Determination of the quenched weak axial-vector coupling through measurements of highly forbidden nuclear decays

Matt Stukel
Research Scientist
Entente 2025
2025/09/30

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Measuring Long lived Isotopes

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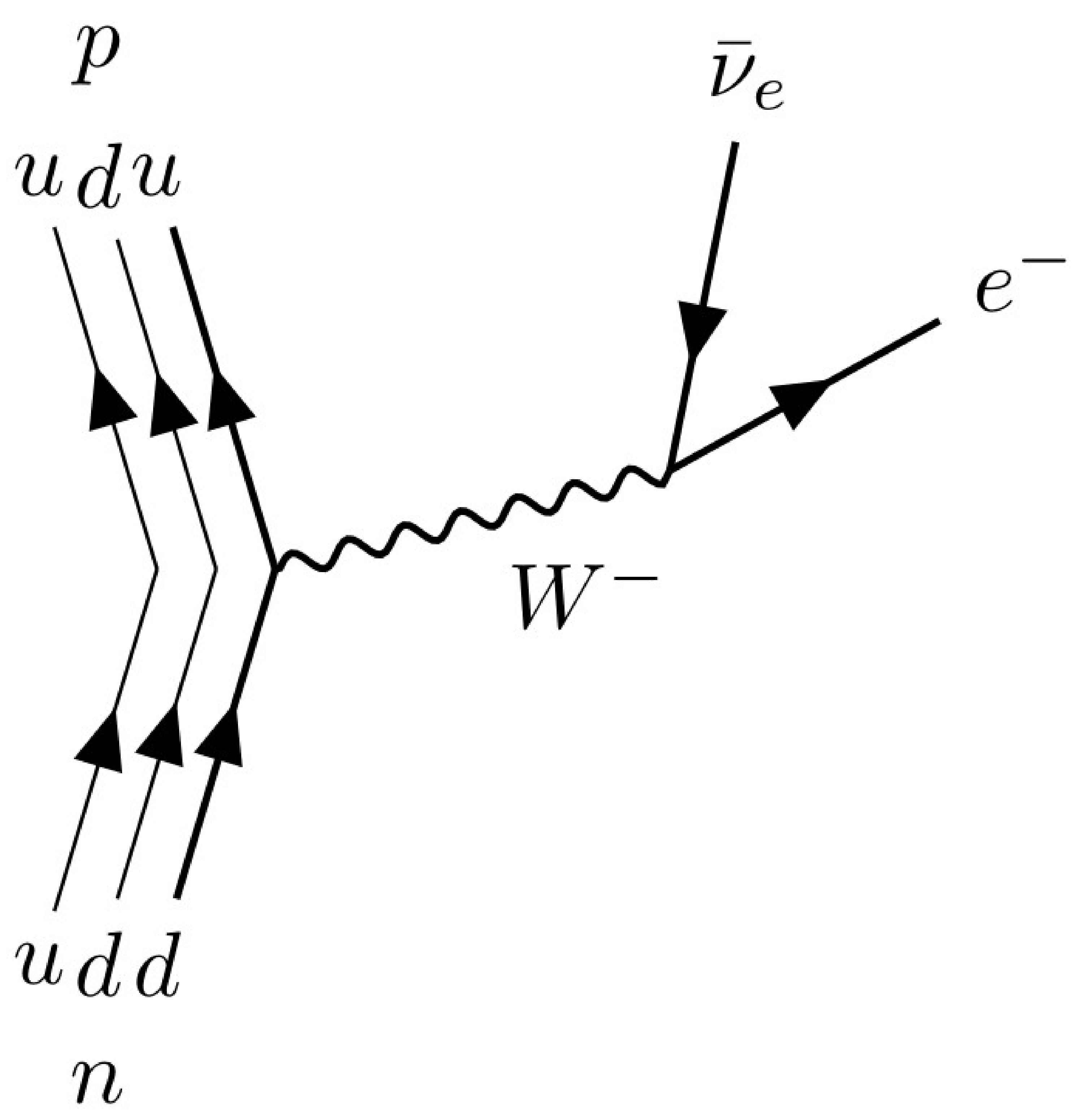
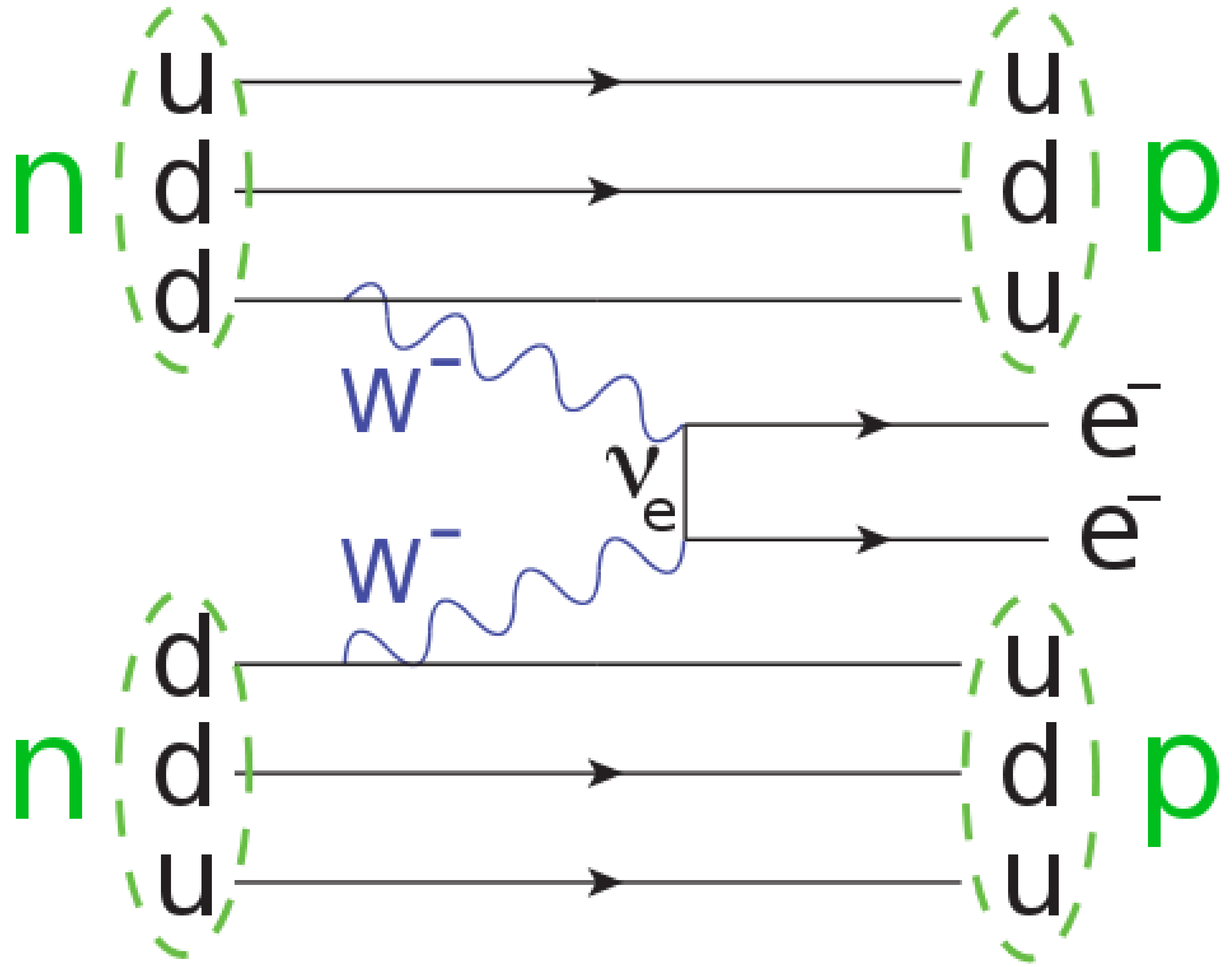
Talk Overview

1. Why these measurements are important
2. Select experimental efforts (KDK, KDK+, RAMPS, LUCE)

β-decay and 0νββ Theory





- At a fundamental nuclear level, β-decay can be considered the mutual interaction between the leptonic and hadronic currents, mediated by the $W^{+/-}$ boson.
- 0vββ is important for investigating beyond standard model physics (lepton number symmetry and baryon asymmetry

Decay Nomenclature

	ΔL	ΔJ	ΔP
Super Allowed	0	0	No
Allowed	0	0, 1	No
First Forbidden	1	0,1,2	Yes
Second Forbidden	2	1,2,3	No
Third Forbidden	3	2,3,4	Yes
Fourth Forbidden	4	3,4,5	No

- Gamow-Teller transition: No parity change of the nuclear state $\Delta \mathrm{J} = J_f - J_i = \begin{cases} 0, J_i = J_f \\ 1, J_i = 0, J_f = 1 \end{cases}$
- Unique transition: L and S are aligned
- Forbidden: $\Delta J > 1$ and (potentially) change in parity

β-decay

ββ-decay

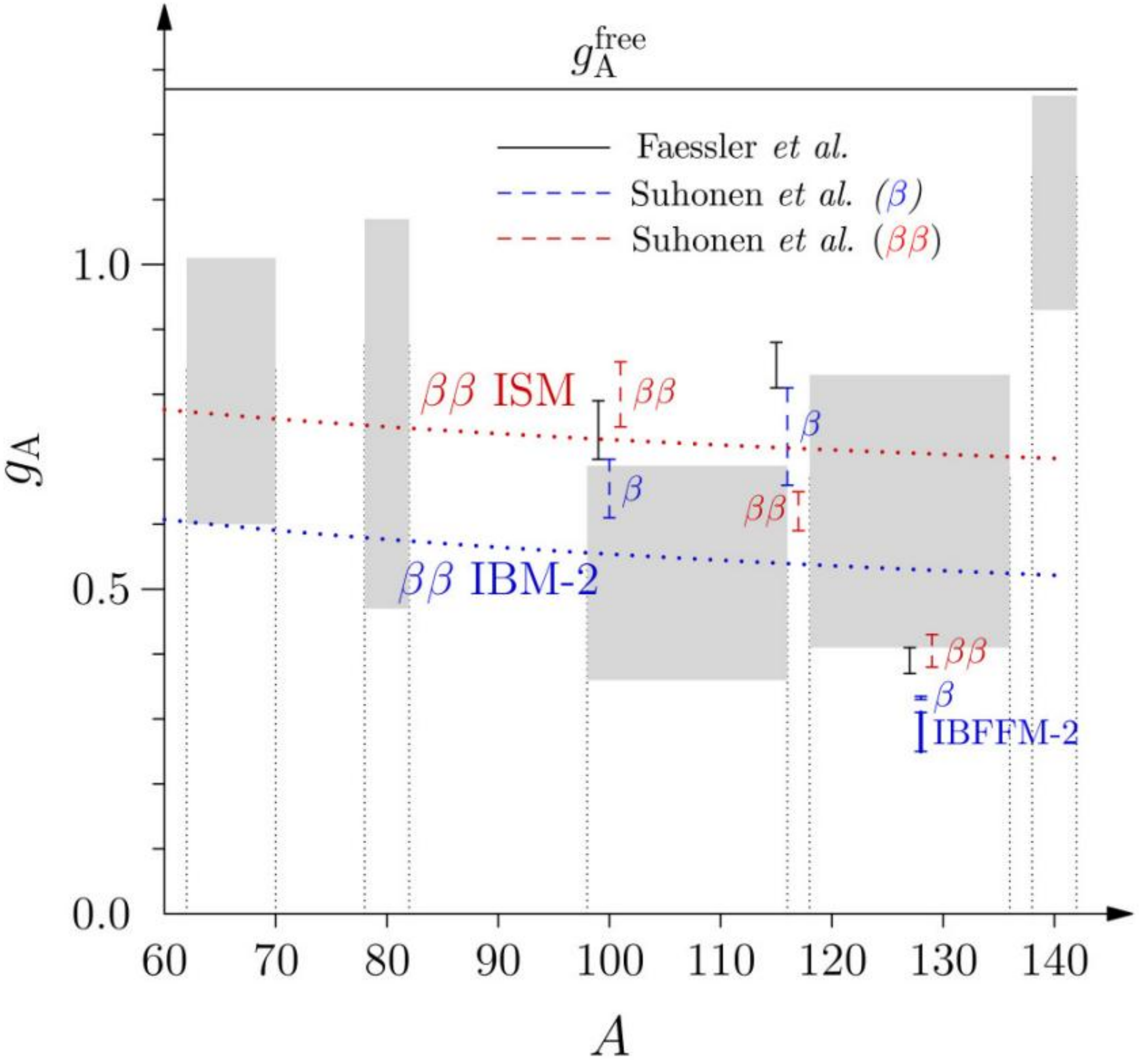
SNOLAB

$$\Gamma \sim \frac{1}{\tau_{1/2}} \sim F_K \frac{g_a^2}{2J_i + 1} |M_k|^2$$

$$\Gamma \sim \frac{1}{\tau_{1/2}} \sim F_{\beta\beta} g_a^4 |M_k|^2$$

- F = phase space factor
- M = Nuclear matric element
- g_v = weak vector strength (coupling)
- g_a = weak axial-vector strength (coupling
- Conserved Vector Current (CVC) hypothesis <u>**g_v = 1.0**</u>
- Partially Conserved axial-vector hypothesis <u>**g_a = 1.27**</u>
- Precise information on the effective values of g_a is crucial when predicting the half-lifes of 0νββ

Quenching of the weak axial-vector coupling strength



$$g_a^{eff} = q\, g_a^{free}$$

- Nuclear medium effects and nuclear many body effects cause a renormalization (higher or lower) of the weak-axial vector strength
  - Meson-exchange currents, interference from non-nucleonic degrees of freedom, deficiencies in the nuclear many-body approach etc….
- It is difficult to relate the quenching in β-decays vs. ββ-decays
- All theory, based calculations, which need experimental measurements to help verify
- Review: Link

Experimental measurement of forbidden decays: KDK

M. Stukel,[1] L. Hariasz,[1] P.C.F. Di Stefano,[1,*] B.C. Rasco,[2] K.P. Rykaczewski,[2] N.T. Brewer,[2,3] D.W. Stracener,[2] Y. Liu,[2] Z. Gai,[4] C. Rouleau,[4] J. Carter,[5] J. Kostensalo,[6] J. Suhonen,[7] H. Davis,[8,9] E.D. Lukosi,[8,9] K.C. Goetz,[10] R.K. Grzywacz,[2,3,11] M. Mancuso,[12] F. Petricca,[12] A. Fijałkowska,[13] M. Wolińska-Cichocka,[2,3,14] J. Ninkovic,[15] P. Lechner,[15] R.B. Ickert,[16] L.E. Morgan,[17] P.R. Renne,[5,18] and I. Yavin

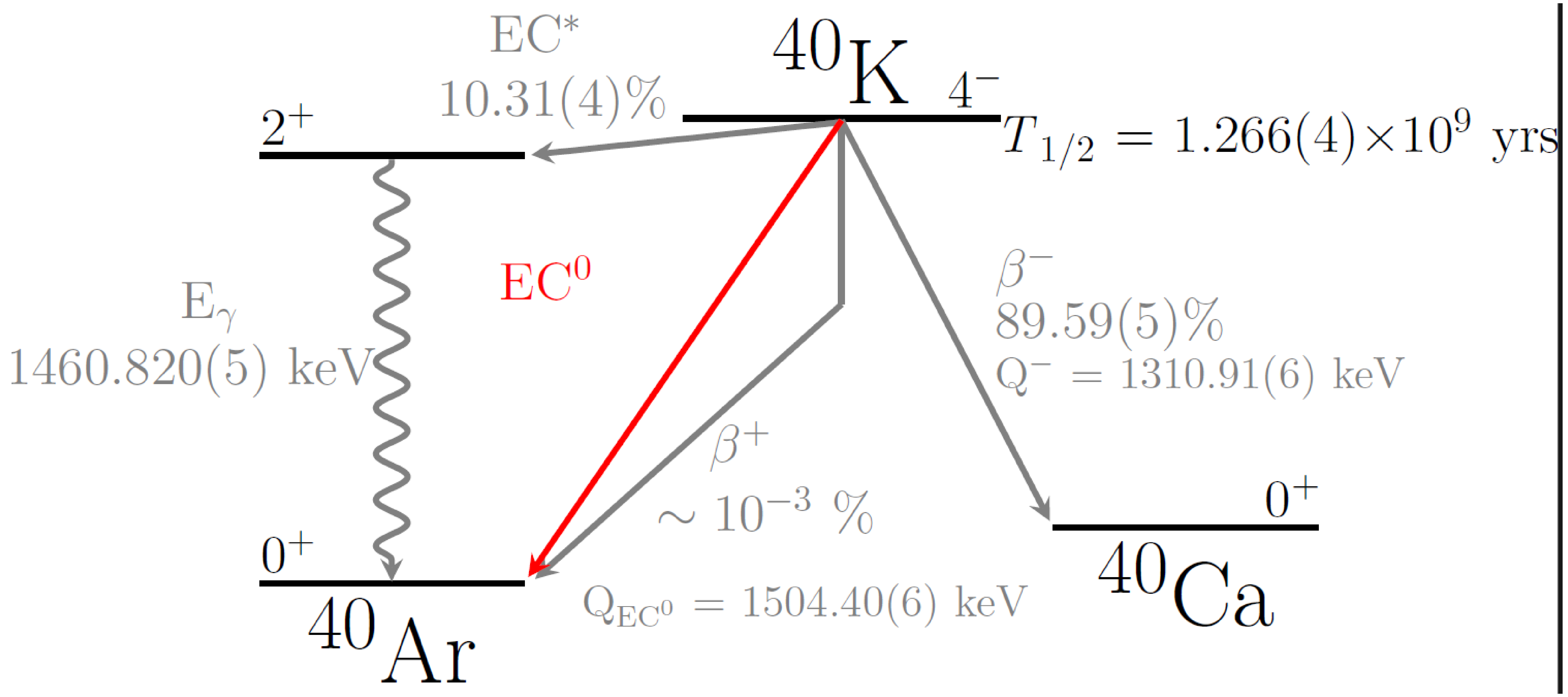
(KDK Collaboration)

