Testing Quantum Mechanics Underground In the Cosmic Silence

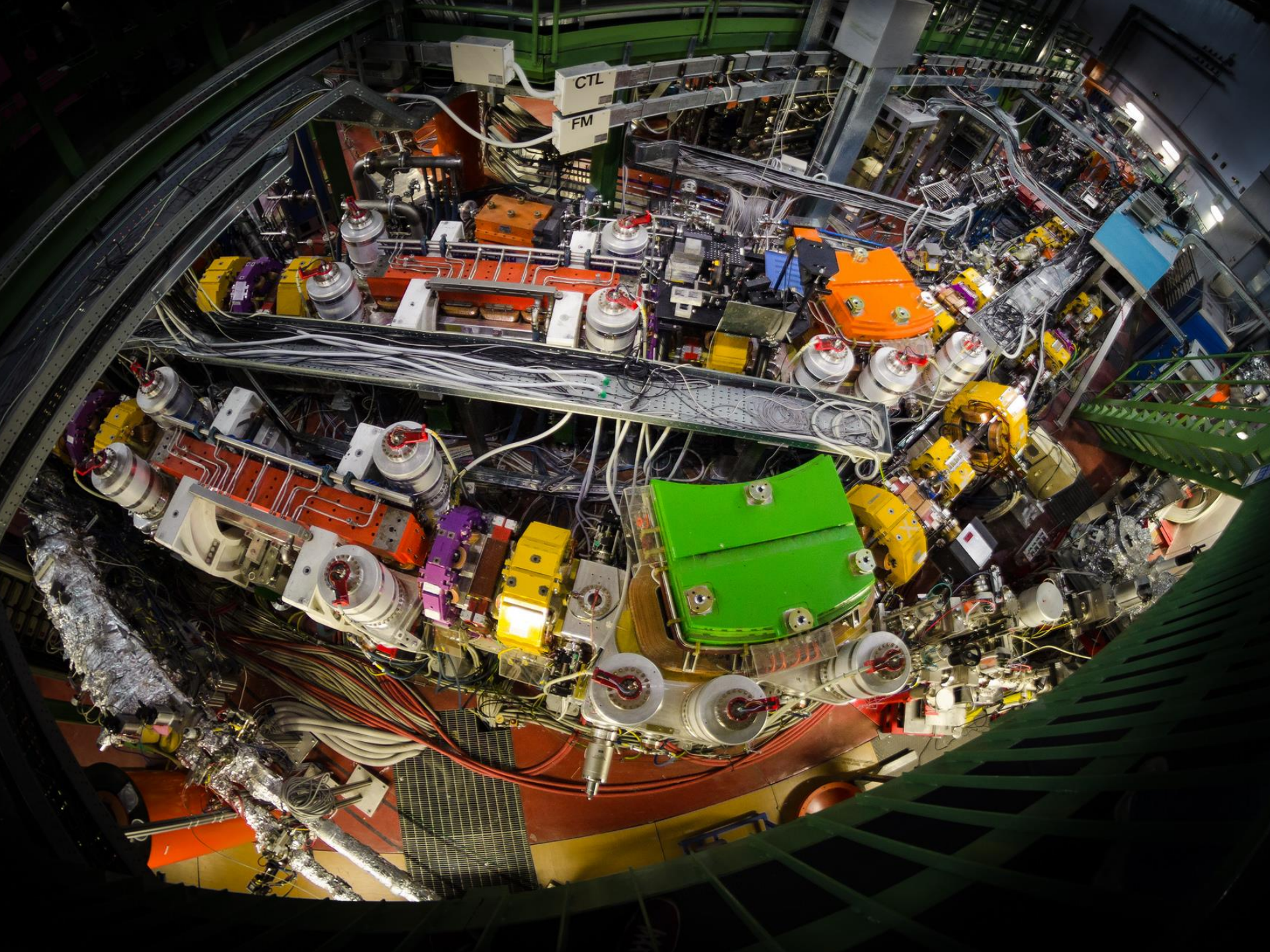
Catalina Curceanu, LNF-INFN, Frascati (Italy)

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

24th Australian Institute of Physics Congress
Adelaide, 11-16 December 2022

My Institute: INFN-LNF

DAΦNE collider


CTL
FM

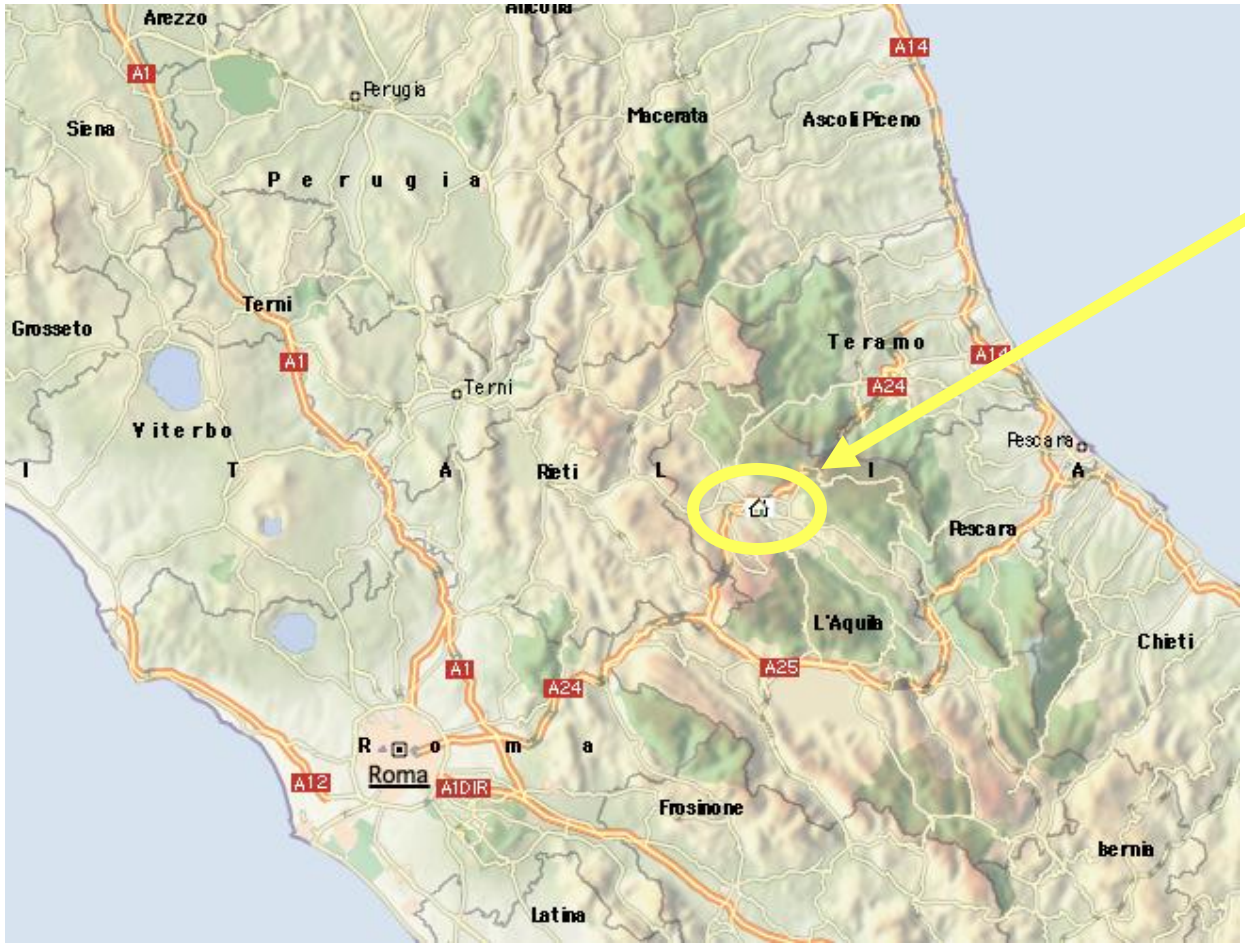
SIDDHARTA

SIlicon Drift Detector for Hadronic Atom Research by Timing Application

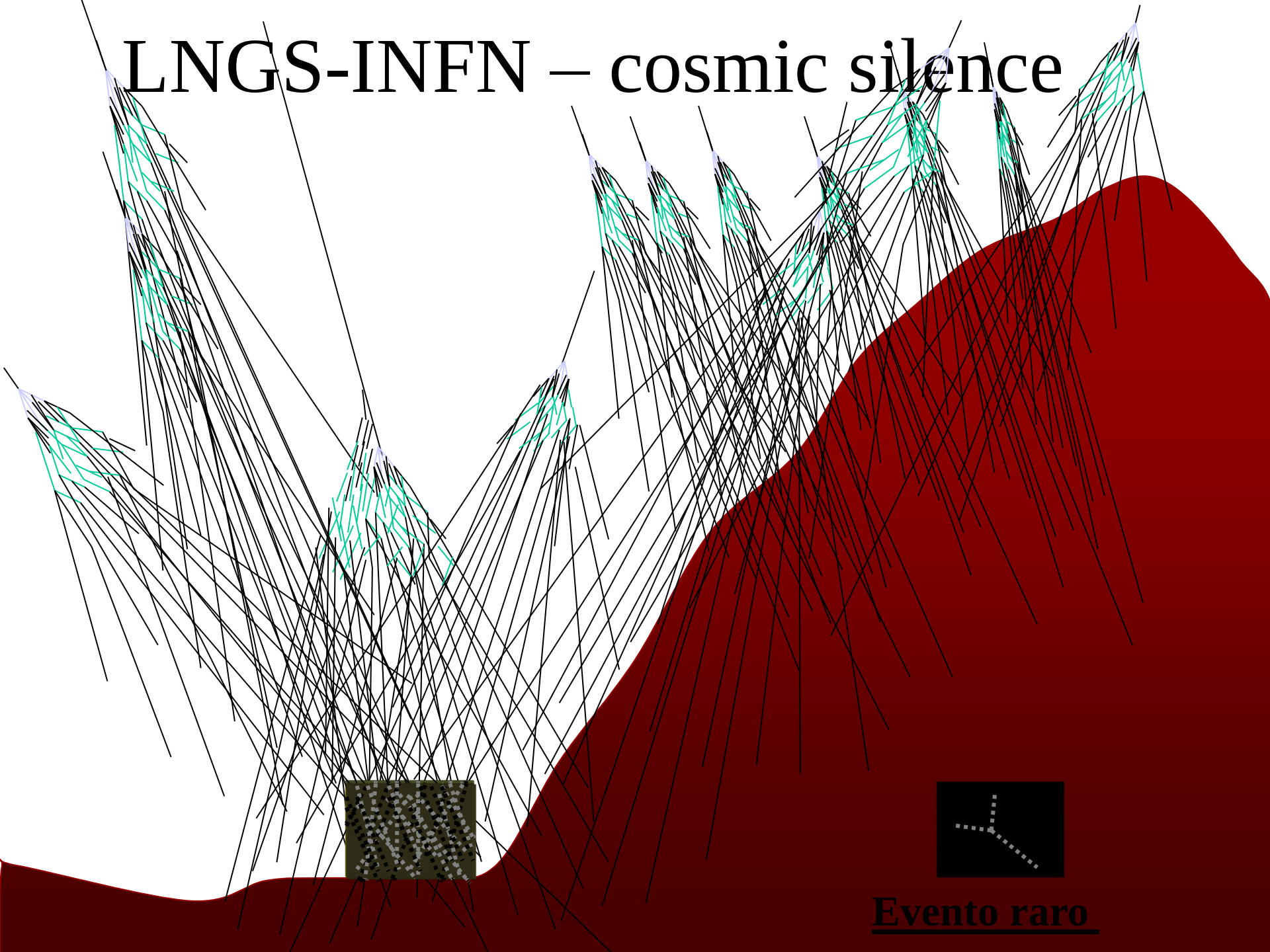
Quantum Mechanics tests:
- Collapse Models
- Pauli Exclusion Principle Violation

