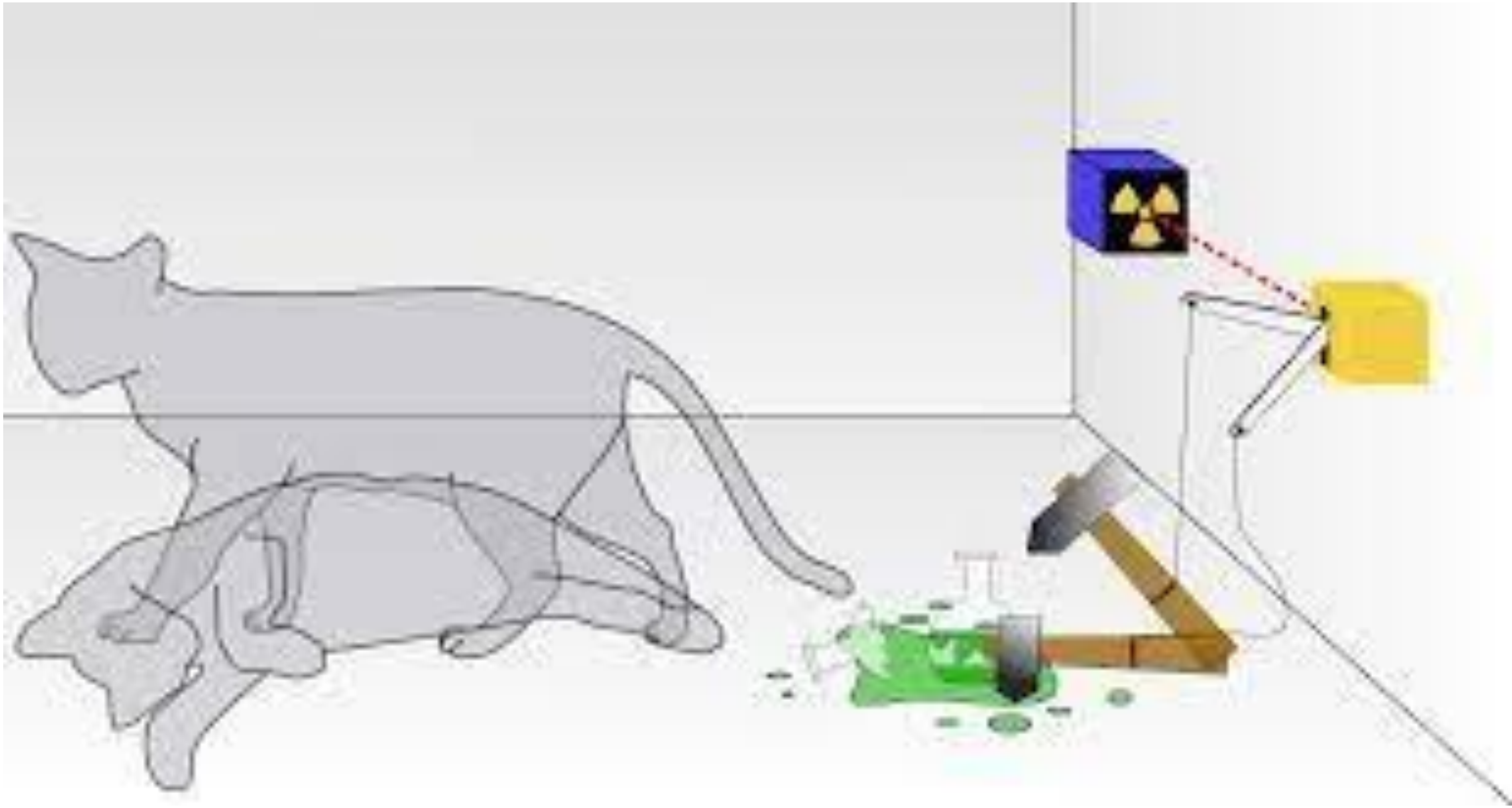
Quantum mechanics tests in the Gran Sasso undergroud laboratory: collapse models and spin-statistics

Catalina Curceanu, LNF-INFN, Frascati (Italy)

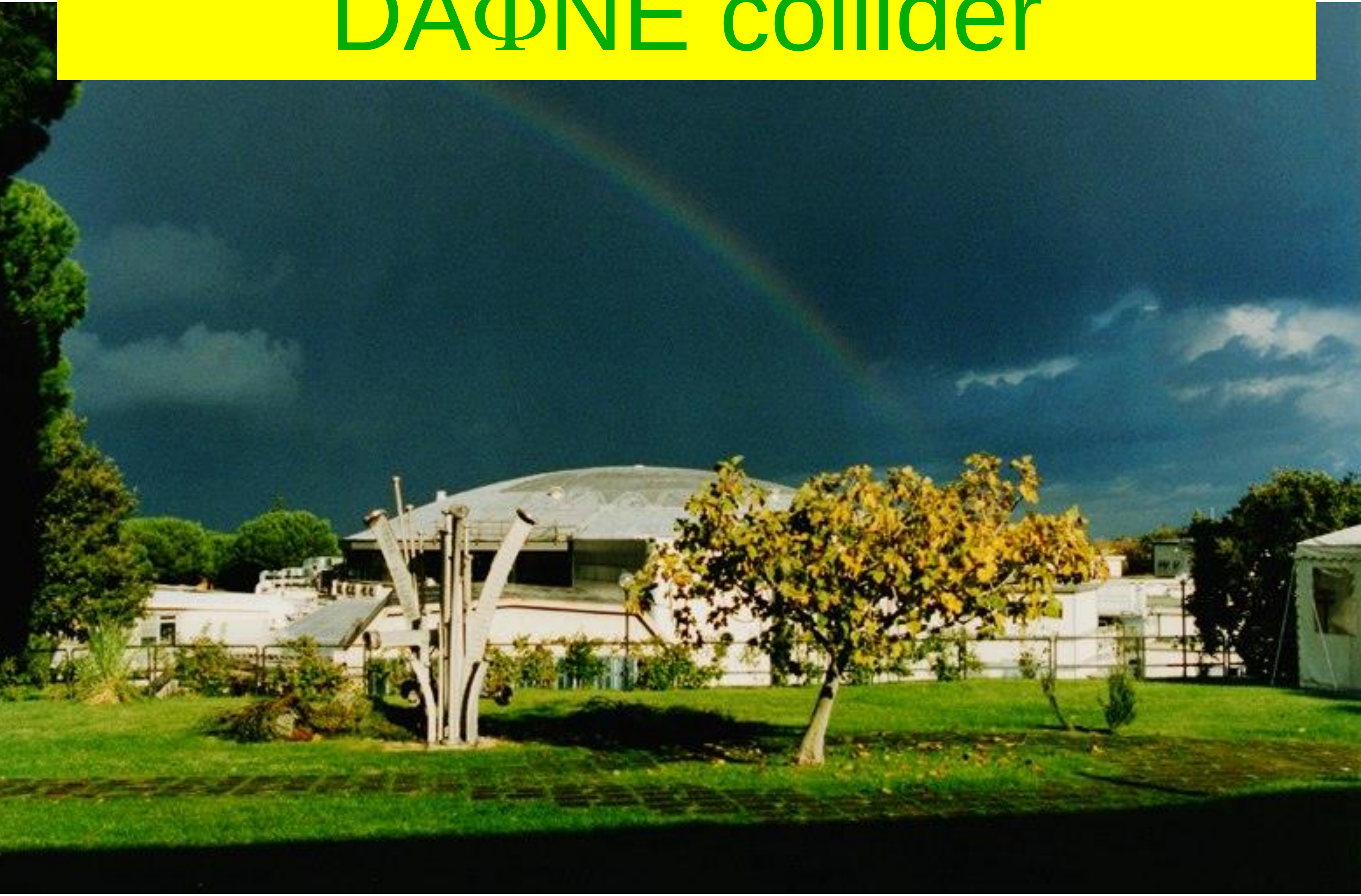
16th Marcel Grossmann Meeting

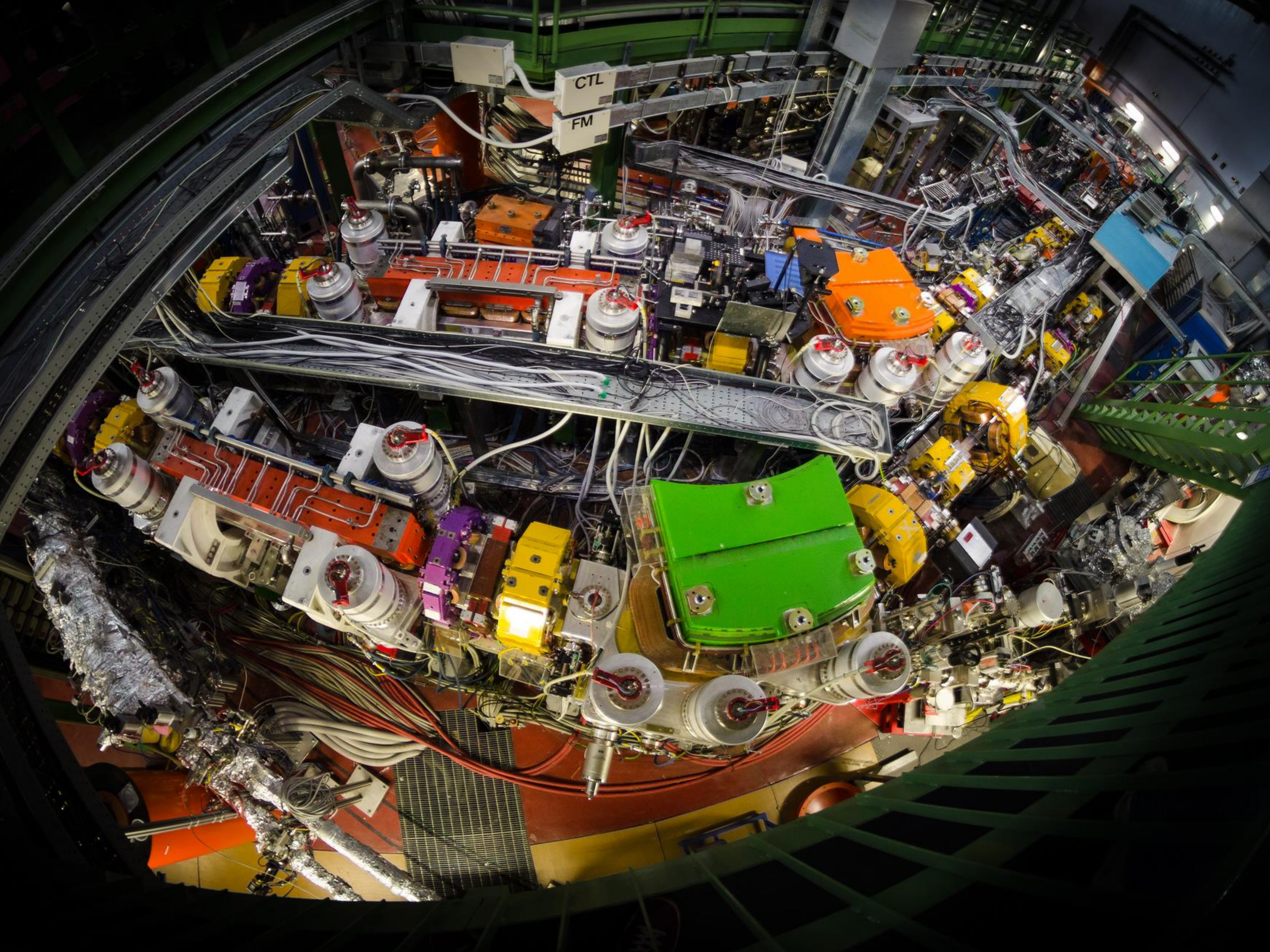
5 – 10 July 2021 (Roma, online)



