IBS CONFERENCE ON DARK WORLD

OCTOBER 27 MON - 30 THU, 2025 · IBS HQ, Daejeon, Korea

Institute for Basic Science
CENTER FOR UNDERGROUND PHYSICS
Center for Theoretical Physics of the Universe
Dark Matter Axion Group

Search for DM annual modulation with NaI-based detectors

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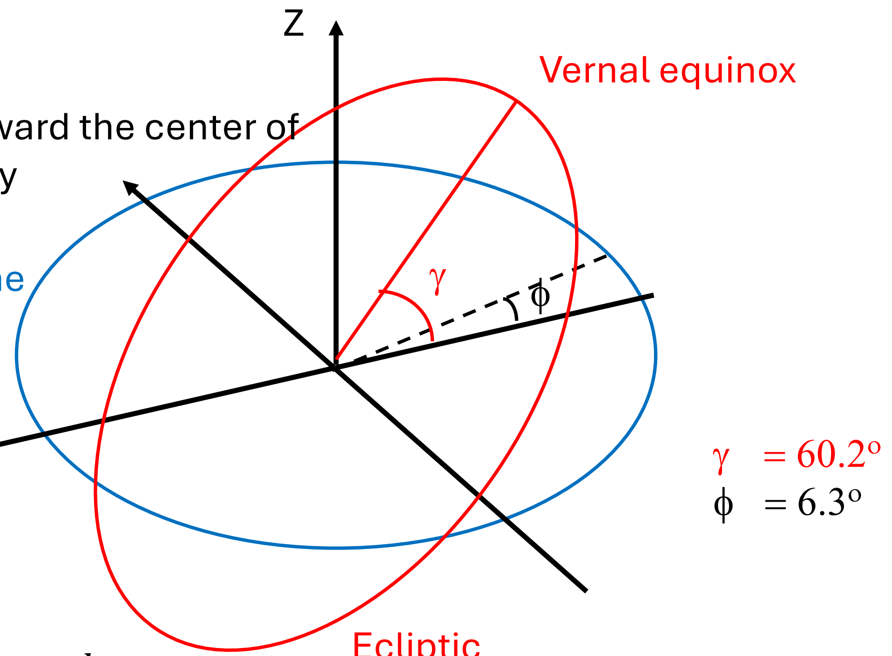
INFN LNGS

Dark World, IBS Science and Culture Center, Daejeon, South Korea, Oct 29th, 2025

DM annual modulation

Considering an isotropic DM halo, the **annual modulation** is due to the combination of the earth's motion about the sun and the sun's motion about the center of the galaxy



$$\vec{v}_{\chi H} = \vec{v}_{\chi L} + \vec{v}_{\odot} + \vec{v}_{\oplus}(t)$$

$$\vec{v}_{\odot} + \vec{v}_{\oplus}(t) = (227 \pm 20) + (14.43 \pm 0.08)\cos\frac{2\pi}{1yr}\left(t - (0.419 \pm 0.002)\right)\frac{km}{s}$$

earth's velocity in the galactic frame

Maximum of velocity expected between June 2nd and 3rd (~152.5 days)

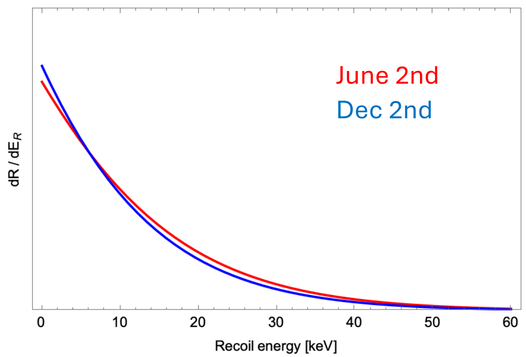
DM interaction rate and annual modulation: an example

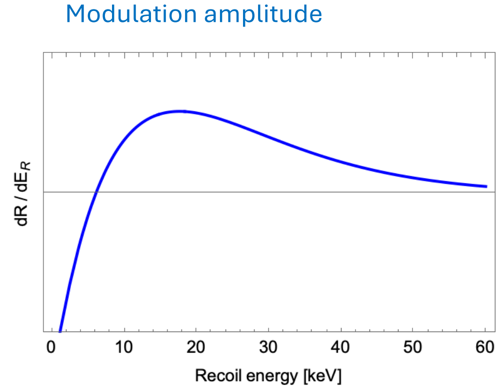
$$\frac{dR}{dE} = N_{target}\frac{\rho_\chi}{M_\chi}\int d^3v\, f(\vec{v})\, v\, \frac{d\sigma}{dE}(E, v)$$

$$\eta(t) = \frac{v_\oplus(t)}{v_0} \simeq 1.03 + 0.066\ \cos\omega(t - t_0)$$

$$\frac{dR}{dE}(\eta(t)) = \frac{dR}{dE}(\eta_0) + \frac{\partial}{\partial\eta}\left(\frac{dR}{dE}\right)_{\eta_0}\Delta\eta\ \cos\omega(t - t_0)$$

in a given energy bin: $S_k(t) = S_{0,k} + S_{m,k}\cos\omega(t - t_0)$





$S_{m,k}$ depends on particle physics parameters, astrophysical parameters, nuclear physics parameters, detector's parameters.

A second order modulation is present due to **diurnal earth's rotation**:
at LNGS latitude: $\mathbf{S_{m,\,day} \sim 0.015\, S_{m,\,year}}$

Searching for DM through annual modulation

- **Strength**:
  - ✓ a model independent approach is very powerful considering the huge parameter space allowed for DM
  - ✓ do not need «large» and «complex» experiments
  - ✓ expected single-hit events in a specific energy window
- **Weakness**:
  - ✓ $S_m/(S_0 + B) \sim \%$ so high radio-purity required
- **Opportunities**:
  - ✓ exploit North and South hemispheres
  - ✓ exploit multi-site detectors
  - ✓ NaI-based detectors offer an opportunity
- **Threats**:
  - ✓ development of low background detectors
  - ✓ need to be very careful with detector stability and monitoring

NaI-based detectors running/proposed to study DM modulation

Experiment	Location	Target	Mass [kg]	Status
DAMA/LIBRA	LNGS	NaI(Tl)	250	finished
ANAIS-112	LSC	NaI(Tl)	112.5	running
COSINE-100	Yemilab	NaI(Tl)	106/61.3	upgrading
COSINE-200	Yemilab	NaI(Tl)	~200	in preparation
SABRE North / South	LNGS + SUPL	NaI(Tl)	~50 each	in preparation
COSINUS	LNGS	NaI	~1	in preparation
PICOLON	Kamioka	NaI(Tl)	~50	in preparation

Features of expected DM interactions

In case annual modulation with expected features (period and phase) is observed, the **DM interpretation** of candidate events depends on:

- Astrophysical parameters
- Target material
- Interaction model
- Nuclear physics for NR
- Quenching factor for NR ($E_{er} = QF \times E_{nr}$)
  - ✓ for NaI-based detectors could depend on crystals properties (growth, radio-purity, etc)
- Channeling in case of crystals and NR
- …

Determine the DM annual modulation signature

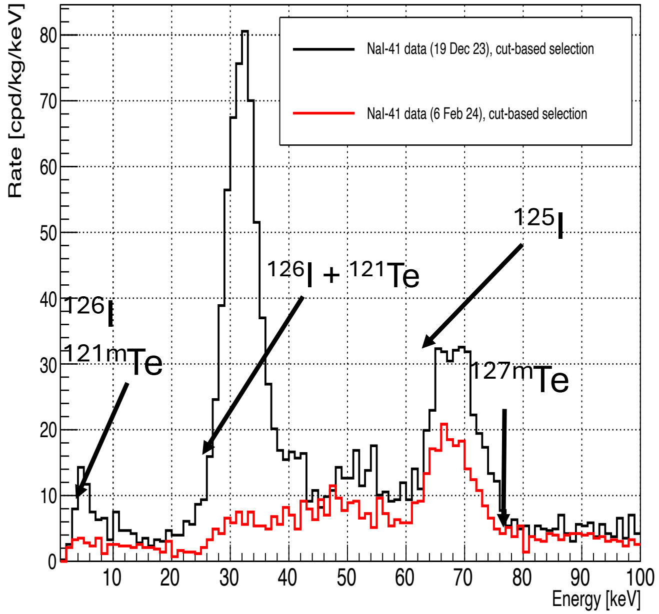
$R(t) = R_0(t) + A\cos\left(\frac{2\pi}{T}(t-\varphi)\right)$ and $R_0(t) \approx C + Be^{-t/\tau} \approx C' - B' \cdot t$

- **Residuals** ($B \approx 0$)
  - ✓ $\boldsymbol{R_i = \langle r_{ijk} - flat_{jk} \rangle_{jk}}$ with R_i the residual rate for single-hit events in the i-th time bin, r_{ijk} the rate in j-th detector, k-th energy bin. $flat_{jk}$ is the average rate of the un-modulated component over the annual period.
  - ✓ It can produce an artificial oscillation pattern (see *JHEP* 04 (2020) 137).
    - Clear evidence of B~0 should be provided. A slowly time-dependent rate becomes a source of an apparent modulation. With C+Bt apparent oscillation would peak at the beginning of June.
- **Analysis of frequency**
  - ✓ Unevenly samples time-series studied by Lomb-Scargle periodogram
- **Maximum Likelihood fit**
  - $L_k = \prod_{i,j} e^{-\mu_{ijk}} \frac{\mu_{ijk}{}^{N_{ijk}}}{N_{ijk}!}$ *with* $\mu_{ijk} = \left(b_{jk} + S_{0,k} + S_{m,k}\cos\left(\frac{2\pi}{T}(t_i - t_0)\right)\right) M_j \Delta t_i \Delta E \varepsilon_{jk}$ and t_0 =152.5 days, T = 1yr
  - Fit parameters: $b_{jk} + S_{0,k}$ and $S_{m,k}$
  - With time-dependent background: $\mu_{ijk} = [R_0(1 + f e^{-t_i/\tau}) + S_m \cos\left(\frac{2\pi}{T}(t_i - t_0)\right)] M_j \Delta t_i \Delta E\, \varepsilon_{jk}$

Cosmogenic backgrounds for NaI-based detectors

Isotope	$T_{1/2}$
^{129}I	1.57×10^7 yr
^{3}H	12.3 yr
^{22}Na	2.6 yr
^{109}Cd	1.3 yr
^{121m}Te	164 d
^{113}Sn	115 d
^{123m}Te	119 d
^{127m}Te	106 d
^{125}I	59 d
^{125m}Te	57 d
^{121}Te	19 d

- Cosmogenic activation in the ROI mainly comes from ^{3}H, ^{113}Sn, ^{109}Cd, ^{22}Na
- Used for low energy calibrations:
  - ✓ 0.87 keV (^{22}Na), 25.5 keV, 3.5 keV (^{109}Cd), 30.5 keV (^{121}Te), 67.8 keV (^{125}I)
- Minimum order of 1 yr underground cooling from cosmogenic activity required
- Underground growth desirable



