STATUS of „NaIce“ DARK MATTER EXPERIMENTS

EDSU – Tools 2024
5th World Summit

June, 2-7 2024

Île de Noirmoutier
France

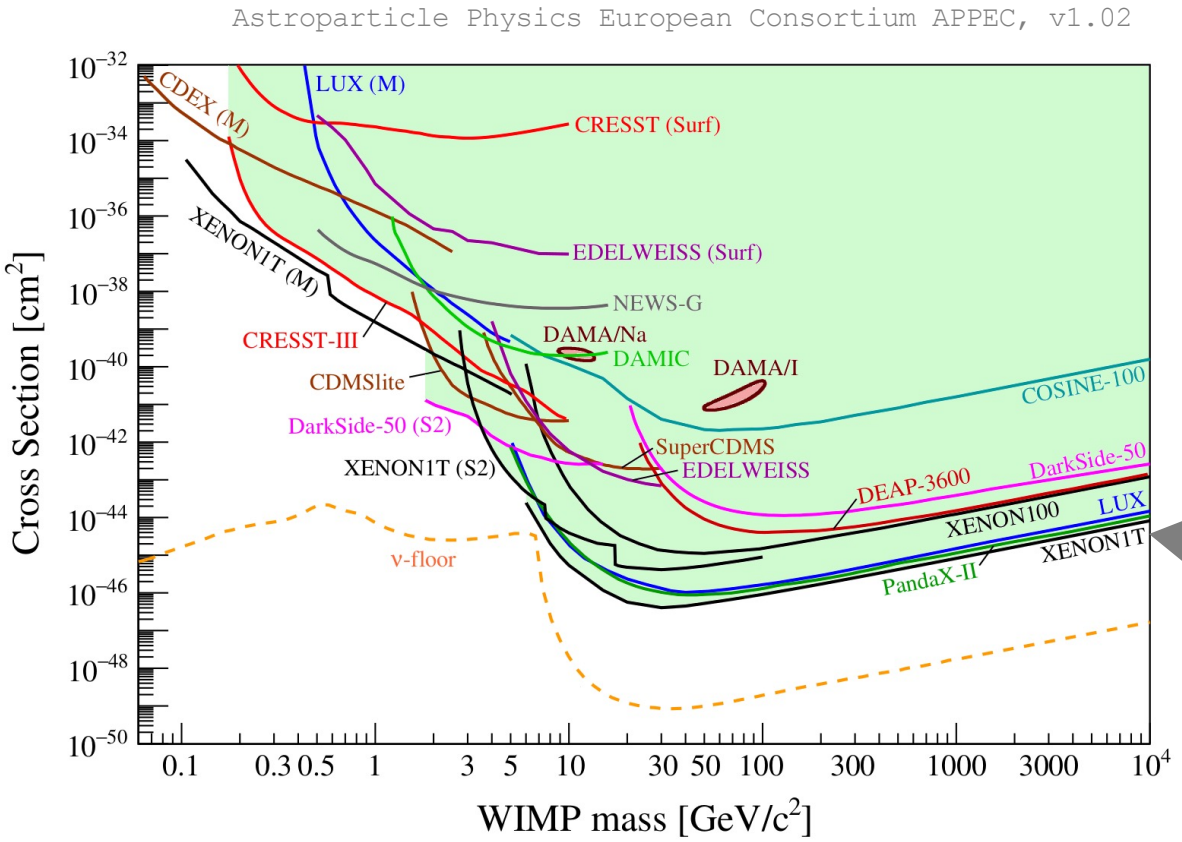
Karoline Schäffner

MPP, Garching, Germany

kschaeff@mpp.mpg.de

MAX-PLANCK-INSTITUT FÜR PHYSIK

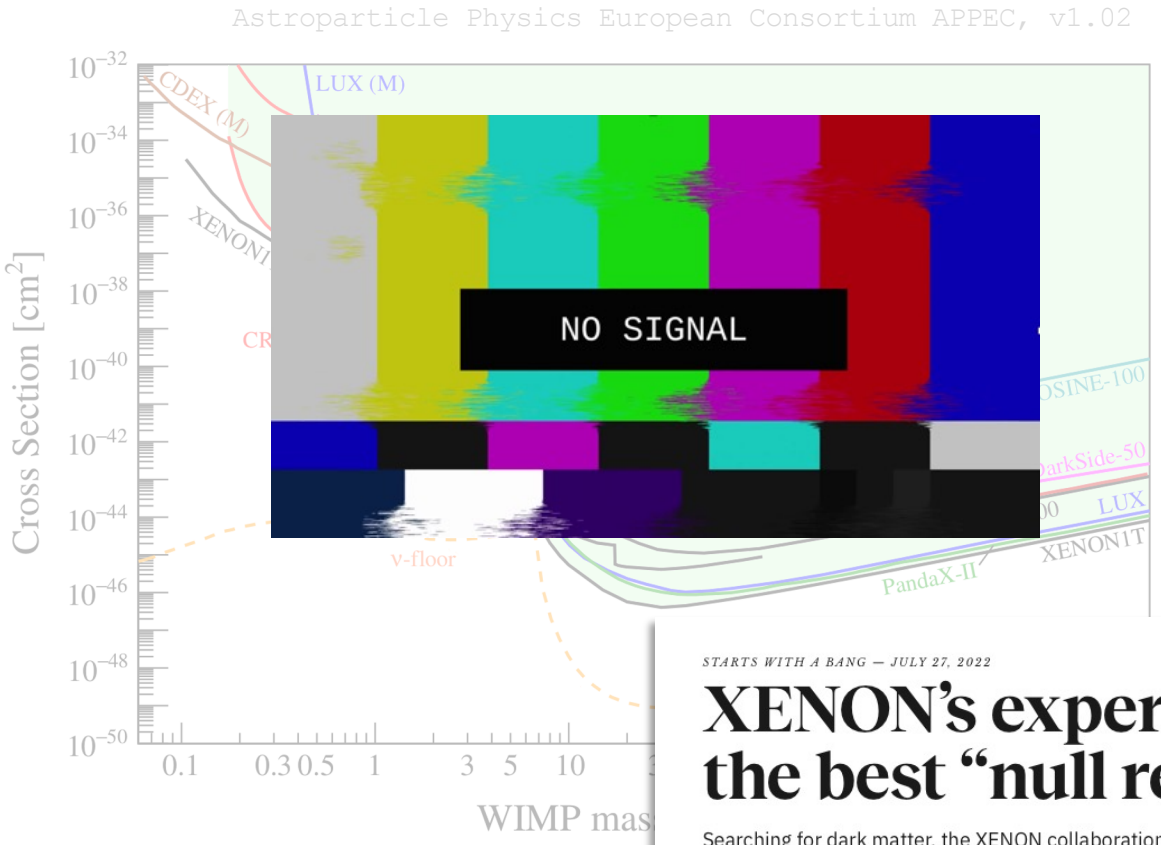
STATUS of DIRECT DARK MATTER SEARCHES



- world-wide effort with enormous technological progress in last decades both for light DM and classical WIMP DM mass regime
- tonne-scale experiments with extremely rare interaction rate
  current limit: $\mathcal{O}$ (0.01) cts/(keV tonne year)

new limits from XENONnT and LZ

STATUS of DIRECT DARK MATTER SEARCHES



- world-wide effort with enormous technological progress in last decades both for light DM and classical WIMP DM mass regime
- tonne-scale experiments with extremely rare interaction rate
  current limit: $\mathcal{O}$ (0.01) cts/(keV tonne year)

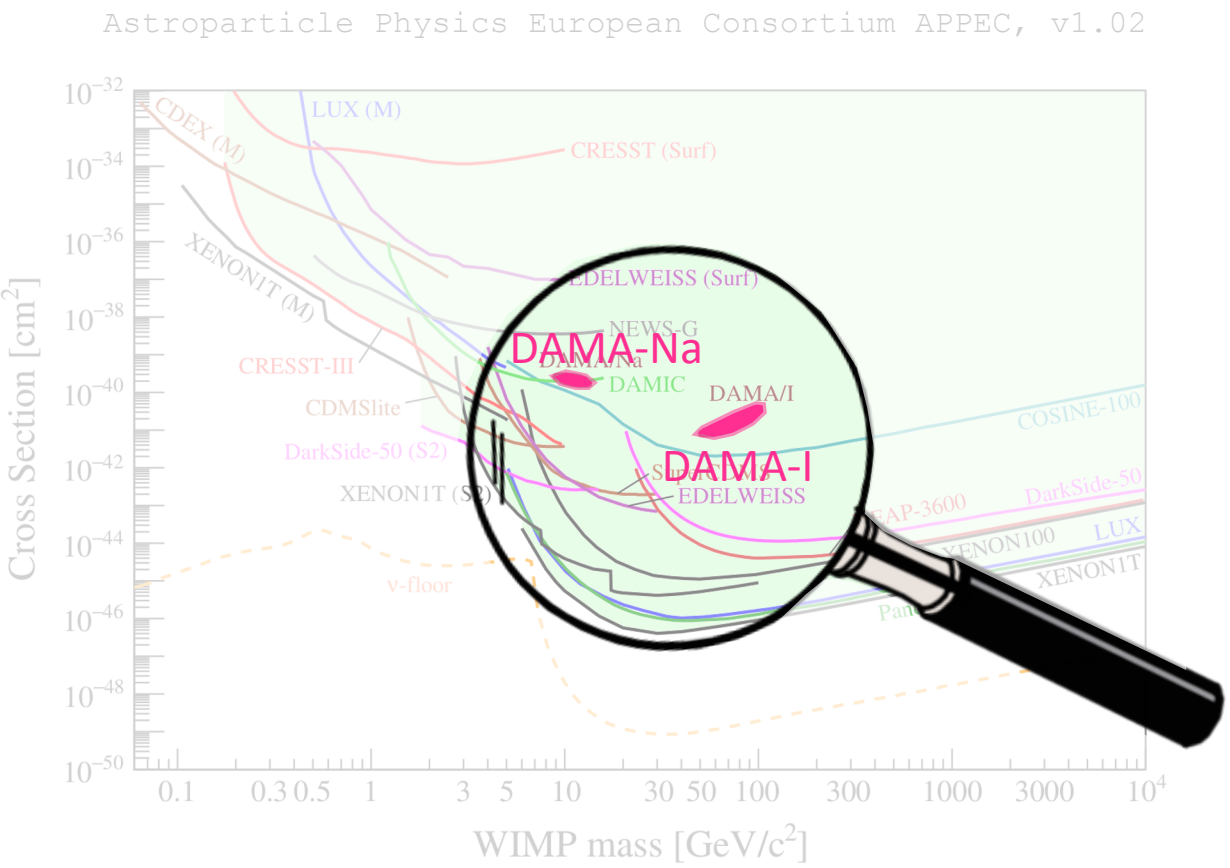
→ **no discovery !**

STARTS WITH A BANG — JULY 27, 2022

XENON's experimental triumph: No dark matter, but the best "null result" in history

Searching for dark matter, the XENON collaboration found absolutely nothing out of the ordinary. Here's why that's an extraordinary feat.

CLAIM BY DAMA/LIBRA



positive evidence reported by **DAMA/LIBRA**

REACTION vs. SCIENTIFIC AGE

Professor:
Ahh, those were the good old days, when we were still excited about DAMA. I was there, you know?

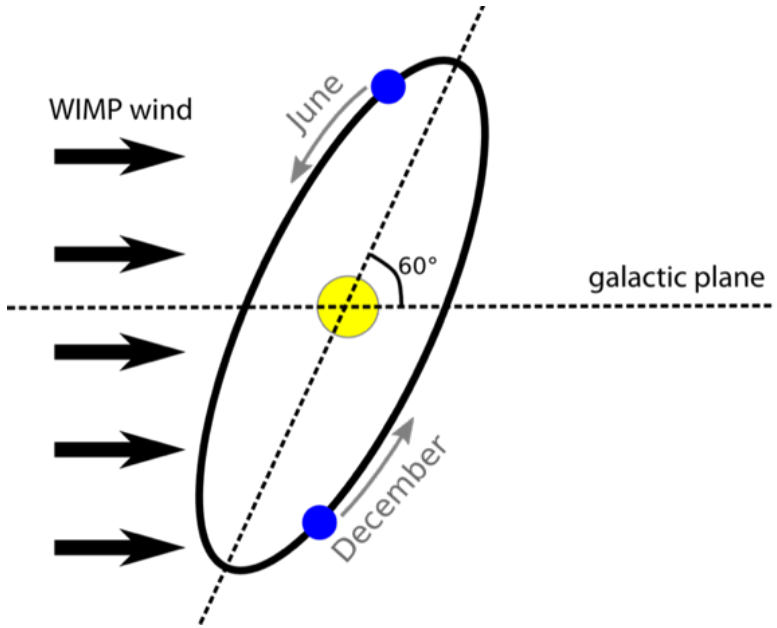
Postdoc:
I. DON'T. WANT. TO. HEAR. ANOTHER. WORD. ABOUT. DAMA

Grad student:
What is DAMA?

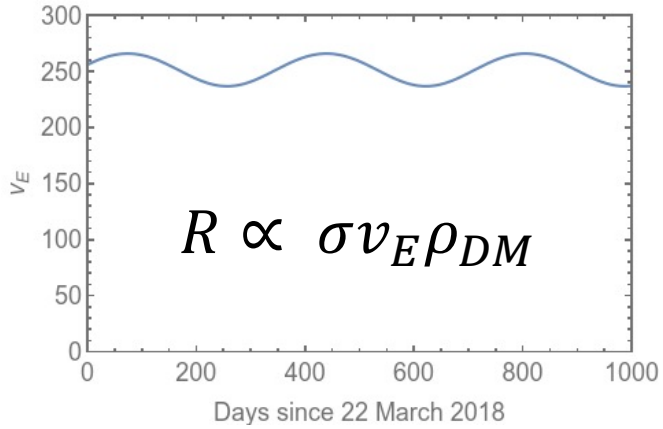
Professor PostDocs Grad students

Credits to F. Kahlhoefer

ANNUAL MODULATION OF DARK MATTER SIGNALS

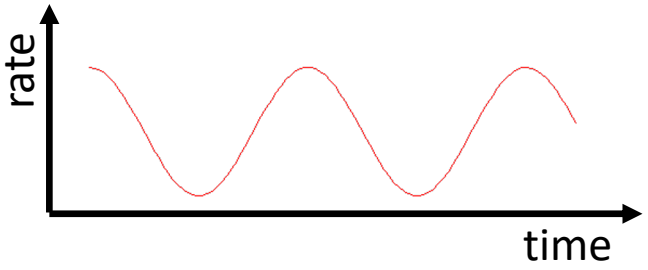


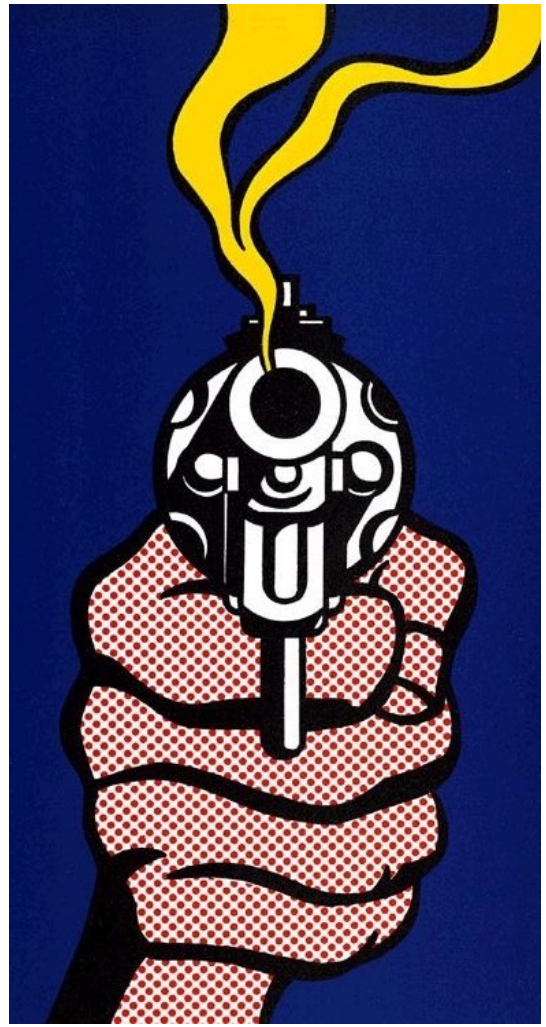
Credits to F. Kahlhoefer



$$R \propto \sigma v_E \rho_{DM}$$

motion of the Earth causes
relative modulation of velocity
→ **annual variation in the rate**





DAMA/LIBRA experiment

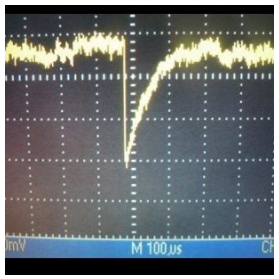


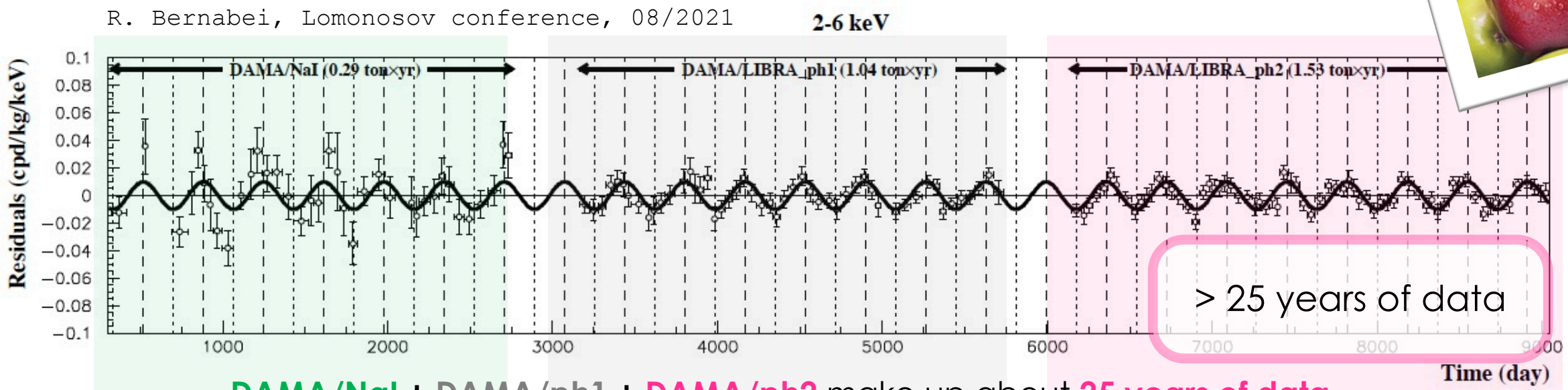
Photo multiplier tube

sodium iodide NaI(Tl) crystals

total mass: 250 kg

DAMA/LIBRA **RESULT**

R. Bernabei, Lomonosov conference, 08/2021



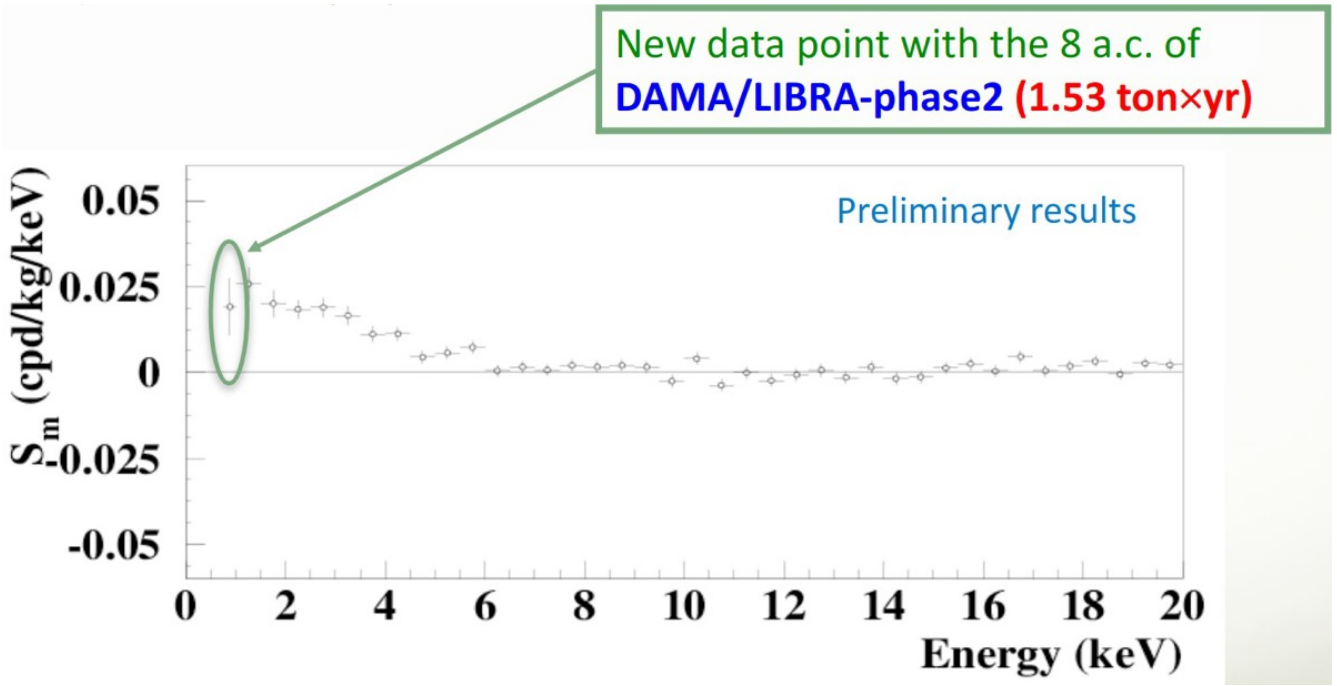
> 25 years of data

DAMA/NaI + **DAMA/ph1** + **DAMA/ph2** make up about **25 years of data**

total exposure:	2.86 tonne years
statistical significance:	13.7 σ
energy region:	2-6 keV_{ee} → ee = electron equivalent

claim: positive evidence for the presence of DM particles in the galactic halo

WHAT'S NEW – LOWER ENERGY THRESHOLD



Credit: P. Belli at UCLA Dark Matter, LA, US - April 2023

Phase 2 upgrade(s):

2010:

new PMTs with higher Q.E.

