Status and Future Prospects of the search for Dark Matter Annual Modulation in NaI

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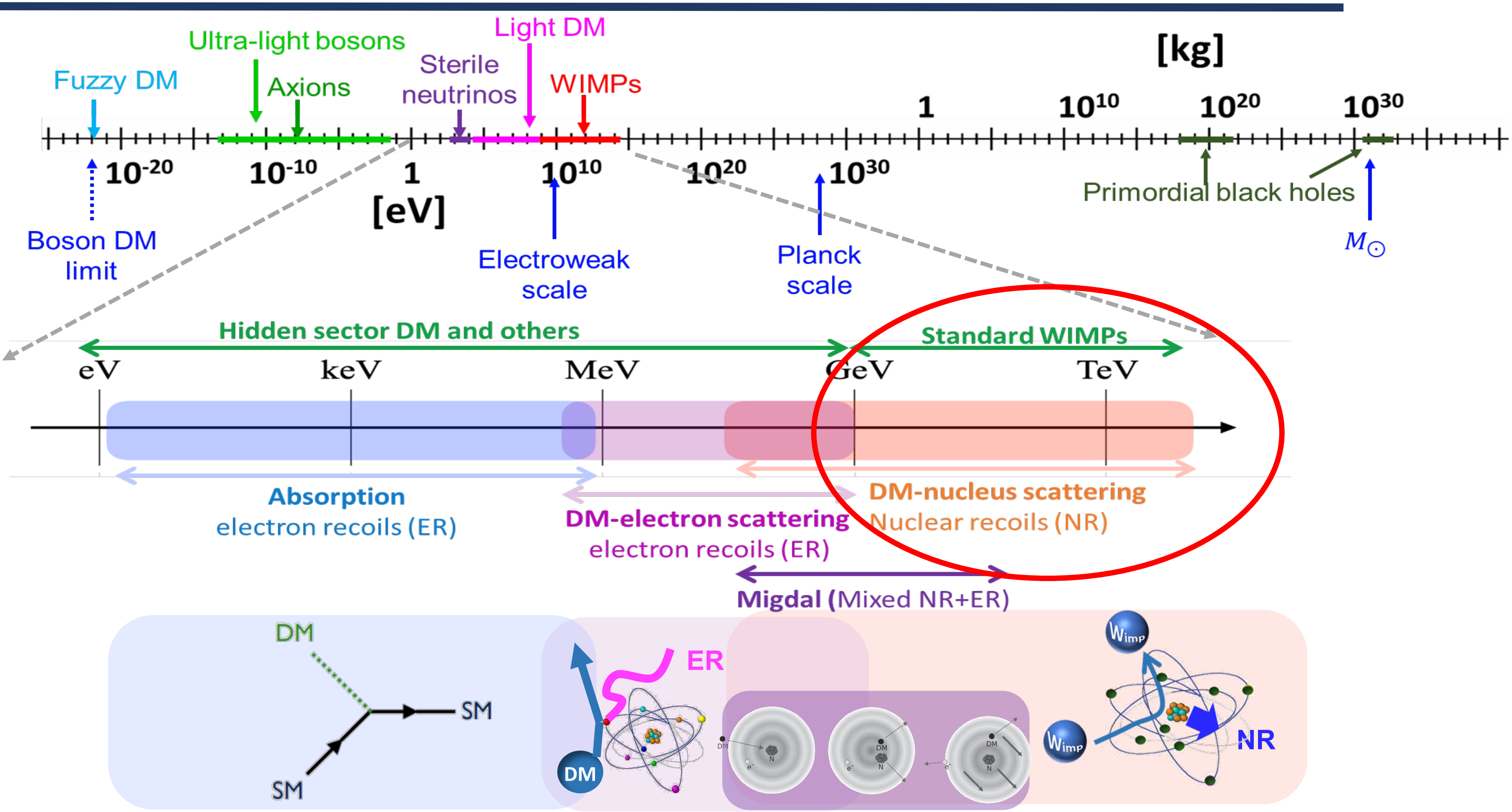
Cosmology, Astrophysics, Theory and Collider Higgs 2024 (CATCH22+2)
DIAS, 1-5 May 2024

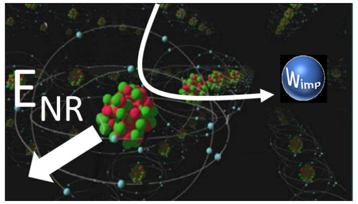
OUTLINE

- Intro: Dark matter annual modulation
- DAMA/LIBRA signal
- Experimental DM searches with NaI(Tl)
  - ANAIS-112 3 years results with improved analysis NEW
- Outlook & Summary

Direct detection: mass ranges



DM Direct detection



DM local density

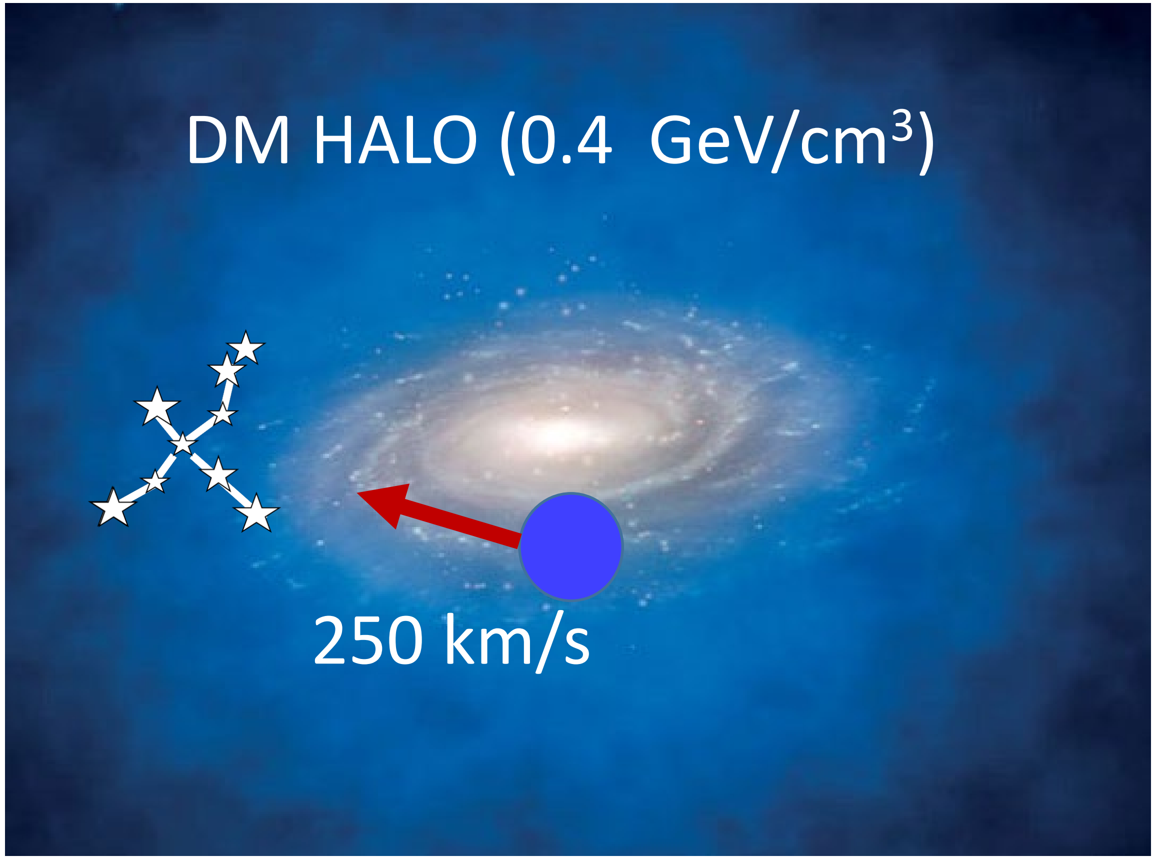
DM velocity distribution in detector's frame

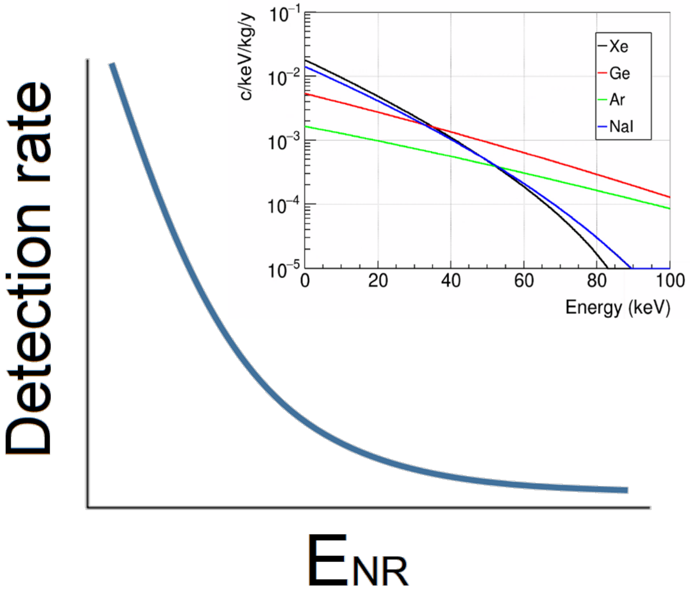
$$\frac{dR}{dE_{NR}} = \frac{M_{det}\rho_\chi}{2m_\chi \mu_{\chi N}^2} \sigma^0 F^2(q) \int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} d^3v$$

DM mass

scattering cross section

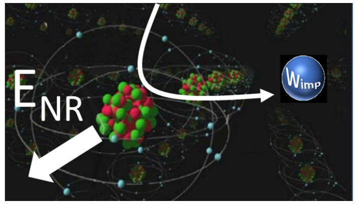
where $v_{min} = \sqrt{\frac{E_{NR} m_N}{2\mu_{\chi N}^2}}$

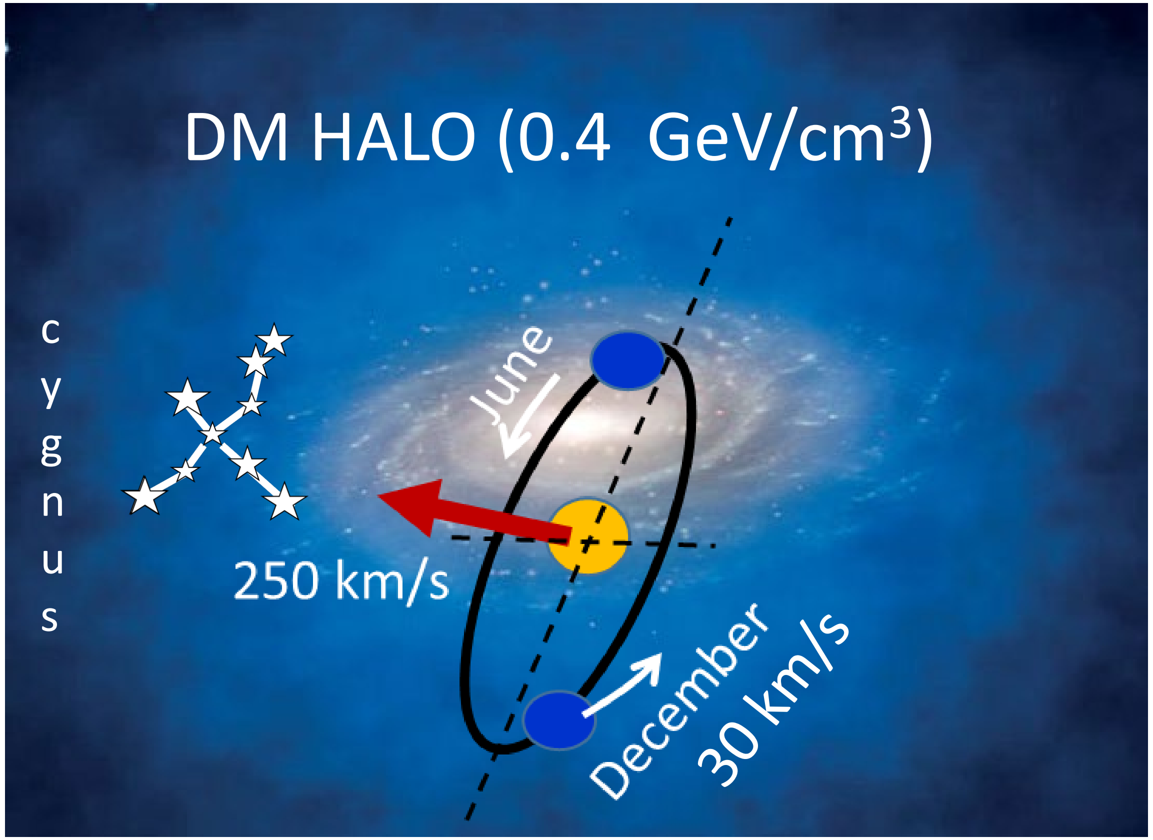




Few counts per kgxyear!
Energy O(10keV)
No distinctive signatures
Target dependent

DM annual modulation





DM local density

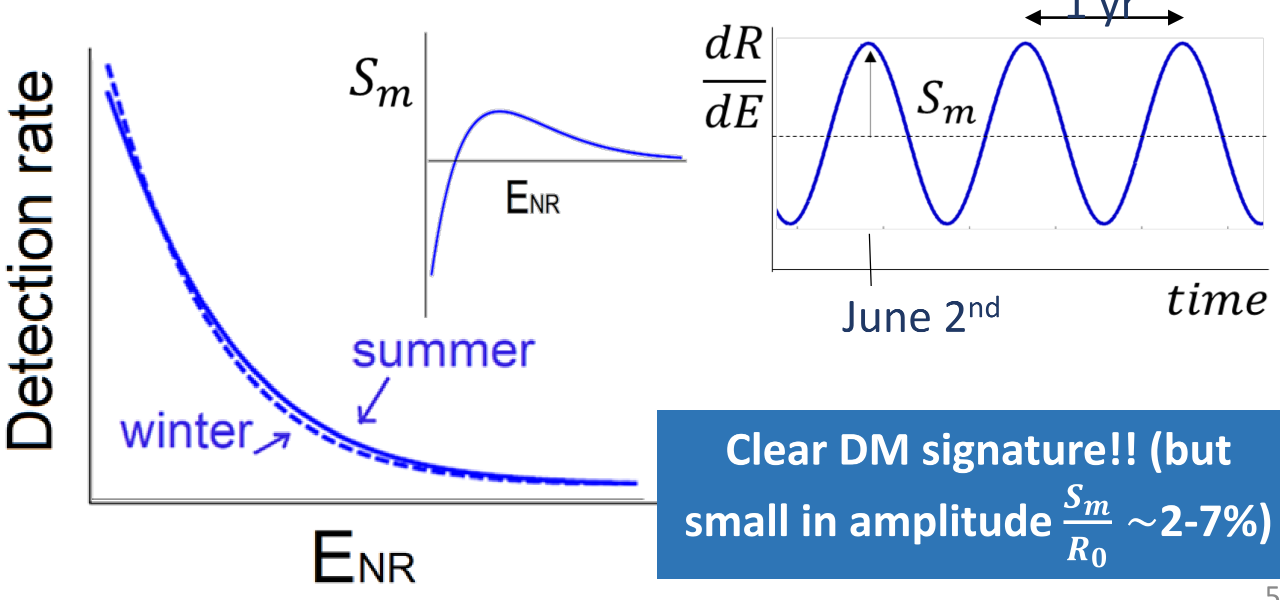
DM velocity distribution in detector's frame

$$\frac{dR}{dE_{NR}} = \frac{M_{det}\rho_\chi}{2m_\chi\mu^2_{\chi N}}\sigma^0 F^2(q)\int_{v_{min}}^{v_{esc}}\frac{f(v,t)}{v}d^3\boldsymbol{v}$$

DM mass

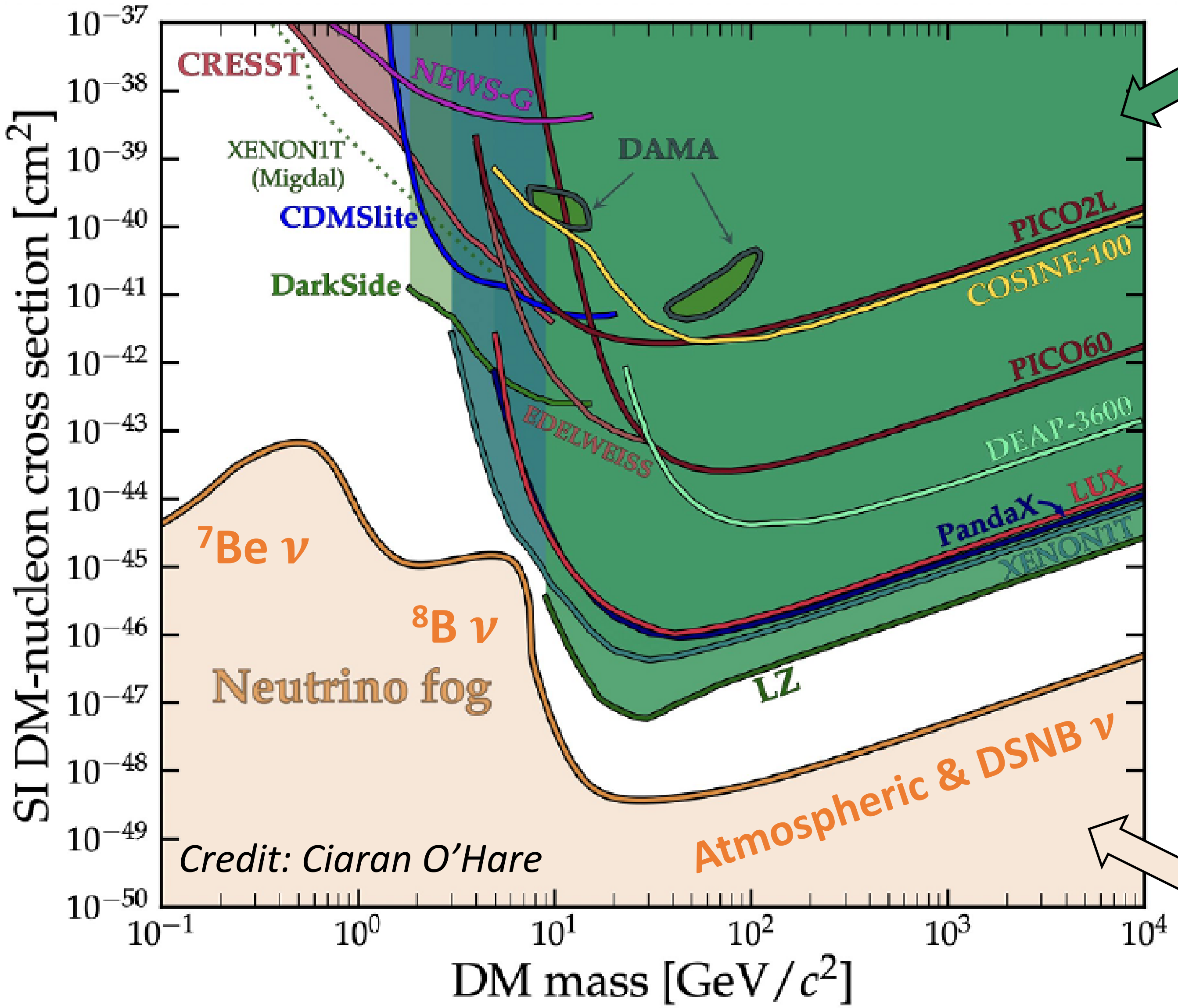
scattering cross section

$$\rightarrow \frac{dR}{dE_{NR}} \approx R_0(E) + S_m(E)\cos\omega(t-t_0)$$



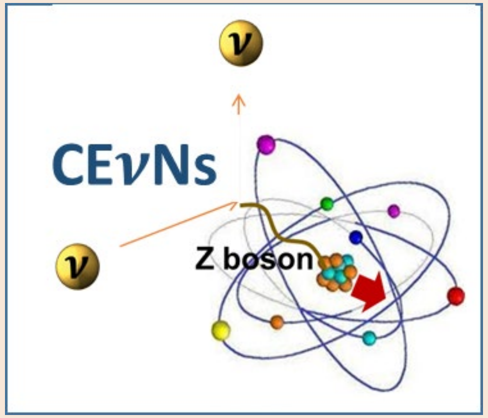
Clear DM signature!! (but small in amplitude $\frac{S_m}{R_0}$ ~2-7%)

