TESTING THE PAULI EXCLUSION PRINCIPLE AND FUNDAMENTAL SYMMETRIES IN UNDERGROUND EXPERIMENTS: THE VIP-2 EXPERIMENT

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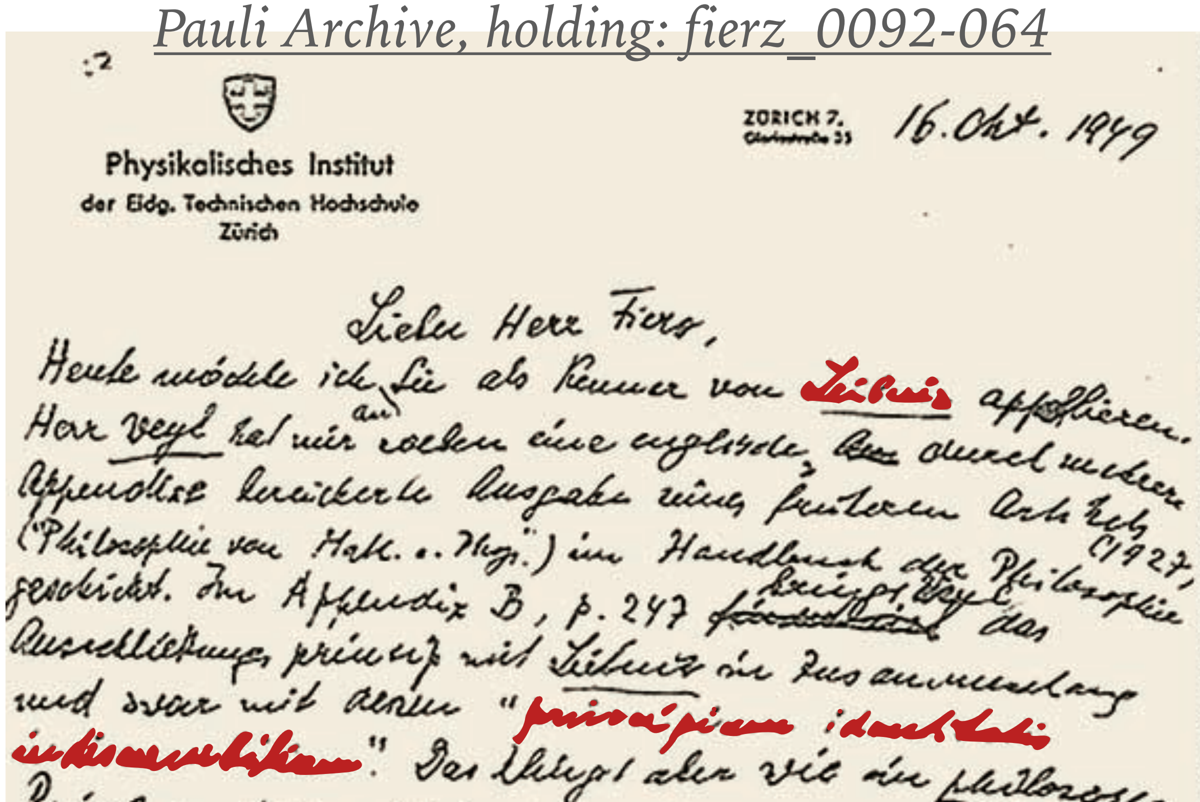
Low Energy Frontier of Particle Physics - Frascati 7/2/25

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, 16. Okt. 1949

Lieber Herr Fierz,
Heute möchte ich Sie als Kenner von Leibniz apostrophieren. Herr Weyl hat mir eine englische, um durch mehrere Appendices bereicherte Ausgabe seines früheren Artikels ("Philosophie von Math. u. Nat.") 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 Beispiel aber wie ein philosoph…

The Pauli Exclusion Principle

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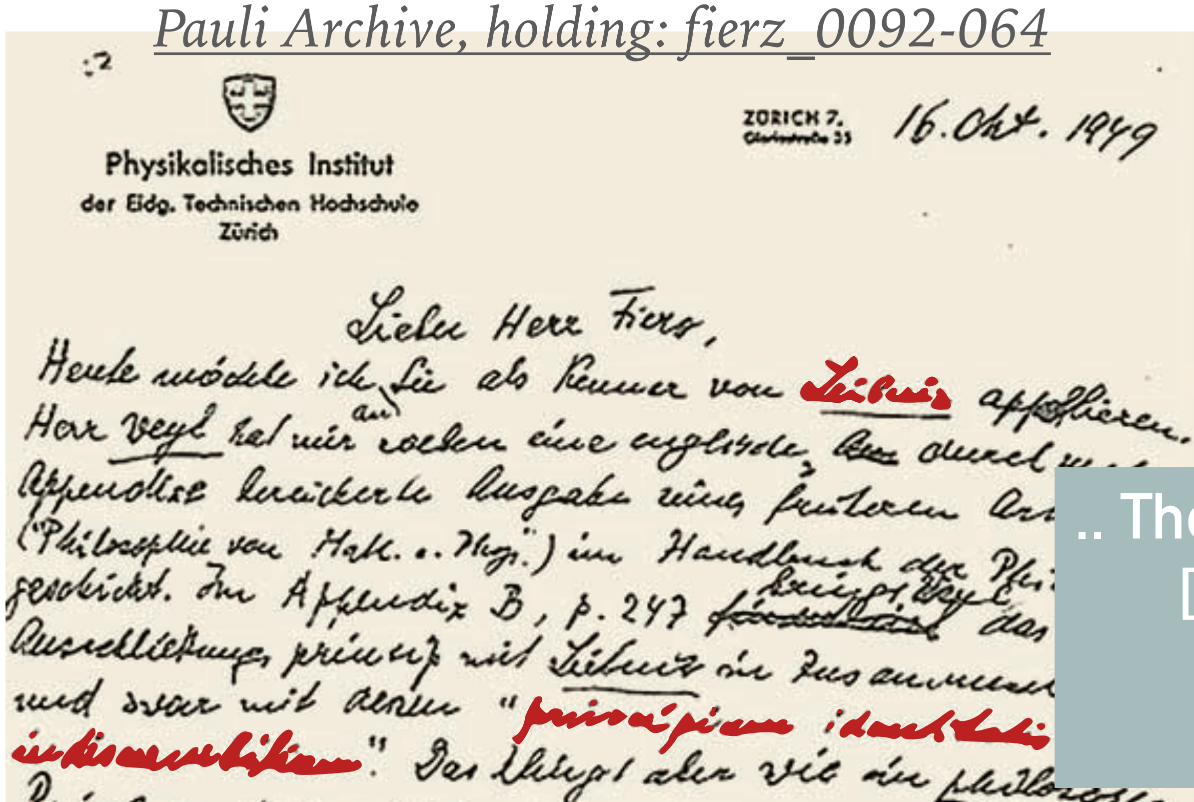


.. The impression that the shadow of some incompleteness [falls] here on the bright light of success of the new quantum mechanics seems to me unavoidable.
W. Pauli, Nobel lecture 1945

The Pauli Exclusion Principle (PEP)

Spin-statistic connection:

half-integer spin particles → antisymmetric wave function & Fermi-Dirac stat

Integer spin particles → symmetric wave function & Bose statistics

Lüders and Zumino: spin-statistics lays on few, general assumption:

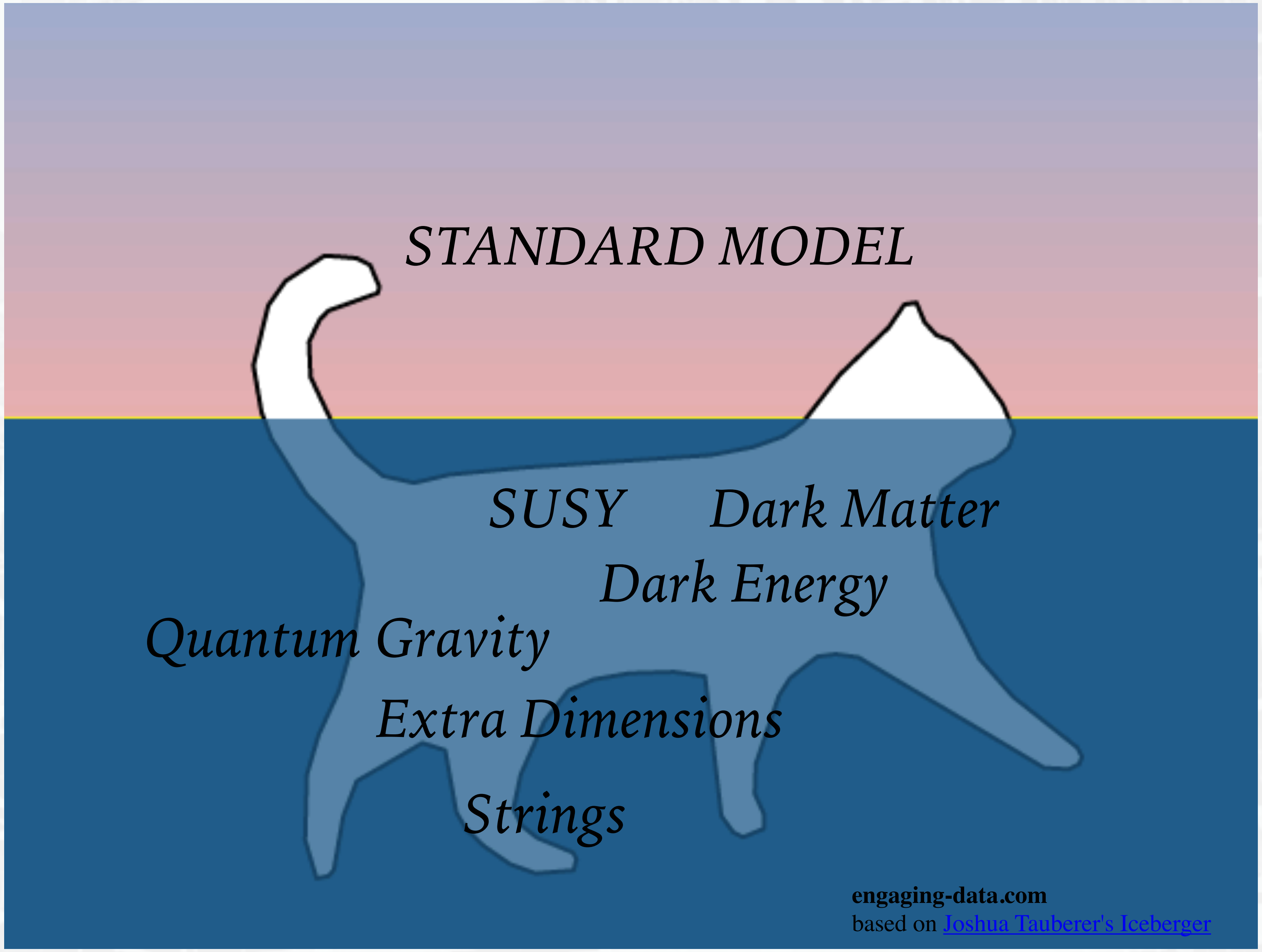
Lorentz/Poincaré Symmetry, CPT, unitarity, locality & causality

Theories of Statistics Violation

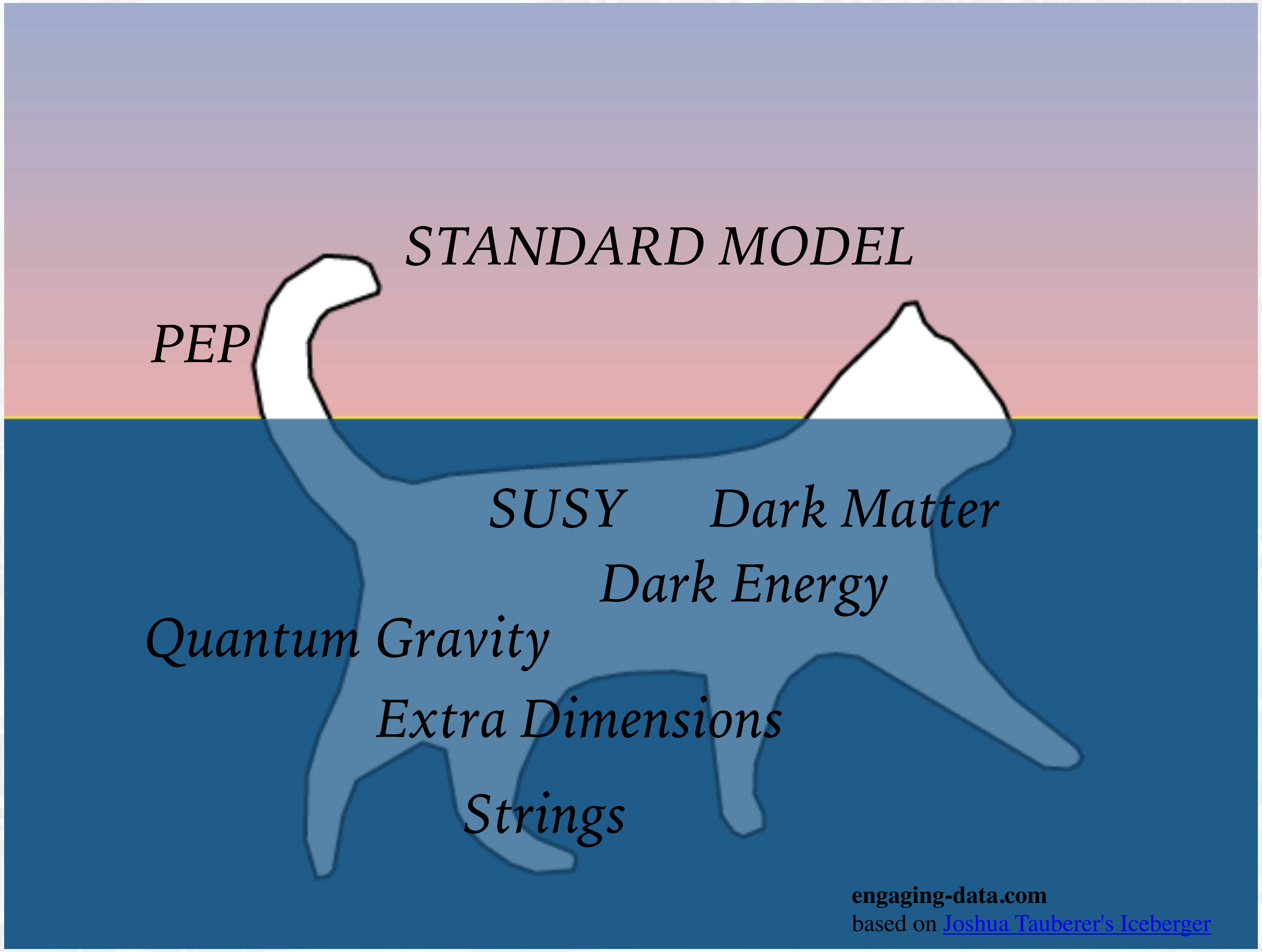
O.W. Greenberg: AIP Conf.Proc.545:113-127,2004

