Status of direct dark matter searches with scintillators

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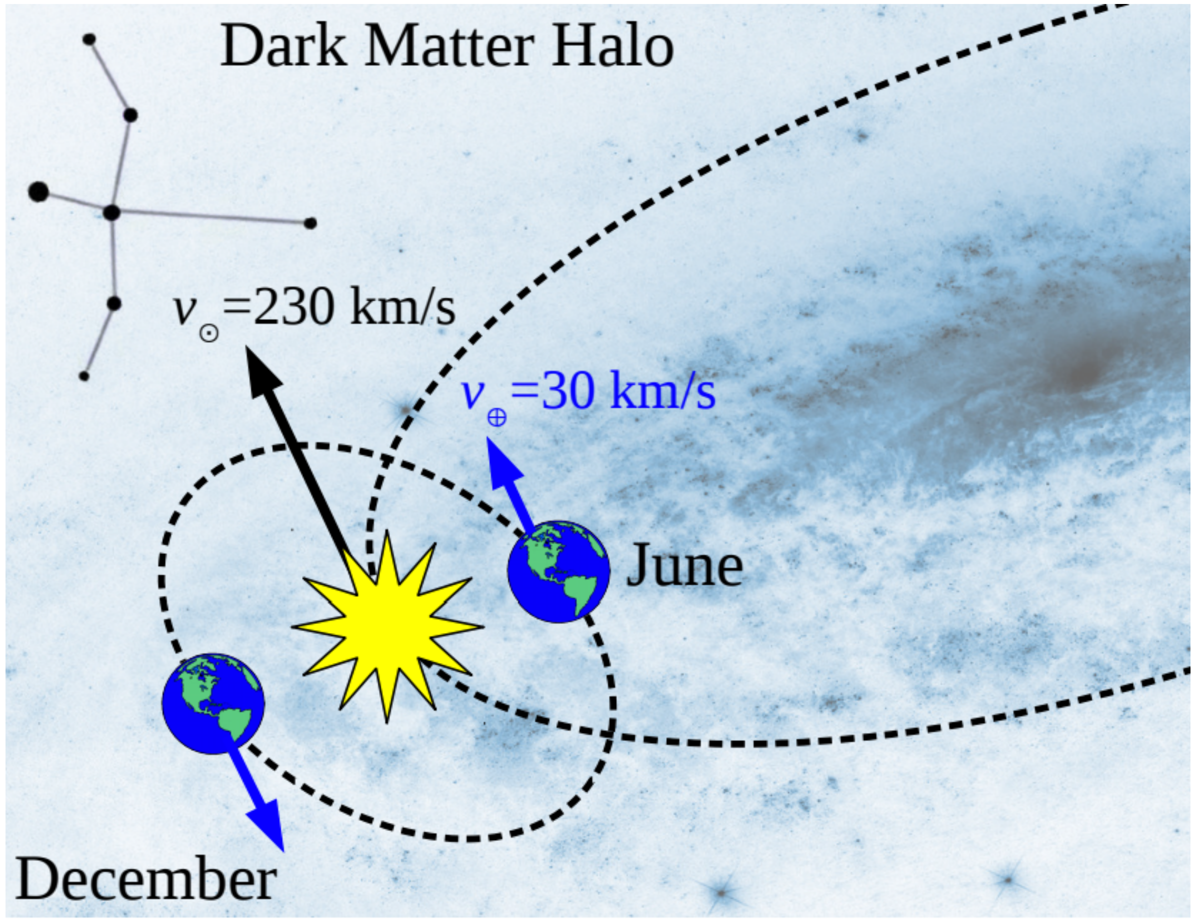
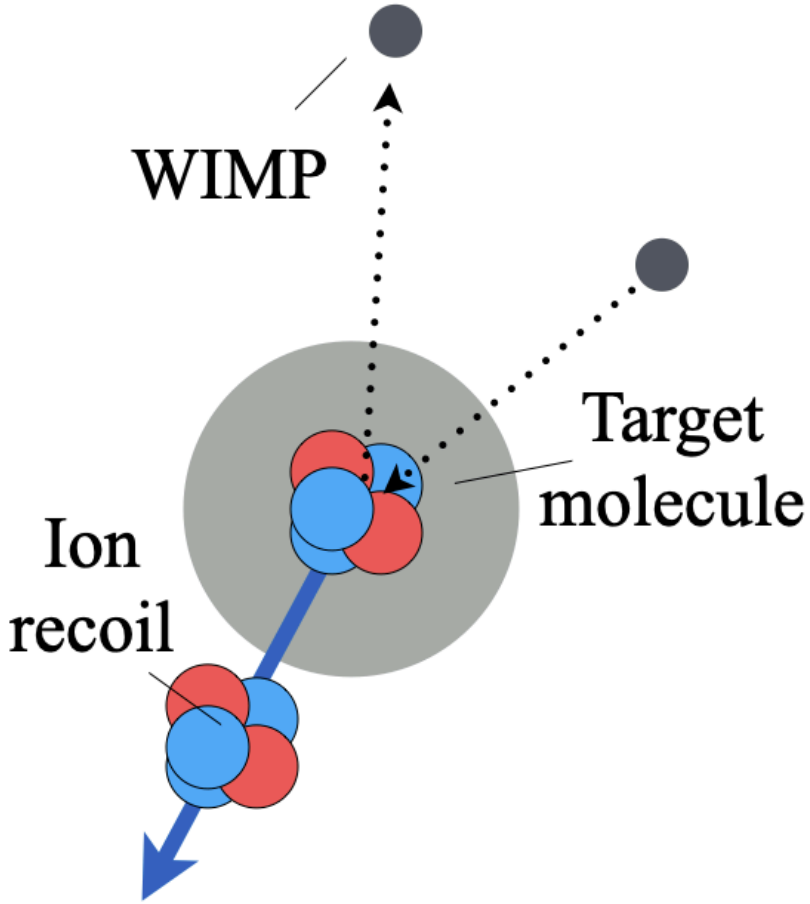
Detection with scintillators



Standard Halo Model:
- Canonical value for density: ρ≈0.3 GeV/cm3.
- WIMP wind:

$$v_E = v_\odot + v_\oplus \cos(\theta) \cos\left[\omega(t - t_0)\right]$$

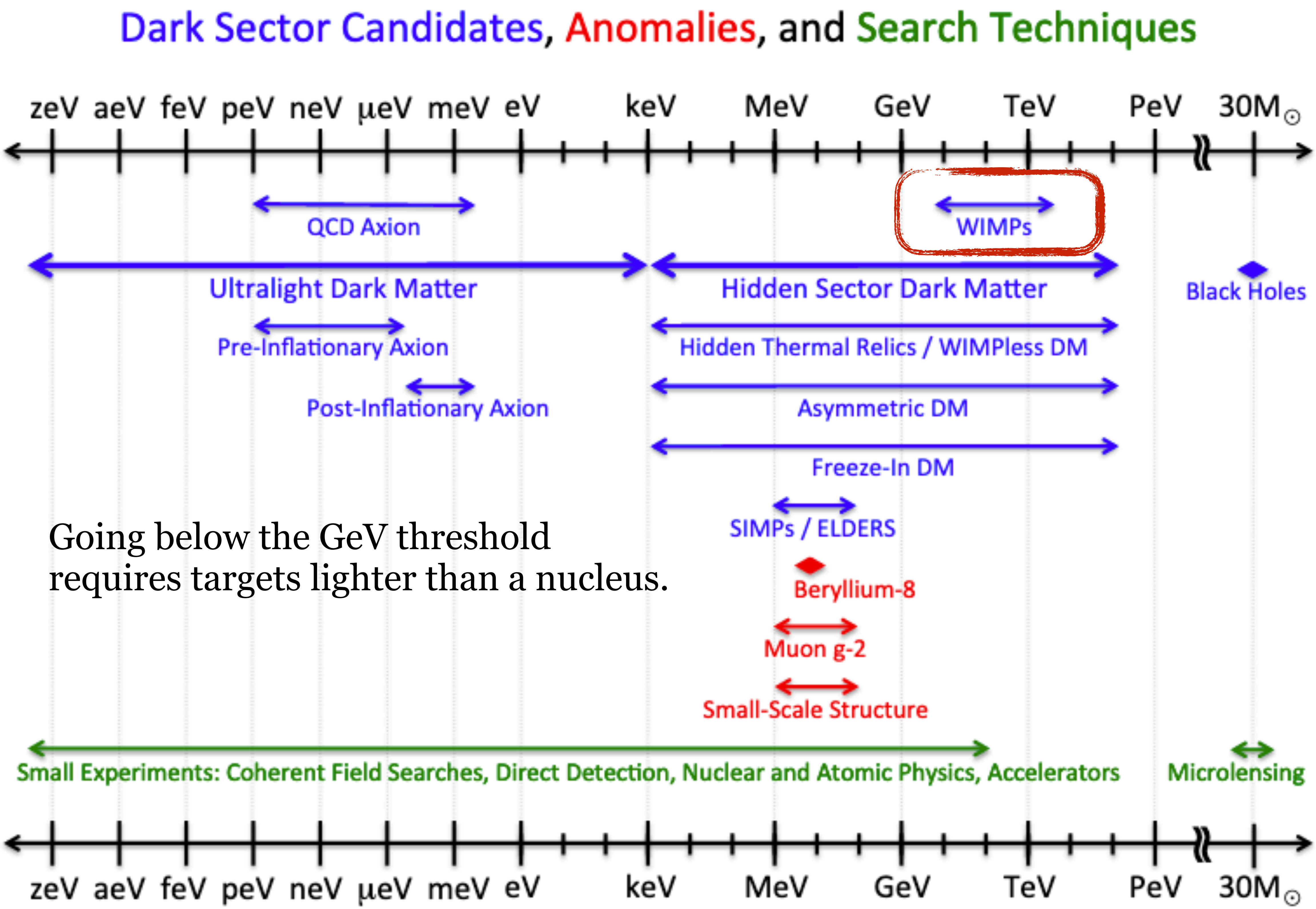
- θ≈60º earth orbit inclination wrt galactic plane.
- Max: 2 June, Min: 2 Dec.



$$S(t) = B + S_0 + S_m \cos\left[\omega(t - t_0)\right]$$

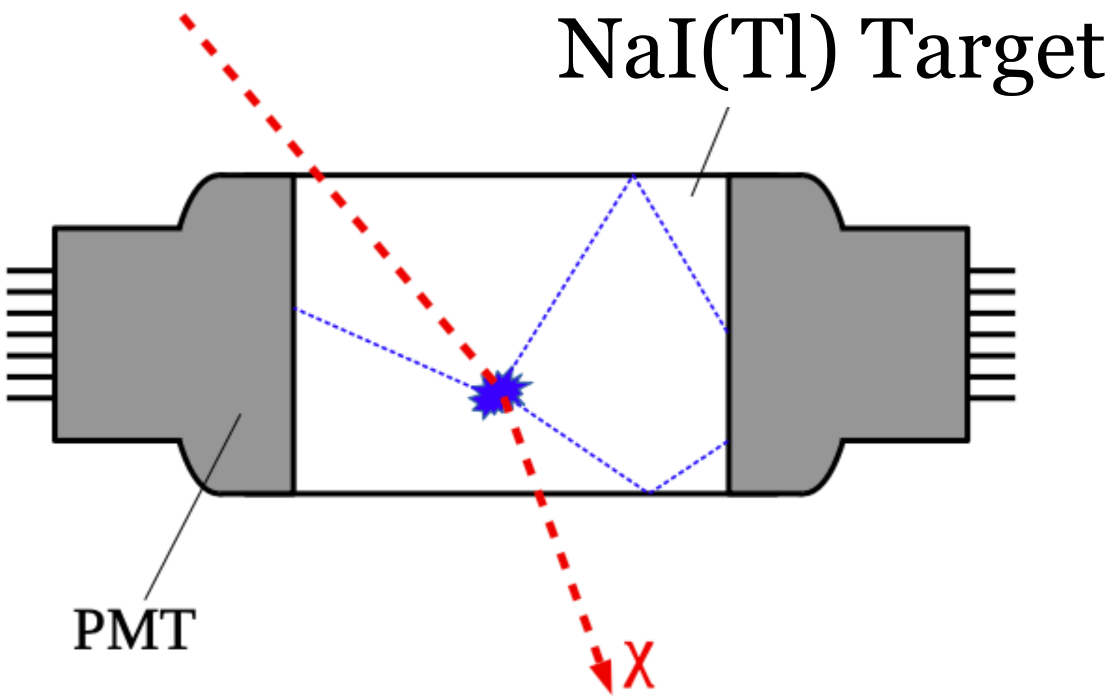
- Elastic scattering of WIMPs on target nuclei.
- Challenging as it produces a **rare signal** concentrated at **low energies ≈keV**.
- Modulation is small: **≈0.01 cpd/kg/keV**.

