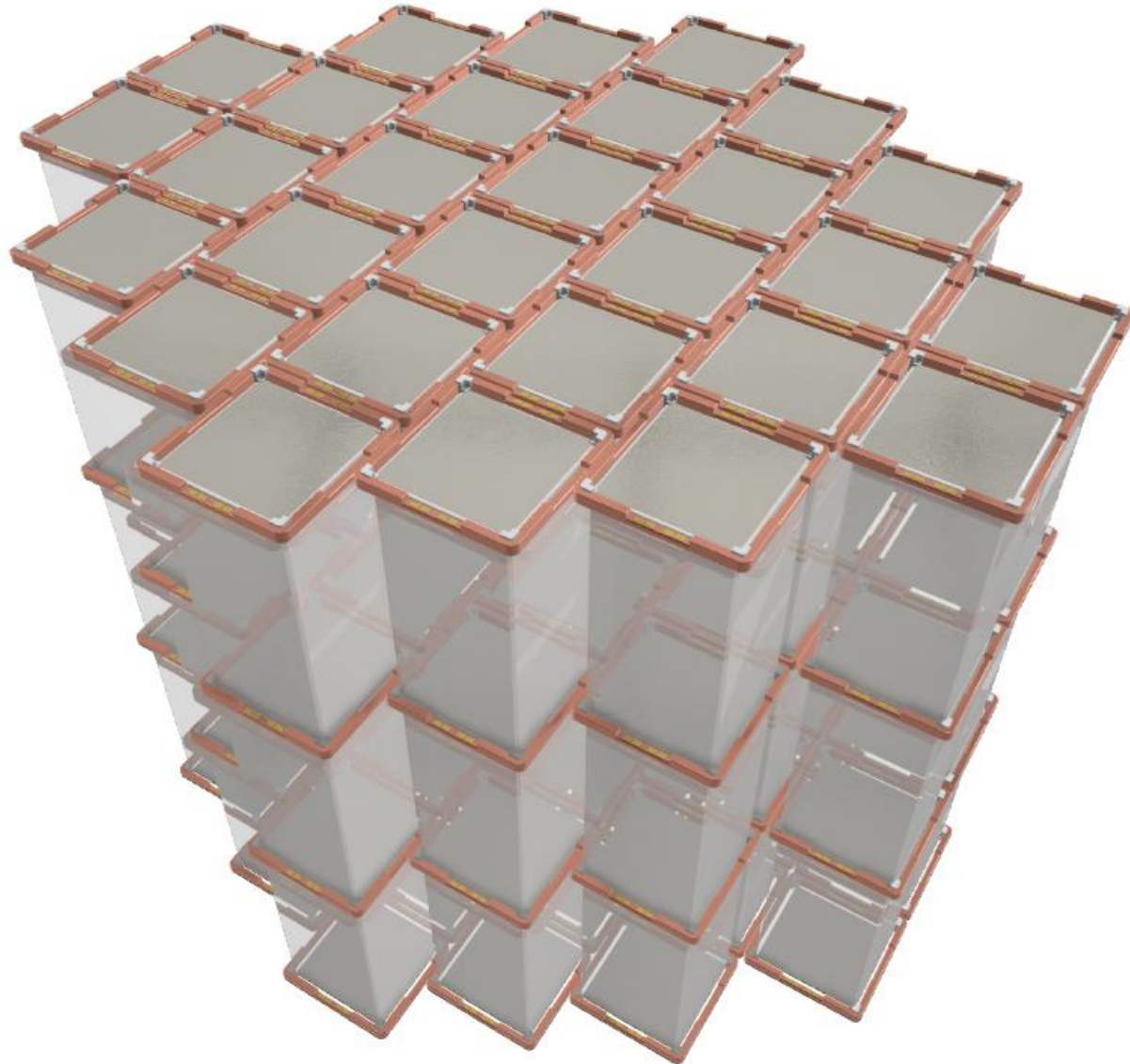


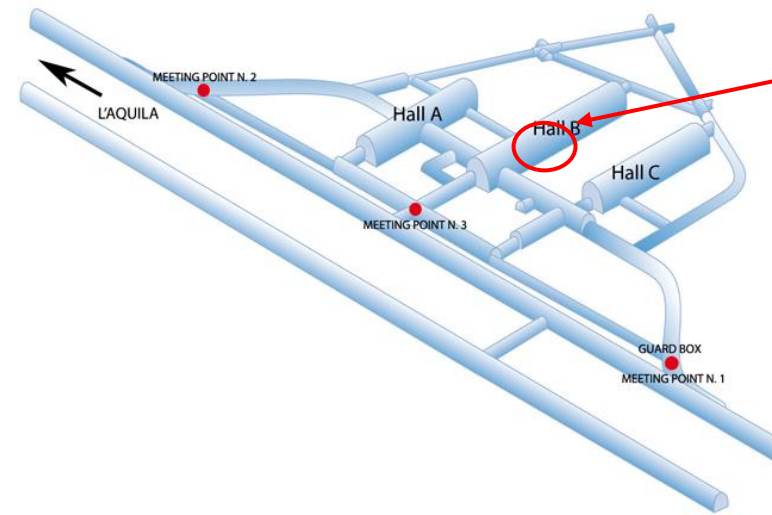
Rapid low-background radioassay techniques for ^{210}Pb and ^3H in materials for rare-events searches



The RES-NOVA detector



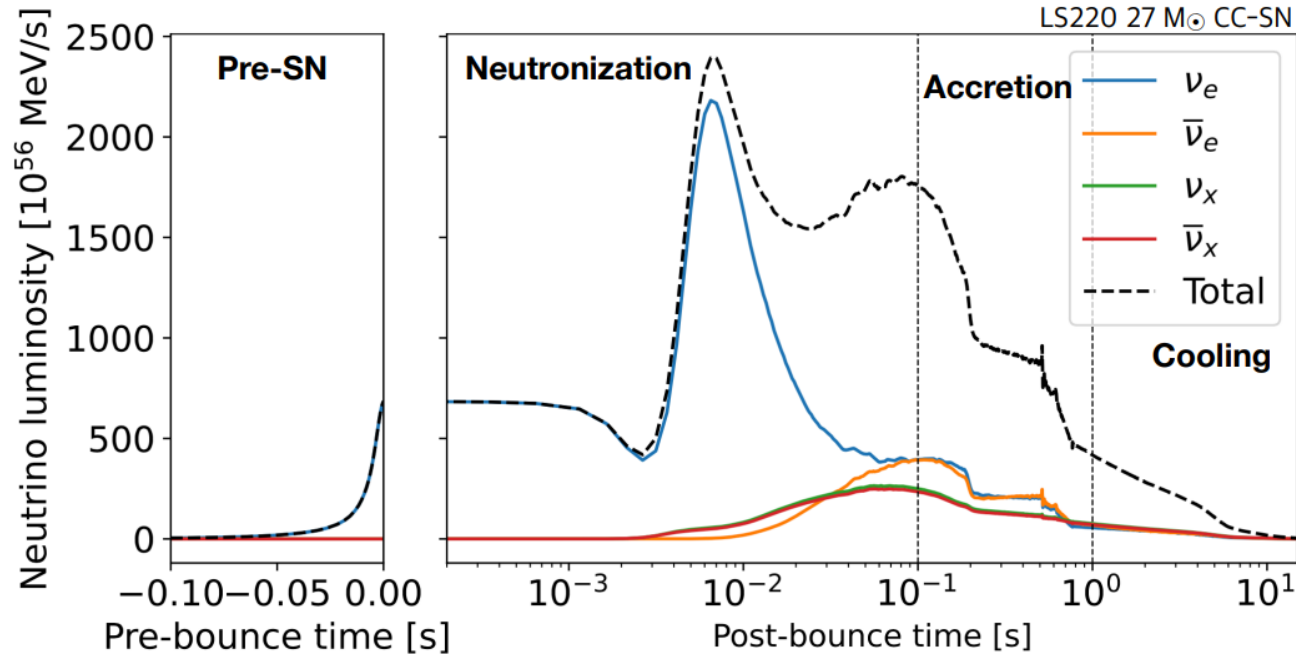
- Modular detector
- Total target mass: 170 Kg
- Cryogenic detector: 10 mK
- Energy threshold: 1 keV
- Archaeological lead target (PbWO_4)
- Main scientific purpose:
 - Observation of neutrinos (all flavors!) from Supernovae bursts.
- Secondary scientific purposes:
 - Observation of Dark Matter candidates (WIMPS)
 - Observation of solar neutrinos



RES-NOVA will be hosted @ LNGS Hall B

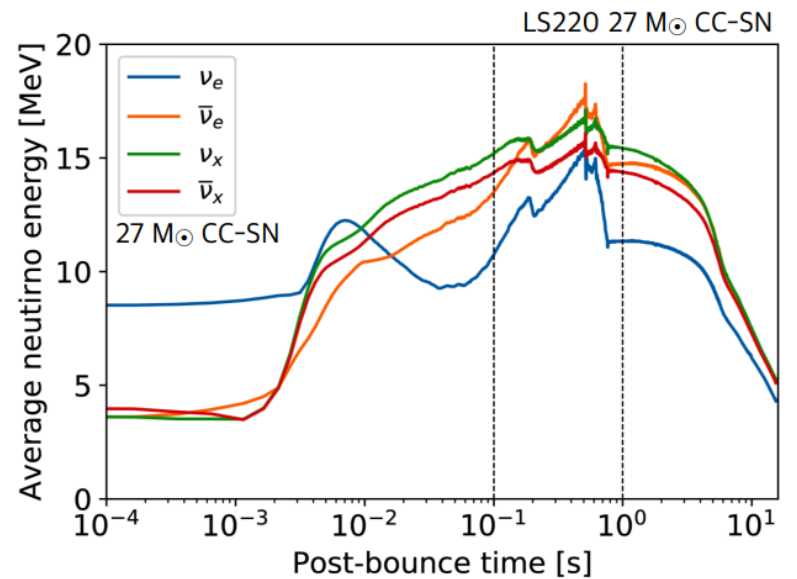
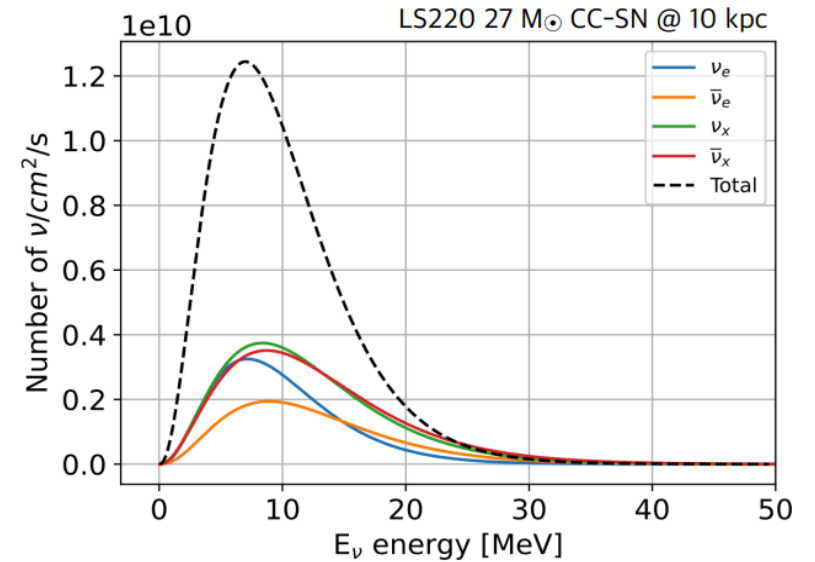
Supernova burst

Neutrino transport simulation of a Core-Collapse SN



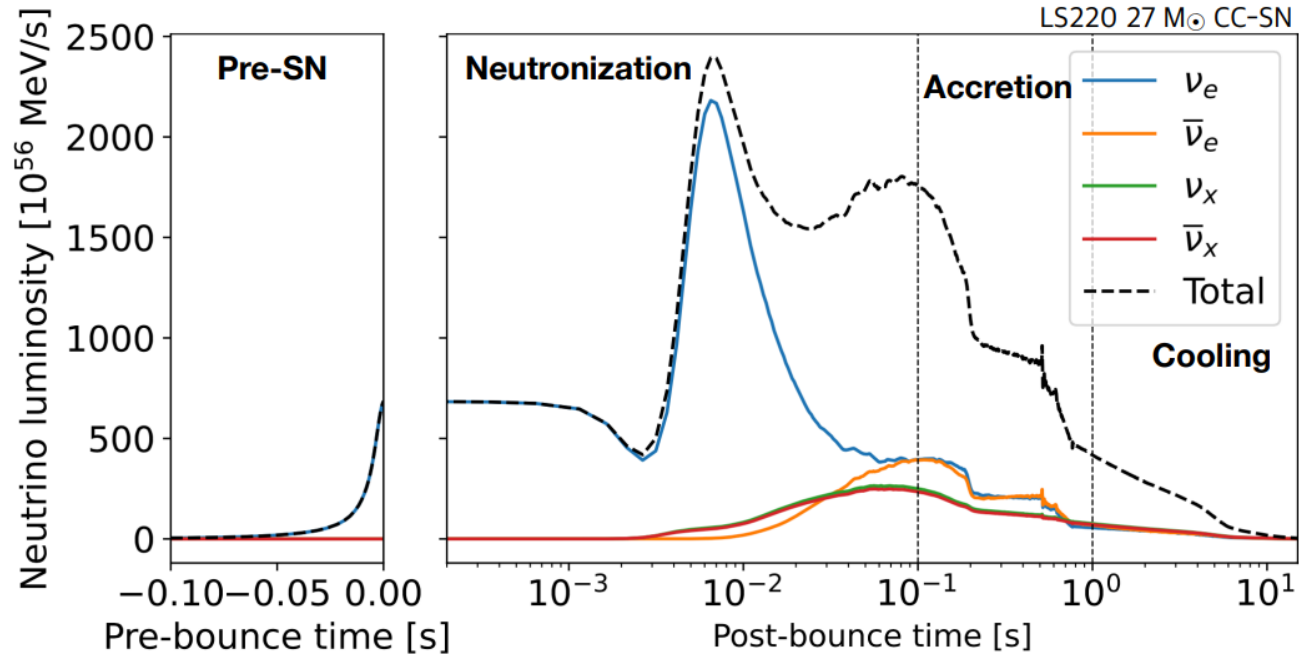
- Supernova: high energy explosion of massive star
- ~90% star binding energy converted in all flavor neutrinos
- ~10% in GW and EM

NEUTRINOS ARE DIRECT PROBES AND
MESSENGERS OF SNe HIDDEN DYNAMICS

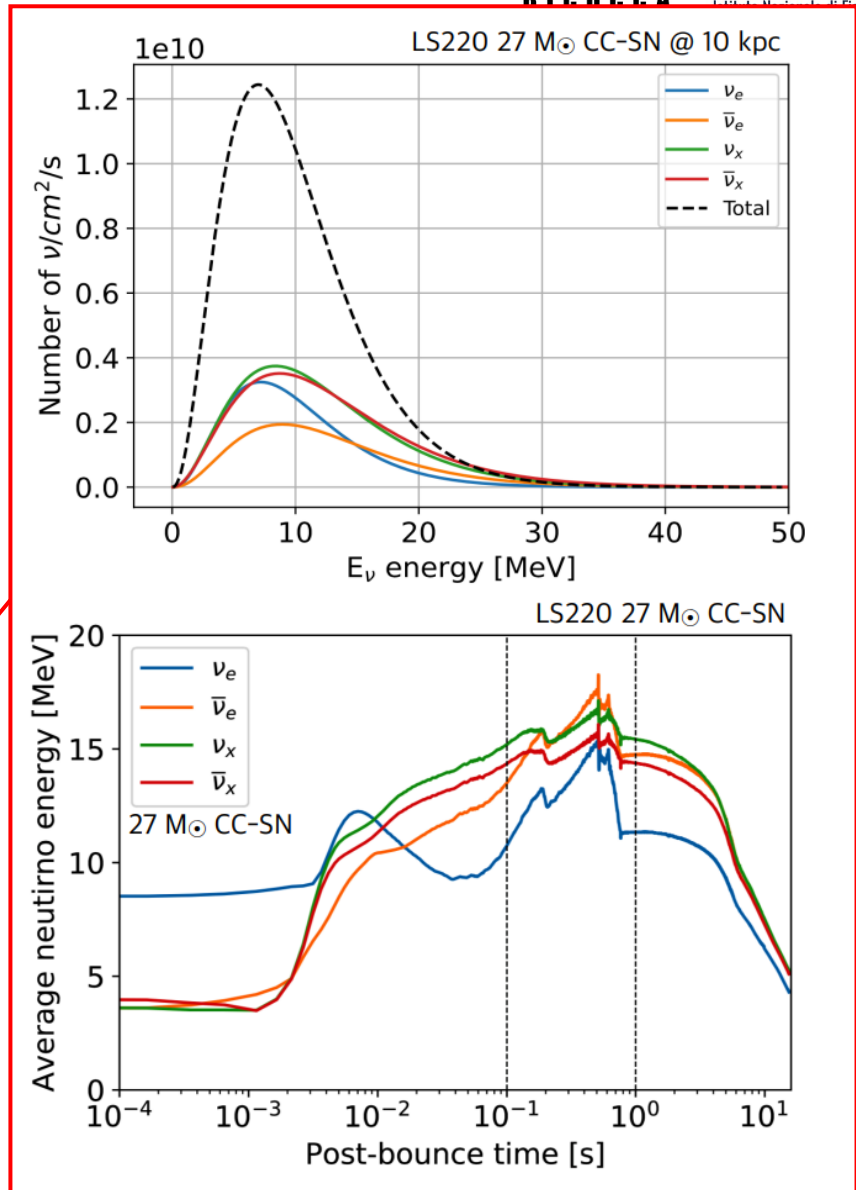


Supernova burst

Neutrino transport simulation of a Core-Collapse SN



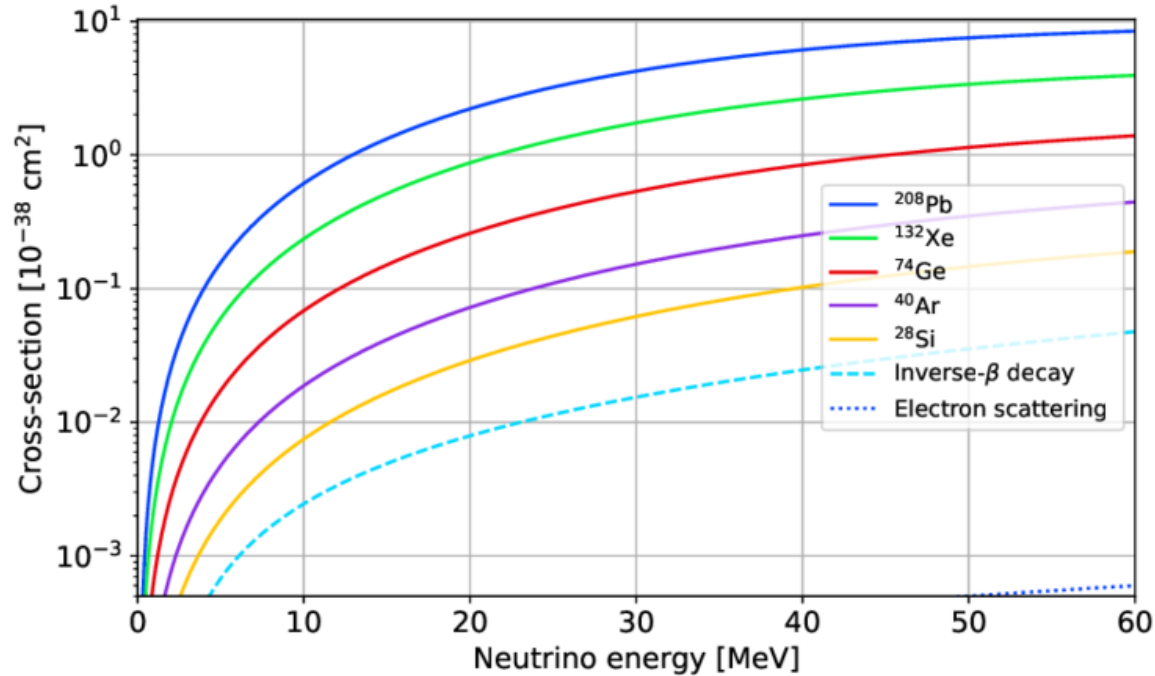
SN NEUTRINO DETECTORS NEED ALL FLAVOR SENSITIVITY!