*"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) non-commutative spacetime……"*

The Pauli Exclusion Principle (PEP)



The Pauli Exclusion Principle (PEP)



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

How to model PEP violations

- *Ignatiev & Kuzmin model: Fermi oscillator with a third state*

(Ignatiev, A.Y., Kuzmin, V. , Quarks '86: Proceedings of the 229 Seminar, Tbilisi, USSR, 1517 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

- *Greenberg & Mohapatra: Local Quantum Field Theory, q parameter deforms anticommutators [Phys. Rev. Lett. 1987,59,2507]:*

$$a_k a^{+}_l - q a^{+}_l a_k = \delta_{k,l}$$

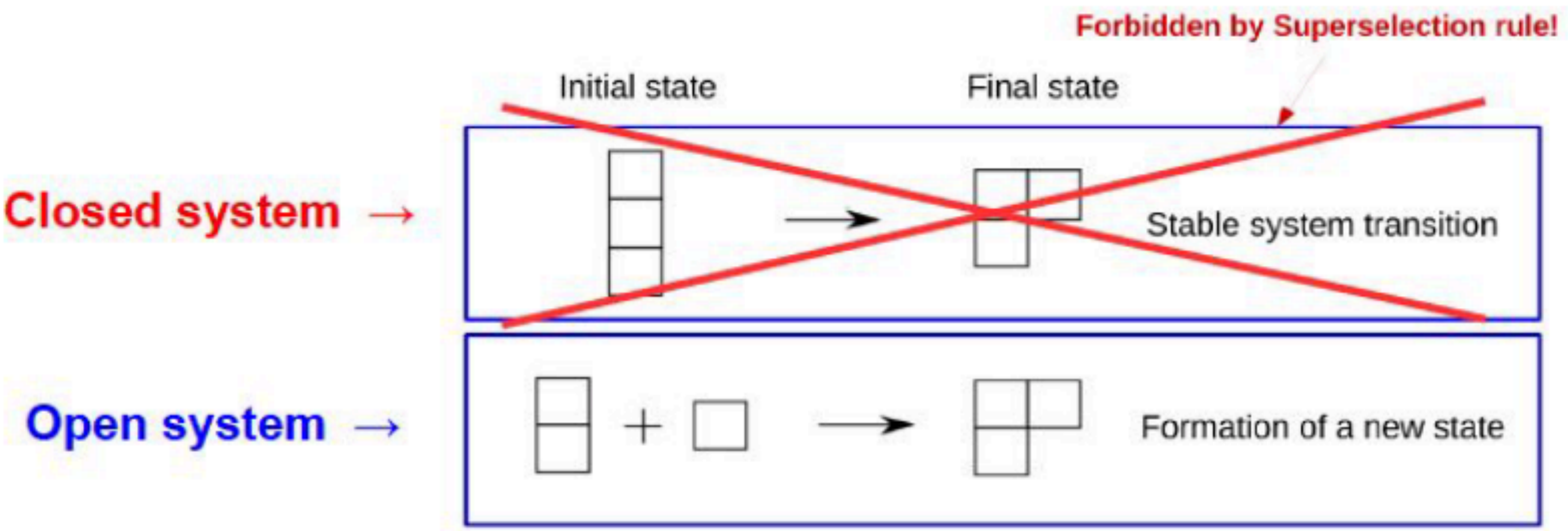
- *Rahal & Campa: global wave function of the electrons not exactly antisymmetric, PEP holds as long as the number of wrongly entangled pairs is small*

All respect the Messiah-Greenberg super-selection rule!

Messiah-Greenberg super-selection rule:

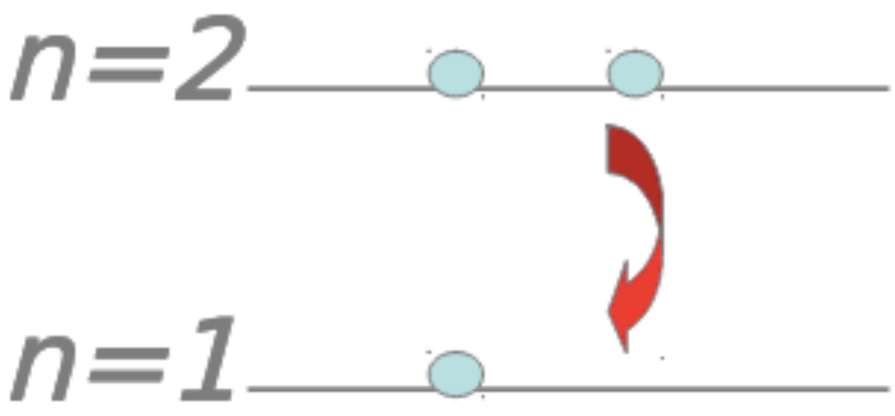
Superposition of states with different symmetry are not allowed →

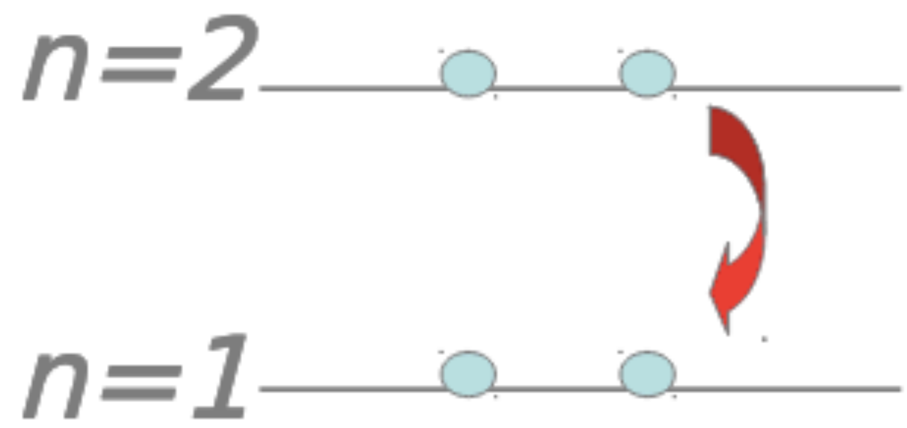
<u>Transition probability between two symmetry states is ZERO</u>



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

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





Normal 2p → 1s transition

2p → 1s transition violating Pauli principle

~ 8.05 keV in Cu

~ 7.7 keV in Cu

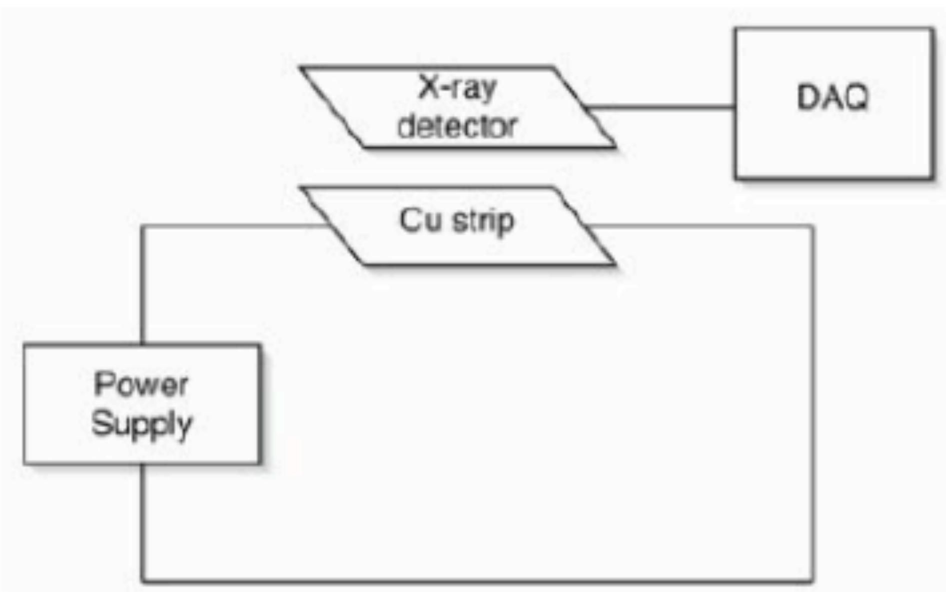
Paul Indelicato (Ecole Normale Supérieure et Université Pierre et Marie Curie)

Multiconfiguration Dirac-Fock approach

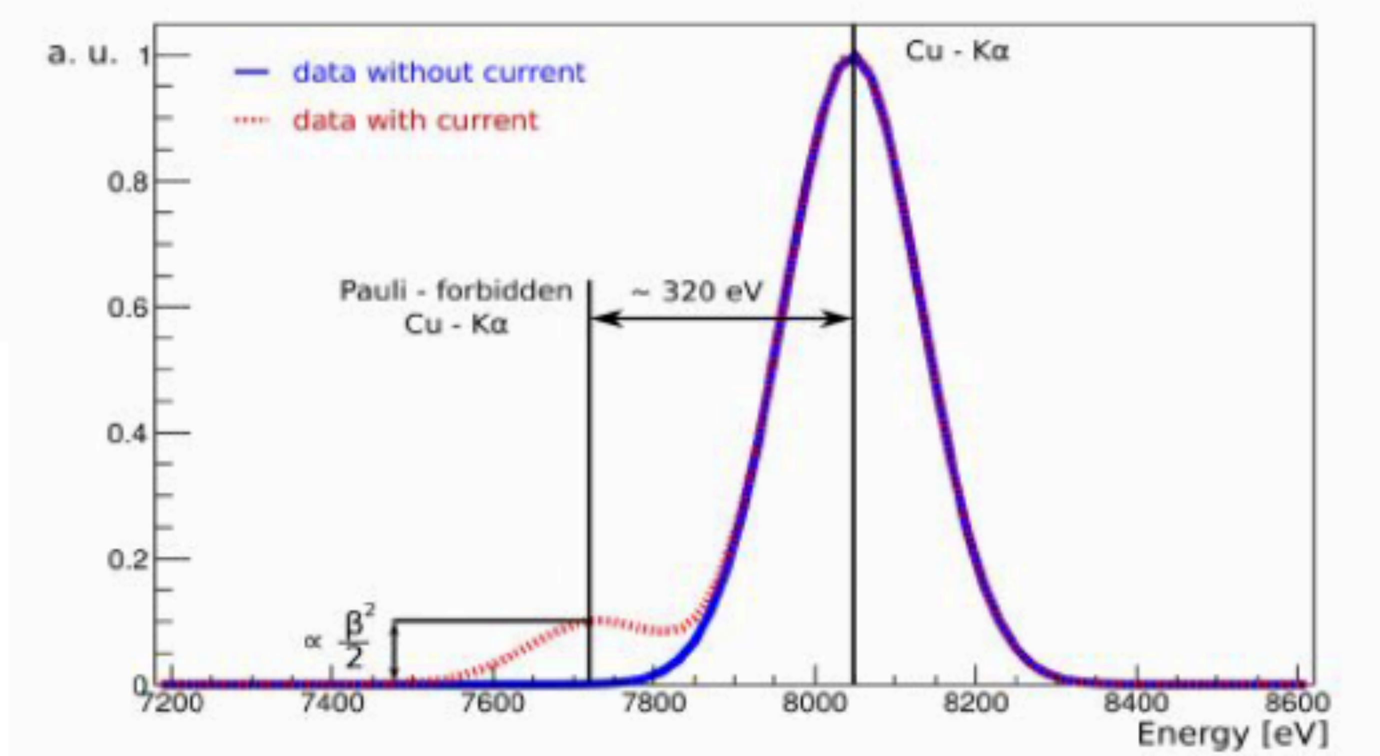
Accounts for the shielding of the two inner electrons