My Institute: INFN-LNF

DAΦNE collider

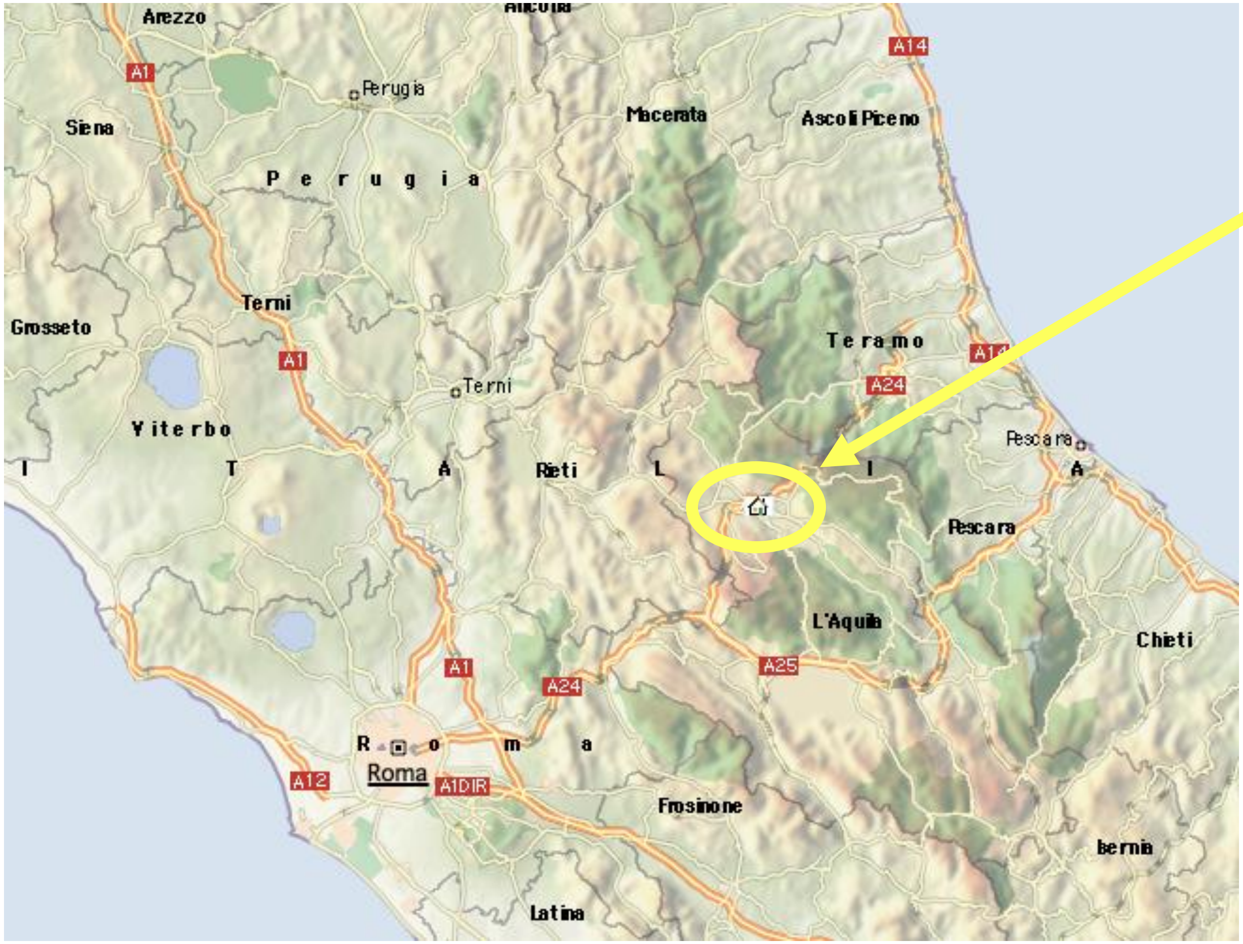



CTL
FM

SIDDHARTA

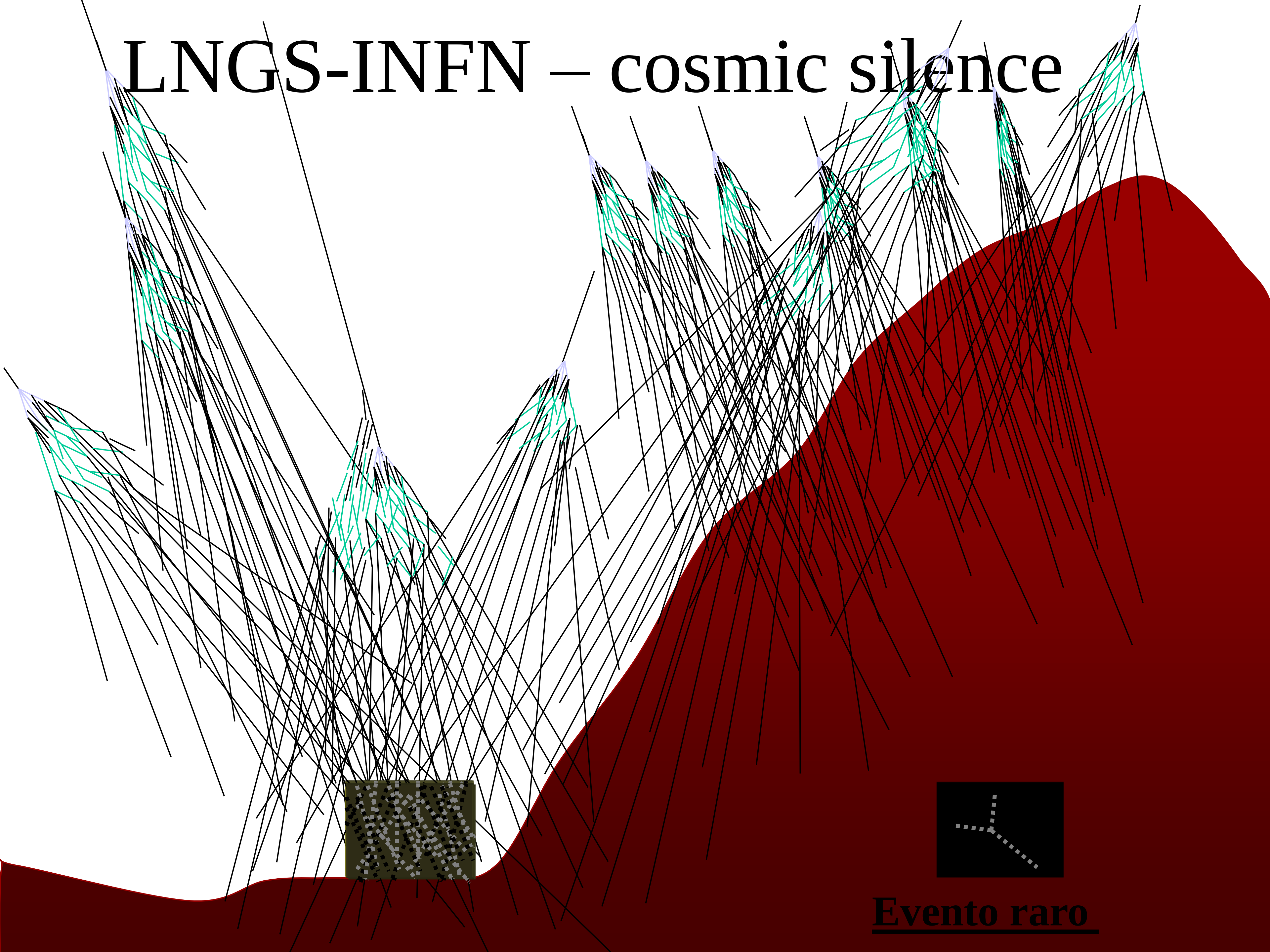
SIlicon Drift Detector for Hadronic Atom Research by Timing Application

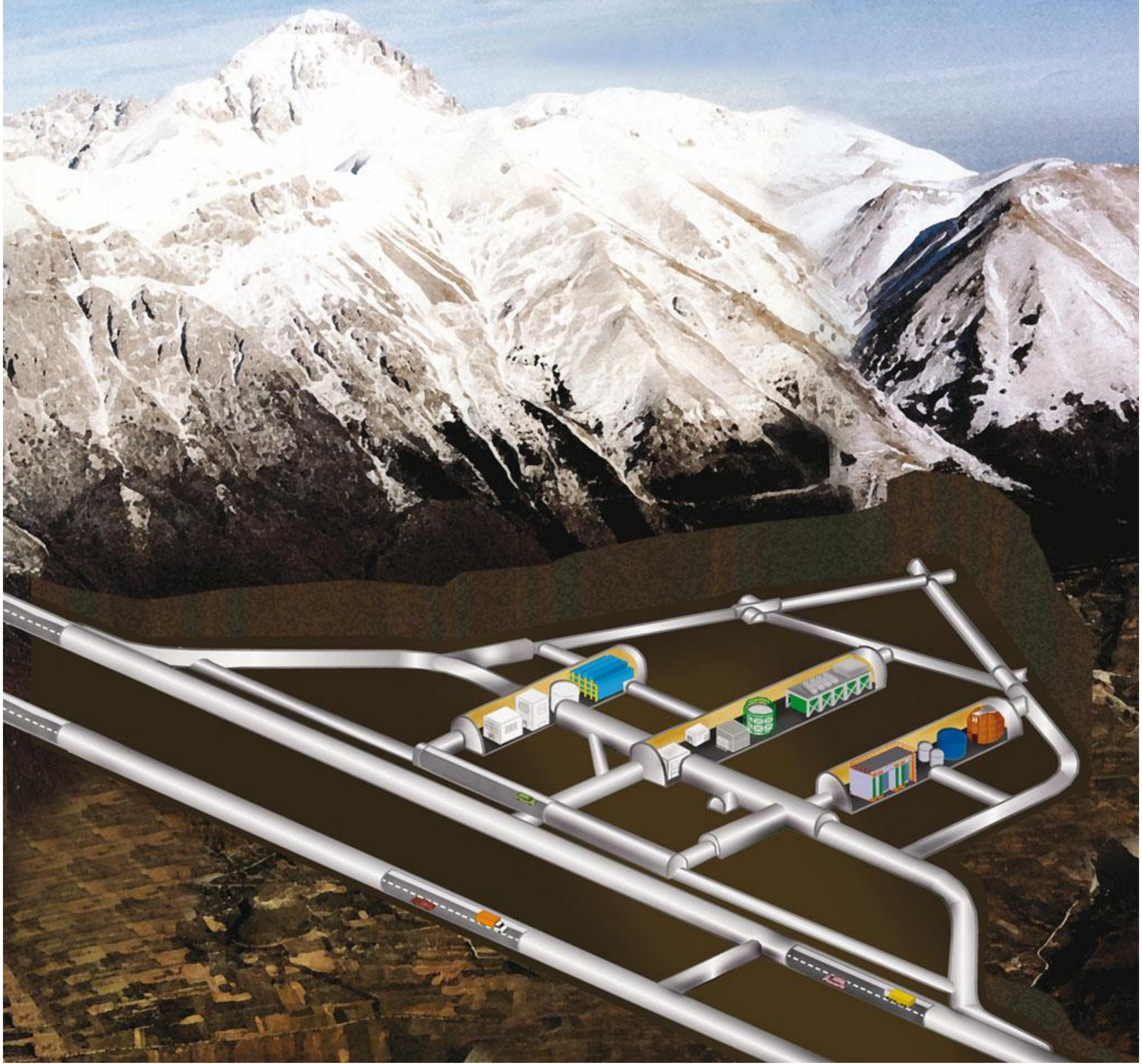
Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare

