Search for Pauli Exclusion Principle Violations with Gator, a High-Purity Germanium Detector at LNGS

L. Baudis, R. Biondi, A. Bismark, A. Clozza, C. Curceanu, M. Galloway, F. Napolitano, K. Piscicchia, A. Porcelli, F. Piastra, D. Ramírez García

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Universität Zürich UZH
INFN LNF Istituto Nazionale di Fisica Nucleare
Max-Planck-Institut für Kernphysik Heidelberg
Centro Ricerche Enrico Fermi

Pauli Exclusion Principle Violations

➔ talk by Kristian Piscicchia

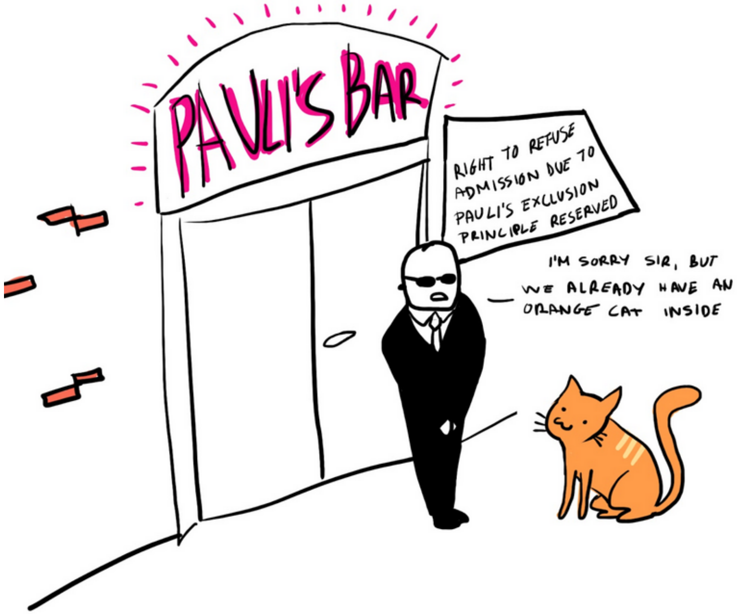
- Small violations of the Pauli Exclusion Principle suggested by physics beyond the Standard Model
- Possibility: altered particle properties, e.g., quon model [Phys. Rev. Lett. 59 (1987) 2507]:

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

- Subject to Messiah-Greenberg superselection rule [Phys. Rev. 136 (1964) B248]

  ➔ can only be tested with open systems

- Typically classification of novelty of the fermion-system interaction (Type I – III) [Found Phys 42 (2012) 1015]



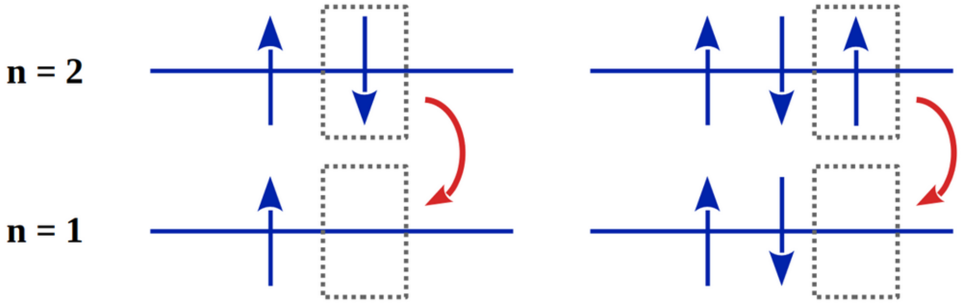
https://dingercatadventures.blogspot.com/

Ramberg-Snow Technique

➔ talk by Kristian Piscicchia

- Search for anomalous X-ray transitions performed by electrons introduced in a target through a direct current (Type II)

  ➔ lower energy PEP-forbidden transition due to screening of nucleus



- Technique pioneered by Ramberg and Snow [Phys. Lett. B 238 (1990) 438]; presently strongest limit on $\beta^2/2$ by VIP-2 experiment with Cu conductor [Symmetry 14 (2022) 893]

- Importance of testing the PEP violation probability for various elements

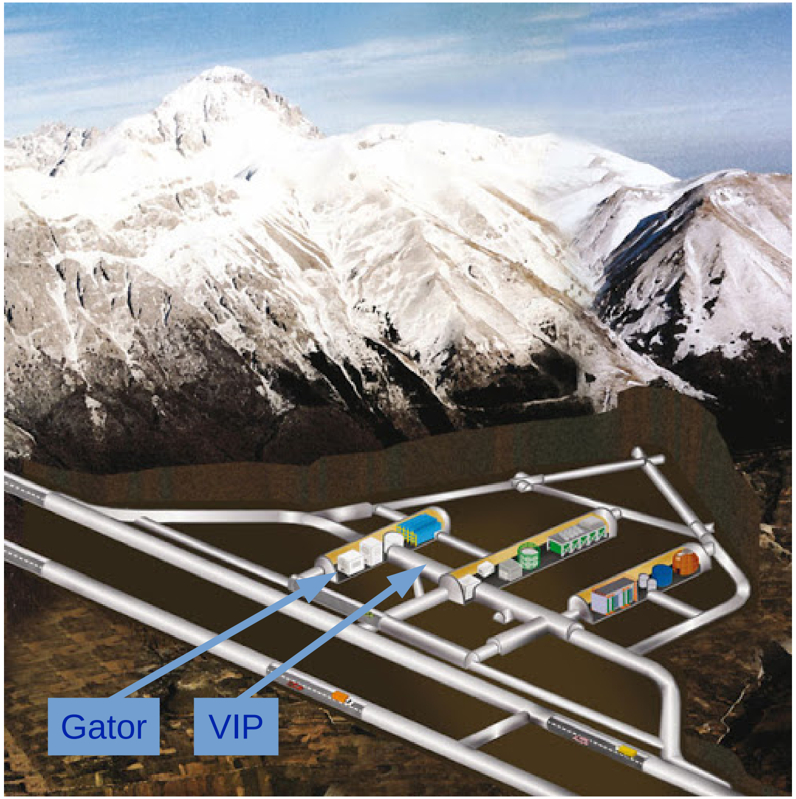
  ➔ here: investigate for Pb
  ➔ previous best limit with Ge detector: $\beta^2/2 < 1.5\cdot 10^{-27}$ [Found Phys 42 (2012) 1015]

Transition	EM energy	PEPV energy
1s - $2p_{3/2}$ $K_{\alpha 1}$	74.969 keV	73.713 keV
1s - $2p_{1/2}$ $K_{\alpha 2}$	72.805 keV	71.652 keV

