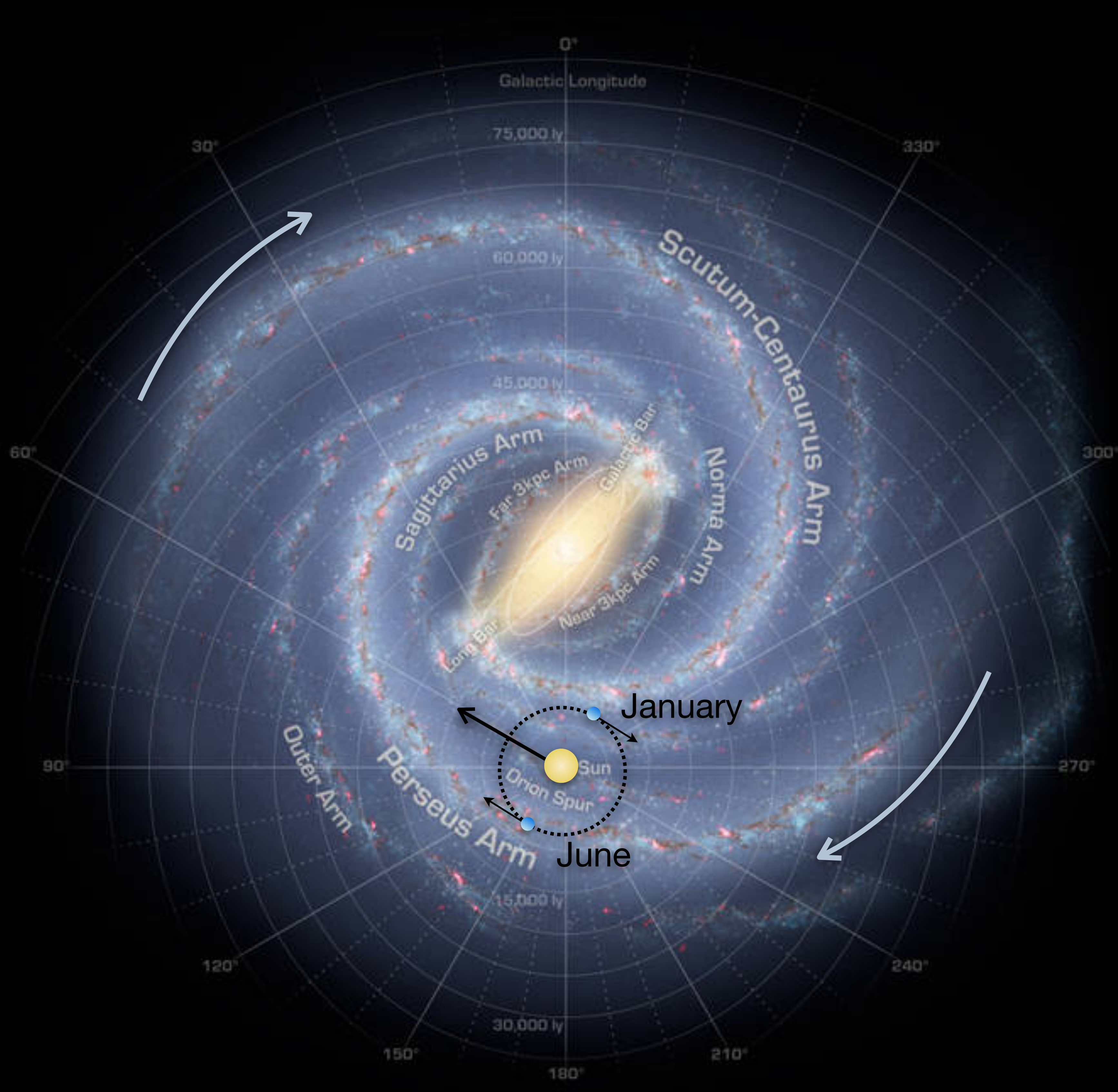
COSINUS

COSINUS and NaI-based Dark Matter Experiments

Vanessa Zema
on behalf of
the COSINUS collaboration

MAX-PLANCK-INSTITUT FÜR PHYSIK

17th PATRAS workshop on Axions, WIMPs and WISPs, 8-12 August 2022



0°
Galactic Longitude
75,000 ly
60,000 ly
45,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
30,000 ly
15,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Orion Spur
Sun
January
June

DAMA

Acknowledgment to P. Belli (DAMA)

DAMA

Acknowledgment to P. Belli (DAMA)

25 NaI(Tl) highly radiopure detectors, 9.70 kg mass, placed in five rows by five columns.

^{nat}K contamination < 60 ppb

^{232}Th contamination < 1.2 ppb

^{238}U contamination < 0.8 ppb

https://arxiv.org/pdf/0804.2738.pdf

Located in the Gran Sasso National Laboratory

Data taking started in 1996

DAMA

Acknowledgment to P. Belli (DAMA)

25 NaI(Tl) highly radiopure detectors, 9.70 kg mass, placed in five rows by five columns.

^{nat}K contamination < 60 ppb

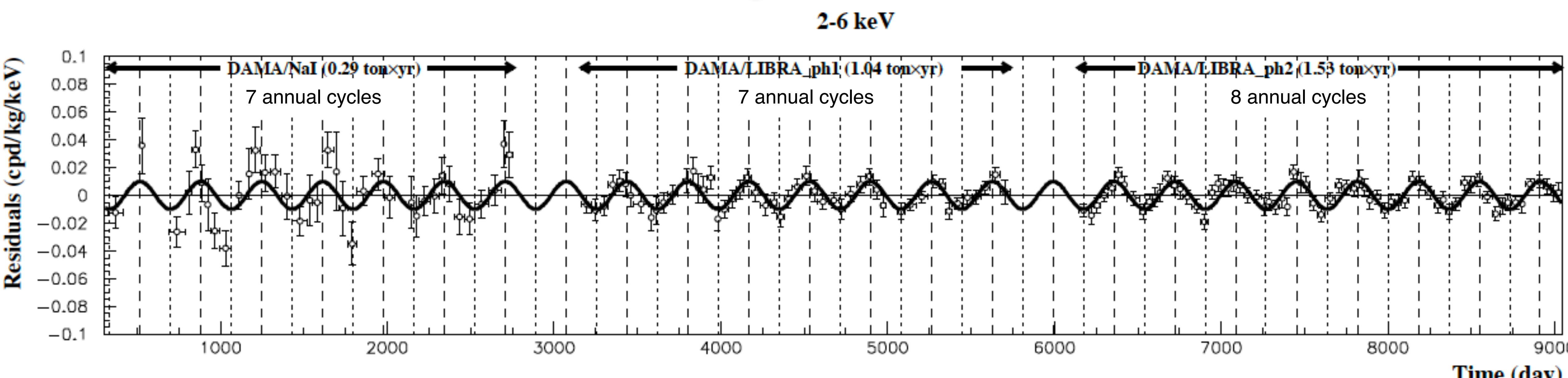
^{232}Th contamination < 1.2 ppb

^{238}U contamination < 0.8 ppb

https://arxiv.org/pdf/0804.2738.pdf

Located in the Gran Sasso National Laboratory

Data taking started in 1996



DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (2.86 ton × yr) favour the presence of a modulated behaviour with proper features at 13.7 σ C.L.

DAMA

Acknowledgment to
P. Belli (DAMA)

25 NaI(Tl) highly radiopure detectors, 9.70 kg mass, placed in five rows by five columns.

^{nat}K contamination < 60 ppb

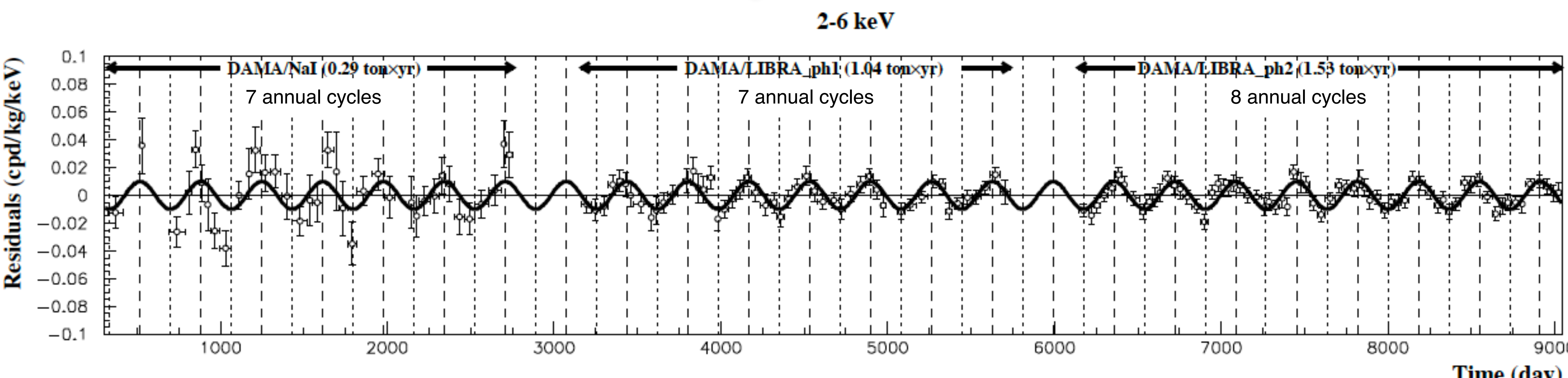
^{232}Th contamination < 1.2 ppb

^{238}U contamination < 0.8 ppb

https://arxiv.org/pdf/0804.2738.pdf

Located in the Gran Sasso National Laboratory

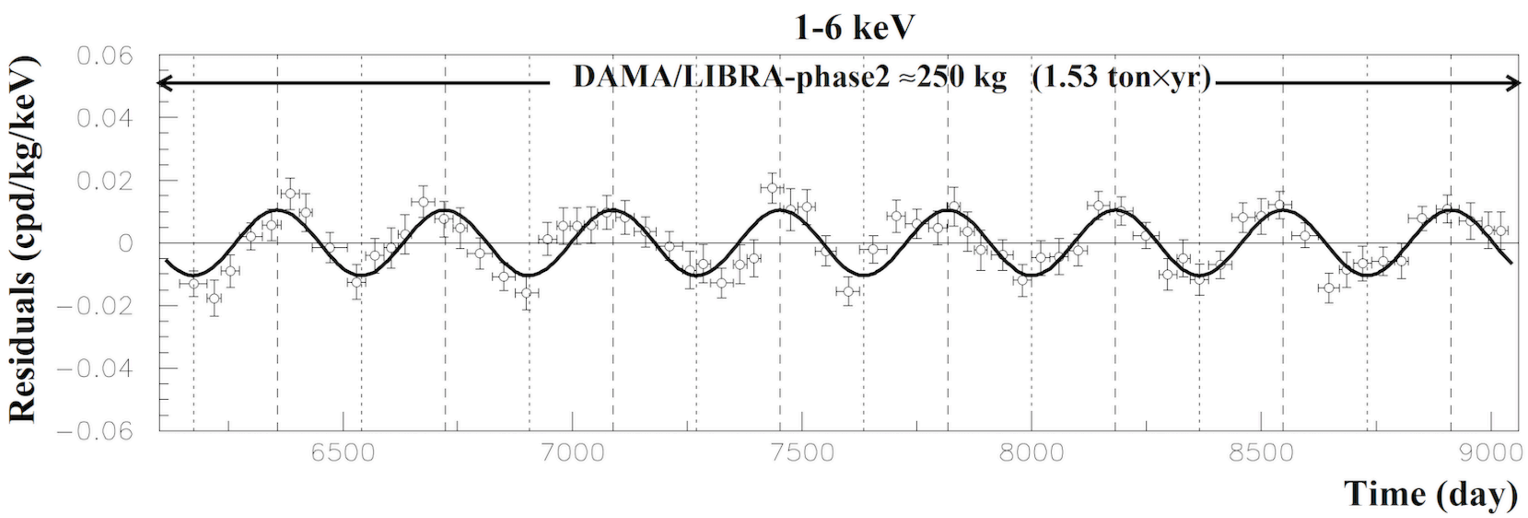
Data taking started in 1996



DAMA/NaI + DAMA/LIBRA-phase1 + **DAMA/LIBRA-phase2** (2.86 ton × yr) favour the presence of a modulated behaviour with proper features at 13.7 σ C.L.

DAMA/LIBRA-phase2

Acknowledgment to P. Belli (DAMA)



<u>(1-6) keV_{ee} modulation</u>

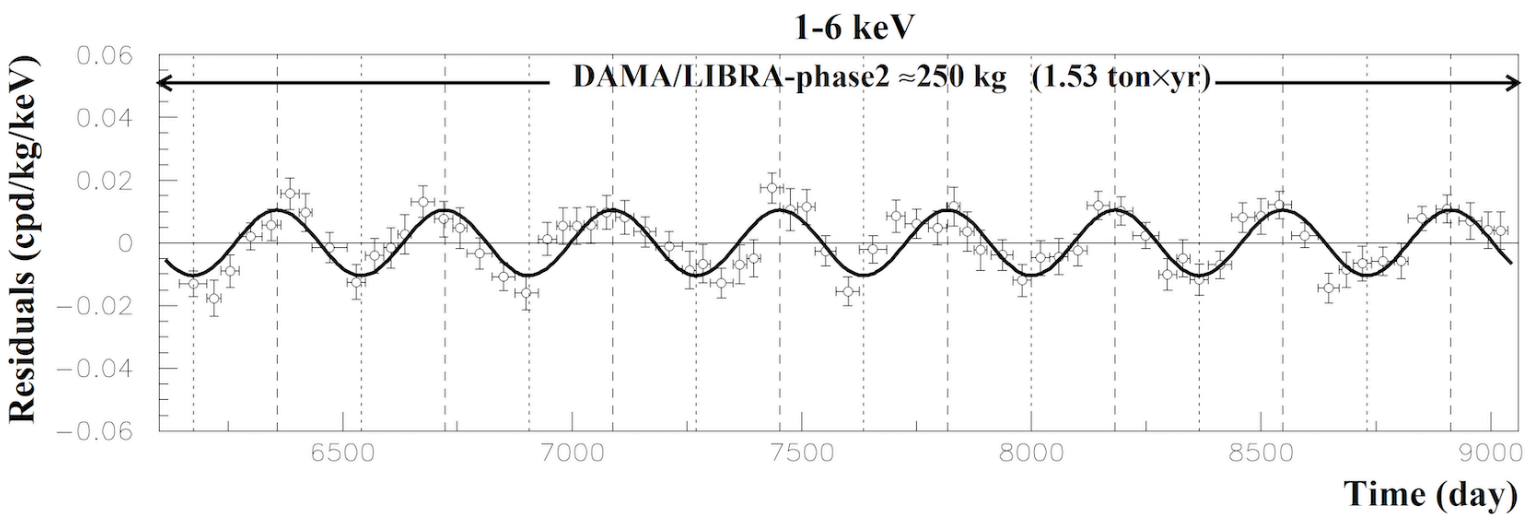
A = (0.01048±0.00090) cpd/kg/keV

χ^2/dof = 66.2/68 (11.6 σ C.L.)

<u>(6-14) keV_{ee} no modulation</u>

DAMA/LIBRA-phase2

Acknowledgment to P. Belli (DAMA)



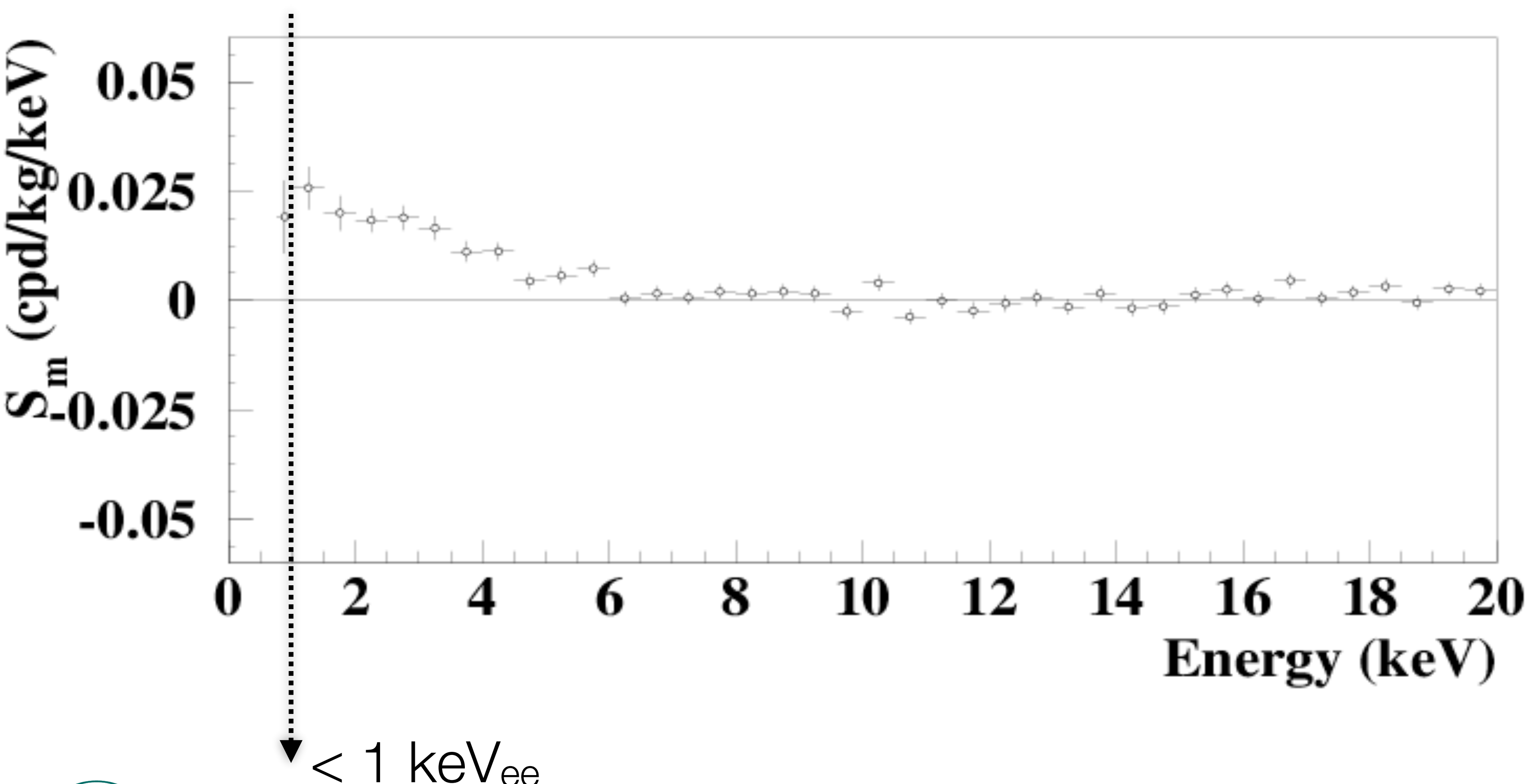
(1-6) keV_{ee} modulation

A = (0.01048±0.00090) cpd/kg/keV

χ^2/dof = 66.2/68 (11.6 σ C.L.)

(6-14) keV_{ee} no modulation

Efforts towards lower software energy threshold

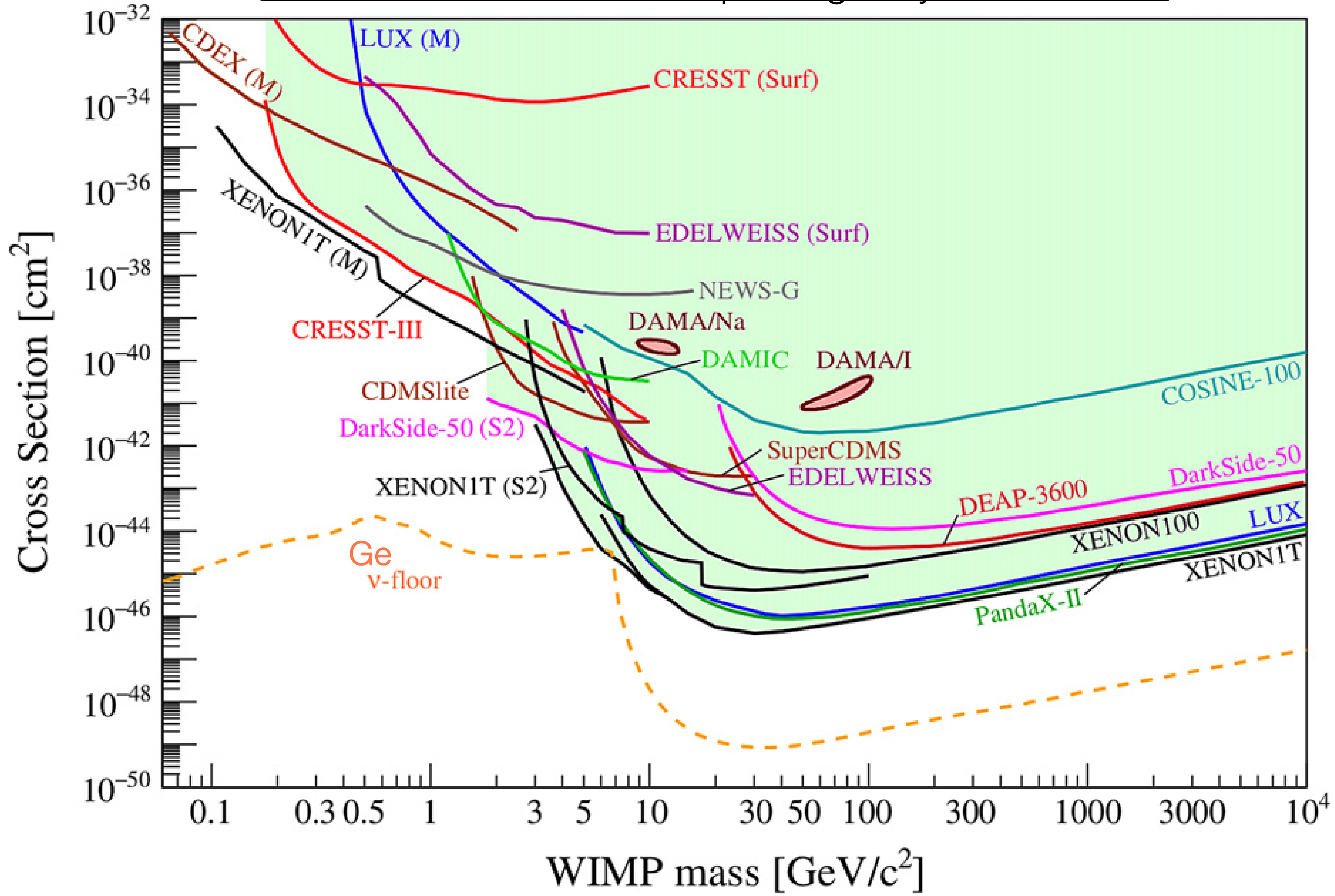


- Modulation present down to 0.75 keVee
- No modulation above 6 keVee
- Upgrade of PMTs and Transient Digitizers
- The data taking in this new configuration **with 0.5 keVee** software energy threshold started on Dec, 1 2021. Running

OTHERS

Julien Billard et al 2022 Rep. Prog. Phys. 85 056201

All other direct detection experiments **do not observe** a signal compatible with the dark matter hypothesis



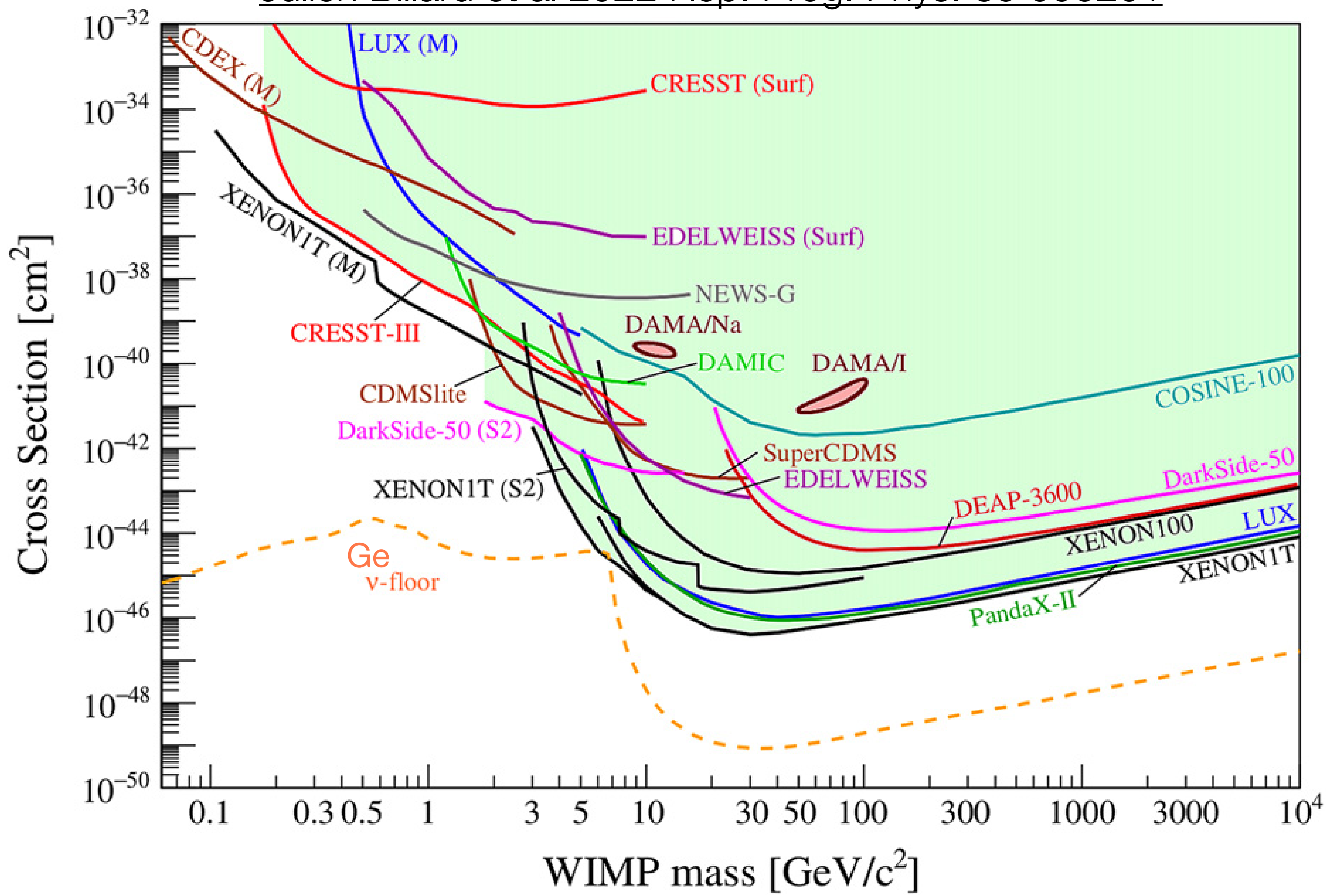
OTHERS

All other direct detection experiments **do not observe** a signal compatible with the dark matter hypothesis

Experiments using the same target material as DAMA and searching for annual modulation are currently working to provide a model and target independent cross-check of DAMA's discovery claim

ANAIS
COSINE
COSINUS ← **MAIN FOCUS OF THIS TALK**
PICOLON
SABRE

Julien Billard et al 2022 Rep. Prog. Phys. 85 056201

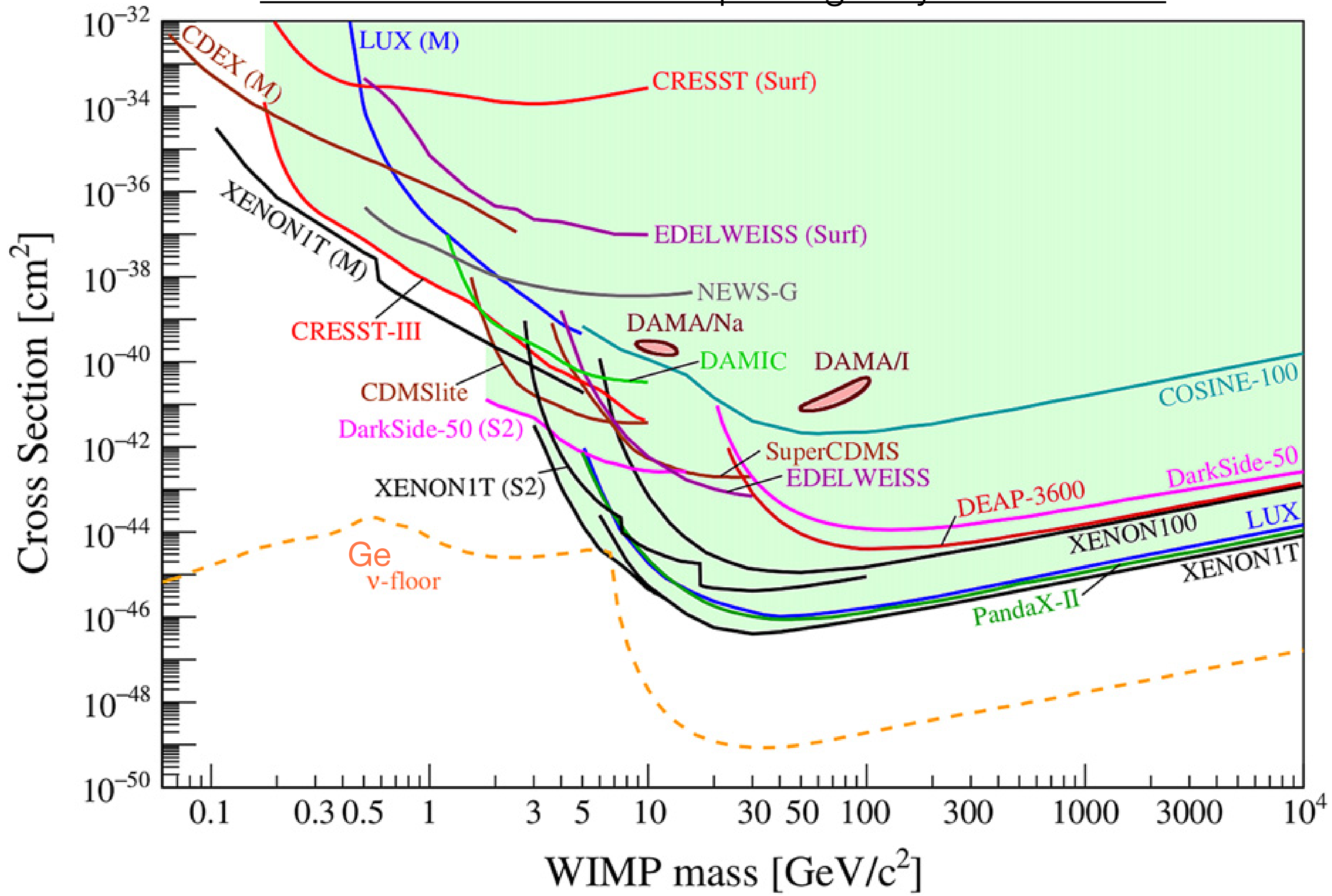


OTHERS

All other direct detection experiments **do not observe** a signal compatible with the dark matter hypothesis

Experiments using the same target material as DAMA and searching for annual modulation are currently working to provide a model and target independent cross-check of DAMA's discovery claim

Julien Billard et al 2022 Rep. Prog. Phys. 85 056201

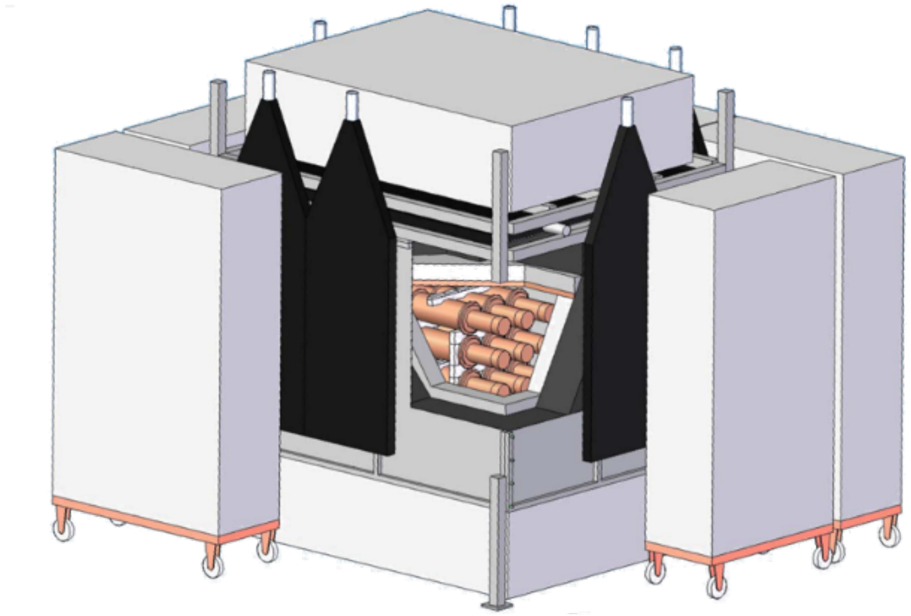


ANAIS
COSINE
COSINUS ← **MAIN FOCUS OF THIS TALK**
PICOLON
SABRE

ASTAROTH project — J.Phys.Conf.Ser. 2156 (2021) 012060

ANAIS-112

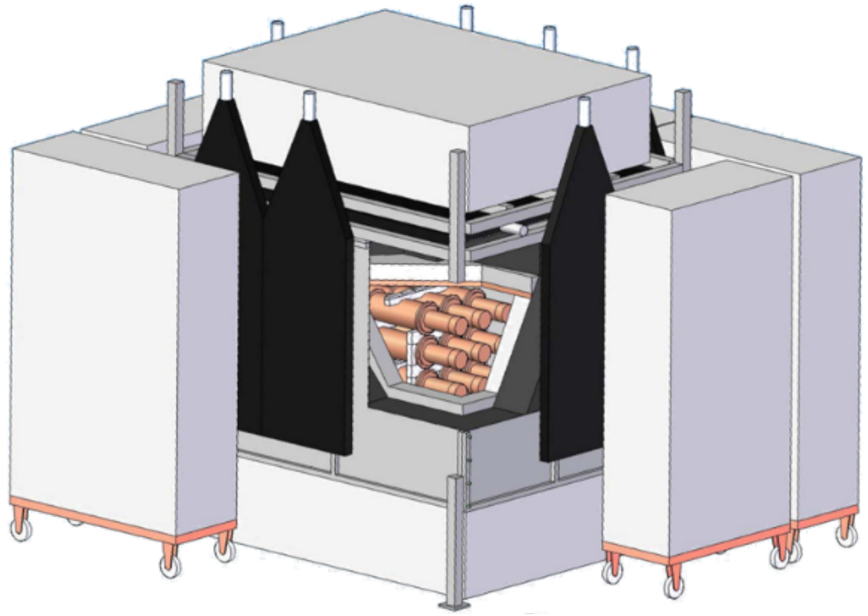
Acknowledgment to M. L. Sarsa (ANAIS)



Link to ANAIS talk at IDM22

ANAIS-112

Acknowledgment to M. L. Sarsa (ANAIS)



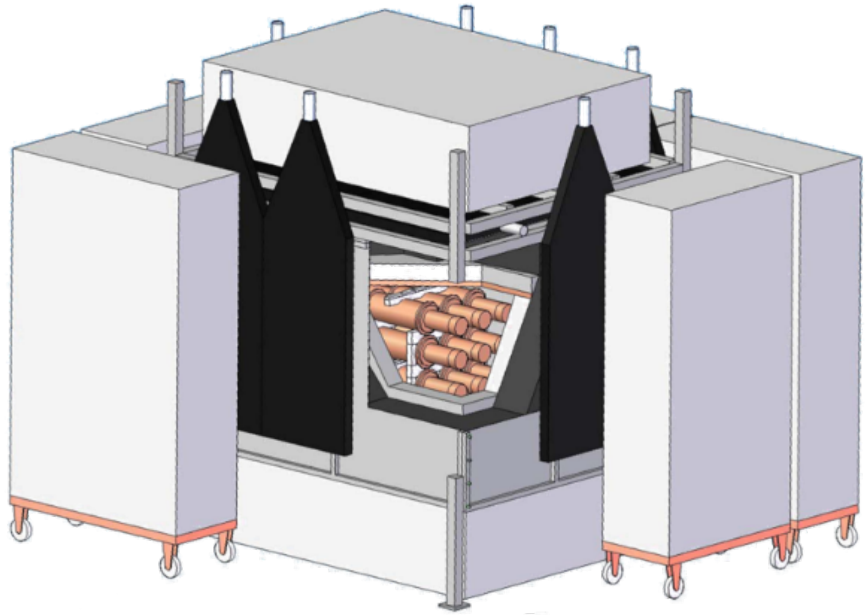
- 3x3 array of NaI(Tl) modules, 112.5 kg
- Located at Canfranc Underground Laboratory
- Taking data since August 2017
- Almost **five years of data** with duty cycle above 95%

- Three-year exposure results published in 2021, Phys. Rev. D 103 (arXiv:2110.10649)