KDK Experiment

Potassium

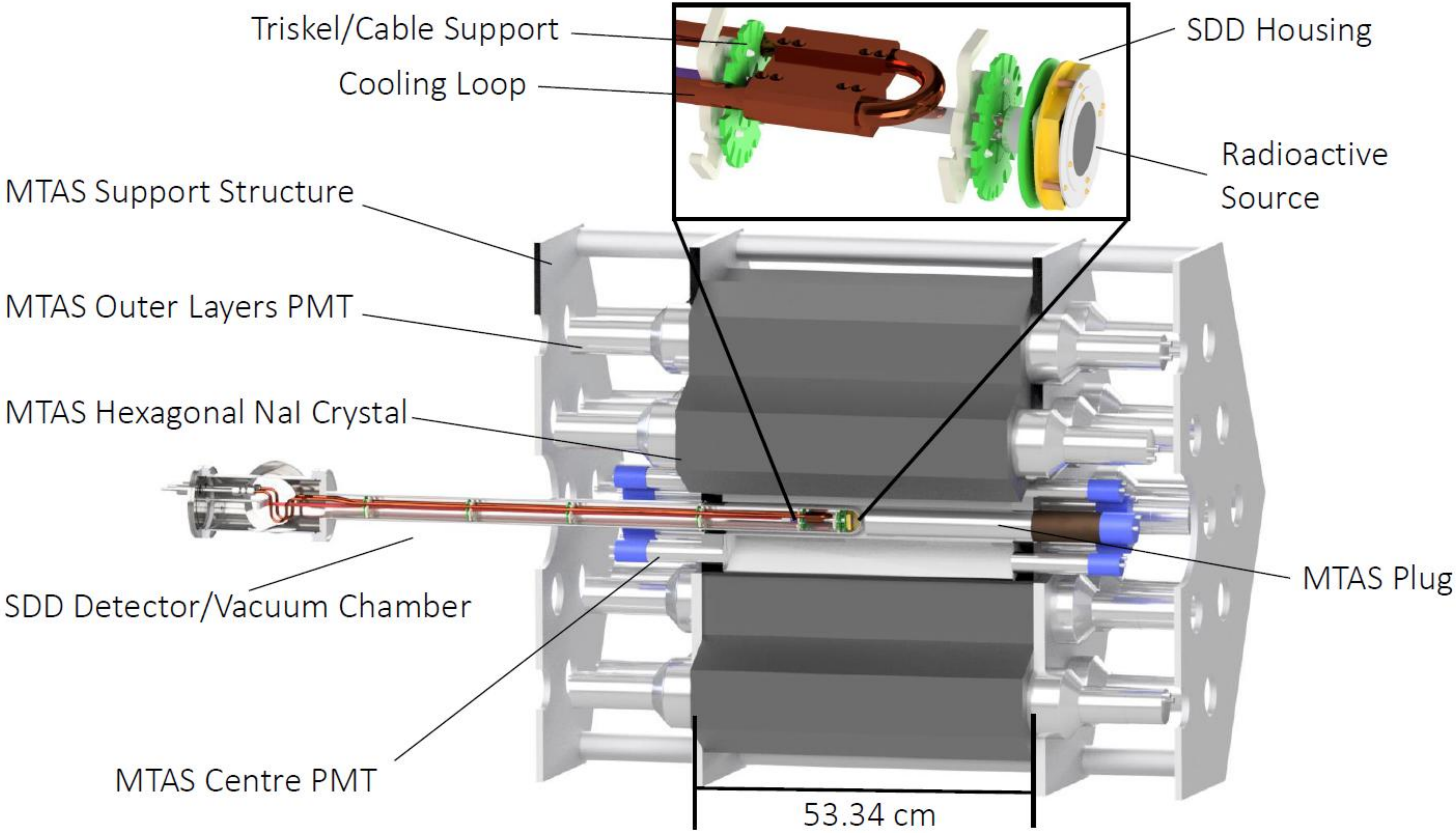
KDK

“Decay”

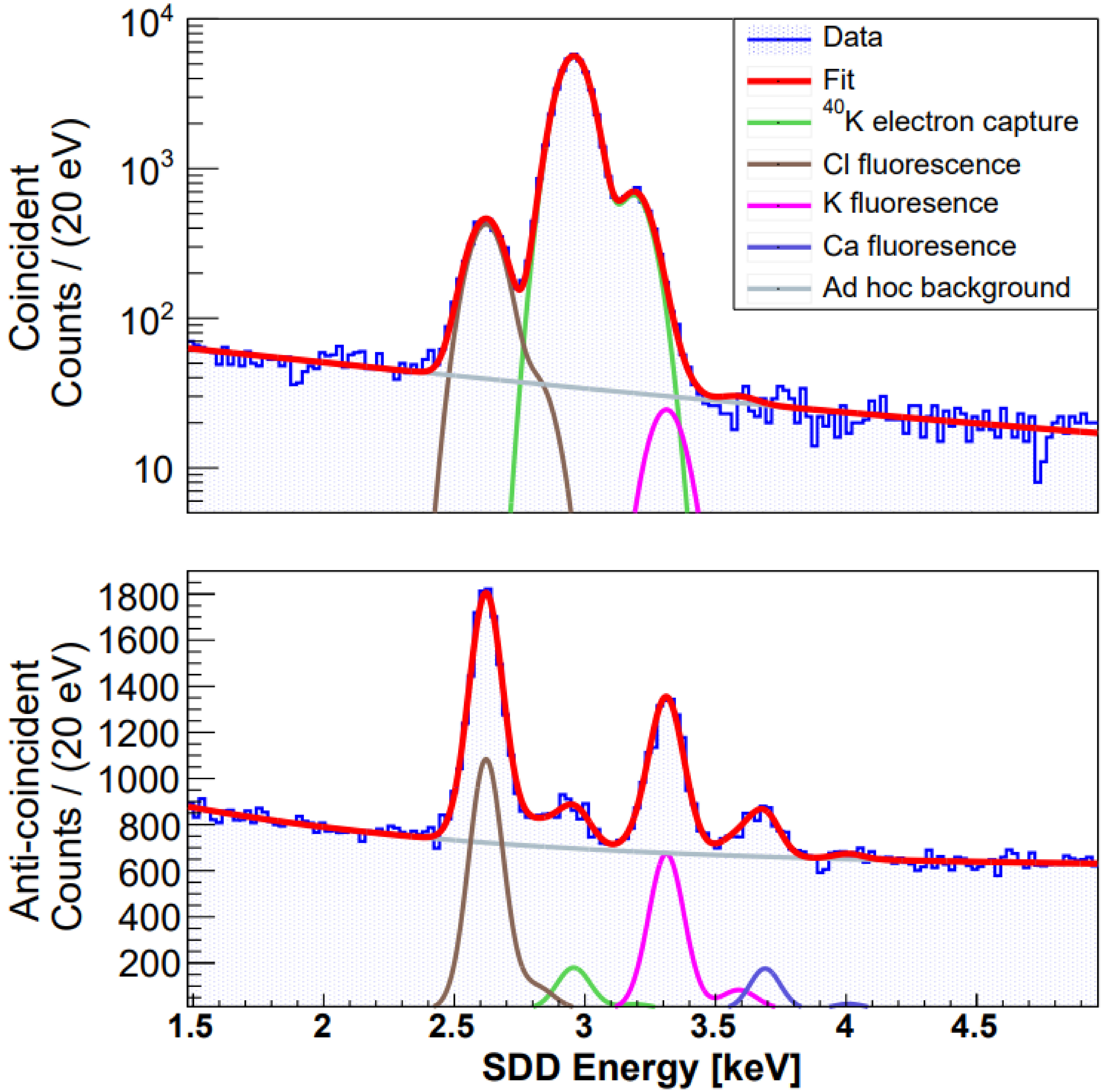


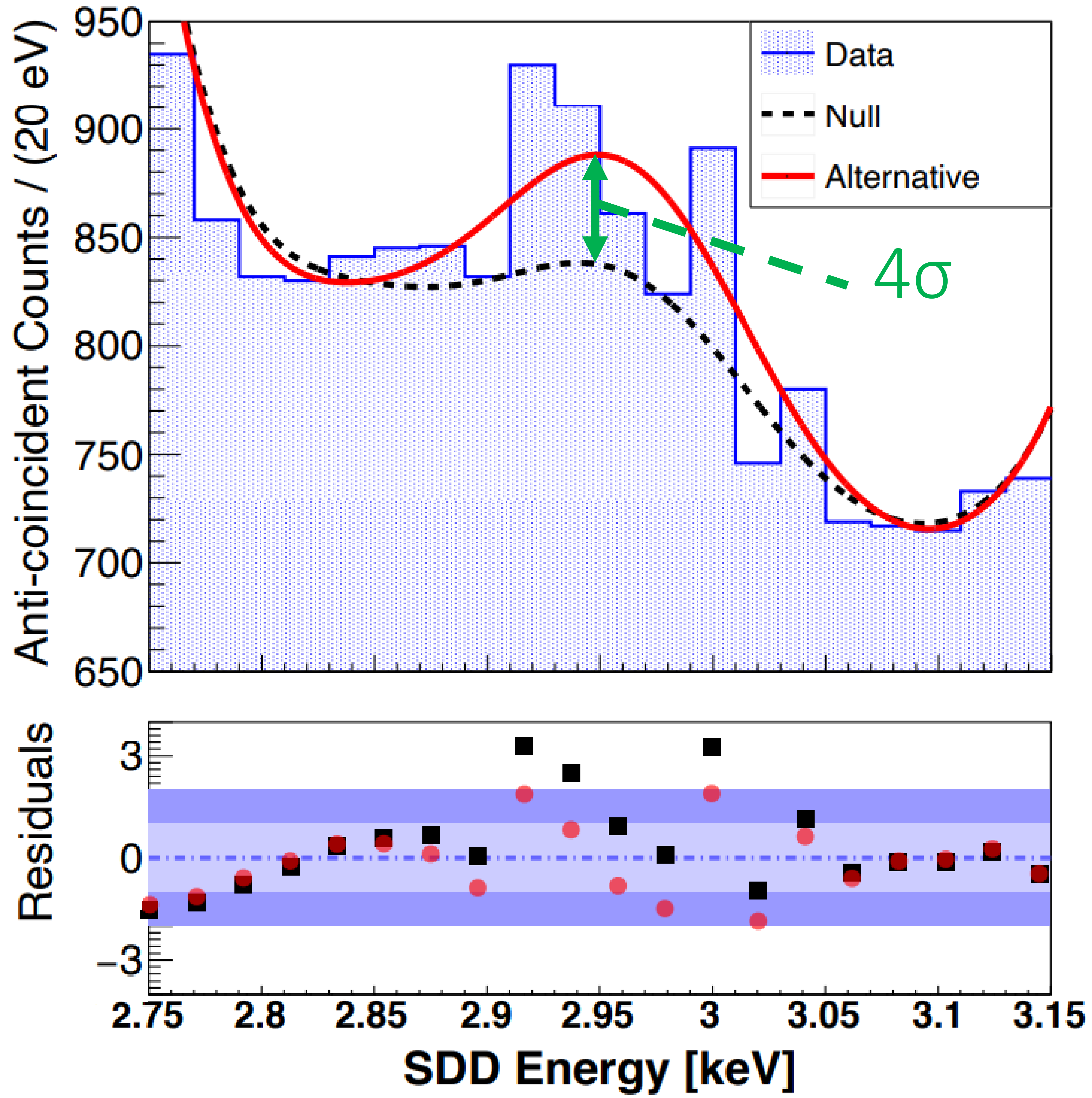
- **Nuclear Theory:** Rare 3U EC transition, weak-axial vector coupling quenching
- **Particle Physics:** ^{40}K is a background in **rare-event searches:** especially in **NaI based detectors**
  - E.g. DAMA, COSINUS, COSINE-100, ANAIS-112 and PICO-LON
- **Geochronology:** ~10^9 years half-life, excellent for dating

KDK Experimental Setup



KDK Results

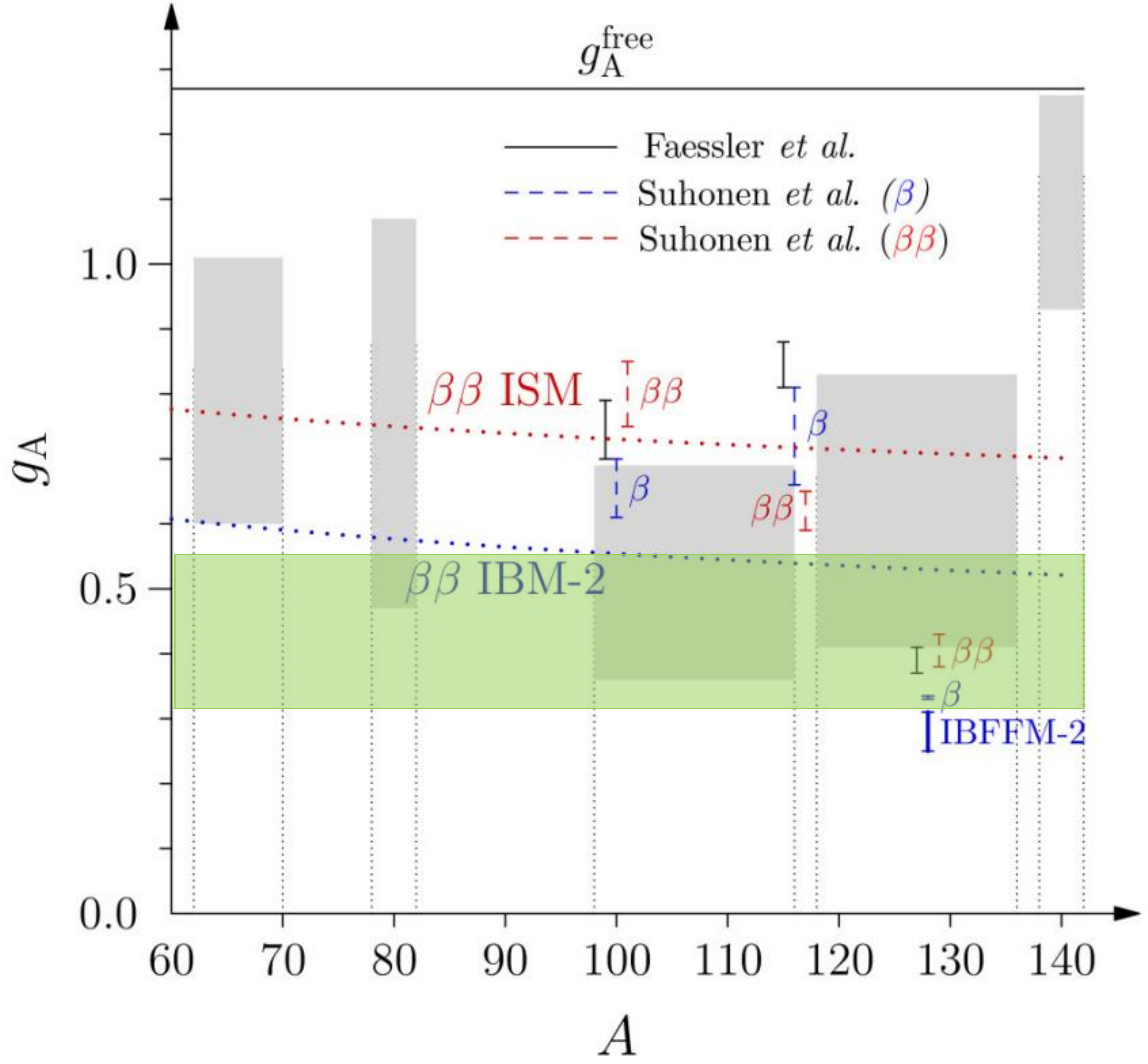




$$\rho = \frac{BR_{EC}}{BR_{EC*}} = 0.0095 \pm 0.0022 \pm 0.0010$$

KDK Implications

- Nuclear Physics
  - First measurement of ^{40}K ground state electron capture (3U): PRL, PRC
  - Decay half-lives give access to the weak-axial vector coupling quenching: g_A
    - First-forbidden Unique (EC*): $g_a^{eff} = 0.34$
    - Third-forbidden Unique (β-): $g_a^{eff} = 0.43$
    - Third-forbidden Unique (EC): $g_a^{eff} = 0.53$
  - Using the NME from here and these new effective weak-axial vector coupling
    - ^{48}Ca 0νββ half-life increases by $\mathbf{7^{+3}_{-2}}$
- Particle Physics:
  - Quantified a previously unknown low energy background present in many dark matter experiments, especially NaI based
- Geochronology
  - Traditional K/Ar ages have been overestimated by not including the ground state decay
  - Ar-Ar dating is indirectly affected as this method requires the use of K-Ar dated calibration sources



