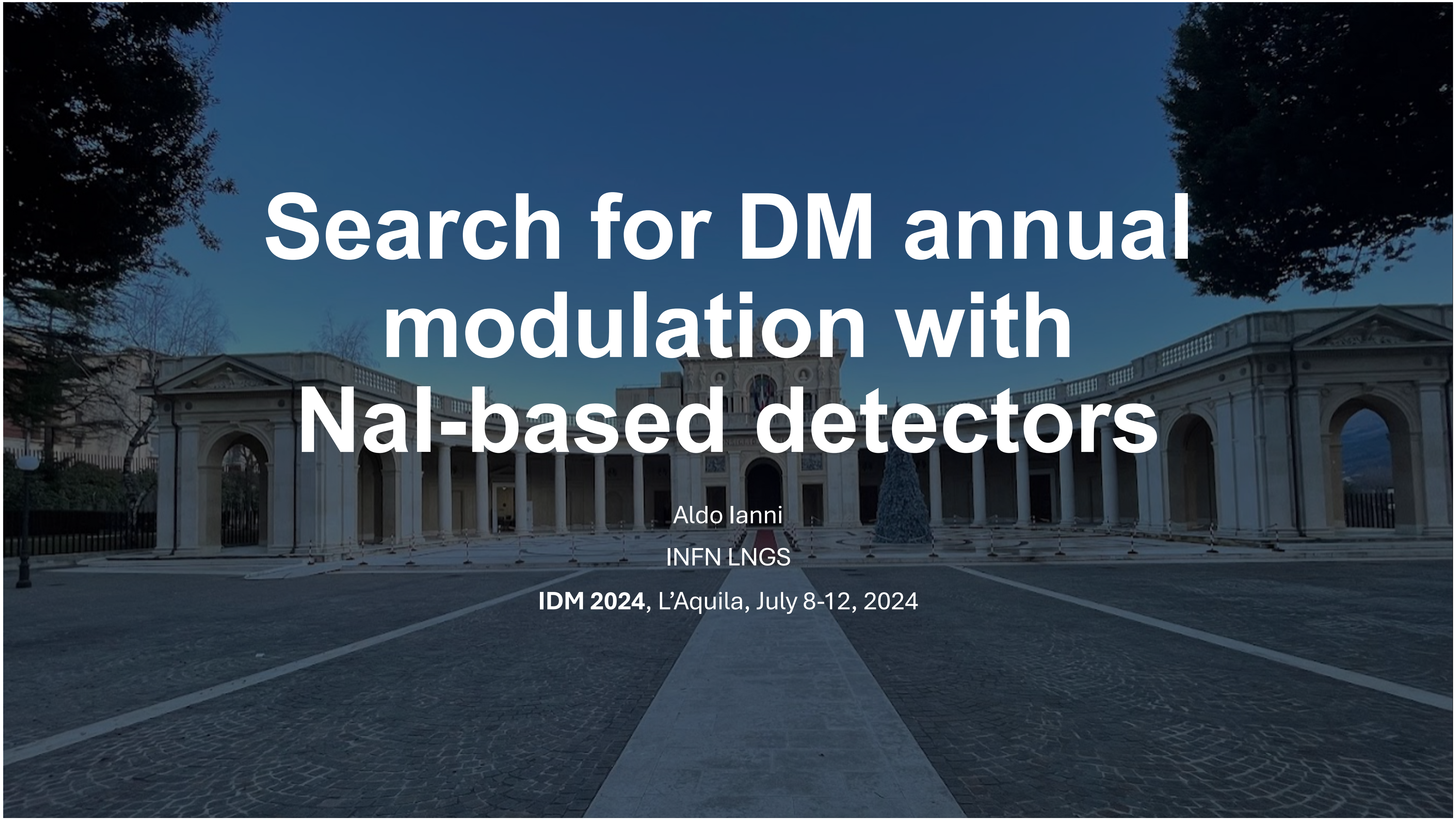


Search for DM annual modulation with NaI-based detectors

Aldo Ianni

INFN LNGS

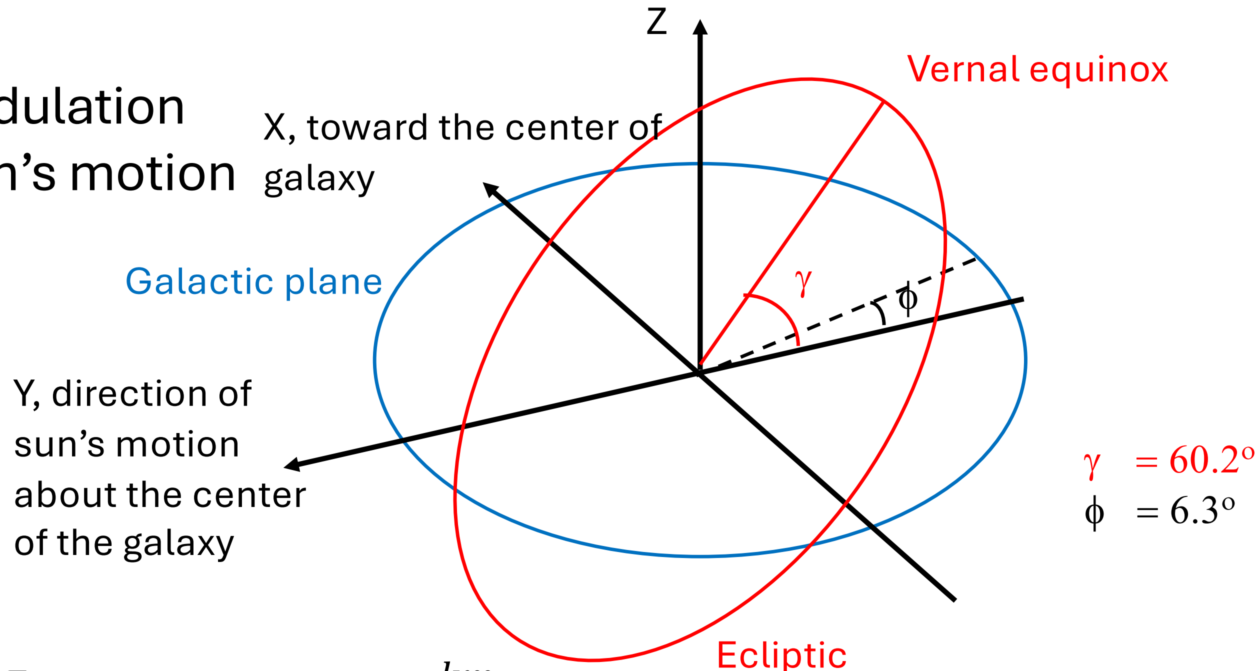
IDM 2024, L'Aquila, July 8-12, 2024

Contributions at this meeting on NaI-based detectors

1. R. Cerulli, Annual modulation results from DAMA/LIBRA
2. D. D'Angelo, Status and prospects of the SABRE North experiment and NaI(Tl) crystal radiopurity
3. I. Coarasa, ANAIS-112: the most sensitive experiment to test the DAMA/LIBRA signal in a model independent way
4. S. Lee, Dark Matter Annual Modulation Search in COSINE-100 Full Dataset and Beyond
5. S. Hollick, A combined search for dark matter with COSINE-100 and ANAIS-112
6. F. Reindl, The COSINUS dark matter search experiment
7. E. Barberio, The SABRE South Experiment at the Stawell Underground Physics Laboratory
8. S. H. Lee, Measurements of low energy nuclear recoil quenching factors for NaI(Tl) scintillating crystal
9. J. Apilluelo Allué, Dark matter search opportunities with NaI scintillating crystals using SiPMs at cryogenic temperatures
10. V. Toso, ASTAROTH, an innovative detector for dark matter direct detection experiments

DM annual modulation

Considering (at least locally)
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)

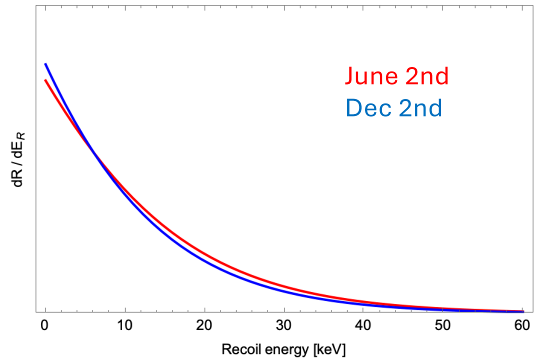
DM interaction rate and annual modulation: an example

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

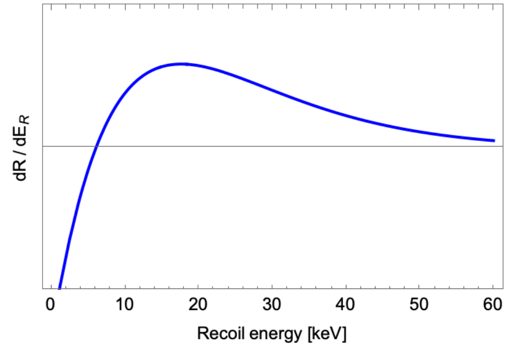
$$\eta(t) = \frac{v_\oplus(t)}{v_0} \backsimeq 1.03 + 0.066\ \cos\omega(t-t_0)$$

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

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



Modulation amplitude



$\mathbf{S_{m,k}}$ 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: $\mathbf{S_{m,\,day} \sim 0.015\ S_{m,\,year}}$

DAMA/NaI 1998 – 2003: the first hint of AM

Nine 9.7 kg crystals
Early study of Sm with the likelihood method

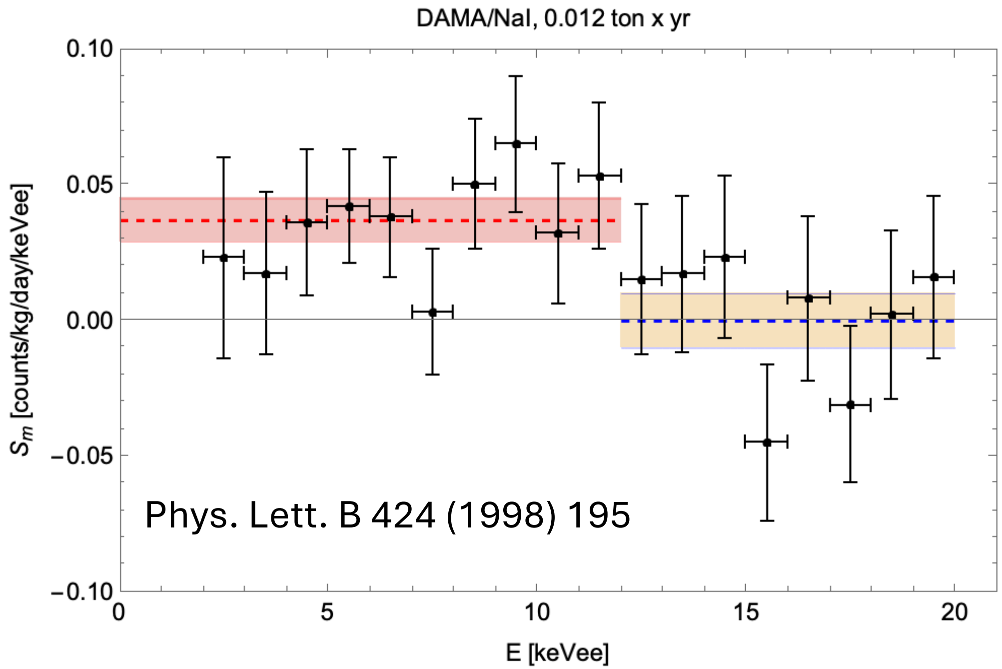
$$L = \prod_{i,j,k} e^{-\mu_{ijk}} \frac{{\mu_{ijk}}^{N_{ijk}}}{N_{ijk}!}$$

$\mu_{ijk} = (b_{jk} + S_{0,k} + S_{m,k} \cos\omega(t-t_0)) M_j \Delta t_i \Delta E \varepsilon_{jk}$

j = detector; k = energy bin; i = time

Fit parameters: $b_{jk} + S_{0,k}$ and $S_{m,k}$
fixed t_0 and ω

Need to improve statistics and radio-purity



$<S_m>_{[2,12]} = 0.0368 \pm 0.008$ dru
$<S_m>_{[12,20]} = 0.0004 \pm 0.0104$ dru

$S_m = 0.0192 \pm 0.0031$ dru in ROI [2,6] keV
with 0.29 ton x yr exposure in 2003 (6.2σ)

NaI-based detectors running/proposed to study DM

The choice of using NaI(Tl) is motivated from:

- **well-known technology**
- possibility to grow large (~10 kg) crystals with high radio-purity
- compact and segmented detector with high duty cycle
- high light output and good α/β pulse shape discrimination
- posssibility to carry on routine calibration in the keV range
- scalability
- no environmental problem in an underground laboratory
- sensitivity to different DM scenarios and interactions

Disadvantage: hygroscopic crystals

Experiment	Location	Target	Mass [kg]	Status
DAMA/LIBRA	LNGS	NaI(Tl)	250	running
ANAIS-112	LSC	NaI(Tl)	112.5	running
COSINE-100	Y2L	NaI(Tl)	106/61.3	upgrading
COSINE-200	Yemilab	NaI(Tl)	~200	in preparation
SABRE North / South	LNGS + SUPL	NaI(Tl)	~50	in preparation
COSINUS	LNGS	NaI	~1	in preparation
PICOLON	Kamioka	NaI(Tl)	~50	in preparation

So far DM-Ice, NaIAD, **DAMA/LIBRA, ANAIS-112, and COSINE-100** have been attempting to search for DM with an array of NaI(Tl) detectors.

