TESTING QUANTUM GRAVITY WITH GERMANIUM DETECTORS AT LNGS

Fabrizio Napolitano for the VIP Collaboration

INFN Istituto Nazionale di Fisica Nucleare

John Templeton Foundation

CENTRO FERMI
MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

FWF Der Wissenschaftsfonds.

TEQ

FQXi FOUNDATIONAL QUESTIONS INSTITUTE

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COLMO: Quantum Collapse Models Investigated with particle, nuclear, atomic and macro systems

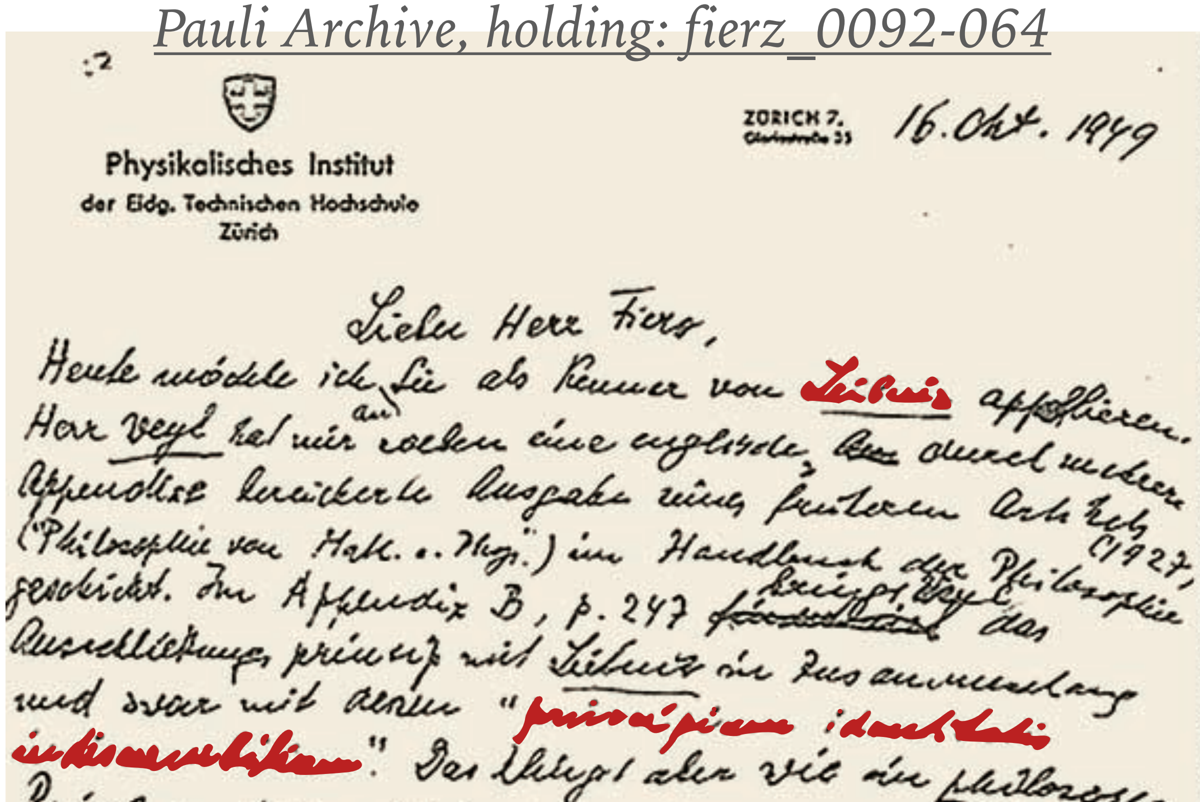
Jul 3th to 7th at ECT Trento, Italy*

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 an diesen eine englische, 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 klingt aber wie ein philosop…

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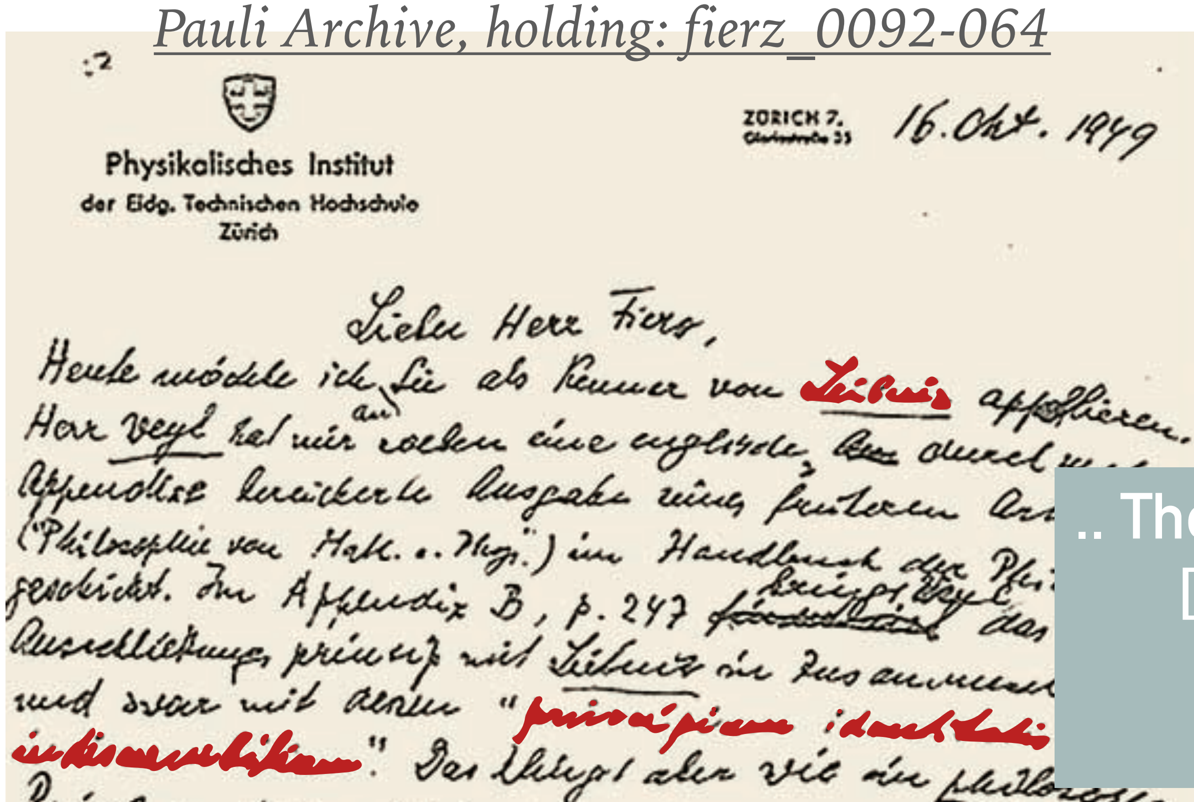
Physikalisches Institut
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ZÜRICH 7, 16. Okt. 1949

Lieber Herr Fierz,

.. 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:

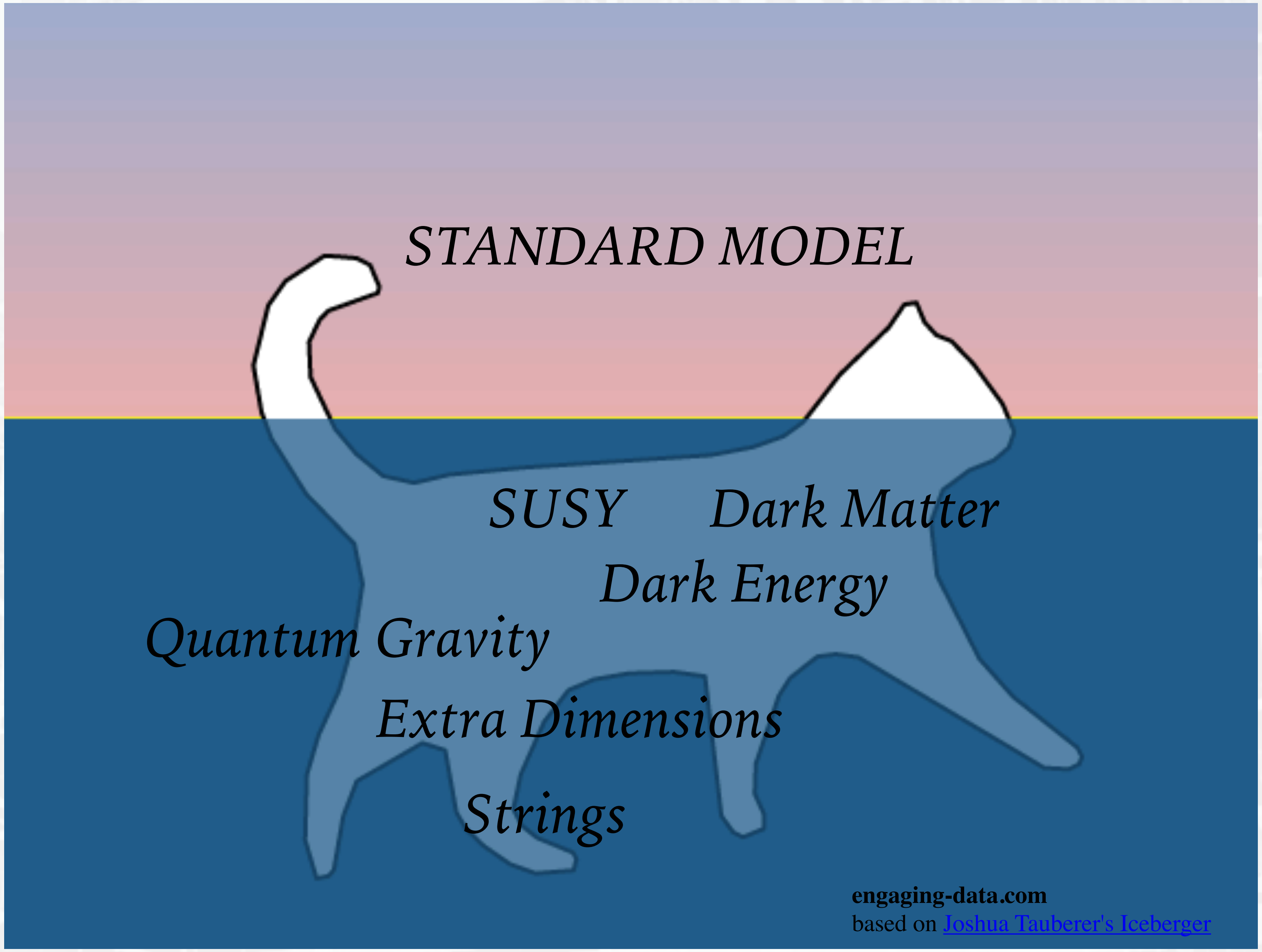
Lorentz/Poincaré Symmetry, CPT, unitarity, locality & causality

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)



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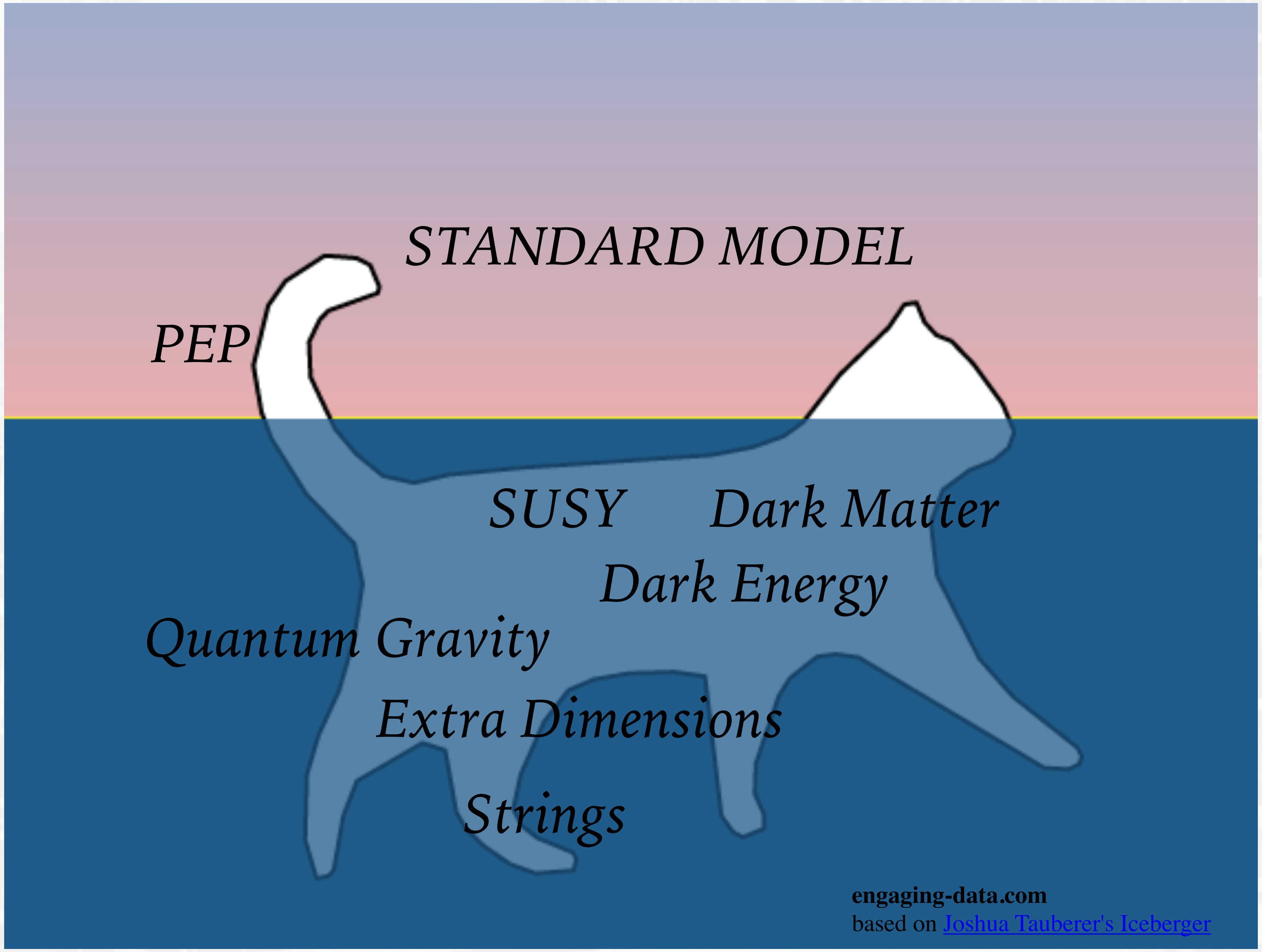