Link to ANAIS talk at IDM22

ANAIS-112

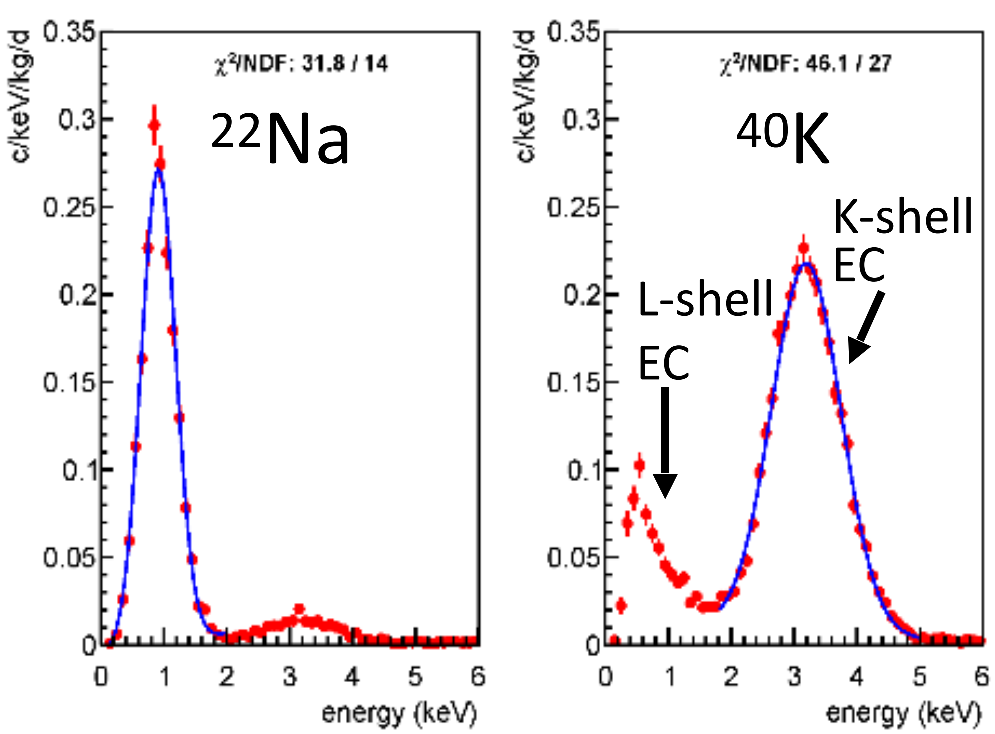
Acknowledgment to M. L. Sarsa (ANAIS)



- 3x3 array of NaI(Tl) modules, 112.5 kg
- Located at Canfranc Underground Laboratory
- Taking data since August 2017
- Almost **five years of data** with duty cycle above 95%

- Three-year exposure results published in 2021, Phys. Rev. D 103 (arXiv:2110.10649)

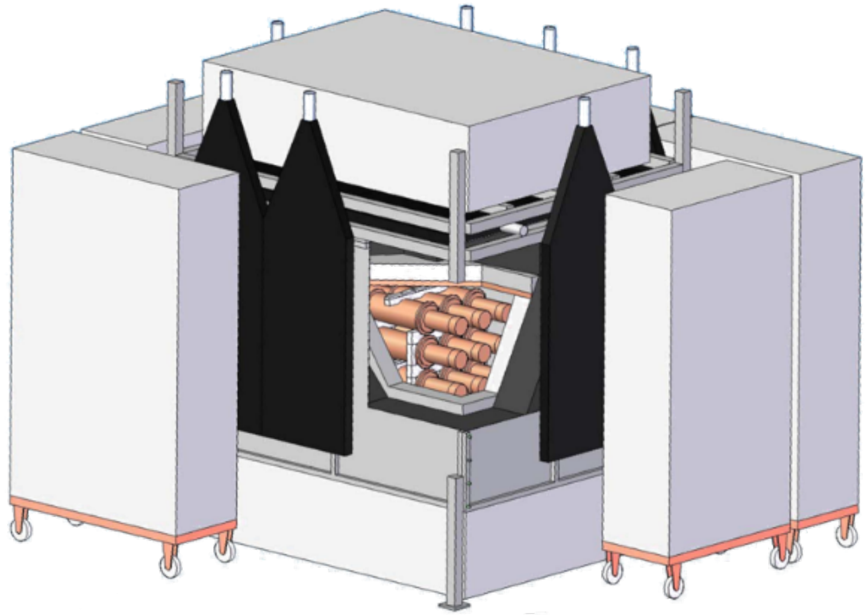
Triggering well below 1 keVee



Link to ANAIS talk at IDM22

ANAIS-112

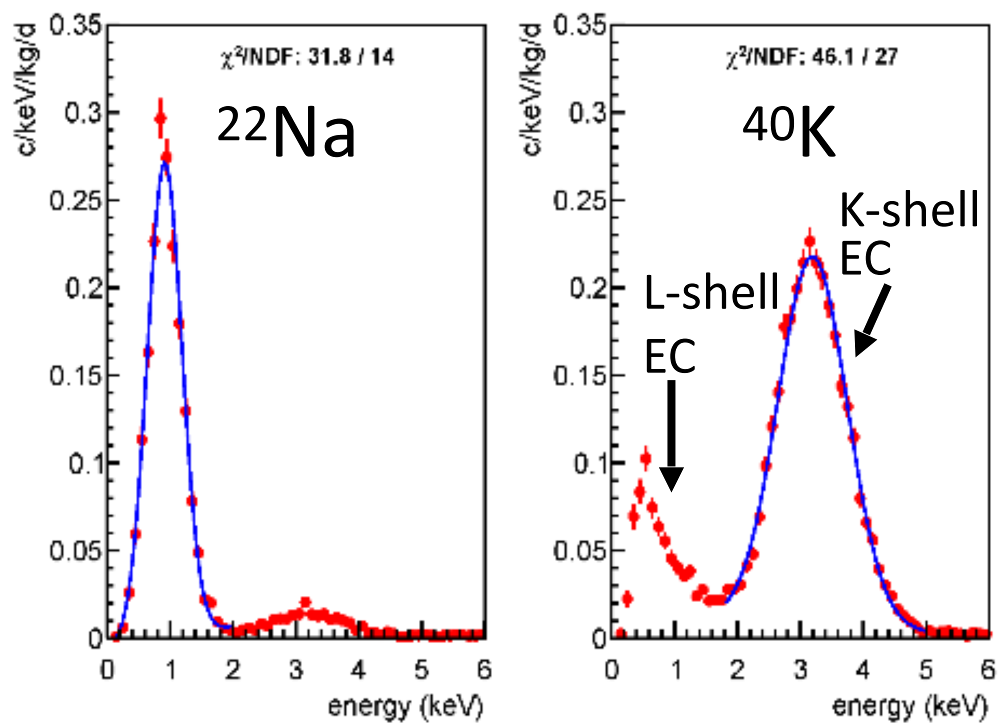
Acknowledgment to M. L. Sarsa (ANAIS)



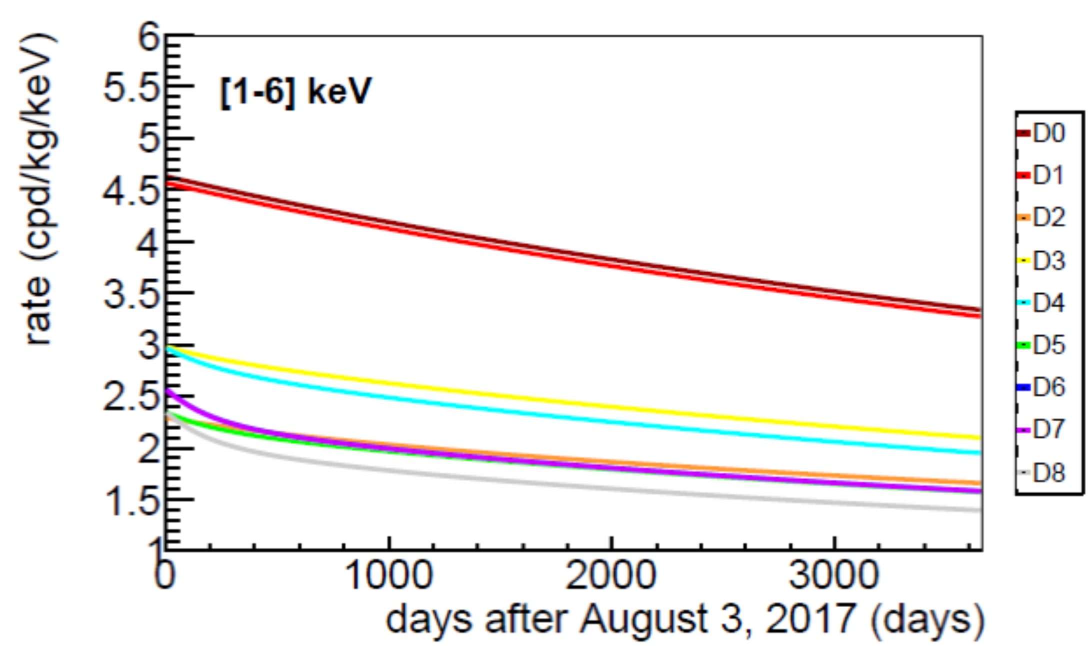
- 3x3 array of NaI(Tl) modules, 112.5 kg
- Located at Canfranc Underground Laboratory
- Taking data since August 2017
- Almost **five years of data** with duty cycle above 95%

- Three-year exposure results published in 2021, Phys. Rev. D 103 (arXiv:2110.10649)

Triggering well below 1 keVee



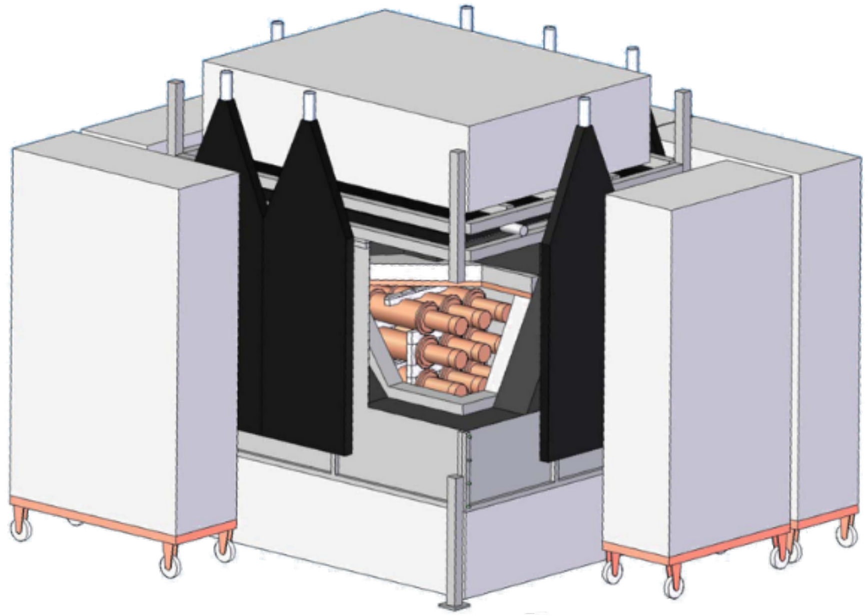
Background model determines the probability distribution function detector by detector



Link to ANAIS talk at IDM22

ANAIS-112

Acknowledgment to M. L. Sarsa (ANAIS)

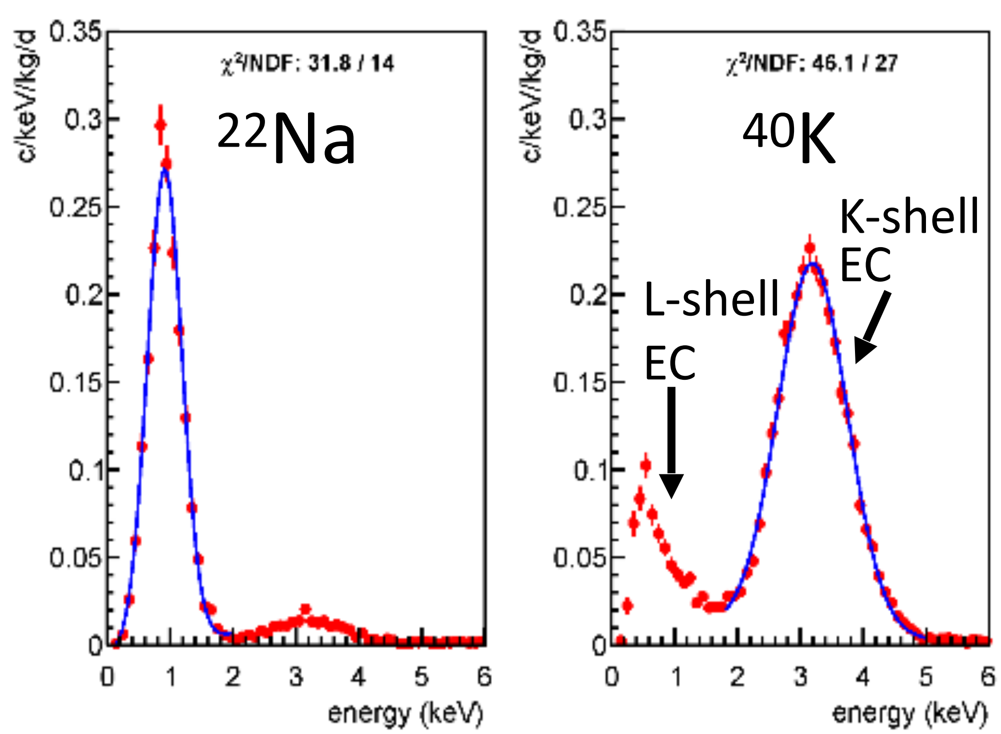


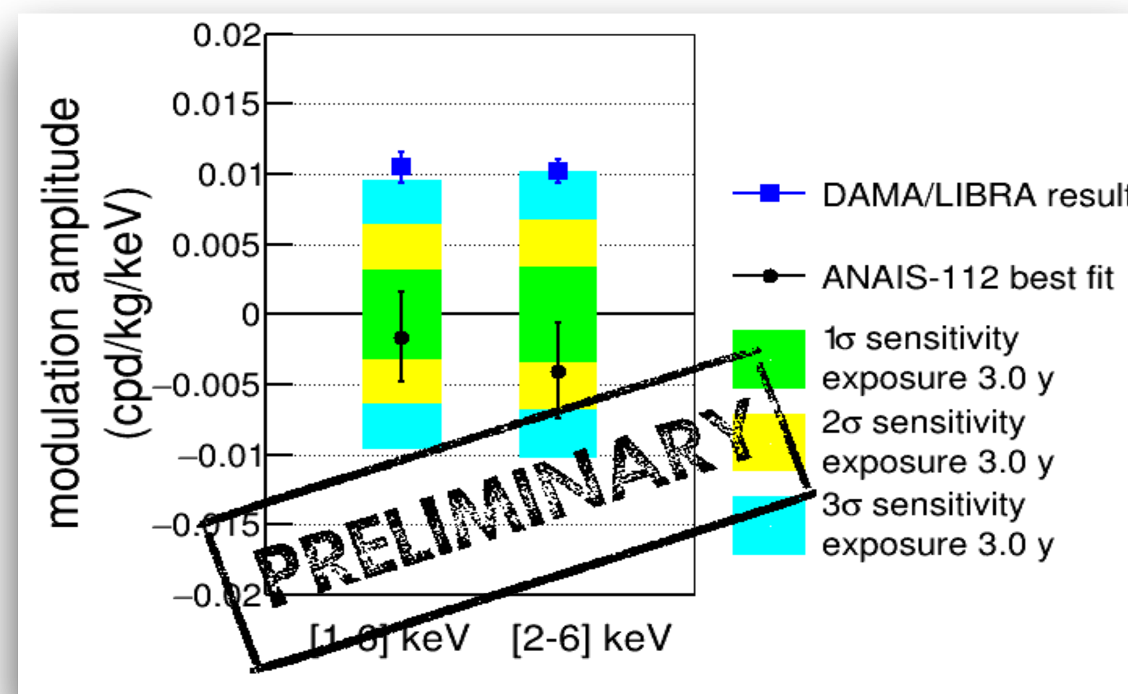
- 3x3 array of NaI(Tl) modules, 112.5 kg
- Located at Canfranc Underground Laboratory
- Taking data since August 2017
- Almost **five years of data** with duty cycle above 95%

- Three-year exposure results published in 2021, Phys. Rev. D 103 (arXiv:2110.10649)

Three-year exposure reanalysis sensitivity is at 3 sigma. PROSPECTS to achieve more than 4 sigma with 5 year exposure and 5 sigma by 2024

Triggering well below 1 keVee





Link to ANAIS talk at IDM22

COSINE-100

Acknowledgment to
R. Maruyama and G. Adhikari
(COSINE)

https://cosine.yale.edu/home

- Joint venture of KIMS and DM-ICE
- Eight NaI (Tl) crystals 106 kg

- Located at Yangyang Underground Lab in South Korea (1800 meters water equivalent)

- Data taking from September 2016 and published result with an exposure of 173 kg year arXiv: 2111.08863.pdf

COSINE-100

Acknowledgment to
R. Maruyama and G. Adhikari
(COSINE)

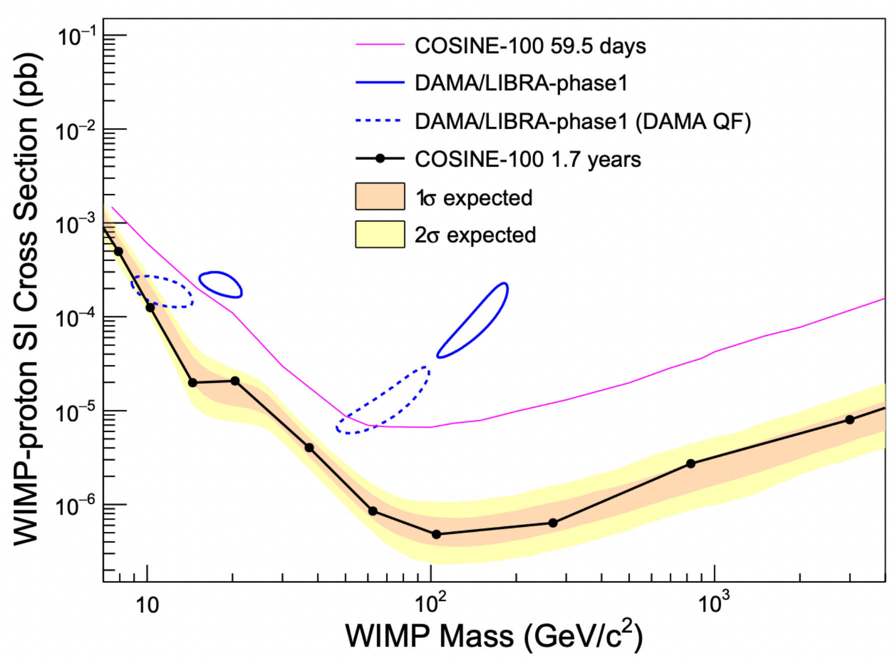
https://cosine.yale.edu/home

- Joint venture of KIMS and DM-ICE
- Eight NaI (Tl) crystals 106 kg

- Located at Yangyang Underground Lab in South Korea (1800 meters water equivalent)

- Data taking from September 2016 and published result with an exposure of 173 kg year arXiv: 2111.08863.pdf

Exclude DAMA/LIBRA phase1's interpretation with the spin-independent WIMP interaction with Standard Halo model in NaI(Tl) crystal



Sci Adv. 2021 Nov 12;7(46):eabk2699

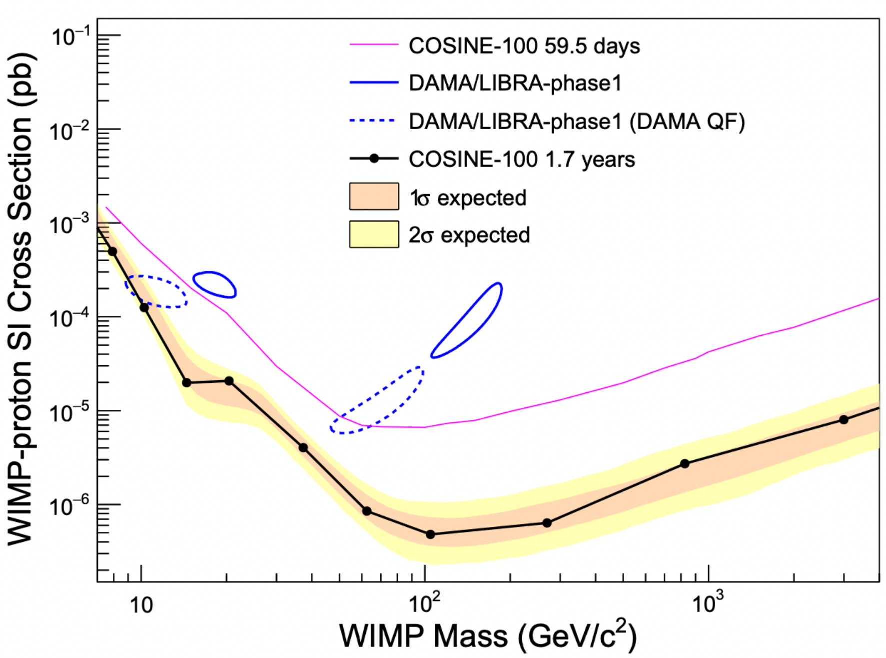
COSINE-100

- Joint venture of KIMS and DM-ICE
- Eight NaI (Tl) crystals 106 kg
- Located at Yangyang Underground Lab in South Korea (1800 meters water equivalent)
- Data taking from September 2016 and published result with an exposure of 173 kg year arXiv: 2111.08863.pdf

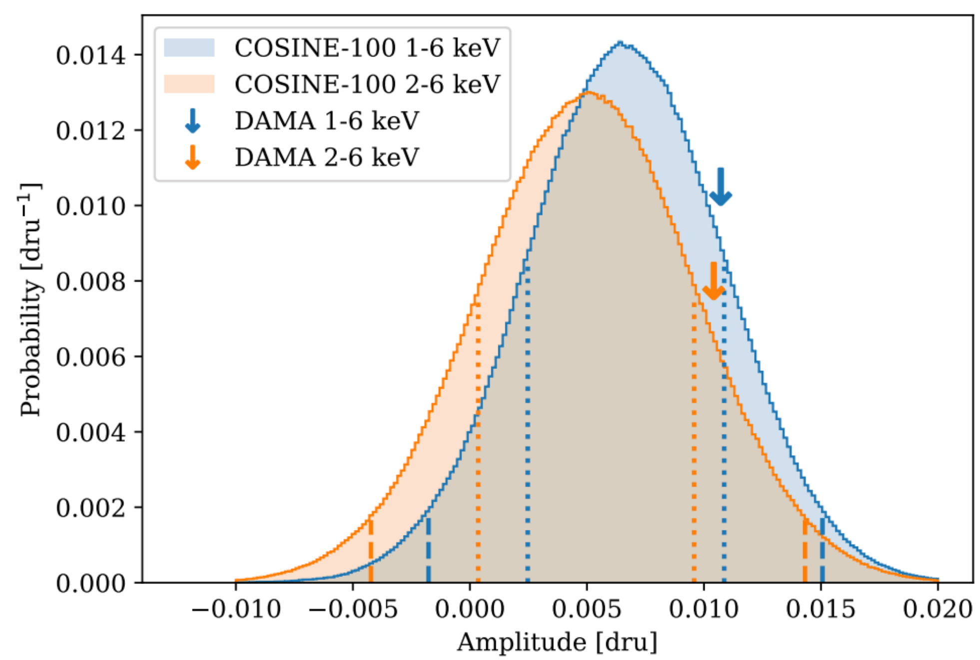
Acknowledgment to R. Maruyama and G. Adhikari (COSINE)
https://cosine.yale.edu/home

Exclude DAMA/LIBRA phase1's interpretation with the spin-independent WIMP interaction with Standard Halo model in NaI(Tl) crystal

Best-fit modulation amplitude of (0.0067 ± 0.0042) cpd/kg/keV at 1- 6 keV. Compatible both with and with no modulation



Sci Adv. 2021 Nov 12;7(46):eabk2699



arXiv:2111.08863v1

COSINE-100

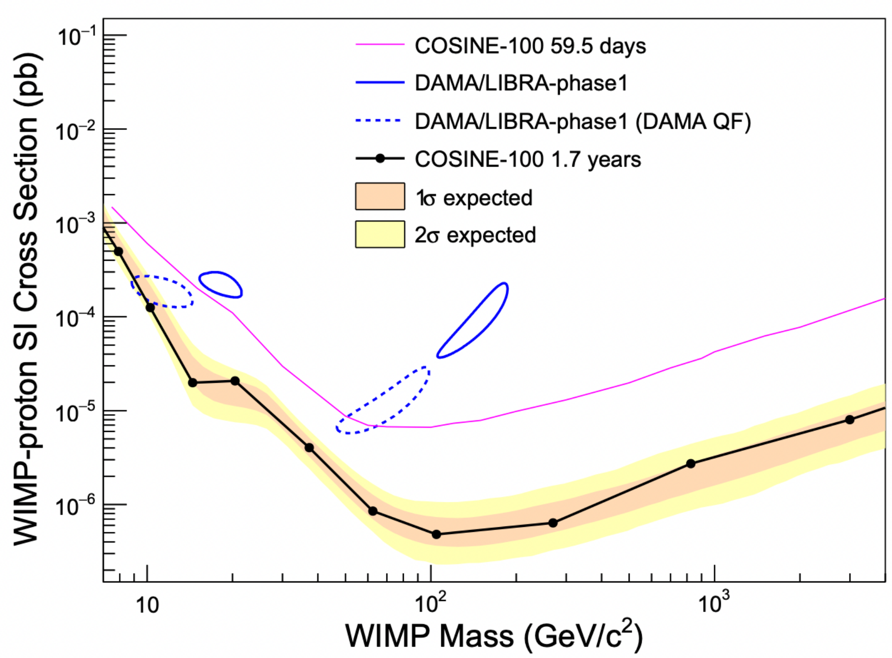
Acknowledgment to
R. Maruyama and G. Adhikari
(COSINE)
https://cosine.yale.edu/home

- Joint venture of KIMS and DM-ICE
- Eight NaI (Tl) crystals 106 kg

- Located at Yangyang Underground Lab in South Korea (1800 meters water equivalent)

- Data taking from September 2016 and published result with an exposure of 173 kg year arXiv: 2111.08863.pdf

Exclude DAMA/LIBRA phase1's interpretation with the spin-independent WIMP interaction with Standard Halo model in NaI(Tl) crystal



Sci Adv. 2021 Nov 12;7(46):eabk2699

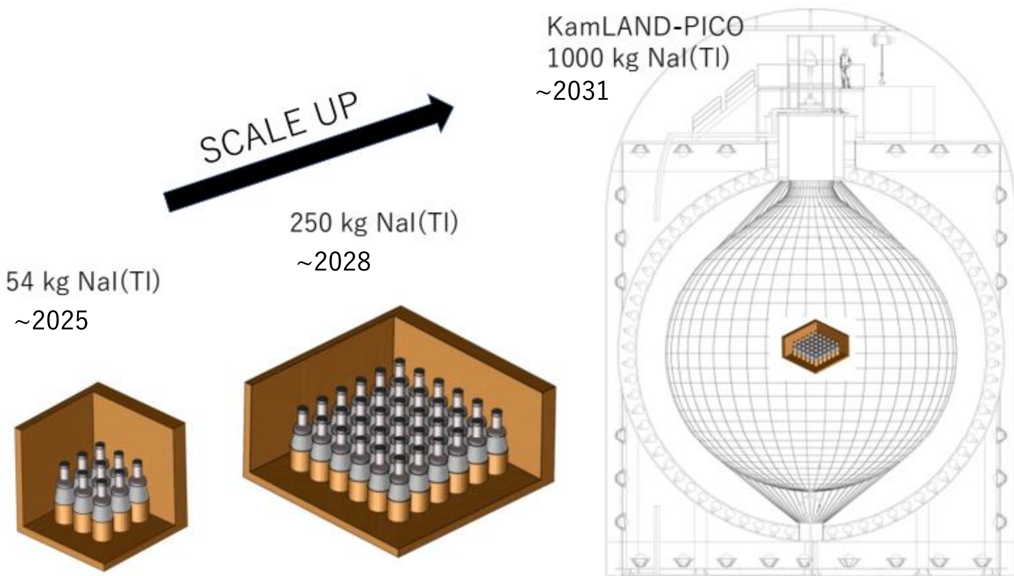
In-house crystal growing protocol is developed by collaboration and achieved promising radio-purity and light collection with R&D crystal (0.6 kg)

Expect < 1 counts/day/kg/keV in COSINE-200 crystals

COSINE-200 will be run by 2023

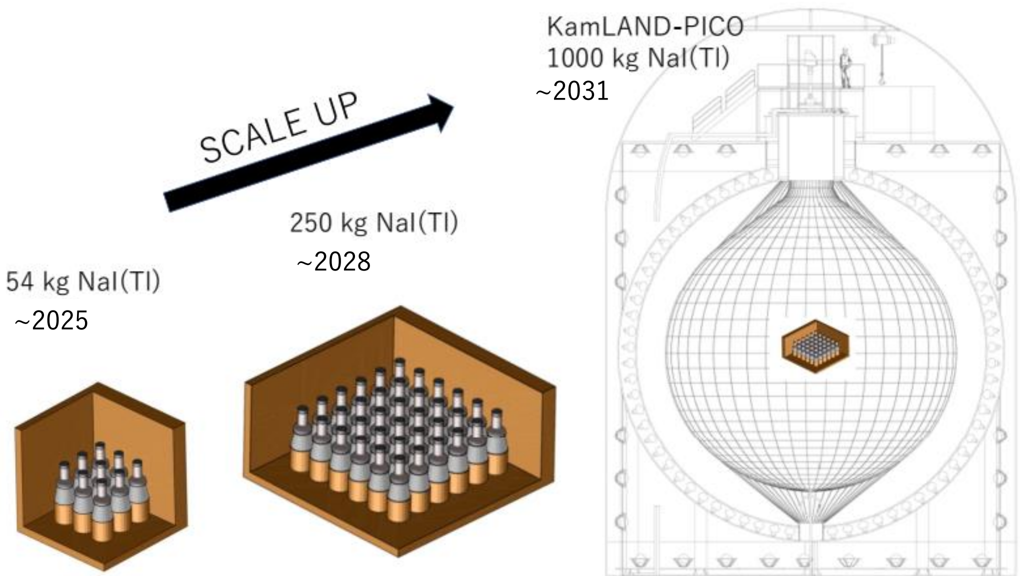
PICOLON

Acknowledgment to
K. Fushimi (PICOLON)



PICOLON

Acknowledgment to K. Fushimi (PICOLON)



- High radiopurity reached in the #85 ingot
- The newest ingot #94 was relatively higher contamination than #85, but as small as DAMA/LIBRA
- New ingot in preparation. It will be delivered in September
- Commissioning is starting

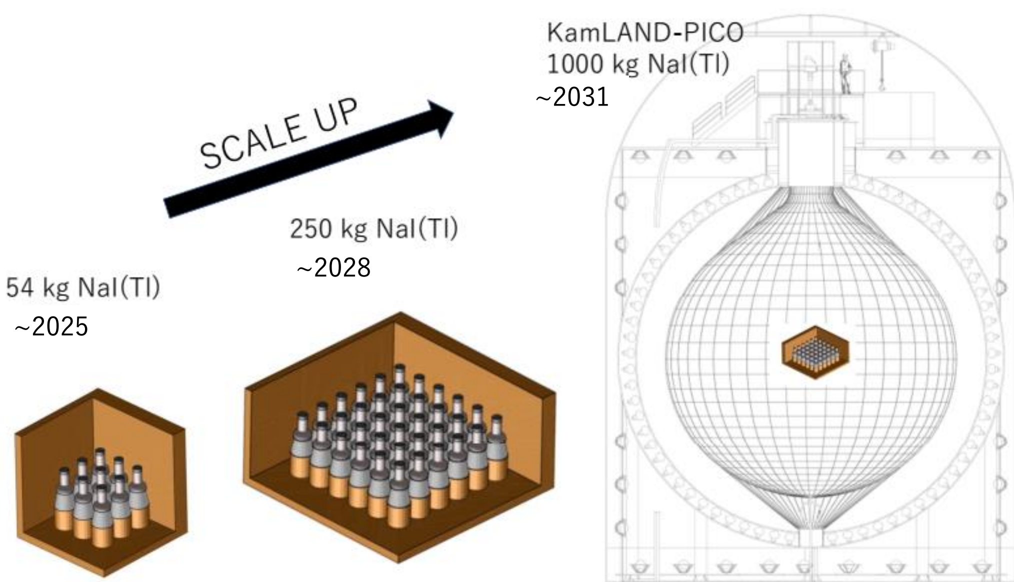
	DAMA/LIBRA (NIM A592 (2008) 297.)	Ingot #85 (2020)	Ingot #94 (This work)
Crystal size	$10.2 \times 10.2 \times 25.4$ cm^3	$7.62\phi \times 7.62$ cm^3	
^{232}Th [μBq/kg]	2~31	0.3 ± 0.5	4.6 ± 1.2
^{226}Ra [μBq/kg]	8.7~124	1.0 ± 0.4	8.7 ± 1.5
^{210}Po [μBq/kg]	5~30	< 5.7	28 ± 5

BG Rate: ~2 Events/(day・kg・keV$_{ee}$).

COSINUS

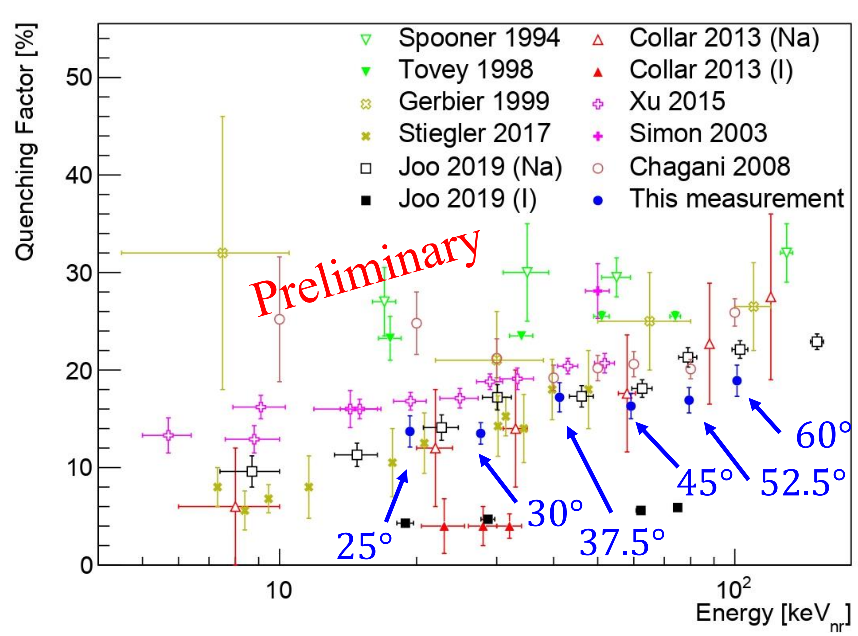
PICOLON

Acknowledgment to
K. Fushimi (PICOLON)



- High radiopurity reached in the #85 ingot
- The newest ingot #94 was relatively higher contamination than #85, but as small as DAMA/LIBRA
- New ingot in preparation. It will be delivered in September
- Commissioning is starting

Result of QFs & Comparison with previous results



H.W.Joo *et al.*, Astroparticle Physics, **108**, 50–56, 2019

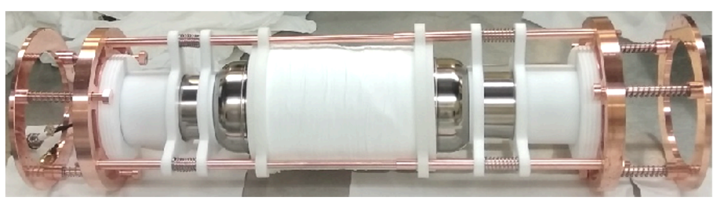
Geant4 calculation of E_{nr} at each scattering angle

Scattering angle [deg.]	E_{nr} (Na) [keV$_{nr}$]	QF_{Na} [%]
25	19.34 ± 0.16	13.7 ± 1.6
30	27.67 ± 0.19	13.5 ± 1.1
37.5	41.22 ± 0.23	17.2 ± 1.5
45	59.15 ± 0.23	16.3 ± 1.3
52.5	79.36 ± 0.33	16.9 ± 1.3
60	101.12 ± 0.36	18.9 ± 1.6

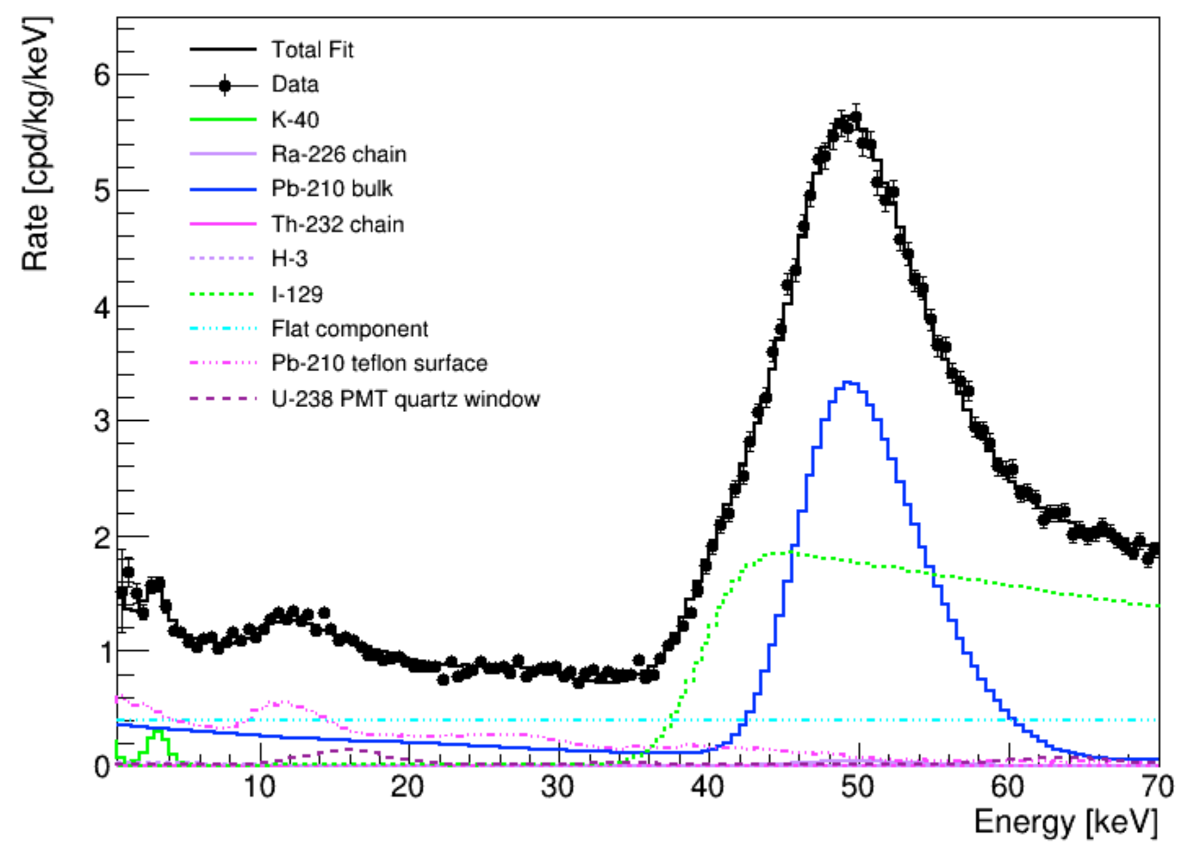
COSINUS

SABRE NORTH

Acknowledgment to
I. Bolognino et al. (SABRE)

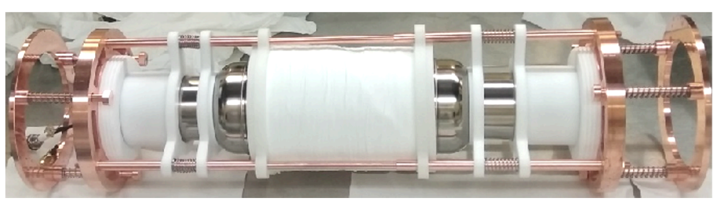


- NaI(Tl) crystals (NaI-31 and NaI-33) tested and characterised.
- Proof-of-principle phase (1 crystal + active veto) concluded
- Full Monte-Carlo background simulation model to identify background components
- Breakthrough background level: ~1 count/day/kg/keV in the 1-6 keV region of interest, lowest since DAMA/LIBRA.



