The KDK+ Experiment: measurement of the β+ branching ratio of potassium 40

Queen's University

Arnaud Lemaire* - 05/08/2024

*Supported by the McDonald Institute

Engineering student from
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ÉCOLE CENTRALE LYON

Visiting research student
on KDK+ with
Philippe Di Stefano

Queen's UNIVERSITY

KDK Group at Queen’s University:

Prof. Philippe Di Stefano
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Contributions from:
Peter Skensved - Senior Scientist
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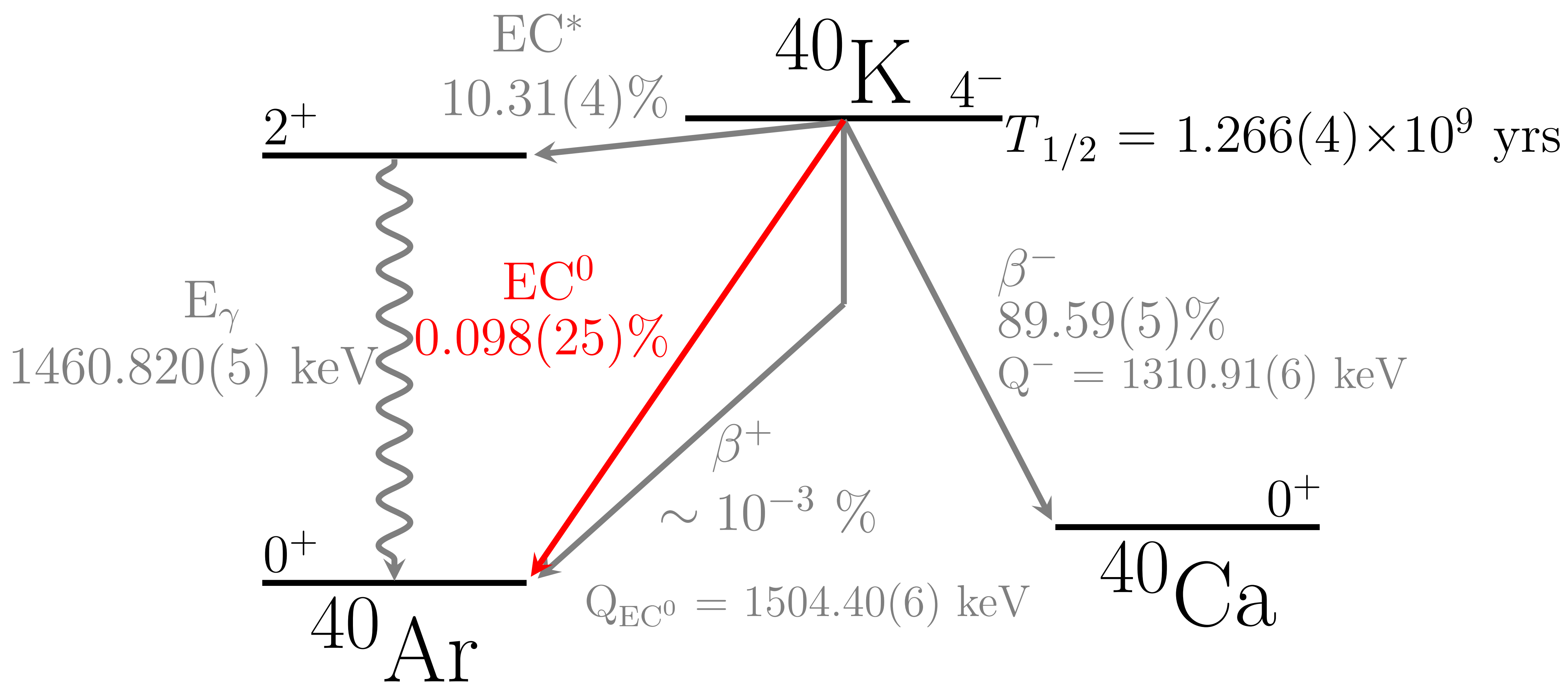
Arnaud Lemaire - Visiting student
Romain Arsenne - Visiting student
David Van Herpt - Engineering project student

Motivation I



Decays

β^- $^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + \beta^- + \bar{\nu}_e$, $K_- \leq Q_- = 1.3$ MeV, $P_- = 0.9$

β^+ $^{40}\mathrm{K} \to {}^{40}\mathrm{Ar} + \beta^+ + \nu_e$, $K_+ \leq Q_+ - 2m_e = 483$ keV, $P_+ = O(10^{-5})$

EC0/EC* See KDK

Previously: KDK https://physics.aps.org/articles/v16/131

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VIEWPOINT

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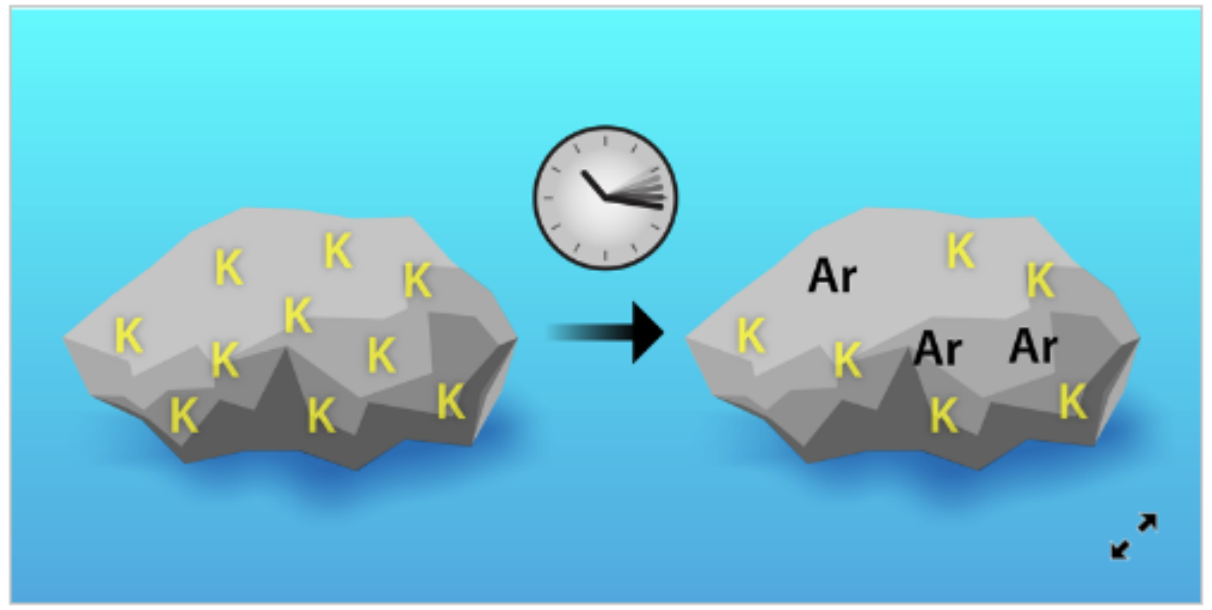
Measuring Decays with Rock Dating Implications

Stephen Ellis Cox

Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, US

July 31, 2023 • *Physics* 16, 131

Researchers revisit a neglected decay mode with implications for fundamental physics and for dating some of the oldest rocks on Earth and in the Solar System.



APS/Alan Stonebraker

Figure 1: As a rock forms, it traps a set of potassium-40 within the solid. Decays of this isotope produce argon-40. By measuring the amount of argon-40 relative to that of potassium-40, geologists can date the rock.

With a half-life of 1.25 billion years, potassium-40 does not decay often, but its decays have a big impact. As a relatively common isotope (0.012% of all potassium) of a very common metal (2.4% by mass of Earth's crust), potassium-40 is one of the primary sources of radioactivity we encounter in daily life. Its decays are the primary

Rare ^{40}K Decay with Implications for Fundamental Physics and Geochronology

M. Stukel *et al.* (KDK Collaboration)

Phys. Rev. Lett. 131, 052503 (2023)

Published July 31, 2023

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Evidence for ground-state electron capture of ^{40}K

L. Hariasz *et al.* (KDK Collaboration)

Phys. Rev. C 108, 014327 (2023)

Published July 31, 2023

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Recent Articles

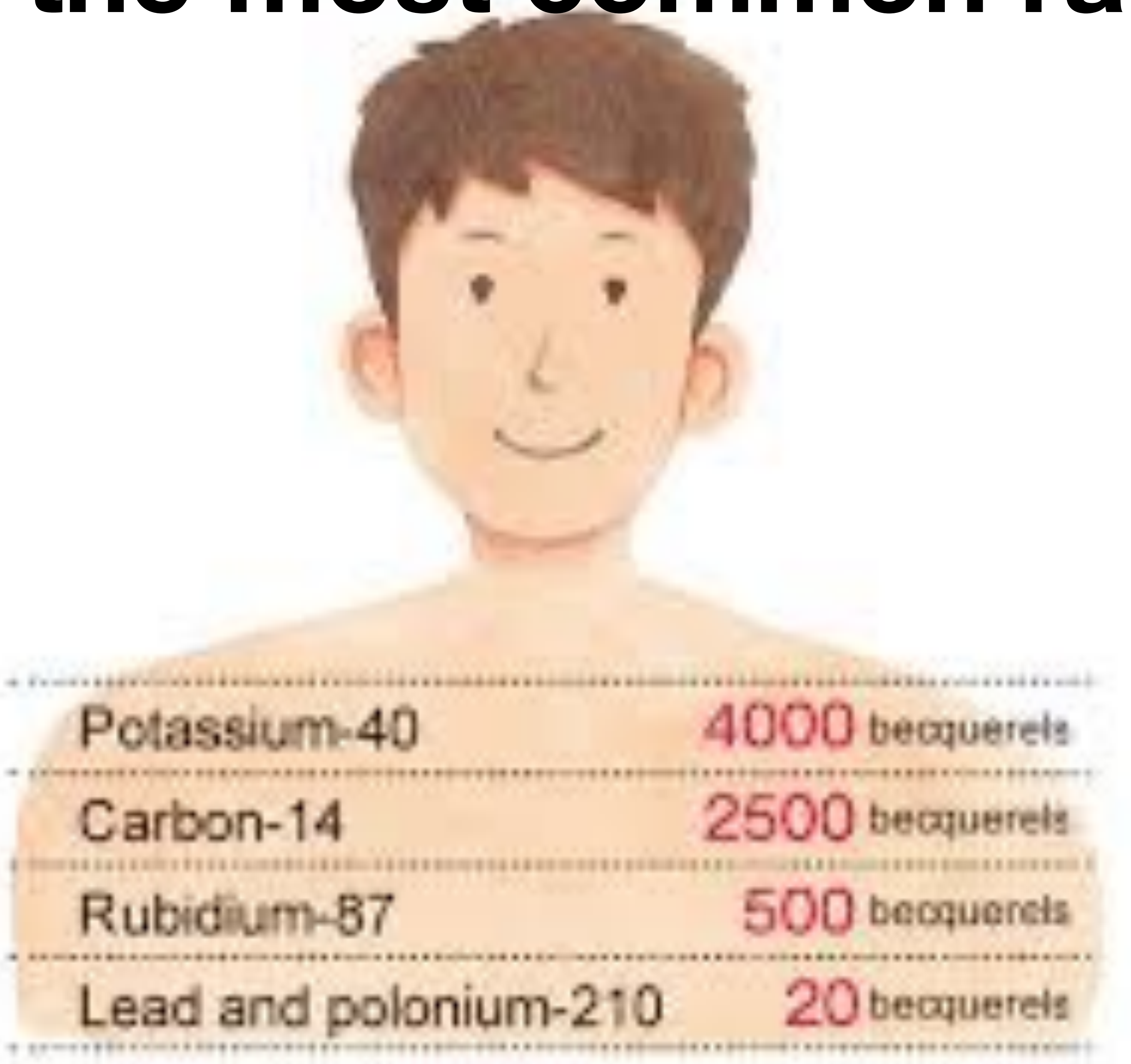
Watching a Quantum System Thermalize

Atoms trapped in a one-dimensional optical lattice can mimic how—in a basic quantum field theory—massive particles reach, or fail to reach, thermal equilibrium.

The Search for WIMPs Continues

Two mammoth underground detectors have delivered more stringent upper limits on how

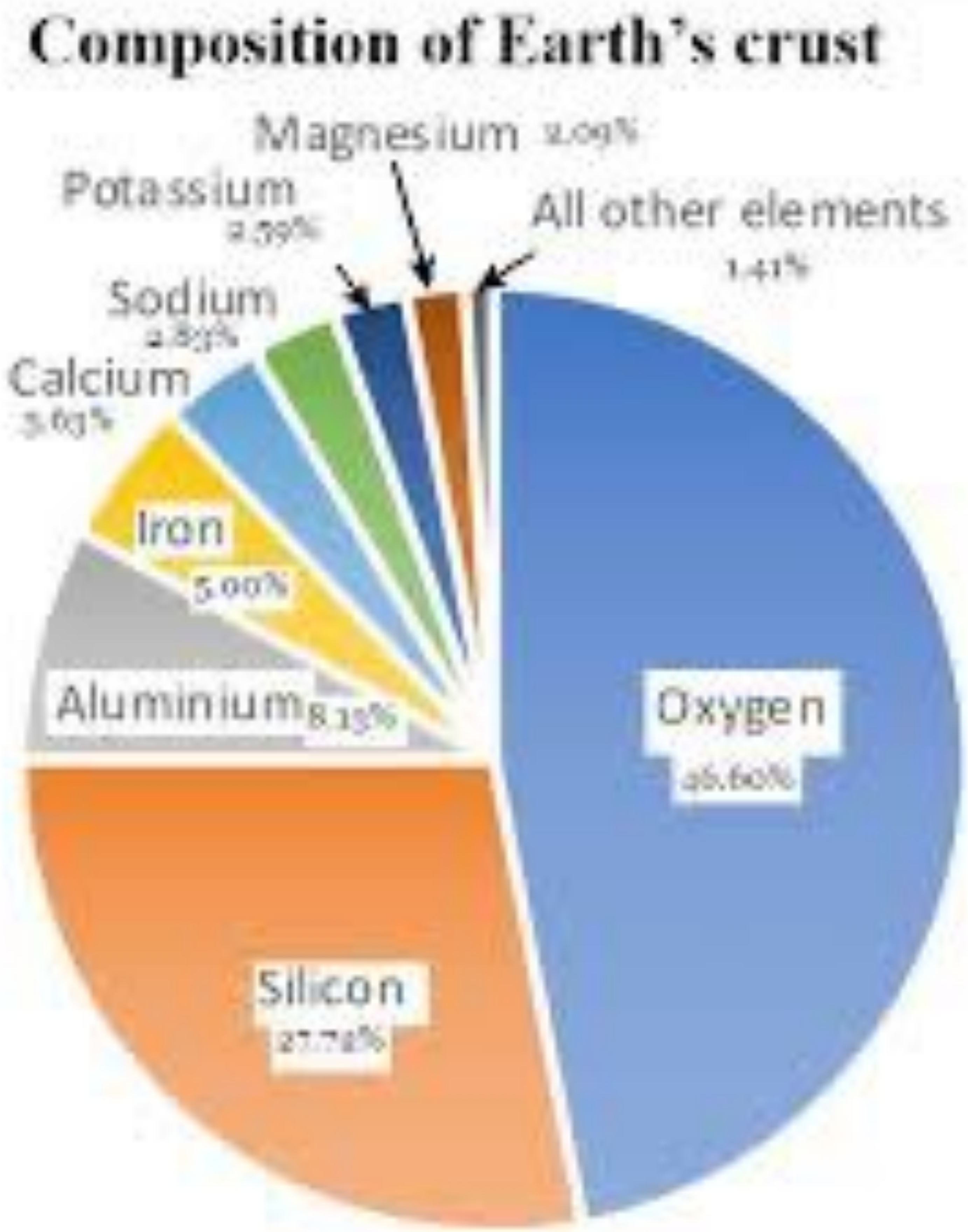
40K, one of the most common radioisotope:



A typical 150-gram banana contains about half a gram of potassium, and has an activity of roughly 15 Bq (per 150 g of banana)

Total earth activity [10^{24}Bq]

40K	232Th	238U
30	11	11



Motivation II

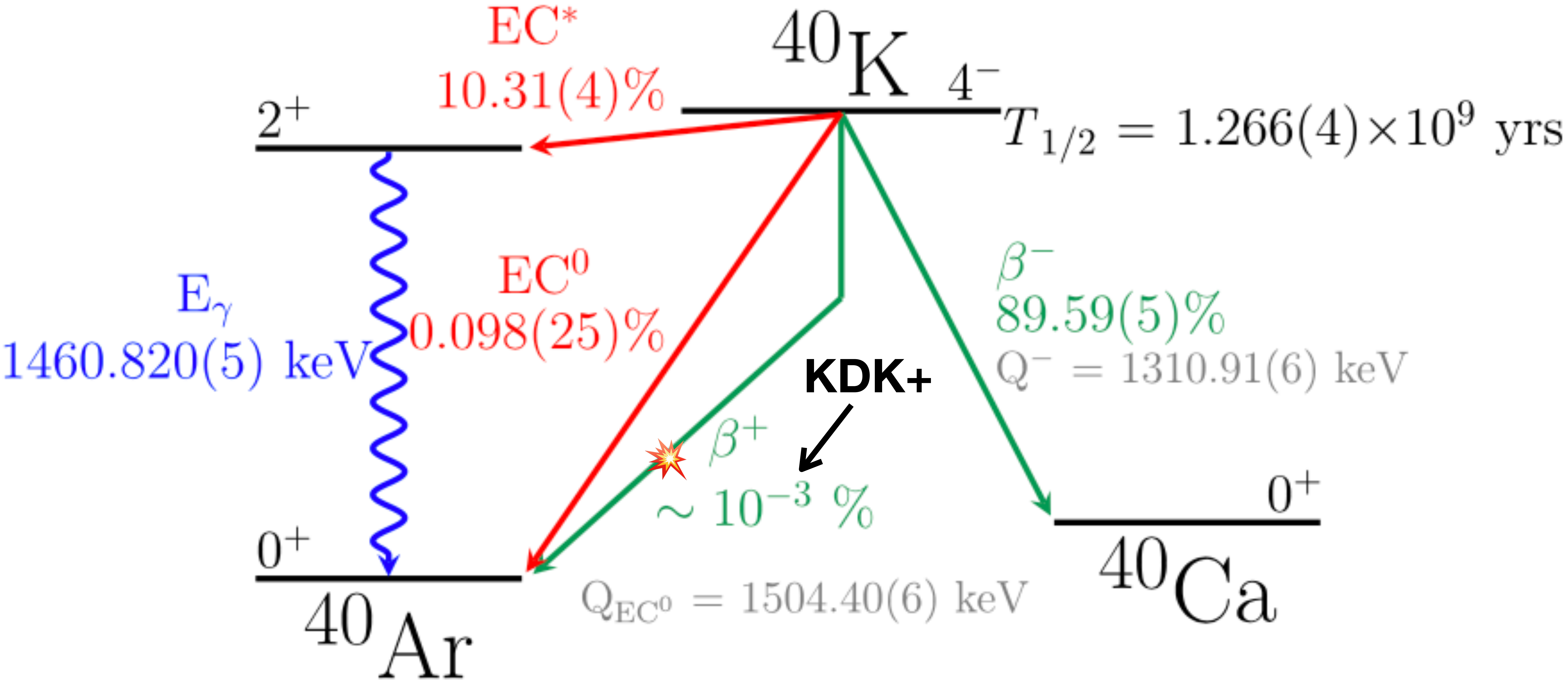
Inconsistency

1. KDK expt 2023 [1]: $BR0/BR* = 0.0095 \pm 0.0022 \pm 0.0010$
2. Engelkemeir expt 1962 [2]:
   $BR+/BR- = (1.12 \pm 0.14) \times 10^{-5}$
3. Mougeot theory 2018 [3]: $BR0/BR+ = 215.0 \pm 3.1$

Assuming 1. is correct, and taking Kossert 2022's evaluation [4] for $\lambda-$ and $\lambda*$, we find inconsistent values for $\lambda+$:

- 1+2) $\lambda+ = (5.5 \pm 0.7) \times 10^{-6}$ /Ga
- 1+3) $\lambda+ = (2.5 \pm 0.6) \times 10^{-6}$ /Ga

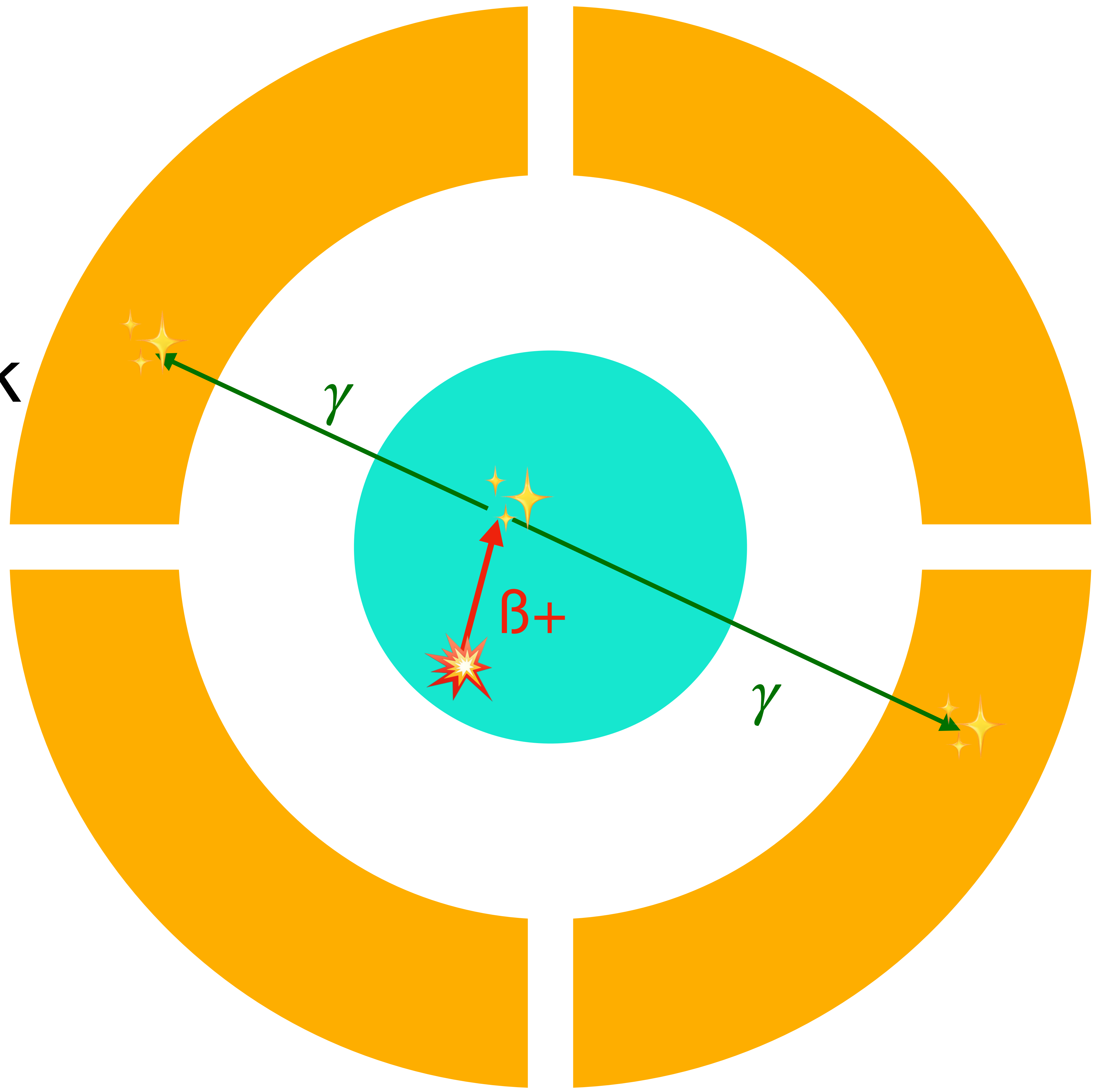
Decay scheme of 40K: Remeasurement of ß+ branching ratio



General concept to measure 40K ß+ to within 10%

Triple coincidence experiment

Emitted ß+ annihilates into two 511keV γ back to back



Gamma detector:
4 NaI crystals quadrants connected to PMTs

Beta detector:
Liquid scintillator + dissolved potassium 40

Positron detector: Choice of Liquid Scintillator

Requirements :

- Positron absorption length in matter is very short
  - ✓ 40K dissolved in the detector: liquid scintillator
  - ✓ Good counting efficiency in liquid scintillator
- Optimize source activity to reduce experiment duration
  - ✓ Use of enriched potassium: natural abundance $\mathbf{1.2 \cdot 10^{-4}}$
  - ✓ Dissolve a lot of 40K in the liquid
- Adapt the geometry to the gamma detector
  - ✓ Multiple design of the vial coupled with PMTs
- Commercial Ultima Gold liquid scintillator
  - ✓ « safer » LSC: easier to manipulate, (DIPN solvent)
  - ✓ High water uptake capacity and ionic strength
  - ✓ Light yield and quenching factor.

