Hunting for Dark Matter with ANAIS-112: latest results and ongoing work

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on behalf of the ANAIS collaboration

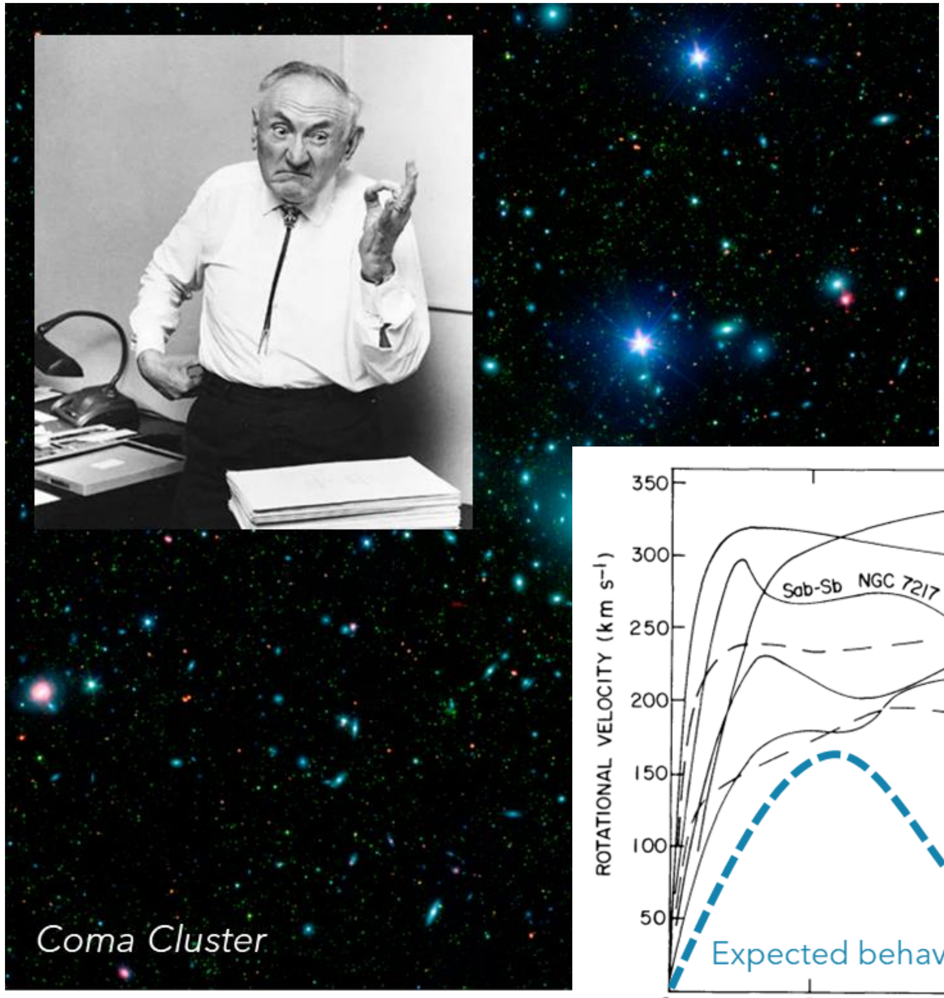
Universidad Zaragoza 1542

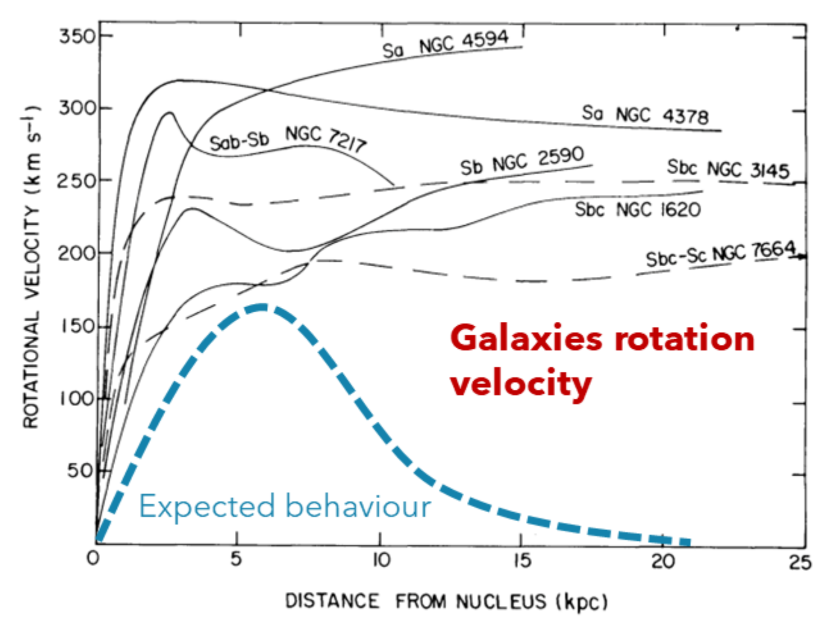
CAPA

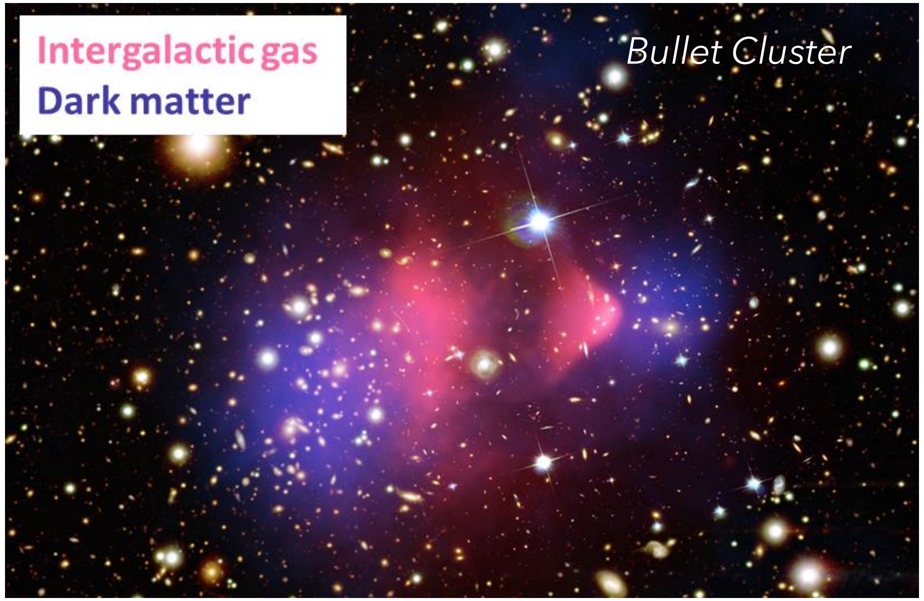
ANAIS

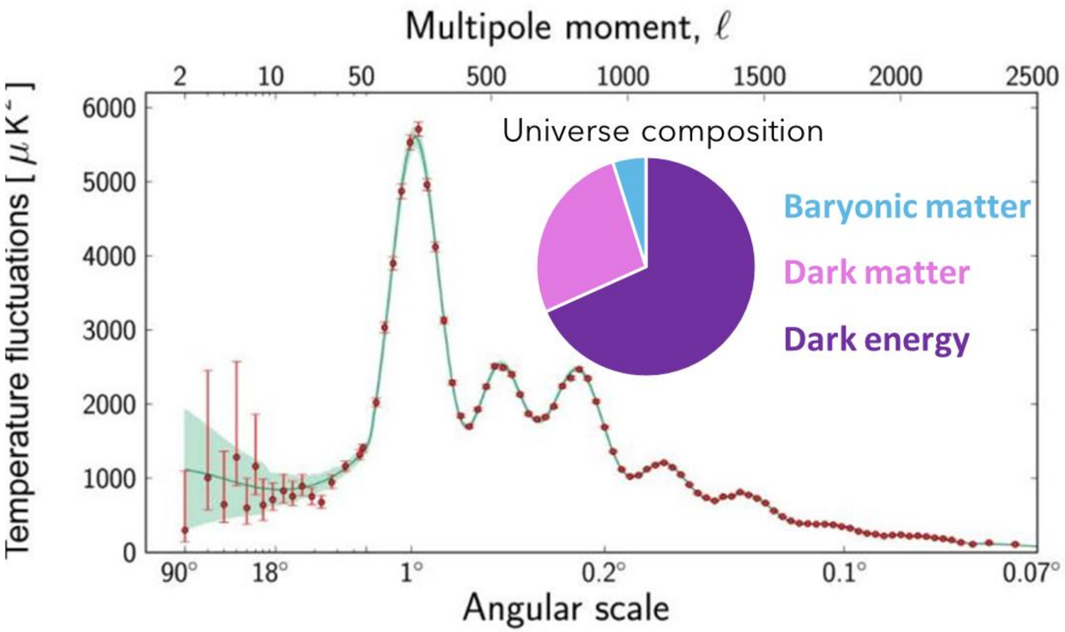
Dark Matter

- Multiple evidences of the presence of dark matter from experimental observations since the 30s.



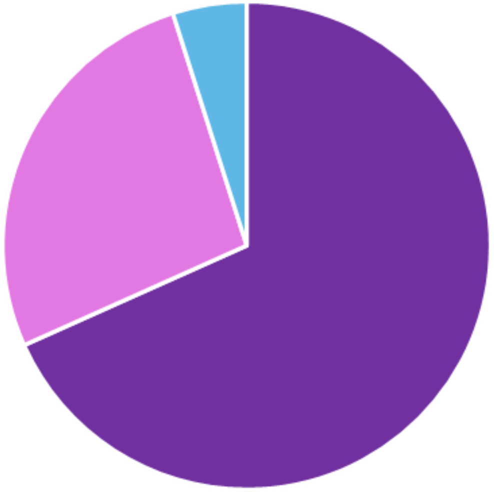






Dark Matter

Universe composition



Baryonic matter

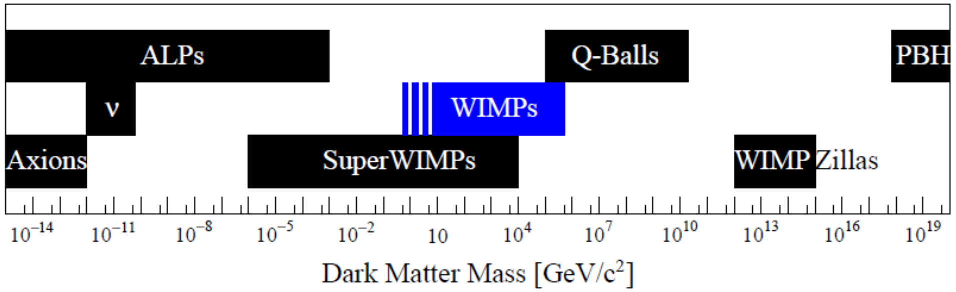
Dark matter

Dark energy

What is DM?

- ❑ Massive particles.
- ❑ Non-baryonic.
- ❑ Without electromagnetic interaction or very weakly coupled to the photon.
- ❑ Weak self-interactions.
- ❑ Weak interactions with baryons.

Axions | WIMPs | Sterile neutrinos | SuperWIMPs | Primordial black holes | ...



Marc Schumann 2019 J. Phys. G: Nucl. Part. Phys. ***46*** *103003*

Dark Matter

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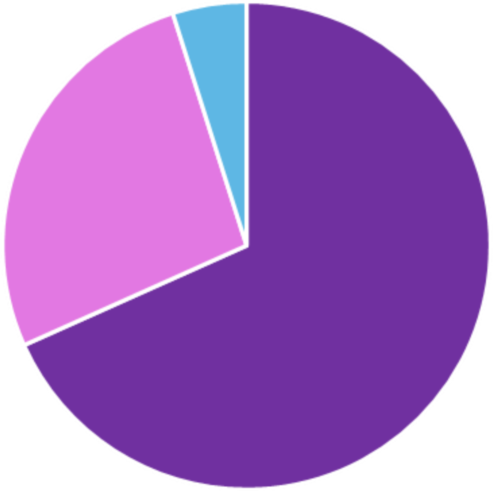

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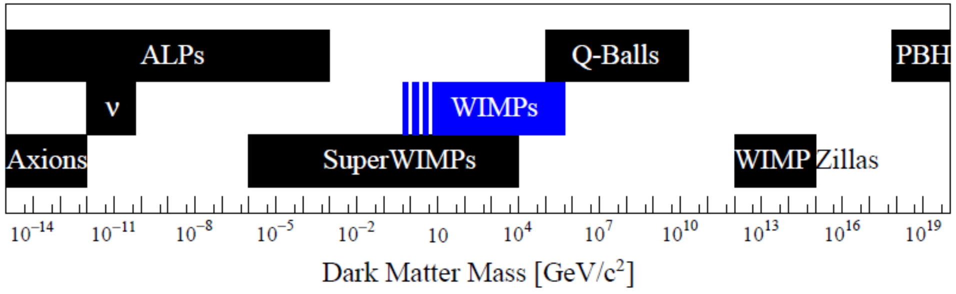
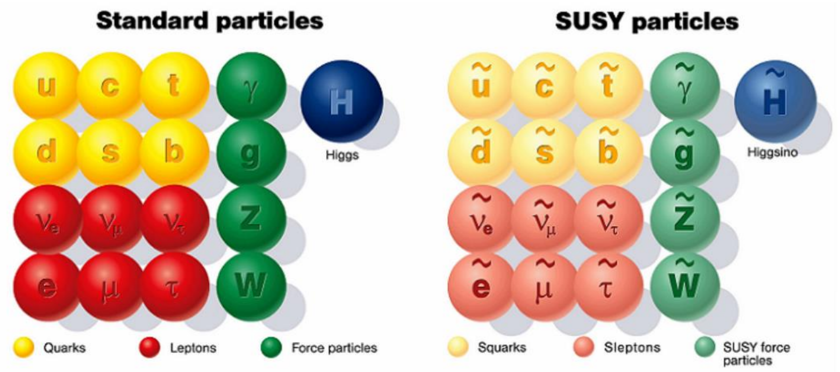
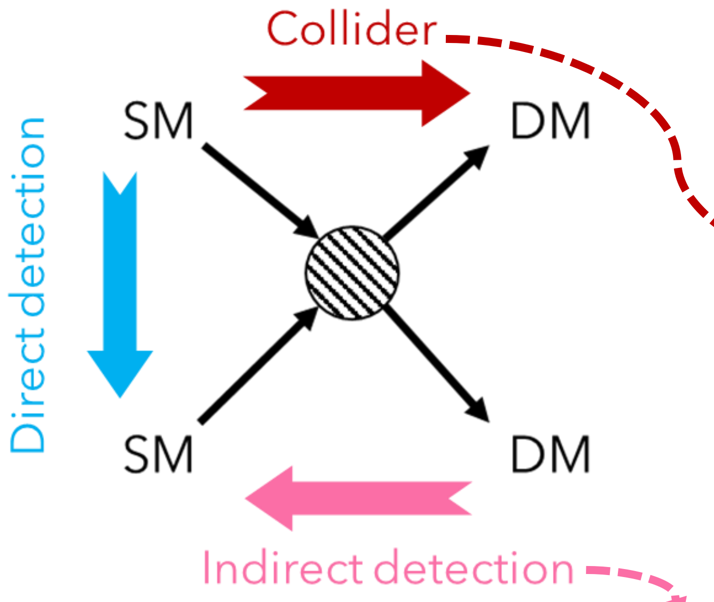


WIMPs (Weakly Interacting Massive Particles)

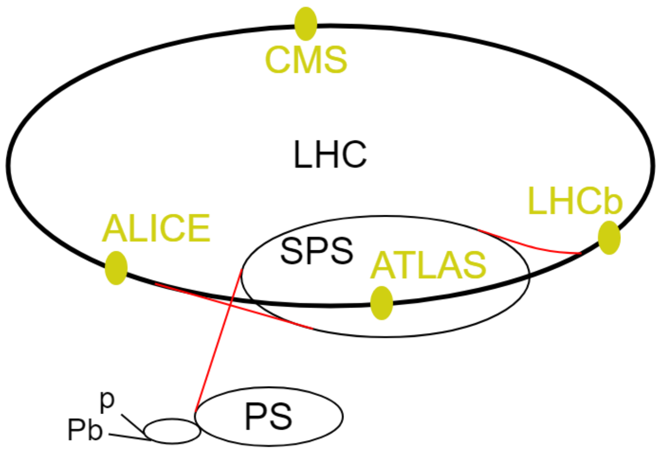
- Mass range: 1 – 10^5 GeV/c^2
- $\sigma_{\text{WIMP-Nucleon}}$: 10^{-41} – 10^{-51} cm^2
- WIMP candidates arise naturally in many extensions of the Standard Model, as SUSY theories
- Its thermal production can explain the dark matter abundance of the universe.