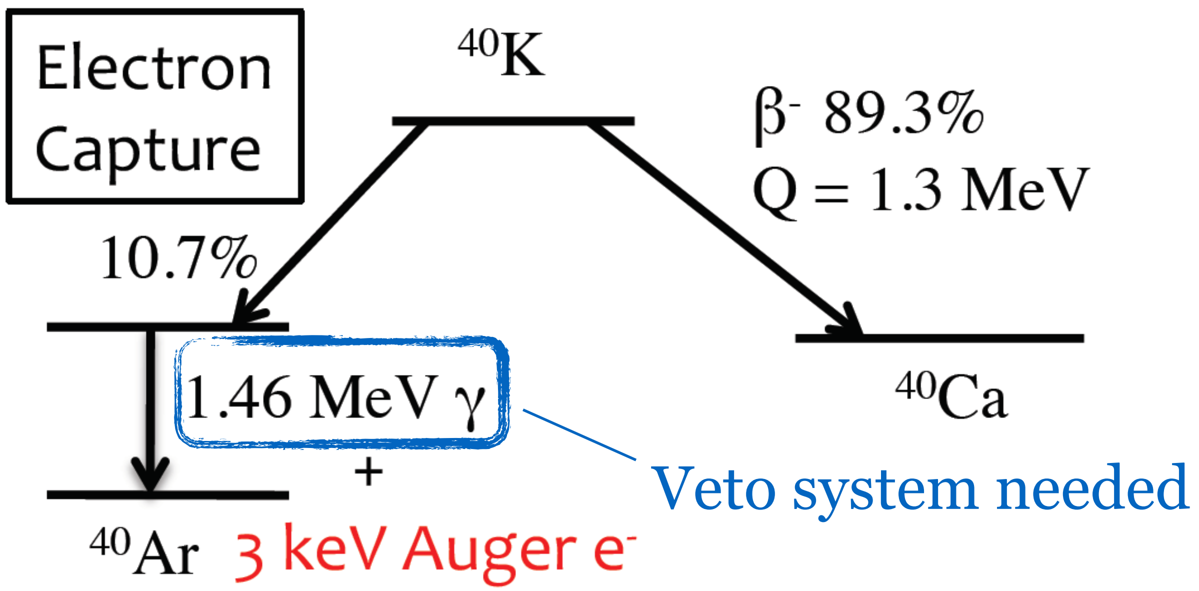
WIMPs



Going below the GeV threshold
requires targets lighter than a nucleus.

Crystal modules

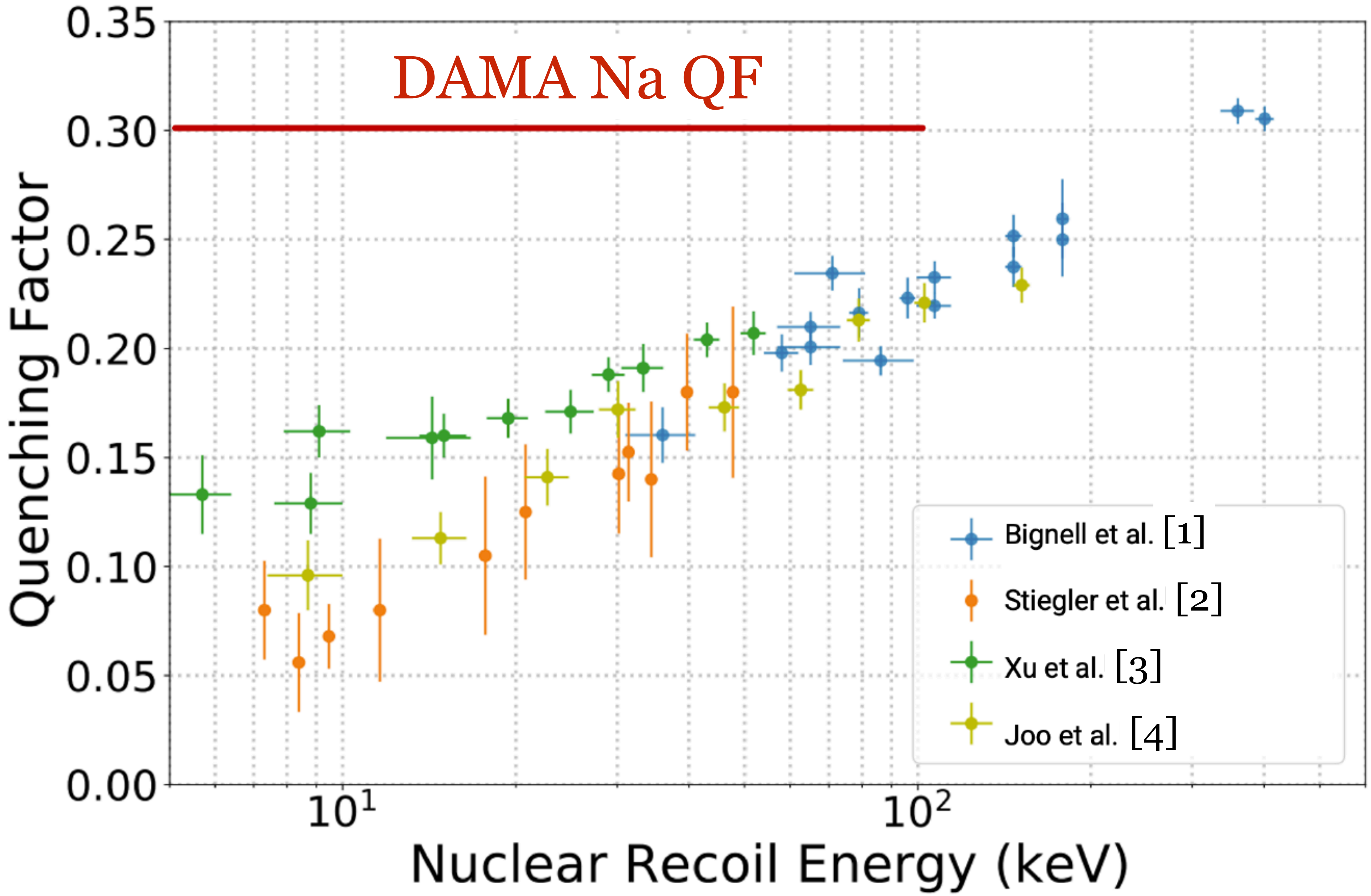




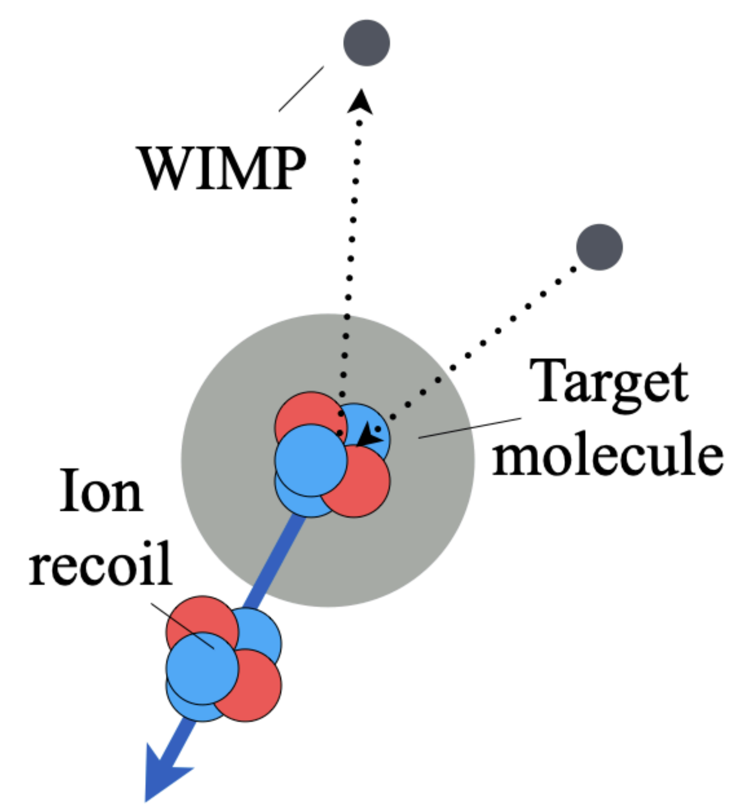
Crystal	^{nat}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	^{210}Pb (mBq/kg)	Active mass (kg)
DAMA [1]	13	0.7-10	0.5-7.5	(5-30) x 10^{-3}	250
ANAIS [2]	31	<0.81	0.36	1.5	112.5
COSINE [3]	35.1	<0.12	<2.4	1-1.7	≈60
SABRE [4]	4.3	0.4	0.2	0.49	≈35+40=75 (goal)

[1] NIMA 592 (3) (2008) , [2] EPJC 79 412 (2019), [3] EPJC 78 490 (2018), [4] Phys. Rev. Research 2, 013223 (2020).

Quenching factors



$$E_{ee} = QF(E_{NR})E_{NR}$$



- Conversion of the nuclear recoil energy into electron equivalent energy.
- Changes both the amplitude and position of the signal.
- Might depend on the optical properties of the crystal affected by its growth method.
- Depends on the type of recoiling nucleus (Na or I).

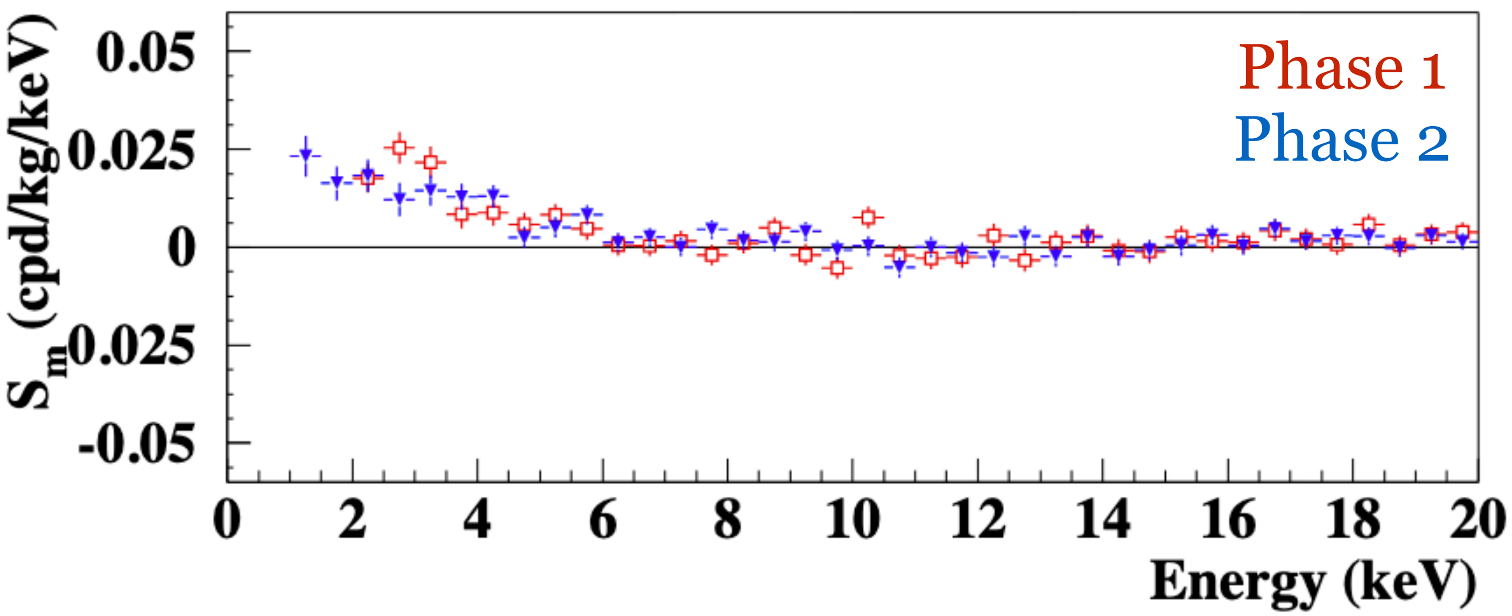
[1] JINST 16 P07034, [2] arxiv:1706.07494 , [3] 10.1103/physrevc.92.015807 , [4] 10.1016/j.astropartphys.2019.01.001.