Experimental sensitivity @ 2022

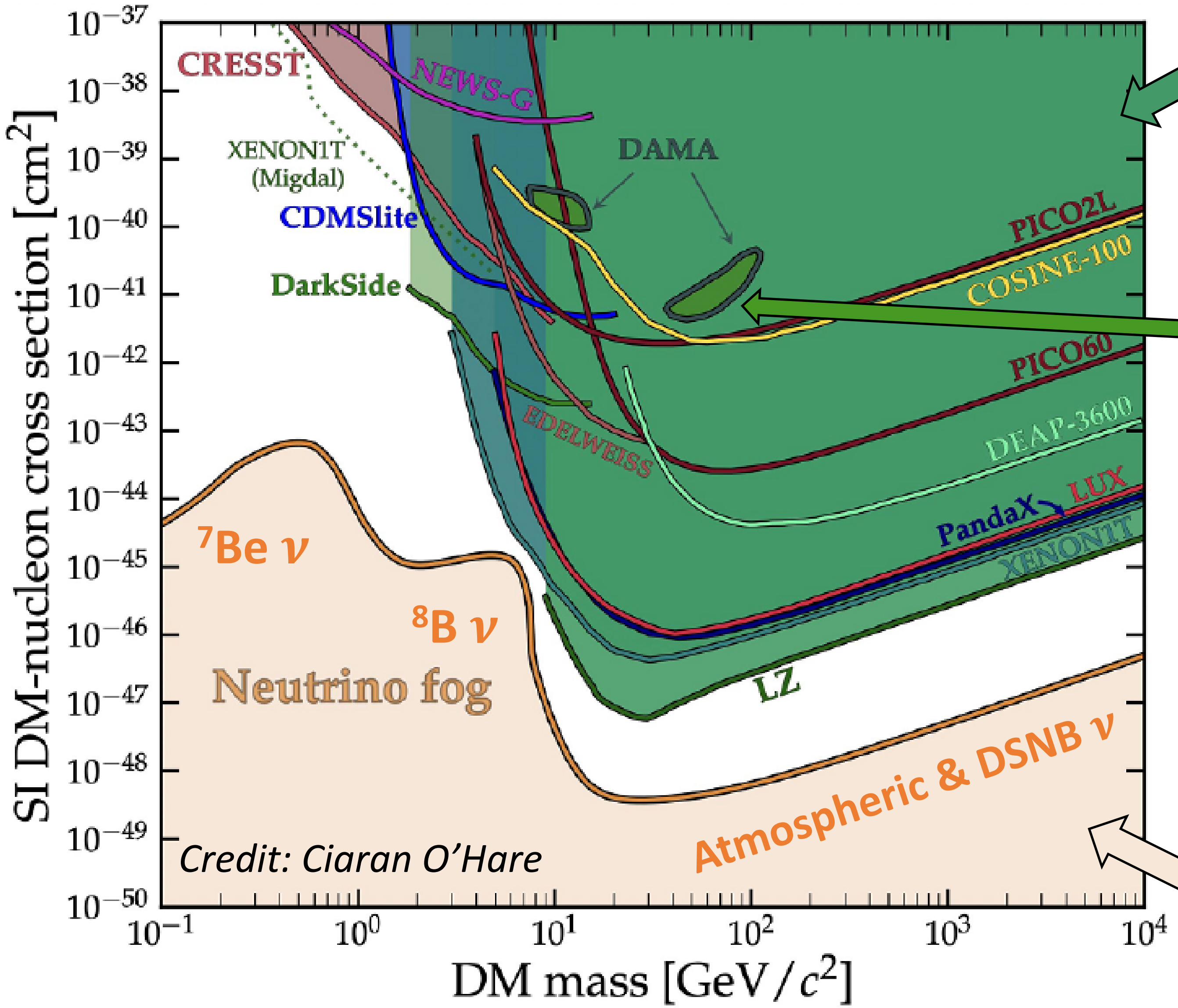


excluded region for SI coupling

Neutrino floor



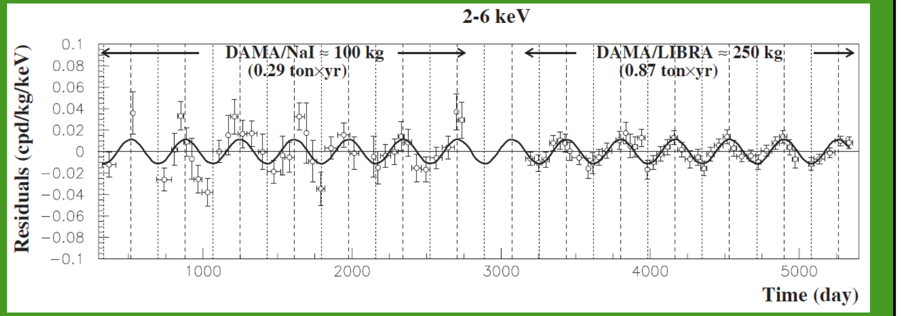
Experimental sensitivity @ 2022



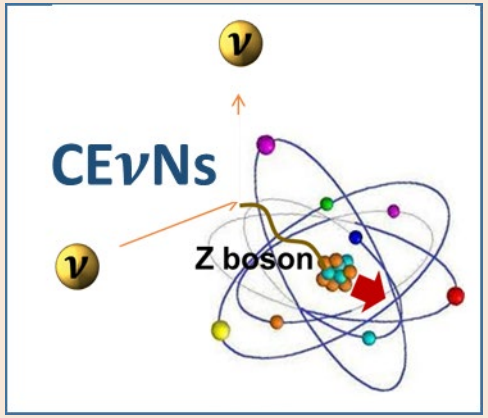
excluded region for SI coupling

One positive signal!!

DAMA/LIBRA annual modulation



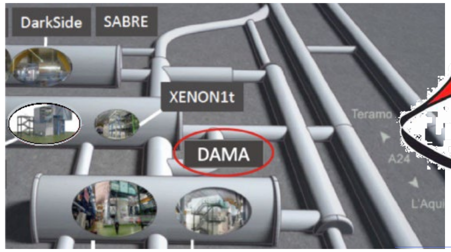
Neutrino floor

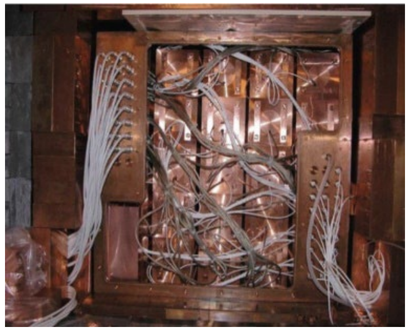


The DAMA/LIBRA annual modulation positive signal

INFN

NaI(Tl) scintillators at LNGS (Italy)





DAMA / NaI (1995-2002)

- 100 kg NaI(Tl) scintillators
- Eth = 2 keVee
- 7 annual cycles

DAMA / LIBRA ph1 (2003-2010)

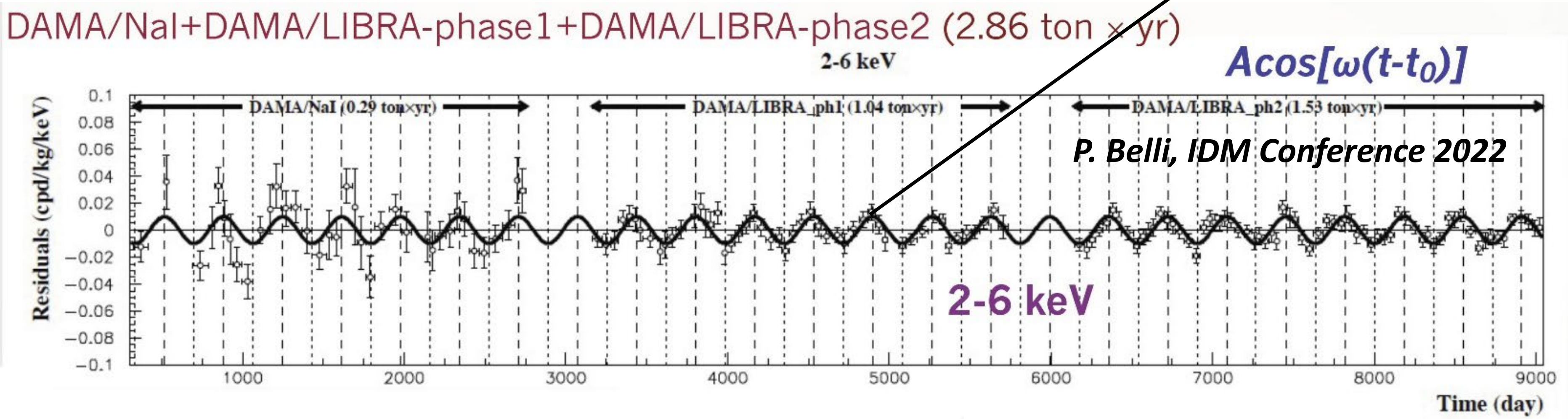
- 250 kg NaI(Tl) scintillators
- Eth = 2 keVee
- 7 annual cycles

DAMA / LIBRA ph2 (2011-today)

- 250 kg NaI(Tl) scintillators
- Eth = 1 keVee
- 10 annual cycles

P. Belli, IDM Conference 2022

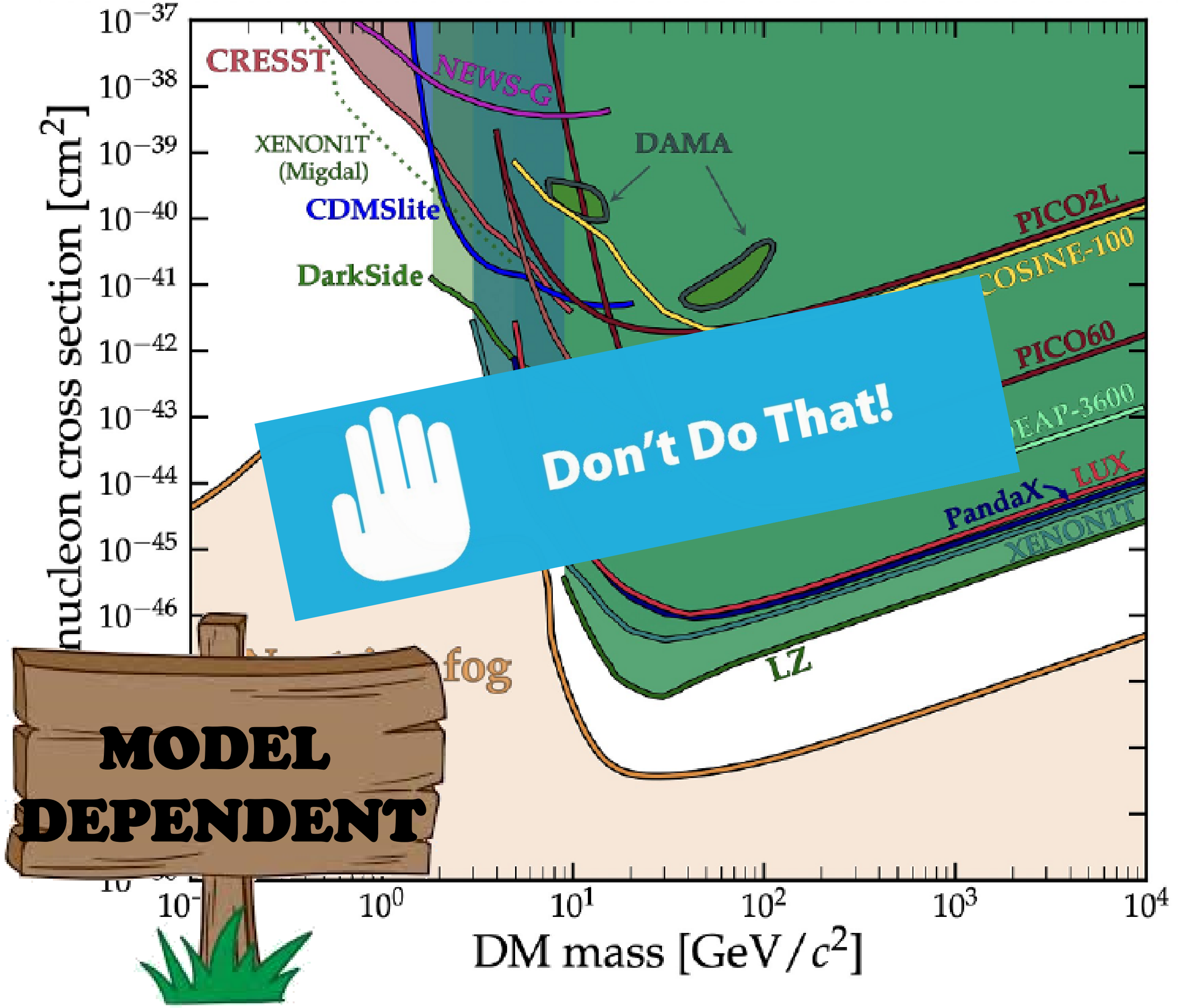
	ΔE	A(cpd/kg/keV)	$T=2\pi/\omega$ (yr)	t_0 (day)	C.L.
	(1-3) keV	0.0191±0.0020	0.99952±0.00080	149.6±5.9	9.6σ
DAMA/LIBRA-ph2	(1-6) keV	0.01058±0.00090	0.99882±0.00065	144.5±5.1	11.8σ
	(2-6) keV	0.00954±0.00076	0.99836±0.00075	141.1±5.9	12.6σ
DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.00959±0.00076	0.99835±0.00069	142.0±4.5	12.6σ
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2	(2-6) keV	0.01014±0.00074	0.99834±0.00067	142.4±4.2	13.7σ



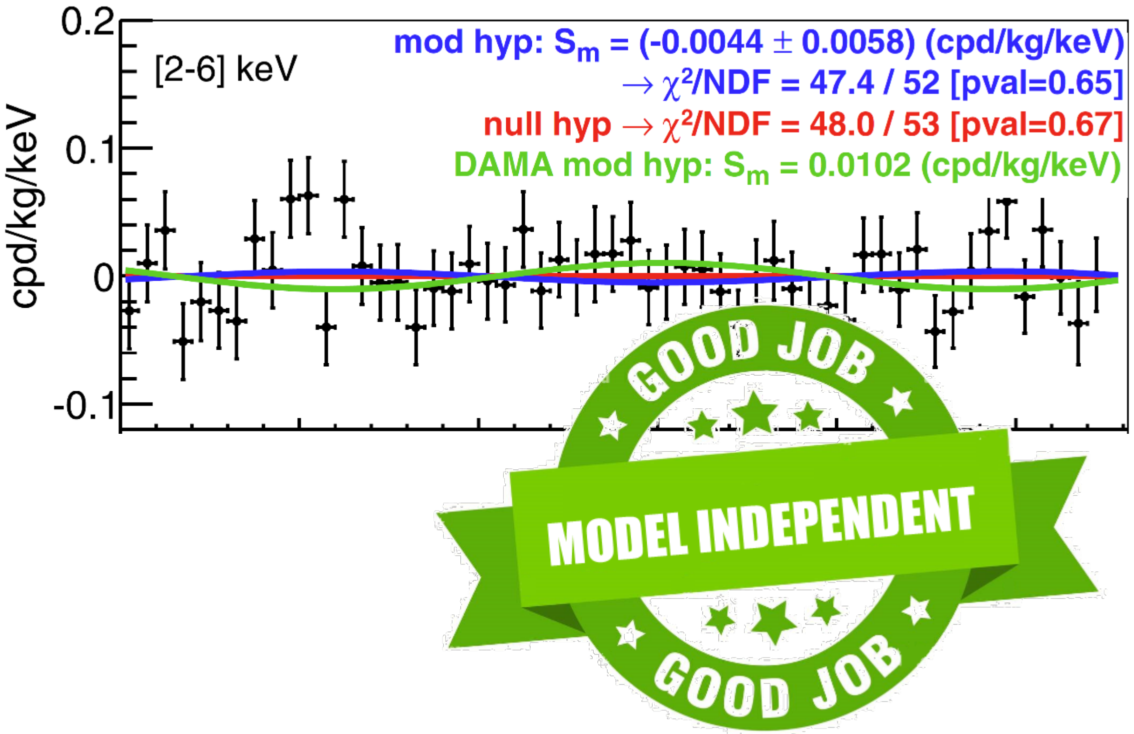
DAMA/LIBRA clearly sees an **annual modulation at 13.7σ compatible with DM**, nevertheless the **best fit WIMP parameter's region is excluded** by other experiments (with different targets)

(BUT YOU NEED A WIMP MODEL TO COMPARE!)

Testing DAMA/LIBRA



Use same target, NaI(Tl), and look for an annual modulation

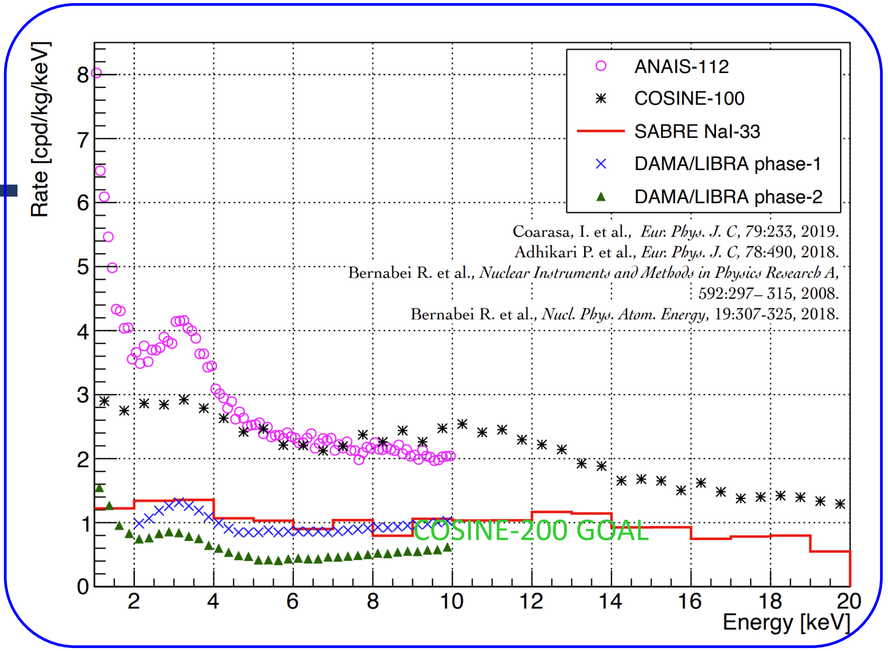


Testing the DAMA/LIBRA signal

Experimental requirements

- **Target: NaI / NaI(Tl)**
- Large exposure
- Very stable operation conditions
- Energy threshold: 1 keVee

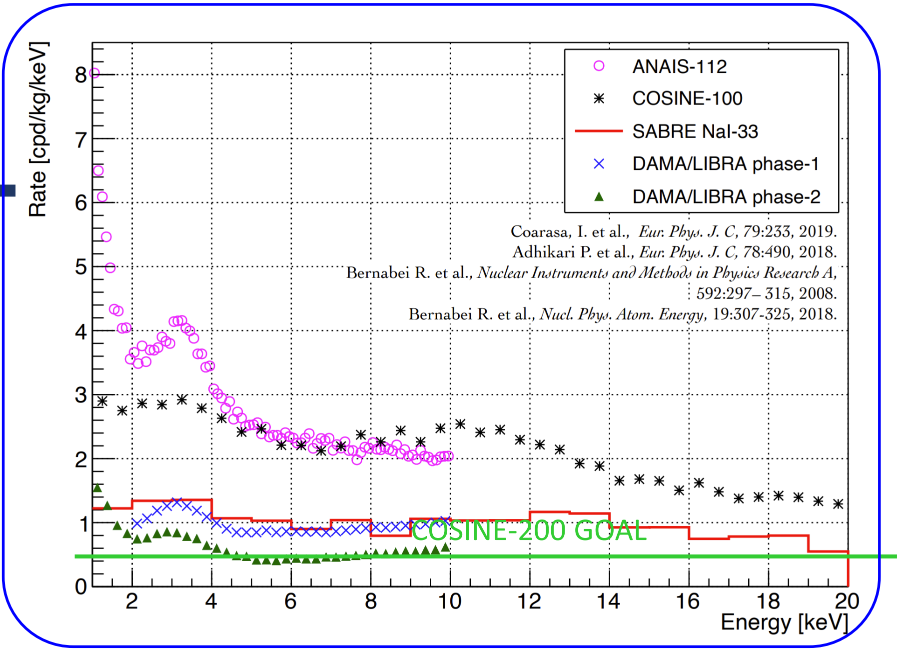
Testing the DAMA/LIBRA signal



Experimental requirements

- **Target: NaI / NaI(Tl)**
- Large exposure
- Very stable operation conditions
- Energy threshold: 1 keVee
- Background level as low as possible (DAMA: 1 cpd/kg/keV @ 2 keVee)

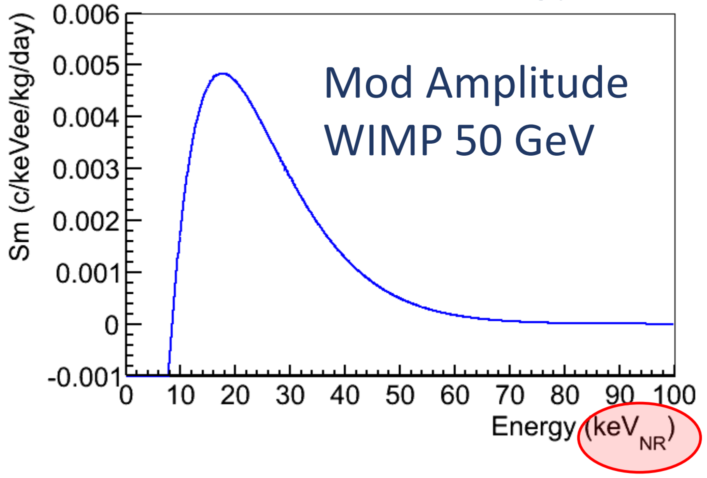
Testing the DAMA/LIBRA signal



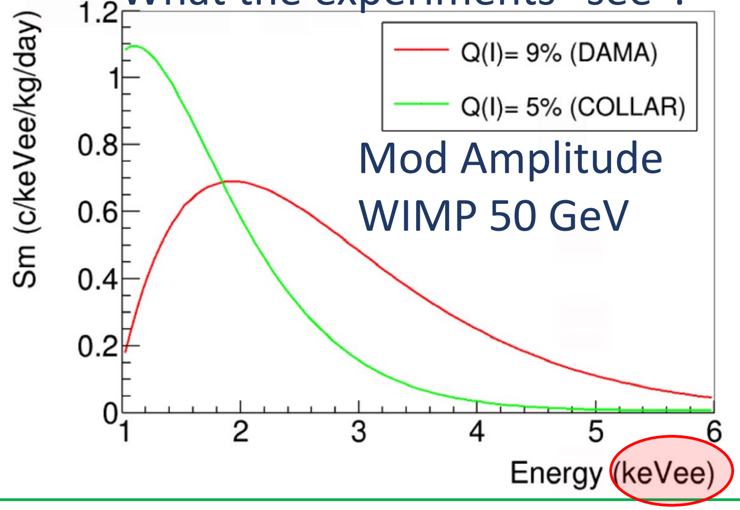
Experimental requirements

- **Target: NaI / NaI(Tl)**
- Large exposure
- Very stable operation conditions
- Energy threshold: 1 keVee
- Background level as low as possible (DAMA: 1 cpd/kg/keV @ 2 keVee)
- Good knowledge of the detector response to nuclear recoils

