Beyond ANAIS-112: ANAIS+

Jaime Apilluelo Allué on behalf of the ANAIS research team

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Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

MultiDark
Multimessenger Approach for Dark Matter Detection

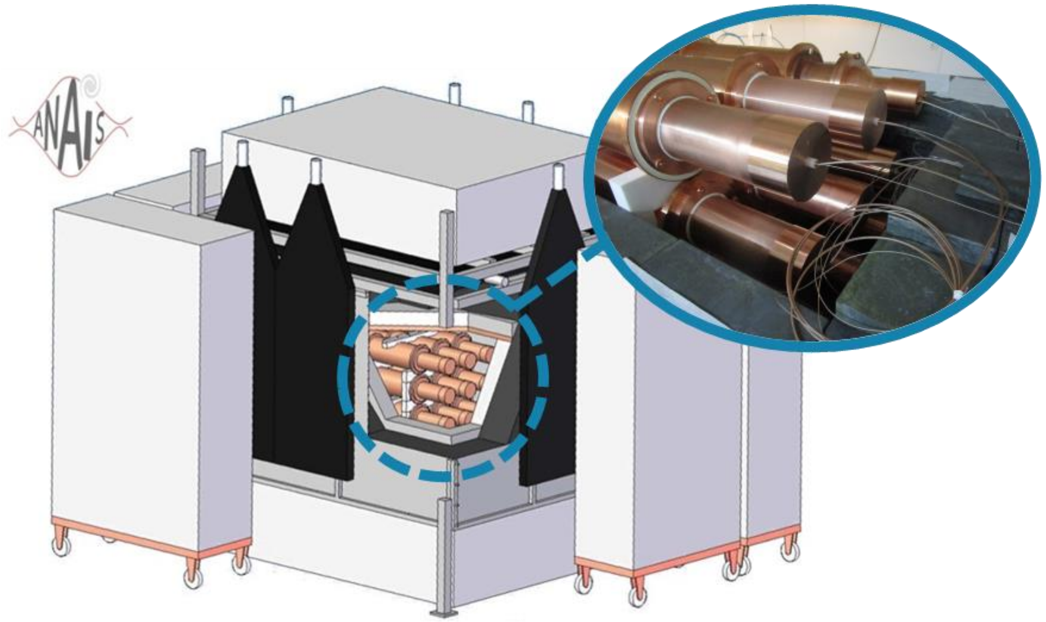
Ministerio de Ciencia e Innovación
Unión Europea
Fondo Europeo de Desarrollo Regional
"Una manera de hacer Europa"
Agencia Estatal de Investigación

Overview

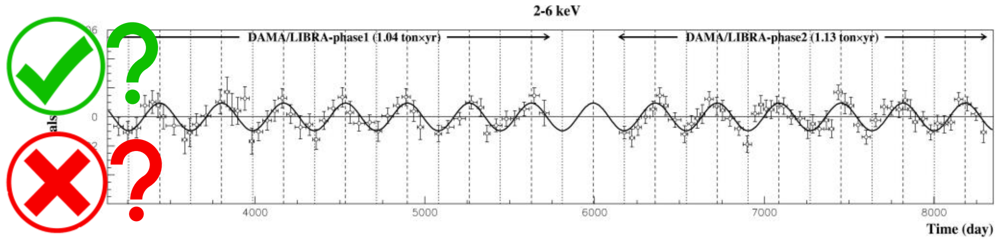
ANAIS-112 EXPERIMENT

Annual Modulation with NaI Scintillators

- ❖ Direct dark matter detection experiment.
- ❖ 9 NaI(Tl) scintallion crystals of 12.5 kg → 112.5 kg.
- ❖ Each crystal is coupled to two high QE PMTs.
- ❖ High light collection: 15 phe/keV.



- ❖ Placed at Canfranc Underground Laboratory.
- ❖ Taking data since 3rd August 2017.
- ❖ GOAL: establishing a model independent test of DAMA/LIBRA results on the annual modulation signal.

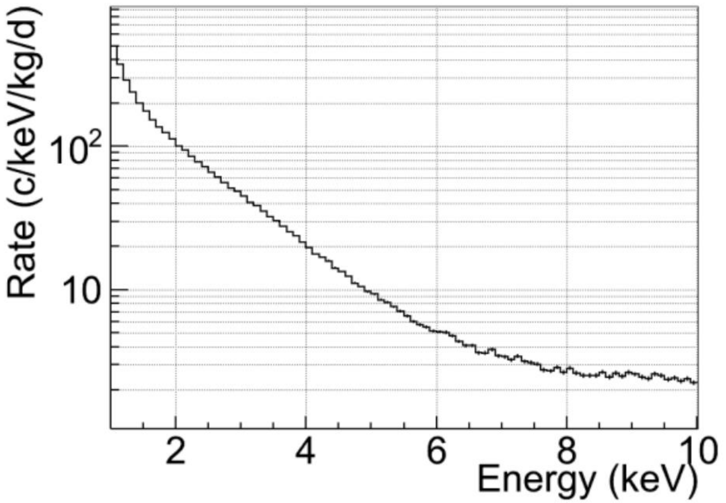


R.Bernabei et al Universe 2018, *4*(11), 116

Same energy region exploration
[1-6] keV and [2-6] keV

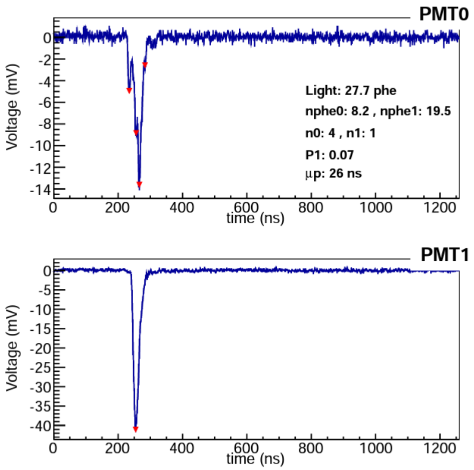
ANAIS-112 EXPERIMENT: background

Noise events population in ANAIS-112

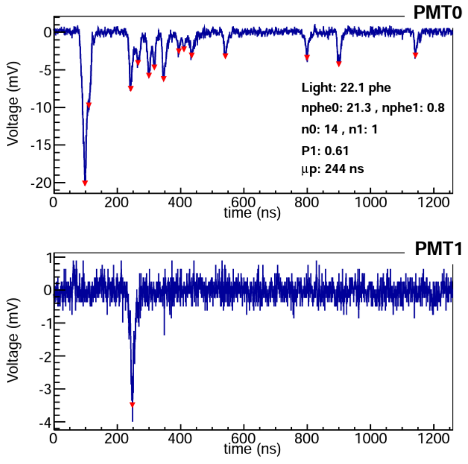


The region of interest is dominated by non-bulk scintillation events.

Blank module: same structure as ANAIS module, but without the NaI(Tl) crystal → used to study the PMTs noise events.



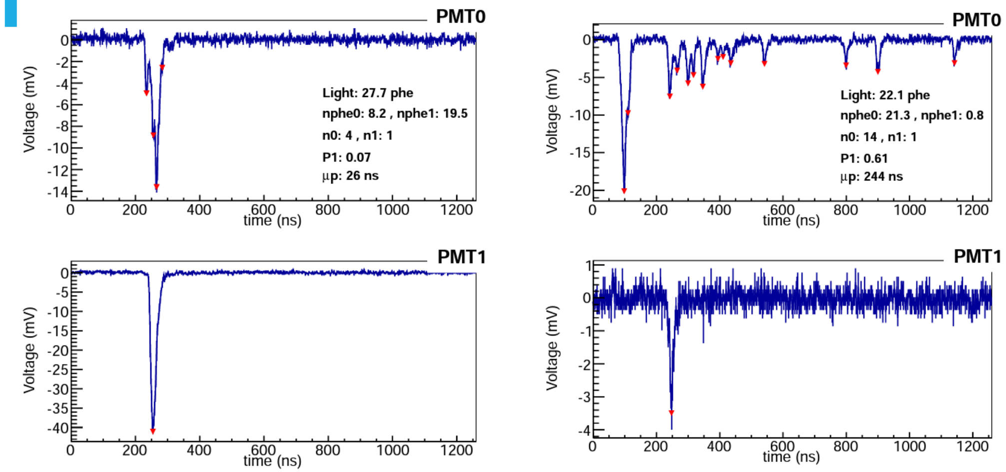
Fast events: non scintillation shape



Asymmetric events: clear different number of photoelectrons in each PMT.

ANAIS-112 EXPERIMENT: background

Easily removed by filtering process



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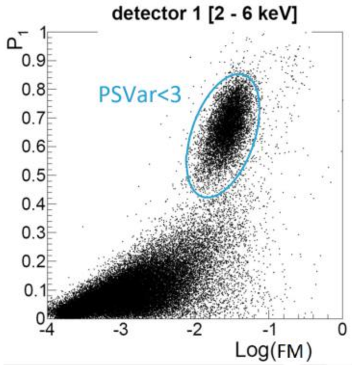
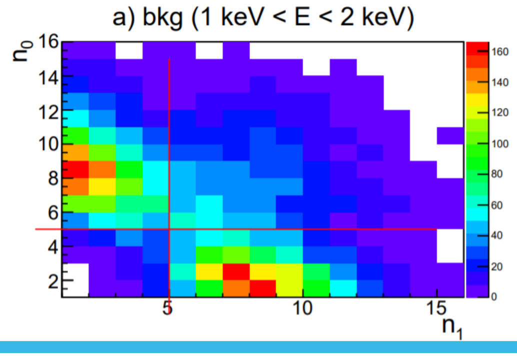
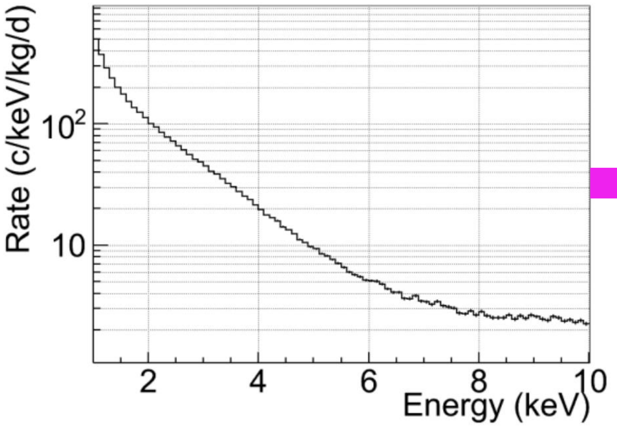
$$P1 = \frac{\sum_{100\,ns}^{600\,ns} A_i}{\sum_{0\,ns}^{600\,ns} A_i} \qquad FM = \frac{\sum_p A_p \cdot t_p}{\sum_p A_p}$$

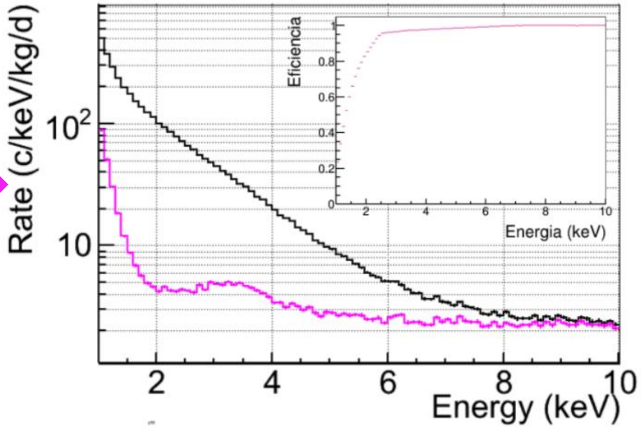
PSVar < 3



Selected events with number of peaks **n0, n1 > 4** in both PMTs.







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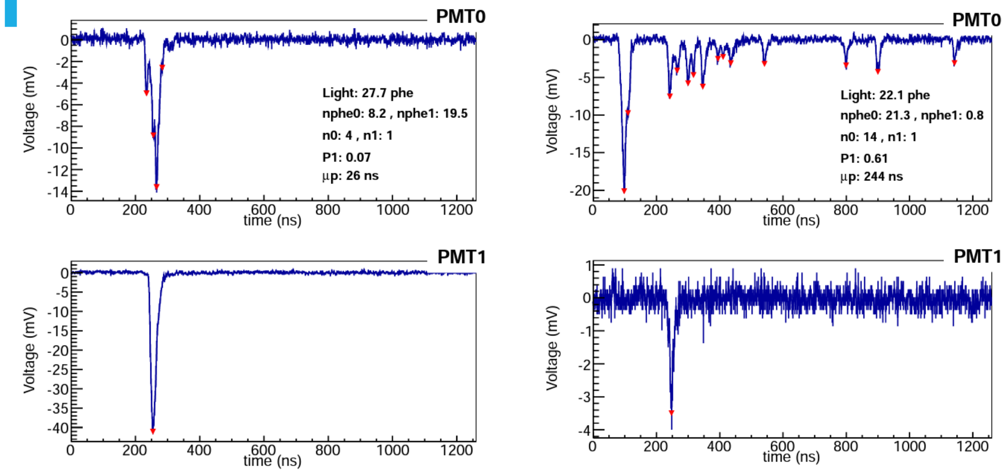

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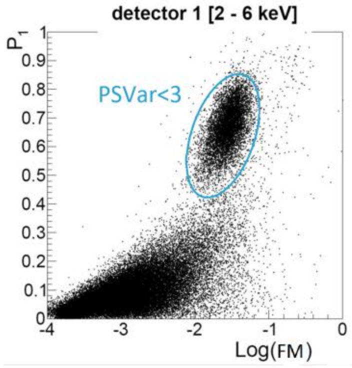

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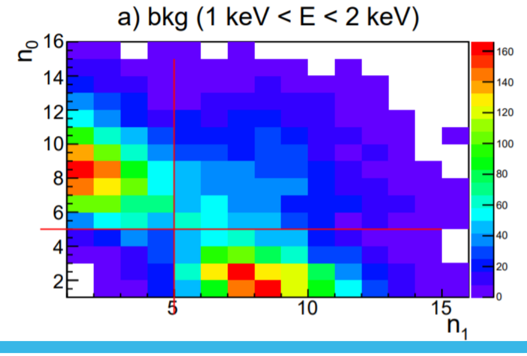
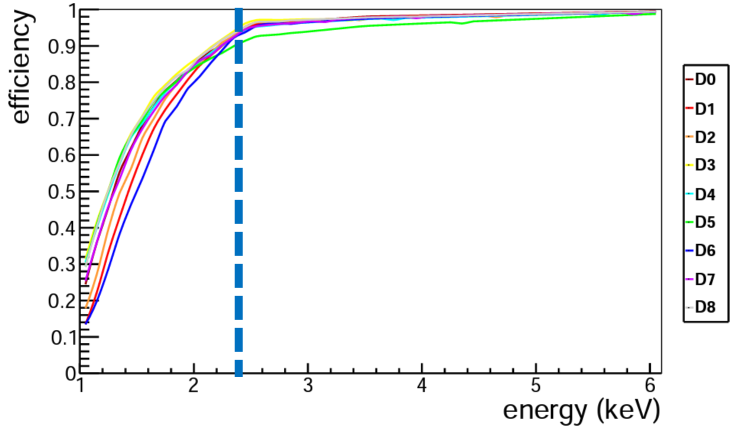


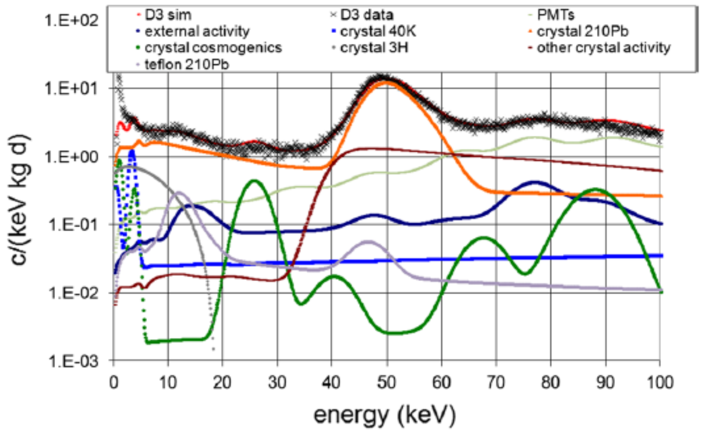


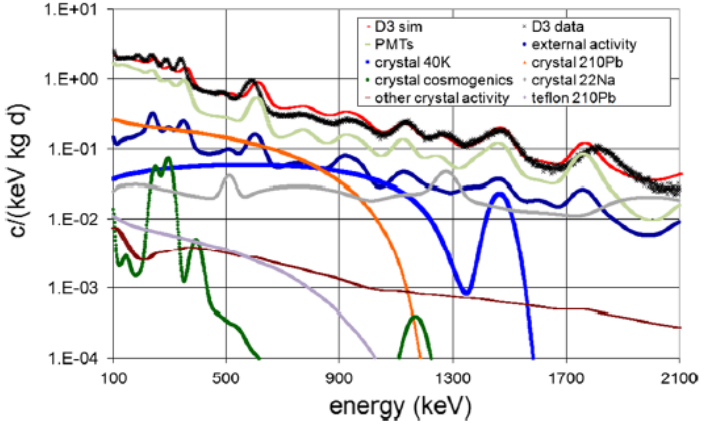
Total efficiency higher than 90% above 2.5 keV.

