Searching for Signal of Quantum Collapse and Quantum Gravity in the cosmic silence of the Gran Sasso Underground Laboratories

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Centro Ricerche Enrico Fermi, LNF (INFN)

on behalf of the VIP collaboration

High Precision X-ray measurements 2025

16-20 June 2025, LNF, (INFN) (Italy)

CENTRO RICERCHE ENRICO FERMI

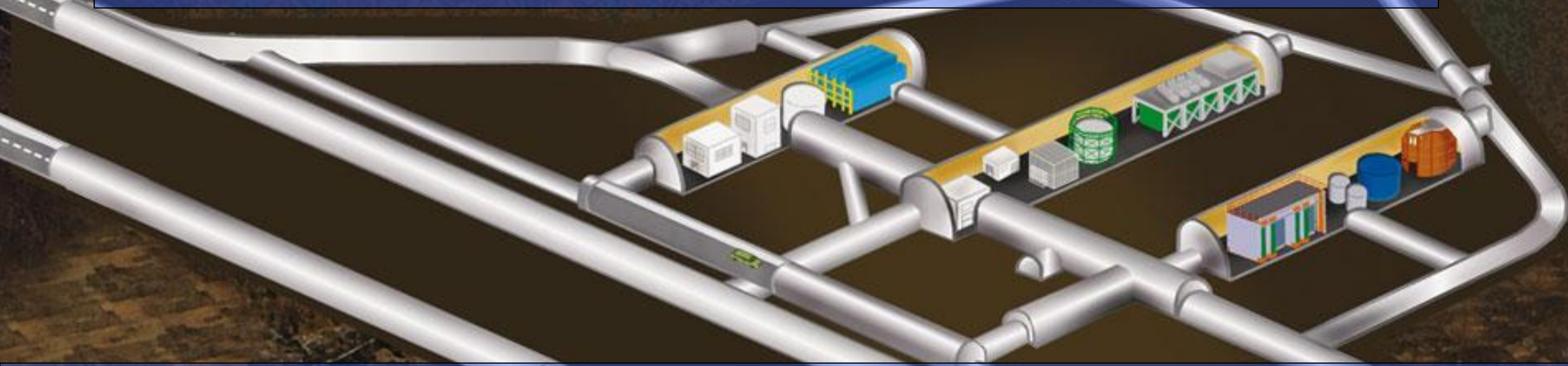
INFN LNF Istituto Nazionale di Fisica Nucleare

JOHN TEMPLETON FOUNDATION Inspiring Awe & Wonder

VIP is testing:

- Fundamental Symmetries through - Atomic transitions tests of the Pauli Exclusion Principle Violation

- Collapse Models - looking for spontaneous radiation

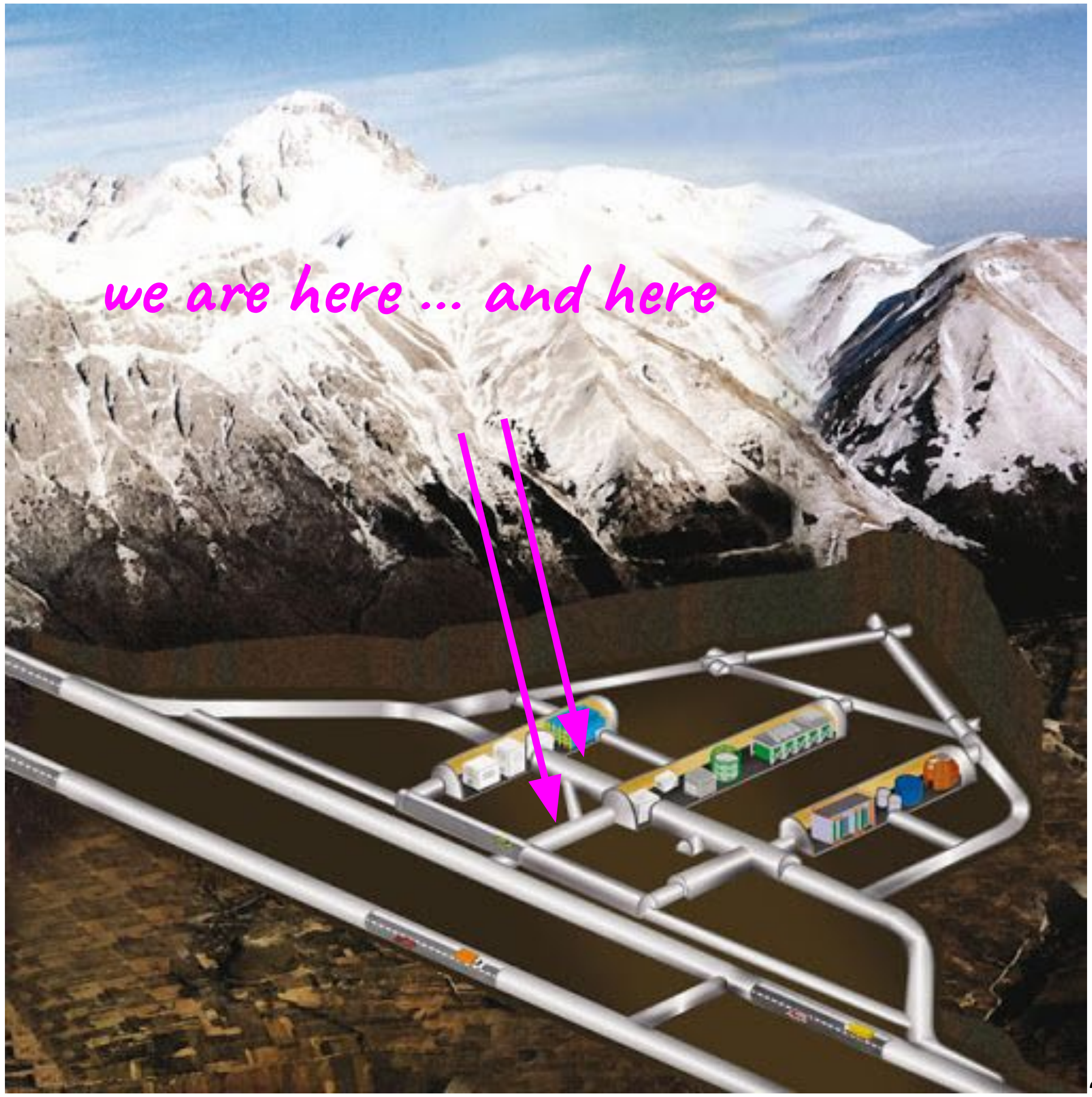


Underlying relation between Quantum and Gravity

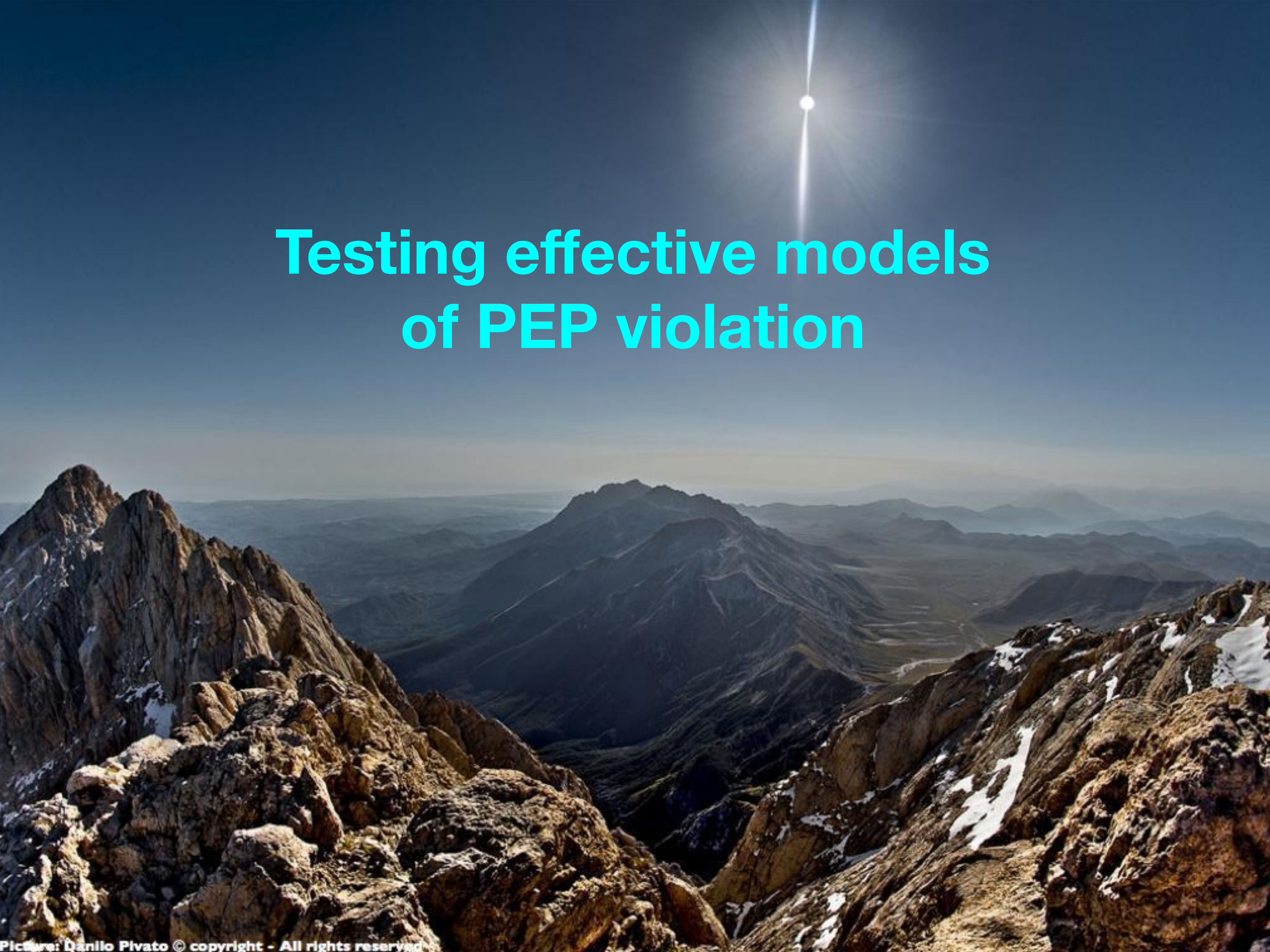
Where? At The LNGS

The experiments are performed in the low-background environment of the underground Gran Sasso National Laboratory of INFN:

- overburden corresponding to a minimum thickness of 3100 m w.e.
- the muon flux is reduced by almost six orders of magnitude, n flux of three oom.
- the main background source consists of γ-radiation produced by long-lived γ-emitting primordial isotopes and their decay products.



Testing effective models of PEP violation



The VIP experiments - PEPV in Quon

Pauli Exclusion Principle (PEP) is a direct consequence of the **Spin-Statistics** Th.

which is fundamentally grounded on:

Lorentz and **CPT symmetries**

PEP tests -> **high sensitivity tests of the Standard Model** pillars

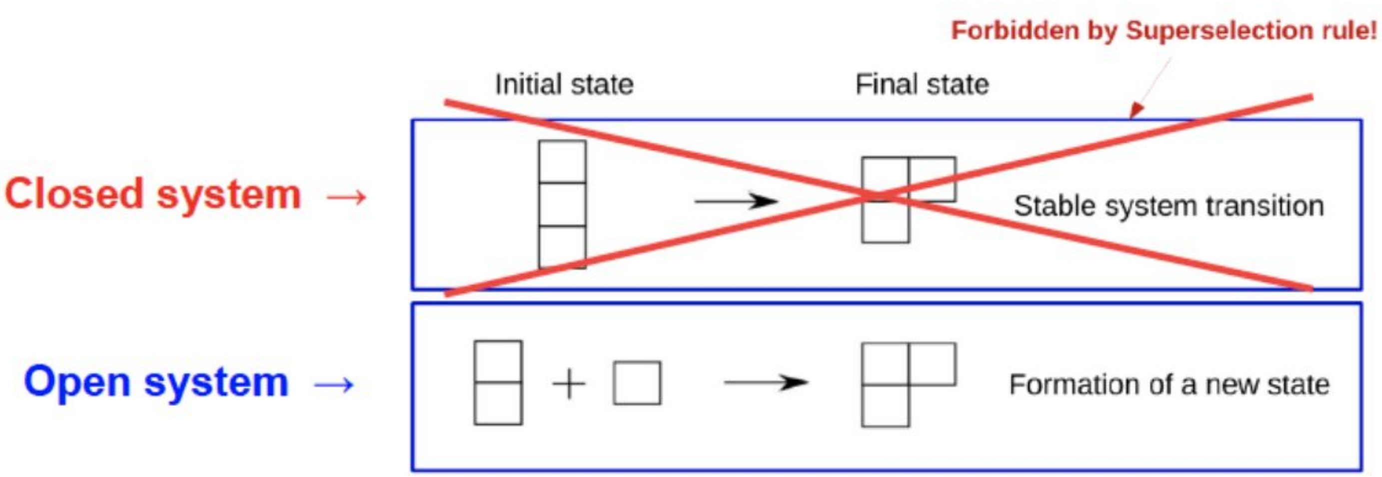
Local QFT - Greenberg & Mohapatra (Quon Model), Ignatiev, Kuzmin, Rahal, Campa…

$$a_k a_l^\dagger - q a_l^\dagger a_k = \delta_{k,l}$$

are subjected to **M-G superselection rule: transition probability between two symmetry states is zero**

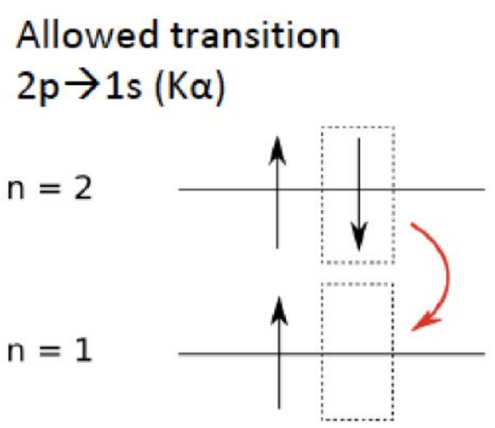
↓

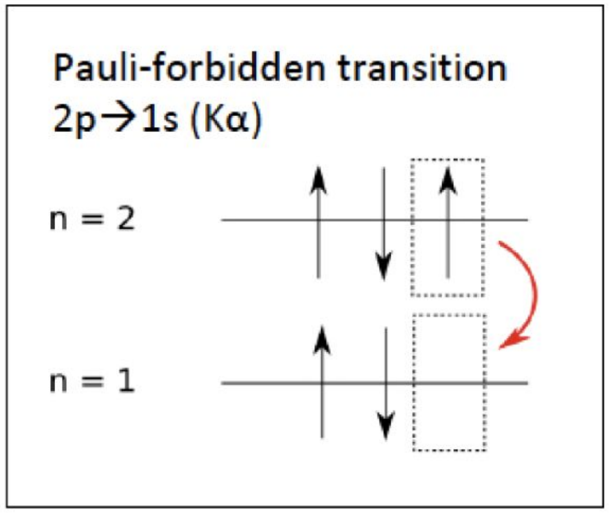
introduce new fermions (current) in a pre-existing identical fermion system and check for PEP-violating atomic transitions **VIP-2 Open Systems**