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

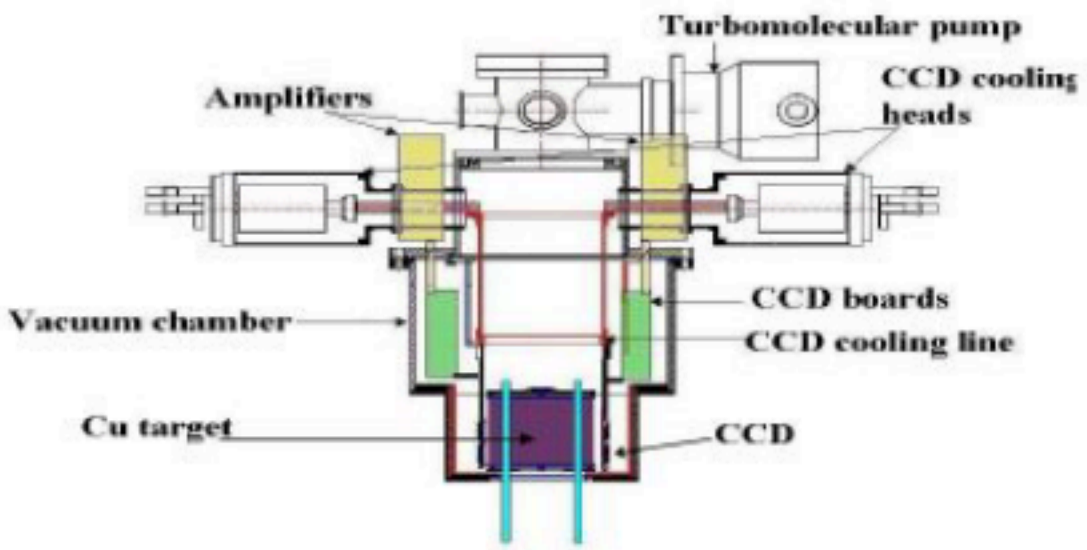


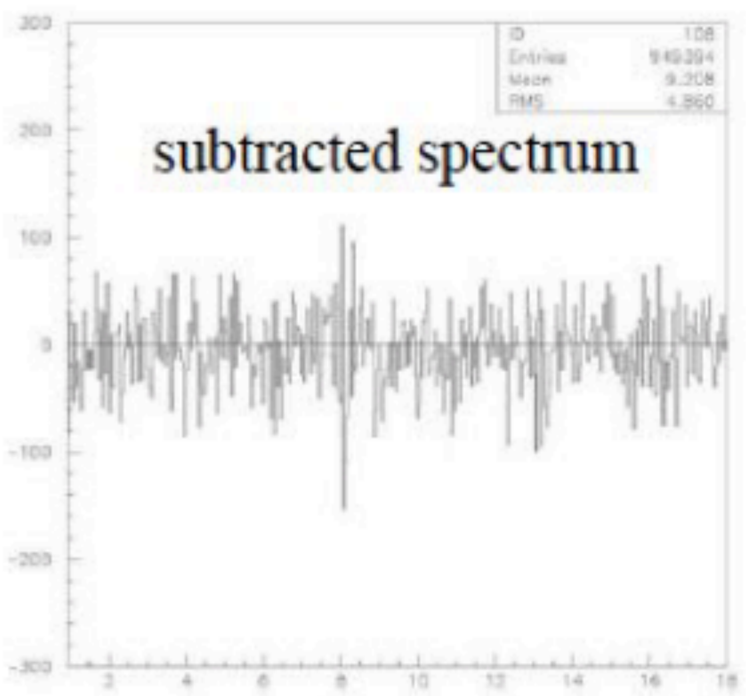
PEP Violation Signal:



From VIP to VIP-2

a) copper ultrapure cylindrical foil
b) surrounded by 16 Charge Coupled Devices (CCD) res. at 8 keV 320 eV (FWHM)
c) inside a vacuum chamber: CCDs cooled to 168K by a cryogenic system
d) amplifiers + read out ADC boards.





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

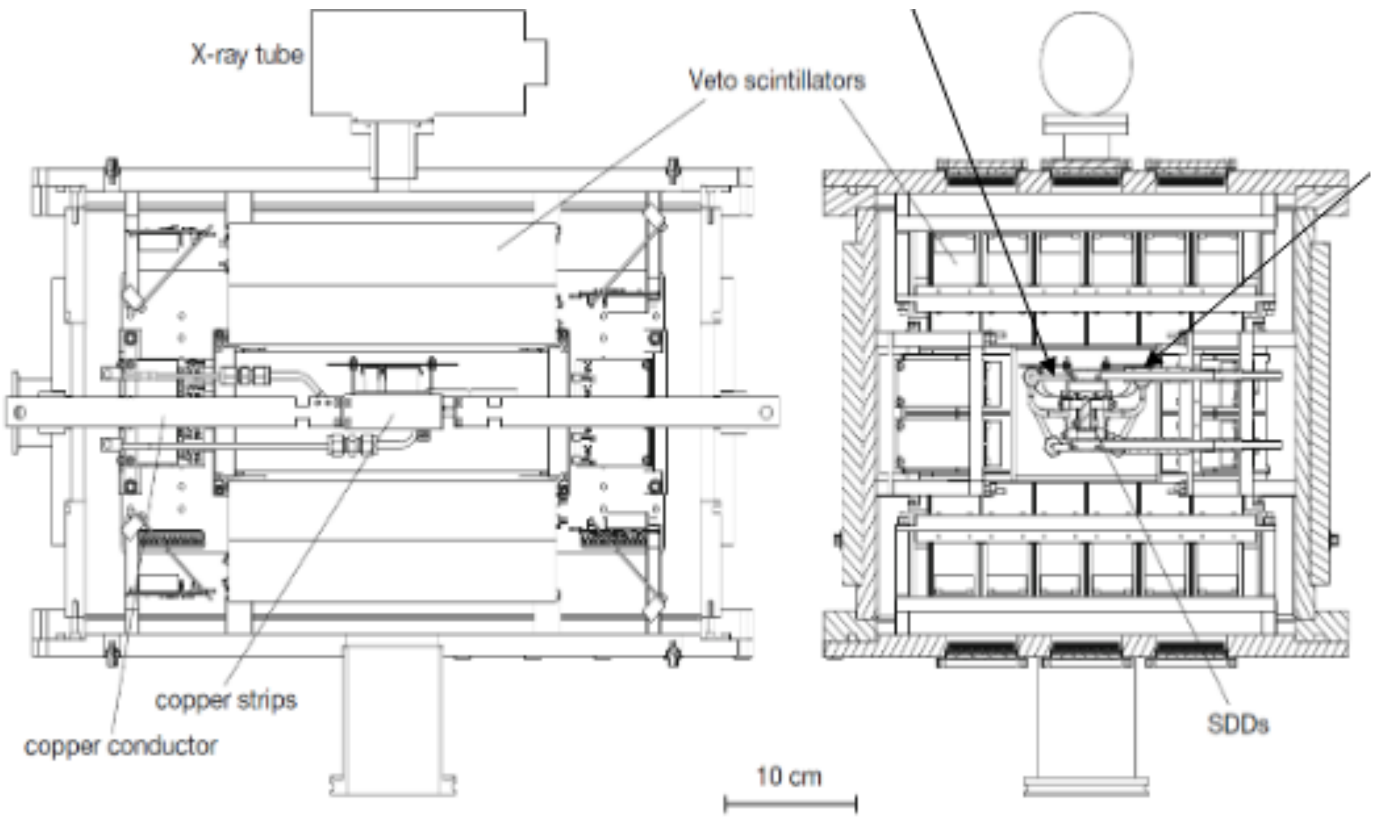
improved the limit obtained by Ramberg & Snow by a factor ~ 400

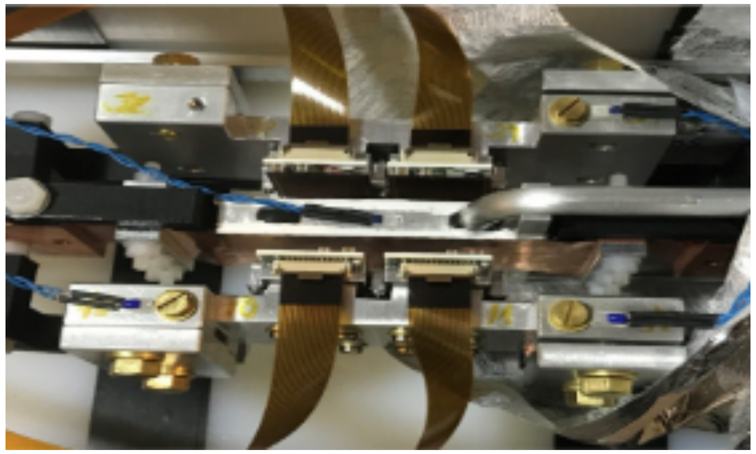
(Foundation of Physics 41 (2011) 282+ other papers)

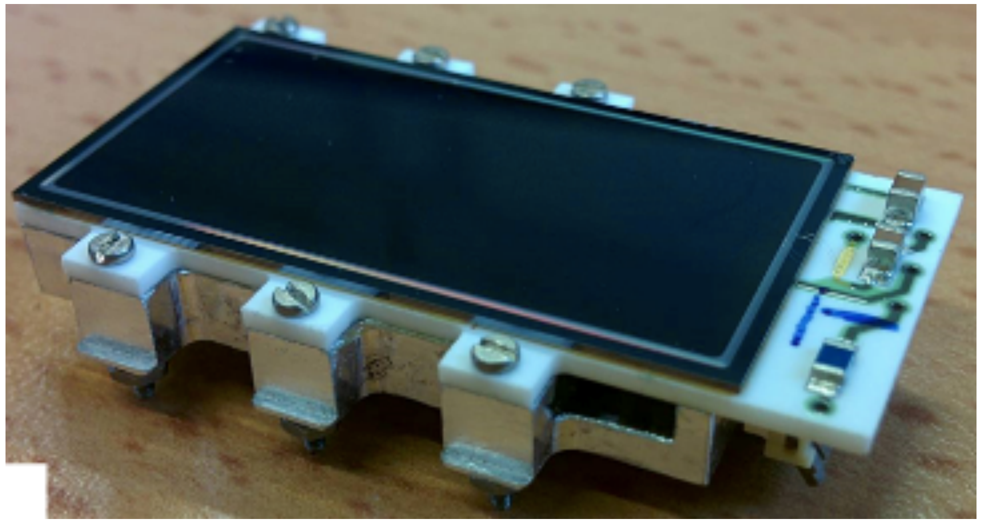
GOAL OF VIP-2 : improve the VIP result of 2 orders of magnitude

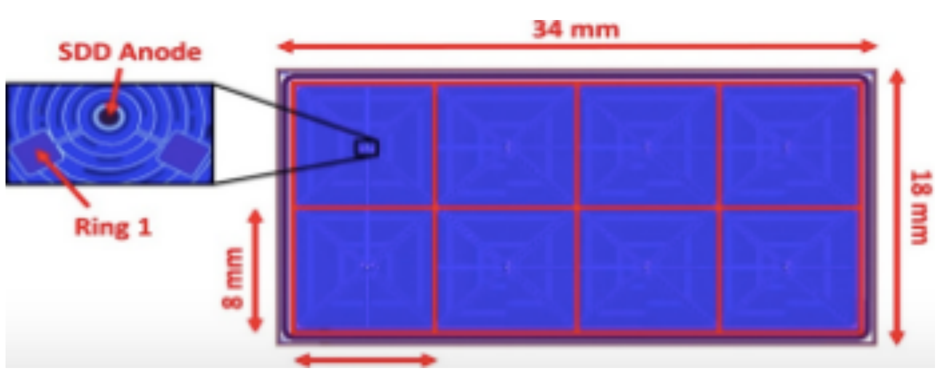
The VIP-2 Experiment

*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

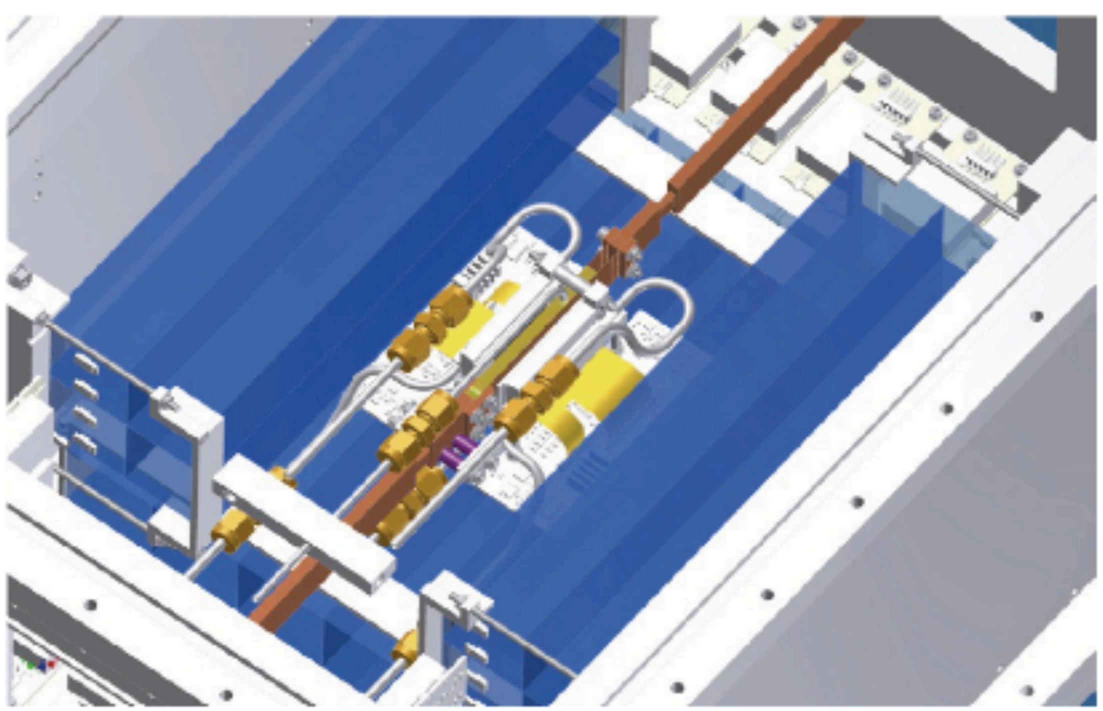
*2 strip shaped Cu targets (25 um x 7 cm x 2 cm) more compact target → higher acceptance, thinner → **higher efficiency***

