ASTAROTH, an innovative detector for dark matter direct detection experiments

V. Toso[1] for the ASTAROTH Collaboration

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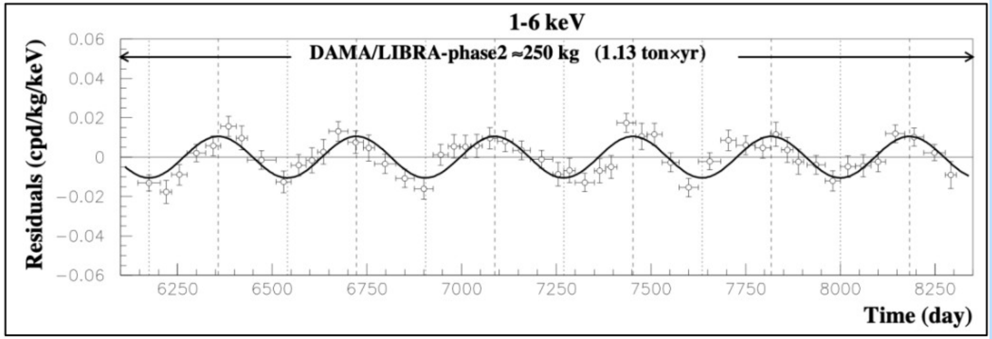
Introduction & Physics case

Using NaI(Tl) is of fundamental importance to test the positive observation of DAMA experiment.



DAMA/LIBRA phase-2

- Exposure: 1.13 ton x year (6 years)
- Sensitive mass: about 250 kg of radio-pure NaI(Tl) crystals
- Read-out with PMTs, no veto

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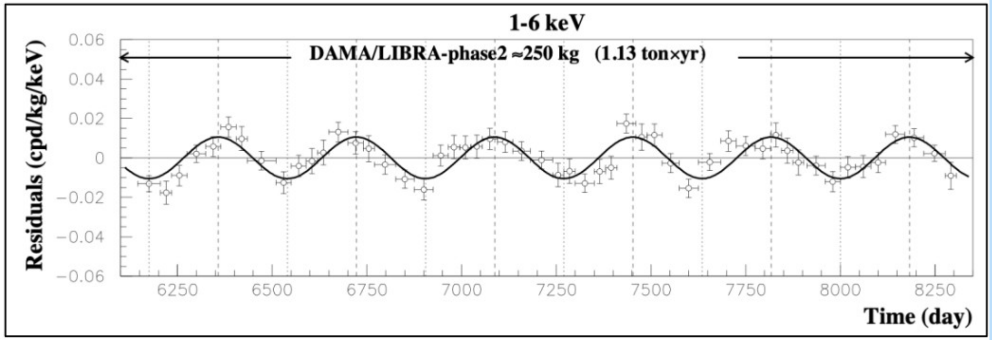

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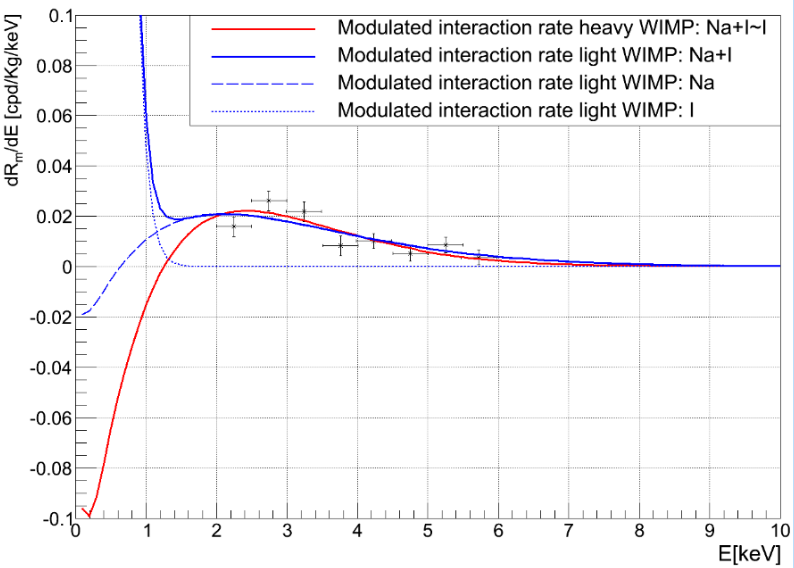

Simplified scenario: Basic hypotheses on DM Interaction (standard Halo distribution, spin-independent coupling).

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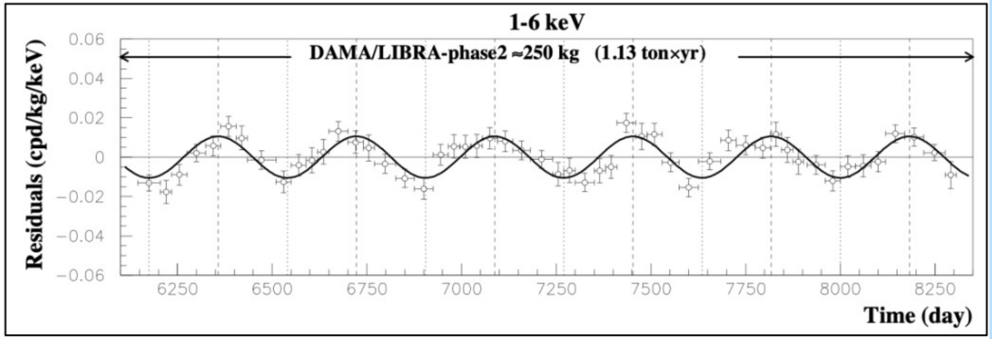

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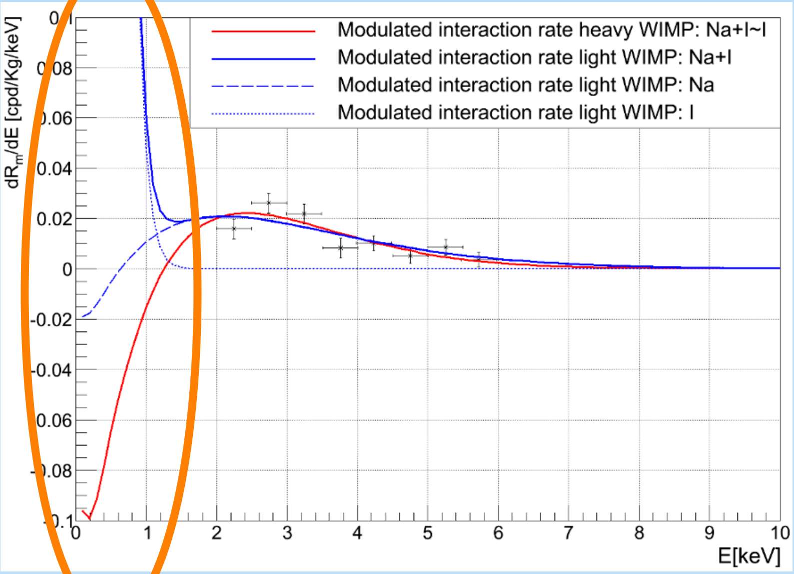
Pushing the detection energy threshold below the 1 keV limit allows disentangling of different DM candidates



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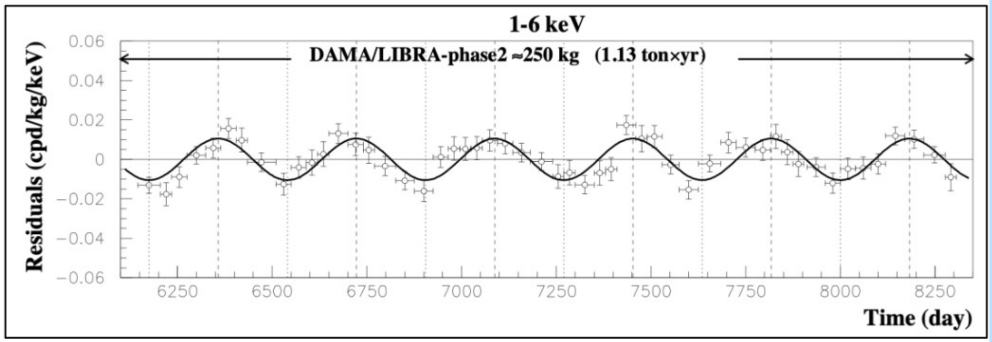

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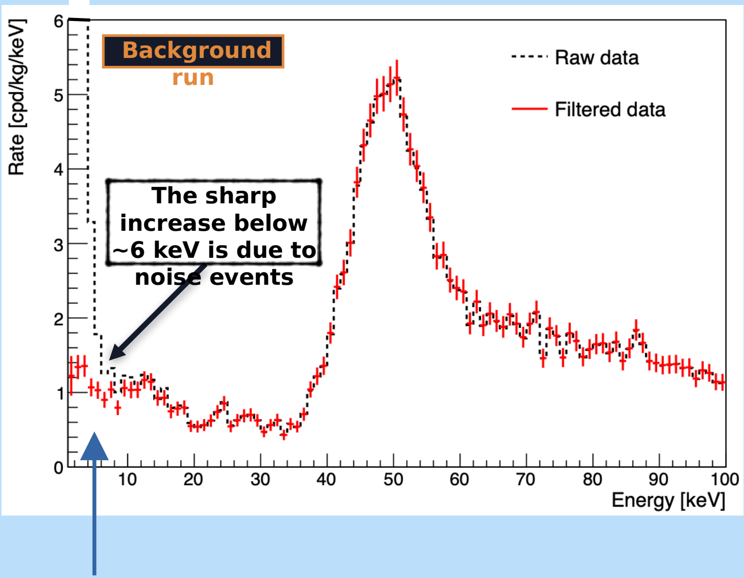
SABRE background at low energy



Noise due to PMTs

Overcoming limitations

Objectives:
- Surpass PMT technology to reduce non scintillating noise
- Enhance Light Yield (phe/keV)

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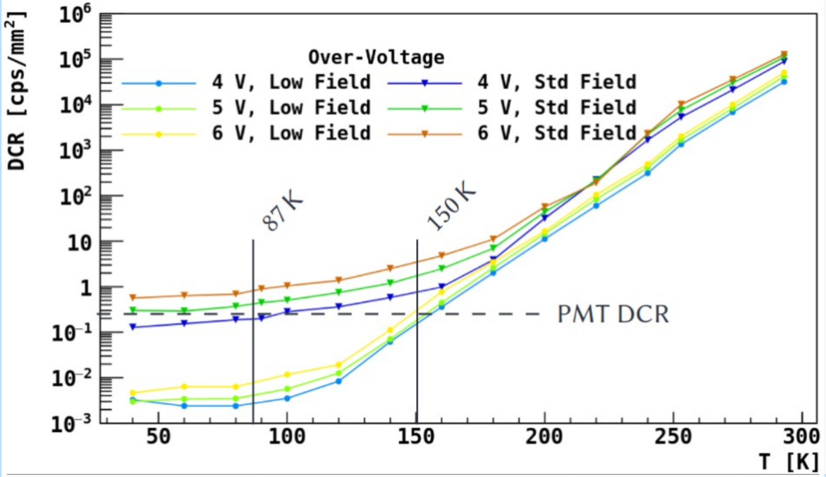
Silicon PhotoMultipliers (SiPM) can replace PMTs:
- Arrays are **more compact**
- SiPM technology features **lower dark noise than PMTs at T < 150 K**
- **Lower intrinsic radioactivity**
- SiPMs have **higher PDE** (> 50%) at NaI(Tl) scintillation wavelength (420 nm) w.r.t. 30 − 35% of PMTs



F. Acerbi *et al.*, IEEE Trans.Elec.Dev. **64** (2017) 521-526

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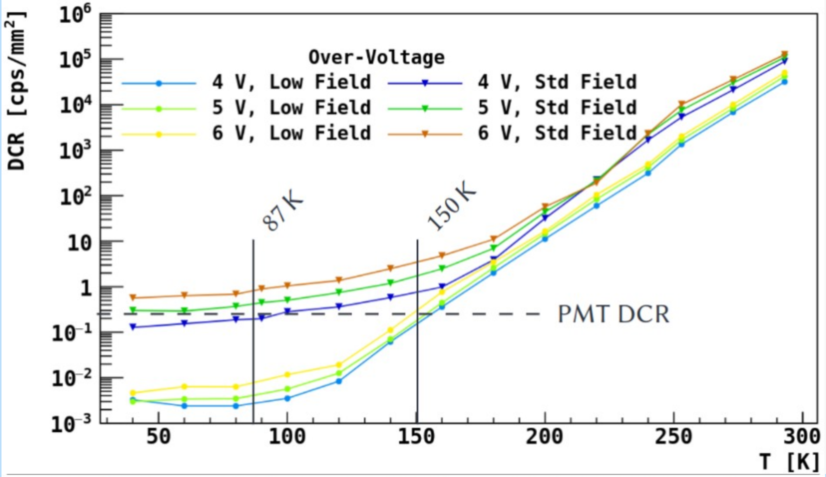

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Use of SiPMs implies a cryogenic setup:
Liquid argon provides cooling power and can double as VETO detector (LAr scintillation at 128 nm) if equipped with PMTs or SiPMs.

ASTAROTH: All Sensitive crysTal ARray with lOw THreshold

INFN R&D project aiming at lowering the detection energy threshold down to the sub-keV region for DM direct detection with NaI(Tl) crystals

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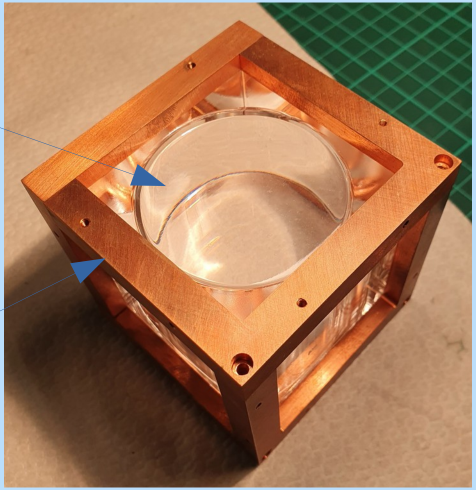
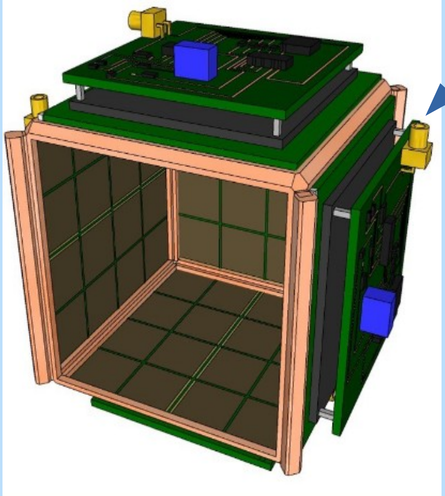
ASTAROTH will use NaI(Tl) crystals (presently: 5×5×5 cm^3) read on all six faces by SiPM matrices, operating at temperatures in the range 80 − 150 K

- Exact temperature to be tuned at runtime considering SiPM and crystals requirement

Crystals must be sealed in special quartz containers (NaI(Tl) is hygroscopic)

A low radioactivity copper frame allows the mounting of SiPMs



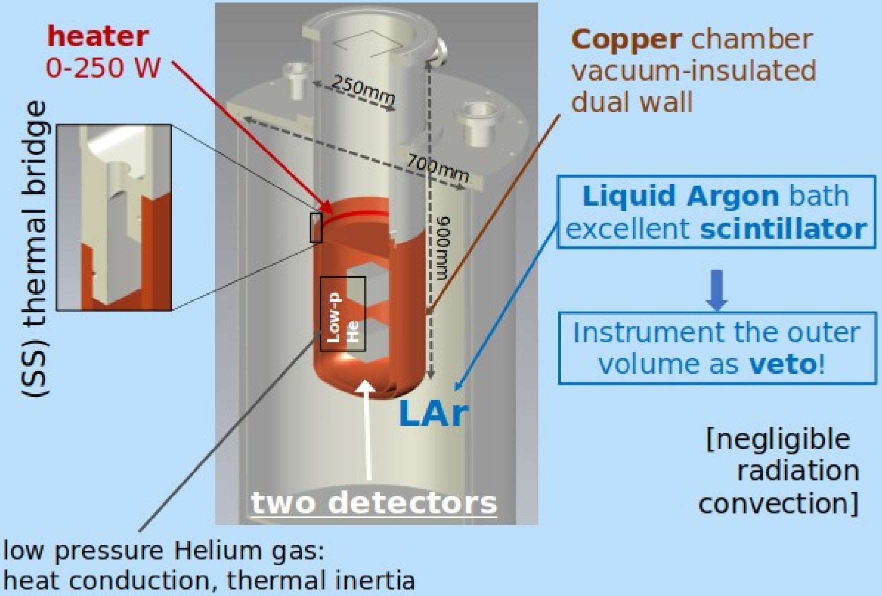


SiPM & readout on PCB mounted on Cu support

Detector design: mechanics

Design requirement: ensuring crystals survival and stable read-out from the Electronics.

- Dual-wall, vacuum-insulated radio-pure copper chamber, featuring a specially designed Stainless Steel (SS) thermal bridge between the two walls.
- Chamber is immersed in a LN2/LAr bath providing cooling power only by conduction through the SS bridge.
- Power is released through a heater to tune the temperature within the range
- Low pressure Helium gas fills the inner volume, serving as heat-transfer medium to the crystals



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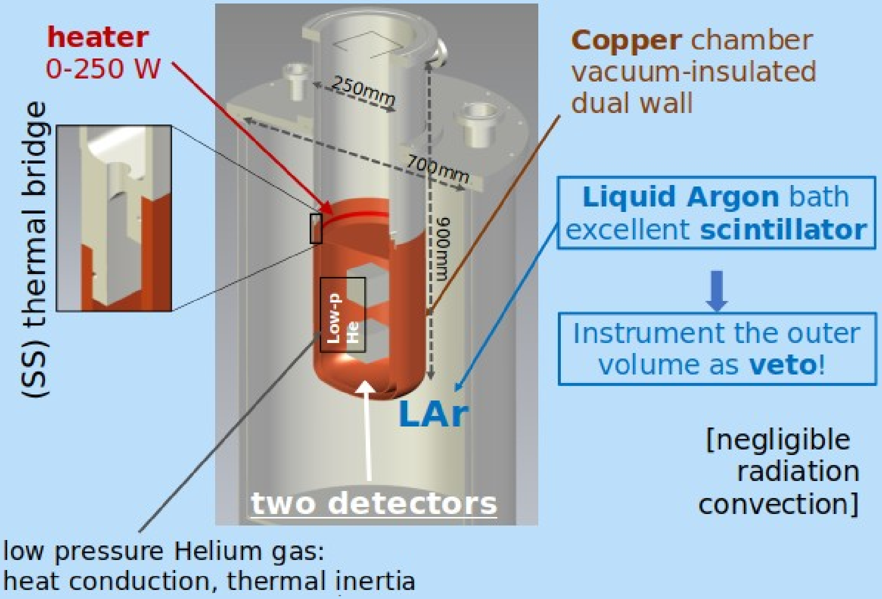
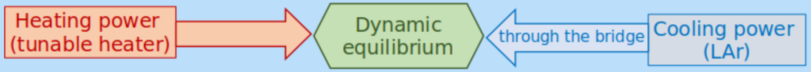
System performance:

- **Investigated range: 80 – 150 K**.
- **Temperature stability in time**, during data taking, **< 0.1 K**.
- Ramp up/down slower than **20 K/h**.
- Spatial gradients (over crystal dimensions) **< 1 K** .





