Testing Quantum Mechanics in the Cosmic Silence

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on behalf of the VIP collaboration

17th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2021)
26 August - 3 Setptember 2021

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The LNGS laboratories environment

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

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

The VIP-2 case

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Proof of spin-statistics theorem by Lüders and Zumino

Postulates: inhomogeneous Lorentz group, locality – microcausality, vacuum is the state of lowest energy, Hilbert space metric positive definite, vacuum is not identically annihilated by a field → (pseudo)scalar fields commute and spinor fields anticommute

Models of PEP violation:

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

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

- **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 w. f. of the electrons not exactly antisymmetric, PEP holds as long as the number of wrongly entangled pairs is small.**

EACH MODEL RESPECTS THE M-G SUPER-SELECTION RULE

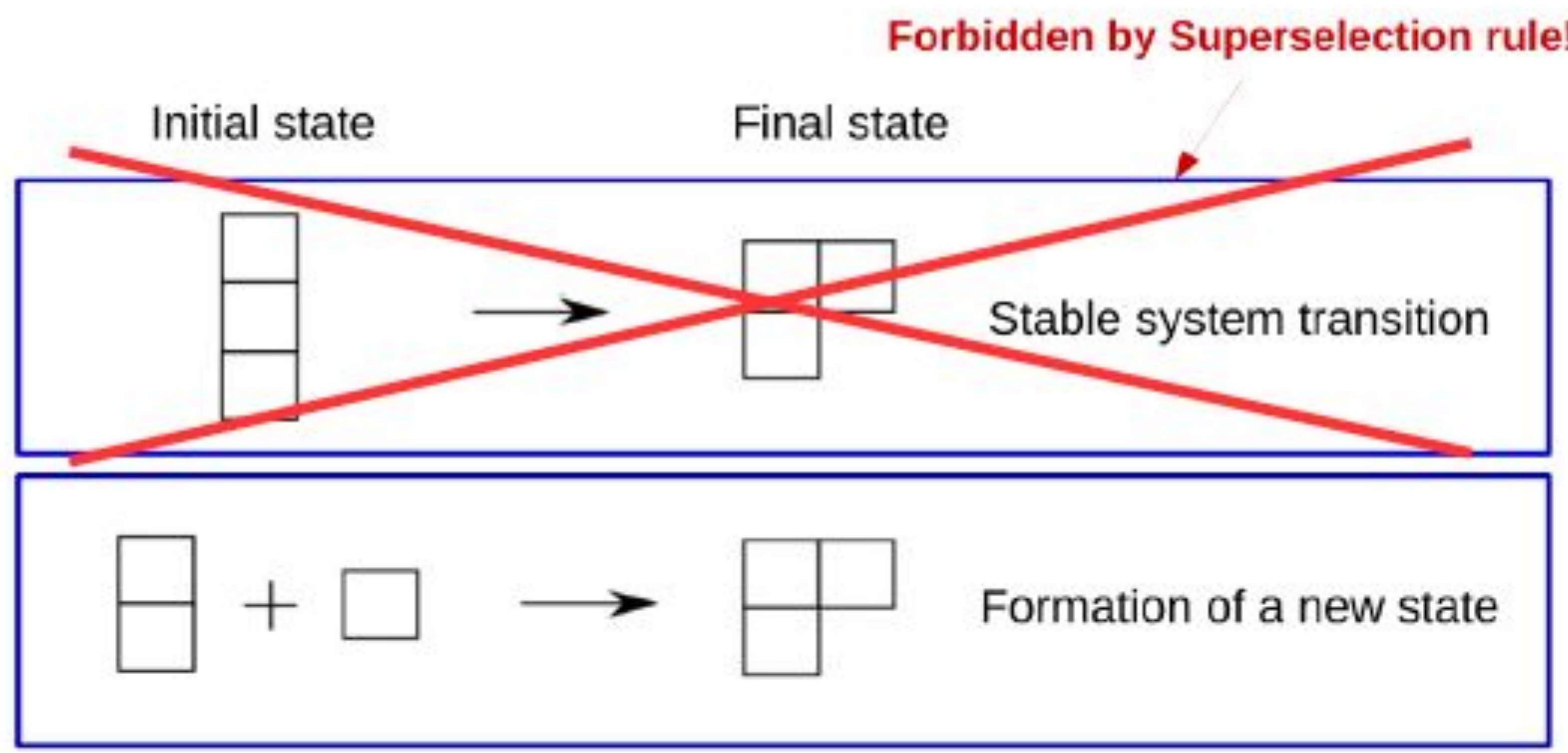
VIP-2 ***tests the Pauli Exclusion Principle (PEP)***
(spin-statistics) for electrons ***in a clean environment (LNGS) using a method which respects the***

Messiah-Greenberg superselection rule :

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

Closed system →

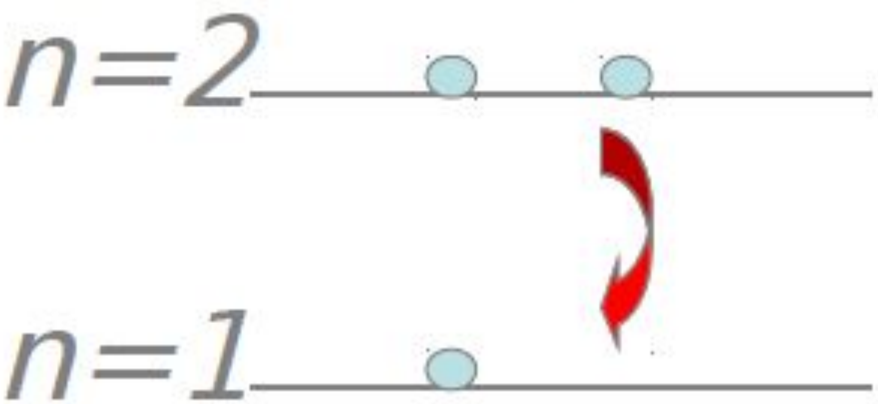
Open system →



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

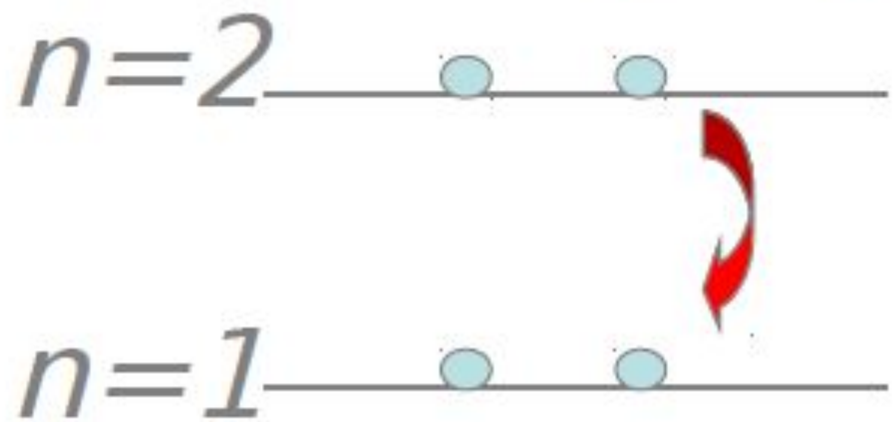
VIP open systems - experimental method

Search for anomalous X-ray transitions performed by electrons introduced in a target *through 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

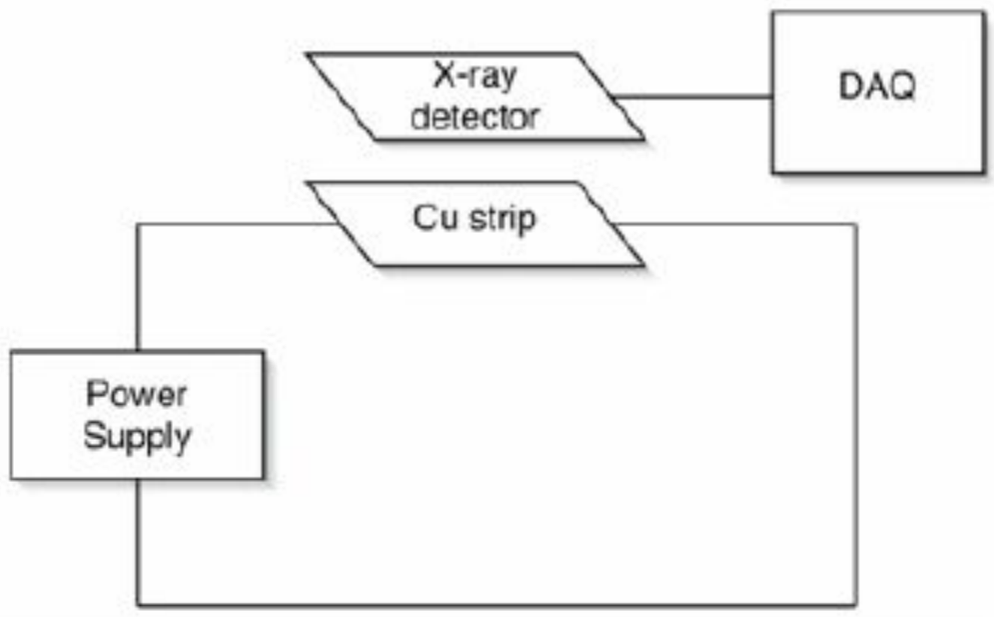
Accounts for the shielding of the two inner electrons

