Open Problems in Quantum Mechanics (PAMQ)

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Place of Work & Collaborations:

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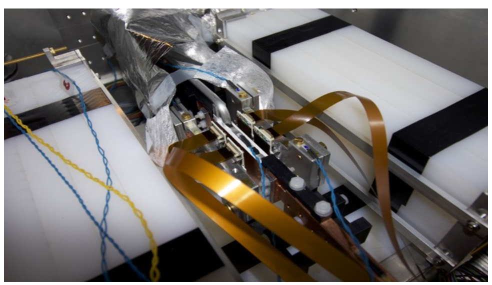
IFIN-HH Bucharest (Romania)
Wigner Institute (Hungary)
Rennes Univ. (France)
Stephen Adler- Inst. For Advanced Study, Princeton, USA
Univ. Melbourne (Australia)
Fudan University, Shanghai (China)
Chengdu University, Chengdu (China)

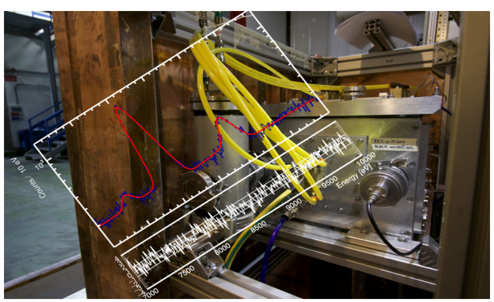
Open Problems in Quantum Mechanics (PAMQ)

PAMQ deals in particular with:

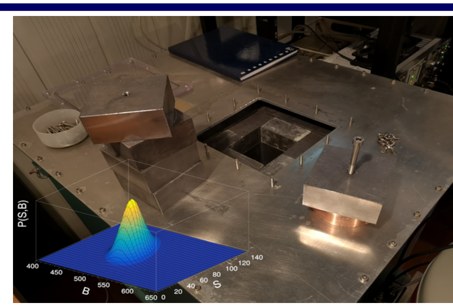
- Tests of the Pauli Exclusion Principle for electrons, the VIP-2 experiment at Gran Sasso Underground Laboratory

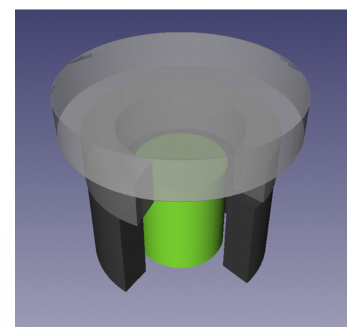
- The *measurement problem* → searching for signal of spontaneous radiation emission predicted in Dynamical Reduction Models of the wave function collapse (Continuous Spontaneous Localization CSL & Diosi-Penrose)

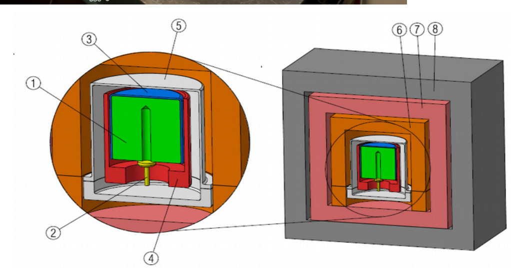




The VIP2 setup in data taking At LNGS







Three setups based on HPGe and BEGe detectors operated at LNGS

Open Problems in Quantum Mechanics (PAMQ)

VIP-2 experiment: the scientific case

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.*"*

VIP-2 open systems

Ignatiev & Kuzmin model: Fermi oscillator with a third state, β quantifies the degree of violation in the transition

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

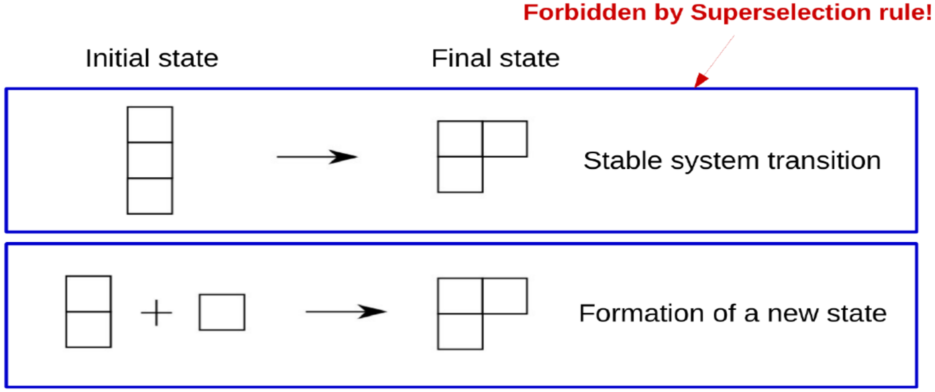
O. W. Greenberg, R. N. Mohapatra, Phys. Rev. Lett. (1987), 59 2507 → quon theory

local quantum field theory violating PEP → q parameter deforms anticommutators

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

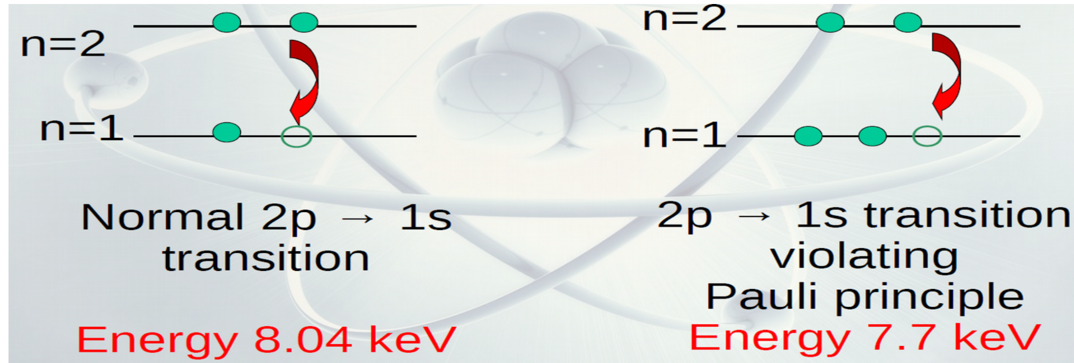
Messiah – Greenberg superselection rule : transition amplitude between two different symmetry states is ZERO

VIP unique experiment respecting the M-G superselection rule



VIP-2 open systems

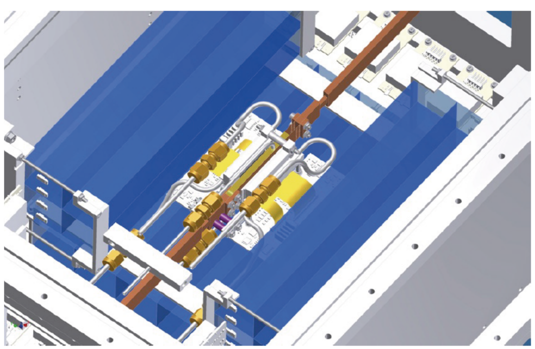
VIP experimental method: search for anomalous X-ray transition, from current e^- in radio-pure Cu target

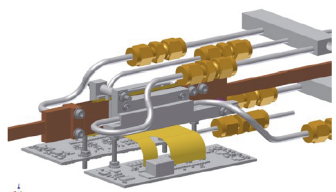


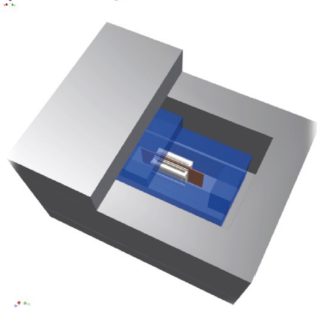
BKG reference spectrum acquired with current off

VIP result : $\beta^2/2 < 4.7\ 10^{-29}$

Sketch of the VIP2 Setup:
Cu foil, 2x3 SDD x-ray detectors







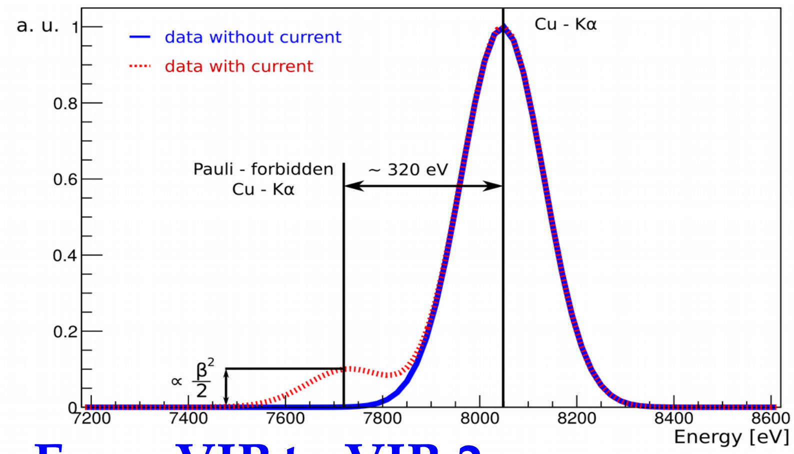
From VIP to VIP-2 :

- CCDs → SDDs better resolution FWHM 188 keV @ 8keV) and triggerable
- VETO system: plastic scintillators read by SiPMs
- higher acceptance
- Cu strips cooled by a closed Fryka chiller circuit → higher current (100 A) @ 20 °C of Cu target implies 1 °K heating in SDDs
- fast calibration system
- new shielding

VIP-2 goal 2 OM improvement

VIP-2 open systems

VIP-2 experimental method: search for anomalous X-ray transition, from current e^- in radio-pure Cu target



