CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza
INFN LNGS
Ciemat
MultiDark Multimessenger Approach for Dark Matter Detection
GOBIERNO DE ARAGON
Plan de Recuperación, Transformació y Resiliencia
Financiado por la Unión Europea NextGenerationEU

Advanced NaI detectors for Dark Matter search and other applications: the ANAIS+ project

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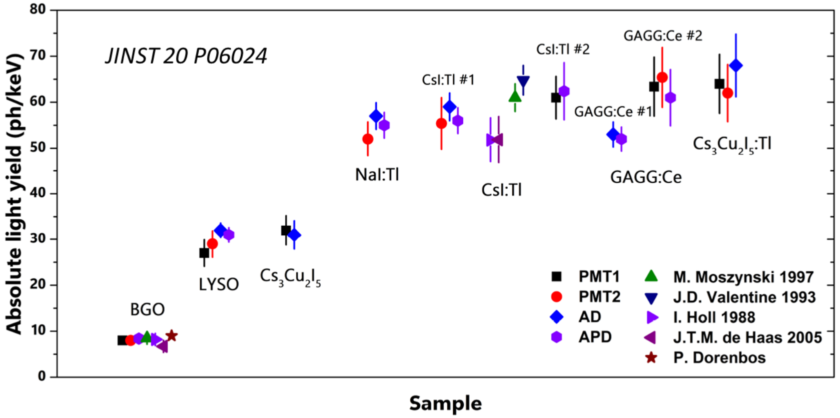
on behalf of the ANAIS+ collaboration

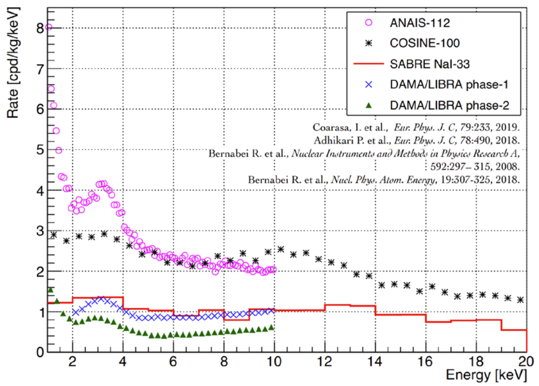
Outline

- Motivation
- The ANAIS+ project
- Current status
- Outlook

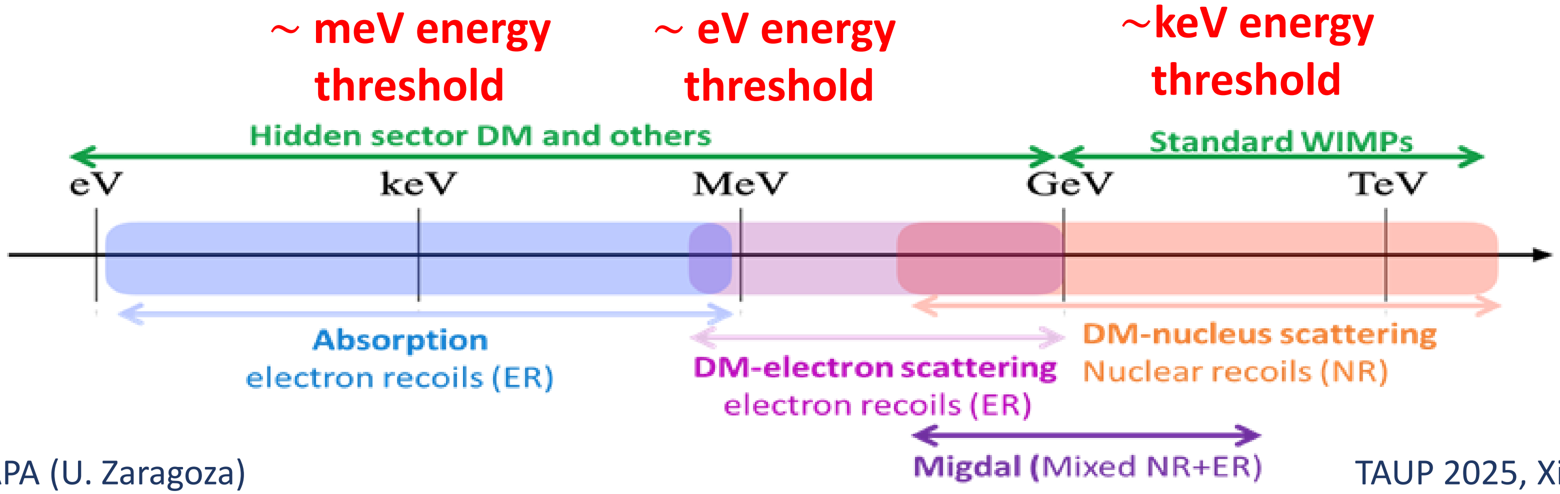
NaI(Tl) scintillators for DM

- well known technology
- easy to scale-up
- cheap
- long stable operation
- high light yield → low energy threshold
- ultra-low background at reach
- Drawback: Highly hygroscopic! ☹





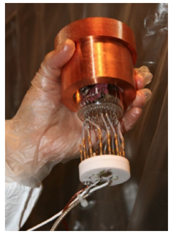
- sensitive to both high (mainly by Iodine target) and low mass (mainly by Na target)
- 100% isotope content sensitive to SD interaction (unpaired proton → complementary search wrt Xe/Ge/Si)
- O(10-100eV) threshold opens the door to dark sector DM searches via electron scattering



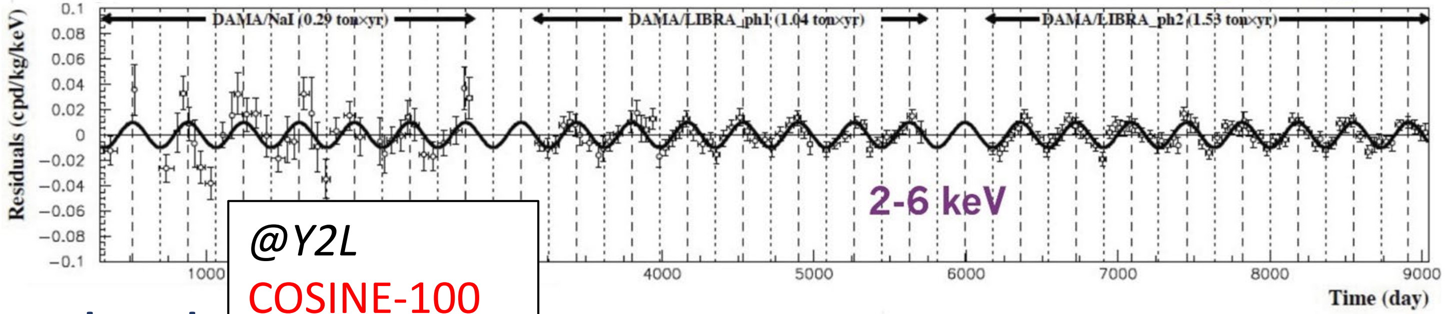
NaI(Tl) scintillators for DM: testing DAMA

NaI(Tl) is the target of the only DM positive signal so far (DAMA/LIBRA annual modulation signal)

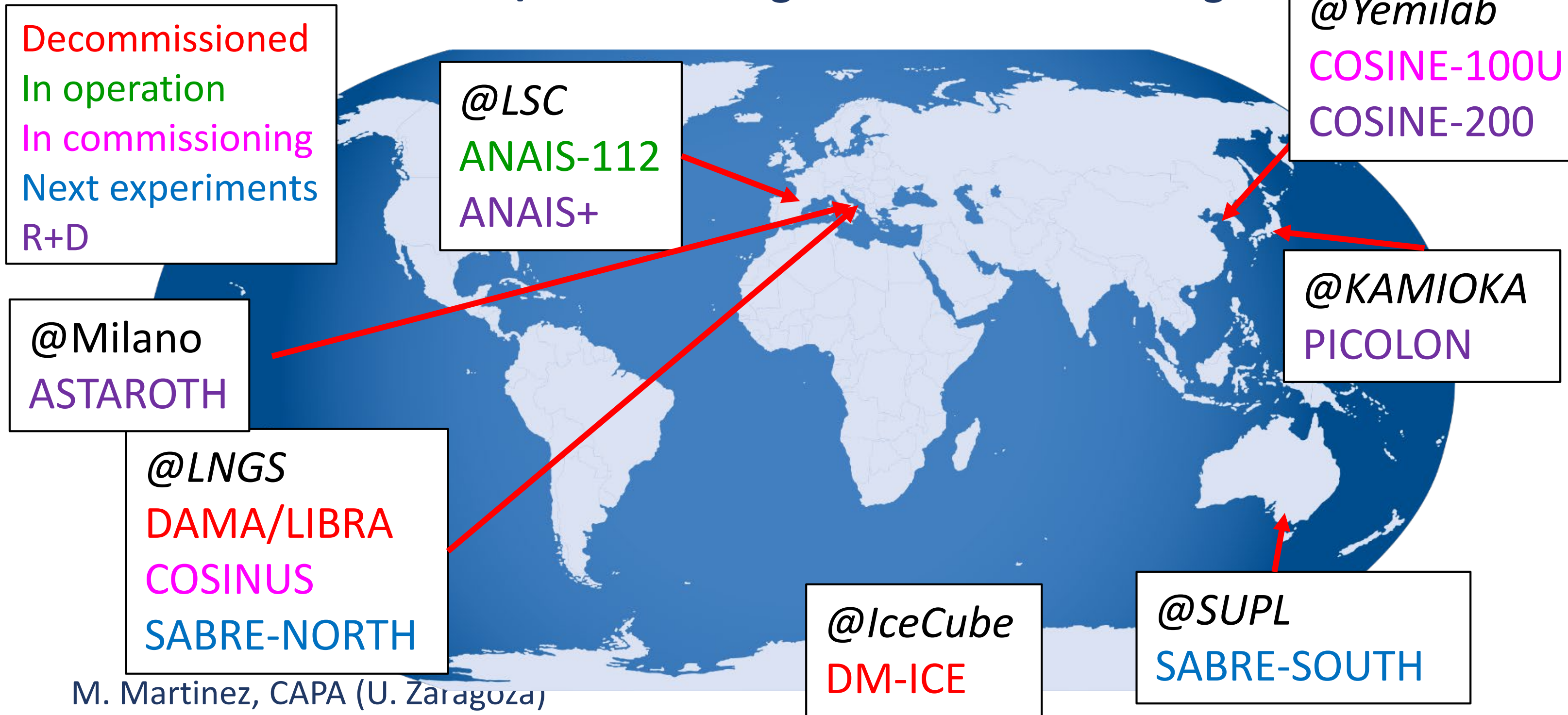
250 kg NaI(Tl) scintillators at LNGS (Italy)