BSM theories embedding extra dimensions, non commutative and/or discrete spacetime could have effect on PEP

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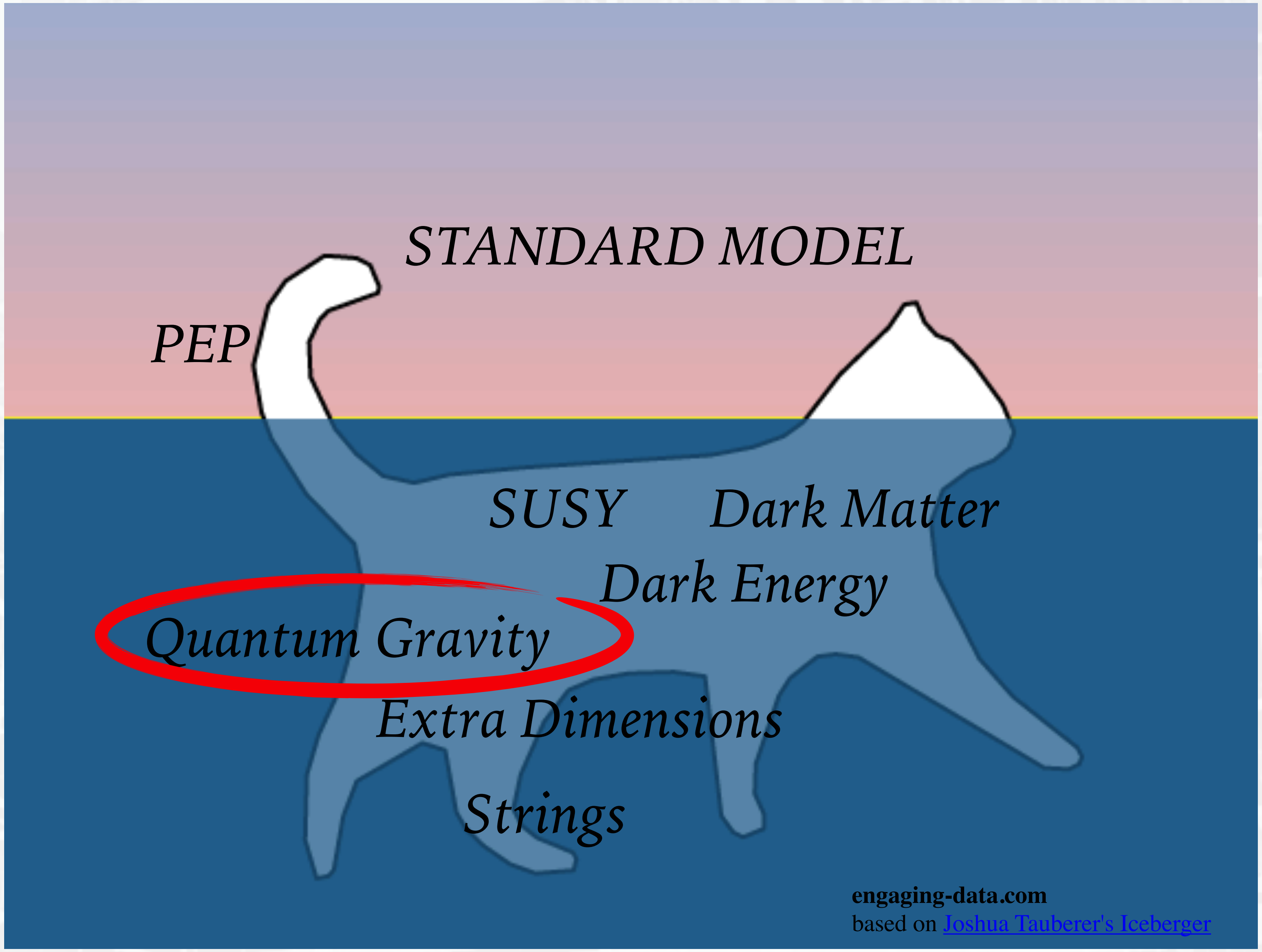


BSM theories embedding extra dimensions, non commutative and/or discrete spacetime could have effect on PEP

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)

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

β quantifies the degree of violation in the transition

Two classes of PEP violation Models:

- ***Deformation of commutation-anticommutation relations***

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

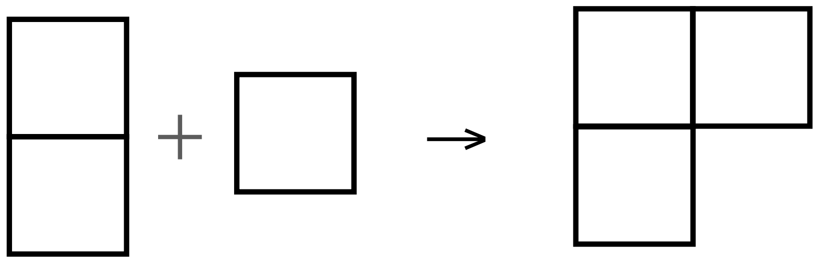
$$a_k a^{+}_l - q a^{+}_l a_k = \delta_{k,l}$$

  Subject to the Messiah-Greenberg (M-G) Superselection Rule!
  Can be tested in Open Systems only

- ***Space-time properties Balachandran, Addazi, Marcianò, Mavromatos- Not subject to the M-G rule - Can be tested in Closed Systems***

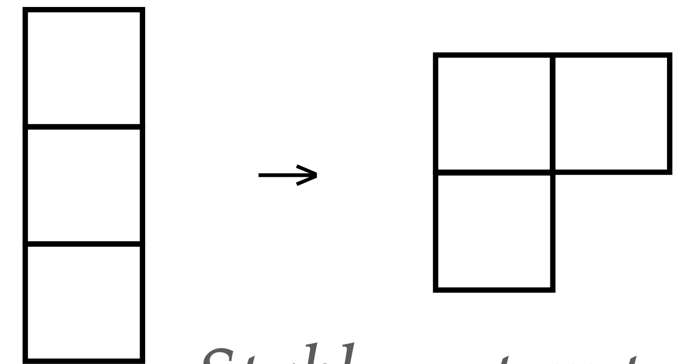
Messiah-Greenberg (M-G) Superselection Rule!

Open systems



Formation of a new state

Closed Systems



Stable system transition

Violations from deformation of anti/comm relations are restricted to open systems

Must introduce a new state from outside to form a new violating state

***VIP-2**: current on target to introduce new electrons*

See talk from A.Porcelli

Violation from space-time properties are NOT restricted to Open Systems

Quantum Gravity models can include space-time non commutativity

Subject of this talk

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].

A. Addazi, A. Marcianò International Journal of Modern Physics A Vol. 35, No. 32, 2042003 (2020)

↓

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.

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

specific calculation of atomic levels transitions probabilities for θ-Poincaré

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

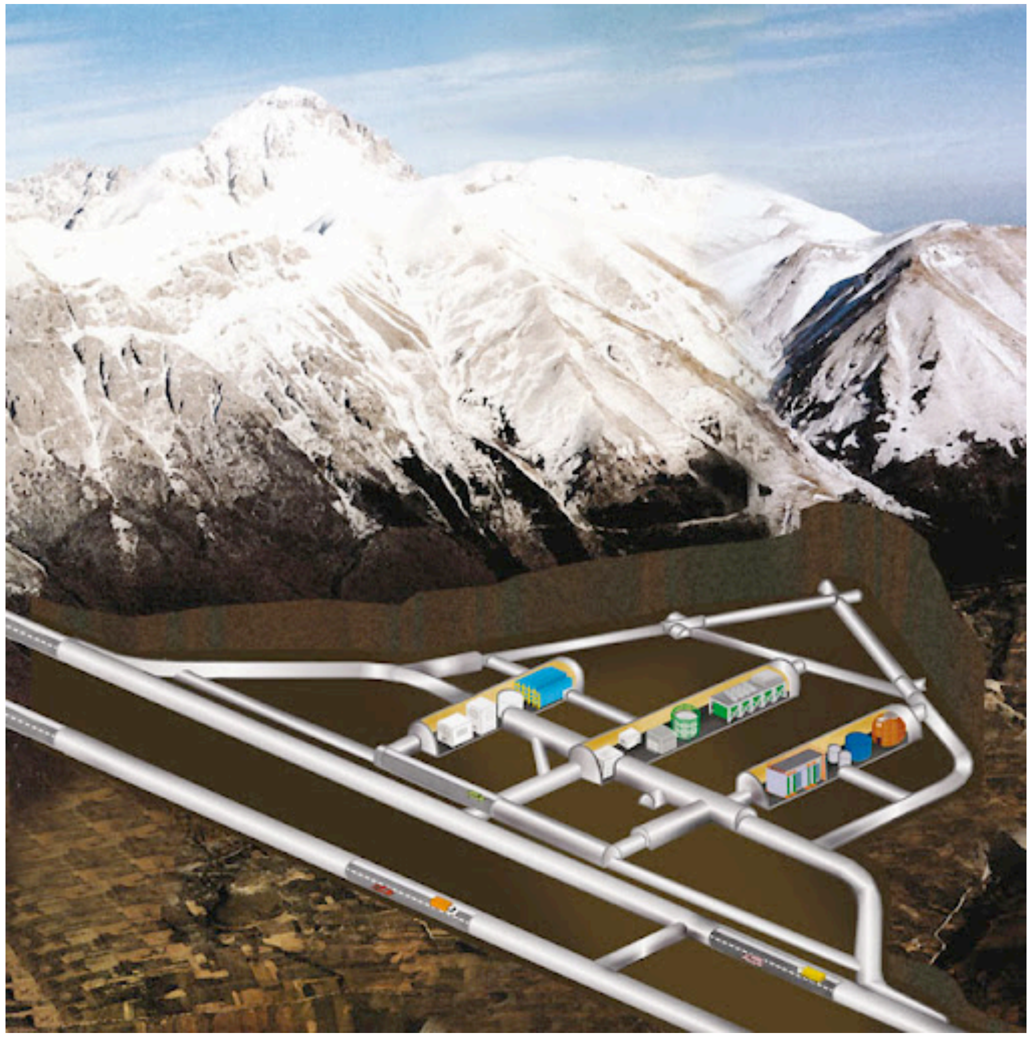
for non-vanishing (vanishing) electric like components of the $\theta^{\mu\nu}$ tensor.

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.

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 orders of magnitudes.

● the main background source consists of γ-radiation produced by long-lived γ-emitting primordial isotopes and their decay products.

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.