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

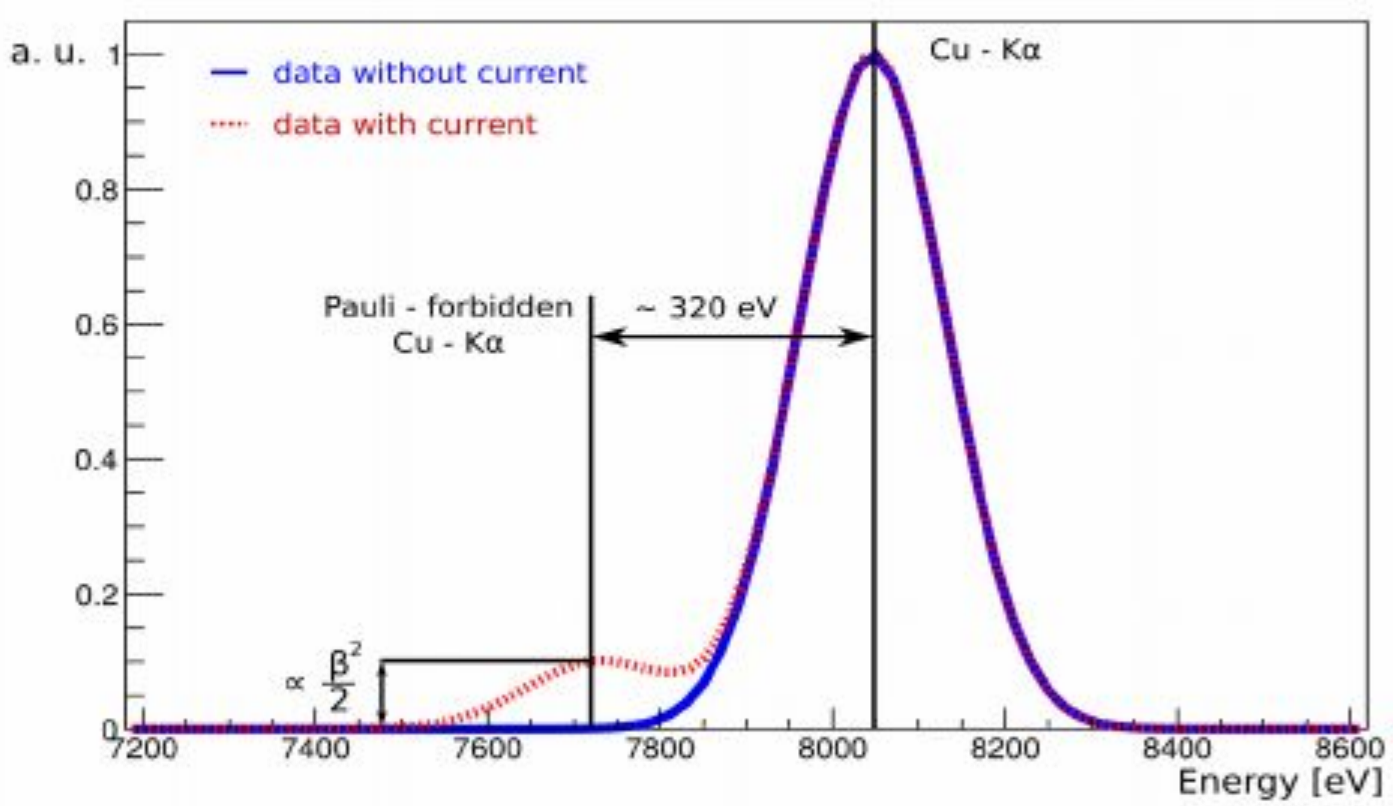
VIP open systems - experimental method

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

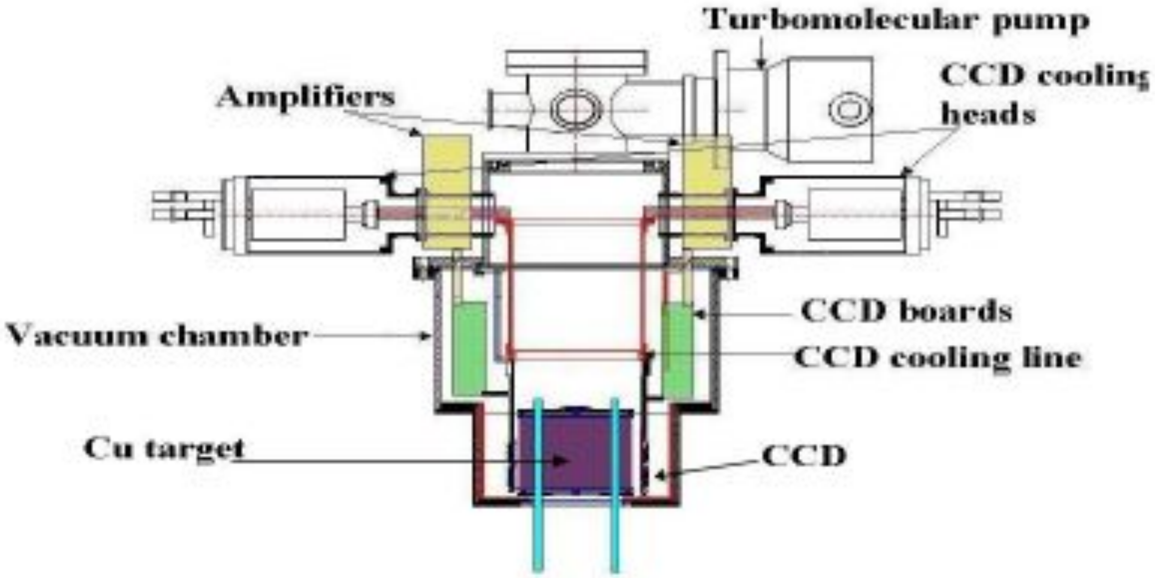


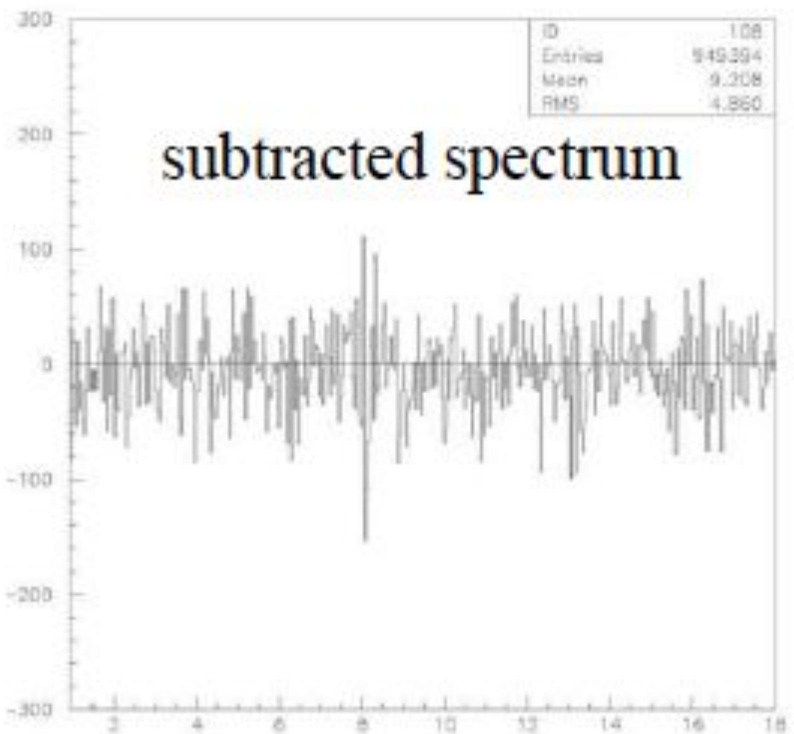
Undesired result :



From VIP to VIP-2, <u>the goal</u>

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

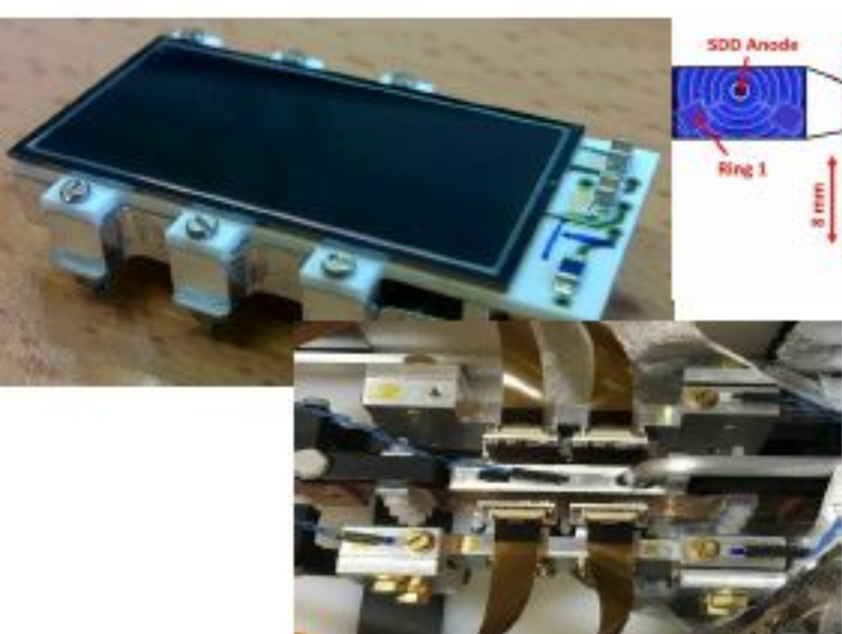
VIP-2 major upgrade

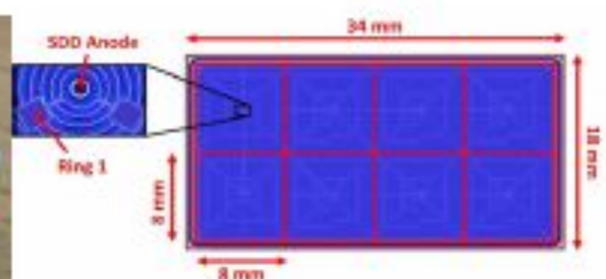
a) Silicon Drift Detectors (SDDs) → higher resolution (190 eV FWHM at 8.0 keV), faster (triggerable) detectors. 4 arrays of 2 x 4 SDDs 8mm x 8mm each, liquid argon closed circuit cooling - 160 °C