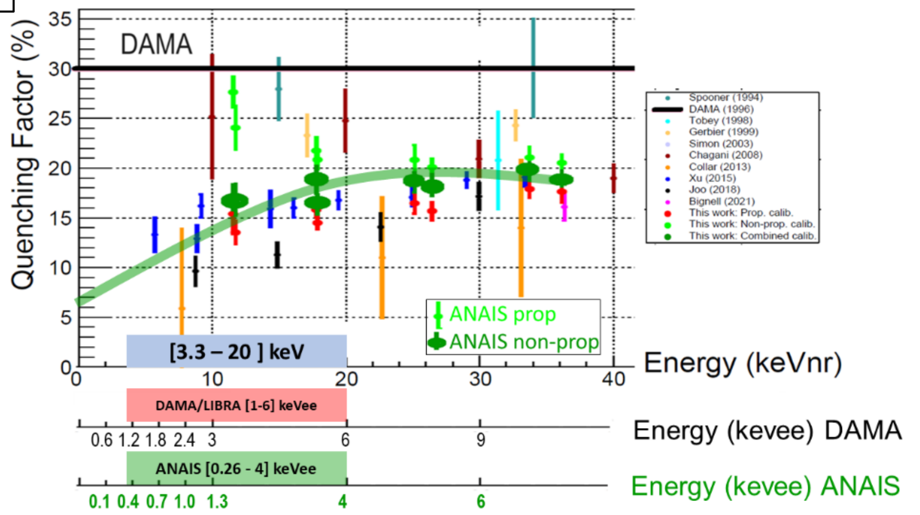
DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr) ***Acos[ω(t-t₀)]***



A lot of efforts to confirm/refute the signal with the same target



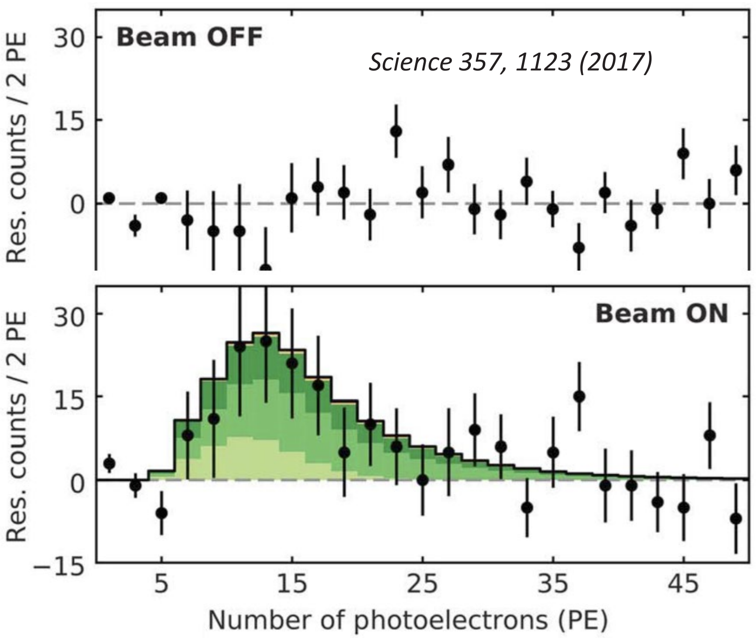
If DAMA QF larger than newer crystals, threshold < 1keVee required

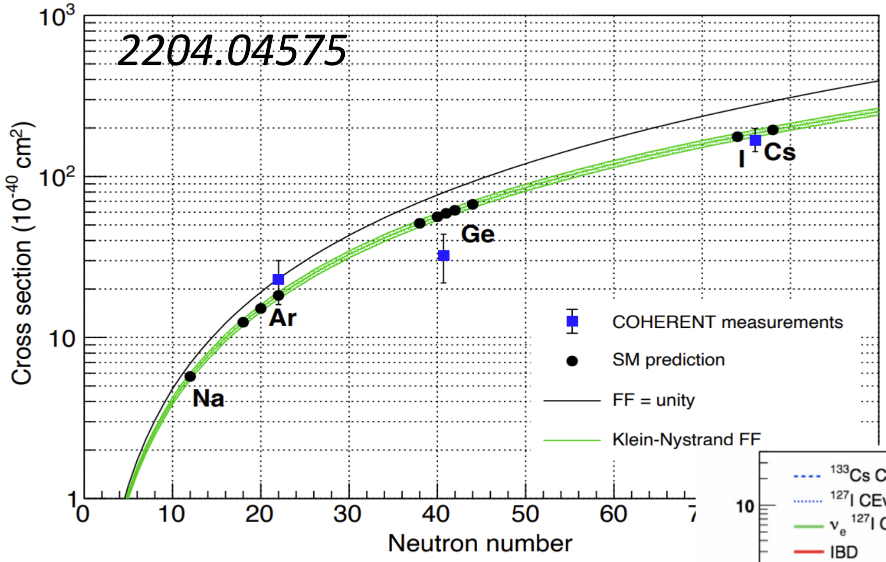


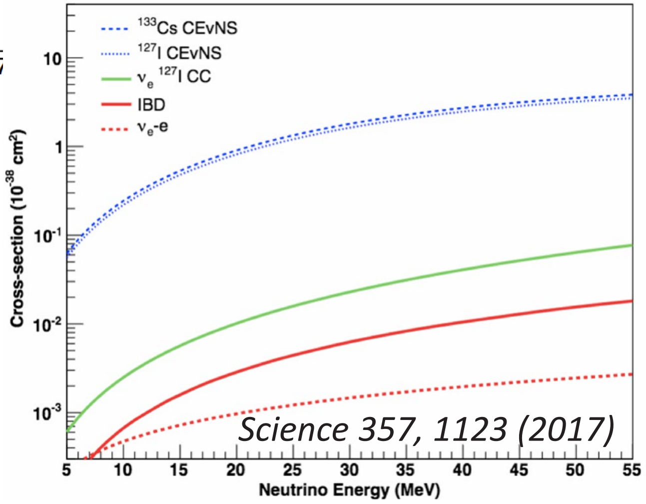
NaI (and CsI) for CEvNS

Threshold below 1 keVee required

CsI[Na] first detector observing CEvNS (COHERENT)







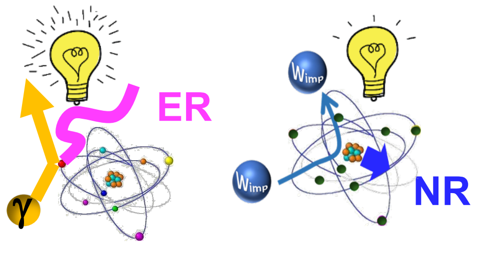
+ broad range of new physics

"Exploring the Sensitivity to Non-Standard Neutrino Interactions of NaI and Cryogenic CsI Detectors at the Spallation Neutron Source", *Phys.Rev.D* 110 (2024) 9, 095027, [2402.16953]

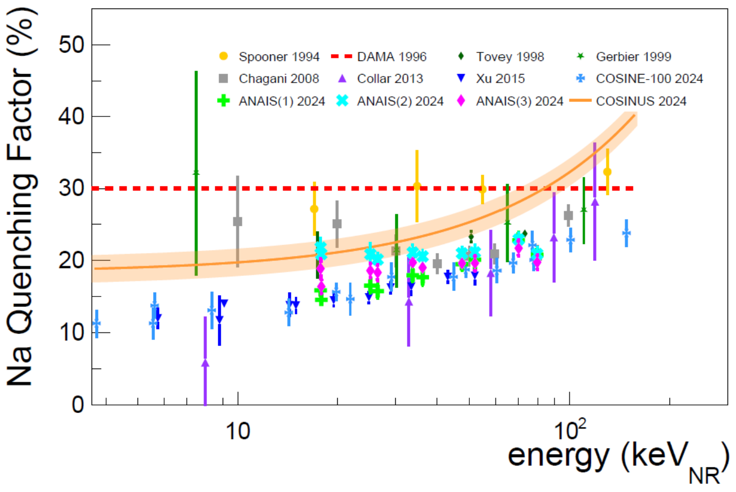
NaI for CEvNS (and DM): nuclear quenching factors

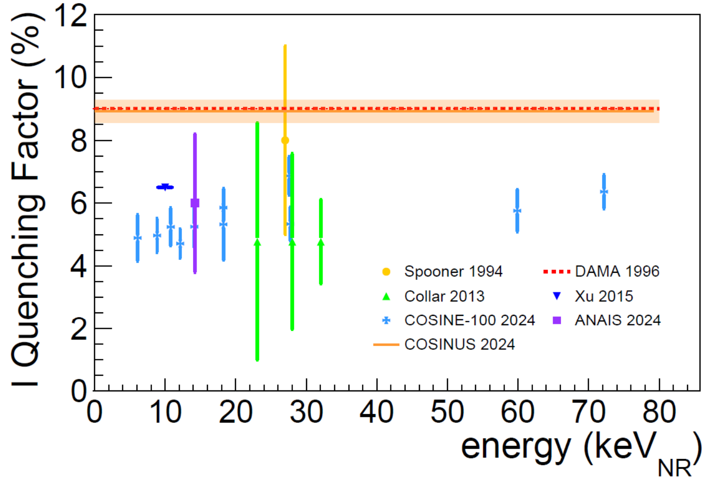
A lot of recent effort to characterize QF (crucial for both DM and CEvNS)