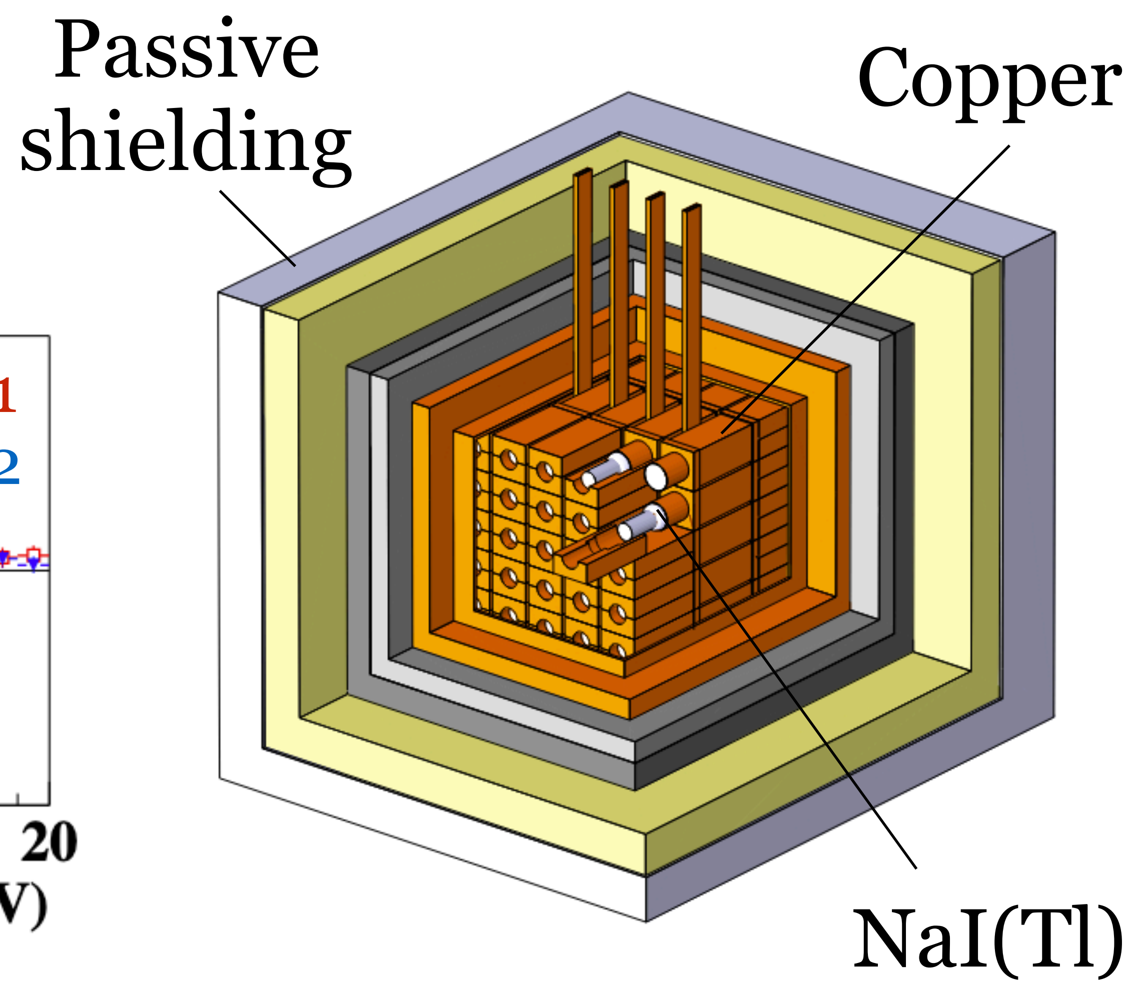
Crystal-based experiments

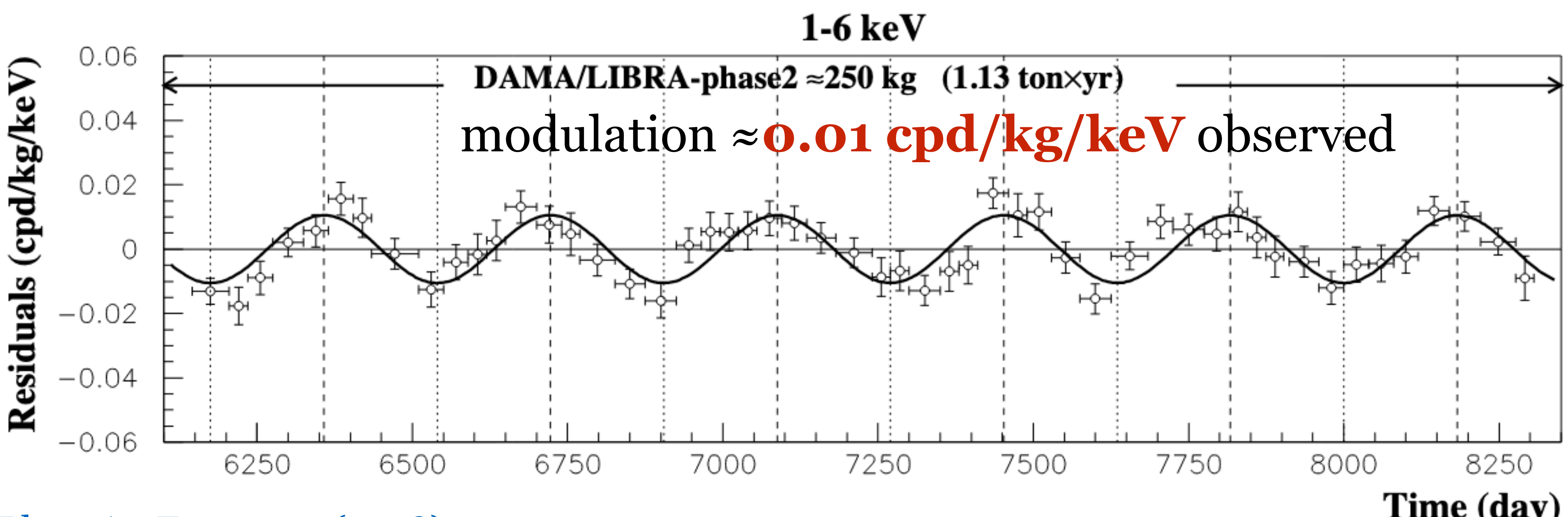
DAMA/LIBRA

DAMA/LIBRA @ LNGS

- Total target mass = 250 kg of NaI(Tl).
- Modulation observed for 14 years.
- **12.9 σ** significance!