The Gator Facility

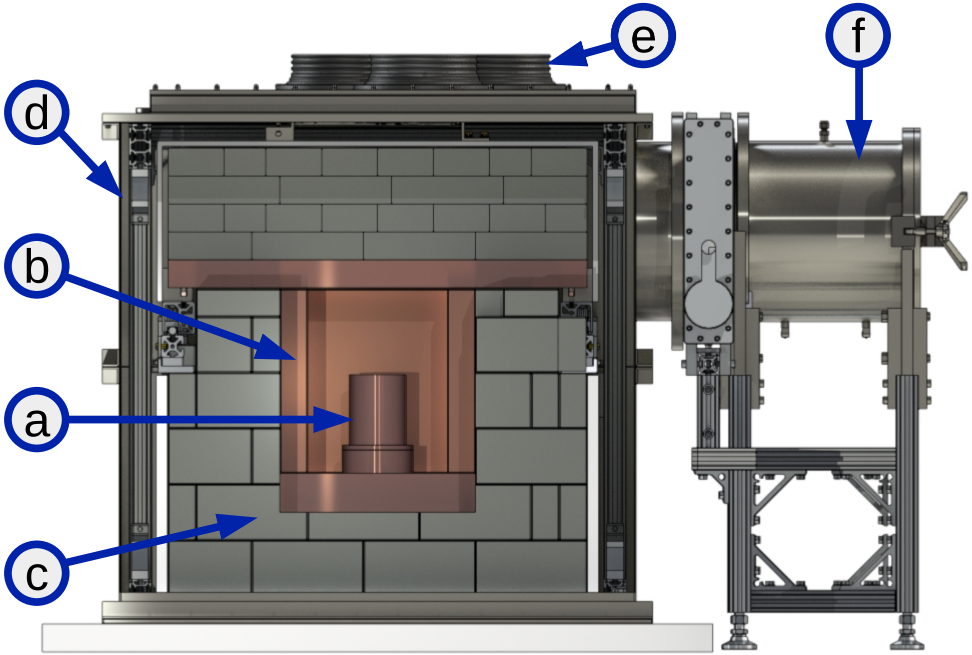
➔ JINST 17 (2022) P08010

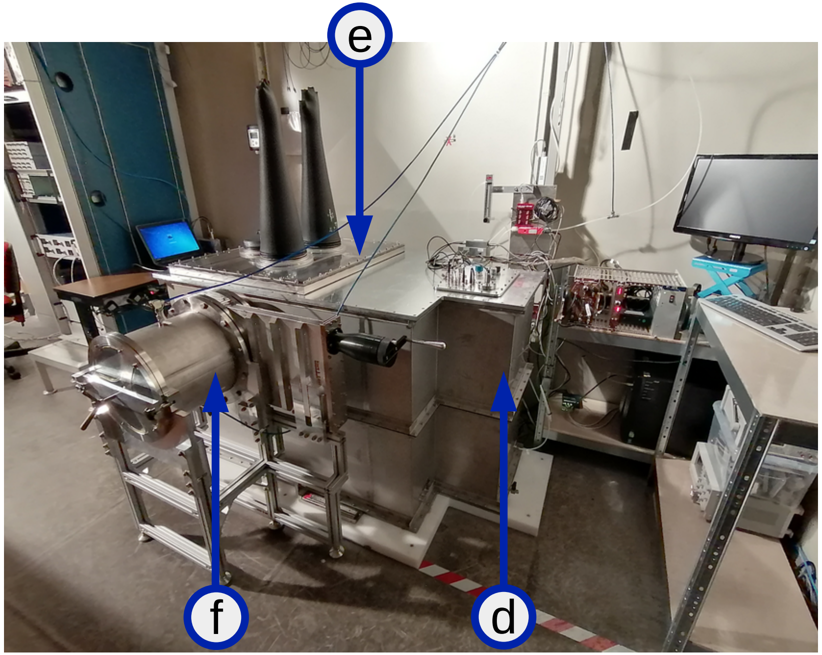
- Low-background germanium counting facility for high-sensitivity γ-ray spectrometry
- Located at the Gran Sasso underground laboratory in Italy (LNGS) at a depth of 3600 m water equivalent
- Core: p-type coaxial high-purity germanium (HPGe) detector with 2.2 kg sensitive mass and a relative efficiency of 100.5%
- Sample chamber volume: 25×25×33 cm^3
- Currently used for material radioassay for rare-event search experiments in astroparticle physic (DARWIN/XLZD, LEGEND,...)



The Gator Detector

➔ JINST 17 (2022) P08010

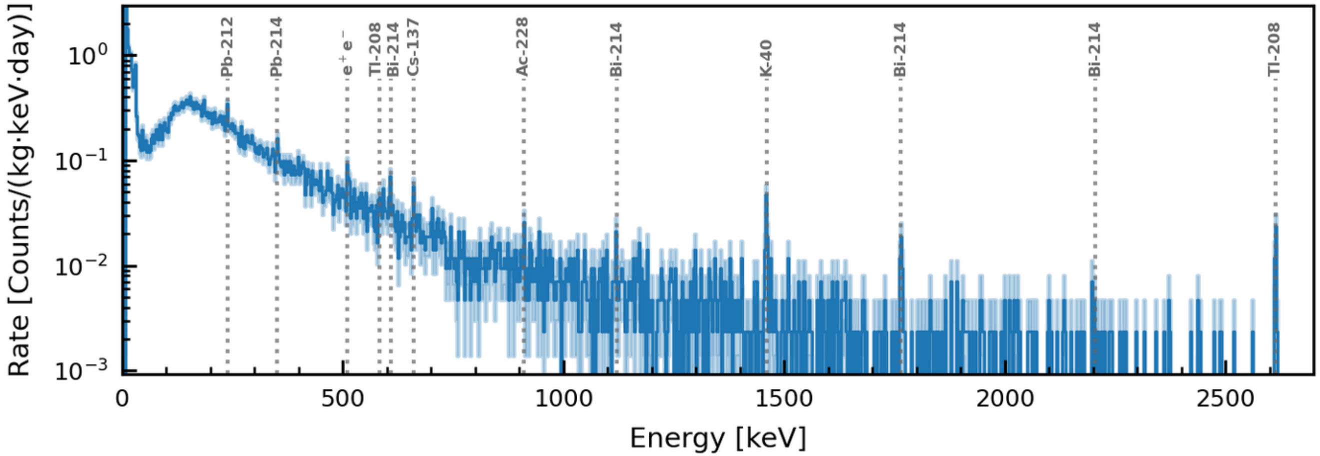


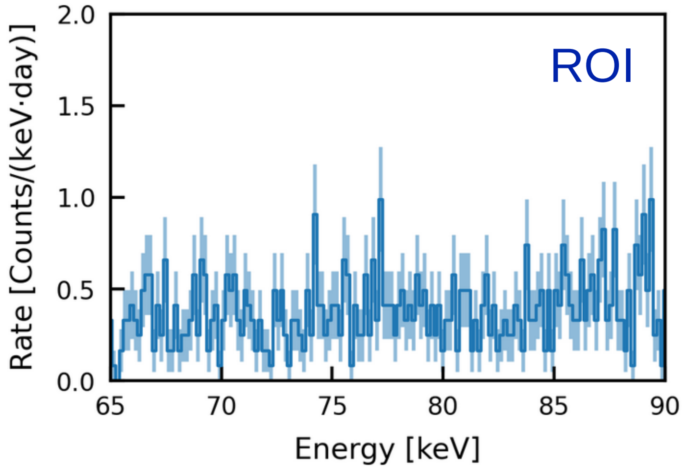


(a) HPGe detector inside Cu-OFE cryostat (cooled with LN_2 via copper coldfinger), **(b)** OFHC Cu cavity, **(c)** lead shield, polyethylene sheet, **(d)** airtight stainless steel enclosure (purged with GN_2), **(e)** glove ports, **(f)** sample load lock

Strength: Low Background

- Main contributions:
  - detector & shielding materials (^{226}Ra, ^{228}Th, ^{40}K, ^{60}Co,...)
  - environmental radon (^{222}Rn in air)
- Integrated rate in range
  - 100-2700 keV: (82.0±0.7) $d^{-1}kg^{-1}$
  - 65-90 keV: (4.4±0.3) $d^{-1}kg^{-1}$





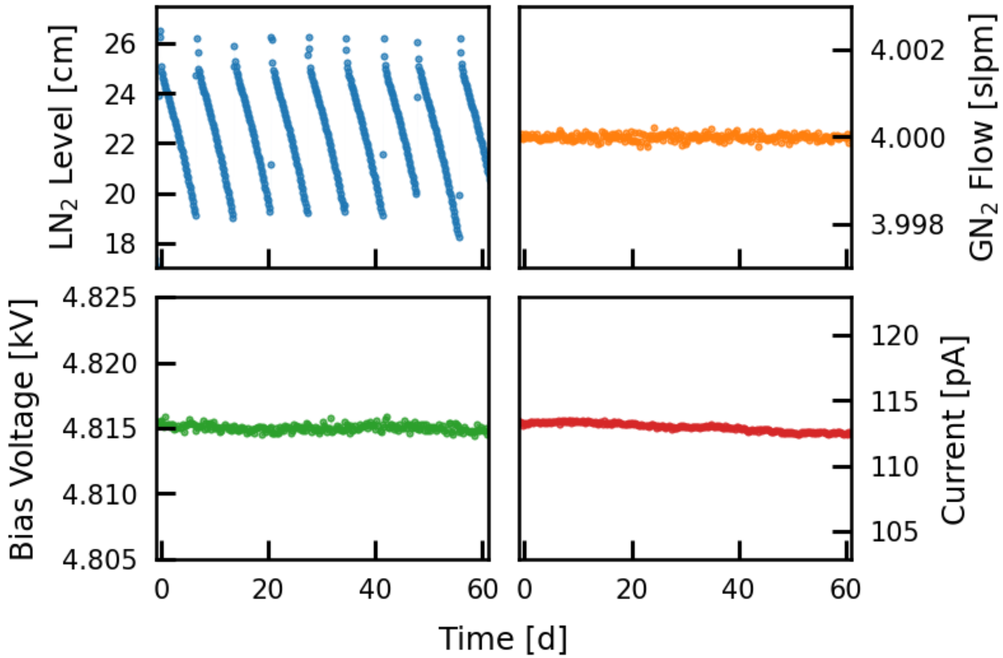
Data Acquisition and Slow Control

- Preamplified signal read out through
  - Ortec Model 672 spectroscopy amplifier and
  - self-triggering Ortec Model ASPEC-927 MCB

  ➔ record MCA spectra in 4h intervals (no pulse information available)