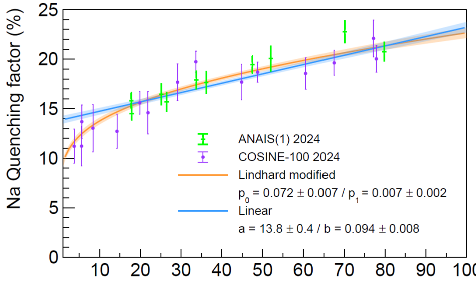
T. Pardo PhD thesis

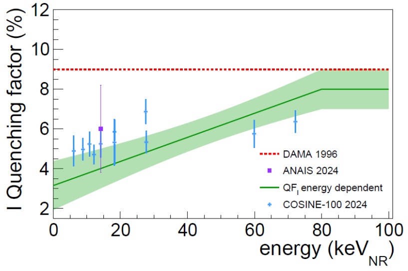


$$QF(E) = \frac{signal_{NR}/keV}{signal_{ER}/keV}$$









- Modified Lindhard model for Na:

$$QF(E_{NR}) = \frac{p_0 g(\epsilon)}{1 + p_0 g(\epsilon)}$$

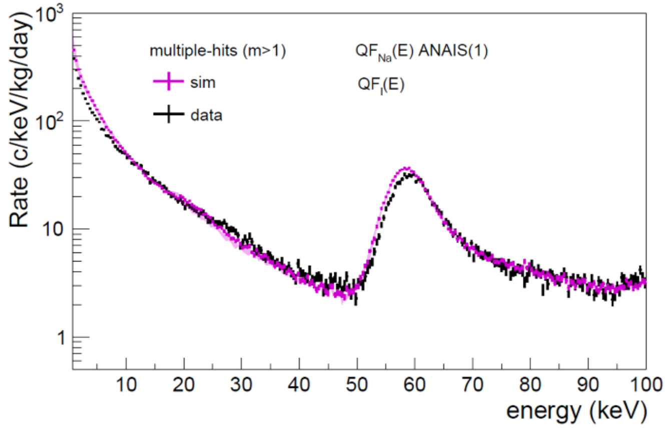
$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

$$\epsilon = p_1 E_{NR}$$

$$p_0 = 0.072 \pm 0.007$$

$$p_1 = 0.007 \pm 0.002$$

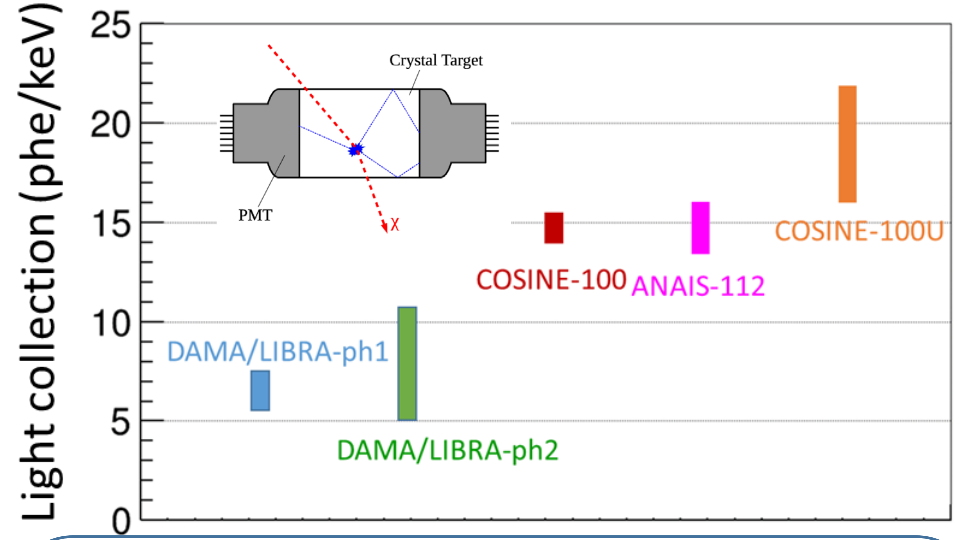
- Linear model for I:



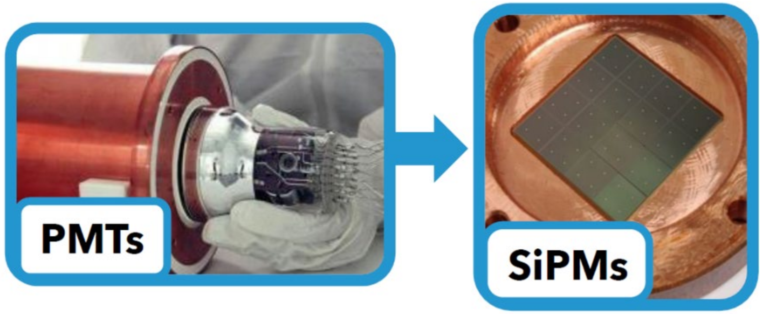
Geant4 simulation of ANAIS-112 on-site neutron calibration in good agreement with these QF

ANAIS+ project: lowering the energy threshold

State-of-the-art with NaI(Tl) + PMTs



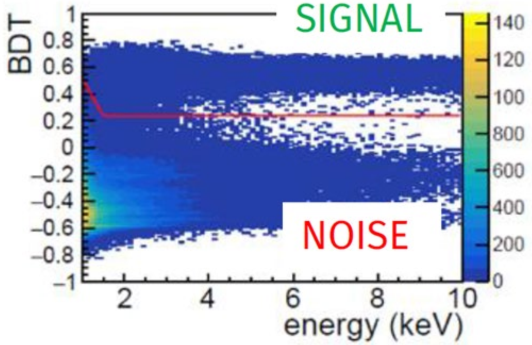
SOLUTION: replace PMTs for SiPMs



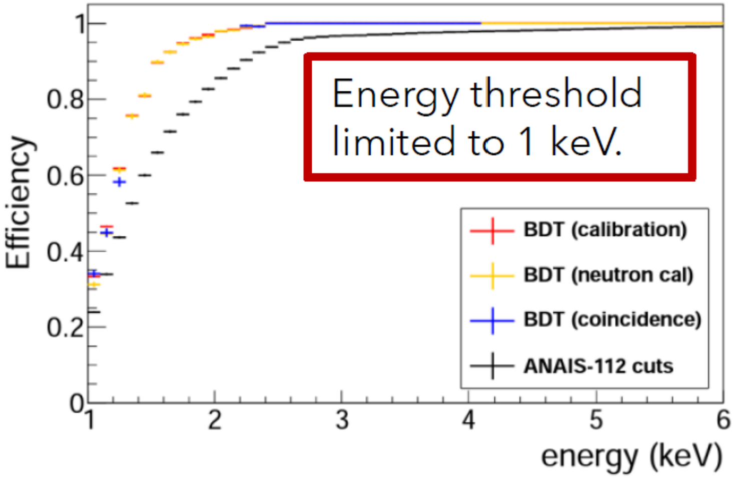
- Reduce "light noise" coming from the PMT (but optical cross-talk has to be carefully handle)
- Increase QE of the light detector

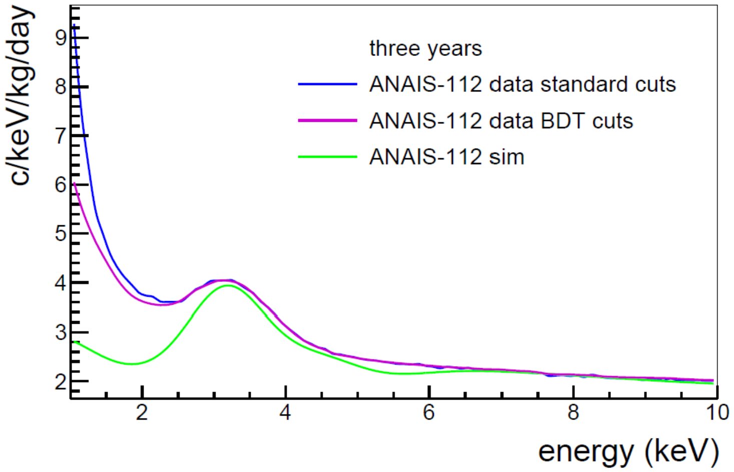
Main problem: **LIGHT NOISE COMING FROM THE PMTs**

At very low energy (<2 keV) population of non-bulk asymmetric events (more light in one PMT wrt the other), possibly with origin in the PMT

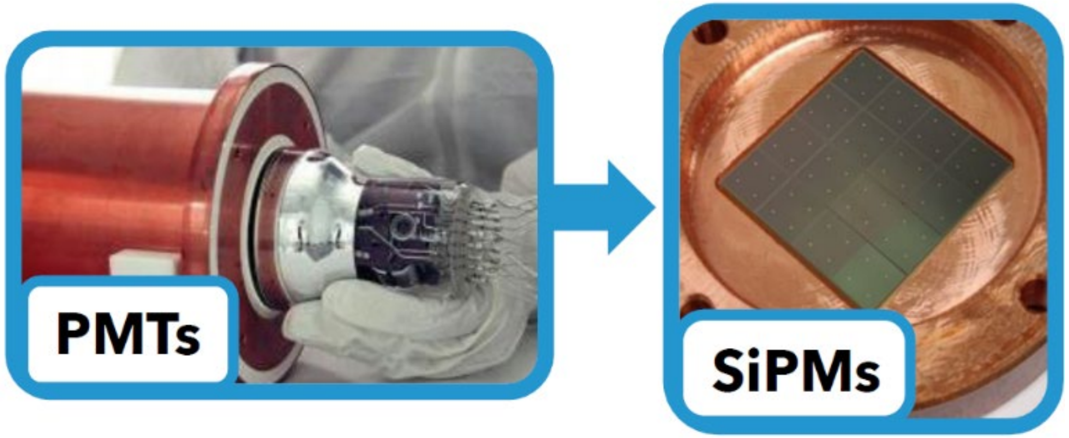


Aggressive filtering has been developed to remove them, but efficiency is low and **limits the energy threshold**

