ANAIS+

Dark matter search opportunities with NaI scintillating crystals using SiPMs at cryogenic temperatures

Jaime Apilluelo Allué

J. Amaré, **J. Apilluelo**, S. Cebrián, D. Cintas, I. Coarasa, E. García, P. García, I. Kochanek, M. Martínez, Y. Ortigoza, A. Ortiz de Solórzano, T. Pardo, V. Pesudo, J. Puimedón, A. Razeto, L. Romero, R. Santorelli, M.L. Sarsa

CAPA Ciemat INFN LNGS
MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA
FONDO EUROPEO DE DESARROLLO REGIONAL
"Una manera de hacer Europa"
AGENCIA ESTATAL DE INVESTIGACIÓN

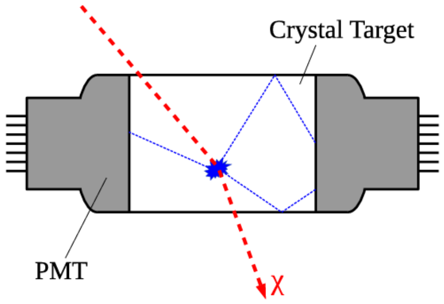
Overview

Dark Matter Direct Detection with NaI(Tl)

Scintillator detectors

Particle energy deposition → scintillation light → photon detector (usually PMTs).

Collected photons ∝ Deposited energy.

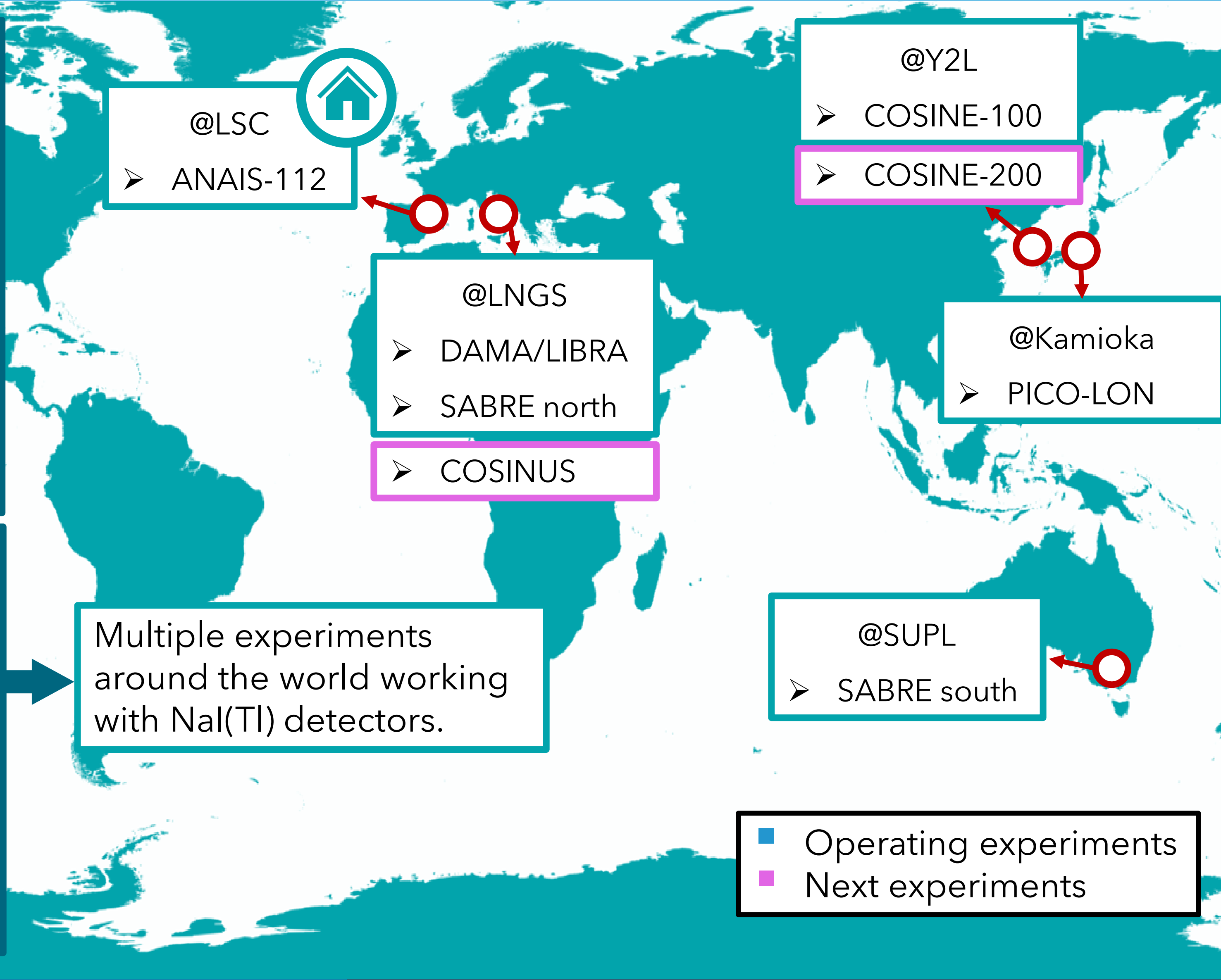


WIMPs would interact with atomic nuclei via elastic scattering, producing a nuclear recoil that could be detected.

Detectors based in NaI(Tl) scintillator crystals for DM search:

- Simple detector design with long stable operation.
- Scalability to produce a large mass target using an array of crystals.
- It combines elements with low and high mass number to increase sensitivity to light and heavy WIMPs.
- As both nuclei, Na and I, have spin, it is also interesting for spin dependent scattering.

Multiple experiments around the world working with NaI(Tl) detectors.

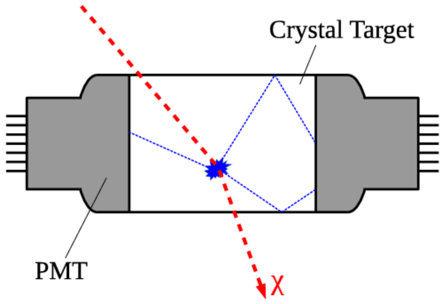


Dark Matter Direct Detection with NaI(Tl)

Scintillator detectors

Particle energy deposition → scintillation light → photon detector (usually PMTs).

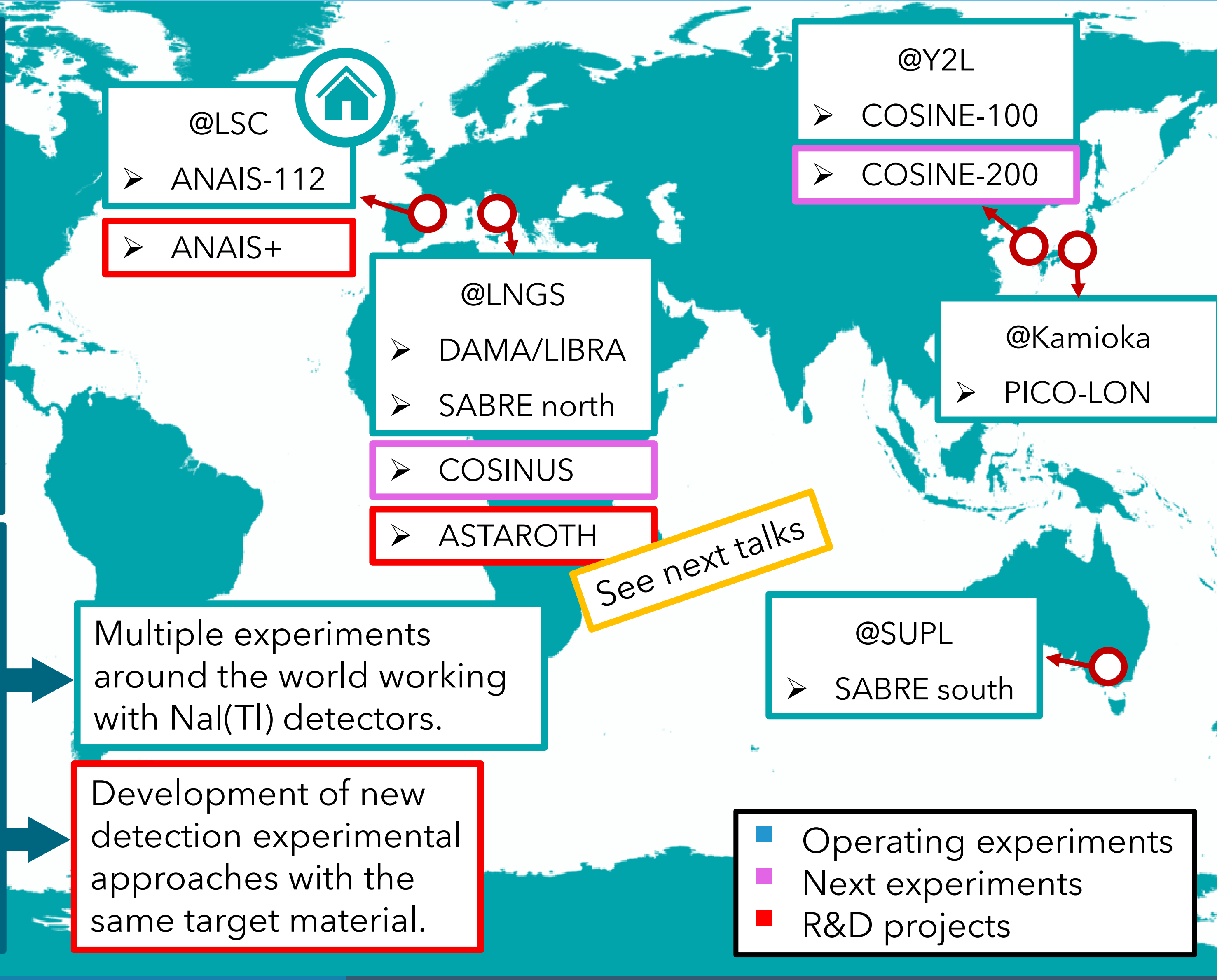
Collected photons ∝ Deposited energy.



WIMPs would interact with atomic nuclei via elastic scattering, producing a nuclear recoil that could be detected.

Detectors based in NaI(Tl) scintillator crystals for DM search:

- ❖ Simple detector design with long stable operation.
- ❖ Scalability to produce a large mass target using an array of crystals.
- ❖ It combines elements with low and high mass number to increase sensitivity to light and heavy WIMPs.
- ❖ As both nuclei, Na and I, have spin, it is also interesting for spin dependent scattering.



Multiple experiments around the world working with NaI(Tl) detectors.

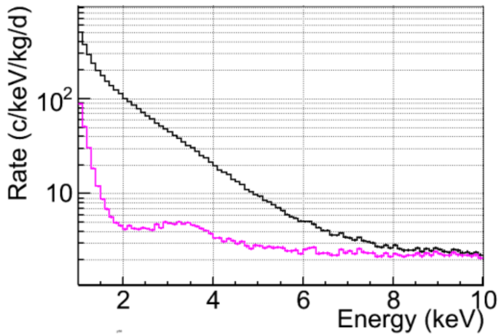
Development of new detection experimental approaches with the same target material.

- Operating experiments
- Next experiments
- R&D projects

Motivation for ANAIS+

At present ANAIS-112 sensitivity is constrained by anomalous light events attributed to the PMTs:

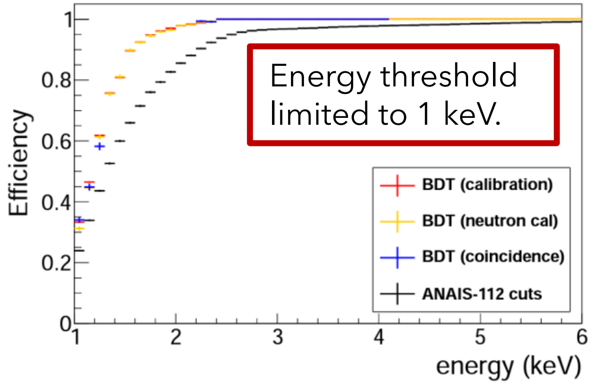
- They are dominating the events rate below 10 keV.

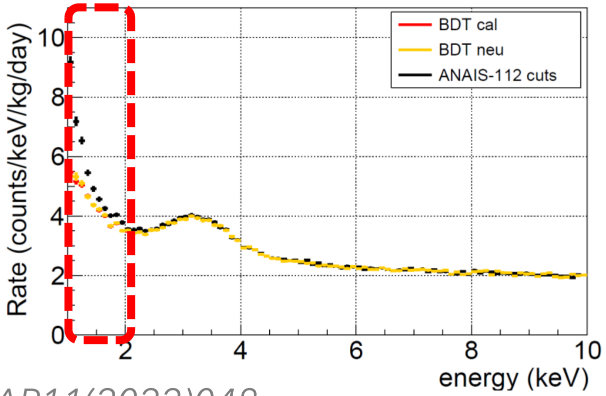


Measured spectrum

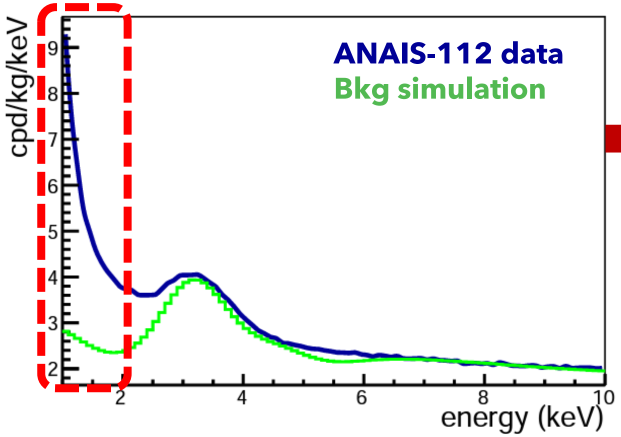
Spectrum after event selection

- Aggressive filtering has been developed to remove them, but efficiency is low (even after improvements by new ML procedure) and **limits the energy threshold**.





I. Coarasa et al JCAP11(2022)048



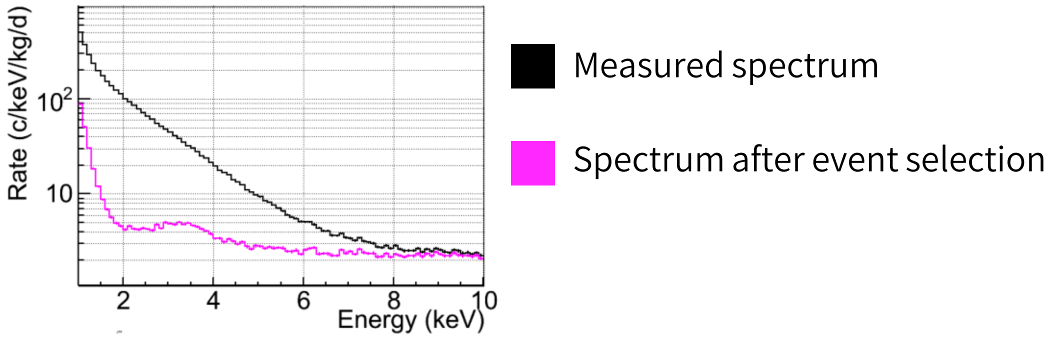
After filtering, there is still discrepancy in the 1-2 keV region between simulations following the bkg model and data → some anomalous events may be leaking into the ROI.

Motivation for ANAIS+

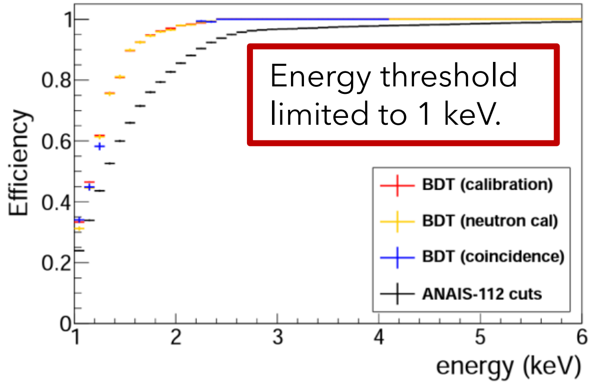
MAIN GOAL
Lower the energy threshold Eth <0.5 keV in NaI detectors

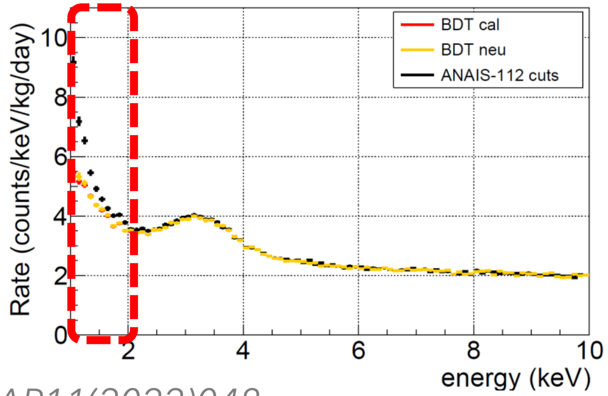
At present ANAIS-112 sensitivity is constrained by anomalous light events attributed to the PMTs:

- They are dominating the events rate below 10 keV.



- Aggressive filtering has been developed to remove them, but efficiency is low (even after improvements by new ML procedure) and **limits the energy threshold**.