87 K < *tunable* working temperature < 150 K

choose the optimal working point for both crystals and SiPM

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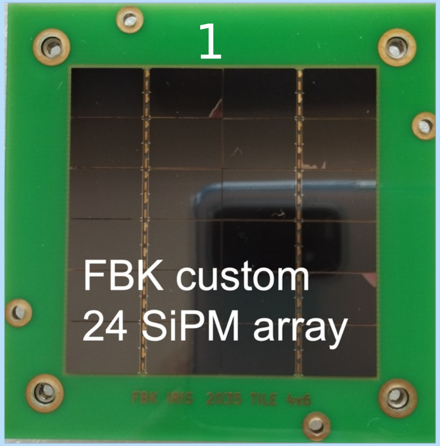
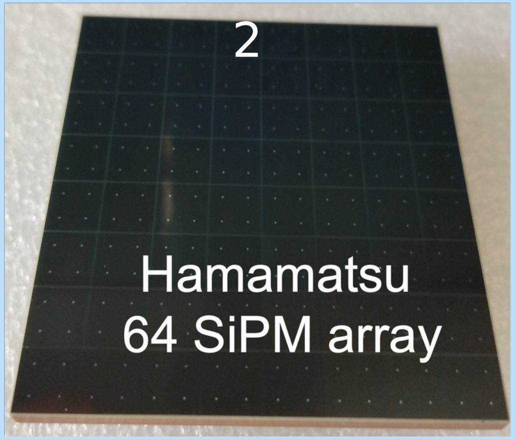
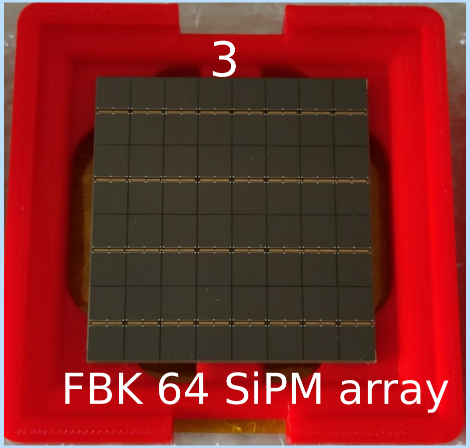
SiPM arrays “tile”

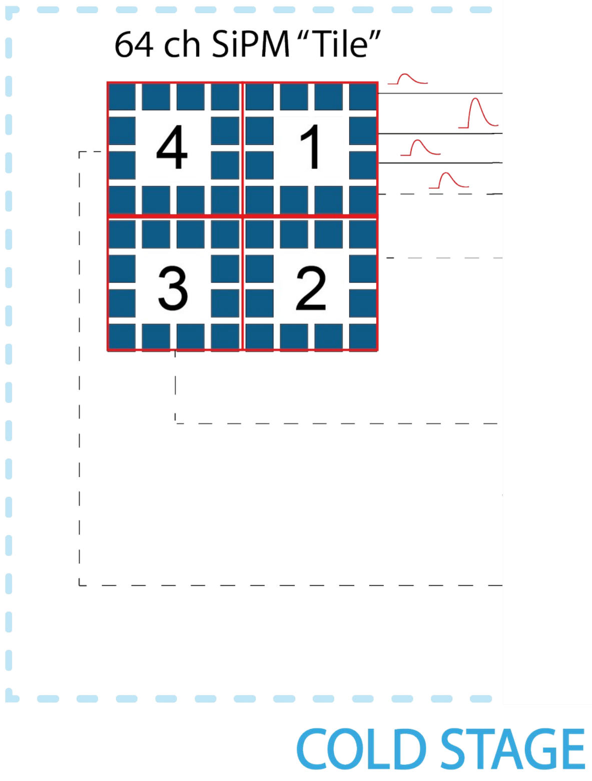
	Firm	Tech	Model	Tile size (mm²)	Devices	Area (mm²)	Also used	Pitch (µm)	Route	Gang	Ch	Resin
1	FBK	NUV-HD-Cryo	custom	50x50	24	8x12	DS-20k	35	Wire bond	2s3p	4	epoxy
2	HPK	S13361	6050AS-08	50x50	64	6x6	Dune	50	TSV	no	64	silicon
3	FBK	NUV-HD-Cryo	custom	50x50	64	6x6	Dune	30	Wire bond	no	64	epoxy







Custom front-end electronics



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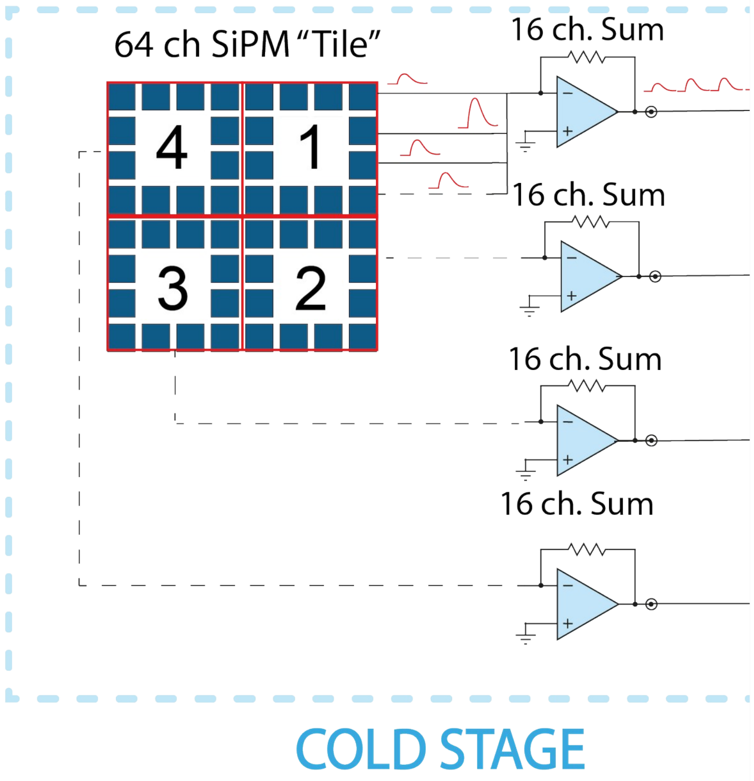

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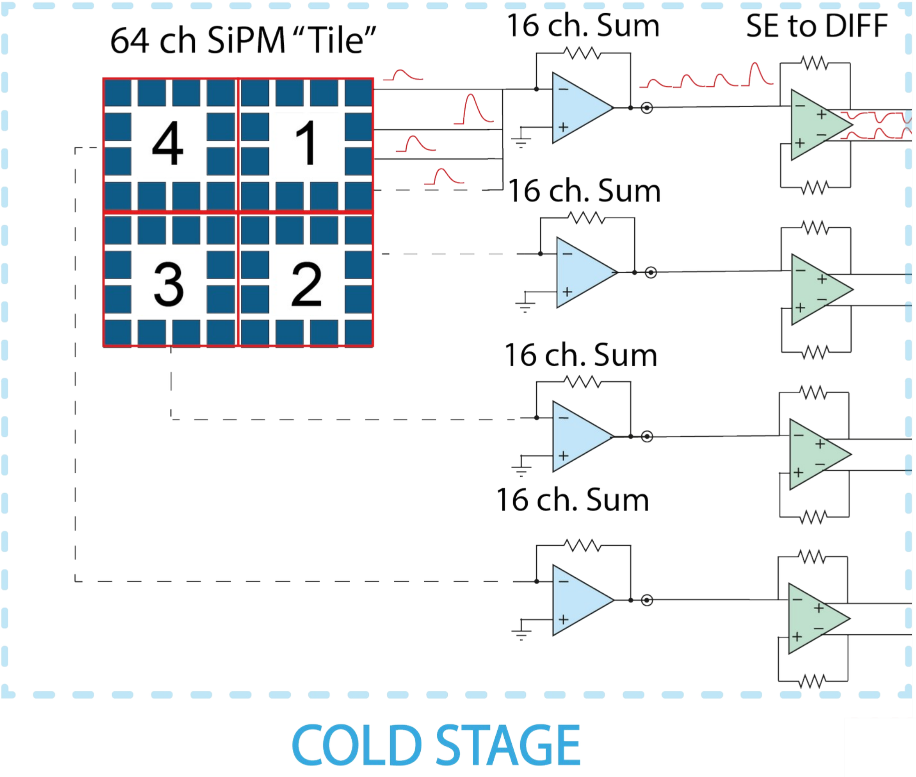

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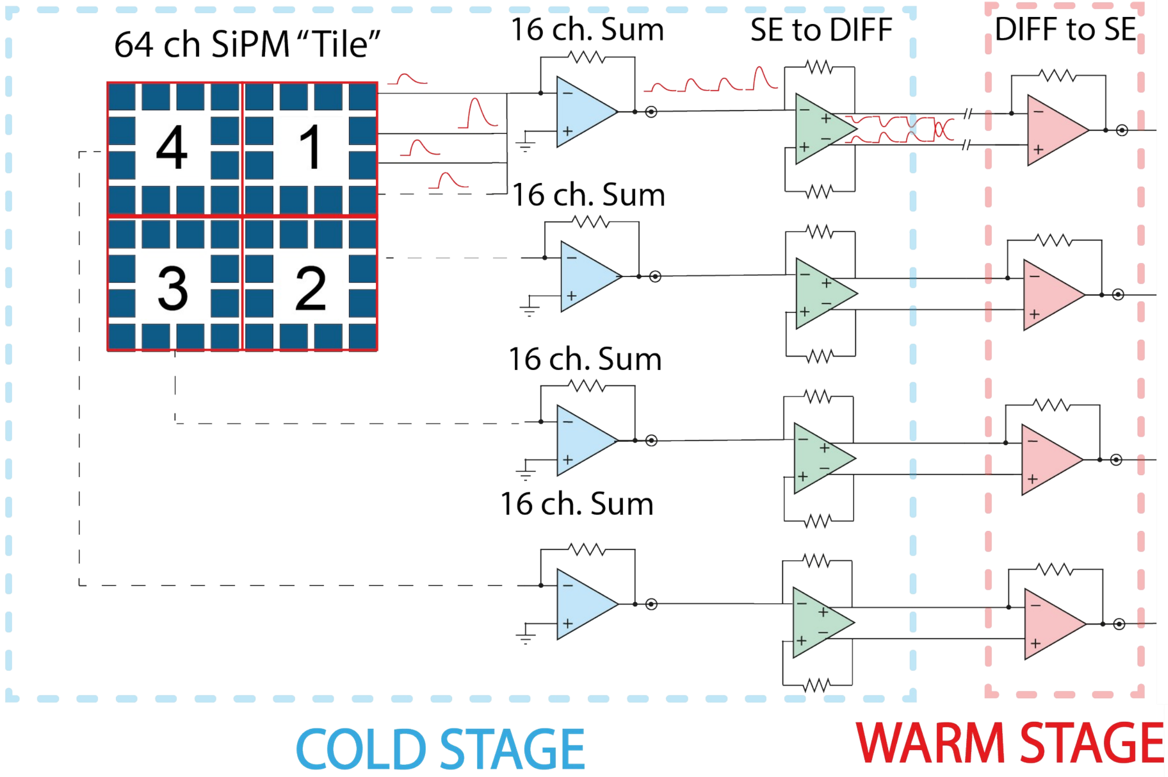

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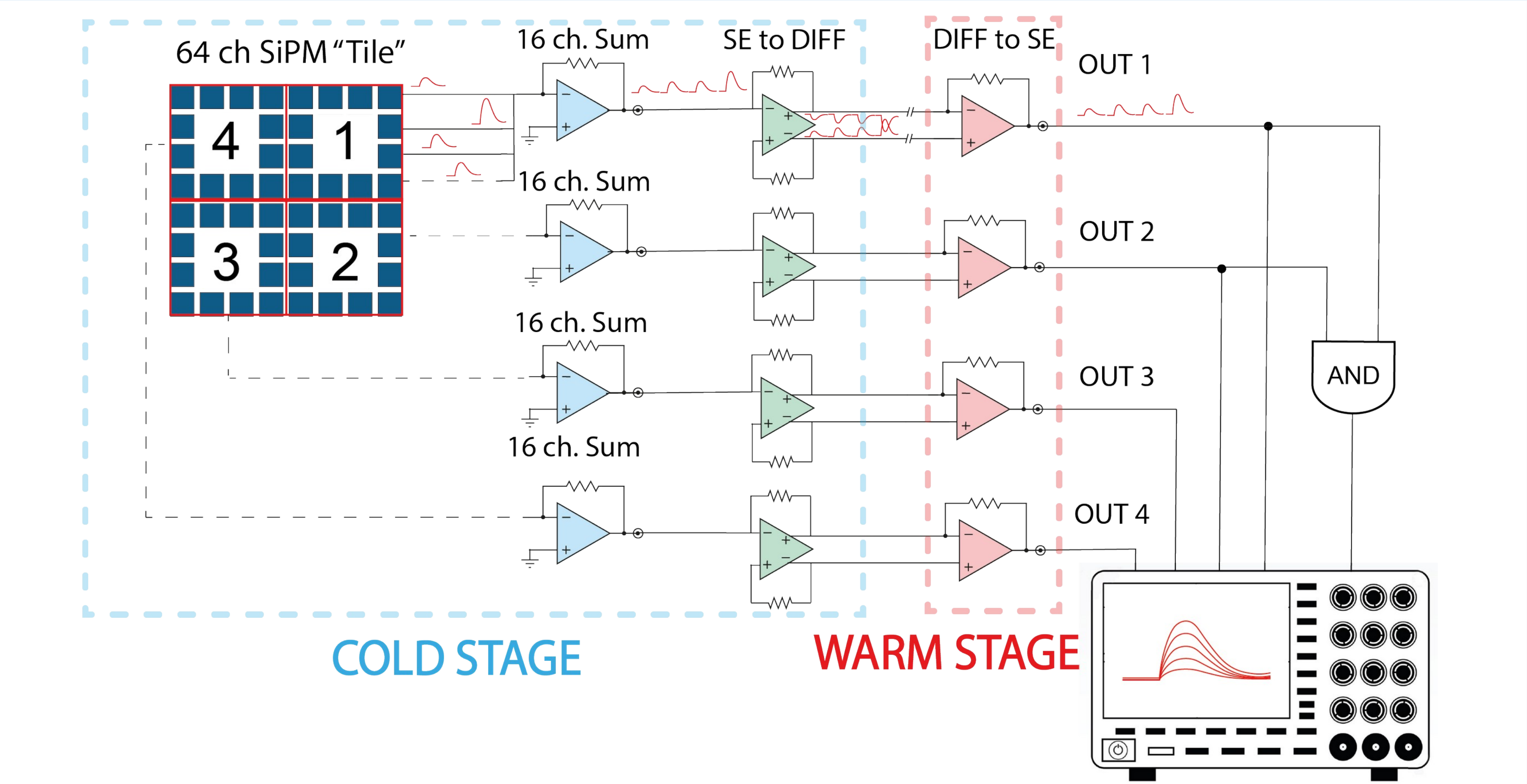

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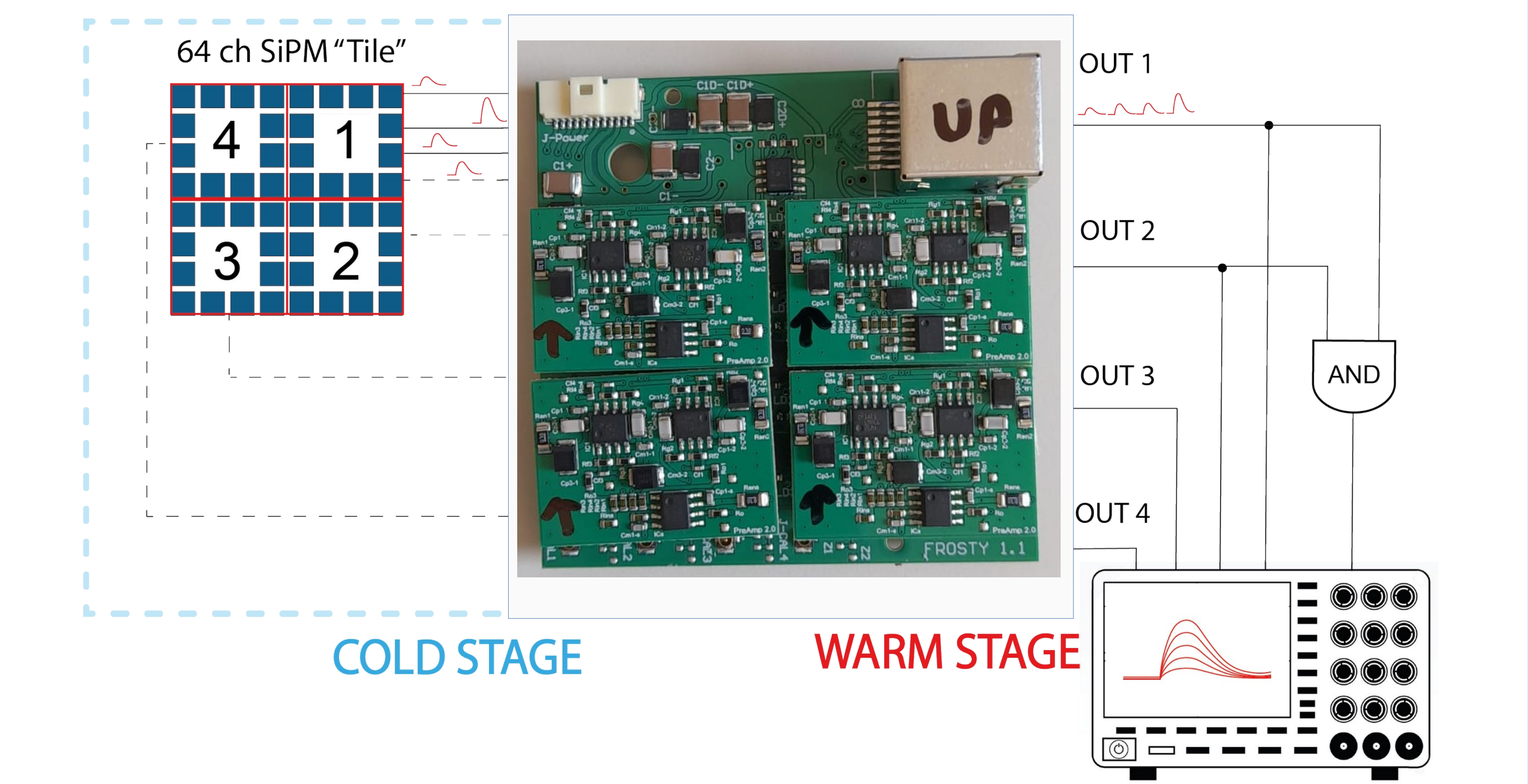
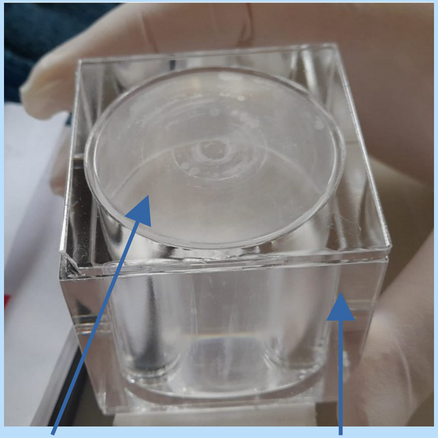


Integrated tests at INFN LASA Milano

Test performed with:

- Cylindrical 5×5 cm ($H \times \varnothing$) NaI(Tl) crystal



NaI(tl) crystal   Quartz case

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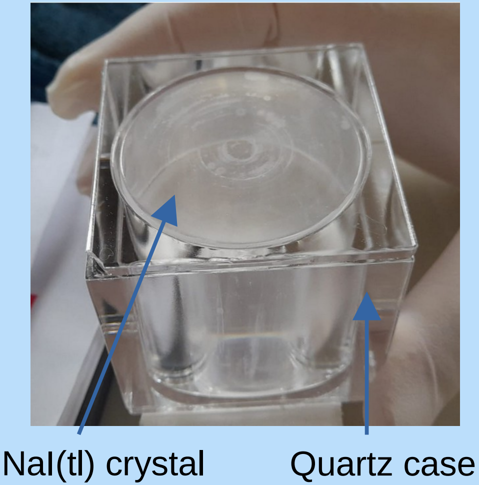
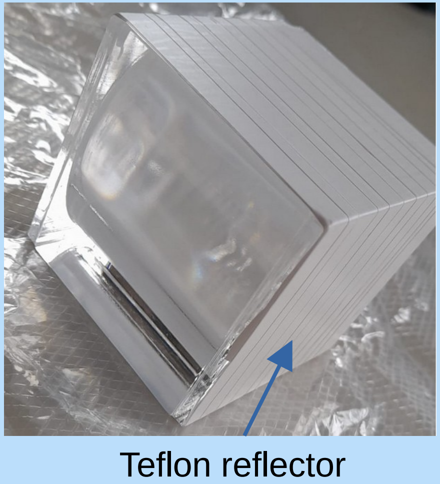
- Teflon reflector on the other faces





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Test performed with:

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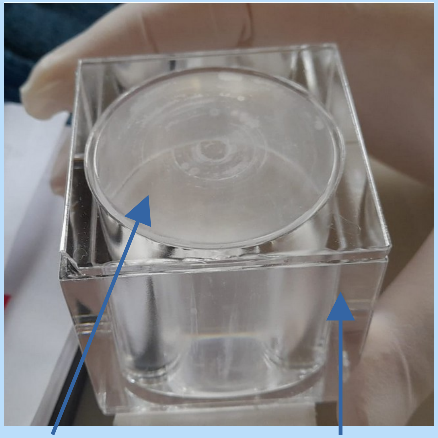
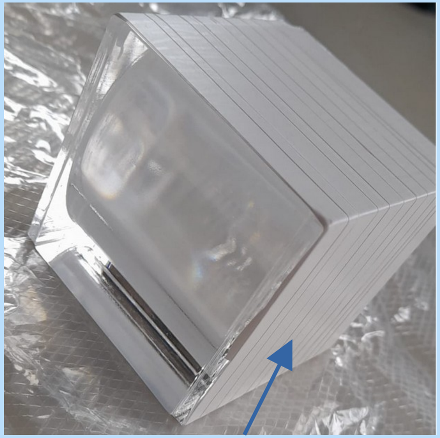
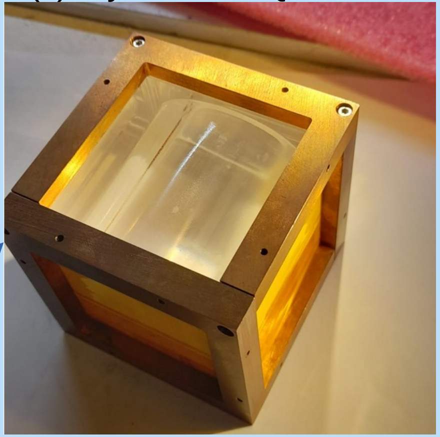
- Copper frame for SiPM array installation



NaI(tl) crystal Quartz case



Teflon reflector



Copper frame

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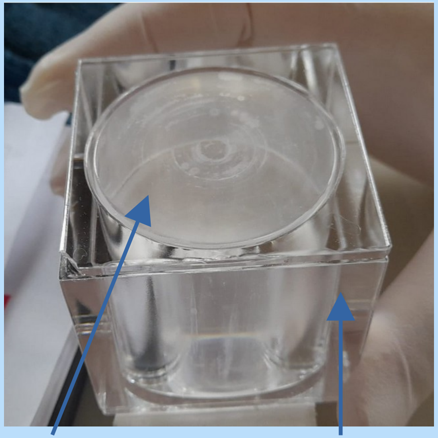
Test performed with:

- Cylindrical 5×5 cm ($H \times \varnothing$) NaI(Tl) crystal
- Teflon reflector on the other faces
- Copper frame for SiPM array installation
- FBK SiPM array on 1 face of the crystal



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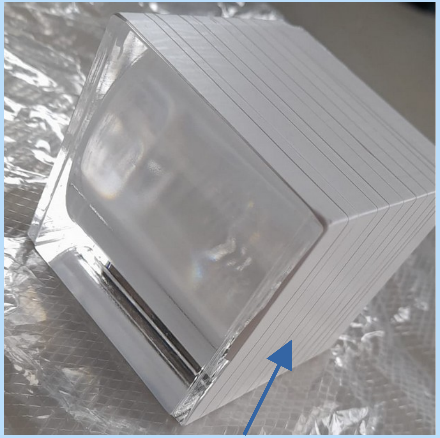

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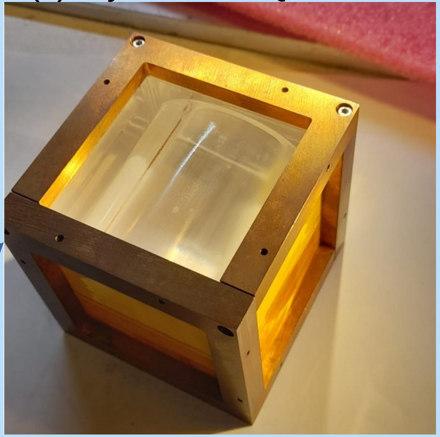

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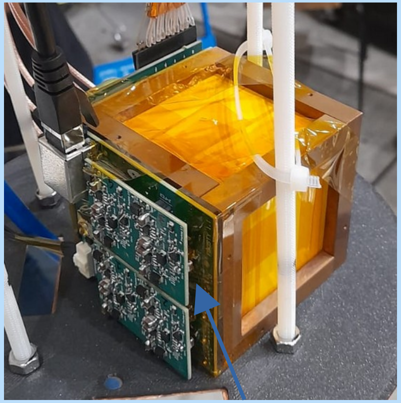

SiPM array

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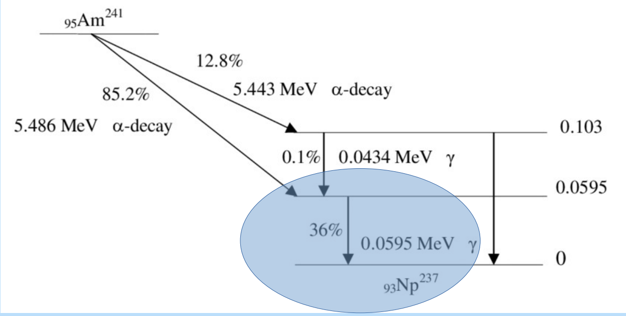
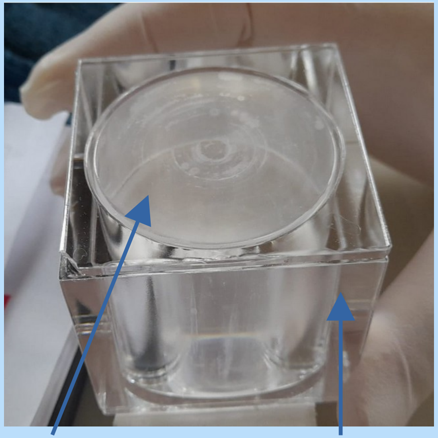
- Teflon reflector on the other faces
- Copper frame for SiPM array installation
- FBK SiPM array on 1 face of the crystal
- ^{241}Am (γ peak @ ~60 keV)





NaI(tl) crystal

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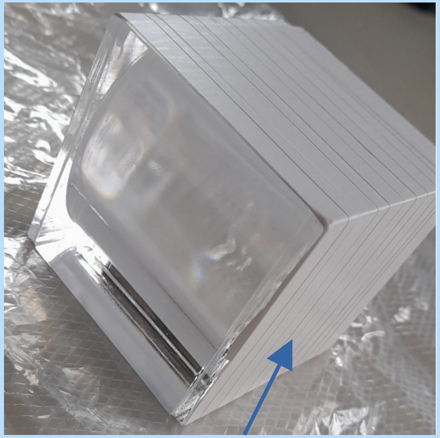

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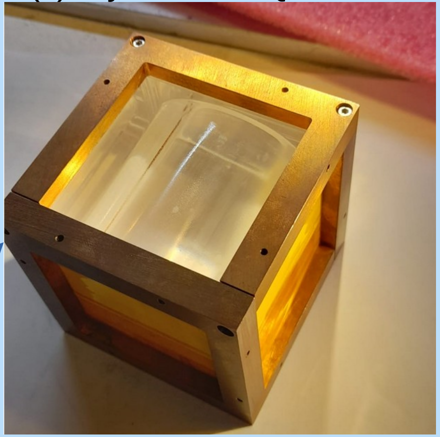

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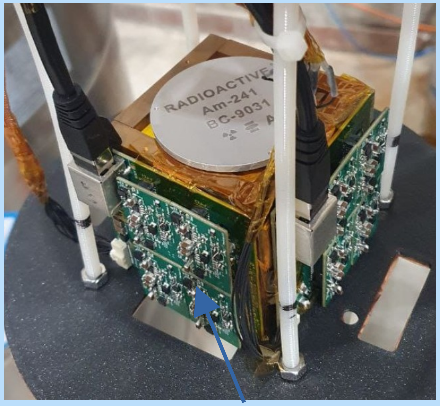
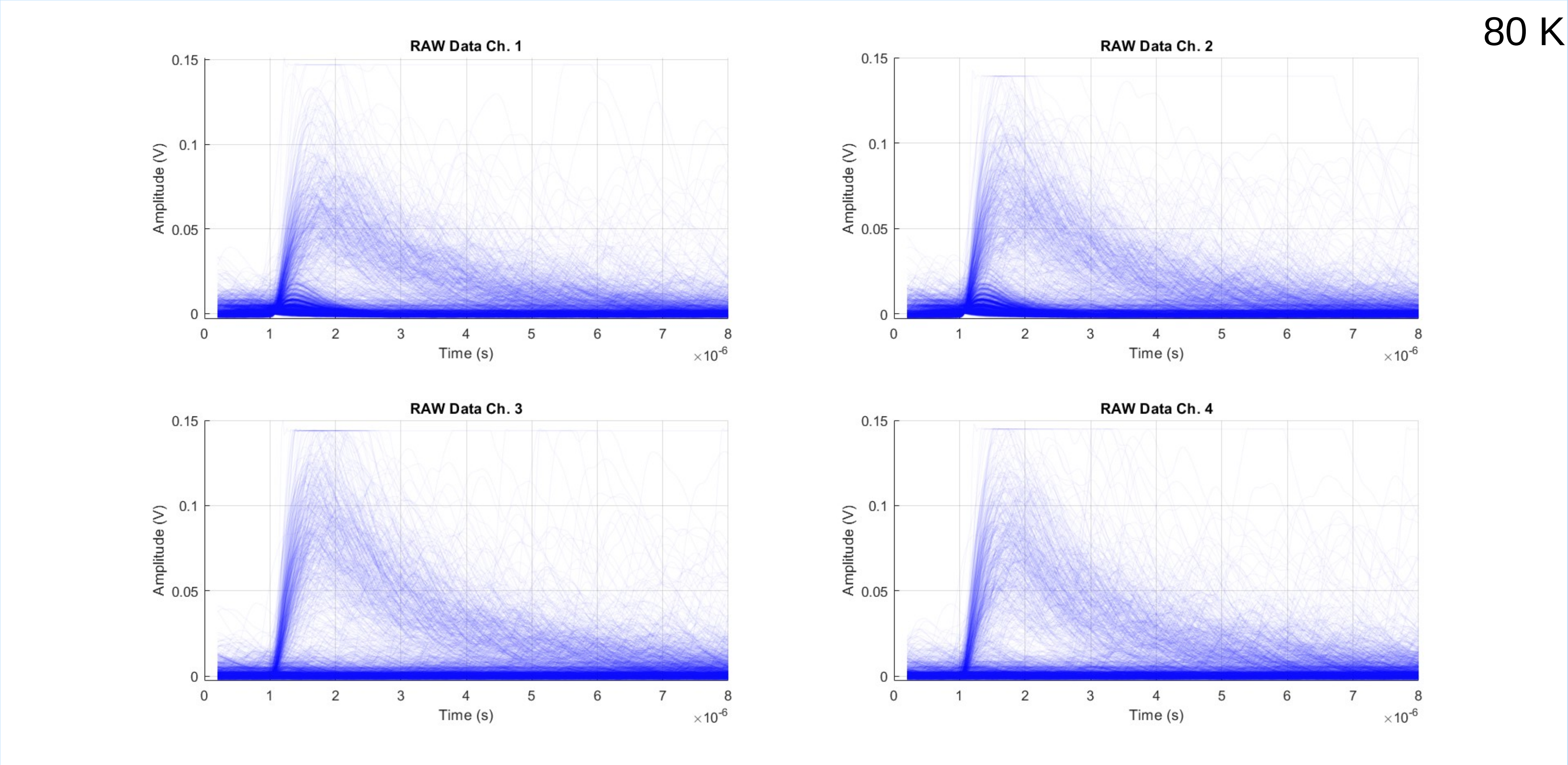


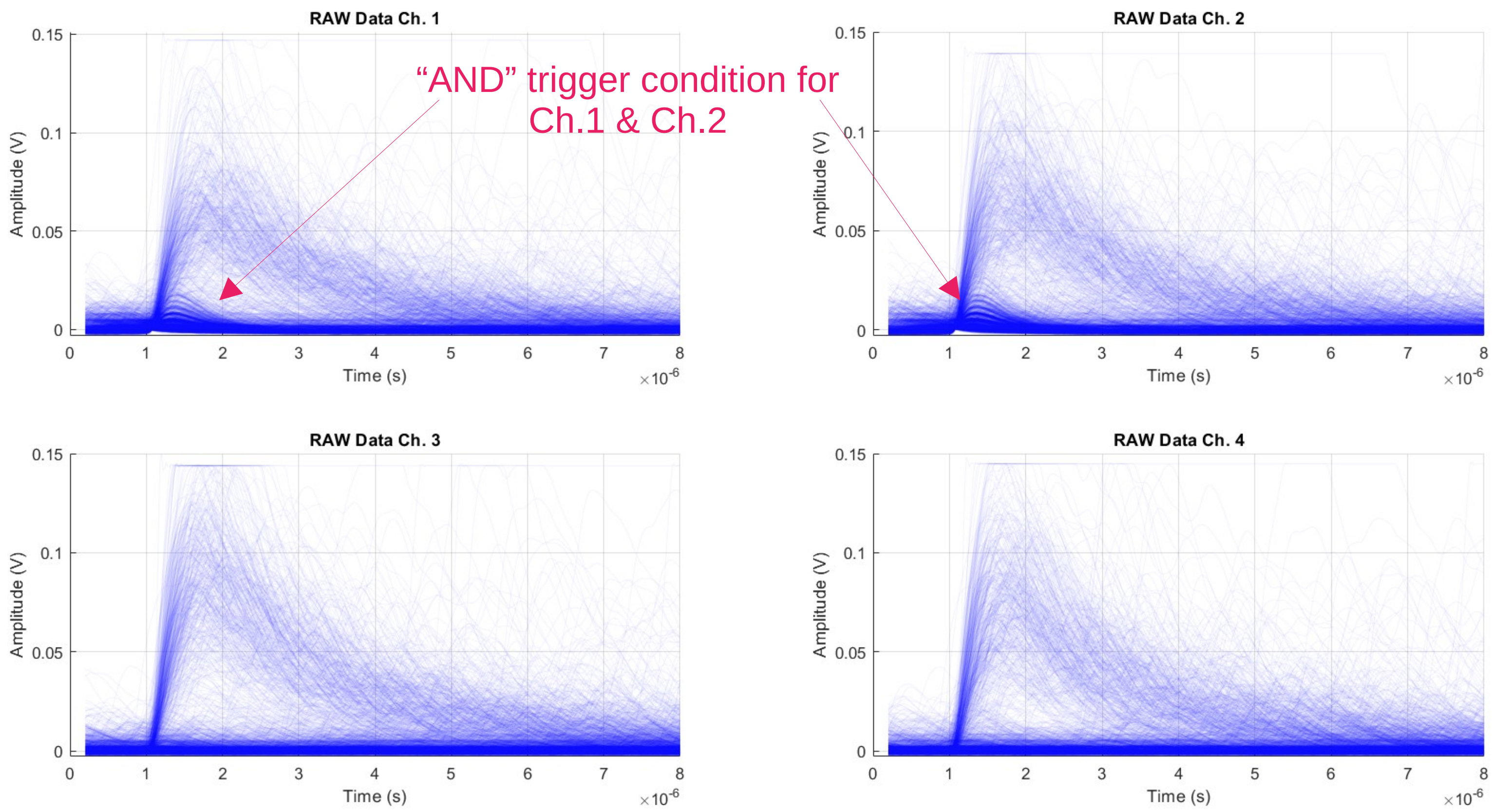
SiPM array

Waveforms

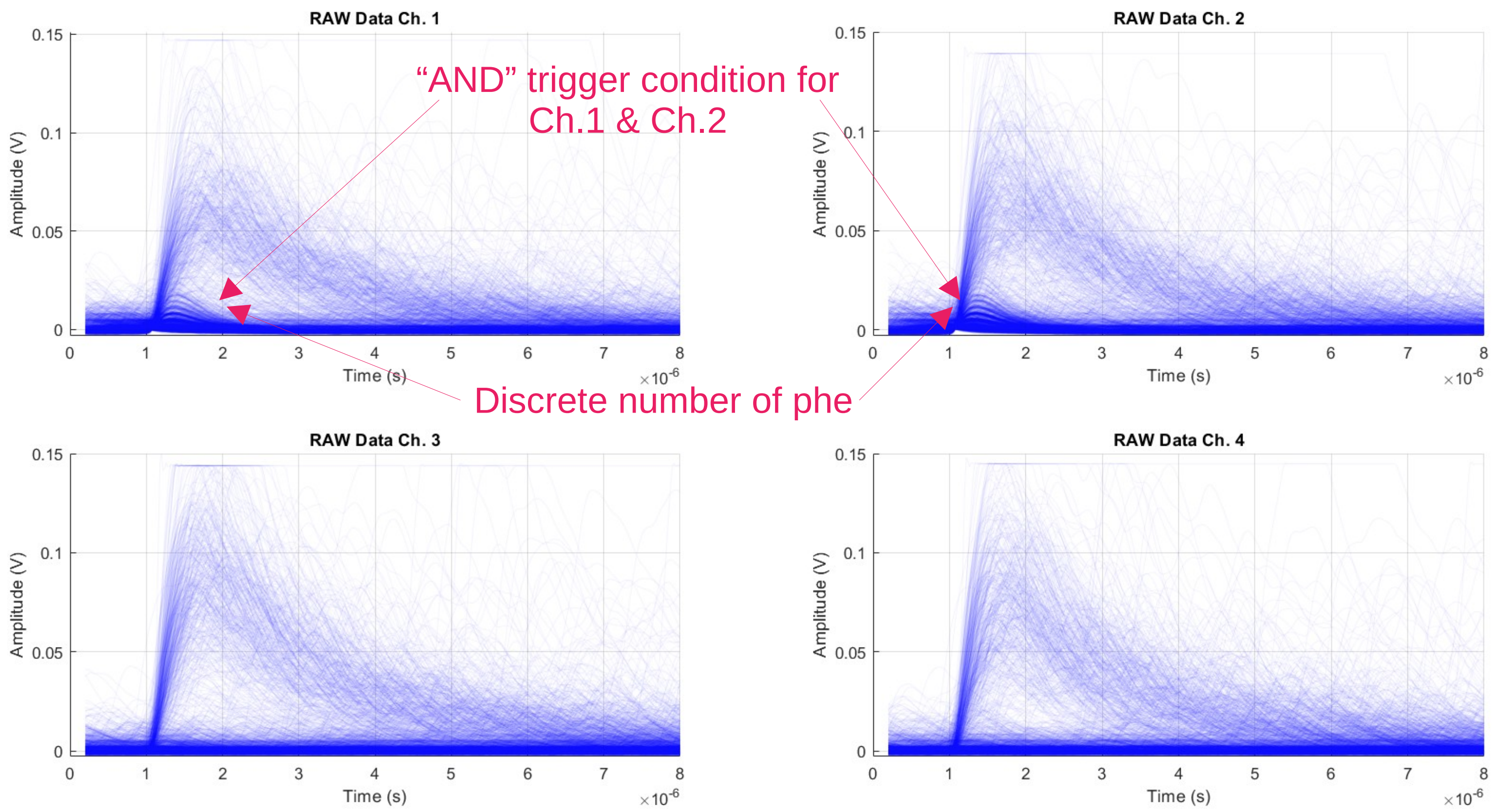


80 K
RAW Data Ch. 1
RAW Data Ch. 2
RAW Data Ch. 3
RAW Data Ch. 4
Amplitude (V)
Time (s)
×10^-6
0.15
0.1
0.05
0
0 1 2 3 4 5 6 7 8

