Status of direct dark matter searches with scintillators

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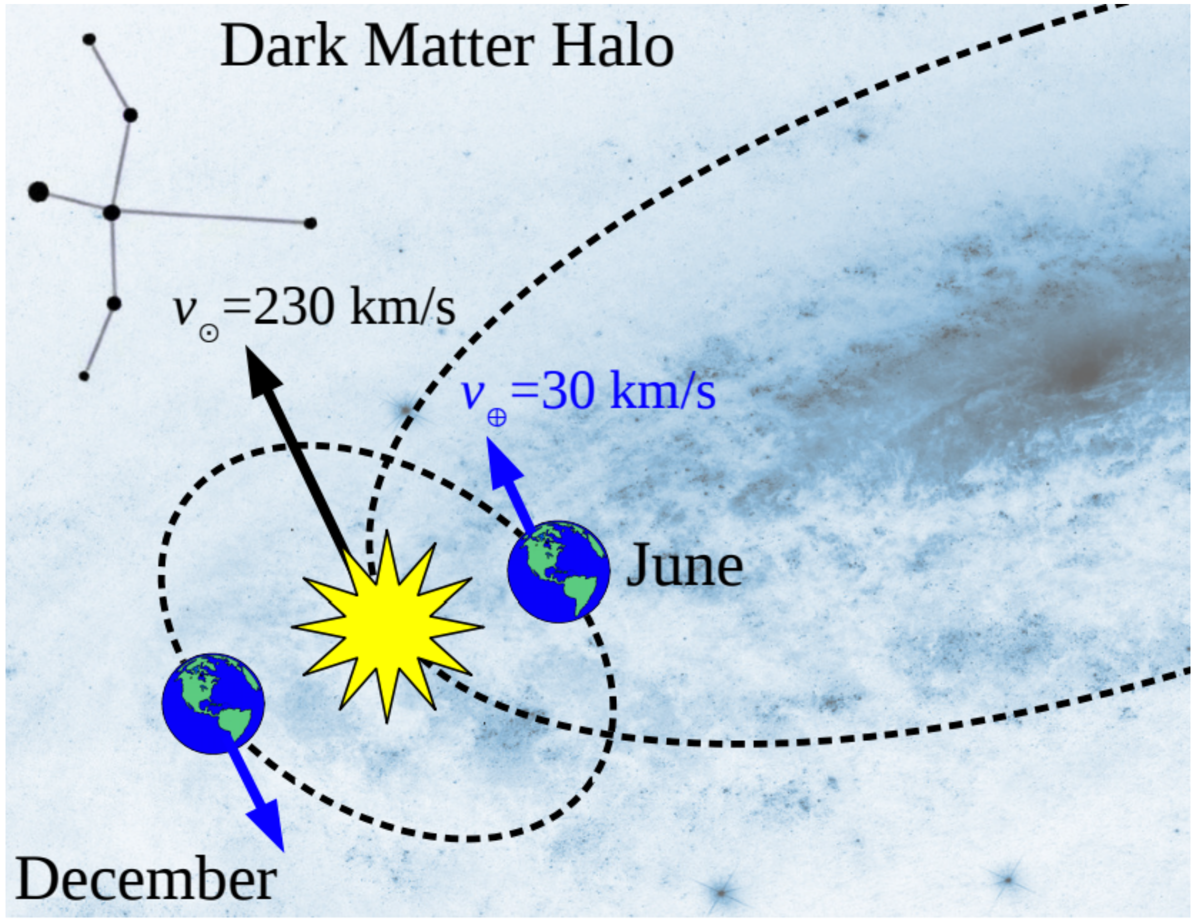
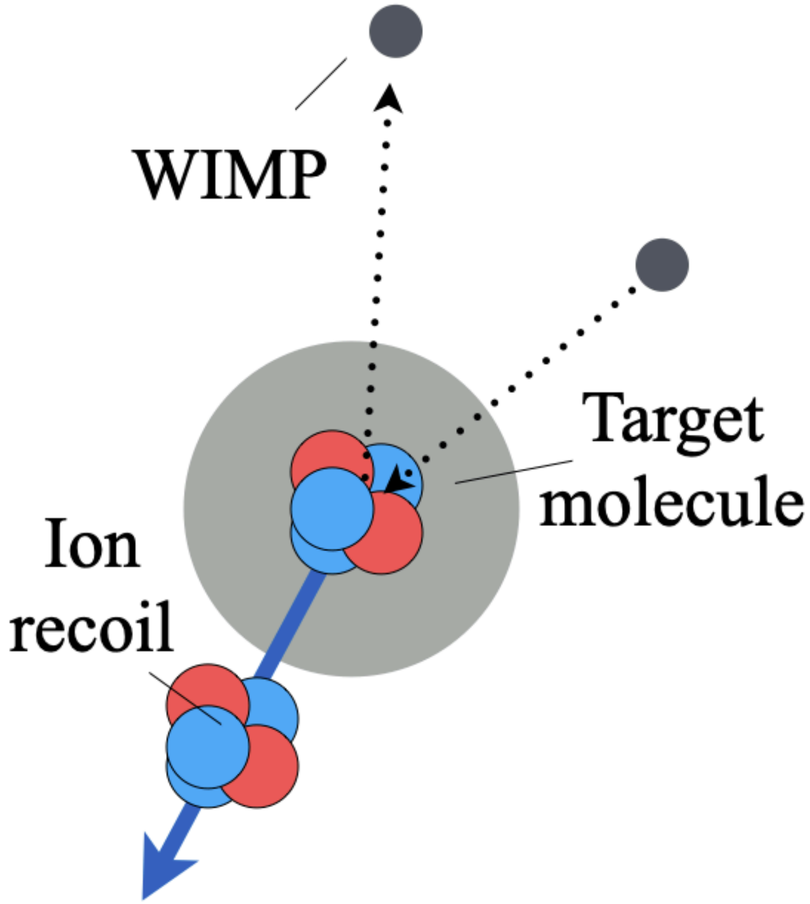
Detection with scintillators

Standard Halo Model:
- Canonical value for density: ρ≈0.3 GeV/cm^3.
- WIMP wind:

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

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

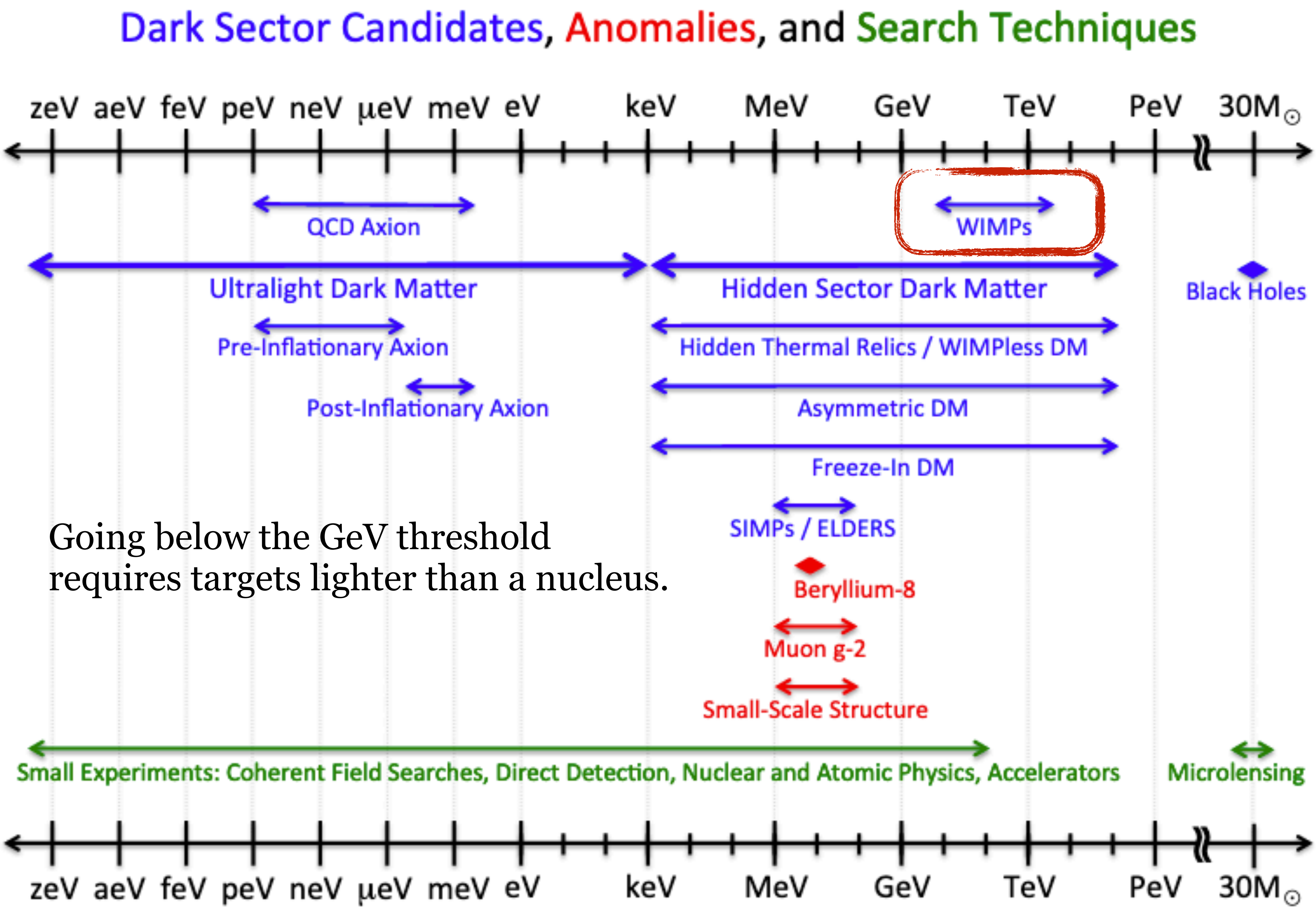




$$S(t) = B + S_0 + S_m \cos[\omega(t - t_0)]$$

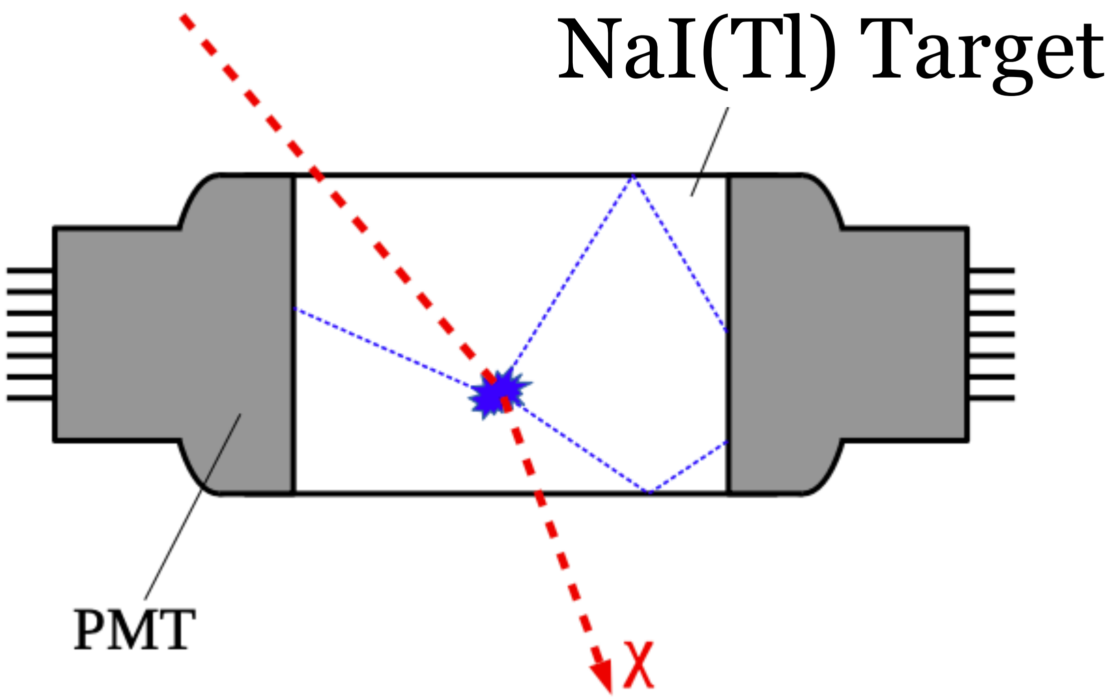
- Elastic scattering of WIMPs on target nuclei.
- Challenging as it produces a **rare signal** concentrated at **low energies ≈ keV**.
- Modulation is small: **≈ 0.01 cpd/kg/keV**.

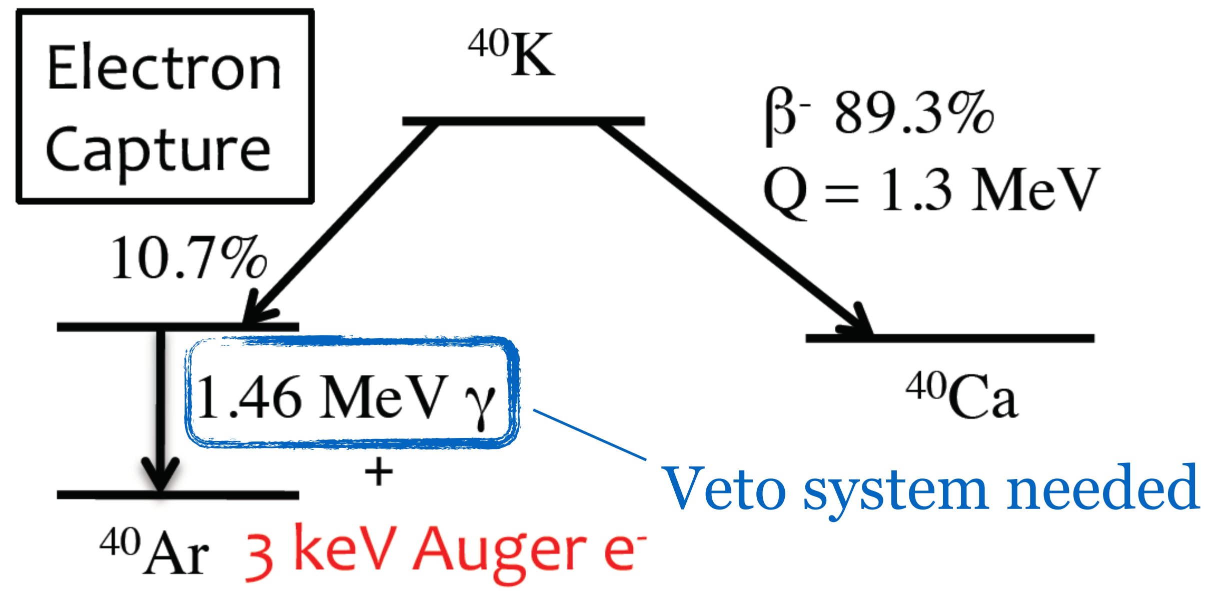
WIMPs



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

Crystal modules

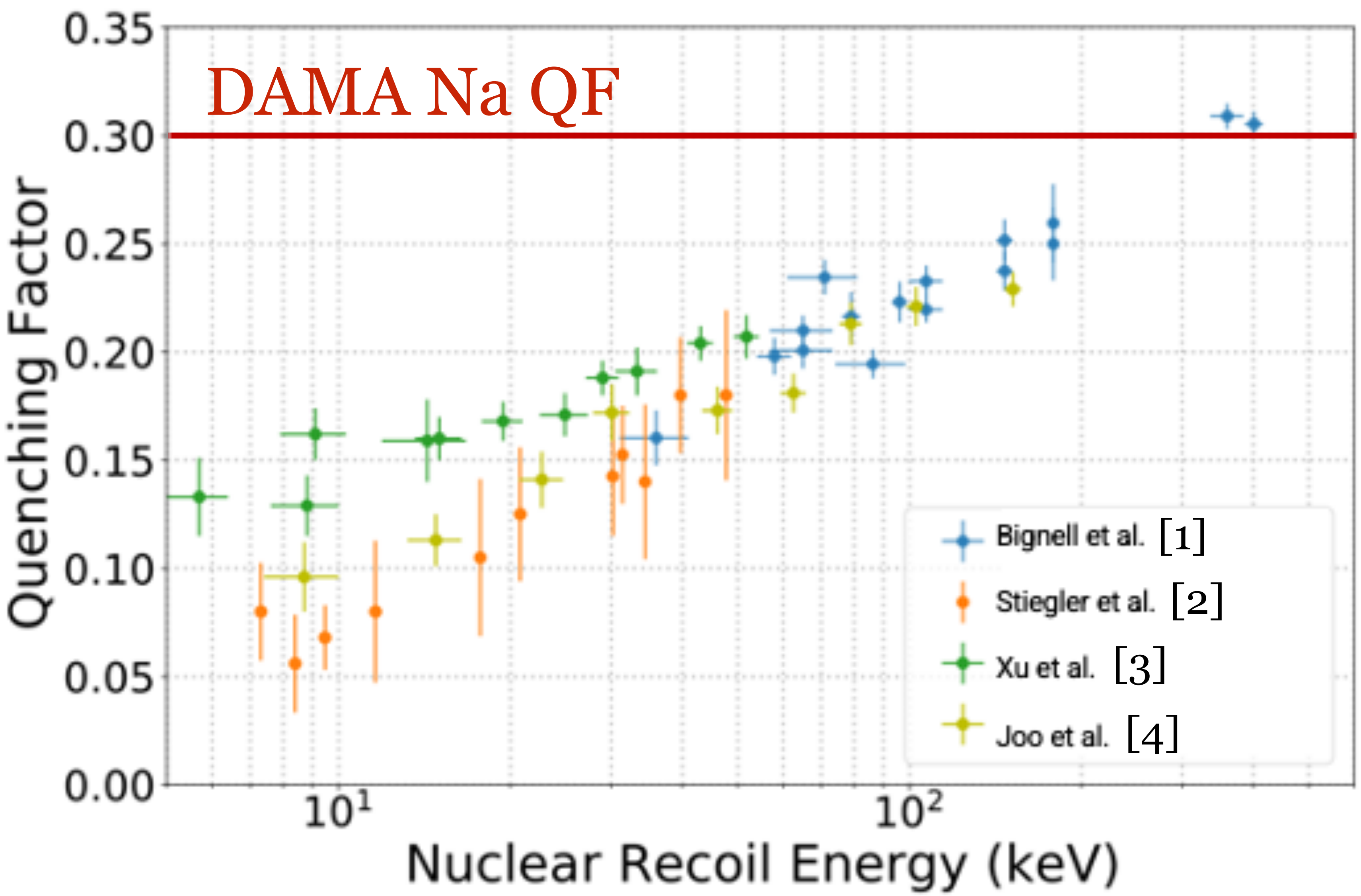




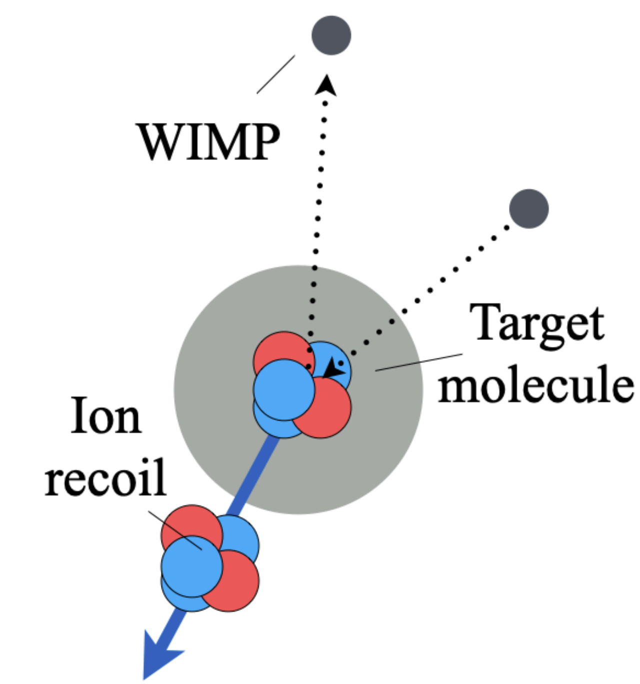
Crystal	natK (ppb)	238U (ppt)	232Th (μBq/kg)	226Ra (μBq/kg)	210Pb (μBq/kg)	Rb in 2-6 keV (cpd/kg/keV)	Active mass (kg)
DAMA [1]	13	0.7-10	2-31	8.7-124	5-30	<0.8	250
ANAIS [2]	31	<0.81	0.4-4	-	1530	3.2	112.5
COSINE [3]	<42	<0.12	7-35	8-60	10-420	2.7	106
SABRE [4]	4.3±0.2	0.4	1.6±0.3	5.9±0.6	410±20	< 1 (goal)	~50 (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.

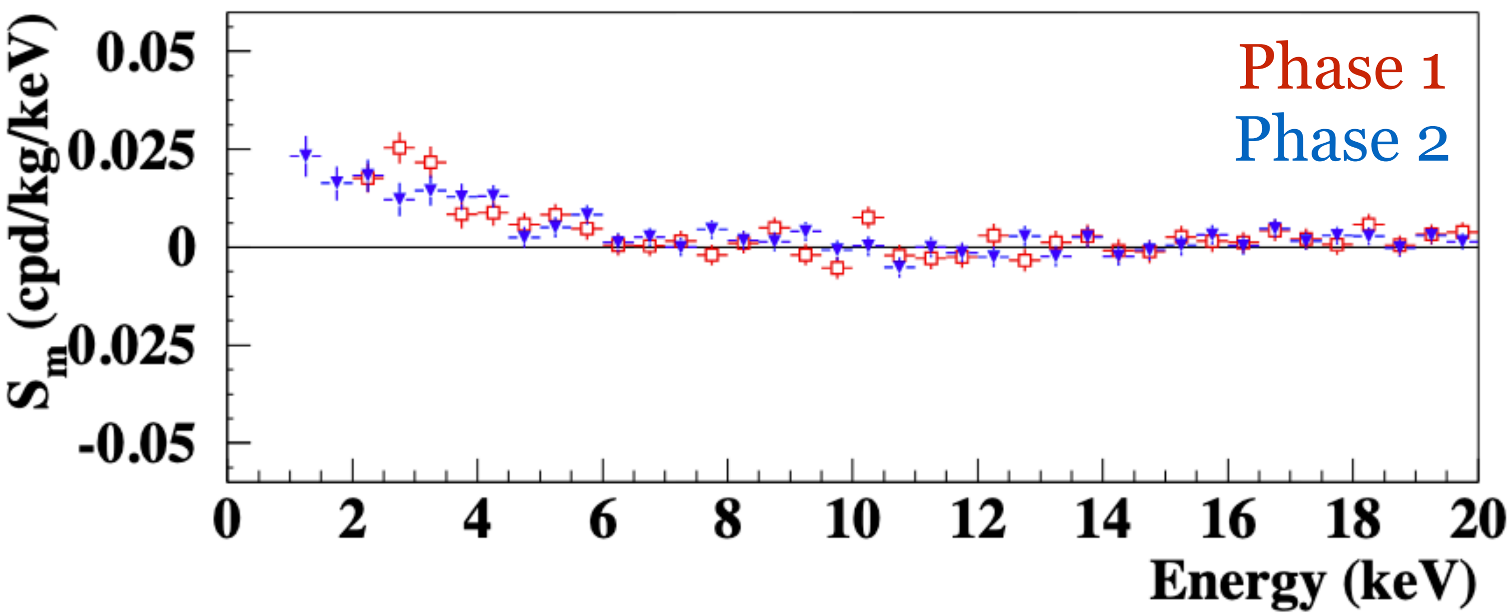
[1] JINST 16 P07034, [2] arxiv:1706.07494 , [3] 10.1103/physrevc.92.015807 , [4] 10.1016/j.astropartphys.2019.01.001.

