Testing Quantum Mechanics Underground: a hunt of the impossible radiation

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21 March 2019

This talk is dedicated to
GianCarlo Ghirardi

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Iaşi
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Cluj-Napoca
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Bicaz
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Târgu Mureş
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Arad
Aiud
Alba Iulia
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Mediaş
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Drobeta-Turnu Severin
Bucharest
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Năvodari
Călăraşi
Craiova
Videle
Constanţa
Calafat
Alexandria
Giurgiu
Mangalia
20°
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0 50 100 mi
0 80 160 km
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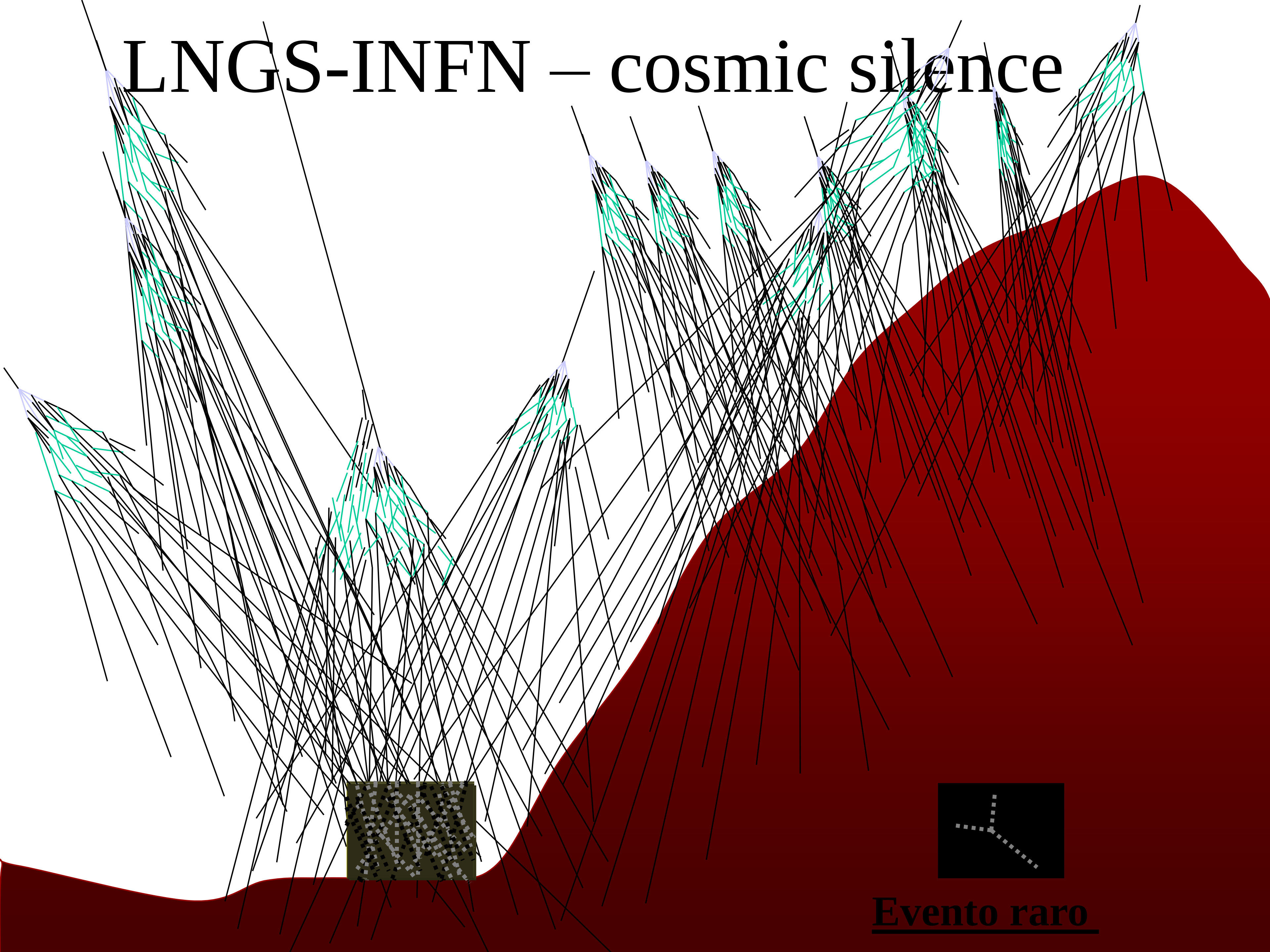
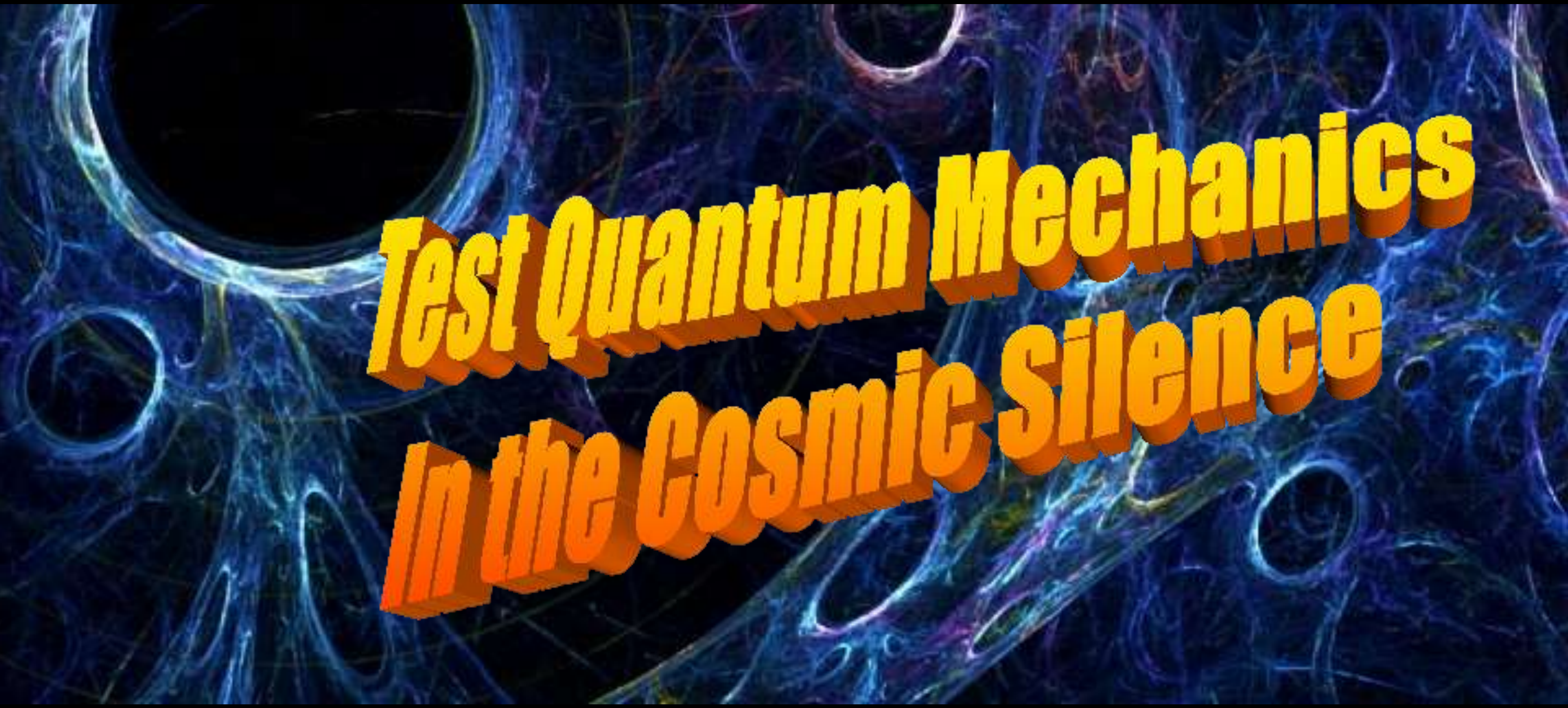
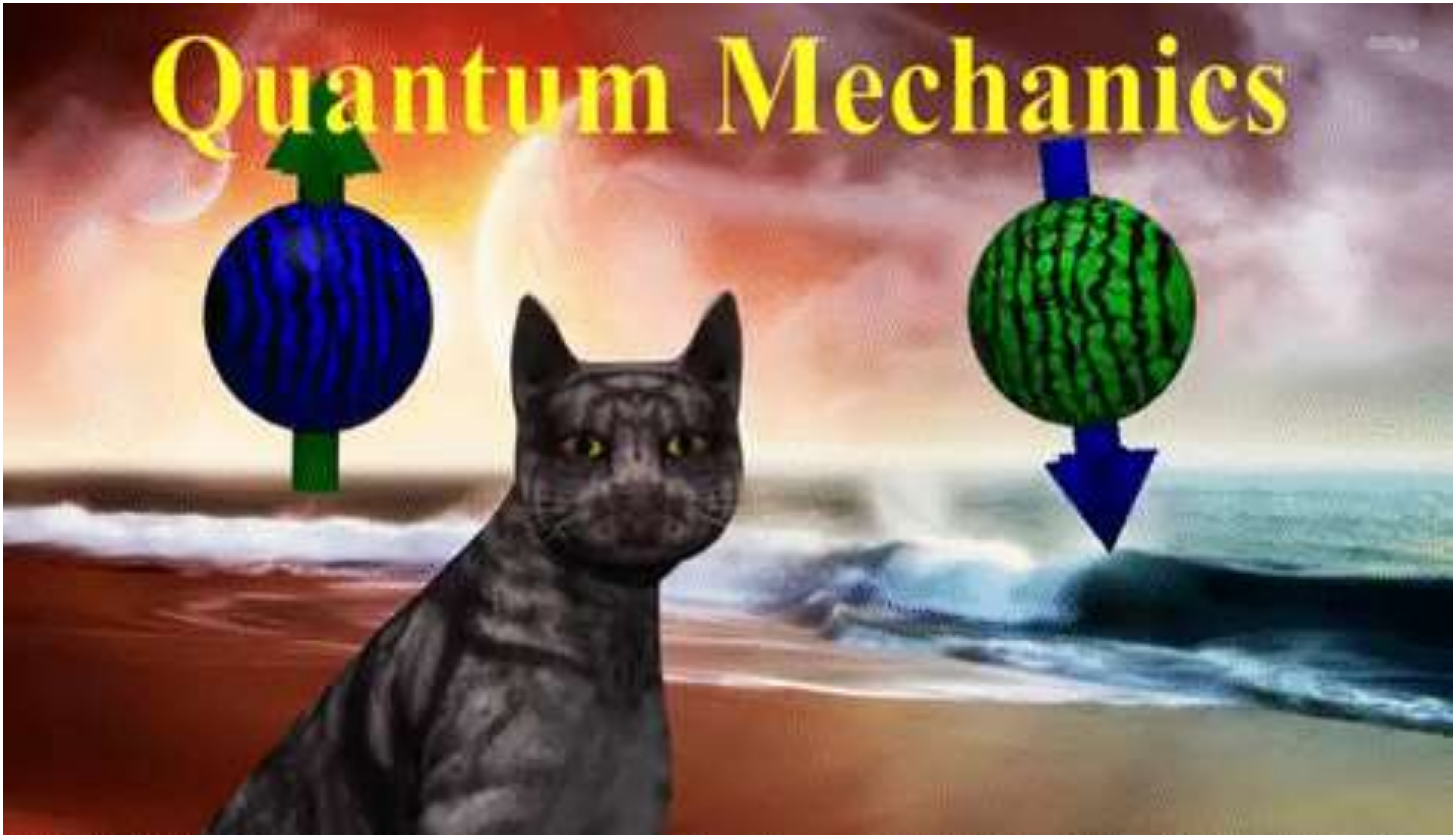
LNGS-INFN – cosmic silence



Test Quantum Mechanics In the Cosmic Silence




Quantum Mechanics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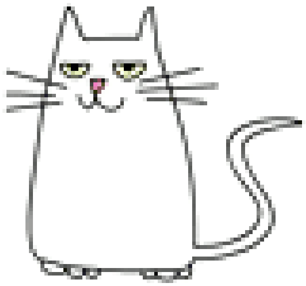


Possible solutions:

-De Broglie – Bohm

- Many-World Interpretations

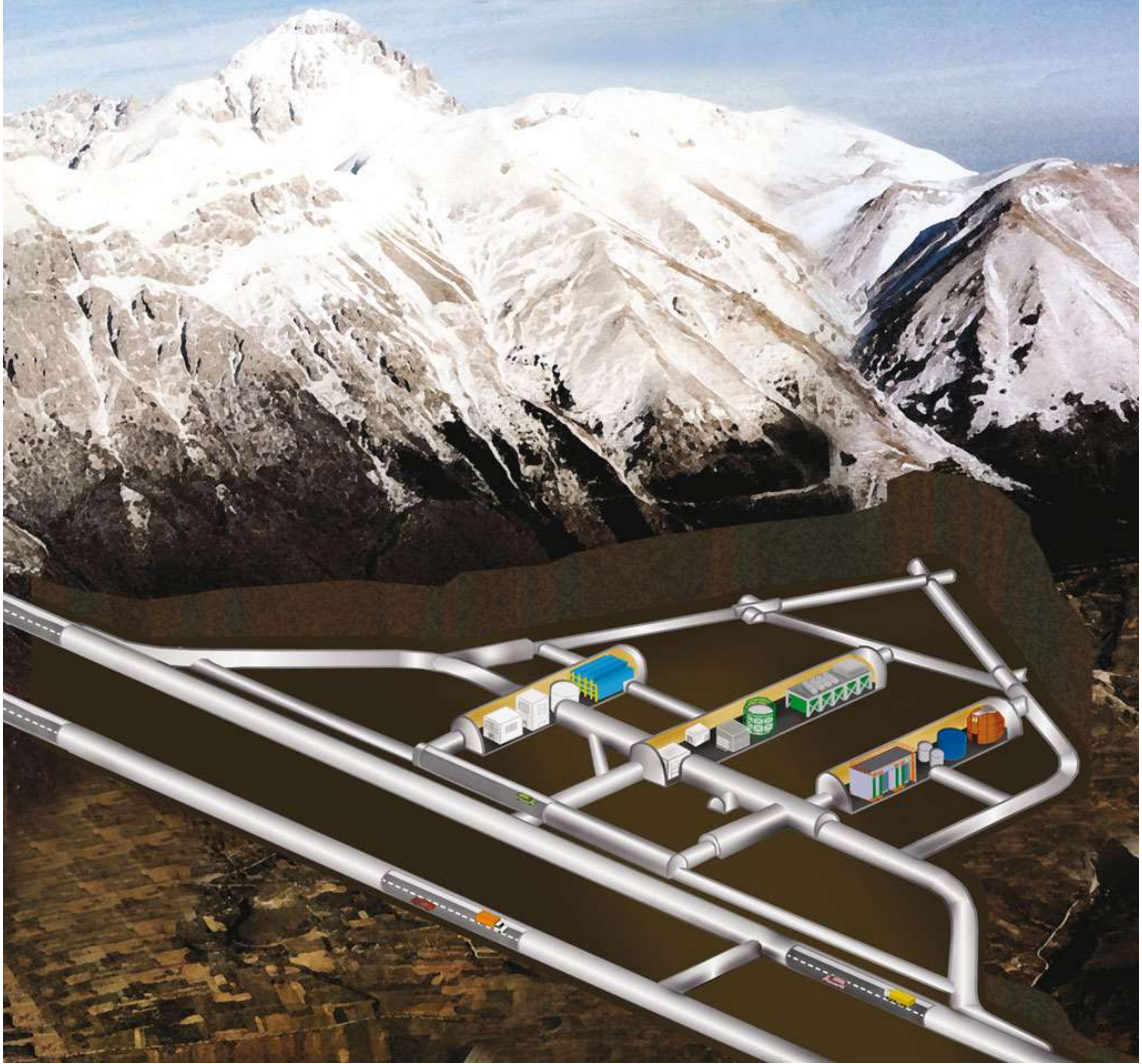
-Collapse of the w.f.

-.....

Laboratori Nazionali del Gran Sasso, Istituto Nazionale di Fisica Nucleare

LNGS


Galilei



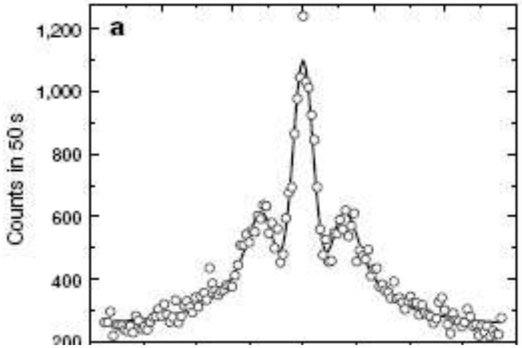
What are collapse models

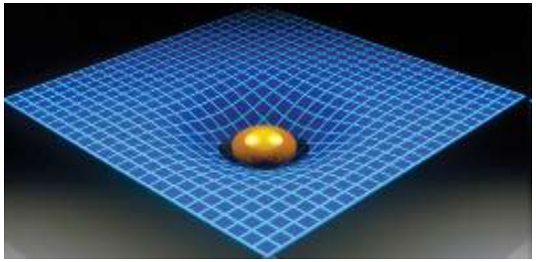
1. **Collapse models = solution of the measurement problem**

   Paradox-free description of the quantum world

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

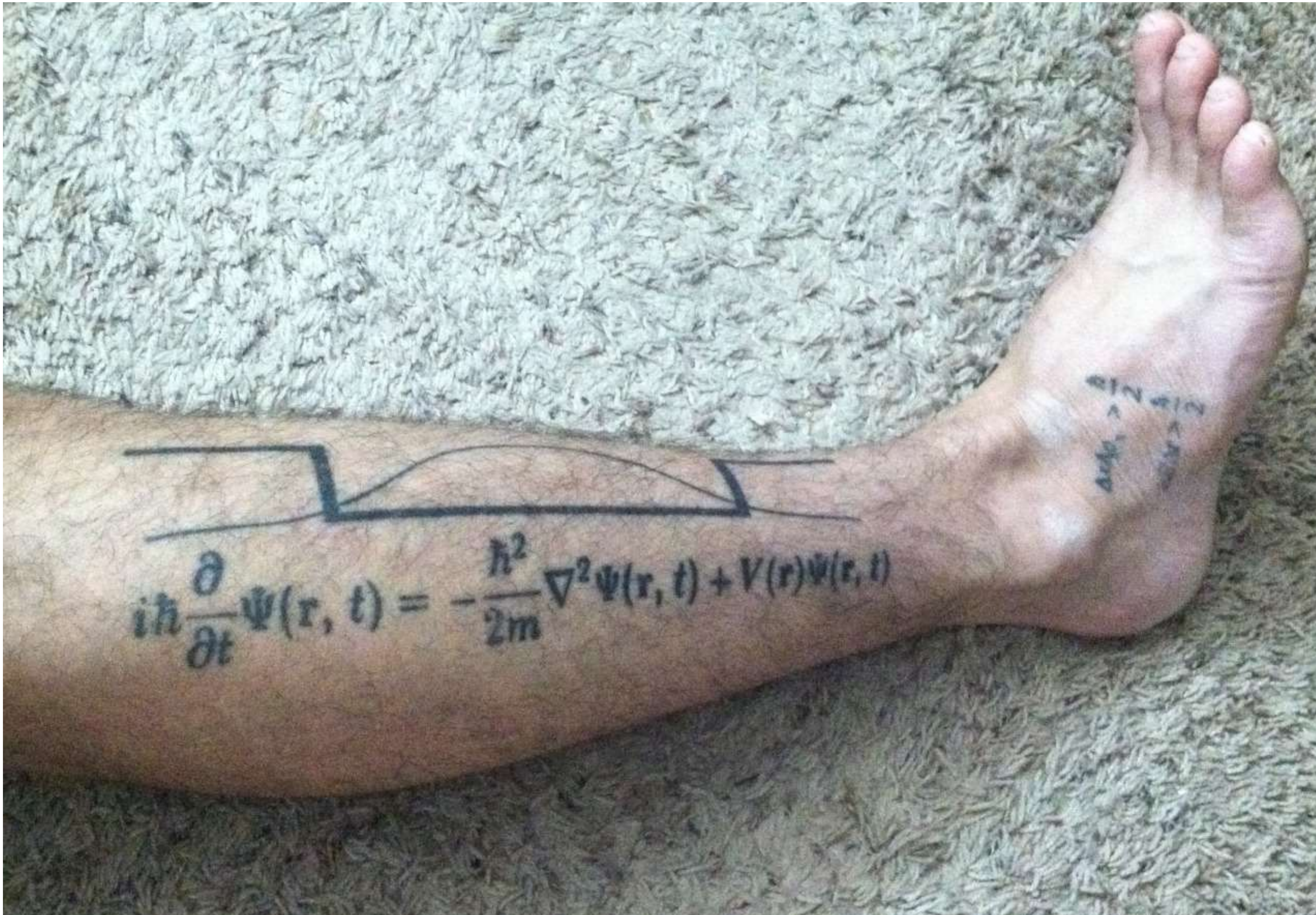
   They give quantitative meaning to experiments testing quantum linearity





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

   Can gravity causes the collapse?


$i\hbar\frac{\partial}{\partial t}\Psi(r, t) = -\frac{\hbar^2}{2m}\nabla^2\Psi(r, t) + V(r)\Psi(r, t)$

CSL model

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

System's Hamiltonian NEW COLLAPSE TERMS ➡ **New Physics**

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

$\langle N(\mathbf{x}) \rangle_t = \langle \psi_t | N(\mathbf{x}) | \psi_t \rangle$ — **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 $\quad r_C = 1/\sqrt{\alpha} =$ correlation length — **two parameters**

the only possible modification of the Schrödinger equation, compatible with the non-faster-than-light signaling condition!

Which values for λ and r_c?

Microscopic world
(few particles)

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

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)

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

QUANTUM – CLASSICAL TRANSITION (GRW – 1986)

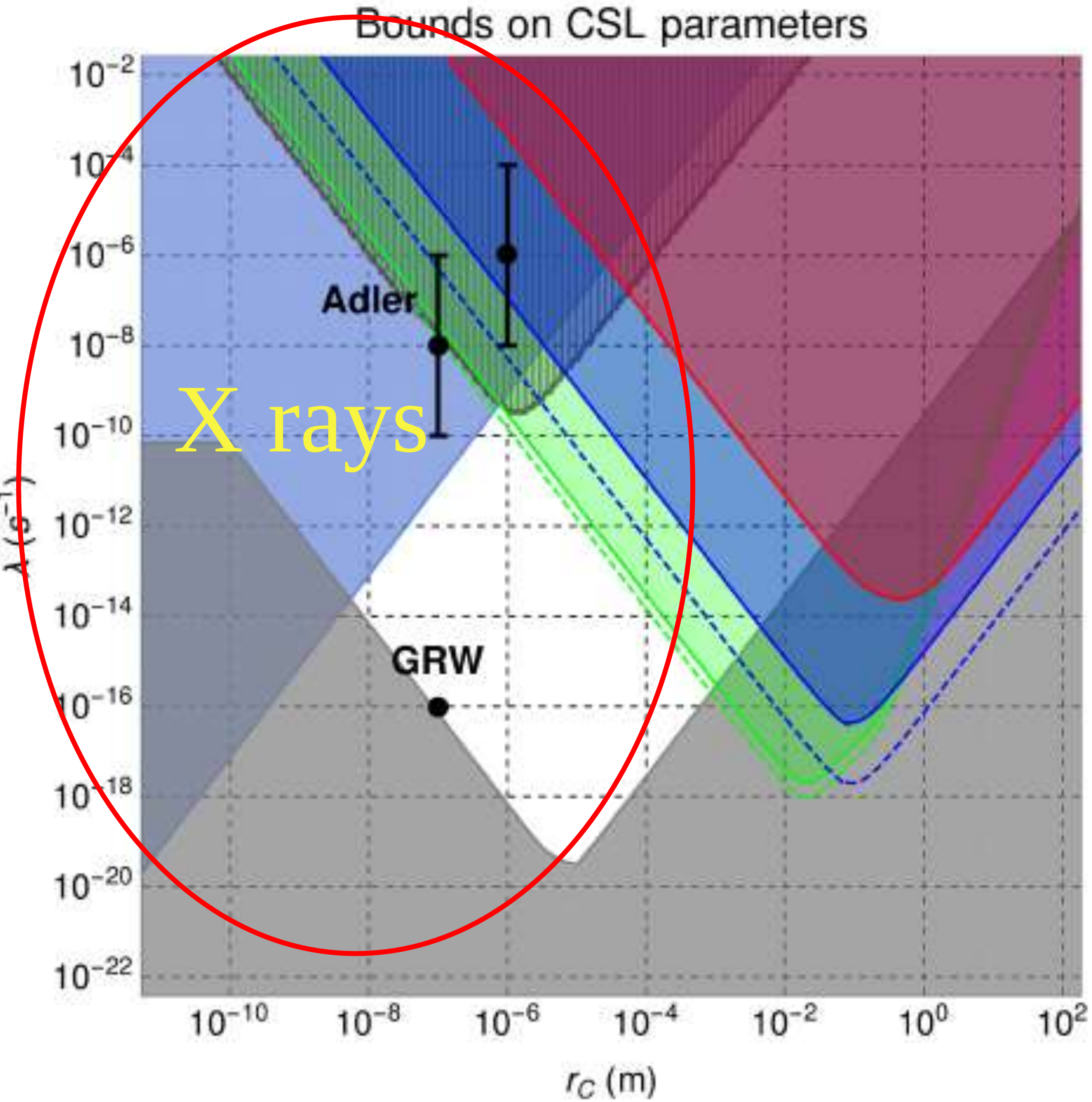
Macroscopic world
(> 10^{13} particles)