The “true” NR energy is:

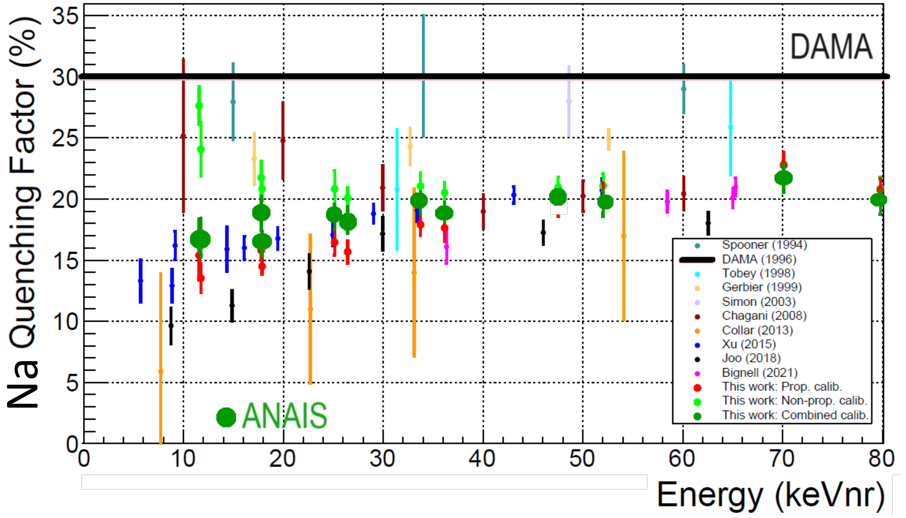


What the experiments “see”:

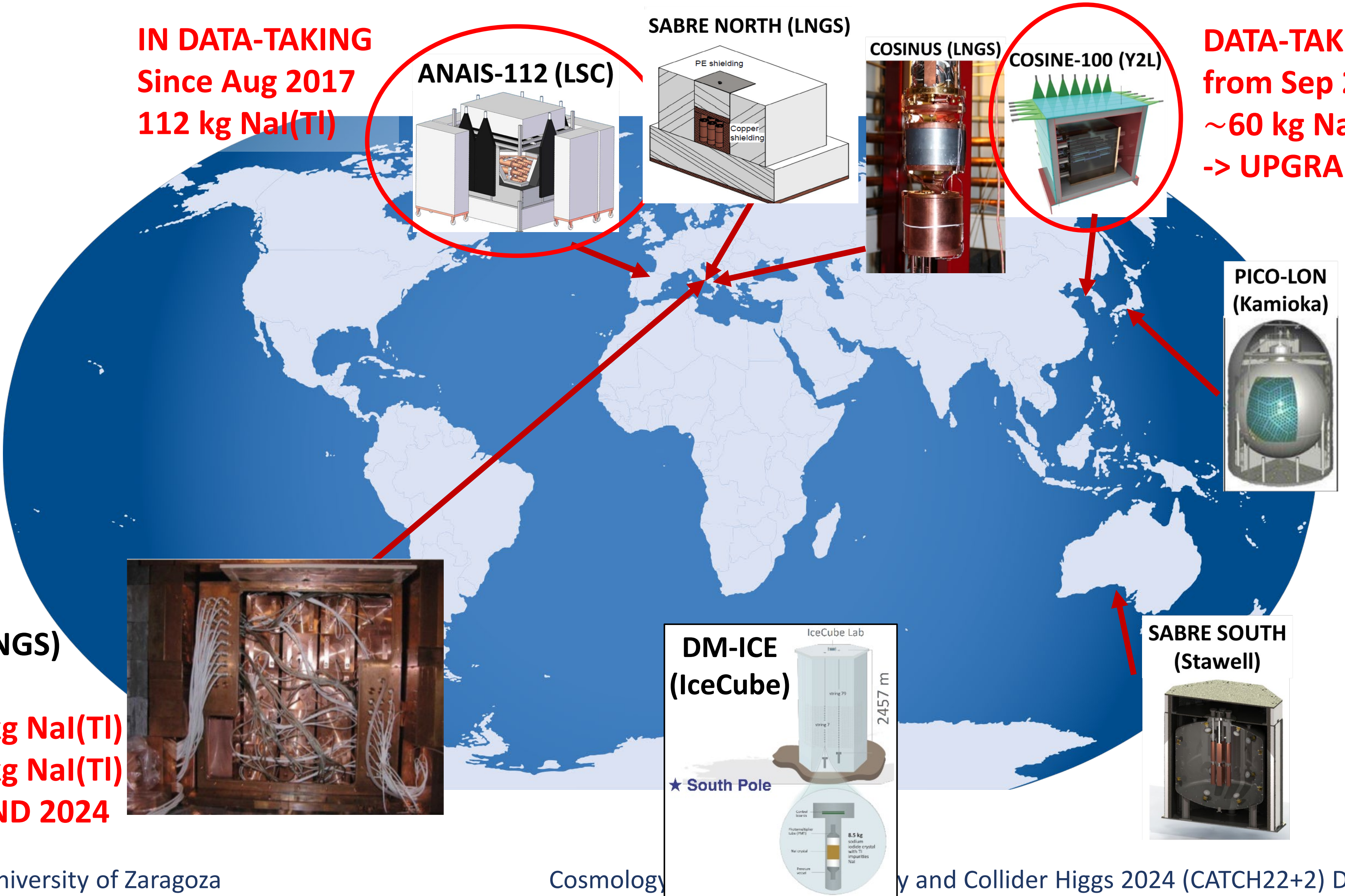


$$QF = \frac{signal_{NR}/keV}{signal_{ER}/keV}$$

Cintas et al, 2402.12480



Testing the DAMA/LIBRA signal



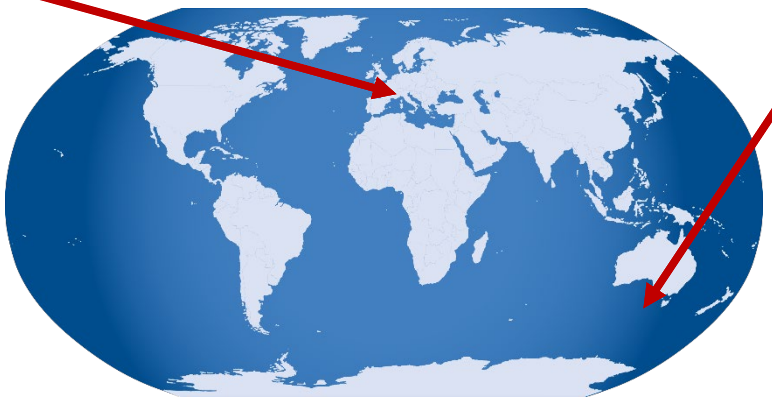
IN DATA-TAKING
Since Aug 2017
112 kg NaI(Tl)

DATA-TAKING
from Sep 2016 – Mar 2023
~60 kg NaI(Tl)
-> UPGRADE COSINE200

DAMA/LIBRA (LNGS)
IN DATA-TAKING
Since 1995 100 kg NaI(Tl)
Since 2003 250 kg NaI(Tl)
Stop foreseen END 2024

SABRE (North & South)

Sabre North:
same location as
DAMA/LIBRA
(LNGS, Italy)



SABRE South
Southern hemisphere location (SUPL)
(seasonal effects inverted)

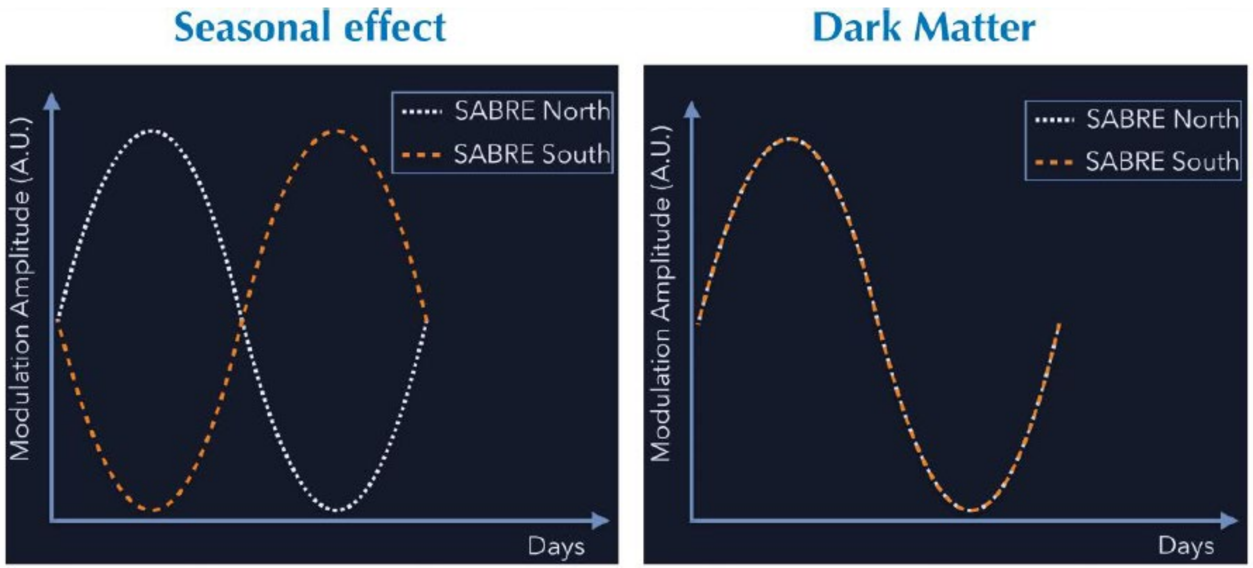
STAWELL UNDERGROUND PHYSICS LAB

SABRE South will be the first experiment in SUPL

“Twin experiments”

- Same detector module concept (ultra-pure NaI(Tl)
- Common DAQ and software frameworks
- Common simulation

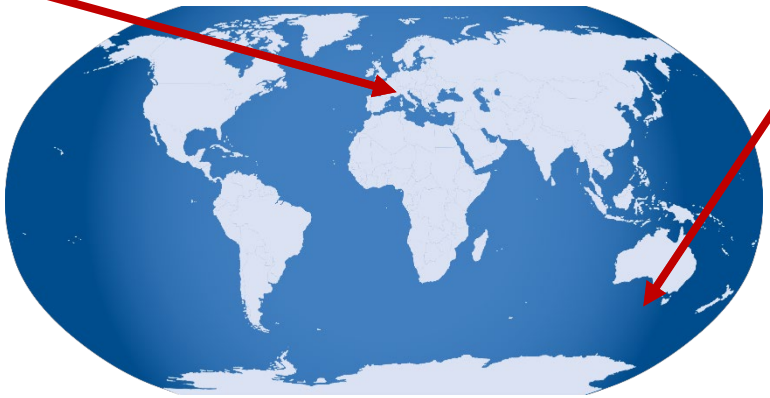
Goal: discard seasonal effects in modulation signal



G. D’Imperio (TAUP23)

SABRE (North & South)

Sabre North: same location as DAMA/LIBRA (LNGS, Italy)

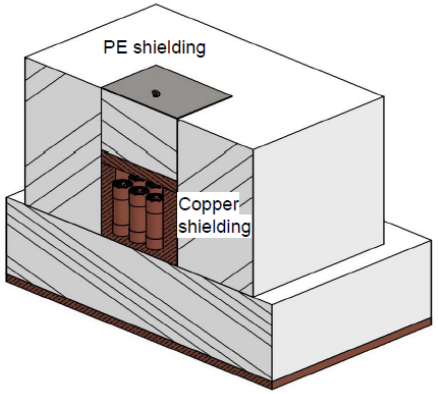


SABRE South
Southern hemisphere location (SUPL) (seasonal effects inverted)

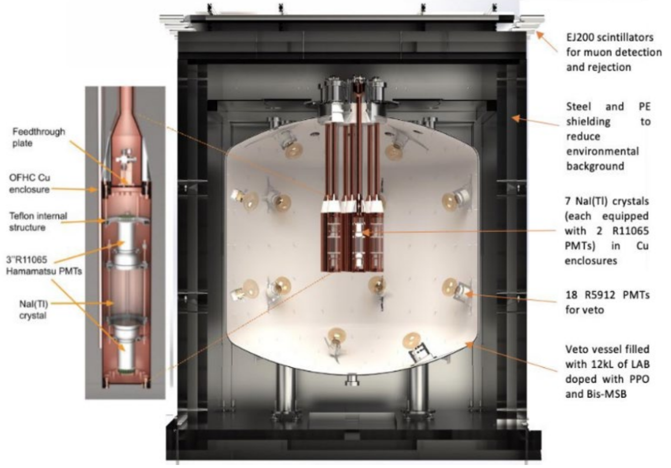
STAWELL UNDERGROUND PHYSICS LAB

SABRE South will be the first experiment in SUPL

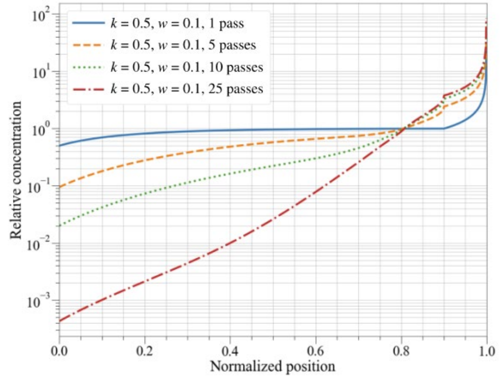
3x3 NaI matrix with 15 cm copper and 80 cm polyethylene



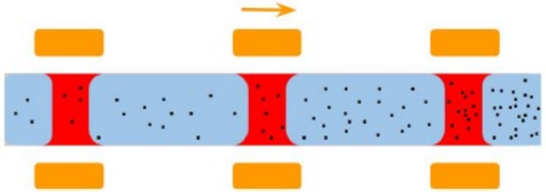
SABRE-NORTH:
3x3 NaI(Tl) matrix, 5 kg each
TDR due in summer 2024



liquid scintillator tank to reject coincident events (^{40}K!)



Large effort to build ultrapure NaI(Tl) crystals
Goal: 0.5 cpd/kg/keV
Zone refining
Reduce:
Pb of factor ~3
K factor ~10

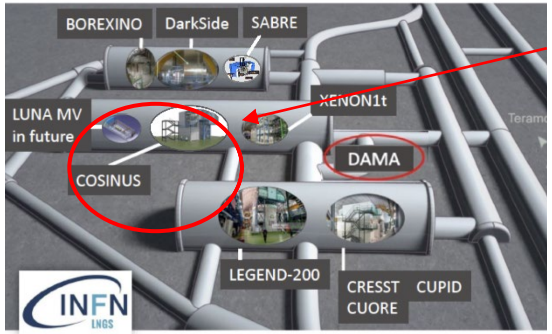


impurities are pushed to the end of the refining tube

SABRE-SOUTH:
Commissioning in 2024 with 50 kg NaI(Tl)

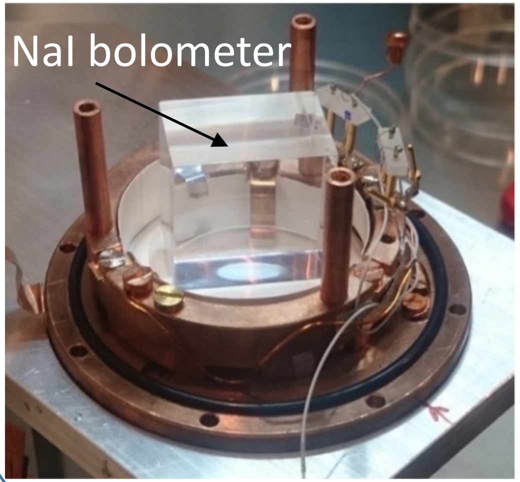
COSINUS

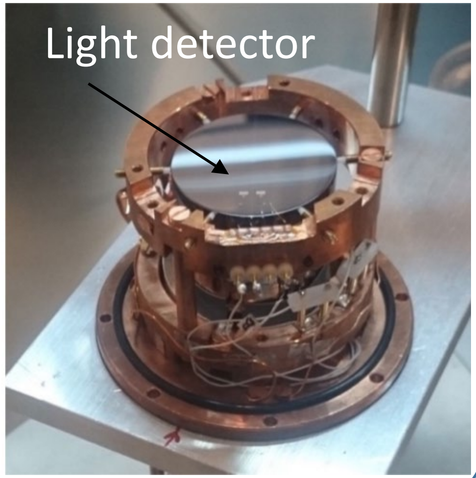
J. Low Temp. Phys. 193 (2018) 1174
JINST 12 (2017) P11007



same location as DAMA/LIBRA (LNGS, Italy)

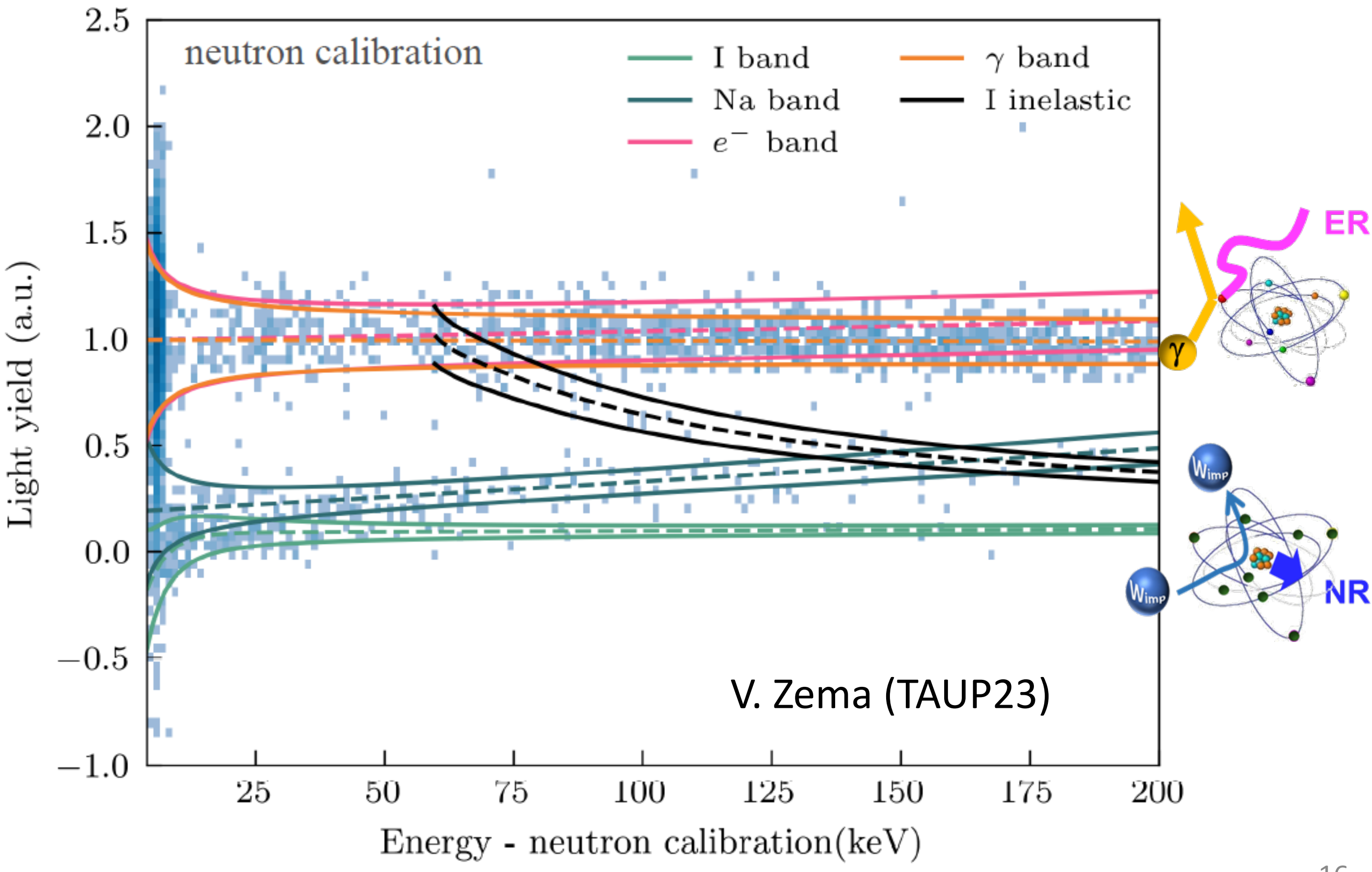
NaI as a cryogenic detector → two energy readouts: HEAT and LIGHT



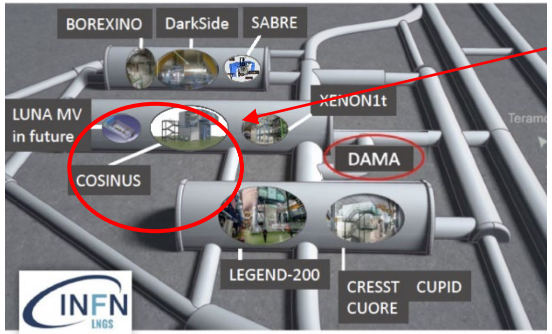


First NaI detector with particle discrimination

With a moderate exposure of few O(100) kg-days , can confirm or rule-out a **nuclear recoil origin** of the DAMA/LIBRA dark matter claim



