Istituto Nazionale di Fisica Nucleare
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High sensitivity Quantum Mechanics tests in the Cosmic Silence

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Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi"
INFN, Laboratori Nazionali di Frascati

Excited QCD 2020
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Pauli Exclusion Principle

In its original form by Pauli:

"In an atom there cannot be two or more equivalent electrons for which the values of all four quantum numbers (n, l, m_l, m_s*) coincide. If an electron exists in an atom for which all of these numbers have definite values, then this state is 'occupied'."*

Then extended to all fermions

Feynman Lectures on Physics:

"Why is it that particles with half-integral spin are Fermi particles (...) whereas particles with integral spin are Bose particles (...)?

We apologize for the fact that we can not give you an elementary explanation.
An explanation has been worked out by Pauli from complicated arguments from quantum field theory and relativity. He has shown that the two must necessarily go together, but we have not been able to find a way to reproduce his arguments on an elementary level.

It appears to be one of the few places in physics where there is a rule which can be stated very simply, but for which no one has found a simple and easy explanation. (...)
This probably means that we do not have a complete understanding of the fundamental principle involved.*"*

Pauli Exclusion Principle

Several proofs exist in QFT which differ in clarity and quality of physical insight.

Proof of spin-statistics theorem by Lüders and Zumino

Postulates:

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

2 - Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality – microcausality)

3 - The vacuum is the state of lowest energy

4 - The metric of the Hilbert space is positive definite

5 - 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)

Models of PEP violation

Theories of Statistics Violation

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…...."

Ignatiev & Kuzmin model: Fermi oscillator with a third state

(Ignatiev, A.Y., Kuzmin, V. , Quarks '86: Proceedings of the 229 Seminar, Tbilisi, USSR, 15-17 April 1986)

$$a^+|0\rangle = |1\rangle \qquad a|0\rangle = 0$$
$$a^+|1\rangle = \beta|2\rangle \qquad a|1\rangle = |0\rangle$$
$$a^+|2\rangle = 0 \qquad a|2\rangle = \beta|1\rangle$$

β quantifies the degree of violation in the transition |1> → |2>

Govorkov, A. can not be genelized to quantum field theory! Physics Letters A 1989, 236 137, 7-10.

Models of PEP violation

- Greenberg, O.W.; Mohapatra, R.N.

Local Quantum Field Theory of Possible Violation of the Pauli Principle.
q parameter deforms anticommutators $a_k a_l^+ - q a_l^+ a_k = \delta_{k,l}$
Physical Review Letters 1987, 59, 2507

Govorkov, A. non relativistic! Physica A: Statistical Mechanics and its Applications 1994, 203, 655

- Q. M. model → Rahal, V.; Campa, A. , Physical Review A (1988) 38, 3728

  the global w. f. describing the totality of the electrons is not exactly antisymmetric → PEP mostly holds as long as the number of wrongly entangled pairs is small.

<u>Common feature</u> :

The non-Paulian character is intrinsic property of the system w. f. → can be tested looking for signature of a violating transition of a wrongly entangled pair, indeed ...

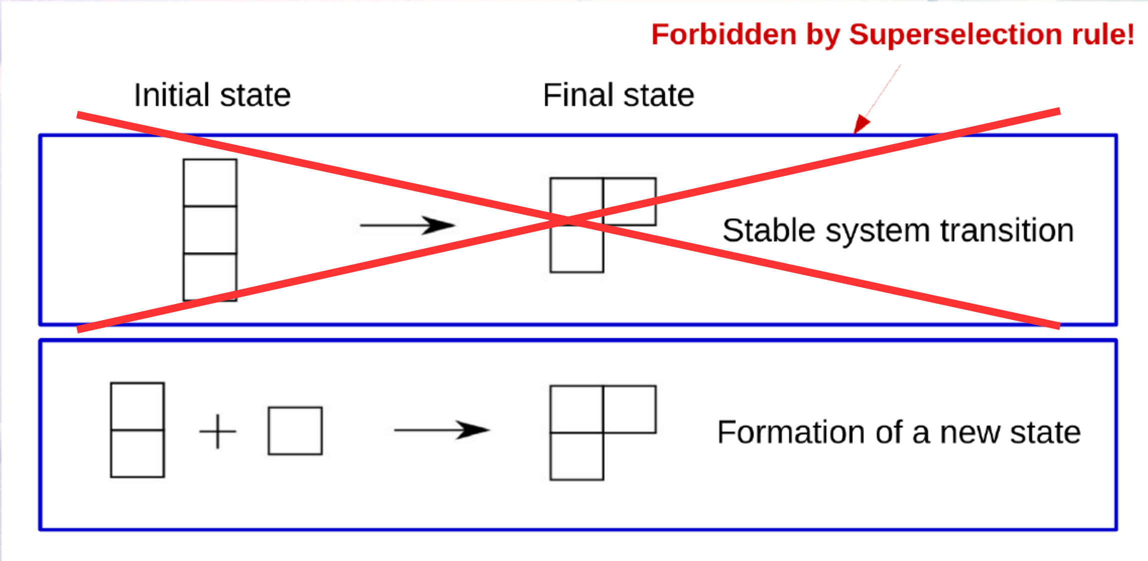
Messiah – Greenberg superselection rule

Superpositions of states with different symmetry are not allowed →
transition probability between two symmetry states is ZERO

<u>Messiah-Greenberg superselection rule</u> :

Closed system →

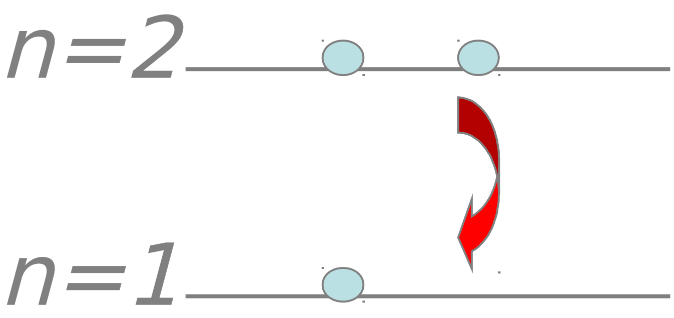
Open system →



VIP-open systems sets the best limit on PEP violation
for an elementary particle
respecting the M-G superselection rule

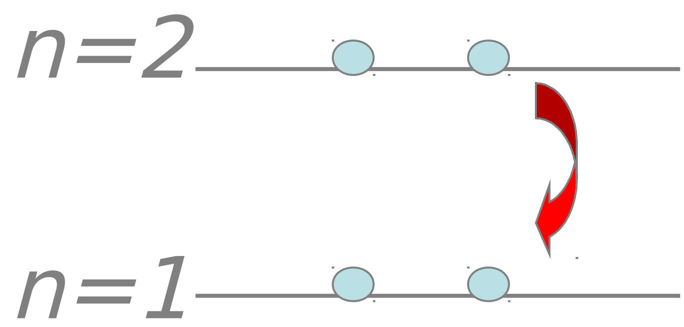
VIP-open systems - experimental method

Search for anomalous X-ray transitions performed by electrons introduced in a target trough a DC current (open system)



Normal 2p → 1s transition

~ 8.05 keV in Cu



2p → 1s transition violating Pauli principle

~ 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

The current-off spectrum provides the estimate of the background.

But the story isn't over yet ...

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****.*

↓

Space-time non commutativity can induce

sudden jumps to “wrong symmetry” states of a system

violating the M-G superselection rule

↓

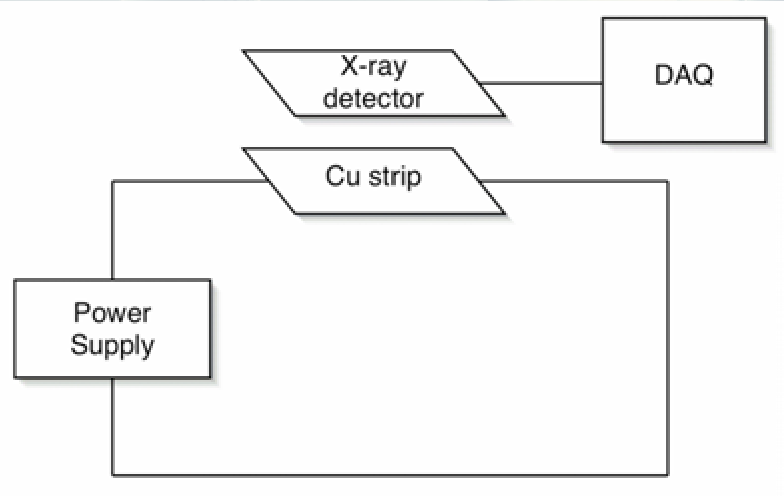
can be tested with violating transitions in CLOSED SYSTEMS

key features: high purity big mass target material

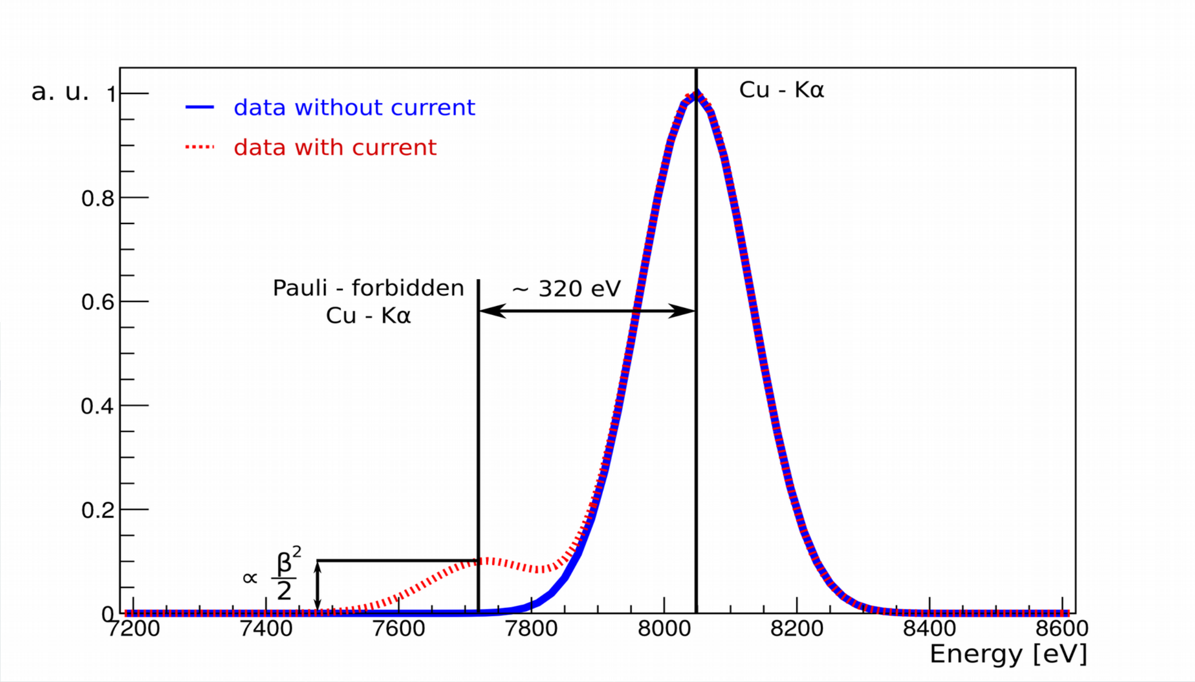
Schematically VIP-open systems

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

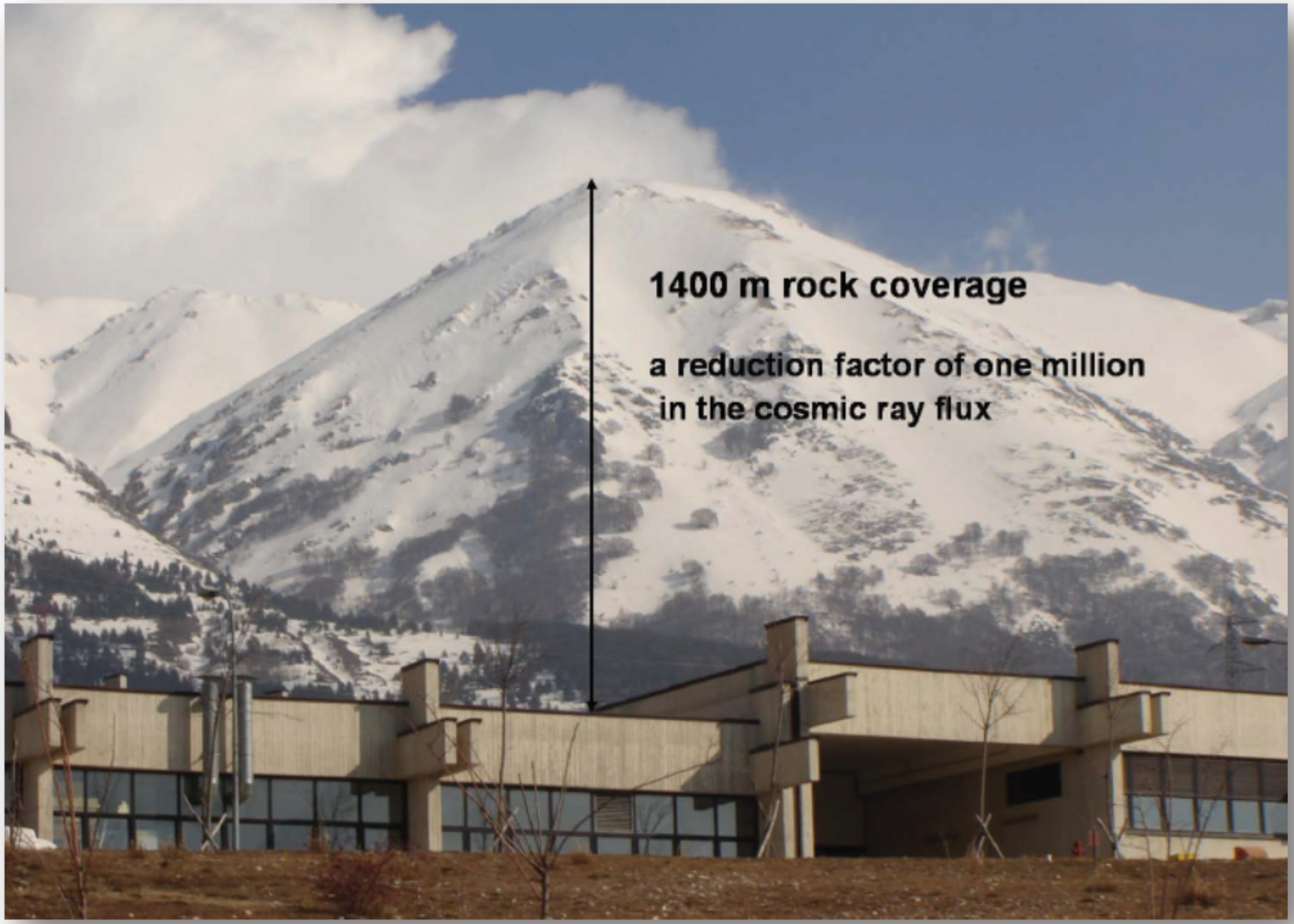
Search for anomalous electronic transitions in Cu
induced by a circulating current
introduced electrons interact with the valence electrons
search transition from 2p to 1s already filled by 2 electrons
alternated to X-ray background measurements without current



Undesired result :