→ 1keV$_{ee}$ software threshold

2021:

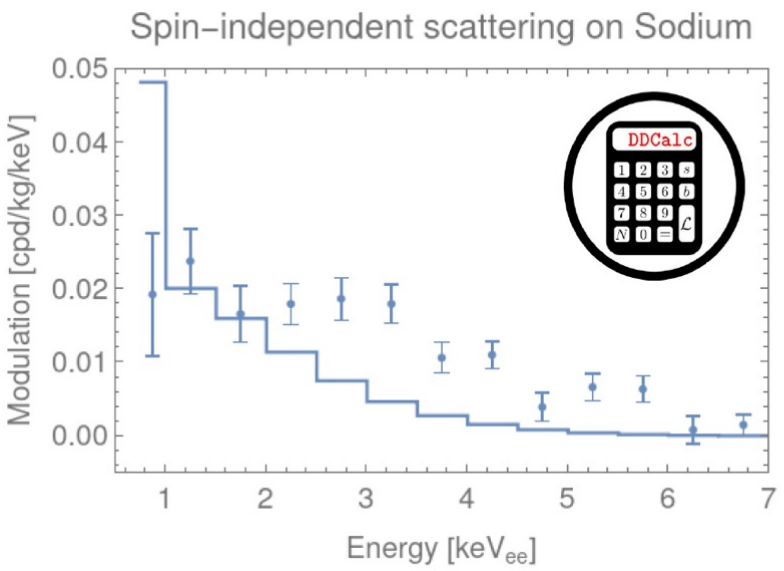
new electronics and digitizers

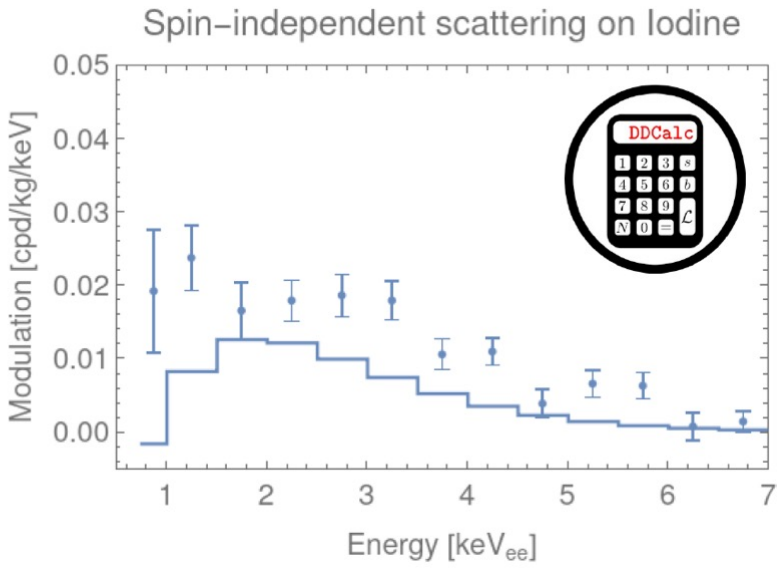
→ < 0.75keV$_{ee}$ software threshold

→ data taking since 12/2021

→ <u>past experience:</u>
DAMA released results after 3 annual cycles → early 2025 ?

WHAT'S NEW – STANDARD SCENARIO





spin-independent scattering no longer gives a good fit!

Credits to F. Kahlhoefer, IDM 2022

THE SMOKING GUN EVIDENCE?

statistics: 13.7 σ ✓

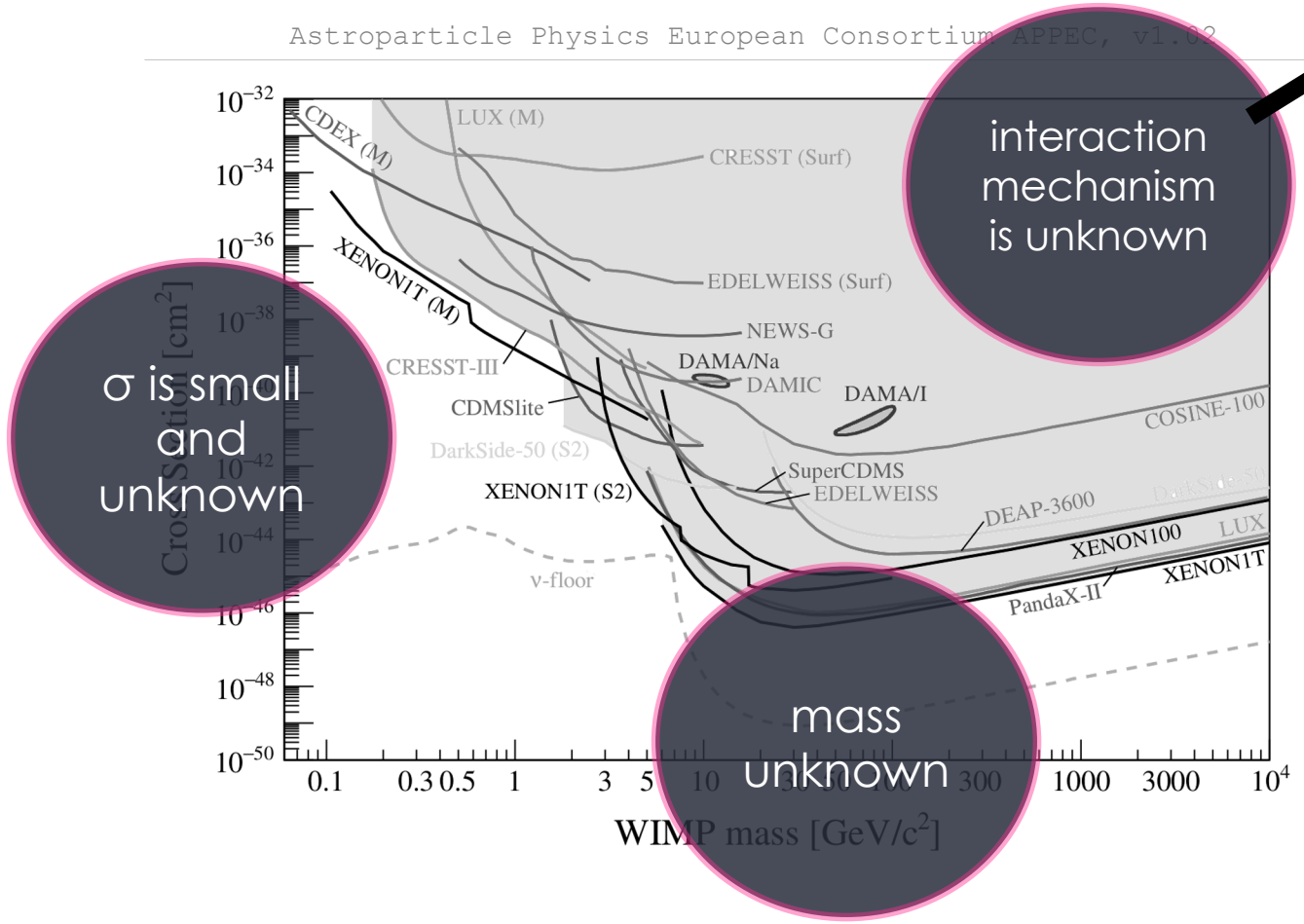
period: 0.99834 ± 0.00067 years * ✓

phase: 22th May +/- 4 days ✓
(cosine peaking June 2nd)

convincing non-DM explanation ✗

*in (2-6) keV$_{ee}$ interval

WHAT ARE THE **UNKNOWNS**?



interaction mechanism is unknown

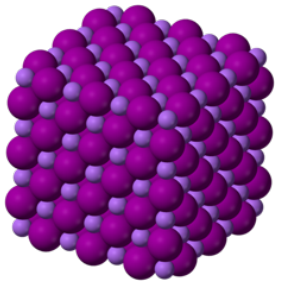
σ is small and unknown

mass unknown

$$\frac{dR}{dE_r} = \frac{\rho_\chi}{m_N m_\chi} \cdot \int_{v_{min}}^{v_{esc}} d^3v\, f(v)\, v \frac{d\sigma(v, E_r)}{dE_r}$$

~ A^2
~ form factor

→ **dependence on target material**



^{11}Na

53I

Sodium Iodide: NaI

WHAT TO CONCLUDE ?

If the DAMA signal is due to dark matter we have **fundamental problems** in **understanding its astrophysical distribution and fundamental interactions.**

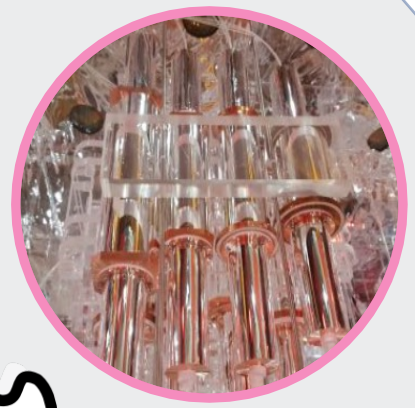
→ same-target experiments offer test without need for assumptions!

APPEC Recommendation:
"The long-standing claim from DAMA/LIBRA […] needs to be independently verified using ***the same target material****."*

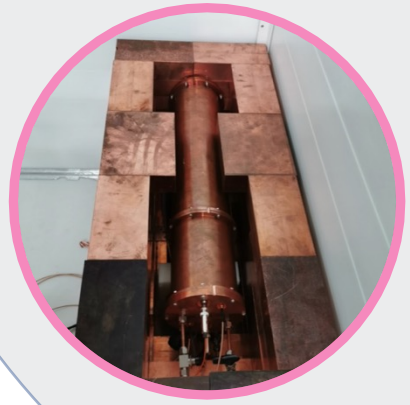
DAMA/LIBRA

ANAIS-112

COSINE-100

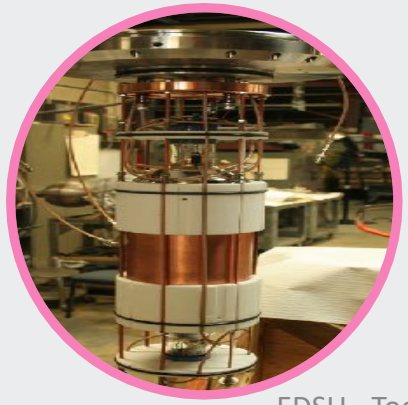


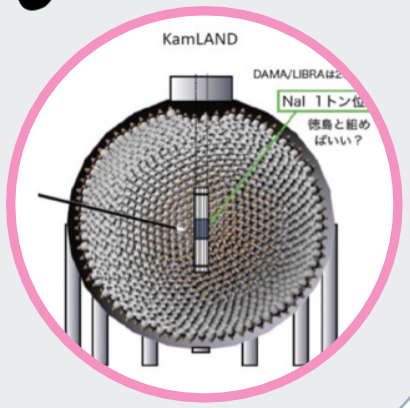
signal background



SABRE

DM-Ice

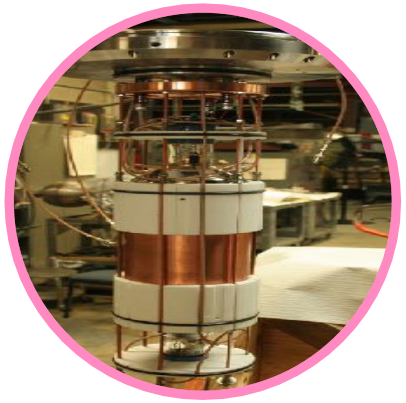




PicoLON

NaI EXPERIMENTS à la DAMA

* not complete list



DM-Ice

South Pole
2200 m.w.e of ice

17 kg

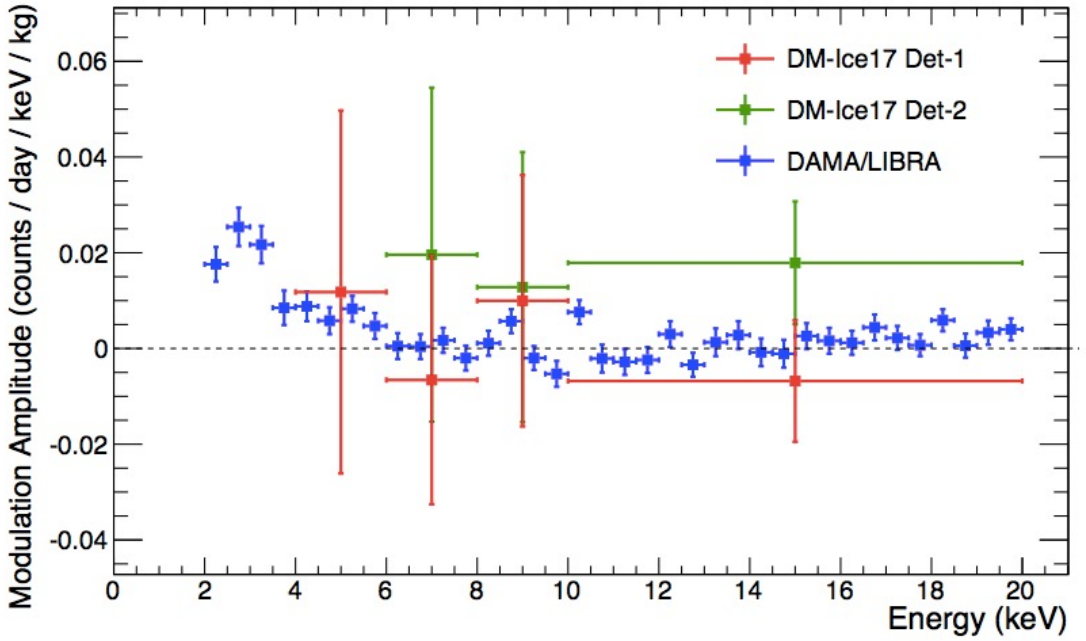
4 keV_{ee}

3.5 y of data

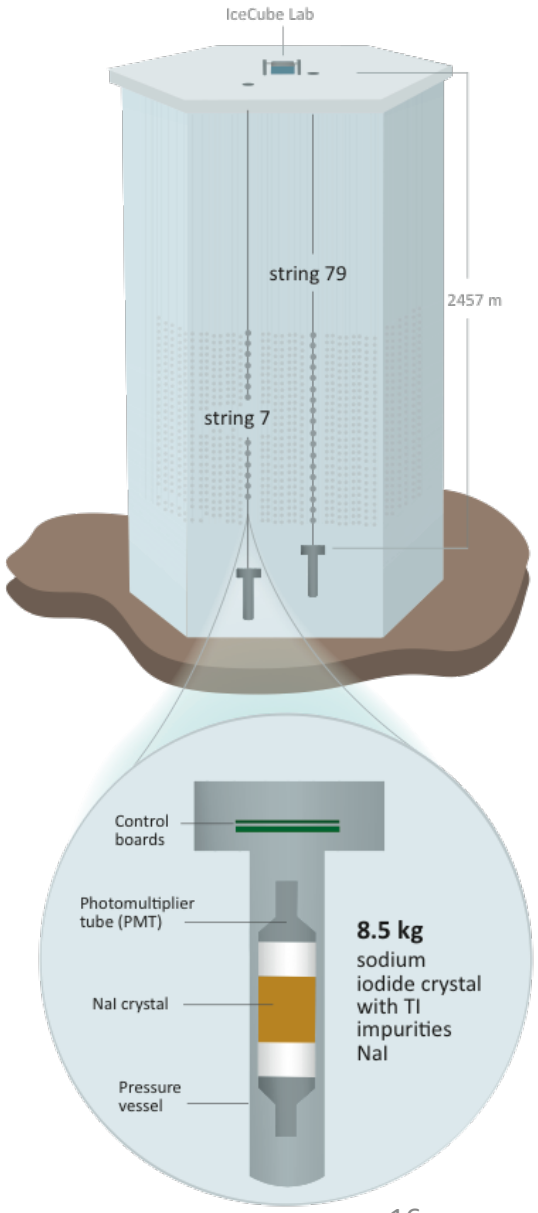
DM-Ice: **Result**

PRD 90 092005 (2014)
PRD 93 042001 (2016)
PRD 95 032006 (2017)

- deployed in Dec, 2010
- > 99% uptime
- total exposure: 60.8 kg yr
- ~10 counts / keV kg d

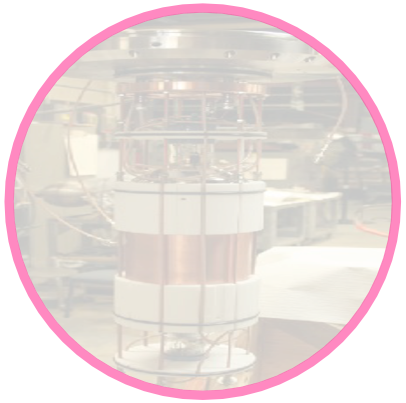


→ → sensitivity not sufficient to cross-check DAMA signal



NaI EXPERIMENTS à la DAMA

* not complete list



DM-Ice

South Pole
2200 m.w.e of ice

17 kg

4 keV_{ee}

3.5 y of data

COSINE-100

Korea @Y2L

106 kg

1 keV_{ee}

6.4 y of data

COSINE-100

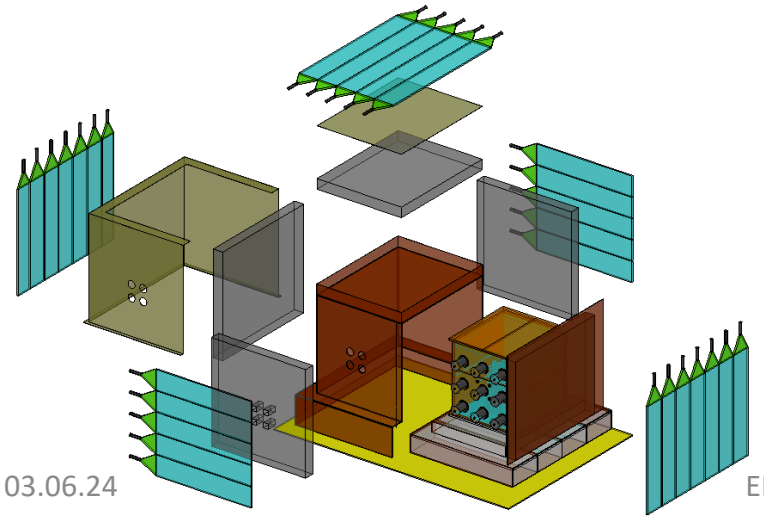
Joint venture KIMS NaI + DM-Ice
@ Y2L, South Korea

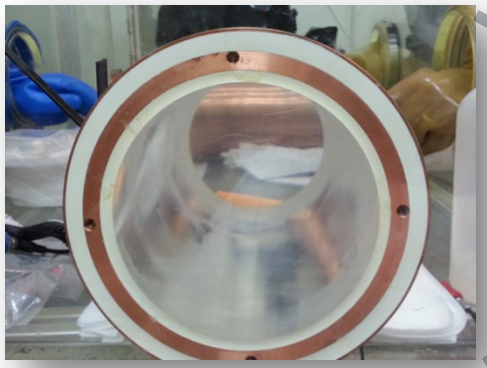
EPJC 78 107 (2018)

- operation: Sep, 2016 – March, 2023
- 8 crystals from Alpha Spectra, 106 kg total
- background: (2 – 4) x DAMA's average

+ muon veto

+ liquid scintillator to veto ^{40}K background

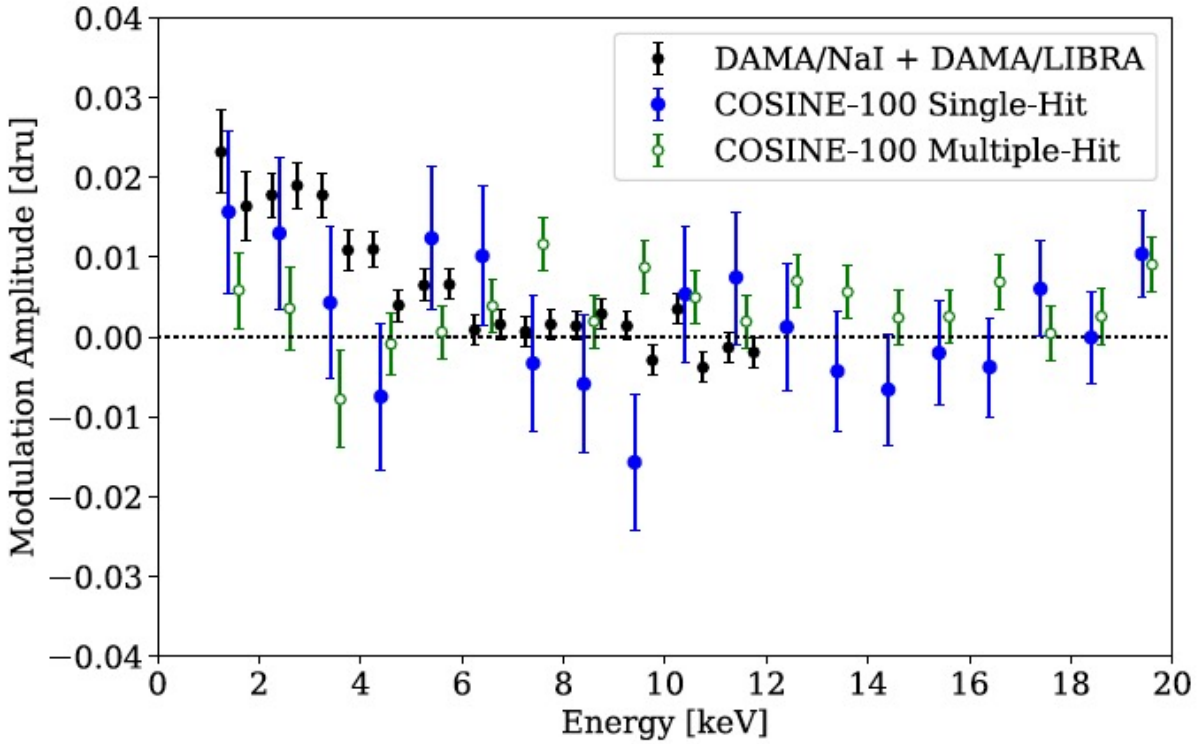


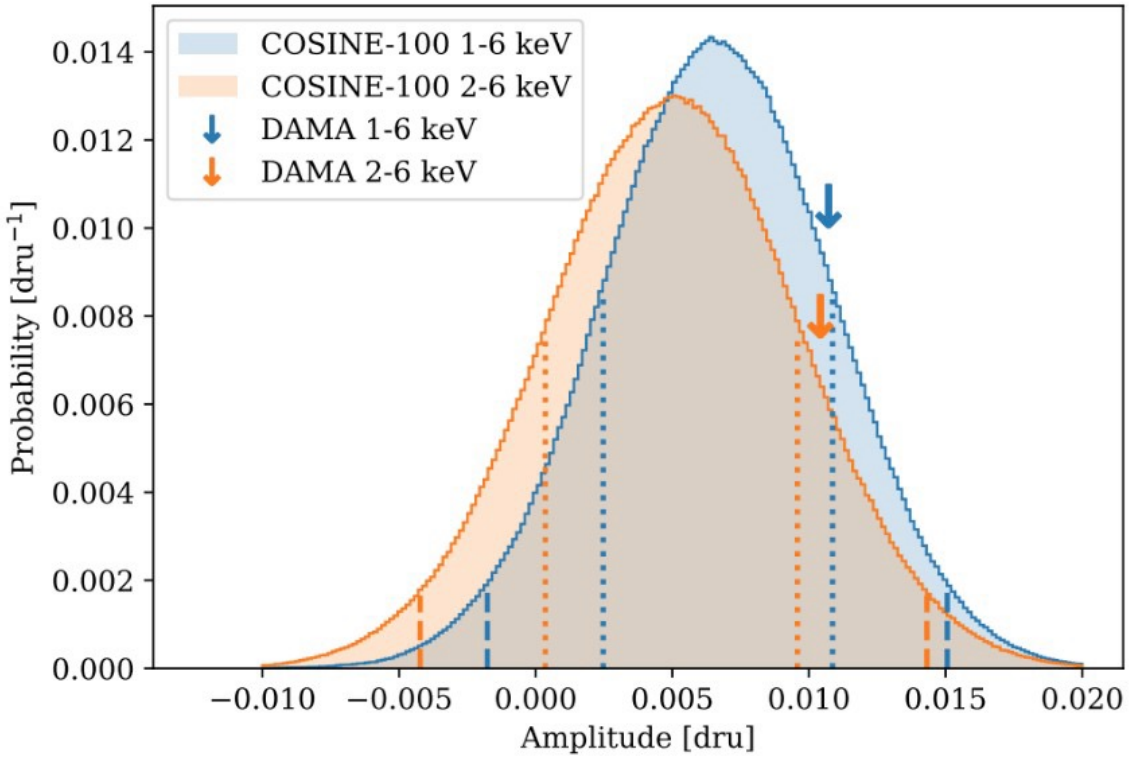


COSINE-100 – MODULATION SEARCH

→ 2.8 years of data (+ addition 3 years on tape to be analyzed)