CEvNS

Coherent Elastic Neutrino-Nucleus Scattering

L. Pattavina, N. Ferreiro Iachellini and I. Tamborra, *Neutrino observatory based on archaeological lead*, *Phys. Rev. D* **102** (2020) 063001 [arXiv:2004.06936] [INSPIRE]

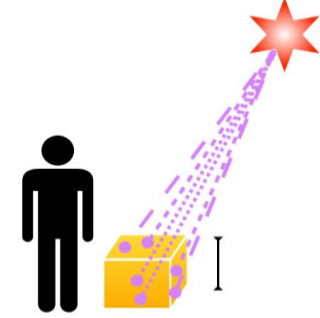


$$\sigma_{\text{CEvNS}} = \frac{G_F^2}{4\pi} F^2(q^2) E_\nu^2 Q_W^2$$

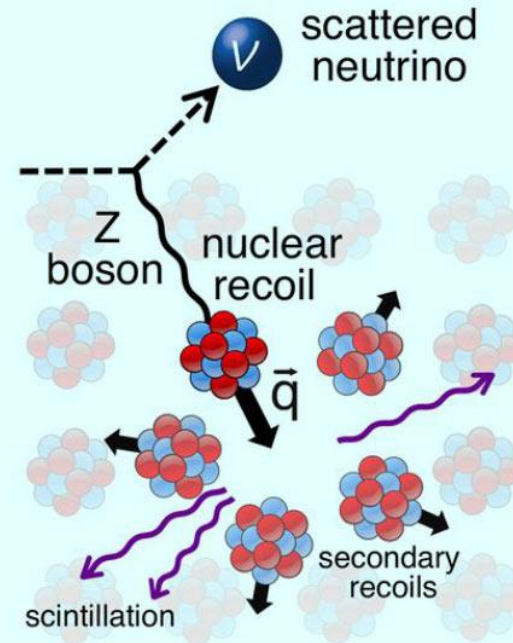
$$Q_W = N - Z(1 - 4\sin^2\theta_w)$$

$$\sigma_{\text{CEvNS}} \propto N^2$$

Lead cross-section 2 orders of magnitude bigger than IBD



Tabletop detector!



Lead in active volume!

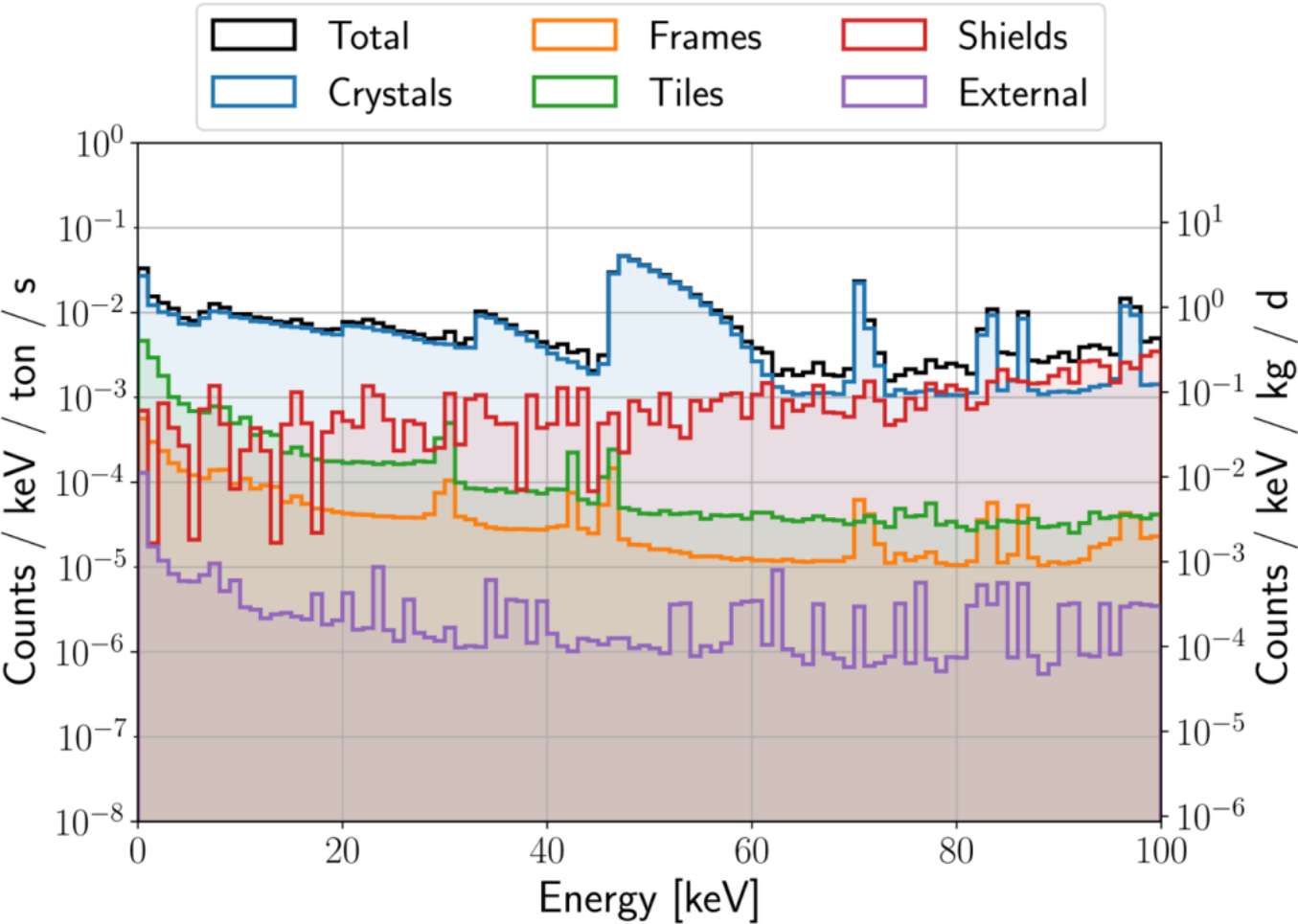
Low background needed

Archaeological lead

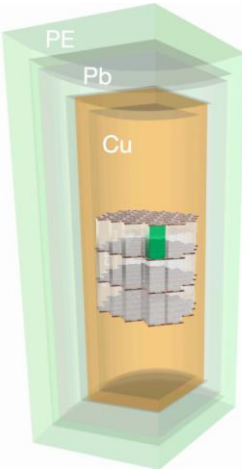
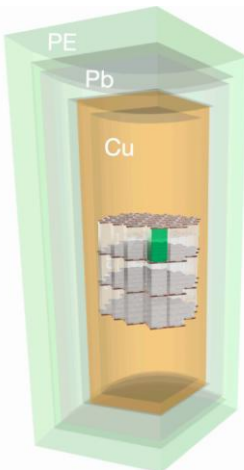
RES-NOVA background



Total detector energy response

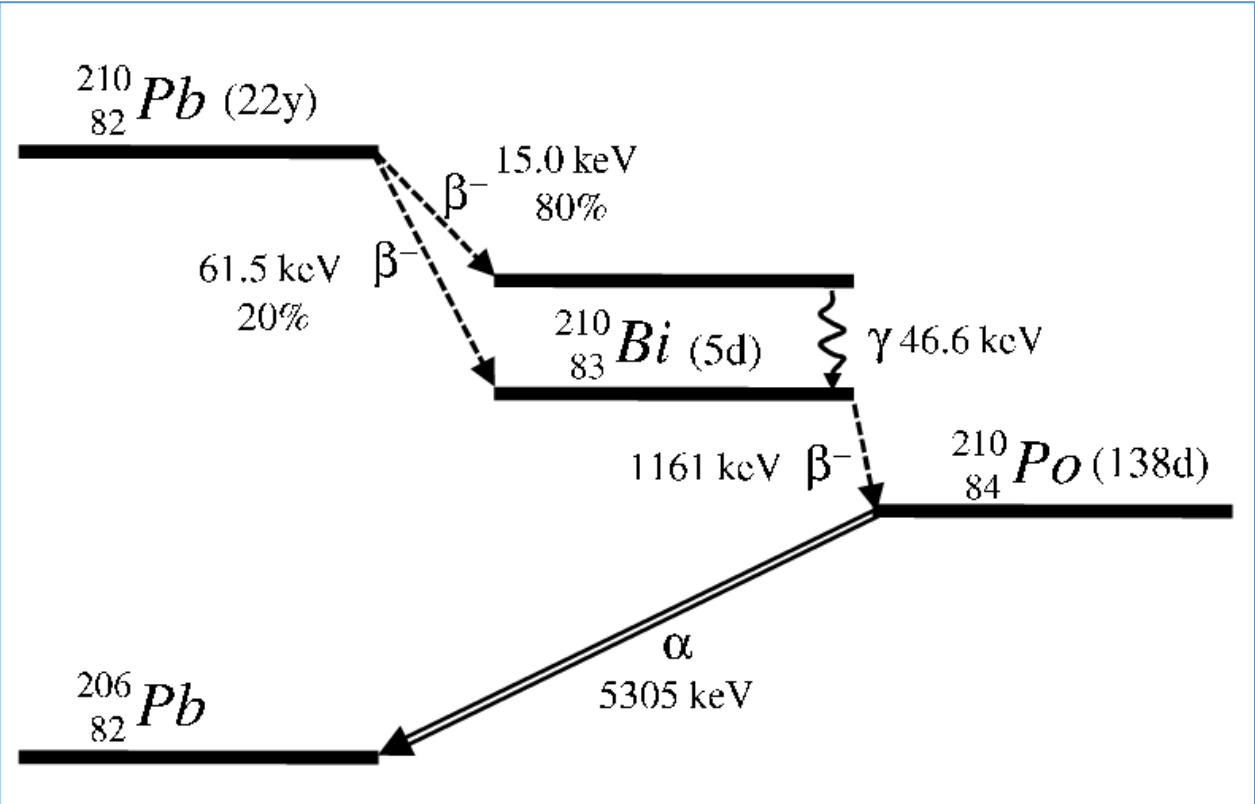


Location	Component	Source	Activity [mBq/kg] ([mBq/cm ²])
Detector	PbWO ₄	²³² Th	$< 2.3 \times 10^{-1}$
		²³⁸ U	$< 7.0 \times 10^{-2}$
		²¹⁰ Pb	$< 7.1 \times 10^{-1}$
		⁴⁰ K	$< 9.0 \times 10^{-2}$
	Cu structure	²³² Th	$< 4.1 \times 10^{-5}$
		²³⁸ U	$< 1.7 \times 10^{-5}$
	PTFE holders	²³² Th	$< 6.1 \times 10^{-3}$
		²³⁸ U	$< 2.2 \times 10^{-2}$
Shields	Polyethylene	²³² Th	$< 9.4 \times 10^{-2}$
		²³⁸ U	< 0.23
	Pb shield	²³² Th	< 2.3
		²³⁸ U	< 3.5
		²¹⁰ Pb	3×10^5
		Cu shield	²³² Th
	²³⁸ U		$< 1.7 \times 10^{-2}$
Surface	PbWO ₄	²¹⁰ Pb - 10 μm	7.4×10^{-6}
		²¹⁰ Pb - 0.01 μm	8.7×10^{-5}
	Cu structure/Tiles PTFE holders	²³² Th - 10 μm	$(1.2 \pm 0.1) \times 10^{-5}$
		²³⁸ U - 10 μm	$(8.3 \pm 0.7) \times 10^{-6}$
		²¹⁰ Pb - 10 μm	1.2×10^{-4}
		²³² Th - 0.01 μm	$(1.4 \pm 0.1) \times 10^{-6}$
		²³⁸ U - 0.01 μm	$(1.2 \pm 0.1) \times 10^{-6}$
		²¹⁰ Pb - 0.01 μm	$(4.1 \pm 0.1) \times 10^{-4}$
Cu shield	²¹⁰ Pb - 0.01 μm	1×10^{-2}	
External		neutrons	$3.9 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$
		muons	$3.1 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$
		gammas	$4.0 \times 10^{-1} \text{ cm}^{-2} \text{ s}^{-1}$



RES-NOVA Coll. New dark matter direct search based on archaeological Pb, Phys.Rev.D 111 (2025) 10, 103050

RES-NOVA background



All the decay chain in secular equilibrium with half-life of 22 y
 ^{210}Pb is a natural occurring radioactive material in lead (10^4 Bq/ton for commercial Pb)

Location	Component	Source	Activity [mBq/kg] ([mBq/cm ²])
Detector	PbWO ₄	^{232}Th	$< 2.3 \times 10^{-1}$
		^{238}U	$< 7.0 \times 10^{-2}$
	Cu structure	^{210}Pb	$< 7.1 \times 10^{-1}$
		^{40}K	$< 9.0 \times 10^{-2}$
Shields	PTFE holders	^{232}Th	$< 4.1 \times 10^{-5}$
		^{238}U	$< 1.7 \times 10^{-5}$
	Polyethylene	^{232}Th	$< 6.1 \times 10^{-3}$
		^{238}U	$< 2.2 \times 10^{-2}$
	Pb shield	^{232}Th	$< 9.4 \times 10^{-2}$
		^{238}U	< 0.23
Surface	Cu shield	^{232}Th	< 2.3
		^{238}U	< 3.5
	PbWO ₄	^{210}Pb	3×10^5
		^{232}Th	$< 4.1 \times 10^{-2}$
	Cu structure/Tiles	^{232}Th	$< 1.7 \times 10^{-2}$
		^{238}U	$< 1.7 \times 10^{-2}$
	PTFE holders	$^{210}\text{Pb} - 10 \mu\text{m}$	7.4×10^{-6}
		$^{210}\text{Pb} - 0.01 \mu\text{m}$	8.7×10^{-5}
External	Cu shield	$^{232}\text{Th} - 10 \mu\text{m}$	$(1.2 \pm 0.1) \times 10^{-5}$
		$^{238}\text{U} - 10 \mu\text{m}$	$(8.3 \pm 0.7) \times 10^{-6}$
	PTFE holders	$^{210}\text{Pb} - 10 \mu\text{m}$	1.2×10^{-4}
		$^{232}\text{Th} - 0.01 \mu\text{m}$	$(1.4 \pm 0.1) \times 10^{-6}$
	Cu shield	$^{238}\text{U} - 0.01 \mu\text{m}$	$(1.2 \pm 0.1) \times 10^{-6}$
		$^{210}\text{Pb} - 0.01 \mu\text{m}$	$(4.1 \pm 0.1) \times 10^{-4}$
External		neutrons	$3.9 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$
		muons	$3.1 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$
		gammas	$4.0 \times 10^{-1} \text{ cm}^{-2} \text{ s}^{-1}$

RES-NOVA Coll. New dark matter direct search based on archaeological Pb, Phys.Rev.D 111 (2025) 10, 103050

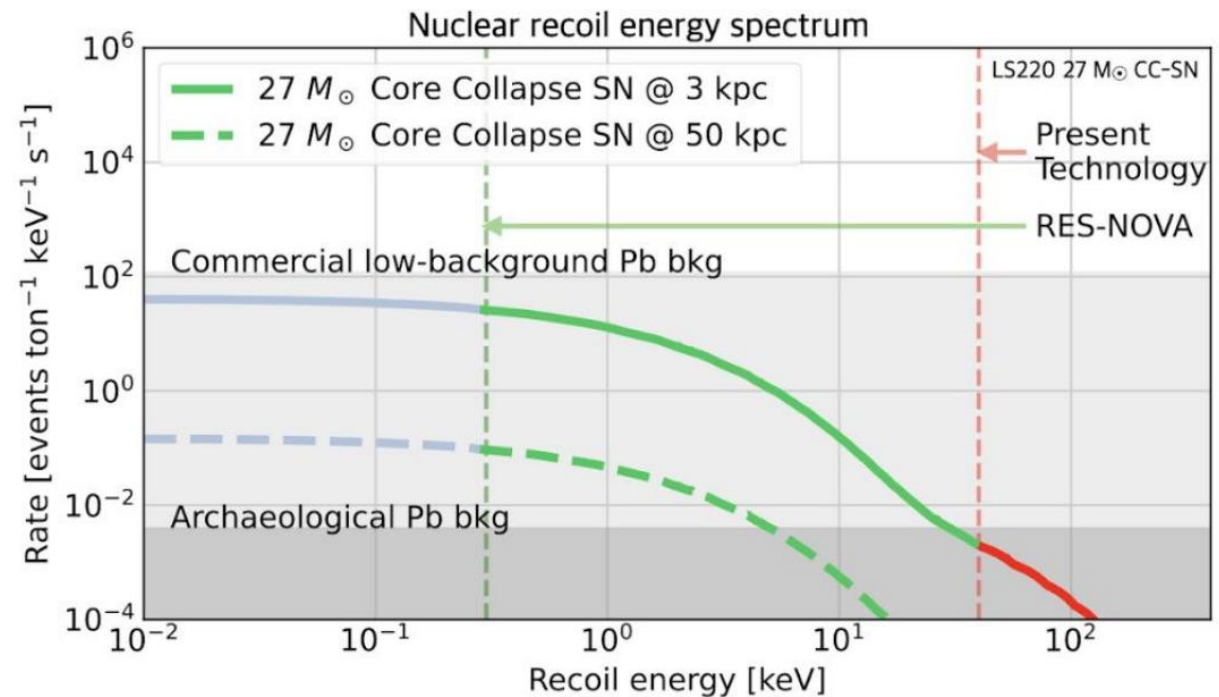
Is there any solution?

Archaeological lead

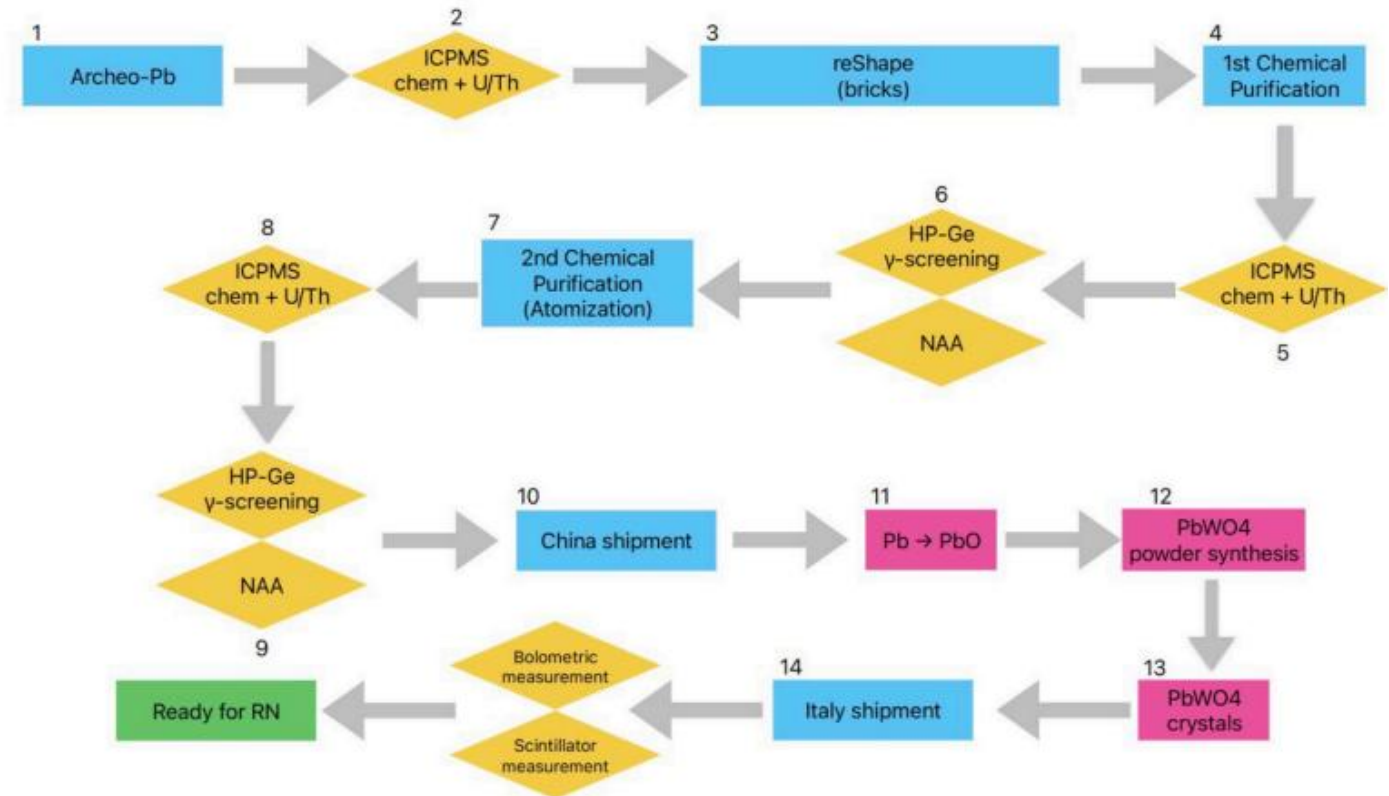


The perks of being stuck in a sunken ship:

- Very old samples! (> 2000 y)
- Natural shielding from cosmogenic activation
- Far “cleaner” (in a radiological way) than normal lead (^{210}Pb expected to be $< 1\text{mBq/Kg}$)
- There is more where they came from!