SABRE NORTH

Acknowledgment to
I. Bolognino et al. (SABRE)



- NaI(Tl) crystals (NaI-31 and NaI-33) tested and characterised.
- Proof-of-principle phase (1 crystal + active veto) concluded
- Full Monte-Carlo background simulation model to identify background components
- Breakthrough background level: ~1 count/day/kg/keV in the 1-6 keV region of interest, lowest since DAMA/LIBRA.

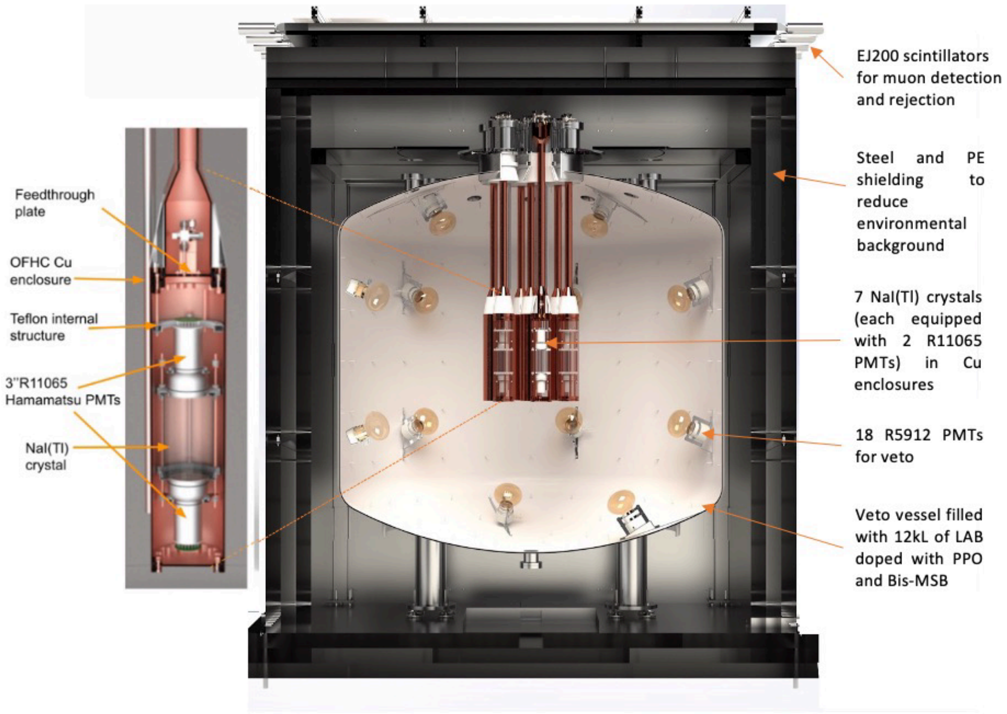
Goals for near future:

- Test the same crystal (NaI-33) with a lower radioactivity reflector
- Test reproducibility of crystal radiopurity
- Assembly of detector modules at LNGS with a new custom glove box.

Demonstrate feasibility of a full-scale experiment without active veto and finalize the design of crystal array + shielding

SABRE SOUTH

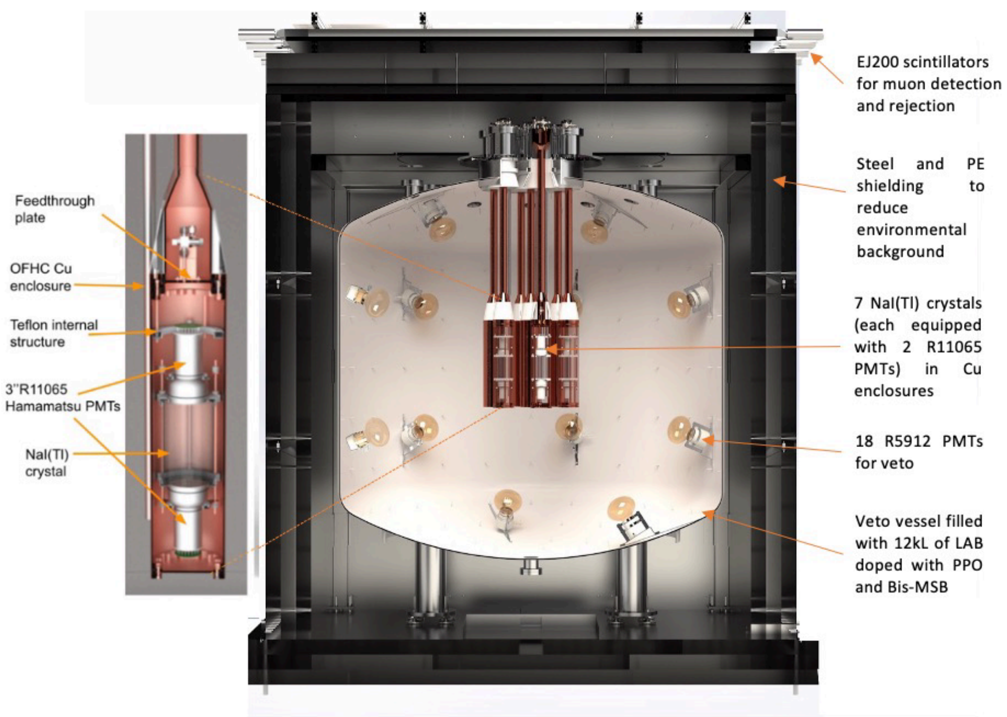
Acknowledgment to
I. Bolognino et al. (SABRE)



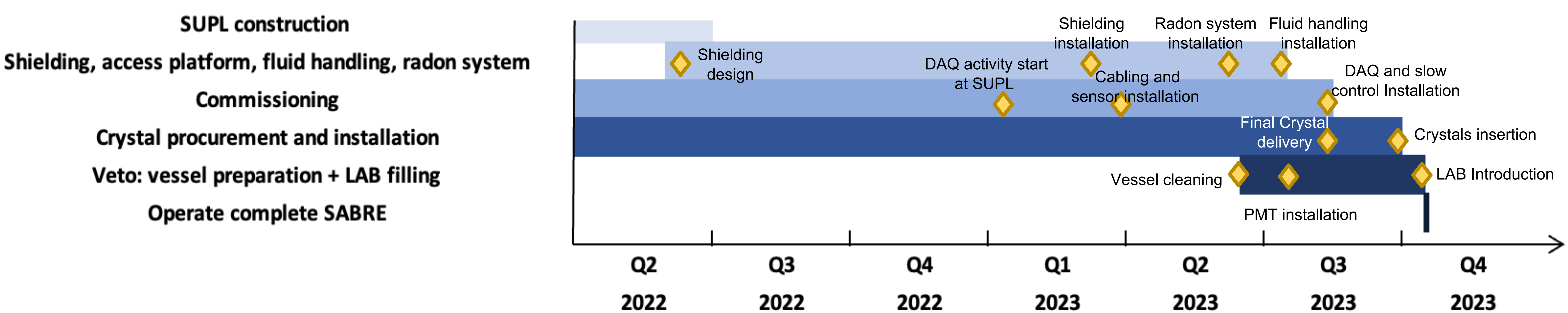
- First experiment in SUPL (Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia), the first underground laboratory in the Southern hemisphere
- Will use the liquid scintillator (LAB) for in-situ evaluation and validation of the background in addition of background rejection and particle identification.
- Vessel + LAB, PMTs, muon detector, DAQ electronics, slow control, Crystal insertion system ... all ready
- One low background NaI(Tl) crystal under test at LNGS

SABRE SOUTH

Acknowledgment to
I. Bolognino et al. (SABRE)



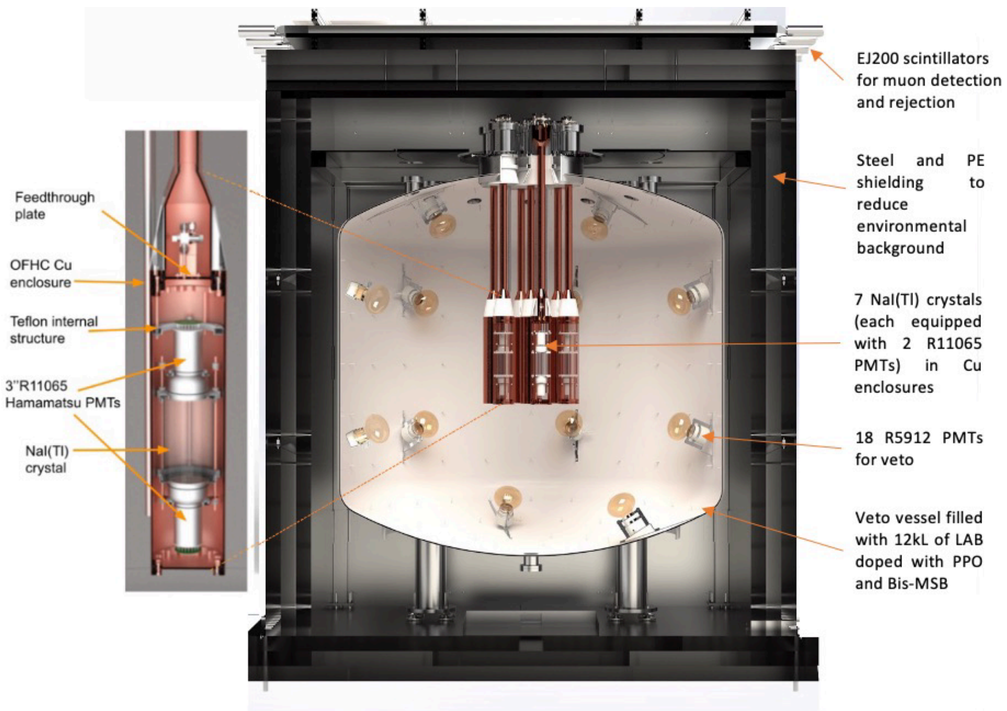
- First experiment in SUPL (Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia), the first underground laboratory in the Southern hemisphere
- Will use the liquid scintillator (LAB) for in-situ evaluation and validation of the background in addition of background rejection and particle identification.
- Vessel + LAB, PMTs, muon detector, DAQ electronics, slow control, Crystal insertion system ... all ready
- One low background NaI(Tl) crystal under test at LNGS



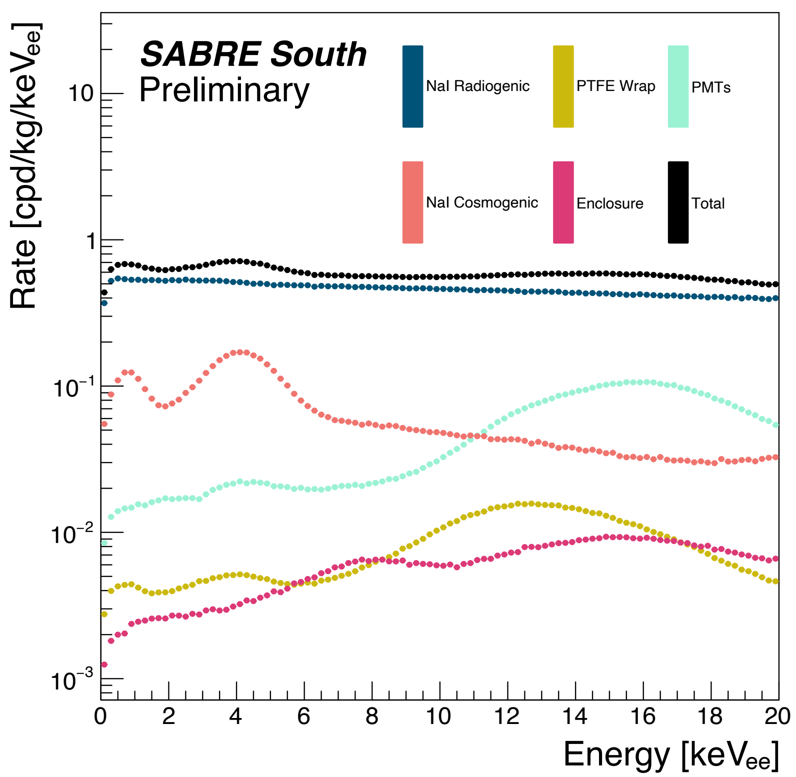
COSINUS

SABRE SOUTH

Acknowledgment to I. Bolognino et al. (SABRE)



- First experiment in SUPL (Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia), the first underground laboratory in the Southern hemisphere
- Will use the liquid scintillator (LAB) for in-situ evaluation and validation of the background in addition of background rejection and particle identification.
- Vessel + LAB, PMTs, muon detector, DAQ electronics, slow control, Crystal insertion system ... all ready
- One low background NaI(Tl) crystal under test at LNGS



Highest purity crystals and largest active veto: 0.72 cpd/kg/keV

arXiv: 2205.13849

SINGLE CHANNEL
ROOM TEMPERATURE SCINTILLATORS
LIGHT

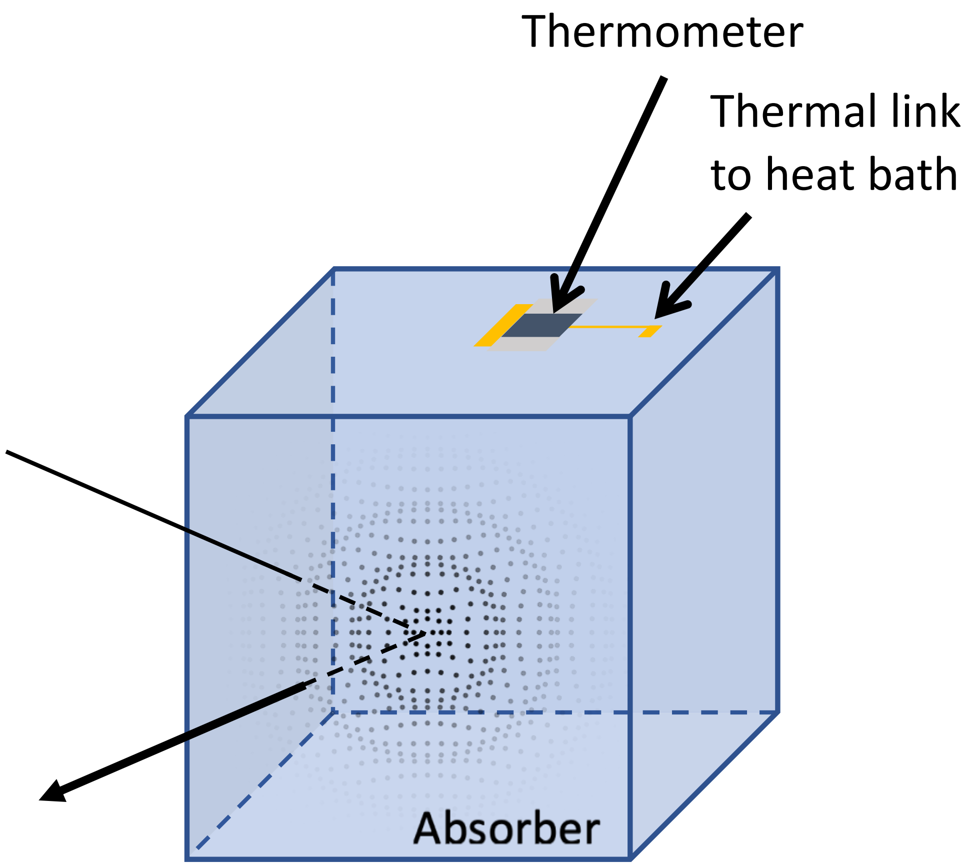
- ANAIS
- COSINE
- PICOLON
- SABRE

DUAL CHANNEL
CRYOGENIC CALORIMETER
HEAT+LIGHT

COSINUS

COSINUS

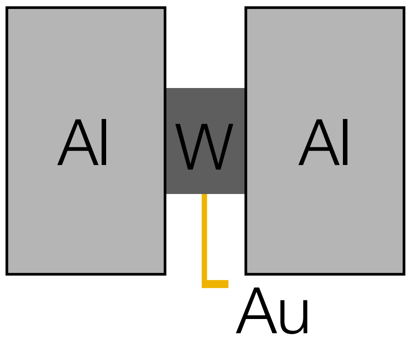
CRYOGENIC CALORIMETER



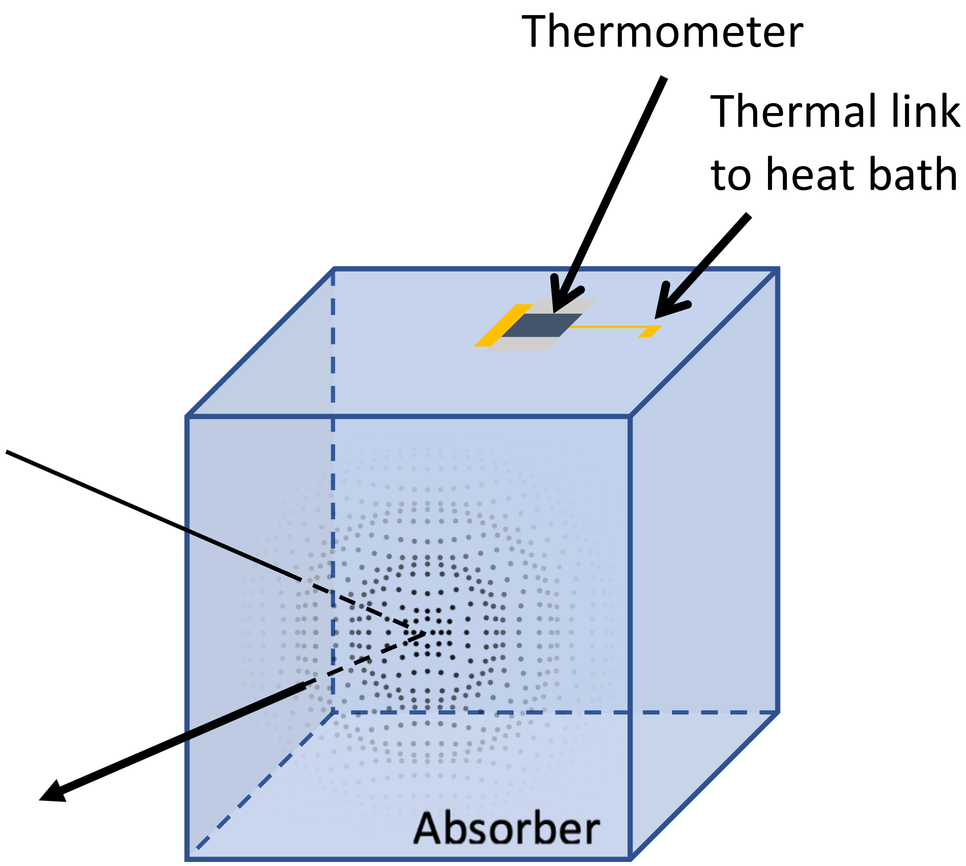
Measure the energy deposited in the absorber and converted into lattice vibrations (phonons)

Phonons flow to the superconducting thermometer operated at milliKelvin temperature

COSINUS uses the Transition Edge Sensors developed by CRESST



CRYOGENIC CALORIMETER

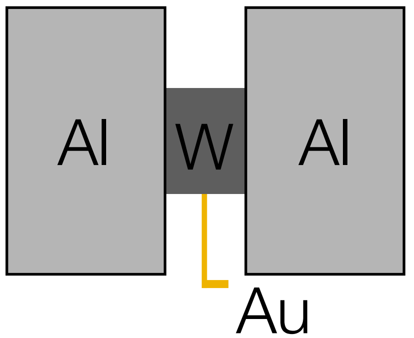


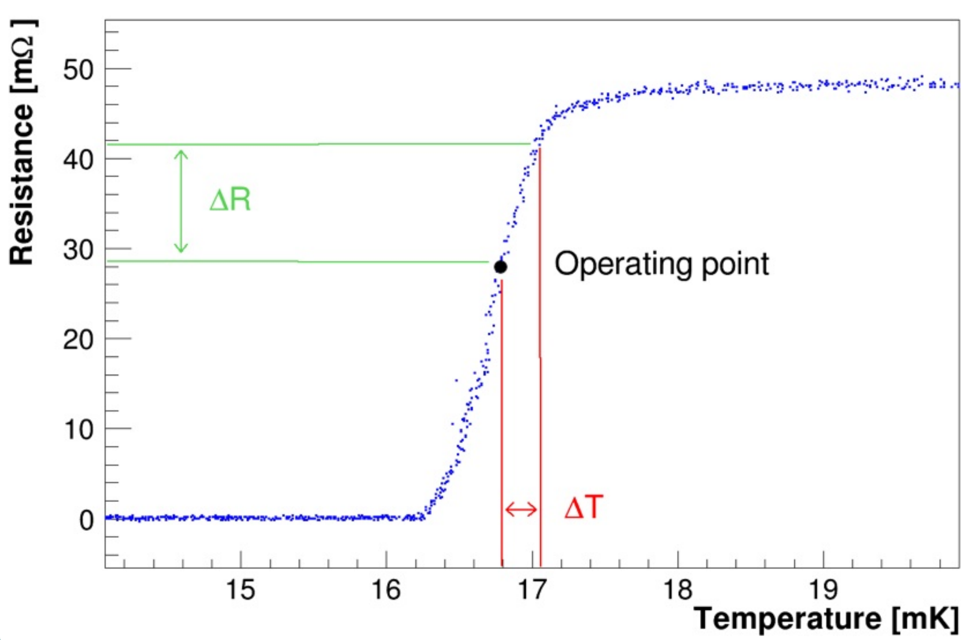
Measure the energy deposited in the absorber and converted into lattice vibrations (phonons)

Phonons flow to the superconducting thermometer operated at milliKelvin temperature

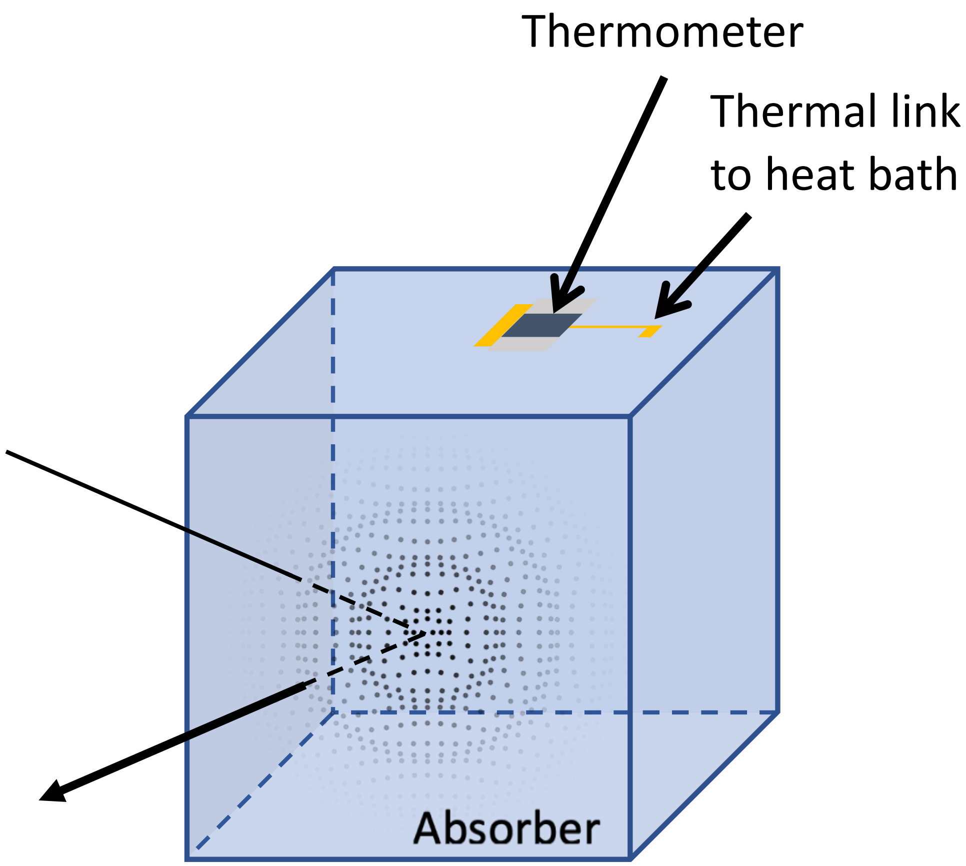
COSINUS uses the Transition Edge Sensors developed by CRESST

CRESST
Cryogenic **Rare Event Search** with Superconducting Thermometers





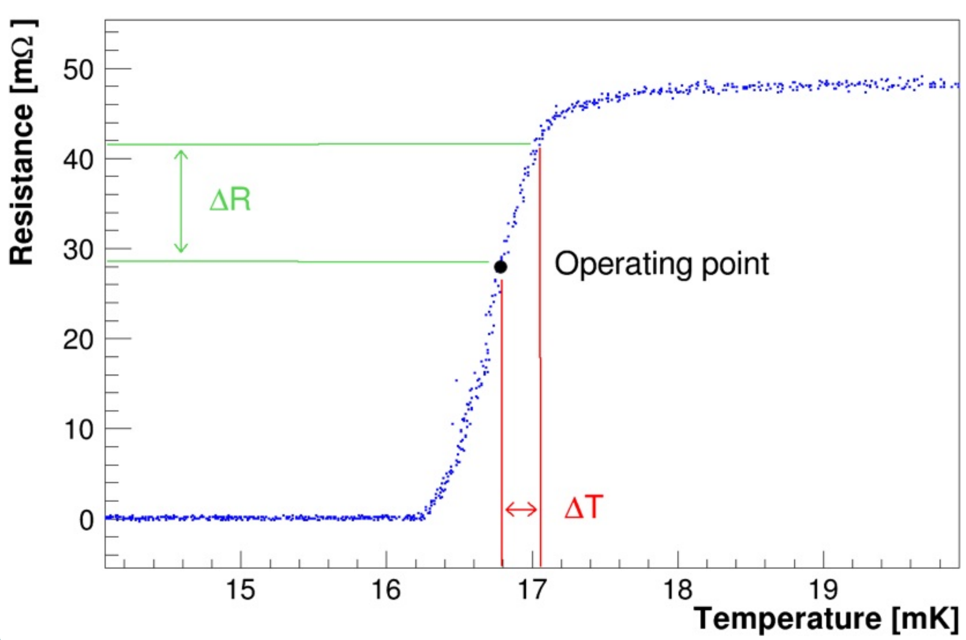
CRYOGENIC CALORIMETER

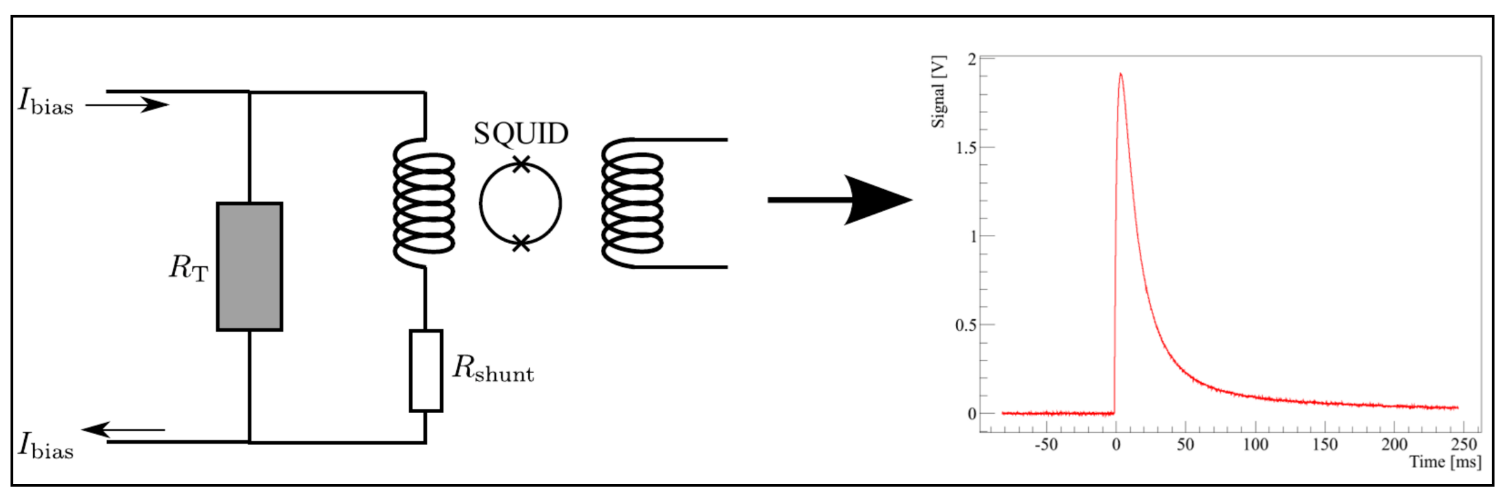


Measure the energy deposited in the absorber and converted into lattice vibrations (phonons)

Phonons flow to the superconducting thermometer operated at milliKelvin temperature

COSINUS uses the Transition Edge Sensors developed by CRESST

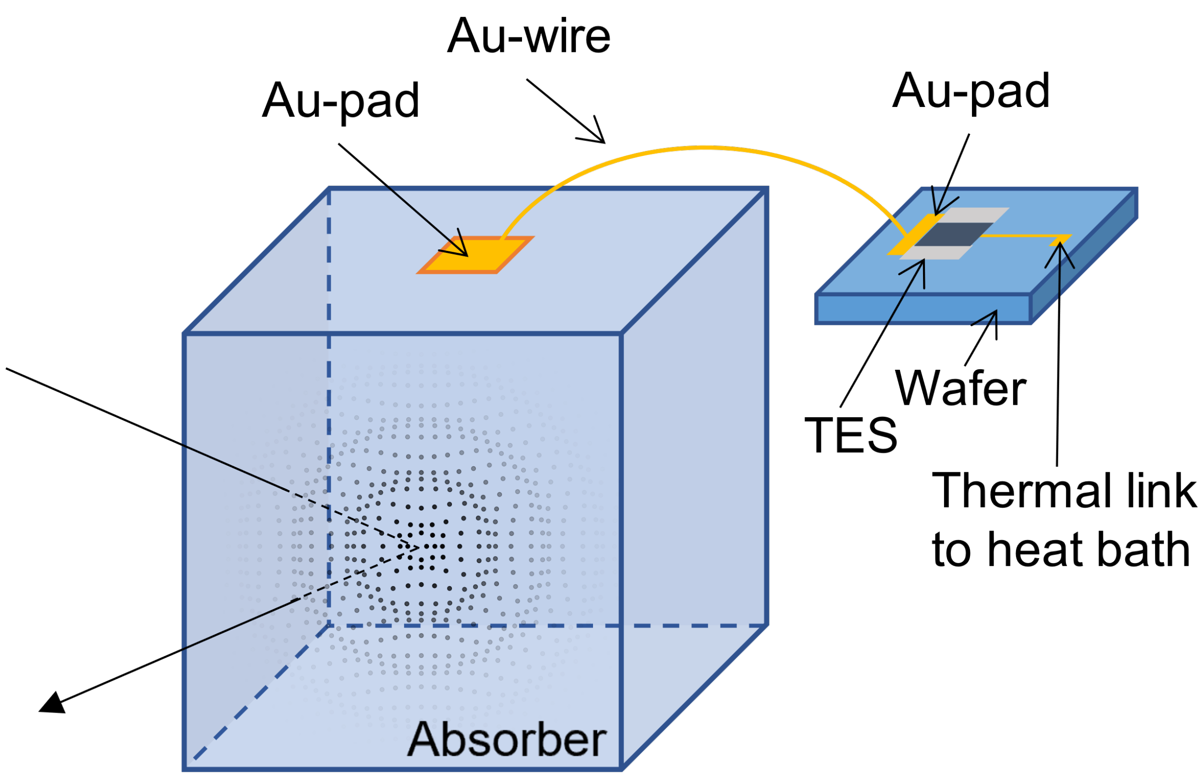




CRYOGENIC CALORIMETER

COSINUS

new remoTES DESIGN

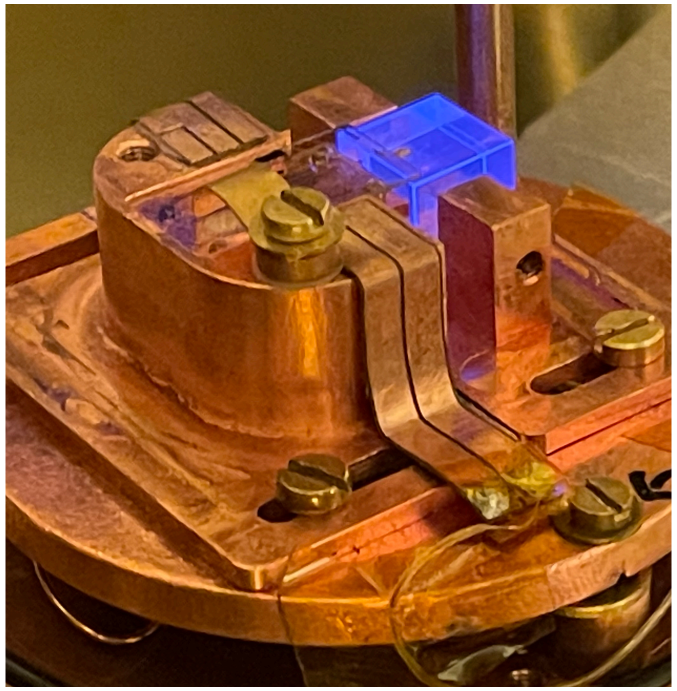


NaI is hygroscopic and has a low melting point. It does not survive any TES fabrication process

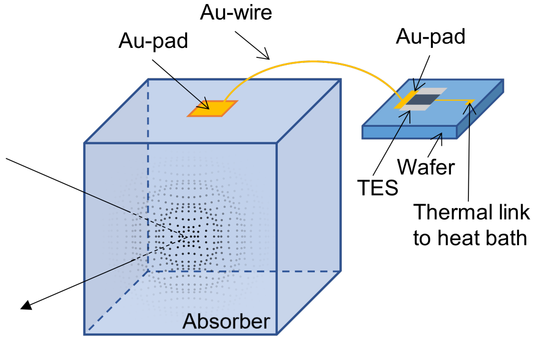
COSINUS implemented the first remoTES design, proposed by Matt Pyle et al, 2015, arXiv:1503.01200

arXiv:2111.00349v1

COSINUS DETECTOR



CHANNEL 1 - PHONON DETECTOR

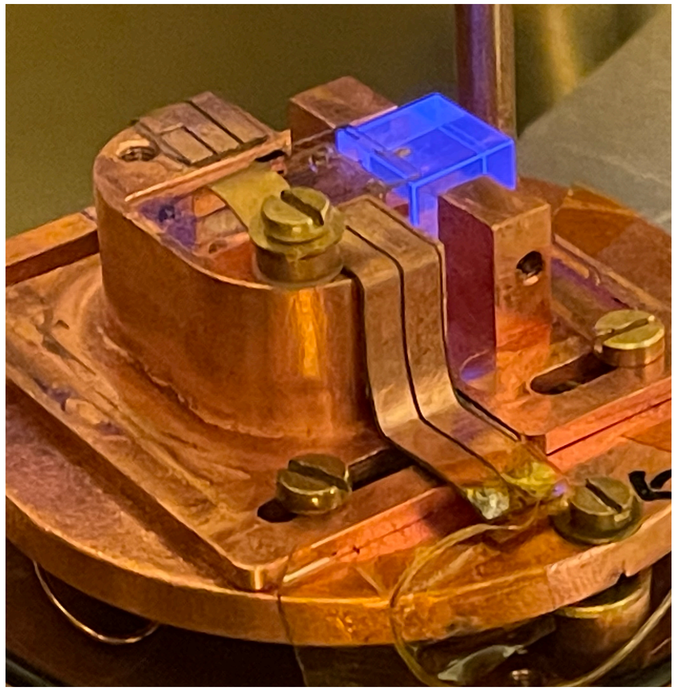


NaI + remoTES
(connected using gold pad and gold wire)

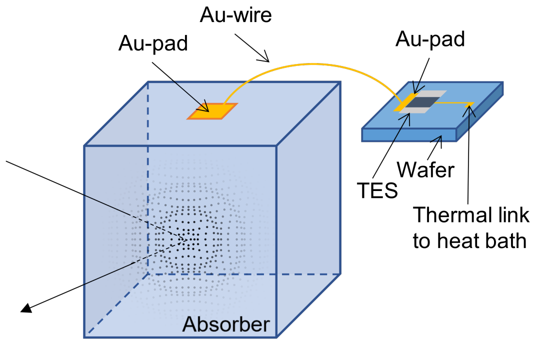
Measure the energy deposited in the absorber as **heat**

