TIPP 2023
4 - 8 SEPTEMBER 2023
CTICC CAPE TOWN SOUTH AFRICA

DIRECT DARK MATTER DETECTION WITH **SODIUM IODIDE** CRYSTALS

TIPP2023
Technology & Instrumentation in Particle Physics Conference
Sep, 4-8 2023
CTICC Cape Town
South Africa

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@Maurizio Verdecchia Photography

DIRECT DARK MATTER DETECTION WITH SODIUM IODIDE CRYSTALS

motivation
and
evidences

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DIRECT DARK MATTER DETECTION WITH SODIUM IODIDE CRYSTALS

technologies and achievements

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DIRECT DARK MATTER DETECTION WITH **SODIUM IODIDE** CRYSTALS

experiments
and
future programs

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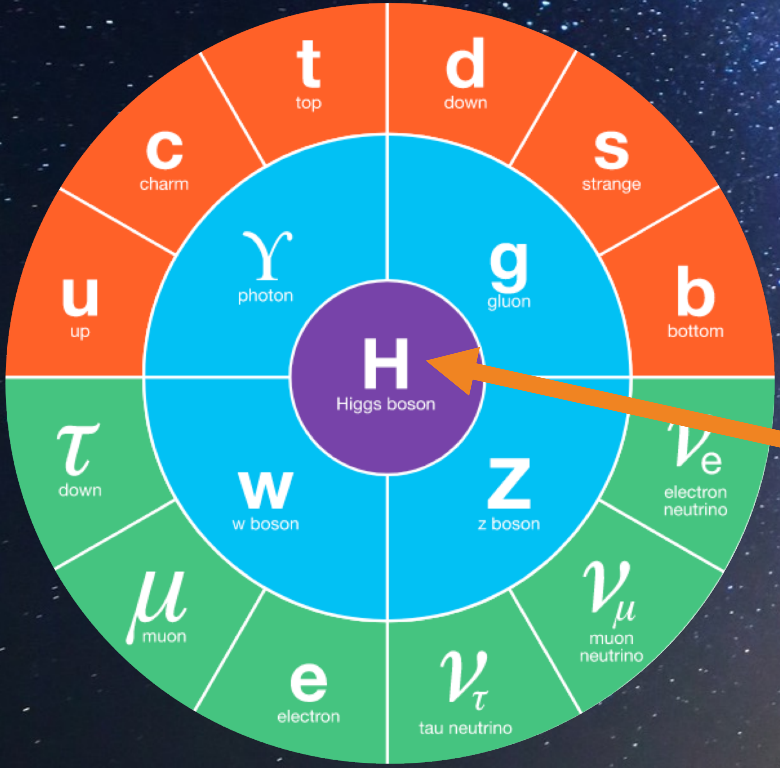
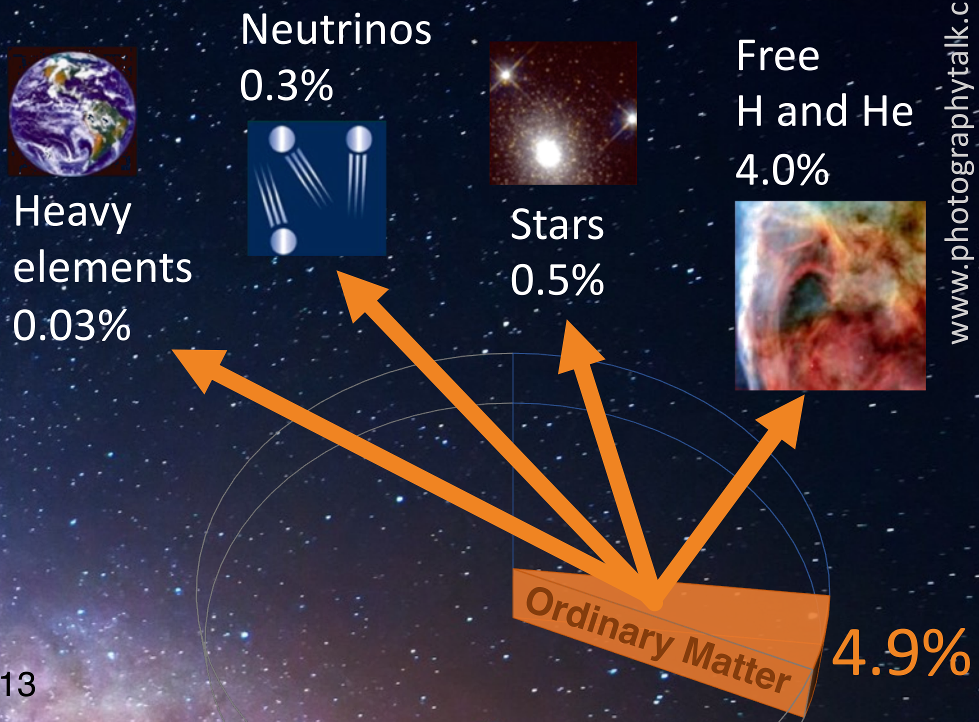
Ordinary Matter

Ordinary Matter



Prof. Peter Higgs
Nobel prize winner, 2013

First observations was made by ATLAS and CMS at LHC at CERN and announced on 4.7.2012



Planck 2018 - A&A 641 (2020)

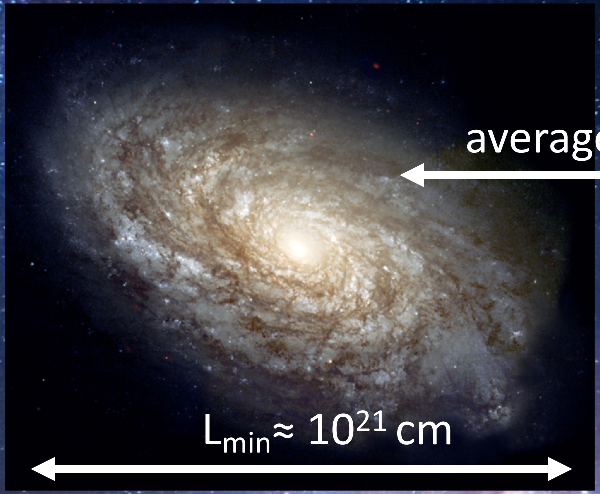
Dark Matter

+ add extra and new ingredient

www.photographytalk.com

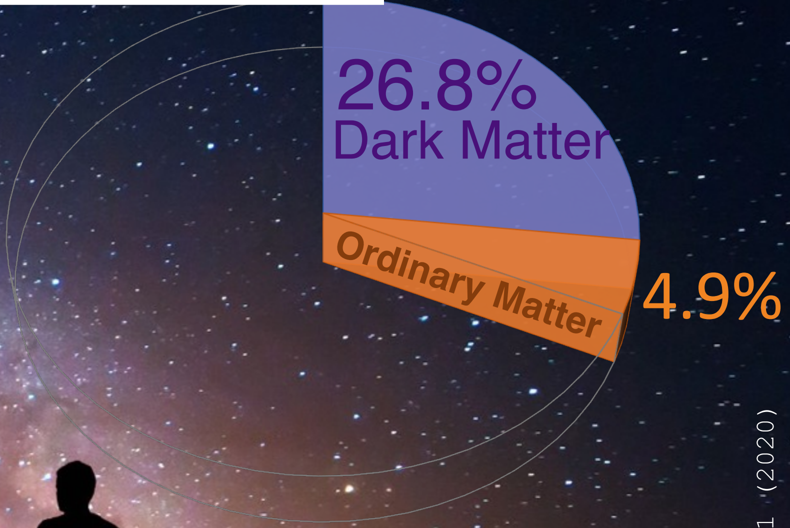
Planck 2018 - A&A 641 (2020)

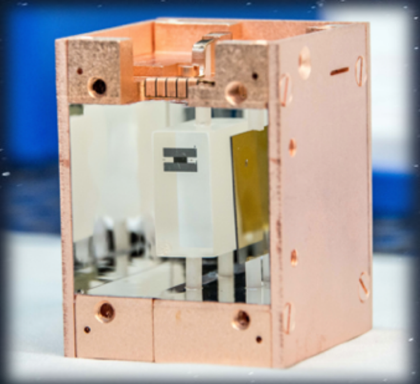
WHY IS THE IDENTIFICATION DIFFICULT?



$L_{min} \approx 10^{21}$ cm

average density ≈ 0.3 GeV / cm^3





$L_{experiment} \approx 0.1\text{-}10^2$ cm

www.photographytalk.com

Planck 2018 - A&A 641 (2020)

Energy Content of the Universe

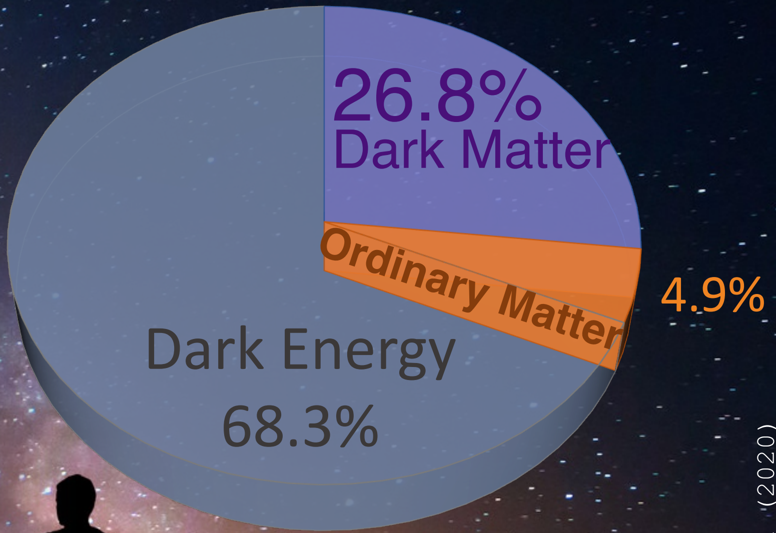
The evidence for DM is **overwhelming** and present on all length scales.

Cosmological observations only make sense if the largest fraction of matter is **non-baryonic.**

+ add (≧1) extra and new ingredient (= Dark Matter)

→ **new physics beyond SM**
→ → **explains huge interest in community**

+ add general relativity



Planck 2018 - A&A 641 (2020)

HUNT FOR DARK MATTER

INDIRECT

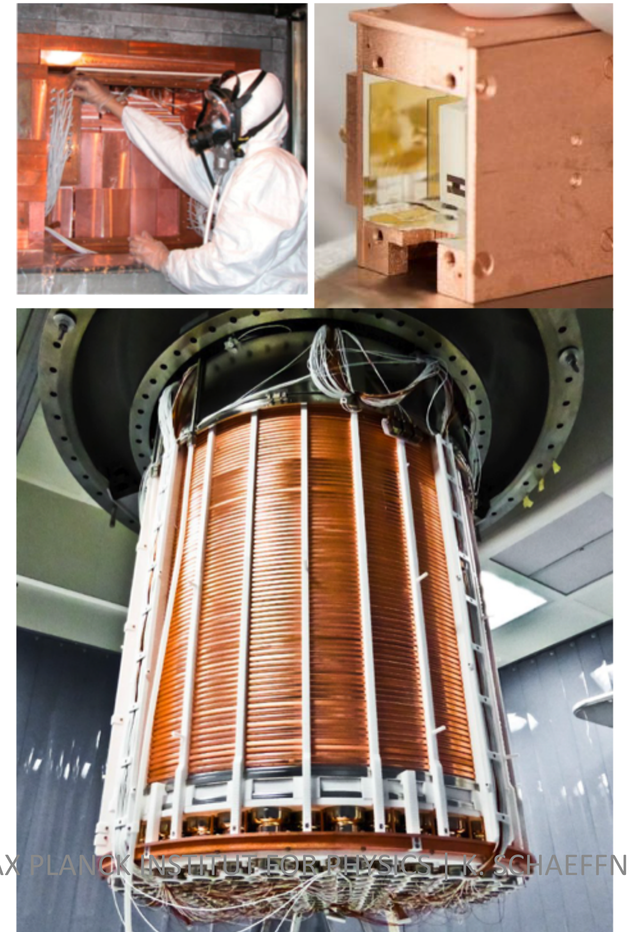
Annihilation

$\chi\bar{\chi} \rightarrow \gamma\gamma, q\bar{q}, \ldots$

DIRECT

scattering

$\chi\,\mathrm{N} \rightarrow \chi\,\mathrm{N}$



COLLIDERS

production

$\mathrm{p} + \mathrm{p} \rightarrow \chi\bar{\chi}$ + products

HUNT FOR DARK MATTER

INDIRECT

Annihilation

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scattering

$\chi\, \mathrm{N} \rightarrow \chi\, \mathrm{N}$

COLLIDERS

production

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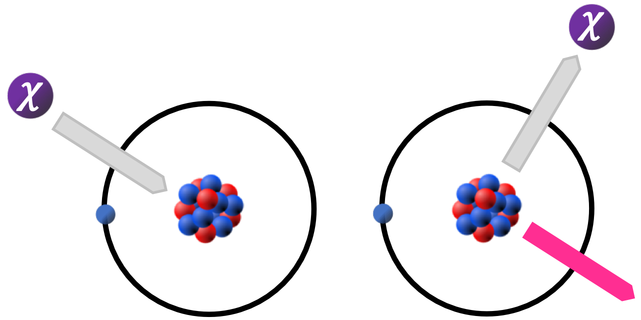
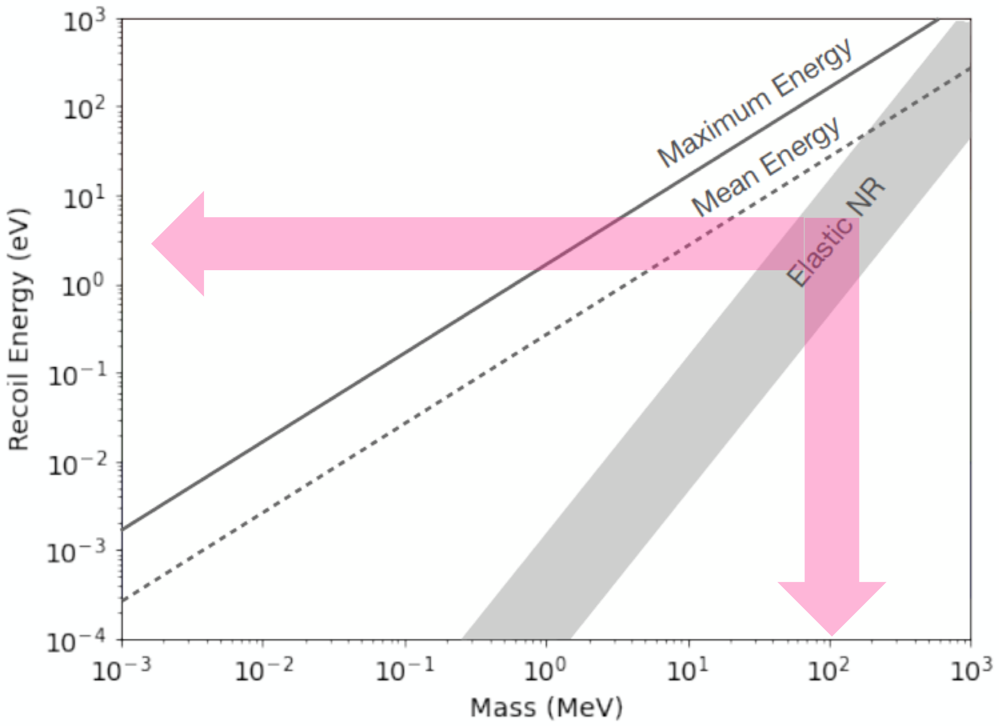
DARK MATTER INTERACTIONS AND SIGNALS

- elastic DM – nucleus scattering (NR)





Credit: R. Essig, modified arXiv: 2203.08297

Elastic NR for H and Xe

DARK MATTER INTERACTIONS AND SIGNALS

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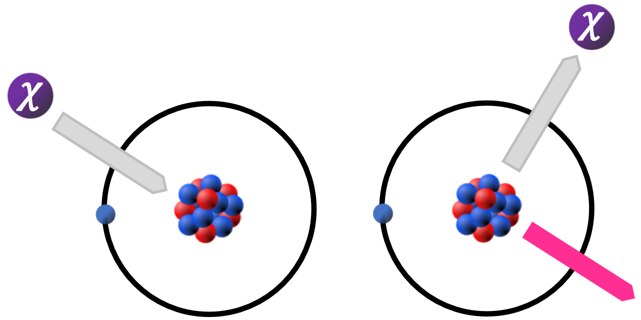

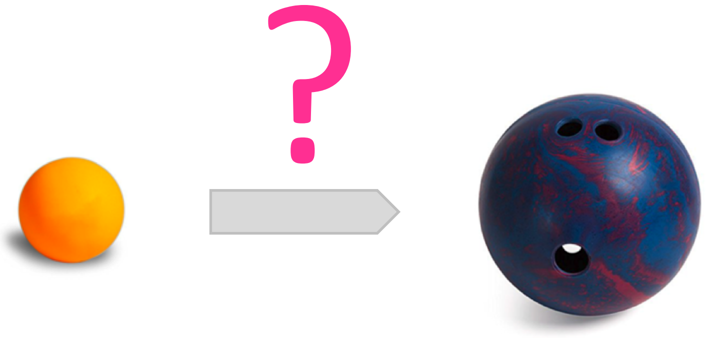

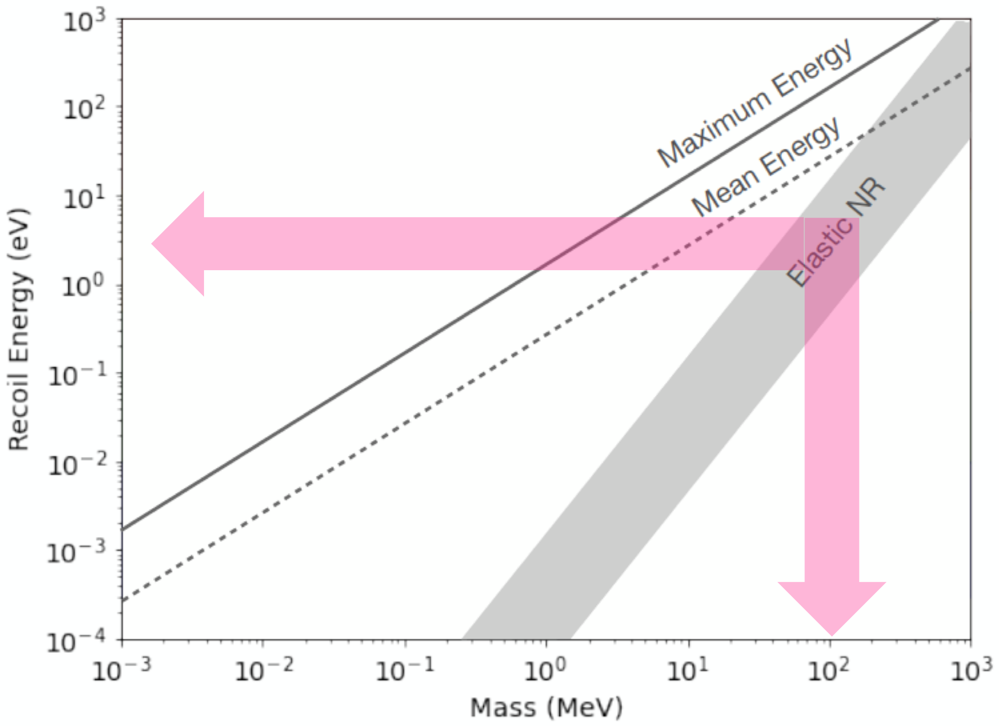

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DARK MATTER INTERACTIONS AND SIGNALS

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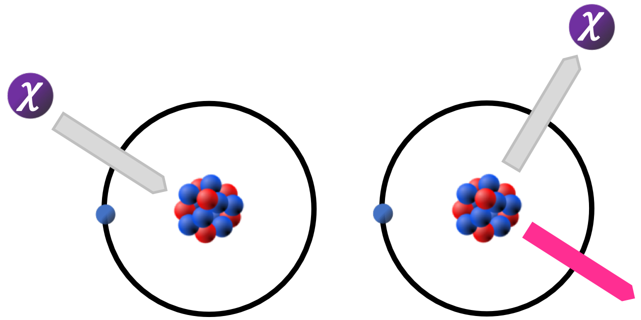
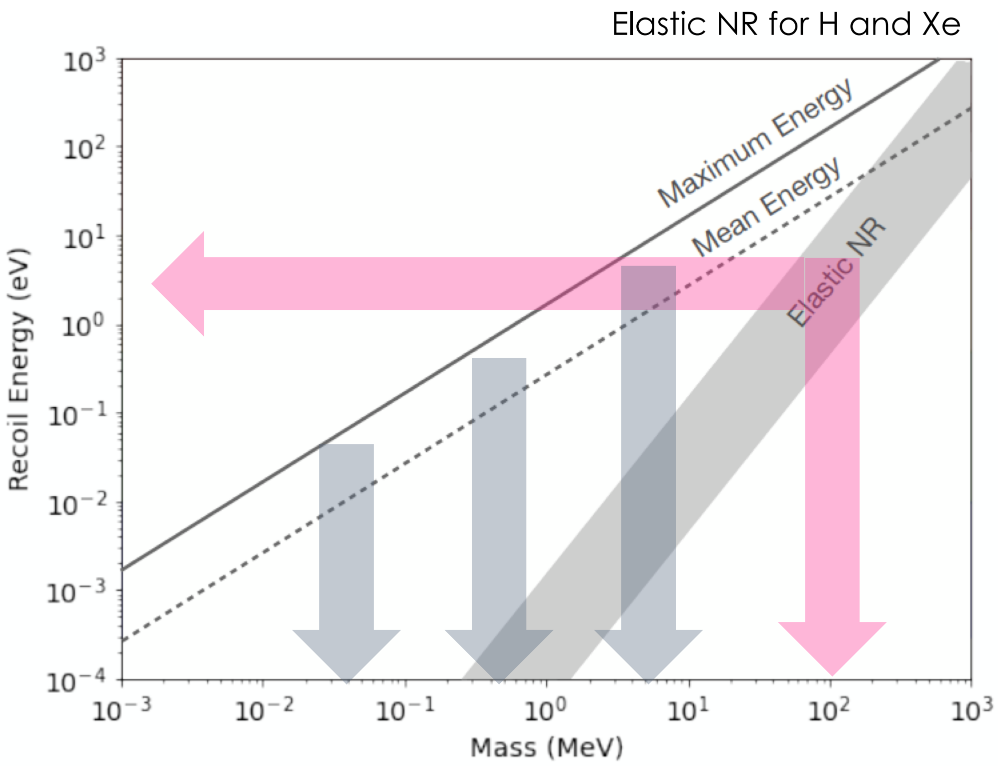
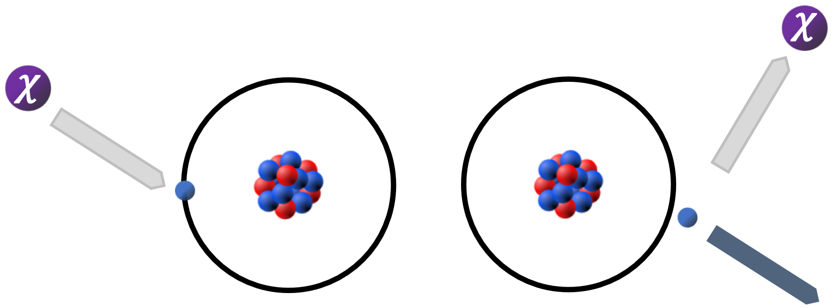




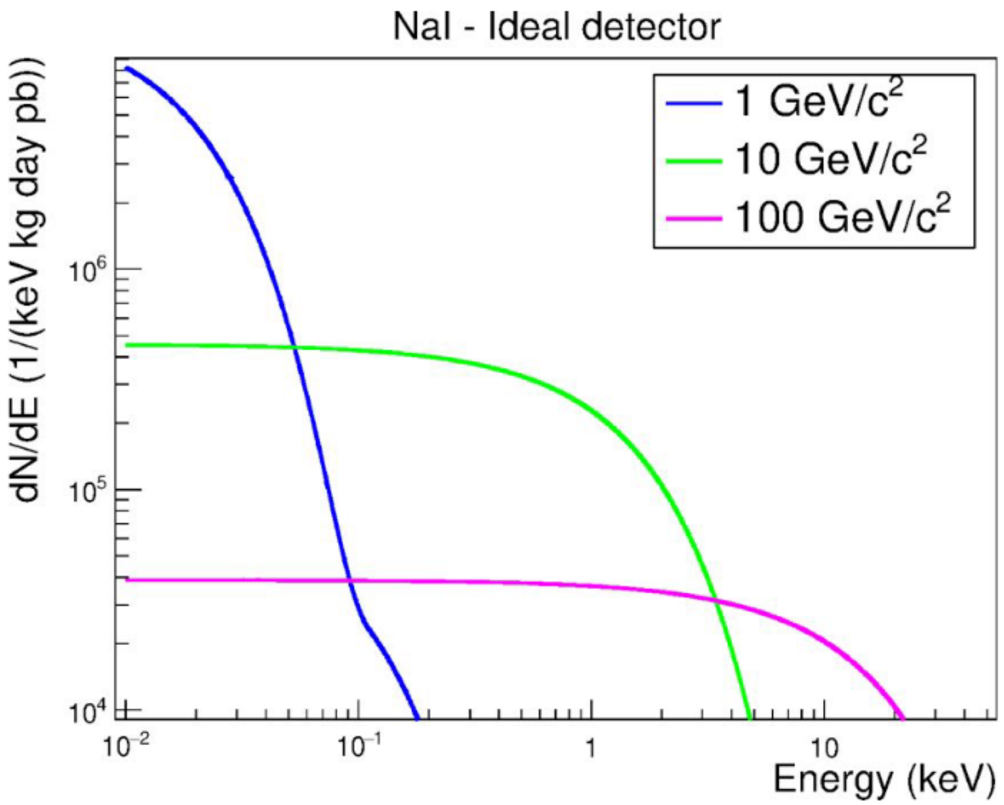
Credit: R. Essig, modified arXiv: 2203.08297