Relation between Quantum and Gravity

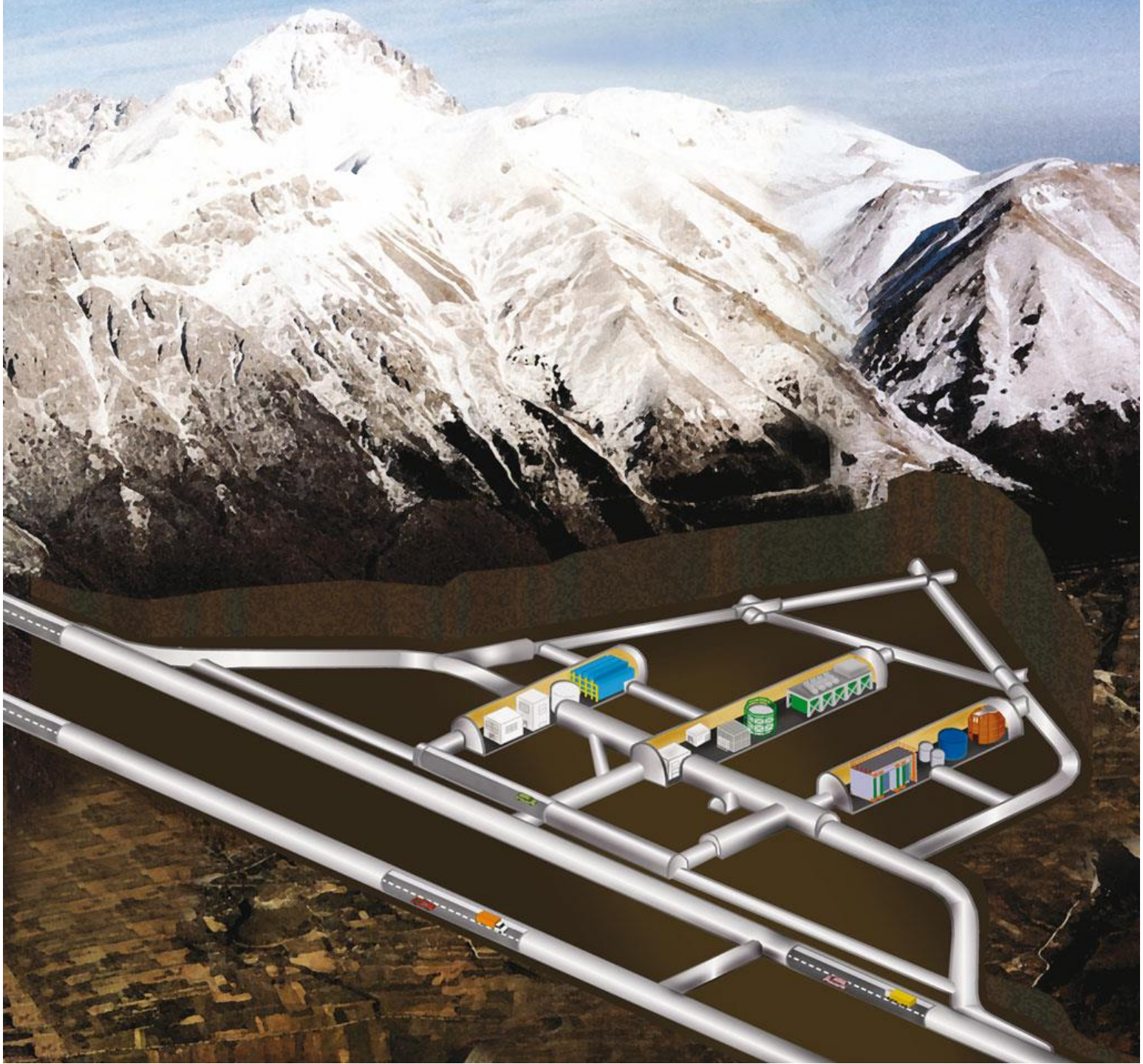
Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare

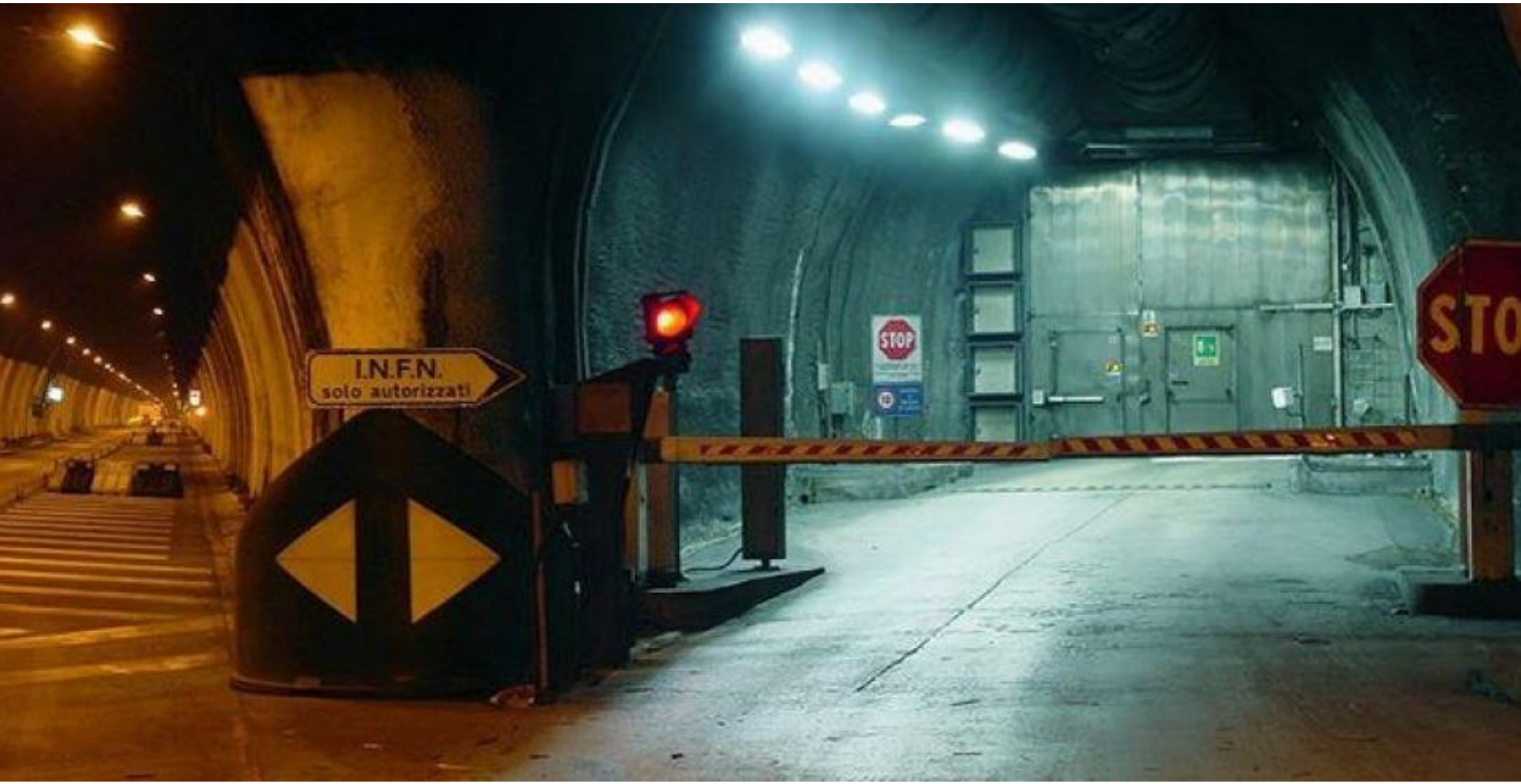


LNGS-INFN – cosmic silence



Evento raro




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


INFN-LABORATORI
NAZIONALI
DEL GRAN SASSO
DAMA

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

The measurement problem

Possible solutions:

-De Broglie – Bohm

- Many-World Interpretations

-Collapse of the w.f.

-.....