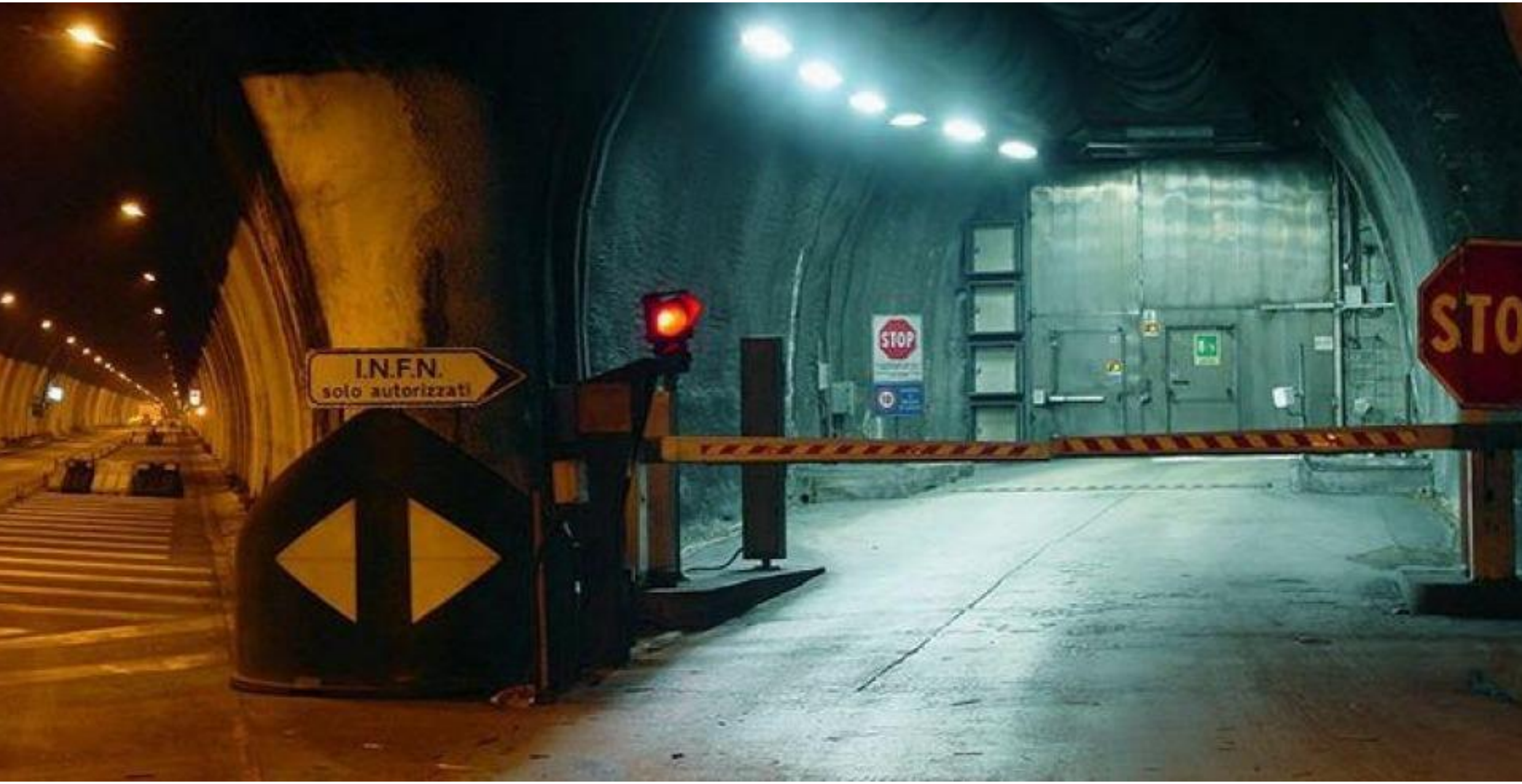


LNGS

LNGS-INFN – cosmic silence





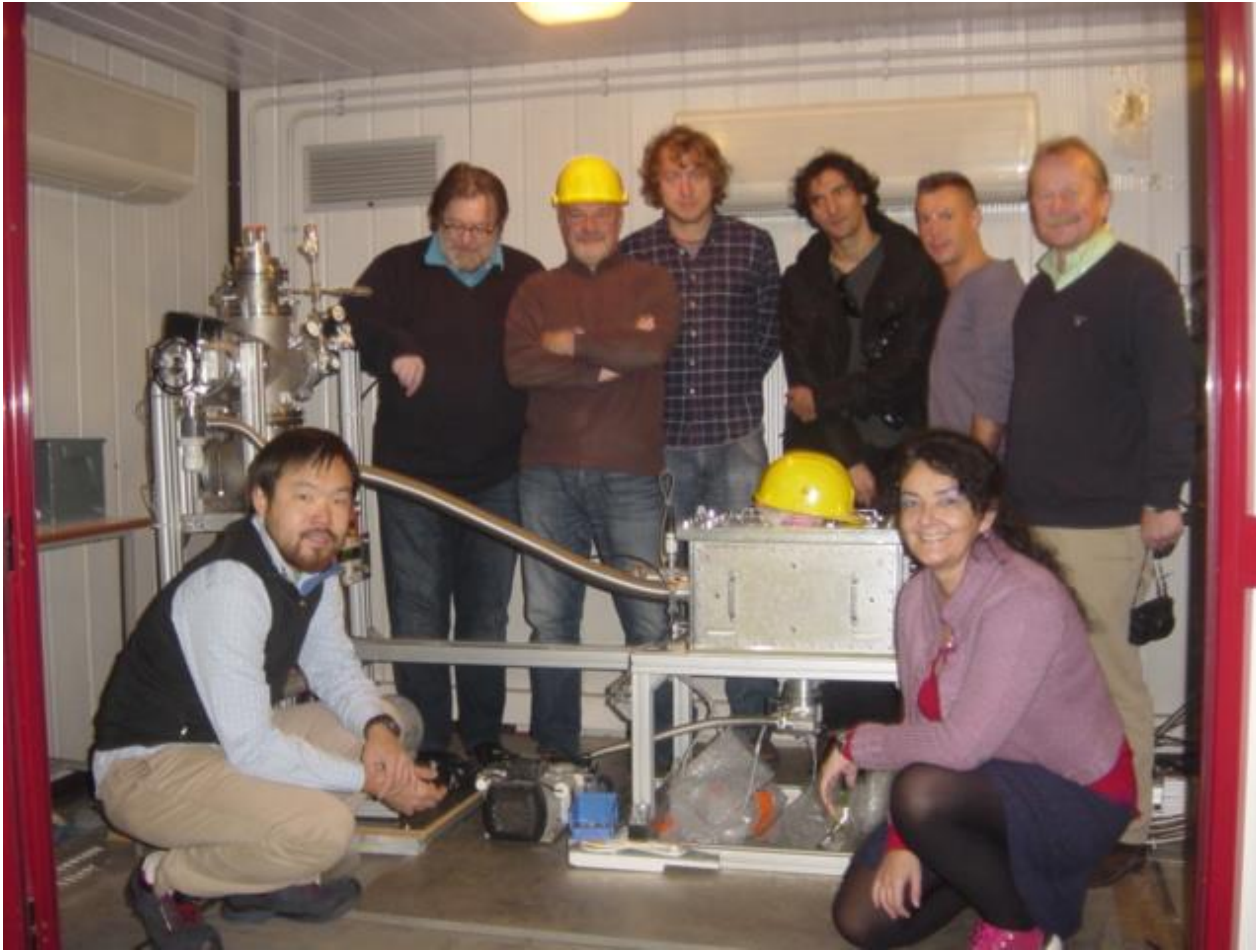

I.N.F.N.
solo autorizzati
STOP


INFN-LABORATORI
NAZIONALI
DEL GRAN SASSO
DAMA
F 40 D

Quantum Mechanics tests:

- Collapse Models

- Pauli Exclusion Principle Violation




GIFsBOOM
.net


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

The measurement problem

Possible solutions:

-De Broglie – Bohm

- Many-World Interpretations

-<u>Collapse of the w.f.</u>

-.....

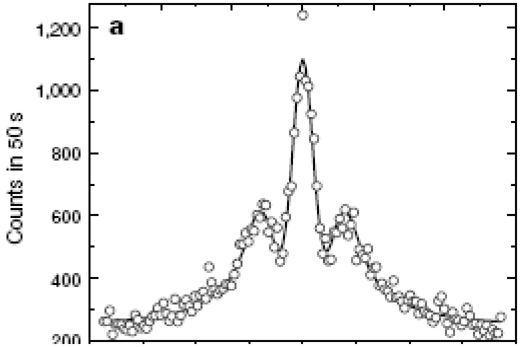
What are collapse models

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

   Paradox-free description of the quantum world

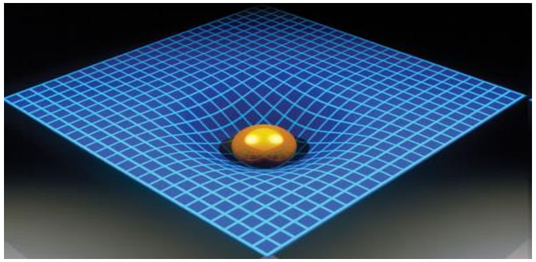
2. **Collapse models = <u>rival theory of Quantum Mechanics</u>**

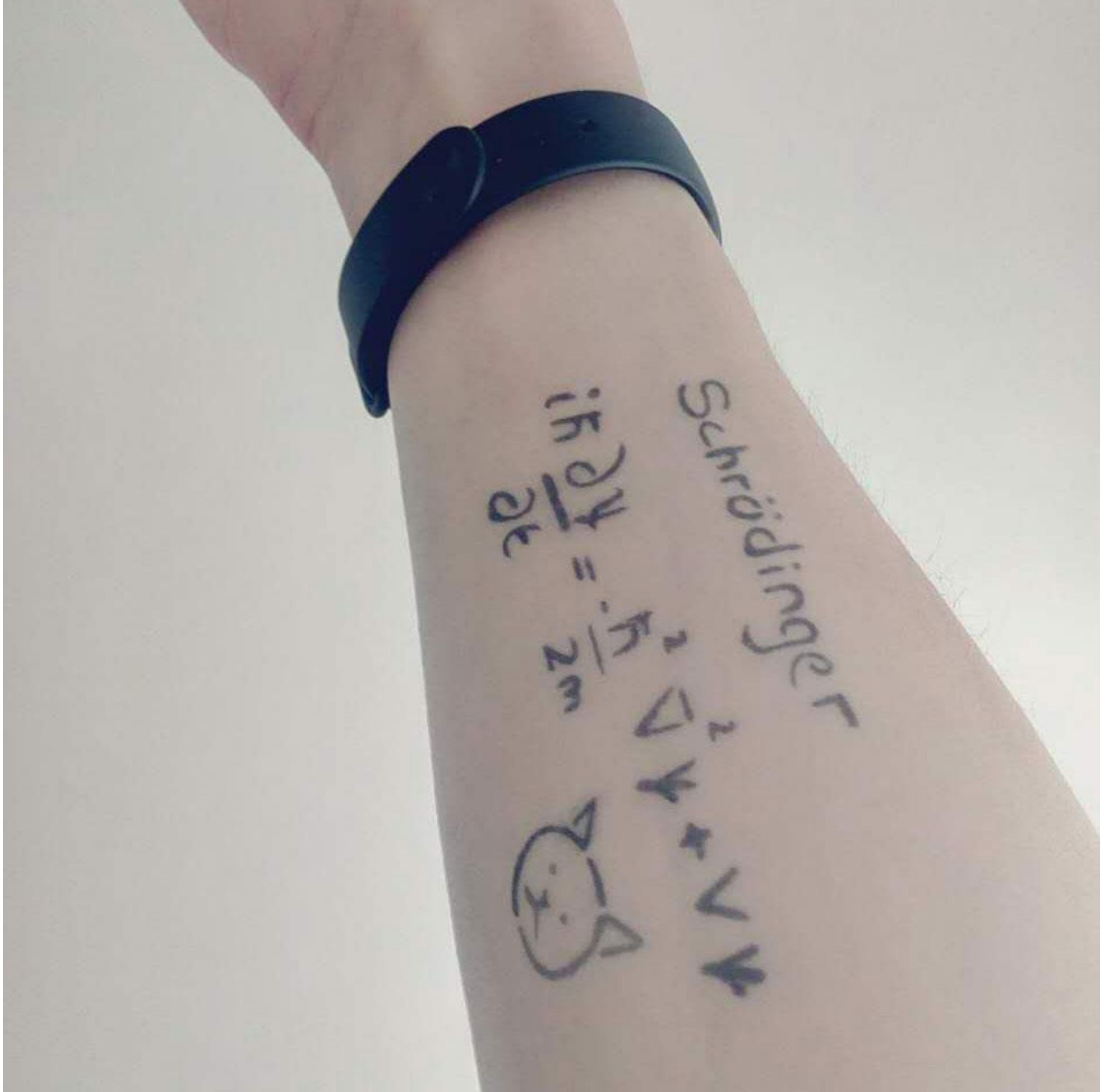
   They are related to experiments testing quantum linearity



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

   Can gravity causes the collapse?




Schrödinger
iħ ∂Ψ/∂t = -ħ²/2m ∇²Ψ + VΨ

Collapse models

A. Bassi and G.C. Ghirardi, *Phys. Rept.* 379, 257 (2003) A. Bassi *et al.*, *Rev. Mod. Phys.* 85, 471 (2013)

The general structure is

$$d|\psi\rangle_t = \left[-\frac{i}{\hbar} H dt + \sqrt{\lambda}(A - \langle A \rangle_t) dW_t - \frac{\lambda}{2}(A - \langle A \rangle_t)^2 dt \right] |\psi\rangle_t$$

$$\langle A \rangle_t = \langle \psi_t | A | \psi_t \rangle$$

New physical effects

Which kind of operators?

Natural assumption: the collapse operators – which identify the "preferred basis", should be **connected to position**

NOTE: The Born rule comes out automatically

CSL model

P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

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

System's Hamiltonian

NEW COLLAPSE TERMS ➡ **New Physics**

$N(\mathbf{x}) = a^\dagger(\mathbf{x}) a(\mathbf{x})$ particle density operator — **choice of the operators**

$\langle N(\mathbf{x}) \rangle_t = \langle \psi_t | N(\mathbf{x}) | \psi_t \rangle$ — **nonlinearity**

$W_t(\mathbf{x}) = \text{noise} \quad \mathbb{E}[W_t(\mathbf{x})] = 0, \quad \mathbb{E}[W_t(\mathbf{x}) W_s(\mathbf{y})] = \delta(t-s) e^{-(\alpha/4)(\mathbf{x}-\mathbf{y})^2}$ — **stochasticity**

$\lambda =$ collapse strength $\qquad r_C = 1/\sqrt{\alpha} =$ correlation length — **two parameters**

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

… spontaneous photon emission

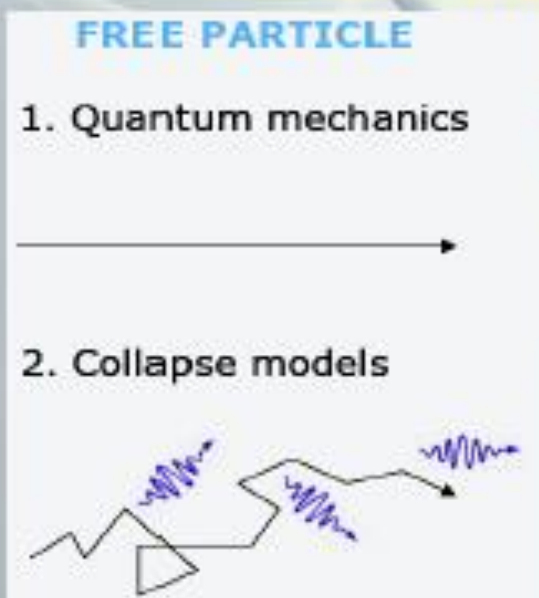
Besides collapsing the state vector to the position basis in non relativistic QM the interaction with the stochastic field increases the expectation value of particle's energy

↓

implies for a charged particle energy radiation (not present in standard QM) !!!

1) **Plausibility test of collapse models (ex. Karolyhazy model, collapse is induced by fluctuations in space-time → unreasonable amount of radiation in the X-ray range).**

2) **The comparison between theoretical prediction and experimental results will provide constraints on the parameters of the CSL model**



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

Q. Fu, Phys. Rev. A 56, 1806 (1997)

S.L. Adler, A. Bassi & S. Donadi, ArXiv 1011.3941

Our analysis: using published data of the IGEX experiment (K. Piscicchia)

The IGEX experiment is a low-activity Ge based experiment dedicated to the $\beta\beta0\nu$ decay research. (C. E. Aalseth et al., IGEX collaboration Phys. Rev. C 59, 2108 (1999))

In (A. Morales et al., IGEX collaboration Phys. Lett. B 532, 8-14 (2002)) the published data acquired for an exposure of 80 *kg day* in the energy range:

Low-energy data from the IGEX RG-II detector (Mt = 80 kg day)