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



EXPECTED NUCLEAR RECOIL SPECTRUM

rate and shape of recoil spectrum depend on target material



extremely rare interaction rate

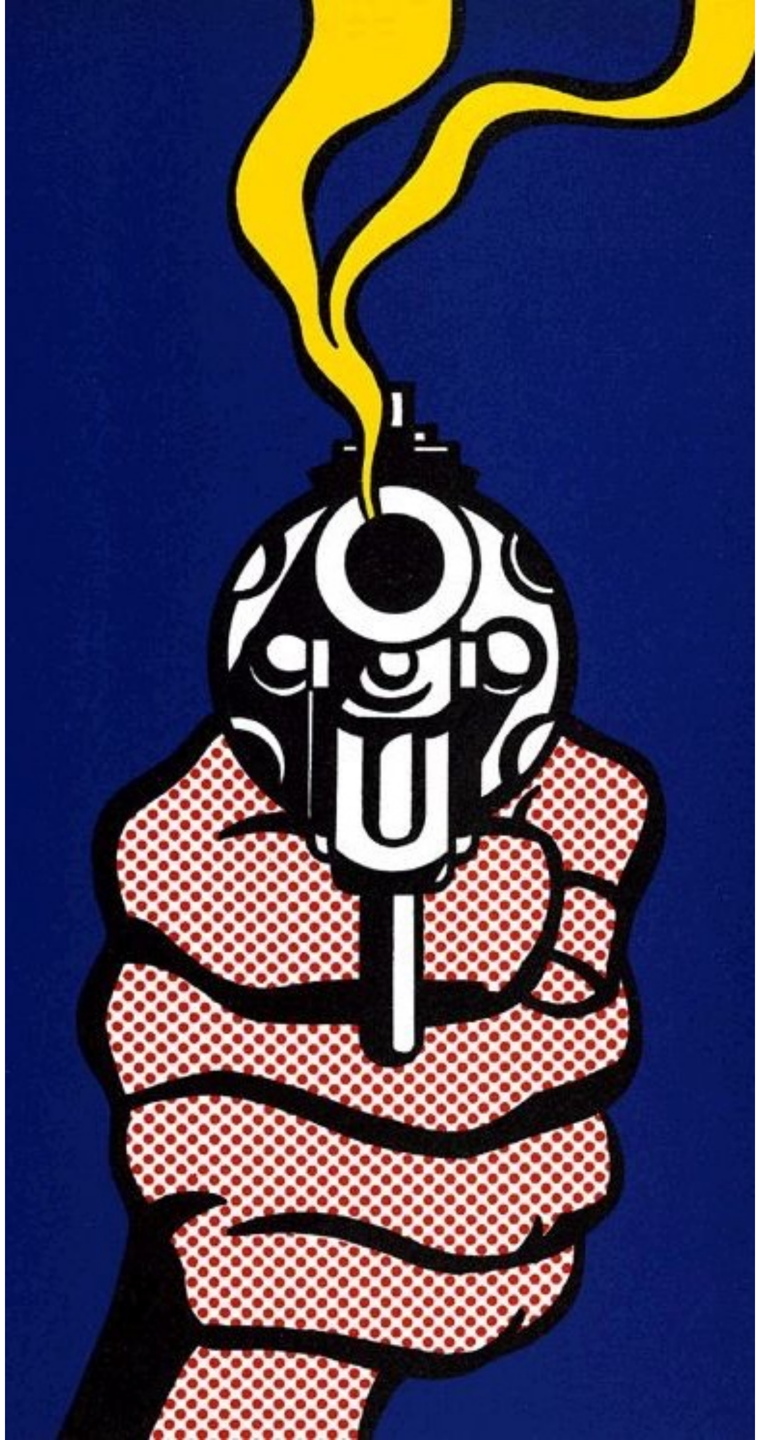
current limit: $\mathcal{O}$ **(0.01) counts/(keV tonne year) ***

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

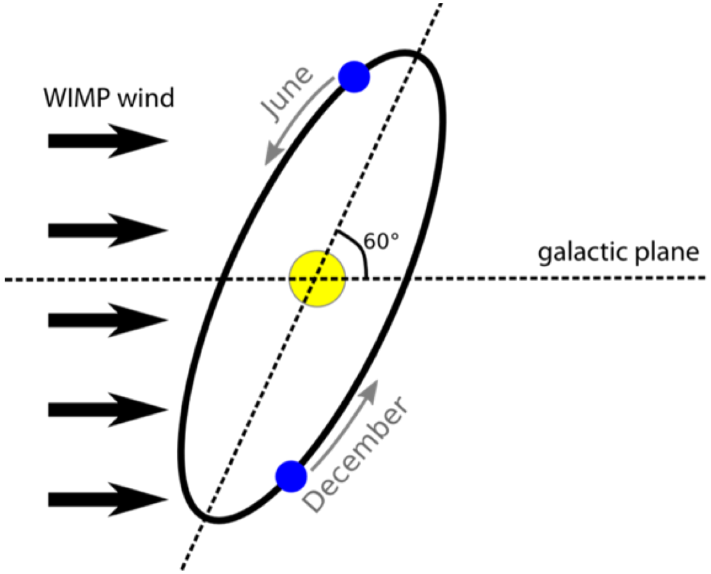
flat and **featureless** spectrum !!

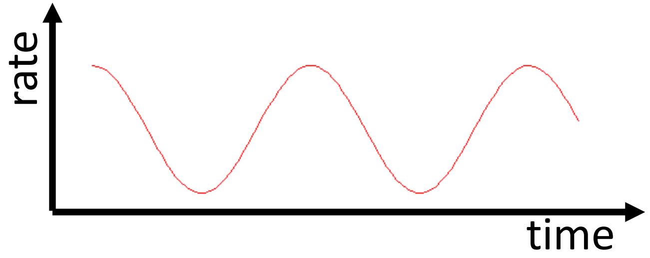
* Xenon1t: PRL 119, 181301 (2017)

Is their a smoking gun signature in direct dark matter searches ?

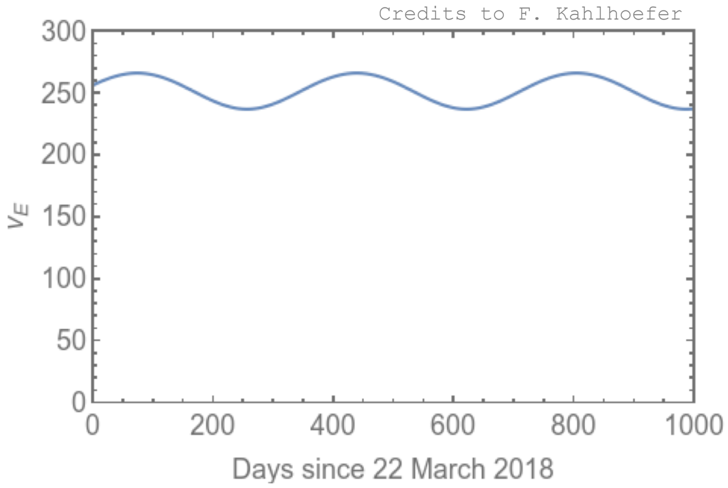


ANNUAL MODULATION OF DARK MATTER SIGNALS





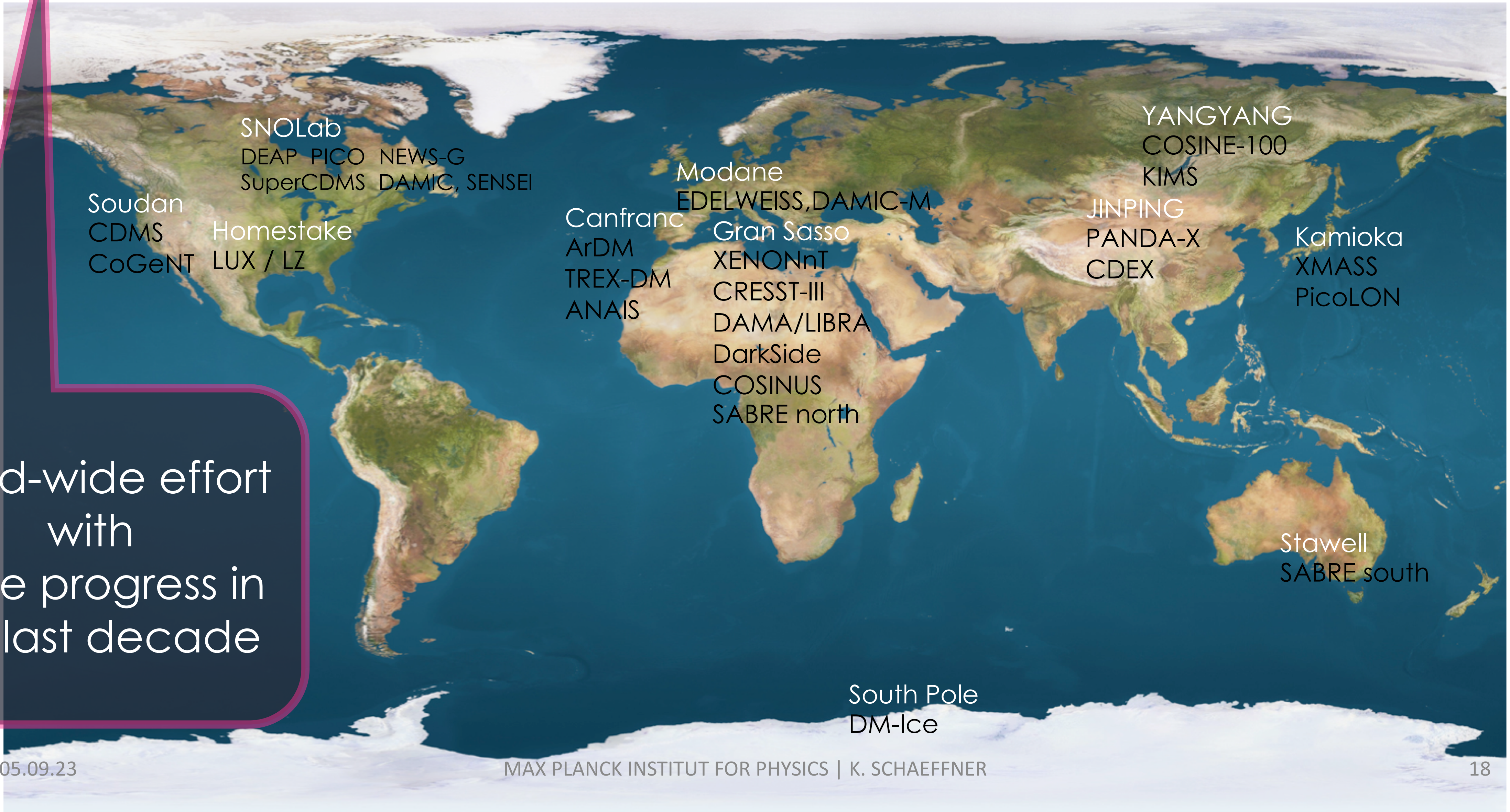
$$R \propto \sigma v_E \rho_{DM}$$



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

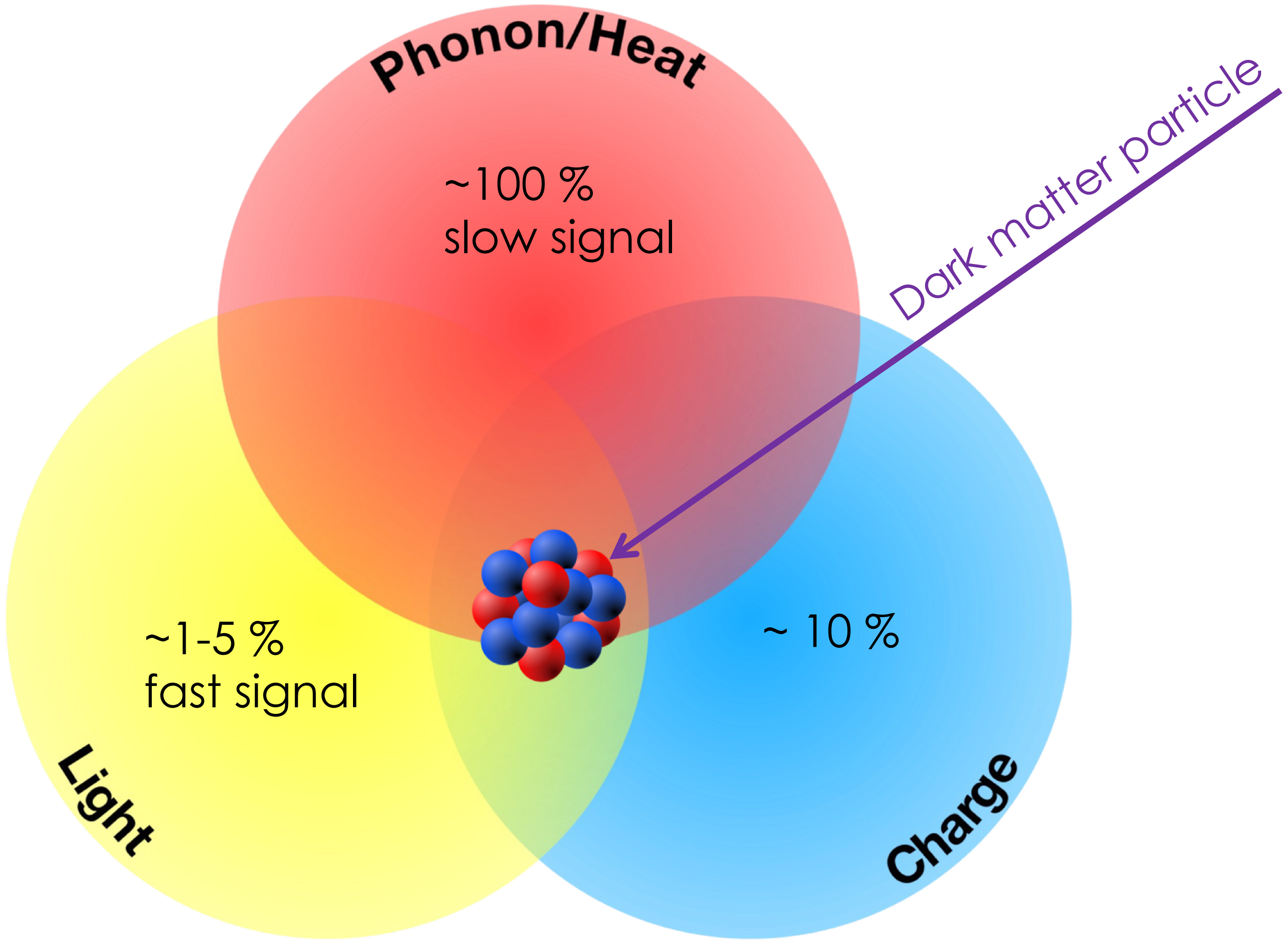
STATUS OF DIRECT SEARCHES

* not complete list



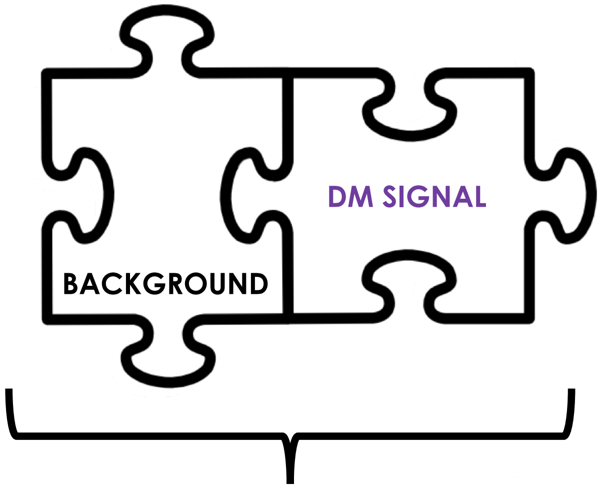
world-wide effort with huge progress in the last decade

SIGNAL CREATION IN DIRECT SEARCHES



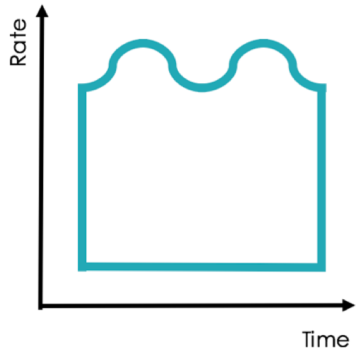
SAME SAME, BUT DIFFERENT

SINGLE CHANNEL



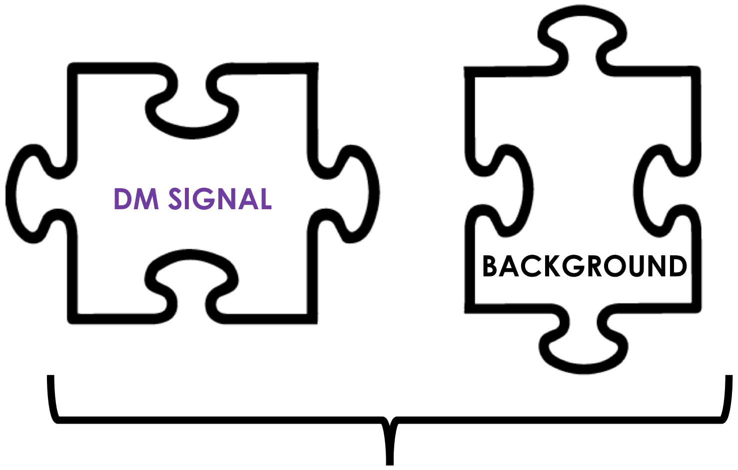
MODULATION

Rate vs. time



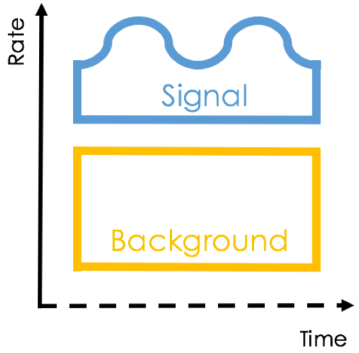
VS.

