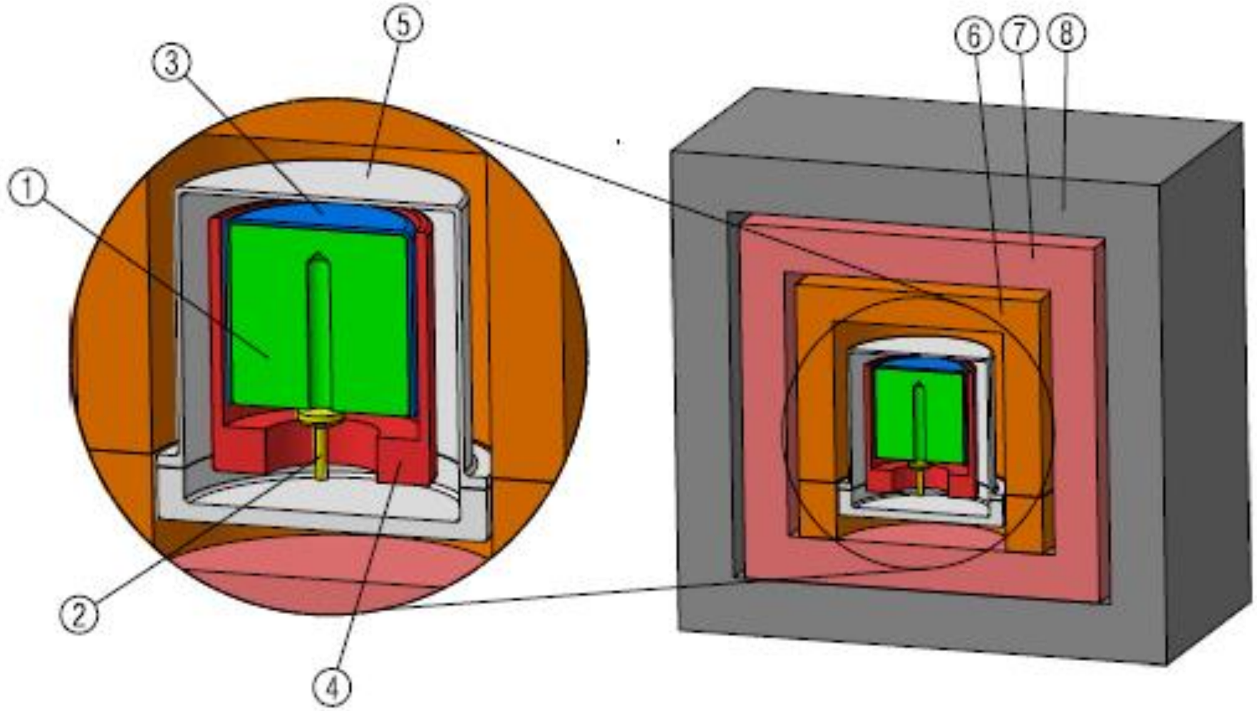


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

HPGe detector based experiment @ LNGS

three months data taking with 2kg Germanium active mass

↓

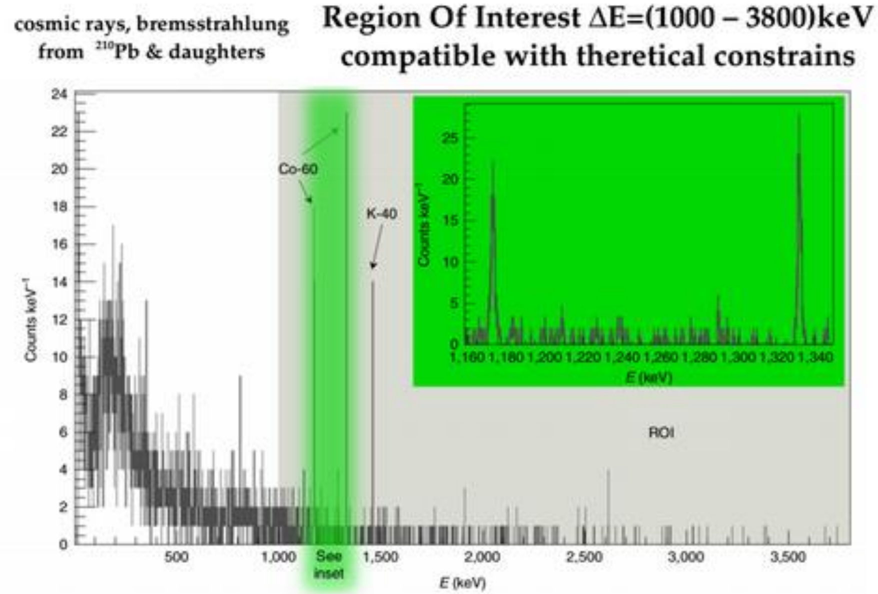
the pdf of the models parameters is obtained within a Bayesian model:

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

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

→ Diosi-Penrose excluded

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



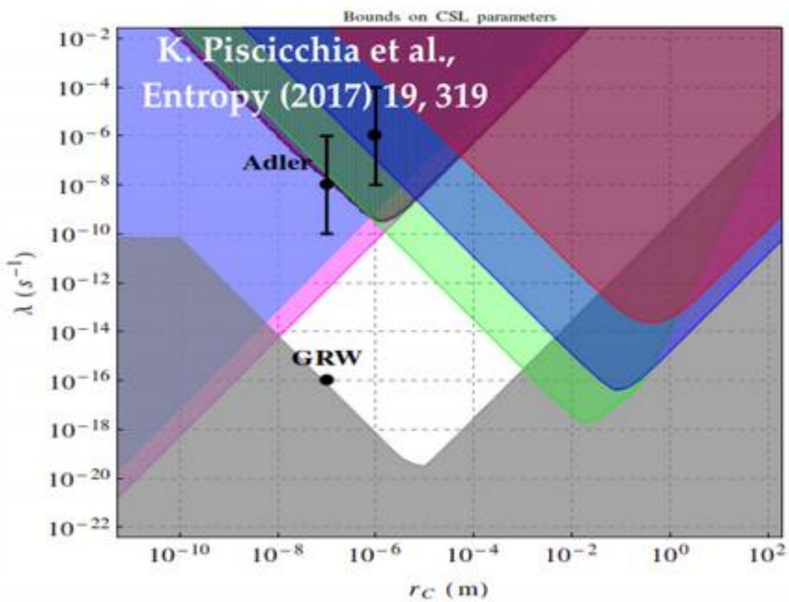
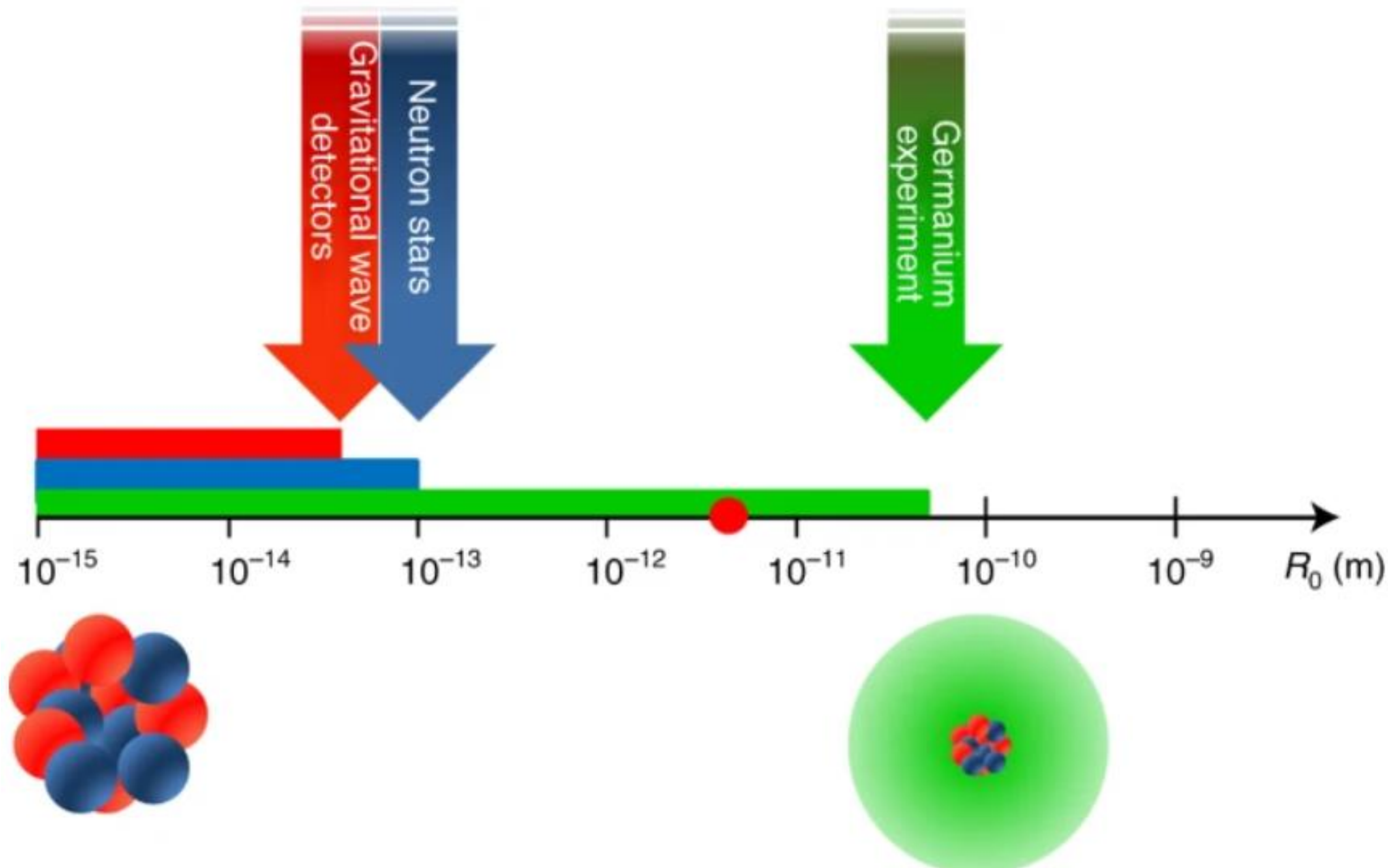


Fig. 5: Lower bounds on the spatial cutoff R_0 of the DP model.