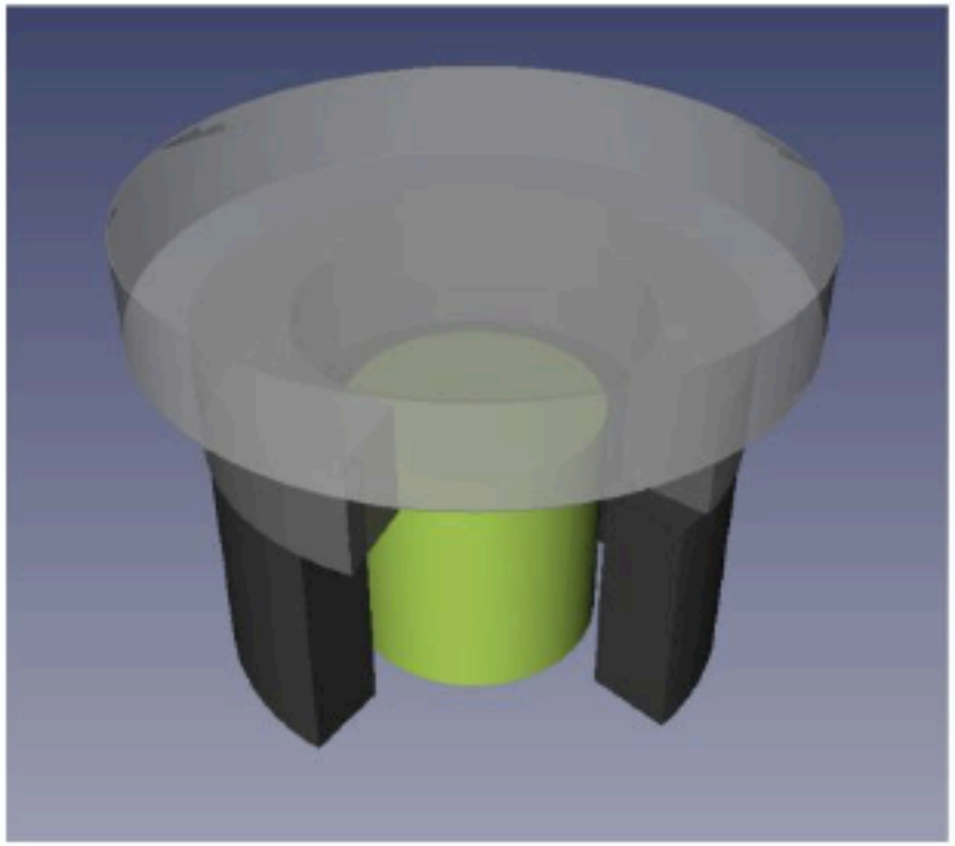
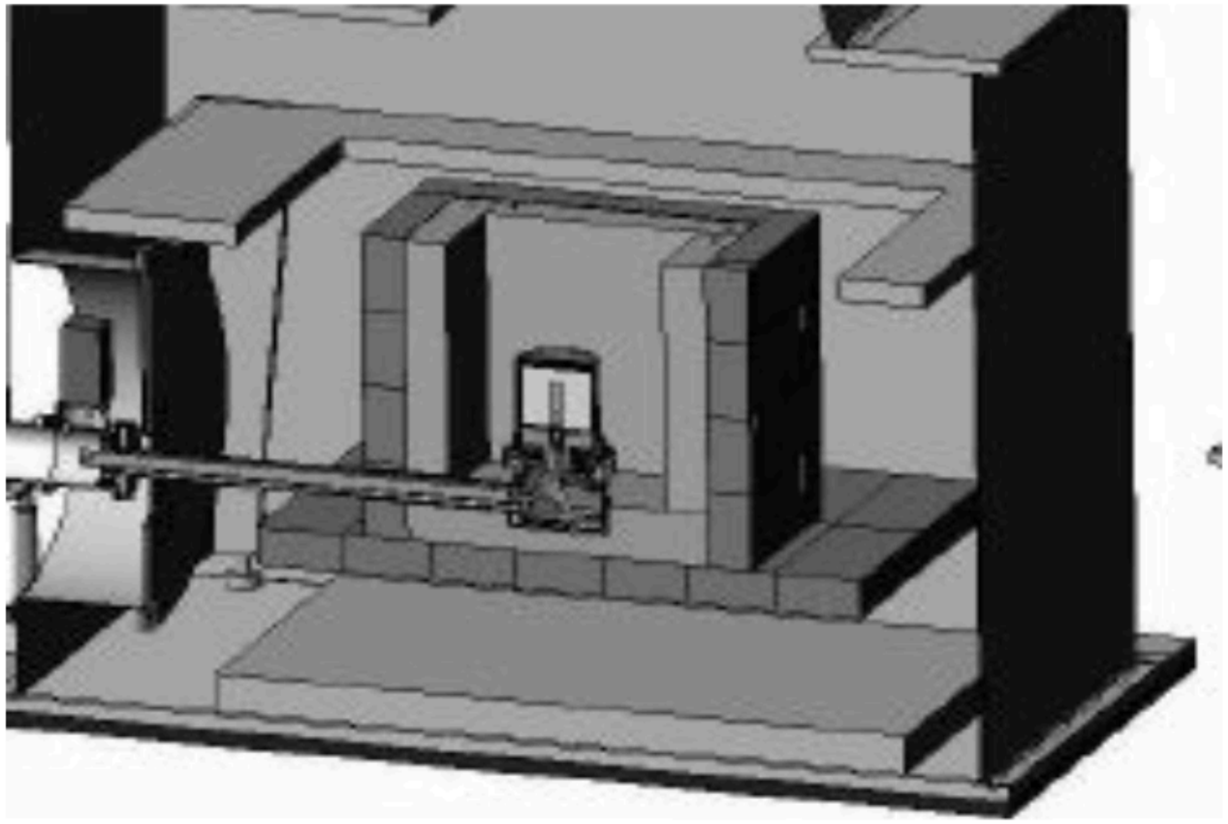


Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

Experimental Setup

- **Passive shielding:**
  outer part lead (30 cm from the bottom and 25 cm from the sides). Inner layer (5 cm) electrolytic copper.
  On the bottom and on the sides 5 cm thick 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 (thus radon).**



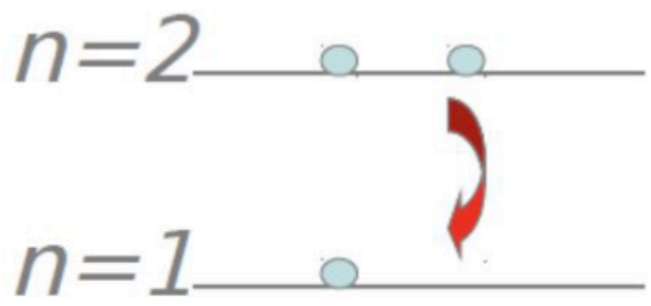
- **Whole detector is characterised and all of its components have been put into a validated Monte Carlo (MC) code based on GEANT4.**

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

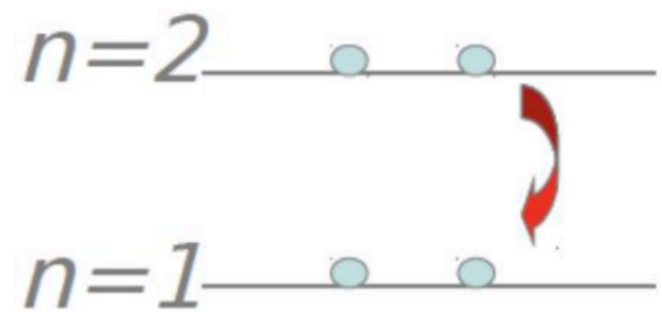
K. P. et al., Eur. Phys. J. C (2020) 80: 508
https://doi.org/10.1140/epjc/s10052-020-8040-5

- **Aim of the measurement: search for the X-rays signature of PEP-violating K_α and K_β 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



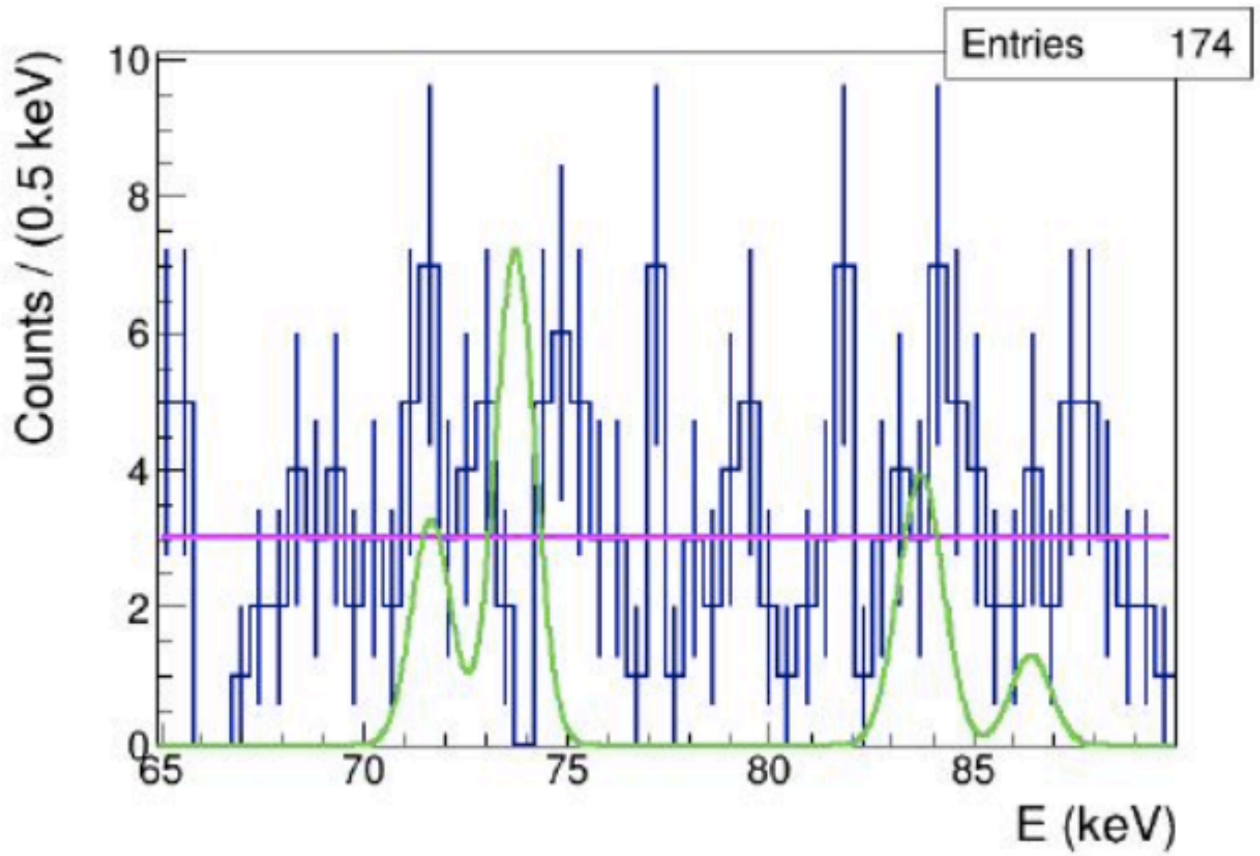
2p → 1s transition violating Pauli principle

- **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



Background

Signal from violating transitions in Lead

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)

Conclusions

- *VIP collaboration tests PEP violation in Open Systems (see talk from A.Porcelli) and Closed Systems*
- *Effective Theories of Quantum Gravity (NCQG) predict PEP violation in Closed Systems through non-commutativity of space-time and thus Lorentz symmetry / locality*
- *Using High-Purity Germanium Detectors, we have set strong bounds on theta Poincaré, excluding beyond the Planck scale the non vanishing electric-like case $\theta_{i,0} \neq 0$ and strongly constrained the vanishing case*

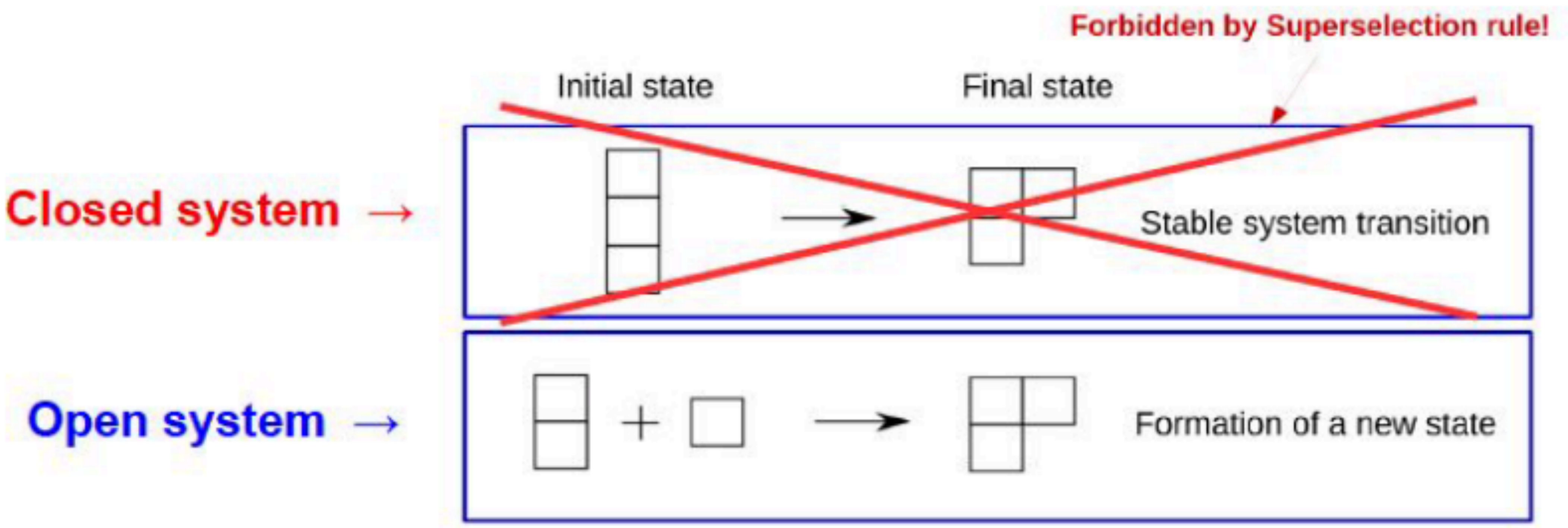
Thank you for your attention!

Questions?