Almost independent from the interacting particle

COSINUS DETECTOR



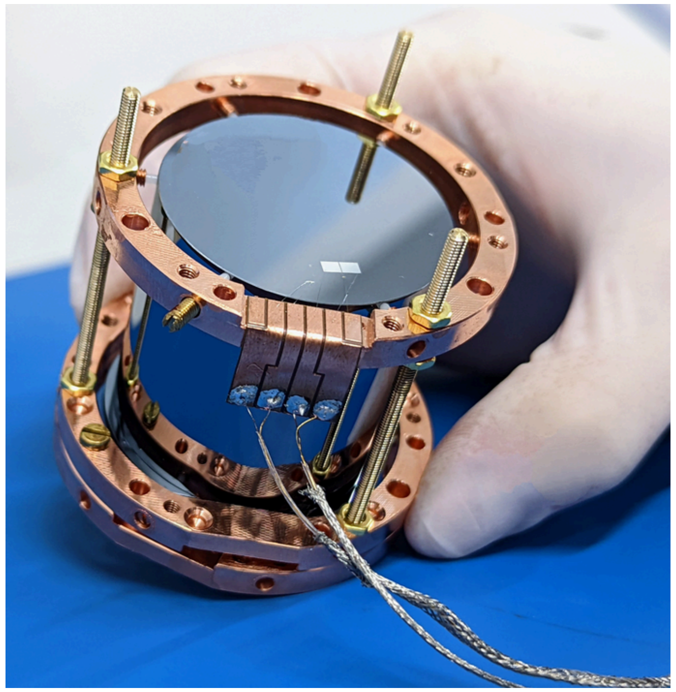
CHANNEL 1 - PHONON DETECTOR



NaI + remoTES
(connected using gold pad and gold wire)

Measure the energy deposited in the absorber as **heat**

Almost independent from the interacting particle



CHANNEL 2 - LIGHT DETECTOR

Silicon beaker + TES

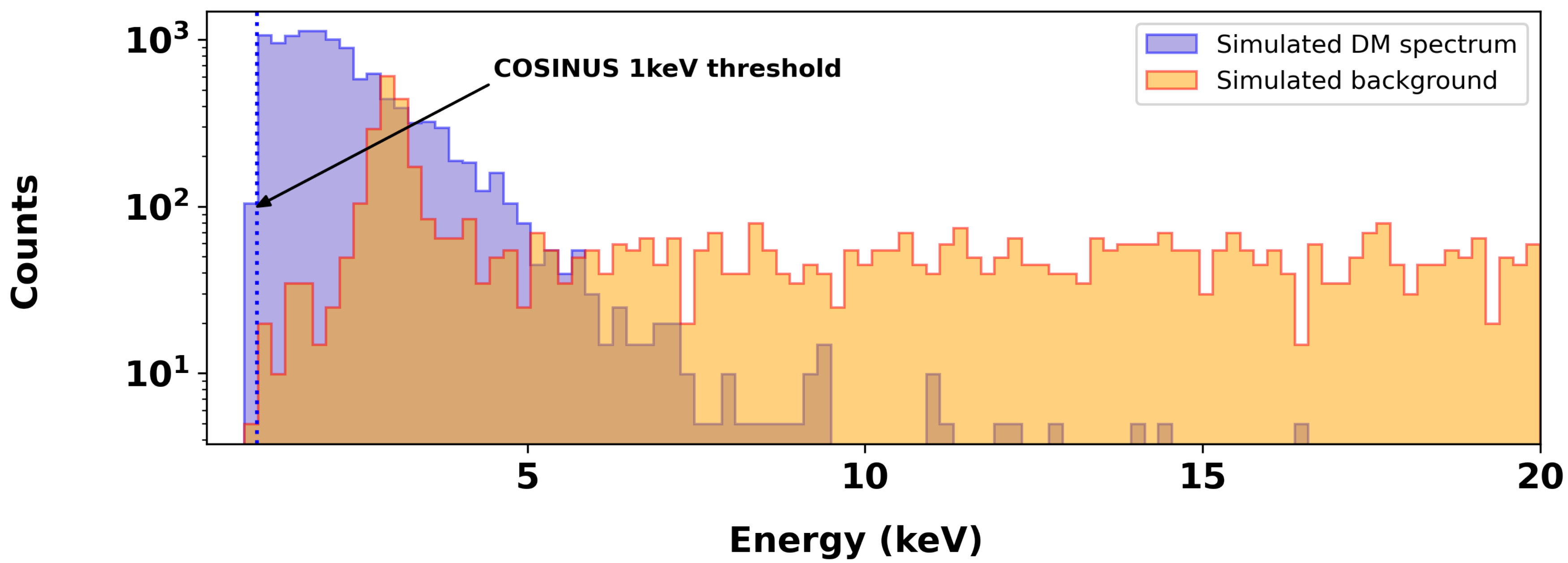
Measure the scintillation light emitted by NaI

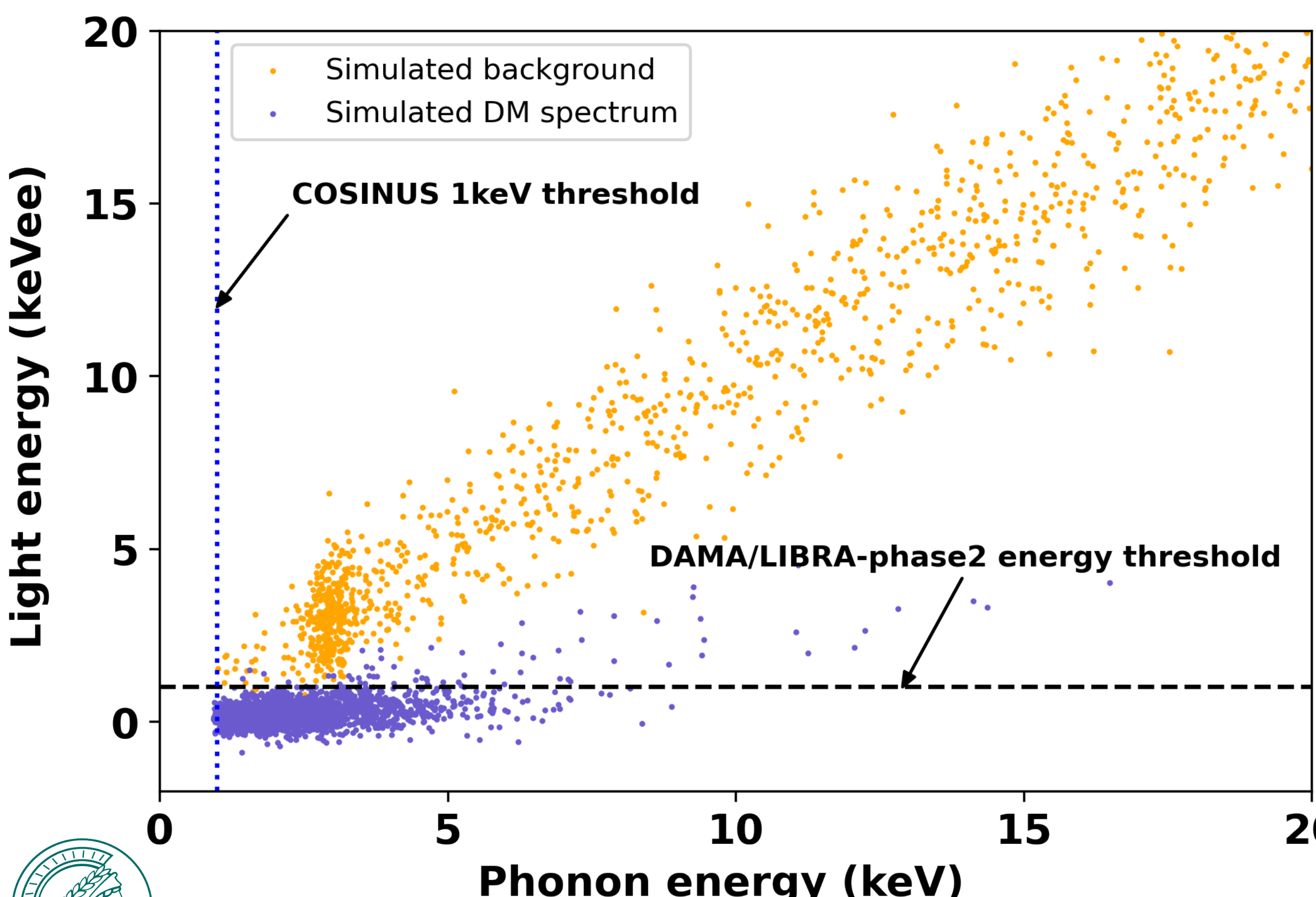
Electromagnetic interactions emit more light than nuclear recoils

→ **PARTICLE DISCRIMINATION**

COSINUS

COSINUS ADVANTAGE



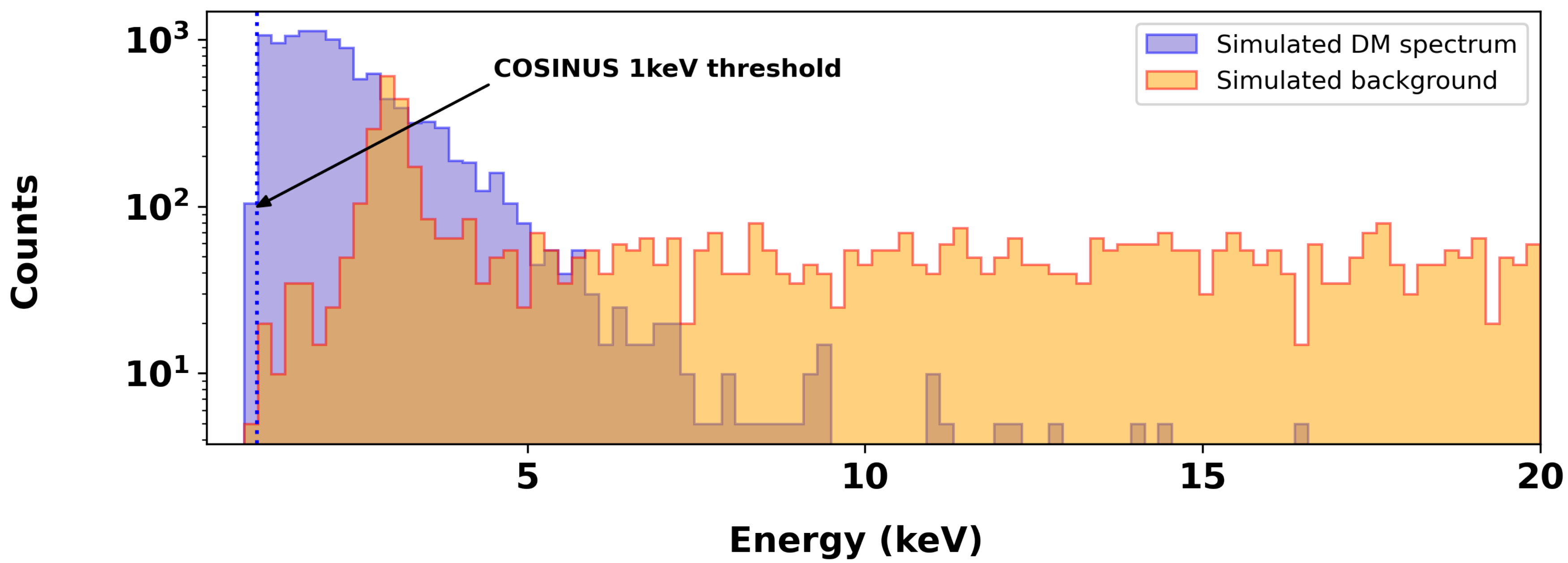


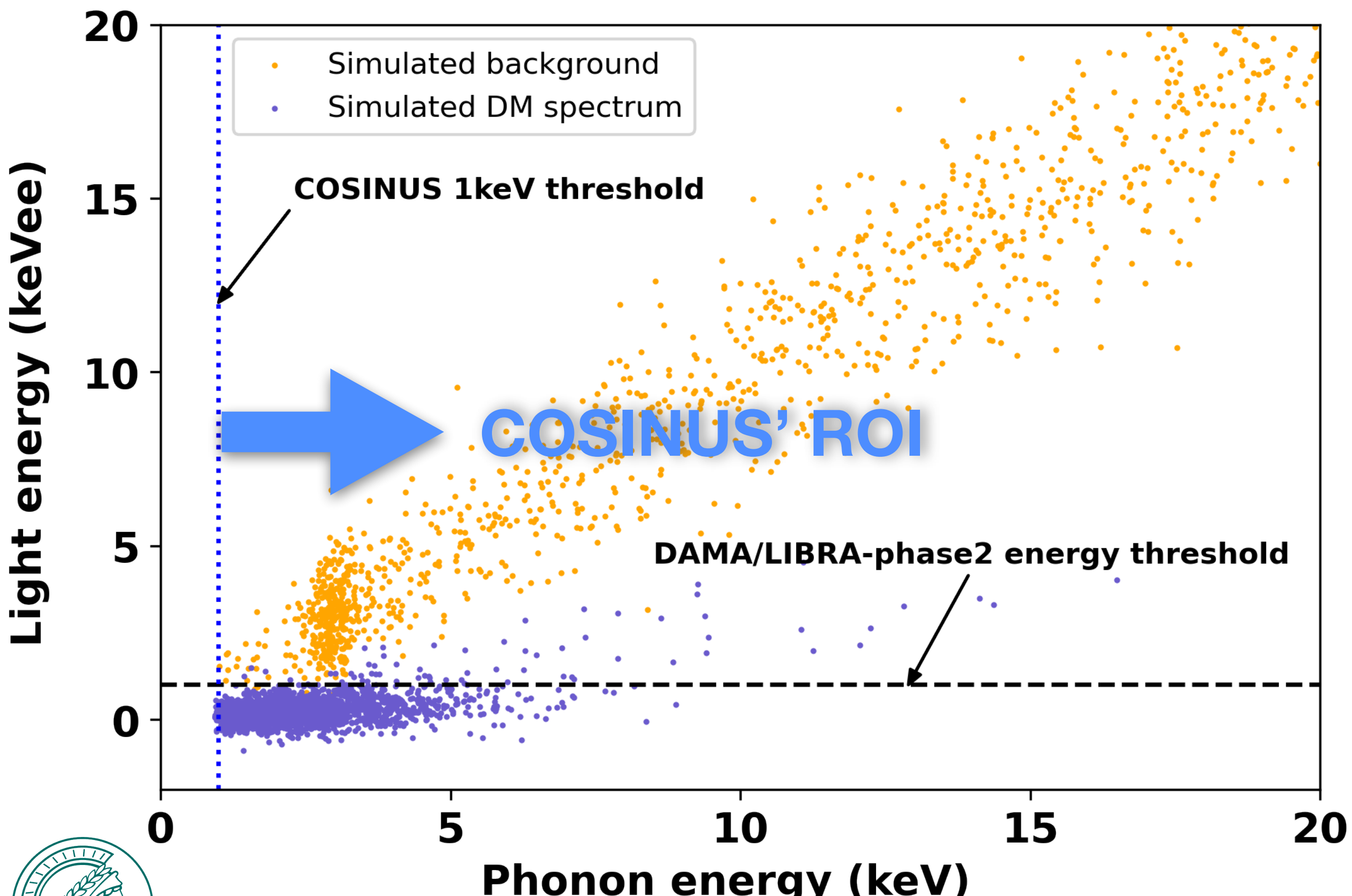
SIMULATED DATA
(100 kg day gross exposure):

- 20 ppb of ^{40}K + 1 cpd/(keV kg)
- Baseline resolution for NaI 0.2 keV
- efficiency between 20-50% at 1-2 keV and at 50% above 2keV
- Energy in light: 4%
- QF for Na ~ 0.3, QF for I ~ 0.09
- σ^{SI}= 2 x 10^{-4} pb (m_{DM}=10 GeV/c^2)

Eur. Phys. J. C 76, 441 (2016)

COSINUS ADVANTAGE



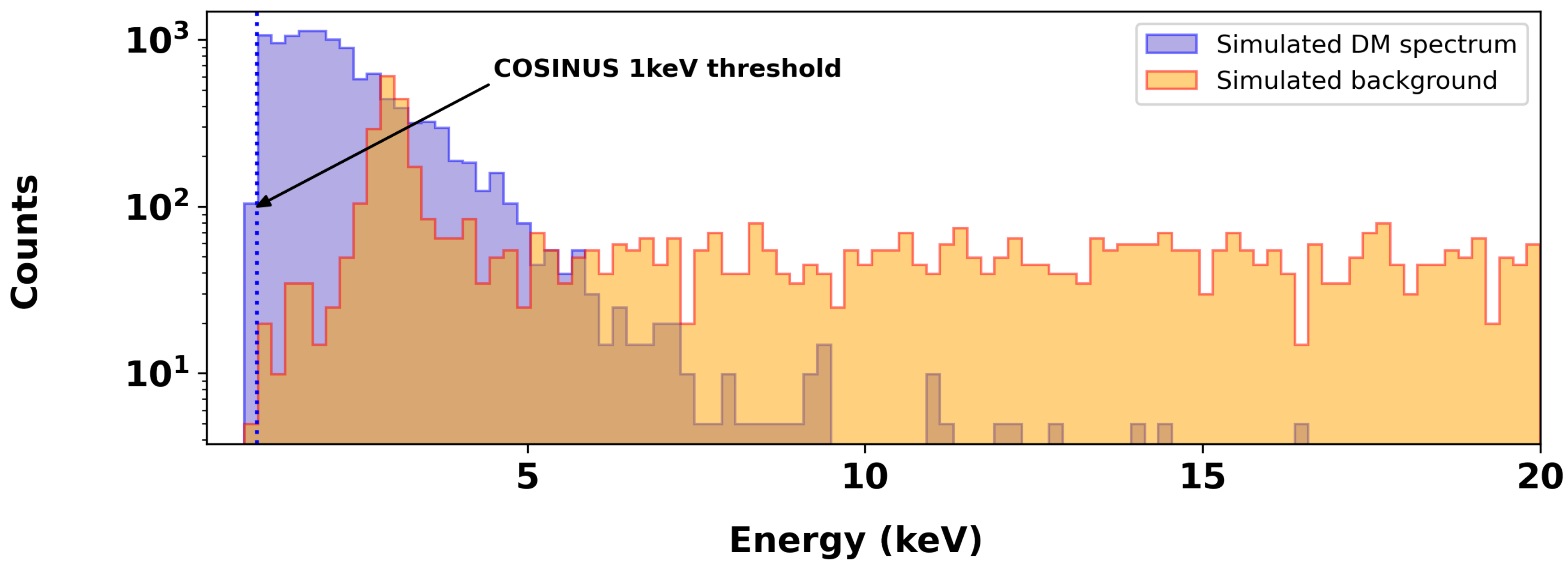


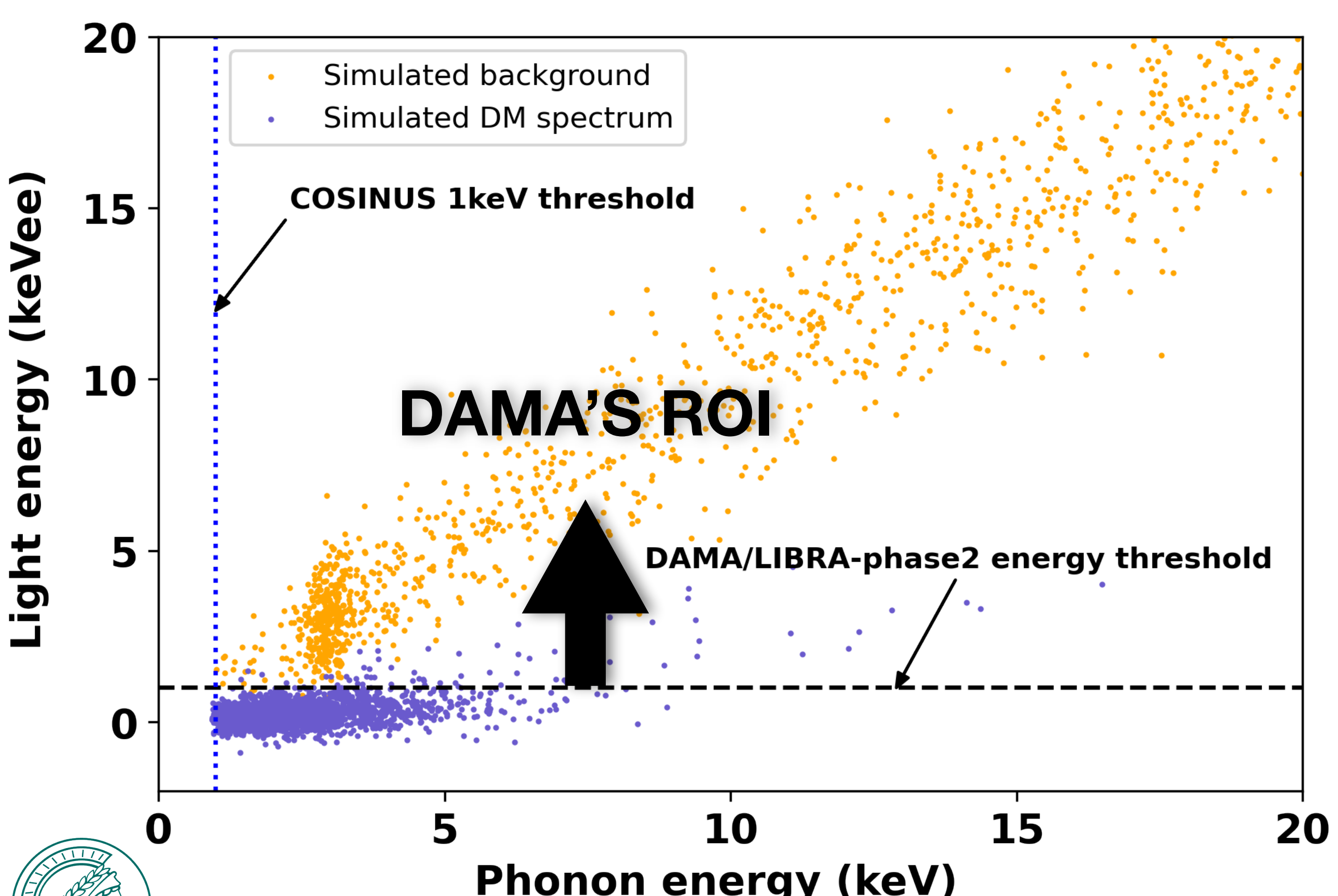
SIMULATED DATA
(100 kg day gross exposure):

- 20 ppb of ^{40}K + 1 cpd/(keV kg)
- Baseline resolution for NaI 0.2 keV
- efficiency between 20-50% at 1-2 keV and at 50% above 2keV
- Energy in light: 4%
- QF for Na ~ 0.3, QF for I ~ 0.09
- σ^{SI}= 2 x 10^{-4} pb (m_{DM}=10 GeV/c^2)

Eur. Phys. J. C 76, 441 (2016)

COSINUS ADVANTAGE



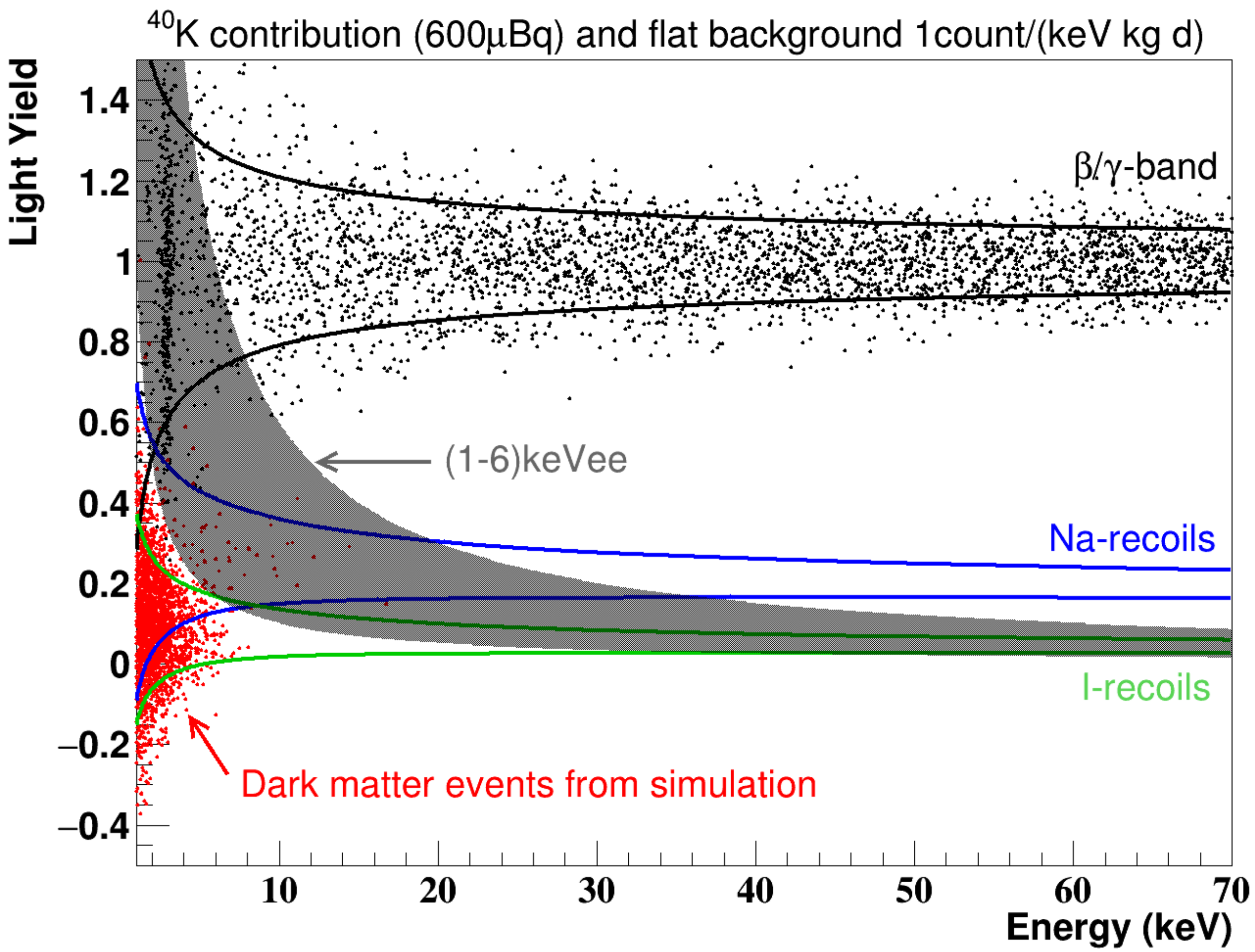


<u>SIMULATED DATA</u>
(100 kg day gross exposure):

- 20 ppb of ^{40}K + 1 cpd/(keV kg)
- Baseline resolution for NaI 0.2 keV
- efficiency between 20-50% at 1-2 keV and at 50% above 2keV
- Energy in light: 4%
- QF for Na ~ 0.3, QF for I ~ 0.09
- σ^{SI}= 2 x 10^{-4} pb (m_{DM}=10 GeV/c^2)

<u>Eur. Phys. J. C 76, 441 (2016)</u>

COSINUS ADVANTAGE



$$\text{Light Yield} = \frac{\text{Light Energy}}{\text{Phonon Energy}}$$

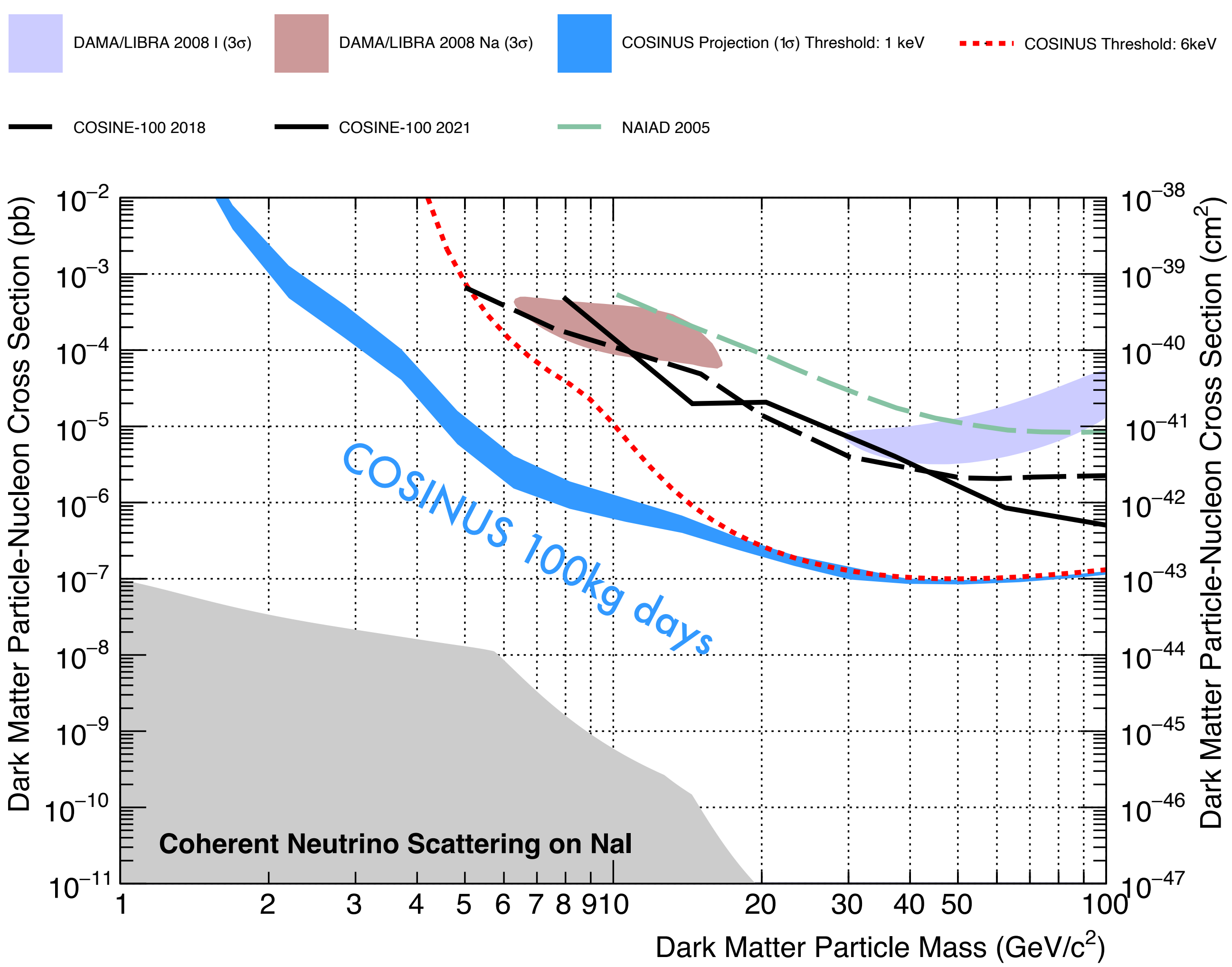
SIMULATED DATA
(100 kg day gross exposure):

- 20 ppb of ^{40}K + 1 cpd/(keV kg)
- Baseline resolution for NaI 0.2 keV
- efficiency between 20-50% at 1-2 keV and at 50% above 2keV
- Energy in light: 4%
- QF for Na ~ 0.3, QF for I ~ 0.09
- σ^{SI}= 2 x 10^{-4} pb (m_{DM}=10 GeV/c^2)

Eur. Phys. J. C 76, 441 (2016)

COSINUS

COSINUS ADVANTAGE



<u>SIMULATED DATA</u>
(100 kg day gross exposure):

- 20 ppb of ^{40}K + 1 cpd/(keV kg)
- Baseline resolution for NaI 0.2 keV
- efficiency between 20-50% at 1-2 keV and at 50% above 2keV
- Energy in light: 4%
- QF for Na ~ 0.3, QF for I ~ 0.09
- σ^{SI}= 2 x 10^{-4} pb (m_{DM}=10 GeV/c^2)

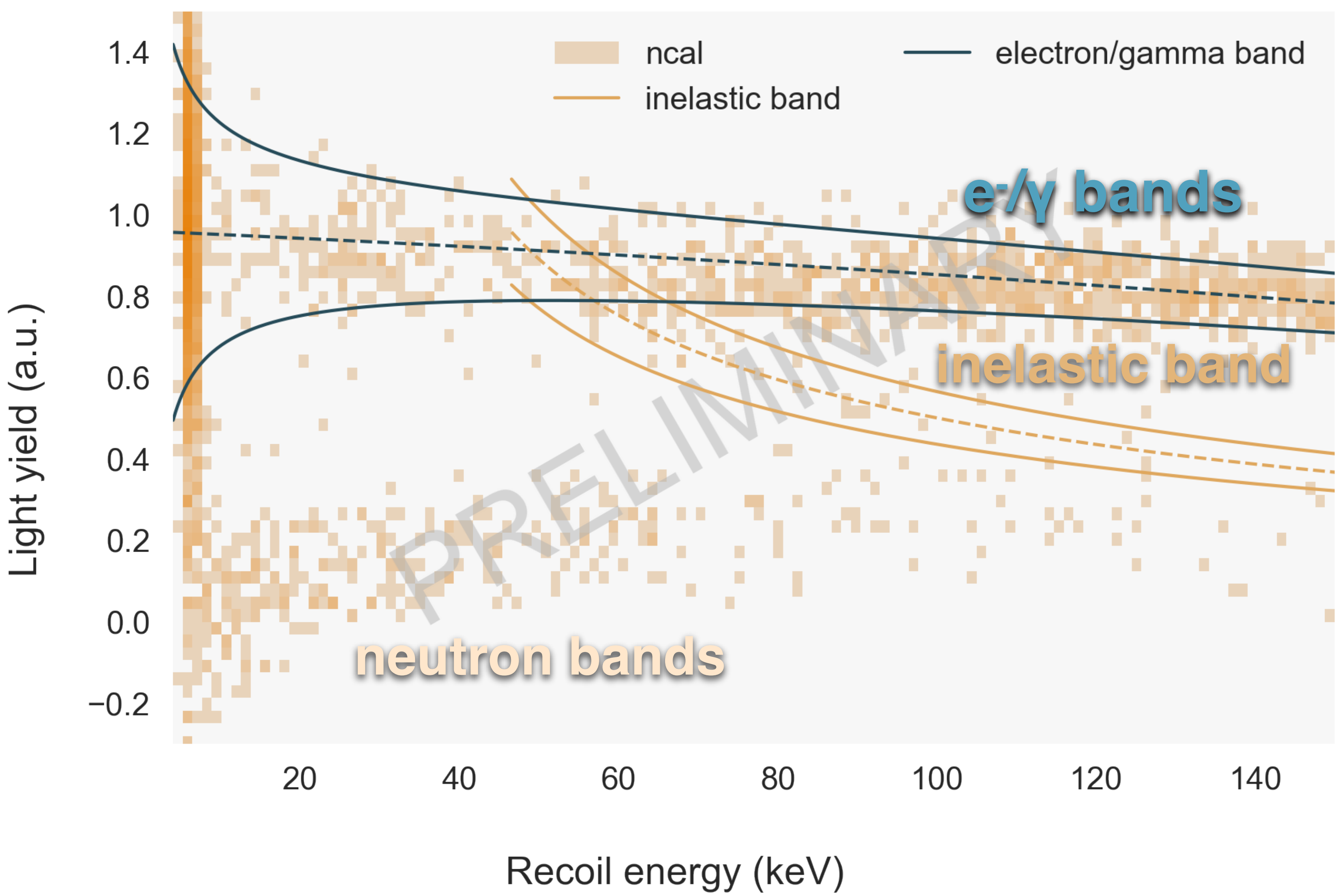
Eur. Phys. J. C 76, 441 (2016)

LATEST RESULTS

NEW

Particle discrimination demonstrated for the first time in NaI

JUNE 2022 : underground measurement at CRESST test facility at LNGS



NaI-remoTES

- NaI grown
- 5-6 ppb of ^{nat}K achieved
- 1 cm^3
- Gold pad glued with epoxy
- Gold pad size 4 mm^2
- W-TES of sapphire wafer

0.39 keV baseline resolution

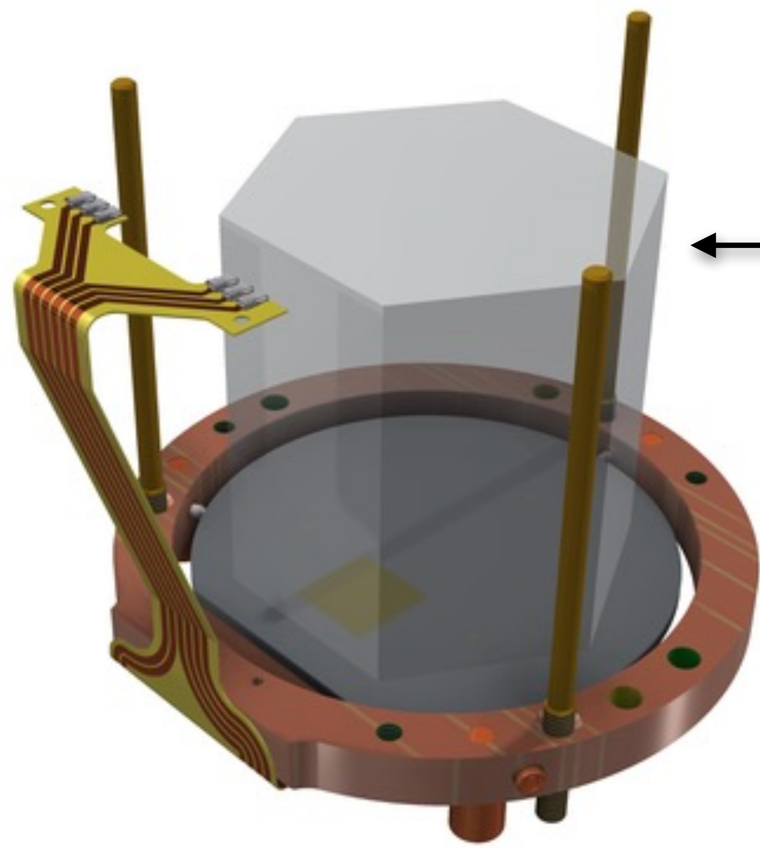
Silicon beaker

- 4 cm diameter and height
- 1 mm thickness
- 15 g
- W-TES evaporated on the surface
- 20 eV baseline resolution

best performance:

10.2 eV baseline resolution

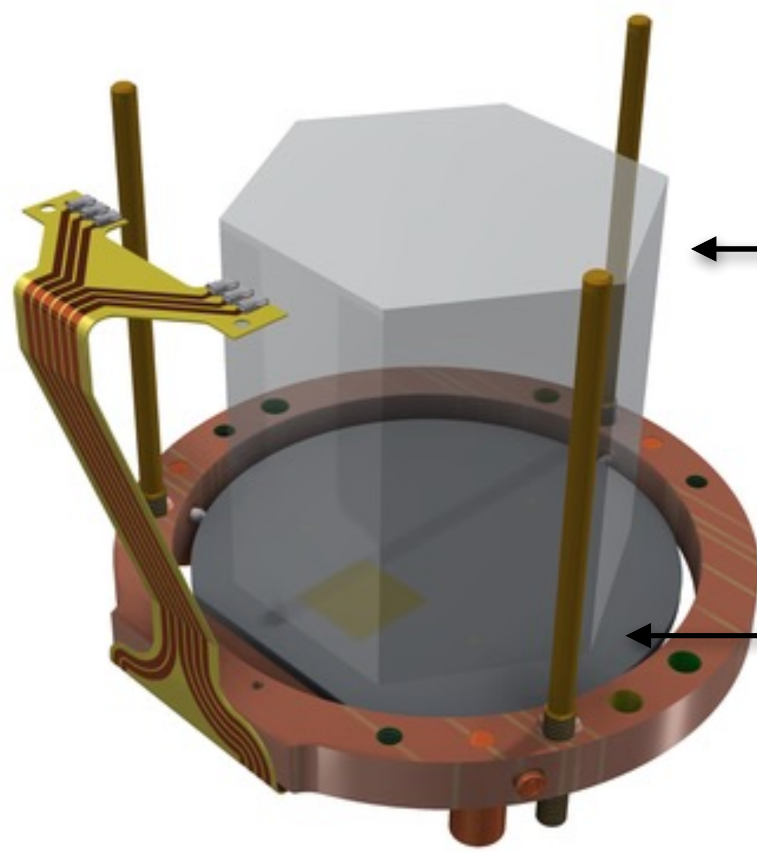
NEXT STEPS



MEASURING NOW AT LNGS

Test larger crystals (60-110) g

NEXT STEPS



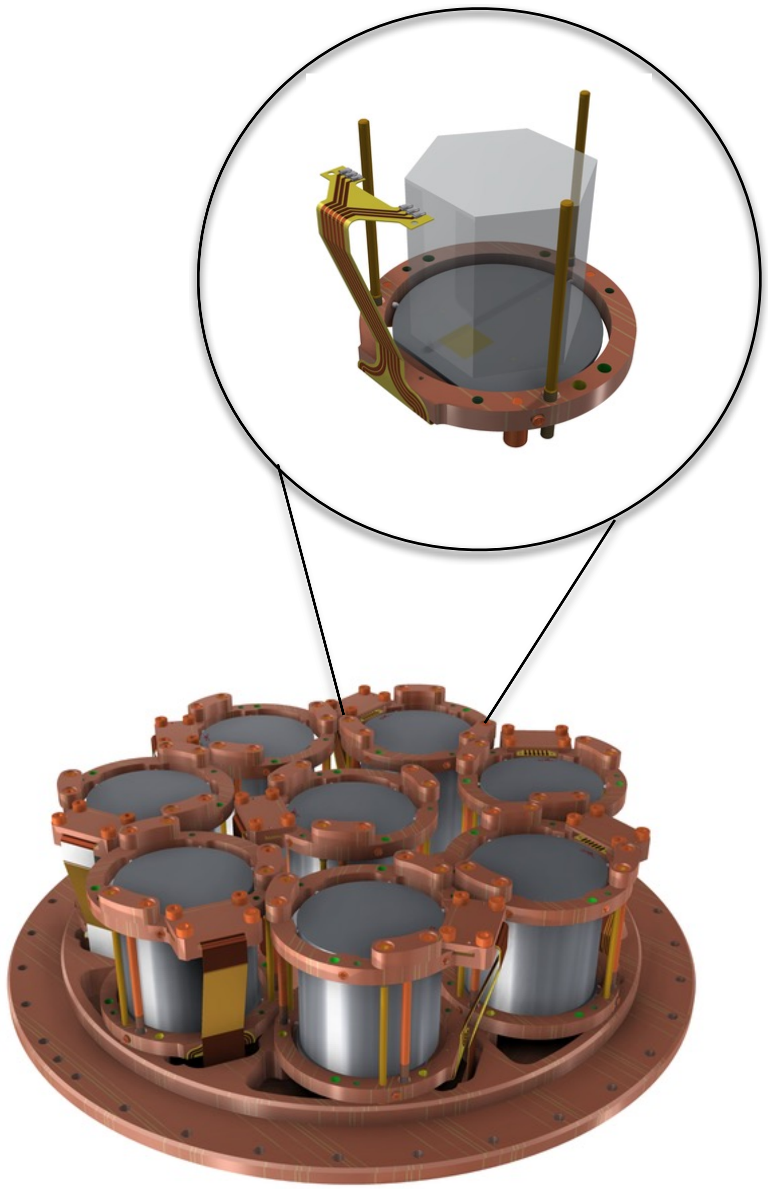
MEASURING NOW AT LNGS

Test larger crystals (60-110) g

Test silicon lid for 4π scintillation light collection

NEXT STEPS

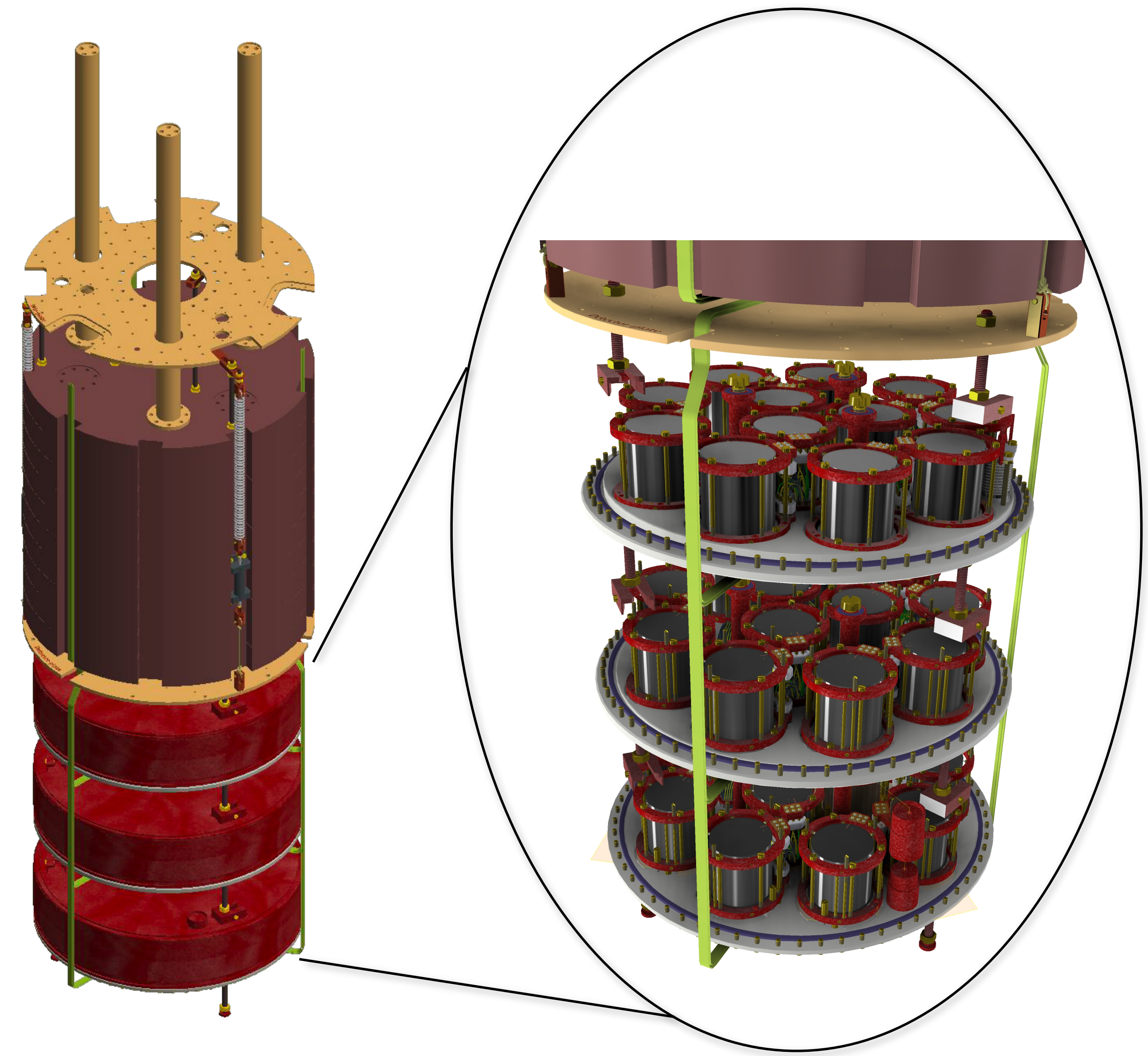
COSINUS 1π (2023-2025)



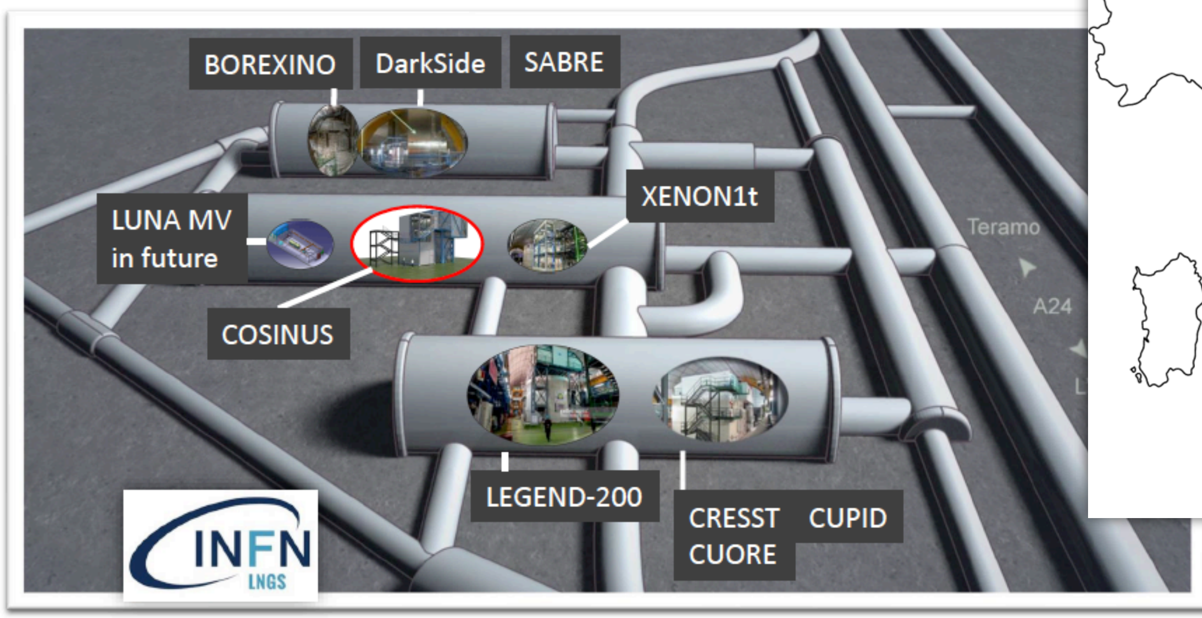
Collect100 kg days of exposure to exclude or confirm nuclear recoil origin

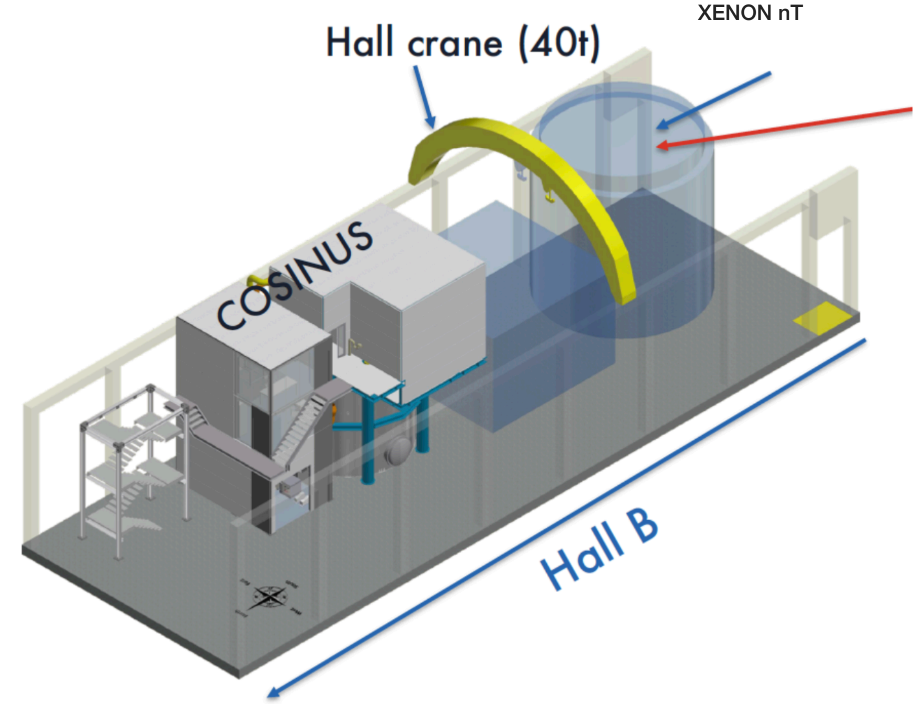
COSINUS 2π (>2025)

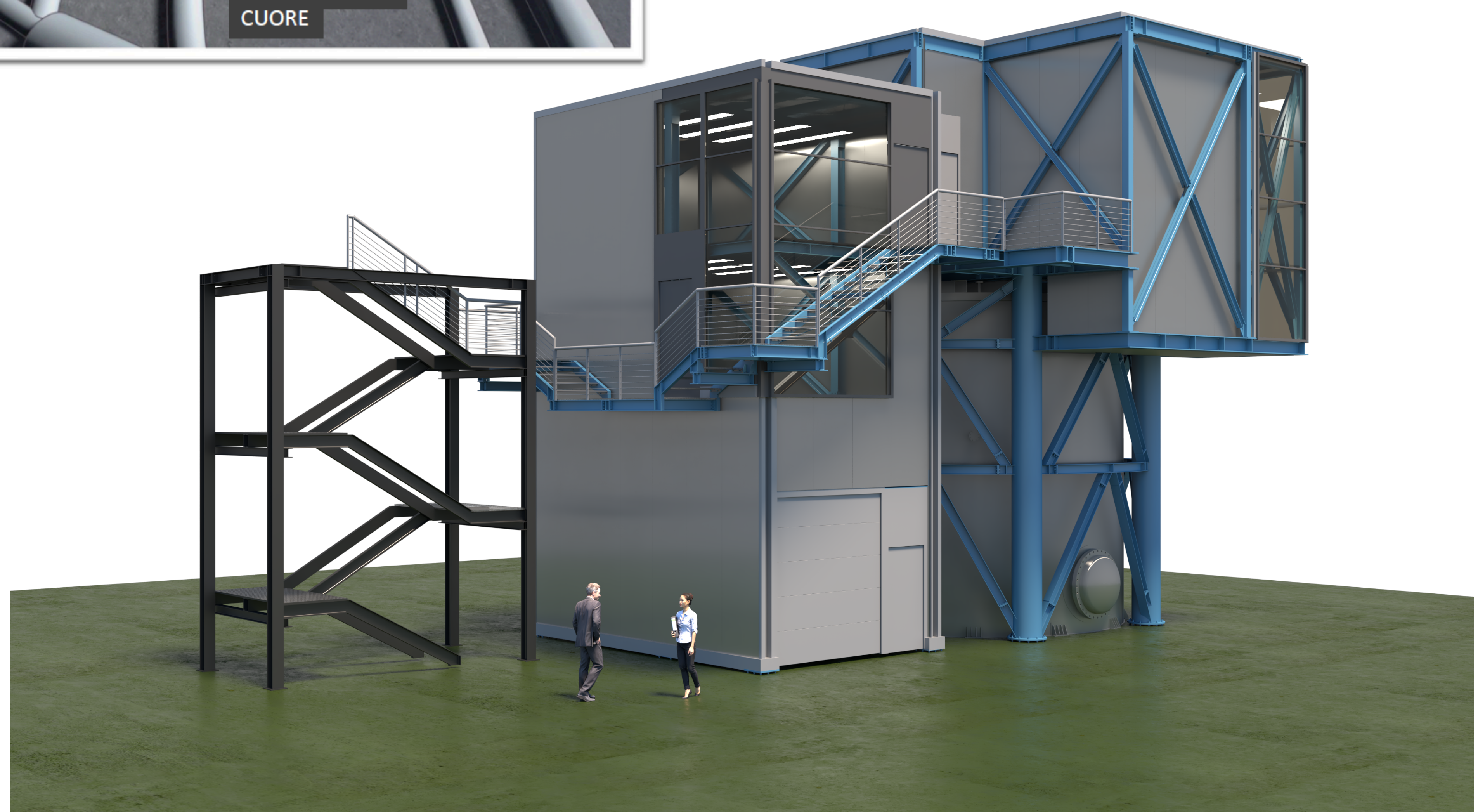
Upgrade of the number of channels
Annual modulation search



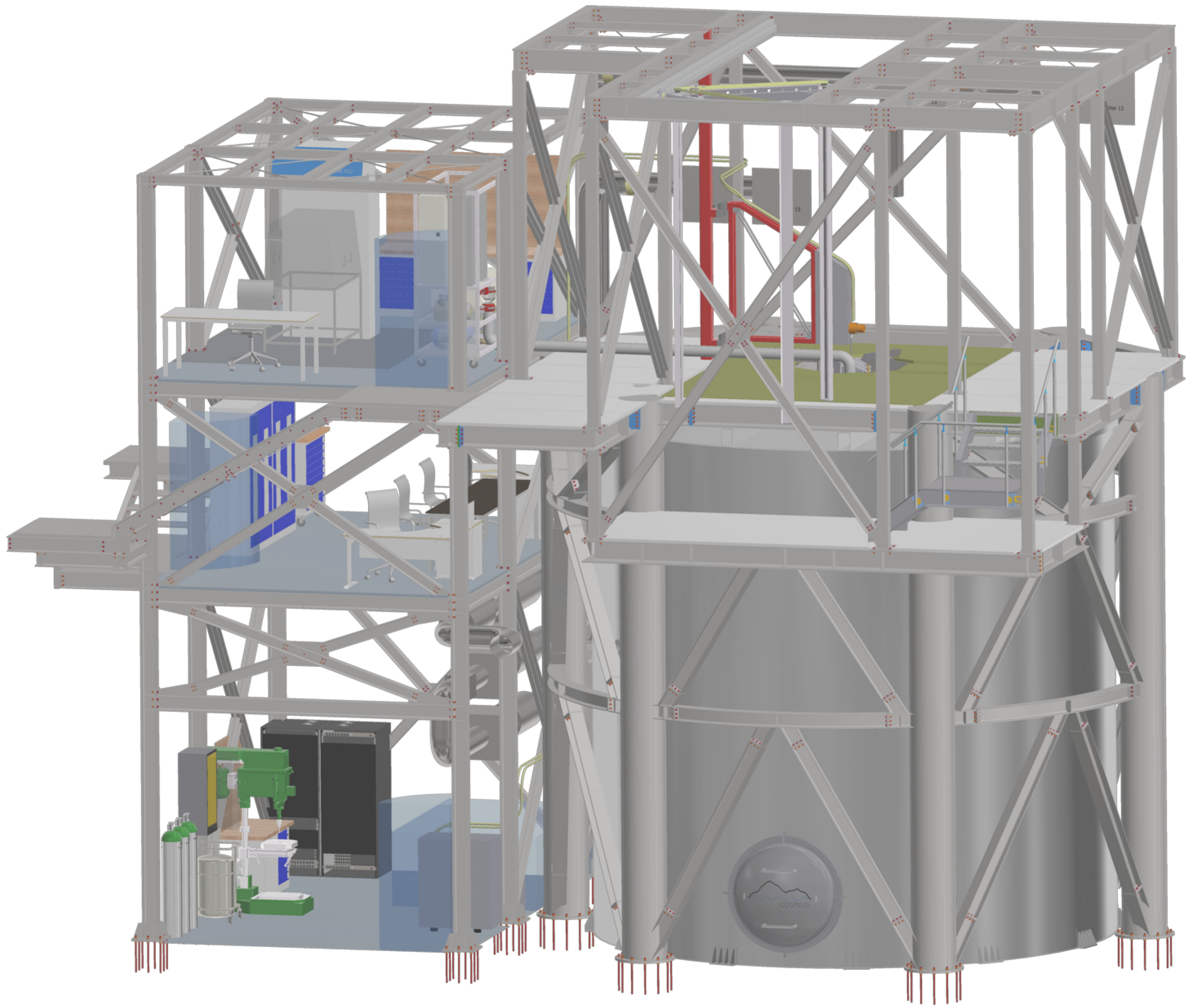
LOCATION


BOREXINO
DarkSide
SABRE
XENON1t
LUNA MV
in future
COSINUS
LEGEND-200
CRESST
CUPID
CUORE
Teramo
A24
INFN
LNGS

