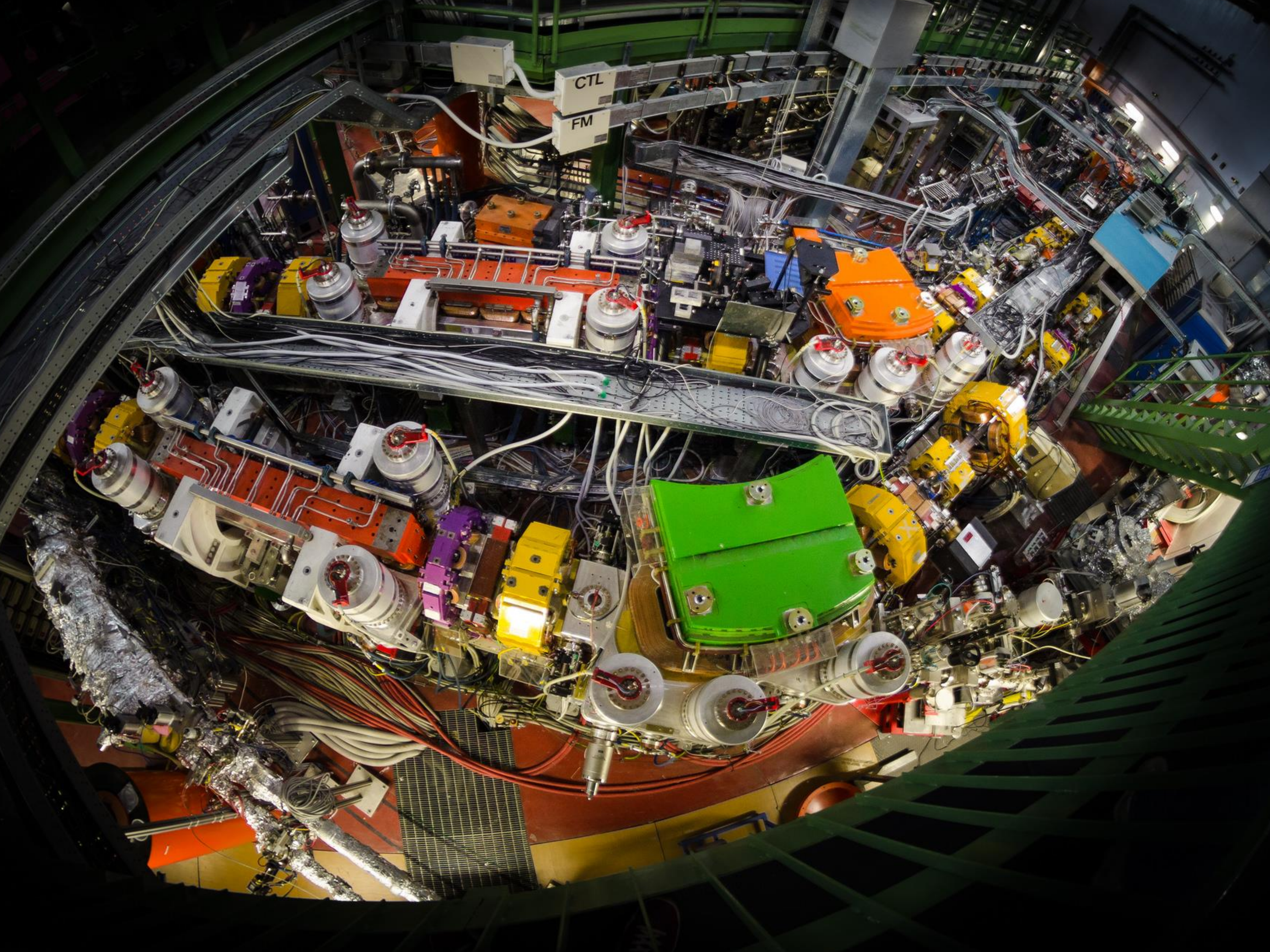
Testing Quantum Mechanics Underground Search for the Pauli Exclusion Principle Violations with the VIP experiment

Catalina Curceanu, LNF-INFN, Frascati (Italy)

LNGS Seminar
20 March 2025

Where all started: INFN-LNF

DAΦNE collider


CTL
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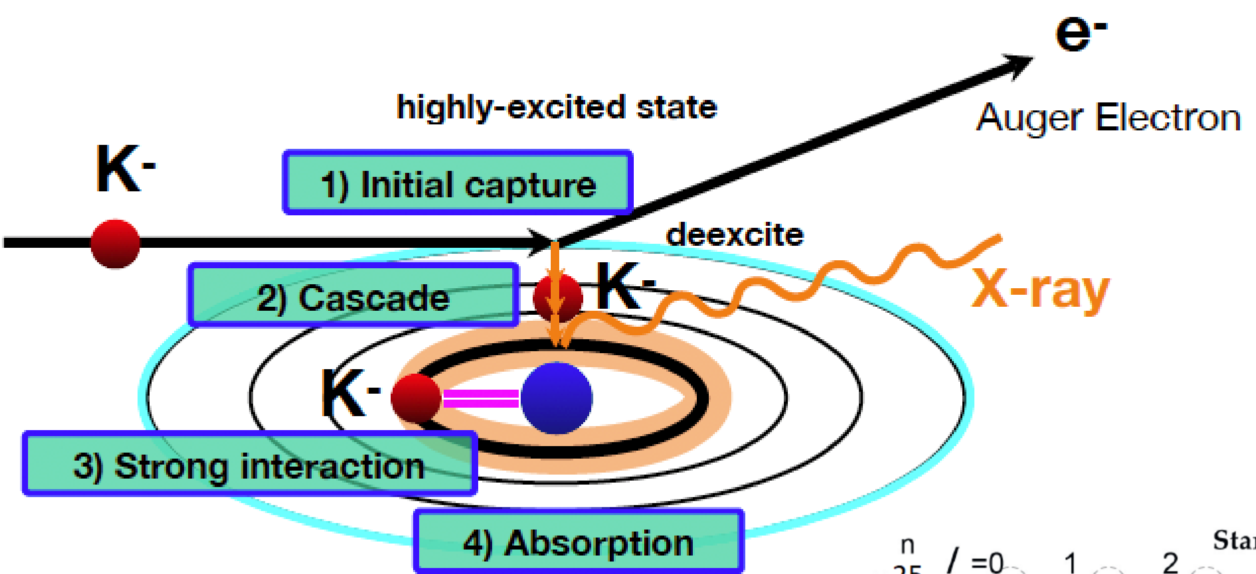
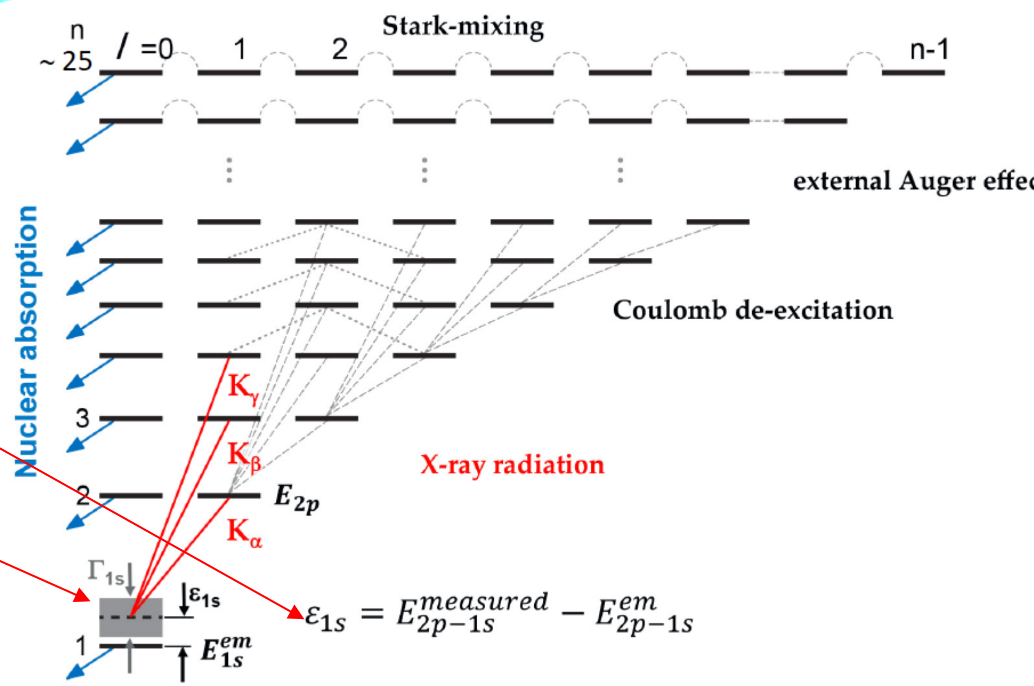
SIDDHARTA