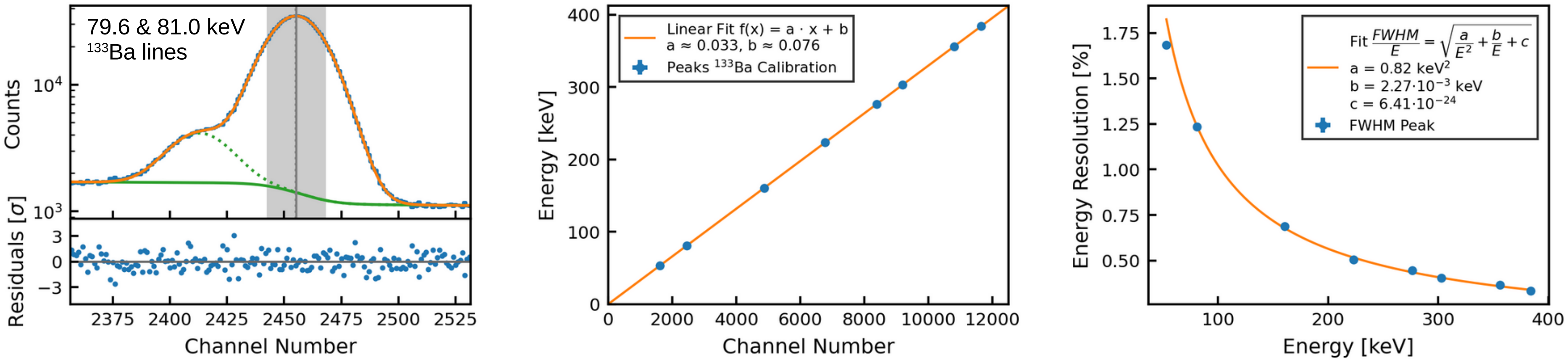
- Slow control monitoring operation parameters (HV, $I_{leakage}$, LN_2 level, temperature, rate,…)

  ➔ detector stability + data quality, removal refill-induced noise

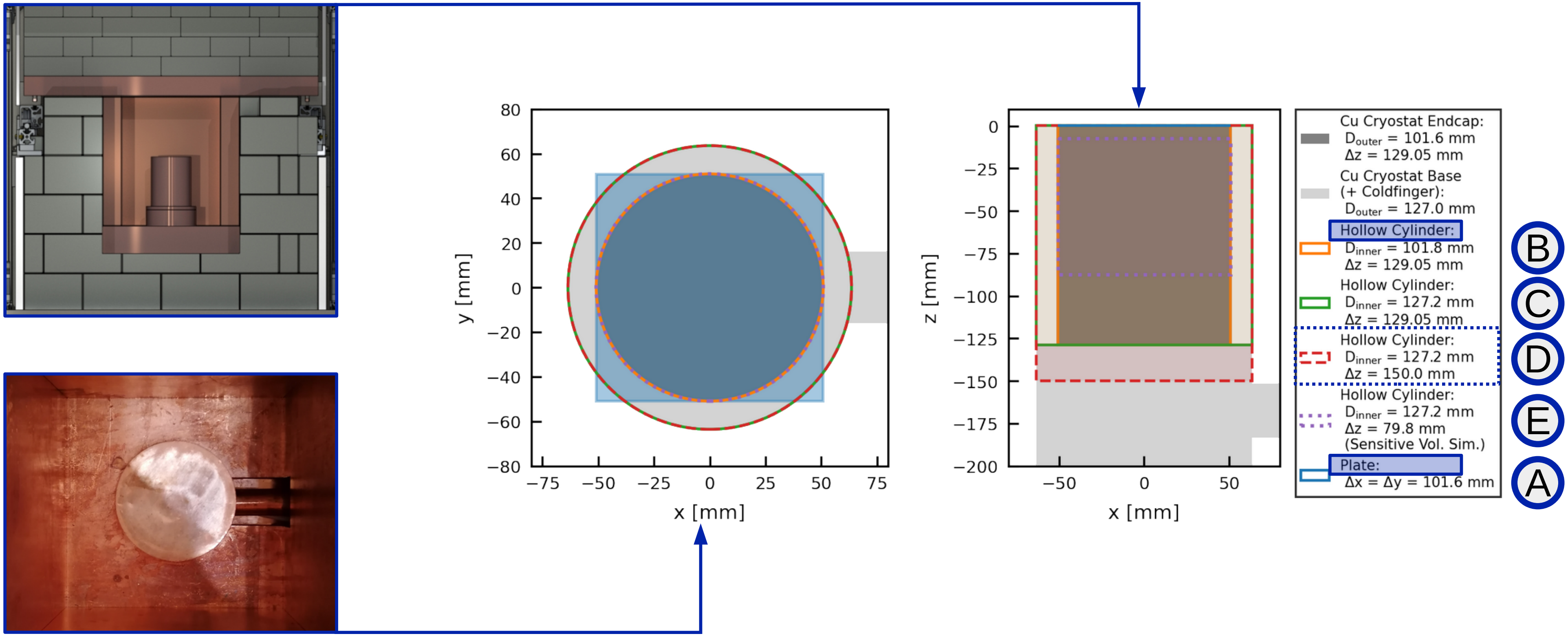


Energy Scale and Resolution

- Regular calibrations with ^{133}Ba and ^{228}Th sources
  ➔ monitoring stability response, verification MC simulations
- Energy range 0 – 540 keV (factor 5 reduction w.r.t. material radioassay)
- Linear energy scale with ~ 0.033 keV/channel
- Resolution ~ 1.0 keV (FWHM) at Pb K_α lines

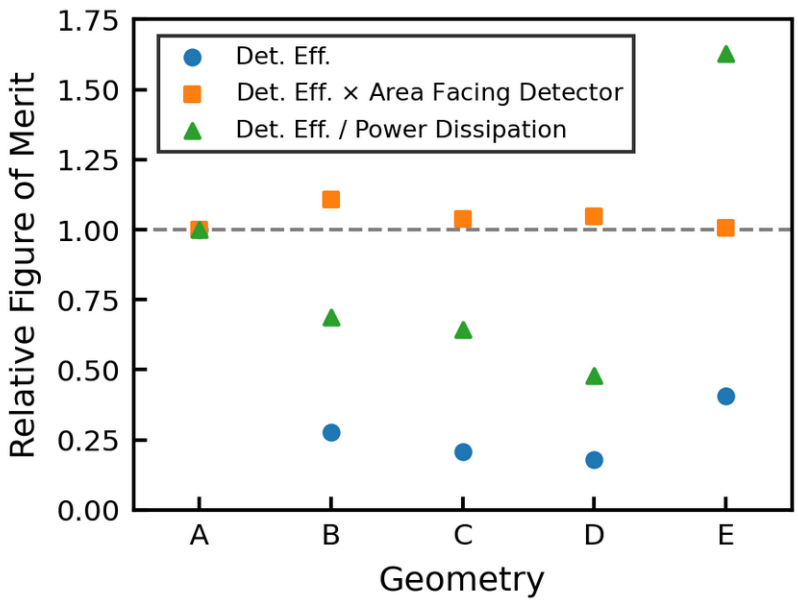


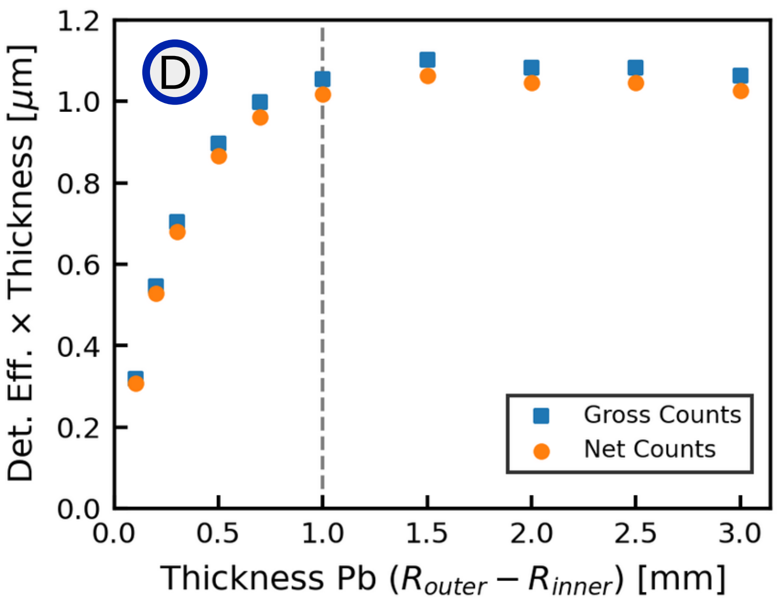
GEANT4 MC Simulations – Pb Conductor Geometry