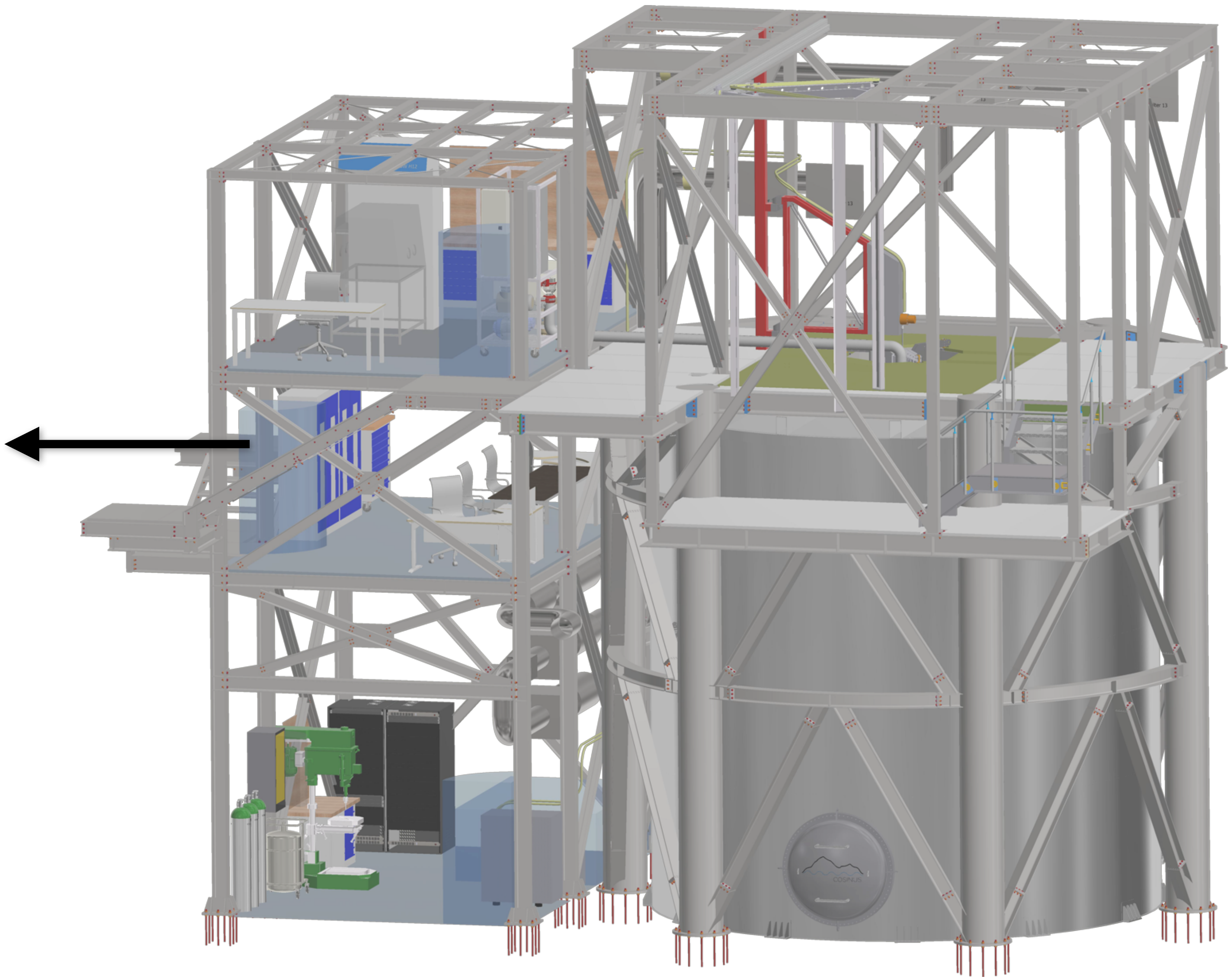

Hall crane (40t)
XENON nT
COSINUS
Hall B



FACILITY

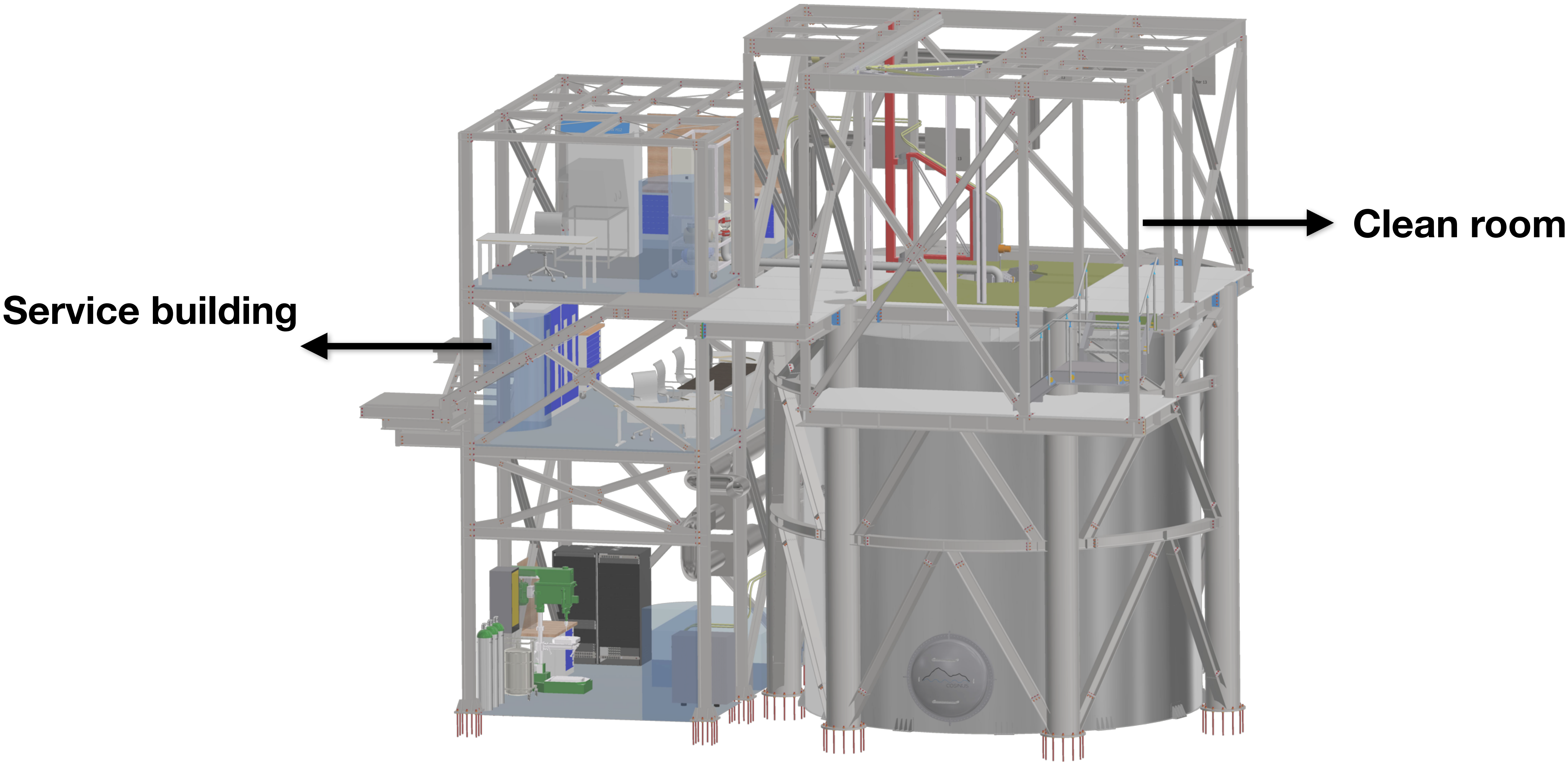


FACILITY

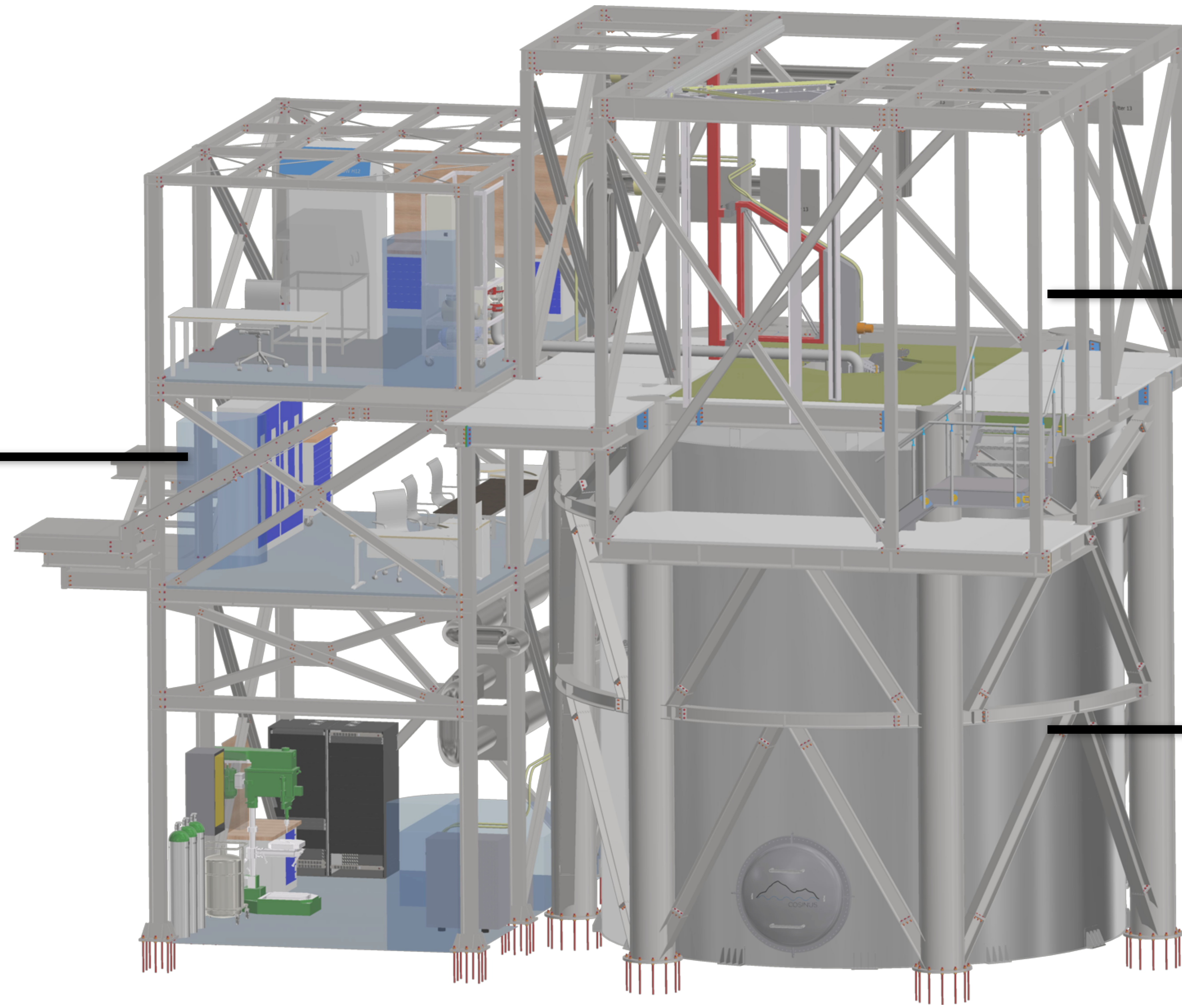


Service building

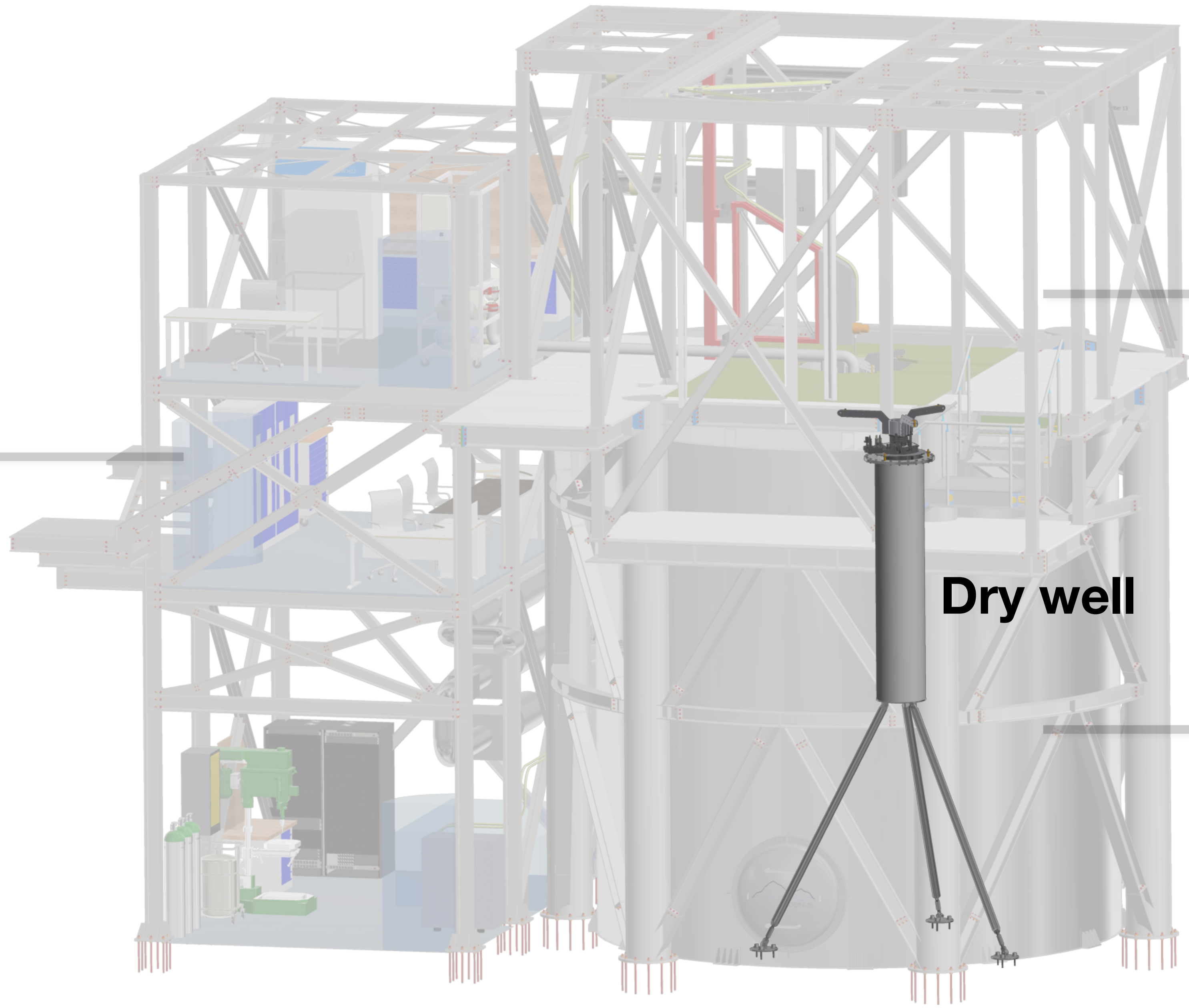
FACILITY



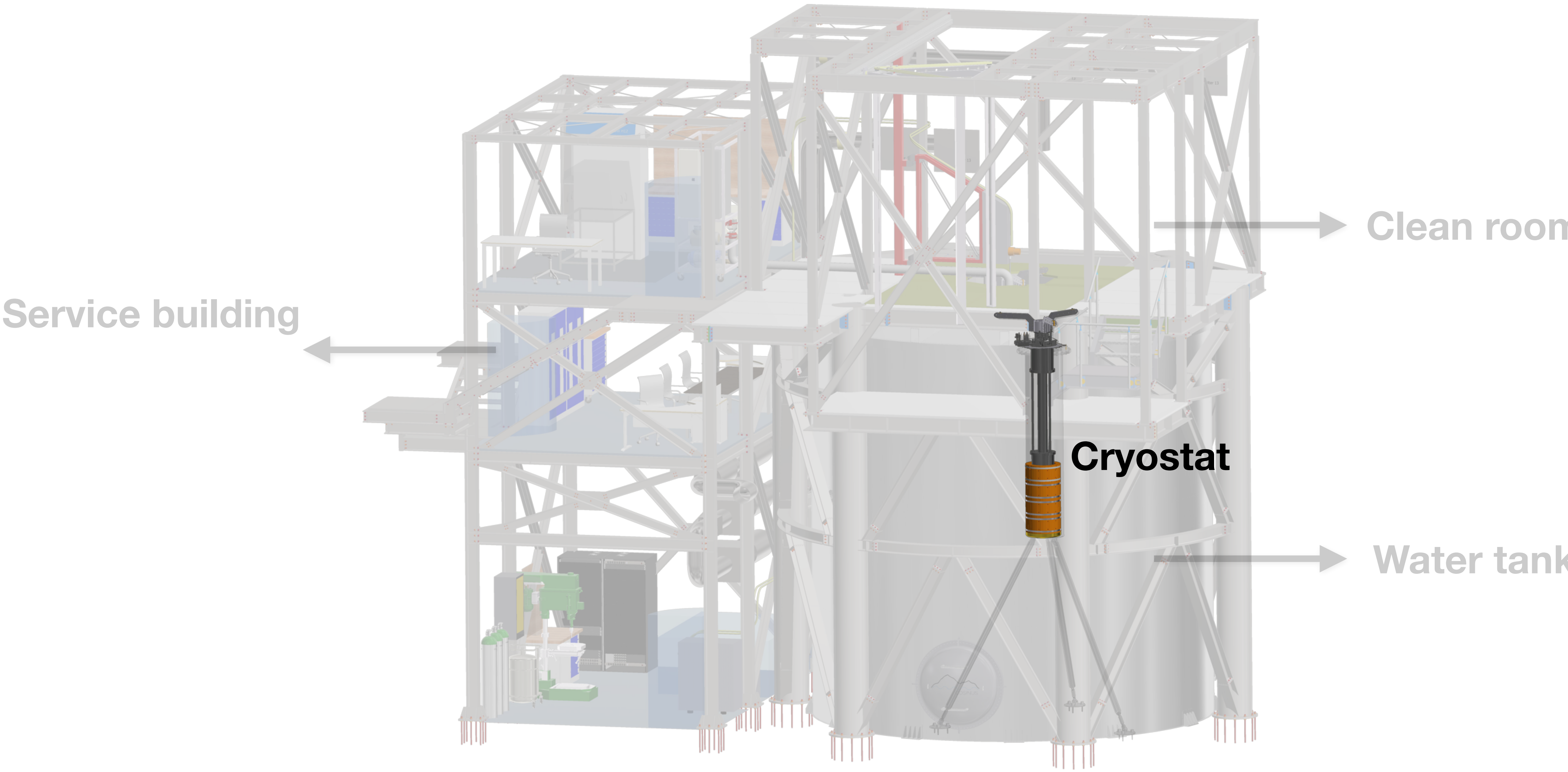
FACILITY



FACILITY

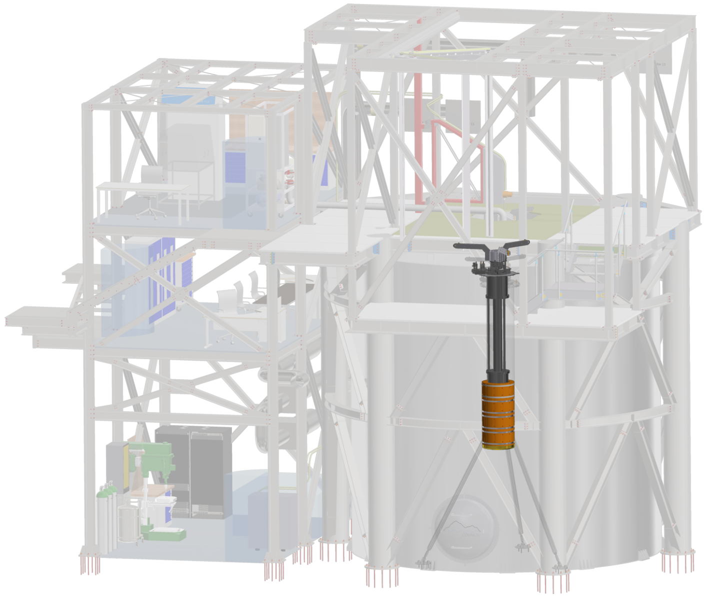


FACILITY



CRYOSTAT: VIBRATION DECOUPLING

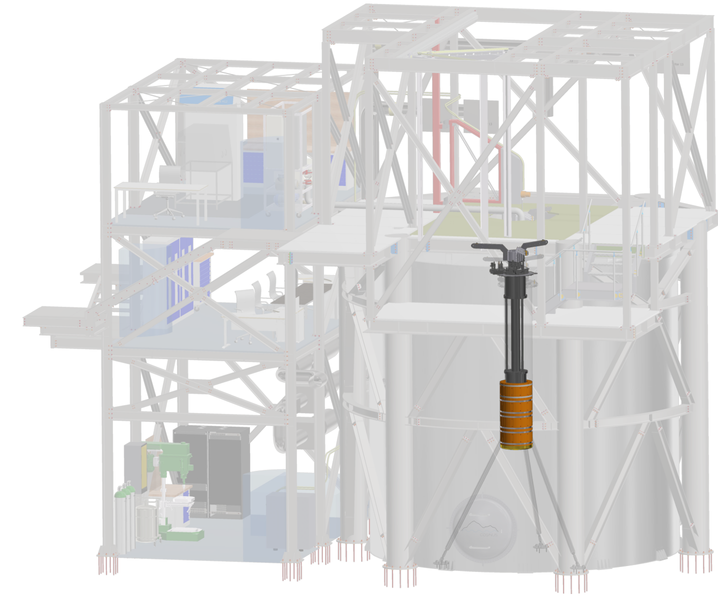
CryoConcept
an Air Liquide affiliate



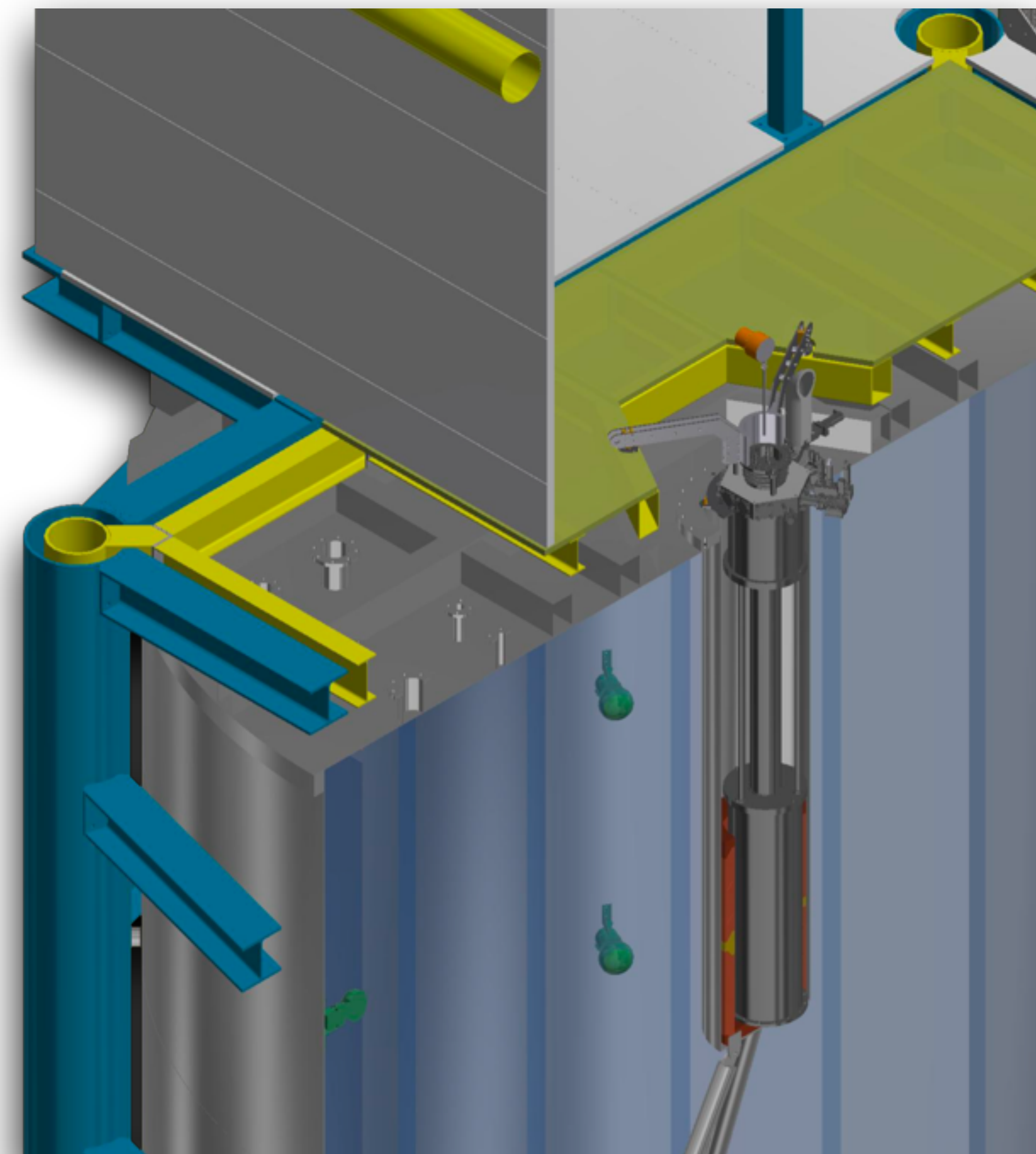
Three stages of decoupling

CRYOSTAT: VIBRATION DECOUPLING

CryoConcept
an Air Liquide affiliate



Three stages of decoupling



1. Global stage

<u>Double frame</u>

The infrastructure is built on the blue frame, subjected to most of the vibrations

The pulse tube on the yellow frame

The cryostat rests on the dry well, which is the most quiet part

<u>Bellow</u>

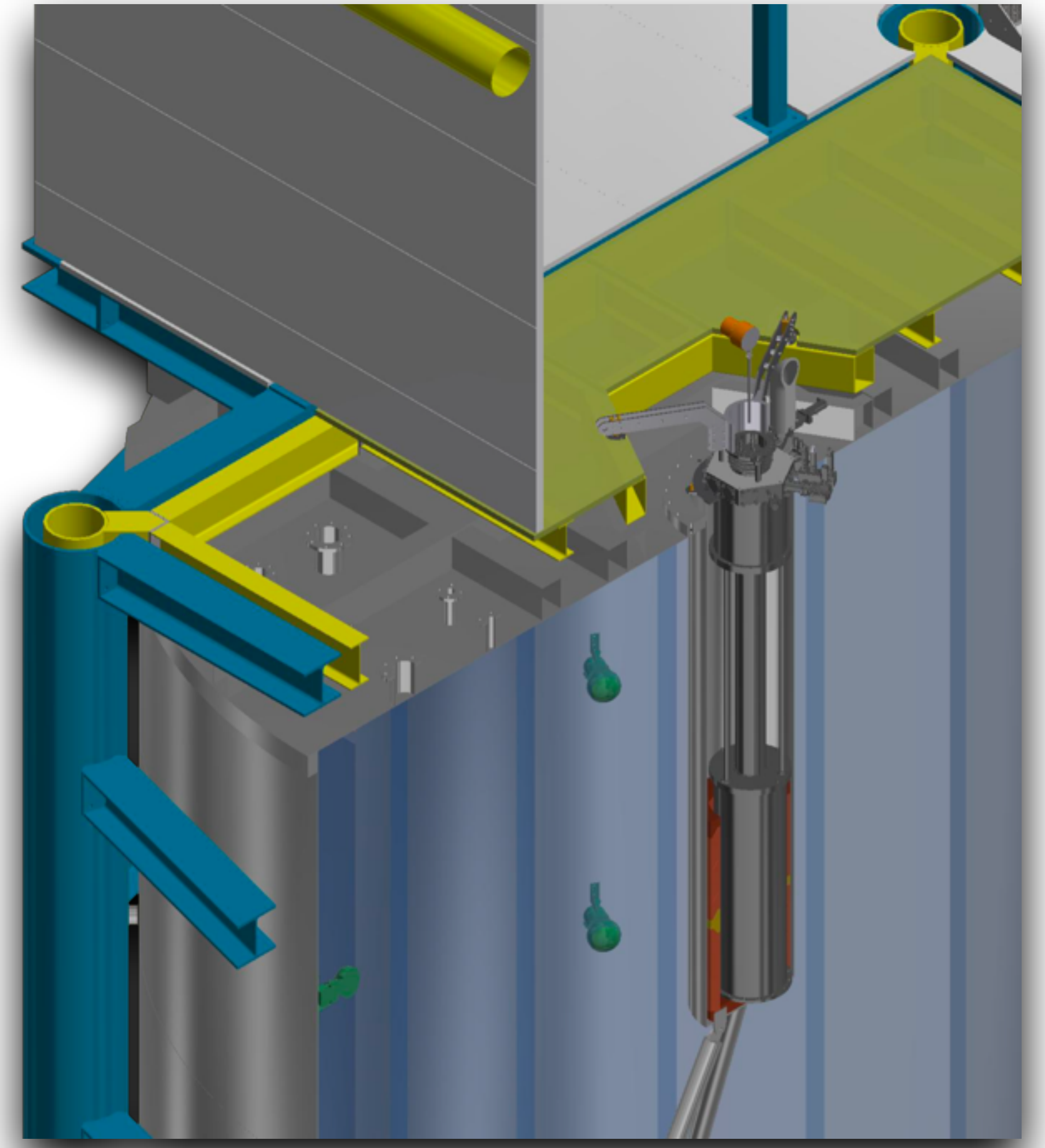
The pulse tube is connected to a supple bellow which dumps the mechanical vibrations of the pulse tube

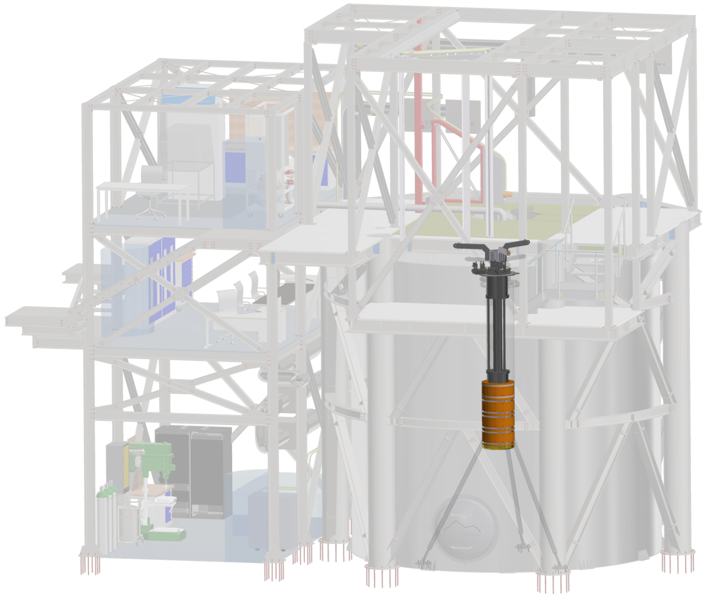
COSINUS

CRYOSTAT: VIBRATION DECOUPLING

CryoConcept
an Air Liquide affiliate

Three stages of decoupling





2. Cryostat stage

Pumping duct gas exchanger

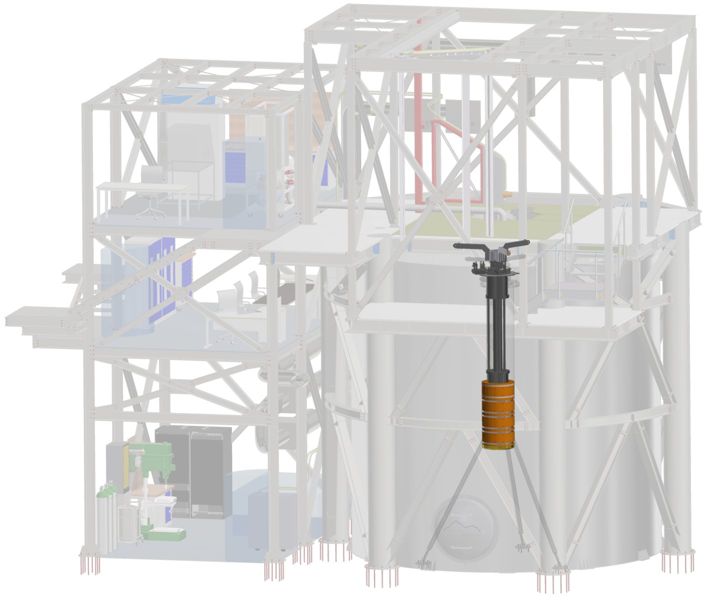
The heat exchange between pulse tube and cryostat occurs via gas, no mechanical contact

The Ultra-Quiet Technology™

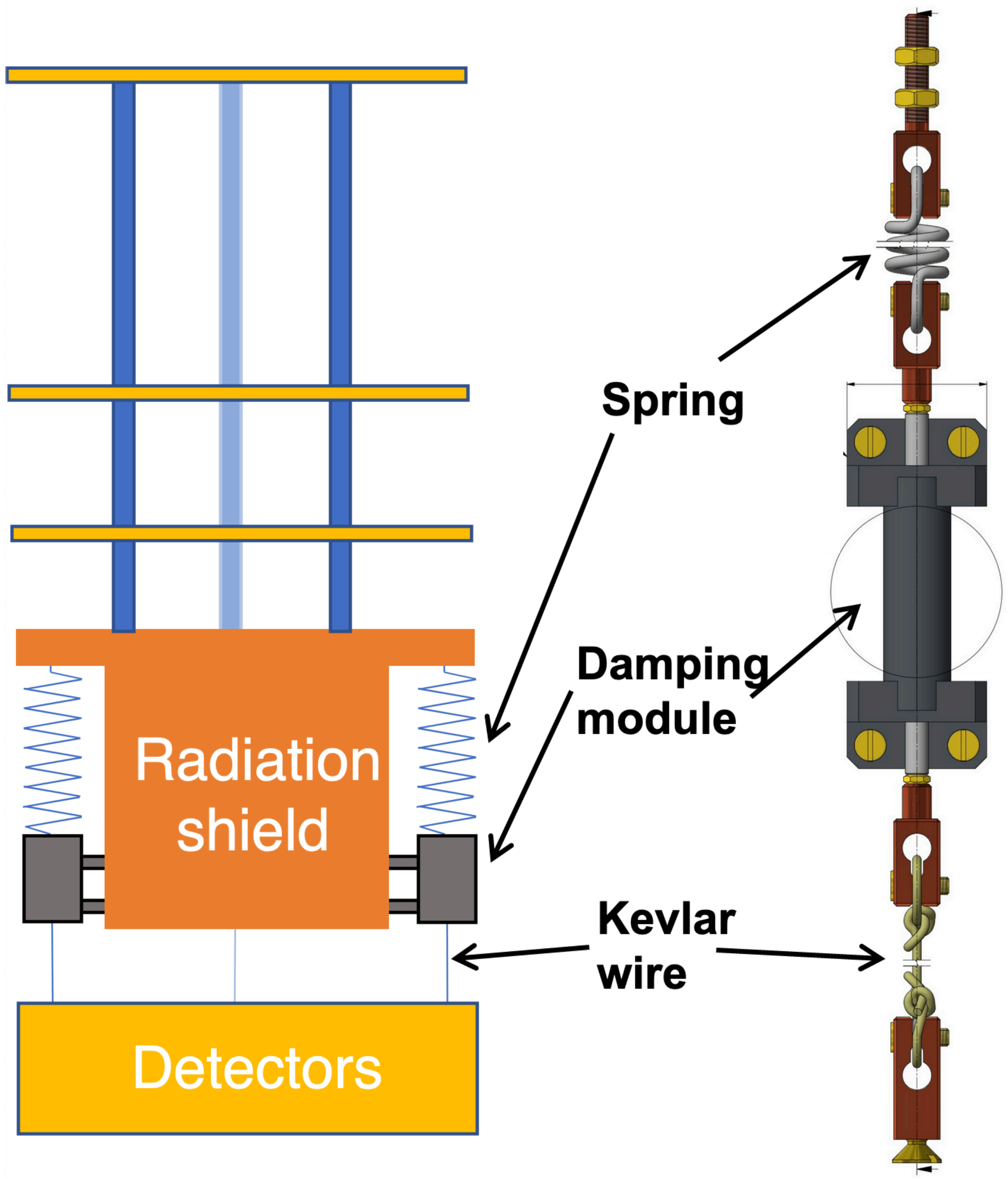
https://cryoconcept.com/product/the-ultra-quiet-technology/

CRYOSTAT: VIBRATION DECOUPLING

CryoConcept
an Air Liquide affiliate



Three stages of decoupling



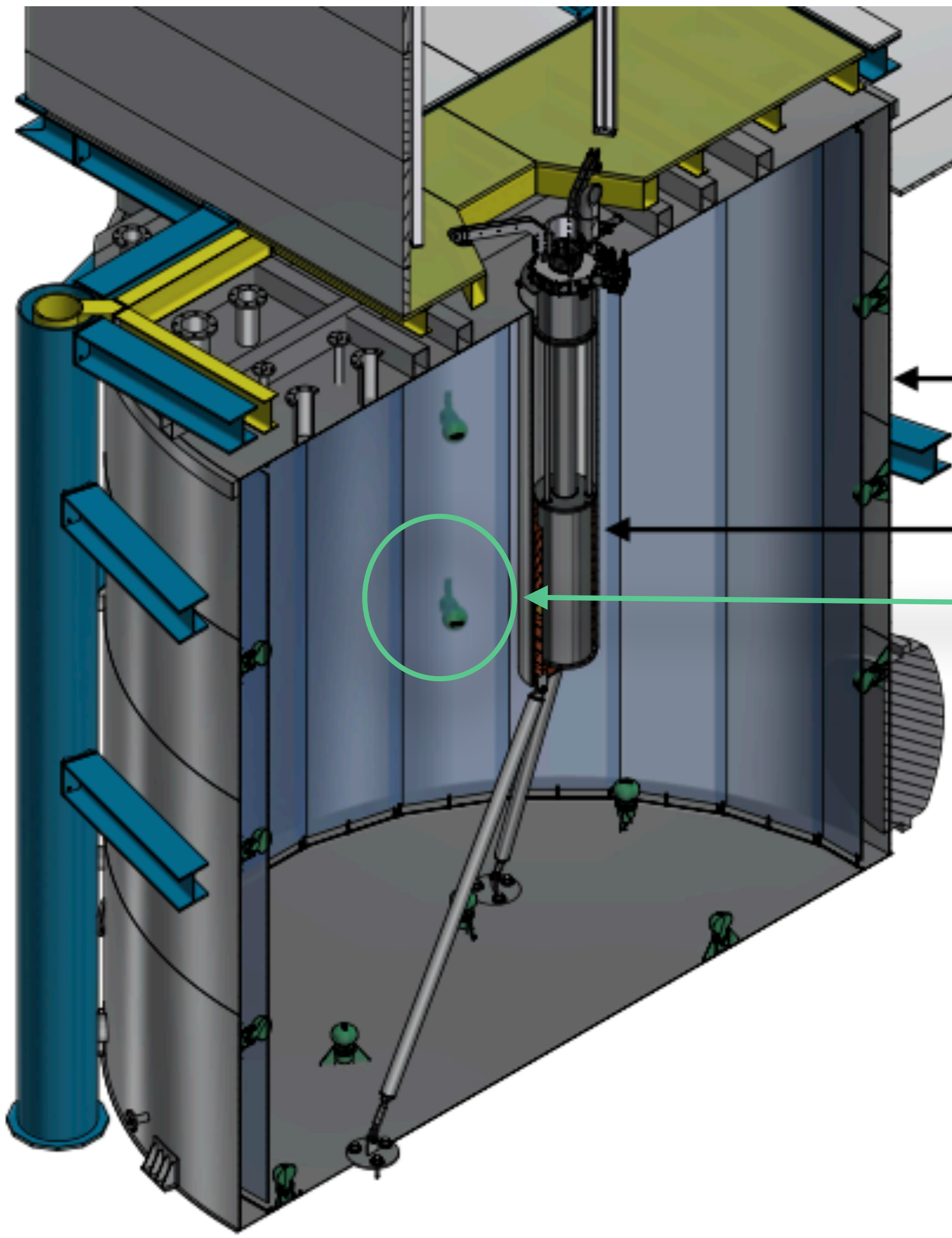
3. Detector stage

Spring and damping modules to decouple the detector plate

Magnetic eddy current damping

Studies ongoing

WATER TANK



The water tank is a neutron moderator and cosmogenic muon veto

Instrumented with about 30 PMTs it will reduce the neutron background rate

Rate of cosmogenic neutrons:

no veto: (3.5 ± 0.7) cts kg^{-1} yr^{-1}

with veto: < 0.05 cts kg^{-1} yr^{-1}

Shielding designed according to simulations in EPJC volume 82, Article number: 248 (2022)

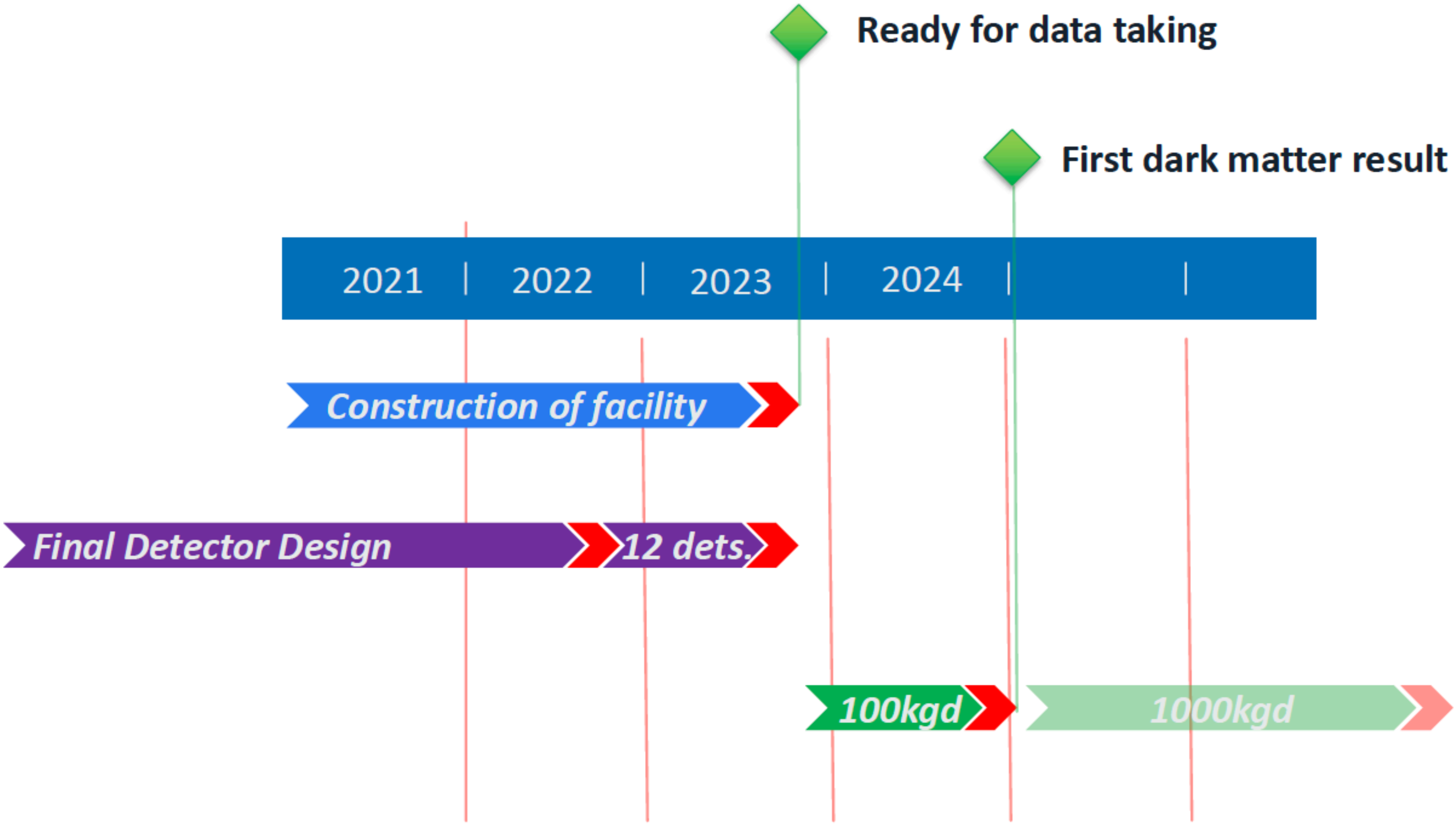
STATUS FACILITY INSTALLATION

Planned to be completed by 2023

October 2021	January 2022	June 2022	August 2022
WATER TANK	DRY WELL	CLEAN ROOM	SERVICE BUILDING
			

COSINUS

COSINUS 1π TIME SCHEDULE



GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

MAX-PLANCK-INSTITUT FÜR PHYSIK

INFN
Istituto Nazionale di Fisica Nucleare

SICCAS Since 1928

TU WIEN

HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

HELSINKI INSTITUTE OF PHYSICS

~ 25 Scientists

www.cosinus.it

STAY TUNED AND THANK YOU

COSINUS

Maria Luìsa Sarsa (ANAIS)

Govinda Adhikari, Reina Maruyama (COSINE)

Pierluigi Belli (DAMA)

Ken-Ichi Fushimi (PICOLON)

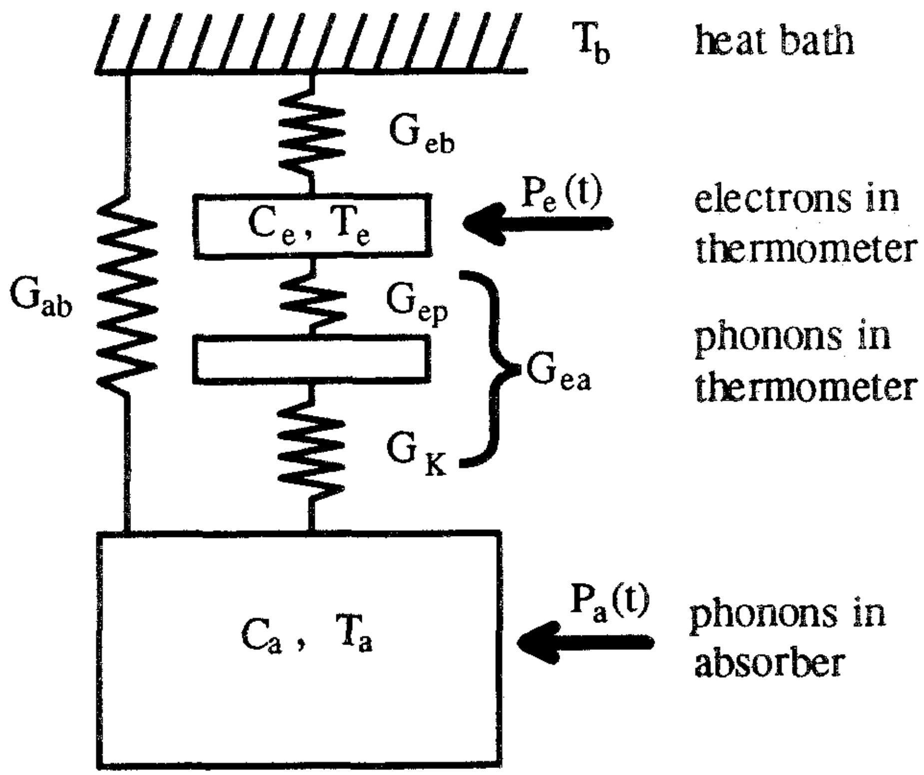
Irene Bolognino, Elisabetta Barberio, Aldo Ianni, Phillip Urquijo, Claudia Tomei, Michaela Froehlich (SABRE)

AKNOWLEDGMENTS

ADDITIONAL MATERIAL

PULSE SHAPE MODEL

The general model for TES-based cryogenic detectors was published by Franz Pröbst et al. in 1995 (F. Pröbst et al, J. Low Temp. Phys. 100,69 (1995))



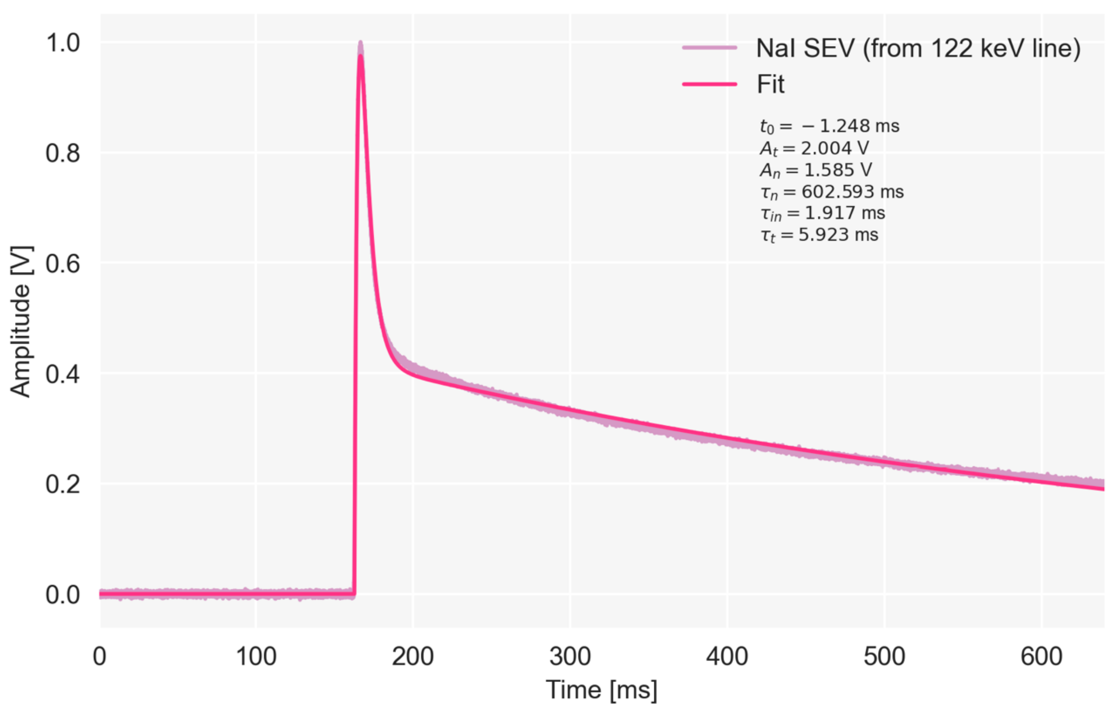
$$\begin{cases} C_e \dfrac{dT_e}{dt} + G_{ea}(T_e - T_a) + G_{eb}(T_e - T_b) & = P_e(t) \\ C_a \dfrac{dT_a}{dt} + G_{ea}(T_a - T_e) + G_{ab}(T_a - T_b) & = P_a(t) \end{cases}$$

$$\begin{cases} \dot{\mathbf{x}}(t) & = \mathbf{A}\ \mathbf{x} + \mathbf{f}(t) \\ \mathbf{x}(t=0) & = \begin{pmatrix} T_b \\ T_b \end{pmatrix} \end{cases}$$

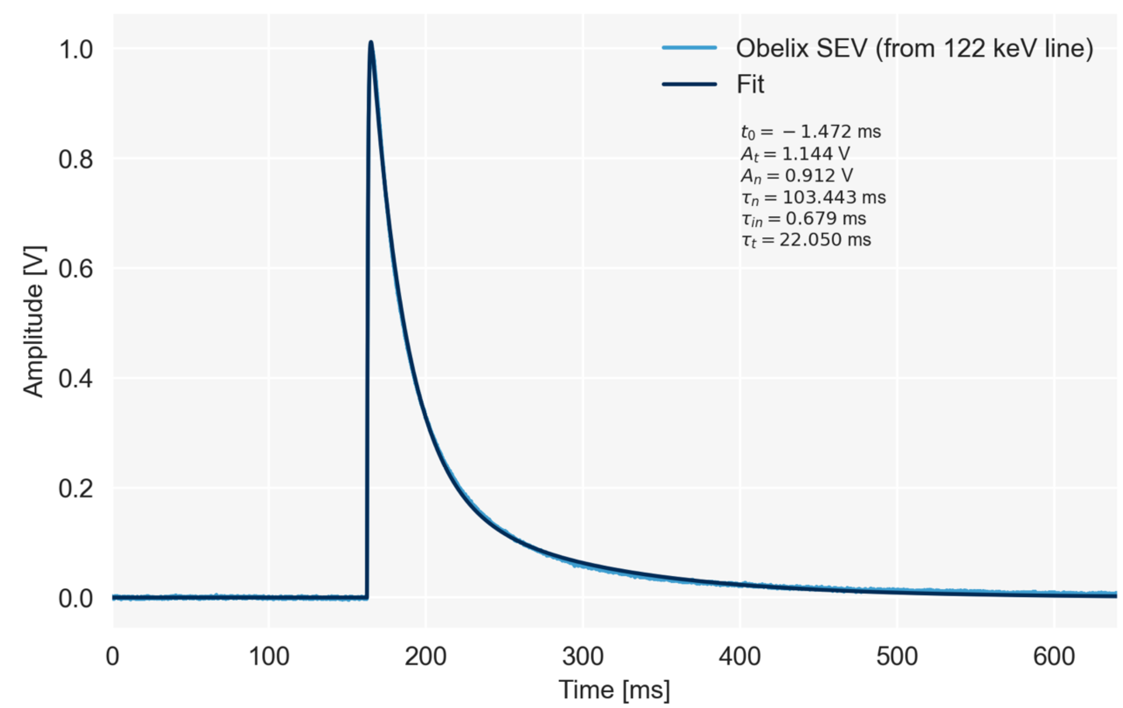
$$\Delta T_e(t) = \theta(t)[\underbrace{A_n\ (e^{-t/\tau_n} - e^{-t/\tau_{in}})}_{Non-thermal} + \underbrace{A_t\ (e^{-t/\tau_t} - e^{-t/\tau_n})}_{Thermal}]$$