New programs are under development: **COSINE-100+, COSINE-200**, **SABRE, COSINUS, and PICOLON**. R&D: **ANAIS+, ASTAROTH**

Determine the DM annual modulation signature

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

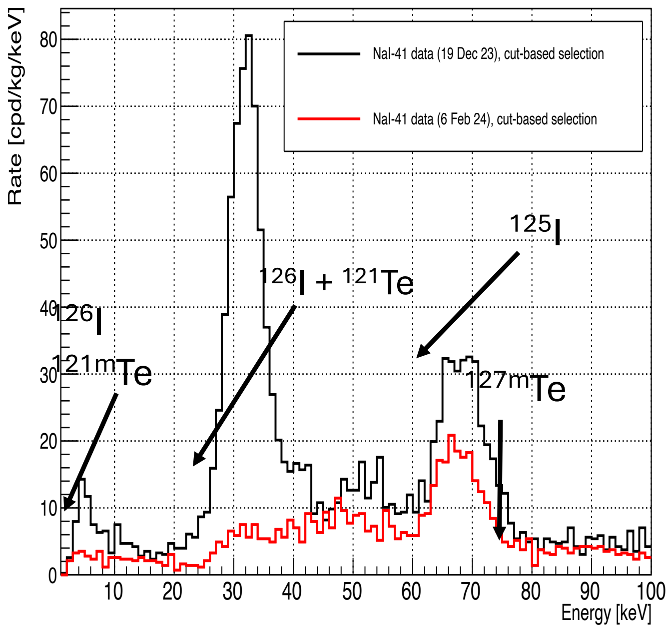
- **Residuals** ($B \approx 0$)
  - ✓ With many annual cycles and large exposure (the case of DAMA/LIBRA)
  - ✓ $\boldsymbol{R_i = \langle r_{ijk} - flat_{jk} \rangle_{jk}}$ with R_i the residual rate for single-hit events in the i-th time bin, r_{ijk} the rate in j-th detector, k-th energy bin. $flat_{jk}$ is the average rate of the un-modulated component over the annual period.
  - ✓ In DAMA: annual cycle starts in Autumn and ends in Summer (DM signal goes from min to max). It reduces effect of long-living radioisotopes.
  - ✓ It can produce an artificial oscillation pattern (see *JHEP* 04 (2020) 137). Clear evidence of B=0 should be provided.
- **Analysis of frequency**
  - ✓ Unevenly samples time-series studied by Lomb-Scargle periodogram
- **Maximum Likelihood fit**
  - $L_k = \prod_{i,j} e^{-\mu_{ijk}} \frac{\mu_{ijk}{}^{N_{ijk}}}{N_{ijk}!}$ $\quad with\ \mu_{ijk} = \left(b_{jk} + S_{0,k} + S_{m,k}\cos\left(\frac{2\pi}{T}(t_i - t_0)\right)\right) M_j \Delta t_i \Delta E \varepsilon_{jk}$ and t_0 =152.5 days, T = 1yr
  - Fit parameters: $b_{jk} + S_{0,k}$ and $S_{m,k}$
  - With time-dependent background: $\mu_{ijk} = [R_0(1 + fe^{-t_i/\tau}) + S_m\cos\left(\frac{2\pi}{T}(t_i - t_0)\right)]M_j \Delta t_i \Delta E\, \varepsilon_{jk}$

Cosmogenic backgrounds

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?



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

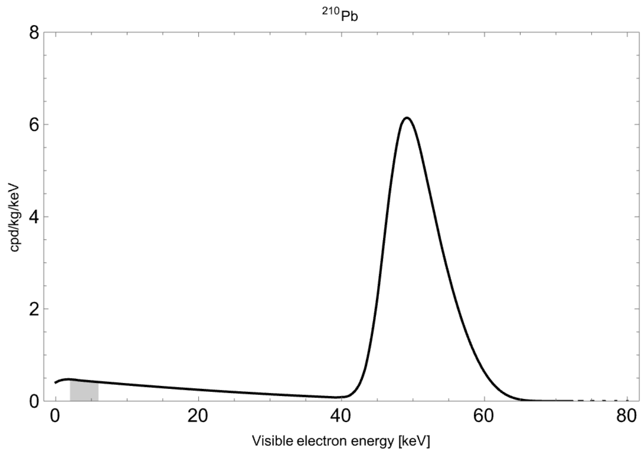
- ANAIS has estimated the production rate at sea level to be **R_H =87±27 atoms/kg/day**
  - ✓ Astropart. Phys. 97, 96 (2018)

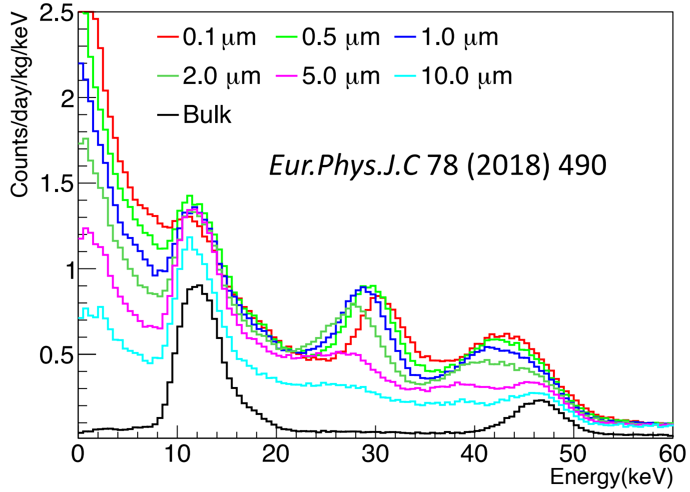
- R. Saldhana et al. PRD 107 (2023) 022006 found **R_H = 80±21 atoms/kg/day** through controlled irradiation of NaI crystals with a neutron beam

- 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

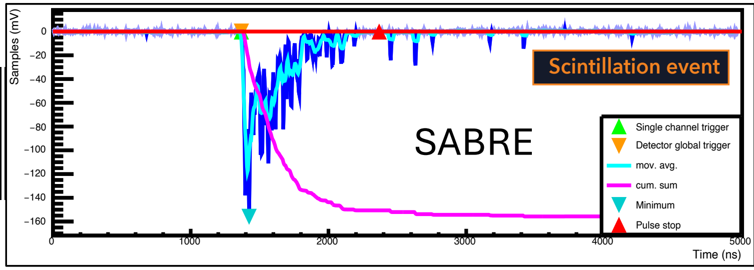
- It can be an important source of background from the crystal bulk
  - fraction of spectrum for intrinsic accounts for **~ 3%** in ROI
- It can **be implanted on the surface** from the ^{222}Rn decay chain
- It can be present in the reflector around the crystal
- The **contribution** to the background 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

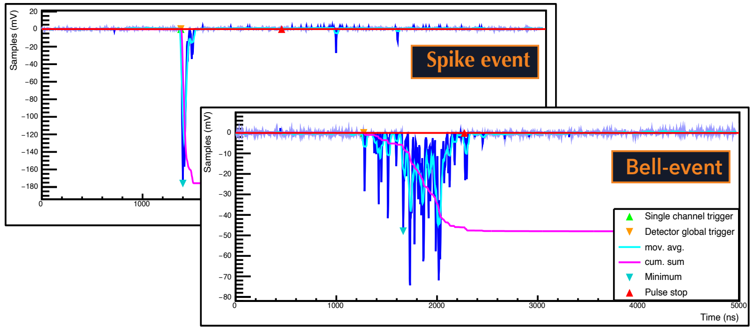




Eur.Phys.J.C 78 (2018) 490

Rejection of background & noise events



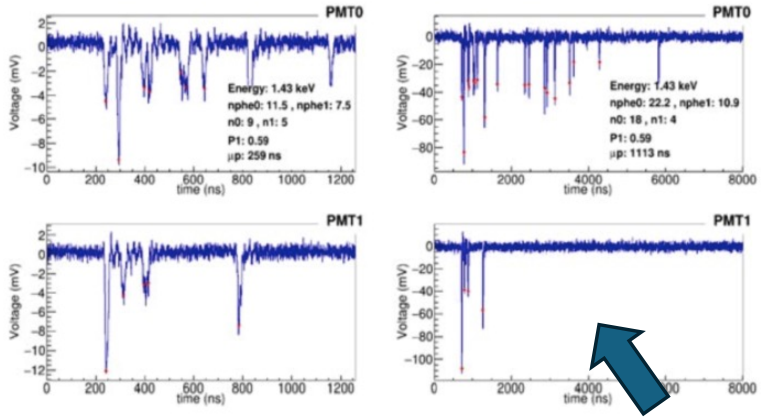


A **DM** signal corresponds to **single-hit events**: only one detector at a time affected by a DM event.
In NaI(Tl) below a few keV scintillation noise events are dominating the energy spectrum

- 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. This is used to build PSD parameters
- 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
  - ✓ **efficiency tested with γ and neutron sources**



Example of anomalous scintillation event from ANAIS-112

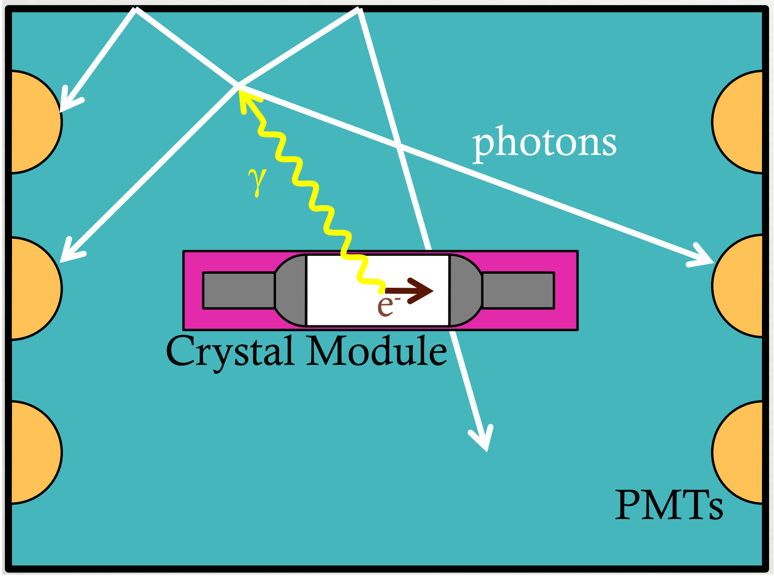
Exploiting an Active Veto

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

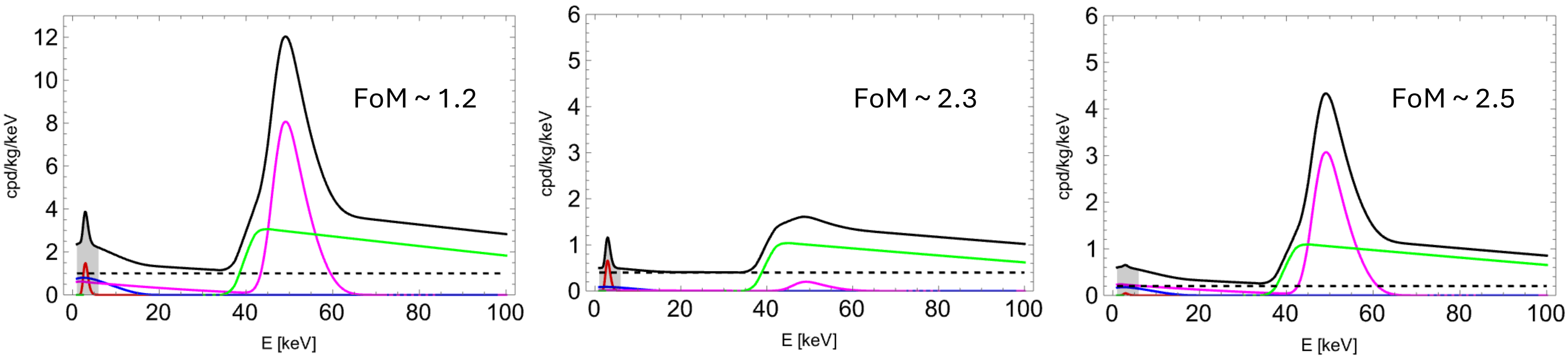
Expected spectrum and sensitivity in DAMA-like detectors