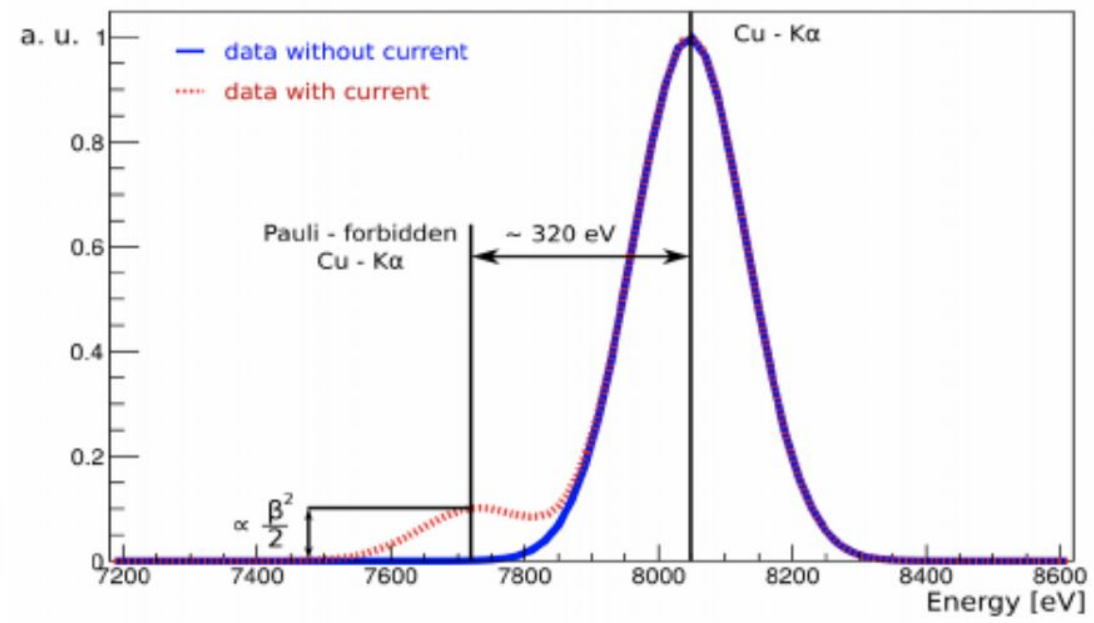


Experimental signature of a PEPV transition

In both VIP Open & Closed Systems we search for electrons transitions to the fundamental level, already filled by 2 electrons, e.g. in Cu target:







~ 8.05 keV in Cu

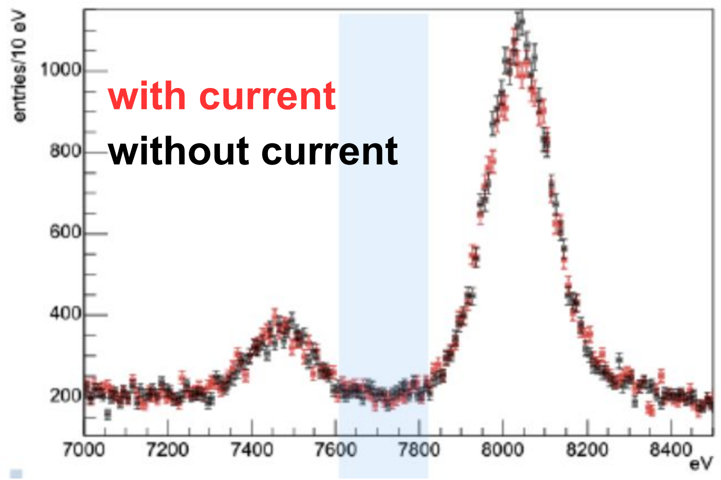
~ 7.7 keV in Cu

Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

Multiconfiguration Dirac-Fock approach

Accounts for the shielding of the two inner electrons

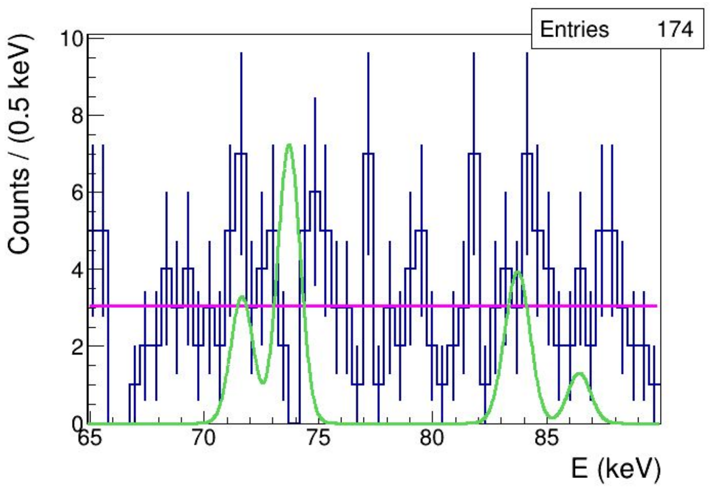
Background in VIP-2 Open Systems : provided by data acquisition without current



$t^{wc} = 27110263 \text{ s} = 314 \text{ days}$

$t^{woc} = 26916404 \text{ s} = 311 \text{ days}$

Background in VIP-2 Closed Systems : accurate characterization of the detector



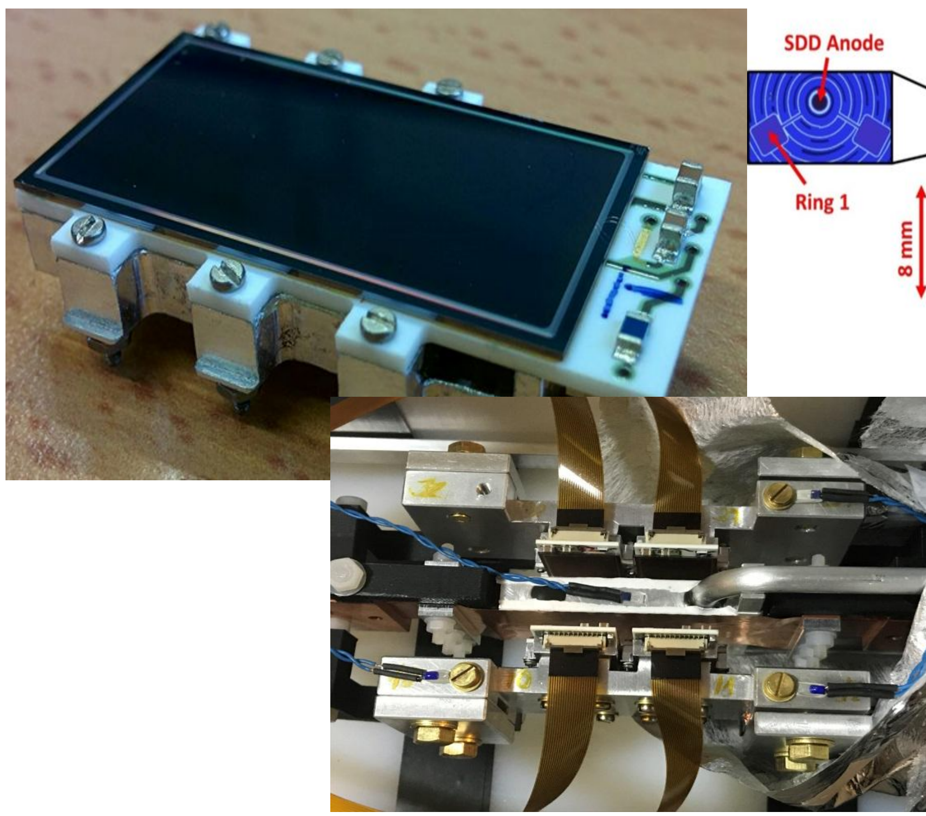
acquisition time

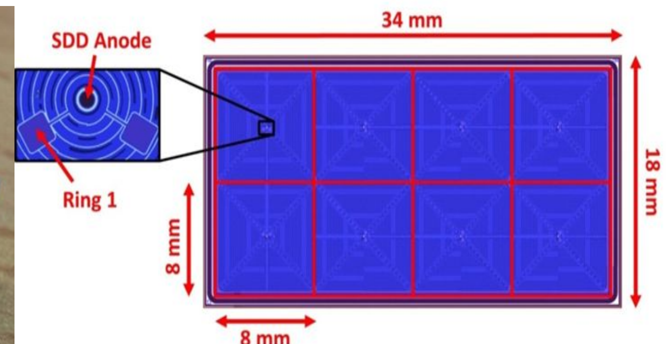
6.1×10^6 s 70 ~ d

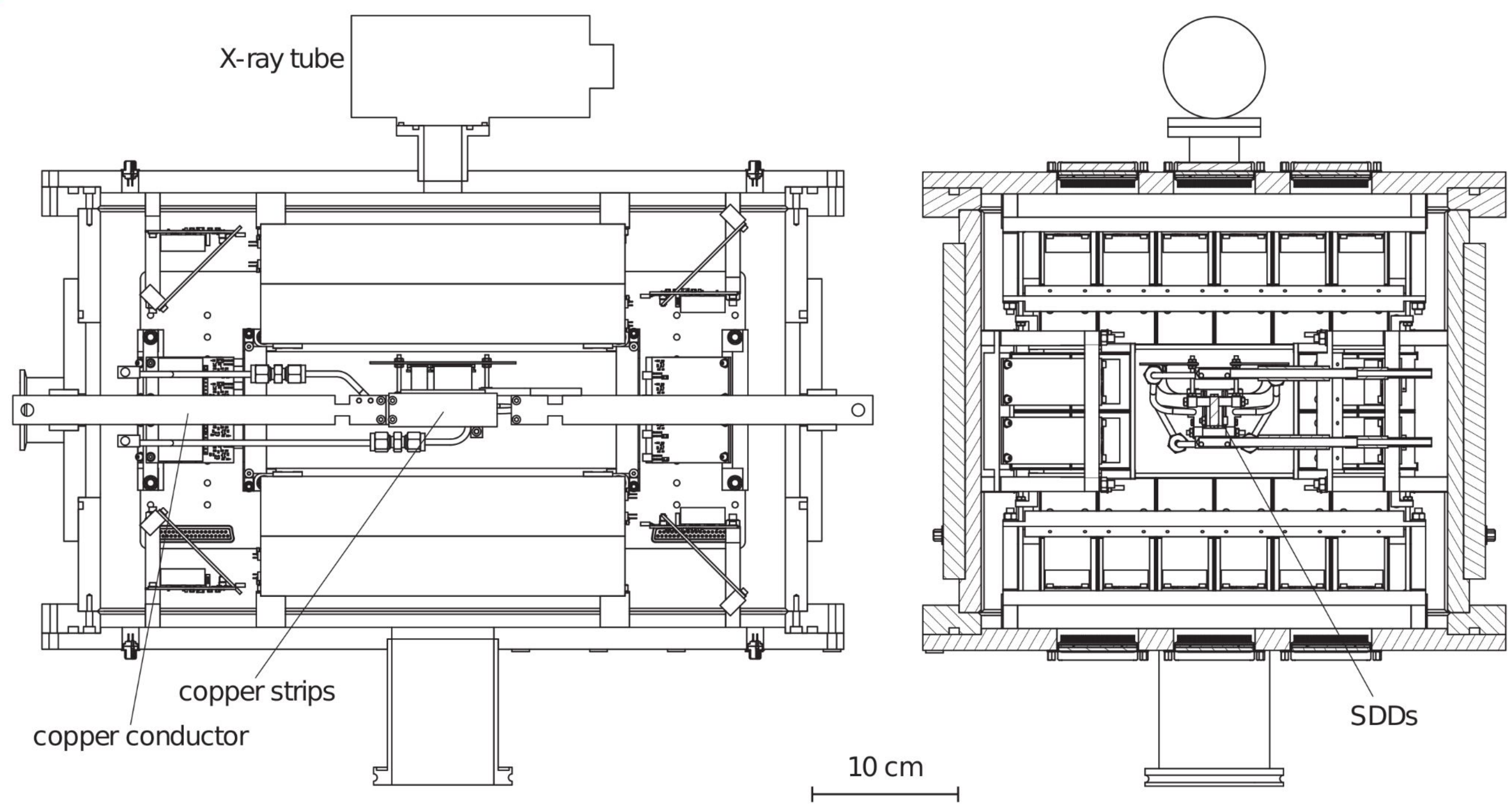
VIP-2 Open Systems - present status and results

VIP-2 Open Systems -

- SDD detectors 450µm thick (resolution 190 eV FWHM at 8 keV)
- 4 arrays of 2x4 SDDs, liquid Argon closed circuit cooling
- 2 strip shaped Cu targets (cooled by closed chiller circuit -> with 200A (peak) circulating current ~1 °K heating in the SDDs)







Statistical model

The statistical model accounts for uncertainties on the parameters of the signal and background shapes, and scale factor of the current on/off spectra:

- **the two spectra are simultaneously analysed by constructing the joint likelihood:**

$$\mathcal{L} = \mathrm{Poiss}(Data^{wc}|\mathrm{f}^{wc}(\boldsymbol{\theta})) \times \mathrm{Poiss}(Data^{woc}|\mathrm{f}^{woc}(\boldsymbol{\theta}) \times \mathrm{SCALE})$$

$$\mathrm{f}^{wc}(\boldsymbol{\theta}) = yield_{Ni} * Ni(\theta_{1,2}) + yield_{Cu} * Cu(\theta_{3,4}) + yield_{pol1} * pol_1(\theta_5) + yield_{PEPV} * PEPV(\theta_4)$$

$$\mathrm{f}^{woc}(\boldsymbol{\theta}) = (yield_{Ni} * Ni(\theta_{1,2}) + yield_{Cu} * Cu(\theta_{3,4}) + yield_{pol1} * pol_1(\theta_5))$$

where $\boldsymbol{\theta}$ is the vector of parameters of the signal and bkg shapes

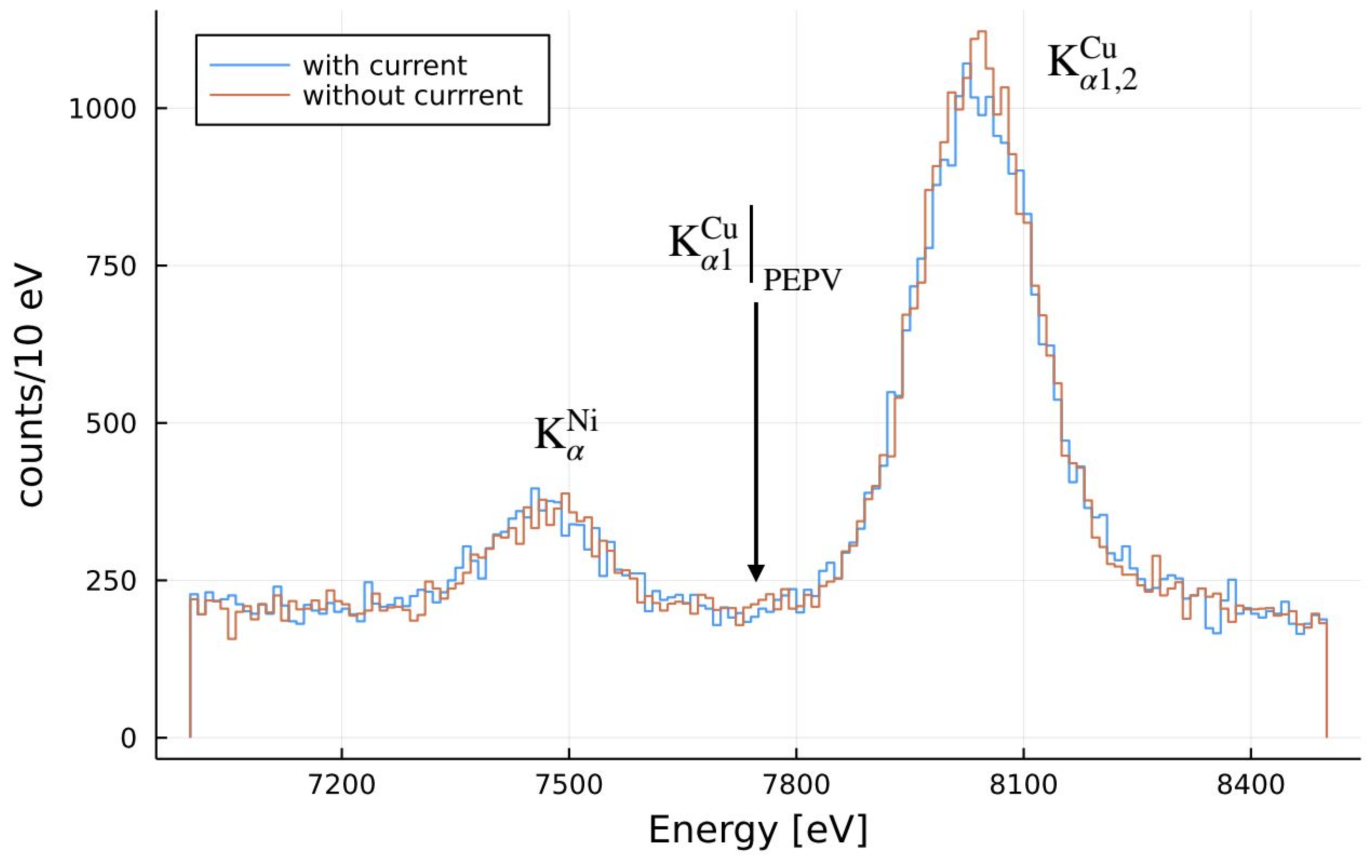
- **The posterior *pdf* is obtained based on the Bayes theorem:**

$$P(S, B, \mathrm{s}, \theta_S, \theta_B|\mathrm{data}_{wc}, \mathrm{data}_{woc}) = \frac{\mathcal{L}}{N} P_0(S) \cdot P_0(B) \cdot P_0(\mathrm{s}) \cdot P_0(\theta_S) \cdot P_0(\theta_B)$$