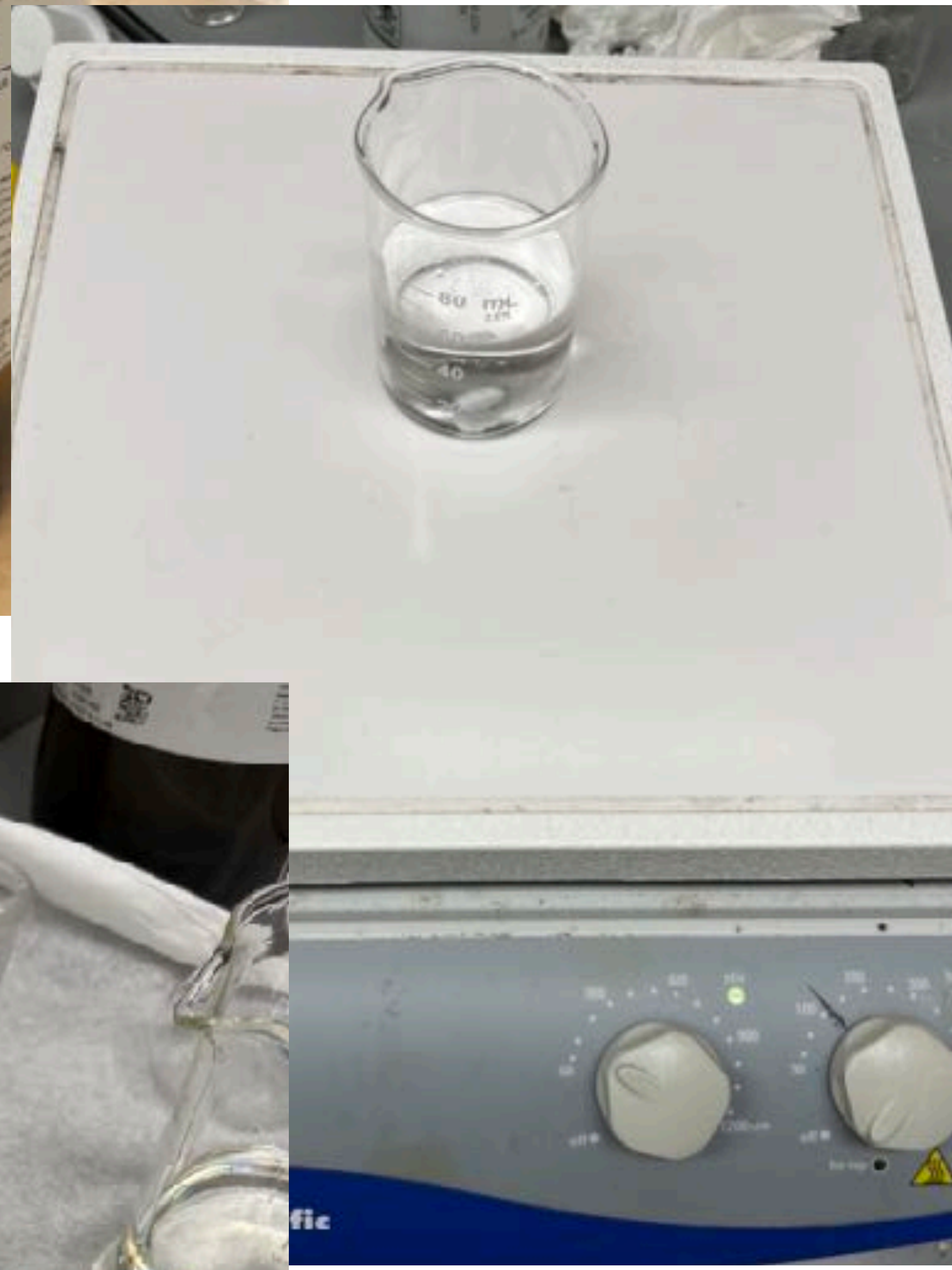
Liquid scintillator cocktail

Goals:

- Dissolving a maximum amount of Potassium in the vial
- Make the cocktail with the best light yield
    - ✓ Find the best potassium salt
    - ✓ Find the right concentration/volume ratio

Protocol:

- Aqueous solution of different salt concentration
- Prepare the cocktail with increasing volume of solution until two phases appear
- 20mL glass vial to observe the cocktail



Potassium salts

	Basic					Toxic	
Potassium Salt	KCl	KOH	KI	K2CO3	KNO3	KF	KIO3
Solubility in water g·L^{-1}	360	1100	1430	1120	357	485	47
K concentration g·L^{-1}	188	766	336	632	138	326	9
Natural 40K concentration µg·mL^{-1}	22,0	89,6	39,3	73,9	16,1	38,1	1,0
3% enriched 40K concentration mg·mL^{-1}	5,6	23,0	10,1	19,0	4,1	9,8	0,3

Choice of salt depends on:

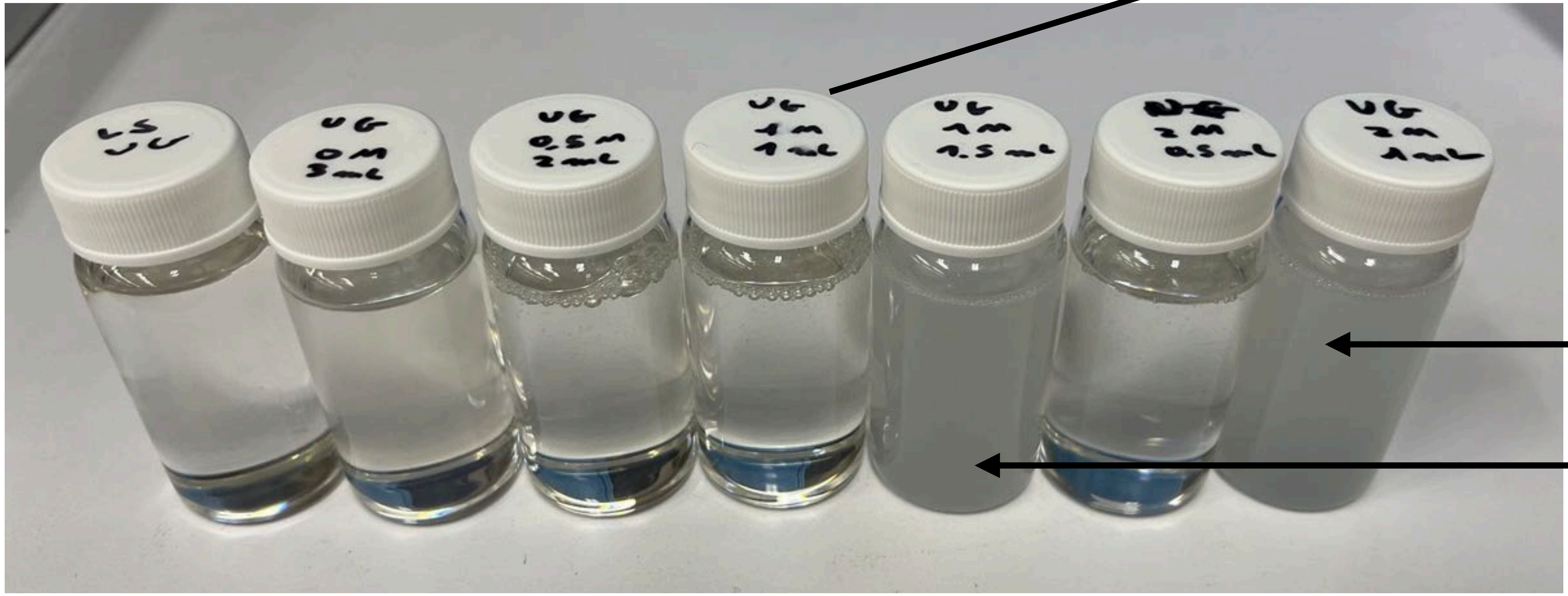
- ✓ Chemical compatibility with LSC and vial
- ✓ High solubility
- ✓ Supply with high purity
- ✓ Possible enrichment

KCl loading in Liquid Scintillator: Ultima Gold, PerkinElmer

Table 3. Sample capacity of selected cocktails for various ionic strength buffers (sample capacities are for 10 mL cocktail at 20 °C).

Ionic Strength	Ultima Gold XR	Hionic-Fluor	Pico-Fluor Plus	Ultima Gold	Ultima Gold MV	Opti-Fl
0.5 M NaCl	9.0 mL	1.4 mL	3.0 mL	1.5 mL	1.25 mL	1.1 mL
0.75 M NaCl	6.5 mL	2.25 mL	2.75 mL	0.75 mL	0.75 mL	0.75 m
1.0 M NaCl	5.5 mL	8.5 mL	2.3 mL	0.5 mL	0.5 mL	0.5 mL

Source: PerkinElmer



Too much aqueous solution or KCl: cocktail separates in 2 phases and becomes cloudy when shaked

KCl loading in Liquid Scintillator: Ultima Gold, PerkinElmer

❌

❌

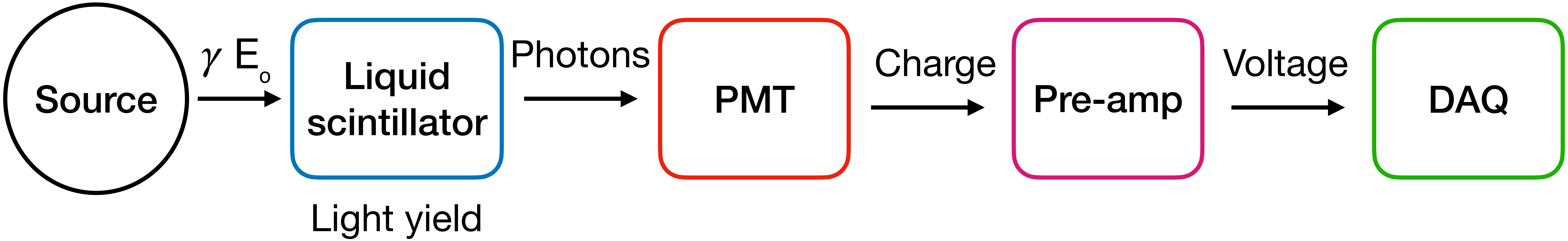
✅

KCl loading in Liquid Scintillator: Ultima Gold, PerkinElmer

Results:

Cocktail in 20mL glass vial	Ultima Gold	Ultima Gold LLT
Quantity of dissolved K mmol	1	3
Mass of dissolved K mg	39	117
For natural potassium abundance		
Mass of 40K µg	4,6	13,8
Atoms of 40K	7E+16	2,1E+17
Activity of the source Bq	1,2	3,6
ß+ emitted in a month	32	96
For 3% enrichment		
Mass of 3% enriched 40K µg	1170	3510
Atoms of 40K	1,8E+19	5,4E+19
Activity of the source Bq	317	951
ß+ emitted in a month	8,3E+03	2,49E+04

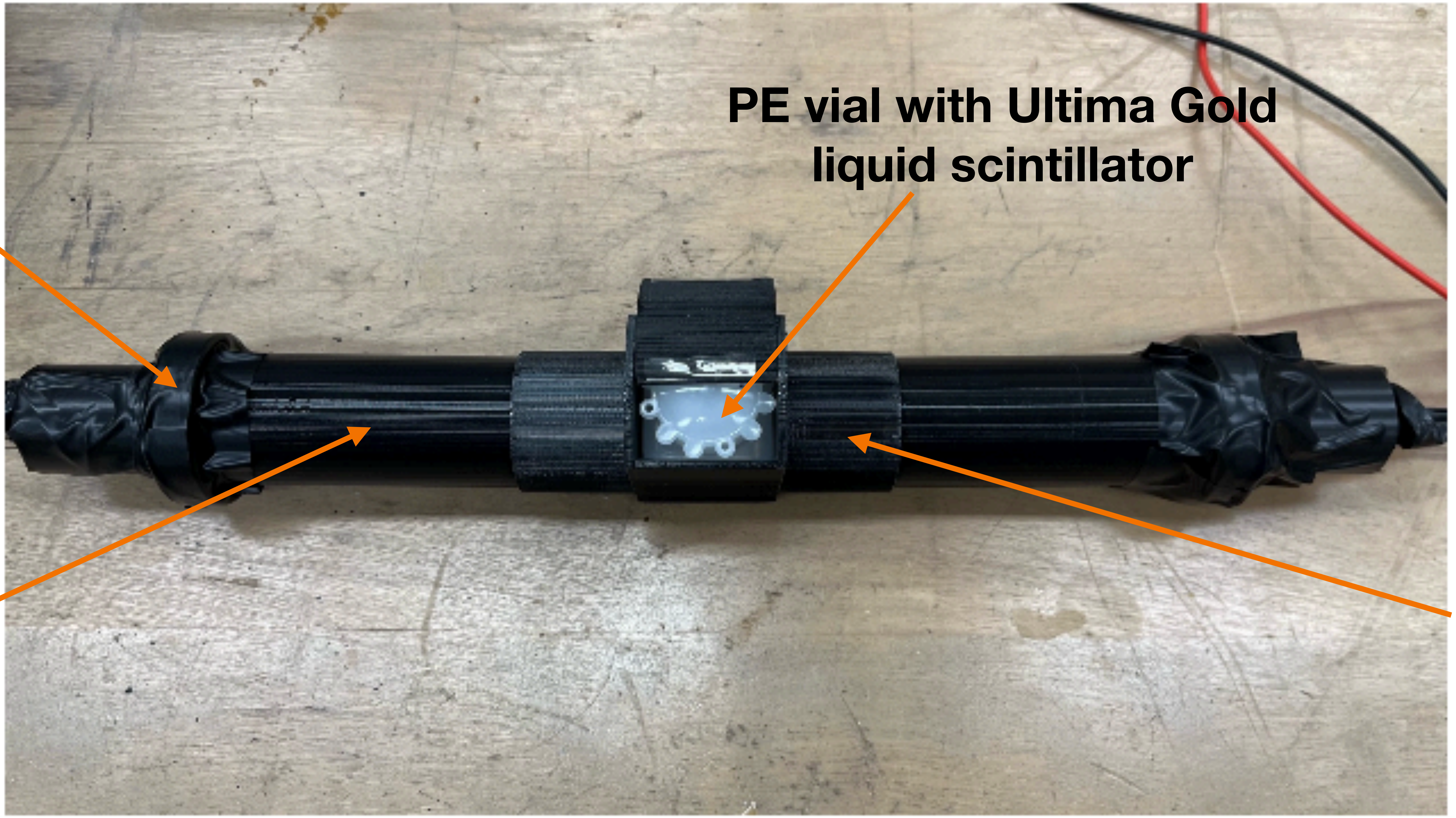
Energy calibration of the liquid scintillator



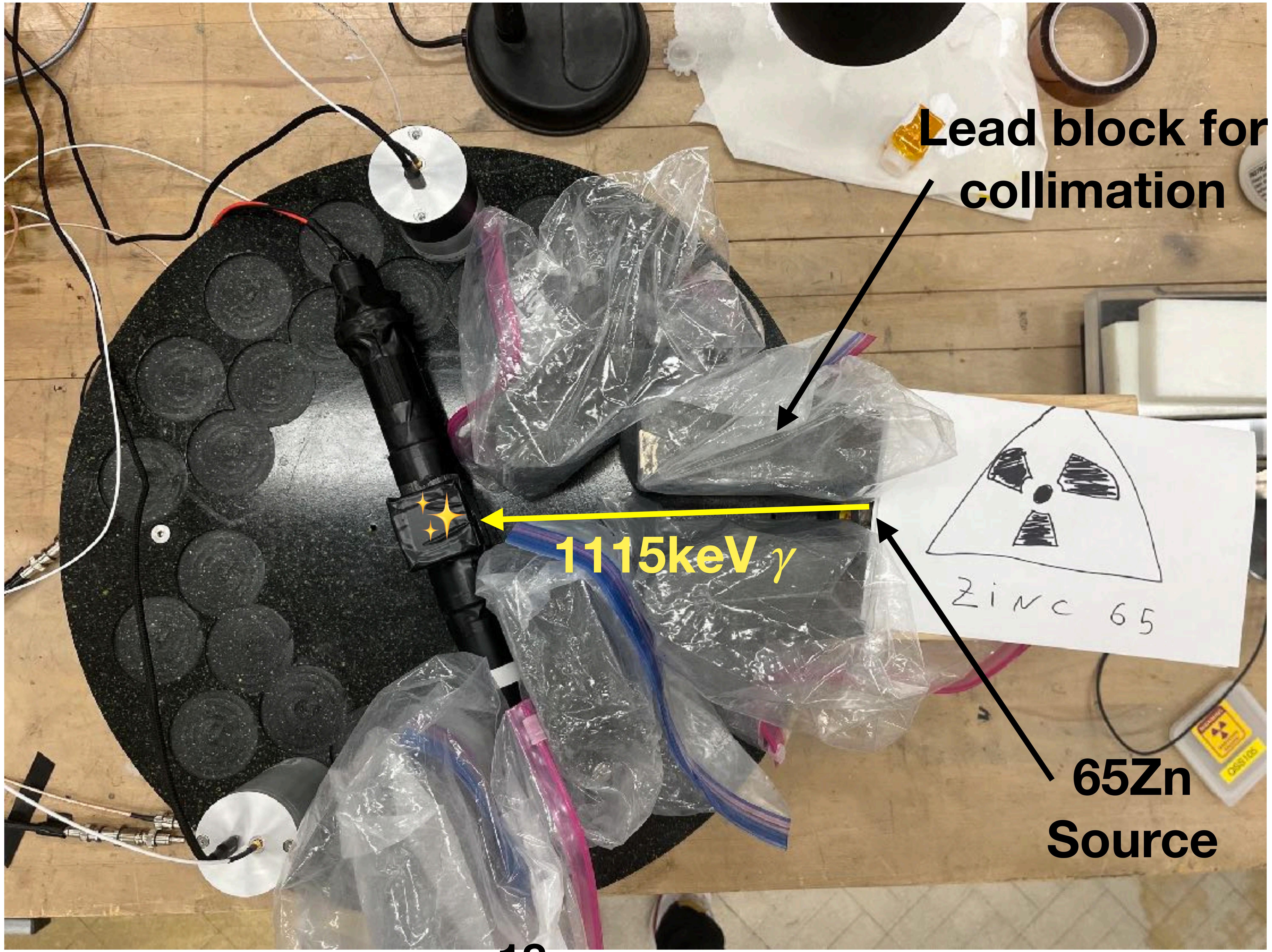
- Bad resolution and small volume of liquid scintillator
- No photopeak on a γ source spectra
- Use the Compton scattering effect to determine the relative light yield between liquid scintillators