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)	^{210}Pb ~ 4% (26 μBq /kg)	^{210}Pb ~ 37% (0.4 mBq/kg)
K ~ 15% (32 ppb)	K ~ 26% (14 ppb)	K ~ 2% (1 ppb)
^{3}H ~ 28% (90 μBq/kg)	^{3}H ~ 12% (10 μBq/kg)	^{3}H ~ 28% (20 μBq/kg)

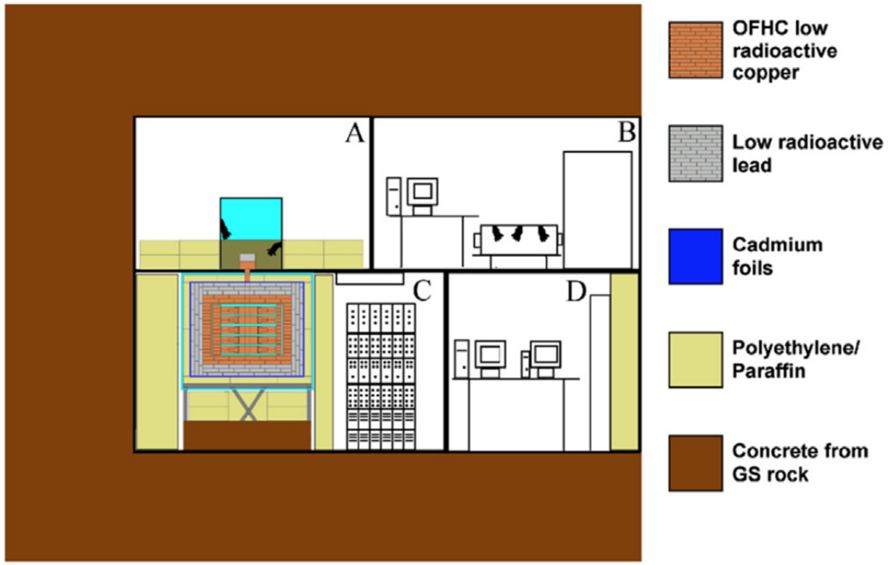
From DAMA/NaI to DAMA/LIBRA

Goal: enhance FoM = $\frac{S_m}{\sqrt{2}} \sqrt{\frac{M\ t}{S_0+B}}$

- Improve crystal radio-purity for enhancing modulation effect
- Increase detector mass: ~ x3
- Improve detector performances

DAMA/LIBRA Phase I and Phase II (Riccardo Cerulli this meeting)

- **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

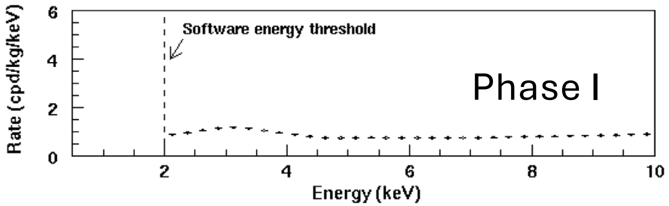


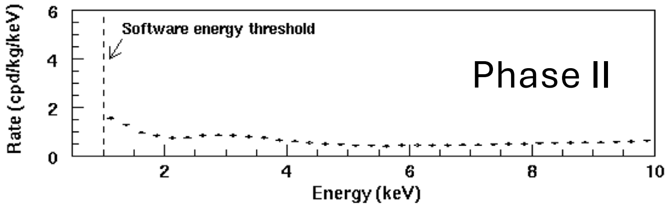
- **DAMA/LIBRA Phase II**
  - From 2011 – present
  - First release in 2018 with 7 annual cycles and 1.13 ton x yr
  - Replaced PMTs (higher QE, lower radioactivity and noise) and improved LY from ~6.8 to 8 ph.e/KeV and σ/E by ~10%
  - Rate in ROI [1,6]keV ~ 0.7 dru

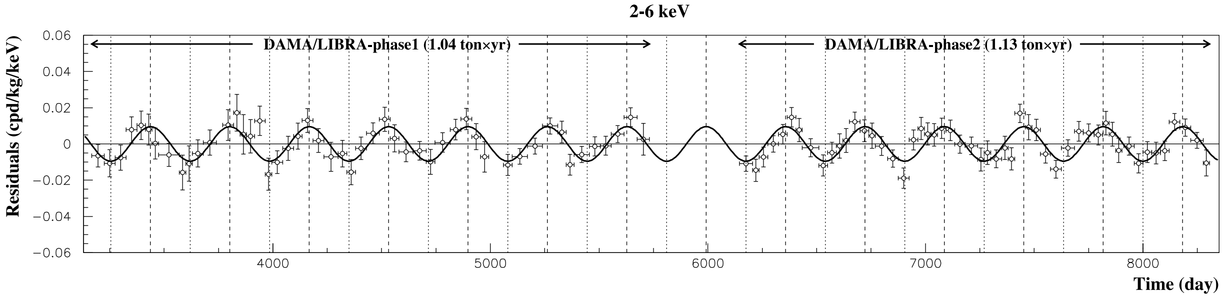
Accumulated ~ 3 ton x yr
20 yr underground

DAMA/LIBRA Phase I and Phase II

Distribution of single-hit events



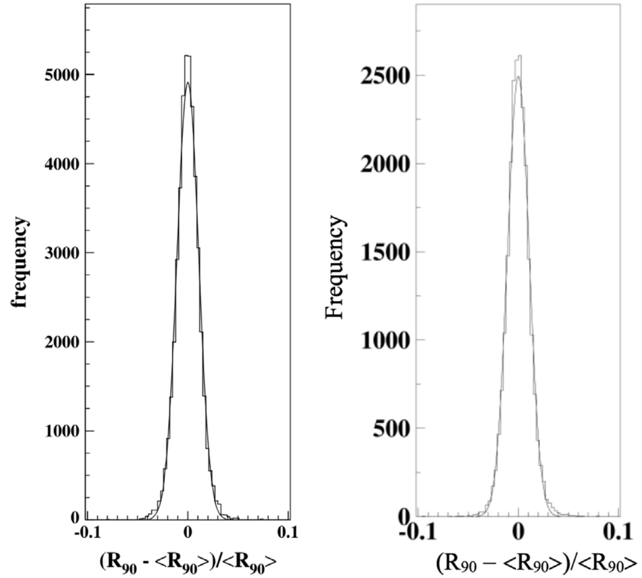




Nucl.Phys.Atom.Energy 22 (2021) 4, 329-342

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

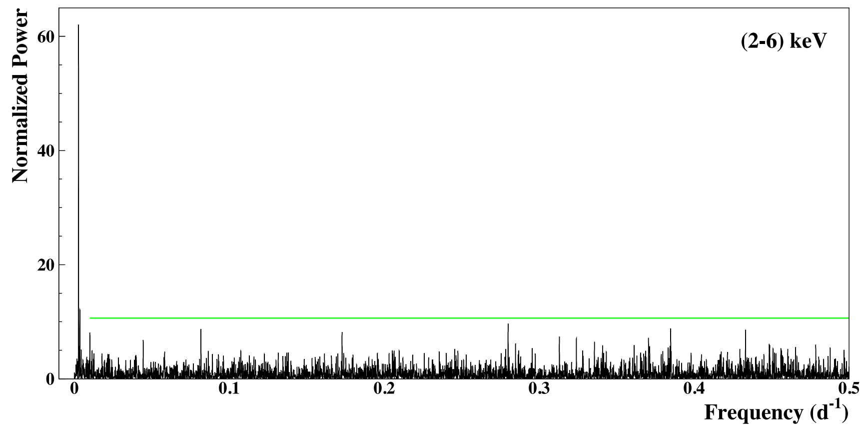
Integral rate above 90 keV for phase I and phase II to exclude a modulation of the background in the high energy region

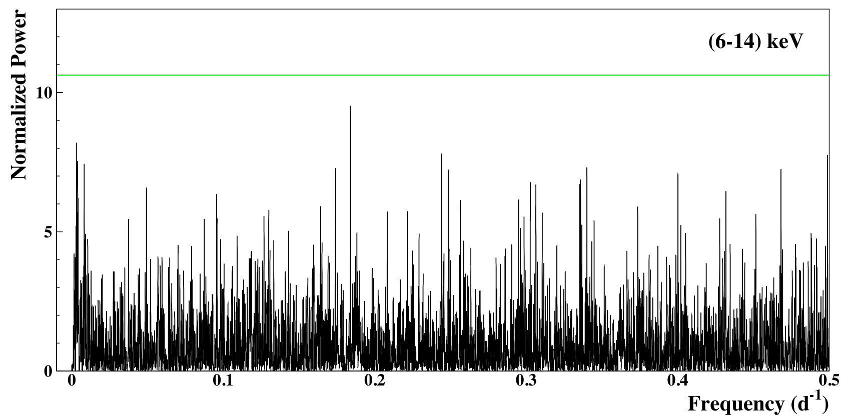


All statistics: **S_m = 0.00996 ± 0.00074 dru [2,6]keV** T and t_0 fixed
S_m = 0.01048 ± 0.00090 dru [1,6]keV T and t_0 fixed

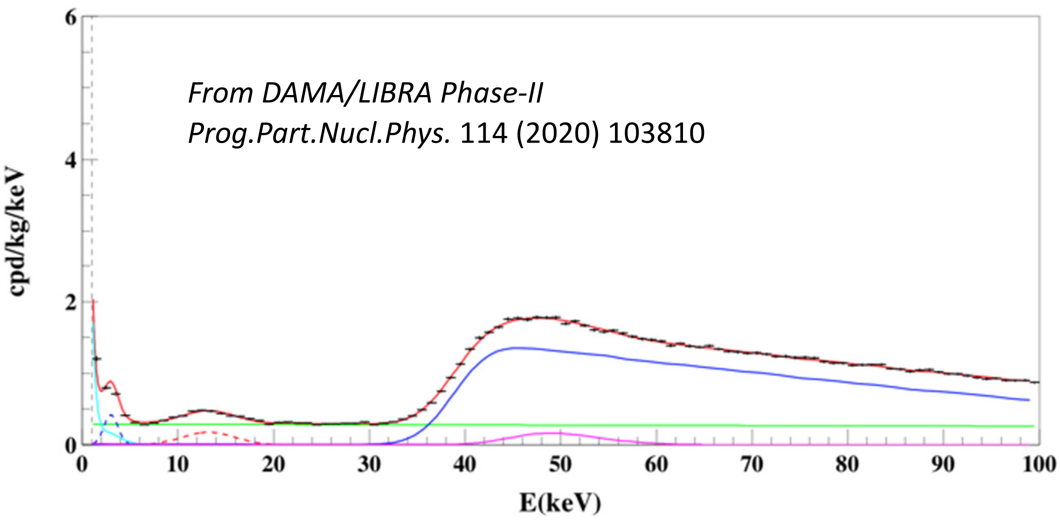
Analysis in frequency

- Single-hit events in 1 day bins
- Method: G. Ranucci, M. Rovere, PRD 75 (2007) 013010
- Phase-1 and Phase-2 data
- Green line shows 90% C.L. from MC
- In the ROI a signal is present with frequency ~ 1 yr^{-1}
- Above ROI no signal is present





DAMA/LIBRA crystals radio-purity



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

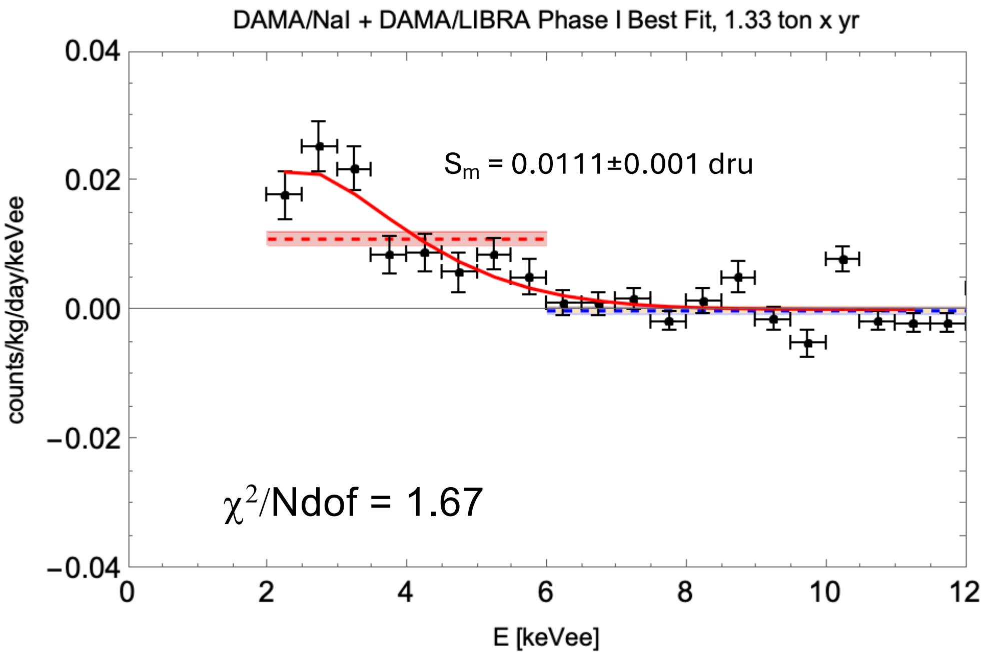
TlI after purification:
^{238}U: 800 ppt
^{232}Th: 120 ppt
^{nat}K: < 0.06 ppm
0.1% used in crystals