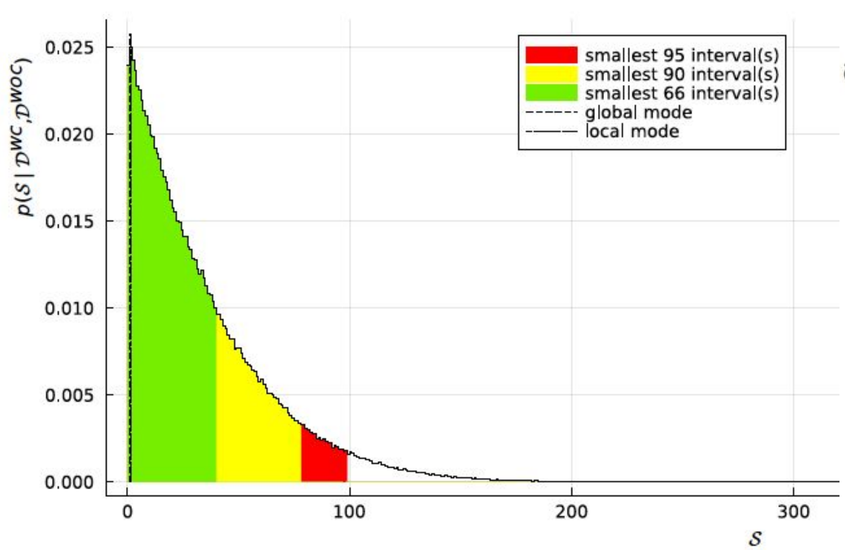
SCALE has a gaussian prior at t_{wc} / t_{woc}

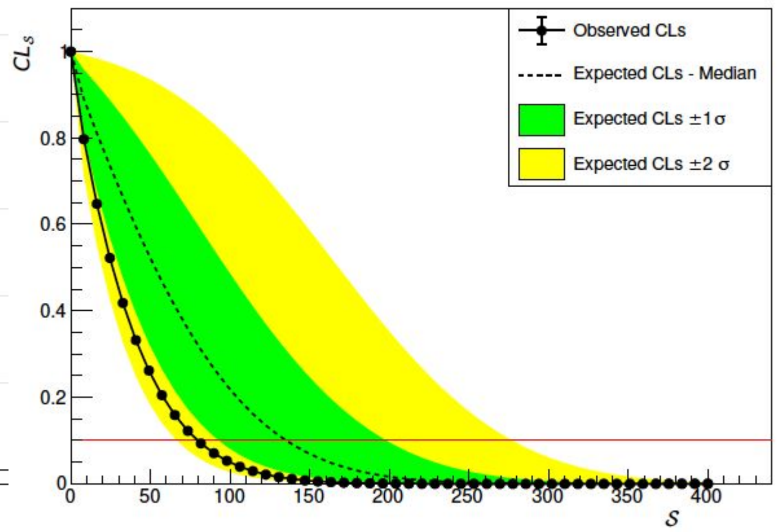
SHAPE par. - have flat priors, except gaussians for transitions positions and *B*

VIP-2 Open Systems



Bayesian analysis validated by means of frequentist CLs exclusion method, exploiting Neyman construction for a robust evaluation of the CLs.
STORGEST BOUND on PEPV probablity for QUON:





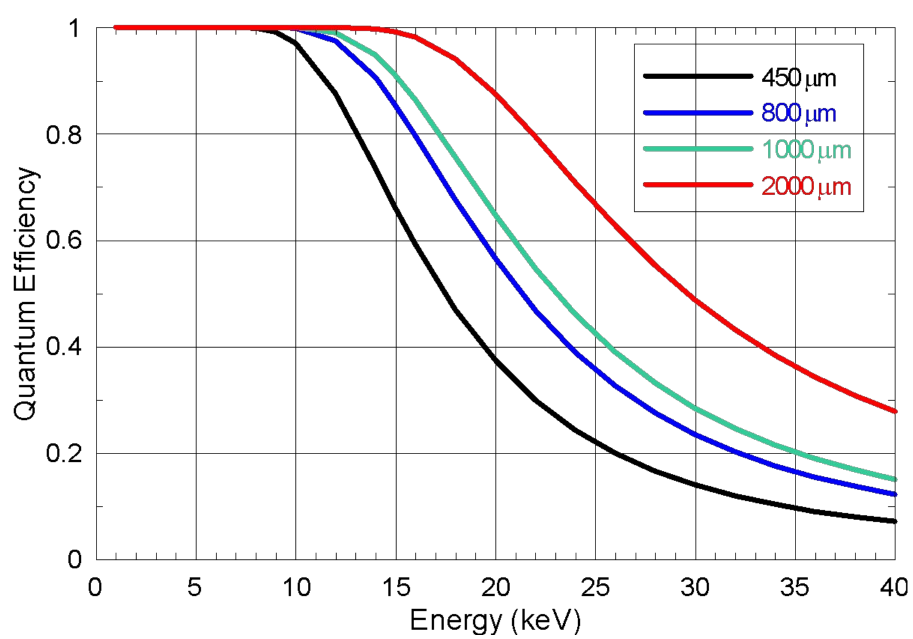
$$\beta^2/2 < 3.1 \cdot 10^{-31}$$

90% CL

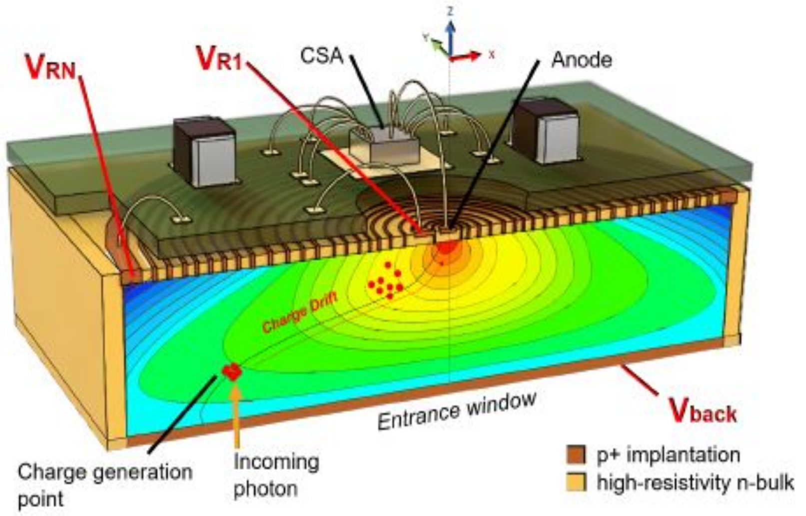
VIP-3 : scanning β^2 over the periodic table

Okun, L.:
“it is specifically the fundamental nature of the Pauli principle which would make such tests, over the entire periodic table, of special interest”
Possible violation of the Pauli principle in atoms. JETP Lett. 1987, 46, 529532

see also K. P. et al., *Universe* 2023, *9*(7), 321



New avantgarde 1mm thick detectors in coll. with FBK (Trento) and PoliMi



Improved quantum efficiency + double active area ~ 41 cm^2 -> increased geometrical efficiency =

scan of β^2 with comparable sensitivity to VIP-2 for zirconium, silver, tin (Z $\in$ 40-50)

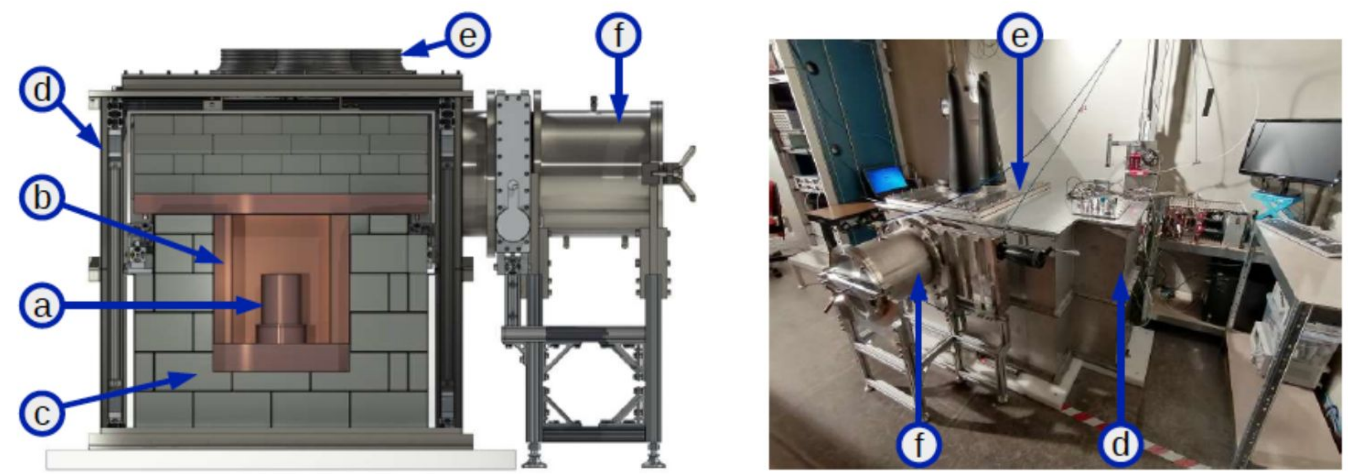
installation late 2025 (*Entropy* 26 (2024) 9, 752)

search for PEP violation with GATOR

THE GOAL:
measurement of $\beta^2/2$ in Pb (Z = 82) respecting MG superselection (*Found.Phys. 42 (2012)*), at energies not accessible with SDD detectors

Transitions in Pb	allow. (keV)	forb. (keV)
1s - $2p_{3/2}$ $K_{\alpha1}$	74.961	73.713
1s - $2p_{1/2}$ $K_{\alpha2}$	72.798	71.652
1s - $3p_{3/2}$ $K_{\beta1}$	84.939	83.856
1s - $4p_{1/2(3/2)}$ $K_{\beta2}$	87.320	86.418
1s - $3p_{1/2}$ $K_{\beta3}$	84.450	83.385

using the GATOR facility: high-performance low-background germanium spectrometer.



(a) HPGe detector inside Cu-OFE cryostat (cooled with LN_2 via copper coldfinger), **(b)** OFHC Cu cavity, **(c)** lead shield, polyethylene sheet, **(d)** airtight stainless steel enclosure (purged with GN_2), **(e)** glove ports, **(f)** sample load lock

Analysis of the data collected during 2023 (41 days with a circulating current of 40 A and 56 days without current):

Eur. Phys. J. C (2024) 84: 1137:

$$\beta^2/2 < 4.8 \cdot 10^{-29}$$

with probability 0.9, 1 O.M. IMPROVEMENT

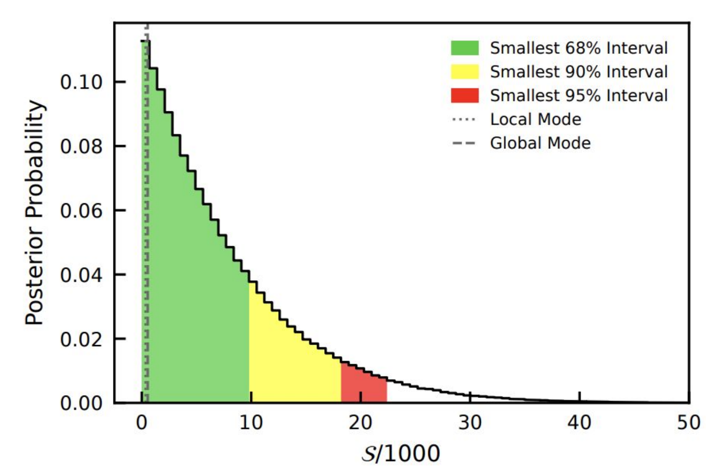
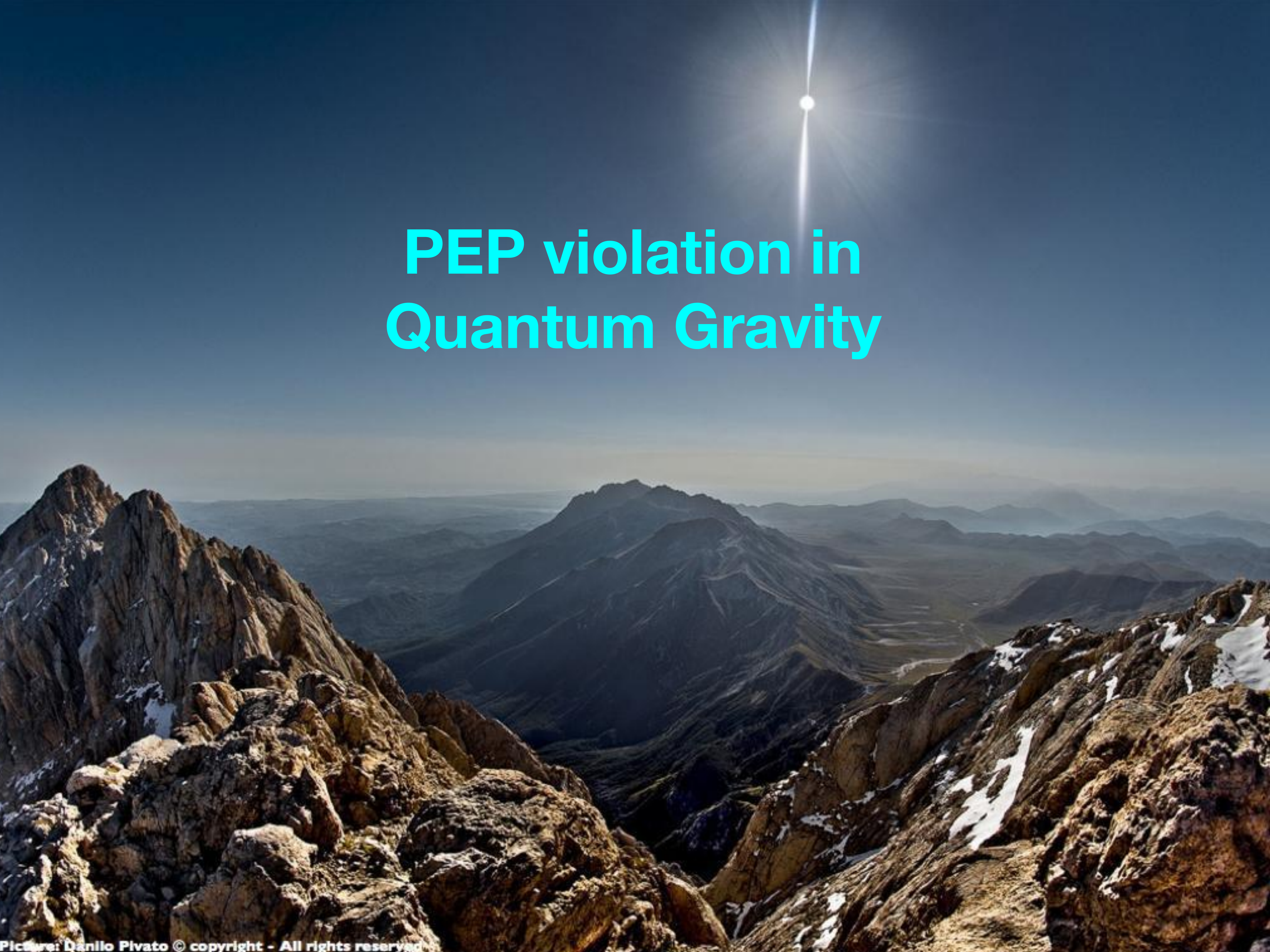


Fig. 5 Marginalized posterior distribution of the parameter of interest $\mathscr{S}/1000$, obtained from the Bayesian analysis. The 90 % upper limit is indicated by the yellow band.