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

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

Increasing size of the system

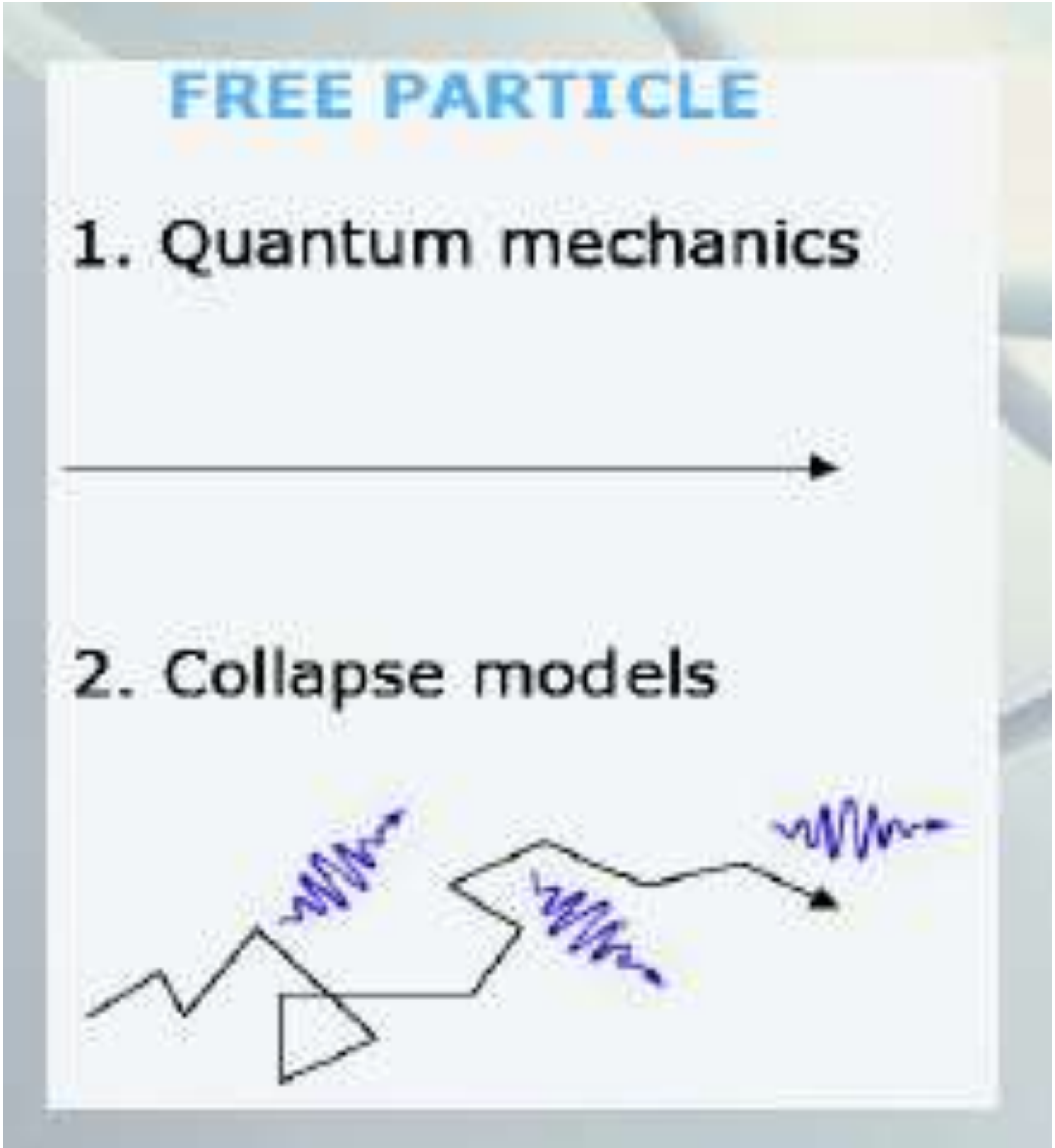
PREDICTIONS of collapse models are different from standard quantum mechanical predictions … they can be tested experimentally! ...



[22] C. Curceanu, B. C. Hiesmayr, and K. Piscicchia, J. Adv. Phys. 4, 263 (2015).

M. Carlesso et al., Phys.Rev. D94 (2016) no.12, 124036

… upper limit estimation on the reduction rate parameter of collapse models …


FREE PARTICLE
1. Quantum mechanics
2. Collapse models

… spontaneous photon emission

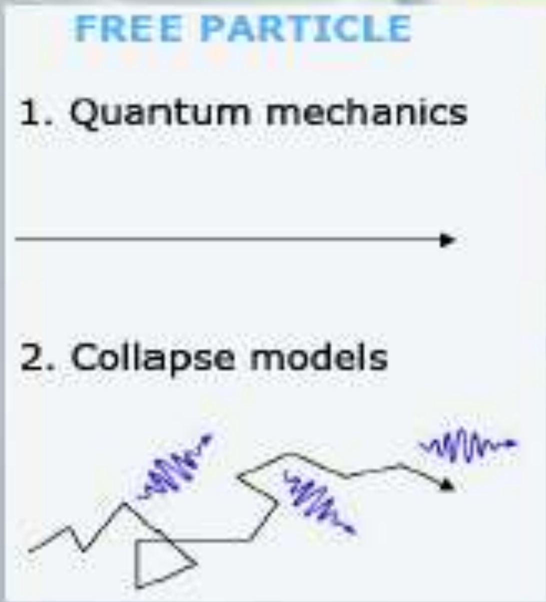
Besides collapsing the state vector to the position basis in non relativistic QM the interaction with the stochastic field increases the expectation value of particle's energy

↓

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

Expected X-ray rate from Ge low activity experiments

Q. Fu, Phys. Rev. A 56, 1806 (1997) ➔ only upper limit on λ based on comparison with the radiation appearing in an isolated slab of Ge (raw data not background subtracted)

H. S. Miley, et al., Phys. Rev. Lett. 65, 3092 (1990)

Energy (keV)	Expt. upper bound (counts/keV/kg/day)	Theory (counts/keV/kg/day)
11	0.049	0.071
101	0.031	0.0073
201	0.030	0.0037
301	0.024	0.0028
401	0.017	0.0019
501	0.014	0.0015

TABLE I. Experimental upper bounds and theoretical predictions of the spontaneous radiation by free electrons in Ge for a range of photon energy values.

Comparison with the lower energy bin, due to the *non-relativistic constraint* of the CSL model

$$\left.\frac{d\Gamma_k}{dk}\right|_{th} = (2.74 \cdot 10^{-31}) \cdot 4 \cdot (8.29 \cdot 10^{24}) \cdot (8.6 \cdot 10^4) \cdot \frac{1}{k} < \left.\frac{d\Gamma_k}{dk}\right|_{ex}$$

$$\frac{e^2\lambda}{4\pi^2 a^2 m^2}$$

4 valence electrons are considered
BE ~ 10 eV « energy of emitted γ ~ 11 keV
***quasi-free* electrons**

(Atoms / Kg) in Ge

1 day

Result ➔ λ < 0.55 x 10^{-16} s^{-1} the GRW theory predicts 45% more radiation than the observed upper bound.

Result <u>possibly biased by the punctual evaluation of the rate</u> at one single energy bin.

Expected X-ray rate from Ge low activity experiments

Q. Fu, Phys. Rev. A 56, 1806 (1997) → only upper limit on λ based on comparison with the radiation appearing in an isolated slab of Ge (raw data not background subtracted)
H. S. Miley, et al., Phys. Rev. Lett. 65, 3092 (1990)

Result → $\lambda < 0.55 \times 10^{-16}\ s^{-1}$

According to S. L. Adler and F. M. Ramazanoglu, J. Phys. A40; 13395 (2007)

such value is to be divided by a factor 4π

↓

No mass-proportional $\lambda < 4.38 \times 10^{-18}\ s^{-1}$

for a mass proportional coupling …

$$\lambda \to \lambda \left(\frac{m_e}{m_N}\right)^2$$

mass-proportional $\lambda < 1.54 \times 10^{-11}\ s^{-1}$

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

The IGEX experiment is a low-activity Ge based experiment dedicated to the ββ0ν 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

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

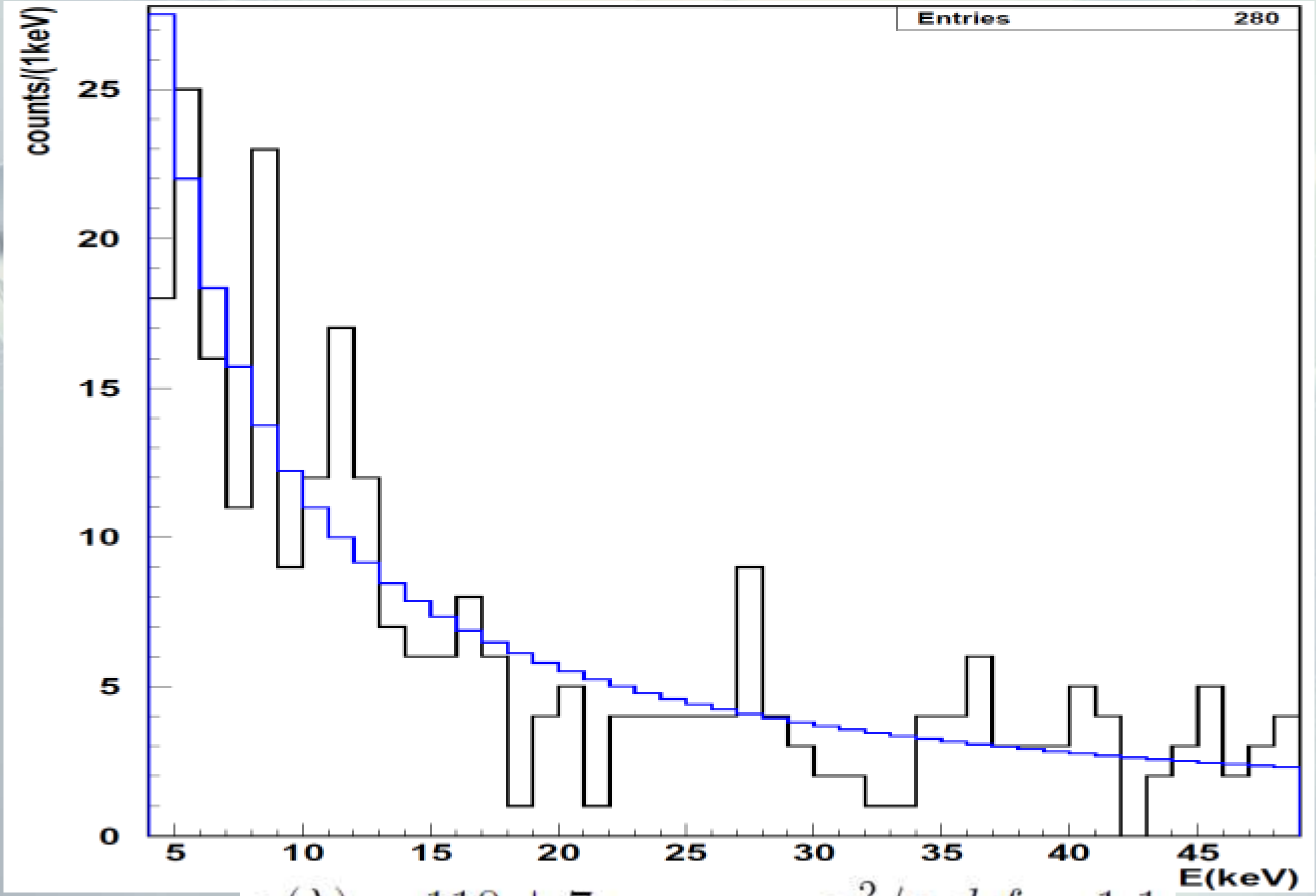
E (keV)	Counts	*E* (keV)	Counts	*E* (keV)	Counts
4.5	18	19.5	4	34.5	4
5.5	25	20.5	5	35.5	4
6.5	16	21.5	1	36.5	6
7.5	11	22.5	4	37.5	3
8.5	23	23.5	4	38.5	3
9.5	9	24.5	4	39.5	3
10.5	12	25.5	4	40.5	5
11.5	17	26.5	4	41.5	4
12.5	12	27.5	9	42.5	0
13.5	7	28.5	4	43.5	2
14.5	6	29.5	3	44.5	3
15.5	6	30.5	2	45.5	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 resul $\alpha(\lambda) = 110 \pm 7 \quad , \quad \chi^2/n.d.f = 1.1$