Waveforms

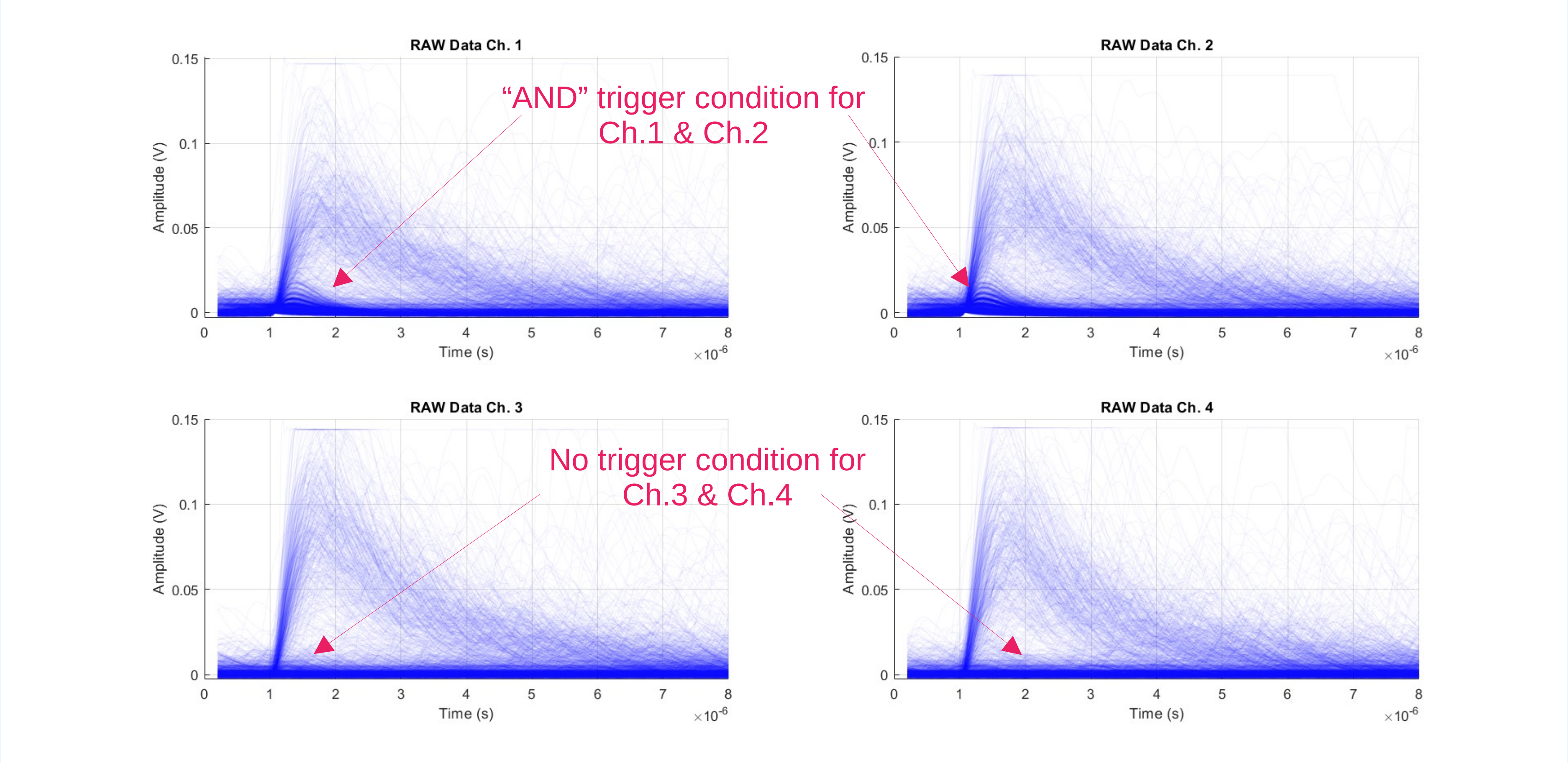

RAW Data Ch. 1
RAW Data Ch. 2
RAW Data Ch. 3
RAW Data Ch. 4
Amplitude (V)
Time (s)
×10^-6
"AND" trigger condition for Ch.1 & Ch.2

Waveforms



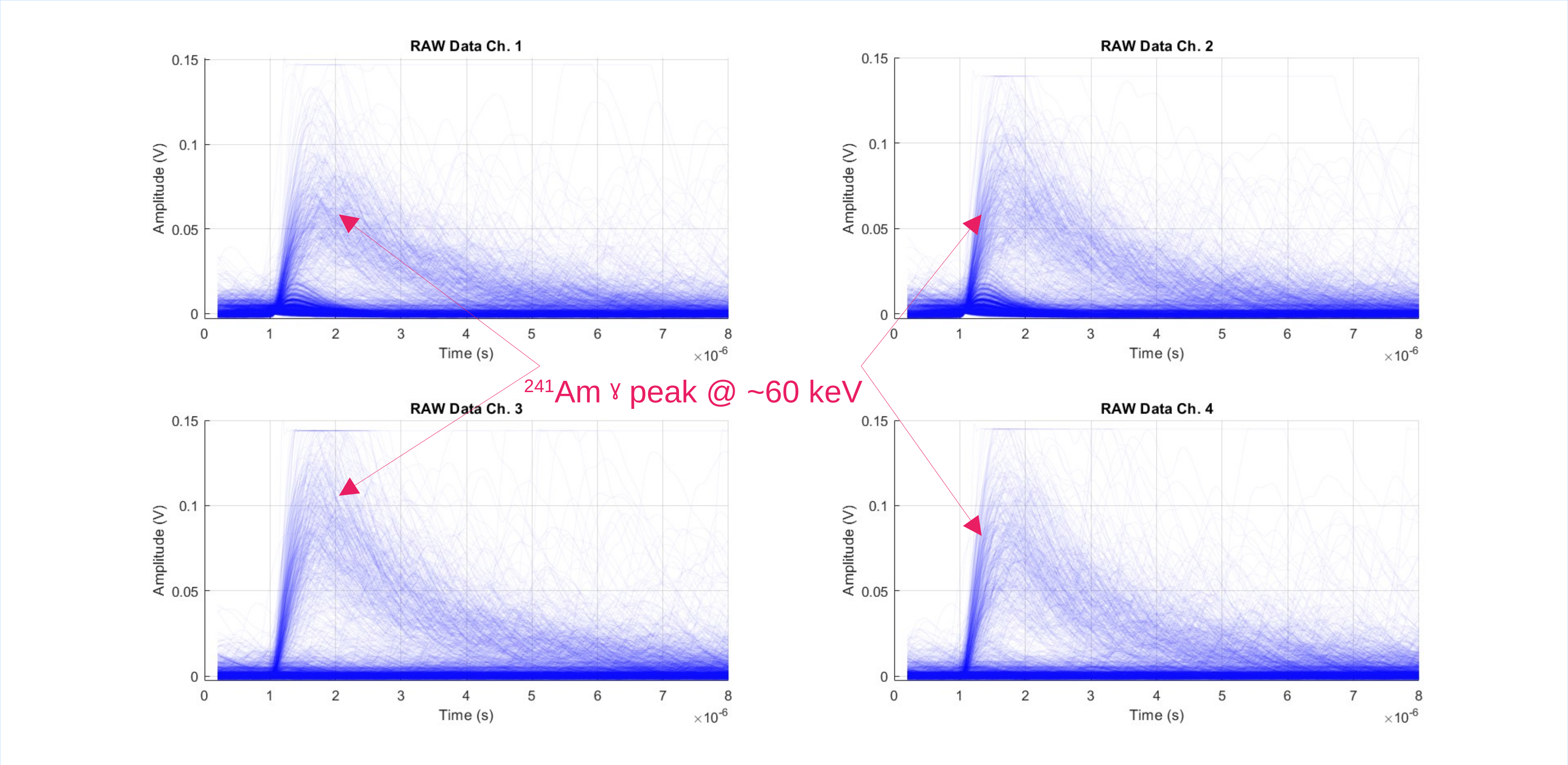
RAW Data Ch. 1
RAW Data Ch. 2
RAW Data Ch. 3
RAW Data Ch. 4
Amplitude (V)
Time (s)
×10^-6
0.15
0.1
0.05
0
1
2
3
4
5
6
7
8
"AND" trigger condition for Ch.1 & Ch.2
Discrete number of phe

Waveforms



RAW Data Ch. 1
RAW Data Ch. 2
RAW Data Ch. 3
RAW Data Ch. 4
Amplitude (V)
Time (s)
$\times 10^{-6}$
0.15
0.1
0.05
0
1
2
3
4
5
6
7
8
“AND” trigger condition for Ch.1 & Ch.2
No trigger condition for Ch.3 & Ch.4

Waveforms


RAW Data Ch. 1
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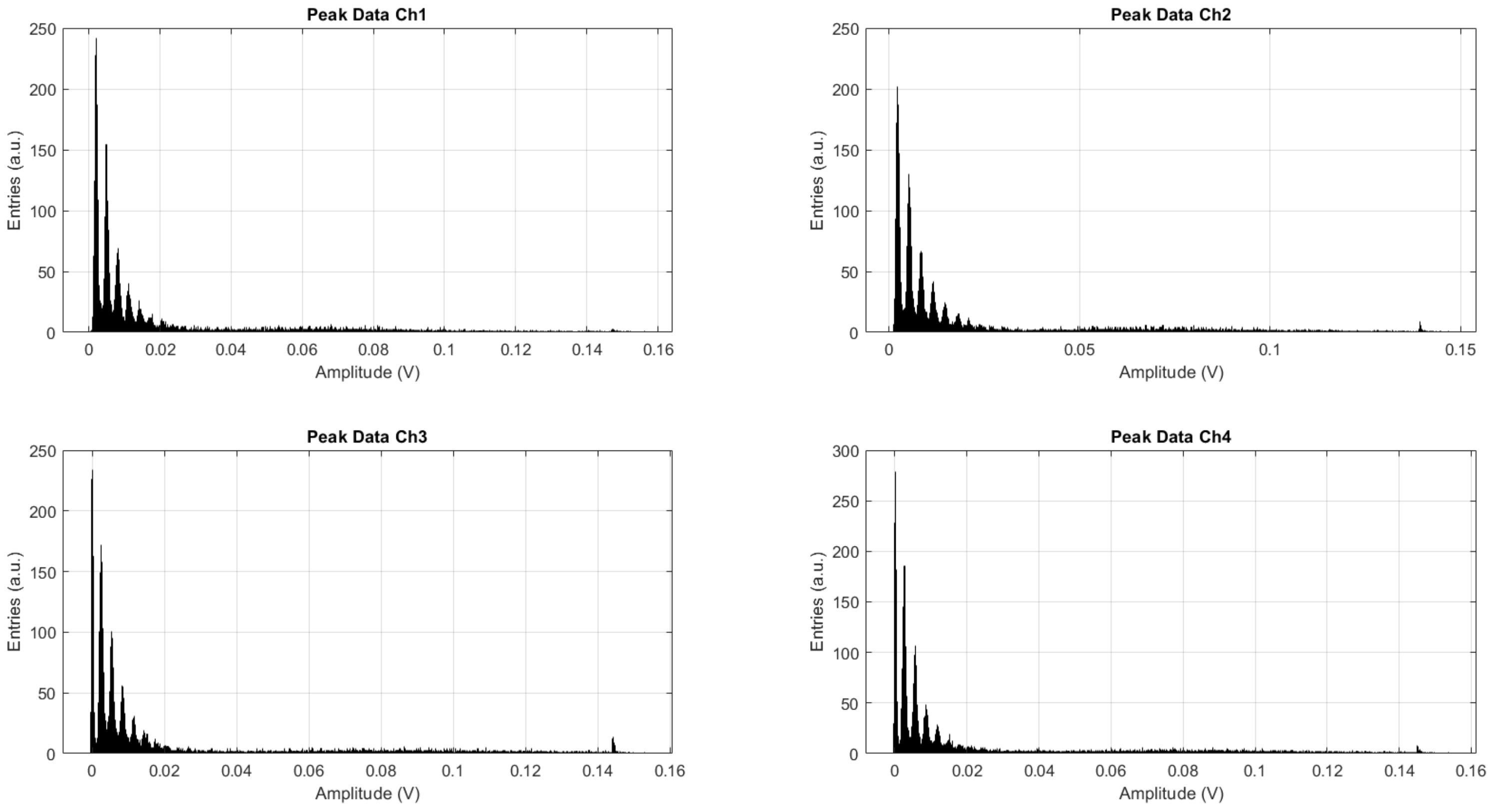
RAW Data Ch. 4
Amplitude (V)
Time (s)
$\times 10^{-6}$
^{241}Am γ peak @ ~60 keV

Histograms of amplitudes



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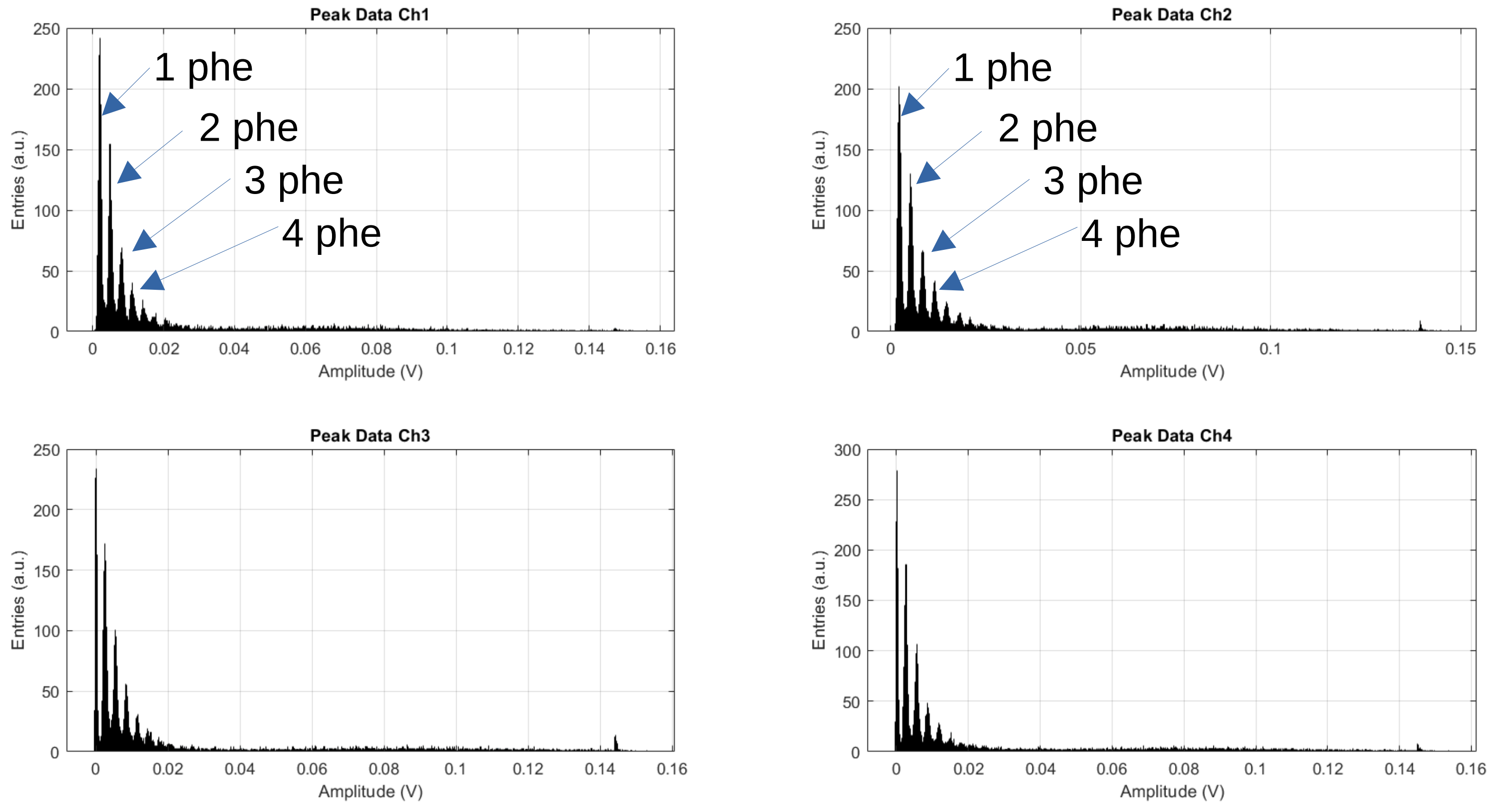