^{nat}K: 14.2 ppb (^{40}K: 440 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

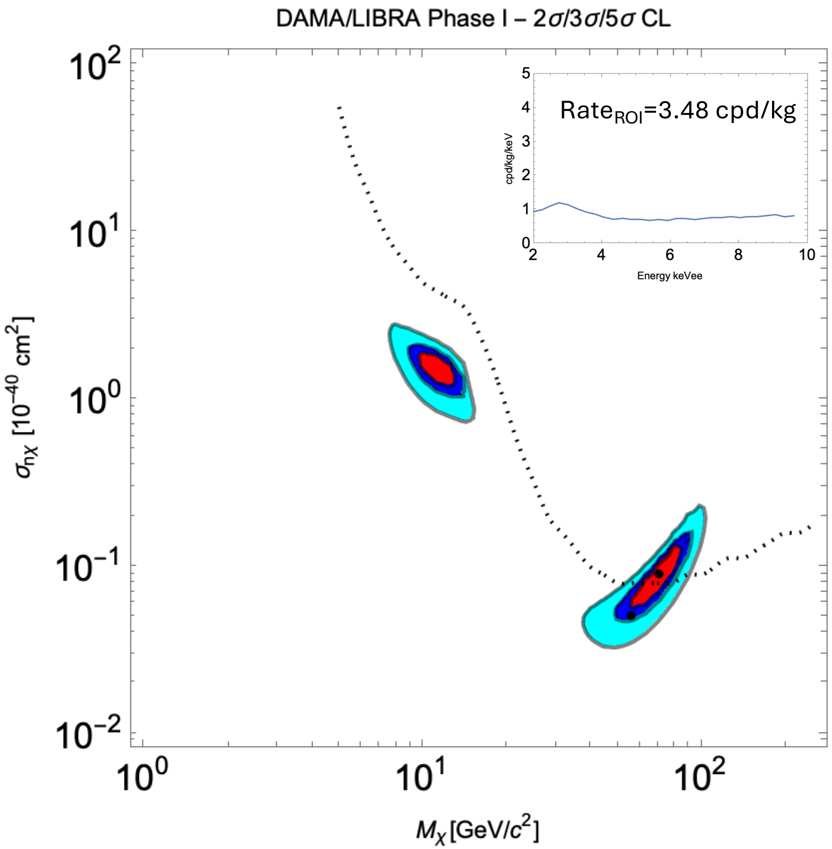
^{3}H: < 90 μBq/kg (95% CL; measured during 1st year of Phase-I) < 15%
^{232}Th: 2-30 μBq/kg (0.5-7.5 ppt) from α decays (^{224}Ra, ^{220}Rn, ^{216}Po) and assuming secular equilibrium.
^{238}U: 8.6-124 μBq/kg (0.7-10 ppt) from α activity assuming secular equilibrium and ^{232}Th content.
$C_{U+Th}(ppt) = 0.093\, N_{\alpha}/M(kg)T(day)$
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/NaI + DAMA/LIBRA Phase I
1.33 ton x yr, Model dependent analysis

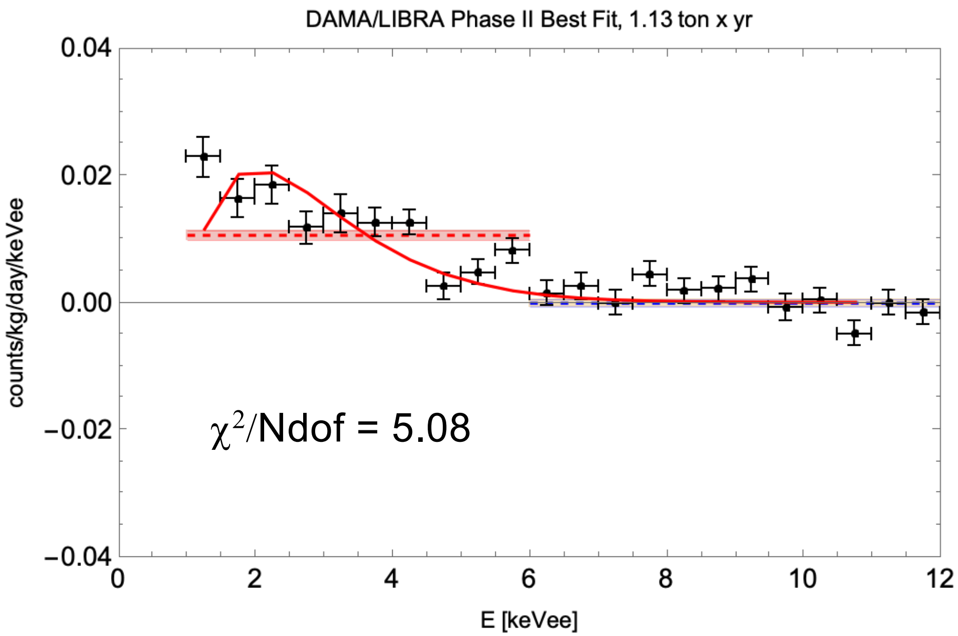


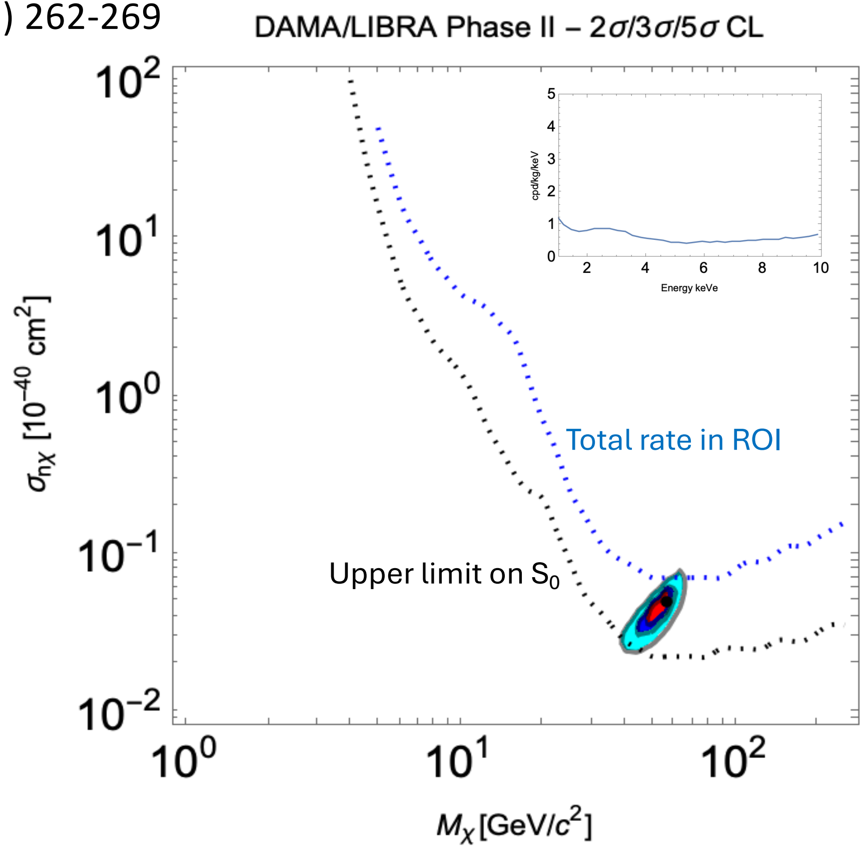
$$n_\sigma = \frac{S_m}{\sqrt{2}} \sqrt{\frac{M\,t}{S_0+B}} = 11.6$$



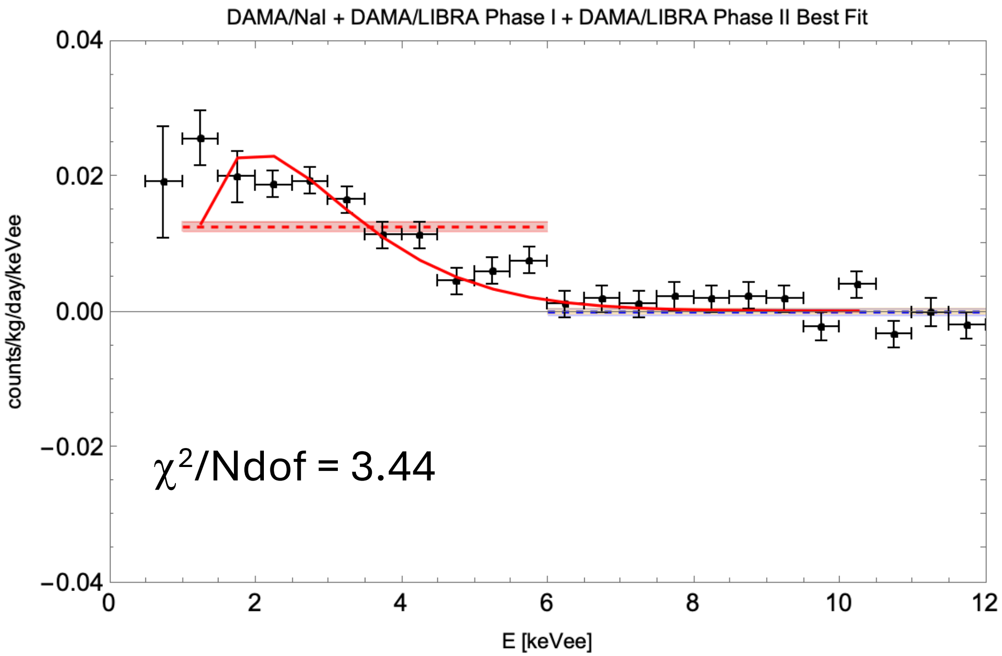
DAMA/LIBRA Phase II only, 1.13 ton x yr
Model dependent analysis

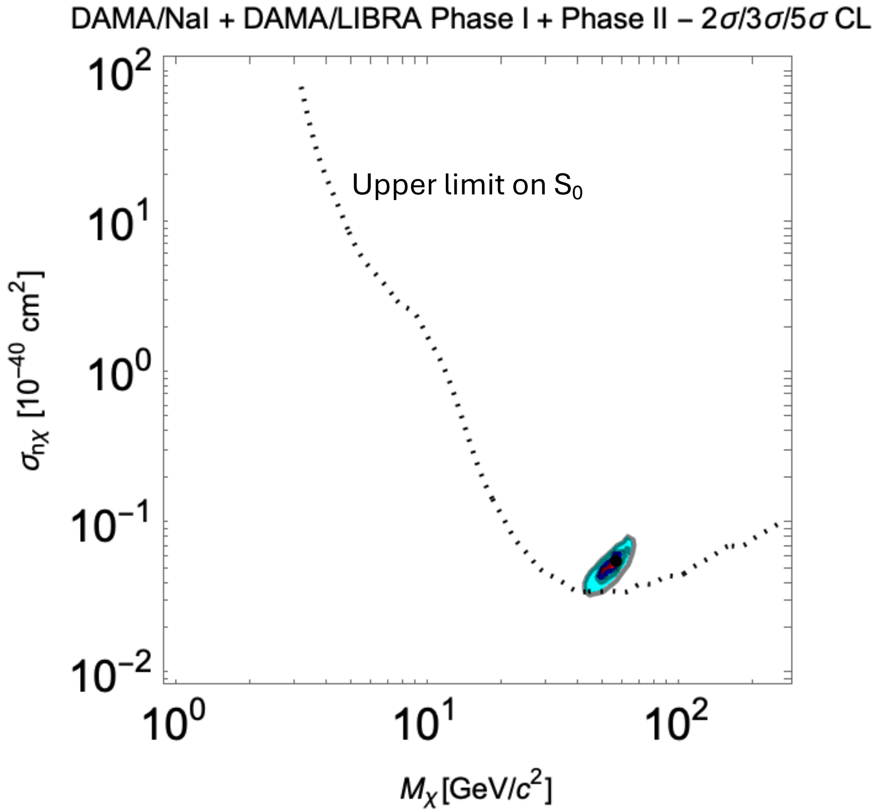
1st analysis from S. Baum, K Freese, C. Kelso, *Phys.Lett.B* 789 (2019) 262-269
same conclusions