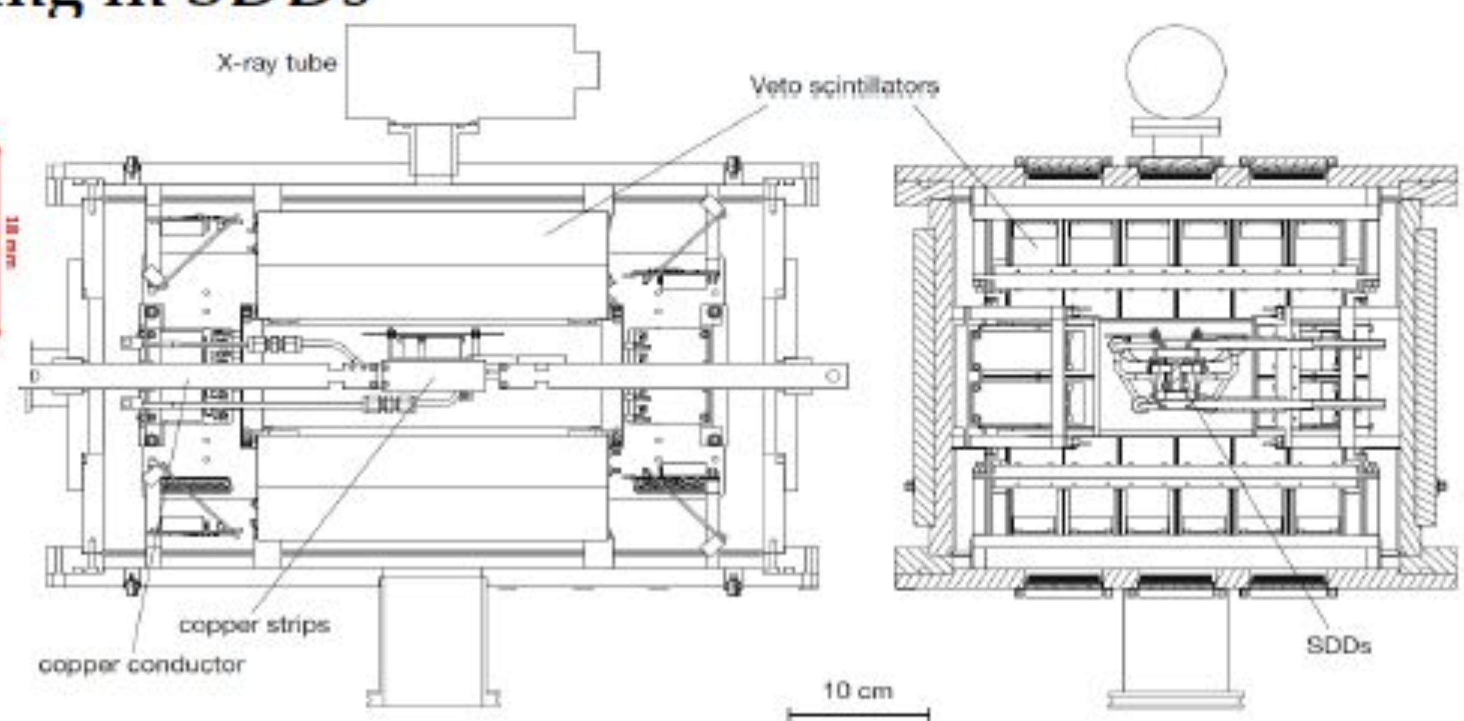
b) 2 strip shaped Cu targets (25 μm x 7 cm x 2 cm) more compact target → higher acceptance, thinner → higher efficiency
DC current supply to Cu bars

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

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





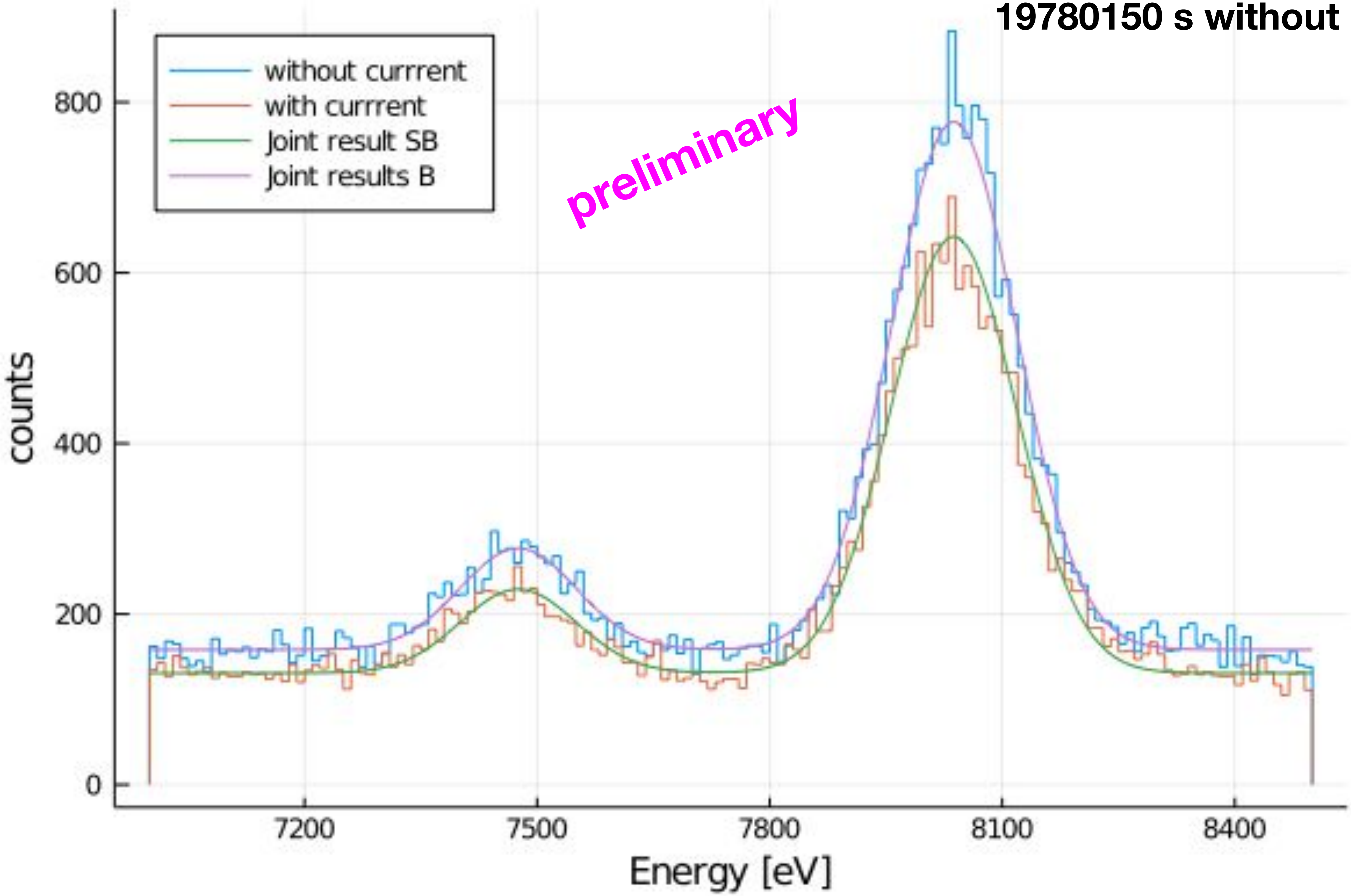


VIP-2 Open Systems results

Picture: Danilo Pivato © copyright - All rights reserved

Statistical model

VIP-2 data taking May 2019 - October 2020
16311209 s with current
19780150 s without current



Statistical model

designed to account for uncertainties on the parameters of the signal and background shapes, and normalization of the current on/off spectra:

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

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

$$P(\mathrm{data}_{wc}|S, B, \theta_S\theta_B) = \prod_{i=1}^{N} \frac{\lambda_i(S, B, \theta_S\theta_B)^{n_i^{wc}} e^{-\lambda_i(S,B,\theta_S\theta_B)}}{n_i^{wc}!} \quad P(\mathrm{data}_{woc}|B, s, \theta_B) = \prod_{i=1}^{N} \frac{\lambda_i(B, s, \theta_B)^{n_i^{woc}} e^{-\lambda_i(S,B,\theta_S,\theta_B)}}{n_i^{woc}!}$$

with θ_S, θ_B being the vectors of parameters of the signal and bkg shapes, *s* = scale parameter.

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

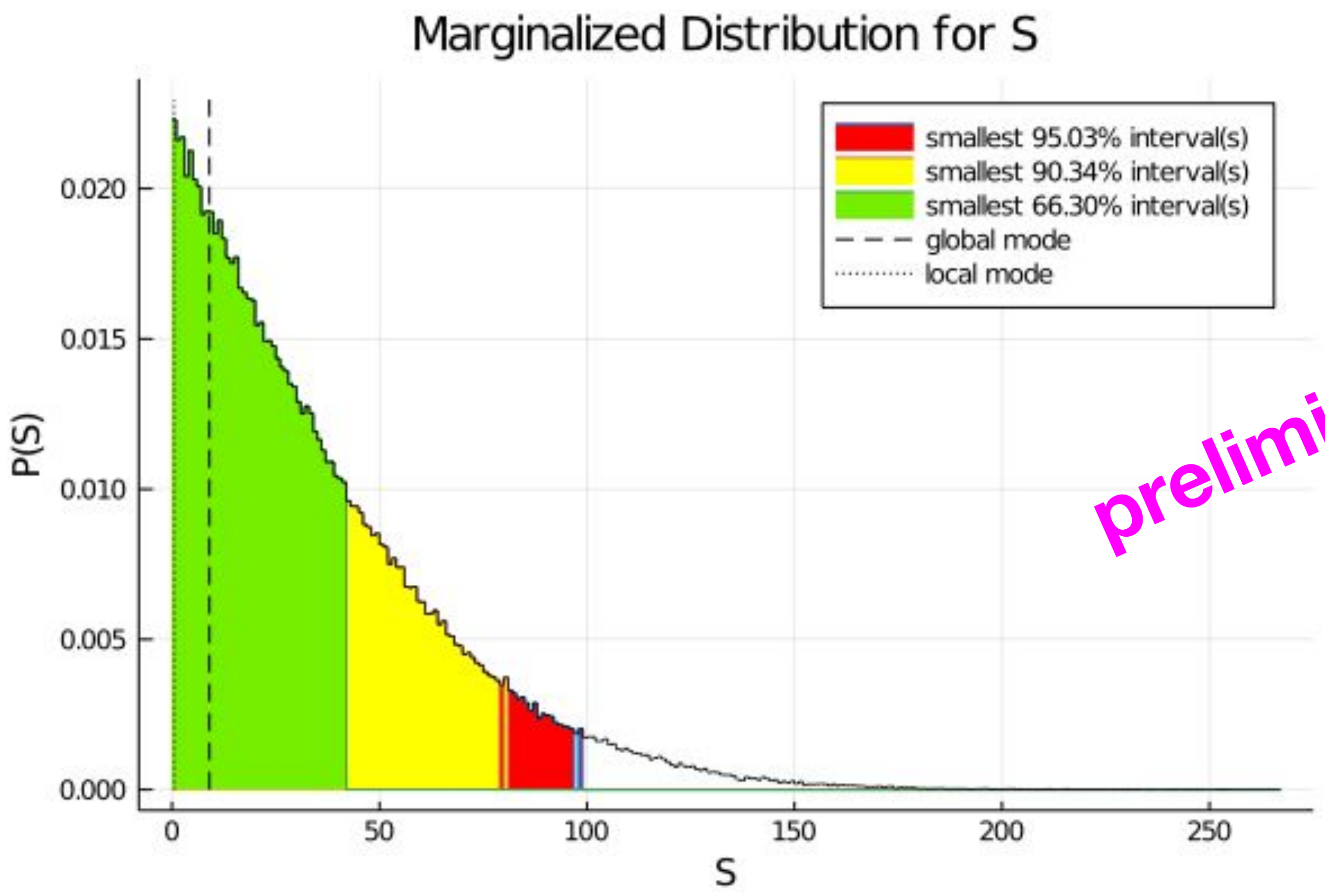
$$P(S, B, s, \theta_S, \theta_B|\mathrm{data}_{wc}, \mathrm{data}_{woc}) = \frac{\mathcal{L}}{N} P_0(S) \cdot P_0(B) \cdot P_0(s) \cdot P_0(\theta_S) \cdot P_0(\theta_B)$$