DUAL CHANNEL

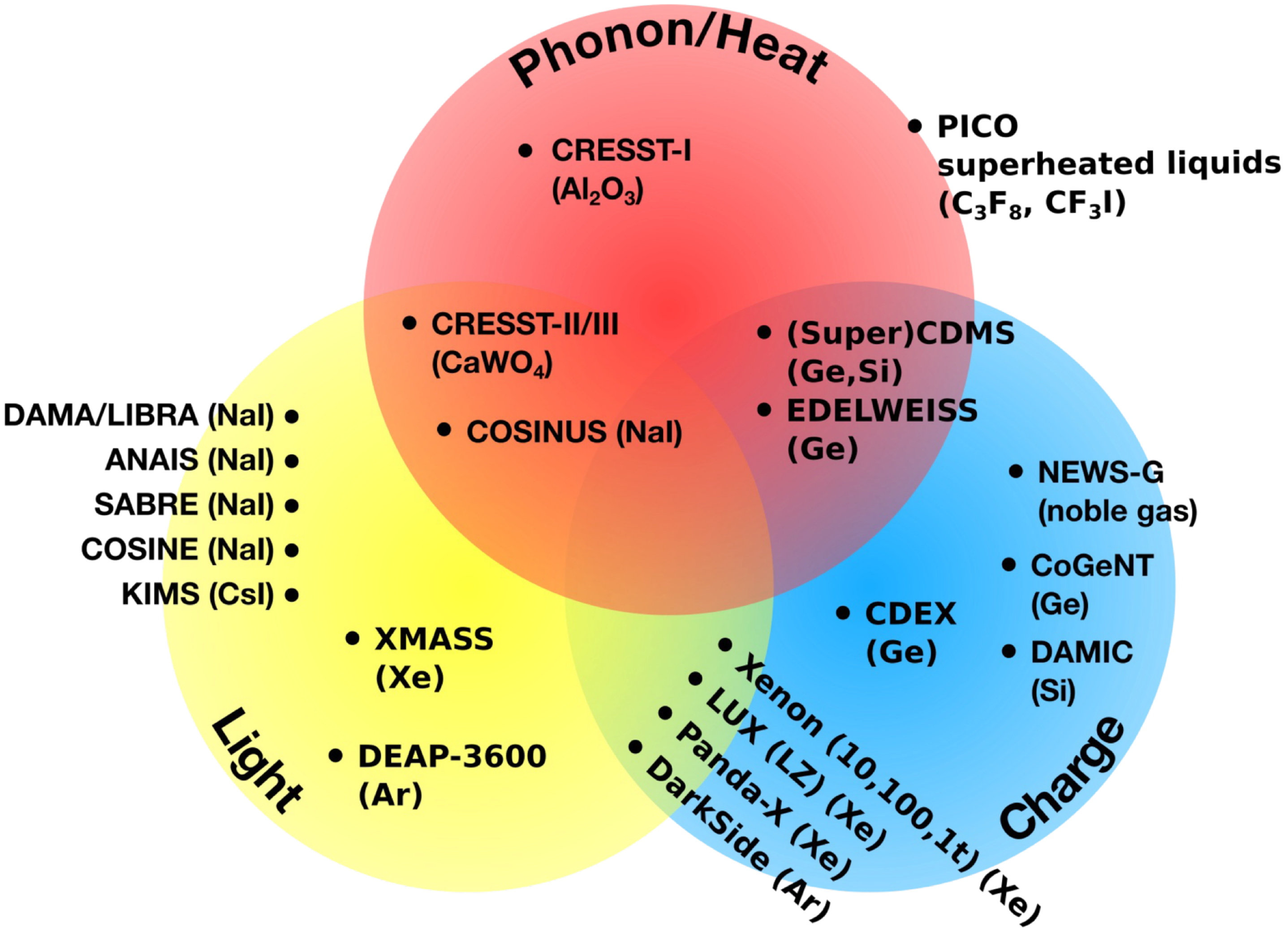


COUNTING

Signal above background

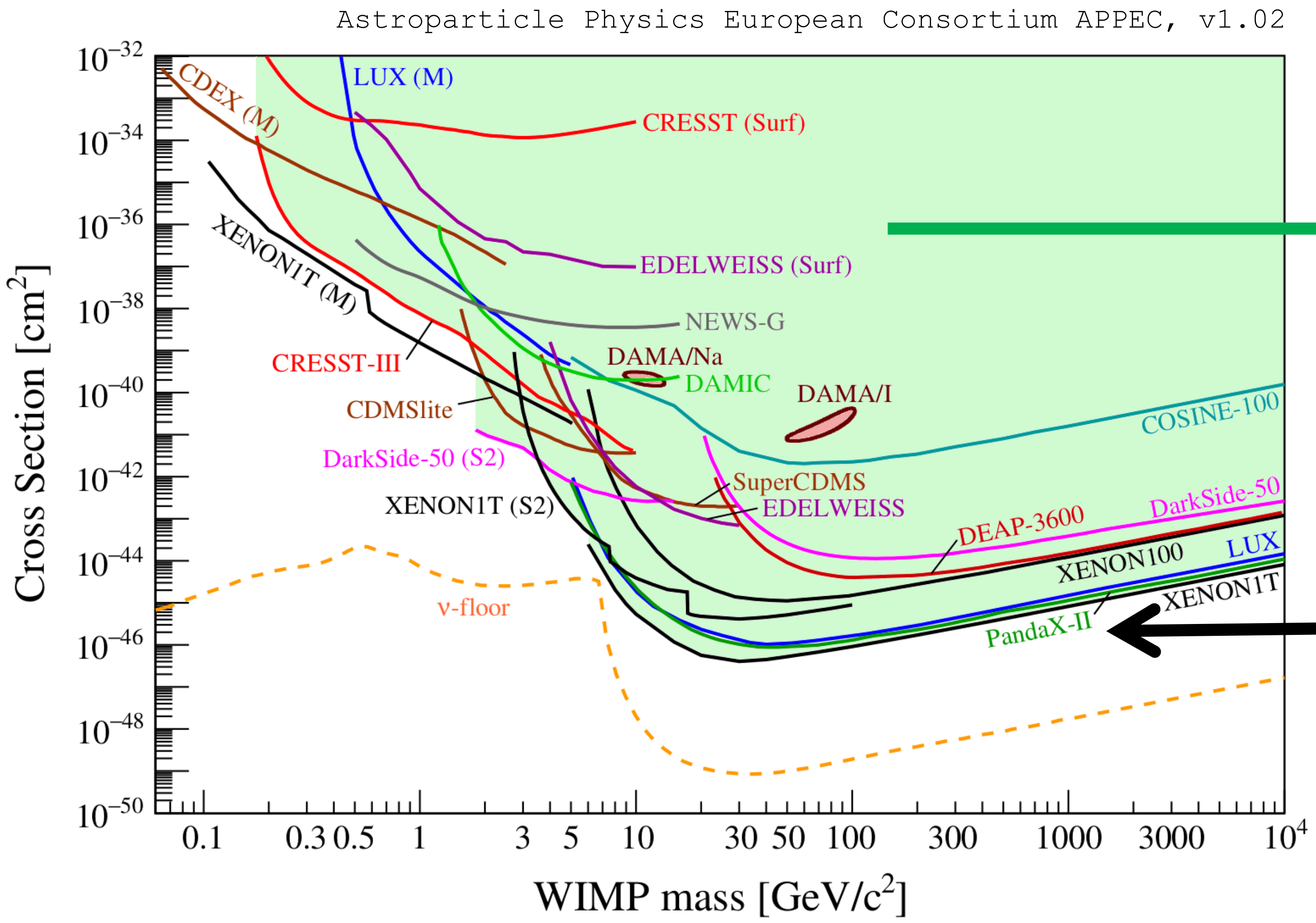


A WORLDWIDE EFFORT



Credits to: F. Reindl

STATUS OF DIRECT SEARCHES

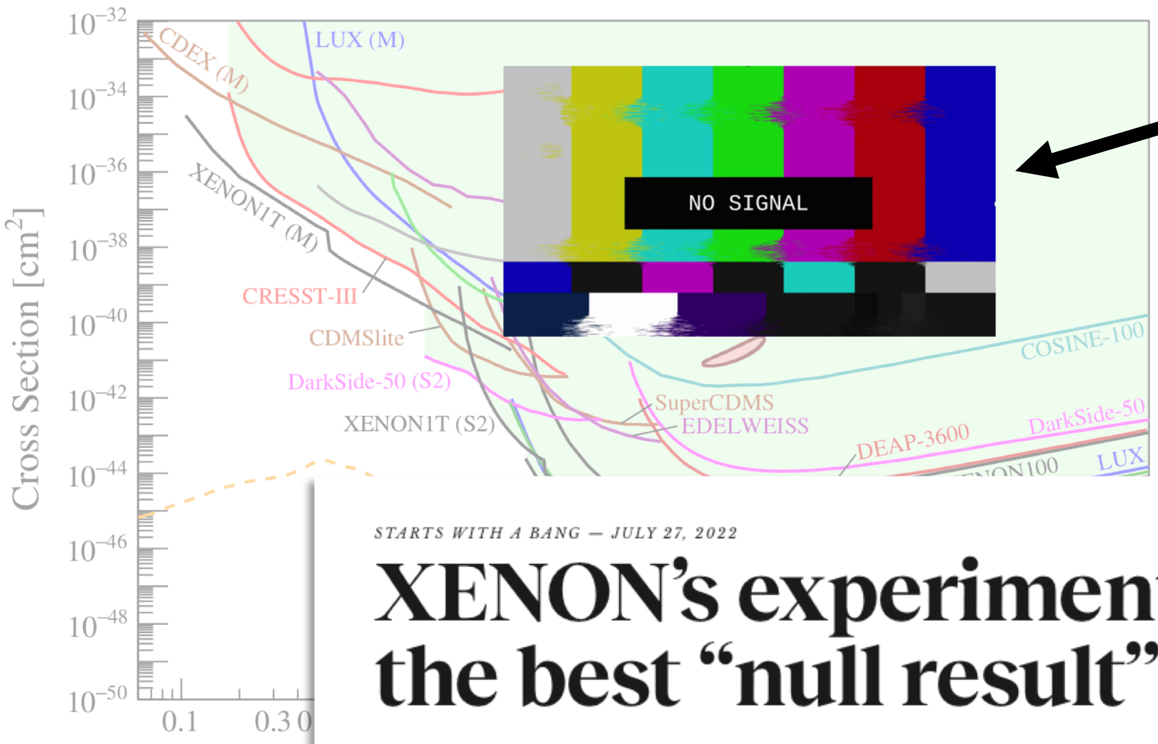


excluded area

new limits from XENONnT and LZ

NULL RESULTS

Astroparticle Physics European Consortium APPEC, v1.02



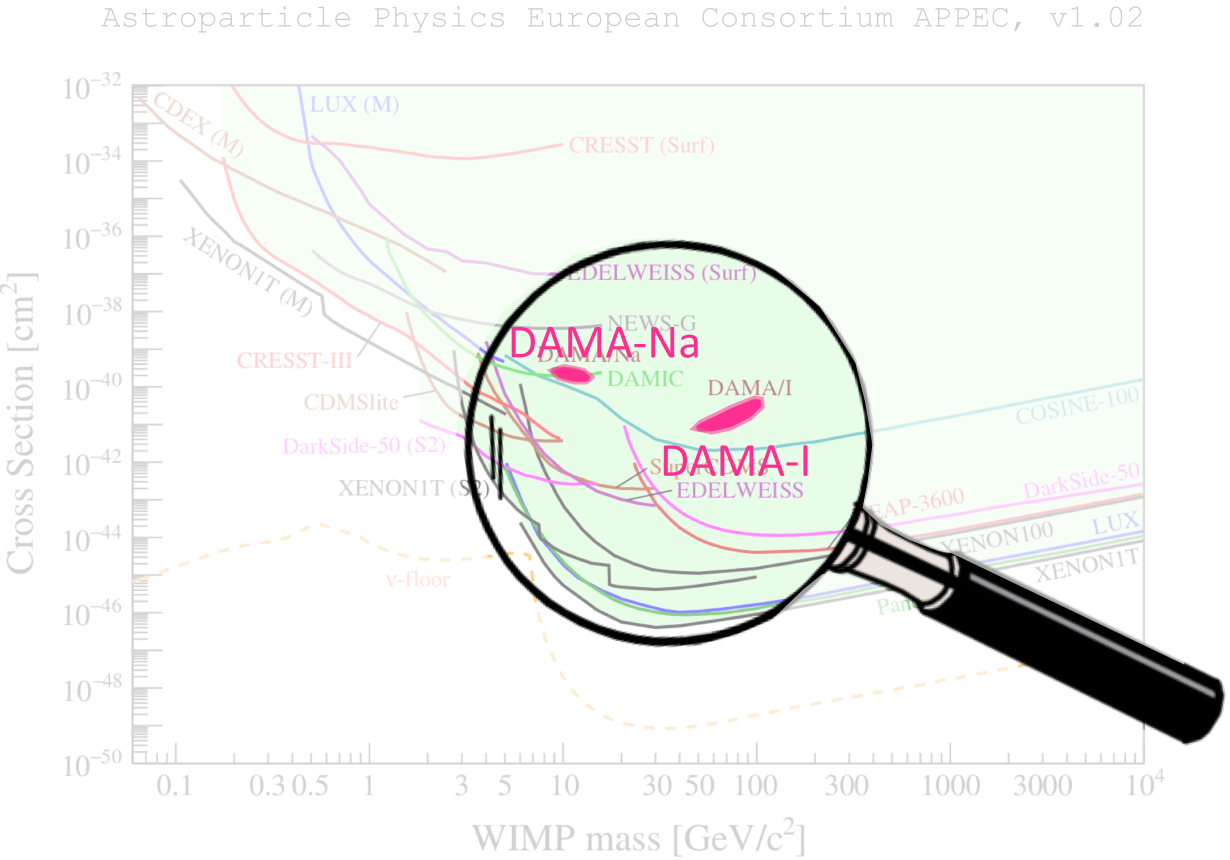
no signal observed by most experiments

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?

Credits to F. Kahlhoefer

V. Zema (Postdoc at MPP on COSINUS) @ TAUP VIENNA 2023

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.

Credits to F. Kahlhoefer

N. Smith (director at TRIUMF)

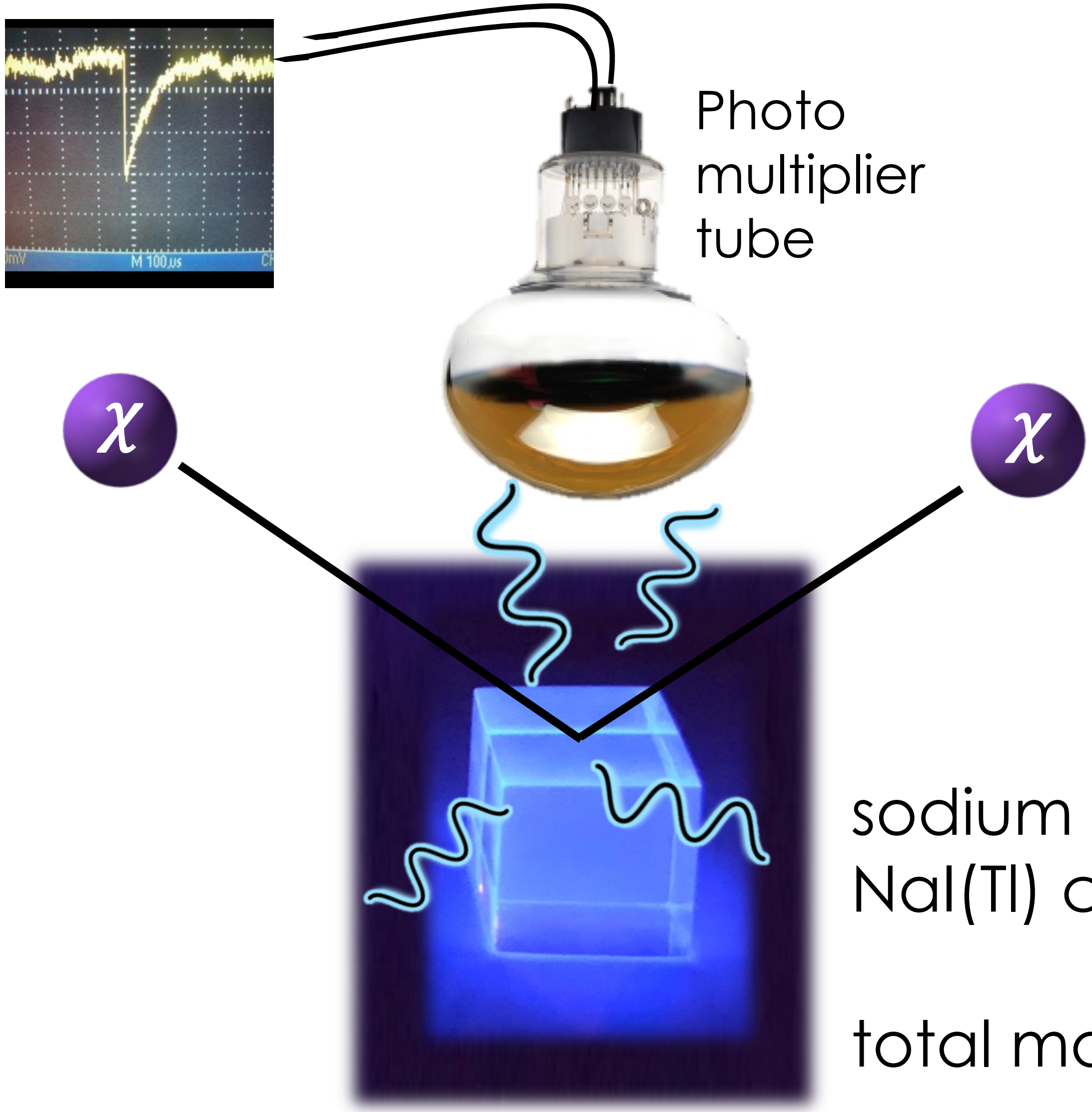
I remember being in the auditorium when it was first announced!

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.

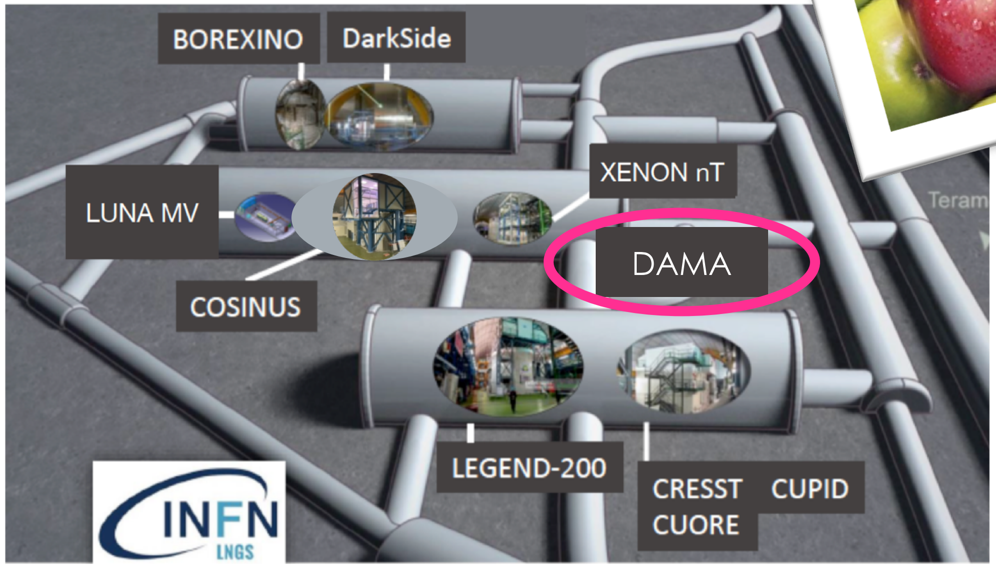
Credits to F. Kahlhoefer

DAMA/LIBRA experiment

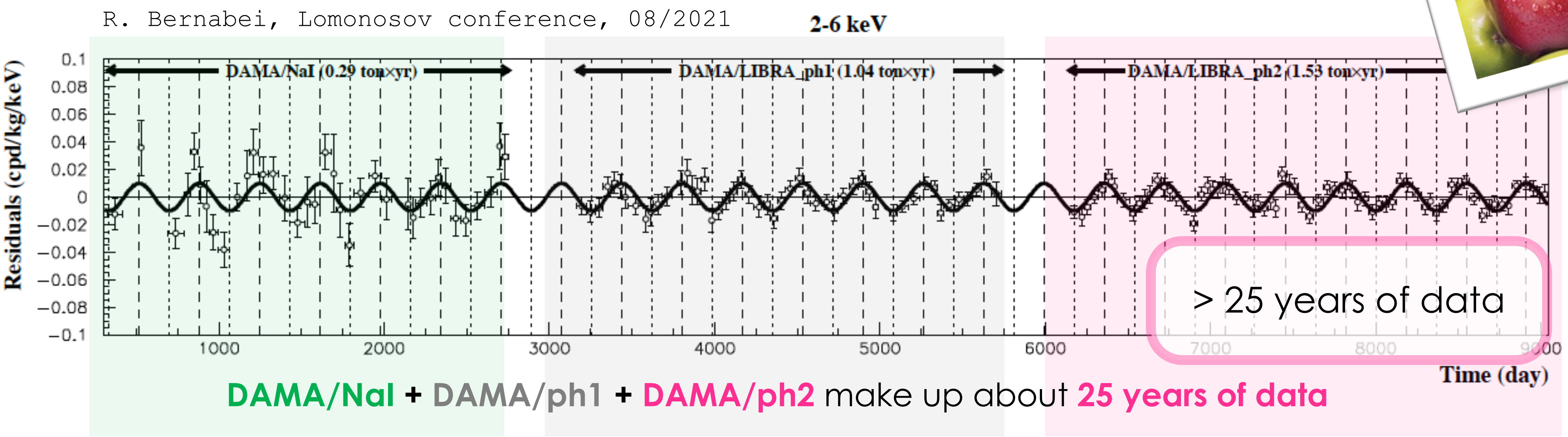


sodium iodide
NaI(Tl) crystals

total mass: 250 kg



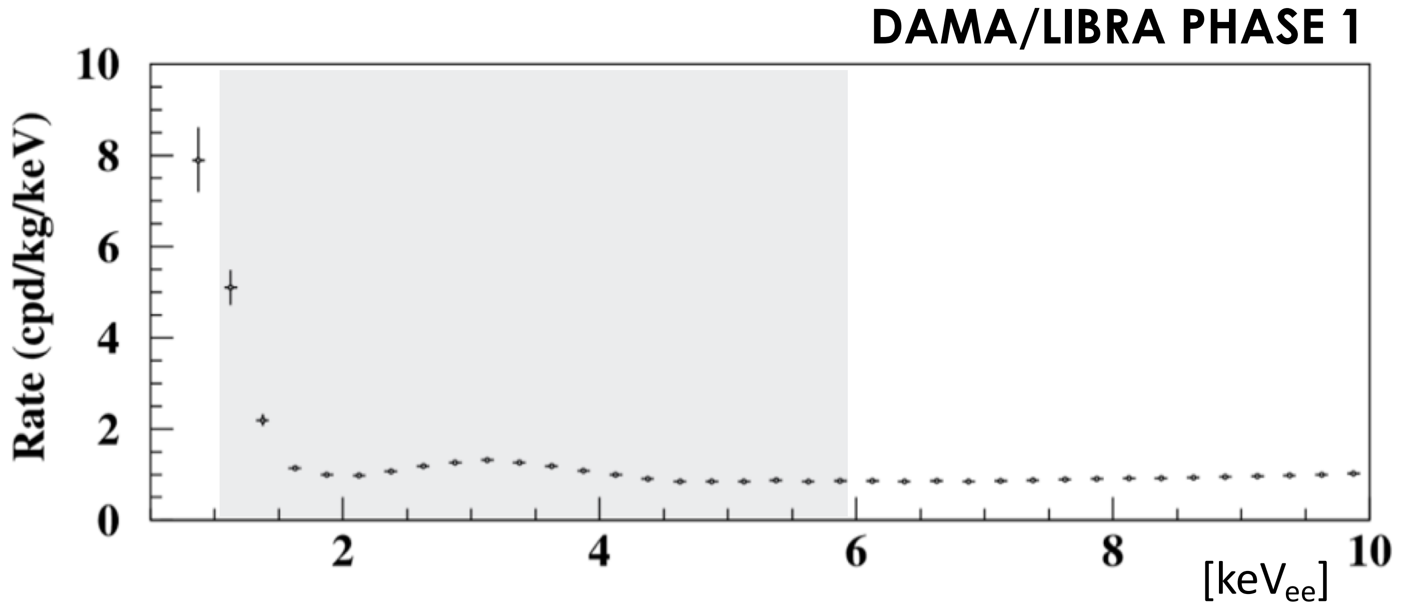
DAMA/LIBRA **RESULT**



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

DAMA/LIBRA: **ENERGY SPECTRUM**



single-hit scintillation events
~ 1 count / (keV kg day)

DAMA/LIBRA BACKGROUND

^{40}K < 20 ppb

^{238}U < 0.7-10 ppt

^{232}Th < 0.5-7.5 ppt

^{210}Po < 0.5 mBq/kg

R. Bernabei et al., EPJ C 56 (2008) 333-355

Plot: Bernabei et al. EPJ (2013) 73:2648

THE SMOKING GUN EVIDENCE?

statistics: 13.7 σ ✓

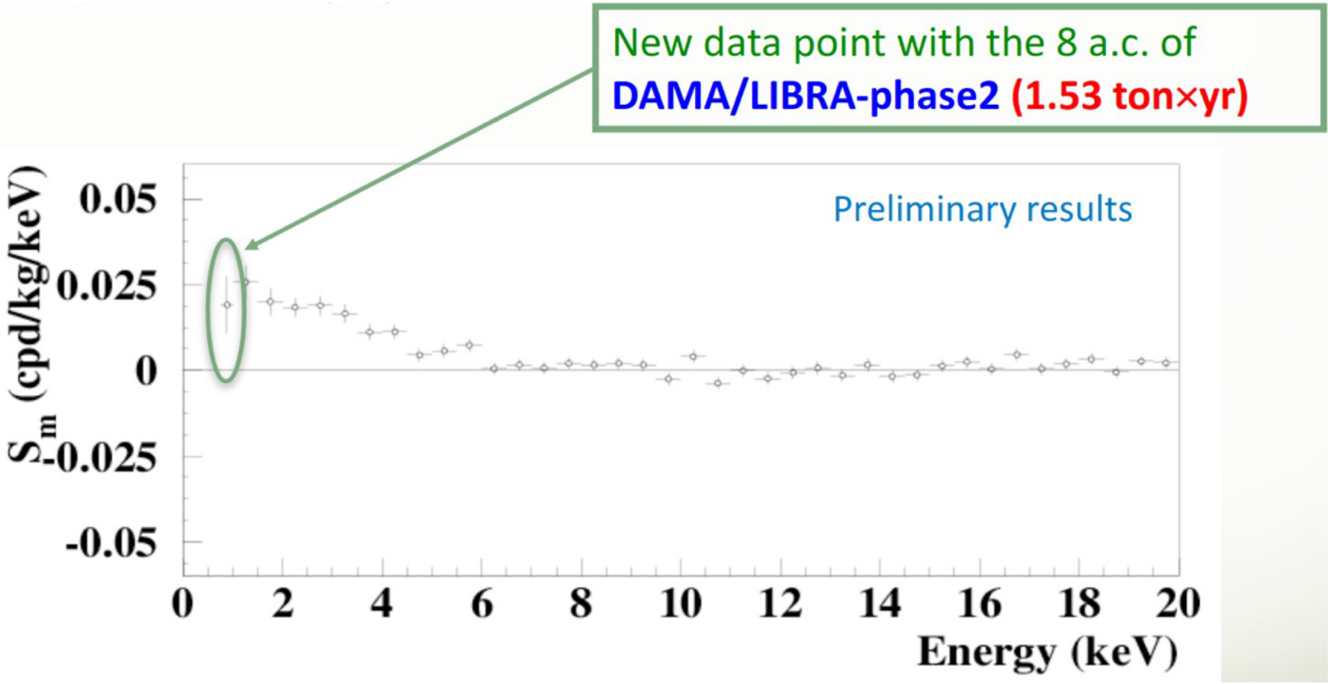
period: 0.99834 ± 0.00067 years * ✓

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

convincing non-DM explanation ✗

*in (2-6) keV_{ee} interval

WHAT'S NEW – LOWER ENERGY THRESHOLD



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

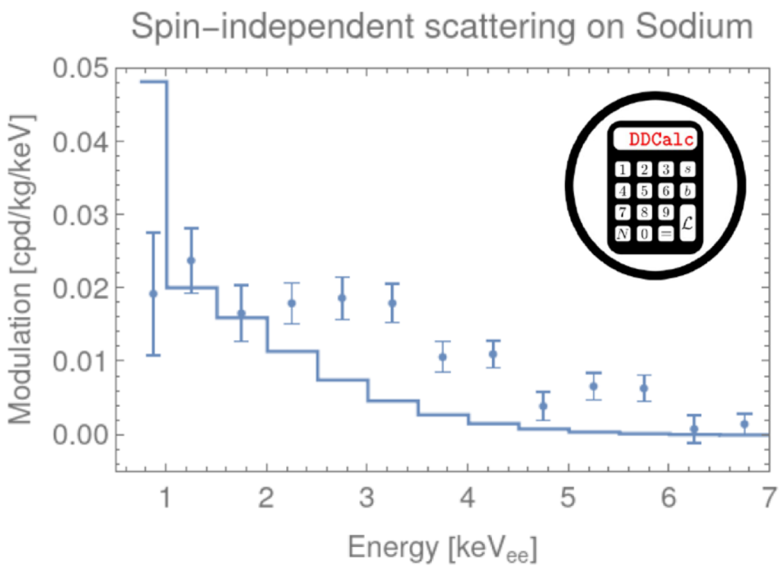
Phase 2 upgrade(s):

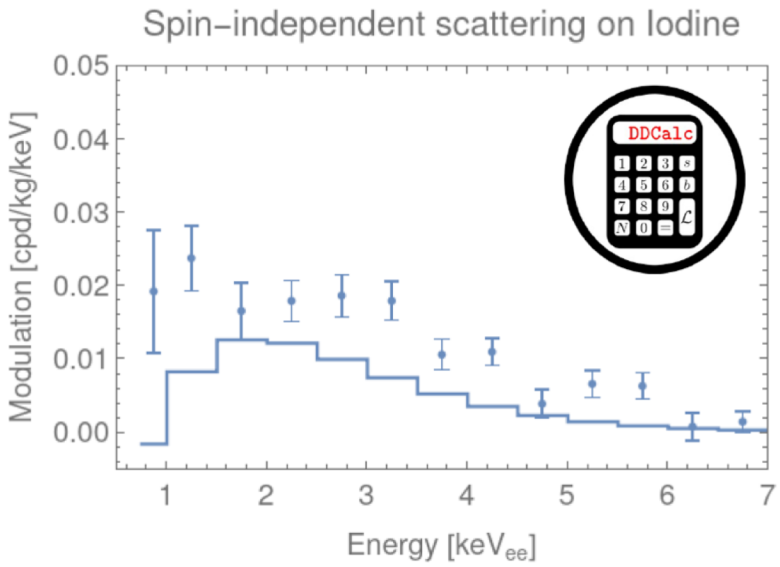
2010:
new PMTs with higher Q.E.
→ 1keV$_{ee}$ software threshold

2021:
new electronics and digitizers
→ 0.5keV$_{ee}$ software threshold
→ data taking since 12/2021

→ past experience:
DAMA released results after 3 annual cycles → early 2025 ?

WHAT'S NEW – STANDARD SCENARIO





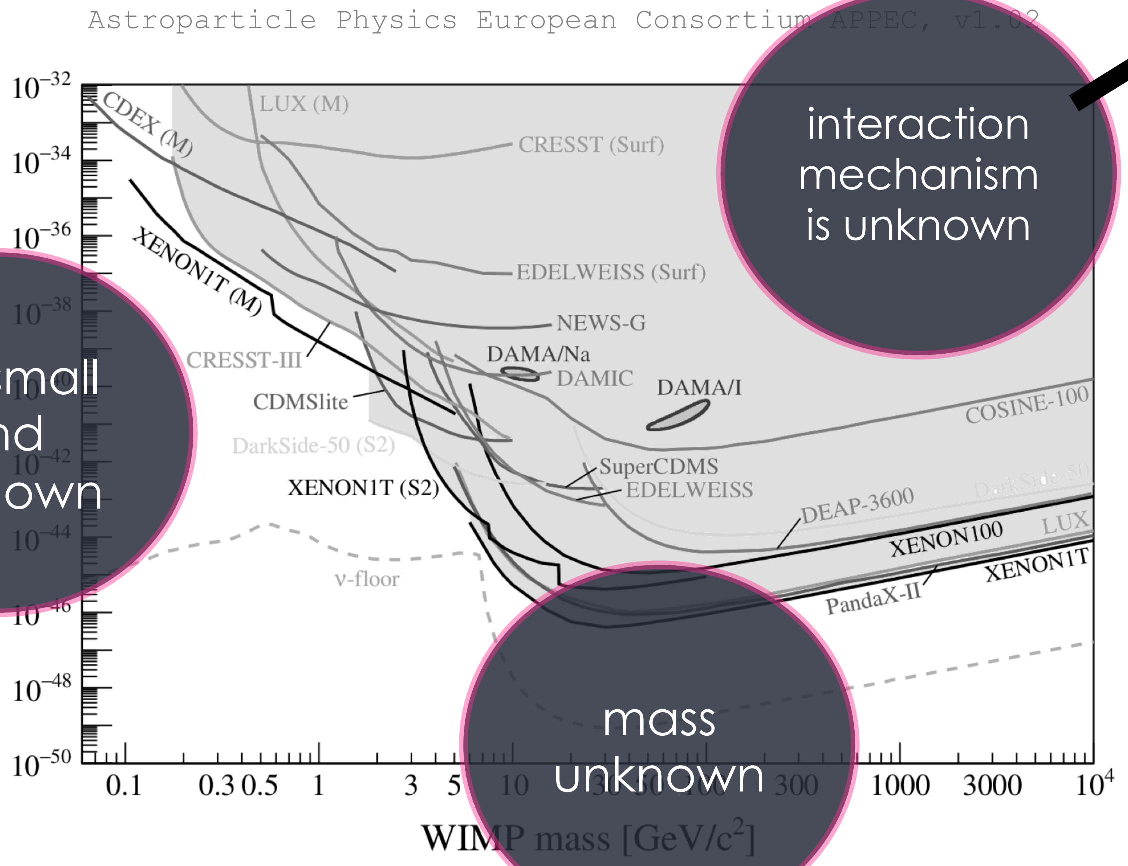
spin-independent scattering
no longer gives a good fit!

Credits to F. Kahlhoefer, IDM 2022

SUMMA SUMARUM – DAMA

- statistically solid observation of modulation in the energy interval (0.75- 6) $\mathrm{keV_{ee}}$
- even lower threshold of 0.5 $\mathrm{keV_{ee}}$ achieved → data taking ongoing
- observed energy dependence of modulation amplitude in tension with standard scenario
- also in 2023 it remains difficult to reconcile DAMA versus other experiments

WHAT ARE THE **UNKNOWNS**?