COSINUS



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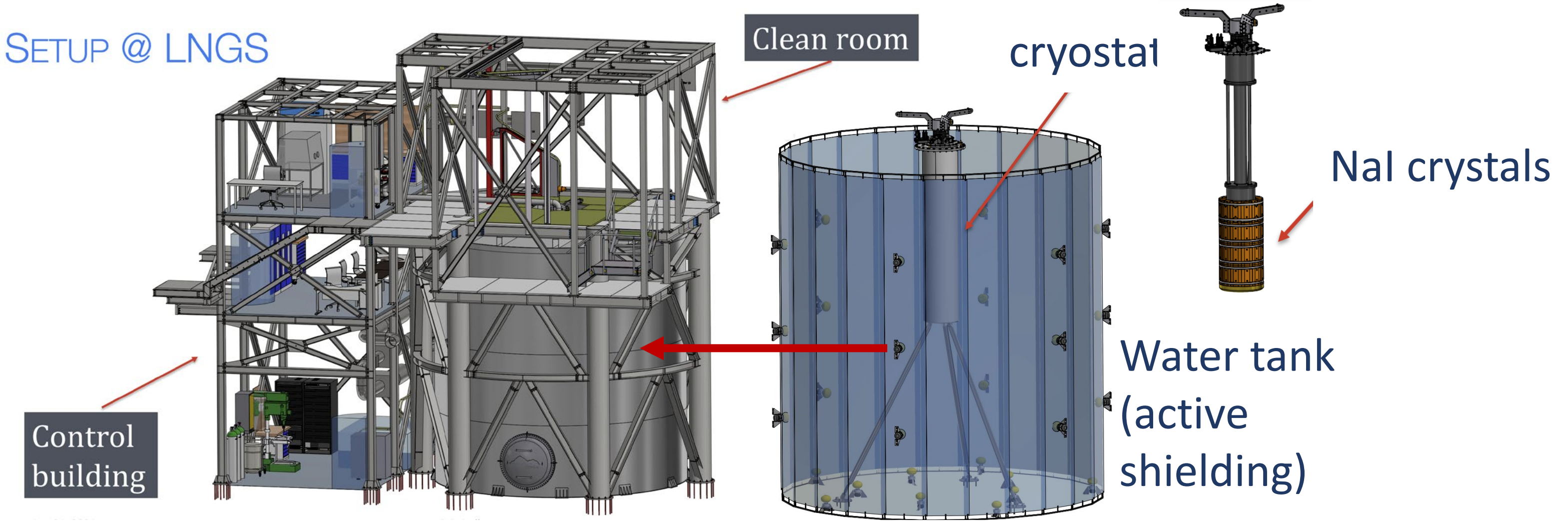
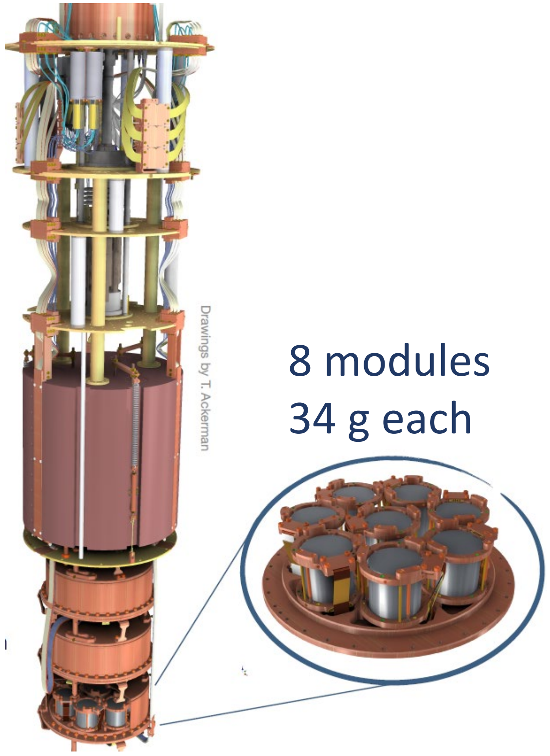




8 modules
34 g each

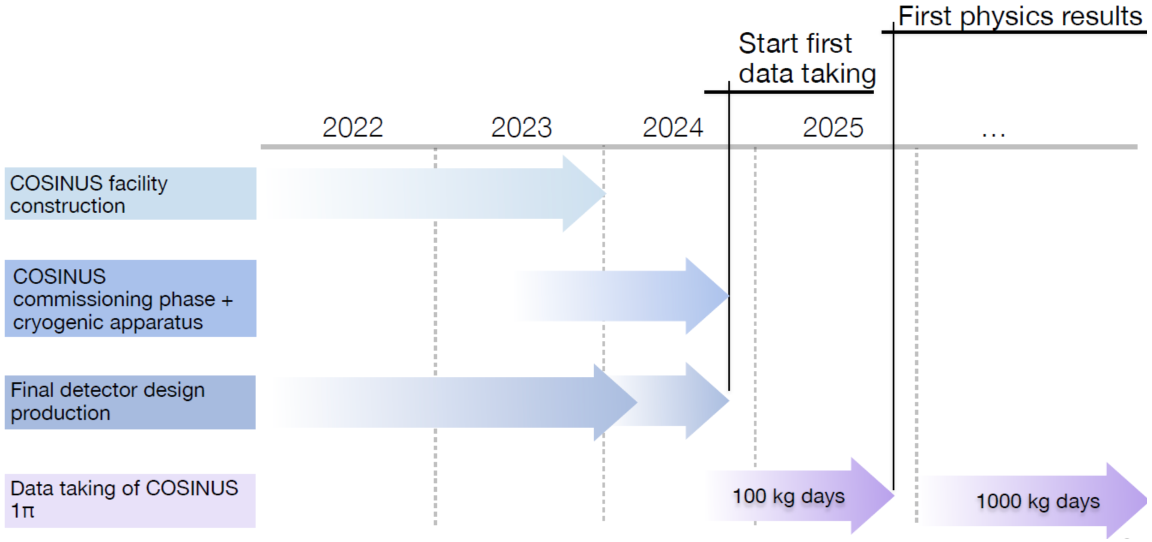
COSINUS 1π (2024-2027)

Probing any DM-nuclei interactions compatible with DAMA/LIBRA signal

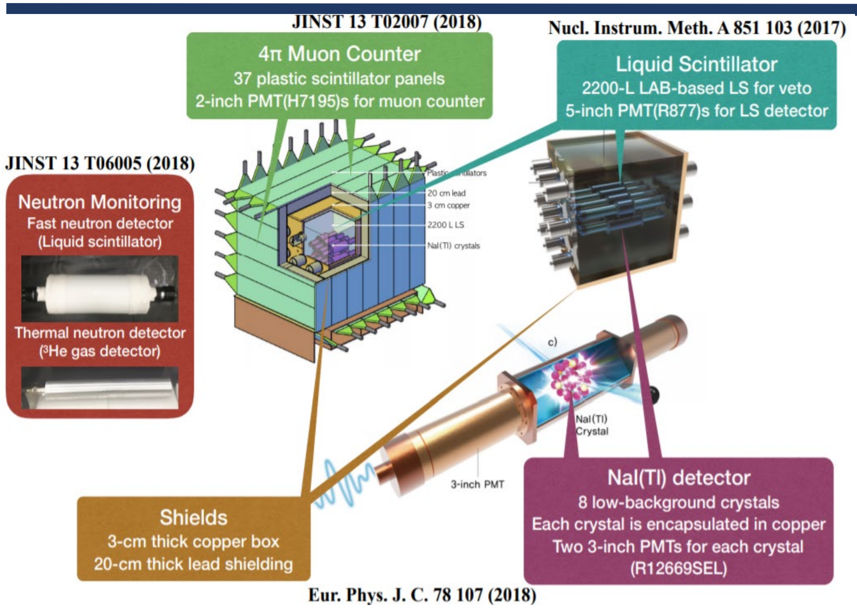
- 100 kgxday (8 modules, 34 g each)
- 1000 kg×day (24 modules, 34 g each)

COSINUS 2π (>2027)

Investigating annually modulating signals

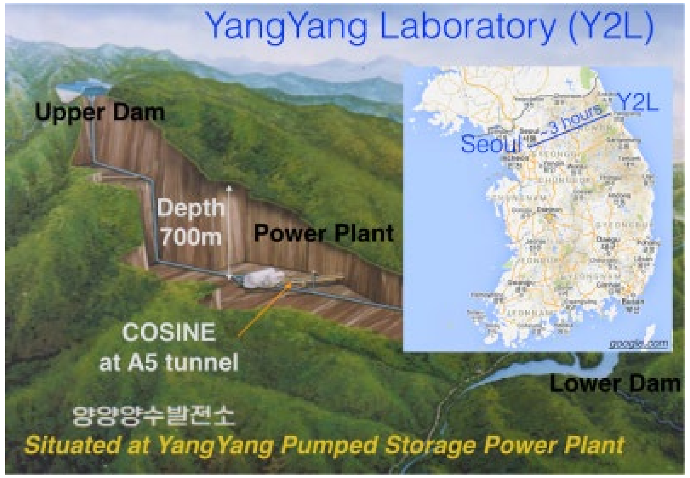


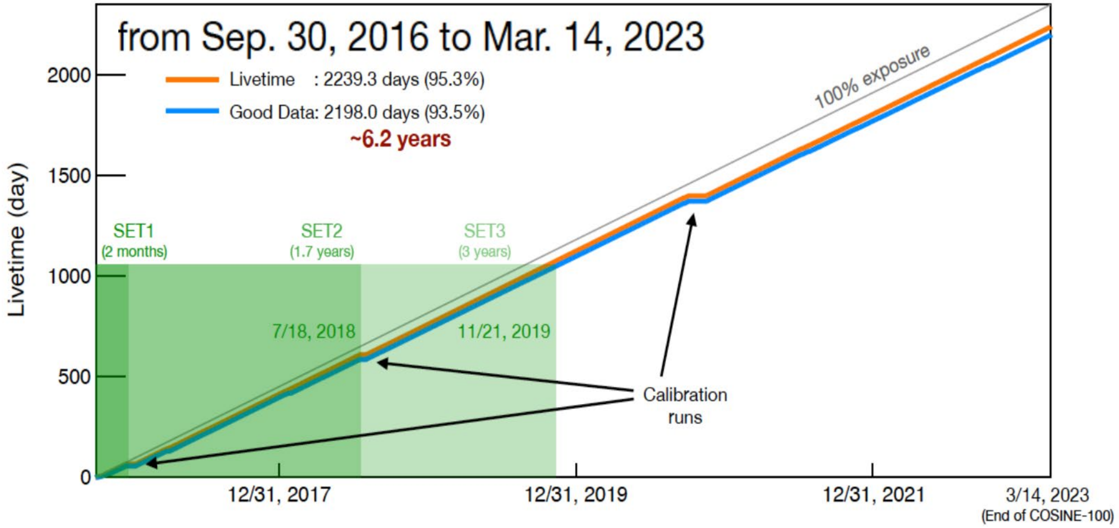
COSINE-100 & COSINE-200



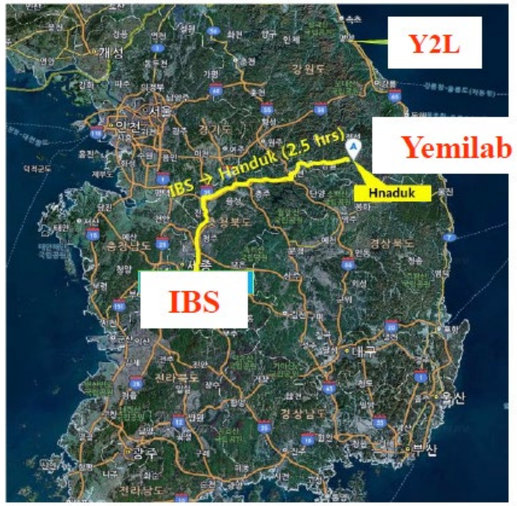
COSINE-100

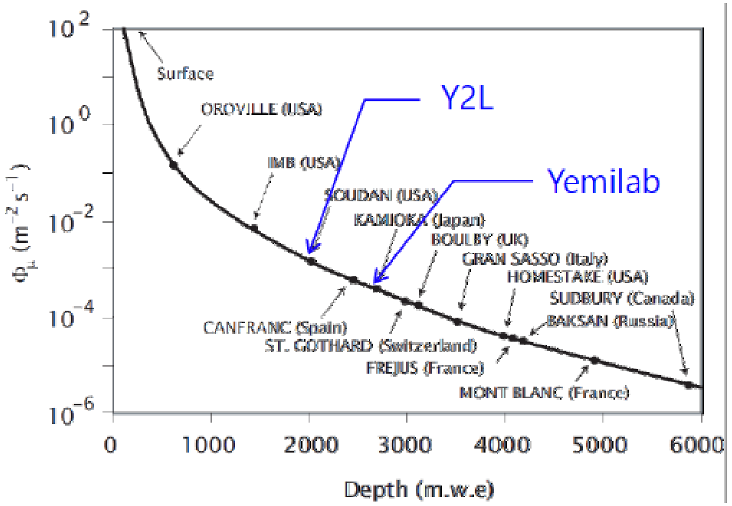
- 106 kg NaI(Tl), **but only ~60 kg usable for DM search**
- liquid scintillator tank to reject coincident events (^{40}K!)
- **Data-taking started in Sep 2016** @YangYang (South Korea), **END in Mar 2024**



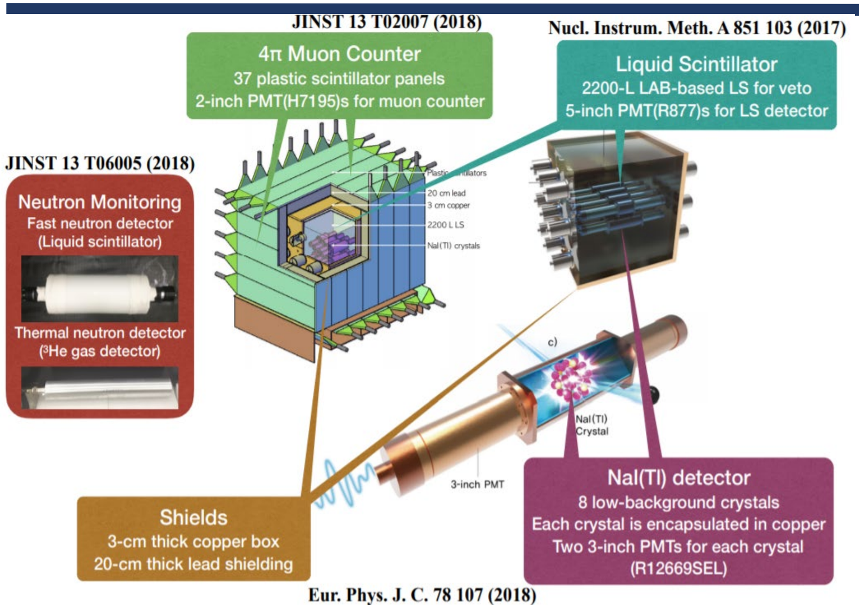


NOW moving to YEMILAB -> COSINE100U, COSINE200





COSINE-100 & COSINE-200



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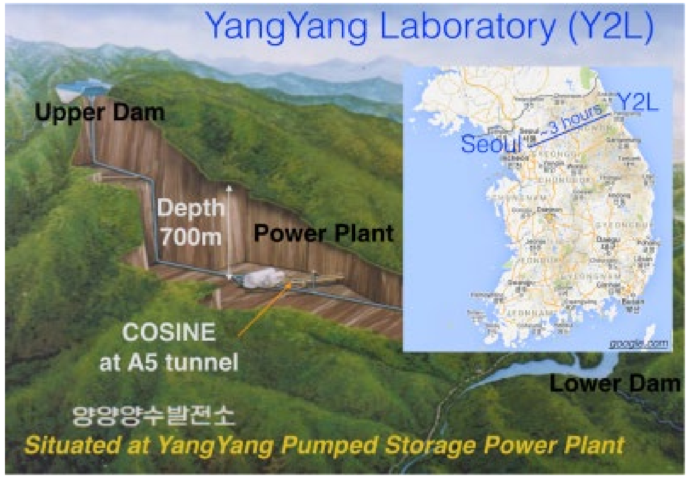
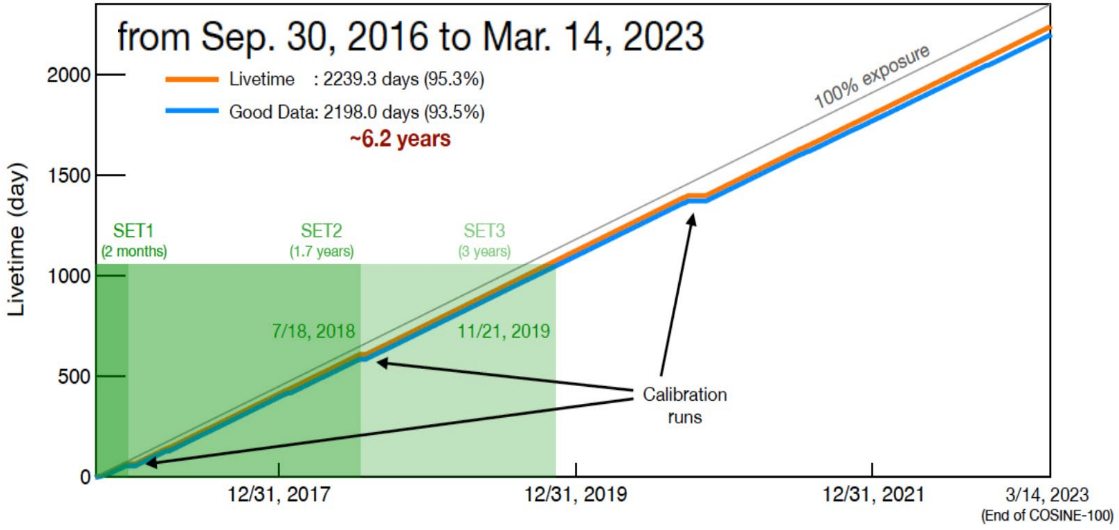
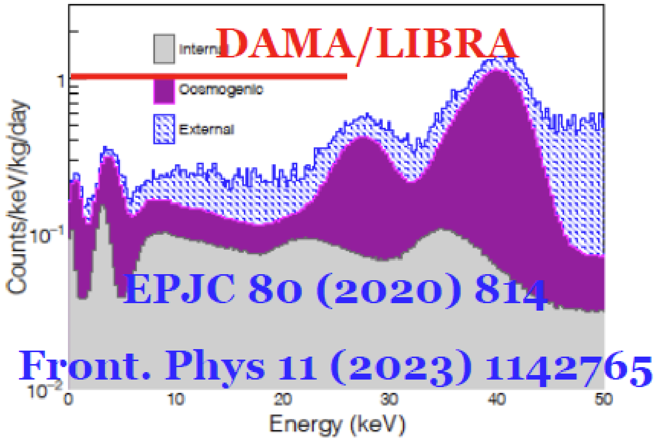




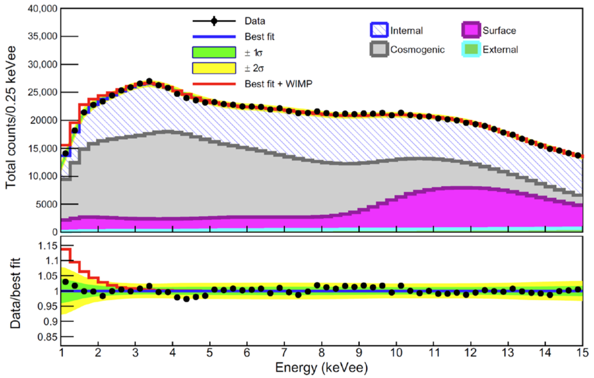
COSINE-200

- 200 kg NaI(Tl) in a liquid scintillator tank
- Large effort to purify the NaI(Tl) cristal. Expected <0.5 cpd/keV/kg @ RoI
- To be installed in the short-mid term @ Yemilab

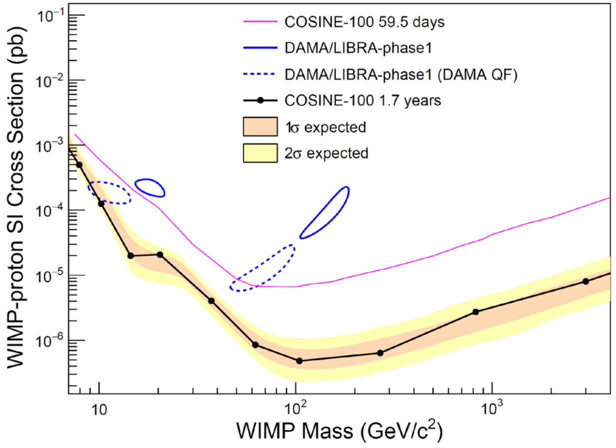


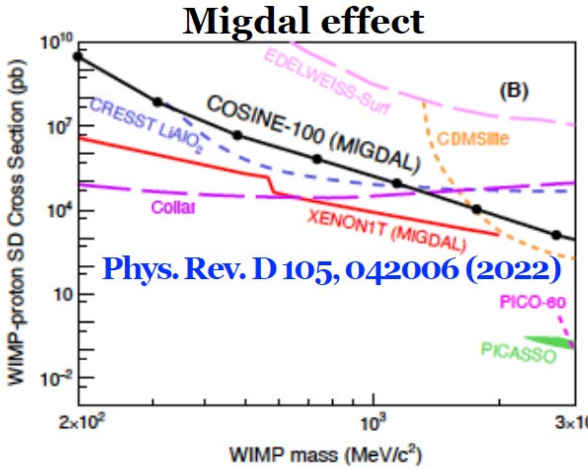
COSINE-100 results

MODEL DEPENDENT ANALYSIS: 1.7 yr (97.7 kg·yr) E_{th}=1 keV



Sci. Adv. **7**, eabk2699 (2021)