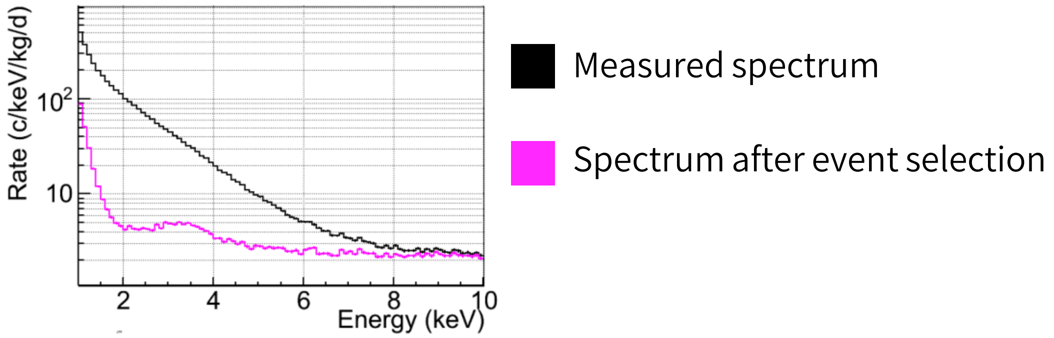


I. Coarasa et al JCAP11(2022)048

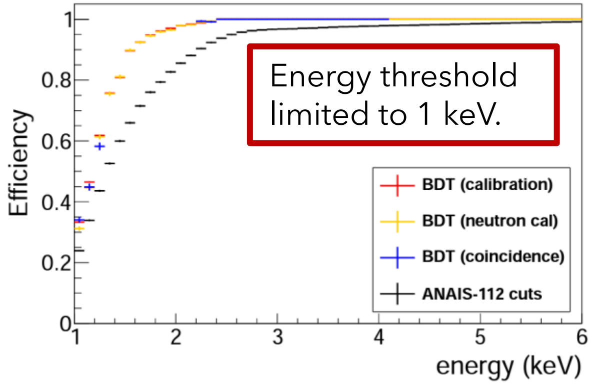
Motivation for ANAIS+

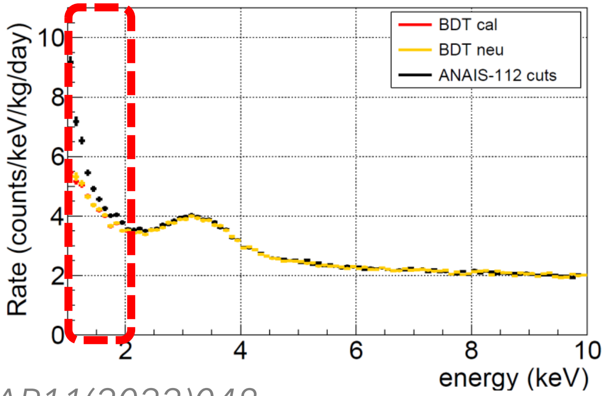
At present ANAIS-112 sensitivity is constrained by anomalous light events attributed to the PMTs:

- They are dominating the events rate below 10 keV.



- Aggressive filtering has been developed to remove them, but efficiency is low (even after improvements by new ML procedure) and **limits the energy threshold**.





I. Coarasa et al JCAP11(2022)048

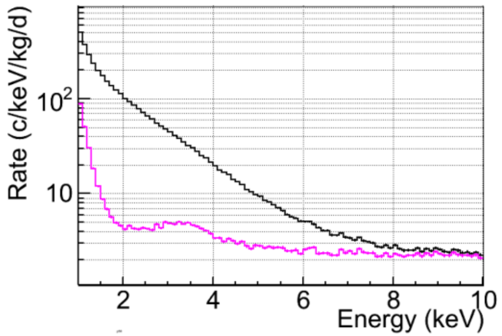
MAIN GOAL
Lower the energy threshold Eth <0.5 keV in NaI detectors

- ❑ Testing DAMA/LIBRA result overcoming the systematics from the uncertainties in the scintillation quenching factors.

Motivation for ANAIS+

At present ANAIS-112 sensitivity is constrained by anomalous light events attributed to the PMTs:

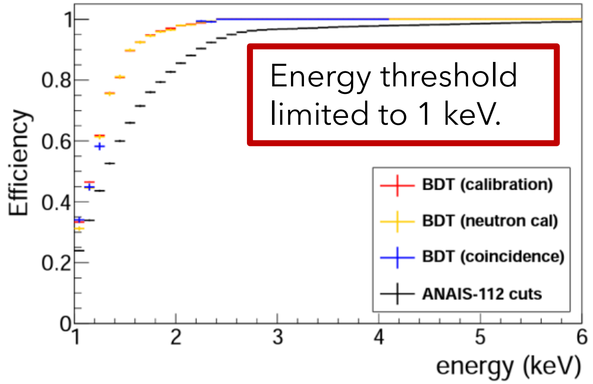
- They are dominating the events rate below 10 keV.

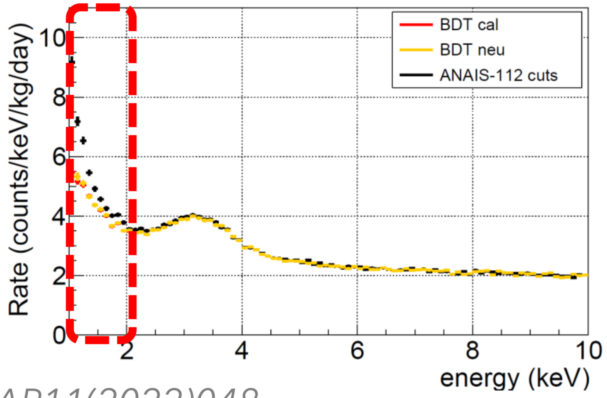


Measured spectrum

Spectrum after event selection

- Aggressive filtering has been developed to remove them, but efficiency is low (even after improvements by new ML procedure) and **limits the energy threshold**.

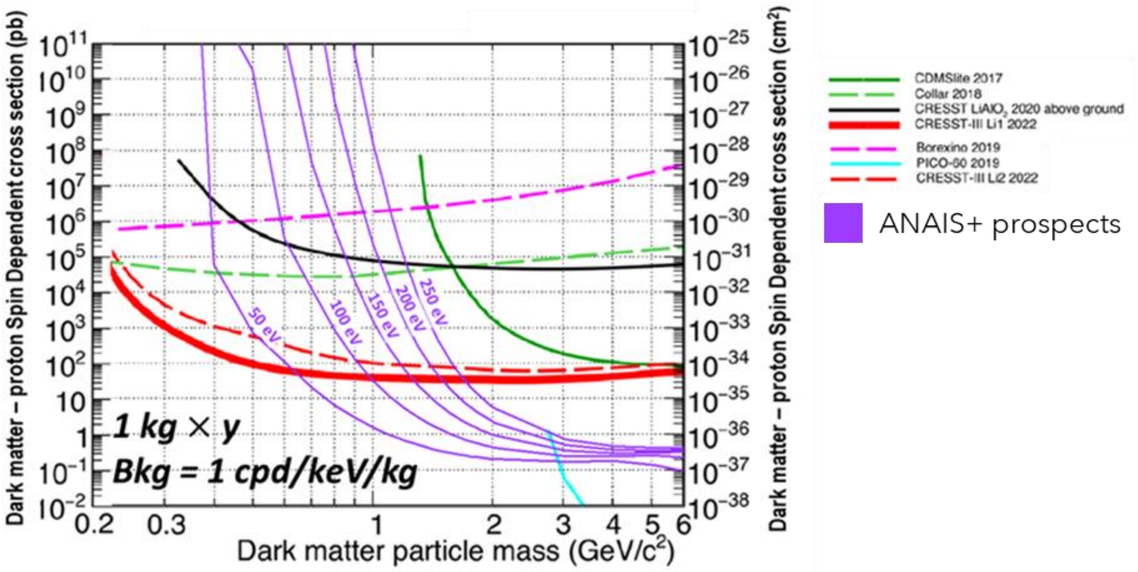




I. Coarasa et al JCAP11(2022)048

MAIN GOAL
Lower the energy threshold Eth <0.5 keV in NaI detectors

- ❑ Testing DAMA/LIBRA result overcoming the systematics from the uncertainties in the scintillation quenching factors.
- ❑ Good sensitivity to light WIMPs even with a reasonable exposure and background level.

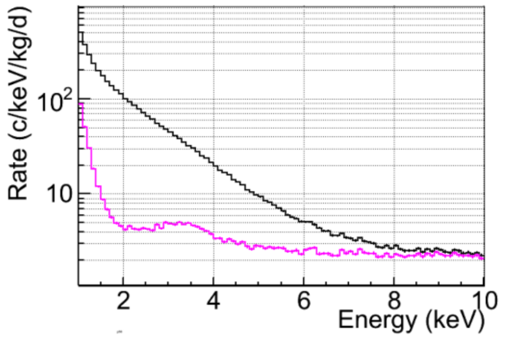


Sensitivity projections of ANAIS+ for spin dependent proton WIMP interaction considering different energy thresholds and a background level of 1 cpd/keV/kg.

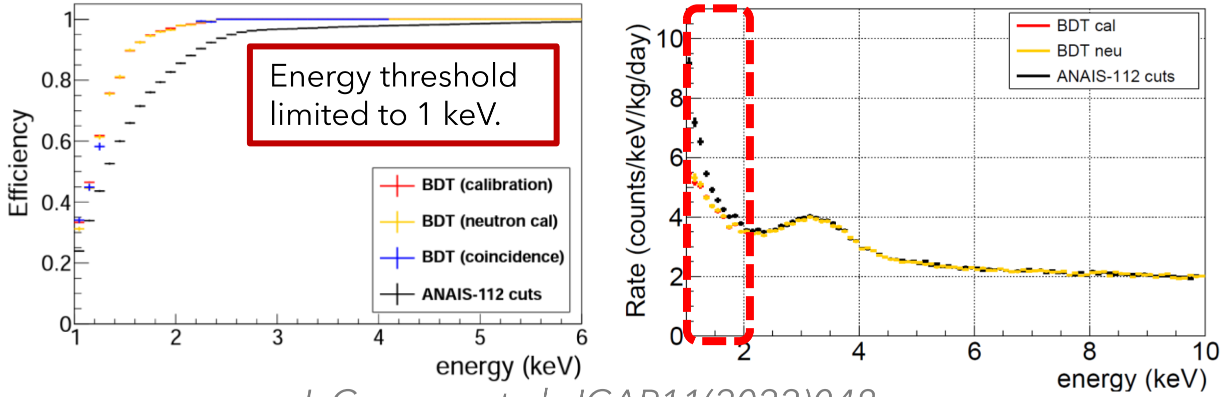
Motivation for ANAIS+

At present ANAIS-112 sensitivity is constrained by anomalous light events attributed to the PMTs:

- They are dominating the events rate below 10 keV.



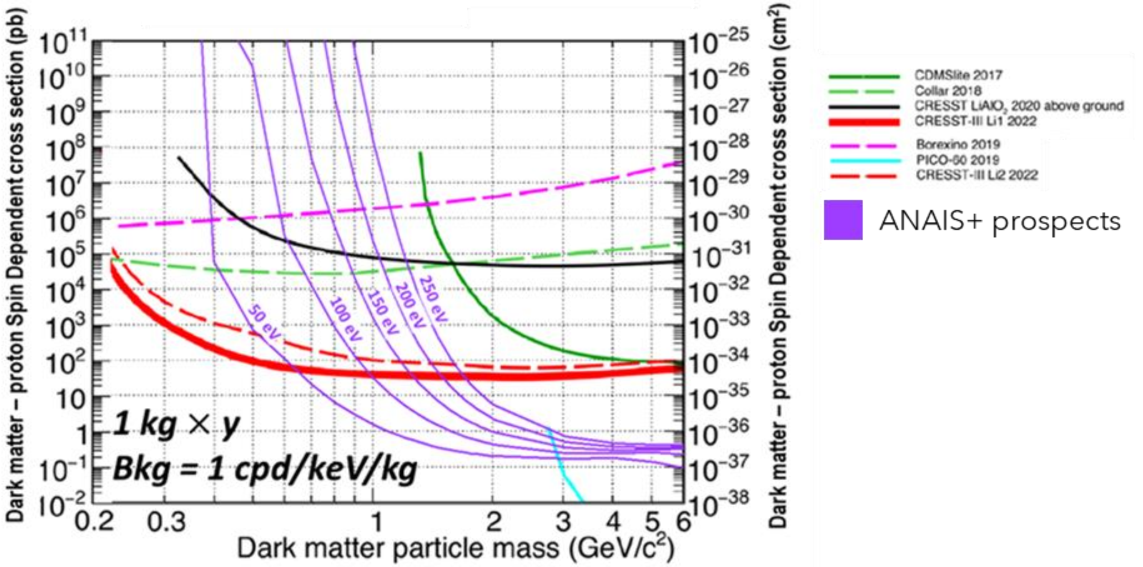
- Aggressive filtering has been developed to remove them, but efficiency is low (even after improvements by new ML procedure) and **limits the energy threshold**.



I. Coarasa et al JCAP11(2022)048

MAIN GOAL
Lower the energy threshold Eth <0.5 keV in NaI detectors

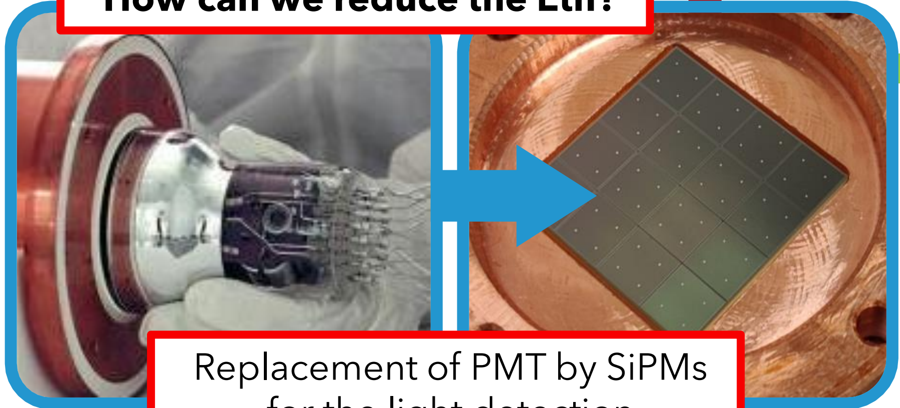
- ❑ Testing DAMA/LIBRA result overcoming the systematics from the uncertainties in the scintillation quenching factors.
- ❑ Good sensitivity to light WIMPs even with a reasonable exposure and background level.



- ❑ Also interesting for neutrino detection via coherent elastic neutrino-nucleus scatterings (CEνNS).

The ANAIS+ Project

How can we reduce the Eth?



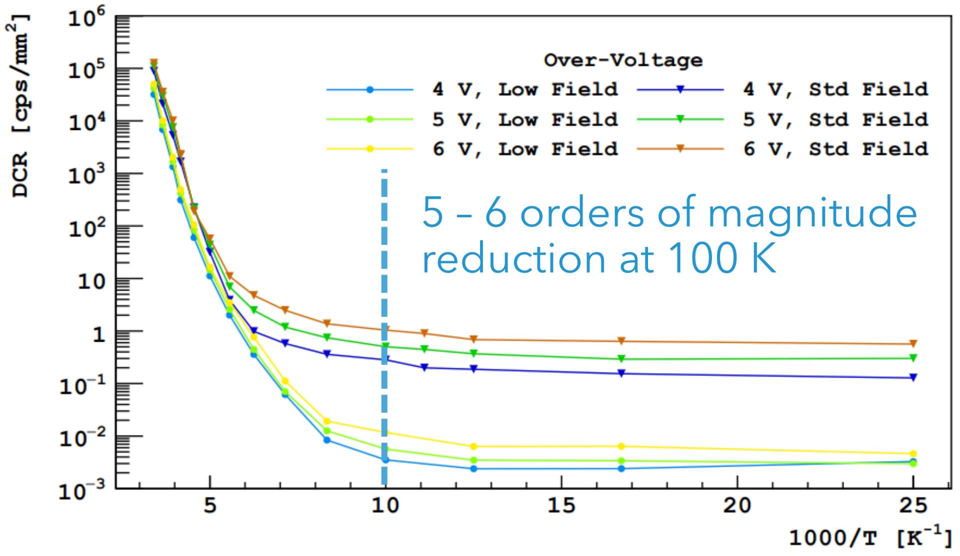
Replacement of PMT by SiPMs for the light detection

ADVANTAGES

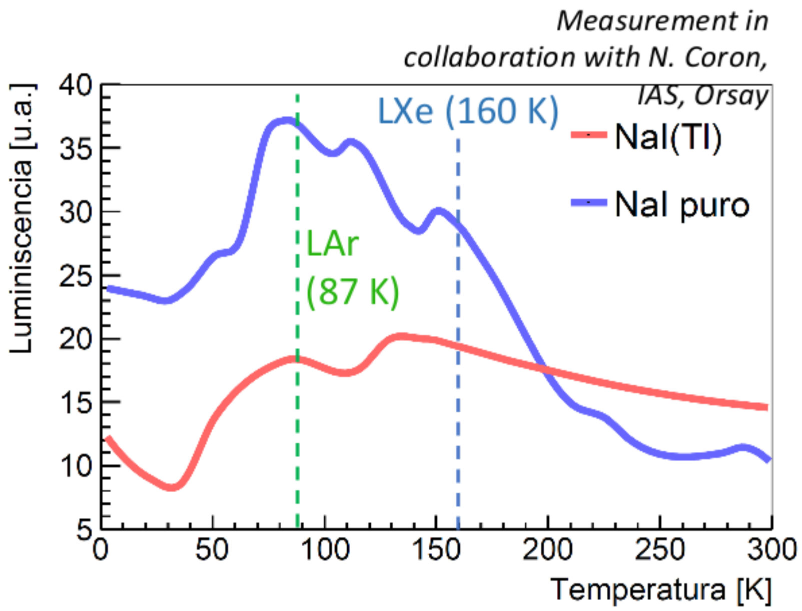
- High QE (≈40 %).
- High radiopurity (lower bkg).
- Low operating voltage (~ 10's V).
- No Cherenkov/HV arc-discharges emissions.

MAIN DRAWBACK

- High dark current rate (depending on the model, typically ~ 50 - 1000 kHz/mm^2 at room T).
- Working at low temperatures (100 K) → lower dark current than in PMTs.