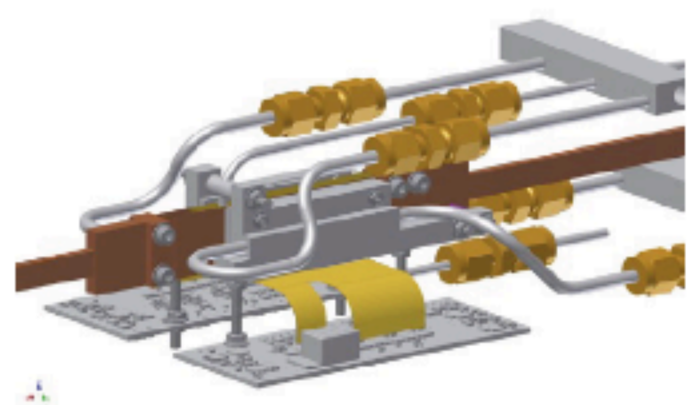
DC current supply to Cu bars

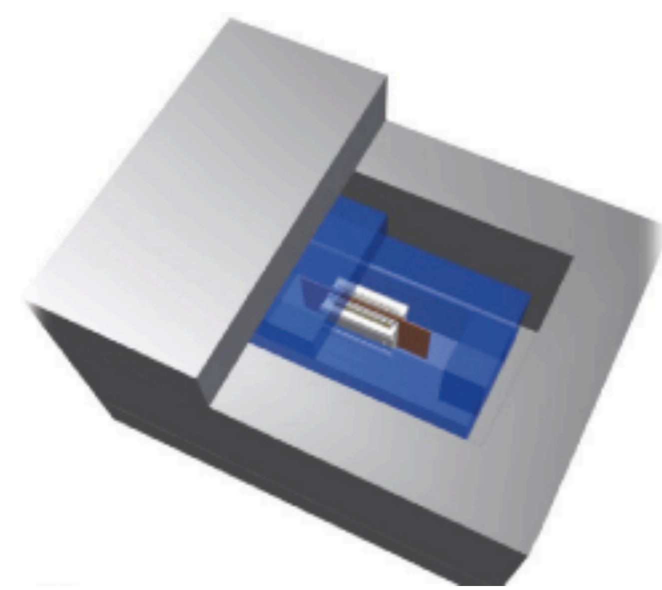
*Cu strips cooled by a closed Fryka chiller circuit →**higher current***

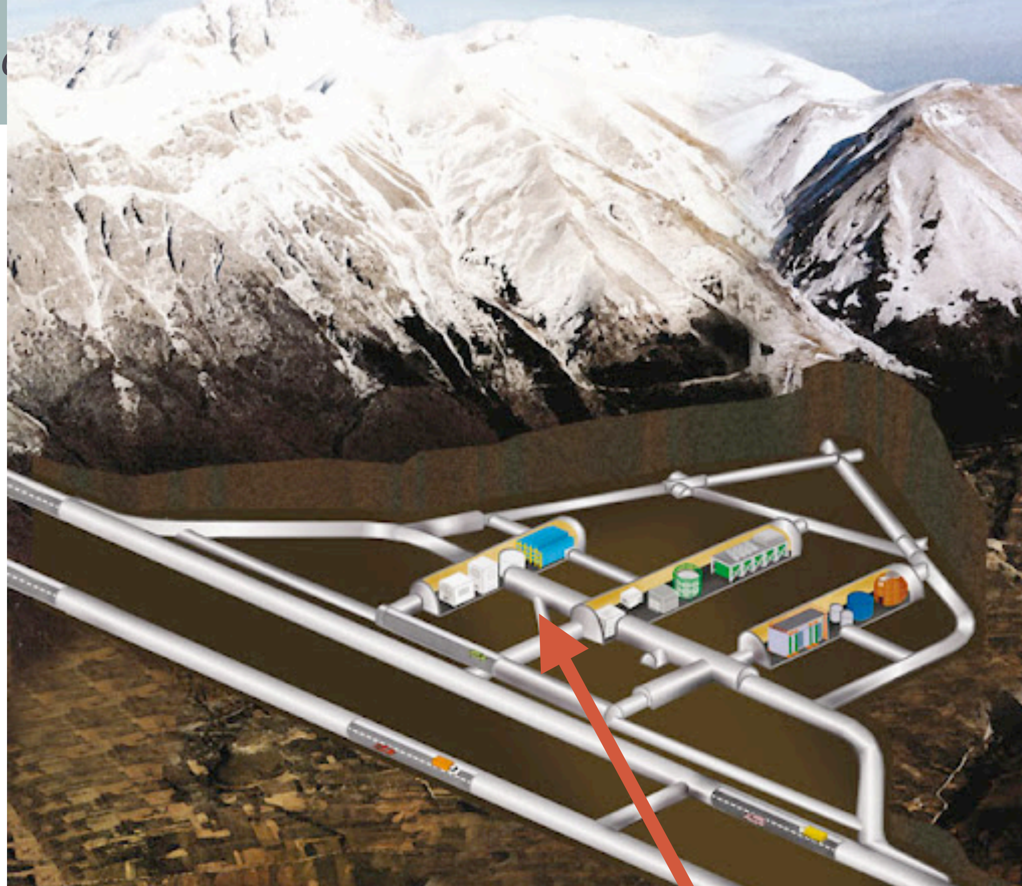
(100 A) @ 20 °C of Cu target implies 1 °K heating in SDDs

Sketch of the VIP2 Setup:



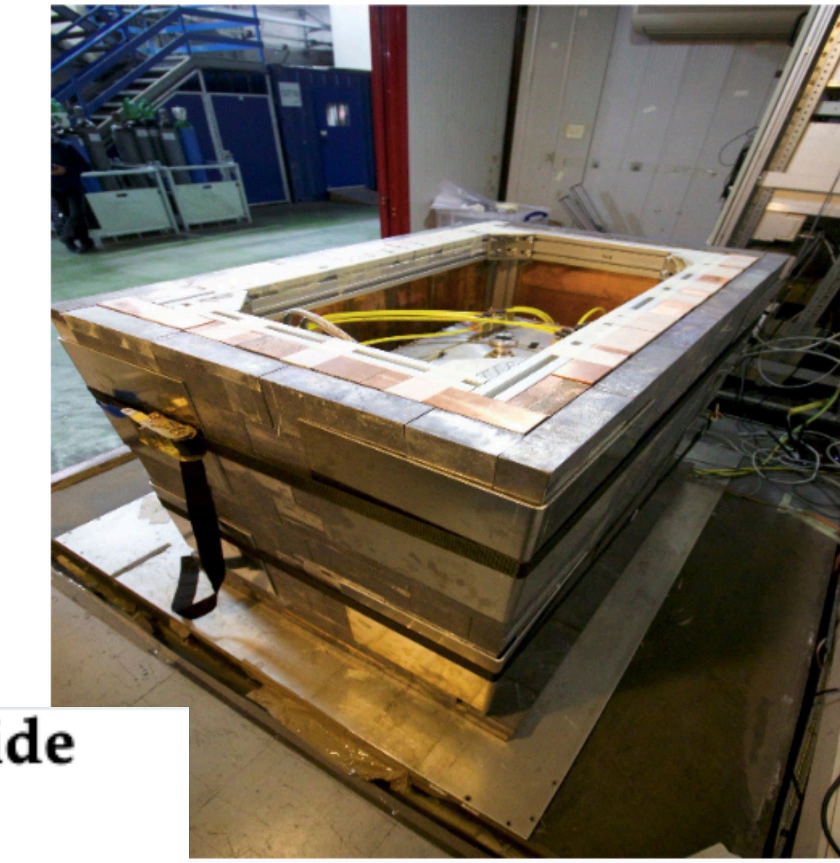




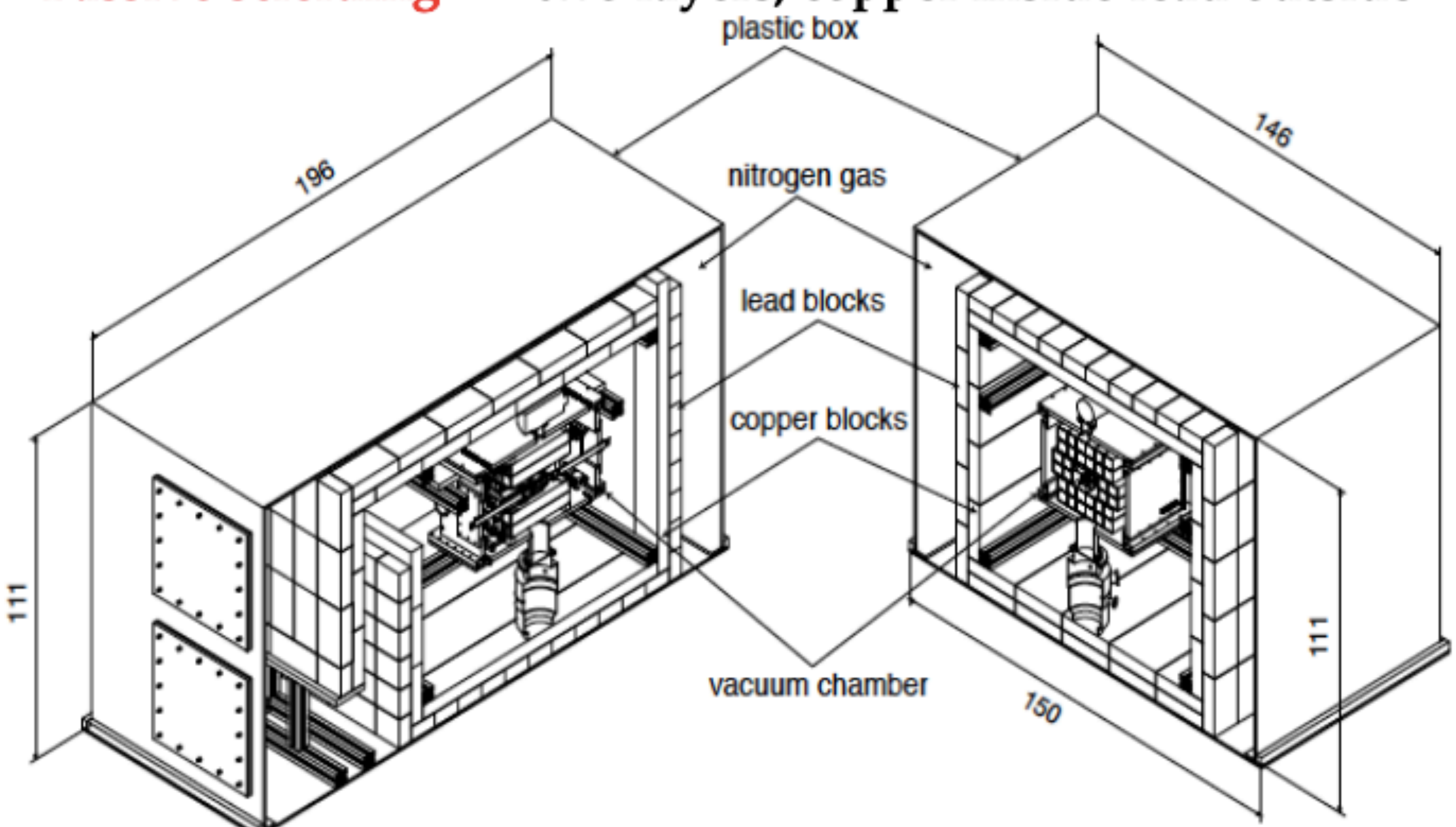


1400 m rock coverage

Upgrade concluded in April 2019:

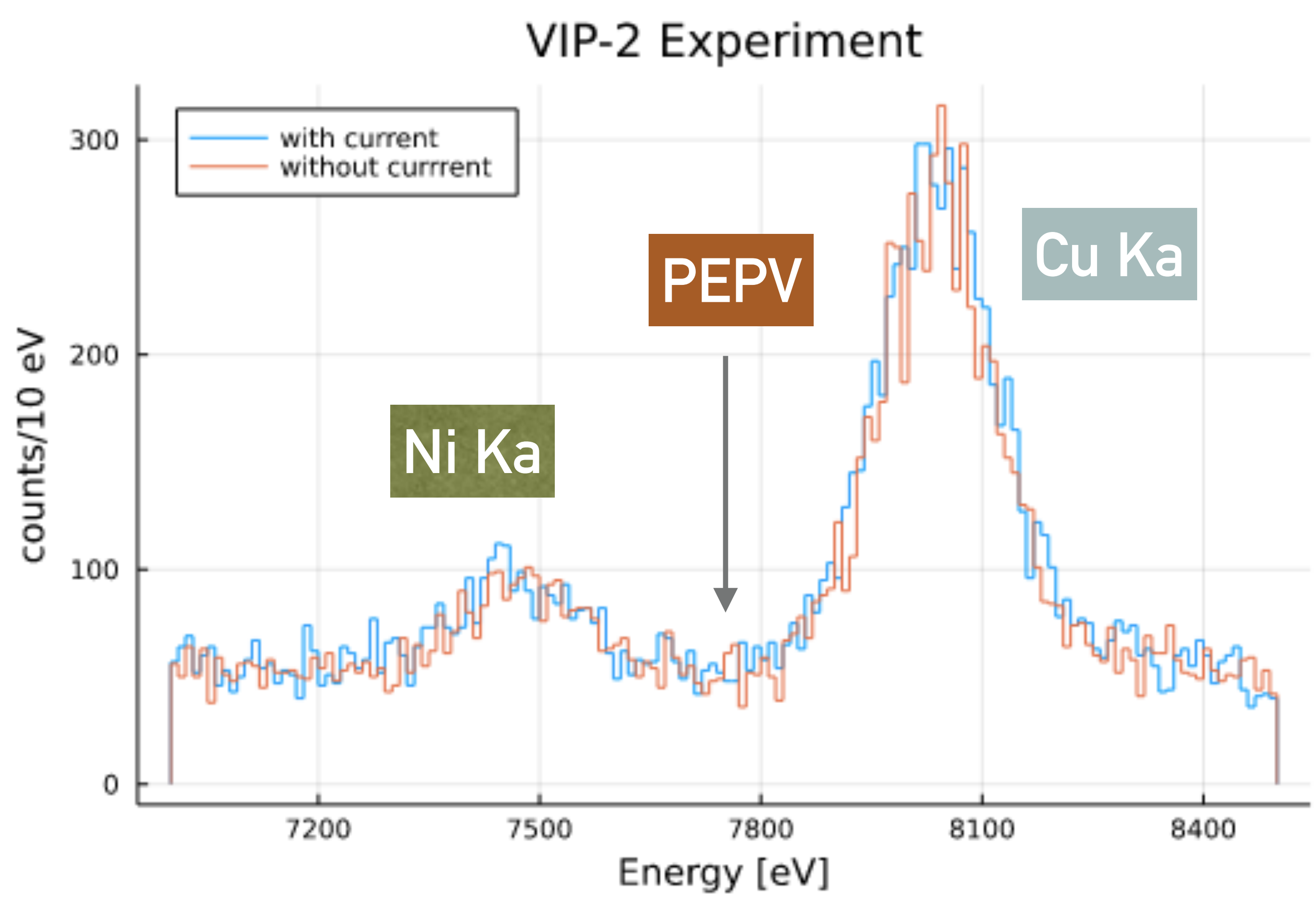


Passive scielding → two layers, copper inside lead outside



Results of six months of data taking

https://doi.org/10.3390/sym14050893



Symmetry **2022**, *14*(5), 893;

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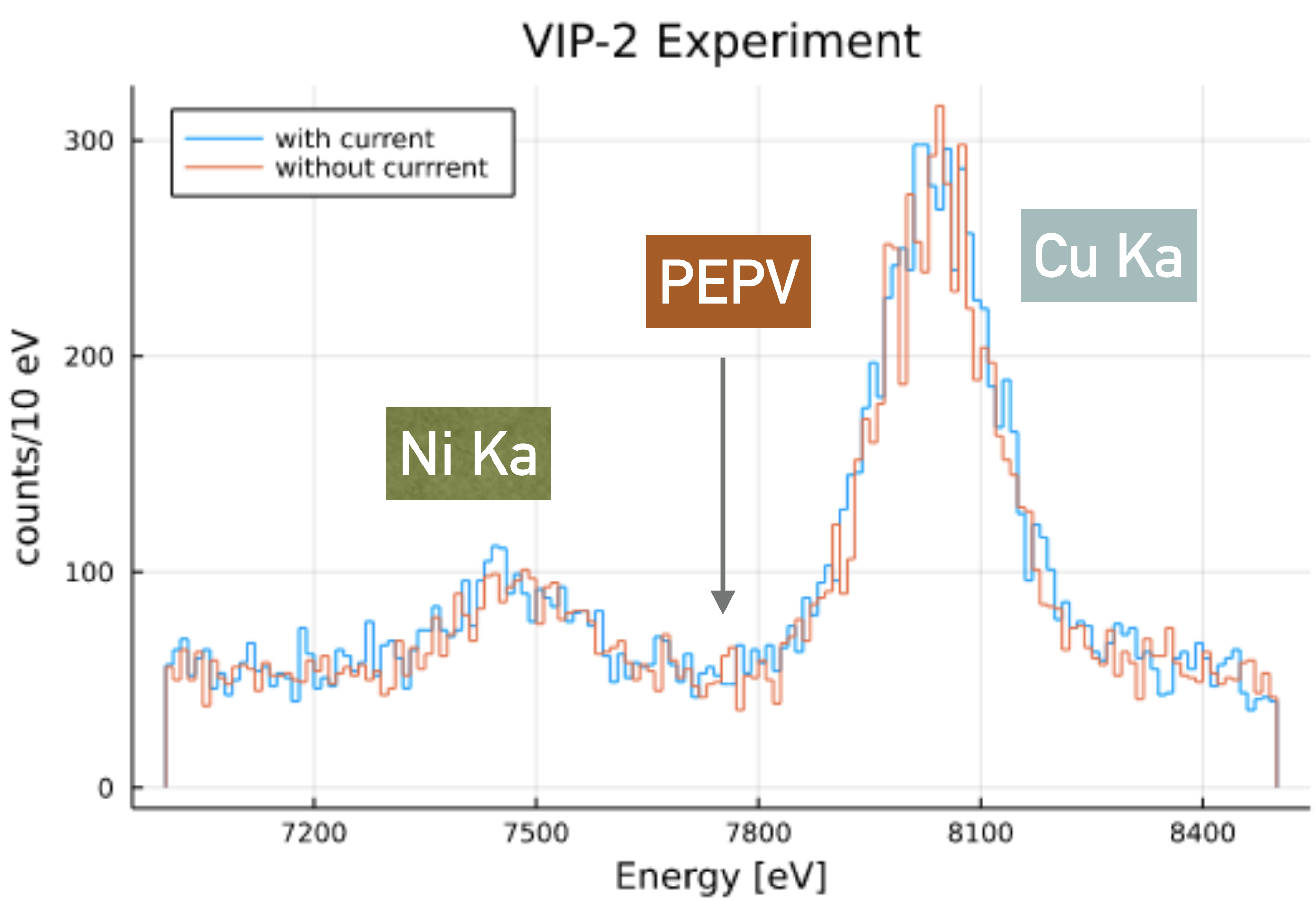


Symmetry **2022**, *14*(5), 893;

Description spectrum with current

$$\mathcal{F}^{wc}(\boldsymbol{\theta},\boldsymbol{y},\mathcal{S}) = y_1 \times Ni(\theta_1,\theta_2) + y_2 \times Cu(\theta_3,\theta_4) + y_3 \times \mathrm{pol}_1(\theta_5) + \mathcal{S} \times PEPV(\theta_4)$$

Description spectrum without current

$$\mathcal{F}^{woc}(\boldsymbol{\theta},\boldsymbol{y}) = y_1 \times Ni(\theta_1,\theta_2) + y_2 \times Cu(\theta_3,\theta_4) + y_3 \times \mathrm{pol}_1(\theta_5)$$

Results of six months of data taking

https://doi.org/10.3390/sym14050893

Likelihood

Data with current *Data without current*

$$\mathcal{L}(\mathcal{D}^{wc},\mathcal{D}^{woc}|\boldsymbol{\theta},\boldsymbol{y},\mathcal{S}) = \mathrm{Poiss}(\mathcal{D}^{wc}|\mathcal{F}^{wc}(\boldsymbol{\theta},\boldsymbol{y},\mathcal{S})) \times \mathrm{Poiss}(\mathcal{D}^{woc}|\mathcal{F}^{woc}(\boldsymbol{\theta},\boldsymbol{y}\times\mathcal{R}))$$

Bayesian

$$p(\boldsymbol{\theta},\boldsymbol{y},\mathcal{S}|\mathcal{D}^{wc},\mathcal{D}^{woc}) = \\ = \frac{\mathcal{L}(\mathcal{D}^{wc},\mathcal{D}^{woc}|\boldsymbol{\theta},\boldsymbol{y},\mathcal{S})p(\boldsymbol{\theta},\boldsymbol{y},\mathcal{S})}{\int d\boldsymbol{\theta}d\boldsymbol{y}\mathcal{L}(\mathcal{D}^{wc},\mathcal{D}^{woc}|\boldsymbol{\theta},\boldsymbol{y},\mathcal{S})p(\boldsymbol{\theta},\boldsymbol{y},\mathcal{S})}.$$

Frequentist

$$t_{\mathcal{S}} = -2\ln\Lambda(\mathcal{S}) = -2\ln\frac{\mathcal{L}(\hat{\hat{\boldsymbol{\theta}}},\hat{\hat{\boldsymbol{y}}},\mathcal{S})}{\mathcal{L}(\hat{\boldsymbol{\theta}},\hat{\boldsymbol{y}},\hat{\mathcal{S}})}$$

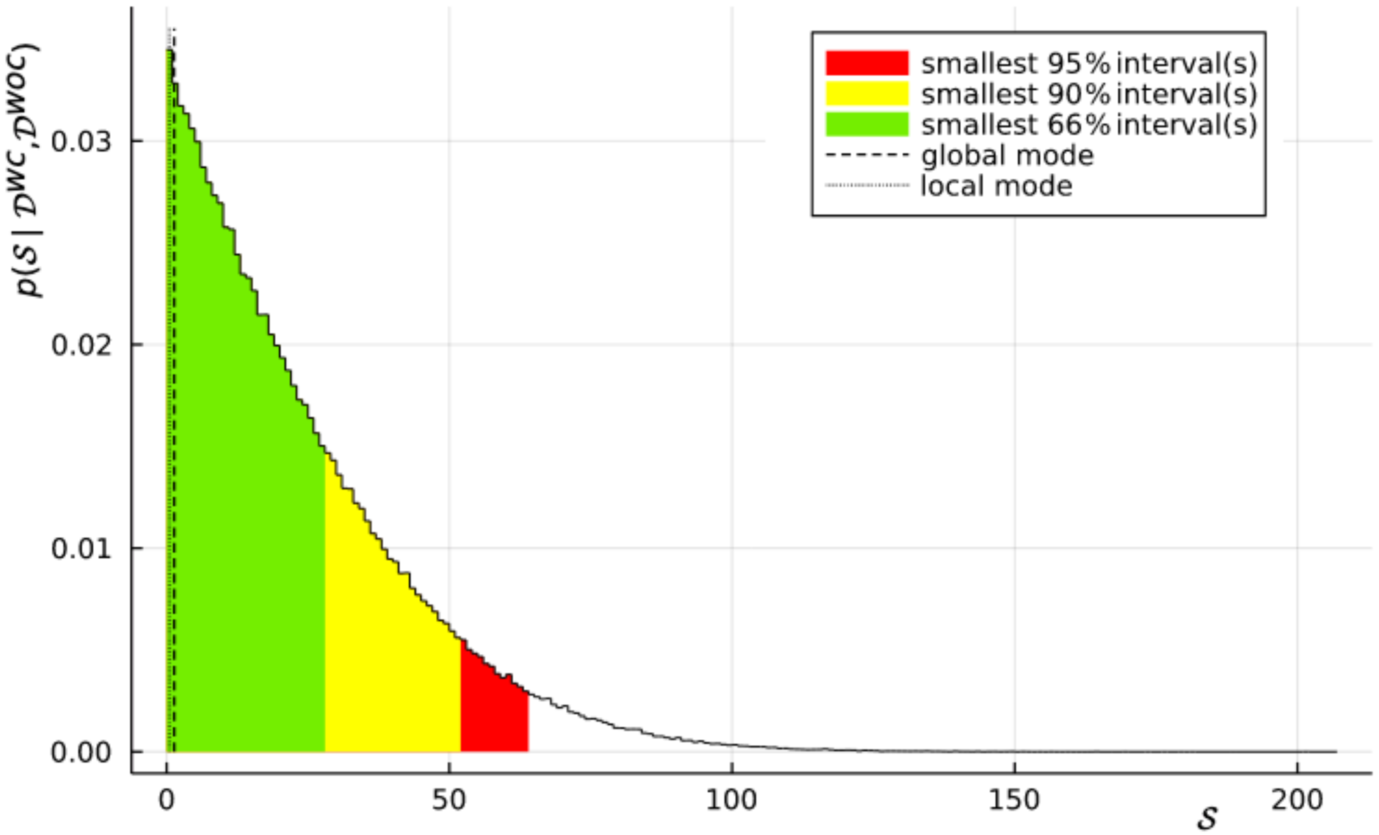
$$p_{\mathcal{S}} = \int_{t_{obs}}^{\infty} f(t_{\mathcal{S}}|\mathcal{S})dt_{\mathcal{S}}$$