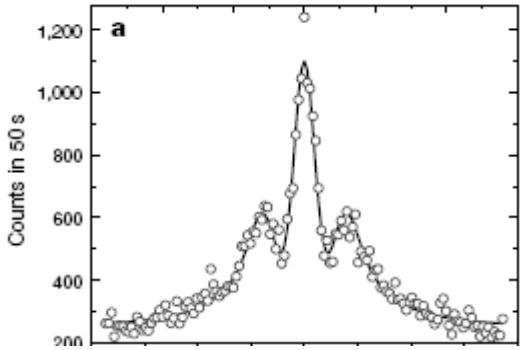
What are collapse models

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

   Paradox-free description of the quantum world

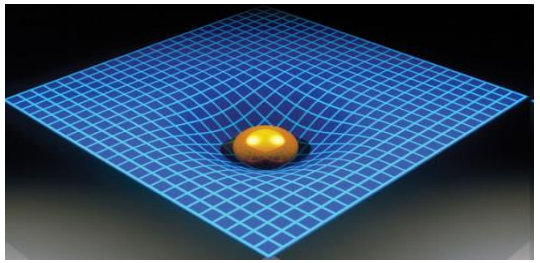
2. **Collapse models = rival theory of Quantum Mechanics**

   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:

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

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

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)

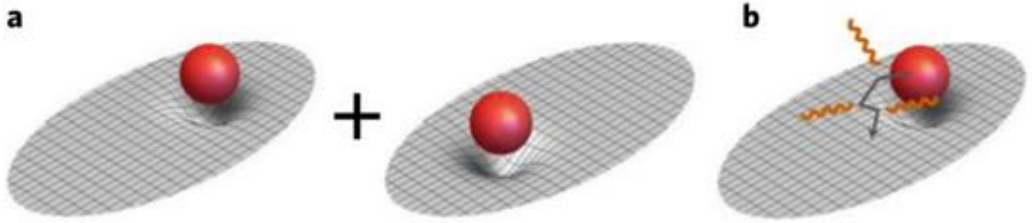
$r_C = 1/\sqrt{\alpha} \sim 10^{-5}\mathrm{cm}$

Increasing size of the system

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

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:**

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

Gravity-related photons rate:

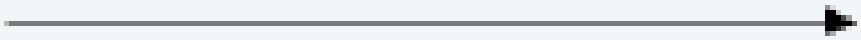
$$\frac{d\Gamma_t}{d\omega} = \frac{2}{3} \frac{G e^2 N^2 N_a}{\pi^{3/2} \varepsilon_0 c^3 R_0^3 \omega},$$

the size of the particle's mass density R0

Penrose – no radiation (but not yet dynamics?)

FREE PARTICLE

1. Quantum mechanics

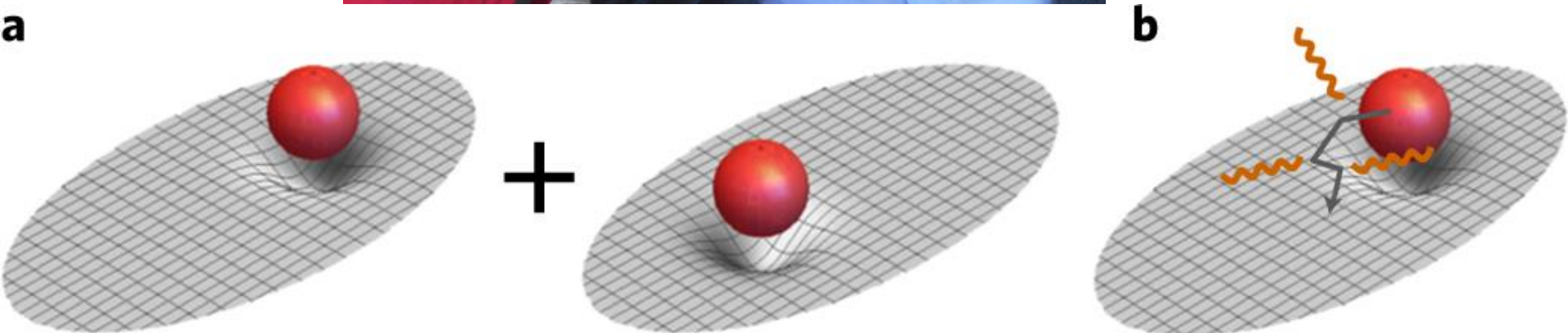


2. Collapse models

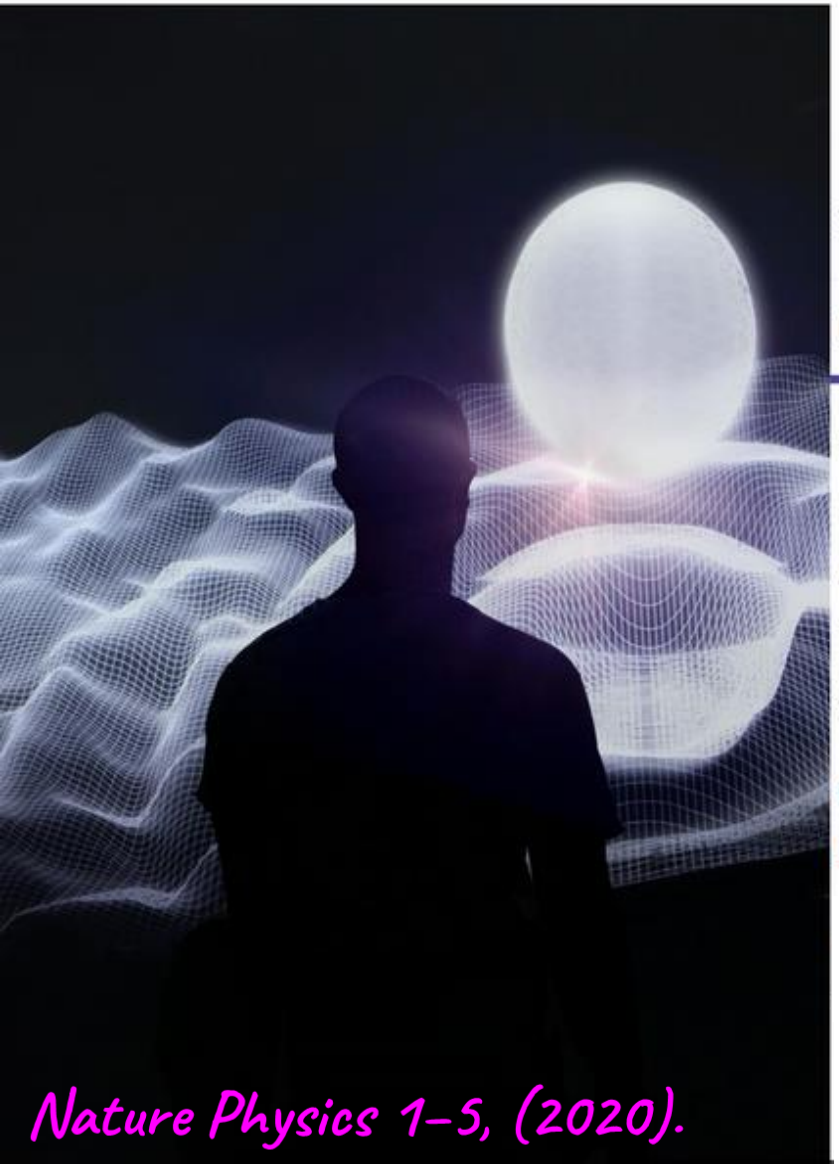
Roger Penrose proposed that a spatial quantum superposition collapses as a back-reaction from spacetime, which is curved in different ways by each branch of the superposition. In this sense, one speaks of gravity-related wave function collapse. He also provided a heuristic formula to compute the decay time of the superposition—similar to that suggested earlier by Lajos Diósi, (hence the name Diósi–Penrose model).

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 (P) of the particles' motion, resulting, if charged, in the emission of radiation. Here, we compute the radiation emission rate, which is faint but detectable. We then report the results of 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.

Con Roger Penrose



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 tested model.



Nature Physics 1–5, (2020).

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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

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-non-covid-19-edition

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

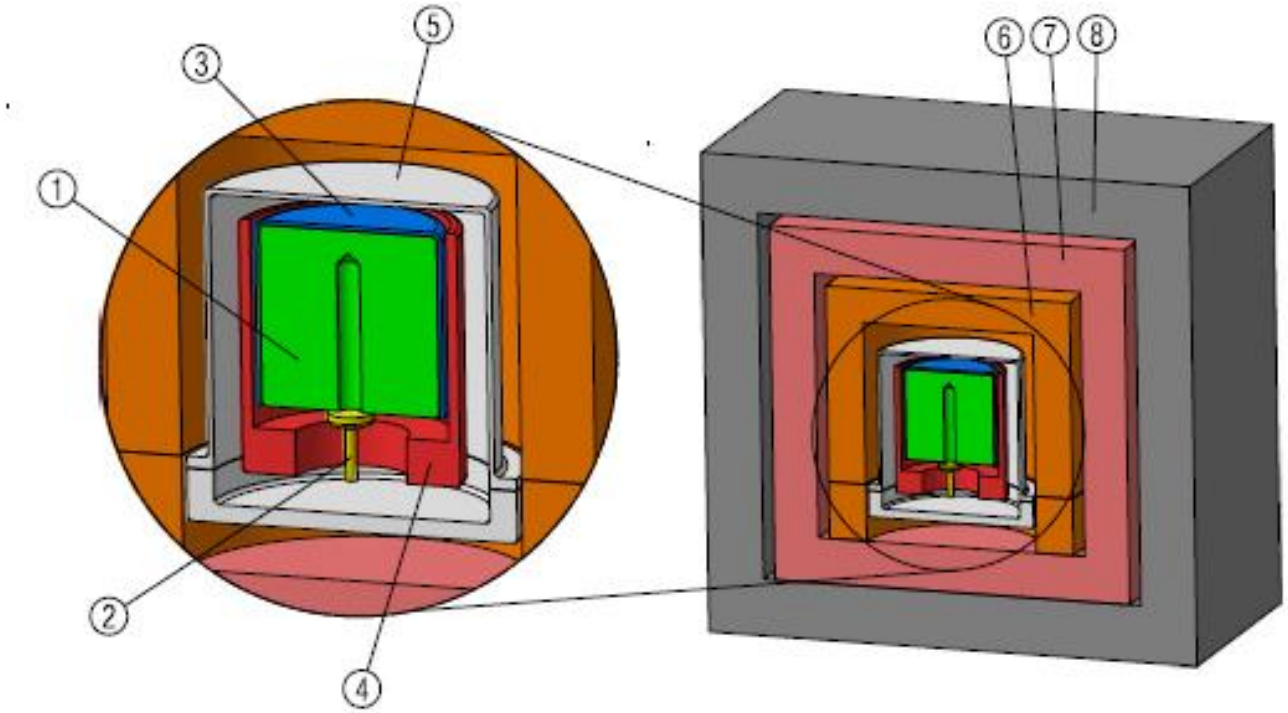


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

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:

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

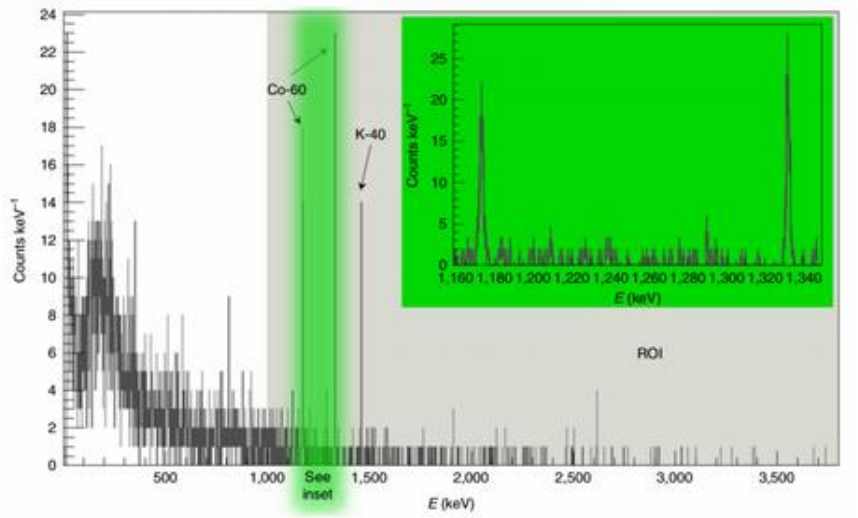
$R_0 > 0.54 \times 10^{-10}$ m **95% C. L.**

→ **Diosi-Penrose excluded**

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

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

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



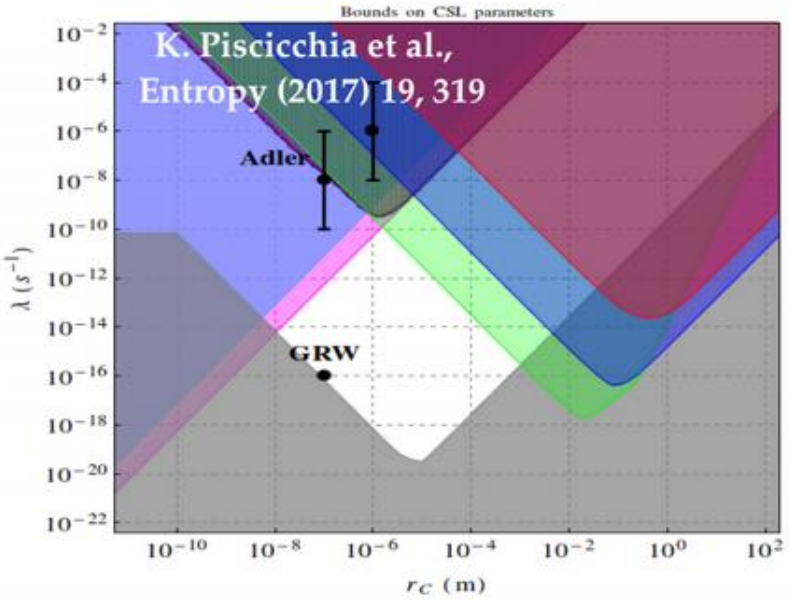
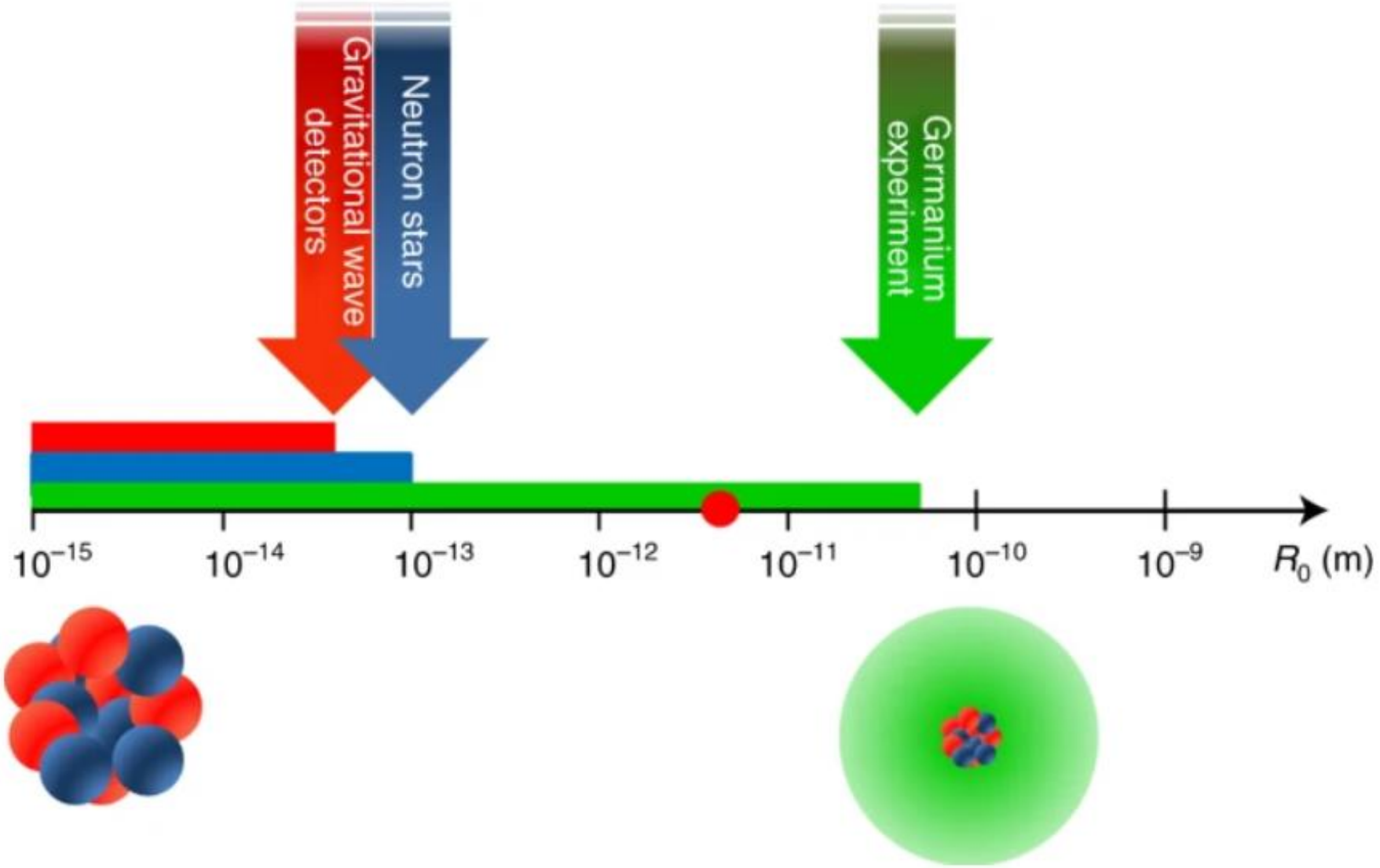


Fig. 5: Lower bounds on the spatial cutoff R_0 of the DP model.



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]

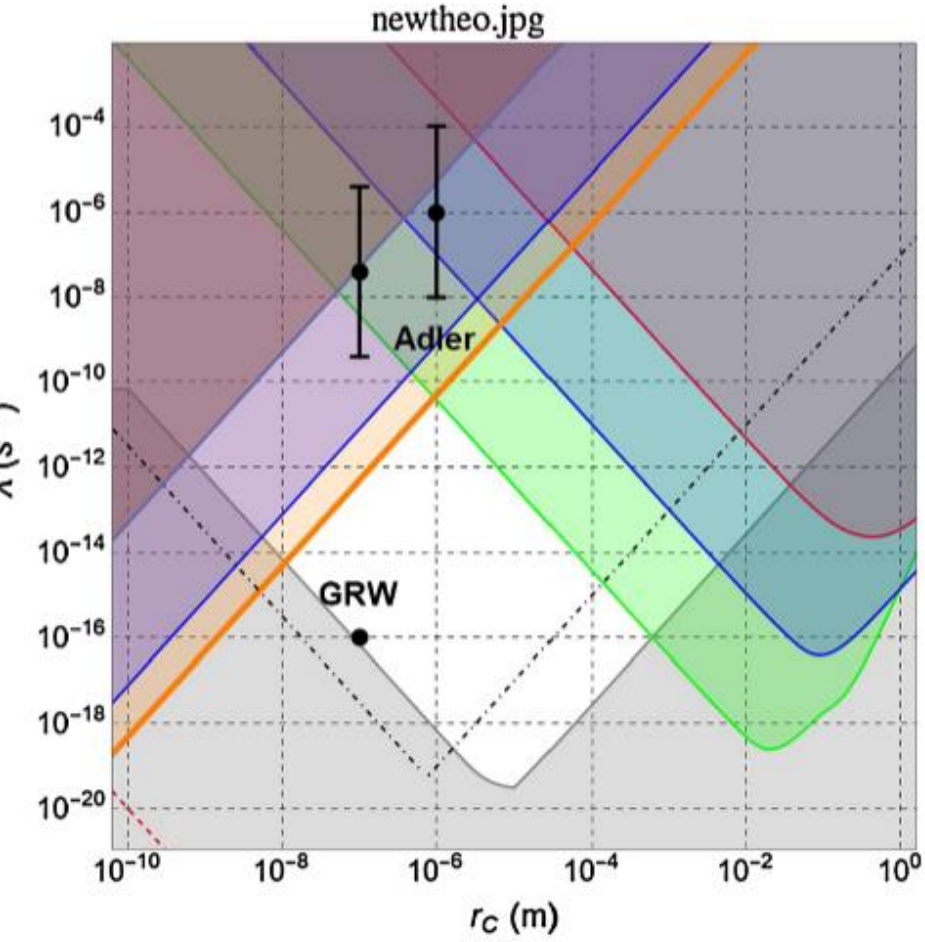


Fig. 4 Mapping of the $\lambda - r_C$ CSL parameters: the proposed theoretical values (GRW [6], Adler [24,25]) are shown as black points. The region excluded by theoretical requirements is represented in gray, and it is obtained by imposing that a graphene disk with the radius of 10 μm (about the smallest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

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

arXiv:2202.01343

A Search for Spontaneous Radiation from Wavefunction Collapse in the Majorana Demonstrator

Cancellation effects?