GEANT4 MC Simulations – Geometry + Thickness

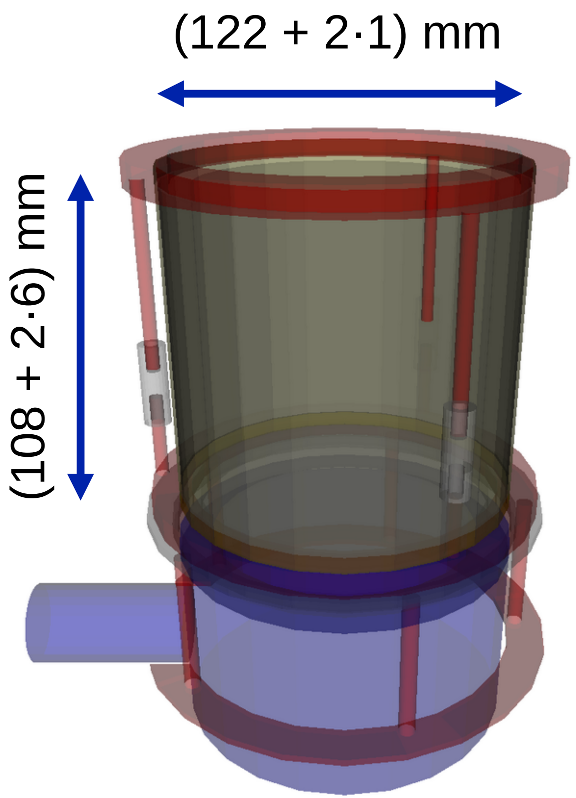
Investigate impact Pb conductor geometry and thickness on detection efficiency:



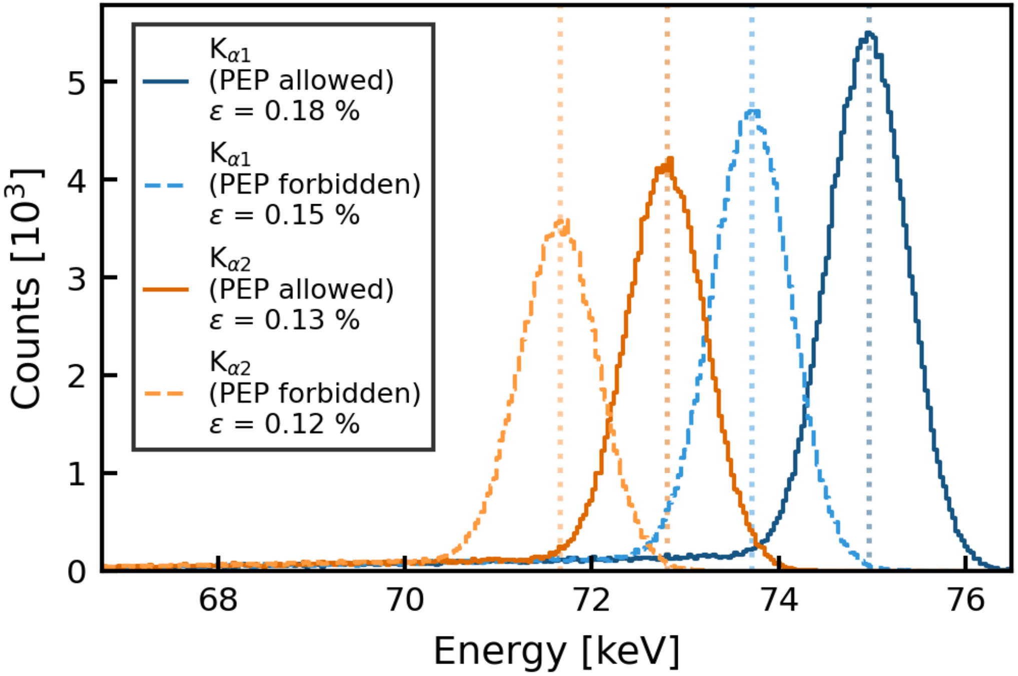


➔ Select cylinder geometry with 1 mm wall thickness

GEANT4 MC Simulations – Final Geometry



Absorption-induced energy dependence detection efficiency ε:



Target Geometry

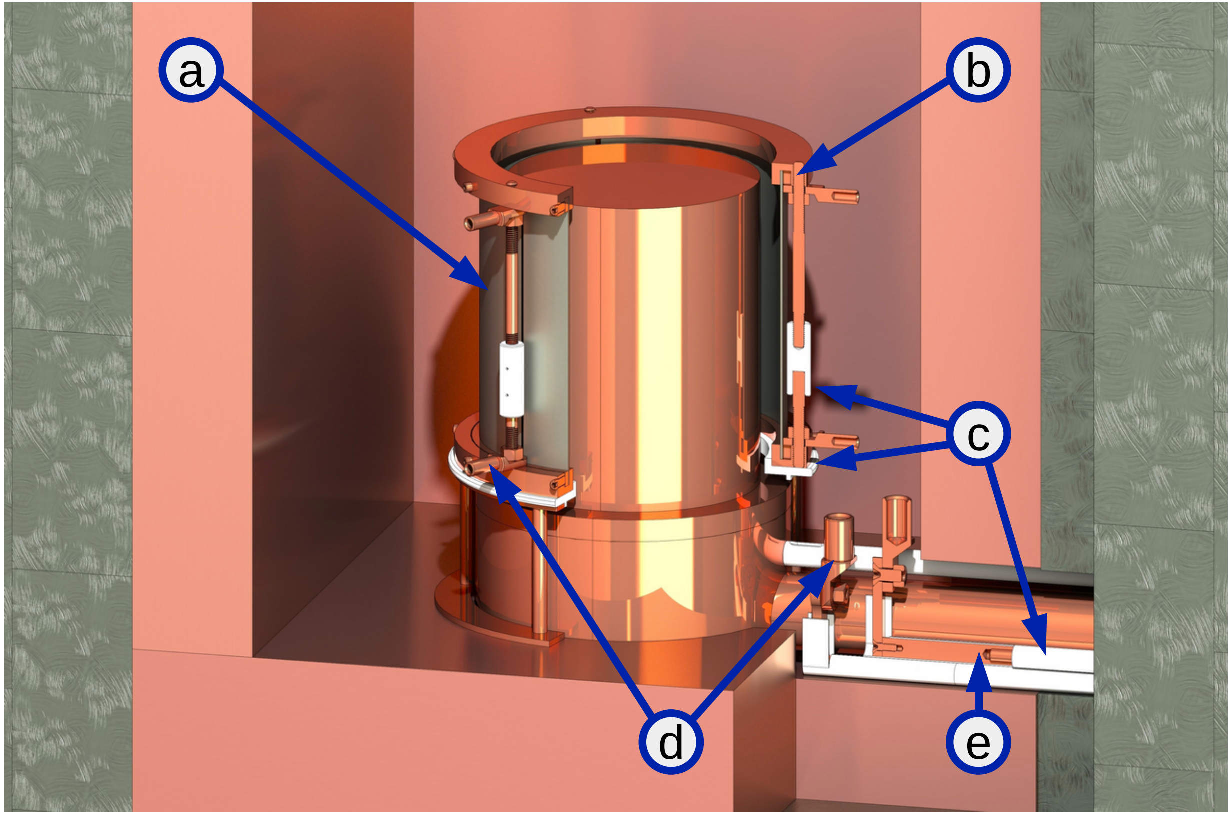
(a) Tripartite Pb foil cylinder

(b) Copper rings with segmented clamping elements + set screws

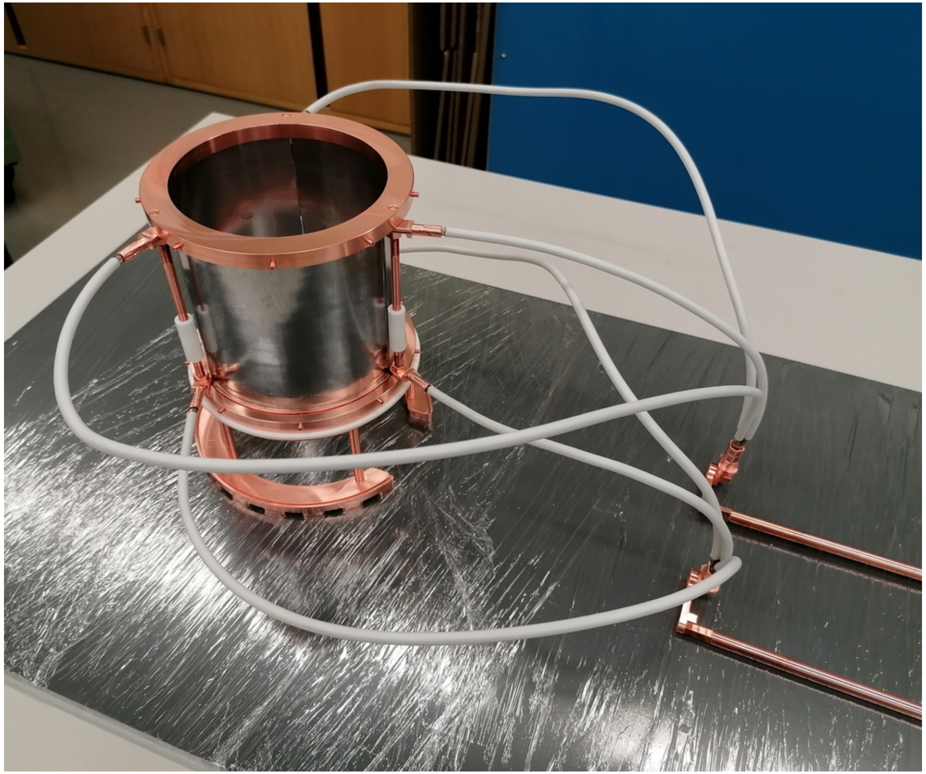
(c) PTFE insulation

(d) Copper cable lugs for 2 sets of 3 cables each ($10\ mm^2$, not shown)