SIlicon Drift Detector for Hadronic Atom Research by Timing Application

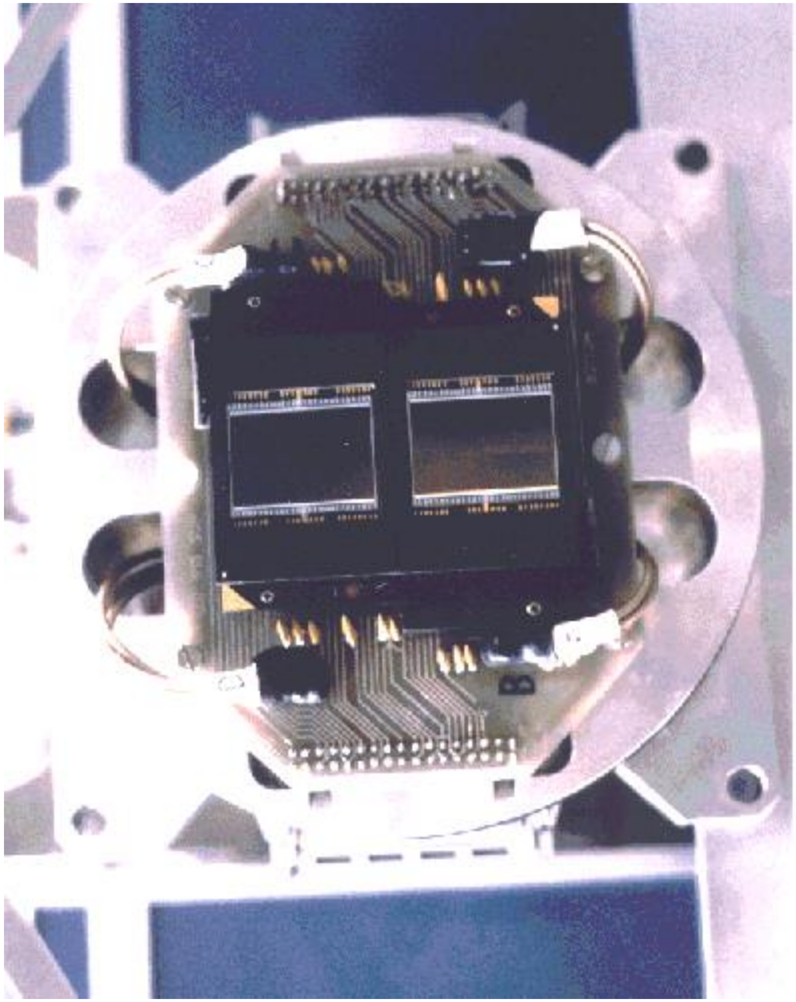
Kaonic atom Formation

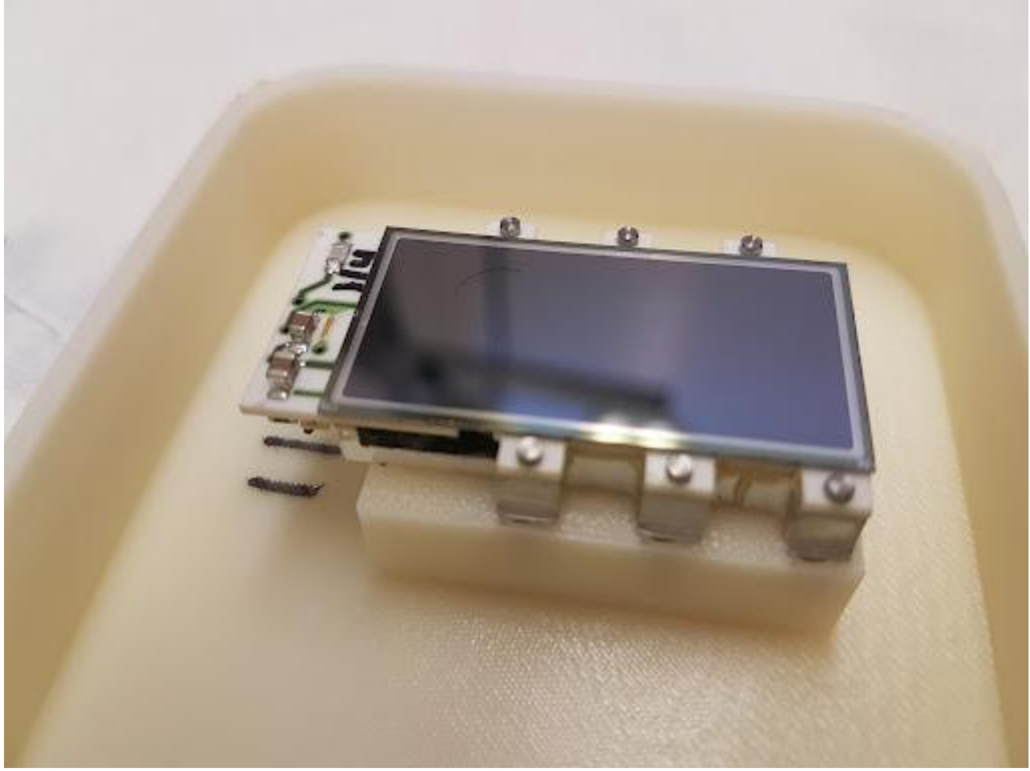




Width Γ and shift ε obtained by measuring the X-rays emitted

X-ray detectors (CCD, SDD)



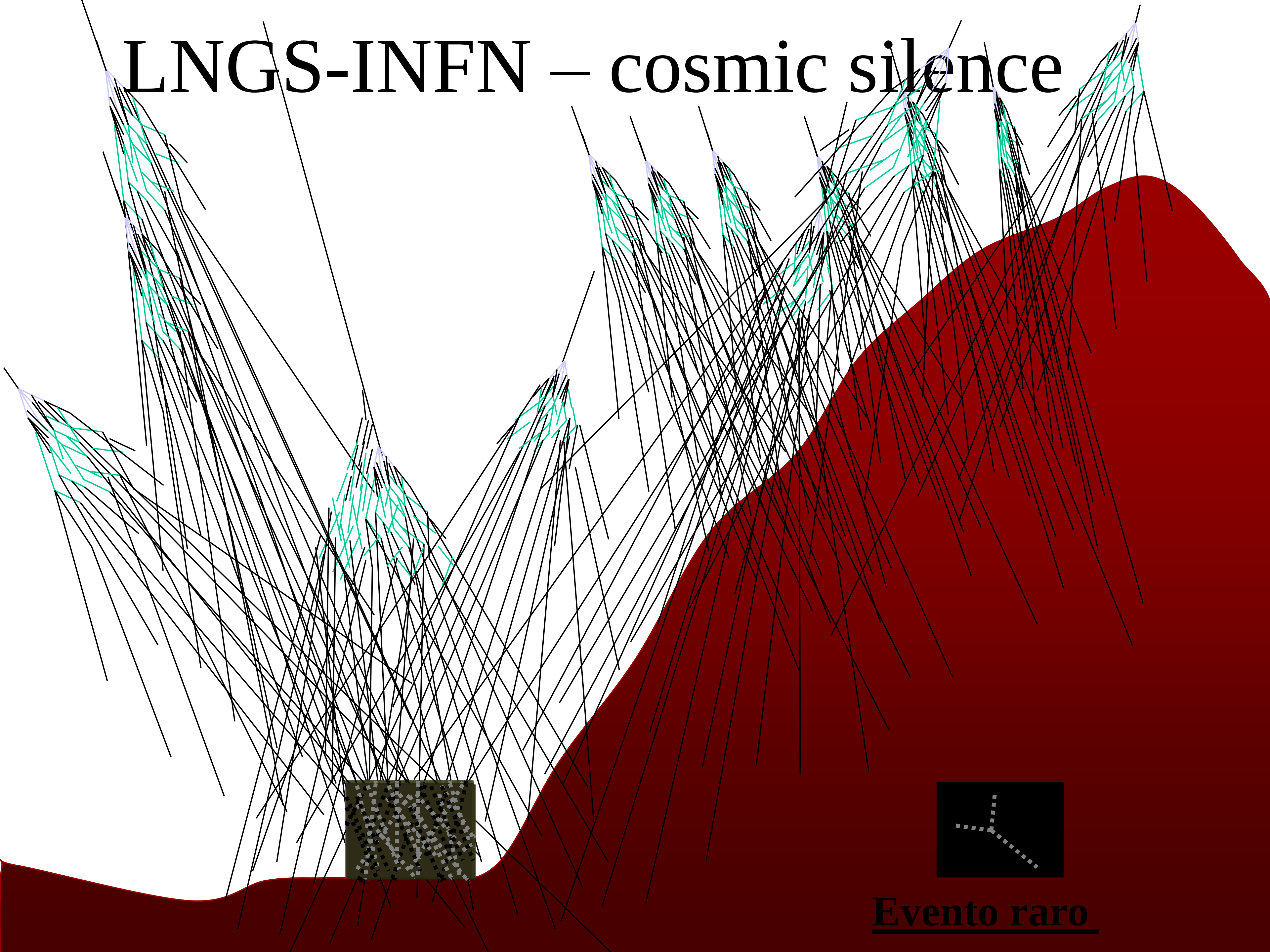


Quantum Mechanics tests:

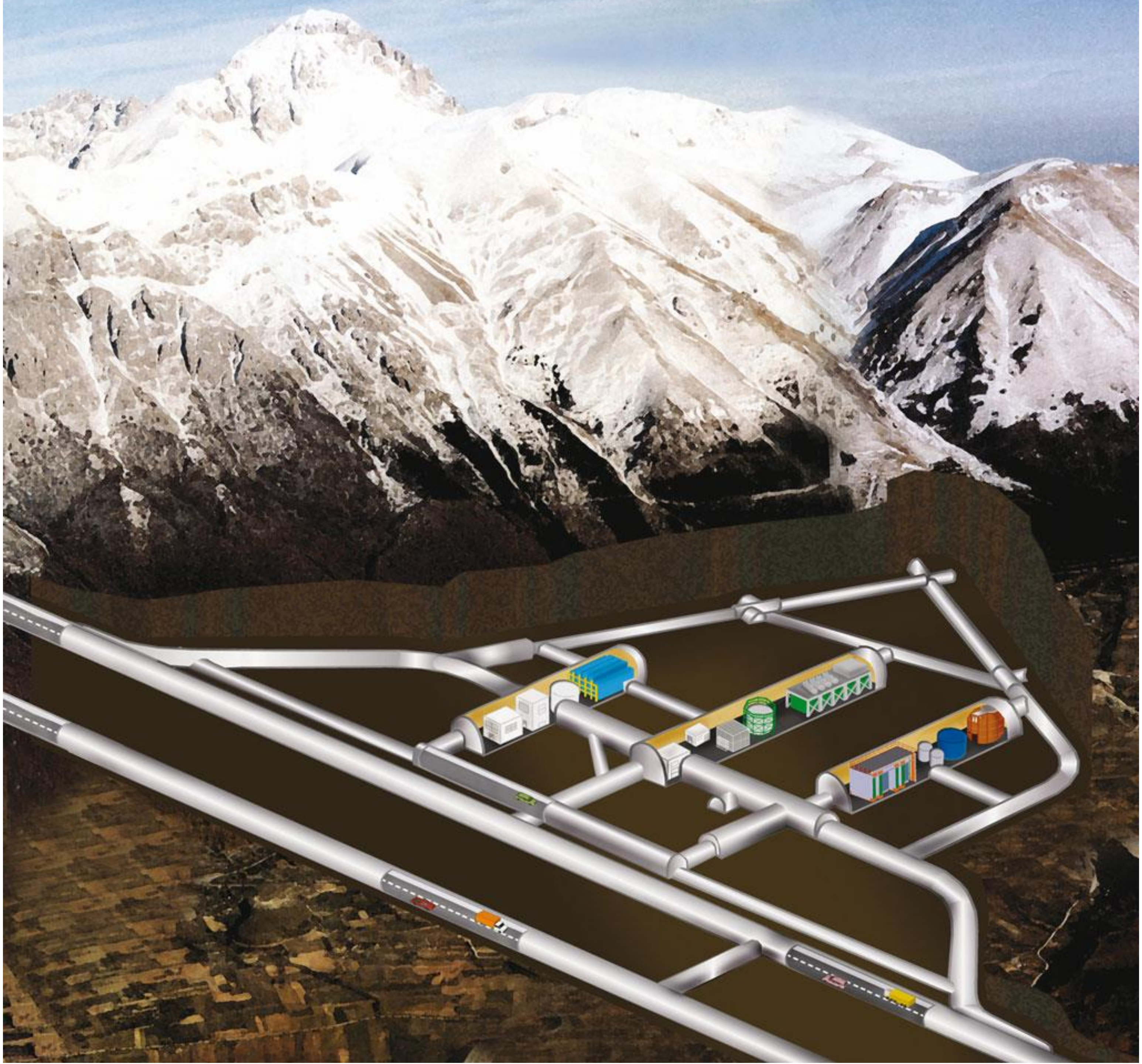
- **Pauli Exclusion Principle Violation**
- **Collapse Models (Kristian)**

Relation between Quantum and Gravity

LNGS-INFN – cosmic silence



Evento raro



We search for the impossible atoms

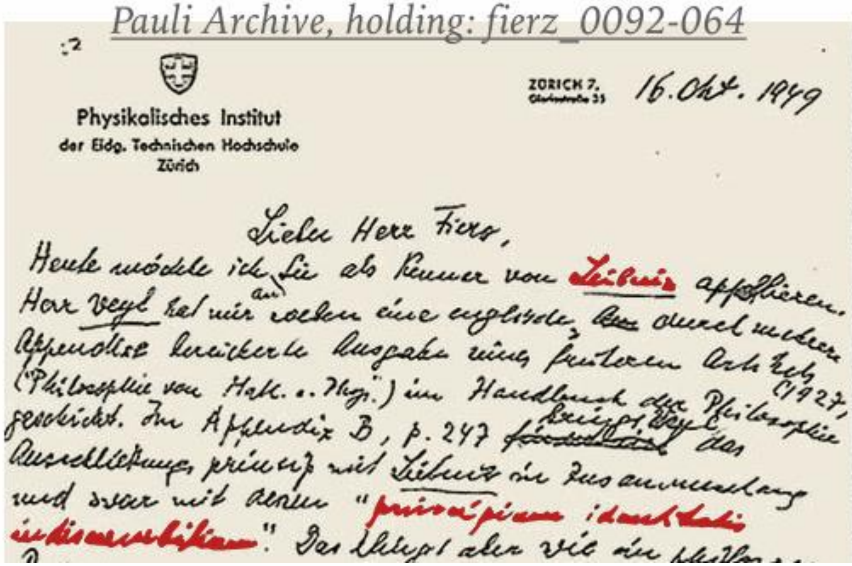
An experiment to test the Pauli Exclusion Principle (PEP) for electrons in a clean environment (LNGS) using atomic physics methods – the VIP experiment

The Pauli Exclusion Principle

In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers coincide. If an electron exists in an atom for which all of these numbers have definite values, then the state is occupied.

W.Pauli, Über den Zusammenhang des Abschlusses der Elektronengruppen im Atom mit der Komplexstruktur der Spektren, Zeitschrift für Physik 31 (1925) 765.

Pauli Archive, holding: fierz_0092-064


Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

ZÜRICH 7, Gloriastrasse 35 16. Okt. 1949

Lieber Herr Fierz,

Heute möchte ich Sie als Kenner von Leibniz apostrophieren. Herr Weyl hat mir eben eine englische, durch mehrere Appendices bereicherte Ausgabe seines früheren Artikels ("Philosophie von Math. u. Naturw.") im Handbuch der Philosophie (1927) geschickt. Im Appendix B, p. 247 bringt Weyl das Ausschliessungsprinzip mit Leibniz in Zusammenhang und zwar mit dessen "principium identitatis indiscernibilium". Das klingt aber wie ein [illegible]

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.

At the root of the Exclusion Principle: proof of spin-statistics theorem by Lüders and Zumino

Postulates:

I. The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)
II. Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality - microcausality)
III. The vacuum is the state of lowest energy
IV. The metric of the Hilbert space is positive definite
V. The vacuum is not identically annihilated by a field

From these postulates it follows that (pseudo)scalar fields commute and spinor fields anticommute.