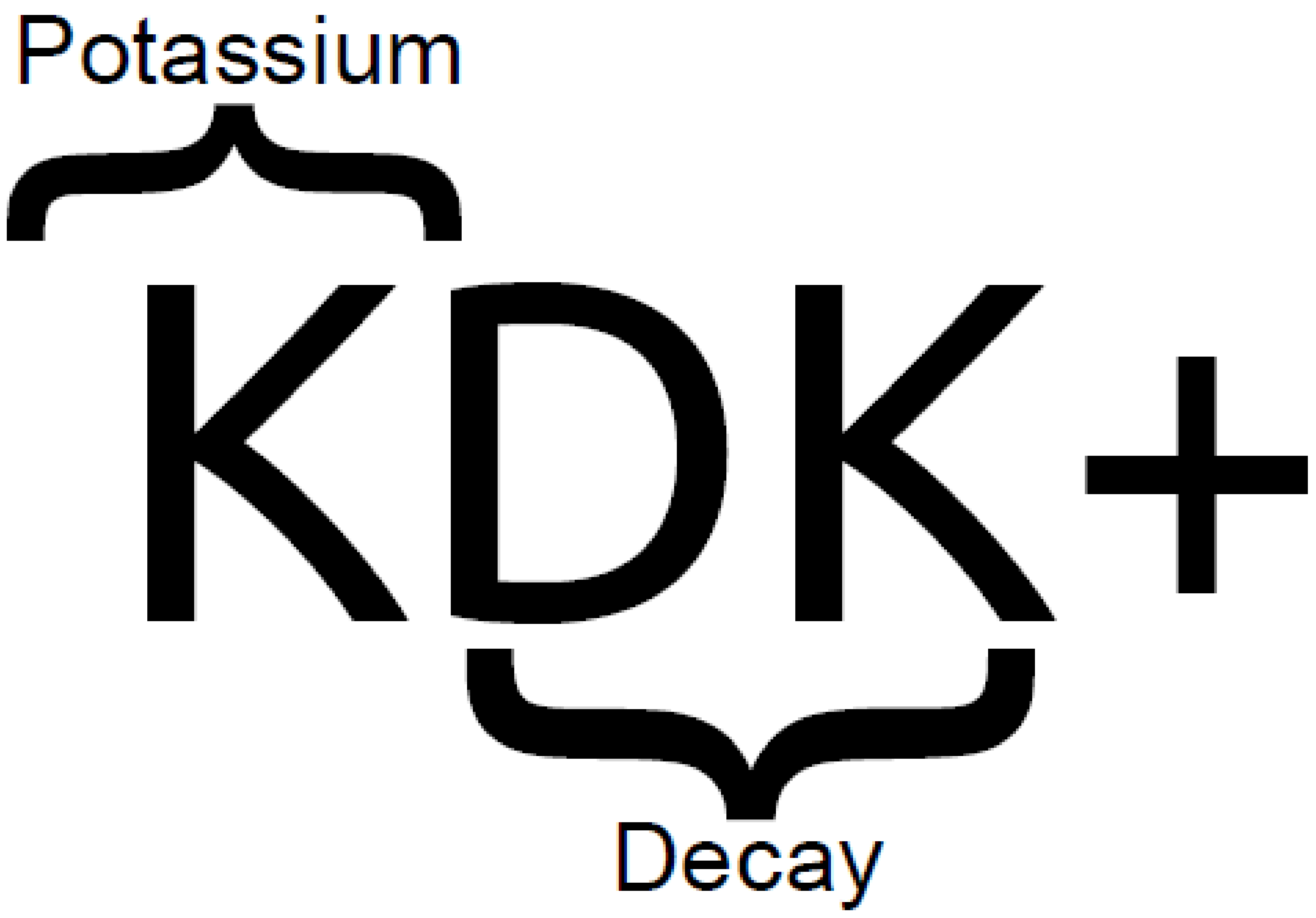
Experimental measurement of forbidden decays: KDK+

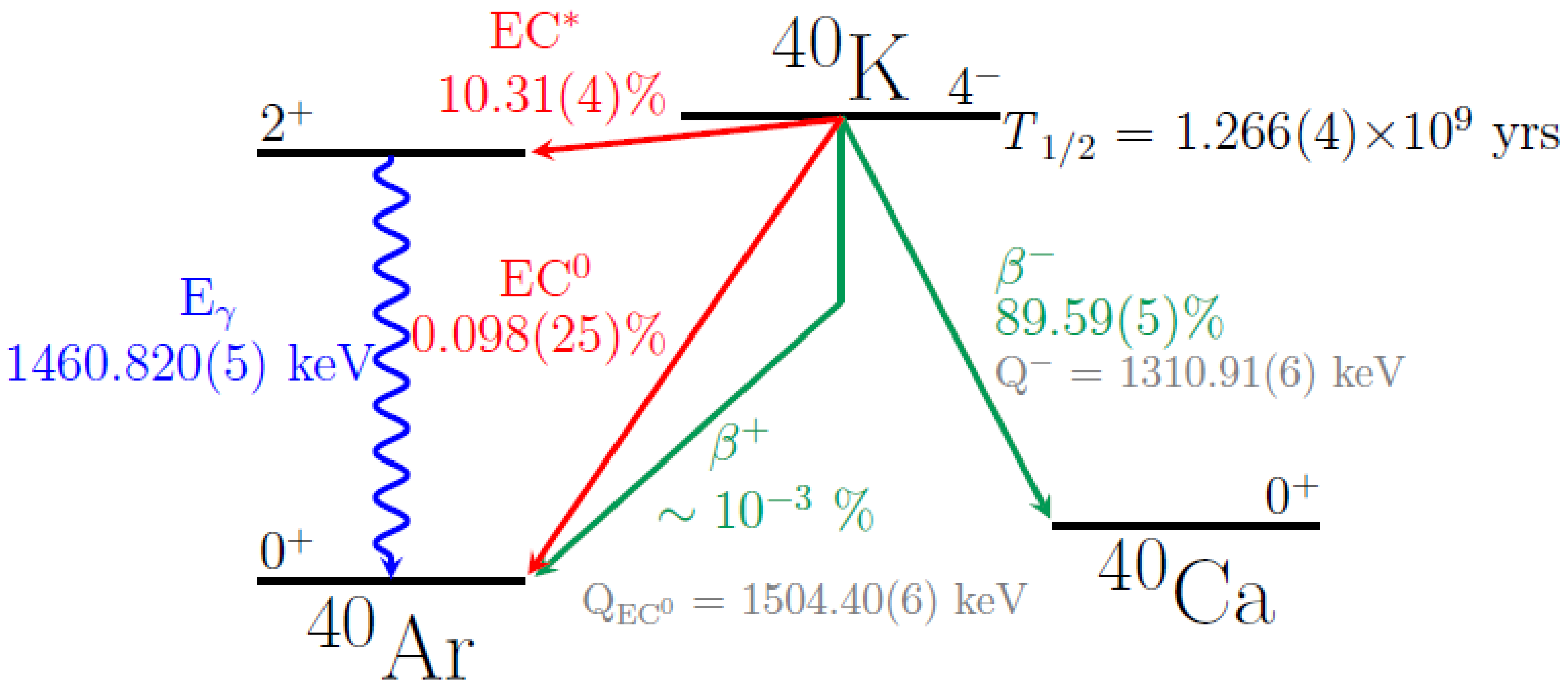
*Slides in this section are modified from a presentation given by Nicklas Swidinsky at CAP 2025

KDK+ Collaboration

Nick Swidinsky, Gavin Croft, Yanoé Coudière, Philippe Di Stefano, Cameron Ingo, Romain Arsenne, Guillaume Bertrand, Andrew Erlandson, Lilianna Hariasz, Arnaud Lemaire, Pavel Samuleev, Matt Stukel, Charlie Rasco, Krzysztof Rykaczewski

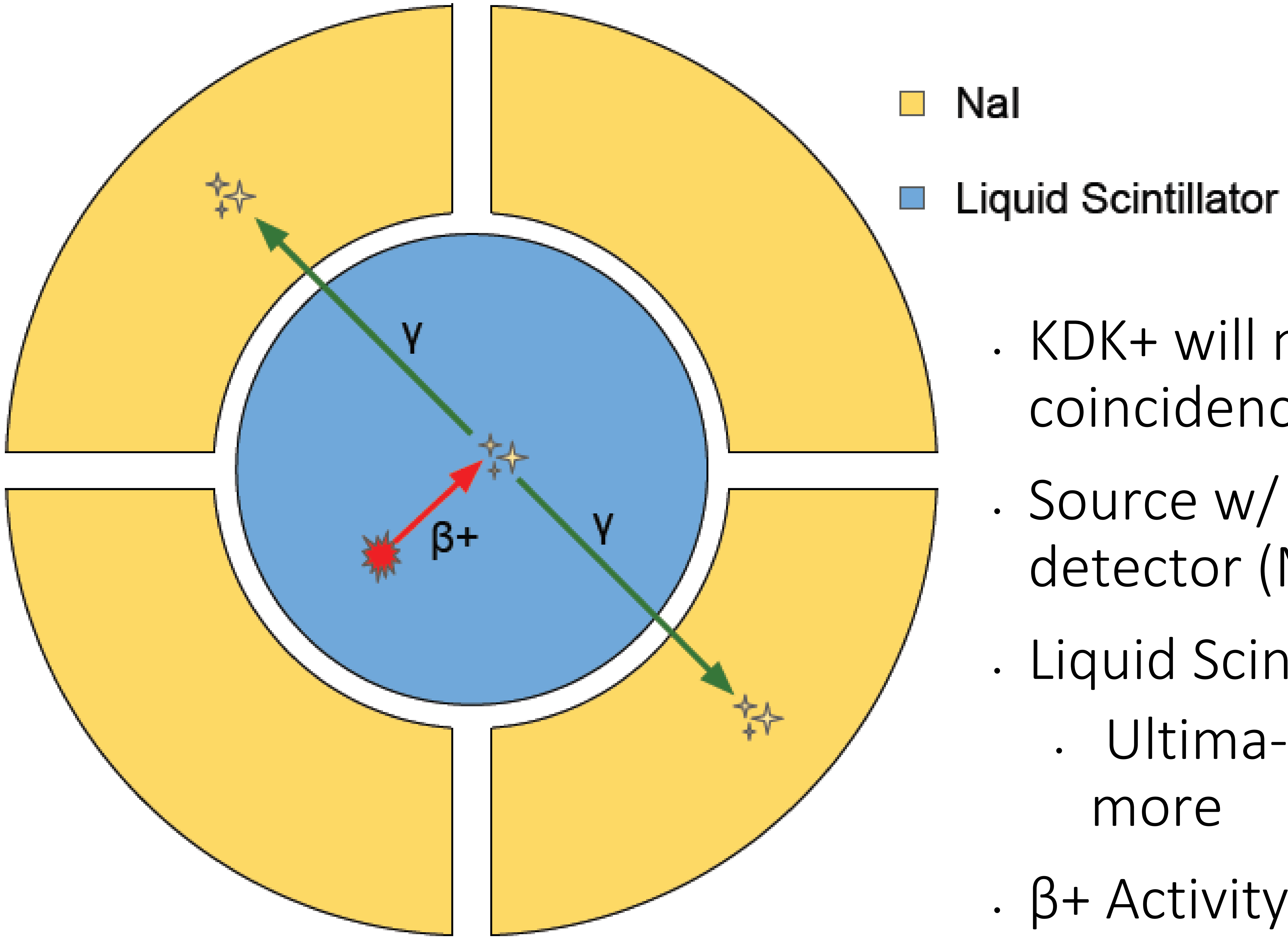
KDK+ Experiment





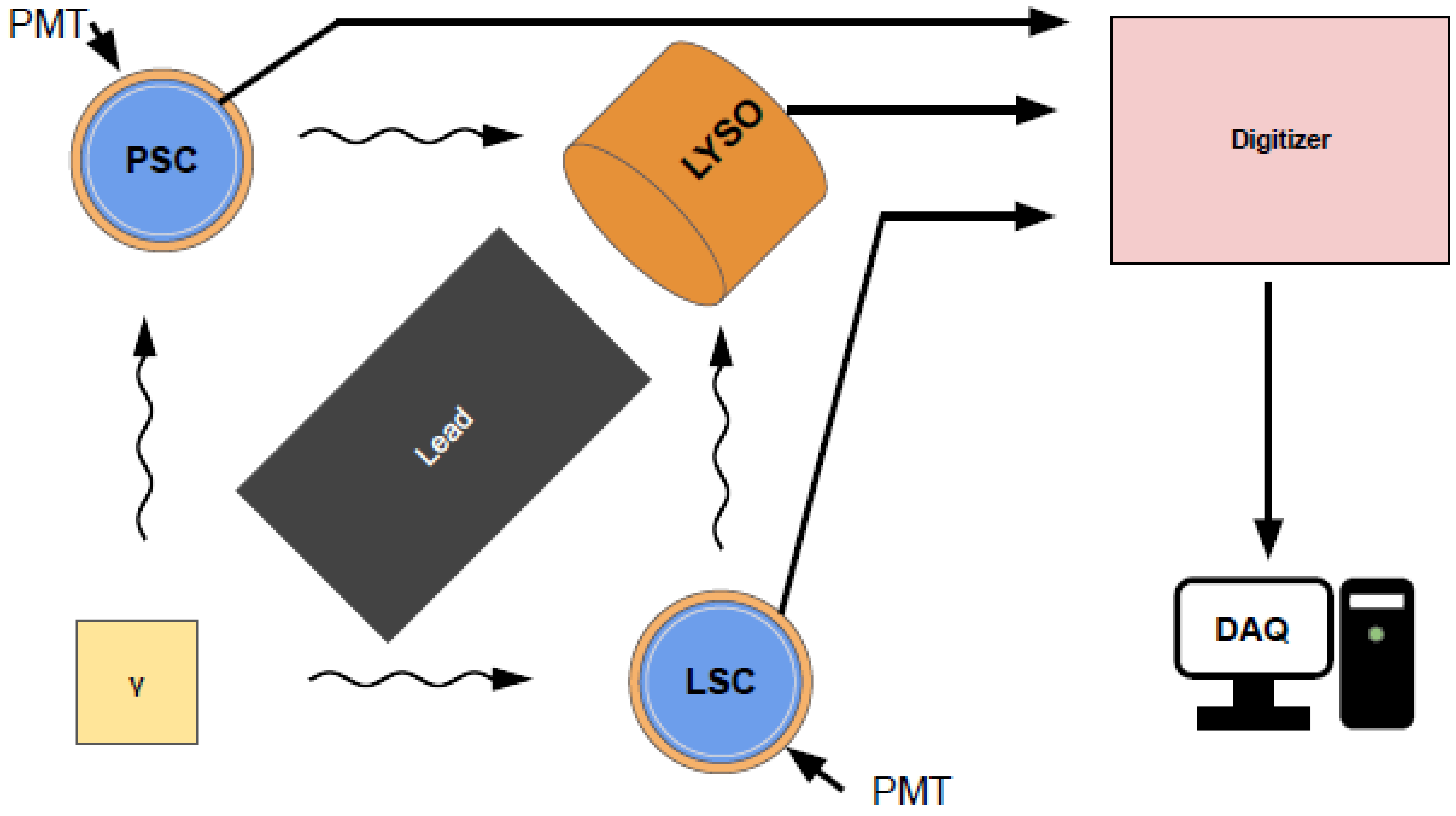
- **Nuclear Theory:** Rare 3U EC transition, weak-axial vector coupling quenching
- KDK+ is a follow-up to the KDK experiment and is looking for the β^{+} decay of ^{40}K
- Previous experimental measurements provide inconsistent results for the decay rate of this channel

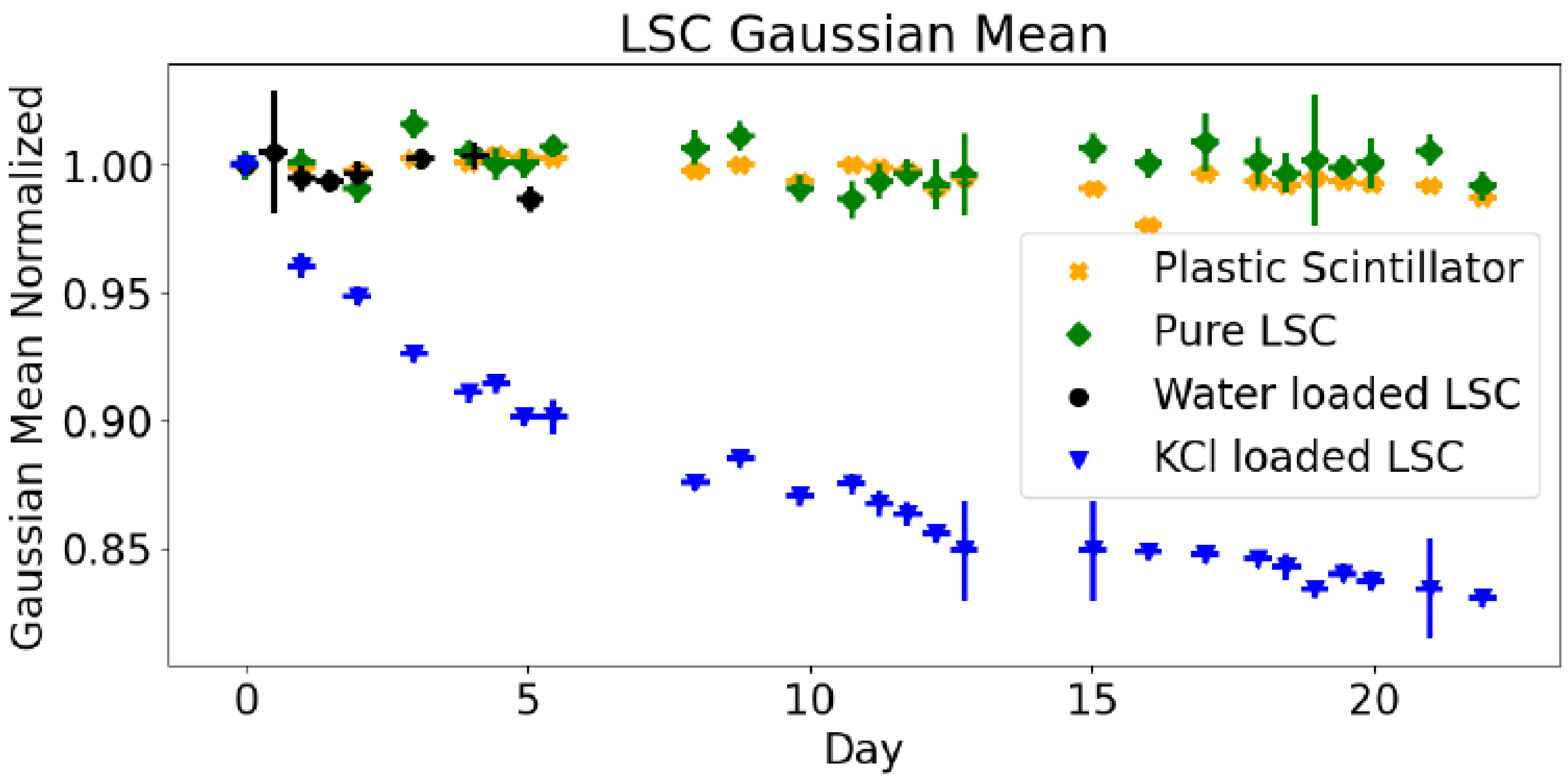
KDK+ Experimental Setup



- KDK+ will measure the β+ decay by using a triple coincidence setup
- Source w/ liquid scintillator and segmented NaI γ-detector (MTAS or other)
- Liquid Scintillators Being Considered:
  - Ultima-Gold, LAB, Loaded plastic Scintillators, + more
- β+ Activity (Natural Potassium): 0.1635 mBq/g
  - ~24 days of runtime needed to get 1000 β+ events