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

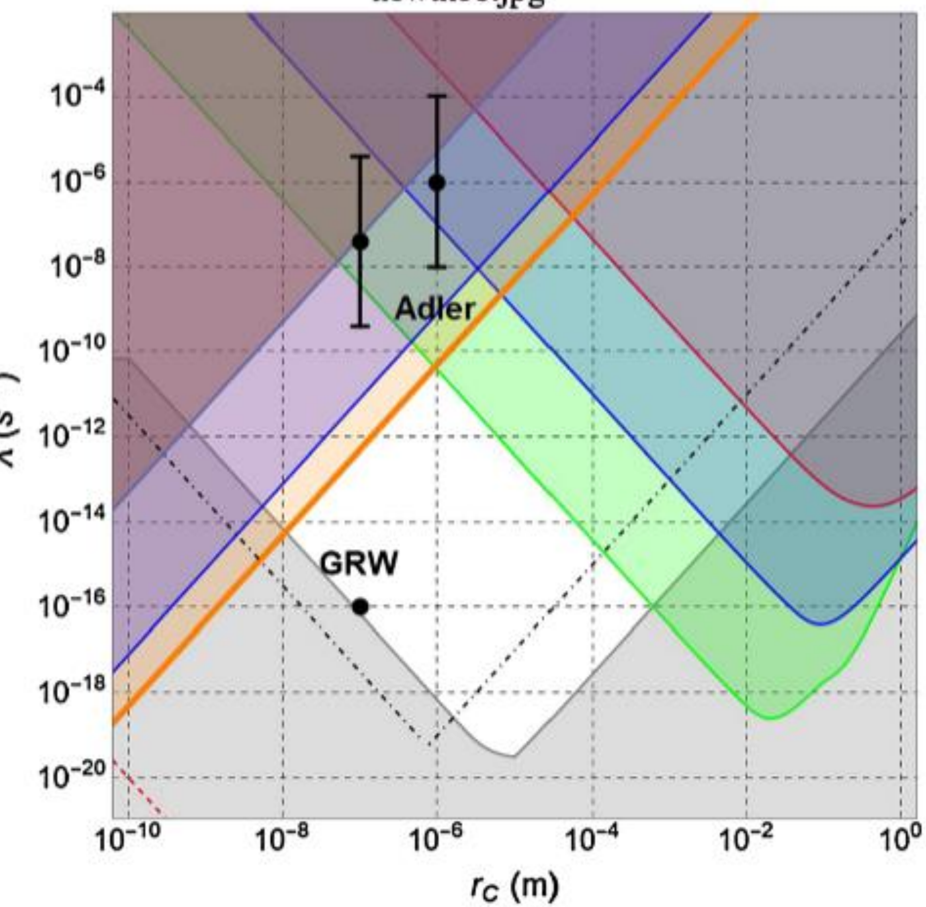
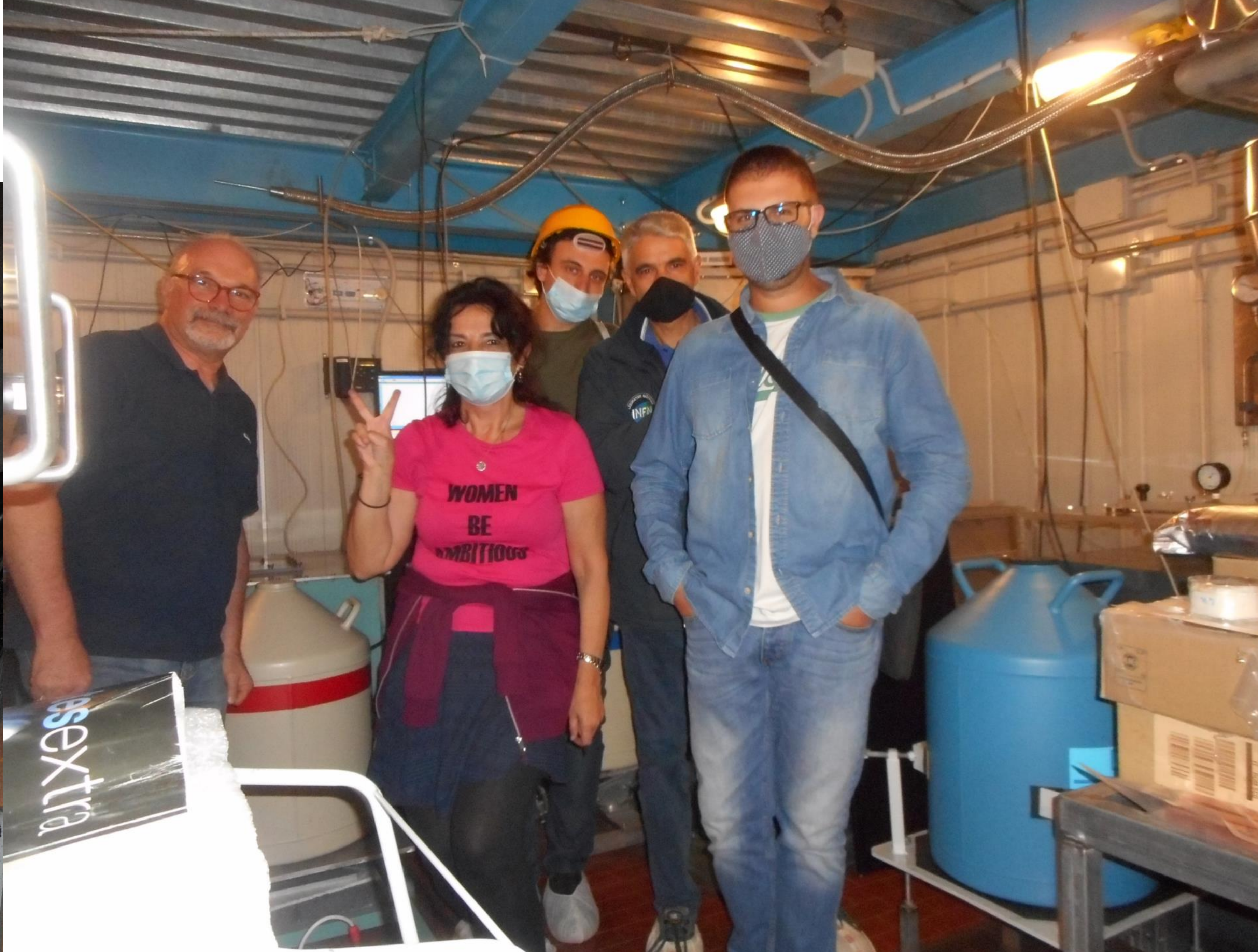


Fig. 4 Mapping of the $\lambda - r_C$ CSL parameters: the proposed theoretical values (GRW [6], Adler [24,25]) are shown as black points. The region excluded by theoretical requirements is represented in gray, and it is obtained by imposing that a graphene disk with the radius of 10 µm (about the smallest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

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


WOMEN
BE
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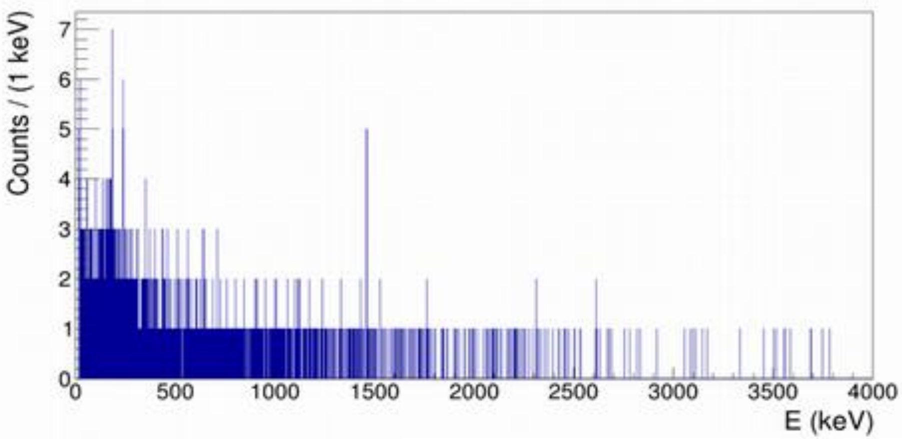
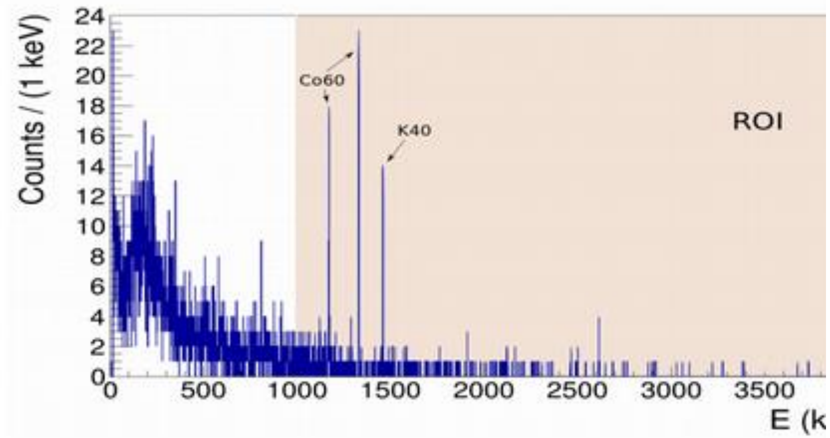
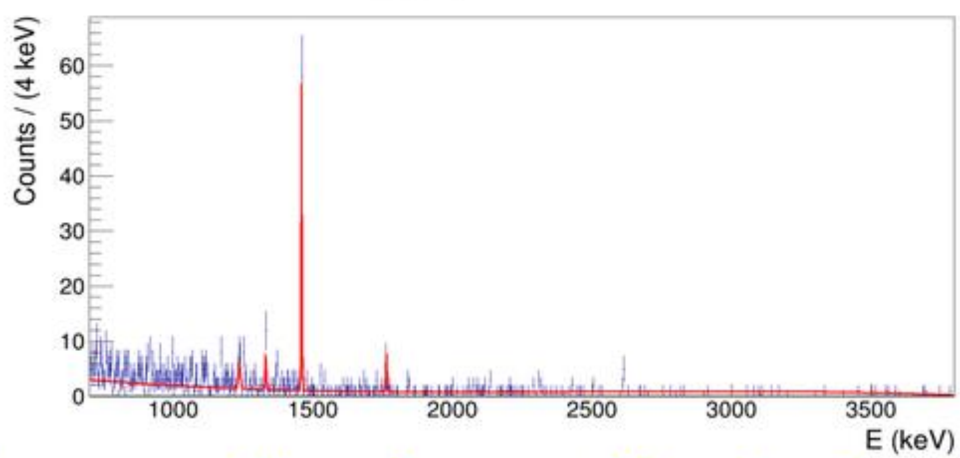
Future perspectives