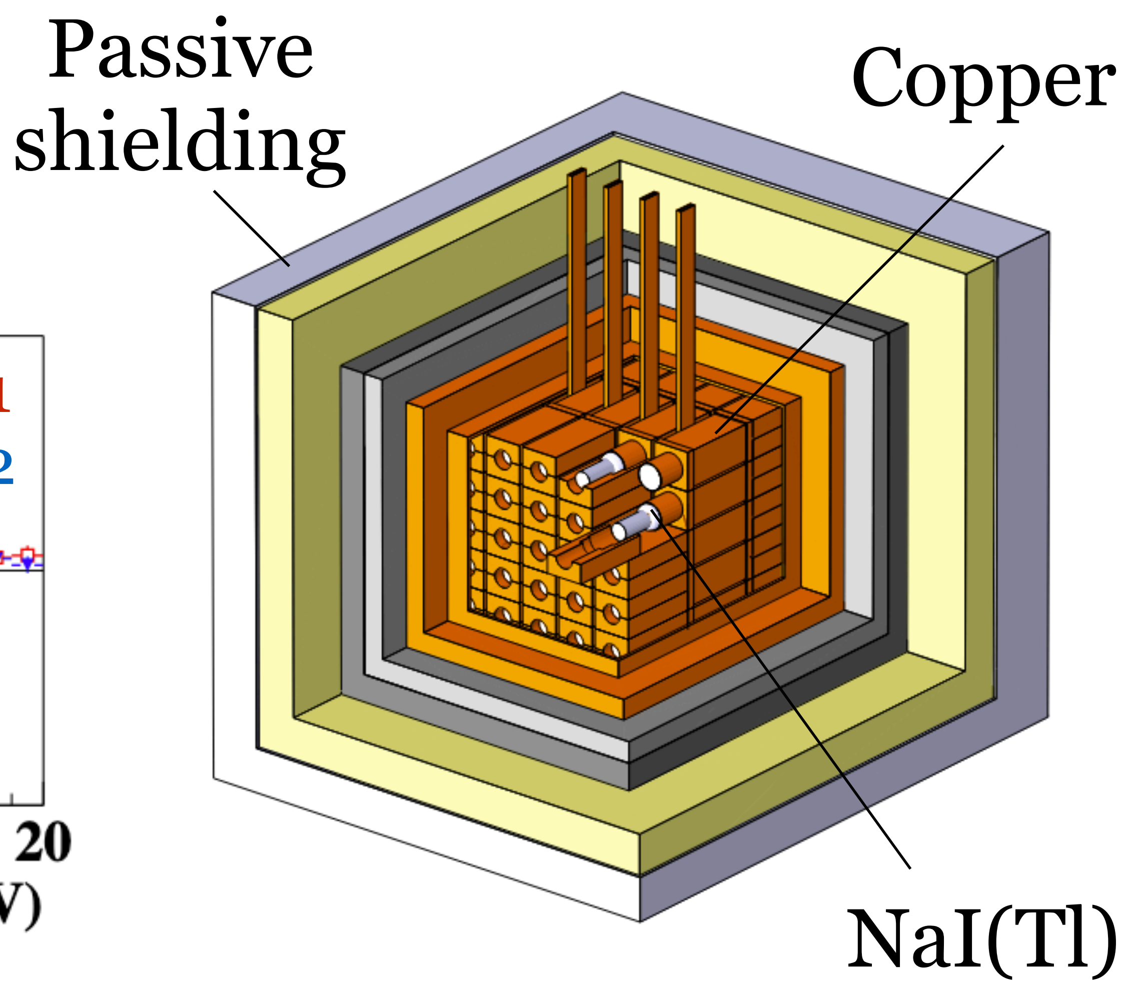
Crystal-based Experiments

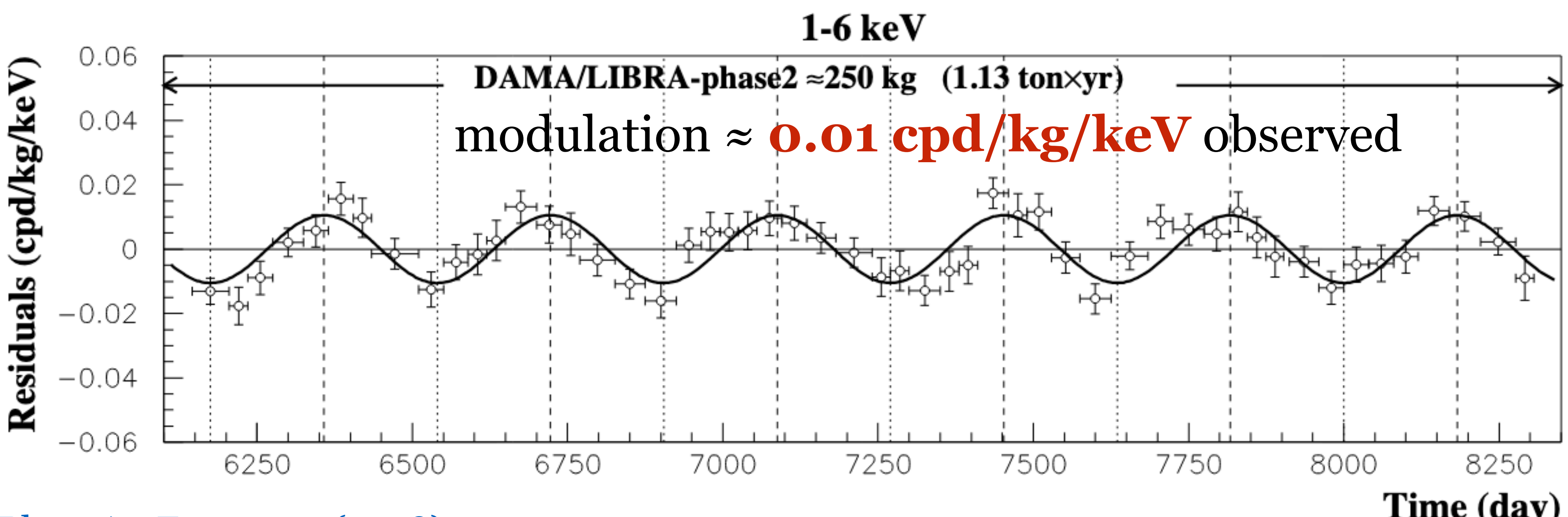
DAMA/LIBRA

DAMA/LIBRA @ LNGS

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

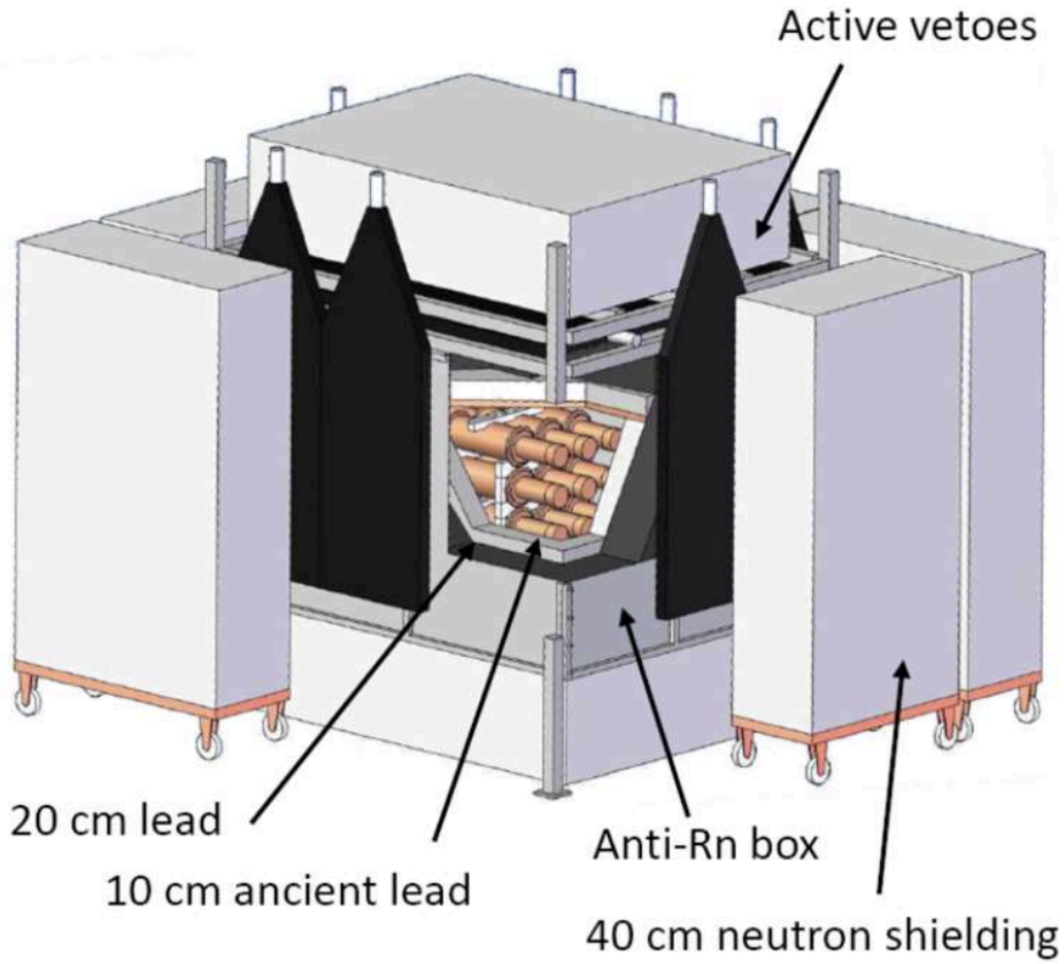


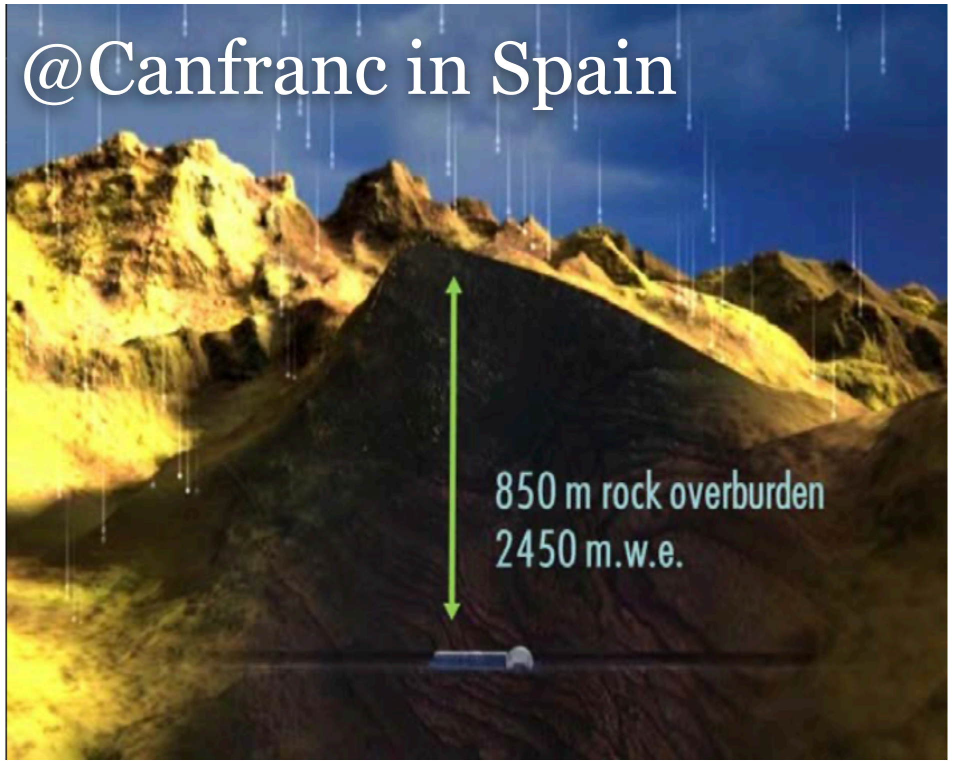


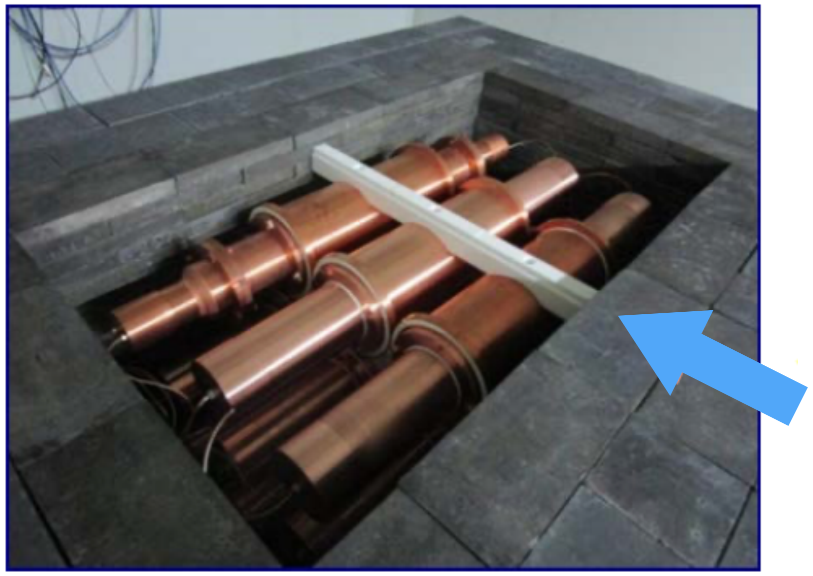


Nucl. Phys. At. Energy 19 (2018) 307-325

ANAIS-112



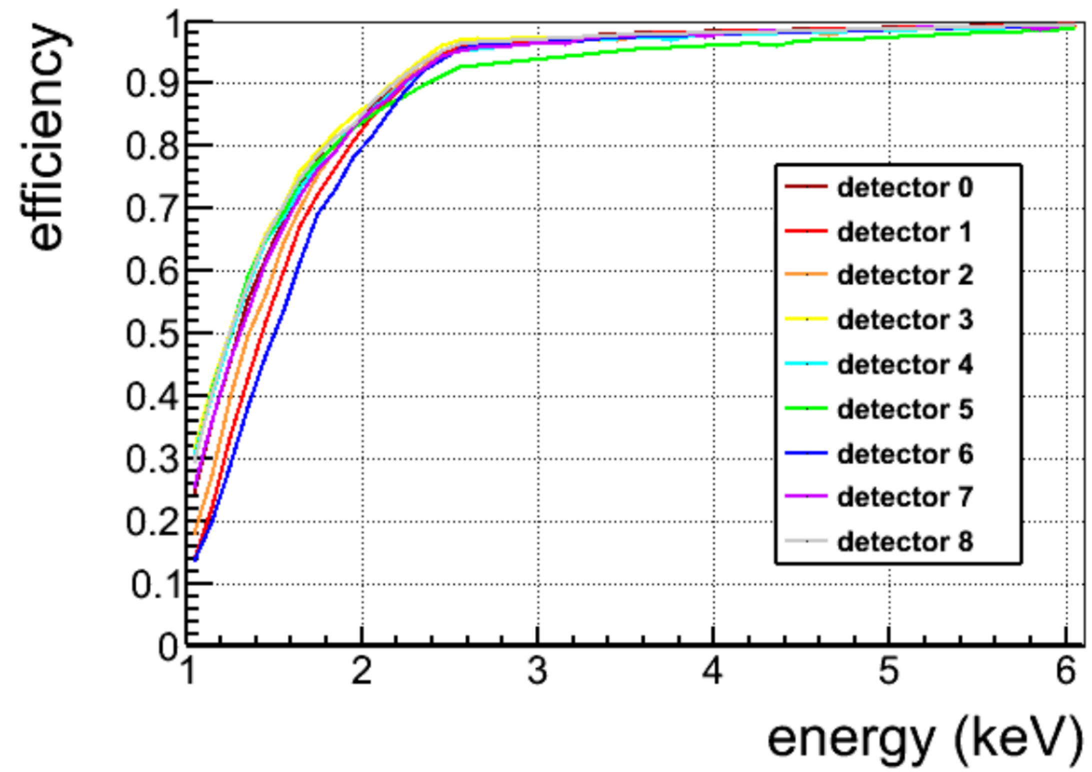


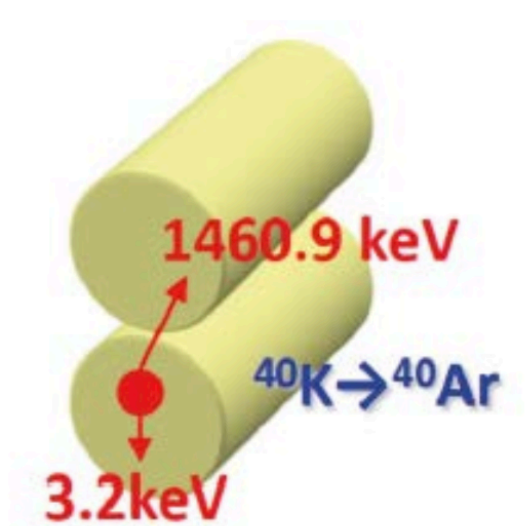


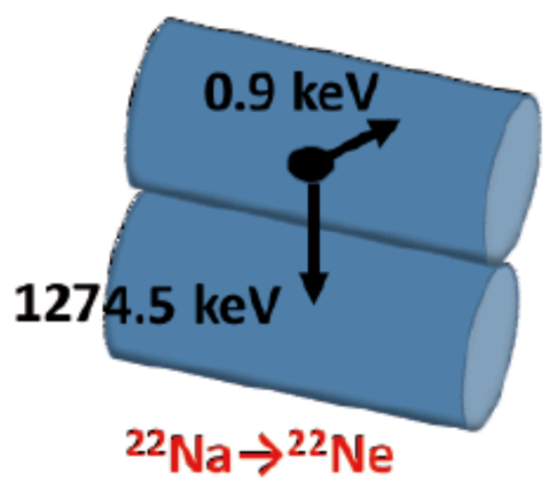
- 3 x 3 detector modules: 112.5 kg of NaI(Tl) built by Alpha Spectra company (US).
- High light yield 15 phe/keV allowing threshold of 1 keV_{ee}.
- Low-energy calibration using ^{109}Cd sources in Mylar windows.
- **Five year exposure** completed by August 2022 with 95% live time. Started 3 August 2017.

Analysis (3 years of data):

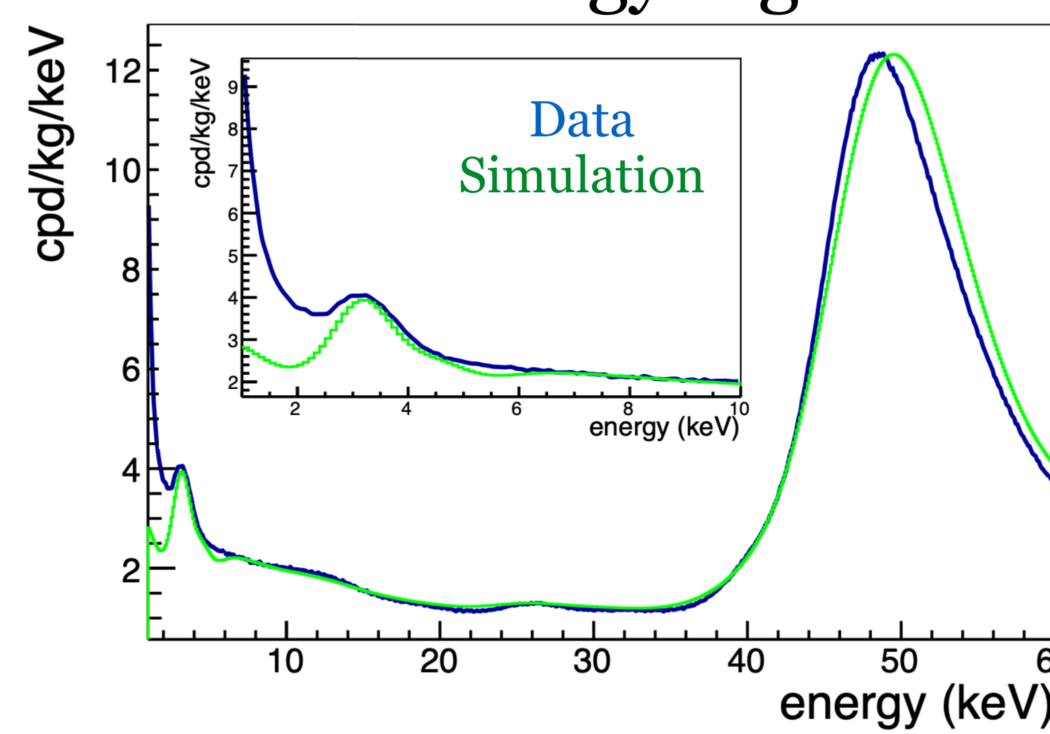
- Pulse shape cut to select events from NaI(Tl) scintillation.
- Asymmetric event rejection (E < 2 keV) to remove PMT-originated events.
- Remove 1 second after a muon passage.
- Multiplicity = 1. Remove multi-module events.