(e) Segmented high current feedthrough rod



Target Geometry (Photographs)

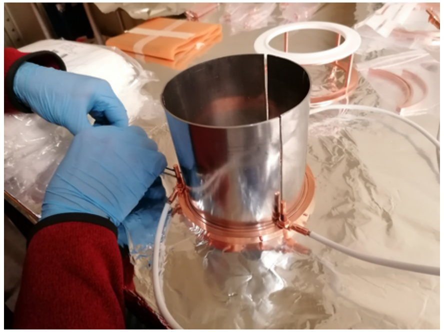


Test assembly at UZH

Inside Gator cavity

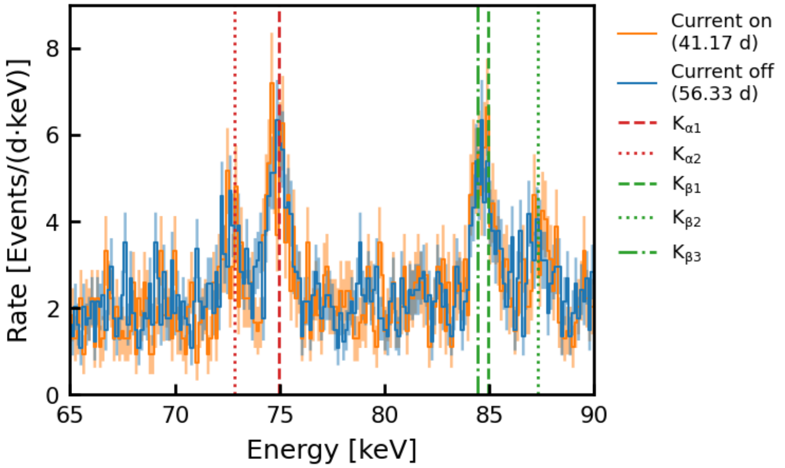
Low-Activity Materials

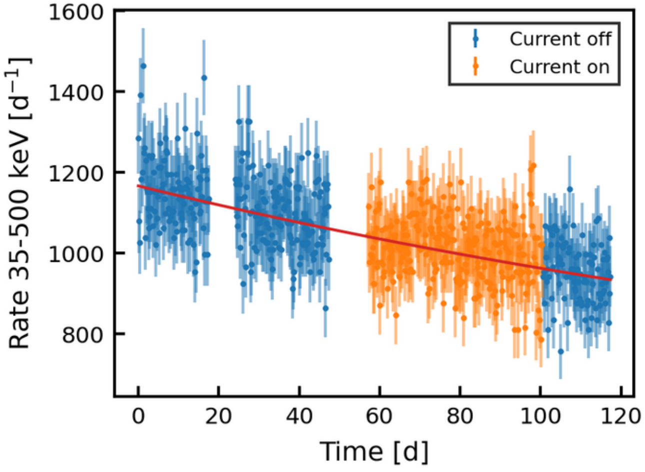
- Material selection:
  - Custom cast and rolled Roman lead sheets from Lemer Pax with <0.2 Bq/kg
  - Oxygen-free high-conductivity copper from XENONnT array support plate [Eur.Phys.J.C 82 (2022) 7, 599]
  - PTFE plates from XENON1T [Eur.Phys.J.C 77 (2017) 12, 890]
  - Tinned fine-strand copper conductor solar cables ➔ material radioassay with Gator
- Minimize component mass to suppress radioactive background; still ensure mechanical stability (➔ SolidWorks simulations) and sufficient conductor cross-sectional and surface areas to reduce heat-up (➔ calculations + thermal tests)



Measurements

- Data taking April – August 2023:
  - 41.17 d current ON (40 A DC from current-stabilized Agilent N5761A Power Supply)
  - 56.33 d current OFF (as background reference)
- Time-dependent background rate from activated radioisotopes
  ➔ expected 5–7% mean rates difference





Analysis – General Assumptions

- Investigate PEP-violating $K_{\alpha1}$ (BR = 0.47) and $K_{\alpha2}$ (BR = 0.23) lines
- Total number of interacting new electrons taken as

$$N_{CE} = \frac{I \cdot \Delta t}{e} \cdot \frac{D}{\mu} \cdot P_{cpt}$$

with
- I = 40 A (current)
- Δt = 41.17 d (current-on live time)
- e = $1.602 \cdot 10^{-19}$ C (elementary charge)
- D = 10.8 cm (effective length Pb conductor)
- μ = $2.34 \cdot 10^{-7}$ cm (mean free path current electron in Pb)
- P_{cpt} = 0.9% (electron capture probability)

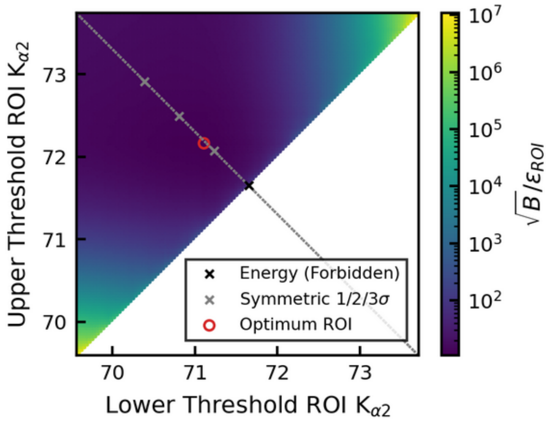
(I, Δt, e: # introduced current electrons)

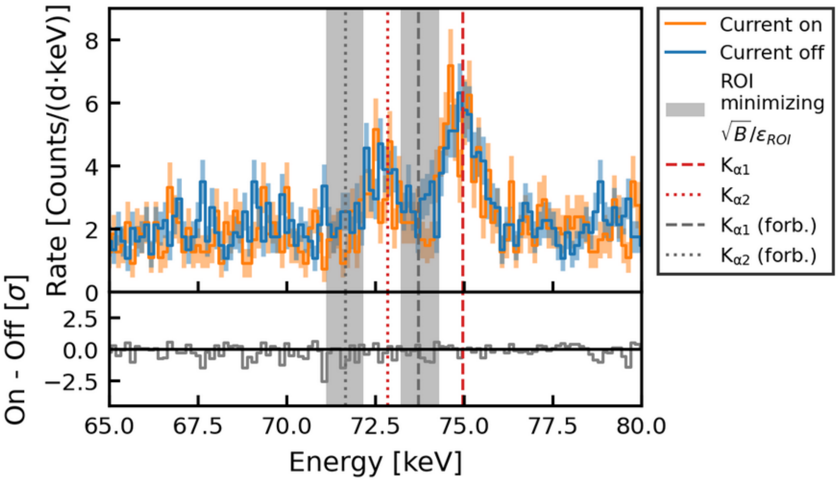
(D, μ: # electron-atom interactions per e^-)

Analysis – Simple Counting Method

- Estimate following [Found Phys 42 (2012) 1015] for comparability
- Gross difference On – Off in ROI minimizing sqrt(B)/ε_{ROI}:
  $N_{\alpha1}$ = -(16±14) cnts ≡ (9±8)%; $N_{\alpha2}$ = -(19±12) cnts ≡ (14±9)%
  ➔ time dependence background + local underfluctuation
  ➔ assume vanishing difference for conservative estimate
- Current-off livetime corrected, weighted average net count Poisson error yields 3σ upper limit electron-atom interactions $N_{3\sigma}/\varepsilon_{tot} \approx 3 \times 1.65\cdot10^4$ (with ε_{tot} including $\varepsilon_{detection}$, BR, and ε_{ROI})
- Resulting limit factor ~ 11 improvement:

$$\frac{1}{2}\beta^2 < \frac{N_{3\sigma}}{\varepsilon_{tot}\cdot N_{CE}} = 1.3\cdot10^{-28}$$





Analysis – Fitting

- Background / signal model:

PEP-allowed peaks

Background continuum

$$\mathcal{F}(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S}) = y_1 \cdot K_{\alpha_1}(\theta_1, \theta_2) + y_2 \cdot K_{\alpha_2}(\theta_3, \theta_4) + y_3 \cdot \mathrm{Pol}_1(\theta_5)$$
$$+ \mathcal{S} \cdot \varepsilon_{det,1} \cdot \varepsilon_{BR,1} \cdot \mathrm{PEPV}_1(\theta_2) + \mathcal{S} \cdot \varepsilon_{det,2} \cdot \varepsilon_{BR,2} \cdot \mathrm{PEPV}_2(\theta_4)$$

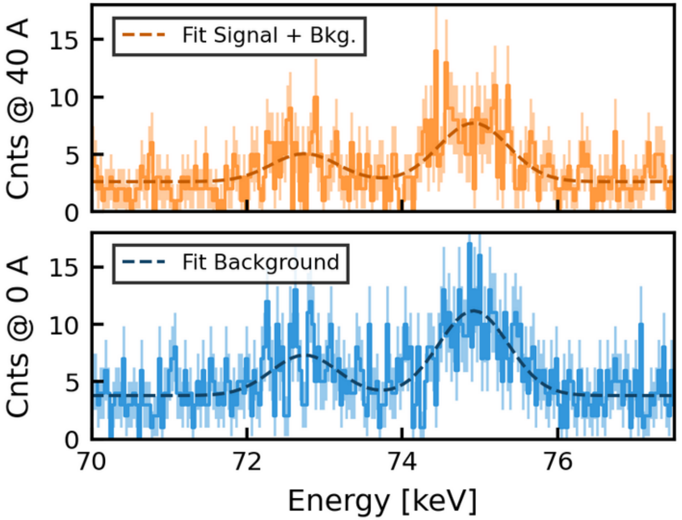
PEP-violating peaks

- Likelihood for simultaneous fit:

$$\mathcal{L}(\mathcal{D}^{on}, \mathcal{D}^{off} | \boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S}) = \mathrm{Poiss}(\mathcal{D}^{on} | \mathcal{F}^{on}(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S})) \cdot \mathrm{Poiss}(\mathcal{D}^{off} | \mathcal{F}^{off}(\boldsymbol{\theta}, \boldsymbol{y} \cdot \mathcal{R}))$$

- Empirical normalization factor:

$$\mathcal{R} = \int_{\mathcal{D}^{on}} \int_E f \, \mathrm{d}t \, \mathrm{d}E \Big/ \int_{\mathcal{D}^{off}} \int_E f \, \mathrm{d}t \, \mathrm{d}E$$



Results – Fitting (Bayesian)

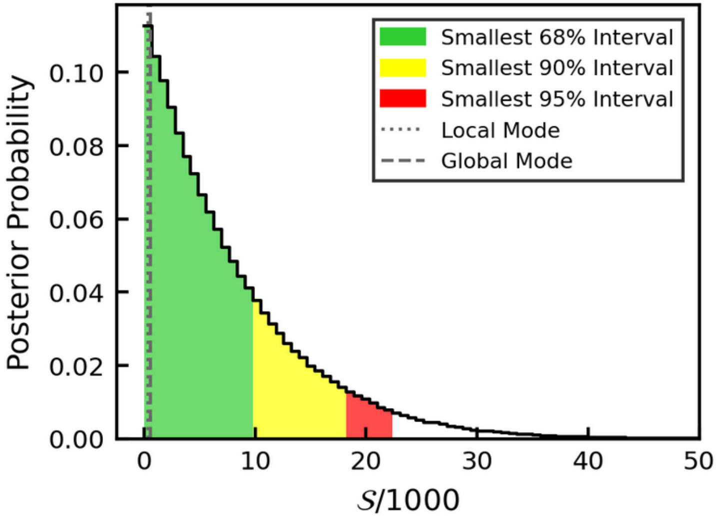
- Gaussian priors for $\boldsymbol{\theta}$ (➔ calibrations) and $\mathcal{R}$ (➔ background time-dependence, t^{on}/t^{off})

- Posterior probability: $$p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S} | \mathcal{D}^{on}, \mathcal{D}^{off}) = \frac{\mathcal{L}(\mathcal{D}^{on}, \mathcal{D}^{off} | \boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S}) p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S})}{\int \mathcal{L}(\mathcal{D}^{on}, \mathcal{D}^{off} | \boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S}) p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S}) \, \mathrm{d}\boldsymbol{\theta} \, \mathrm{d}\boldsymbol{y}}$$

- Marginalized posterior probability distribution of signal yield $\mathcal{S}$ via MCMC integration:

$$p(\mathcal{S} | \mathcal{D}^{on}, \mathcal{D}^{off}) = \int p(\boldsymbol{\theta}, \boldsymbol{y}, \mathcal{S} | \mathcal{D}^{on}, \mathcal{D}^{off}) \, \mathrm{d}\boldsymbol{\theta} \, \mathrm{d}\boldsymbol{y}$$

- Mode at $\mathcal{S} = 0$ ➔ upper limits using $\beta^2/2 = \mathcal{S}/N_{CE}$:
  - 90% C.L.: $\mathcal{S} < 1.84 \cdot 10^4$ ➔ $\beta^2/2 < 4.8 \cdot 10^{-29}$
  - 99% C.L.: $\mathcal{S} < 32.9 \cdot 10^4$ ➔ $\beta^2/2 < 8.7 \cdot 10^{-29}$



Results – Fitting (Frequentist)

- Cross-check with modified frequentist CL_s analysis
- Exclusion requirement at nominal C.L. of 1−α:

$$\mathrm{CL}_s = \frac{p_\mathcal{S}}{1-p_0} < \alpha$$

with p-value:

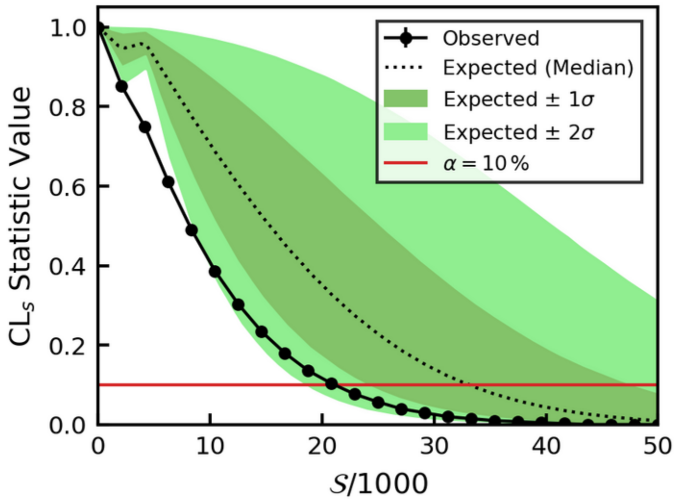
$$p_\mathcal{S} = P(t_\mathcal{S} \geq t_{obs}|\mathcal{S}) = \int_{t_{obs}}^{\infty} f(t_\mathcal{S}|\mathcal{S})\,\mathrm{d}t_\mathcal{S}$$

- Resulting 90% C.L. upper limit (α = 0.1) of

$\mathcal{S} < 2.1\cdot 10^4 \rightarrow \beta^2/2 < 5.7\cdot 10^{-29}$

slightly more conservative than Bayesian approach

- ~ 1.5σ deviation from the median expected CL_s statistic



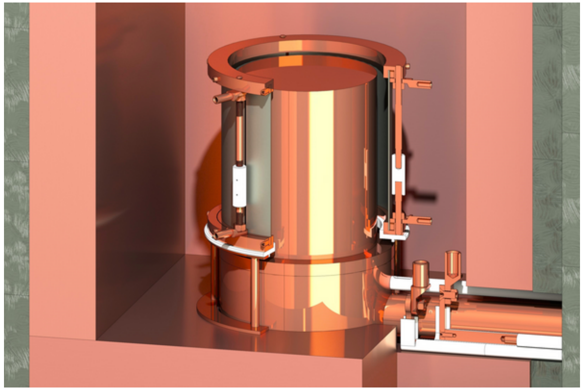
Summary and Conclusion

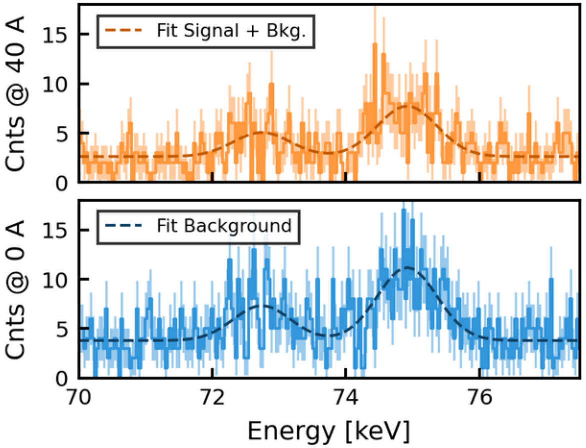
→ **Manuscript in preparation**

- Search for small Pauli Exclusion Principle violations with Gator, a low-background HPGe detector at LNGS
- Applied Ramberg-Snow technique to probe PEP-forbidden $K_{\alpha1}$ and $K_{\alpha2}$ transitions in a current-carrying Pb conductor in compliance with the Messiah-Greenberg superselection rule (type II experiment)
- No signs of PEP violations observed
  → set limits improving previous most stringent bounds for this type of measurement and material by more than one order of magnitude:

$$\frac{1}{2}\beta^2 < 4.8 \cdot 10^{-29}$$

Bayesian analysis (90% C.L.)