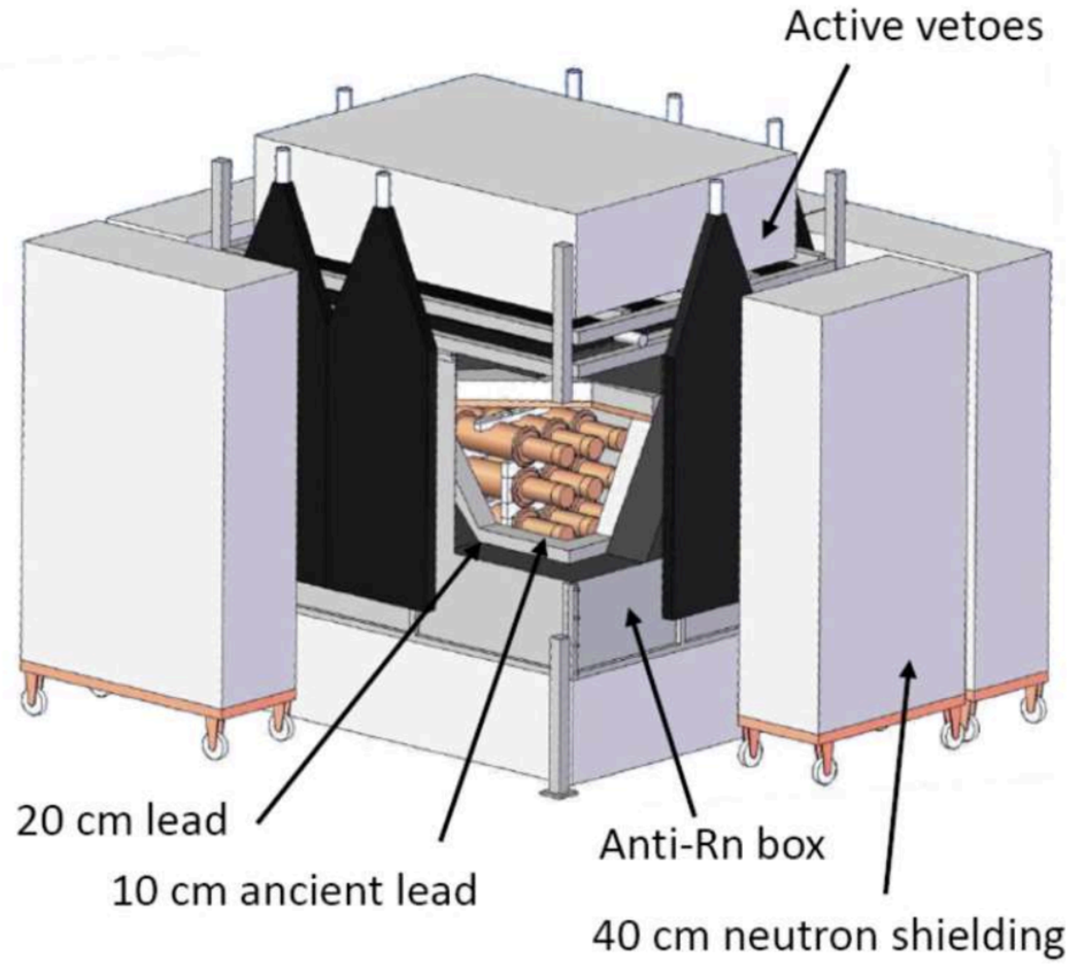


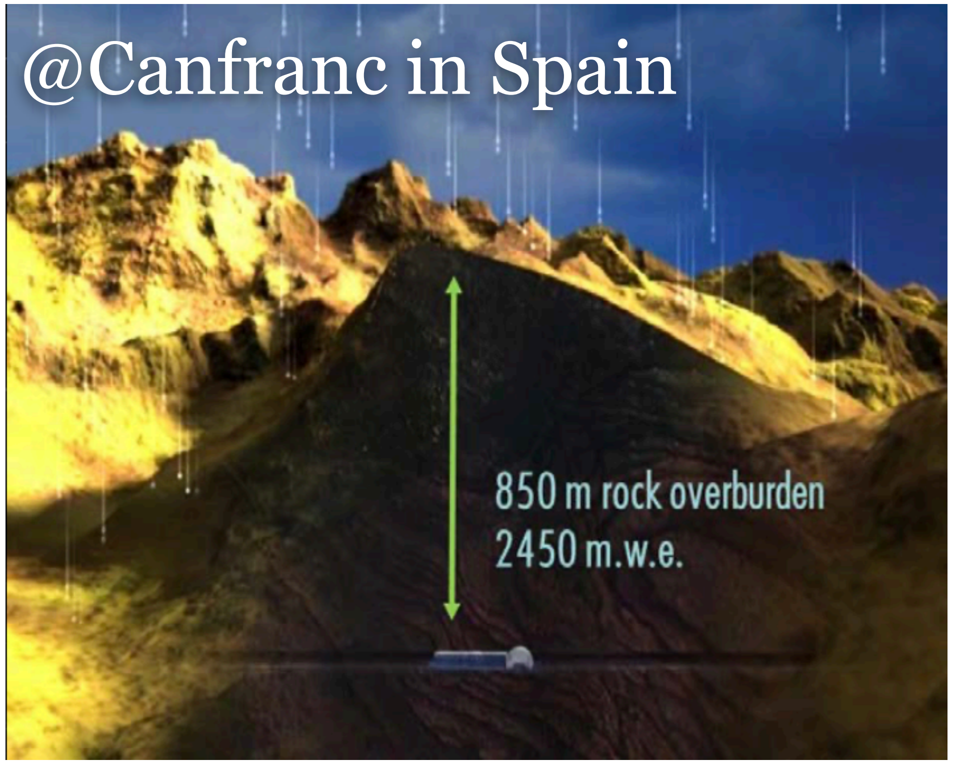


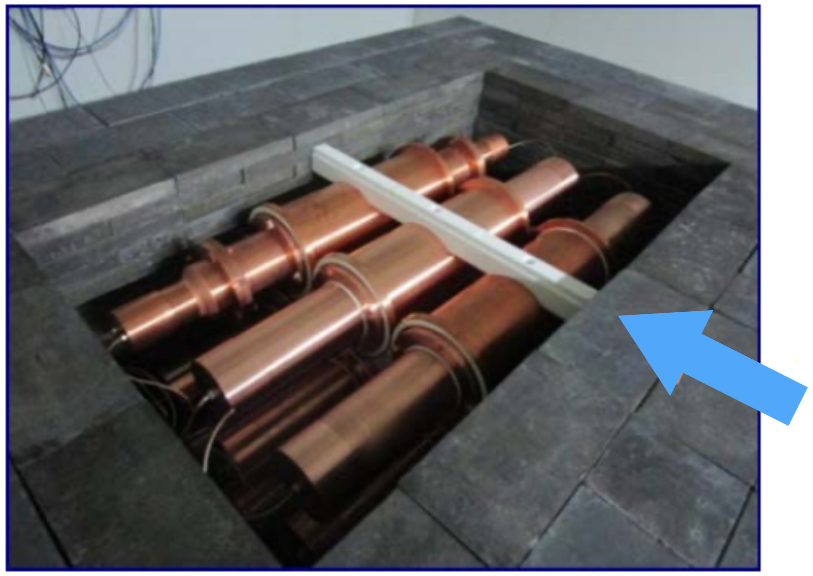


Nucl. Phys. At. Energy 19 (2018) 307-325

ANAIS-112







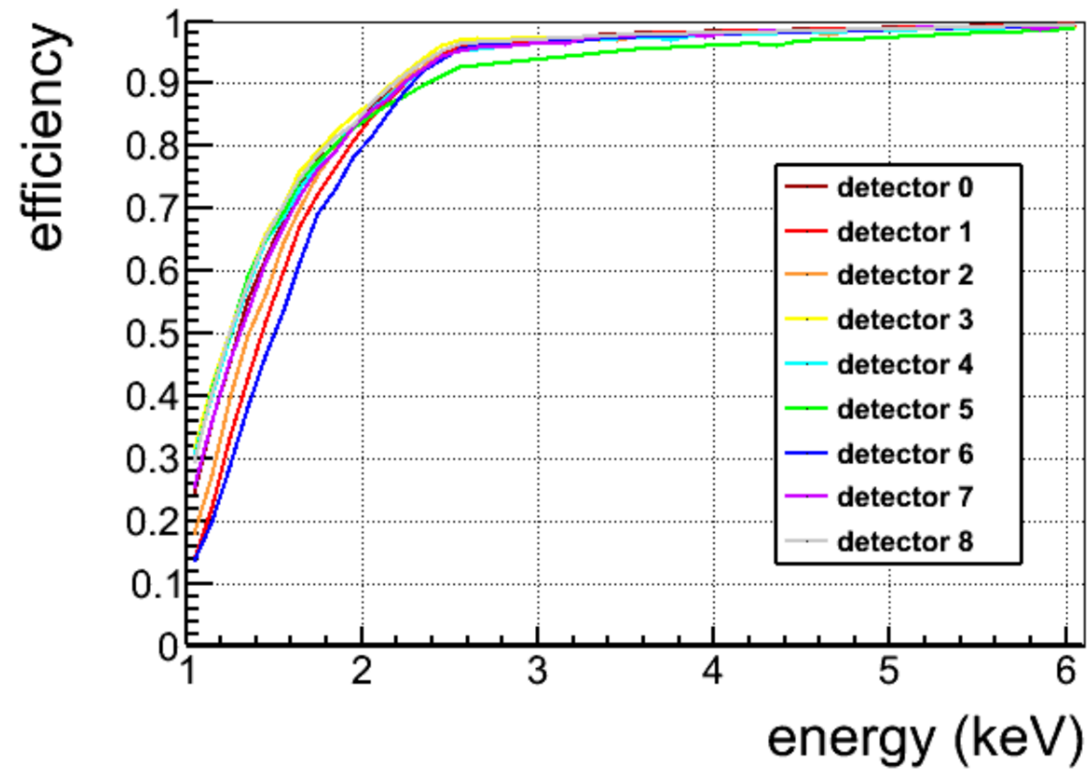
- 3 x 3 detector modules: 112.5 kg of NaI(Tl) built by Alpha Spectra company (US).
- High light yield 15 phe/keV allowing threshold of 1 keV_{ee}.
- Low-energy calibration using ^{109}Cd sources in Mylar windows.
- **Five year exposure** completed by August 2022 with 95% live time. Started 3 August 2017.

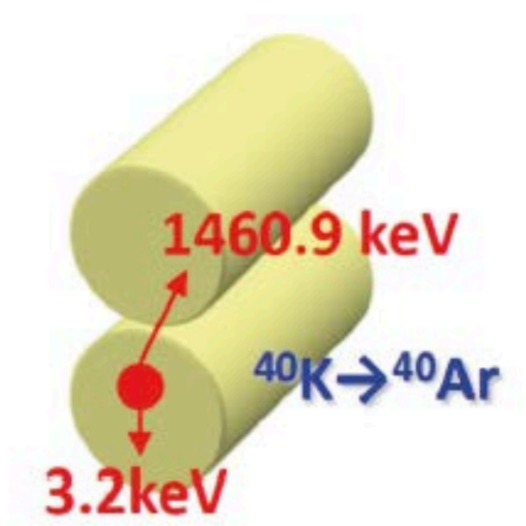
ANAIS-112

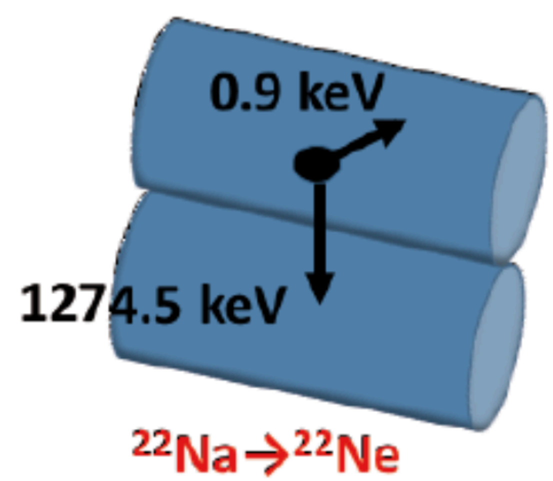
Phys. Rev. D 103, 102005

Analysis (3 years of data):

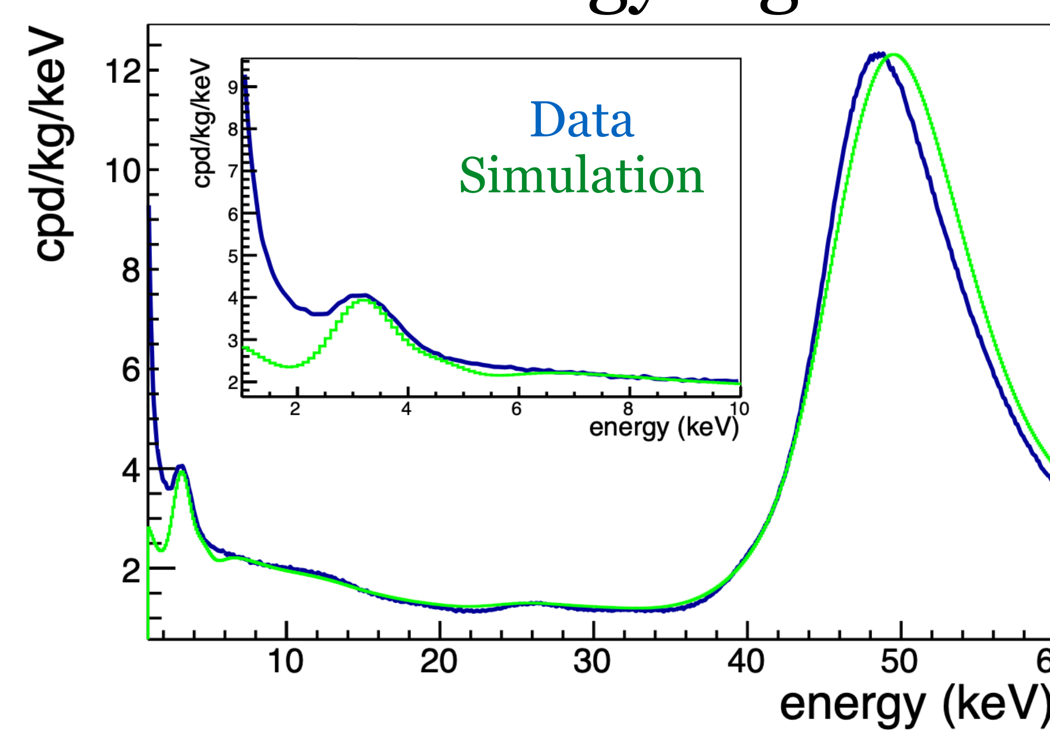
- Pulse shape cut to select events from NaI(Tl) scintillation.
- Asymmetric event rejection (E < 2 keV) to remove PMT-originated events.
- Remove 1 second after a muon passage.
- Multiplicity = 1. Remove multi-module events.







Low-energy region



Revision of background model underway

ANAIS-112

Phys. Rev. D 103, 102005

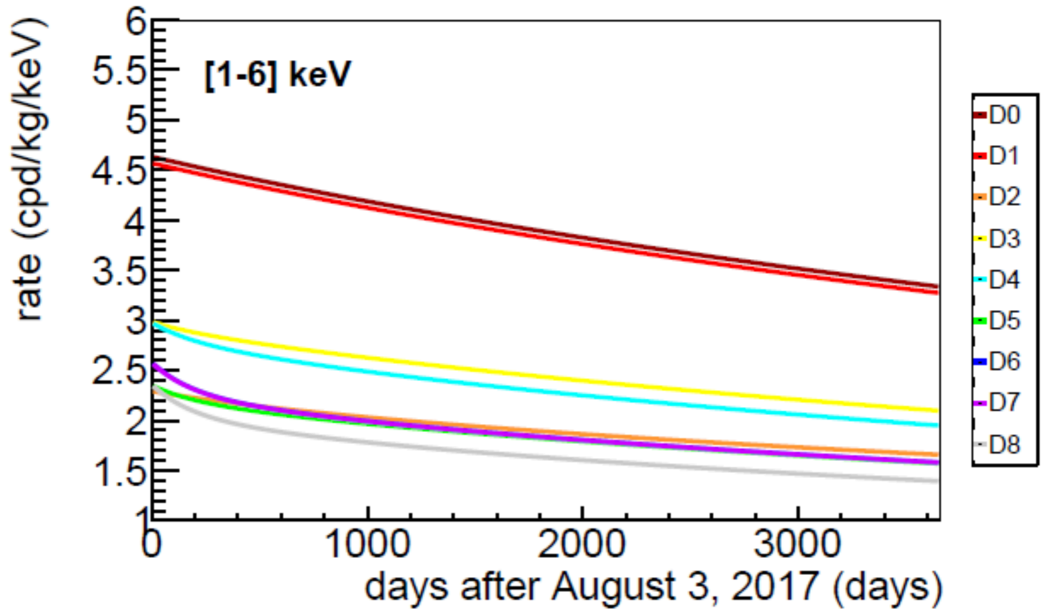
- Minimising: $\chi^2 = \sum_{i,d} \frac{(n_{i,d} - \mu_{i,d})^2}{\sigma_{i,d}^2}$

  where $n_{i,d}$, $\sigma_{i,d}$ are computed in 10 days bins i corrected by live time and efficiency for each detector d.

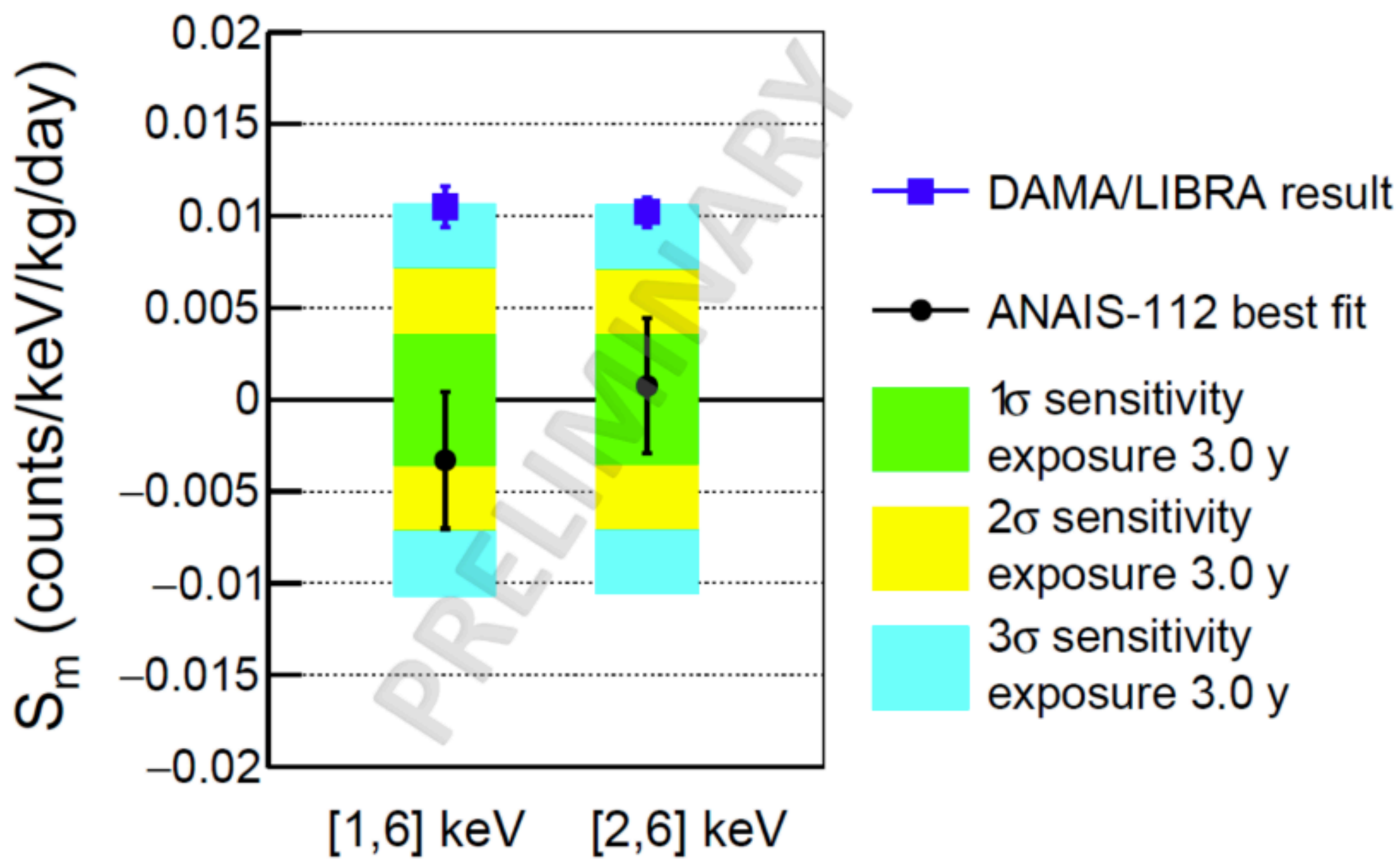
- Background probability distribution drawn from the background model for every detector.