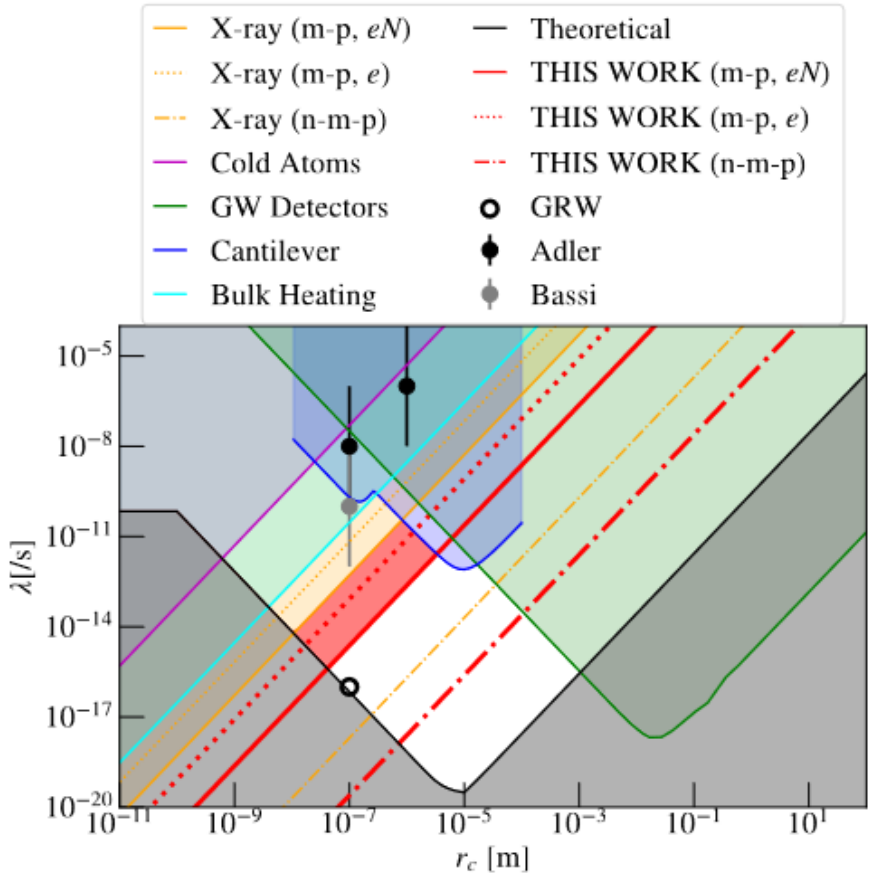
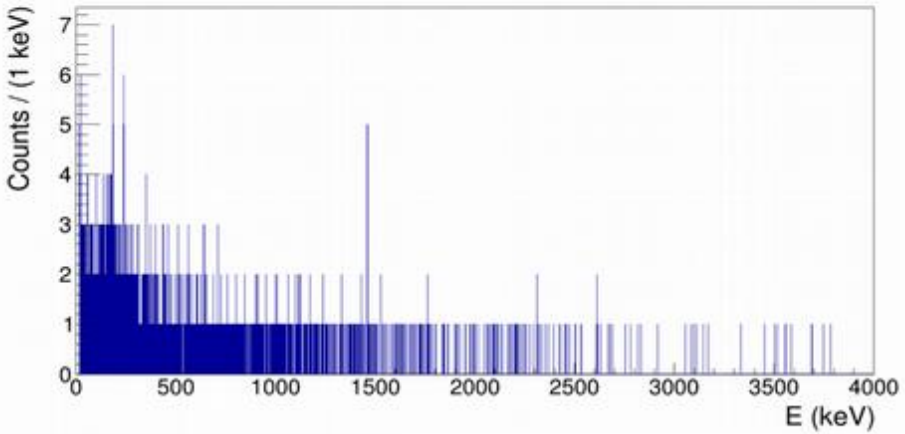


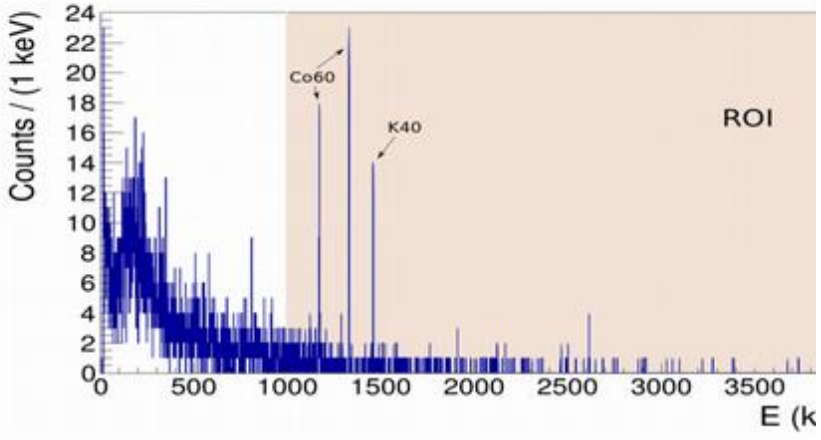
FIG. 2. Upper limits on the wavefunction collapse parameters compared to existing upper limits from other experiments.

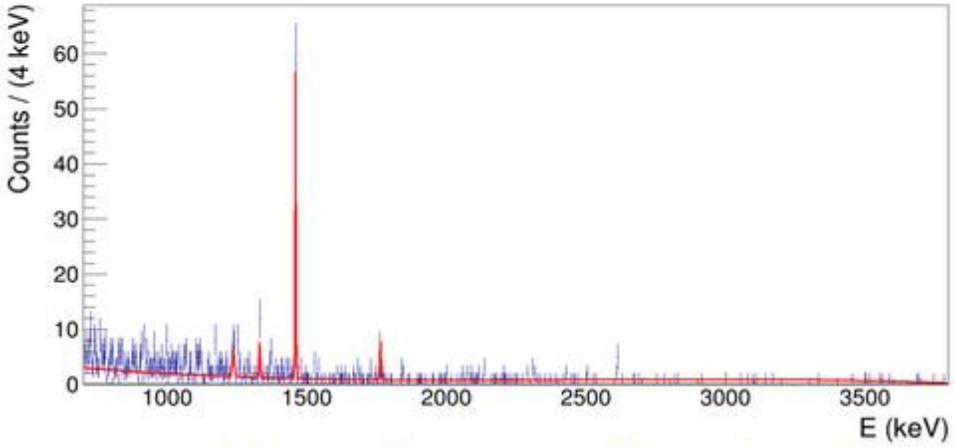

WOMEN
BE

Future perspectives

HPGe detector + ultrapure Pb active shielding:







BEGe detector + pulse shape discrimination

pushing the lower E threshold to few keV

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.

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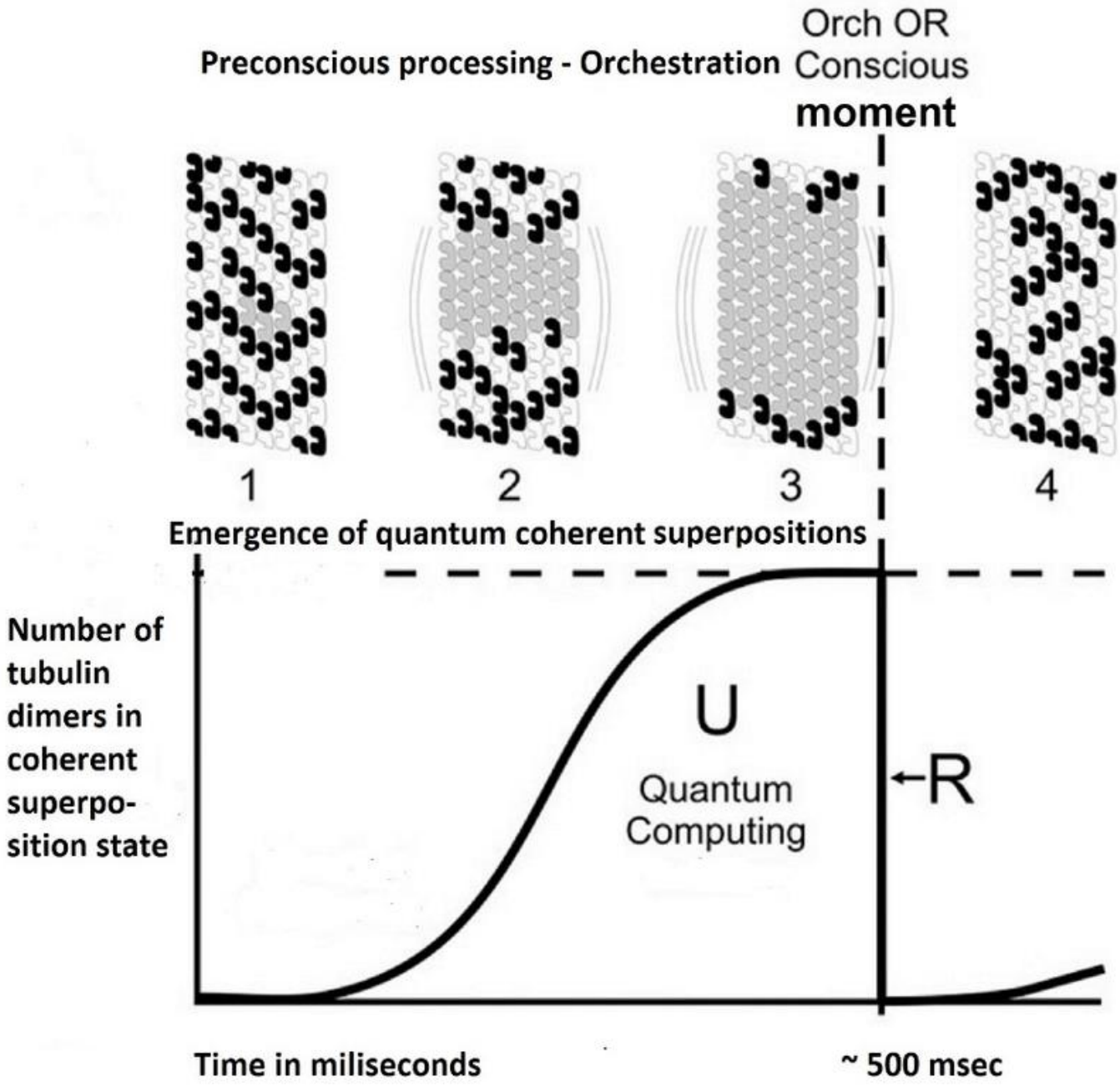
Review