Appendix

Novelty Fermions

- Categorization experiments by how “new” the fermion-system interaction can be assumed to be according to [Found Phys 42 (2012) 1015]:
  - **Type I:** fermion has not previously interacted with any other fermions
    - primordial system formation
    - recently created fermions, e.g., from β-decay or pair production (Type Ia)
  - **Type II:** fermion has not previously interacted with that investigated system
    - distant fermions brought to interact with system, e.g., Ramberg-Snow technique employed here
    - nearby fermions brought to interact with system, e.g., electrons in the Fermi sea of a conductor (Type IIa)
  - **Type III:** fermion within investigated system
    - violate the MG superselection rule, but can set stringent bounds on the spin-statistics deformation induced by Non-Commutative Quantum Gravity models

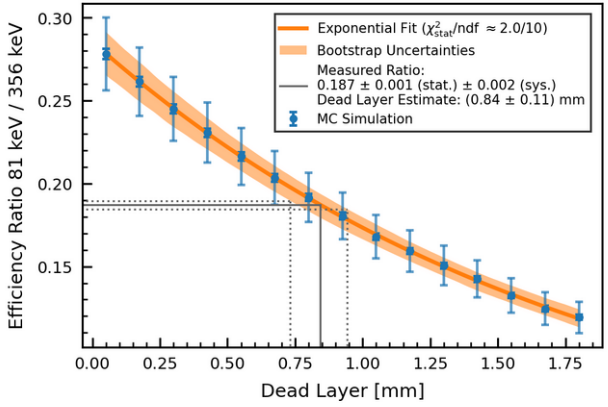
Comparison to Other HPGe Spectrometers

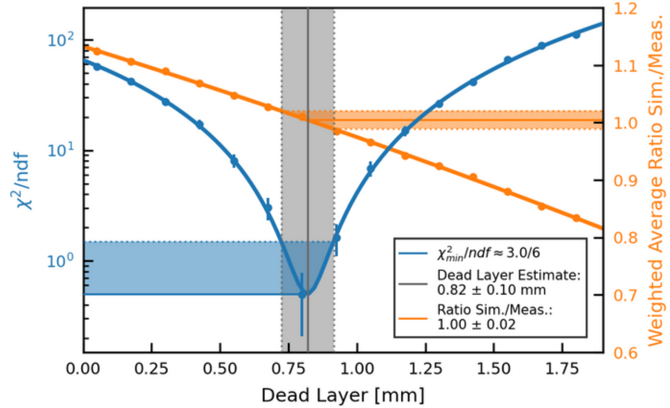
Detector	Location (Depth m.w.e.)	Mass [kg]	Efficiency [%]	FWHM [keV]	Rate 60-2700 keV [cnts/(kg·day)]	Ref.
Gator	LNGS (3600)	2.2	100.5	1.98	89.0 ± 0.7	
Maeve	SURF (4300)	2.0	85	3.19	956.1	[1]
GeMPI 3	LNGS (3600)	2.2	98.7	2.20	24 ± 1	[2]
Belmont	Boulby (2805)	3.2	160	1.92	135.0	[1]
GeOroel	LSC (2450)	2.2	109	1.85	165.3	[3]
GeMSE	LVdA (620)	2.0	107.7	1.96	88 ± 1	[4]

[1] Eur. Phys. J. C 80 (2020) 1044
[2] N. Ackermann, private communication
[3] Bandac, “Ultra-Low Background Services in the LSC”, DS-Mat Meeting, GSSI, 2019
[4] JINST 17 (2022) P04005

Dead Layer Estimation

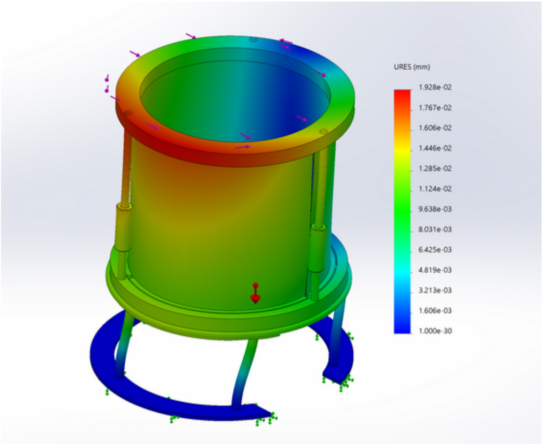
- Thickness insensitive volume from Ba-133 calibration data:
  - Top and lateral source position in Marinelli beaker
  - Consistent estimates from ratio dominant lines with large energy difference and χ^2 minimization of all lines w.r.t. variable ratio sim./meas.
- Resulting values implemented in GEANT4 simulation code

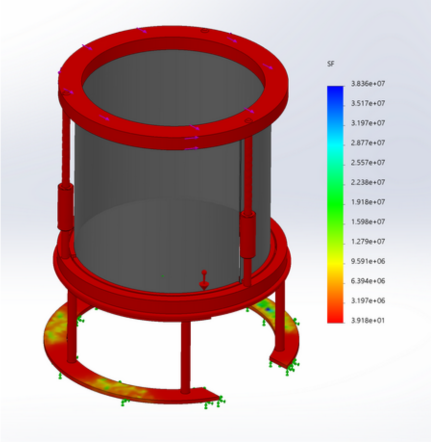


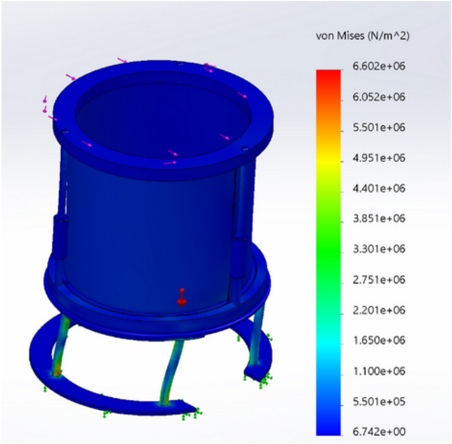


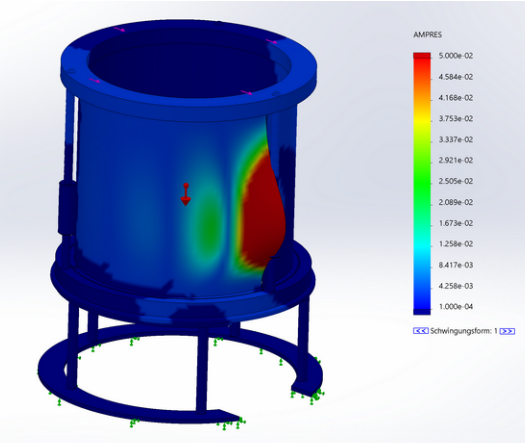
Stability Simulations

- SolidWorks stability simulations: static (stress, displacement, strain, safety factor) + buckling
- Gravity + different force / torque scenarios (shown: extreme case, i.e. gravity + 10 N lateral force top + 1 Nm torque)
- Minimum safety factor:
  - 570 (gravity only)
  - 39 (extreme case)