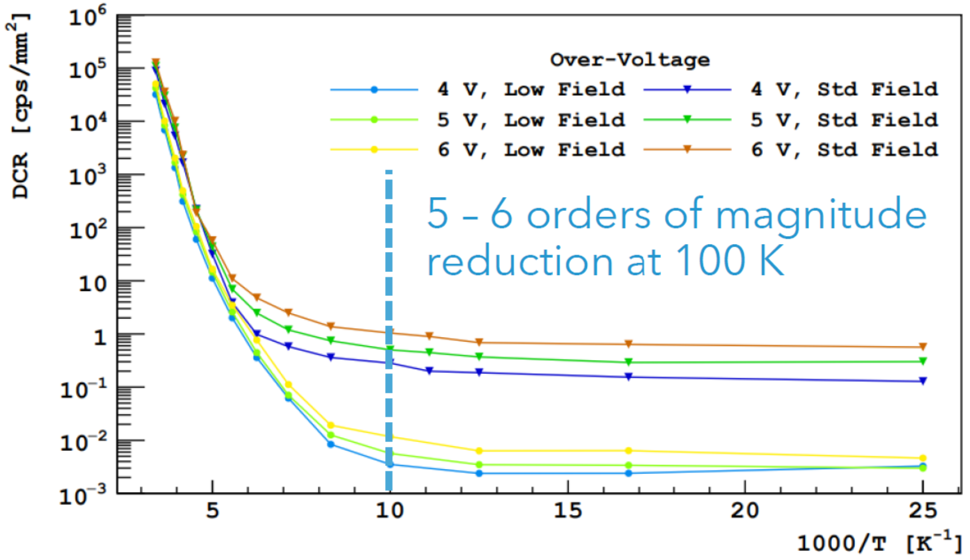




ANAIS+ project: NaI + SiPM @ low T



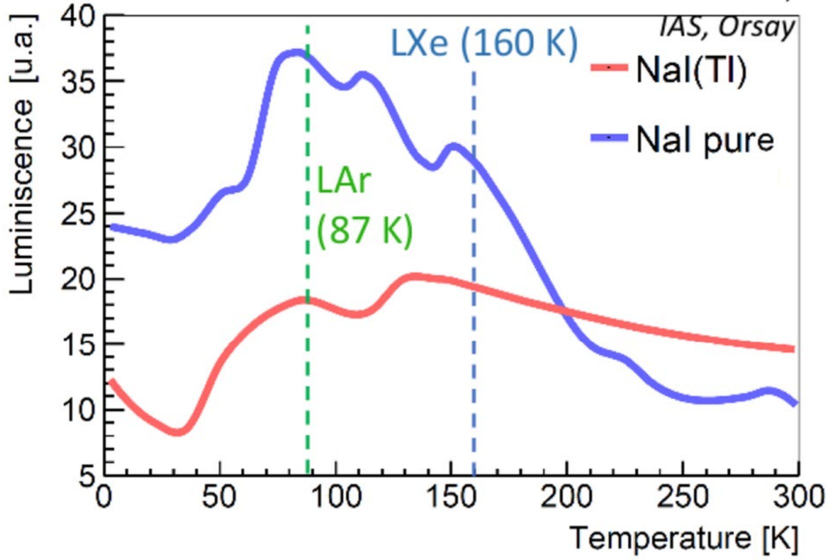
- High QE (≈40 %)
- High radiopurity (lower bkg).
- Low operating voltage (~ 10's V)
- No Cherenkov/HV arc-discharges emissions.
- But high dark current at room T (0.1-1 MHz/mm^2 vs 100-1000 Hz PMTs)
  → **WORK AT LOW T**



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

BONUS:
Undopped NaI is a very good scintillator at low T

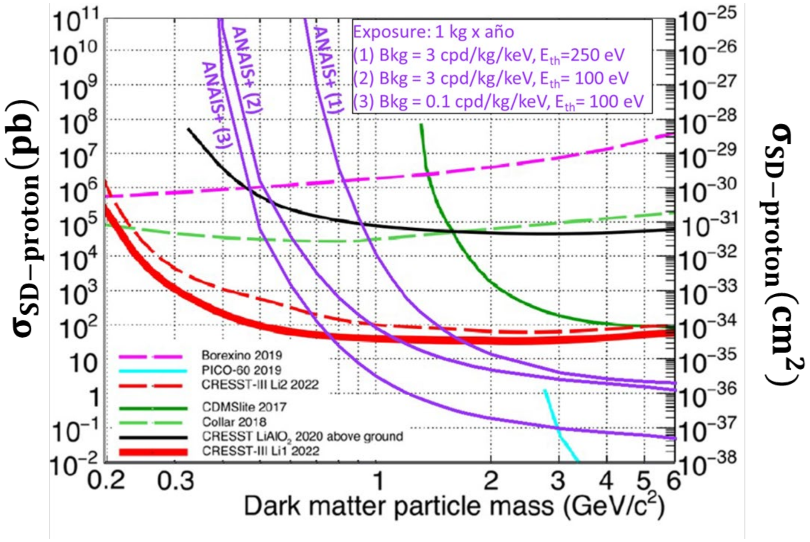
Measurement in collaboration with N. Coron, IAS, Orsay



ANAIS+ project: NaI + SiPM @ low T

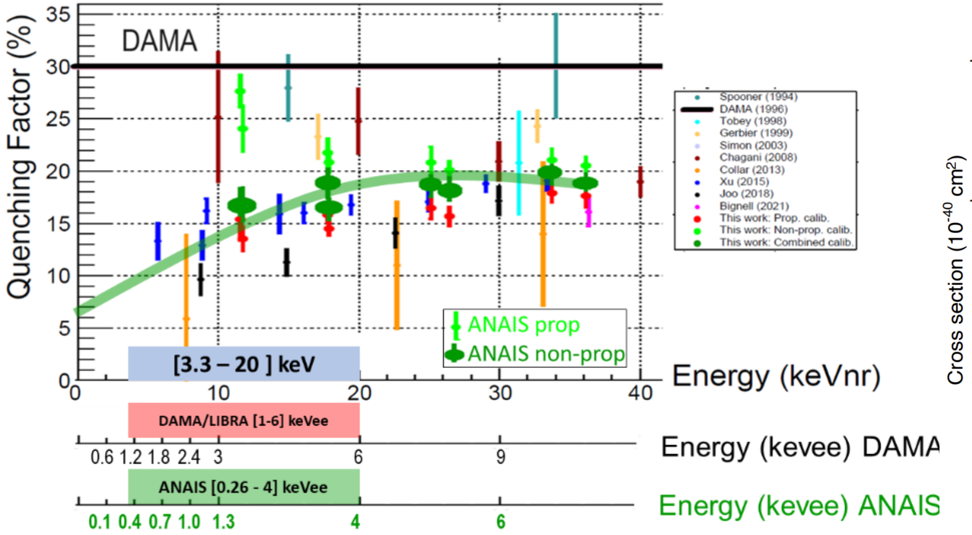
ANAIS+ :O(1kg) NaI+SiPM scintillator at low T in Ar/Xe bath (active veto)
Goal threshold: O(100 eV)

- DM search (especially SD-proton)

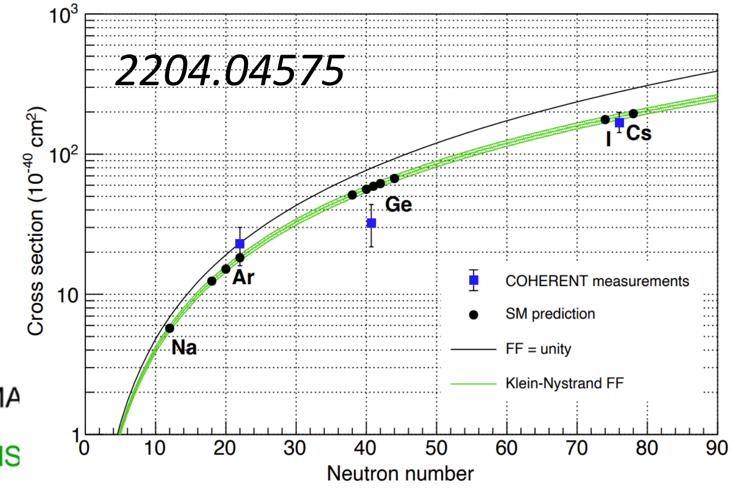


(not considering Migdal)