PEP violation in Quantum Gravity



PEP violation in quantum gravity

Non-commutativity of S-T:

- in quantum mechanics (relatively large-scales/low-energies) phase space is a smooth manifold.
- On distances of the order of ℓ_P this breaks down, Heisenberg uncertainty + GR -> black hole formation -> the smooth manifold structure is lost.
- The notion of a point becomes meaningless and the simple commutation relation between space-time points is no longer expected to hold (first suggested by Snyder (1947) and Heisenberg (1954).

Non-commutative Quantum Gravity, GUP, CPT deformation … - Bosso, Illuminati, Petruzziello, Marcianò, Addazzi, Balachandran, Mavromatos …

- Messiah-Greenberg superselection rule is violated
- PEP violation probability: *a)* depends on the transition energy *b)* depends on the energy scale of new-physics emergence *c)* is subject to not isotropic corrections

↓

VIP-2 Closed Systems - High Purity Ge detectors, set of ultra-radiopure targets to check $\delta^2(E)$ with a systematic scan over Z.

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

$\downarrow$

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

$\downarrow$

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

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, A. Marcianò *Int.J.Mod.Phys.A* 35 (2020) 32, 204200

Closed Systems experimental apparatus

High Purity Ge detector based setup:

- high purity co-axial p-type germanium detector (HPGe), diameter of 8.0 cm, length of 8.0 cm, surrounded by an inactive layer of lithium-doped germanium of 0.075 mm.
- The target material is composed of three cylindrical sections of radio-pure Roman lead, completely surrounding the detector.

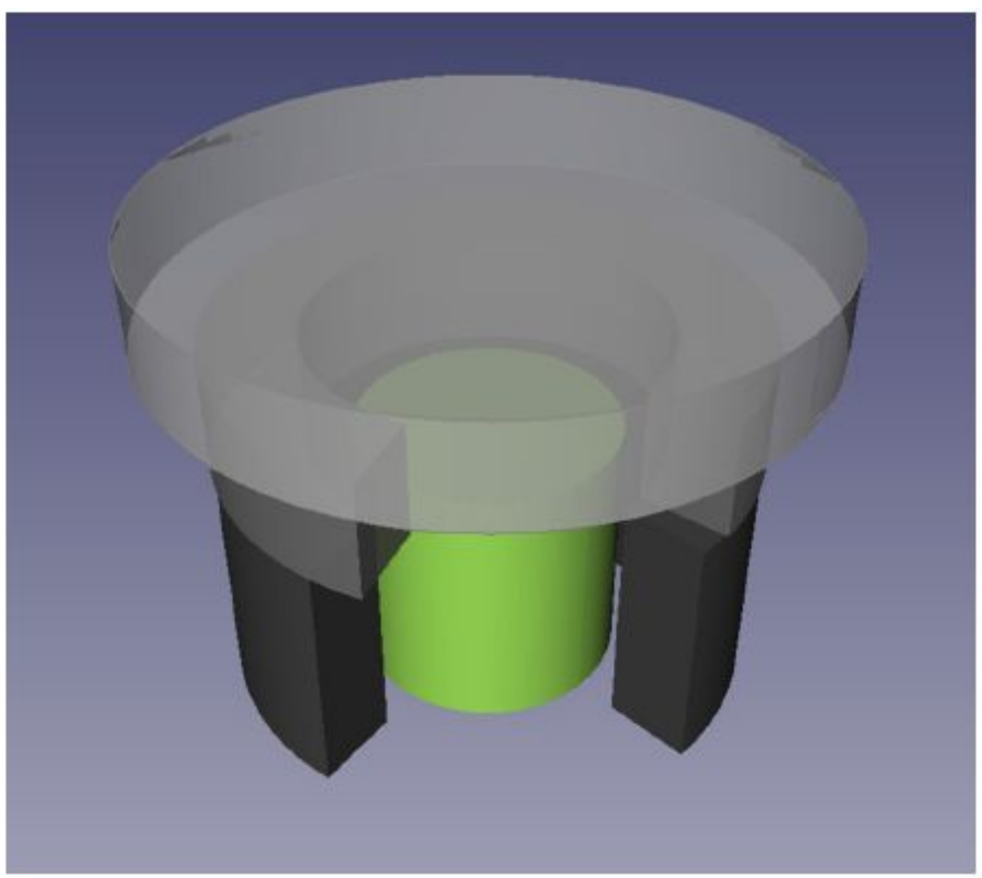


Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

- Passive shielding: inner - electrolytic copper, outer - lead

- 10B-polyethylene plates reduce the neutron flux towards the detector

- shield + cryostat enclosed in air tight steel housing flushed with nitrogen to avoid contact with external air (and thus radon).

- Acquisition time $\Delta t \approx 70d \approx 6.1\ 10^6 s$

K. P. et al., Eur. Phys. J. C (2020) 80: 508
https://doi.org/10.1140/epjc/s10052-020-8040-5

Parametrization

- Analytic expansion of the PEP violation prob. :

$$\delta^2(E) = c_k \left(\frac{E}{\Lambda_{NC}^{(k)}}\right)^{k} + \mathcal{O}\left(\frac{E}{\Lambda_{NC}^{(k)}}\right)^{k+1}$$

Diffenent ***k*** represent different models

- *k* = 1 corresponds to *k*-Poincaré. Different quantization procedures lead to different predictions:

- **Arzano-Marcianò procedure - PEP violation is suppressed with a probability proportional to $\delta^2 = E / \Lambda$**
- **Freidel-Kowalski-Glikman-Nowak procedure - PEP violation is missing.**

So experimental investigation of statistics violations provides important down-top indications on the “right" quantization procedure: the AM *k*-Poincaré field’s quantization model is ruled out.

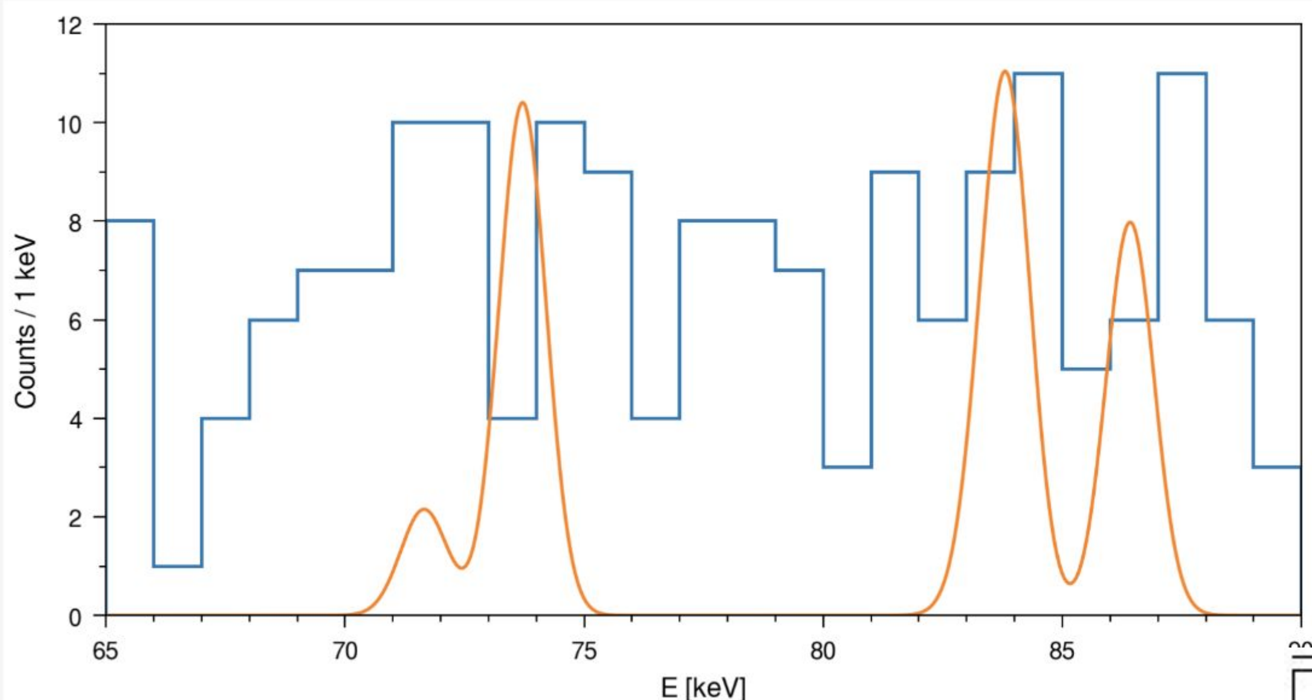
- *k* = 2 corresponds to *θ*-Poincaré: excluded up to $\Lambda > 1.6\ 10^{-1}$ Planck scales

- *k* = 3 corresponds to “triply special relativity” model by Kowalski-Glikman–Smolin (KS). First measurement ever, excluded up to $\Lambda > 5.6\ 10^{-9}$ Planck scales -> experimental guidance towards future developments of the model with two invariant energy scales accounting for the deformation of the (non-commutative) space-time symmetries.

Generalized analysis

- The normalised signal shape for the M_3 parametrization:

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.



- The sensitivity on Λ increases with E -> the analysis is repeated by searching for PEP violation signal in Kα, Kβ and Kα + Kβ transitions.

A_i, M_k	$\bar{S}$	lower limit on Λ in unit of Planck scale
A_1, $k=1$	11.4913	$3.1 \cdot 10^{21}$
A_1, $k=2$	11.3776	$1.4 \cdot 10^{-1}$
A_1, $k=3$	11.2610	$4.9 \cdot 10^{-9}$
A_2, $k=1$	15.1408	$2.8 \cdot 10^{21}$
A_2, $k=2$	15.1640	$1.4 \cdot 10^{-1}$
A_2, $k=3$	15.1859	$5.1 \cdot 10^{-9}$
A_3, $k=1$	18.7270	$4.2 \cdot 10^{21}$
A_3, $k=2$	19.1847	$1.6 \cdot 10^{-1}$
A_3, $k=3$	19.5993	$5.6 \cdot 10^{-9}$

K. P. et al., PRL 129, 131301 (2022)

K. P. et al., PRD 107, 026002 (2023)

KP et al., Universe 2023, 9(7), 321

Preliminary analysis on PEPV in Generalized Uncertainty Principle models

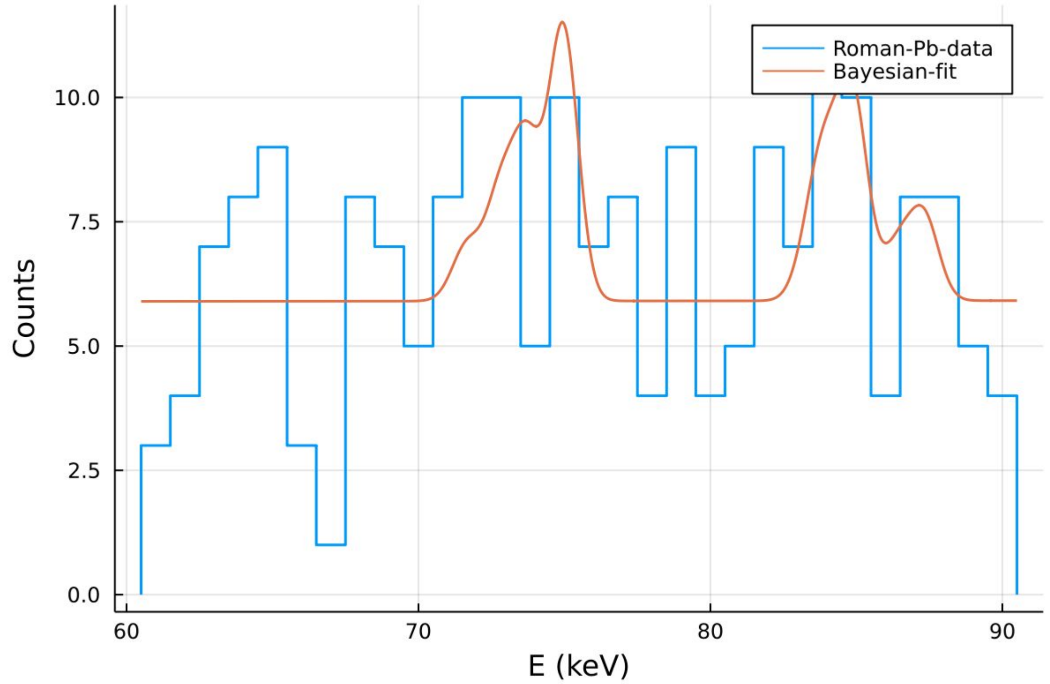
Several QG candidates predict the existence of a **minimal length** on the order of the Planck scale -> deformation of the Heisenberg uncertainty principle: $\delta x\,\delta p \geq \frac{\hbar}{2}\left(1+\beta\,\delta p^2\right)$

E.g. GUP structure emerges from **string theory** in the high energy limit.

The construction of field theories in this context implies **deformations of the statistics:**
Theory already developed by Bosso, Petruzziello, Illuminati

PEP atomic tests suitable to investigate GUP models. **FIRST STUDY EVER!**

Violation of the PEP depends on the energy and on Λ_{GUP} as $\boxed{\delta^2(E,\beta) = \frac{m\,\Delta E}{\Lambda_{GUP}^2}}$



Preliminary result!