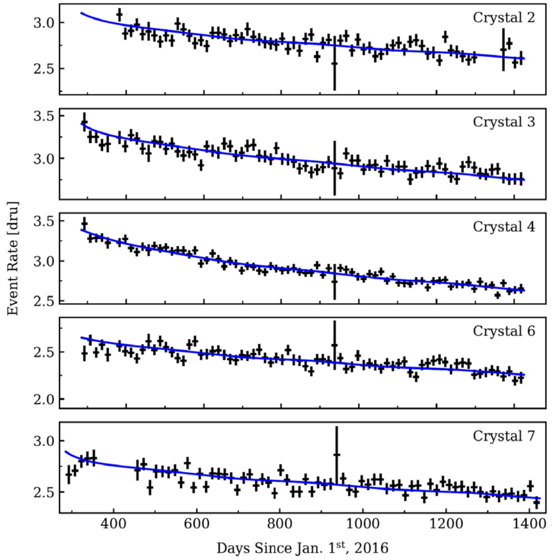


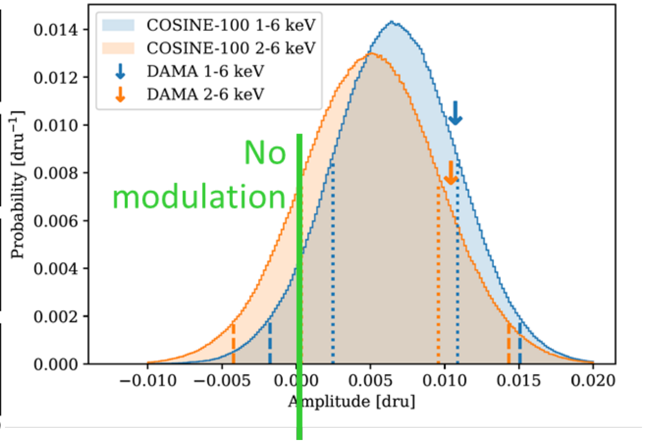


MODEL INDEPENDENT ANALYSIS: 2.8 yr (173 kg·yr)

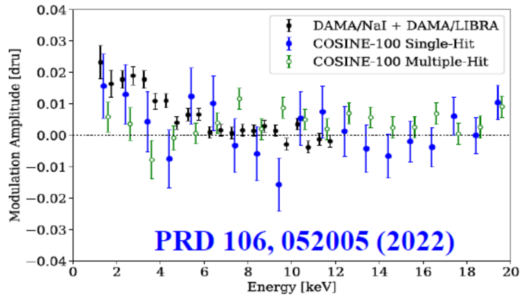
$[1-6]$ **keV:** $S_m = 0.0067 \pm 0.0042$ **cpd/keV/kg**

$[2-6]$ **keV:** $S_m = 0.0050 \pm 0.0047$ **cpd/keV/kg**





PRD 106, 052005 (2022)



1-6 keV modulation amplitude

COSINE-100	**0.0067 ± 0.0042**
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	-0.0034 ± 0.0042

ANAIS-112

https://gifna.unizar.es/anais/

Universidad Zaragoza

LSC Laboratorio Subterráneo de Canfranc

Annual Modulation with NaI Scintillators

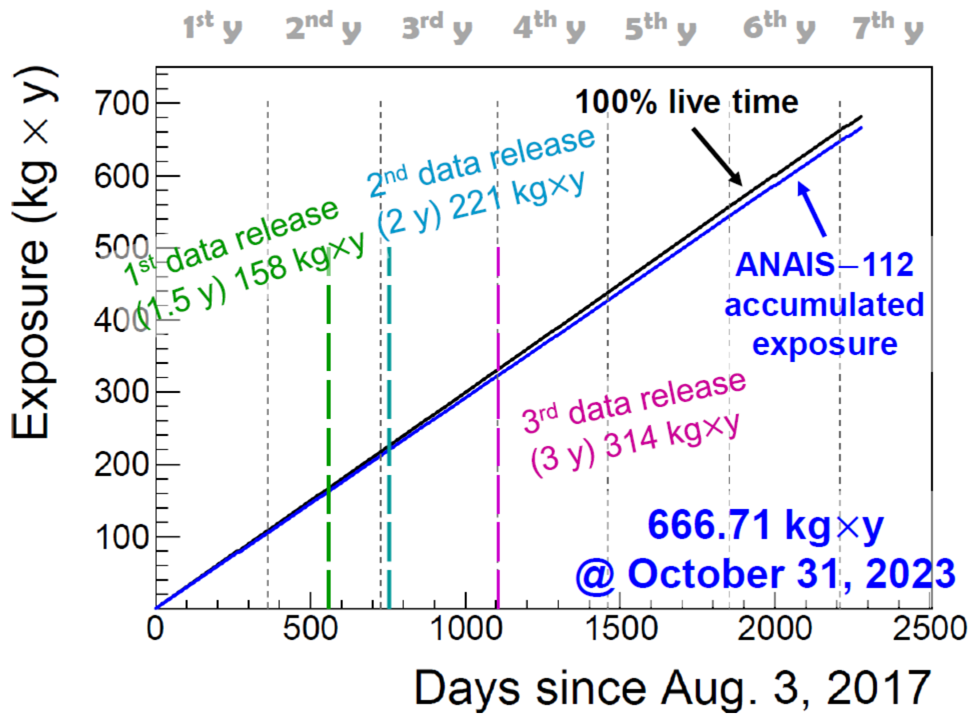
3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules = **112.5 kg** of active mass

Two high QE PMTs per detector

taking data since August 2017 at the Canfranc Underground Laboratory (LSC) Spain (2450 m.w.e.)

ANAIS-112 data releases:

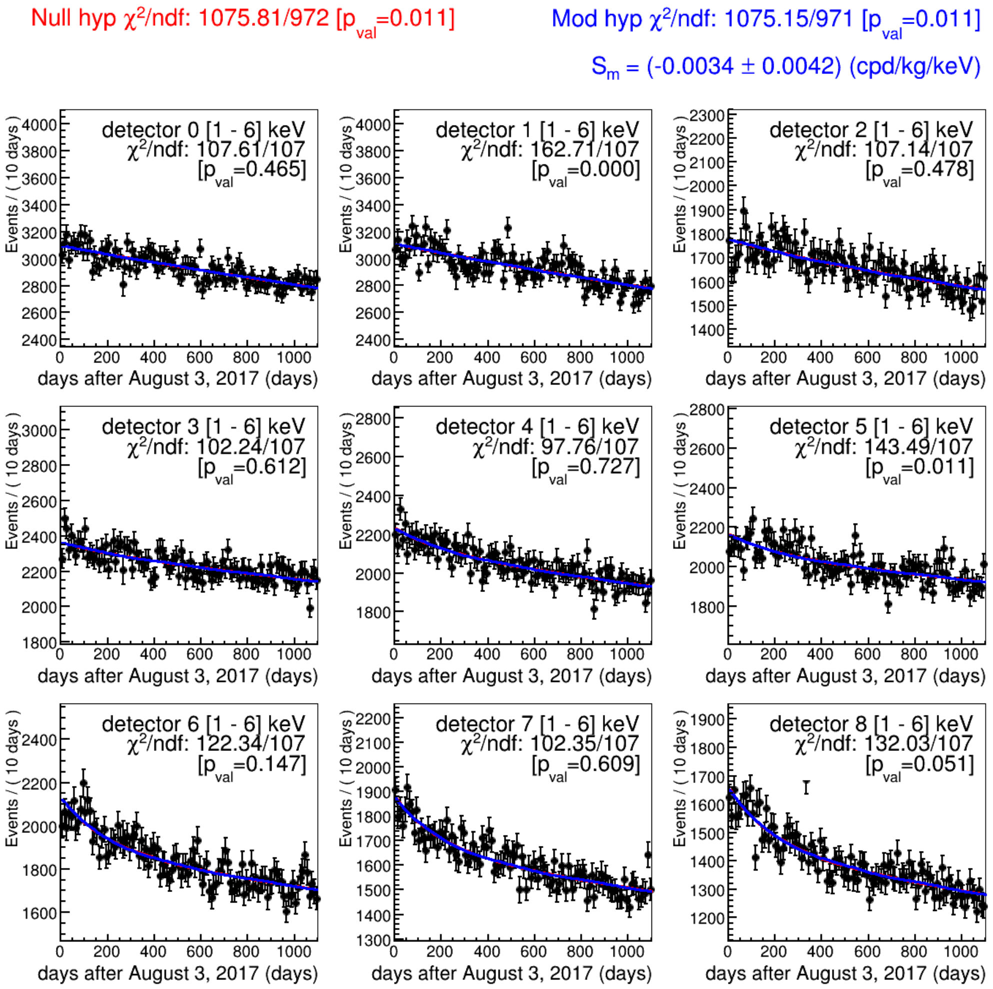
- 1.5y: Phys. Rev. Lett. 123, 031301 (2019)
- 2y: J. Phys. Conf. Ser. **1468,** 012014 (2020)
- 3y: Phys. Rev. D 103, 102005 (2021
- **3y + ML: 2404.17348**



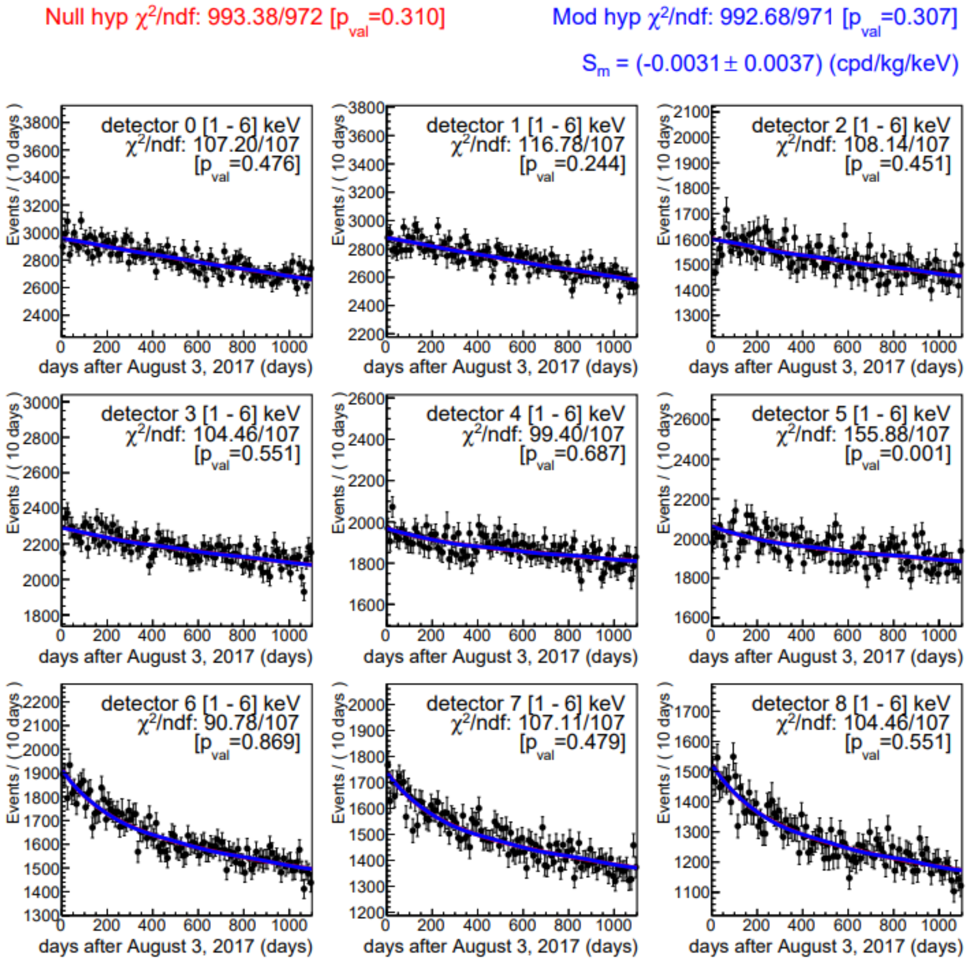
Improved 3-years results [1-6] keV $2.5\sigma \rightarrow 2.8\sigma$

NEW

PRD 103, 102005 (2021)



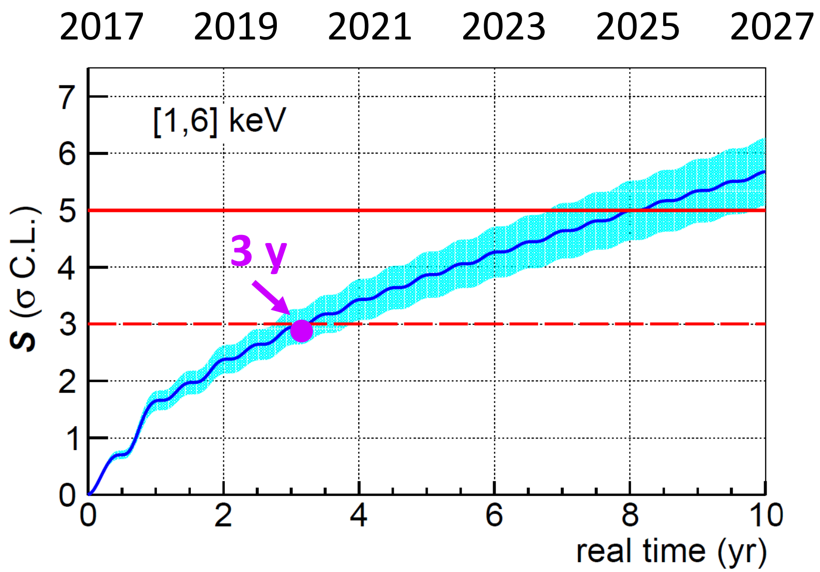
Coarasa et al, 2404.17348

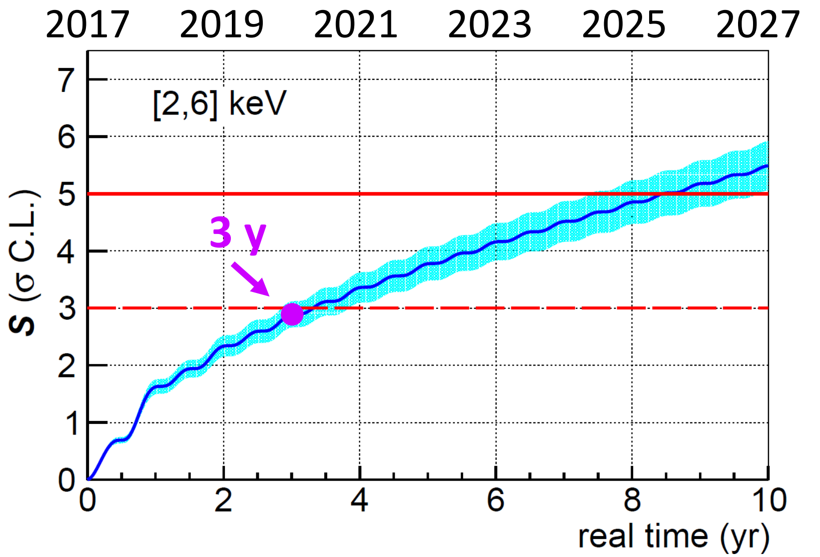


Thanks to the support of the Dark Matter Data Center, funded by the ORIGINS excellence cluster, **ANAIS-112 3-years data is freely available for downloading @** https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais

ANAIS-112 3-years annual modulation with ML

Coarasa et al, 2404.17348





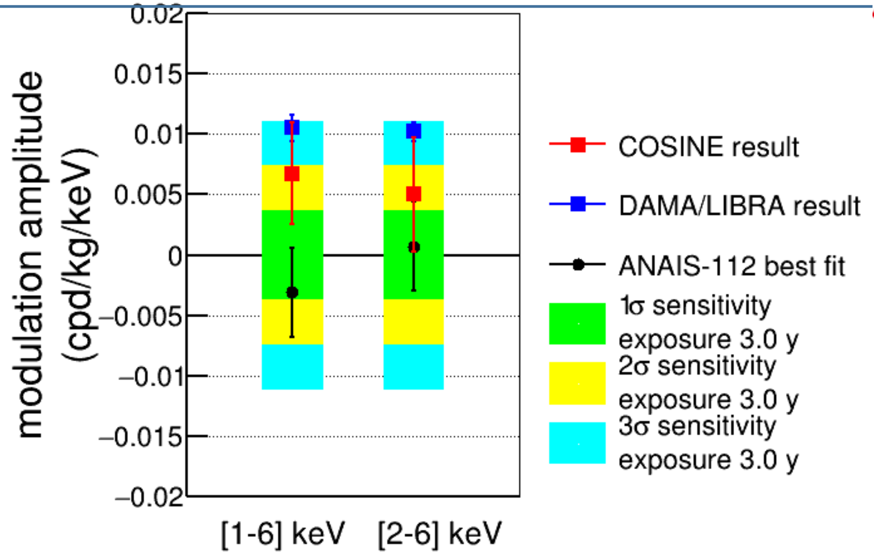
best fit modulation amplitudes compatible with zero at ~1σ

Best fit incompatible with DAMA/LIBRA at 3.9 (2.8) σ for [1-6] ([2-6]) keV

Sensitivity with 3 years data: 2.8σ for [1-6] & [2-6] keV

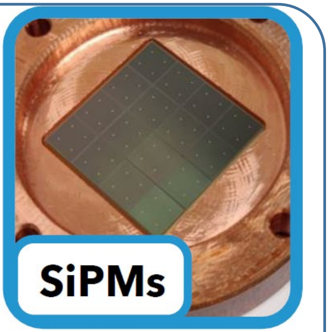
5σ sensitivity at reach in late 2025

NEW



	S_m(cpd/keV/ton)		
E (keV)	**ANAIS-112**	**COSINE-100**	**DAMA/LIBRA**
[1-6]	-3.7±3.7	6.7±4.2	10.5±1.1
[2-6]	0.7±3.7	5.0±4.7	10.2±0.8

Next step: ANAIS+

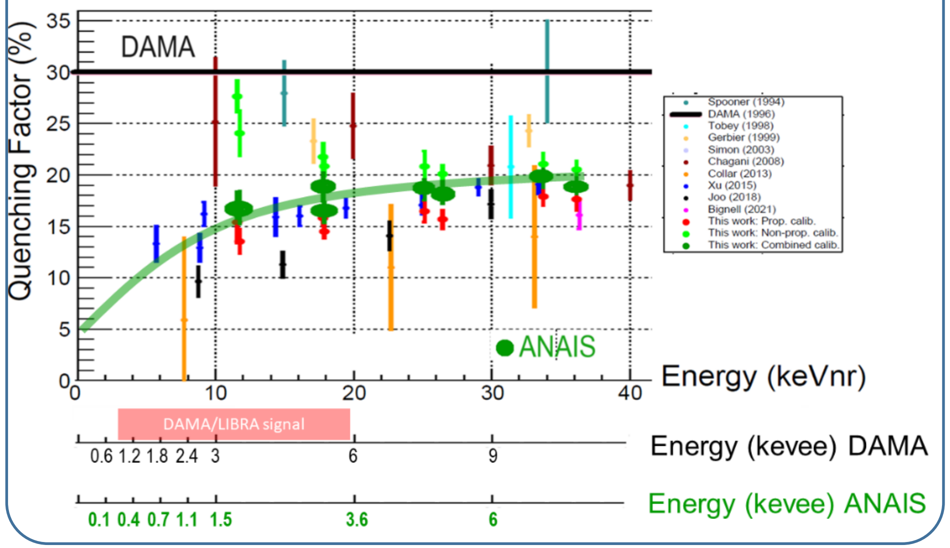


Replace PMTs for SiPM at low T (∼100 K)

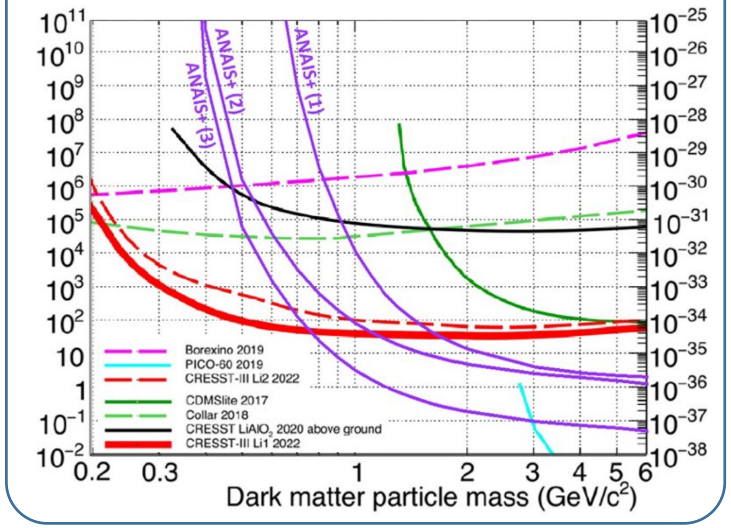
- Reduce "light noise" coming from the PMT
- Increase QE of the light detector
- Increase light yield (NaI very good scintillator at cold)

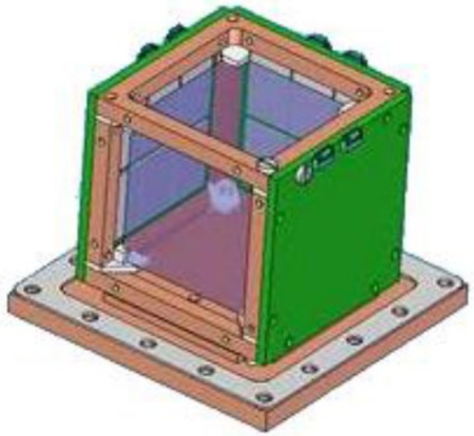
Energy threshold ∼ 100 eV could be achieved

rule out any effect related to QF differences



Very sensitive to light WIMPs (SI, SD)