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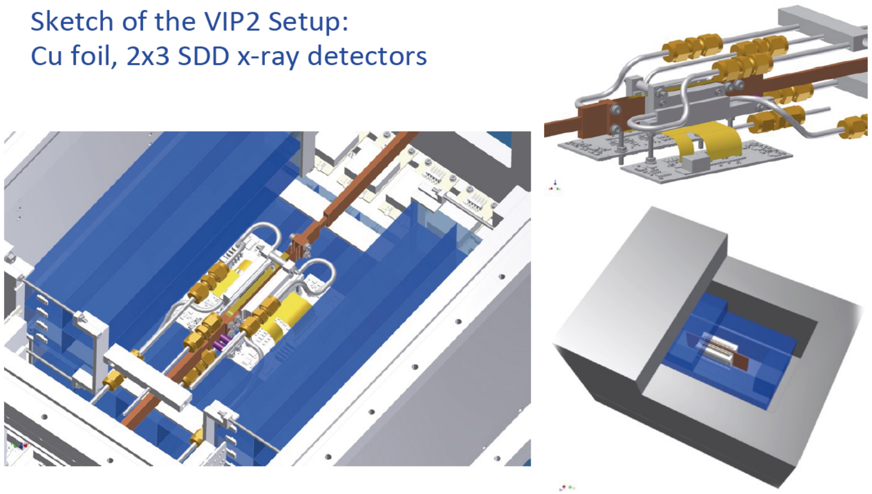

From VIP to VIP-2 :

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VIP-2 goal 2 OM improvement

VIP-2 (open system) preliminary results

May. 2019 – Sep. 2019 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.*

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

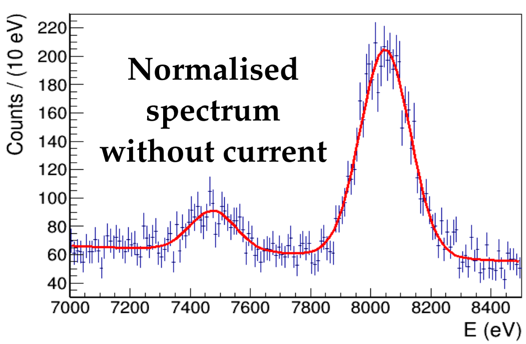
Bin contents fluctuate around the mean according to a Pois. Dist.

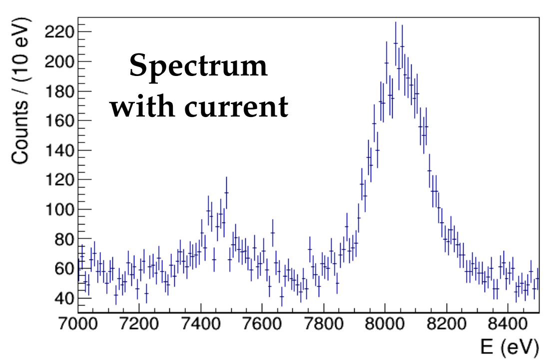
Posterior *p.d.f.* (model needs in input the bkg. and sig. normalised shapes):

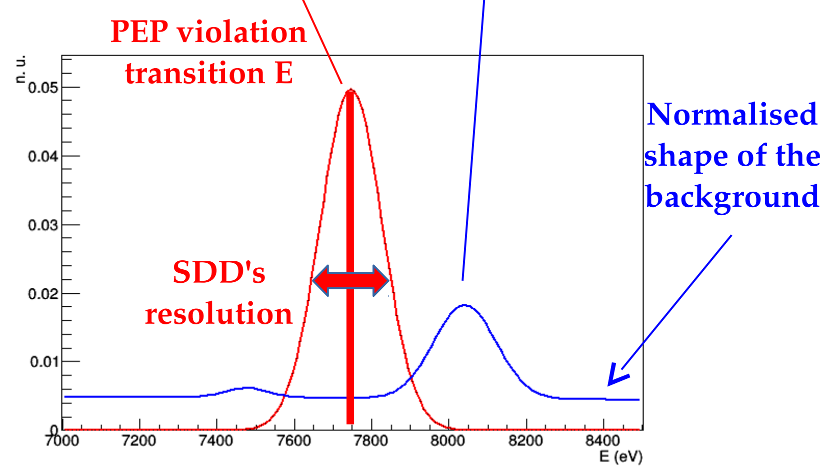
$$P(S|data) = \int P(S, B|data)\, dB$$

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

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







May. 2019 – Sep. 2019 Data analysis

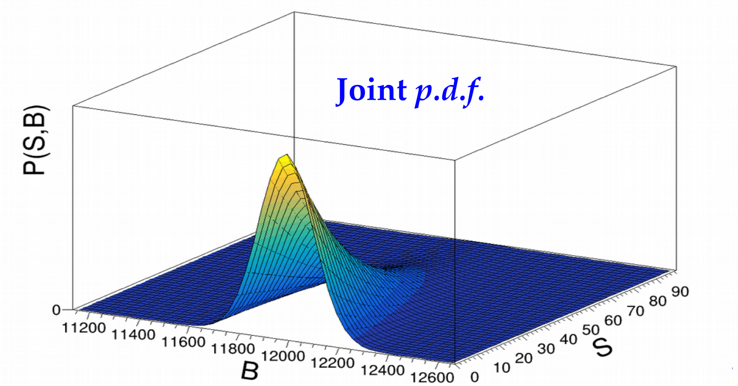
The prior probability for S is flat up to a maximum S_{max} consistent with existing limits [Eur. Phys. J. C (2018) 78:319].

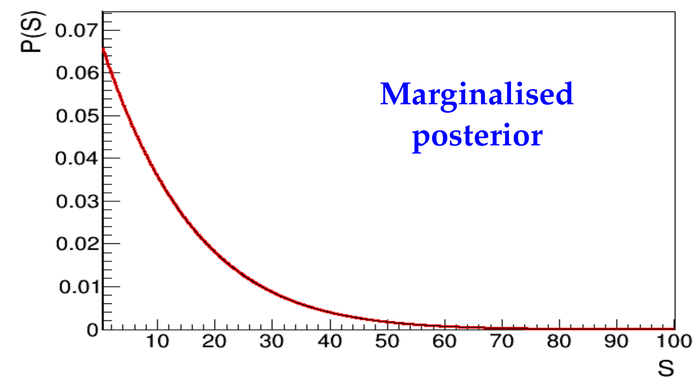
$$p_0(S) = \begin{cases} \frac{1}{S_{\max}} & 0 \le S \le S_{\max} \\ 0 & \text{otherwise} \end{cases}$$

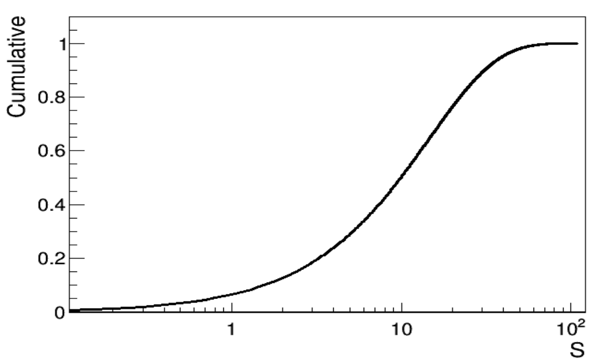
The mean value for the expected number of bkg. Events μ_b obtained from bkg. Spectrum. Prior is Gaussian with a width $\sigma_b = \mu_b/2$.

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

Posterior calculated with Markow chain Monte Carlo techniques:







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

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

$$\beta^2/2 < 9.4 \cdot 10^{-31}$$

preliminary
about 47 days
with current


Non-commutative space-time induced PEP violation
VIP-2 (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]

Seminar: "Underground Experimental tests ..." 26 Nov. 2019, Fudan University, Shanghai

Talk: "Testing spin statistics at Gran Sasso underground laboratory" Cosmic Neutrinos and Multi-messenger, 27-30 November 2019, Tsung-Dao Lee Institute, https://indico-tdli.sjtu.edu.cn/event/43/timetable/#20191128.detailed

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

↓

popular 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 ...)

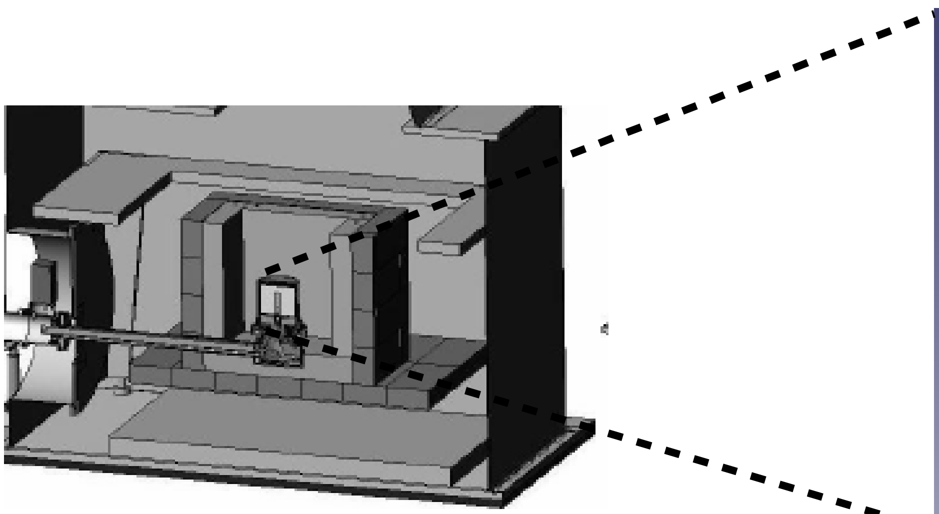
VIP-2 closed systems experimental setup

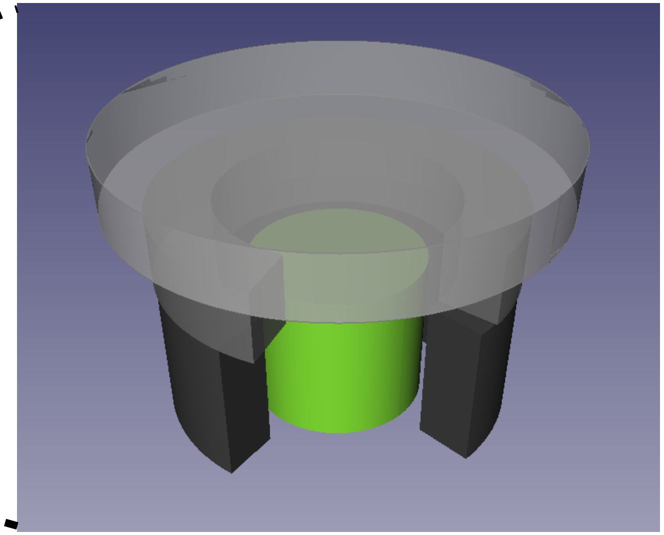
High purity Ge detector measurement:

- 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-2 closed systems results

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

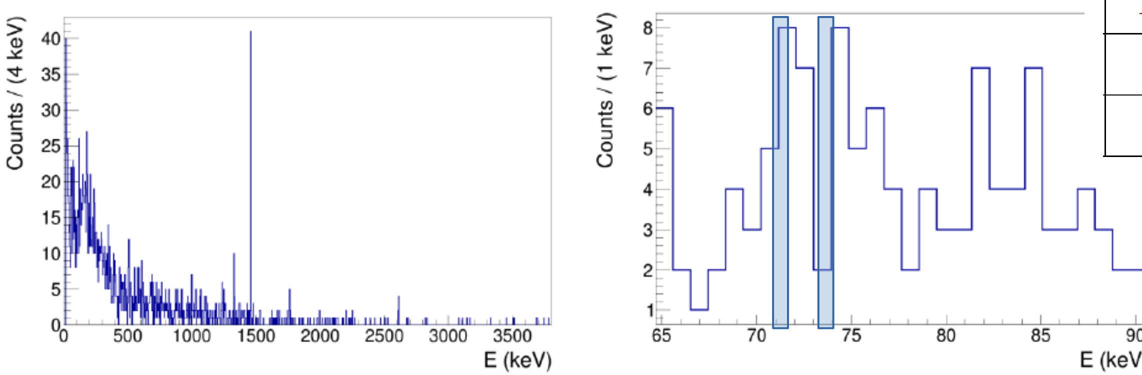
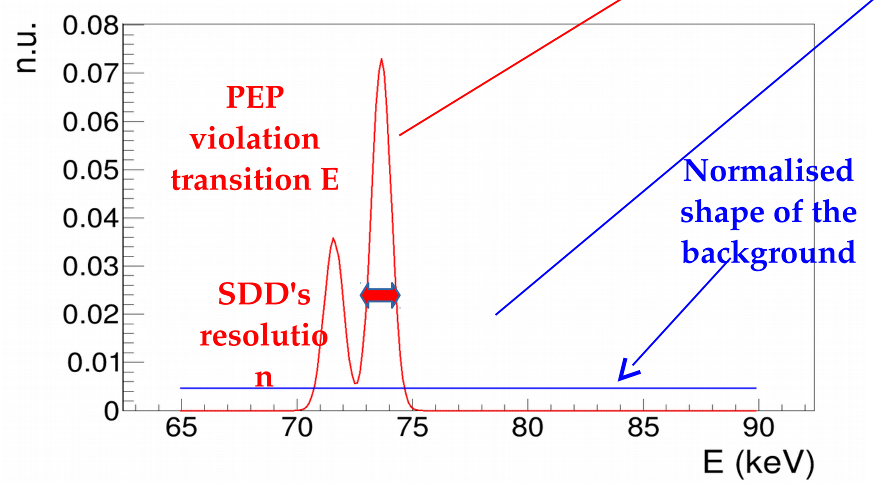


Figure 1. Total measured X-ray spectrum (left); same spectrum in the region of the K_α standard and violating transitions in Pb (right).

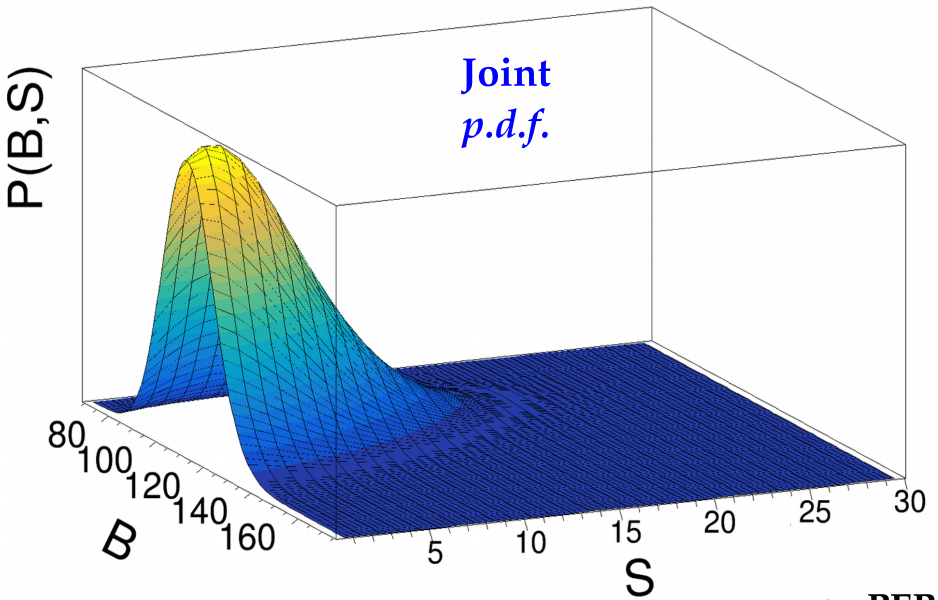
$$\lambda_i = \lambda_i(S, B) = S \cdot \int_{\Delta E_i} f_S(E) dE + B \cdot \int_{\Delta E_i} f_B(E) dE,$$

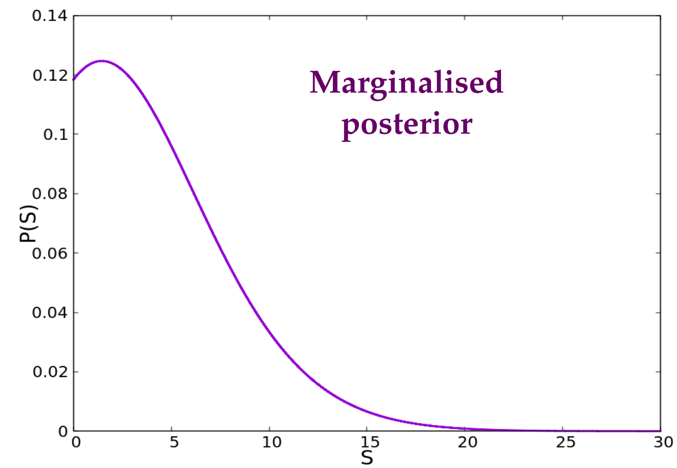
The prior probability for the number of expected signal events is assumed flat
up to a maximum S_{max} consistent with existing limits [Eur. Phys. J. C (2018)]

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



VIP-2 closed systems results

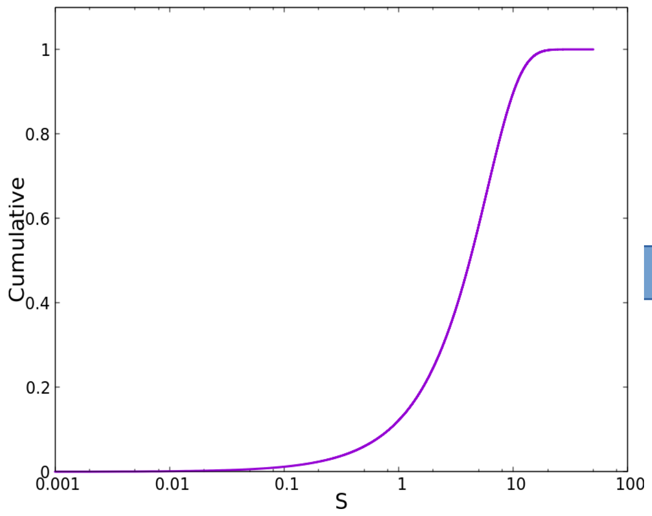




From which an upper limit on the

- PEP violation probability is obtained (90% Probability):

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



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

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

θ-Poincarè - excluded up to Λ > 0.3 Planck scale

Collapse Models experimental tests

Experimental tests of the Dynamical Reduction Models:

Bassi, A., & Ghirardi, G. (2003). Dynamical reduction models. Physics Reports, 379(5-6), 257-426.
S. Adler, Stud.Hist.Philos.Mod.Phys.34:135-142,2003

- CSL – non-linear and stochastic modification of the Schrödinger equation …

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar} H\, dt + \sqrt{\lambda} \int d^3x (N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t) dW_t(\mathbf{x}) - \frac{\lambda}{2} \int d^3x (N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)^2 dt \right] |\psi_t\rangle$$

System's Hamiltonian | NEW COLLAPSE TERMS → New Physics

λ - collapse rate | **$r_c \sim 10^{-7}$ m – correlation length**

measures the strength of the collapse
strongly debated, see e. g. S. L. Adler, JPA 40, (2007) 2935

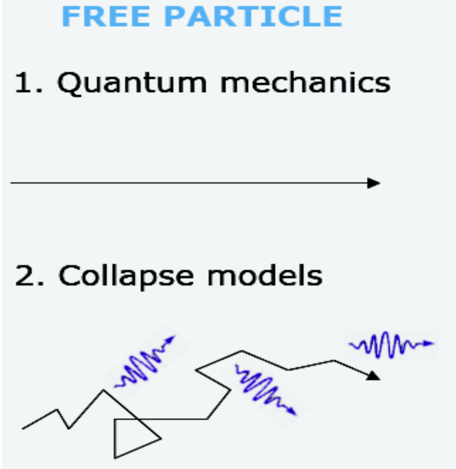
Adler, S.L.; Bassi, A.; Donadi, S., JPA 46, (2013) 245304.