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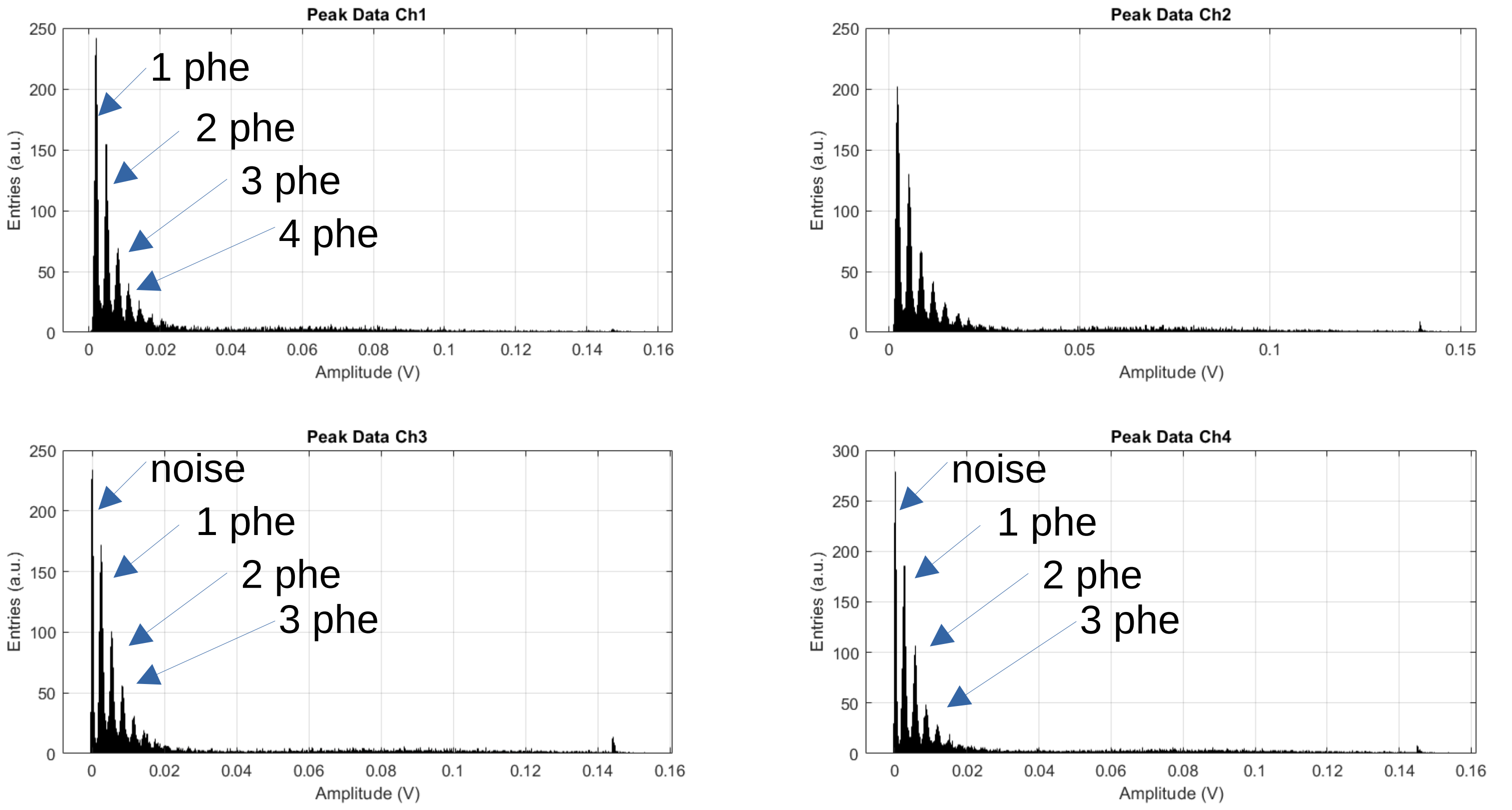
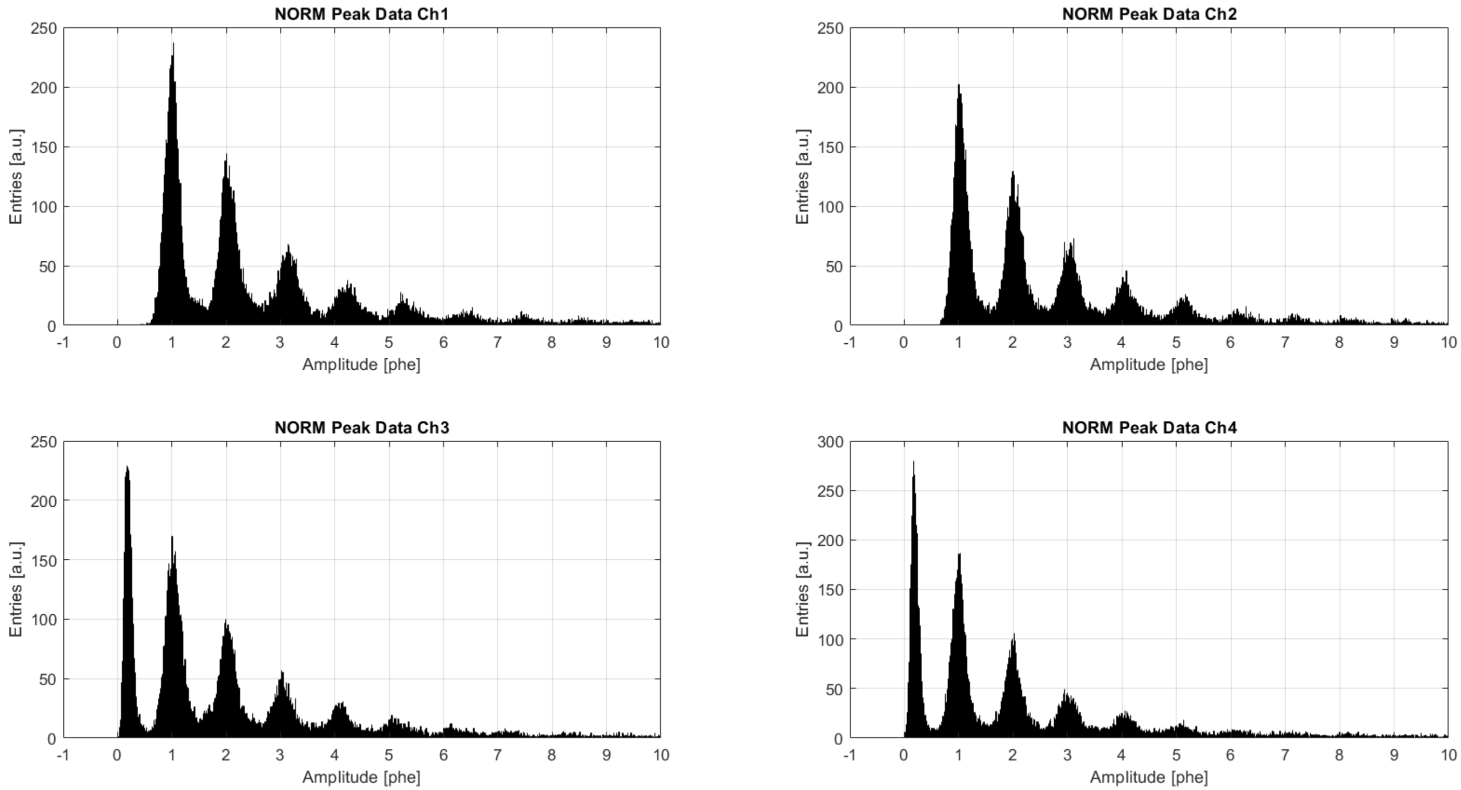
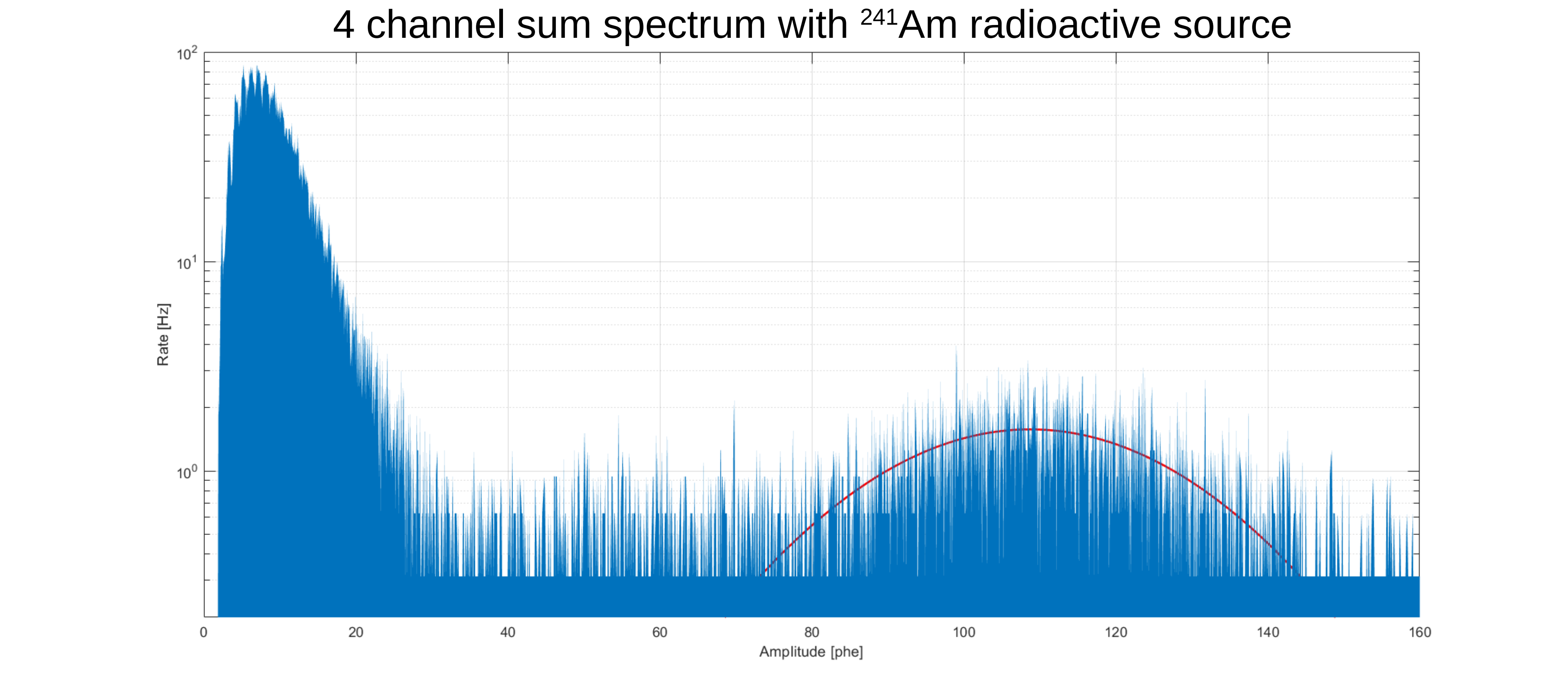


Histograms of photo-electrons



Energy calibration



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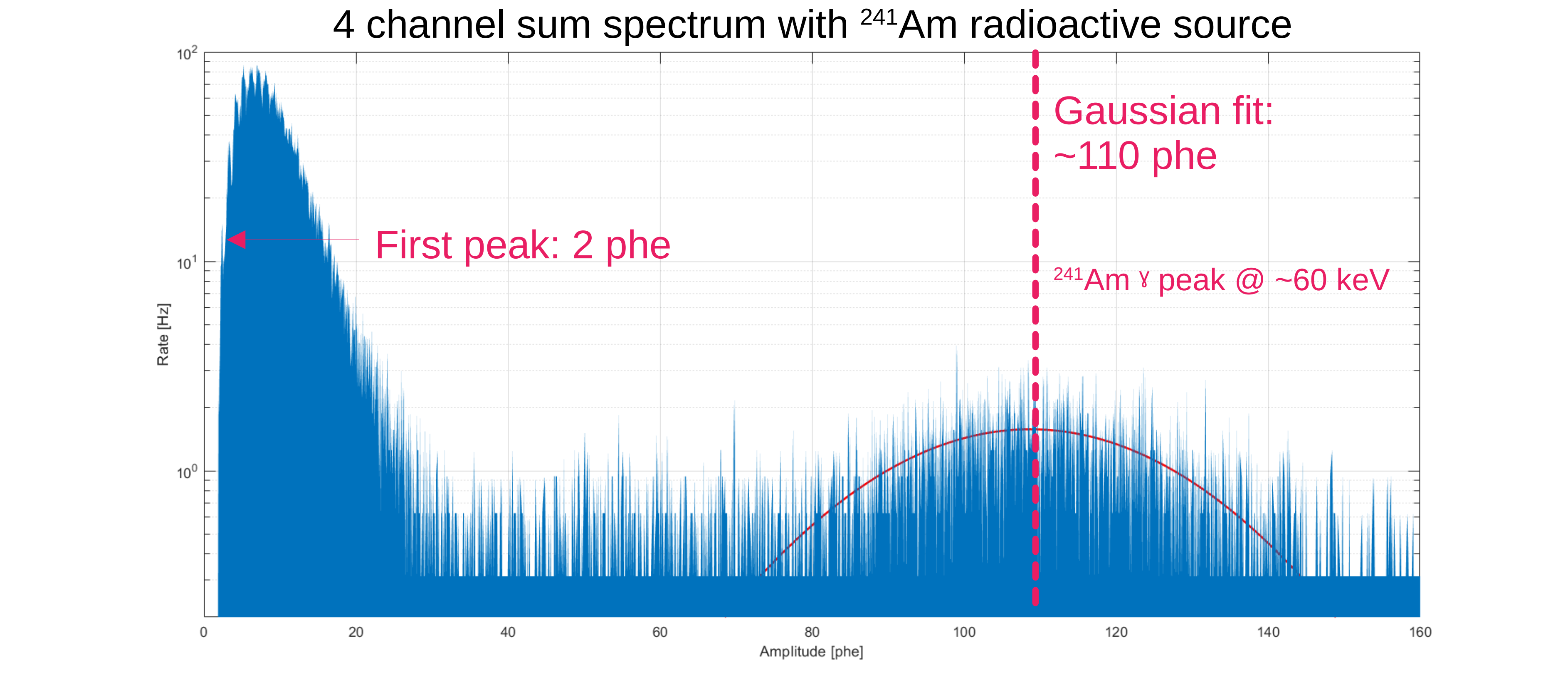

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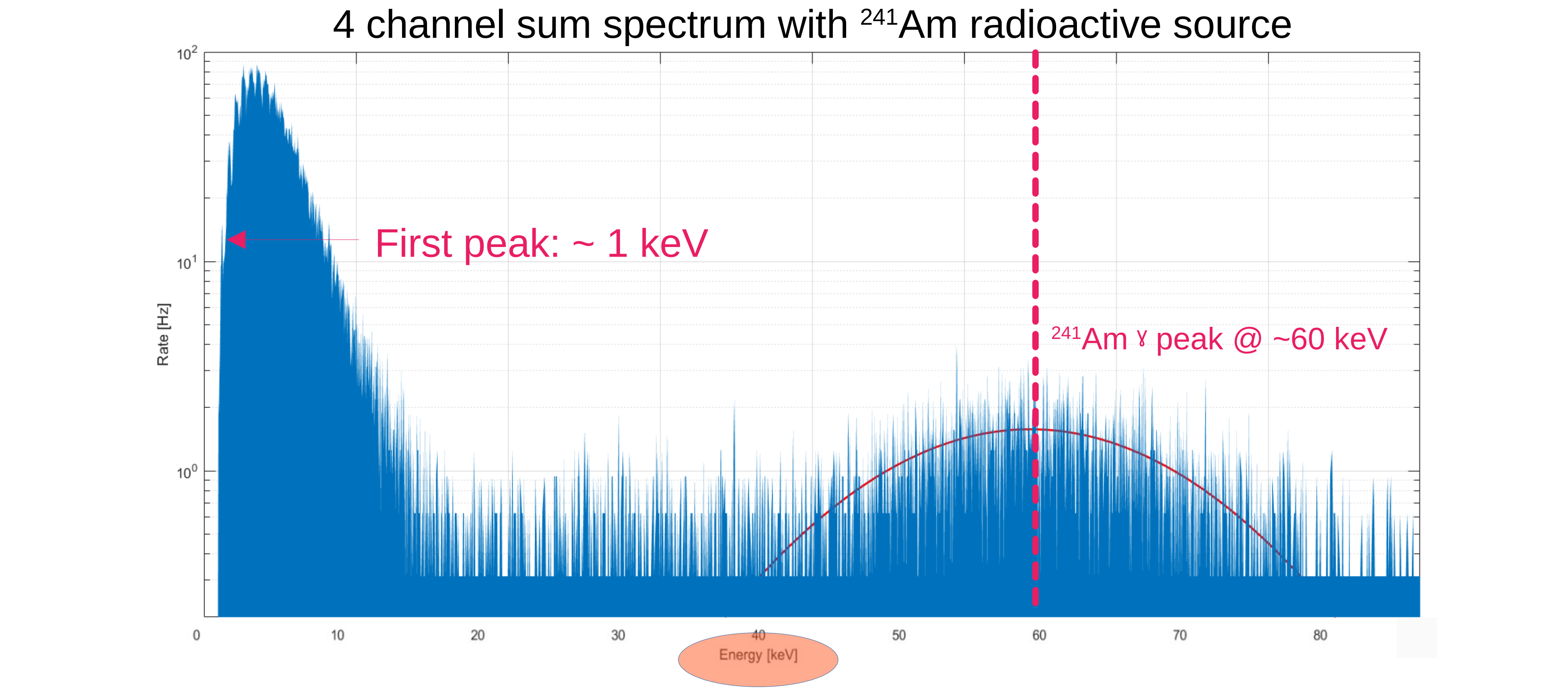
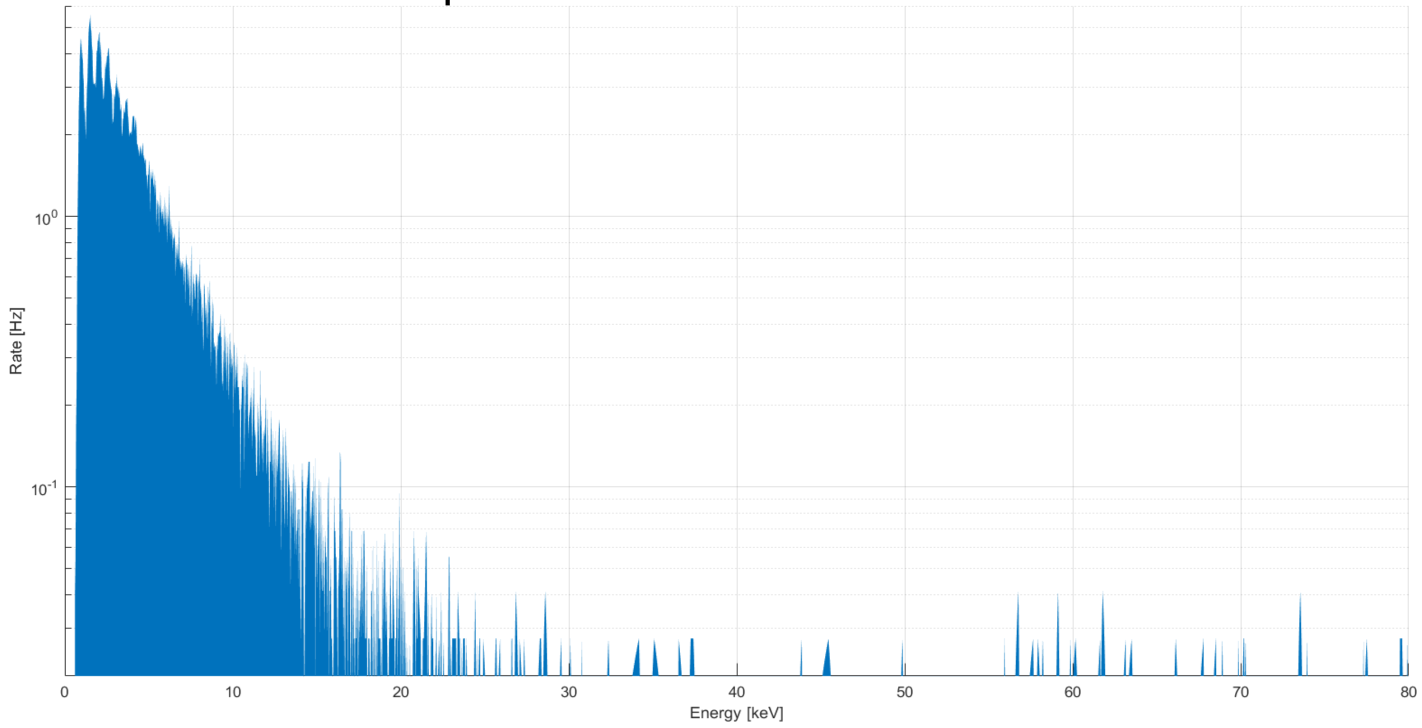
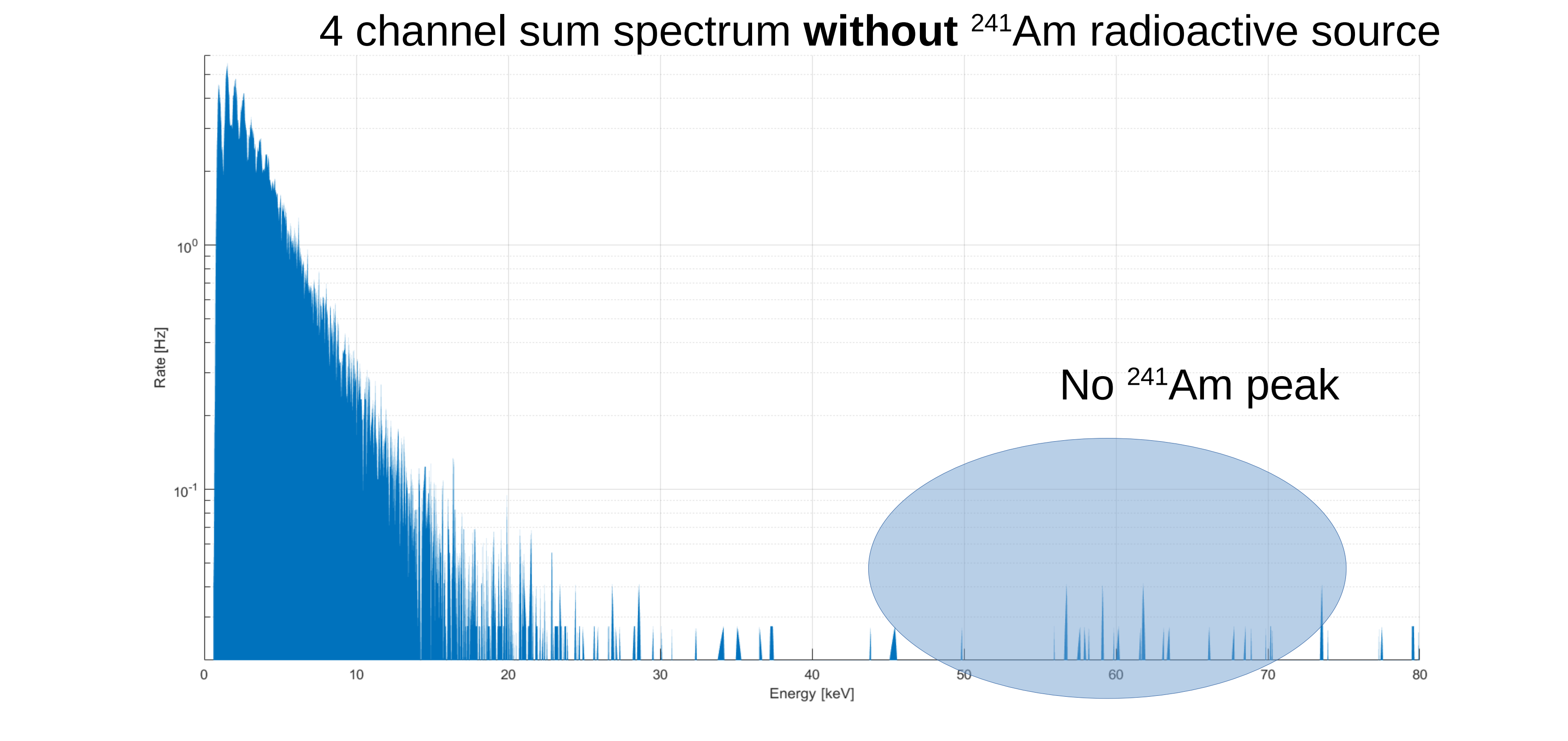