Low-energy region



Revision of background model underway

ANAIS-112

Phys. Rev. D 103, 102005

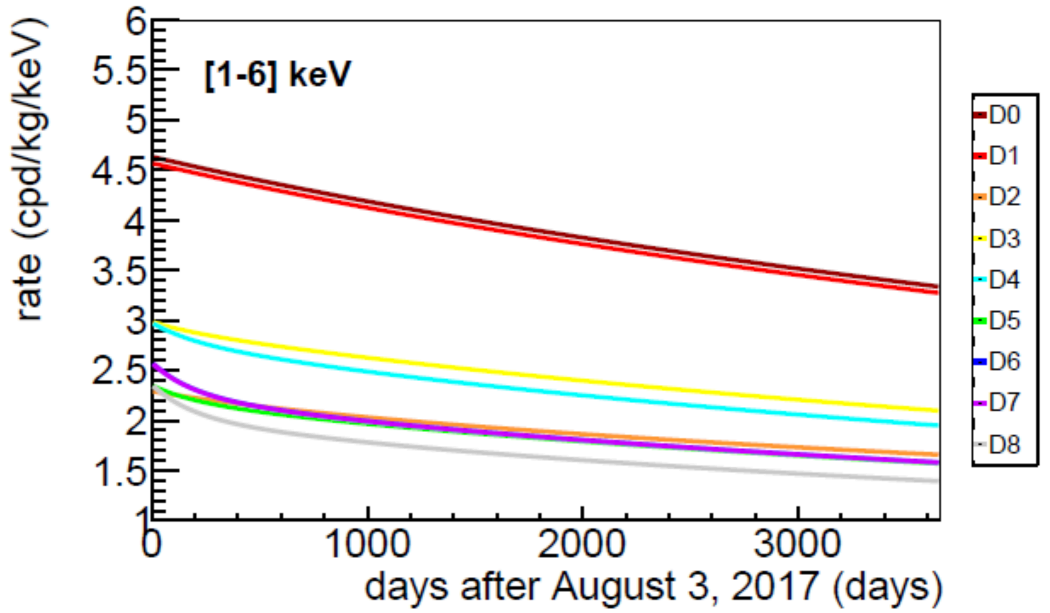
- Minimising: $\chi^2 = \sum_{i,d} \frac{(n_{i,d} - \mu_{i,d})^2}{\sigma_{i,d}^2}$

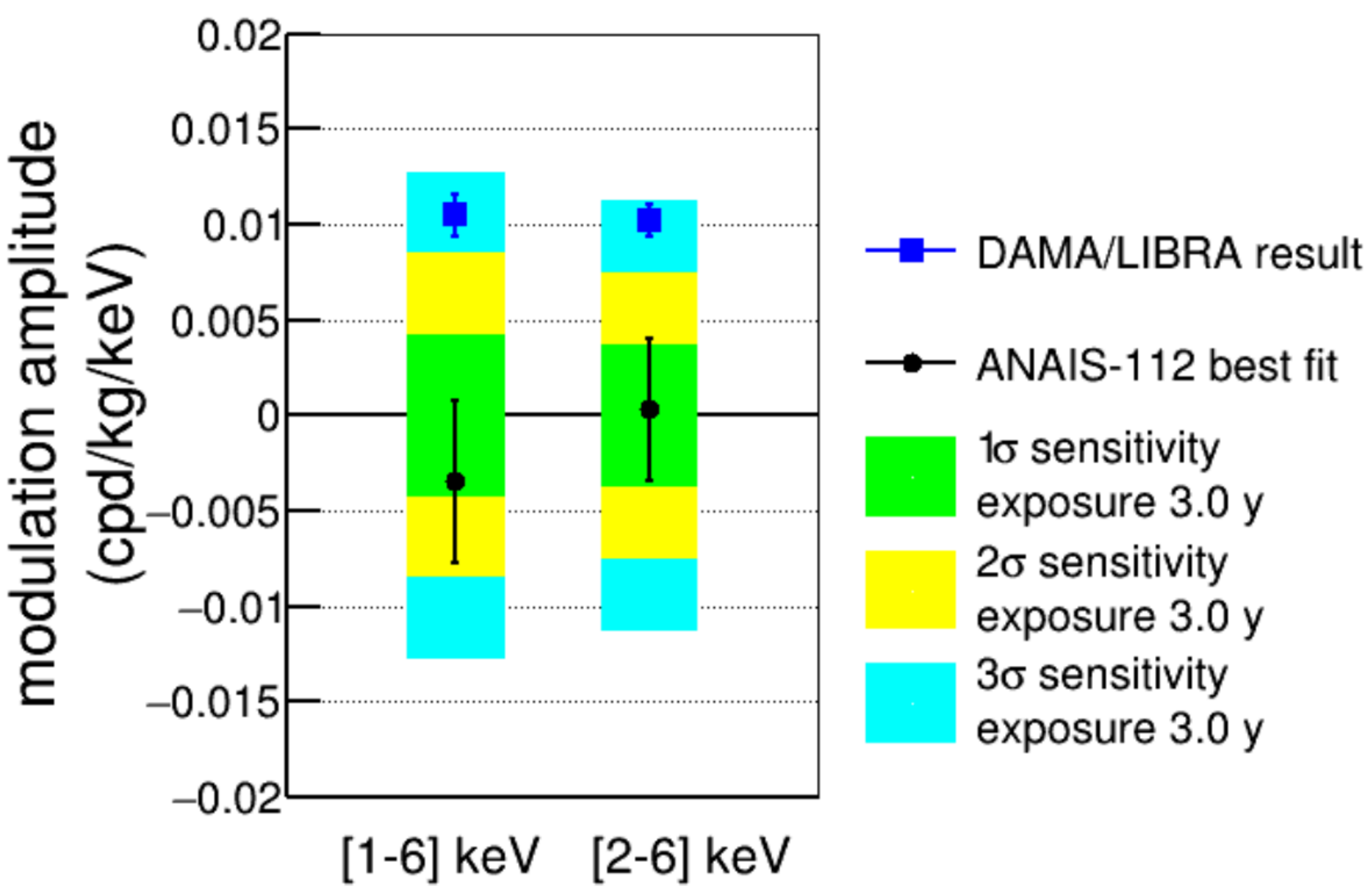
  where $n_{i,d}$, $\sigma_{i,d}$ are computed in 10 days bins i corrected by live time and efficiency for each detector d.

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

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

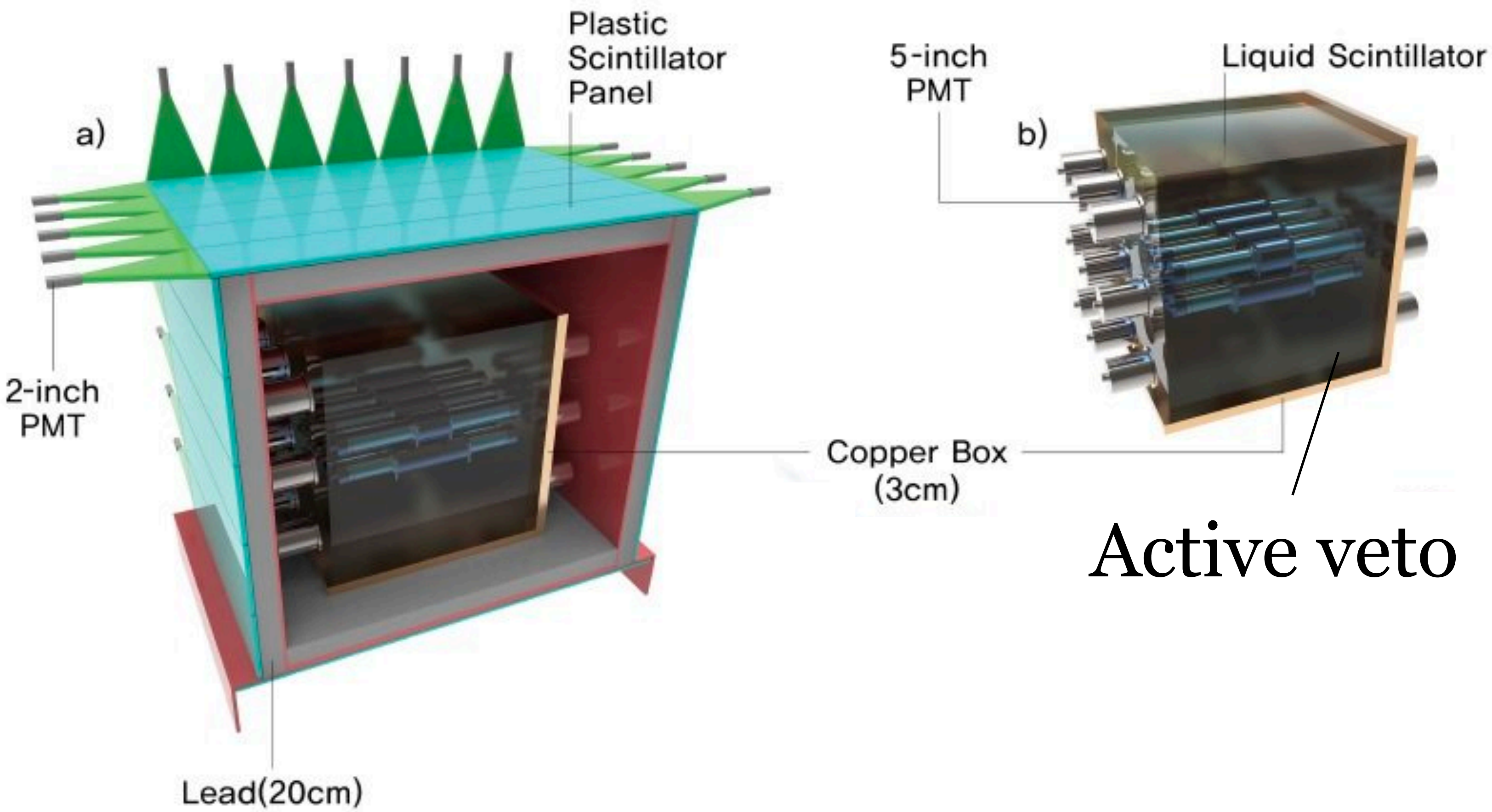
Simulated background

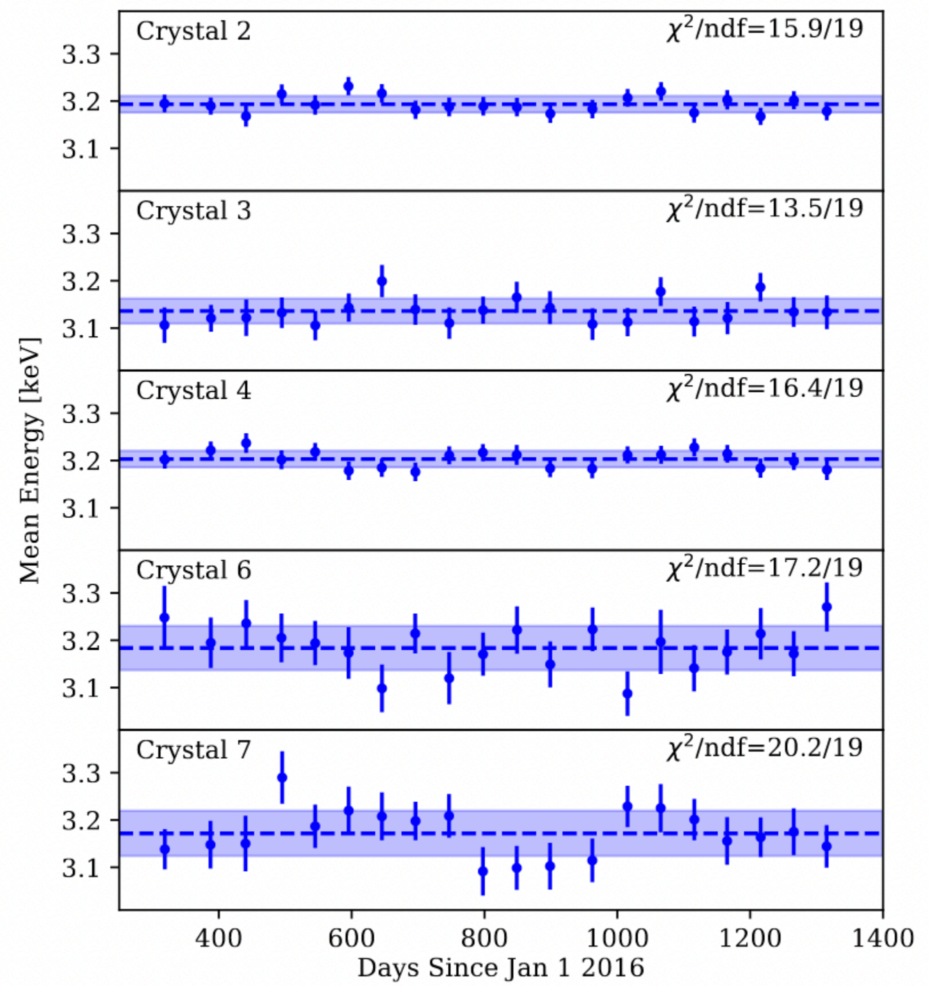




- Best fits are incompatible with DAMA/LIBRA at 3.3 σ and 2.6 σ in [1-6] and [2-6] keV regions.
- Sensitivity is at 2.5 σ and 2.7 σ in the same regions respectively.
- New BDT-based analysis is in progress expected to reach a 5 σ sensitivity to DAMA/LIBRA with two more years of data.

COSINE-100





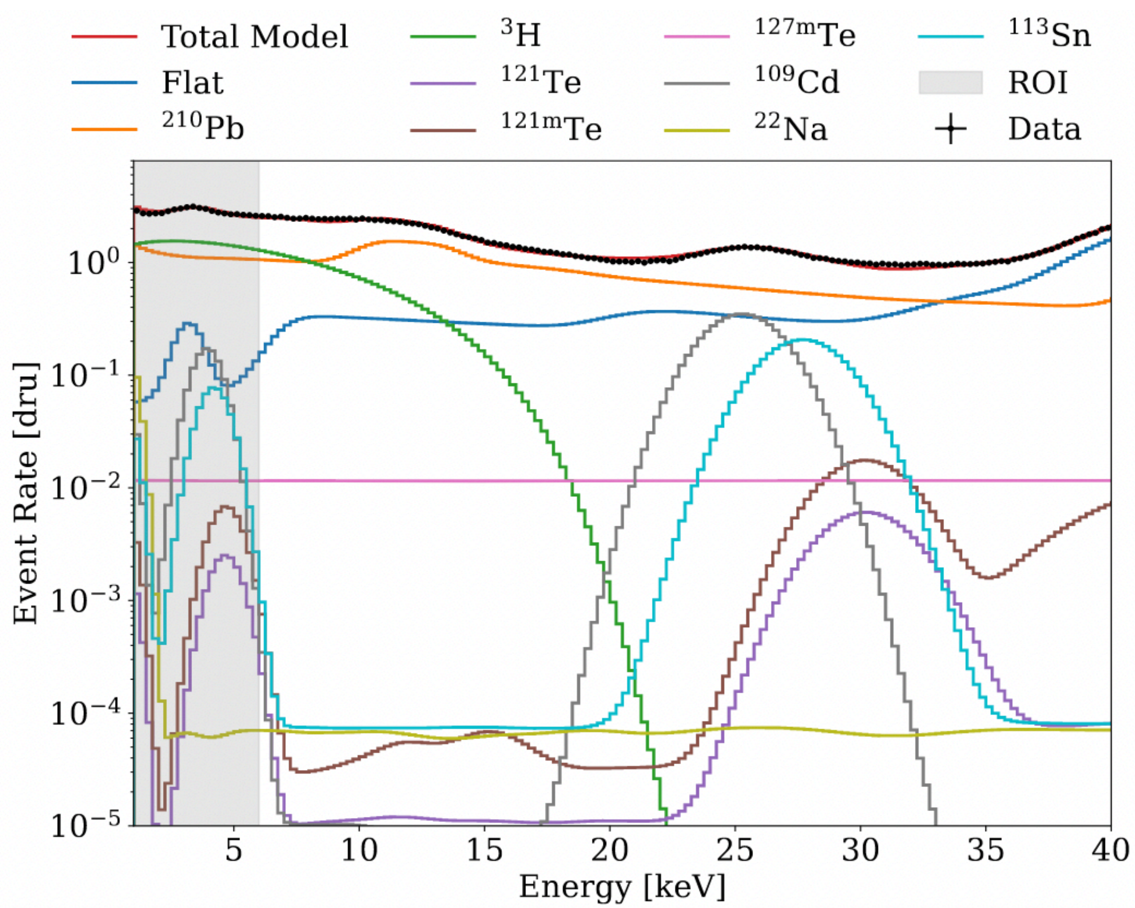
- 8 detector modules from Alpha Spectra: 106 kg of NaI(Tl).
- Active since 2016.
- About 93% of good data taken.
- Liquid scintillator active veto 2200 L.
- Calibration with ^{60}Co and ^{22}Na.
- Energy scale stability verified by monitoring ^{40}K decay energy.

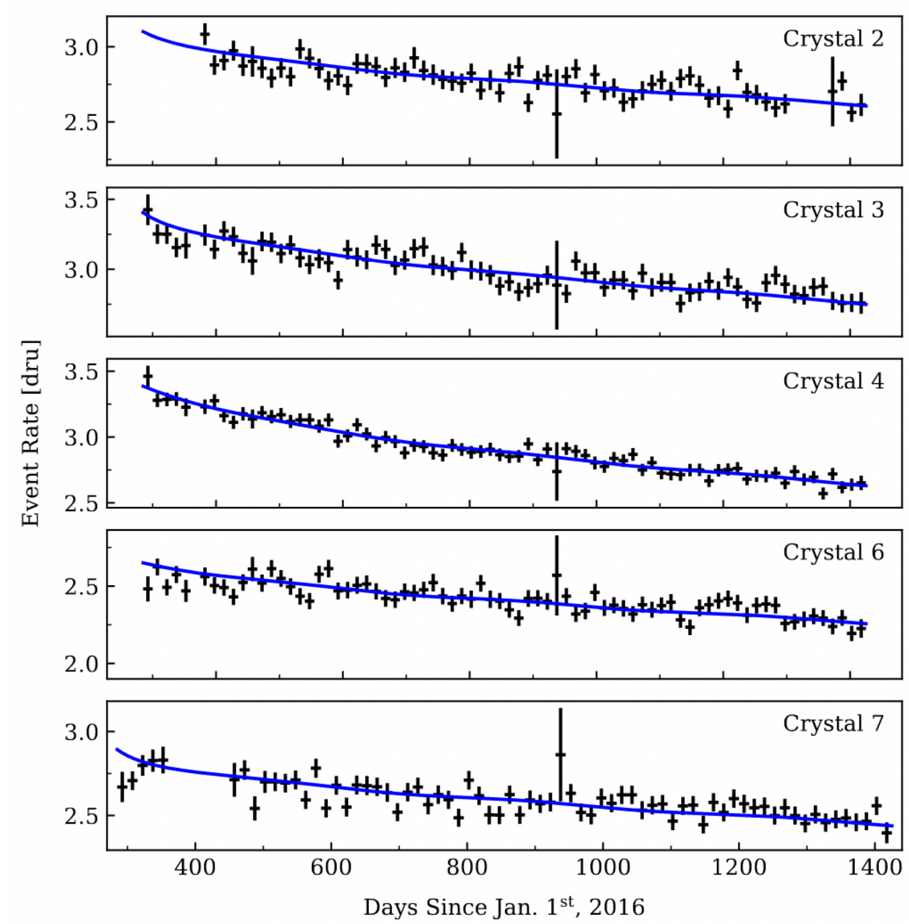
COSINE-100

Phys. Rev. D 106, 052005

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

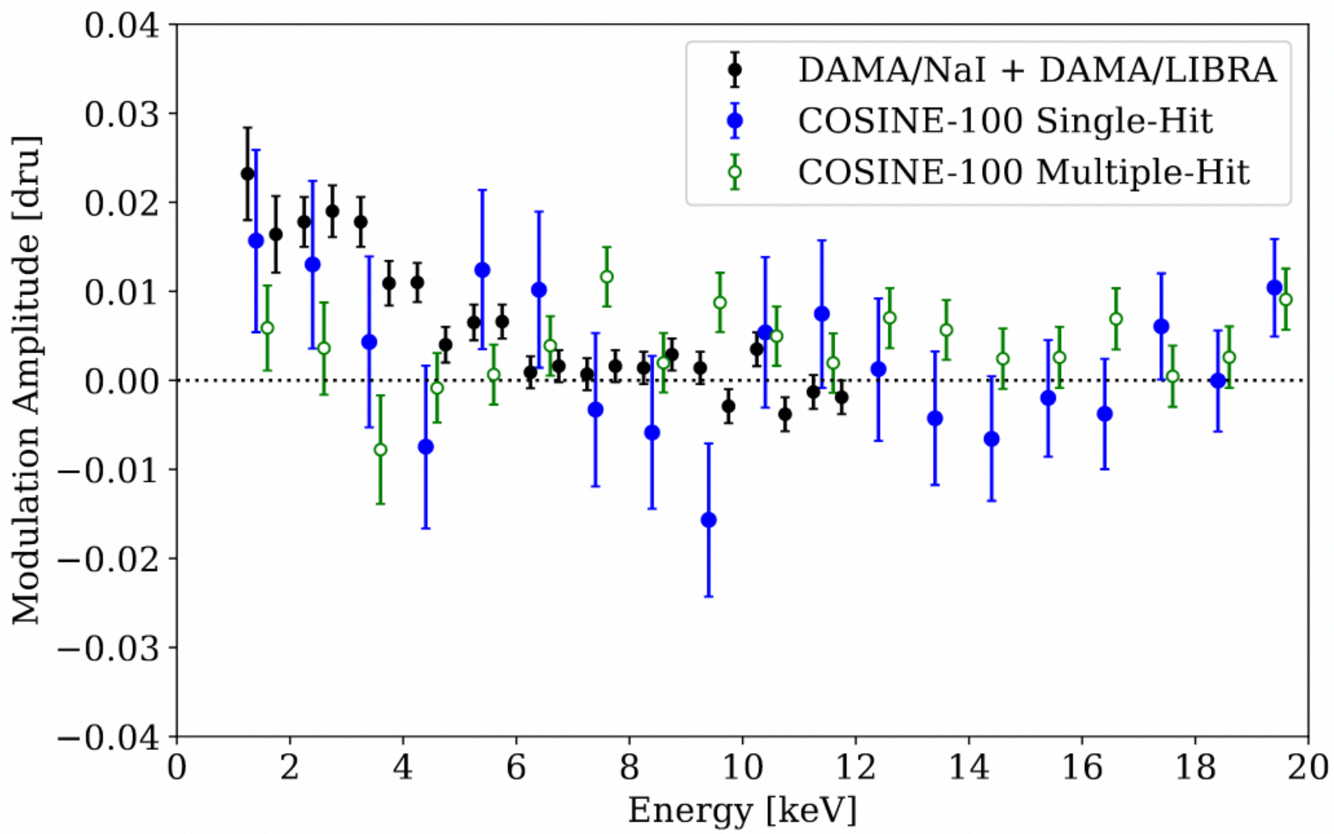
- Dedicated model for detector *i* and background *k*.
- Flat: long lived backgrounds: ^{40}K, ^{238}U, ^{232}Th.
- Exponential: decaying backgrounds. Separate model for ^{210}Pb, ^{3}H etc.
- Modulation.



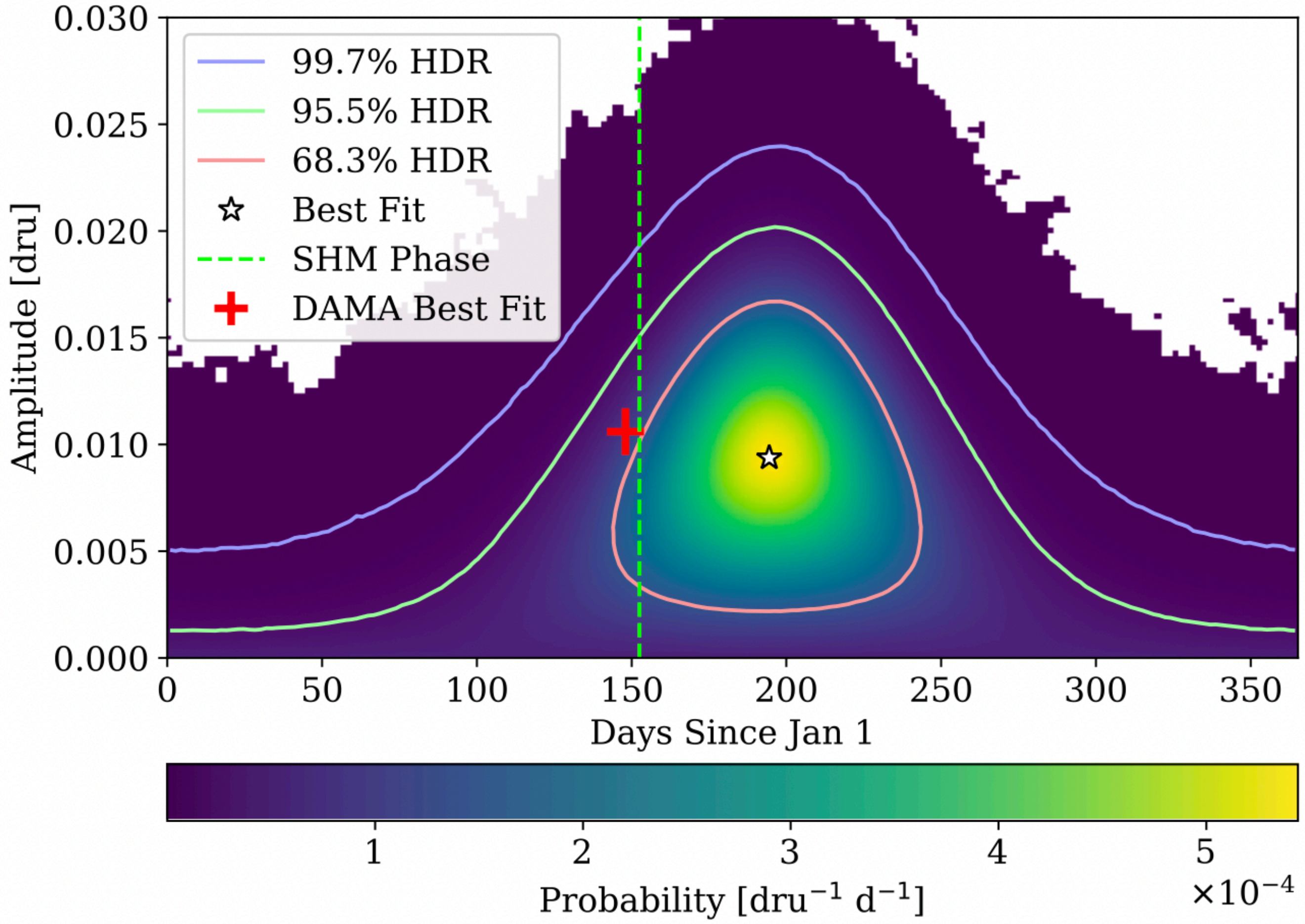


- Background model created using first 1.7 years of data + MC simulations.
- Data normalised by live-time and efficiency in 15 days bins before fitting.