It is strongly reduced for 1 keV .

ANAIS-112 EXPERIMENT: background

Background model (simulated with Geant4) in good agreement with the overall spectrum.





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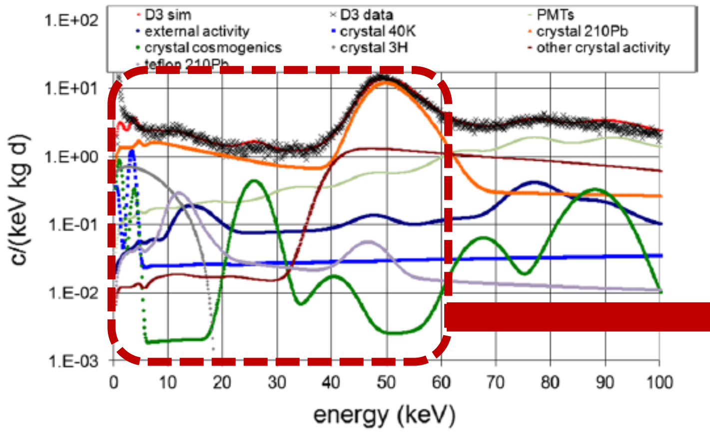

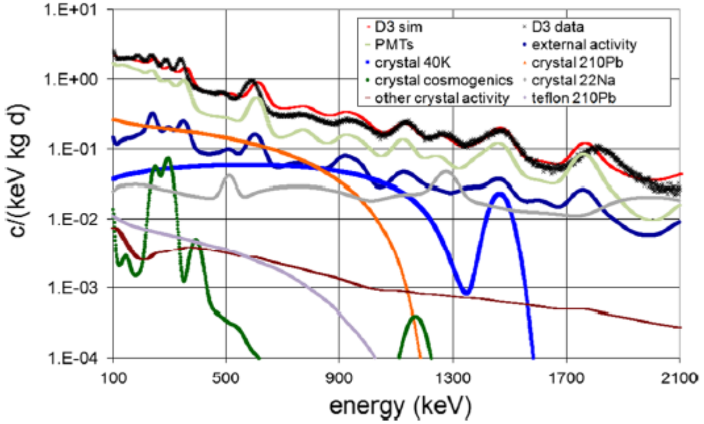

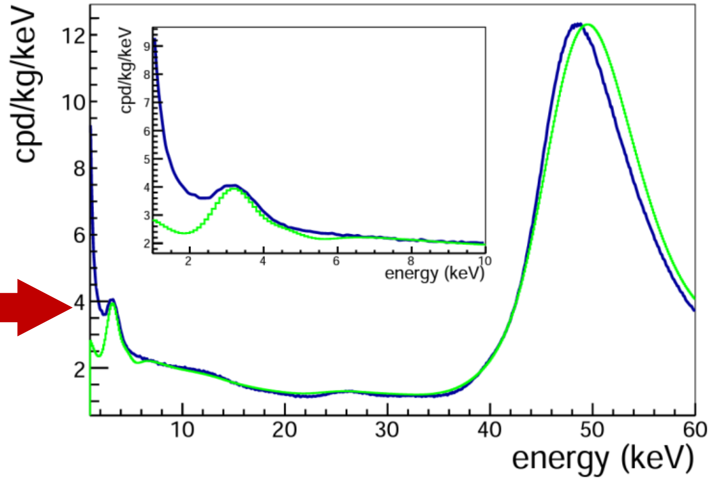

ANAIS-112 data
Simulation data

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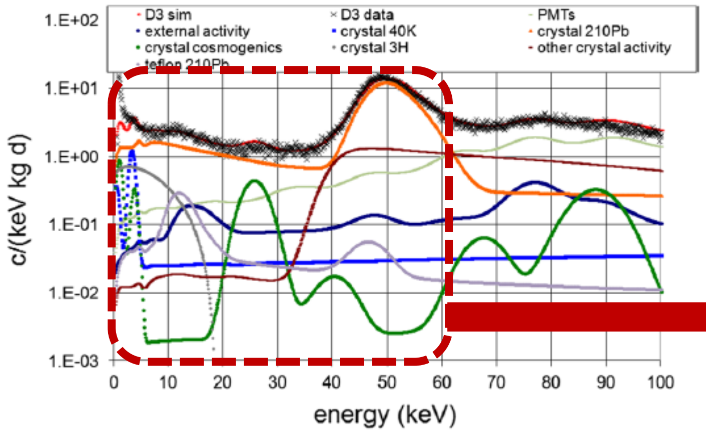

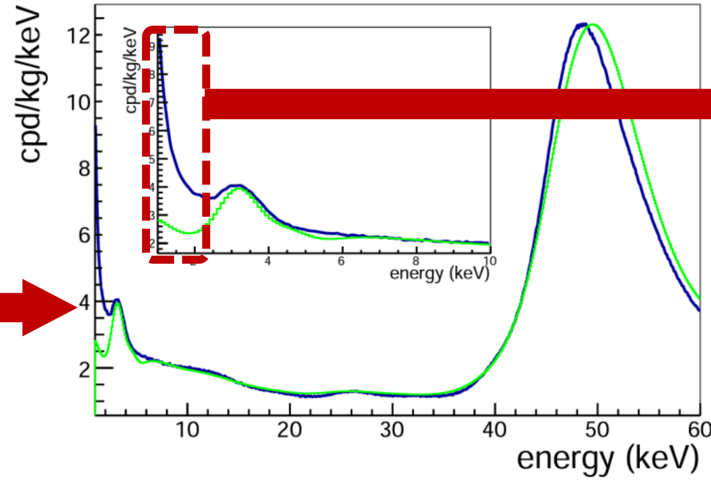

Still a big discrepancy between simulation and data for E < 2 keV

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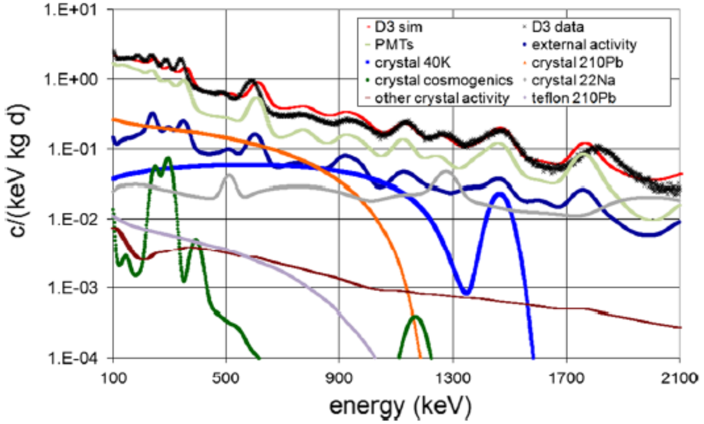

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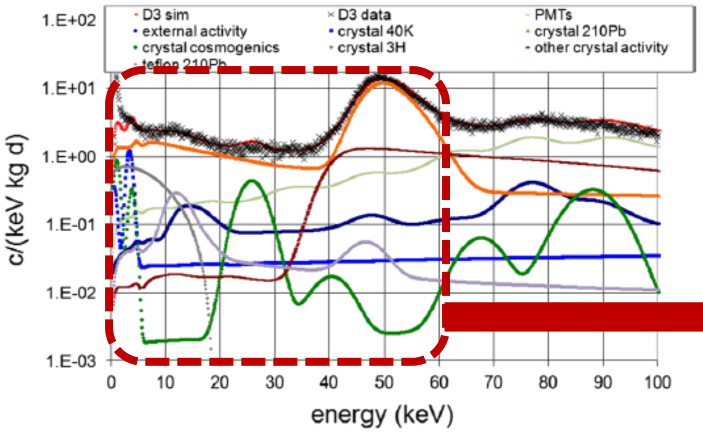

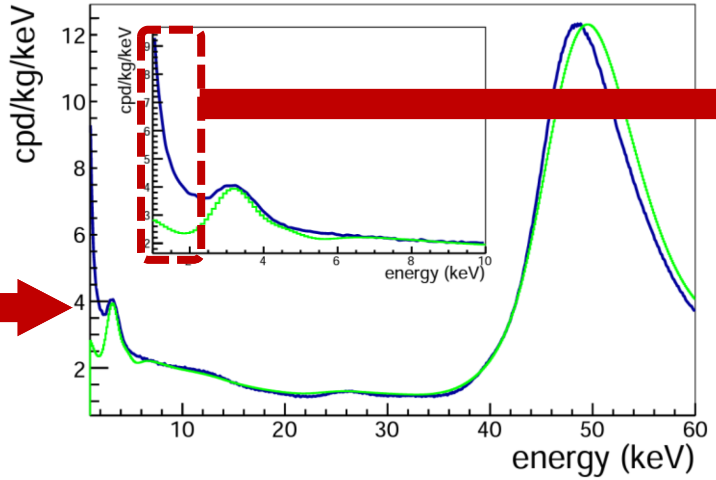

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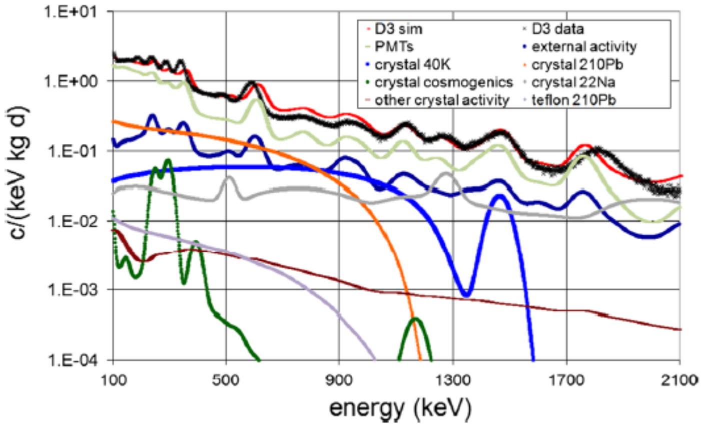

- Incomplete background description in our model?
- Noise events that overcome our filter process

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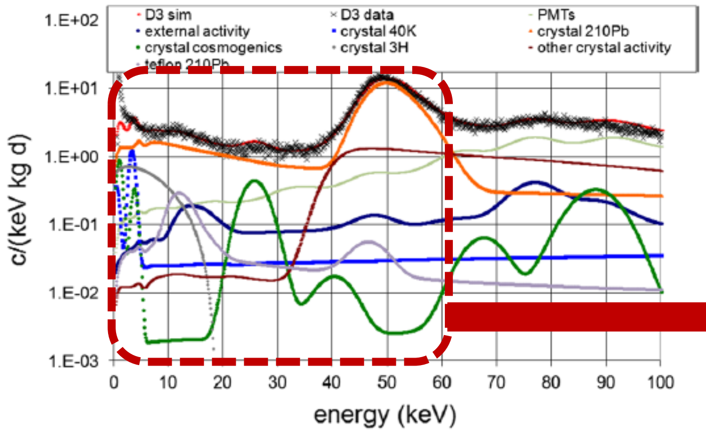

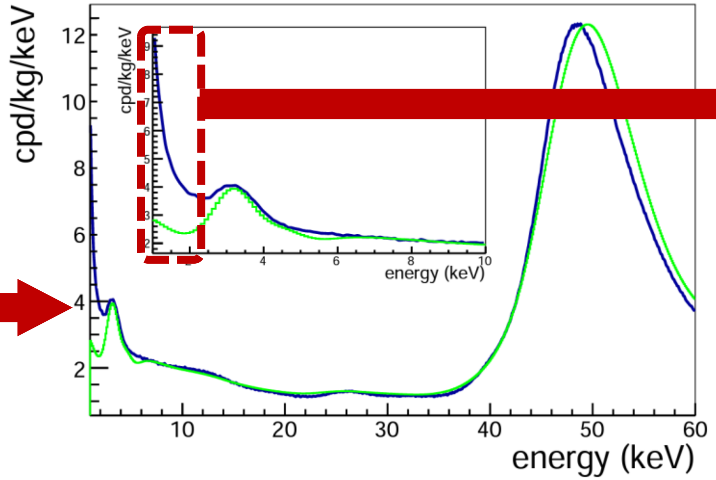

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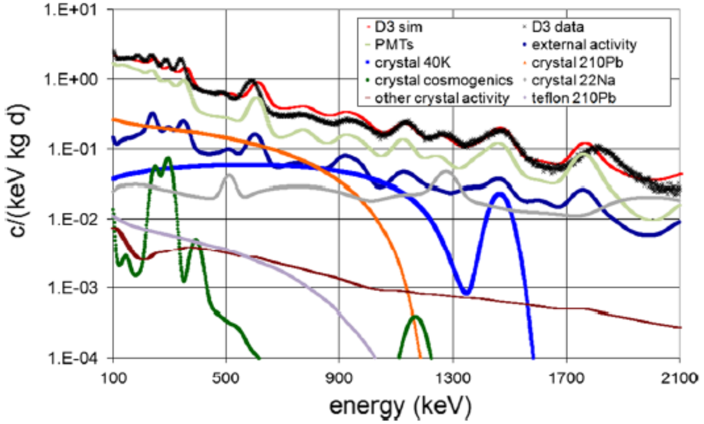

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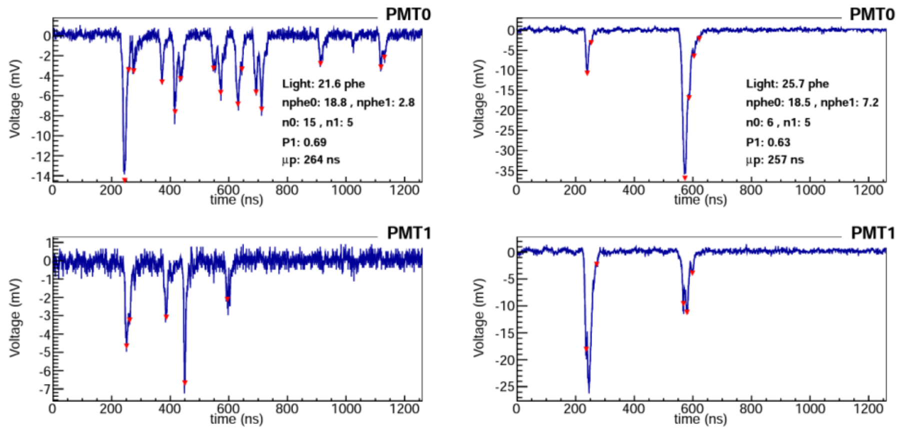
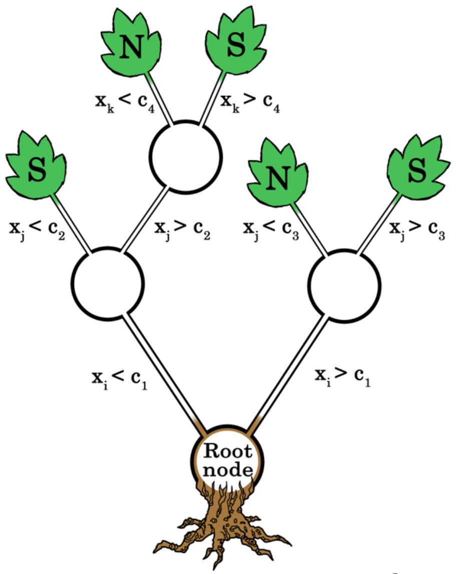
Classification method based on Machine Learning

ANAIS-112 EXPERIMENT: background

Event calssification using Boosted Decision Trees



Noise events observed in the blank module that are difficult to reject.