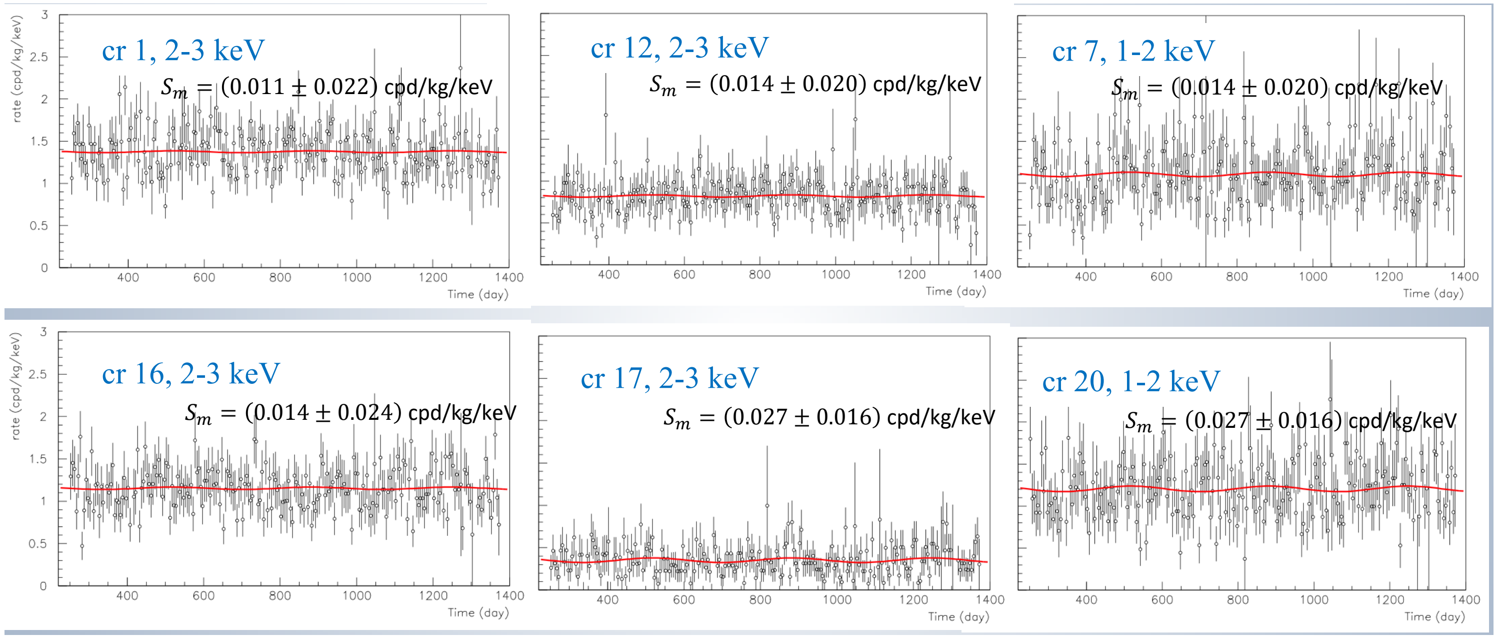
DAMA/NaI + DAMA/LIBRA Phase I + DAMA/LIBRA Phase II
(2.86 ton x yr above 2 keV)
Model dependent analysis





DAMA/LIBRA Phase 2: investigation on time dependent background

R. Cerulli at this meeting: use last 3 year published data Phase 2 (0.61 ton x yr)



No evidence of significant time dependence

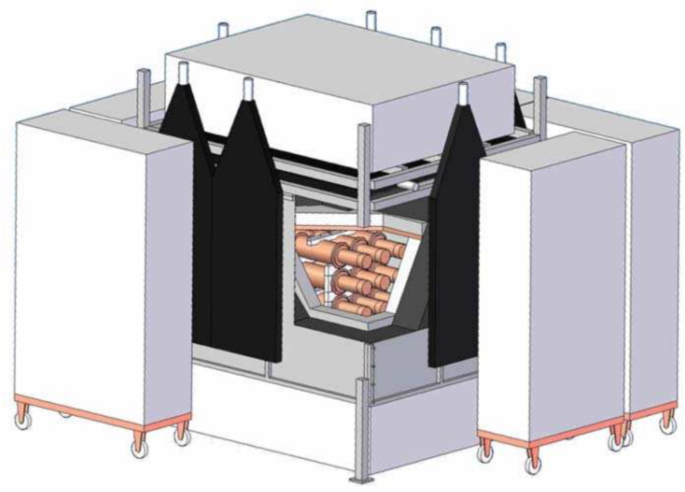
More data (~3yr) available before closing data taking end of 2024

Desirable: a detailed report with all fit parameters and correlations

$$\sigma_{Sm}(1\text{ crystal}) \simeq 0.02 \rightarrow \sigma_{Sm}(25\text{ crystals}) \simeq \frac{0.02}{\sqrt{25}} \simeq 0.004\text{ cpd/kg/keV}$$

ANAIS-112 (Ivan Coarasa this meeting)

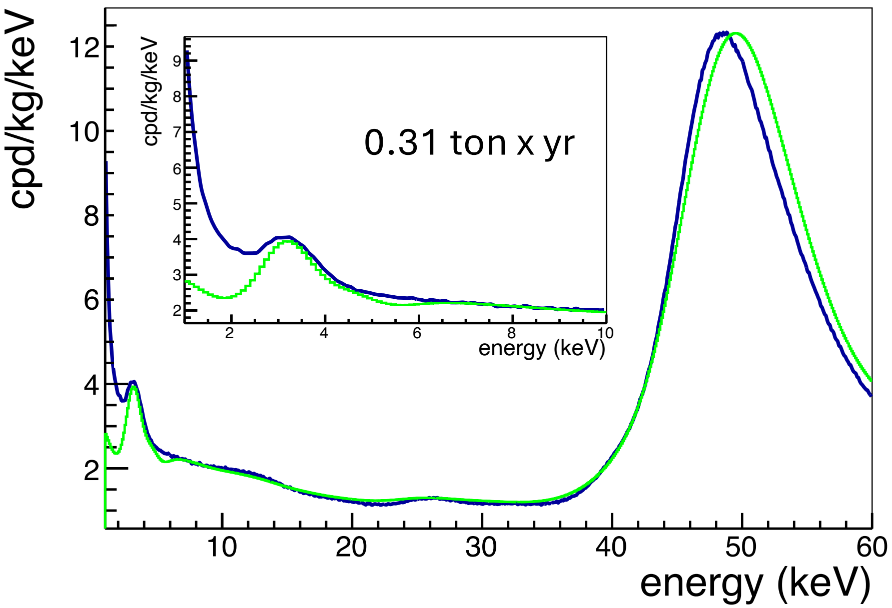
- In operation since Aug. 2017 at **LSC, Spain**
- 9 crystals 12.5 kg each maufactured by Alpha Spectra Inc. (CO, USA)
- Passive shielding with archeologival Pb (10 cm), low-activity Pb (20 cm), and neutron moderator (40 cm)
- Rn box (0.6 Bq/m^3) and muon veto with plastic scintillator
  - ✓ Events with 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, ^{22}Na (internal control populations)
- Average light yield ~ 14.5 phe/keV
- Effective exposure as of Aug. 2023: **0.621 ton x yr (6 years) + improved MC simulation + BDT**



Accumulated ~ 0.6 ton x yr
7 yr underground

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

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)

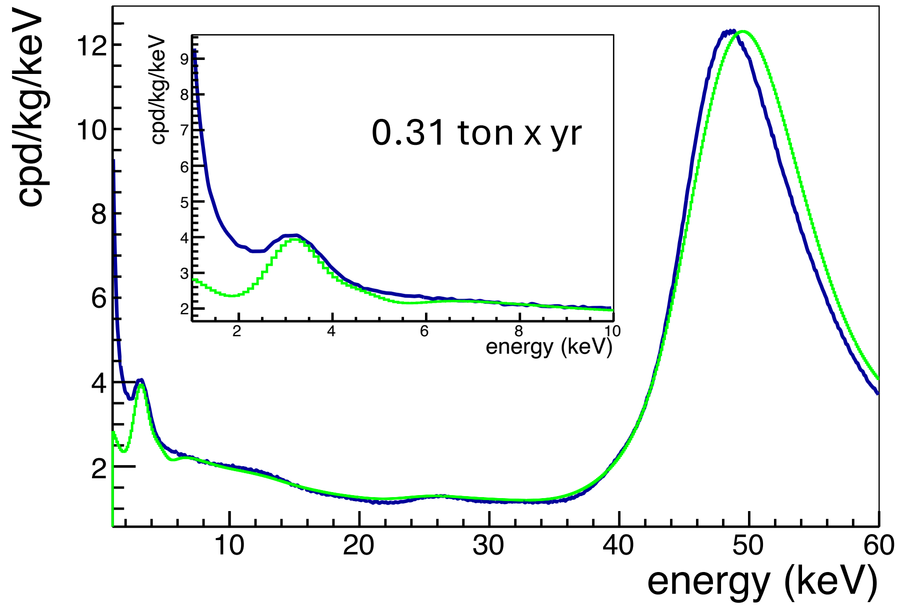
^{210}Po build-up indicates that: a) ^{210}Pb contamination occurs at the end of growth; b) ^{210}Po and not ^{210}Pb is removed during growth

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

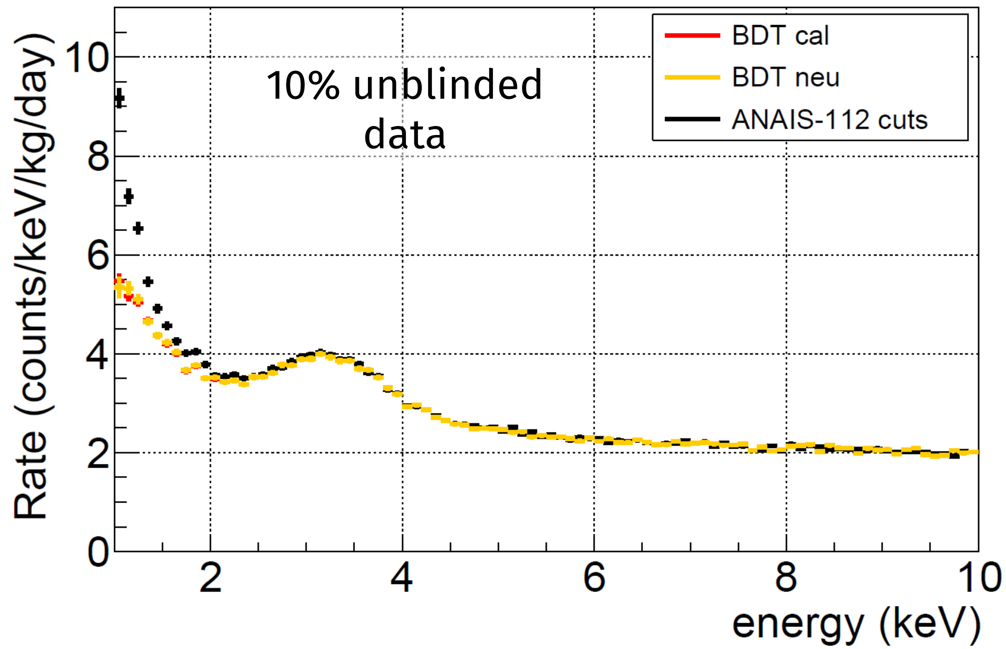
With 8 yr exposure n_σ ~ 5 (only statistical error)

ANAIS-112 @ IDM 2024

J. of Phys. 2156 (2022) 012175



IDM 2024



18% background reduction in [1,2] keV
exploiting output of blank module, BDT

ANAIS-112 2024 results (before IDM 2024)

- Total exposure: 0.312 ton x yr
- χ^2 fit including time dependent background model from MC simulations
  - ✓ different background models show a variation on S_m of order 10^{-3} dru