(G. Lüders and B. Zumino, Phys. Rev. 110 (1958) 1450)

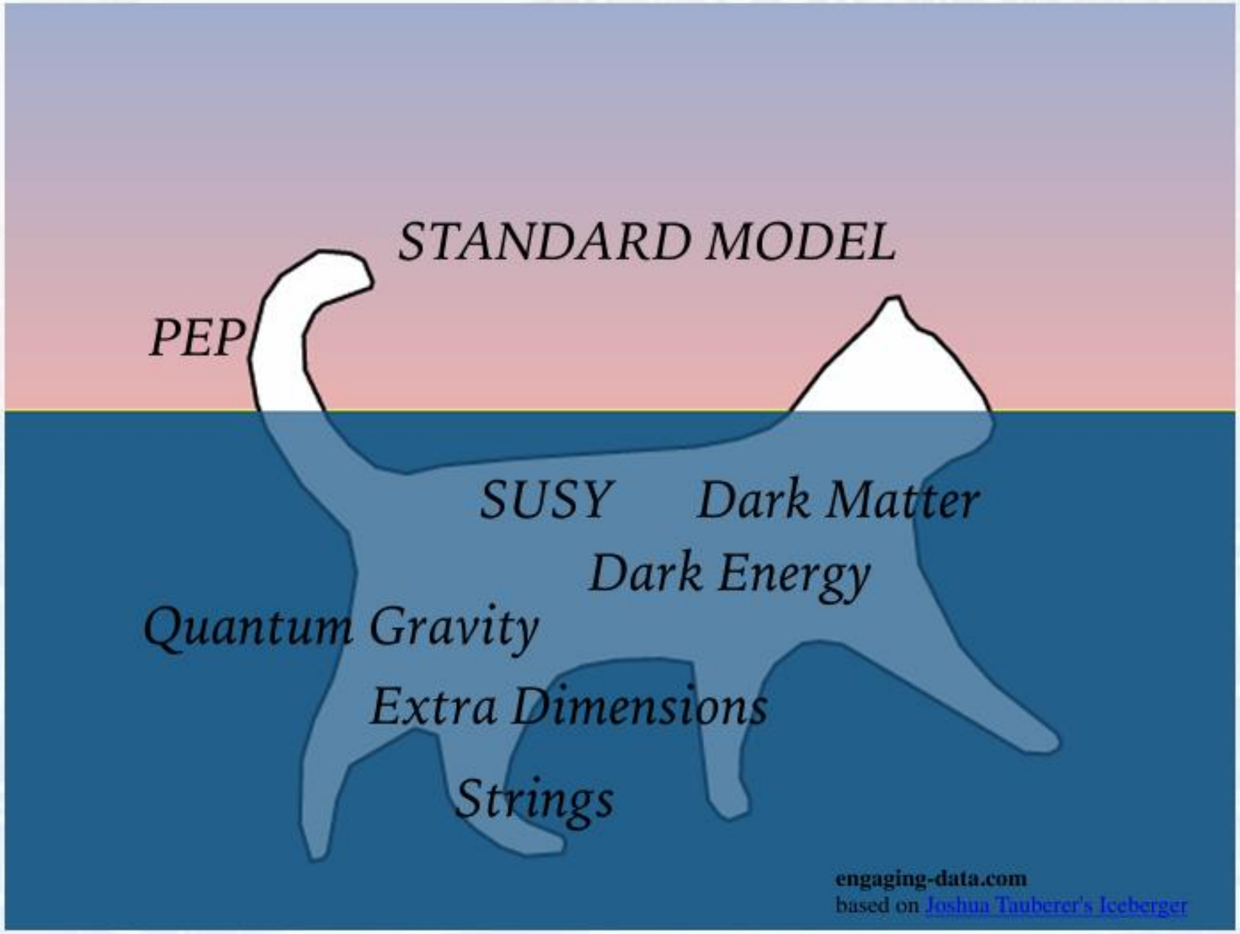
Theories of Violation of Statistics

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

"Possible external motivations for violation of statistics include: (a) violation of CPT, (b) violation of locality, (c) violation of Lorentz invariance, (d) extra space dimensions, (e) discrete space and/or time and (f) noncommutative spacetime. Of these (a) seems unlikely because the quon theory which obeys CPT allows violations, (b) seems likely because if locality is satisfied we can prove the spin-statistics connection and there will be no violations, (c), (d), (e) and (f) seem possible………….

Hopefully either violation will be found experimentally or our theoretical efforts will lead to understanding of why only bose and fermi statistics occur in Nature."

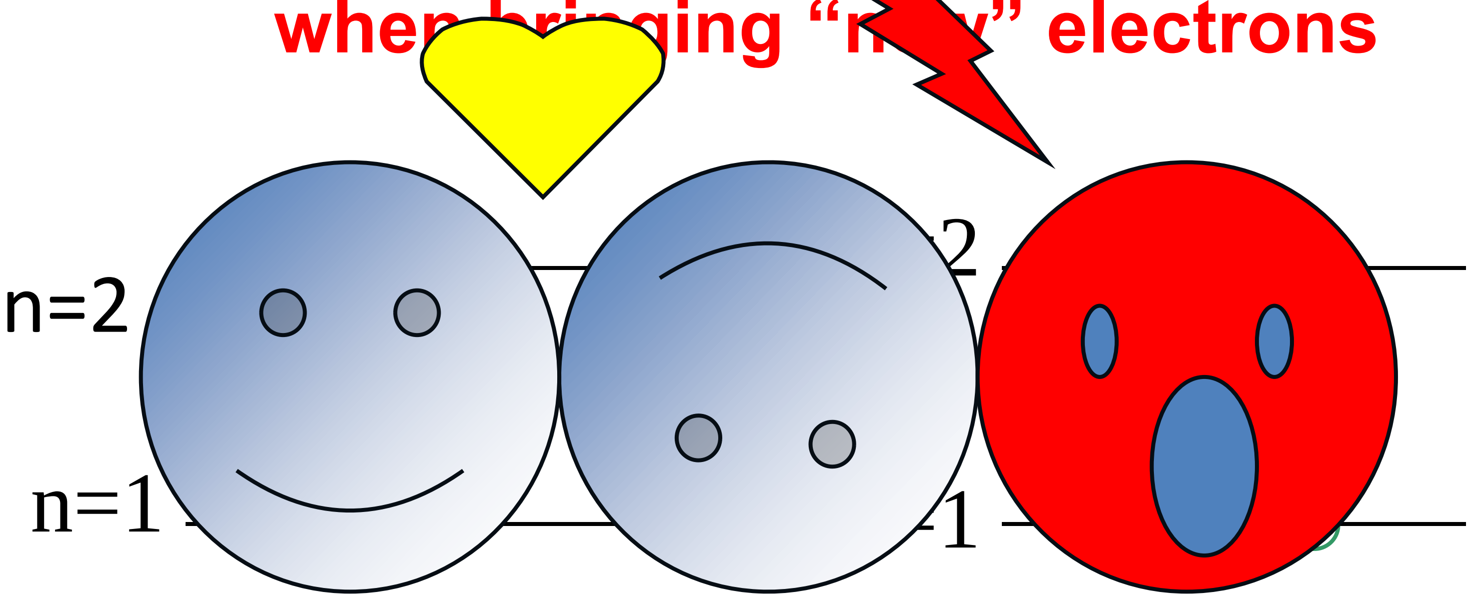
The Pauli Exclusion Principle (PEP)



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

Experimental method:

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



Normal 2p –>1s transition

Energy 8.04 keV

2p –>1s transition violating Pauli principle

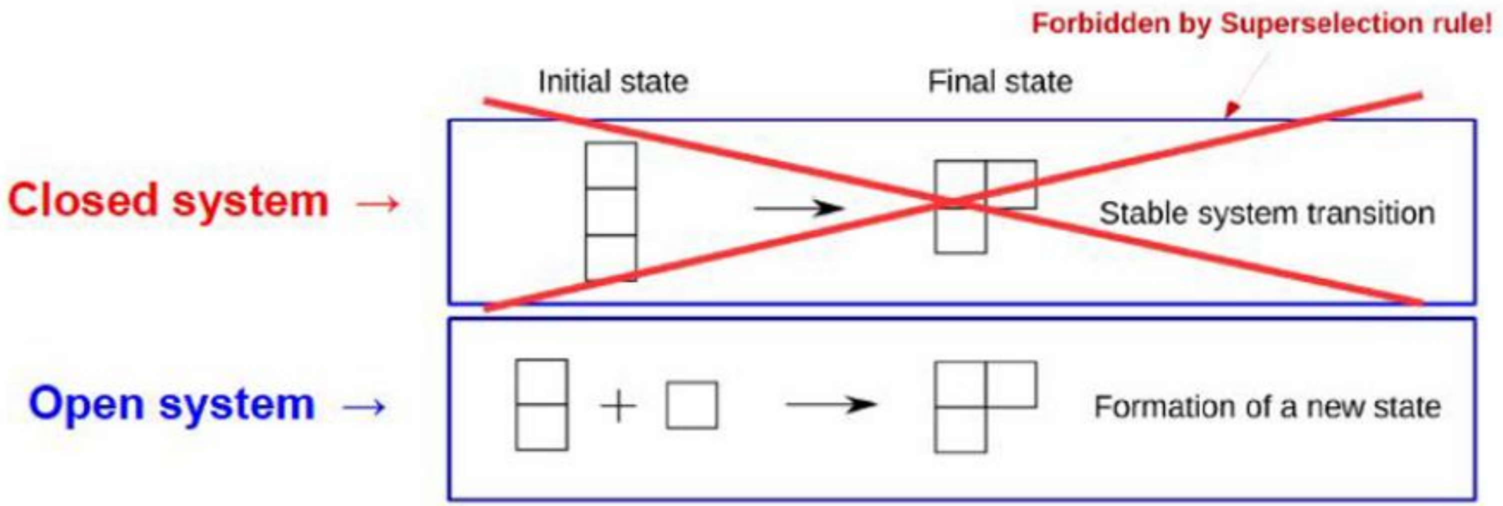
Energy 7.7 keV

Messiah Greenberg superselection rule

Messiah-Greenberg super-selection rule:

Superposition of states with different symmetry are not allowed →

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



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

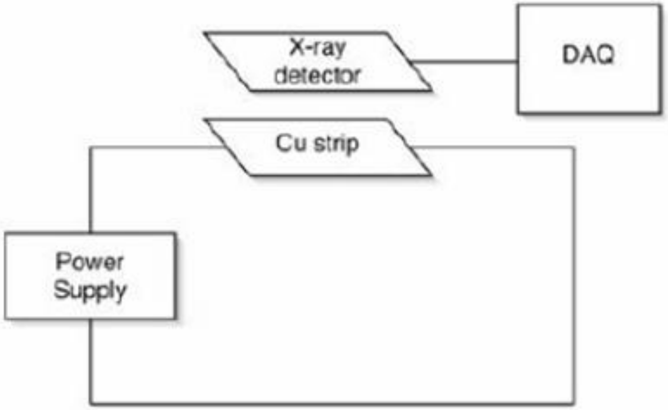
Greenberg, O. W. & Mohapatra, R. N., Phys Rev Lett 59, (1987).
E. Ramberg and G. A. Snow, Phys Lett B 238, 438–441(1990)

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

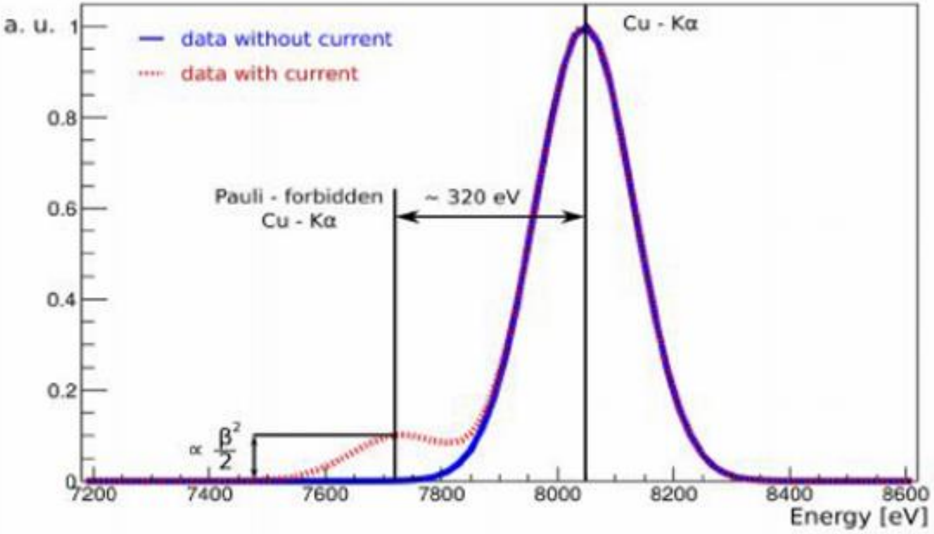
introduced electrons interact with the valence electrons

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

alternated to X-ray background measurements without current

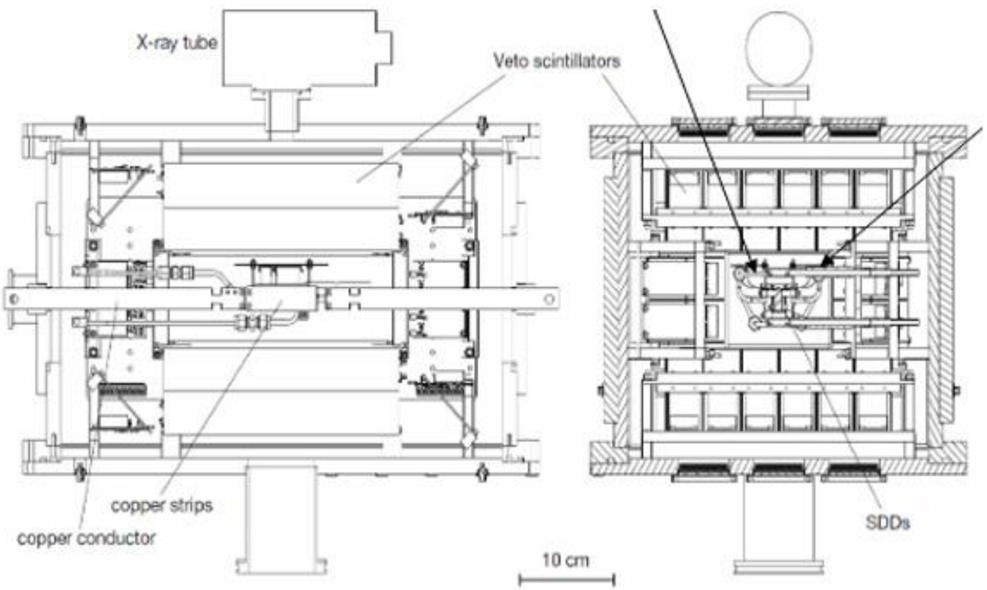


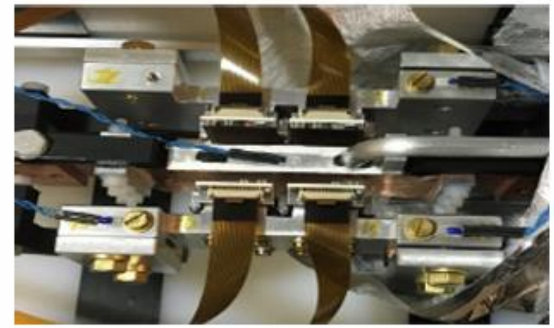
PEP Violation Signal:

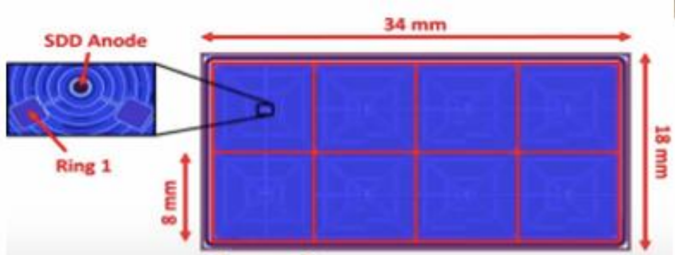


The VIP-2 Experiment

*Silicon Drift Detectors (**SDDs**) higher resolution (190 eV FWHM at 8.0 →keV), faster (triggerable) detectors. 4 arrays of 2 x 4 SDDs 8mm x 8mm each, liquid argon closed circuit cooling 170 °C*







The VIP-2 Experiment

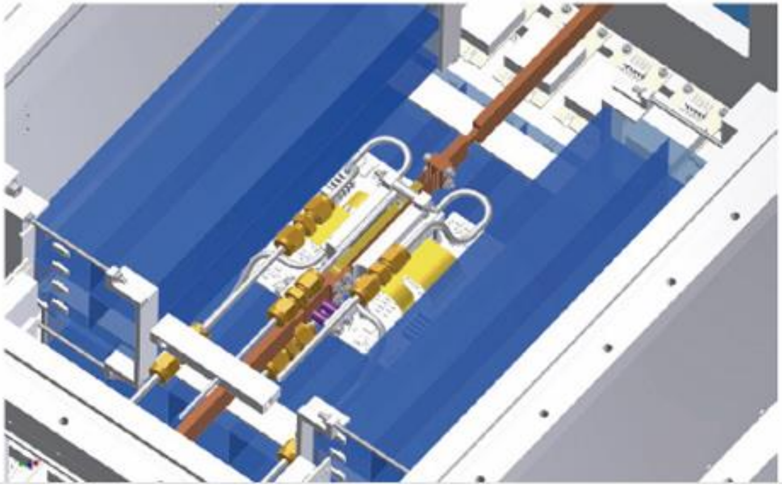
*2 strip shaped Cu targets (25 um x 7 cm x 2 cm) more compact target → higher acceptance, thinner → **higher efficiency***