- 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

collapse → 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

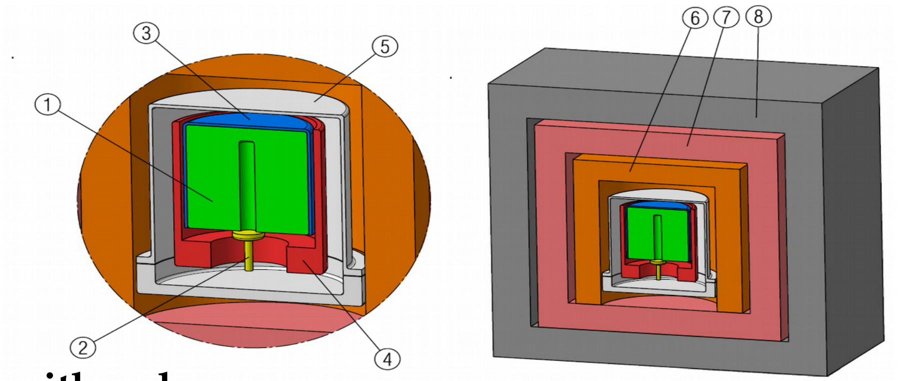
- **CSL – spontaneous photons emission rate:**

$$\frac{d\Gamma'}{dE} = \{(N_p^2 + N_e) \cdot (N_a\, T)\} \frac{\lambda \hbar e^2}{4\pi^2 \varepsilon_0 c^3 m_0^2 r_C^2 E}$$

- **Diosi – Penrose – spontaneous photons emission 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

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



- **active HPGe detector surrounded by 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 radon.**

HPGe detector based experiment @ LNGS

124 kg day exposure
2kg Germanium active mass

↓

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

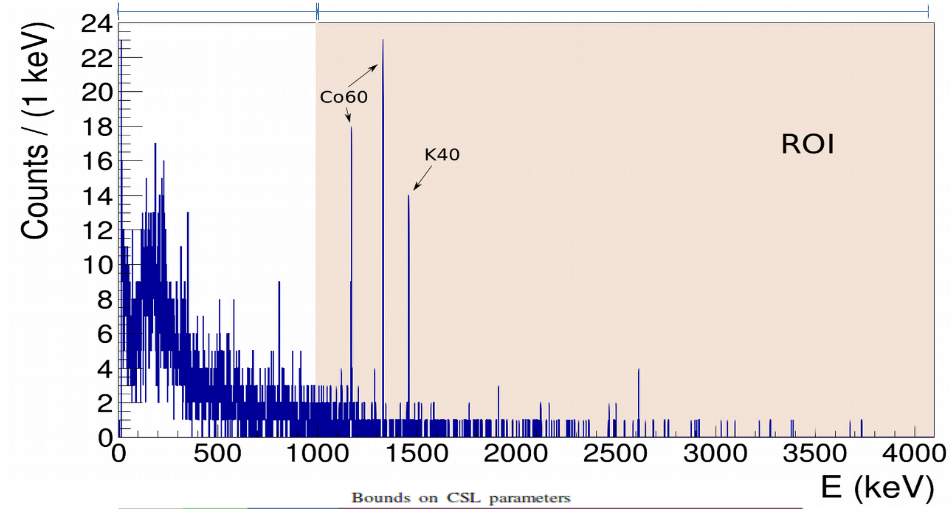
$$\tilde{p}\left(\Lambda_c|p(z_c|\Lambda_c)\right) = \frac{\Lambda_c^{z_c}\, e^{-\Lambda_c}\, \theta(\Lambda_c^{max} - \Lambda_c)}{\int_0^{\Lambda_c^{max}} \Lambda_c^{z_c}\, e^{-\Lambda_c}\, d\Lambda_c}$$

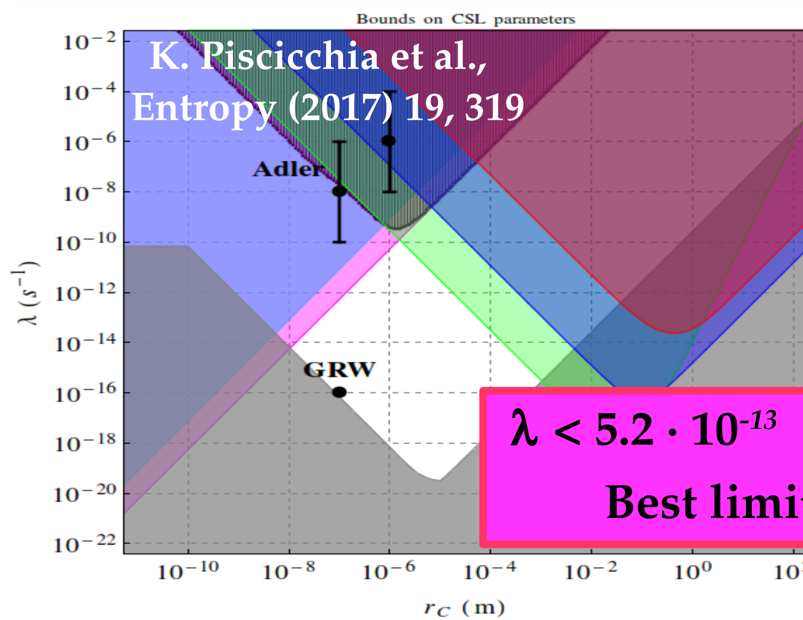
$R_0 > 0.54 \times 10^{-10}$ m **95% C. L.**

Diosi – Penrose proposal Rouled out!

cosmic rays, bremsstrahlung from ^{210}Pb & daughters

Region Of Interest ΔE=(1000 – 3800)keV compatible with theretical constrains





λ < 5.2 · 10^{-13} 95% C. L.
Best limit ever

New Bayesian approach

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

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

Joint *p.d.f.*

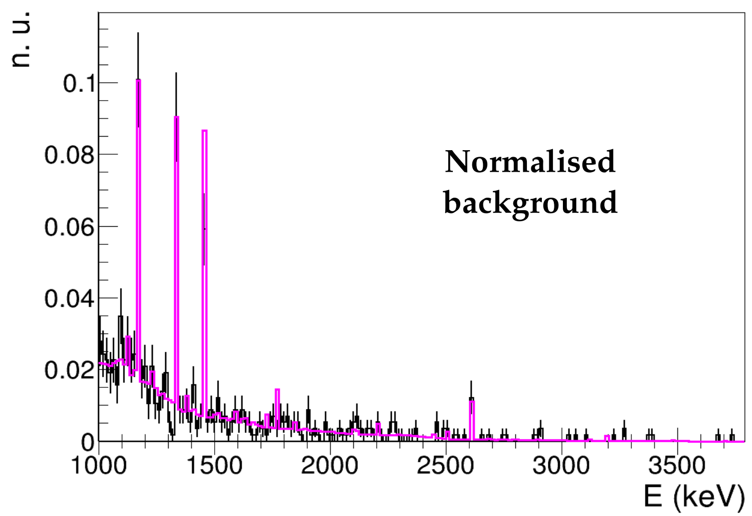
Bin contents fluctuate around the mean according to a Pois. Dist.

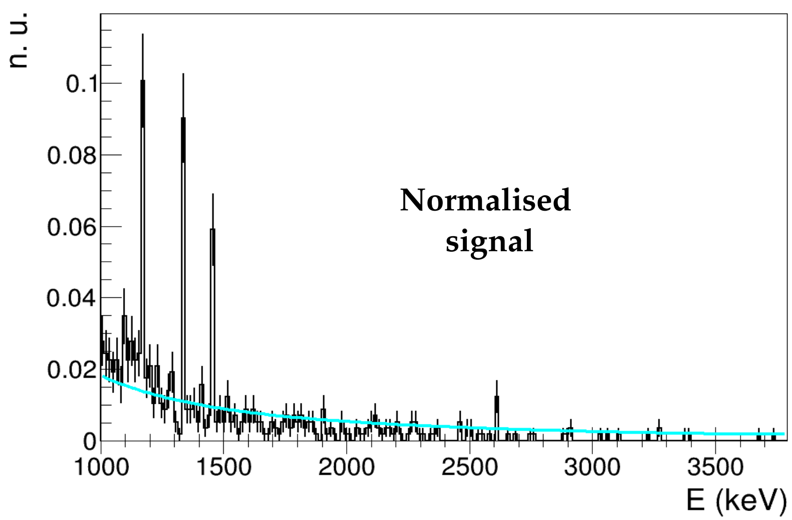
Likelihood **→** $$P(data|S,B) = \prod_{i=1}^{N} \frac{\lambda_i(S,B)^{n_i}\cdot e^{-\lambda_i(S,B)}}{n_i!}$$

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 → from the MC simulation Signal → theory convoluted with exp. resolution





New Bayesian approach

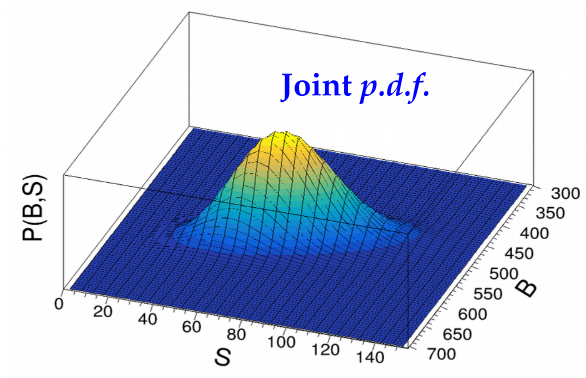
The prior probability for S is flat up to a maximum S_{max} consistent with existing limits [Entropy 2017, 19(7) 319].