At the crossroad of the search for spontaneous radiation and the Orch OR consciousness theory

Maaneli Derakhshani [a], Lajos Diósi [b,c], Matthias Laubenstein [d], Kristian Piscicchia [e,f,*], Catalina Curceanu [f]


Preconscious processing - Orchestration
Orch OR
Conscious
moment
1
2
3
4
Emergence of quantum coherent superpositions
Number of tubulin dimers in coherent superpo-sition state
U
Quantum Computing
R
Time in miliseconds
~ 500 msec

……the model is based on Penrose's particular hypothesis of gravity-related wave function collapse. ….
This being said, there does exist a dynamical theory of gravity-related wave function collapse due to Lajos Diósi which also predicts a collapse time of the form $\tau = h/E_g$. After the coincidence of this major figure and the underlying structure of decoherence, the two theories are often called the "Diósi-Penrose" (DP) theory in the literature. Behind the joint name DP, there is a particular difference. Unlike Penrose's approach, which lacks general dynamics, Diósi's general dynamics predicts violations of energy conservation that are appreciable enough to be experimentally tested and constrained. Indeed Penrose has expressed to us that he regards this feature of the DP theory as unphysical, expects it to be definitively ruled out by future experiments, and seeks a physical theory of gravity-related wave function collapse that avoids this (in his view) unphysical feature of energy conservation violation.

We have considered a variant of the Orch OR theory of consciousness that's based on the **simplest version of the DP theory of gravity-related dynamical wavefunction collapse,** at the crossroad of the search for spontaneous radiation providing recent experimental constraints on this simplest version of DP theory from . After reanalyzing the most plausible tubulin superposition scenarios described by HP, using the framework of this Orch OR theory variant, along with the recent experimental constraints, we are led to conclude that none of the scenarios (with possible exception to the case of partial separation of tubulins) are plausible.

The results in this paper **do not rule out Orch OR theory in general**. Rather, they rule out variants of Orch OR based on the simplest version of the DP theory of gravity-related dynamical wavefunction collapse. As mentioned earlier, Penrose and Diósi seek alternative theories of gravity-related dynamical wavefunction collapse that do not imply energy-nonconservation.

It is (also) possible that, when the **DP collapse dynamics is modified to include dissipation and/or non-Markovianity**, the scenario may change. In future work, we intend to develop such variants of the DP collapse dynamics and then reexamine the tubulin superposition scenarios discussed above. *Of course, objections to the Orch OR theory based on environmental decoherence considerations will likely still remain, barring unexpected discoveries in neurobiology showing decisively that microtubules can maintain coherent tubulin quantum states on scales required by Orch OR theory*

THOUGHT LEADERS

Can Quantum Phenomena Solve the Mystery of Consciousness?

What does this mean for the quantum-consciousness connection?

It means that if we take Diosi's dynamics for gravity-related collapse as the simplest version thereof, it looks rather improbable that this model can be at the root of consciousness in the way that the ORCH OR theory prescribes [8]. Nothing more, nothing less! We did not claim that we excluded the consciousness model put forward by Penrose and Hameroff, as we made clear in our paper!

We, however, made the first step in the direction of experimental tests which, we hope, will be followed by many others – with different systems, and various models. We proved that this is becoming possible!

Banff – Canada (aug. 2022)
Discussing about Consciousness…

JOHN TEMPLETON FOUNDATION

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

Grant 62099

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

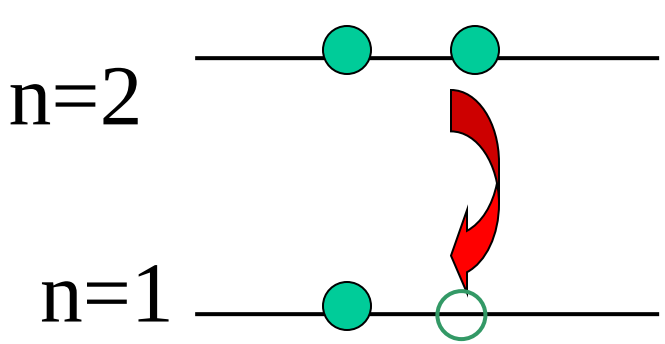
O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

"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."

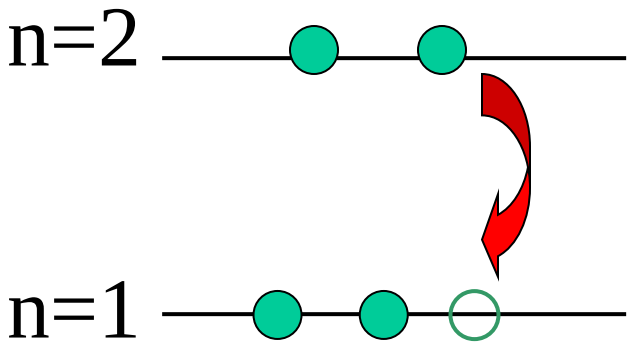
Experimental method:

Search for anomalous X-ray transitions when bringing "new" electrons



Normal 2p –>1s transition

Energy 8.04 keV



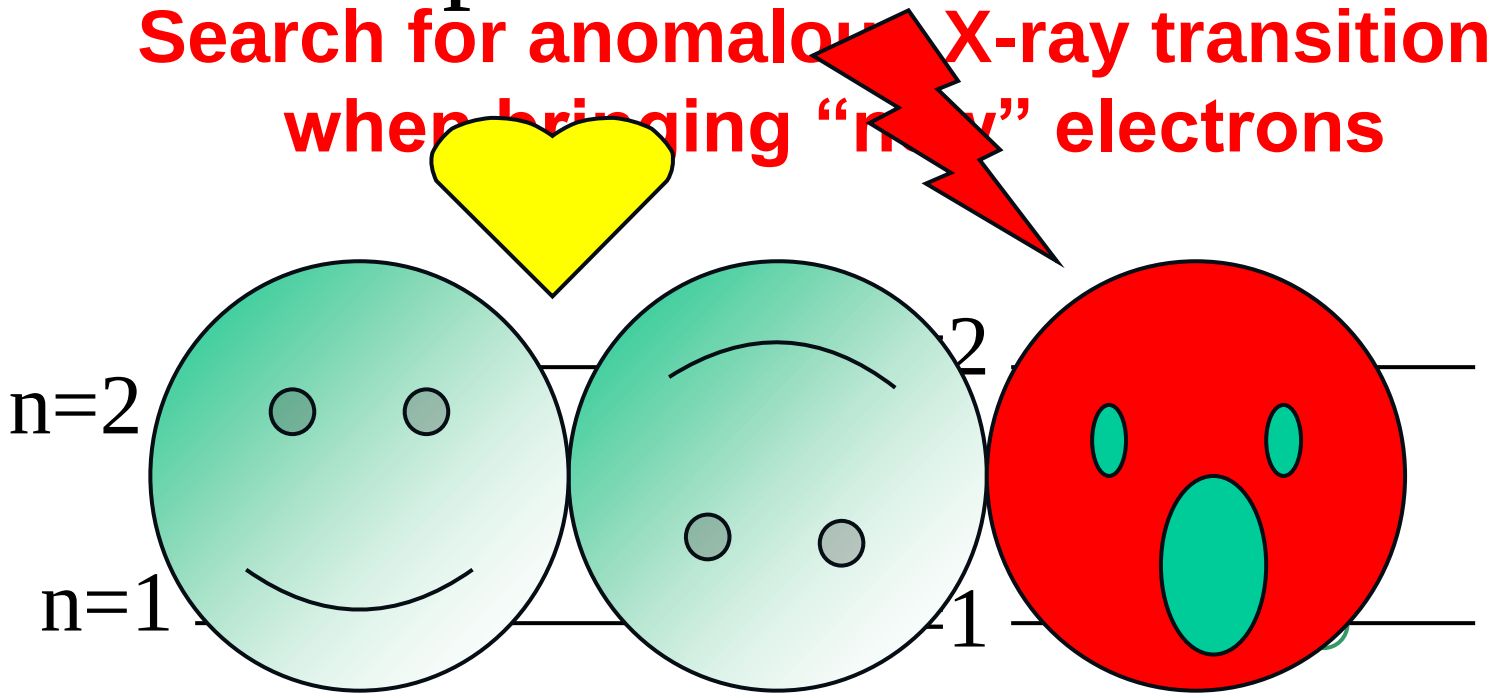
2p –>1s transition violating Pauli principle

Energy 7.7 keV

Messiah Greenberg superselection rule

Experimental method:

Search for anomalous X-ray transitions when bringing "n" electrons



Normal 2p –>1s transition

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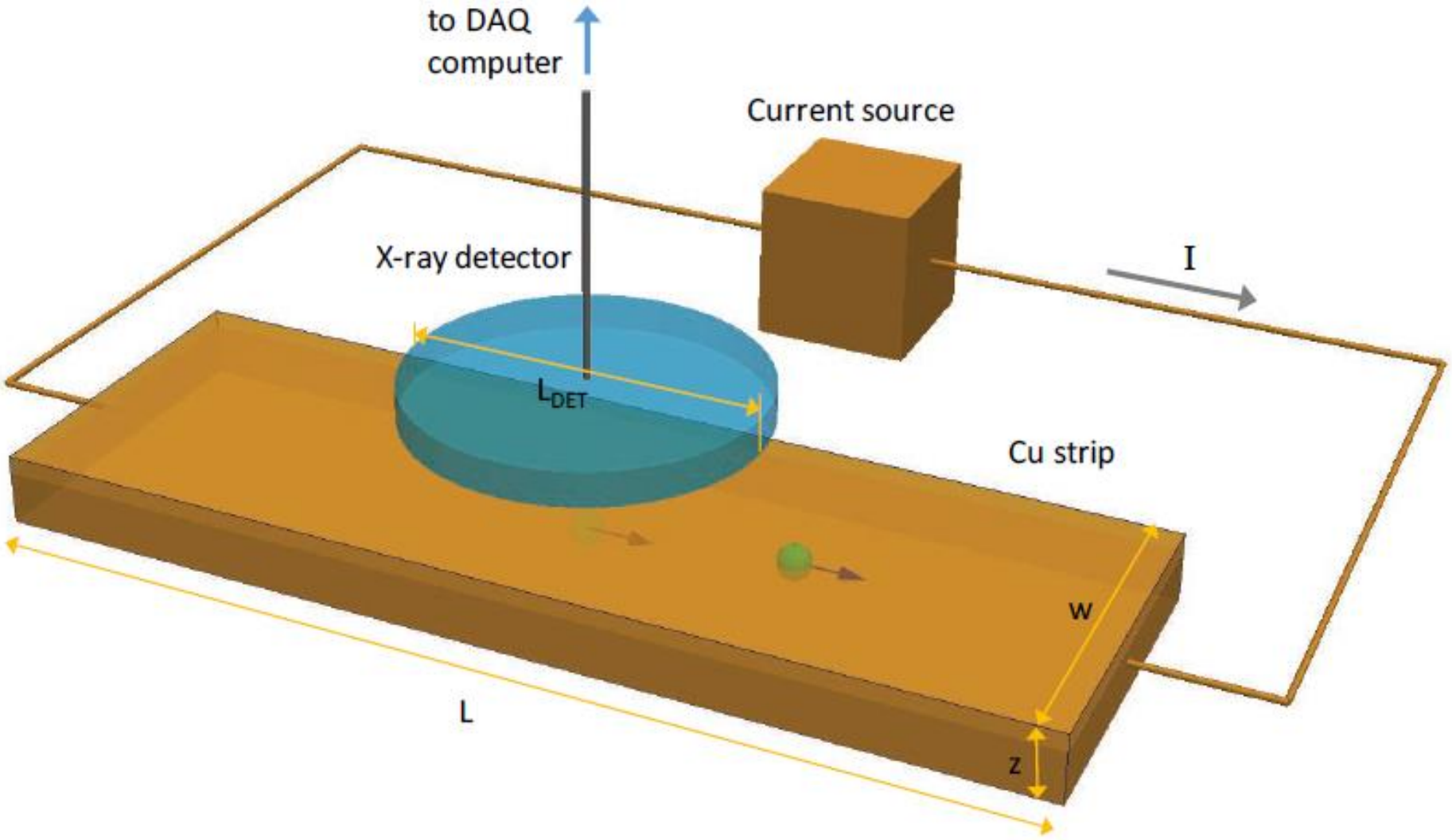
Messiah Greenberg superselection rule


to DAQ
computer
Current source
X-ray detector
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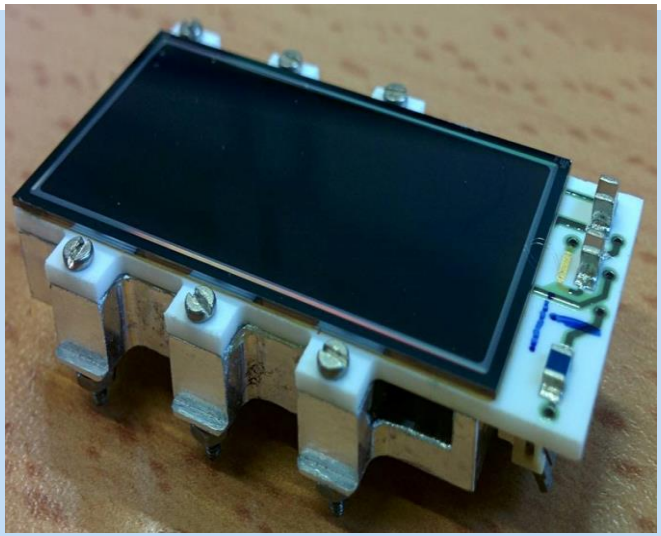
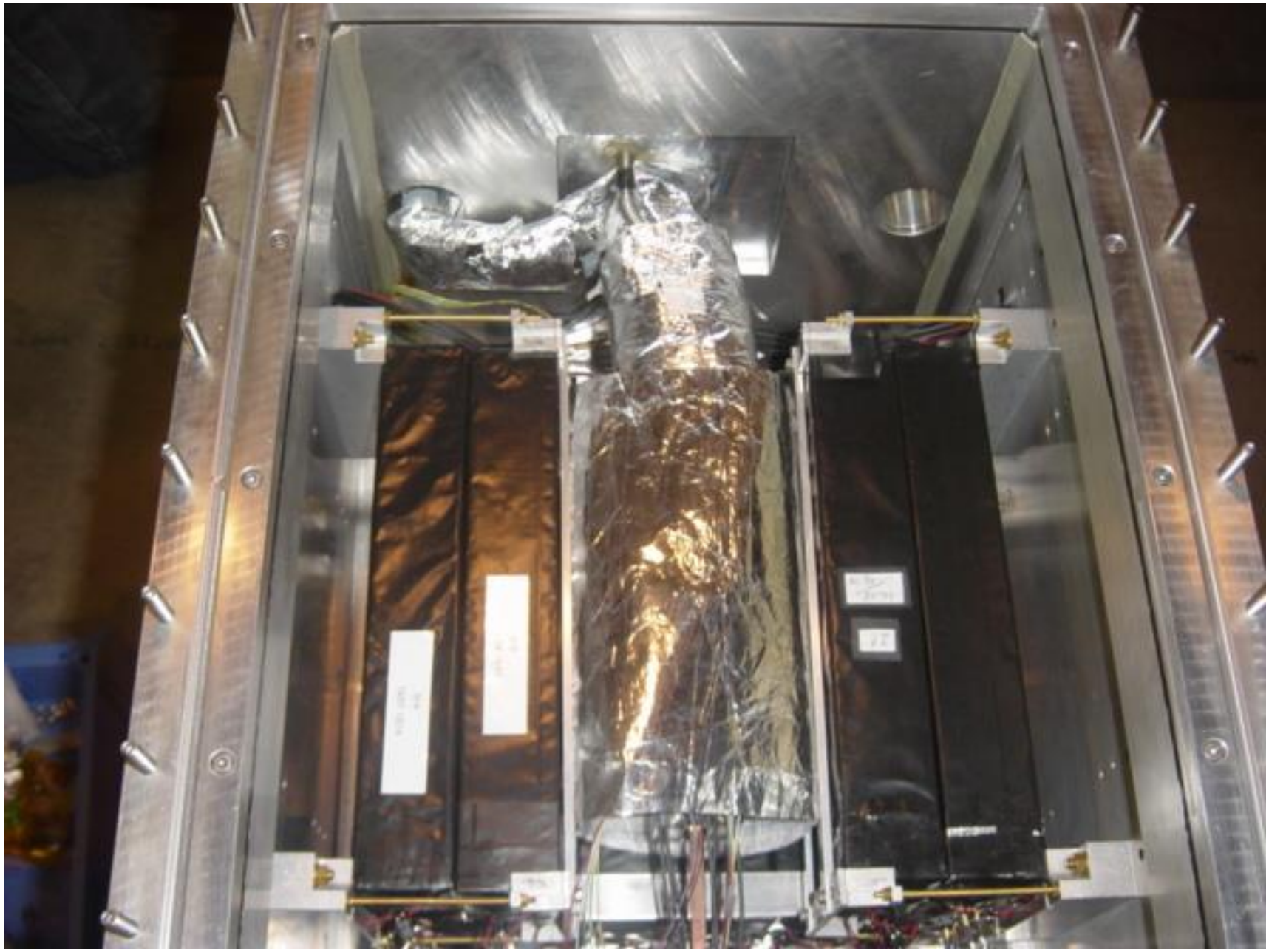
L_{DET}
Cu strip
w
L
z






Nat. Phys. (2020)

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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

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

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

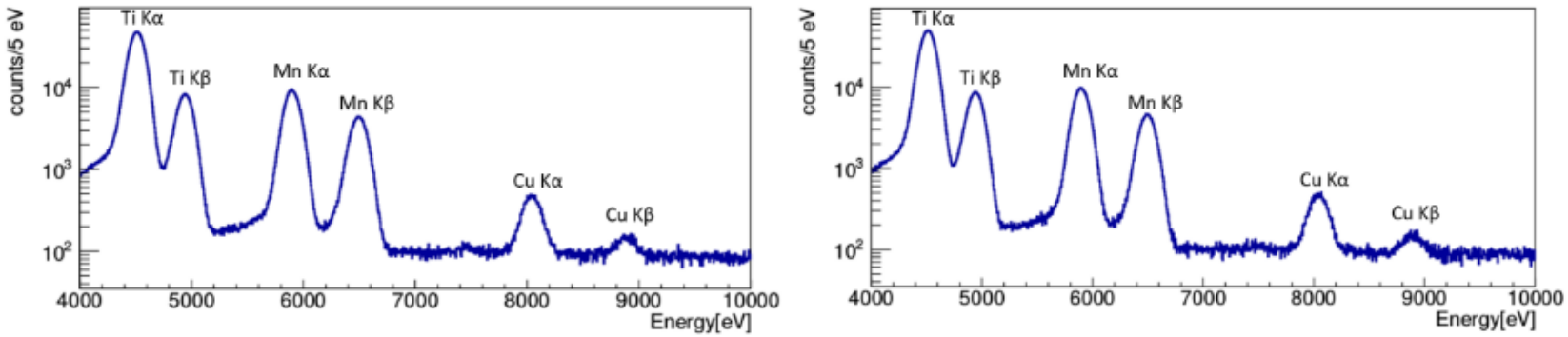

Figure 3. Energy calibrated spectra corresponding to about 42 days of data taking (during 2018) collected with current on (left), the spectrum collected with current off (right), which is normalized to the time of data taking with current on.