PRD 106, 052005



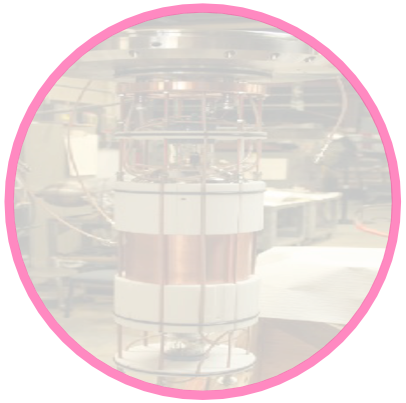


COSINE-100	**0.0067 ± 0.0042**
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	−0.0034 ± 0.0042

→ → data consistent with both DAMA and no modulation

NaI EXPERIMENTS à la DAMA

* not complete list



DM-Ice

South Pole
2200 m.w.e of ice

17 kg

4 keV_{ee}

3.5 y of data

COSINE-100

Korea @Y2L

106 kg

1 keV_{ee}

6.0 y of data

ANAIS-112

Spain @LSC

112 kg

<1 keV_{ee}

since 2017
7 y of data

ANAIS-112

LSC Laboratorio Subterráneo de Canfranc

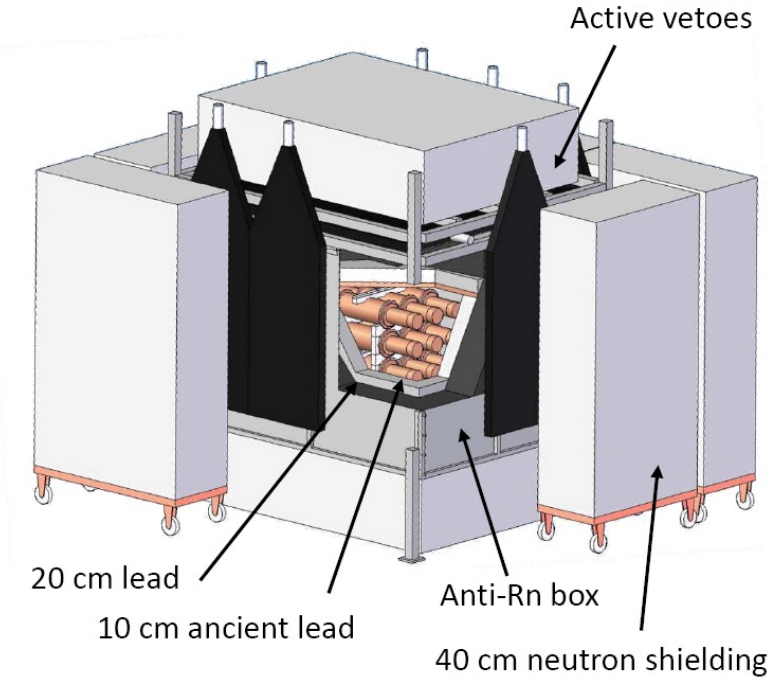
112 kg of pure NaI
@ Canfranc, Spain

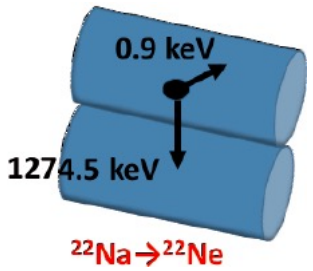
- operation since Aug, 2017
- 9 crystals in 3x3 array, 112.5 kg total

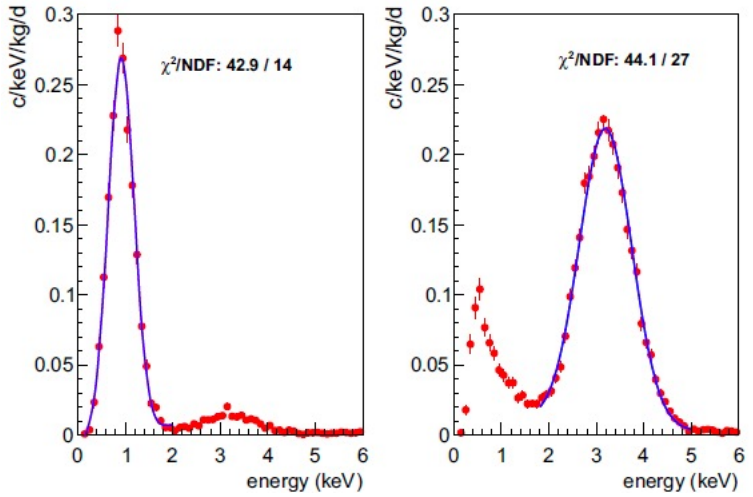
+ **sub-keV calibration with internal**

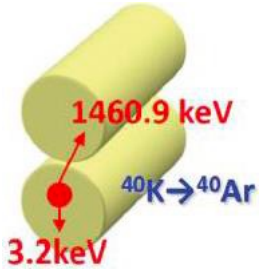
  ^{22}Na @ 0.9 keV and ^{40}K @ 3.2 keV

+ **muon veto**







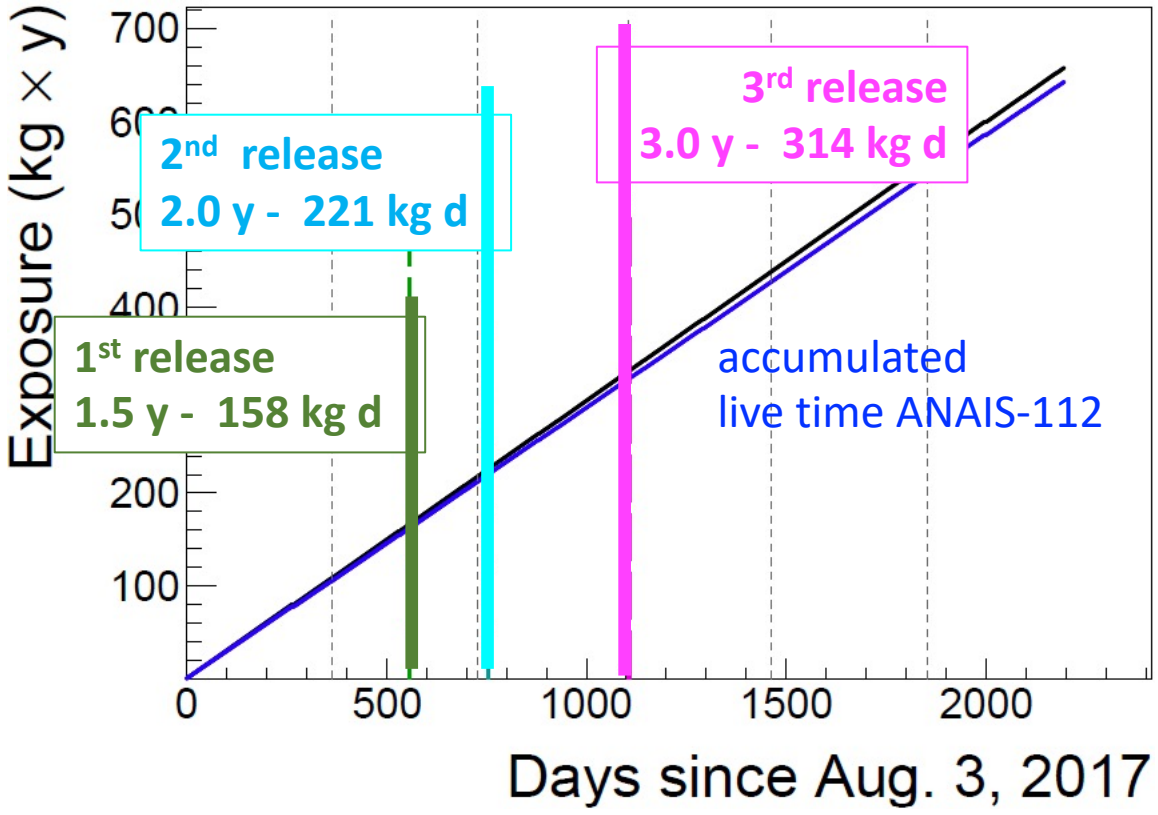


credits to M. Martinez

ANAIS-112

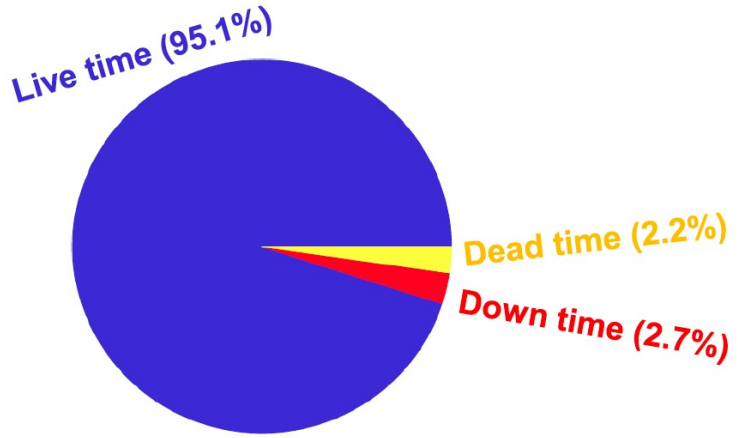
112 kg of pure NaI
@ Canfranc, Spain

Credits to I. Coarasa



six-year data completed Aug, 2023
(95% of live time)

→ exposure: 643.48 kg y

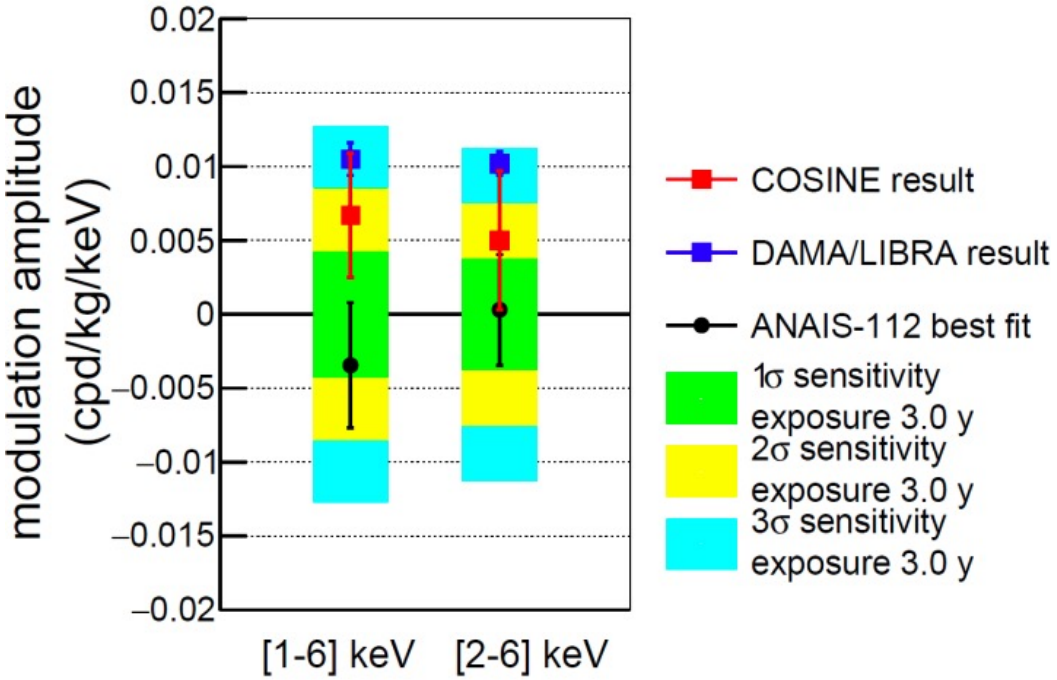


PRL 123, 031301 (2019)
J. Phys. Conf. Ser. 1468, 012014 (2020)
PRD 103, 102005 (2021)

ANAIS-112

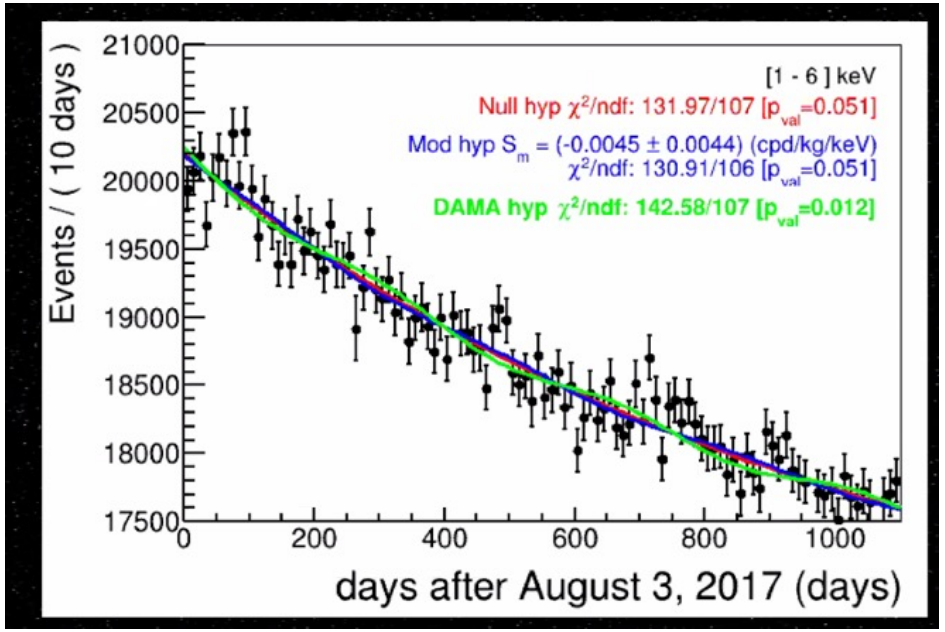
PRD 103, 102005 (2021)
PRL 123, 031301 (2019)

112 kg of pure NaI
@ Canfranc, Spain



3 years of data

→ incompatible with modulation at the level of >2.5 σ



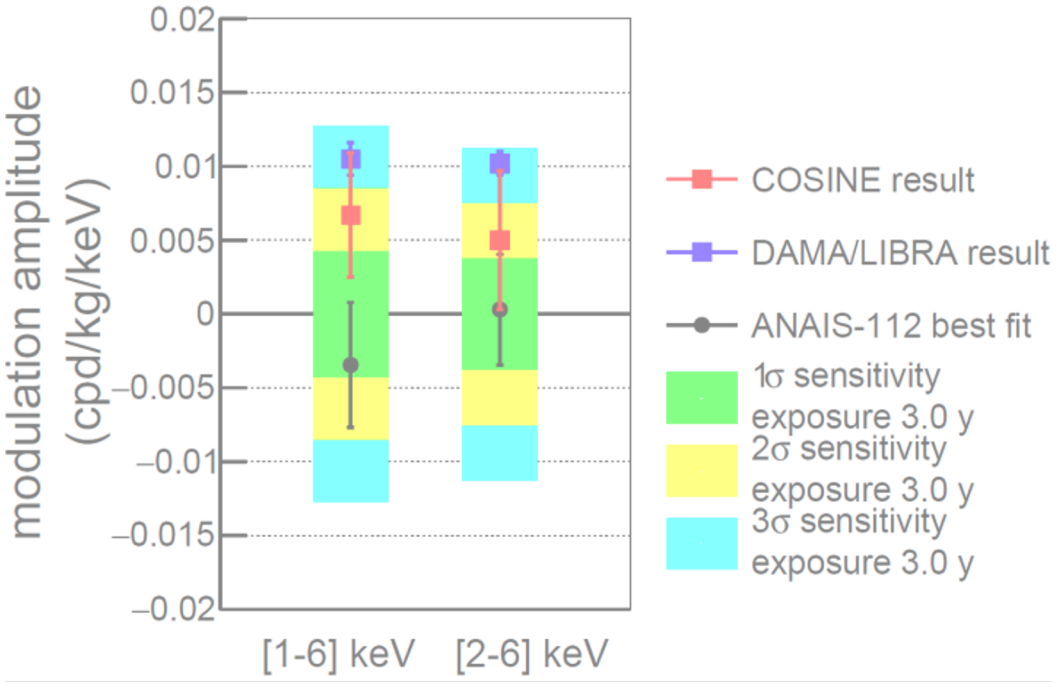
Moriond 2021: M.L. Sarsa

LATEST RESULTS (3 y)

E (keV)	S_m (counts/keV/kg/day)		
	ANAIS−112	COSINE−100 (*)	DAMA/LIBRA (†)
[1-6]	-0.0034±0.0042	0.0067±0.0042	0.0105±0.0011
[2-6]	0.0003±0.0037	0.0050±0.0047	0.0102±0.0008