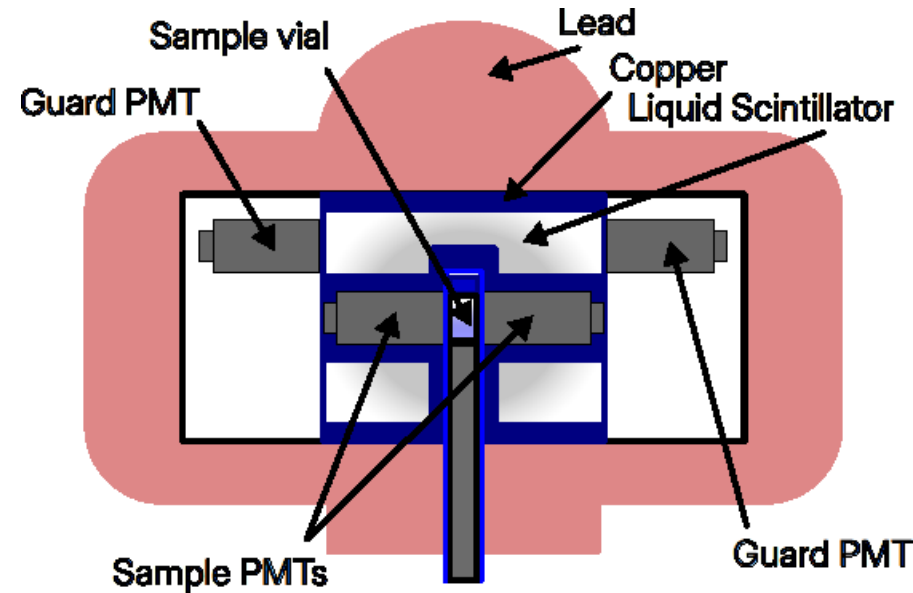
Archaeological lead



Chemical purification chain from Pb to PbWO₄ crystals

For each step, contamination can be introduced in archaeological lead samples!

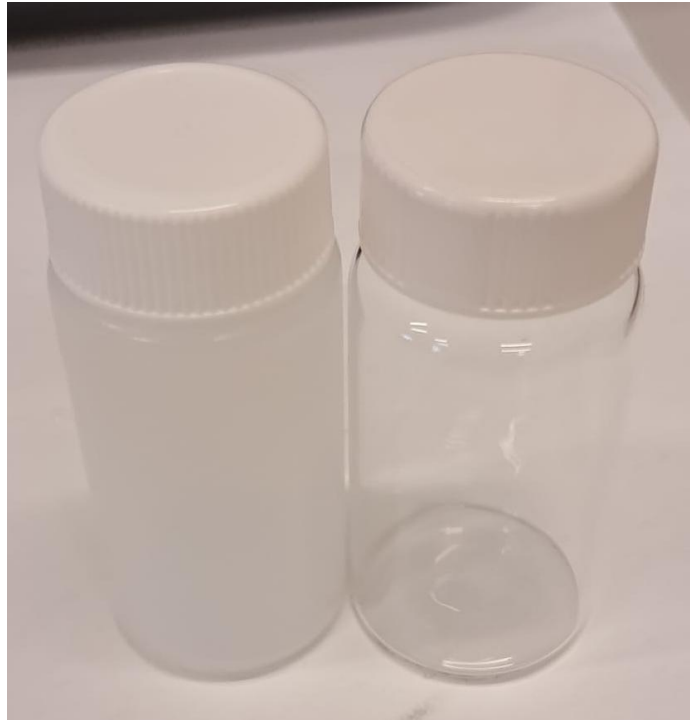
LS detection with Quantulus 1220



Commercial
detector!

- Lead casing for cosmic ray protection
- Active veto system
- PMTs for coincidence measurements
- Accepted/rejected spectra splitting
- α/β discrimination via Pulse Shape Analysis (PSA)
- Liquid Scintillator Counting (LSC)
- Cherenkov Counting

Set-up for a ^{210}Pb LSC campaign



2 Quantulus vials
made of PTFE (left)
or glass (right)

1. Finding the optimal detection set-up
2. Finding the optimal PSA set-up to allow correct α/β discrimination
3. Calibration curve with sample spiked with known activity of ^{210}Pb to identify ROIs and check detector linearity.
4. Samples measurements.

WHAT IS A QUANTULUS SAMPLE?

20 ml vials containing a cocktail of mixed LS and liquid samples.

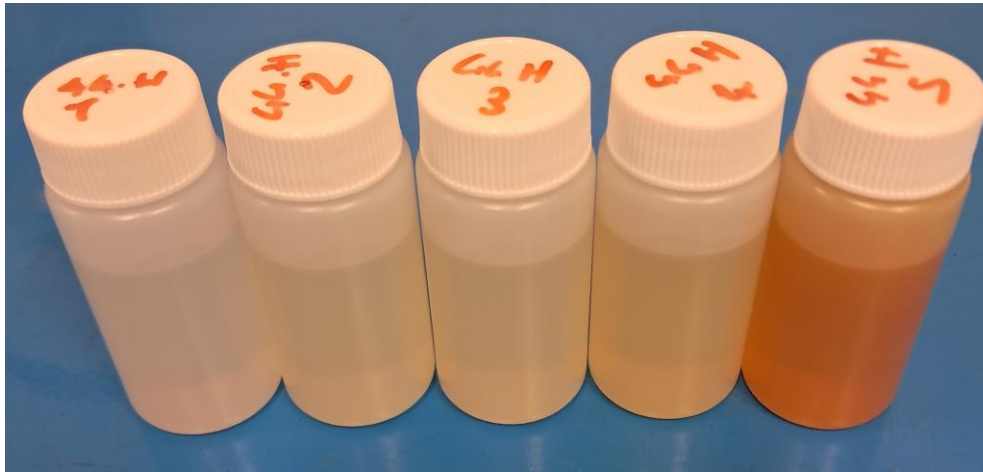
Usual LS to sample ratio are:

15 ml LS + 5 ml liquid sample

12 ml LS + 8 ml liquid sample (the one we used)

Set-up for a ^{210}Pb LSC campaign

Each measurement campaign requires a new calibration process, since chemical conditions of samples may strongly differ even between “intuitively similar” samples (such as atomized Pb and metallic Pb).



From left to right: samples with the same archaeological Pb mass but increasing HNO_3 concentration



A sample of atomized Pb (left) and metallic Pb (right) with same Pb concentration

Preparation of lead samples

2-3 g of lead are dissolved in 20-30 ml of
20% concentrated HNO_3 solution



The solution is heated in an ultrasonic bath
(50°C)

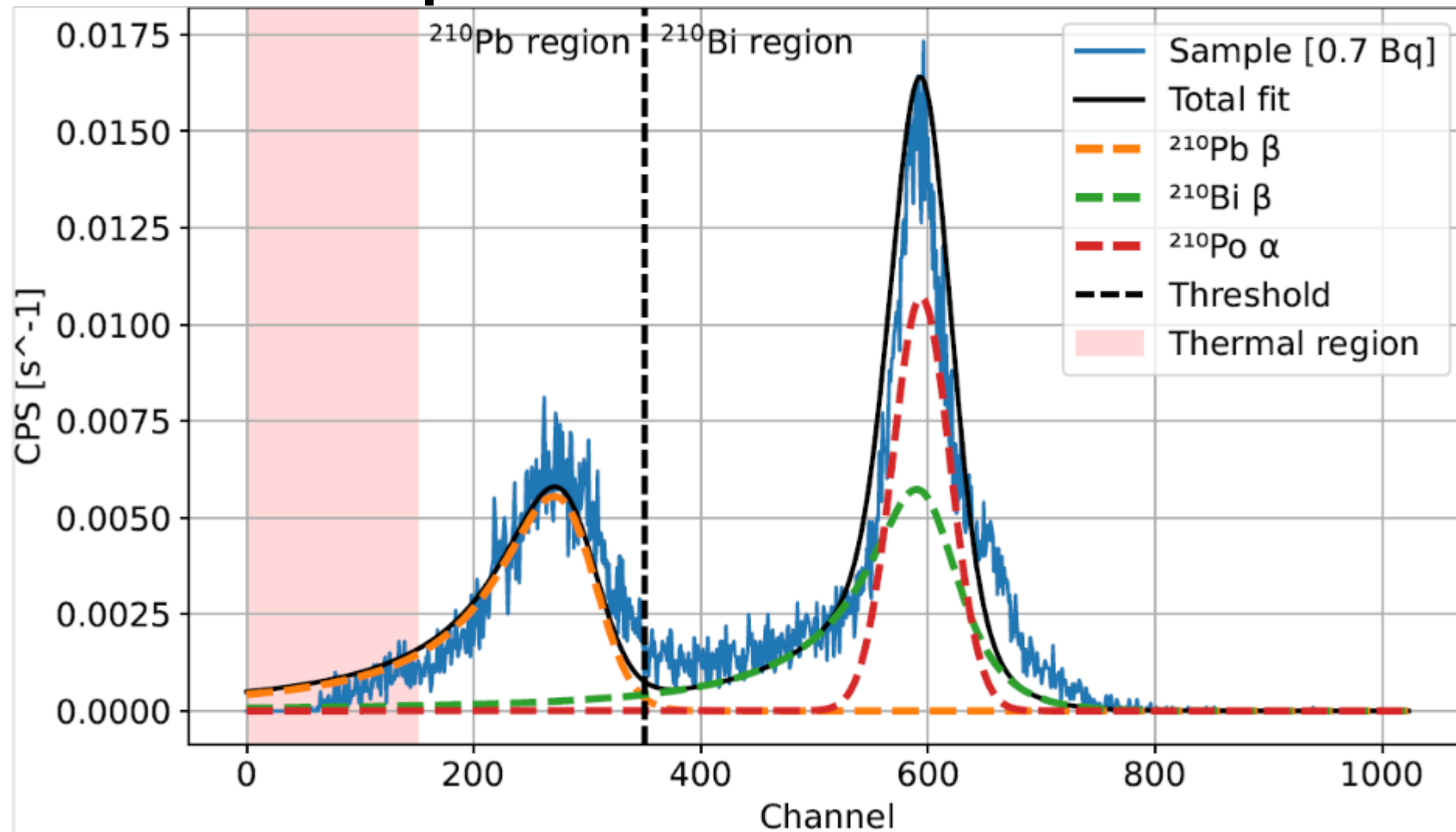


8 ml of dissolved lead samples are mixed
with 12 ml of ULTIMAGoldAB

NOTE: This is the **optimized sample preparation procedure**. Different Pb concentrations, HNO_3 concentrations, and LS-to-sample ratios were tested before selecting these conditions.



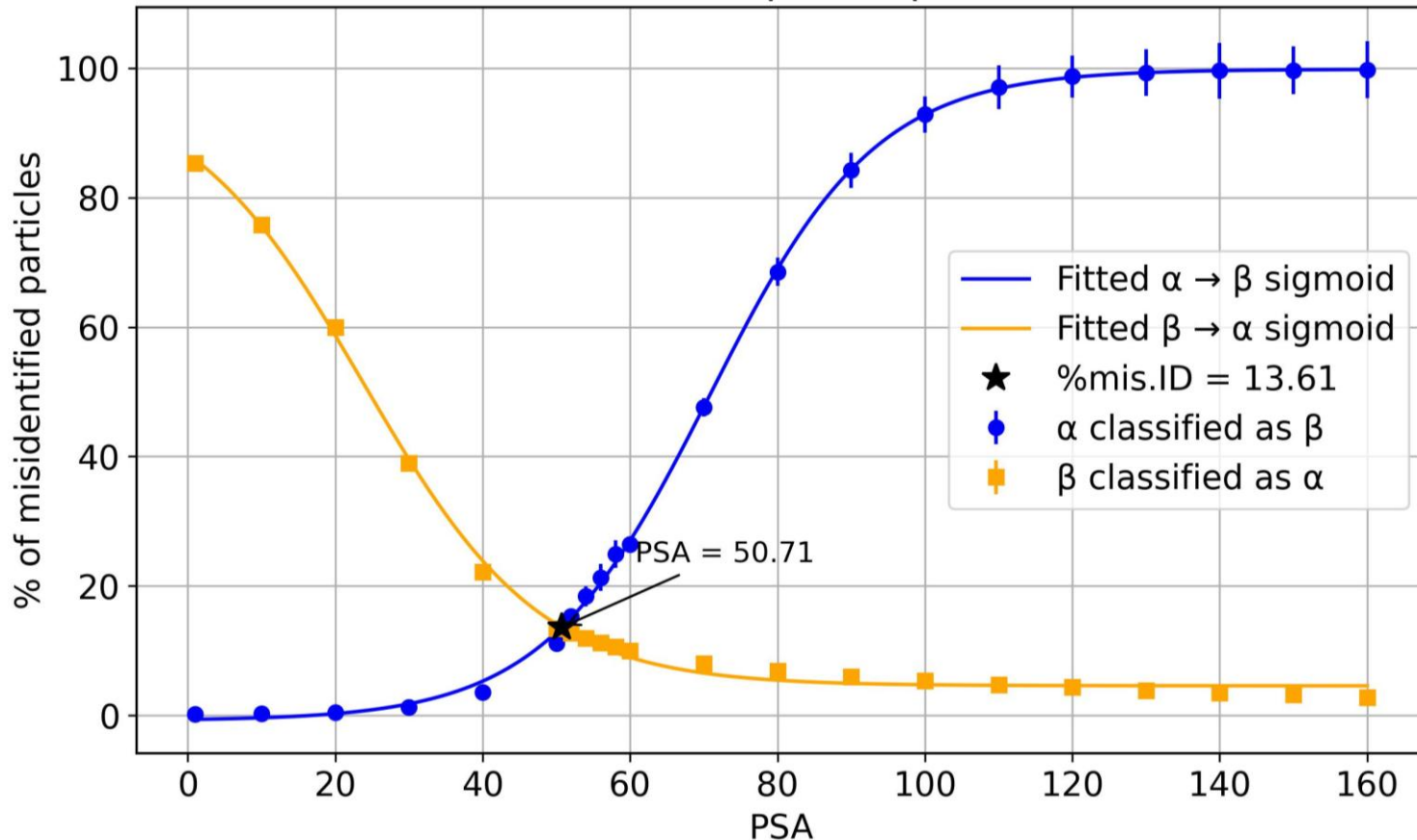
Intermission: visualizing Quantulus spectra



PSA Set-Up



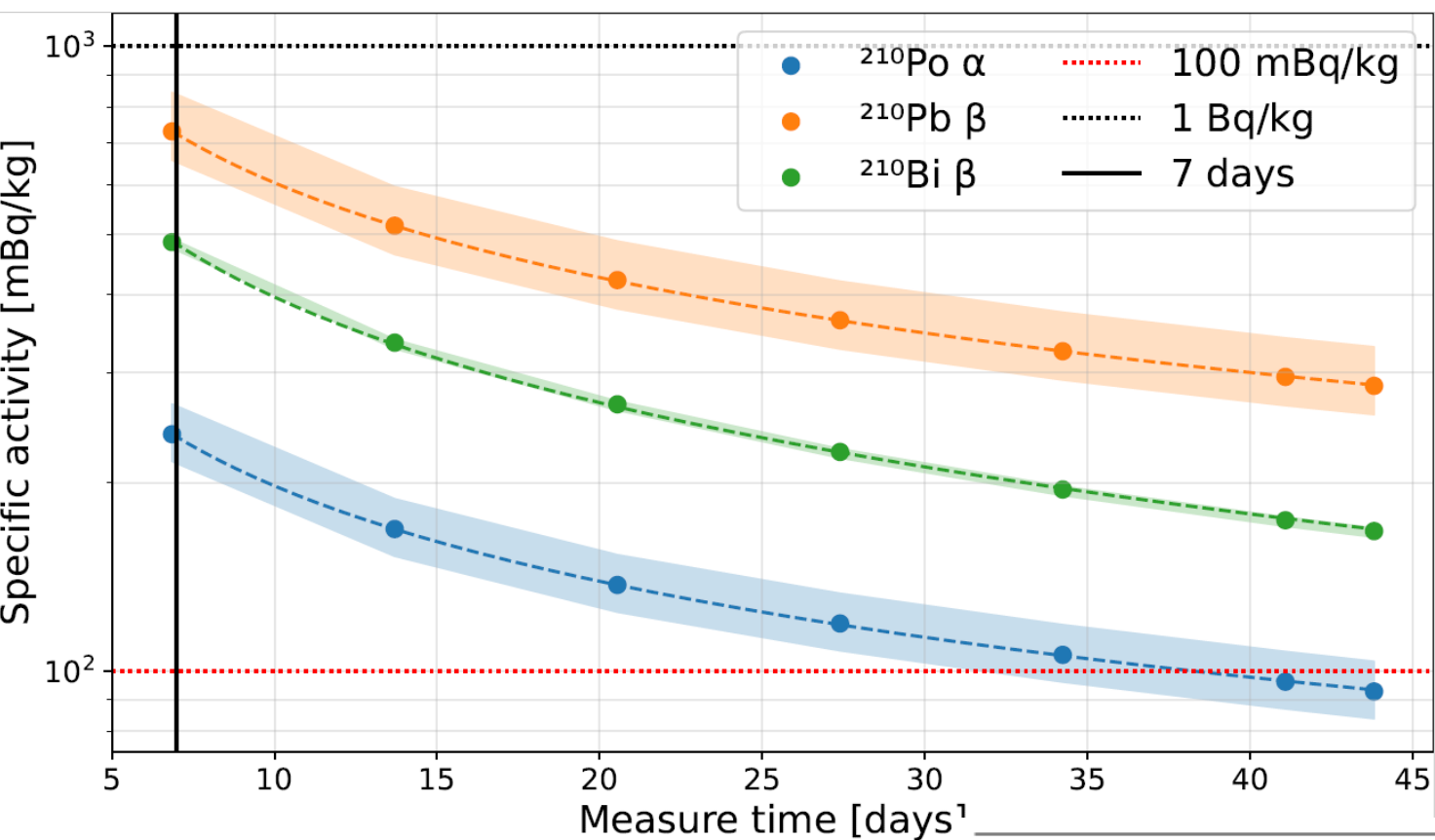
PSA curves for pure α/β sources



PSA SCANNING PROCEDURE

1. Preparation of 2 PSA samples chemically identical to optimal sample.
2. Spiking both samples with pure α/β emitter.
3. Measurement of both samples while scanning all possible PSA values
4. Determination of optimal setup through:
 - minimization of total mis-identification
 - symmetry of mis-identification

Results on metallic archaeo-Pb



- 4 samples:
- 1. Archaeolead 1: 0.79 g
 - 2. Archaeolead 2: 0.79 g
 - 3. High-purity Pb (CSC Pure Technologies): 0.75 g
 - 4. Opera Pb: 0.76 g

$$DL \left[\frac{\text{Bq}}{\text{kg}} \right] = \frac{k_{\alpha} \sigma_s}{m \epsilon T \mathcal{B}}$$

Simultaneous monitoring and measurement of the full ²¹⁰Pb decay chain!