Energy calibration of the liquid scintillator

Compton coincidence experiment - setup

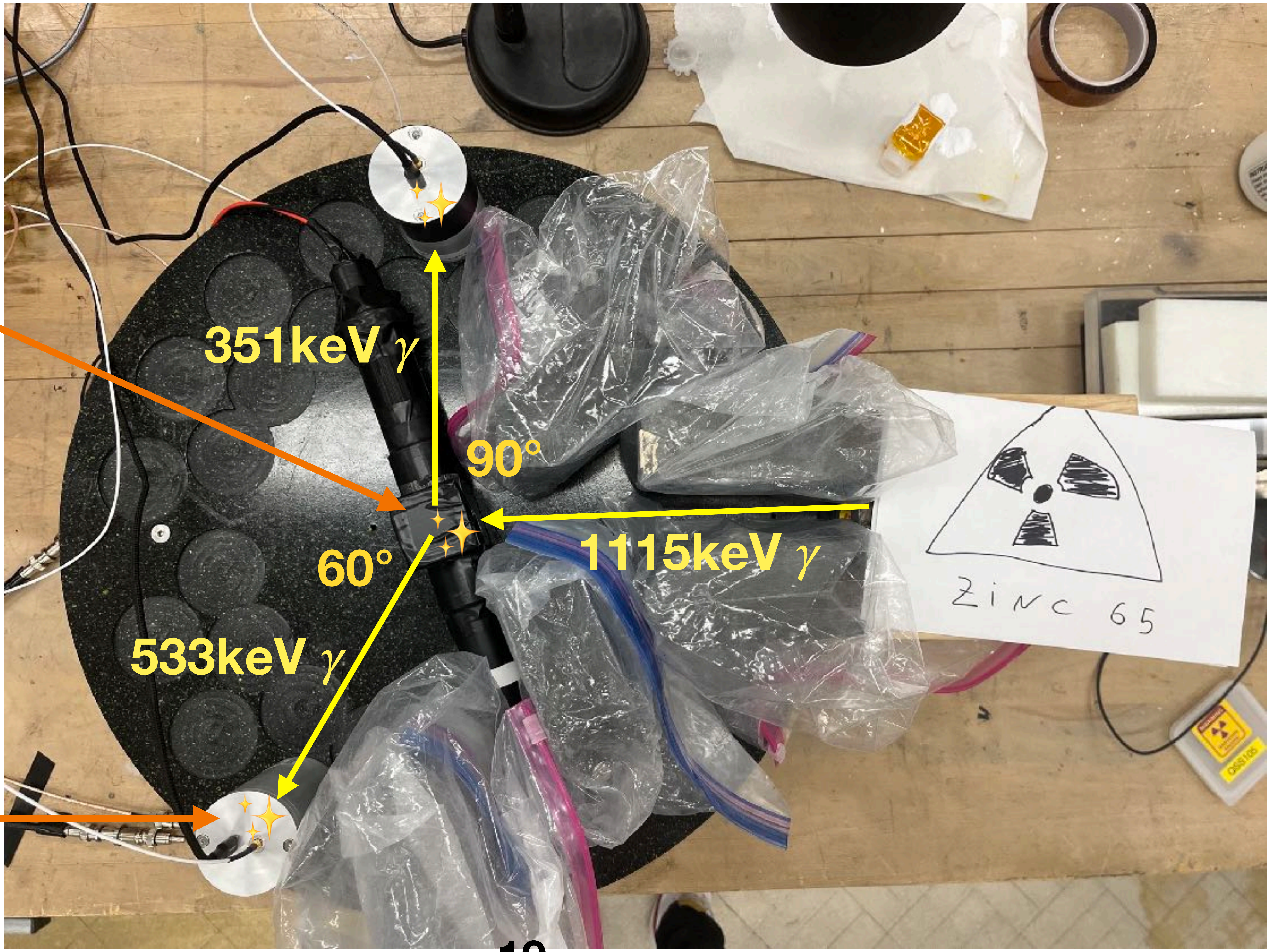


Energy calibration of the liquid scintillator



Energy calibration of the liquid scintillator

Incident gamma scatters and deposits energy in the liquid scintillator



Scattered gamma detected on NaI crystal

Energy calibration of the liquid scintillator

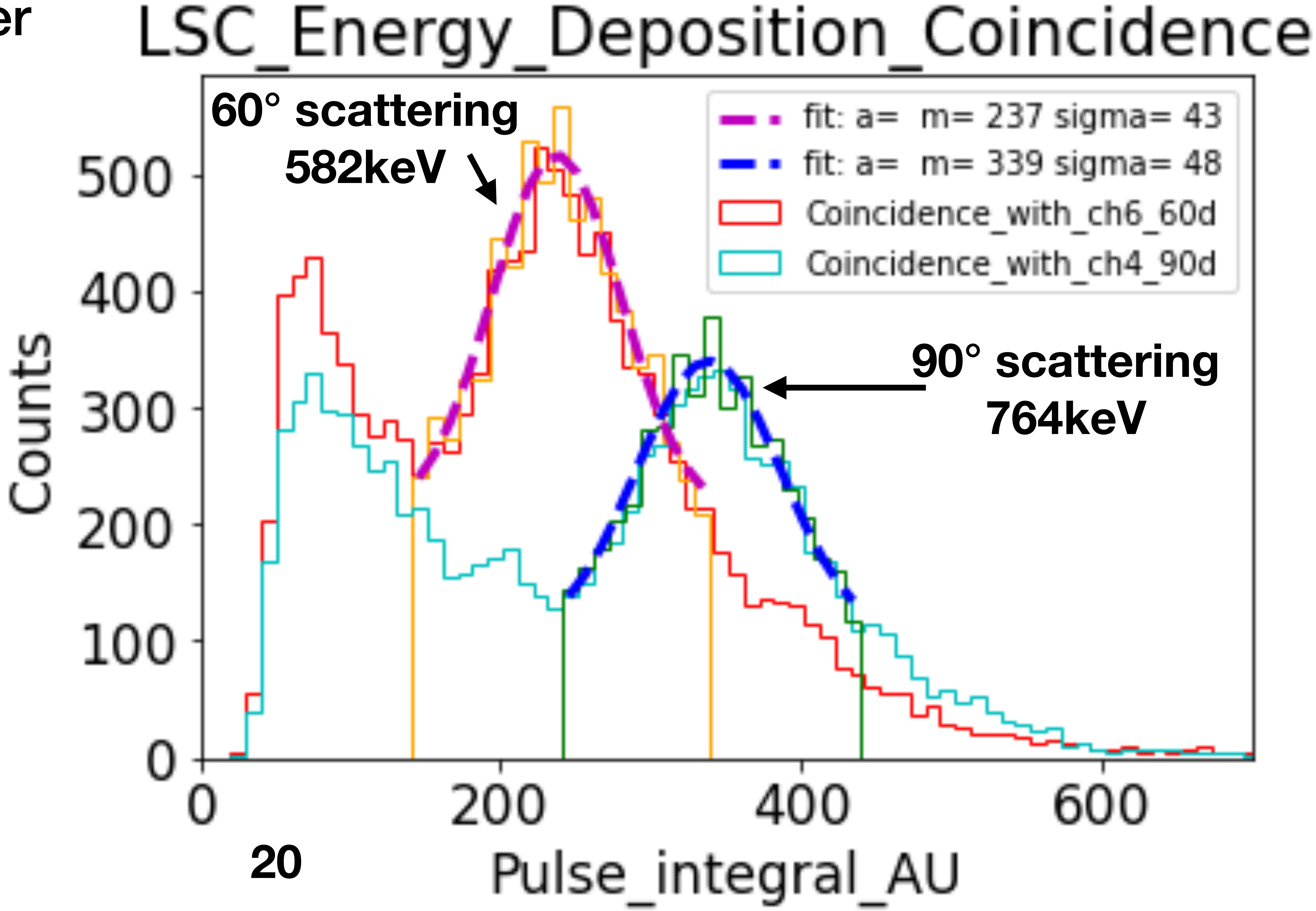
60° - 90°, UltimaGold, 2 PMT Hamamatsu R6095
65Zn Source - 240ns Coincidence Window
400lsb LSC - 200lsb NaI - 1050V high voltage 15h

Kinetic energy of the electron after scattering with incident γ E_o:

$$T_e = E_0 - E = E_0 - \frac{E_0}{1 + \alpha(1 - \cos\theta)}$$

$$\alpha = \frac{E_0}{m_e\, c^2}$$

- ✓ Compare light yield of different cocktail
- ✓ Compare light collection of different setup
- ✓ Energy calibration of beta detector



Liquid scintillation study Campaign

Goal: Determining which cocktail should be used for KDK+ experiment:

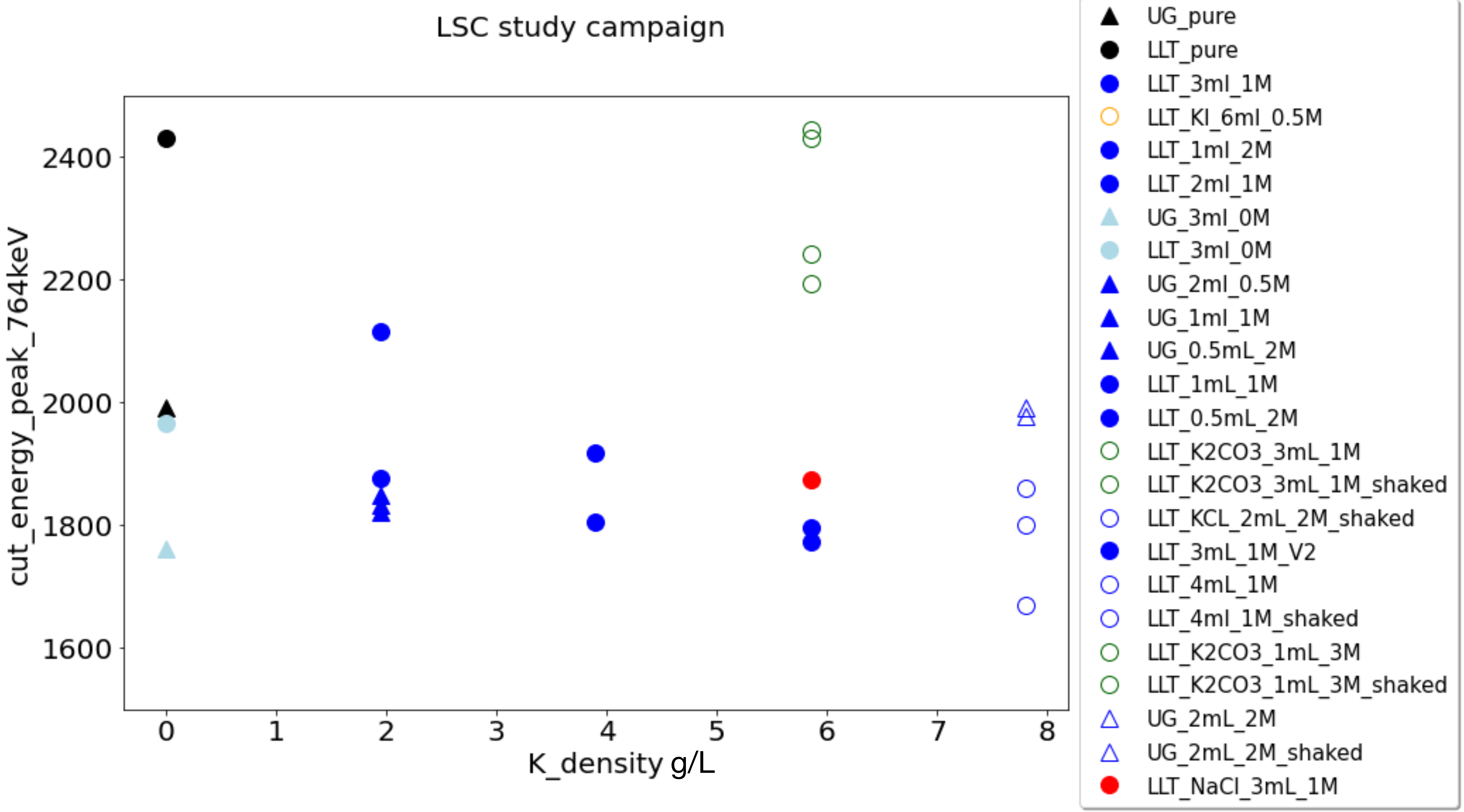
- Liquid scintillator type: Ultima Gold, Ultima Gold LLT
- Potassium Salt: KCl, K2CO3, KI, KOH.
- Volume and concentration of the aqueous solution mixed with the LSC

Requirements:

- Liquid scintillator stable over time; experiment can be longer than a week.
- Maximum light yield.
- Potassium homogeneously dissolved in the vial.

Liquid scintillation study Campaign

Quantitative results



Different kind a vial for liquid scintillation

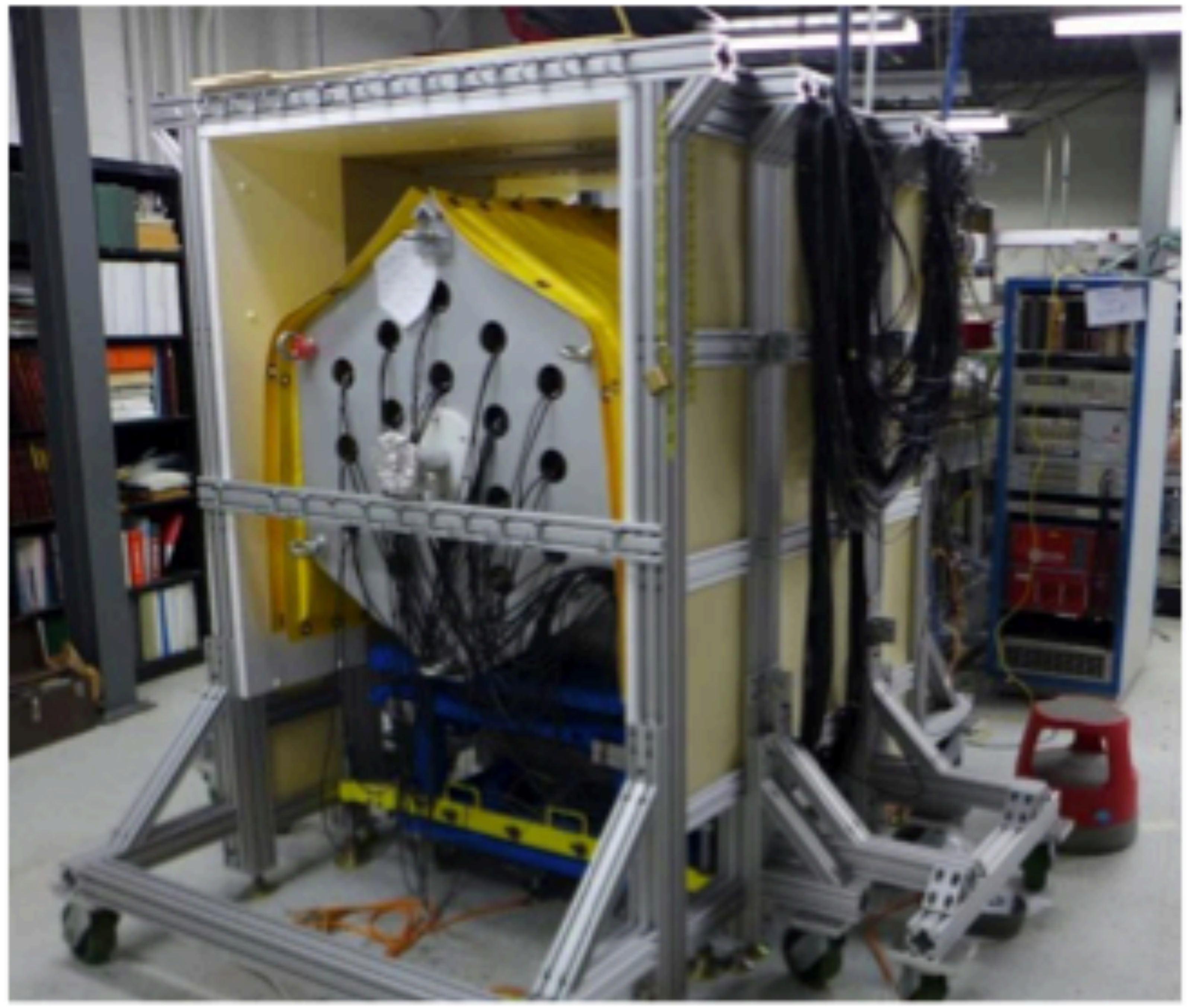
Machined Teflon vial with borosilicate window 35mL

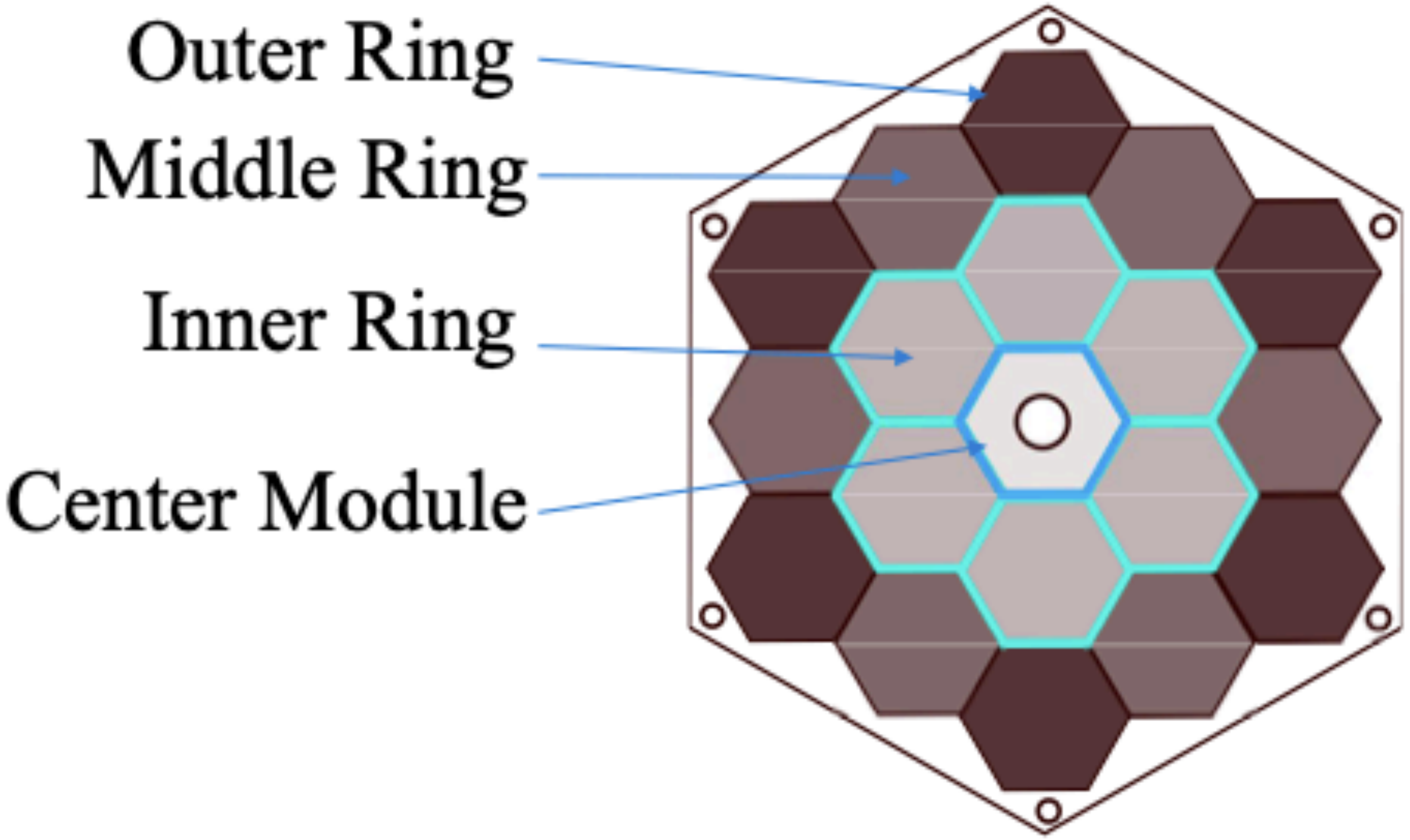
PE vial 25mL

Borosilicate vial 20mL

Gamma detector - MTAS at Michigan State University

- MTAS: Modular Total Absorption Spectrometer, at Facility of Rare Isotope Beam (FRIB).
- 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





Source: Matthew Stukel, KDK, 2023/08/30

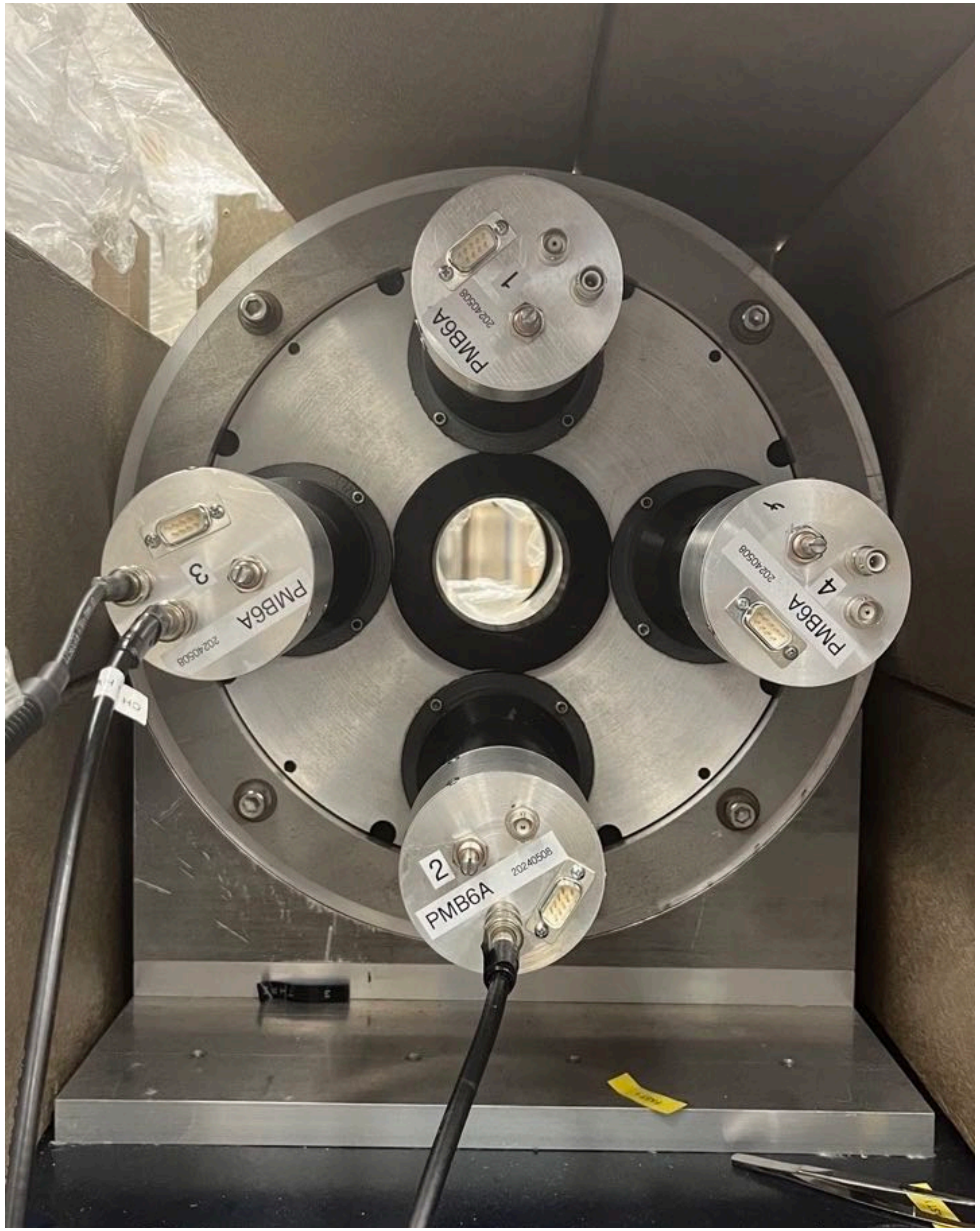
Gamma detector: NaI(Tl) annulus

Features:

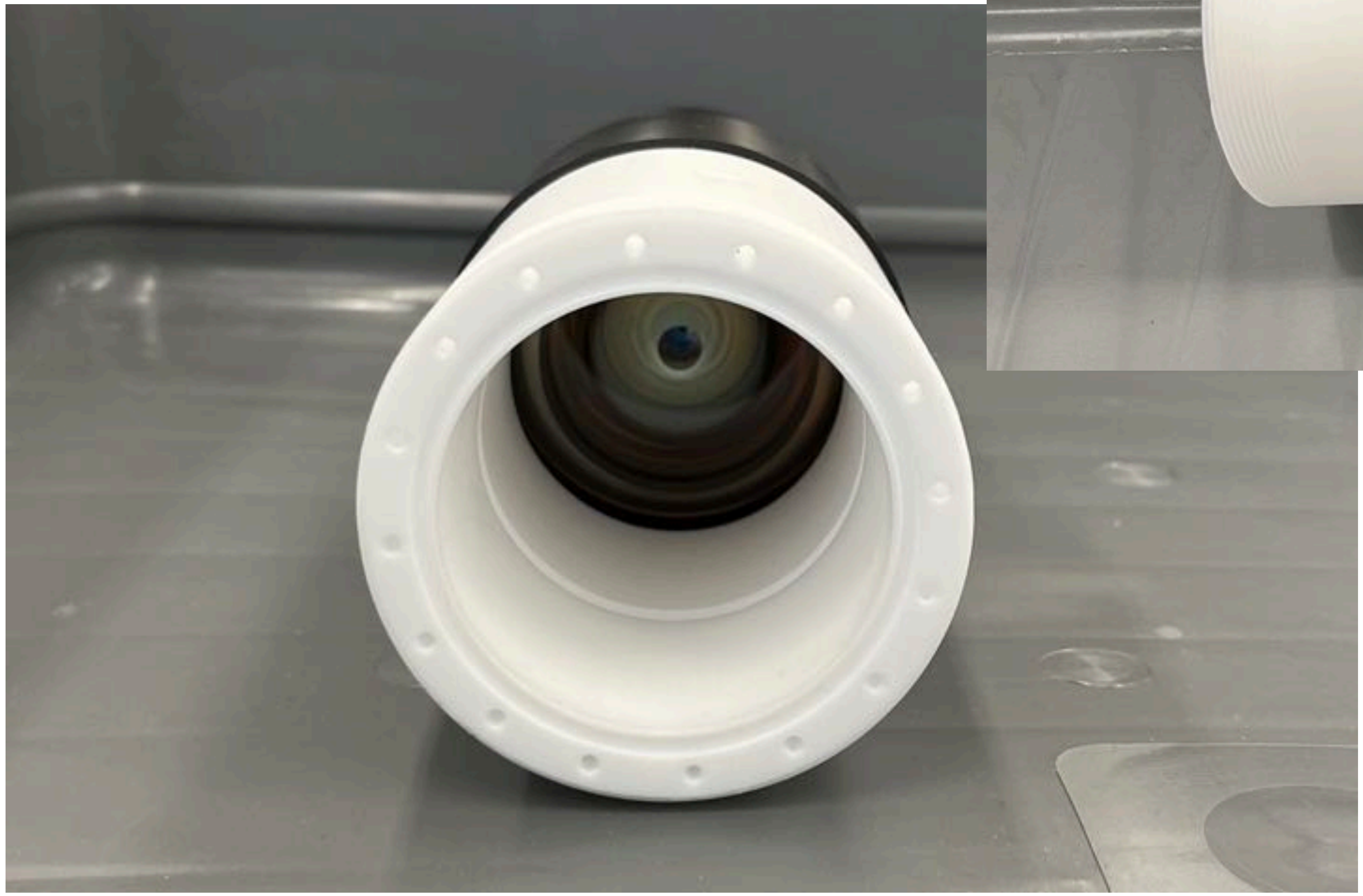
- Dating from the 1970s
- 23cm deep
- 8.5cm inner diameter hole
- 4 big Quadrant of 8cm thickness to stop 511keV gammas
- Simulation by Lilianna gives a 35% Triple-coincidence efficiency

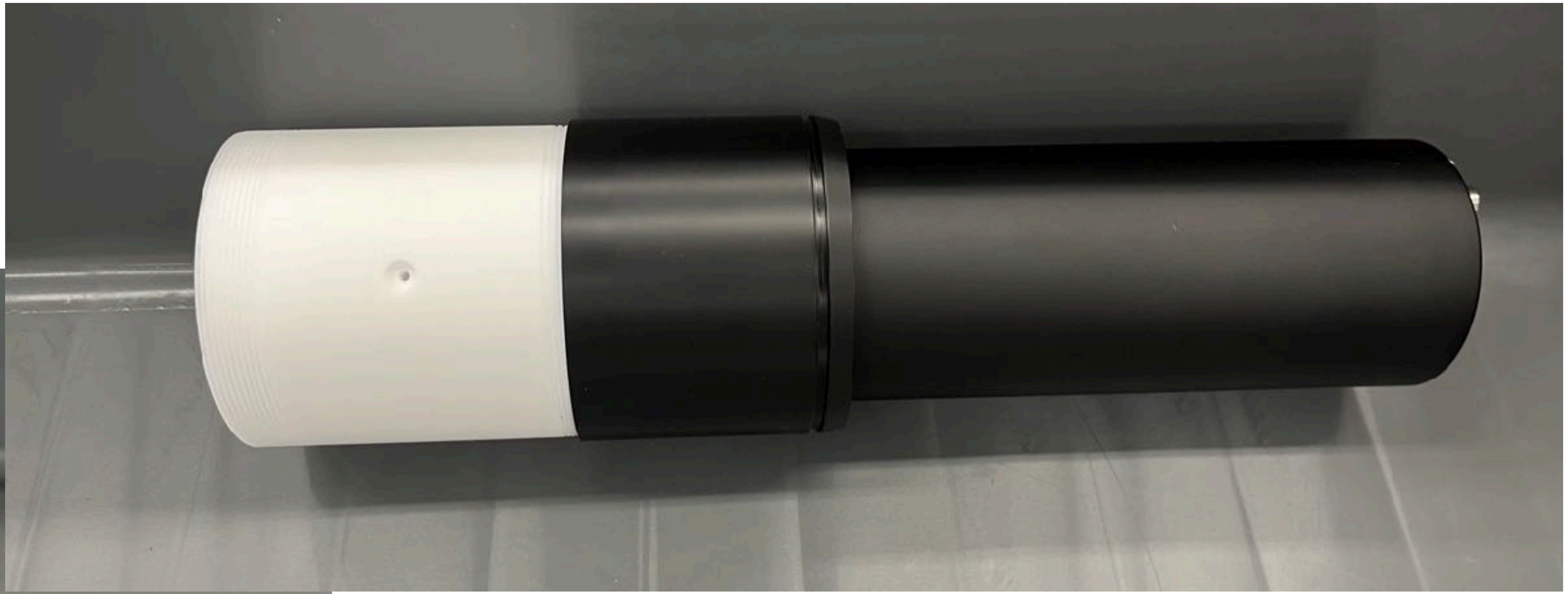
Work to be done:

- Check if the crystals are well preserved
- Determine the efficiency



Design of a 300mL liquid scintillator for our detector



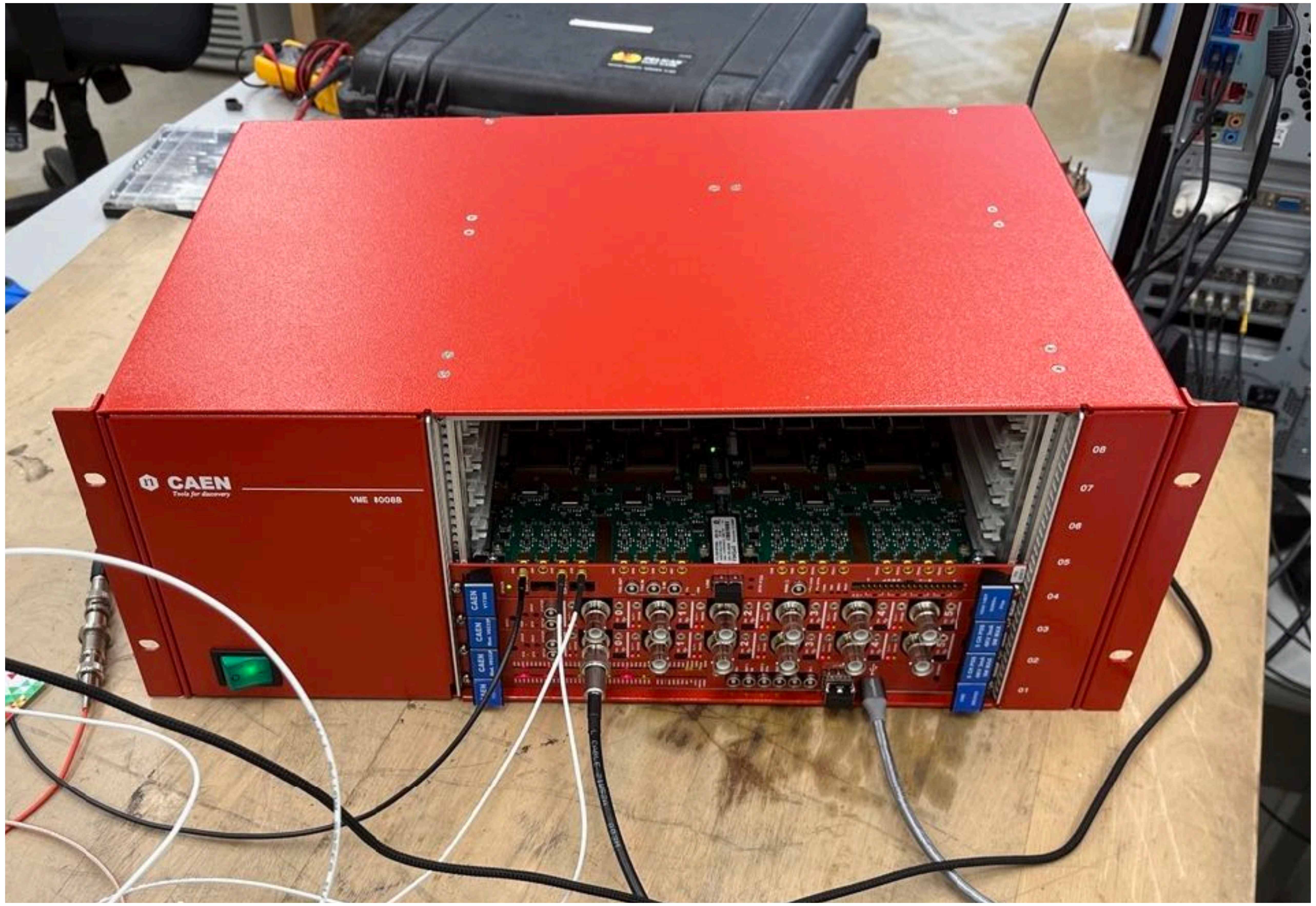


Energy calibration of the liquid scintillator

Data acquisition

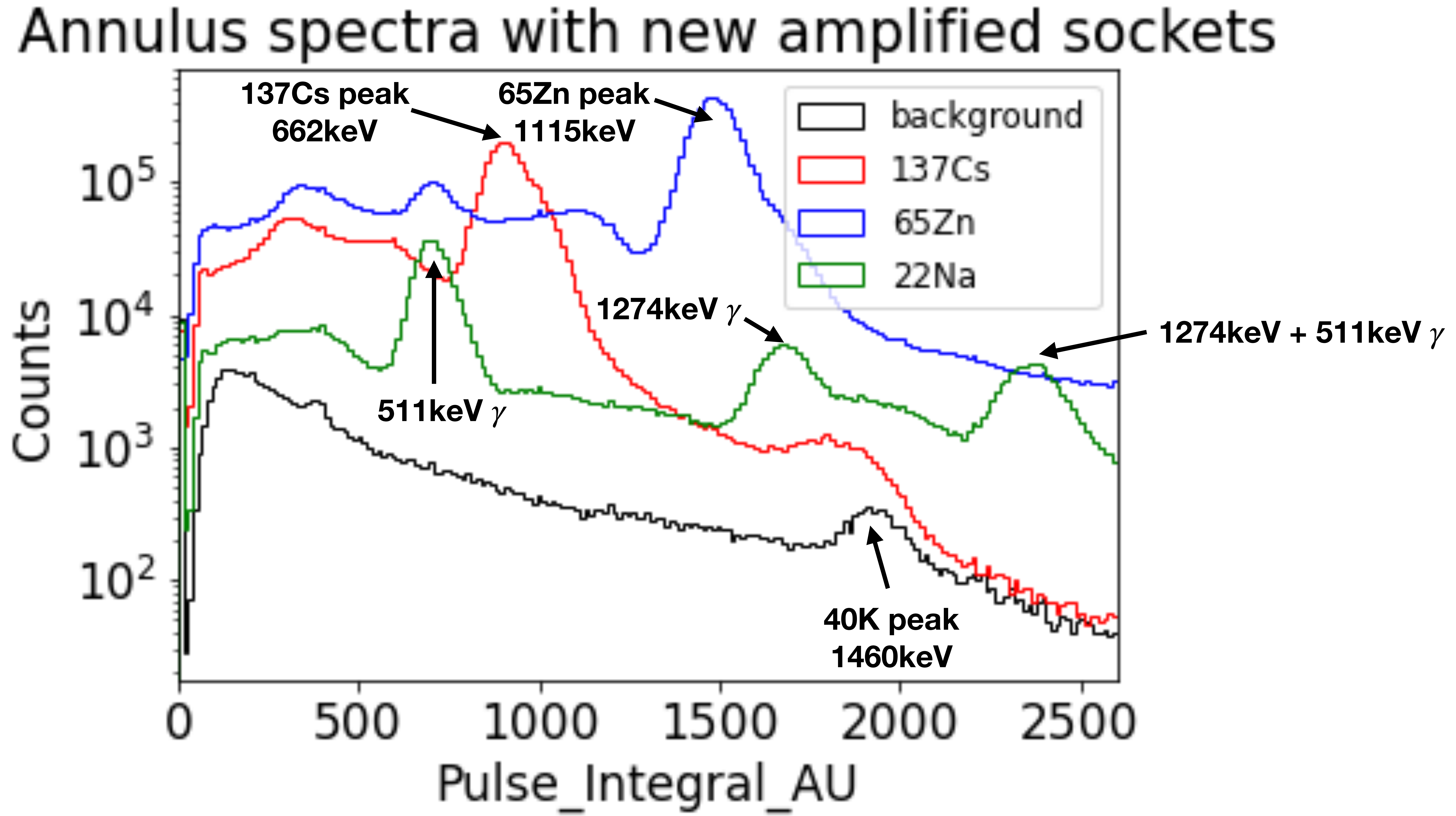
CAEN Digitizer V1730

- 16 channels
- CoMPASS software
- Spectra and Coincidence in live
- Data written on CSV, binary or root files. Analysis carried out offline



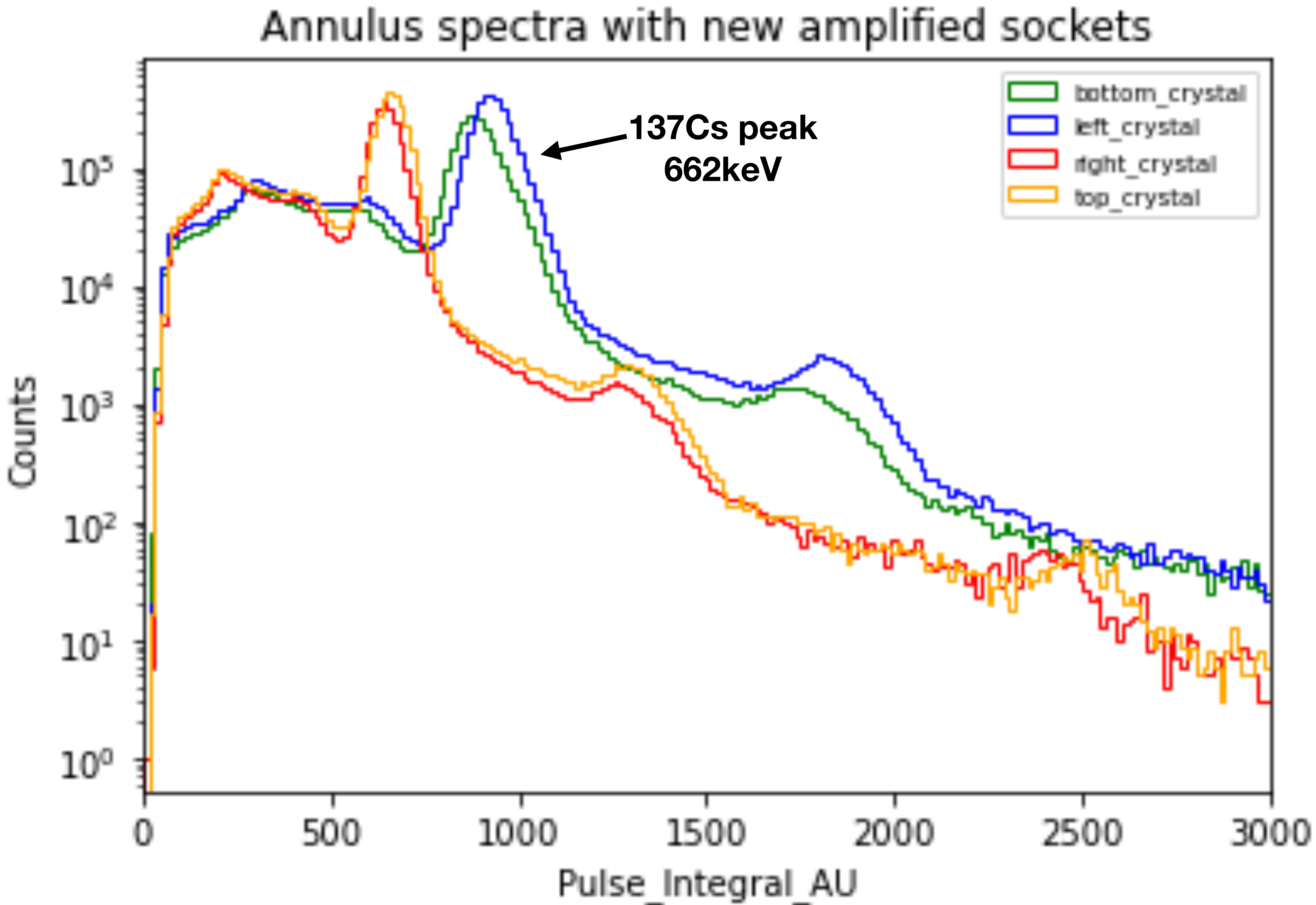
With the help of Emma and Nick to set up the computer and the configuration

Gamma detector: NaI(Tl) annulus



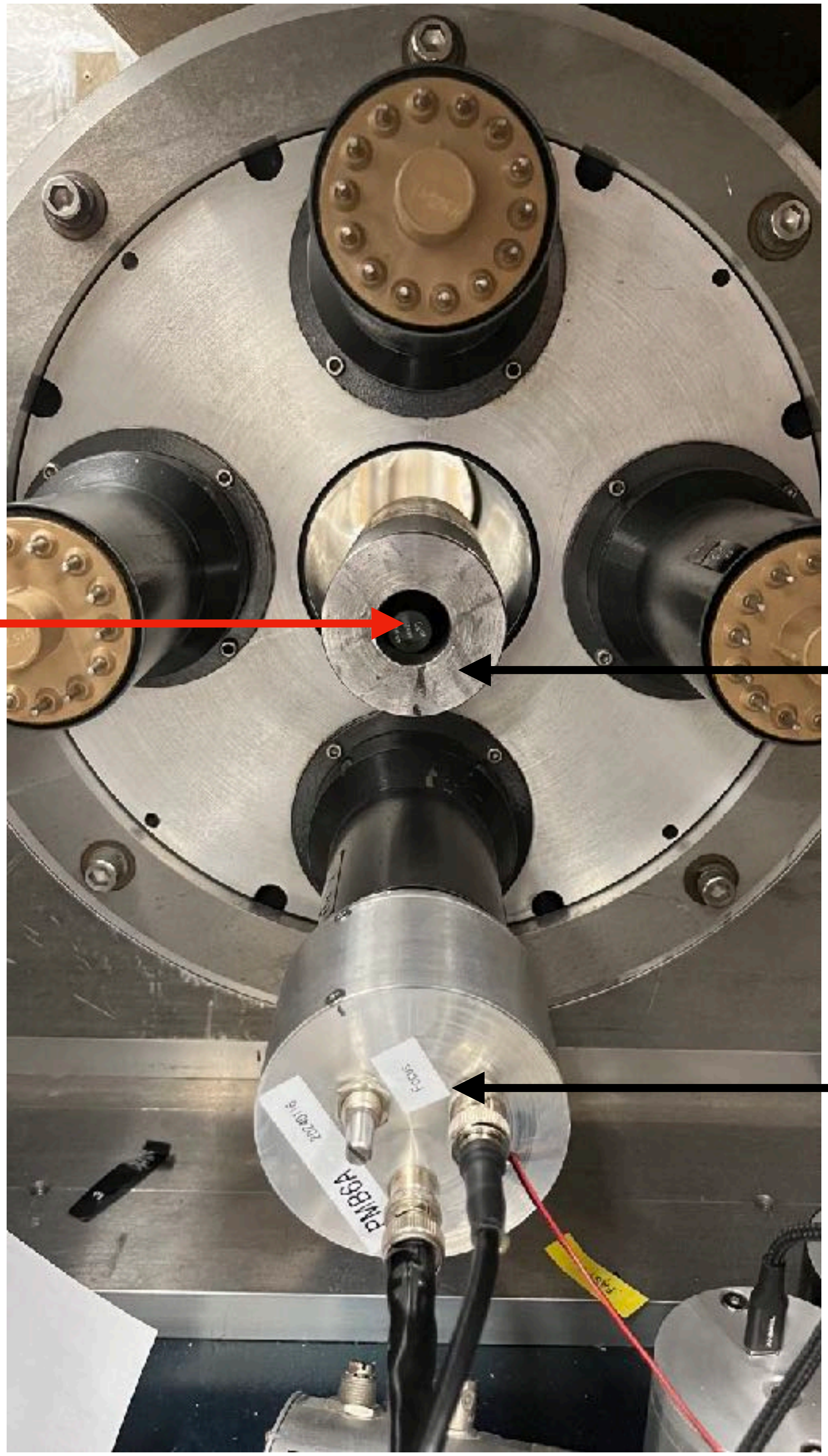
Annulus PMT - New socket - 4 crystals comparison