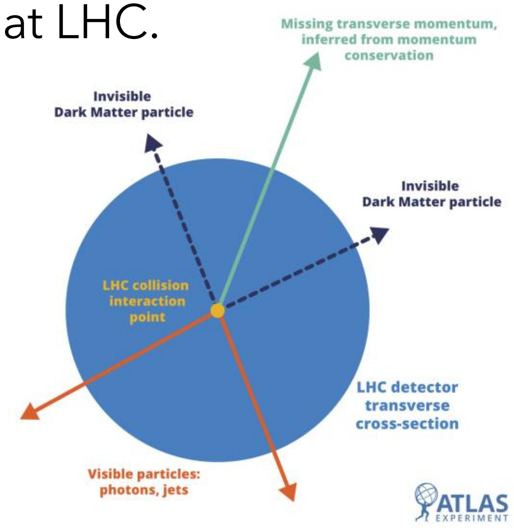


Dark Matter: detection



Looking for Dark Matter production at LHC.



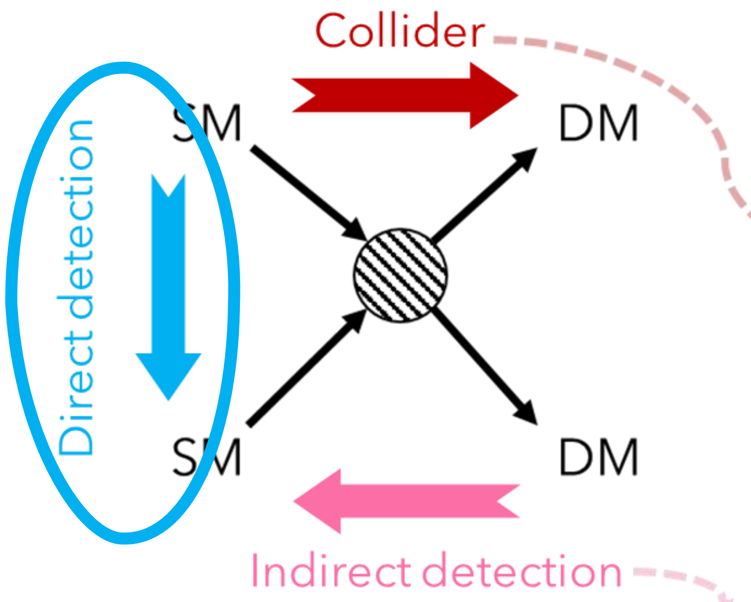


Aiming to detect SM particles produced by the annihilation/decay of DM particles.

For example: neutrino telescopes.

ANTARES: ν telescope placed at the bottom of the Mediterranean sea.

Dark Matter: detection



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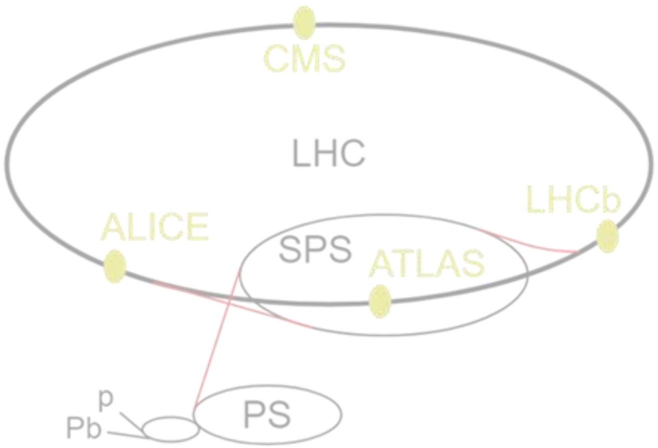

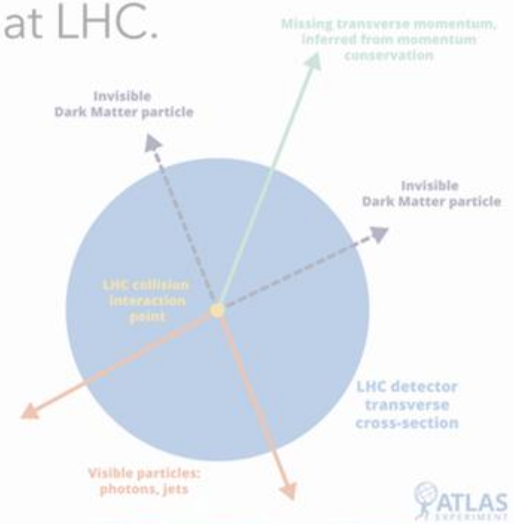

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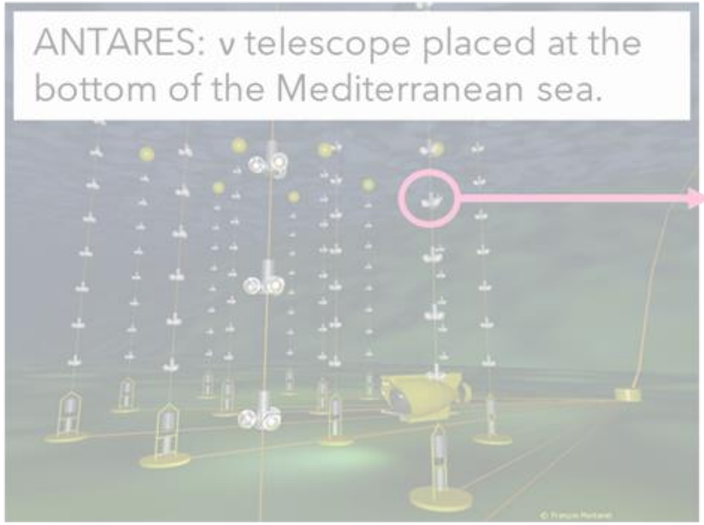
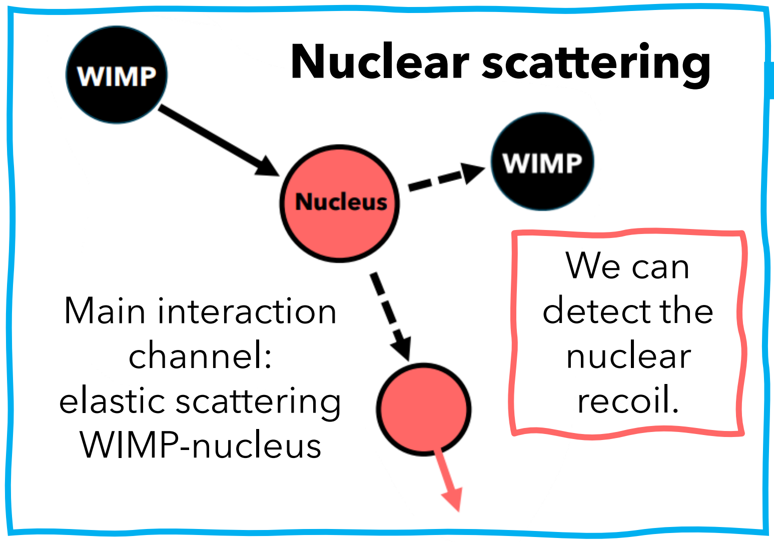


ANTARES: ν telescope placed at the bottom of the Mediterranean sea.

Dark Matter: direct detection



$$\frac{dR}{dE_{nr}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{min}}^{v_{max}} v f(v) \frac{d\sigma}{dE_{nr}} dv$$

Expected interaction rate

Dependency with the relative velocity between WIMPs and nuclei.

ρ_0= local dark matter density

M= target mass

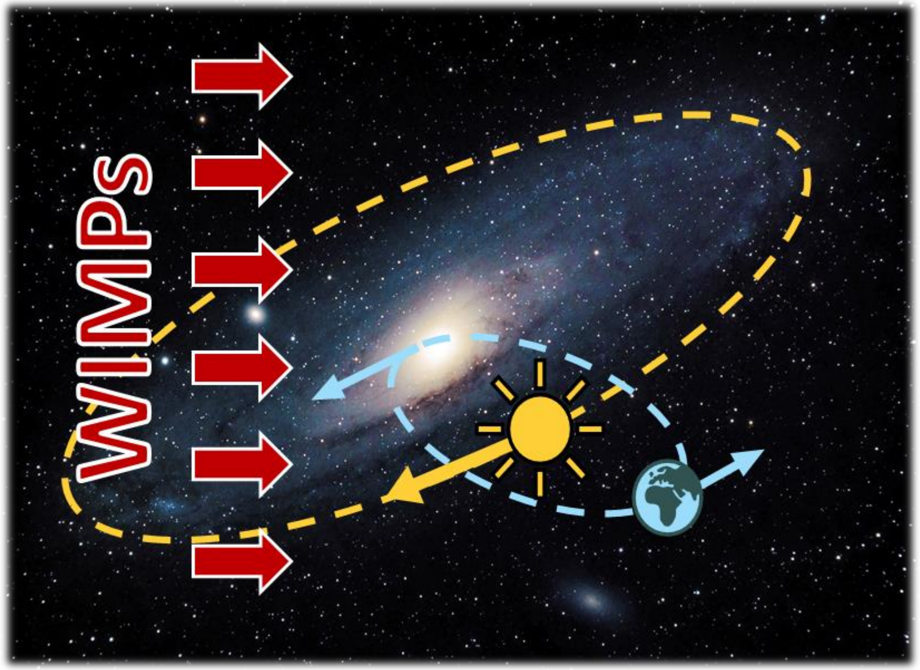
m_N= nucleus mass

m_χ= WIMP mass

$f(v)$= normalized WIMP velocity distribution

v_{max}= maximum velocity

v_{min}= minimal detectable velocity (limited by the energy threshold of the experiment)



Due to the rotation of Earth in the Solar System and the movement of it inside the Milky Way, the velocity of DM particles relative to Earth varies seasonally, producing an **annual modulation** in the rate of nuclear recoil events.

- Maximum relative velocity: June
- Minimum relative velocity : December
- Period: 1 year

✓ Event search: nuclear recoil.

✓ DM signal search: annual modulation.

Which kind of experiment can we design to look for this signal?

Dark Matter: direct detection

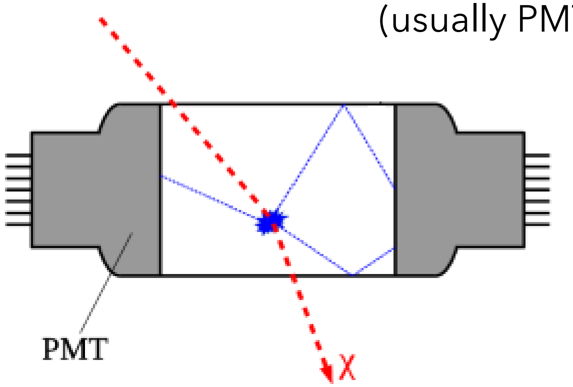
Experimental status

Multiple detection techniques and different targets → complementary searches in the parameter space of WIMPS:

- ❖ Cryogenic detectors: SuperCDMS (Si,Ge), Edelweiss (Ge), CRESST ($CaWO_4$)…
- ❖ Noble liquid detectors: DarkSide (Ar), XENON, PandaX, LUX-ZEPLIN (Xe)…
- ❖ Other techniques: Si-CCDs (DAMIC), **scintillating crystals** (ANAIS, COSINE), bubble chambers (PICO)…

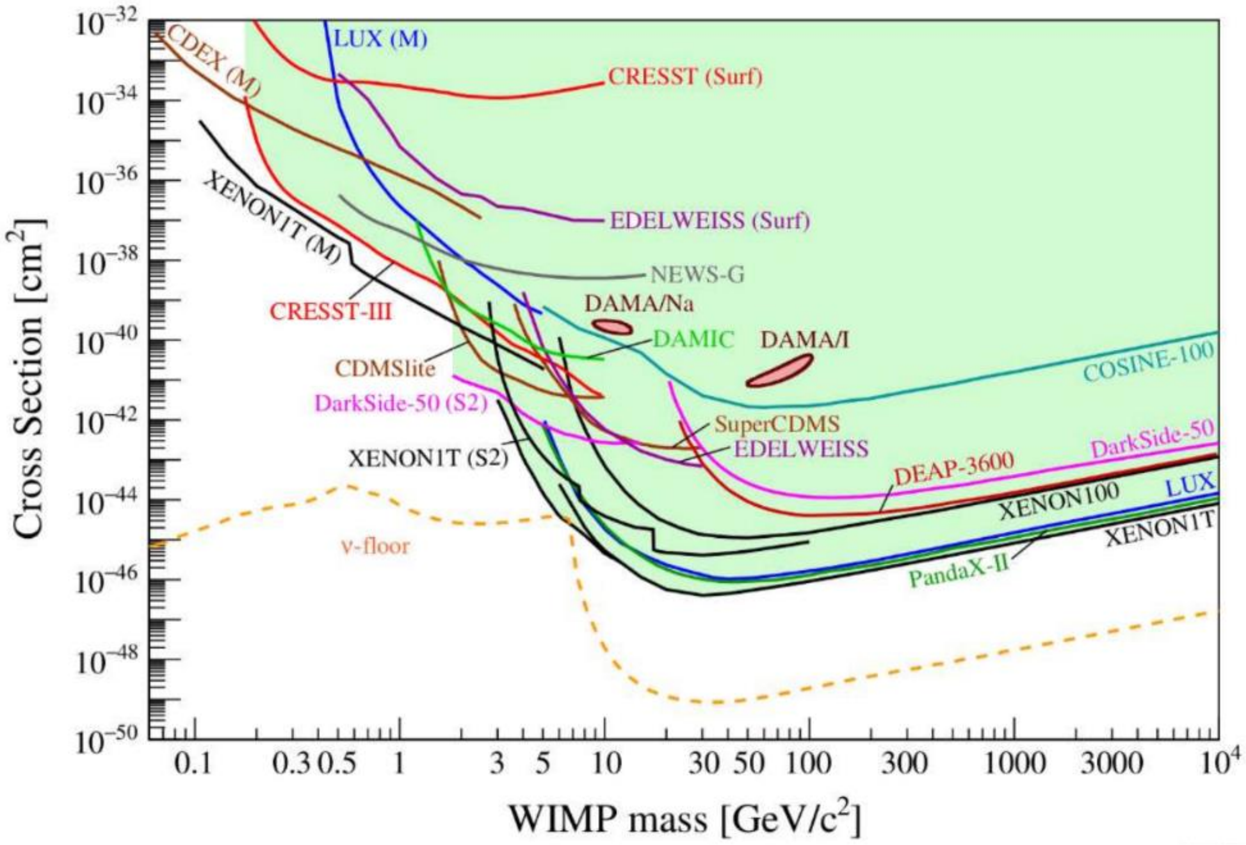
Scintillator detectors

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



Collected photons
∝
Deposited energy.