15 parameters used for calssification

Training populations:

- SIGNAL = neutron calibrations
- NOISE = blank module events

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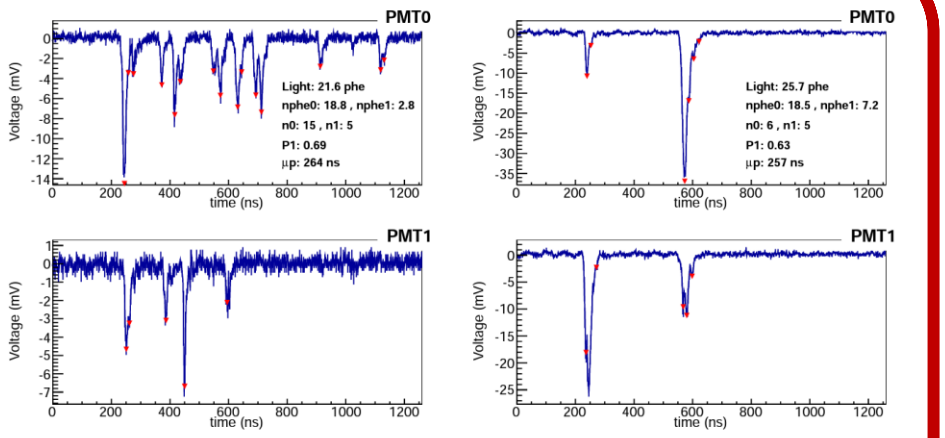

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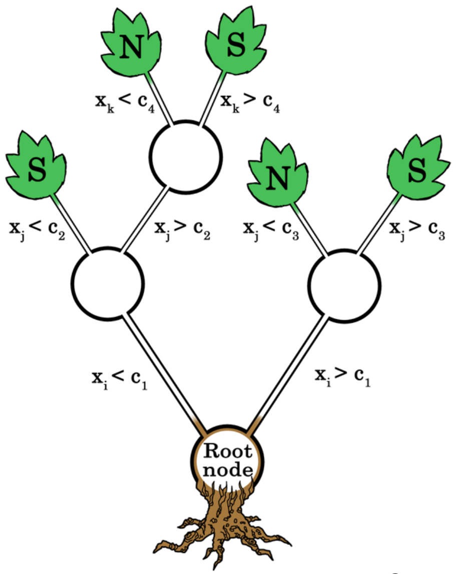

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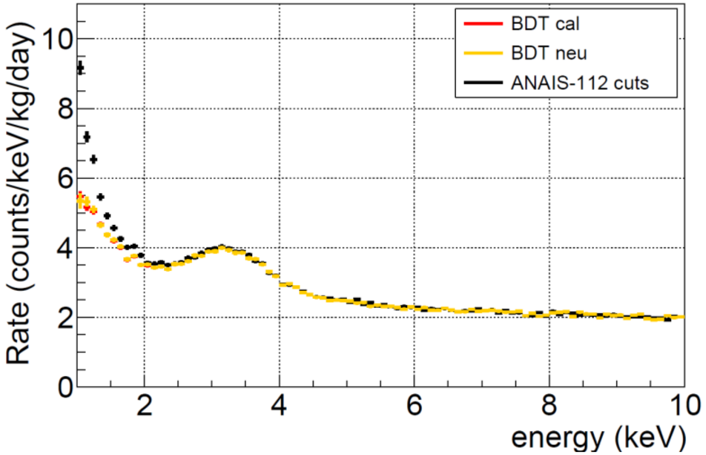
I. Coarasa et al JCAP11(2022)048



Background reduction of ≈ 18% in [1-2] keV

There are still noticeable differences with our background model for E < 2 keV

ANAIS-112 EXPERIMENT: background

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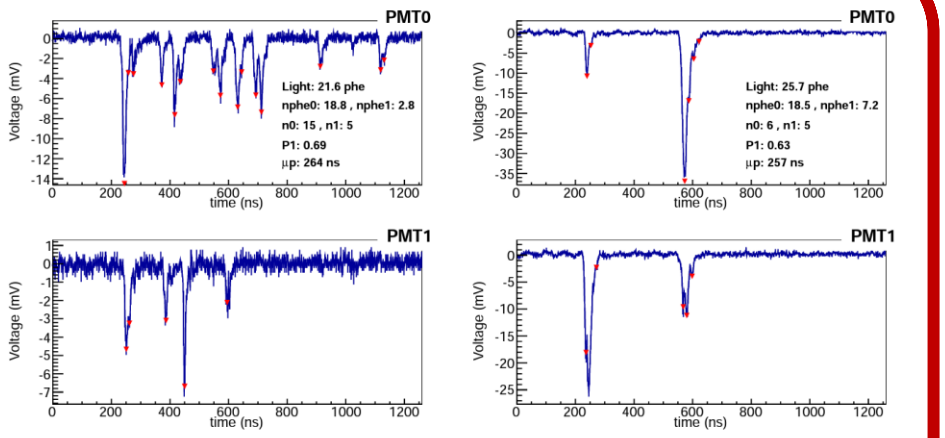

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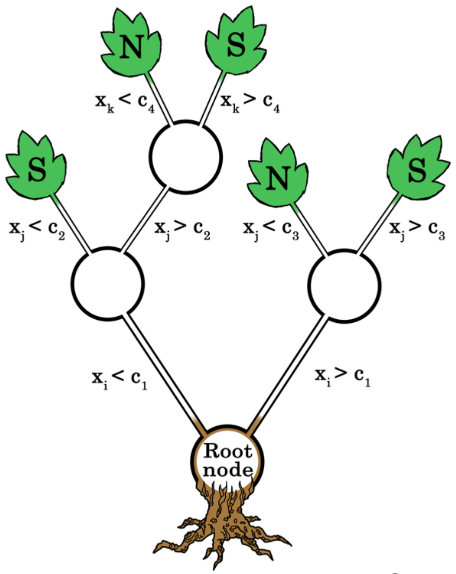

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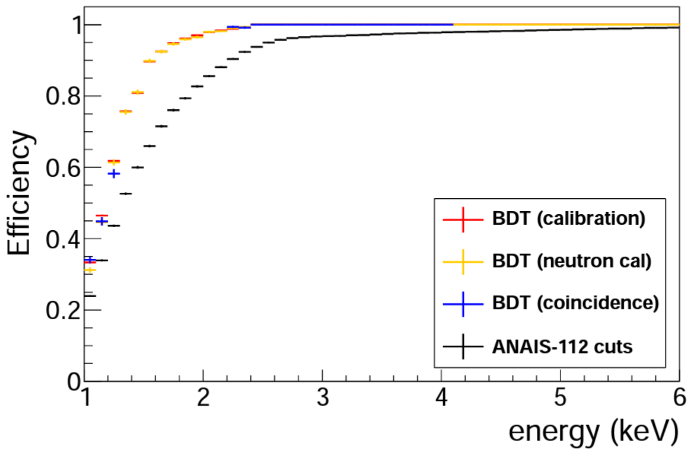


Efficiency improvement of ≈ 30%

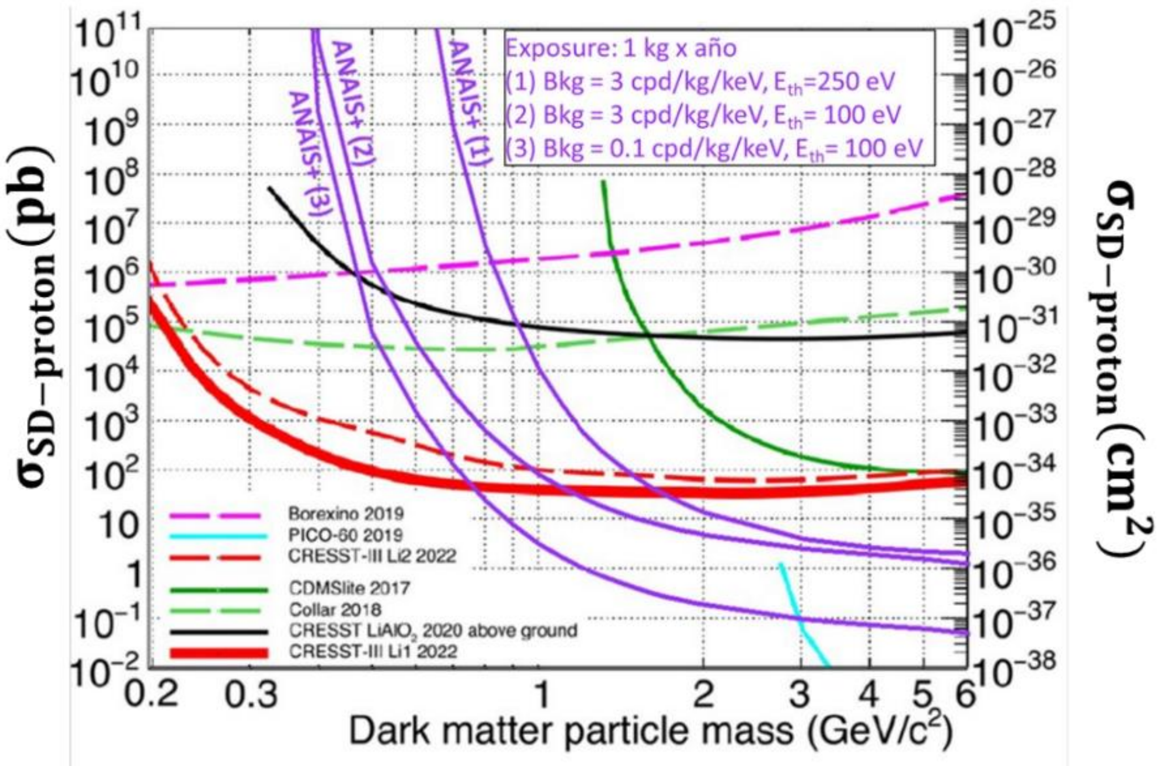
However, it is still highly reduced for 1 keV, **limiting our energy threshold**.

ANAIS+ PROJECT

MOTIVATION

Lower the energy threshold Eth <0.5 keV.

- ✓ DAMA/LIBRA comparison overcoming possible differences in the quenching factor.
- ✓ Increase our sensitivity.
- ✓ Other DM search possibilities.



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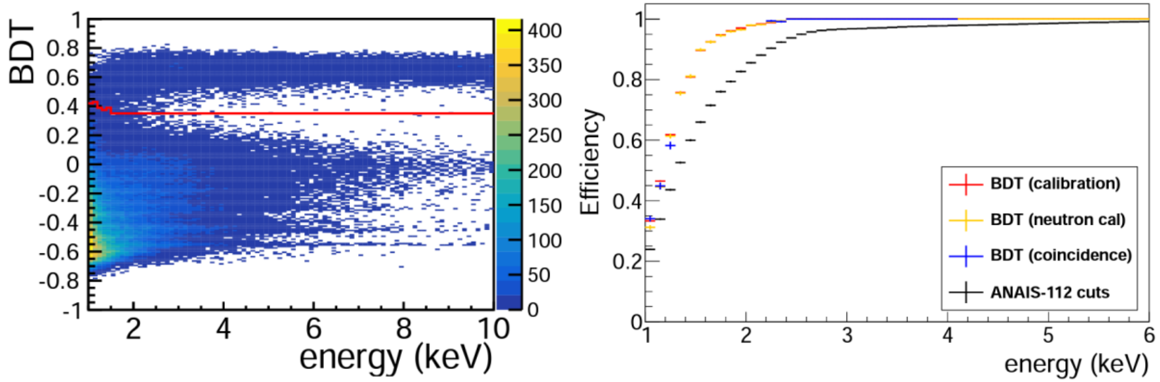

It is necessary to establish aggressive filter protocols to reduce these noise events. At low energies (< 2 keV), it is hard to separate noise from signal events, getting a big efficiency reduction due to the filter mechanism.

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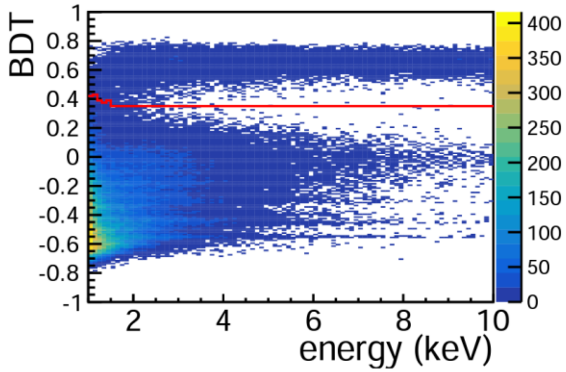

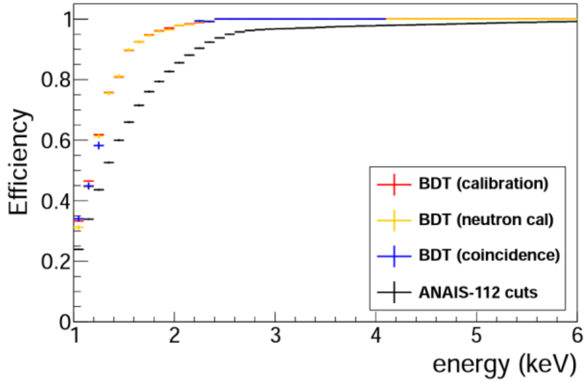

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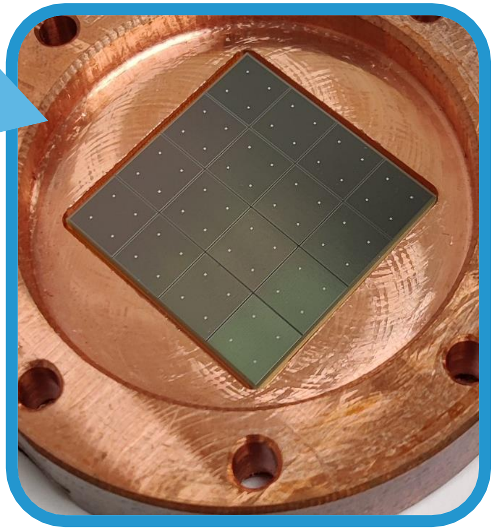
Getting rid of these noise events would allow us to increase our efficiency, allowing to decrease our energy threshold.