ANAIS-112

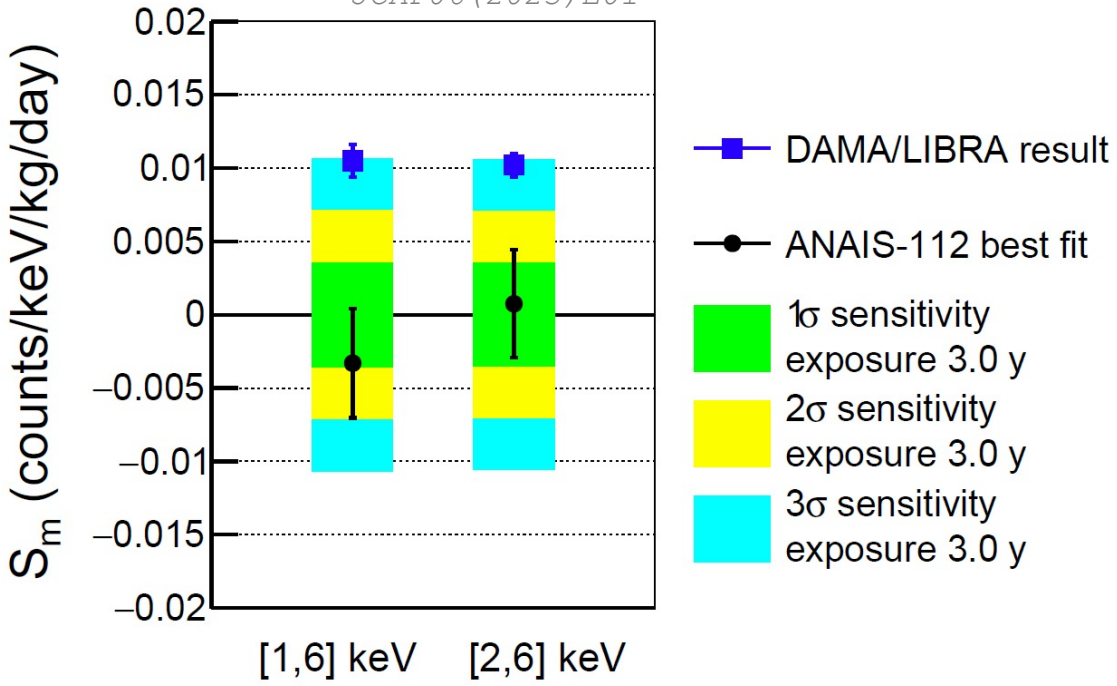
112 kg of pure NaI
@ Canfranc, Spain



3 years of data

→ incompatible with modulation at the level of >2.5 σ

JCAP11(2022)048
JCAP06(2023)E01

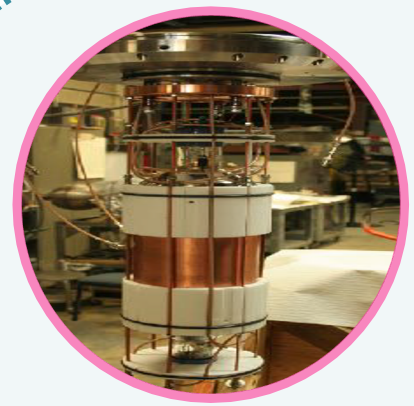


new multivariate analysis enhances sensitivity >2.5σ → ~ 2.9σ

→ 5 σ exclusion at reach in late 2025

NaI EXPERIMENTS à la DAMA

* not complete list



DM-Ice

South Pole
2200 m.w.e of ice

17 kg

4 keV_{ee}

3.5 y of data

COSINE-100

Korea @Y2L

106 kg

1 keV_{ee}

6.0 y of data

ANAIS-112

Spain @ LSC

112 kg

<1 keV_{ee}

since 2017
7 y of data

DATA TAKING

IN MAKING

NaI EXPERIMENTS à la DAMA

* not complete list

DM-Ice

South Pole
2200 m.w.e of ice

17 kg

4 keV_{ee}

3.5 y of data

COSINE-100

Korea @Y2L

106 kg

1 keV_{ee}

6.0 y of data

ANAIS-112

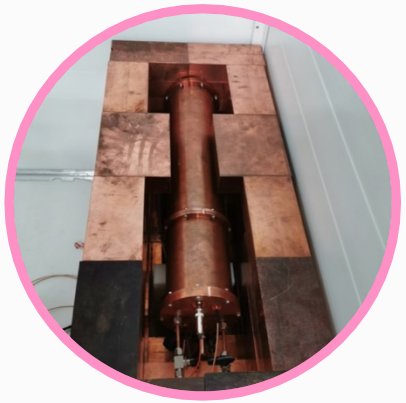
Spain @ LSC

112 kg

<1 keV_{ee}

since 2017
7 y of data

DATA TAKING



SABRE

Italy @ LNGS
Australia @ Stallwell

30-50 kg

PoP 2021

in construction/
commissioning

IN MAKING

NaI EXPERIMENTS à la DAMA

* not complete list

DM-Ice

South Pole
2200 m.w.e of ice

17 kg

4 keV_{ee}

3.5 y of data

COSINE-100

Korea @Y2L

106 kg

1 keV_{ee}

6.0 y of data

ANAIS-112

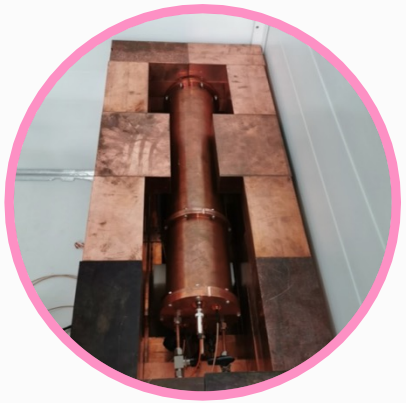
Spain @ LSC

112 kg

<1 keV_{ee}

since 2017
7 y of data

DATA TAKING



SABRE

Italy @ LNGS
Australia @ Stallwell

30-50 kg

PoP 2021

in construction/
commissioning

→ see talk by Owen Stanley in this session

IN MAKING

NaI EXPERIMENTS à la DAMA

* not complete list

DM-Ice

South Pole
2200 m.w.e of ice

17 kg

4 keV_{ee}

3.5 y of data

COSINE-100

Korea @Y2L

106 kg

1 keV_{ee}

6.0 y of data

ANAIS-112

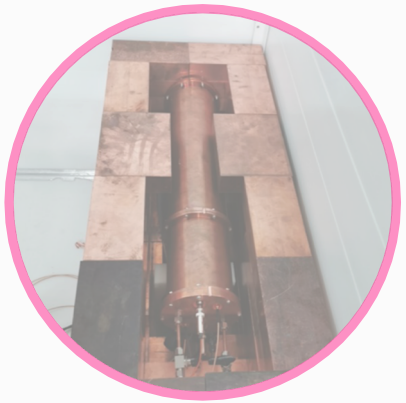
Spain @ LSC

112 kg

<1 keV_{ee}

since 2017
7 y of data

DATA TAKING



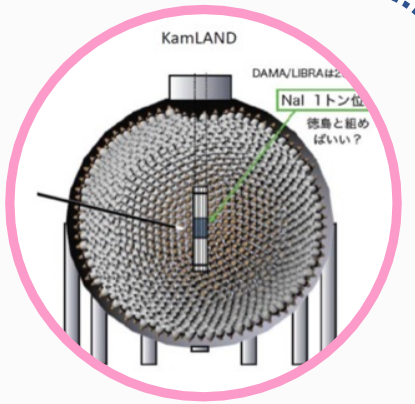
SABRE

Italy @ LNGS
Australia @ Stallwell

30-50 kg

PoP 2021

in construction/
commissioning



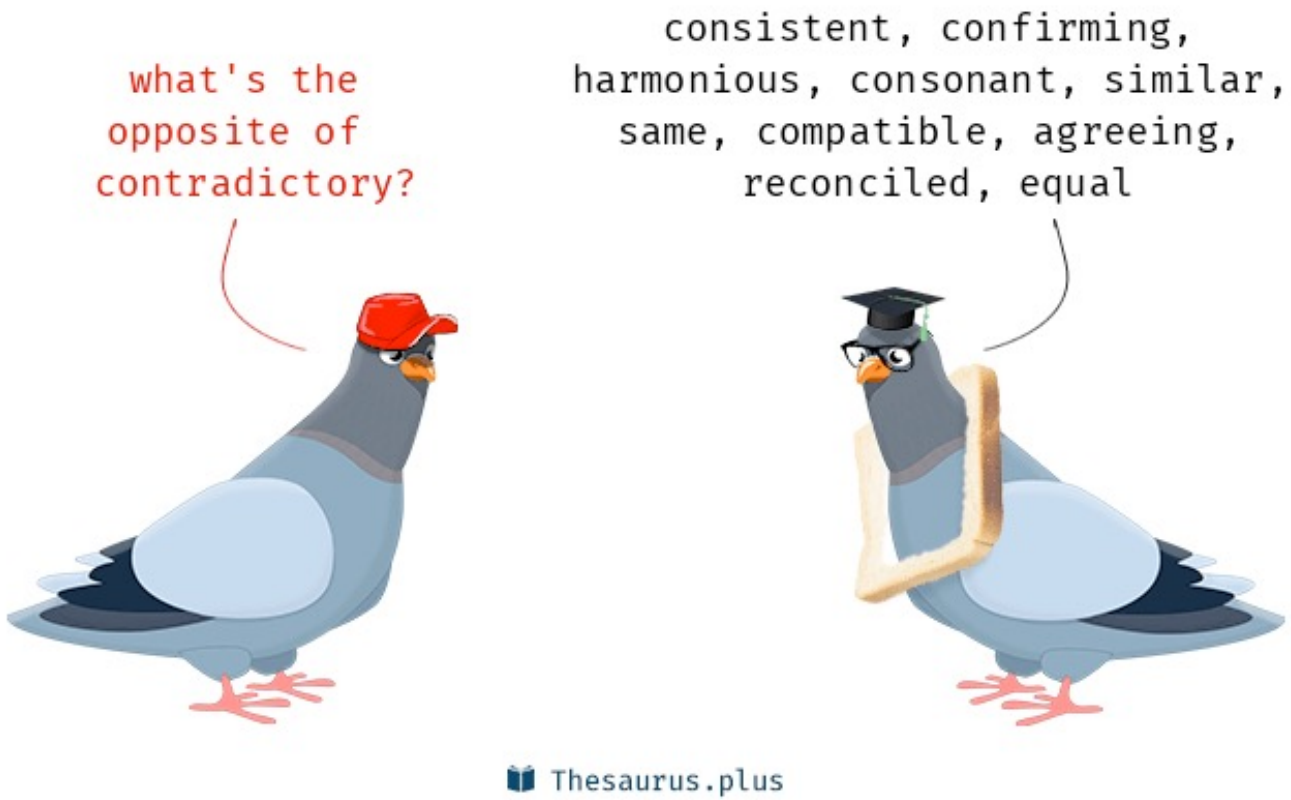
PicoLON

Japan @ Kamland

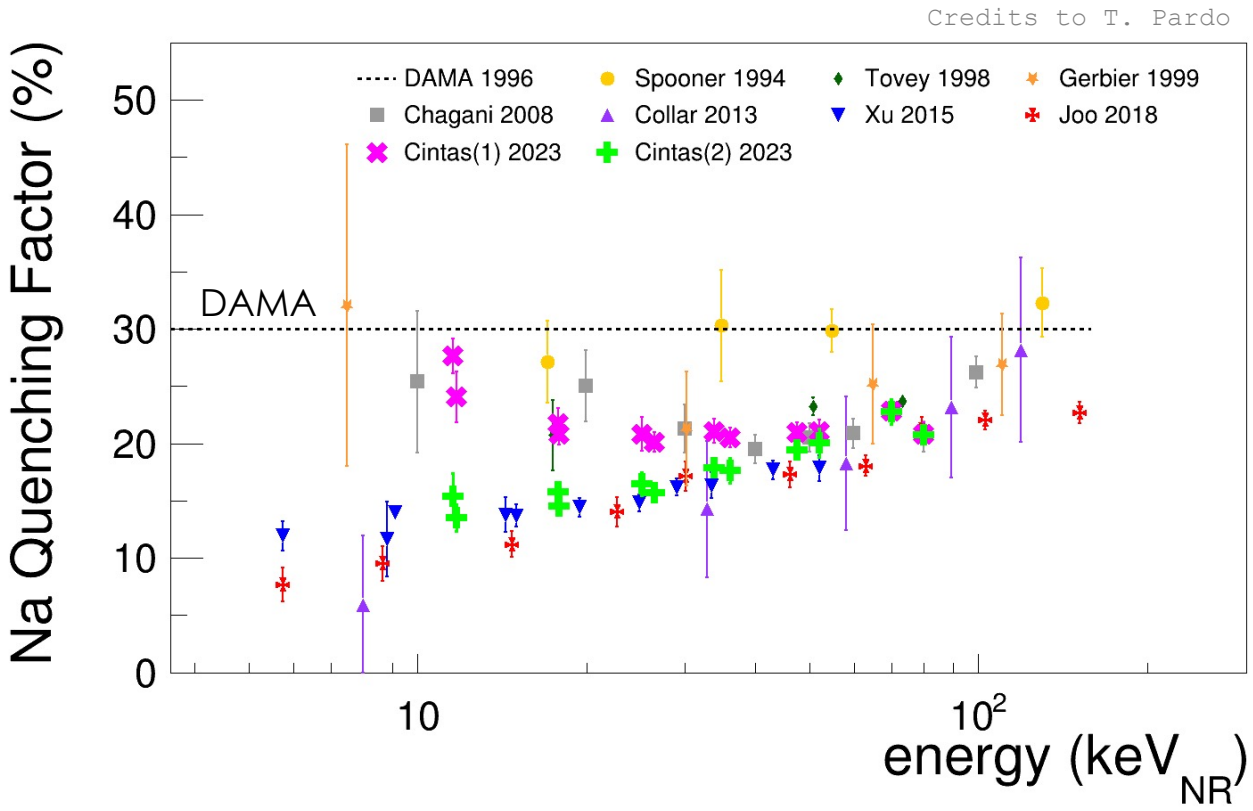
staged approach
54→250→1000 kg

planning phase

IN MAKING


what's the opposite of contradictory?
consistent, confirming, harmonious, consonant, similar, same, compatible, agreeing, reconciled, equal
Thesaurus.plus

CHALLENGE 1: QUENCHING FACTOR



- large number of QF measurements for NaI
- not consistent picture

→ systematics in experimental procedure ?

→ are QFs an inherent property ?
(TI dependence, defects, ...)

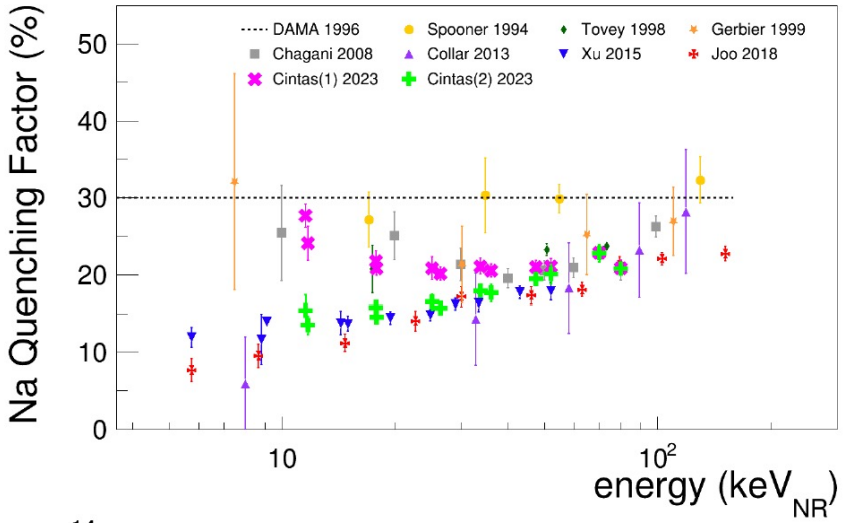
quenching factors are uncertain:

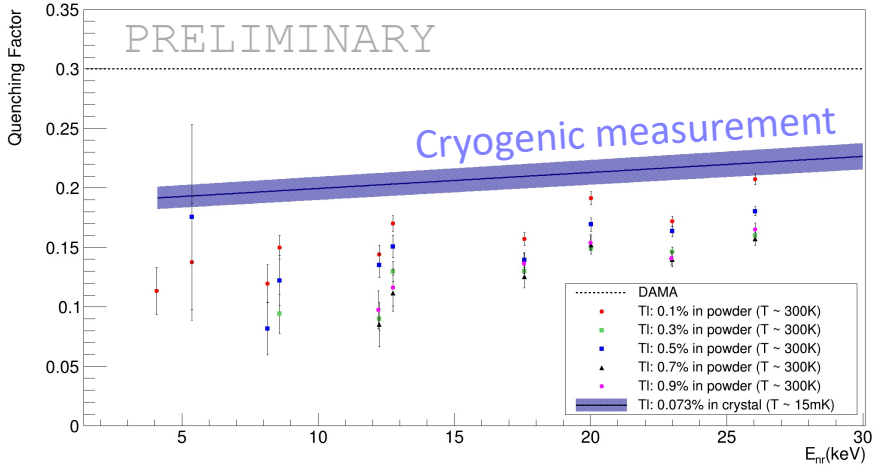
→ uncertainty on the nuclear recoil energy scale

→ comparison of results not solid

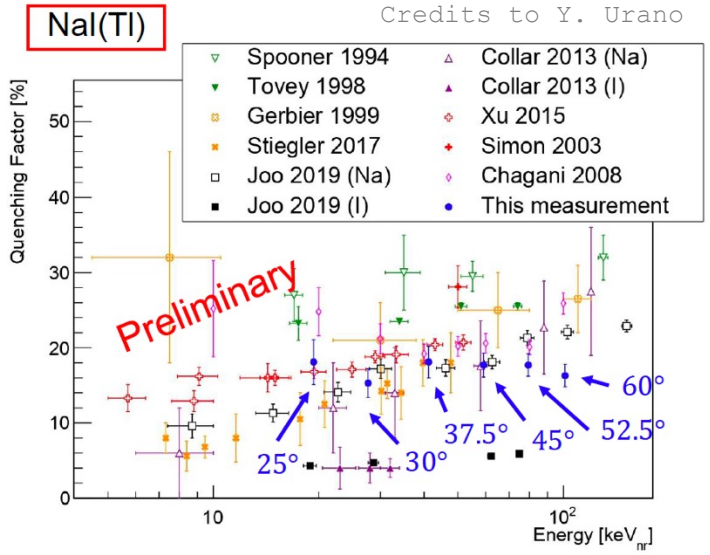
WORKING ON THE QUENCHING FACTOR(S)…

Credits to T. Pardo





Credits to Y. Urano



ANAIS-112
→ studies of QFs @ TUNL
→ systematics in different energy calibrations

+ neutron calibrations using a ^{252}Cf source in the ANAIS setup at LSC

COSINUS
→ study of Tl-dopant level on QF @ TUNL facility
→ first data point at 4 keV$_{NR}$

+ in-situ QF measurement at mK temperatures of a NaI(Tl) crystal

PicoLON
→ first QF studies done @IAE facility, Japan

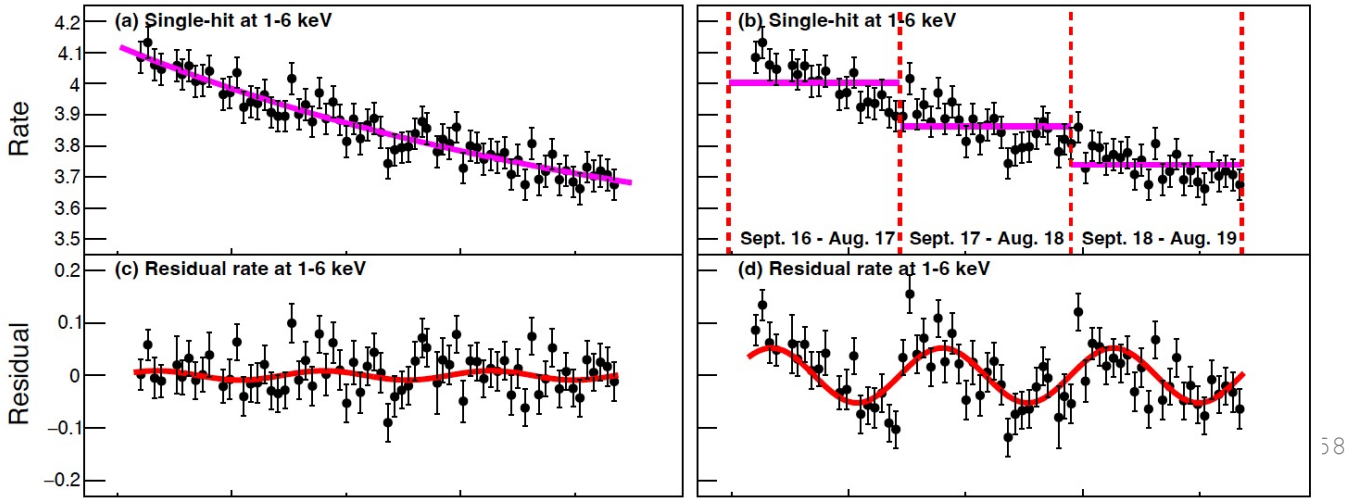
… → progress

CHALLENGE 2 - ANALYSIS TECHNIQUES

Rate in detector is: $R(t) = R_0(t) + A\cos\left(\frac{2\pi}{T}t - \varphi\right)$ → DAMA-strategy: subtract average / dataset

COSINE-100 case study: *Sci. Rep. 13 (2023) 4676*

exponential subtracted | yearly-averaged subtracted



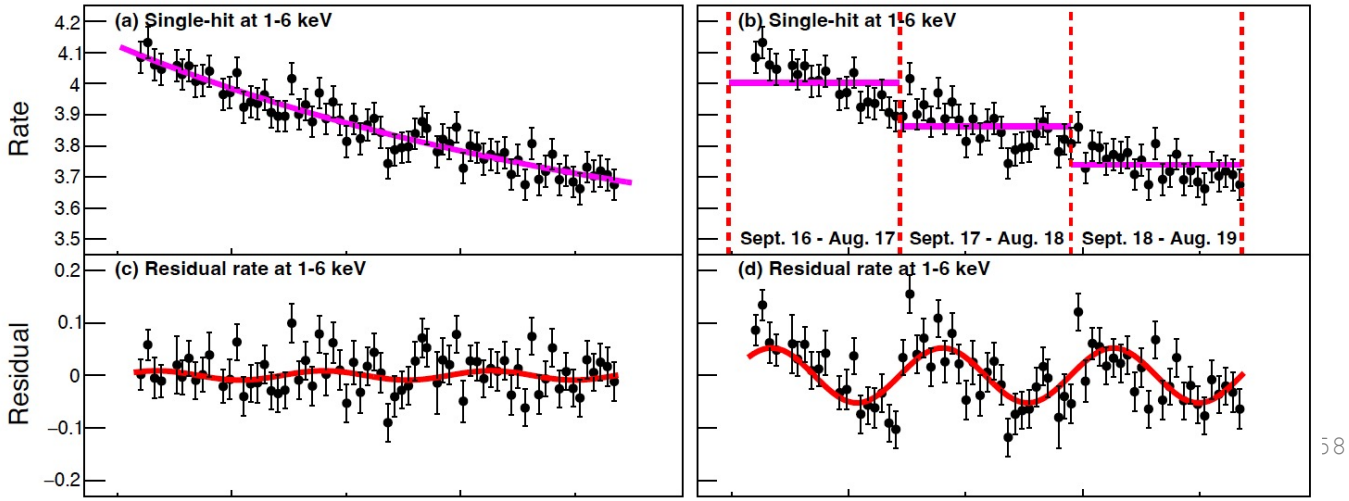
→ **high modulation amplitude (4 x DAMA) at 7σ C.L.**

CHALLENGE 2 - ANALYSIS TECHNIQUES

Rate in detector is: $R(t) = R_0(t) + A\cos\left(\frac{2\pi}{T}t - \varphi\right)$ → DAMA-strategy: subtract average / dataset

COSINE-100 case study: *Sci. Rep. 13 (2023) 4676*

exponential subtracted | yearly-averaged subtracted



→ **high modulation amplitude (4 x DAMA) at 7σ C.L.**

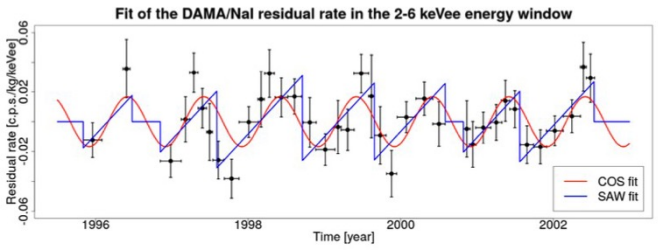
BUT

1) DAMA claims constant bckg. (but does not show rate vs. time)

2) wrong by 1pi (= sign)

3) comparison to the correct model (sawtooth-like)