APPEC DM Report (2021)



Status of searches for spin-independent elastic WIMP-nucleus scattering

Dark Matter: direct detection

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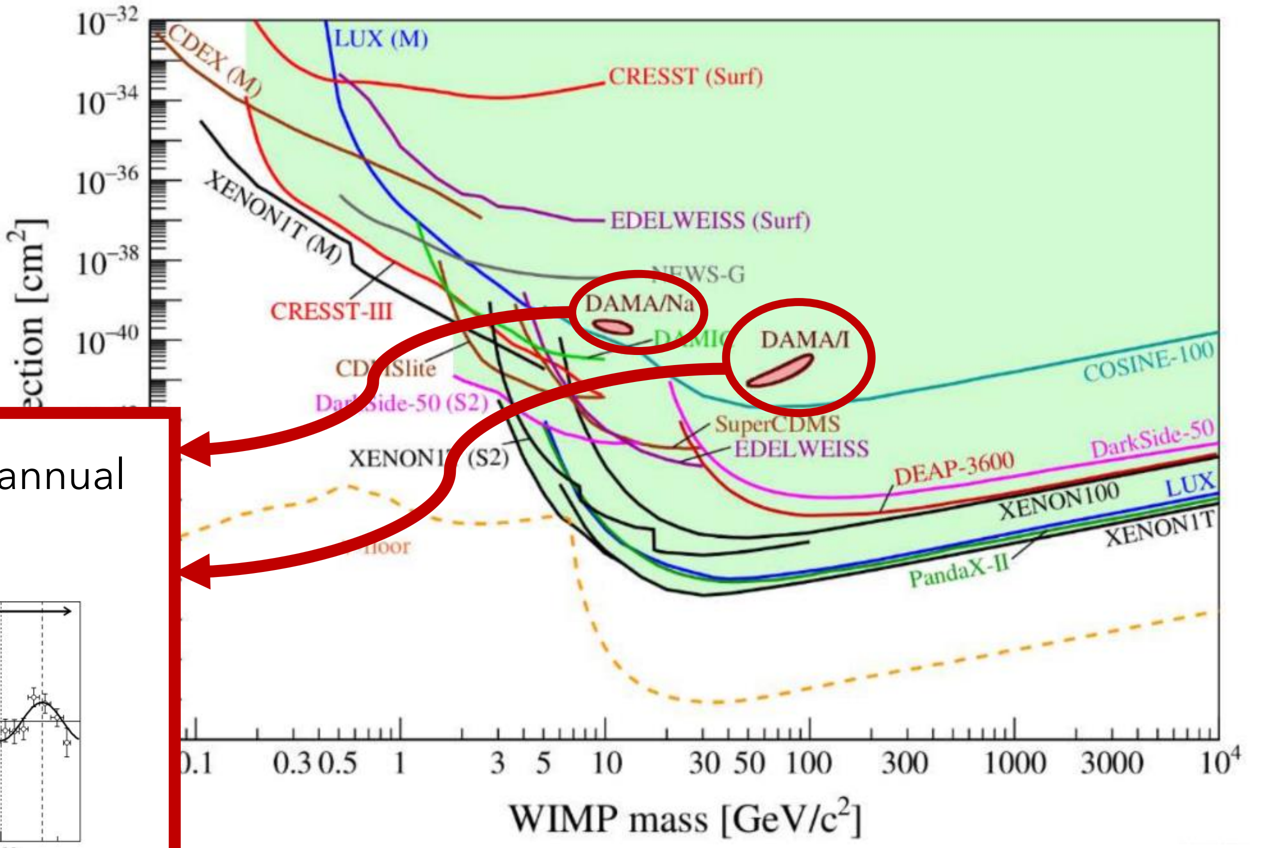
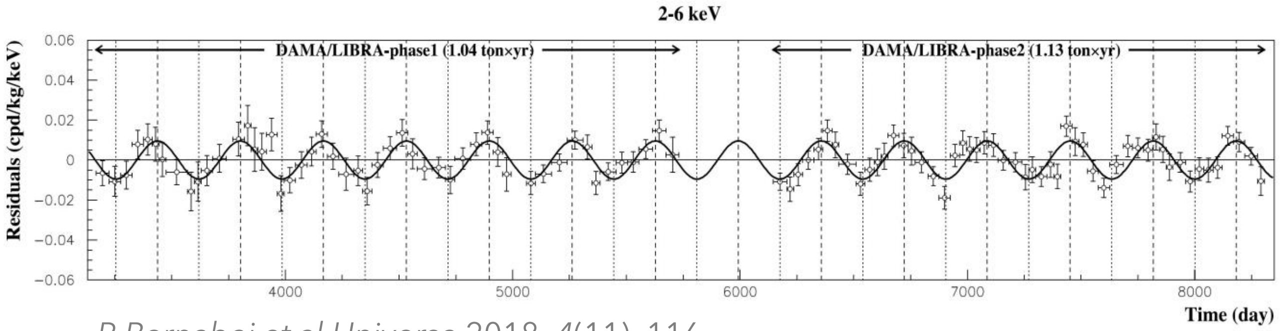


Status of searches for spin-independent elastic WIMP-nucleus scattering

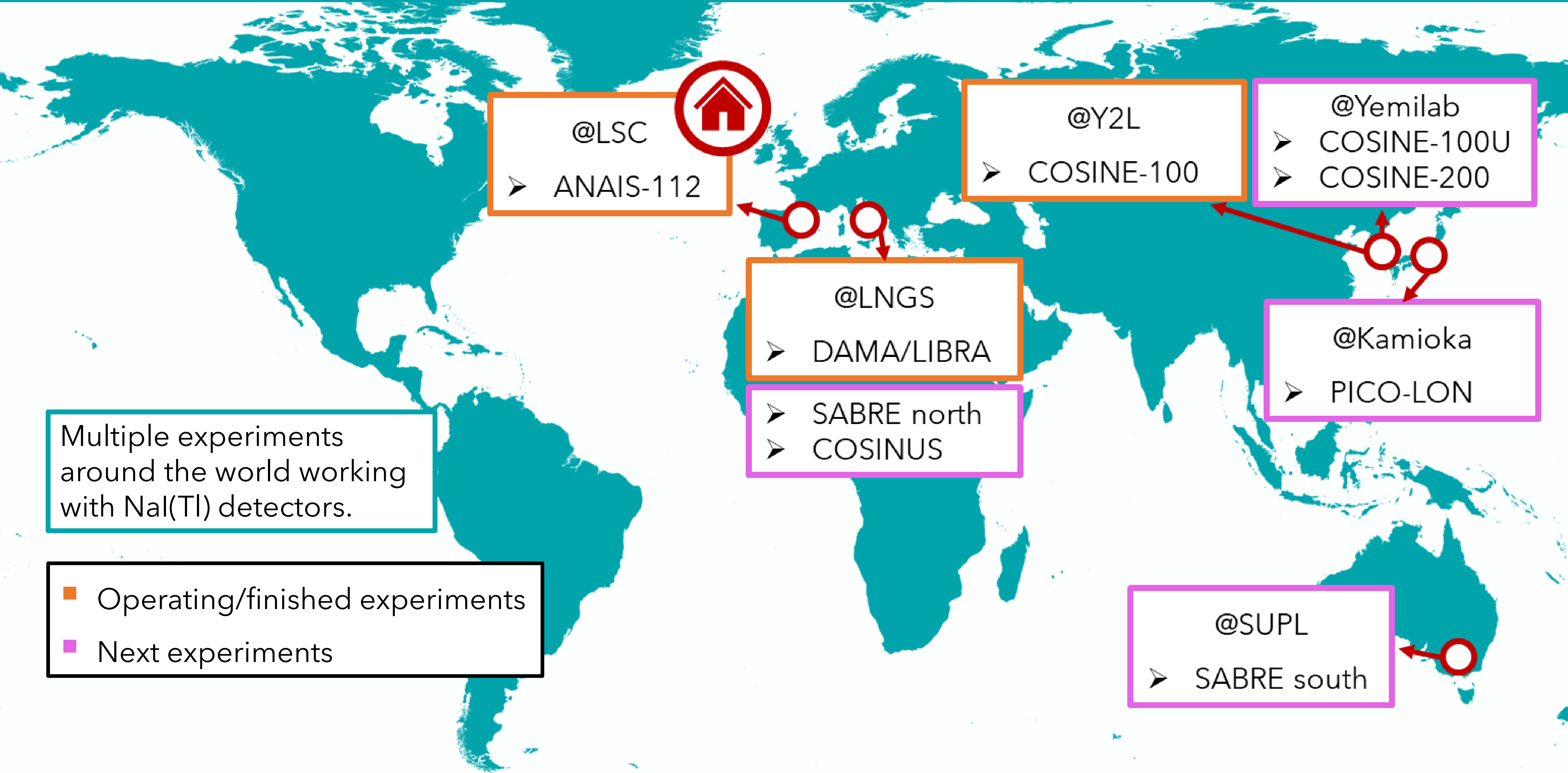
- DAMA/LIBRA, a experiment based on NaI(Tl), observes an annual modulation and claims to have detected dark matter.



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

- More sensitive experiments have ruled out this signal in the considered scenarios, but comparison is model-dependent because they use different target.

NaI detectors



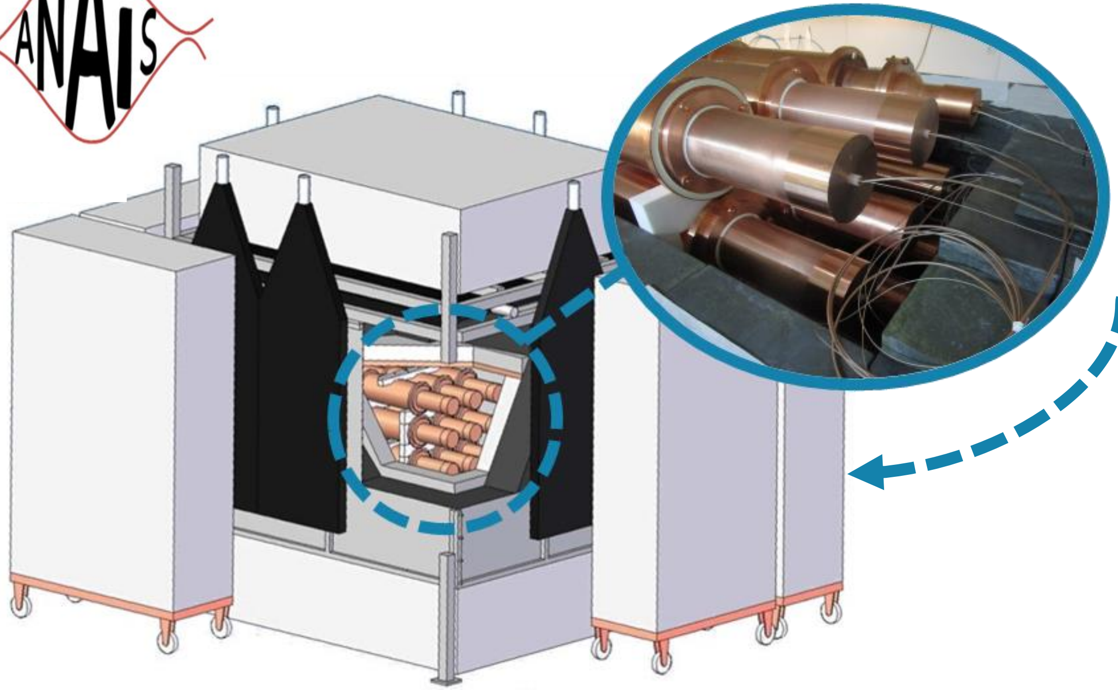
Multiple experiments around the world working with NaI(Tl) detectors.

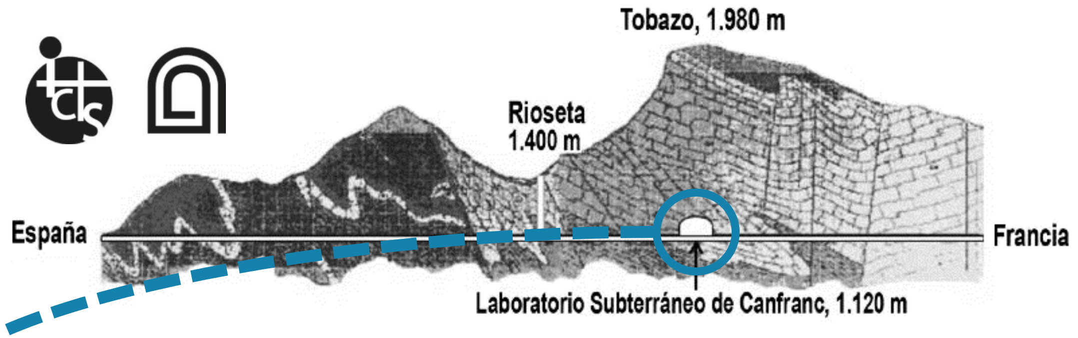
ANAIS-112

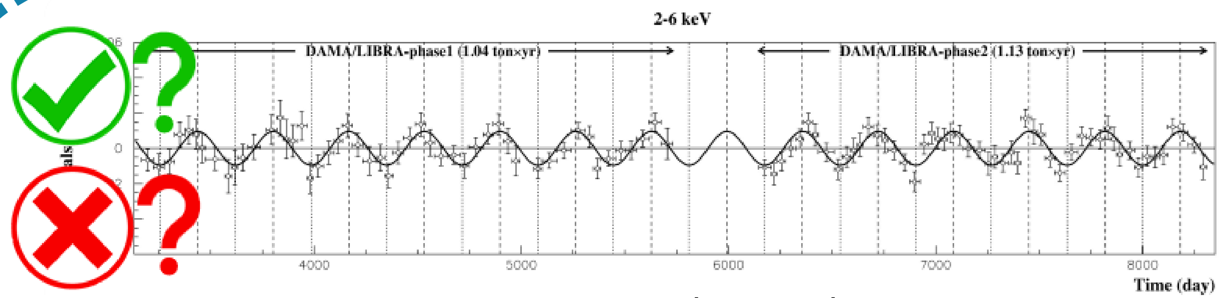
Annual Modulation with NaI Scintillators

- ❖ Direct dark matter detection experiment.
- ❖ 9 ultrapure NaI(Tl) crystals 12.5 kg (112.5 kg) in 3 × 3.
- ❖ 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.