Energy calibration

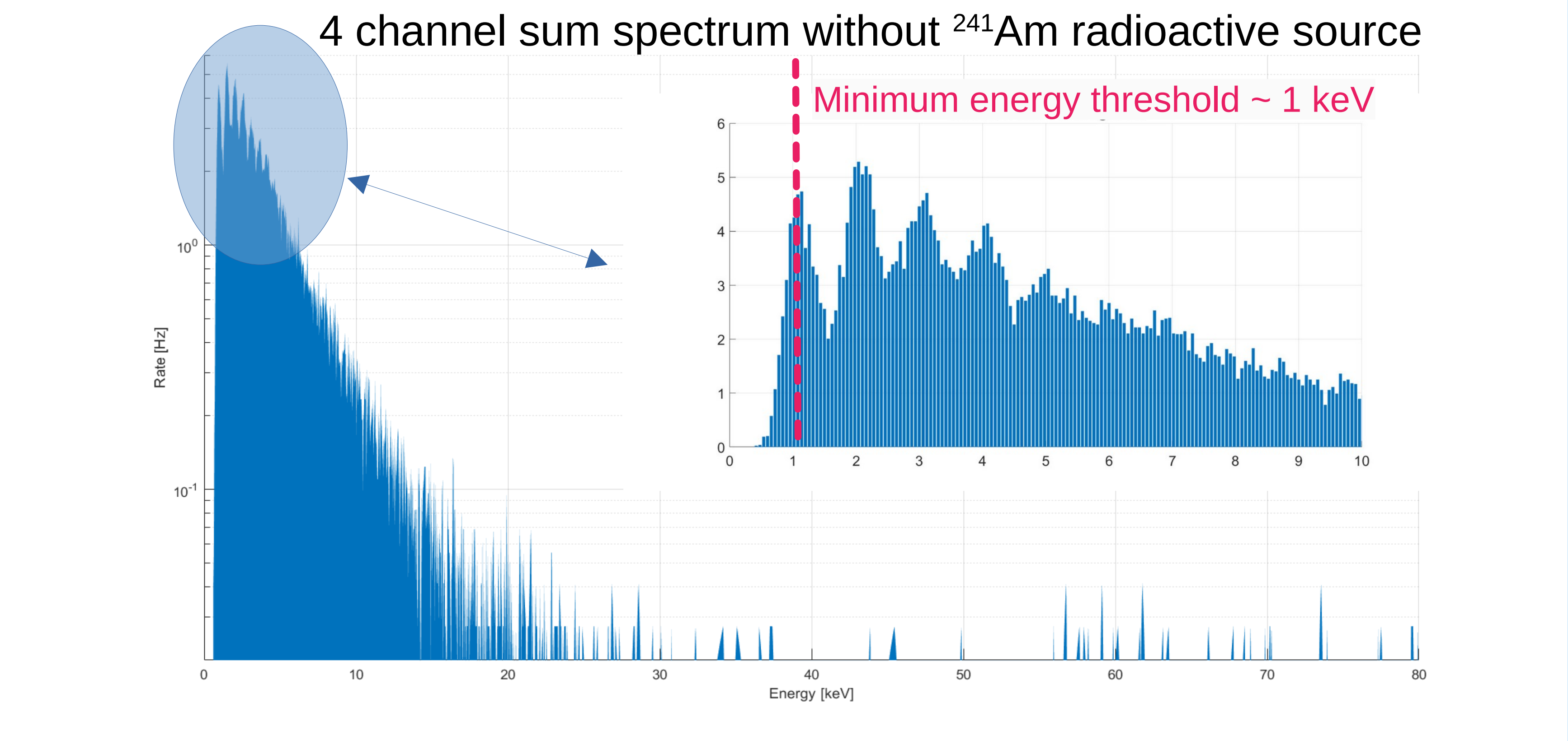
4 channel sum spectrum **without** ^{241}Am radioactive source



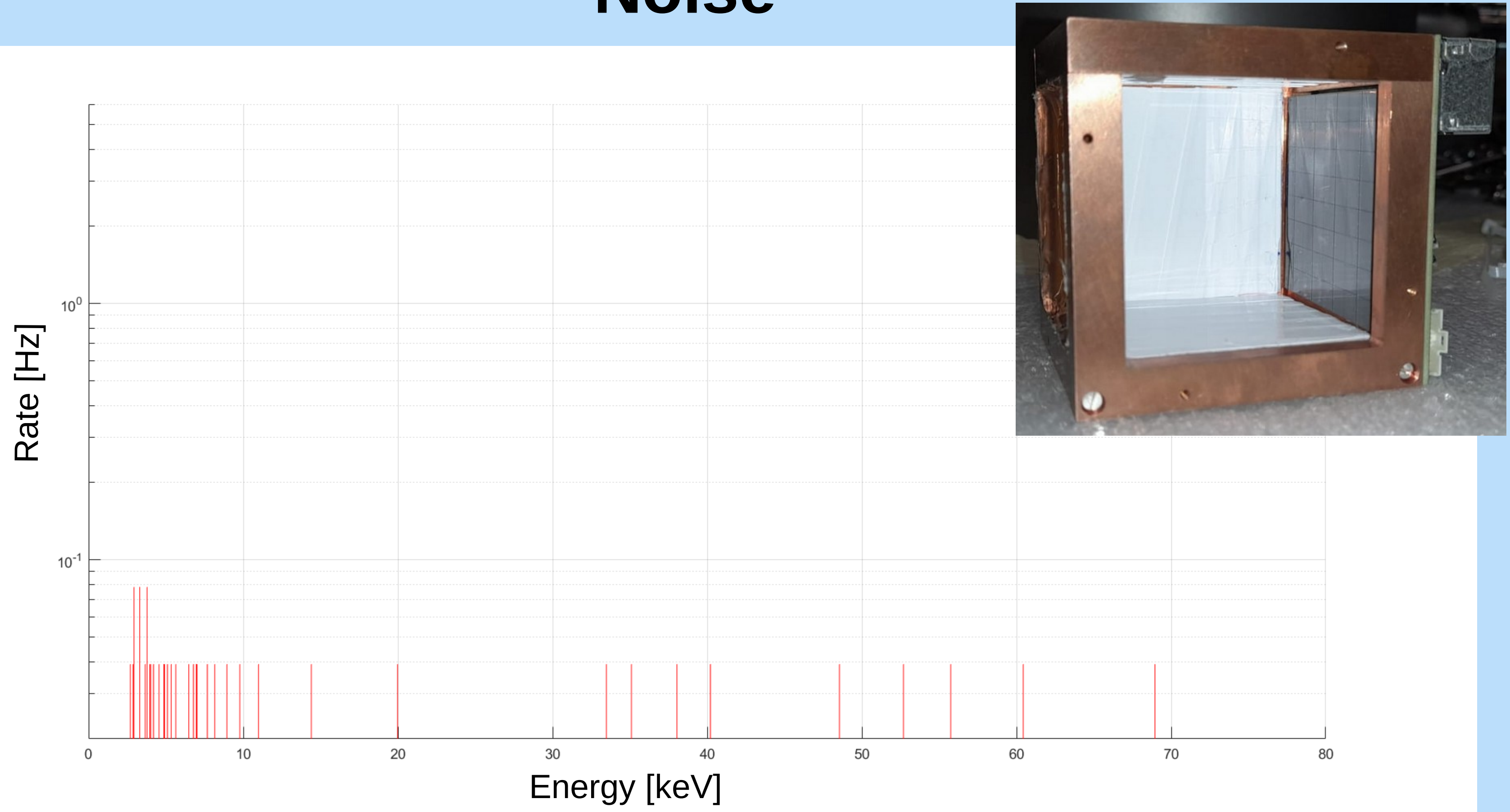
Energy calibration



Low-energy region



Noise

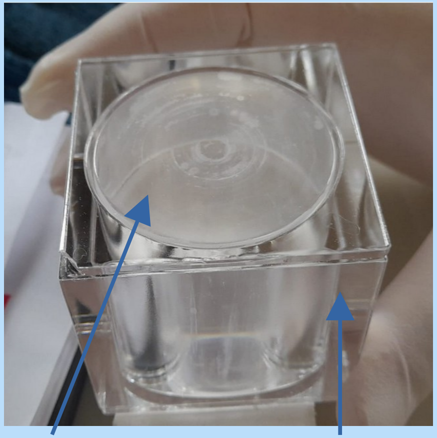


Crystal encapsulation

Essential for manipulating the crystals while avoiding degradation caused by air moisture

Different encapsulation techniques:

1) **Quartz case:**



NaI(tl) crystal   Quartz case

Crystal encapsulation

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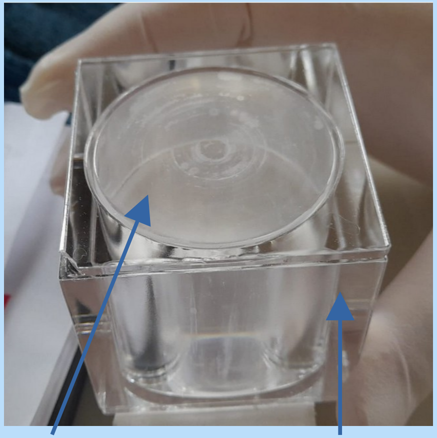
Different encapsulation techniques:

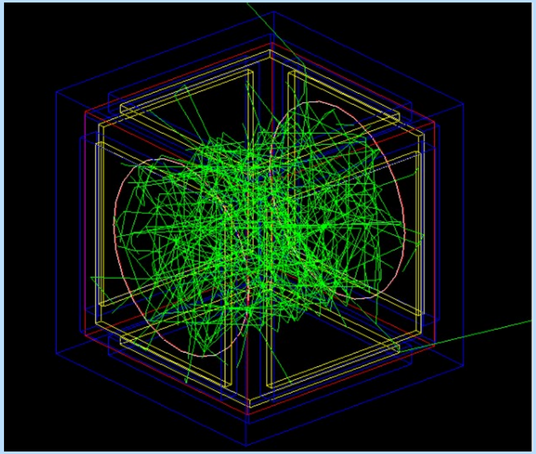
1) **Quartz case:**



NaI(tl) crystal

Quartz case

Geant4 optical simulation:



Multiple scattering

↓

More than 50% of photons absorbed

Crystal encapsulation

Essential for manipulating the crystals while avoiding degradation caused by air moisture

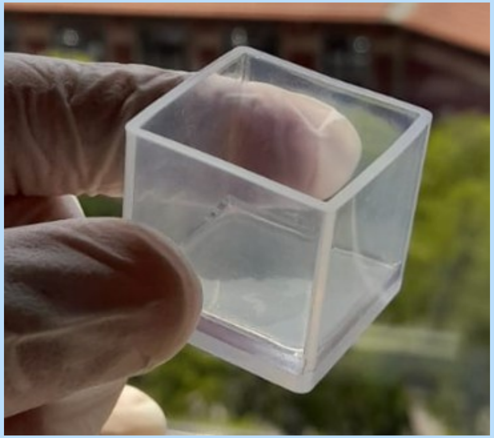
Different encapsulation techniques:

2) **Encapsulation with epoxy resin:**

A “cooking recipe”: Step 1: prepare the resin substrate

1

2



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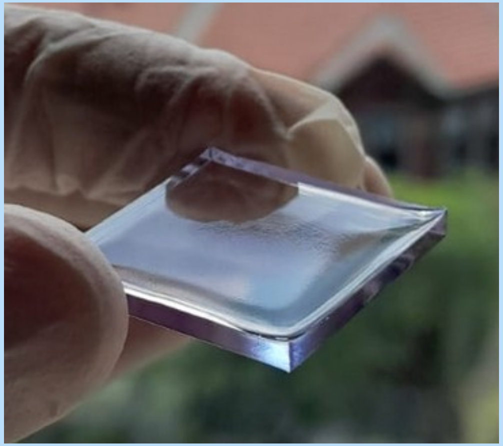


4

Crystal encapsulation

Essential for manipulating the crystals while avoiding degradation caused by air moisture

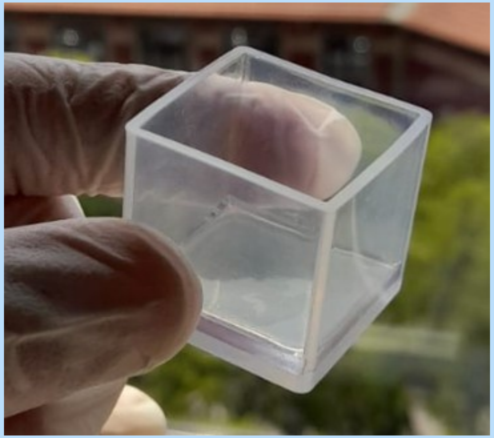
Different encapsulation techniques:

2) **Encapsulation with epoxy resin:**

A “cooking recipe”: Step 1: prepare the resin substrate

1

2



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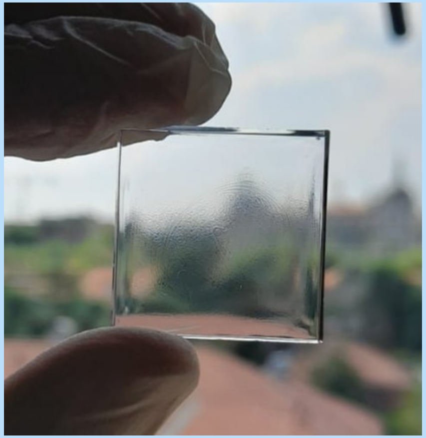


4

Crystal encapsulation

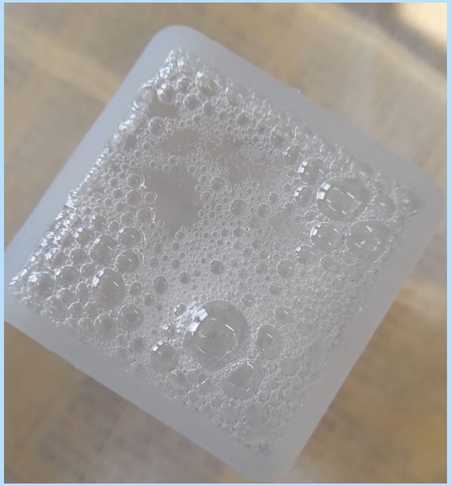
Essential for manipulating the crystals while avoiding degradation caused by air moisture

Different encapsulation techniques:

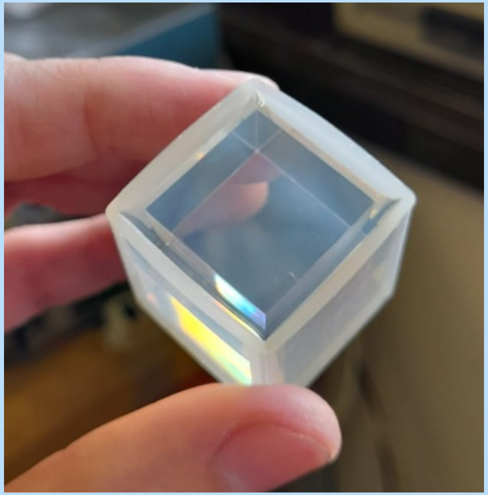
2) **Encapsulation with epoxy resin:**

A “cooking recipe”: Step 2: crystal encapsulation

1



2



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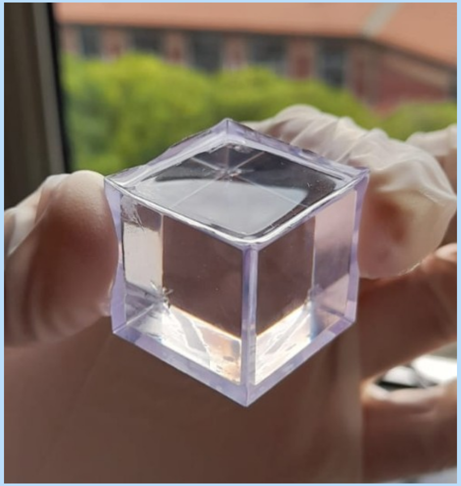