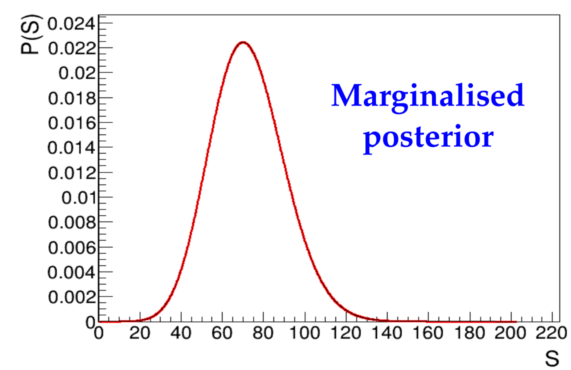
$$p_0(S) = \begin{cases} \frac{1}{S_{\max}} & 0 \leq S \leq S_{\max} \\ 0 & \text{otherwise} \end{cases}$$

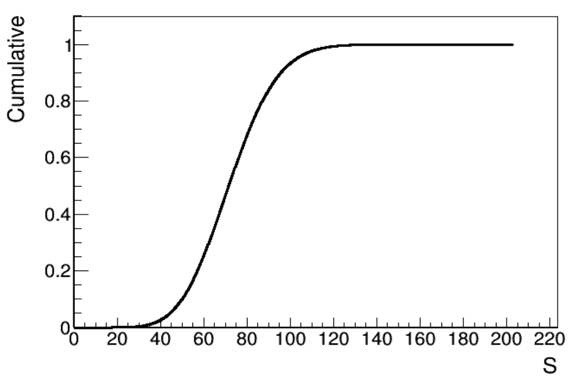
The mean value for the expected number of bkg. Events μ_b obtained from bkg. Spectrum. Prior is Gaussian with a width σ_b = sqrt(μ_b).

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

Posterior calculated with Markow chain Monte Carlo techniques:







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

$\lambda < 4 \cdot 10^{-13}$

VERY VERY Preliminary

New Bayesian approach

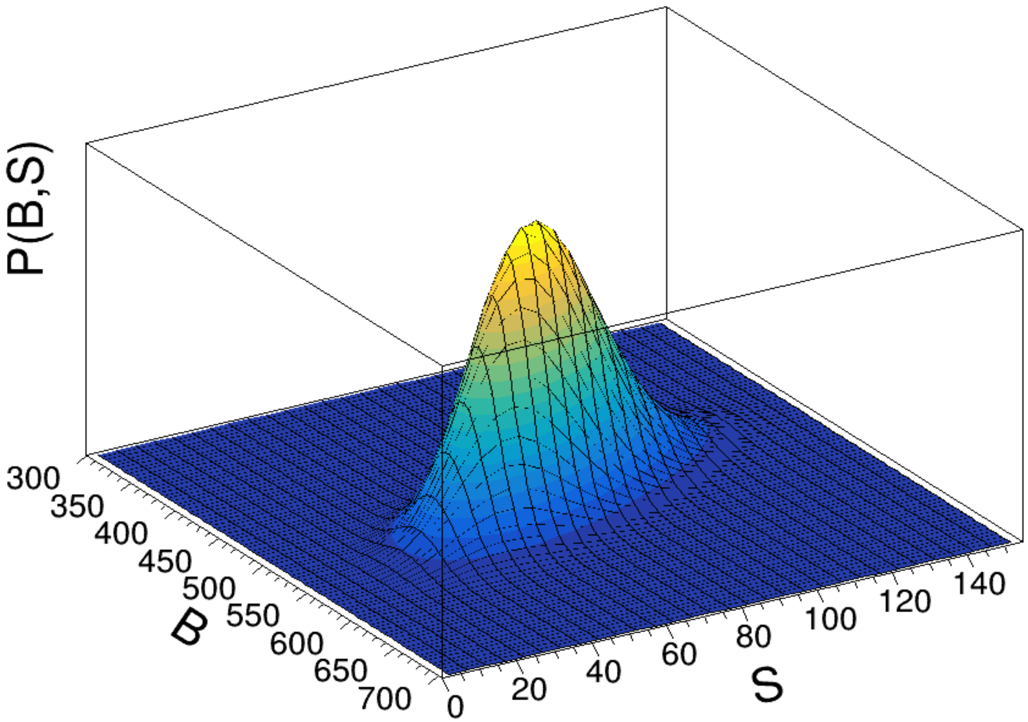
The prior probability for S is flat up to a maximum S_{max} consistent with existing limits [Entropy 2017, 19(7) 319].

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

The mean value for the expected number of bkg. Events μ_b obtained from bkg. Spectrum. Prior is Gaussian with a width $\sigma_b = \mathrm{sqrt}(\mu_b)$.

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

Posterior calculated with Markow chain Monte Carlo techniques:

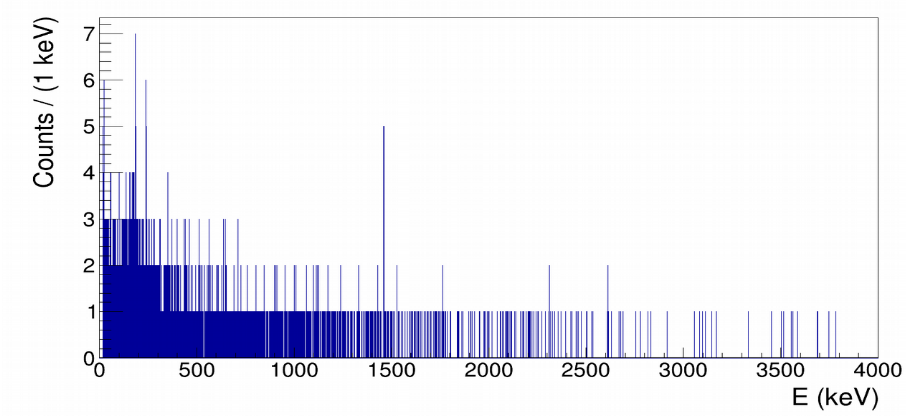


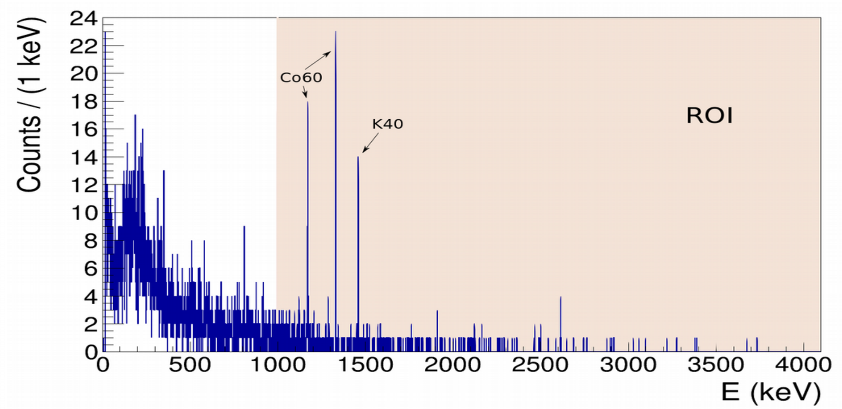
Intense interaction with theoretitians for interpretation

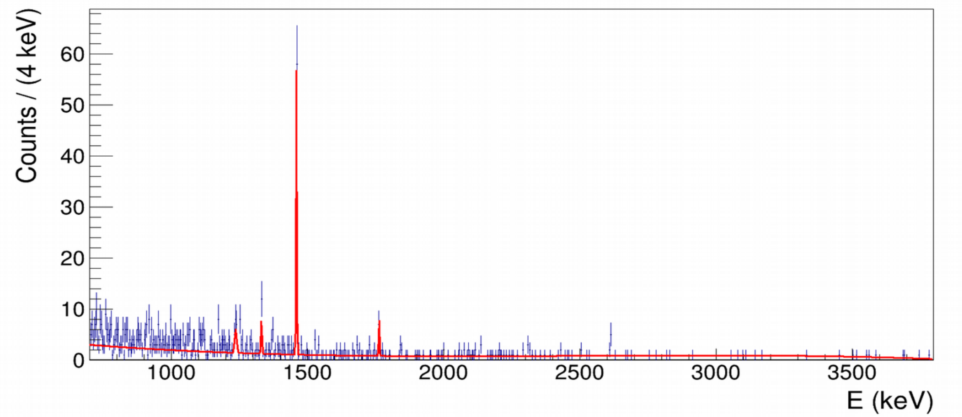
Penrose
Adler
Diosi
Bassi
...

check of eventual systematic contributions..

HPGe detector + ultrapure Pb active shielding:







BEGe detector + pulse shape discrimination

pushing the lower E threshold to few keV

PAMQ project

2019 milestones, scientific activity:

1) Pubblicazione di un articolo peer-reviewed con il nuovo risultato sul limite della probabilità di violazione del principio di Pauli per elettroni ottenuto dall'analisi dati 2017-2018 di VIP-2 → 100% + 2 accepted for publication

1) Preparazione e caratterizzazione di un setup di test per misure di radiazione di altissima precisione per la meccanica quantistica con cristalli HAPG → 100% setup realised and characterised in laboratory.

3) Analisi dati e pubblicazione di un articolo peer-reviewed con nuovi limiti sui modelli collasso ottenuti dalle misure dedicate a PAMQ ai LNGS con rivelatori ultrapuri di Germanio → 90% paper submitted for pubblication + 1 in preparation

4) Organizzazione di un workshop sulla quantum foundations and applications, nell'ambito del prog. PAMQ → 100% https://agenda.infn.it/event/19468/

PAMQ project

2019 milestones, scientific activity:

- Total number of papers published in 2019 : 4 + 2 accepted for publication + 2 submitted

  + 13 conference proceedings

- Total number of attended conferences in 2018 : 14 + 1 seminar

- 1 Bachelor degree thesis (at La Sapienza University) on VIP (Marco Veith)

- 1 conference organised: "Is Quantum Theory exact? From quantum foundations to quantum applications" https://agenda.infn.it/event/19468/

PAMQ project

Dissemination activity in 2019:

- PAMQ activities were presented at the:

international school INSPYRE 2019
Festival delle Eccezioni (Casperia) 2019,
TEDxFrascati 2019.