ROI: [1-6] and [2-6] keV

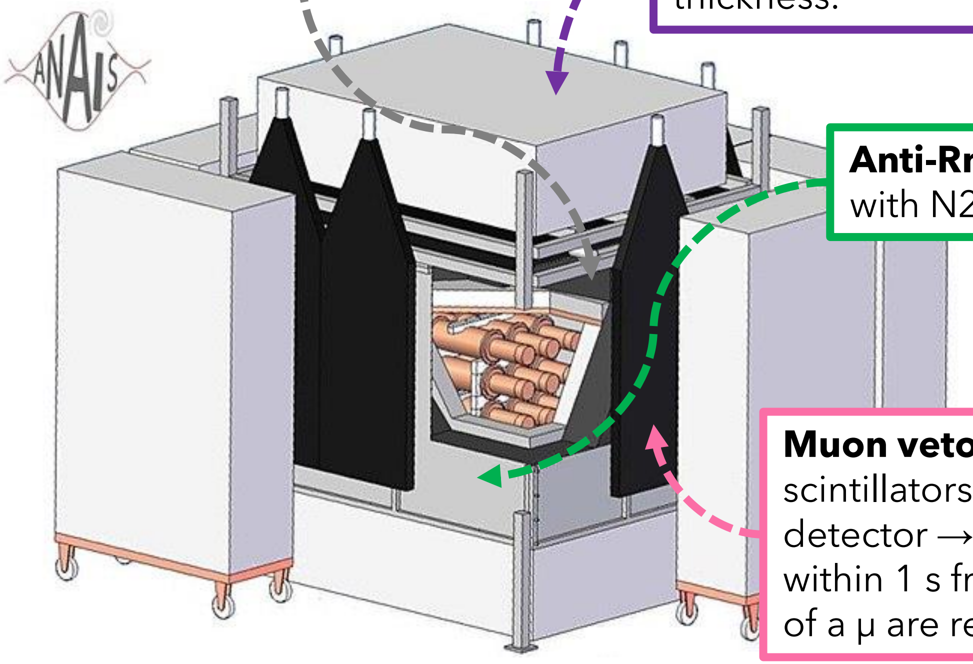
R.Bernabei et al Universe 2018, *4*(11), 116

ANAIS-112

Shielding configuration

Gamma shielding: 10 cm of ancient Pb + 20 cm of Pb.

Neutron shielding: mixture of PE/water tanks with 40 cm of thickness.



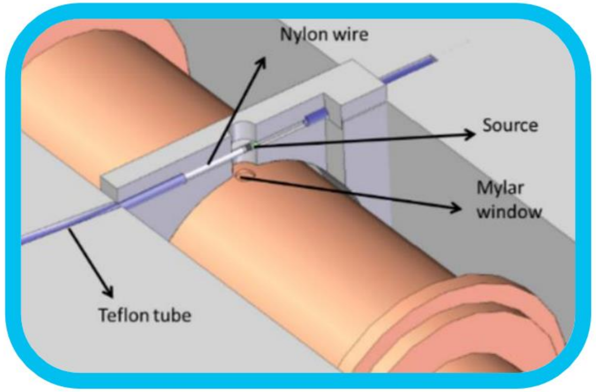
Anti-Rn box: filled with N2 gas.

Muon vetoes: plastic scintillators around the inner detector → events arriving within 1 s from the detection of a μ are removed.

Energy calibration

❖ Low energy calibration: our ROI is from 1 to 6 keV.

❖ Modules equipped with a mylar window: external source of ^{109}Cd (producing 3 peaks below 100 keV).



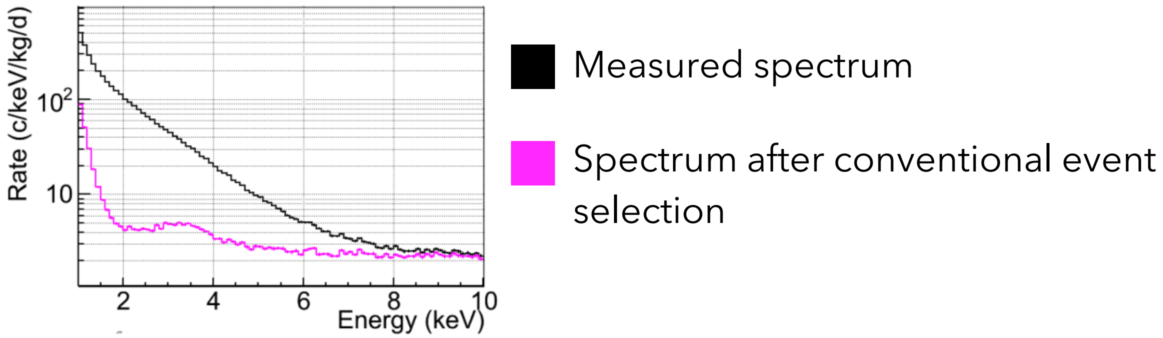
❖ Calibration with internal sources (selected by coincidence with a HE gamma):

- K-40: 3.2 keV and 1460.8 keV γ
- Na-22: 0.9 keV and 1274.5 keV γ

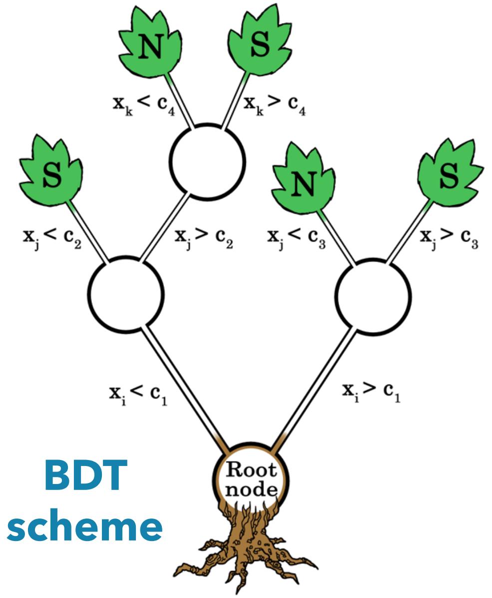
ANAIS-112: event selection

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

- They are dominating the event rate below 10 keV.



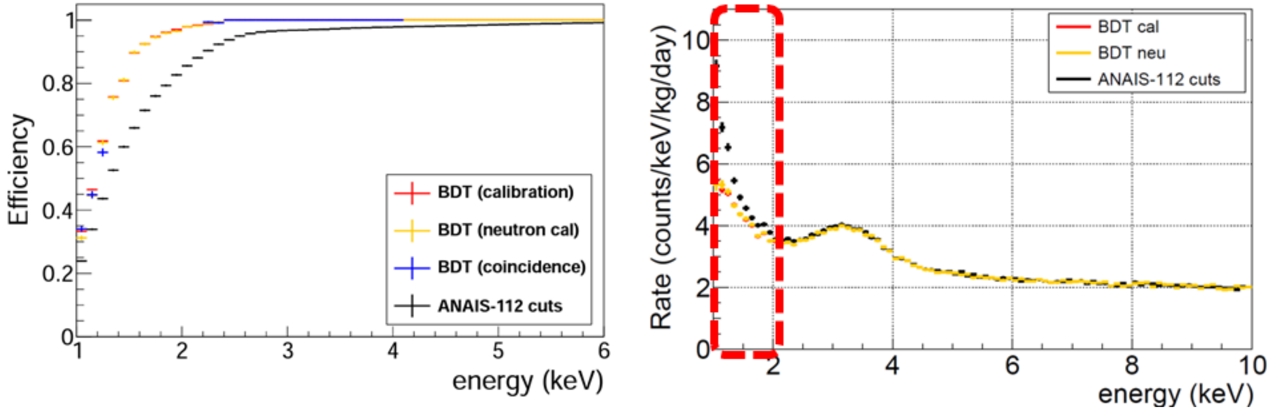
Blank module: same structure as ANAIS module, but without the NaI(Tl) crystal → used to study the PMTs noise events.



Classification method based on BDT (Boost Decision Trees).

- Use of 15 parameters defined for the detector signal: taking into account the pulse shape and the assymetric light sharing between both PMTs.
- Training populations:
  - Signal population: neutron calibrations of ANAIS (same signal as the expected for WIMPs → nuclear scattering) made with a Cf-252 source.
  - Noise population: blank module events.

This filtering protocol improves the event selection and its efficiency, but it still **limits the energy threshold** to 1 keV.



I. Coarasa et al JCAP11(2022)048

ANAIS-112: modulation analysis

Model independent test

- GOAL: establishing a model independent test of DAMA/LIBRA results on the annual modulation signal.
- We look for the anual modulation in the same energy regions, [1-6] and [2-6] keV, and we fix its period (1 year) and phase (2nd June).
- The modulation is searched with a simultaneous fit of the 9 detectors in 10-day bins, following a χ^2 minimization:

$$\chi^2 = \sum_{i,d} \frac{\left(n_{i,d} - \mu_{i,d}\right)^2}{\sigma_{i,d}^2}$$

$n_{i,d}$ = number of events in time bin t_i for detector d

$\sigma_{i,d}$ = statistical uncertainty associated to $n_{i,d}$

$$\mu_{i,d} = \left[R_{0,d}\left(1 + f_d \phi_{bkg,d}^{MC}(t_i)\right) + S_m \cos(\omega(t_i - t_0))\right] M_d \Delta E \Delta t$$

ANAIS-112: modulation analysis

Model independent test

- GOAL: establishing a model independent test of DAMA/LIBRA results on the annual modulation signal.
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Background contribution:

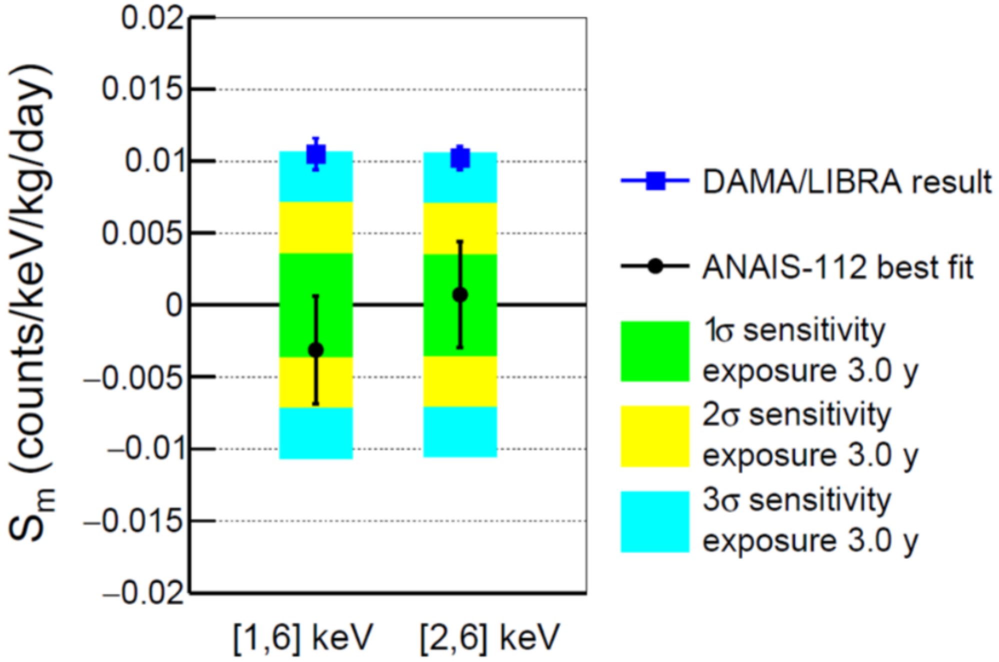
- Constant component (long-life isotopes and noise).
- Decaying component (based on MC simulations).

Modulation signal expected by DM detection. Phase and period fixed, amplitude (S_m) as a free parameter.

Mass of the detector, energy and time intervals considered in the analysis.

ANAIS-112: latest results

3 year analysis (using BDT filtering protocol)



- Modulation amplitudes compatible with zero at ~ 1σ.
- Best fit incompatible with DAMA/LIBRA at 3.7 (2.6) σ for [1-6] ([2-6]) keV.
- Sensitivity: 2.8 σ for [1-6] and [2-6] keV.

I. Coarasa et al. Communications Physics volume 7, n 345 (2024)

ANAIS-112: latest results

NEW

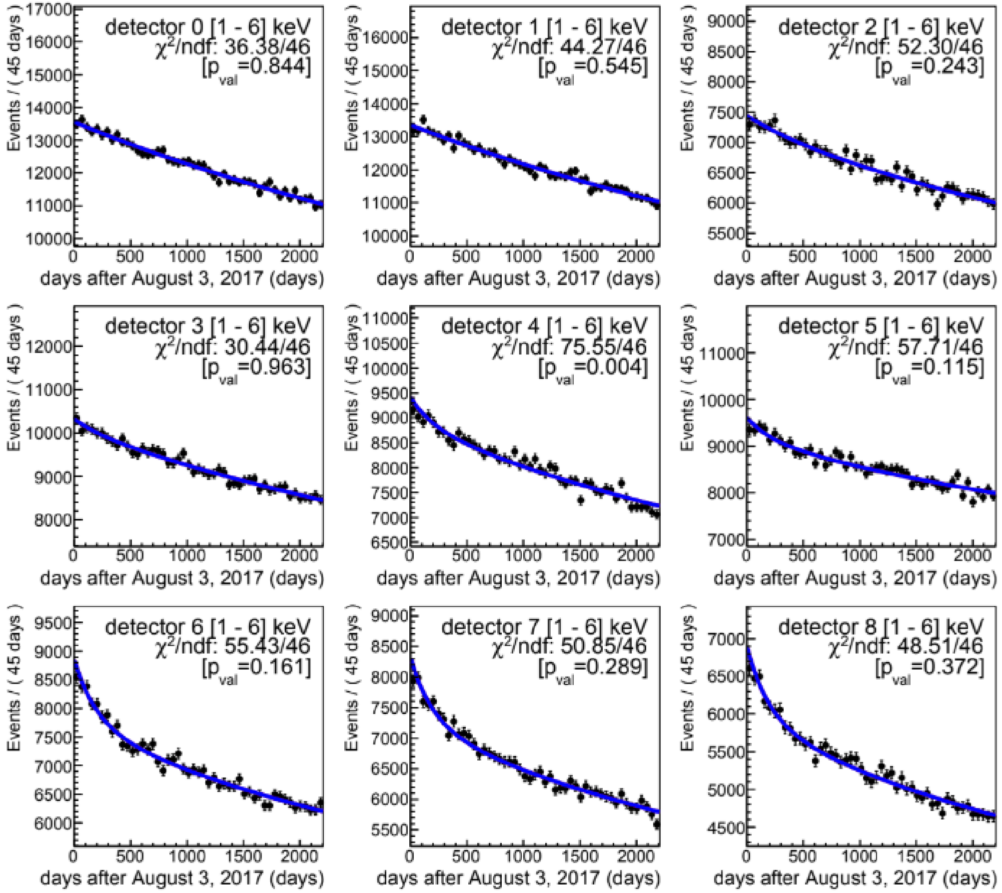
6 year analysis (using BDT filtering protocol): background fit to event rate of the nine modules.