$\Lambda_{GUP} > 0.52$ **Planck scales**

Preliminary analysis on PEPV in Generalized Uncertainty Principle models

PHYSICS	β in Λ_{Pl}^2 *units*
PEPV preliminary result!	$< \mathbf{3.7}$
Macroscopic harmonic oscillator	$< 5\times10^6$
Broadening times of large molecular wave-packets	$< 10^{12}$
Violation of the equivalence principle	$< 10^{21}$
Lack of deviations from the standard model at the electroweak scale	$\ll 10^{34}$
Harmonic oscillator (charmonium, J/ψ shift energy)	$< 10^{34}$
Lamb shift	$< 10^{36}$
Gravitational waves	$< 10^{36}$
First Landau level through scanning tunnel microscope	$< 10^{50}$
Black holes deformation	$< 10^{69}$

Future perspectives

Improve the limit on Λ_{NC}

- *Improve on efficiency* → use Ge as active material
- BEGe + Pulse Shape analysis → rejection of electronic noise, disentangle multi vs single hits events (photons from Ge vs photons from outside)

***see e.g. K.P. et al, Condens.Mat.* 9 (2024) 2, 22**

Introduce tests of directionality

$$[x_i, x_j] = i\frac{C_{ij}}{\Lambda_{NC}^2}$$

Λ_{NC}: Number of PEPV transitions

C_{ij}: Photon's angular distribution

- Better characterization of the NCST
- Ongoing work on both theoretical and experimental side

High sensitivity X-ray measurements

to characterize the spontaneous collapse mechanism

Collapse theories

- Why the quantum properties (superposition) do not carry over to the macro-world?
- Stochastic and non-linear modifications of the Schroedinger dynamics -> spontaneous collapse: progressive reduction of the superposition, proportional to the increase of the mass of the system
  (Penrose, Diosi, Ghirardi, Rimini, Weber, Pearle, Adler, Karojhazi, Lukacs, Milburn, Bassi ...) the two most studied models:

Continuous Spontaneous Localization (CSL) & Diosi-Penrose (DP)

STRONG CONNECTION WITH QG:

Spontaneous decoherence induced by space-time uncertainty

&

Irreversibility in Quantum Gravity/Cosmology at the Planck scale

lead to the same structure of master equations

L. Diosi (2023) J. Phys.: Conf. Ser. 2533 012005)

Physical Review X, 13(4):041040, 2023, J. Phys. A, 57:395303, 2024, Nat. Comm. 12, 4449 (2021)

this spectacular connection points toward a potential reconciliation between quantum mechanics and gravity

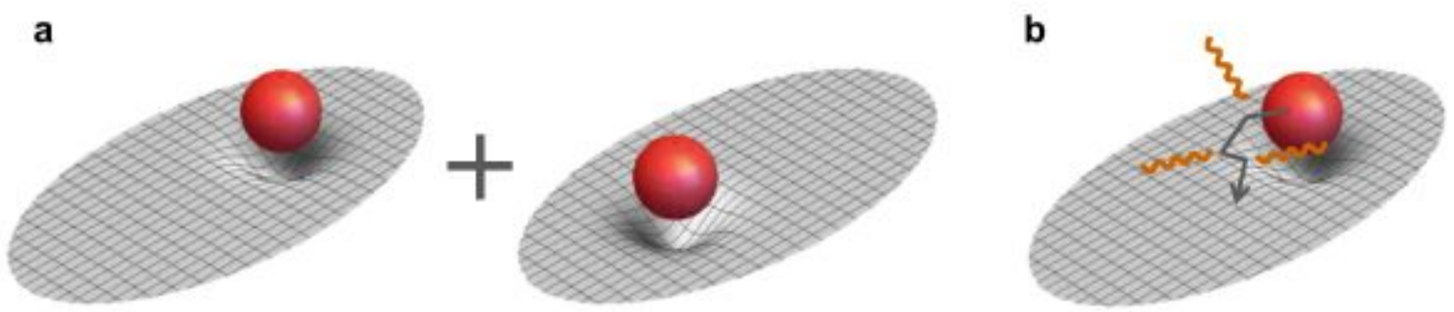
can be tested with VIP

Radiation measurements to test the collapse

- Unavoidable side effect of the stochastic collapse dynamics:

a Brownian-like diffusion of the system in space Phys. Rev. Lett. 130, 230202 (2023).

Collapse probability is Poissonian in t -> Lindblad dynamics for the statistical operator -> free particle average square momentum increases in time.



- Then charged particles emit spontaneous radiation. We search for spontaneous radiation emission from a germanium crystal and the surrounding materials in the experimental apparatus.

Strategy: simulate the background from all the known emission processes -> perform a Bayesian comparison of the residual spectrum with the theoretical prediction -> extract the pdf of the model parameters -> bound the parameters.

Spontaneous emission in the γ-rays regime

- *CSL - s. e. photons rate:*

$$\left.\frac{d\Gamma}{dE}\right|_t^{CSL} = \frac{\hbar\,\lambda}{4\,\pi^2\,\epsilon_0\,c^3\,r_C^2\,m_0^2\,E}\,(N_p^2 + Ne)$$

- *DP - s. e. photons rate:*

$$\left.\frac{d\Gamma}{dE}\right|_t^{DP} = \frac{G}{12\pi^{3/2}\epsilon_0 c^3 R_0^3 E}\,\{N_p^2 + N_e\}$$

the photon w.l. λ_γ is intermediate between the nuclear dimension and the lower atomic orbit radius -> protons emit coherently, electrons emit independently

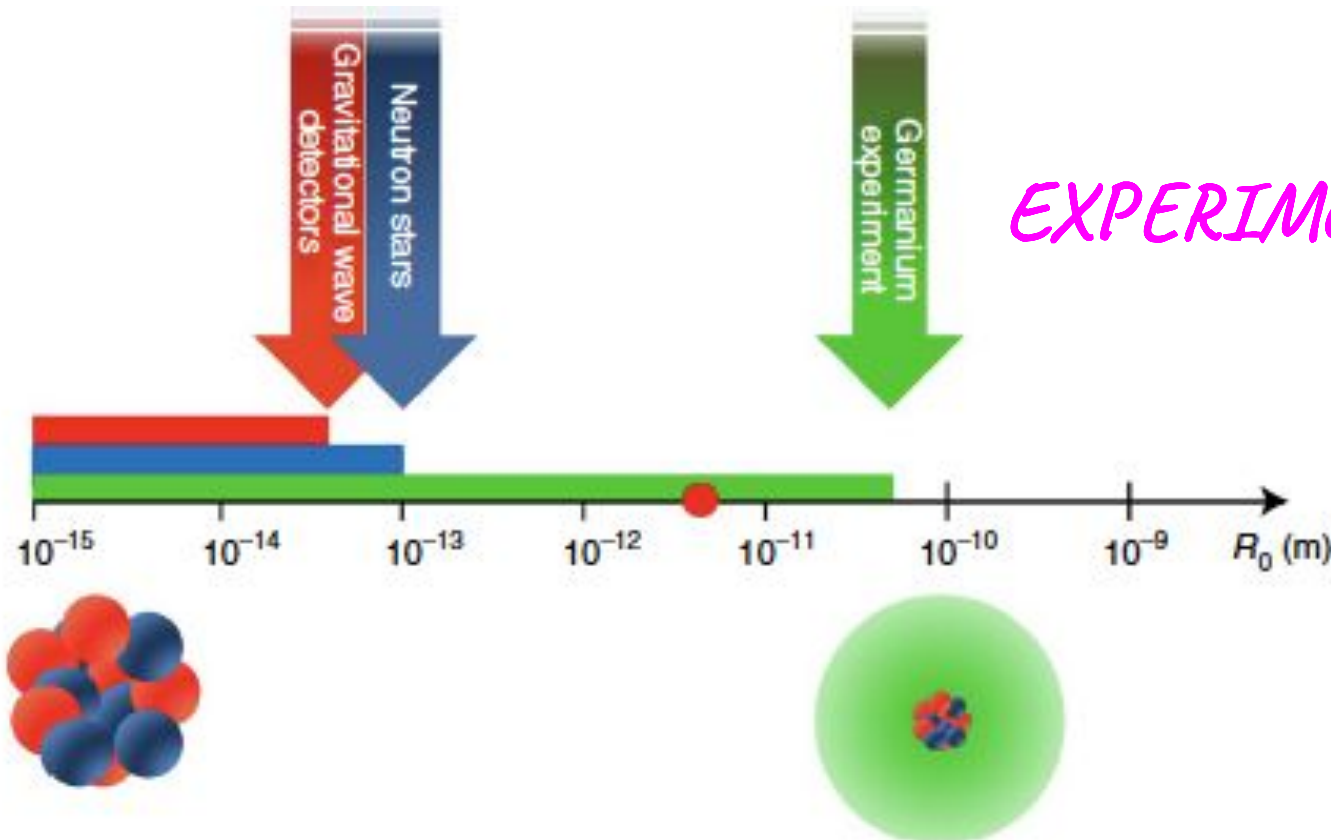
λ - *collapse strength*

r_C - *correlation length*

see e. g. S. L. Adler, JPA 40, (2007) 2935, Adler, S.L.; Bassi, A.; Donadi, S., JPA 46, (2013) 245304.

R_0 - *size of the particle mass density. See e.g. Diósi, L. J. Phys. Conf. Ser. 442, 012001 (2013)., Penrose, R. Found. Phys. 44, 557–575 (2014).*

Lower bound on R_0



EXPERIMENTAL : $R_0 > 0.54 \cdot 10^{-10}$ m

If R_0 is the size of the nucleus's wave function as suggested by Penrose, we have to compare the limit with the properties of nuclei in matter.

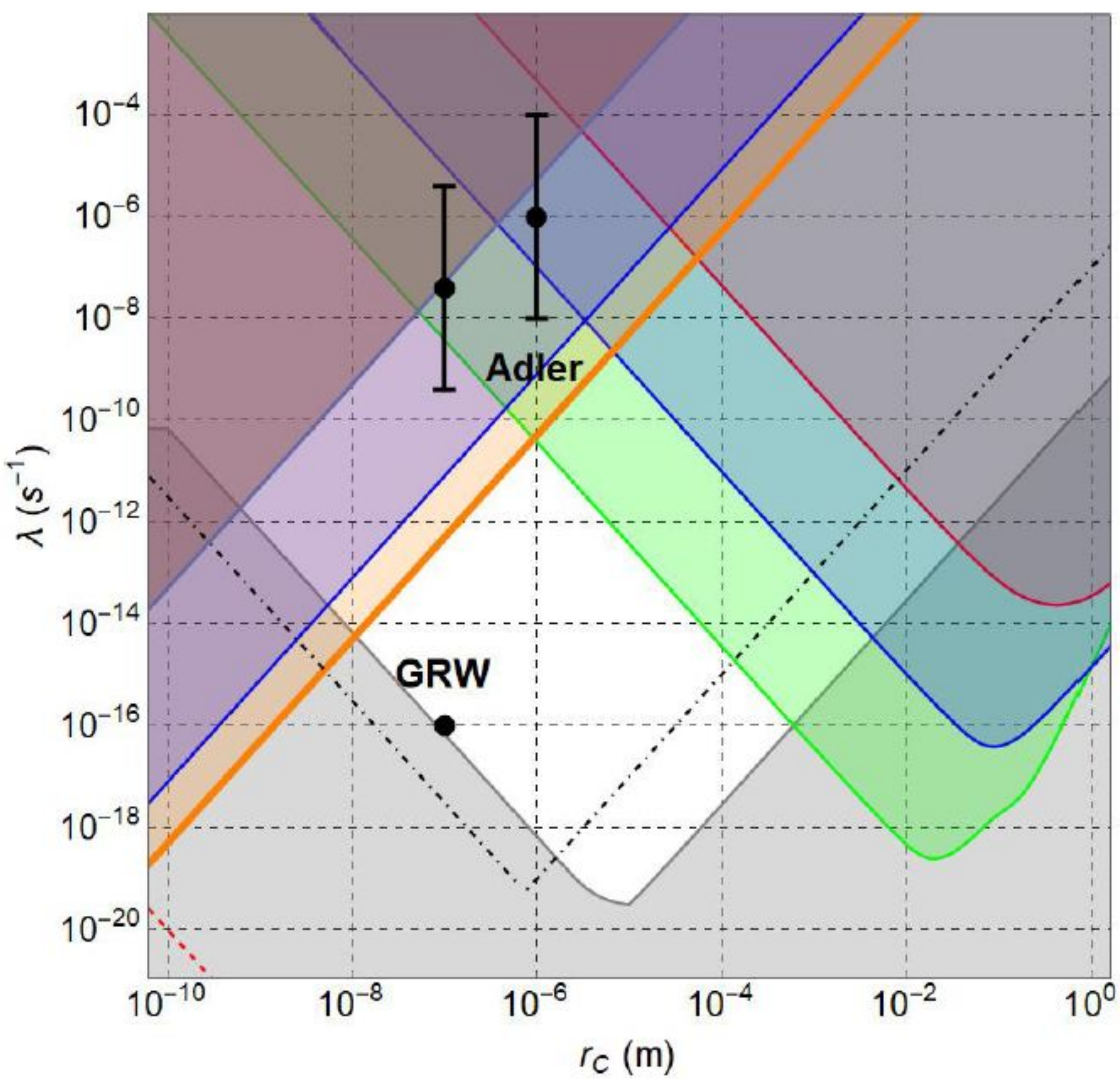
In a crystal $R^2_0 = \langle u^2 \rangle$ is the mean square displacement of a nucleus in the lattice, which, for the germanium crystal, cooled to liquid nitrogen temperature amounts to:

THEORETICAL EXPECTATION $R_0 = 0.05 \cdot 10^{-10}$ m

"Underground test of gravity-related wave function collapse". Nature Physics 17, pages 74–78 (2021)

Constraints on the CSL

Similar analysis leads to bounds on the strength and correlation length of the CSL (Eur. Phys. J. C (2021) 81: 773)



$\lambda/r_C^2 < 52\ m^{-2}\ s^{-1}$

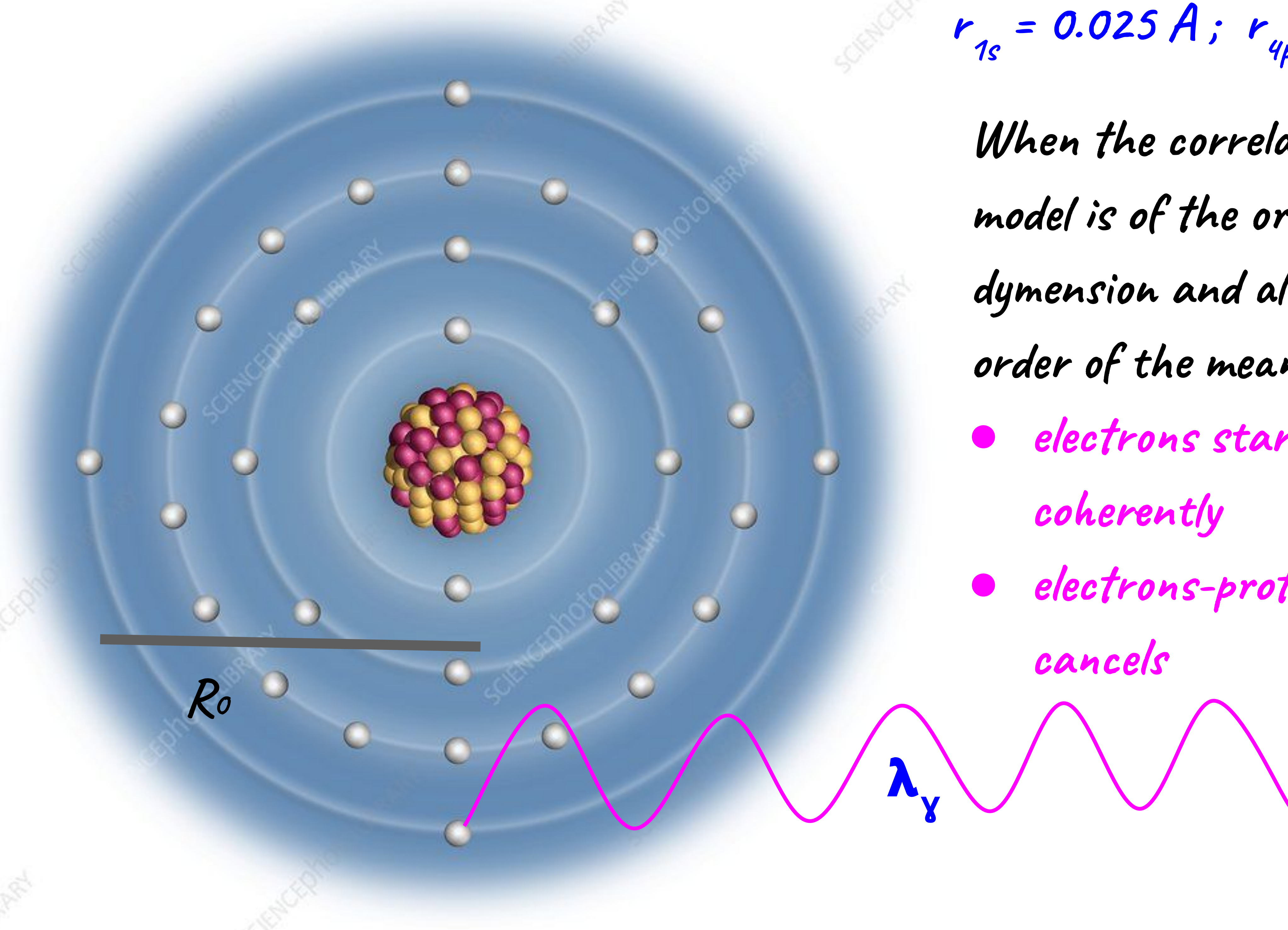
Fig. 4 Mapping of the $\lambda - r_C$ CSL parameters: the proposed theoretical values (GRW [6], Adler [24,25]) are shown as black points. The region excluded by theoretical requirements is represented in gray, and it is obtained by imposing that a graphene disk with the radius of 10 µm (about the smallest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