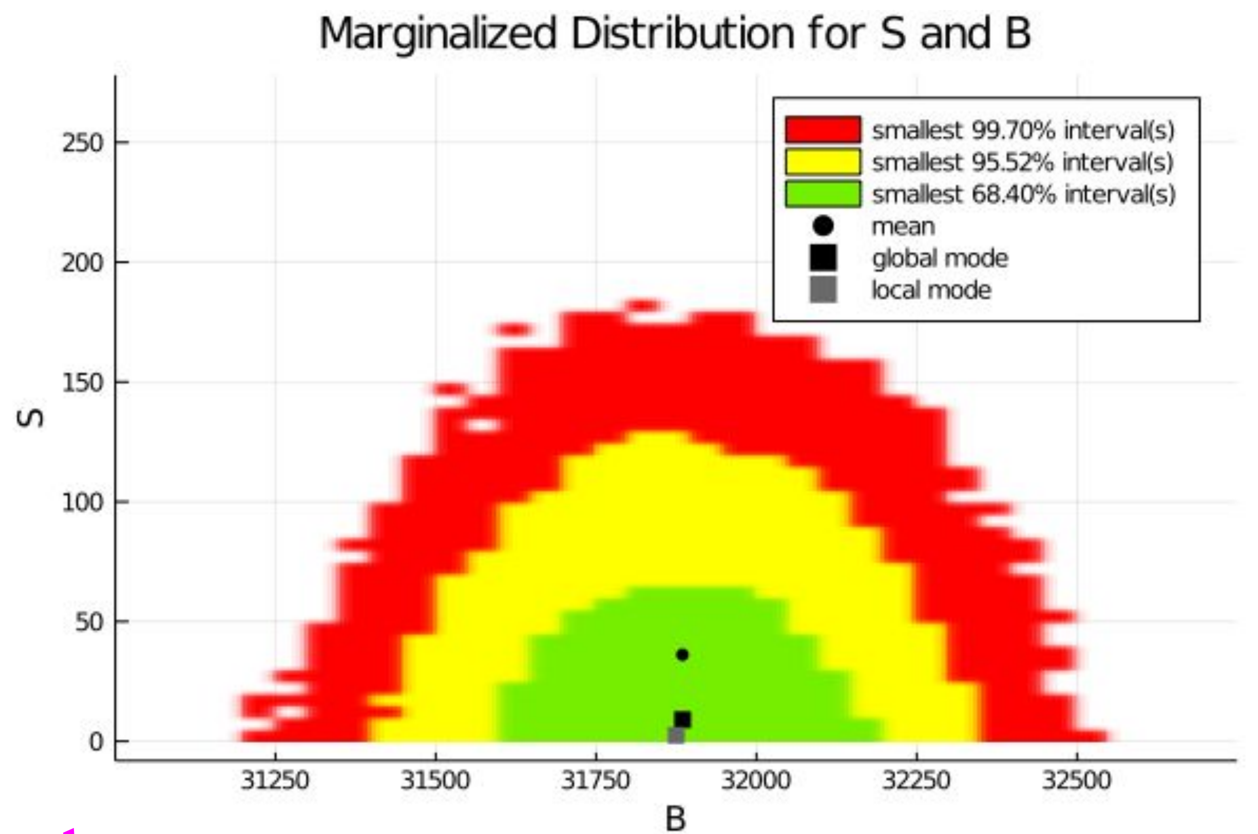
SCALE has a gaussian prior at t_{wc} / t_{woc}

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

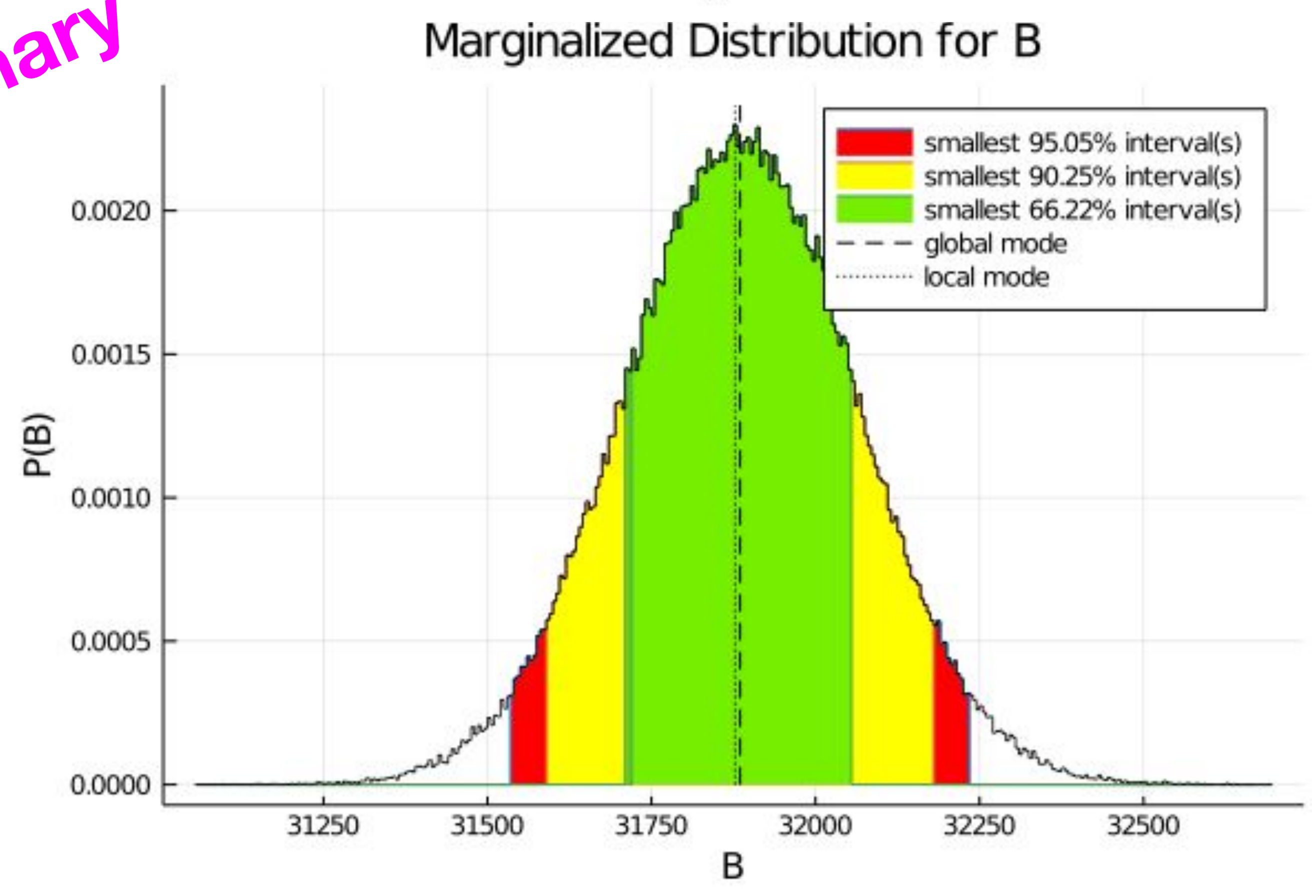
Results VIP-2 Open Systems

Data collected with VIP-2 in final configuration in the period May 2019 - October 2020
corresponding to acquisition times:
16311209 s with current
19780150 s without current