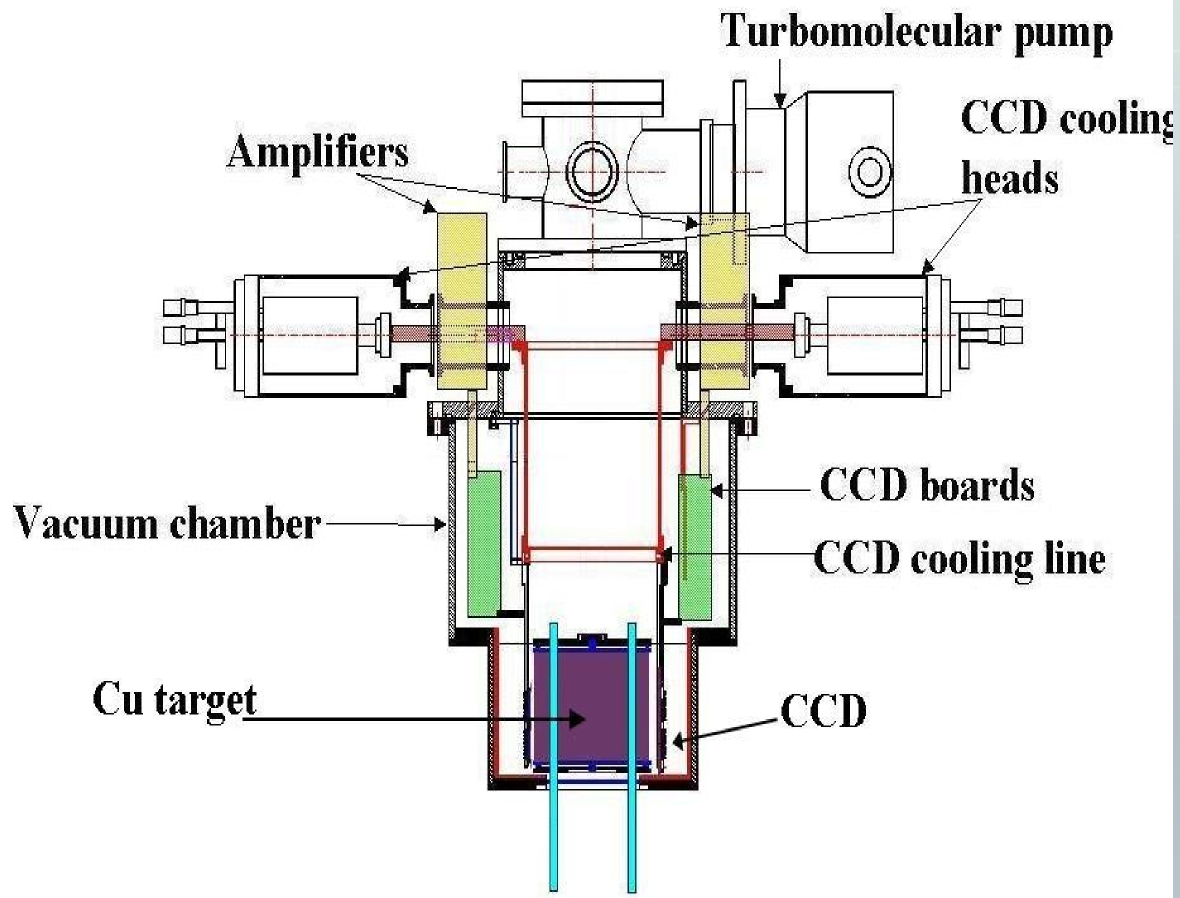
VIP Experiment & LNGS



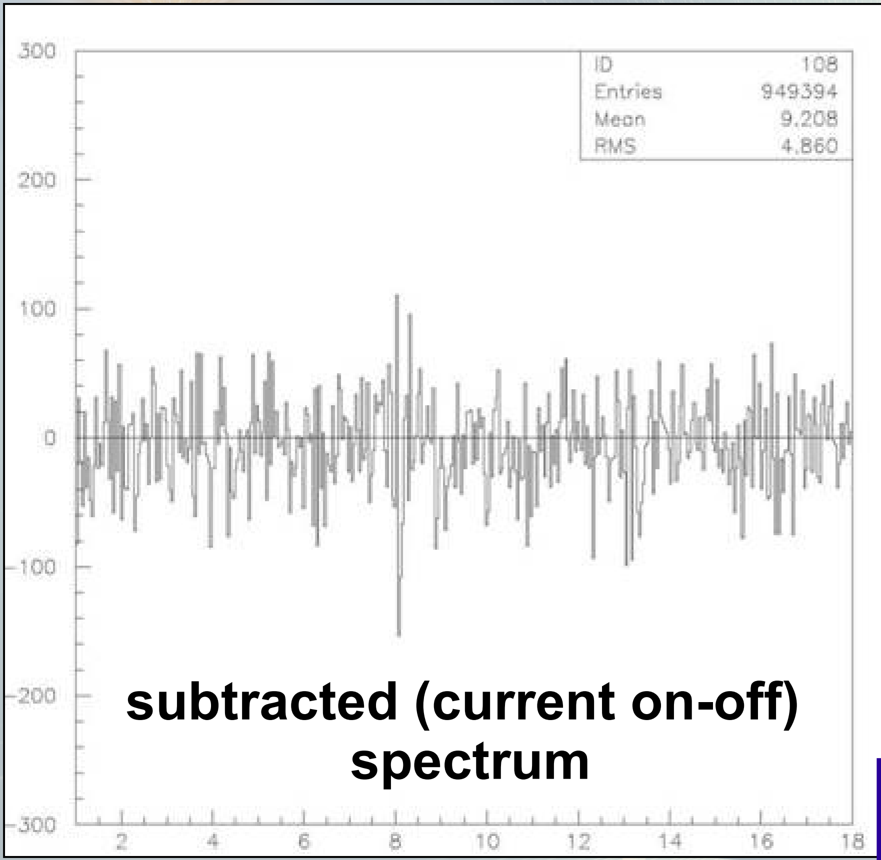
VIP Experiment & LNGS

VIP setup:

a) copper ultrapure cylindrical foil
b) surrounded by 16 Charge Coupled Devices (CCD)
c) inside a vacuum chamber: CCDs cooled to 168K by a cryogenic system
d) amplifiers + read out ADC boards.



VIP Experiment



After about 2 years running

$$\beta^2/2 < 4.7 \times 10^{-29}$$

Foundation of Physics 41 (2011) 282, (2015) Phys. Scr. 90, 028003 ...

VIP-2 goal 2 OM improvement

VIP-2 goal 2 OM improvement

a) 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

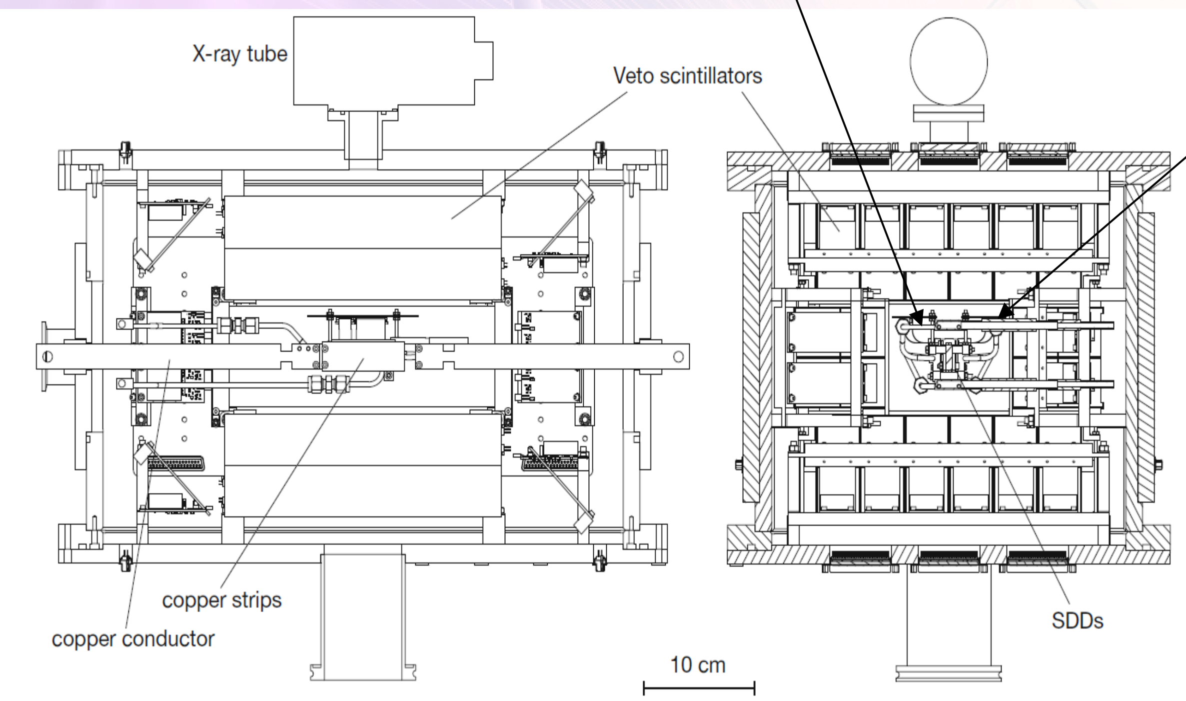
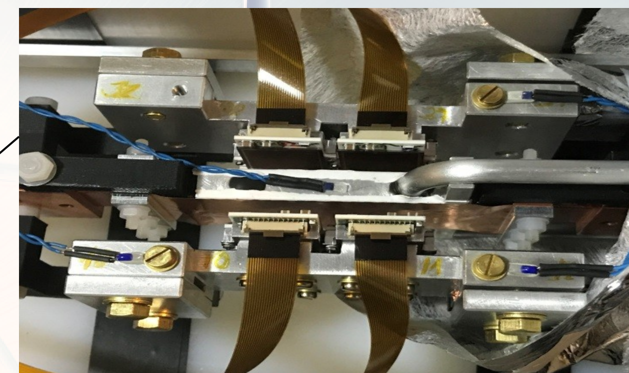
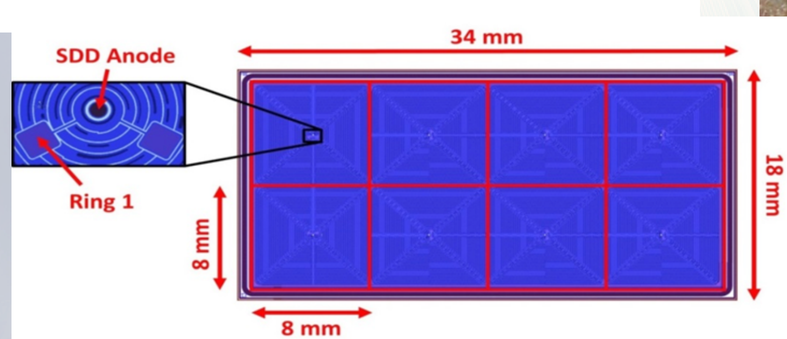


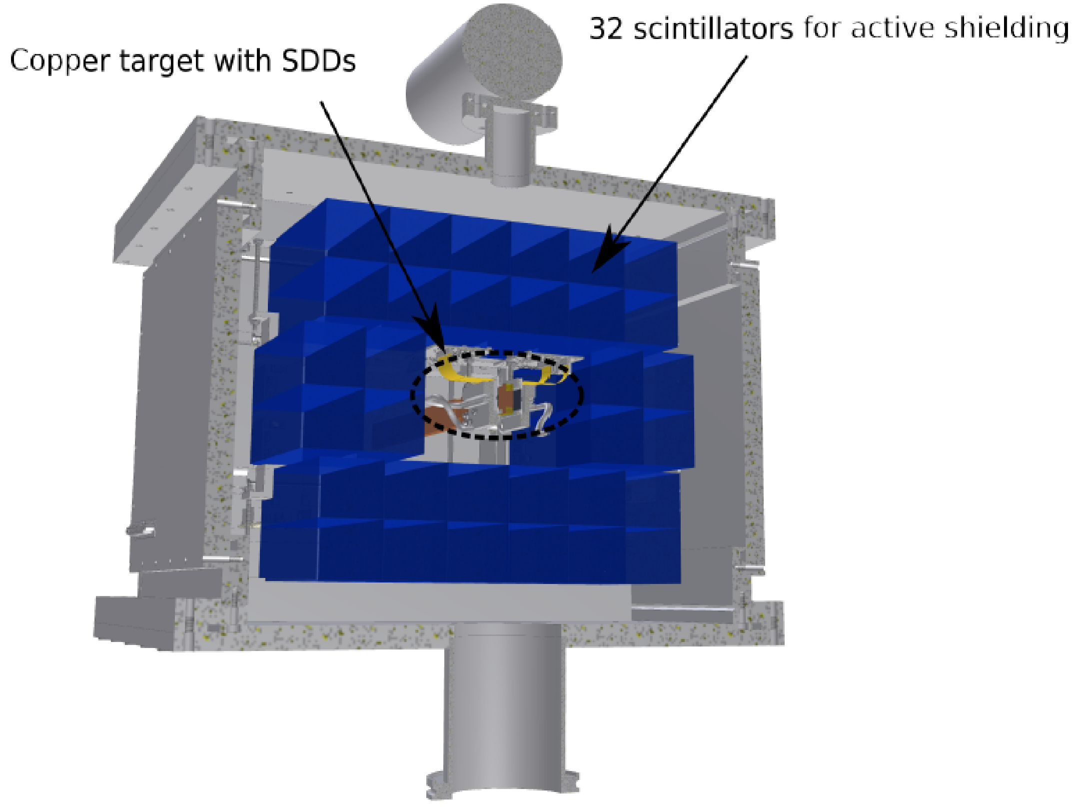
Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout





VIP-2 goal 2 OM improvement

b) VETO system → (32 plastic scintillators + SiPMs read out) → rejection of background (high energy charged particles) from outside the detector



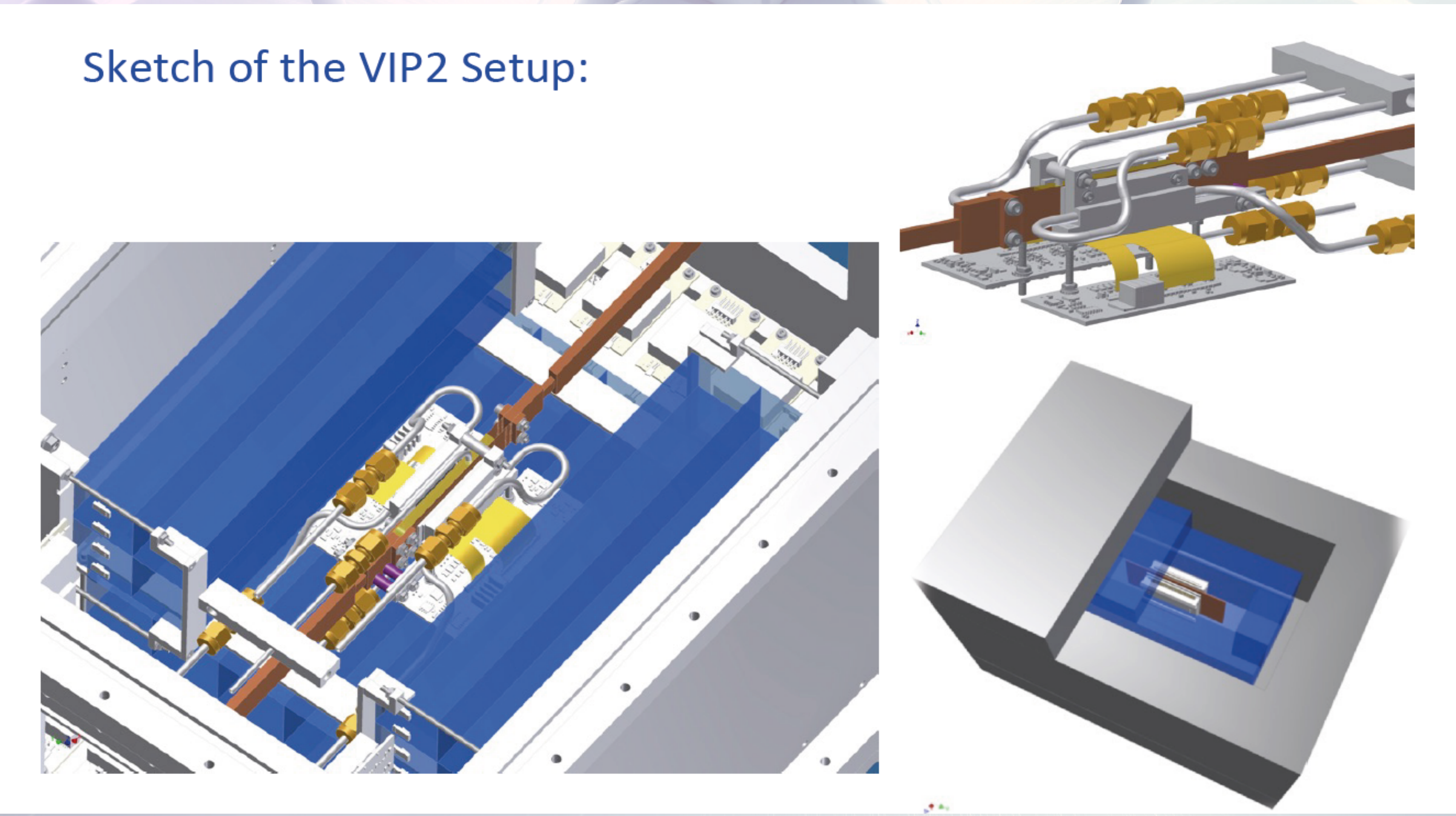
32 scintillators (blue) read out by two Silicon Photomultipliers each, are installed around the SDDs to give an active veto signal.