Messiah-Greenberg super-selection rule:

Superposition of states with different symmetry are not allowed →

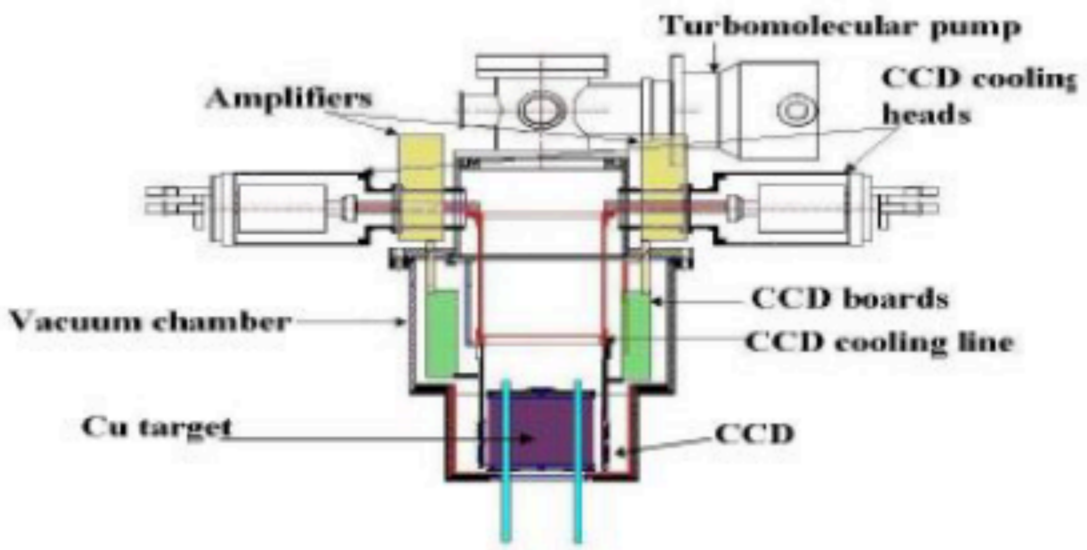
Transition probability between two symmetry states is ZERO

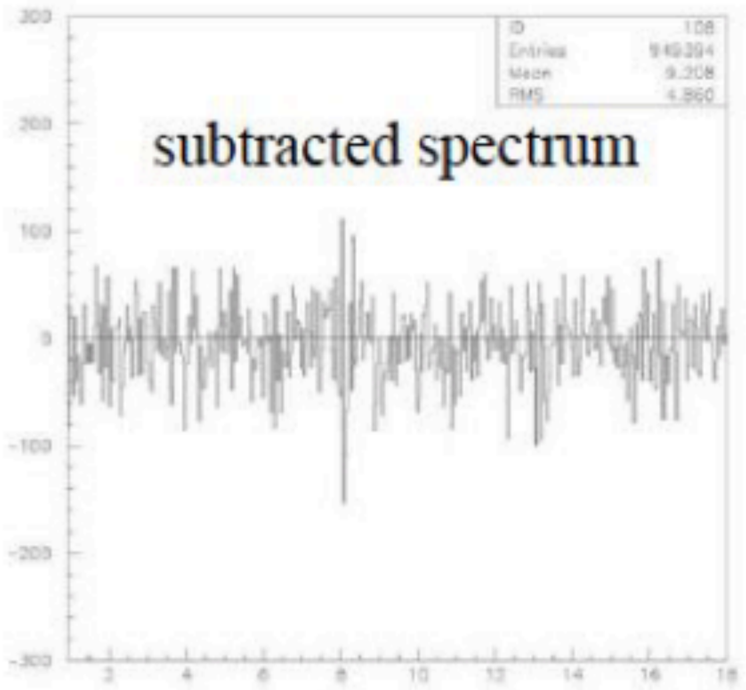


VIP-2 Experiment: best limits on PEP violation of an elementary particle respecting the Messiah-Greenberg super-selection rule

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.





$$\beta^2/2 \leq 4.7\times10^{-29}$$

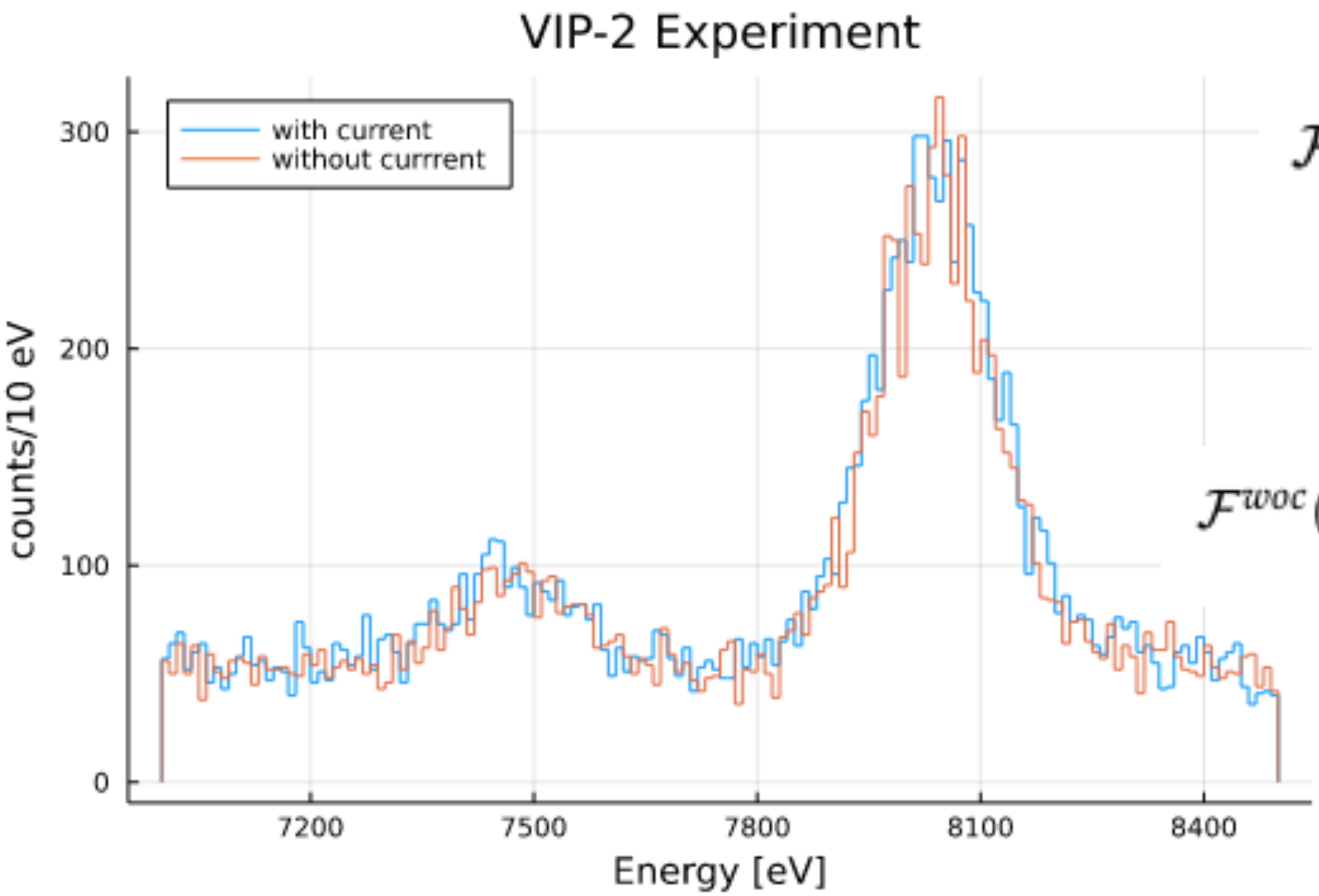
improved the limit obtained by Ramberg & Snow by a factor ~ 400

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

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

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

Six months of data taking



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

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

Likelihood

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

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

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

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

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.

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]

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

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

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):

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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.**
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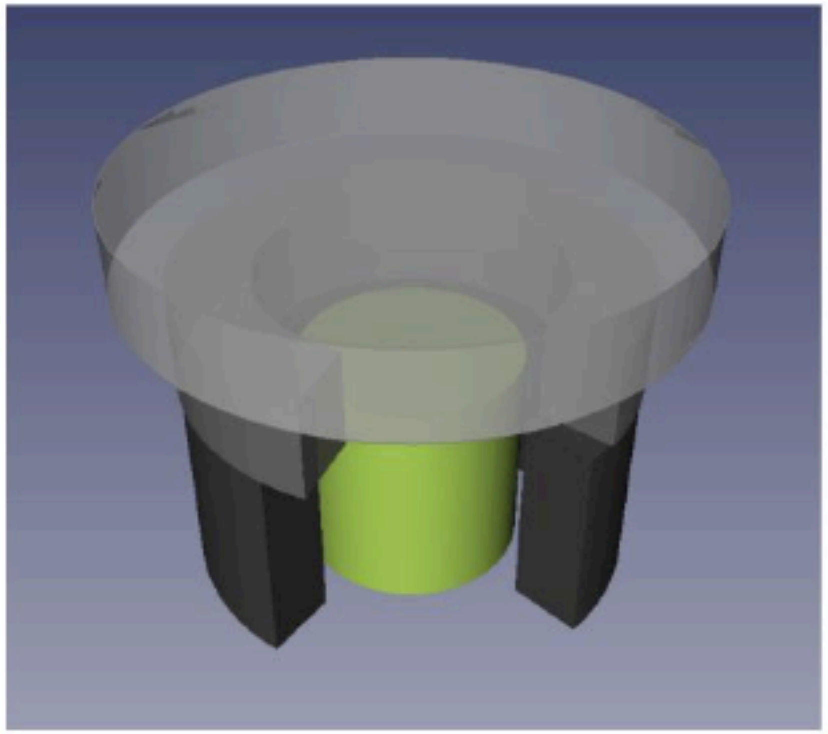

Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

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- Passive shielding: inner - electrolytic copper, outer - lead
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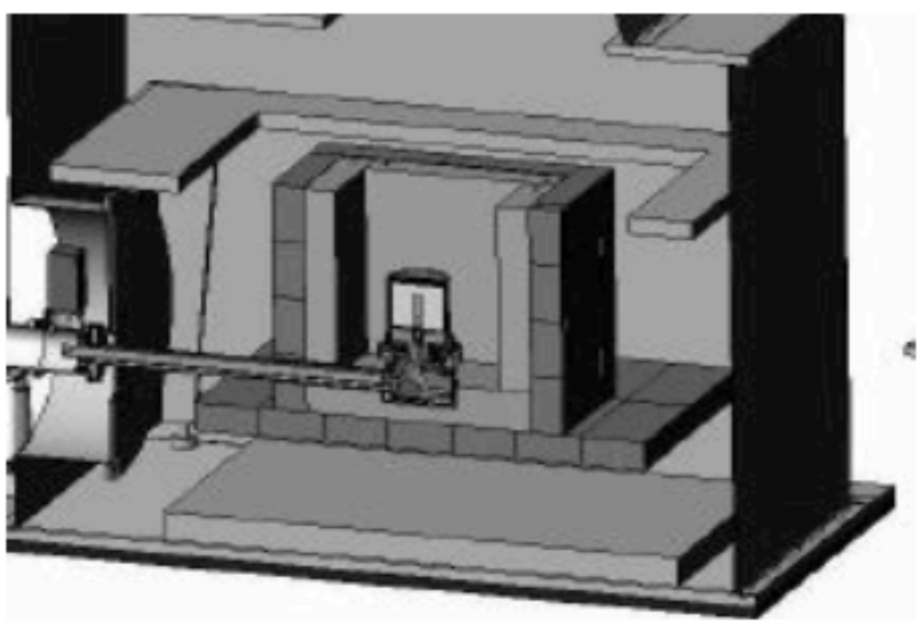
K. Piscicchia et al., Eur. Phys. J. C (2020) 80: 508
https://doi.org/10.1140/epjc/s10052-020-8040-5