- rule out any effect related to QF differences to check DAMA/LIBRA

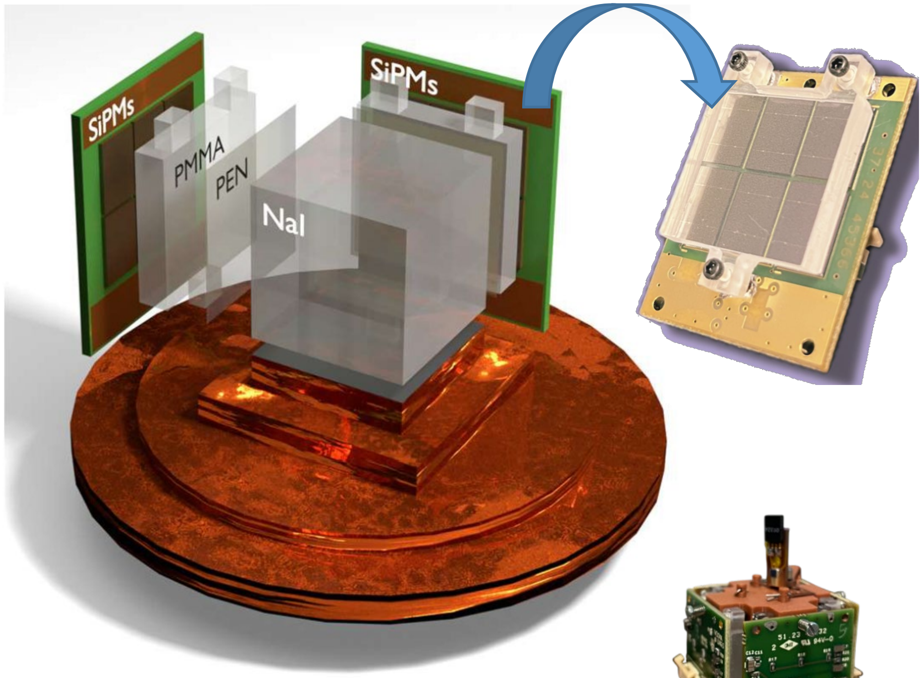


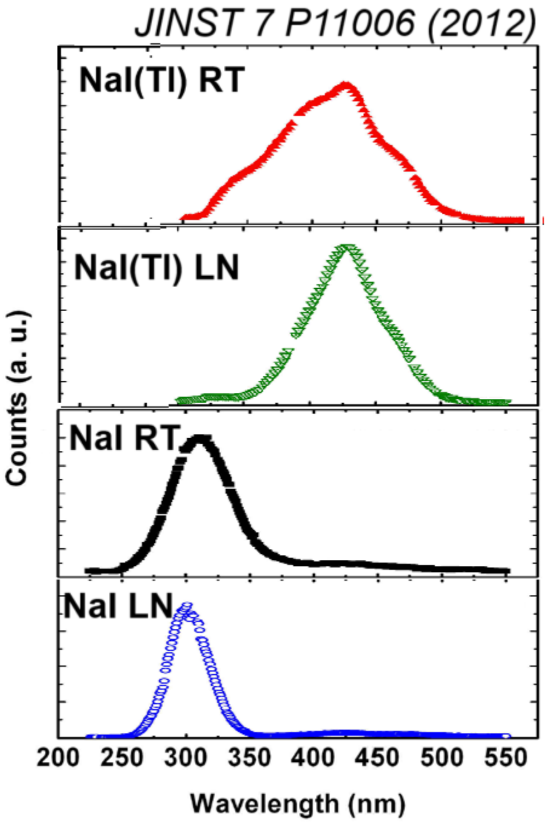
- Explore neutrino detection via CEνNS (NaI & CsI)



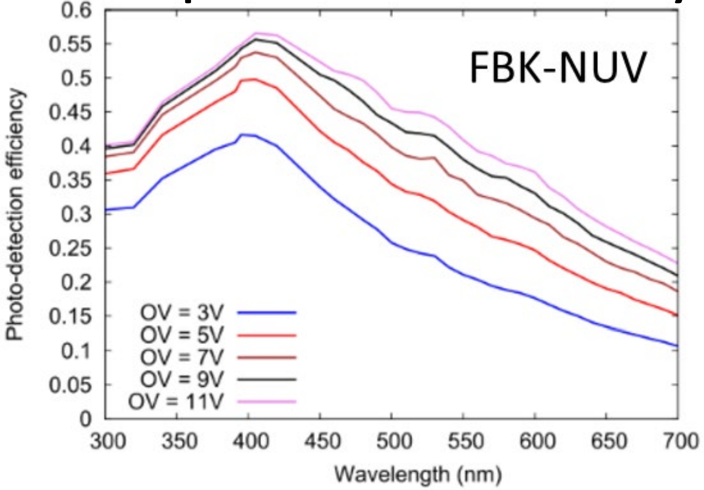
ANAIS+ prototypes

- Cubic **scintillator crystal** (1 in x 1 in x 1 in)
- **4 SiPM boards**, designed and produced at **LNGS**
- Each board is an **array of 6 SiPMs (**FBK-NUV). Sum output
- **PMMA** pieces to **protect** the SiPMs **bonding wires**
- **PEN** (Polyethylenenaphthalate) wavelength shifter ($\lambda_{emission} \approx 420\ nm$)

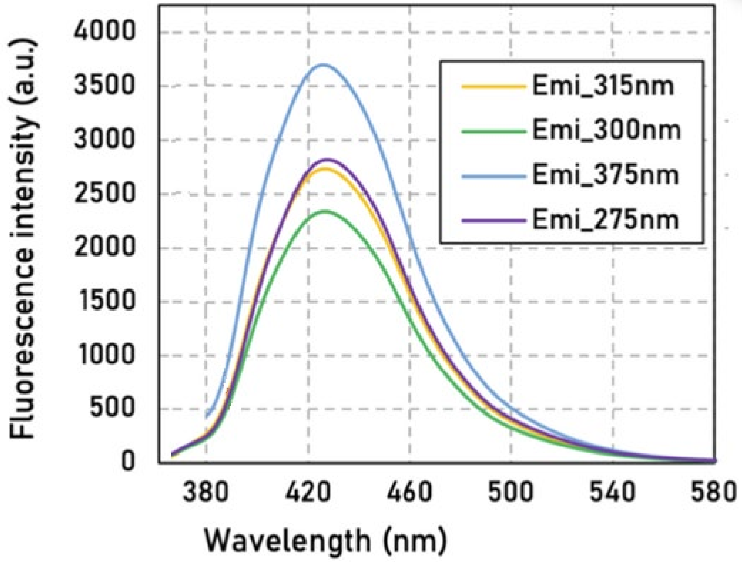




FBK-NUV photodetection efficiency



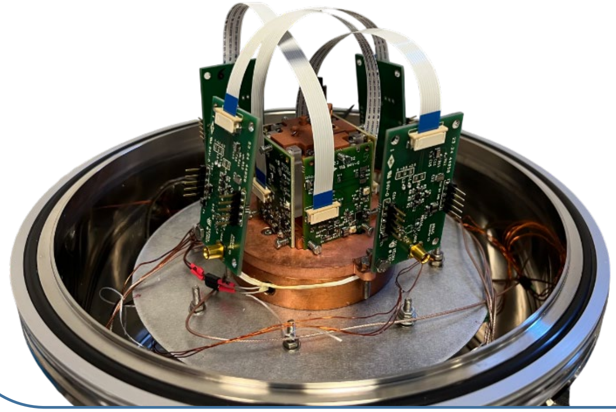
PEN emission for different excitations

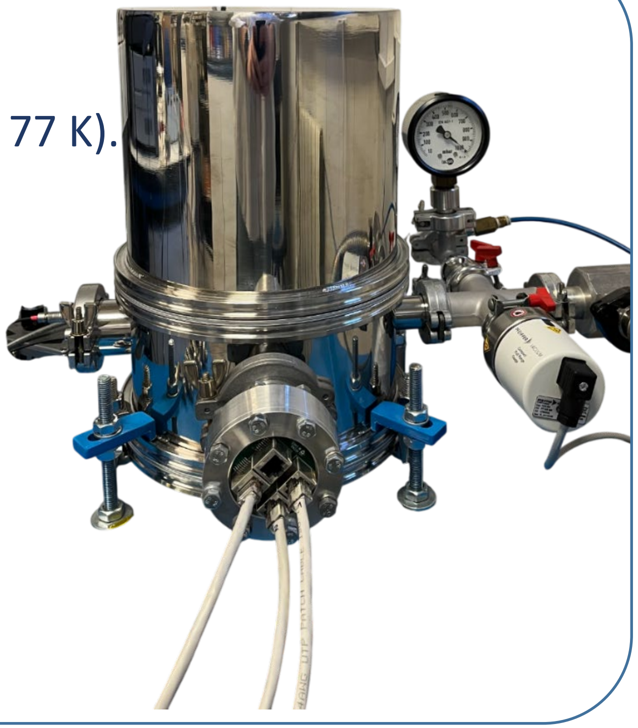


Experimental setup

Cooling system:

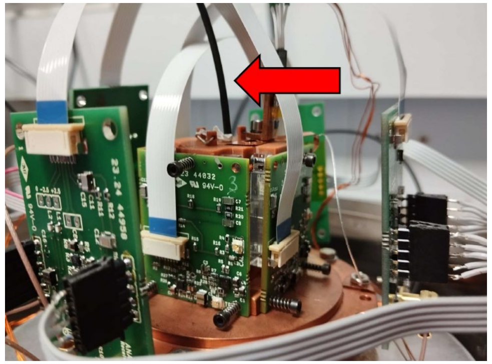
- Cryocooler Sumitomo CH-104 (34 W at 77 K).
- He Sumitomo Compressor FA-20.
- Cold head minimum **T≈30 K.**





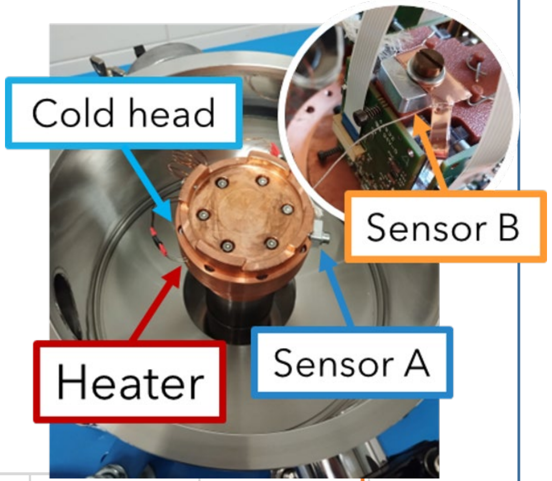
Calibration system

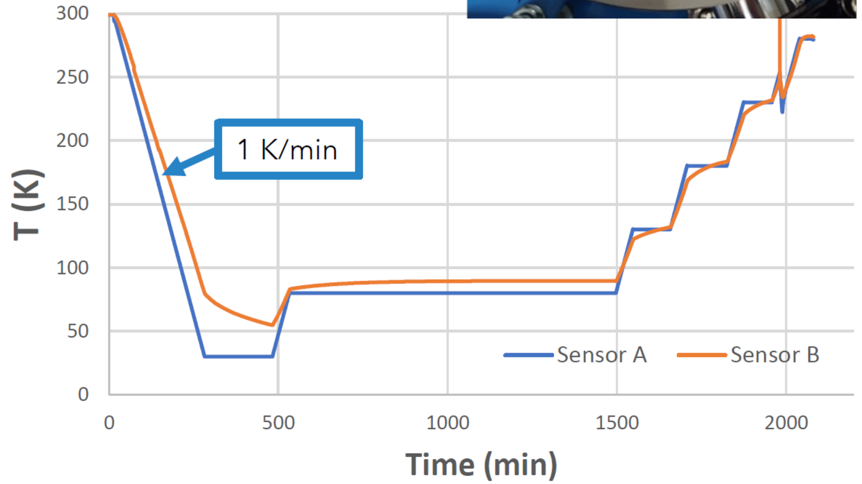
- Low intensity LED + optical fiber
- ^{133}Ba internal source
  (6.6, 31, 81, keV in the ROI)