Sample	²¹⁰ Pb [mBq/kg]	²¹⁰ Bi [mBq/kg]	²¹⁰ Po [mBq/kg]	Time [d]
Archaeolead 1	< 720	< 661	< 203	7
	< 300	< 249	< 103	42
Archaeolead 2	< 731	< 485	< 239	7
	< 286	< 167	< 93	44
High-purity Pb	< 802	< 636	< 258	7
OPERA Pb	(67 ± 7) × 10 ³	(58 ± 7) × 10 ³	(27 ± 8) × 10 ³	7

Quantulus paper



Eur. Phys. J. C (2026) 86:698
<https://doi.org/10.1140/epjc/s10052-026-15922-7>

THE EUROPEAN
PHYSICAL JOURNAL C



Regular Article - Experimental Physics

A rapid low-background assay of ^{210}Pb in archaeological lead

M. Consonni^{1,2,a} , M. Clemenza^{1,2,b} , E. Di Stefano^{2,3} , N. Ferreiro Iachellini^{1,2} , F. Filippini^{1,2,3} , A. Gardini^{4,5}, G. Grosso⁴, L. Pattavina^{2,1} , R. Della Pergola³ , S. Quitadamo^{1,2} , E. Sala^{2,6} , F. Saliu^{2,3} , A. Salvini^{4,5} , L. Trombetta^{1,2}

¹ Dipartimento di Fisica, Università di Milano-Bicocca, Piazza della Scienza 3, 20126 Milan, Italy

² INFN Sezione di Milano-Bicocca, Piazza della Scienza 3, 20126 Milan, Italy

³ DISAT, Università di Milano-Bicocca, Piazza della Scienza 1, 20126 Milan, Italy

⁴ Laboratorio Energia Nucleare Applicata, Via Aselli 41, 27100 Pavia, Italy

⁵ INFN Sezione di Pavia, Via Bassi 6, 27100 Pavia, Italy

⁶ Center for Underground Physics, Institute for Basic Science, Daejeon 34126, Korea

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Abstract In this work, we present a fast and highly efficient method for the measurement of ^{210}Pb in metallic archaeological lead using the commercial low-background liquid scintillation counter Wallac Quantulus 1220 installed at the University of Milano-Bicocca (Italy). By combining an optimized chemical preparation with pulse-shape analysis

ground events generated by environmental radioactivity and cosmic rays.

Natural radioactivity is unavoidably present in all materials used in detector construction, making it challenging to achieve the ultra-low-background conditions required to detect such elusive signals. Moreover, the massive shielding

Come and check the RES-NOVA collaboration!

<https://res-nova.unimib.it/>

DOI: [10.1140/epjc/s10052-026-15922-7](https://doi.org/10.1140/epjc/s10052-026-15922-7)

RES-NOVA cosmogenic background



background

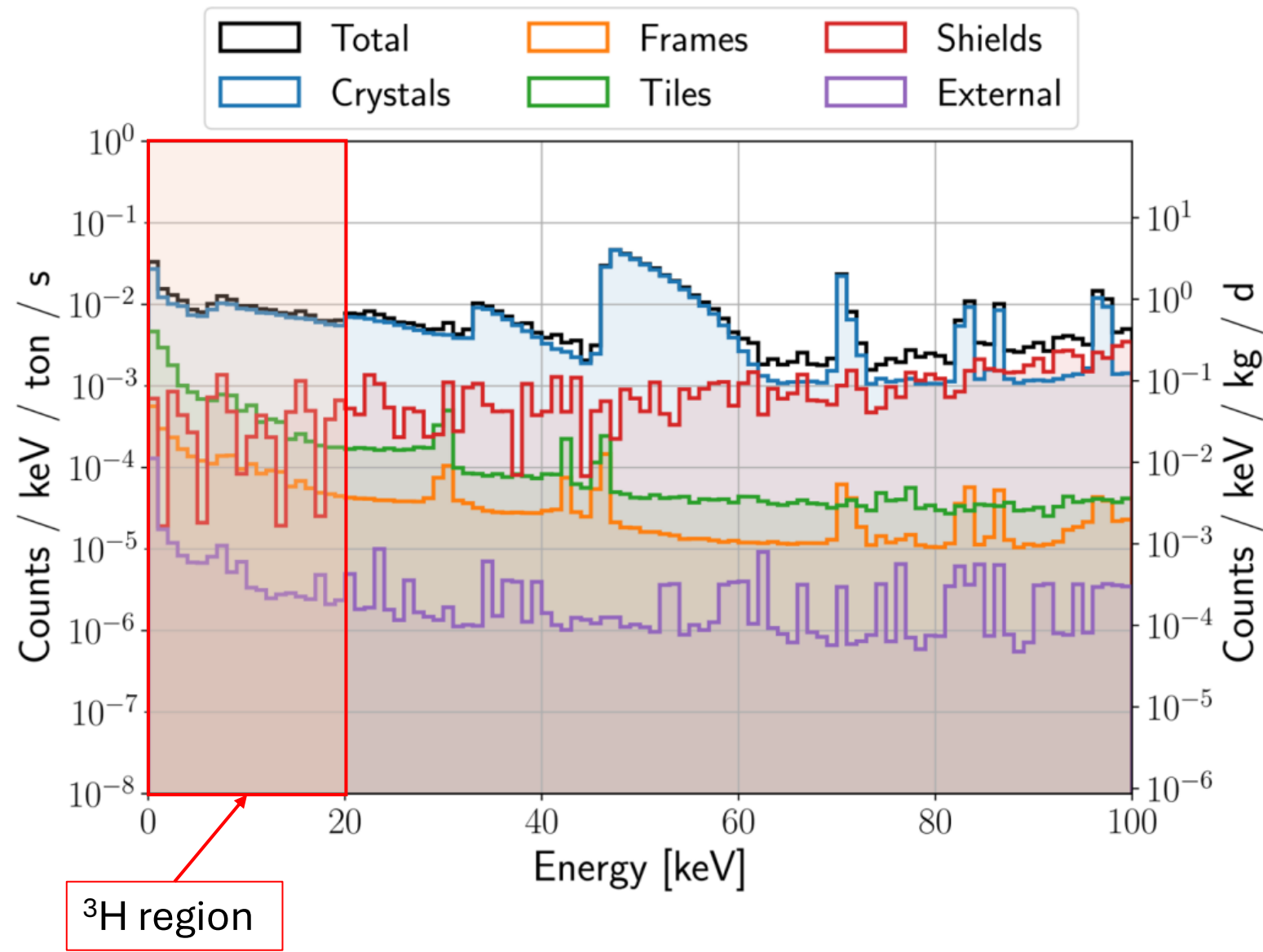
Cosmogenic radionuclides are an additional source of background in rare-event detectors.

Activation studies for RES-NOVA

To investigate cosmogenic activation, PWO crystals and archaeological Pb were neutron-irradiated at ChipIR (ISIS).

Here: preliminary results on ^3H in activated PWO

Poster session: activation studies of archaeological PWO
(*hopefully, you already noticed!*)



Measurement of ^3H in activated PWO



1. Optimal detection set-up $\rightarrow$ 12 ml LS + 8 ml liquid sample mix.
2. NO PSA CALIBRATION NEEDED.
3. Calibration curve with sample spiked with known activity of ^3H .
4. Measurements of samples (PRELIMINARY).

ISSUES:

1. Phase separation of NaOH solvent with LS $\rightarrow$ detection efficiency temporal dependance.
2. PWO Blank samples slightly ^3H contaminated, hard to correctly measure.
3. Overall low detection efficiency expected.

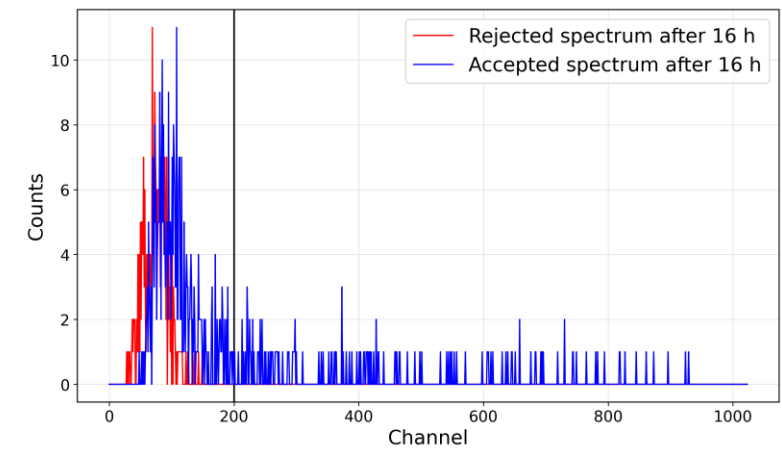
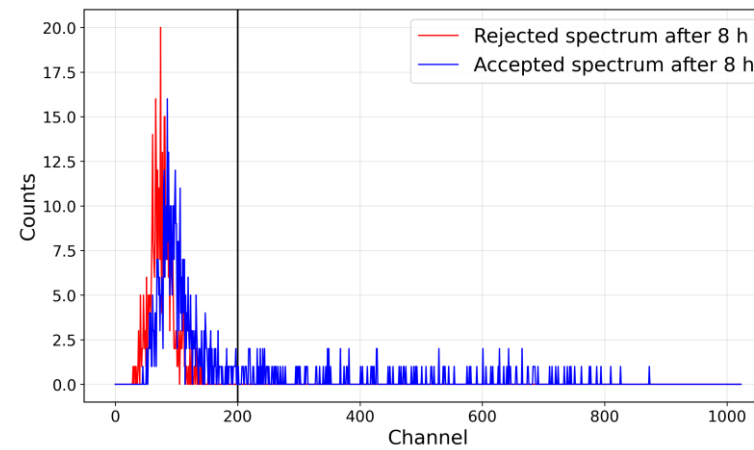
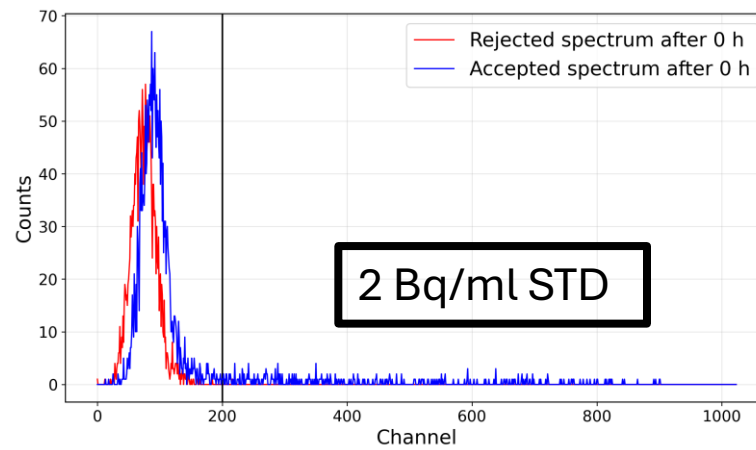


PWO sample few minutes after preparation

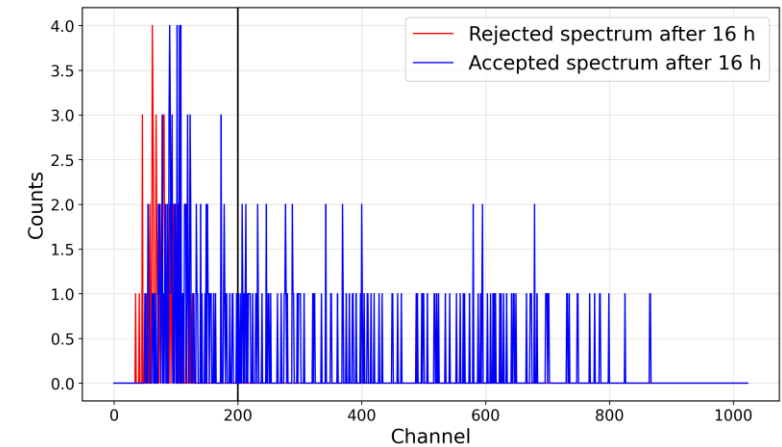
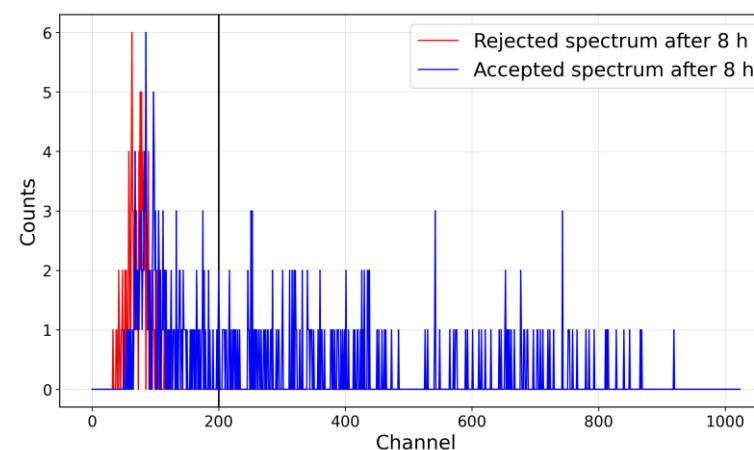
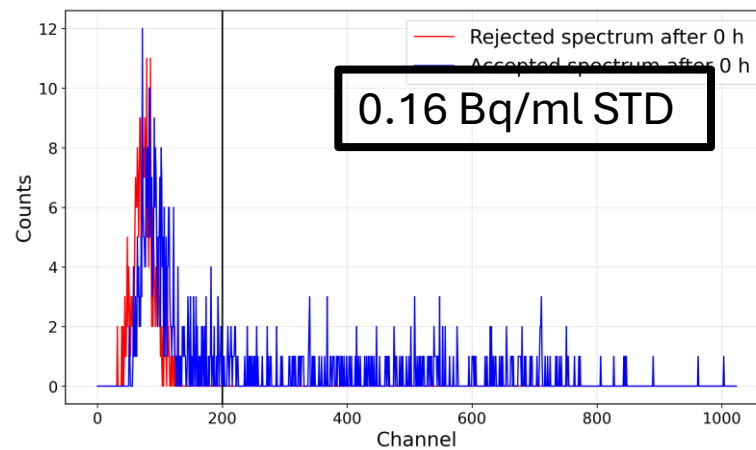
PWO sample 5 hours after preparation



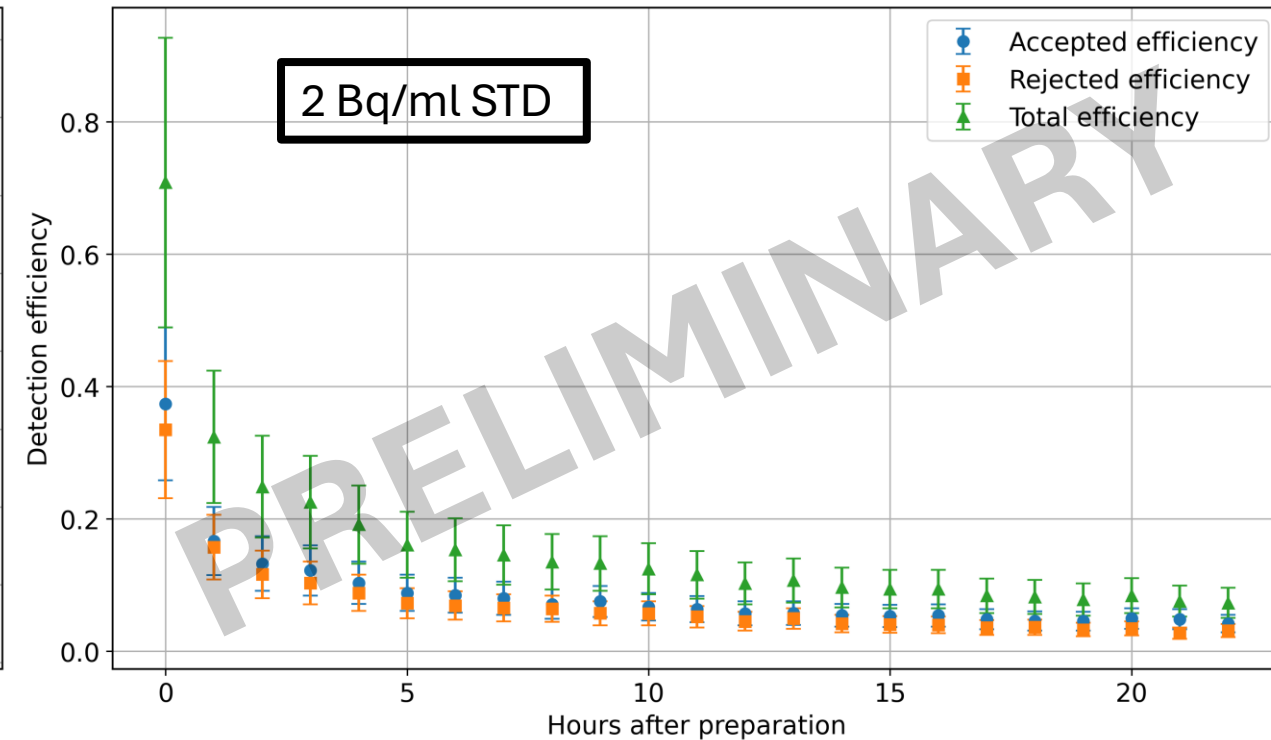
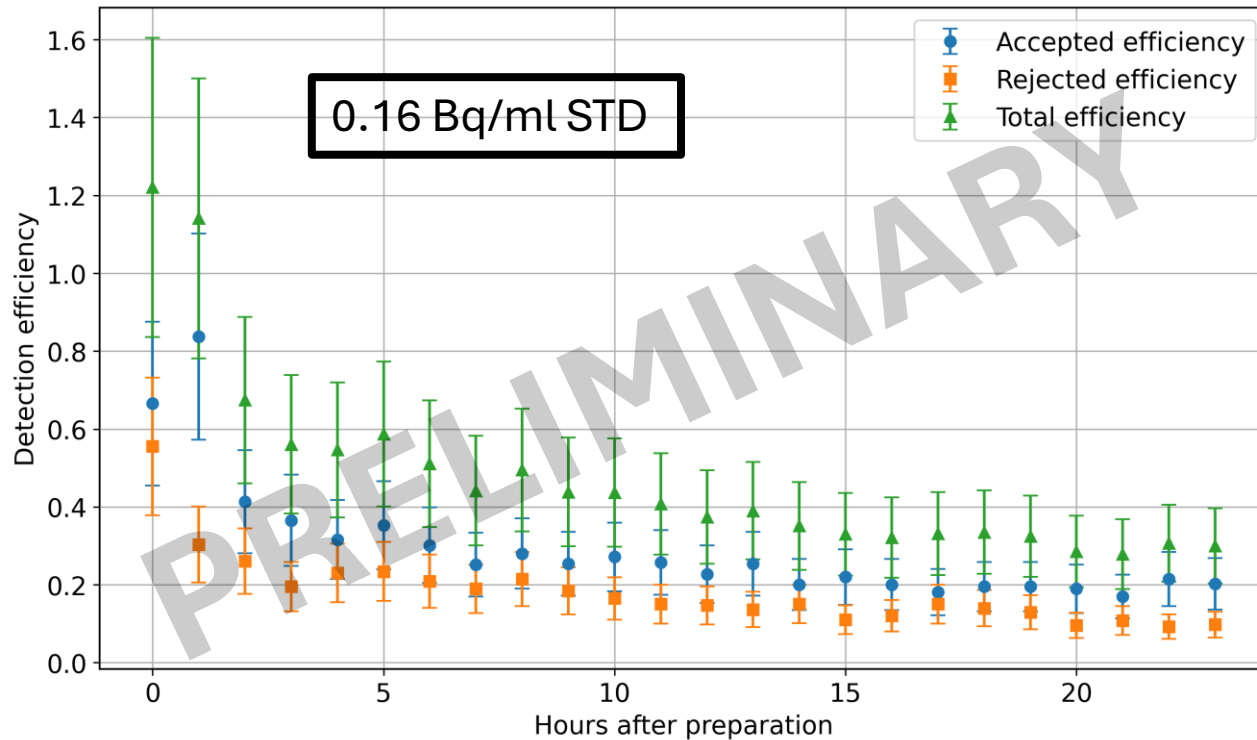
^3H ROIs