HPGe detector + ultrapure Pb active shielding:



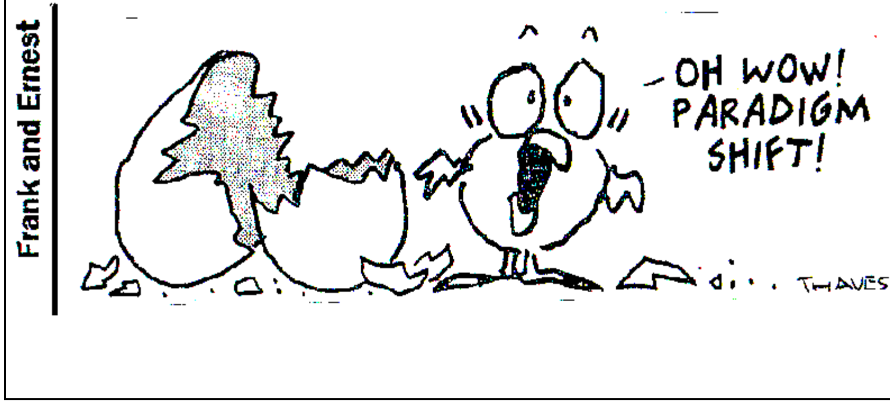




BEGe detector + pulse shape discrimination

pushing the lower E threshold to few keV

PARADIGM: **PAtterns in the spontaneous RAdiation as high-sensitivity probe for DIssipative colored Gravity-related collapse Models**



Questions:

-What induces the collapse:

Could be related with gravity?

-Has it anything to do with dark Sector (matter, energy)?

- Is there any theory beyond QM?

Exploring Quantum Boundaries

Workshop: Is Quantum Theory exact? Exploring Quantum Boundaries.

10-11 December 2020

Europe/Rome timezone

- Overview
- Timetable
- Participant List
- Registration
- Contribution List
- Workshop Gadget

Contact

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Nobel Laureates in Physics Albert Einstein and Niels Bohr walking.
Photo taken in the 1930 Solvay Conference in Bruxelles.
Source: Danish Film Institute Photo: Paul Ehrenfest

https://agenda.infn.it/event/24187/overview

https://fqxi.org/community/forum/topic/3638

HOW TO GO FROM "TO BE AND NOT TO BE" TO "TO BE OR NOT TO BE" FQXI AND JTF RECENT POJECTS

Catalina Curceanu
INFN - Laboratori Nazionali di Frascati

Lajos Diósi
Wigner Research Centre for Physics

Maaneli Derakhshani
Rutgers University

Project Title

ICON: Novel intertwined theoretical and experimental approach to test the ORCHestrated Objective Reduction theory as physical basis of consciousness

Project Summary

The nature of human consciousness, the most extraordinary phenomenon experienced by all of us, is the most important of all yet unsolved problems. Is consciousness rooted in the realm of natural sciences? This question is overarching biology, physics, mathematics, philosophy. We plan to contribute answering this question, by setting up and applying an innovative approach. Within the ICON project, we will critically investigate at an unprecedented level, the Orch OR unique theory (Orchestrated objective reduction), put forward by Hameroff and Penrose, theory which places consciousness within the empirical sciences, musing about its connection with quantum mechanics and gravity, and sneaking into the "pretty hard problem" of consciousness: is there a theoretical framework that can determine which physical systems and processes can be associated with consciousness? We will break the chain of long-lasting debates by setting the ground for an intertwined theoretical and experimental validation, performing fundamental dedicated measurements, setting Orch OR on a much more solid ground. Our ICON project represents a major progress in bridging the gap between physical laws and consciousness, by studying the intimate mechanisms of those phenomena proposed to generate consciousness in humans and the Universe, with a potential monumental breakthrough in consciousness studies.

QUBO: Exploring the QUantum Boundaries of many-body systems – an Odyssey into the gravity related collapse models

<u>Grant 62099</u>

Project for the John Templeton Foundation

Started 1 October 2021

Dr. *Catalina Oana Curceanu*, LNF-INFN, Italy
Prof. *Lajos Diósi*, Eötvös Loránd University, Budapest, Hungary
Dr. *Maaneli Derakhshani*, Department of Mathematics,
Rutgers University, New Brunswick, USA
Dr. *Kristian Piscicchia*, Enrico Fermi Research Center, Italy

We also 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

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.