Tritium

- It is a **relevant background source in the low energy ROI** [1,6] keV
  - ✓ pure beta emitter with Q_β = 18.591 keV and $T_{1/2}$ = 12.312 years
  - ✓ the fraction of the spectrum in the ROI corresponds to **~50 %**
  - ✓ its activity in the crystal depends on the exposure on surface

- Estimated production rate at sea level: **R_H =87±27 atoms/kg/day**
  - ✓ Astropart. Phys. 97, 96 (2018)

- R. Saldhana et al. PRD 107 (2023) 022006 found **R_H = 80±21 atoms/kg/day** through controlled irradiation of NaI crystals with a neutron beam

- If the exposure history is known:
  - ✓ $A_{Tritium}(t) = f \cdot R_H \cdot \left(1 - e^{-t_{exposure}/\tau}\right)$ with f a factor to account for the altitude at the production site

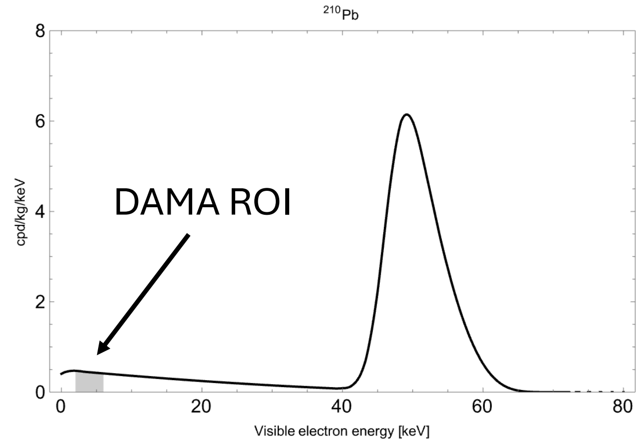
^{210}Pb

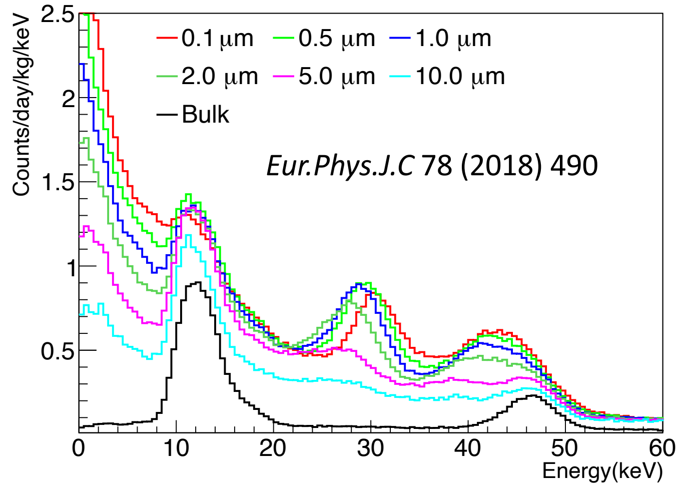
- It can be an important source of background from the crystal bulk
  - fraction of spectrum accounts for **~ 3%** in ROI

- It can **be implanted on the surface** from the ^{222}Rn decay chain

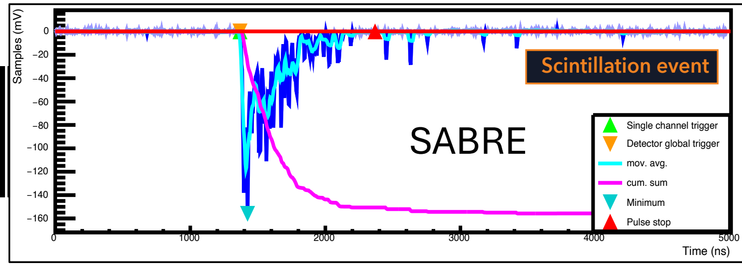
- It can be present in the reflector around the crystal

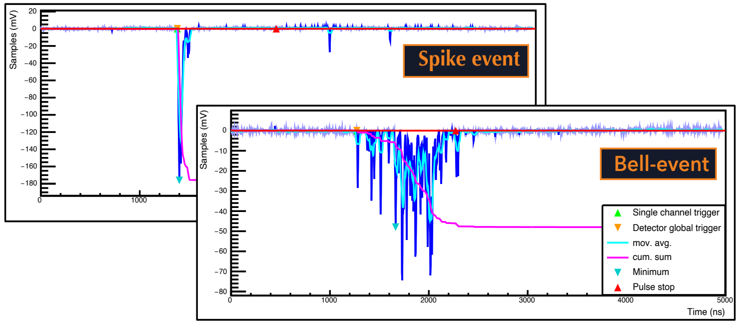
- The **contribution** to the background in the ROI **depends on the depth distribution** on the crystal surface or on the reflector
  - a dedicated study is reported in Astrop. Phys. 126 (2021) 102518
  - The energy spectrum depends on the depth profile ranging ~0.1-1.5 μm which can show features due to ^{210}Pb producing conversion e^- at 30.2 keV or Auger e^- at ~ 12 keV





Rejection of background & noise events



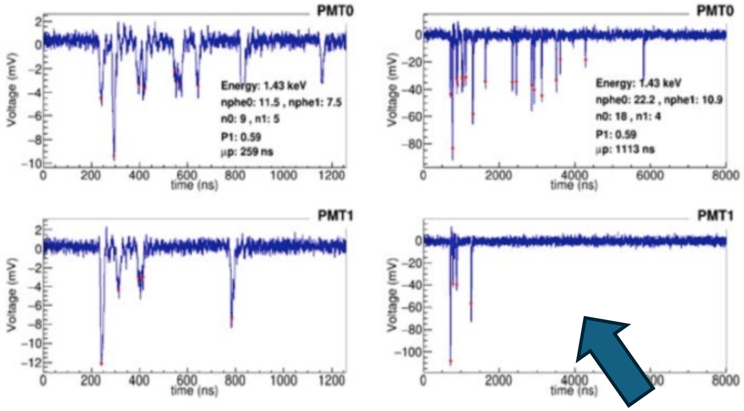


A **DM** signal corresponds to **single-hit events**: only one detector at a time affected by a DM event.
In NaI(Tl) below a few keV scintillation noise events are dominating the energy spectrum

- PMT-induced events that mimic scintillation signals + internal abnormal events

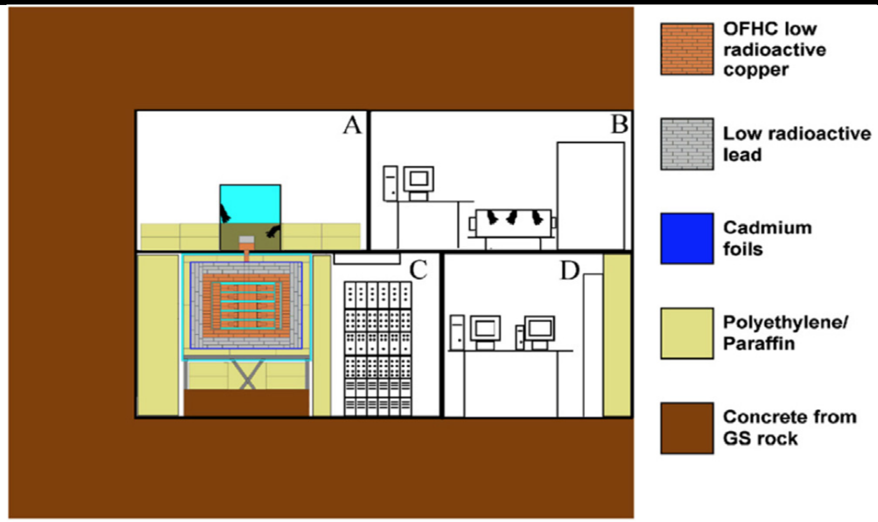
Required PSD tools in event selection procedure

- Scintillation events have a characteristic time of order 250 ns.
- Mean time is used to distinghuish β-like vs α-like events
- Asymmetry in the energy partition between PMTs
- BDT tools are exploited to remove low energy noise events
- A *likelihood score* method developed by COSINE-100 to compare PMT waveforms for signal and noise events using calibration data
  - ✓ coupled with BDT this method achieves **80% selection efficiency** in 1-1.5 keV energy bin



Example of anomalous scintillation event from ANAIS-112

DAMA/LIBRA Phase I and Phase II



- **DAMA/LIBRA Phase I**
  - ✓ From 2003 to 2010
  - ✓ 7 annual cycles and 1.04 ton x yr
  - ✓ Rate in ROI [2,6]keV ~ 1 dru

- **DAMA/LIBRA Phase II**
  - From 2011 – 2024
  - First release in 2018 with 7 annual cycles and 1.13 ton x yr
  - Replaced PMTs (higher QE, lower radioactivity and noise) and improved LY from ~6.8 to 8 ph.e/KeV and σ/E by ~10%
  - Rate in ROI [1,6]keV ~ 0.7 dru
  - In 2021 hardware upgrade to lower threshold at 0.75 keV

Accumulated ~ 3 ton x yr
20 yr underground

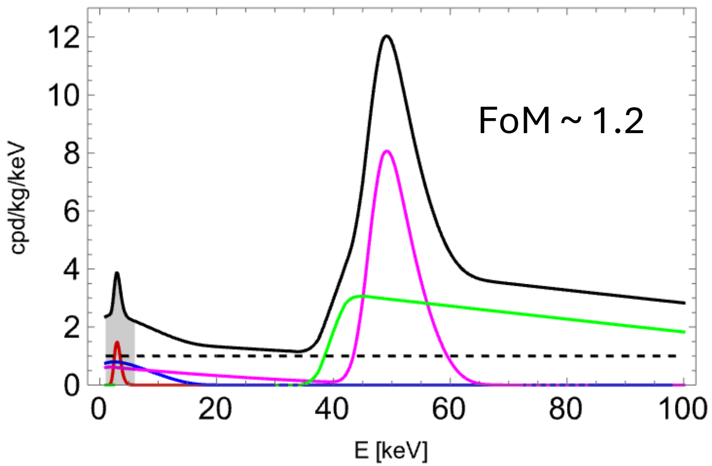
Expected spectrum and sensitivity in DAMA-like detectors

For an *ideal* detector main background contributions in ROI expected from: **^{210}Pb, ^{3}H, ^{40}K**, ^{87}Rb, ^{238}U, ^{232}Th