First prototype in construction

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

INFN LNGS

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Outlook & Summary

- DAMA/LIBRA has already reached 2.86 ton×yr over 22 annual cycles . It observes a clear modulation with amplitude Sm =10.5±1.1 (10.2±0.8) cpd/keV/ton in [1–6] ([2–6]) keV energy region with very high CL (13.7σ)
  - DAMA/LIBRA will stop data-taking by the end 2024. Plan to measure again the quenching factors of their crystals
- Currently, many efforts trying to provide an independent test of DAMA/LIBRA signal with the same target.
  - COSINE-100 (1.7 y) rule out DAMA/LIBRA signal [background subtraction, model-dependent]
  - ANAIS-112 (3 y) annual modulation (model independent) analysis do not confirm DAMA/LIBRA signal (2.8σ)
- In the short-term:
  - ANAIS-112 plan to unblind 6 y data in summer 2024 (expected sensitivity: 4.5σ). 5σ sensitivity in late 2025.
  - ANAIS-112/COSINE-100 working to combine results. Preliminary 3 y combination in summer 2024
- In the medium/long term:
  - COSINUS 1π will confirm or rule-out a nuclear recoil origin of the DAMA/LIBRA signal
  - SABRE NORTH/SOUTH will check for seasonal effects in the modulation signal
  - COSINE-200 will check the signal with high statistics / low background
  - ANAIS+/ COSINUS 2π : rule out any effect related to quenching factors differences

} interesting searches for DM, independently of DAMA

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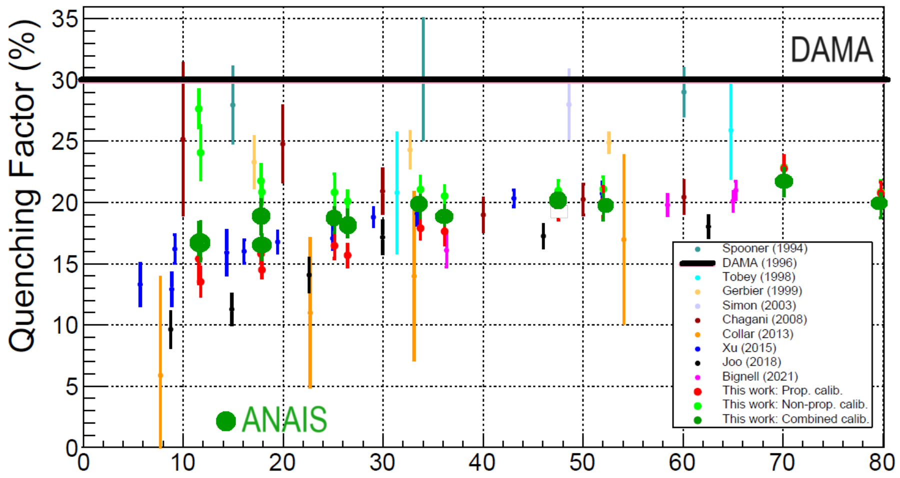
} interesting searches for DM, independently of DAMA

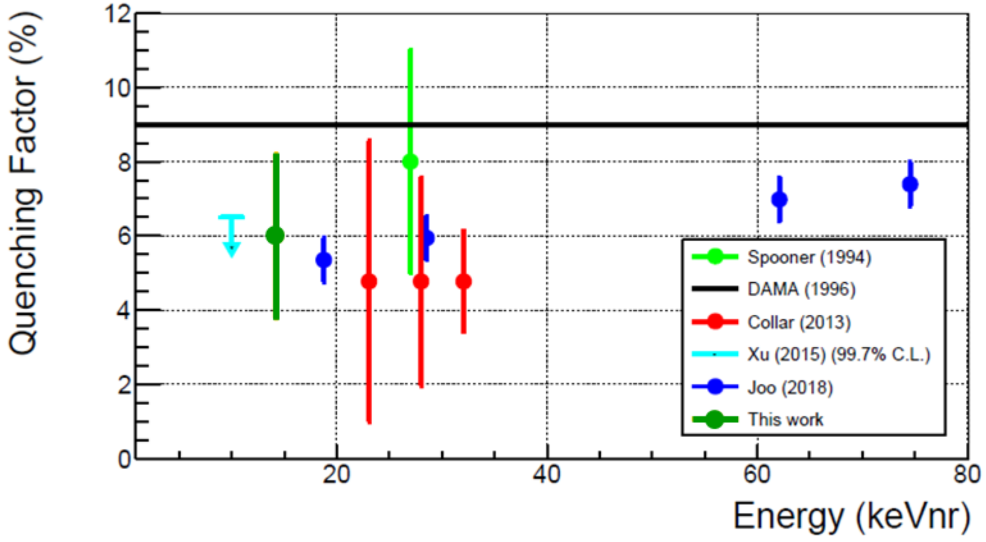
Thanks!!

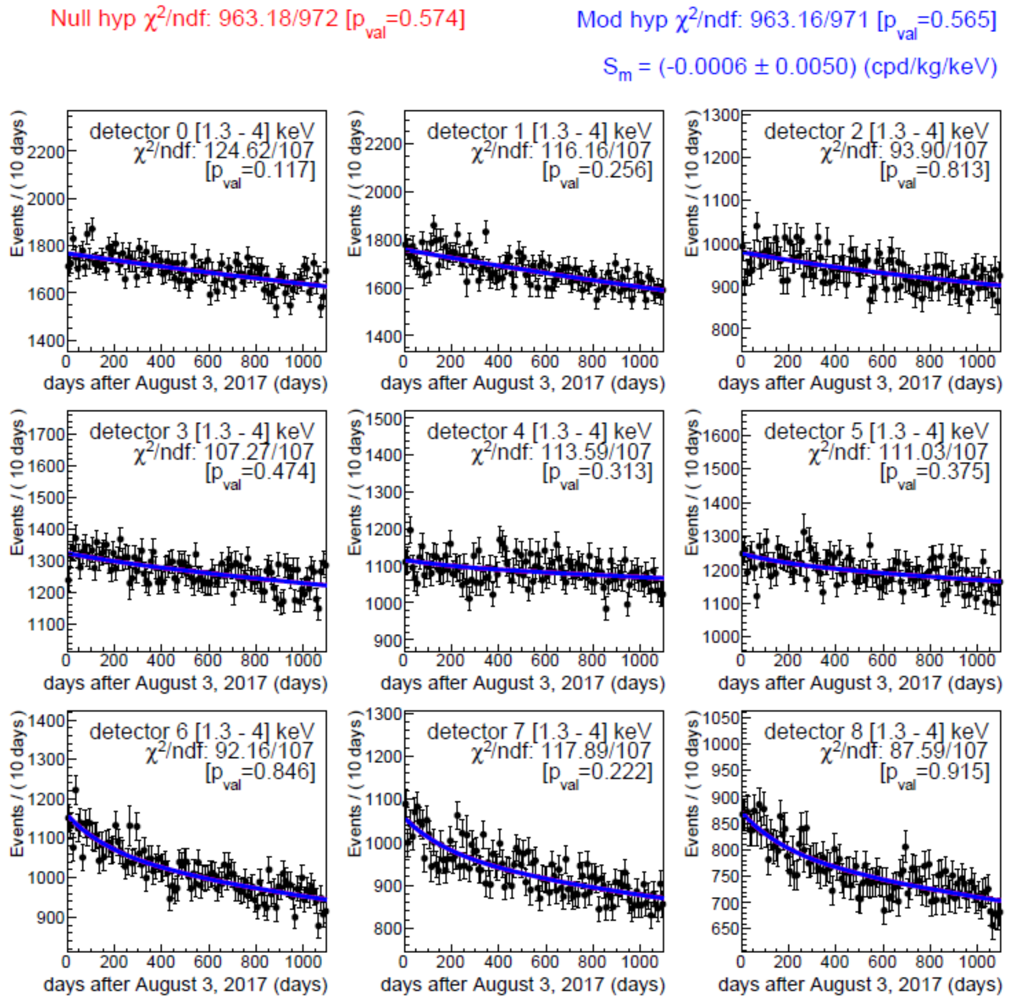
gifna.unizar.es/anais/

Backup

ANAIS-112 3y with different QF





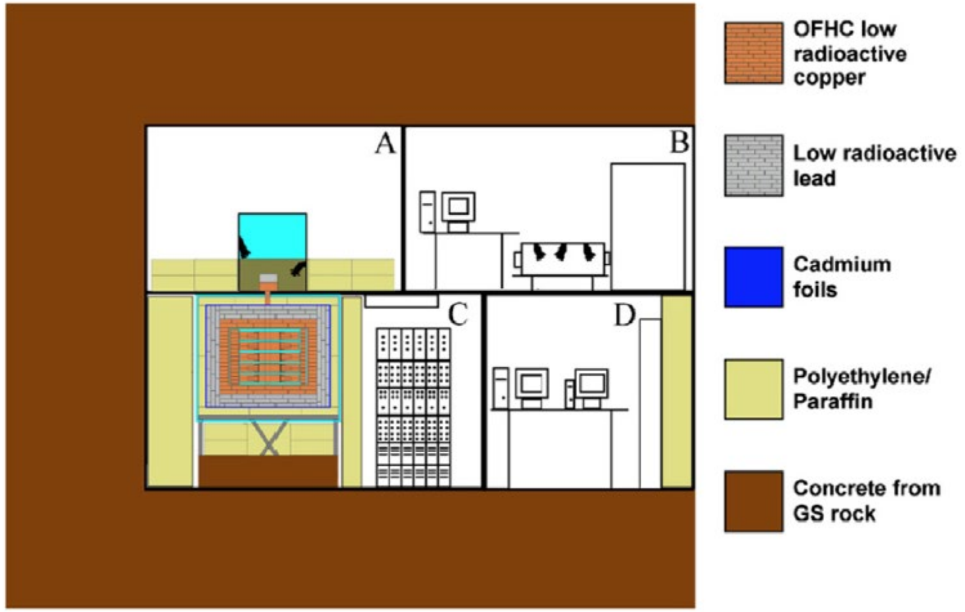


Result compatible with no modulation (~2σ)

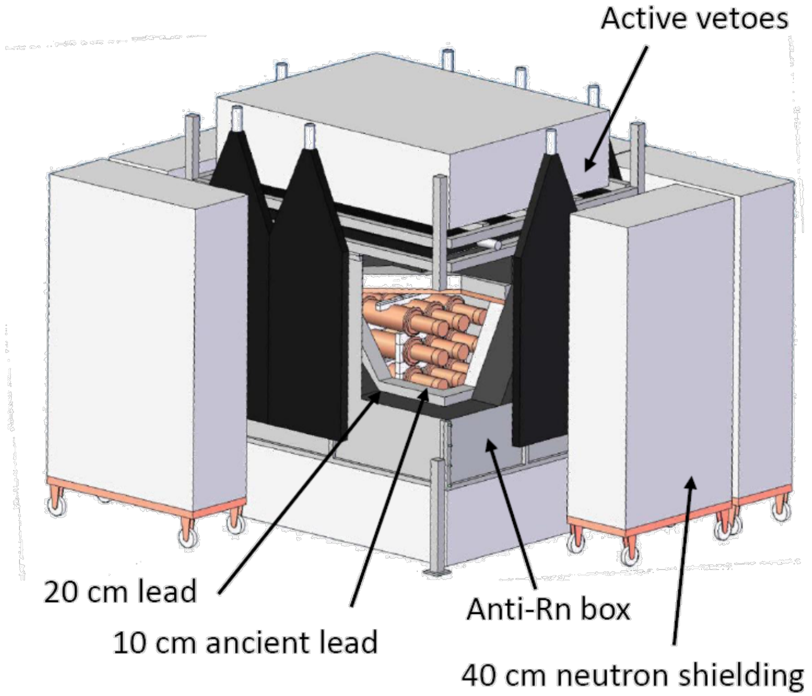
What is different wrt DAMA/LIBRA

Shielding

- Gamma shielding:
  >10 cm of OFHC Cu + 15 cm of Pb
- Anti-Rn: Plexiglas box fluxed with N2 gas
- Neutron shielding:
  10/40 cm Polyethylene/paraffin + Cd foils



- Gamma shielding:
  10 cm of ancient Pb + 20 cm of Pb
- Anti-Rn metallic box fluxed with N2 gas
- Active muon vetoes
- Neutron shielding:
  40 cm Polyethylene/water tanks

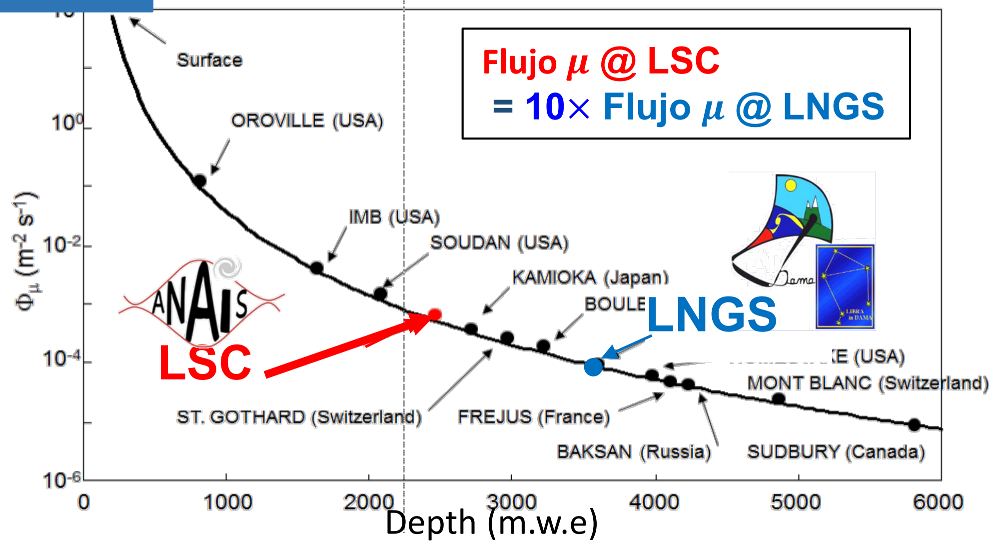


What is different wrt DAMA/LIBRA

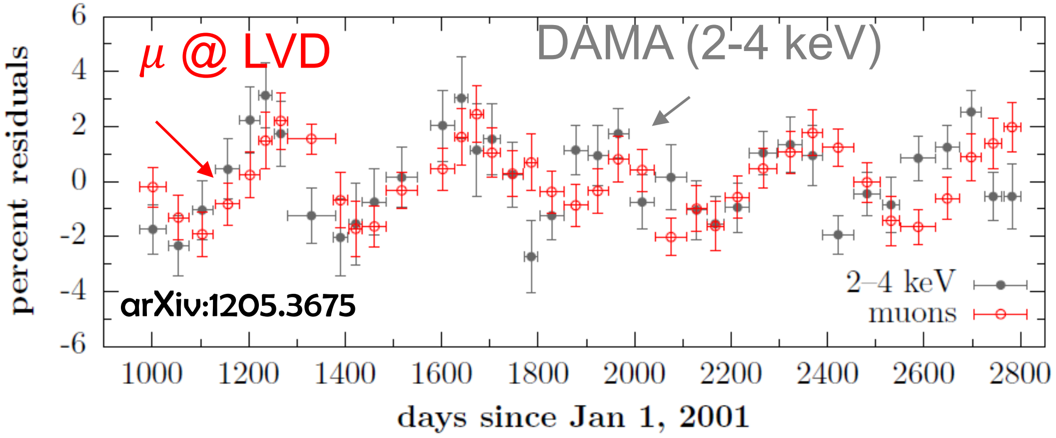
Muon veto

In ANAIS we flag every muon that cross the shielding
We set a (configurable) dead-time after every passage

DAMA/LIBRA has no muon veto



The underground muon flux is annual-modulated!



Can muons explain DAMA signal?

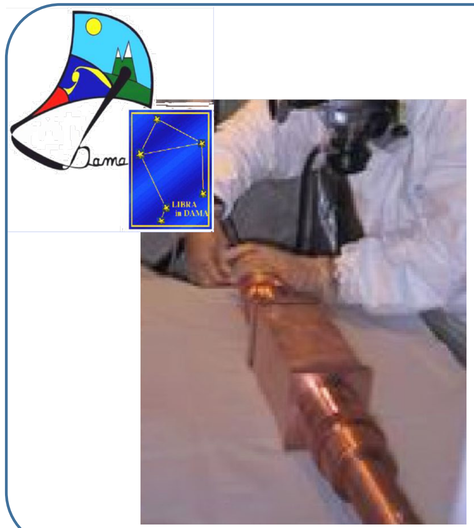
- Modulation phase inconsistency
- Muons interacting directly in the detectors do not fulfill the DM requisites
- Not enough muon-induced fast neutrons to account for the signal

But still some open questions:

- (delayed) effect of muons in PMTs?
- slow phosphorescence in NaI?

What is different wrt DAMA/LIBRA

NaI(Tl) scintillating detectors

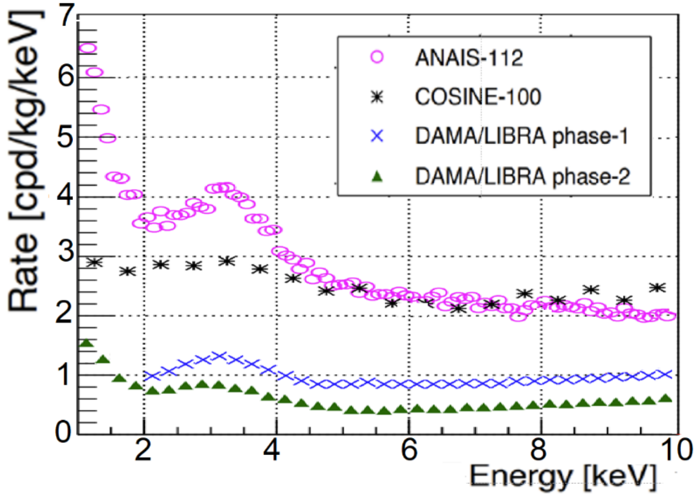


- 25 crystals, 10.2×10.2×25.4 cm^3, 9.7 kg each
- Sain Gobain, Kyropoulos method with a platinum crucible
- PMTs phase-1: ETL 9265–B53/FL and 9302–A/FL (QE~30%)
- PMTs phase-2: Hamamatsu R6233MOD (QE ~38%)
- Light guides: 10 cm Suprasil B

- 9 cylindrical crystals, 12 cm ϕ ×30 cm, 12.5 kg each
- Alpha Spectra (same as COSINE)
- PMTS: Hamamatsu R12669SEL2 (QE ~40%)
- Quartz window (no light guides)

Superior radiopurity of DAMA/LIBRA crystals wrt ANAIS/COSINE

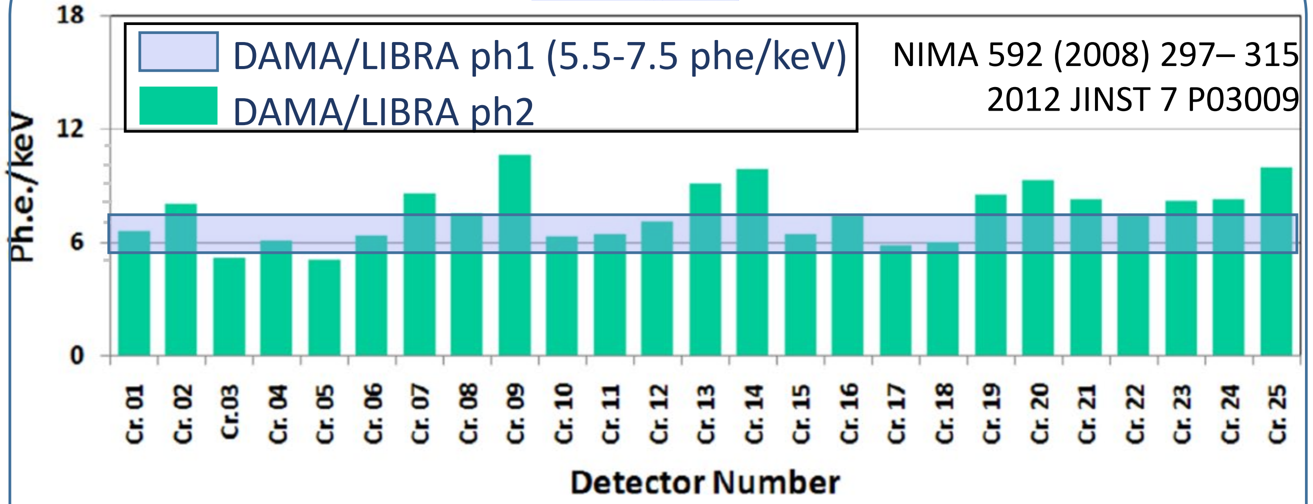
	K (ppb)	^{210}Pb (mBq/kg)
DAMA (Saint Gobain)	13	0.01-0.03
ANAIS/COSINE (Alpha Spectra)	18-44	0.7-3



ANAIS: EPJC 79:233, 2019
COSINE: EPJC 78:490, 2018
DAMA-ph1: NIMA 592 (2008) 297– 315
DAMA-ph2: Nucl. Phys. At. Energy, 19:307-325, 2018

What is different wrt DAMA/LIBRA

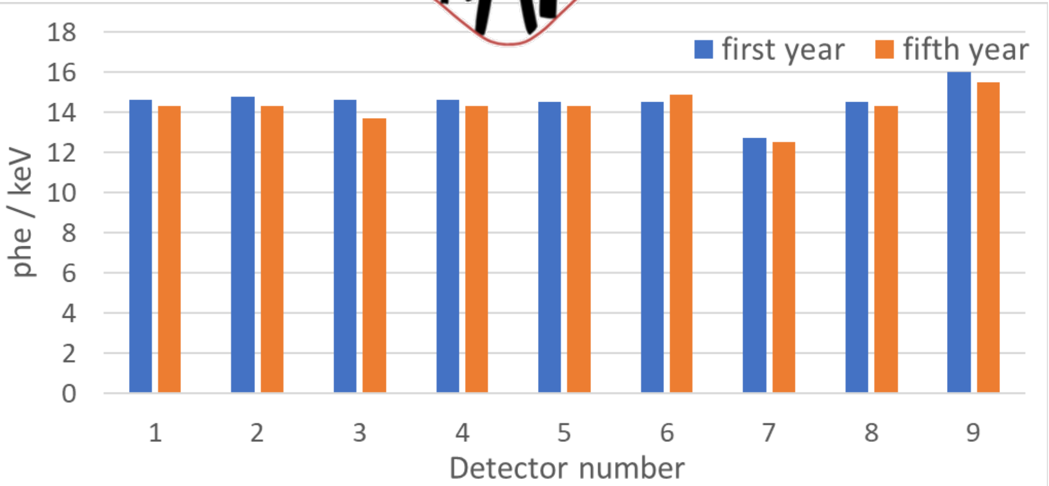
Light collection



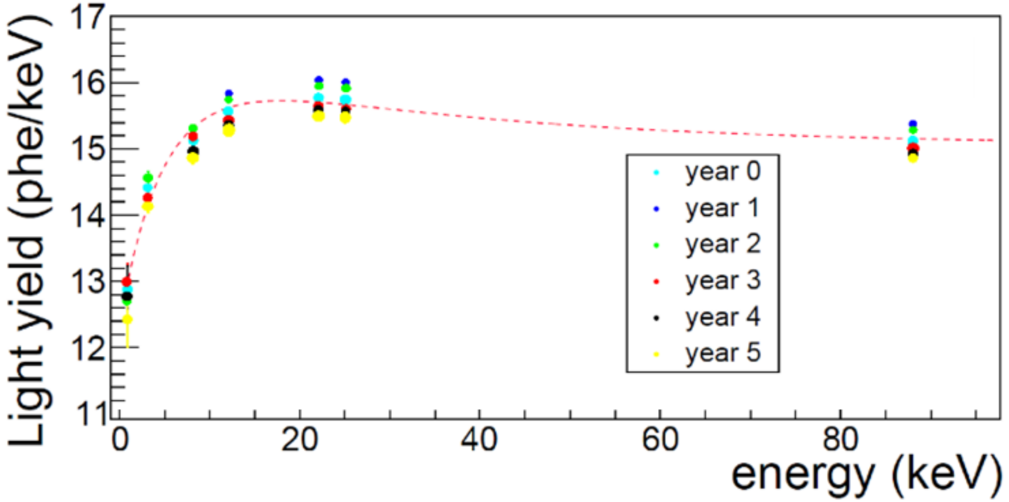
NIMA 592 (2008) 297– 315
2012 JINST 7 P03009

- DAMA/LIBRA-phase1 showed a very good linearity between the calibration with the 59.5 keV line of ^{241}Am and the tagged 3.2 keV line of ^{40}K
- in DAMA/LIBRA-phase2 a slight nonlinearity is observed(it gives a shift of about 0.2 keV at the software energy threshold and vanishes above 15 keV).