ANAIS+

ANAIS+ PROJECT



Evolution of ANAIS detector: replacing PMTs by SiPMs.

ANAIS+ PROJECT

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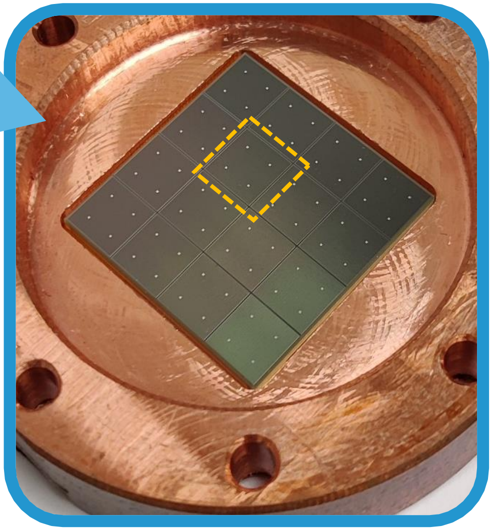


Silicon photomultiplier

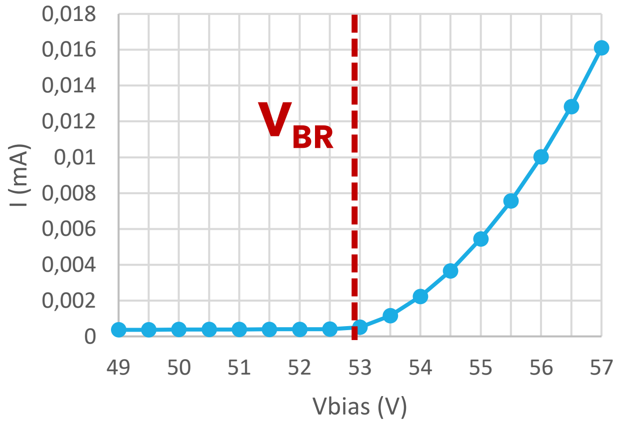
Each SiPM = array of multiple pixels (~ μm)

↓

Single-photon avalanche diodes (SPAD)

SINGLE PHOTOELECTRON RESPONSE (SER)

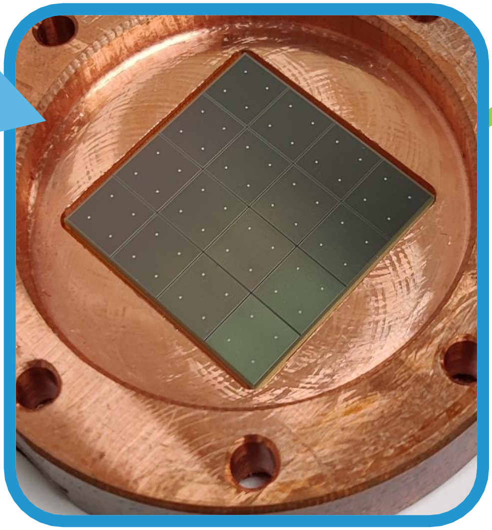
- Incident photon → e^- - hole pair
- Bias Voltage > Breakdown Voltage (V_{BR})



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

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

ANAIS+ PROJECT



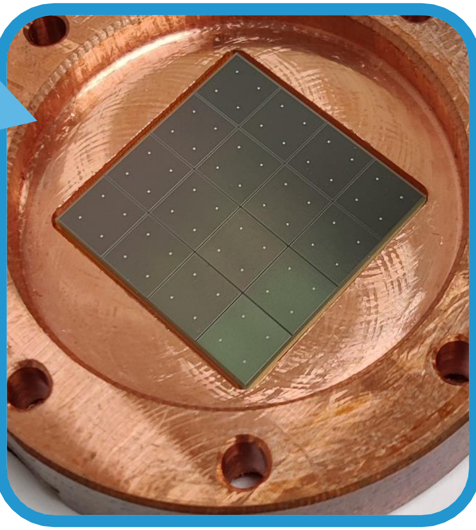
Evolution of ANAIS detector: replacing PMTs by SiPMs.

ADVANTAGES

- High QE.
- High radiopurity.
- Low operating voltage.
- **Elimination of PMTs noise events.**

If anomalous light events are removed, the high light yield of NaI(Tl) - NaI would allow to reduce the threshold below 1 keVee, increasing strongly the sensitivity.

ANAIS+ PROJECT



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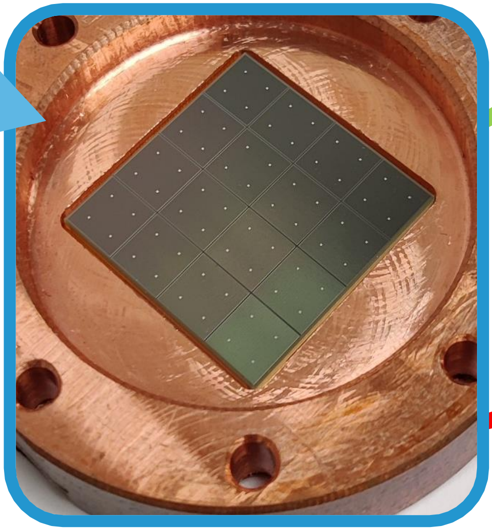
DISADVANTAGES

- High dark current.
- Cross-talk effect (signal distortion).

ANAIS+ PROJECT



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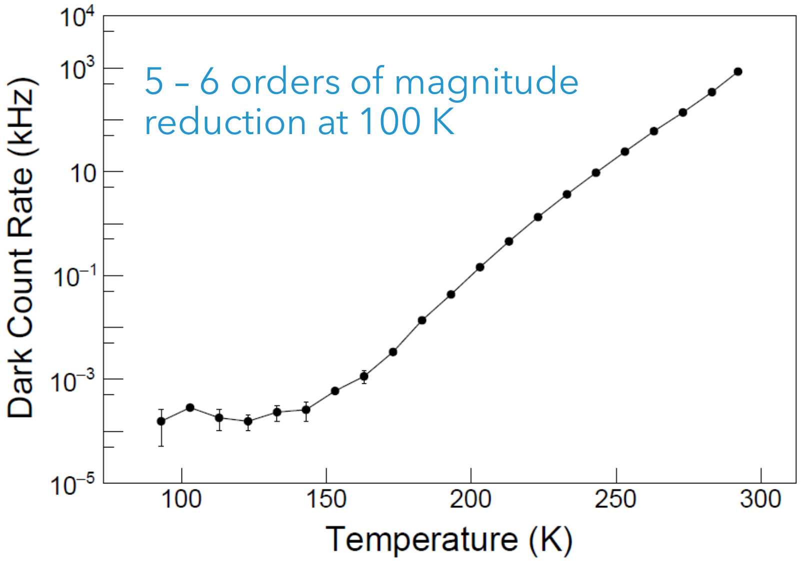
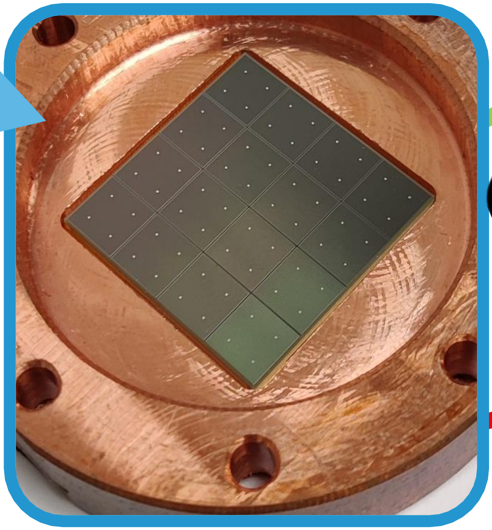
H.Y. Lee et al 2022 JINST 17 P02027



- Working at low temperatures (100 K) → lower noise than in PMTs.
- Modelling and understanding of SiPMs properties.

ANAIS+ PROJECT



Evolution of ANAIS detector: replacing PMTs by SiPMs.

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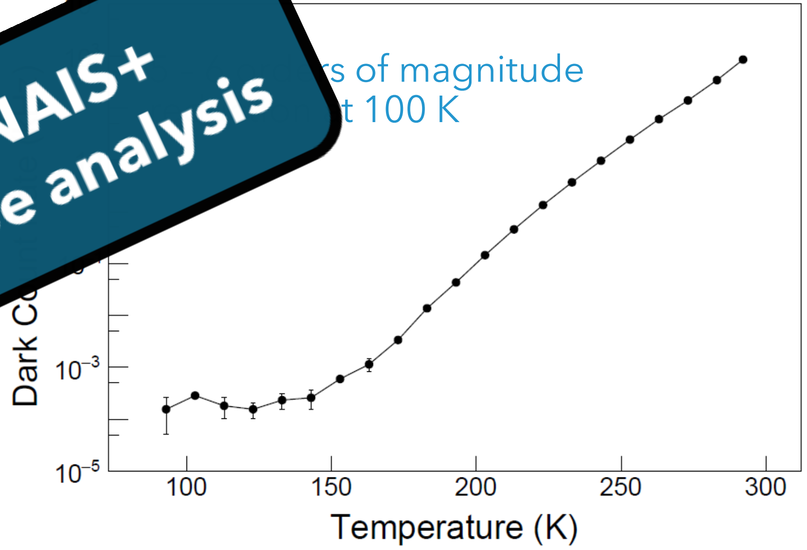
Studies for the feasibility of this project must be done. → **First ANAIS+ prototype analysis**

et al 2022 JINST 17 P02027



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ANAIS+ PROTOTYPE

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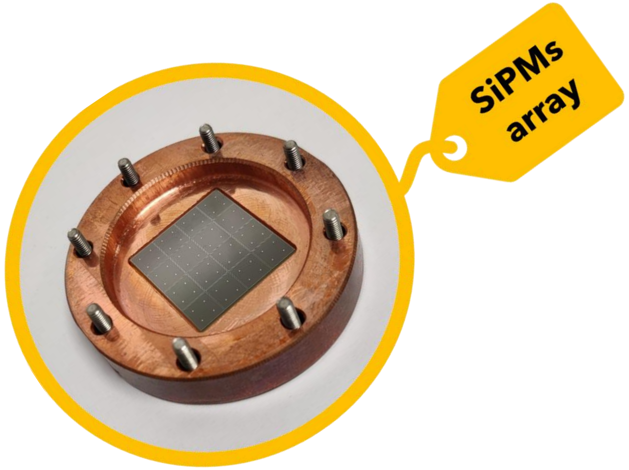
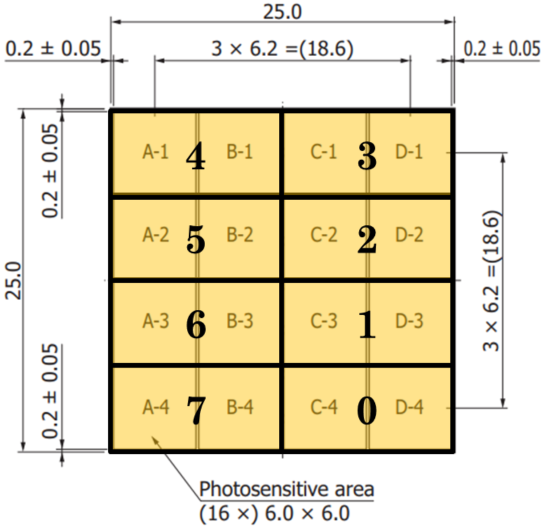
SiPMs array: HAMAMATSU S13361-6050AE-04 (25 x 25 mm).



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



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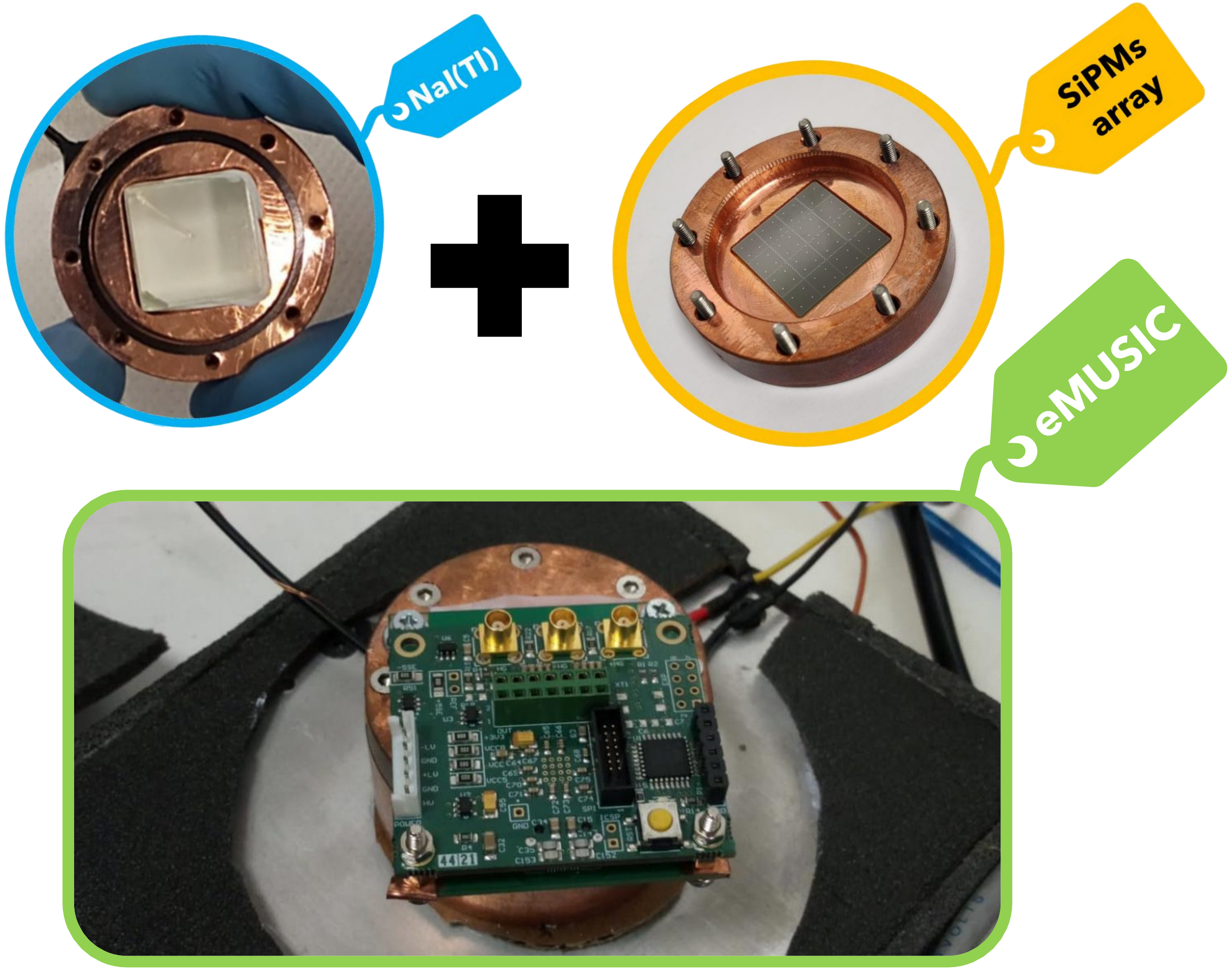
Readout electronics: MUSIC (Multiple Use SiPM Integrated Circuit).