1300 positive high voltage



Annulus PMT - New socket - bottom crystal

137Cs source

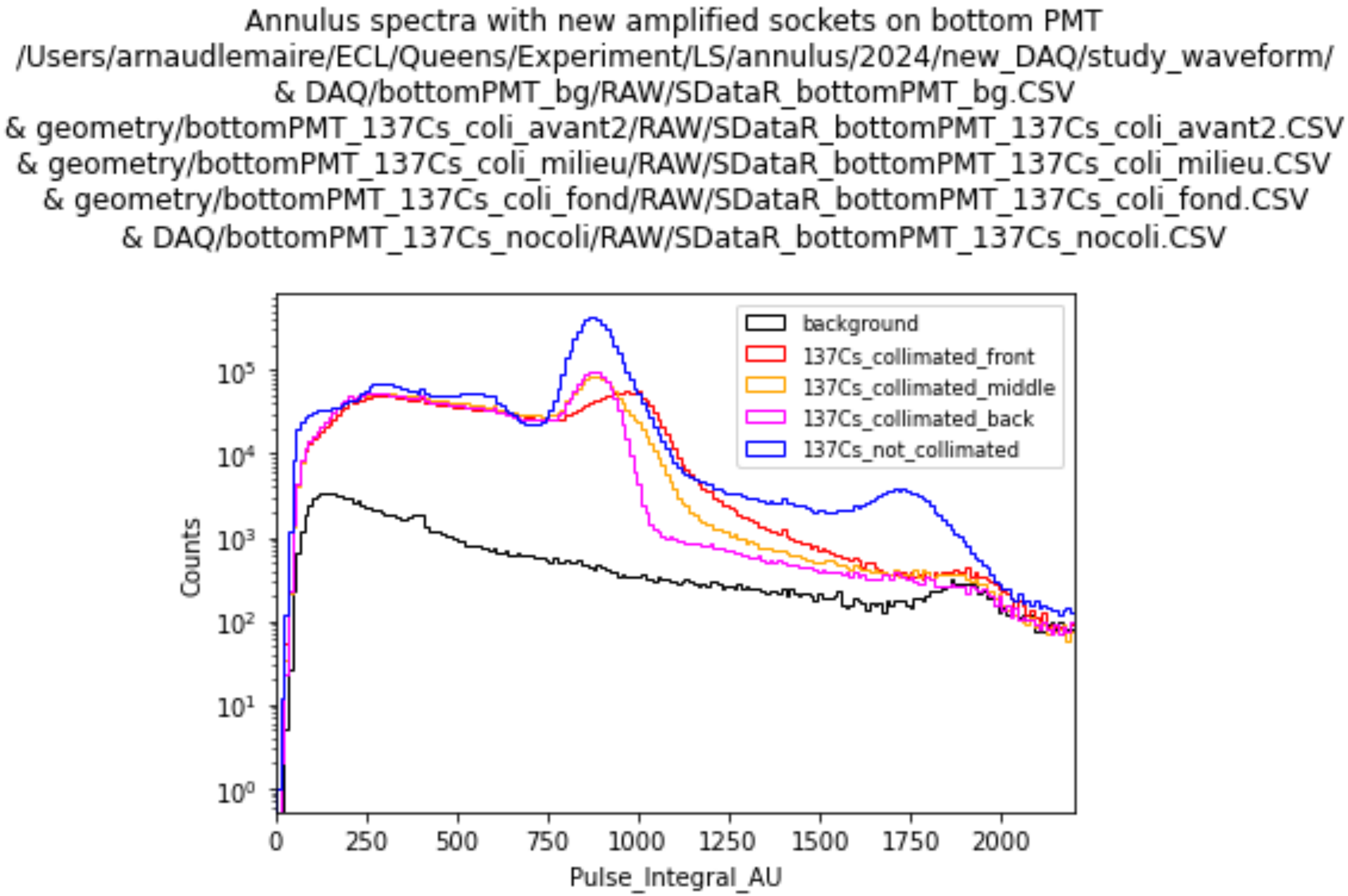


Iron collimator

New socket

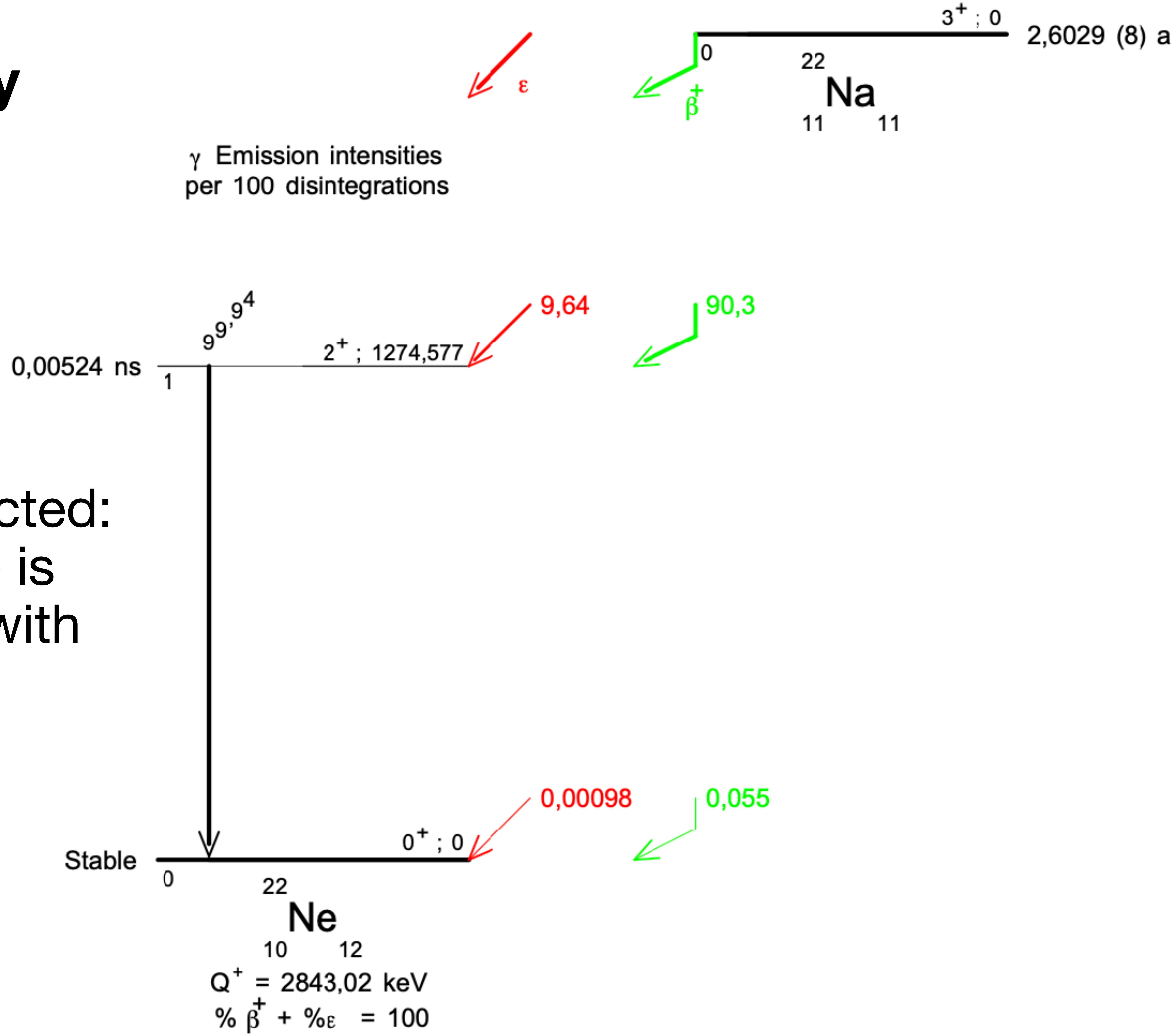
Annulus PMT - New socket - bottom crystal

1300 positive high voltage - 137Cs source

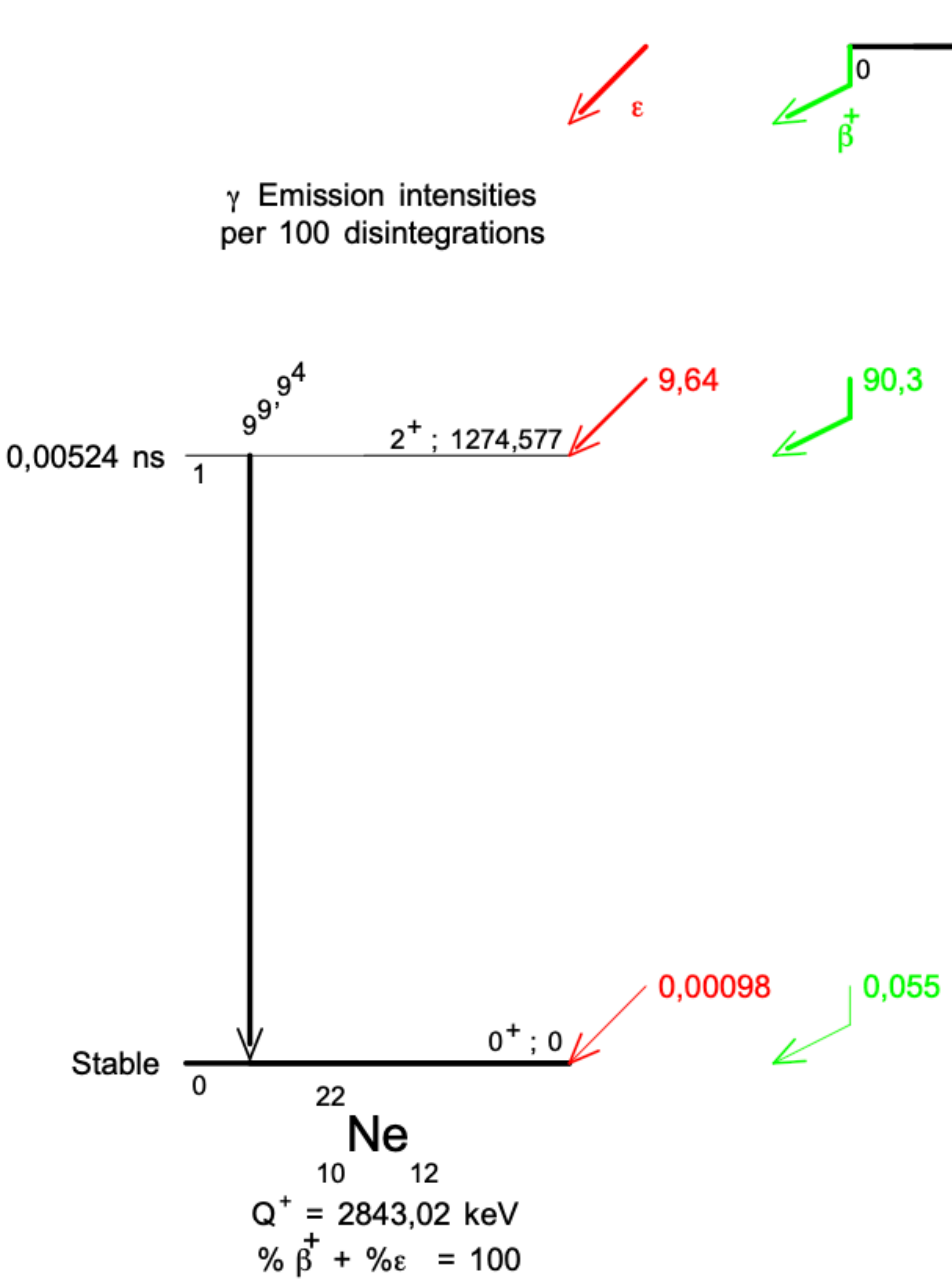


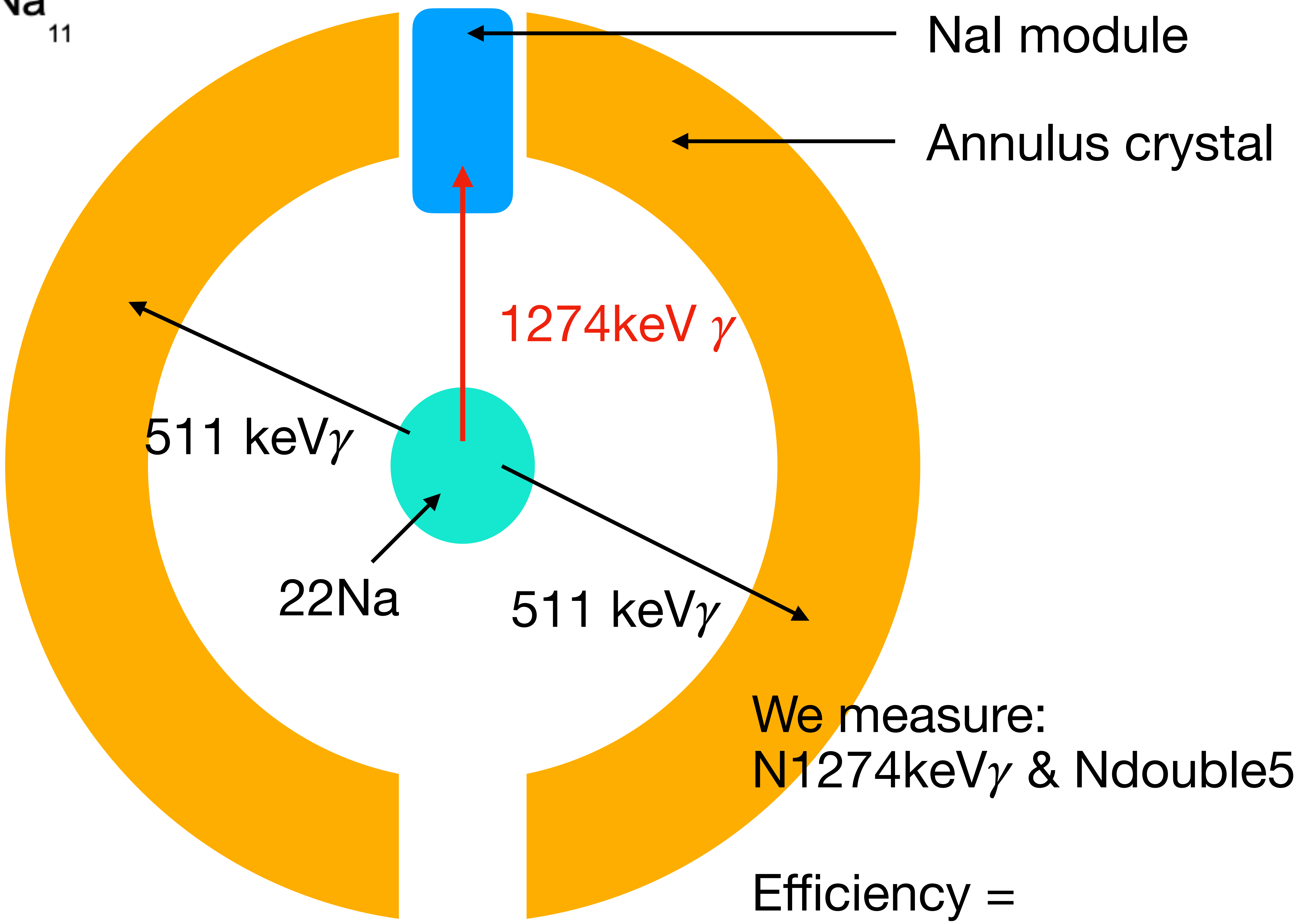
Triple coincidence efficiency

- Sodium very close chemically to potassium
  - ✓ Dissolve itself in the liquid scintillator the same way
- When a 1275 keV gamma is detected: 90.3% of the time, a beta particle is emitted and should be detected with two 511 keV back-to-back γs
- Determine experimentally the efficiency