σ is small and unknown

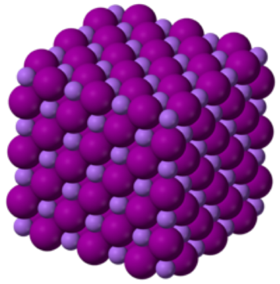
interaction mechanism is unknown

mass unknown

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

~ A²
~ form factor

→ **dependence on target material**



^{11}Na 53 I

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 <u>without need for assumptions!</u>

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

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!

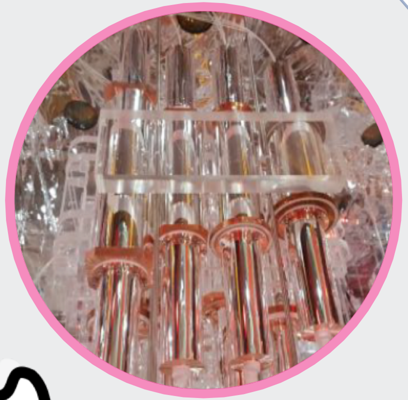
Challenge for DAMA-like searches:

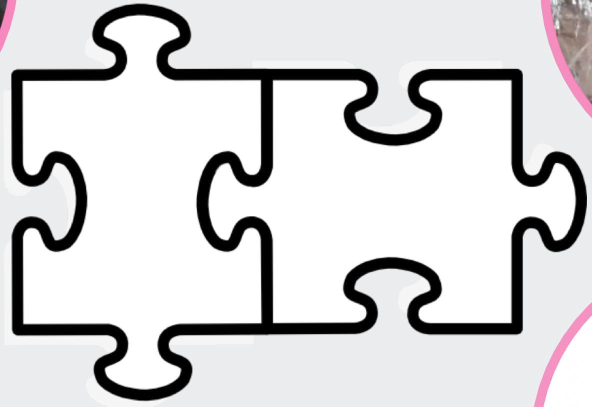
- sensitivity in the range (<1-6) keV_{ee}
- rate of ~ 1 count / (keV kg day), radiopure NaI crystal required
- large mass $\mathcal{O}$ (100 kg) and stable operation over multiple annual cycles

DAMA/LIBRA

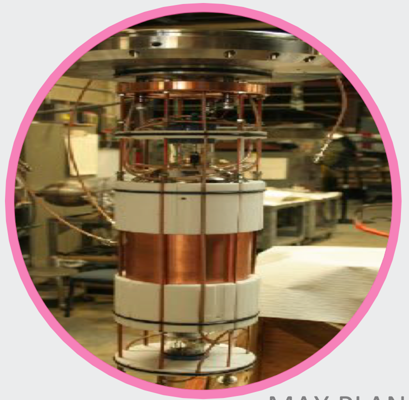
ANAIS-112

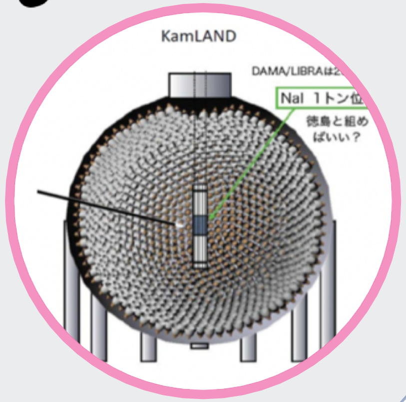
COSINE-100



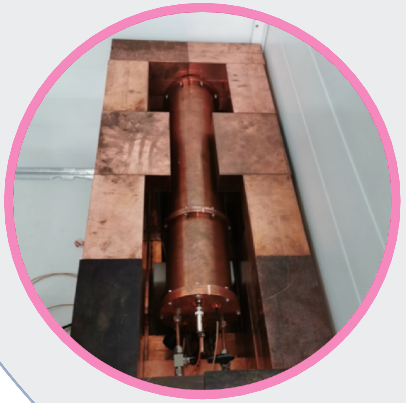


DM-Ice





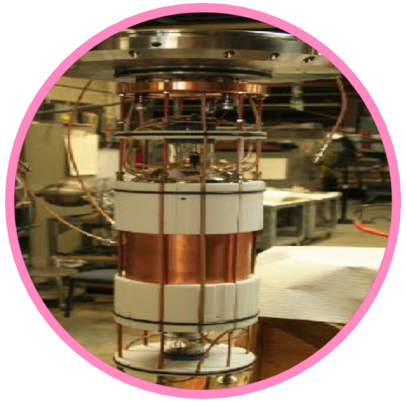
PicoLON



SABRE

NaI EXPERIMENTS à la DAMA

* not complete list



DM-Ice

South Pole
2200 m.w.e of ice

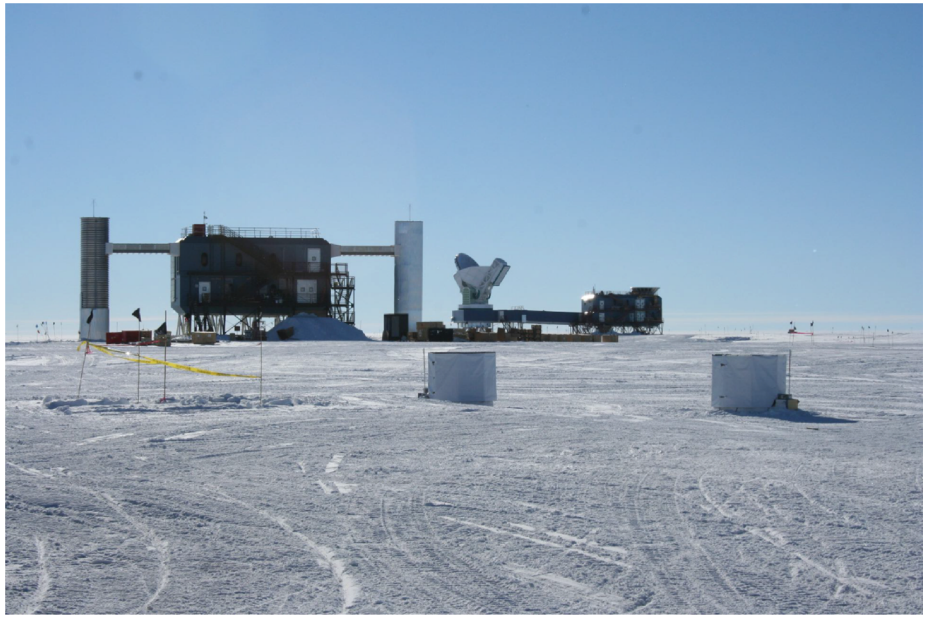
17 kg

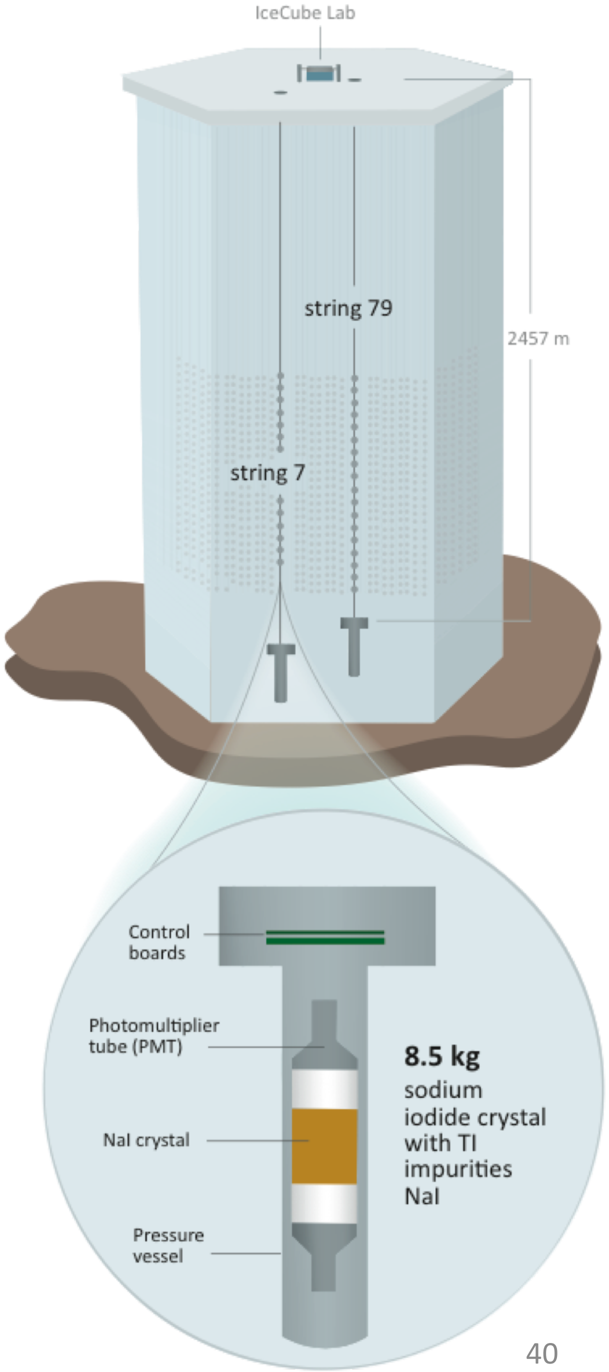
4 keV_{ee}

3.5 y of data

DM-Ice: **BACKGROUND**

- deployed in Dec, 2010
- 2200 m.w.e of overburden
- > 99% uptime
- total exposure: 60.8 kg yr
- ~10 counts / keV kg d
- energy range: 4–20 keVee

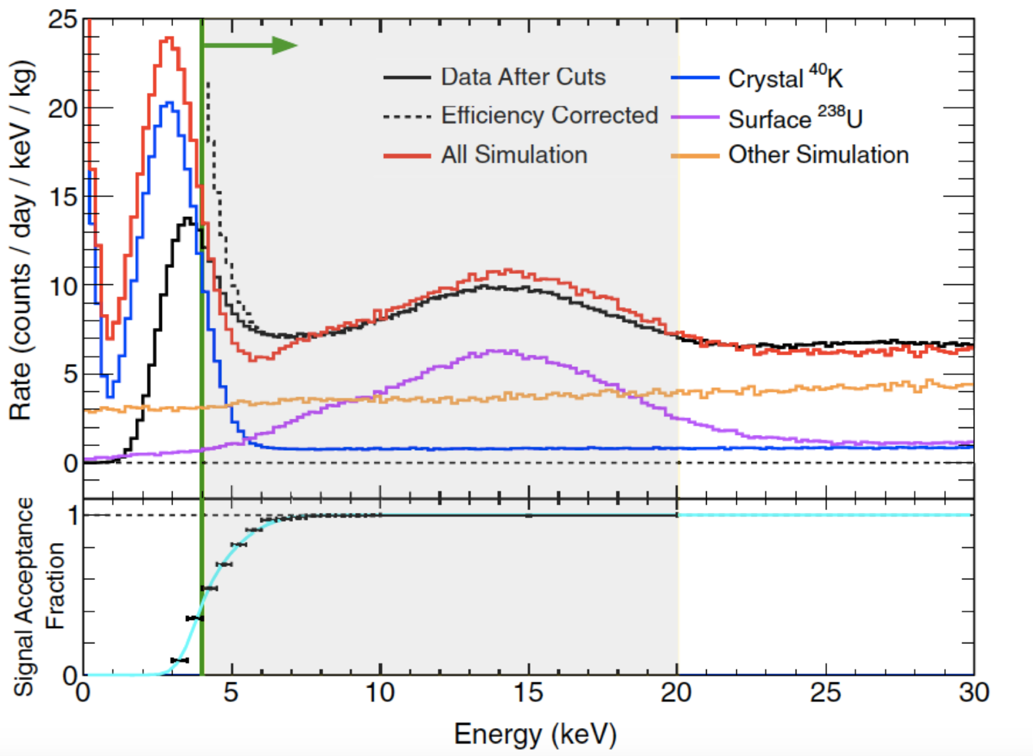


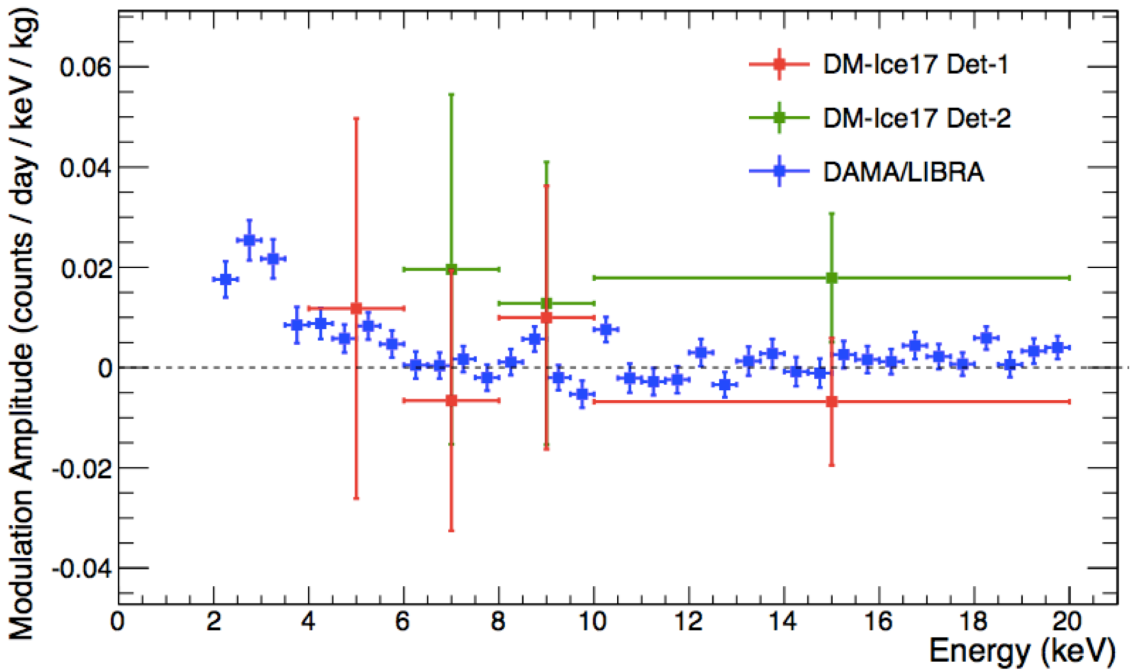


DM-Ice: **RESULT**

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

PHYSICAL REVIEW D **95,** 032006 (2017)

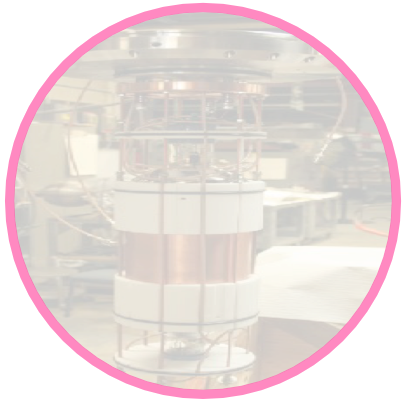




→ → sensitivity not sufficient to cross-check DAMA signal

* not complete list

NaI EXPERIMENTS à la DAMA



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4 keV_{ee}

3.5 y of data

COSINE-100

Korea @Y2L

106 kg

1 keV_{ee}

6.0 y of data

COSINE-100

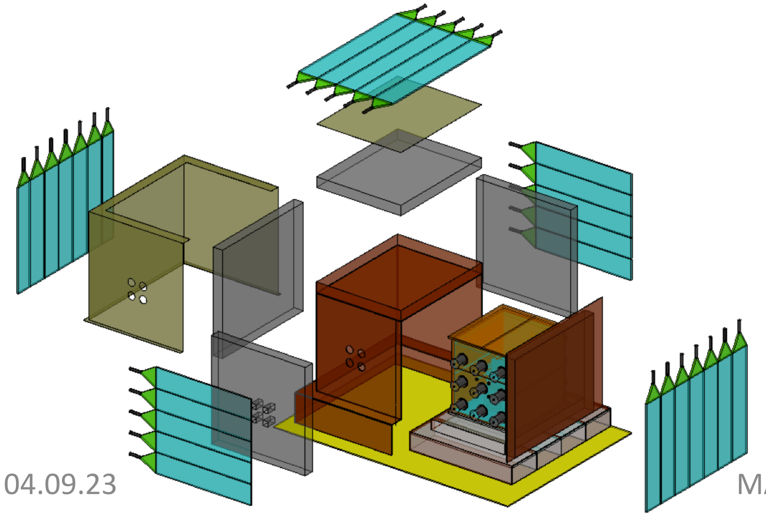
Joint venture KIMS NaI + DM-Ice
@ Y2L, South Korea

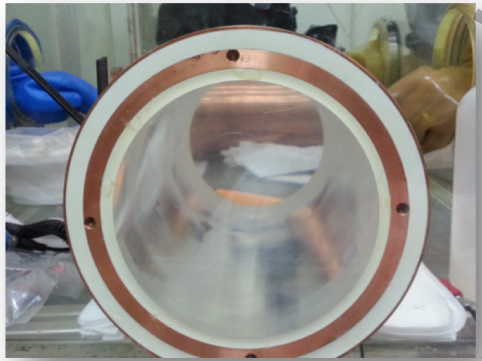
EPJC 78 107 (2018)

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

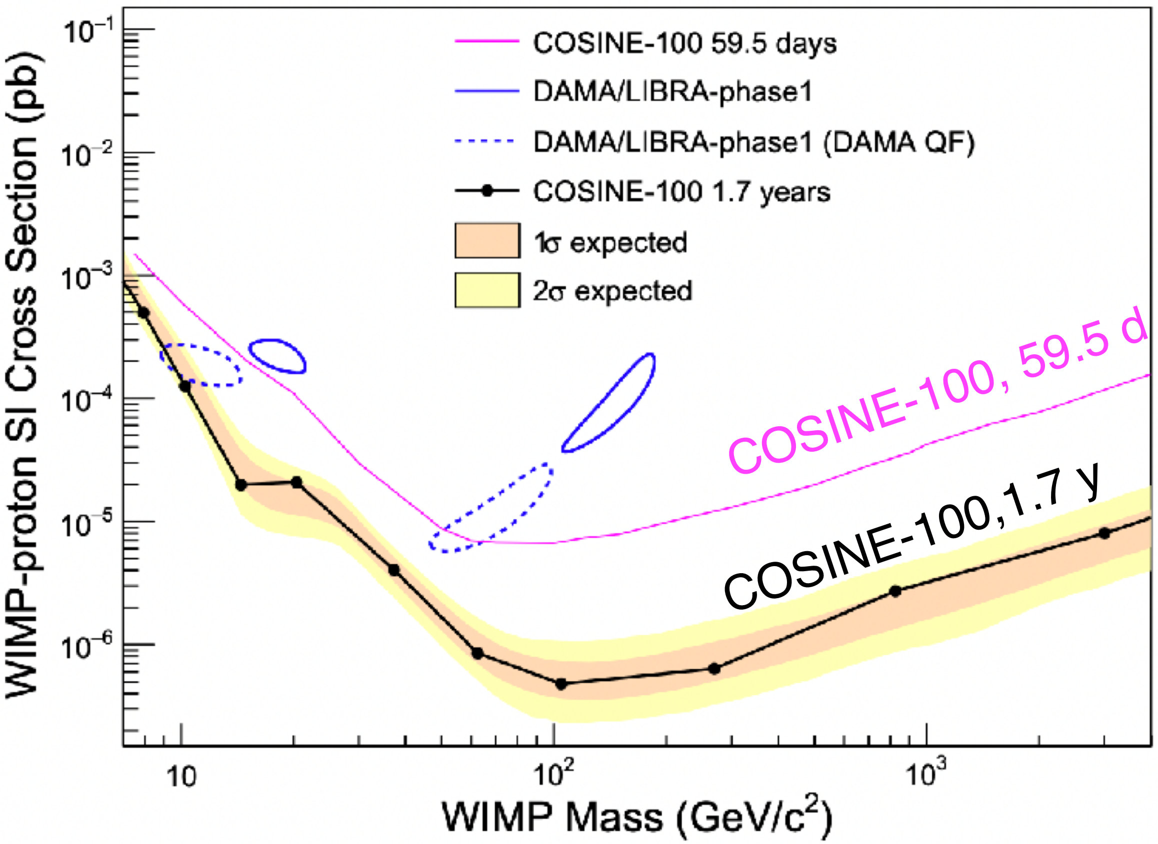
\+ **muon veto**

\+ **liquid scintillator to veto ^{40}K background**

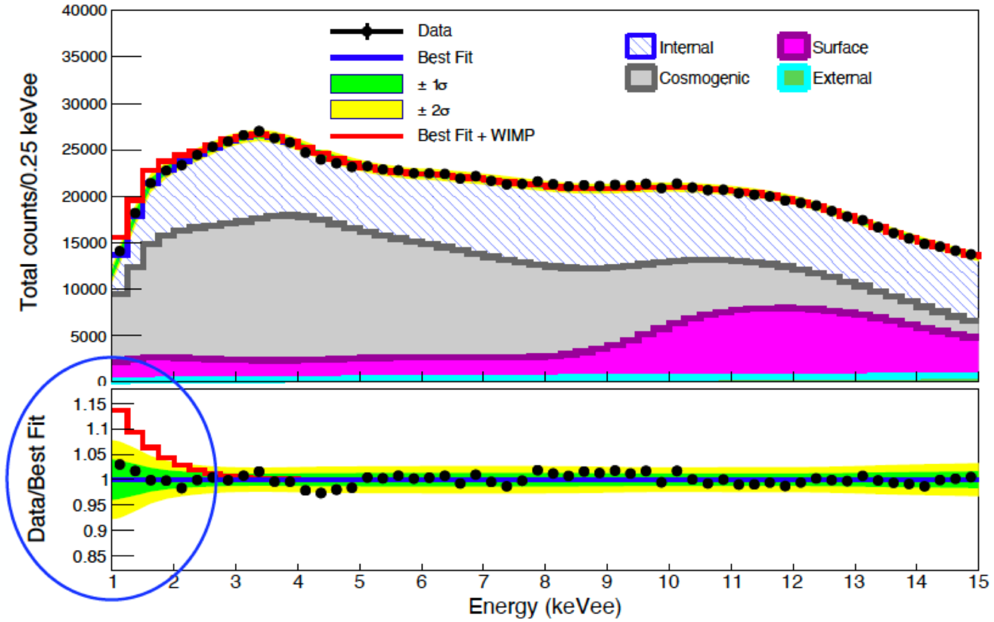




COSINE-100 – STANDARD SCENARIO



Nature 564, 83 (2018)
Sci Adv. 7, eabk2699 (2021)

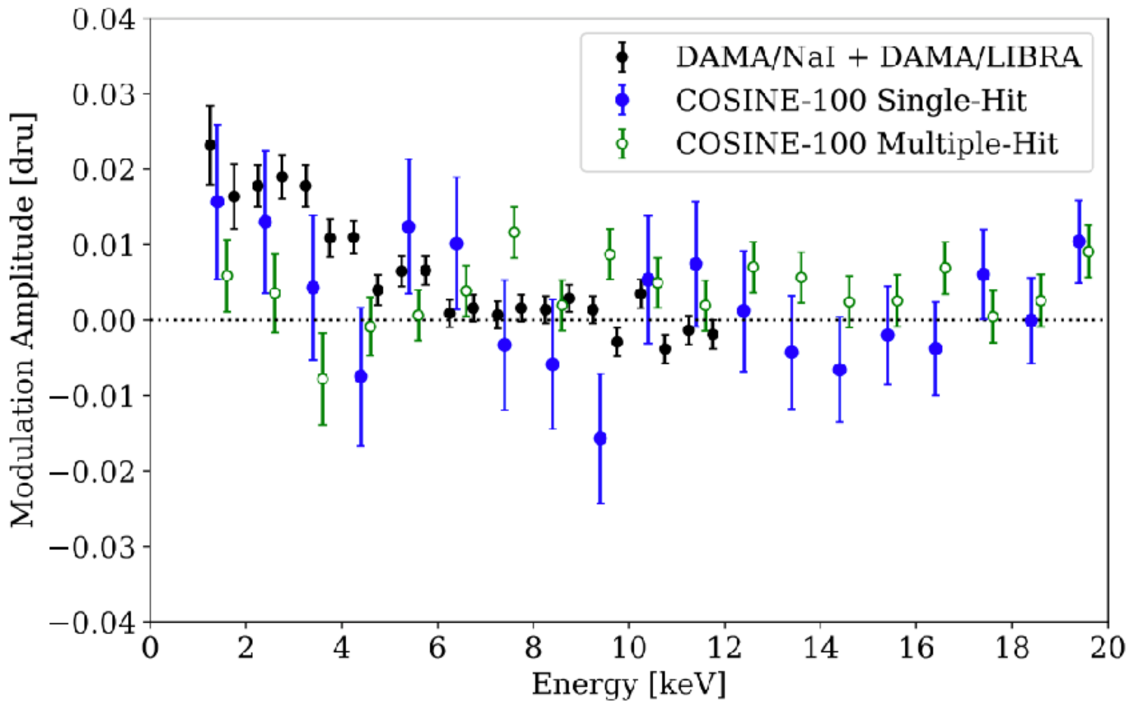


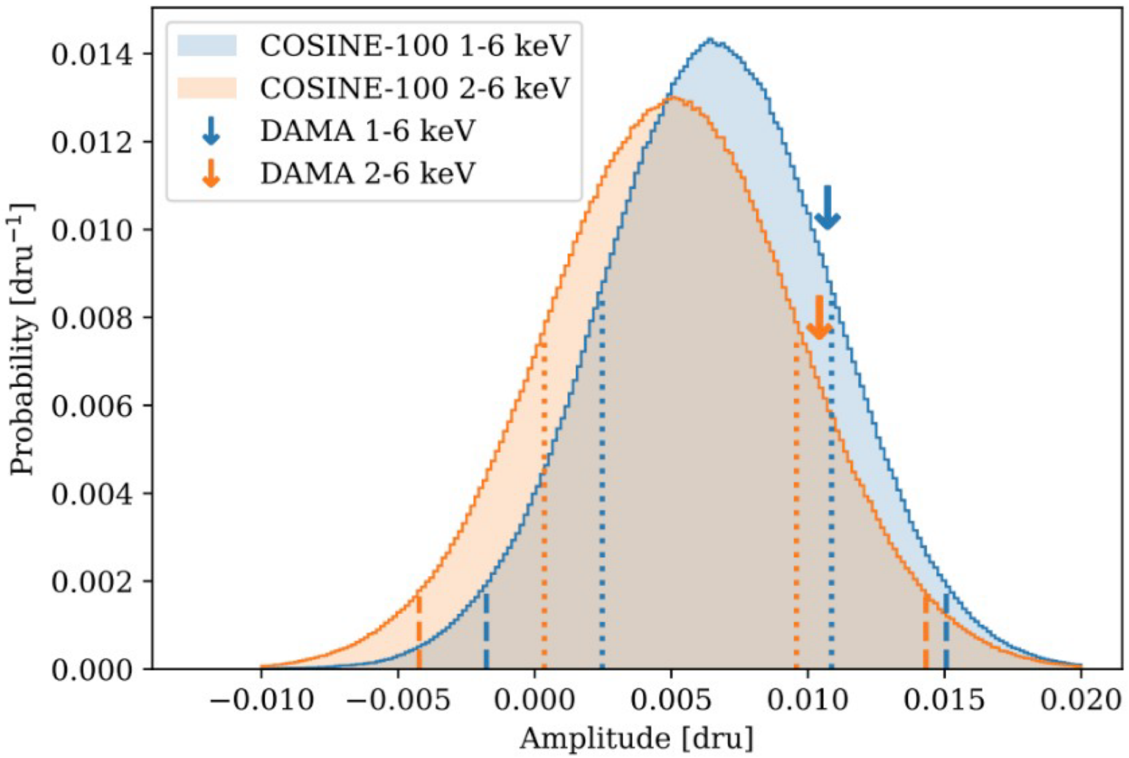
→ → DAMA excluded in standard scenario with cut + count