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



Floated phase: [1 - 6] keV

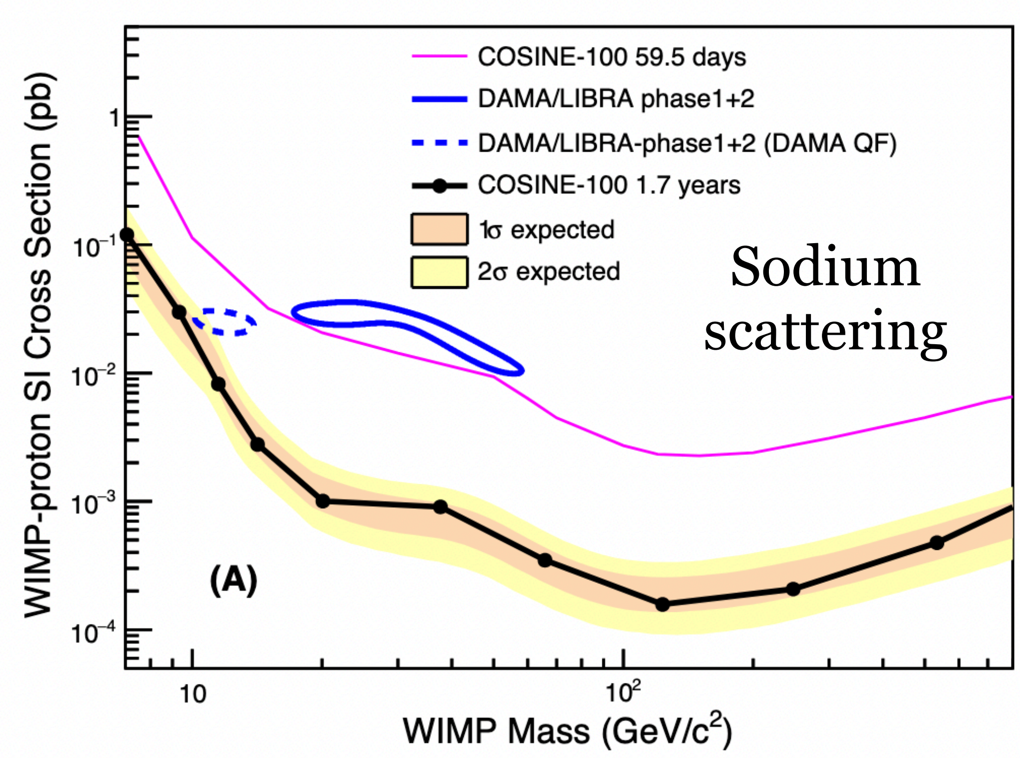


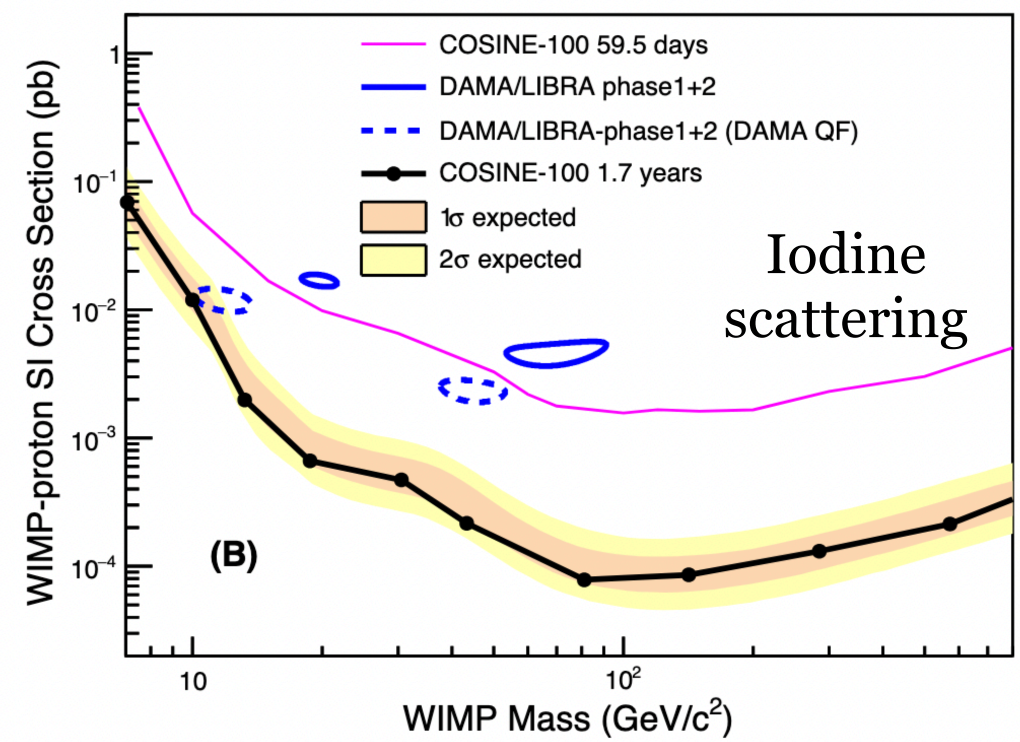
- 2.8 years of data and 60 kg of NaI(Tl)
- Both results constistent with DAMA and null hypothesis.
- Operations scheduled until late 2022 when commissioning of COSINE-200 will start.

COSINE-100

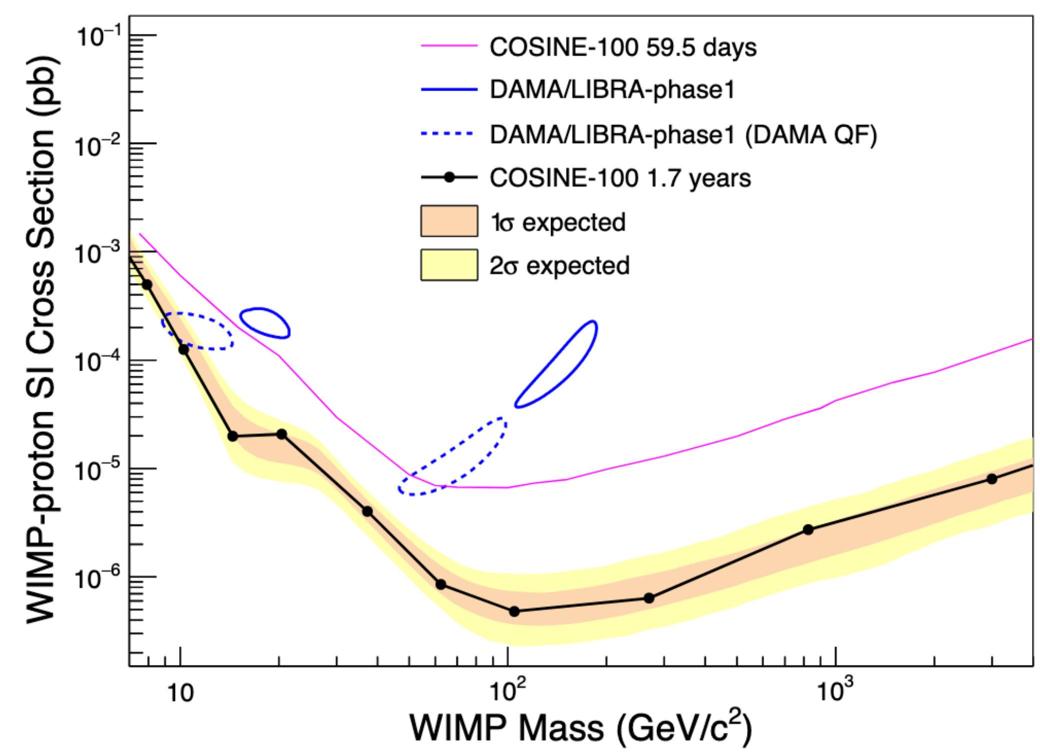
Sci. Adv. 7, eabk2699 (2021)

WIMP proton spin-independent cross section for isospin violating interactions





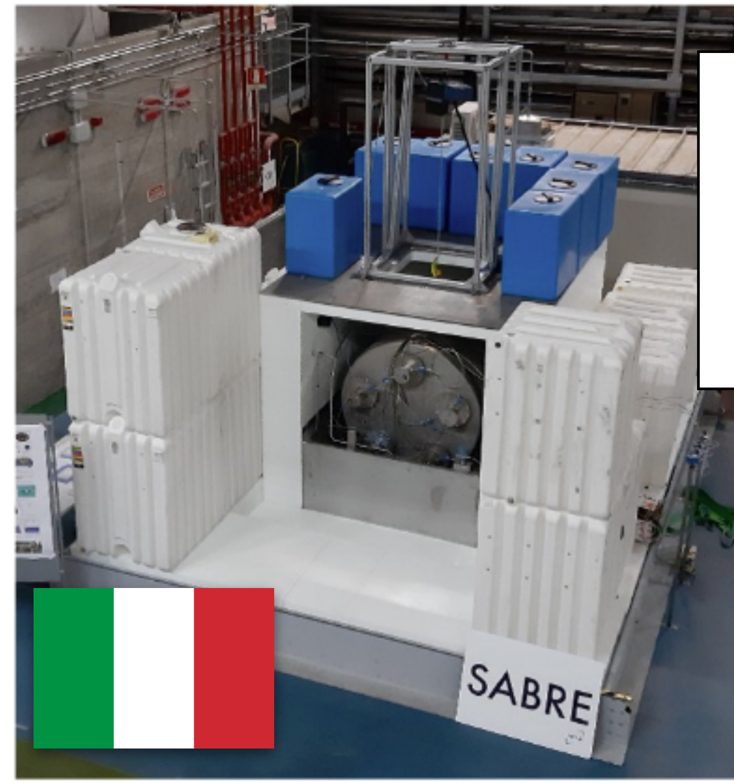
- Search performed using 1.7 years of data.
- Fully excludes DAMA with alternative WIMP EFT operators and QFs.



WIMP nucleon spin-independent cross section for isospin conserving interaction

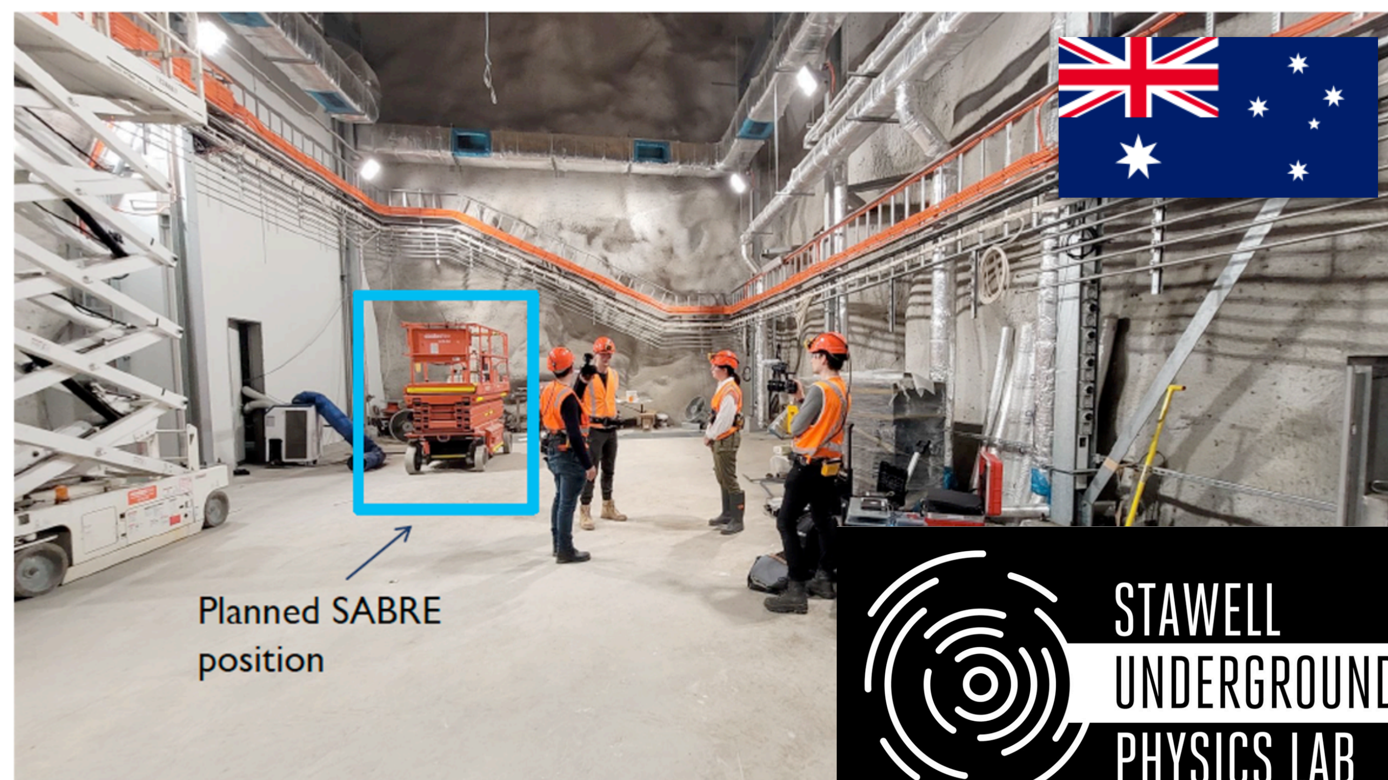
SABRE

- In the commissioning phase as a **dual location** experiment: Italy (LNGS), Australia (SUPL). Same detector module: high purity NaI(Tl) + HPK R11065 PMTs.
- SABRE North (LNGS):
  - fully passive shielding due to organic scintillators phased off at LNGS.



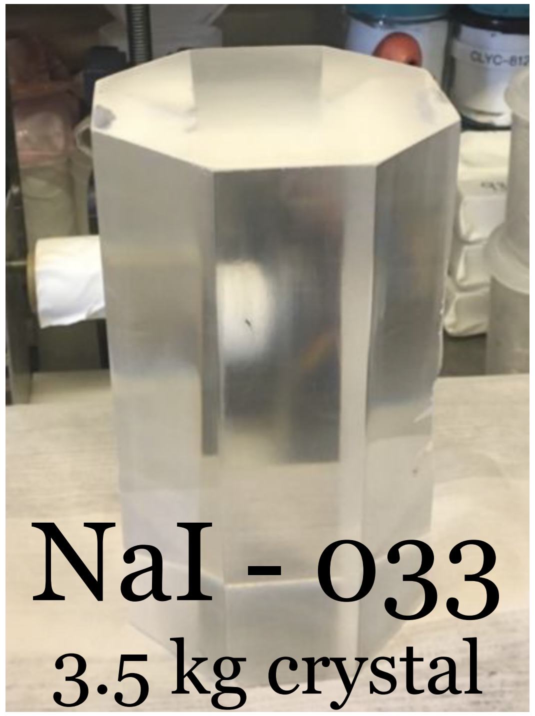
Stawell **U**nderground **P**hysics **L**aboratory:

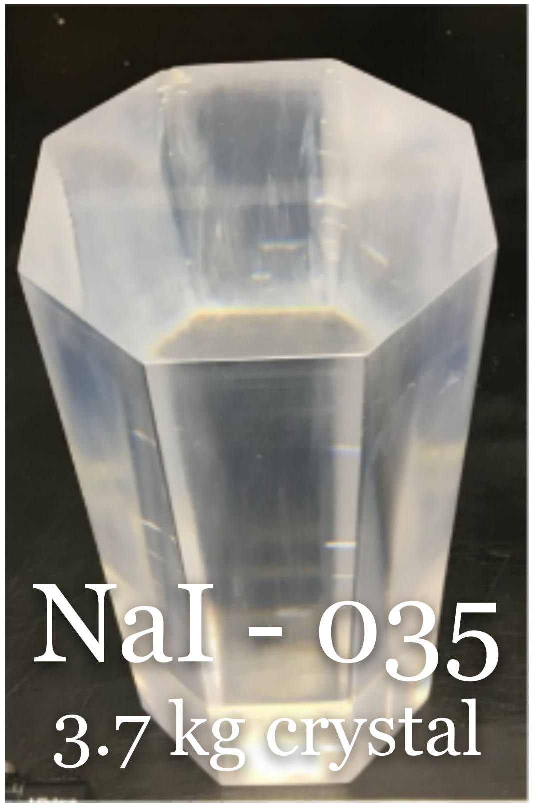
- First underground laboratory in the southern hemisphere 1025 m deep (2900 m water equivalent) with flat overburden.
- Located in the Stawell gold mine 240 km west of Melbourne.
- Construction complete with operations started in September.



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.

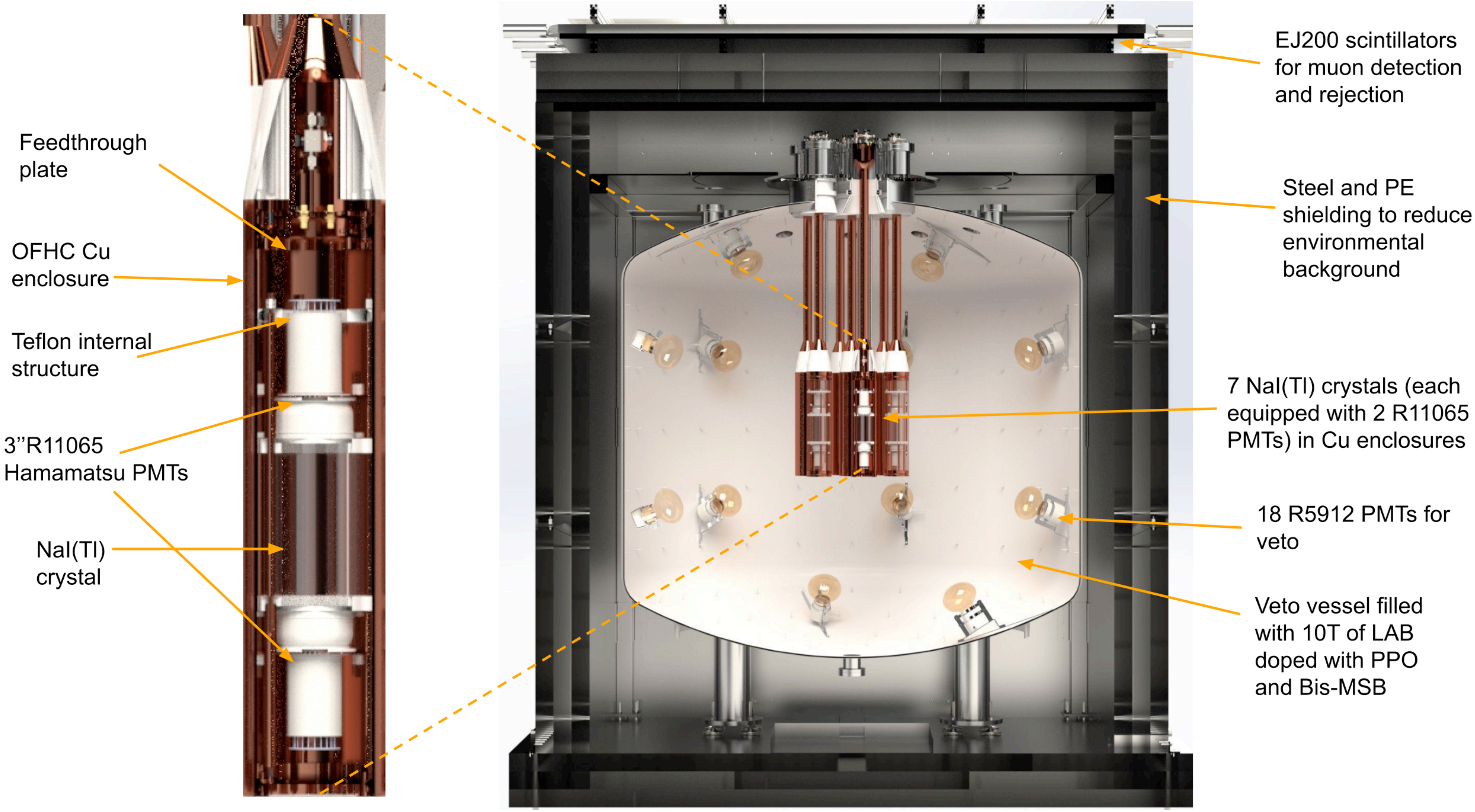




Eur. Phys. J. C 81, 299 (2021)