Prog. Part. Nucl. Phys. 114 (2020) 103810



In ANAIS non proportionality is observed < 25 keV (20%)

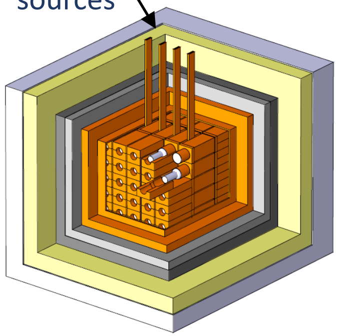


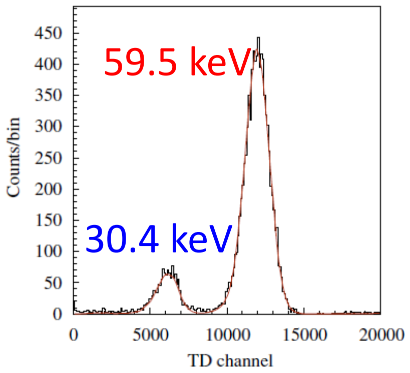
What is different wrt DAMA/LIBRA

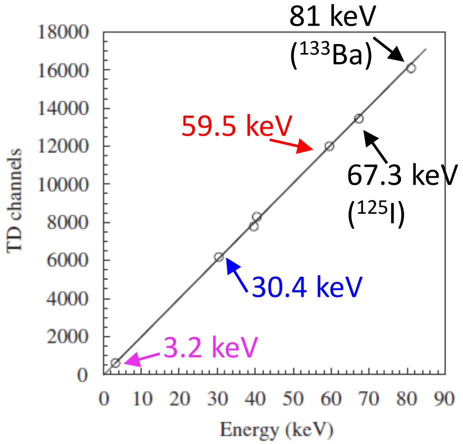
Low energy calibration – RoI [1-6 keV]

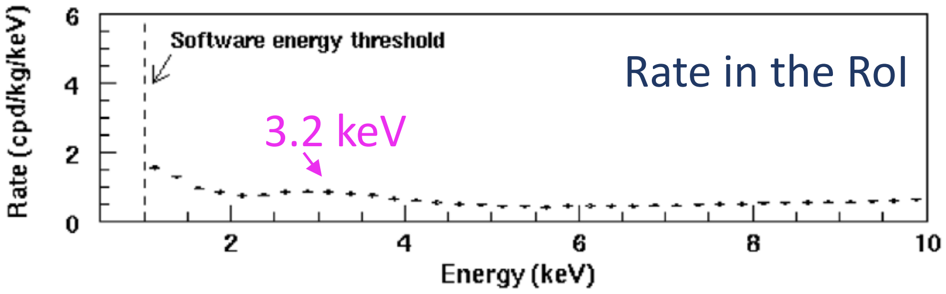
- Periodical calibrations every ~10 days with a ^{241}Am source (30.4 keV (composite), 59.5 keV). Linear calibration down to threshold
- Linearity check and corrected @ 3.2 keV with whole statistics

Guides for ^{241}Am sources

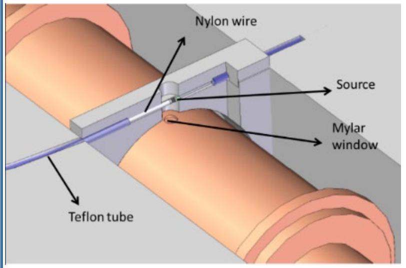


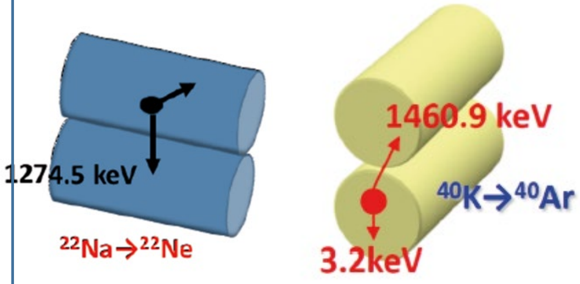


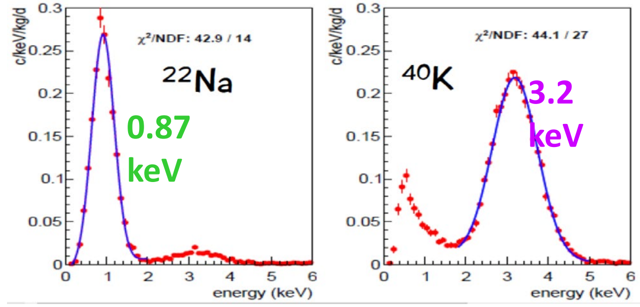


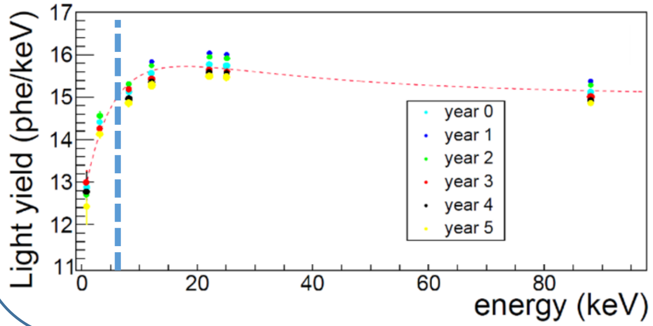


- Detectors equipped with a **Mylar window**
- Calibration with **^{109}Cd sources** (11.9 keV, 22.6 keV and 88.0 keV) every two weeks for gain correction
- Calibration in the ROI with internal bulk contaminants ^{22}Na (0.9 keV) and ^{40}K (3.2 keV) (whole statistics)









Non proportionality < 25 keV (20%)

Linear calibration in 2 ranges:

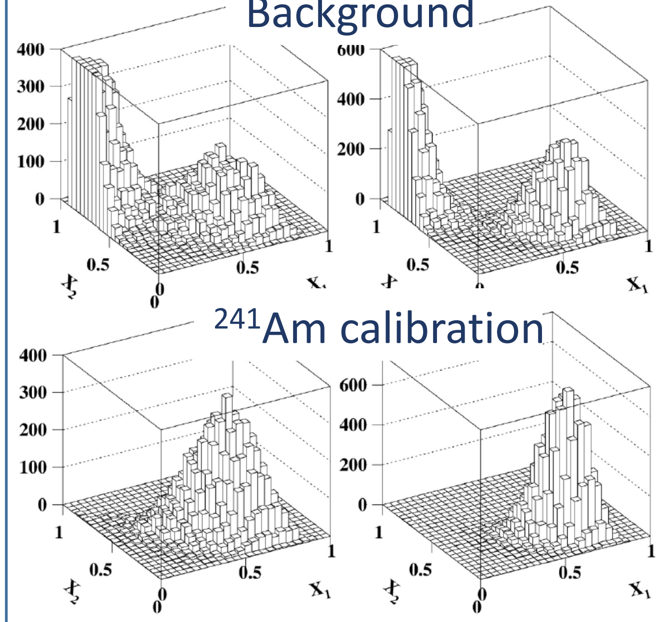
- 1-10 keV [ROI]
- 10-100 keV

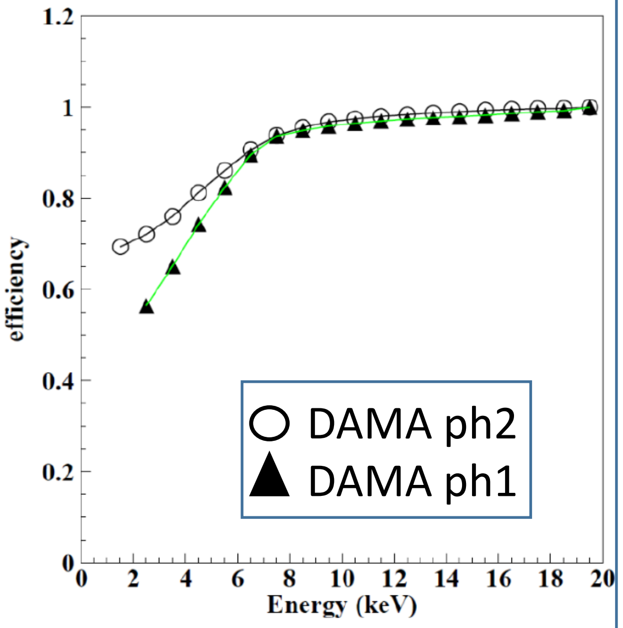
What is different wrt DAMA/LIBRA

Event selection & efficiency

X_1 = Area(from 100 to 600 ns)=Area(from 0 to 600 ns)
X_2 = Area(from 0 to 50 ns)=Area(from 0 to 600 ns)

$$ES = \frac{1-(X_2-X_1)}{2} \qquad ES > 0.54\ (0.60) \text{ in } 1\text{–}3\ (3\text{–}6) \text{ keV}$$

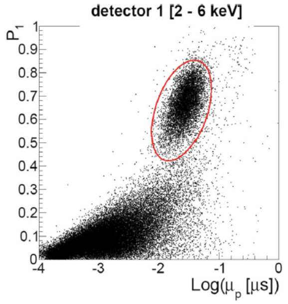




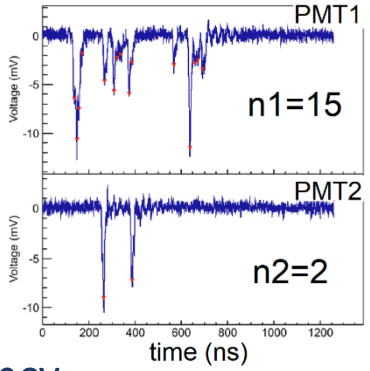
JINST 7 P03009 (2012)

ANAIS

$$P_1 = \frac{\int_{100\,ns}^{600\,ns} A(t)dt}{\int_{0}^{600\,ns} A(t)dt} \qquad \mu_p = \frac{\sum A_p t_p}{\sum A_p}$$

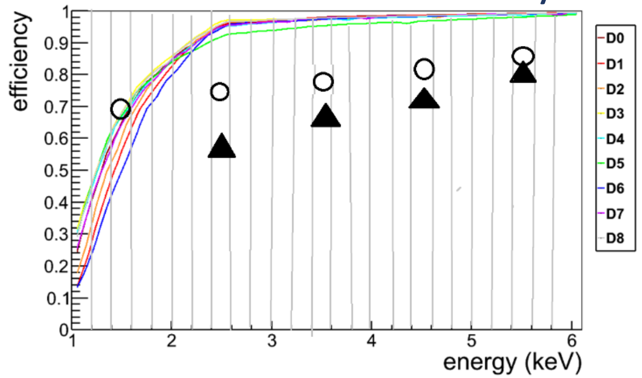


Between 1-2 keV, in ANAIS-112 there is a population of asymmetric events (more light in one PMT wrt the other)



Select events with n1>4 & n2>4

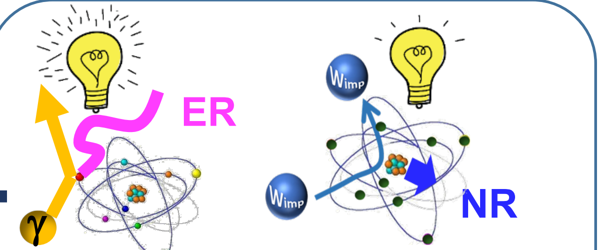
ANAIS vs DAMA efficiency



Continuos lines: ANAIS eff, from ^{109}Cd and $^{22}Na/^{40}K$

- ○ DAMA ph2
- ▲ DAMA ph1

What is different wrt DAMA/LIBRA



$$QF(E) = \frac{signal_{NR}/keV}{signal_{ER}/keV}$$

NR Quenching factors
Required for the WIMP interpretation

Phys. Lett. B 389 (1996) 757-766

^{252}Cf calibration

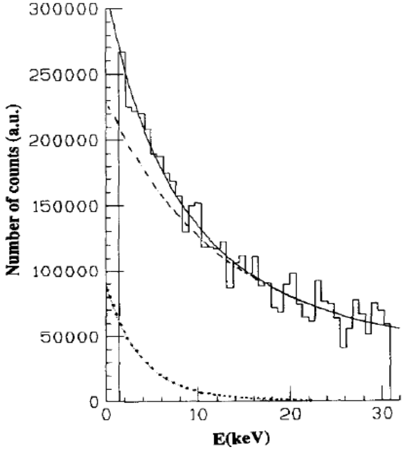
$$E_R = E_{det}/QF$$

Hypothesis: constant QF

Spectrum fitted to:

$$Y(E_{det}) = \alpha_{Na} G_{Na}\left(\frac{E_{det}}{q_{Na}}\right) + \alpha_I G_I\left(\frac{E_{det}}{q_I}\right)$$

$$G_X(E_R) = \exp(a_{1,X}E_R^3 + a_{2,X}E_R^2 + a_{3,X}E_R$$



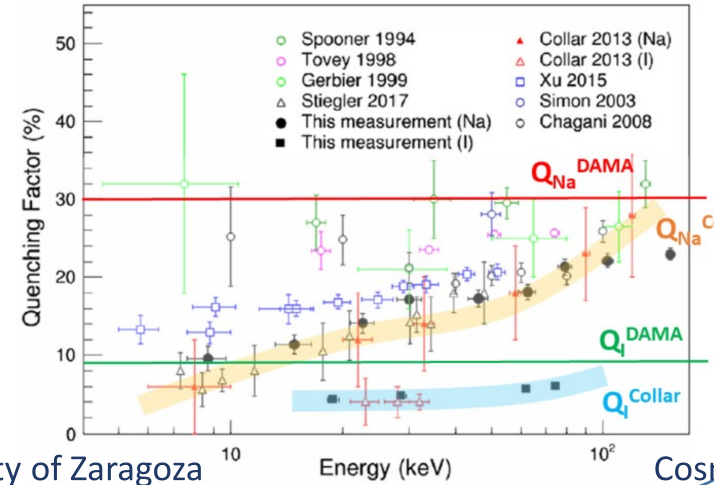
Result:

$QF_{Na} = 30\%$

$QF_I = 9\%$

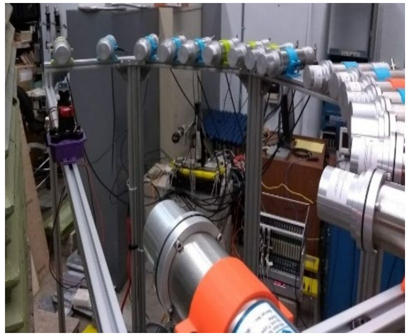
Comparison with other measurements:

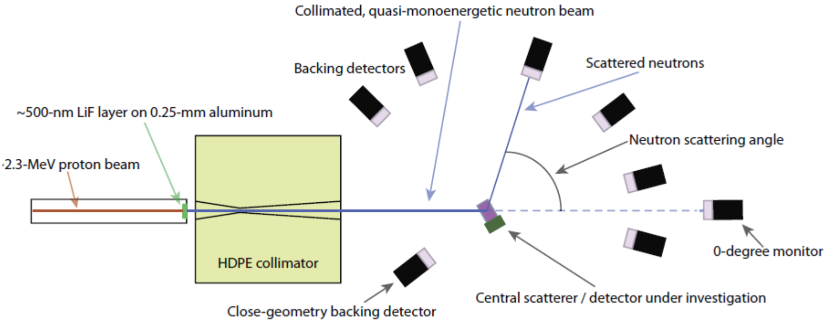
Joo, et al. Astrop. Phys. 108 (2019) 50

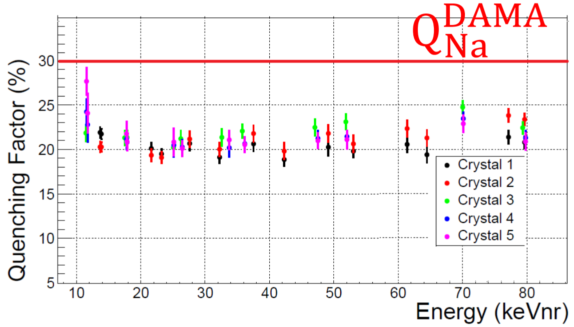


Measurements @ TUNL (Duke Univ.)