STANDARD EVENTS

NaI-remoTES

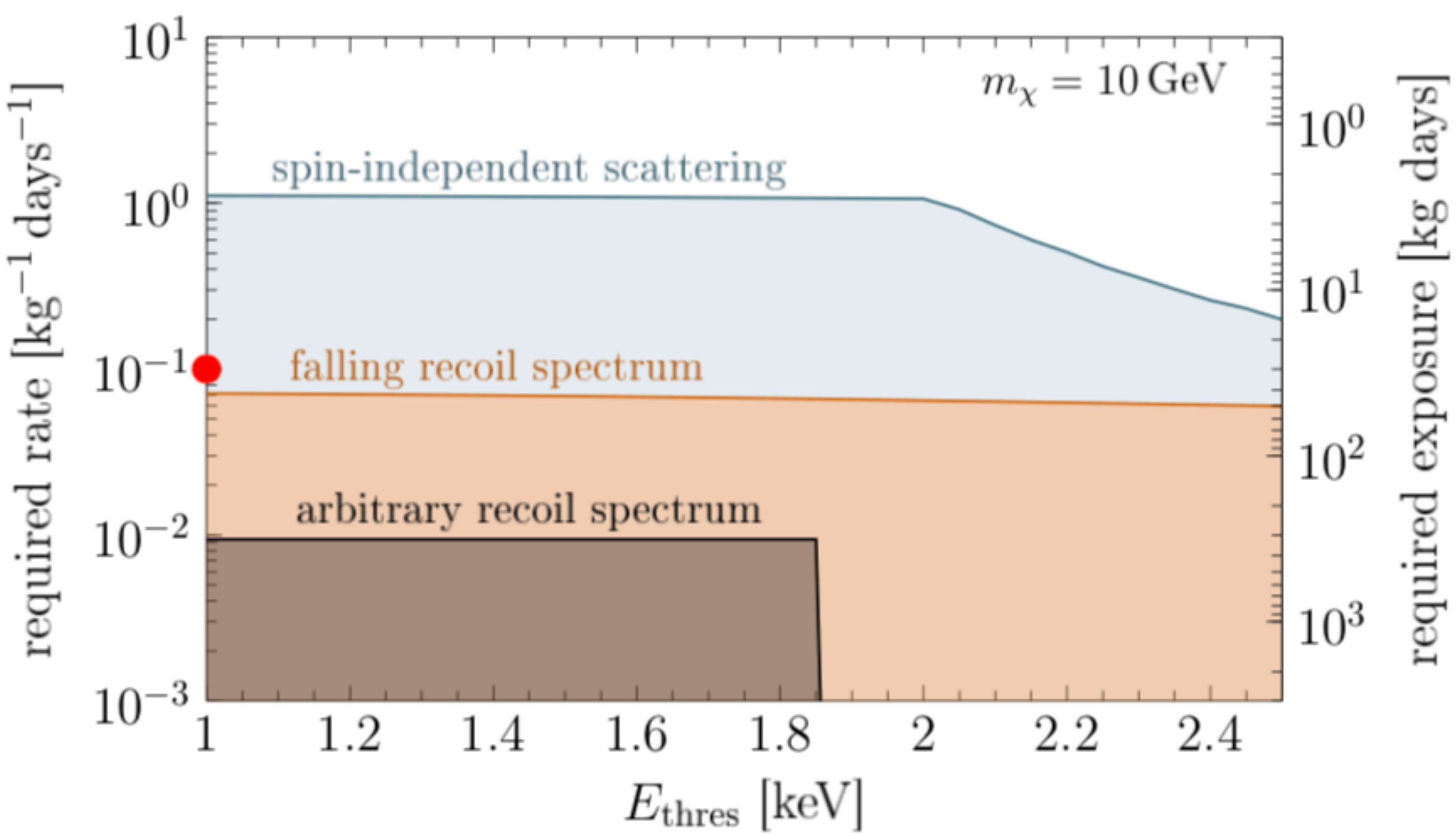


Obelix (Si-beaker)



PHYSICS REACH

F. Kahlhöfer et al., JCAP 1805 (2018) no.05, 074



For background-free case

New DAMA/LIBRA-phase2 threshold not included

red dot: event rate corresponding to 100 kg days of gross exposure (COSINUS 1π)

QUENCHING FACTOR MEASUREMENT

NaI(Tl) crystals with different Tl dopant concentrations

^{nat}K contamination < 10 ppb (benchmark: 60 ppb)

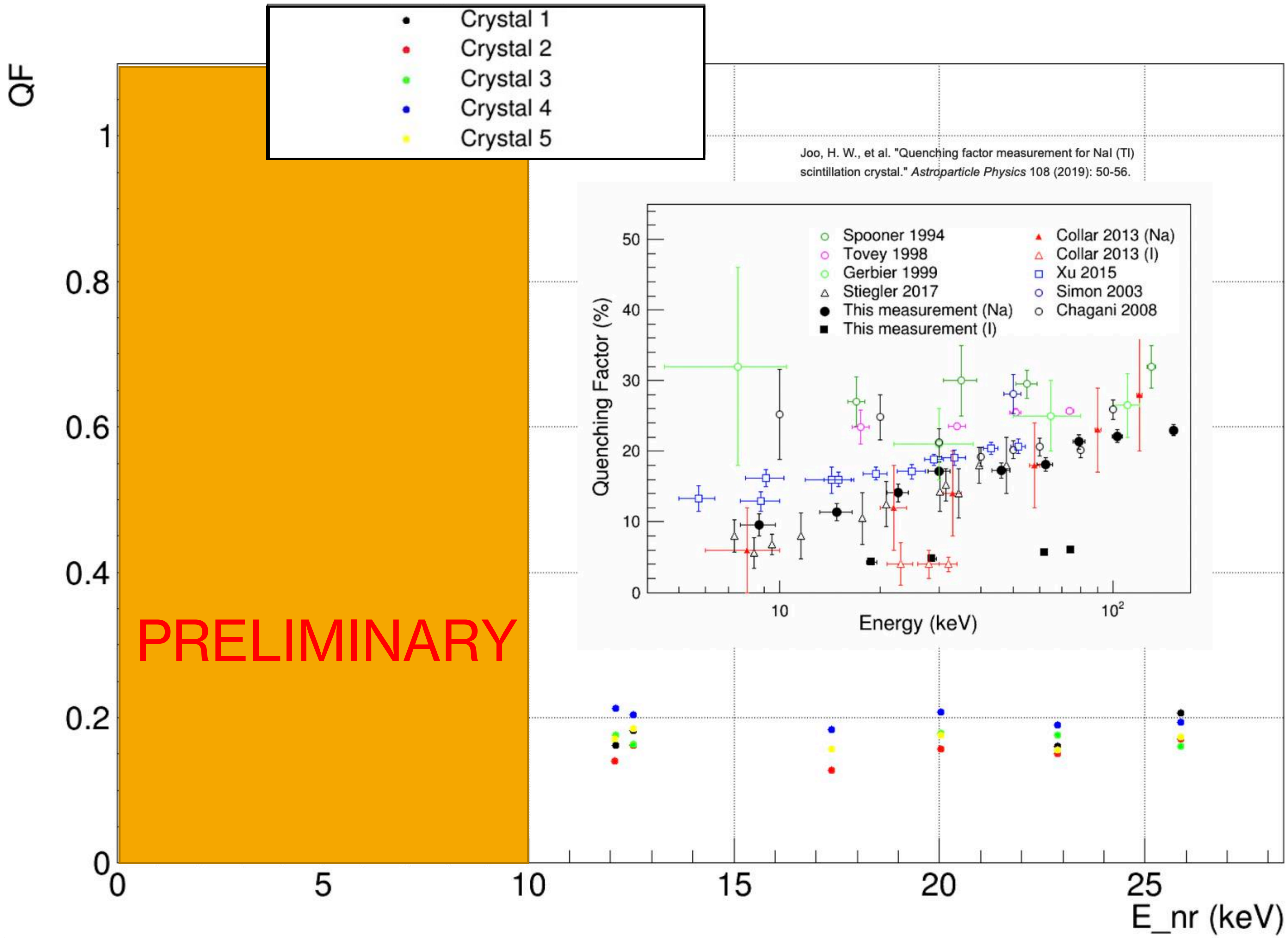
^{232}Th contamination < 0.01 ppb (benchmark: 1.2 ppb)

^{238}U contamination < 0.02 ppb (benchmark: 0.8 ppb)

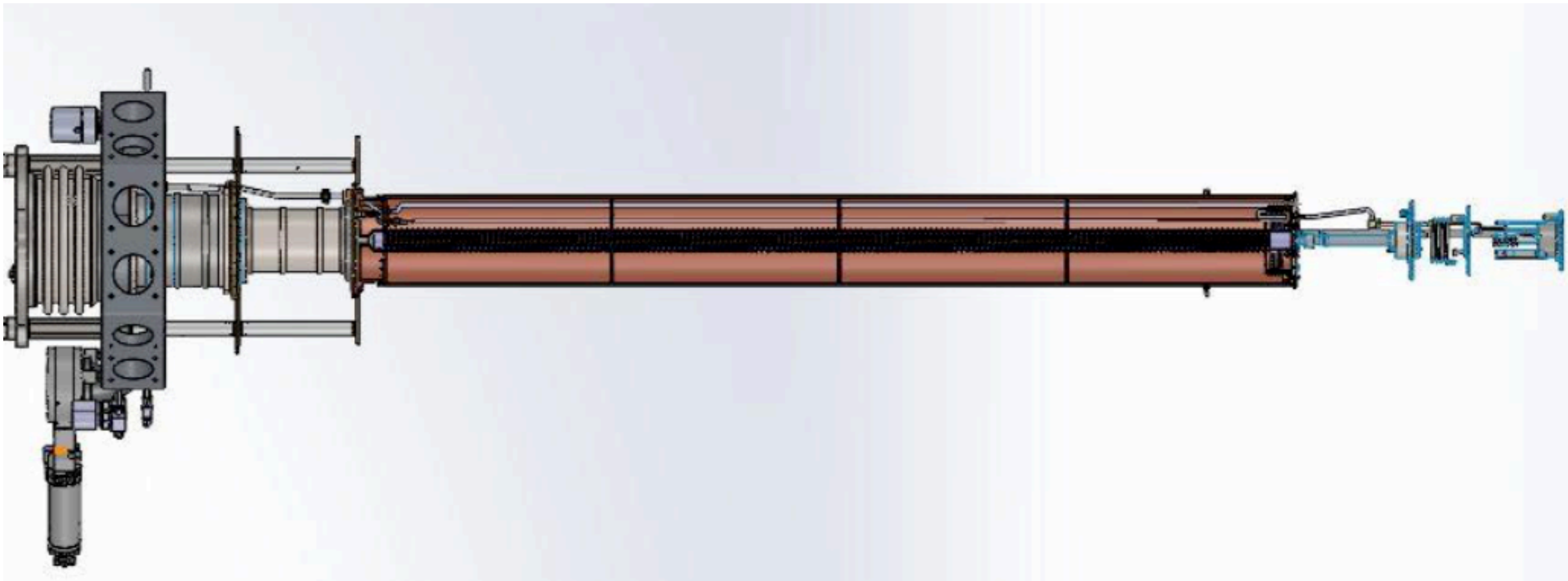
Detector No.	Tl conc. (initial powder)	Tl conc. (grown crystal)
8-1-01-B	0.1%	0.13%
8-2-03-B	0.3%	0.21%
8-3-05-B	0.5%	0.39%
8-4-07-B	0.7%	0.62%
8-5-09-B	0.9%	0.68%
Dummy	-	-

QUENCHING FACTOR MEASUREMENT

QF estimation (Na recoils)

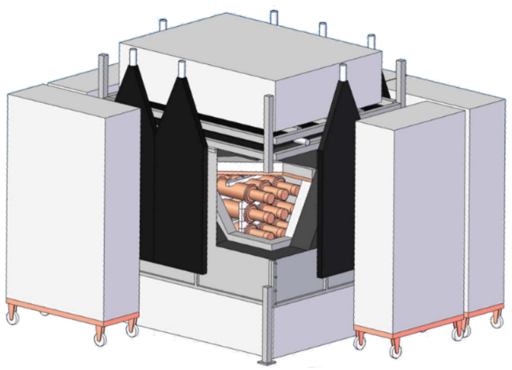


DRY DILUTION REFRIGERATOR



ANAIS-112

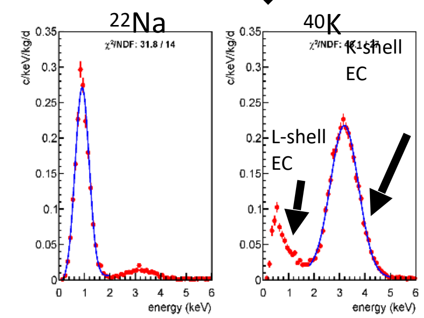
Maria Luìsa Sarsa (ANAIS)

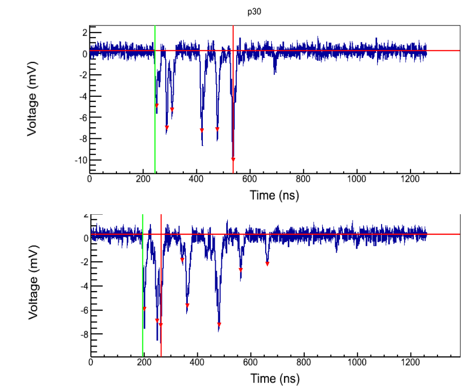


ANAIS-112 consists of a 3x3 array of NaI(Tl) modules, **112.5 kg**, taking data at Canfranc Underground Laboratory since August 2017.
Almost five years of data with duty cycle above 95%

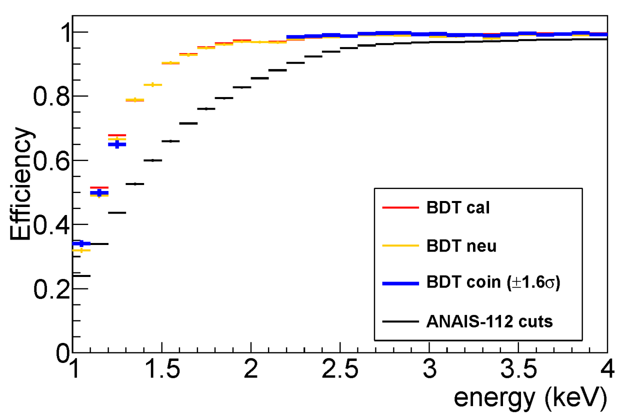
Three-year exposure results published in 2021, [Phys. Rev. D 103](#) ([arXiv:2110.10649](#))

Excellent light collection in all the nine modules, larger and more homogeneous than that of DAMA/LIBRA
Triggering well below 1 keVee



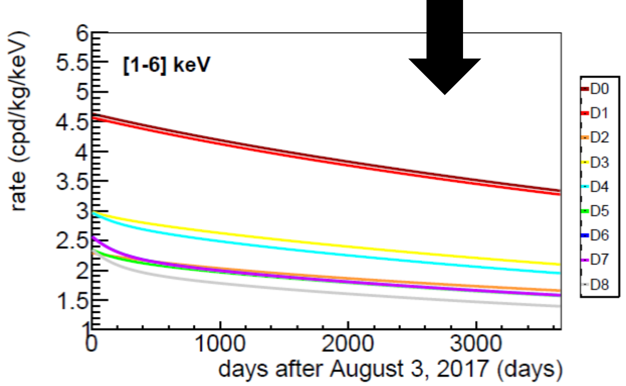


New analysis based on BDT using neutron events (^{252}Cf), electron events (^{109}Cd) and internal lines (^{40}K and ^{22}Na)
STRONG IMPROVEMENT ON THE EFFICIENCIES



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

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

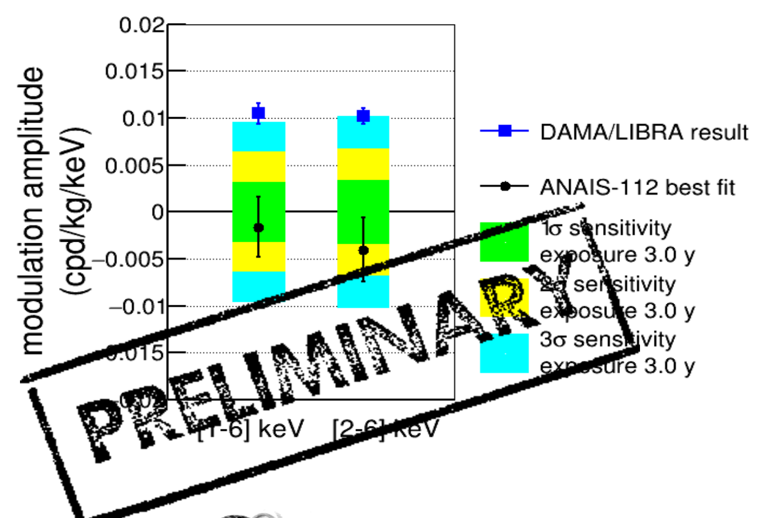


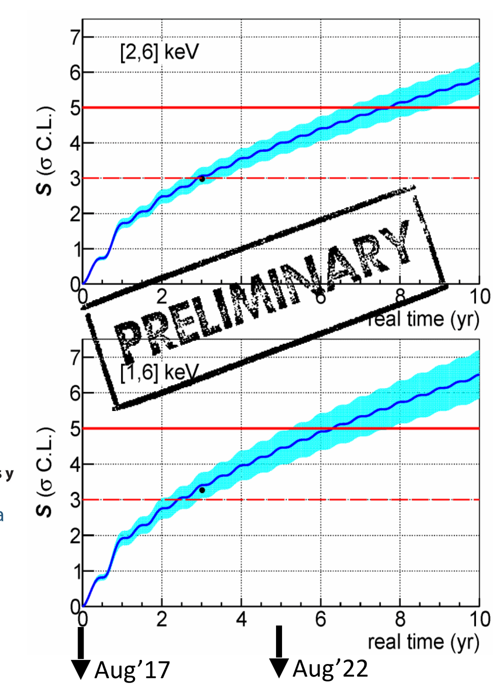
Background model determines the probability distribution function detector by detector

MODEL INDEPENDENT SEARCH FOR ANNUAL MODULATION carried out for three-year exposure
PRELIMINARY RESULTS AT IDM 2022

https://indico.cern.ch/event/922783/contributions/4892762/attachments/2482431/4261919/ANAIS_IDM2022.pdf

Three-year exposure reanalysis sensitivity is at 3 sigma
PROSPECTS to achieve more than 4 sigma with 5 year exposure and 5 sigma by 2024





Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

COSINE

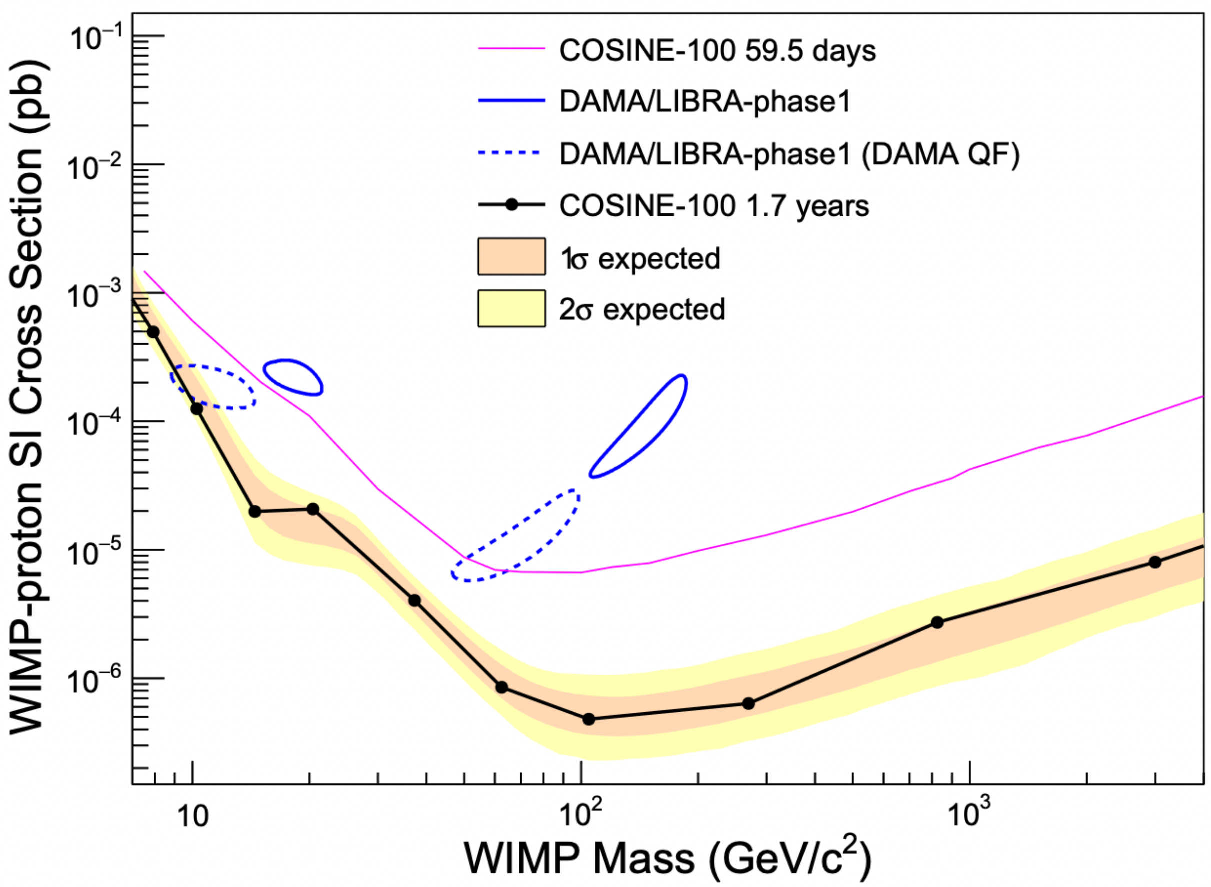
COSINE-100 searches

https://cosine.yale.edu/home

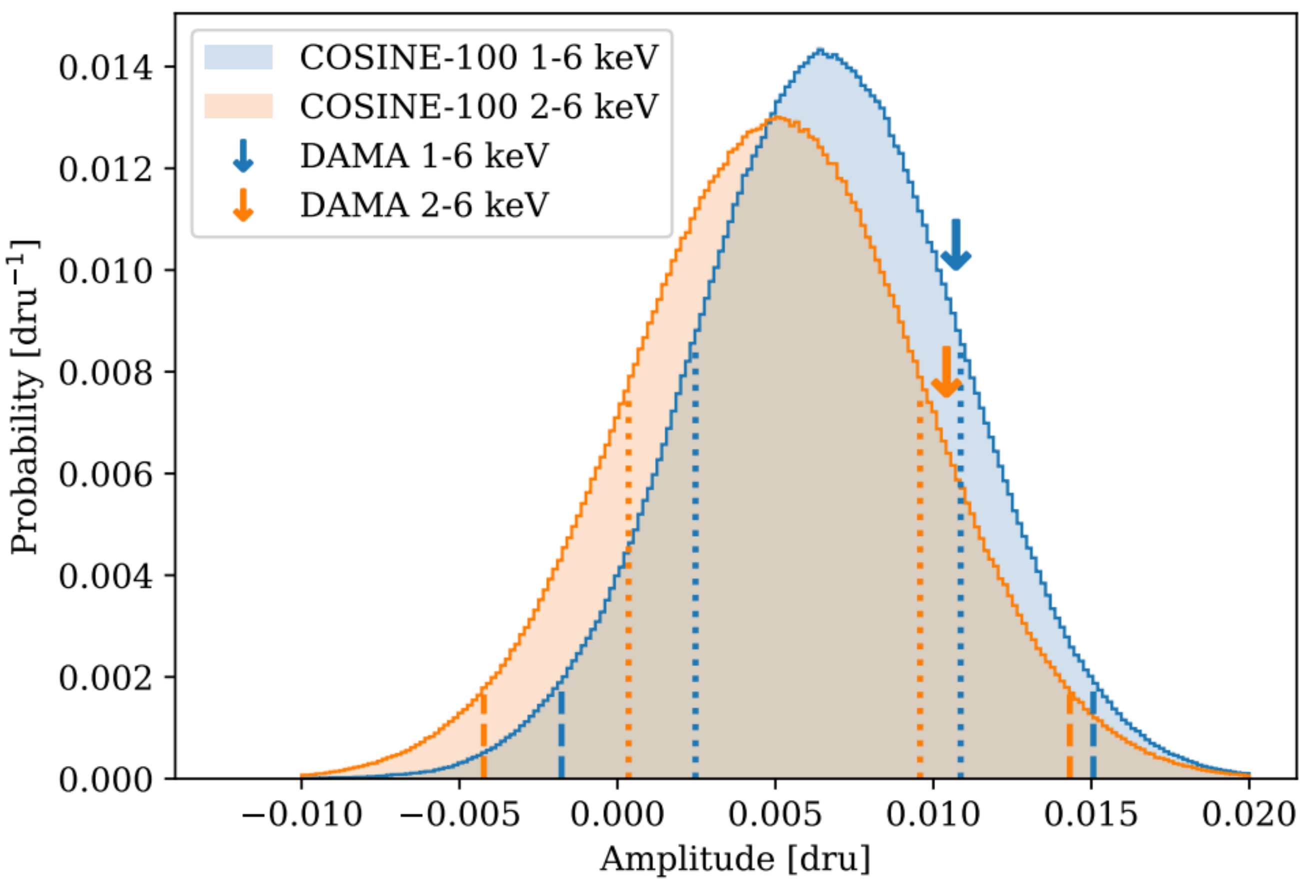
- Joint venture of KIMS and DM-ICE
  - Data taking from Sep 2016 and published result with an exposure of 173kg.year
  - Exclude DAMA/LIBRA phase 1's interpretation with the spin-independent WIMP interaction with Standard Halo model in NaI(Tl) crystal
  - Best-fit modulation amplitude of 0.0067 ± 0.0042 cpd/kg/keV at 1- 6 keV

- In-house crystal growing protocol is developed by collaboration and achieved promising radio-purity and light collection with R&D crystal (0.6 kg)
  - Expect < 1 counts/day/kg/keV in COSINE-200 crystals
  - COSINE-200 will be run by 2023

Sci Adv. 2021 Nov 12;7(46):eabk2699



arXiv:2111.08863v1



DAMA

DAMA/LIBRA–phase2

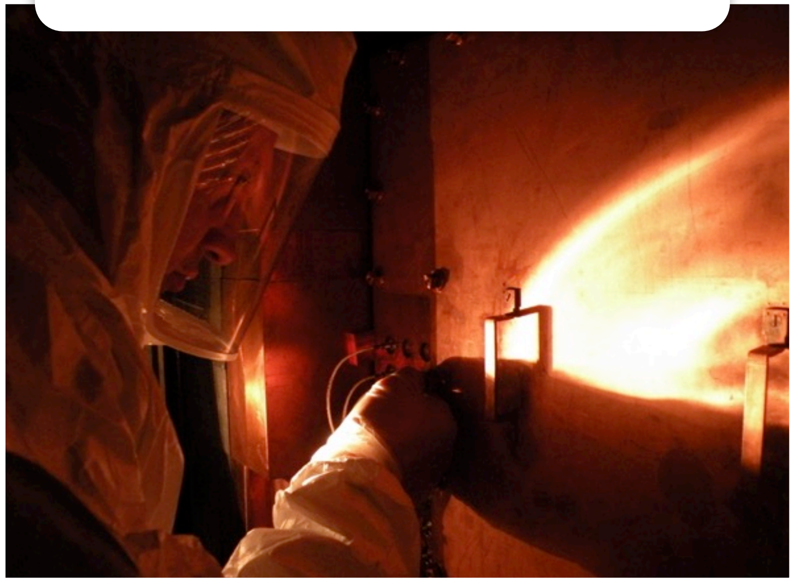
Upgrade on Nov/Dec 2010: all PMTs replaced with new ones of higher Q.E.

JINST 7(2012)03009
Universe 4 (2018) 116
NPAE 19 (2018) 307
Bled 19 (2018) 27
NPAE 20(4) (2019) 317
PPNP114(2020)103810
NPAE 22(2021) 329

Pierluigi Belli (DAMA)

Goal: software energy threshold at 1 keV – accomplished

Q.E. of the new PMTs:
33 – 39% @ 420 nm
36 – 44% @ peakc



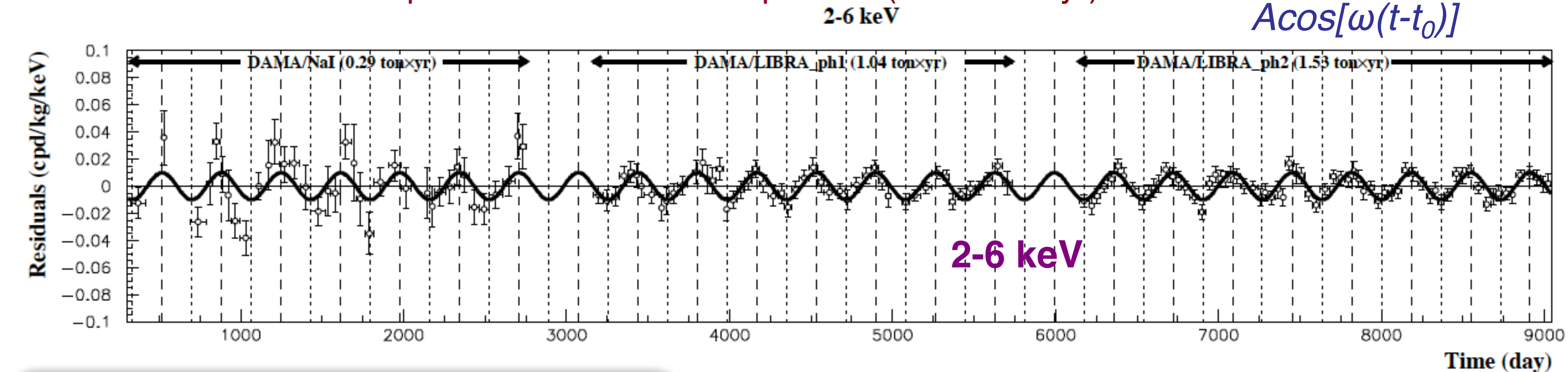
DM model-independent Annual Modulation Result

experimental residuals of the single-hit scintillation events rate vs time and energy

DAMA/NaI+DAMA/LIBRA-phase1+DAMA/LIBRA-phase2 (2.86 ton × yr)

P. Belli (DAMA)

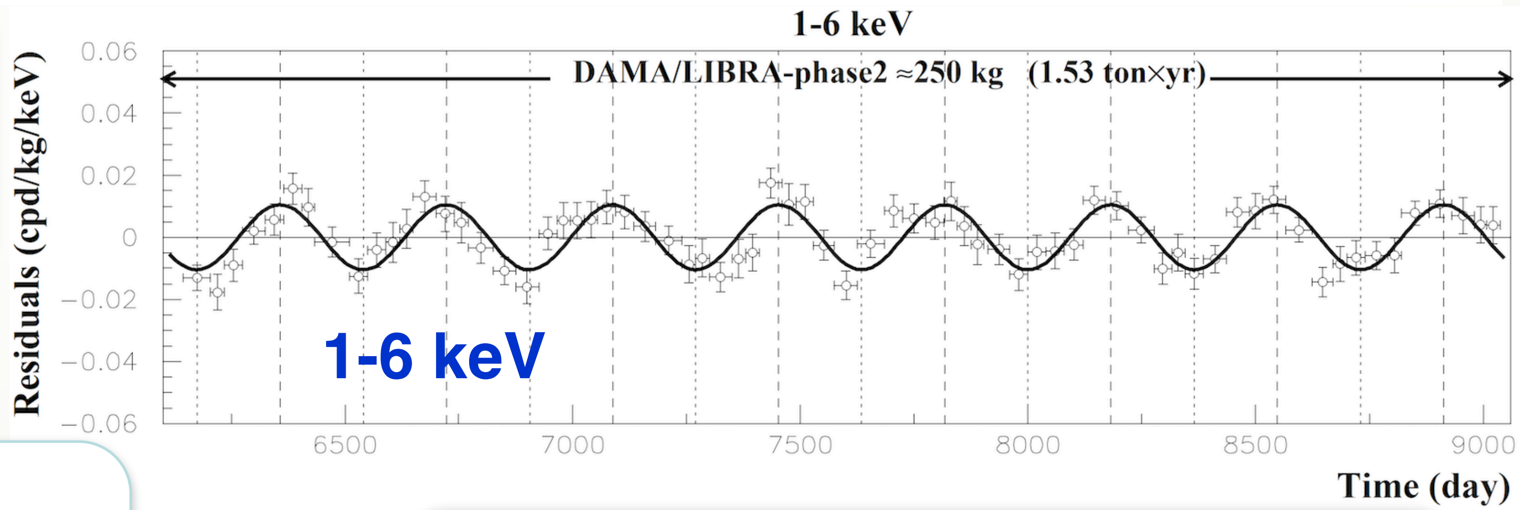
$A\cos[\omega(t-t_0)]$



continuous lines: t_0 = 152.5 d, T = 1.00 y

A=(0.00996±0.00074) cpd/kg/keV

χ^2/dof = 130/155



DAMA/NaI (0.29 ton x yr) – 7 annual cycles
DAMA/LIBRA-ph1 (1.04 ton x yr) – 7 annual cycles
DAMA/LIBRA-ph2 (1.53 ton x yr) – 8 annual cycles

total exposure = 2.86 ton×yr

Fit on DAMA/LIBRA-phase2

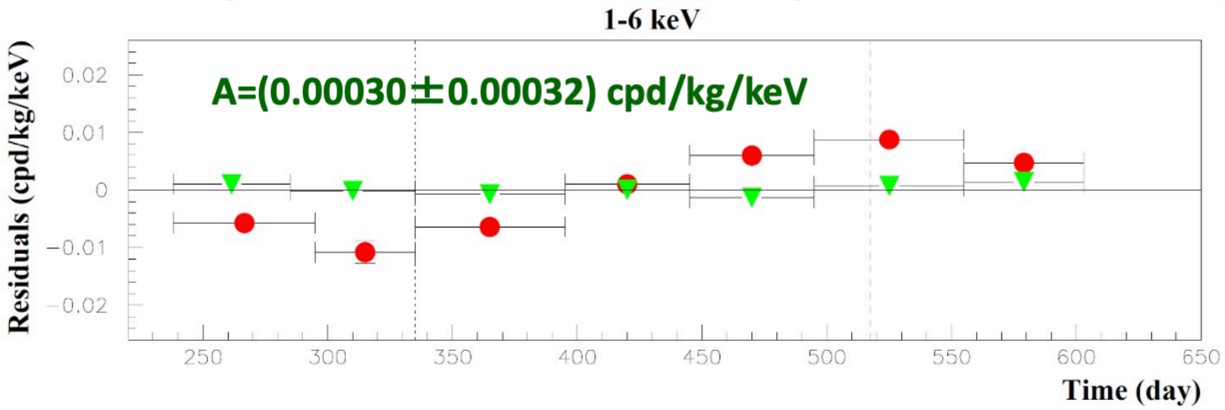
1-6 keV A=(0.01048±0.00090) cpd/kg/keV

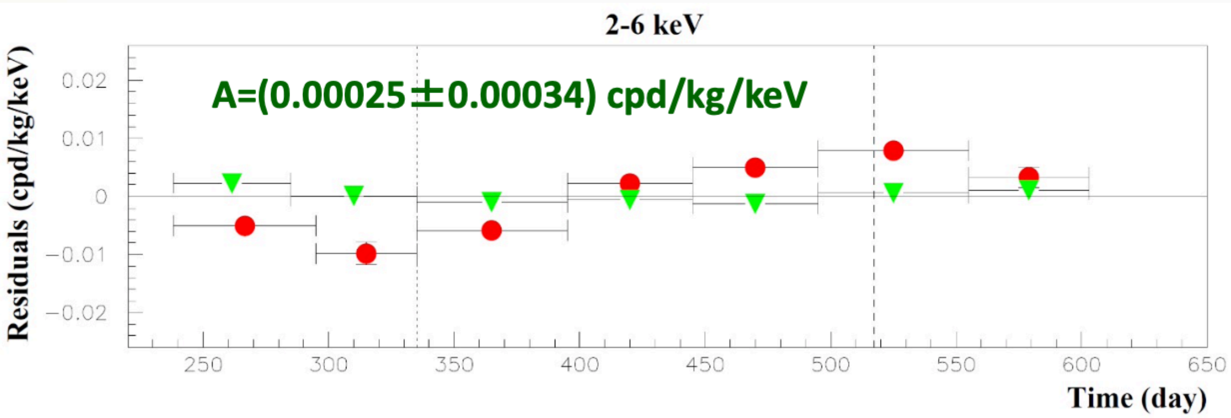
χ^2/dof = 66.2/68 **11.6 σ C.L.**

The data of DAMA/NaI + DAMA/LIBRA-phase1 +DAMA/LIBRA-phase2 favour the presence of a modulated behaviour with proper features at 13.7 σ C.L.