VIP-2 goal 2 OM improvement

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

DC current supply to Cu bars

d) Cu strips cooled by a closed Fryka chiller circuit → higher current (100 A) @ 20 °C of Cu target implies 1 °K heating in SDDs



VIP-2 goal 2 OM improvement

e) quick (one hour) resolution and energy calibration. X-ray tube irradiates zirconium & titanium

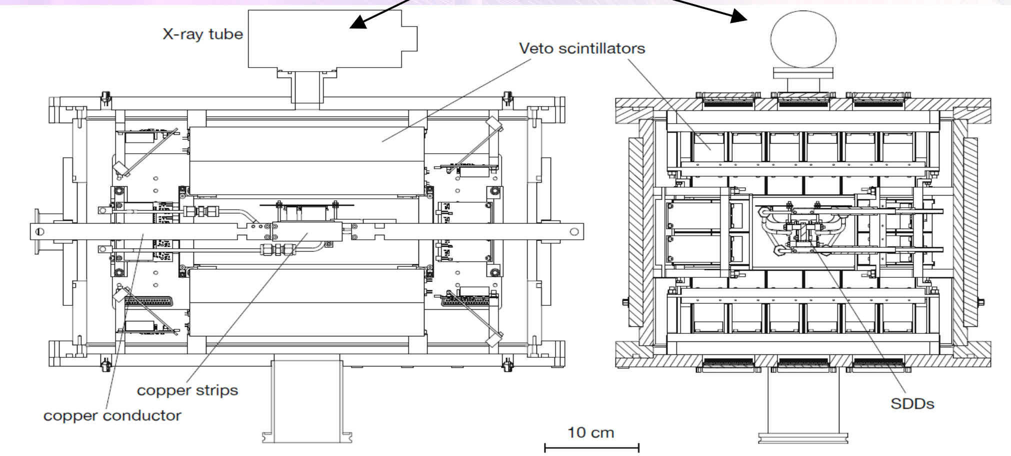
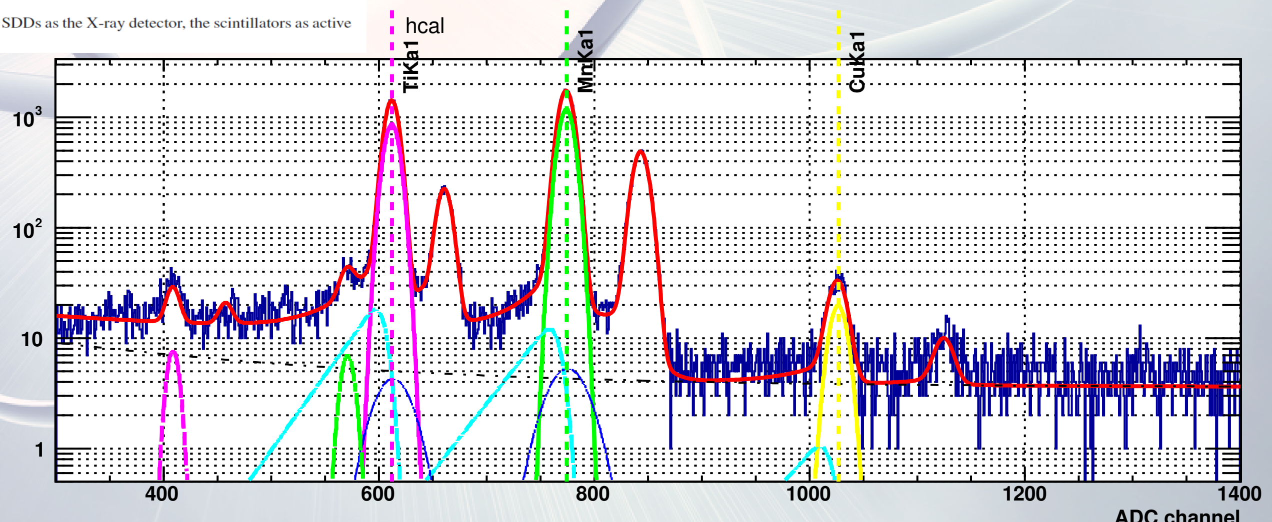


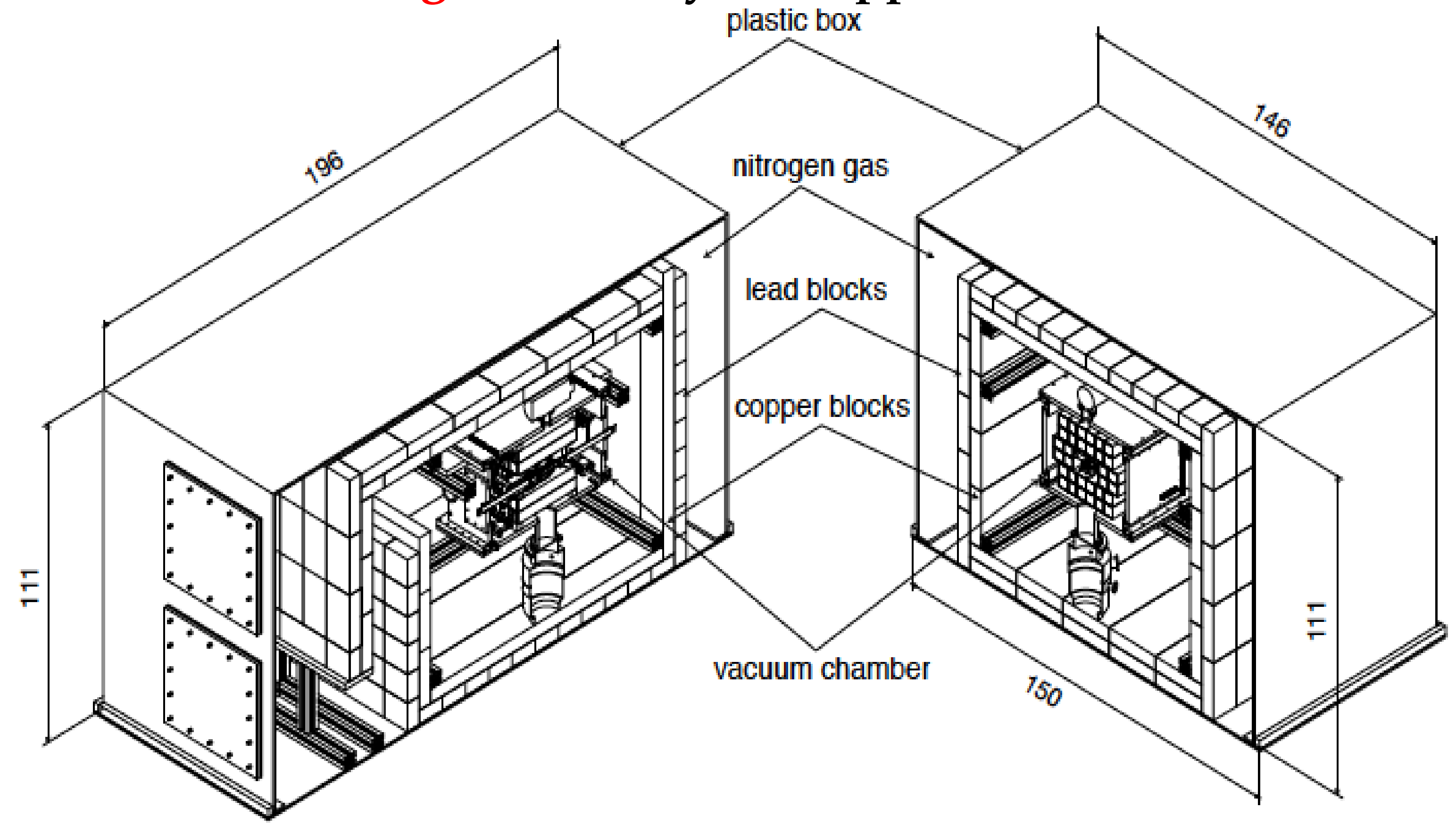
Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout



- SDD calibration spectrum at 125 K
- Energy resolution 150 eV (FWHM) for Mn Kα

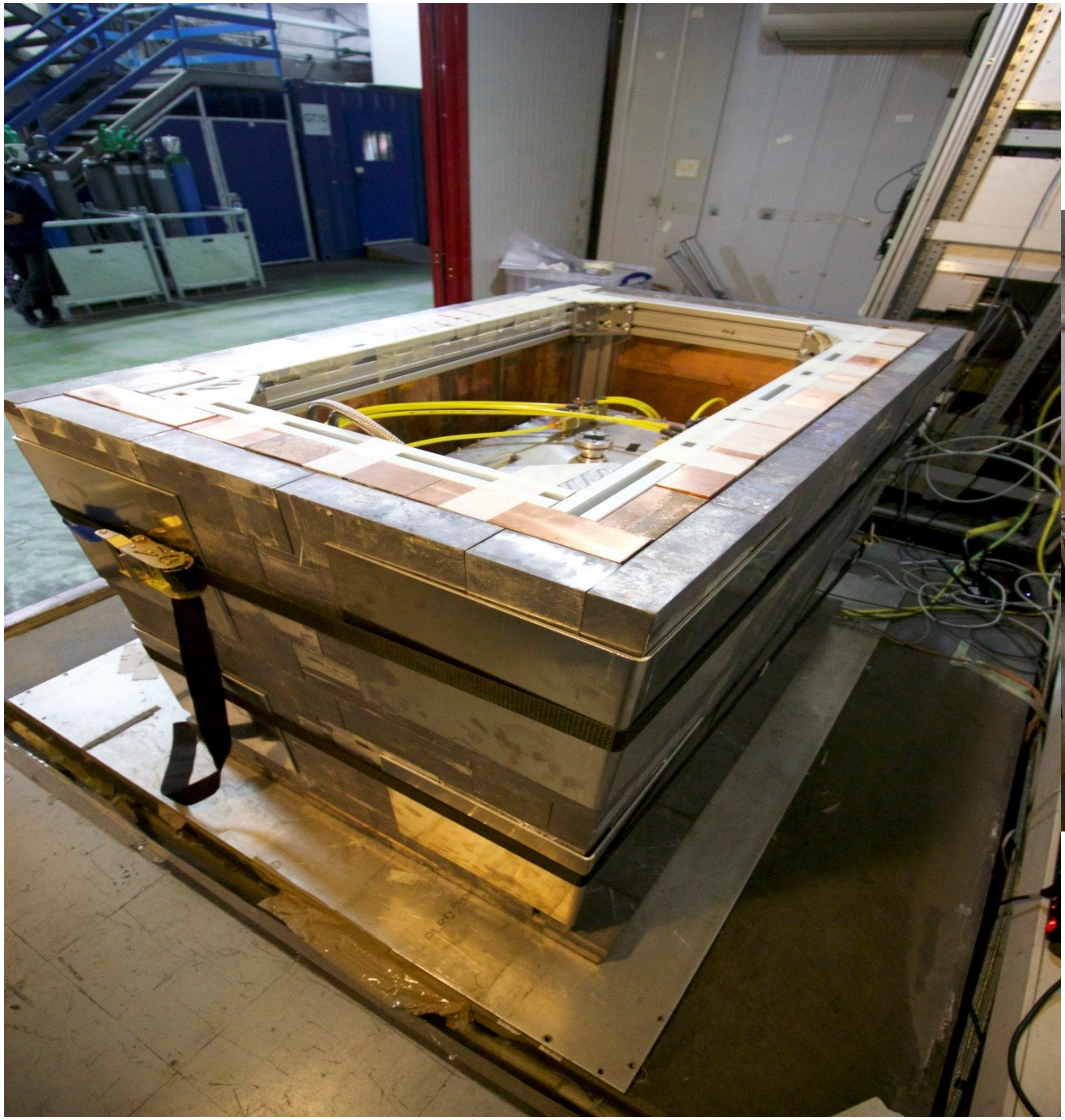
VIP-2 goal 2 OM improvement

Passive scielding → two layers, copper inside lead outside



VIP-2 final configuration

Upgrade concluded in April 2019:



VIP-2 (open system) preliminary results

Picture: Danilo Pivato © copyright - All rights reserved

May. 2019 – Jan. 2020 Data analysis

Upper limit on the PEP violation probability is obtained extracting the p.d.f. of the expected violation signal contribution S :

$$p(S,B|\text{data}) = \frac{p(\text{data}|S,B)\cdot p_0(S)\cdot p_0(B)}{\int p(\text{data}|S,B)\cdot p_0(S)\cdot p_0(B)\,dS\,dB}.$$

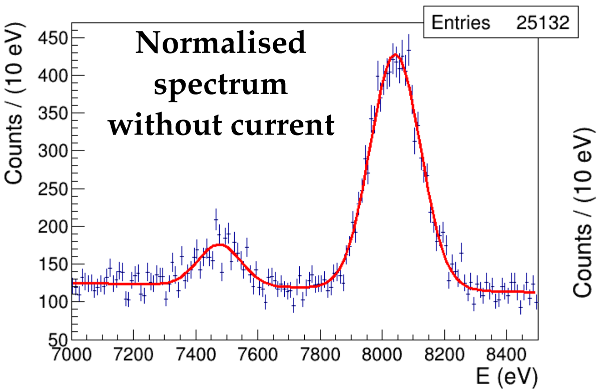
Joint *p.d.f.*
Bin contents fluctuate around the mean according to a Pois. Dist.