Developed at University of Barcelona

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



ANAIS+ PROTOTYPE

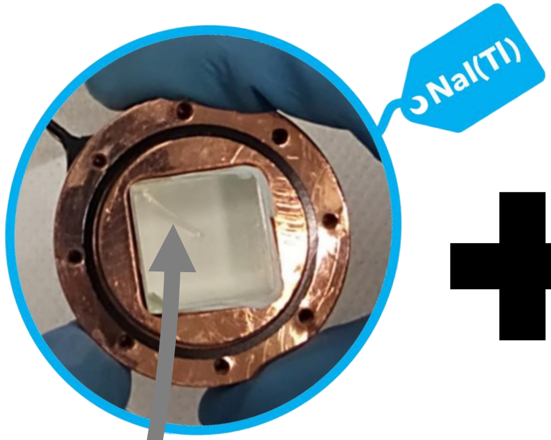
First ANAIS+ prototype:

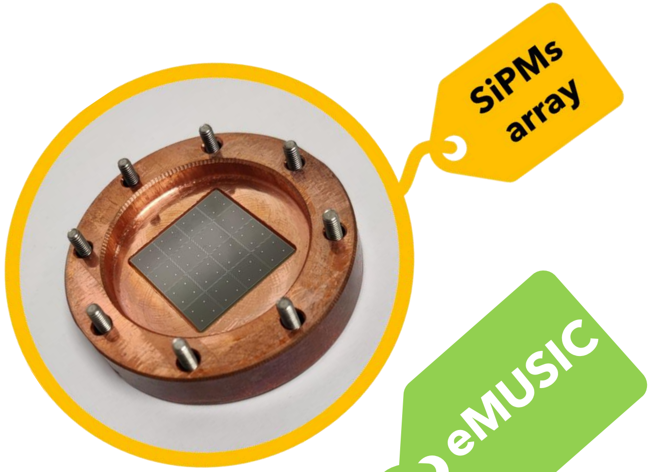
Scintillator crystal: NaI(Tl) 1″ cube.

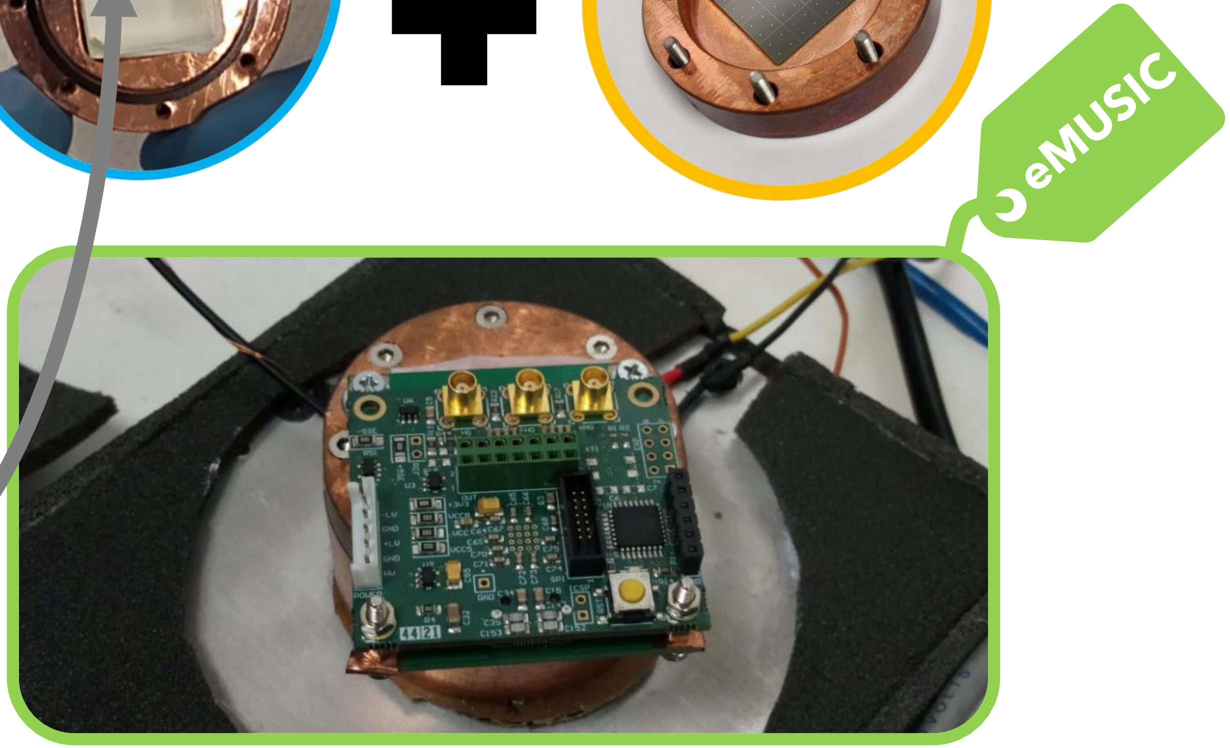
SiPMs array: HAMAMATSU S13361-6050AE-04 (25 x 25 mm).

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

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



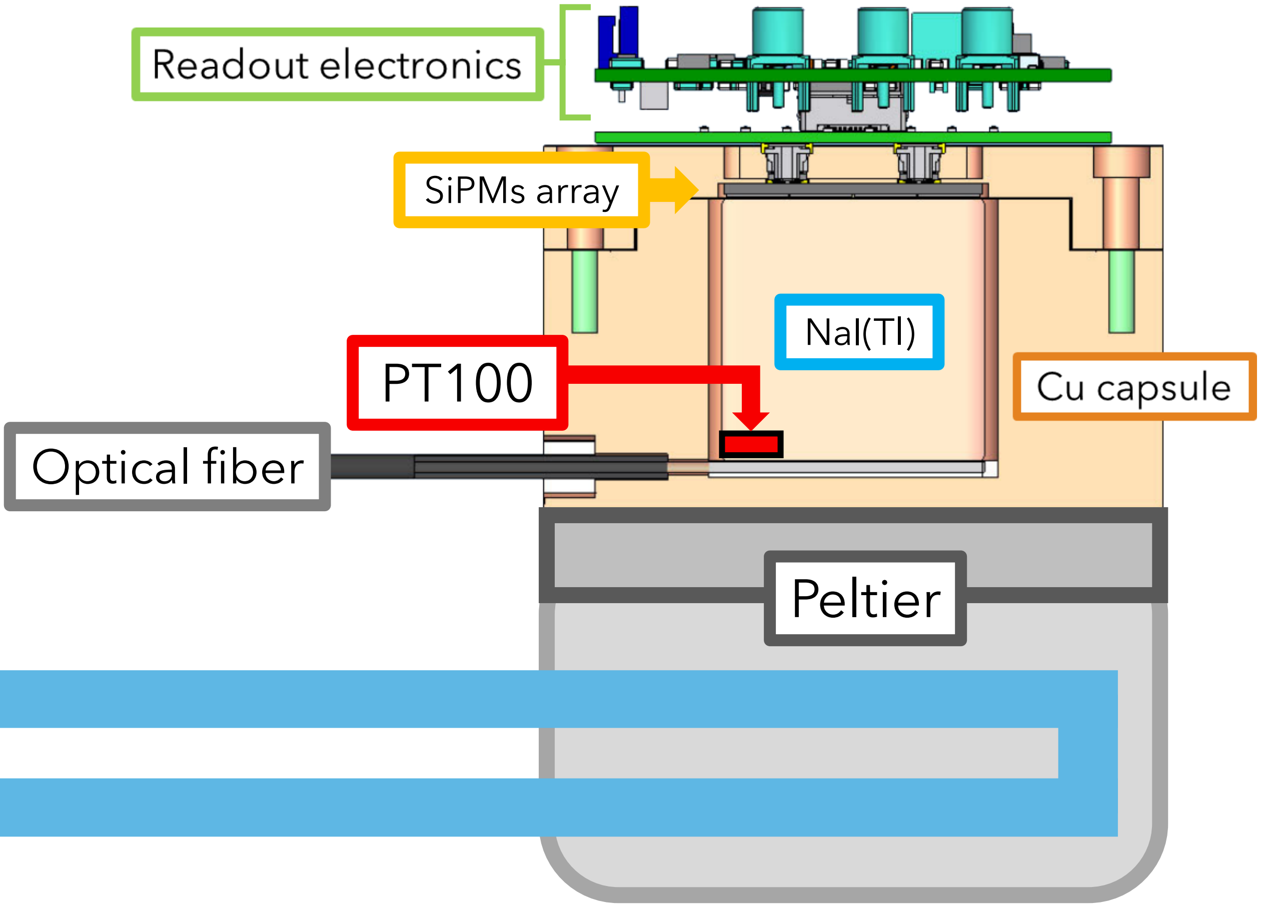




ANAIS+ PROTOTYPE

First ANAIS+ prototype (temperature control):

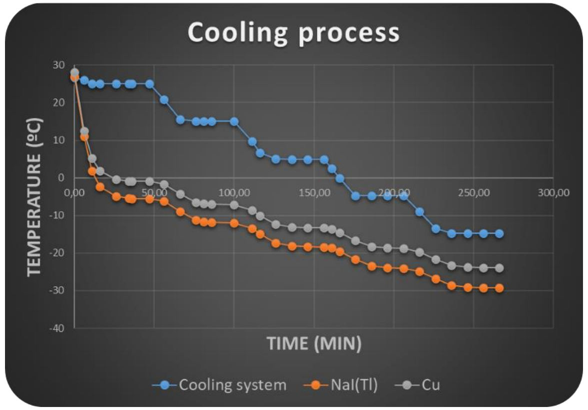
- **PT100 thermistor** in contact with the NaI(Tl) cube to monitor its temperature.
- **Cooling system**: peltier with convenient anti-freeze refrigeration allowing to cool down to temperatures near -40 °C.



ANAIS+ PROTOTYPE: measurement process

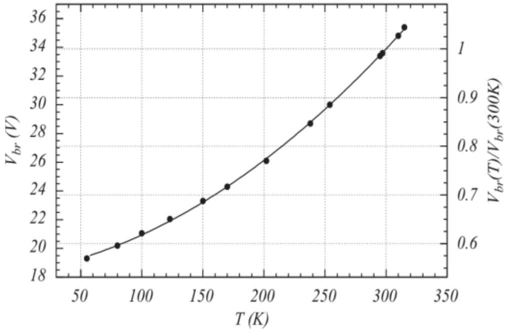
Cooling process

System cool down until NaI(Tl) temperature stabilizes.



V_{BR} estimation

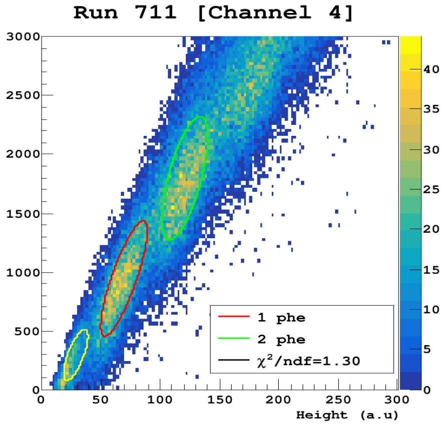
Measured at each temperature (as V_{BR} decreseases with it).



G. Collazuol, et al., Nuclear Instruments and Methods in Physics Research Section A 628 (2011) 389

SER characterization

SER calibration for all channels as a function of Vov under LED illumination.



Scintillation measurements

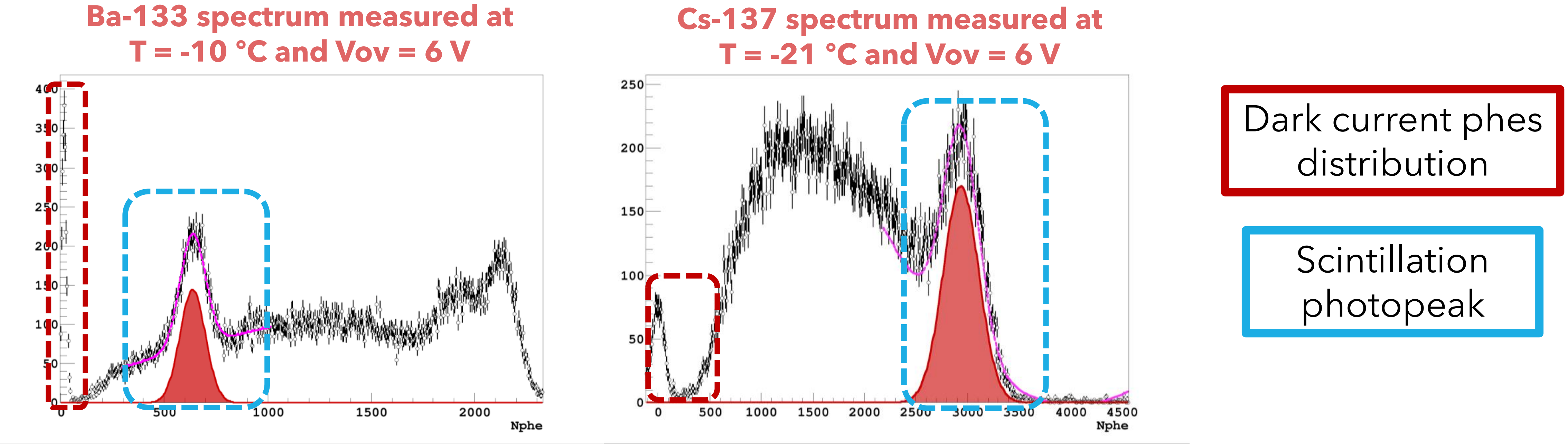
Under Ba-133 and Cs-137 irradiation at different Vov's.

- Cs-137 → 662 keV γ
- Ba-133 → 81 keV γ

ANAIS+ PROTOTYPE: analysis

Analysis of the scintillation measurements:

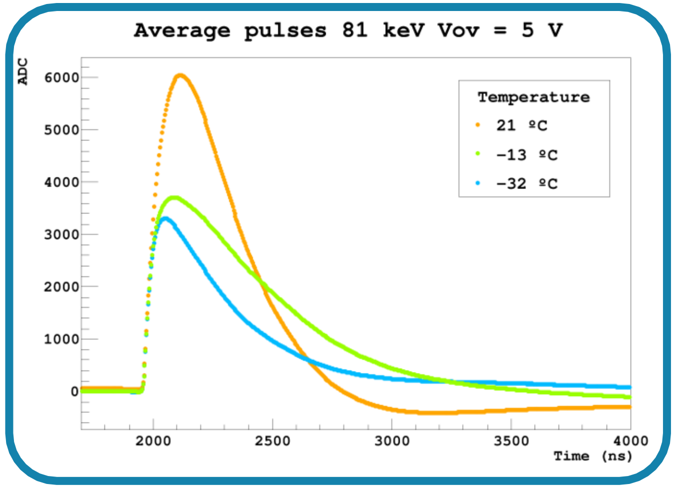
- ❖ Construction of the photoelectron scintillation spectra applying the SER calibration relation with Vov.
- ❖ Estimation of light collection (phe/keV) and photopeak resolution.