F. Acerbi et al., IEEE Transactions on Electron Devices, vol. 64, no. 2, pp. 521-526, Feb. 2017

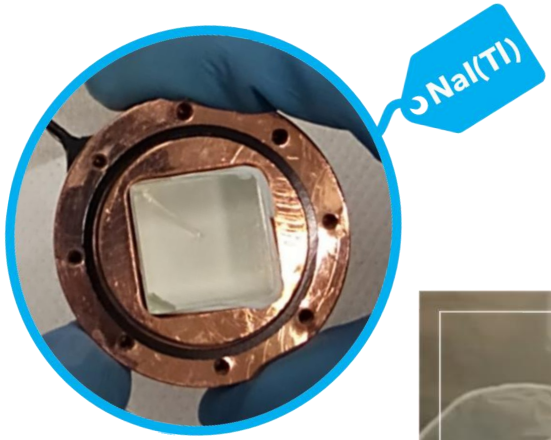


At this temperature, pure NaI become an interesting target as its light yield is expected to increase at the level or above the NaI(Tl) at room T.

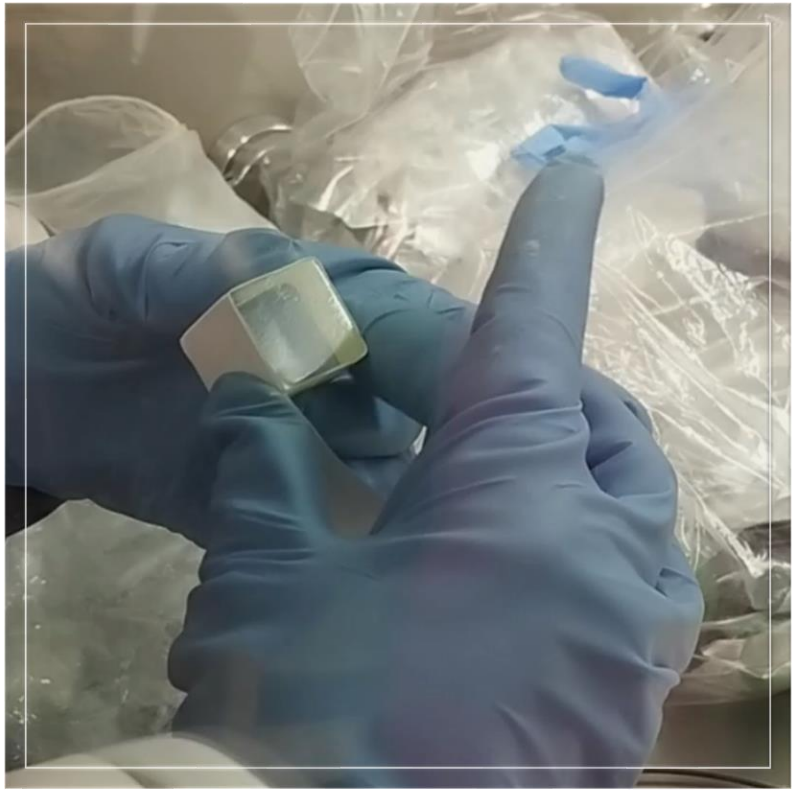
The ANAIS+ Project: preliminary tests

ANAIS+ test set-up:

Scintillator crystal: NaI(Tl)/NaI 1″ cube.



The crystals are stored and manipulated inside a dedicated glove box with low humidity atmosphere (filled with nitrogen gas).

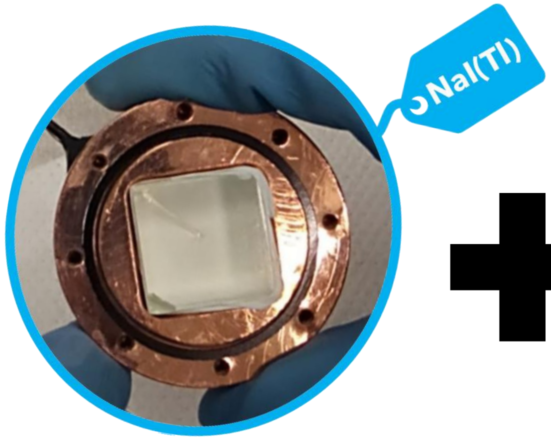


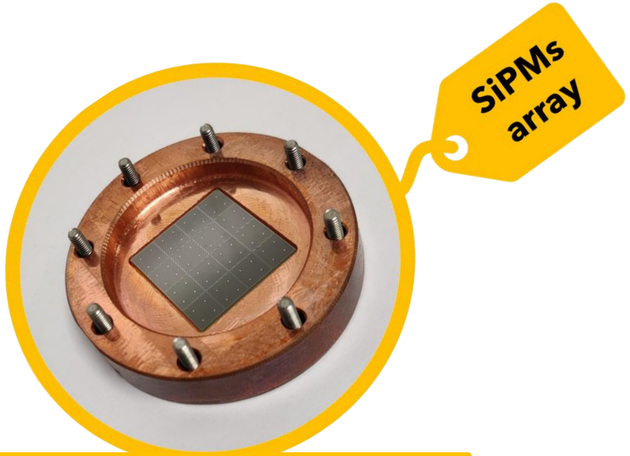
The ANAIS+ Project: preliminary tests

ANAIS+ test set-up:

Scintillator crystal: NaI(Tl)/NaI 1" cube.

SiPMs array: HAMAMATSU S13361-6050AE-04 (25 x 25 mm → 4 x 4 SiPMs)





16 (4x4) SiPMs grouped in 8 readout channels.

The ANAIS+ Project: preliminary tests

ANAIS+ test set-up:

Scintillator crystal: NaI(Tl)/NaI 1″ cube.

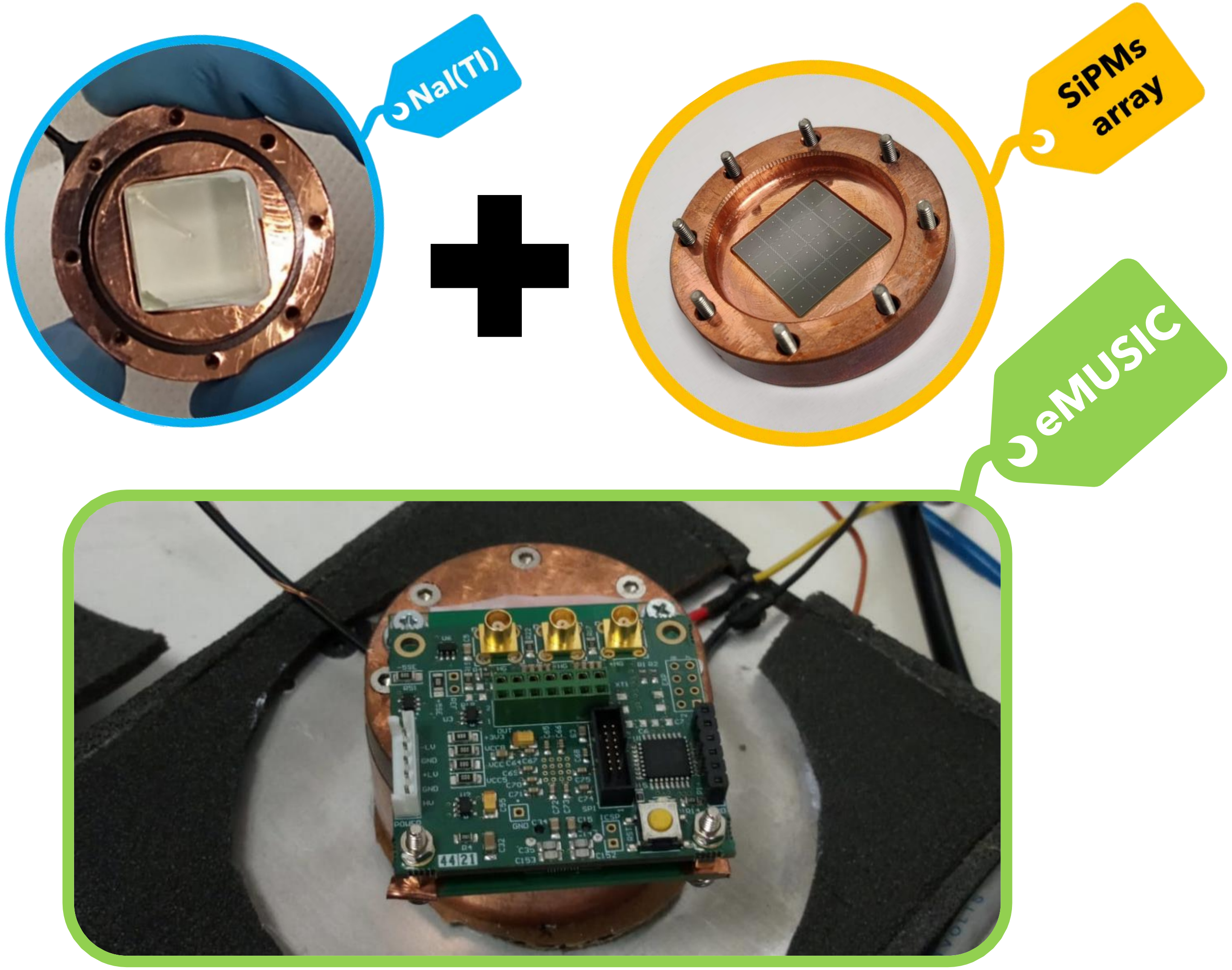
SiPMs array: HAMAMATSU S13361-6050AE-04 (25 x 25 mm → 4 x 4 SiPMs).

Readout electronics: MUSIC (Multiple Use SiPM Integrated Circuit).

Developed at University of Barcelona

Gómez, S. et al. Electronics 2021, 10, 961.

Possibility to configure some readout features: filter, channel selection …



The ANAIS+ Project: preliminary tests

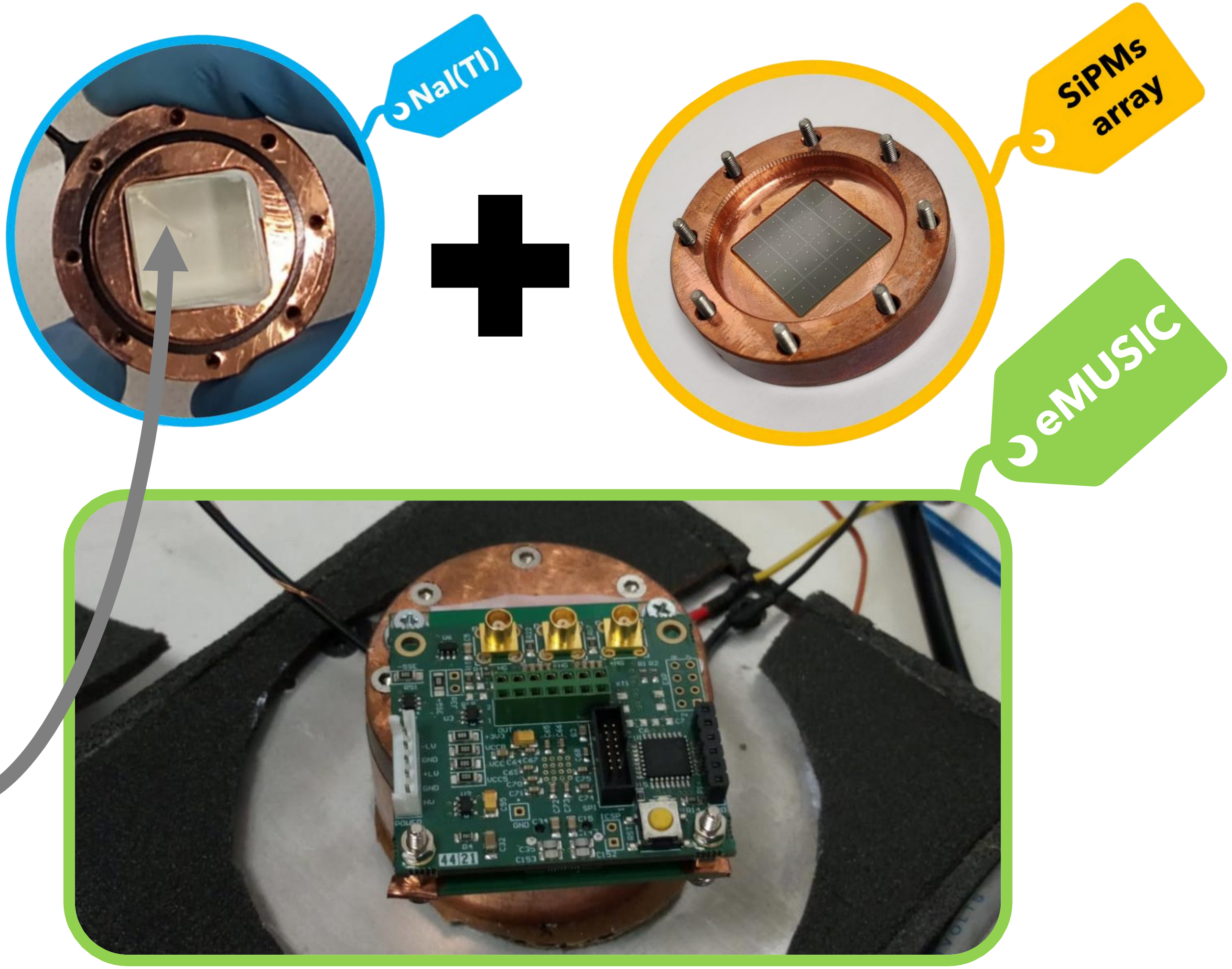
ANAIS+ test set-up:

Scintillator crystal: NaI(Tl)/NaI 1″ cube.

SiPMs array: HAMAMATSU S13361-6050AE-04 (25 x 25 mm → 4 x 4 SiPMs).

Readout electronics: MUSIC (Multiple Use SiPM Integrated Circuit).

Optical fiber placed under the scintillator cube used to inject LED light to the SiPMs array.



The ANAIS+ Project: preliminary tests

ANAIS+ test set-up:

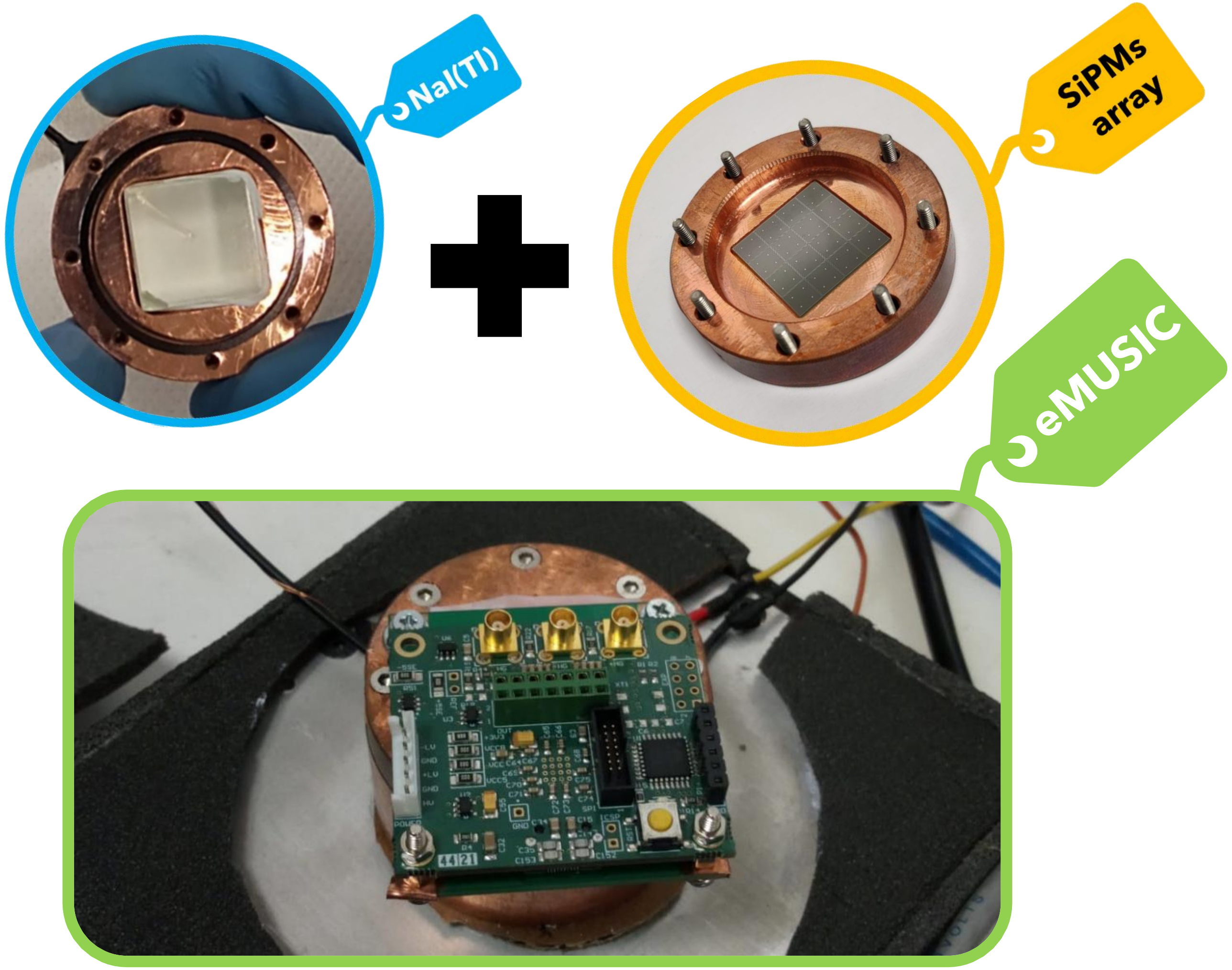
Goals of first tests:

✓ Study the cooling system response including the crystal thermal charge at different temperatures down to 100 K.

✓ Test the NaI / NaI(Tl) mechanical response under thermal cycles.