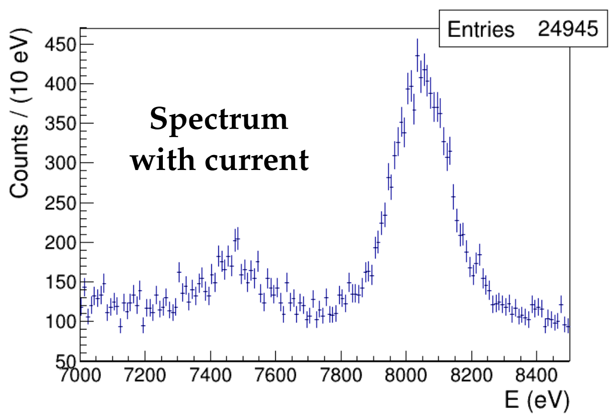
Likelihood →
$$P(data|S,B) = \prod_{i=1}^{N} \frac{\lambda_i(S,B)^{n_i}\cdot e^{-\lambda_i(S,B)}}{n_i!}$$

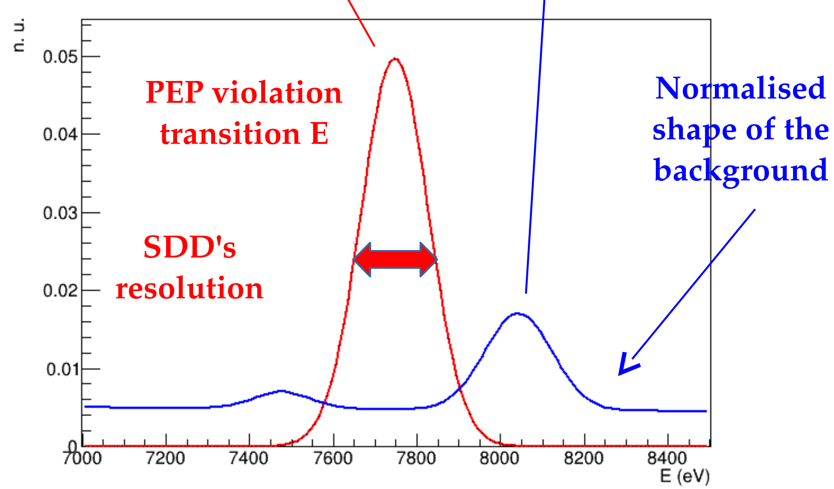
Posterior *p.d.f.* (model needs in input the bkg. and sig. normalised shapes):

$$P(S|data) = \int P(S,B|data)\; dB \qquad \lambda_i = \lambda_i(S,B) = S\cdot\int_{\Delta E_i} f_S(E)dE + B\cdot\int_{\Delta E_i} f_B(E)dE,$$

Background → fit of the bkg spectrum. Signal → theory convoluted with exp. resolution







May. 2019 – Jan. 2019 Data analysis

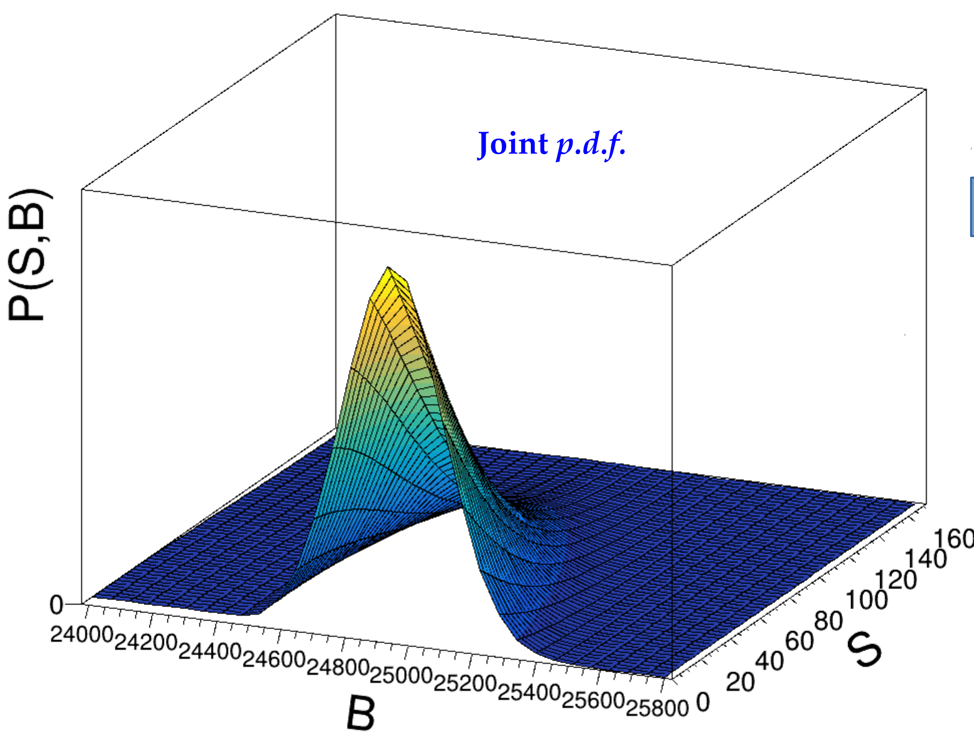
The prior probability for S is flat up to a maximum S_{max} consistent with existing limits [Eur. Phys. J. C (2018) 78:319].

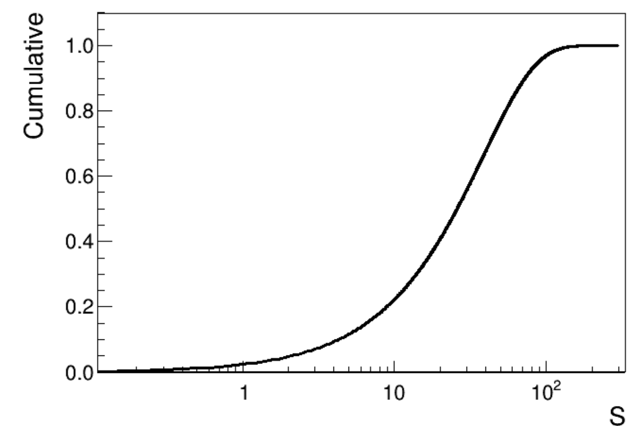
$$p_0(S) = \begin{cases} \frac{1}{S_{max}} & 0 \leq S \leq S_{max} \\ 0 & \text{otherwise} \end{cases}$$

The mean value for the expected number of bkg. Events μ_b obtained from bkg. Spectrum. Prior is Gaussian with a width $\sigma_b = \mu_b/2$.

$$p_0(B) = \begin{cases} \frac{e^{-((B-\mu_B)^2/2\sigma_B^2)}}{\int_0^\infty e^{-((B-\mu_B)^2/2\sigma_B^2)} dB} & B \geq 0 \\ 0 & B < 0 \end{cases}$$

Posterior from Markow chain Monte Carlo calculation:





From which an upper limit on the PEP violation probability is obtained (90% Probability):

$$\frac{\beta^2}{2} < \frac{\bar{S}}{N_{free} \cdot N_{int} \cdot P_{cpt} \cdot \epsilon_{tot}}$$

$$\beta^2/2 < 9.9 \cdot 10^{-31}$$

Preliminary
In about 100 days

K.P., et al. Condens. Matter 2019, 4(2), 45


Non-commutative space-time induced PEP violation
VIP-closed systems
Picture: Danilo Pivato © copyright - All rights reserved

A new paradigm in experimental tests of quantum gravity models

Are Quantum Gravity models experimentally testable?

A. Addazi (Chengdu Univ.)   A. Marcianò (Fudan University)

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

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.

See also A. Addazi et al., 2018 Chinese Phys. C 42 094001, arXiv:1712.08082 [hep-th]

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 $(E/\Lambda)^n$, n 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.

PEP violation in quantum gravity

Differences of θ-Poincarè w. r. to effective models:

- does not respect the M-G superselection rule (transition amplitude from a state of two different fermions to a state of two identical fermions is not zero) →

can be tested with closed systems (ex. using cunduction electrons in the conductor as test electrons, no current);

- the violation probability depends on the PEP violating process transition energy (suppressed with the non-commutativity energy scale) →

it is important to test different atomic species → different Z → different ΔE for the measured transition;

Preliminary test was already performed for $_{82}$Pb, we plan to repeat with other elements ($_{73}$Ta, $_{23}$V ...)

Pb target HPGe detector at LNGS

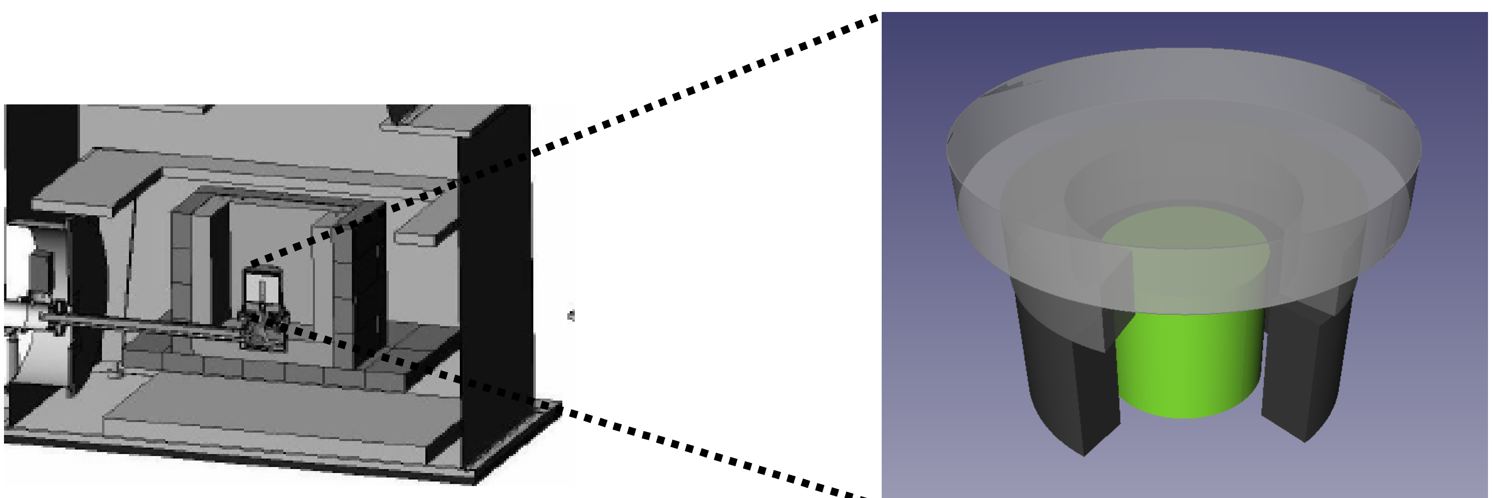
High purity Ge detector measurement:

- Ge detector surrounded by roman lead target + complex electrolytic Cu + Pb shielding

- 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).

To appear in EPJ C



Testing new materials: Pb target HPGe detectord

Extremely low statistics in the two ROI regions compatible with the mean bkg: b = 4.4 counts/keV

Transitions in Pb	forb.	allow.
1s - $2p_{3/2}$ $K_{\alpha 1}$	73713	74961
1s - $2p_{1/2}$ $K_{\alpha 2}$	71652	72798

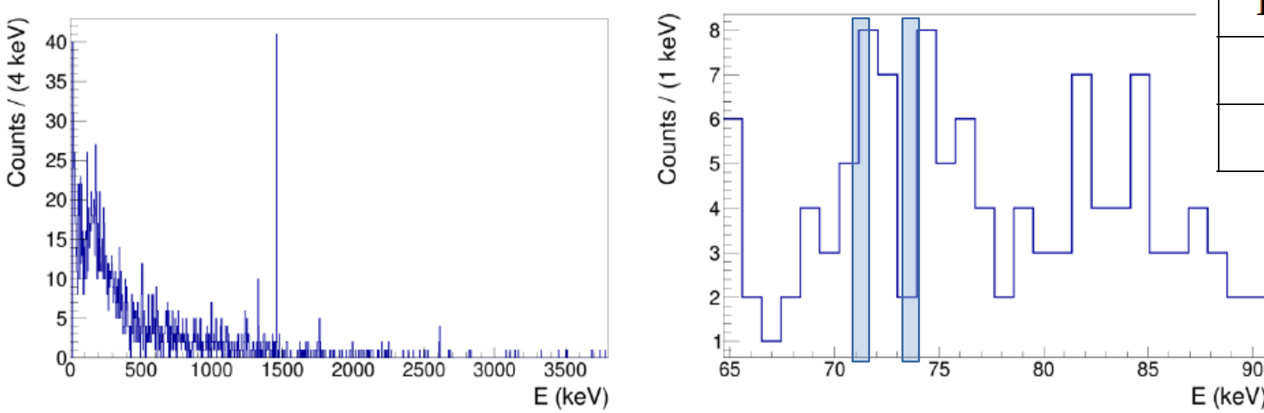
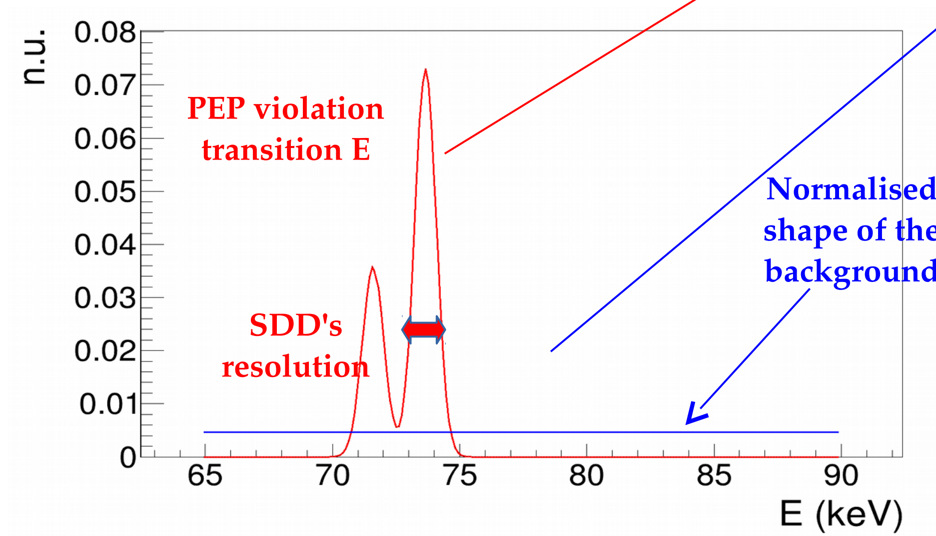


Figure 1. Total measured X-ray spectrum (left); same spectrum in the region of the K_α standard and violating transitions in Pb (right).