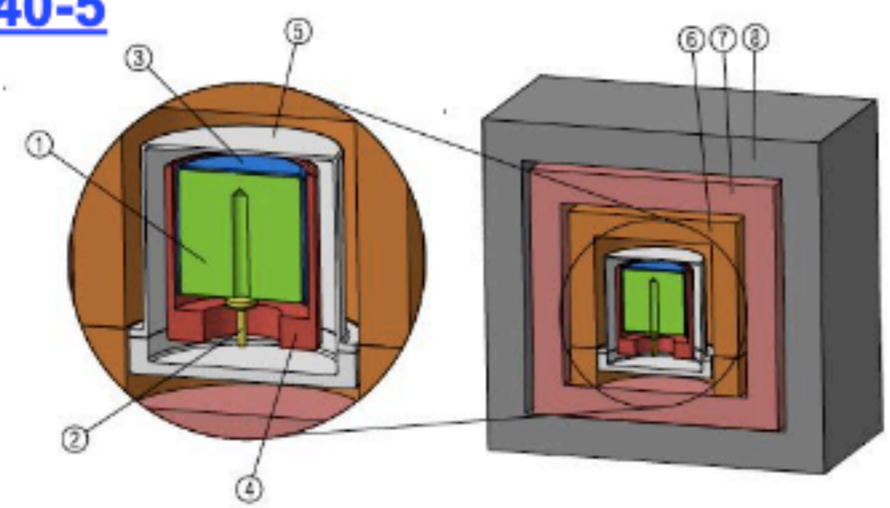
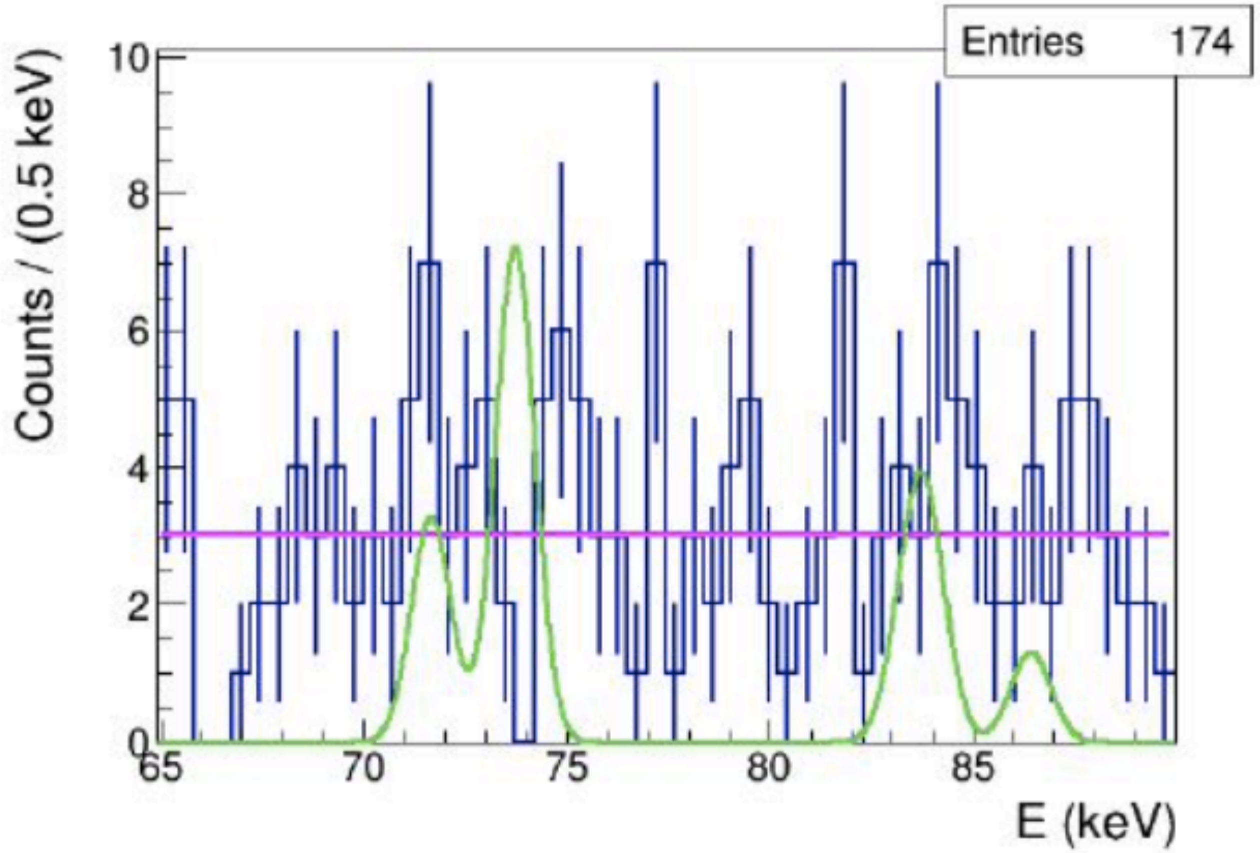


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

Results



Background

Signal from violating transitions in Lead

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

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

accepted PRL: "Strongest atomic physics bounds on Non-Commutative Quantum Gravity Models"

Proof of spin-statistics theorem by Lüders and Zumino

Postulates:

- *The theory is invariant with respect to the proper inhomogeneous Lorentz group (includes translations, does not include reflections)*
- *Two operators of the same field at points separated by a spacelike interval either commute or anticommute (locality – microcausality)*
- *The vacuum is the state of lowest energy*
- *The metric of the Hilbert space is positive definite*
- *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 Pauli Exclusion Principle (PEP) Violations

Some more PEP Violating models:

Greenberg, O.W. Mohapatra, R.N. Physical Review Letters 1987, 59, 2507
Govorkov, A. Physica A: Statistical Mechanics and its Applications 1994, 203, 655
Rahal, V.; Campa, A. , Physical Review A (1988) 38, 3728

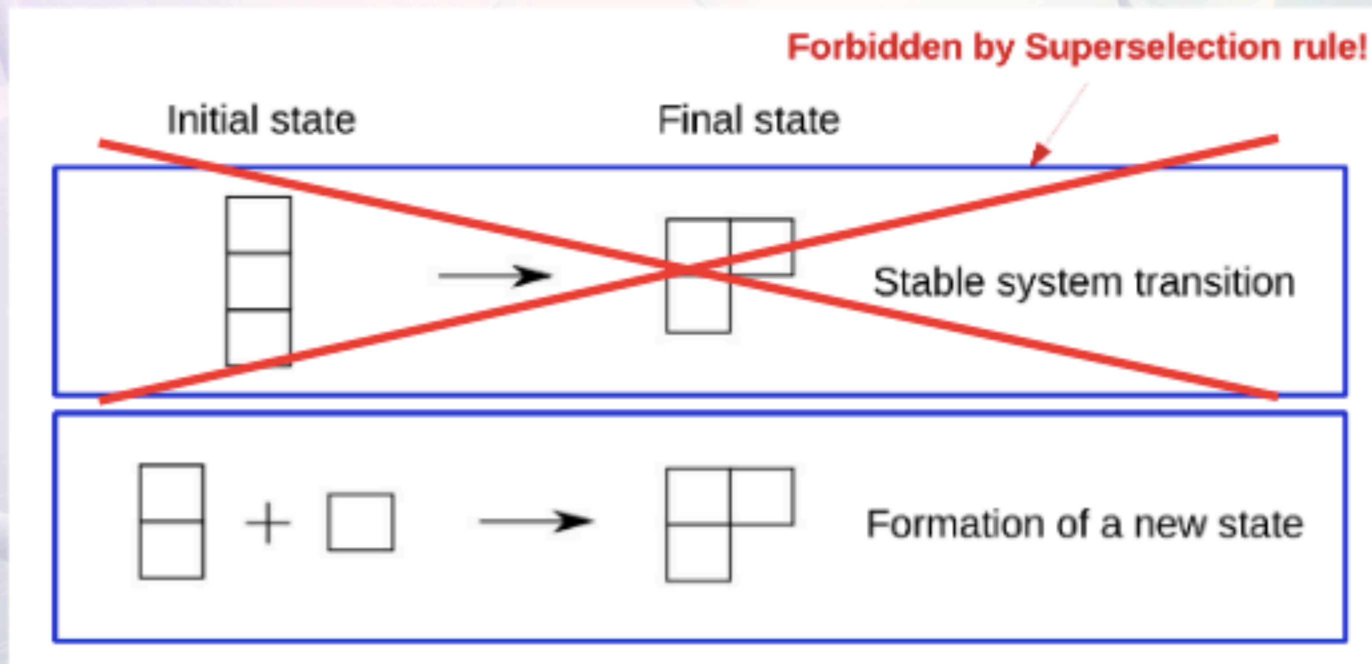
Messiah - Greenberg superselection rule

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

Messiah-Greenberg superselection rule :

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-2 experiment goal

(Upper limit not using Close Encounters (CE) treatment)

As reference for past experiments

Experiment	Target	Upper limit of $\beta^2/2$	reference
Ramberg-Snow	Copper	1.7×10^{-26}	[5]
S.R. Elliott et al.	Lead	1.5×10^{-27}	[14]
VIP(2006)	Copper	4.5×10^{-28}	[12]
VIP(2012)	Copper	4.7×10^{-29}	[13]
VIP2(goal)	Copper	$\times 10^{-31}$	[15]

New paradigm for VIP-2

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

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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].
A. Addazi, A. Marcianò International Journal of Modern Physics A Vol. 35, No. 32, 2042003 (2020)

↓

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.

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)

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

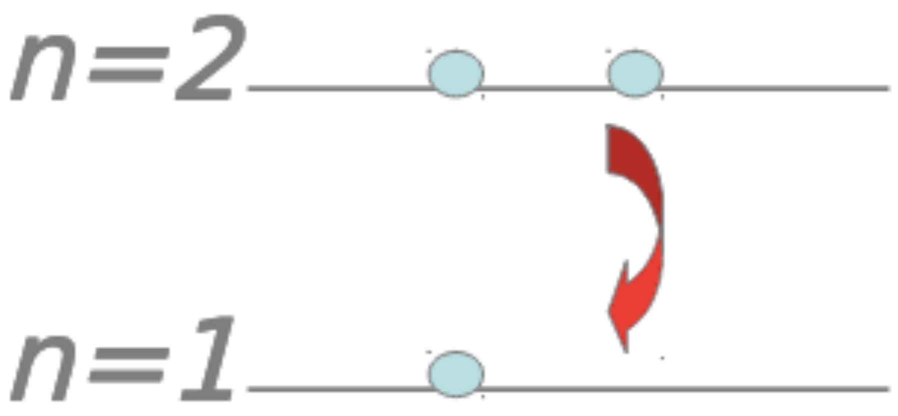
β quantifies the degree of violation in the transition

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

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

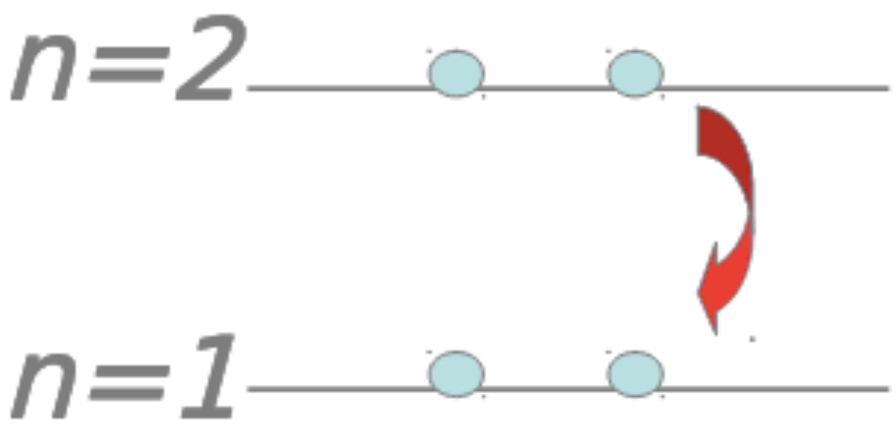
- Rahal & Campa: global wave function of the electrons not exactly antisymmetric, PEP holds as long as the number of wrongly entangled pairs is small

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

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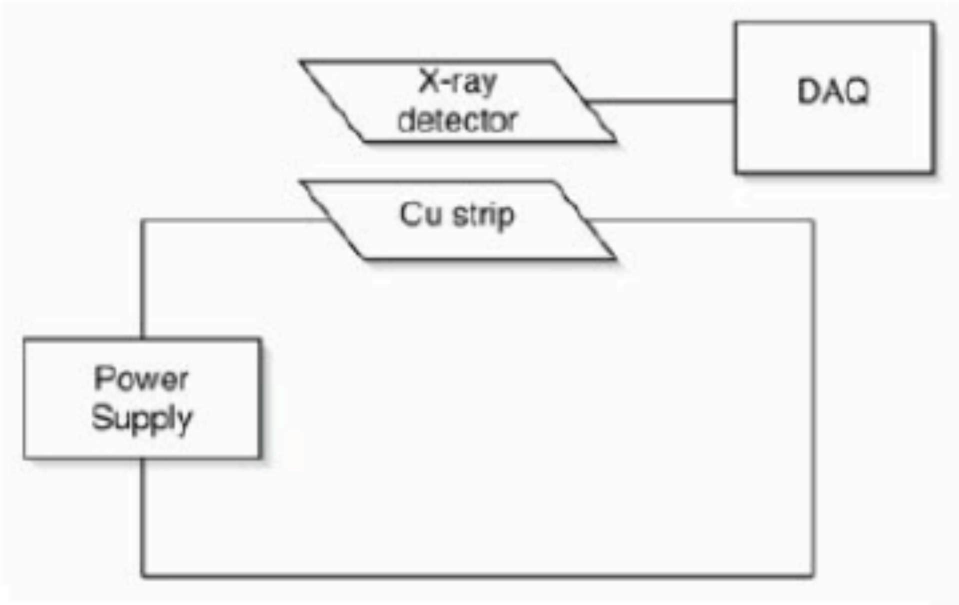
Multiconfiguration Dirac-Fock approach