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

	ROI	χ^2/Ndof	p-value	S_m ANAIS [dru]	S_m DAMA [dru]	$\frac{S_m^{DAMA} - S_m^{ANAIS}}{\sqrt{\sigma^2_{DAMA} + \sigma^2_{ANAIS}}}$
null hypotehsis	1-6	993.38/972	0.310	_		
modulation hypothesis	1-6	992.68/971	0.307	-0.0031±0.0037	0.01048±0.0009	3.6
null hypotehsis	2-6	953.49/972	0.658	_		
modulation hypothesis	2-6	953.45/971	0.650	0.0007±0.0037	0.00996±0.00074	2.5
ρ				0.42	0.20	

arXiv:2404.1738v1

ANAIS-112 @ IDM 2024 (preliminary)

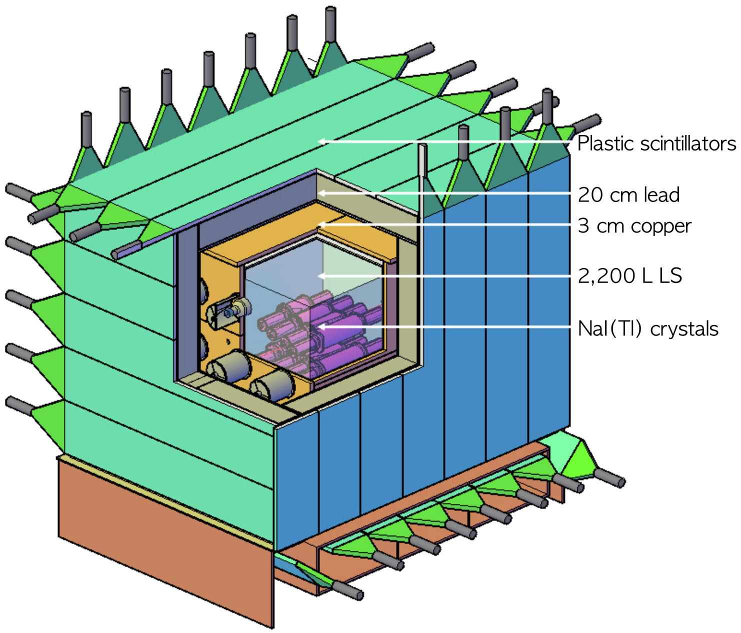
- Total exposure: 0.621 ton x yr

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

	ROI	χ^2/Ndof	p-value	S_m [dru]	S_m DAMA [dru]	$\frac{S_m^{DAMA} - S_m^{ANAIS}}{\sqrt{\sigma^2_{DAMA} + \sigma^2_{ANAIS}}}$
null hypotehsis	1-6	699.6/639	**0.048**	_		
modulation hypothesis	1-6	699.53/638	**0.046**	0.0007±0.0025	0.01048±0.0009	3.7
null hypotehsis	2-6	723.68/723	**0.011**	_		
modulation hypothesis	2-6	722.17/638	**0.011**	0.0030±0.0025	0.00996±0.00074	2.7

COSINE-100 (Lee Seung Mok this meeting)

- Conceived in 2013 and in operation since Sept. 2016 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
8 yr underground

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 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:

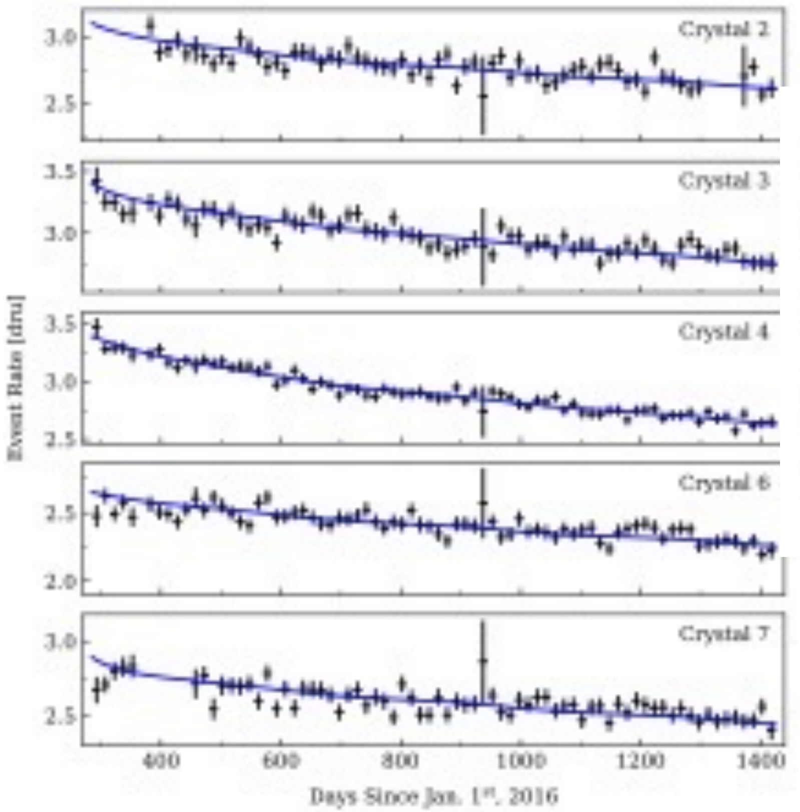
$$R^i(\,t|S_m\,,\alpha^i\,,\beta_k^i\,) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m \cos(\omega(t-t_0))$$

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

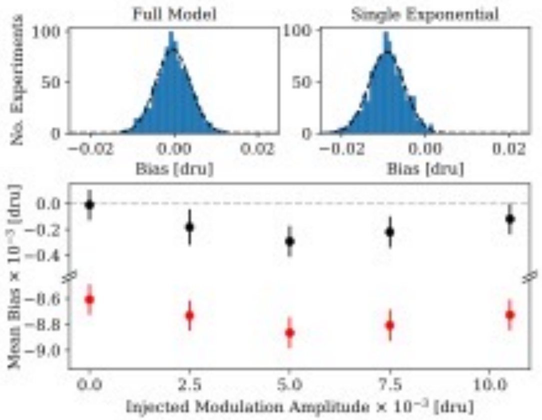
COSINE-100 annual modulation search

Phys.Rev.D 106 (2022) 5, 052005

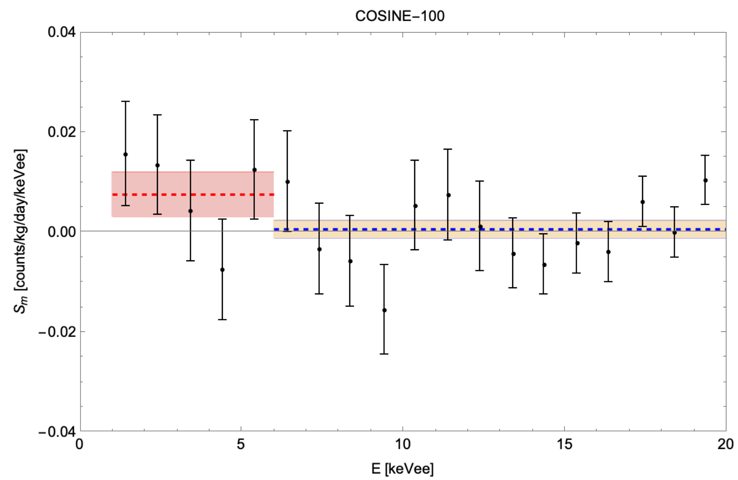
With fixed phase: $\mathbf{S_m = 0.0067 \pm 0.0042}$ based on a time-dependent background model



Bias of S_m vs background model



S_m best fit vs energy



DAMA, ANAIS-112, and COSINE-100 results (prior to IDM2024)

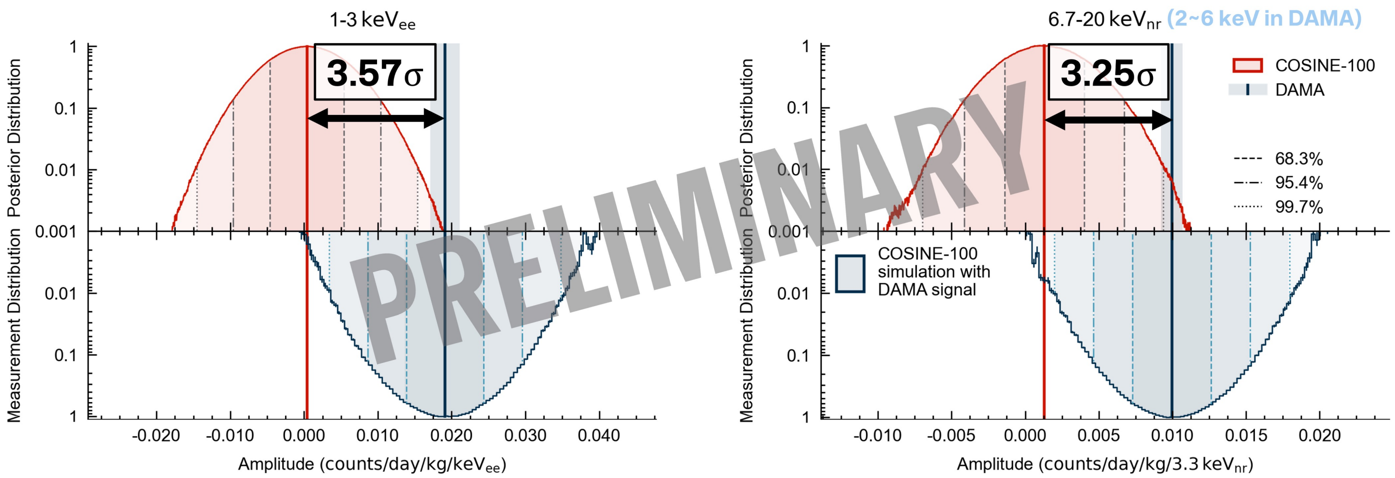
Method:

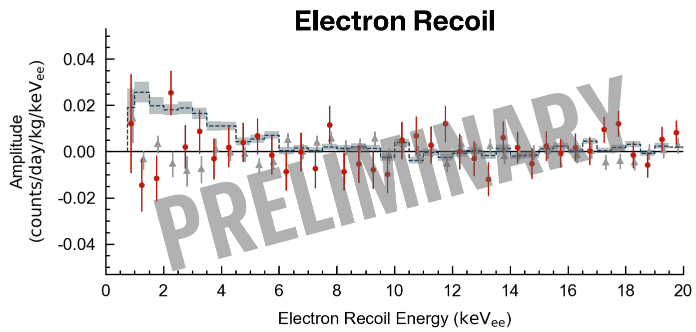
- DAMA: χ^2 fit of residual after subtraction of annual average rate
- ANAIS: χ^2 fit using a time-dependent background model
- COSINE: binned likelihood fit using a time-dependent background model

	ROI	S_m ANAIS 3yr [dru]	S_m COSINE 3yr (with single exponential) [dru]	S_m DAMA [dru]	$\frac{S_m^{DAMA} - S_m^{ANAIS/COSINE}}{\sqrt{\sigma^2_{DAMA} + \sigma^2_{ANAIS/COSINE}}}$ ANAIS/COSINE
Exposure [ton x yr]		**0.31**	**0.173**	**1.13/2.86**	
$S_m \neq 0$ fixed phase	1-6	-0.0031±0.0037	0.0067±0.0042 (0.0019±0.0042)	0.01048±0.0009	3.6/0.88 (2.5)
$S_m \neq 0$ fixed phase (new QF)	2-6	0.0007±0.0037 (-0.0006±0.0050)	0.0051±0.0047	0.00996±0.00074	2.5/1.0 (2.1)
ρ ~ 0.2 back. only ~ 0.1 best fit DM DAMA		0.53	0.06	0.20	

Both ANAIS and COSINE discuss the bias distribution of fitted S_m
The bias can be as large as the DAMA observed modulation amplitude.
An accurate background model is crucial.