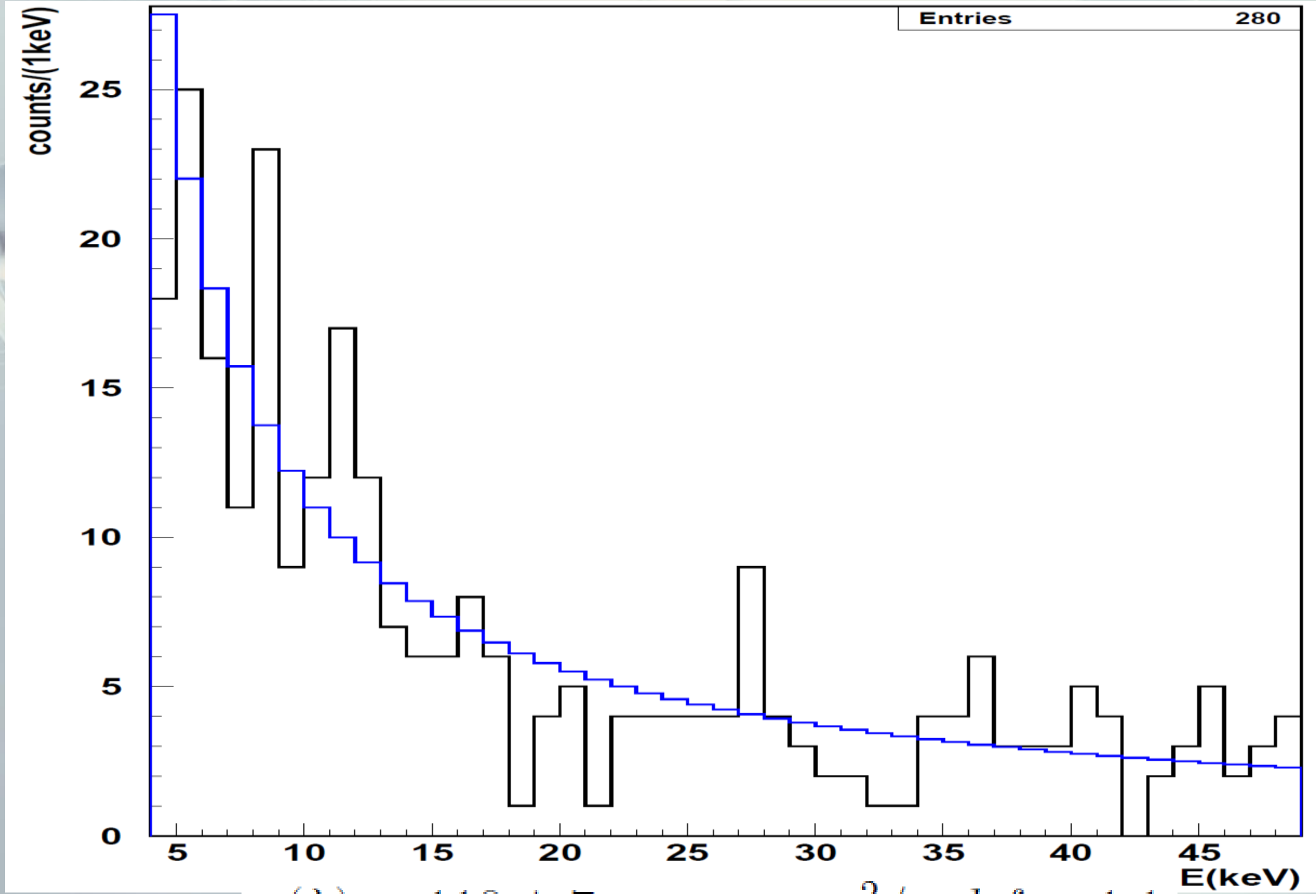
E (keV)	Counts	*E* (keV)	Counts	*E* (keV)	Counts
4.5	18	19.5	4	34.5	4
5.5	25	20.5	5	35.5	4
6.5	16	21.5	1	36.5	6
7.5	11	22.5	4	37.5	3
8.5	23	23.5	4	38.5	3
9.5	9	24.5	4	39.5	3
10.5	12	25.5	4	40.5	5
11.5	17	26.5	4	41.5	4
12.5	12	27.5	9	42.5	0
13.5	7	28.5	4	43.5	2
14.5	6	29.5	3	44.5	3
15.5	6	30.5	2	45.5	5
16.5	8	31.5	2	46.5	2
17.5	6	32.5	1	47.5	3
18.5	1	33.5	1	48.5	4

New analysis: results and discussion

The X-ray spectrum was fitted assuming the predicted energy dependence:

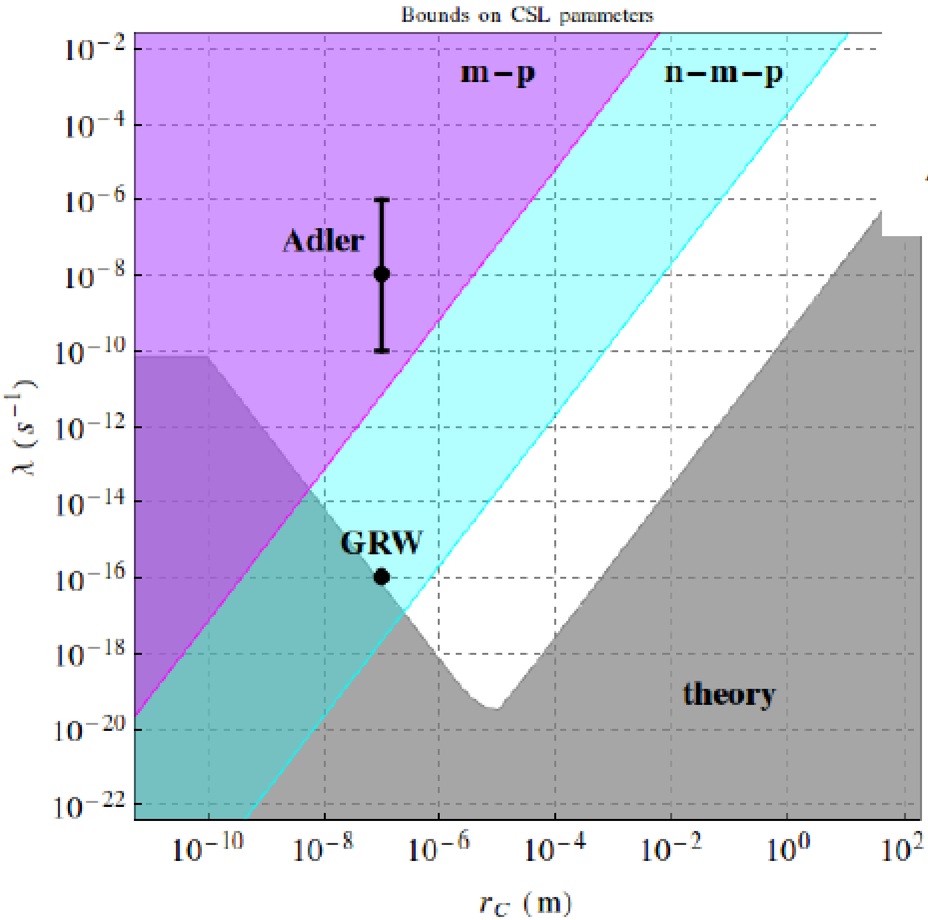
$$\frac{d\Gamma_k}{dk} = \frac{\alpha(\lambda)}{k}$$

With $\alpha(\lambda)$ free parameter, bin contents are treated with Poisson statistics.



Fit result $\alpha(\lambda) = 110 \pm 7 \quad , \quad \chi^2/n.d.f = 1.1$

New limit on colapse model parameters – Entropy 19 (2017) 319



$\lambda \leq 6.8 \cdot 10^{-12}\ \mathrm{s}^{-1}$ mass prop.,

$\lambda \leq 2.0 \cdot 10^{-18}\ \mathrm{s}^{-1}$ non-mass prop.

Figure 2. Mapping of the $\lambda - r_C$ Continuous Spontaneous Localization (CSL) parameters: the originally proposed theoretical values (GRW, Adler) are shown as black points; the region excluded by theory (theory) is represented in gray. The excluded region according to our analysis is shown in cyan for the non-mass proportional case (n-m-p) and in magenta for the mass proportional case (m-p).

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

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.

Even without proposing a detailed mathematical model, Penrose provides a formula that estimates, in non-relativistic and weak-gravitational-field limits, the expected time τ_{DP} of the collapse of a quantum superposition[14]:

$$\tau_{\mathrm{DP}} = \frac{\hbar}{\Delta E_{\mathrm{DP}}} \tag{1}$$

where ΔE_{DP} measures how large, in gravitational terms, the superposition is. Given a system with mass density $\mu(\mathbf{r})$, in the simple case of the centre of mass being in a superposition of two states displaced by a distance $\mathbf{d}$,

$$\Delta E_{\mathrm{DP}}(\mathbf{d}) = -8\pi G \int \mathrm{d}\mathbf{r} \int \mathrm{d}\mathbf{r}' \frac{\mu(\mathbf{r})\left[\mu(\mathbf{r}'+\mathbf{d}) - \mu(\mathbf{r}')\right]}{|\mathbf{r}-\mathbf{r}'|} \tag{2}$$

Equations (1) and (2), which are valid in the Newtonian limit, were previously proposed by Diósi[17,18], following a different approach. For a point-like $\mu(\mathbf{r}) = m\delta(\mathbf{r} - \mathbf{r}_0)$, with m the mass of the particle and δ the Dirac delta distibution, equation (2) diverges because of the $1/r$ factor, leading to an instantaneous collapse, which is clearly wrong. To avoid this problem, one has to smear the mass density. This is implemented in different ways by Diósi and Penrose. Diósi suggests introducing a new phenomenological parameter, measuring the spatial resolution of the mass density[19,20]; Penrose instead suggests that the mass density of a particle is given by $\mu(\boldsymbol{r}) = m|\psi(\boldsymbol{r}, t)|^2$ (ref. [15]), where $\psi(\boldsymbol{r}, t)$ is a stationary solution of the Schrödinger–Newton equation[21,22]. For either choice, we will call the size of the particle's mass density R_0.

The collapse depends on the <u>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.</u> We computed the radiation emission rate, which is faint but detectable

Lindblad dynamics for the statistical operator $\rho(t)$ describing the state of the system (Supplementary Information):

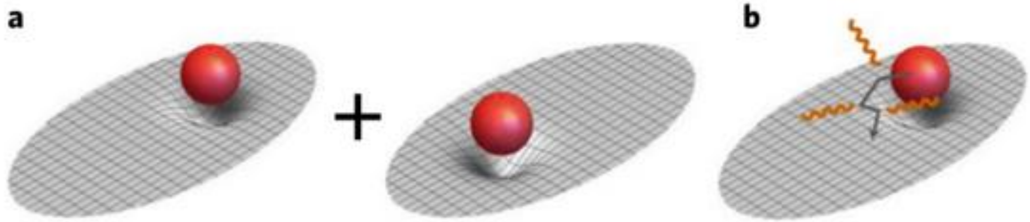
$$\frac{d\rho(t)}{dt} = -\frac{i}{\hbar}[H,\rho(t)] - \frac{4\pi G}{\hbar}\int d\mathbf{x}\int d\mathbf{y}\,\frac{1}{|\mathbf{x}-\mathbf{y}|}\left[\hat{M}(\mathbf{y}),\left[\hat{M}(\mathbf{x}),\rho(t)\right]\right] \tag{3}$$

ond term accounts for the gravity-related collapse. In equation (3) H is the system's Hamiltonian and $\hat{M}(\mathbf{x}) = \sum_n \mu_n(\mathbf{x},\hat{\mathbf{x}}_n)$ gives the total mass density, with $\mu_n(\mathbf{x},\hat{\mathbf{x}}_n)$ the mass density of the nth particle, centred around $\hat{\mathbf{x}}_n$. Taking for example a free particle with momentum operator $\hat{\mathbf{p}}$, the contribution of the second term to the average momentum $\langle\mathbf{p}\rangle \equiv \mathrm{Tr}[\hat{\mathbf{p}}\rho]$ is zero, while the contribution to the average square momentum $\langle\mathbf{p}^2\rangle$ increases in time. This is diffusion.

Starting from equation (3), we computed the radiation emission rate, that is the number of photons emitted per unit time and unit frequency, integrated over all directions, in the range of wavelength $\lambda \in (10^{-5}–10^{-1})$ nm, corresponding to energies $E \in (10–10^{5})$ keV. The reason for choosing this range can be understood in terms of a semi-classical picture: each time a collapse occurs, particles are slightly and randomly moved. This random motion makes them emit radiation, if charged. When their separation is smaller than λ, they emit as a single object with charge equal to the total charge, which can be zero for opposite charges as for an atom. In contrast, when their separation is larger than λ, they emit independently. Therefore, in order to maximize the emission rate, electrons and nuclei should be independent ($\lambda <$ atomic radius), while protons in the same nucleus should behave coherently ($\lambda >$ nuclear radius). This is achieved by considering the emission of photons with wavelength in the range mentioned above. In this range, the coherent emission of protons contributes with a term proportional to $(Ne)^2$ (N is the atomic number), while electrons contribute incoherently with a weaker term proportional to Ne^2. For this reason, and also because in the range of energies considered in our experiment the electrons are relativistic, while our derivation is not, to be conservative we will neglect the contribution of the electrons to the emission rate.

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)

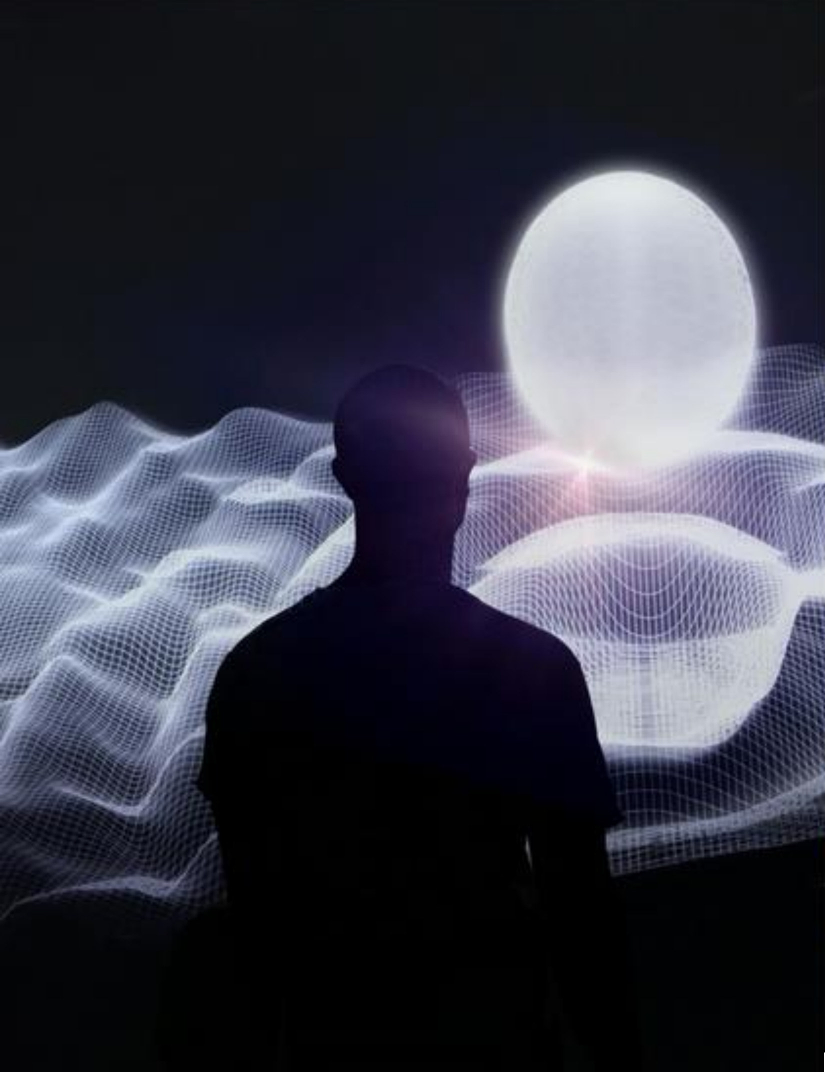
- CSL – s. e. photons rate:

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

- 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).

top 10 of all 2020 favorite scientific news stories

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

-non-covid-19-edition

nature physics

Explore our content ⌄ Journal information ⌄

nature › nature physics › articles › article

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 (2020) | Cite this article

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

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

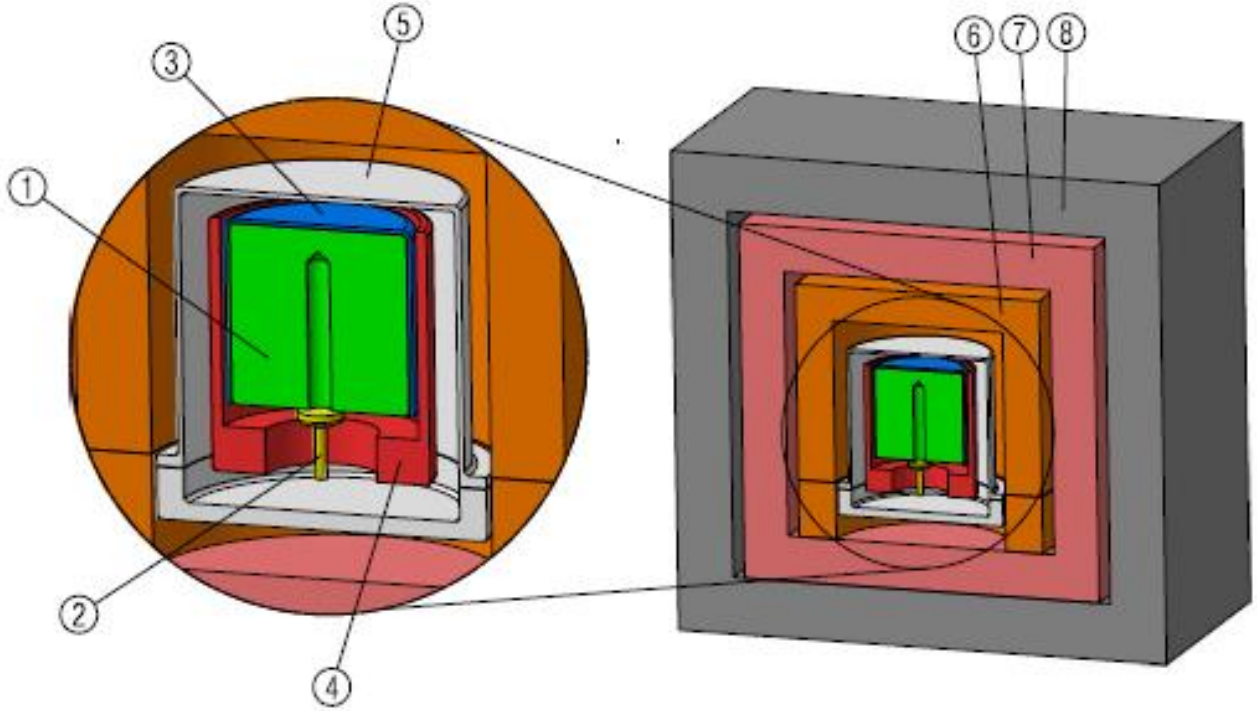


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

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:

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

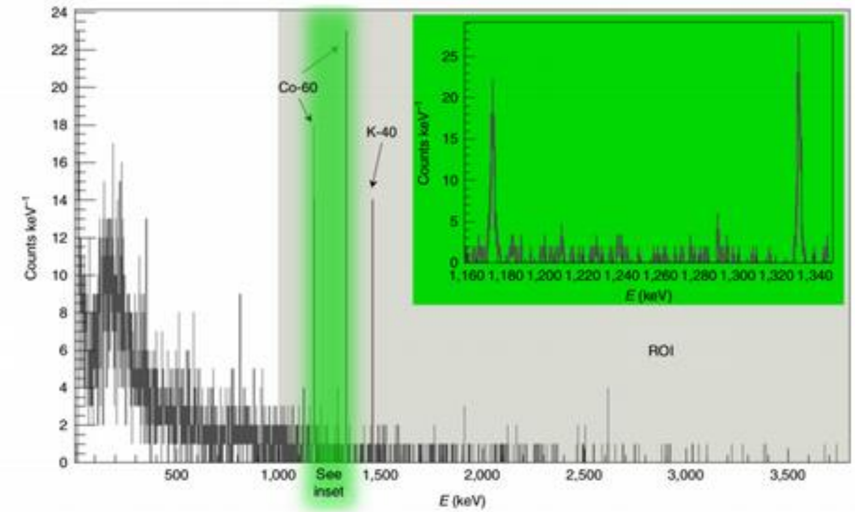
$R_0 > 0.54 \times 10^{-10}$ m **95% C. L.**

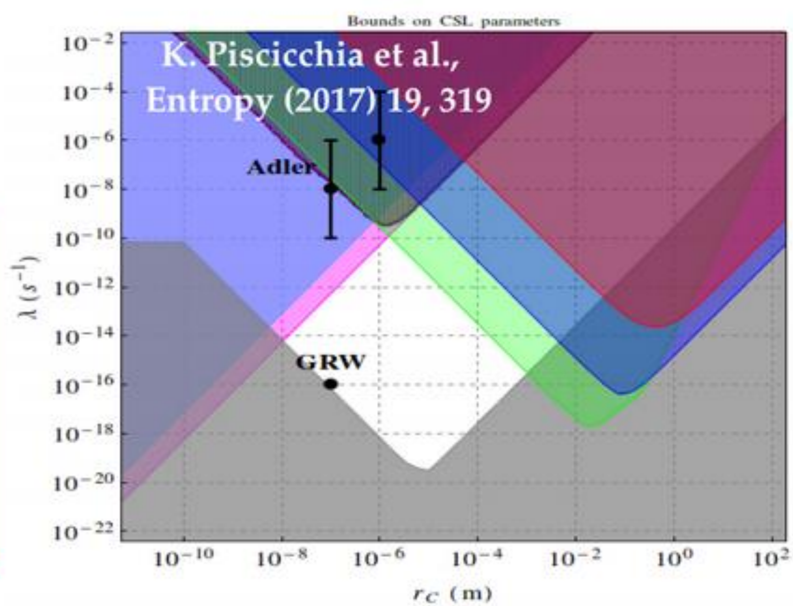
→ Diosi-Penrose excluded

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

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

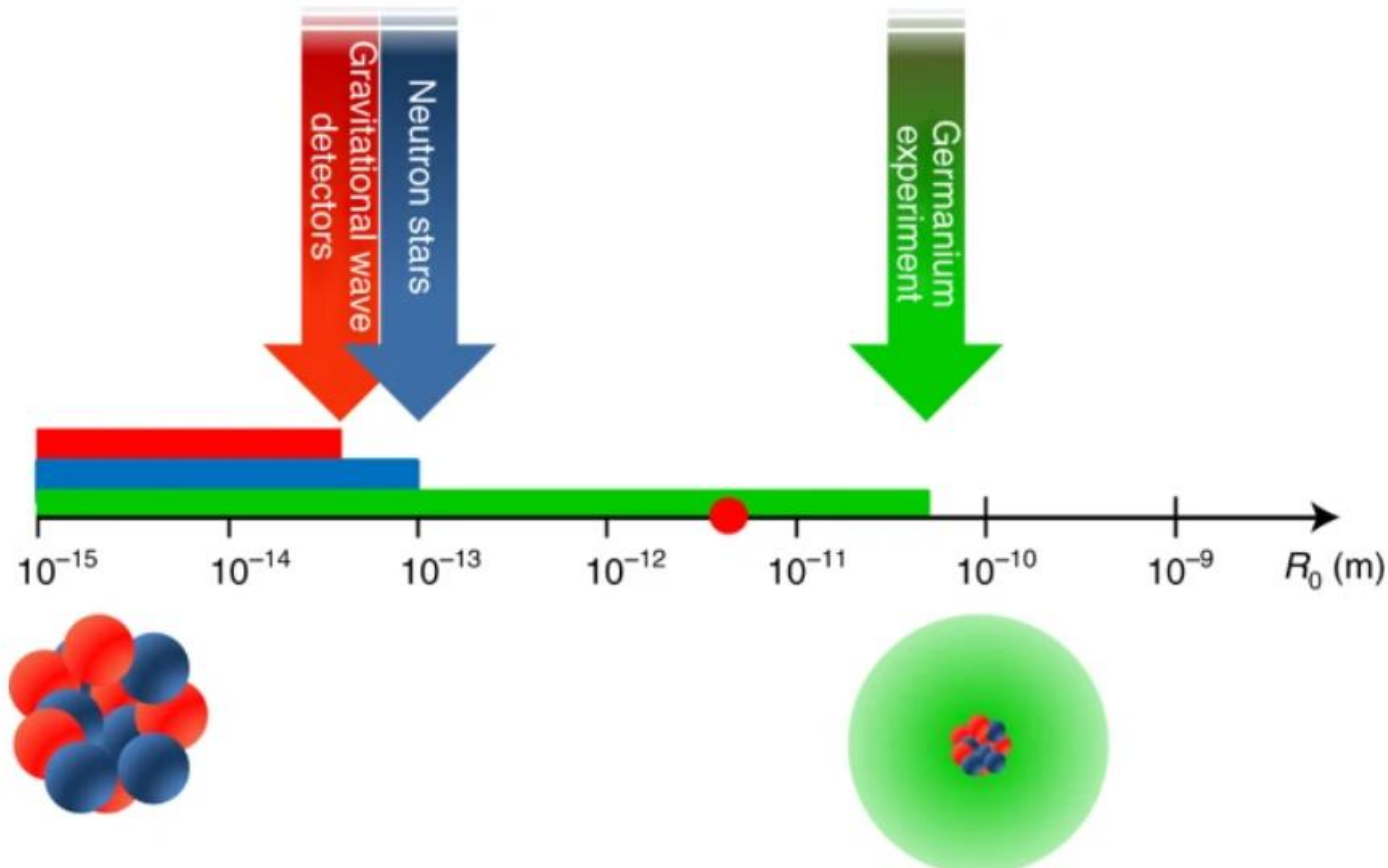
Region Of Interest ΔE=(1000 – 3800)keV compatible with theretical constrains





Our experiment sets a lower bound on R_0 of the order of 1 A, which is about three orders of magnitude stronger than previous bounds in the literature[36,42]; see Fig. 5. If R_0 is the size of the nucleus's wave function as suggested by Penrose, we have to confront our result with known properties of nuclei in matter. In a crystal, $R_0 = \sqrt{\langle u^2 \rangle}$ where $\langle u^2 \rangle$ is the mean square displacement of a nucleus in the lattice, which can be computed by using the relation[43,44] $\langle u^2 \rangle = B/8\pi^2$, where $B = 0.20$ Å^2 is the Debye–Waller factor for the germanium crystal[45], cooled to liquid nitrogen temperature. One obtains $R_0 = 0.05 \times 10^{-10}$ m, which is more than an order of magnitude smaller than the lower limit set by our experiment. Therefore, we conclude that Penrose's proposal for a gravity-related collapse of the wave function, in the present formulation, is ruled out.

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



Of course, alternatives are always possible. Following Diósi, one option is to leave R0 completely free; however, this comes at the price of having a parameter whose value is unjustified, apparently disconnected from the mass density of the system as well as from gravitational effects. Another option is to change the way the collapse is modelled (Poissonian decay), thereby adding extra terms and parameters to take into account a more complex dynamics, as done for other collapse models. This kind of extension has not been envisaged in the literature so far. Our result indicates that the idea of gravity-related wave function collapse, which remains very appealing, will probably require a radically new approach.

Narrowing the parameter space of collapse models with ultracold layered force sensors

A. Vinante et al. Phys.Rev.Lett. 125 (2020) 10, 100404

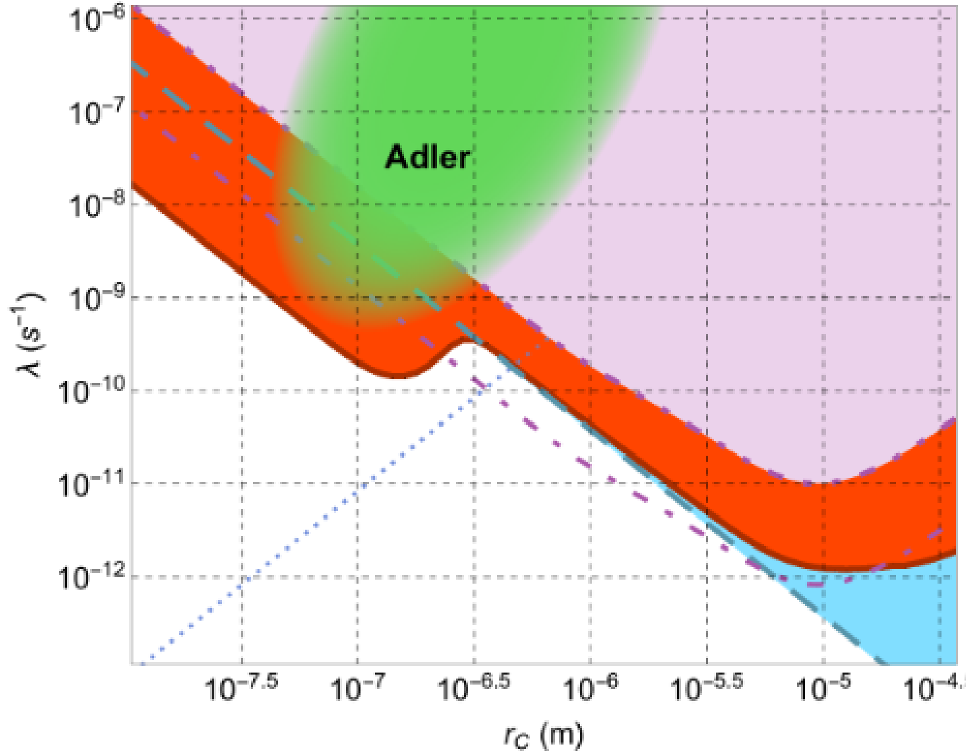


FIG. 4: Exclusion plot for the CSL collapse parameters. Red solid line and shaded area: upper bound and excluded region from the present experiment at the 95% confidence level. Cyan dashed line and shaded area: upper bound and excluded region from LISA Pathfinder [34]. Light purple dash-dot-dotted line and shaded area: upper bound and excluded region from a previous cantilever experiment [31]. Purple dot-dashed line: lower limit of a possible CSL effect from the excess noise observed in the latter experiment [31]. Blue dotted line: upper bound from X-ray emission from a Germanium sample [20]. Since this experiment probes CSL at much higher energies $\sim 10^{19}$ Hz, the upper bound is easily evaded by assuming a spectral cutoff of the CSL noise [38]. The green region represents estimations of CSL parameters from Adler, assuming CSL is effective at mesoscopic scale [10].