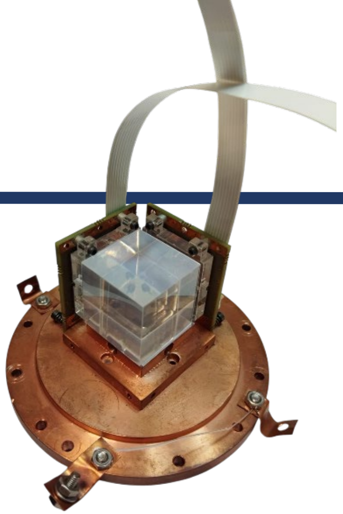
Temperature control:

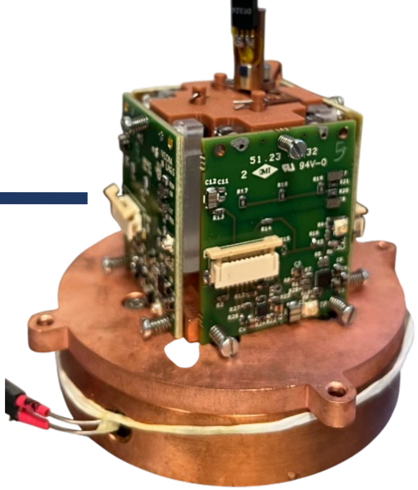
- T controller LakeShore 335
  (heater to regulate temperature).
- Two T sensors
  (cold head & crystal)





ANAIS+ prototypes: OCTOPUS

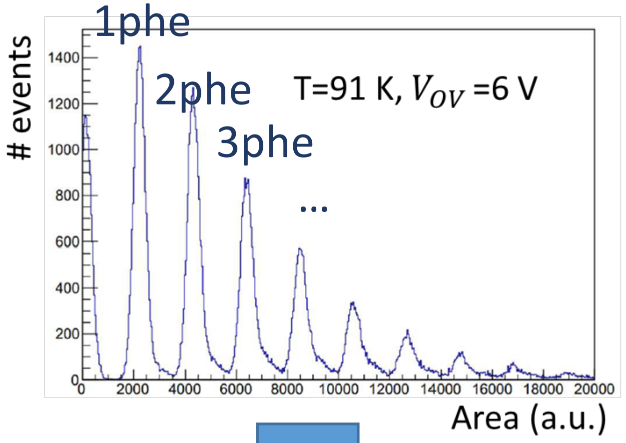


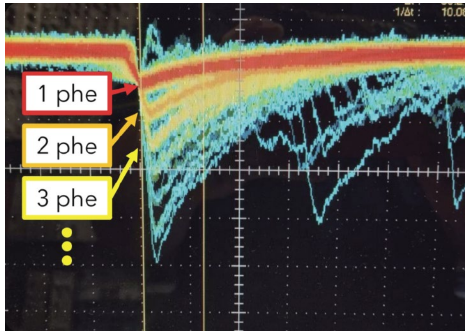


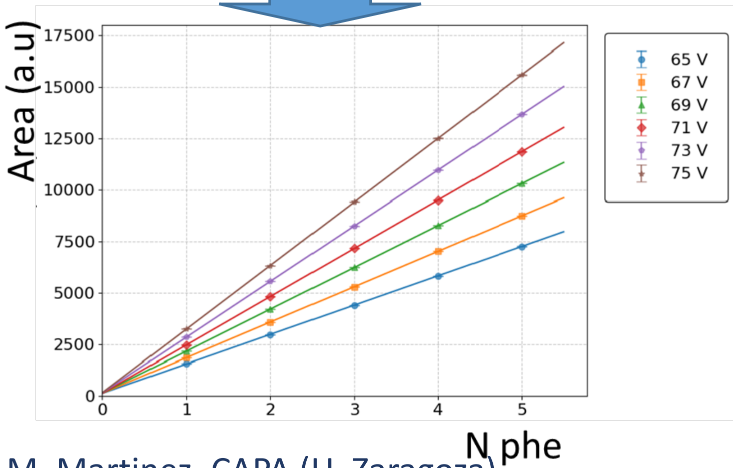
OCTOPUS: First prototype, not hermetically sealed

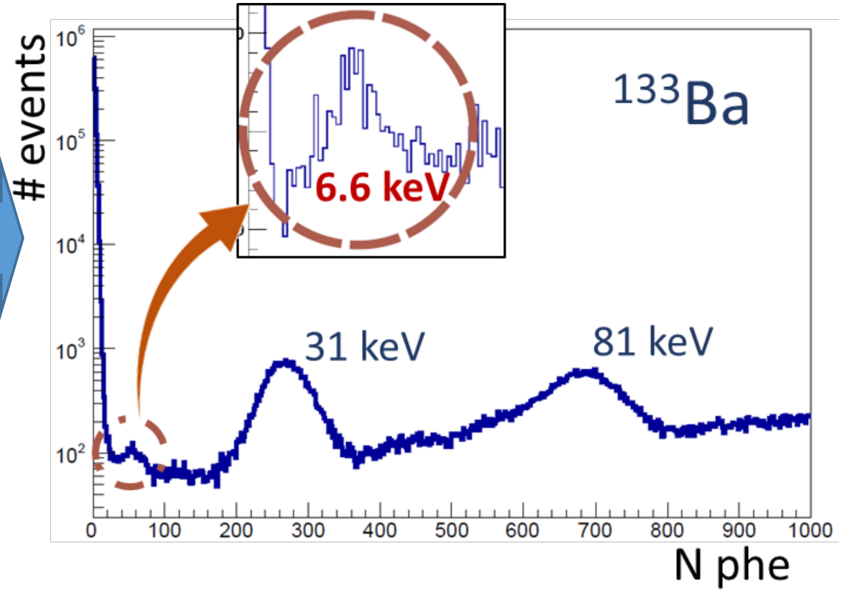
Used with **CsI** to test electronics and calibration systems

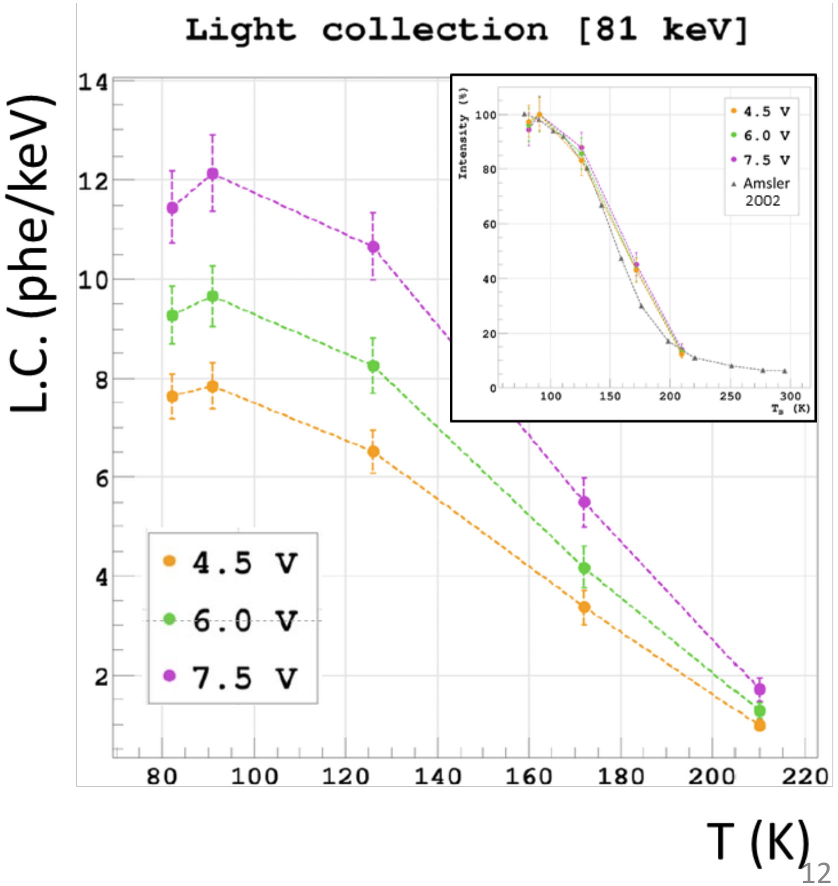
Single electron response calibrated at different T and V using LED pulses











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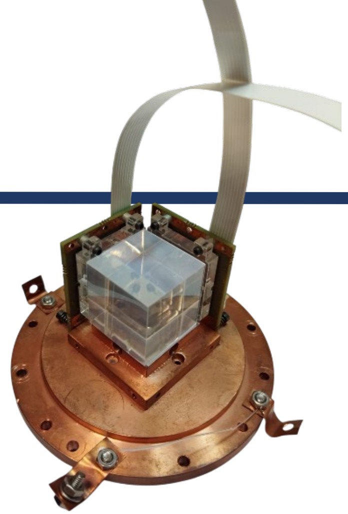