COSINE-100 @ IDM 2024





ROI [keVee]	S_m COSINE-100 from ER [dru]	S_m DAMA/LIBRA [dru] *Nucl.Phys.Atom.Energy 22 (2021) 4, 329-342*	$\frac{S_m^{DAMA} - S_m^{COSINE}}{\sqrt{\sigma_{DAMA}^2 + \sigma_{COSINE}^2}}$
1-6	0.0017±0.0029	0.01048±0.0009	2.9
2-6	0.0053±0.0031	0.00996±0.00074	1.5

PICOLON

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

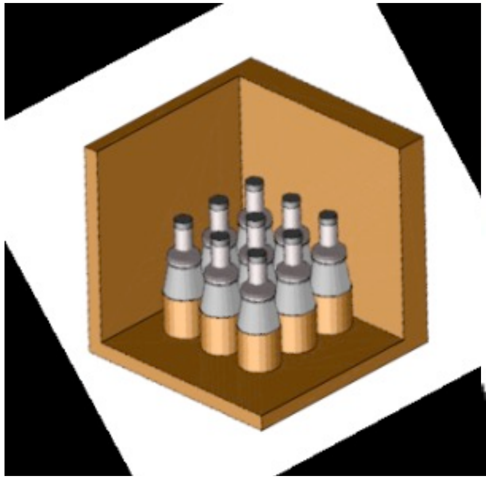
	Ingot71 (2018)	Ingot73 (2018)	Ingot85 (2020)	Ingot94 (2021)	Goal
Crystal size	3”ϕ×3”	3”ϕ×3”	3”ϕ×3”	3”ϕ×3”	5”ϕ×5”
^{40}K (μBq/kg)	<600 (< 19.8ppb)	<900 (<29.8ppb)	<600	<480 (<15.9ppb)	<600 (<20ppb)
^{232}Th (μBq/kg)	1.7±0.2	1.8±0.2	0.3±0.5	<6 (<1.5ppt)	<4 (<1ppt)
^{238}U (μBq/kg)	9.7±0.8	9.4±0.8	1.0±0.4	2 (0.16ppt)	<10 (<1ppt)
^{210}Pb (μBq/kg)	1500	1300	<5.7	<5	<30
Method	Recryst.×2	Recryst.× 3	Recryst.×2 Resin	Recryst.×2 Resin	-

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

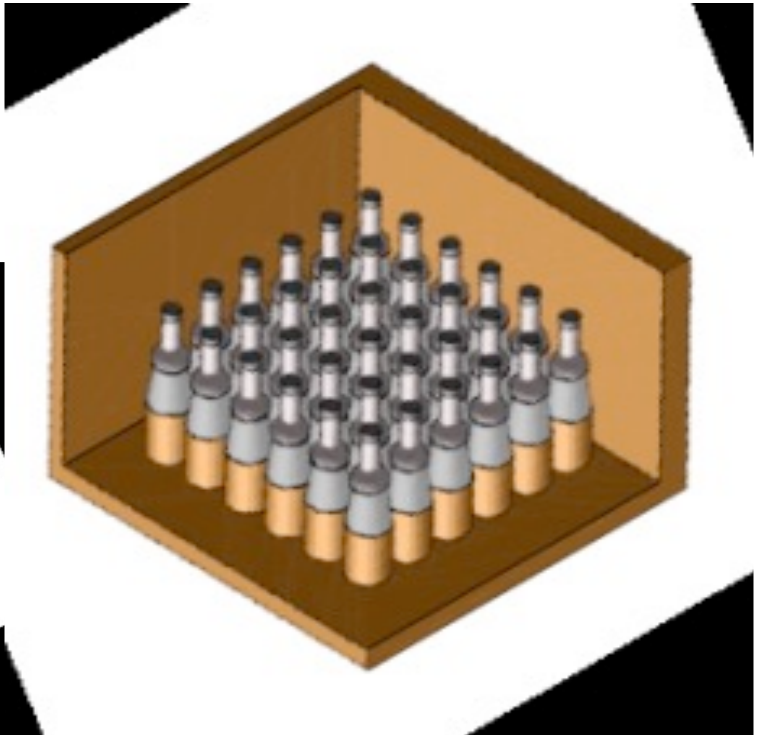
PICOLON long-term plan

PICOLON has a staged program

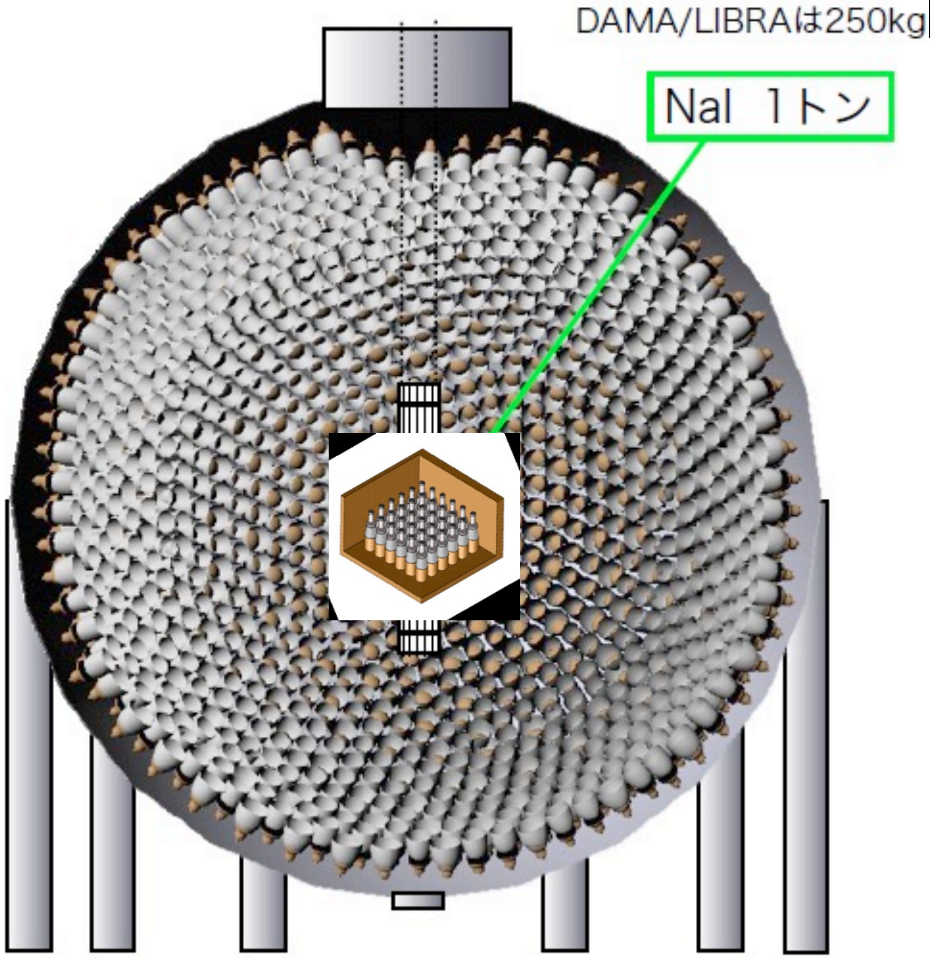
54 kg ~2025



250 kg ~2030

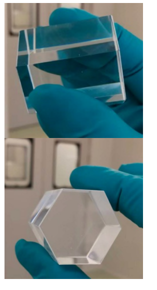


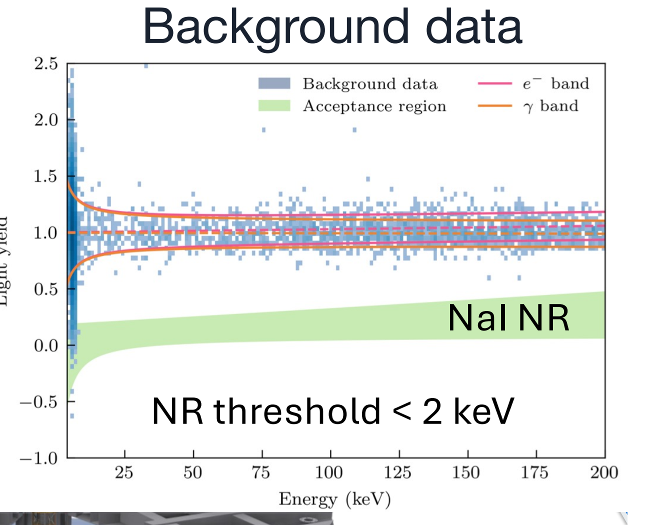
KamLAND-PICO: 1ton

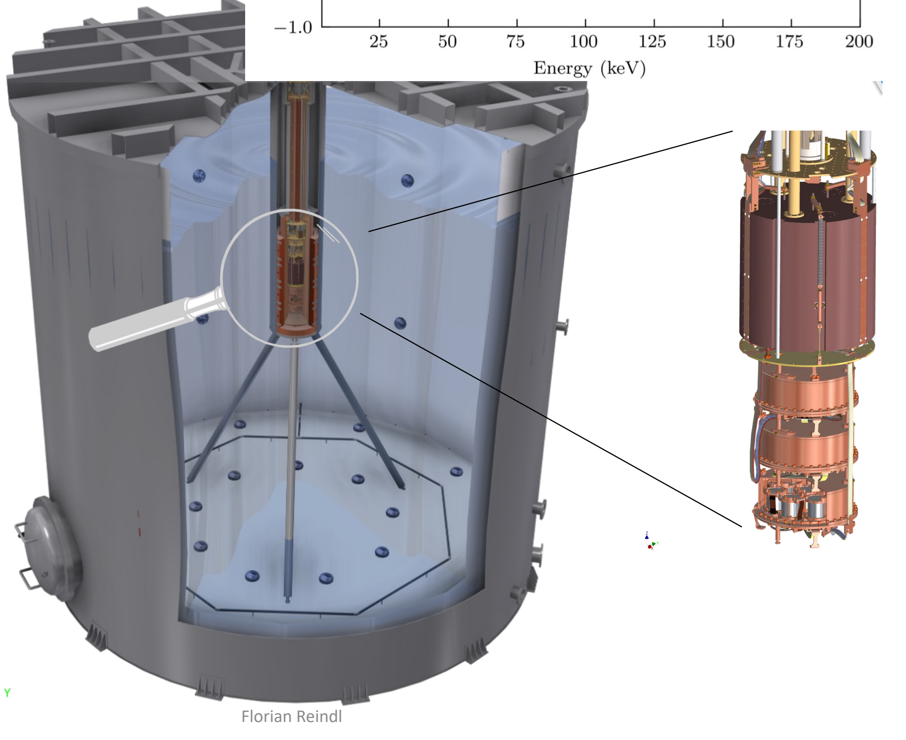


COSINUS (Florian Reindl at this meeting)

- 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
  - ✓ 35 g (108 g) for Phase I (II)
- **Detector under installation/commissioning at LNGS**
- External Water Tank as active muon veto
  - ✓ It also reduces cosmogenic neutron flux ~x100
- Staged approach
  - ✓ 2025 start data taking with 8 detectors
  - ✓ 2025-2026 Run1:100 kg x day
  - ✓ >2026 Run2: 1000 kg x day







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)

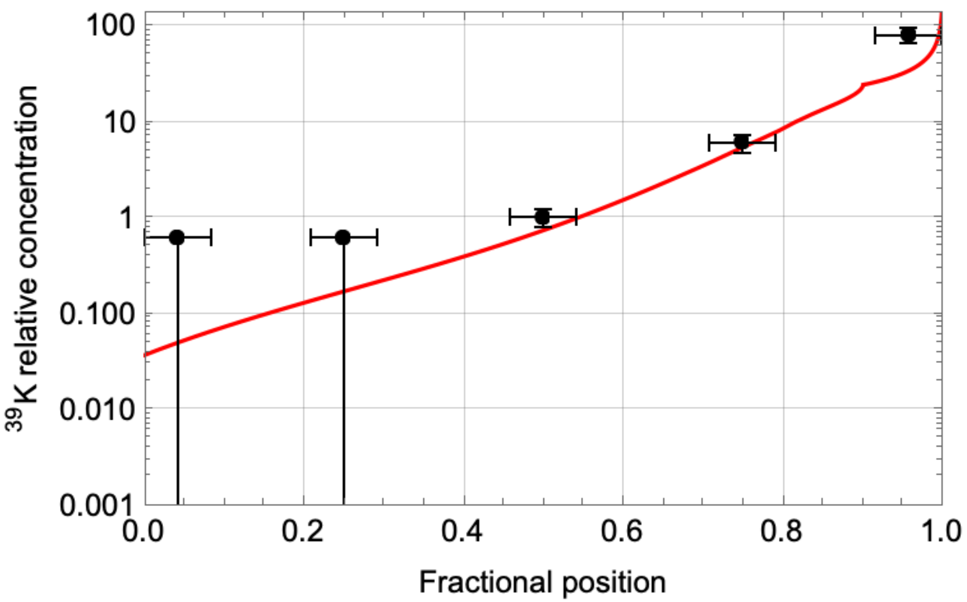
Recrystallization has been used by Merck and COSINE to remove radioactive impurities from the powder taking advantage of the decrease in solubility with temperature