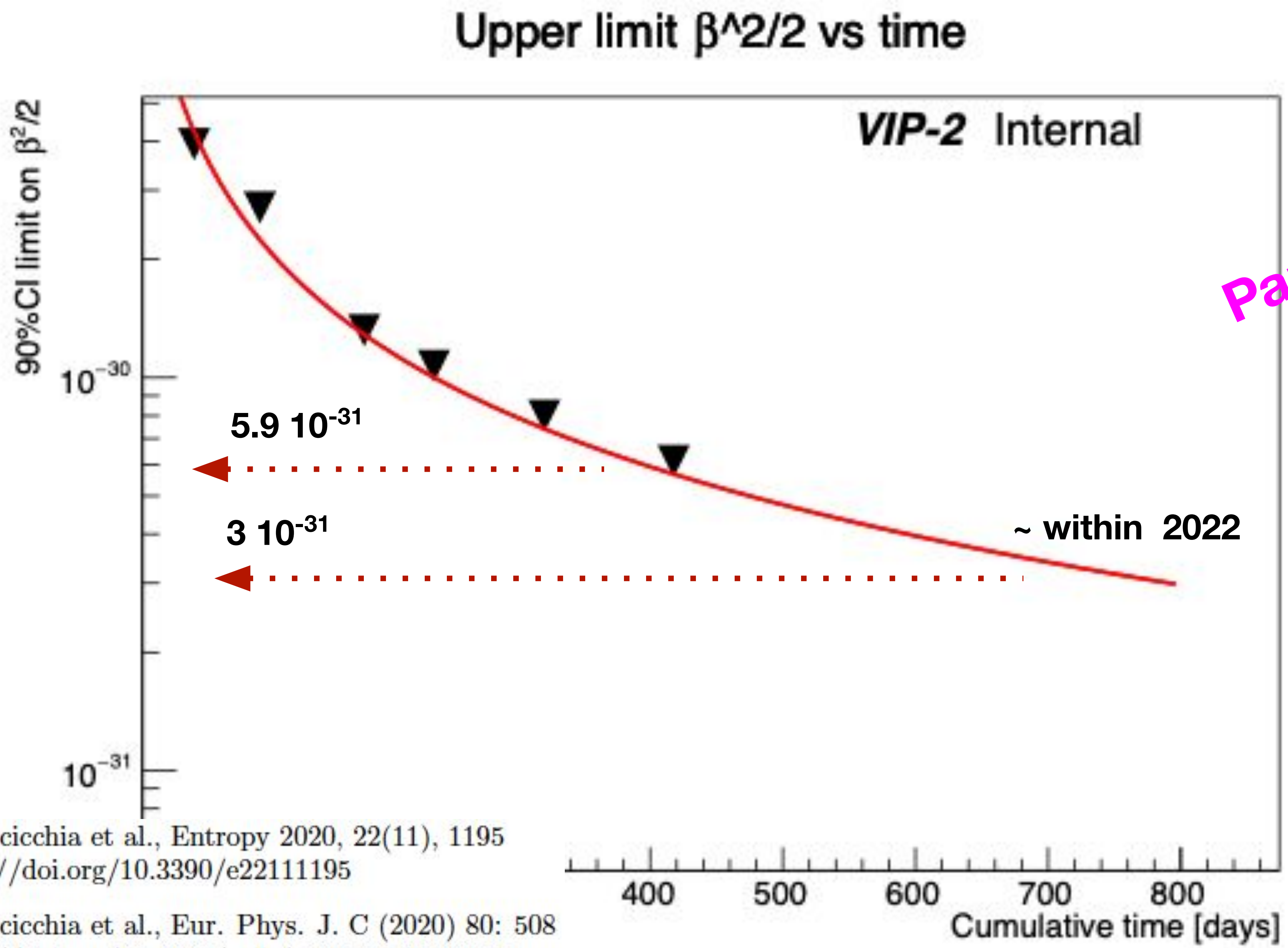
preliminary



S_bar = 79

B = 31885

Sensitivity projection against time



Paper in preparation

K. Piscicchia et al., Entropy 2020, 22(11), 1195
https://doi.org/10.3390/e22111195

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

E. Milotti et al., Entropy 2018, 20(7), 515
https://doi.org/10.3390/e20070515

E. Milotti et al., Symmetry 2021, 13(1), 6
https://doi.org/10.3390/sym13010006

Progress in theoretical interpretation

Picture: Danilo Pivato © copyright - All rights reserved

PEP violation in quantum gravity

Quantum gravity models can embed PEP violating transitions!

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

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 $\delta^2 = (E/\Lambda)^k$, *k* 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 conduction 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:

- **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.**

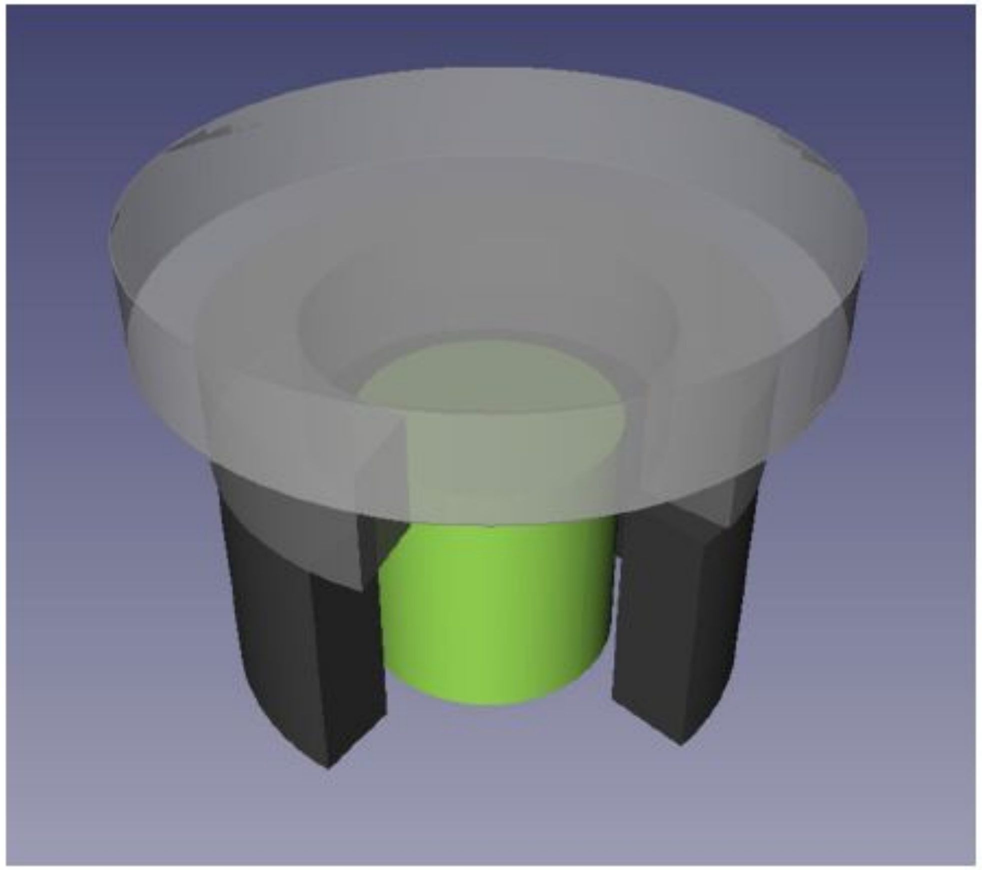


Fig. 1 Schematic representation of the Ge crystal (in green) and the surrounding lead target cylindrical sections (in grey)