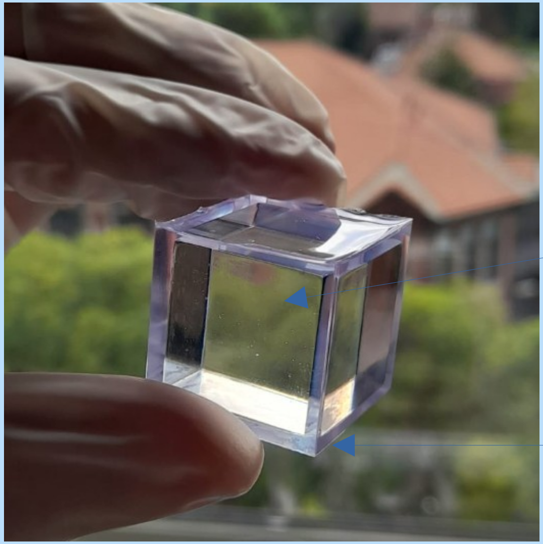
4

Crystal encapsulation

Essential for manipulating the crystals while avoiding degradation caused by air moisture

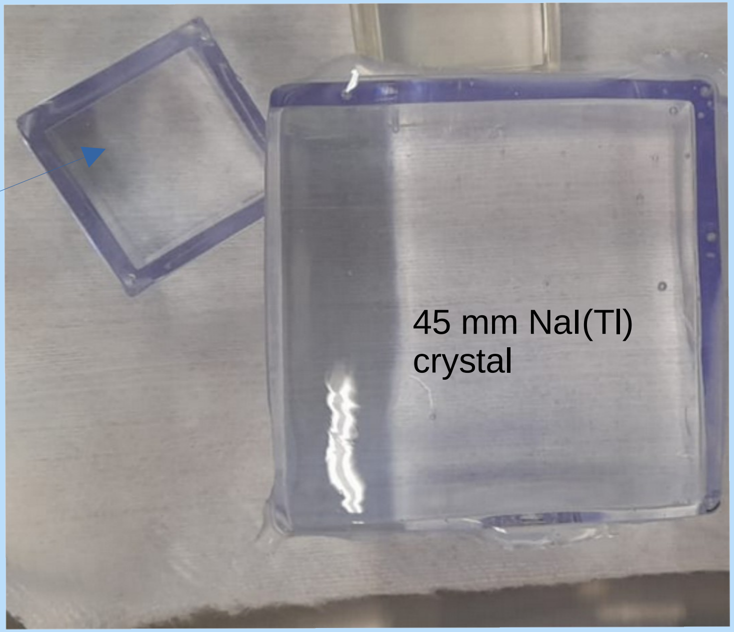
Different encapsulation techniques:

2) **Encapsulation with epoxy resin:**



21 mm NaI(Tl) crystal

Loctite Stycast 1266 resin



Crystal encapsulation

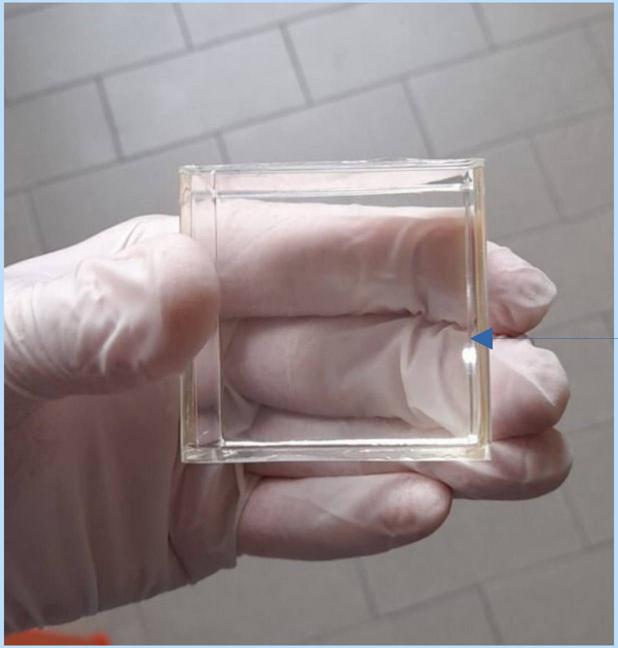
Essential for manipulating the crystals while avoiding degradation caused by air moisture

Different encapsulation techniques:

2) **Encapsulation with epoxy resin:**

21 mm NaI(Tl) crystal

EPO-TEK resin



45 mm NaI(Tl) crystal

Conclusions and outlook

- The ASTAROTH project aims to use **SiPMs to improve the sensitivity** of state-of-art dark matter direct detection experiments with NaI(Tl)

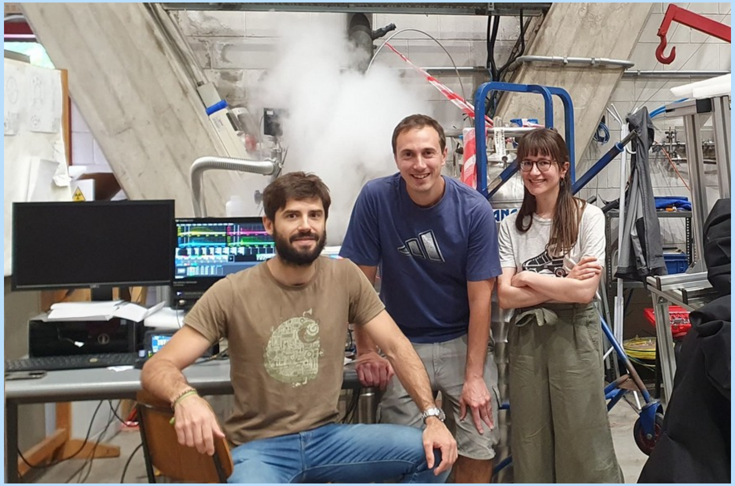
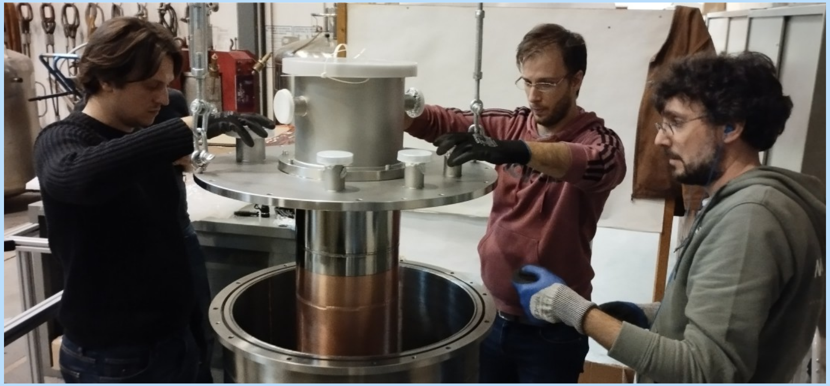
- A demonstrator detector has been produced, featuring an encapsulated cubic crystal (5×5×5 cm^3) operated at tunable temperatures in a specially built cryostat

- By covering **only one face** of the crystal, ASTAROTH has demonstrated that it is possible to observe scintillation events at or below the keV_{ee} scale

- Given the success achieved in this first phase, the project proceeds towards a second step: **ASTAROTH_beyond**

- A **better light collection** given by an innovative crystal encapsulation method and the **complete coverage of the crystal** will allow to increase the LY and to reduce the **energy threshold**



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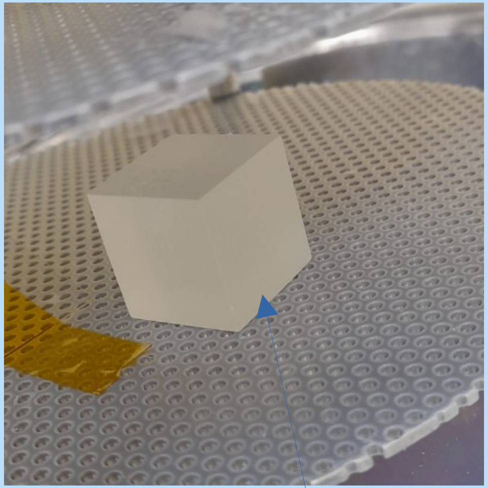
Backup slides

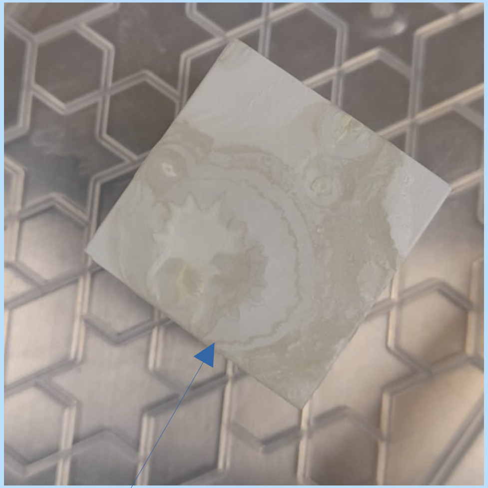
Crystal encapsulation

Essential for manipulating the crystals while avoiding degradation caused by air moisture

Different encapsulation techniques:

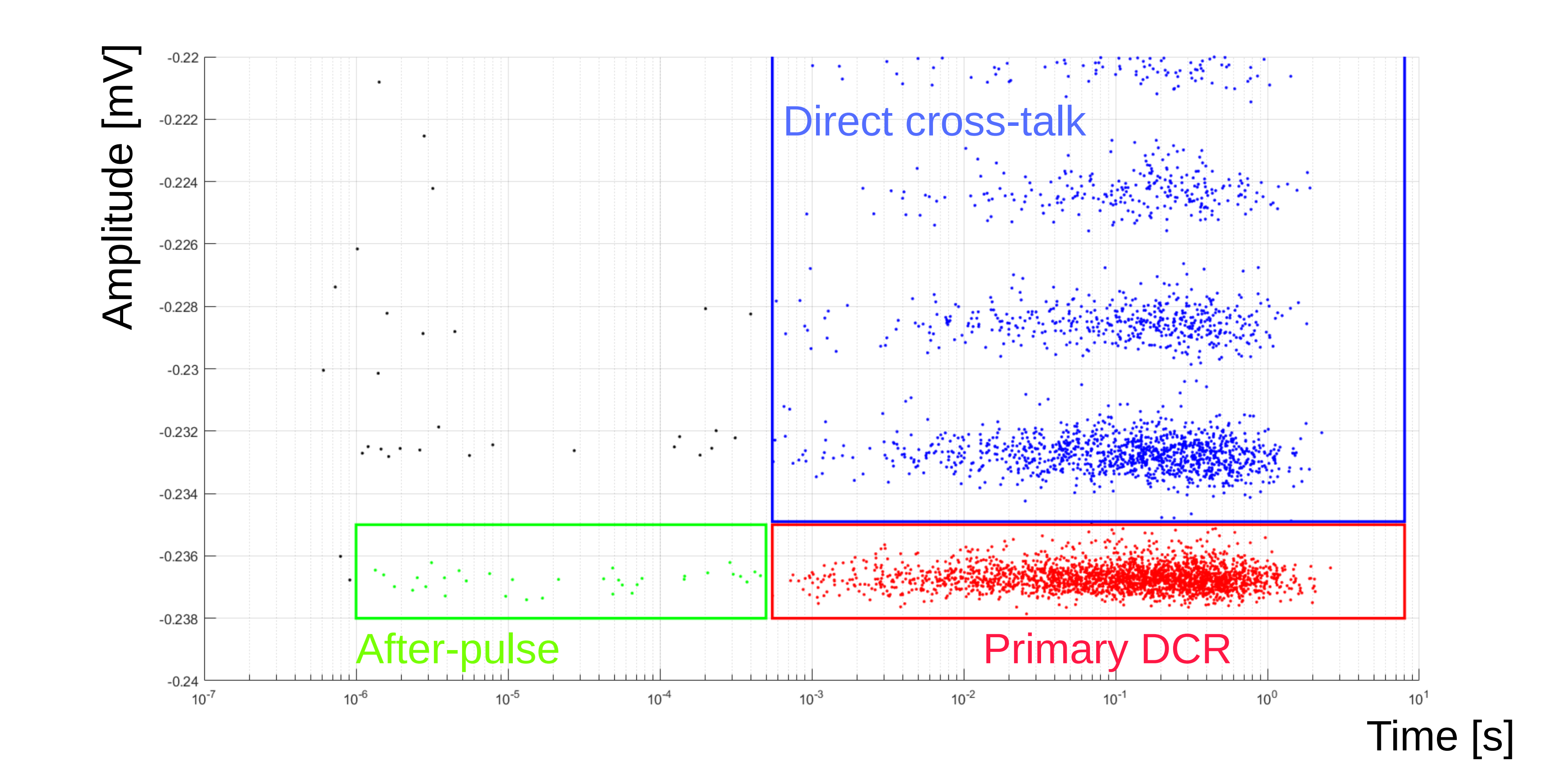
Deposition of a thin parylene film (1-10 μm):