Spontaneous emission in the X-rays regime

In the low-energy regime, the photon w.l. is comparable to the atomic orbits dimensions

e.g. $\lambda_{dB}(E=15\ keV) = 0.8\ A$

$r_{1s} = 0.025\ A\ ;\ r_{4p} = 1.5\ A$



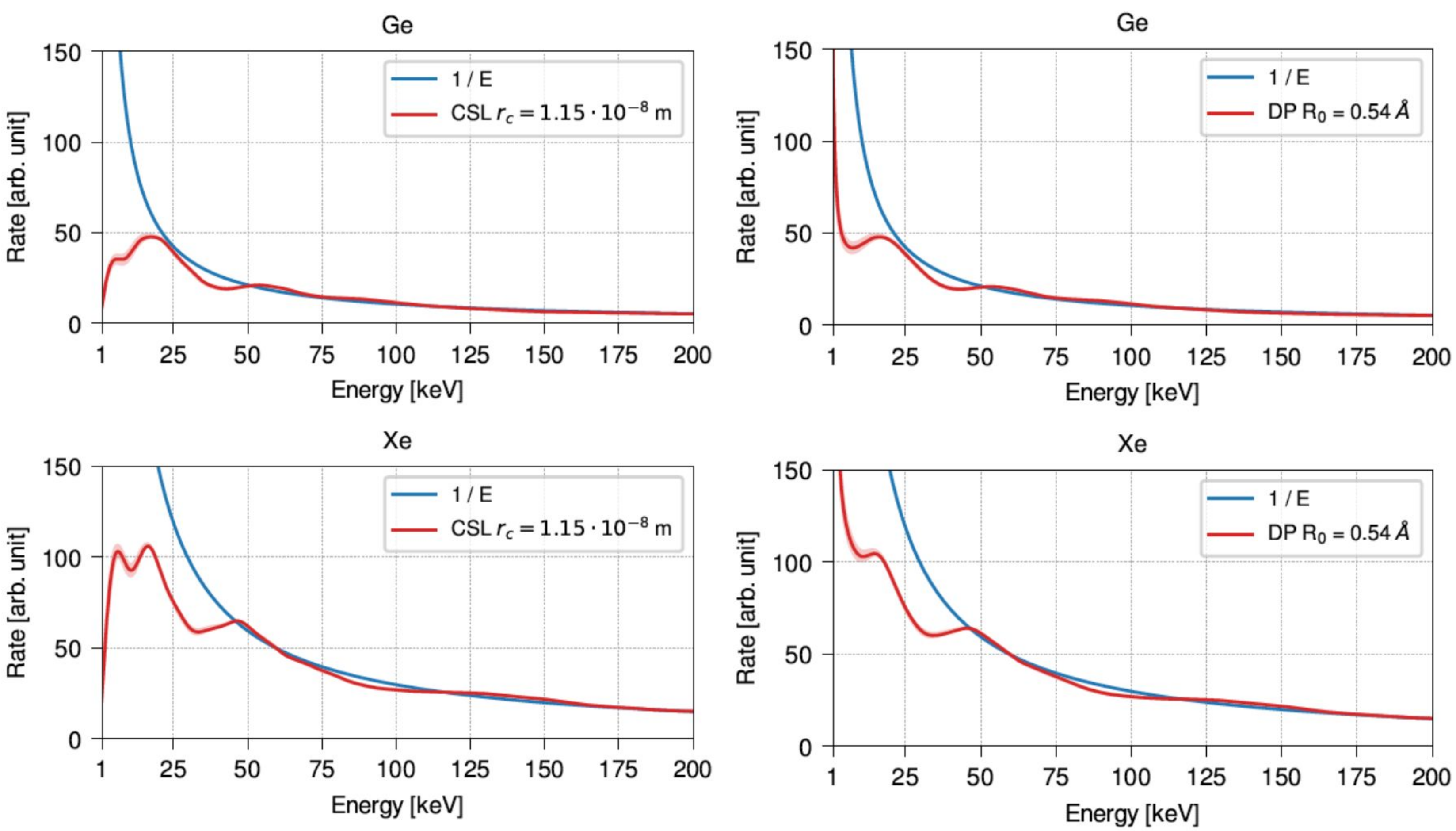
When the correlation length of the model is of the order of the atomic dymension and also λ_γ is of the order of the mean atomic radii:

- electrons start to emit coherently
- electrons-protons contribution cancels

Spontaneous emission in the X-rays regime

First model which predicts a characteristic spontaneous E. M. radiation distinctive of the decoherence mechanism:

Phys. Rev. Lett. 132, 250203 (2024)



- **The energy spectrum of this radiation is influenced by the atomic structure of the emitter.**
- **The spontaneous radiation rate, within the range of (1-15) keV, is unique to the specific decoherence mechanism.**

Spontaneous radiation rate for the CSL model (left) and DP (right) calculated for a Ge atom (top panels) and a Xe atom (bottom panels. In blue the approximated theory.

Thank you!

Spin statistics theorem (Fierz 1939, Pauli 1940, Schwinger, Lüders, Zumino…)

Postulates: inhomogeneous Lorentz group, locality, microcausality, vacuum is the state of lowest energy, Hilbert space metric positive definite, vacuum is not identically annihilated by a field →

(pseudo)scalar fields commute and spinor fields anticommute

Models of PEP violation:

- **Pioneering work of Fermi, Gentile, Green …**
- **Igniatiev and Kuzmin [**A.Y. Ignatiev,V.A.Kuzmin, Proceedings of the Seminar, Tbilisi, USSR, 15-17 April 1986**] (deformation of the standard Fermi oscillator)**

$$
\begin{array}{ll}
a^{+}|0\rangle = |1\rangle & a|0\rangle = 0 \\
a^{+}|1\rangle = \beta|2\rangle & a|1\rangle = |0\rangle \\
a^{+}|2\rangle = 0 & a|2\rangle = \beta|1\rangle
\end{array}
$$

- **Rahal and Campa [**V. Rahal, A. Campa, Thermodynamical implications of a violation of the pauli principle. Phys. Rev. A 38(7), 3728–3731 (1988)**] global w.f. of the electrons is not exactly antisymmetric, PEP holds as long as the number of wrongly entangled pais is small.**

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 end or time and (f) non commutative spacetime"

Two classes of PEP violation models:

Static deformation of comm/anticomm relations (Particle properties) - Greenberg & Mohapatra, quon model [O.W. Greenberg, R.N. Mohapatra, Phys. Rev. Lett. 59(22), 2507–2510 (1987)**]**

$$a_k a_l^\dagger - q a_l^\dagger a_k = \delta_{k,l}$$

is subject to the M-G Superselection Rule -> can be only tested with open systems.

Space-time properties - Bosso, Illuminati, Petruzziello, Marcianò, Addazzi, Balachandran, Mavromatos … unrestricted by M-G Superselection Rule -> can be tested with closed systems.

From theory to Open Systems experiments

In standard QFT **it is difficult to violate the statistics of identical particles;**

SUPERSELECTION RULE : Messiah, Greenberg, Amado and Primakoff:

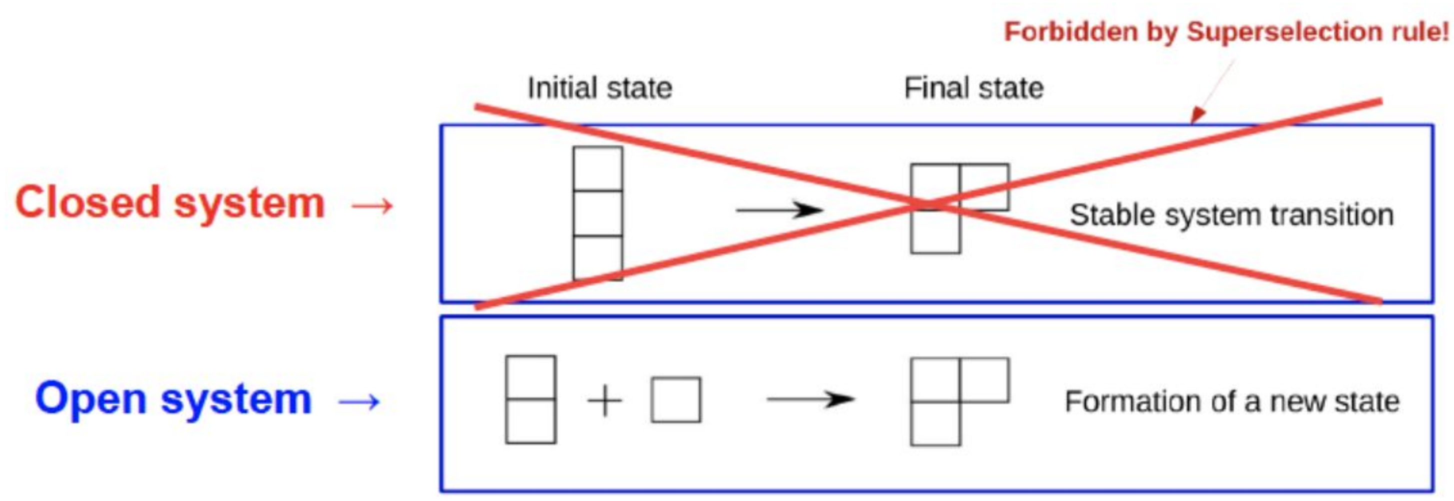
The $\mathcal{H}$ must be totally symmetric in the dynamical variables of the identical particles; $\mathcal{H}$ cannot change the permutation symmetry type of the wave function.

If the w.f. has a small mixed symmetry component the symmetric world Hamiltonian would only connect mixed symmetry states to mixed symmetry states.

Local QFT - Greenberg & Mohapatra (Quon Model), Ignatiev, Kuzmin, Rahal, Campa … are subjected to M-G superselection rule: transition probability between two symmetry states is zero

↓

introduce new fermions (current) in a pre-existing identical fermion system and check for PEP-violating atomic transitions **VIP Open Systems & GATOR-VIP**



From theory to Open Systems experiments

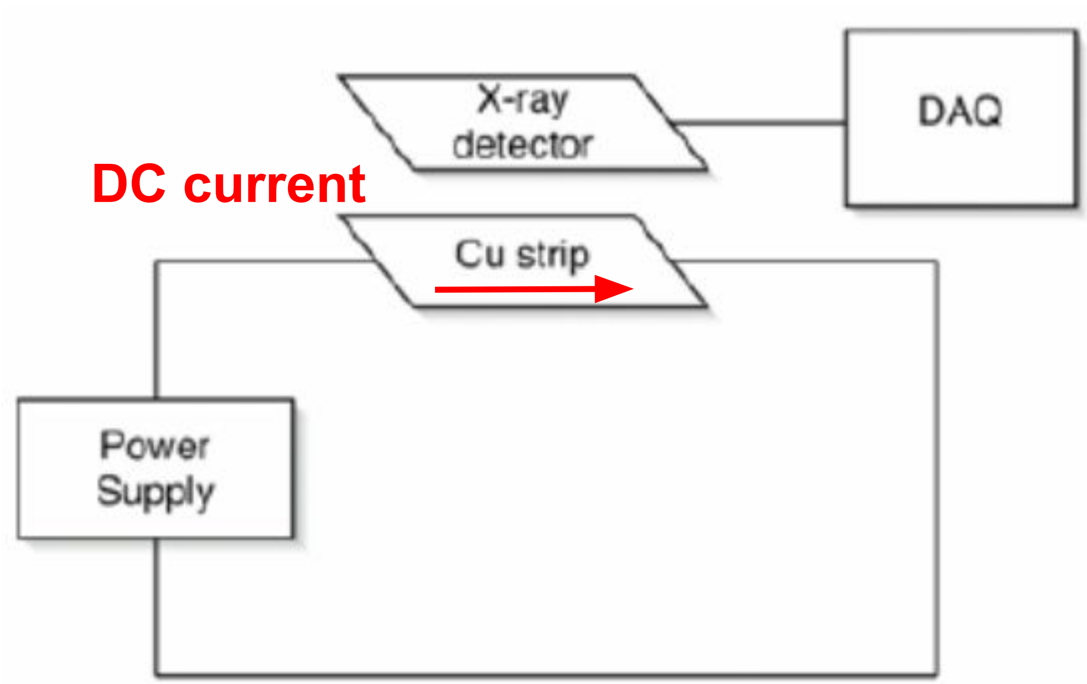
The PEP violation probability β^2 is related to the q parameter by

$$\beta^2 = 1 + q$$

such probability is the anomalous component of the two-identical fermions density matrix

$$\rho_2 = (1-\beta^2)\rho_a + \beta^2 \rho_s$$

a high sensitivity test of β^2 consists in (Ramberg E. and Snow G. A. 1990 Phys. Lett. B 238 438)

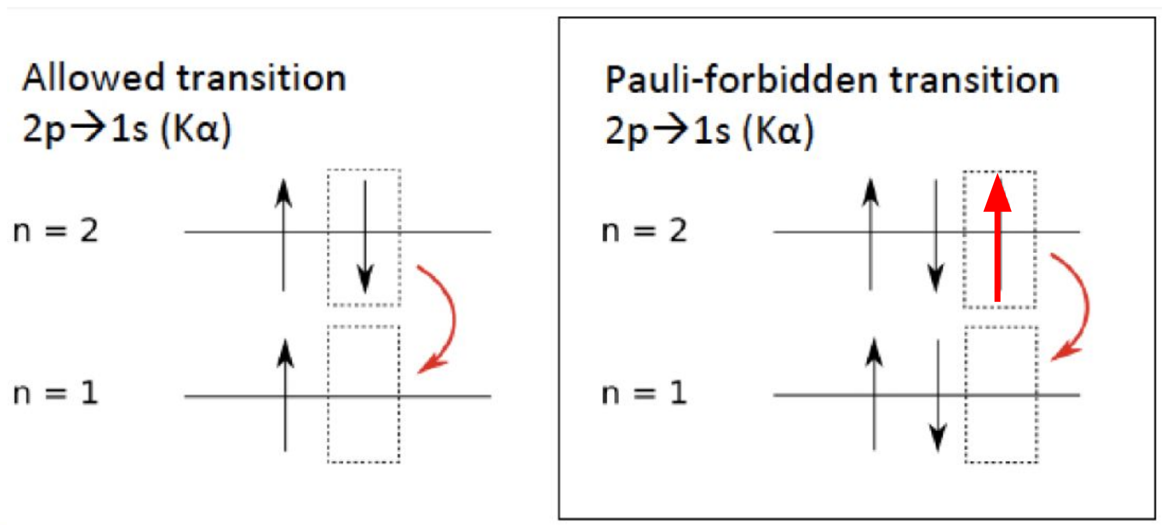


If the symmetry state formed by a *new current* electron with the electrons of the target is such that the K shell of an atom accommodates two equal spin electrons:

Then the X-ray detector will measure (with a certain efficiency) .....