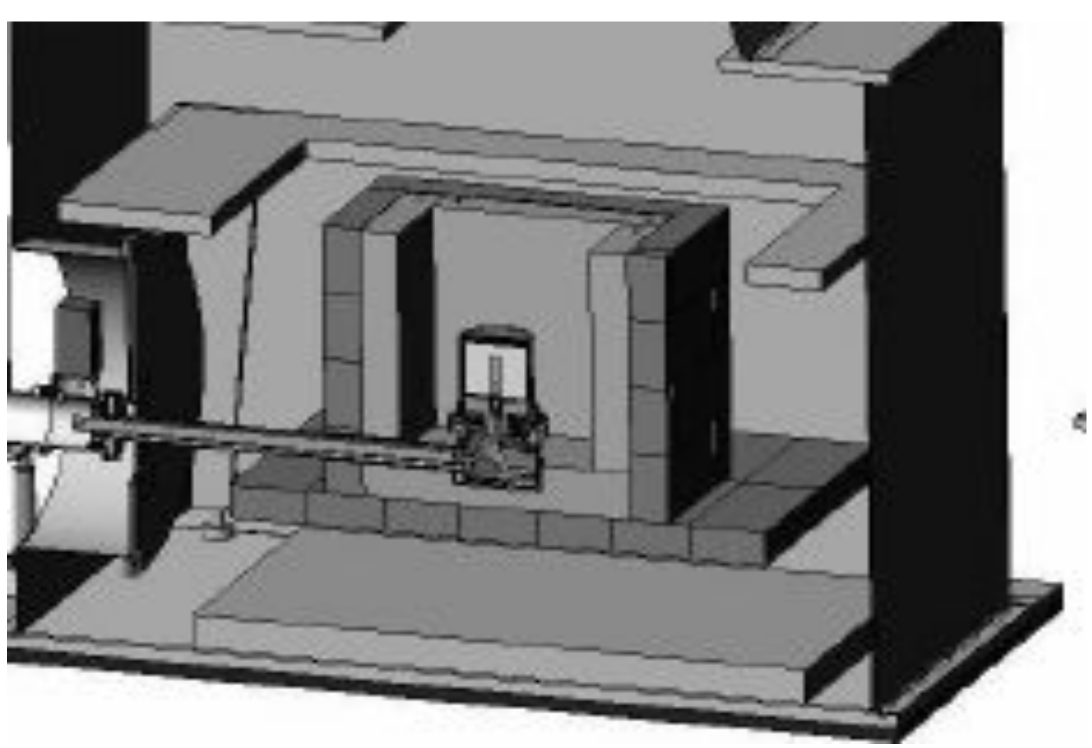
Experimental Setup

- **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



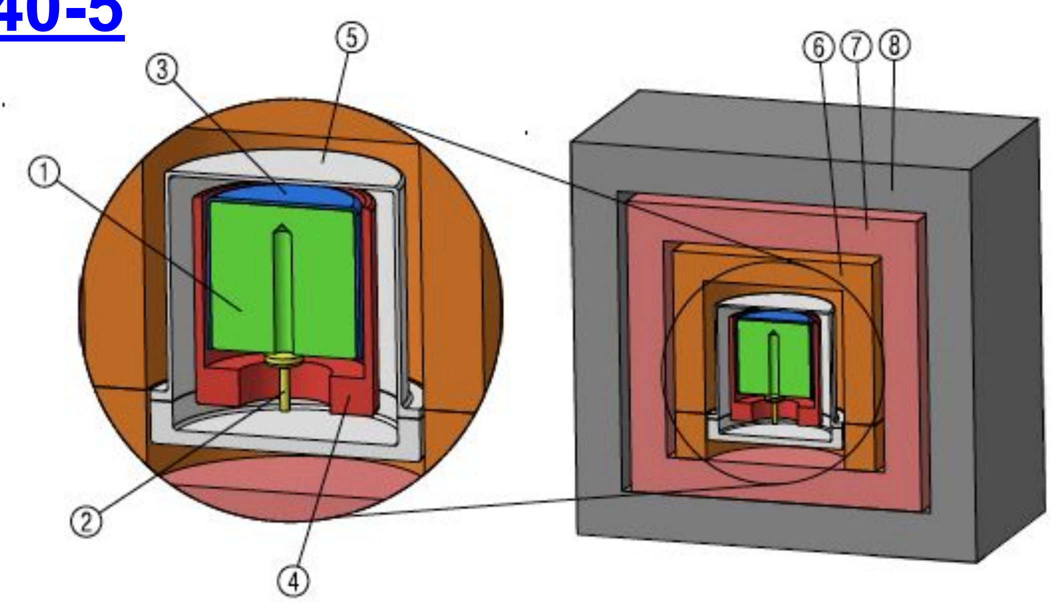


Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

Statistical model

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

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

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

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

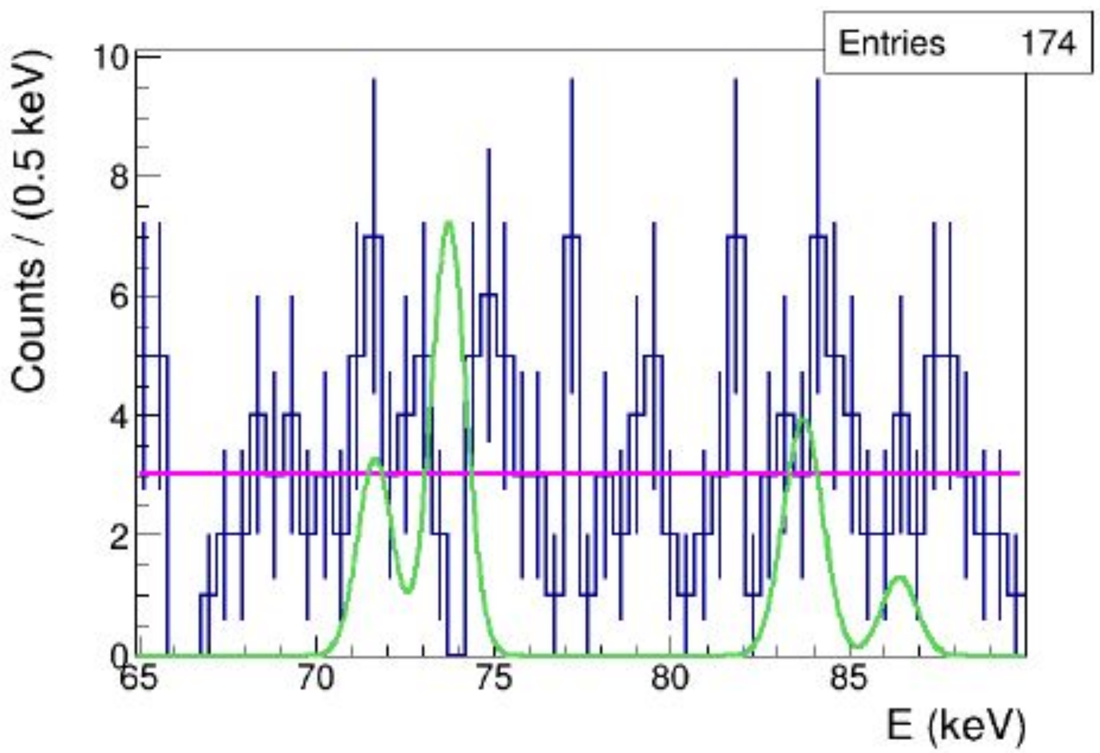


FIG. 1. The measured X-ray spectrum, in the region of the K_α and K_β standard and violating transitions in Pb, is shown in blue; the magenta line represents the fit of the background distribution. The green line corresponds to the shape of the expected signal distribution (with arbitrary normalization) for the A_3 analysis and the M_3 parametrization.

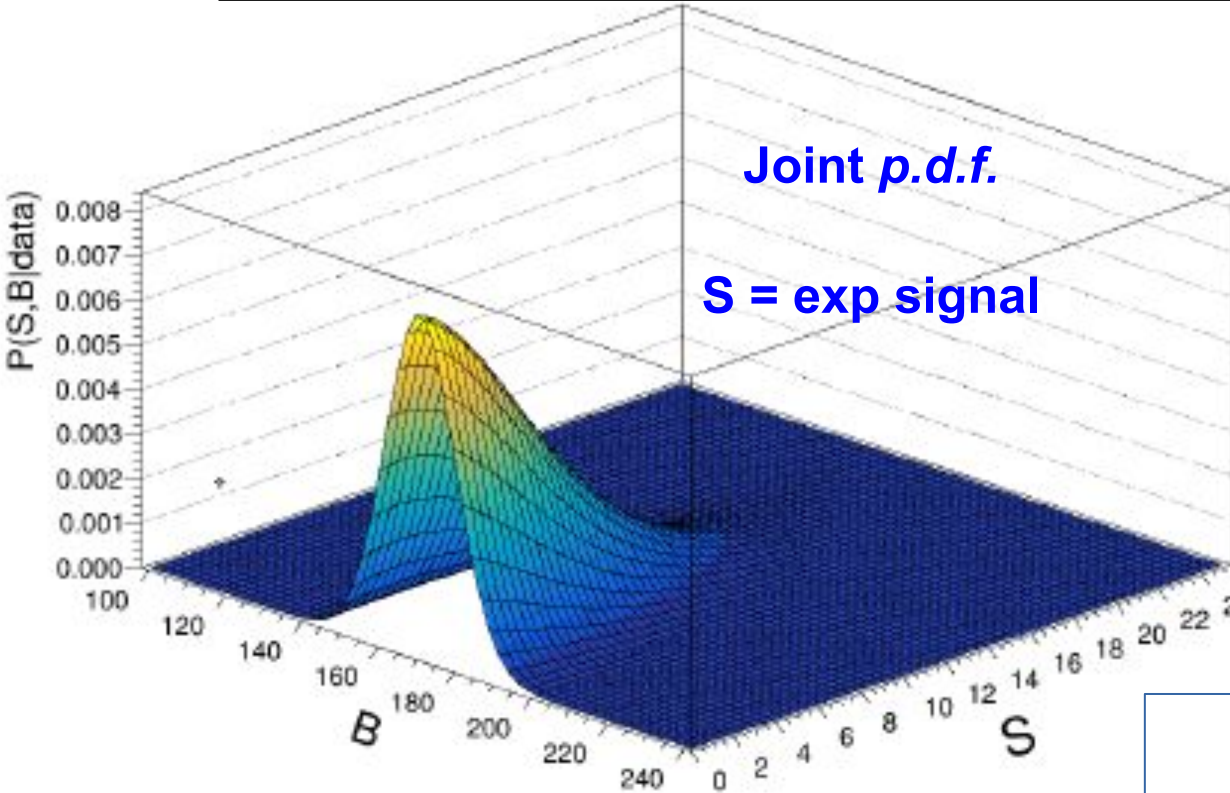
The prior for S consistent with existing limits [Found. Phys. 42, 1015-1030 (2012)**].**

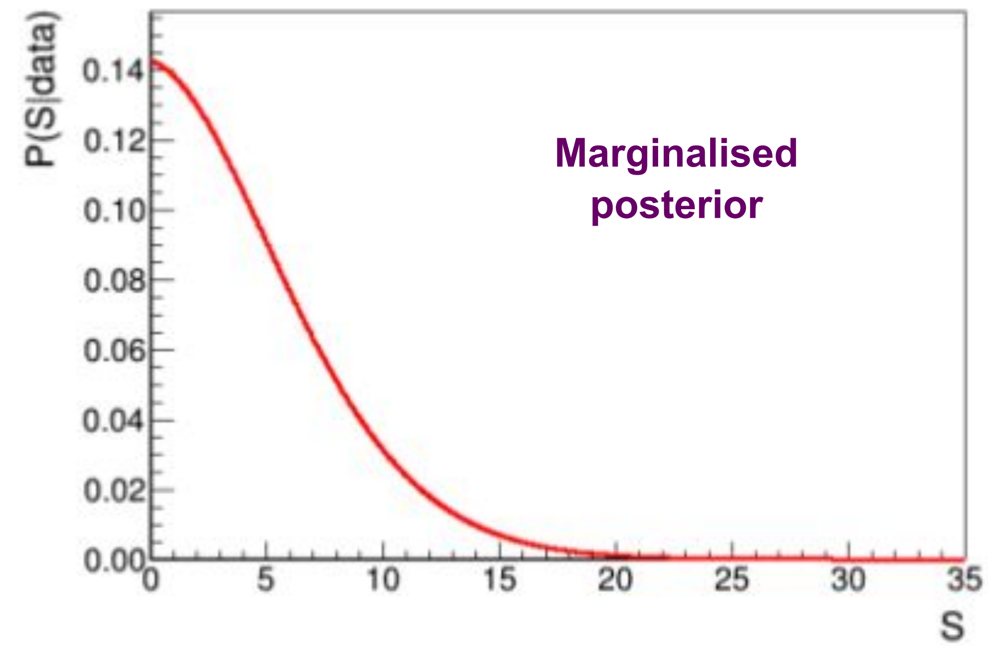
- the likelihood is weighted on the joint *pdf* of the experimental parameters