Annulus Efficiency - 2 crystals

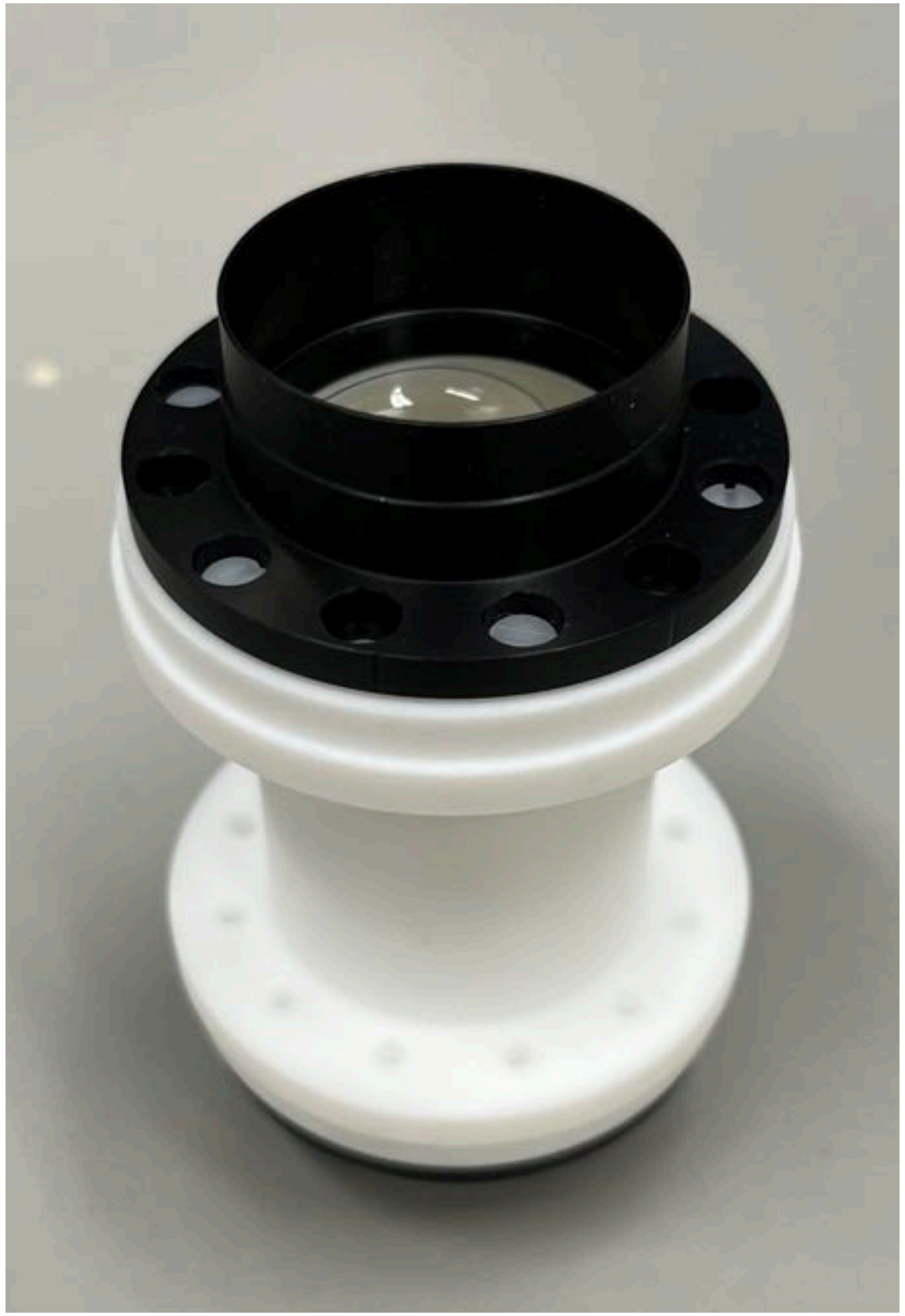


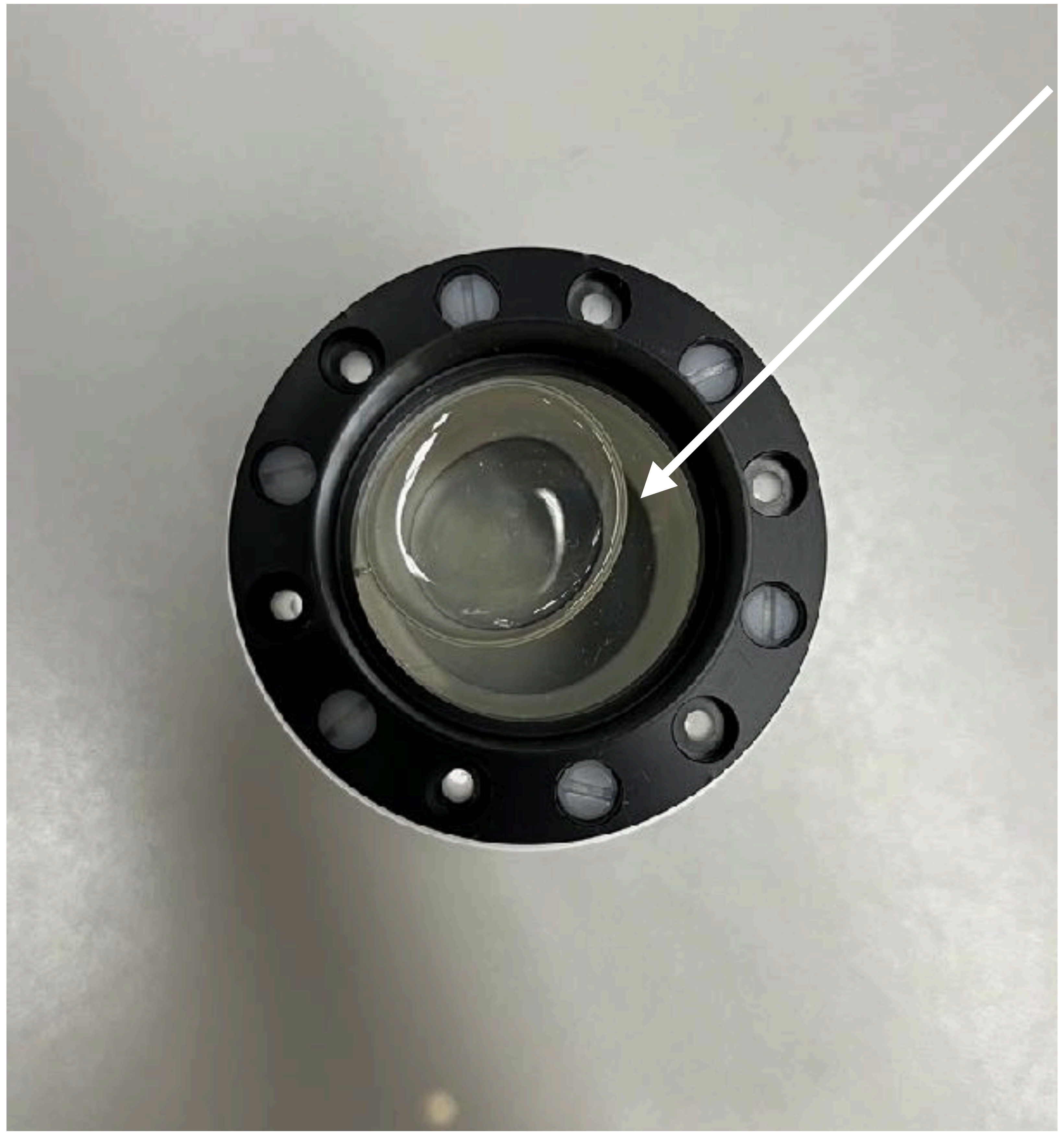


We measure:
N1274keVγ & Ndouble511keVγ

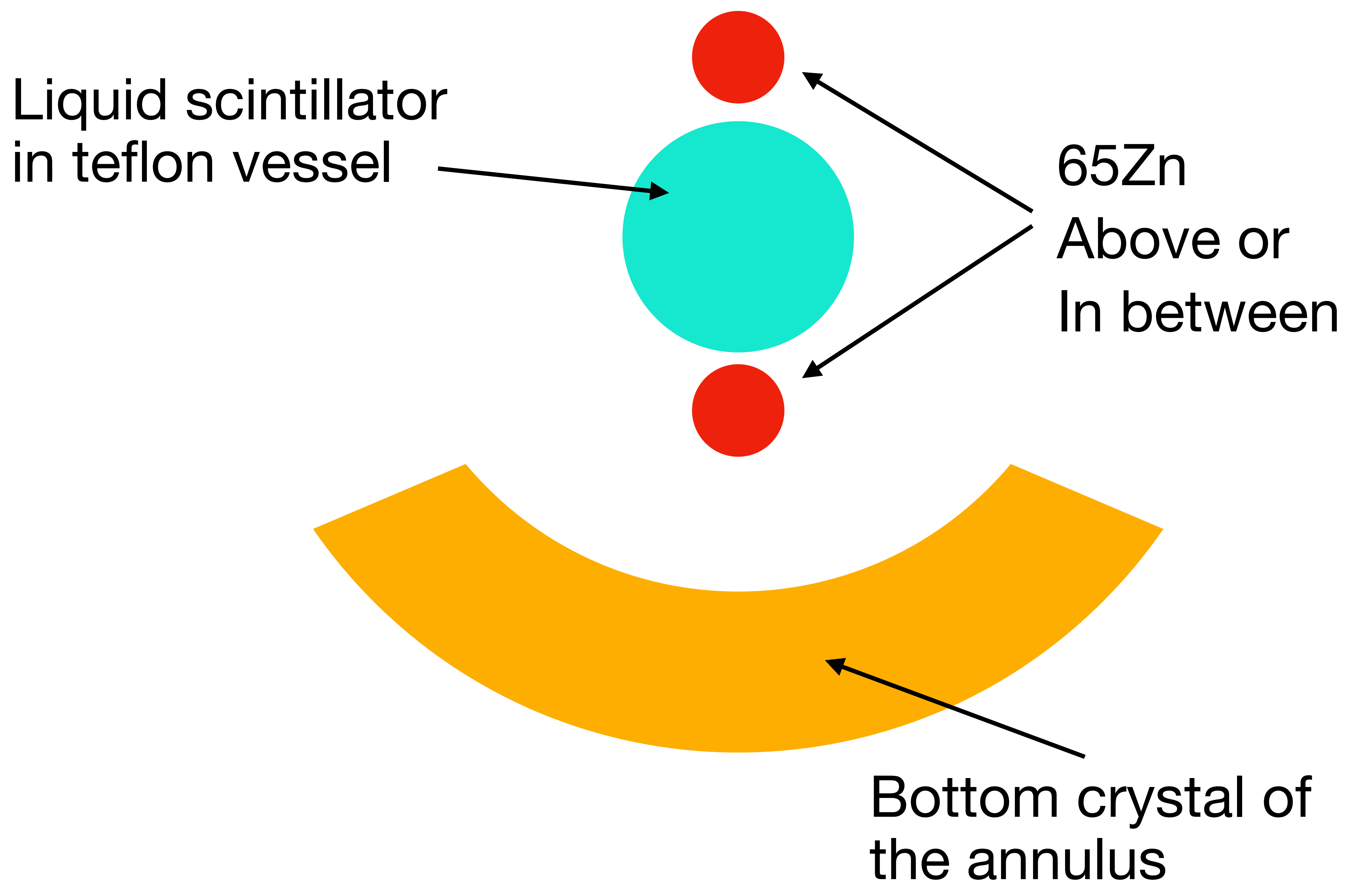
Efficiency =
Ndouble511γ / (0.903* N1274γ)

Teflon Vessel for liquid scintillator

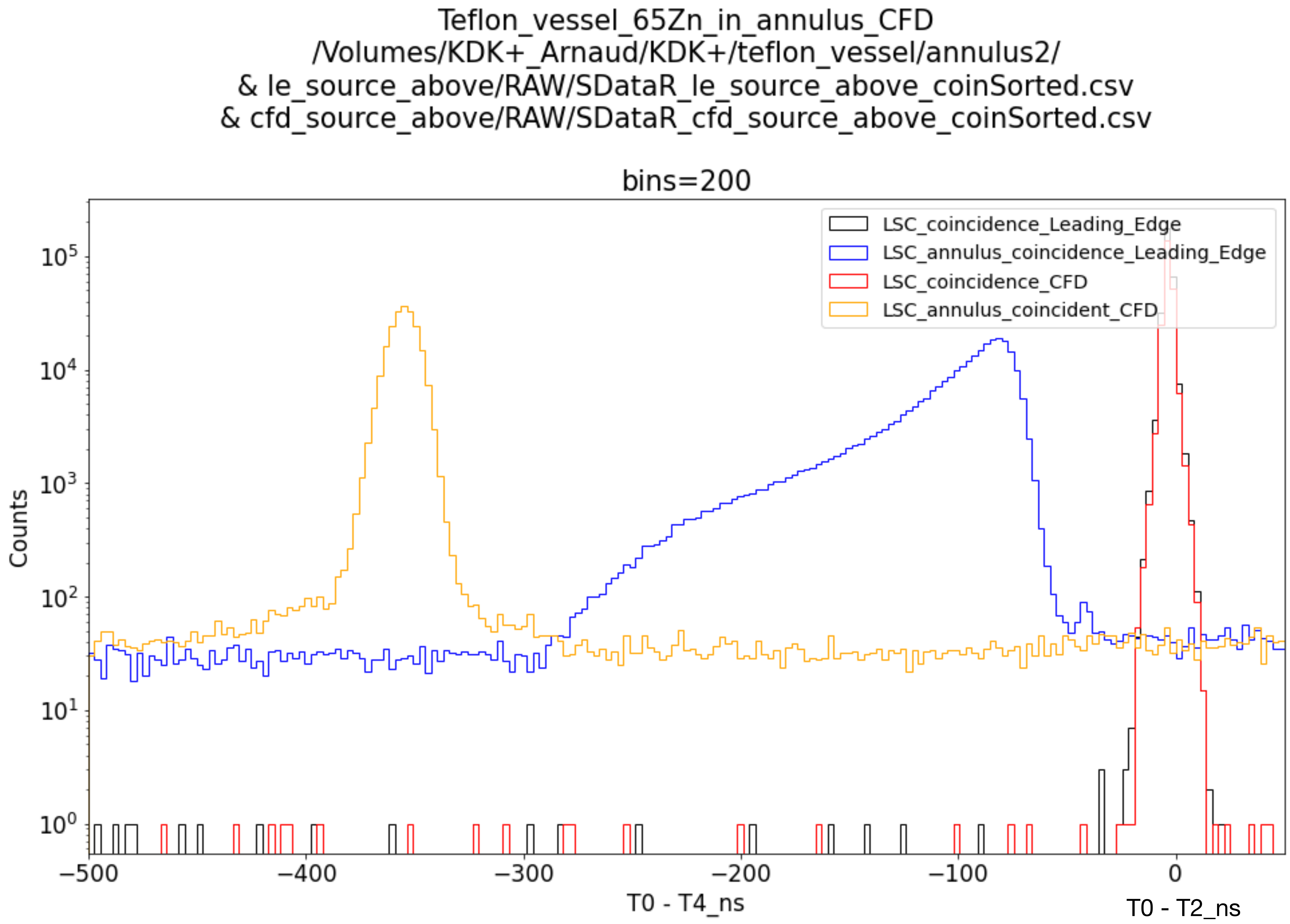


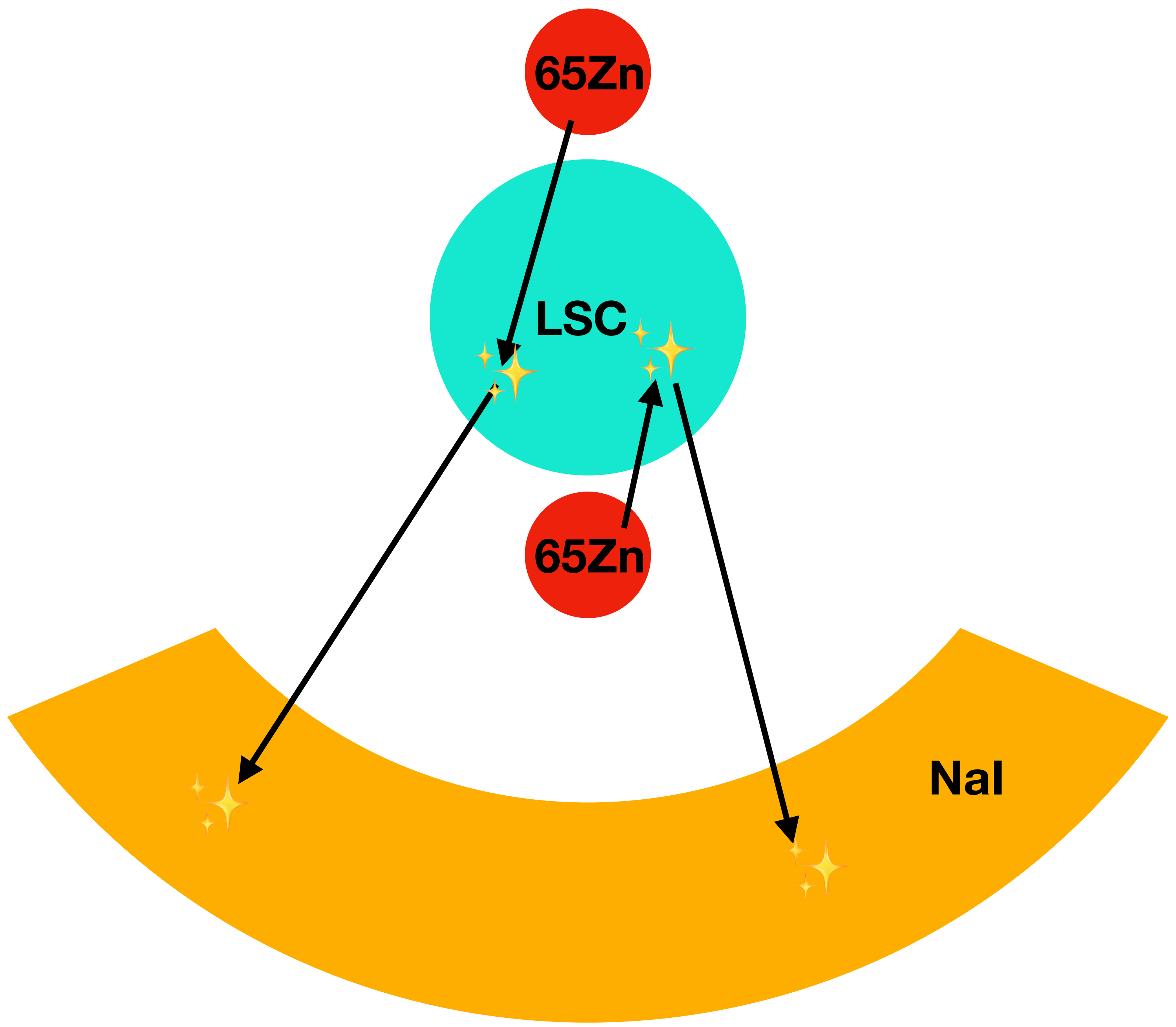


Teflon Vessel in the annulus

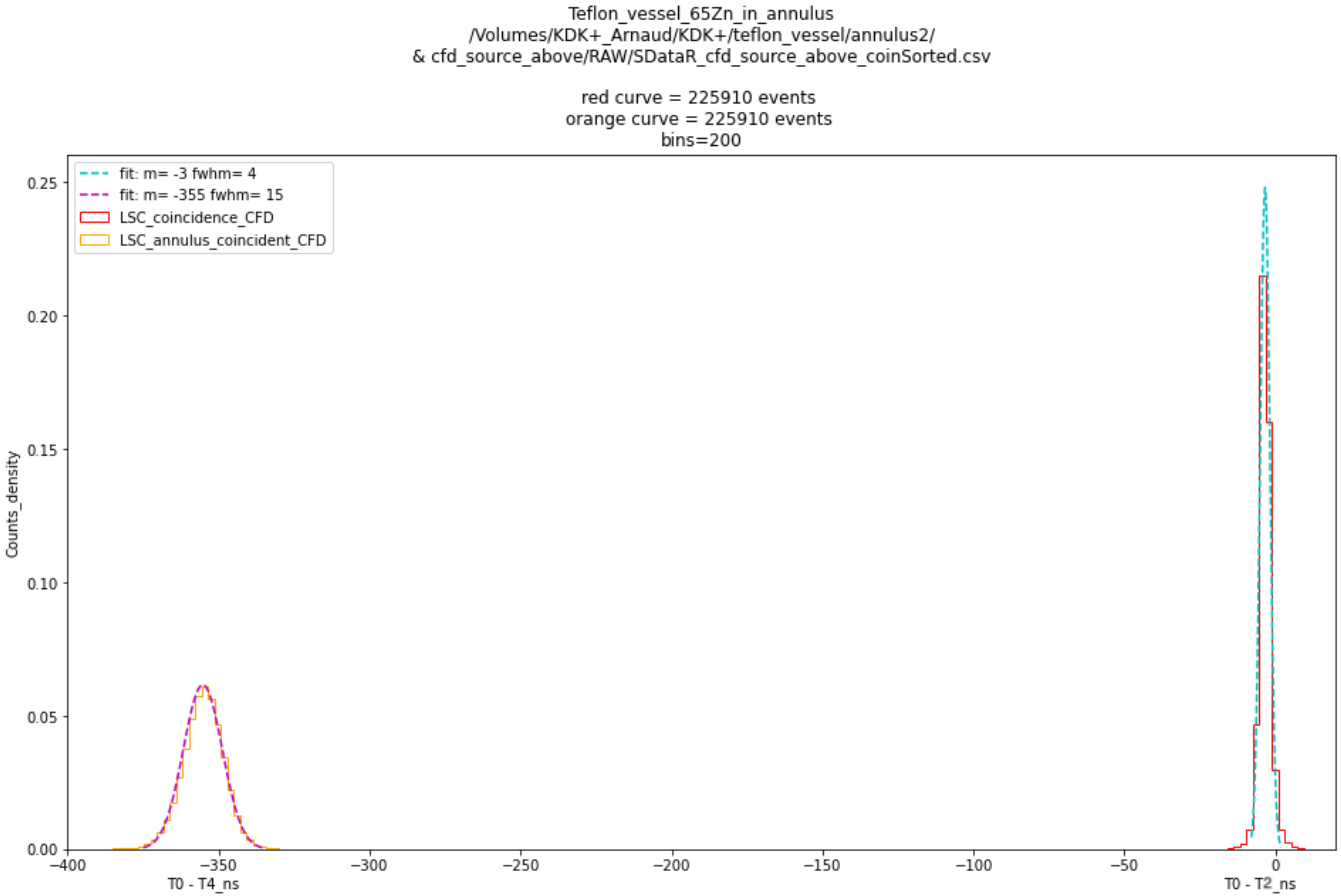


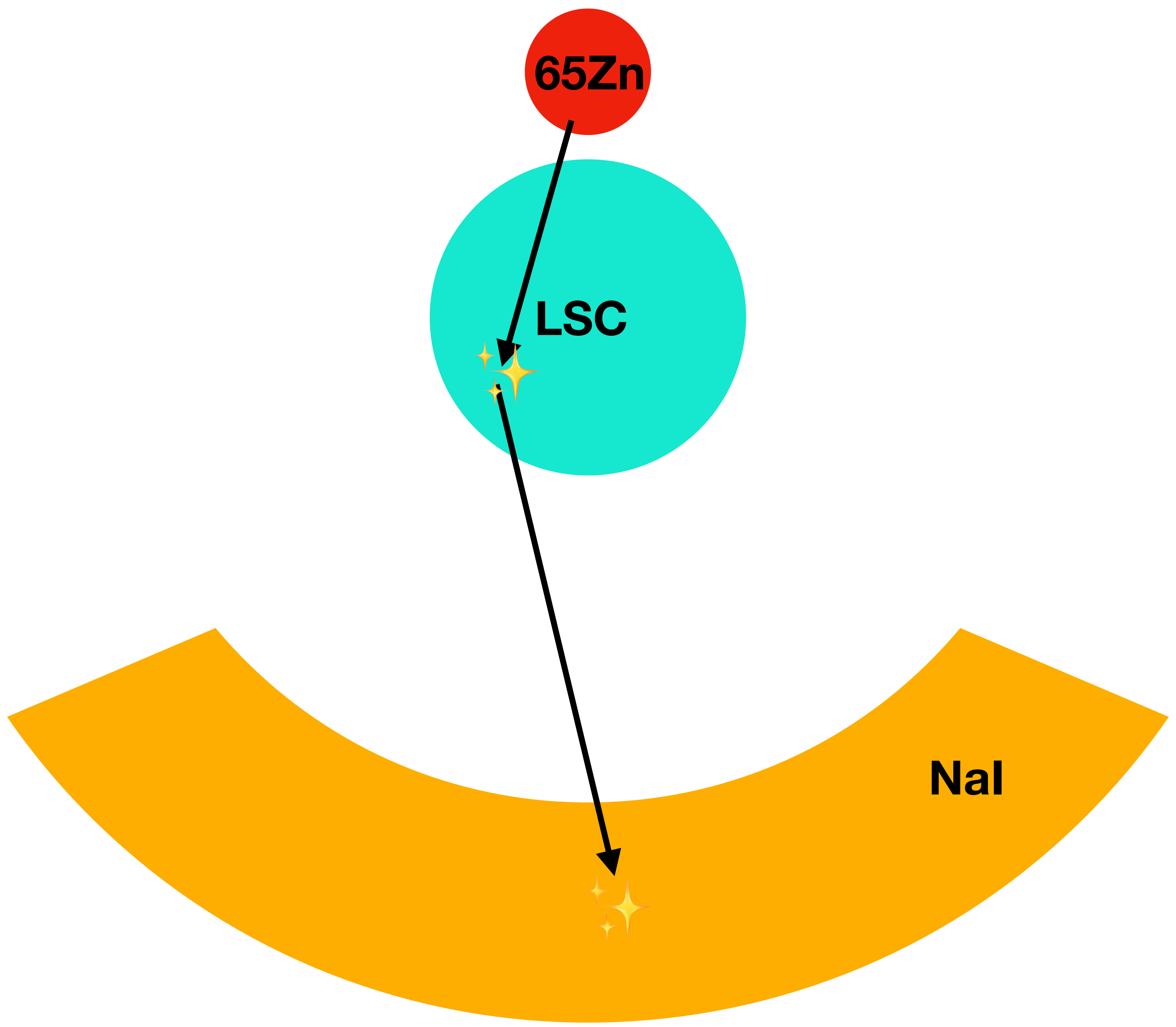
Teflon Vessel in the annulus - coincidence window





Teflon Vessel in the annulus - coincidence window





Conclusion

Results:

✓ Method to load potassium in the LSC
✓ Choose the optimum LSC cocktail loaded with 40K
✓ Working Compton coincidence to calibrate energy and resolution of LSC
✓ Make the socket for NaI annulus and determine time resolution

Next steps:

✓ Run test with 22Na for detector efficiency
✓ Do experiment with 40K at natural abundance in 300mL Teflon vessel

Annexe

Energy calibration of the liquid scintillator

2nd setup, less plastic

Reflective foil to improve light collection by the PMT

Energy calibration of the liquid scintillator

2nd setup, less plastic

Reflective foil to improve light collection by the PMT

Energy calibration of the liquid scintillator

Platform

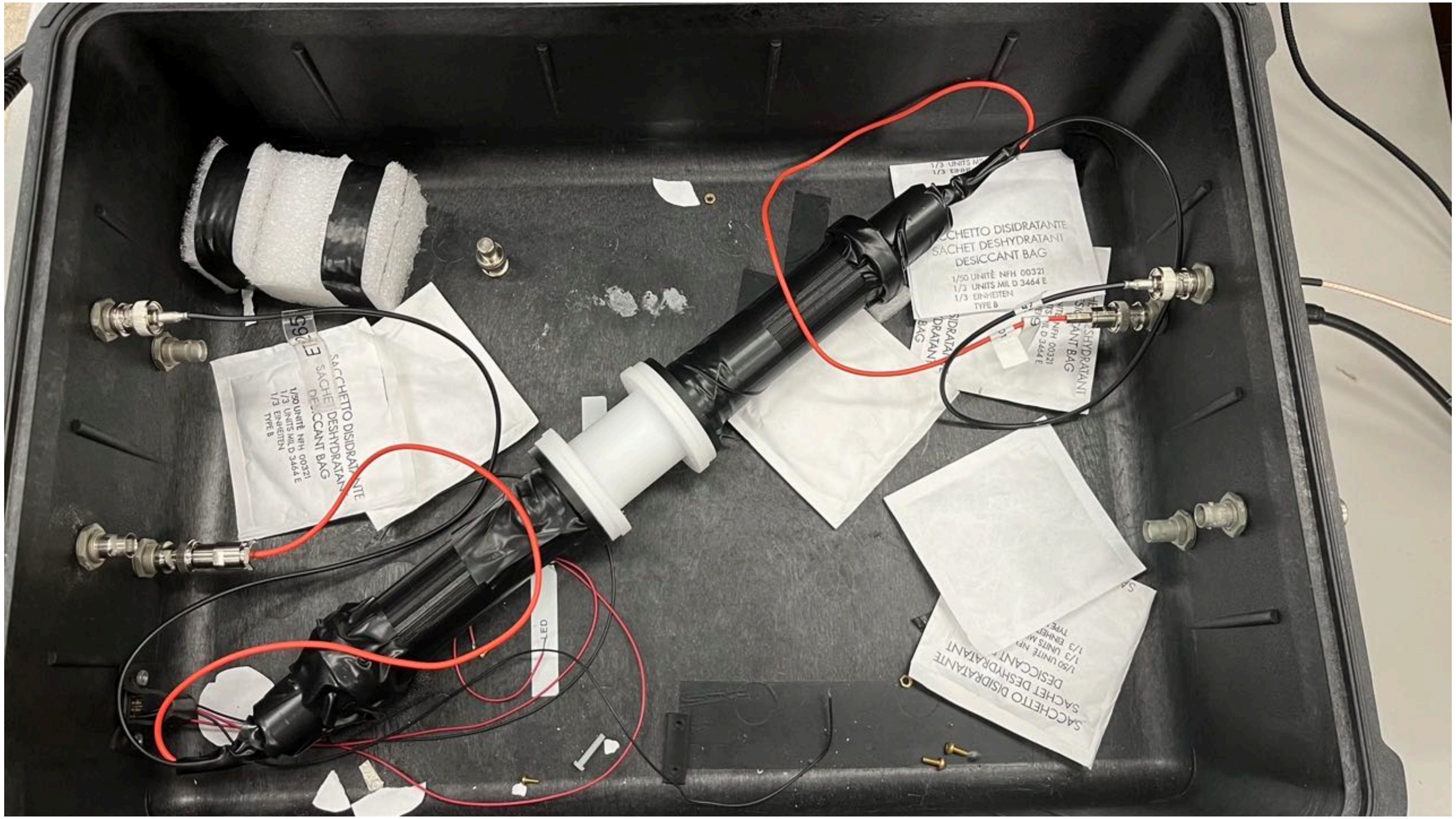
Sodium Iodide module:
2" deep x 2" dia. crystals
with SiPM