From theory to Open Systems experiments

Then the X-ray detector will measure (with a certain efficiency) a photon emitted by the new electron when performing the PEP-violating atomic transition



~ 8.05 keV in Cu

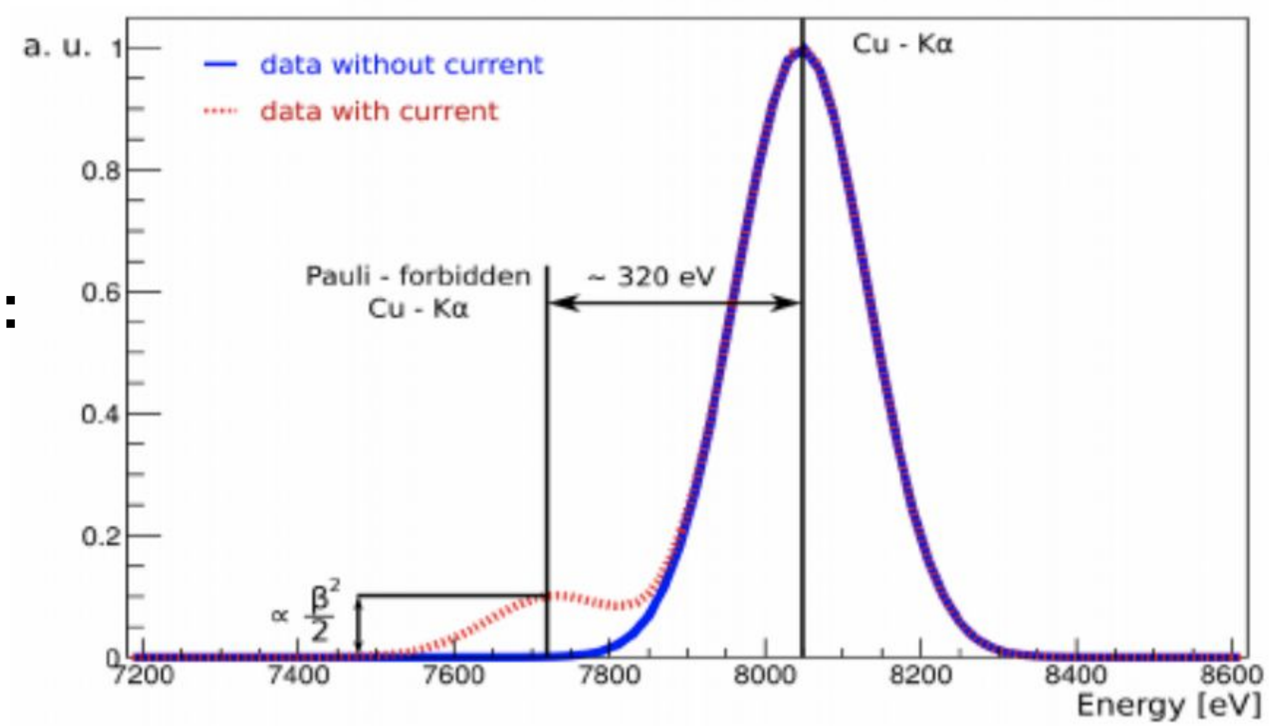
~ 7.7 keV in Cu

Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

Multiconfiguration Dirac-Fock approach

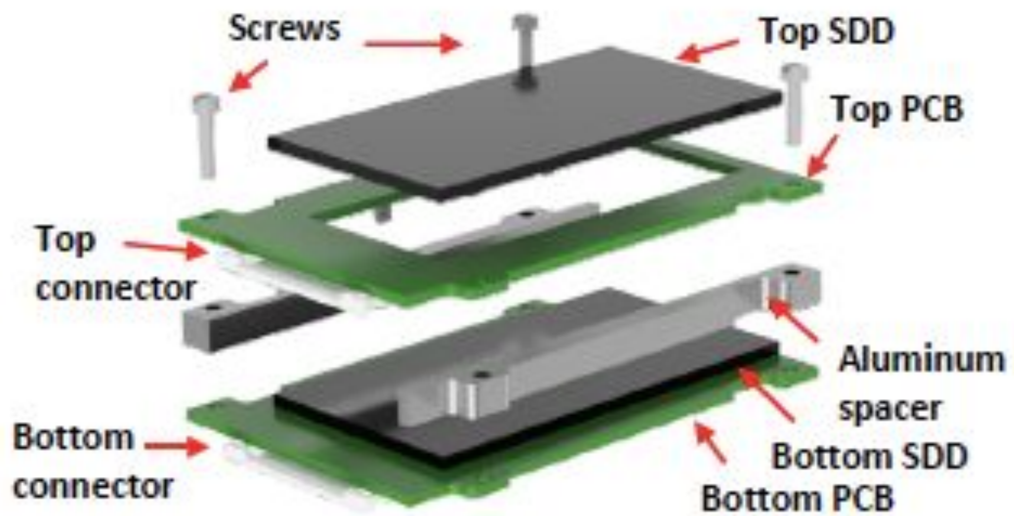
Accounts for the shielding of the two inner electrons

In presence of signal you expect to measure:



R&D of a possible VIP-3.5

VIP-3.5 - further improvement in the quantum efficiency -> layered structures of 1mm thick SDDs to perform a scan of $\beta^2/2$ with comparable sensitivity to VIP-2/3 till Z ~ 60:



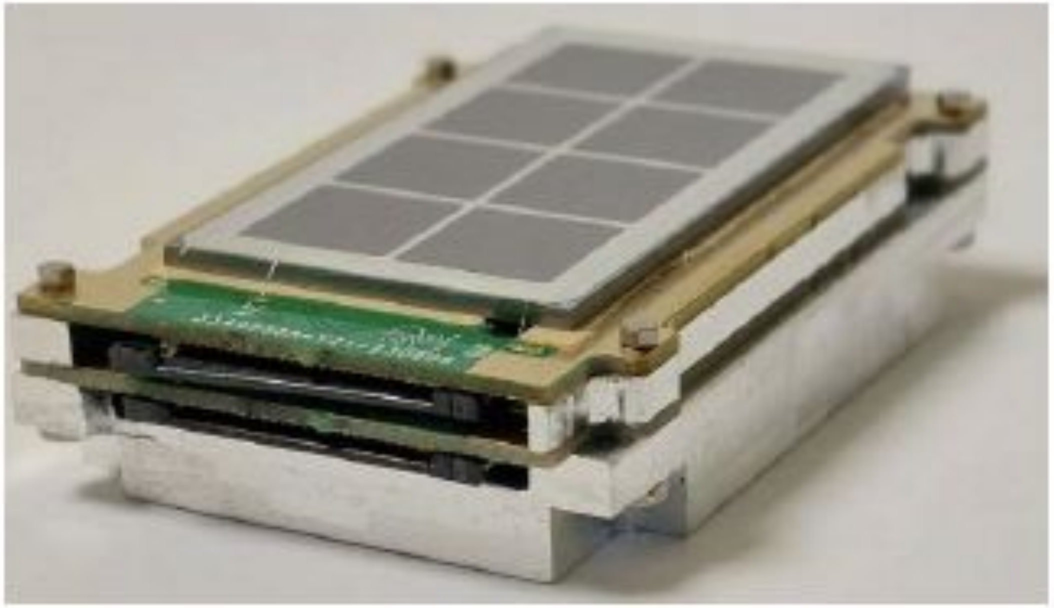
R&D ongoing

Stacked-detector assembly:

- two identical PCB carriers, at a distance of 2mm;
- Aluminum spacers on the sides for mechanical support and thermal conduction;
- Four screws to hold the system together and provide additional thermal conductivity.

A first stacked detection module has been assembled and tested:

- readout performed with the SFERA ASIC, a 16-channel analog pulse processor designed for both X and γ-ray detectors;



Statistical model

- The *pdf* of the expected number of total signal counts *S* given the measured distribution is:

$$P(S|data) = \int_0^\infty \int_{\mathcal{D}_\mathbf{p}} P(S, B|data, \mathbf{p})\; d^m\mathbf{p}\; dB$$

$$P(S, B|data, \mathbf{p}) =$$

$$= \frac{\boxed{P(data|S, B, \mathbf{p}) \cdot f(\mathbf{p})} \cdot P_0(S) \cdot P_0(B)}{\int P(data|S, B, \mathbf{p}) \cdot f(\mathbf{p}) \cdot P_0(S) \cdot P_0(B)\; d^m\mathbf{p}\; dS\; dB}$$

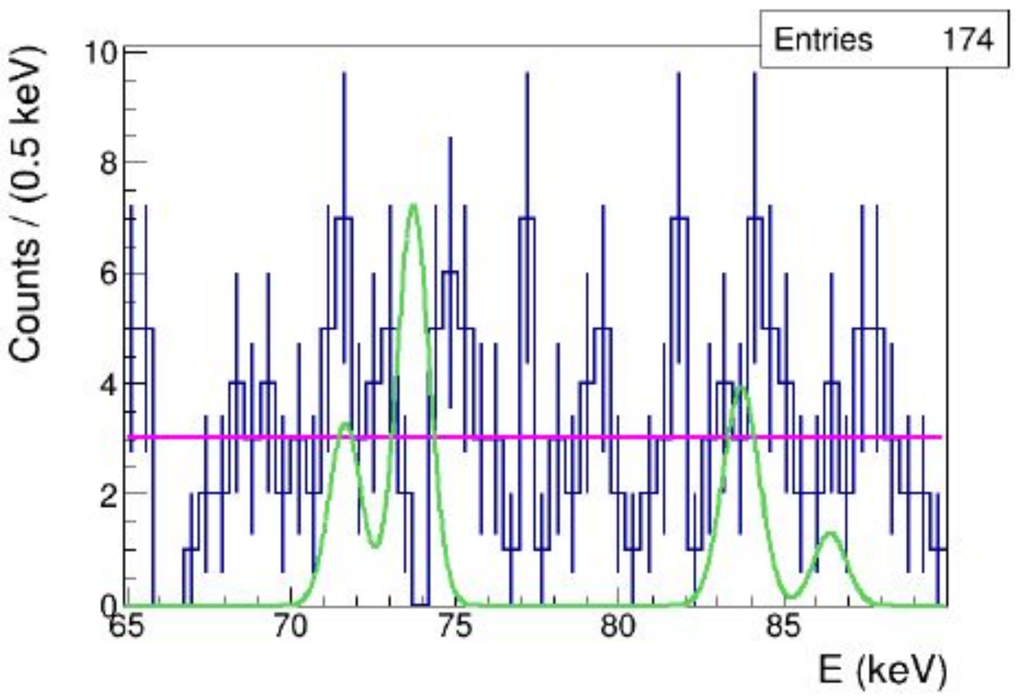


FIG. 1. The measured X-ray spectrum, in the region of the K_α and K_β standard and violating transitions in Pb, is shown in blue; the magenta line represents the fit of the background distribution. The green line corresponds to the shape of the expected signal distribution (with arbitrary normalization)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

- the likelihood is weighted on the joint *pdf* of the experimental parameters

$$P(\mathrm{data}|S, B, \mathbf{p}) = \prod_{i=1}^{N} \frac{\lambda_i(S, B, \mathbf{p})^{n_i} e^{-\lambda_i(S,B,\mathbf{p})}}{n_i!}$$

$$\lambda_i(S, B) = B \cdot \int_{\Delta E_i} f_B(E, \alpha)\; dE + \\ + S \cdot \int_{\Delta E_i} f_S(E, \sigma)\; dE$$

The prior for S consistent with existing limits [Found. Phys. 42, 1015-1030 (2012)**].**

Statistical model

- First analysis which accounts for the predicted energy dependence of the PEP violation probability. Expected rate of Kalpha1 transitions:

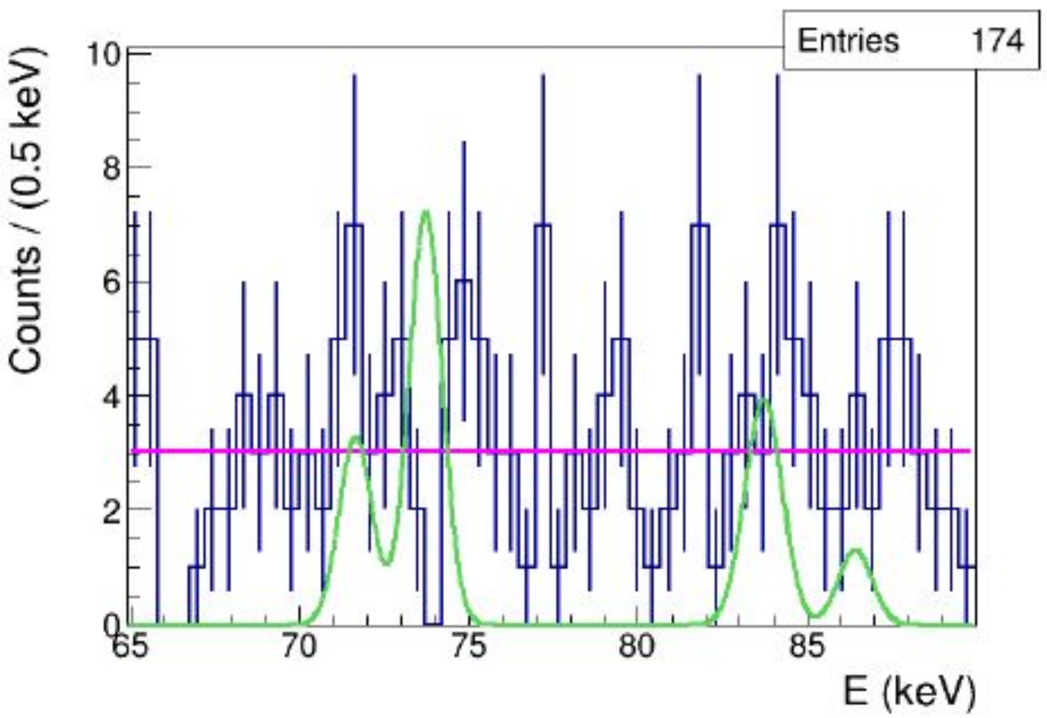


FIG. 1. The measured X-ray spectrum, in the region of the K_α and K_β standard and violating transitions in Pb, is shown in blue; the magenta line represents the fit of the background distribution. The green line corresponds to the shape of the expected signal distribution (with arbitrary normalization)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

$$\Gamma_{K_{\alpha 1}} = \frac{\delta^2(E_{K_{\alpha 1}})}{\tau_{K_{\alpha 1}}} \cdot \frac{BR_{K_{\alpha 1}}}{BR_{K_{\alpha 1}} + BR_{K_{\alpha 2}}} \cdot 6 \cdot N_{atom} \cdot \epsilon(E_{K_{\alpha 1}}).$$