Priors: gaussian distributions for parameters constrained within experimental uncertainties; flat distribution for signal

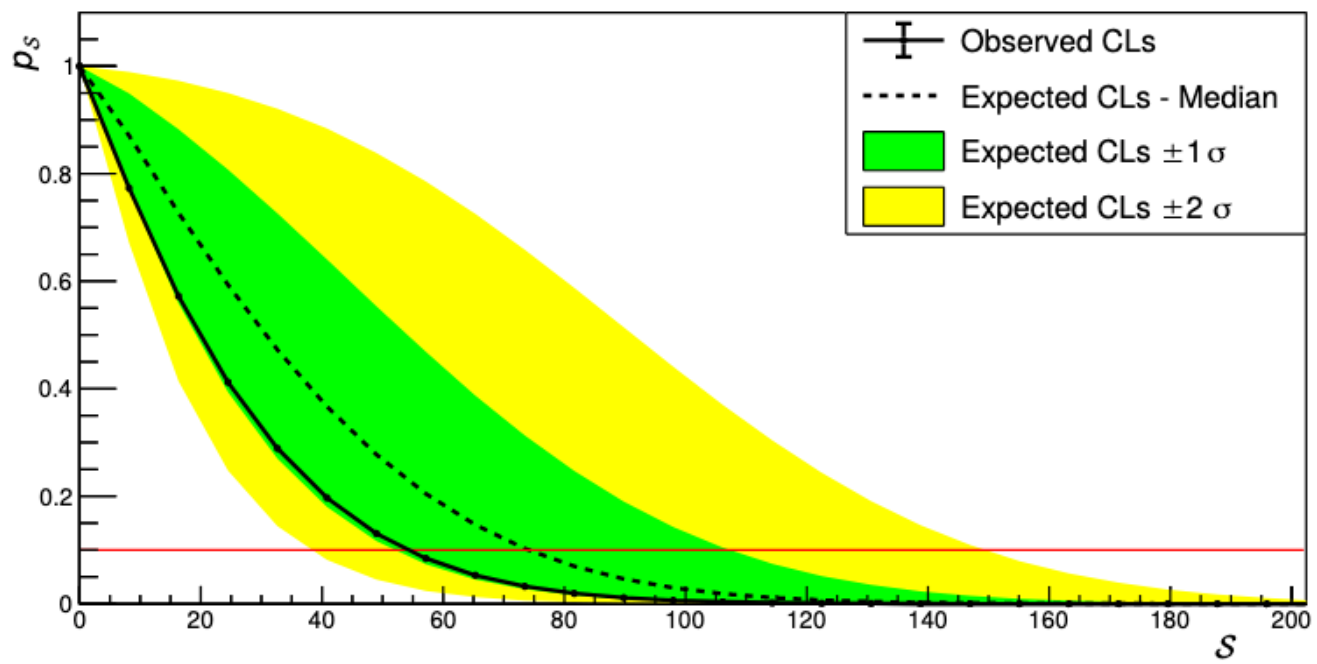
Experimental uncertainty (e.g. energy scale) included via additional penalty terms in Likelihood

Symmetry **2022**, *14*(5), 893;
https://doi.org/10.3390/sym14050893

Bayesian



Frequentist



Small under-fluctuation in the ROI

$$\beta^2/2 \leq 8.6 \times 10^{-31} \text{ (Bayesian)}, \qquad \beta^2/2 \leq 8.9 \times 10^{-31} \text{ (CL}_s\text{)}$$

New article in preparation with all the available statistics!

VIP-2 experimental upgrade: VIP-3

Scan the PEP violation probability as a function of Z (i.e. of Energy)

Okun, L.:

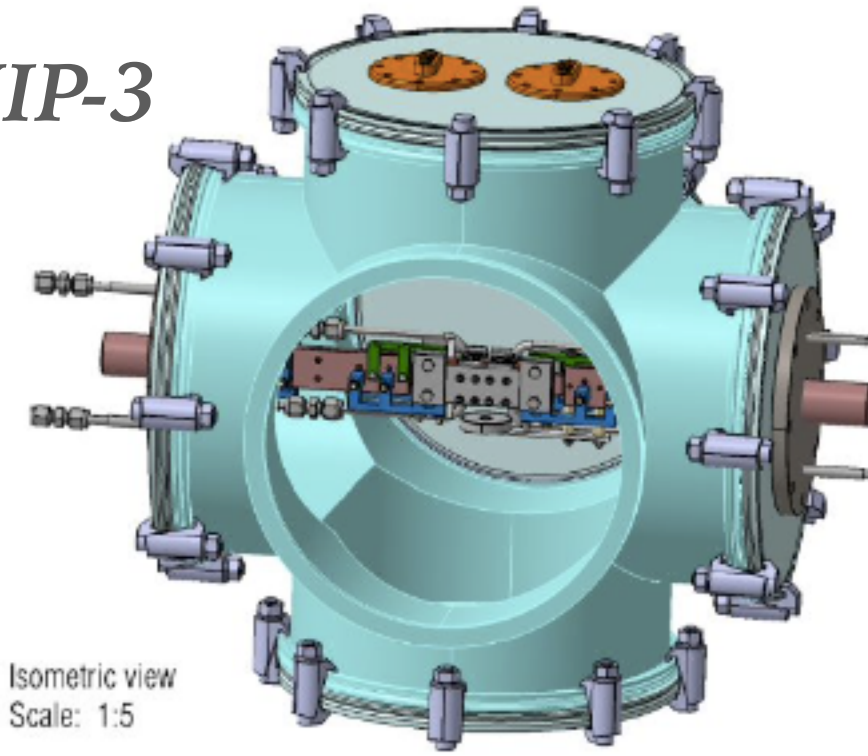
"The special place enjoyed by the Pauli principle in modern theoretical physics does not mean that this principle does not require further and exhaustive experimental tests. On the contrary, it is specifically the fundamental nature of the Pauli principle which would make such tests, over the entire periodic table, of special interest"
L. Possible violation of the Pauli principle in atoms. JETP Lett. 1987, 46, 529532

"High sensitivity Pauli Exclusion Principle tests by the VIP experiment: status and perspectives"

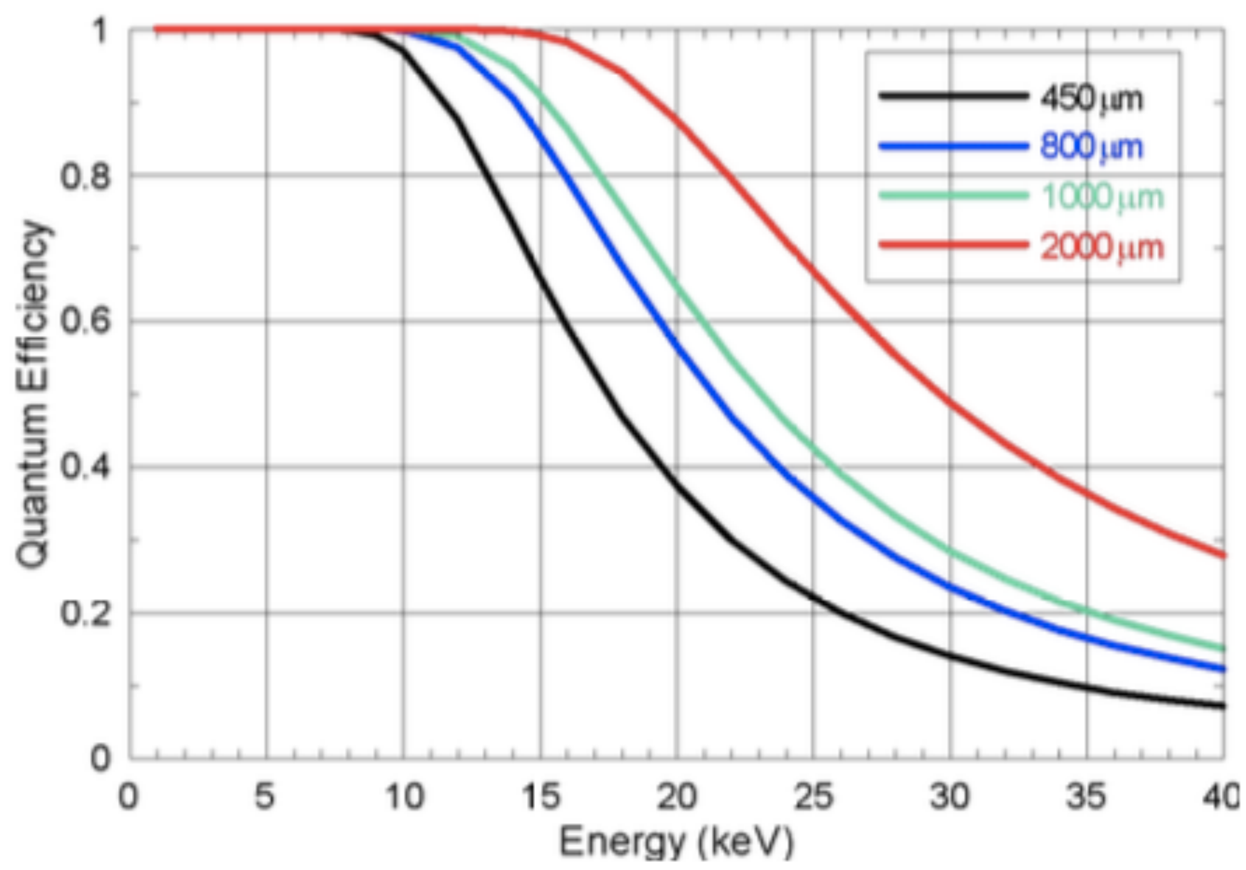
Paper on the preparation of VIP-3 experiment accepted in APPA.

VIP-2 experimental upgrade: VIP-3

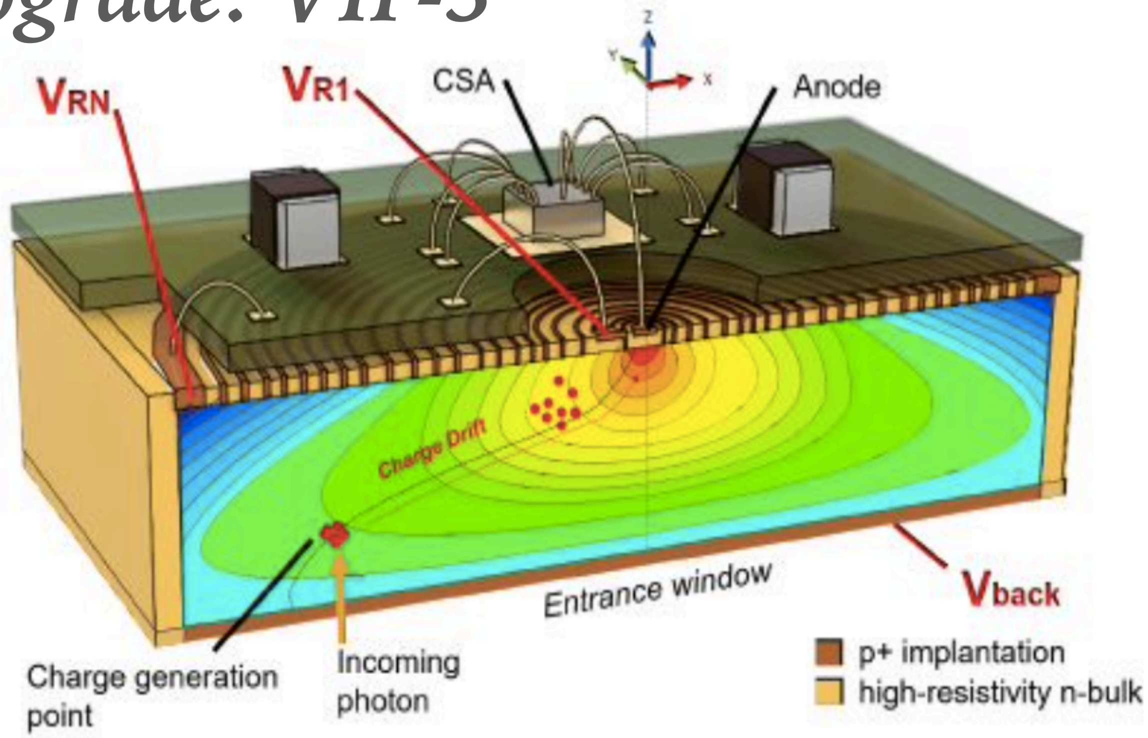
- ***new vacuum chamber,*** *increase the number of SDD detectors, increase the geometrical efficiency, higher current up to* ***400 A***
- *New thermal contact between cold finger and SDDs*
- *New target cooling system*