Slots for NaI module
For every 10° from 0
to 140° at 20cm

Energy calibration of the liquid scintillator

Vial holder for plastic vial with PMT on each side

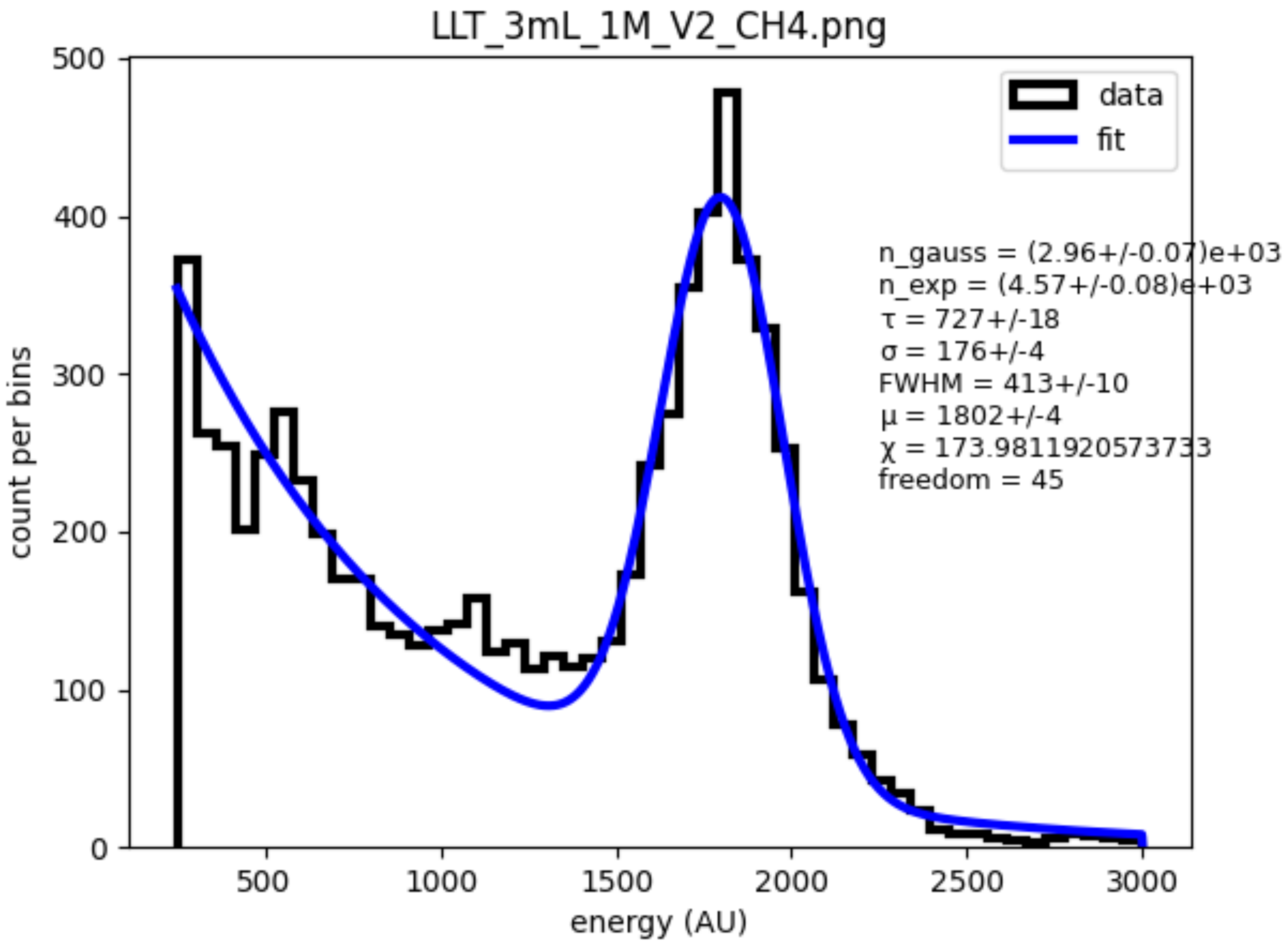
Teflon Vessel test



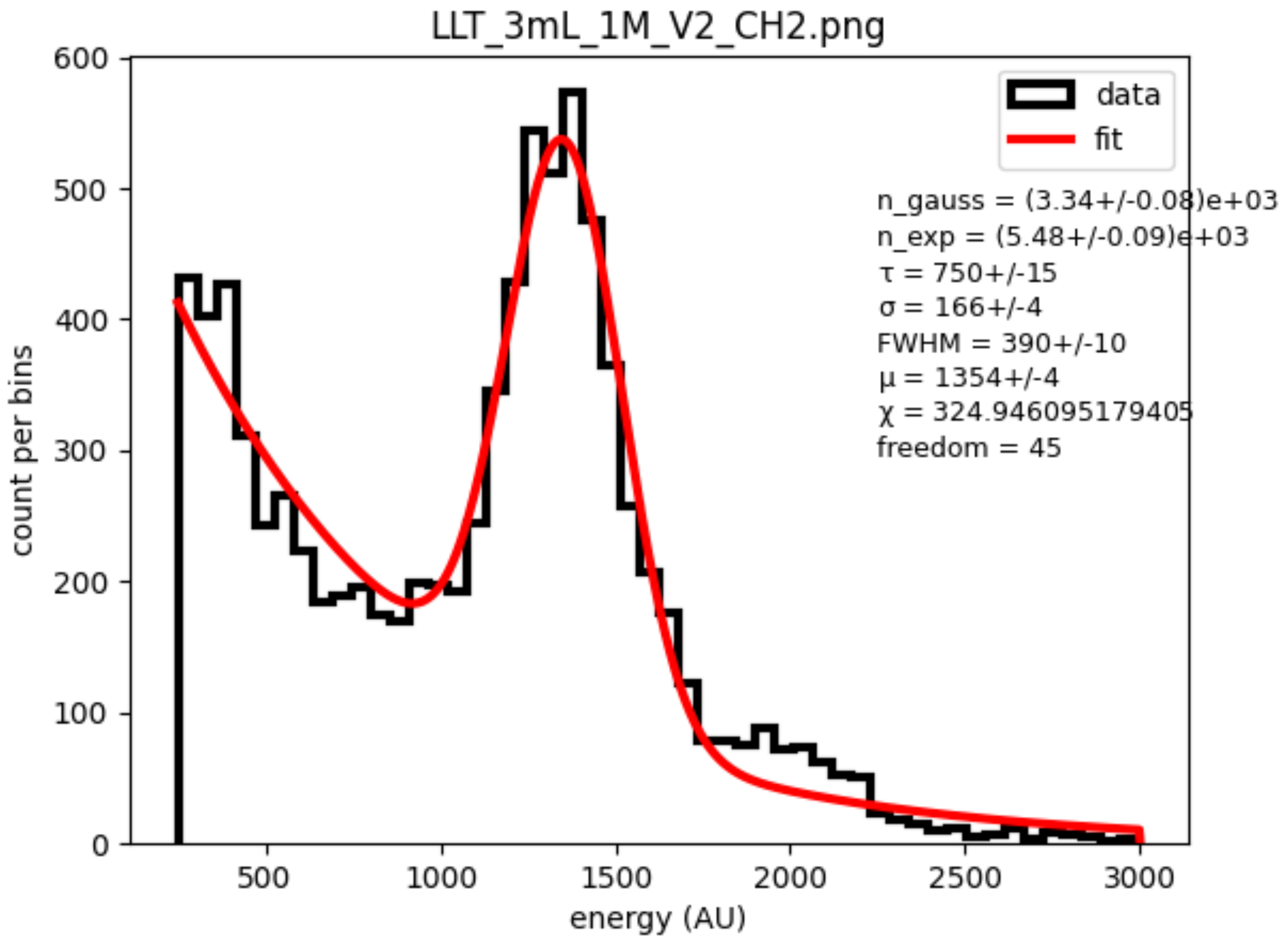
Liquid scintillation study Campaign

Quantitative results: Fitting the Compton peak

90° scattering
764keV



60° scattering
582keV

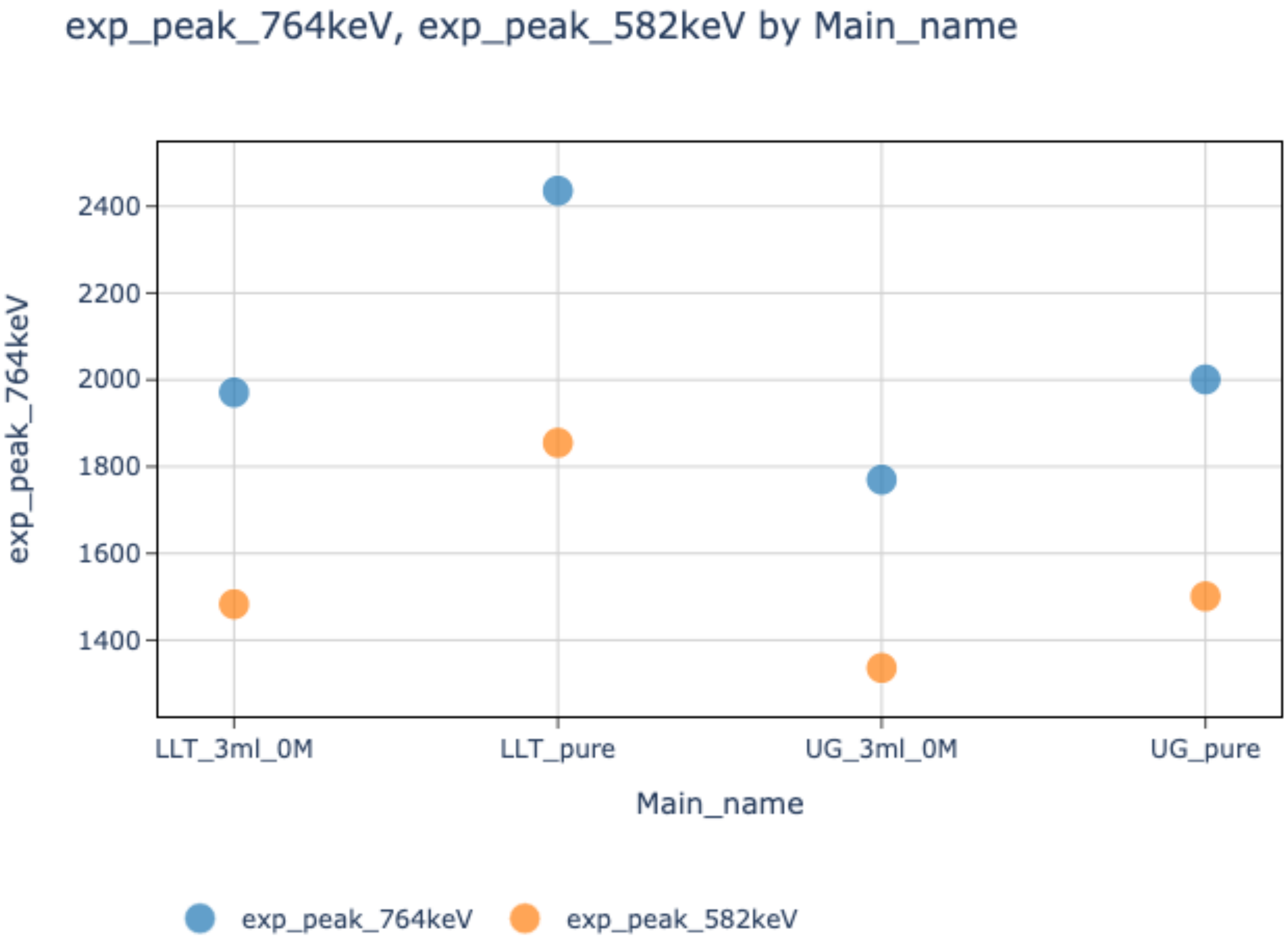


Liquid scintillation study Campaign

Quantitative results: LLT 3mmol

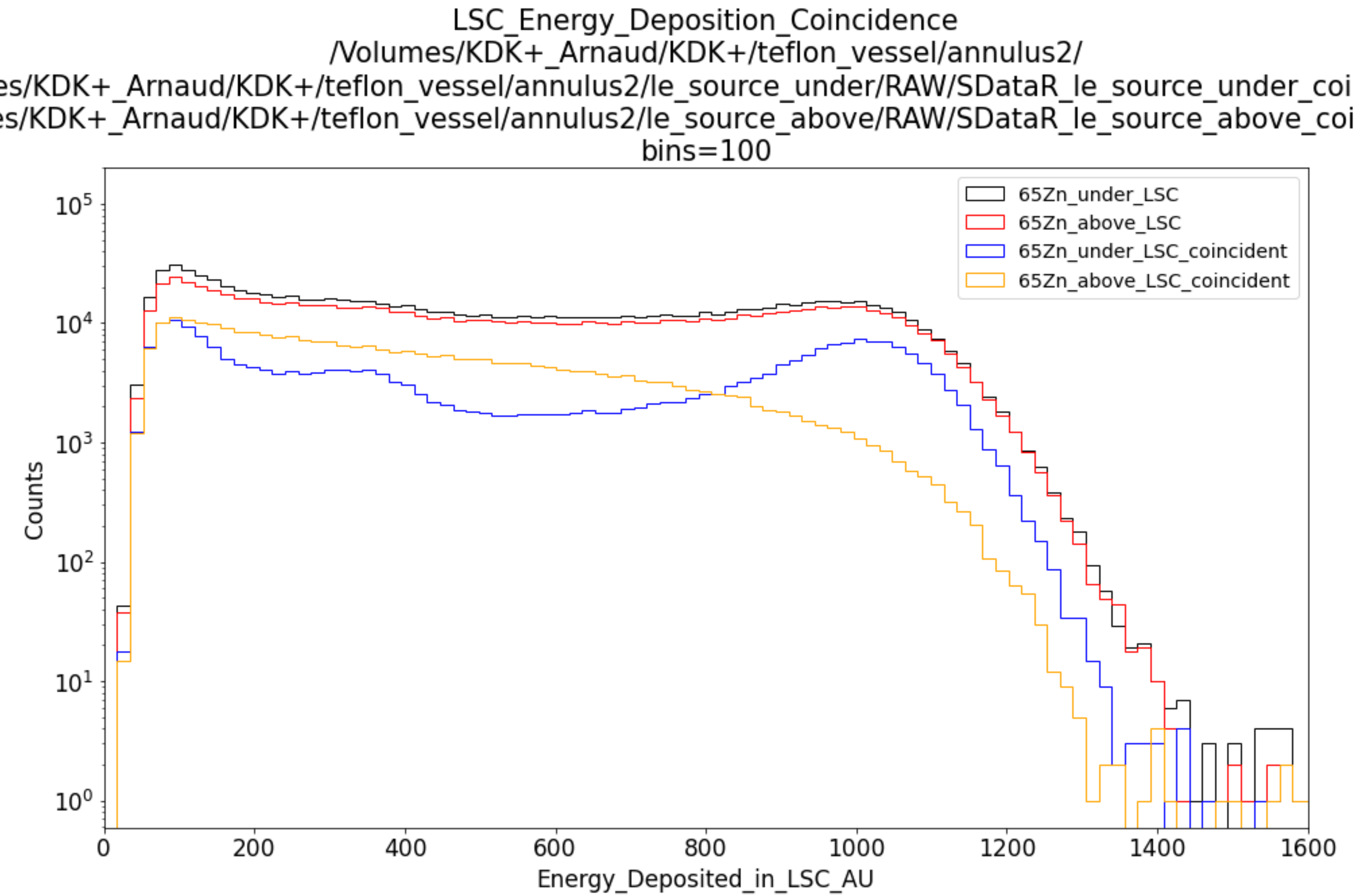
Liquid scintillation study Campaign

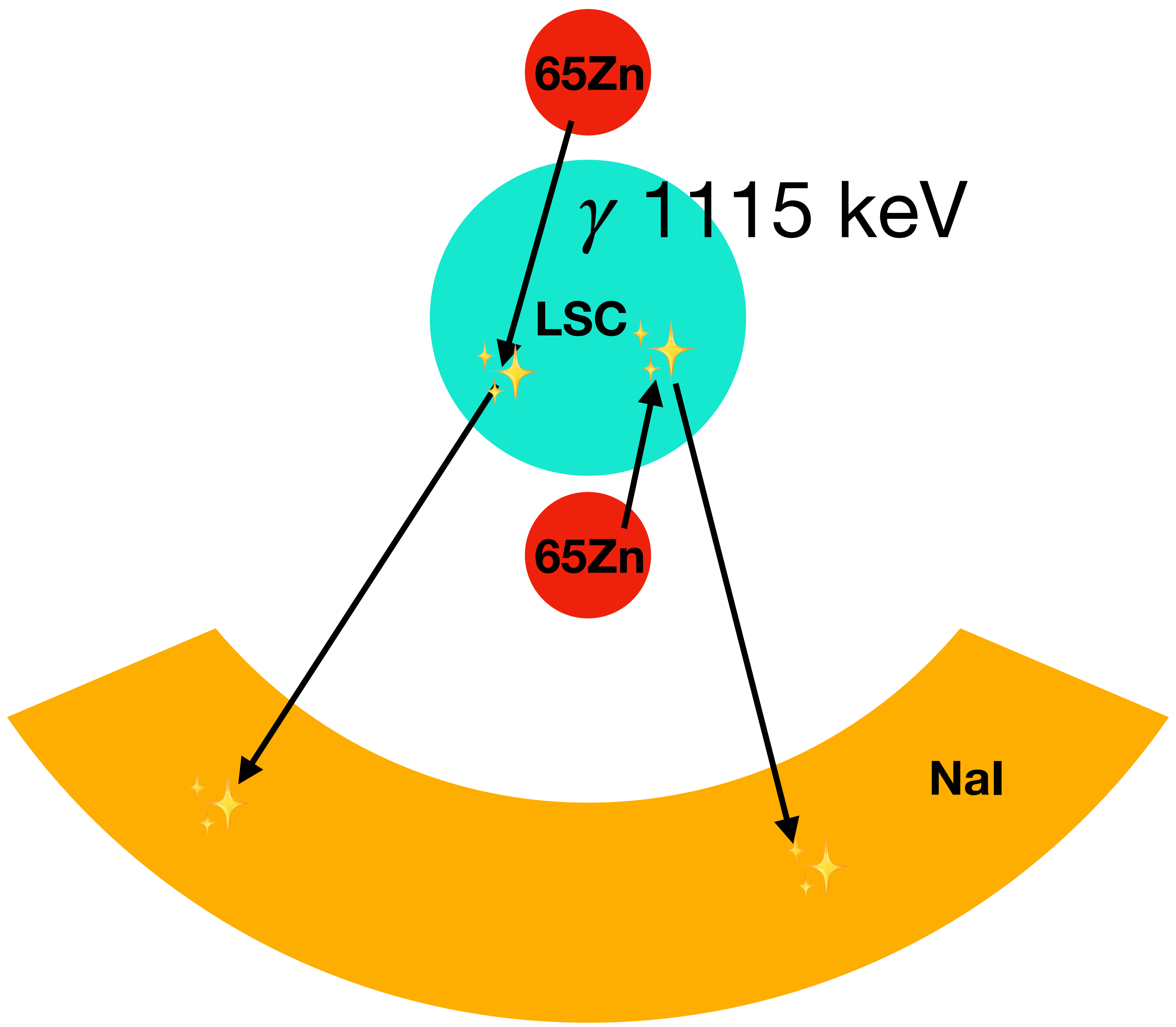
Quantitative results: UG vs LLT



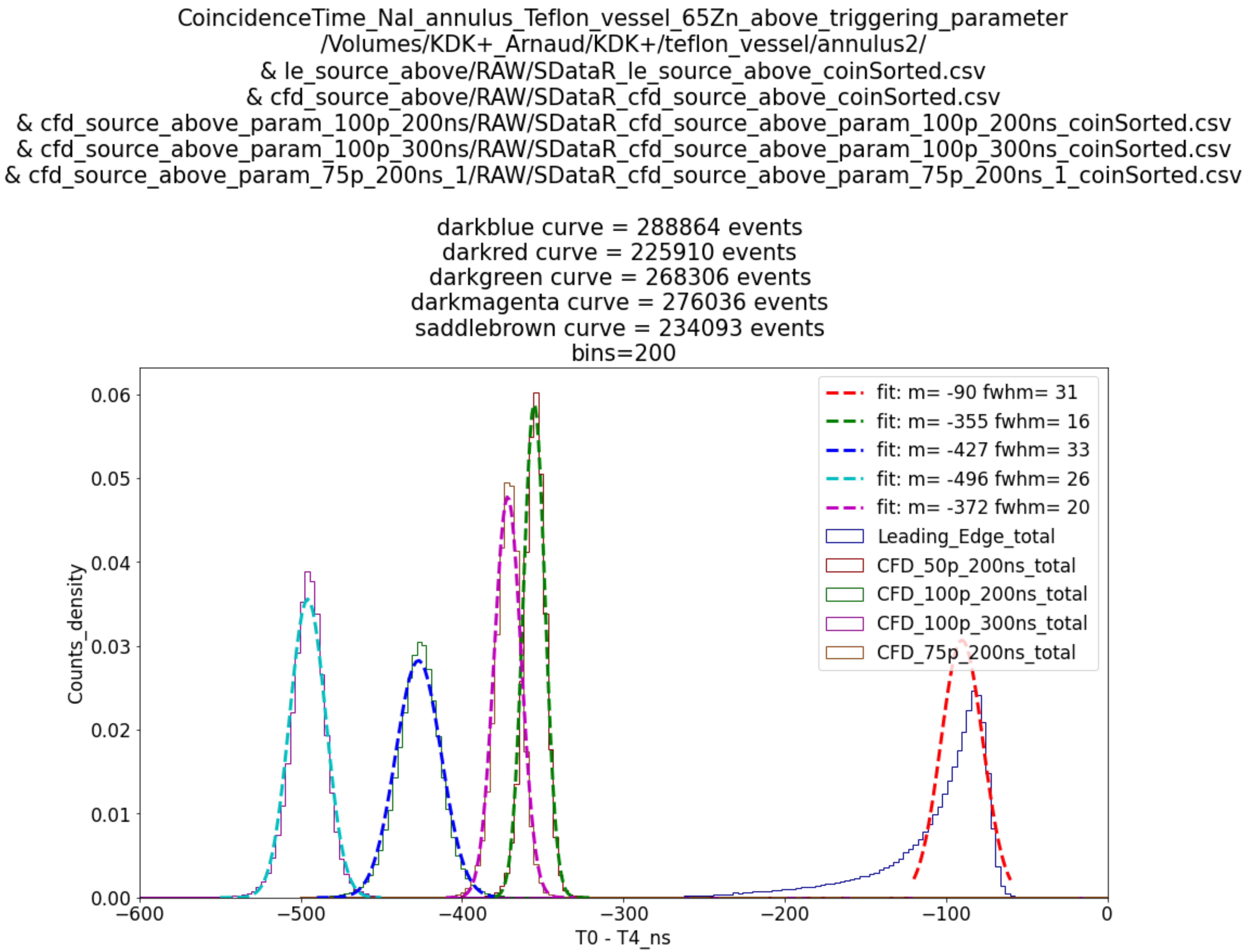
- Ultima Gold LLT has a better relative light yield
- Ultima Gold LLT diluted with water lose some light yield but less than UG does