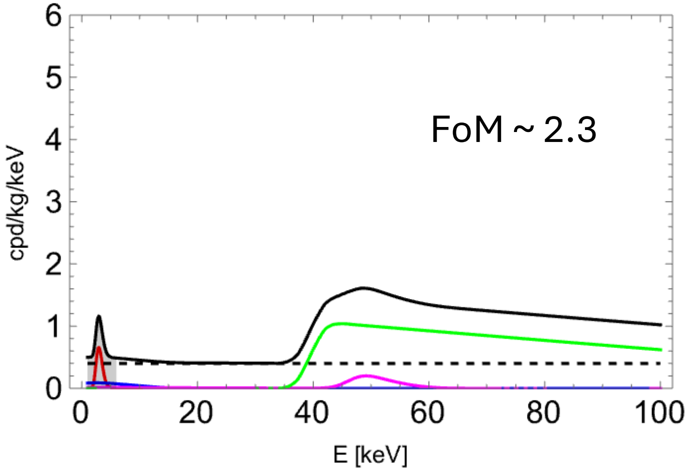
Different background contributions can produce similar overall statistical effect

$$\mathbf{FoM} = \frac{S_m}{\sqrt{2}}\sqrt{\frac{M\,t}{S_0+B}}$$

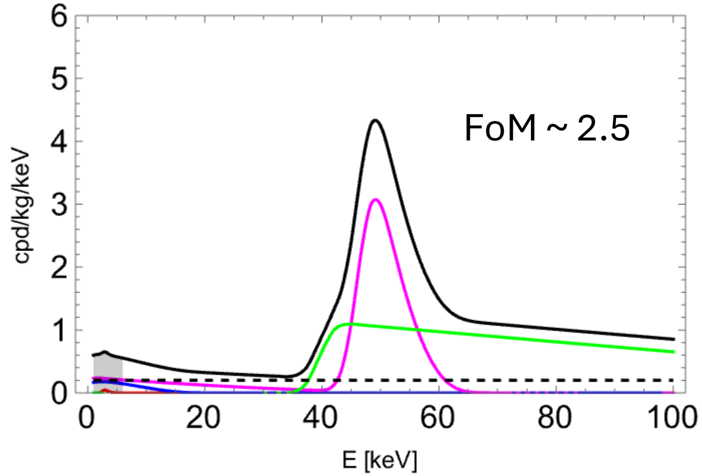
assume an exposure of 1000 kg x yr and S_m = 0.01 dru



^{210}Pb ~ 20% (1 mBq/kg)
K ~ 15% (32 ppb)
^{3}H ~ 28% (90 μBq/kg)



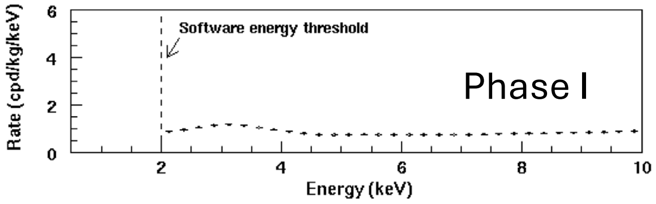
^{210}Pb ~ 4% (26 μBq /kg)
K ~ 26% (14 ppb)
^{3}H ~ 12% (10 μBq/kg)

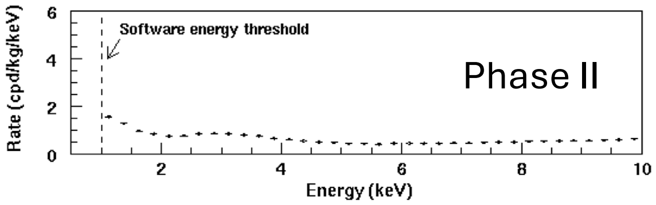


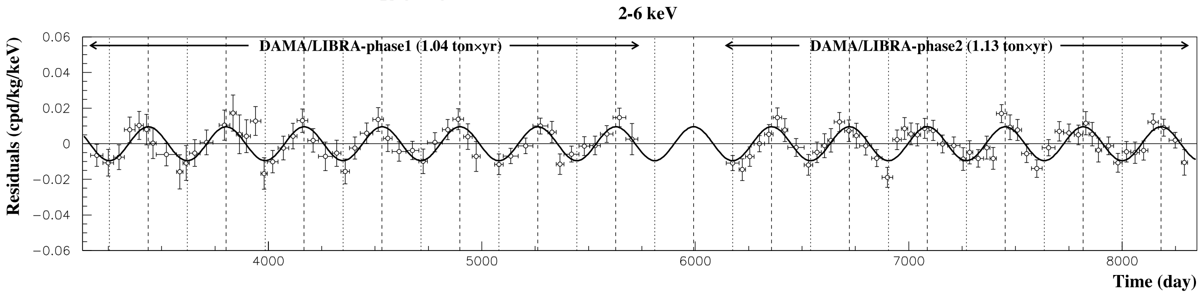
^{210}Pb ~ 37% (0.4 mBq/kg)
K ~ 2% (1 ppb)
^{3}H ~ 28% (20 μBq/kg)

DAMA/LIBRA Phase I and Phase II

Distribution of single-hit events



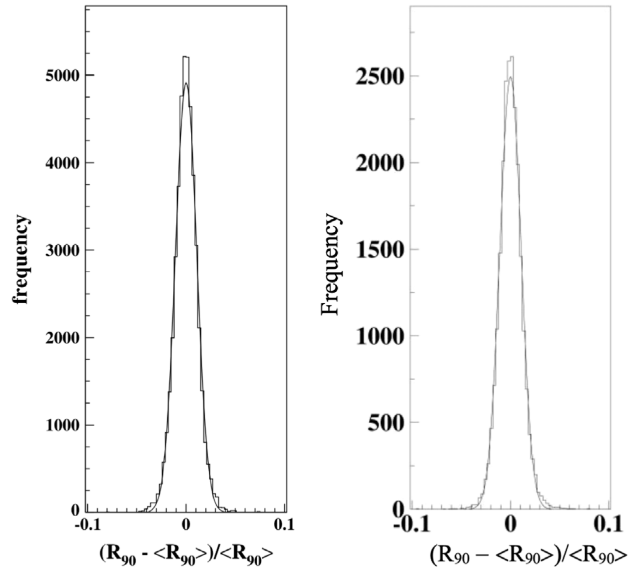




Nucl.Phys.Atom.Energy 22 (2021) 4, 329-342

Phase I + Phase II
n_σ ~ 15 with S_m~0.01 dru
and rate in ROI ~ 1 dru

Integral rate above 90 keV for phase I and phase II to exclude a modulation of the background in the high energy region



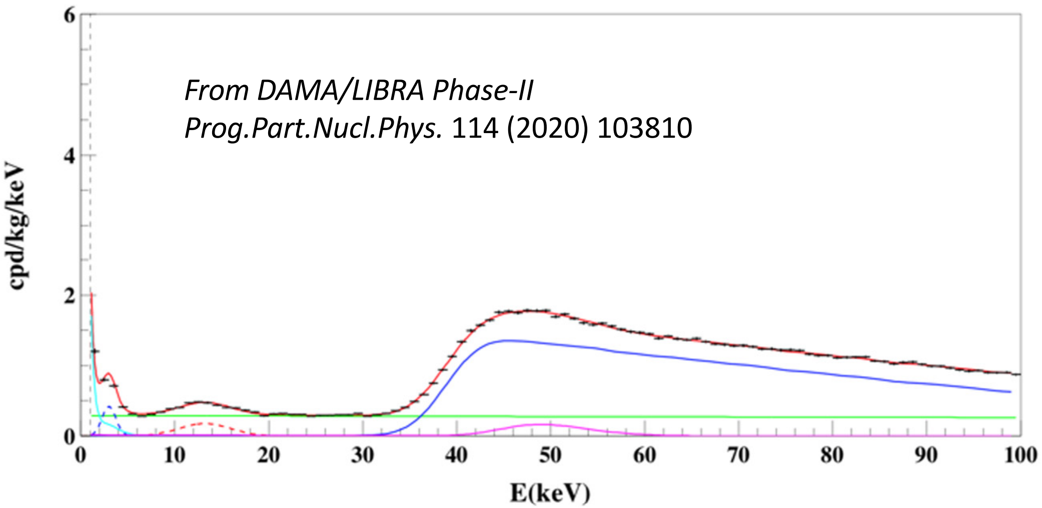
All statistics: **S_m = 0.00996 ± 0.00074 dru [2,6]keV** T and t_0 fixed
S_m = 0.01048 ± 0.00090 dru [1,6]keV T and t_0 fixed

DAMA/LIBRA analysis strategy

1. Data collected for each annual cycle starts before the expected DM signal minimum (~ December 2nd)
2. Data collected ends after the expected DM signal maximum (~ June 2nd)
3. A constant background from the average of the annual cycle is evaluated
4. Calibration and stability monitoring
   - Sources: ^{55}Fe(5.9 keV), ^{109}Cd(22 keV, 88 keV), ^{241}Am(59.5 keV), ^{210}Pb(46.5 keV)

- Any long-lived background is expected to decrease during the annual cycle producing an underestimation of the DM signal.
- No evidence of significant time dependence shown by DAMA/LIBRA
- Last three years of DAMA/LIBRA phase-2 analysed without interruption: no change wrt previous results
- Still to be published data with lower threshold w/o interruption

DAMA/LIBRA crystals radio-purity



Powder after purification:
^{238}U: 20 ppt
^{232}Th: 20 ppt
^{nat}K: < 0.1 ppm

TlI after purification:
^{238}U: 800 ppt
^{232}Th: 120 ppt
^{nat}K: < 0.06 ppm
0.1% used in crystals

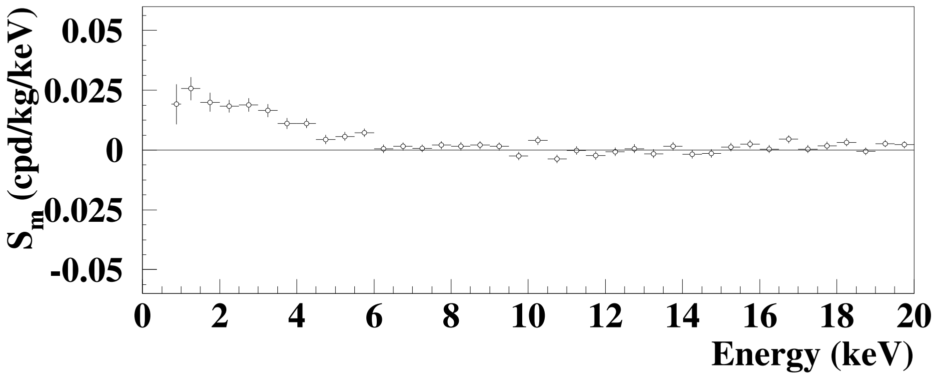
^{nat}K: 14.2 ppb (^{40}K: ~430 μBq/kg) ~ 20%
^{210}Pb: 26±3 μBq/kg ~ 13%
^{129}I: 947±20 μBq/kg
^{210}Pb from PTFE/Cu housing: 1.20 cpd/kg

^{3}H: < 90 μBq/kg (95% CL; measured during 1st year of Phase-I) < 15%
^{232}Th: 2-30 μBq/kg (0.5-7.5 ppt) from α decays (^{224}Ra, ^{220}Rn, ^{216}Po) and assuming secular equilibrium.
^{238}U: 8.6-124 μBq/kg (0.7-10 ppt) from α activity assuming secular equilibrium and ^{232}Th content.
$C_{U+Th}(ppt) = 0.093\, N_{\alpha}/M(kg)T(day)$
Observations show that ^{238}U chain is not in out of equilibrium.