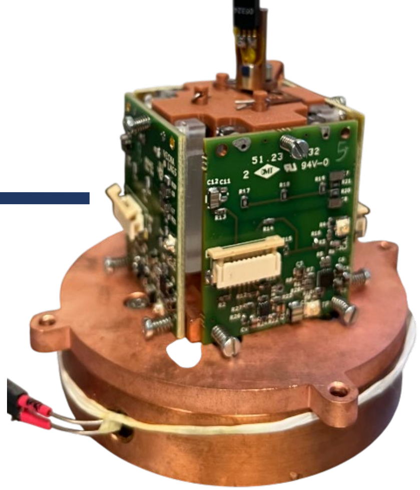

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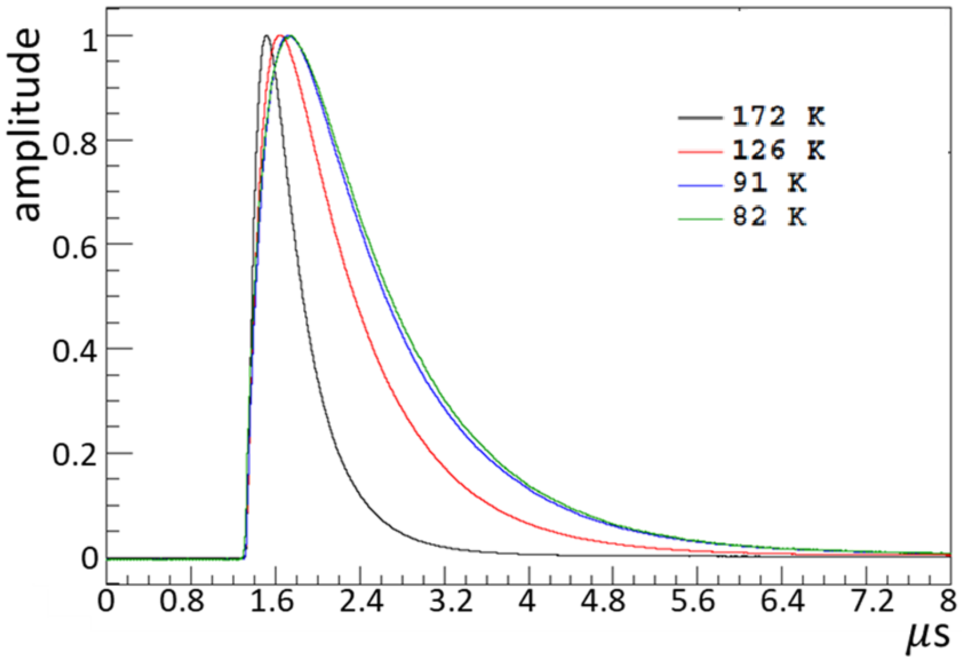
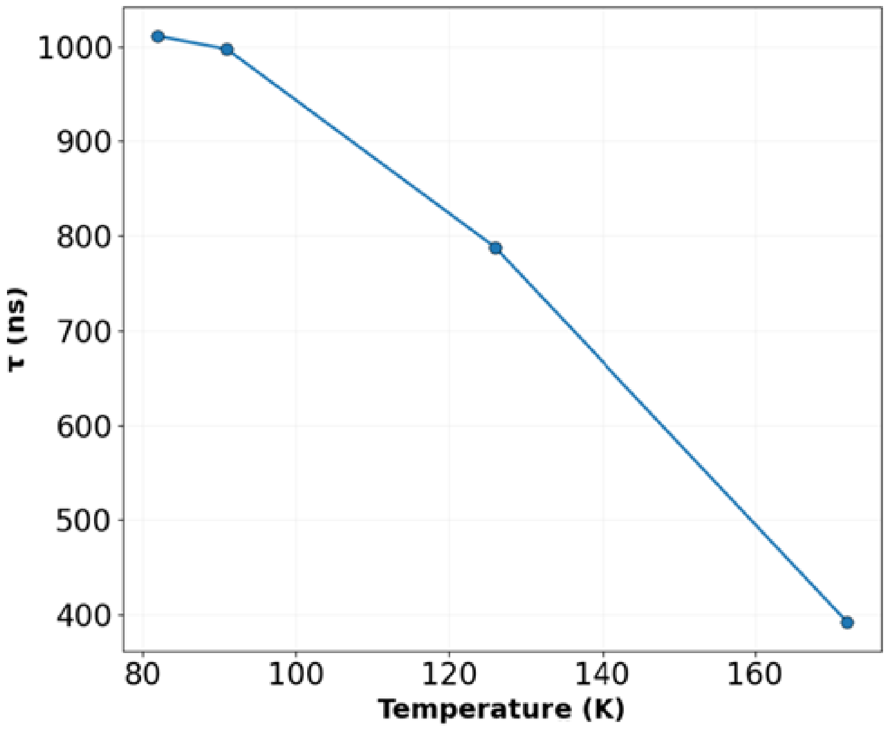
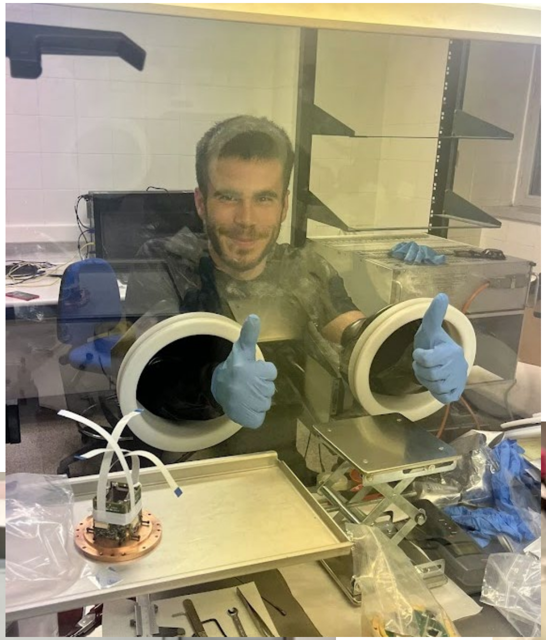
Undoped CsI sctinillating ctes vs T