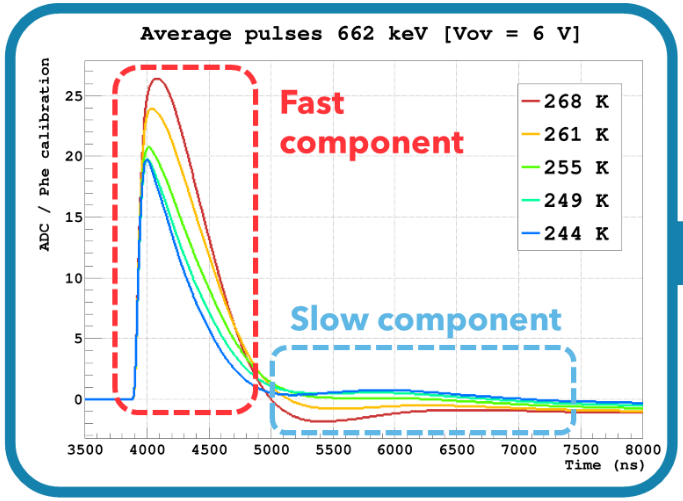


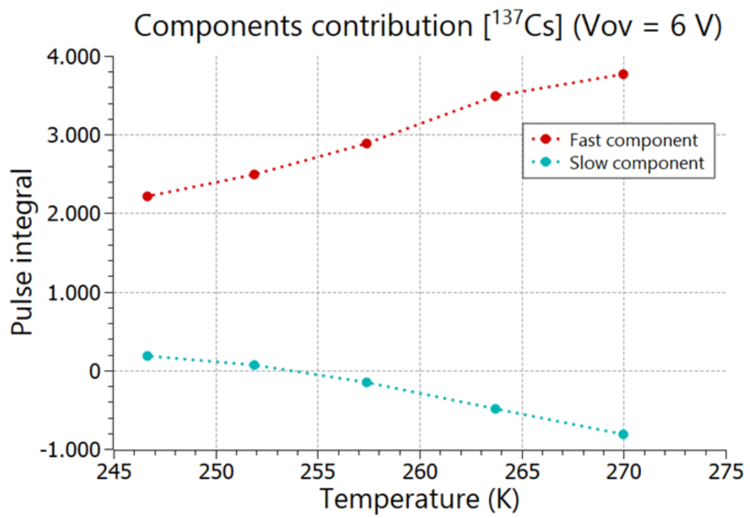
FIRST RESULTS

Scintillation behavior with temperature [Preliminary]

Measurements taken at the same Vov, varying the NaI(Tl) temperature.







Measurements with Ba and Cs shows a change in the scintillation pulse shape, increasing the contribution of the low component and decreasign for the fast component.

Looking at the pulse integral for the "fast component" a clear reduction in light collected is observed, as expected.

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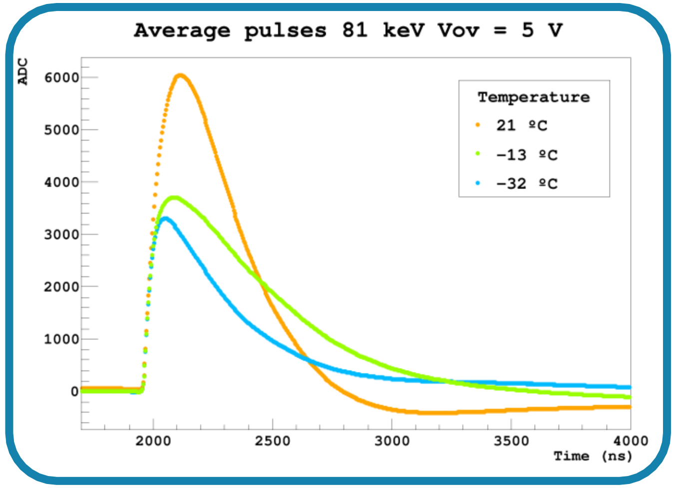
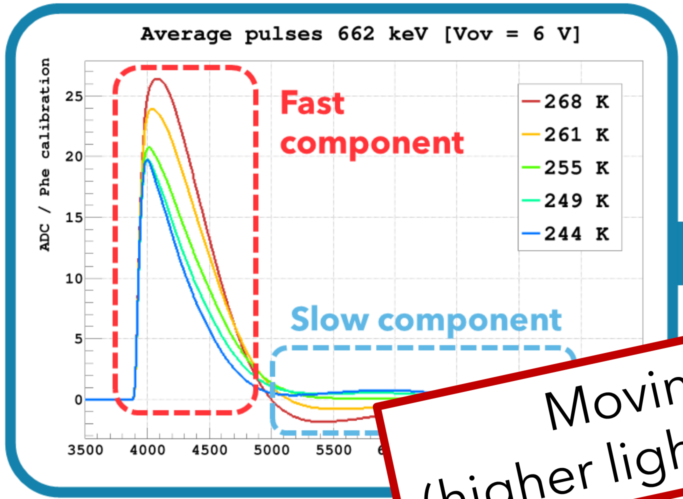
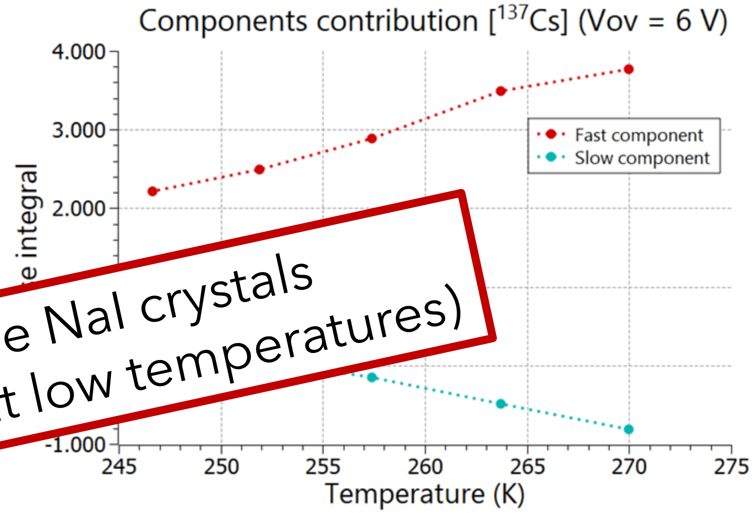






Moving to pure NaI crystals
(higher light yield at low temperatures)

Measurements with Ba and Cs shows a change in the scintillation pulse shape, increasing the contribution of the low component and decreasign for the fast component.

Looking at the pulse integral for the "fast component" a clear reduction in light collected is observed, as expected.

FIRST RESULTS

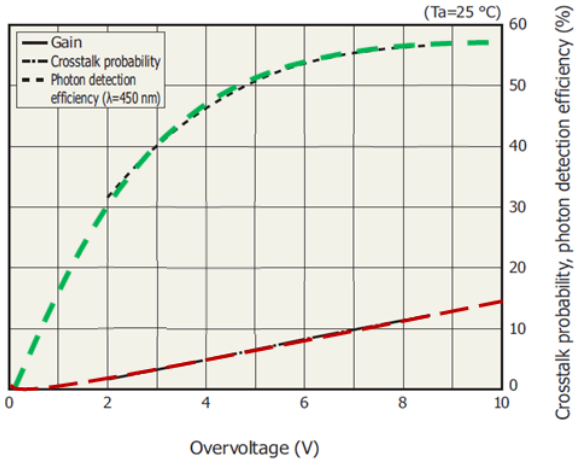
SiPM light-collection model

- **Scintillation light** produced by an ionizing particle detected with a certain photodetection efficiency (**PDE**), which grows with Vov following an asymptotic behaviour.

- **Cross-talk** produce an increase in the phe gain related to the cross-talk probability (λ_{CT}). This probability grows almost linearly with Vov.

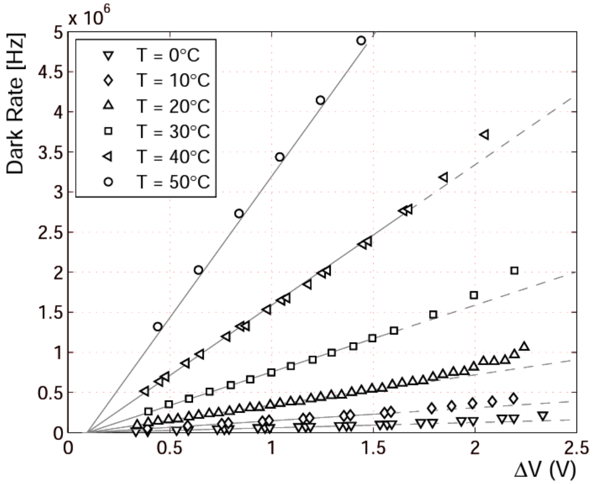
- **Afterpulses** have not been considered as an additional effect → included in the phe gain dependence with Vov. 

- **Dark-current** phes can be present inside the integration window of the scintillation pulse. The dark current rate (DCR) also grows with Vov.



Hamamatsu MPPC S13361-6050 series datasheet

PDE, CT and DCR behaviour with Vov



A. Vacheret et al., Nucl.Instrum.Meth.A , 656,1 (2011) 69-83

FIRST RESULTS

SiPM light-collection model

$$LC\ (Vov)\ \left(\frac{phe}{keV}\right) = \frac{1}{1-\lambda_{CT}(Vov)}\ (LC_{max}^{scint}\cdot PDE(Vov)) + DC(Vov)$$

FIRST RESULTS

SiPM light-collection model

Total number of phe per keV measured (affected by SiPMs properties)

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The maximum detected phes would be LC_{max}^{scint}(asymptotic) = $LC_{max}^{scint} \cdot PDE(Vov \to \infty)$

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Gain produced by cross-talk (higher λCT leads to higher gain and LC)

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Gain produced by cross-talk (higher λCT leads to higher gain and LC)

Dark current phes that lay inside the scintillation pulse. Its contribution would depend strongly on temperature.

FIRST RESULTS

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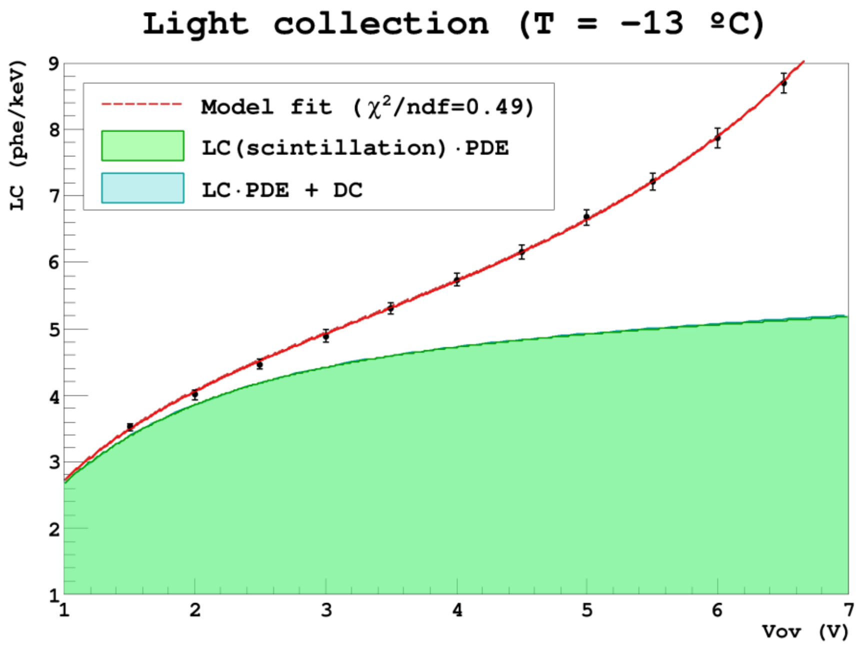
Ba-133 photopeak (81 keV)



FIRST RESULTS

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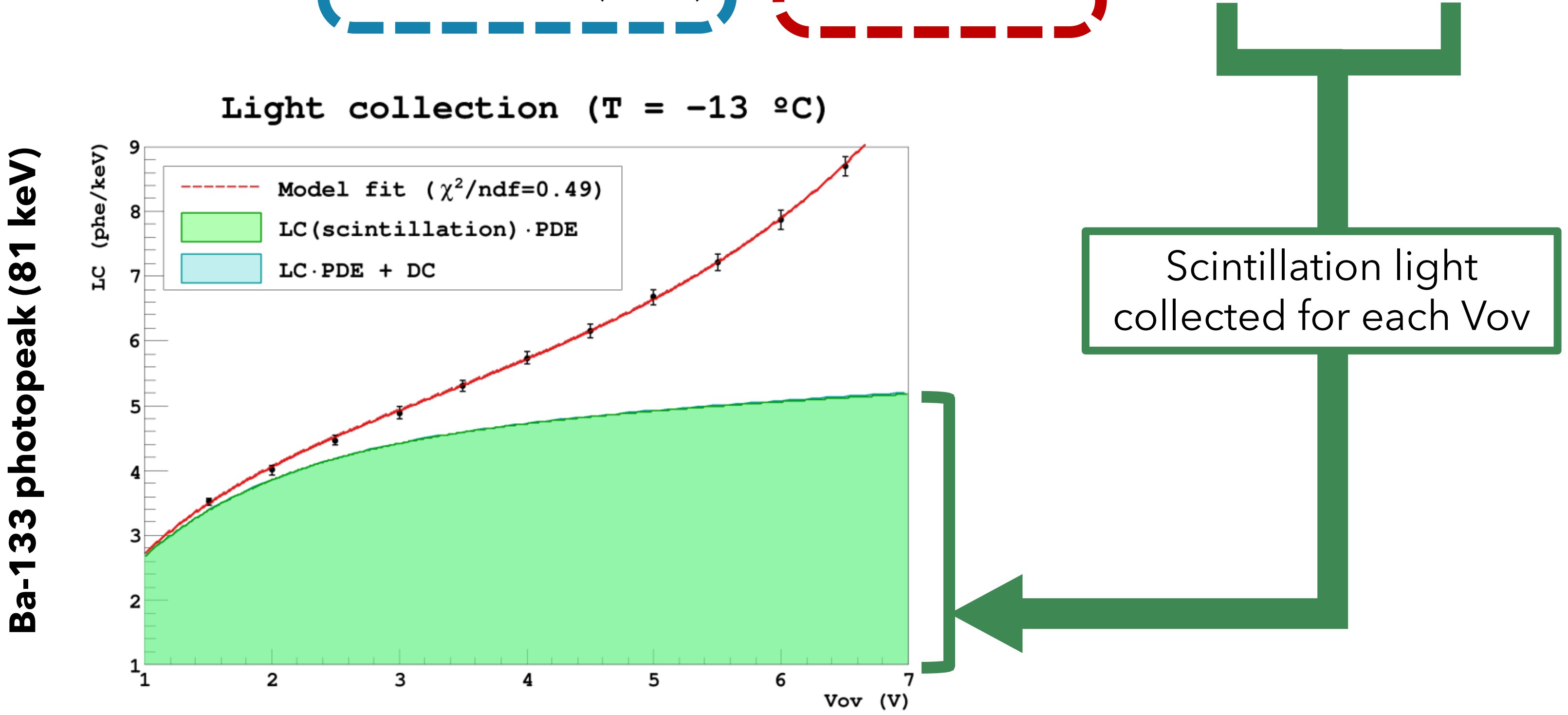