Sharp increase below 3 keV can be used to set a limit on S_0

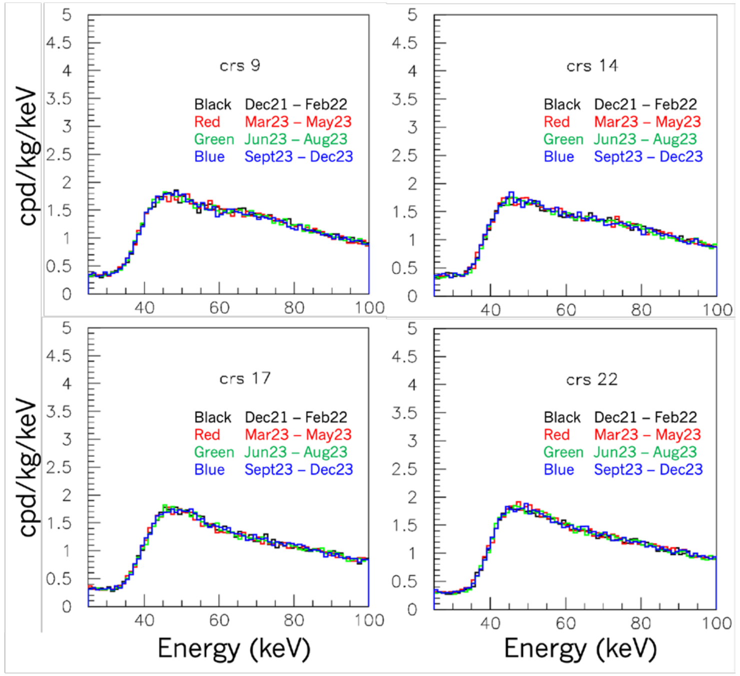
DAMA/LIBRA final data

S_m for full statistics of 2.86 ton x year.
Data below 2 keV from Phase 2 only



EPJ Web Conf. 319 (2025) 10001

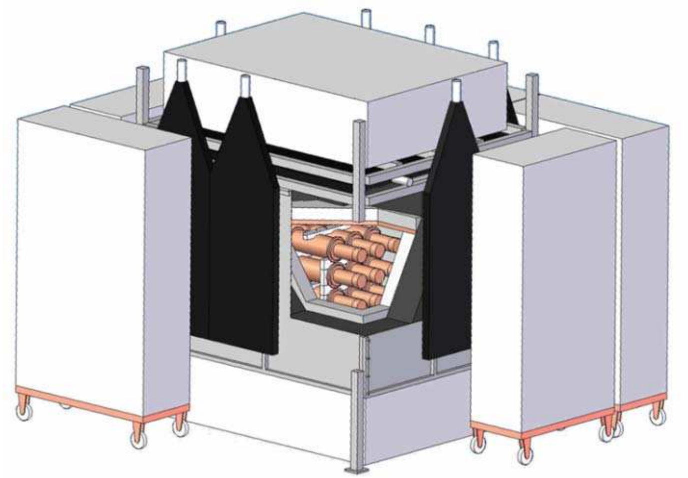
Stability of count rate and energy scale in 4 detectors with improved hardware in Phase 2



Rate in ROI [2,6] keV ~ 1 dru

ANAIS-112

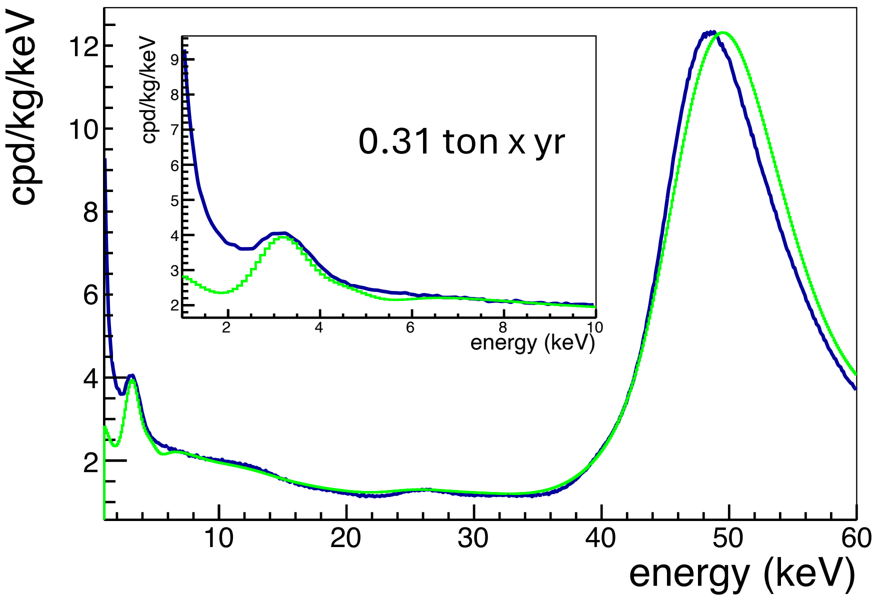
- In operation since Aug. 2017 at **LSC, Spain**. Expected to **end in 2025**
- **9 crystals** 12.5 kg each maufactured by Alpha Spectra Inc. (CO, USA) + **1 blank module**
- Passive shielding with archeologival Pb (10 cm), low-activity Pb (20 cm), and neutron moderator (40 cm)
- Rn box (0.6 Bq/m^3) and muon veto with plastic scintillator
  - ✓ Events with less than one second from a muon are rejected
- Crystals received between 2012-2017
  - ✓ A **significant improvement** has been observed in radio-purity between first and last crystal due to improvements suggested by the collaboration to the producer
  - ✓ **Different powder and protocols** used for the 9 detectors. ^{210}Pb reduction x4 from first to last detector.
- Periodic calibrations with ^{109}Cd (88, 22,11.6 keV) and ^{40}K(3.2 keV), ^{22}Na (0.9 keV)
- Average light yield ~ 14.5 phe/keV
- Effective total exposure: **0.625.75 ton x yr (6 years)**



Accumulated ~ 0.625 ton x yr 6 yr

ANAIS-112 crystals radio-purity

J. of Phys. 2156 (2022) 012175



Blank module in operation since 2nd year to help understading unexplained events below 2 keV
BDT algorithm enhance noise reduction

Background in ROI dominated by:

- ^{210}Pb: 32.5% ($T_{1/2}$ = 22.2 yr) on average 0.8 mBq/kg
- ^{3}H: 26.5% ($T_{1/2}$ = 12.3 yr)
- K: 12% on average 30 ppb
- ^{22}Na: 2% ($T_{1/2}$ = 2.6 yr)

^{210}Po build-up indicates that: a) ^{210}Pb contamination occurs at the end of growth; b) ^{210}Po and not ^{210}Pb is removed during growth

Rate in ROI [2,6] keV ~ 3.2 dru

ANAIS-112: analysis strategy

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

- χ^2 fit including time dependent background model from MC simulations, mainly ^{210}Pb($T_{1/2}$=22.3y), ^{3}H ($T_{1/2}$=12.3y), ^{22}Na ($T_{1/2}$=2.6y)
  - ✓ different background models show a variation on S_m of order 10^{-3} dru

$$\mu_{i,d} = \left[\boldsymbol{R_{0,d}} \left((1 - \boldsymbol{f_d}) \phi_{flat}(t_i) + \boldsymbol{f_d} \phi^{MC}_{bkg,d}(t_i) \right) + \boldsymbol{S_m} \cos\left(\frac{2\pi}{T}(t_i - t_0) \right) \right] M_d \Delta t_i \Delta E$$ **19 free parameters**

$\phi^{MC}_{bkg,d}$ pdf from MC model and ϕ_{flat} constant pdf that accounts the the noise not described by MC + S_0

S_m = 0 for null hypothesis

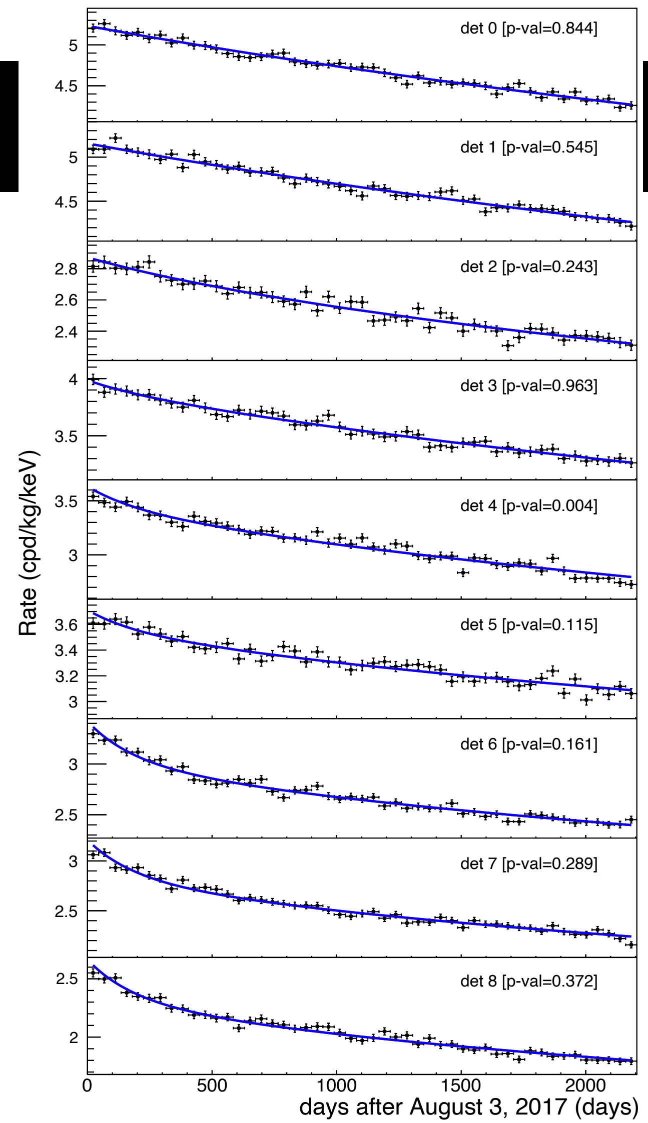
T and t_0 fixed

ANAIS-112: results

- Total exposure: 0.625 ton x yr

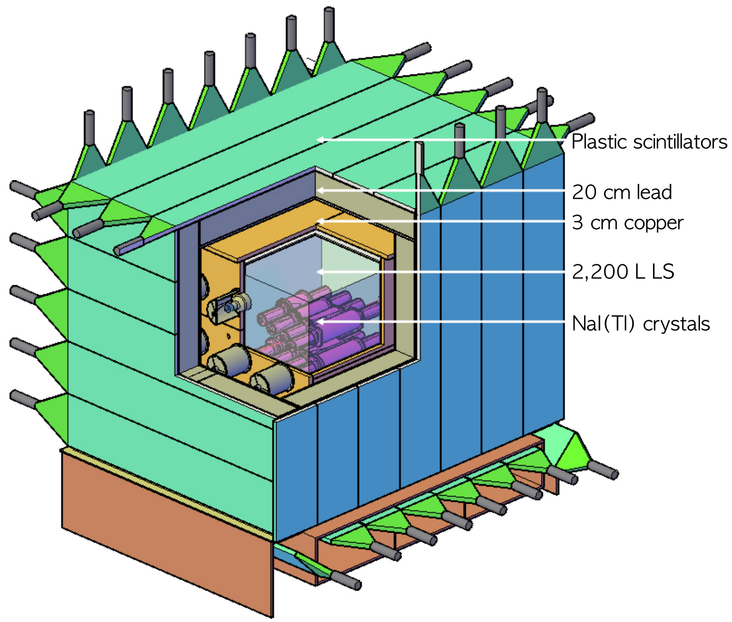
	ROI	p-value	S_m ANAIS [cpd/ton/keV]	S_m DAMA [cpd/ton/keV]	$\frac{S_m^{DAMA} - S_m^{ANAIS}}{\sqrt{\sigma_{DAMA}^2 + \sigma_{ANAIS}^2}}$
modulation hypothesis	1-6	0.156	-0.4±2.5	10.5±1.1	4.0
modulation hypothesis	2-6	0.596	1.1±2.5	10.2±1.2	3.4