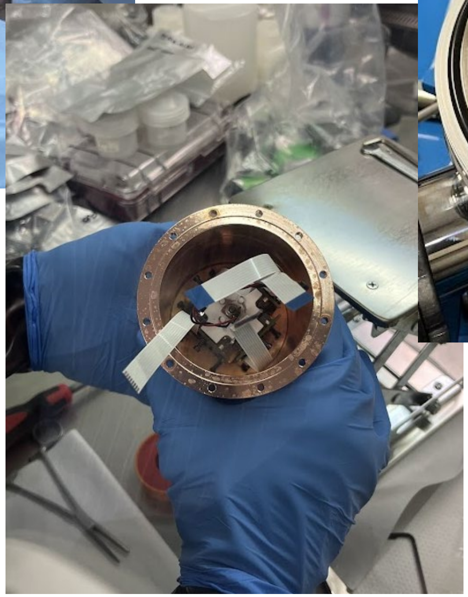


ANAIS+ prototypes: SQUID

SQUID (NaI): same design, but with hermetic Cu encapsulation



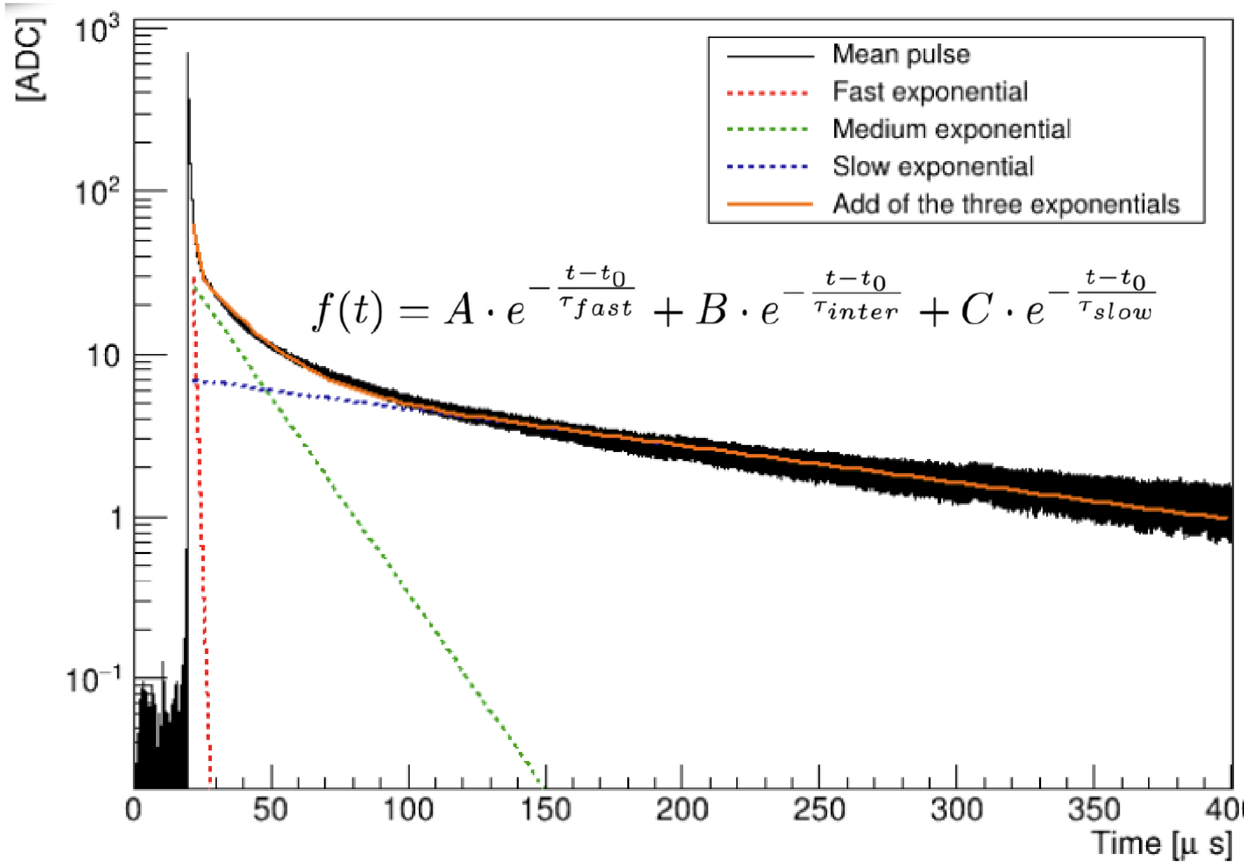


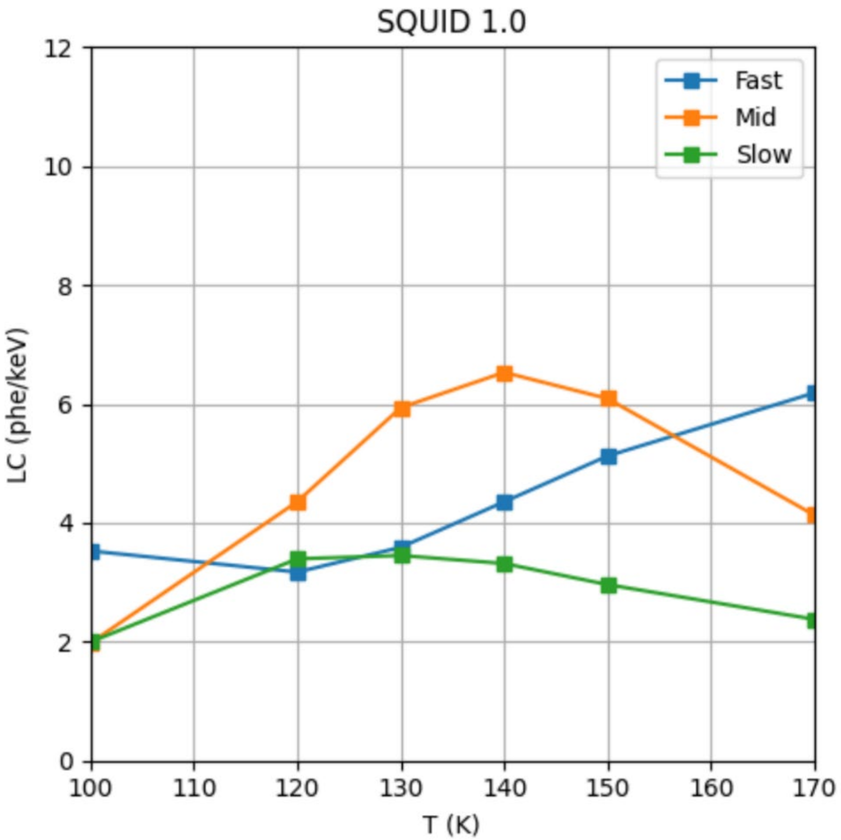



ANAIS+ prototypes: SQUID

SQUID (NaI): same design, but with hermetic Cu encapsulation

Long decay constants. Pulses between [100-200] K well fitted to 3 exponentials



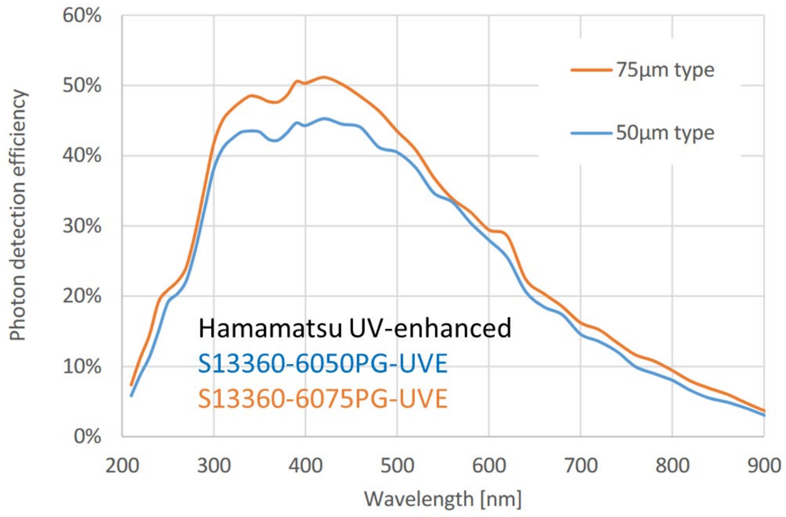


Short/mid term goals

Reduction of the energy threshold:
• Test Hamamatsu SiPM, easier to integrate and with VUV sensitivity
• Remove the PMMA layer that protects the SIPM & PEN

Reduction of the background level:
Testing the ANAIS+ prototype in a liquid Ar tank in collaboration with Ciemat @LSC:
• 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 (40K, 210Pb)



Summary

- 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 processes (e.g. CEvNS)
- ANAIS+ is one of the R&D projects working in this direction.
- First ANAIS+ prototypes under test with SiPM designed in LNGS. Successful detection of low-energy signals in pure CsI and NaI crystals. Work on UV-optimized system to improve light collection
- Long scintillating constants observed in NaI at [100-200] K can limit operation in this temperature range.
- More radiopure crystals are needed to reach the ANAIS+ goals. Work is ongoing.
- Coming soon: 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 for your attention!

Centro de Astropartículas y Física de Altas Energías
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Plan de Recuperación, Transformación y Resiliencia

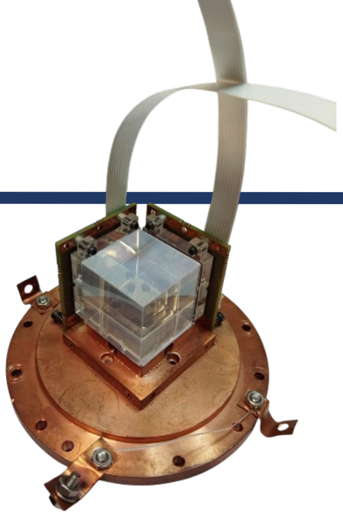
Financiado por la Unión Europea NextGenerationEU

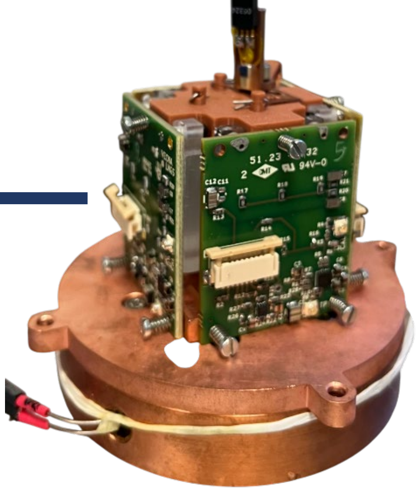
MultiDark Multimessenger Approach for Dark Matter Detection

ANAIS experiment operation is presently financially supported by MICIU/AEI/10.13039/501100011033 (Grants No. PID2022-138357NB-C21 and PID2019-104374GB-I00), and Unión Europea NextGenerationEU/PRTR (AstroHEP) and the Gobierno de Aragón. Funding from Grant FPA2017-83133-P, Consolider-Ingenio 2010 Programme under grants MULTIDARK CSD2009-00064 and CPAN CSD2007-00042, the Gobierno de Aragón and the LSC Consortium made possible the setting-up of the detectors. The technical support from LSC and GIFNA staff as well as from Servicios de Apoyo a la Investigación de la Universidad de Zaragoza (SAIs) is warmly acknowledged.

backup

ANAIS+ prototypes: OCTOPUS

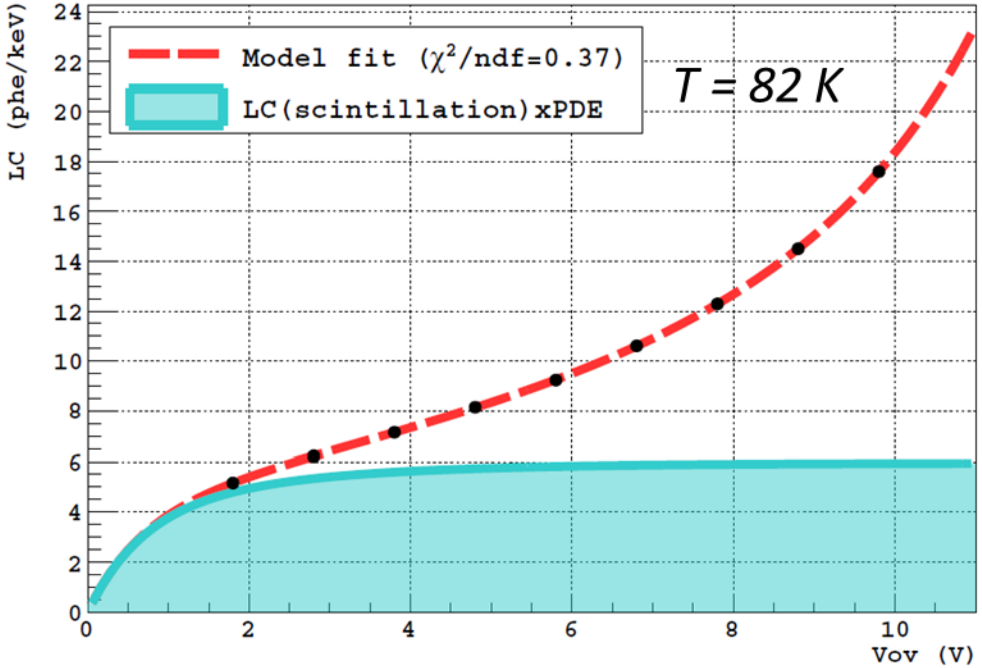




OCTOPUS: First prototype, not hermetically sealed

Used with **CsI** to test electronics and calibration systems

Disentangling dark current and cross-talk contributions



$$LC(V_{OV}) = \mu_{CT}\left(LC_{max}^{scint}\frac{PDE(V_{OV})}{PDE_{max}} + DC(V_{OV})\right)$$

$\mu_{CT}(V_{OV})$ = cross-talk gain = $\frac{1}{1-\lambda_{CT}(V_{OV})}$

$\lambda_{CT}(V_{OV})$ =cross-talk prob = $\xi_{CT}\left(1 - \exp\left(\frac{V_{OV}}{V_h}\right)\right)$

$DC(V_{OV})$ = dark current contribution

Following "SiPM cross-talk in liquid argon detectors", [2201.01632]