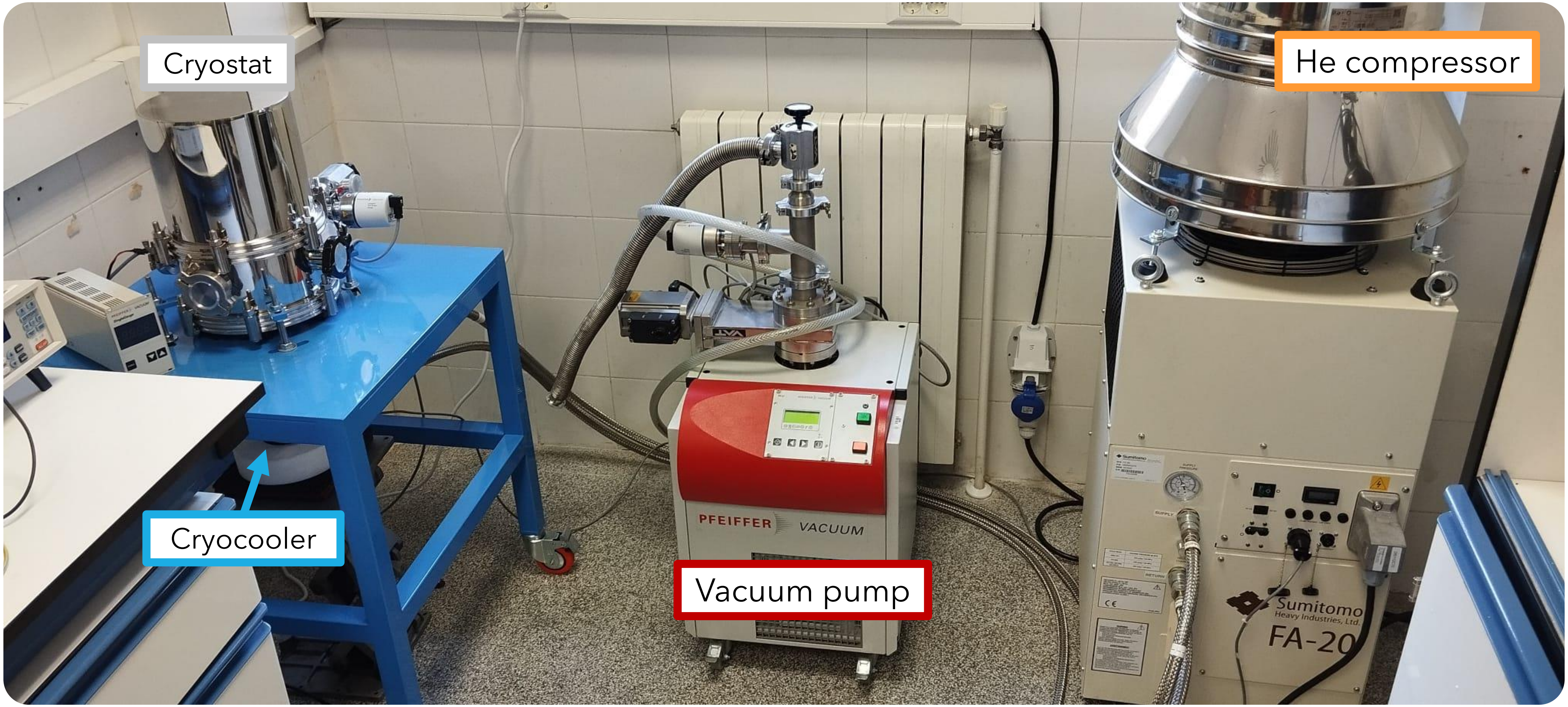
✓ Study the light collection in a wide range of temperatures (from room temperature to ≈30 K).

Cryogenic installation at Universidad de Zaragoza



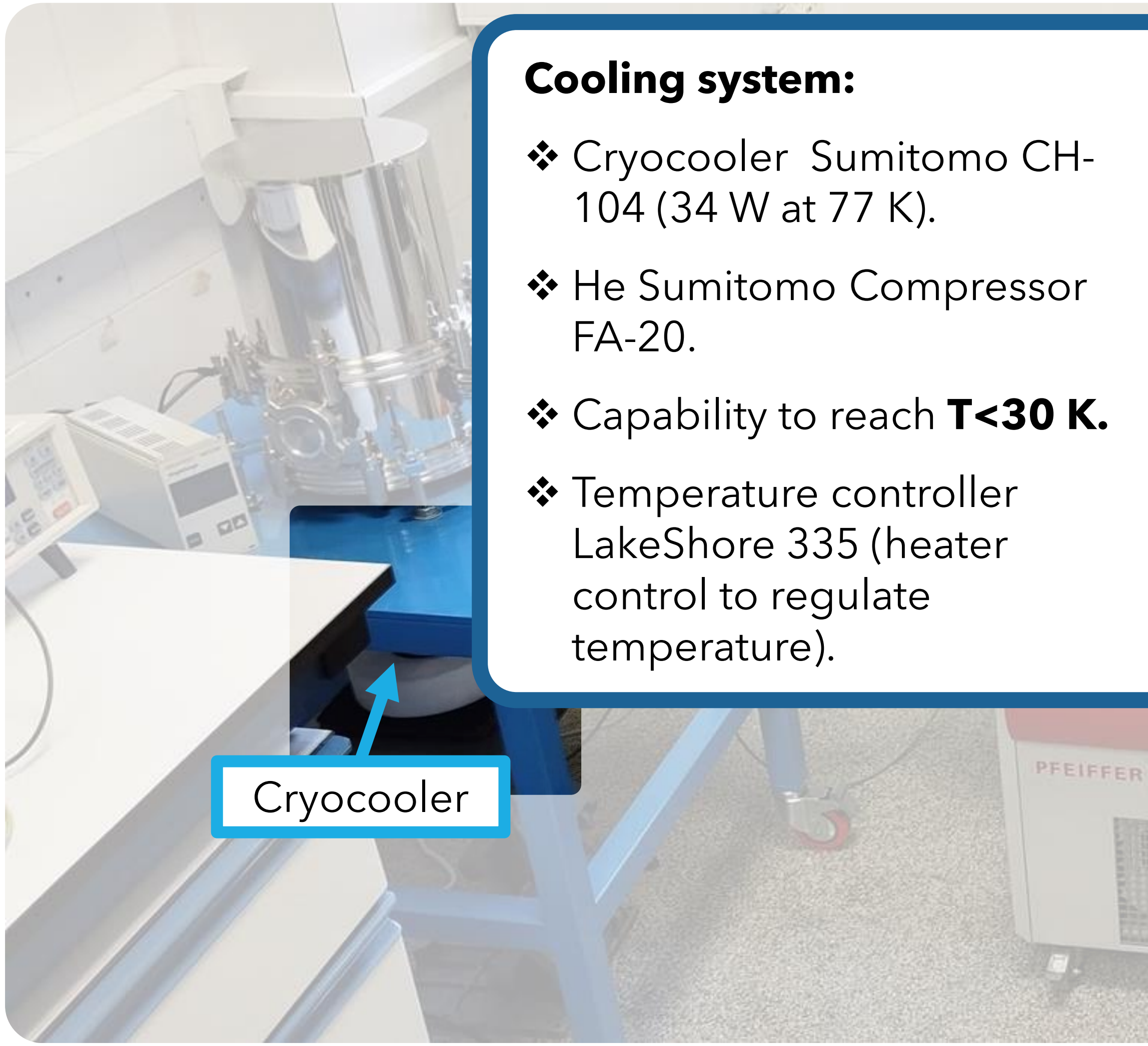
The ANAIS+ Project: preliminary tests

ANAIS+ cryogenic installation (Universidad de Zaragoza):



The ANAIS+ Project: preliminary tests

ANAIS+ cryogenic installation (Universidad de Zaragoza):



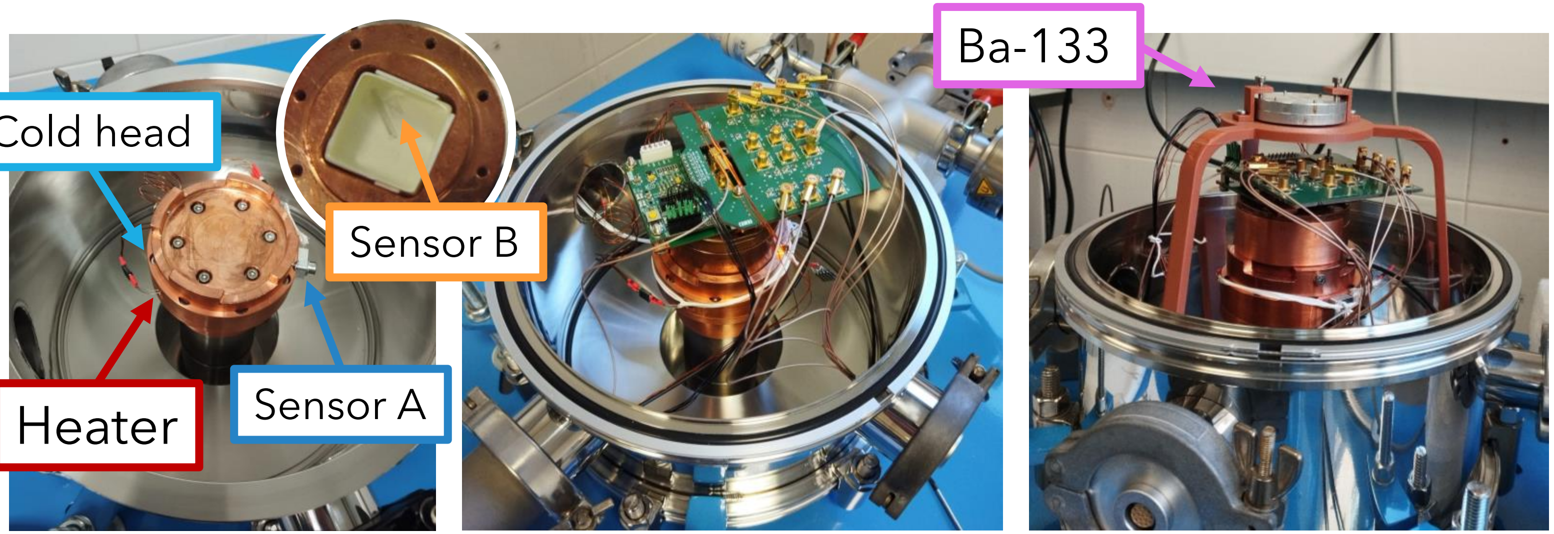
Cooling system:

- Cryocooler Sumitomo CH-104 (34 W at 77 K).
- He Sumitomo Compressor FA-20.
- Capability to reach **T<30 K.**
- Temperature controller LakeShore 335 (heater control to regulate temperature).

The ANAIS+ Project: preliminary tests

ANAIS+ cryogenic installation (Universidad de Zaragoza):

- Detector kept inside vacuum (during cooling) or nitrogen atmosphere (to protect the NaI cristal against humidity).
- Radioactive source placed just above the detector.
- Two temperature sensors: **A** (next to cold head), **B** (inside the detector, in contact with the NaI crystal).

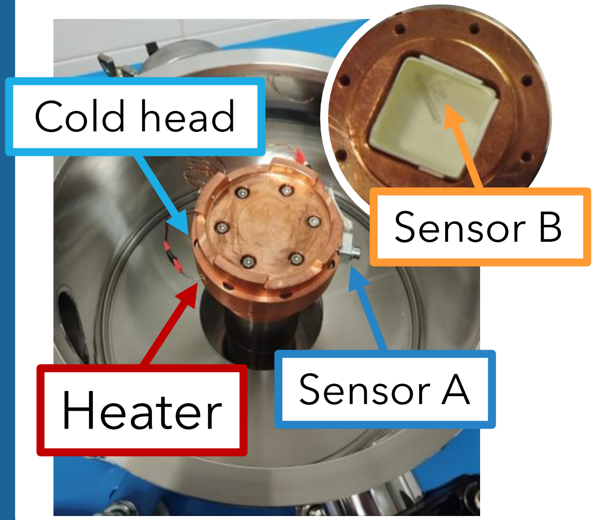


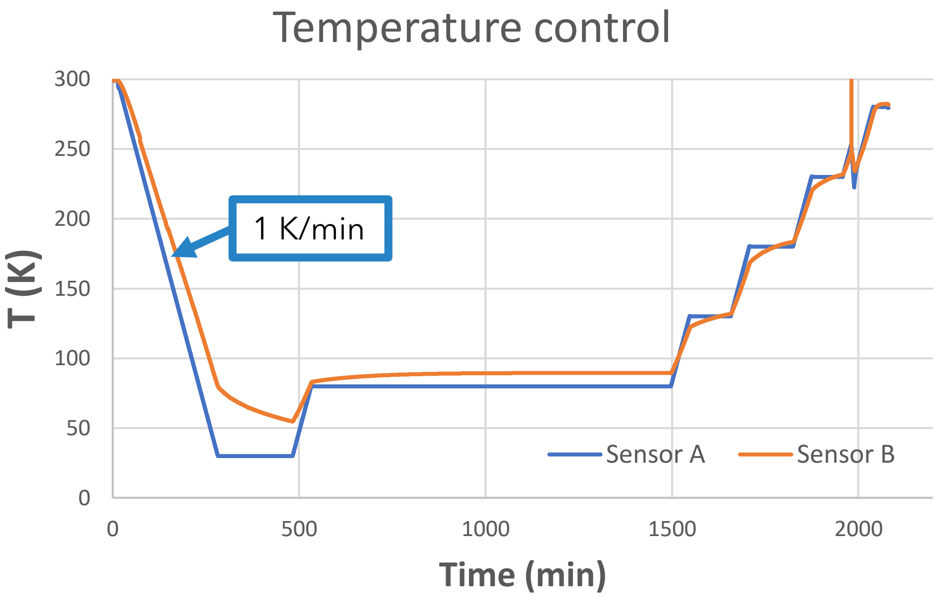
The ANAIS+ Project: preliminary tests

ANAIS+ cryogenic installation (Universidad de Zaragoza):

Cooling system tests: from 30 K to room temperature in steps of 50 K.

- Sensor **A** is used to set a constant temperature thanks to the controlled heater output.
- It is also possible to control the cooling rate, which is important to avoid damages in the NaI crystals.





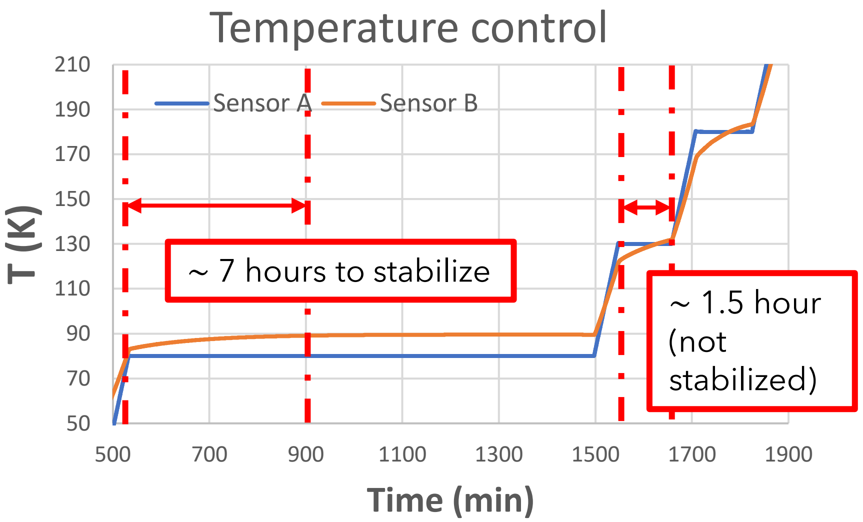
The ANAIS+ Project: preliminary tests

Goals of first tests:

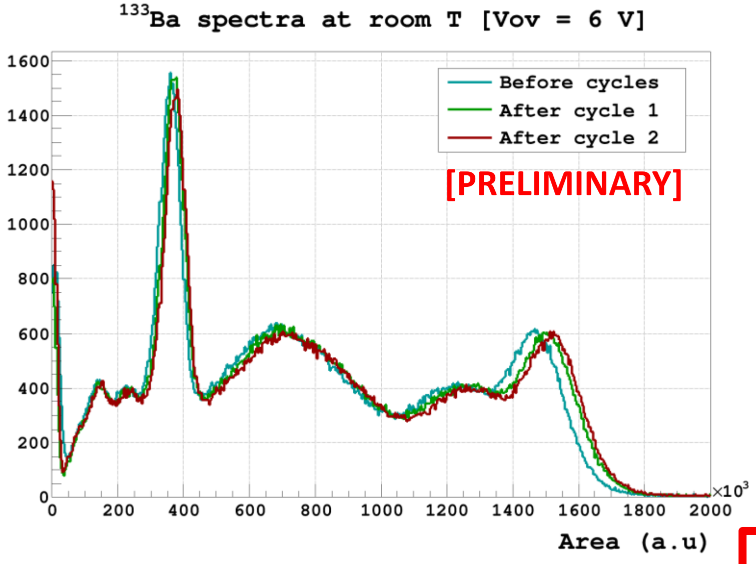
✓ Study the cooling system response including the crystal thermal charge at different temperatures down to 100 K.

✓ Test the NaI / NaI(Tl) mechanical response under thermal cycles.