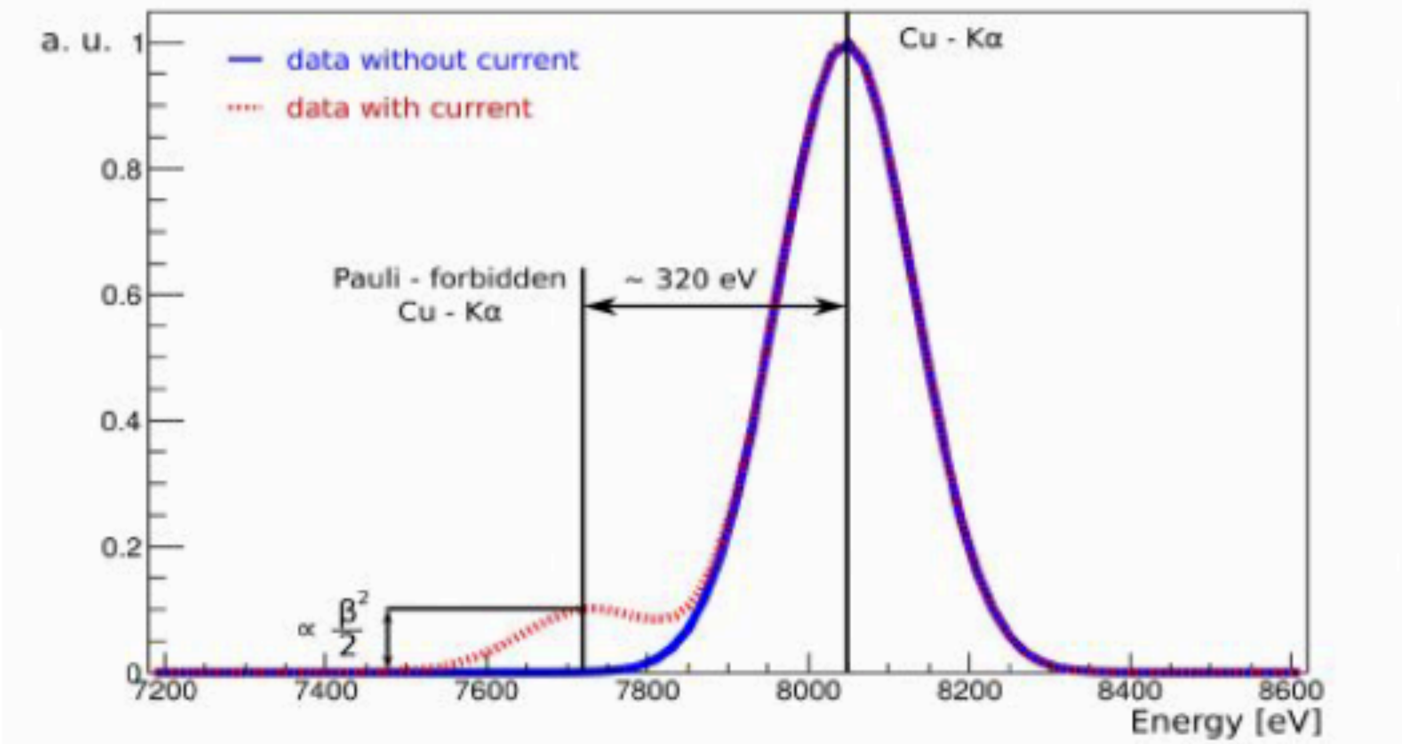
Accounts for the shielding of the two inner electrons

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

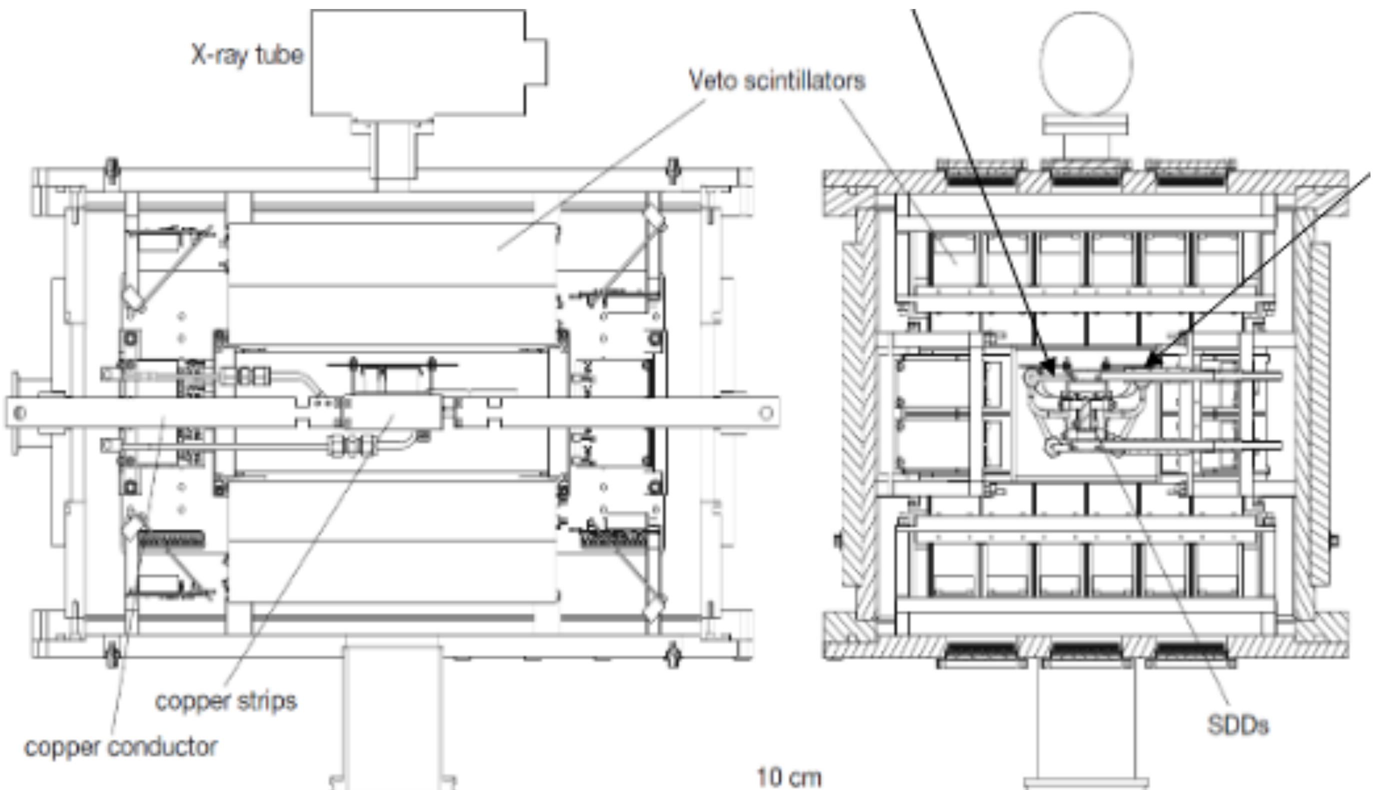


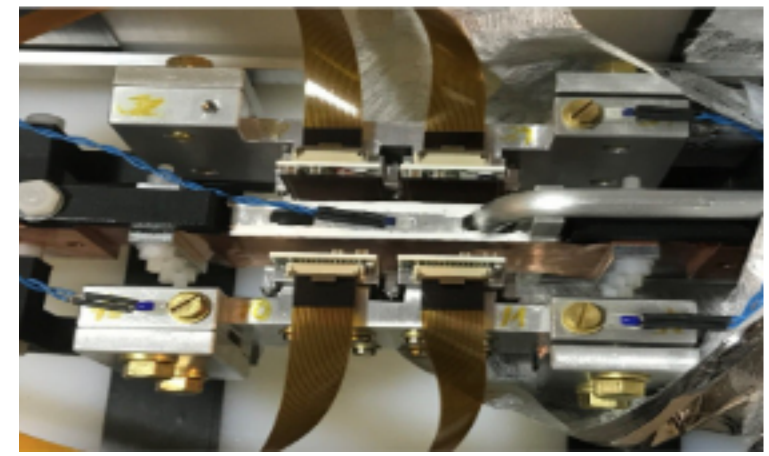
PEP Violation Signal:

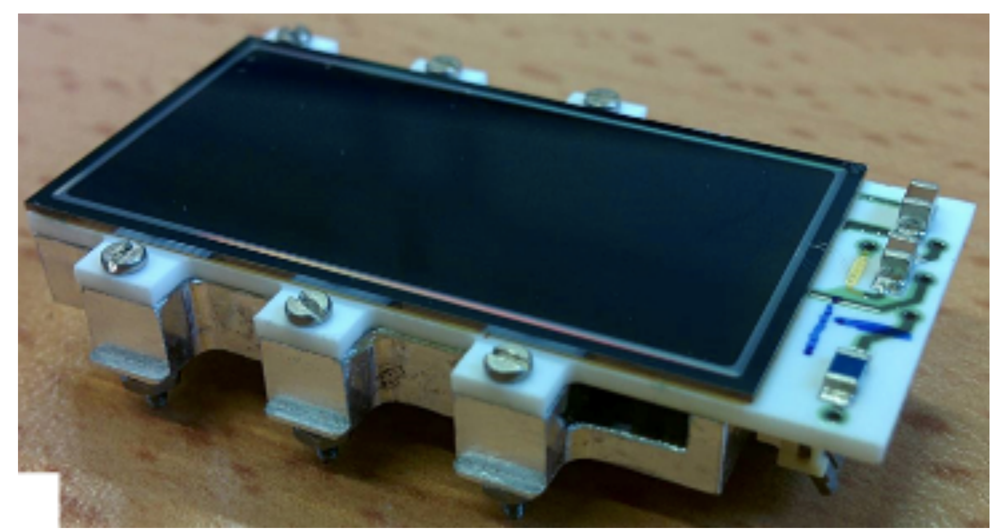


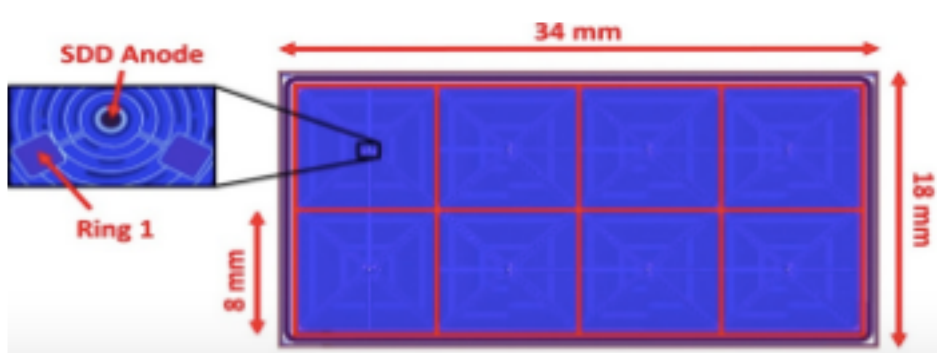
The VIP-2 Experiment

*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

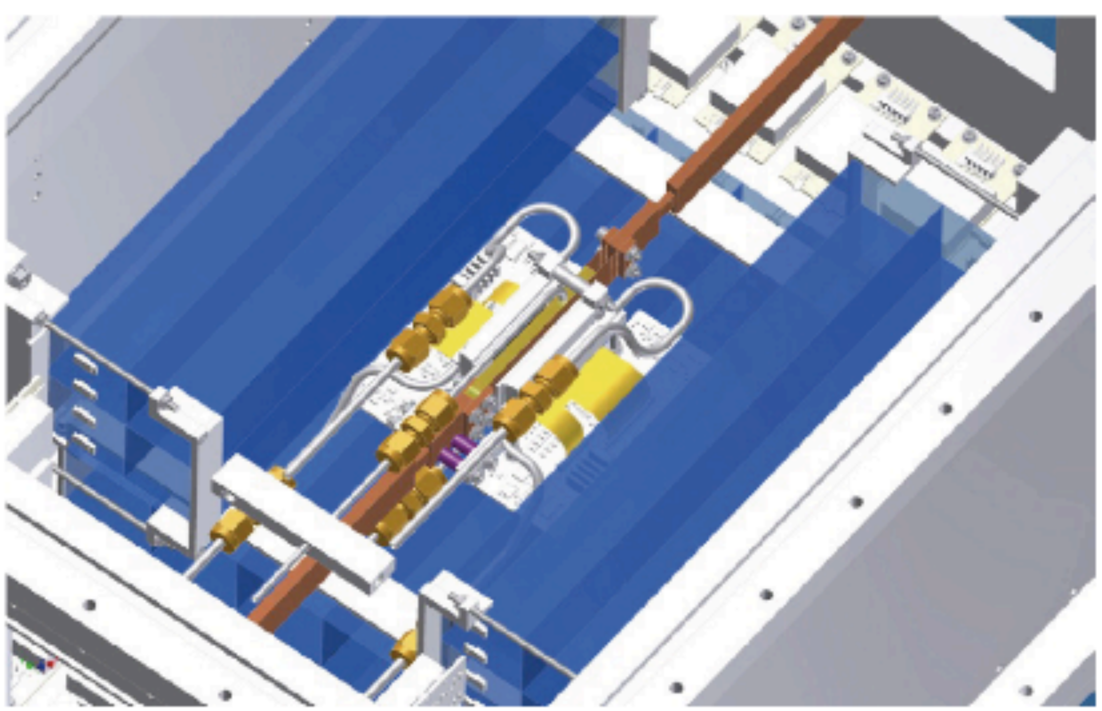
*2 strip shaped Cu targets (25 um x 7 cm x 2 cm) more compact target → higher acceptance, thinner → **higher efficiency***