KDK+ Current Experimental Efforts





- The LSC scintillator loaded with potassium salt shows a decrease of ~20% over 20 days
- New current scintillator seems to have much better stability
- R&D is continuing to develop the ideal experimental setup

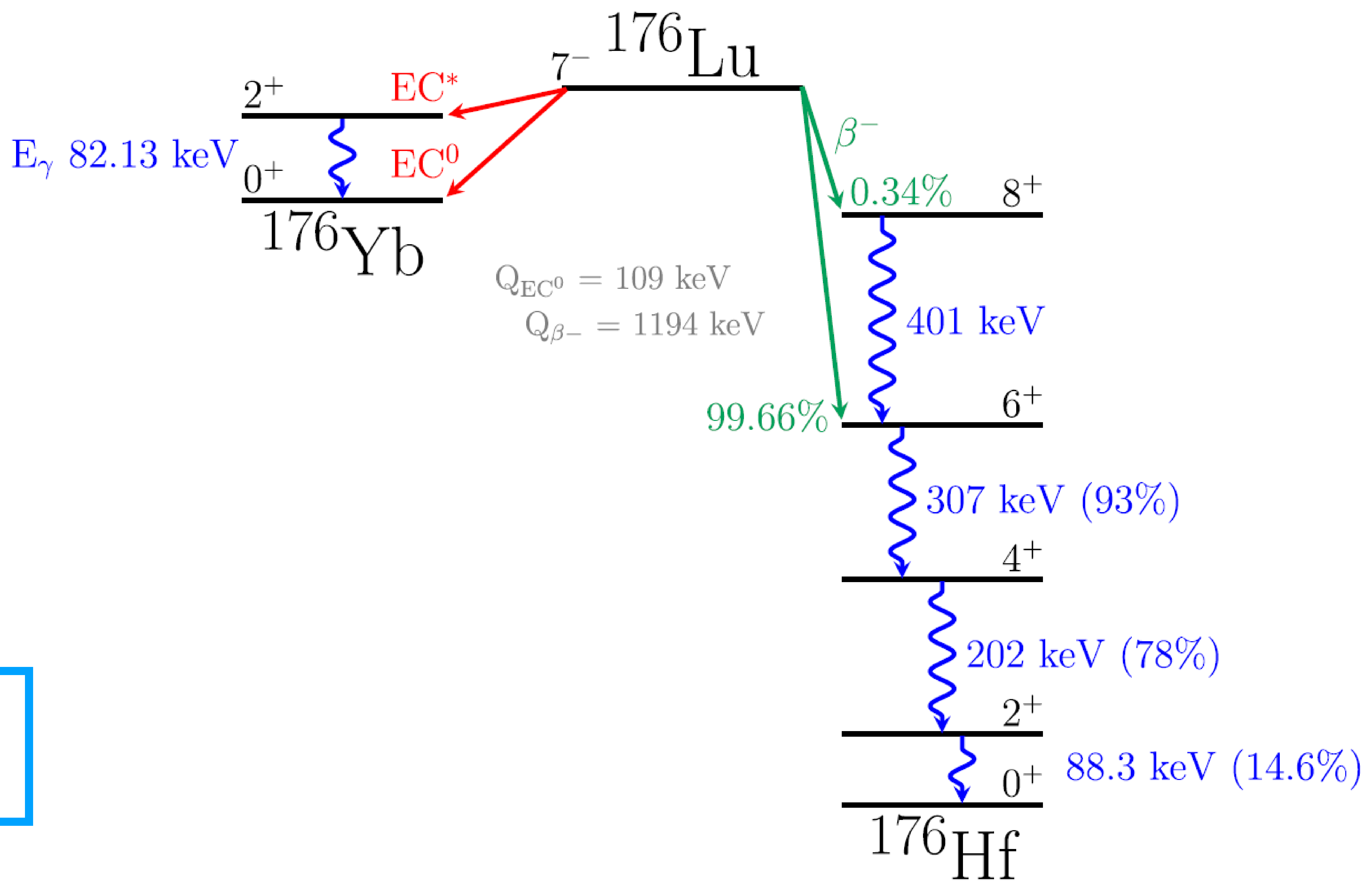
Experimental measurement of forbidden decays: RAMPS

RAMPS Collaboration:
Matthew Stukel, Ian Lawson, Steffon Luoma, Diba Toyserkani

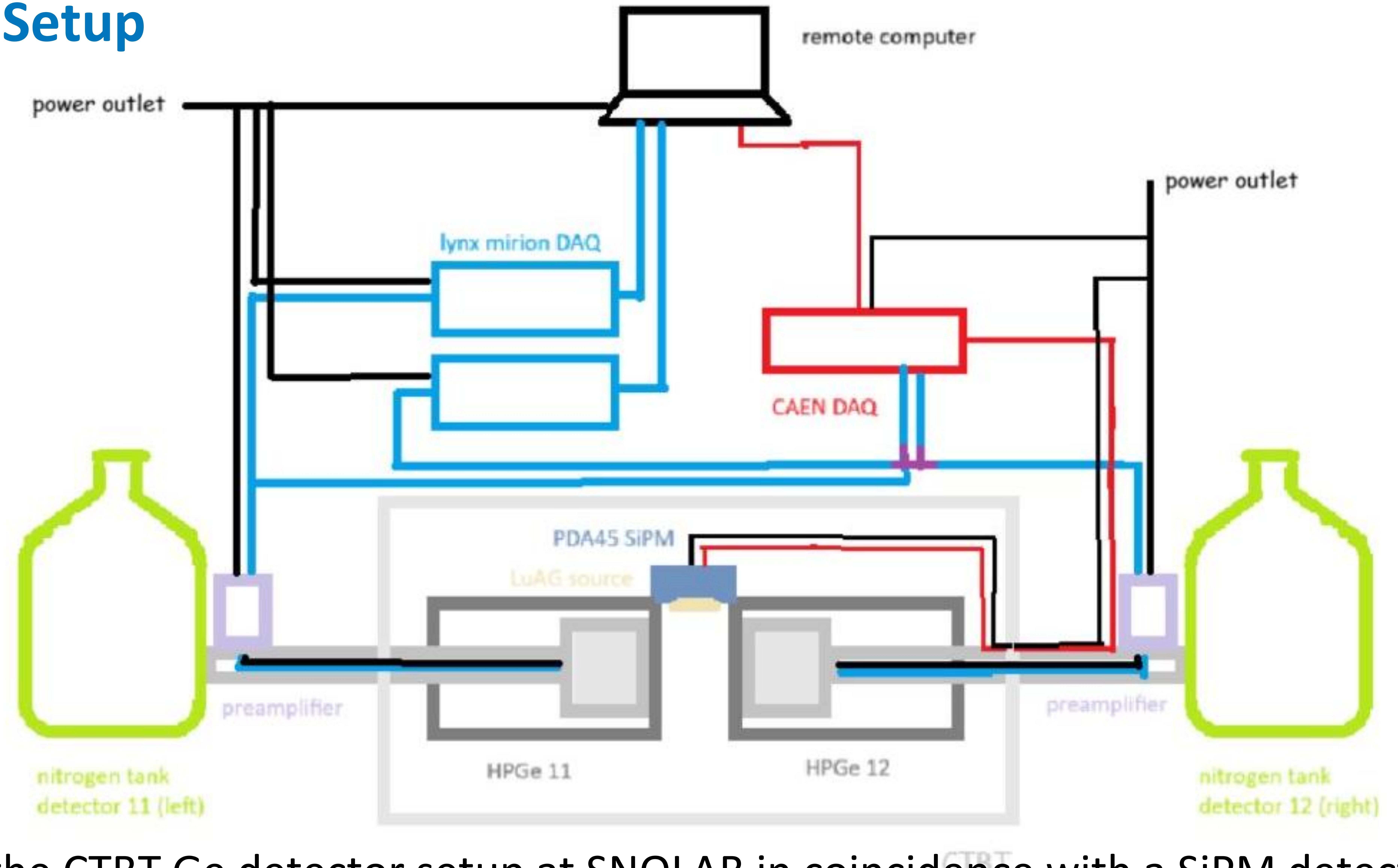
RAMPS (RadioActive isotope Measurement Program at SNOLAB)

- GOAL: Perform novel, precision or standardization measurement of long-lived isotopes
  - Identify lack of nuclear data for isotopes in multi-disciplinary fields (particle physics, astrophysics, geology, chemistry etc..)

Isotope	Half-life (yrs)
^{40}K	1.29×10^{12}
^{50}V	2.2×10^{17}
^{138}La	1.6×10^{11}
^{123}Te	$>10^{16}$-10^{19}
^{180}Ta	$> 2.0 \times 10^{17}$
^{176}Lu	$> 10^{13}$-10^{14}

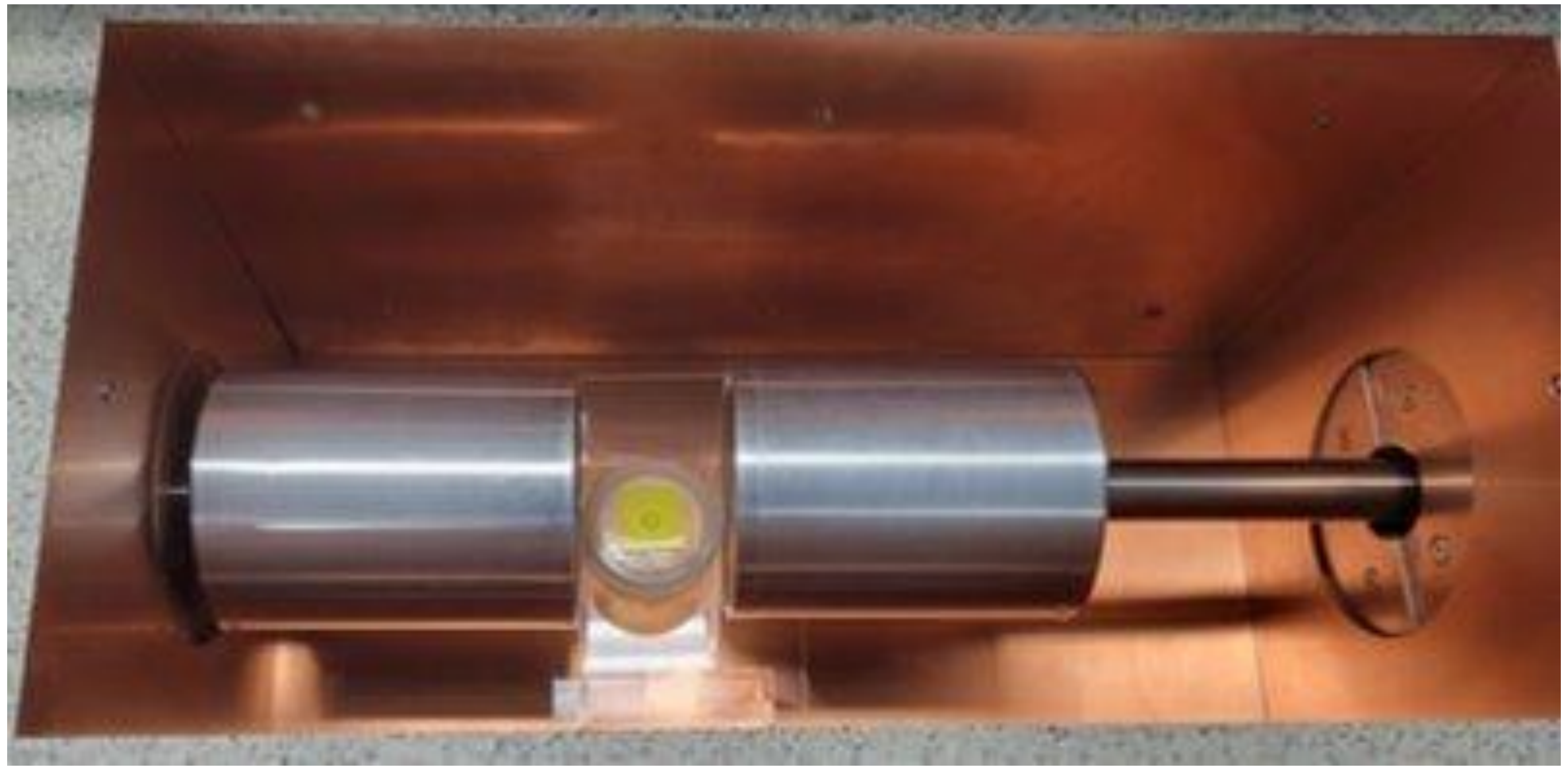


RAMPS Setup



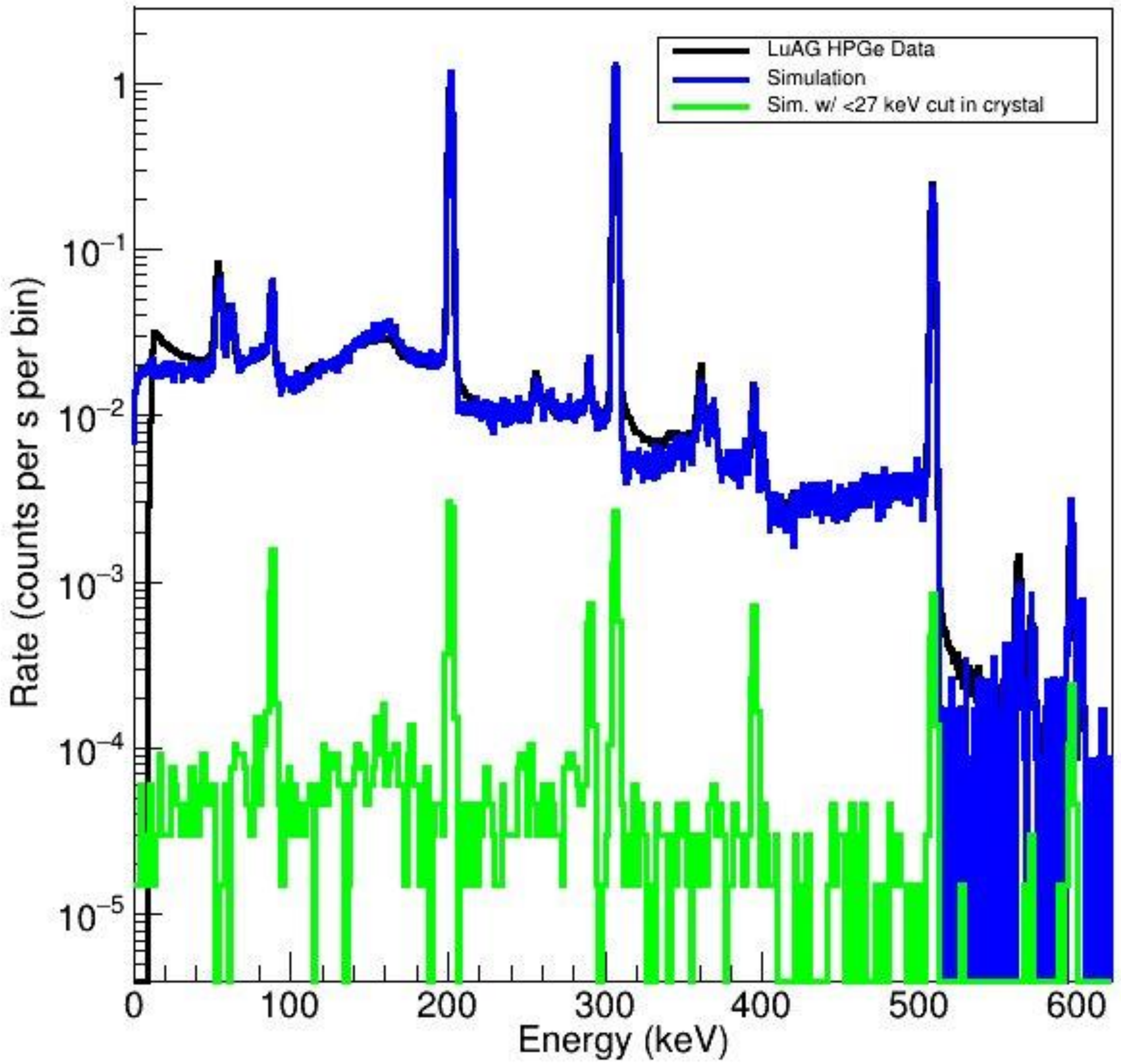
- Uses the CTBT Ge detector setup at SNOLAB in coincidence with a SiPM detector
- LuAG scintillating crystal is used both as a source and scintillator