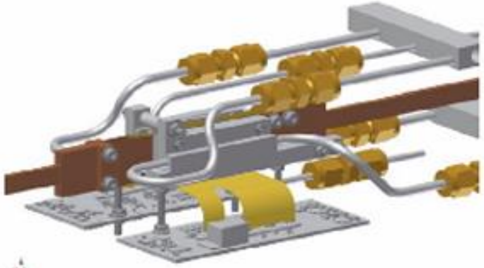
DC current supply to Cu bars

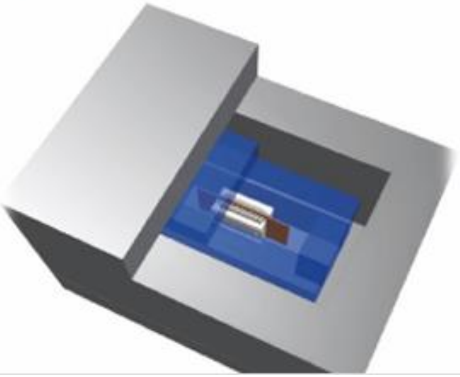
*Cu strips cooled by a closed Fryka chiller circuit →**higher current***

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

Sketch of the VIP2 Setup:







Nat. Phys. (2020)

Open Access Feature Paper Article

VIP-2 —High-Sensitivity Tests on the Pauli Exclusion Principle for Electrons

by Kristian Piscicchia [1,2], Johann Marton [2,3,*], Sergio Bartalucci [2], Massimiliano Bazzi [2], Sergio Bertolucci [4], Mario Bragadireanu [2,5], Michael Cargnelli [3], Alberto Clozza [2], Raffaele Del Grande [1,2,6,*], Luca De Paolis [2], Carlo Fiorini [7], Carlo Guaraldo [2], Mihail Iliescu [2], Matthias Laubenstein [8], Marco Miliucci [2], Edoardo Milotti [9], Fabrizio Napolitano [2], Andreas Pichler [3], Alessandro Scordo [2], Hexi Shi [3], + Show full author list

Entropy 2020, *22*(11), 1195;
https://doi.org/10.3390/e22111195

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

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

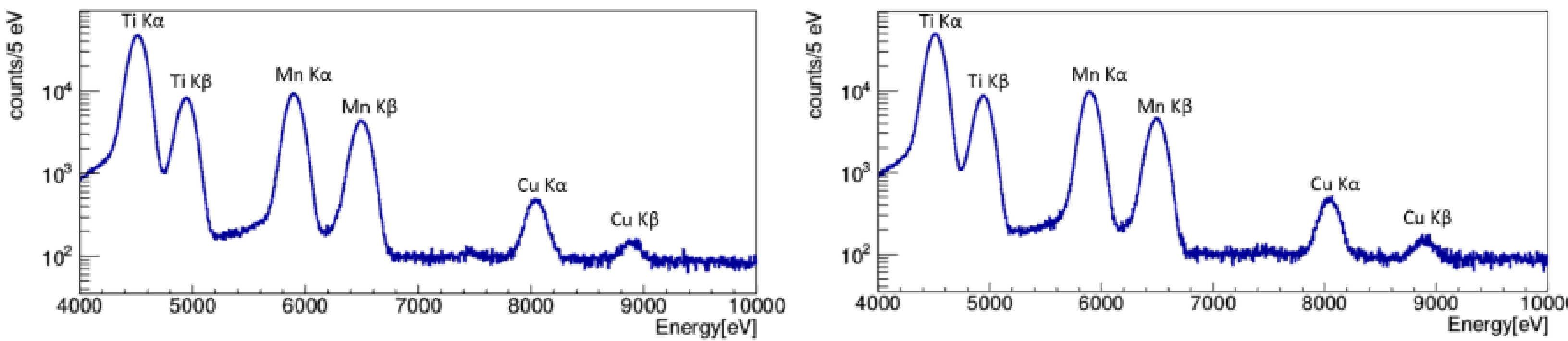


Figure 3. Energy calibrated spectra corresponding to about 42 days of data taking (during 2018) collected with current on (left), the spectrum collected with current off (right), which is normalized to the time of data taking with current on.

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

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

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

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

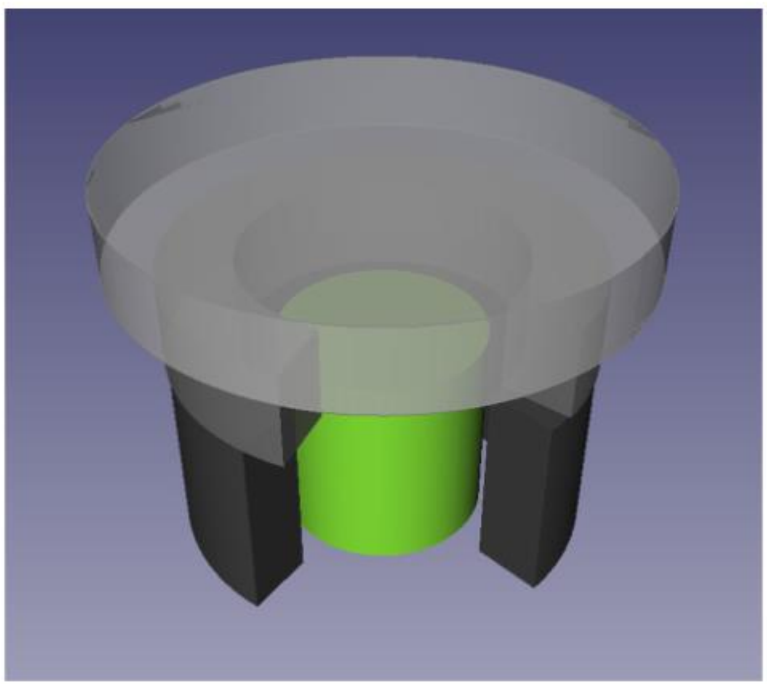


Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

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

provides a limit to Λ_K.

The acquired energy spectrum, corresponding to a total acquisition time $\Delta t \approx 6.1 \cdot 10^6$ s ≈ 70 d is shown in Figure 1.