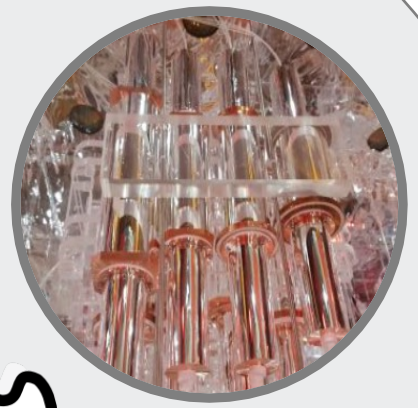
JCAP 04 (2020) 037



DAMA/LIBRA

ANAIS-112

COSINE-100

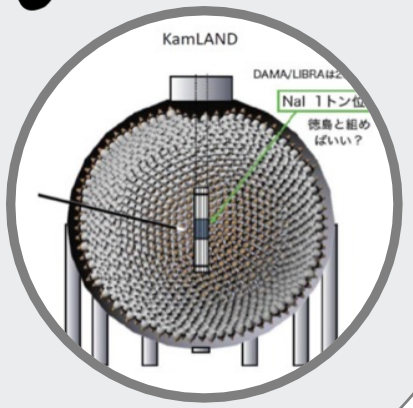


signal background

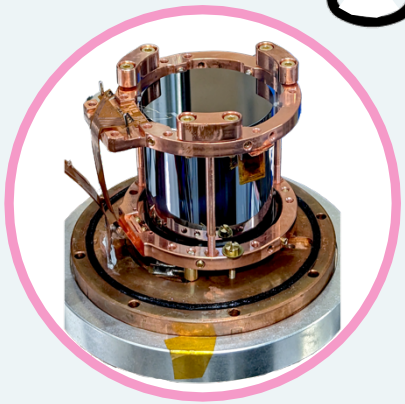
SABRE

DM-Ice

PicoLON



background signal



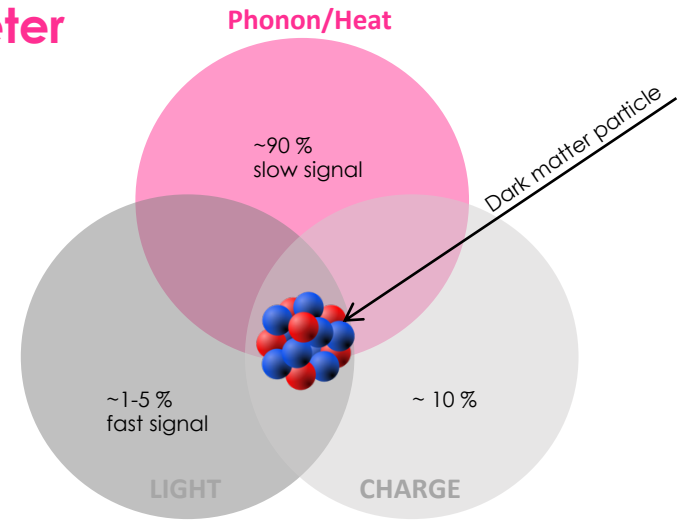
COSINUS

COSINUS SEARCH **STRATEGY**

model- and target independent test of DAMA

→ *novel* and *unique*: **sodium iodide target as low-temperature calorimeter**

- HEAT CHANNEL: precise energy information
  + low threshold for nuclear recoils

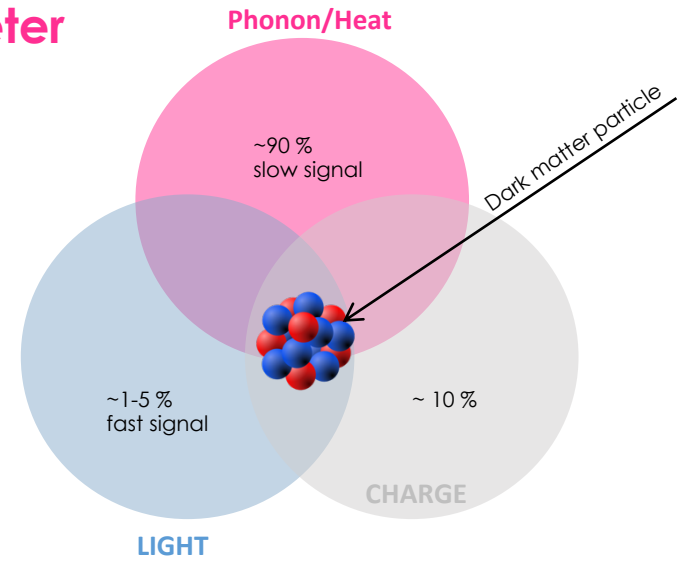


COSINUS SEARCH **STRATEGY**

model- and target independent test of DAMA

→ *novel* and *unique*: **sodium iodide target as low-temperature calorimeter**

- HEAT CHANNEL: precise energy information
  + low threshold for nuclear recoils
- LIGHT CHANNEL: particle identification on event-by-event basis



COSINUS SEARCH **STRATEGY**

model- and target independent test of DAMA

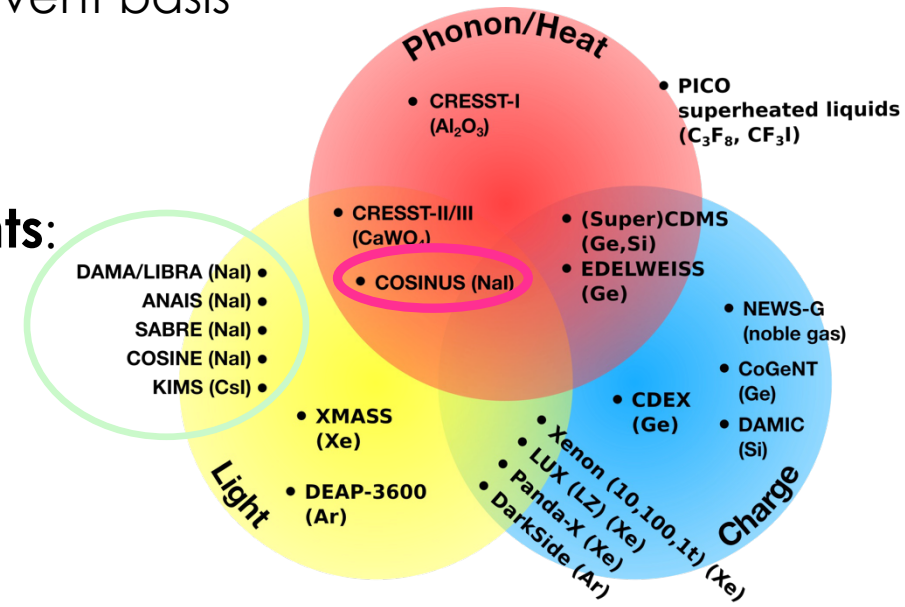
→ *novel* and *unique*: **sodium iodide target as low-temperature calorimeter**

- HEAT CHANNEL: precise energy information
  + low threshold for nuclear recoils
- LIGHT CHANNEL: particle identification on event-by-event basis

IMMUNE to challenges of the DAMA-like experiments:

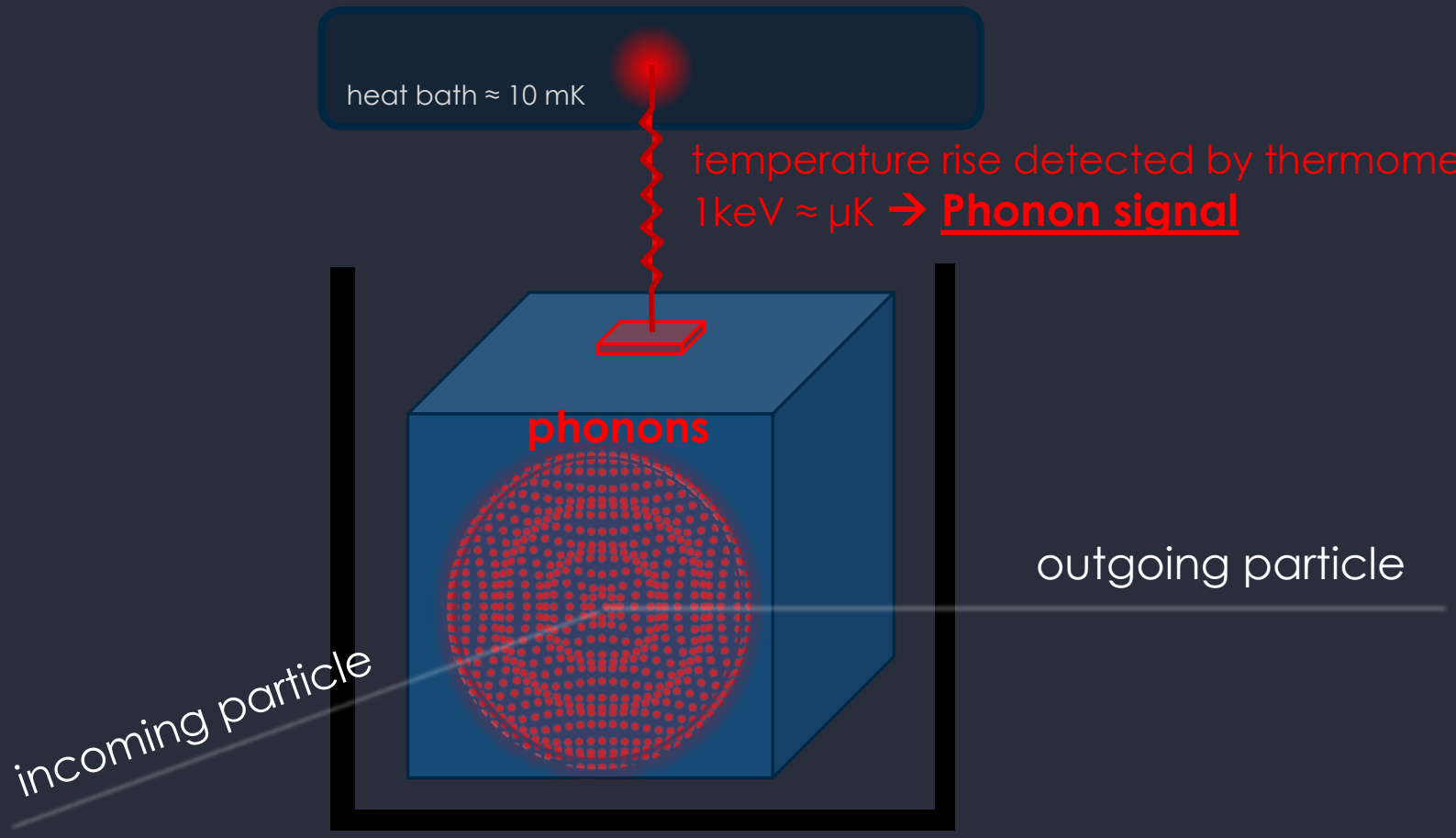
→ signal-only measurement of potential DM signal

→ in-situ measurement of the quenching factor

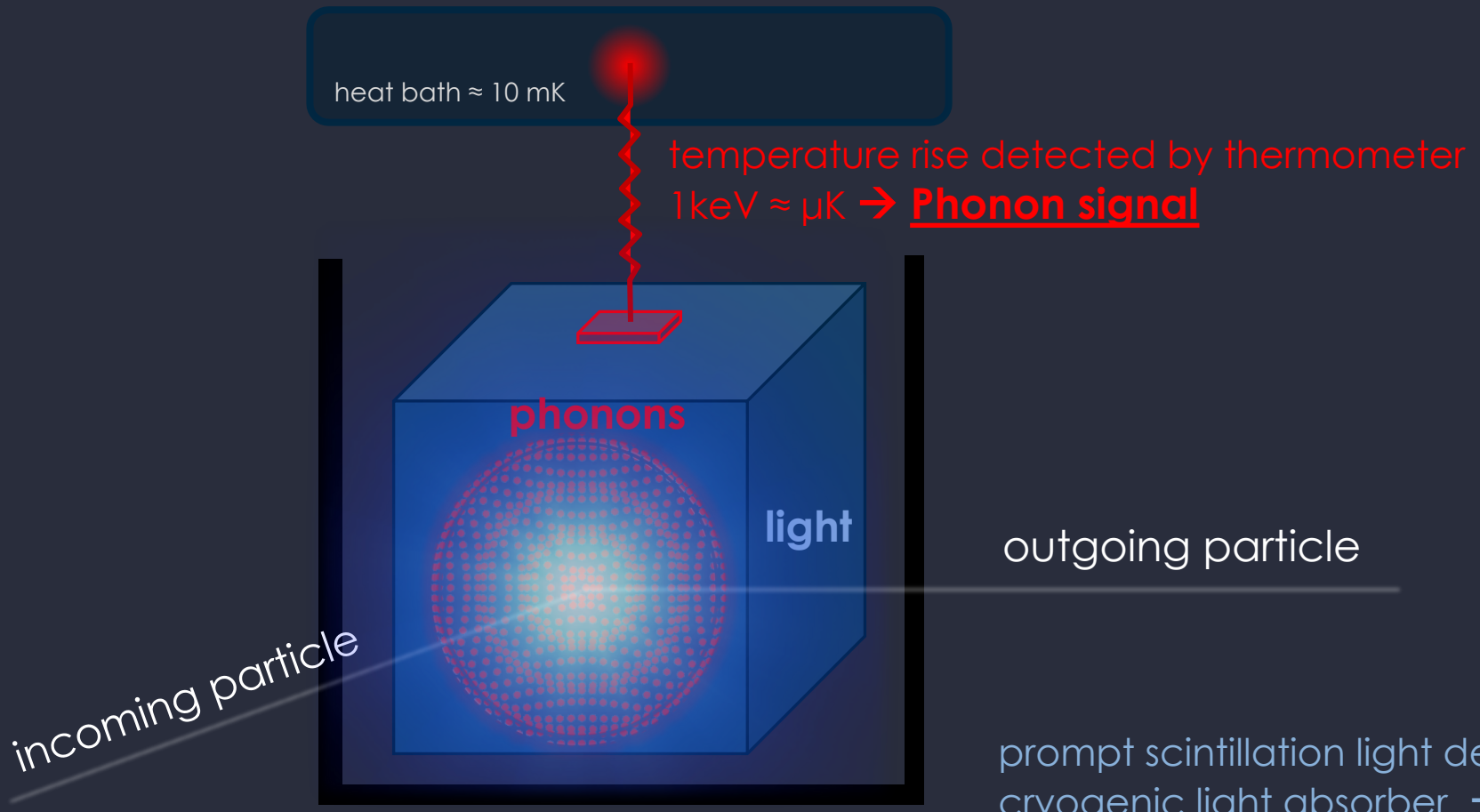


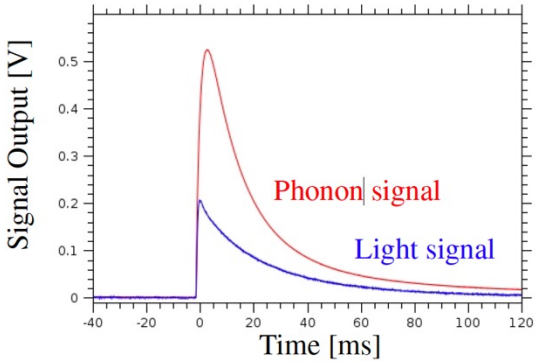
Credits to: F. Reindl

LOW-TEMPERATURE CALORIMETER



LOW-TEMPERATURE CALORIMETER

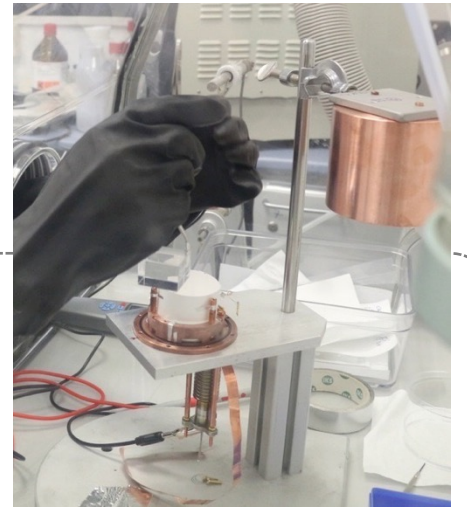




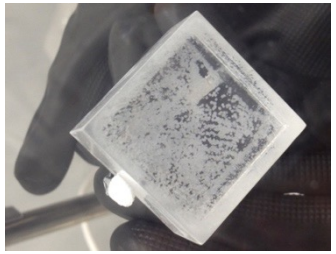
particle discrimination via the **ratio of light to phonon signal**

prompt scintillation light detected by separate, cryogenic light absorber → **Light signal**

… NaI is not that NaIce !



hygroscopic nature



handle only in controlled atmosphere

^{40}K in the NaI crystal

NaI grown in collaboration with SICCAS Since 1928

5-9 ppb of K at crystals' nose and 22-35 ppb at crystals' tail

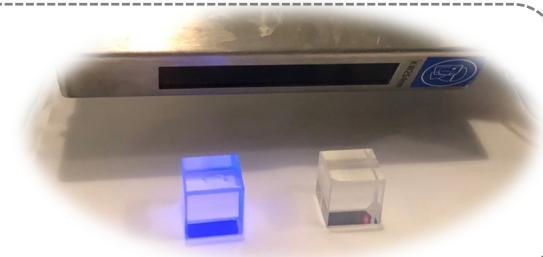
(3-inch crystal, Astrograde powder from Merck) Zhu, Y. et al, IEEE, 2018

low Debye temperature

NIM A 1045, 167532

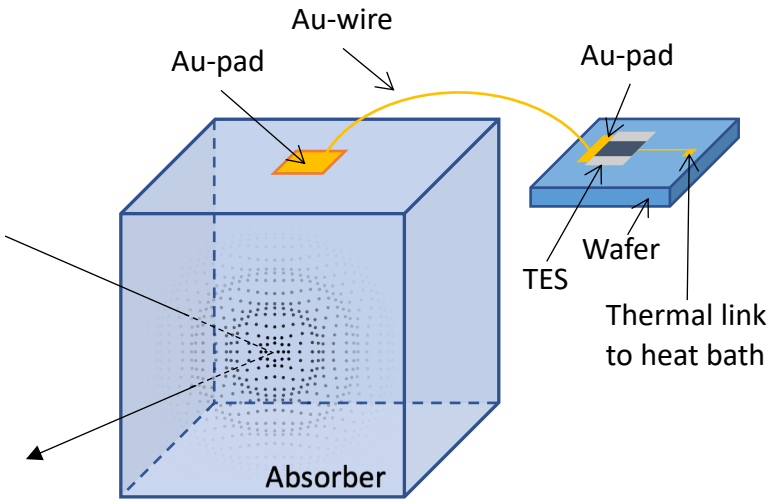
adapted thermometer → remoTES

+ avoid other phonon-loss channels



remoTES design

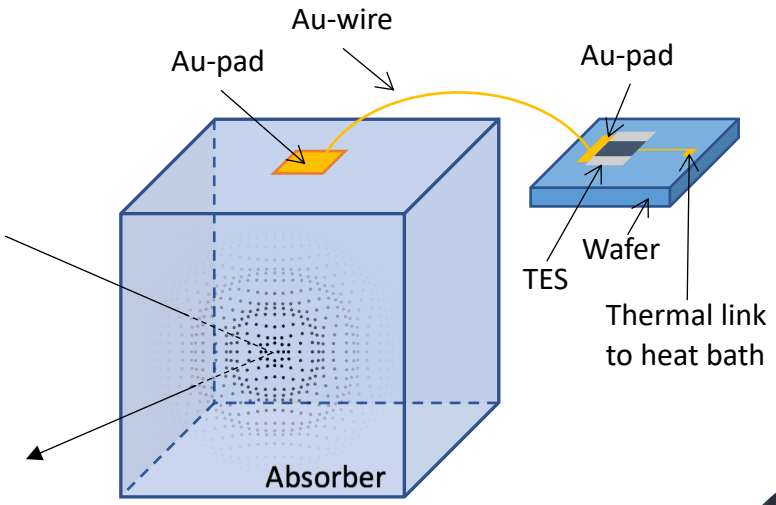
NIM A 1045, 167532

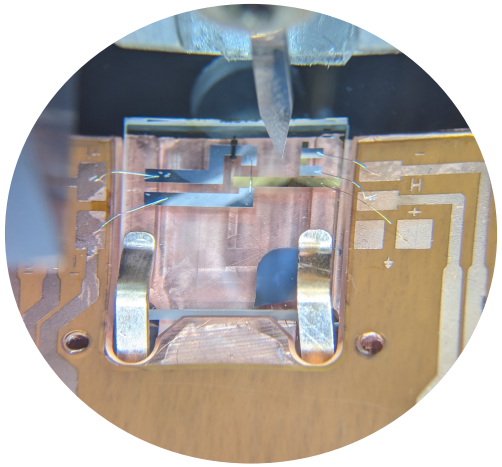


- separate wafer
  hosts the thermometer
  → **TES = transition edge sensor**

remoTES design

NIM A 1045, 167532



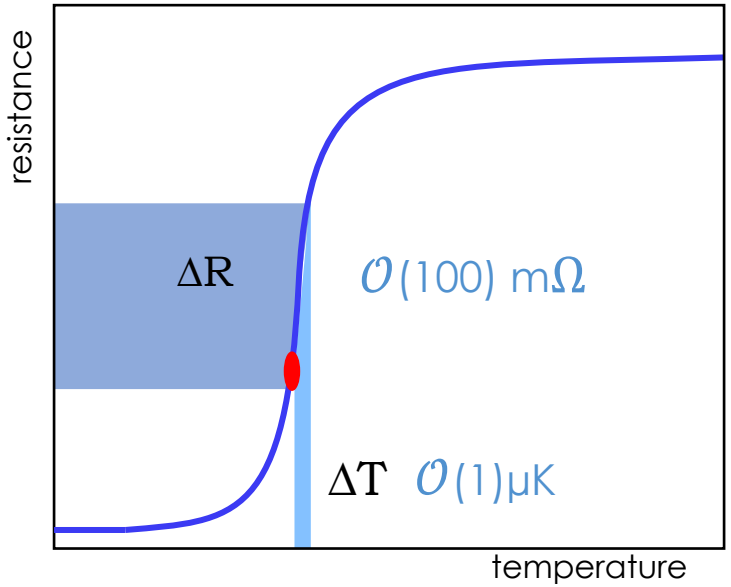


→ **TES = transition edge sensor**

tungsten superconducting thin films
→ technology developed by

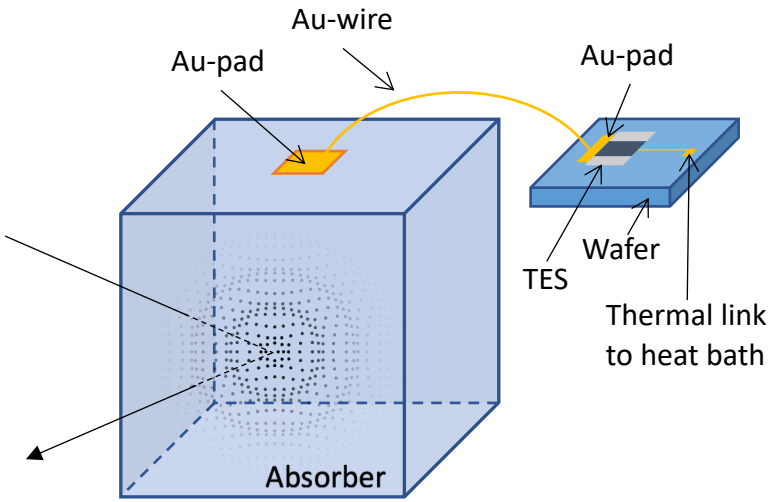
CRESST

Transition temperature: $T_c \approx 15$ mK



remoTES design

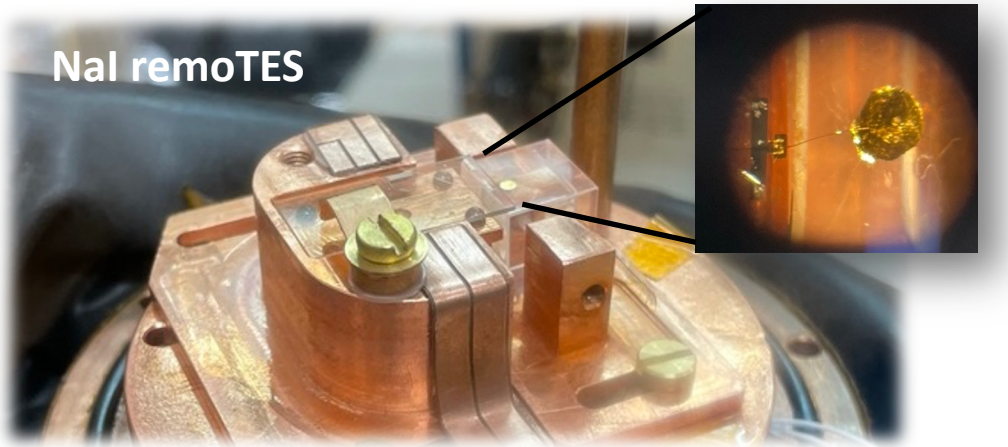
NIM A 1045, 167532



- separate wafer
  hosts the thermometer
  (TES = transition edge sensor)
- gold pad glued onto NaI crystal
  phonons propagate in NaI and couple to the electron system of the Au pad
- gold bond wire
  connection to the temperature sensor