- In Italian high schools dissemination talks concerning the PAMQ activities.

- 6 talks were given in Australia and USA (Princeton, IAS) and at the TEDxCluj event, Brasov (Romania), concerning the PAMQ project.

awards 2019:

C. Curceanu - Gordon and Betty Moore Foundation Fundamental Physics Innovation Award

Next three years activity:

1.1 VIP-2 open systems: data taking at LNGS. Bayesian analysis of 2019 data & papers. Finalization model for current modulation regime & corresponding data taking (1 month per year) & papers.

1.2 VIP-2 closed systems: finalization data analysis (HPGe+Roman Pb target) and interpretation in context of non-commutative Qunatum Gravity & papers. Feasibility study for tests of PEP violation induced in non-commutative QG models with other targets (wolfram, platinum ...) to test energy dependence. Assembling the new BEGe detector, readout e DAQ; analisys of the acquired spectra & papers.

1.3 Collapse Models tests: finalization data analyses (HPGe+Roman Pb target) and papers. Interaction with theoreticians for feasibility study of new models experimental tests Coloured CSL and gravity-related models.

1.5 Study of high energy resolution detectors (HAPG) and possible application of SDD and HAPG in medicine and industry. Study of the implication of PAMQ in future quantum technologies.

2.1 Organization of one Workshop in Quantum Foundation every year, organization of Training School in Quantum Foundations and Applications, dissemination: OpenLab, INSPYRE, Reaserch Nights of LNF-INFN and other events related to PAMQ.

3.1 Presentations at international conferences and colloquia (at least 18)
3.2 At least 15 papers.

Milestones for 2020:

- Bayesian data analysis and publication of (at leat one) paper with new limits on collapse models obtained with HPGe detecors based measuerements at LNGS.

- Publication of (at leat one) paper on new results concerning the PEP violation probability obtained by VIP-2.

- Organization of one workshop on quantum foundations and applications in the context of the PAMQ project.

- Mounting and characterization of the new BEGe setup.

Fundings in the 3-year period:

- **Request of funding by Centro Fermi**

  Research grant: 2020 – 2022

  Funds for organising 3 workshops: 5 kEuro/year

  Contribution to the organisation of 2 conferences at ECT 2kEuro (total)*

  Consumables for the setups: 10 kEuro/year

- **Co-funding in 3 years period (estimate)**

  INFN: 120 kEuro (VIP)

  EU TEQ: 100 kEuro (for next 2 years)

  SMI-Vienna: 40 kEuro

  Austrian Science Foundation (FWF) supports the VIP2 project with the grants P25529-N20, project P 30635-N36 and W1252-N27: total 280 kEuro started 2 years ago

- **Potential external funding**

  FQXI, Templeton: 50 kEuro

  EU Funding (COST Actions, MCurie, FET,….): 100 kEuro

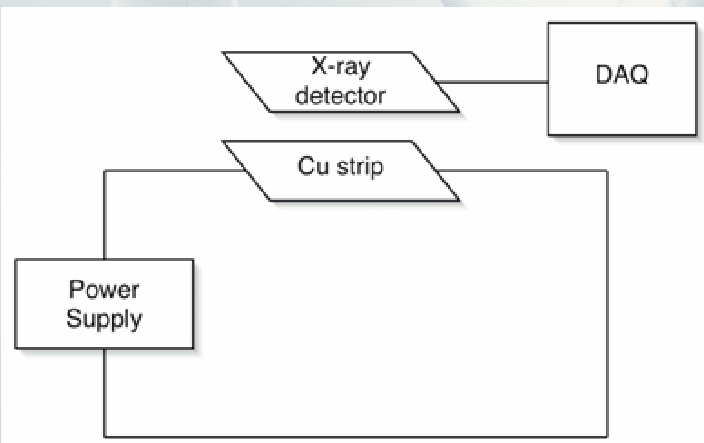
  Other nationals and internationals possible fundings: 50 kEuro

THANK YOU

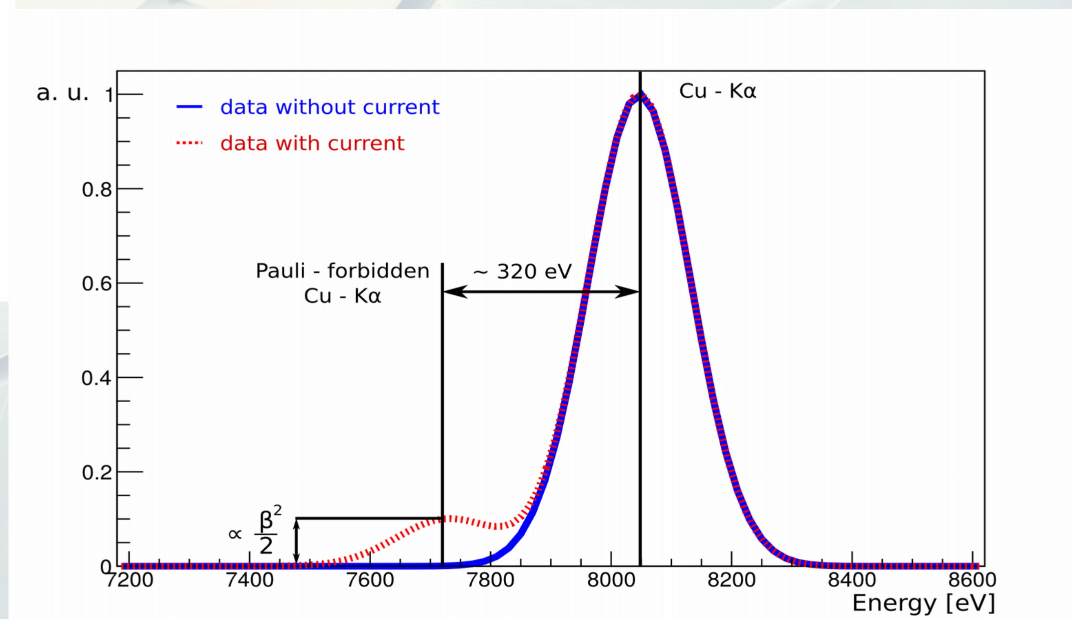
Schematically VIP-open systems

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 :



Quantum Mechanics (PAMQ)

VIP-2 already achieved good results:

published result with a subset of the whole pre-VIP-2 data. Second paper in preparation with the whole statistics.

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

- Big effort also devoted to model the electron diffusion process across the target:

Entropy **2018**, *20*(7), 515; https://doi.org/10.3390/e20070515 Open Access Article

On the Importance of Electron Diffusion in a Bulk-Matter Test of the Pauli Exclusion Principle

- Random walks of the electrons described in terms of a diffusion transport model ($\beta^2/2 < 2.6\ 10^{-40}$).

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 ci

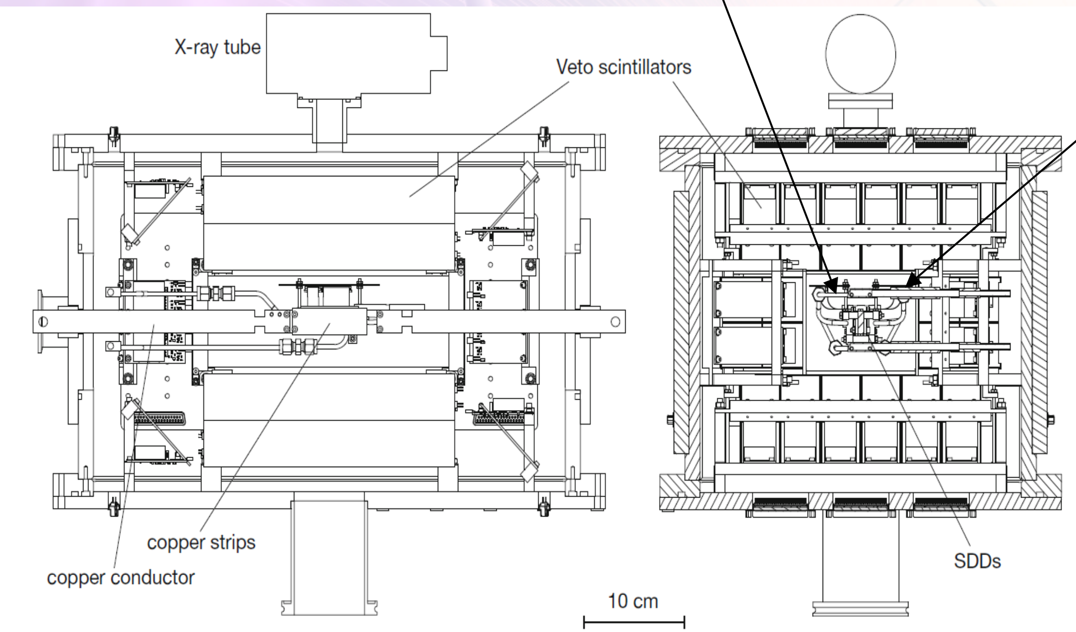
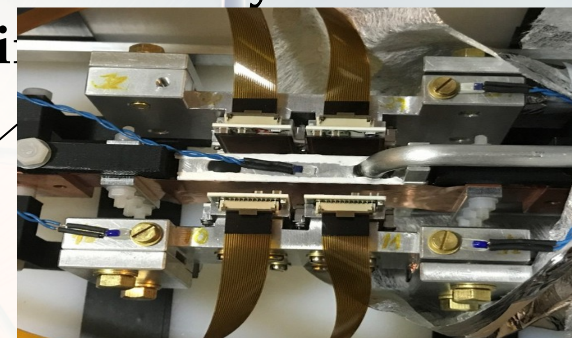
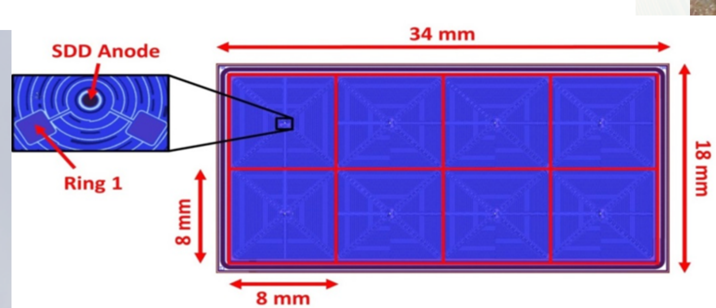