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

Simulated background

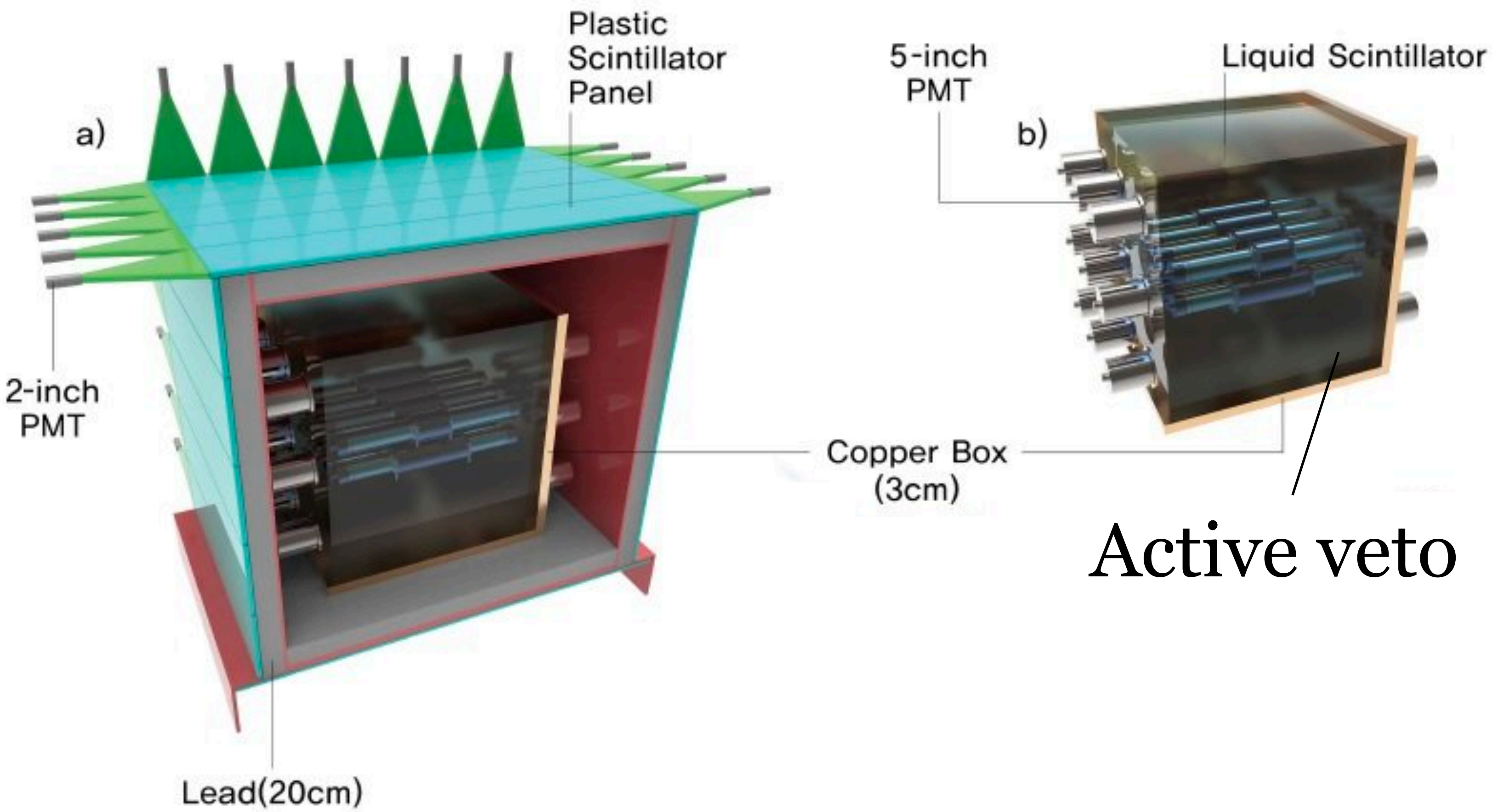


Credit: Maria Martinez, PCP23 Daejeon Korea

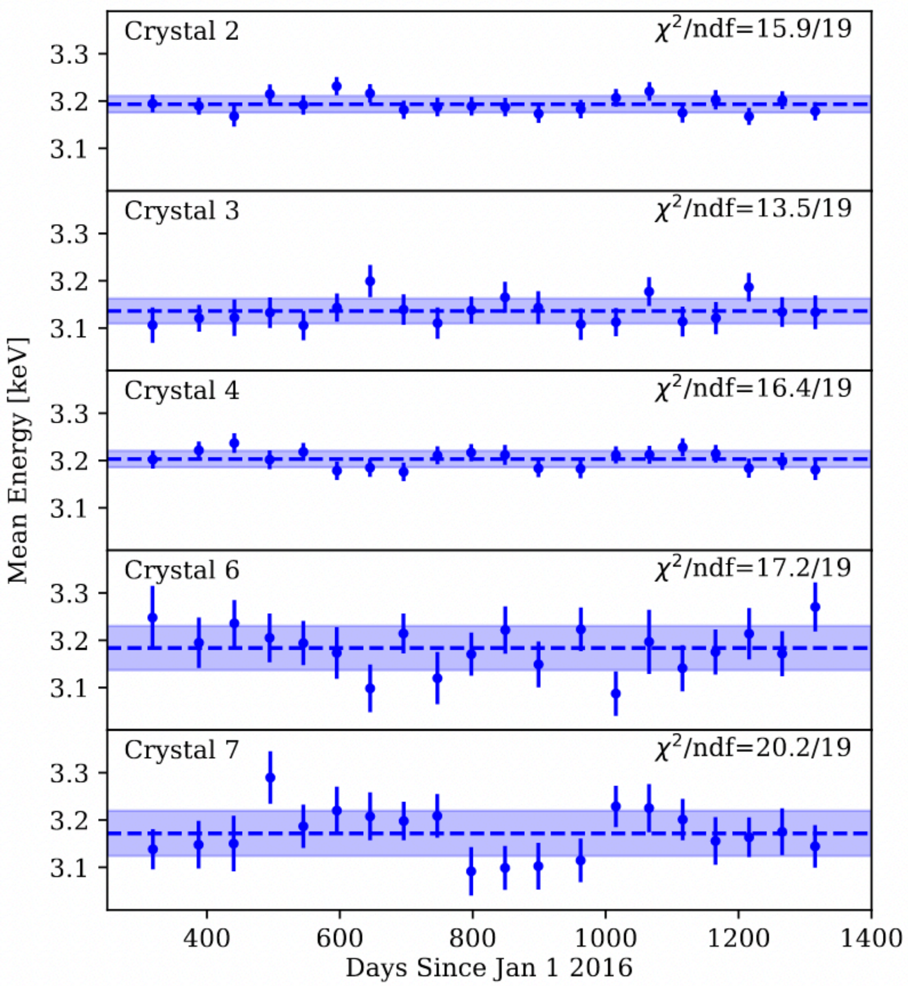


- Best fits are incompatible with DAMA/LIBRA at 3.9 σ and 2.8 σ in [1-6] and [2-6] keV regions for a sensitivity of ≈2.9 σ.
- New BDT-based analysis released: JCAP11 (2022) 048.
- Expected to yield a 5 σ sensitivity to DAMA/LIBRA by late 2025.

COSINE-100



- 8 detector modules from Alpha Spectra: 106 kg of NaI(Tl).
- Active since 2016.
- About 93% of good data taken (6.2 years of good data).
- Liquid scintillator active veto 2200 L.
- Calibration with ^{60}Co and ^{22}Na.
- Energy scale stability verified by monitoring ^{40}K decay energy.

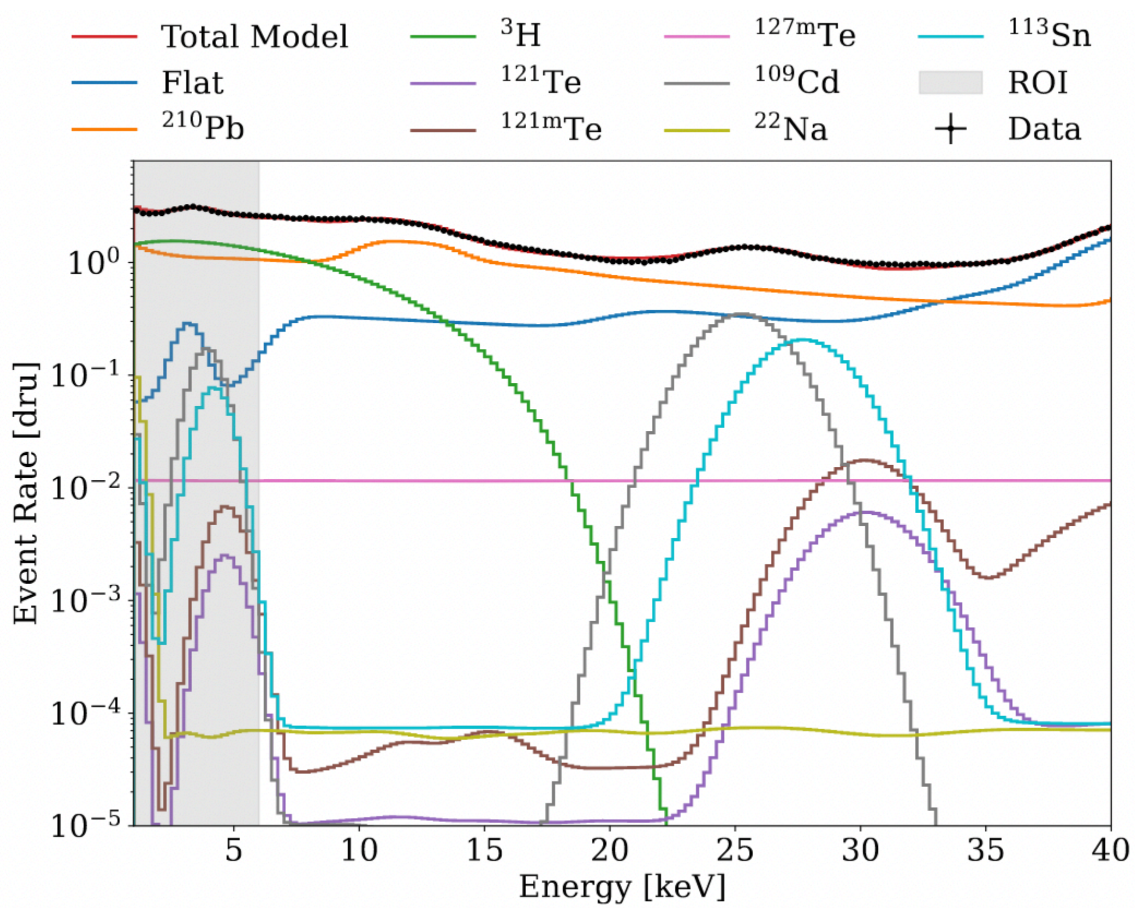


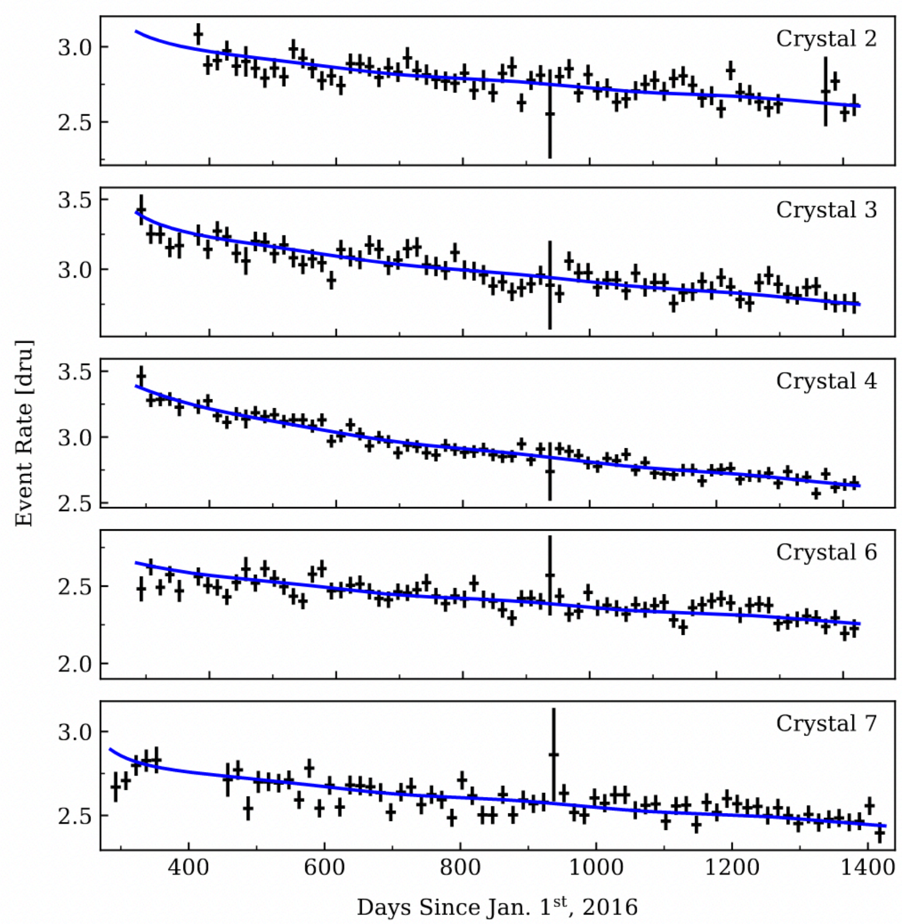
COSINE-100

Phys. Rev. D 106, 052005

Total rate: $$R_i(t|S_m, \alpha_i, \beta_i) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m \cos(\omega(t - t_0))$$

- Dedicated model for detector *i* and background *k*.
- Flat: long lived backgrounds: ^{40}K, ^{238}U, ^{232}Th.
- Exponential: decaying backgrounds. Separate model for ^{210}Pb, ^{3}H etc.
- Modulation.