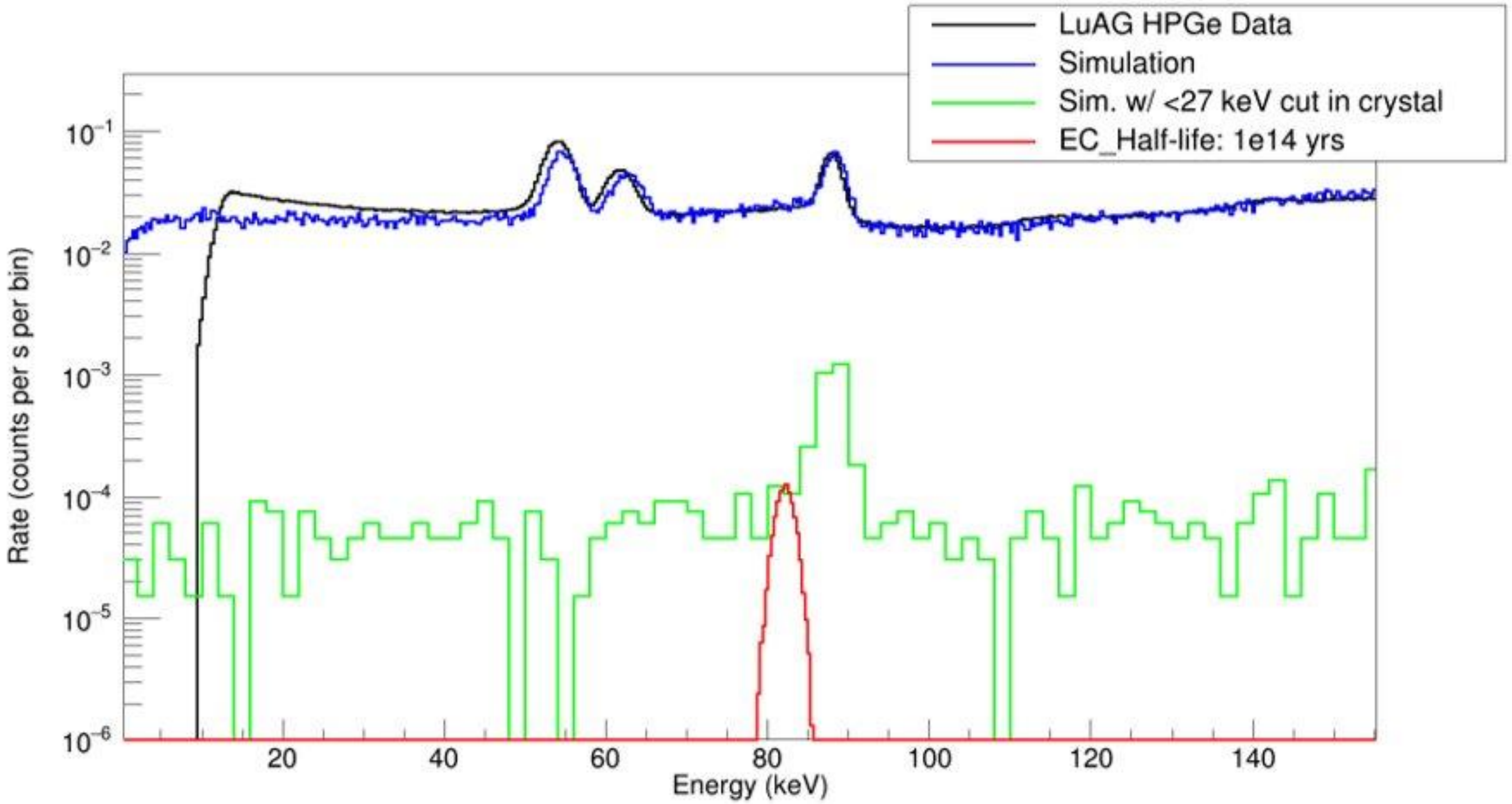
RAMPS: CTBT



- CTBT – Two parallel HPGe detectors, 50 cm^2 surface area, 3 cm thick
- Energy threshold ~1 keV, resolution 0.6 keV at 81 keV
- Movable probes in a shielded box

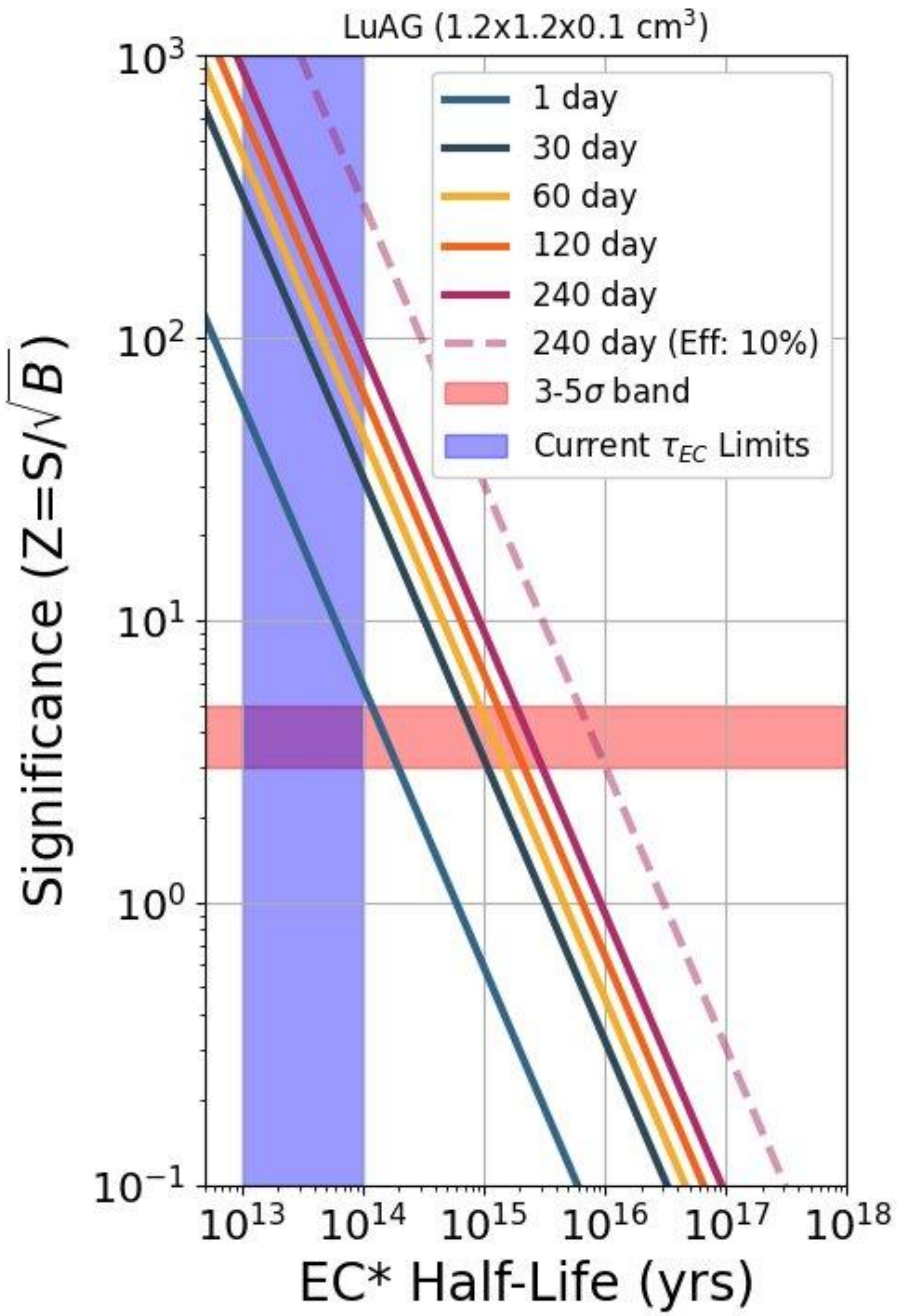
RAMPS: Experimental Technique

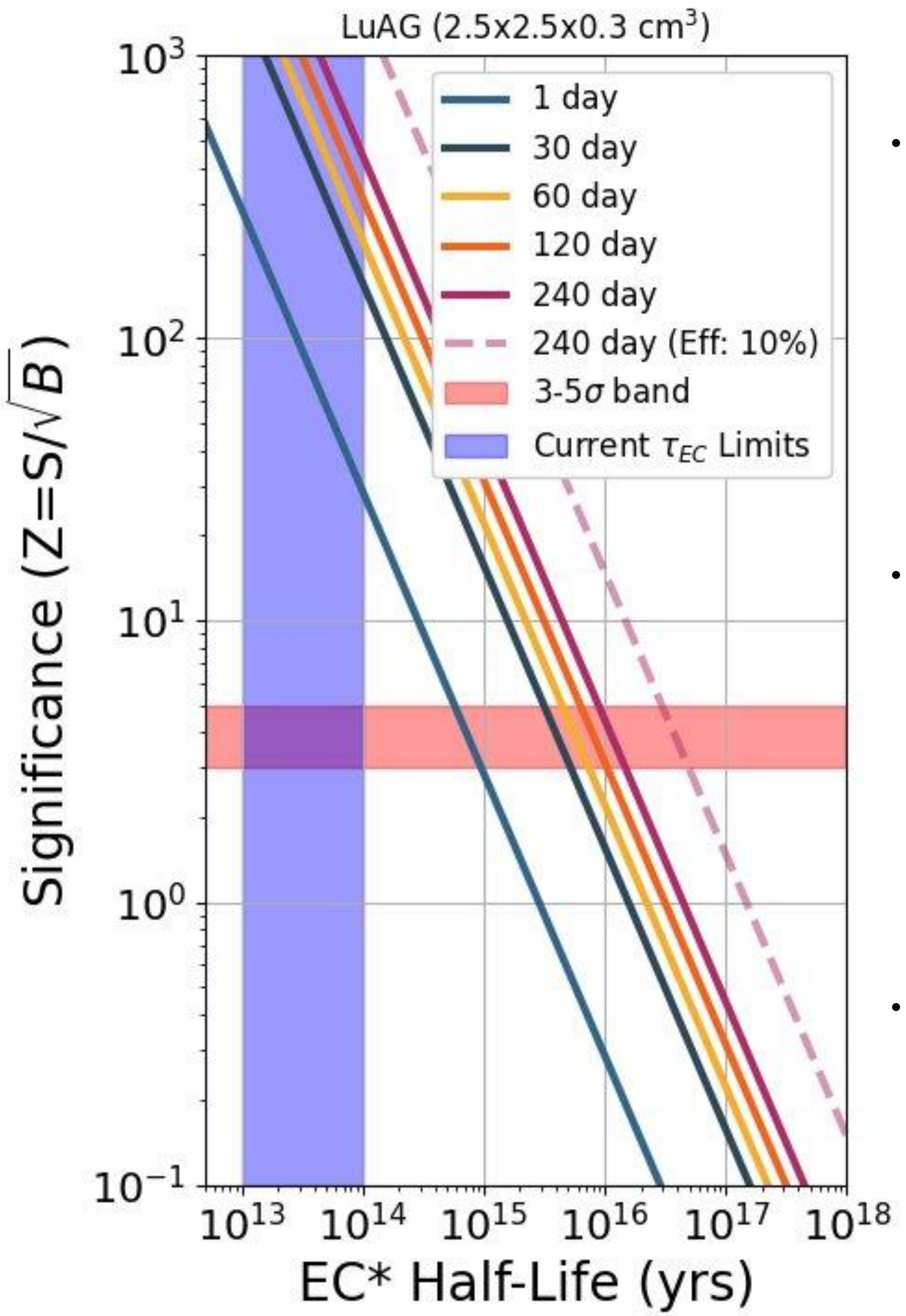




- The largest background will be from the β- decay chain
- Both β- and EC will deposit almost the entirety of their energy in the crystal
- An energy cut of <27 keV in the SiPM channel will reduce the β- events by >99%

RAMPS: Sensitivty





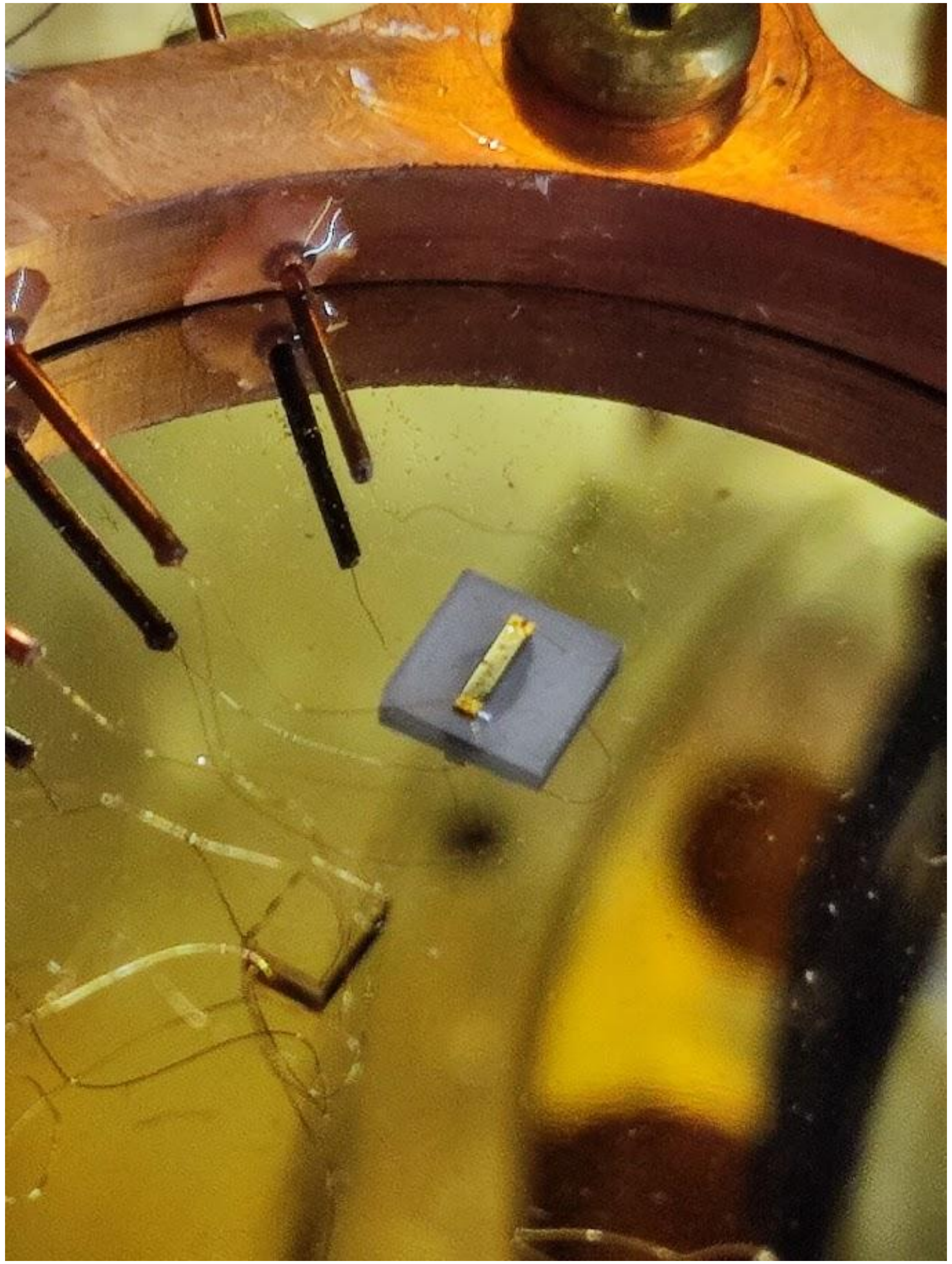
- Plot assumes a gamma efficiency of 3%
- Meet current limits with a single day of runtime
- Potentially surpass by 2 orders of magnitude

Experimental measurement of forbidden decays: LUCE

LUCE Collaboration:

Shihong Fu[1] · Giovanni Benato[2,3] · Carlo Bucci[3] · Paolo Gorla[3] · Pedro V. Guillaumon[3] · Jiang Li[4] · Serge Nagorny[5,8] · Francesco Nozzoli[6,7] Lorenzo Pagnanini[2,3] · Andrei Puiu[3] · Matthew Stukel[2,3]

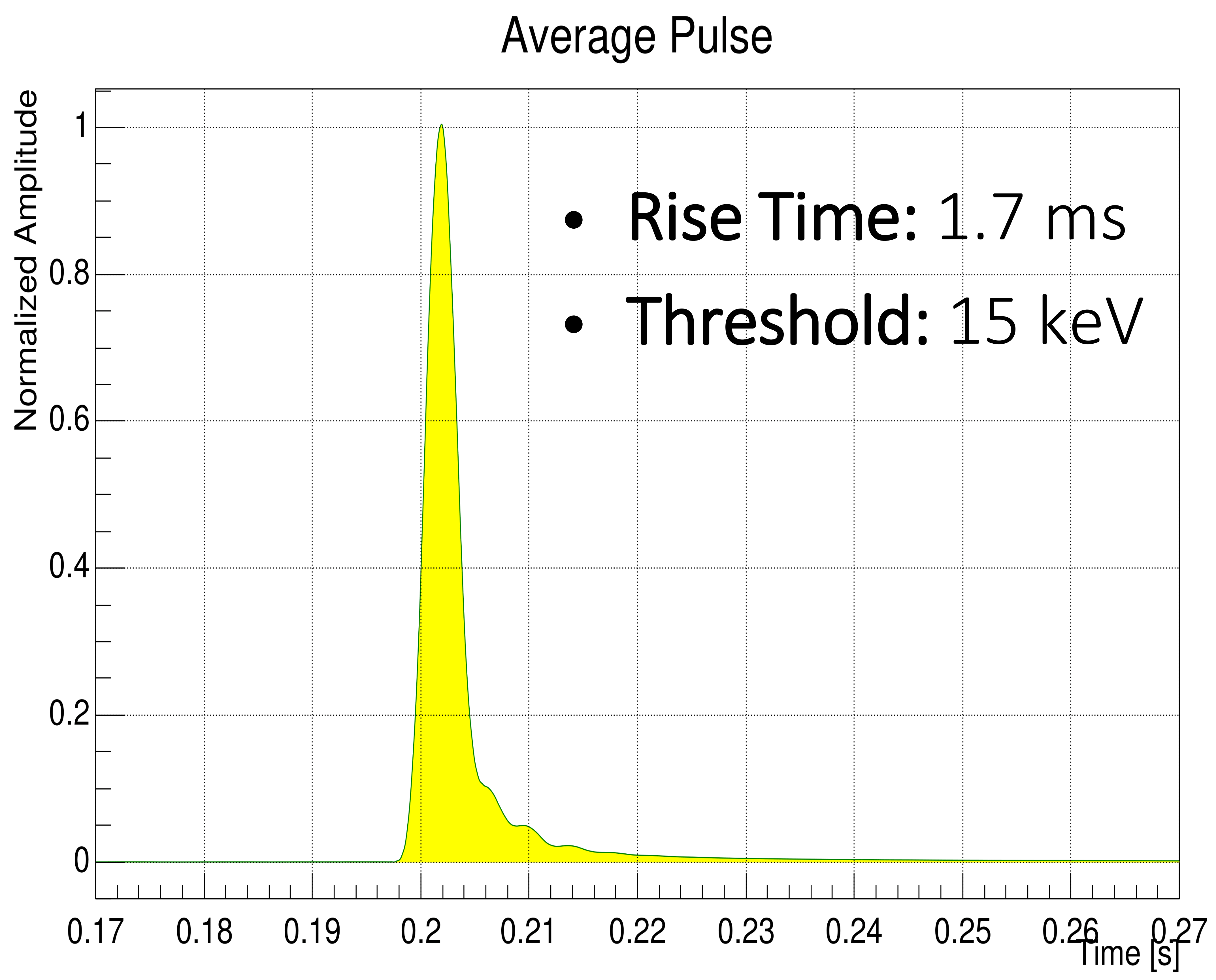
LUCE (Lutetium sCintillation Experiment)