	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

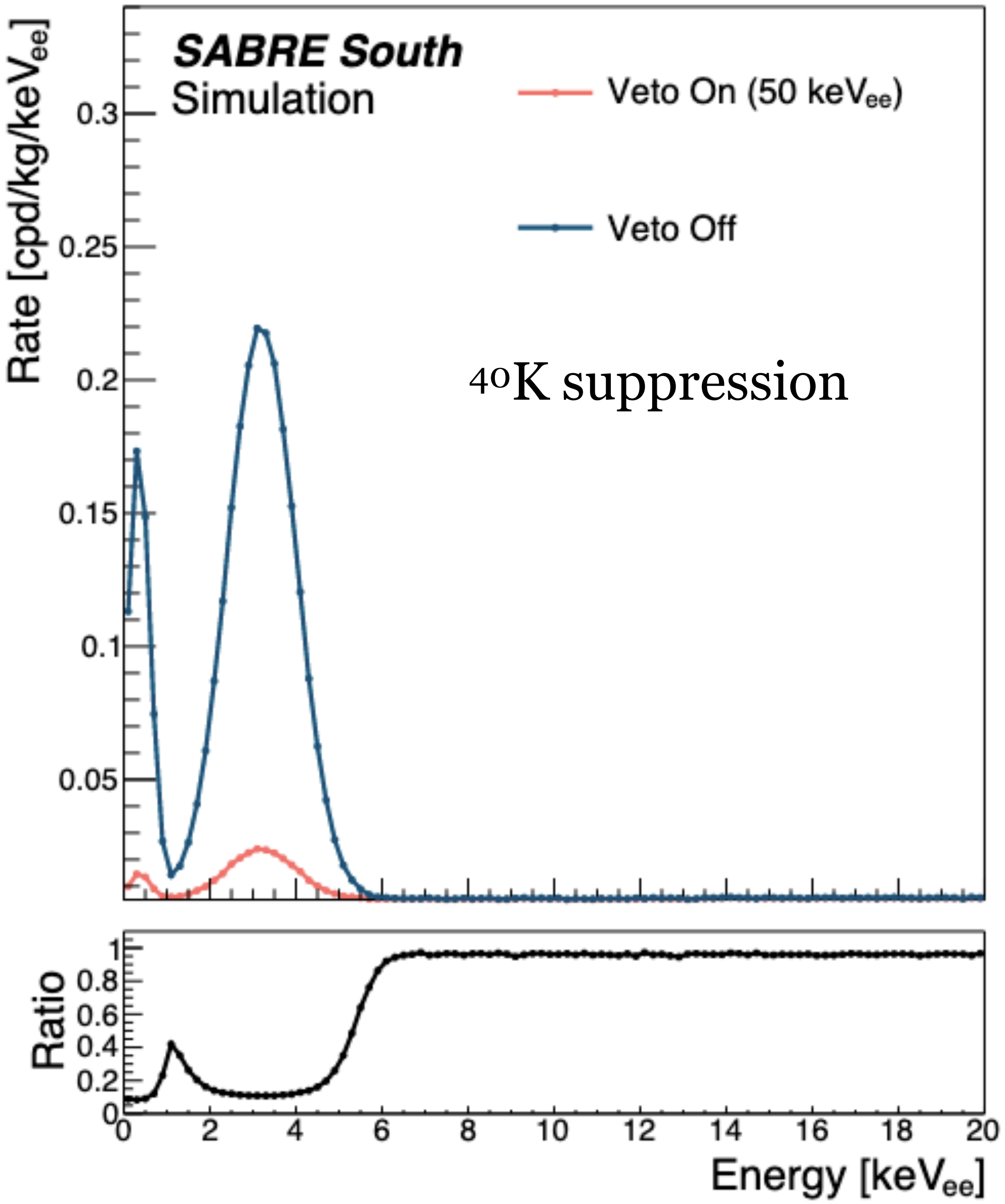
SABRE South

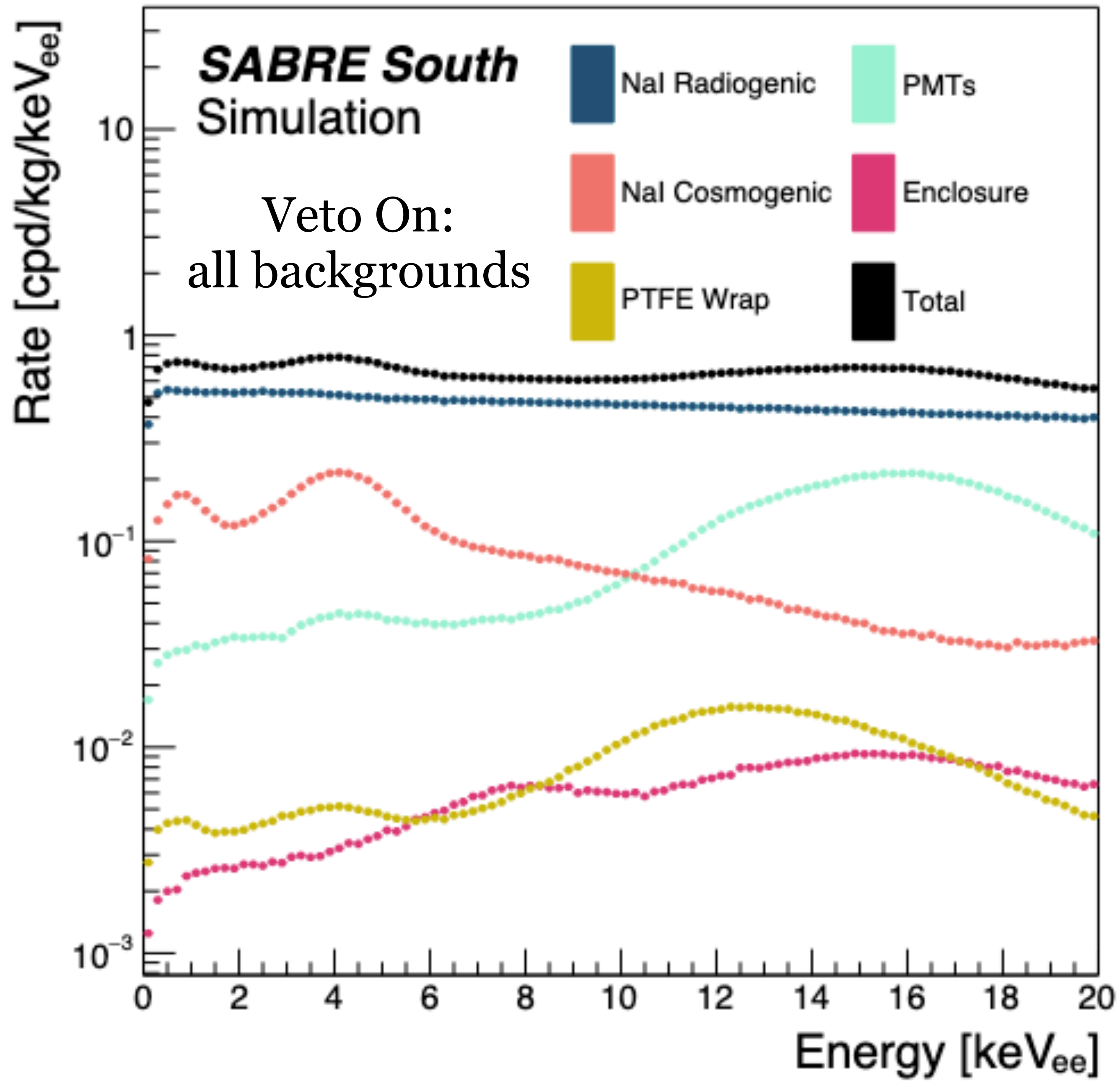


- In situ evaluation and validation of the background using the large active veto.
- Highest purity crystals and largest active veto.

SABRE South

arXiv: 2205.13849





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

SABRE South

[arXiv: 2205.13849](https://arxiv.org/abs/2205.13849)

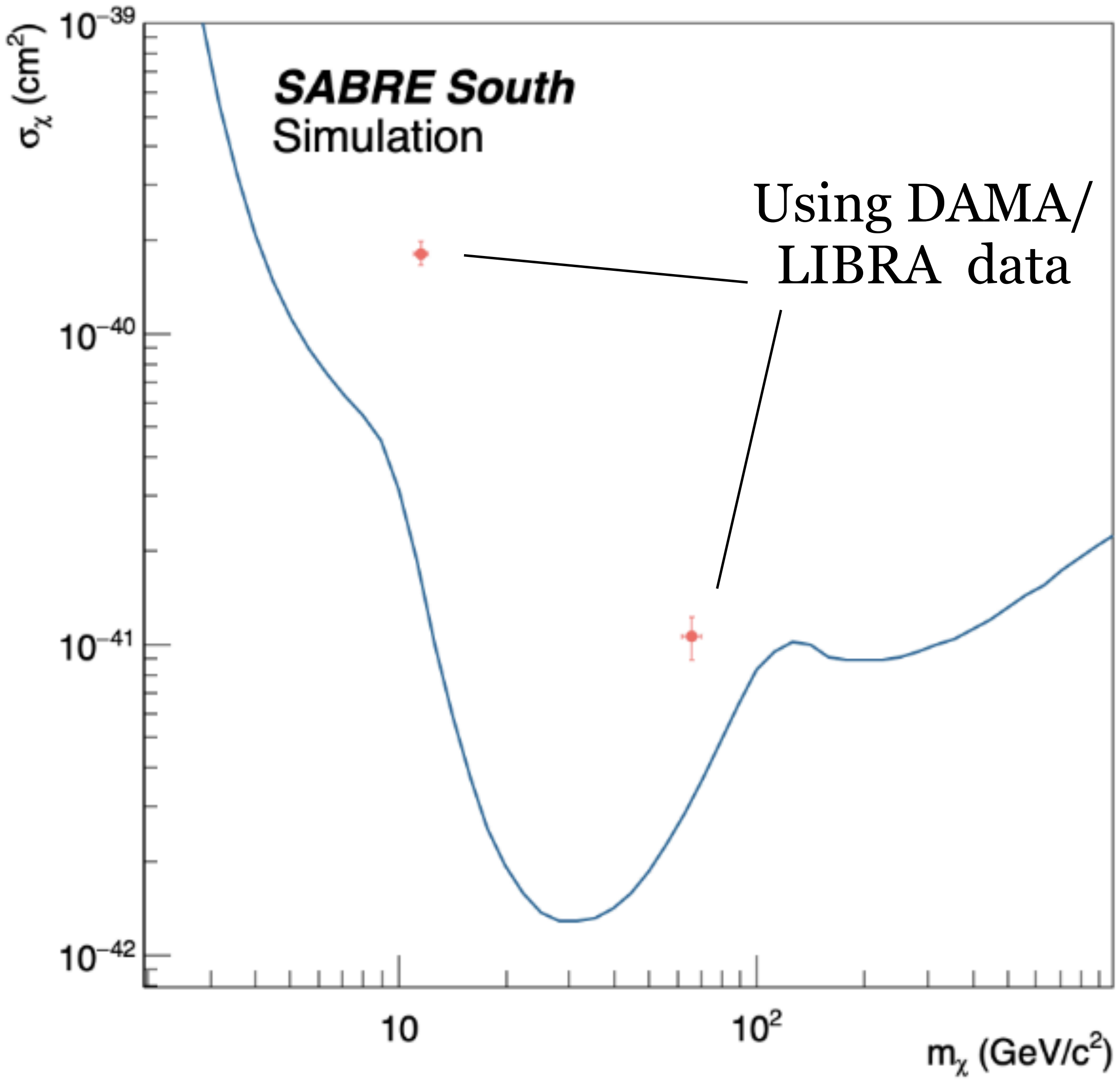


Fig. 8 90% exclusion curve for the SABRE South experiment after three years of data taking (in blue) assuming a background model in the 1–6 keV_{ee} region given by Figure 2 and an exposure mass of 50 kg. The best fits to the DAMA/LIBRA data for this model in both the low- and high-mass region are shown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

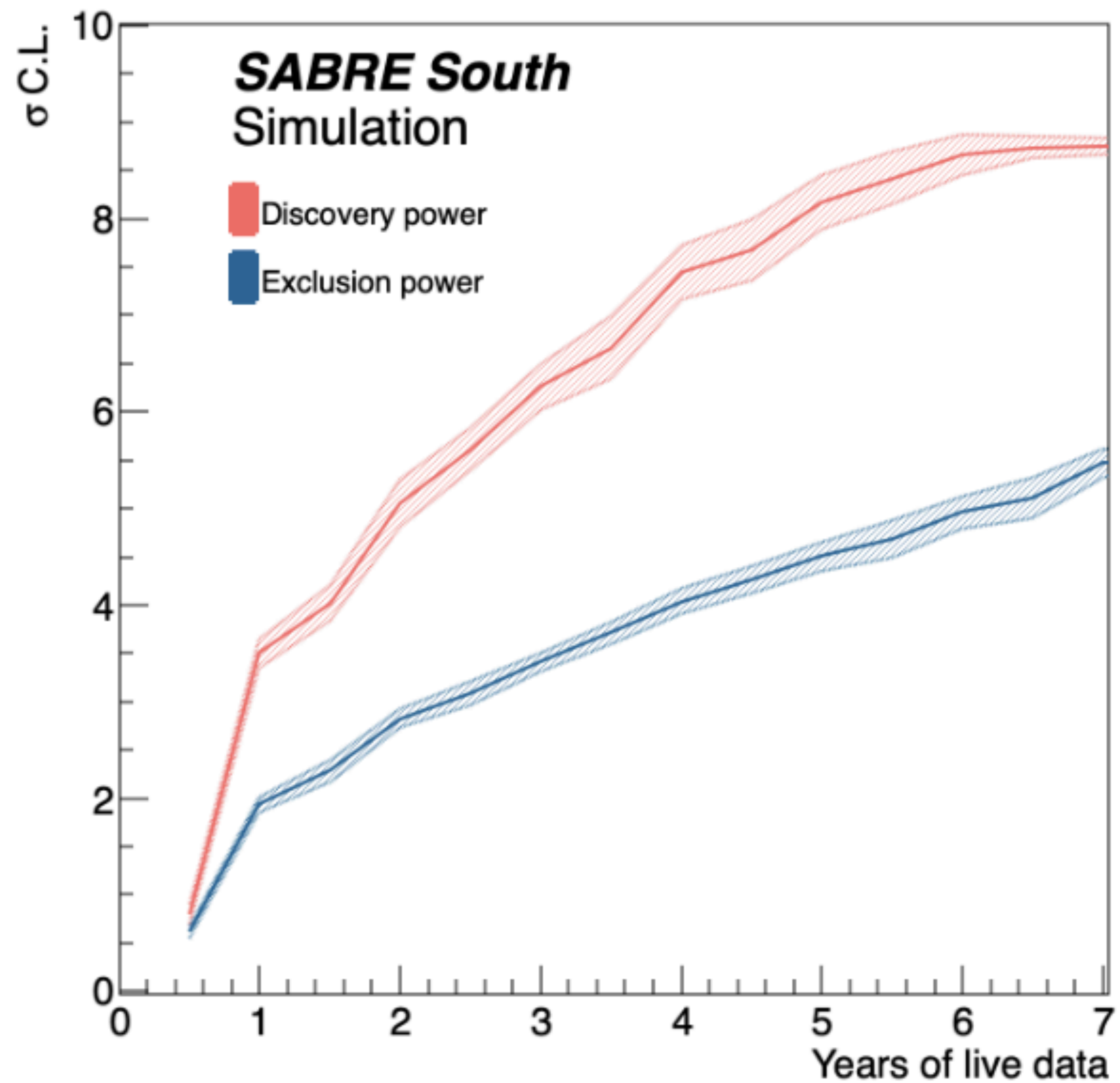


Fig. 9 The exclusion and discovery power of SABRE South for a DAMA/LIBRA-like signal. The shaded regions indicate 1σ statistical uncertainty bands.

- Based on simulations SABRE South will be able to refute the DAMA/LIBRA modulation signal at 3σ (5σ) using 2.3 (6.1) annual cycles of data assuming constant background.

Conclusions

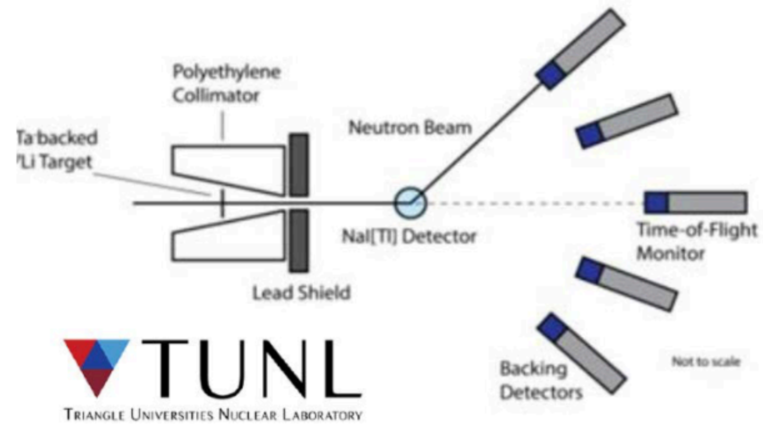
- Several experiments based on crystal scintillators are well under way in testing the DAMA/LIBRA results: ANAIS, COSINE, and very soon SABRE.
- No sign of a signal yet but more data is needed to reach a conclusive result. Might just be a few years away…
- Many improvement are foreseen from enhanced 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.

Backup

ANAIS-112

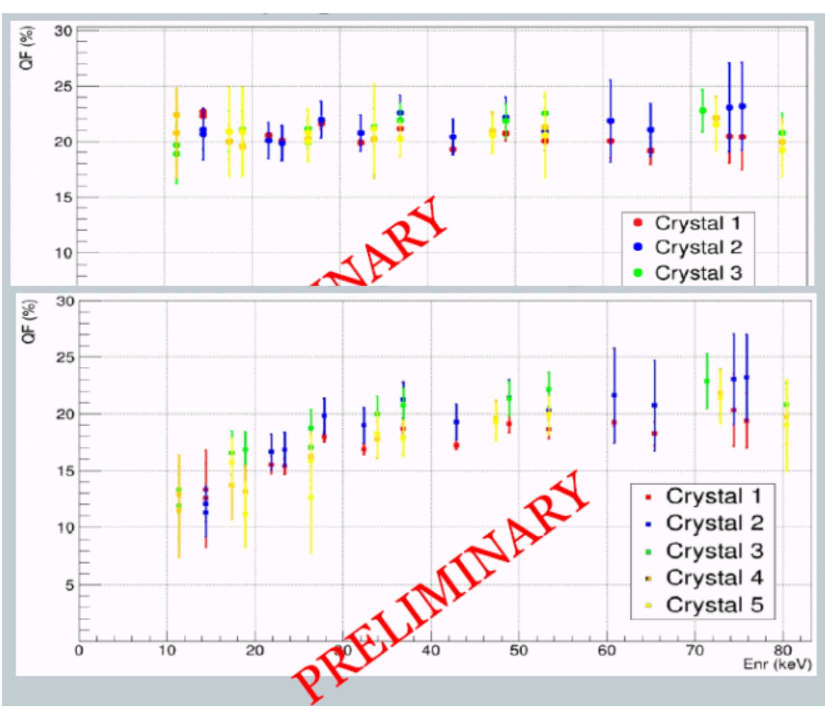
UNCERTAINTIES IN SCINTILLATION QUENCHING FACTORS ARE A RELEVANT SYSTEMATIC EFFECT for the comparison between DAMA/LIBRA and ANAIS

Na - QF derived using different methods and different calibration procedures do not agree. Dependences on the crystal properties can not be discarded



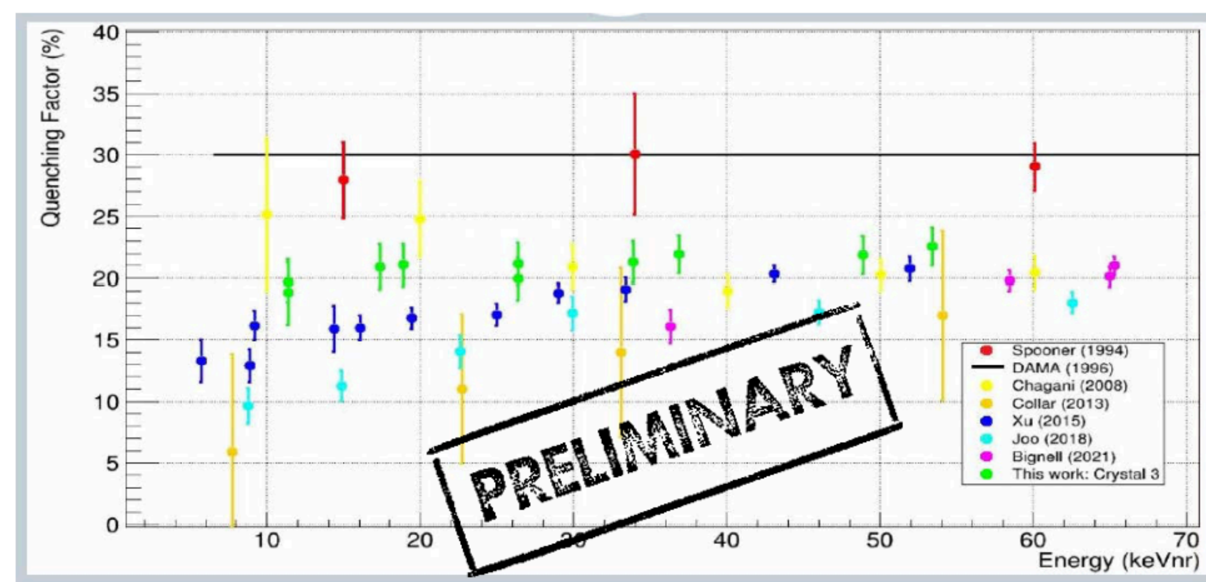
Five small AS crystals
Collaboration between Yale, Duke and Zaragoza
Measurements in 2018 @TUNL

Our best (preliminary) estimate for Na-QF in NaI(Tl)-AS crystals is 20%



Linearizing response in energy using ^{133}Ba data

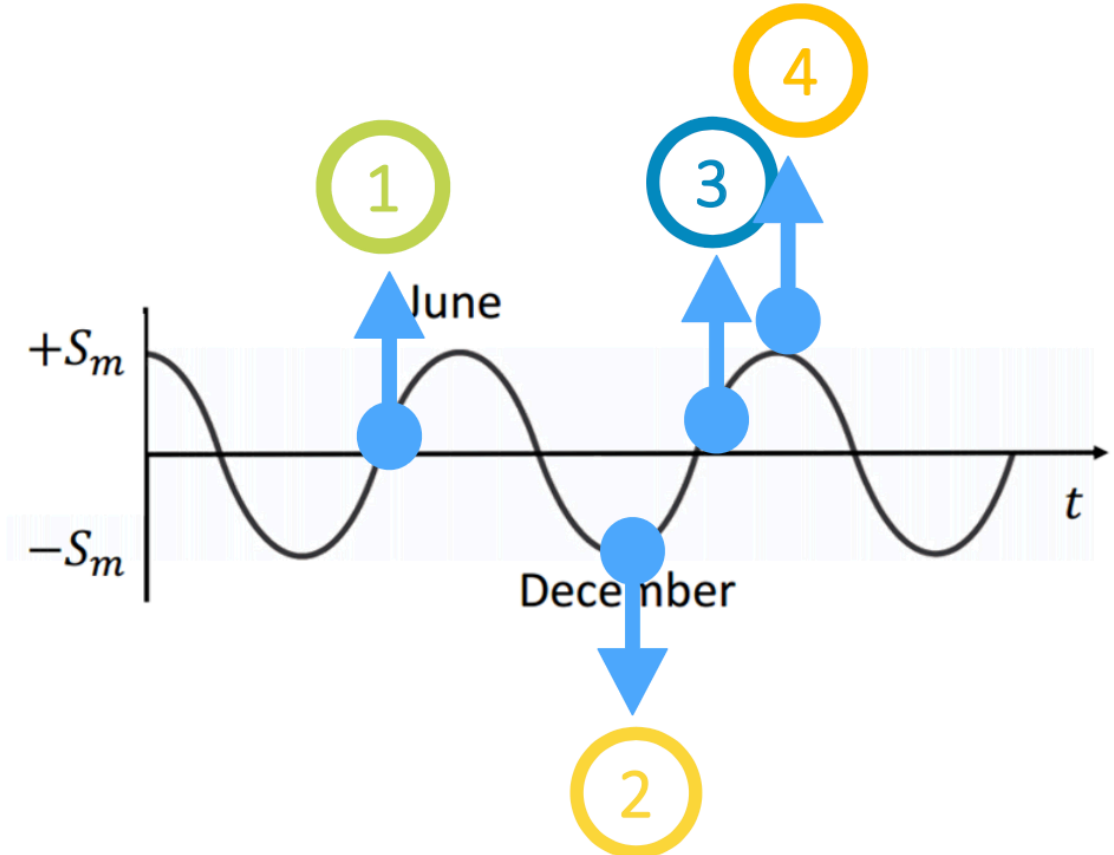
Assuming proportional response using 57.6 keV energy deposition

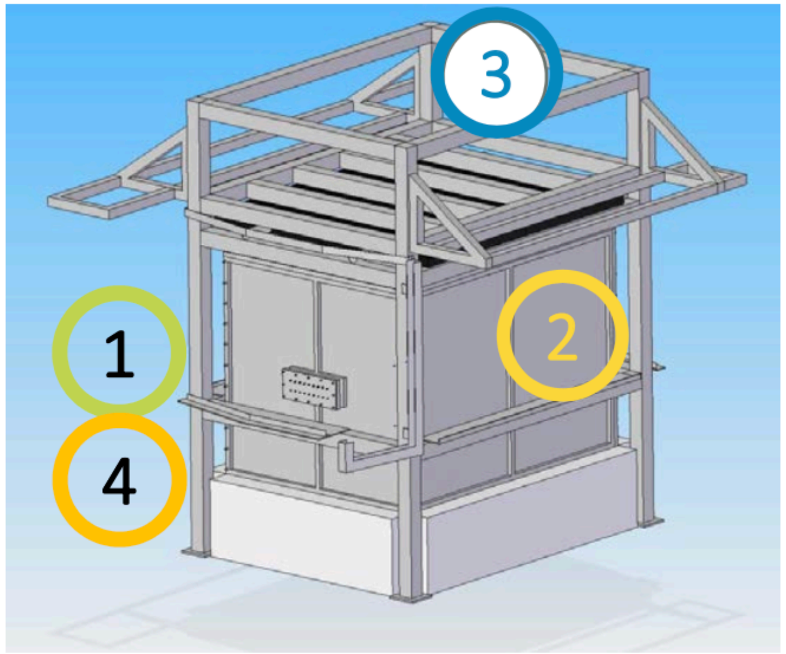


ANAIS-112

"onsite" neutron calibrations with the full ANAIS-112 set-up

Four calibration runs since April 2021 using ^{252}Cf neutron source at different positions in the ANAIS-112 set-up