[1-6] keV

Null hyp χ^2/ndf: 451.34/423 [p_{val}=0.164]

Mod hyp χ^2/ndf: 451.31/422 [p_{val}=0.156]

S_m = (-0.0004 ± 0.0025) (cpd/kg/keV)

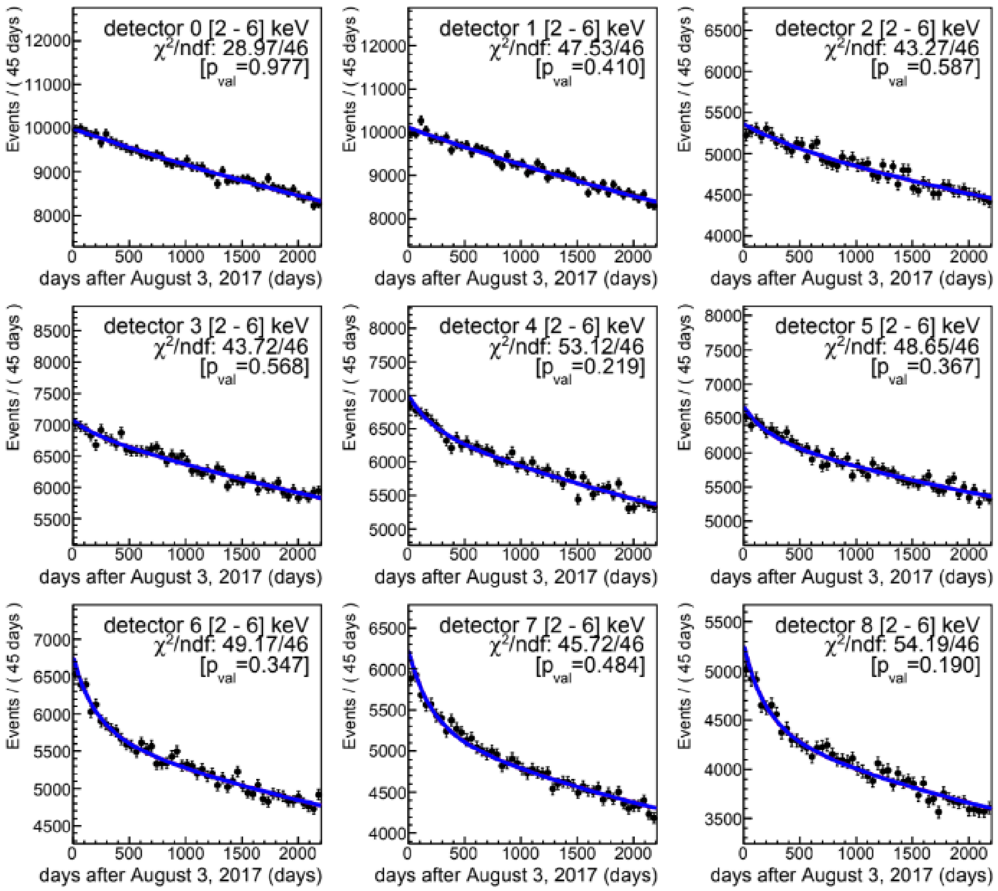


[2-6] keV

Null hyp χ^2/ndf: 414.46/423 [p_{val}=0.607]

Mod hyp χ^2/ndf: 414.28/422 [p_{val}=0.596]

S_m = (0.0011 ± 0.0025) (cpd/kg/keV)



Publication in preparation (internal reviewing)

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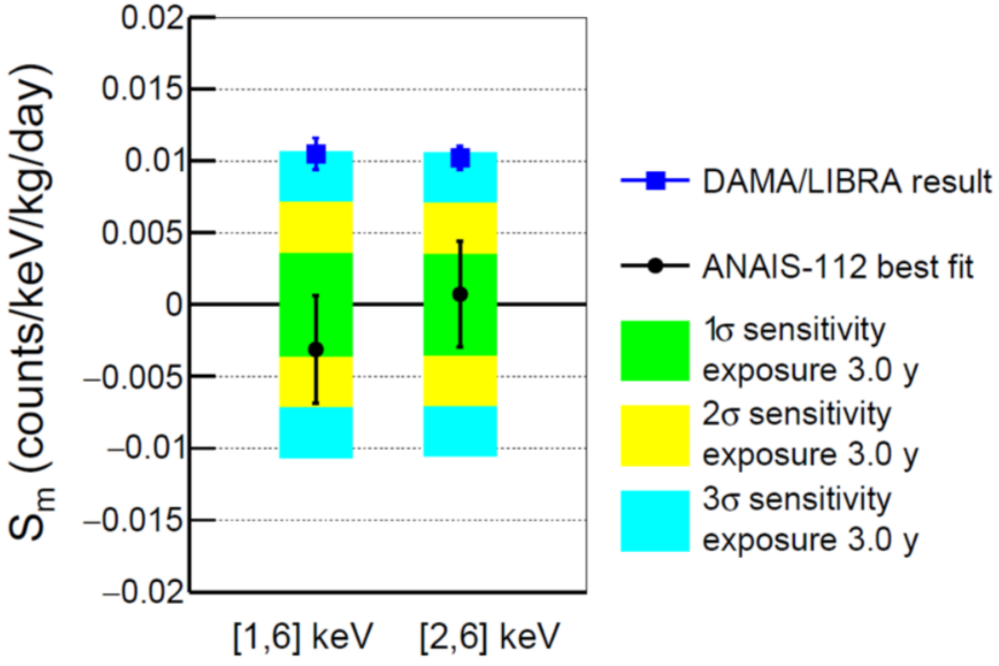

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I. Coarasa et al. Communications Physics volume 7, n 345 (2024)

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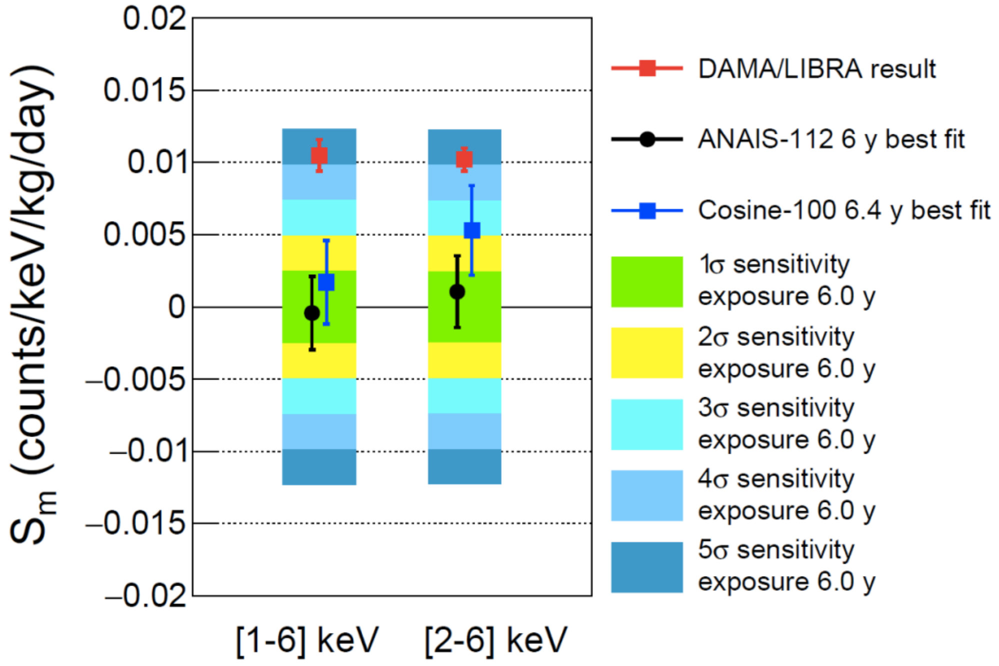
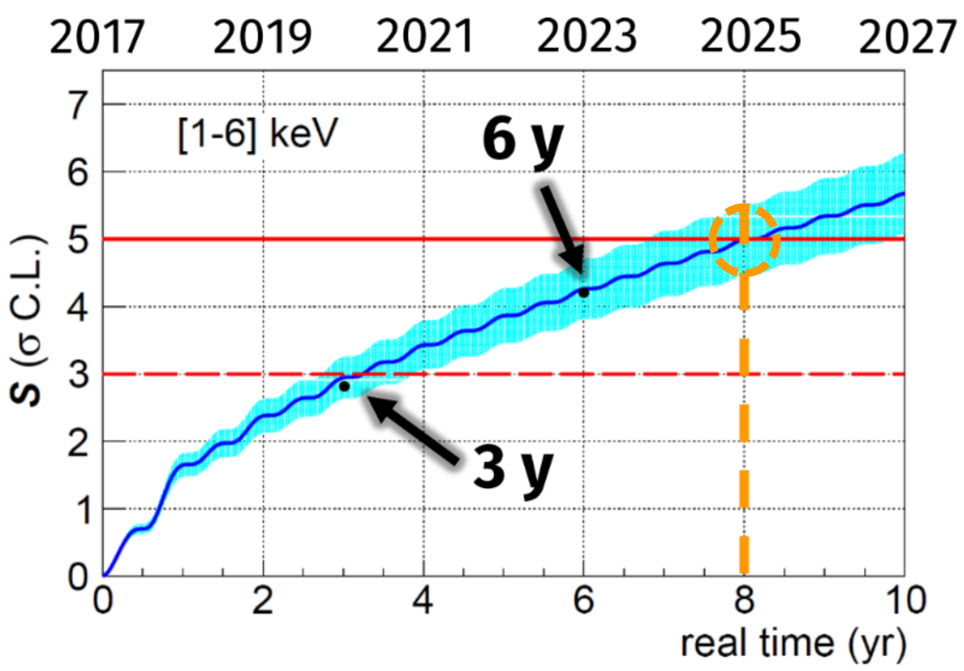


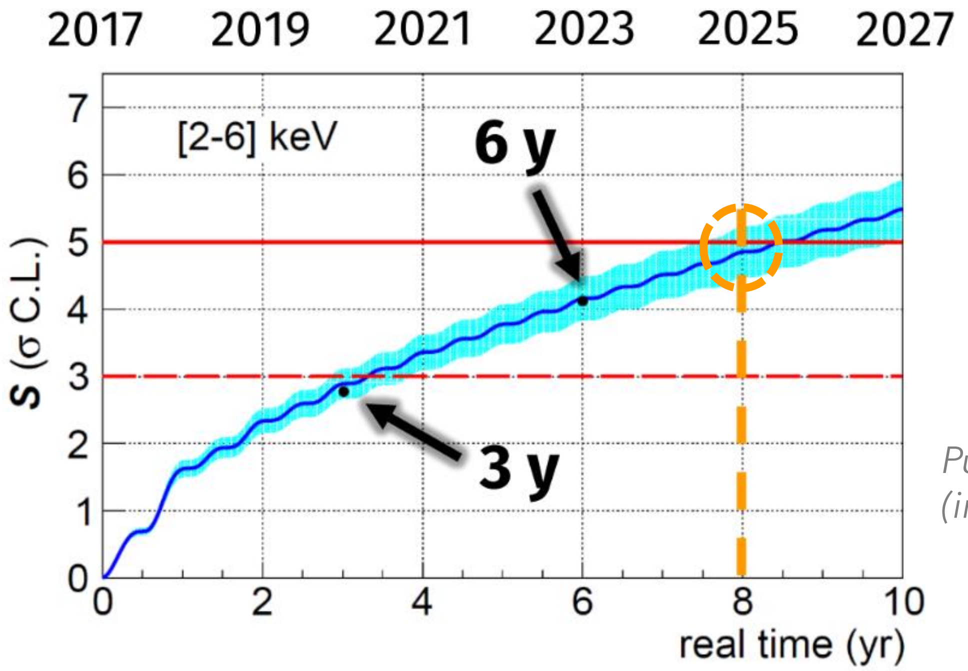
- Modulation amplitudes compatible with zero at ~ 1σ.
- Best fit incompatible with DAMA/LIBRA at 4.0 (3.5) σ for [1-6] ([2-6]) keV.
- Sensitivity: 4.2 (4.1) σ for [1-6] ([2-6]) keV.

Publication in preparation (internal reviewing)

ANAIS-112: latest results

6 year analysis (using BDT filtering protocol)





Publication in preparation (internal reviewing)

We expect to achieve 5 σ sensitivity by the end of 2025 (8 years of data taking).

Open data available for independent analysis at Dark Matter Data Center → 3 year annual modulation analysis and the reanalysis can be downloaded at: https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais
6 year analysis will be included in the near future.

ANAIS-112: the QF systematic

Is ANAIS directly comparable with DAMA/LIBRA?

- **Calibration with electron recoils!**
- In a scintillator, the amount of light produced by a electron recoil (ER) is much larger tan a nuclear recoil (NR) of the same energy.

$$QF = \frac{L_{nr}}{L_{er}}$$

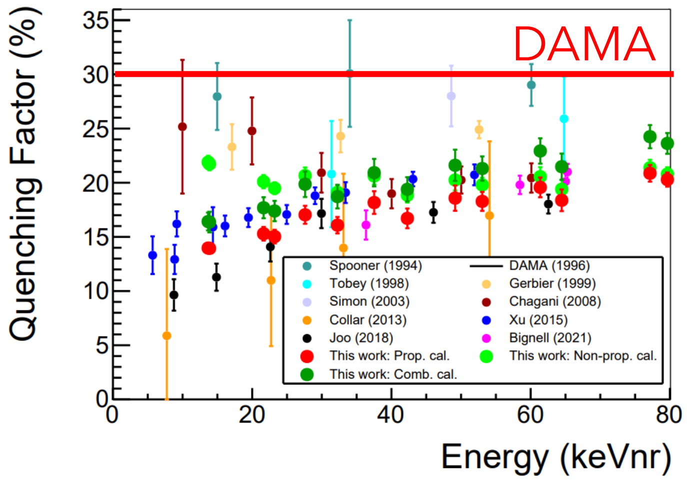
- DM is expected to produce NR, therefore experiments must be compared in the NR-energy scale, which requires a precise knowledge of the QFs.

QF determination for ANAIS−112 crystals ongoing following two approaches:

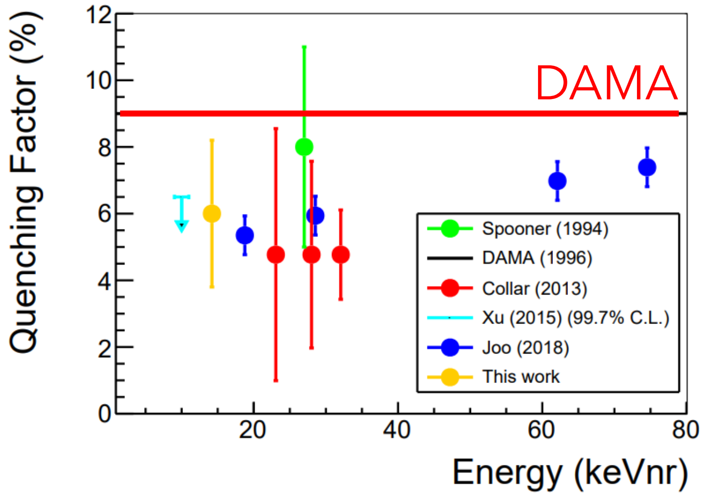
- Direct measurements at TUNL (Duke University, US).
- Comparing neutron calibration data taken in ANAIS-112 at LSC with 252Cf source with MC simulation.