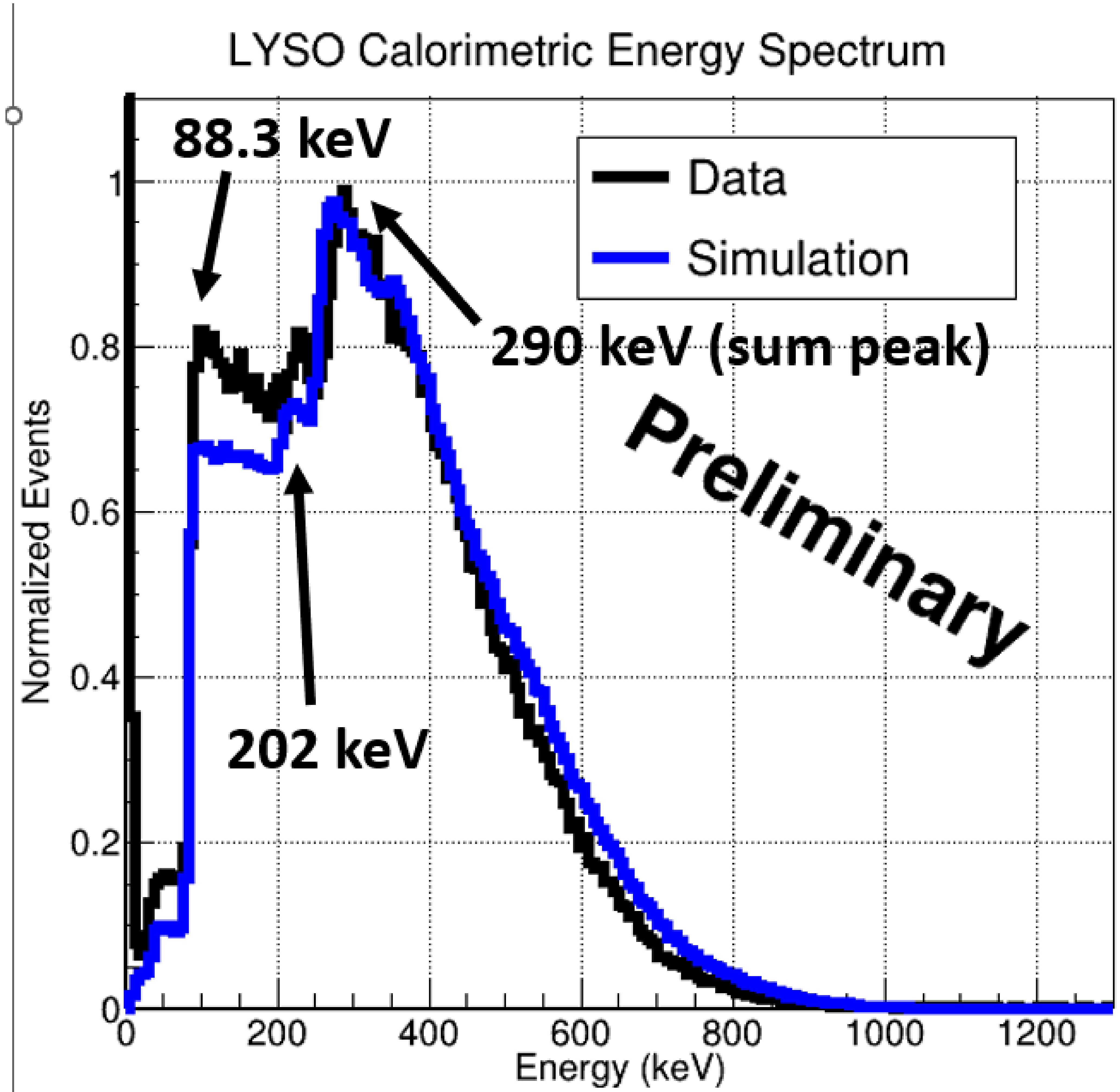


SNOLAB

- The half-life of the excited state decay of ^{176}Lu is theoretically predicted to be 10^{22}-10^{24} years
- LUCE aims to use cryogenic calorimetric techniques to measure EC* of ^{176}Lu
- A 4x4x1 mm LYSO:Ce was operated as a calorimeter underground at the Laboratori Nazionali del Gran Sasso
- The crystal was equipped with an NTD-Ge and operated at base temperature for twelve days

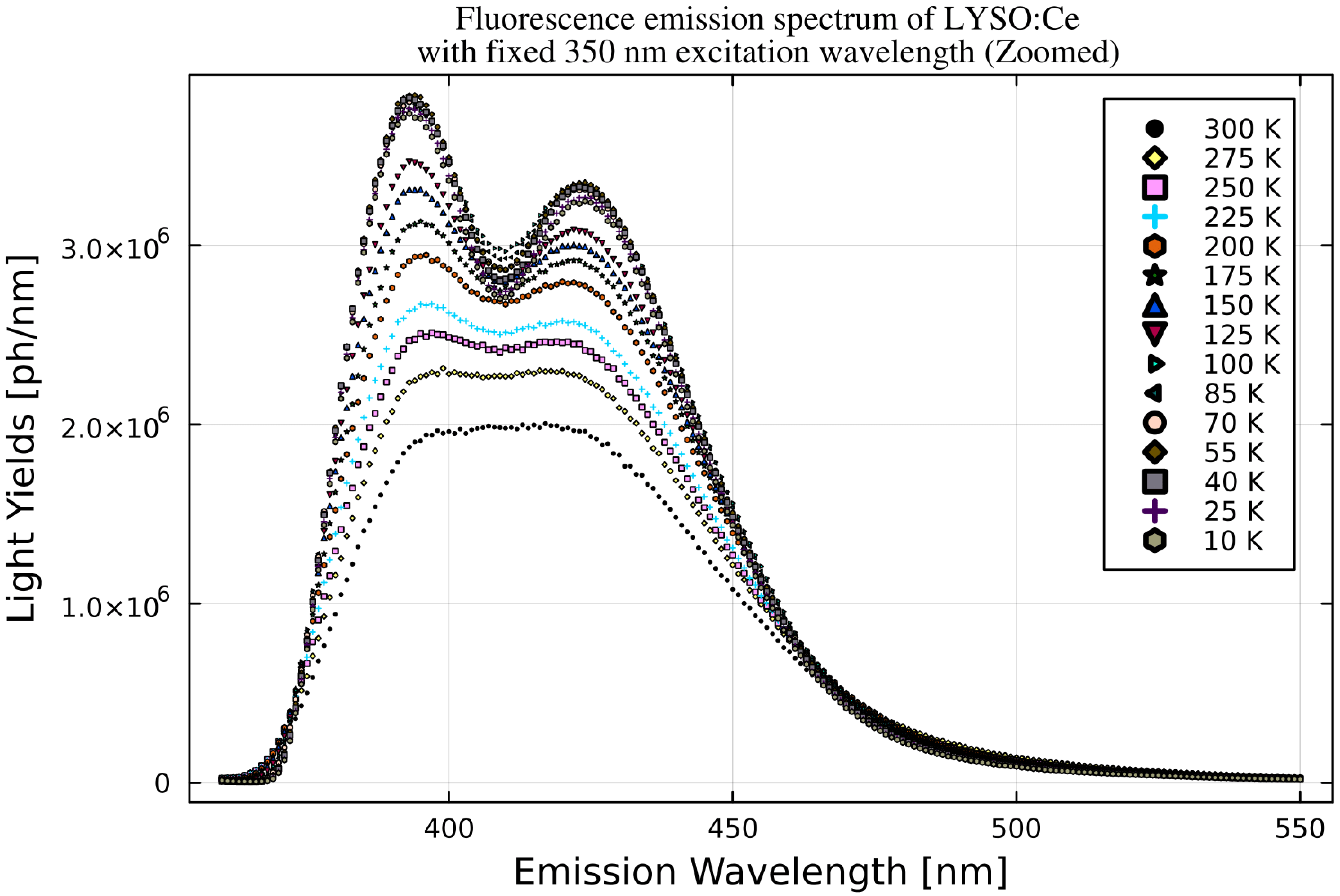
LUCE: First Cryogenic Results

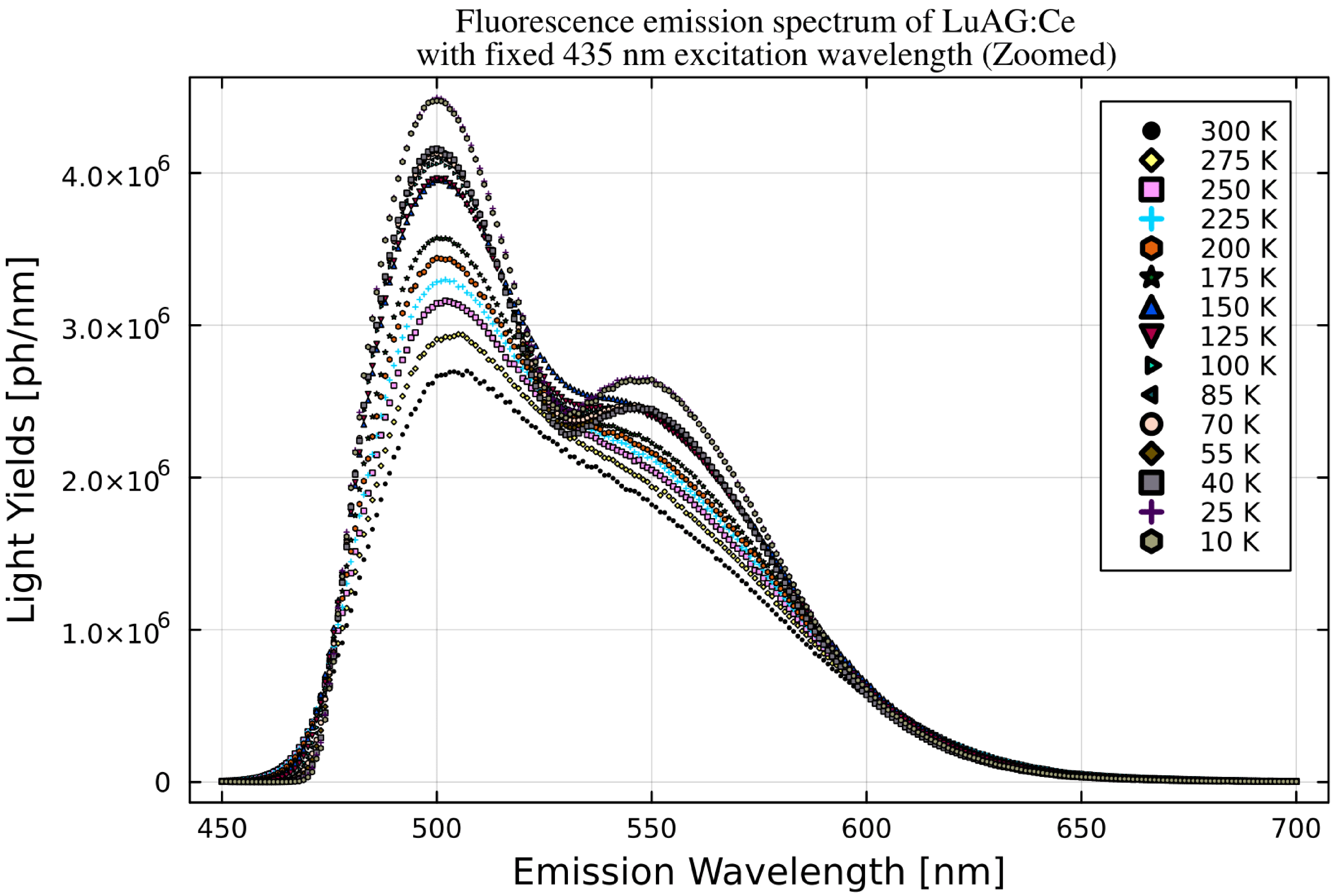




- First ever cryogenic measurment of a Lu-based crystal
- Simulations *generally* agree but currently do not include efficiencies or detector effects

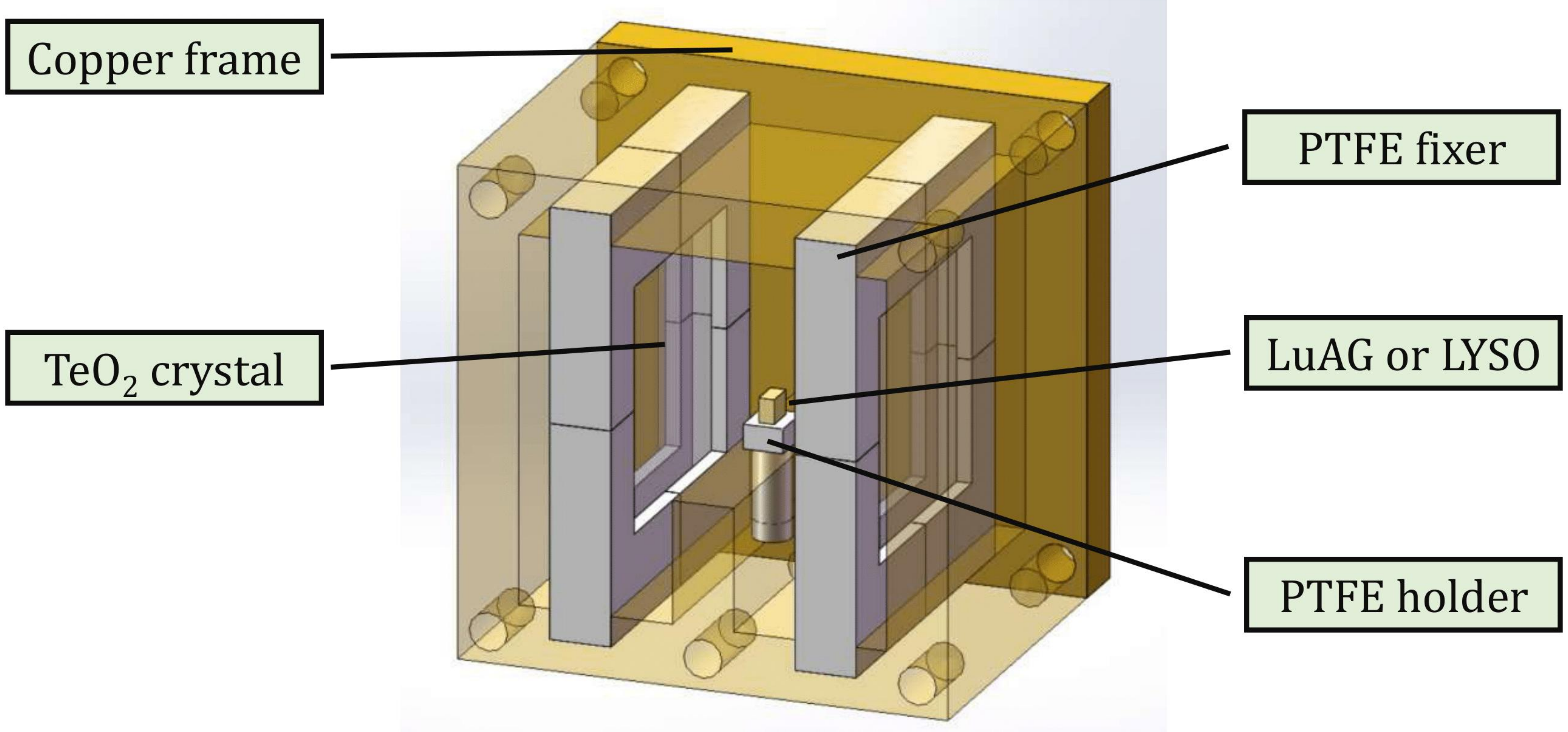
LUCE: Cryogenic Light Yield Characterization





- Characterized the light-yield as a function of temperature
- Sample was placed in an optical cryostat and excited with a Xenon arc lamp
- For both LYSO and LuAG crystals the light yield increases with a decrease in temperature, making particle discrimination possible