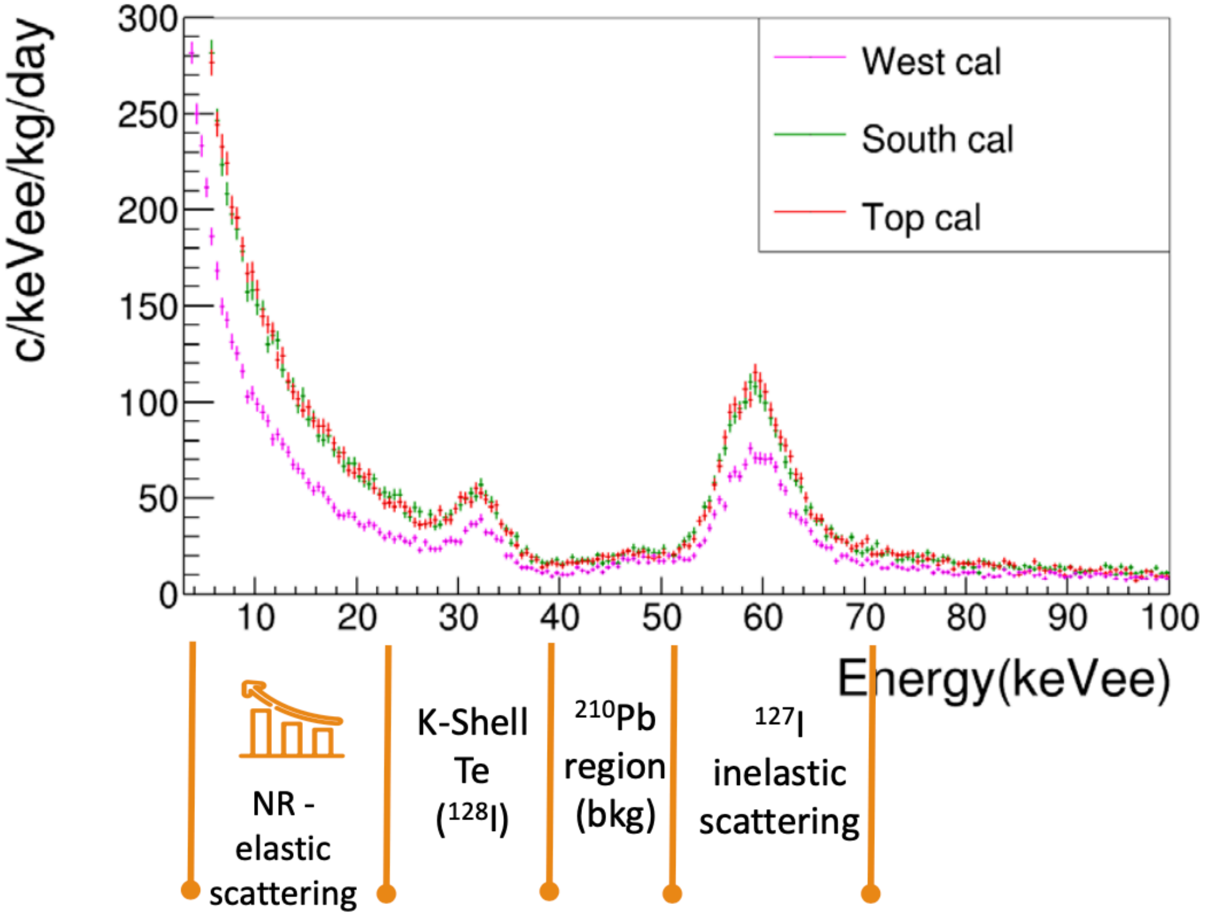


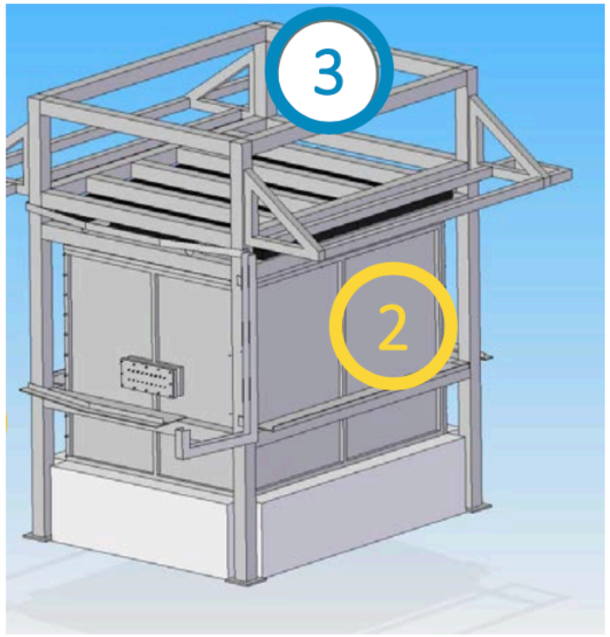
Neutrons produce many "bulk scintillation events" at very low energy

- We have a large population of events for training our new ML analysis and checking efficiency stability
- We expect to derive some information on QF by comparing simulations and measurements

"onsite" neutron calibrations with the full ANAIS-112 set-up

Four calibration runs since April 2021 using ^{252}Cf neutron source at different positions in the ANAIS-112 set-up





Neutrons produce many "bulk scintillation events" at very low energy

- We have a large population of events for training our new ML analysis and checking efficiency stability
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Background model

Detailed **background models** for each detector, based on Geant4 Monte Carlo simulation and accurate quantification of **background sources**

Assessment of backgrounds of the ANAIS experiment for dark matter direct detection, J. Amaré et al, Eur. Phys. J. C 76 (2016) 429
Analysis of backgrounds for the ANAIS-112 dark matter experiment, Eur. Phys. J. C 79 (2019) 412

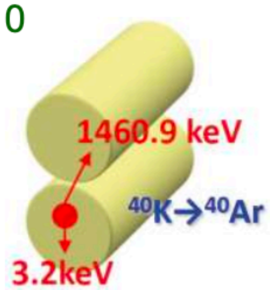
- **Activity from external components** measured with HPGe detectors at Canfranc
- **Internal activity** directly assessed: mainly ^{40}K, ^{210}Pb

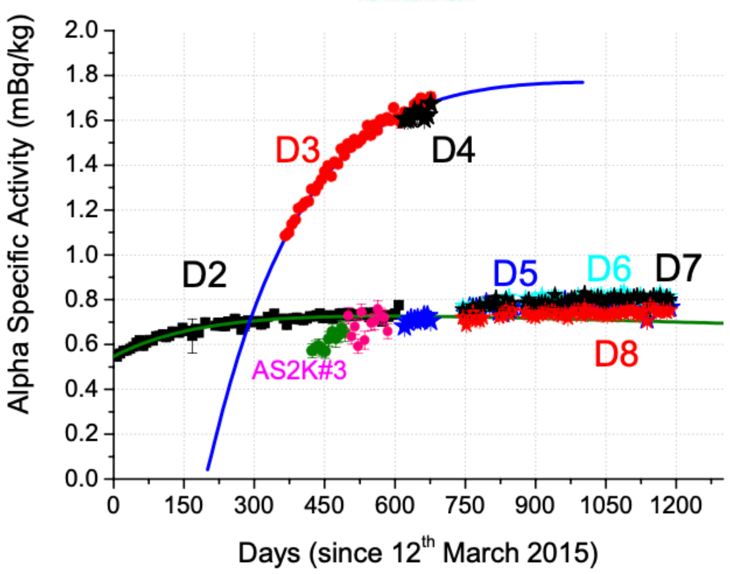
Detector	^{40}K (mBq/kg)	^{232}Th (mBq/kg)	^{238}U (mBq/kg)	^{210}Pb (mBq/kg)
D0	1.33±0.04	(4±1) 10^{-3}	(10±2) 10^{-3}	3.15±0.10
D1	1.21±0.04			3.15±0.10
D2	1.07±0.03	(0.7±0.1) 10^{-3}	(2.7±0.2) 10^{-3}	0.7±0.1
D3	0.70±0.03			1.8±0.1
D4	0.54±0.04			1.8±0.1
D5	1.11±0.02			0.78±0.01
D6	0.95±0.03	(1.3±0.1) 10^{-3}		0.81±0.01
D7	0.96±0.03	(1.0±0.1) 10^{-3}		0.80±0.01
D8	0.76±0.02	(0.4±0.1) 10^{-3}		0.74±0.01

^{232}Th, ^{238}U: determined by alpha rate following PSA and analysis of BiPo sequences at a level of a few µBq/kg, but **^{210}Pb out of equilibrium**

^{40}K: by identifying coincidences

C. Cuesta et al., Int. J. Mod. Phys. A. 29 (2014) 1443010





S. Cebrián, ECU2021

Background model

Detailed **background models** for each detector, based on Geant4 Monte Carlo simulation and accurate quantification of **background sources**

- **Cosmogenic activity** in crystals: short-lived Te and I isotopes, ^{3}H, ^{22}Na, ^{109}Cd, ^{113}Sn

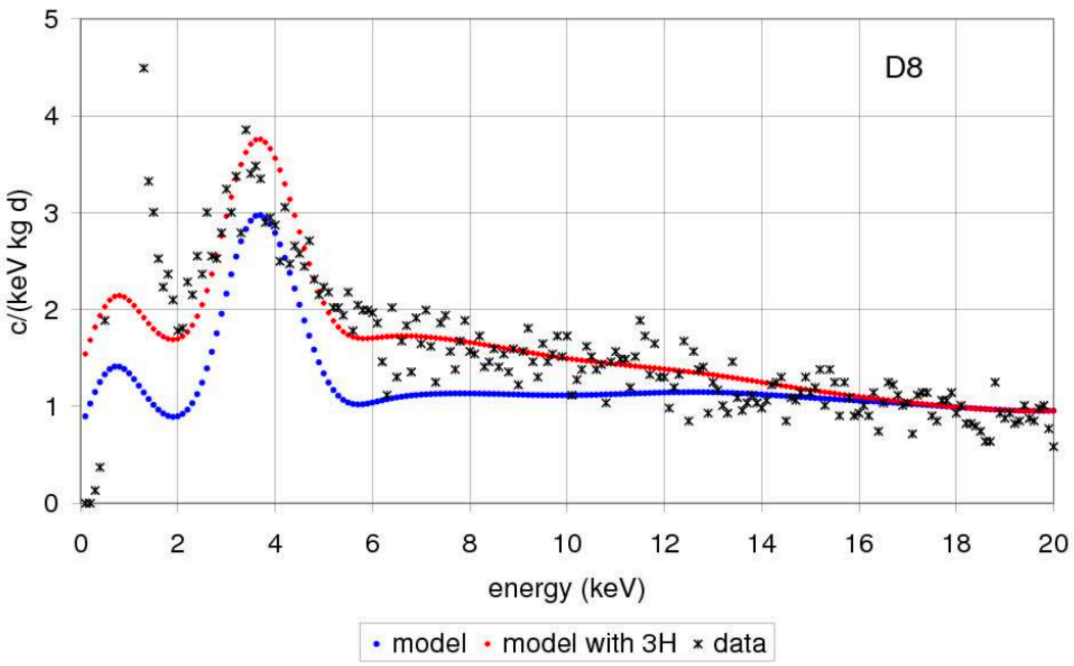
J. Amaré et al, JCAP 02 (2015) 046
J. Amare et al, Astropart. Phys.97 (2018) 96
P. Villar et al, Int. J. Mod. Phys. A 33 (2018) 1843006

^{22}Na: from analysis of coincidences

^{109}Cd, ^{113}Sn: from peaks at binding energies of K-shell electrons (after EC)

^{3}H: additional background source contributing only in the very low energy region required, which could be tritium

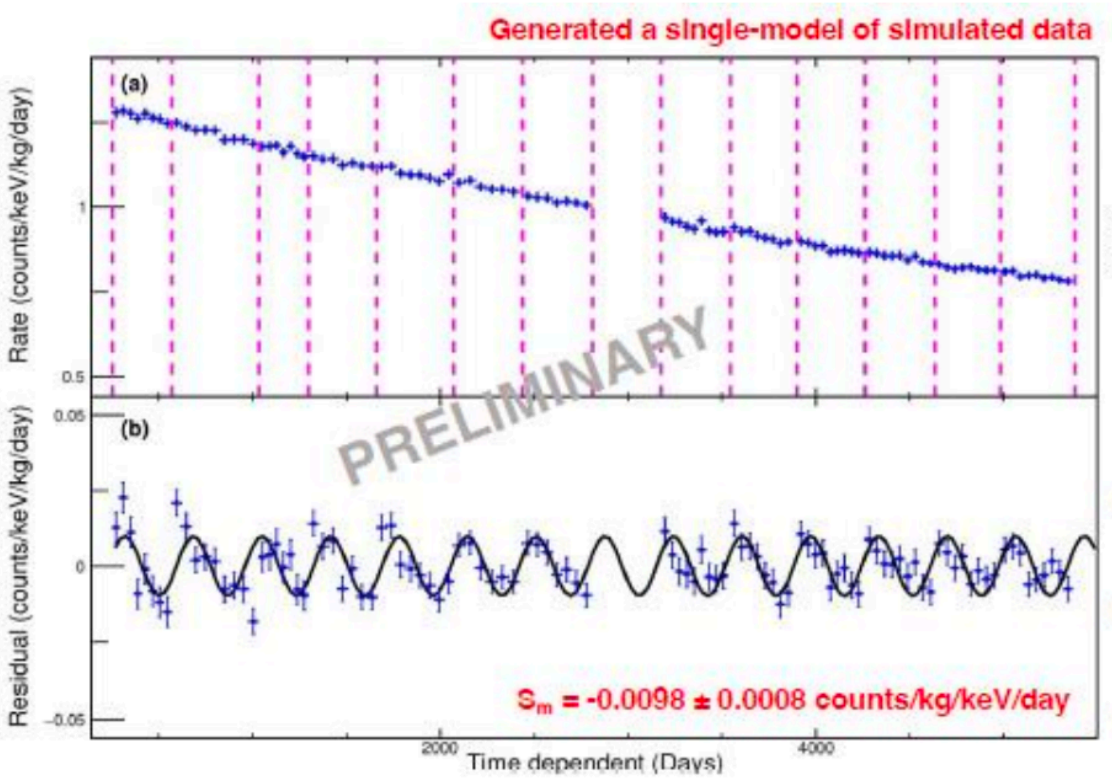
D0-D1: 0.20 mBq/kg
D2-D8: 0.09 mBq/kg (upper limit set by DAMA/LIBRA)

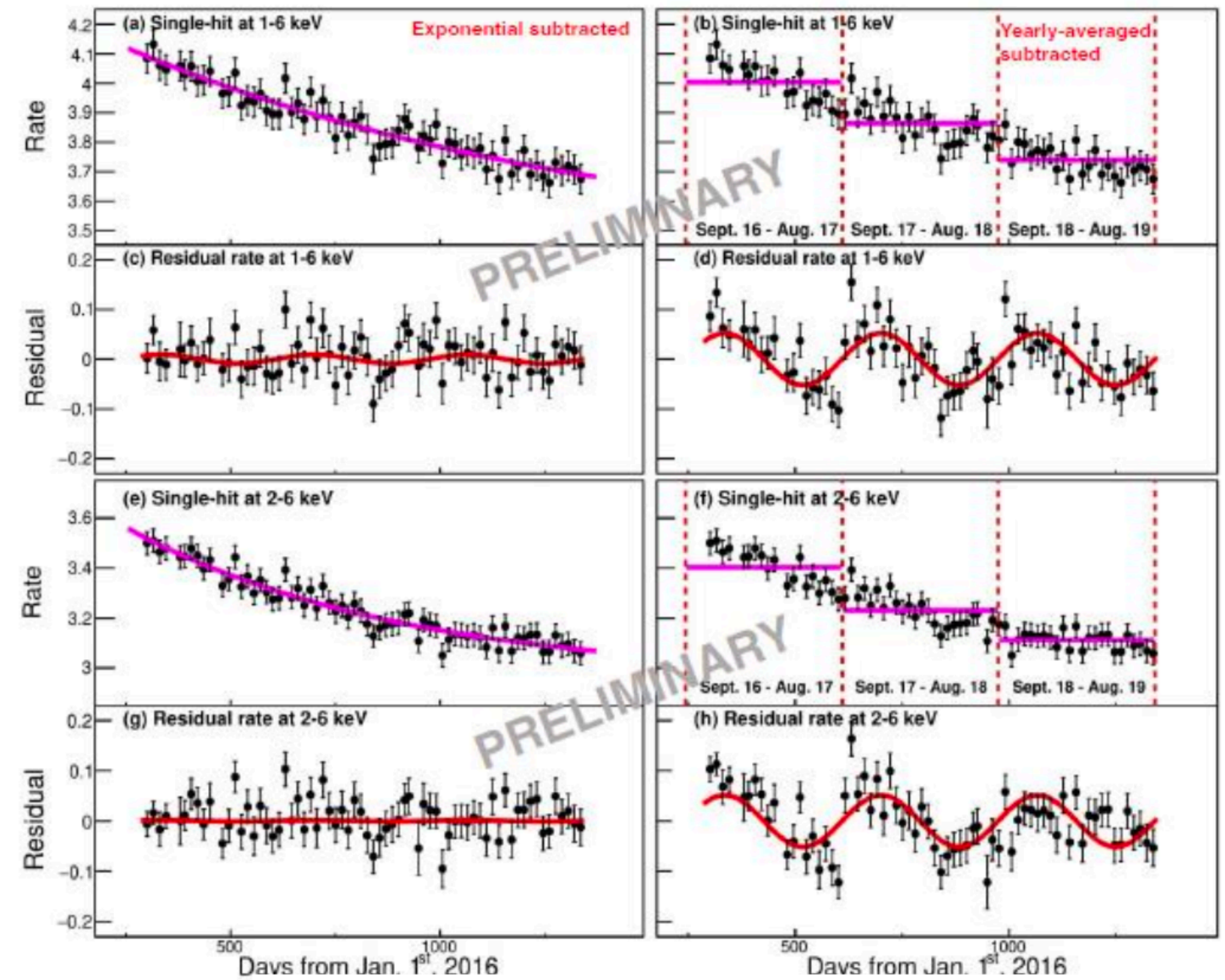


S. Cebrián, ECU2021

COSINE data with DAMA technique

- Suggested that DAMA's analysis can generate modulation signal
- Tested with COSINE-100 data with DAMA technique and in pseudo-data to replicate DAMA data
- Negative modulation amplitude induced at DAMA phase in both cases



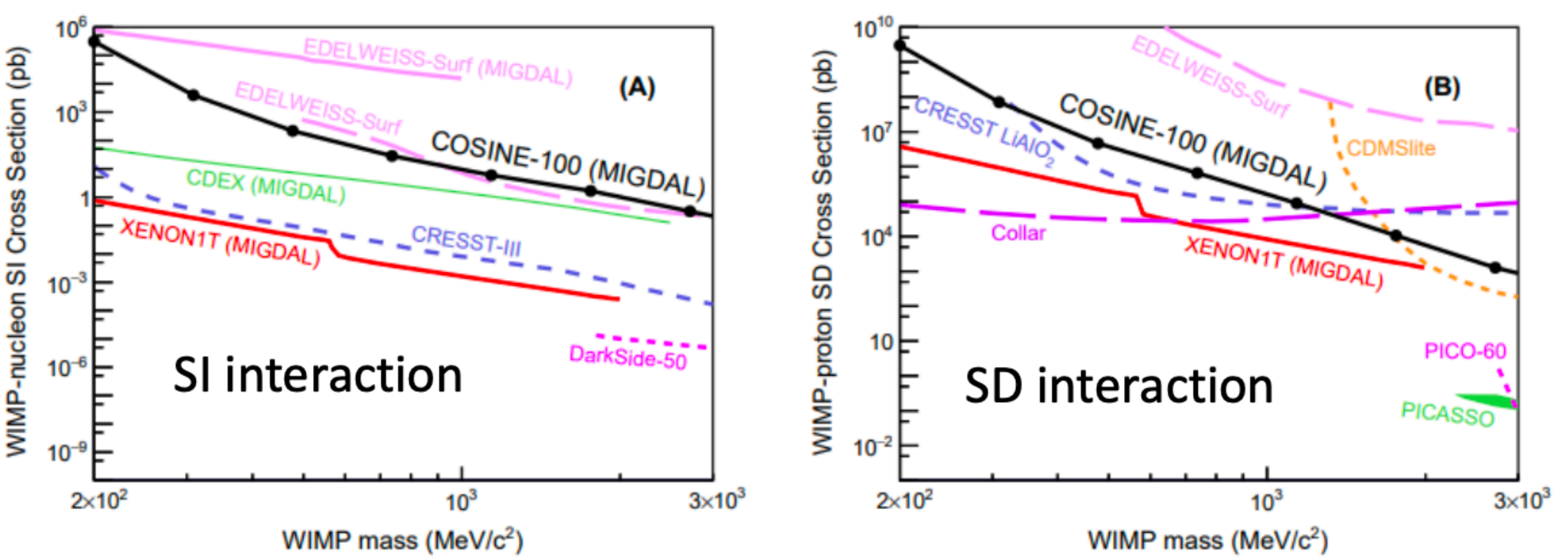


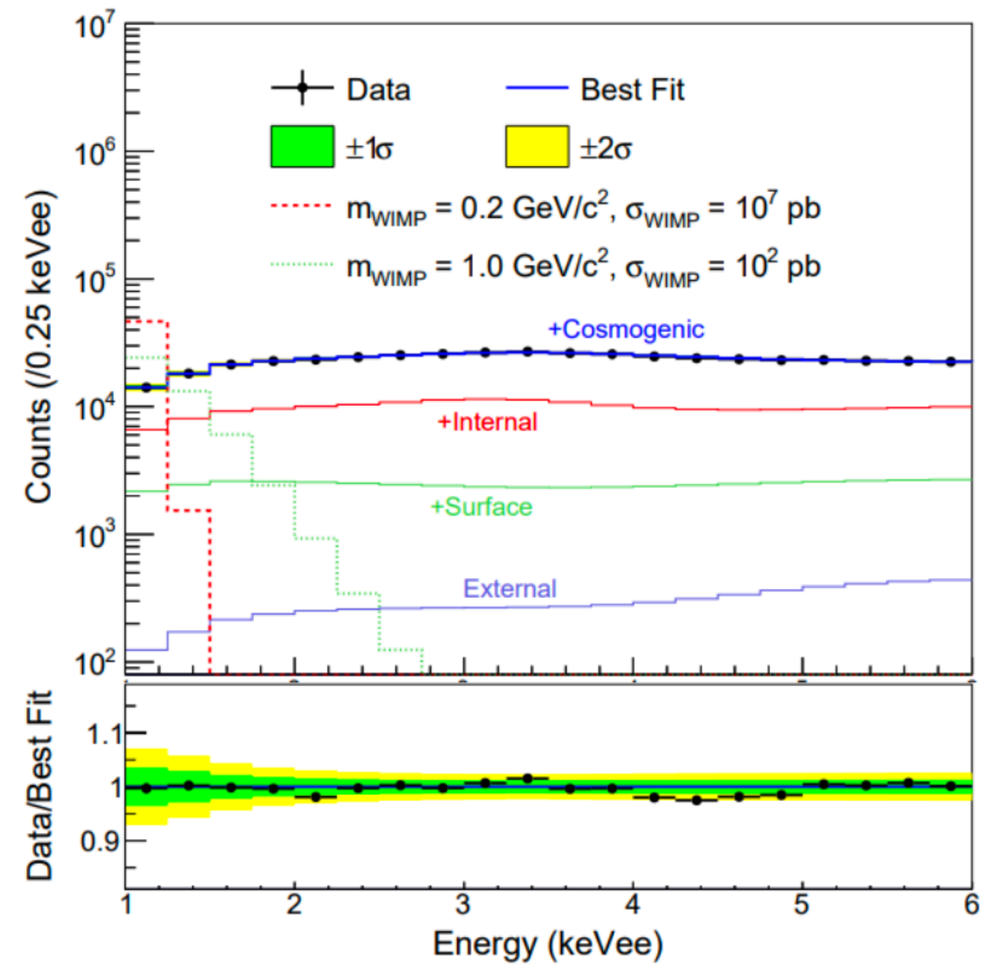
Results

counts/kg/keV/day	1–6 keV	2–6 keV
This work ✓	-0.0441±0.0057	-0.0456±0.0056
DAMA/LIBRA	0.0105±0.0011	0.0095±0.0008
COSINE-100	0.0067±0.0042	0.0050±0.0047
ANAIS-112	-0.0034±0.0042	0.0003±0.0037

WIMP search via Migdal effect

- WIMPs can interact with NaI crystals and produce energetic electrons alongside nuclear recoil via Migdal effect
  - Good candidate for searching for low mass DM
  - Search window of COSINE-100 lowered to 200 MeV/c²
- Search using 1.7 years data with 1 keV low energy threshold
- No WIMP signal observed
- Adhikari, G., et al. "Searching for low-mass dark matter via the Migdal effect in COSINE-100." Physical Review D 105.4 (2022): 042006.