DM model-independent Annual Modulation Result

DAMA/LIBRA-phase2 (8 a.c., 1.53 ton × yr)





This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

Multiple hits events = Dark Matter particle "switched off"

P. Belli (DAMA)

Single hit residual rate (red) vs Multiple hit residual rate (green)

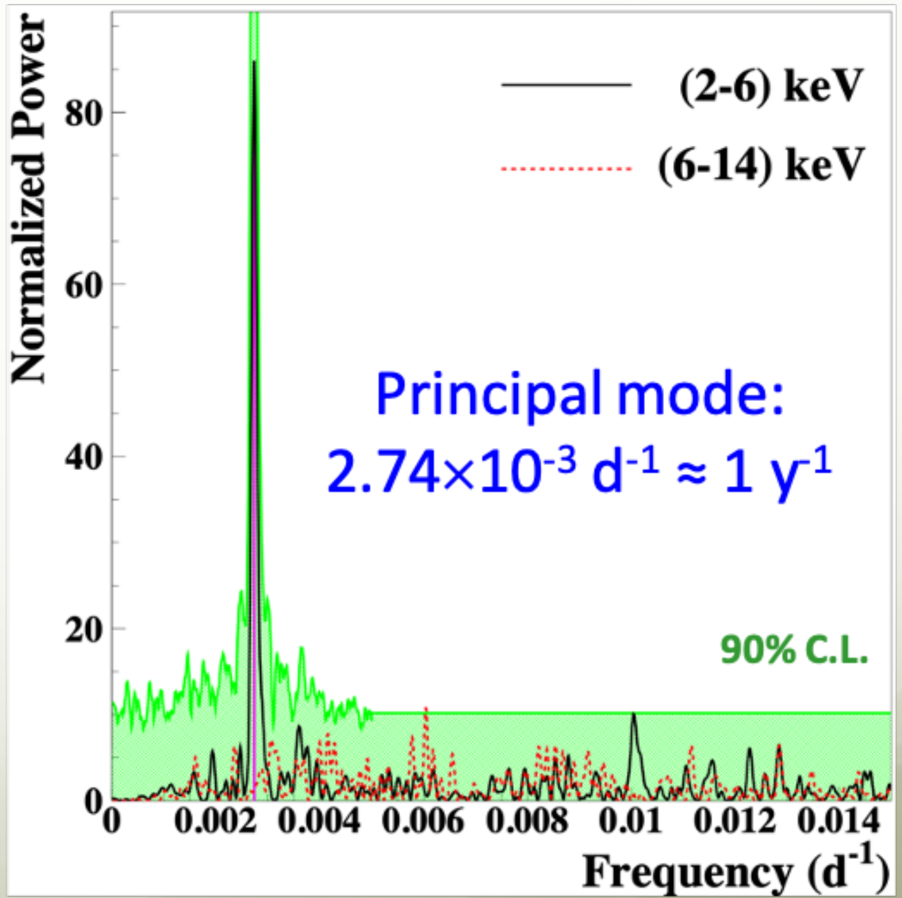
- Clear modulation in the single hit events
- No modulation in the residual rate of the multiple hit events

The analysis in frequency

DAMA/NaI + DAMA/LIBRA-(ph1+ph2) (22 yr)
total exposure: 2.86 ton×yr

Clear annual modulation in (2-6) keV + only aliasing peaks far from signal region

Zoom around the 1 y^{-1} peak



Green area: 90% C.L. region calculated taking into account the signal in (2-6) keV

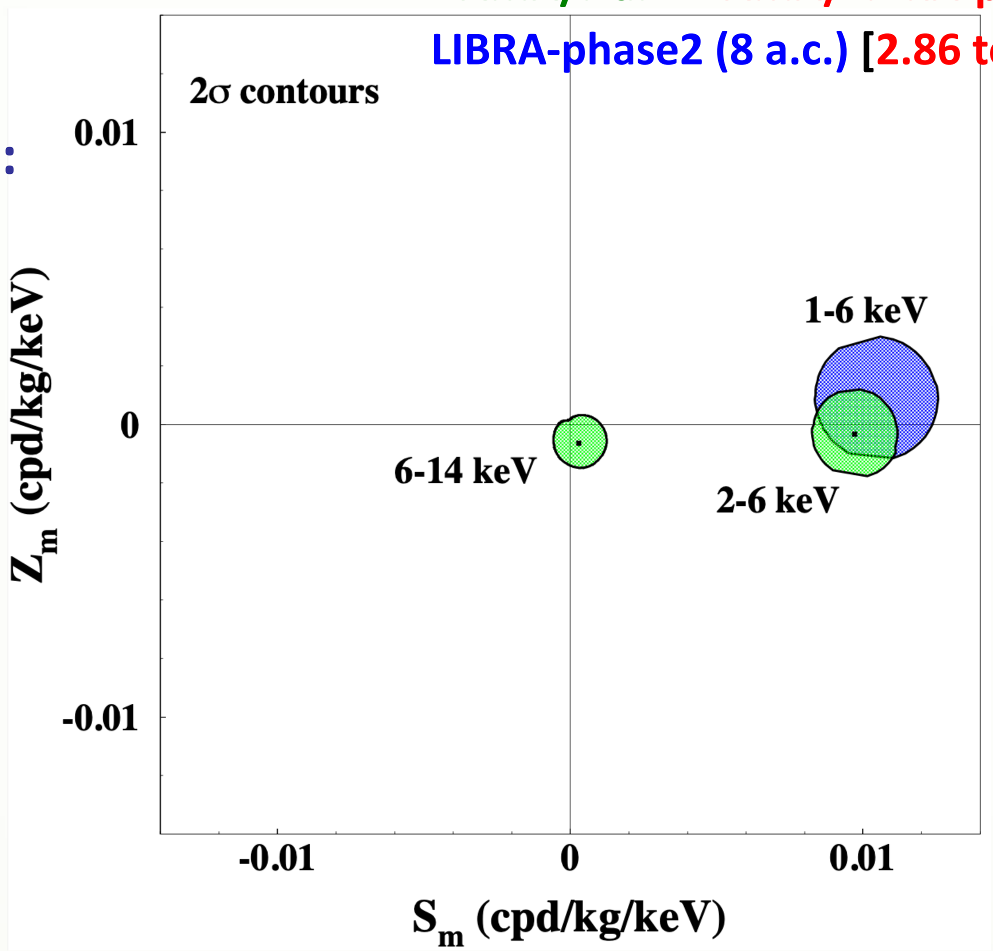
Is there a sinusoidal contribution in the signal? Phase $\neq$ 152.5 day?

P. Belli (DAMA)

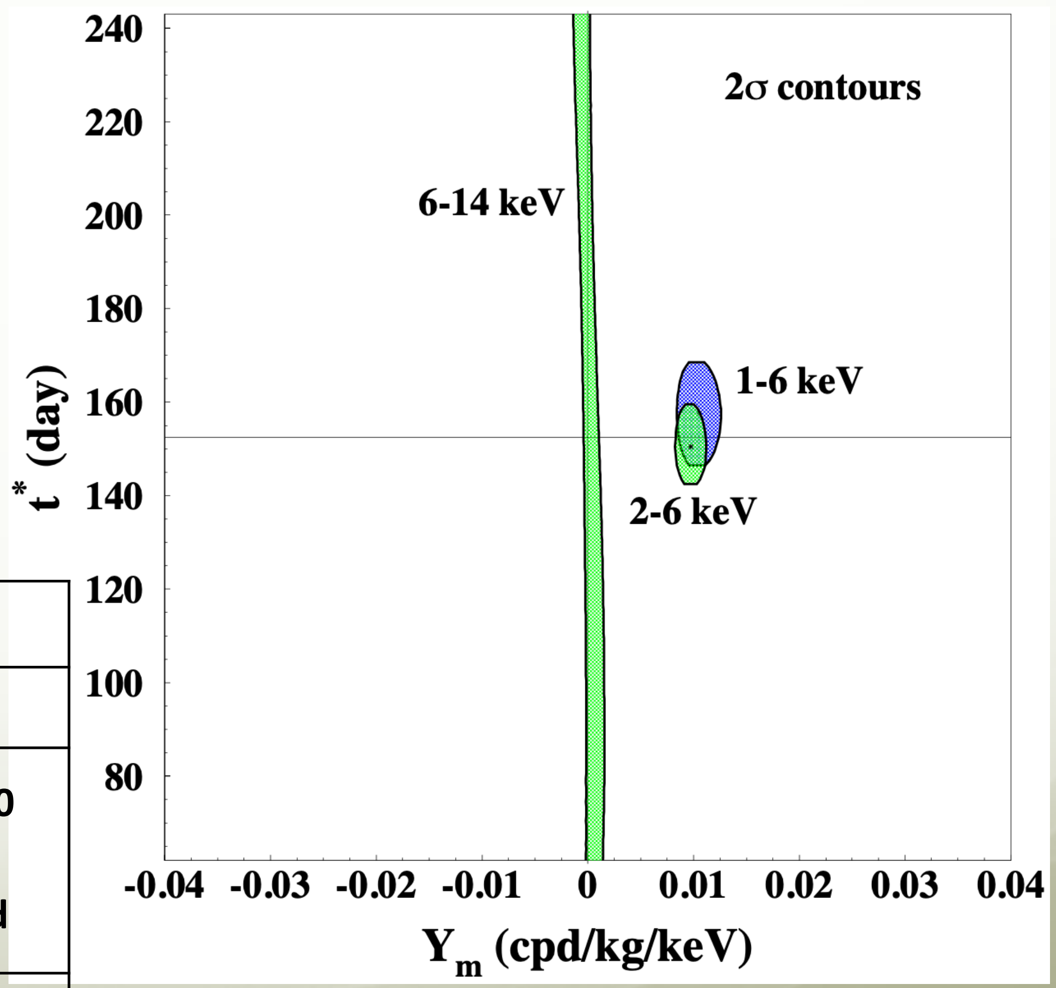
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2 (8 a.c.) [2.86 ton $\times$ yr]

For Dark Matter signals:

- $|Z_m| \ll |S_m| \approx |Y_m|$
- $t^* \approx t_0 = 152.5d$
- $\omega = 2\pi/T$
- $T = 1$ year



Slight differences from 2nd June are expected in case of contributions from non thermalized DM components (as e.g. the SagDEG stream)



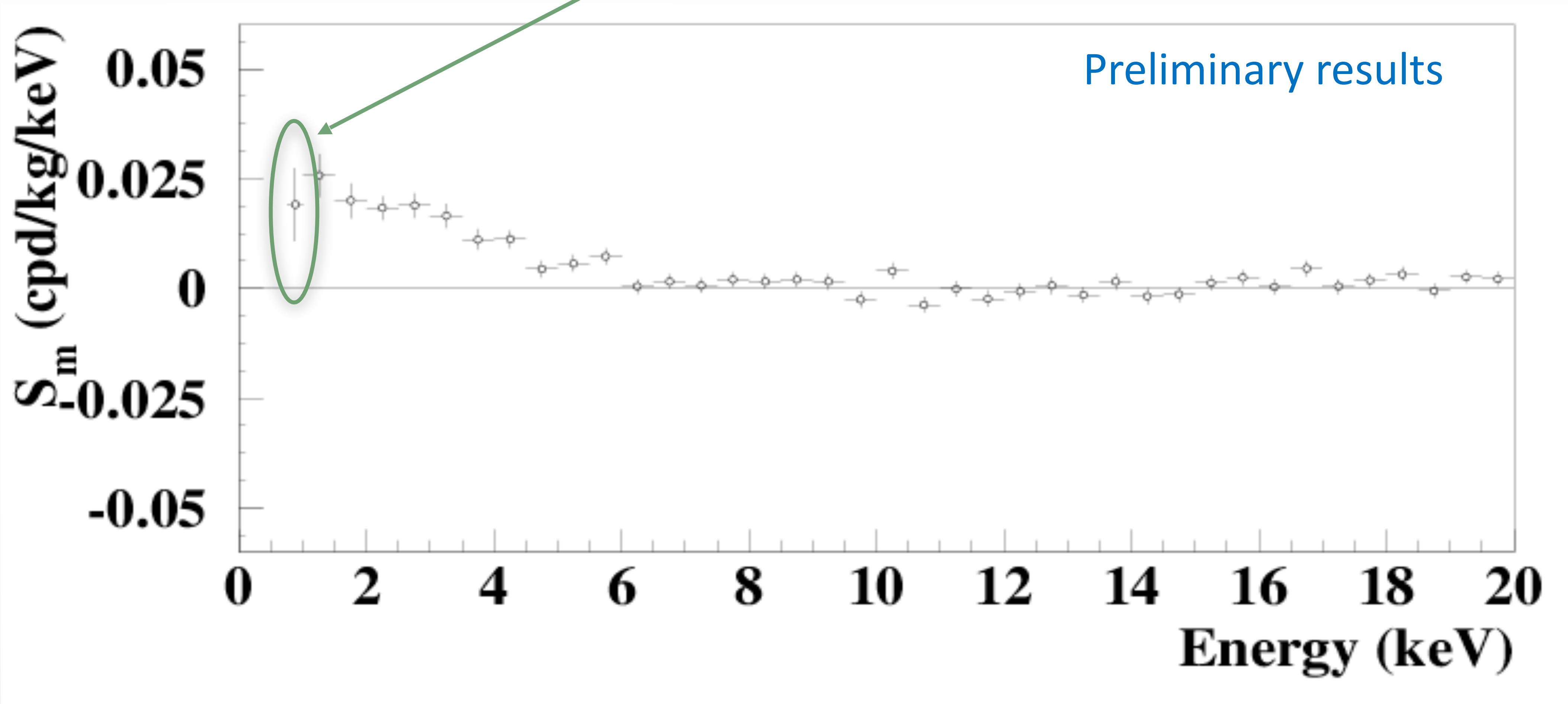
E (keV)	S_m (cpd/kg/keV)	Z_m (cpd/kg/keV)	Y_m (cpd/kg/keV)	t* (day)
DAMA/NaI + DAMA/LIBRA-ph1 + DAMA/LIBRA-ph2				
2-6	0.0097 ± 0.0007	- 0.0003 ± 0.0007	0.0097 ± 0.0007	150.5 ± 4.0
6-14	0.0003 ± 0.0005	-0.0006 ± 0.0005	0.0007 ± 0.0010	undefined
1-6	0.0104 ± 0.0007	0.0002 ± 0.0007	0.0104 ± 0.0007	153.5 ± 4.0

Efforts towards lower software energy threshold

P. Belli (DAMA)

- decreasing the software energy threshold down to 0.75 keV
- using the same technique to remove the noise pulses
- evaluating the efficiency by dedicated studies

New data point with the 8 a.c. of **DAMA/LIBRA-phase2 (1.53 ton×yr)**

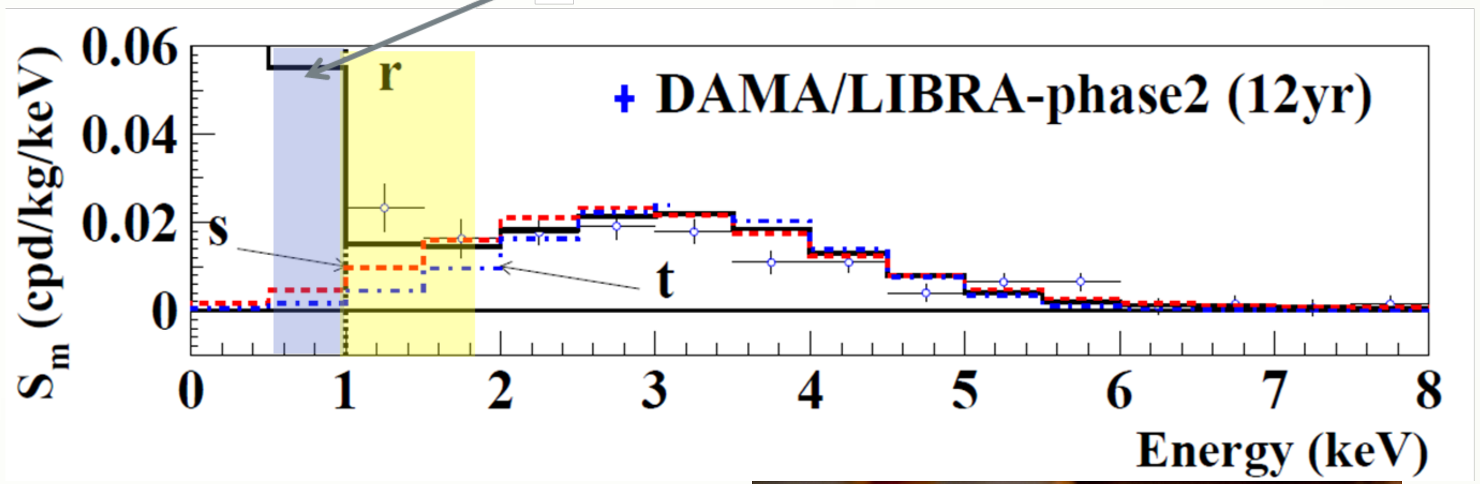


- ❑ A clear modulation is also present below 1 keV, from 0.75 keV, while S_m values compatible with zero are present just above 6 keV
- ❑ This preliminary result suggests the necessity to lower the software energy threshold and to improve the experimental error on the first energy bin

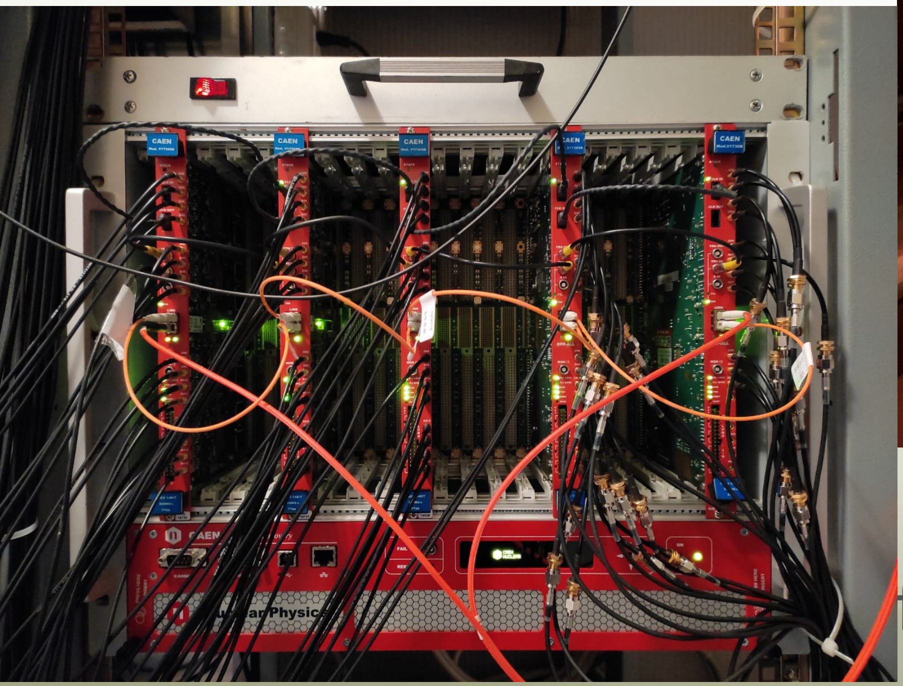
Running phase2 with software energy threshold at 0.5 keV with suitable high efficiency

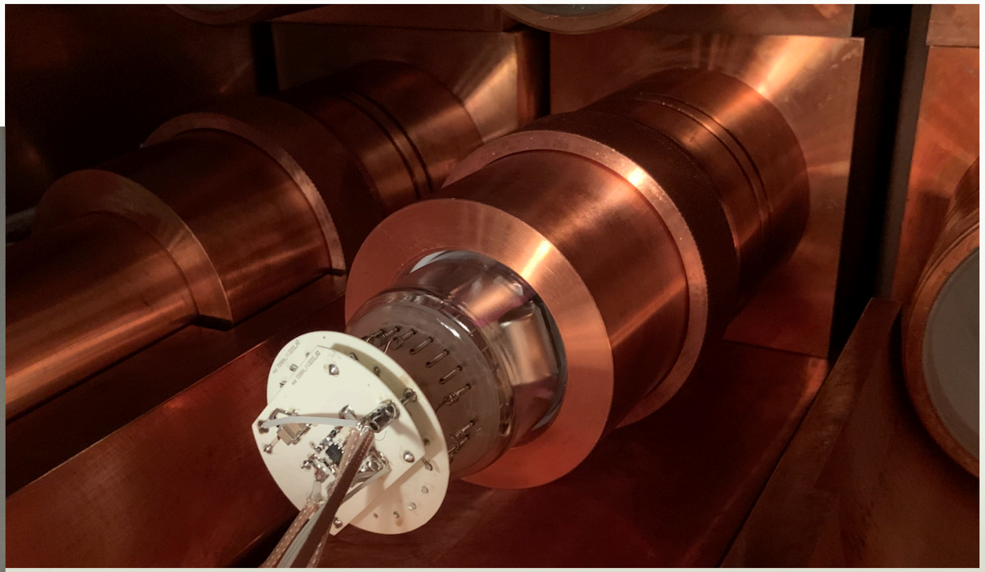
P. Belli (DAMA)

Enhancing experimental sensitivities and improving DM corollary aspects by lowering the software energy threshold to 0.5 keV, other DM features, second order effects and other rare processes



1) During fall 2021, DAMA/LIBRA–phase2 set-up heavily upgraded:
   a. equipping the PMTs with new low-background voltage dividers with pre-amps on the same board
   b. using Transient Digitizers with higher vertical resolution (14 bits)
2) After a dedicated R&D and data taking, the chosen implementation was demonstrated to be effective





e data taking in this new configuration with 0.5 keV ftware energy threshold started on Dec, 1 2021. Running

SABRE

SABRE North status

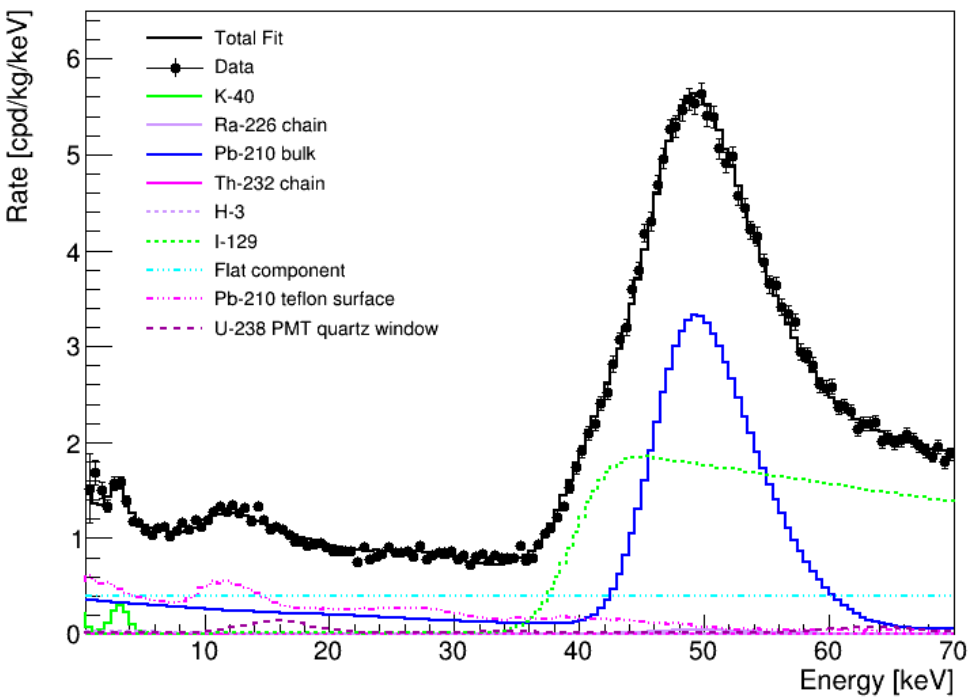
Two low background NaI(Tl) crystals (NaI-31 and NaI-33) tested and characterised.
Proof-of-principle phase (1 crystal + active veto) concluded.

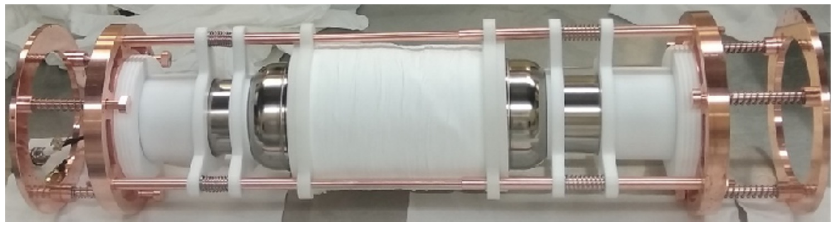
Results:

- Full Monte-Carlo simulation model to identify background components
- Breakthrough background level: ~1 count/day/kg/keV in the 1-6 keV region of interest, lowest since DAMA/LIBRA.

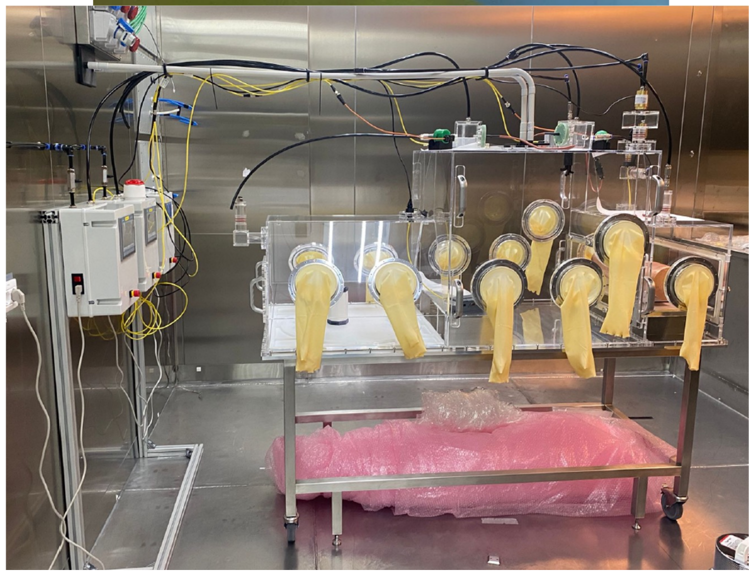
Goals for near future:

- Test the same crystal (NaI-33) with a lower radioactivity reflector
- Test reproducibility of crystal radiopurity
- Assembly of detector modules at LNGS with a new custom glove box.



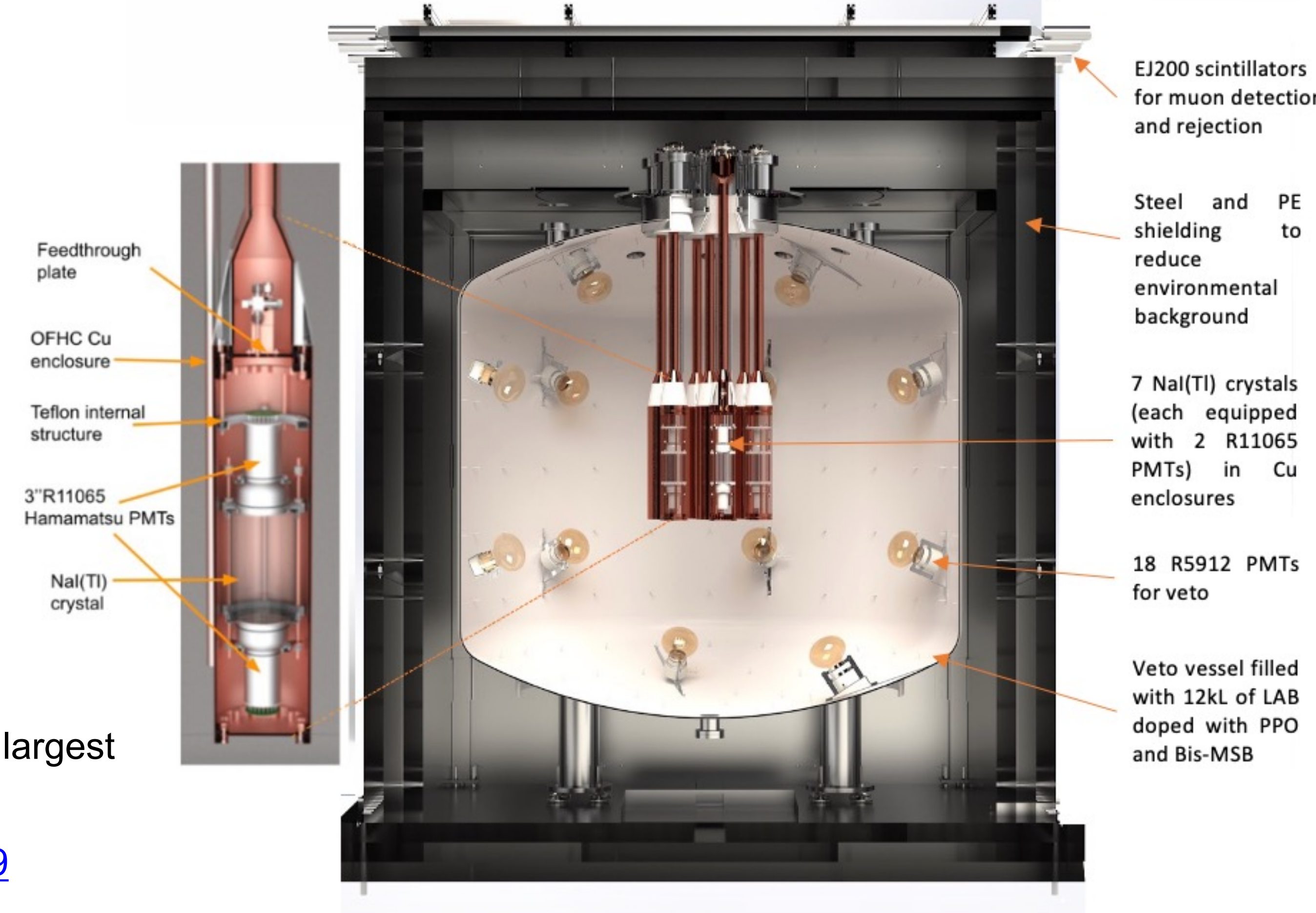


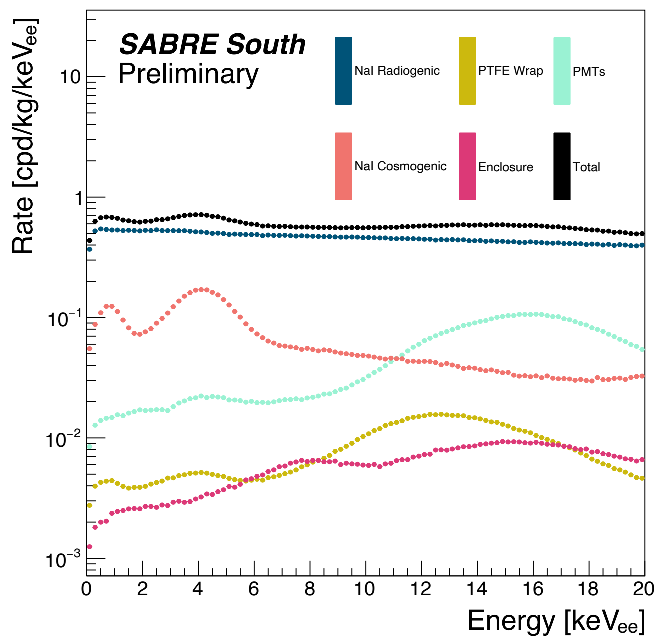
Demonstrate feasibility of a full-scale experiment without active veto and finalize the design of crystal array + shielding



SABRE South status

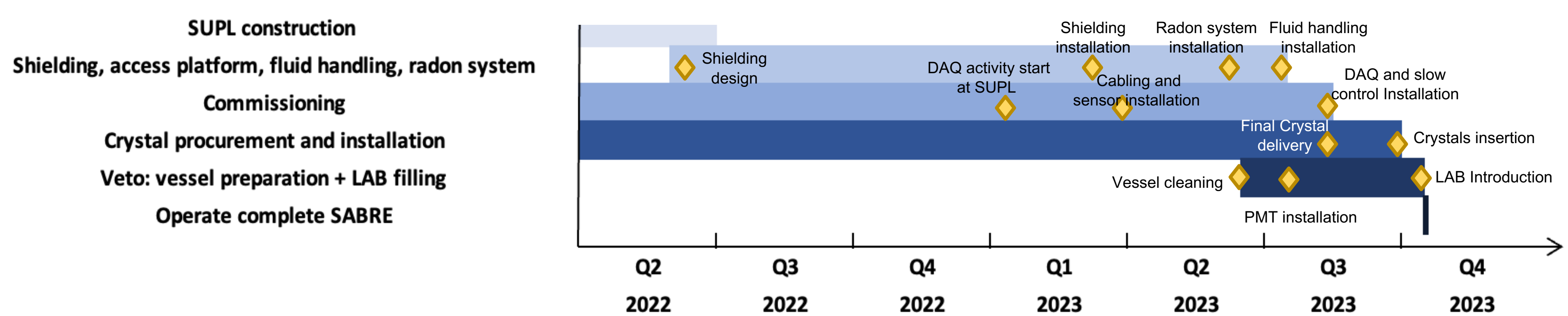
- SABRE South will be the first experiment in SUPL.
- SUPL is the first deep underground laboratory in the Southern Hemisphere 1025 m deep (2900 m water equivalent) located in the Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia.
- SABRE South will use the liquid scintillator (LAB) for in-situ evaluation and validation of the background in addition of background rejection and particle identification.
- Vessel + LAB, PMTs, muon detector, DAQ electronics, slow control, Crystal insertion system ... all ready.
- One low background NaI(Tl) crystal in testing phase at LNGS.





Highest purity crystals and largest active veto: 0.72 cpd/kg/keV.

http://arxiv.org/abs/2205.13849



SUPL

STAWELL UNDERGROUND PHYSICS LAB

https://www.supl.org.au

- First deep underground laboratory in the Southern Hemisphere
- Located in the Stawell Gold Mine, 240 km west of Melbourne, Victoria, Australia

Strong support of the local community

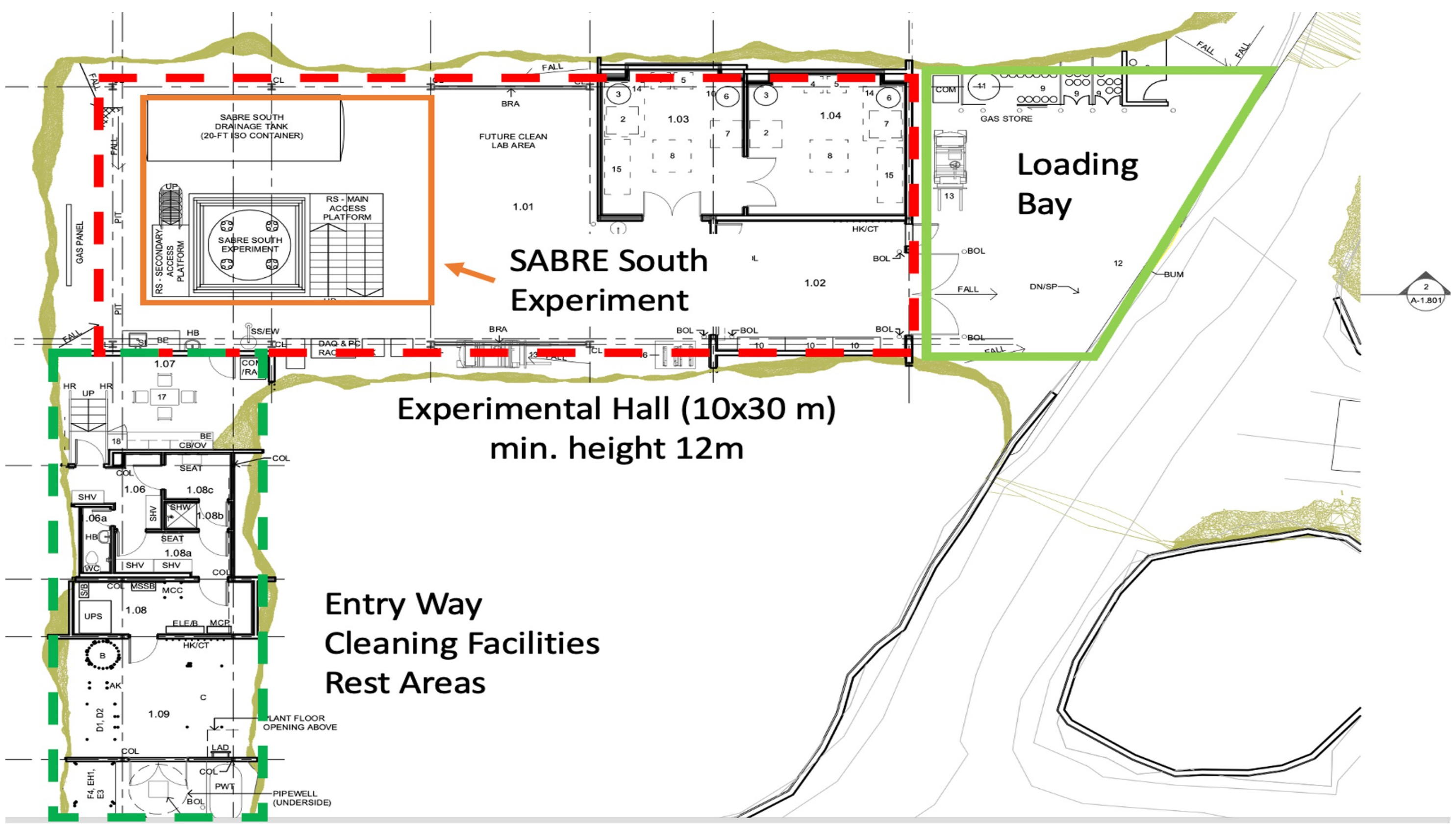
SUPL

Construction complete and installation of experiment will start in August/September 2022.

STAWELL UNDERGROUND PHYSICS LAB

https://www.supl.org.au

- **First deep underground laboratory in the Southern Hemisphere**
  - 1025 m deep (2900 m water equivalent) with flat overburden
  - Helical drive access
  - Low background screening facilities



SUPL TIMELINE

- ***2014*** Lab proposed, Project Leaders E. Barberio (University of Melbourne), J. Mould (Swimburne)
- ***2016*** Lab design ready
- ***2017*** Hiatus - SGM in caretaker mode
- ***2018*** the project restart: ARETE capital acquires SGM
- ***2019*** construction starts by H.Troon (Ballarat) led by The University of Melbourne
- ***2022*** SUPL ready to be used
- ***2022*** SABRE-South to commence assembly underground
- **2023** SABRE starts operations