COSINE-100 – MODULATION SEARCH

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

PRD 106, 052005



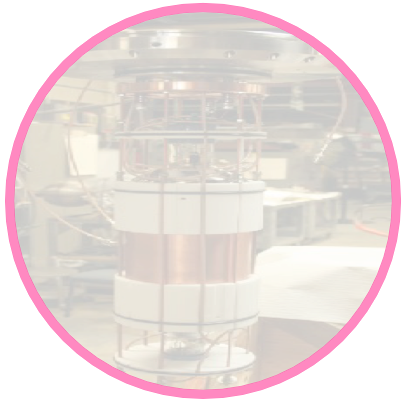


COSINE-100	**0.0067 ± 0.0042**
DAMA/LIBRA	0.0105 ± 0.0011
ANAIS-112	−0.0034 ± 0.0042

→ → data consistent with both DAMA and no modulation

NaI EXPERIMENTS à la DAMA

* not complete list



DM-Ice	COSINE-100	ANAIS-112
South Pole 2200 m.w.e of ice	Korea @Y2L	Spain @ LSC
17 kg	106 kg	112 kg
4 keV_{ee}	1 keV_{ee}	<1 keV_{ee}
3.5 y of data	6.0 y of data	since 2017 6 y of data

ANAIS-112

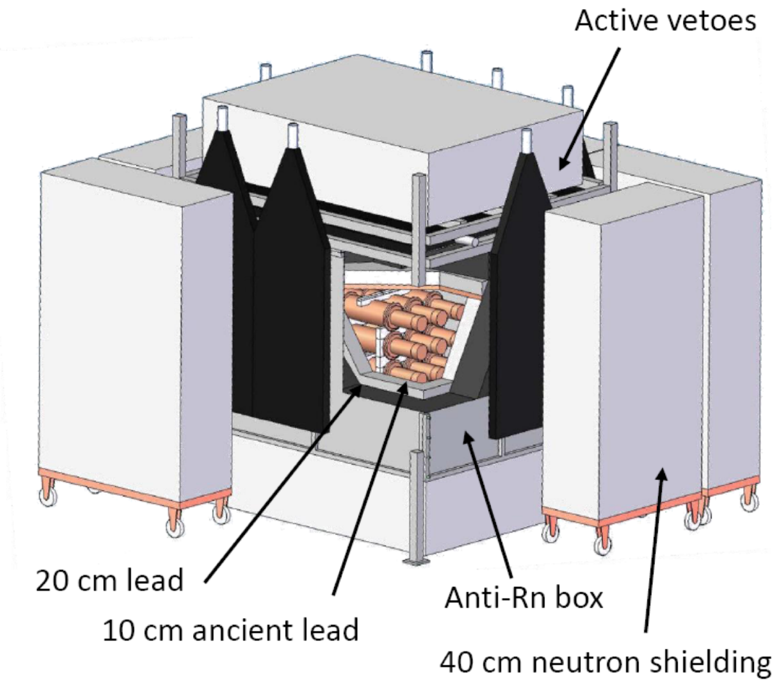
112 kg of pure NaI
@ Canfranc, Spain

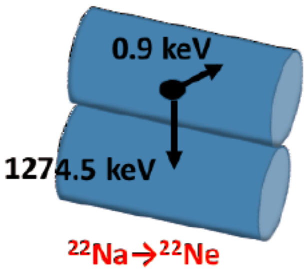
- operation since Aug, 2017
- 9 crystals in 3x3 array, 112.5 kg total

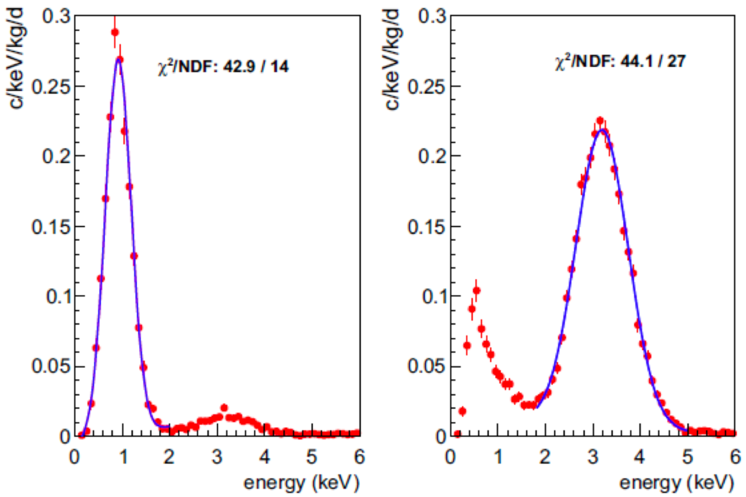
+ sub-keV calibration with internal

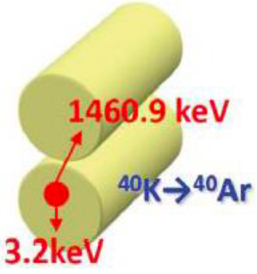
^{22}Na @ 0.9 eV and ^{40}K @ 3.2 keV

+ muon veto







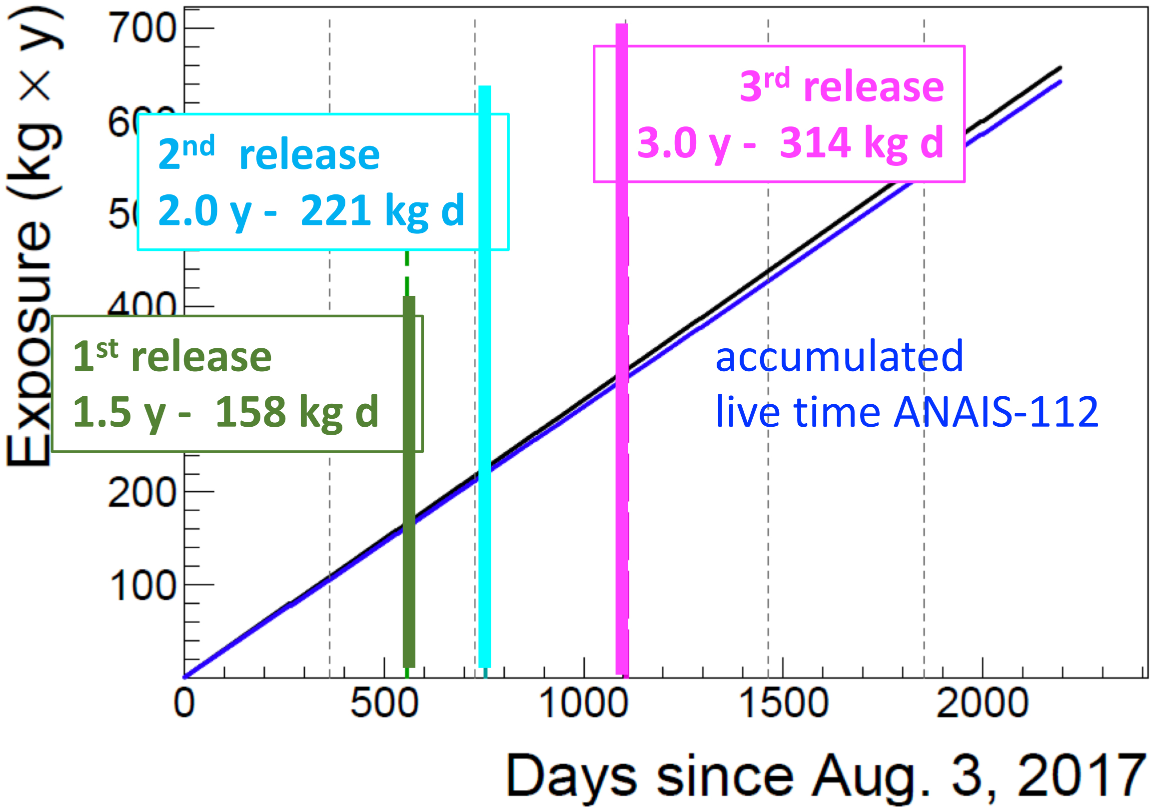


credits to M. Martinez

ANAIS-112

112 kg of pure NaI
@ Canfranc, Spain

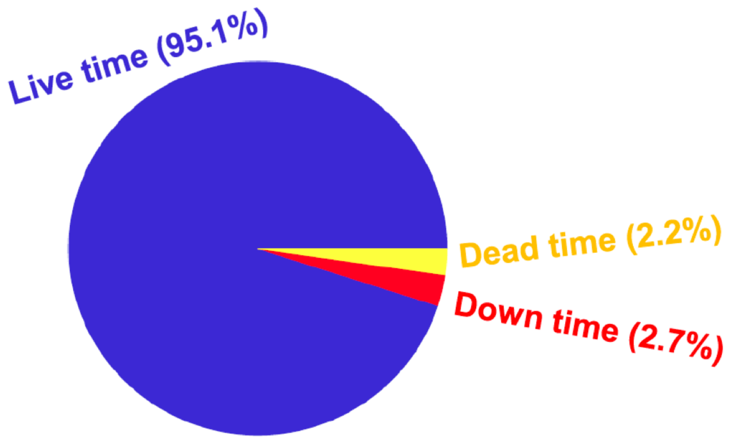
Credits to I. Coarasa



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

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

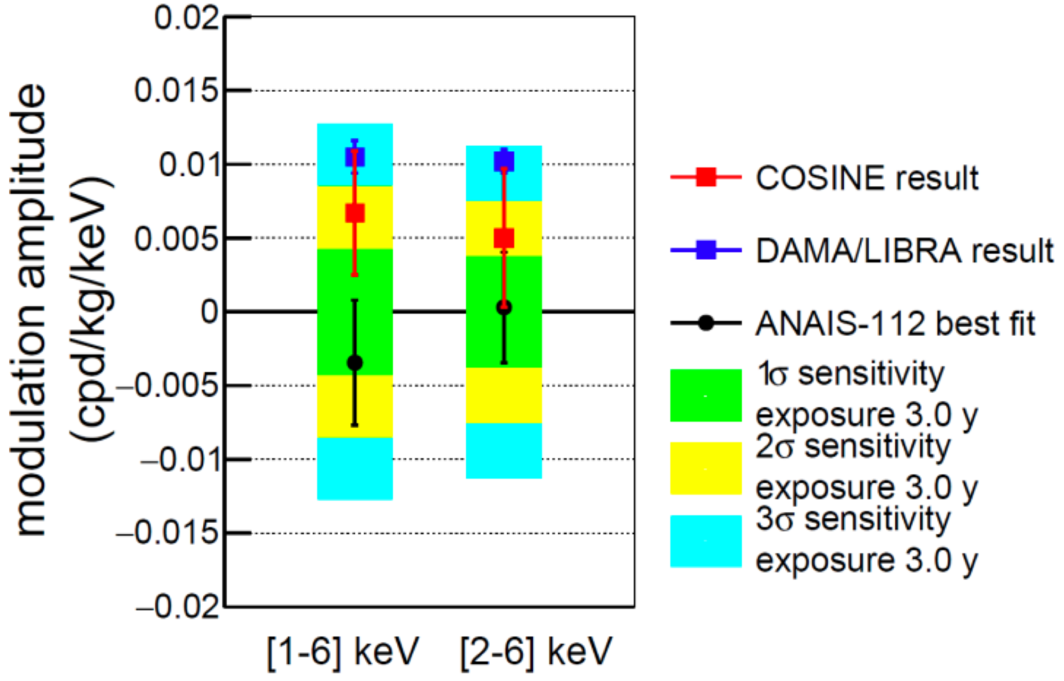
→ exposure: 643.48 kg y



ANAIS-112

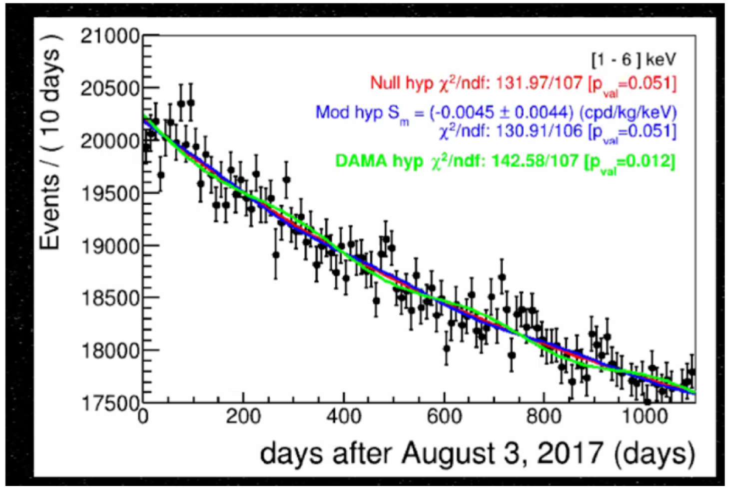
PRD 103, 102005 (2021)

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

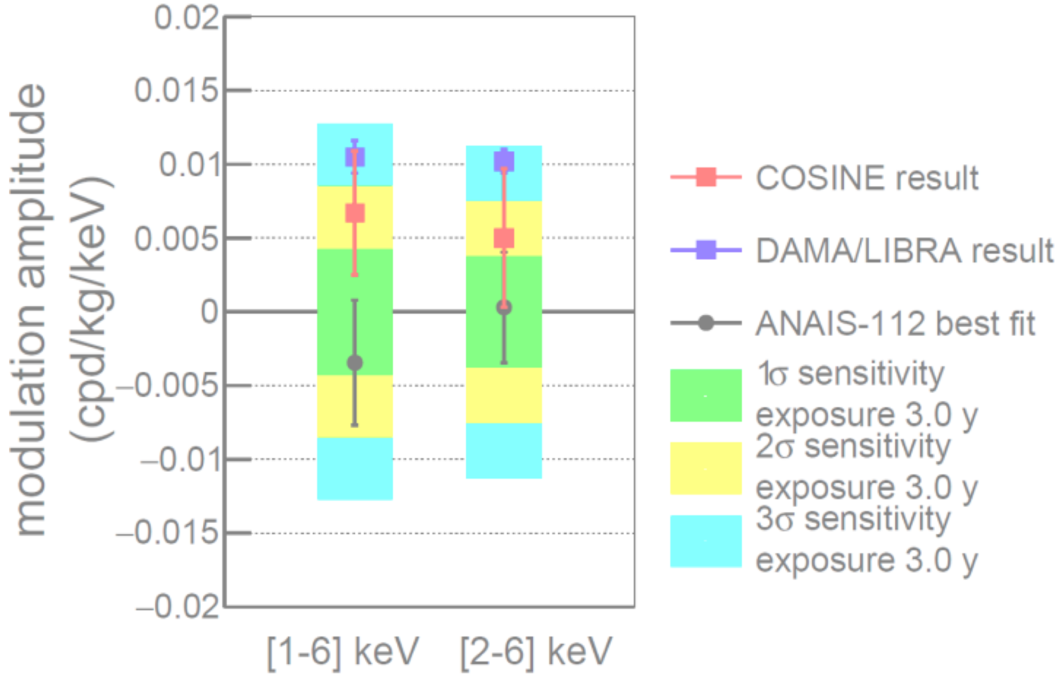
LATEST RESULTS (3 y)

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

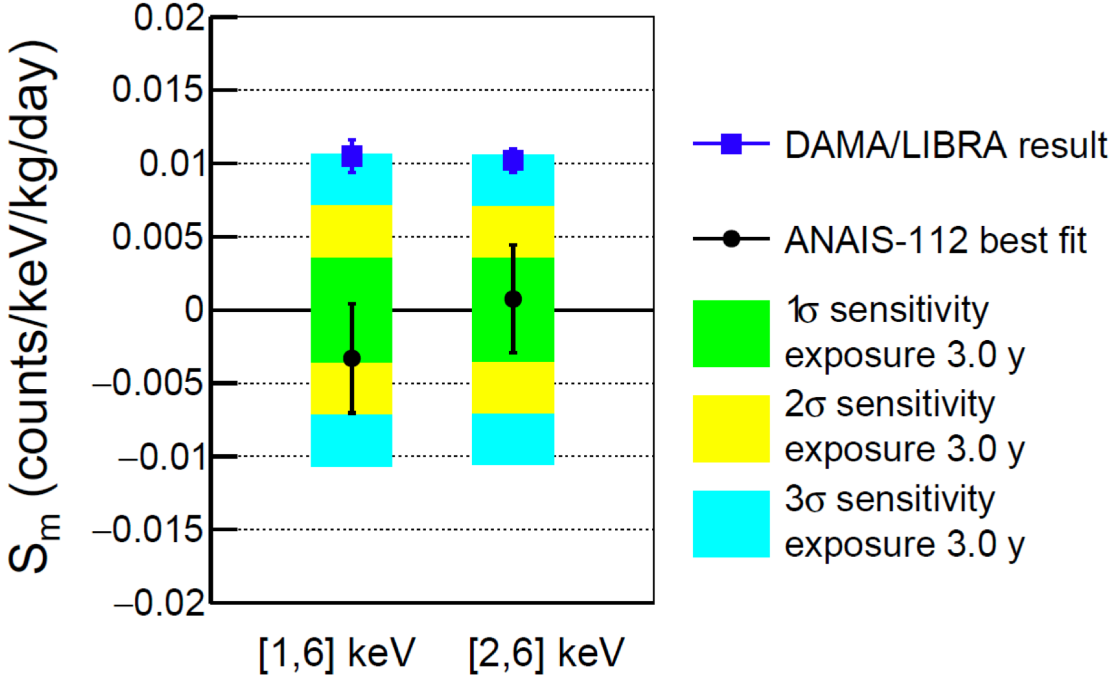
PRELIMINARY

112 kg of pure NaI
@ Canfranc, Spain



3 years of data

→ incompatible with modulation at the level of ~ 2.5 σ

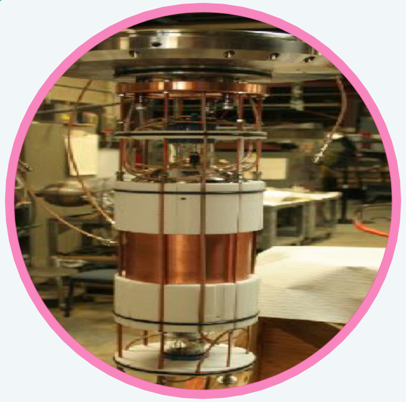


new multivariate analysis enhances sensitivity ~2.5σ → 2.9σ

5 σ exclusion at reach in late 2025

* not complete list

NaI EXPERIMENTS à la DAMA



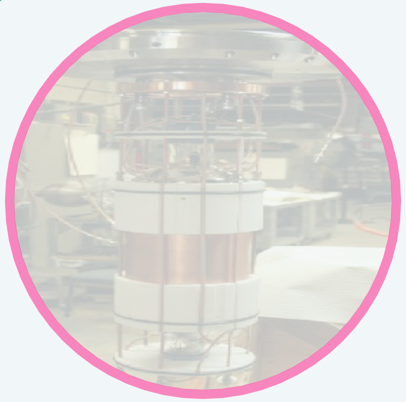
DM-Ice	COSINE-100	ANAIS-112
South Pole 2200 m.w.e of ice	Korea @Y2L	Spain @ LSC
17 kg	106 kg	112 kg
4 keV_{ee}	1 keV_{ee}	<1 keV_{ee}
3.5 y of data	6.0 y of data	since 2017 6 y of data

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

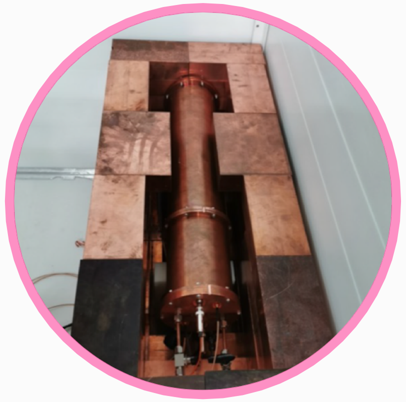
Spain @ LSC

112 kg

<1 keV_{ee}

since 2017
6 y of data

DATA TAKING



SABRE

Italy @ LNGS
Australia @ Stallwell

30-50 kg

PoP 2021

in construction

IN MAKING

SABRE north + south

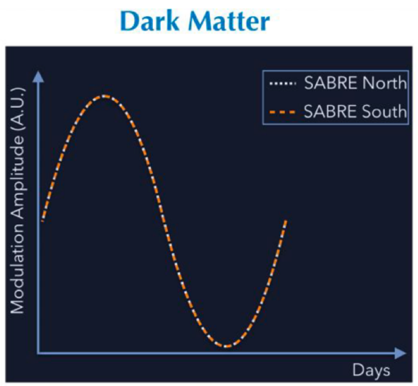
+ two experimental side:
→ northern hemisphere @ LNGS, Italy
→ southern hemisphere @ Stawell, Australia

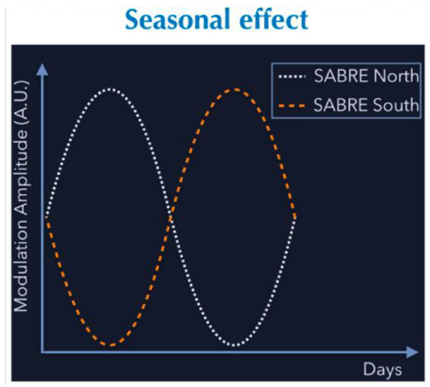
+ low background crystal production:
→ rate goal: ~0.5 count/d kg keV

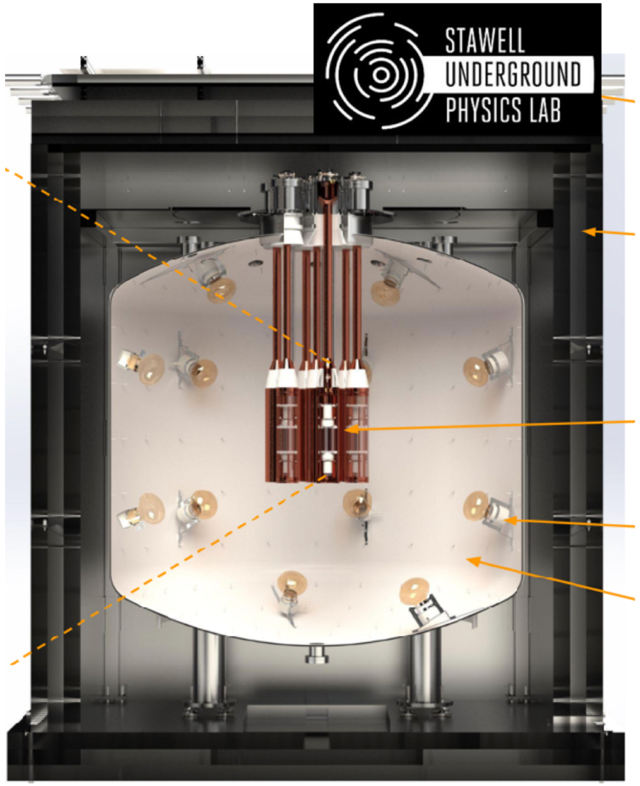
proof-of-principle detector operated without active shield at LNGS in 2021:

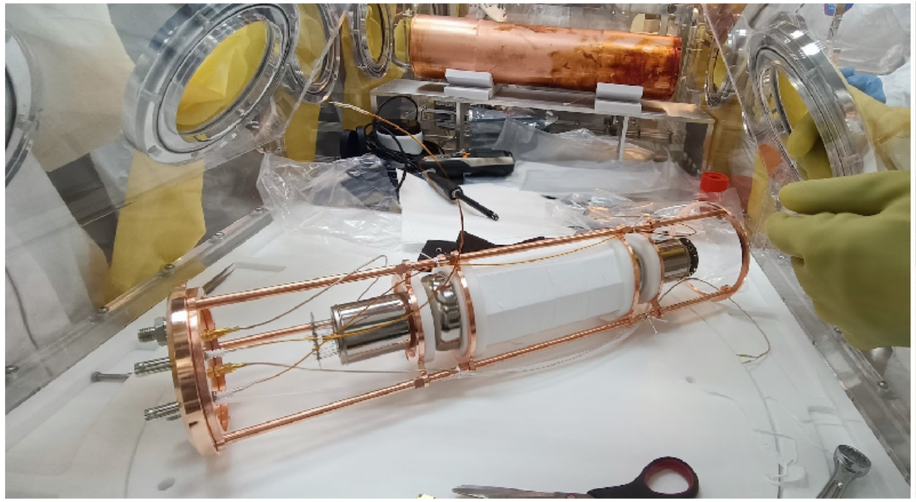
~ 1 count/d kg keV

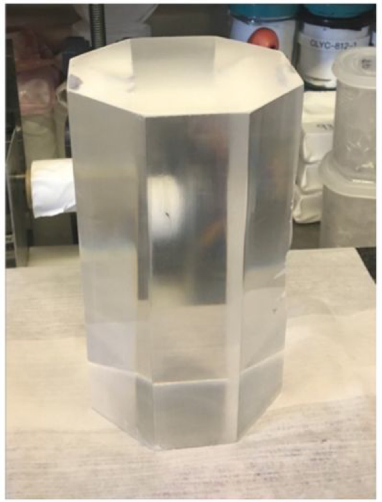
→ aim for (30 – 50) kg total mass





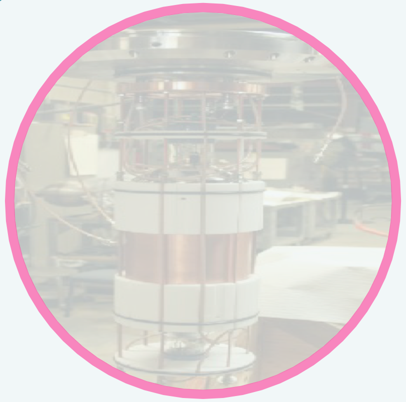


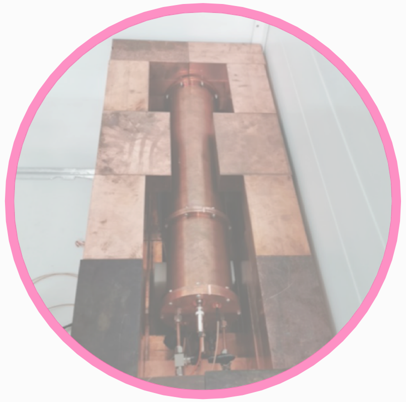
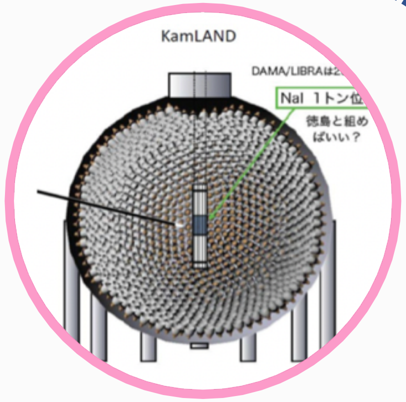