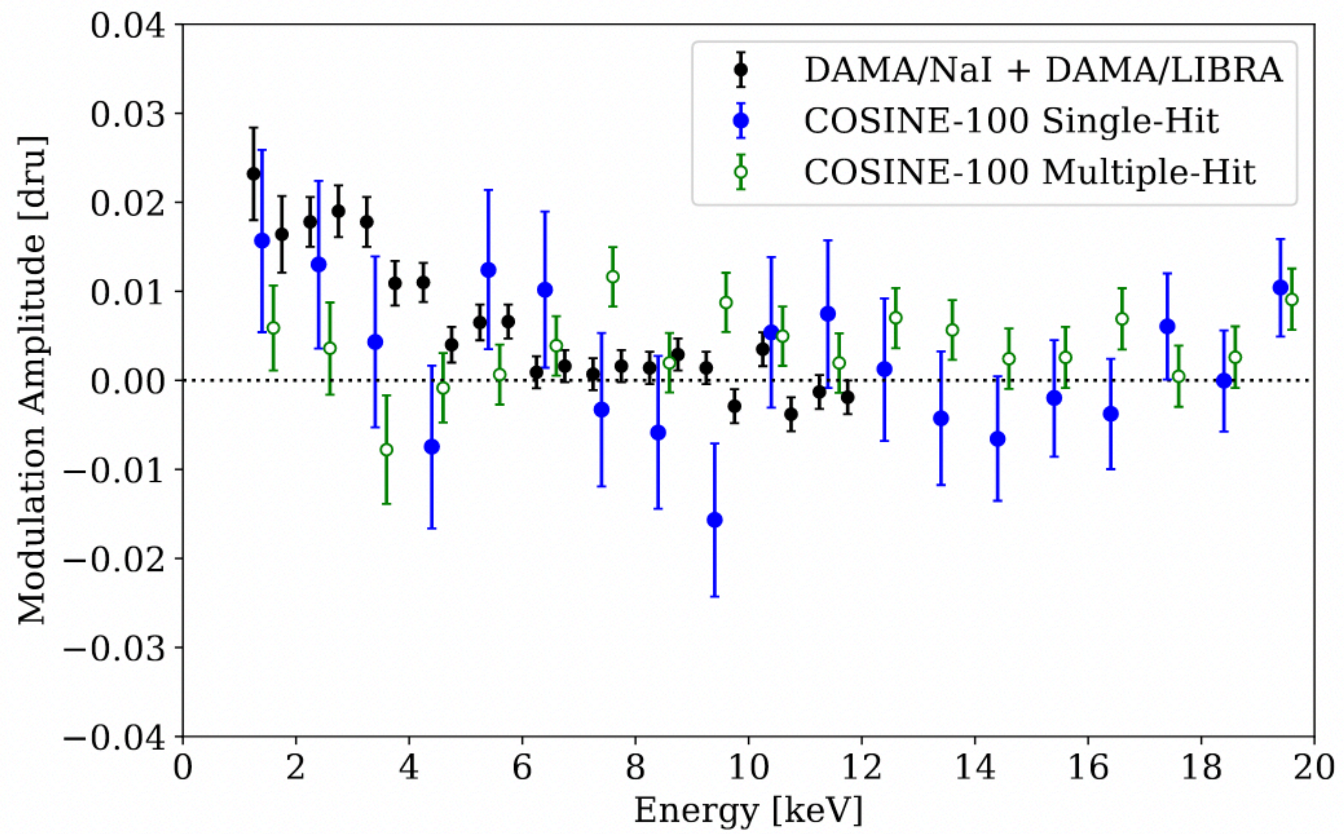




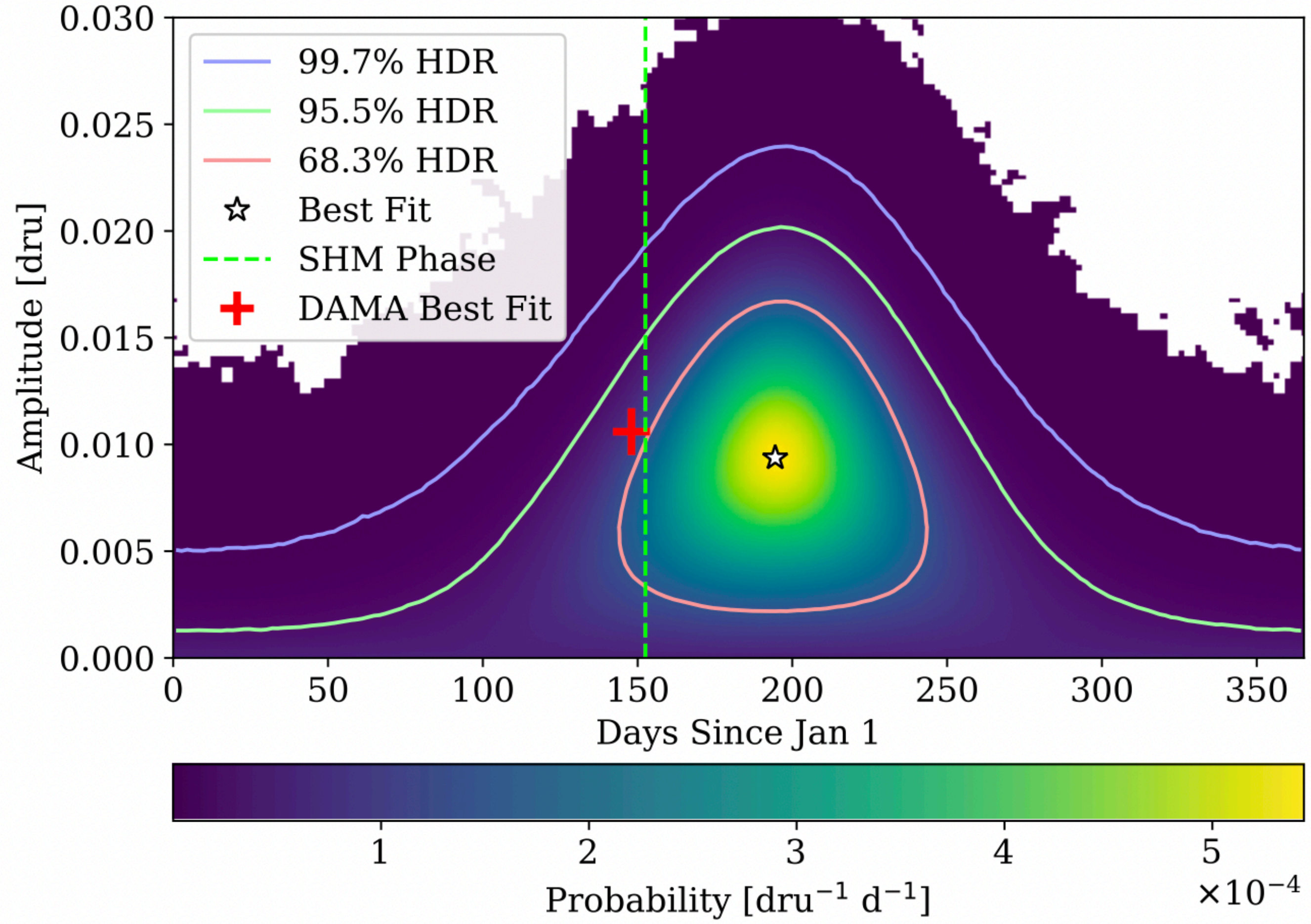
- Background model created using first 1.7 years of data + MC simulations.
- Data normalised by live-time and efficiency in 15 days bins before fitting.

Phys. Rev. D 106, 052005

Fixed phase and period
- Period = 365.25 days.
- Phase = 152.5 days.



Floated phase: [1 - 6] keV



- 2.8 years of data and 60 kg of NaI(Tl).
- The best fit amplitude is consistent with DAMA and null hypothesis.
- Commissioning of COSINE-200 has started. First physics runs by the end of 2024.

SABRE

- The ambitious program of SABRE foresees two detectors in two underground locations:
  - SABRE North: at Laboratori Nazionali del Gran Sasso (LNGS) in Italy.
  - SABRE South: at the Stawell Underground Physics Laboratory (SUPL) in Australia.
  - Same detector module: high purity NaI(Tl) + HPK R11065 PMTs.

INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

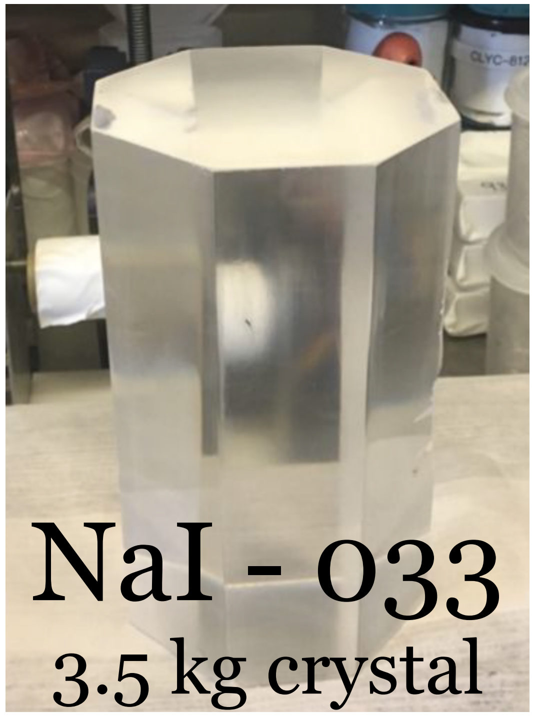
STAWELL UNDERGROUND PHYSICS LAB

Stawell **U**nderground **P**hysics **L**aboratory:

- First underground laboratory in the southern hemisphere 1025 m deep (2900 m water equivalent) with flat overburden.
- Located in the Stawell gold mine 240 km west of Melbourne.

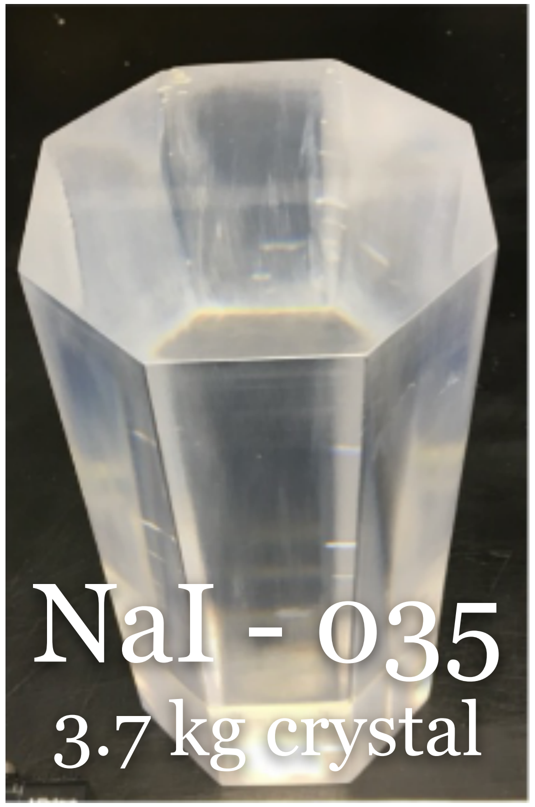
SABRE crystals

- Crystals grown from Astrograde NaI powder from Merk using the vertical Bridgman-Stockbarger method.
- RMD has previously grown a 3.5 kg crystal (NaI-33) for SABRE with very low background.
- NaI-033 tested at LNGS: ^{nat}K contamination determined with ICPMS is the lowest ever measured.
- New crystal NaI-035 produced by RMD in Boston is currently being characterised at LNGS.