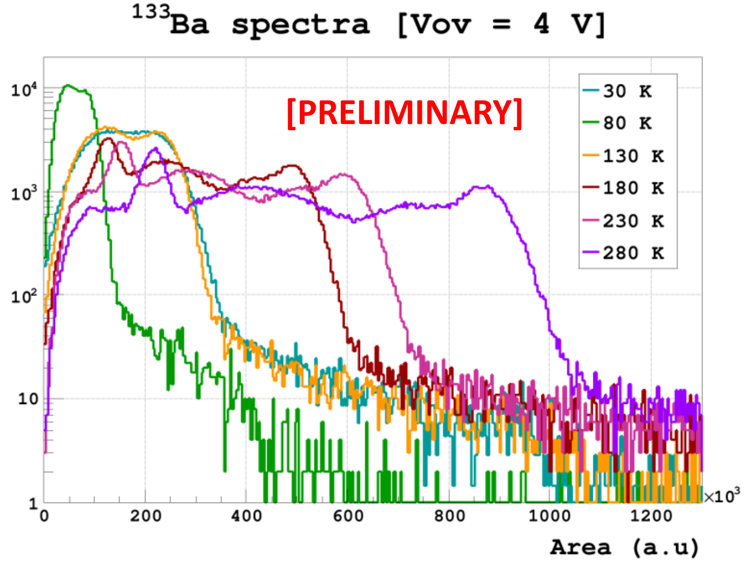
✓ Study the light collection in a wider range of temperatures (from room temperature to ≈30 K).



The stabilization of Sensor B temperature takes several hours (depending on the temperature). More time is needed for the correct stabilization of the bulk cristal.



The first crystal tested in two thermal cycles seems to be undamaged.



We oberved the loss of LC when lowering the T. Possible contributions of the reduction of LY in NaI(Tl) and the emission spectra shifting to wavelengths where the SiPMs are less sensitive.

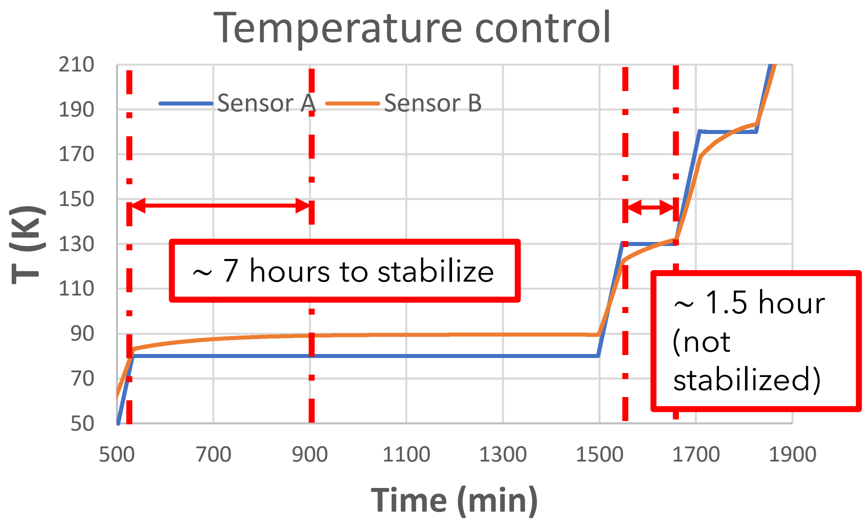
The ANAIS+ Project: preliminary tests

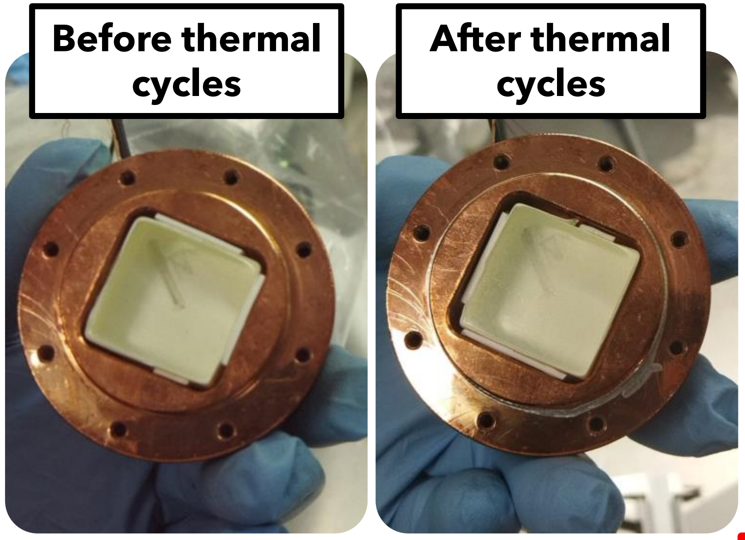
Goals of first tests:

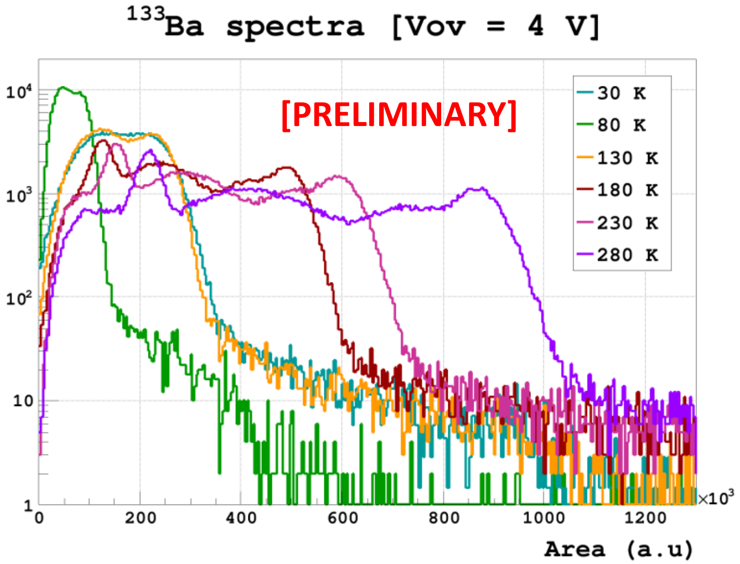
✓ Study the cooling system response including the crystal thermal charge at different temperatures down to 100 K.

✓ Test the NaI / NaI(Tl) mechanical response under thermal cycles.

✓ Study the light collection in a wider range of temperatures (from room temperature to ≈30 K).







The stabilization of Sensor B temperature takes several hours (depending on the temperature). More time is needed for the correct stabilization of the bulk cristal.

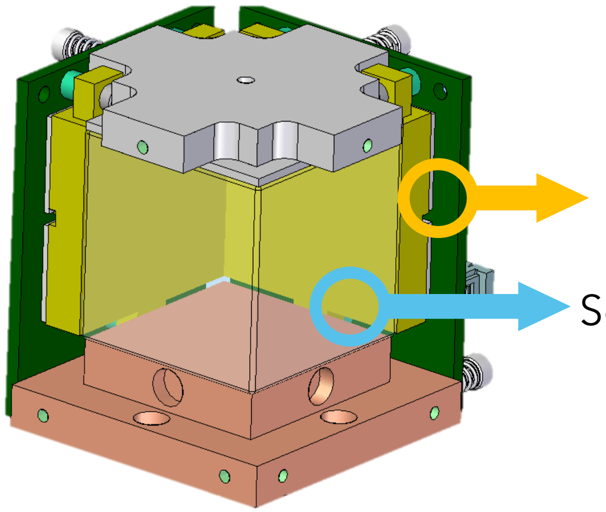
The first crystal tested in two thermal cycles seems to be undamaged.

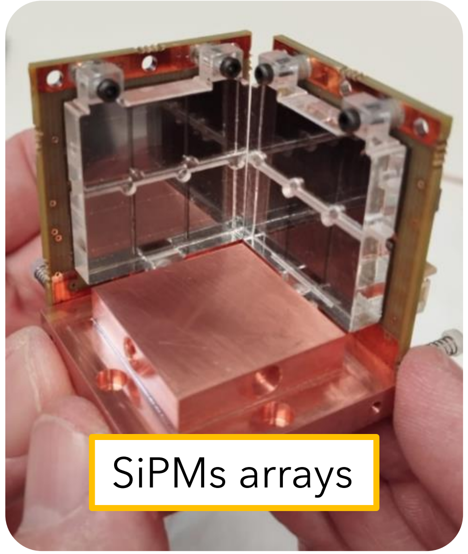
We oberved the loss of LC when lowering the T. Possible contributions of the reduction of LY in NaI(Tl) and the emission spectra shifting to wavelengths where the SiPMs are less sensitive.

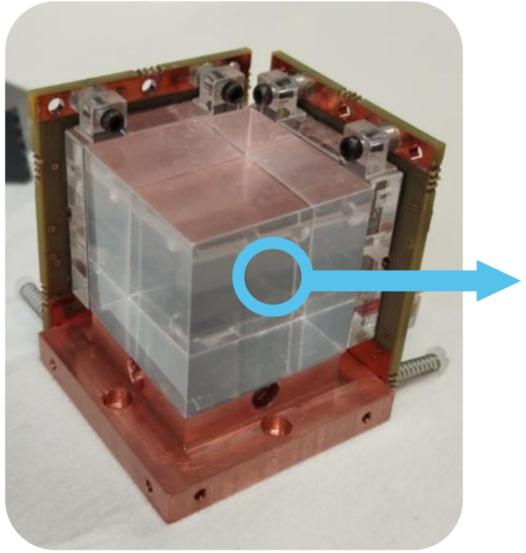
The ANAIS+ Project: first prototype

Design and construction of the first ANAIS+ prototype:

- SiPMs have been designed and produced at LNGS (A.Razeto and I.Kochanek):
  - Arrays of 6 SiPMs in each side of the housing with one channel (sum) output → 4 sides.
  - PMMA pieces to protect the SiPMs bonding wires.
- The prototype has been tested in the LNGS during last week.



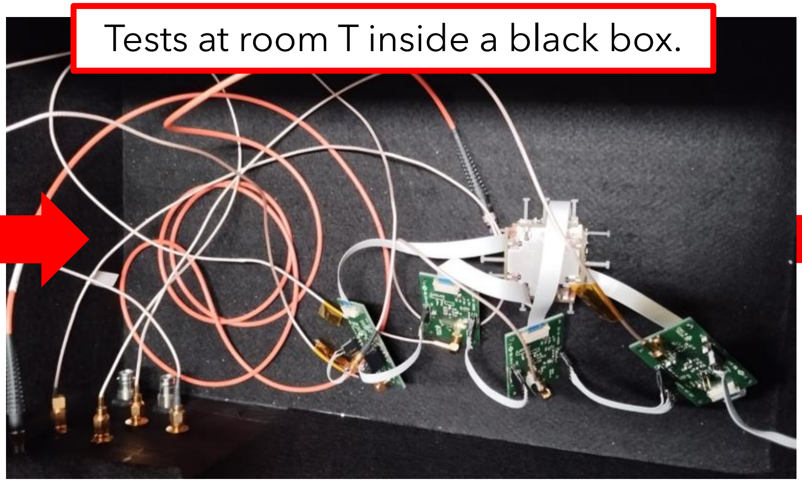




The ANAIS+ Project: first prototype

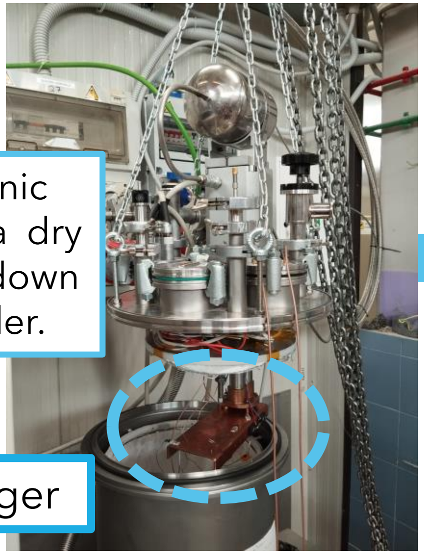
Operational tests at LNGS with the set-up completly assembled (4 SiPMs arrays)

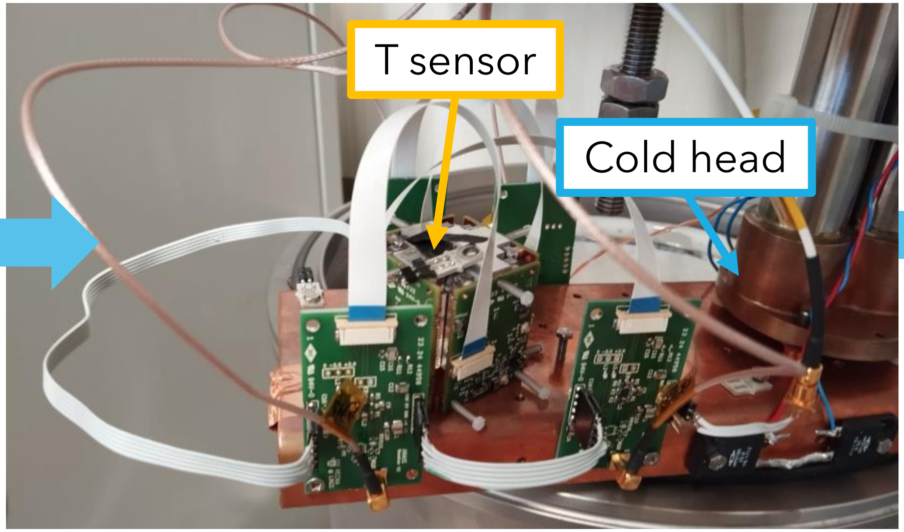
Tests at room T inside a black box.

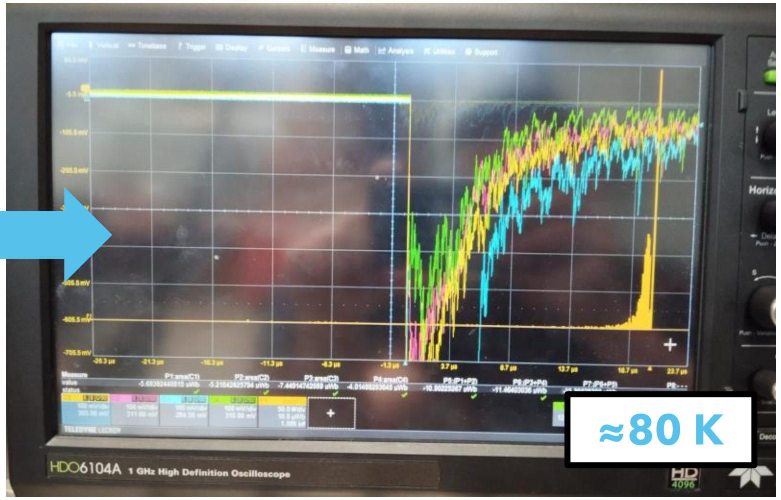


Scintillation pulse for each SiPM array:

Tests at cryogenic temperatures in a dry cryostat cooled down with a cryocooler.

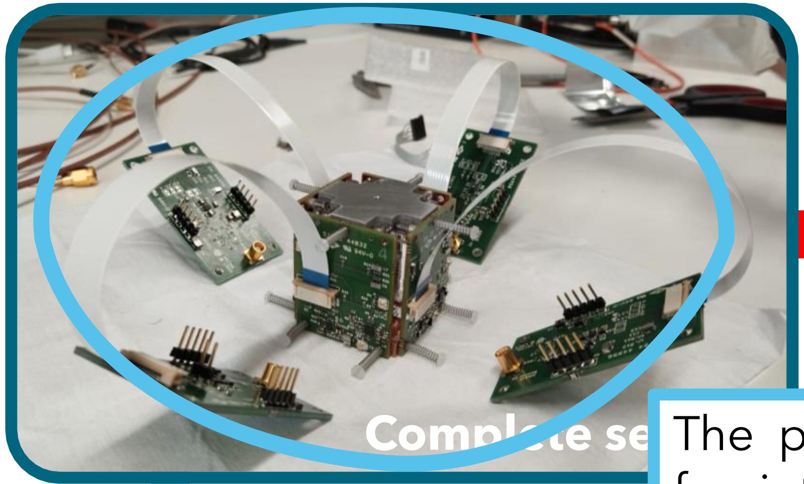


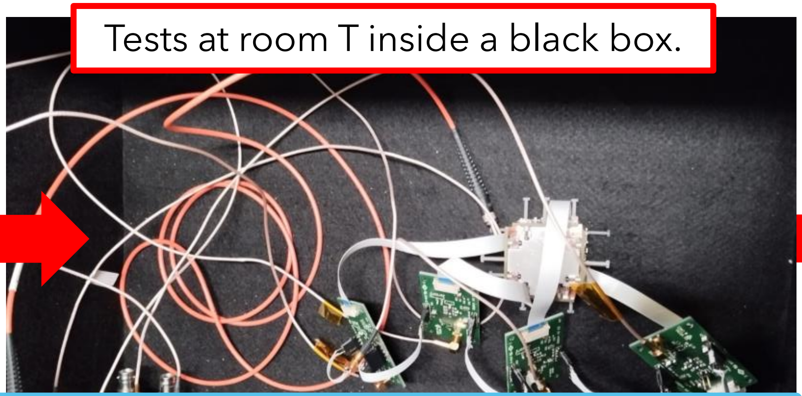




The ANAIS+ Project: first prototype

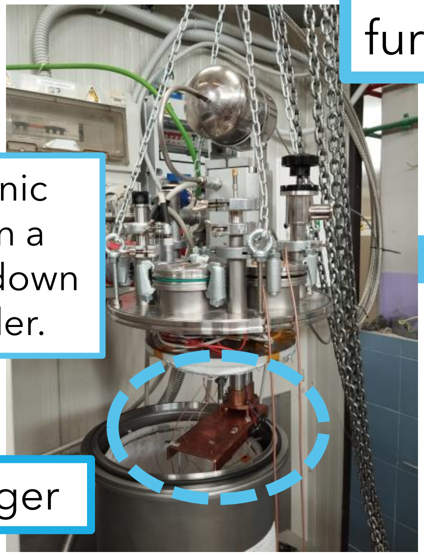
Operational tests at LNGS with the set-up completly assembled (4 SiPMs arrays)

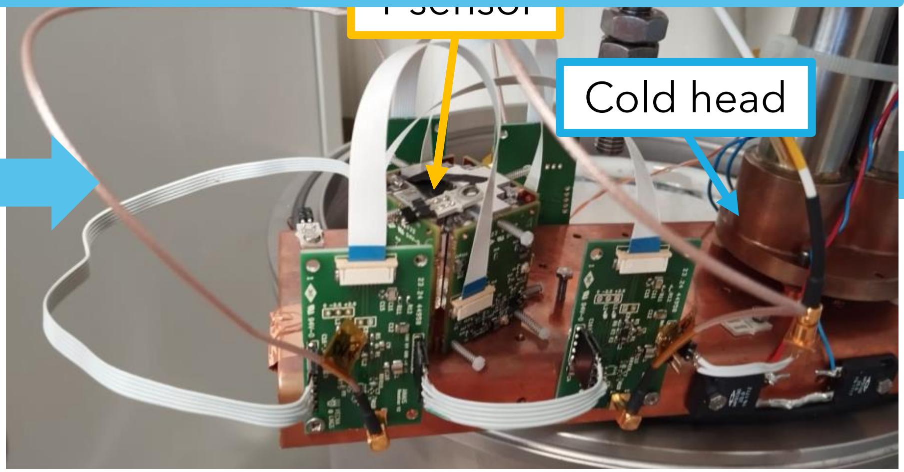




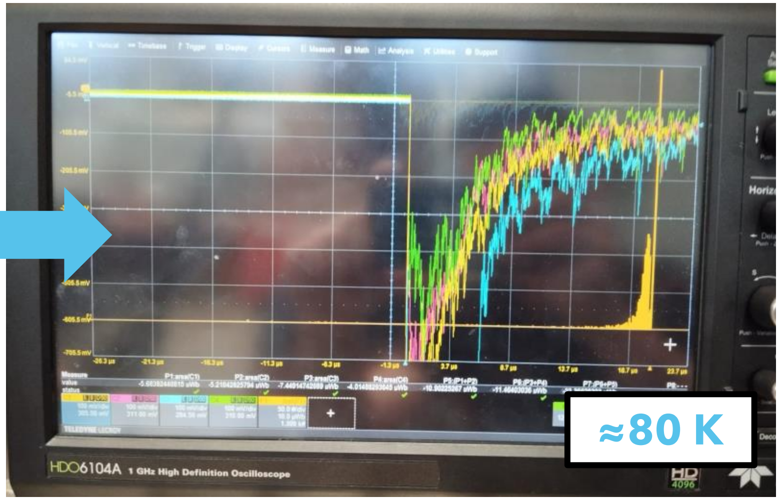
The prototype has been sent to Zaragoza for integrating the scintillator crystals and further testing at the cryogenic facility.