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

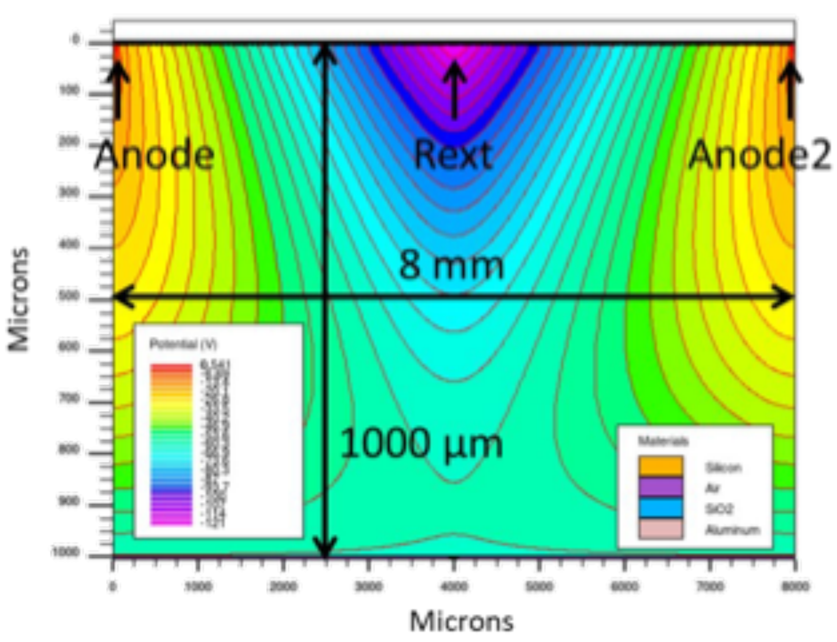


VIP-2 experimental upgrade: VIP-3

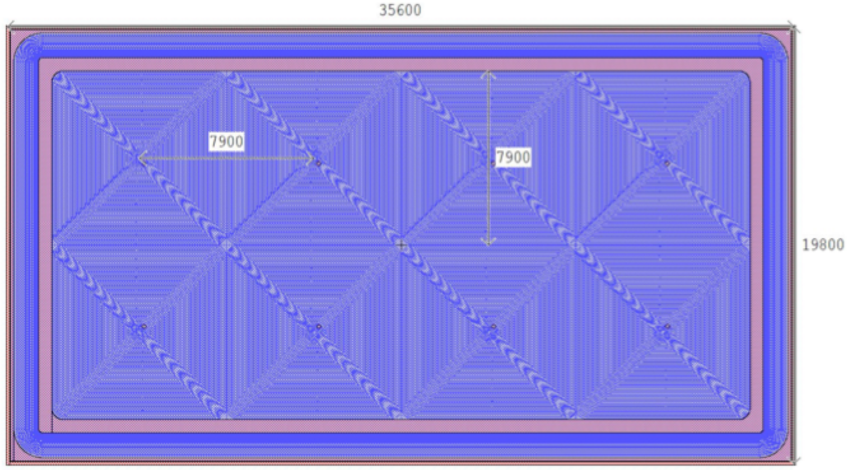


- 2x4 SDDs, 8x8 mm² each, in production with FBK & politecnico di Milano

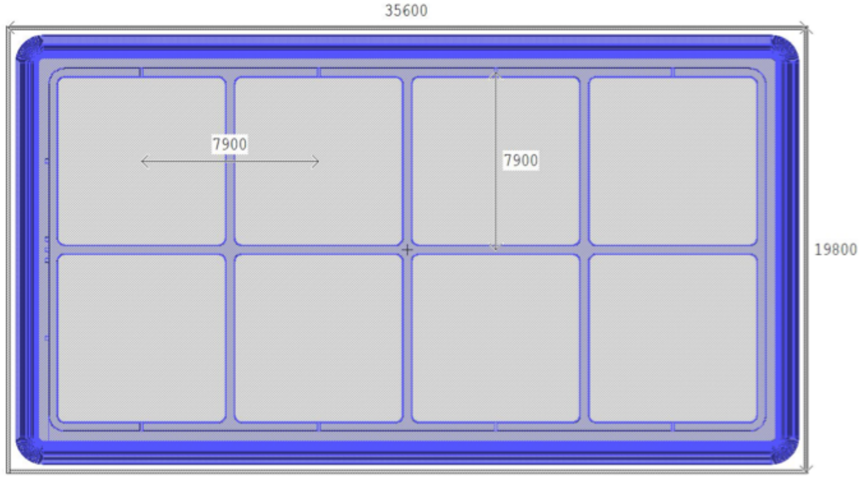
- Improved charge collection at border of the active area
- Wider than previous chip
- Reduced charge sharing via focusing electrode on the window



Anode side



Window side



New paradigm for VIP-2

Are Quantum Gravity models experimentally testable?

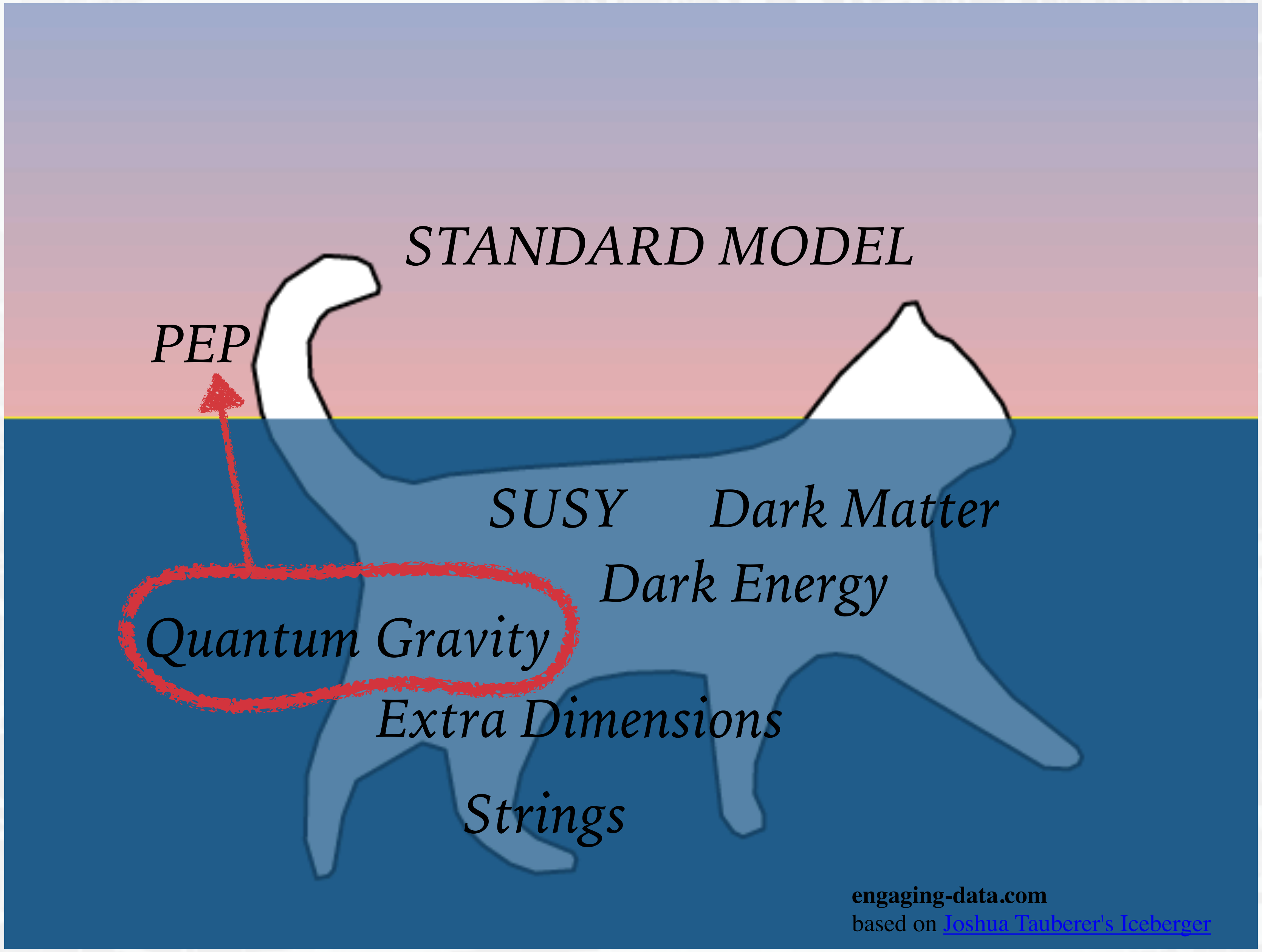
A. Addazi (Chengdu Univ.) A. Marcianò (Fudan University)

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]

The Pauli Exclusion Principle (PEP)



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

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

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

specific calculation of atomic levels transitions probabilities for θ-Poincaré

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

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.

Experimental Setup

High purity Ge detector measurement:

- **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.**

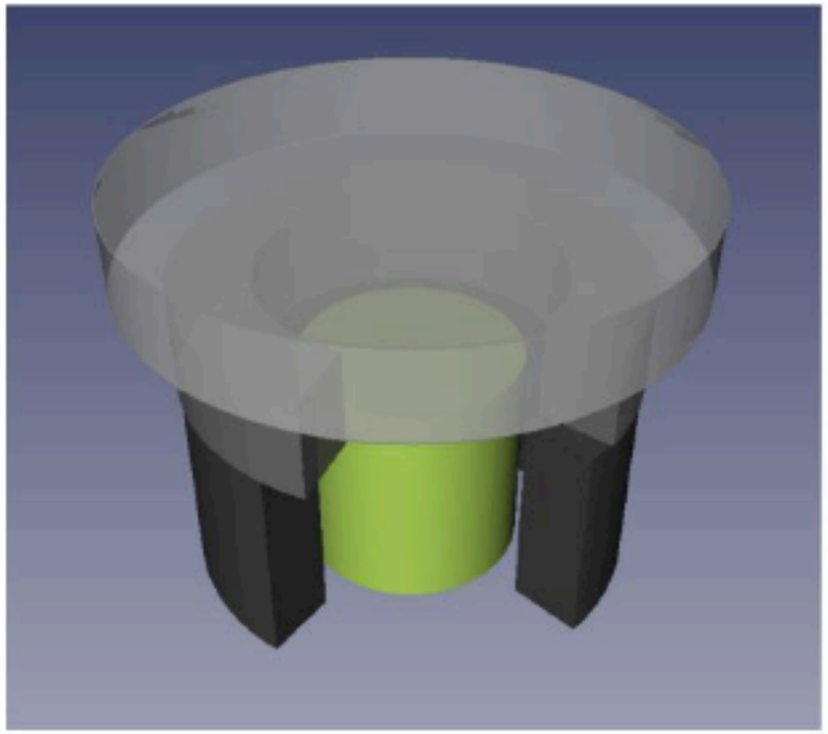


Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

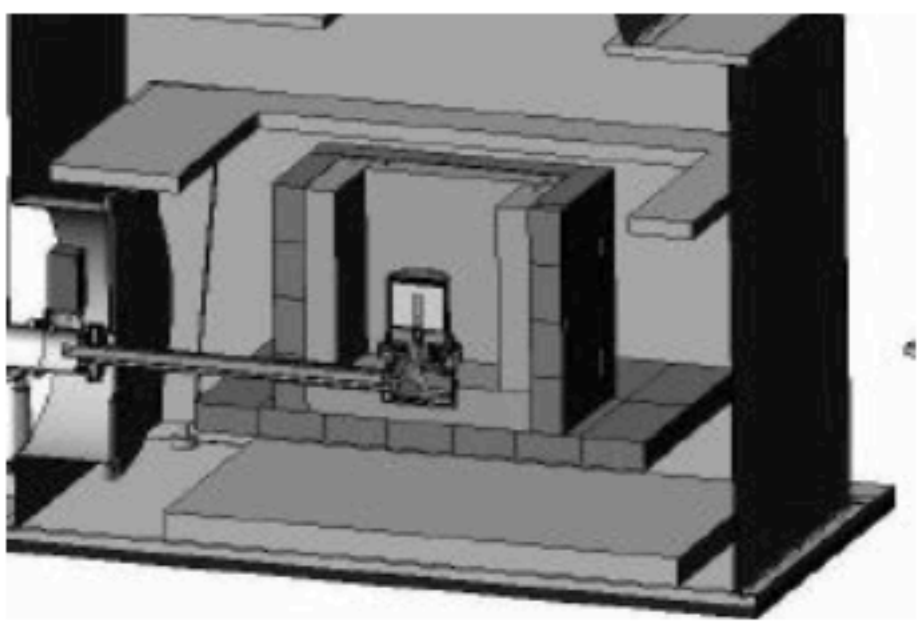
Experimental Setup

- **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).**

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



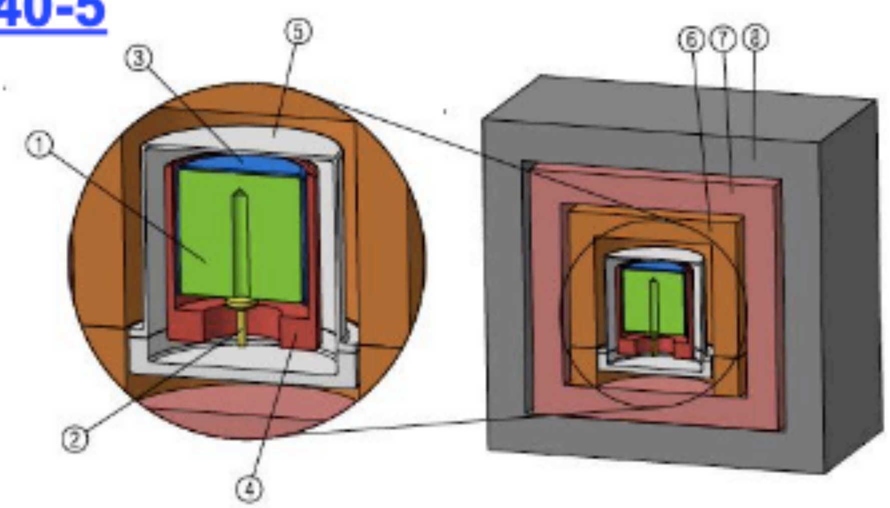
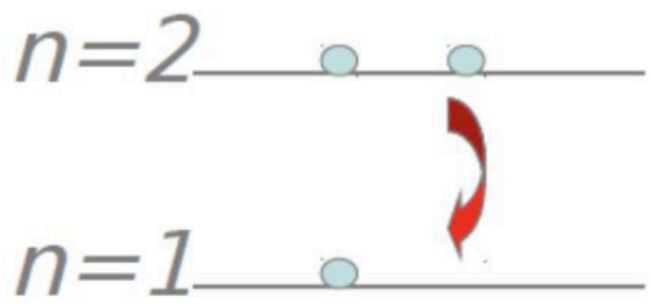