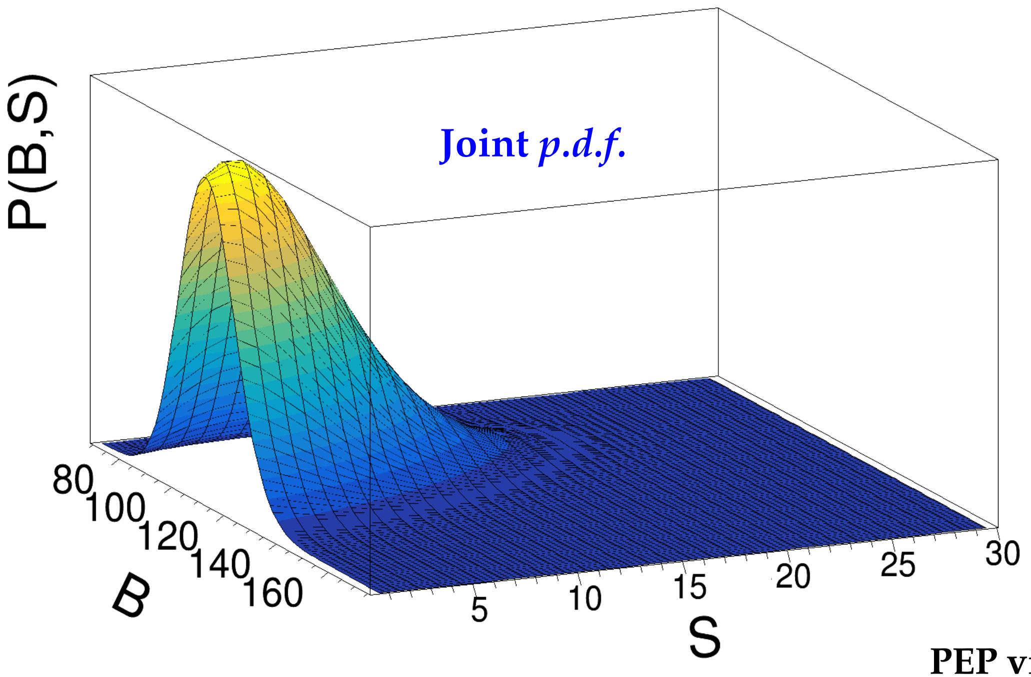
$$\lambda_i = \lambda_i(S, B) = S \cdot \int_{\Delta E_i} f_S(E)dE + B \cdot \int_{\Delta E_i} f_B(E)dE,$$

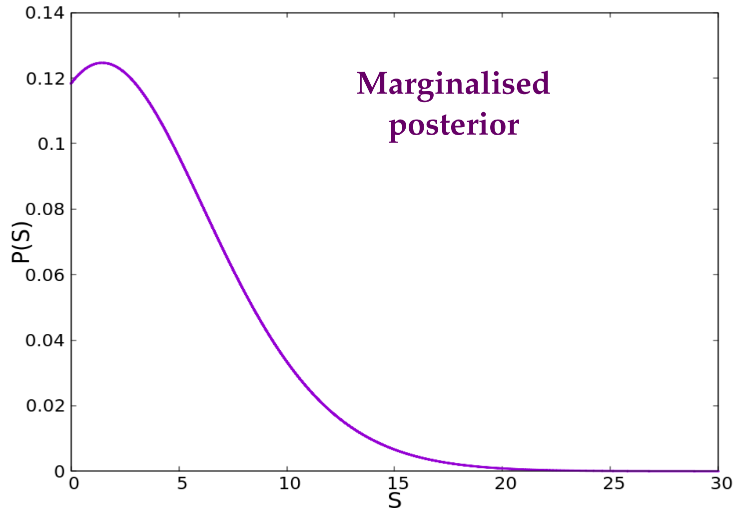
The prior probability for the number of expected signal events is assumed flat up to a maximum S_{max} consistent with existing limits [Eur. Phys. J. C (2018) 78:319].

$$p_0(S) = \begin{cases} \frac{1}{S_{\max}} & 0 \leq S \leq S_{\max} \\ 0 & \text{otherwise} \end{cases}$$

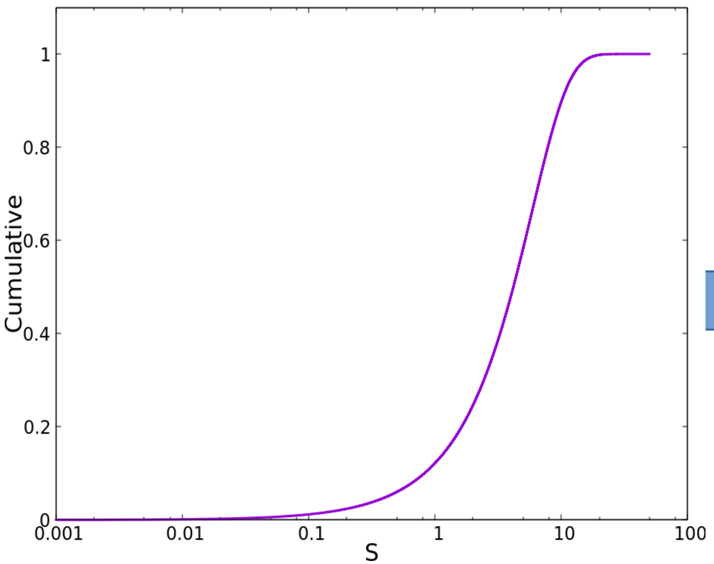


VIP-2 Pb results





From which an upper limit on the PEP violation probability is obtained (90% Probability):



$$\delta^2 = \frac{\beta^2}{2} < \frac{\bar{S}_1 + \bar{S}_2}{\epsilon_{tot} \cdot N_{free} \cdot (\frac{\Delta t_1 + \Delta t_2}{\tau_E}) + \epsilon_{tot} \cdot N_{Pb} \cdot (\frac{\Delta t_1 + \Delta t_2}{\tau_0})}$$

$$\delta^2 < 3.1 \cdot 10^{-46}$$

K-Poincarè - excluded up to $\Lambda > 10^{22}$ Planck scale

θ-Poincarè - excluded up to $\Lambda > 0.3$ Planck scale


spontaneous radiation –
X-ray test for collapse models
Picture: Danilo Pivato © copyright - All rights reserved

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 ~ 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 prediction ~ 1 fm

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

HPGe detector based experiment @ LNGS

- **shield + cryostat enclosed in air tight steel housing flushed with nitrogen to avoid contact with radon.**

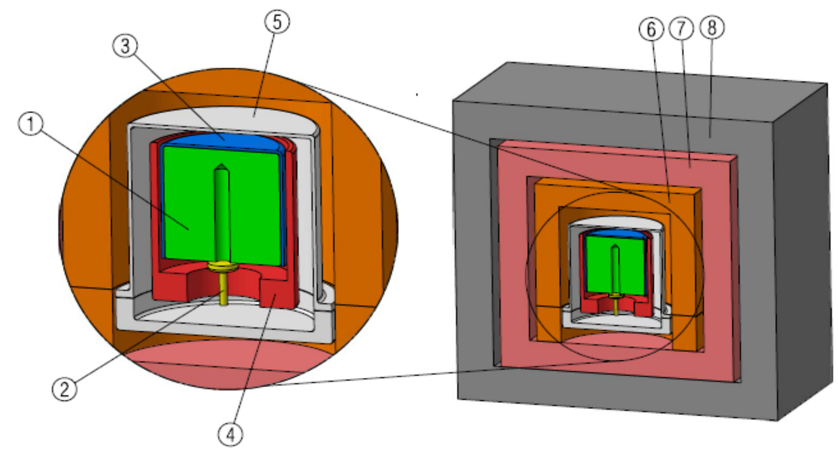


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

HPGe detector based experiment @ LNGS

three months data taking with 2kg Germanium active mass

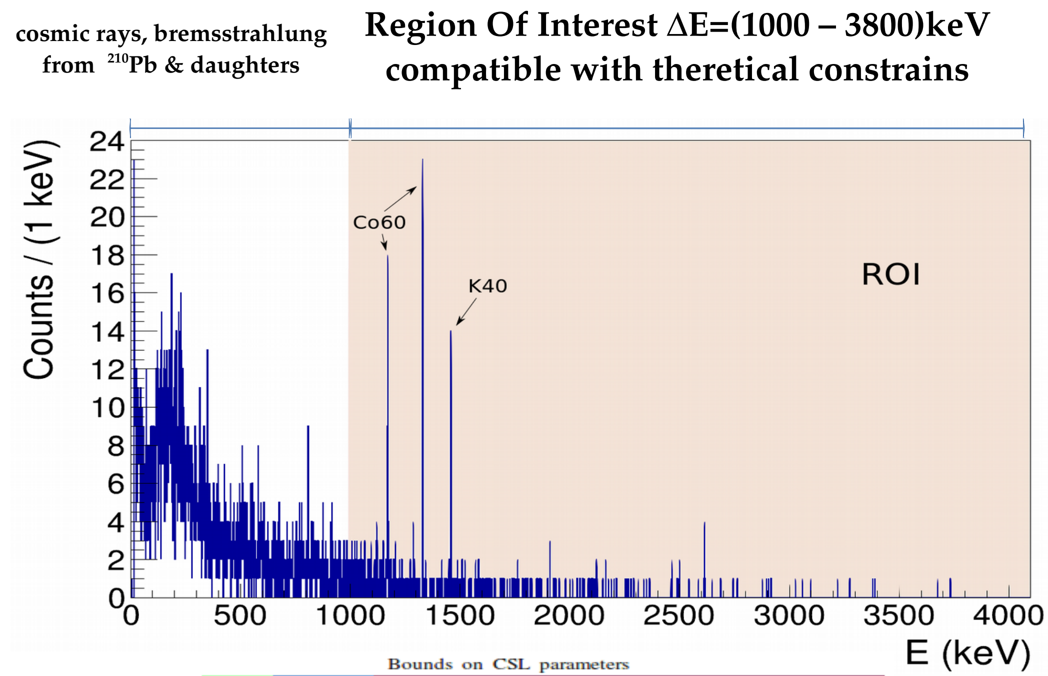
the pdf of the models parameters is obtained within a Bayesian model:

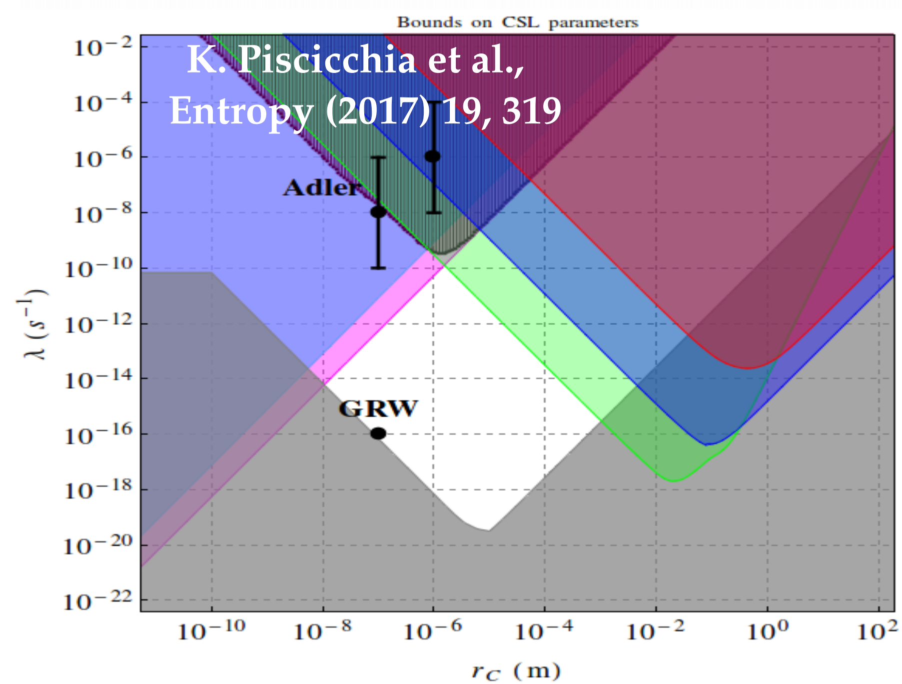
$$\tilde{p}\left(\Lambda_c | p(z_c|\Lambda_c)\right) = \frac{\Lambda_c^{z_c}\, e^{-\Lambda_c}\, \theta(\Lambda_c^{max} - \Lambda_c)}{\int_0^{\Lambda_c^{max}} \Lambda_c^{z_c}\, e^{-\Lambda_c}\, d\Lambda_c}$$

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

→ Diosi-Penrose excluded

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

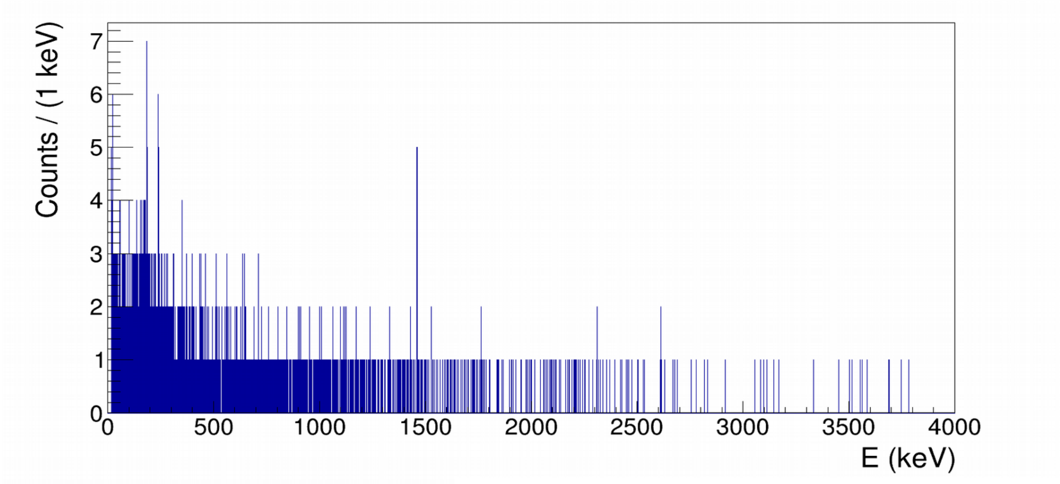


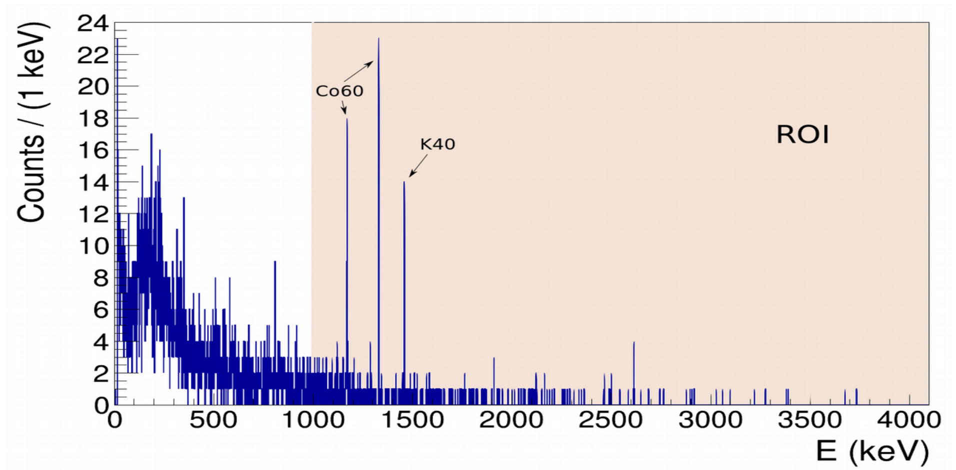


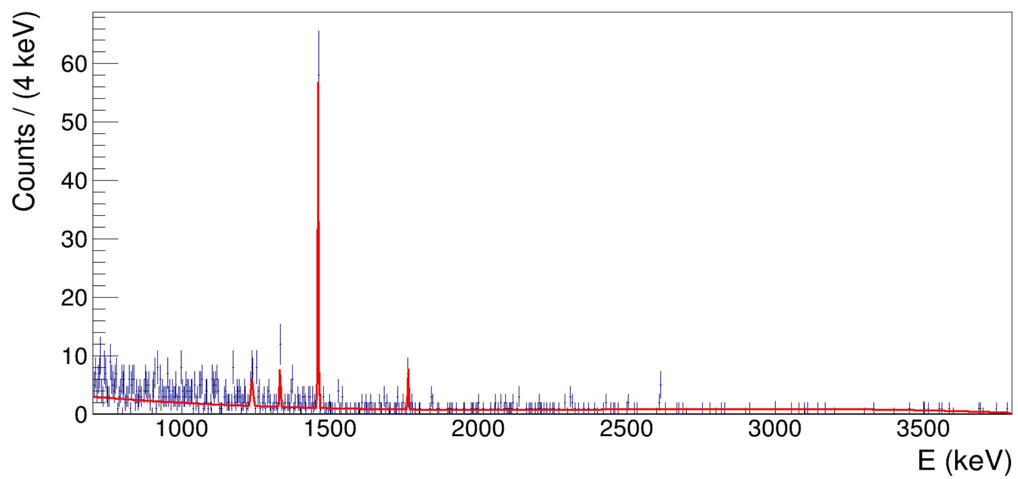

Thanks

Future perspectives

HPGe detector + ultrapure Pb active shielding:







BEGe detector + pulse shape discrimination

pushing the lower E threshold to few keV

The β parameter

$$N_X \geq \frac{1}{2} \beta^2 N_{new} \frac{N_{\text{int}}}{10} = \frac{\beta^2 (\Sigma I \Delta t) D}{e \mu \rho z \sigma}$$

$$\int_T I(t)\, dt = 15.44 \cdot 10^6\, C$$

$$D = 0.025\, m$$

$$m = 3.9 \cdot 10^{-8}\, m$$

$$\rho = 8.96 \cdot 10^3\, kg \cdot m^{-3}$$

$$s = 10\, m^2 \cdot kg^{-1}$$

$$z = 1.5 \cdot 10^{-3}\, m$$

$$N_X \geq \beta^2 (0.90 \cdot 10^{28})$$

$$\beta^2 / 2 \leq 1.7 \cdot 10^{-26}\ (>95\ C.L.)$$

The β parameter

Ignatiev & Kuzmin model ➡ **creation and destruction operators connect 3 states**

- ***the vacuum state*** $|0\rangle$
- ***the single occupancy state*** $|1\rangle$
- ***the <u>non-standard</u> double occupancy state*** $|2\rangle$

through the following relations:

$a^{+}|0|1$

$a^{+}|1=\beta\,|2a^{+}|2=0$

$a|0\ 0$

$a|1$

$=|0a|2=\beta\,|1$

The parameter β quantifies the degree of violation in the transition.