Tests at cryogenic temperatures in a cryostat cooled down with a cryocooler.





Scintillation pulse for each SiPM array:



The ANAIS+ Project: future work

Collaboration between Universidad de Zaragoza - CIEMAT - LNGS

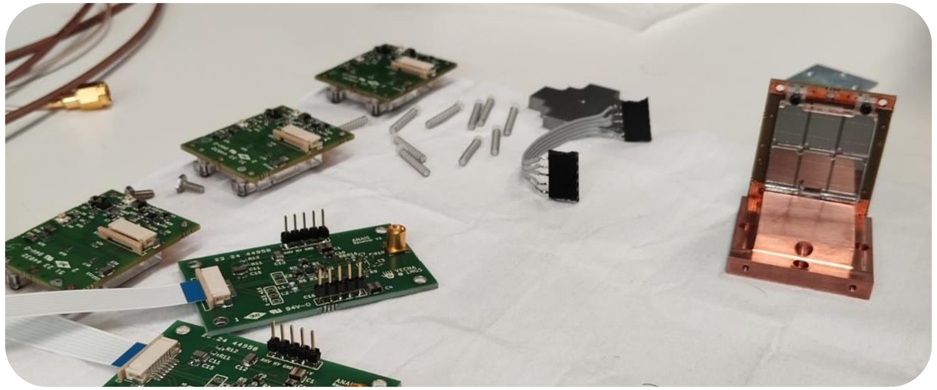
Short/mid term goals of ANAIS+:

Reduction of the energy threshold:

- Design and production of SiPMs specifically prepared to operate at low temperatures for future prototypes.

Reduction of the background level:

- Testing the ANAIS+ prototype in a liquid Ar tank:
  - Acting as thermal bath for stabilizing the temperature
  - Enabling the operation inside a 4π active veto.
- Collaborating in the production of high radiopurity NaI crystals to minimize internal background contributions (^{40}K, ^{210}Pb).



SiPMs and electronics developped at LNGS.

CIEMAT cryostat facility.

Summary and next steps

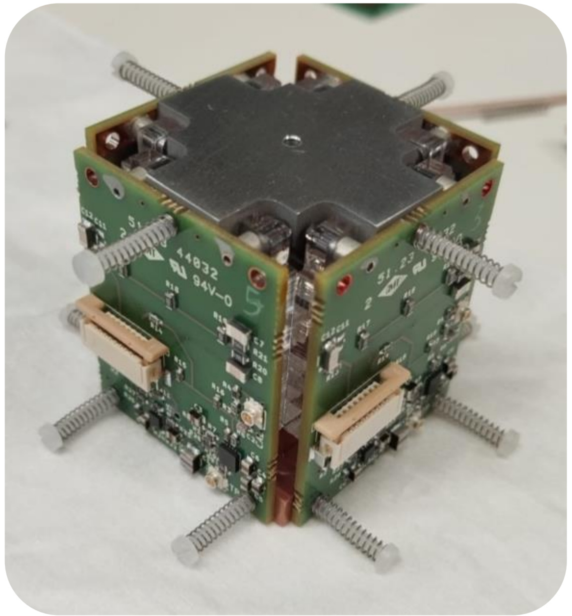
- The use of SiPMs coupled to pure NaI operating at cryogenic temperatures could lead to an important reduction on the energy threshold, increasing the sensitivity of these experiments and allowing the exploration of DM candidates and other interesting process.

- ANAIS+ is one of the R&D projects working in this direction.

- The SiPMs designed in LNGS have been tested and the complete first ANAIS+ prototype will be soon assembled in Zaragoza. We will test pure NaI crystals and its response at low temperatures to evaluate the gain in light collection and achievable energy threshold.

- More radiopure crystals are needed to reach the ANAIS+ goals. Work is ongoing.

- Tests at LSC where we will check the performance of the detector immersed in a liquid Ar tank, that in a second step could be instrumented for serving as active veto system.



Thank you!

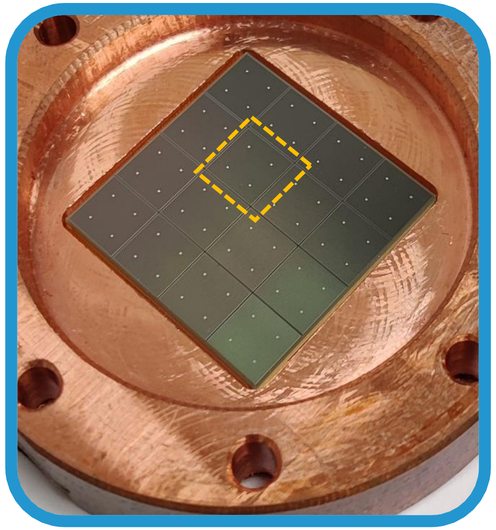
Funded by MCIN/AEI/10.13039/501100011033 under grant PID2022-138357NB-C21 and Gobierno de Aragón (Departamento de Educación, Ciencia y Universidades)

Collaborative support from MoU LSC@LNGS and PPCC-AstroHep

Back-up

SiPMs

SiPM overview



Silicon photomultiplier

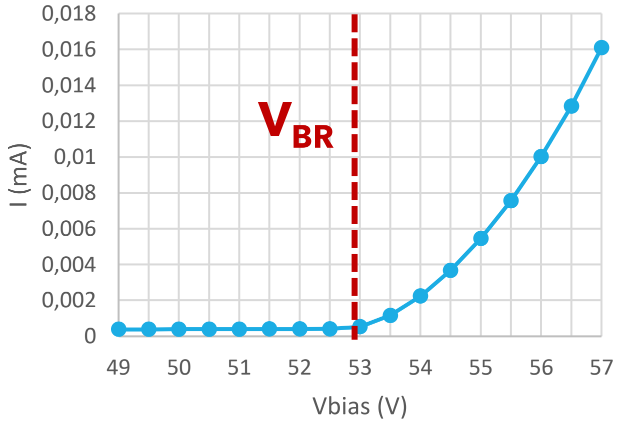
Each SiPM = array of multiple pixels (~ μm)

↓

Single-photon avalanche diodes (SPAD)

SINGLE PHOTOELECTRON RESPONSE (SER)

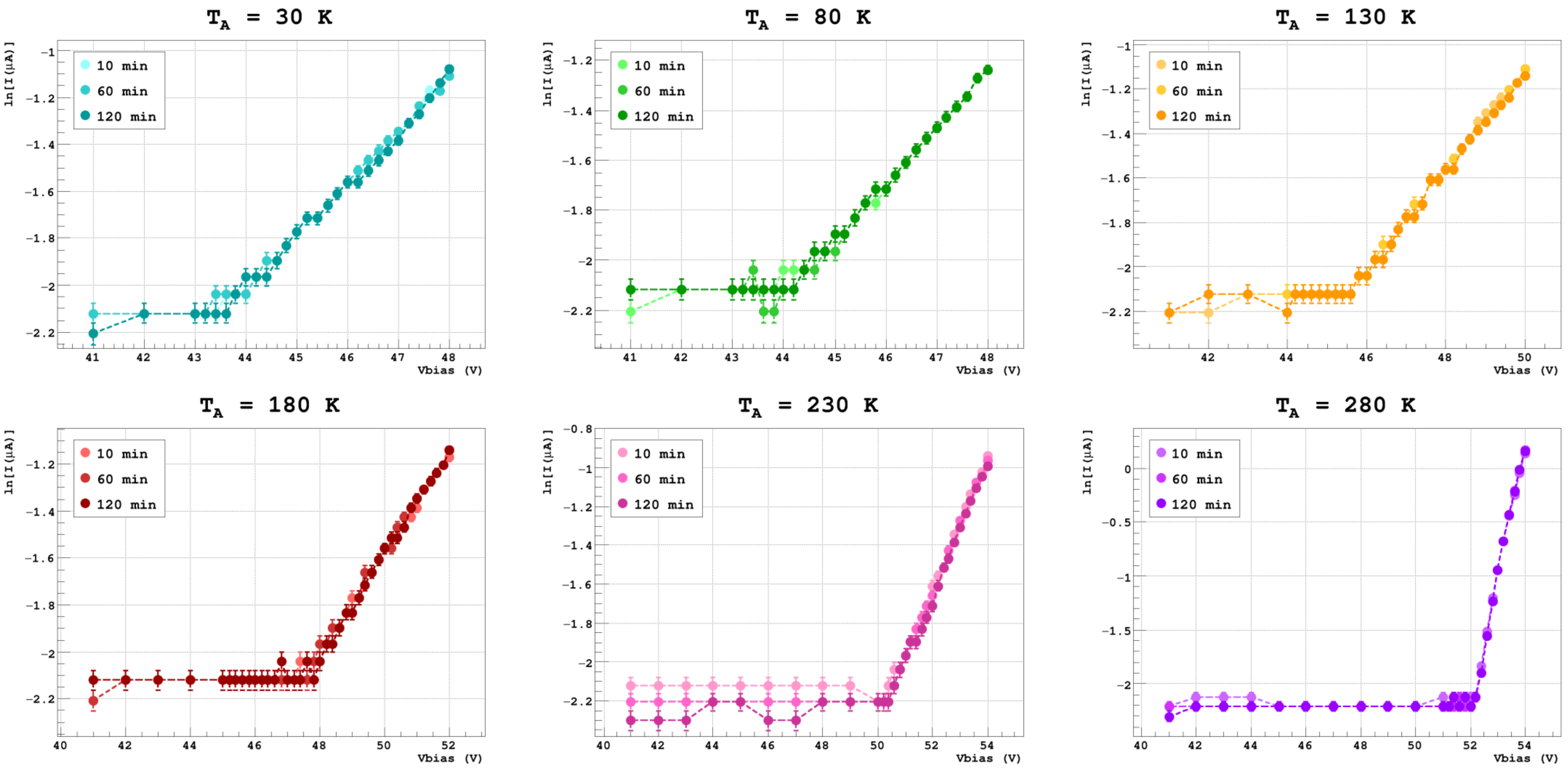
- Incident photon → e^- - hole pair
- Bias Voltage > Breakdown Voltage (V_{BR})



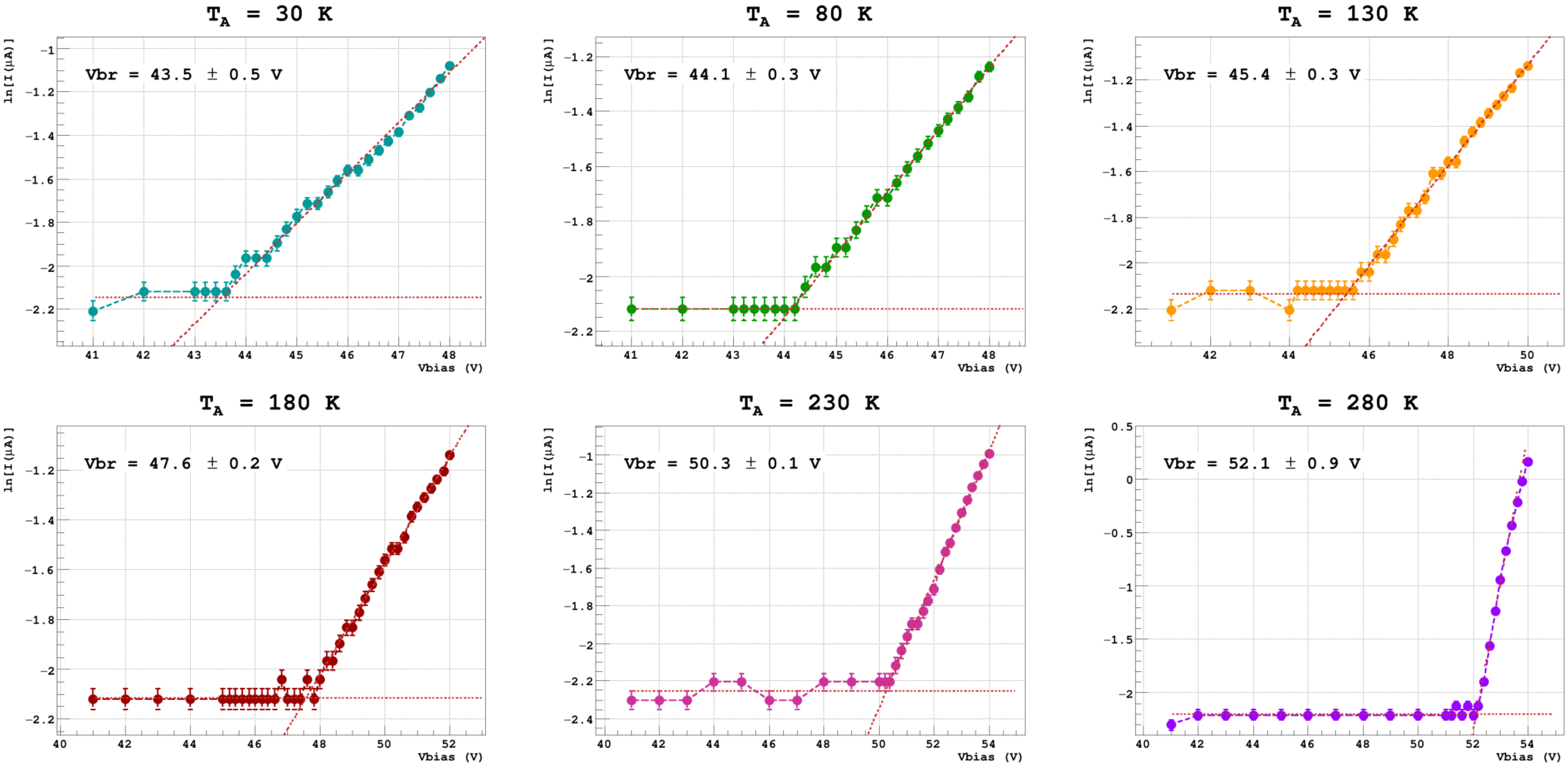
$$V_{OV} = V_{bias} - V_{BR}$$

- Avalanche → voltage pulse of a certain area
- Photoelectron area is ∝ Gain ∝ Vov