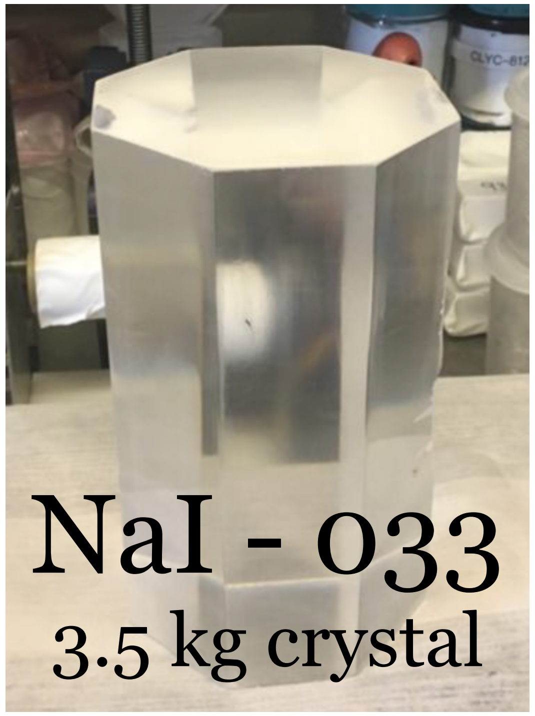




Example of fit to 1.1 GeV/c² WIMP

SABRE crystals

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



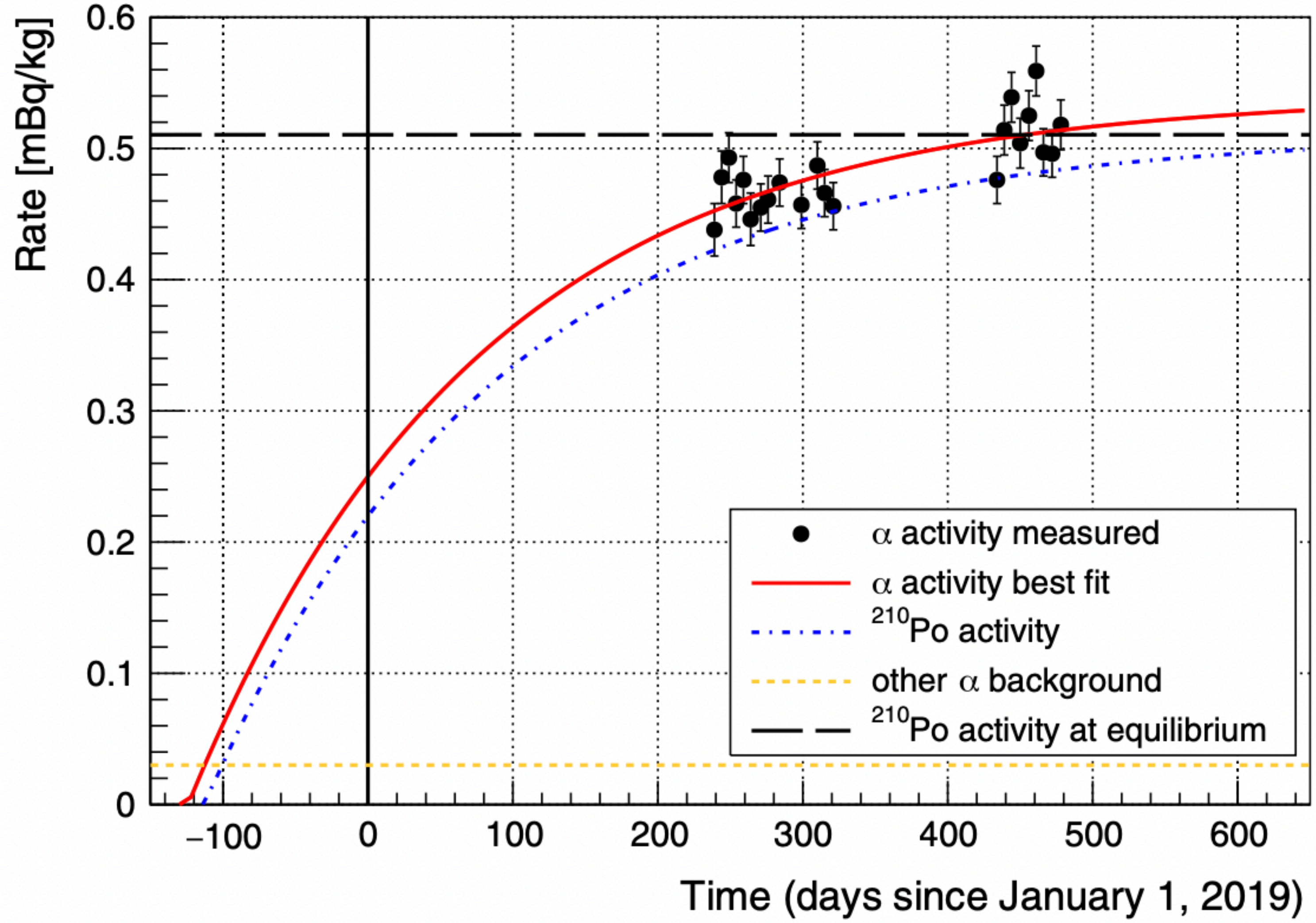
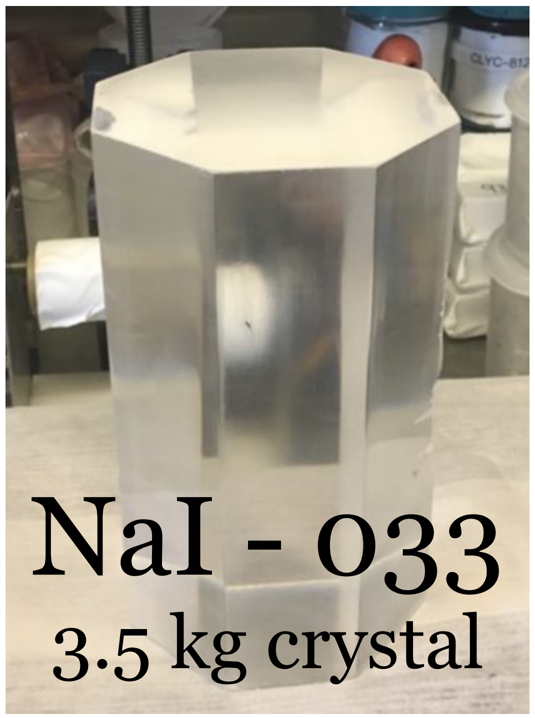


Fig. 5 α activity in ^{210}Po energy region as a function of time with 5-days binning. The best fit function to the data (red solid line) is the sum of the build-up function with the mean life of ^{210}Po (blue dotted line) and a constant component independently determined (orange dotted line). The black dashed line shows the activity of ^{210}Po at equilibrium

SABRE crystals [Eur. Phys. J. C 81, 299 (2021)]



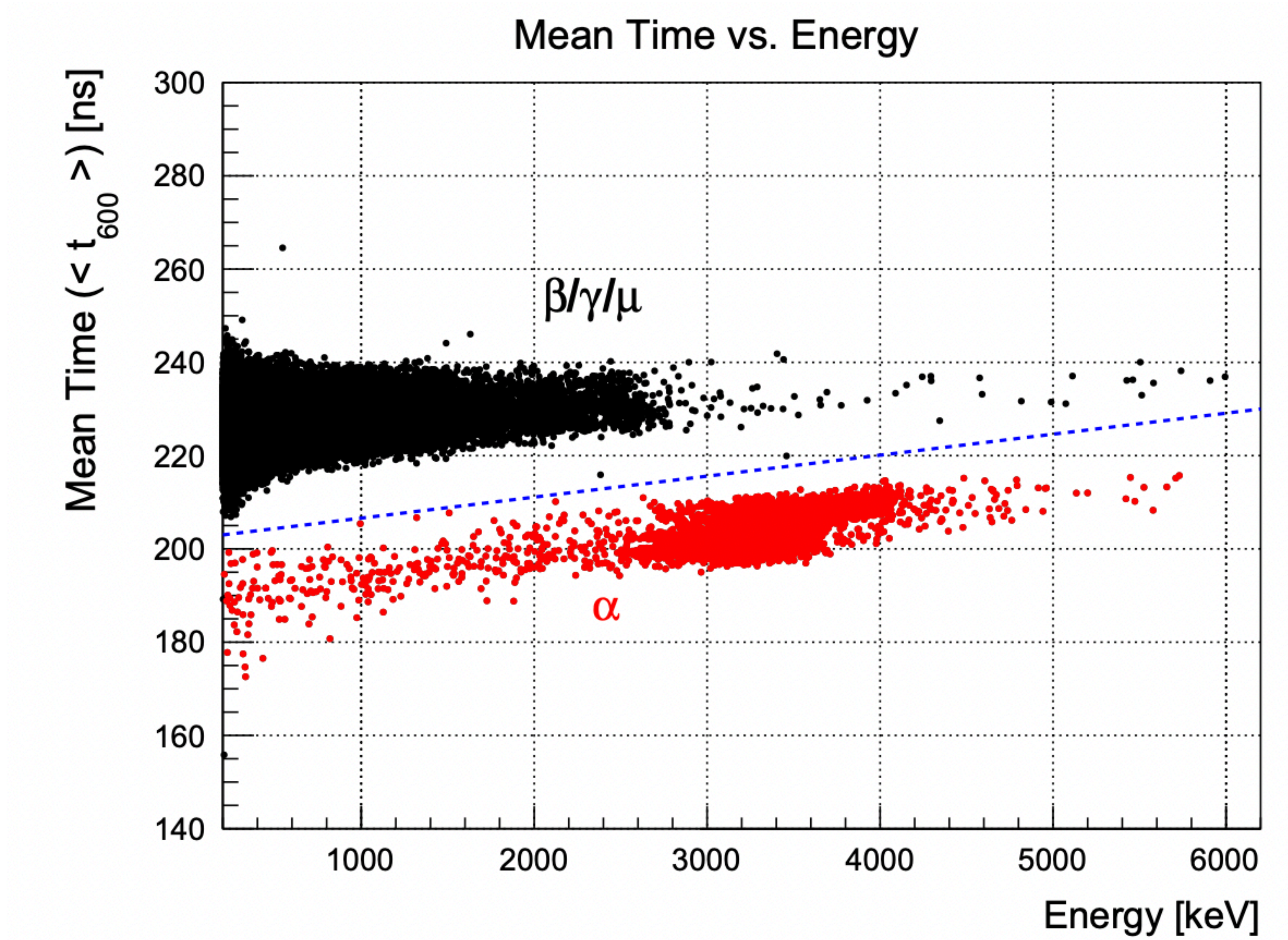
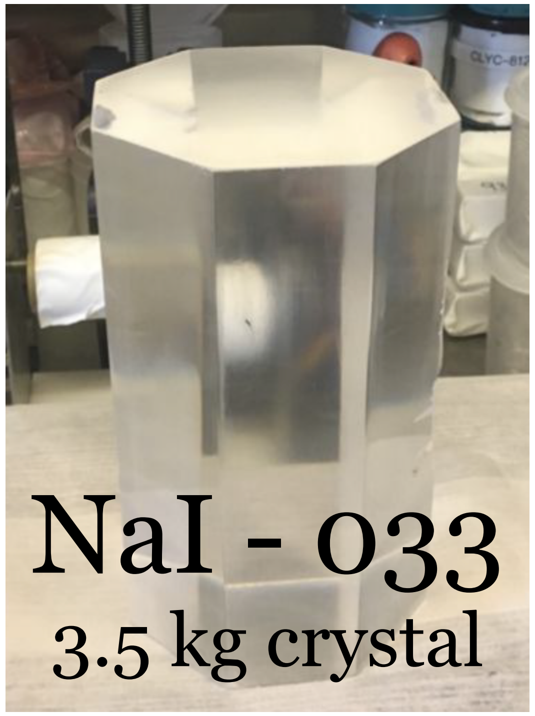


Fig. 4 Distribution of mean time vs. energy of α (red) and β/γ (black) events. The blue dotted line shows our typical separation cut

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



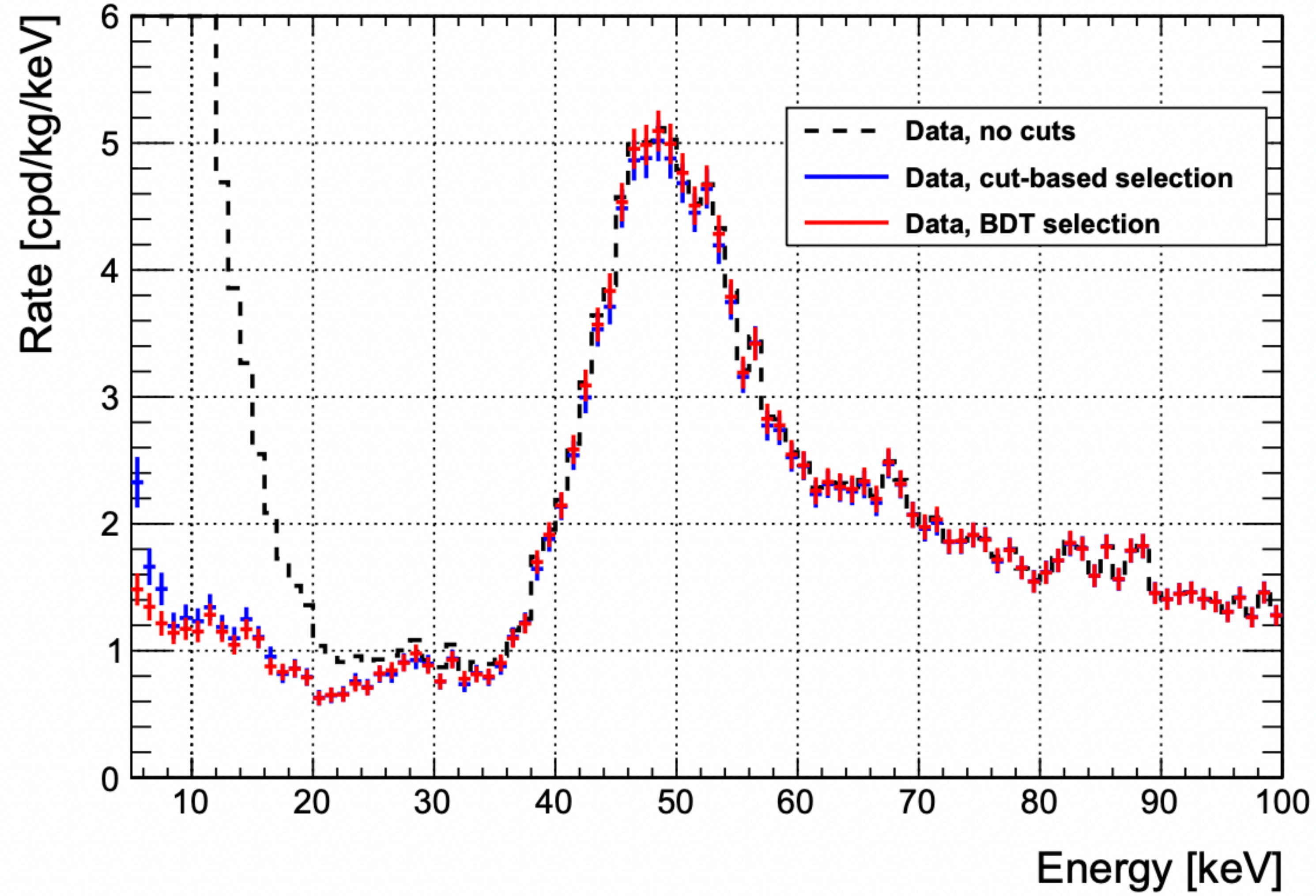
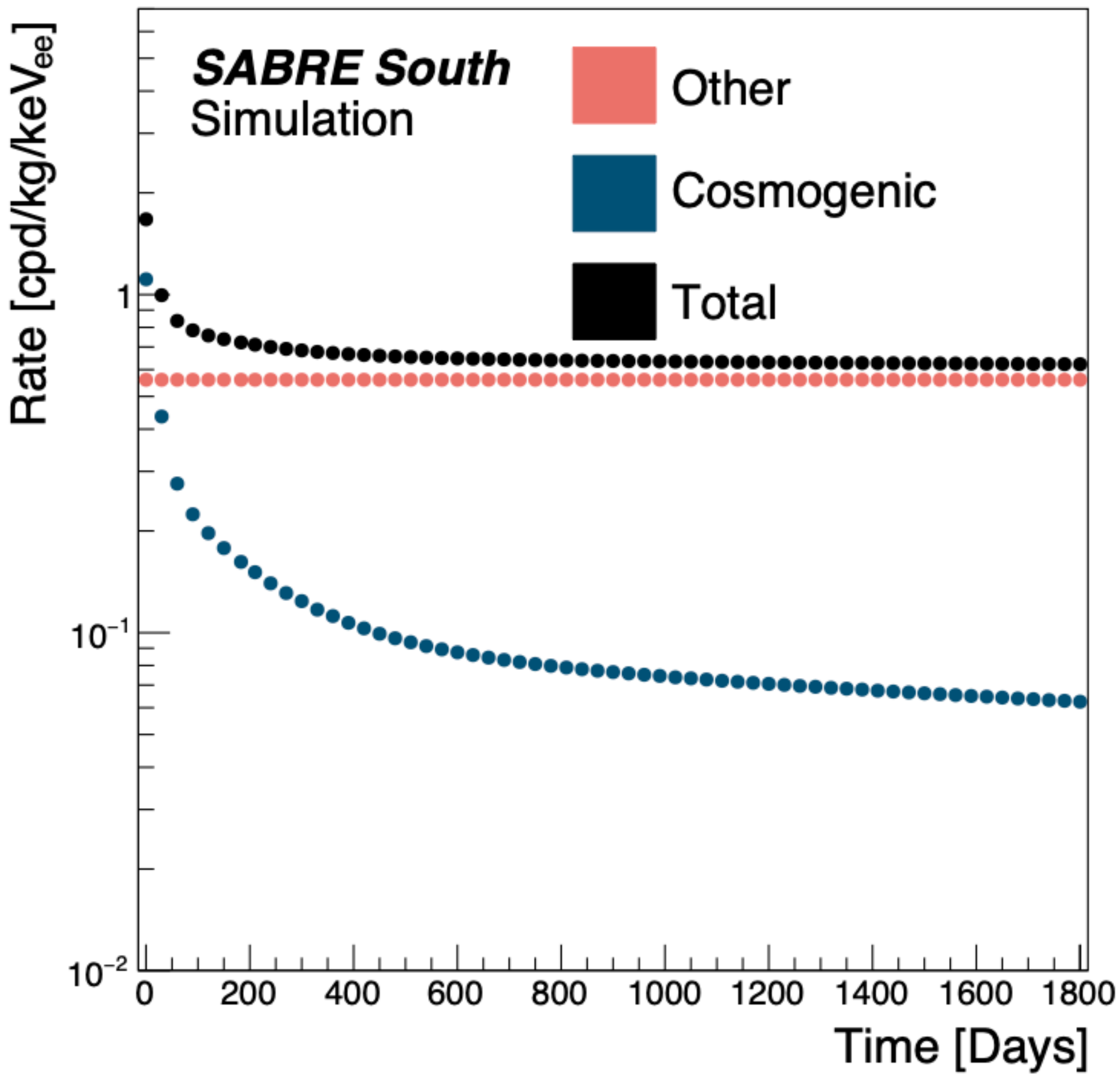


Fig. 11 NaI-33 low energy spectrum before (black dashed line) and after noise rejection. We show the result of the cut-based (blue points) and multivariate BDT (red points) analyses. The blue and red histograms are corrected by the respective cut acceptance