$|1\rangle \rightarrow |2\rangle$

It is very small and for <u>$\beta \rightarrow 0$</u> we recover the <u>Fermi - Dirac statistic</u>.

The β parameter

this β can be simply related to the *q* parameter of the quon theory of Greenberg and Mohapatra

$$\frac{1}{2}\beta^2 = \frac{1+q}{2}$$

quon algebra is a sort of weighted average between fermion and boson algebra:

$$\frac{1+q}{2}\left[a_k, a_l^+\right]_- + \frac{1-q}{2}\left[a_k, a_l^+\right]_+ = \delta_{kl}$$

or also

$$a_k a_l^+ - q a_l^+ a_k = \delta_{kl}$$

Best Limits for PEP Violation

Nuclear transition	${}^{12}C \rightarrow {}^{11}B + p$	BOREXINO	$\frac{\beta^2}{2} < 7.4 \cdot 10^{-60}$	G. Bellini et al., PRC 81 (2010) 034,317
Atomic transition	$I \rightarrow I + \gamma$	DAMA	$\frac{\beta^2}{2} < 1{,}28 \cdot 10^{-47}$	R. Bernabei et al., Eur. Phys. J. C62 (2009) 327
	$Ge \rightarrow Ge + \gamma$ (K_α)	MALBEK	$\frac{\beta^2}{2} < 2{,}92 \cdot 10^{-47}$	N.Abgrall et al., Eur. Phys. J. C (2016) 76.

PHYSICAL REVIEW C 81, 034317 (2010)

New experimental limits on the Pauli-forbidden transitions in ^{12}C nuclei obtained with 485 days Borexino data

G. Bellini,[1] S. Bonetti,[1]
L. Ludhova,[1] E. Meroni,[1]
F. Calaprice,[4] A. Chavan
J. Xu,[4] C. Carraro,[5] S. D
S. Zavatarelli,[5] H. de Ker
I. Machulin,[8] A. Sabelni
S. Gazzana,[10] C. Ghiano,[10] Aldo Ianni,[10] G. Korga,[10] D. Montanari,[10] A. Razeto,[10] R. Tartaglia,[10] M. Goeger-Neff,[11]
T. Lewke,[11] Q. Meindl,[11] L. Oberauer,[11] F. von Feilitzsch,[11] Y. Winter,[11] M. Wurm,[11] C. Grieb,[12] S. Hardy,[12] M. Joyce,[12]
S. Manecki,[12] L. Papp,[12] R. S. Raghavan,[12] D. Rountree,[12] R. B. Vogelaar,[12] W. Maneschg,[13] S. Schönert,[13] H. Simgen,[13]
G. Zuzel,[13] M. Misiaszek,[14] M. Wojcik,[14] F. Ortica,[15] and A. Romani[15]
(Borexino Collaboration)

However: Stable system transitions !

Nuclear Physics in Astrophysics IV — IOP Publishing
Journal of Physics: Conference Series 202 (2010) 012039 — doi:10.1088/1742-6596/202/1/012039

...Exclusion

...J. Dai[6],
A.d'Angelo..., H.L. He..., A. Incicchitti..., H.H. Kuang[6], X.H. Ma[6],
F. Montecchia[7,2], F. Nozzoli[1,2], D. Prosperi[3,4], X.D. Sheng[6], Z.P. Ye[6,8]
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[3] Dip. di Fisica, Università di Roma "La Sapienza", I-00185 Rome, Italy
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[7] Lab. Sperimentale Policentrico di Ingegneria Medica, Università di Roma "Tor Vergata"
[8] University of Jing Gangshan, Jiangxi, China

Abstract. Searches for non-paulian nuclear processes, i.e. processes normally forbidden by the Pauli-Exclusion-Principle (PEP) with highly radiopure NaI(Tl) scintillators allow the test of this fundamental principle with high sensitivity. Status and perspectives are briefly addressed.

PEP Tests with atomic transitions

From S.R. Elliott et al., Found. Phys. 42 (2012) 1015

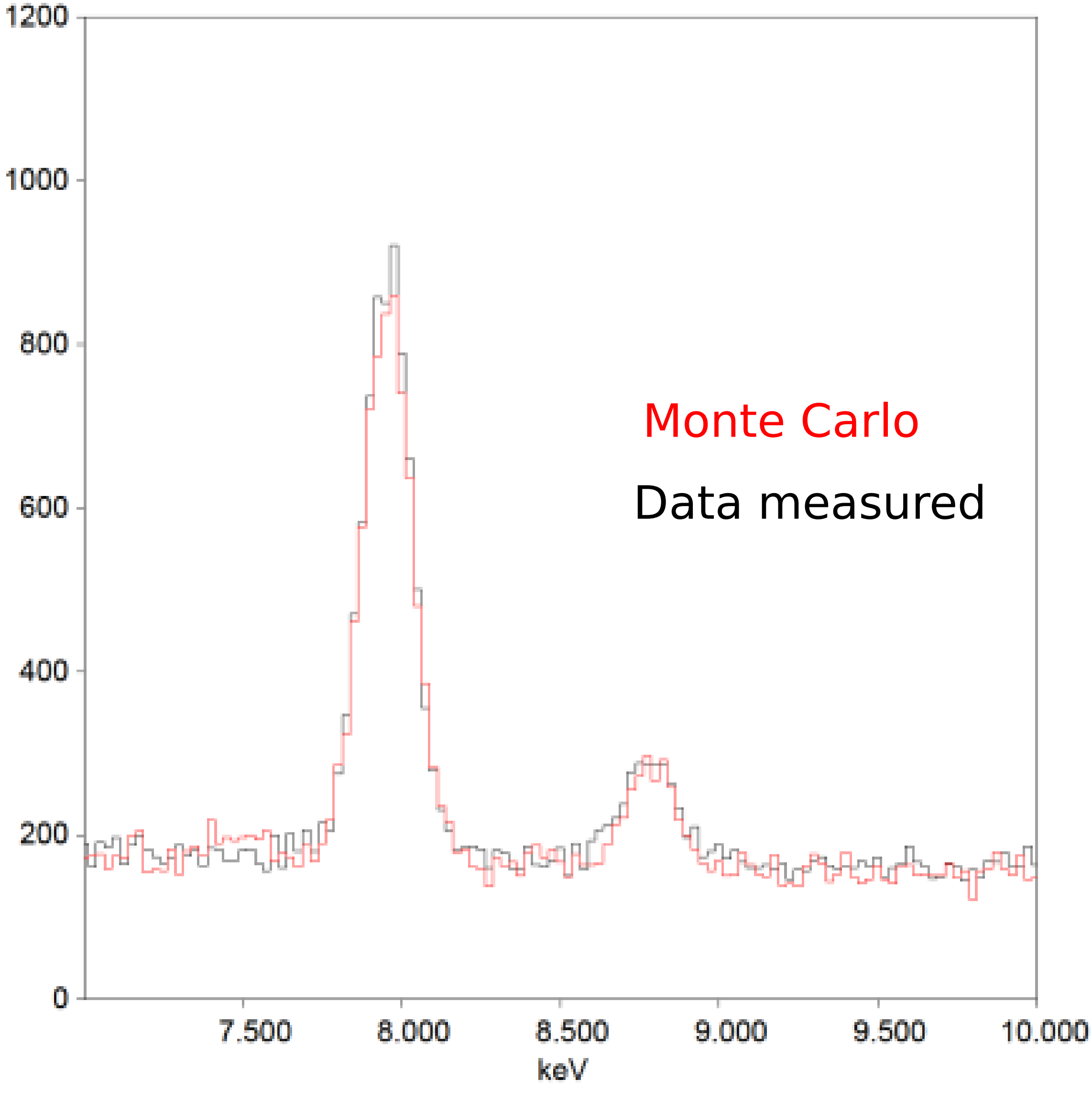
Process	Type	Experimental limit	$\frac{1}{2}\beta^2$ limit
Atomic transitions			
$\beta^- + \mathrm{Pb} \rightarrow \check{\mathrm{Pb}}$	Ia		3×10^{-2}
$e^-_{pp} + \mathrm{Ge} \rightarrow \check{\mathrm{Ge}}$	Ia		1.4×10^{-3}
$e^-_I + \mathrm{Cu} \rightarrow \check{\mathrm{Cu}}$	II		1.7×10^{-26}
$e^-_I + \mathrm{Cu} \rightarrow \check{\mathrm{Cu}}$	II		4.5×10^{-28}
$e^-_I + \mathrm{Cu} \rightarrow \check{\mathrm{Cu}}$	II		6.0×10^{-29}
$e^-_I + \mathrm{Pb} \rightarrow \check{\mathrm{Pb}}$	II		1.5×10^{-27}
$e^-_f + \mathrm{Pb} \rightarrow \check{\mathrm{Pb}}$	IIa		2.6×10^{-39}
$\mathrm{I} \rightarrow \check{\mathrm{I}} + \text{X-ray}$	III	$\tau > 2 \times 10^{27}$ sec	3×10^{-44}
$\mathrm{I} \rightarrow \check{\mathrm{I}} + \text{X-ray}$	III	$\tau > 4.7 \times 10^{30}$ sec	6.5×10^{-46}

Recently created fermions interacting with system

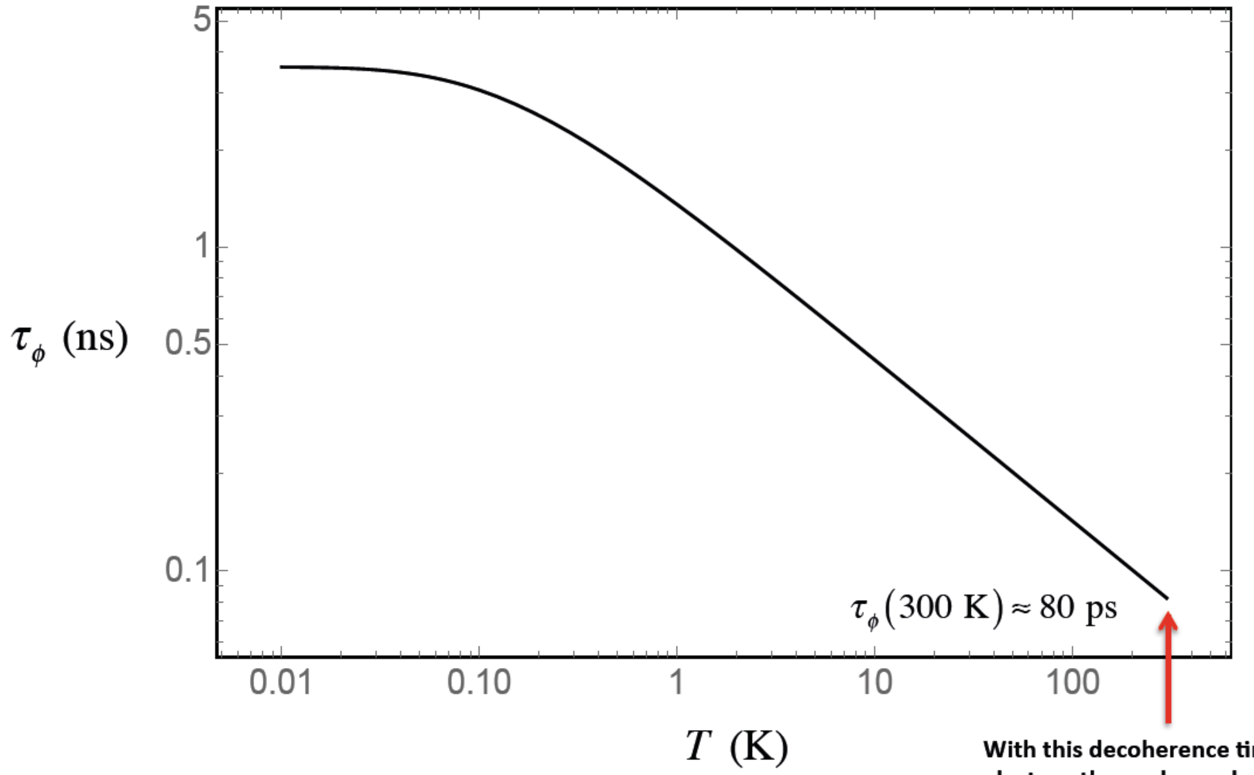
Distant fermions interacting with system

Stable system transition

LNGS Background studies with Monte-Carlo



Electron decoherence time at room temperature

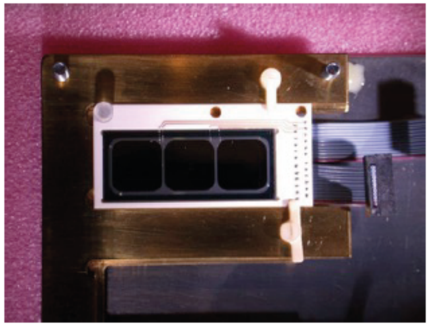


E. Milotti, Talk, May 29, 2015, Vienna

With this decoherence time and the electron thermal speed we find a decoherence length of about 10 μm

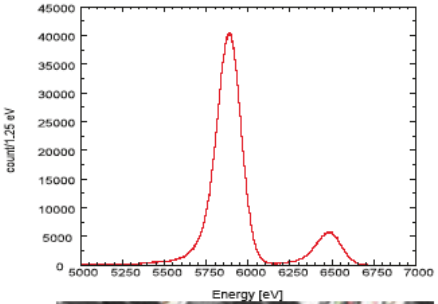
The conclusion is that after a time of the order of the *decoherence time* the electron wavefunctions are effectively decoupled and the environment acts on electrons by enforcing an effective locality.