Theories of Violation of Statistics

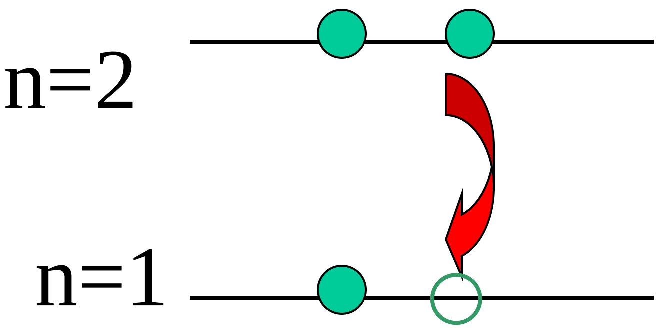
O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

"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."

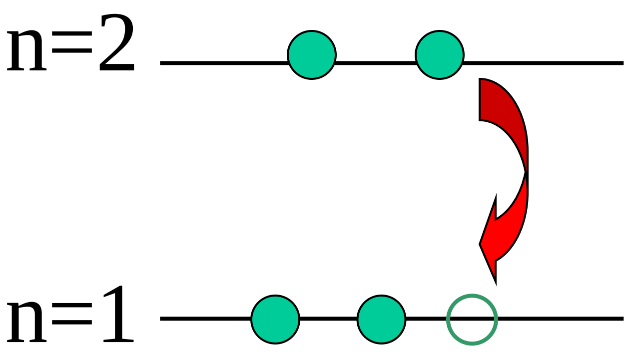
Experimental method:

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



Normal 2p –>1s transition

Energy 8.04 keV



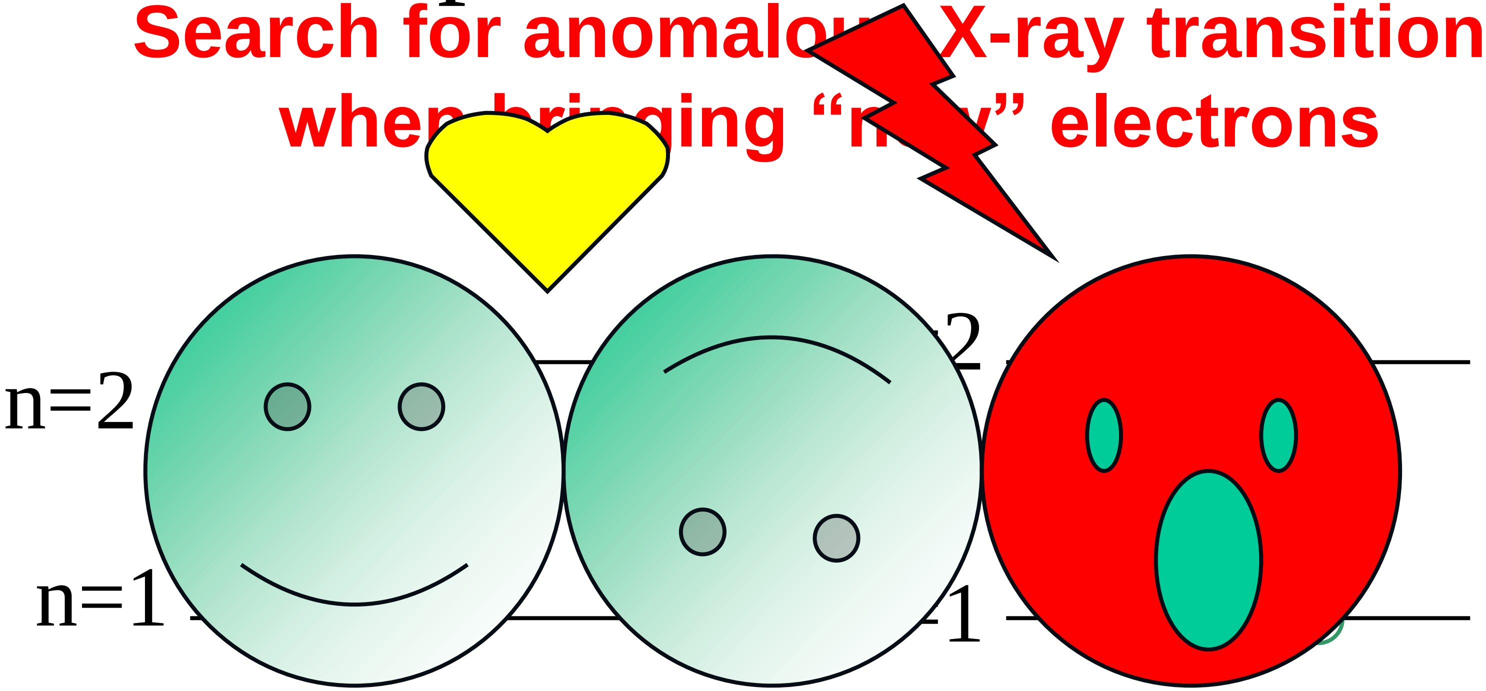
2p –>1s transition violating Pauli principle

Energy 7.7 keV

Messiah Greenberg superselection rule

Experimental method:

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



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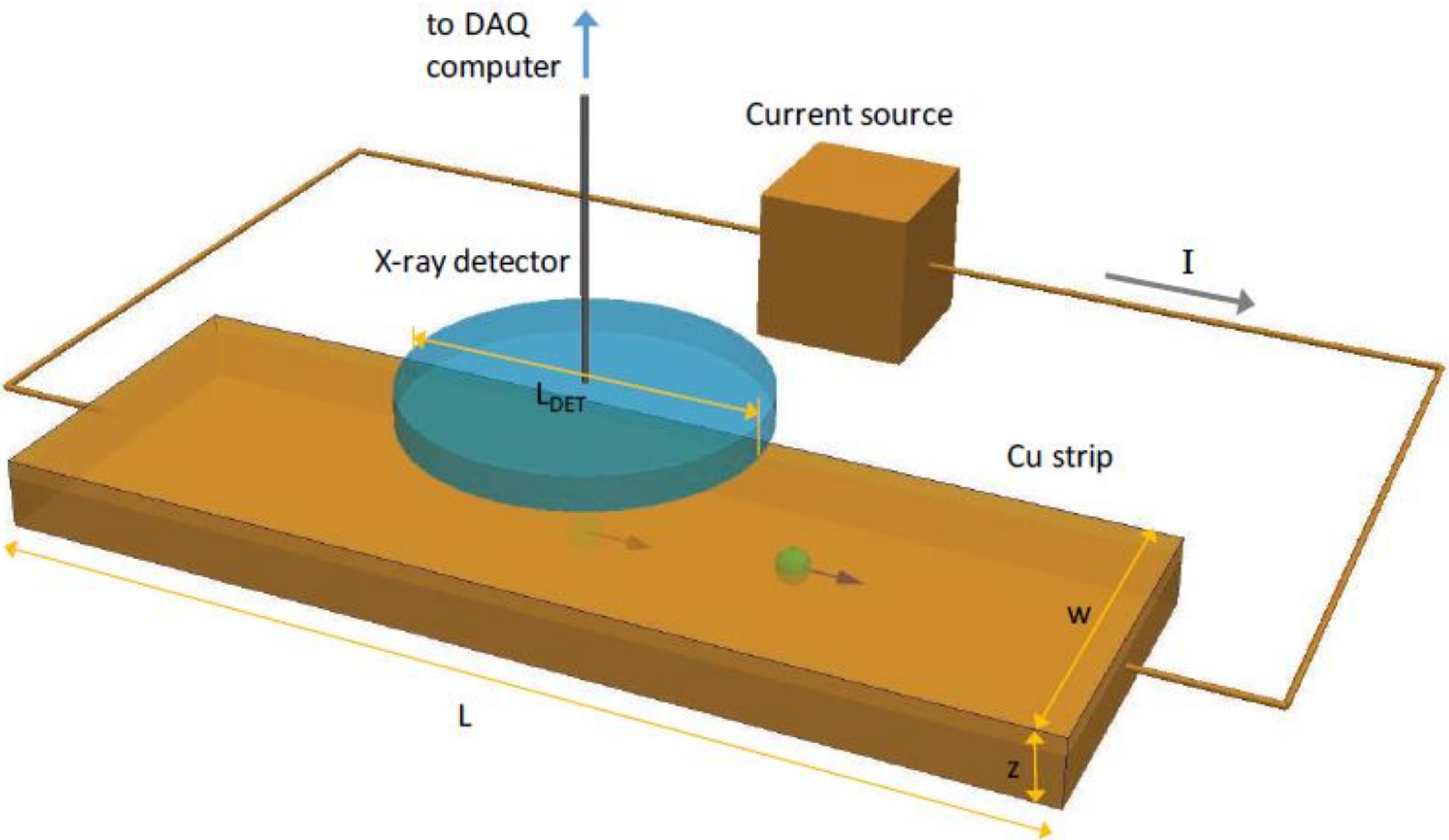
to DAQ
computer
Current source
X-ray detector
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L_{DET}
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w
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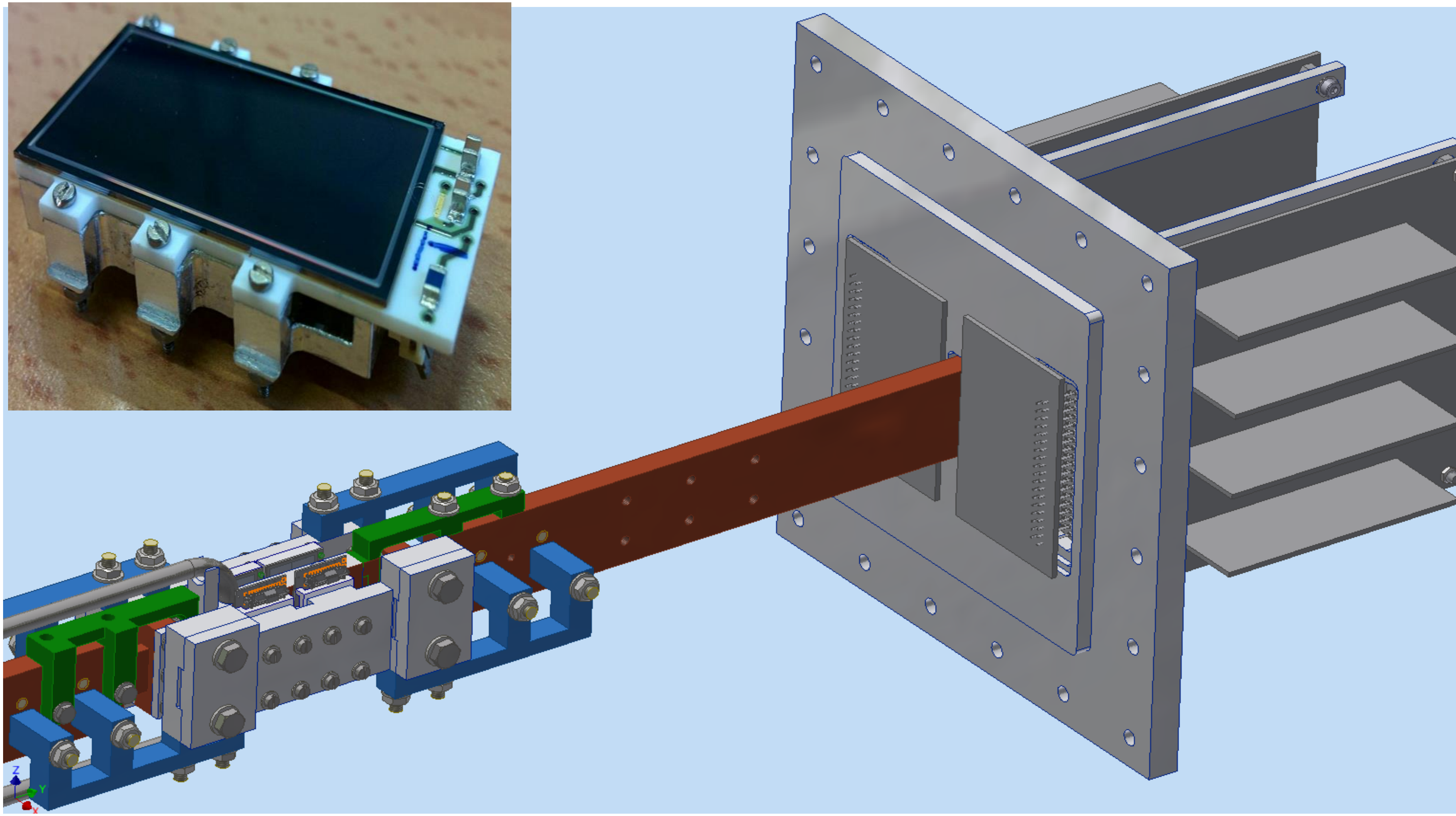
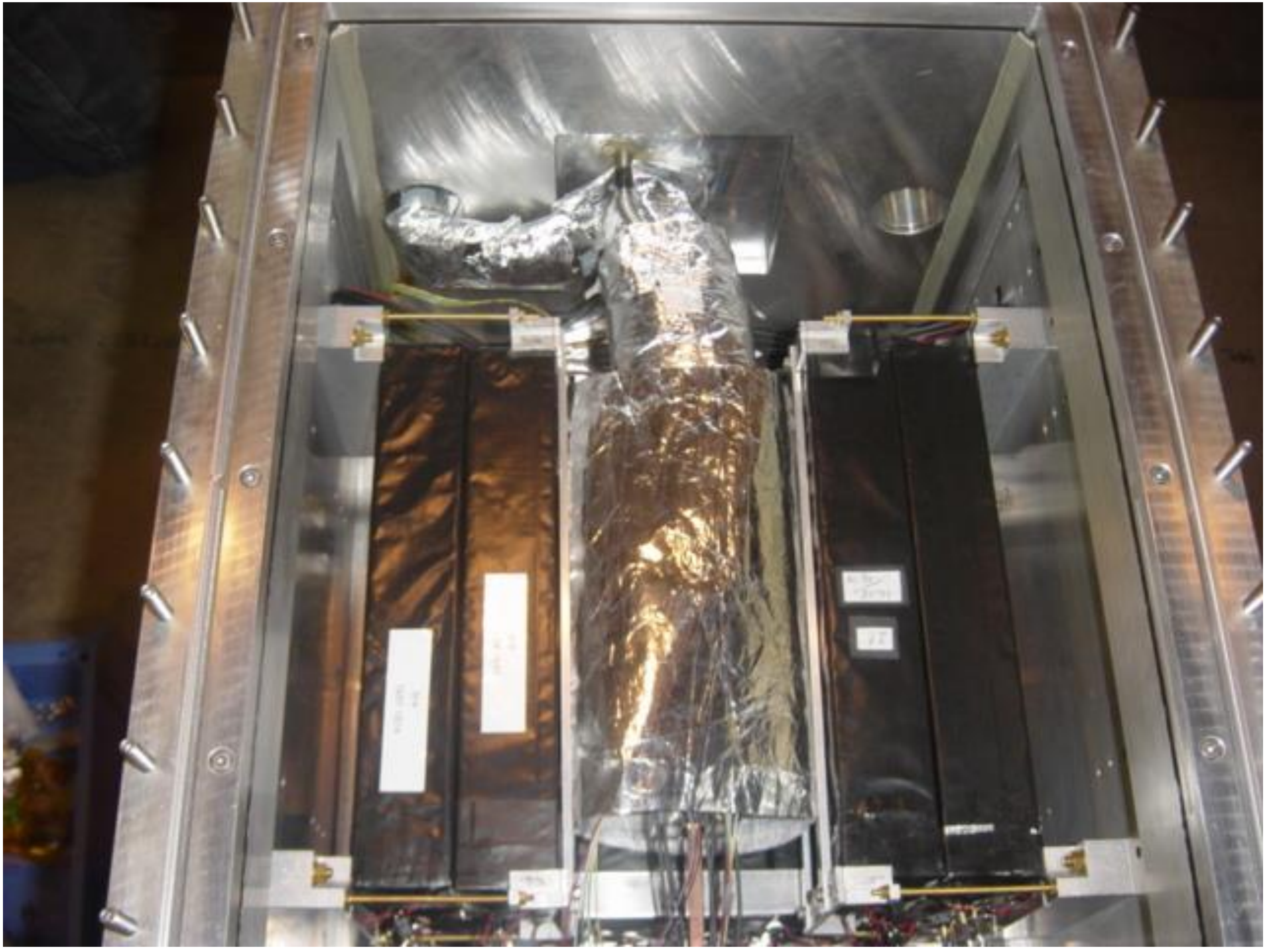