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

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

$$\lambda \leq 2.0 \cdot 10^{-18}\ \mathrm{s}^{-1} \quad \text{non-mass pro}$$

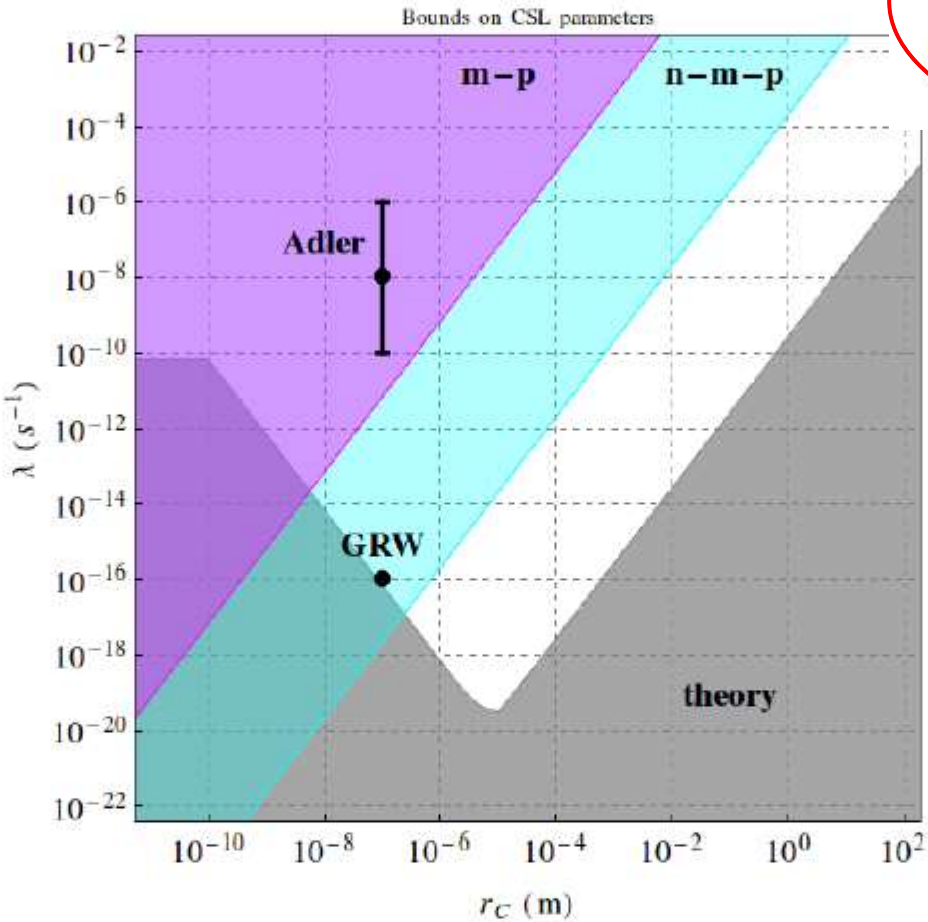
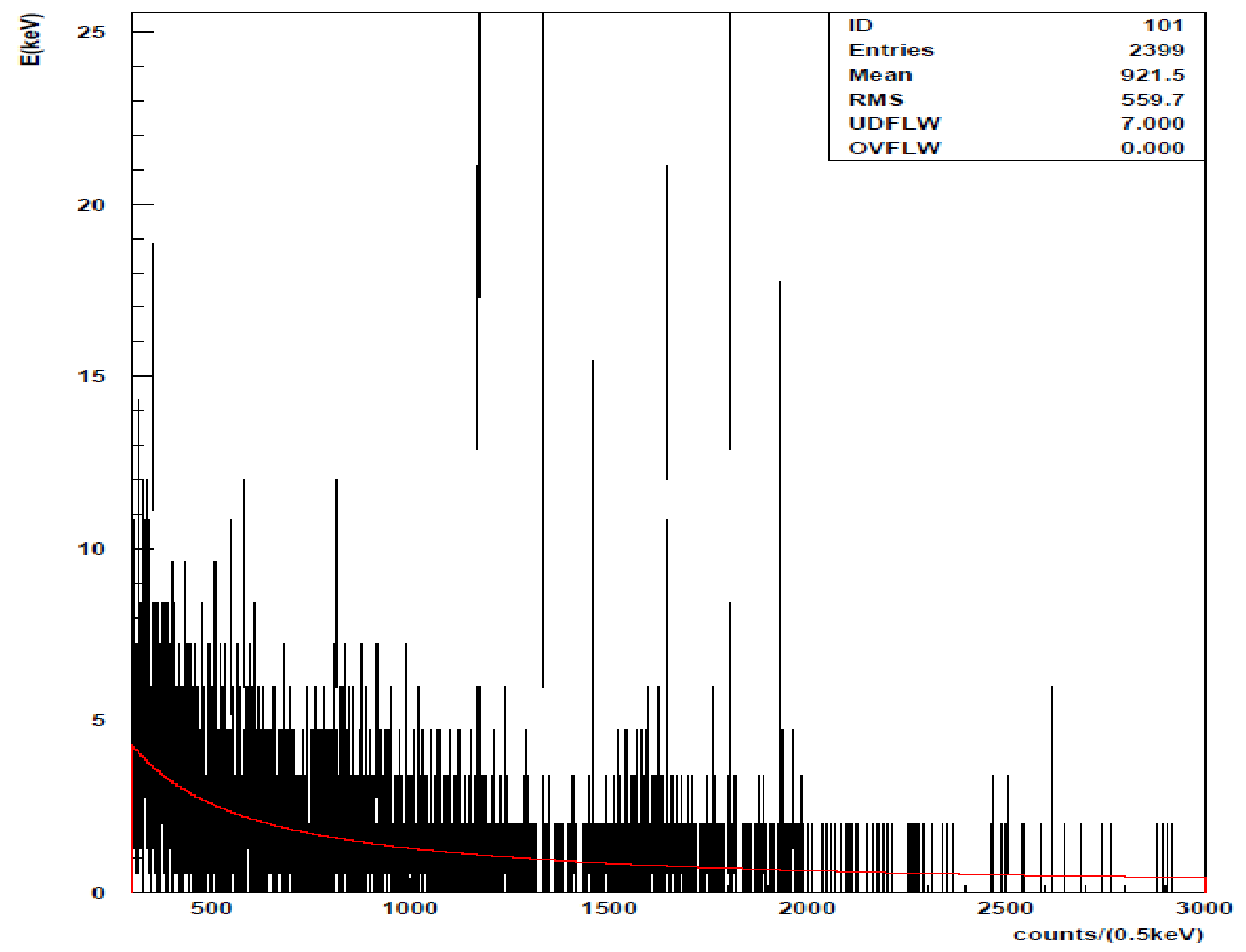


Figure 2. Mapping of the $\lambda - r_C$ Continuous Spontaneous Localization (CSL) parameters: the originally proposed theoretical values (GRW, Adler) are shown as black points; the region excluded by theory (theory) is represented in gray. The excluded region according to our analysis is shown in cyan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

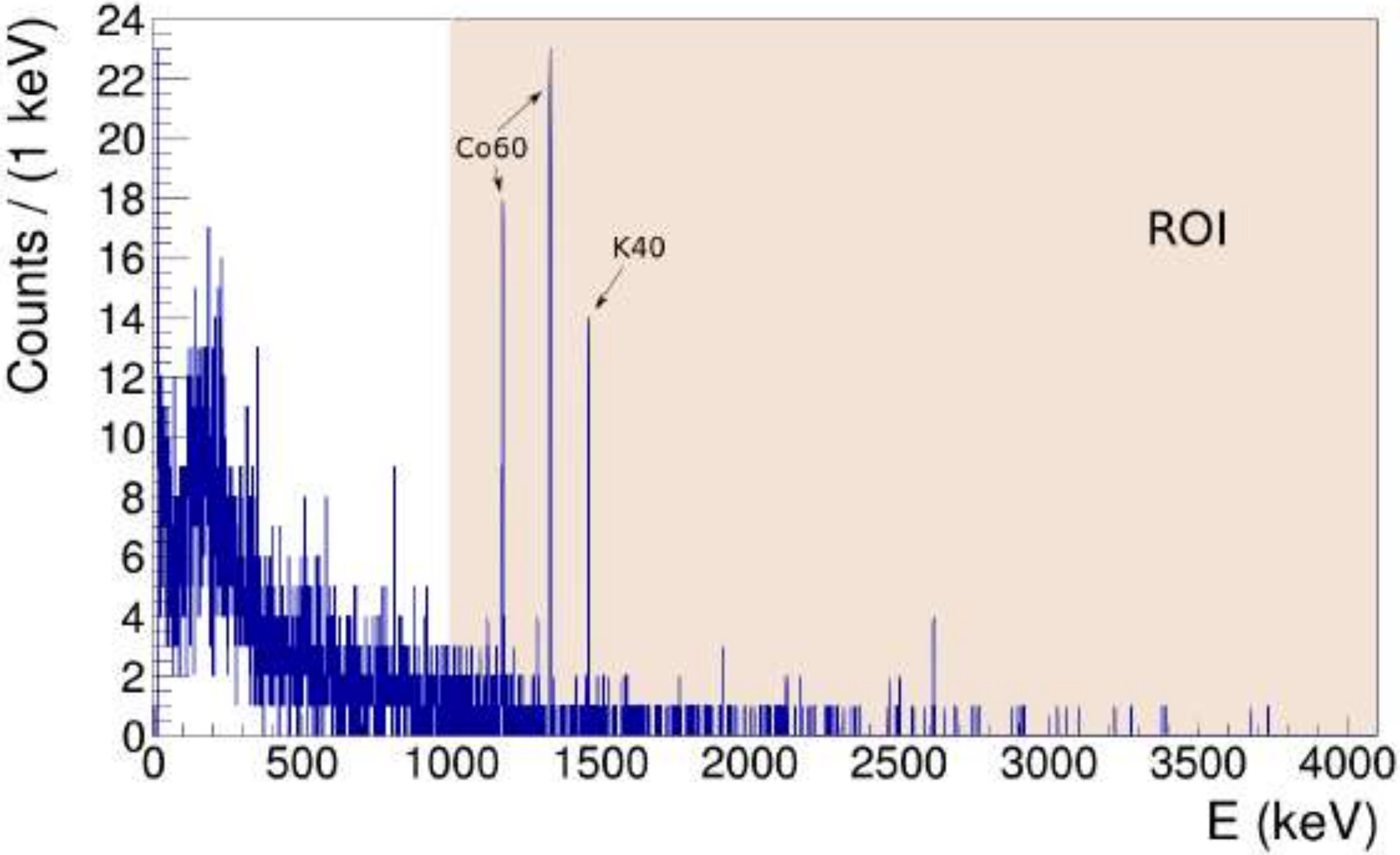
Spontaneous emission including nuclear protons – data taking at LNGS (ultrapure Ge)!

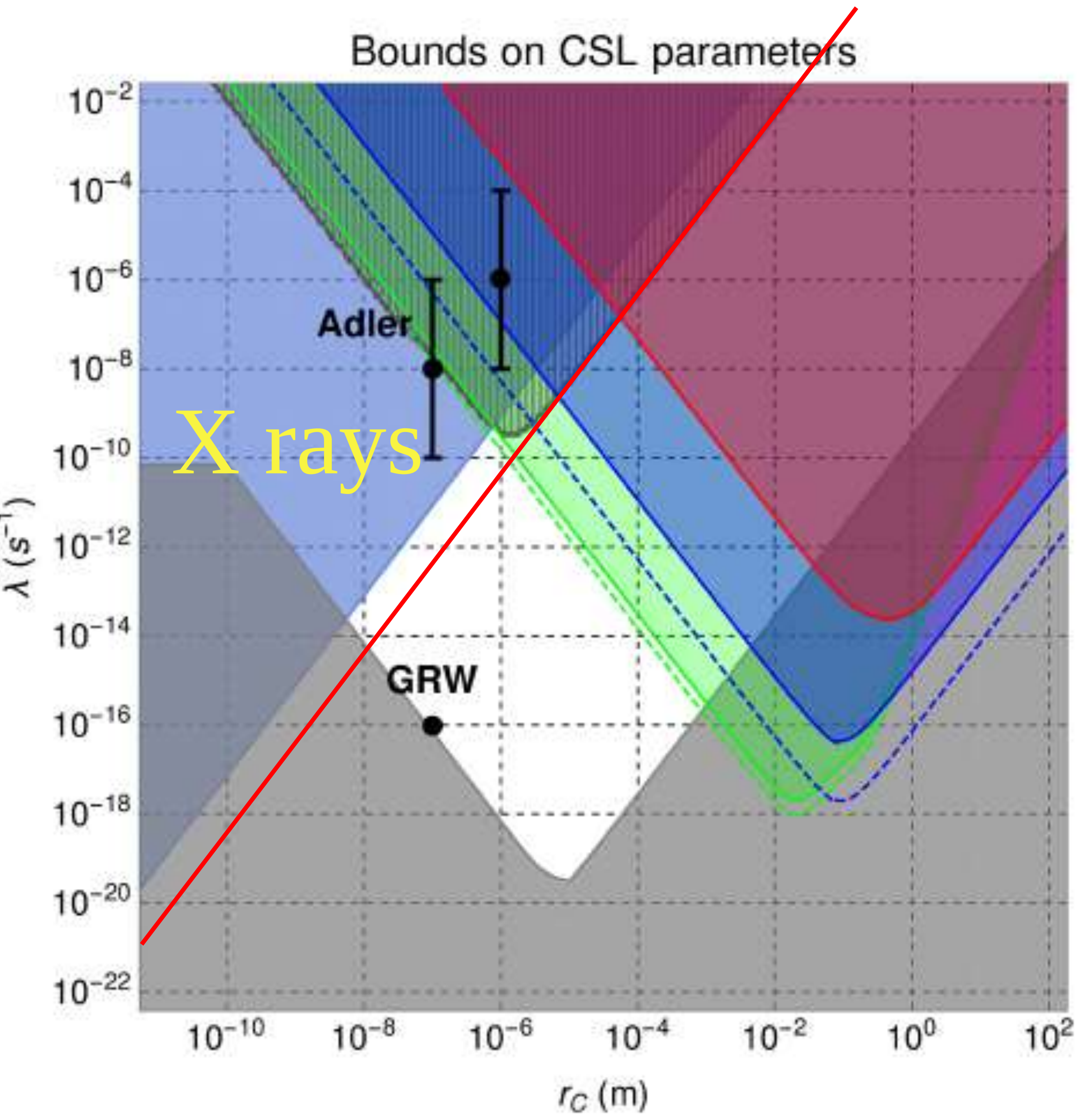
Spontaneous emission – data taking at LNGS (ultrapure Ge)! - analysis including PROTON emission

Spontaneous emission – ultrapure Ge



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





[22] C. Curceanu, B. C. Hiesmayr, and K. Piscicchia, J. Adv. Phys. 4, 263 (2015).