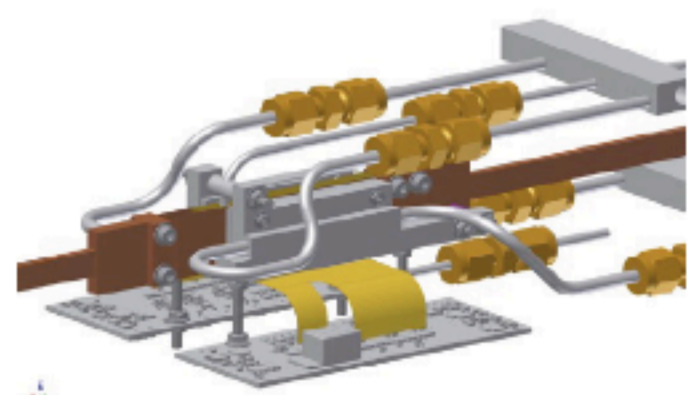
DC current supply to Cu bars

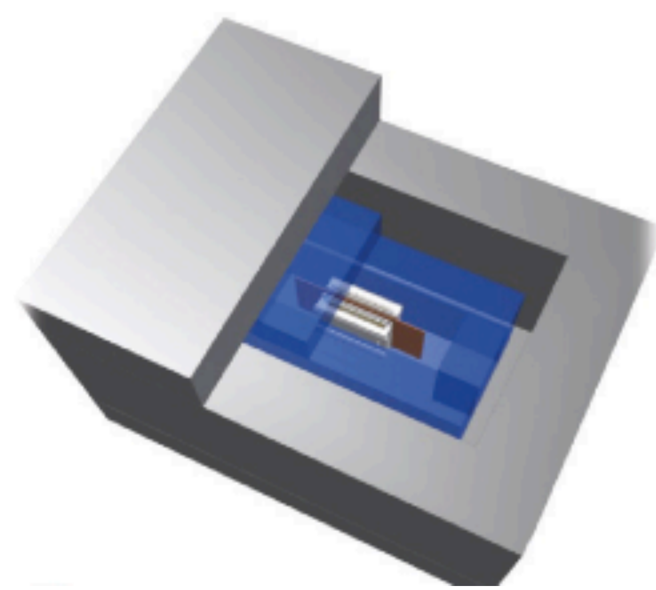
*Cu strips cooled by a closed Fryka chiller circuit →**higher current***

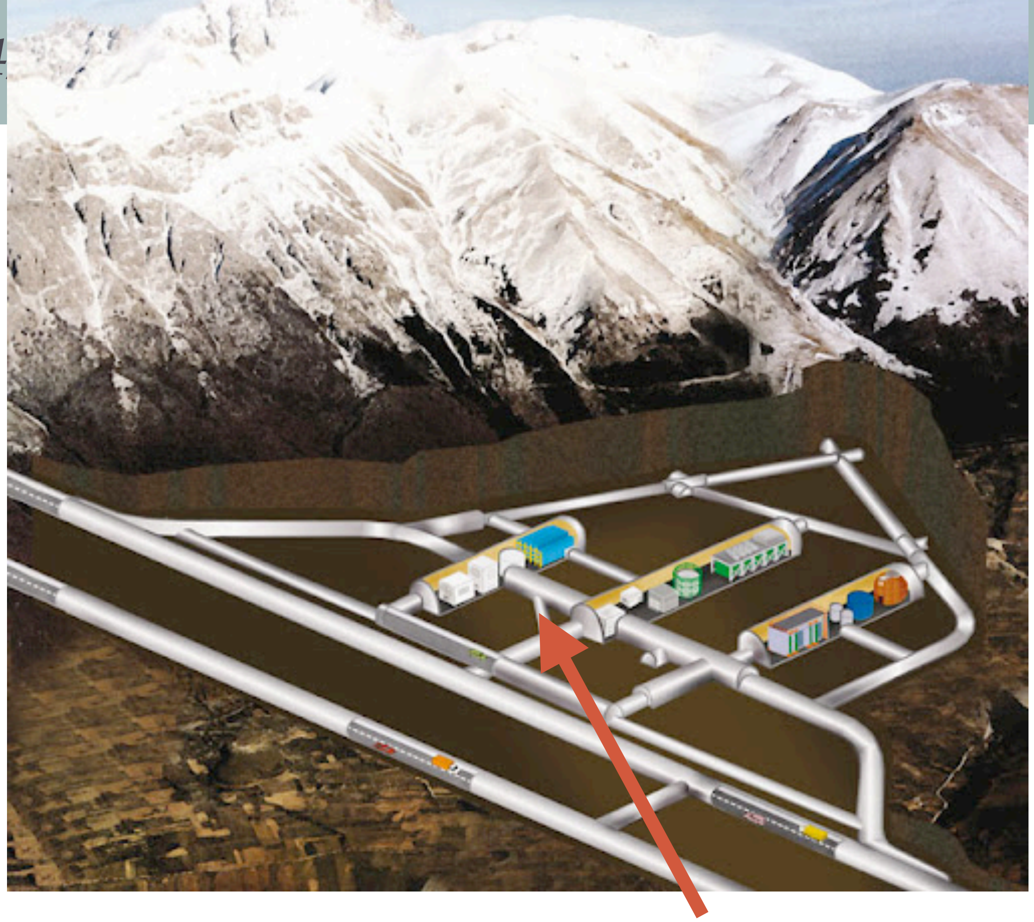
(100 A) @ 20 °C of Cu target implies 1 °K heating in SDDs

Sketch of the VIP2 Setup:



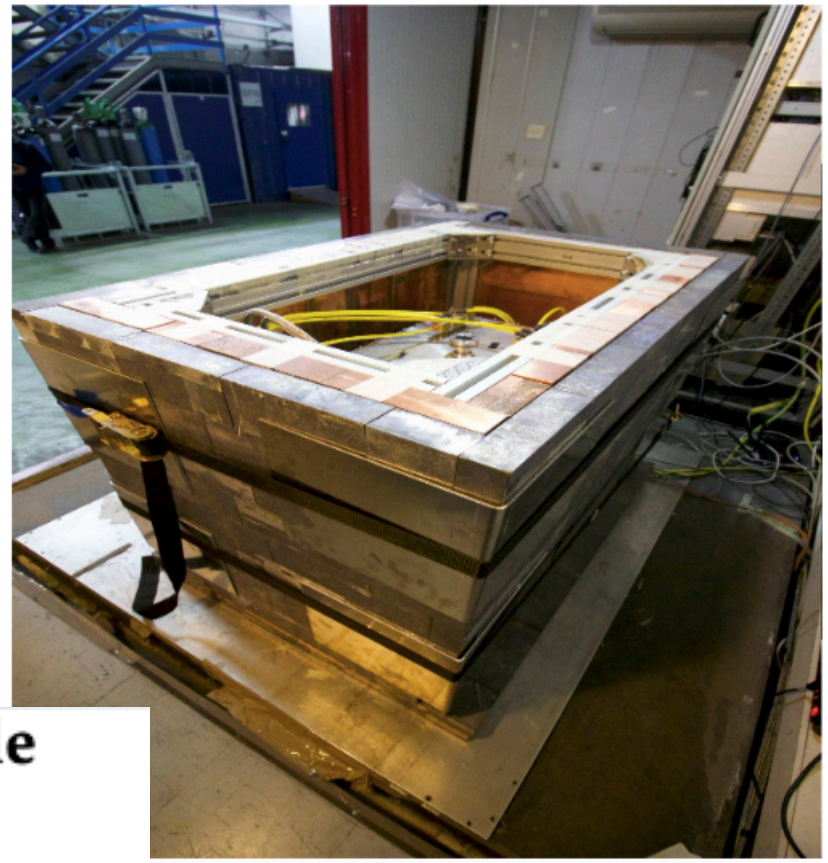




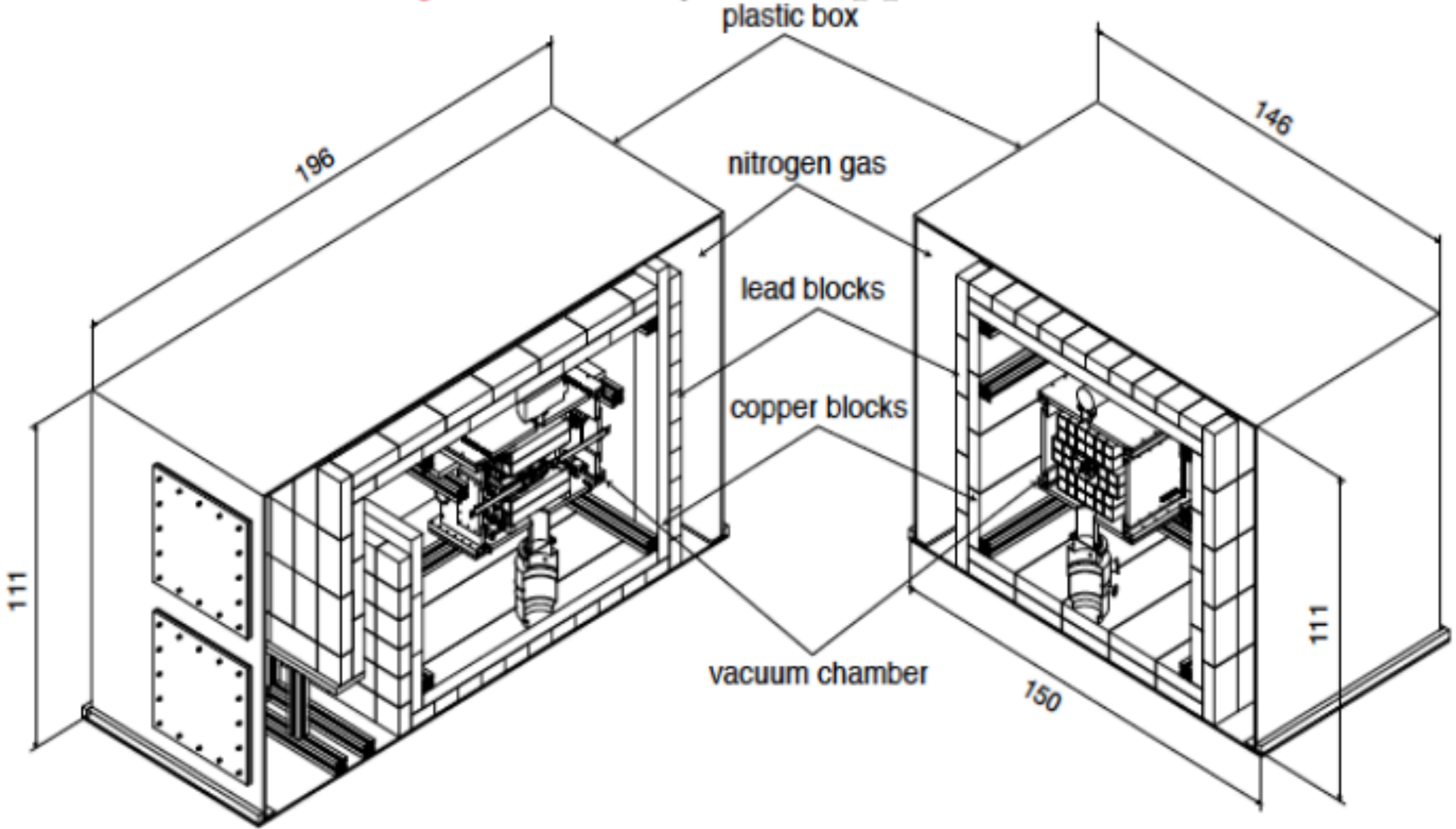


1400 m rock coverage

Upgrade concluded in April 2019:

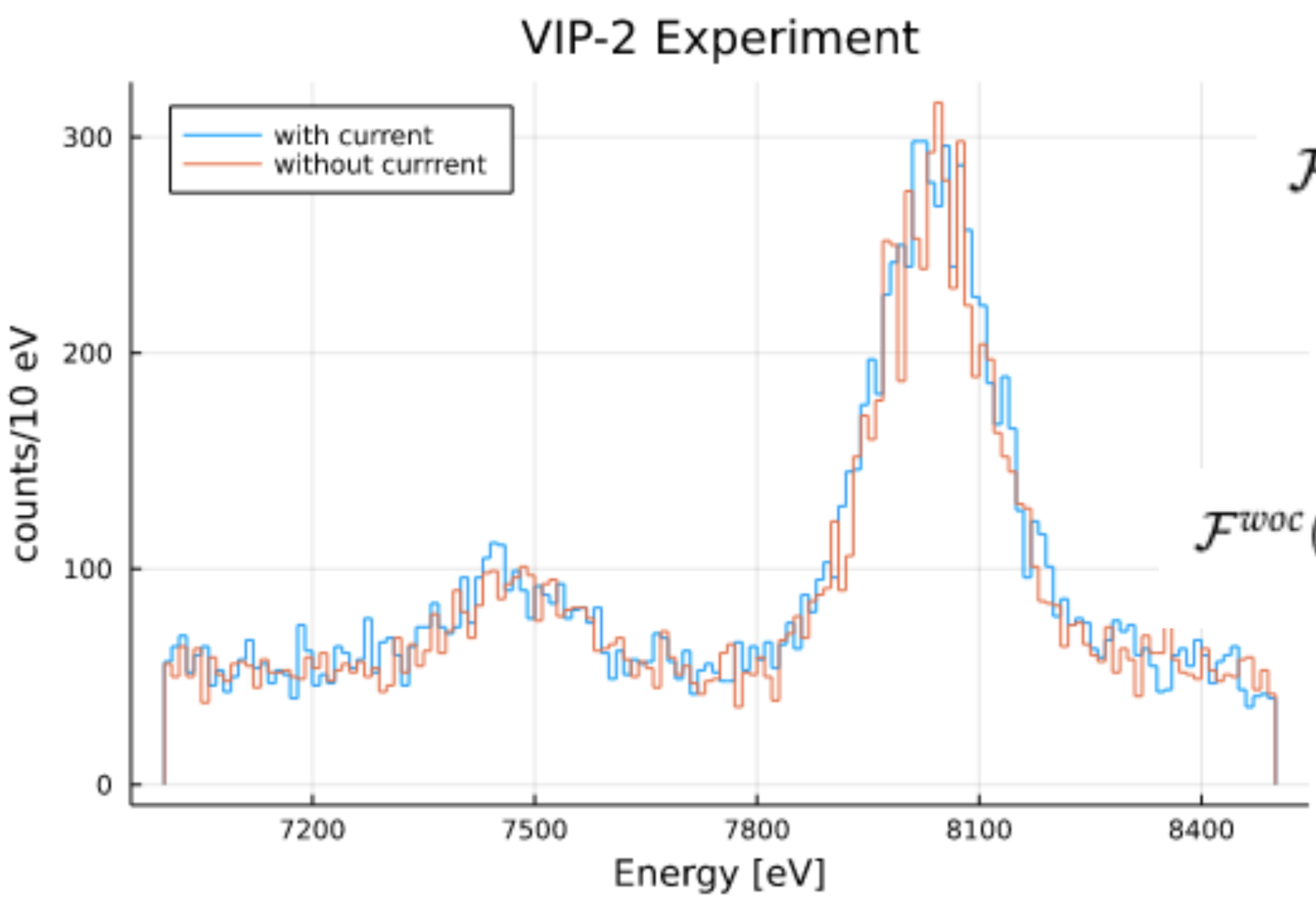


Passive scielding → **two layers, copper inside lead outside**



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

Six months of data taking



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

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

Likelihood

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

Bayesian

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

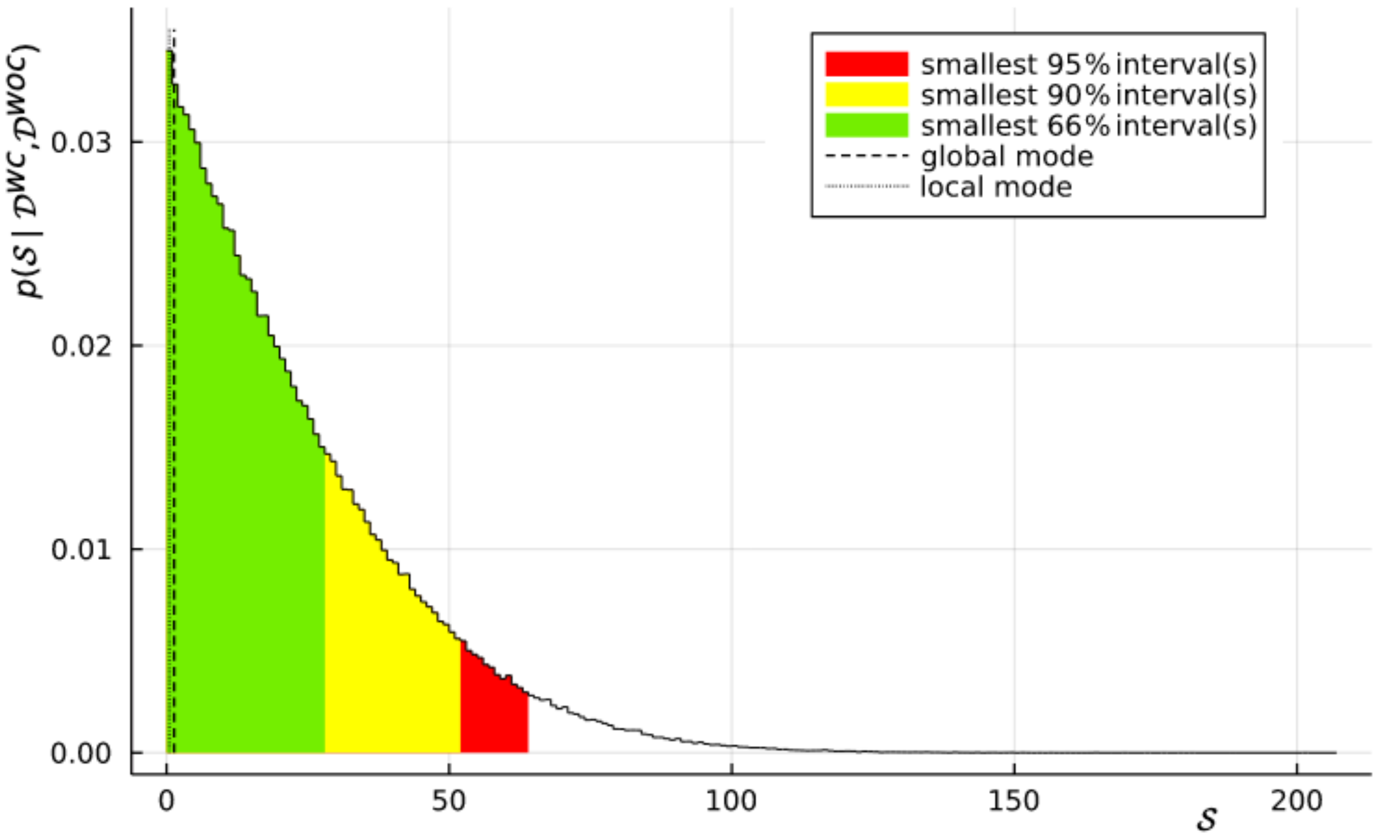
Frequentist

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

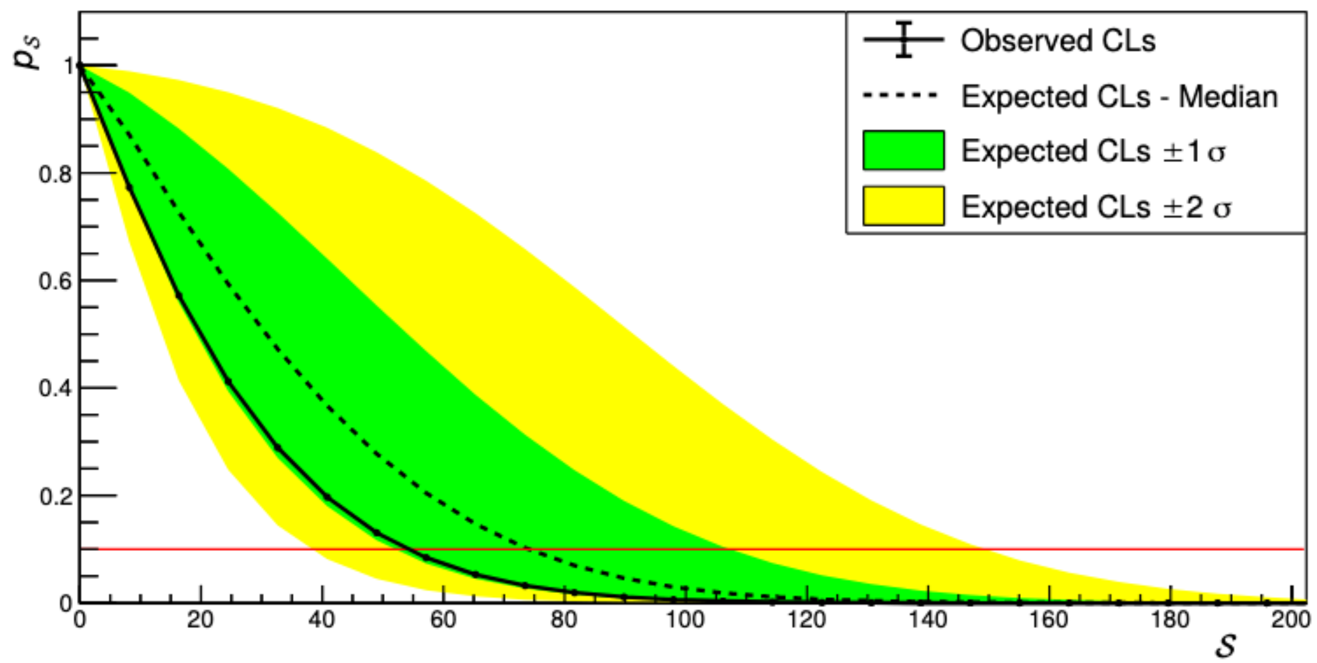
$$p_\mathcal{S} = \int_{t_{obs}}^{\infty} f(t_\mathcal{S}|\mathcal{S})dt_\mathcal{S}$$

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

Bayesian



Frequentist

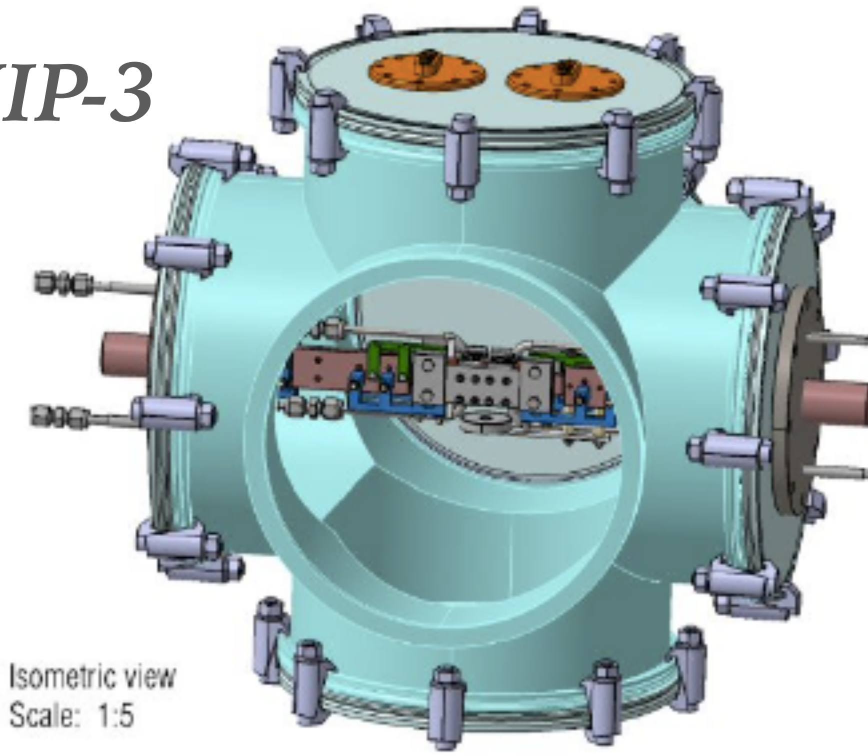


$$\beta^2/2 \leq 8.6 \times 10^{-31} \text{ (Bayesian)}, \qquad \beta^2/2 \leq 8.9 \times 10^{-31} \text{ (CL}_s\text{)}$$

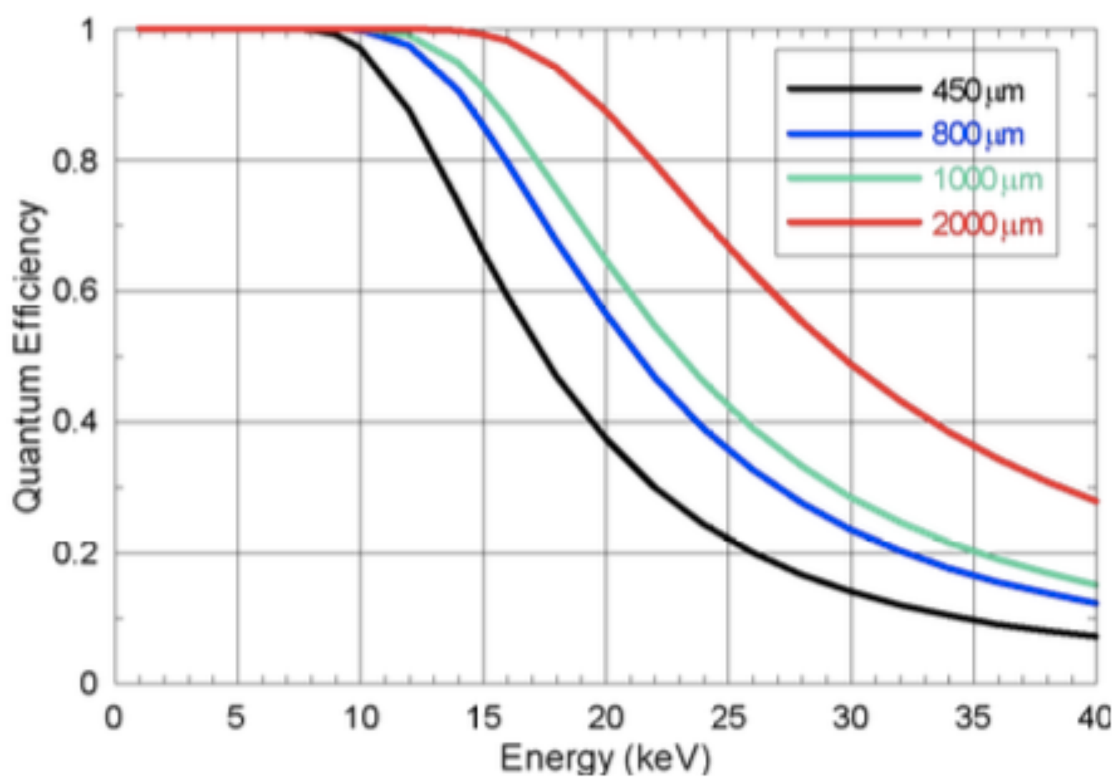
New article in preparation with all the available statistics!

VIP-2 experimental upgrade: VIP-3

- ***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***



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