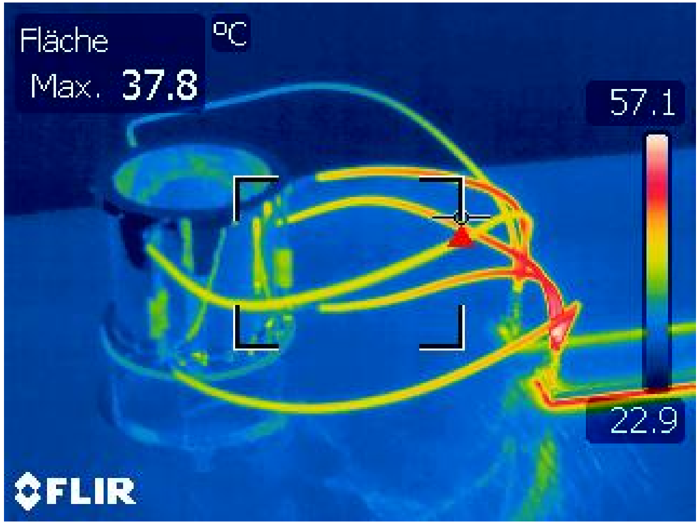




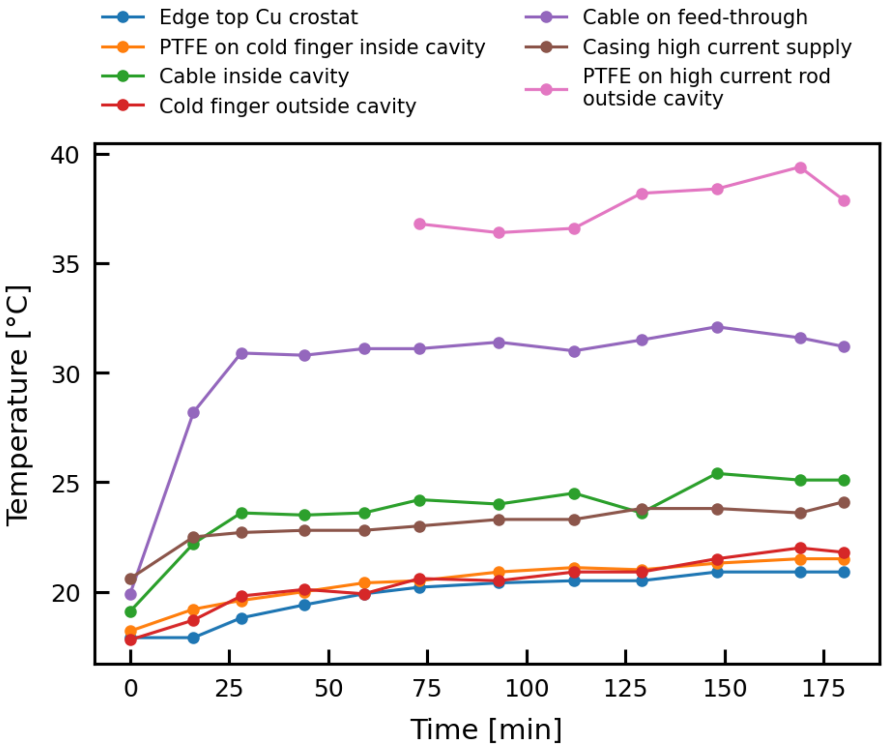




Thermal Tests (100 A)

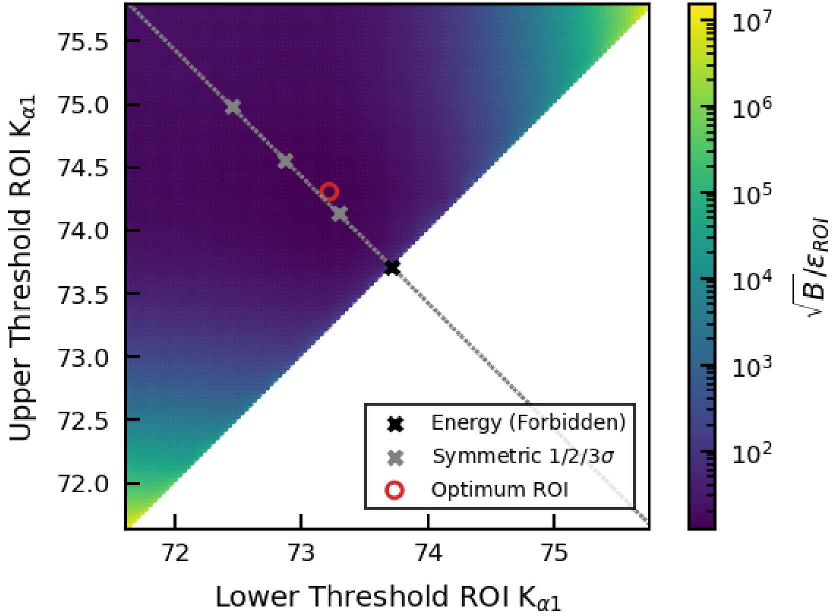


Test assembly at UZH
(FLIR camera)

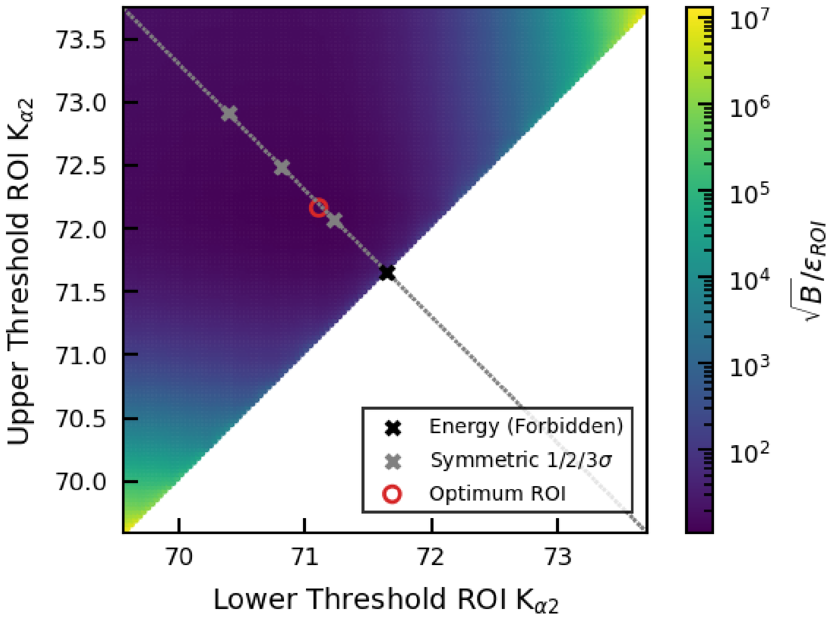


Inside Gator cavity
(contact thermometer)

Optimization ROI

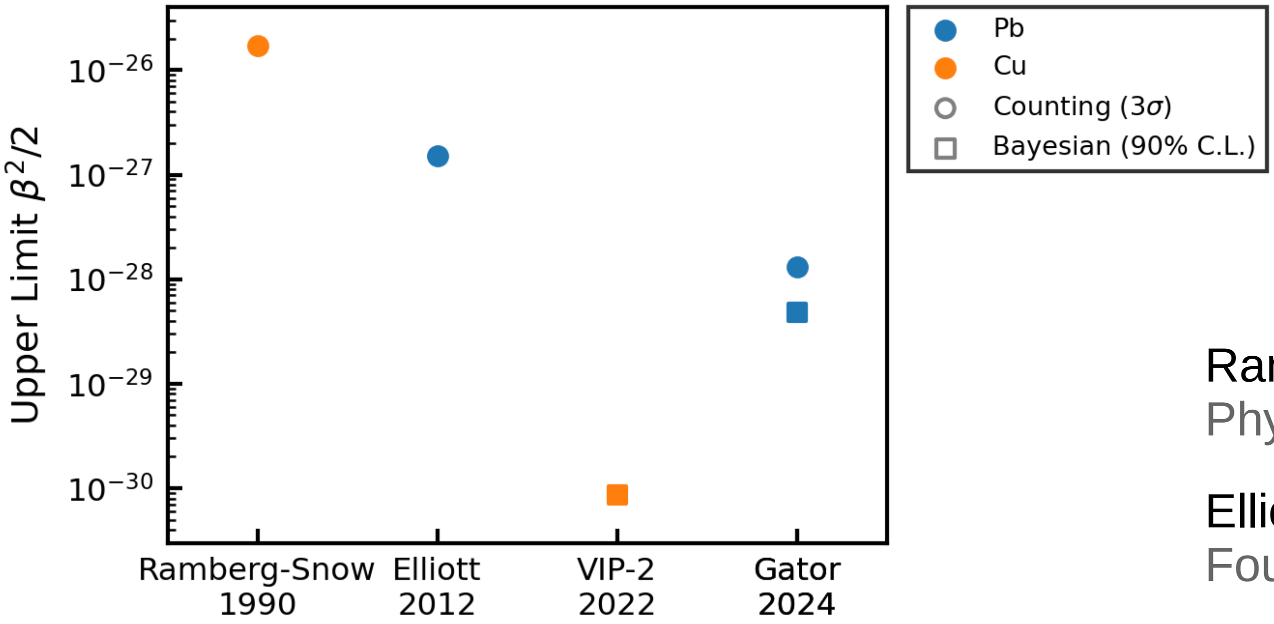


E_{ROI1} = [73.22, 74.31] keV
ε_{ROI1} = 0.7995



E_{ROI2} = [71.11, 72.16] keV
ε_{ROI2} = 0.7895

Comparison Other RS-Technique Experiments



Ramberg-Snow:
Phys. Lett. B 238 (1990) 438

Elliot et al.:
Found Phys 42 (2012) 1015

VIP-2:
Symmetry 14 (2022) 893