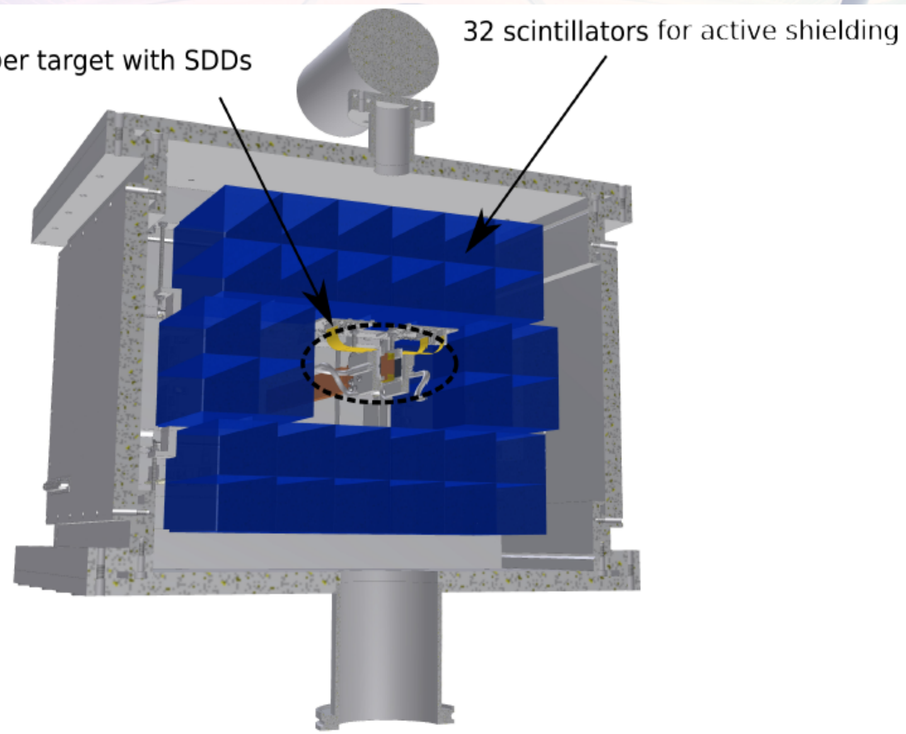
Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout





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



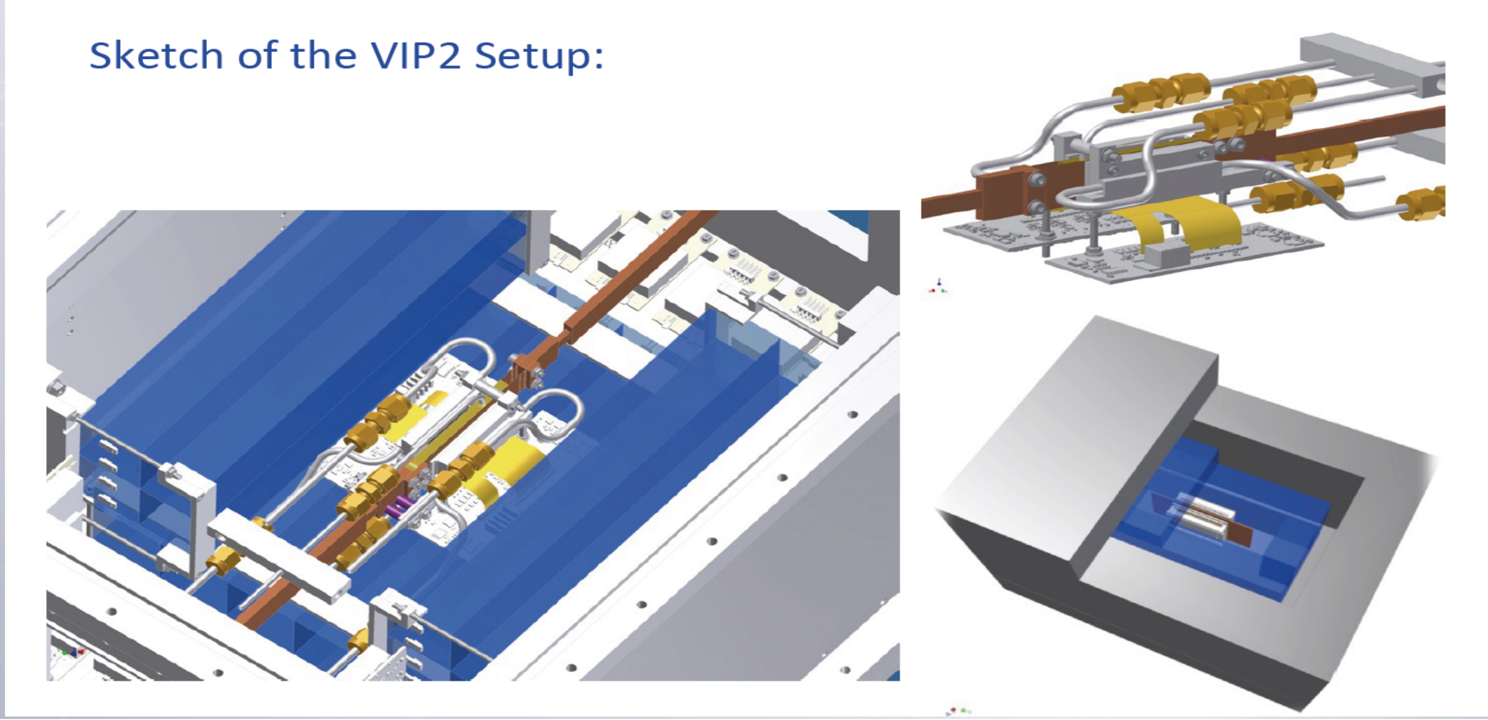
32 scintillators (blue) read out by two Silicon Photomultipliers each, are installed around the SDDs to give an active veto signal.

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

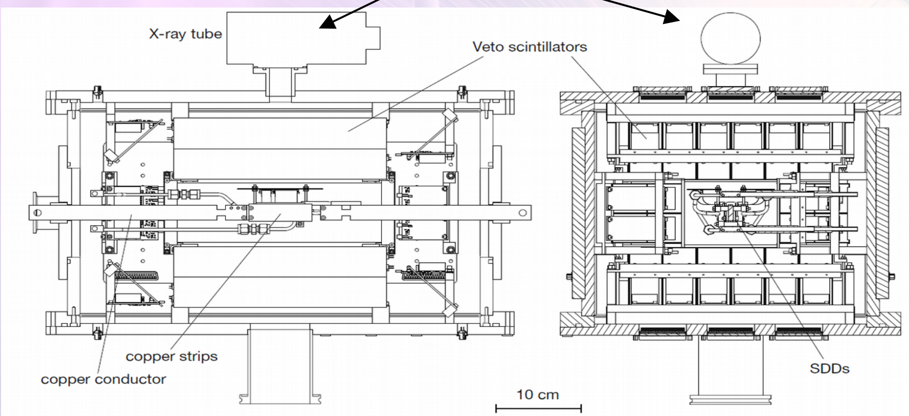
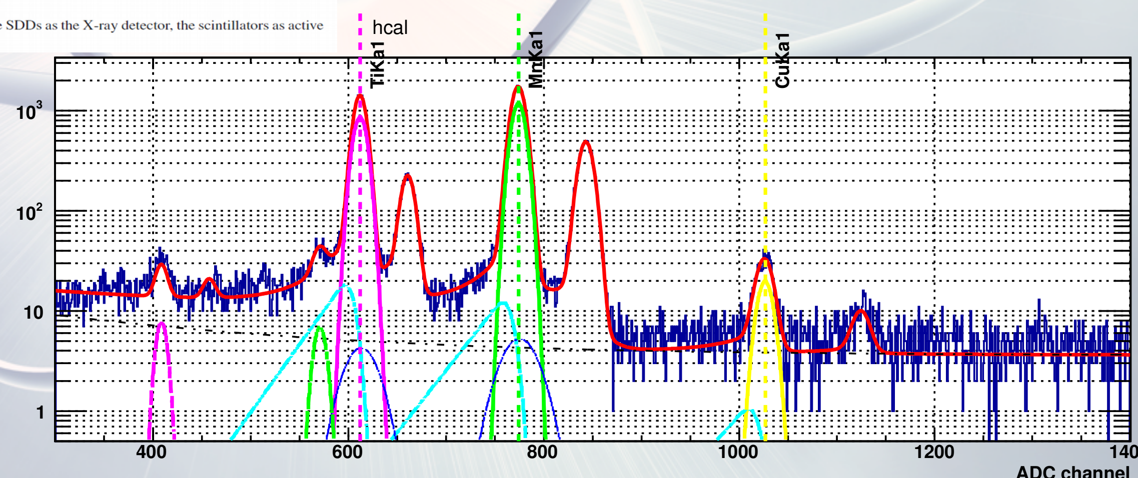