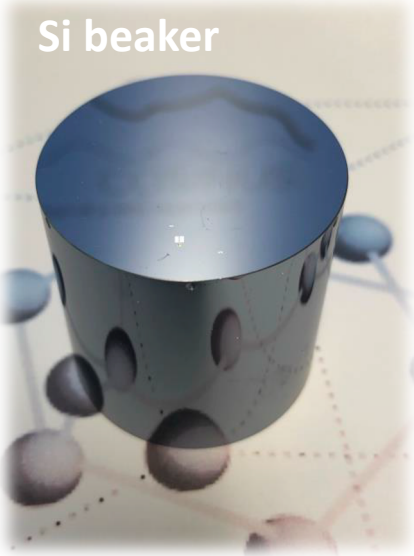
→ → absorber excluded from fabrication process

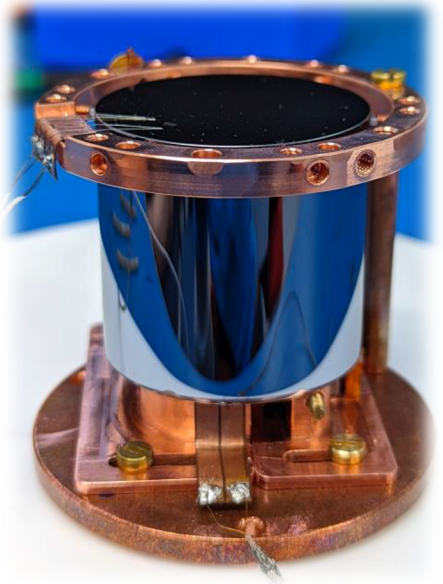
NaI-remoTES – measurement in June 2022



- NaI (undoped) grown by SICCAS
- ~ 4 g
- wafer with W-TES

- silicon light absorber of beaker-shape
- mass: 15.1 g
- W-TES directly on the Si beaker

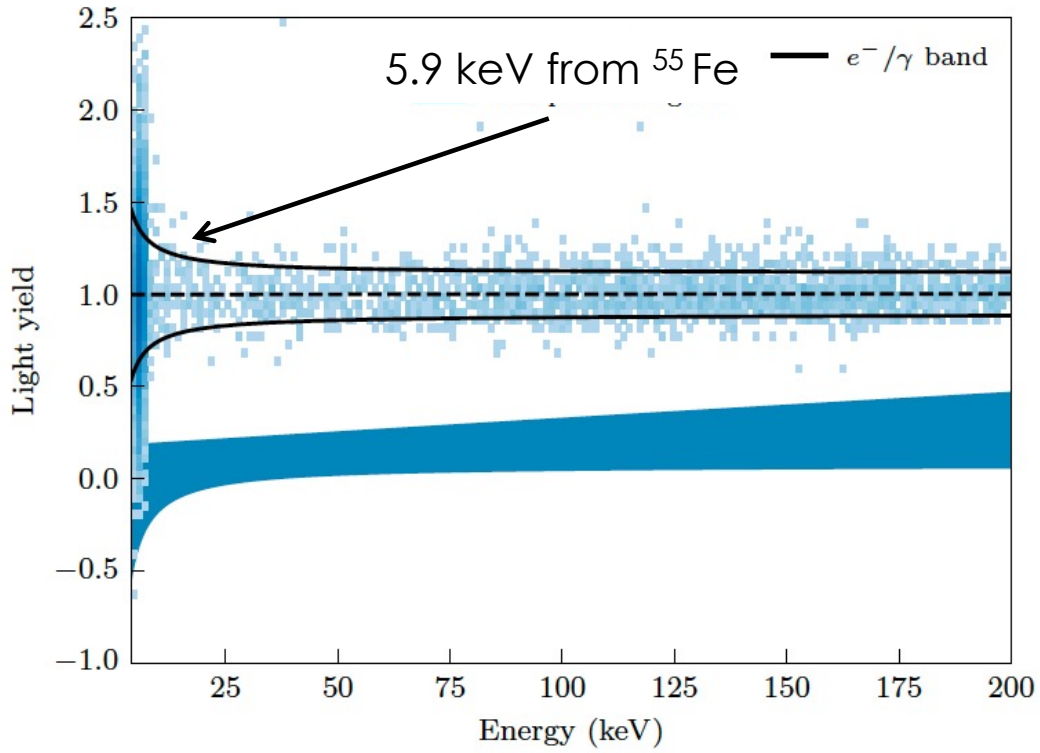


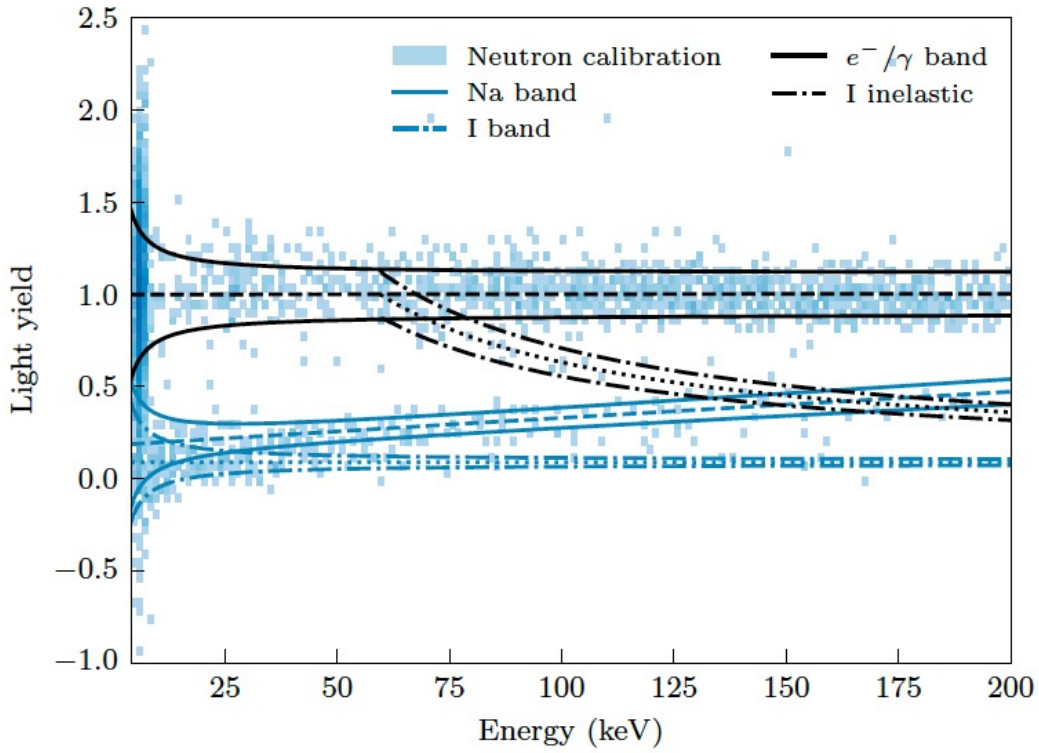


RESULTS

Measurement carried out at the test facility of CRESST @ LNGS

arXiv 2307.11139 - accepted in PRD





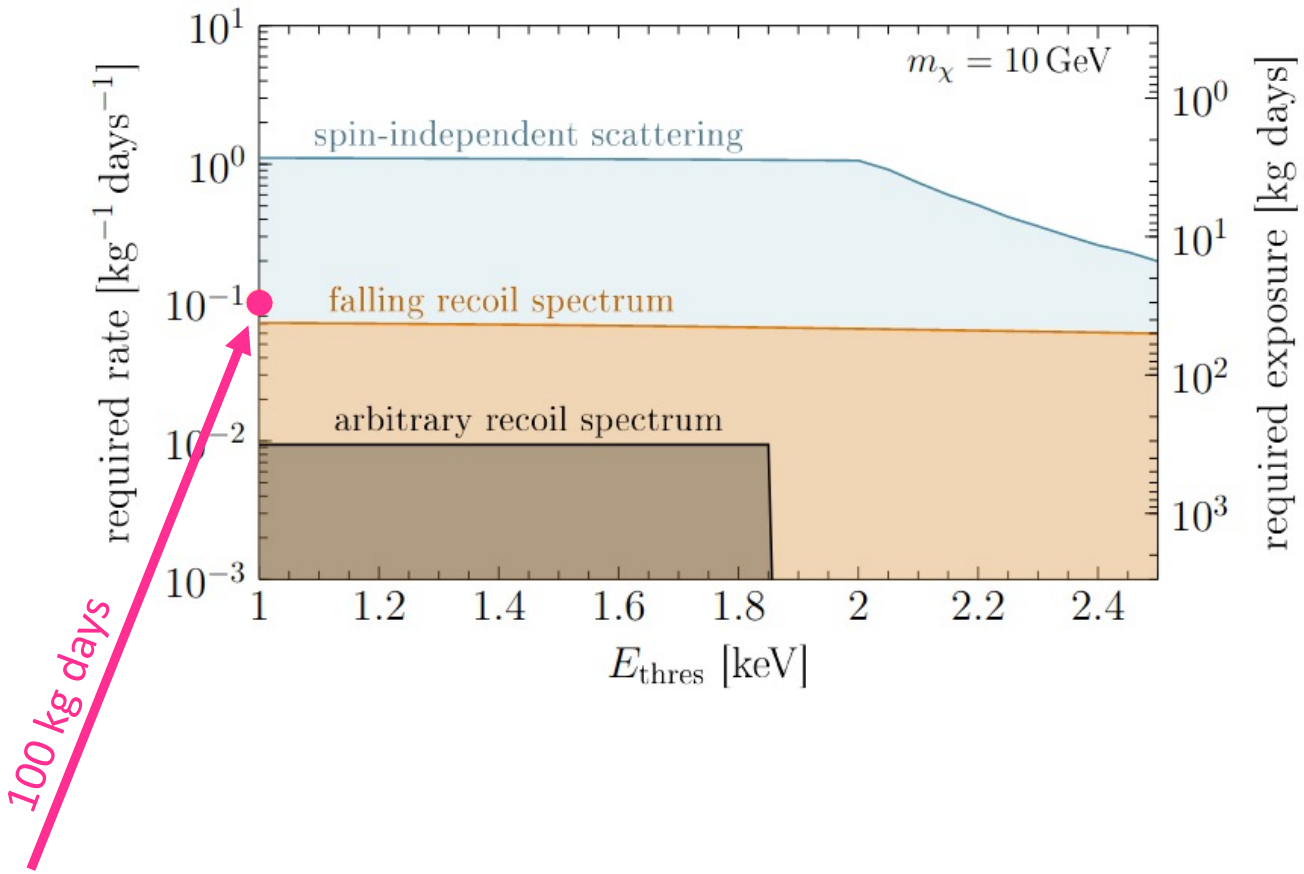
σ_{NaI} = (0.441 ± 0.011) keV **E_{thr} < 2 keV$_{NR}$**

QF_{Na}(10 keV): 0.2002 ± 0.0093 QF_{I}(10 keV): 0.0825 ± 0.0034

proof of particle identification in a NaI-based detector

COSINUS PHYSICS REACH

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



COSINUS – 1π (2025-2027)

exclude or confirm **nuclear recoil origin** of DAMA:

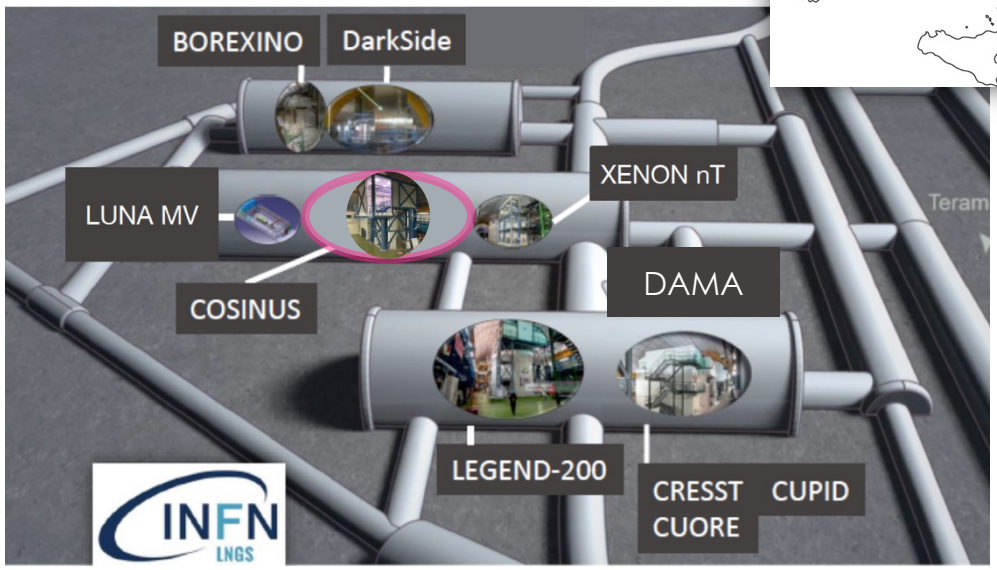
- independent of DM halo
- for any interaction of DM with nuclei

COSINUS – 2π (≥ 2027)

Investigate annual modulation signature with COSINUS

Warning:
not updated for DAMA result with 1keVee !!

COSINUS experimental site



- COSINUS is located in hall B
- full approval end of 2020

COSINUS experimental facility

view from COSINUS to XENONnT 2023

COSINUS facility completed in Aug, 2023

WATER CHERENKOV VETO

EPJ C 82, 2022
EPJ C 84, 2024

- good moderator for neutrons
- veto of (cosmogenic) muons via Cherenkov light emitted in water

→ instrumentation of water tank with 30 PMTs

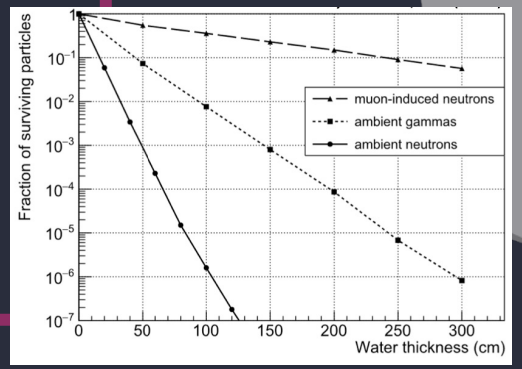
Rate of cosmogenic neutrons:

no veto:

(3.5 ± 0.7) counts kg^{-1} yr^{-1}

with veto:

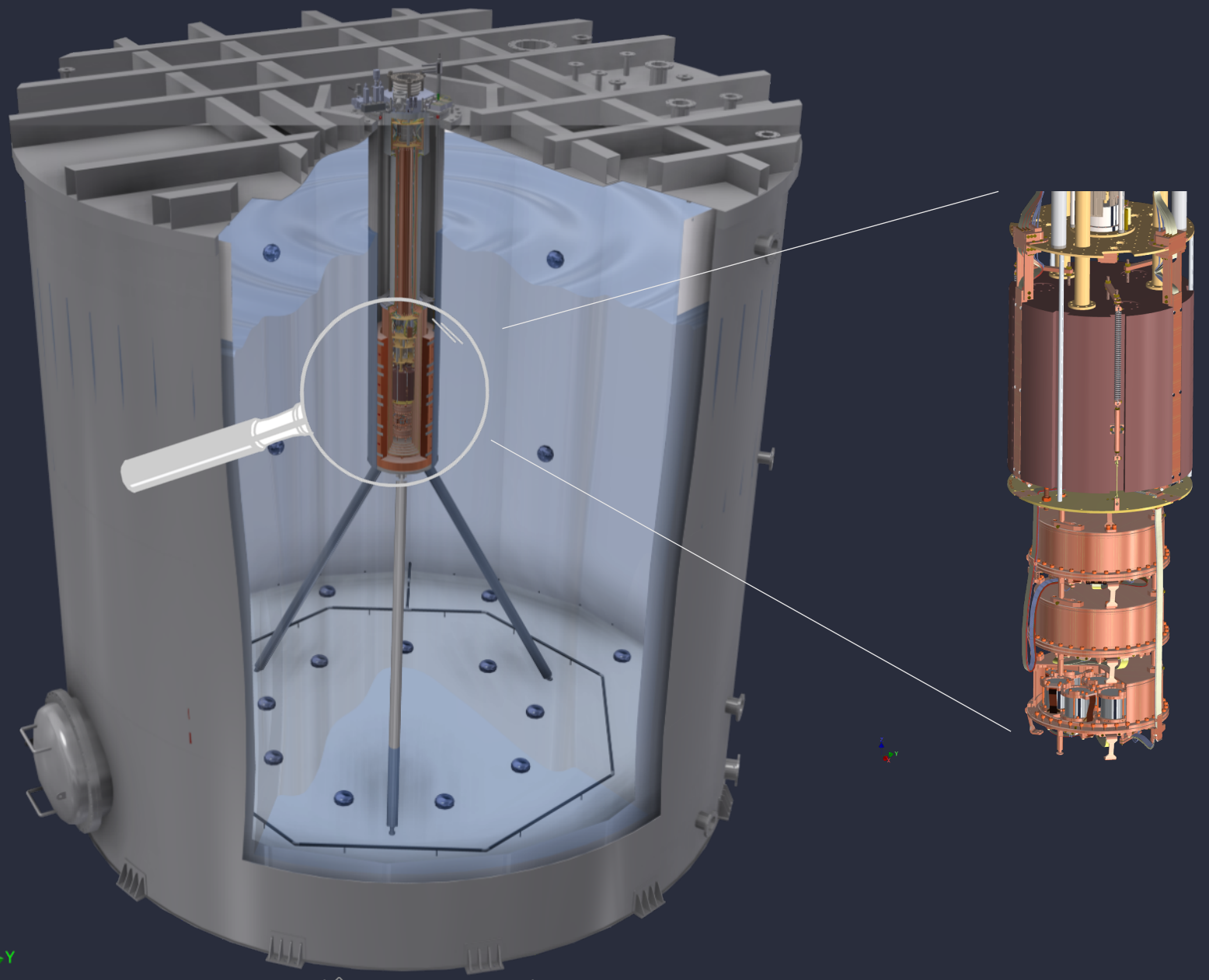
< 0.05 counts kg^{-1} yr^{-1}



CRYOSTAT

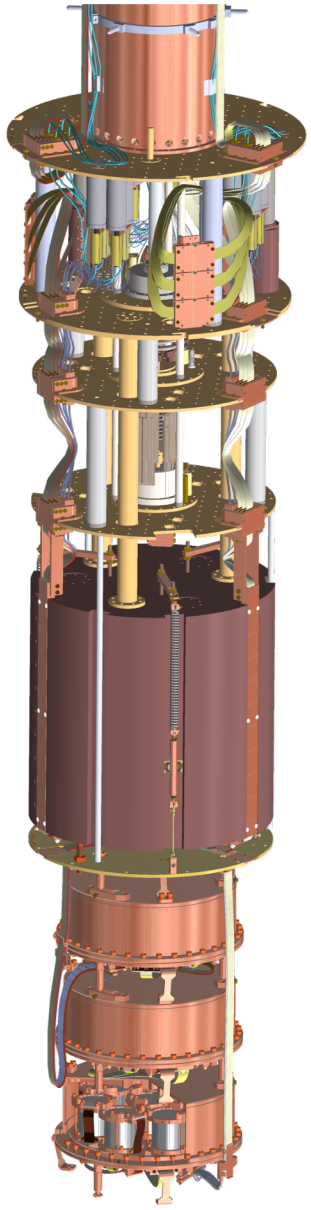
Dry dilution refrigerator to reach 10 mK:

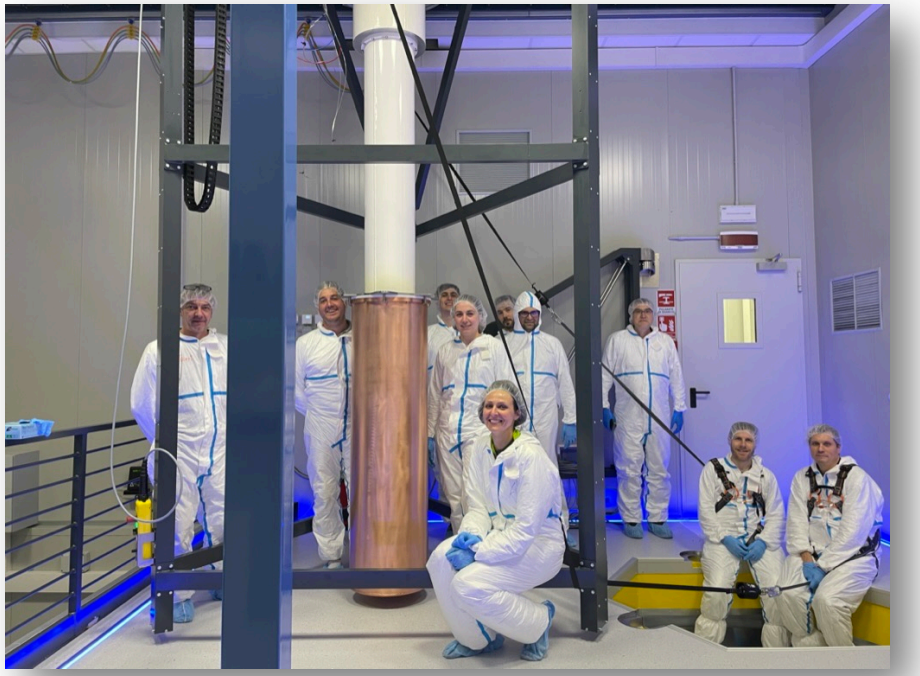
- 3500 mm total lengths
- custom-made design
- UltraQuiet Technology (UQT)
- internal copper shield (190 kg)



What's next?