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

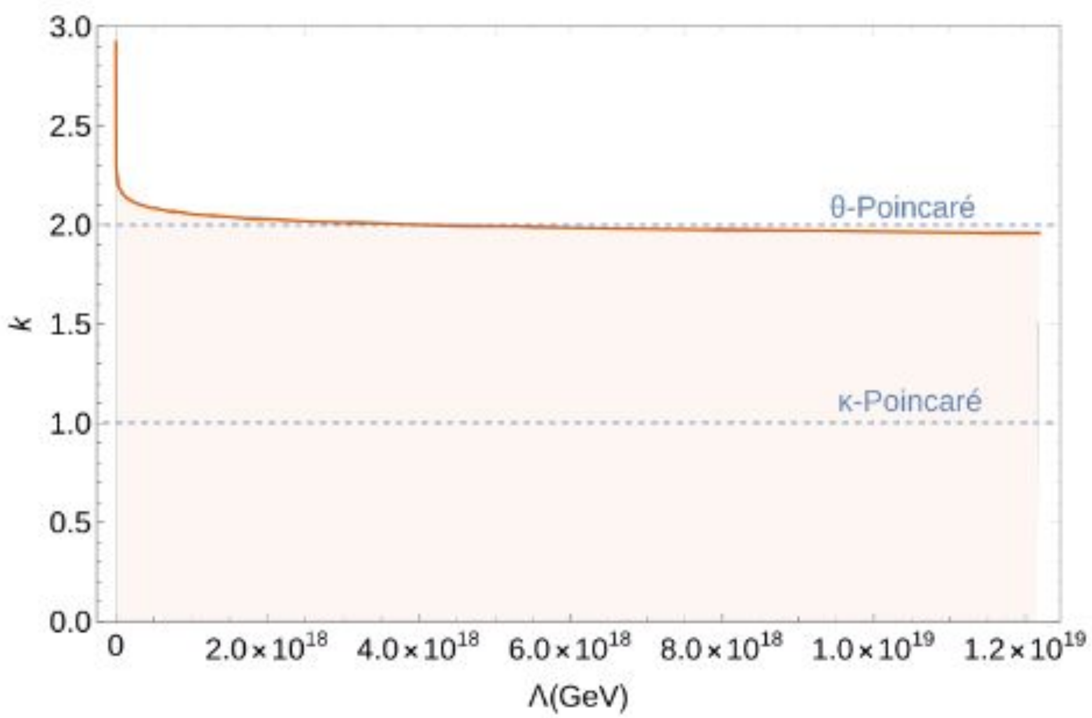
$$\lambda_i(S, B) = B \cdot \int_{\Delta E_i} f_B(E, \alpha) \; dE + + S \cdot \int_{\Delta E_i} f_S(E, \sigma) \; dE = B \cdot c_{Bi} + S \cdot c_{Si}$$

Results





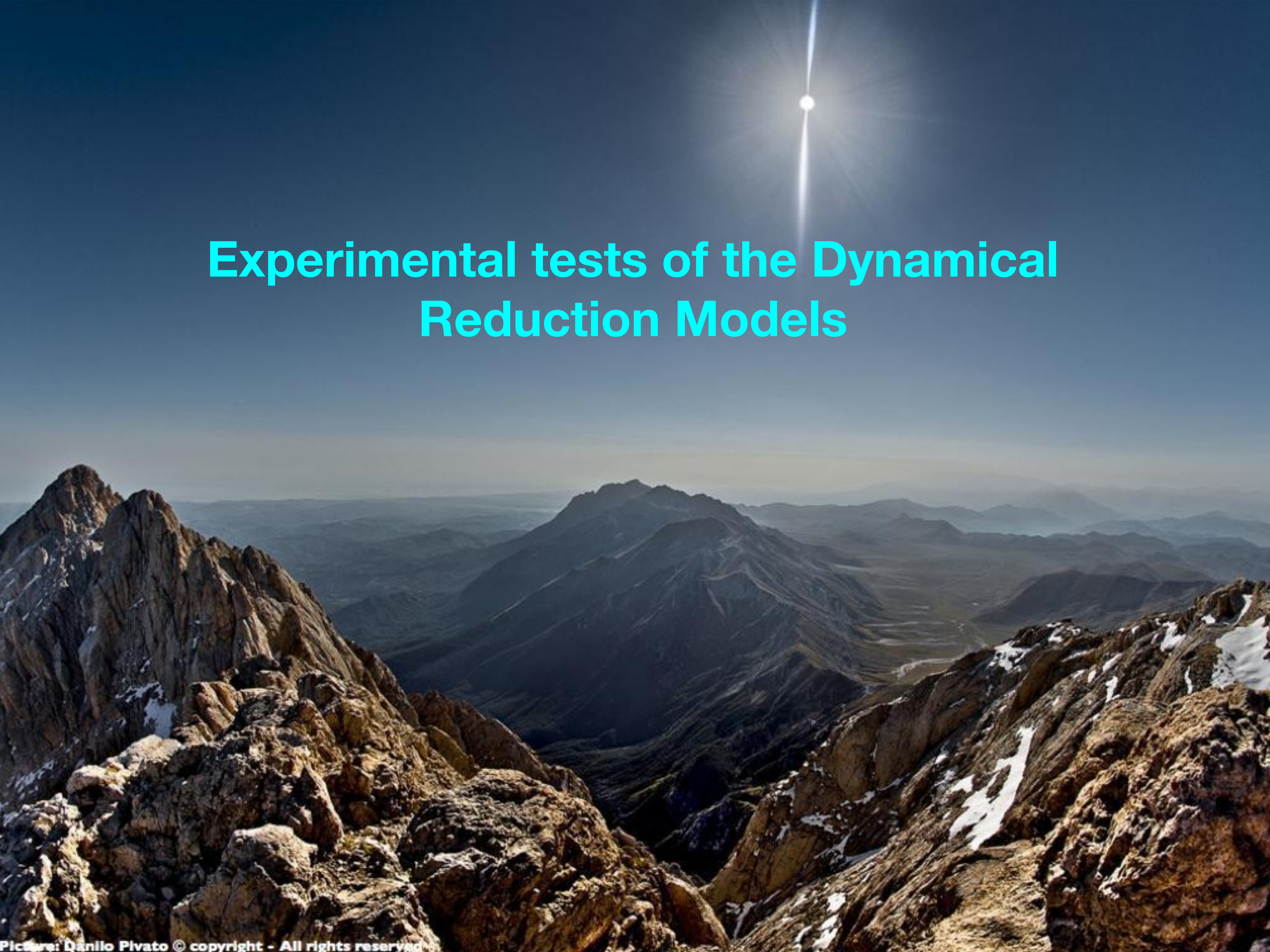
From which an upper limit on the non-commutativity scale is obtained (90% Probability):



***K*-Poincarè - excluded up to $\Lambda > 10^{21}$ Planck scale**

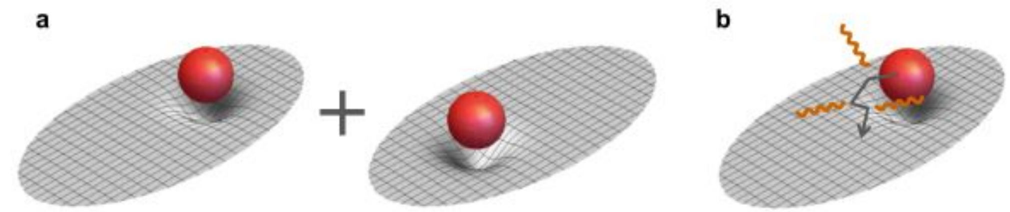
θ-Poincarè - excluded up to $\Lambda > 0.2$ Planck scale

Experimental tests of the Dynamical Reduction Models



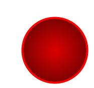
Dynamical reduction models

Why the quantum properties of microscopic systems, most notably, the possibility of being in the superposition of different states at once, do not seem to carry over to larger objects? A debate which is as old as the quantum theory itself.

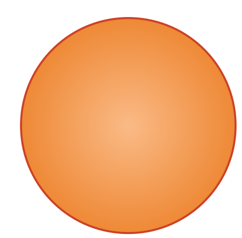


Diosi-Penrose model - when a system is in a spatial quantum superposition, a corresponding superposition of two different space-times is generated. The superposition is unstable and decays in time.

$$\tau_{\mathrm{DP}} = \frac{\hbar}{\Delta E_{\mathrm{DP}}}$$



Proton: $m \simeq 10^{-27}$ Kg, $R \simeq 10^{-15}$ m
$\tau_{DP} \simeq 10^{6}$ years



Dust grain: $m \simeq 10^{-12}$ Kg, $R \simeq 10^{-5}$ m
$\tau_{DP} \simeq 10^{-8}$ s

Indirect tests of collapse models exploit an unavoidable side effect of the collapse: a Brownian-like diffusion of the system in space. Charged particles emit spontaneous radiation.

Theoretical prediction for the expected spontaneous emission rate

- DP - s. e. photons rate:

$$\frac{d\Gamma_t}{d\omega_k} = \frac{2}{3}\frac{Ge^2N^2N_a}{\pi^{3/2}\varepsilon_0 c^3 R_0^3 \omega_k}$$

Calculated in collaboration with
L. Diosi, A. Bassi & S. Donadi

In our range ΔE = (1 - 4)MeV electrons are relativistic, only the contribution of protons (N) is considered.