Test of gravity-induced wave function collapse

Paper in preparation

Penrose proposed that a spatial quantum superposition collapses as a backreaction from spacetime, which is curved in different ways by each branch of the superposition; in this sense, people speak of gravity-induced wave function collapse. He also provided a heuristic formula to compute the decay time of the superposition, which is equivalent to that suggested earlier by Diósi, hence the name Diósi-Penrose model. The collapse is random, and this randomness

The photon emission rate for a crystal turns out to be:

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

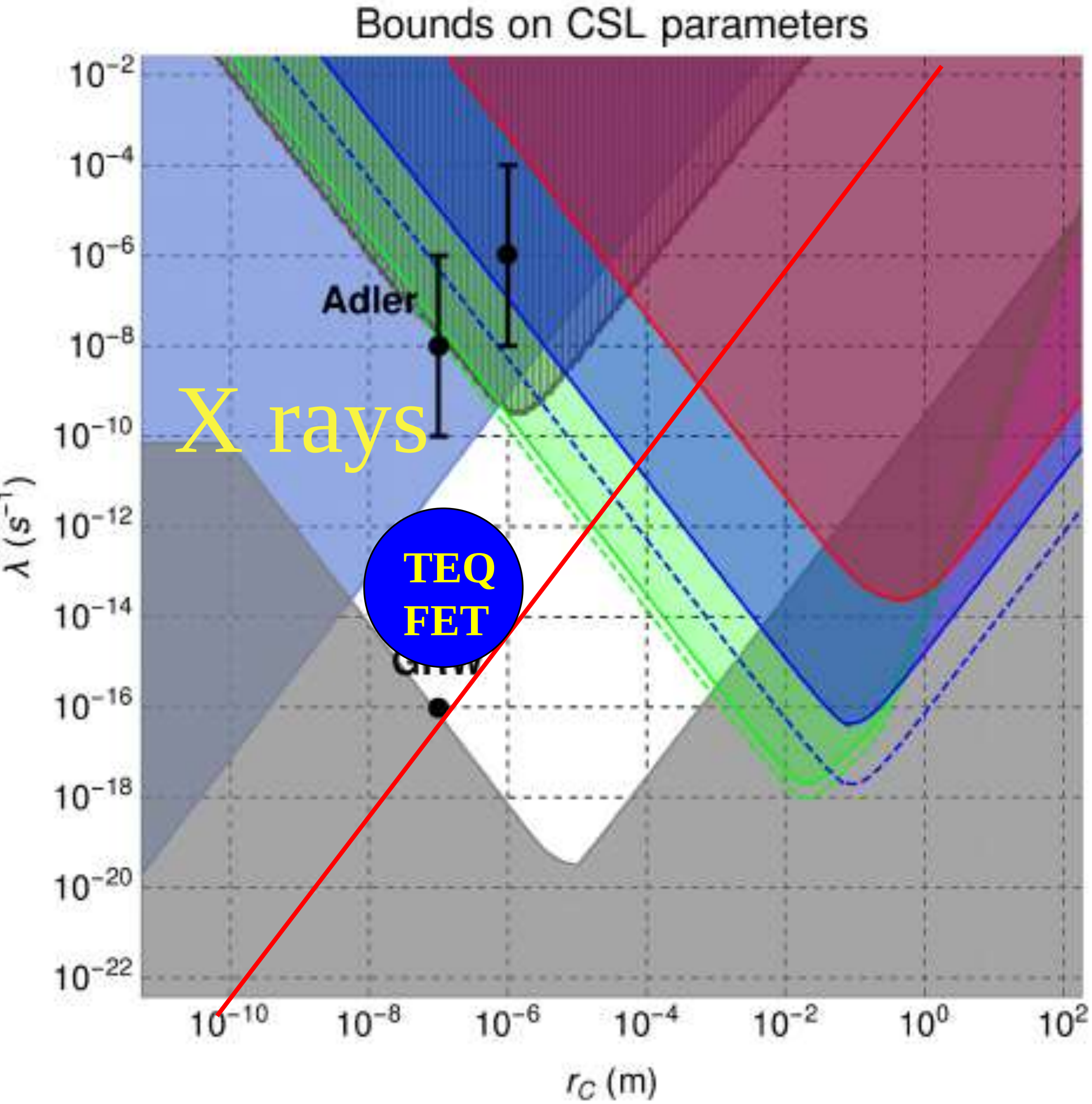
N_a the total number of atoms; R_0 which according to Penrose corresponds to the width of the nucleus wave function in the stationary state of the crystal ($\sim 10^{-14}$ m (*32*)), is left as a free

$$R_0 > 0.54 \times 10^{-10}\,\mathrm{m}$$

Therefore, we conclude that the model of a gravity-induced collapse of the wave function, as proposed by Penrose is ruled out.

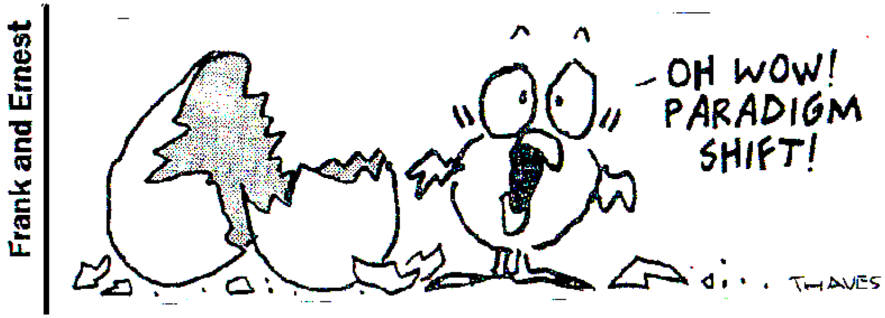
Future plans:

- we have other data taking with pure -lead target (roman lead) -> data analyses
- Work on the “color of the noise”
- Other measurements at LNGS and at Stawell (Australia)



TEQ

[22] C. Curceanu, B. C. Hiesmayr, and K. Piscicchia, J. Adv. Phys. 4, 263 (2015).



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?

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

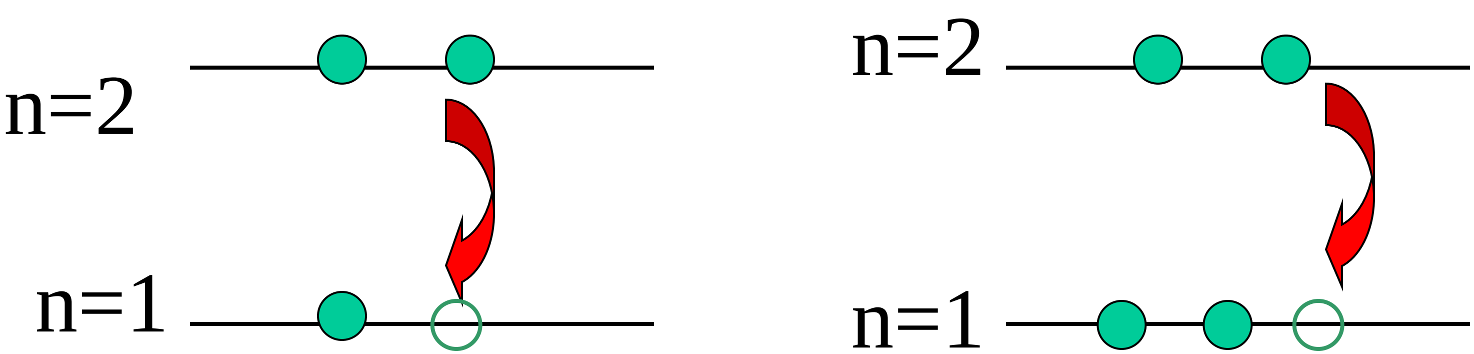
O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

"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) <u>noncommutative spacetime</u>. 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

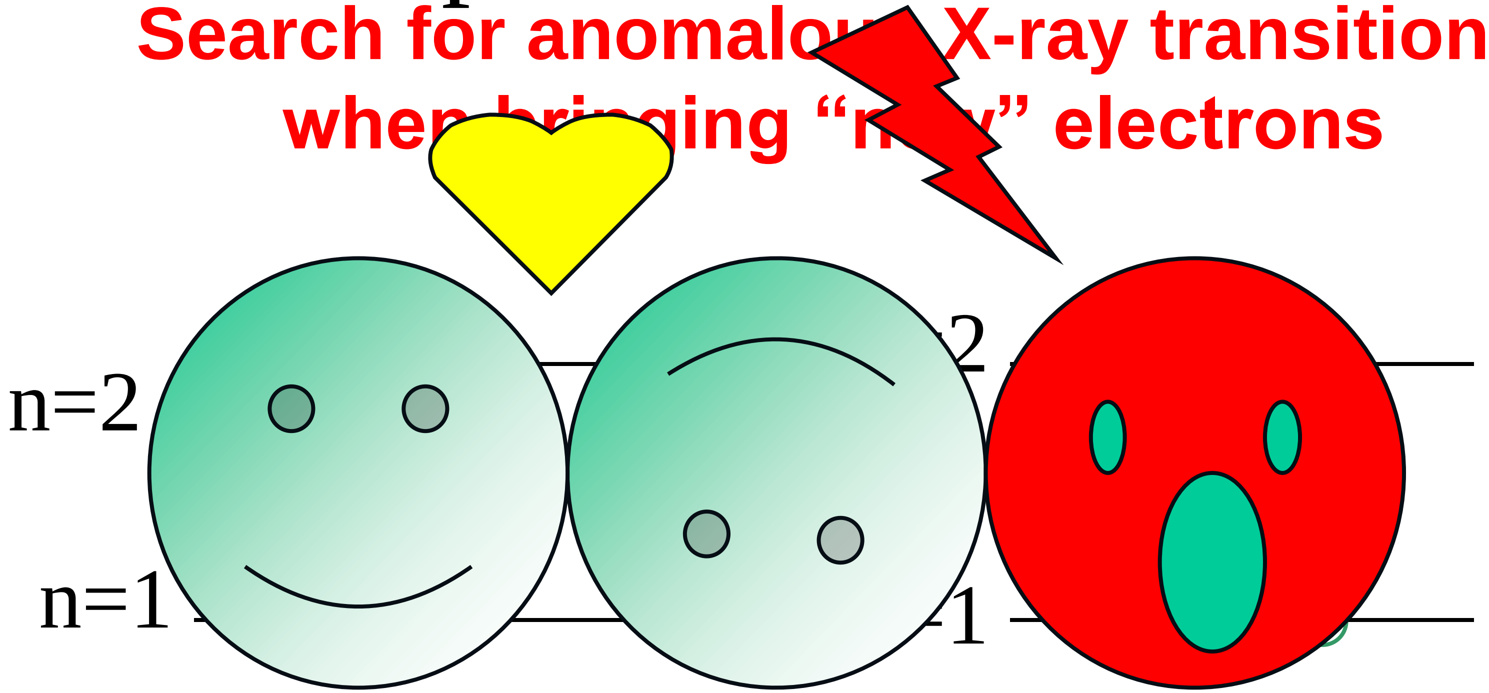
2p –>1s transition violating Pauli principle

Energy 7.7 keV

Messiah Greenberg superselection rule

Experimental method:

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



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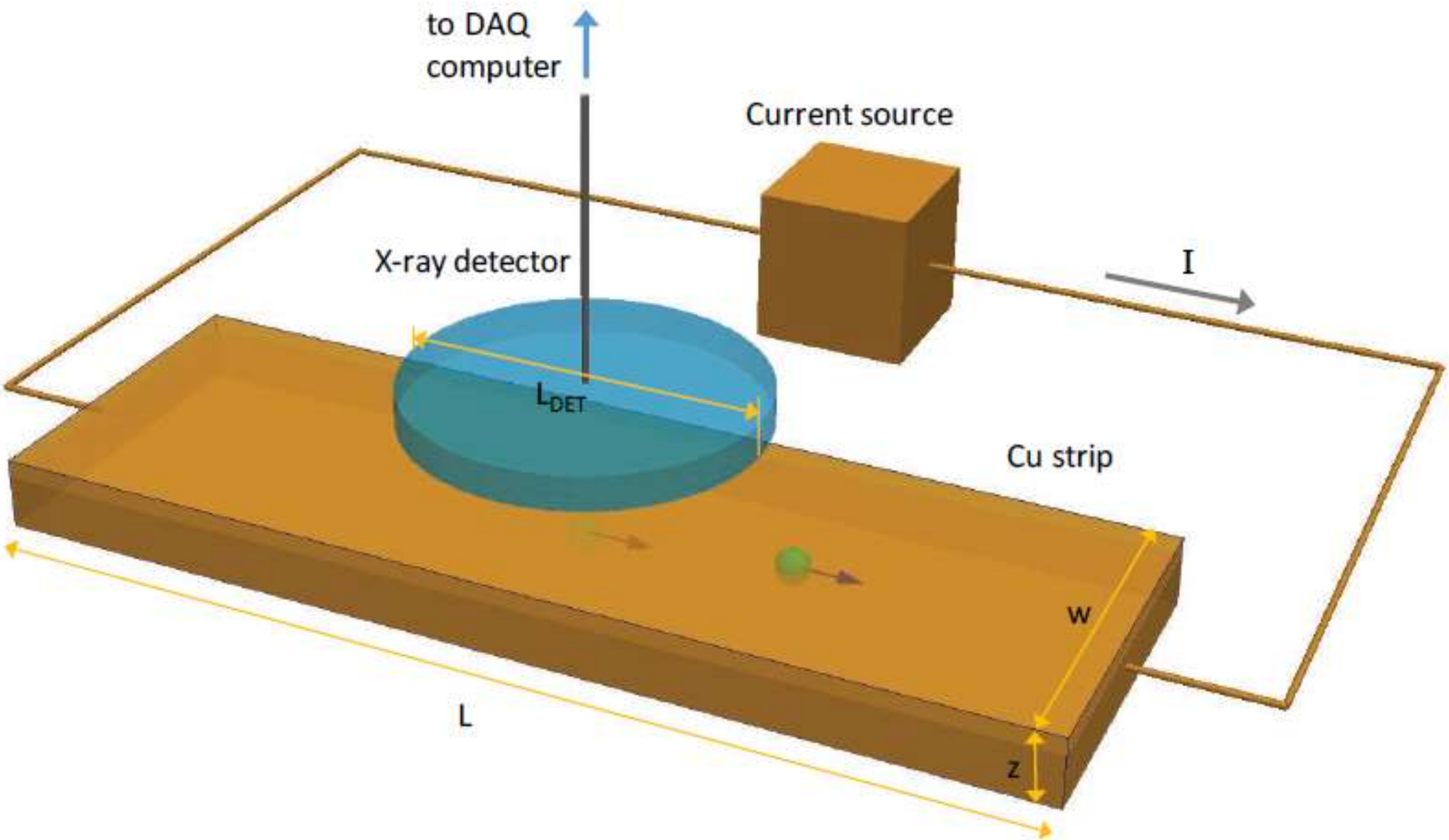
to DAQ
computer
Current source
X-ray detector
I
L_DET
Cu strip
w
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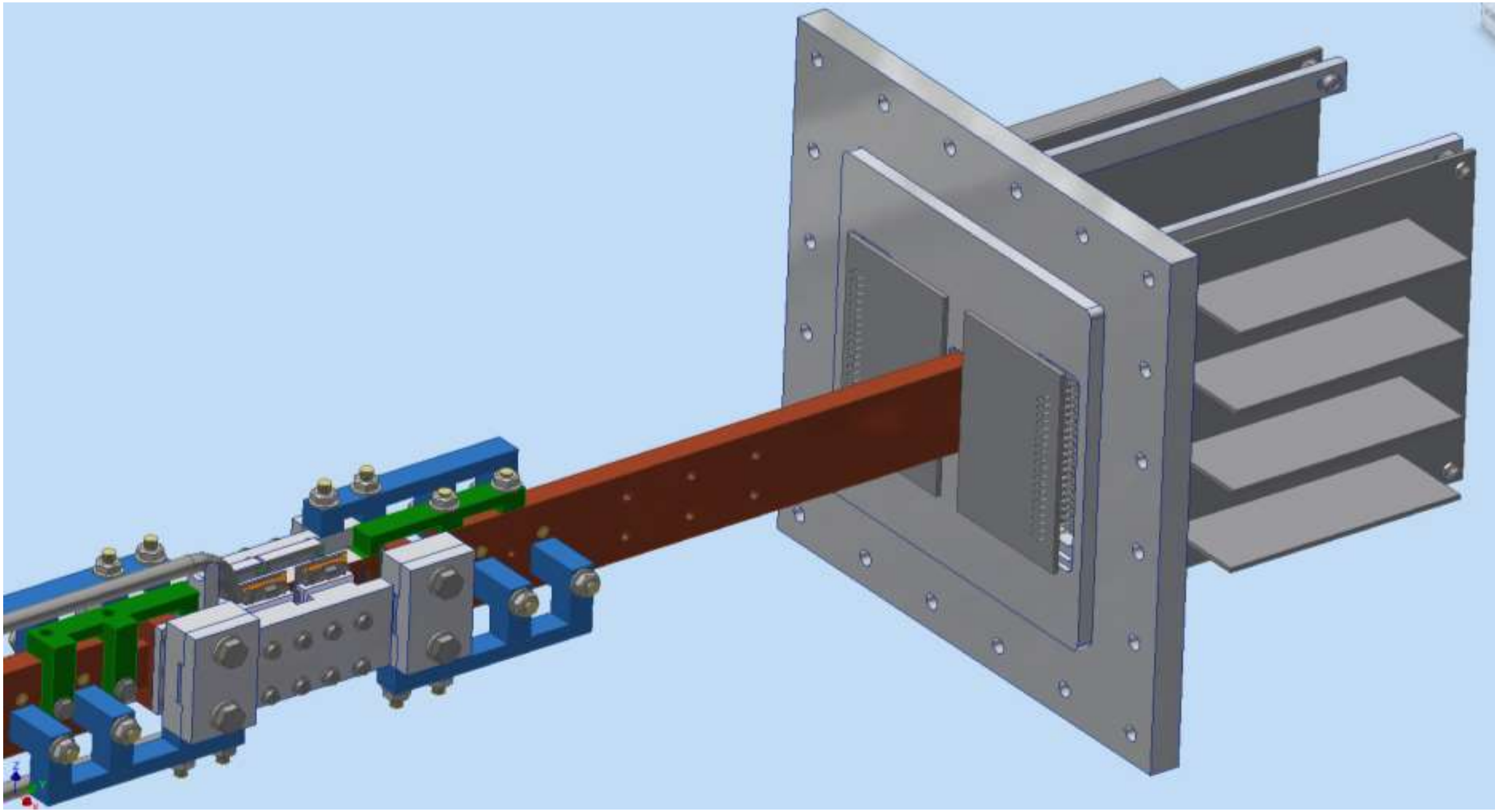
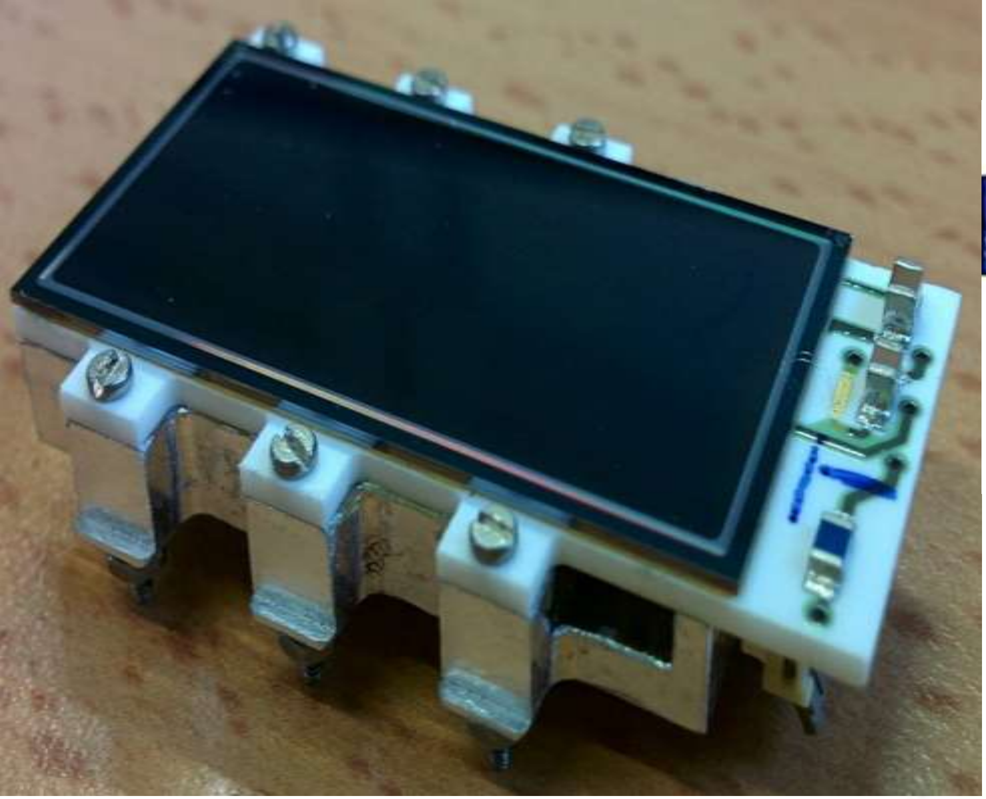
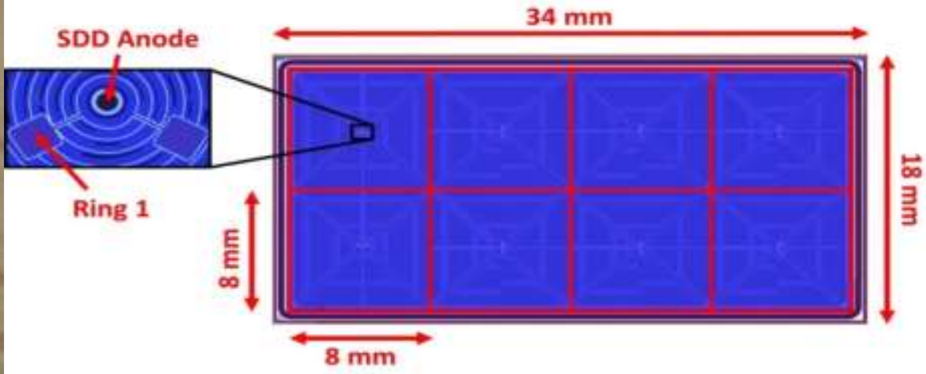
z






34 mm
SDD Anode
Ring 1
18 mm
8 mm
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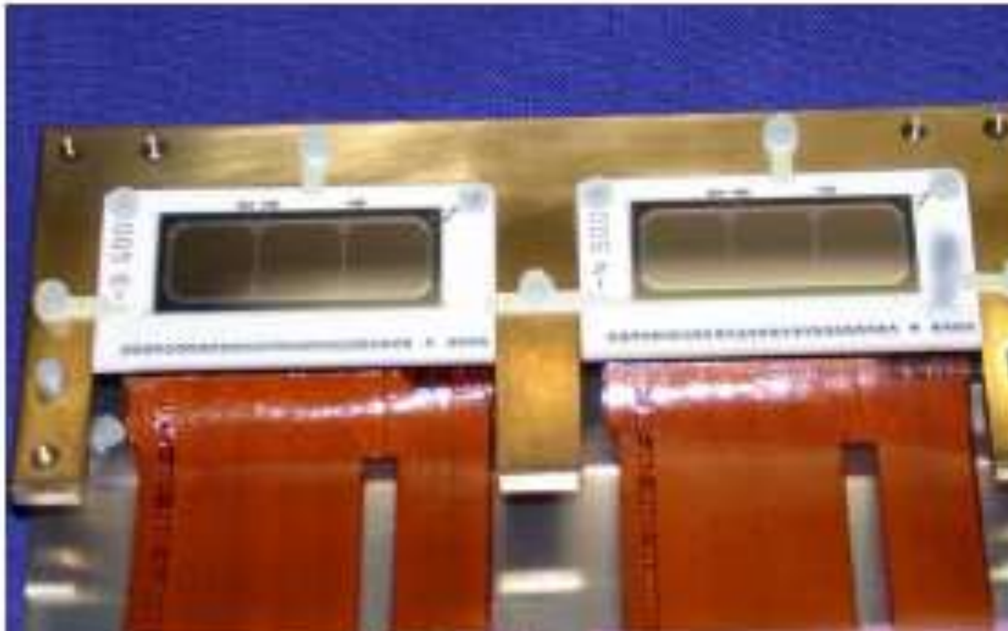