Systematics: toy MC simulations of experiments equivalent to 6 years of ANAIS data w/ and w/o annual modulation as from DAMA/LIBRA confirm results



COSINE-100

- In operation **2016-2023** at Yangyang, South Korea
- **8 crystals** (4x2 array) with total mass of 106 kg maufactured by Alpha Spectra Inc. (CO, USA)
  - ✓ **different mass** from 8.3 to 18.3 kg
  - ✓ 4 **different powder grades** udes for growth
    - C1, C5, and C8 are excluded due to low LY and high noise
  - ✓ **total effective mass is 61.3 kg**
- **Active shielding** with 2,200 L of LAB LS in an acrylic box viewed by 8 5-inch PMTs
- Additional passive shielding with Cu (3 cm) and Pb (20 cm)
- Muon veto with plastic scintillators (3 cm)
  - ✓ events within 30 ms from a tagged muon are removed
- Set-up inside an environmentally controlled room and supplied with Rn-free air during installation
  - ✓ energy scale stability monitored through the 46.5 keV γ from internal ^{210}Pb decay and tested with 3.2 keV X-ray from ^{40}K
- BTD analysis to remove PMT noise
- Average light yield ~ 12.4 phe/keV (14.8 in selected sub-set)



Accumulated ~ 0.4 ton x yr
6.4 yr

COSINE-100 crystals radio-purity and annual modulation search

Phys.Rev.D 106 (2022) 5, 052005
With fixed phase: $\mathbf{S_m = 0.0067 \pm 0.0042}$

Rate in ROI [1,6] keV ~ 3 dru
With 2022 exposure (0.173 ton x yr) $n_\sigma \sim 2.3$
With 10 yr exposure $n_\sigma \sim 4$

COSINE has successfully developed

- detailed background model
- detailed background studies including surface ^{210}Pb
- exploited BDT for noise rejection

Time-dependent background model includes: ^{3}H, ^{22}Na, ^{109}Cd, ^{210}Pb in the bulk, ^{210}Pb on surface, ^{113}Sn, ^{121m}Te, ^{127m}Te, plus a constant term

Time-dependent background model in ROI:

^{210}Pb: 40.9% ($T_{1/2}$ = 22.2 yr) on average 0.8 mBq/kg
^{3}H: 51.5% ($T_{1/2}$ = 12.3 yr)
flat: 5% includes ^{40}K + ^{238}U + ^{232}Th +^{87}Rb
^{22}Na+^{109}Cd+^{113}Sn+^{127}Te+^{121m}Te+^{121}Te: 2.6%
8 exponentially decaying components with fixed initial activity

For each detector:

$$R^i(\,t|S_m\,,\alpha^i\,,\beta_k^i\,) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m\,cos(\omega(t-t_0))$$

$$L\left(\vec{x}\,|\,S_m\,,\vec{\alpha}\,,\vec{\beta}\right) = \prod_{i}^{N_{det}} \prod_{j}^{N_{bin}^i} \exp\left[-\frac{1}{2}\left(\frac{x_{ij}-\mu_{ij}}{\sigma_{ij}}\right)^2\right]$$

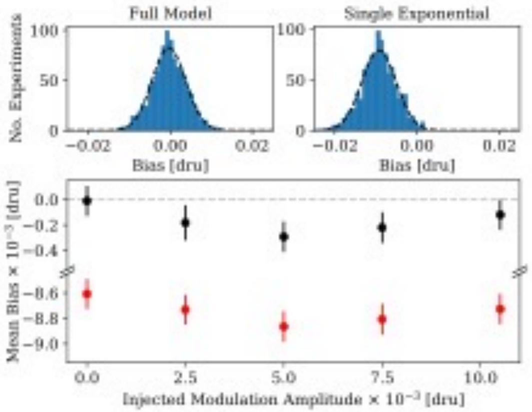
COSINE-100: results

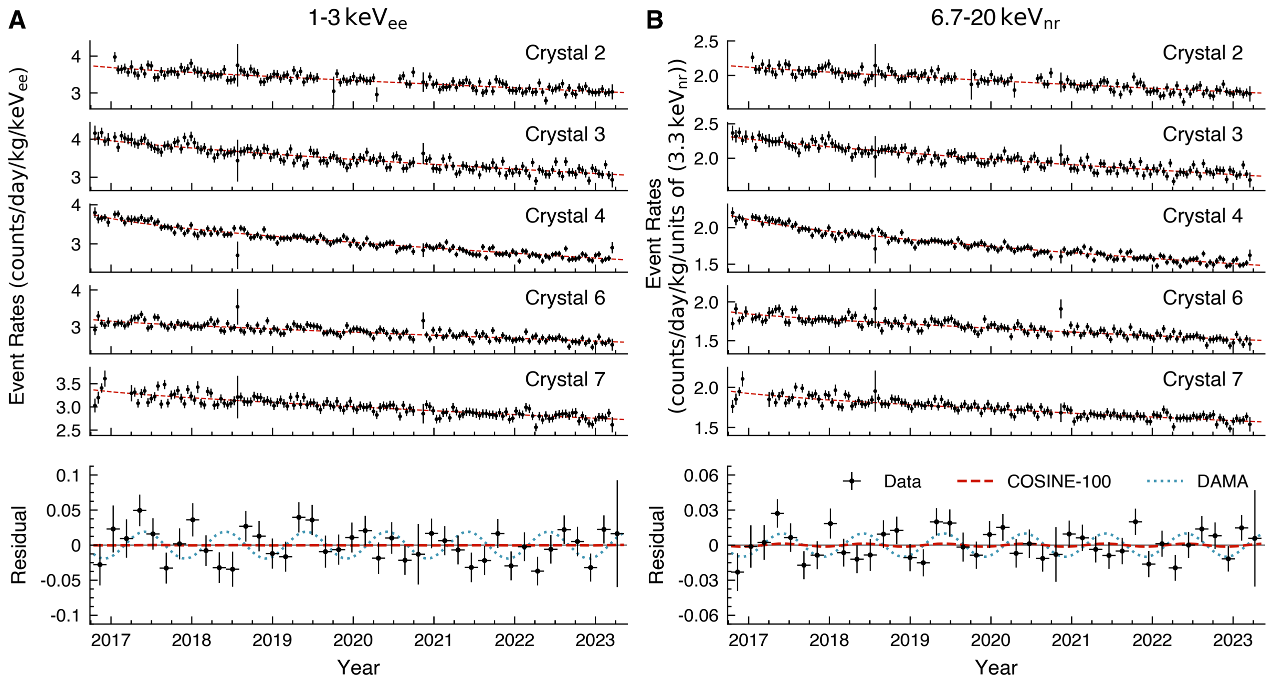
Exposure: 6.4 yr x 61.3 kg

Red dashed line: fixed-phase best-fit

Residuals: fitted background subtracted

Background model critical:
as show in *Phys.Rev.D* 106 (2022) 5, 052005
it can introduce a bias on S_m





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Rate in ROI [2,6] keV ~ 3 dru

COSINE-100: results

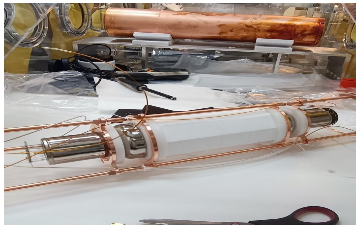
ROI [keV]	S_m COSINE-100 from ER fixed-phase [cpd/ton/yr]	S_m COSINE-100 from NR fixed-phase [cpd/ton/yr]	S_m DAMA/LIBRA [cpd/ton/yr]	$\frac{S_m^{DAMA} - S_m^{COSINE}}{\sqrt{\sigma_{DAMA}^2 + \sigma_{COSINE}^2}}$
1-3	0.4±5		-	-
1-6	1.7±2.9		10.5±1.1	2.8
2-6	5.3±3.1		10.2±1.2	1.5
6.7-20		1.3±2.7	10.2±1.2	3.0

SABRE

STRATEGY:

- **Development of ultra-high purity NaI(Tl) crystals (goal ~ 0.1 x DAMA/LIBRA)**
  - High purity NaI powder + zone refining
  - Clean crystal growth method (Bridgman)

- **Low energy threshold**
  - High QE PMTs directly coupled to the crystal



- **Passive shielding + active veto**

- **Two "almost" identical detectors in Northern (LNGS) and Southern hemispheres (SUPL)**
  - seasonal backgrounds have opposite phase in Northern and Southern hemispheres
  - dark matter signal has same phase

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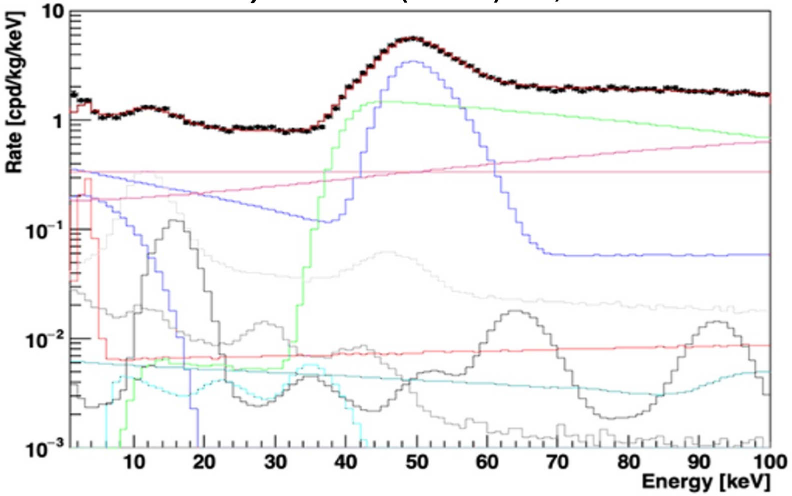
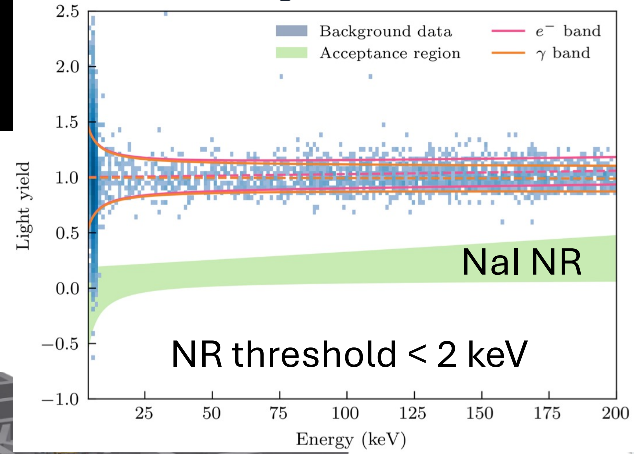