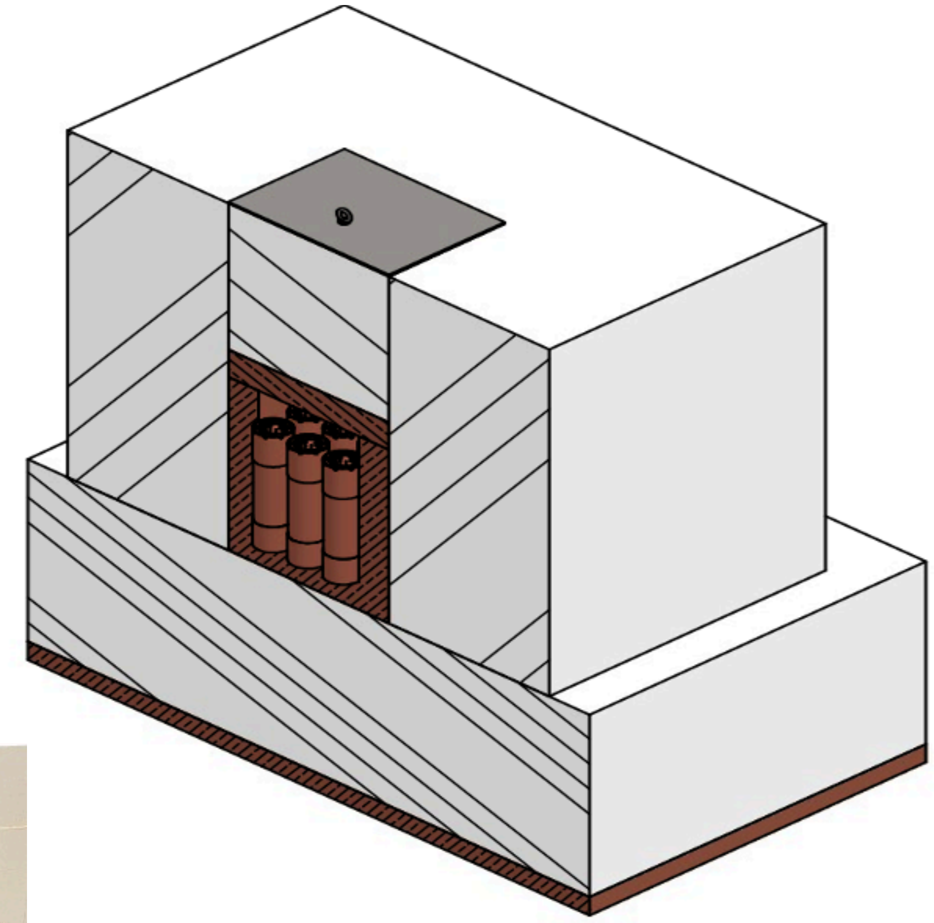
Eur. Phys. J. C 81, 299 (2021)

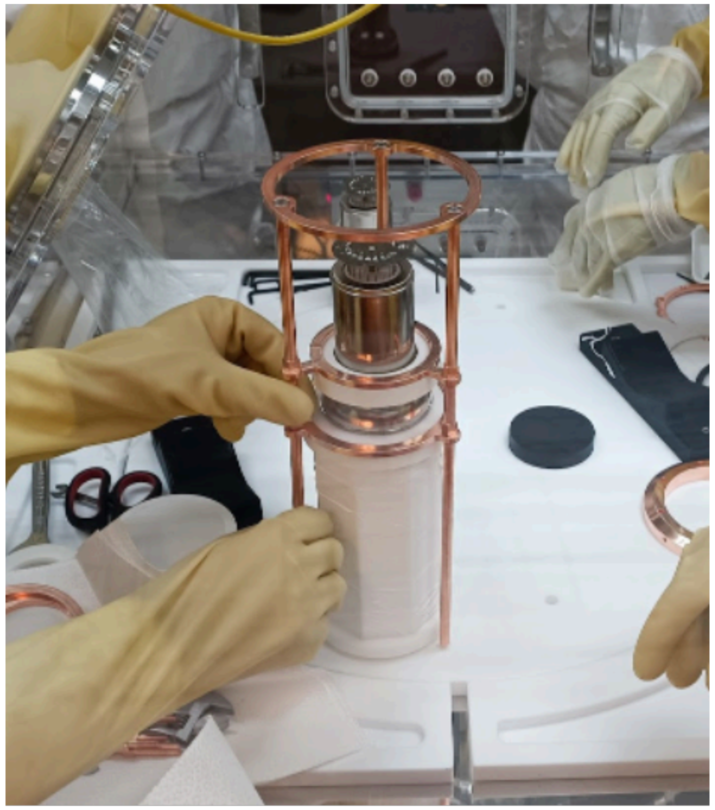
	NaI-33	DAMA/LIBRA crystals	ANAIS crystals	COSINE crystals
LY [phe/keV]	12.1 ± 0.2	6-10	15	15
FWHM/E @59.5 keV	13%	16%	11%	12%
^{238}U [ppt]	< 0.5	0.7-10	0.2-0.8	< 0.02-0.12
^{232}Th [ppt]	< 0.5	0.5-7.5	0.1-1	0.3-2.4
Alpha rate [mBq/kg]	0.54 ± 0.01	0.08-0.12	0.7-3.15	0.74-3.20
^{nat}K [ppb] (from ICP-MS)	4.6 ± 0.2	< 20	17-43	17-82



SABRE North

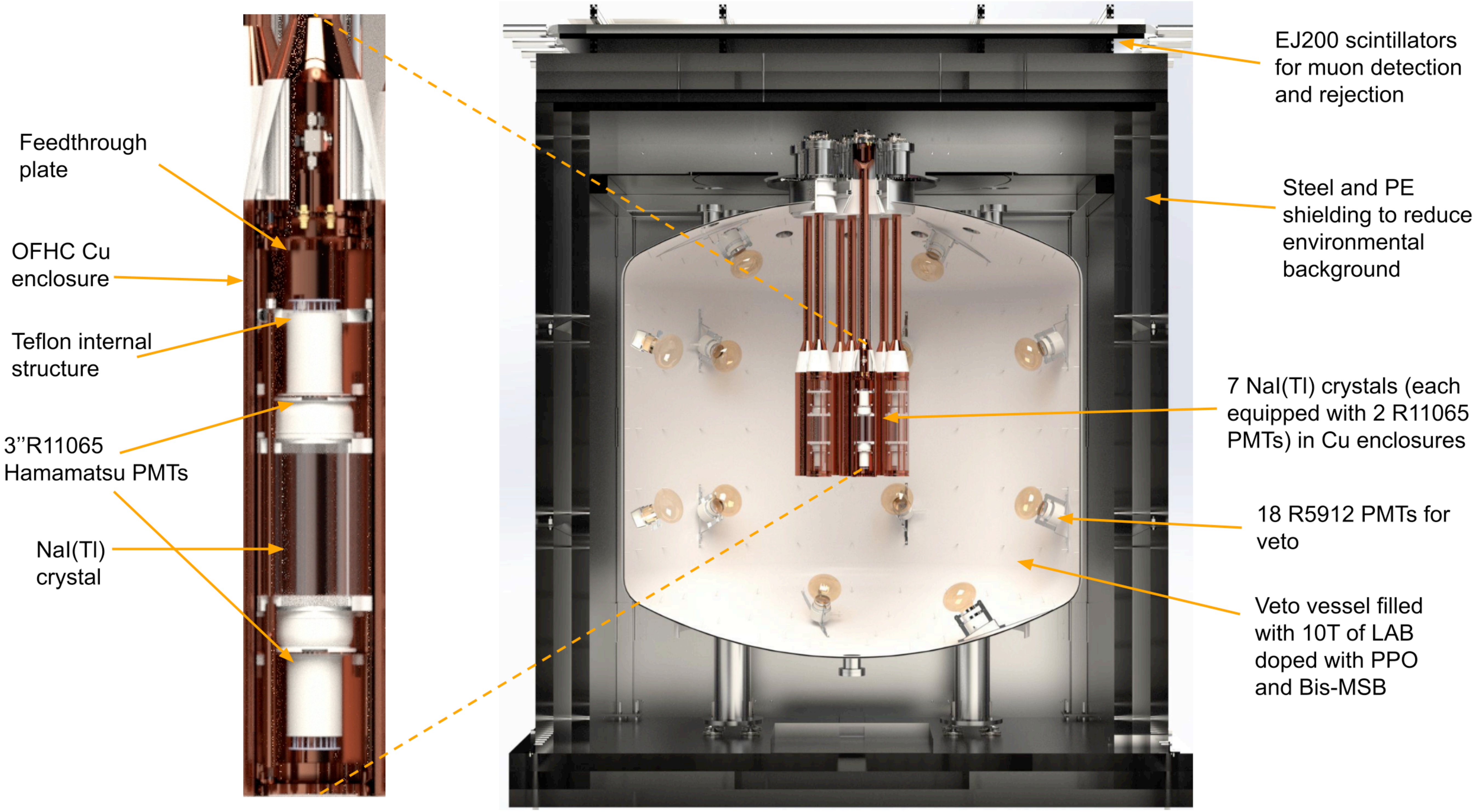
- Fully passive shielding and no active veto rejection due to organic scintillators phased off at LNGS.
- 3 x 3 matrix of NaI(Tl) detectors (≈**40 kg**).
- Inner 5 mm thick ultra pure Cu box.
- 10-15 cm Cu and 80 cm PE shielding structure (≈30 t).
- Predicted background from environmental gamma and neutrons ≈0.01 cpd/kg/keV in the region of interest.





- Currently four crystals underground at LNGS.
- Two more crystals foreseen by 2023 to complete crystal characterisation prior to full production.