* not complete list

NaI EXPERIMENTS à la DAMA

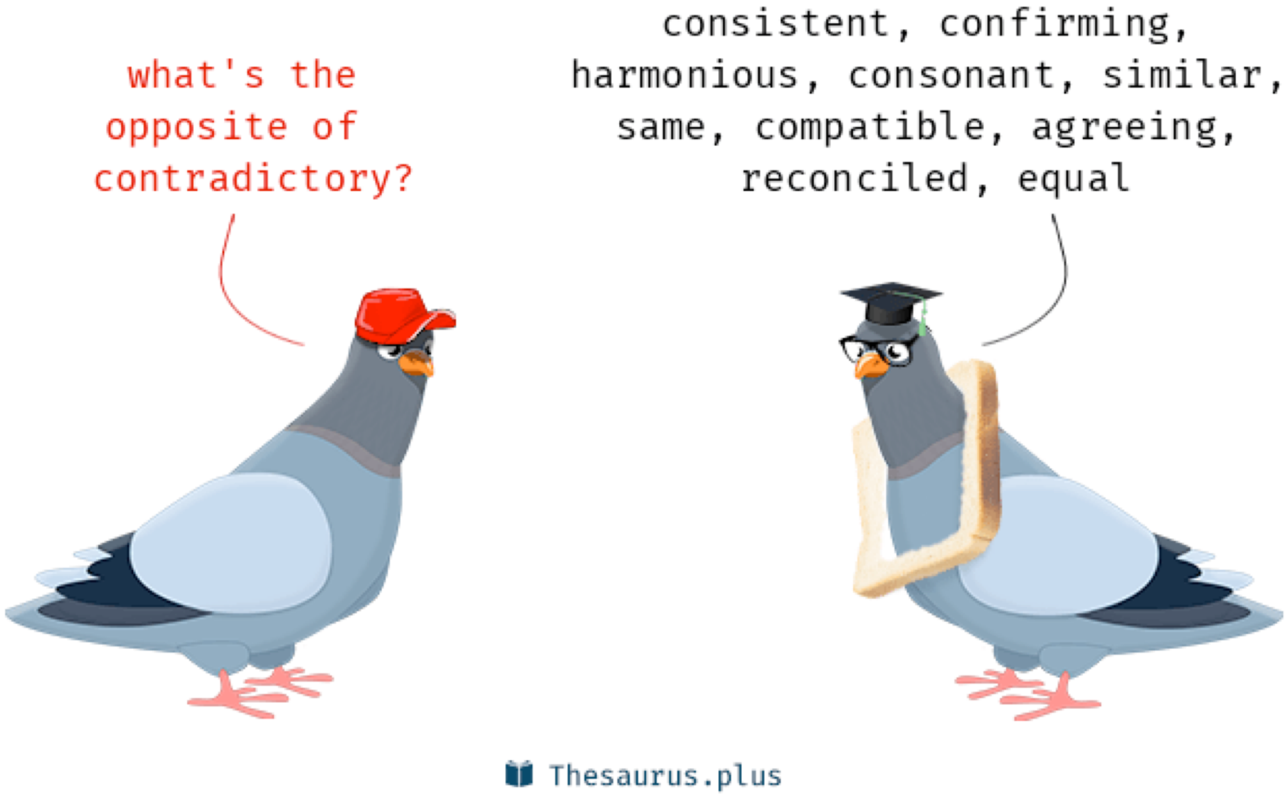


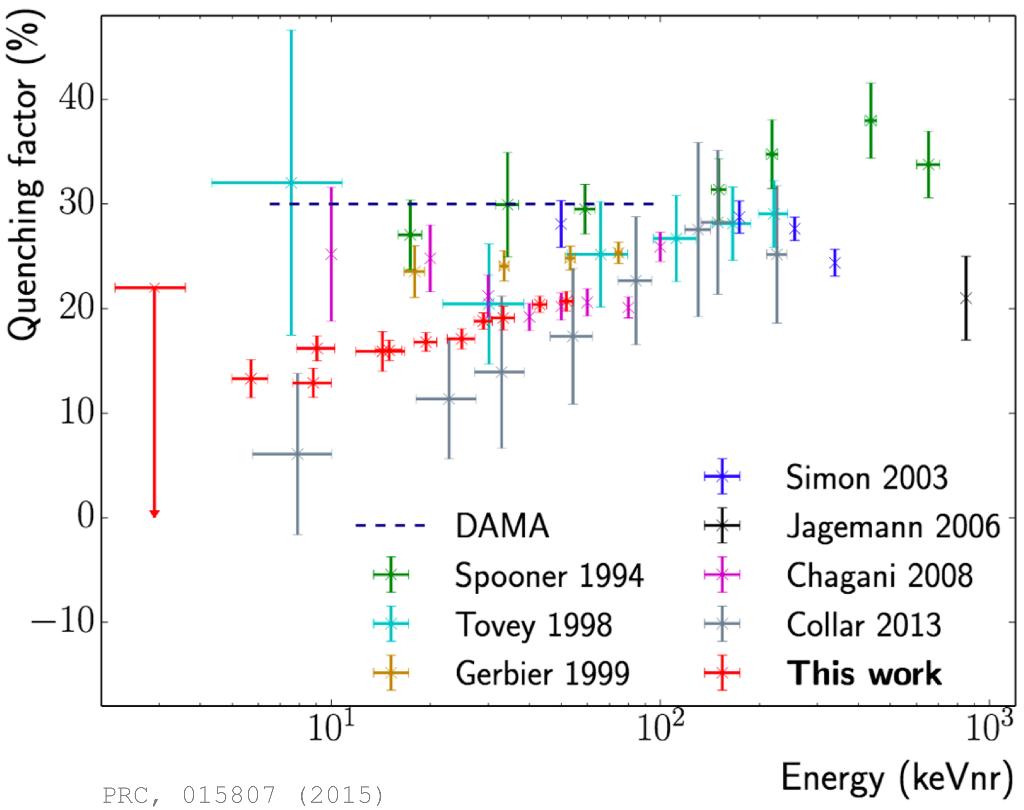
DM-Ice	**COSINE-100**	**ANAIS-112**	**SABRE**	**PicoLON**
South Pole 2200 m.w.e of ice	Korea @Y2L	Spain @ LSC	Italy @ LNGS Australia @ Stallwell	Japan @ Kamland
17 kg	106 kg	112 kg	30-50 kg	staged approach 54→250→1000 kg
4 keV_{ee}	1 keV_{ee}	<1 keV_{ee}	PoP 2021	
3.5 y of data	6.0 y of data	since 2017 6 y of data	in construction	planning phase

DATA TAKING

IN MAKING


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

CHALLENGE 1: SYSTEMATIC UNCERTAINTY



PRC, 015807 (2015)

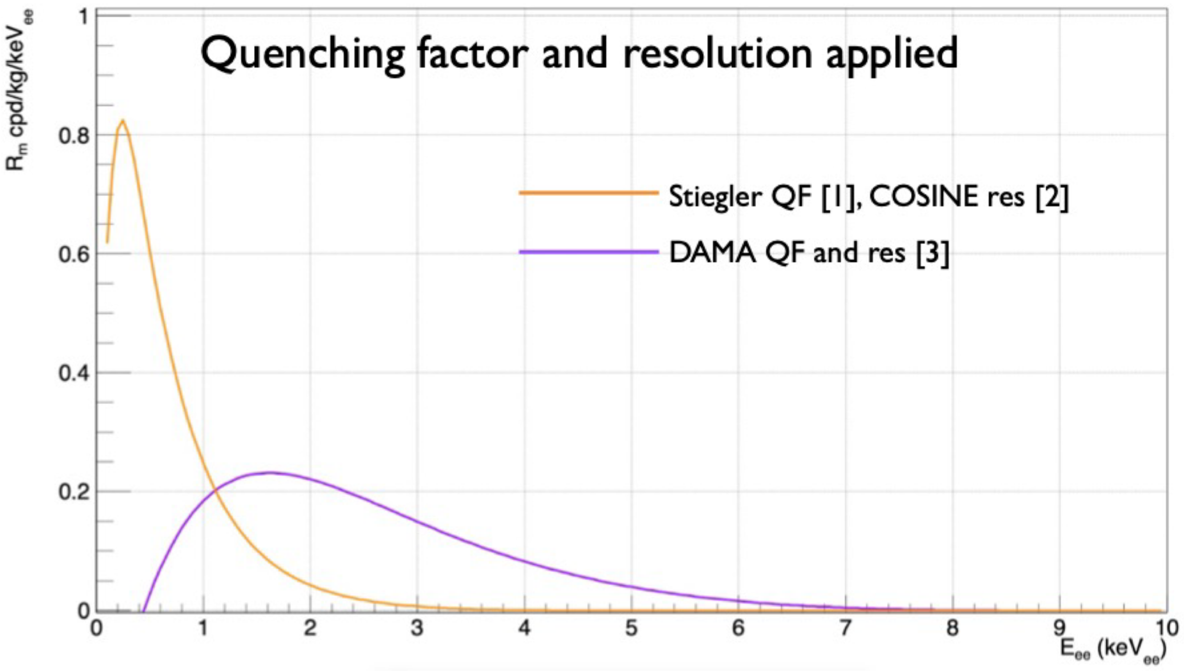
quenching factors are uncertain

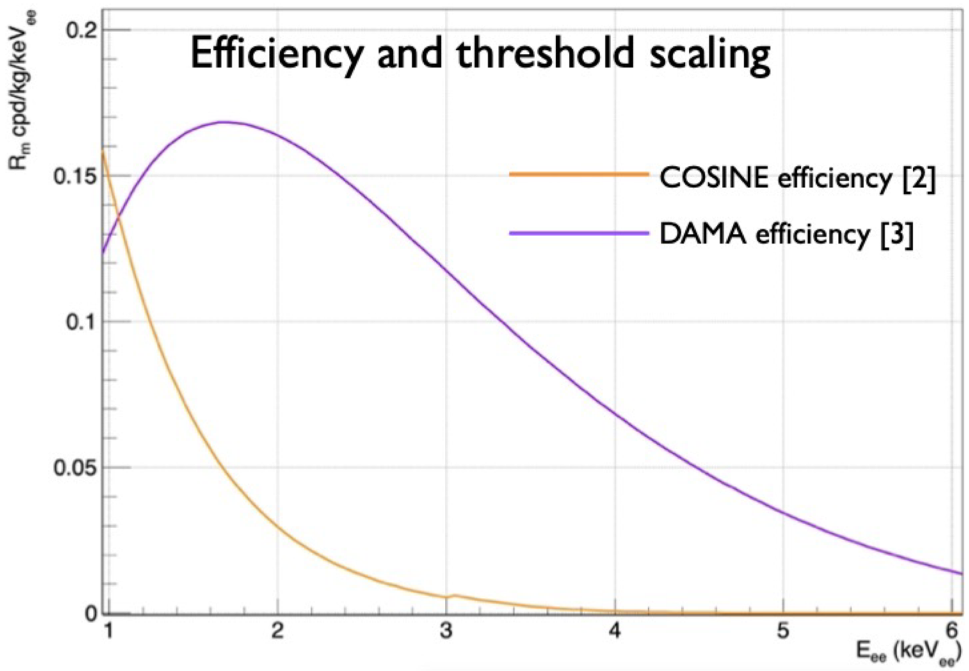
→ uncertainty on the nuclear recoil energy scale

→ comparison of results not solid

CHALLENGE 1: SYSTEMATIC UNCERTAINTY

DM with m=10 GeV, σ=1.15×10^{-39}cm^2 → Plots from M. Zurowski @ IDM 2022

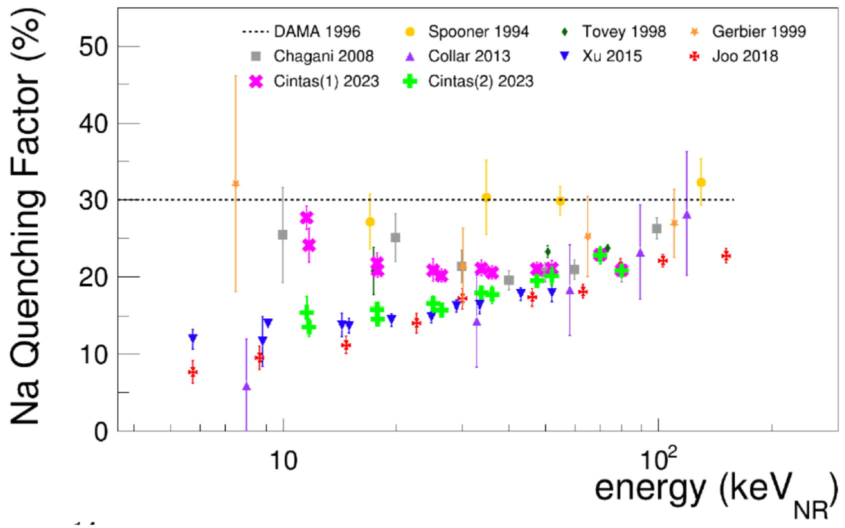




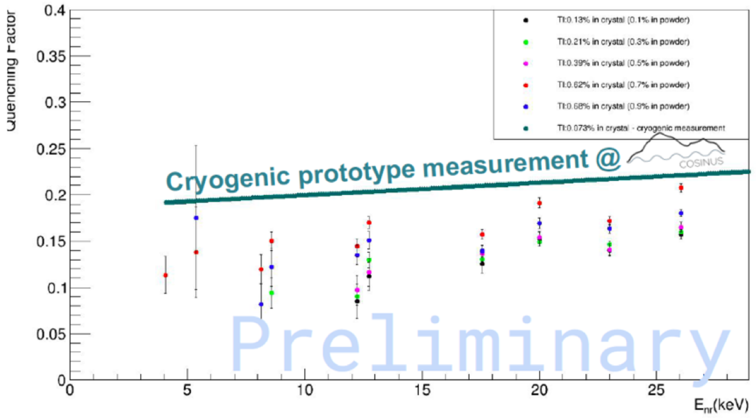
→ comparison of results suffers from systematics

WORKING ON THE QUENCHING FACTOR(S)…

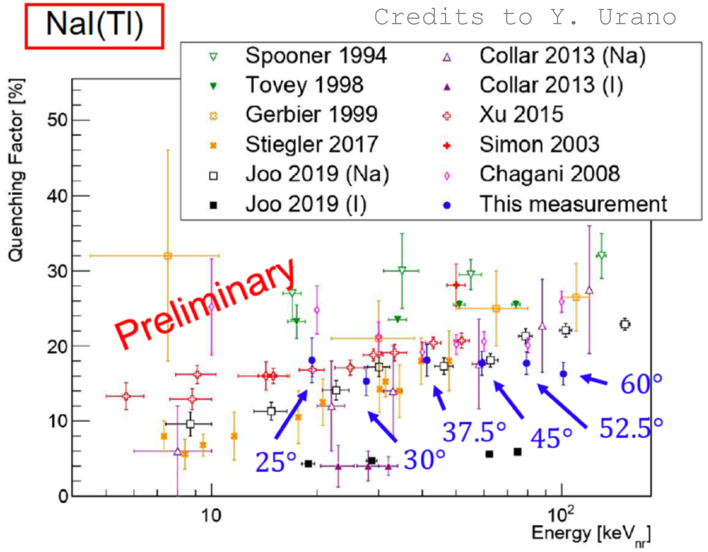
Credits to T. Pardo



This study Credits to R. Maji



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

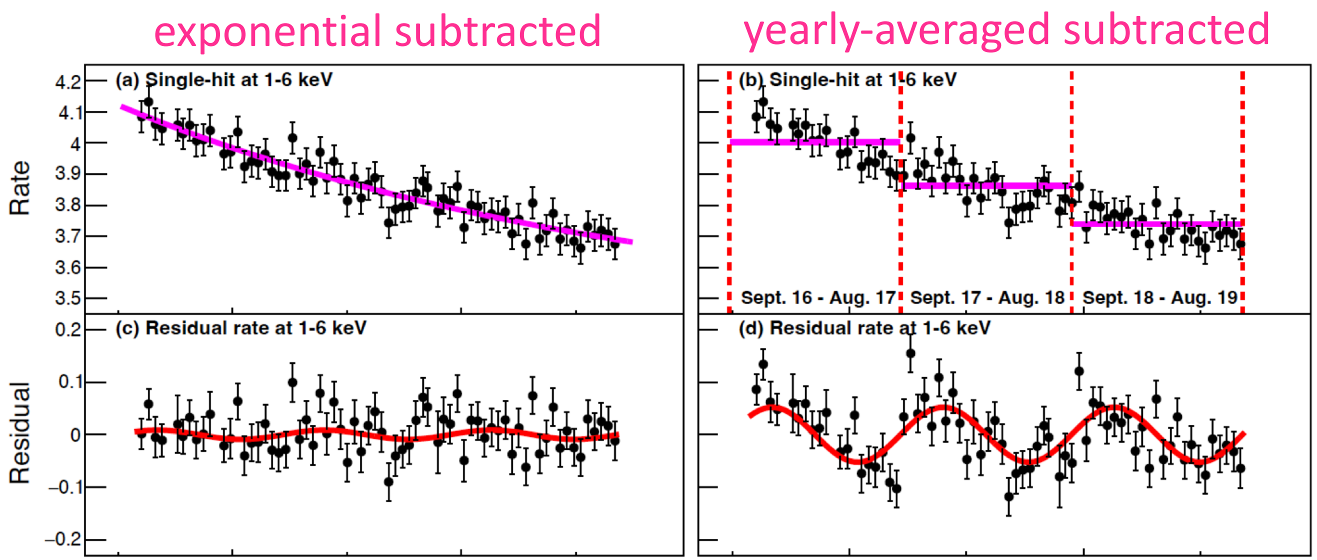
→ first QF studies done @ IAE facility, Japan

… → 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:



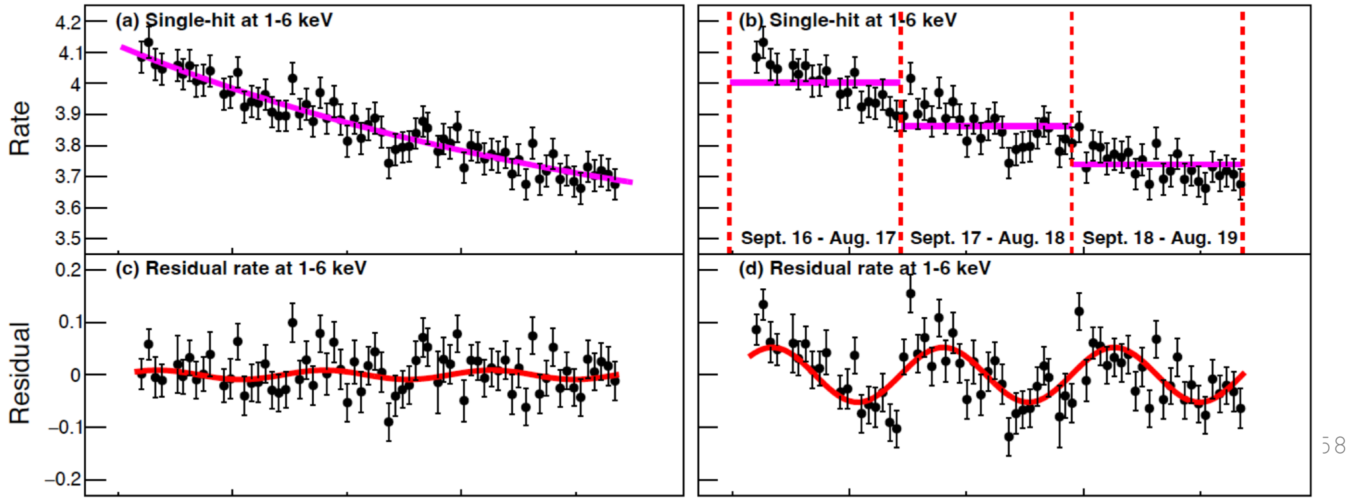
→ **high modulation amplitude (4 x DAMA) at 7σ C.L.**

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:

exponential subtracted   yearly-averaged subtracted



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

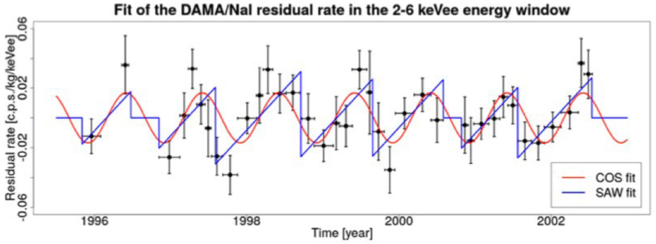
BUT

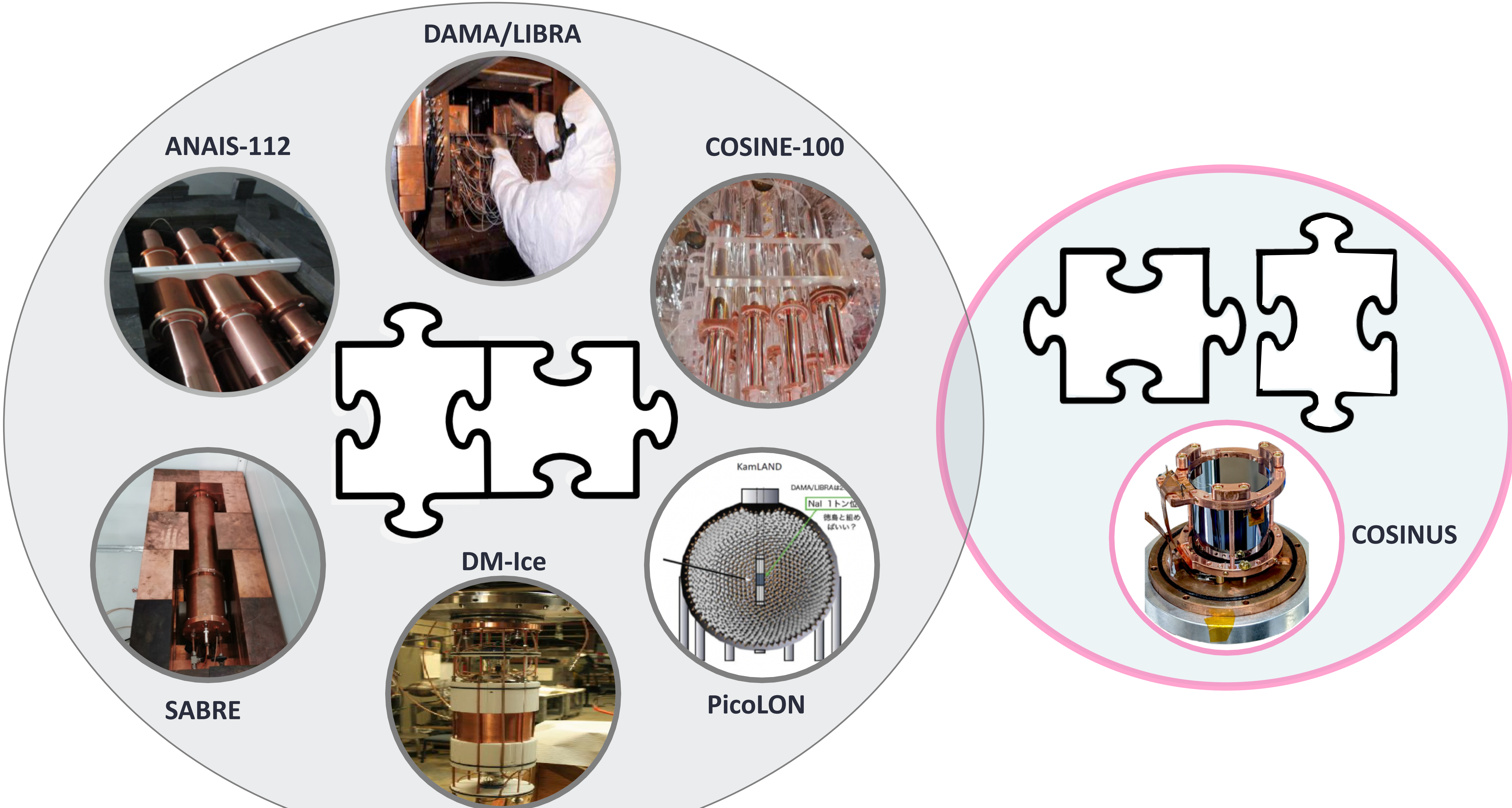
1) DAMA claims constant bckg. (but does not show rate vs. time)

2) wrong by 1pi (= sign)