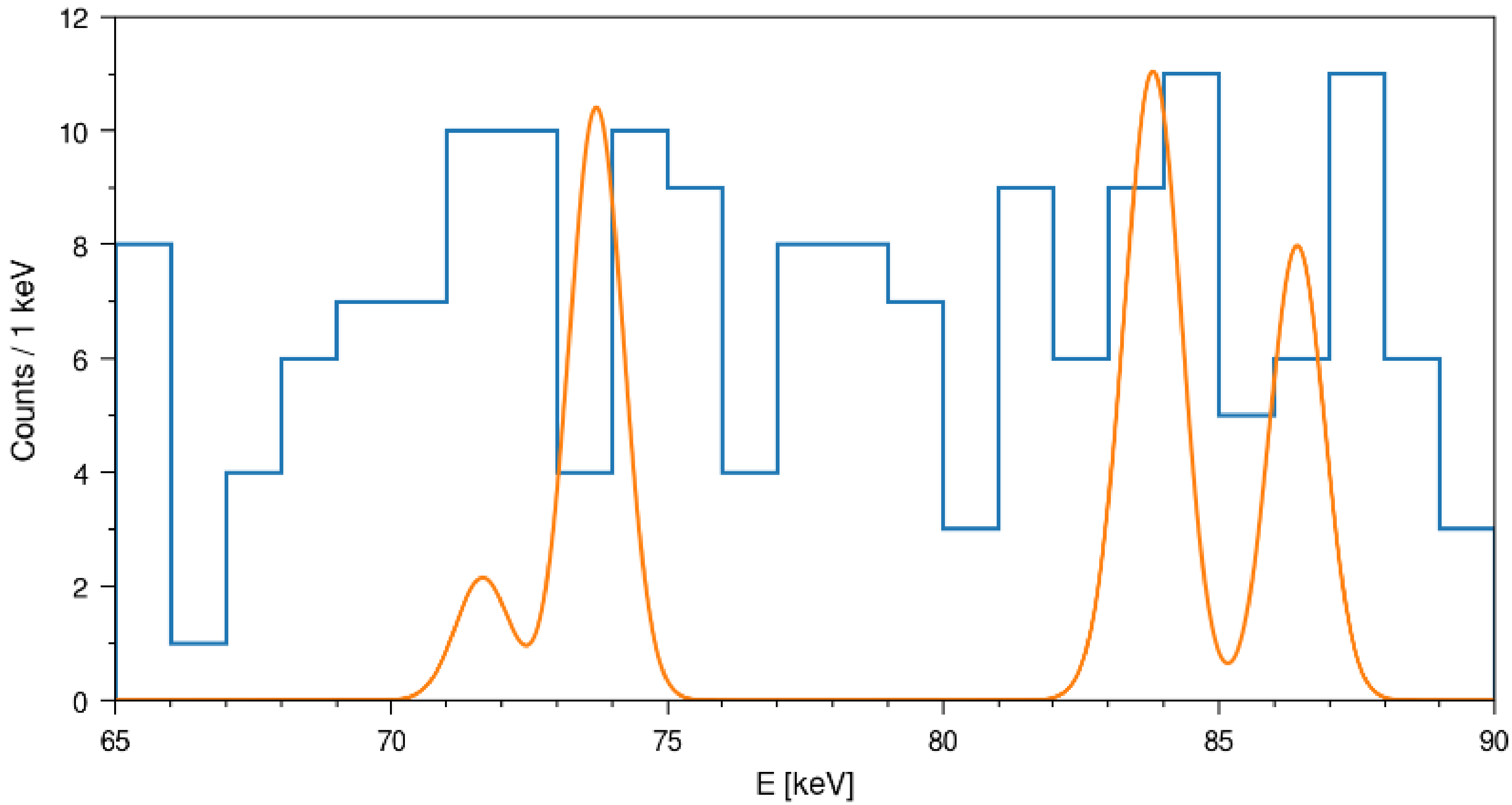


Figure 1. The figure shows the measured X-ray spectrum corresponding to an acquisition time of $\Delta t \approx 6.1 \cdot 10^6$ s in the region of interest. For a comparison, the expected signal distribution (with arbitrary normalization) is also shown in orange for the A_3 analysis and the M_3 parametrization.

PEP violation in quantum gravity

Quantum gravity models can embed PEP violating transitions

PEP is a consequence of the spin statistics theorem based on: Lorentz/Poincaré and CPT symmetries; locality; unitarity and causality. Deeply related to the very same nature of space and time

↓

Non-commutativity of space-time is common to several quantum gravity frameworks (e.g. *k*-Poincarè, θ-Poincarè)

↓

non-commutativity induces a deformation of the Lorentz symmetry and of the locality → naturally encodes the violation of PEP not constrained by MG

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

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

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

A. Addazi, P. Belli, R. Bernabei and A. Marciano, Chin. Phys. C 42 (2018) no.9

Strongest Atomic Physics Bounds on Noncommutative Quantum Gravity Models

Kristian Piscicchia,[2,3] Andrea Addazi,[1,3,*] Antonino Marcianò,[4,3,†] Massimiliano Bazzi,[3] Michael Cargnelli,[5,3] Alberto Clozza,[3] Luca De Paolis,[3] Raffaele Del Grande,[6,3] Carlo Guaraldo,[3] Mihail Antoniu Iliescu,[3] Matthias Laubenstein,[7] Johann Marton,[5,3] Marco Miliucci,[3] Fabrizio Napolitano,[3] Alessio Porcelli,[5,3] Alessandro Scordo,[3] Diana Laura Sirghi,[3,8] Florin Sirghi,[3,8] Oton Vazquez Doce,[3] Johann Zmeskal,[5,3] and Catalina Curceanu[3,8]

The analysis yields stringent bounds on the noncommutativity energy scale, which exclude θ-Poincaré up to 2.6×10^2 Planck scales when the "electriclike" components of the $\theta_{\mu\nu}$ tensor are different from zero, and up to 6.9×10^{-2} Planck scales if they vanish, thus providing the strongest (atomic-transitions) experimental test of the model.

Accepted Paper

Experimental test of noncommutative quantum gravity by VIP-2 Lead

Phys. Rev. D

Kristian Piscicchia, Andrea Addazi, Antonino Marcianò, Massimiliano Bazzi, Michael Cargnelli, Alberto Clozza, Luca De Paolis, Raffaele Del Grande, Carlo Guaraldo, Mihail Antoniu Iliescu, Matthias Laubenstein, Johann Marton, Marco Miliucci, Fabrizio Napolitano, Alessio Porcelli, Alessandro Scordo, Diana Laura Sirghi, Florin Sirghi, Oton Vazquez Doce, Johann Zmeskal, and Catalina Curceanu

Accepted 7 December 2022

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

First Experimental Survey of a Whole Class of Non-Commutative Quantum Gravity Models in the VIP-2 Lead Underground Experiment, *Universe 2023, 9, 32*

$$\delta^2 = c_k \left(\frac{E}{\Lambda'_k} \right)^k = \left(\frac{E}{\Lambda_k} \right)^k ,$$

The case k = 3, introduces a deformation of the space-time and momentum algebra that is appropriate for the "triply special relativity" model and involves a third invariant scale (other than the velocity of light and the Planck energy), associated to the cosmological constant by the authors.

As a consequence, the measurement is very sensitive to high orders in the power series expansion of the Pauli violation probability, which allows to set the first constraint to the "triply special relativity" model proposed by Kowalski-Glikman and Smolin.

The characteristic energy scale of the model is bound to Λ > 5.6 · 10−9 Planck scales**

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

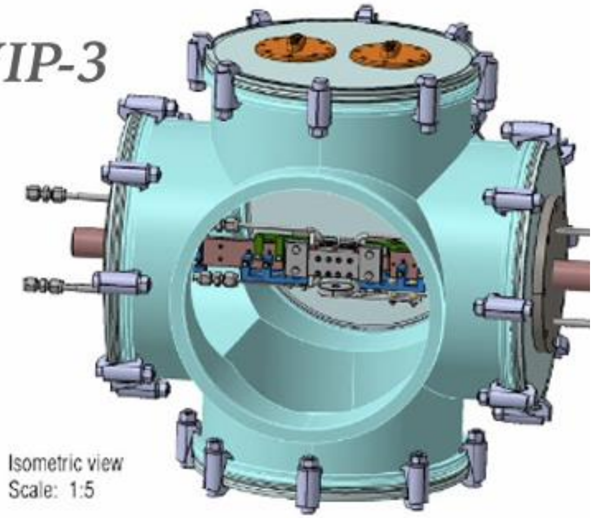
Lev Okun' wrote in his 1987 paper (JETP Lett. 1987 46:11, 529–532) that

"***The special place enjoyed by the Pauli principle in modern theoretical physics does not mean that this principle does not require further and exhaustive experimental tests. On the contrary, it is specifically the fundamental nature of the Pauli principle which would make such tests, over the entire periodic table, of special interest***"

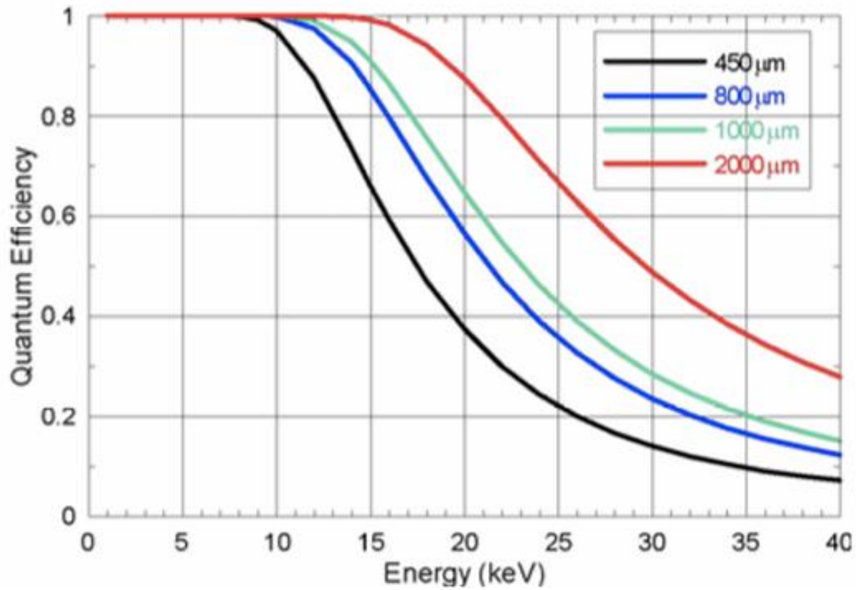
New setup: VIP3 – new SDDs
In preparation
Study PEP violation
Along the periodic table