Narrowing the parameter space of collapse models with ultracold layered force sensors

A. Vinante et al.
Phys.Rev.Lett. 125 (2020) 10, 100404

Paper in preparation

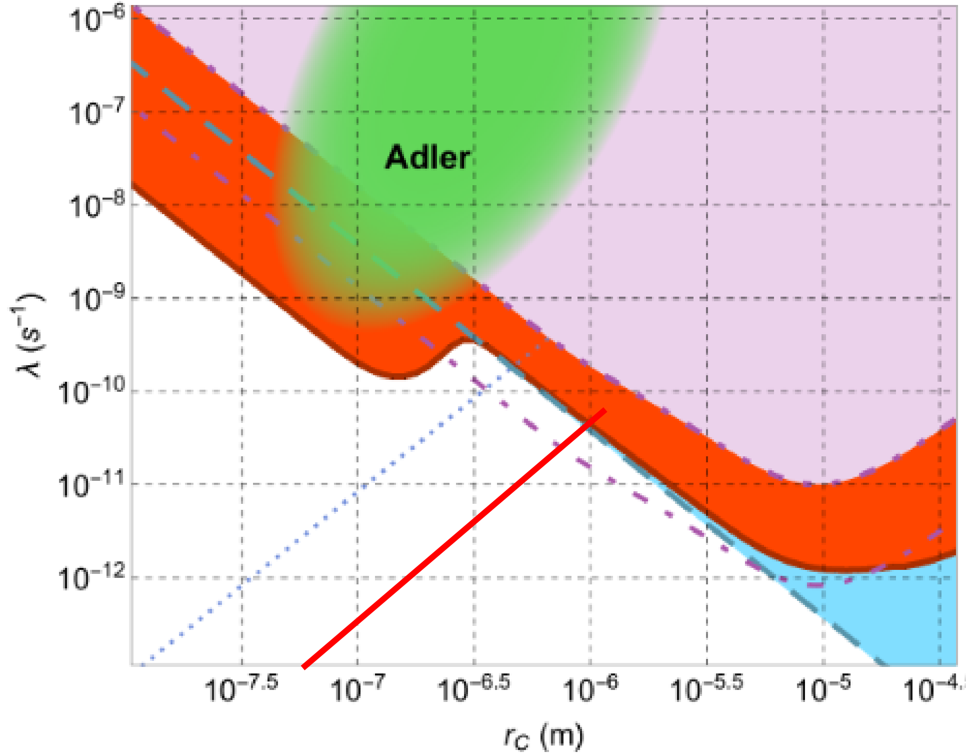
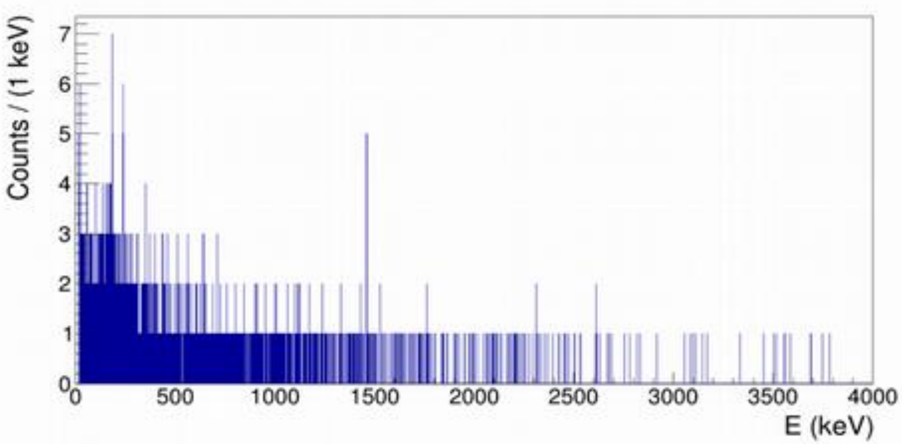
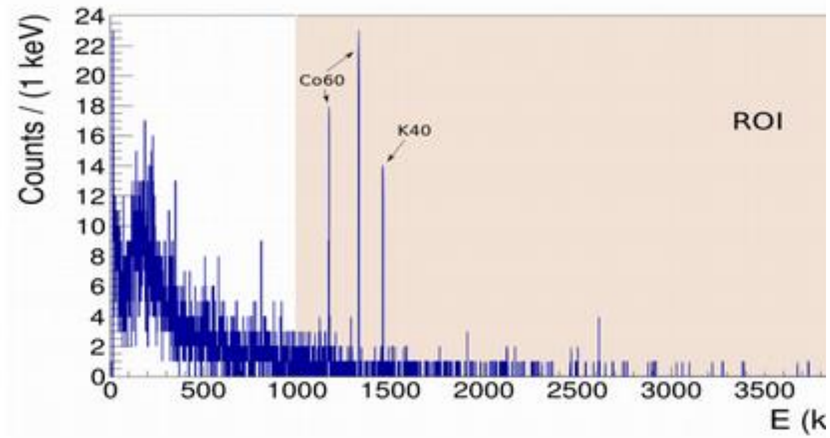


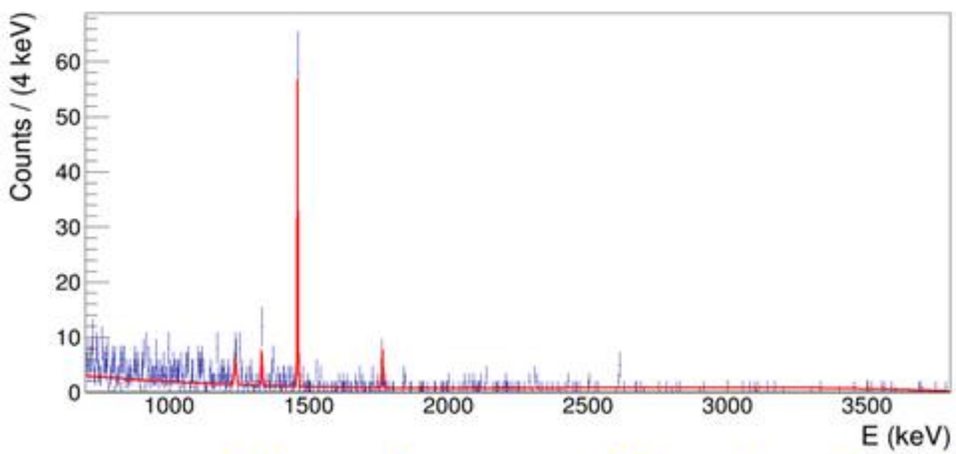
FIG. 4: Exclusion plot for the CSL collapse parameters. Red solid line and shaded area: upper bound and excluded region from the present experiment at the 95% confidence level. Cyan dashed line and shaded area: upper bound and excluded region from LISA Pathfinder [34]. Light purple dash-dot-dotted line and shaded area: upper bound and excluded region from a previous cantilever experiment [31]. Purple dot-dashed line: lower limit of a possible CSL effect from the excess noise observed in the latter experiment [31]. Blue dotted line: upper bound from X-ray emission from a Germanium sample [20]. Since this experiment probes CSL at much higher energies $\sim 10^{19}$ Hz, the upper bound is easily evaded by assuming a spectral cutoff of the CSL noise [38]. The green region represents estimations of CSL parameters from Adler, assuming CSL is effective at mesoscopic scale [10].

Future perspectives

HPGe detector + ultrapure Pb active shielding:





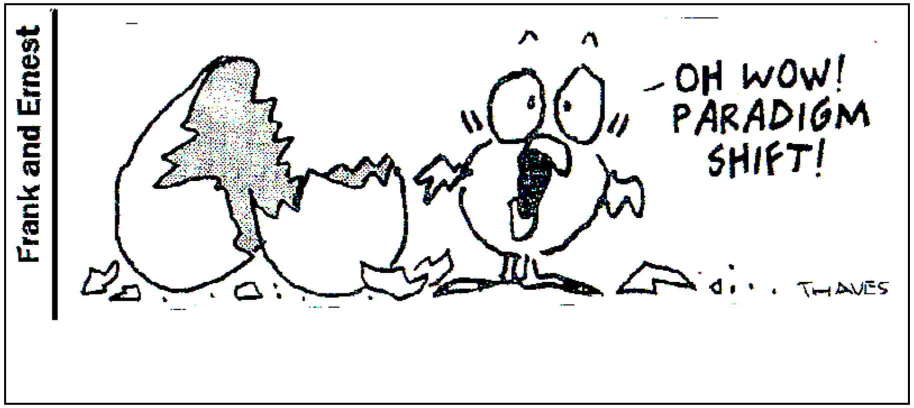


BEGe detector + pulse shape discrimination

pushing the lower E threshold to few keV

“Is Quantum Theory exact? From quantum foundations to quantum applications” , 23 – 27 September 2019 (Frascati, LNF-INFN)

“Is Quantum Theory exact? Exploring the quantum boundaries” , 101-11 December 2020 (https://agenda.infn.it/event/24187/overview)



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

- catalina.curceanu@lnf.in...
- mskurzok@gmail.com
- fnapolit@lnf.infn.it

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 RECENT POJECT

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.

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

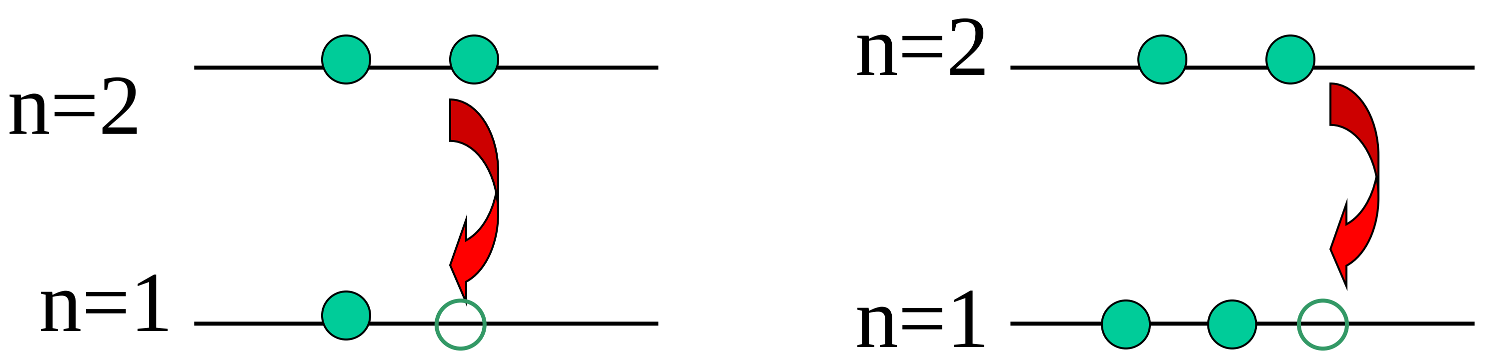
O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

"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

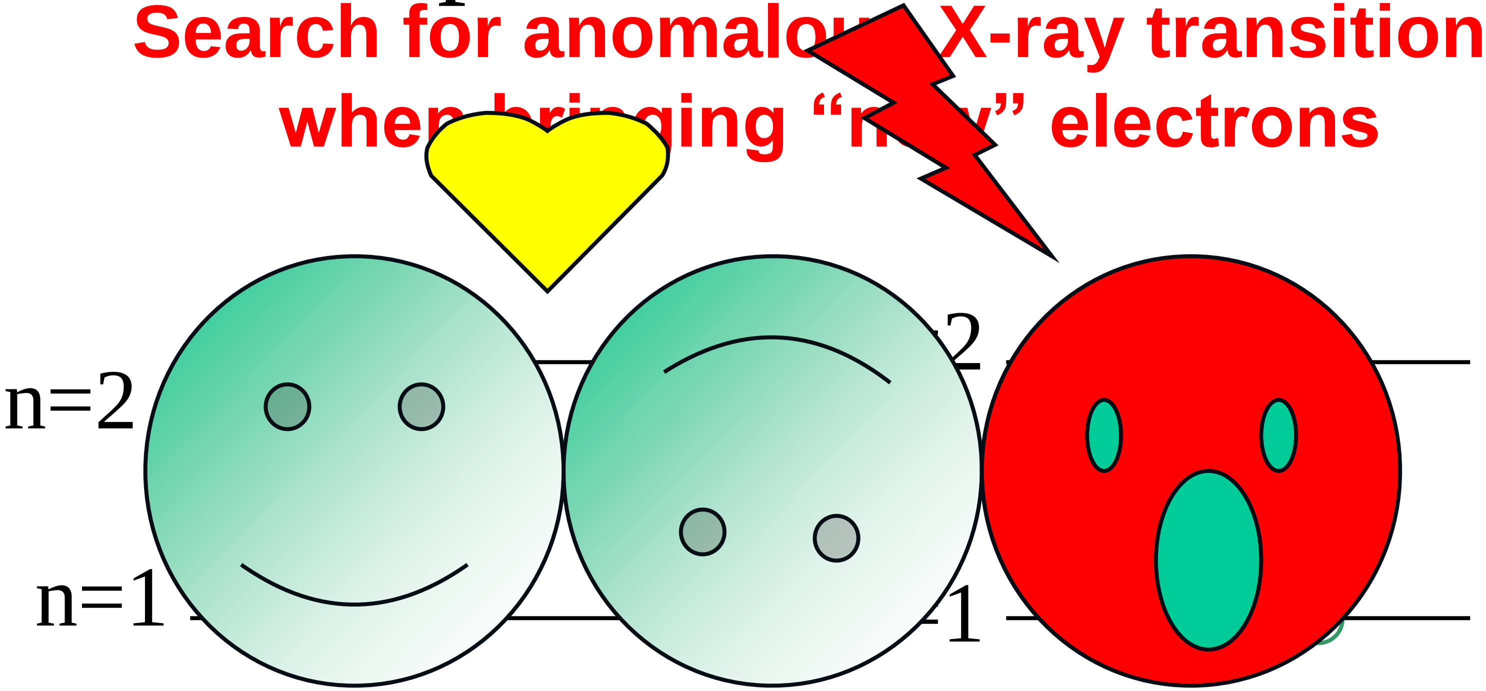
2p –>1s transition violating Pauli principle