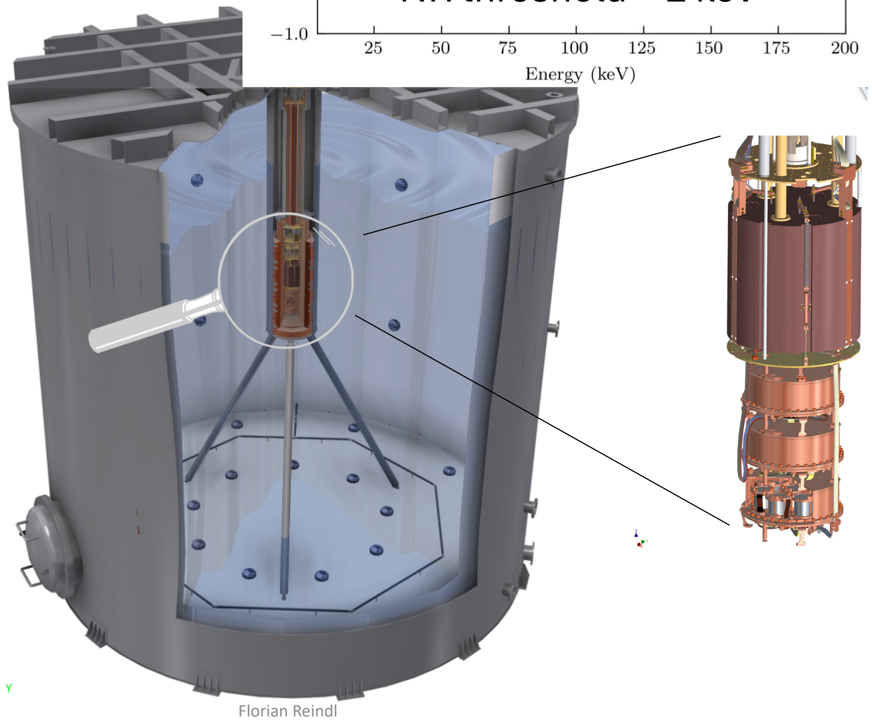
Rate in ROI [2,6] keV ~ 1 dru

COSINUS

- Exploit a novel technique for NaI-based detectors: NaI as cryogenic detector
  - ✓ particle identification on event-by-event basis
    - ○ ratio of light to phonon signal
  - ✓ energy measurement (heat channel)
    - ○ low threshold
  - ✓ **high discrimination for NR signals**
- NaI undoped crystals made by SICCAS
  - ✓ 30 g x8 (30-100 g x24) for Phase I (II)
  - ✓ K: 6-22 ppb
- External Water Tank as active muon veto
  - ✓ < 1 neutron background for 1000 kg x day
- Staged approach
  - ✓ 2025 start data taking: <u>only NR rate</u>
  - ✓ 2025-2026 Run1:100 kg x day
  - ✓ >2026 Run2: 1000 kg x day

Background data





Making a high radio-purity detector is crucial

Strategy:

- **Need better crystal radio-purity**
  - ✓ underground growth would be desirable

- Need high purity powder to get started: **powder purification**
  - ✓ COSINE and PICOLON have developed in-house purification methods
  - ✓ SABRE exploits in addition zone refining

- Need a crystal growth which is not introducing contaminations

- Need a «good» design to reduce external background

Make a high radio-purity detector: NaI powder

Strategy:

1. Powder purification adopted by COSINE/PICOLON to produce high purity powder
   - Recrystallization of NaI powder from water shown by COSINE to be very effective on Crystal grade commerical product
   - Decontamination factors: $^{39}K \sim 8$; $^{138}Ba \sim 12$; $^{208}Pb \sim 4$; $^{65}Cu \sim 12$ [J. Rad Nucl. Chem. (2018) 317:1329-1332]
   - COSINE purification facility [DOI 10.3389/fphys.2023.1142849]

	K [ppb]	Fe [ppb]	Sr [ppb]	Ba [ppb]	Pb [ppb]	Th [ppt]	U [ppt]
Raw	250	33	19	3	40	<6	<6
Purified	11	<10	0.3	0.9	0.5	<6	<6

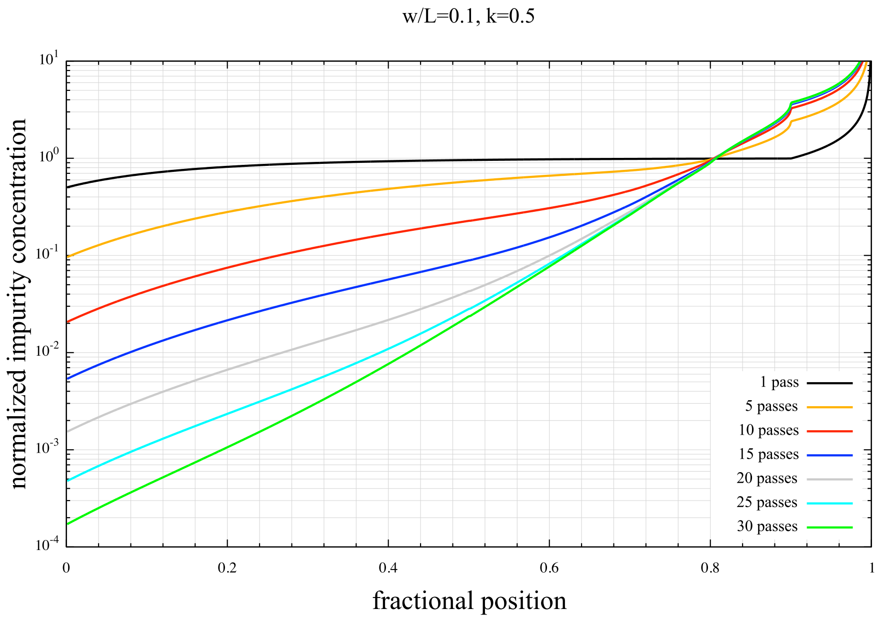
2. Use of Astro Grade powder and zone refining adopted by SABRE
   - Astro Grade purity similar to COSINE purified powder
   - Zone refining removes significantly different impurities components

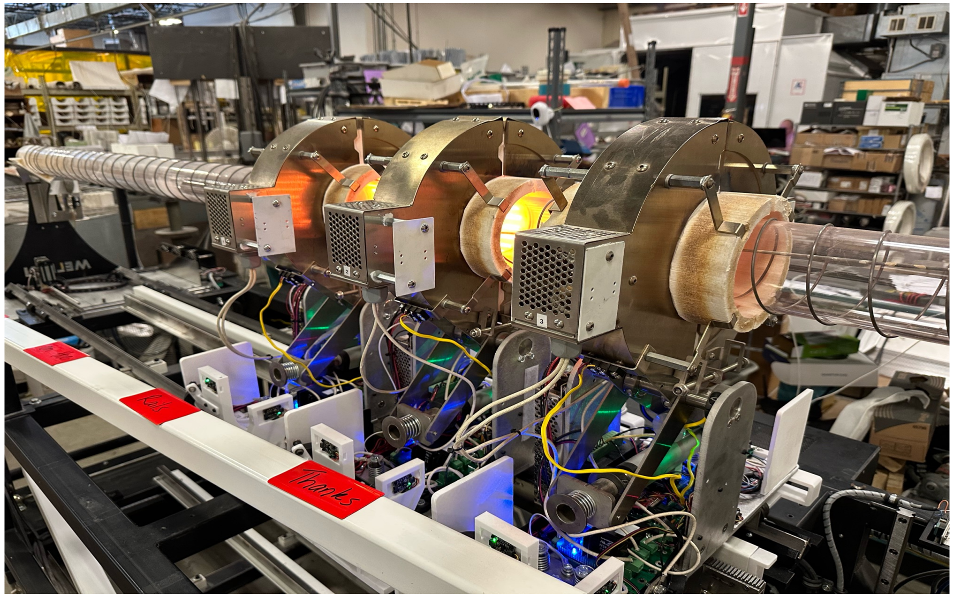
Make a high radio-purity detector: NaI powder

	DAMA/LIBRA Saint-Gobain (DAMA-NaI)	COSINE-100/ ANAIS-112 Alpha-Spectra	SABRE from Merck Astro Grade	COSINE-200 from Merck Optipure Purified (initial)
^{238}U	0.02 ppb (0.56±0.04)		<0.07 ppb	< 6 ppt
^{232}Th	0.02 ppb (0.21±0.01)		<0.08 ppb	< 6 ppt
^{nat}K	<0.1 ppm (<4.8)	16-50 ppb	~3-10 ppb	~6 ppb (~250 ppb)
^{85}Rb			< 0.4 ppb	
^{208}Pb			~1 ppb	~0.5 ppb (~20 ppb)

Zone refining purification of NaI powder in SABRE

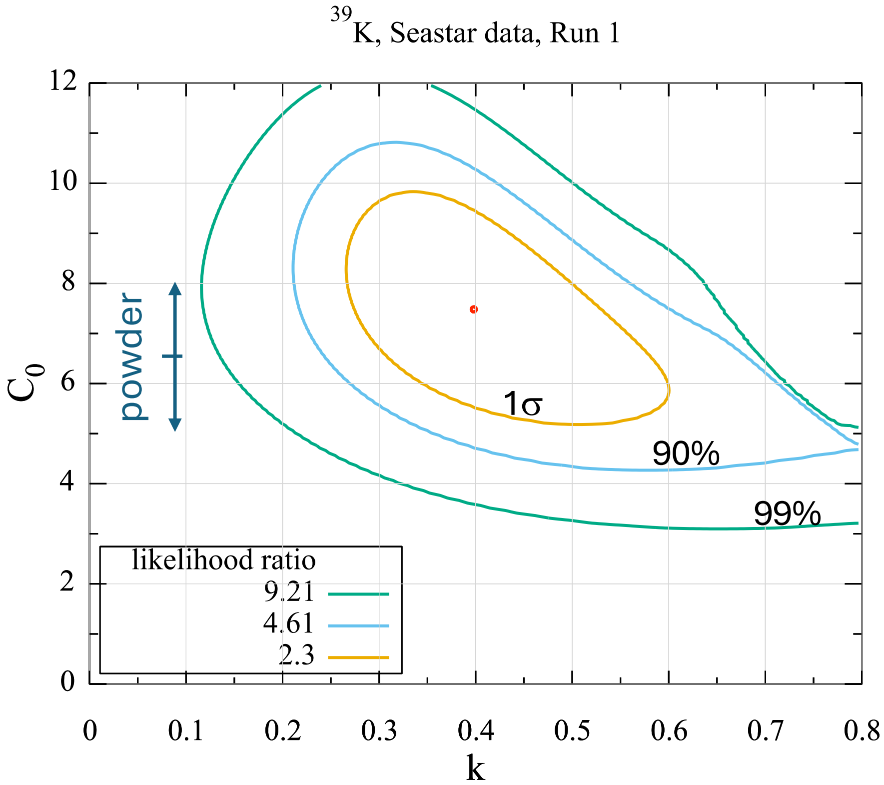
To achieve a lower background crystals will be grown from zone refined powder