VIP-2 experimental upgrade: VIP-3

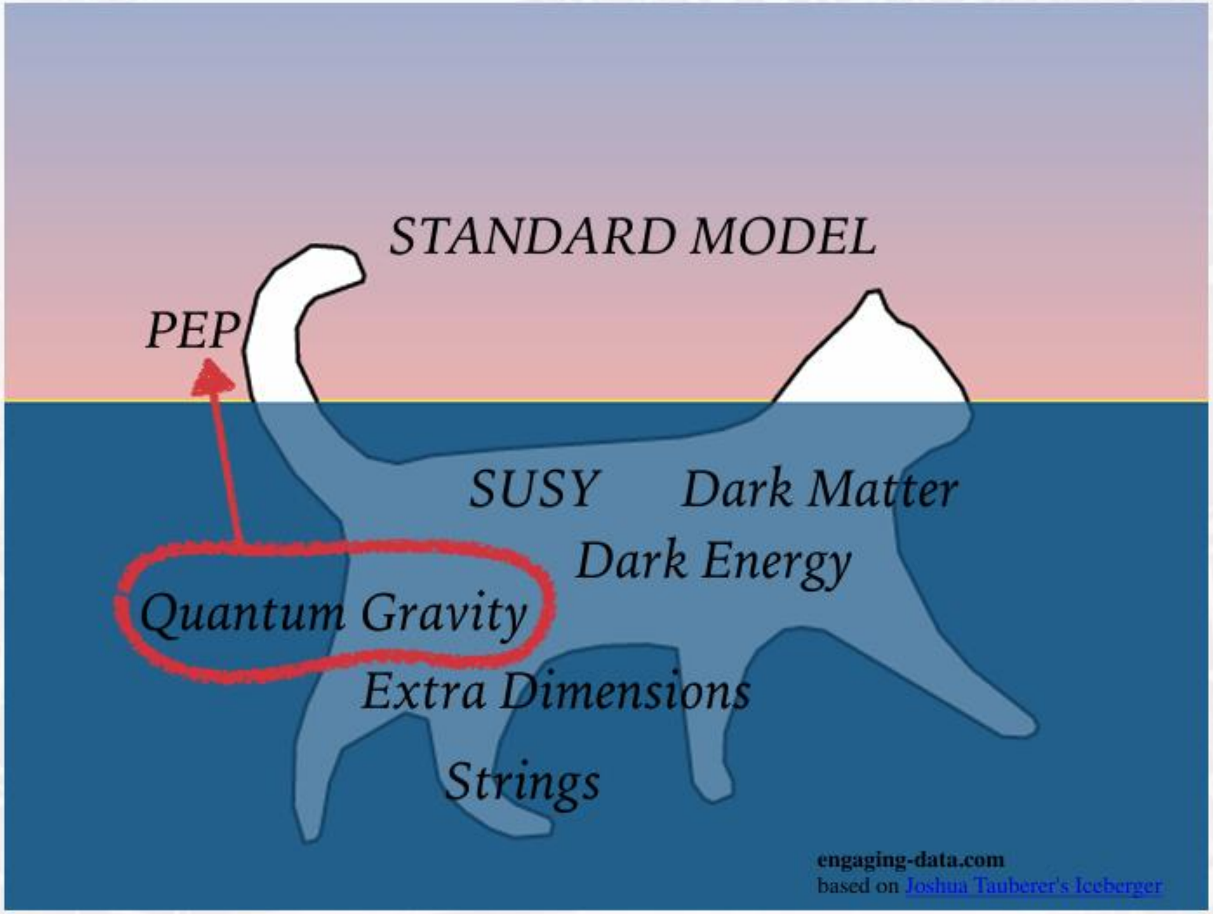
- ***new vacuum chamber,*** *increase the number of SDD detectors, increase the geometrical efficiency, higher current up to* ***400 A***
- *New thermal contact between cold finger and SDDs*
- *New target cooling system*



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



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



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

Conclusions and future plans:

VIP tested the PEP at unprecedented precision for electrons both in open and closed systems

VIP investigated Quantum Gravity models predicting PEP violation – pioneering this type of research

Future plans: VIP-3: test PEP across the periodic table (Ag, Sn, Pd and more)

Develop new theories/models predicting PEP violation, including directionality ones

Extending class of experiments (HPGe detectors)

Any suggestion/idea welcome!

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

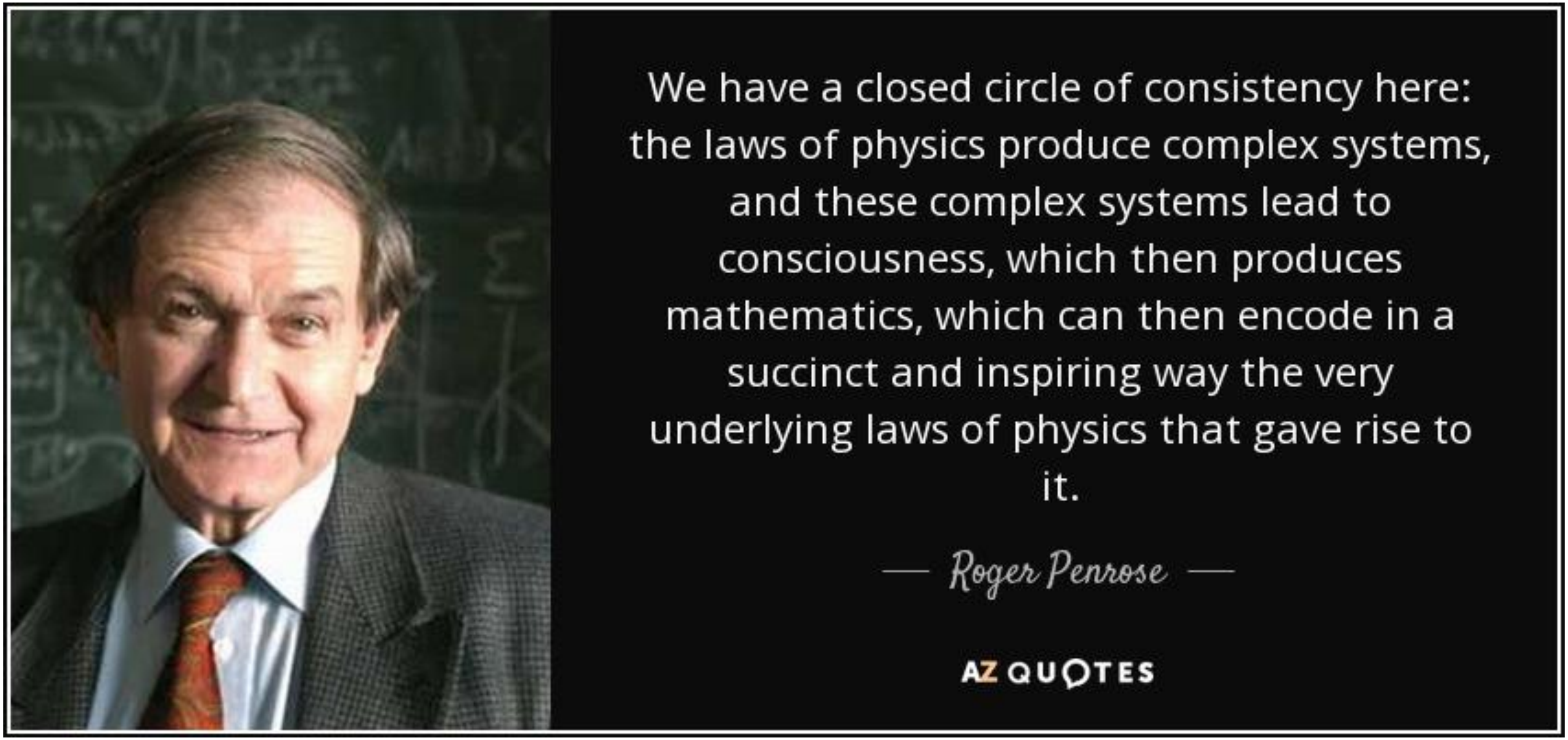
Portrait of a young Pauli at Svein Rosseland's institute in Oslo in the early 1920s, when he was thinking deeply on the applications of quantum mechanics to atomic physics.

We can do many wonderful experiments in our lab

A new era has begun: in the future more and more extremely interesting and fascinating experiments

Many thanks to LNGS and its Management, in particular Ezio Previtali (LNGS Director)

Many thanks to Matthias Laubenstein!



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STRONG 2020

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Foundational Questions Institute