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

JCAP 04 (2020) 037



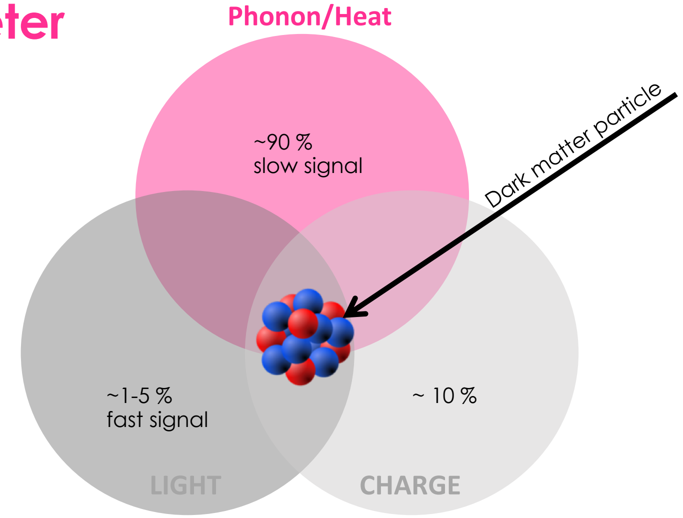

DAMA/LIBRA
ANAIS-112
COSINE-100
SABRE
DM-Ice
KamLAND
PicoLON
COSINUS

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**

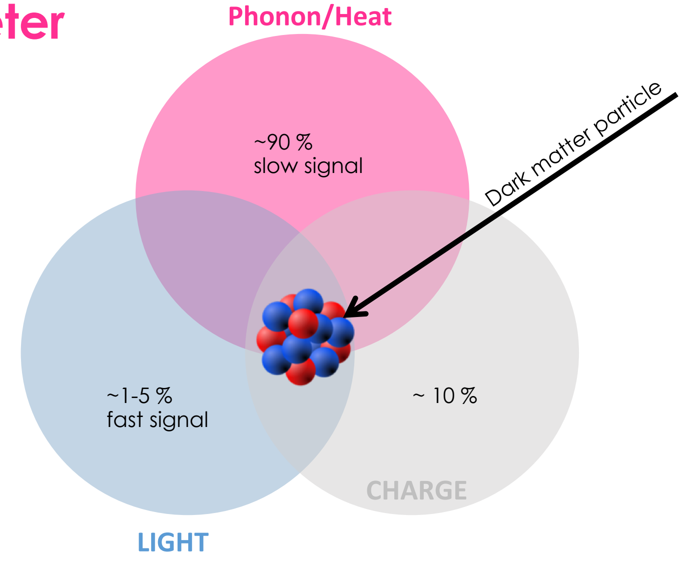
COSINUS

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**

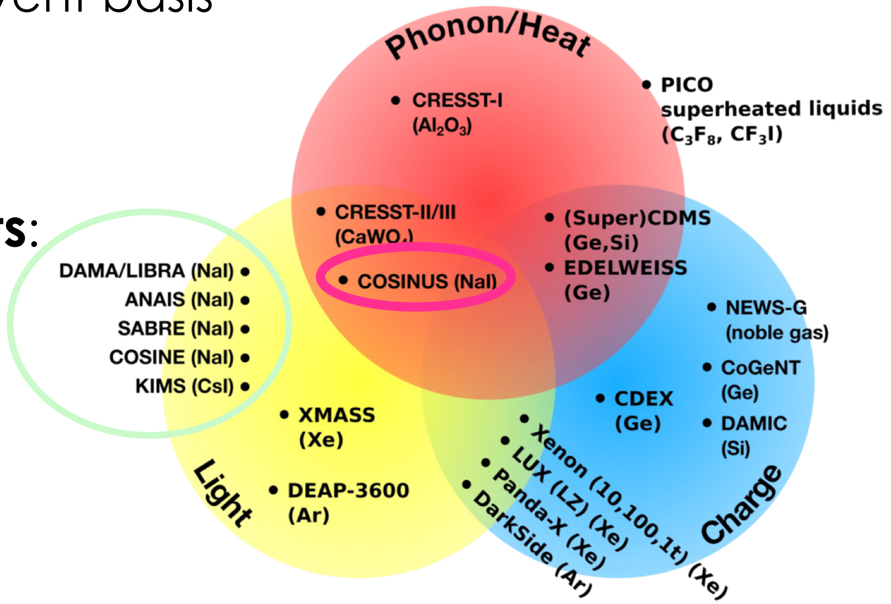
- HEAT CHANNEL: precise energy information
  \+ low threshold for nuclear recoils

- LIGHT CHANNEL: particle identification on event-by-event basis

IMMUNE to challenges of the DAMA-like experiments:

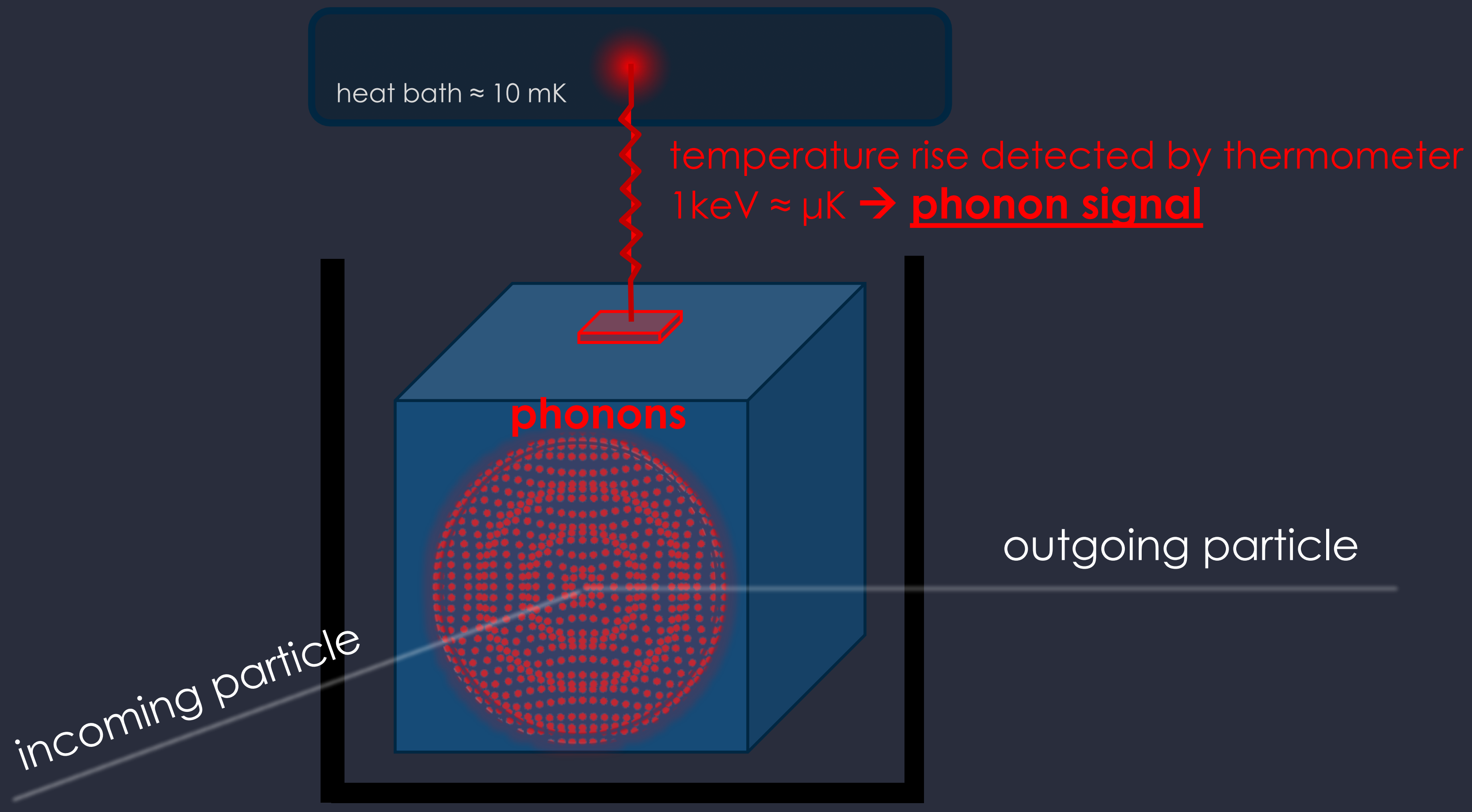
→ signal-only measurement of potential DM signal

→ in-situ measurement of the quenching factor

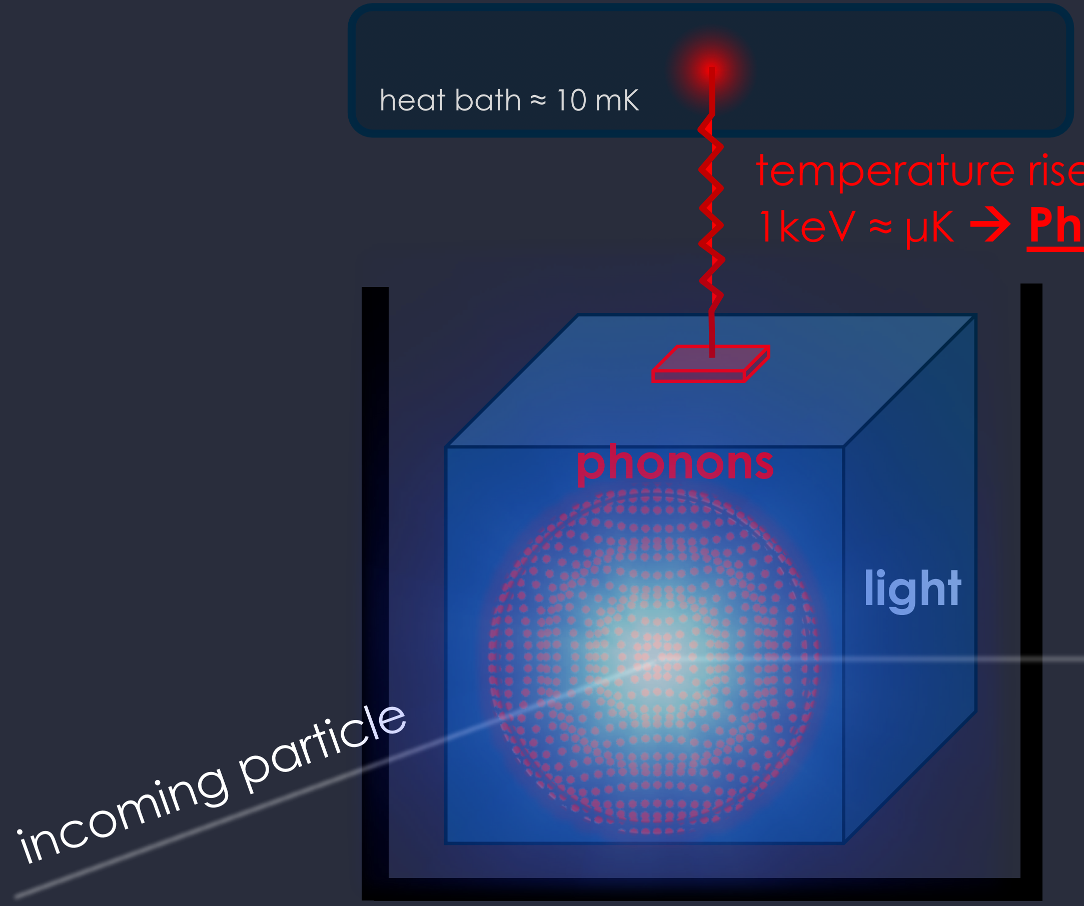


Credits to: F. Reindl

LOW-TEMPERATURE CALORIMETER

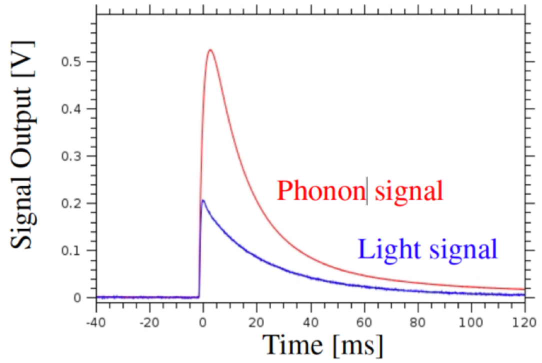


LOW-TEMPERATURE CALORIMETER



temperature rise detected by thermometer
1keV ≈ µK → **Phonon signal**

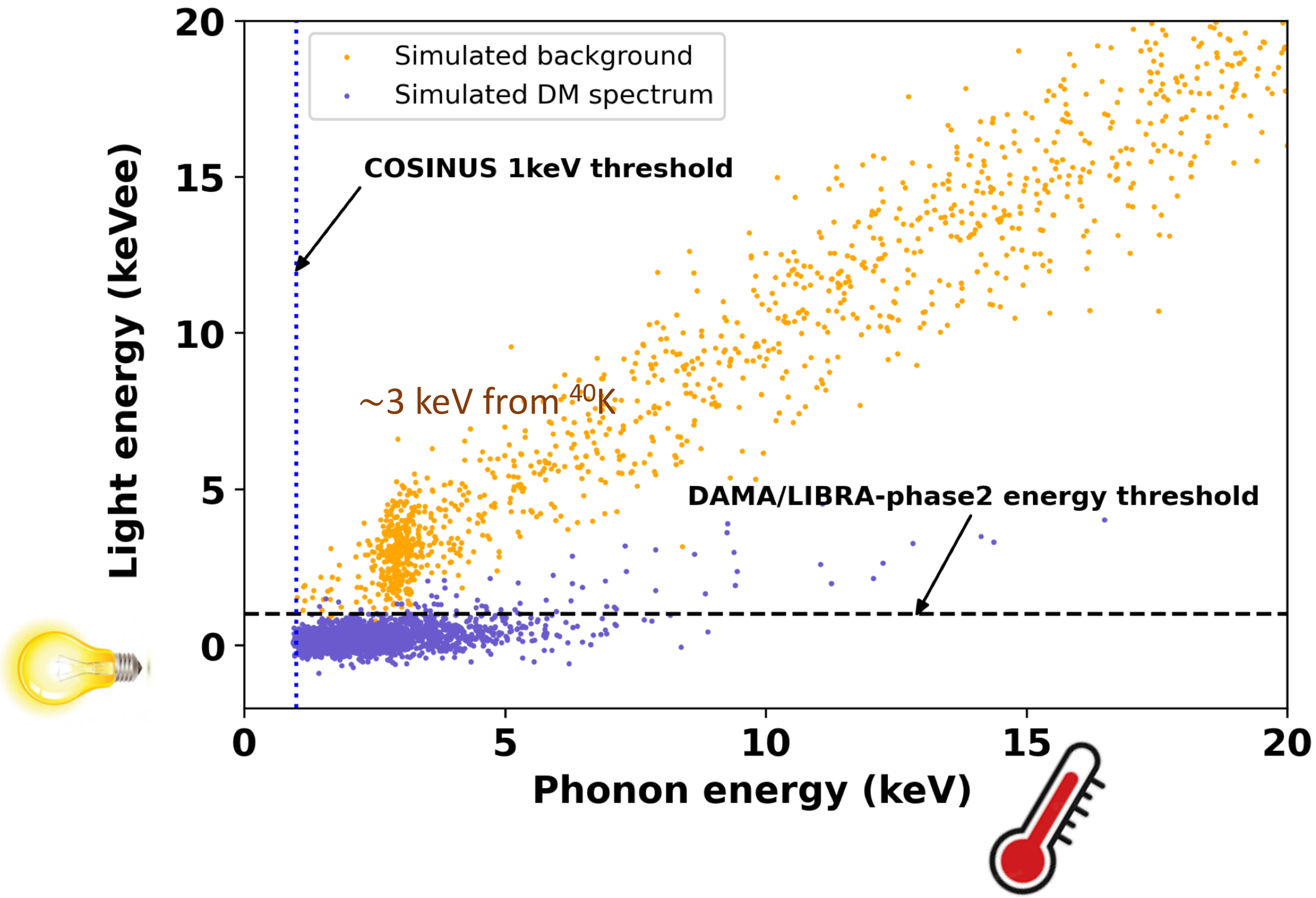
outgoing particle



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

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

SIMULATED DATA FOR 100 kg days (gross-exposure)

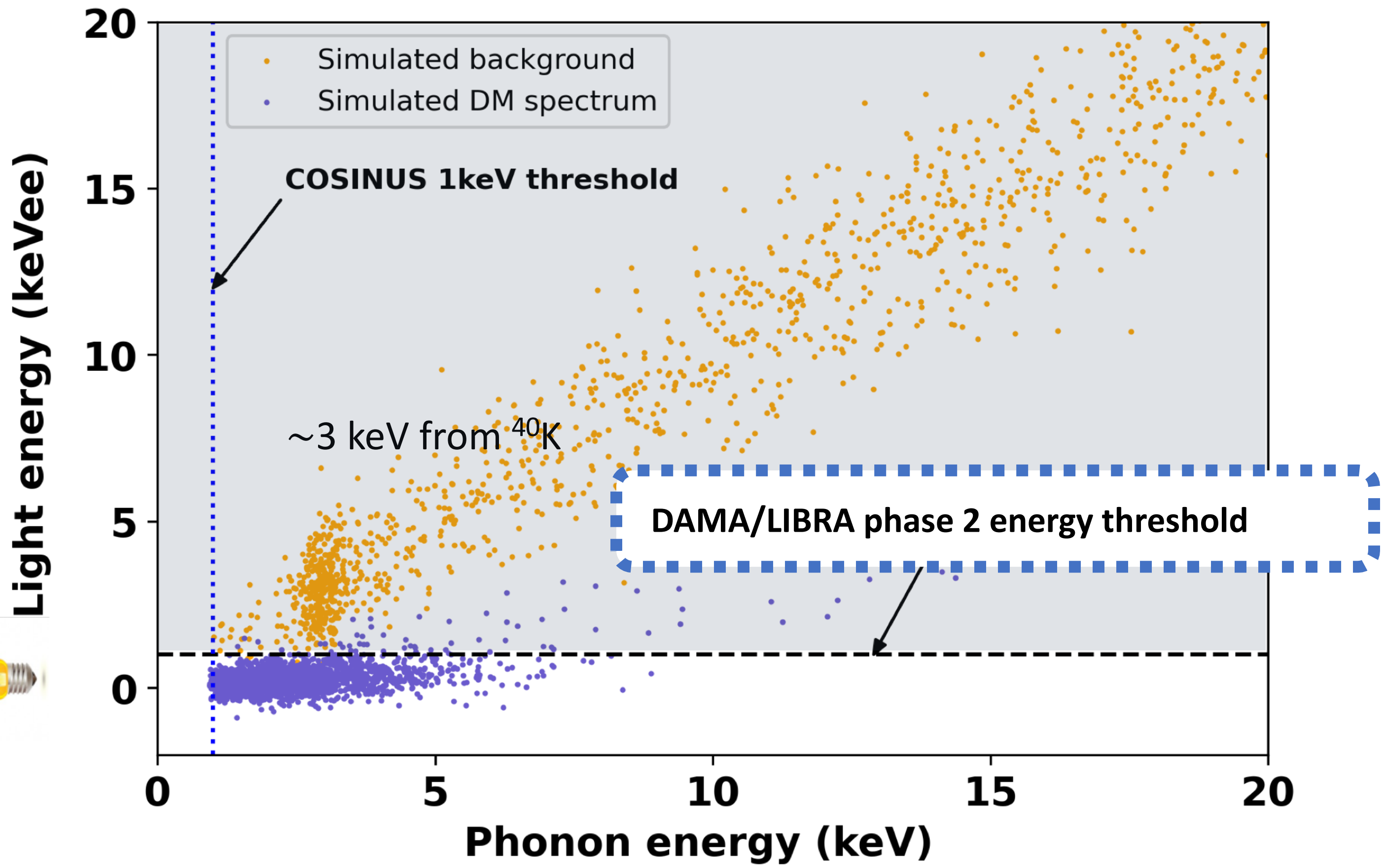


- 1keV nuclear recoil threshold
- flat background: 1 /(keV kg d)
  + ^{40}K background: 600μBq/kg
- dark matter spectrum:
  10 GeV/c^2, 2x10^{-4} pb
- **values for quenching factors** from:

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

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

WHAT **DAMA/LIBRA** SEES …

- 1keV nuclear recoil threshold
- flat background: 1 /(keV kg d)
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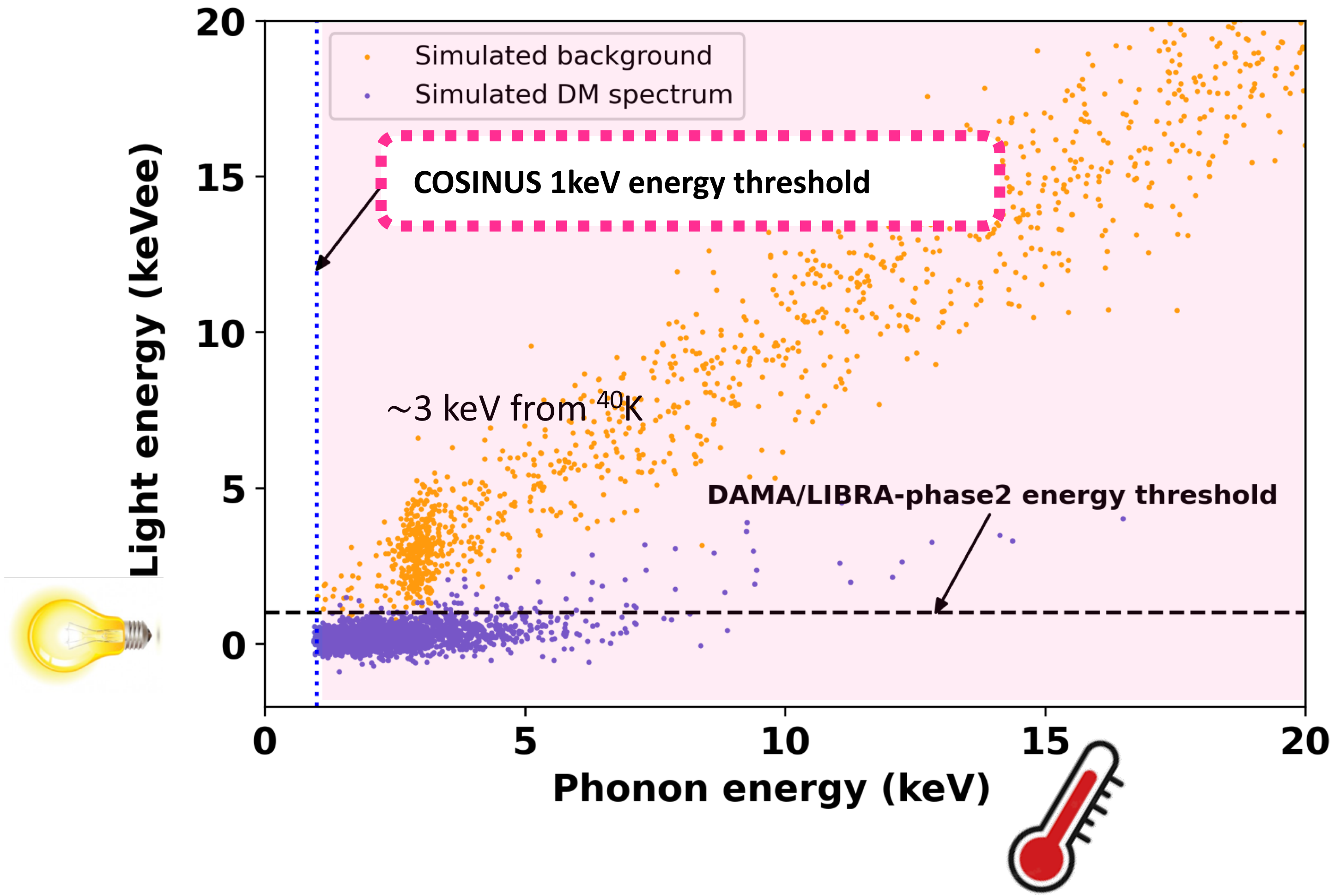
Eur. Phys. J. C (2016) 76:441
DOI 10.1140/epjc/s10052-016-4278-3

WHAT **COSINUS** SEES …



- 1keV nuclear recoil threshold
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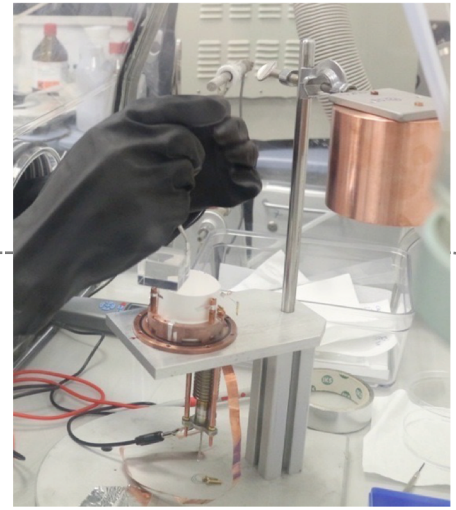
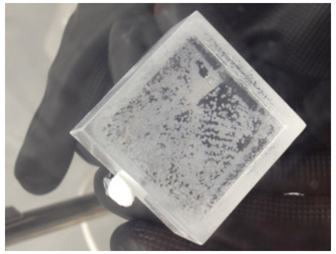
Tretyak, Astropart. Phys. 33, 40 (2010)