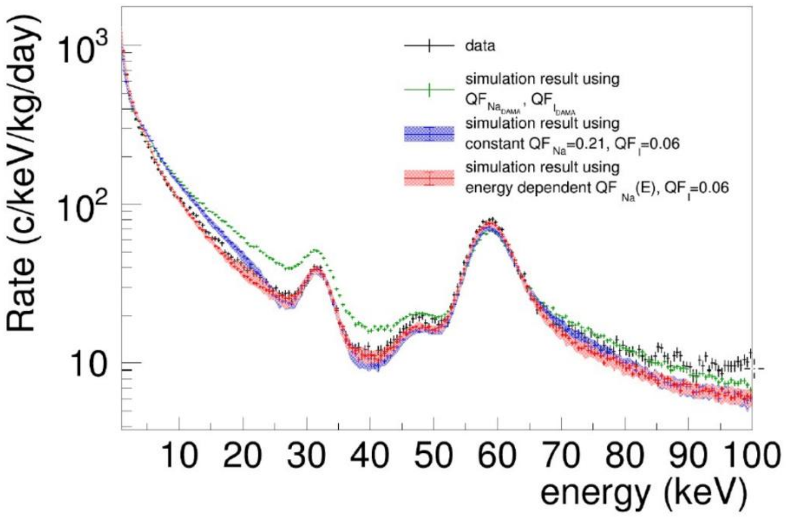
D. Cintas et al, Phys. Rev. C 110 (2024) 014613

QF_{Na}



QF_I





T. Pardo et al., PoS(TAUP2023)078

- Energy dependent QF favoured by the studies made with ANAIS data.
- Mean values obtained at TUNL:

$$Q_{Na} = (21.2 \pm 0.8)\%$$
$$QF_I = (6.0 \pm 2.2)\ \%$$

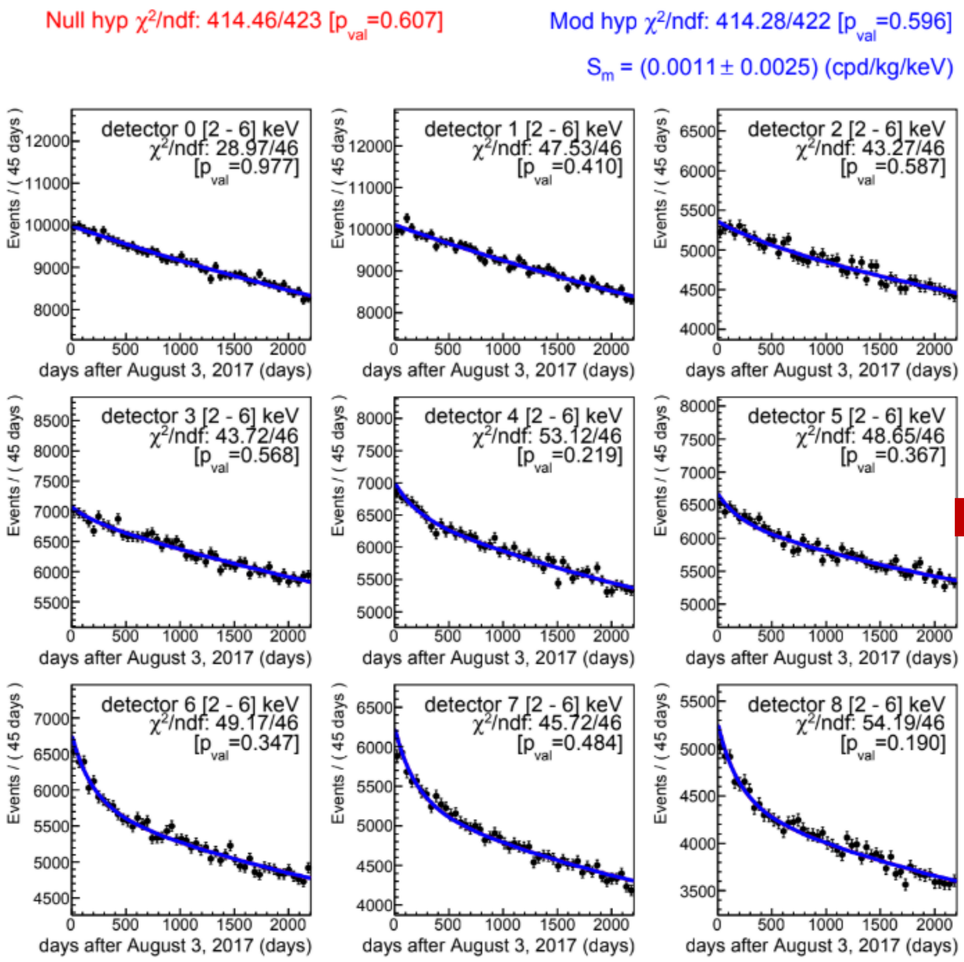
- Values lower than the DAMA/LIBRA measurement.

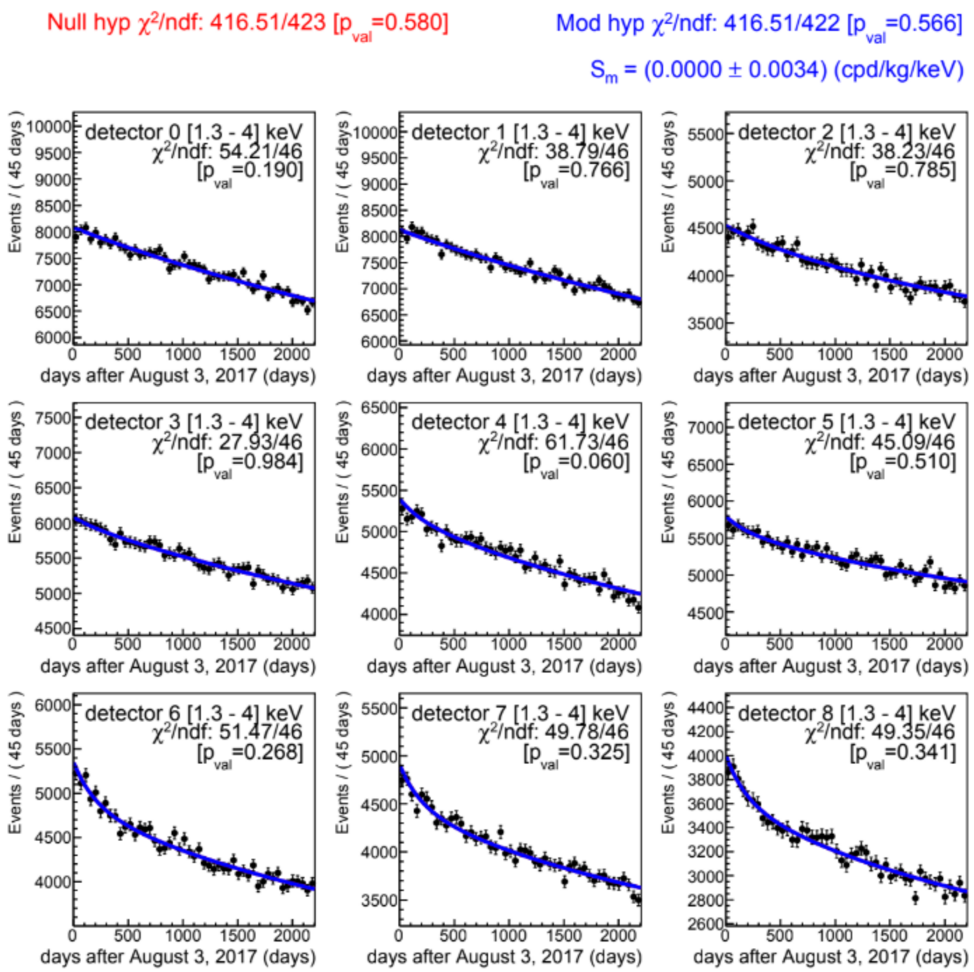
ANAIS-112: the QF systematic

NEW

6 year analysis (using BDT filtering protocol): background fit to event rate of the nine modules.

[2-6] keV → Considering for ANAIS the QF given by TUNL measurements → **[1.3-4] keV** → Corresponding energy range in ANAIS for nuclear recoils in the 2-6 keV range in DAMA/LIBRA.





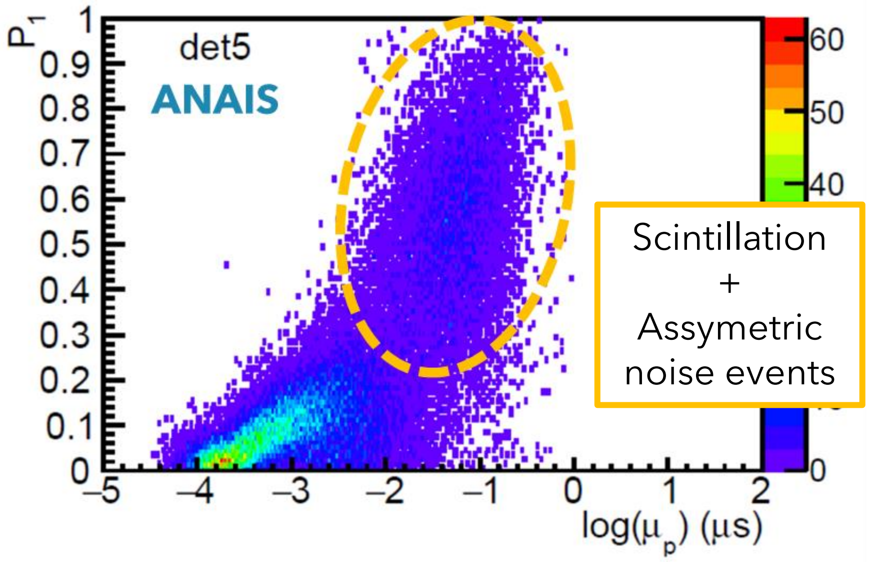
Compatible results in both cases with the absence of modulation.

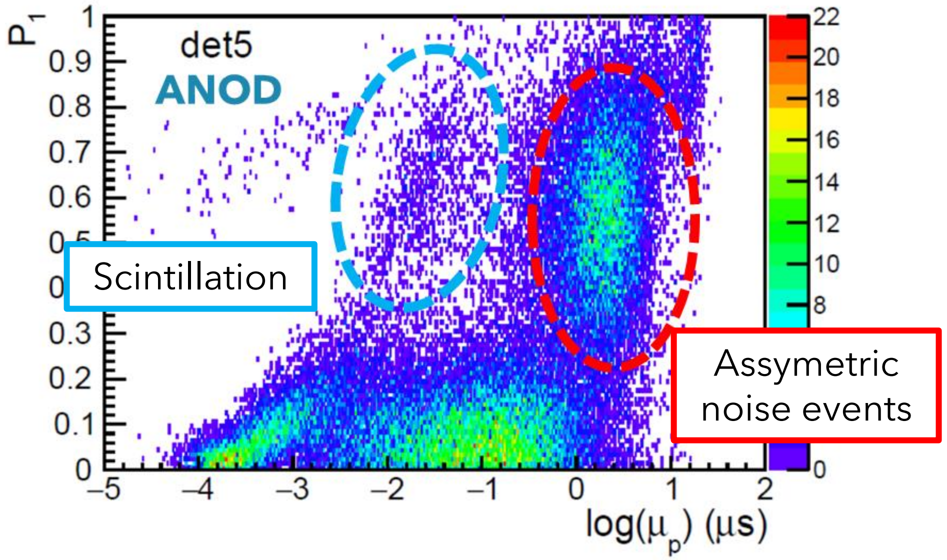
Publication in preparation (internal reviewing)

ANAIS-112: ongoing work

ANOD (Anais NO Dead time)

- New parallel DAQ system in ANAIS-112 (CAEN DT5730).
- Bigger digitization window: 1.25 μs → 8 μs.
- For the moment, we have been reading only 4 modules (8 channels) → we expect to improve the identification of anomalous scintillation events and then, increase our sensitivity.





Pulse shape parameters

$$P1 = \frac{\sum_{100\,ns}^{600\,ns} A_i}{\sum_{0\,ns}^{600\,ns} A_i}$$

$$\mu_p = \frac{\sum_p A_p \cdot t_p}{\sum_p A_p}$$

- A new digitizer with 32 channels (CAEN VX2730) that will allow us to digitize the full detector (9 modules) and the blank module has been installed yesterday.

NEW

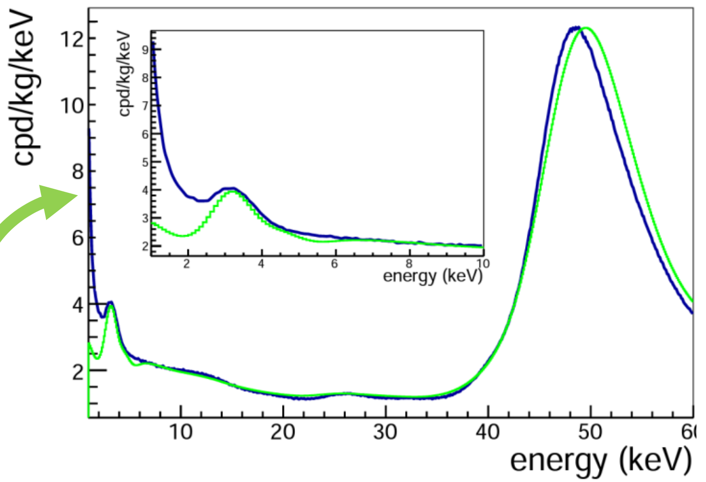
ANAIS-112: ongoing work

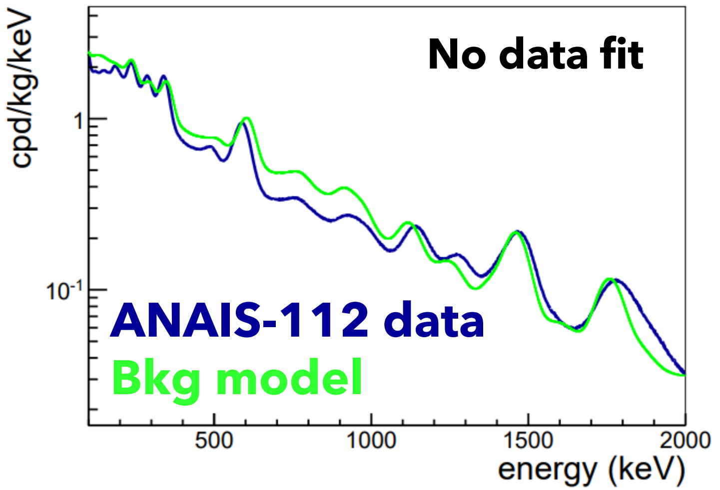
J. Amaré et al, Phys. Rev. D 103 (2021) 102005

Improving the background model

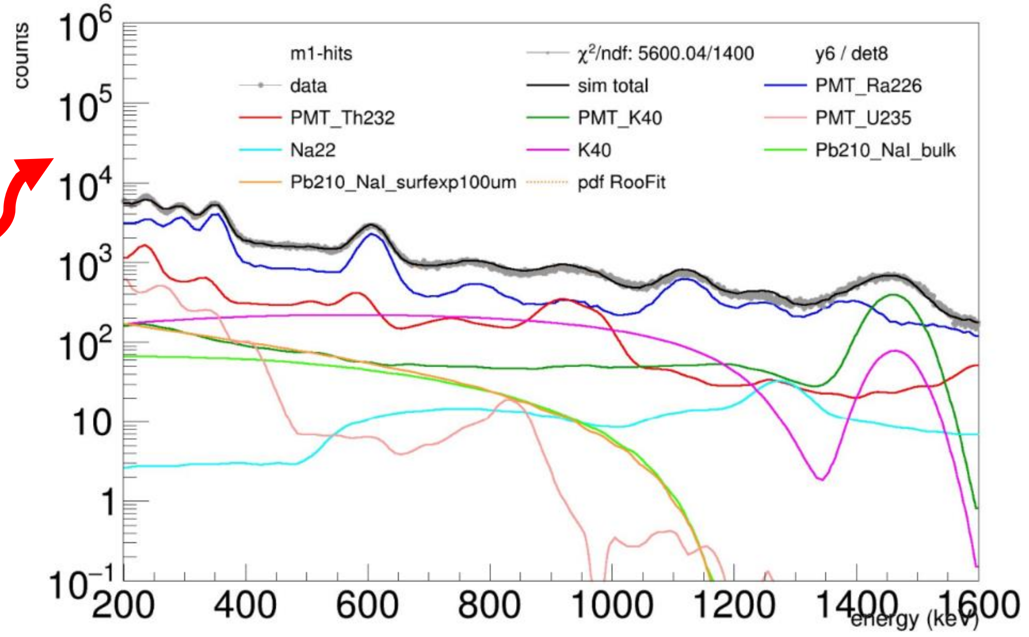
- Having a good model of the background of the experiment is a key point in the analysis of the modulation signal.