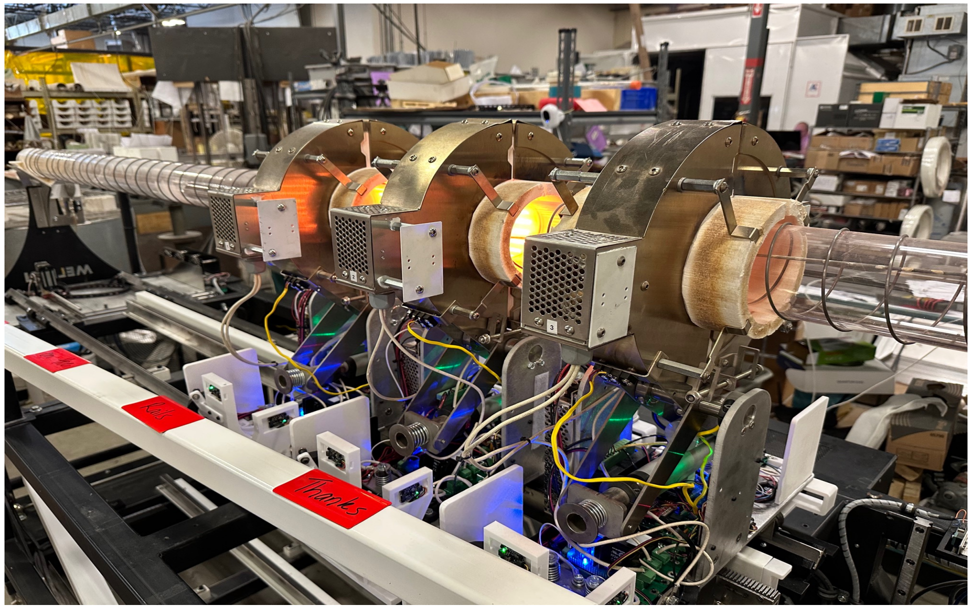
COSINE:
- 400 kg of purified powder produced
- Production rate ~ 70 kg/month

Zone refining purification of NaI powder in SABRE (Davide D'Angelo at this meeting)

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

26 passes and k=0.6





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

More on SABRE from Elisabetta Barberio and Davide D'Angelo at this meeting

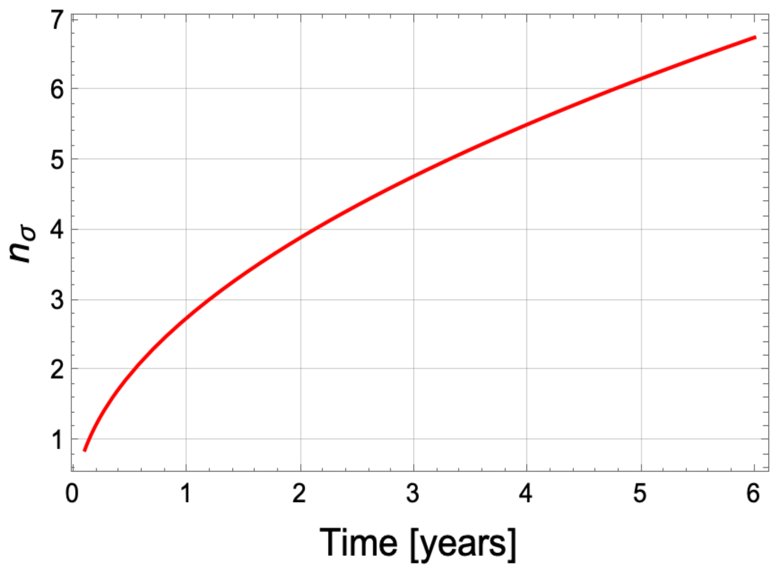
Make a high radio-purity detector: crystal radio-purity

	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 4 kg	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



About comparisons

Exposure

- underground livetime reduces systematics (background model)
- outstanding effort from ANAIS and COSINE collaborations in facing this issue vs DAMA/LIBRA

Data acquisition

- **DAMA/LIBRA**
  - ✓ 500 μs veto activated after events selected by PMT coincidence to reject noise and Bi-Po
  - ✓ 2 μs acquisition window after coincidence detected
- **ANAIS-112**
  - ✓ Dead time 4.5 ms
  - ✓ 1.2 μs acquisition window after coincidence detected
- **COSINE-100**
  - ✓ Dead time 1 ms
  - ✓ Recorded waveform is 8 μs long starting 2.4 μs before trigger after coincidence detected
- **SABRE**
  - ✓ Dead time 1 μs (good events minimum time gap is 500 μs)
  - ✓ Recorded waveform is 5 μs long starting 1.5 μs before trigger after coincidence detected

Quenching (E_{er} = QF x E_{nr})

- This parameter could affect NR energy windows in comparing different experiments
  - ✓ crystal size (multiple scattering), intrinsic impurities, growth method, ...

Take away [1]

- **DAMA/LIBRA**: end of data taking by 2024
  - ✓ Outstanding crystal development achieved, still unmatched
  - ✓ A **crucial anomaly** in DM direct detection standing still
  - ✓ Currently taking data with new PMT dividers since 2021
  - ✓ Since 2021 in data taking without interruptions till Feb 2024 (Phase 2 empowered, ~0.5 ton x yr)
  - ✓ Crucial comprehensive analysis of background time dependence ongoing

- **ANAIS-112 and COSINE-100**
  - ✓ Achieved outstanding noise events rejection in the ROI
  - ✓ Time-dependent background MC simulations: more details on systematics
  - ✓ Stronger **tests of DAMA/LIBRA accessible** from preliminary analysis reported at this meeting (goal: towards 5σ)

Take away [2]

- **Future perspectives**
  - ✓ ANAIS
    - ❖ New DAQ with 8 μs acquisition time, no dead time < 100 Hz
    - ❖ ANAIS+: replace PMTs with SiPMs working at T~100 K
  - ✓ COSINE-100U(pgrade)
    - ❖ COSINE-100U at Yemilab in summer 2024
    - ❖ Operate at -35C with new encapsulation; 40% LY increased
  - ✓ COSINE-200
    - ❖ Significant amount of high radio-purity powder (Astro Grade level) produced
    - ❖ High radio-purity achieved in kg size crystals
  - ✓ SABRE crystal production and detectors (North and South) deployment 2025-2026
    - ❖ First crystal after zone refining underground by 2024
  - ✓ COSINUS
    - ❖ A new technique available to exploit NaI-based detectors for DM
    - ❖ Advanced detector deployment and commissioning underway
  - ✓ PICOLON
- **Crucial effort required** in improving exchanges and comparisons between experiments
  - ✓ Expression of intent to merge know-how, experience, and equipment to solve this long lasting conundrum (ANAIS, COSINE, SABRE)

Acknowledgements
for materials and discussions

Yeongduk Kim, Hyun Su Lee, Seung Mok Lee, Reina Murayama, Marisa Sarsa, Ivan Coarasa, Ken-Ichi Fushimi, Florian Reindl, Giuseppe Di Carlo, Elisabetta Barberio, Claudia Tomei, Sofia Hollick

Thank you for your attention!

Features of expected DM interactions

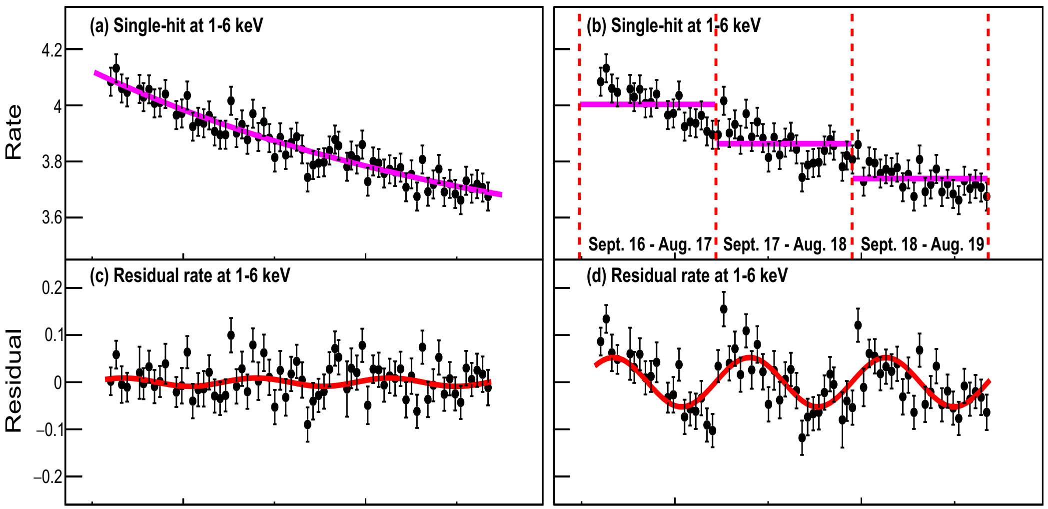
In case annual modulation with expected features (period and phase) is observed, the **DM interpretation** of candidate events depends on:

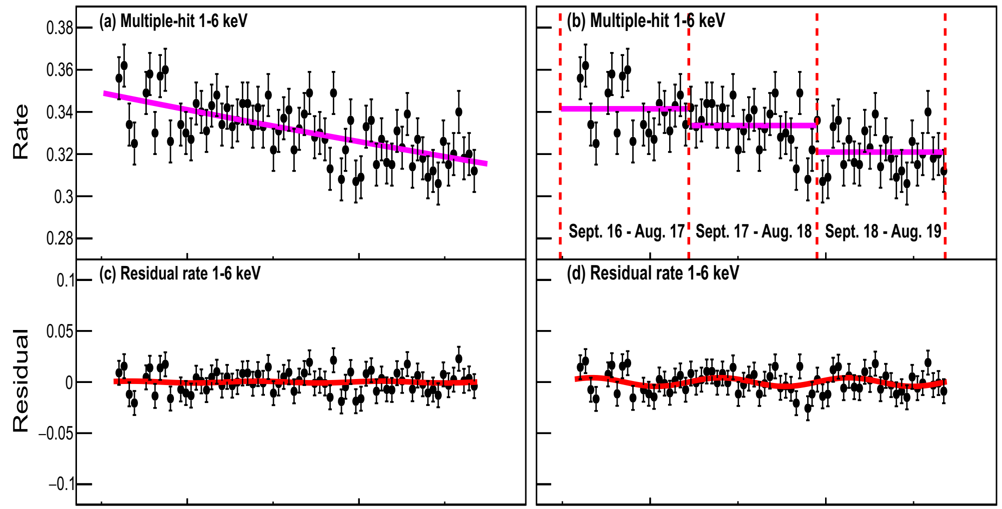
- Astrophysical parameters
- Target material
- Interaction model
- Nuclear physics for NR
- Quenching factor for NR (E_{er} = QF x E_{nr})
  - ✓ for NaI-based detectors could depend on crystals properties (growth, radio-purity, etc)
- Channeling in case of crystals and NR
- …

Induced annual modulation

COSINE-100 Collaboration has exploited data selection similar to DAMA/LIBRA and determined residuals by:

- performing a fit with a model-dependend background with a single exponential
- by using yearly averaged rate





A modulation is found for single-hit events in [1,6] keV using the averaged rate with negative S_m
What about the phase?

Sci.Rep. 13 (2023) 4676 also *JHEP* 04 (2020) 137

SABRE (Sodium-iodide with Active Background RejEction)

Proposed in 2011 by Frank Calaprice.

Strategy:

Higher signal-to-background ratio by **ultra-high purity NaI(Tl) crystals**

✓ aim to 0.1 dru in ROI

North-South «twin» experiments at **LNGS (Italy) and SUPL (Australia)**

✓Rule out seasonal effects

Proof-of-Principle (PoP) at LNGS

✓Exploit active background rejection with a liquid scintillator

✓Test crystals radio-purity

The effort made led to the following results

✓ the **Astro Grade NaI powder** was developed in collaboration between Princeton University and Sigma-Aldrich (today Merck) with potassium < 10ppb after fractional recrystallization purification (Astro Grade), available on the market

✓ exploitation of zone refining purification to achieve radio-purity goal

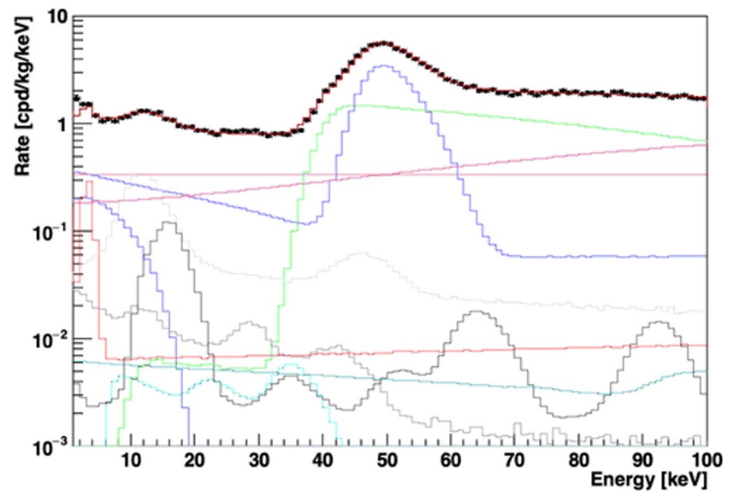
- **Status**: SABRE North, TDR submitted for review; SABRE South detector deployment to be completed in 2025

SABRE crystal radio-purity

Eur.Phys.J.C 82 (2022) 12, 1158

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



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