I-V stabilization

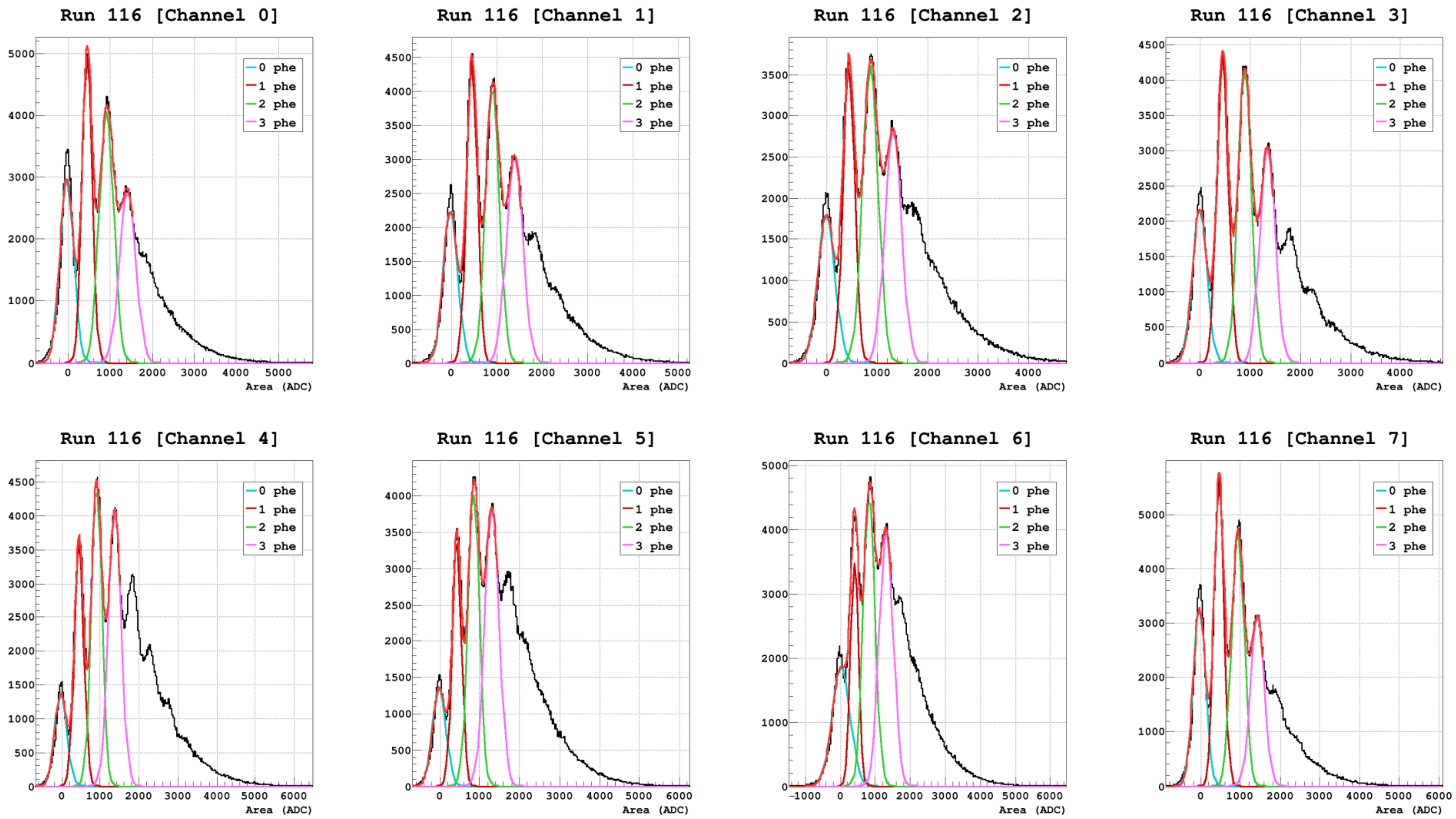


I-V Vbr

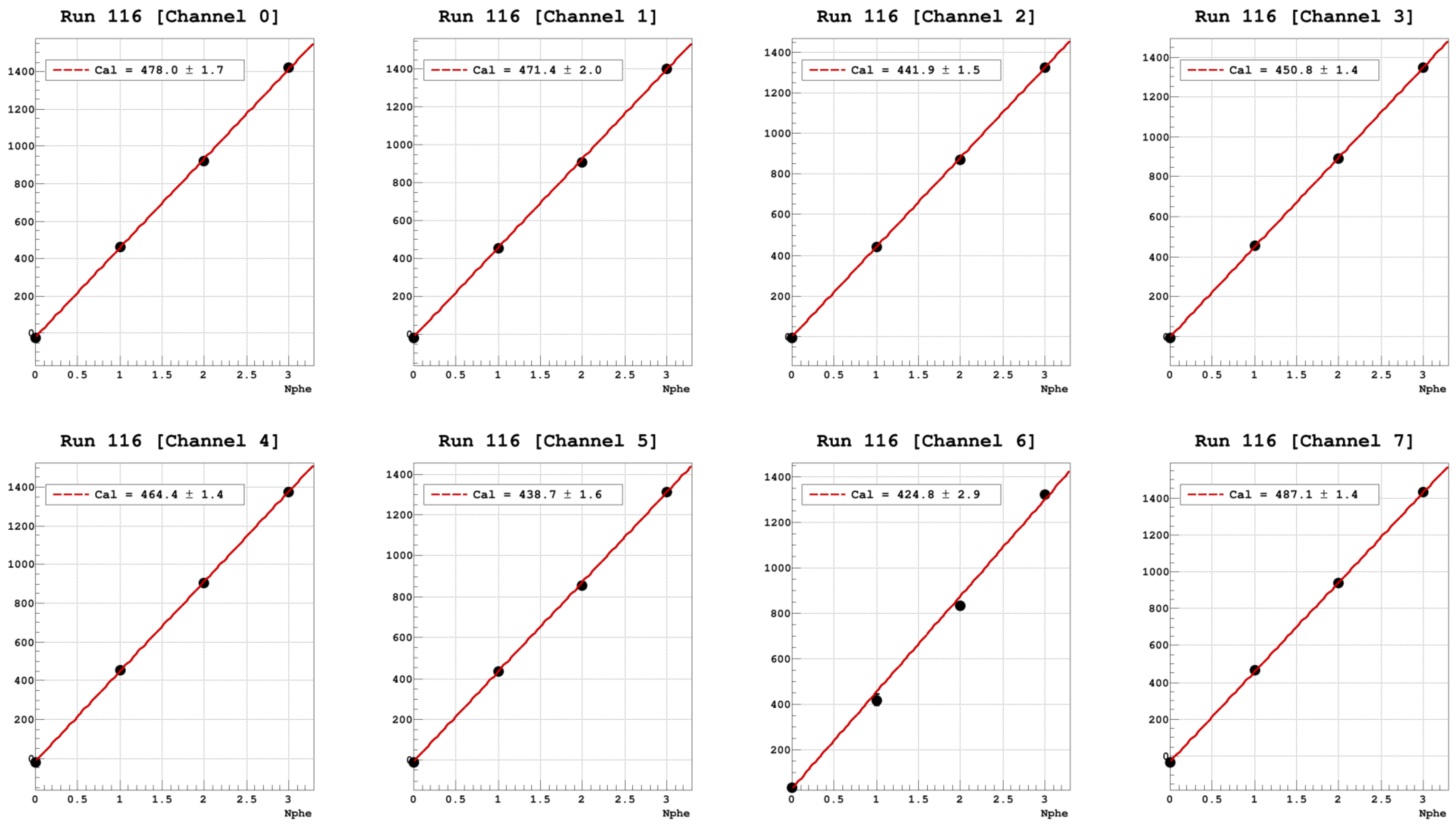


T_A = 30 K
Vbr = 43.5 ± 0.5 V
T_A = 80 K
Vbr = 44.1 ± 0.3 V
T_A = 130 K
Vbr = 45.4 ± 0.3 V
T_A = 180 K
Vbr = 47.6 ± 0.2 V
T_A = 230 K
Vbr = 50.3 ± 0.1 V
T_A = 280 K
Vbr = 52.1 ± 0.9 V
ln[I (μA)]
Vbias (V)