- First background model based on MC simulations using Geant4.





- Updated background model:
  - Extended geometry and more detailed description of PMTs.
  - Multiparametric fit using RooFit considering different simulated contributions from all sources (9 crystals + 18 PMTs + other components.)

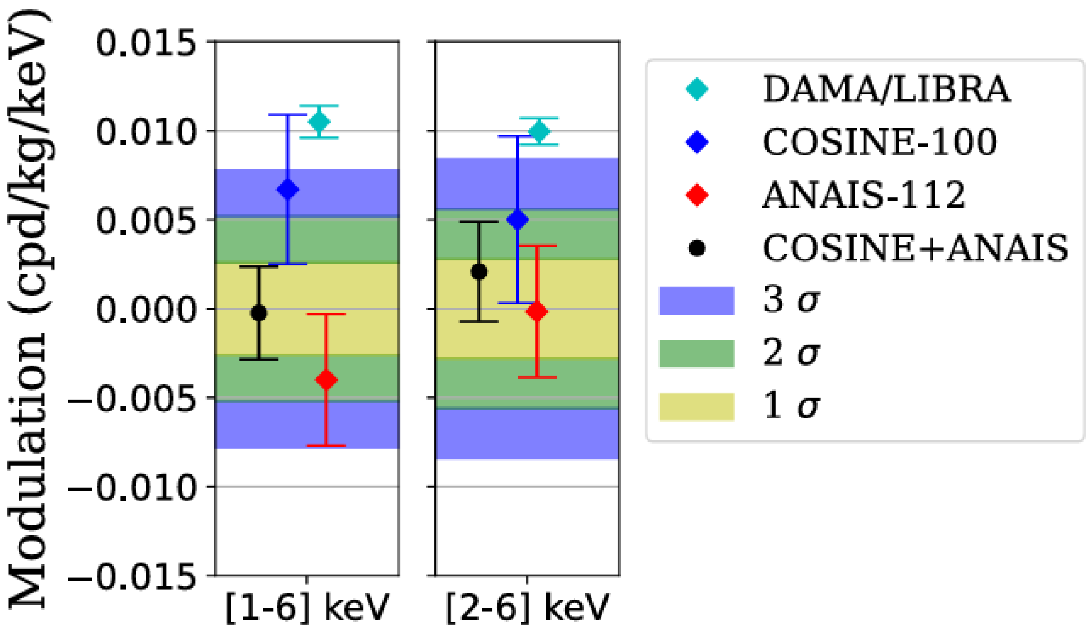


ANAIS-112: ongoing work

Combined ANAIS + COSINE 3 year

- ANAIS-112 and COSINE-100 are compatible NaI(Tl) experiments trying to solve the DAMA/LIBRA puzzle.
- Separate treatment of experiment backgrounds allows for direct combination of residuals.
- Combined annual modulation search provides 3σ sensitivity to DAMA for 3-years data

Publication in preparation



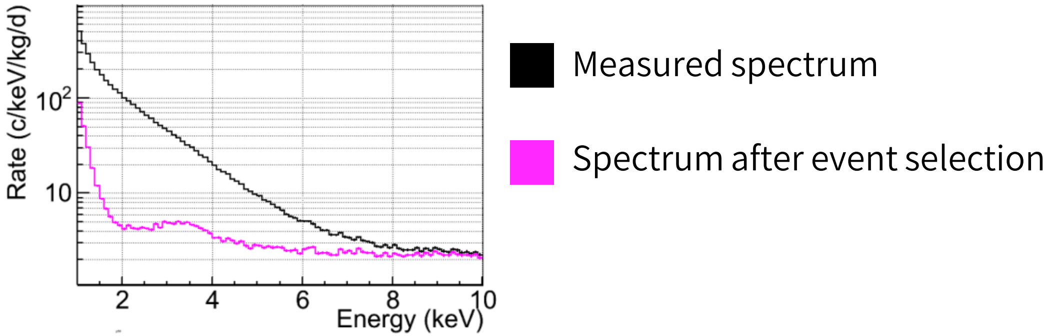
S.Hollick, @IDM2024

ANAIS-112: ongoing work

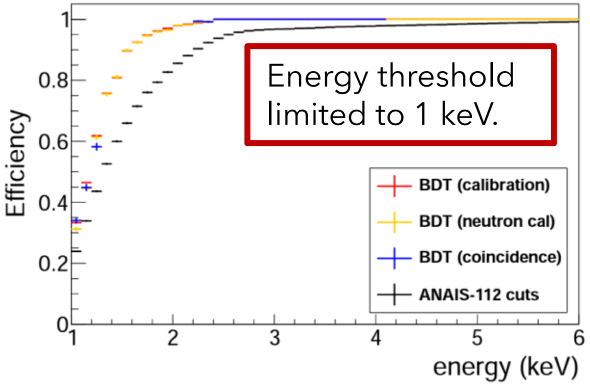
ANAIS+

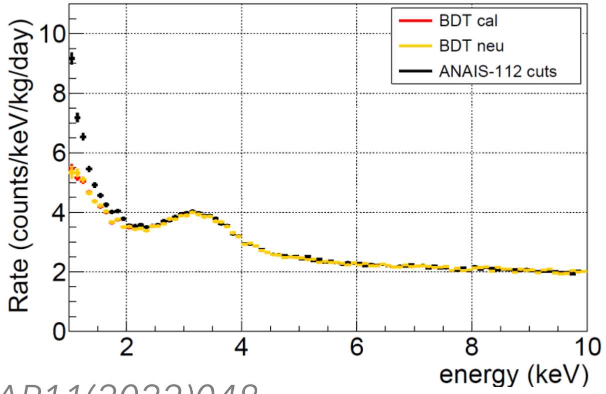
At present ANAIS-112 sensitivity is constrained by anomalous light events attributed to the PMTs:

- 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**.

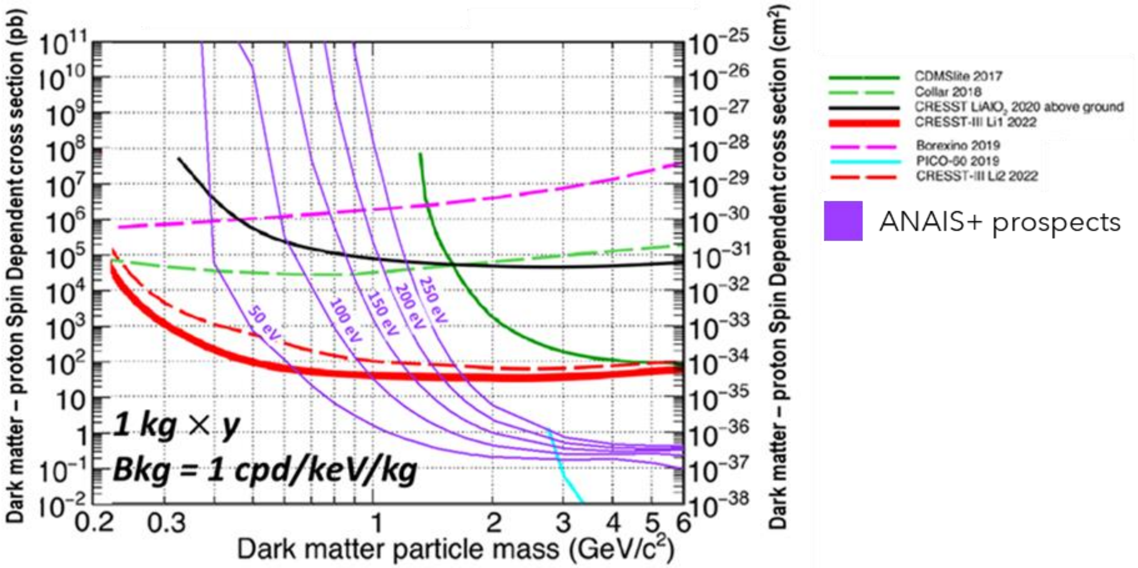




I. Coarasa et al JCAP11(2022)048

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.



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

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

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How can we reduce the Eth?

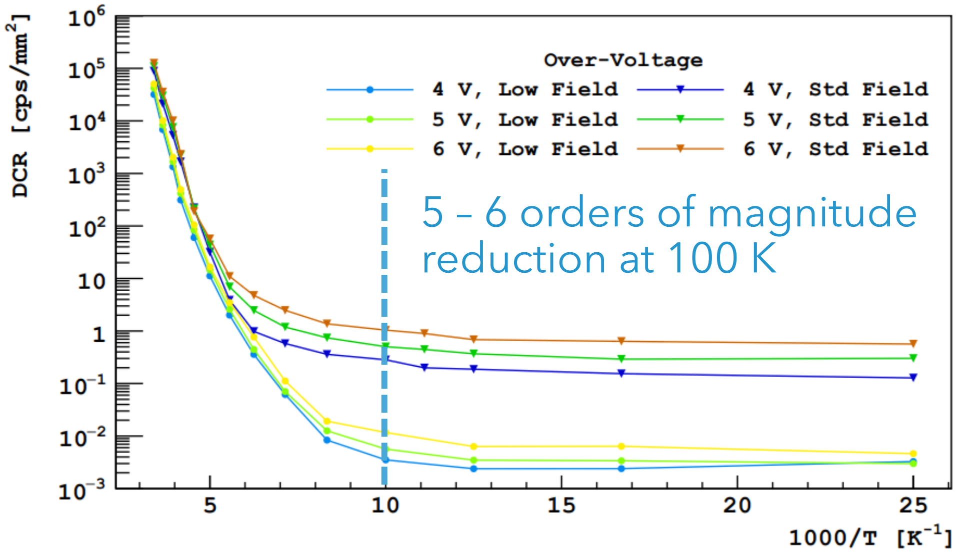
Replacement of PMT by SiPMs for the light detection

ADVANTAGES

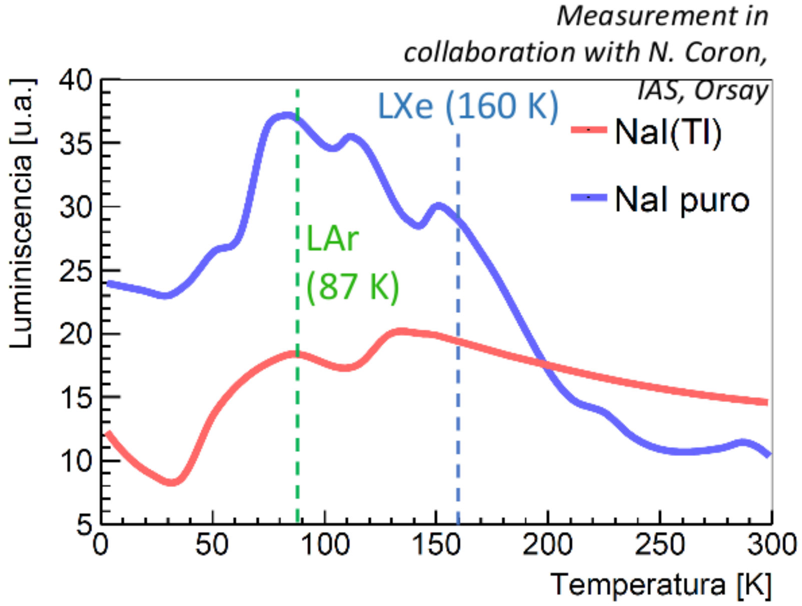
- High QE (≈40 %).
- High radiopurity (lower bkg).
- Low operating voltage (~ 10's V).
- No Cherenkov/HV arc-discharges emissions.

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.

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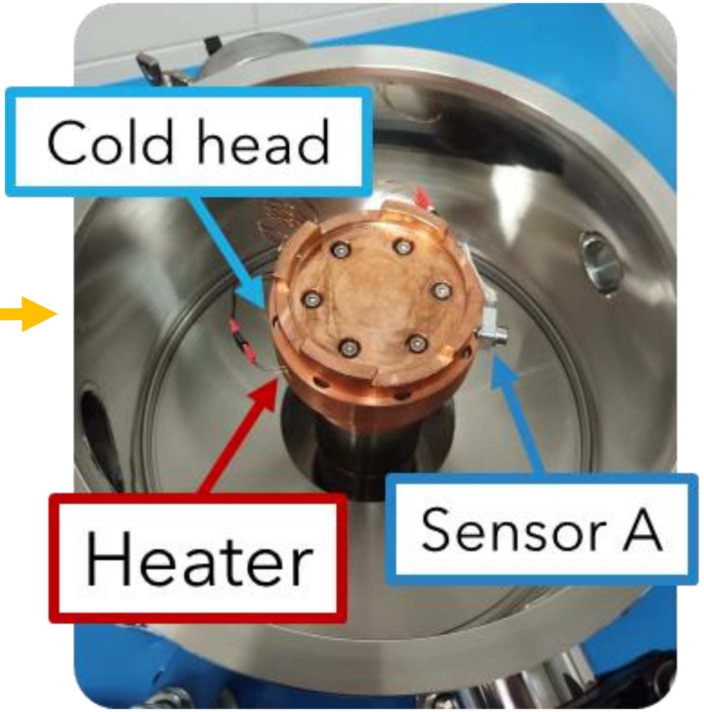
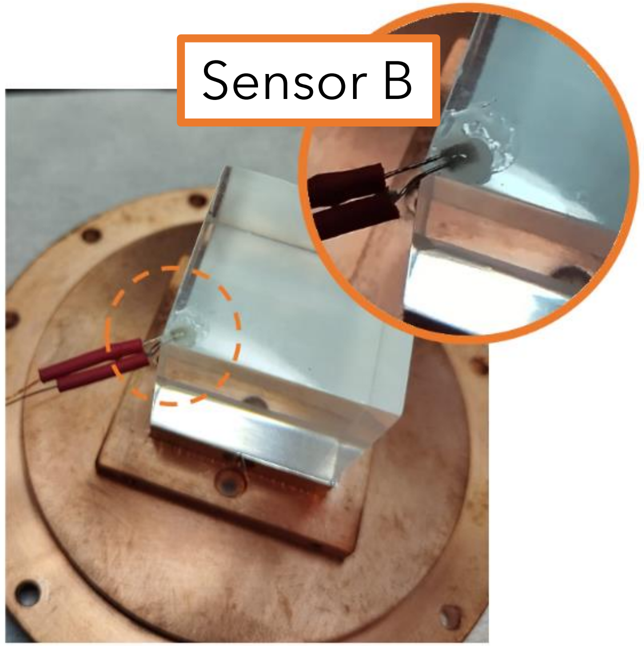
Cryogenic installation

Cryocooler + He Compressor
Capability to reach **T<30 K.**

- Two PT-100 temperature sensors: **A** (next to cold head), **B** (inside the detector, in contact with the NaI crystal).
- 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.