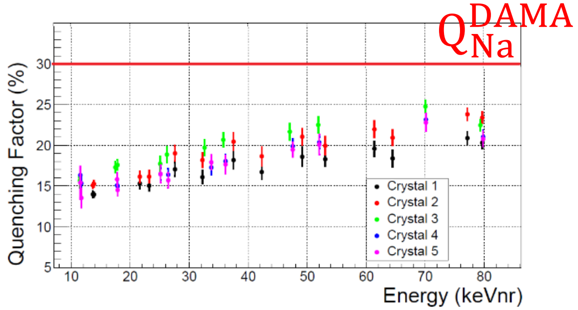
5 different NaI(Tl) crystals (ANAIS & Yale group of COSINE) in the same setup







Calibration lines in the RoI (6.6, 30.8, 35.1 keV)



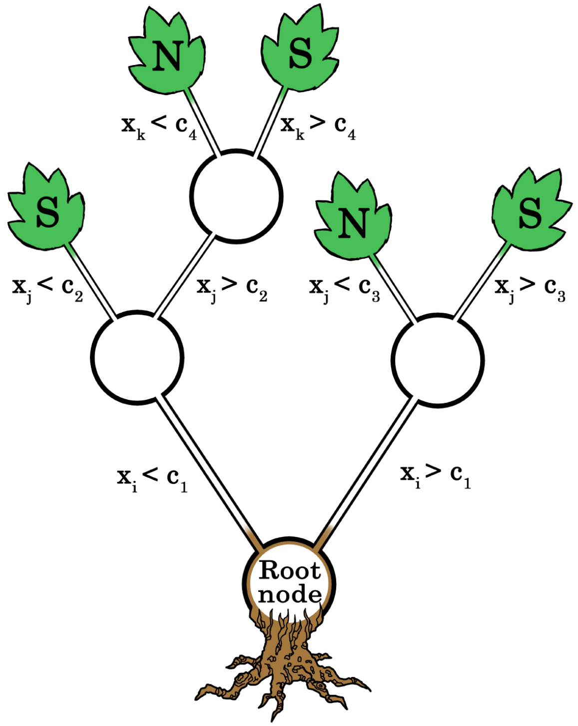
Calibration line: 57 keV (assuming proportional response)

NaI non-linearity could explain QF measurements disagreement

Improving ANAIS-112 sensitivity

"Improving ANAIS-112 sensitivity to DAMA/LIBRA signal with machine learning techniques", I. Coarasa et al, JCAP11(2022)048

Improve the "bulk scintillation" event selection with machine learning techniques



15 discrimination parameters combined in a boosted decision tree (instead of the 4 parameters used in the standard analysis)

Std analysis

$$P_1 = \frac{\sum_{100\text{ ns}}^{600\text{ ns}} A(t)}{\sum_{0\text{ ns}}^{600\text{ ns}} A(t)} \qquad \mu_p = \frac{\sum_i A_i t_i}{\sum_i A_i} \qquad n_0, n_1$$

$$P_2 = \frac{\sum_{0\text{ ns}}^{50\text{ ns}} A(t)}{\sum_{0\text{ ns}}^{600\text{ ns}} A(t)} \qquad Asynphe = \frac{nphe_0 - nphe_1}{nphe_0 + nphe_1}$$

$$\text{CAP}_x = \frac{\sum_{0\text{ ns}}^{x\text{ ns}} A(t)}{\sum_{0\text{ ns}}^{t_{\max}} A(t)}$$

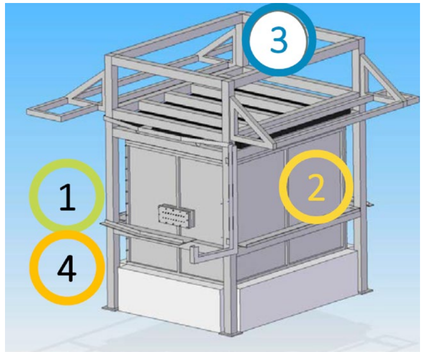
$$x = 50,\ 100,\ 200,\ 300,\ 400,\ 500,\ 600,\ 700 \text{ and } 800 \text{ ns}$$

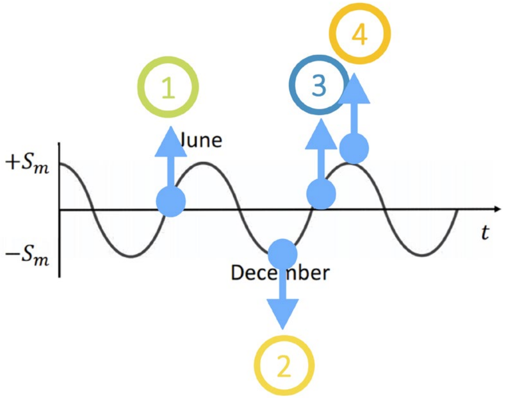
Training populations

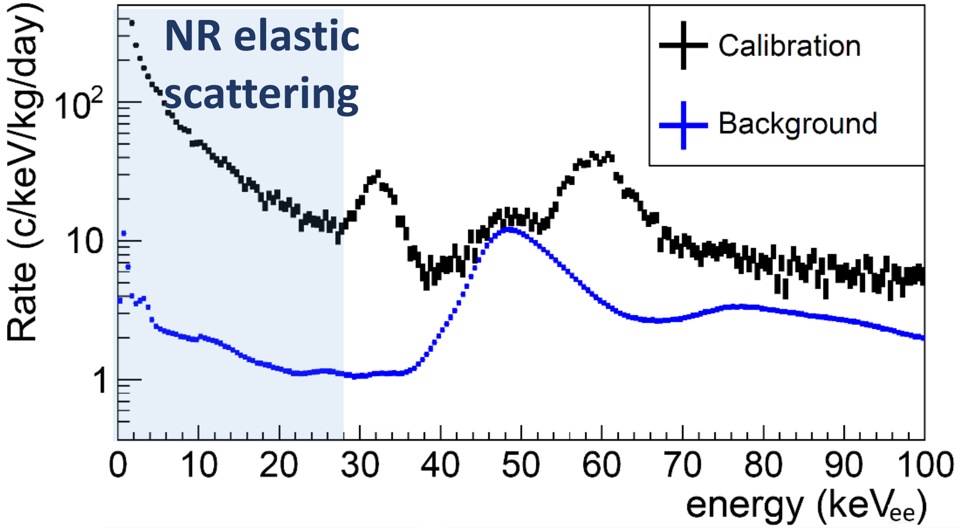
JCAP11(2022)048

SIGNAL EVENTS: Neutron calibrations

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

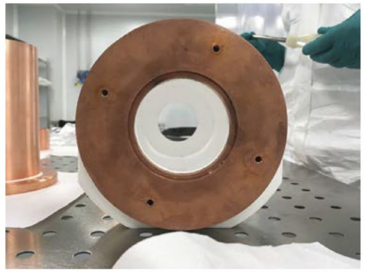


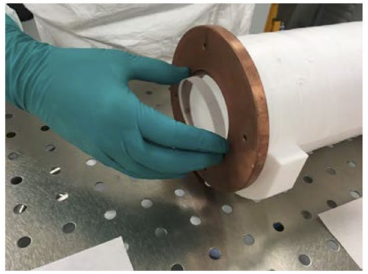


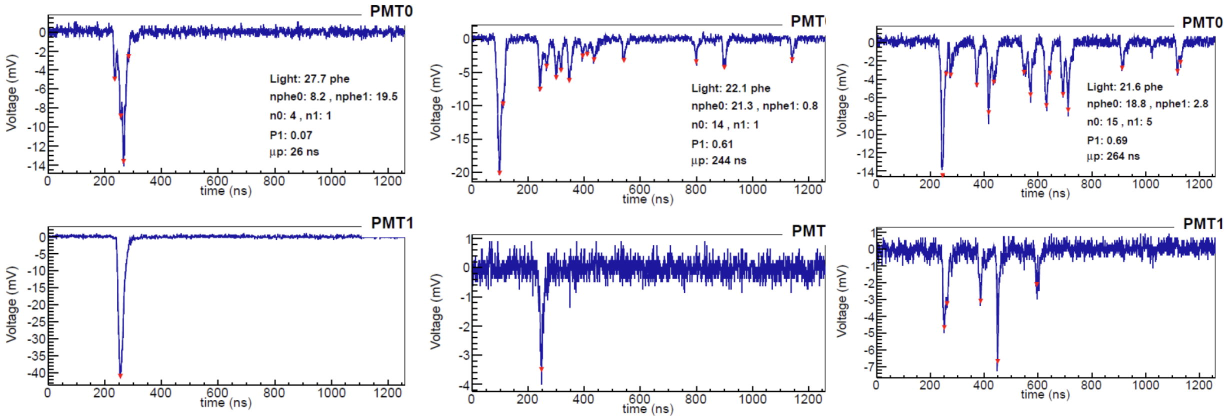


NOISE EVENTS: “Blank” module (No NaI(Tl))

Since 2018 a BLANK module (similar to ANAIS-112 modules, but without NaI(Tl) crystal) is taking data with the same DAQ, but in an independent shielding close to ANAIS-112



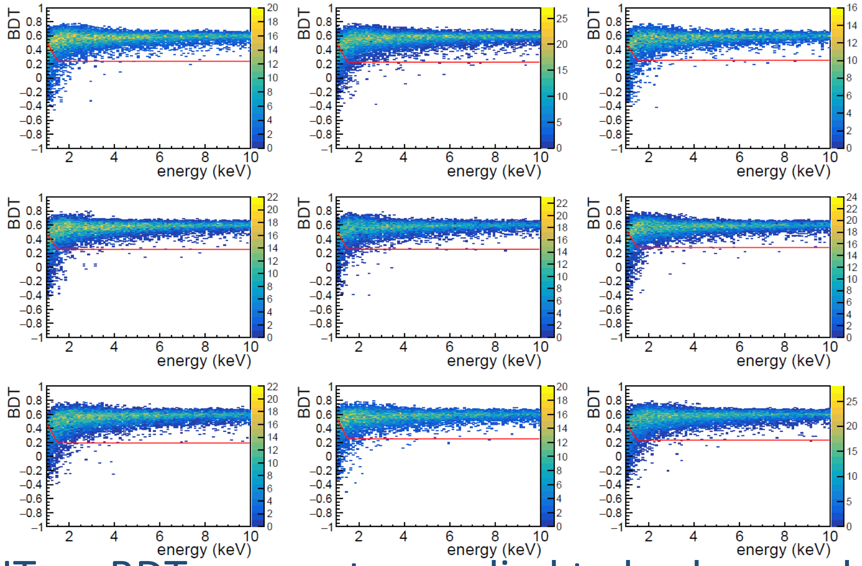


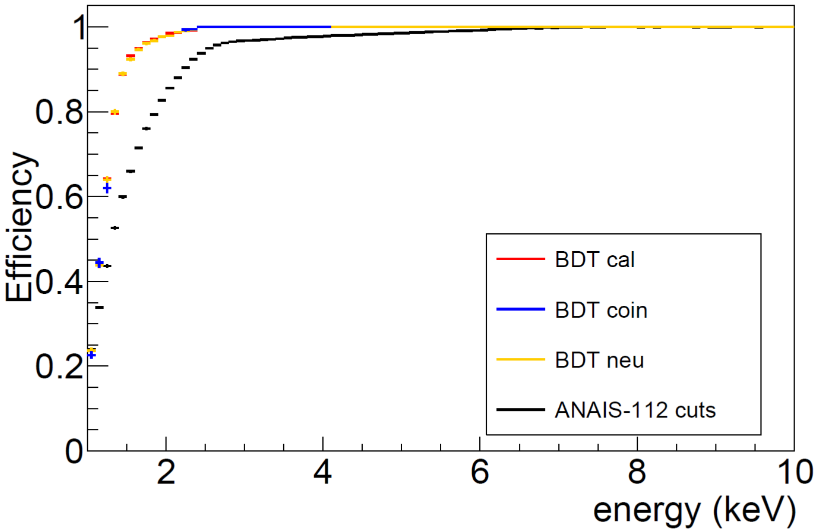


Event selection with BDT

JCAP11(2022)048

Neutron calibration

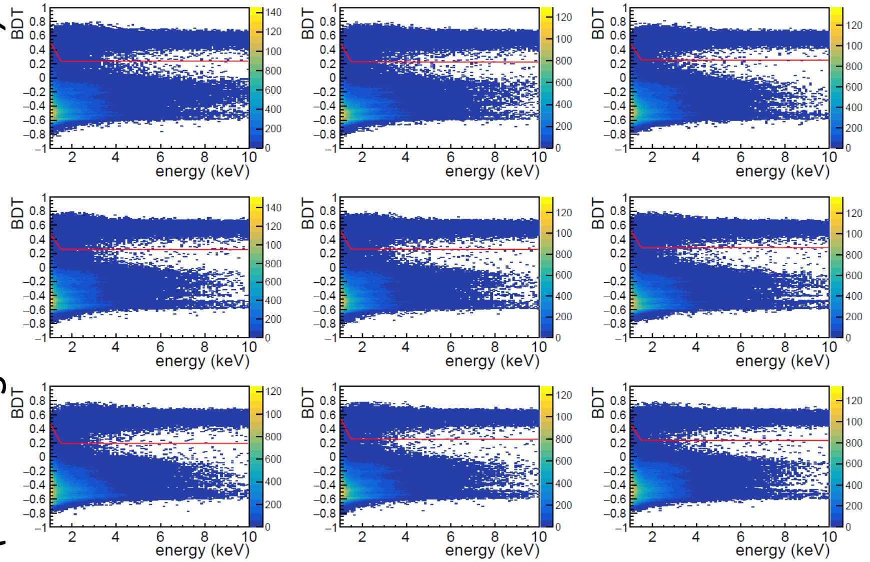


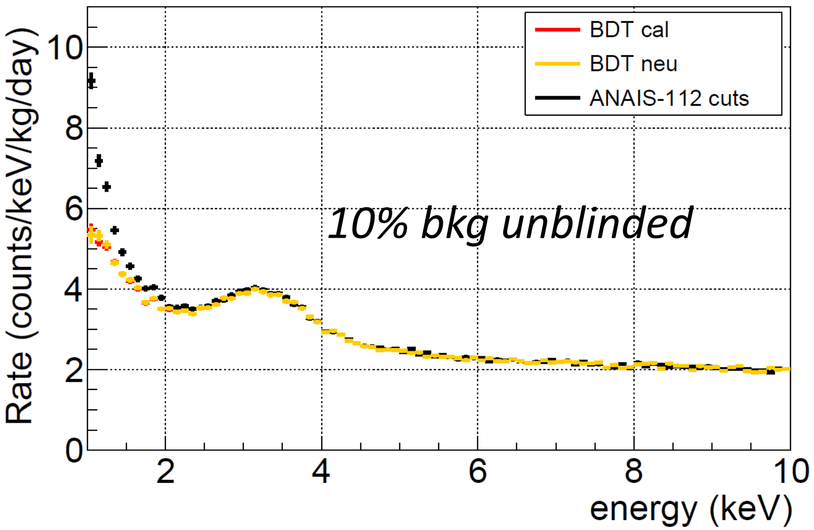


∼30% improvement in efficiency

CUT on BDT parameter applied to background

(10% bkg unblinded events)



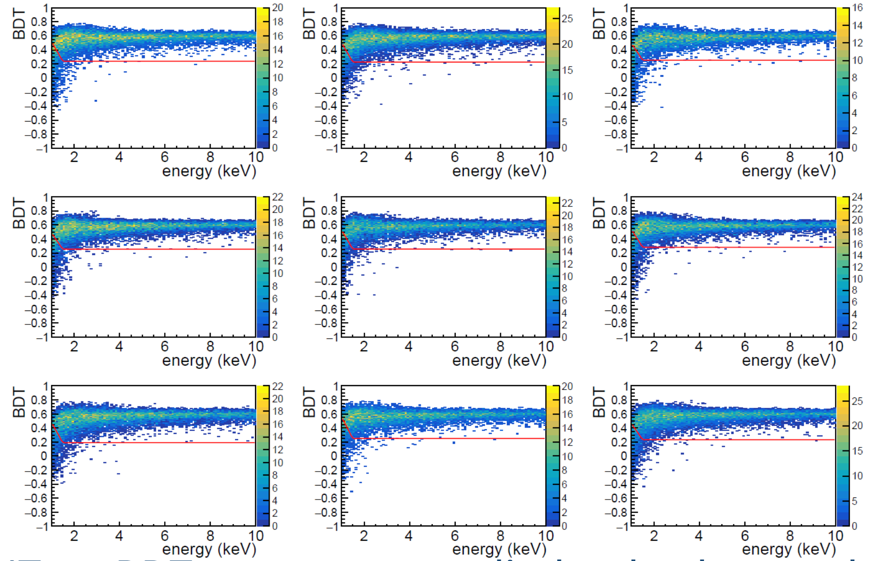


∼18% bkg reduction in [1-2] keV

Event selection with BDT

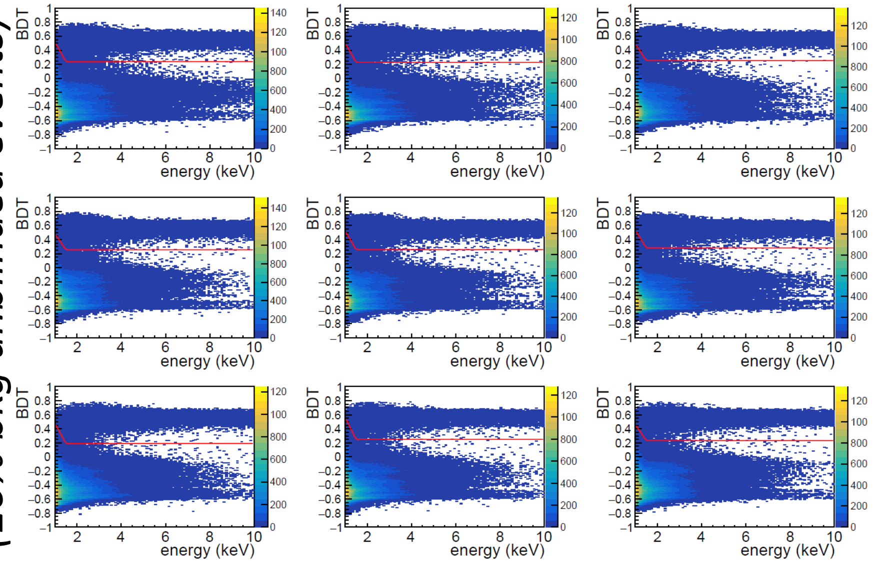
JCAP11(2022)048

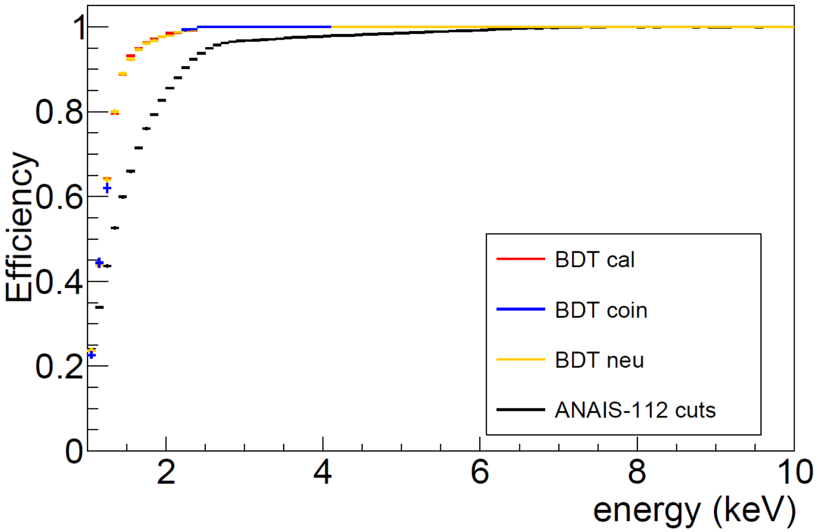
Neutron calibration

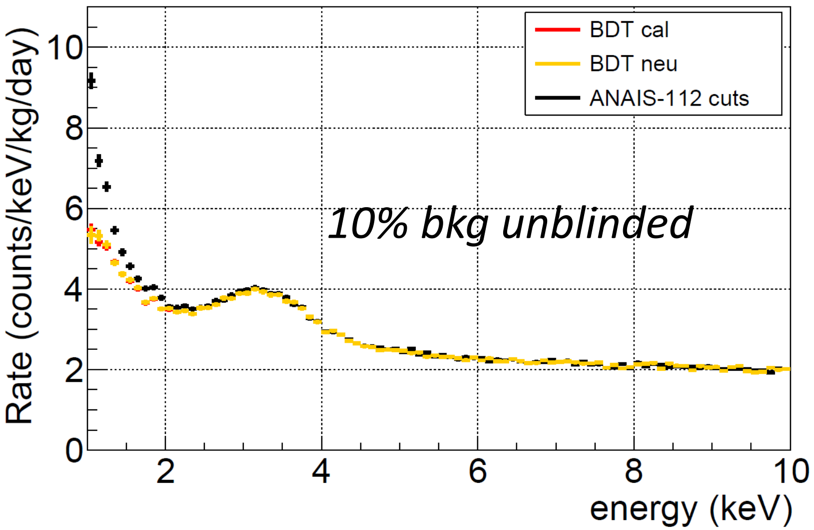


CUT on BDT parameter applied to background

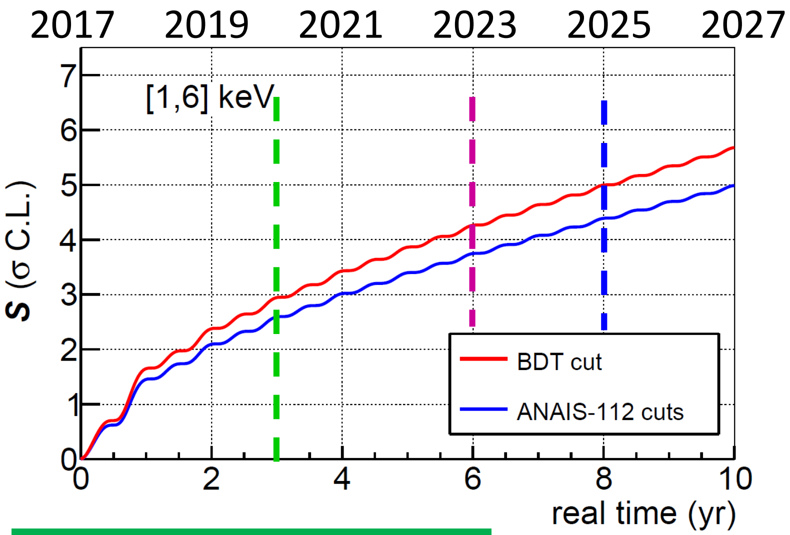
(10% bkg unblinded events)







DM Sensitivity $\propto \sqrt{\frac{MT\epsilon}{B}}$



3σ sensitivity with 3y

$>4\sigma$ sensitivity with 6y (this summer)

5σ sensitivity in late 2025

Annual modulation with new analysis

Focus on model independent analysis searching for modulation

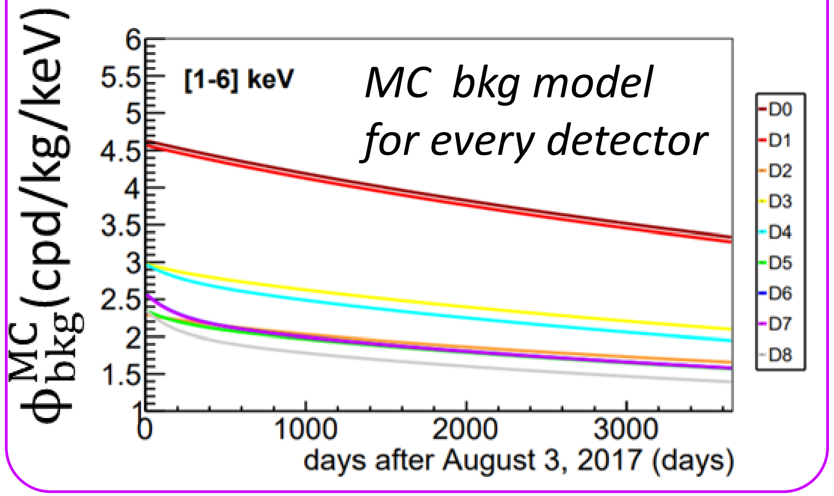
- In order to better compare with DAMA/LIBRA results
  - **use the same energy regions ([1-6] keV, [2-6] keV)**
  - **fix period 1 year and phase to June 2nd**
- Simultaneous fit of the 9 detectors. 10 days bins. ChiSquare minimization: $\chi^2 = \sum (n_i - \mu_i)^2/\sigma_i^2$

where the expected number of events μ_i for detector d in time bin i is given by:

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

Constant background (long-lived isotopes and residual noise)

Decayig background, modeled by MC



Modulation signal (fixed period and phase)

19 Free parameters: $R_{o,d}$, f_d, S_m