1. Commissioning of the cryostat → ongoing



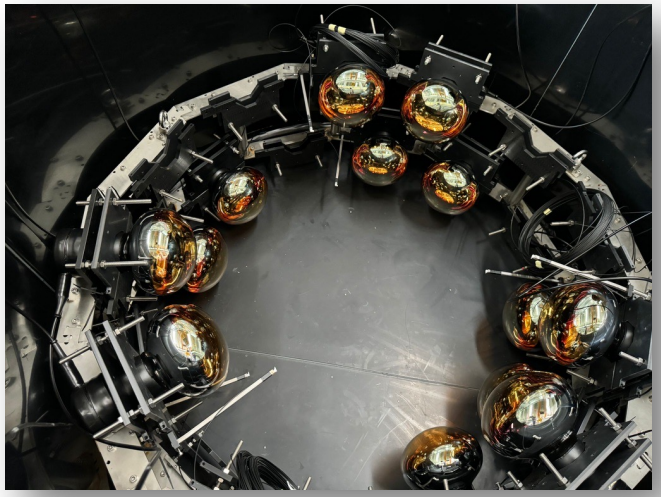


Cryostat installed
and reached <10 mK in April, 2024

What's next?

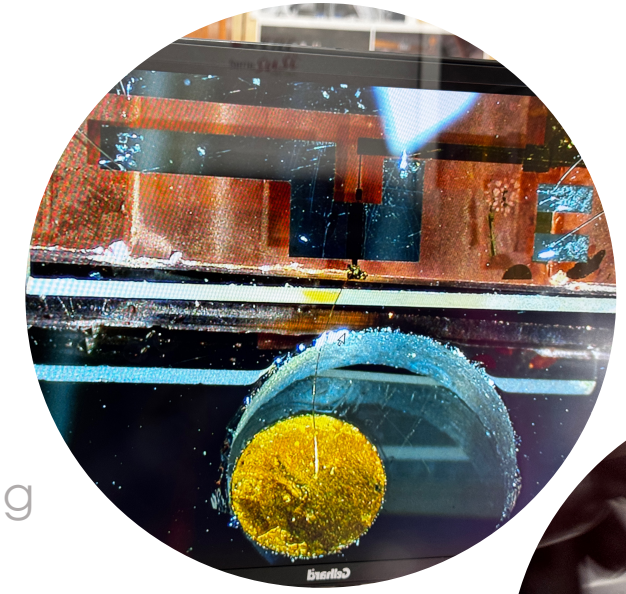
1. Commissioning of the cryostat → ongoing

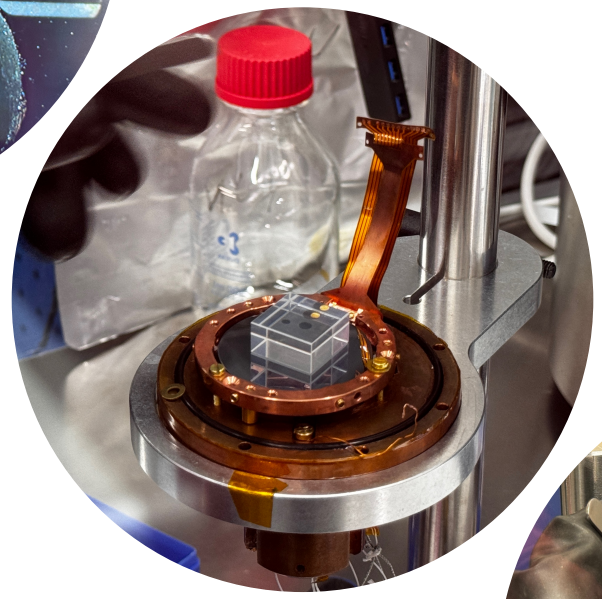
2. Commissioning of the muon veto – ongoing
   → PMTs tested
   → Drywell equipped with reflective layer
   → TYVEK reflector curtain prototyping ongoing

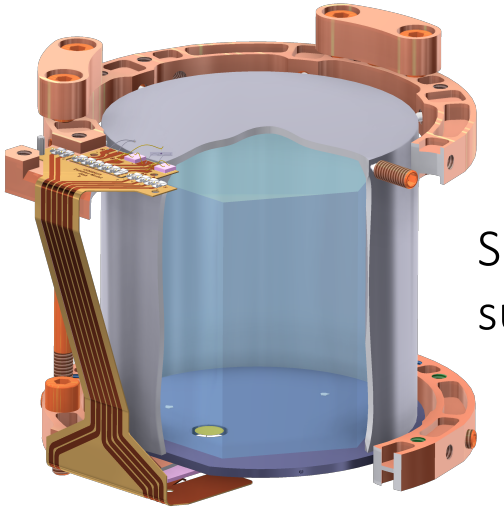


What's next?

1. Commissioning of the cryostat → ongoing
2. Commissioning of the muon veto → ongoing
3. Test of final prototype detector → ongoing







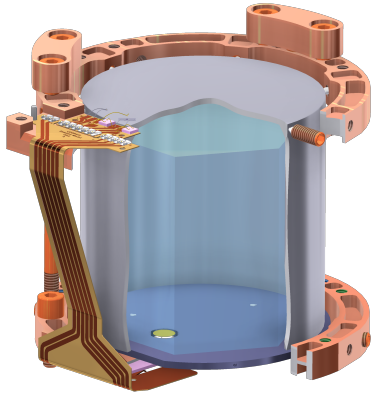
Si-beaker for 4π active surrounding of the crystal

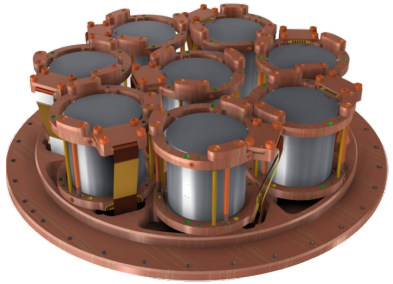
FIRST DATA TAKING – RUN 1 early 2025

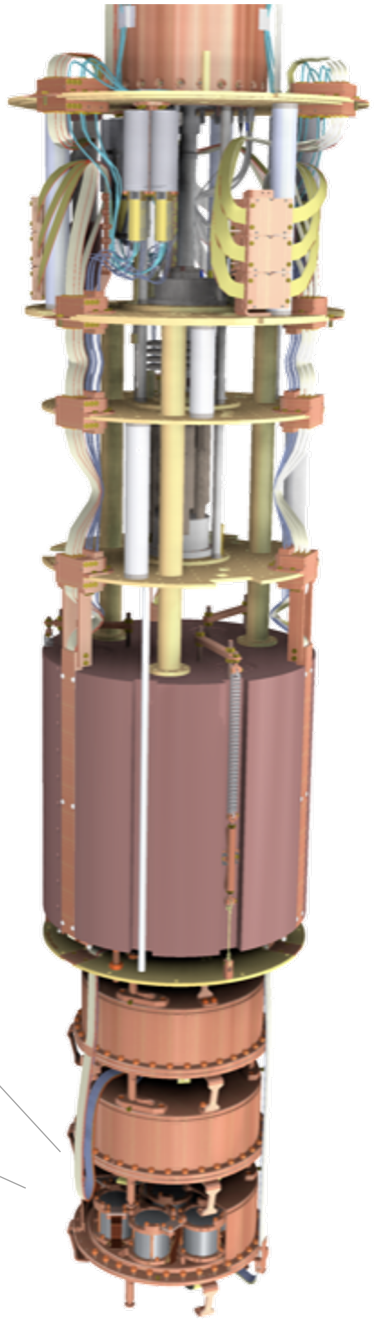
Production and assembly of
8 detector modules for Run 1

Start data taking
@LNGS beginning 2025

→ collect **100 kg days**

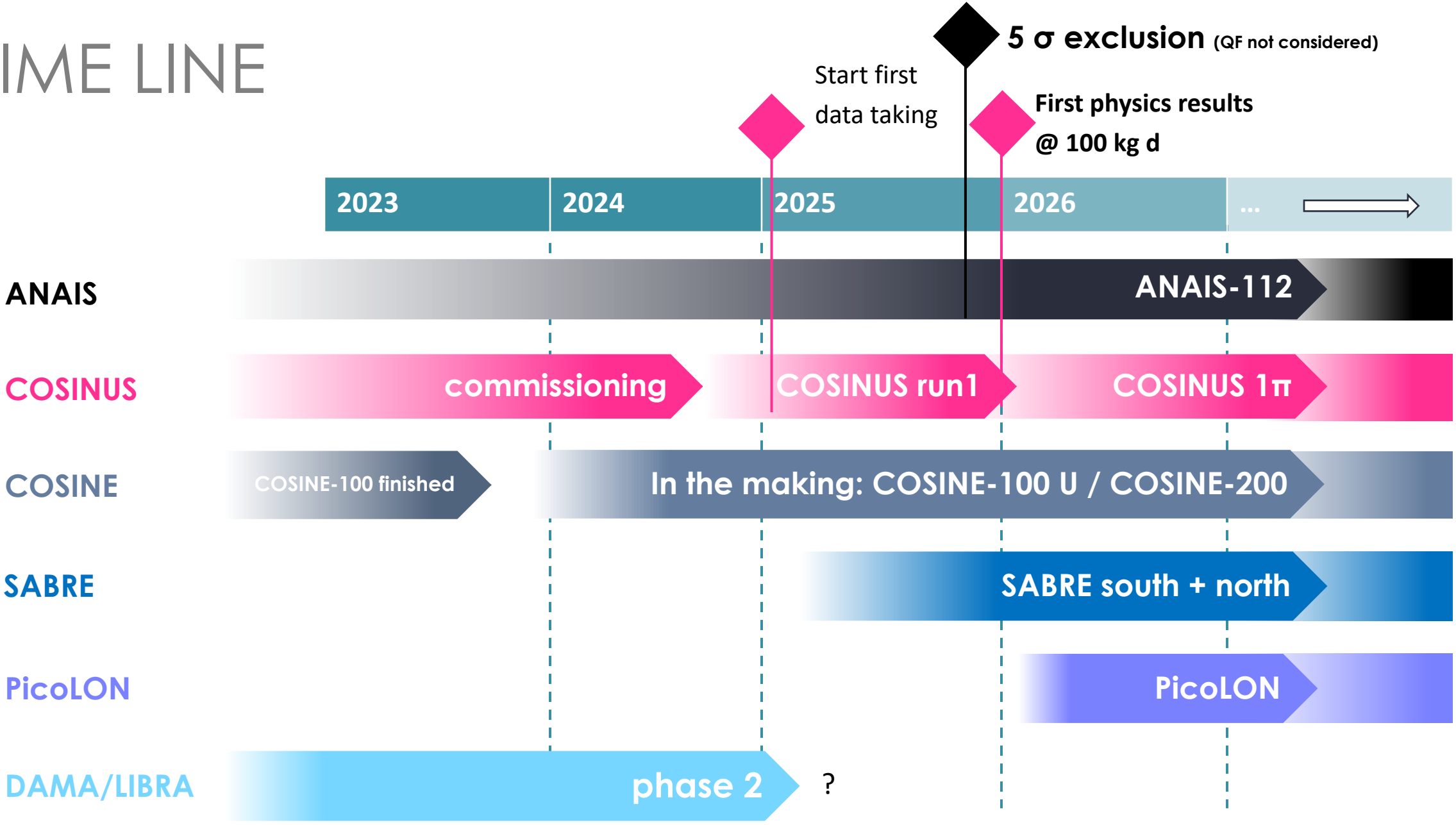






- 8 detector modules per level
- 3 levels in final stage

TIME LINE


5 σ exclusion (QF not considered)
Start first data taking
First physics results @ 100 kg d
2023
2024
2025
2026
...
ANAIS
ANAIS-112
COSINUS
commissioning
COSINUS run1
COSINUS 1π
COSINE
COSINE-100 finished
In the making: COSINE-100 U / COSINE-200
SABRE
SABRE south + north
PicoLON
PicoLON
DAMA/LIBRA
phase 2
?

2023 at TAUP

N. Smith (director at TRIUMF)

I remember being in the auditorium when it was first announced!

V. Zema (Postdoc at MPP on COSINUS) @ TAUP2023

It’s been an outstanding question for 26 years now.
I think there are people in the room this age.
So, we need to figure it out.

Professor PostDocs Grad students

In the year ~2027

I did not expect it to take that long, but it's good that it's solved now.

It's been an outstanding question for 30 years and now, working hard, we finally have a conclusive picture!

Professor

PostDocs

Grad students

What is DAMA?

SUMMARY

Dark matter is a fundamental question of present-day physics and DAMA's signal after 26 years remains still an unsolved mystery

DAMA lowered energy threshold to 0.5 keV_{ee} ; standard scenario does not fit anymore

ANAIS does not see a modulation and starts to constrain DAMA at 3 σ – level

Systematic uncertainties of QF are investigated recently but yet still a conclusive picture is missing

COSINE-100U, SABRE north and south and PicoLON are in making

COSINUS developed the first NaI dark matter detector with **particle discrimination** and finished the construction of the experimental facility, data taking starts early 2025

THANK YOU FOR YOUR ATTENTION

EXTRA MATERIAL

DARK MATTER RATE

Total rate: $$R = \frac{M_{target}}{m_N} \cdot \frac{\rho_\chi}{m_\chi} \cdot v \cdot \sigma(v)$$

$$\frac{dR}{dE_r} = \frac{\rho_\chi}{m_N m_\chi} \cdot \int_{v_{min}}^{v_{esc}} d^3v \, f(\vec{v}) \, v \, \frac{d\sigma(\vec{v}, E_r)}{dE_r}$$

galactic escape velocity

velocity distribution

DM-nucleus cross-section

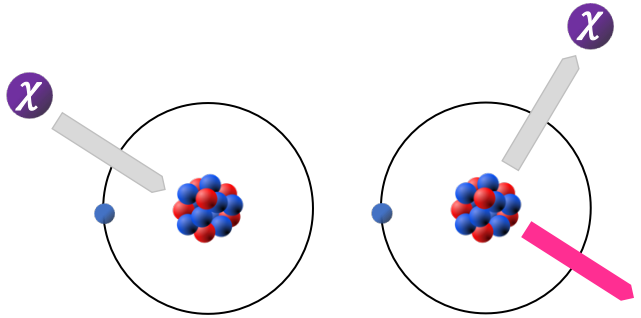
minimal velocity to produce a recoil of energy E_r

~ A^2

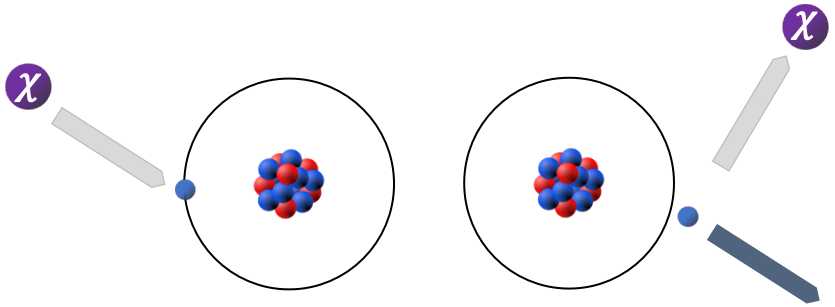
~ form factor

DARK MATTER INTERACTIONS AND SIGNALS

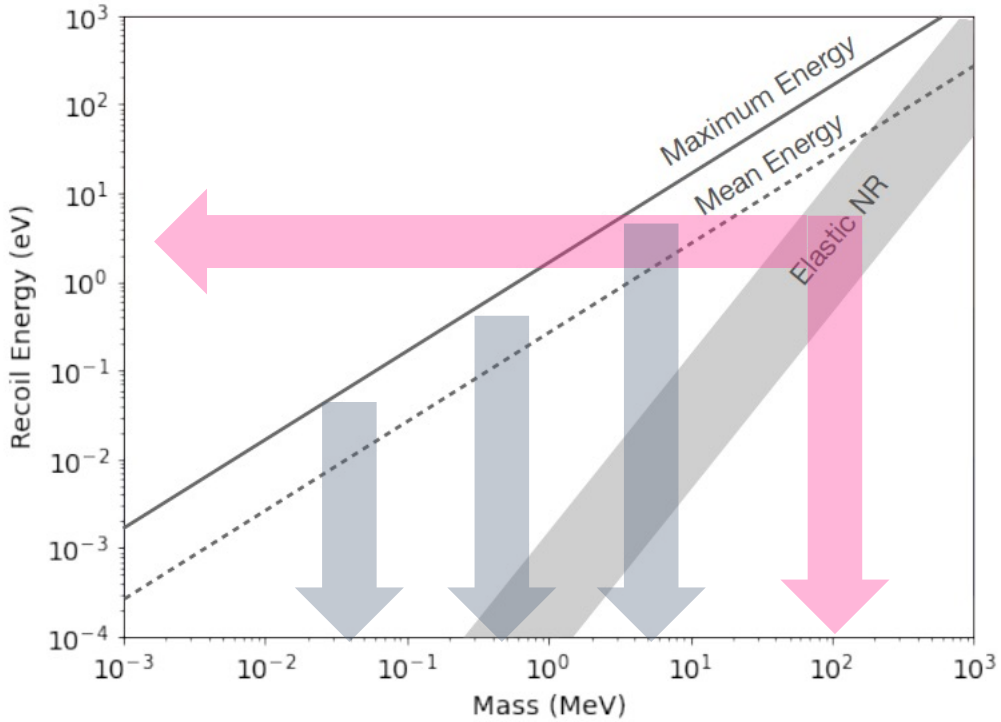
- elastic DM – nucleus scattering (NR)



- also:
  DM – electron – scattering (ER) (inelastic)



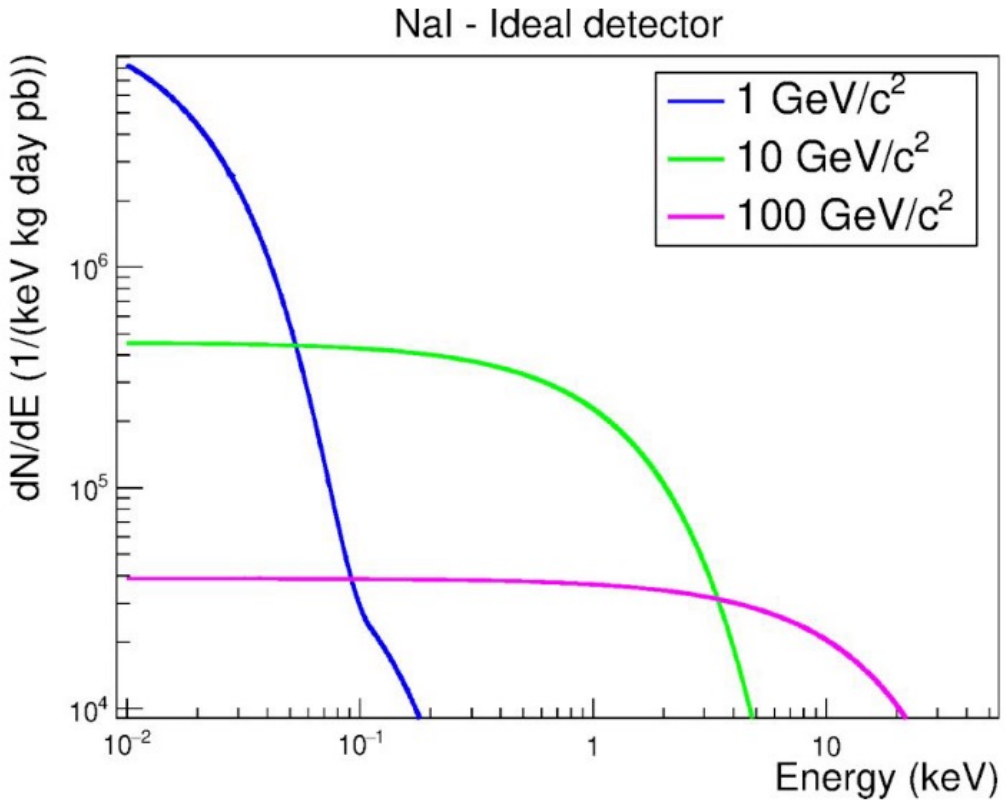
Elastic NR for H and Xe



Credit: R. Essig, modified arXiv: 2203.08297

EXPECTED NUCLEAR RECOIL SPECTRUM

rate and shape of recoil spectrum depend on target material



extremely rare interaction rate

current limit: ***0*** **(0.01) counts/(keV tonne year) ***

small recoil energies of few ~ **keV range**

flat and **featureless** spectrum !!