Measure time

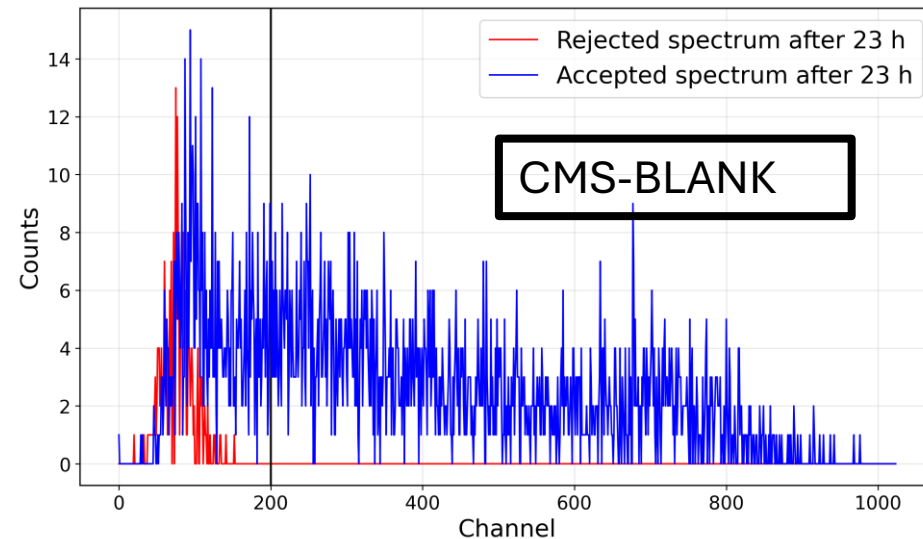
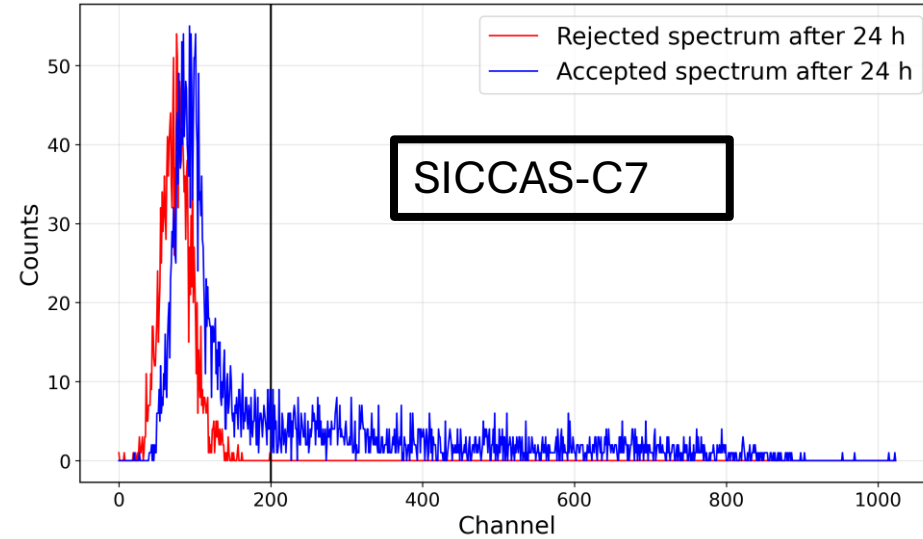
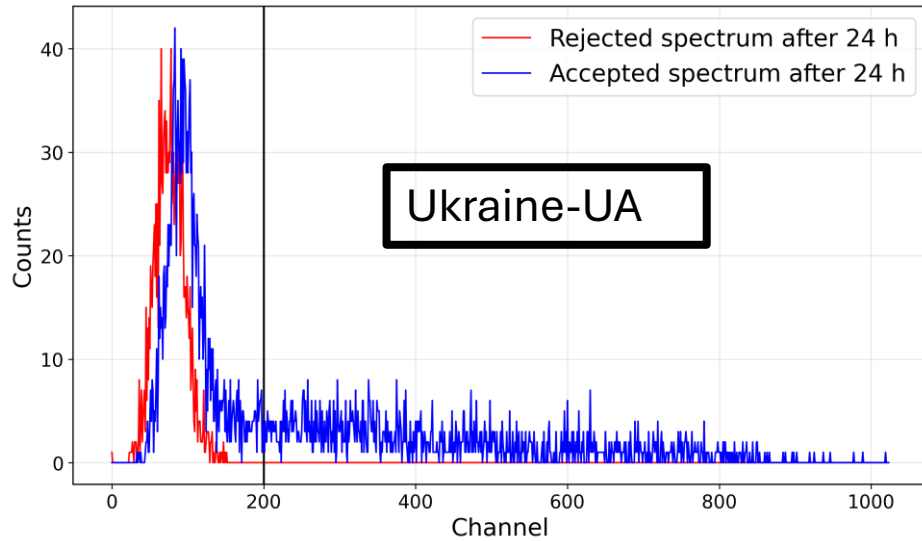


Detection efficiency stability in time



- Phase separation changes detection stability
- Stability reached after 15-20 h from sample preparation

^3H measures in PWO crystals

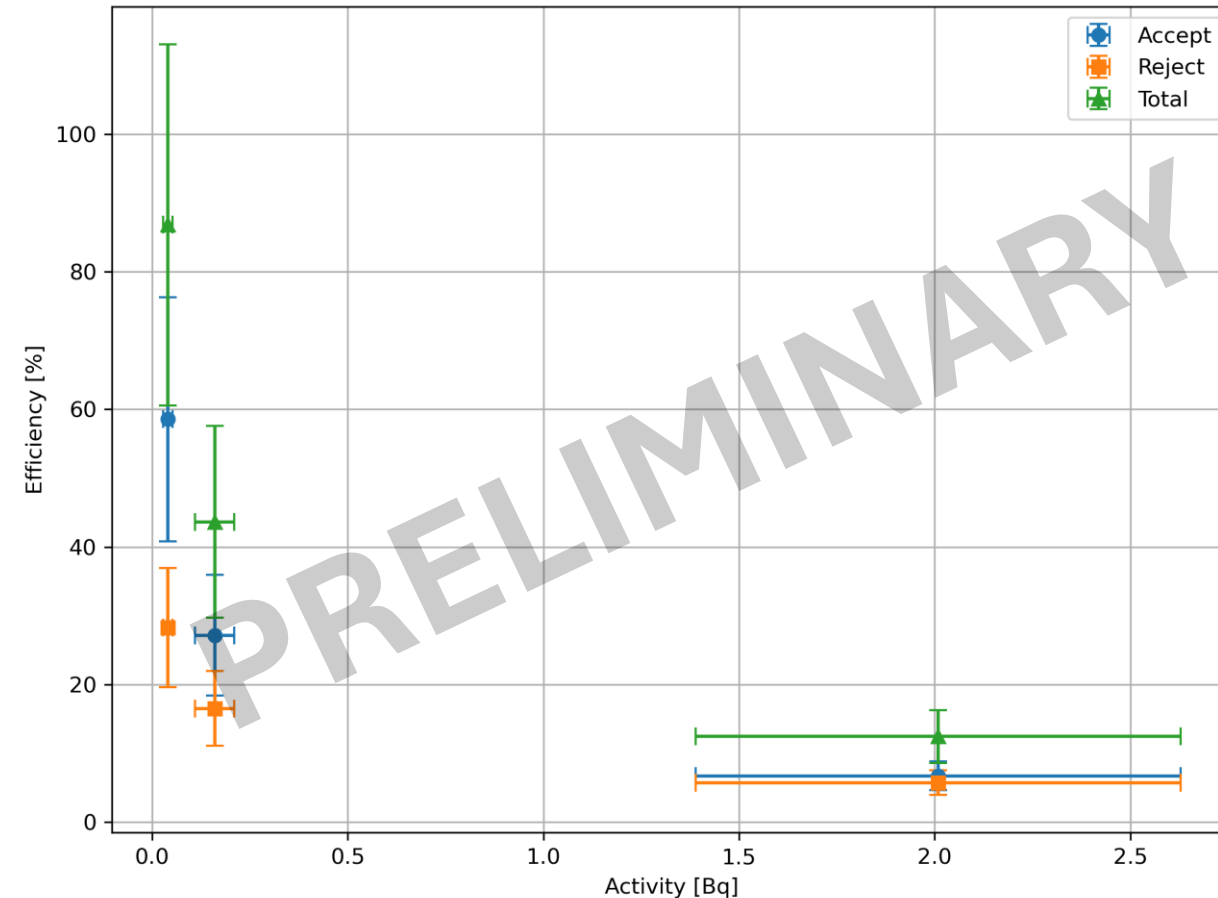


PRELIMINARY ^3H results



Sample	Method	Activity [Bq/kg]
C7	Accepted	307.0 ± 95.8
	Rejected	285.1 ± 89.4
	All	296.7 ± 92.2
UA	Accepted	117.5 ± 36.7
	Rejected	110 ± 34.6
	All	114 ± 35.5
CMS		$\sim 10\text{-}20$

NOTE: the C7 (Siccias) and UA (Ukraine) samples were neutron-activated at ChipIR, ISIS neutron source that mimics the fast atmospheric neutron spectrum with a flux enhanced by a factor 10^9 .



A rapid and versatile method for low-background radioassays



Funded by
the European Union



European Research Council
Established by the European Commission



RAPID

~1 week for $O(10^2)$ mBq/kg
sensitivity

LOW SAMPLE MASS

< 1g of sample

SIMPLE AND ACCESSIBLE

based on commercial LSC detector

SIMULTANEOUS detection of the
 ^{210}Pb decay chain

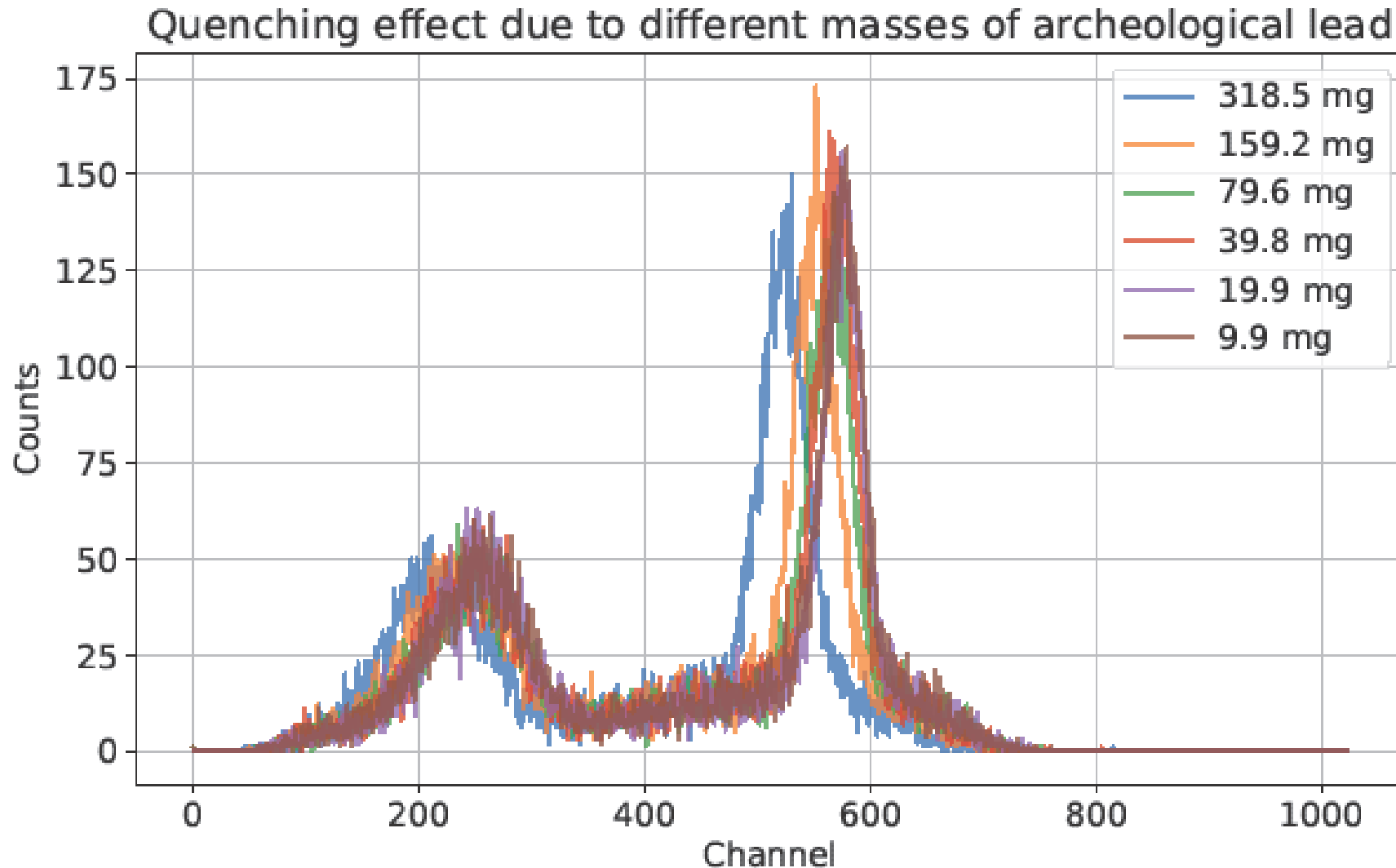
Thank you!



The background image shows two offshore oil rigs in a calm sea under a grey, overcast sky. The rig on the left is a smaller, yellow and red structure with a small orange 'X' on its top. The rig on the right is larger and has a dark statue of a person with arms raised on its deck. The text 'Backup slides' is centered over the image.

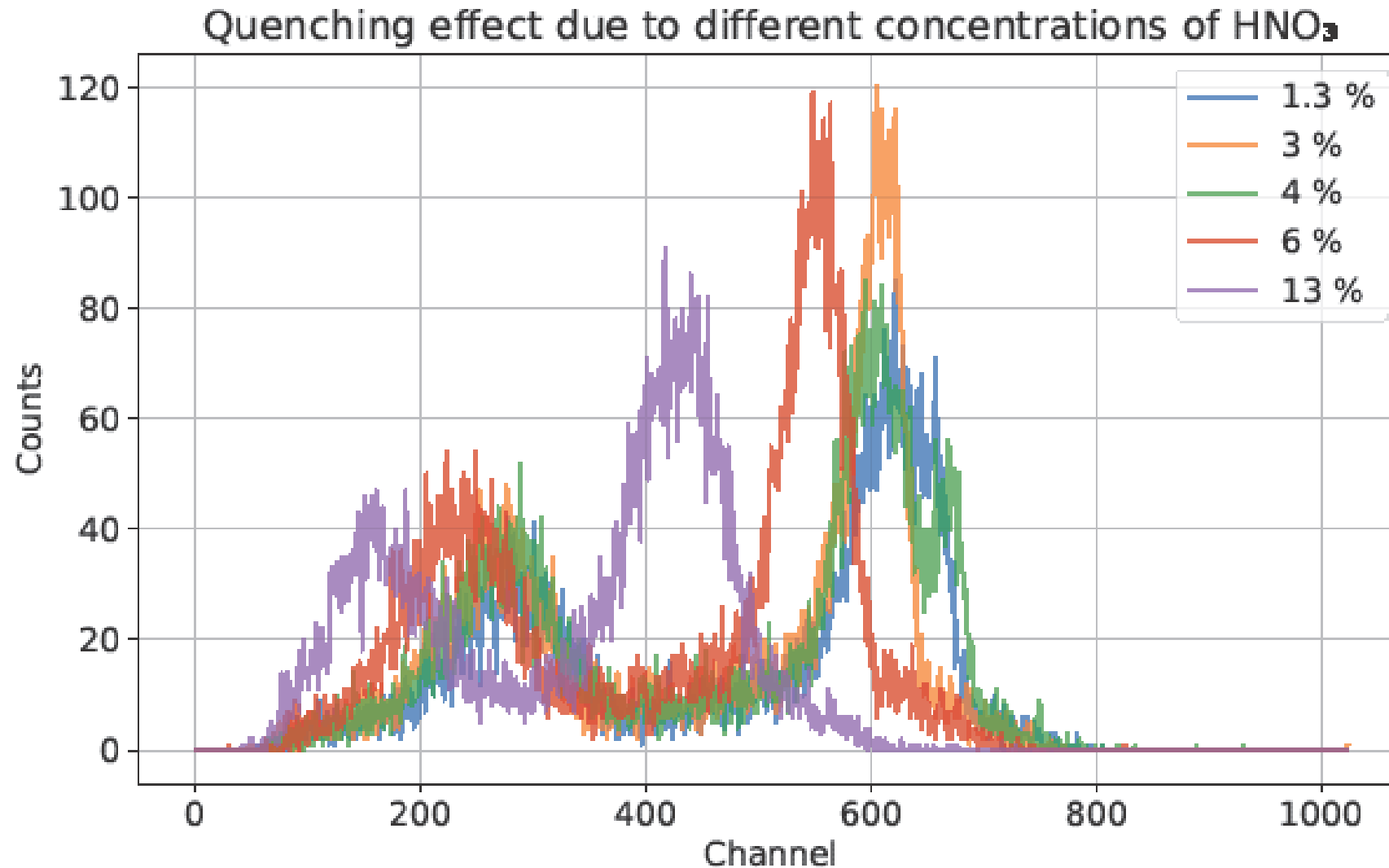
Backup slides

Quenching: Pb mass



- No α/β discrimination
- Low measure time (15 min)
- 8/20 set
- Quenching effects visible but not excessively impactful.