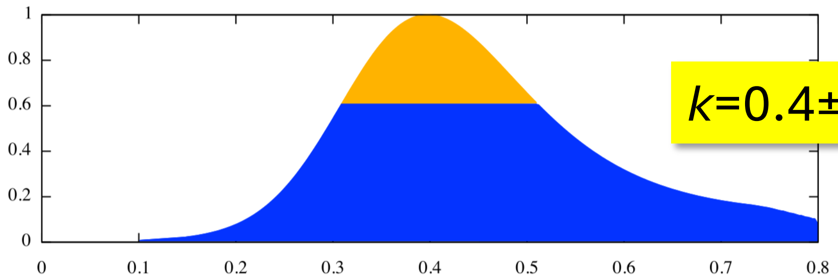


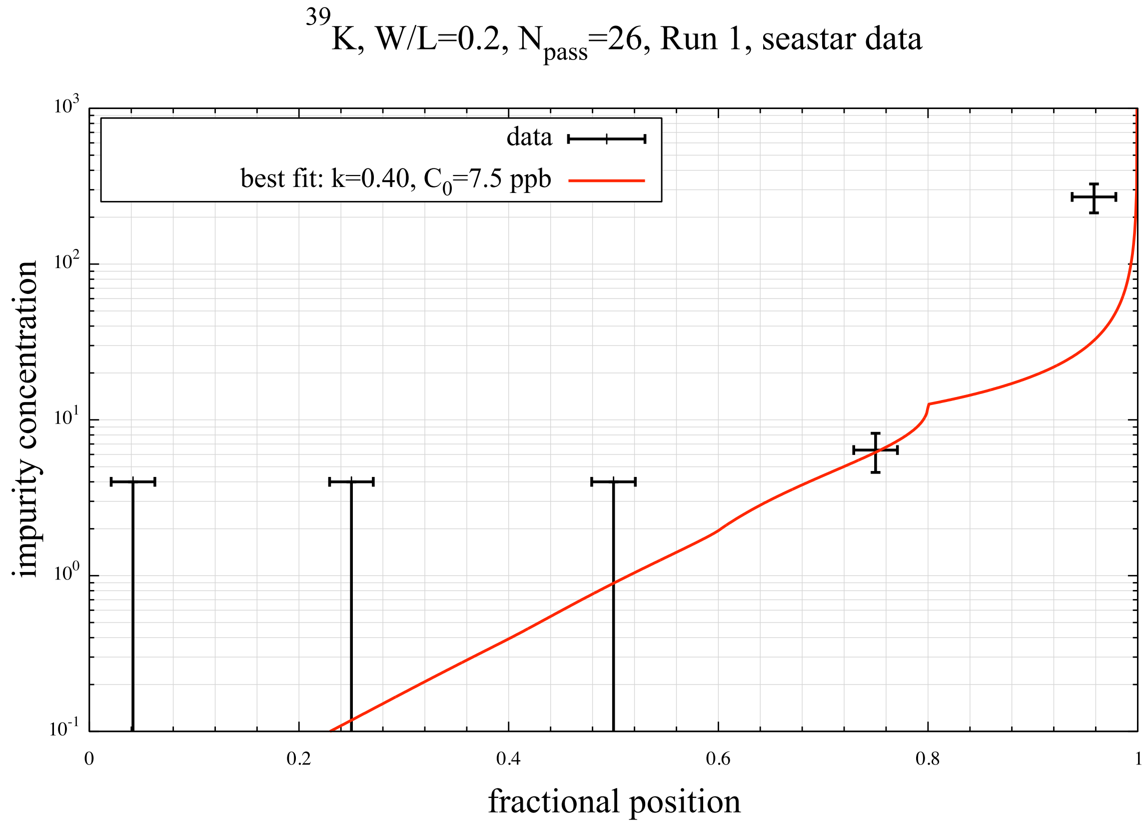


Measurements show strong segragation for screened elements such as K, Rb, Cs, Ba

Expected background in the ROI [1,6] keV of order 0.5 dru







k=0.4±0.1 @ 1σ

Method of analysis: likelihood ratio with gaussian uncertainty on measures and uniform probability for upper limit. A prior on powder measure on C_0 is included.

Zone refining of NaI distribution coefficients: results

		^{138}Ba	^{44}Ca	^{44}K	^{24}Mg	^{208}Pb	^{88}Sr
With prior on powder	k	0.34±0.15	1.36±0.05	0.4±0.1	0.89±0.07	1.16±0.03	-
	C_0 (ppb)	0.21	68.7	7.5	2.6	1.9	-
W/o prior on powder	k	-	1.36±0.05	-	0.82±0.07	1.16±0.03	1.42±0.03
	C_0 (ppb)	-	68.7	-	3.3	2.0	135
	C_0 Powder	0.18±0.04	<100	6.5±1.6	2.1±0.5	1.6±0.3	1.2**±0.3**

PICOLON

Intense effort to remove radioactive impurities from NaI powder by multiple recrystallization and cation exchange resin.

	Ingot#71 (2018)	Ingot#73 (2018)	Ingot#85 (2020)	Ingot#94 (2021)	Goal
Crystal size	3"ϕ×3"	3"ϕ×3"	3"ϕ×3"	3"ϕ×3"	5"ϕ×5"
^{40}K (μBq/kg)	<600 (< 20ppb)	<900 (<29.8ppb)	<600	<480 (<15.9ppb)	<600 (<20ppb)
^{232}Th (μBq/kg)	1.7±0.2	1.8±0.2	1.2±1.4	4.6±1.2 (~1ppt)	<4 (<1ppt)
^{238}U (μBq/kg)	9.7±0.8	9.4±0.8	13±4	7.9±4.4 (0.6ppt)	<10 (<1ppt)
^{210}Pb (μBq/kg)	1500	1300	<5.7	19±6	<30
Method	Recryst.×2	Recryst.× 3	Recryst.×2 Resin	Recryst.×2 Resin	-

K.Fushimi et al., PTEP 2021 043F01
arXiv:2112.10116 (TAUP2021 Proc.)
arXiv:2509.22021v1 (2025)

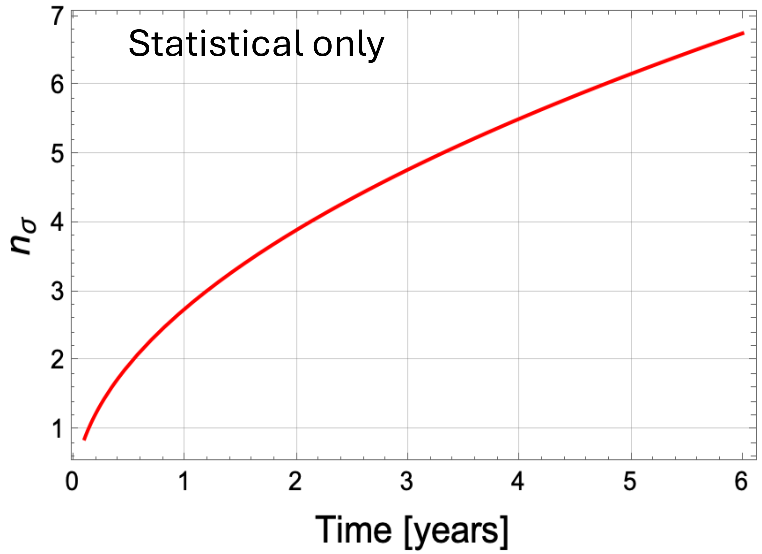
Make a high radio-purity detector: crystal radio-purity

	DAMA/LIBRA	COSINE-100	ANAIS-112	SABRE	COSINUS
^{238}U	0.3-2 ppt	< 0.12 ppt	0.2-0.8 ppt	0.2-0.6 ppt	< 1ppb
^{232}Th	0.5-7.5 ppt	0.4-2.4 ppt	0.1-1 ppt	0.3-0.4 ppt	< 1ppb
^{nat}K	$\lesssim$ 20 ppb	17-82 ppb	17-43 ppb	2-8 ppb	6-22 ppb
^{210}Pb	5-30 μBq/kg	0.7-3 mBq/kg	0.7-3.2 mBq/kg	0.5-0.8 mBq/kg	
^{210}Pb reflector	~ 5 μBq/cm^2 (spectral fit)	0.8-1.6 μBq/cm^2 (from ^{210}Po)	~ 3 mBq/detector for D3 and D4	~ 1 μBq/cm^2 (spectral fit)	
^{3}H	< 90 μBq/kg	100-250 μBq/kg	90-200 μBq/kg	24±2 μBq/kg	
^{87}Rb	< 0.3 mBq/kg	-	-	< 0.4 mBq/kg	
^{22}Na	< 15 μBq/kg	0.4-0.8 mBq/kg	0.5-2 mBq/kg	-	
Rate in ROI [1,6]keV	~ 0.7 dru	~ 3 dru	~ 3.5 dru	~ 1 dru	

Near future perspectives

	SABRE after ZR 5 kg expectation	COSINE-200 from NaI-37 0.71 kg *Front.in Phys.* 11 (2023) 1142765	COSINE-200 from NaI-35 0.61 kg *Front.in Phys.* 11 (2023) 1142765	PICOLON Prog. Theor. Exp. Phys. 2021, 043F01
^{238}U	< 0.1 ppt	1.0±0.6 ppt	0.9±0.3 ppt	< 2 ppt
^{232}Th	< 0.1 ppt	0.2±0.3 ppt	1.7±0.5 ppt	< 6 ppt
^{nat}K	< 1 ppb	8.3±4.6 ppb	< 42 ppb	< 20 ppb
^{210}Pb	~0.5 mBq/kg	0.38±0.10 mBq/kg	0.01 ±0.02 mBq/kg	< 6 µBq/kg
^{210}Pb reflector	~ 1 µBq/cm^2 (spectral fit)			
^{3}H	~ 4 µBq/kg	~ 4 µBq/kg		~ 4 µBq/kg
^{87}Rb	< 0.4 mBq/kg			
^{22}Na	-			
Rate in ROI [1,6] keV	**~ 0.5 dru**	**~ 0.5 dru**		**~ 0.5 dru**

Assuming:
- **50 kg** target mass
- modulation amplitude of **0.01 dru**
- rate in ROI dominated by internal radioactivity



DAMA/LIBRA facility at present

- All DAMA/LIBRA crystals kept under nitrogen purging in the original set-up at LNGS
- LNGS management is encouraging an international group to make use of the DAMA/LIBRA facility

Take away

- **DAMA/LIBRA**: stopped in 2024
  - ✓ Outstanding crystal development achieved, **still unmatched**
  - ✓ A **crucial anomaly** in DM direct detection standing still

- **ANAIS-112 and COSINE-100**
  - ✓ Achieved outstanding noise events rejection in the ROI
  - ✓ Time-dependent background MC simulations: more details on systematics
  - ✓ Strong **tests of DAMA/LIBRA**

- **Improve crystal radio-purity**
  - ✓ Crucial efforts ongoing within SABRE, COSINE, and PICOLON
  - ✓ SABRE North expected to deliver first crystal early next year

- **Possible re-use of DAMA/LIBRA crystals**

Thank you for your attention!