* Xenon1t: PRL 119, 181301 (2017)

RATE vs. MODULATION AMPLITUDE

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

Central idea: modulation amplitude
cannot be larger than (average) absolute rate:

$$\overline{R} \geq S$$

COSINUS

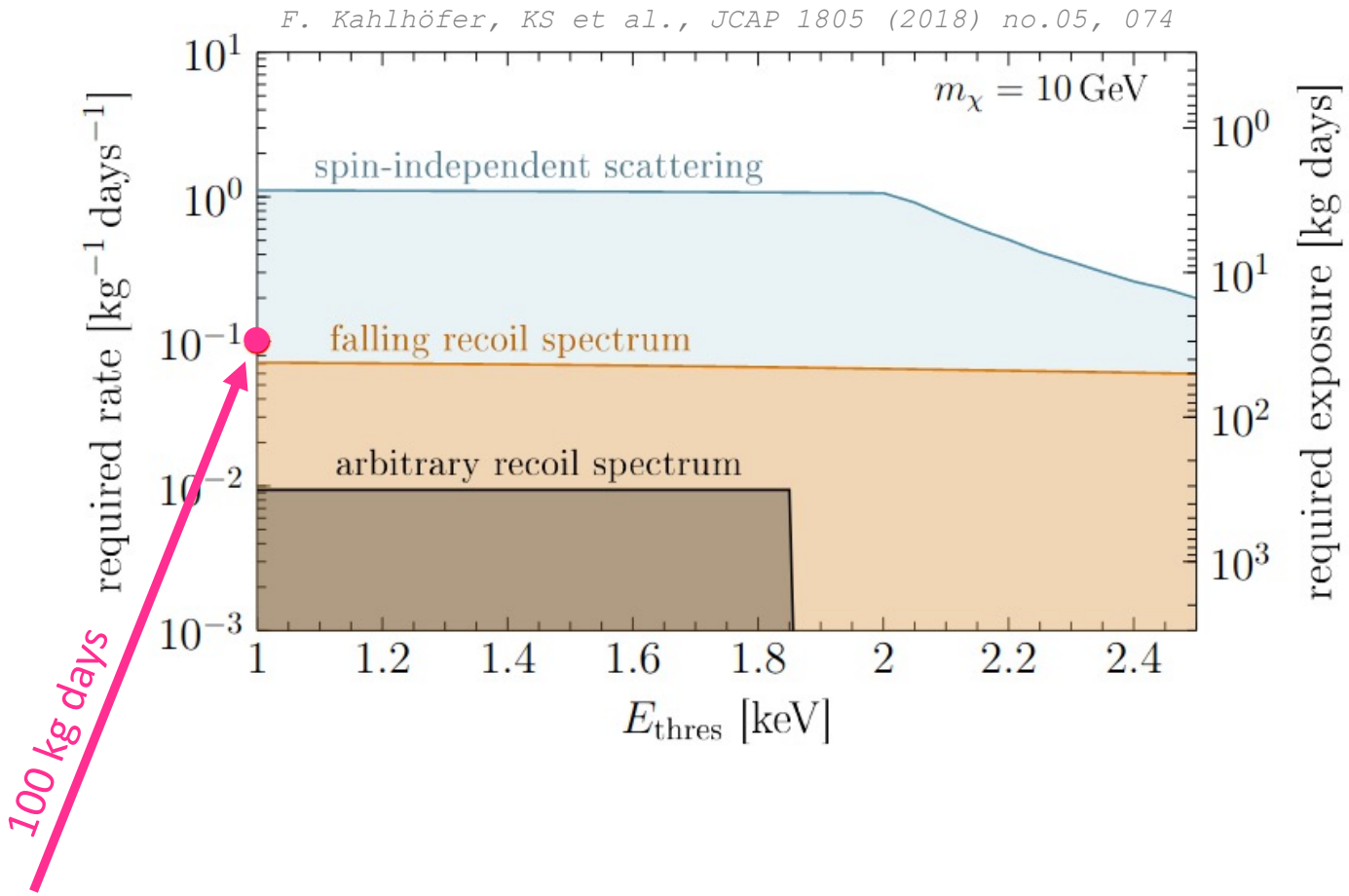
Mean rate $\overline{R} = \frac{1}{2}\,[R(t = \text{June } 1^{st}) + R(t = \text{Dec. } 1^{st})]$

DAMA

Modulation Amplitude $S = \frac{1}{2}\,[R(t = \text{June } 1^{st}) - R(t = \text{Dec. } 1^{st})]$

→ low background condition makes it possible to test DAMA
in a single annual cycle

PHYSICS STRATEGY OF COSINUS



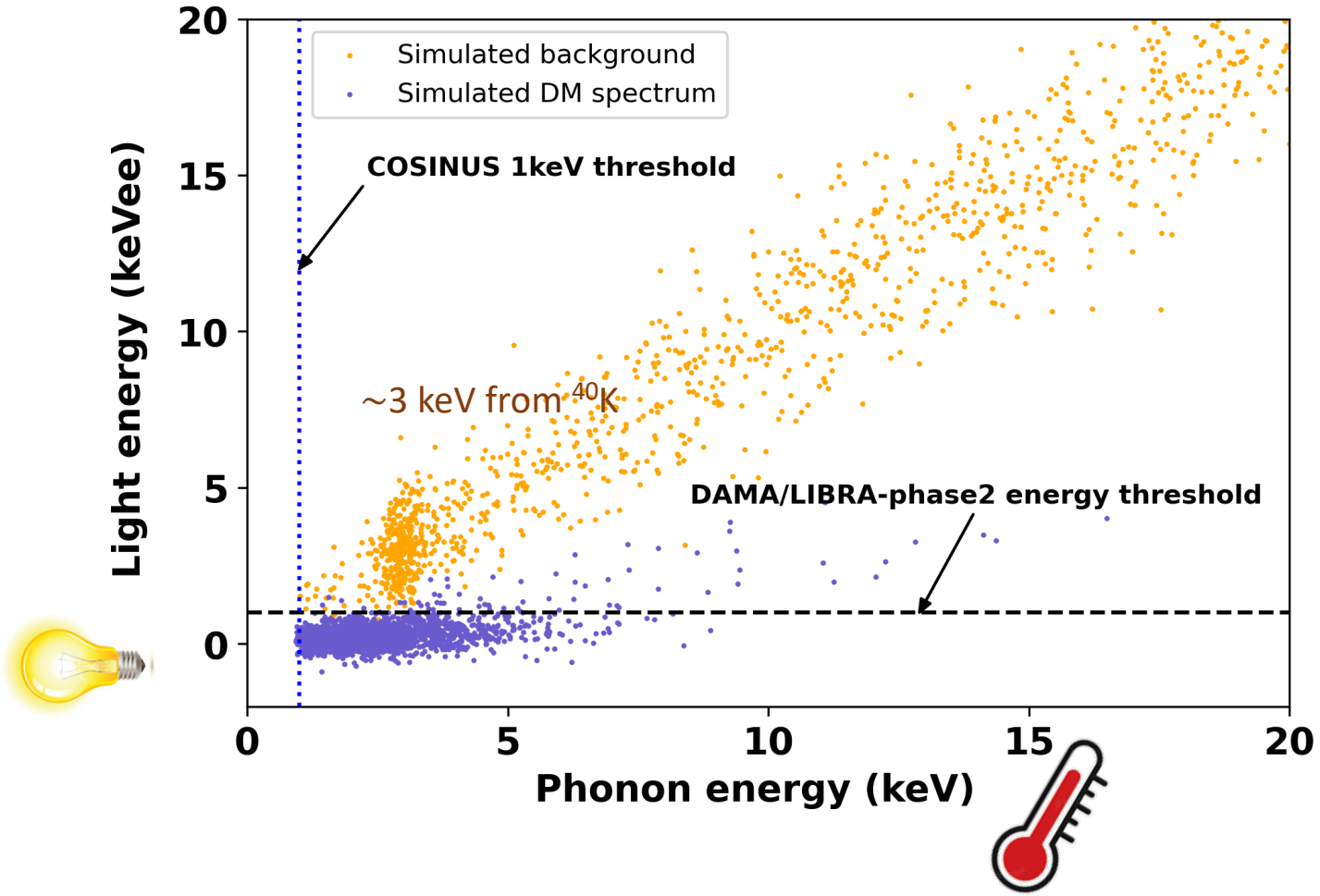
1.8 keV energy threshold sufficient

optimize rather exposure (mass) than threshold

Warning: Not updated for DAMA result with 1keV$_{ee}$ threshold

Outlook: Cut and count only → make use of spectral information for potentially stronger bounds

SIMULATED DATA FOR 100 kg days (gross-exposure)

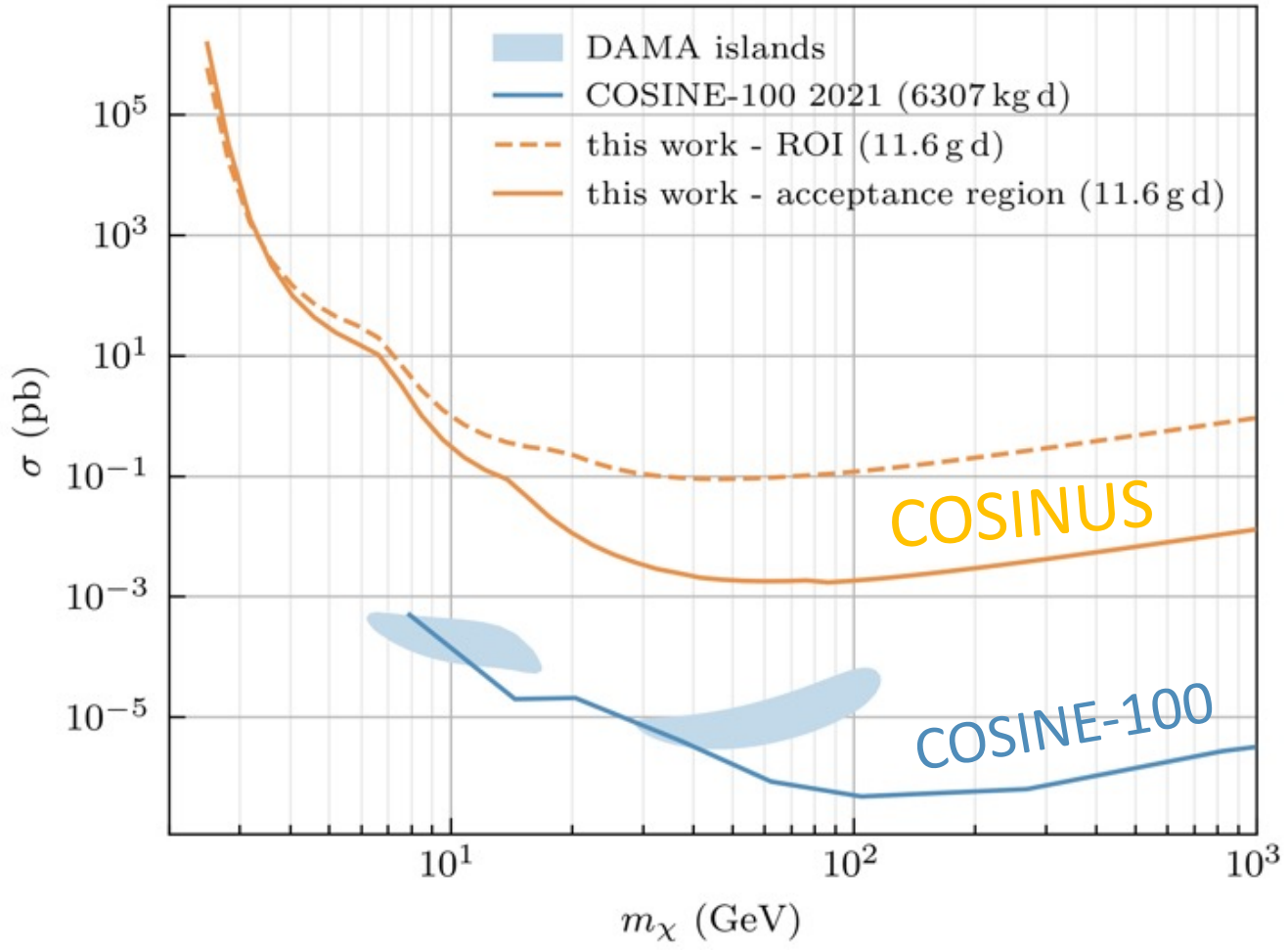


- 1keV nuclear recoil threshold
- flat background: 1 /(keV kg d)
  + ^{40}K background: 600µBq/kg
- dark matter spectrum:
  10 GeV/c^2, 2x10^{-4} pb
- **values for quenching factors** from:

  Tretyak, Astropart. Phys. 33, 40 (2010)

Eur. Phys. J. C (2016) 76:441
DOI 10.1140/epjc/s10052-016-4278-3

COSINUS – FIRST DARK MATTER RESULT

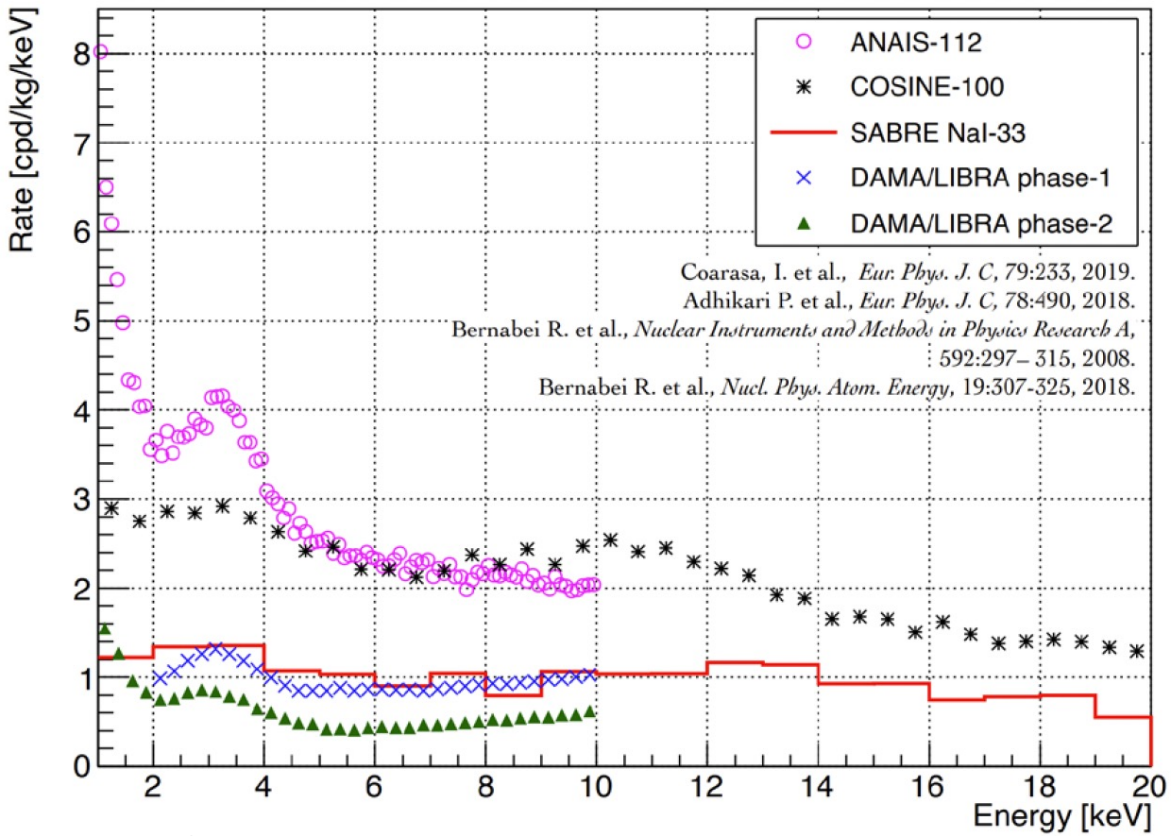


11 g d

↓ ~10^6

6307 kg d

CHALLENGE 0: before starting …



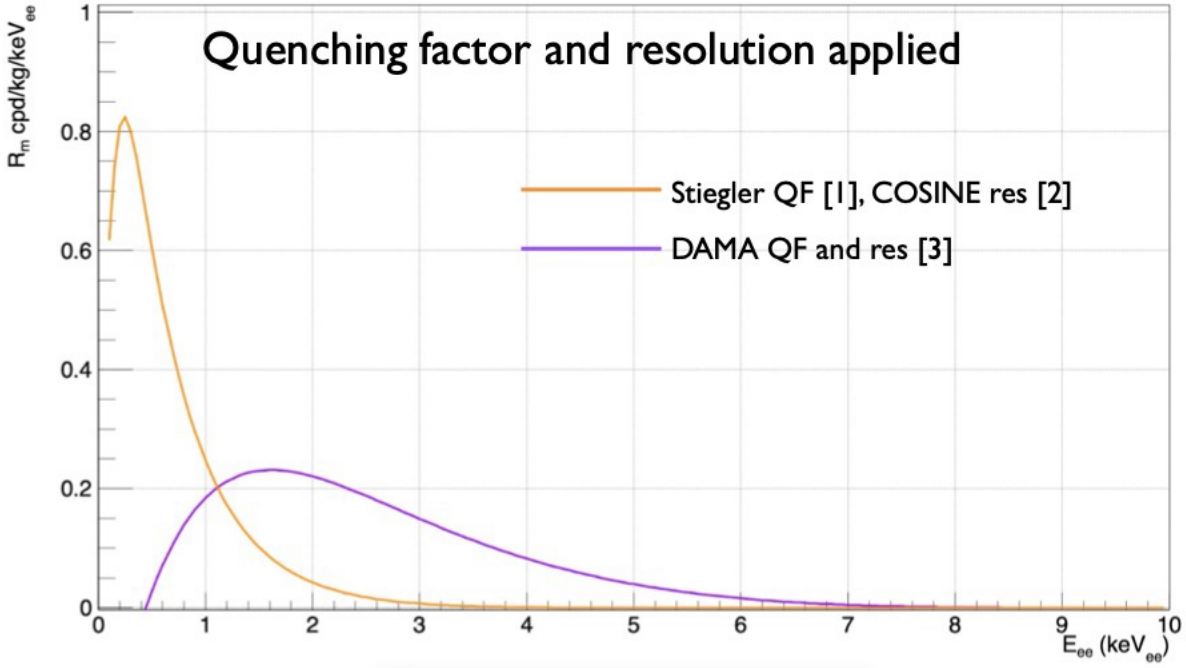
Credits to M. L. Sarsa

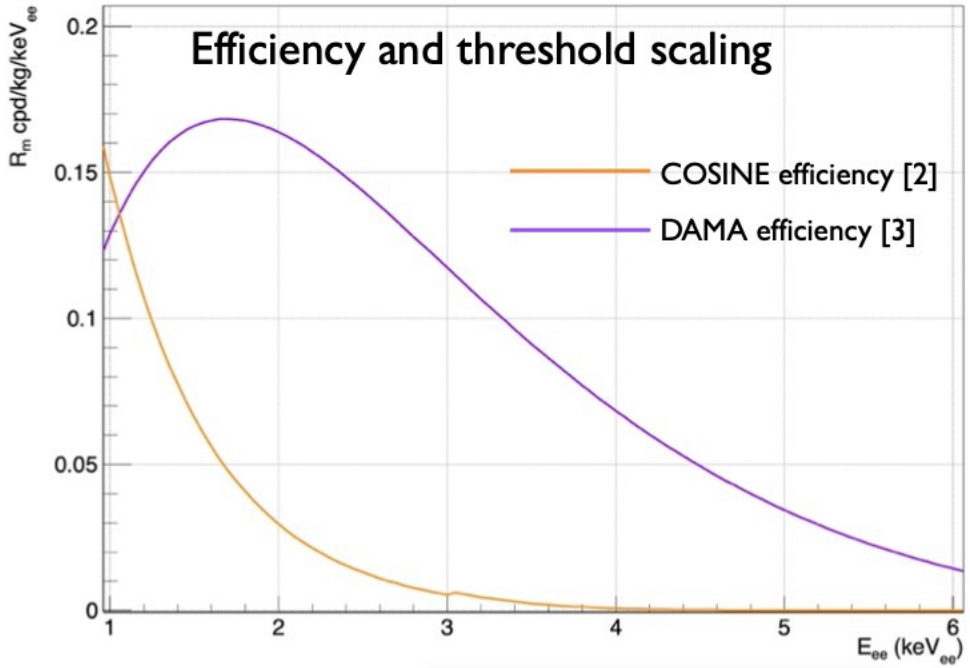
- sensitivity in the range (<1-6) keV_{ee}
- rate of ~ 1 count / (keV kg day), radiopure NaI crystal required
- large mass $\mathcal{O}$ (100 kg) and stable operation over multiple annual cycles

CHALLENGE 1: SYSTEMATIC UNCERTAINTY

DM with m=10 GeV, $\sigma=1.15\times10^{-39}\text{cm}^2$

→ Plots from M. Zurowski @ IDM 2022





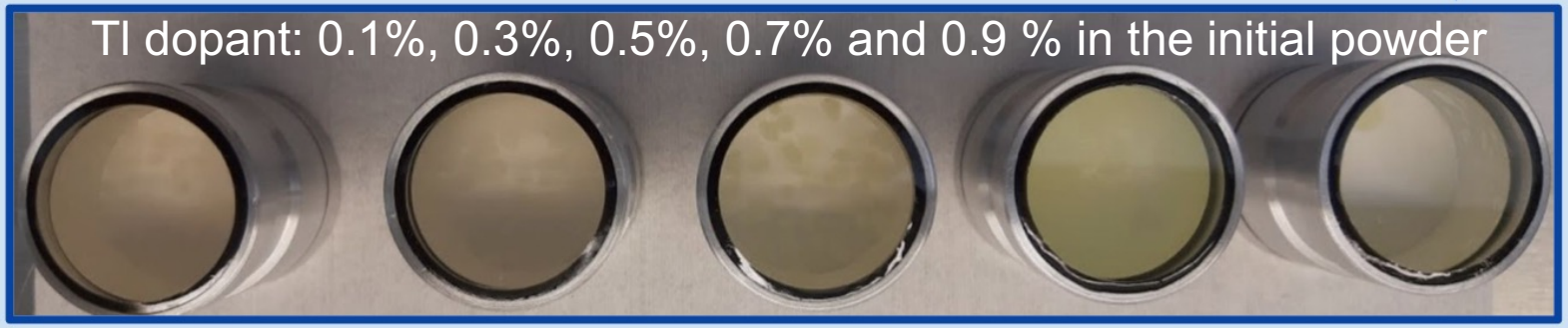
→ comparison of results suffers from systematics

Crystals produced by SICCAS

Since 1928

COSINUS

- 5 ultra-pure NaI crystals with different Tl dopant
- Crystals were produced by SICCAS, China using Astro-Grade powder
- Cylindrical crystals with diameter and height of 1 inch.
- As NaI is hygroscopic, each crystal is sealed in Al casing of ~1.5mm thickness
- Assembly done in a Nitrogen flushed glove box
- ICP-MS studies @LNGS showed
  - Potassium: 10 ppb
  - Uranium: 0.2 ppb
  - Thorium: 0.1 ppb



- 28-36 hours exposure on each crystal, placed on a rotating stand to ensure uniform neutron flux
- Hamamatsu PMT (H11934-200) attached with the NaI crystal.

QF measurement setup

TUNL
Triangle Universities Nuclear Laboratory

- Collimator and lead shielding guide the neutron beam to NaI(Tl) placed at 75 cm distance
- One Hamamatsu PMT(H11934-200) with the NaI crystal
- 14 BDs placed at a distance of 1-1.5 m from NaI covering 7-40 degrees of angles
- Additional backing detector at 0 degree to measure time of flight (TOF) to monitor the spread of neutron energy
- Liquid scintillator (EJ-309) covered by Al casing and lead caps to reduce background gamma trigger rate. Scintillator coupled to a Hamamatsu pmt (R7724)