Energy 7.7 keV

Messiah Greenberg superselection rule

Experimental method:

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



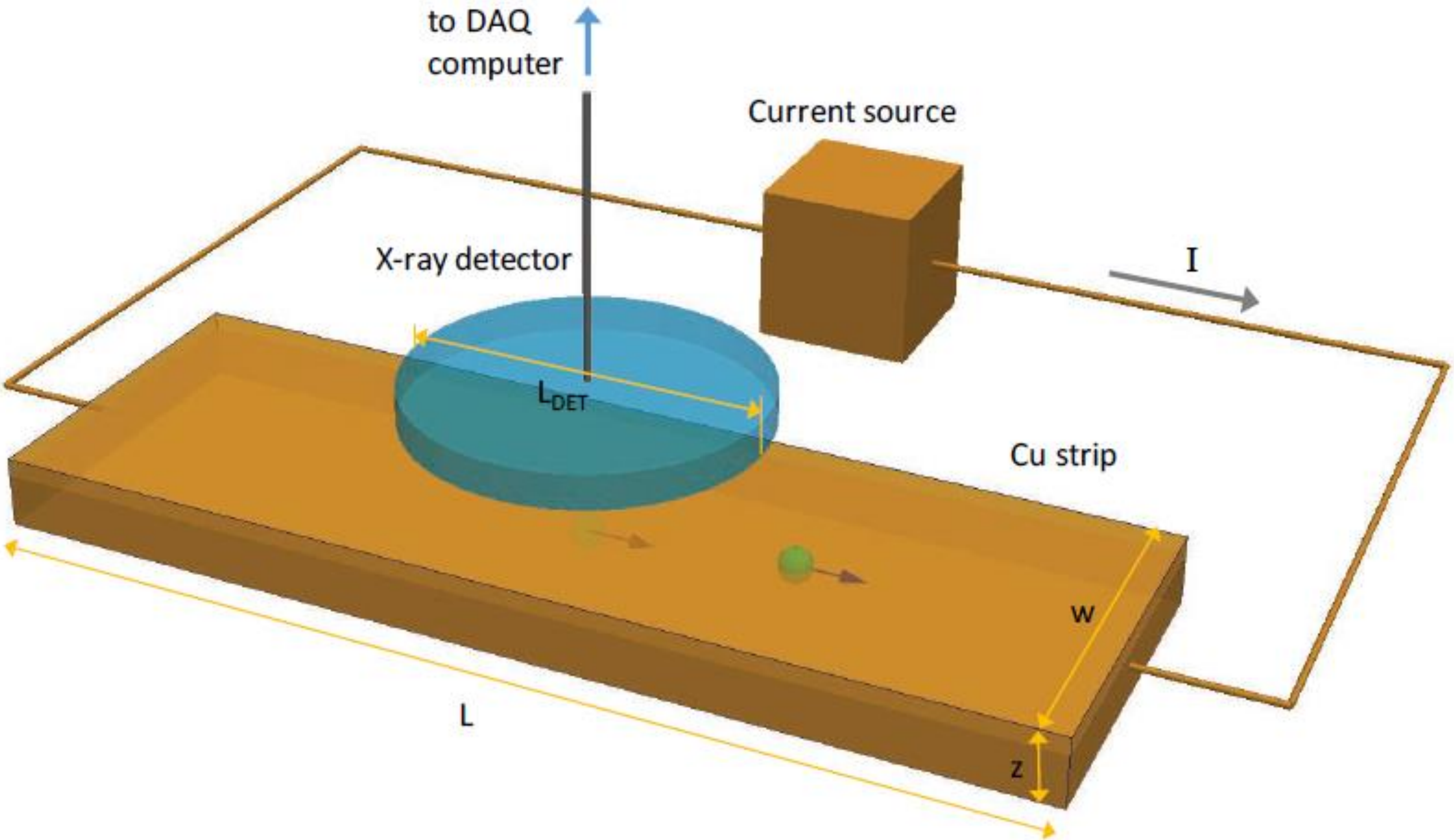
Normal 2p –>1s transition

Energy 8.04 keV

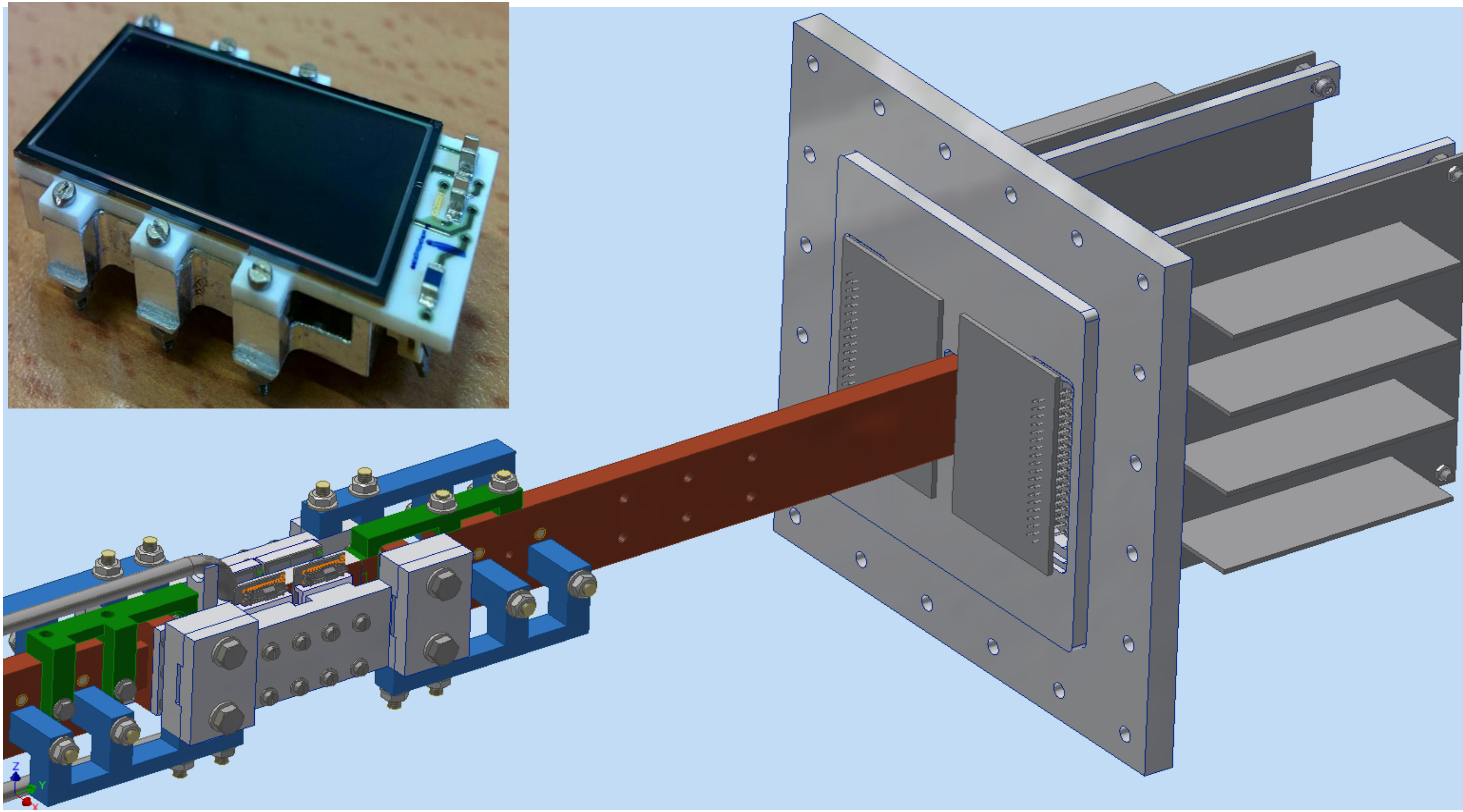
2p –>1s transition violating Pauli principle

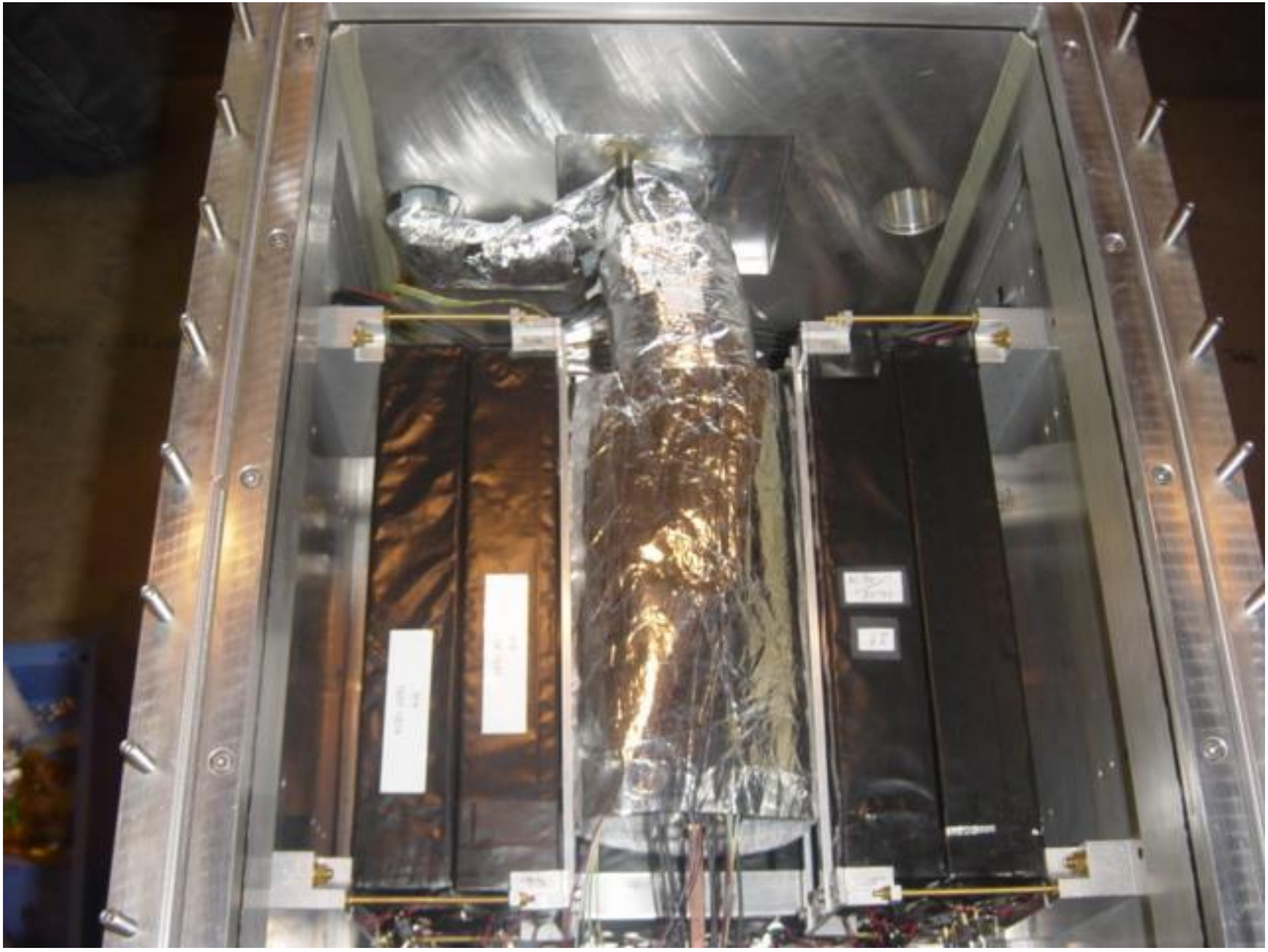
Energy 7.7 keV

Messiah Greenberg superselection rule



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





Eur. Phys. J. C (2018) 78:319
https://doi.org/10.1140/epjc/s10052-018-5802-4

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

Experimental search for the violation of Pauli exclusion principle

VIP-2 Collaboration

H. Shi[1,2,12,a], E. Milotti[3,b], S. Bartalucci[1], M. Bazzi[1], S. Bertolucci[4], A. M. Bragadireanu[1,5], M. Cargnelli[1,2], A. Clozza[1], L. De Paolis[1], S. Di Matteo[6], J.-P. Egger[7], H. Elnaggar[8], C. Guaraldo[1], M. Iliescu[1], M. Laubenstein[9], J. Marton[1,2], M. Miliucci[1], A. Pichler[1,2], D. Pietreanu[1,5], K. Piscicchia[1,10], A. Scordo[1], D. L. Sirghi[1,5], F. Sirghi[1,5], L. Sperandio[1], O. Vazquez Doce[1,11], E. Widmann[2], J. Zmeskal[1,2], C. Curceanu[1,5,10]

[1] INFN, Laboratori Nazionali di Frascati, Via E. Fermi 40, Frascati, 00044 Rome, Italy
[2] Stefan-Meyer-Institut für Subatomare Physik, Boltzmanngasse 3, 1090 Wien, Austria
[3] Dipartimento di Fisica, INFN-Sezione di Trieste, Università di Trieste, Via Valerio, 2, 34127 Trieste, Italy
[4] Dipartimento di Fisica e Astronomia, Università di Bologna, Viale Berti Pichat 6/2, Bologna, Italy
[5] IFIN-HH, Institutul National Pentru Fizica si Inginerie Nucleara Horia Hulubbei, Reactorului 30, Magurele, Romania
[6] UMR 6251, IPR (Institut de Physique de Rennes), CNRS, Université de Rennes, 35000 Rennes, France
[7] Institut de Physique, Université de Neuchâtel, 1 Rue A.-L. Breguet, 2000 Neuchâtel, Switzerland
[8] Debye Institute for Nanomaterial Science, Utrecht University, P.O. Box 80.000 , 3508 TA Utrecht, The Netherlands
[9] INFN, Laboratori Nazionali del Gran Sasso, S.S. 17/bis, 67010 Assergi , AQ, Italy
[10] Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi, Piazza del Viminale 1, 00183 Rome, Italy
[11] Excellence Cluster Universe, Technische Universität München, Boltzmannstraße 2, 85748 Garching, Germany
[12] Present address: Institut für Hochenergiephysik der Österreichischen Akademie der Wissenschaften, Nikolsdorfer Gasse 18, 1050 Wien, Austria