SABRE crystal radio-purity

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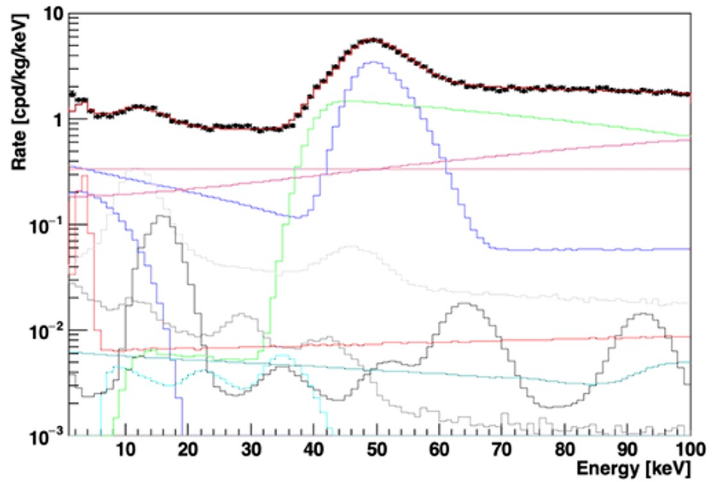
Source	Rate in ROI [1,6]keV in cpd/kg/keV	Fit results
^{40}K	0.125	0.16±0.01 mBq/kg
^{210}Pb bulk	0.333	0.49±0.05 mBq/kg
^{210}Pb reflector bulk	0.054	11±1 mBq/kg$_{PTFE}$
^{210}Pb reflector surface	0.023	<0.6 mBq/m^2
^{3}H	0.198	24±2 μBq/kg
^{129}I	0.0003	1.03±0.05 mBq/kg
^{238}U	0.006	5.9±0.6 μBq/kg
^{232}Th	0.0003	1.6±0.3 μBq/kg
PMT	0.003	1.9±0.4 mBq/PMT
External	0.185	0.89±0.05
Other β's	0.333	297±15
TOTAL	**1.26±0.27**	

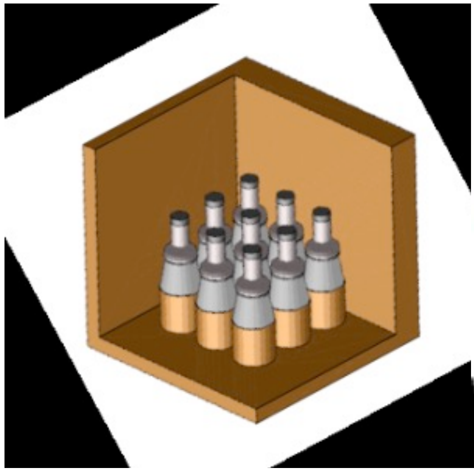
SABRE NaI-33 crystal



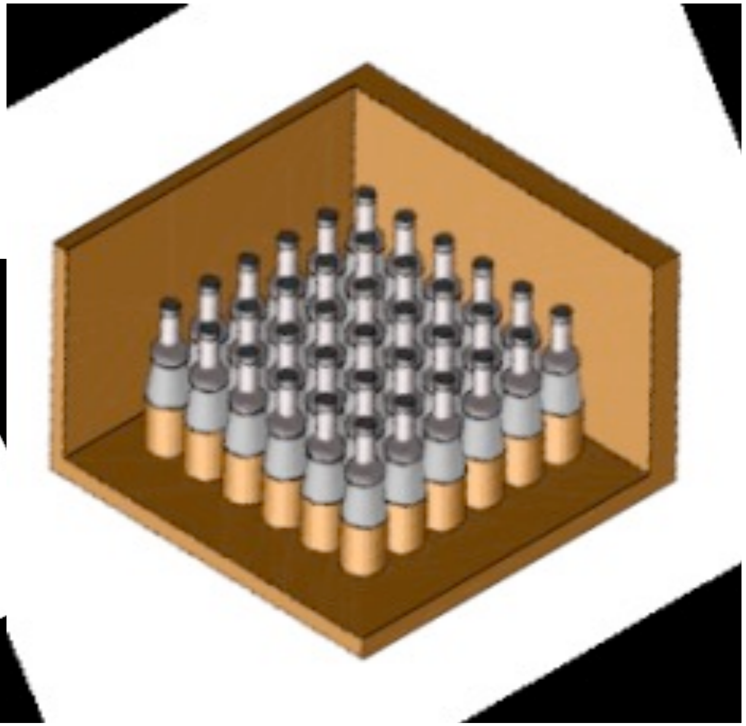
PICOLON long-term plan

PICOLON has a staged program

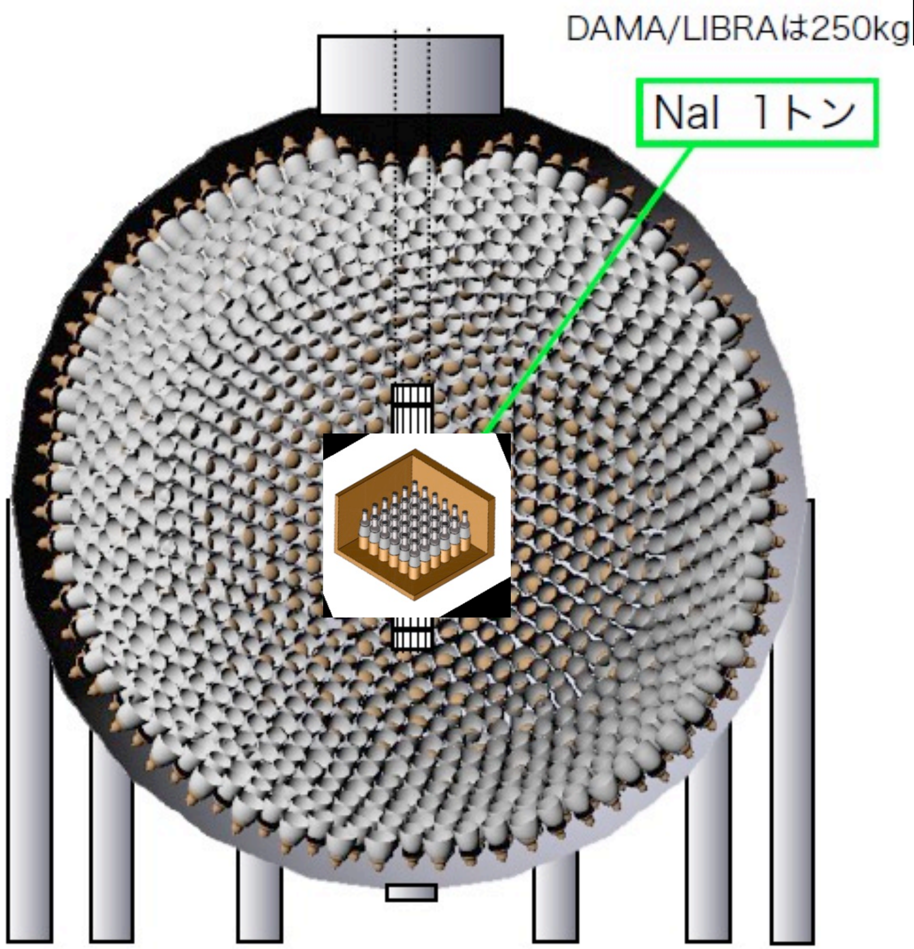
54 kg ~2025



250 kg ~2030



KamLAND-PICO: 1ton



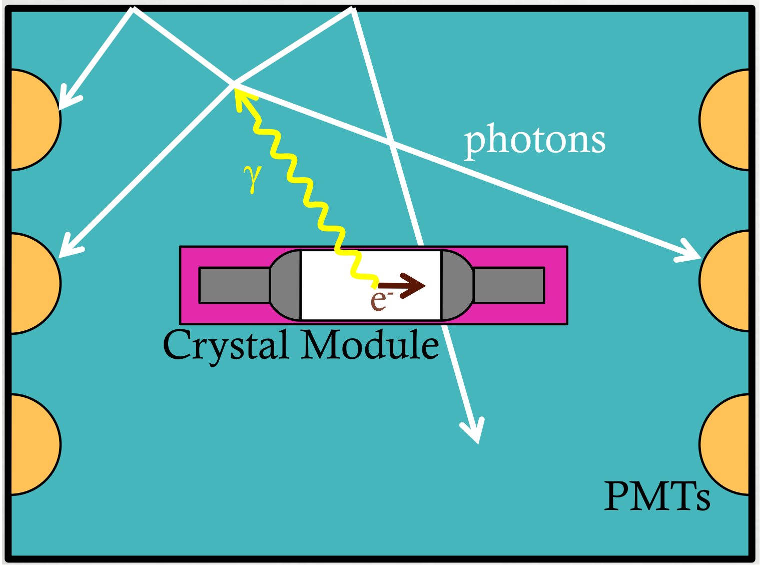
Exploiting an Active Veto

A **liquid scintillator based active veto** has been exploited by COSINE and SABRE to improve background rejection in the ROI. Internal low-energy single-hit events accompanied by a high-energy emission can be efficiently suppressed.

Frank Calaprice proposed the use of an active veto in 2009 in the framework of SABRE (Sodium iodide with Active Background Rejection Experiment)

With an active veto:

- single-hit events are events with only one crystal triggered with no measurable energy in the LS
- multi-hit events are events with more than one crystal triggered or with at least one crystal and a measurable energy deposition in the LS.



- **COSINE-100** makes use of 2,200 L of LAB +% of PPO + trace of bis-MSB
  - ✓ PPO is purified by water extraction
  - ✓ 20 keV LS threshold with 200 ns coincidence is required between LS and crystal signals
  - ✓ Veto efficiency requiring sing-hit events without LS signal is ~ 80%
- **SABRE PoP** makes use of 1,970 L of PC (distilled from Borexino) + 2.86 g/L of PPO
  - ✓ PPO is purified by water extraction
  - ✓ ~84%
  - ✓ Proved feasibility to observeK at the level of ppb contamination in crystals

QF measurement in ANAIS-112

In case annual modulation with expected features (period and phase) is observed DM interpretation of candidate events depends on:

- Two methods:
  - ✓ with a monochromatic neutron source at TUNL
    - smaller QF than in DAMA/LIBRA (0.2 and 0.06 for Na and I)
  - ✓ with a ^{252}Cf source at LSC
    - ✓ MC dependet
    - ✓ compatible with lower QF than in DAMA/LIBRA
    - ✓ more compoatible with QF energy dependent

DAMA/LIBRA [2,6]keV --> ANAIS-112 [1.3,4]keV