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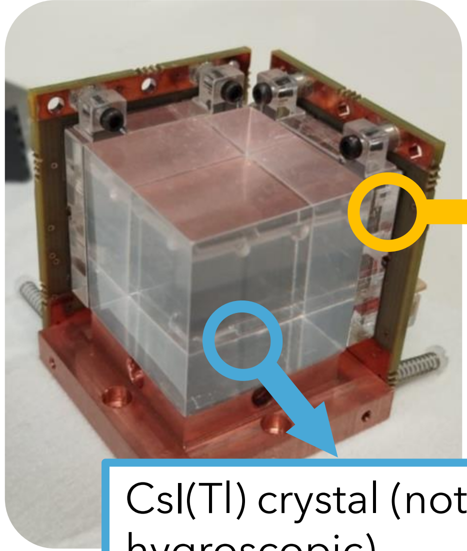
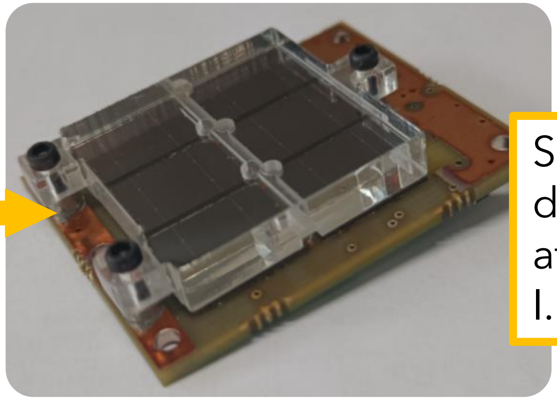
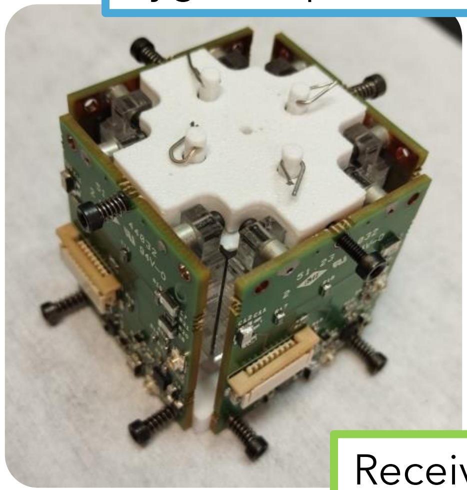
ANAIS+: tinyOCTOPUS

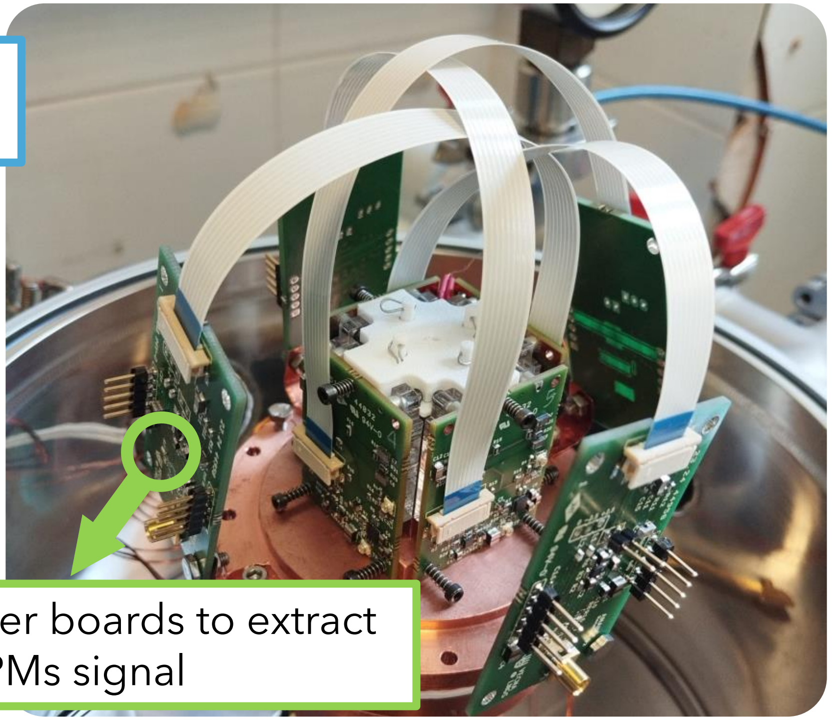




SiPMs + electronics designed and produced at LNGS (A.Razeto and I.Kochanek)

CsI(Tl) crystal (not hygroscopic)





Receiver boards to extract the SiPMs signal

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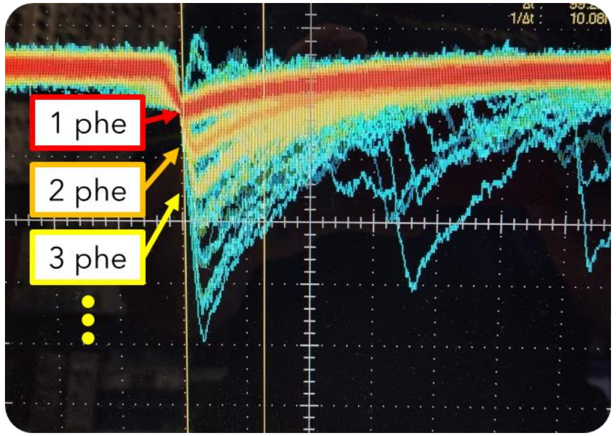
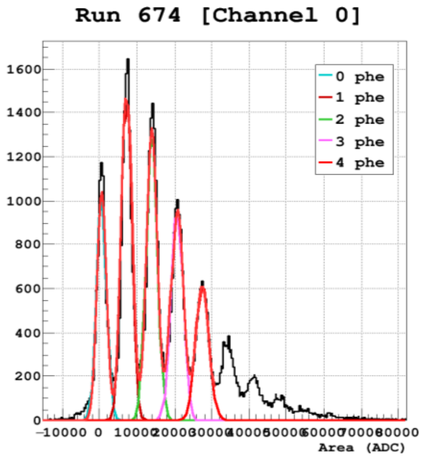
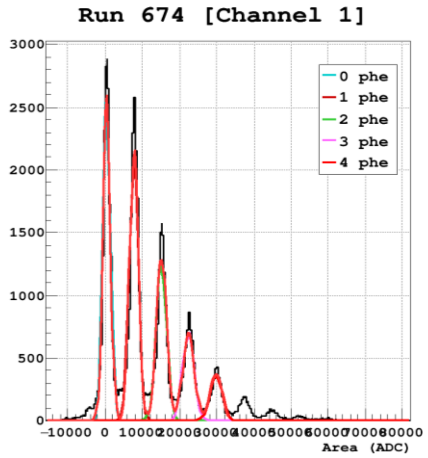
ANAIS+: ^{tiny}OCTOPUS

Single photoelectron response: signal calibrated using a LED injected via optical fiber.

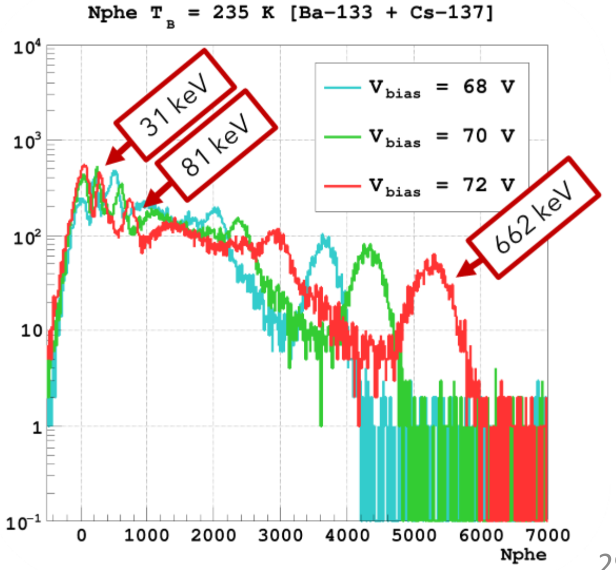






Radioactive sources: Ba-133 and Cs-137

- ❖ Increase of LC for higher Vov.
- ❖ Important decreases of LC for CsI(Tl) at lower temperatures (as observed for the NaI(Tl)).



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ANAIS+: ^{tiny}OCTOPUS

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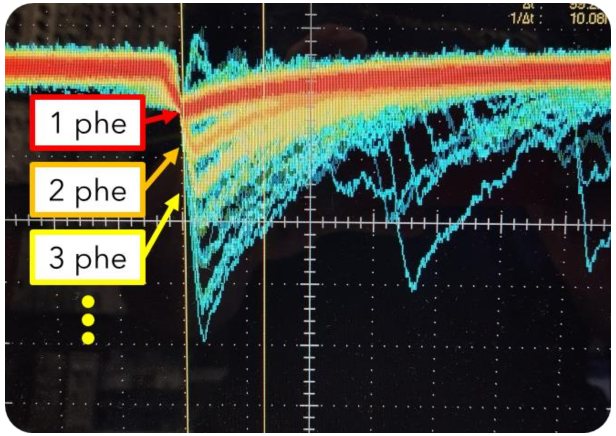

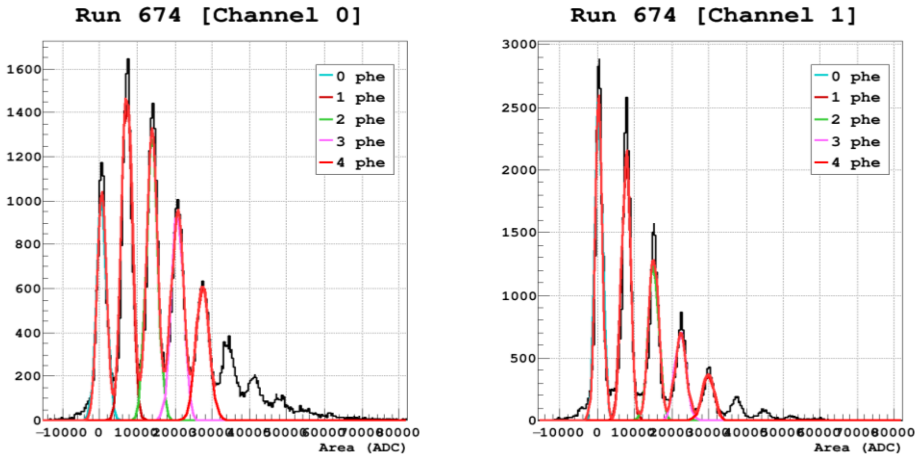

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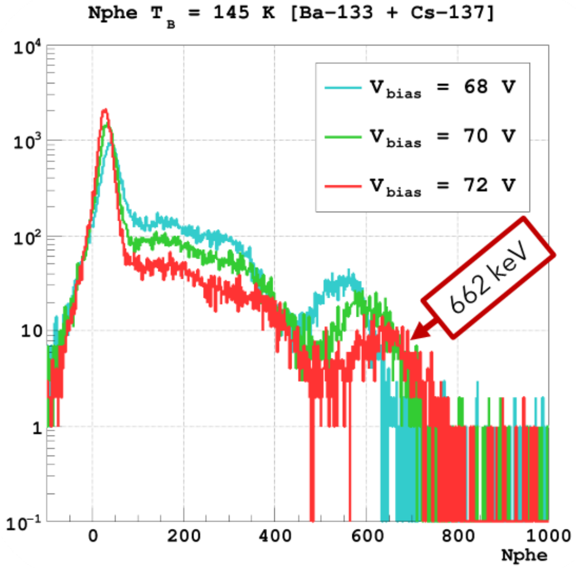

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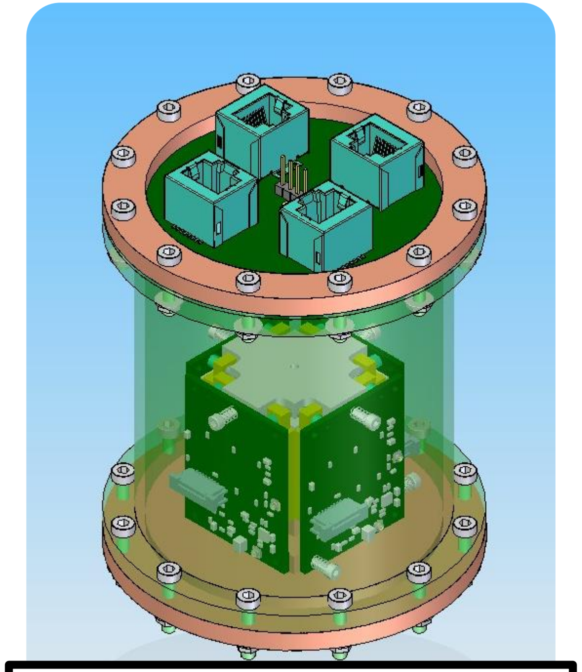
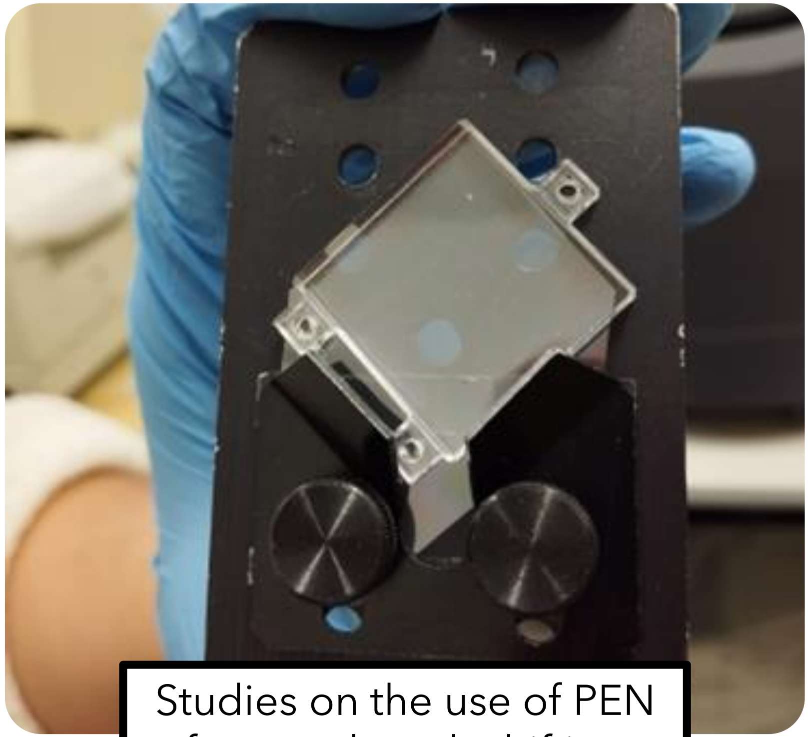
ANAIS+: ^{tiny}OCTOPUS



Production of a Cu case to hold NaI crystals



Studies on the use of PEN for wavelength shifting

- Testing the ANAIS+ prototype in a liquid Ar tank (in collaboration with CIEMAT):
  - 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).

Summary

- ANAIS-112 is an experiment conceived to study and establish a model independent comparison with the positive signal on annual modulation given by DAMA/LIBRA. It started the data taking in 2017 at the Underground Laboratory of Canfranc and has worked smoothly since then.

- The analysis of 3-year of data has been carried out introducing a machine-learning technique to improve the event classification. No modulation is observed, discarding DAMA/LIBRA result with $\approx 3\,\sigma$ sensitivity.

- The latest results, analysing 6-year of data, are consistent with previous results, being incompatible with DAMA/LIBRA at $\approx 4\,\sigma$ sensitivity. We expect to reach $5\,\sigma$ at the end of 2025.

- These results are leading the DAMA/LIBRA test, but they are affected by an important systematic, the scintillating QF of NaI(Tl).

- Multiple lines of work are ongoing:
  - Studies on the QF of the detector.
  - Improvements on the background model.
  - Use of a new parallel DAQ that allows us to better identify noise events via Pulse Shape Discrimination.
  - Collaboration with COSINE experiment for data combination.
  - We are working in the R&D project ANAIS+, with first prototypes in development, that could increase the sensitivity of NaI experiments and allow the exploration of new regions of the WIMP sector and other interesting process.


Thank you!
Merry Christmas!