Improved experiment VIP2



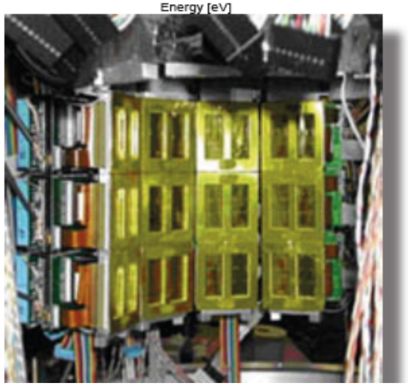
- Large (1 cm^2) SDDs provide excellent energy resolution (even superior than CCDs at 8keV)

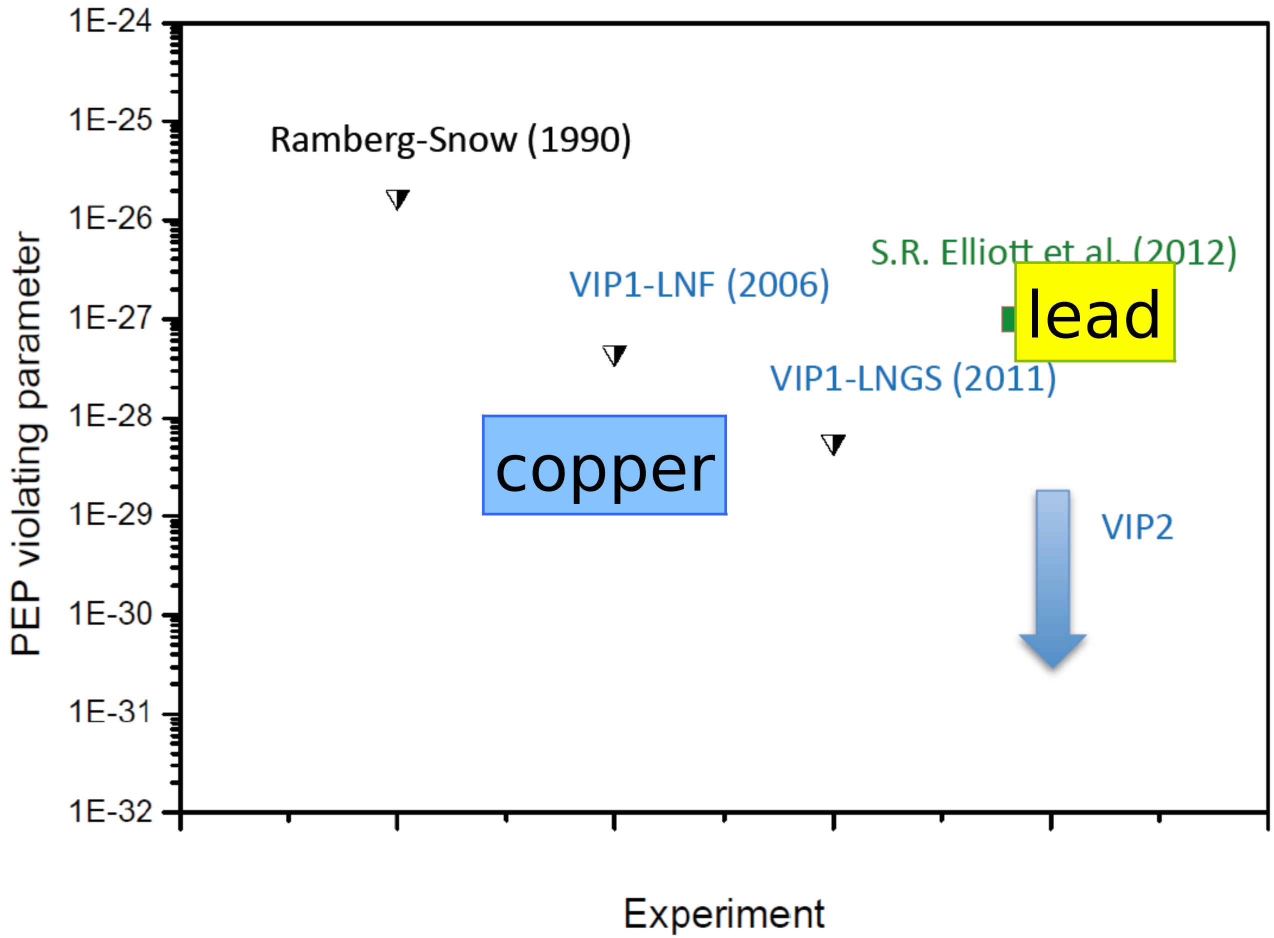
- Timing capability for triggering



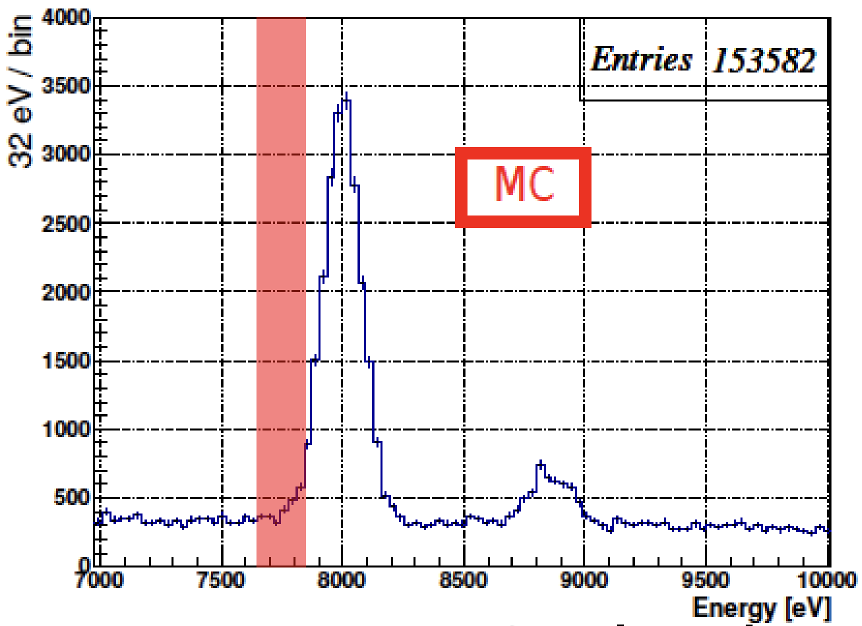
- Compact design suitable for gaining larger solid angle

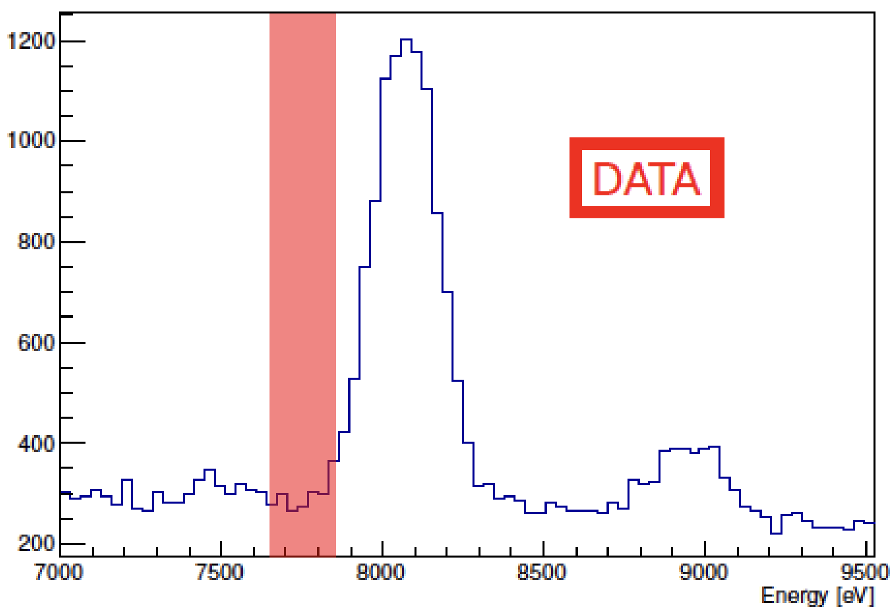
- Successfully used in the detection of kaonic atom x-ray spectroscopy at DAFNE (SIDDHARTA) with large background reduction




1E-24
1E-25
1E-26
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
PEP violating parameter
Ramberg-Snow (1990)
S.R. Elliott et al. (2012)
VIP1-LNF (2006)
lead
VIP1-LNGS (2011)
copper
VIP2
Experiment

Comparison MC and Data @ LNGS

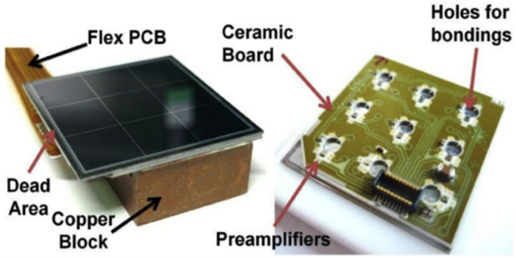




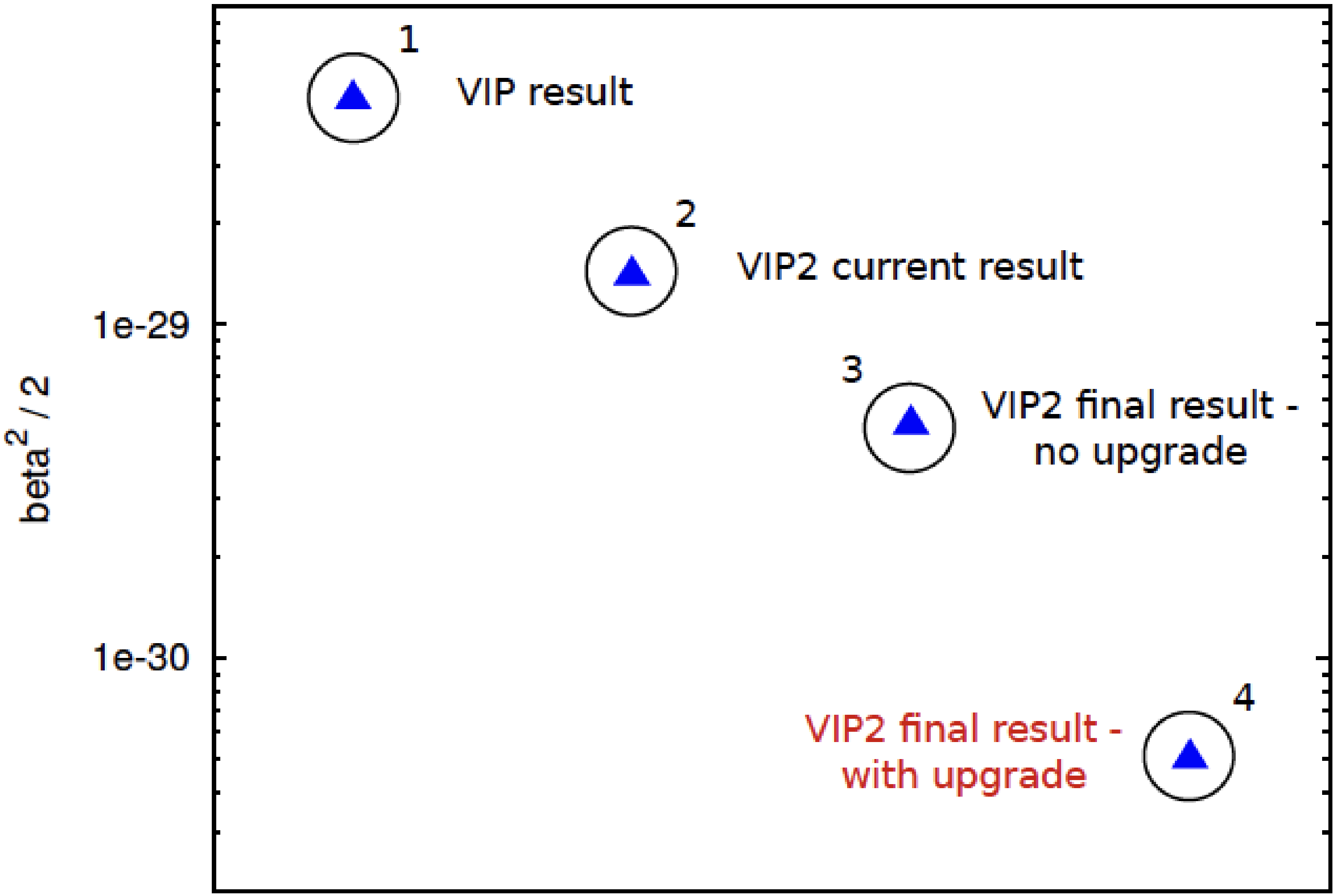
Monte Carlo simulation of 30 days data taking and actual data taken in 30 days

Future Research Plan

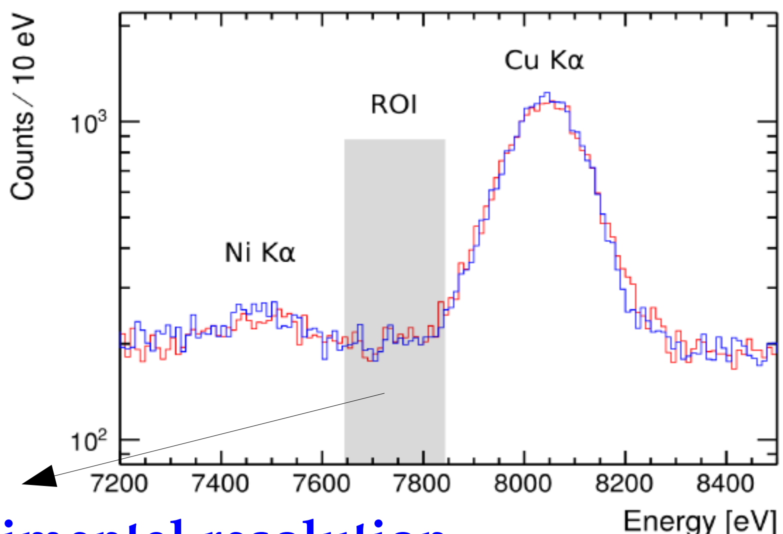
- Installation of part of the passive shielding
- New SDD detector system with new copper targe
- In 2017 new copper target with new SDDs will be installed
- Optimized shielding with data taking of about 3 years (i.e. approx. 2020)
- Goal after 3 years data taking with and without current
  → 10^2 improvement of VIP limit

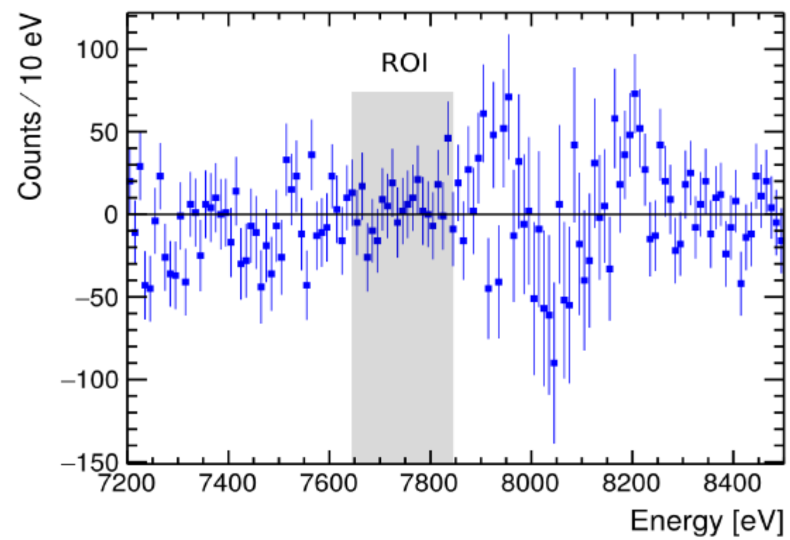


Toward the final result



pre-VIP-2 (w.o. shielding) results





experimental resolution

The data measured at LNGS with current (red) and without current (blue) on the left side. The subtracted spectrum is shown on the right. No excess of events is found in the region of interest (ROI - grey) of the searched PEP violating.