Quenching: HNO_3

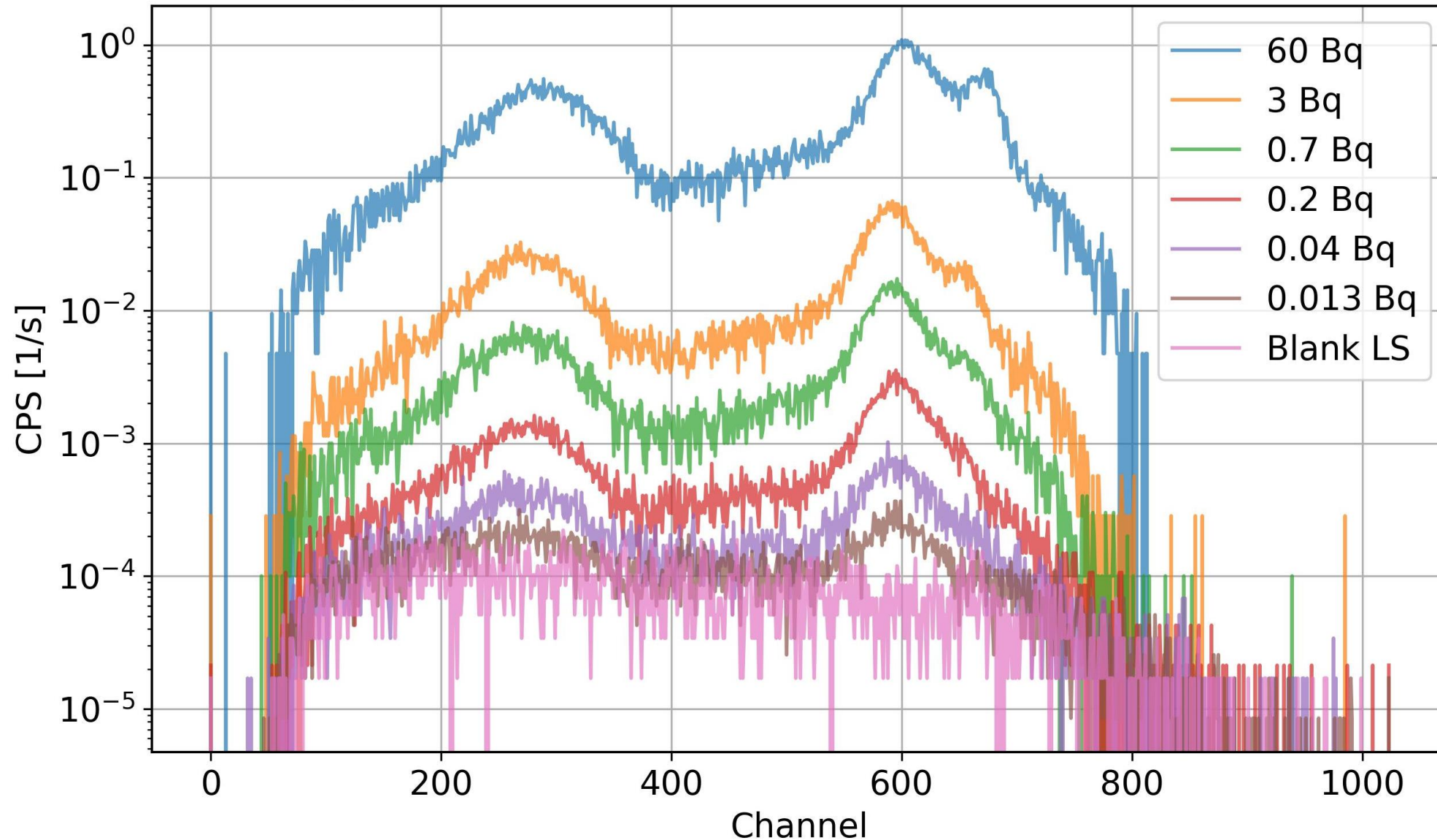


- No α/β discrimination
- Low measure time (15 min)
- 8/20 set
- Highly impactful quenching effects

No PSA tests

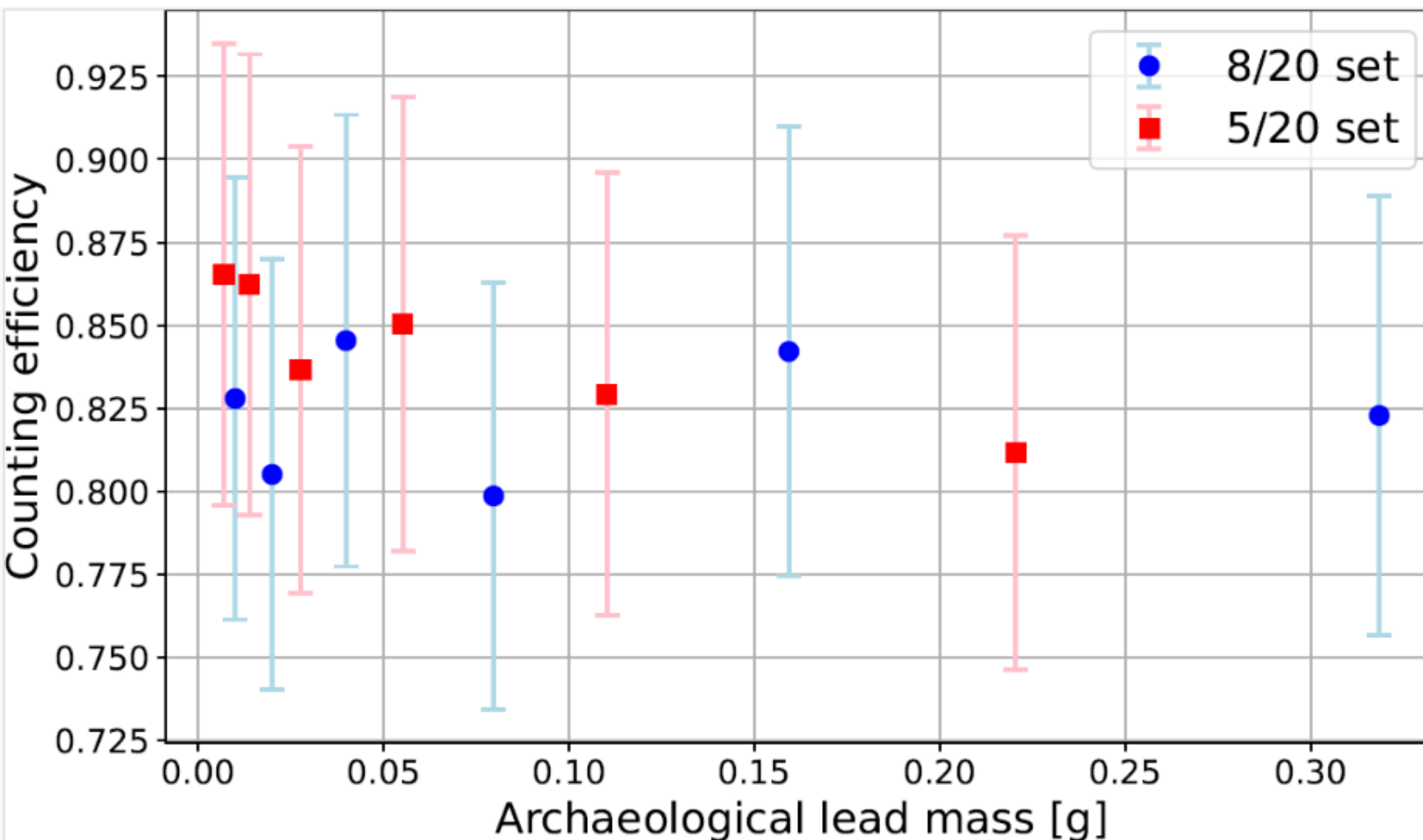


Samples with different concentrations of ^{210}Pb marker



- No α/β discrimination
- Different measure times (5 min up to 2 d)
- 8/20 set

Efficiency



2 set of samples:

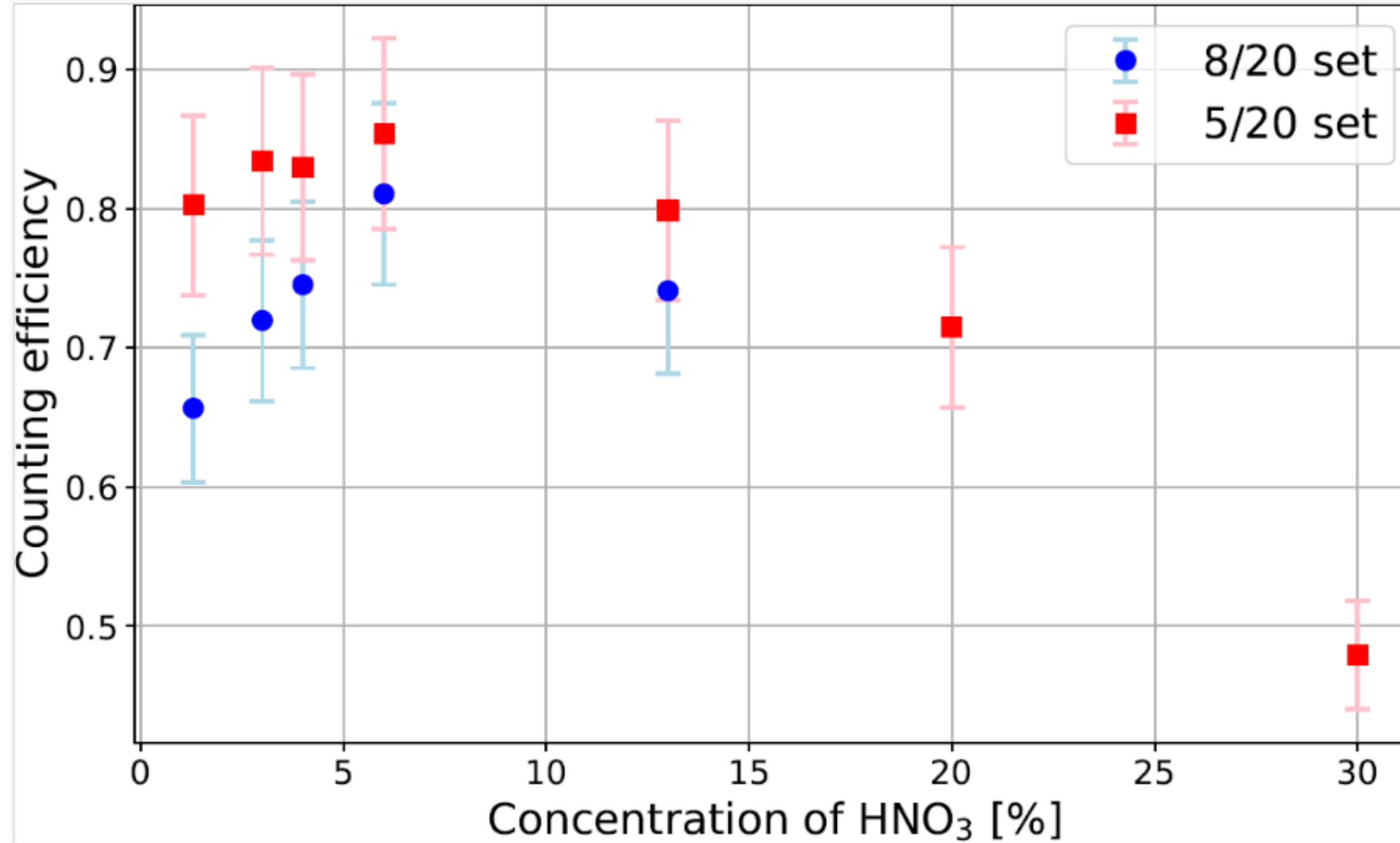
8/20 = 8 ml sample + 12 ml LS

5/20 = 5 ml sample + 15 ml LS

$$\varepsilon_{8/20} = 82 \pm 2 \%$$

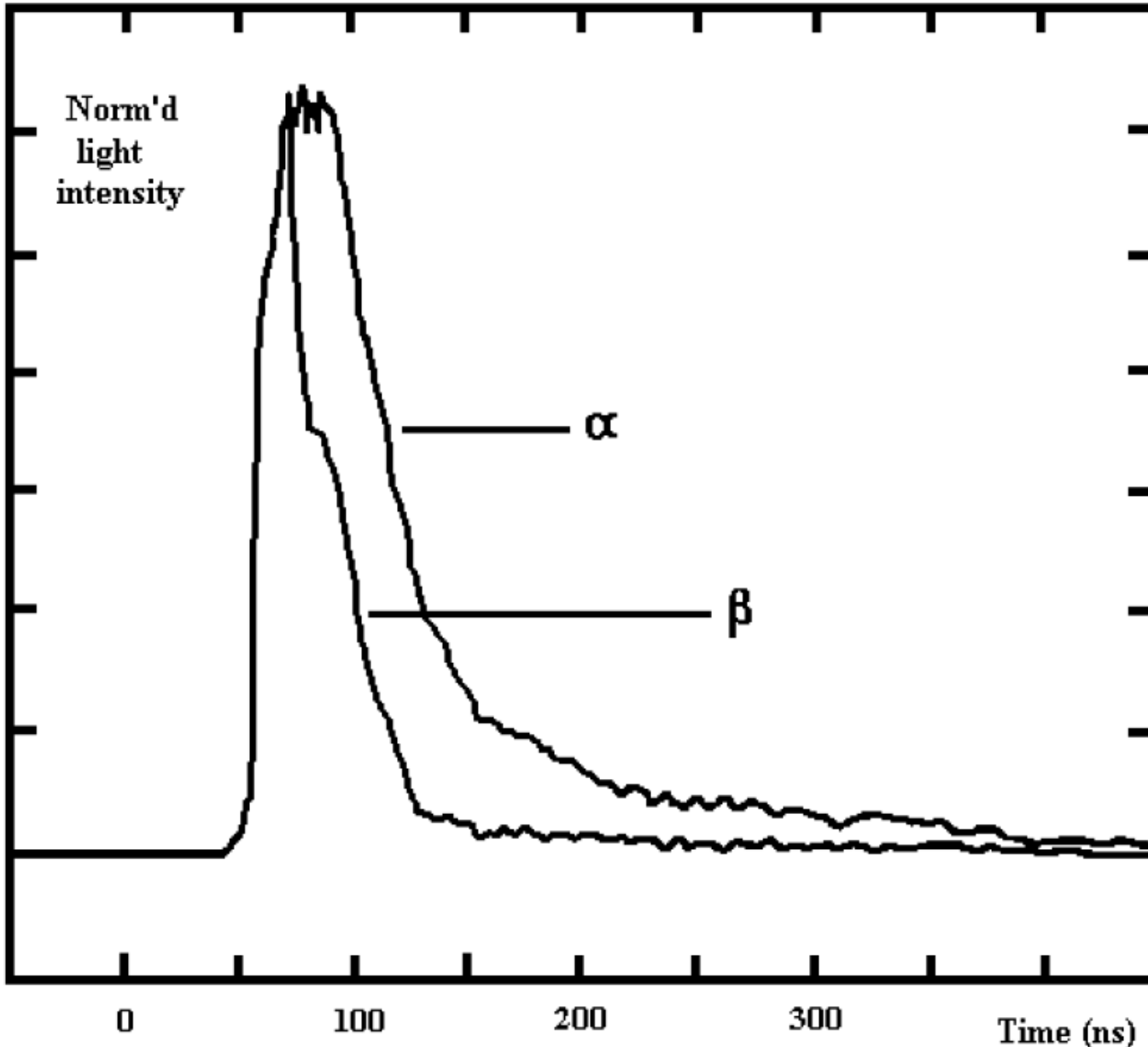
$$\varepsilon_{5/20} = 85 \pm 2 \%$$

Efficiency



Quenching and therefore counting efficiency strongly depends on HNO_3 concentration

Pulse Shape Analysis



Quantulus allows α/β discrimination analyzing the signal length.

PSA-dedicated samples are required to determine the optimal PSA value. PSA samples should closely resemble actual samples to ensure accuracy.

PSA is an arbitrary integer value from 1 to 200. Since it is not possible to save pulse shape, to operate a posterior pulse-shape discrimination, it is necessary to scan all possible PSA values with pure α/β emitters

PSA samples

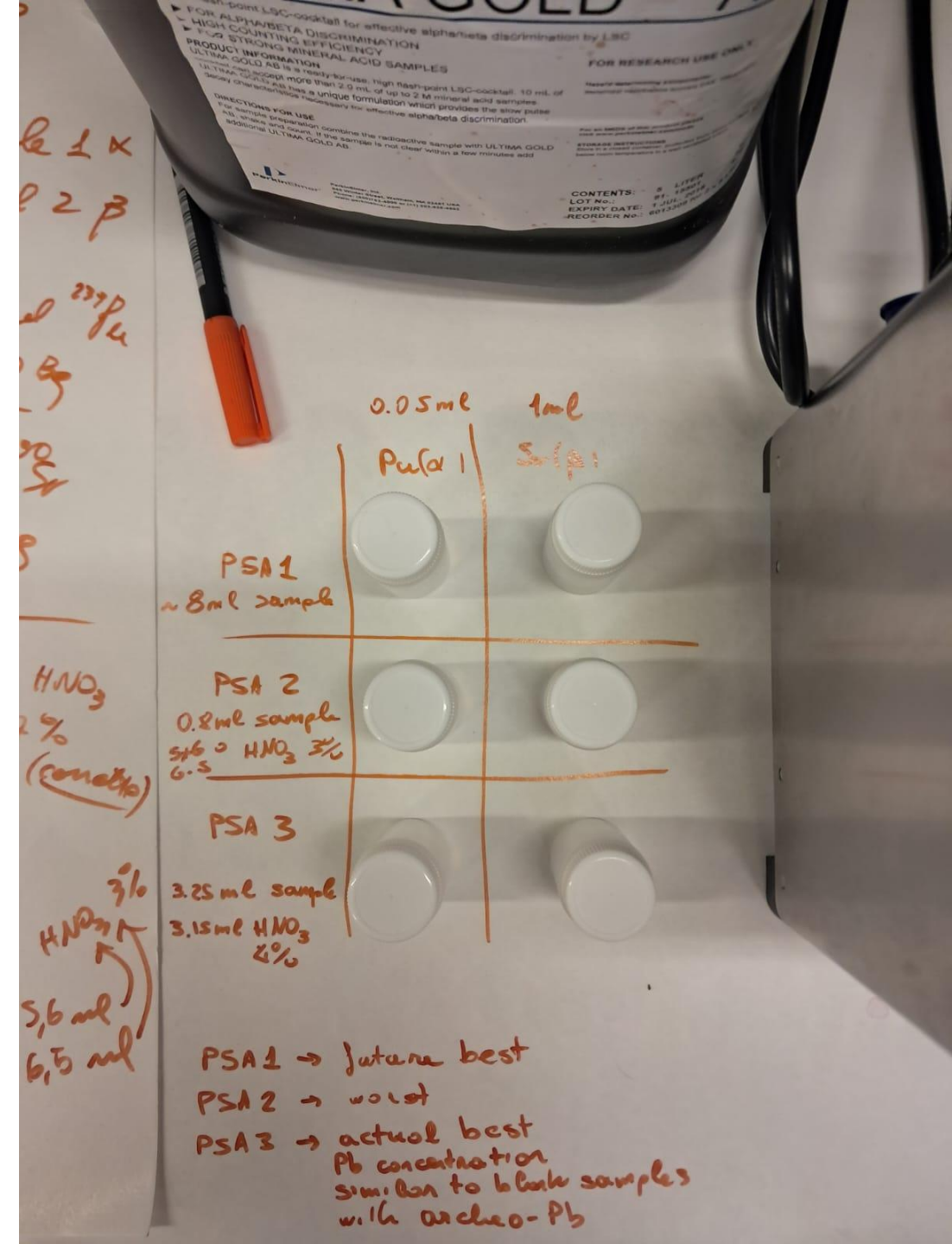
Preparation of 3 sets of 8/20 samples:

1. Sample with 0.704 g of dissolved archeological lead: optimal setup to maximize Pb sensitivity
2. Sample with 0.062 g of dissolved archeological lead: least favorable setup to maximize Pb sensitivity
3. Sample with 0.286 g of dissolved archeological lead: midpoint for the possible mass of dissolvable lead.