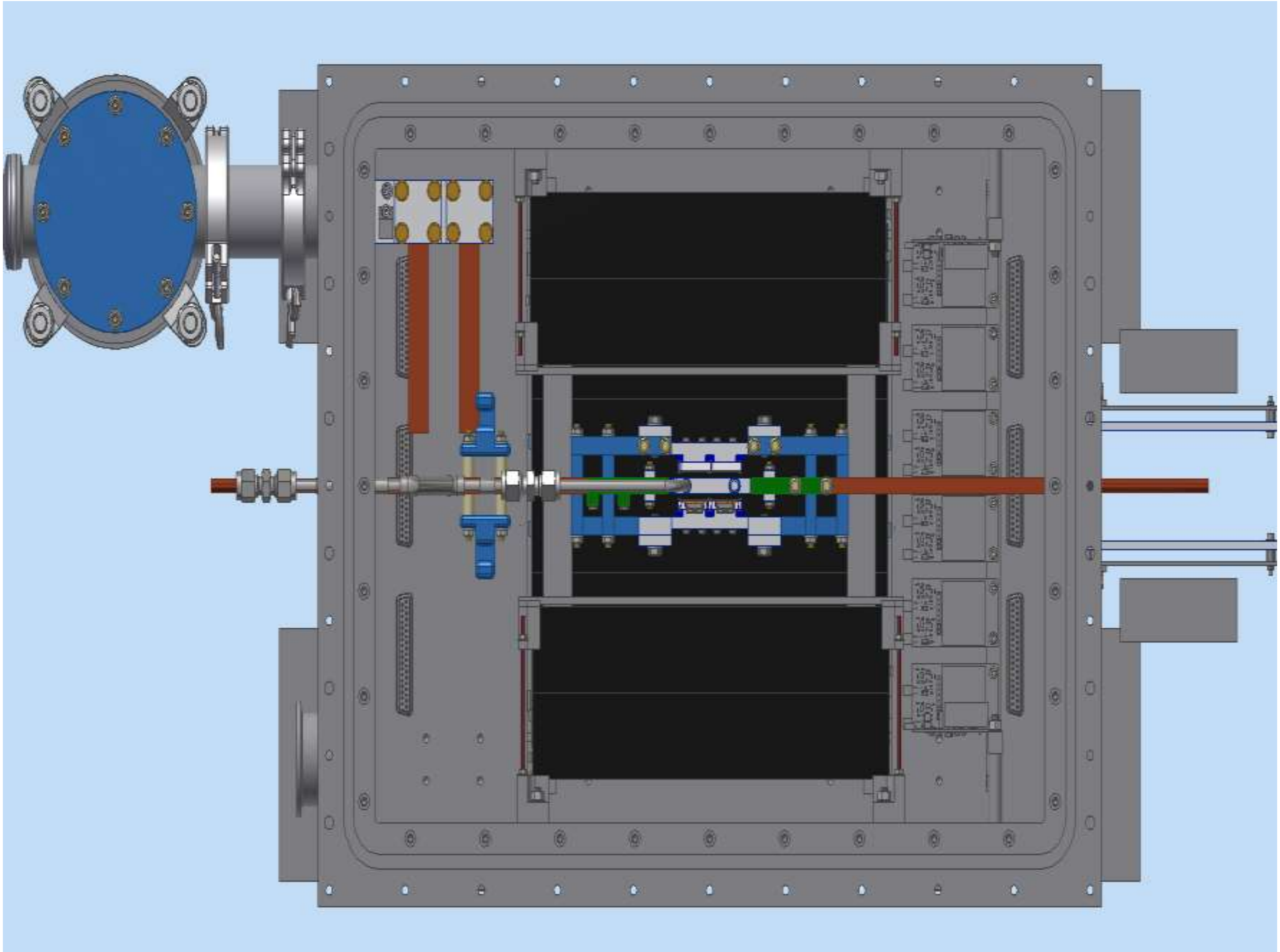

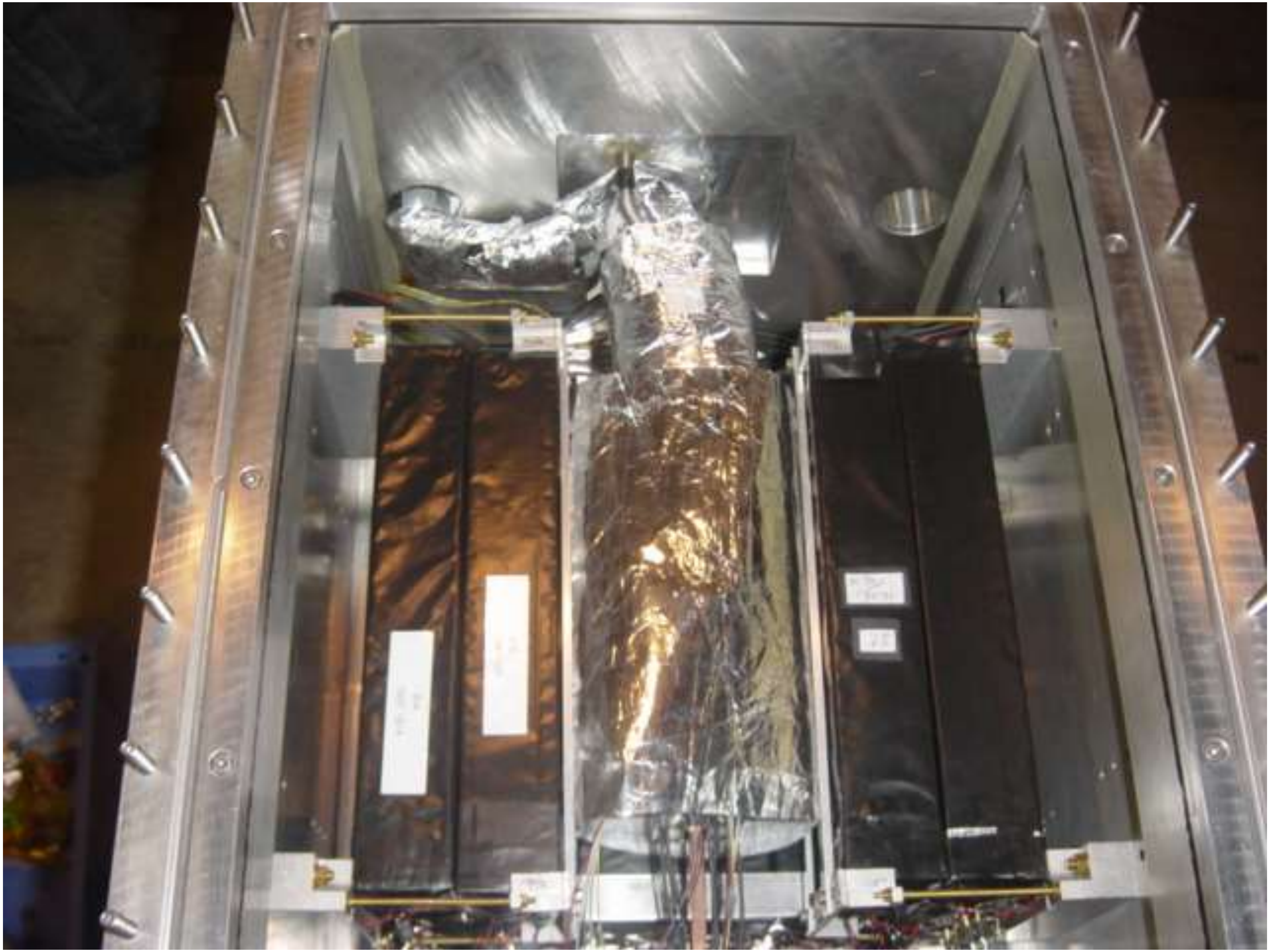

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https://doi.org/10.1140/epjc/s10052-018-5802-4

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Experimental search for the violation of Pauli exclusion principle

VIP-2 Collaboration

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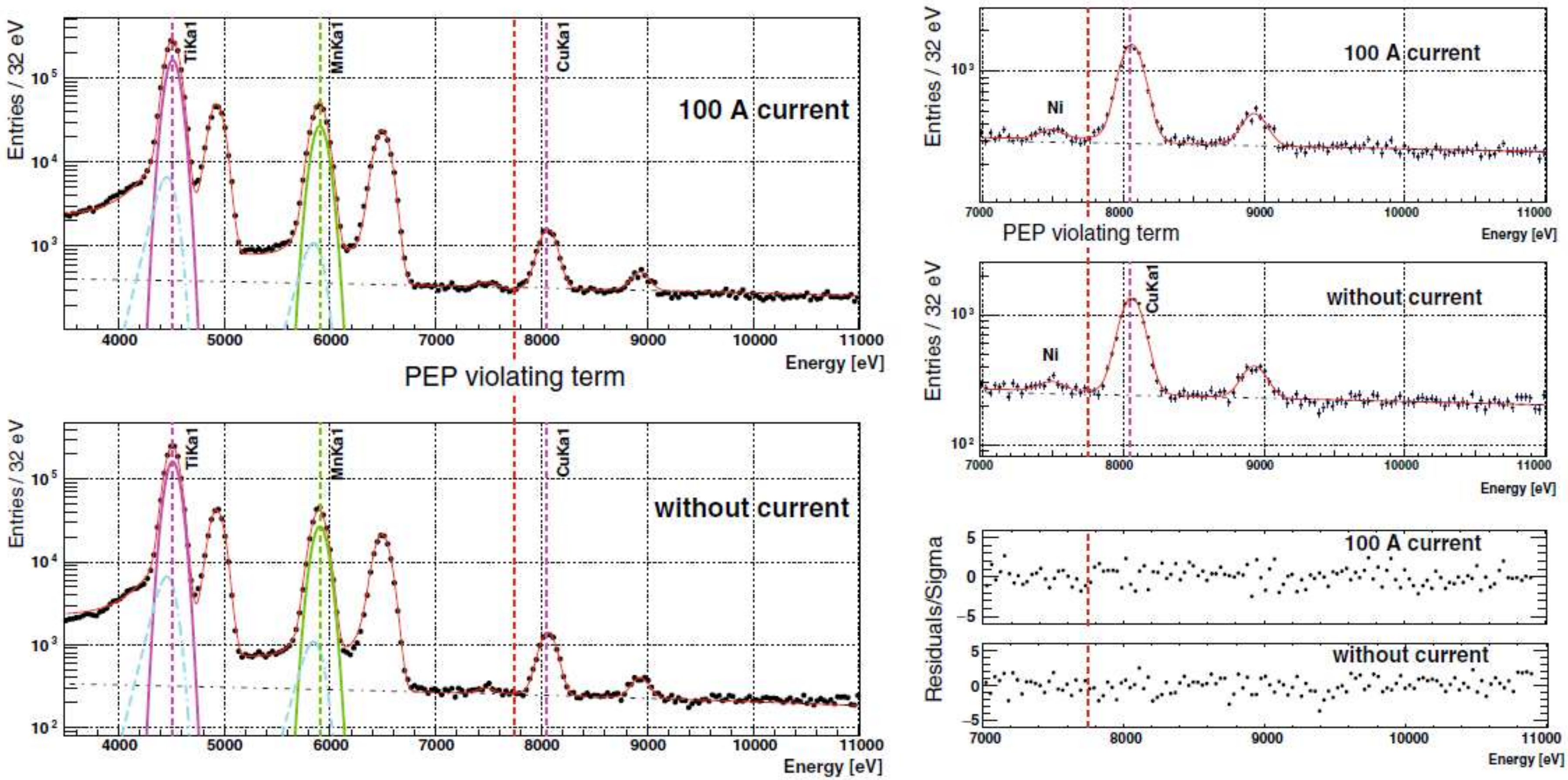

(a)

(b)

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

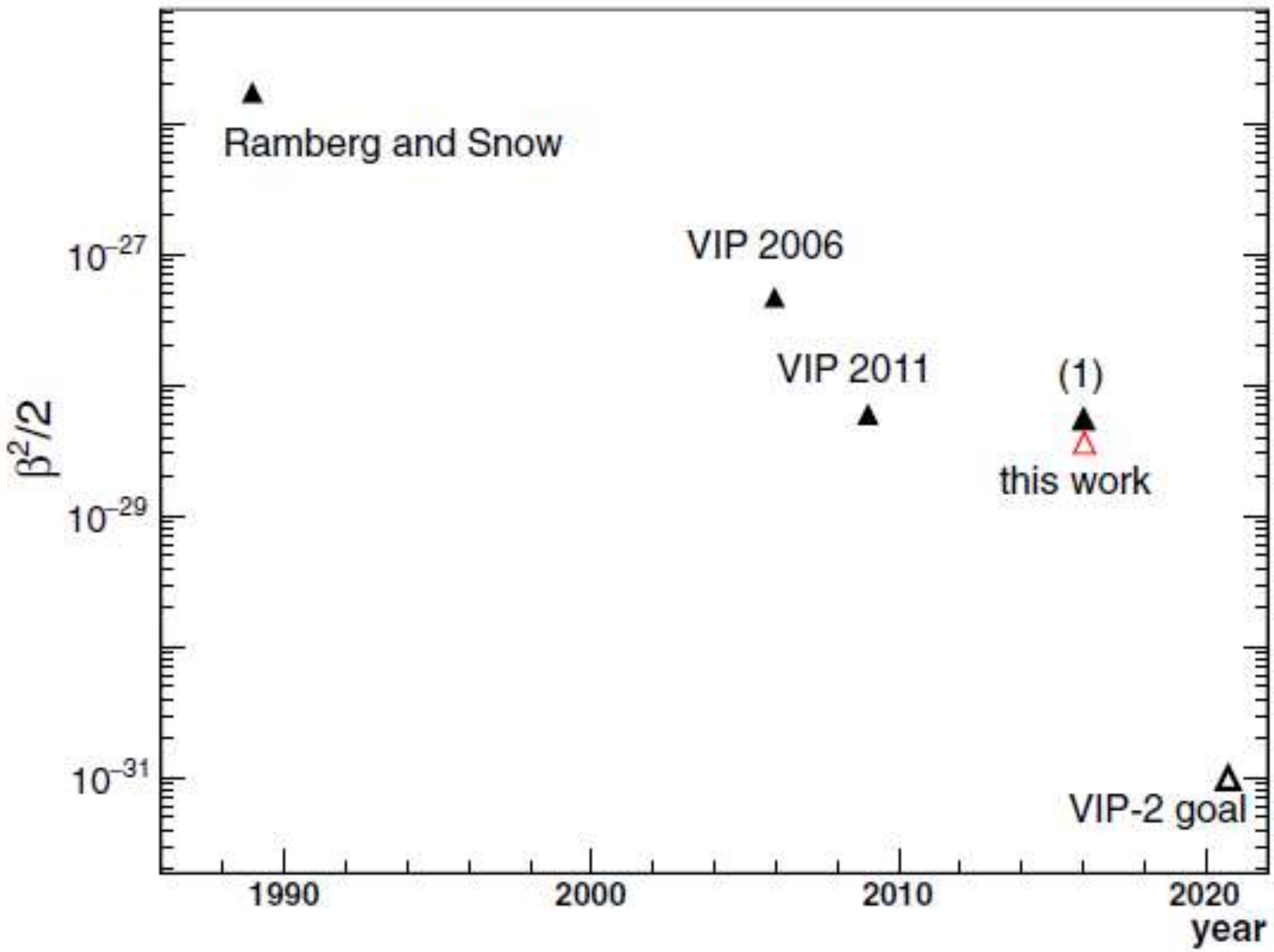

Fig. 10 Past results from PEP violation tests for electrons with a copper conductor, together with the result from this work and the anticipated goal of VIP-2 experiment. The result (1) is based on the same data set of this work, but using the spectra subtraction in the analysis

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 to 10^{-31}

Pauli Exclusion Principle violation:
- as particle property
- <u>space-time property</u>

VIP-2 underground experiment as a *Crash-Test* of Non-Commutative Quantum Gravity

With Andrea Addazi and Antonino Marciao' (Fudan University – China)

Pauli Exclusion Principle (PEP) violations induced from non-commutative space-time can be searched VIP-2 experiment set-up. We show that the limit from VIP-2 experiments on non-commutative space-time scale Λ, related to energy dependent PEP violations, are severe: κ-Poincaré non-commutativity is ruled-out up to the Planck scale. In the next future θ-Poincaré will be probed until the Grand-Unification scale! This highly motivates Pauli Exclusion Principle tests from underground experiments as a test of quantum gravity and space-time microscopic structure.