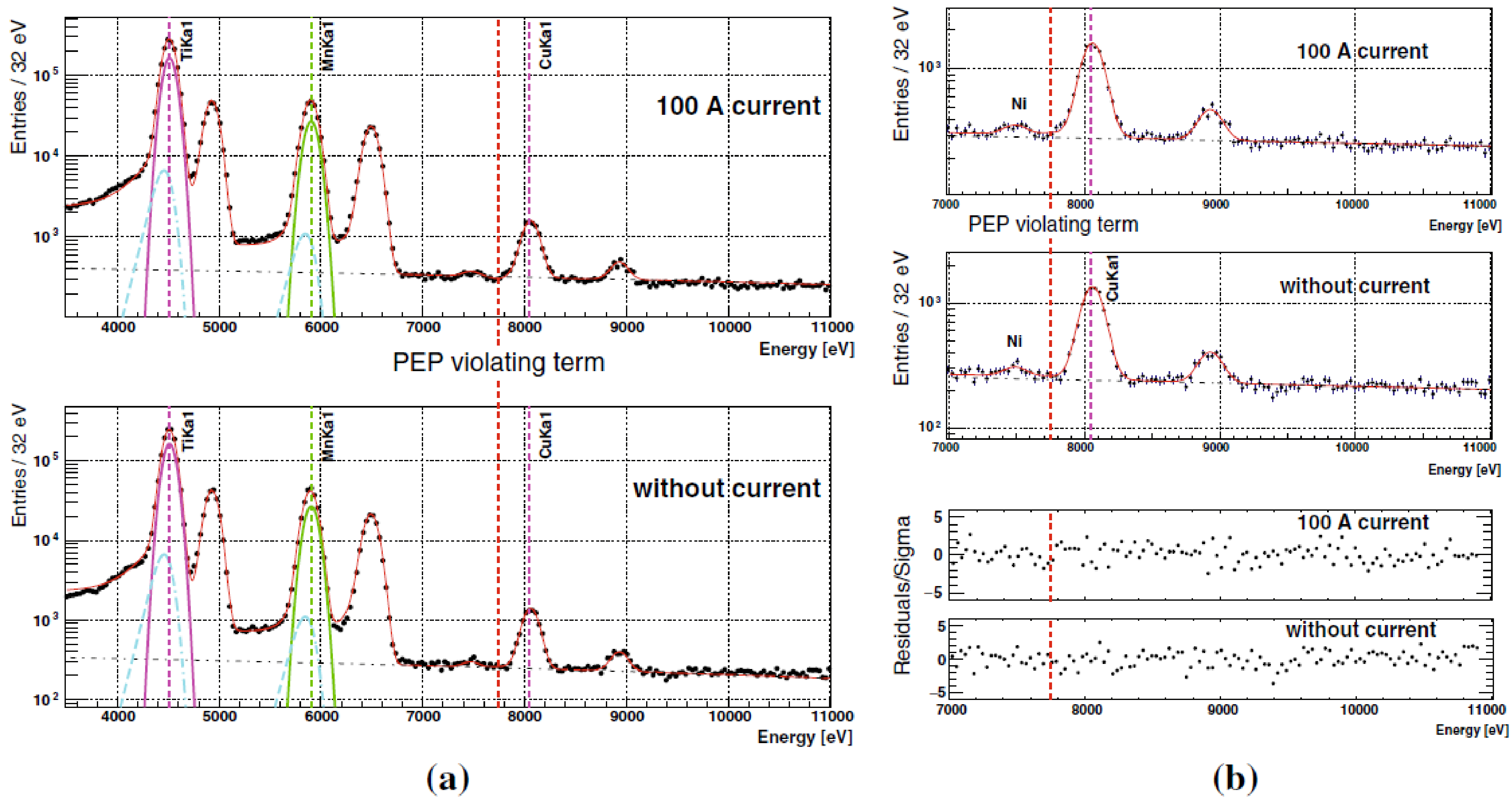


Fig. 8 A global chi-square function was used to fit simultaneously the spectra with and without 100 A current applied to the copper conductor. The energy position for the expected PEP violating events is about 300 eV below the normal copper $K_{\alpha 1}$ transition. The Gaussian function and the tail part of the $K_{\alpha 1}$ components and the continuous background from the fit result are also plotted. **a** The fit to the wide energy range from 3.5 keV to 11 keV, **b** the fit and its residual for the 7–11 keV range where there is no background coming from the calibration source. See the main text for details

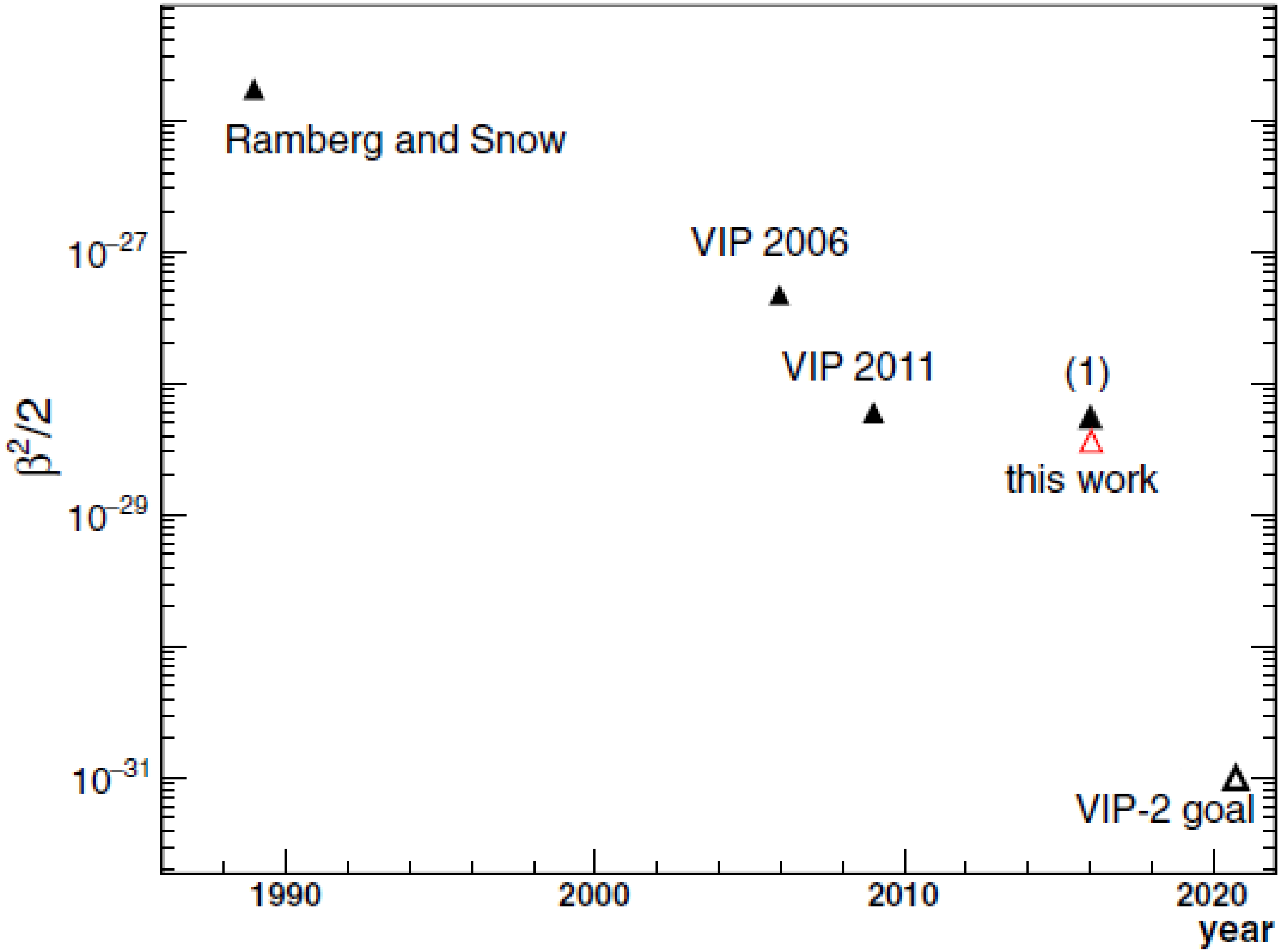


Fig. 10 Past results from PEP violation tests for electrons with a copper conductor, together with the result from this work and the anticipated goal of VIP-2 experiment. The result (1) is based on the same data set of this work, but using the spectra subtraction in the analysis

On the Importance of Electron Diffusion in a Bulk-Matter Test of the Pauli Exclusion Principle

Entropy 2018, 20(7), 515

$$\beta^2/2 < 2.6 \times 10^{-40}$$

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

↓

most effective theories of QG foresee the non-commutativity of the space-time quantum operators (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

S. Majid, Hopf algebras for physics at the Planck scale, Class. Quantum Grav. 5 (1988) 1587.
S. Majid and H. Ruegg, Bicrossproduct structure of Kappa Poincare group and noncommutative geometry, Phys. Lett. B 334 (1994) 348, hep-th/9405107.
M. Arzano and A. Marciano, Phys. Rev. D 76, 125005 (2007) [arXiv:0707.1329].
G. Amelino-Camelia, G. Gubitosi, A. Marciano, P. Martinetti and F. Mercati, Phys. Lett. B 671, 298 (2009) [arXiv:0707.1863].

↓

PEP violation is suppressed with $\delta^2 = (E/\Lambda)^k$, *k* depends on the specific model, *E* is the energy of the PEP violating transition, Λ is the scale of the space-time non-commutativity emergence.

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.

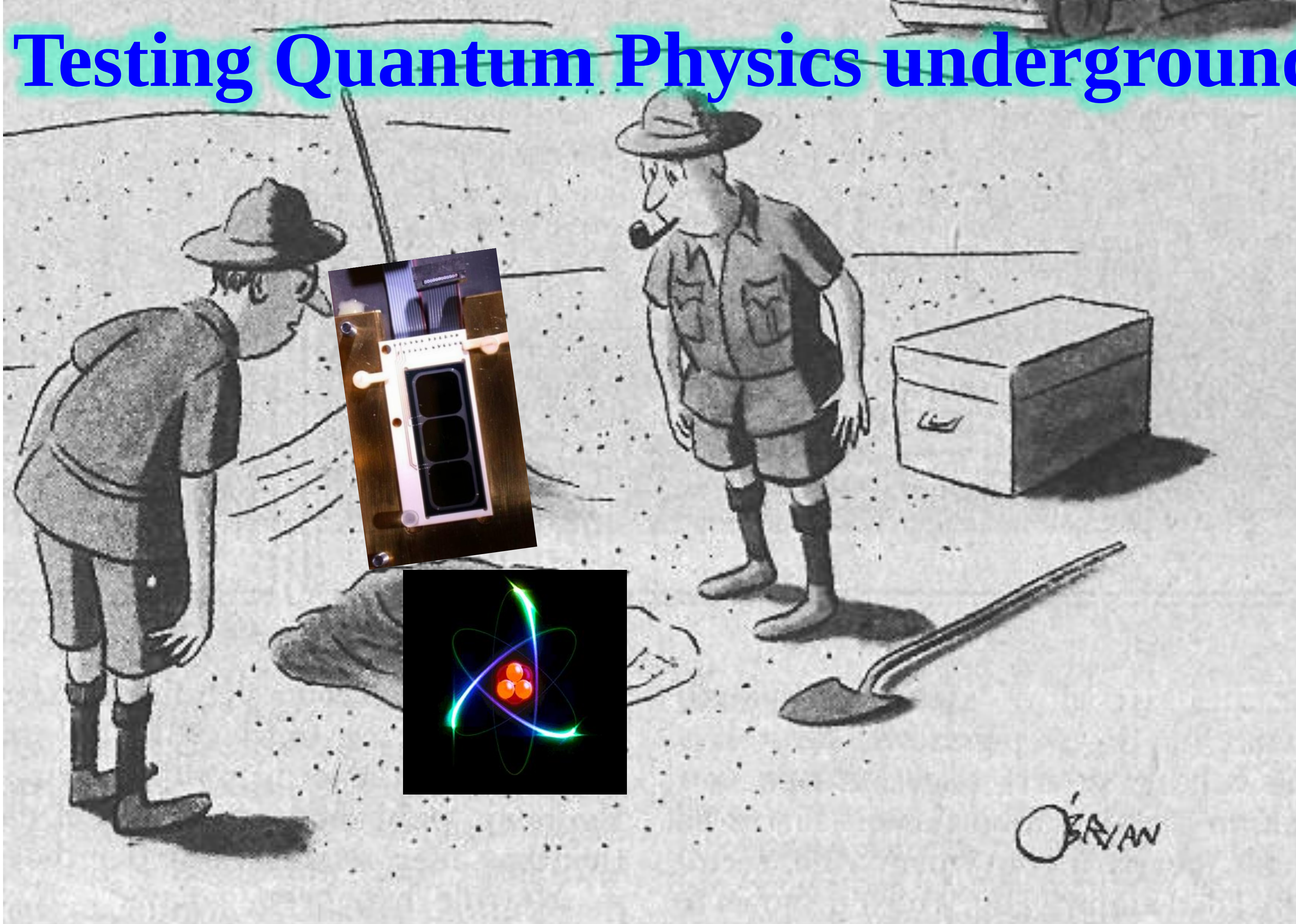
PAULI-ARCHIVE-PHO-011-1

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.

Testing Quantum Physics underground



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

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

MUSEO
STORICO DELLA FISICA
E
CENTRO
STUDI E RICERCHE
ENRICO FERMI

FQXi
FOUNDATIONAL QUESTIONS INSTITUTE

TEQ