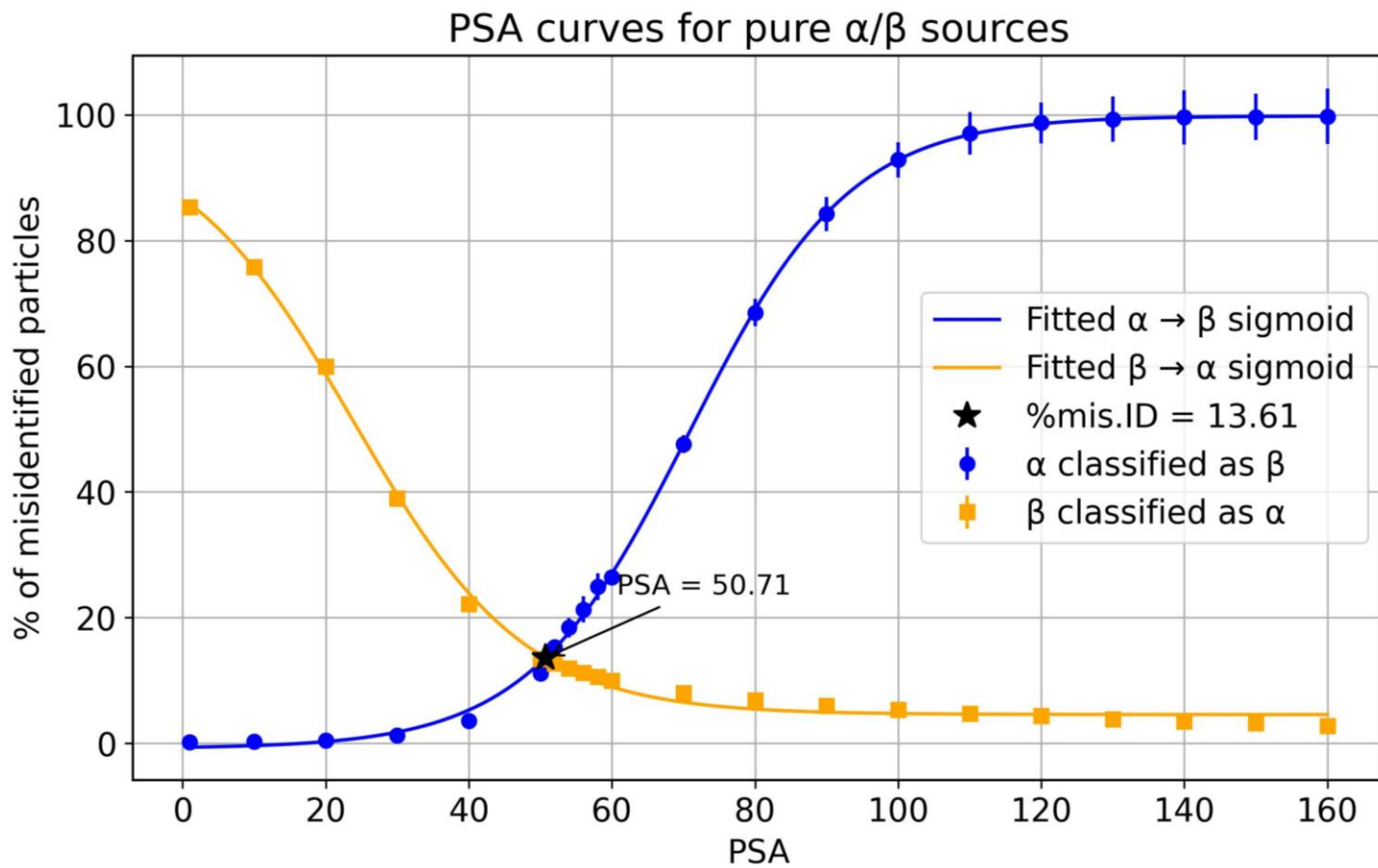
For each condition, 2 samples are prepared and subsequently spiked with a pure α/β emitter

Pure α source: ^{238}Pu

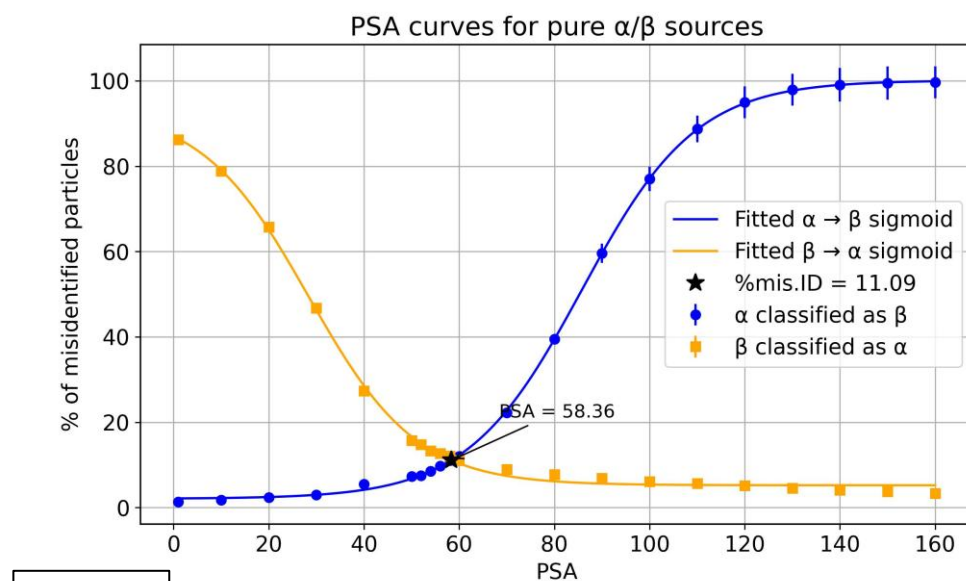
Pure β source: ^{90}Sr



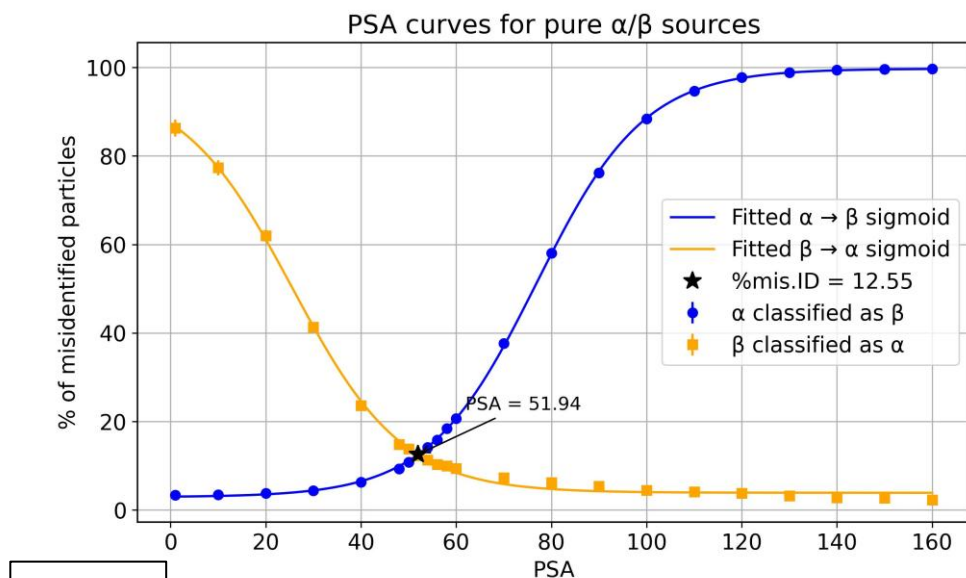
PSA Tests



PSA1, for best sensitivity samples!

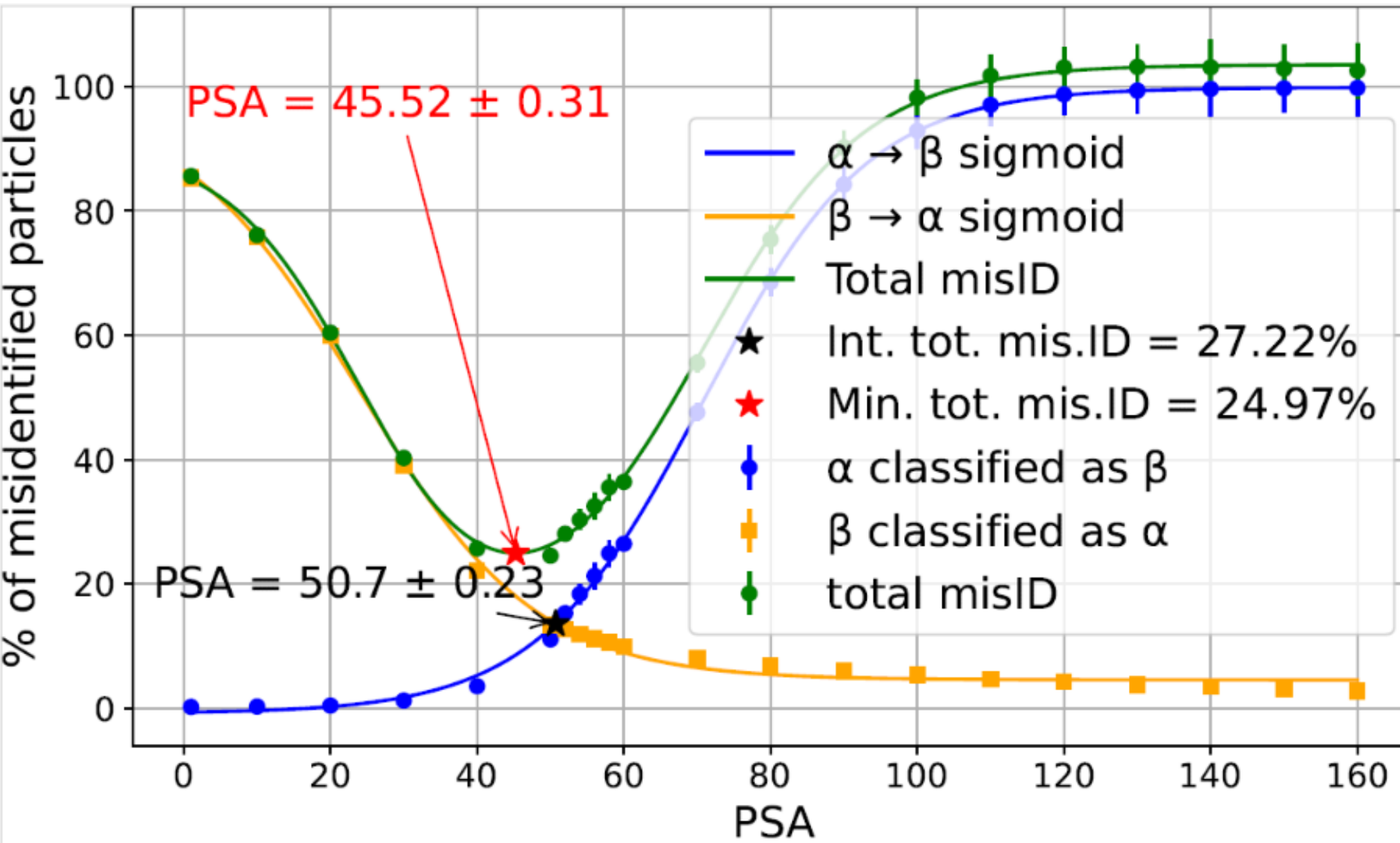


PSA2



PSA3

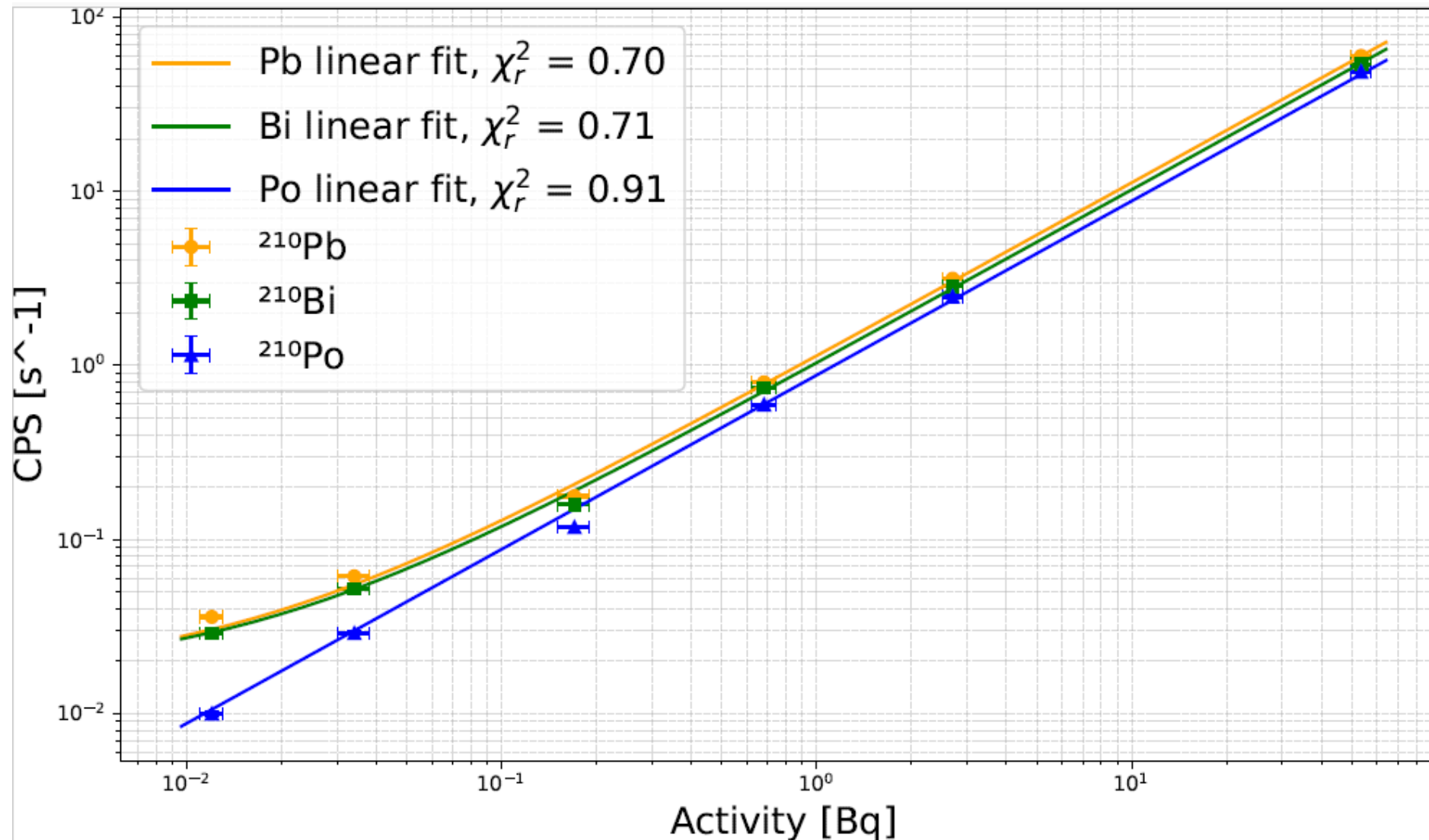
PSA optimum



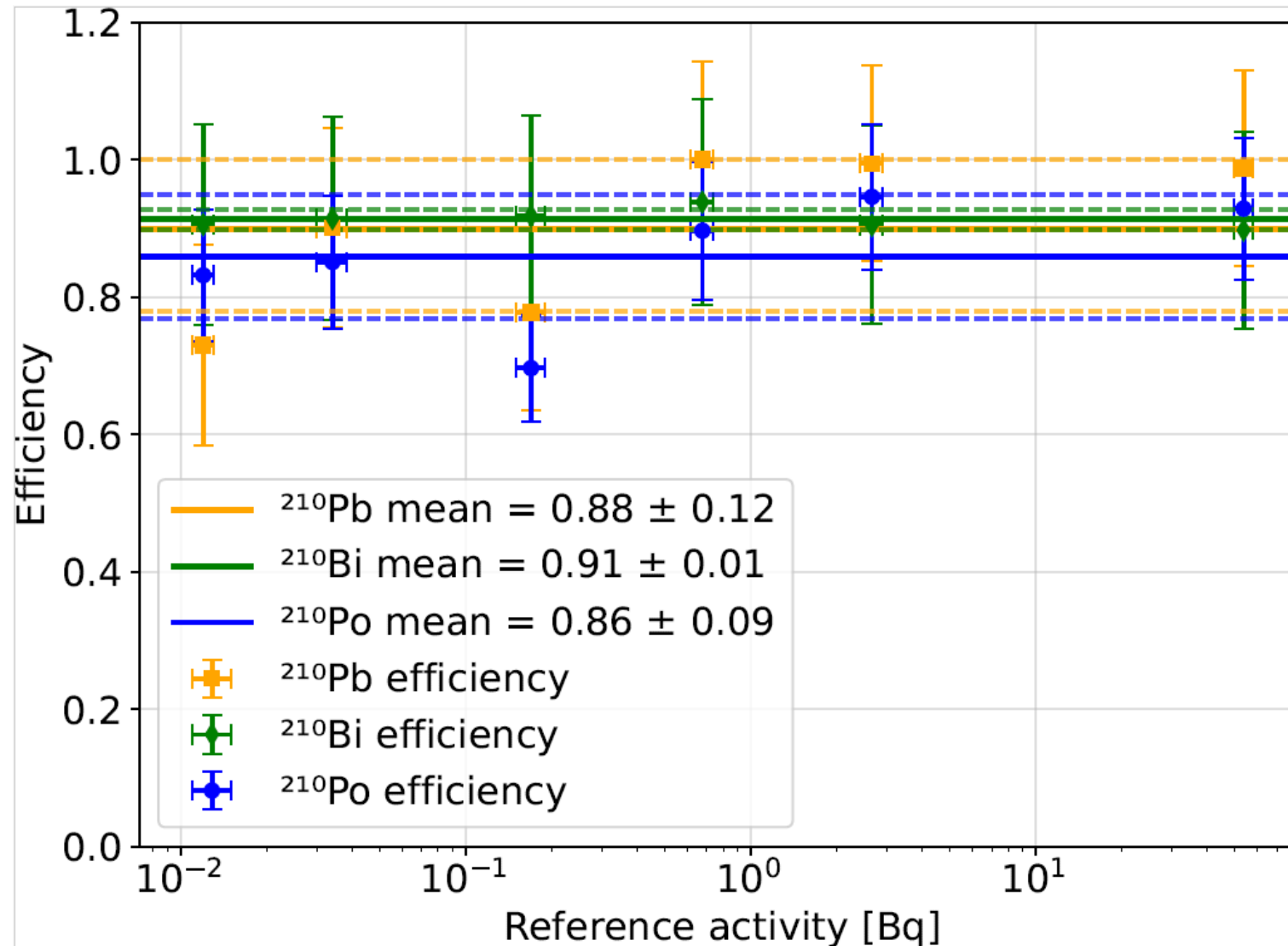
RED STAR:
Minimization of total
particle misID, resulting in
higher leakage of $\beta \rightarrow \alpha$