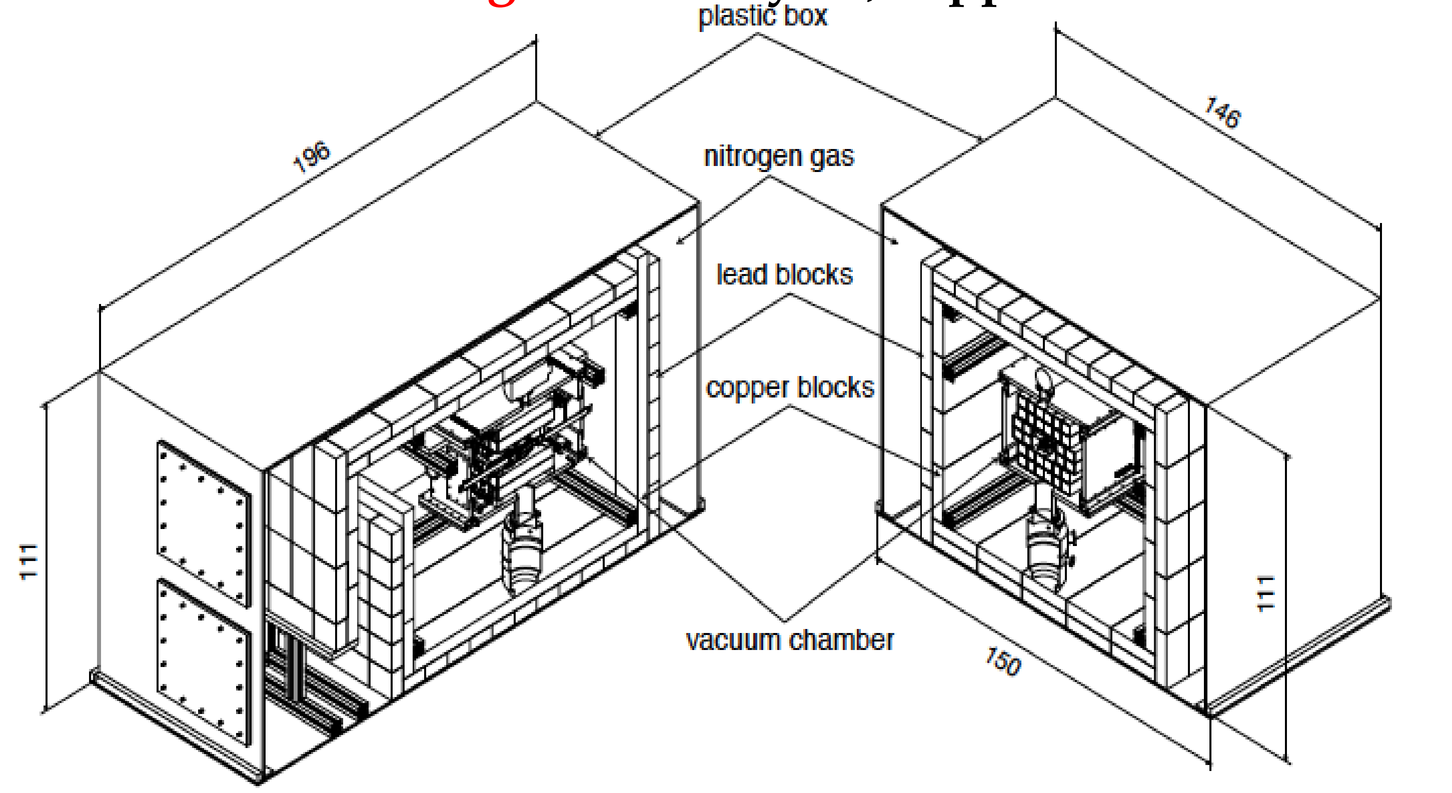
Fig. 1 The side views of the design of the core components of the VIP-2 setup, including the SDDs as the X-ray detector, the scintillators as active shielding with silicon photomultiplier readout



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

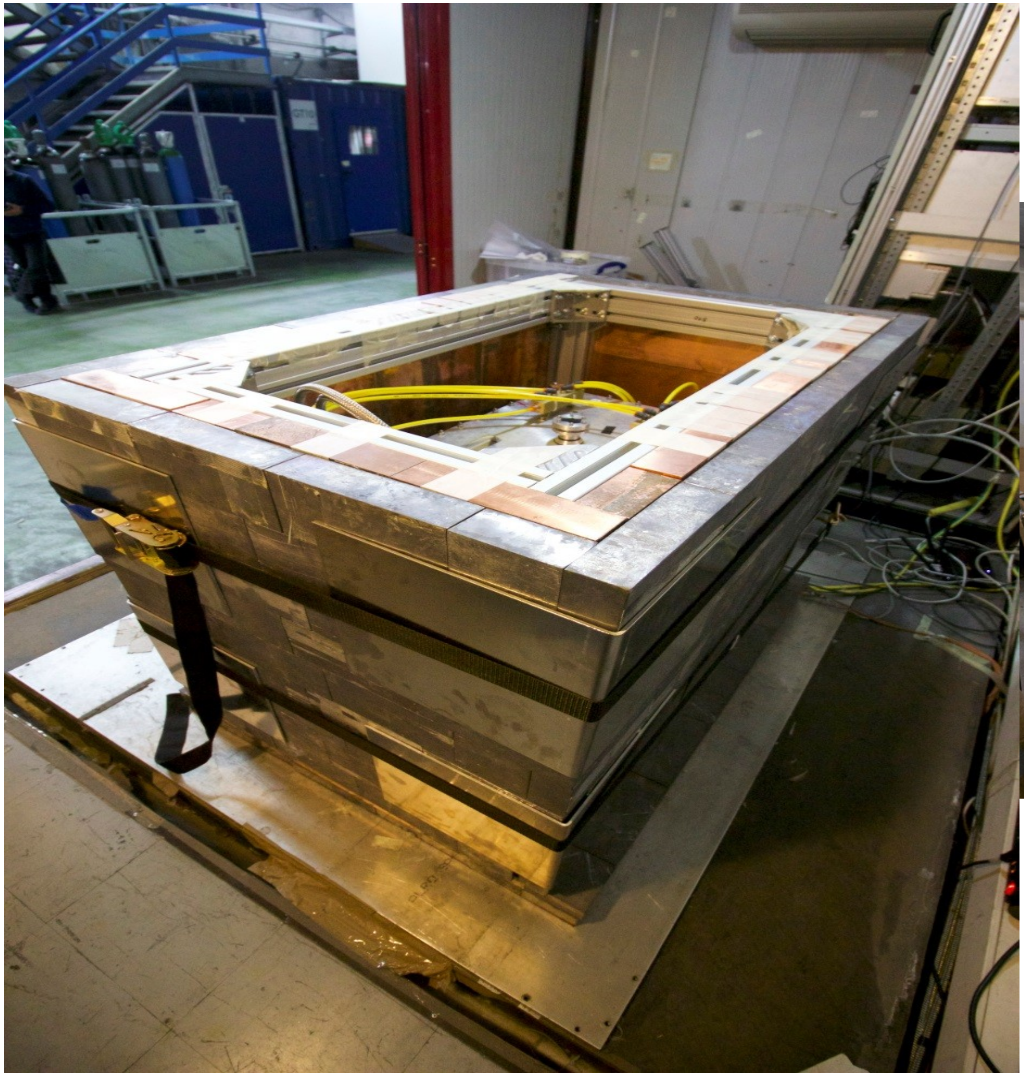
VIP-2 goal 2 OM improvement

Passive scielding → two layers, copper inside lead outside



VIP-2 final configuration

Upgrade concluded in April 2019:



current modulation, simulation of signal

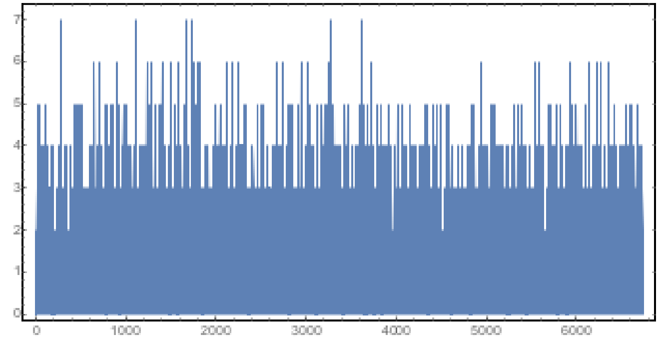


FIG. 1. The simulated X-ray signal (counts/timestep vs. timestep number) with the conditions described in the text.

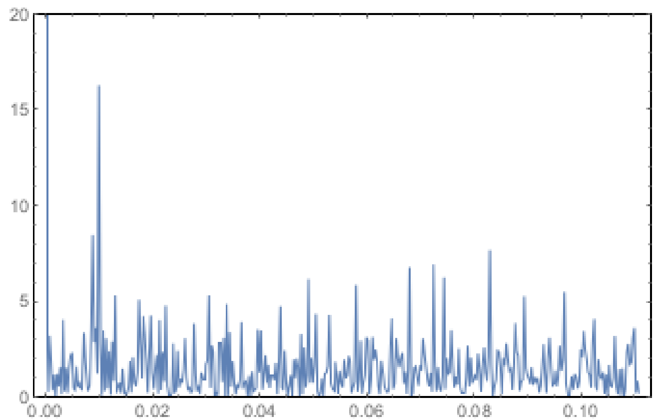


FIG. 2. Power spectrum of the signal in figure 1, (a.u. vs. frequency (Hz)). The large peak at 0.01 Hz shows that the modulation is well recognizable in the spectrum. The estimate of the violation can be recovered from the amplitude of this peak using the usual spectral techniques.