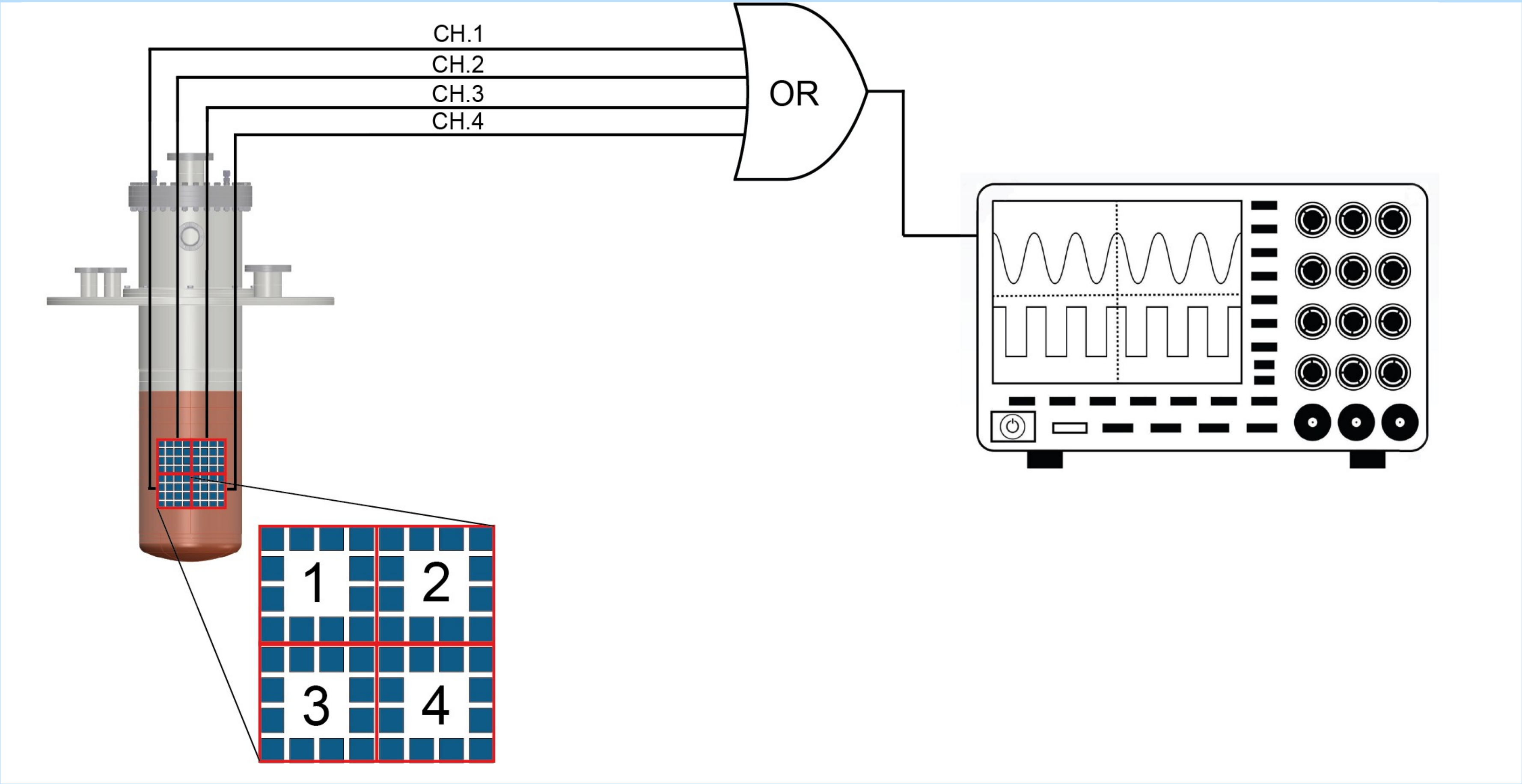


Not transparent, poor adhesion, non-uniformity

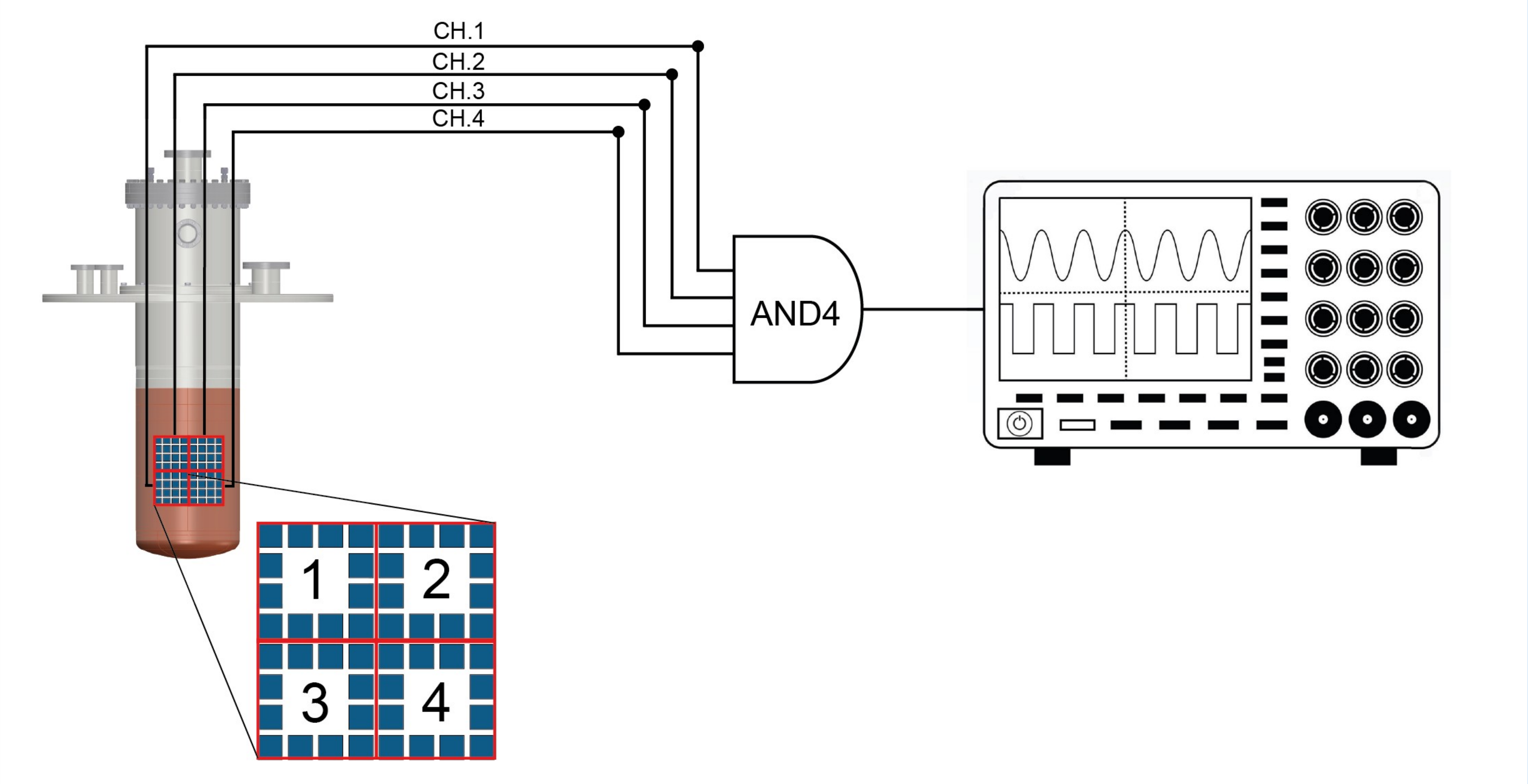
Delay time versus amplitude @ 77 K



Trigger conditions



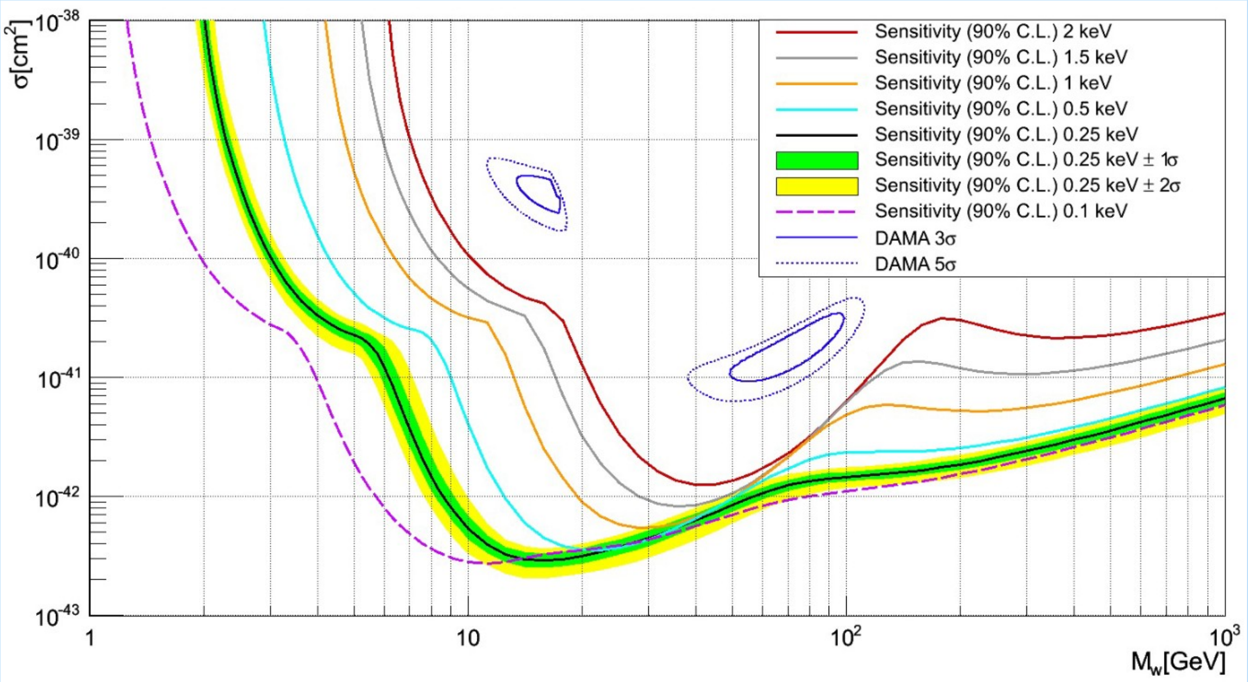
Trigger conditions



Sensitivity study

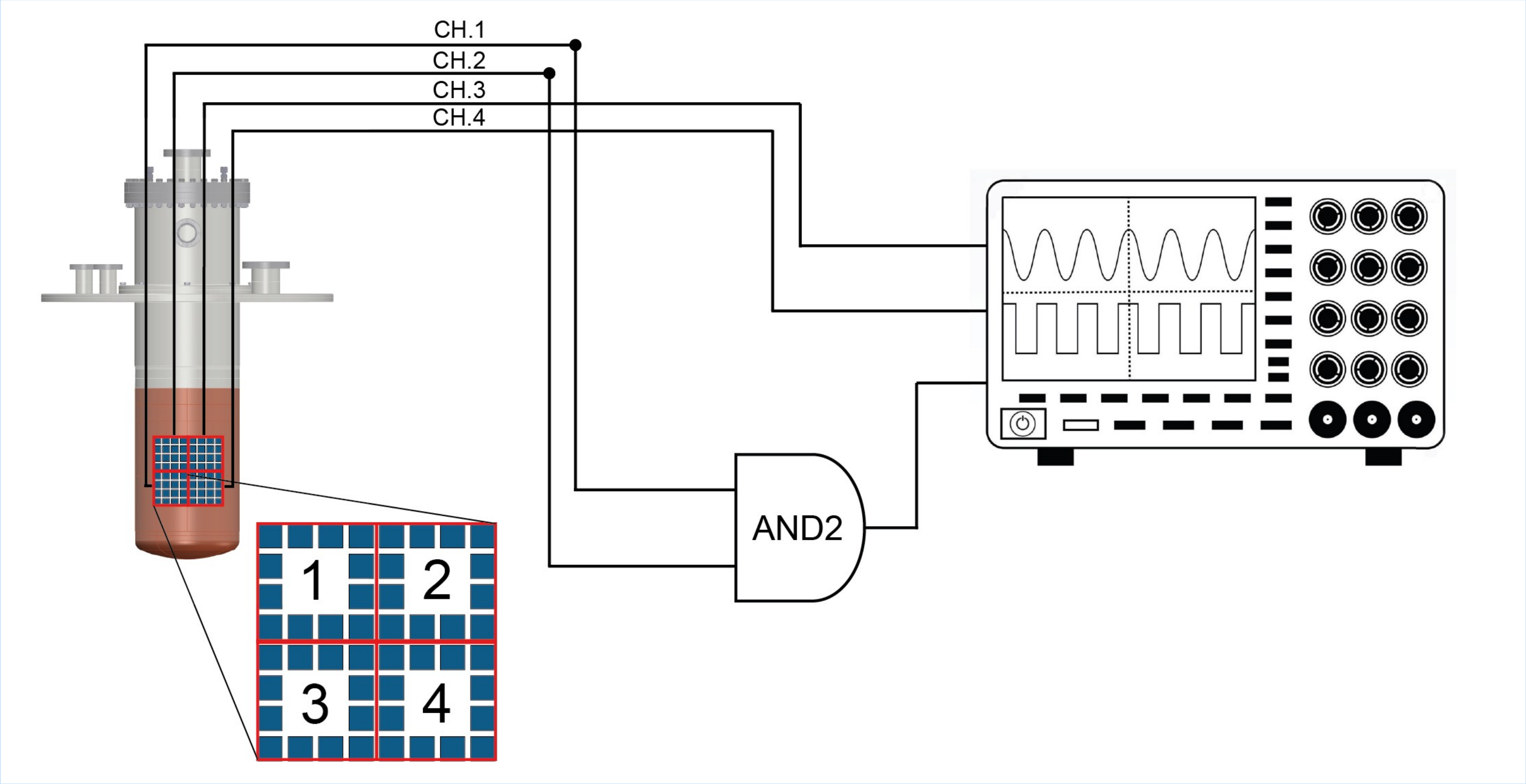
The ASTAROTH technology demonstrator will feature 1-2 encapsulated, 5×5×5 cm^3 NaI(Tl) crystals (0.46 kg each), operated on the surface.

Early **sensitivity studies** were performed on a **full-scale detector** featuring 8 encapsulated, 10×10×10 cm^3 NaI(Tl) crystals operated underground.



In the plot, 0.19 events/kg/day/keV (dru) in the [0.2-6.0] keV window are assumed.
Exposure: 30 kg x 3 y

Experimental setup



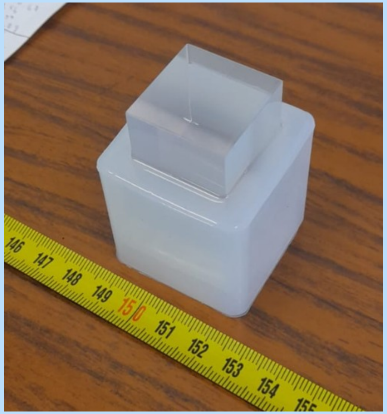
Crystal encapsulation

Essential for manipulating the crystals while avoiding degradation caused by air moisture

Different encapsulation techniques:

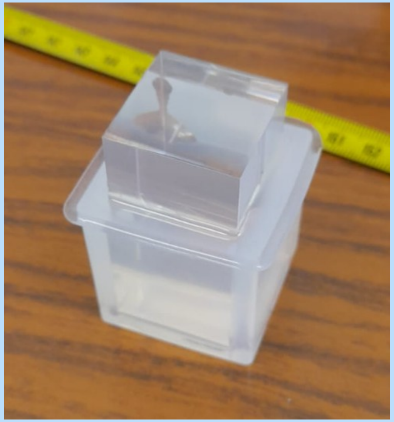
2) **Encapsulation with epoxy resin:**

A “cooking recipe”: Step 1: making the silicone mold



1

2



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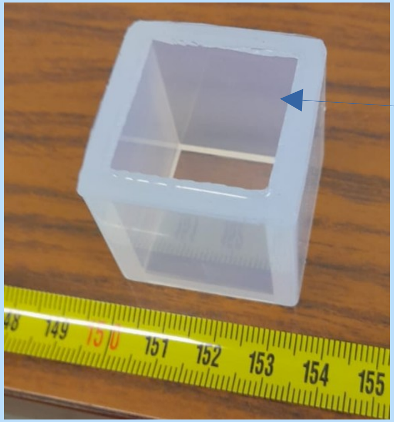

4

Internal dimensions
=
crystal dimensions
+
resin thickness

Crystal encapsulation

Essential for manipulating the crystals while avoiding degradation caused by air moisture

Different encapsulation techniques:

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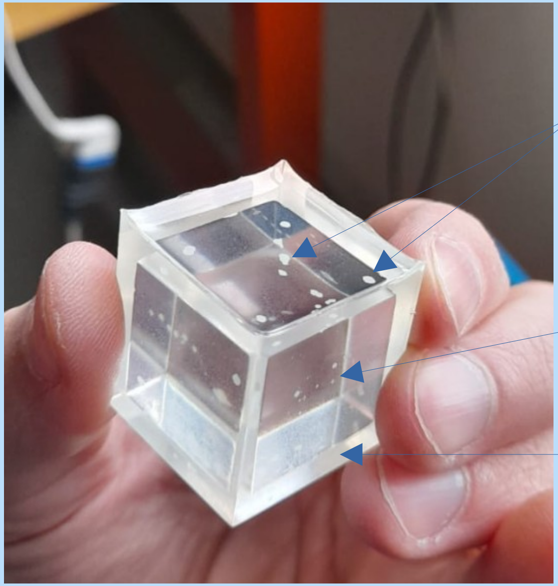
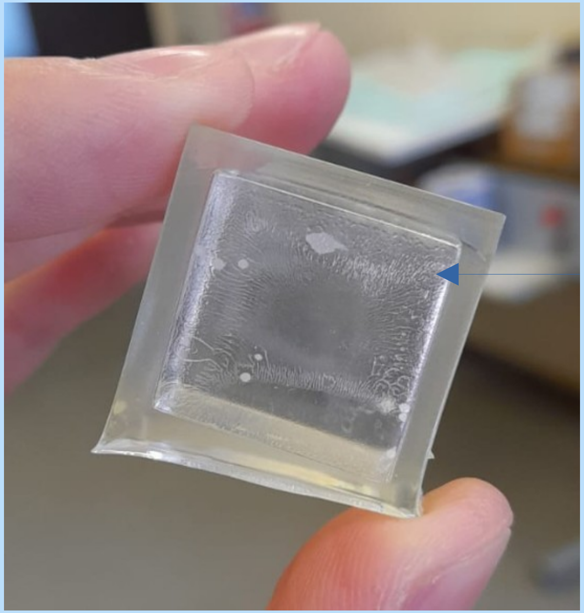
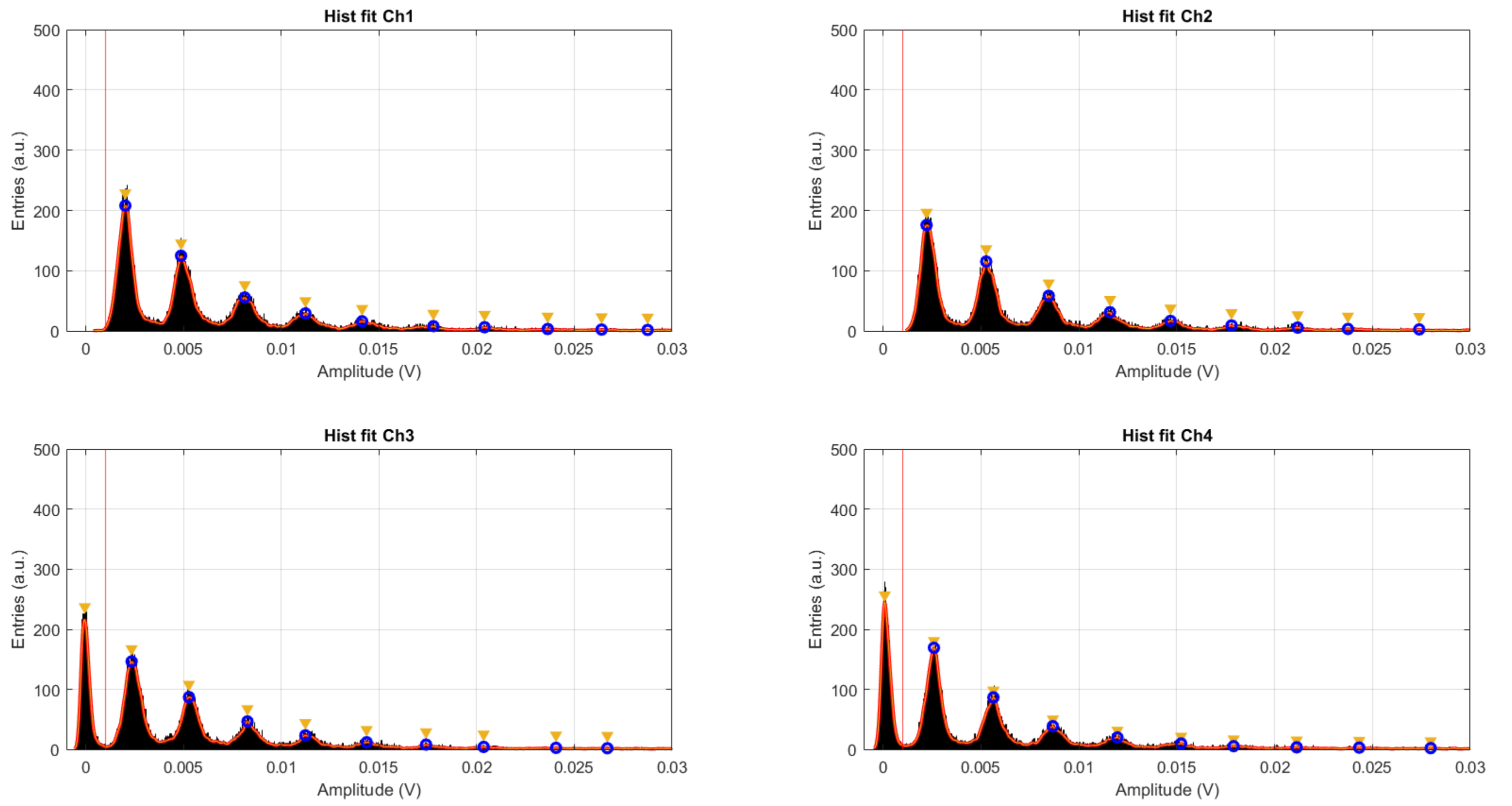
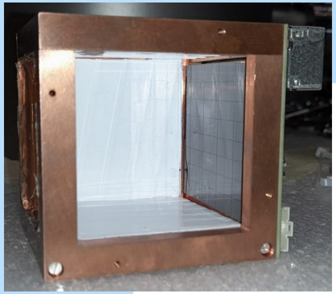


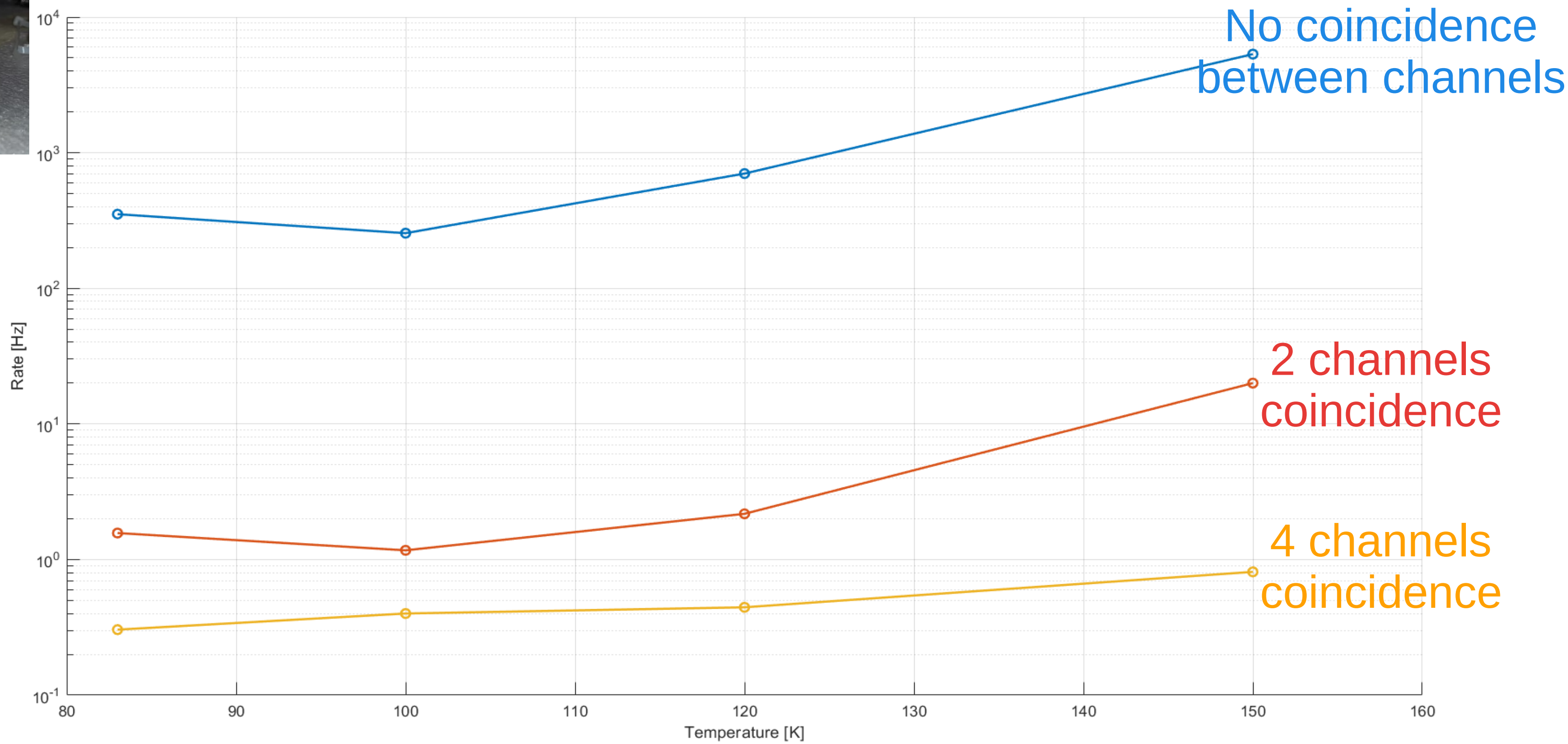


Identification of the peaks for amplitude normalization



DCR vs Temperature





DCR vs Temperature