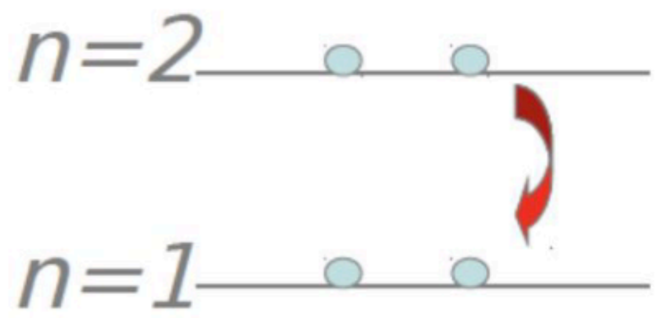
Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

- **Aim of the measurement: search for the X-rays signature of PEP-violating Kα and Kβ transitions in Pb, when the 1s level is already occupied by two electrons.**

- **Transitions are shifted with respect to the standard ones due to additional shielding.**



Normal 2p → 1s transition



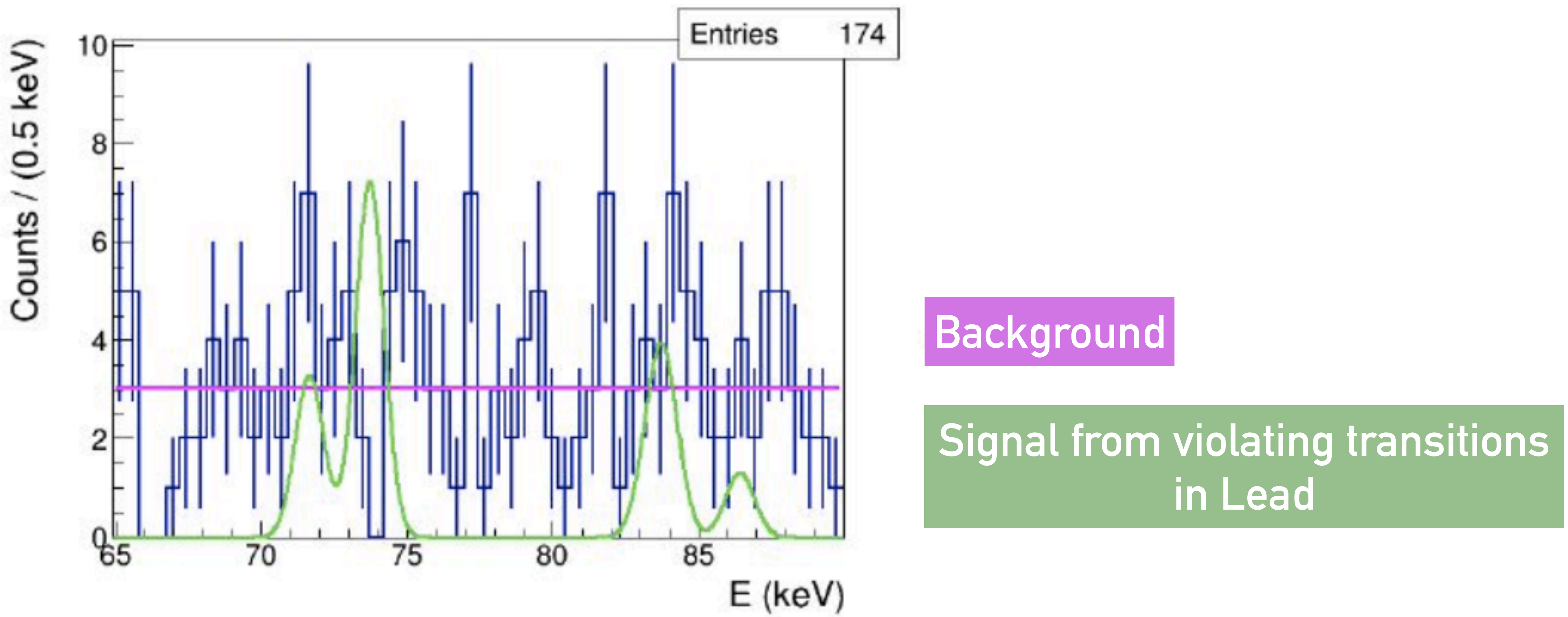
2p → 1s transition violating Pauli principle

- **Deformation of the algebra preserves, at the first order, standard atomic transition probabilities, the violating transition probabilities being dumped by factors $\delta^2(E)$ -> transitions to the 1s level from levels higher then 4p can be neglected.**

- **PEP violating K lines energies based on multi configuration Dirac-Fock and General Matrix Elements numerical code.**

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

Results



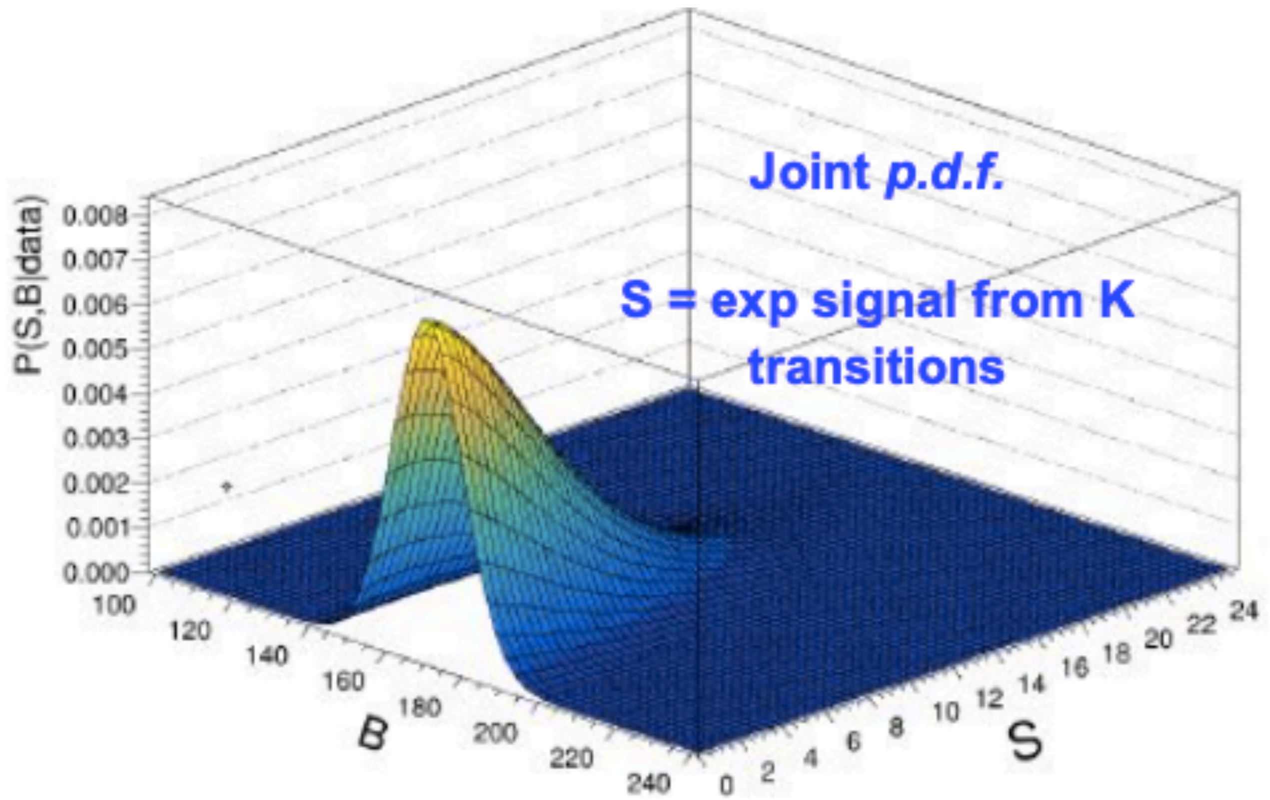
First analysis which accounts for the predicted energy dependence of the PEP violation probability. Expected rate of Kalpha1 transitions:

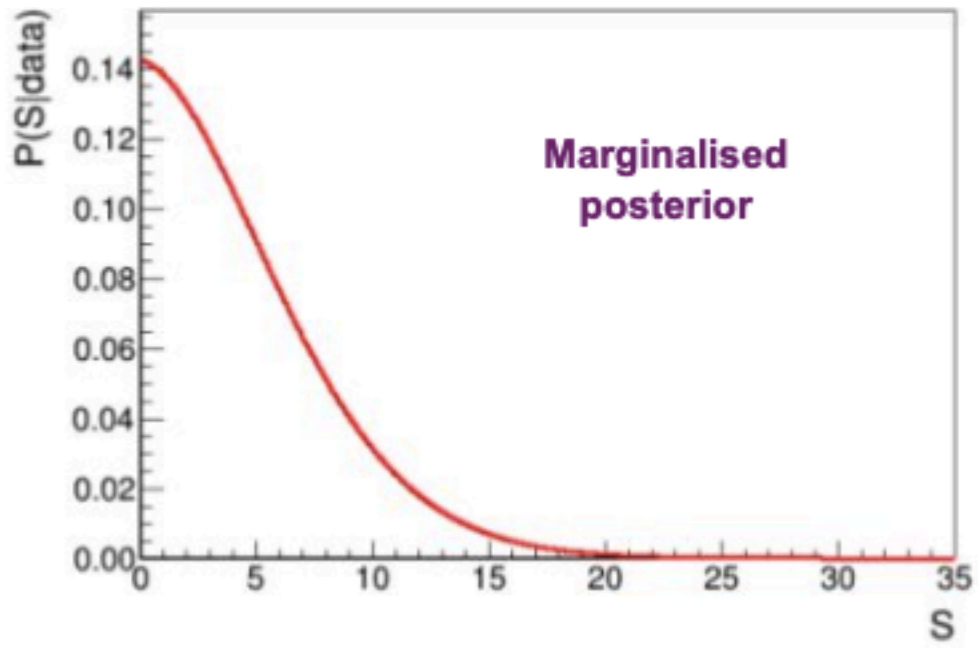
$$\Gamma_{K_{\alpha 1}} = \frac{\delta^2(E_{K_{\alpha 1}})}{\tau_{K_{\alpha 1}}} \cdot \frac{BR_{K_{\alpha 1}}}{BR_{K_{\alpha 1}} + BR_{K_{\alpha 2}}} \cdot 6 \cdot N_{atom} \cdot \epsilon(E_{K_{\alpha 1}}).$$

- 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	$2.6 \cdot 10^{2}$

PHYSICAL REVIEW LETTERS 129, 131301 (2022)
PHYSICAL REVIEW D 107, 026002 (2023)

Bonus: investigate a whole class of quantum gravity theories

https://doi.org/10.3390/universe9070321
Universe 2023, 9, 321

Analytical expansion

$$M_k : \quad \delta^2(E) = \frac{E^k}{\Lambda_k^k} + O(E^{k+1}),$$

k=1	*κ-Poincaré*	*Λ > 4.2 · 10²¹ Planck scales*
k=2	*θ-Poincaré*	*Λ > 1.6 · 10⁻¹ Planck scales*
k=3	*Triply special relativity**	*Λ > 5.6 · 10−9 Planck scales.*

A_i, M_k	$\bar{s}$	Lower Limit on Λ in Planck Scale Units
$A_1, k = 1$	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	$5.6 \cdot 10^{-9}$

Kowalski-Glikman and Smolin
** Phys. Rev. D 2004, 70, 065020*

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Kowalski-Glikman and Smolin
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First constraint!

Conclusions

- *VIP-2 Experiment in data taking: pushing the limit on Pauli exclusion principle violations*
- *BSM scenario motivate precision tests on PEP*
- *VIP-2 set the strongest limit in the MG super selection rule*
- *Publication of full statistics data soon!*
- *Quantum gravity model predict PEP violation in closed systems*
  - *Analyzed with high purity germanium detectors*
  - *Obtained upper limit on non-commutativity scale*
  - *Entire class of QG investigated*

Thank you for your attention!

Questions?