3s of the subtracted number of counts in the ROI

$$\Delta N_x \geq \frac{\beta^2}{2}\frac{1}{10}\frac{D\sum(I\Delta t)}{\mu e}(\text{detection efficiency})$$

$$\frac{\beta^2}{2} \leq \frac{10\mu e}{D\sum(I\Delta t)}\frac{\Delta N_x}{(\text{detection efficiency})}$$

mean free path μ	target length D	current I	data taking time Δt	detection efficiency
3.91×10^{-6} cm	7.1 cm	100 A	81 days 10 hours	1.82 %

$$\frac{\beta^2}{2} \leq \frac{3\times 91}{1.46\times10^{31}} = 1.87\times10^{-29}$$

factor 2.5 gain respect to VIP

pre-VIP-2 (w.o. shielding) results

Same data set - simultaneous fit of the "sig + bkg" and bkg spectra, in order to use all the information available for the background shape from the data. The obtained fits:

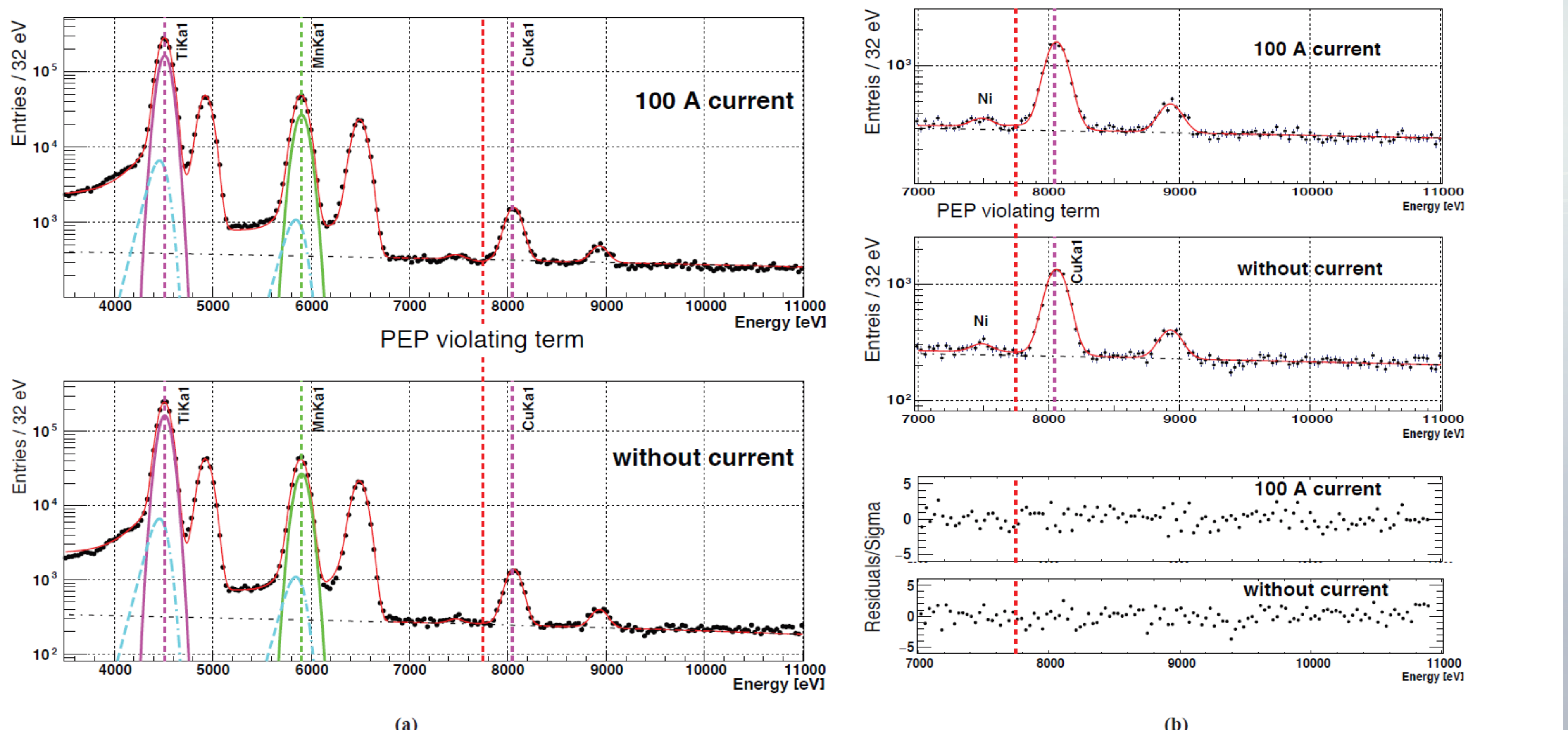


Fig. 8 A global chi-square function was used to fit simultaneously the spectra with and without 100 A current applied to the copper conductor. The energy position for the expected PEP violating events is about 300 eV below the normal copper $K_{\alpha 1}$ transition. The Gaussian function and the tail 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 keV to 11 keV range where there is no background coming from the calibration source.

pre-VIP-2 (w.o. shielding) results

Detalis of the analysis can be found in :

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

Present limit with all the pre-VIP2 collected satatistiscs :

$$\frac{\beta^2}{2} \leq \frac{3 \times 82}{1.46 \times 10^{31}} = 1.69 \times 10^{-29}$$

Paper in preparation

pre-VIP-2 (w.o. shielding) results

Deeper investigation of the electrons diffusion and interaction in a bulk-matter:

On the Importance of Electron Diffusion in a Bulk-Matter Test of the Pauli Exclusion Principle, Entropy 2018, 20(7), 515; https://doi.org/10.3390/e20070515:

MDPI

Article

On the importance of electron diffusion in a bulk-matter test of the Pauli Exclusion Principle

Edoardo Milotti[1,*], Sergio Bartalucci[2], Sergio Bertolucci[3], Massimiliano Bazzi[2], Mario Bragadireanu[2,4], Michael Cargnelli[2,5], Alberto Clozza[2], Catalina Curceanu[2,4,6], Luca De Paolis[2], Jean-Pierre Egger[7], Carlo Guaraldo[2], Mihail Iliescu[2], Matthias Laubenstein[8], Johann Marton[2,5], Marco Miliucci[2], Andreas Pichler[2,5], Dorel Pietreanu[2,4], Kristian Piscicchia[2,6], Alessandro Scordo[2], Hexi Shi[9], Diana Laura Sirghi[2,4], Florin Sirghi[2,4], Laura Sperandio[2], Oton Vazquez Doce[2,10], Eberhard Widmann[5] and Johann Zmeskal[2,5]

The random walks of the electrons as they move from the entrance to the exit of the copper sample is fully described in terms of a diffusion transport model.

PEP violation studies with Pb target & Ge detector

S.R. Elliott et al., Found Phys (2012) 42:1015–1030

relax the definition of *new* (fermion – fermion system interaction) giving rise to violating Ψ_{sym} .

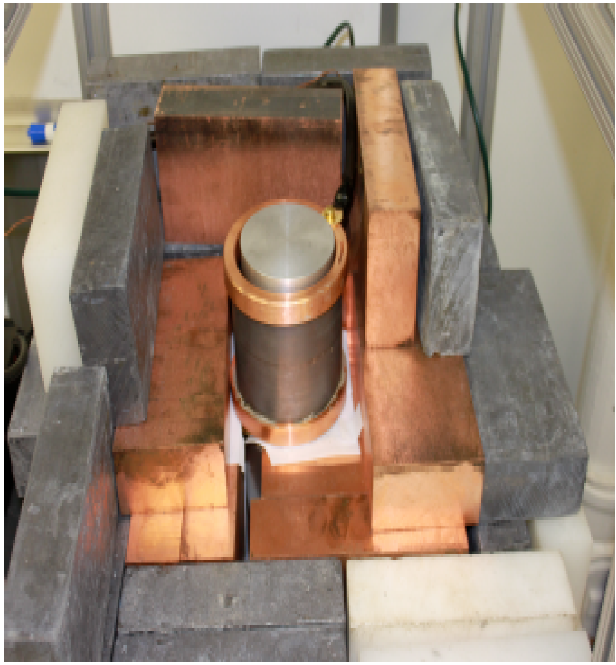
Exploit free electrons in a conductor (Pb is ideal) → specific electron – specific atom interactions are so rare $\sim 10^4$ ys each interaction is a new PEP test

$$\frac{1}{2}\beta^2 < \frac{N_{3\sigma}}{\epsilon_{tot}} \frac{1}{P_{cpt} N_{new}^{free} N_{int}^{free}}$$

where N_{int}^{free} and N_{new}^{free} are given by

$$N_{int}^{free} = \Delta t \frac{v_f}{\mu}$$

$$N_{new}^{free} = N_e V$$



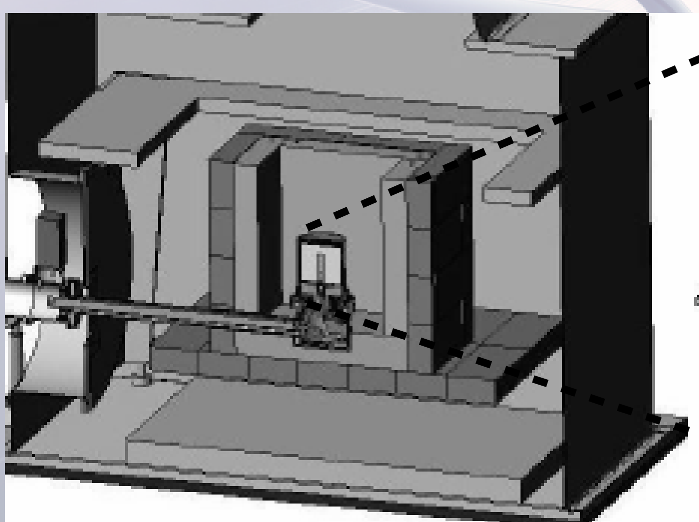
VIP lead with HPGe & LNGS

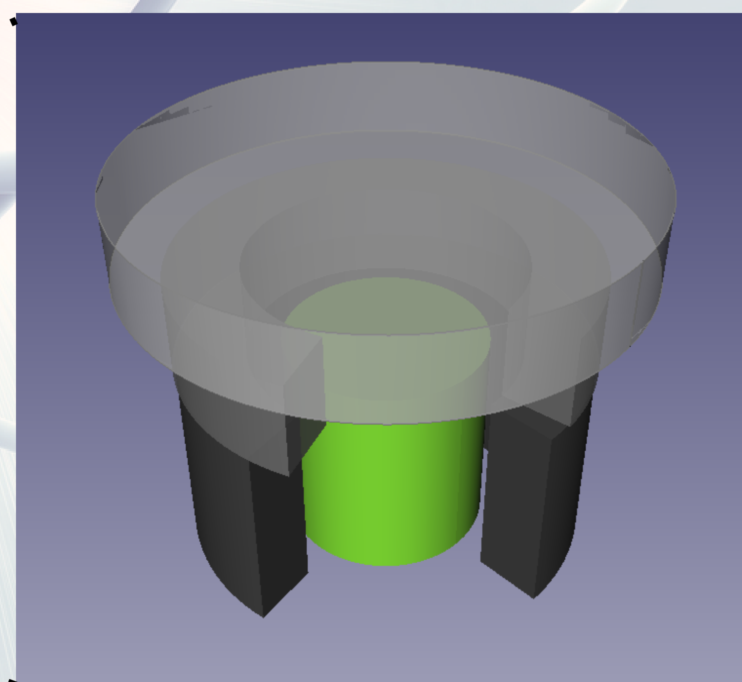
High purity Ge detector measurement:

- Ge detector surrounded by roman lead target + complex electrolytic Cu + Pb shielding

- 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).





VIP lead with HPGe & LNGS

What does rare interactions mean? How many "violating electrons" in the roman lead block could already do violating transitions?

$$P(k) = \frac{(T/N\tau)^k}{k!}\exp(-T/N\tau), \quad \longrightarrow \quad p = P(0) = \exp(-T/N\tau),$$

$$\begin{aligned} p &= \exp(-T/N\tau) + (1 - P_{\text{cpt}})\frac{(T/N\tau)}{1!}\exp(-T/N\tau) + \cdots + (1 - P_{\text{cpt}})^k \frac{(T/N\tau)^k}{k!}\exp(-T/N\tau) + \ldots \\ &= \sum_{k=0}^{k=\infty}(1 - P_{\text{cpt}})^k \frac{(-T/N\tau)^k}{k!}\exp(-T/N\tau) \\ &= \exp\left[-T/(N\tau/P_{\text{cpt}})\right], \end{aligned}$$

so the PEP violation probability is to be corrected accordingly:

$$\frac{\beta^2}{2}\exp(-T_i P_{\text{cpt}}/N\tau) < \frac{N_X}{\epsilon_{\text{tot}} P_{\text{cpt}} N_{\text{free}} N_{\text{int}}}$$

considering our 119 moles of roman Pb samples:

$$\exp(-T_i P_{\text{cpt}}/N\tau) \approx 1.$$

VIP lead with HPGe & LNGS

Extremely low statistics in the two ROI regions compatible with the mean bkg: b = 4.4 counts/keV

Transitions in Pb	forb.	allow.
1s - $2p_{3/2}$ $K_{\alpha 1}$	73713	74961
1s - $2p_{1/2}$ $K_{\alpha 2}$	71652	72798

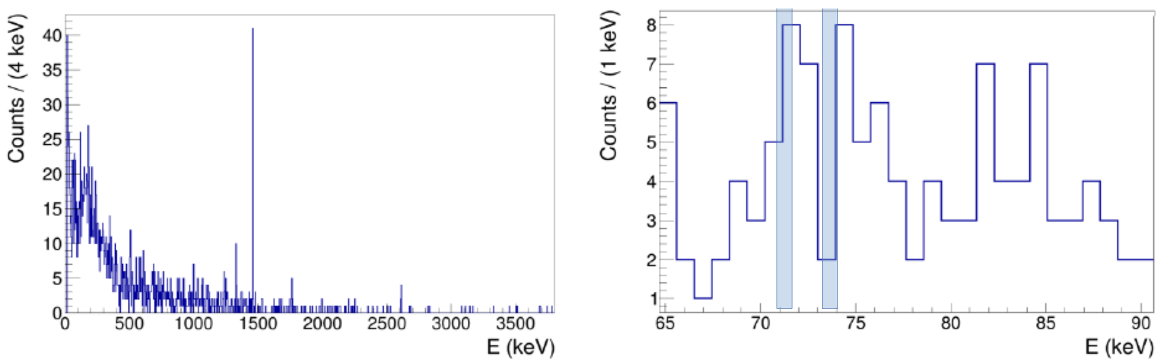
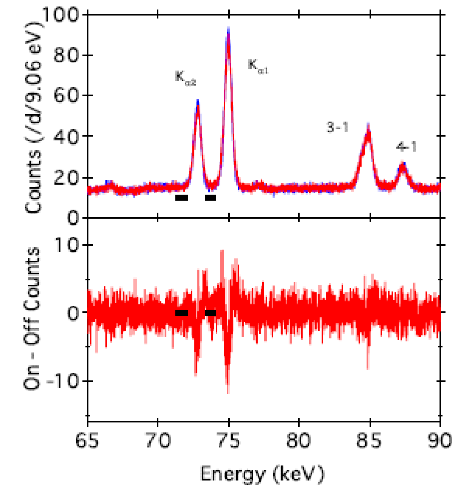


Figure 1. Total measured X-ray spectrum (left); same spectrum in the region of the K_α standard and violating transitions in Pb (right).



S.R. Elliott et al., Found Phys (2012) 42:1015–1030

The p value (probability of having measured an excess with respect to b in the two ROIs):

$$p = \sum_{j=z_1+1}^{\infty} \frac{b^{z_1}}{z_1!} \exp(-b) \sum_{j=z_2+1}^{\infty} \frac{b^{z_2}}{z_2!} \exp(-b) = \left[1 - \sum_{j=0}^{z_1} \frac{b^{z_1}}{z_1!} \exp(-b)\right] \left[1 - \sum_{j=0}^{z_2} \frac{b^{z_2}}{z_2!} \exp(-b)\right]$$

p = 0.051 corresponding to 1.95 standard deviations.

$$\frac{1}{2}\beta^2 < 1.58 \cdot 10^{-40}$$

Factor 16 better then Elliott

Paper in preparation