Open Access | Feature Paper | Article

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

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

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

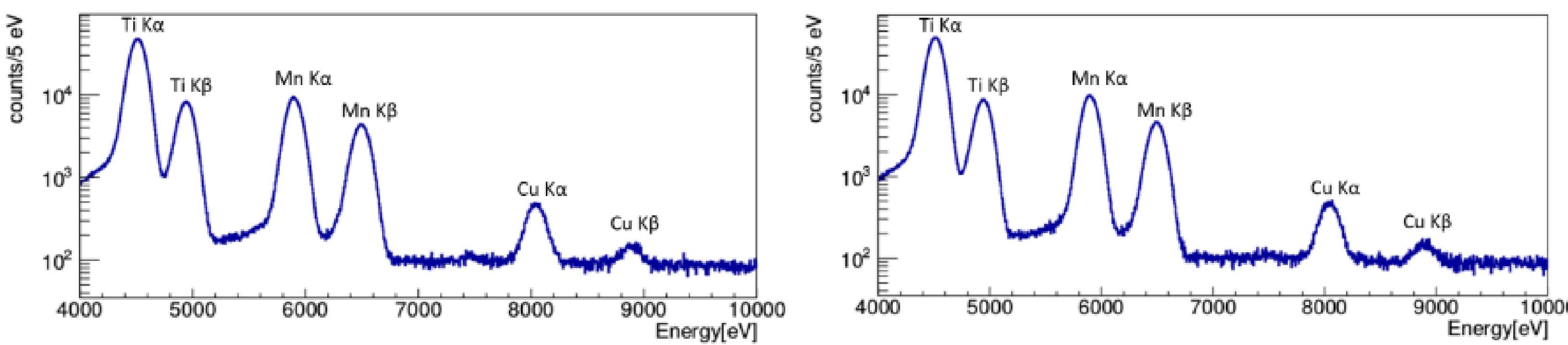


Figure 3. Energy calibrated spectra corresponding to about 42 days of data taking (during 2018) collected with current on (left), the spectrum collected with current off (right), which is normalized to the time of data taking with current on.