LUCE: Future Work



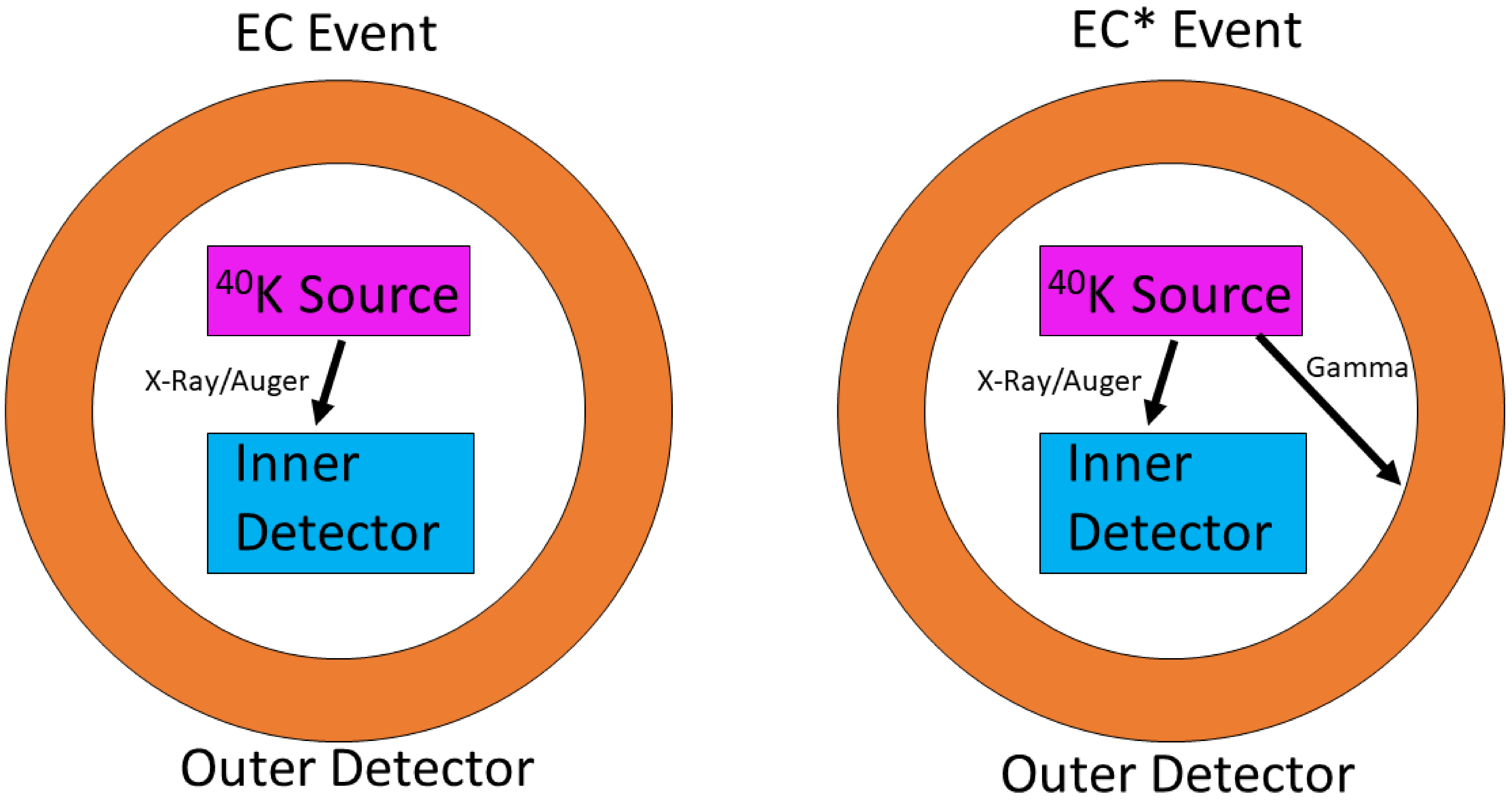
- Future Work:
  - Evaluate α/γ quenching factor in Lu-based scintillators as a function of temperature (Queens, Di Stefano)
  - Transition Edge Sensor for testing or Kinetic Induction Detectors ????
  - Complete design/testing of the first, physics-grade module

Conclusion

- The weak-axial vector coupling is important for understanding future 0νββ experiments
- Highly forbidden nuclear decays can give us insight into the quenching of the weak-axial vector strength
  - KDK: Measured EC of ^{40}K
  - KDK+: Will measure β^+ of ^{40}K
  - LUCE/RAMPS: Will measure EC^* of ^{176}Lu

Extra Slides

KDK Experiment

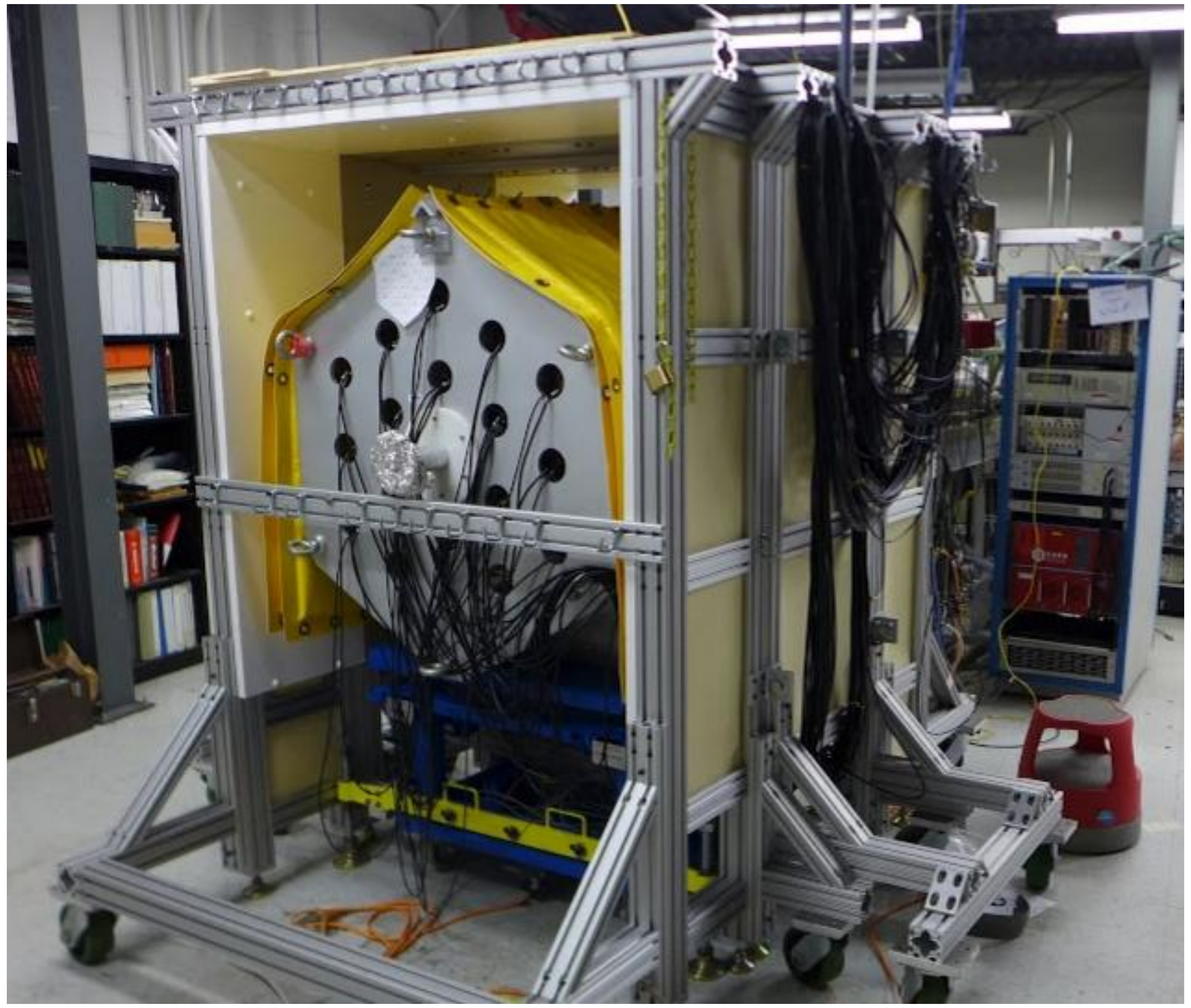


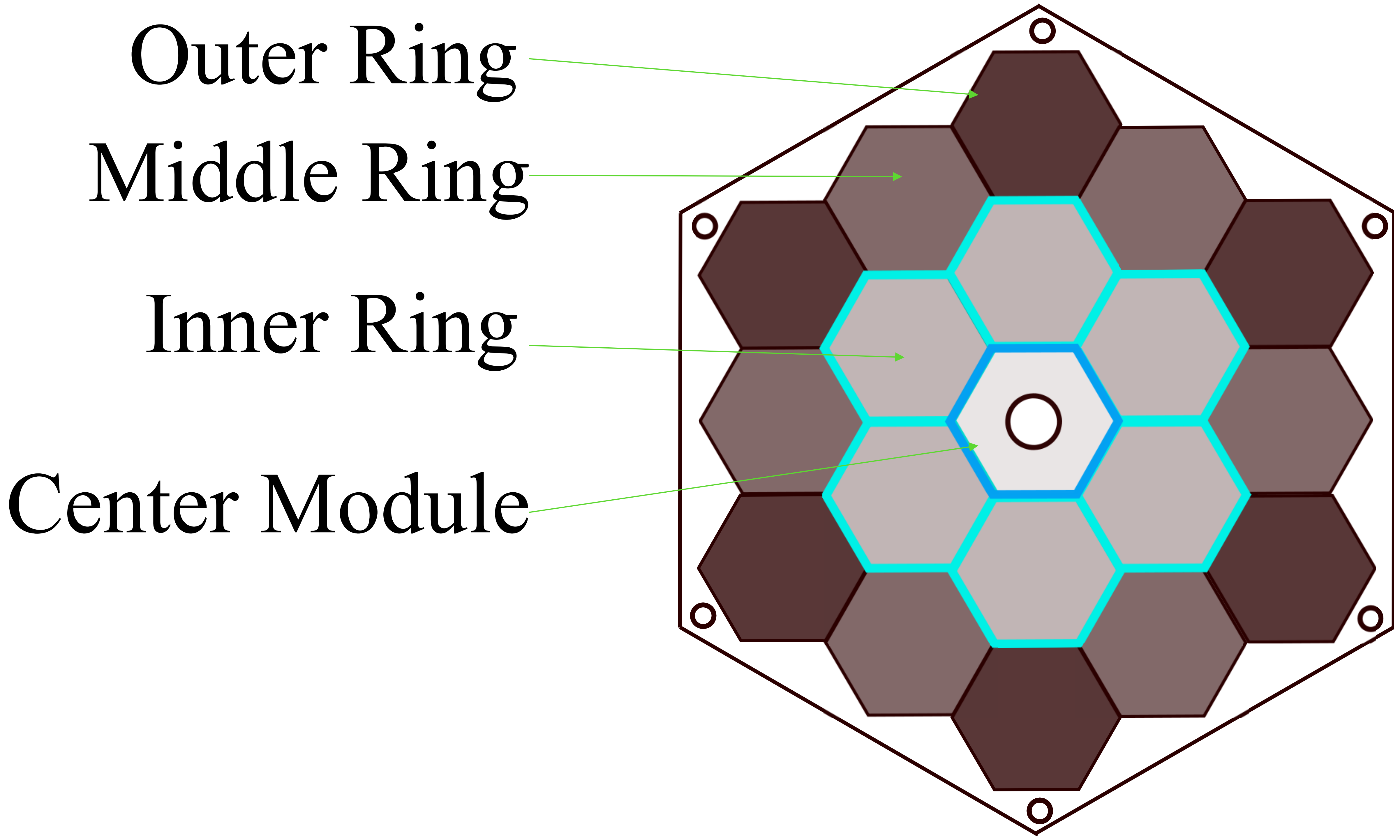
$$\frac{BR_{EC}}{BR_{EC*}} = \rho$$

- Instrumentation paper published in NIM A (2021) [4]

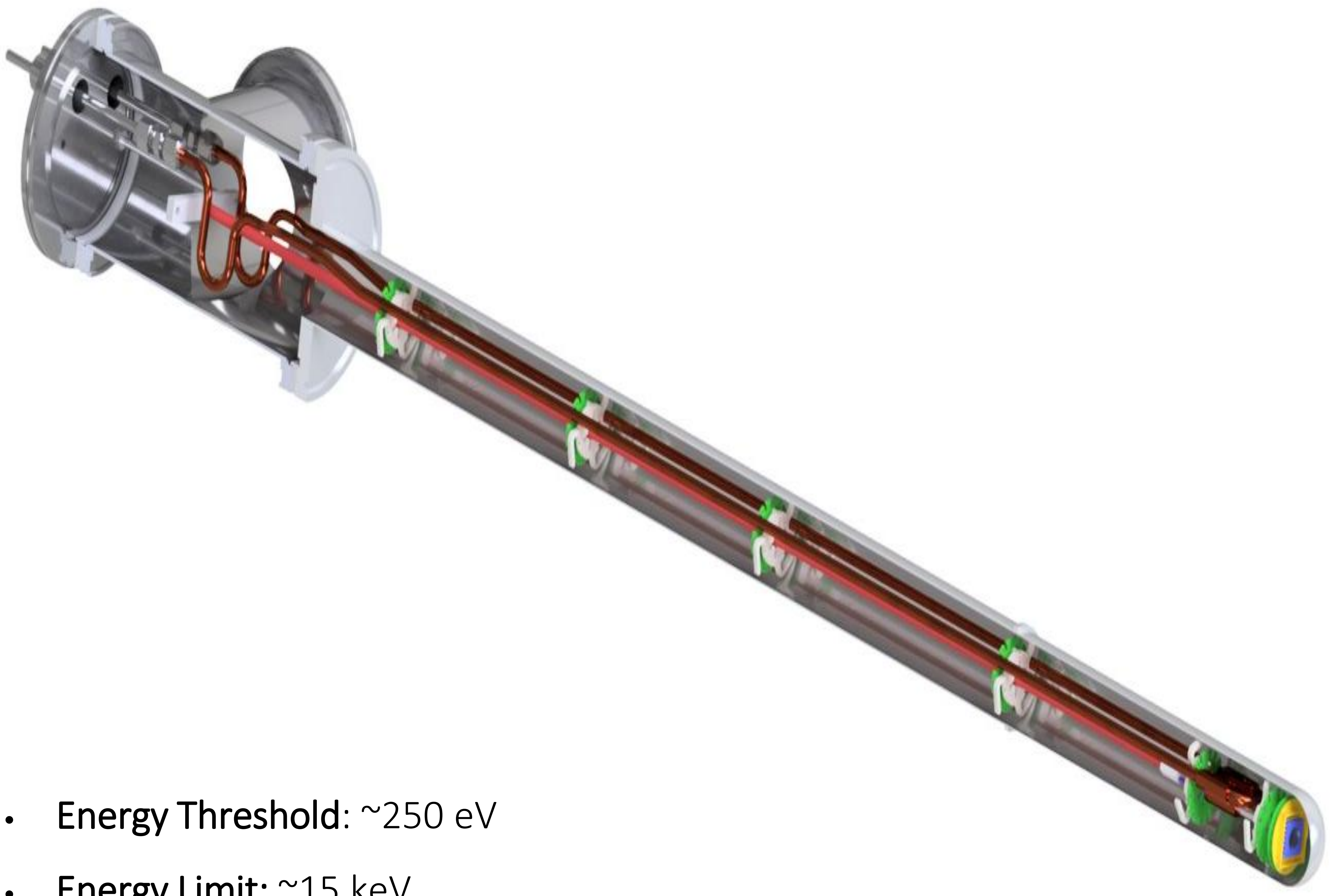
MTAS – External Detector

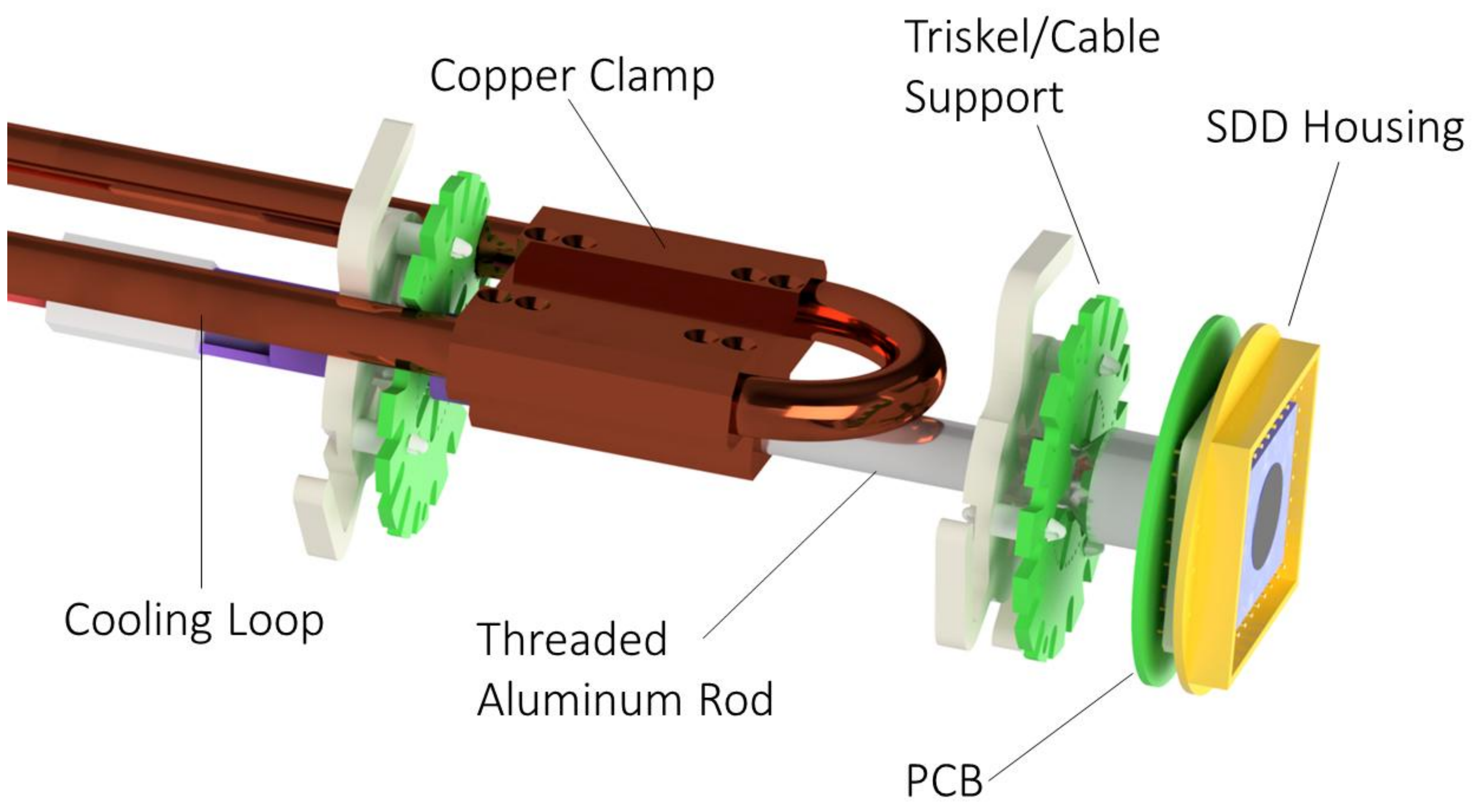
- Modular Total Absorption Spectrometer (MTAS) from Oak Ridge National Lab (ORNL) [5]
- Consists of 19 NaI(Tl) hexagonal shaped detectors (53cm x 20cm) weighing in at ~54 kg each
- MTAS provides ~4π coverage on tagging the 1460 keV gammas