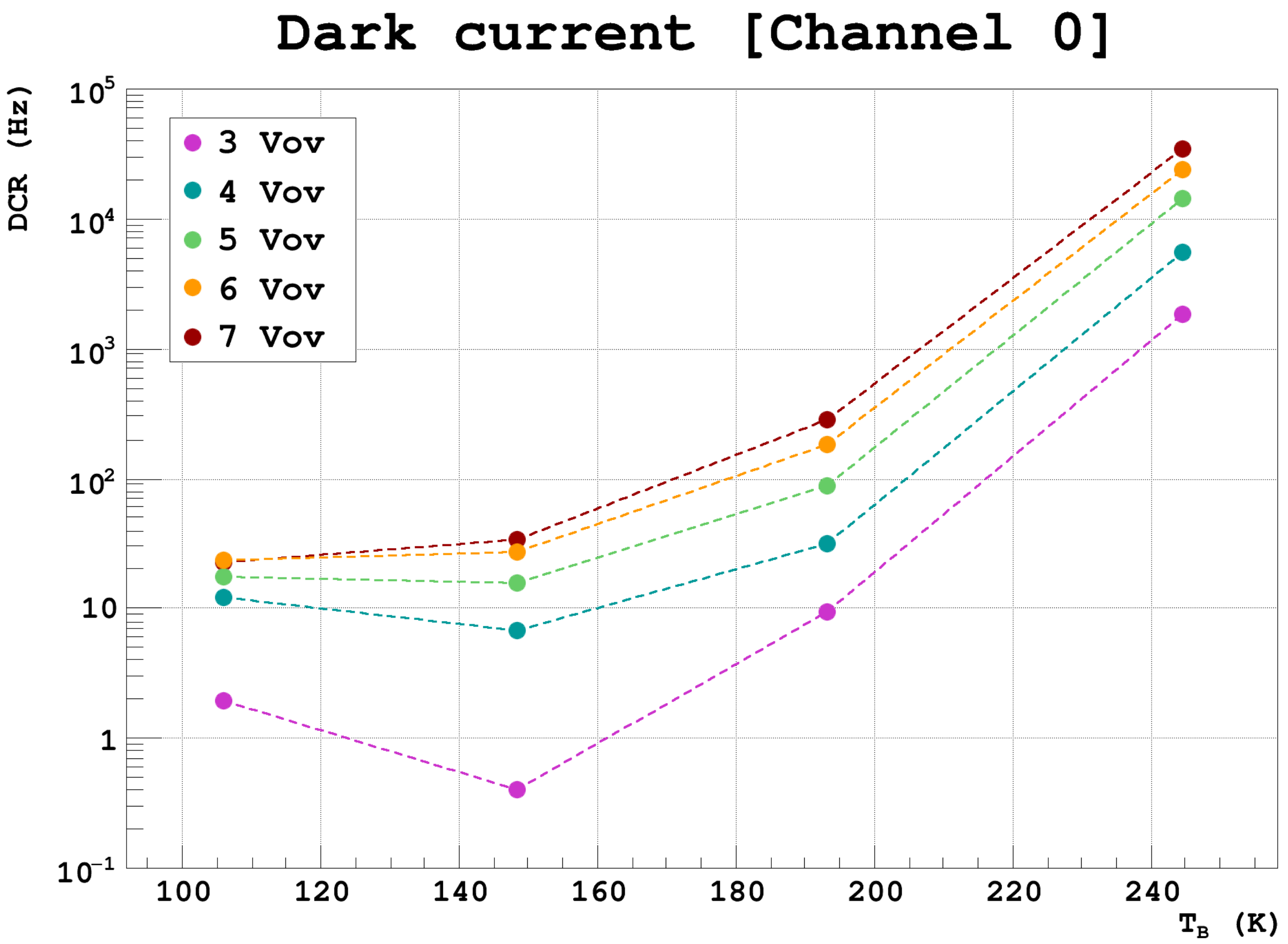
SER calibration



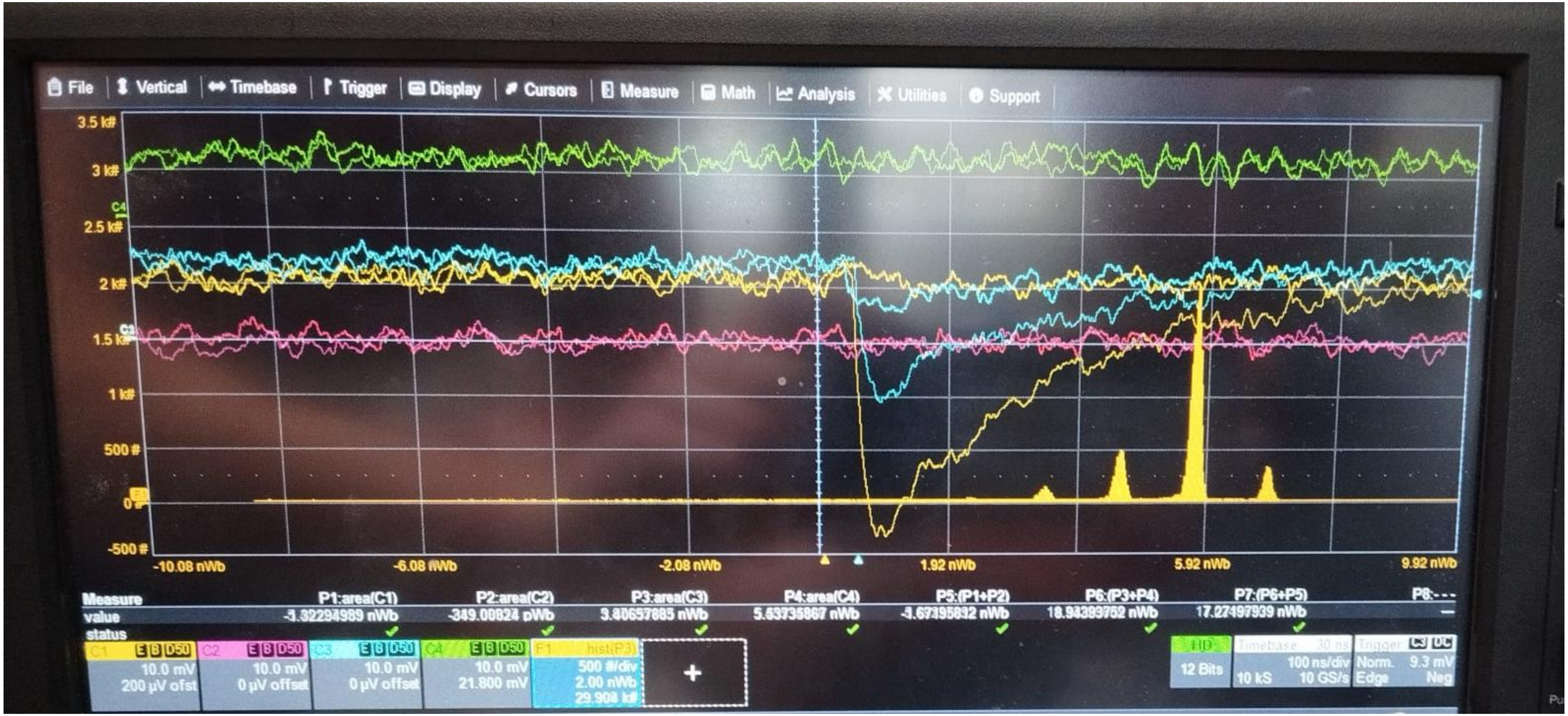
SER calibration



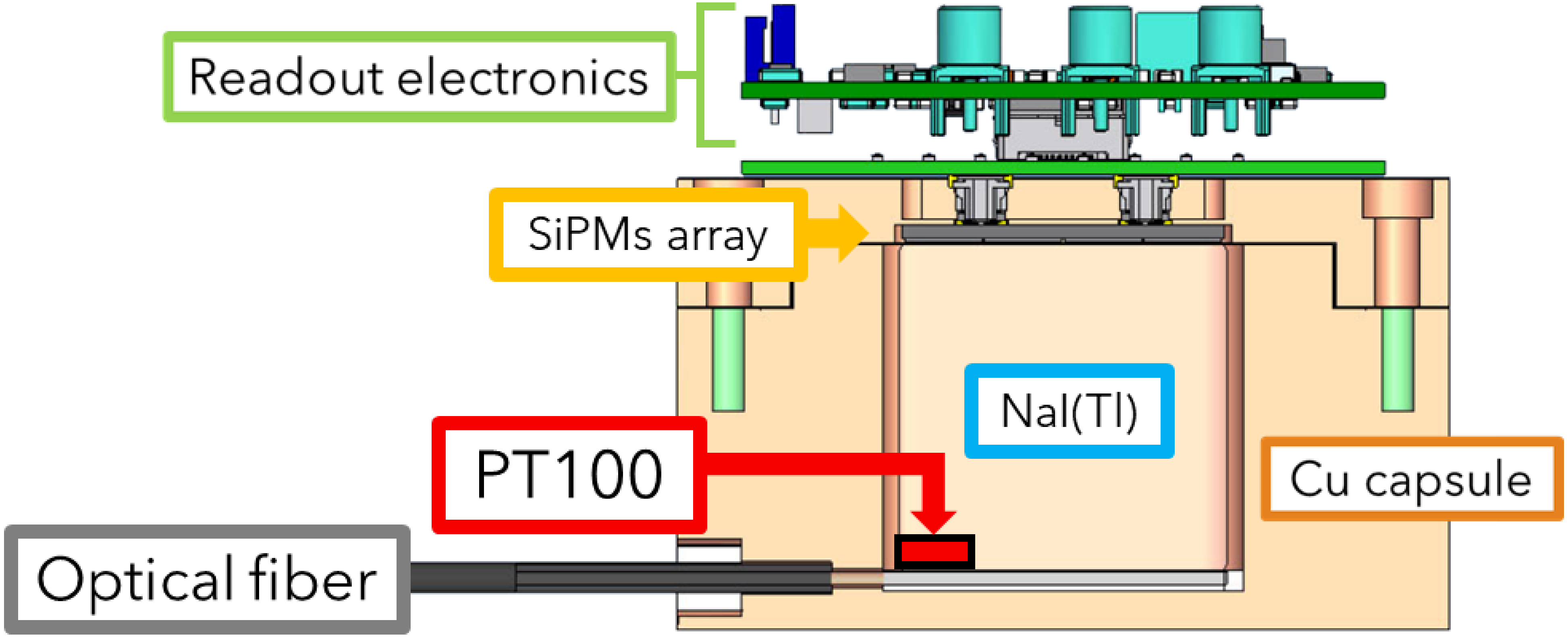
DCR stimation



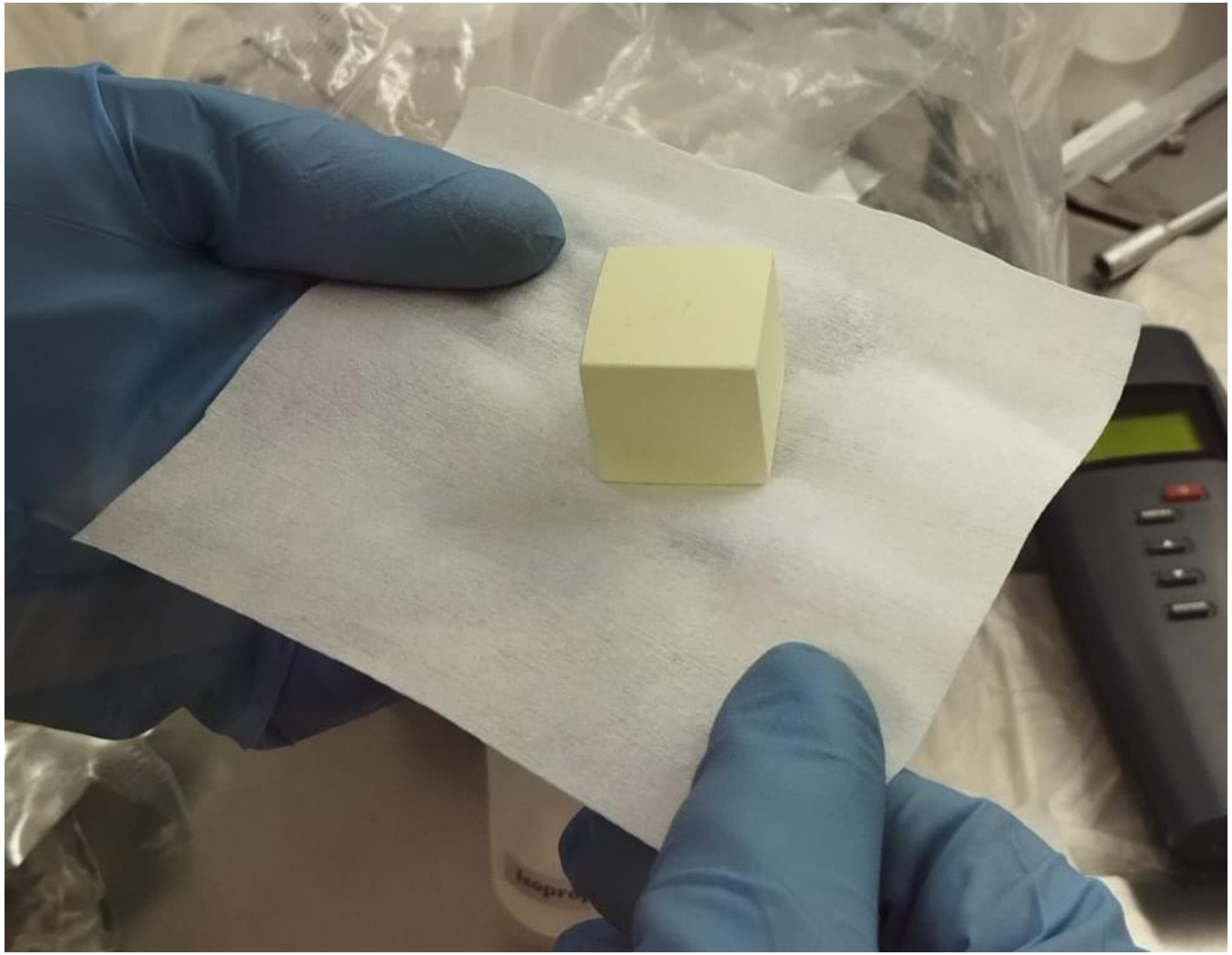
Finger plot first prototype



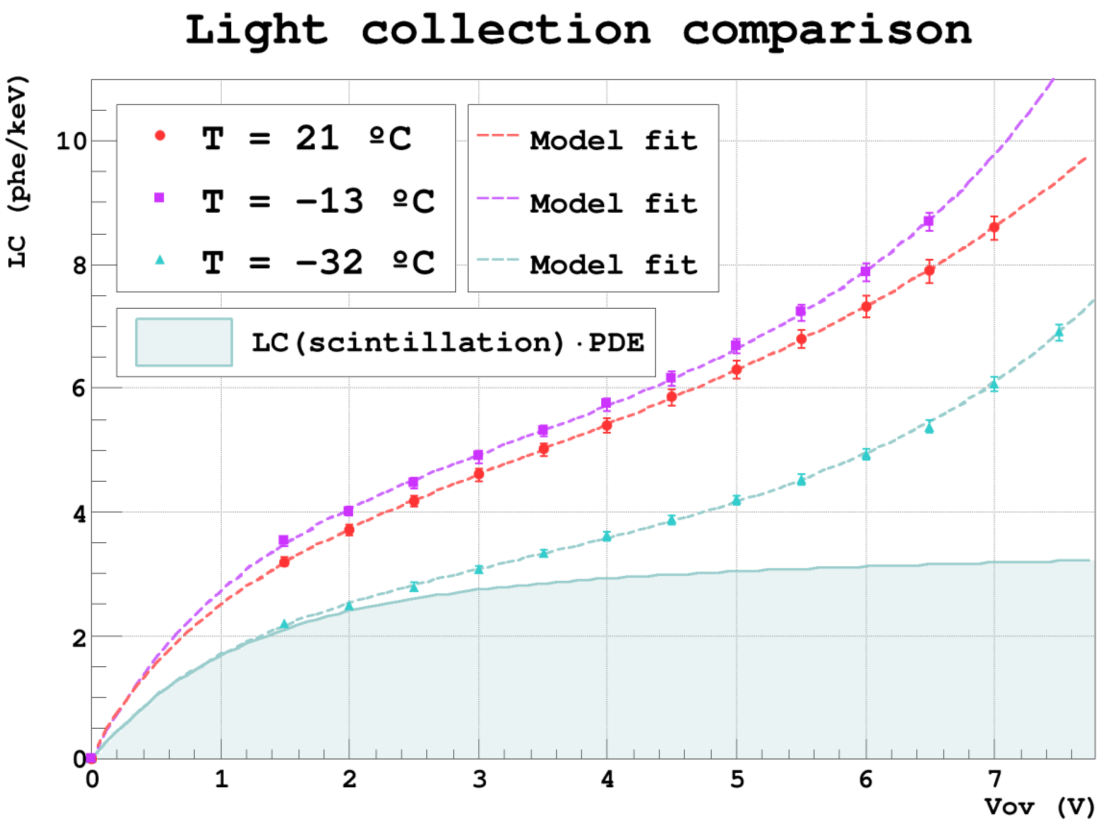
Test set-up design

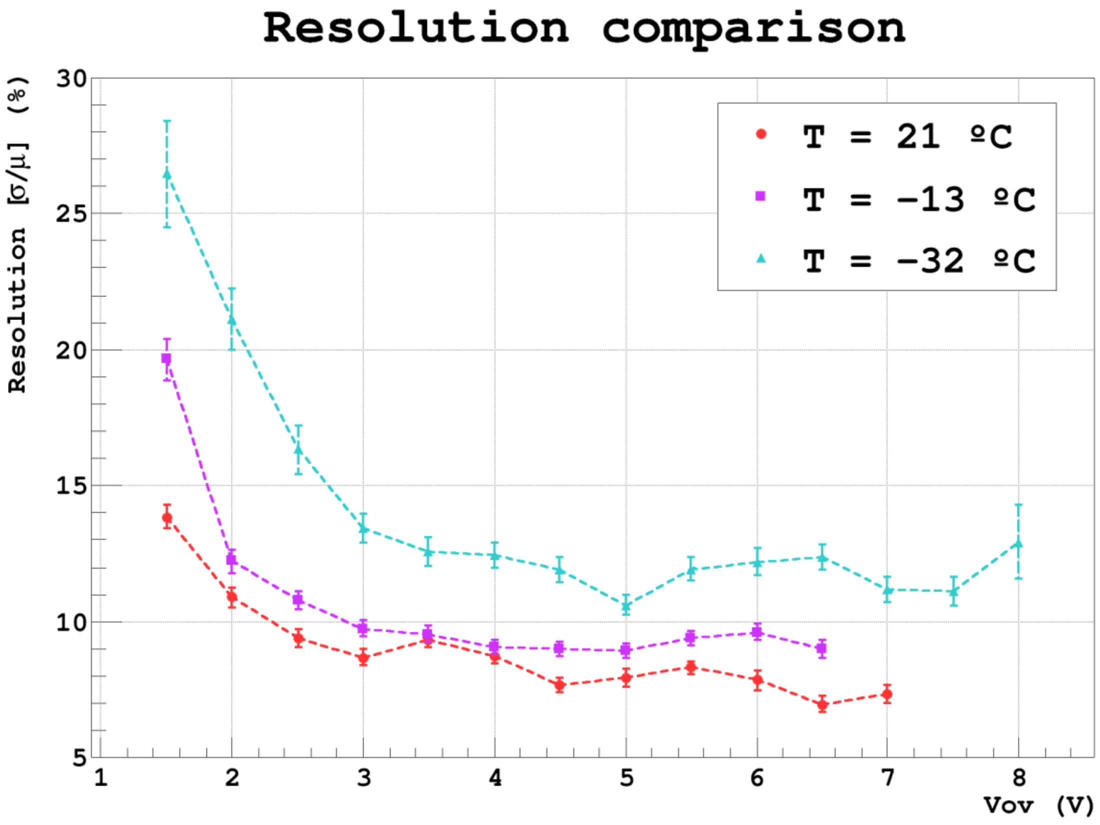


Damaged NaI(Tl) crystal



LC vs Vov [first tests]



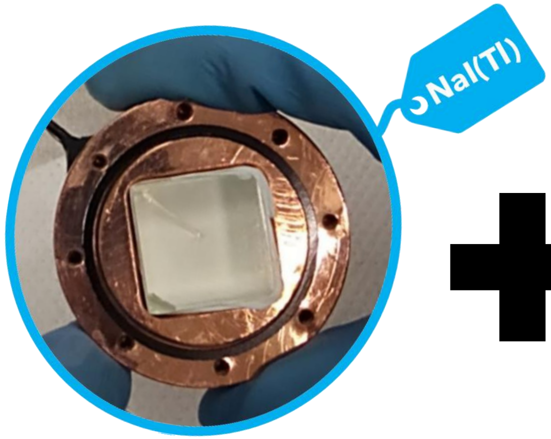


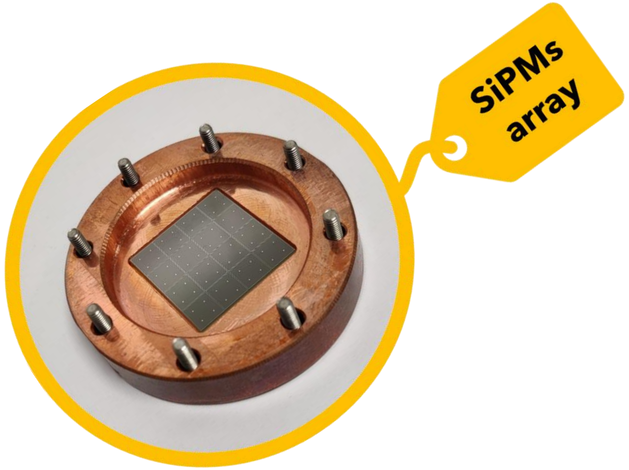
Hamamatsu SiPM properties

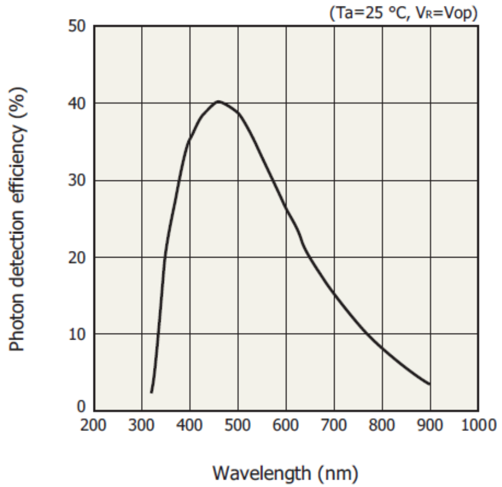
ANAIS+ test set-up:

Scintillator crystal: NaI(Tl)/NaI 1″ cube.

SiPMs array: HAMAMATSU S13361-6050AE-04 (25 x 25 mm → 4 x 4 SiPMs)



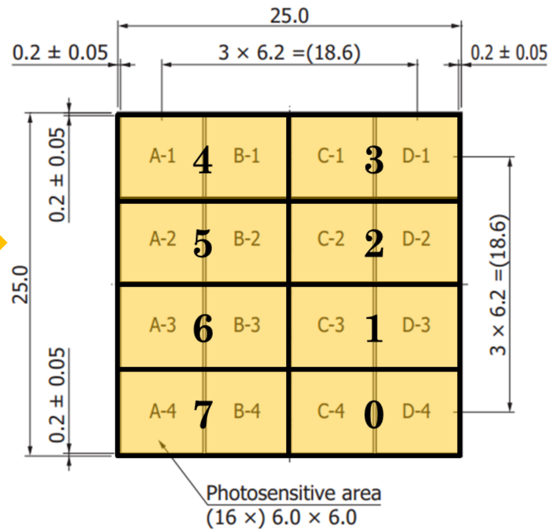




Blue sensitive SiPMs

MPPC characteristics
Fill factor = 74 %
DCR ≈ 2 MHz / SiPM
Epoxy resin window
V_{BD}(room T) = 53 ± 5 V

16 (4x4) SiPMs grouped in 8 readout channels.



The ANAIS+ Project: preliminary tests

Thermal cycle:

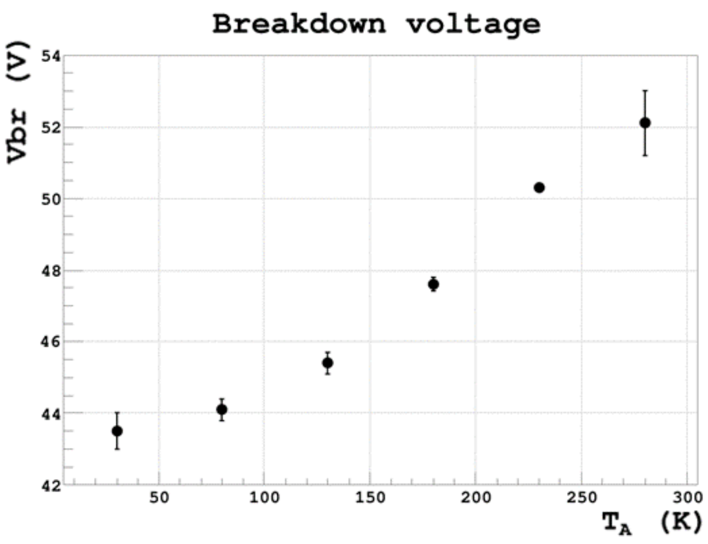
- Stabilization at different temperatures: T_A = 30 K – 280 K, steps of 50 K.

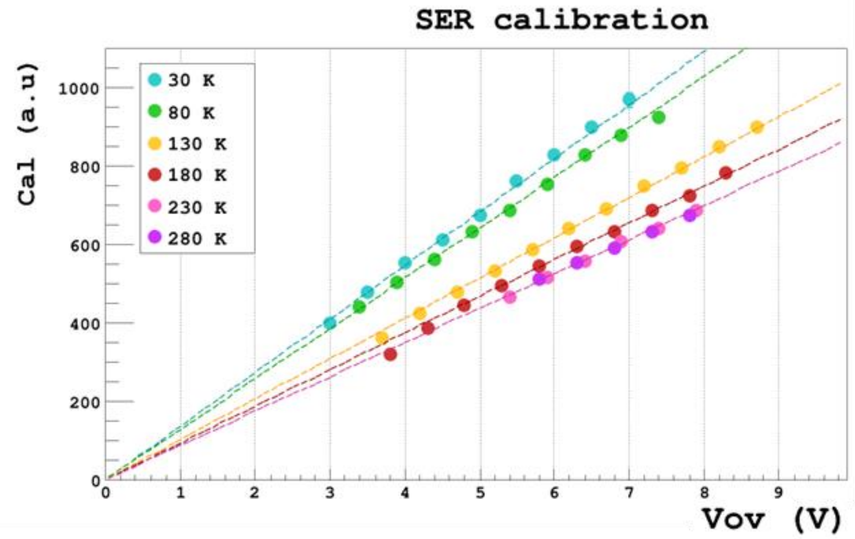
SiPMs characterization:

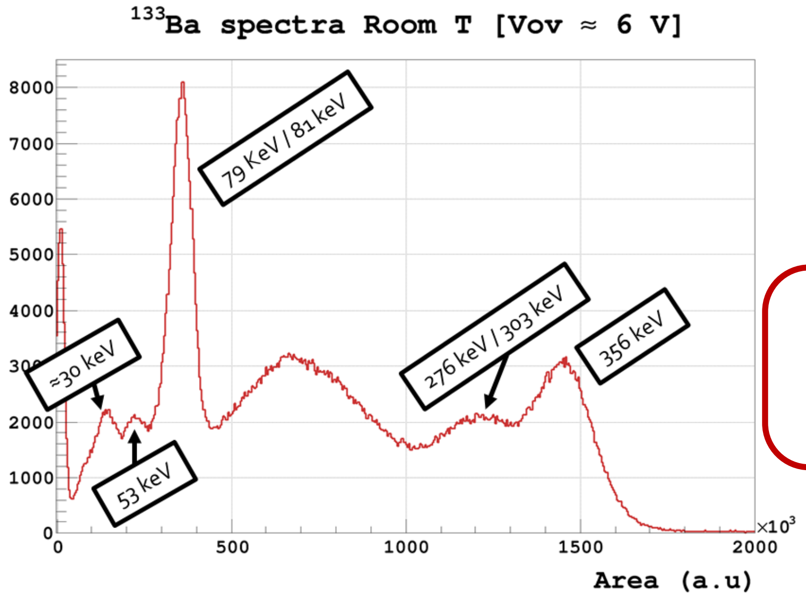
- We measure the V_{BR} at each temperature step.
- We calibrate the single photoelectron response (SER) of each channel for different overvoltages (Vov).

Scintillation measurements:

- Ba-133 spectra at each temperature for a Vov of 4 V.







Change in V_{BR} and SER response for the different temperatures.

Ba-133 spectra at room temperature: identification of the photopeaks, down to ≈30 keV.