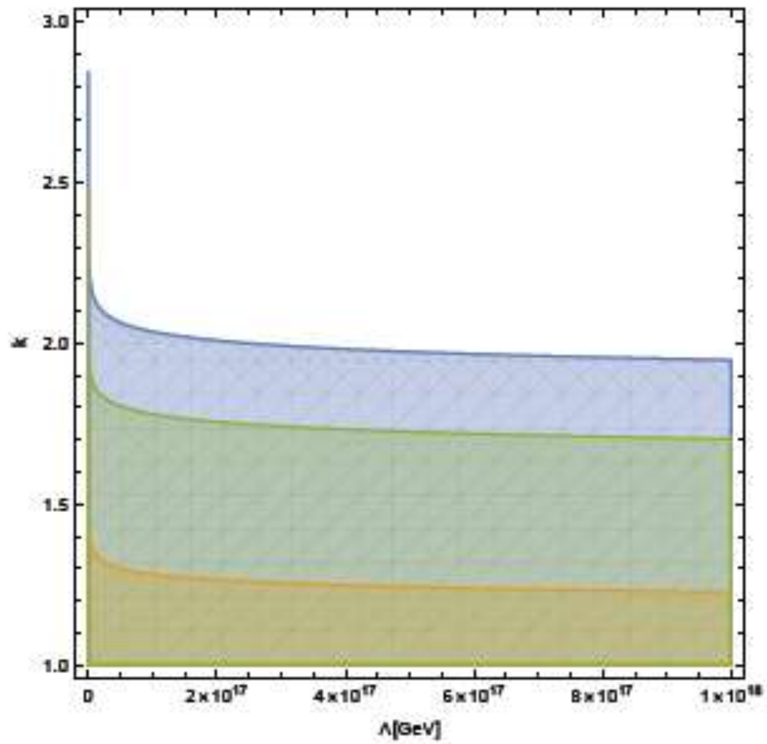

FIG. 1. Exclusion region plots, in the Planck scale window, of the non-commutative scale Λ (x-axis) and the energy powers k (y-axis) from Eq.1 are shown from present, next future and *futuristic* bounds from VIP-2 experiments $\delta(E) < 10^{-29}, 10^{-40}, 10^{-45}$ (orange, green, blue respectively).

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

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

Search for a remnant violation of the Pauli Exclusion Principle in a Roman lead block

$$\frac{1}{2}\beta^2 < 2.75 \cdot 10^{-44},$$

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.

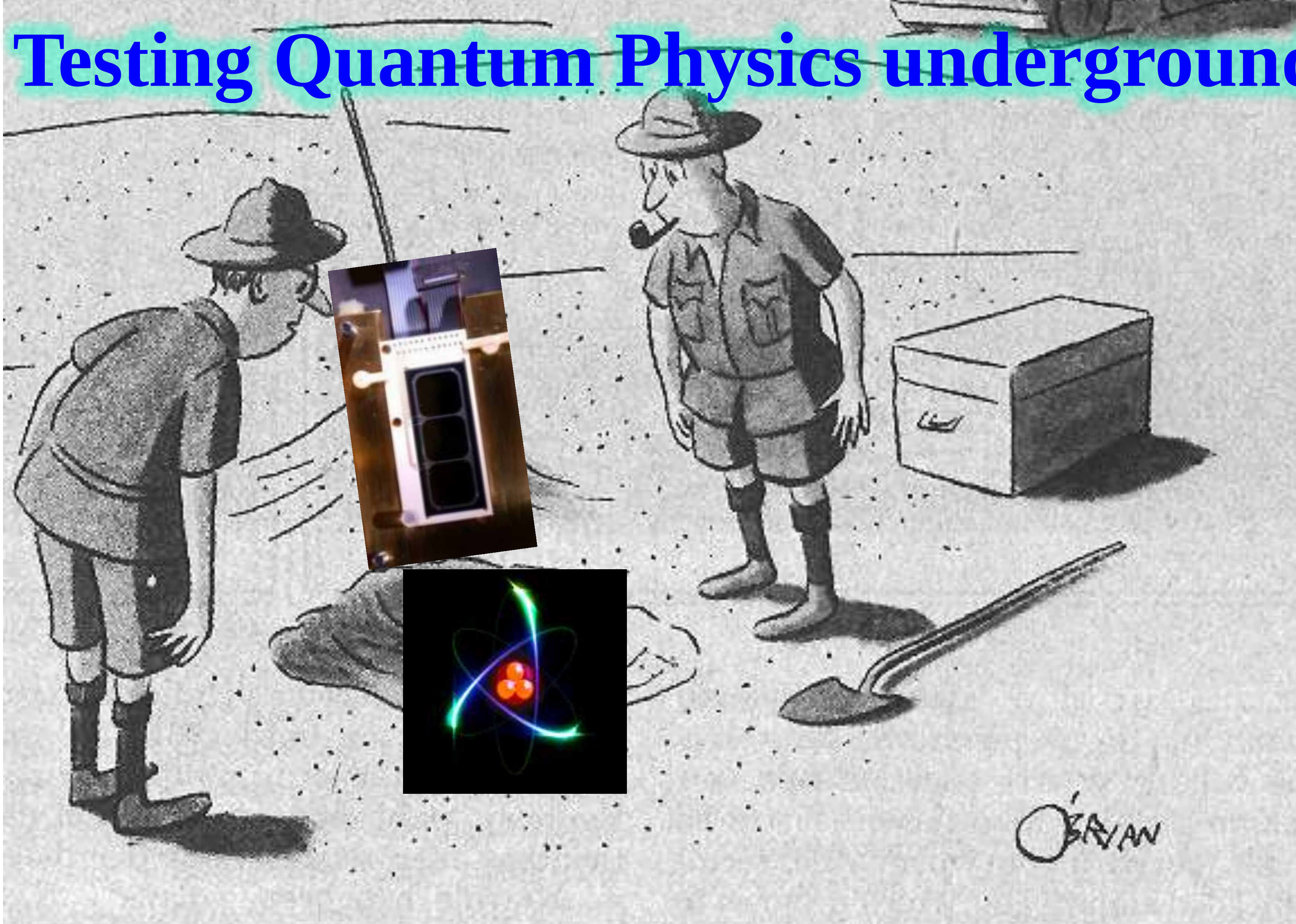
If we tightly grasp a stone in our hands, we neither expect it to vanish nor leak through our flesh and bones. Our experience is that stone and, more generally, solid matter is stable and impenetrable. Last year marked the 50th anniversary of the demonstration by Freeman Dyson and Andrew Lenard that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

Testing Quantum Physics underground



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

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MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

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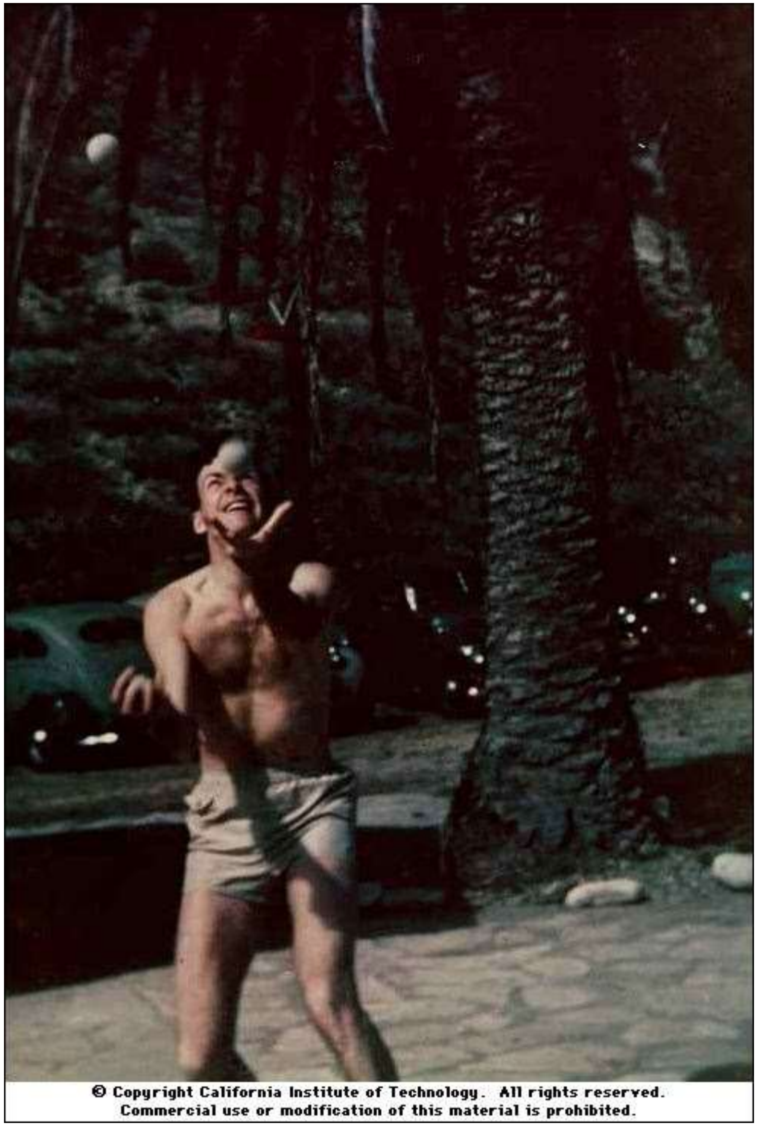
Thank you

Feynman



the patterns of another
till complex new ones are formed.
They make others like themselves
and a new dance starts.
Growing in size and complexity
living things
masses of atoms
DNA, protein
dancing a pattern ever more intricate.
Out of the cradle

onto dry land
here it is
standing:
atoms with consciousness;
matter with curiosity.
Stands at the sea, wondering: I
a universe of atoms
an atom in the universe.

2. What does a violation of PEP mean?

There are several not quite equivalent proofs of the symmetrization principle in the loose context of field theory. Consider, e.g., the proof by G. Lüders and B. Zumino, Phys. Rev. **110** (1958) 1450). Its postulates are:

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.

A necessary (though not sufficient) condition for violation is that at least one of the postulates is violated

I. The theory is non-invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)

Lorentz violation, would have far-ranging consequences and mark the appearance of new physics.

II. Two operators of the same field at points separated by a spacelike interval neither commute nor anticommute

This would entail a violation of locality (microcausality) at very short distances.

III. The vacuum is not the state of lowest energy

Unstable vacuum !!!

IV. The metric of the Hilbert space is not positive definite

States with negative norm !!!

V. The vacuum is identically annihilated by some field

Weird physics !!!

“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” (Greenberg)

FQXi
FOUNDATIONAL QUESTIONS INSTITUTE

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58158: Hunt for the "impossible atoms": the quest for a tiny violation of the

Pauli Exclusion Principle, ***Implications for physics, cosmology and philosophy***

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Spontaneous emission including nuclear protons

When the emission of nuclear protons is also considered, the spontaneous emission rate is:

$$\frac{d\Gamma_k}{dk} = \left(N_P^2 + N_e\right) \frac{e^2\lambda}{4\pi^2 a^2 m_N^2 k}$$

(the stochastic field is assumed to be coupled to the particle mass density)

provided that the emitted photon wavelength $\boldsymbol{\lambda}_{ph}$ satisfies the following conditions:

1) $\boldsymbol{\lambda}_{ph} > 10^{-15}$ m (nuclear dimension) → protons contribute coherently

2) $\boldsymbol{\lambda}_{ph} <$ (electronic orbit radius) → electrons and protons emit independently →

→ NO cancellation