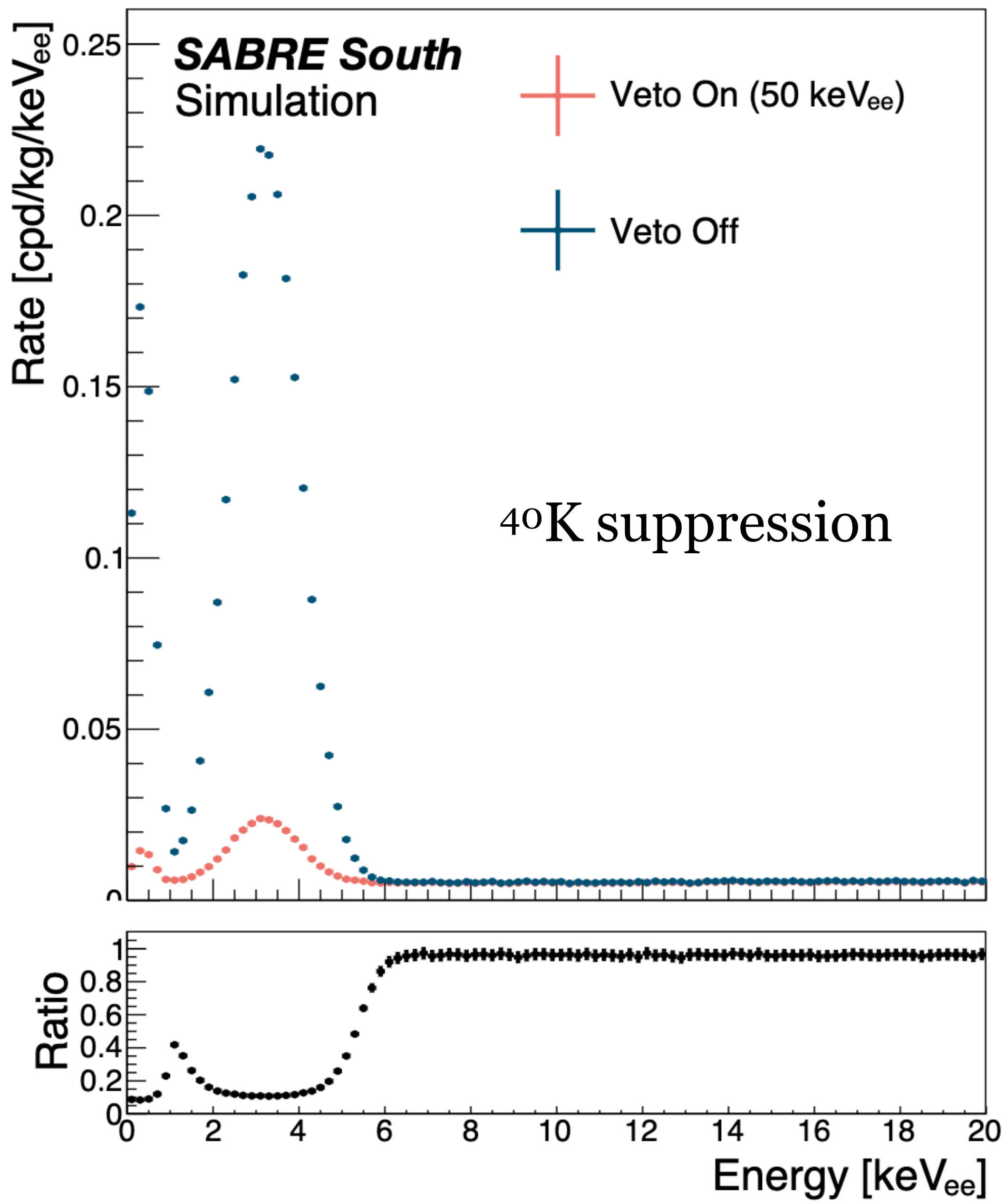
SABRE South

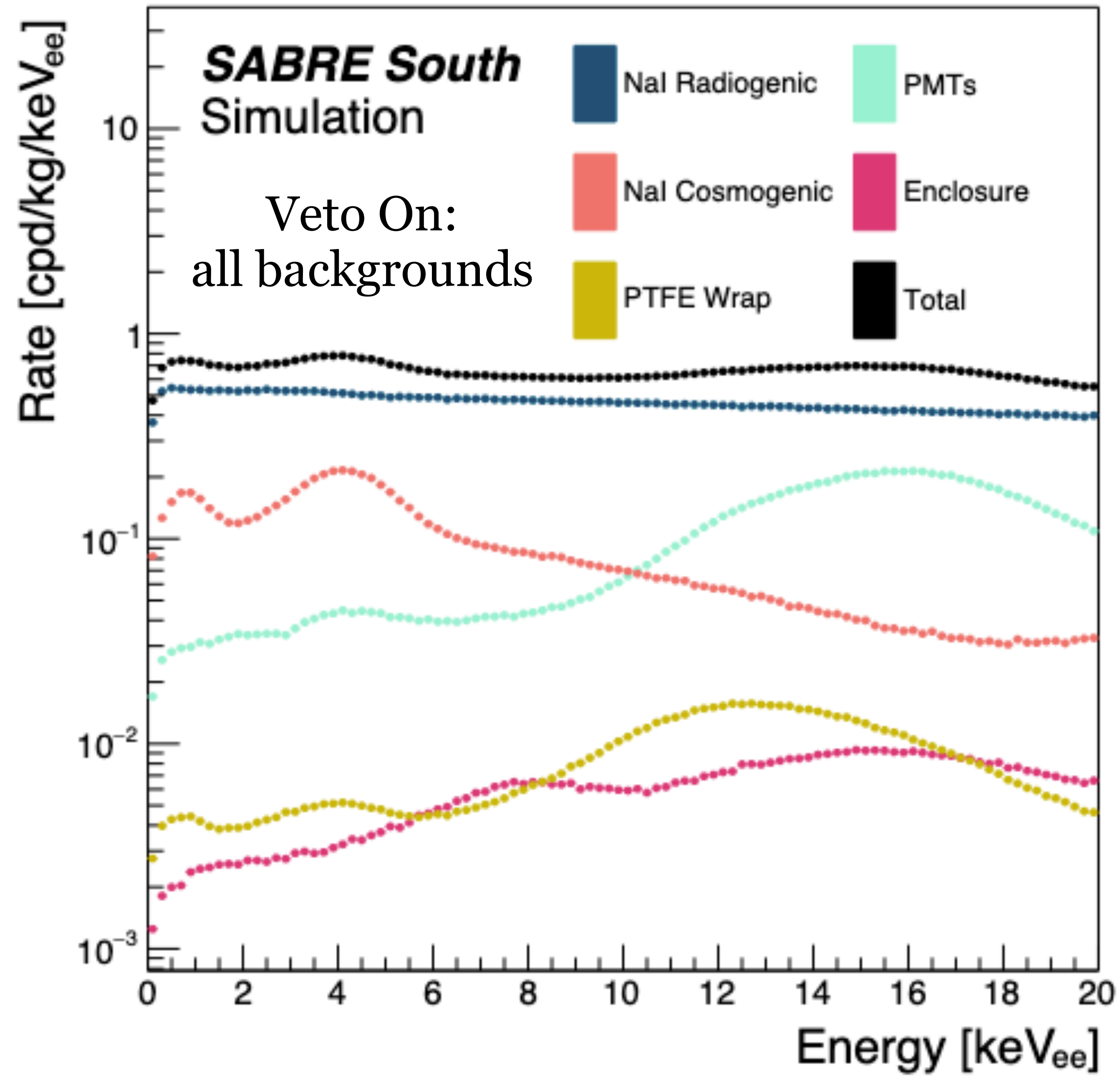


- In situ evaluation and validation of the background using the large active veto.
- Highest purity crystals (total mass **35 kg**) and largest active veto.

SABRE South

arXiv: 2205.13849





- Overall veto requirement is expected to suppress **27%** of the total background.

SABRE South

arXiv: 2205.13849

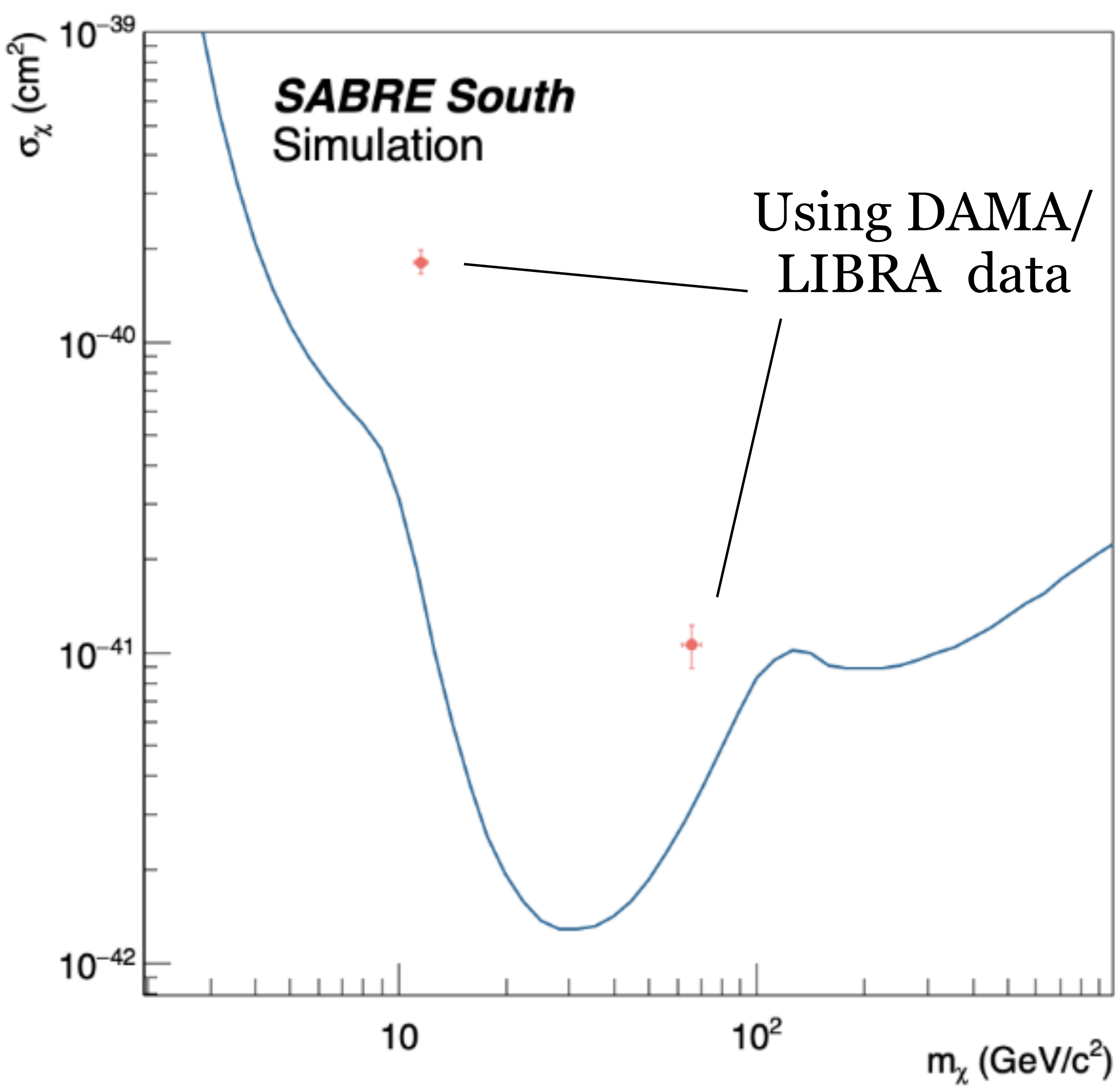


Fig. 8 90% exclusion curve for the SABRE South experiment after three years of data taking (in blue) assuming a background model in the 1–6 keV$_{ee}$ region given by Figure 2 and an exposure mass of 50 kg. The best fits to the DAMA/LIBRA data for this model in both the low- and high-mass region are shown in pink.

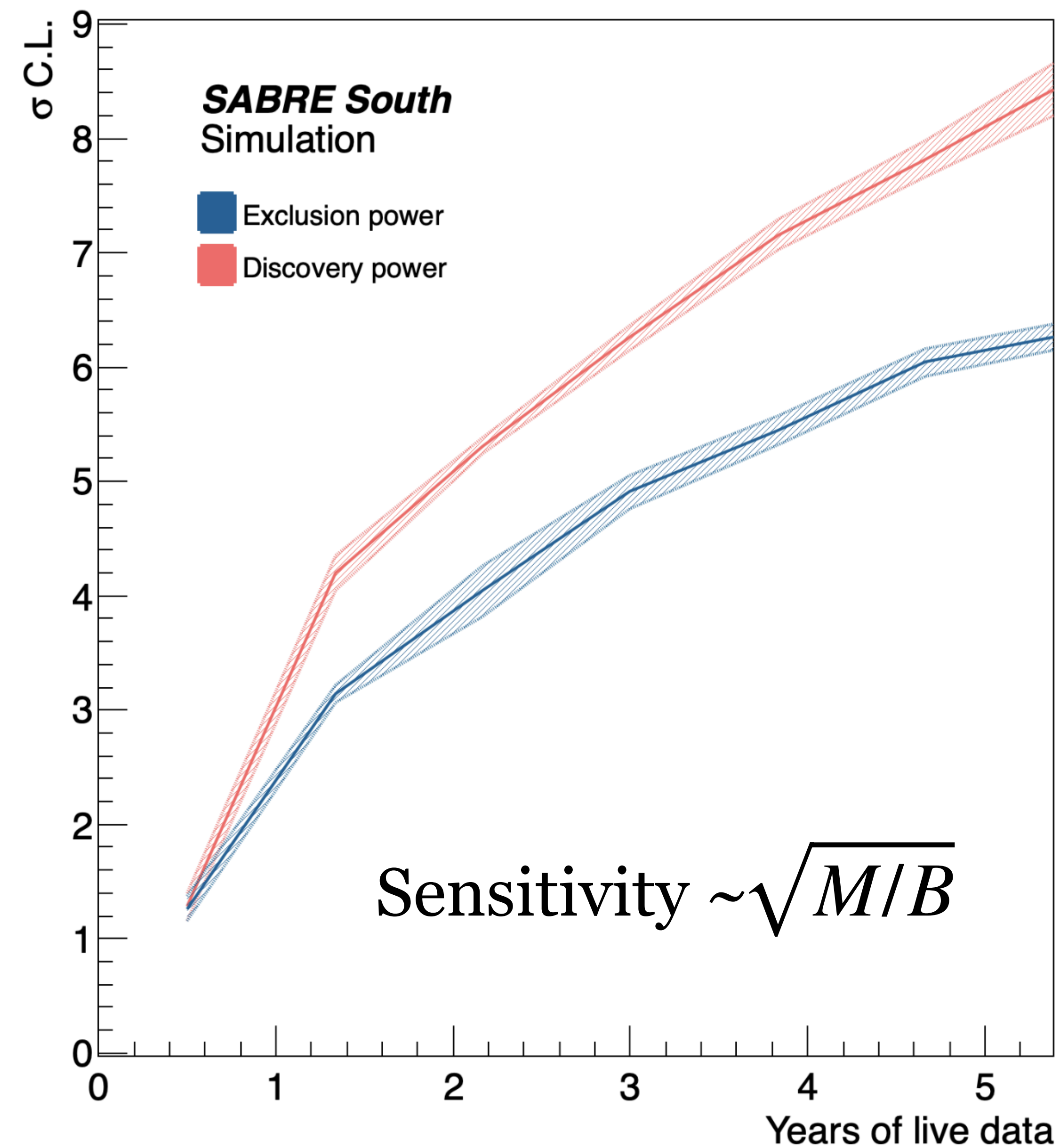


Fig. 9 The exclusion and discovery power of SABRE South for a DAMA/LIBRA-like signal. The shaded regions indicate 1σ statistical uncertainty bands.

- SABRE South is expected to reject the DAMA/LIBRA modulation at 4σ (null results) or confirm it at 5σ (for a compatible modulation) within 2.5 years.
- SABRE South full detector deployment by end of 2024. TDR available!

Conclusions

- Several experiments based on crystal scintillators are well under way in testing the DAMA/LIBRA results: ANAIS, COSINE, and very soon SABRE.
- No sign of a signal yet but more data is needed to reach a conclusive result. Might just be a few years away…
- Many improvement are foreseen from enhanced target purity to analysis methods and interpretation of results:
  - Updated QF measurements.
  - Migdal effect to lower WIMP mass reach.
  - Enhanced target mass and purity.
  - Machine learning methods in analysis.