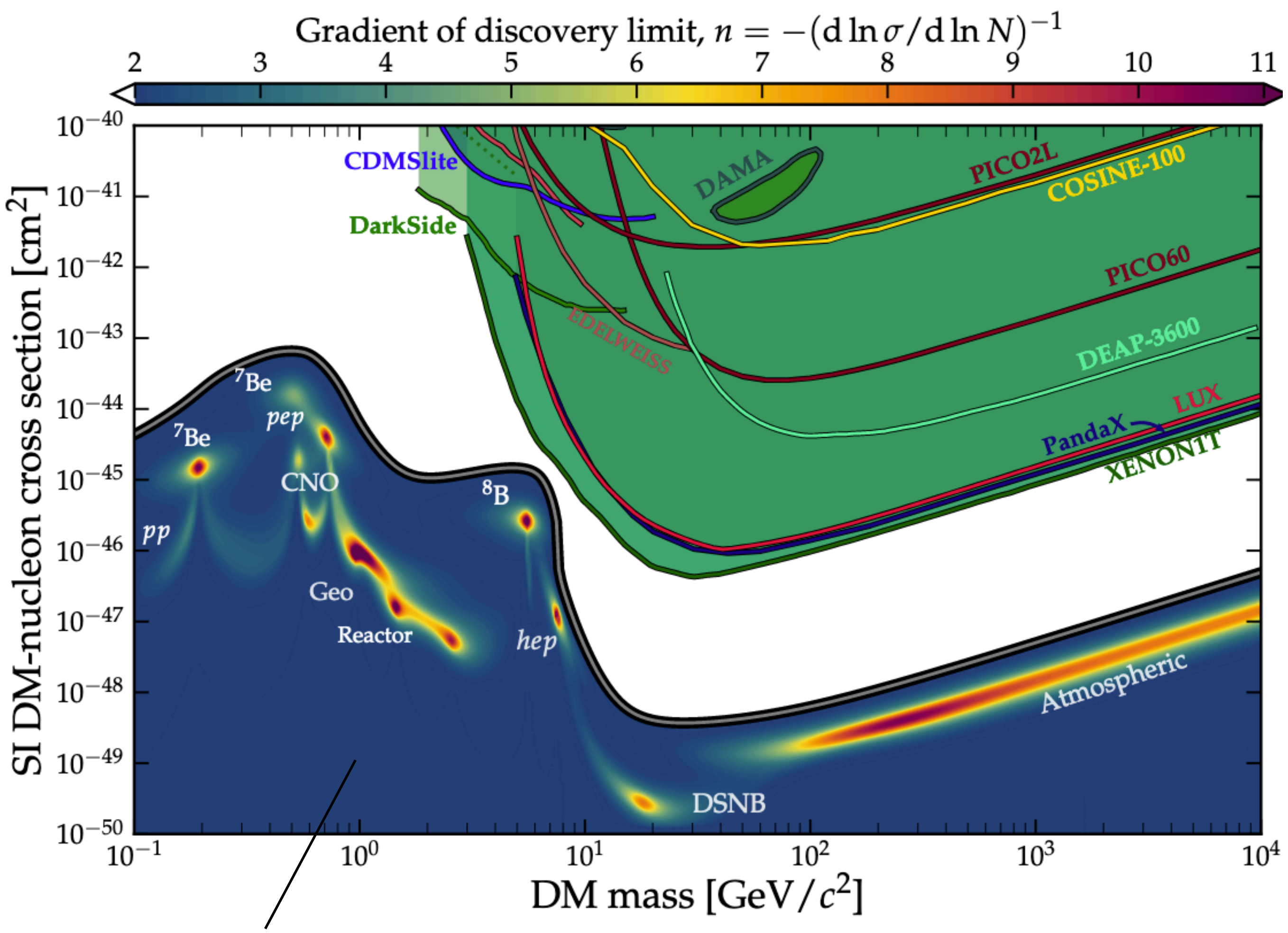
SABRE South

arXiv: 2205.13849

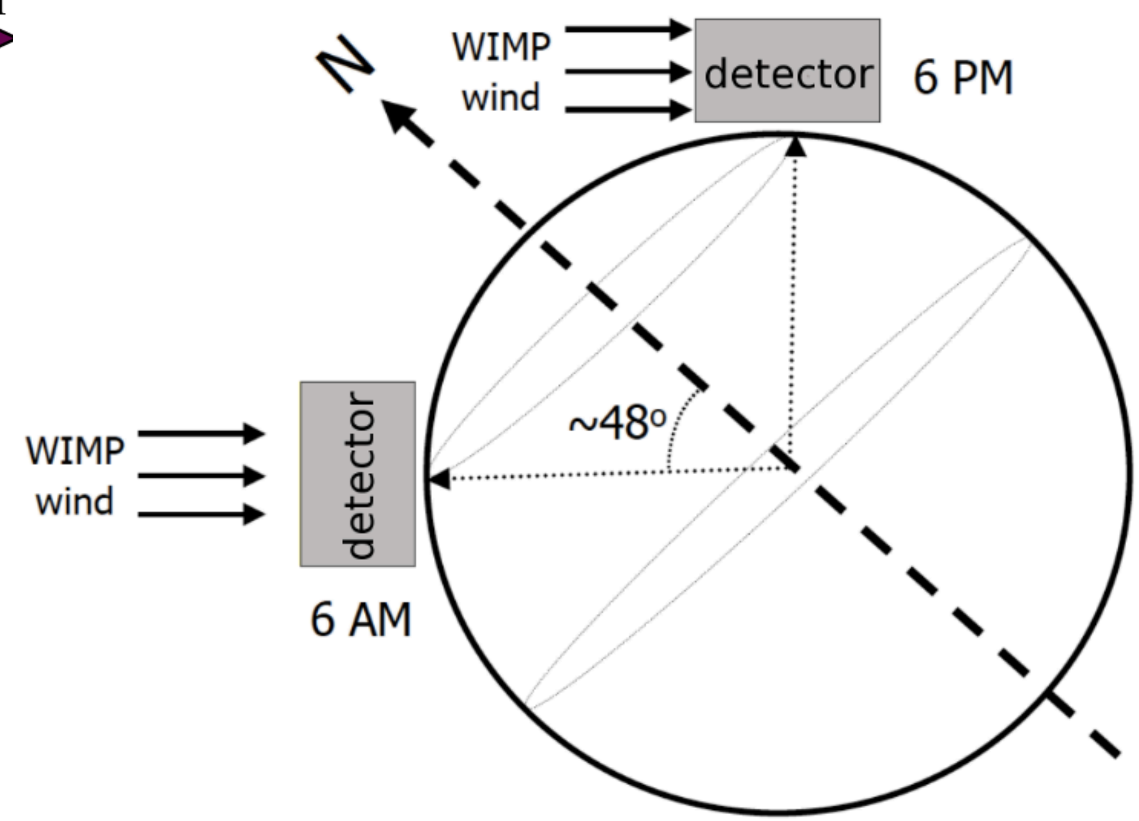


Directional detection

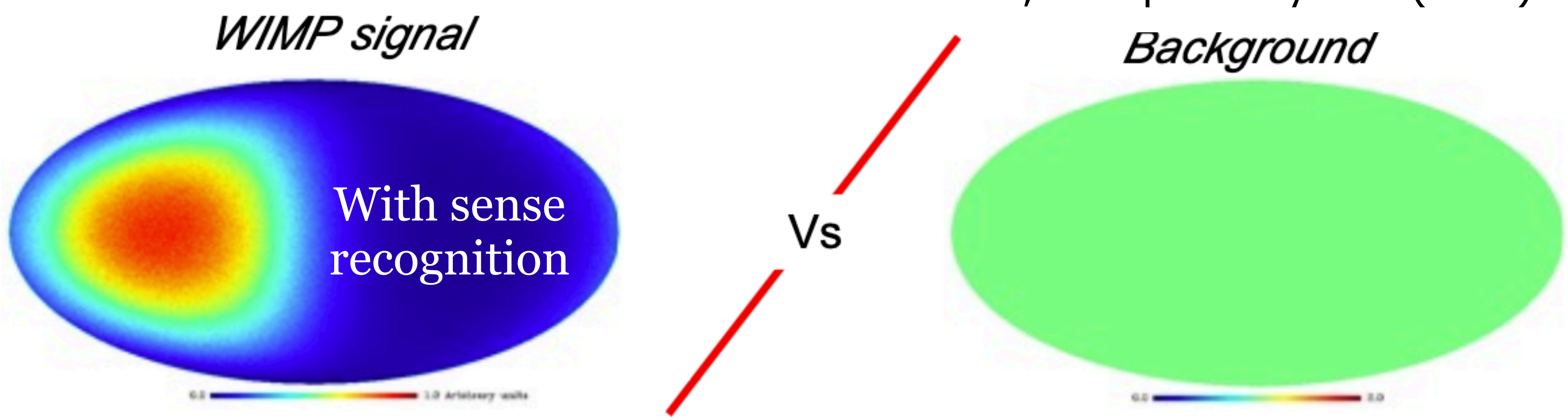
arXiv: 2203.05914



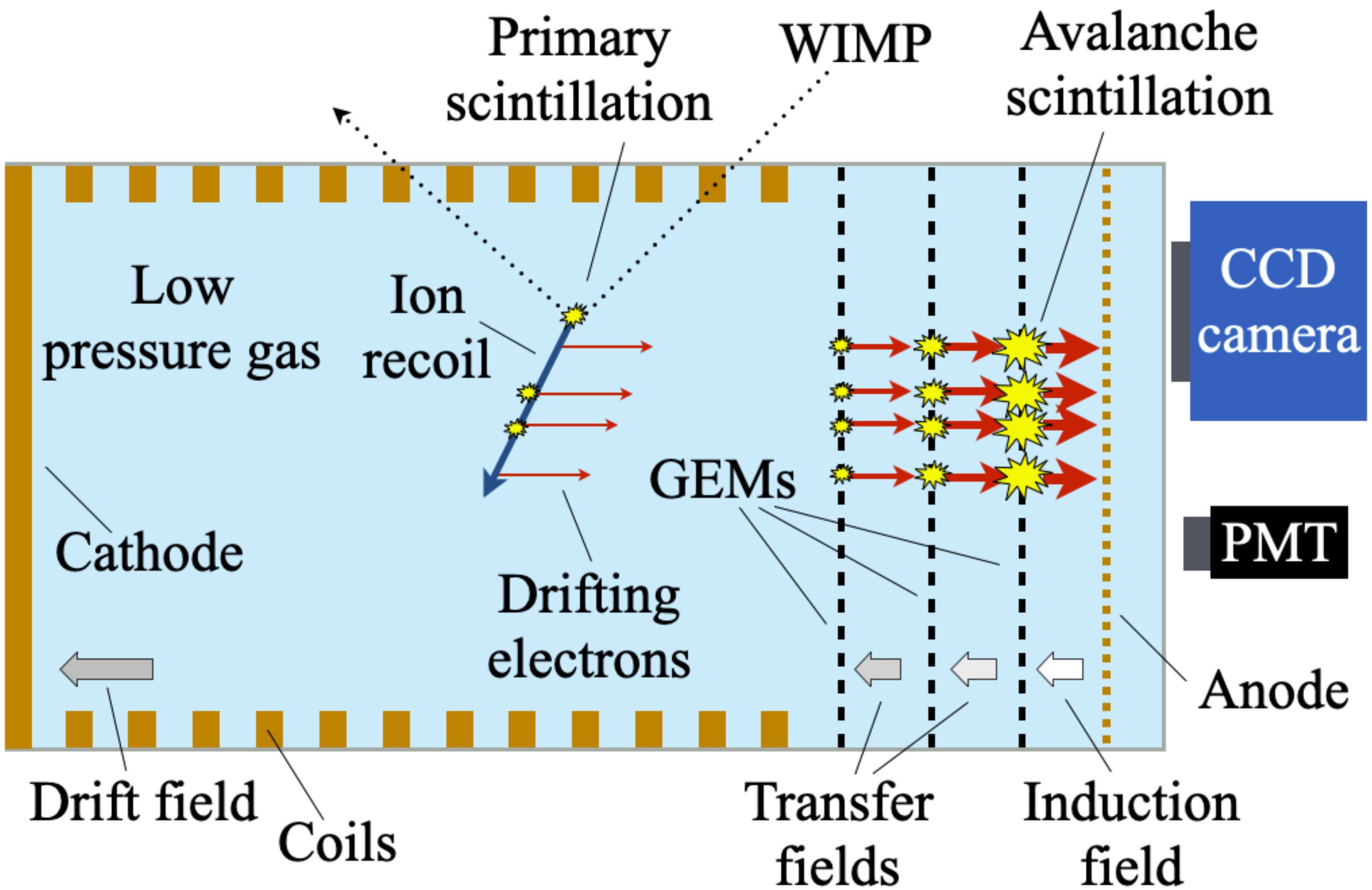
Neutrino fog

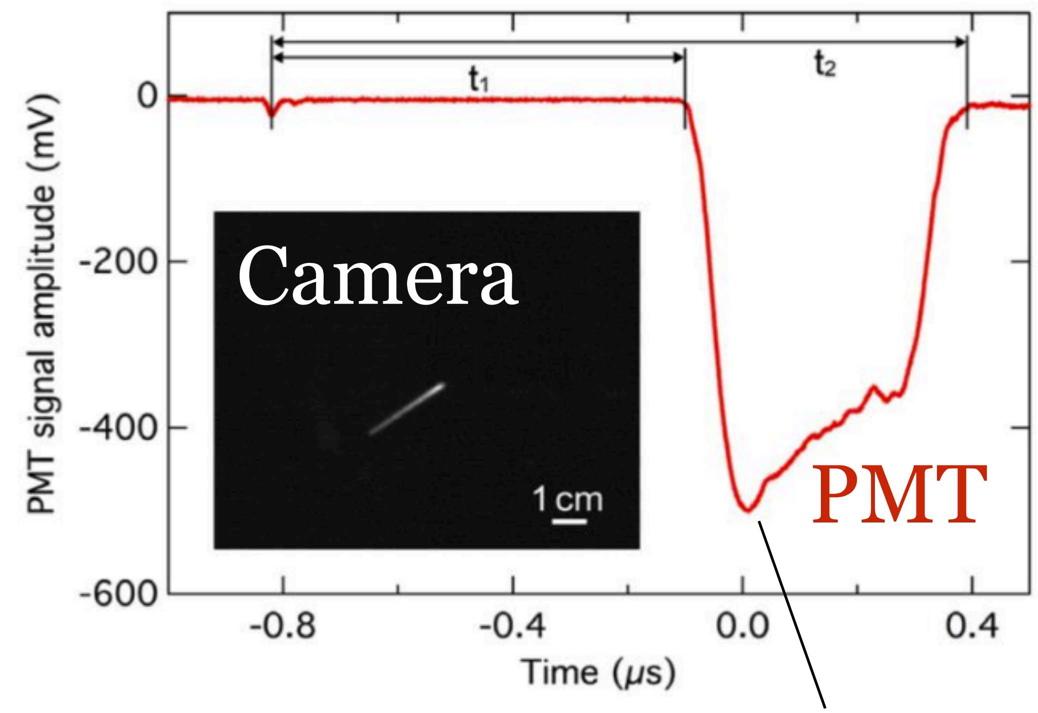


A. M. Green et. al, Astropart. Phys. 27 (2007) 142

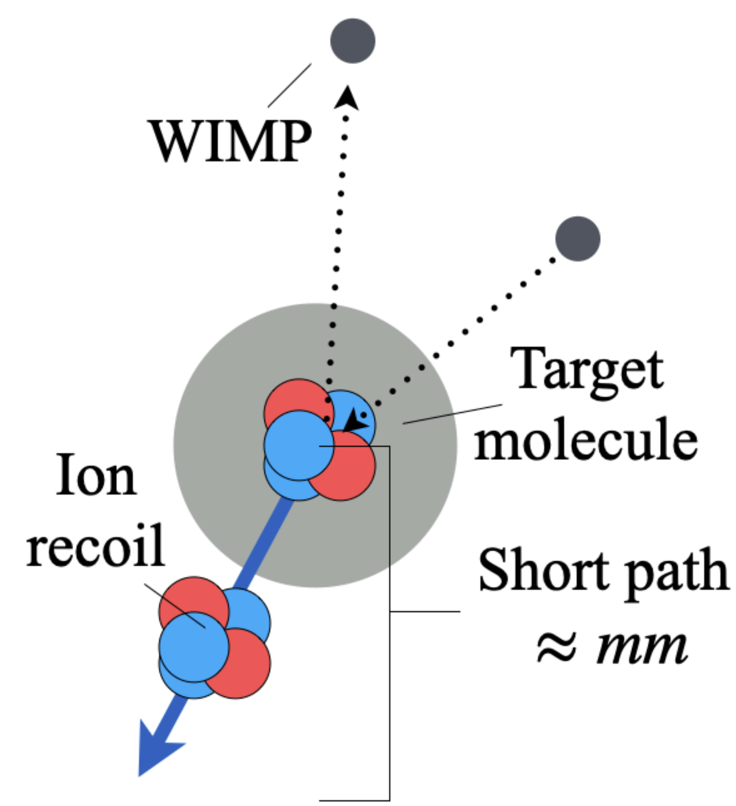


Directional detectors



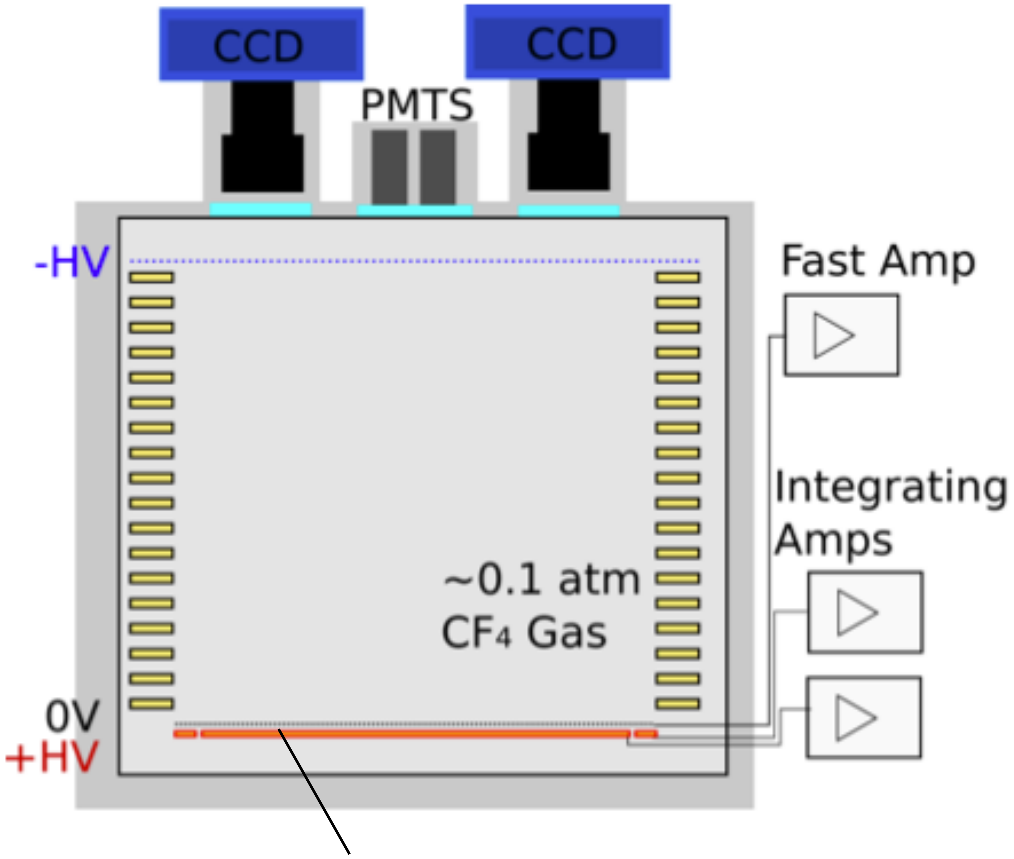


Bragg peak at earlier times indicates motion toward readout



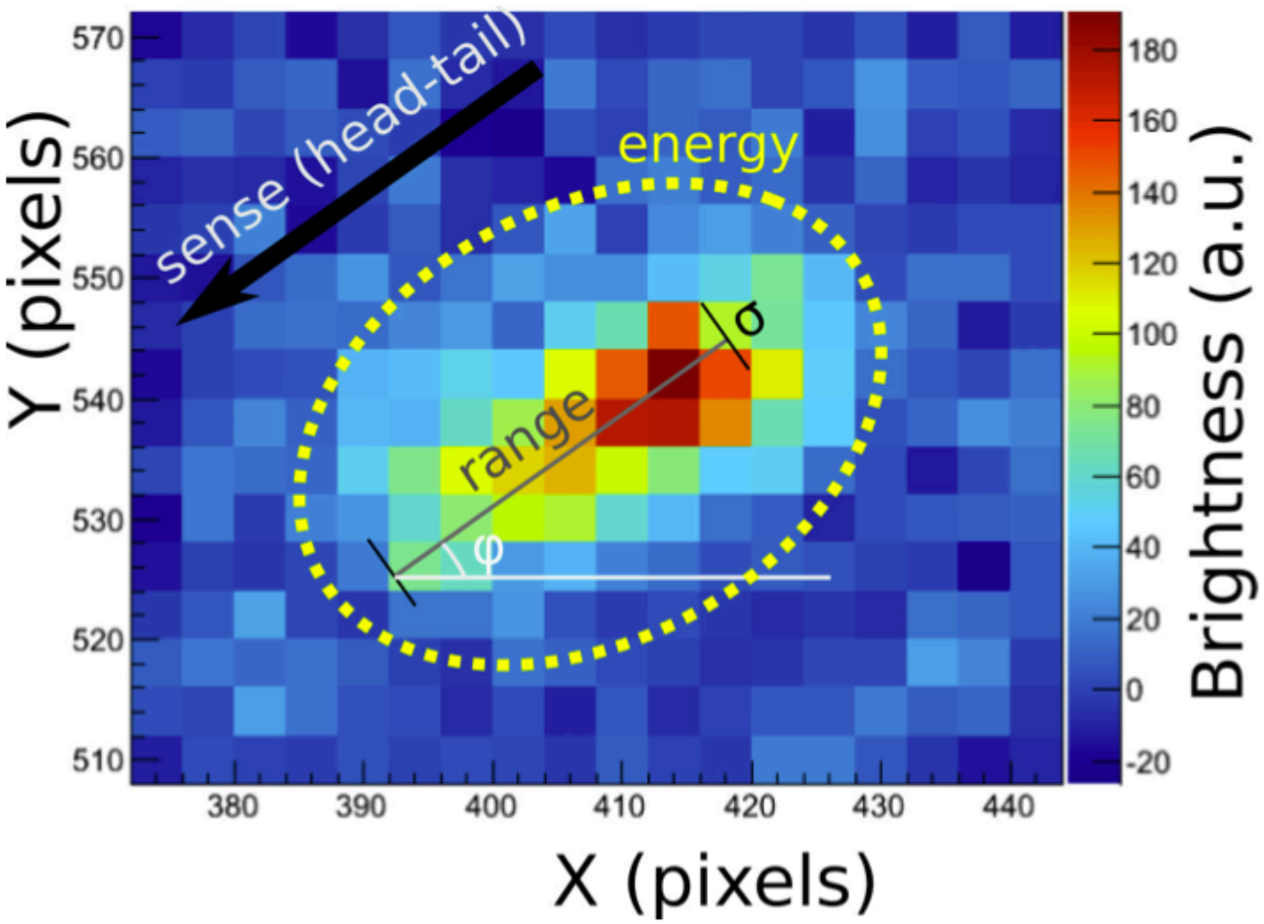
- **Low pressure**:
  - good for directionality discrimination.
- **Low target mass**:
  - sensitivity to lighter WIMPs.

DMTPC



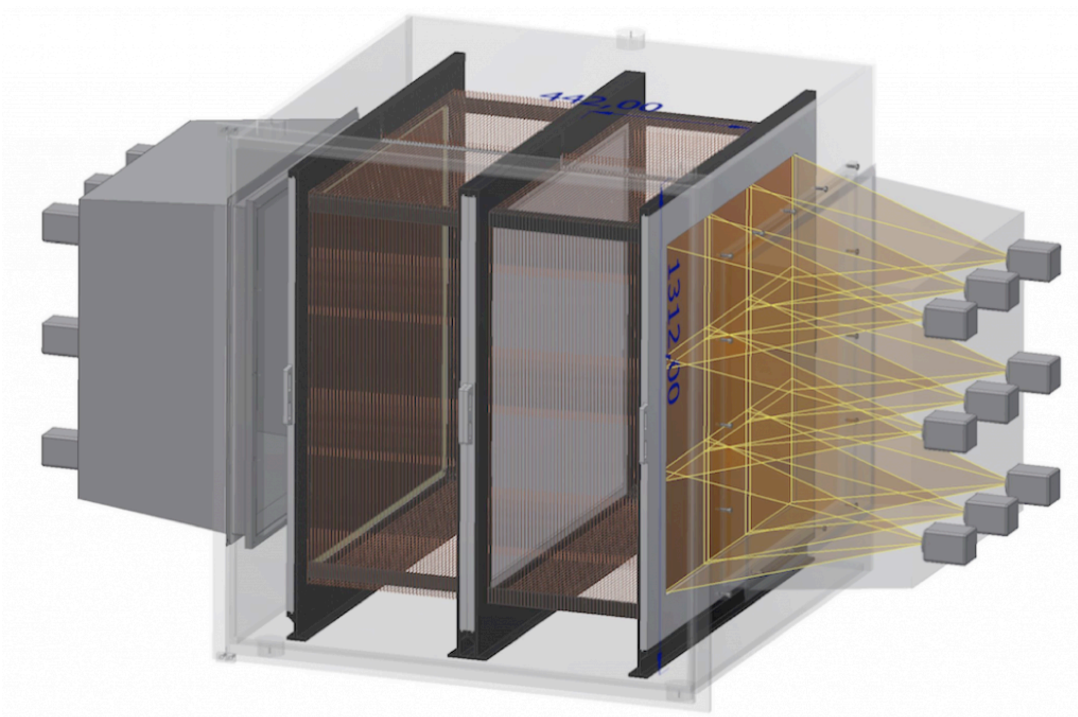
Micromash amplification

https://doi.org/10.1016/j.phpro.2014.12.008



- Several prototypes developed over the years (10 l, 20 l) first operated at MIT and then at the WIPP (US) facility underground.
- CF_4 provides sensitivity mostly to spin-dependent WIMP coupling due to relatively light constituents and high nuclear spin factor of ^{19}F.
- A detector at the scale of 1 m^3 is in preparation using four TPCs.

Cygno and Cygnus



CYGNO/INITIUM @ LNGS

- Will be a 1 m^3 symmetric detector.
- Filled with $He:CF_4$ (60:30, ≈ 1 kg).
- Volumes equipped with triple-GEMs.
- Readout: sCMOS + fast PMT or SiPMs.
- Many prototypes already built: 10.1088
- Exploring possibility to use $He:CF_4:SF_6$.

Cygnus: network of similar observatories