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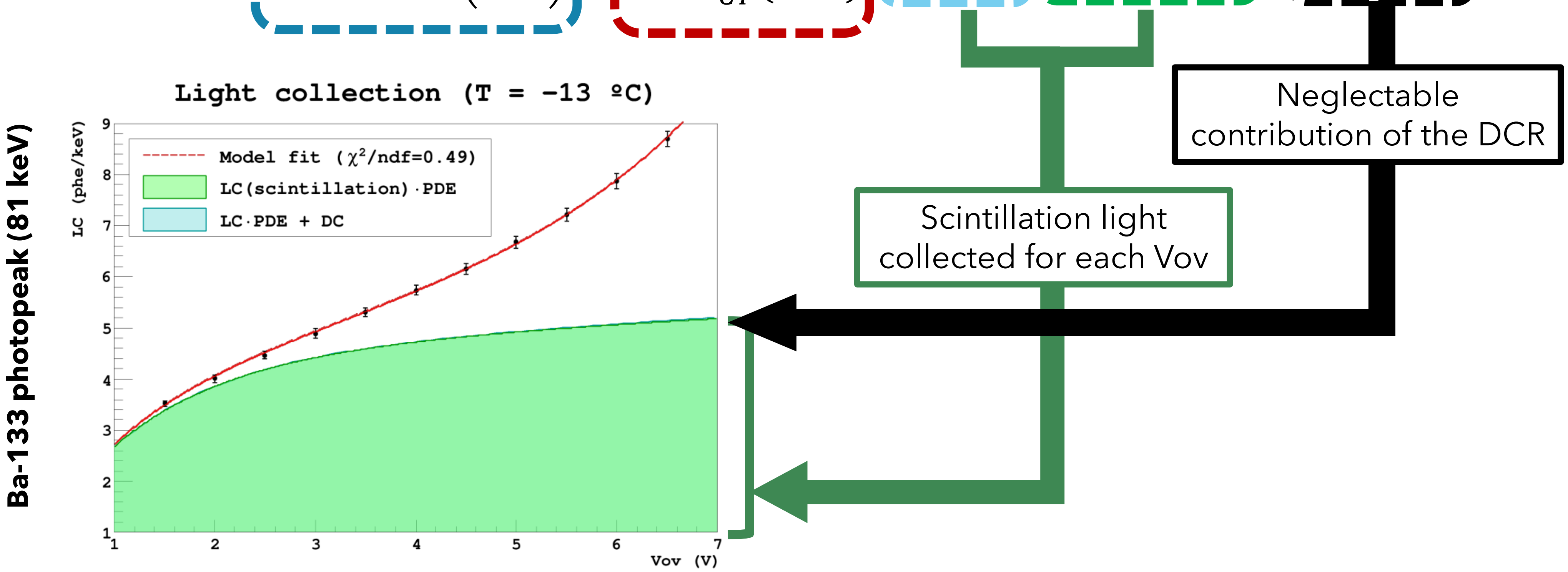

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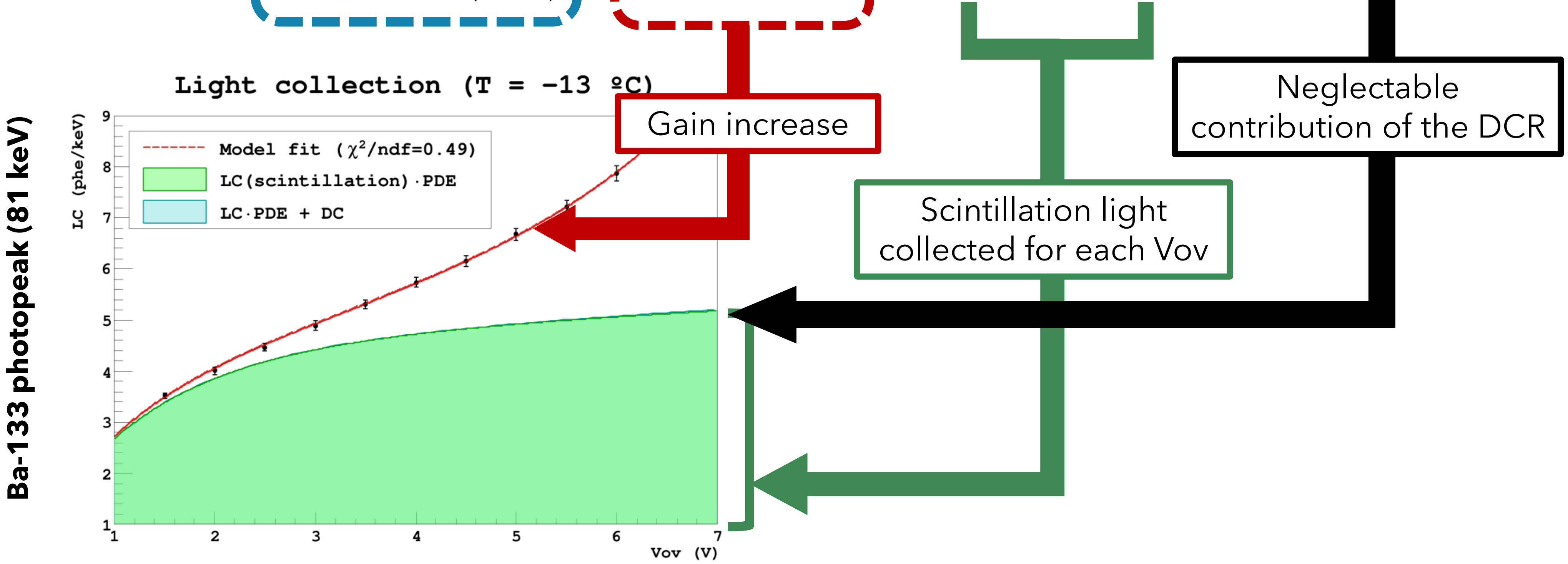
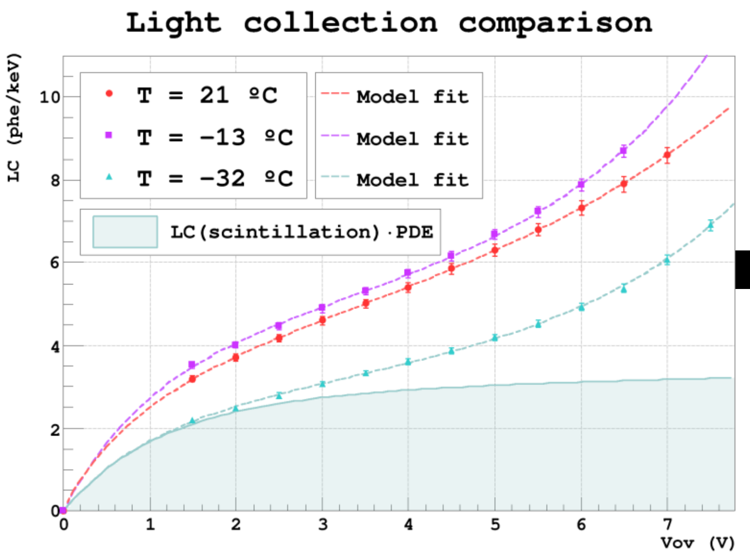


FIRST RESULTS

Ba-133 photopeak (81 keV) results [Preliminary]

Analysis of the overall light collection and resolution, important to decide the **operating voltage** of SiPMs.



T (ºC)	LC @ 4 V	LC^{scint} @ 4 V	LC^{scint}_{max} (asymptotic)
Room	5.4 (phe/keV)	4.5 (phe/keV)	6.8 (phe/keV)
-13	5.7 (phe/keV)	4.7 (phe/keV)	6.5 (phe/keV)
-32	3.6 (phe/keV)	2.9 (phe/keV)	3.6 (phe/keV)

Measured light collection

Scintillation contribution to light collection

Asymptotic scintillation contribution (Vov → ∞)

FIRST RESULTS

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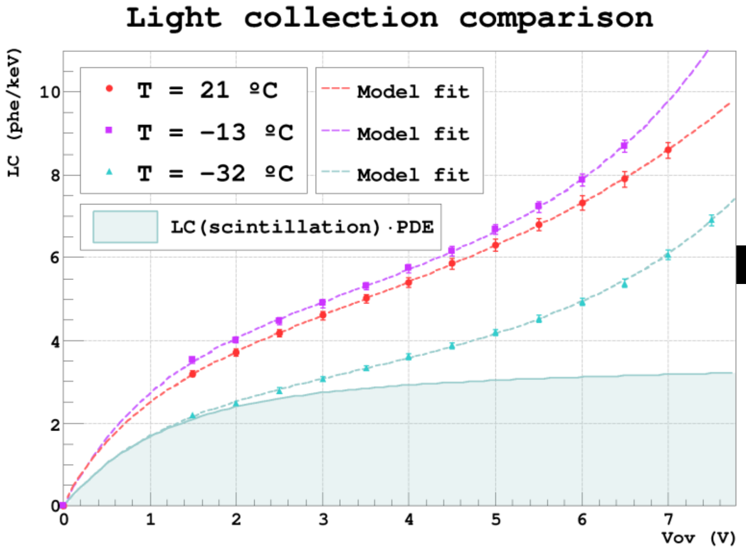
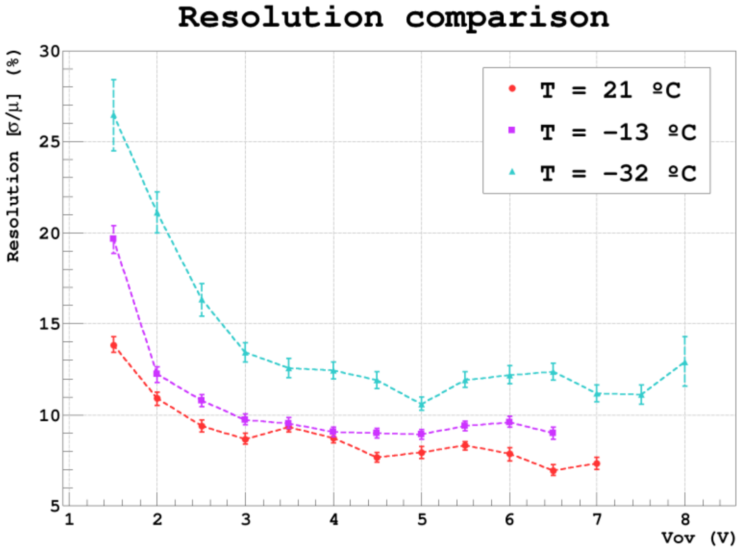


T (ºC)	LC^{scint} @ 4 V
Room	4.5 (phe/keV)
-13	4.7 (phe/keV)
-32	2.9 (phe/keV)



Setting the operation point is a balance between resolution, high scintillation light detection and low cross-talk contribution.

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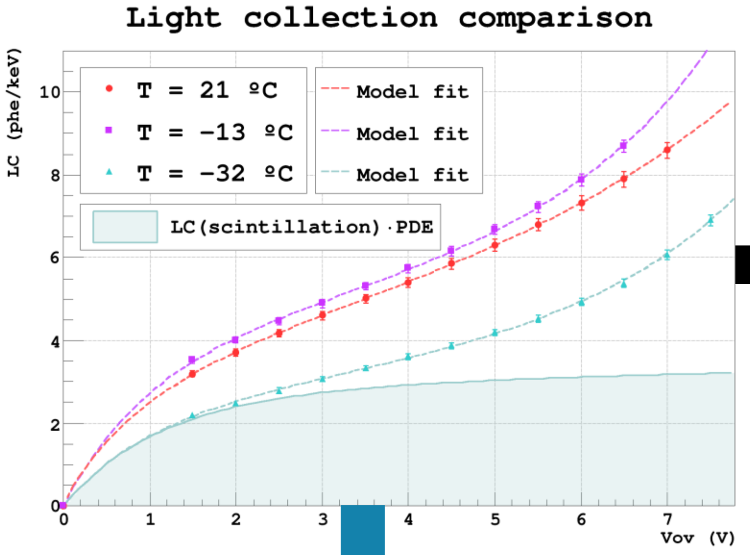

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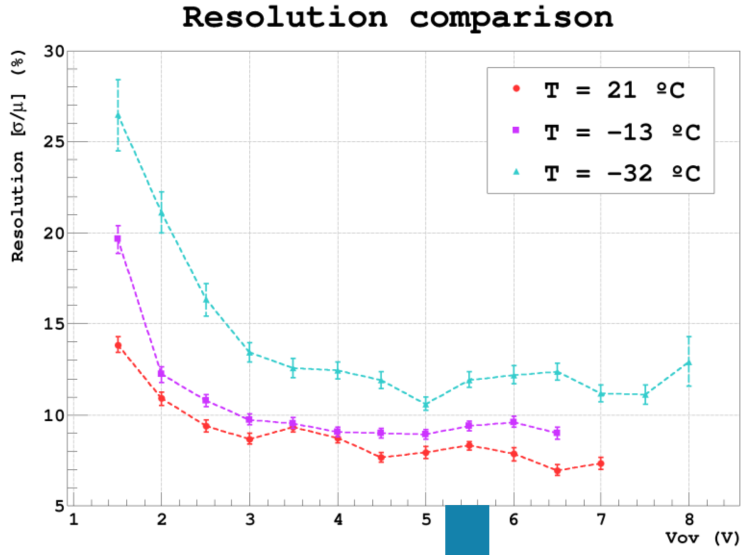
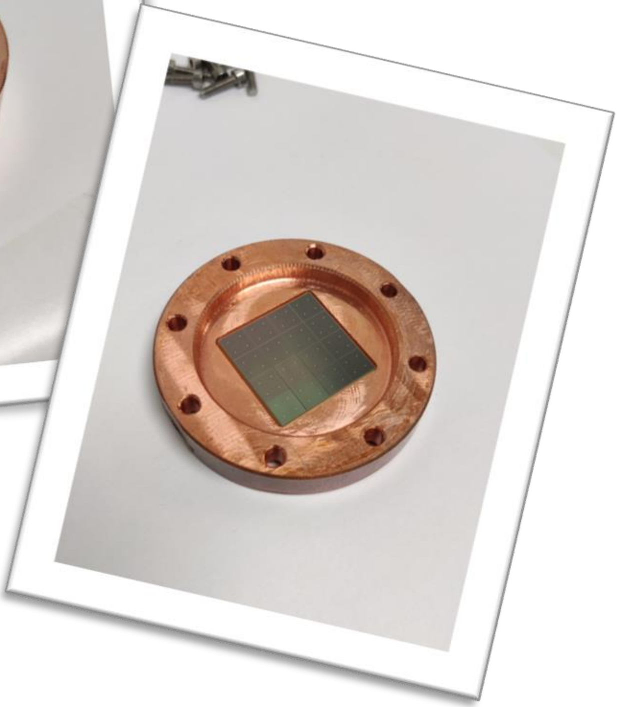


Vov = 4 V (T=-32 ºC) gives a LC^{scint} of 2.9 phe/keV (24% cross-talk) and a stabilized resolution of ≈12% (81 keV).