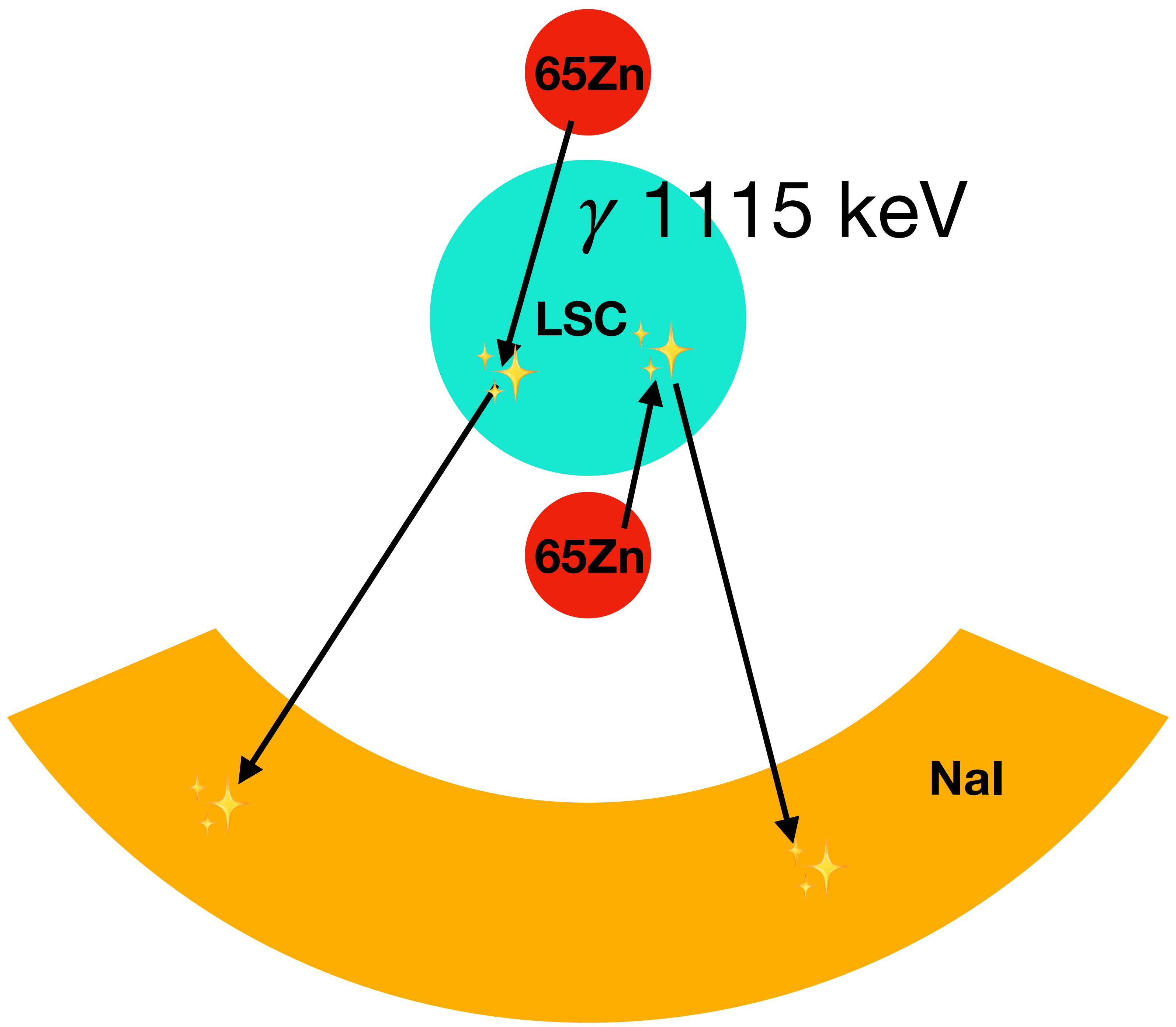
Teflon Vessel in the annulus - Gamma Compton coincidences



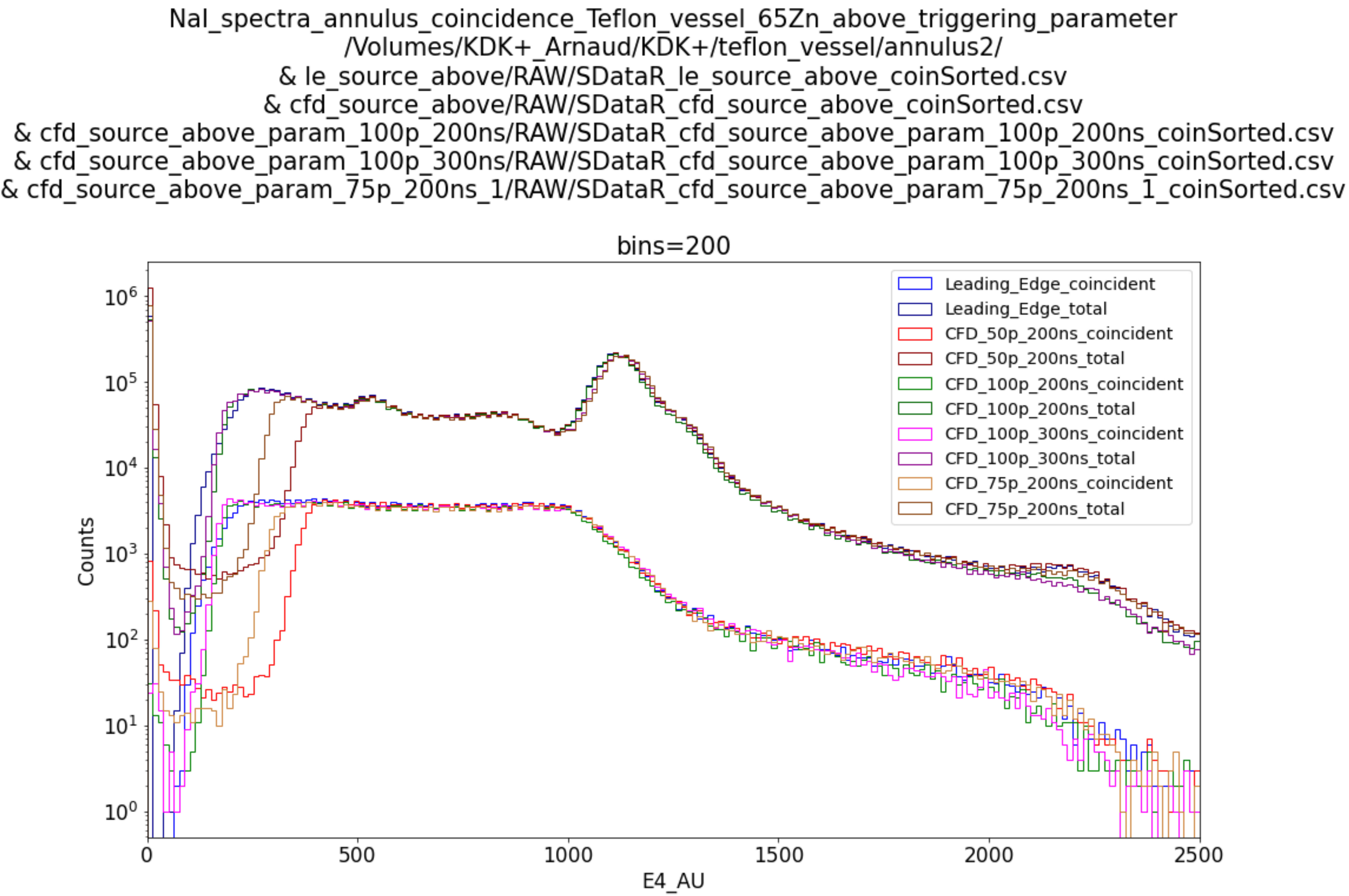


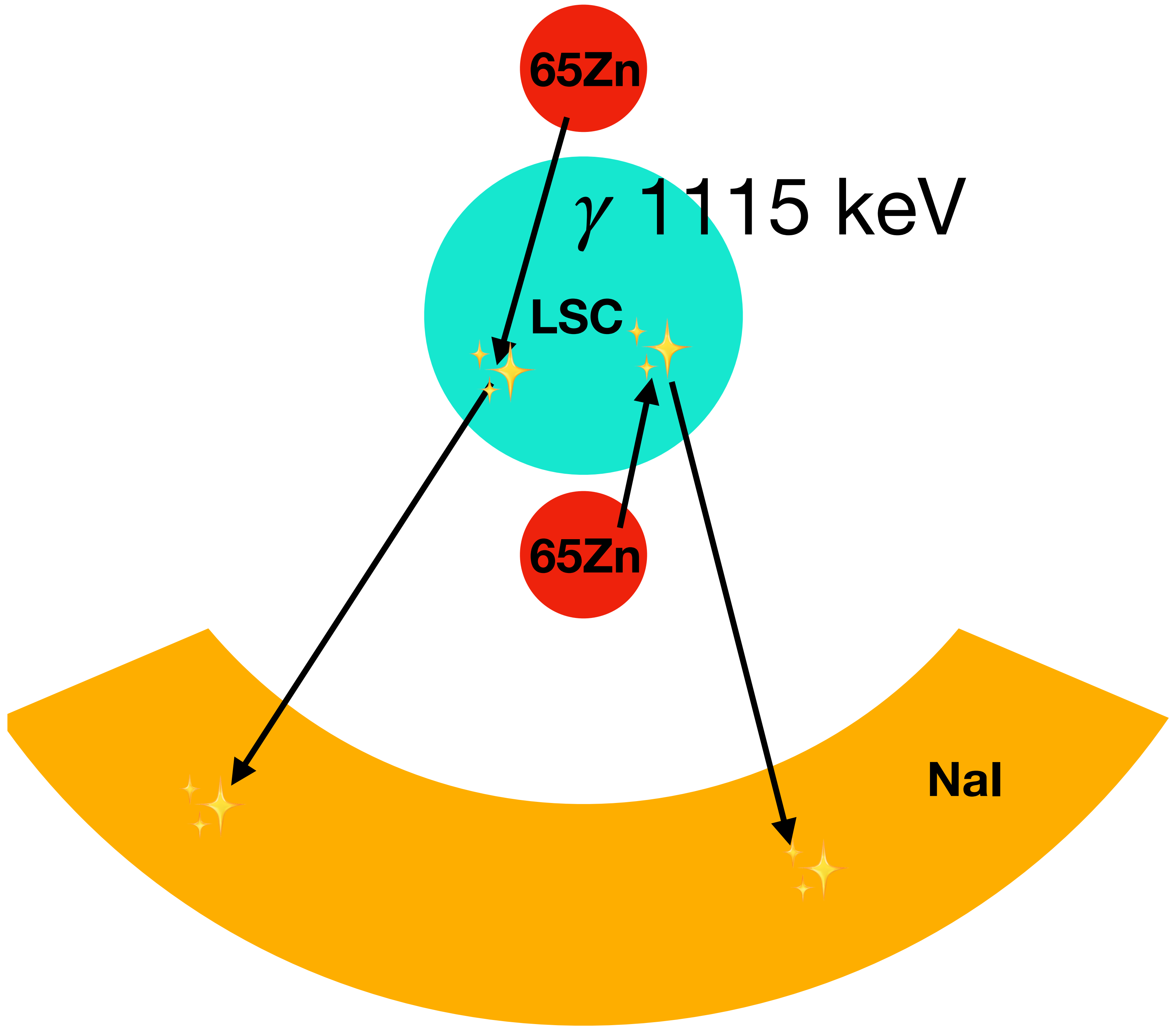
Teflon Vessel in the annulus - Gamma Compton coincidences



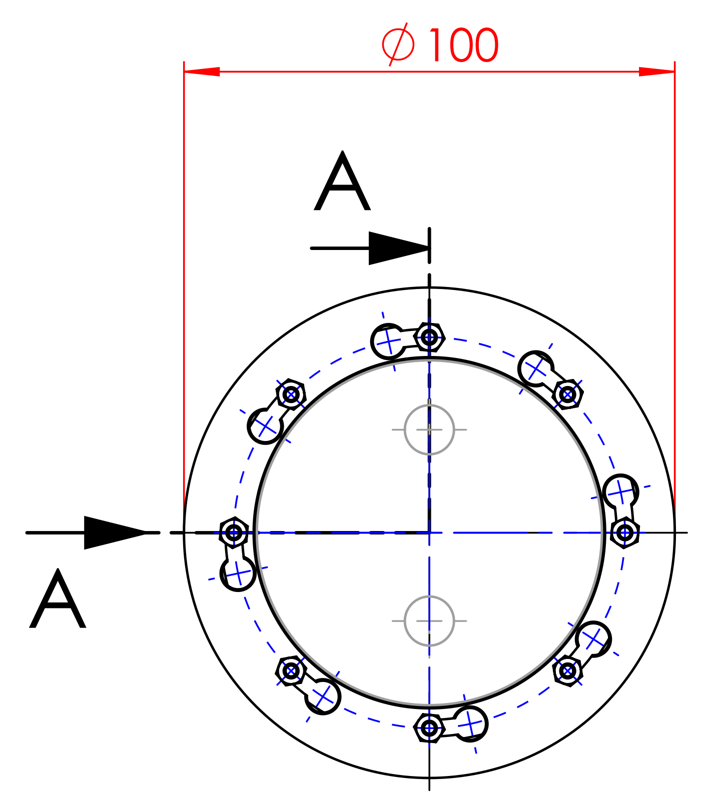


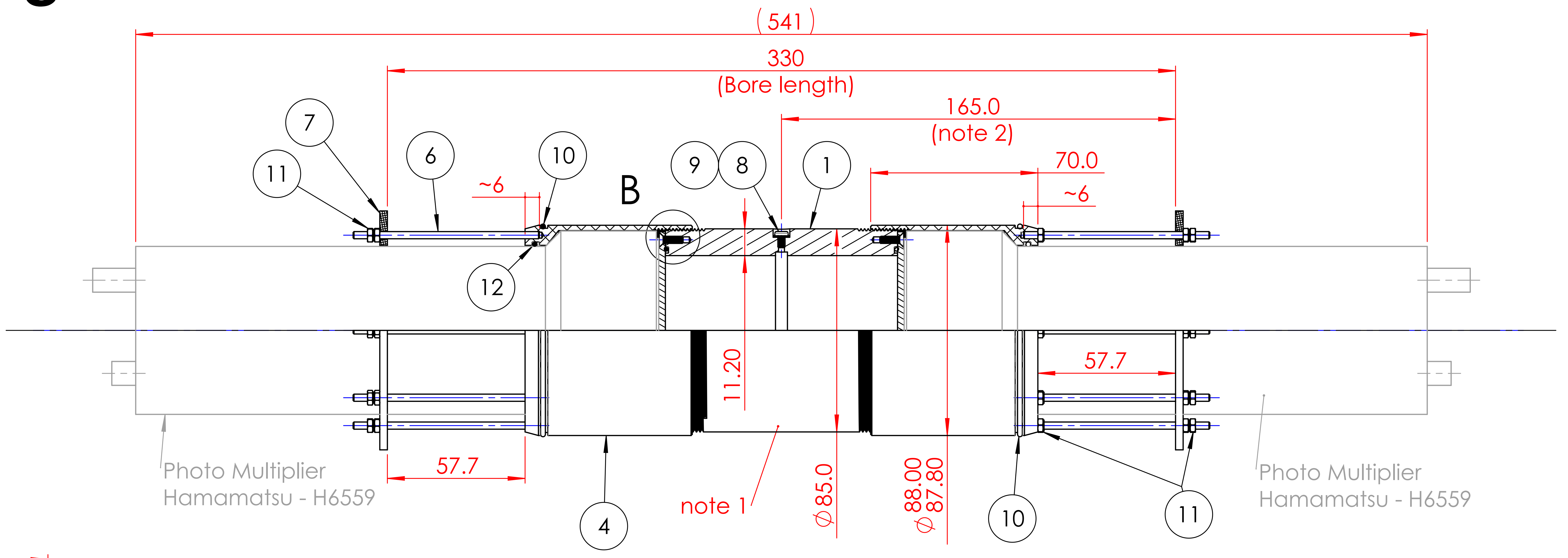
Teflon Vessel in the annulus - Gamma Compton coincidences





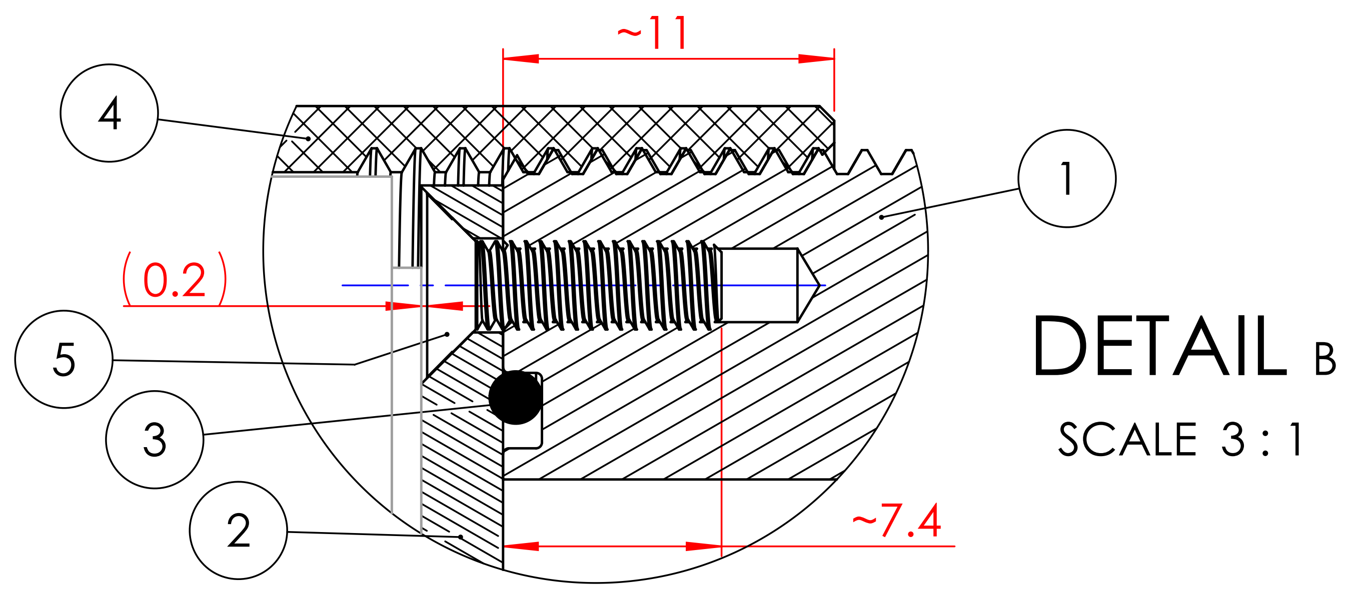
Teflon Vessel design





SECTION A-A

SCALE 1 : 2



DETAIL B

SCALE 3 : 1

Notes:
1. Vessel (part 1) will be wraped with reflective sheets. Location of the filling hole should be marked on the reflective cover.
2. Adjust this dimension and lock the nuts before inserting the assembly into the bore to align the centerline of the vessel with that of the bore.

ITEM	QTY	PART NUMBER	DESCRIPTION	MATERIAL	RAW MATERIAL
1	1	P01	Teflon Vessel - 300ml	PTFE	McMaster - 8546K23 or similar
2	2	P02	Window - Thickness 7/64in	Clear Acrylic	McMaster - 4615T14 or similar
3	2	McMaster - 9464K381	Chemical-Resistant Viton® Fluoroelastomer O-Ring, 1/16in Fractional Width, Dash Number 038	Viton	
4	2	P03	Sleeve - OD 88 mm, Length 70mm	Delrin	McMaster - 8582K25 or similar
5	32	McMaster - 93840A120	Nylon Slotted Flat Head Screw, Thread M3 x 0.50mm, Total length 10mm	Nylon Plastic	
6	16	P05	Nylon threaded rod - Thread M3 x 0.5mm, Length 78mm	Nylon	Essentra components - 38M030050TR or similar
7	2	P04	Support disc - Thickness 1/8in	Aluminum 6061	McMaster - 89015K239 or similar
8	1	McMaster - 94701A058	Filling hole's PTFE Plastic Screw - Extreme-Temperature, Pan, Slotted, Thread M3 x 0.5mm, Thread length 5mm	PTFE Plastic	
9	1	P06	Custom-made filling hole's gasket, OD 6.5mm, Thickness 0.6mm (max. thickness 1.2mm)	Viton	McMaster - 86075K21 or similar
10	2	McMaster - 9262K715	Oil-Resistant Buna-N O-Ring, Width 2mm, ID 85mm	Buna-N Rubber	
11	40	McMaster - 93800A116	Nylon Hex Nut, Thread M3 x 0.5mm	Nylon 6/6 Plastic	
12	2	McMaster - 1295N274	Chemical-Resistant Viton® Fluoroelastomer O-Ring, Super-Resilient, 2 mm Wide, 70 mm ID	Viton® Fluoroelastomer Rubber	

RELEASED FOR INFORMATION

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN **mm**

DECIMALS
X ± 0.5
X.X ± 0.1
X.XX ± 0.02

ANGLE ± 1°
WELDMENTS ± 2

ROUNDS AND FILLETS 0.5 mm
SURFACE FINISH 3.2 µm

	NAME	DATE (YYYY-MM-DD)
DRW.	A. Mir	2024-02-02
CHK.	-	-
SUB.	-	-
APPR.	-	-

KDK+

Arthur B. McDonald Institute
Queen's University, Physics Department

TITLE

Vessel & PMs assembled

Part Number: A01-KDK+

DWG NO. A01-A-KDK+-1 | QTY. 1 | REV. A

WEIGHT: 838.2 g | MATERIAL: -

SHEET SIZE: ANSI B | SCALE: 1:5 | SHEET 1 OF 1