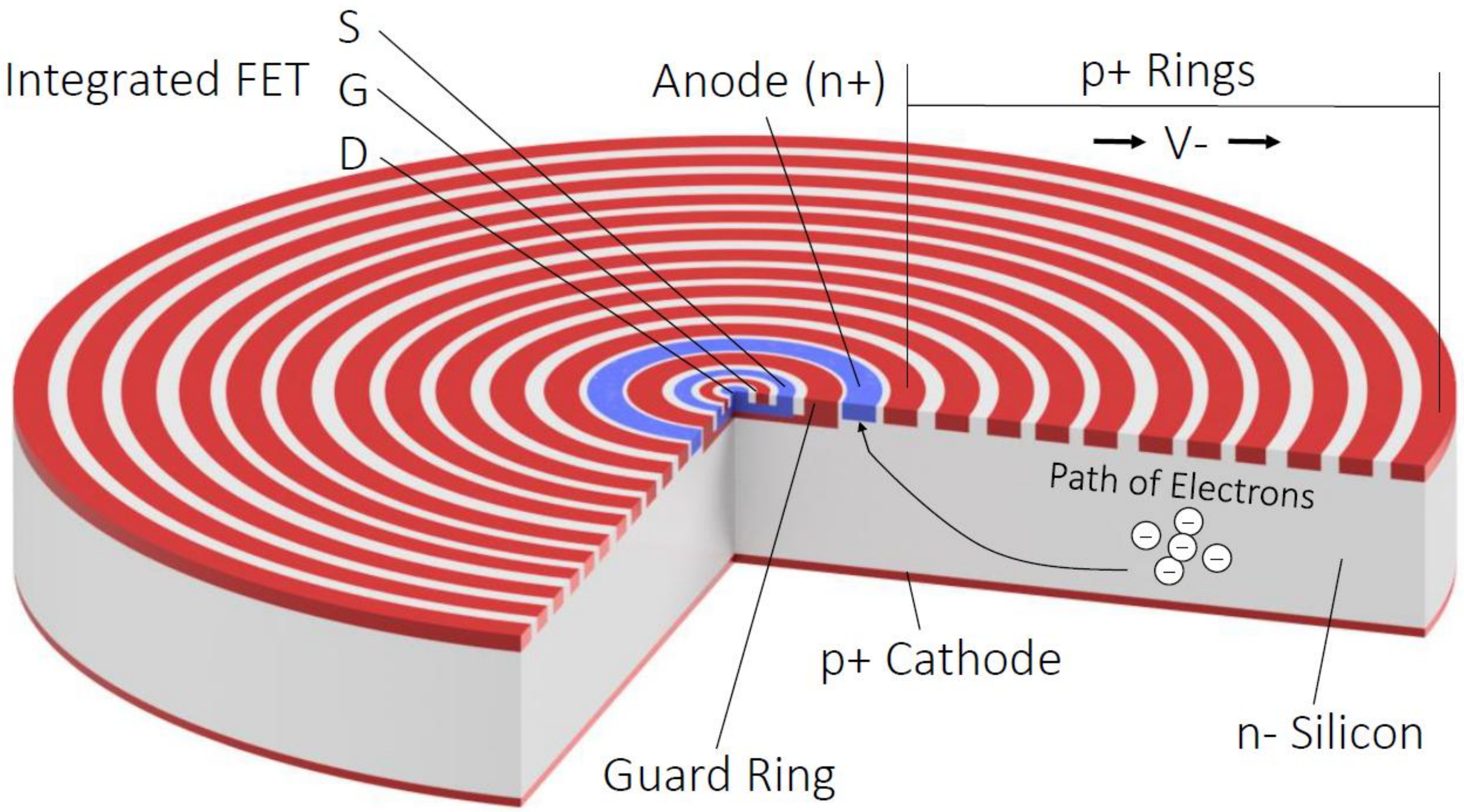




SDD – Silicon Drift Detector

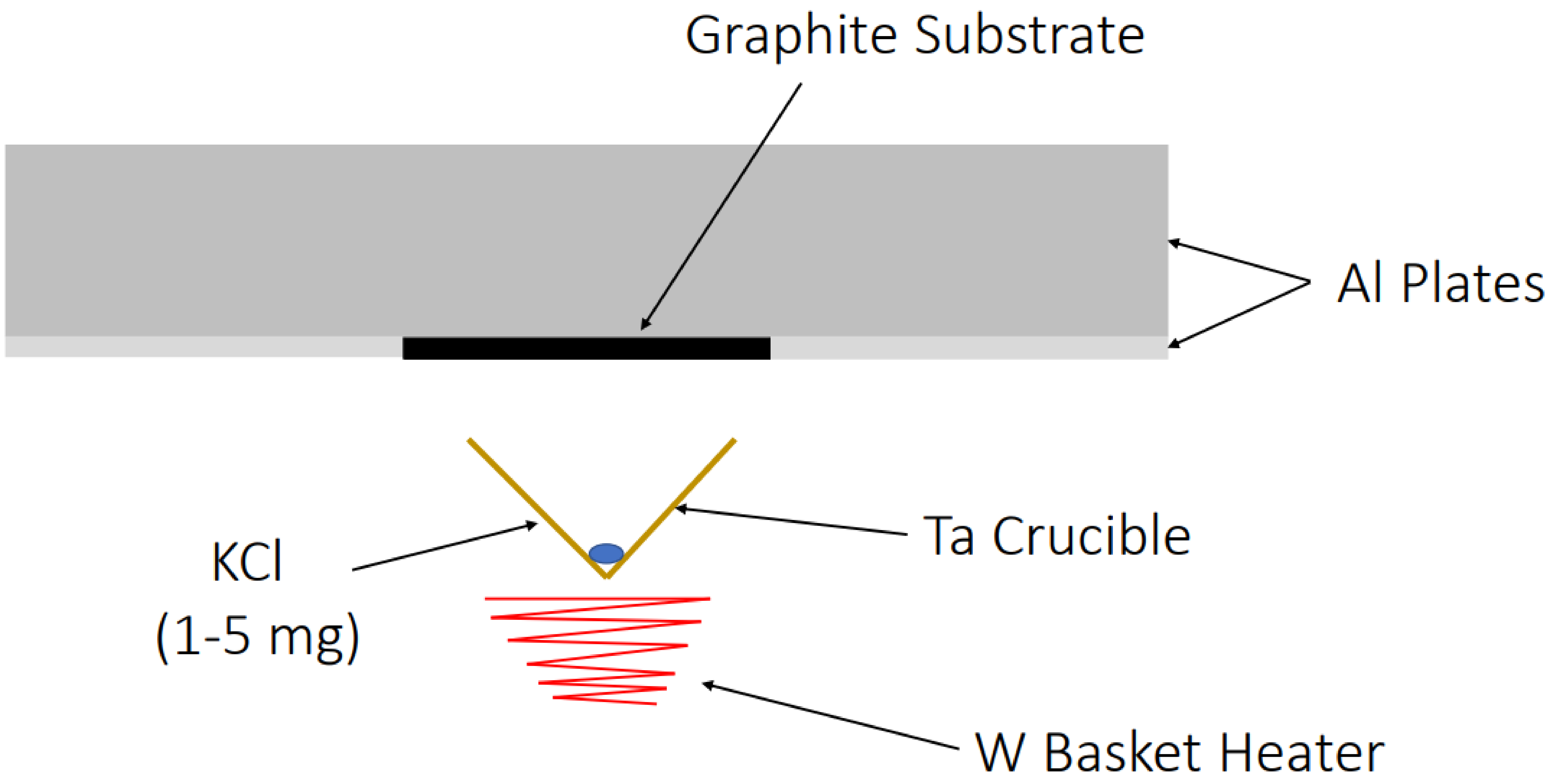


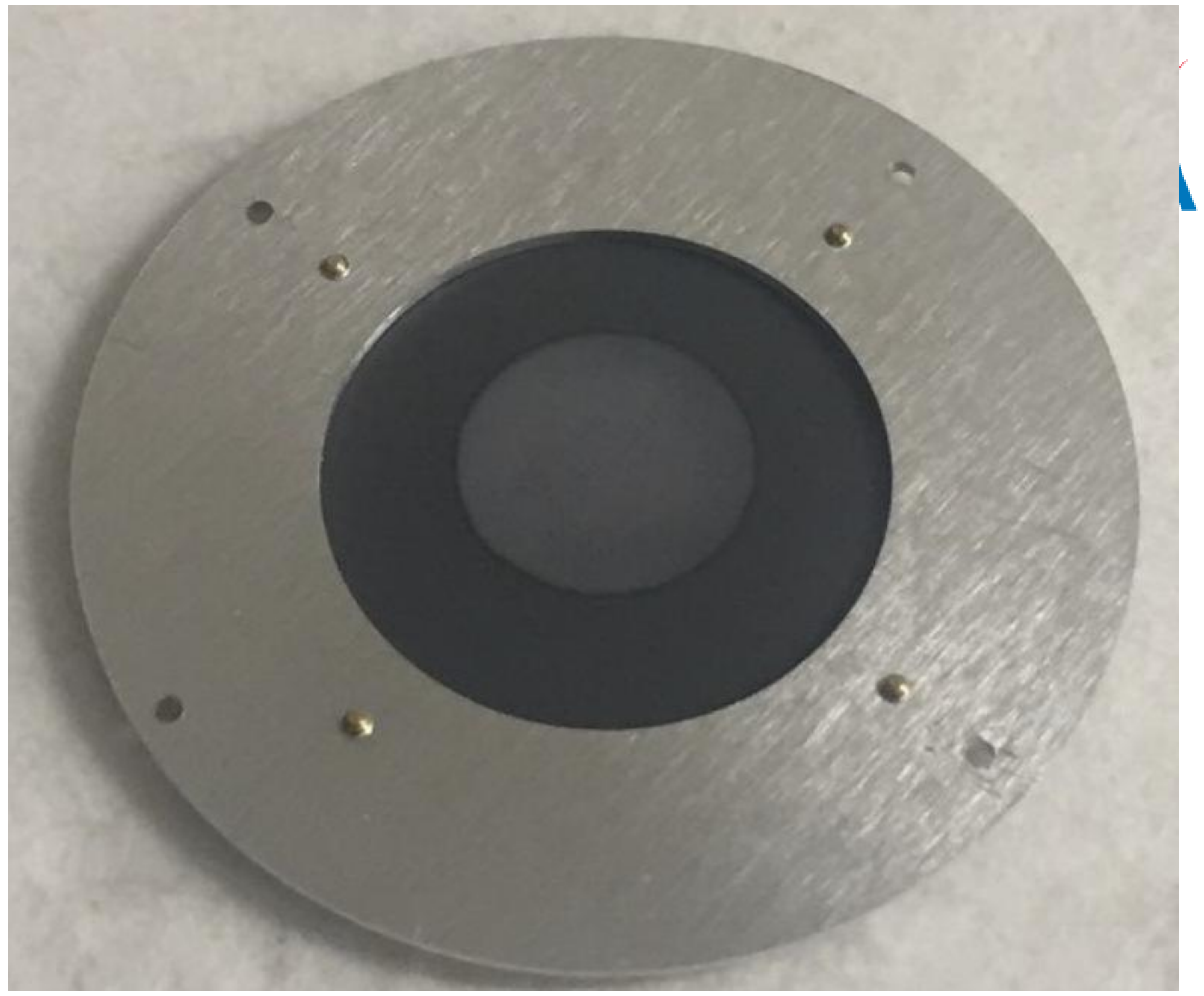


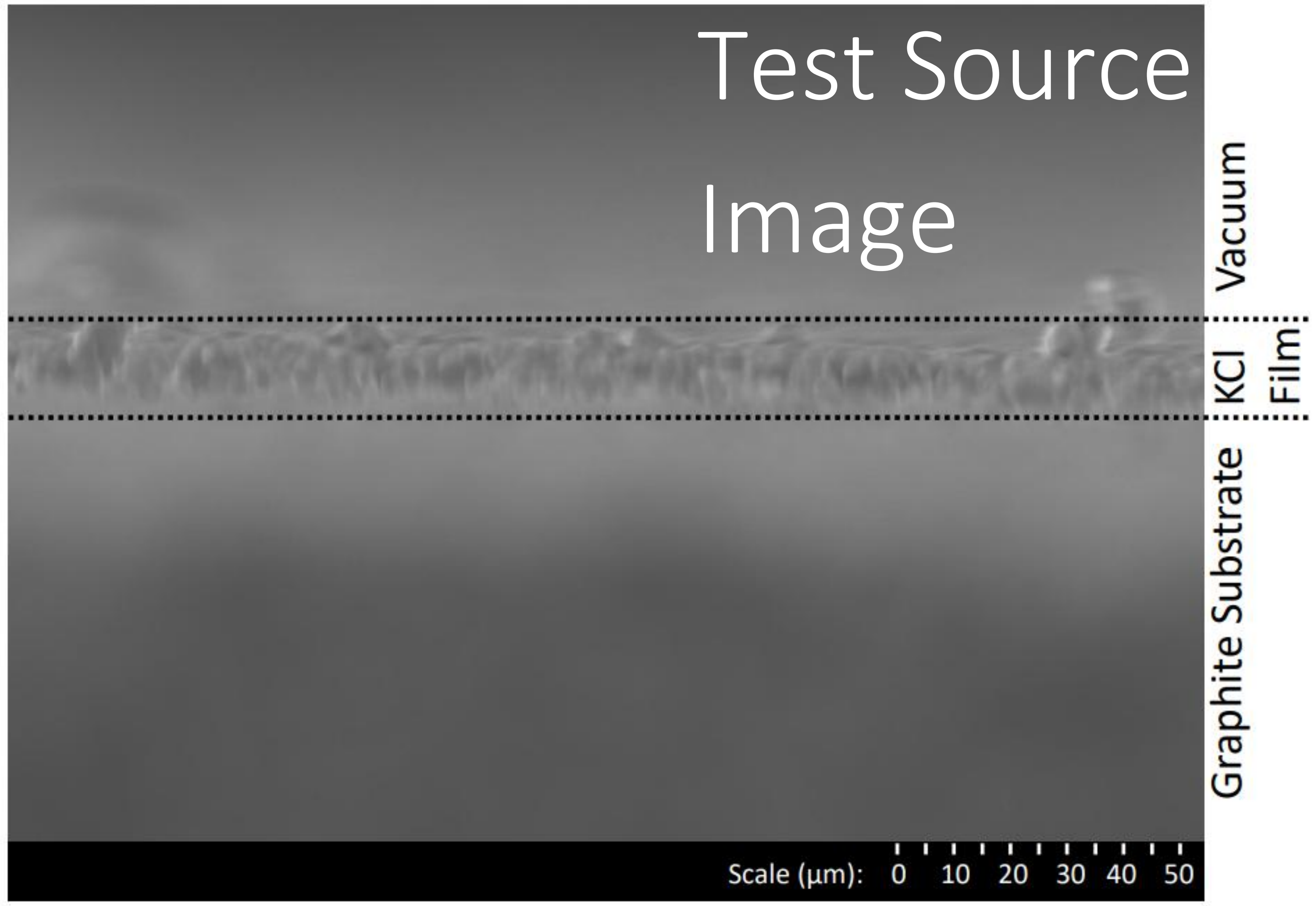


- **Energy Threshold**: ~250 eV
- **Energy Limit:** ~15 keV
- **FWHM:** ~170 eV @ 6keV

^{40}K – Source Development







- ELECTRON BEAM DEPOSITION
- 3.0 mg of enriched (^{40}K/^{Tot}K: 0.01% -> 16%) KCl
- Source used is 5 μm thick

^{40}K – Source Development

Previous experimental measurements for the branching ratios have been conducted.

i **KDK (2023)[6]:** BR0/BR* $= 0.0095 \pm 0.0022 \pm 0.0010$

ii **Engelkemeir experiment (1962)[7]:** BR+/BR- $= (1.12 \pm 0.14)*10^{-5}$

iii **Mougeot theory (2018)[8]:** BR0/BR+ $= 215.0 \pm 3.1$

If [i] is assumed to be correct, and taking the results from Kossert (2022)[9] for the partial decay constants, λ- and λ*, **we find inconsistent values for $\lambda+$**

1. i+ii) $\lambda+ = (5.5 \pm 0.7)*10^{-6}$ /Ga
2. i+iii) $\lambda+ = (2.5 \pm 0.6)*10^{-6}$ /Ga