- probability to observe n transitions in the time t:

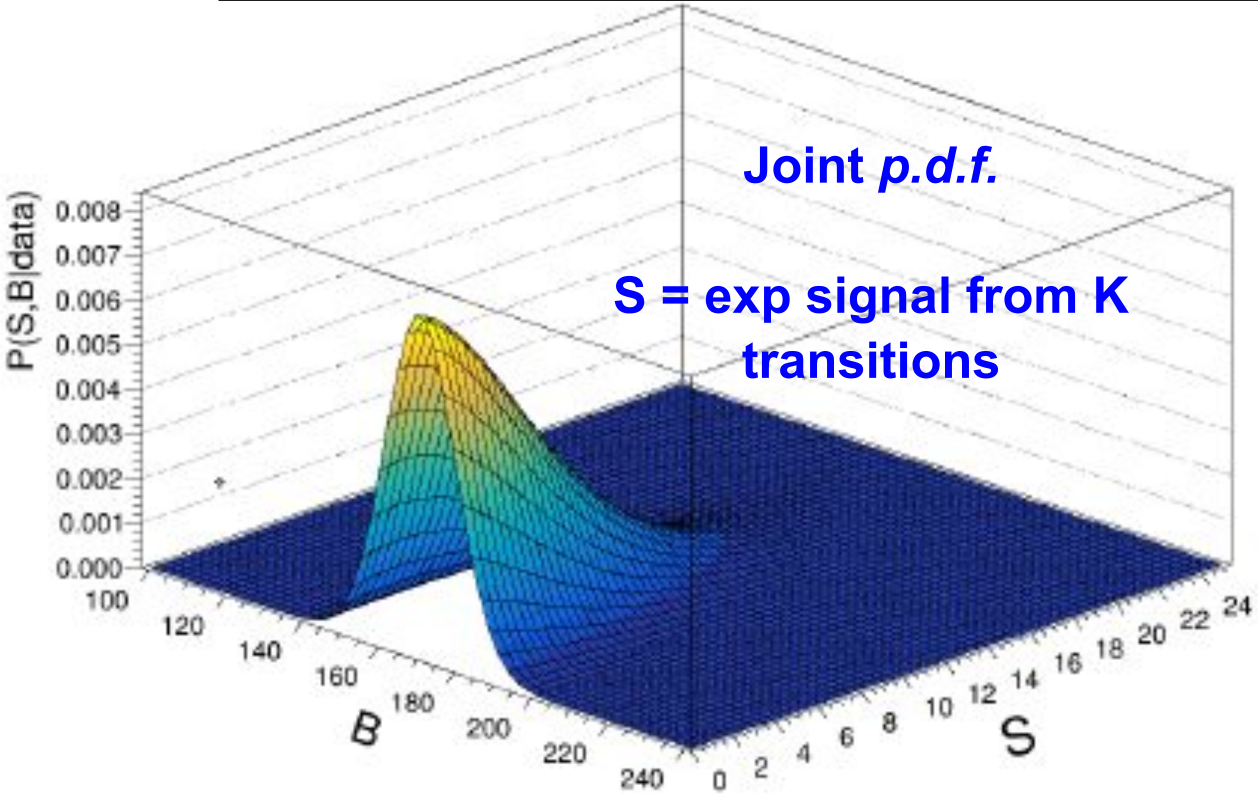
$$P(n;t) = \frac{(\Gamma_{K_{\alpha 1}}\, t)^n e^{-\Gamma_{K_{\alpha 1}}\, t}}{n!},$$

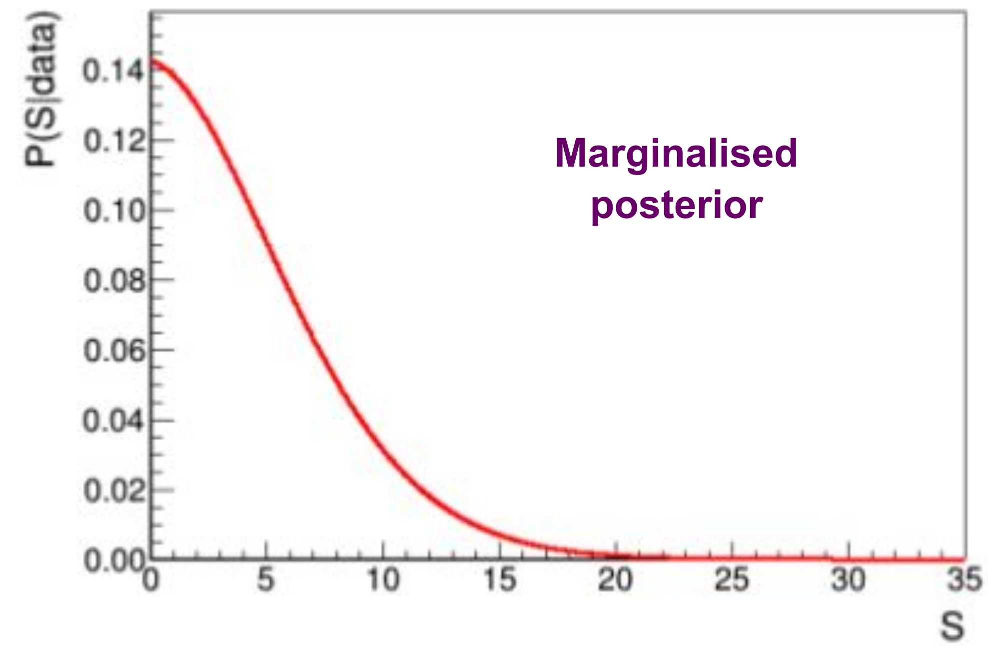
$$f_S(E,k) = \frac{1}{N} \cdot \sum_{K=1}^{N_K} \Gamma_K \frac{1}{\sqrt{2\pi\sigma_K^2}} \cdot e^{-\frac{(E-E_K)^2}{2\sigma_K^2}}$$

- upper limit on the non-commutativity scale:

$$\mu = \sum_{K=1}^{N_K} \mu_K = \frac{\aleph}{\Lambda^k} < \bar{S}$$

Results





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

θ_{0i}	$\bar{S}$	lower limit on Λ (Planck scales)
$\theta_{0i} = 0$	13.2990	$6.9 \cdot 10^{-2}$
$\theta_{0i} \neq 0$	18.1515	$2.6 \cdot 10^{2}$

K. P. et al., PRL 129, 131301 (2022)

K. P. et al., PRD 107, 026002 (2023)

see also A. Addazi, P. Belli, R. Bernabei and A. Marciano, Chin. Phys. C 42 (2018) no.9, 094001

PEP violation in θ-Poincaré

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

specific calculation of atomic levels transitions probabilities for θ-Poincaré

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

for non-vanishing (vanishing) electric like components of the $\theta_{\mu\nu}$ tensor.

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

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

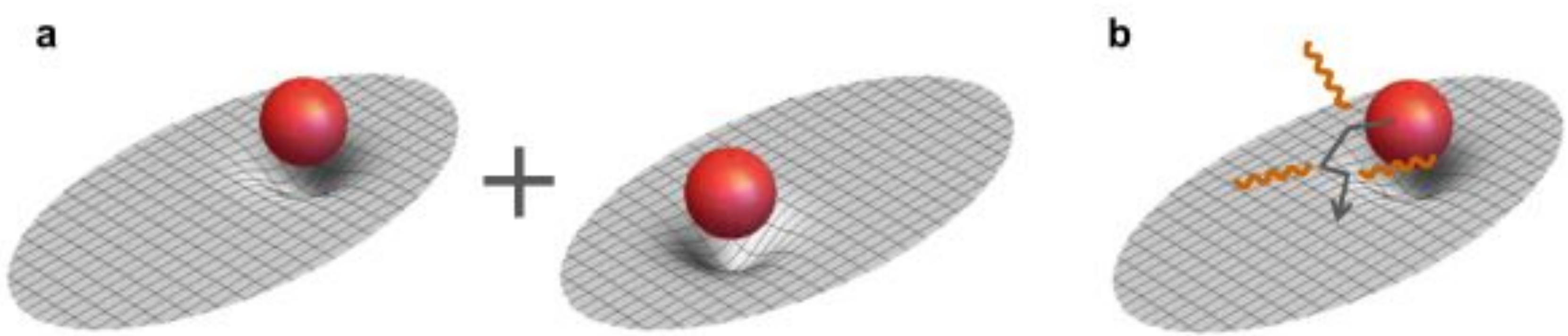
An experimental bound on the probability that PEP may be violated in atomic transition processes, straightforwardly translates into a bound on the new physics scale Λ, consistently with the choice of the θ_{0i} components.

Gravity induced collapse: the Diosi-Penrose model

Diósi: QT requires an absolute indeterminacy of the gravitational field, -> the local gravitational potential should be regarded as a stochastic variable, whose mean value coincides with the Newton potential, and the correlation function is:

$$< \phi(\mathbf{r},t)\,\phi(\mathbf{r}',t') > - < \phi(\mathbf{r},t) >< \phi(\mathbf{r}',t') > \sim \frac{\hbar\, G}{|\mathbf{r}-\mathbf{r}'|}\,\delta(t-t')$$

Penrose: When a system is in a spatial quantum superposition, a corresponding superposition of two different space-times is generated. The superposition is unstable and decays in time. The more massive the system in the superposition, the larger the difference in the two space-times and the faster the wave-function collapse.



L. Diósi and B. Lukács, Ann. Phys. 44, 488 (1987), L. Diósi, Physics letters A 120 (1987) 377, L. Diósi, Phys. Rev. A 40, 1165–1174 (1989), R. Penrose, Gen. Relativ. Gravit. 28, 581–600 (1996), R. Penrose, Found. Phys. 44, 557–575 (2014).

Global time uncertainty and decoherence

Diosi, L. (2005), Braz. J. Phys. 35, 260, Diosi, L., and B. Lukacs (1987), Annalen der Physik 44, 488, Diosi, L. (1987), Physics Letters A 120, 377, A. Bassi et al.,Rev. Mod. Phys. 85,471

Initial state of a quantum system is a superposition of two eigenstates of total Hamiltonian

$$|\psi\rangle = c_1|\varphi_1\rangle + c_2|\varphi_2\rangle$$

time evolution

$$|\psi(t)\rangle = c_1 \exp(-i\hbar^{-1}E_1 t)|\varphi_1\rangle + c_2 \exp(i\hbar^{-1}E_2 t)|\varphi_2\rangle$$

Let us add an uncertainty to the time $t \to t + \delta t$

and assume that is distributed Gaussian, with zero mean, and dispersion which is proportional to the mean time, $\mathbf{M}[(\delta t)^2] = \tau t$ then the density matrix evolves as:

$$\begin{aligned} & \rho(t) \equiv \mathbf{M}\left[|\psi(t)\rangle\langle\psi(t)|\right] = \\ = \; & |c_1|^2|\varphi_1\rangle\langle\varphi_1| + |c_2|^2|\varphi_2\rangle\langle\varphi_2| + \\ + \; & \left\{c_1^\star c_2 \exp(i\hbar^{-1}\Delta E t)\mathbf{M}\left[\exp(i\hbar^{-1}\Delta E \delta t)\right]|\varphi_2\rangle\langle\varphi_1| + \right. \\ + \; & \left. \quad \text{h.c.} \quad \right\} . \end{aligned}$$

Global time uncertainty and decoherence

Diosi, L. (2005), Braz. J. Phys. 35, 260, Diosi, L., and B. Lukacs (1987), Annalen der Physik 44, 488, Diosi, L. (1987), Physics Letters A 120, 377, A. Bassi et al.,Rev. Mod. Phys. 85,471

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$$\boxed{\mathbf{M}\left[\exp(i\hbar^{-1}\Delta E \delta t)\right] = e^{-t/t_D} \qquad t_D = \frac{\hbar^2}{\tau}\frac{1}{(\Delta E)^2}}$$

Global time uncertainty and decoherence

The time evolution for the density matrix

$$\hat{\rho}(t+\tau)=\exp\left[\frac{-i\hat{H}\tau}{\hbar}\right]\hat{\rho}(t)\exp\left[\frac{i\hat{H}\tau}{\hbar}\right]$$

Described by the von Neumann equation $$\frac{d\rho}{dt}=-i\hbar^{-1}[H,\rho]$$

turns to $$\frac{d\rho}{dt}=-i\hbar^{-1}[H,\rho]-\frac{1}{2}\tau\hbar^{-2}[H,[H,\rho]]$$

G. J. Milburn Prys. Rev. A 44 5401 (1991)

Local time uncertainty and decoherence

To generalize the concept for a local time $t_{\mathbf{r}} \rightarrow t + \delta t_{\mathbf{r}}$

one defines the correlation $\mathbf{M}[\delta t_{\mathbf{r}} \delta t_{\mathbf{r}'}] = \tau_{\mathbf{r}\mathbf{r}'} t$

Galileo invariant spatial correlation function

If the total Hamiltonian is decomposed in the sum of the local ones

$$\frac{d\rho}{dt} = -i\hbar^{-1}[H, \rho] - \frac{1}{2}\hbar^{-2} \sum_{\mathbf{r},\mathbf{r}'} \tau_{\mathbf{r}\mathbf{r}'} [H_{\mathbf{r}}, [H_{\mathbf{r}'}, \rho]]$$

The master equation suppresses superpositions of eigenstates of local energy

$$[\tau_d(X, X')]^{-1} = \frac{G}{2\hbar} \int \int d^3r\, d^3r' \times \frac{[f(\mathbf{r}|X) - f(\mathbf{r}|X')][f(\mathbf{r}'|X) - f(\mathbf{r}'|X')]}{|\mathbf{r} - \mathbf{r}'|}$$

Self-gravitational energy of the difference between the mass distributions of two states |X> and |X'> in superposition.

Diverges for point-like particles -> a short-length cutoff R_0 is introduced to regularize the theory.

Spontaneous emission in the X-rays regime

K. P. et al., Phys. Rev. Lett. 132, 250203 (2024)

$$\left.\frac{d\Gamma}{dE}\right|_t^{DP} = \frac{Ge^2}{12\pi^{5/2}\epsilon_0 c^3 R_0^3 E}\left\{N_p^2 + N_e + 2\sum_{o\,o'\ \mathrm{pairs}} N_o\,N_{o'}\,\frac{\sin\left[\frac{\beta|\rho_o-\rho_{o'}|\,E}{\hbar\,c}\right]}{\left[\frac{\beta|\rho_o-\rho_{o'}|\,E}{\hbar\,c}\right]}e^{-\frac{\beta^2(\rho_o-\rho_{o'})^2}{4R_0^2}} + \right.$$
$$\left. + \sum_o N_o\,(N_o-1)\,e^{-\frac{(\alpha\,\rho_o)^2}{4R_0^2}}\cdot\frac{\sin\left(\frac{\alpha\,\rho_o\,E}{\hbar\,c}\right)}{\left(\frac{\alpha\,\rho_o\,E}{\hbar\,c}\right)} - 2N_p\sum_o N_o\,\frac{\sin\left(\frac{\rho_o\,E}{\hbar\,c}\right)}{\left(\frac{\rho_o\,E}{\hbar\,c}\right)}\cdot e^{-\frac{\rho_o^2}{4R_0^2}}\right\}$$

first prediction of a distinctive experimental signature for different collapse mechanisms!

Opens up a world of new experimental challenges, to test established and new models linking gravitation to quantum mechanics.

R&D of a dedicated experiment ongoing.