SUMMARY



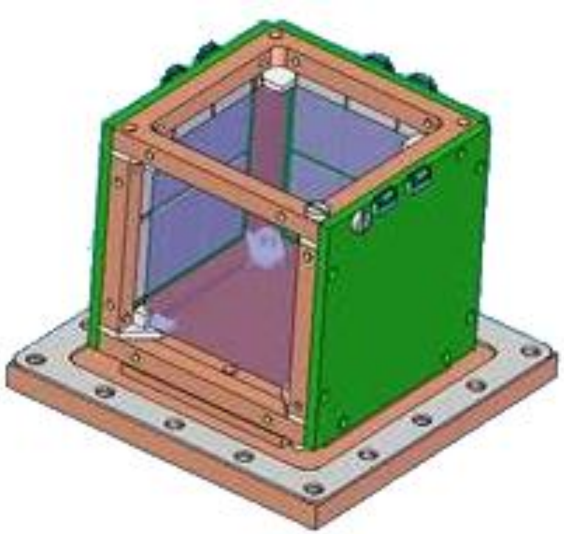
01 **ANAIS+** could lead to an improvement on the ANAIS-112 experiment, replacing the PMTs by **SiPMs** to read the scintillation light of the detector. That could allow a reduction in its energy threshold that would give a better sensitivity and reduction in some systematic effects on the comparison with DAMA/LIBRA.

02 A **prototype** has been built and first measurements show the expected behaviour of the SiPMs and NaI(Tl) scintillator with temperature.

03 This first prototype results in a LC of **3 phe/keV** at temperatures of ≈ **-30 °C** .

NEXT STEPS

- Working to better understand the SiPM response and improve the DAQ to avoid signal saturation and undershoot effects.
- Studies using pure NaI will be carried out in near future. We expect an increase on the light collection when decreasing the temperature.
- A new cooling system will be incorporated, allowing to reduce temperature ≈100 K to explore the properties of NaI - NaI(Tl) + SiPMs down to this temperature.
- Assembly of a new prototype, coupling four of the six faces of the NaI cube to SiPMs arrays. As part of a posible collaboration with the Laboratori Nazionali del Gran Sasso, this prototype may integrate a specifically designed SiPM model.



Thank you!

ANAIS

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

MultiDark Multimessenger Approach for Dark Matter Detection

MINISTERIO DE CIENCIA E INNOVACIÓN

UNIÓN EUROPEA FONDO EUROPEO DE DESARROLLO REGIONAL "Una manera de hacer Europa"

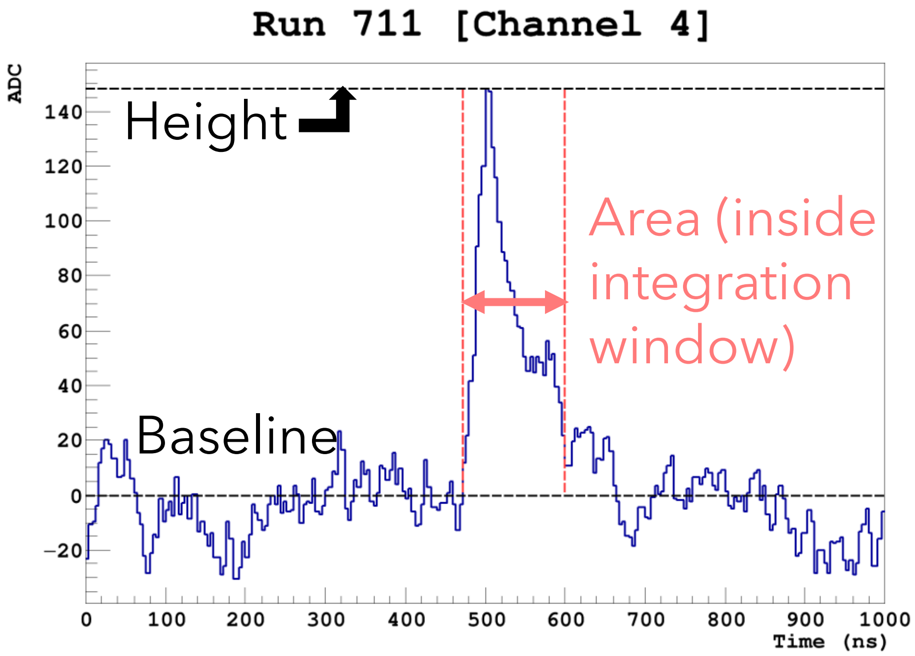
AGENCIA ESTATAL DE INVESTIGACIÓN

Back-up

ANAIS+ PROTOTYPE: SER calibration

LED light (λmax ≈ 400 nm, UV range) used to calibrate the single photoelectron response of each channel:

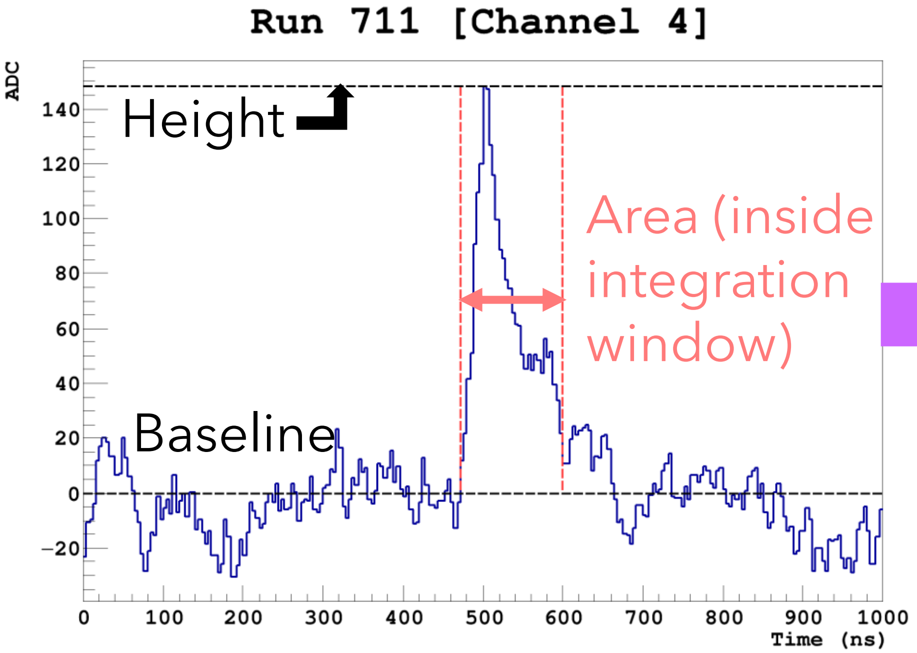
- ❖ Injected via **optical fiber** giving a good illumination of all channels.
- ❖ Activated by a **pulse generator** with constant frequency → used simultaneously as acquisition trigger. Each pulse has a square shape and a width of 40 ns.
- ❖ The light level can be controlled with a light filter to guarantee a low number of phes identified in all channels.



Typical LED light signal measurement

Vov = 6.5 V
Temperature ≈ -22 °C

ANAIS+ PROTOTYPE: SER calibration



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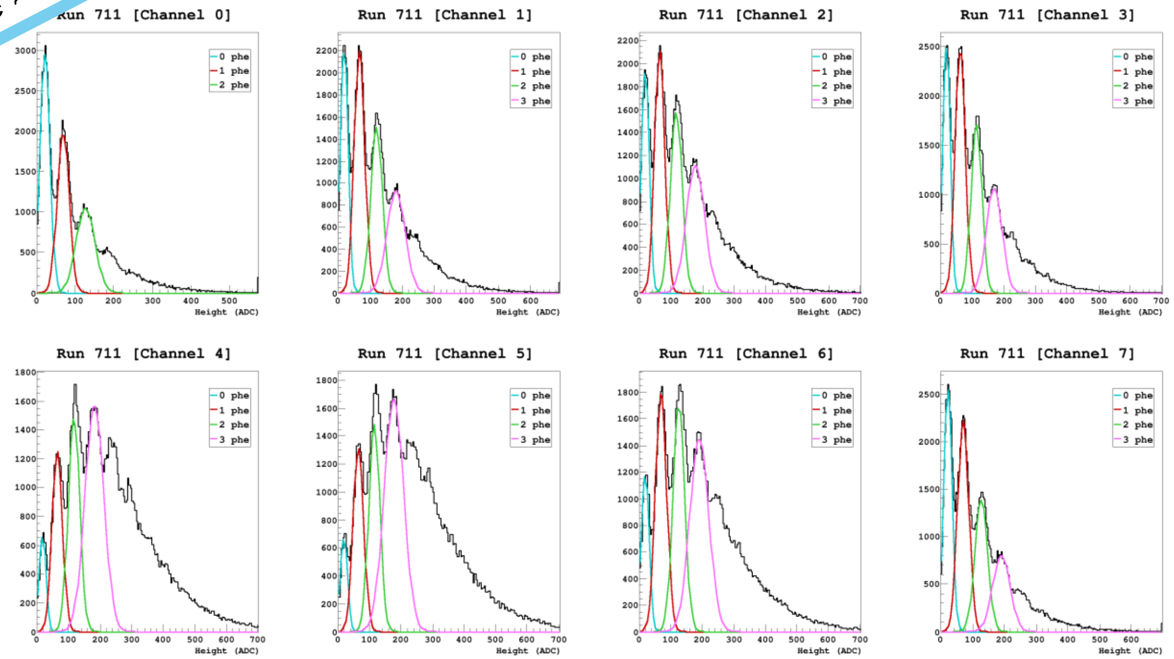
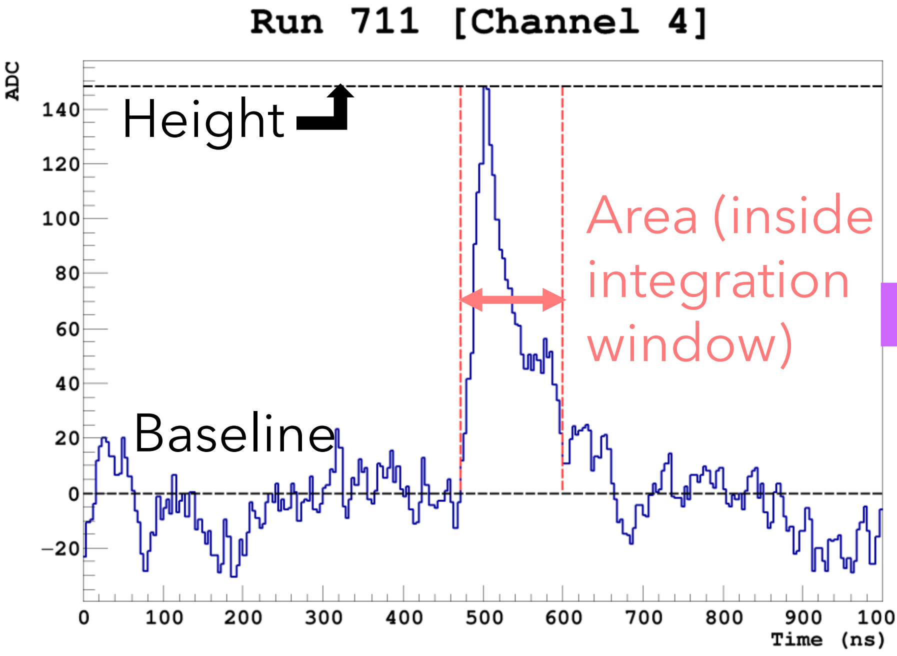


Clear identification of 1,2,3 … photoelectrons peaks in the height spectrum of each channel.

ANAIS+ PROTOTYPE: SER calibration



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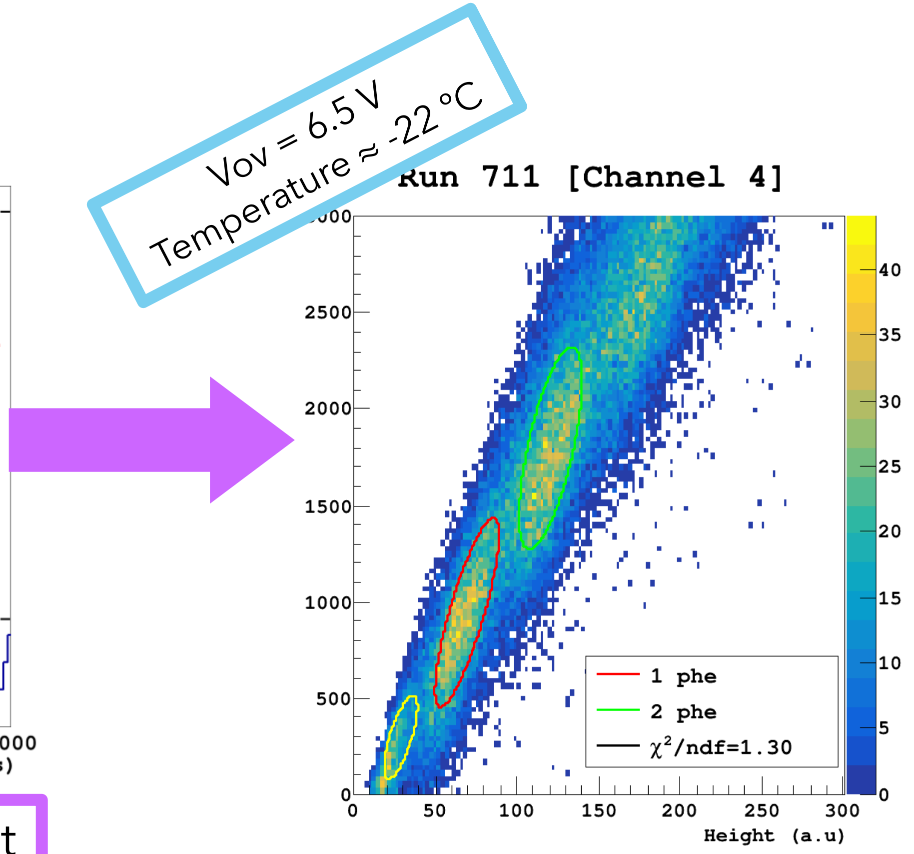
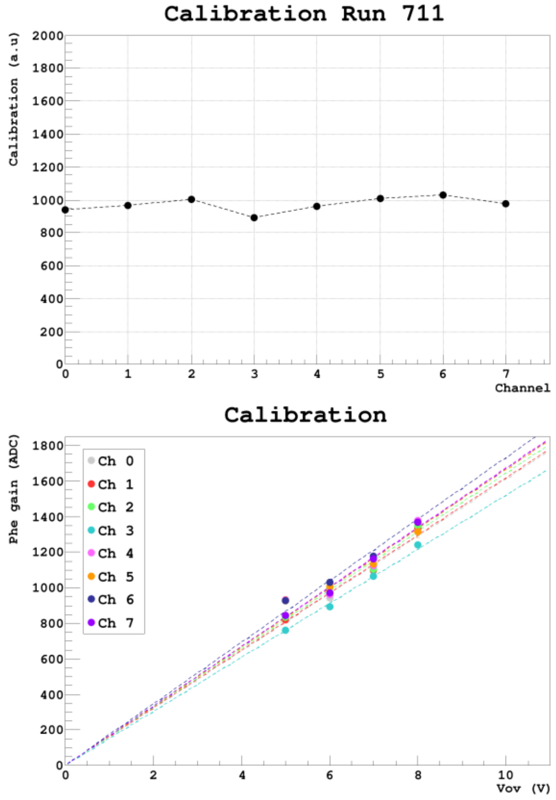


Two-dimensional (area vs height) calibration of the SER for different overvoltage (Vov) values.



Calibration stability between channels.