In the coming years we expect either to find a small violation or to be able to bound the probability that PEP is violated by electrons pushing it about 2 orders of magnitude lower

Regular Article - Experimental Physics | Open Access | Published: 06 June 2020

Search for a remnant violation of the Pauli exclusion principle in a Roman lead target

Kristian Piscicchia, Edoardo Milotti, ... Catalina Curceanu + Show authors

The European Physical Journal C **80**, Article number: 508 (2020) | Cite this article

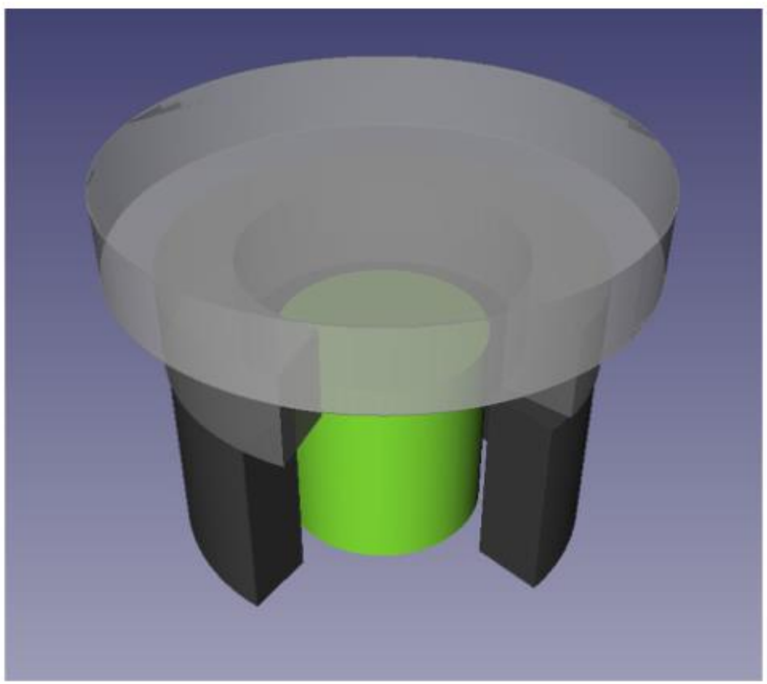


Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

$$\frac{1}{2}\beta^2 < 1.53 \cdot 10^{-43},$$

TESTING VIOLATIONS OF THE PAULI EXCLUSION PRINCIPLE INDUCED FROM NON-COMMUTATIVE SPACE-TIME

Andrea Addazi,
Fudan University, Shanghai.

in collaboration with A. Marcianò (Fudan),

We propose underground experiments!!!

Claim:

Pauli Exclusion principle violations induced from quantum gravity can be tested

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 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

testing PEP violation in quantum gravity

Theoretical prediction *Int.J.Mod.Phys.A* 35 (2020) 32, 2042003

specific calculation of atomic levels transitions probabilities for θ-Poincaré

$$W \simeq W_0 \phi_{PEPV} \,, \qquad \phi_{\rm PEPV} = \delta^2 \simeq \frac{D}{2}\frac{E_N}{\Lambda}\frac{\Delta E}{\Lambda} \qquad \phi_{\rm PEPV} = \delta^2 \simeq \frac{C}{2}\frac{\bar{E}_1}{\Lambda}\frac{\bar{E}_2}{\Lambda}$$

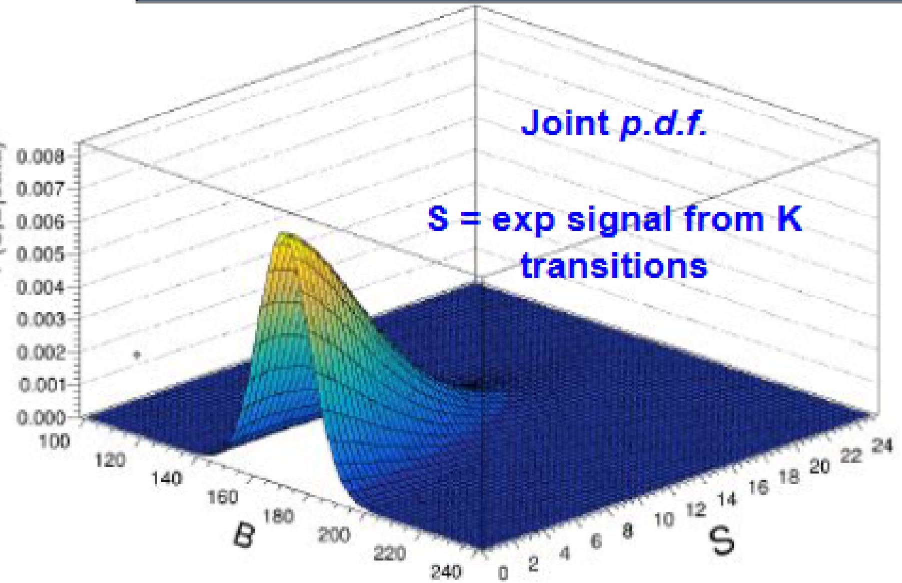
for non-vanishing (vanishing) electric like components of the θμν tensor.

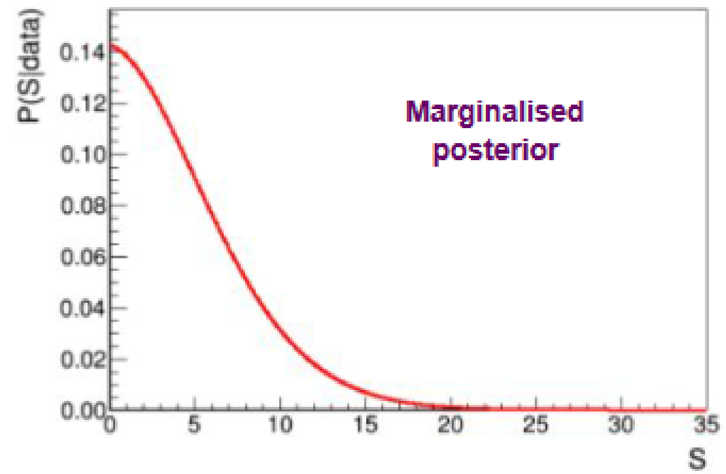
Connection with quon algebra (in the case of quon fields however the q factor does not show any energy dependence):

$$q(E) = -1 + 2\delta^2(E)$$

An experimental bound on the probability that PEP may be violated in atomic transition processes, straightforwardly translates into a bound on the new physics scale Λ, consistently with the choice of the θ_{0i} components.

Results





From which an upper limit on the non-commutativity scale is obtained (90% Probability):

θ-Poincarè - excluded up to $\Lambda > 6.9\ 10^{-2}$ Planck scale if $\theta_{0i} = 0$

<u>Submitted for publication</u>

or

excluded up to $\Lambda > 2.6\ 10^{2}$ Planck scale if $\theta_{0i} \neq 0$

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

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.

Acknowledgements

Farnesina
Ministero degli Affari Esteri e della Cooperazione Internazionale

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

INFN LNF
Istituto Nazionale di Fisica Nucleare

JOHN TEMPLETON FOUNDATION

CENTRO FERMI
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Stawell underground laboratory: experiments testing quantum mechanics?