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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

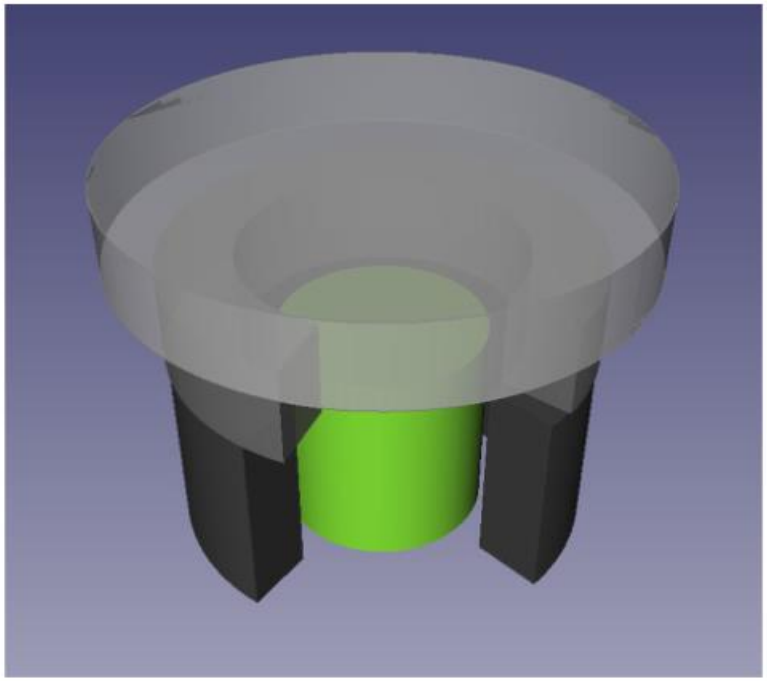

Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

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

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

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]

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

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

Investigations of possible violations of the Pauli exclusion principle represent critical tests of the microscopic space-time structure and properties. Space-time noncommutativity provides a class of universality for several quantum gravity models. In this context the VIP-2 lead experiment sets the strongest bounds, searching for the Pauli exclusion principle violating atomic transitions in lead, excluding the θ-Poincaré noncommutative quantum gravity models far above the Planck scale for nonvanishing $\theta_{\mu\nu}$ electriclike components, and up to 6.9×10^{-2} Planck scales if $\theta_{0i} = 0$.

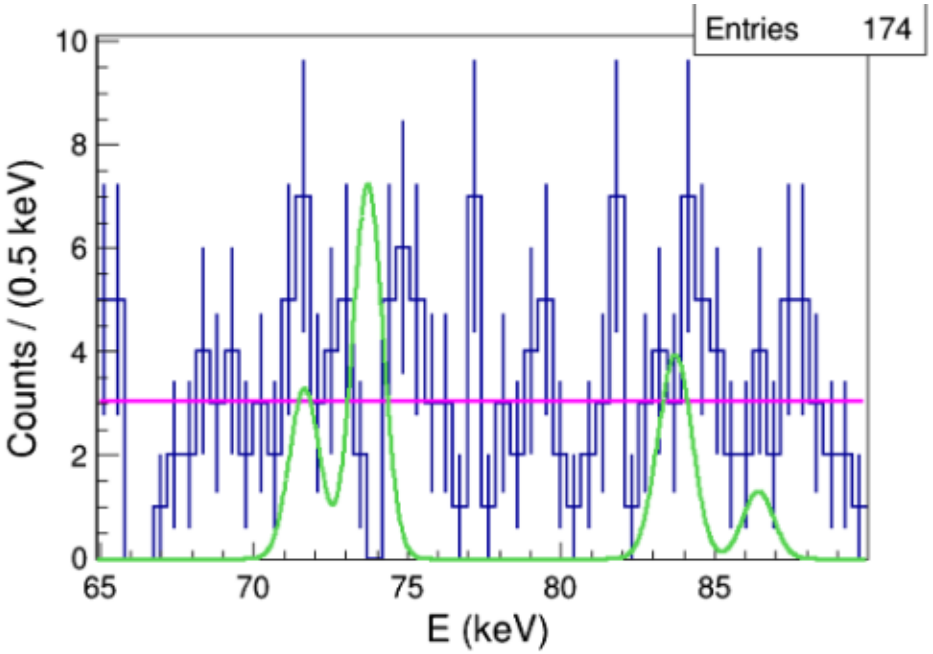


FIG. 1. The measured x-ray spectrum, in the region of the K_α and K_β standard and PEP-violating transitions in Pb, is shown in blue; the magenta line represents the fit of the background distribution. The green line corresponds to the shape of the expected signal distribution (with arbitrary normalization)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

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.

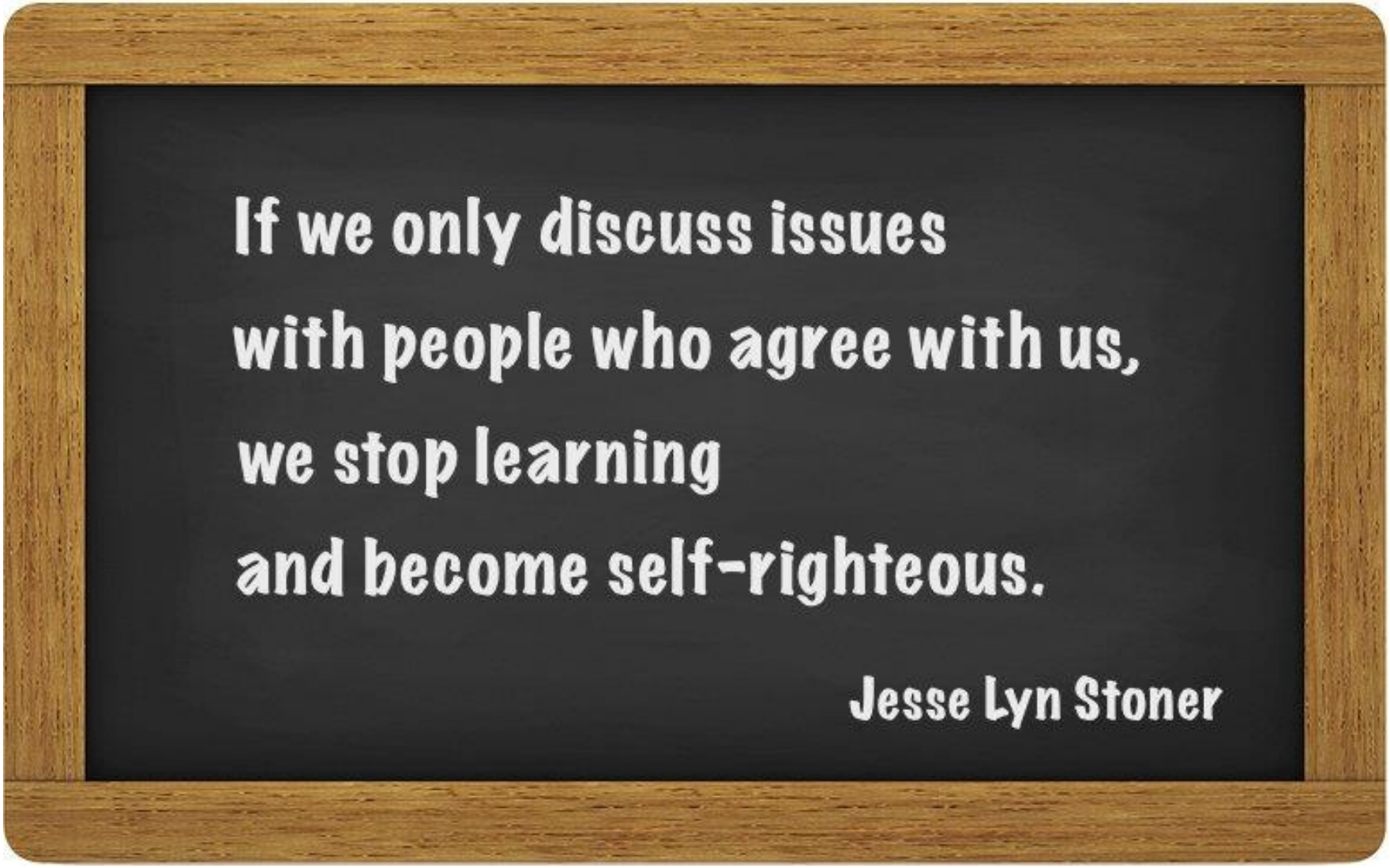
PAULI-ARCHIVE-PHO-011-1

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.

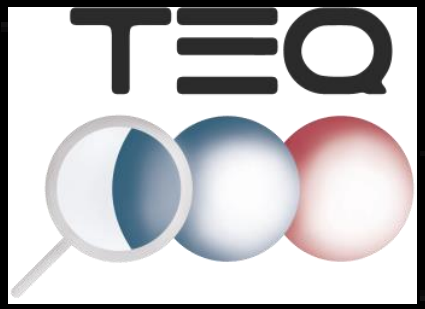
If we tightly grasp a stone in our hands, we neither expect it to vanish nor leak through our flesh and bones. Our experience is that stone and, more generally, solid matter is stable and impenetrable. Last year marked the 50th anniversary of the demonstration by Freeman Dyson and Andrew Lenard that 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.

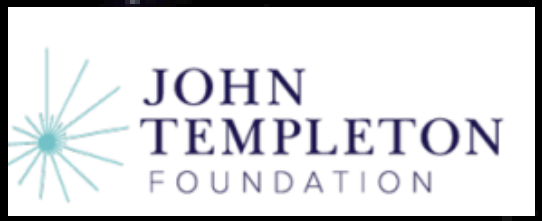
The exclusion principle (EP), which states that no two fermions can occupy the same quantum state, has been with us for almost a century. In his Nobel lecture, Pauli provided a deep and broad-ranging account of its discovery and its connections to unsolved problems of the newly born quantum theory. In 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.

Stawell underground laboratory: experiments testing quantum mechanics? We would be very interested to collaborate!


If we only discuss issues
with people who agree with us,
we stop learning
and become self-righteous.
Jesse Lyn Stoner

Acknowledgements





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