BLACK STAR:
Symmetrical misID rateo,
lower $\beta \rightarrow \alpha$ leakage

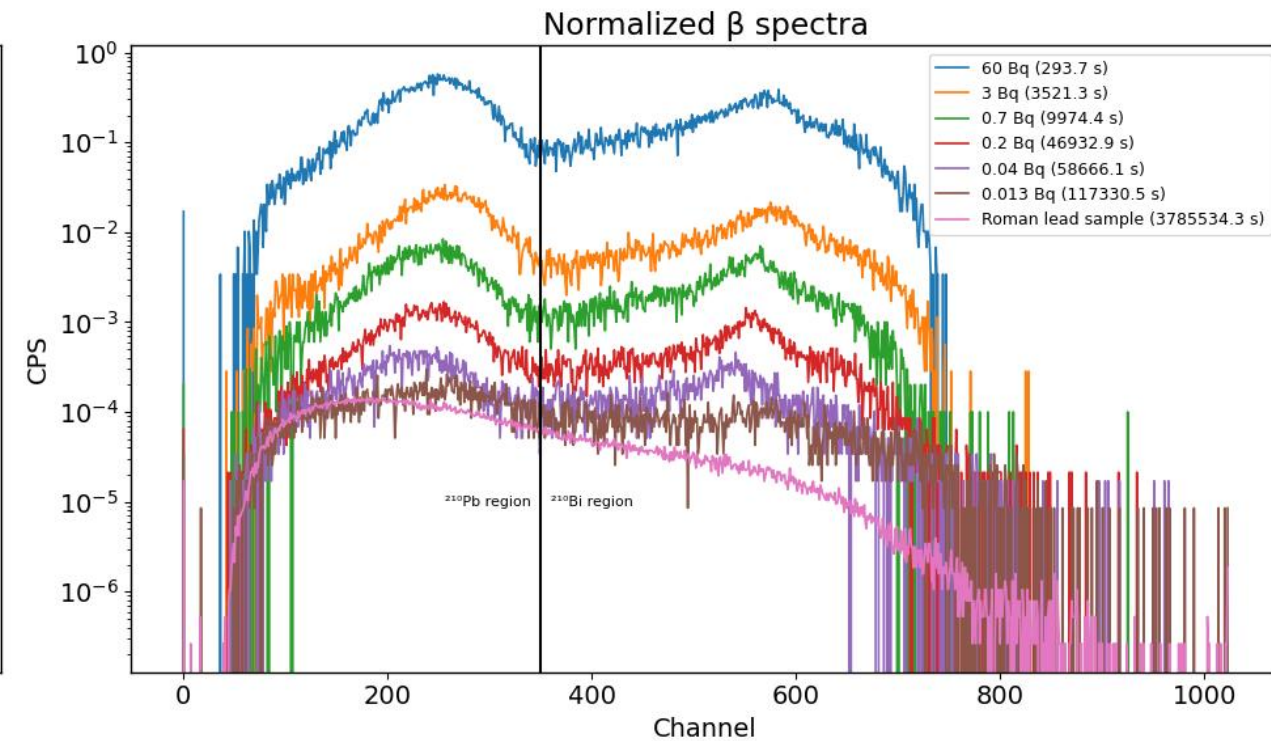
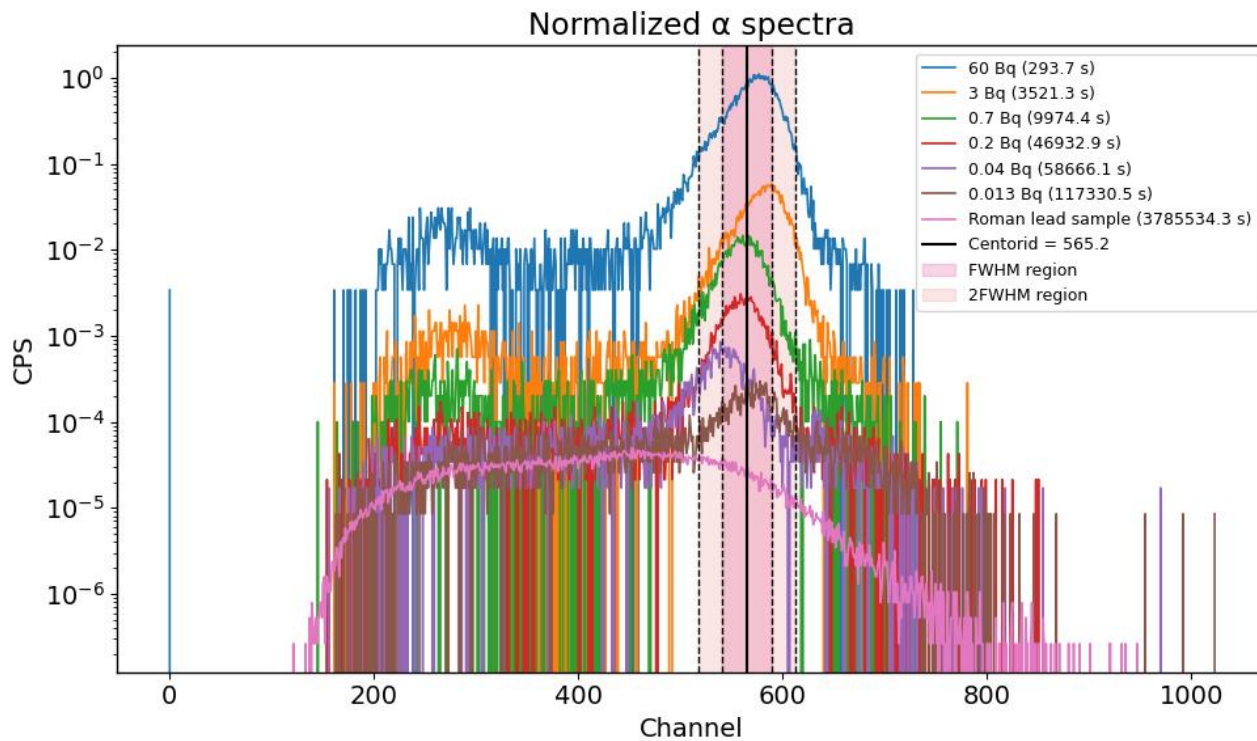
Linearity



Efficiency



ROIs



Issues on atomized Pb



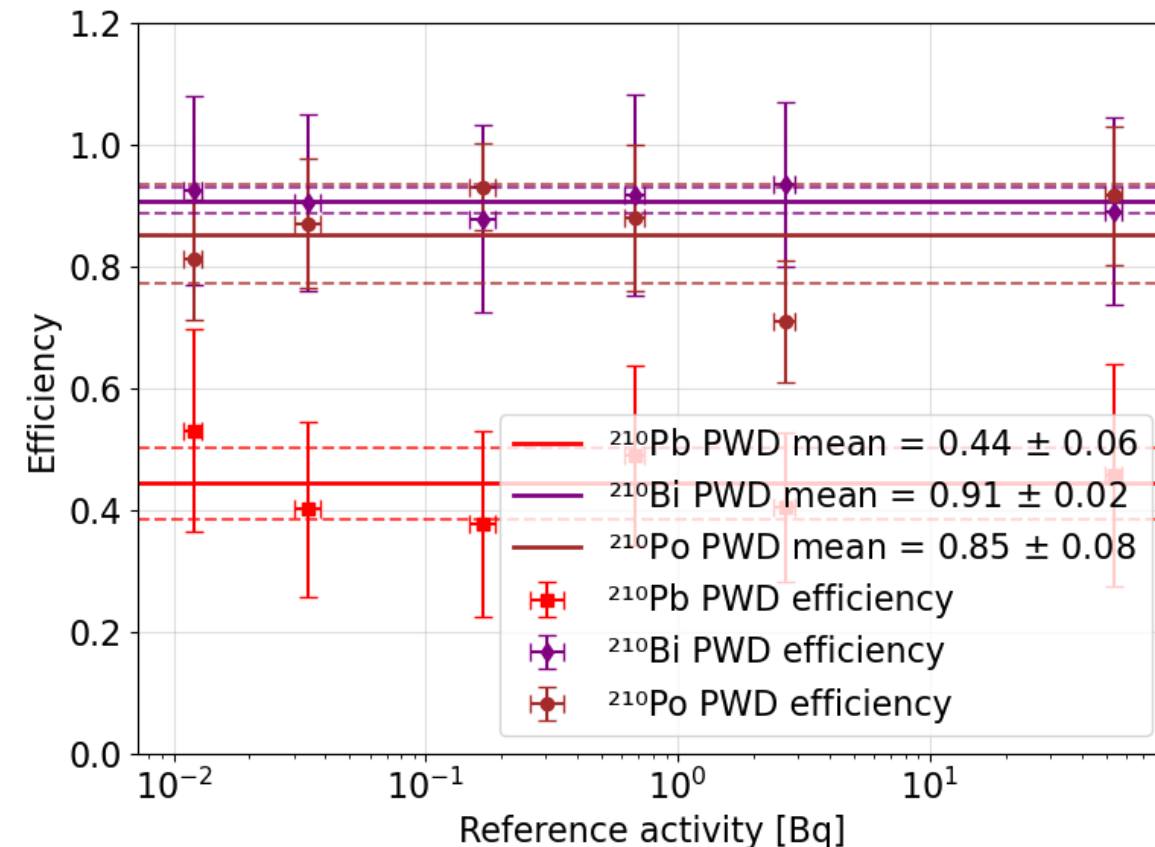
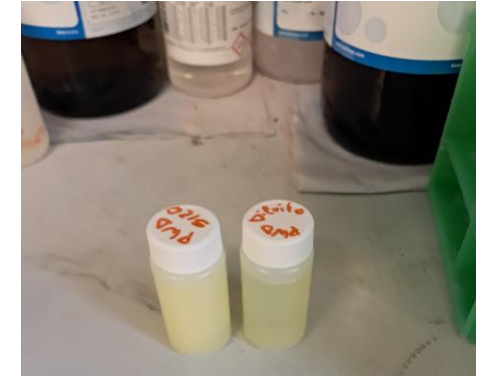
Chemistry issues:

Highly concentrated samples of atomized Pb react with LS, producing yellow-colored samples with strong energy quenching (likely due to Pb oxidation).

Different set of measurements were carried out to investigate and mitigate the issue.

Solution: lower Pb concentration in samples:
when 0.3 g of atomized Pb is dissolved, detection efficiency for ^{210}Bi and ^{210}Po become comparable to metallic Pb; only the energy quenching differs.
 ^{210}Pb efficiency remains significantly lower ($44 \pm 6 \%$).

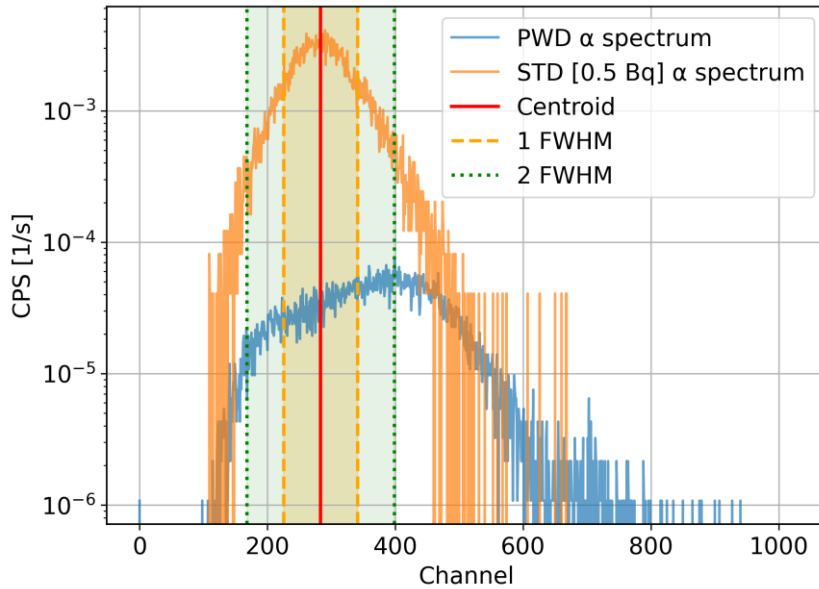
New PSA set-up as necessary.
Samples degrade faster in time.



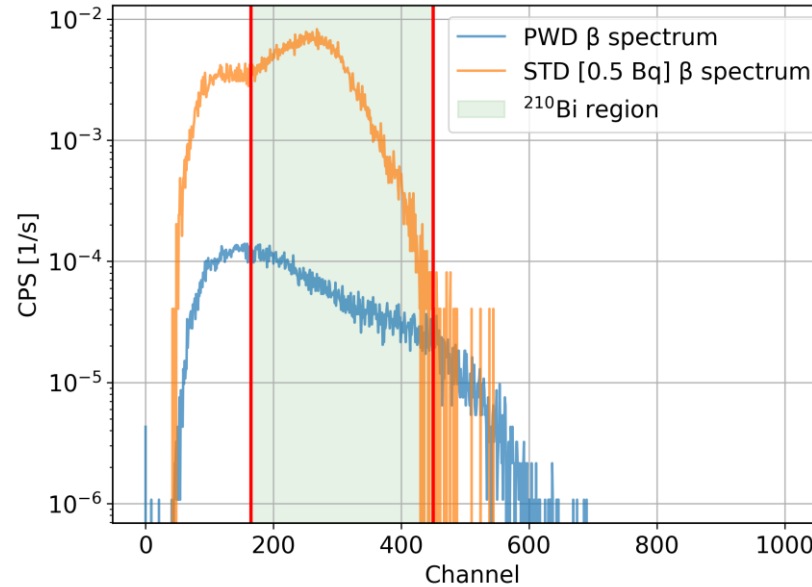
Results on atomized Pb



α spectra



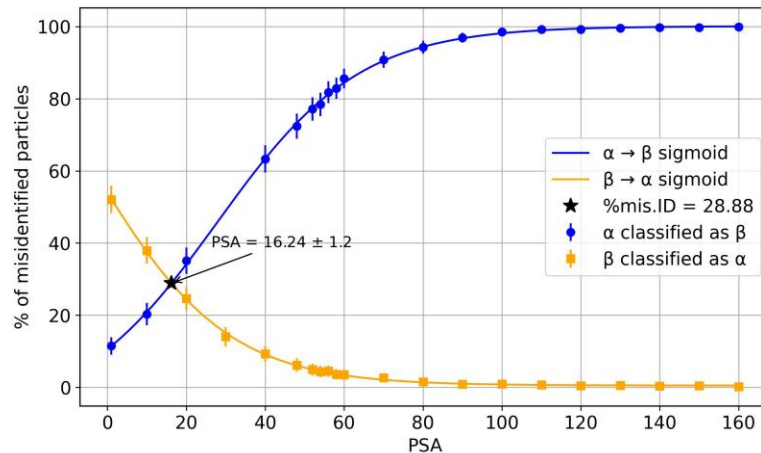
β -spectra



Expected ^{210}Po sensitivity
after a 45 d measure < 282
mBq/kg.

$$m_{\text{powder}} = 0.3 \text{ g}$$

$$m_{\text{metallic}} = 0.79 \text{ g}$$



Sample	^{210}Pb [mBq/kg]	^{210}Bi [mBq/kg]	^{210}Po [mBq/kg]	Time [d]
Atomized Pb	< 2100	< 1150	< 563	11
Archaeolead 2	< 286	< 167	< 93	44

Set-up for a ^{210}Pb LSC campaign



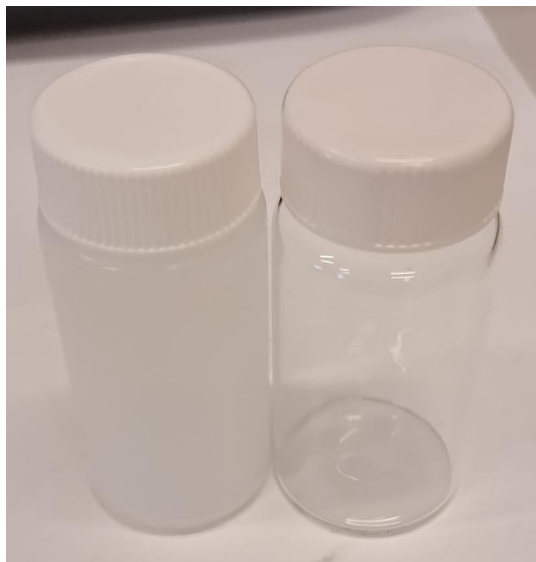
WHAT IS A QUANTULUS SAMPLE?

20 ml vials containing a cocktail of mixed LS and liquid samples.

Usual LS to sample ratio are:

15 ml LS + 5 ml liquid sample

12 ml LS + 8 ml liquid sample (the one we used)



2 Quantulus vials
made of PTFE (left)
or glass (right)

1. Finding the optimal detection set-up
 - Testing different ratio of LS vs liquid samples
 - Testing quenching effects due to sample acidity and concentration
2. Finding the optimal PSA set-up to allow correct α/β discrimination
 - Preparing 2 chemically identical samples to the optimized one
 - Spiking samples with pure α/β emitters
 - Scanning different PSA values (more on that later!)
3. Calibration curve with sample spiked with known activity of ^{210}Pb to identify ROIs and check detector linearity.
4. Samples measurements.

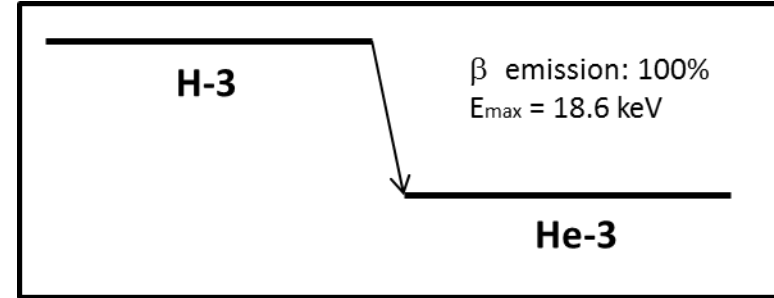
Preparation of PWO samples



1. 0.2 g of PWO are dissolved in a 10 ml aqueous solution of NaOH 1:10.
2. The process is fairly rapid, no ultrasound heating needed.
3. 8 ml of dissolved sample are mixed with 12 ml of UltimaGoldAB LS.

Blank samples prepared with a CMS PWO crystal that resulted slightly contaminated with ^3H ($< 10\text{-}20\text{ Bq/kg}$).

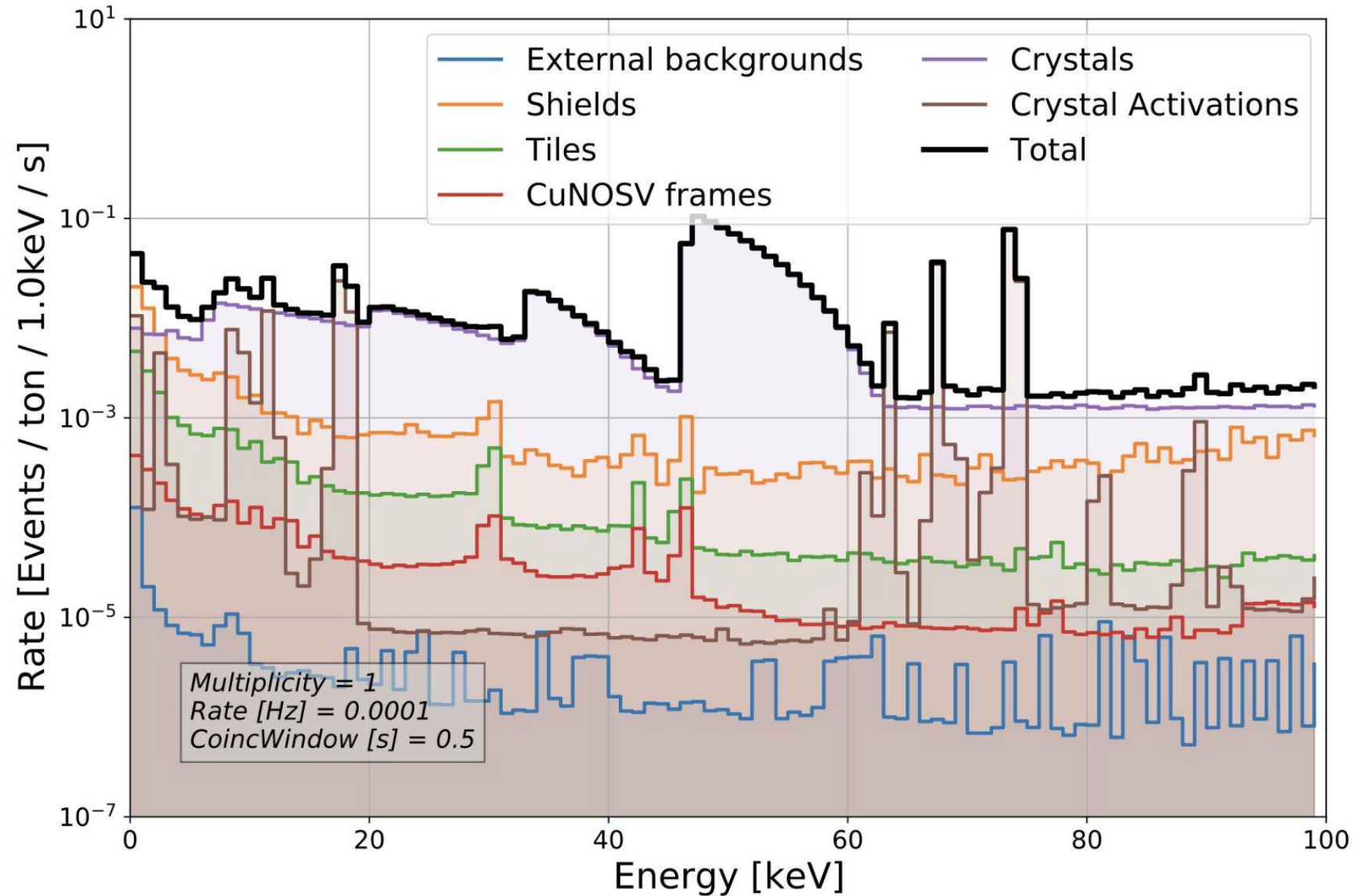
More calibration point needed since few ^3H standard were available.



Dissolved PWO sample
(because apparently taking photos of the original crystal was too much to ask of me)



RES-NOVA full Background



RES-NOVA sensitivity