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

The experimental setup

The experimental apparatus is based on a coaxial p-type high purity germanium detector (HPGe):

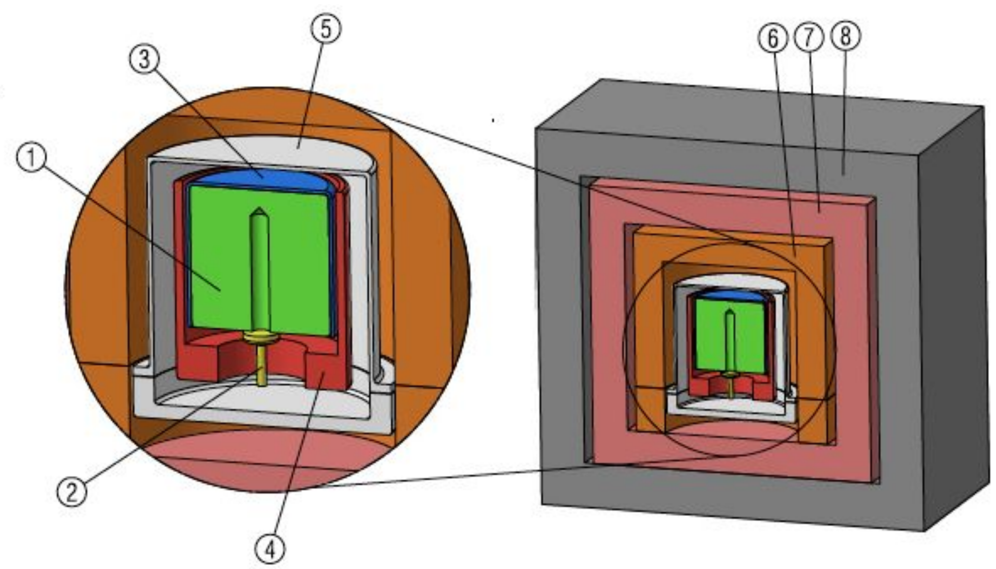
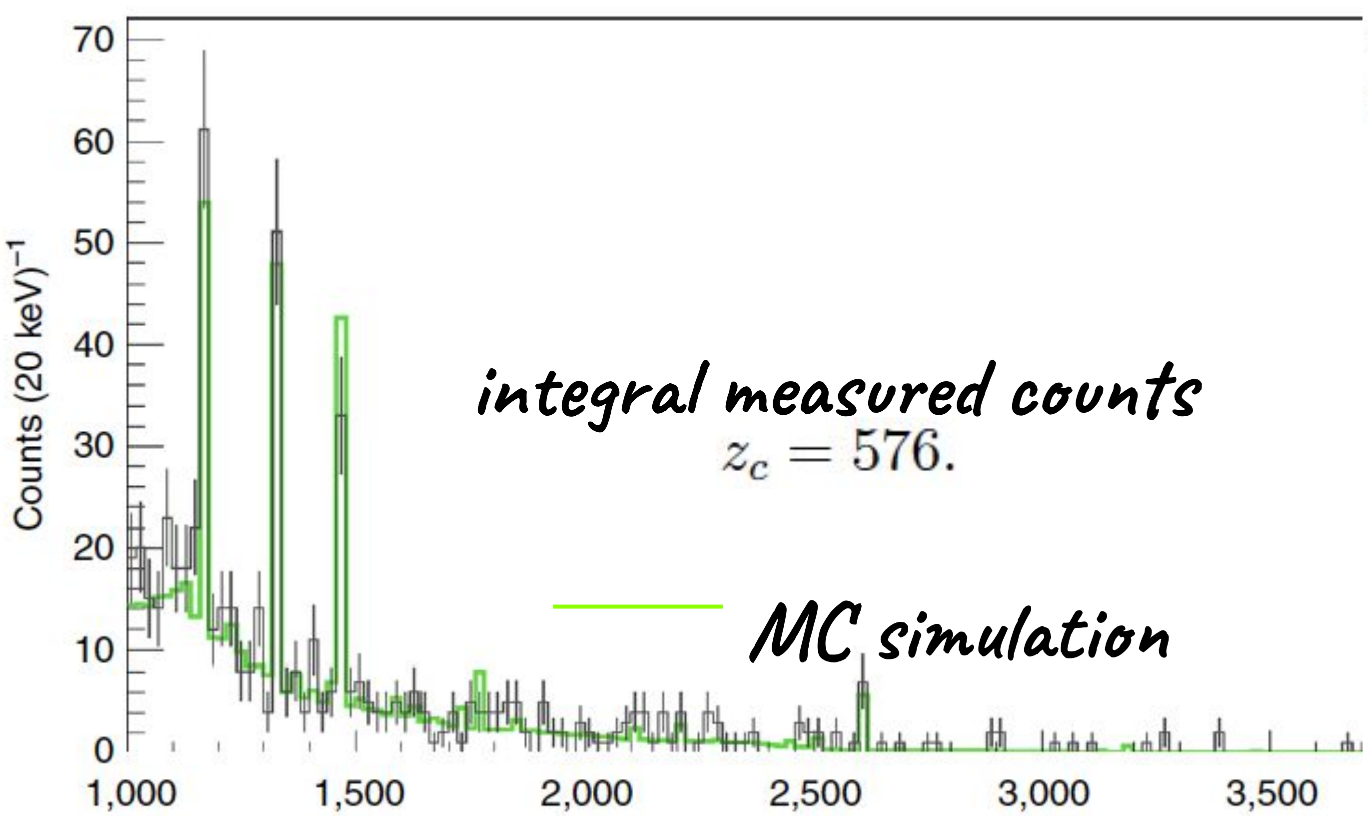


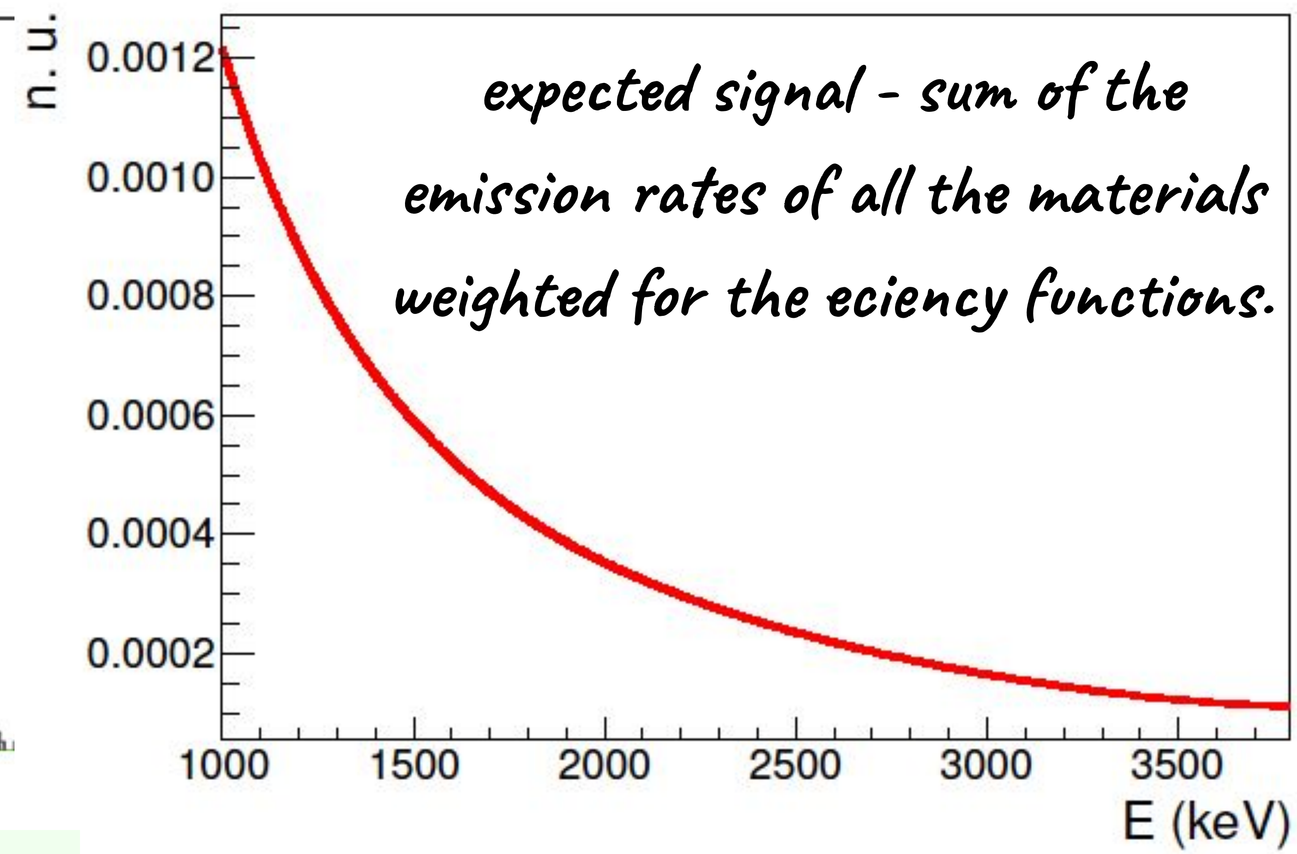
Figure 1: *Schematic representation of the experimental setup: 1 - Ge crystal, 2 - Electric contact, 3 - Plastic insulator, 4 - Copper cup, 5 - Copper end-cup, 6 - Copper block and plate, 7 - Inner Copper shield, 8 - Lead shield.*

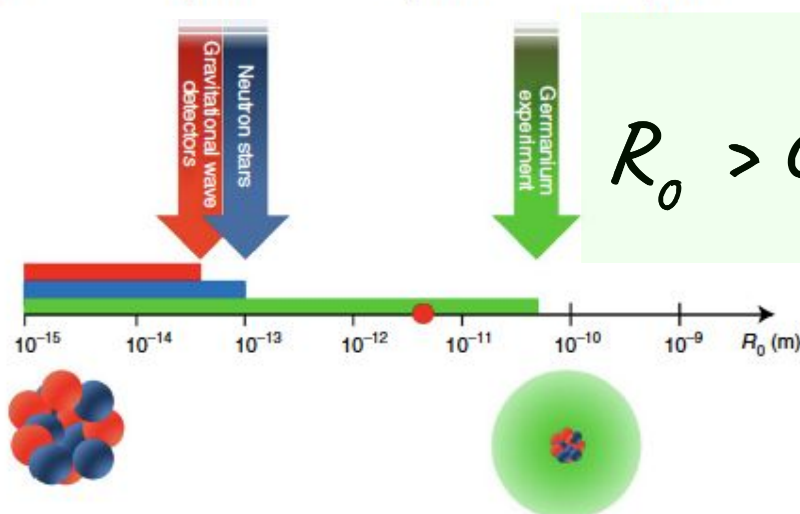
- Exposure 124 kg · day, m_{Ge} ~ 2kg
- on the bottom and on the sides 5 cm thick borated polyethylene plates give a partial reduction of the neutron flux
- an airtight steel housing encloses the shield and the cryostat, flushed with boil-off nitrogen to minimize the presence of radon.

Measured spectrum and background simulation

The experimental apparatus is characterised, through a validated MC code, based on the GEANT-4 software library. The background is due to emission of residual radio-nuclides:







$R_0 > 0.54 \cdot 10^{10}$ m

Donadi, S., Piscicchia, K., Curceanu, C. et al. Underground test of gravity-related wave function collapse. Nature Physics , volume 17, 74–78 (2021)

Thank you