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

... 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

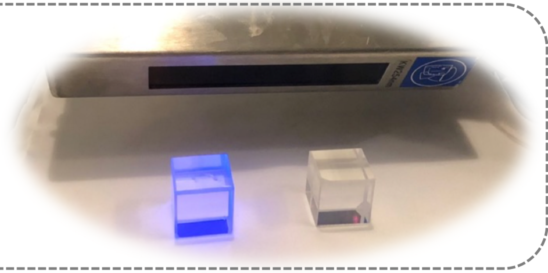
(3-inch crystal, Astrograde powder from Merck) Zhu, Y. et al, IEEE, 2018

low Debye temperature

NIM A 1045, 167532

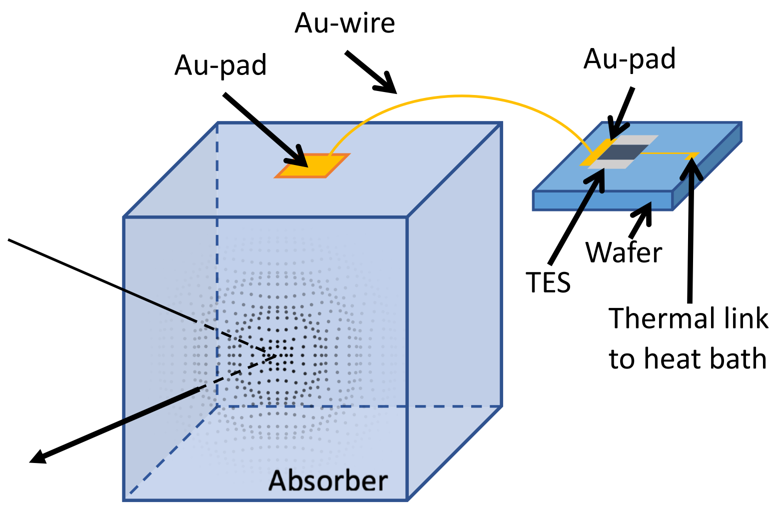
adapted thermometer → remoTES

+ avoid other phonon-loss channels



remoTES design

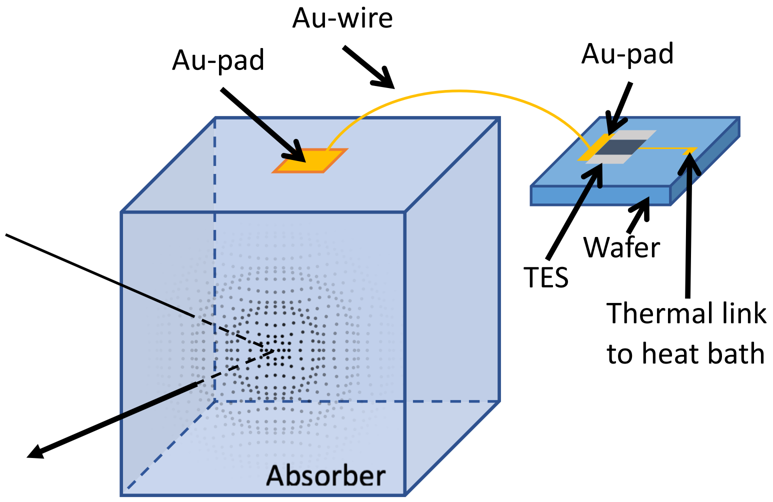
NIM A 1045, 167532

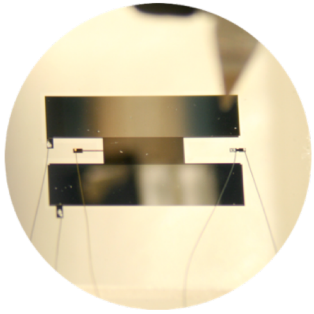


- separate wafer
  hosts the thermometer
  → **TES = transition edge sensor**

remoTES design

NIM A 1045, 167532



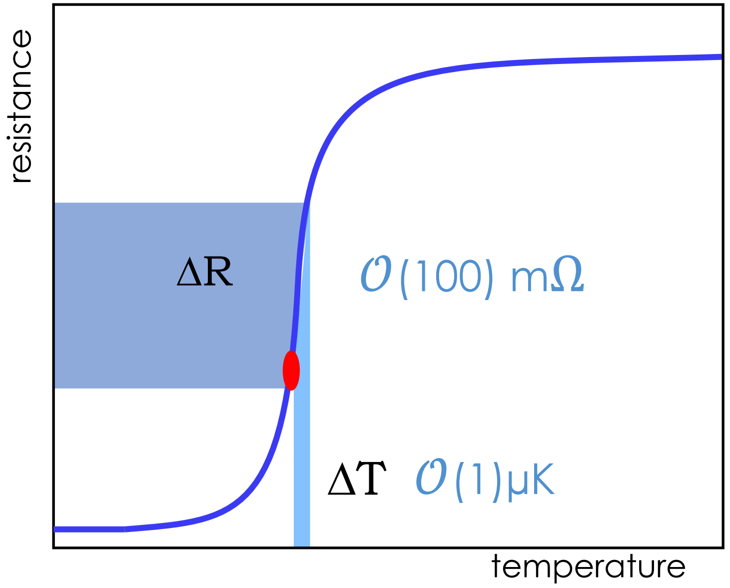


→ **TES = transition edge sensor**

tungsten superconducting thin films
→ technology developed by

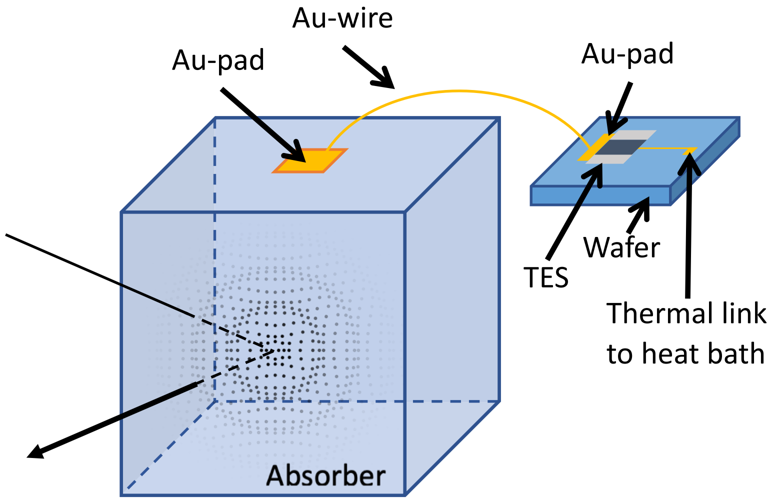
CRESST

Transition temperature: $T_C \approx 15$ mK



remoTES design

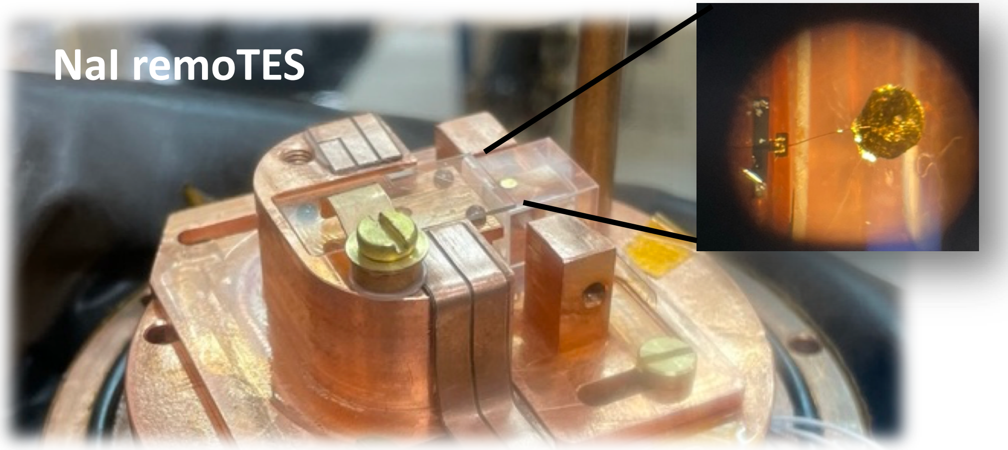
NIM A 1045, 167532



- 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

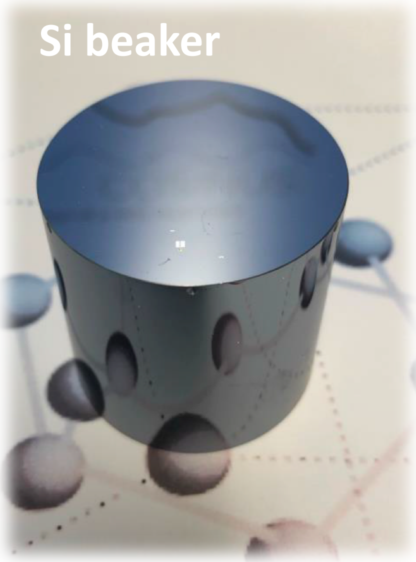
→ → absorber excluded from fabrication process

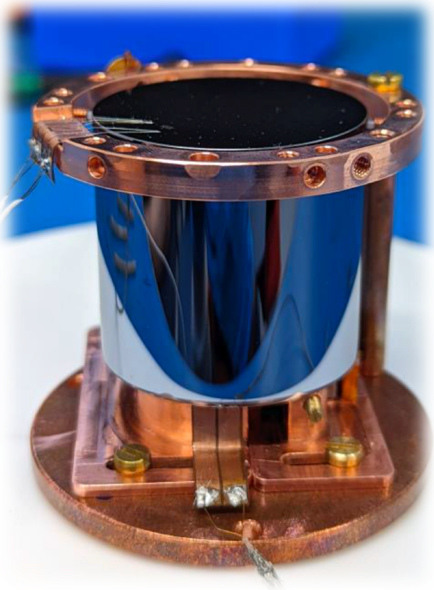
NaI-remoTES – measurement in June 2022



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

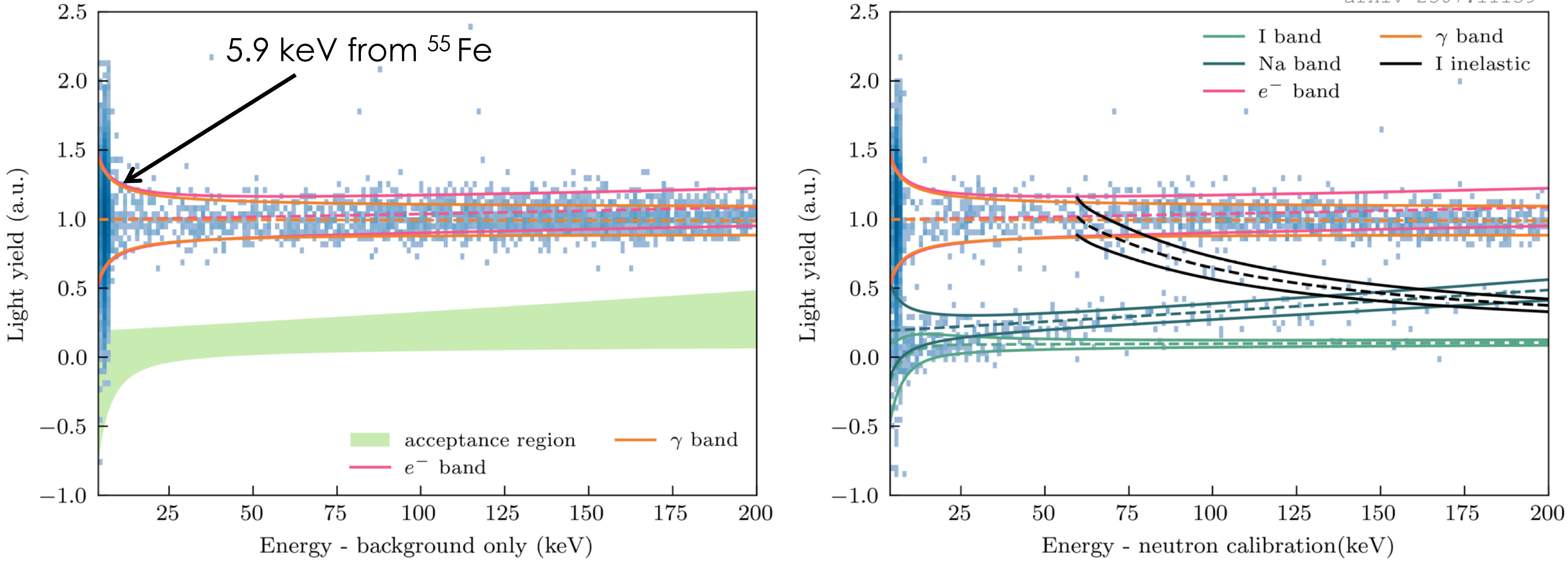
- silicon light absorber of beaker-shape
- mass: 15.1 g
- W-TES directly on the Si beaker





RESULTS

Measurement carried out at the test facility of CRESST @ LNGS

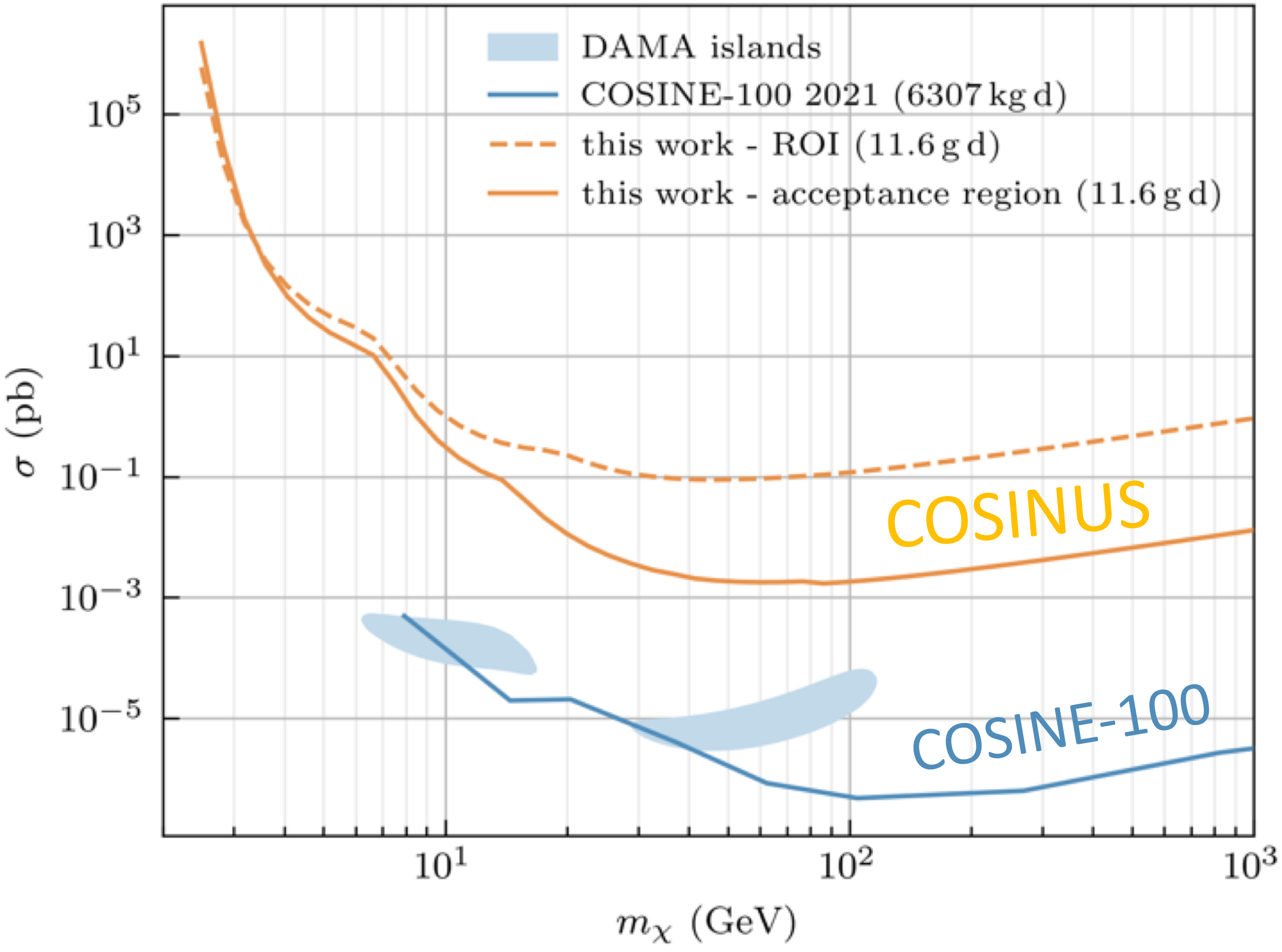


σ_{NaI} = (0.441 ± 0.011) keV (threshold < 2 keV_{NR})

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 – FIRST DARK MATTER RESULT



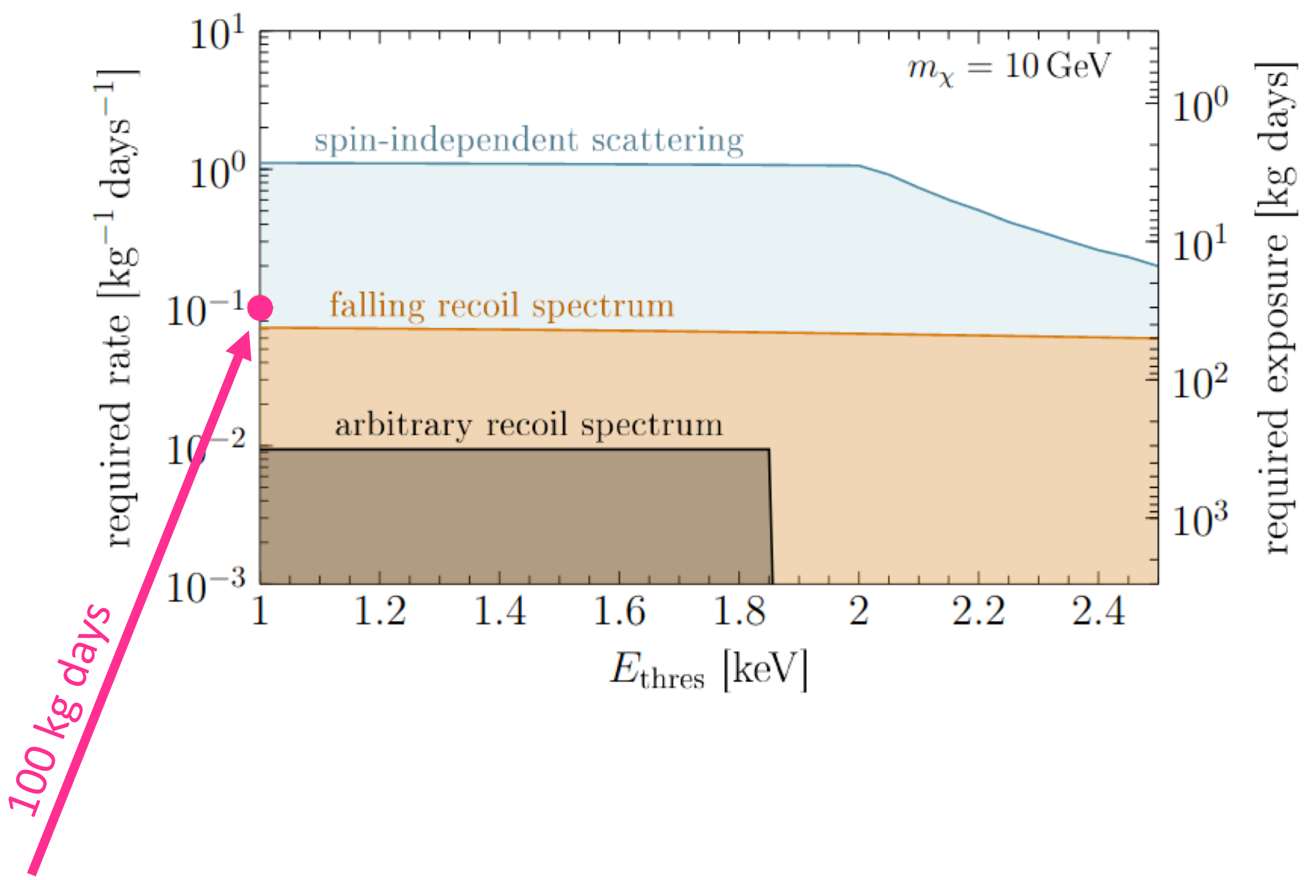
11 g d

$\sim 10^6$

6307 kg d

PHYSICS REACH

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



COSINUS – 1π (2024-2027)

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

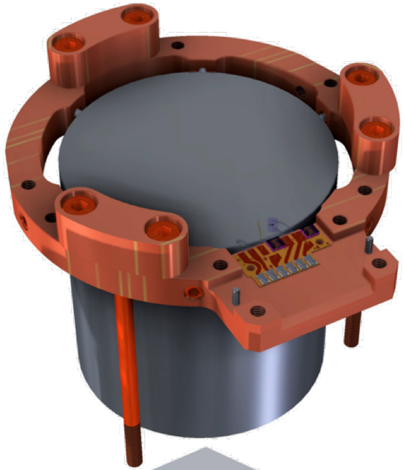
- independent of DM halo
- for any interaction of DM with nuclei

COSINUS – 2π (≥ 2027)

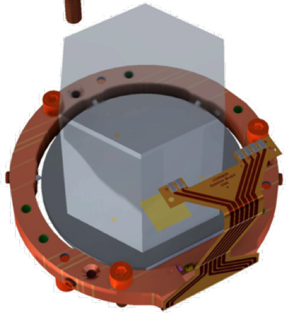
Investigate annual modulation signature with COSINUS

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

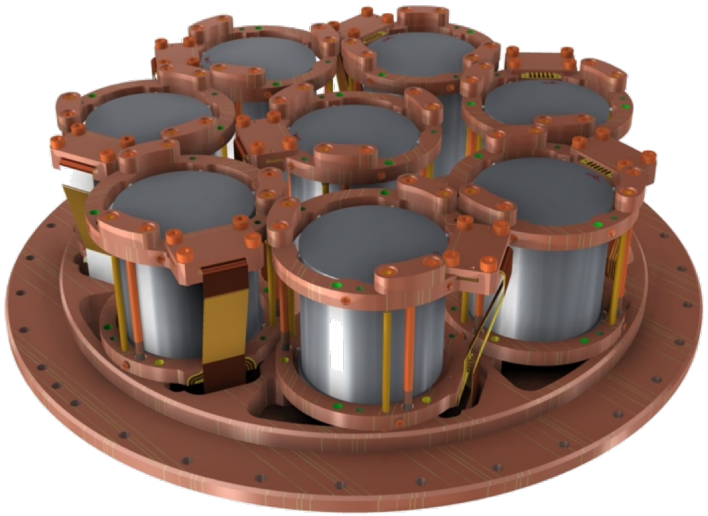
OUTLOOK

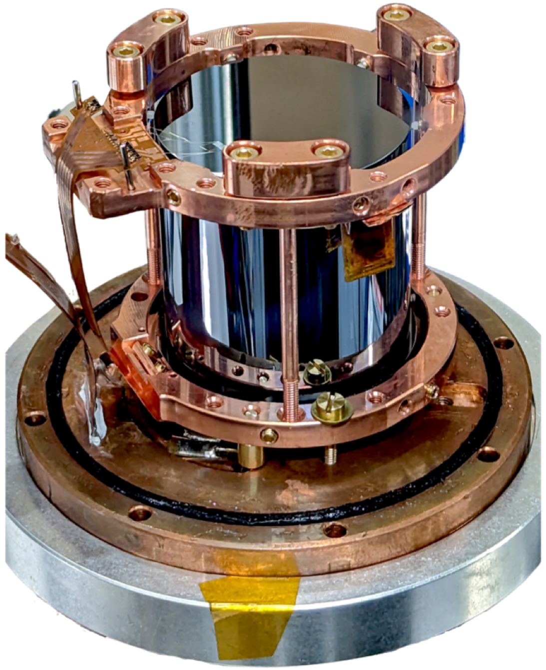


- Si-beaker for 4π active surrounding of the crystal

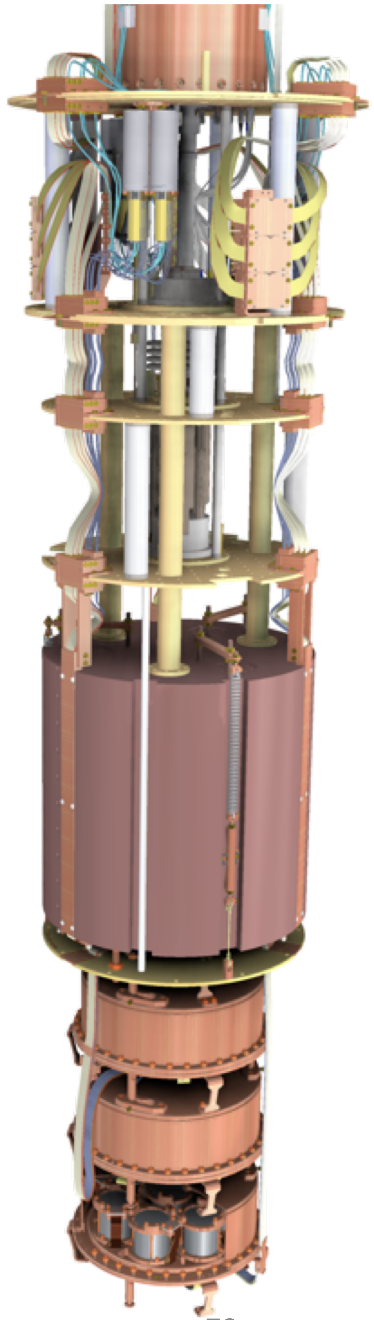


- hexagonal crystal (30 g / 110 g)
- lid to host crystal

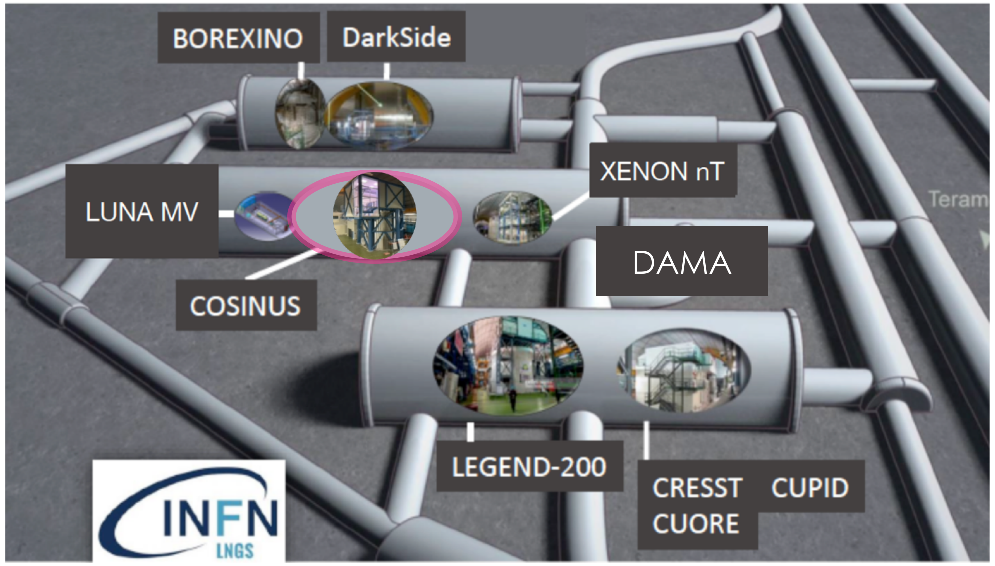




- 8 detector modules per level
- 3 levels in final stage



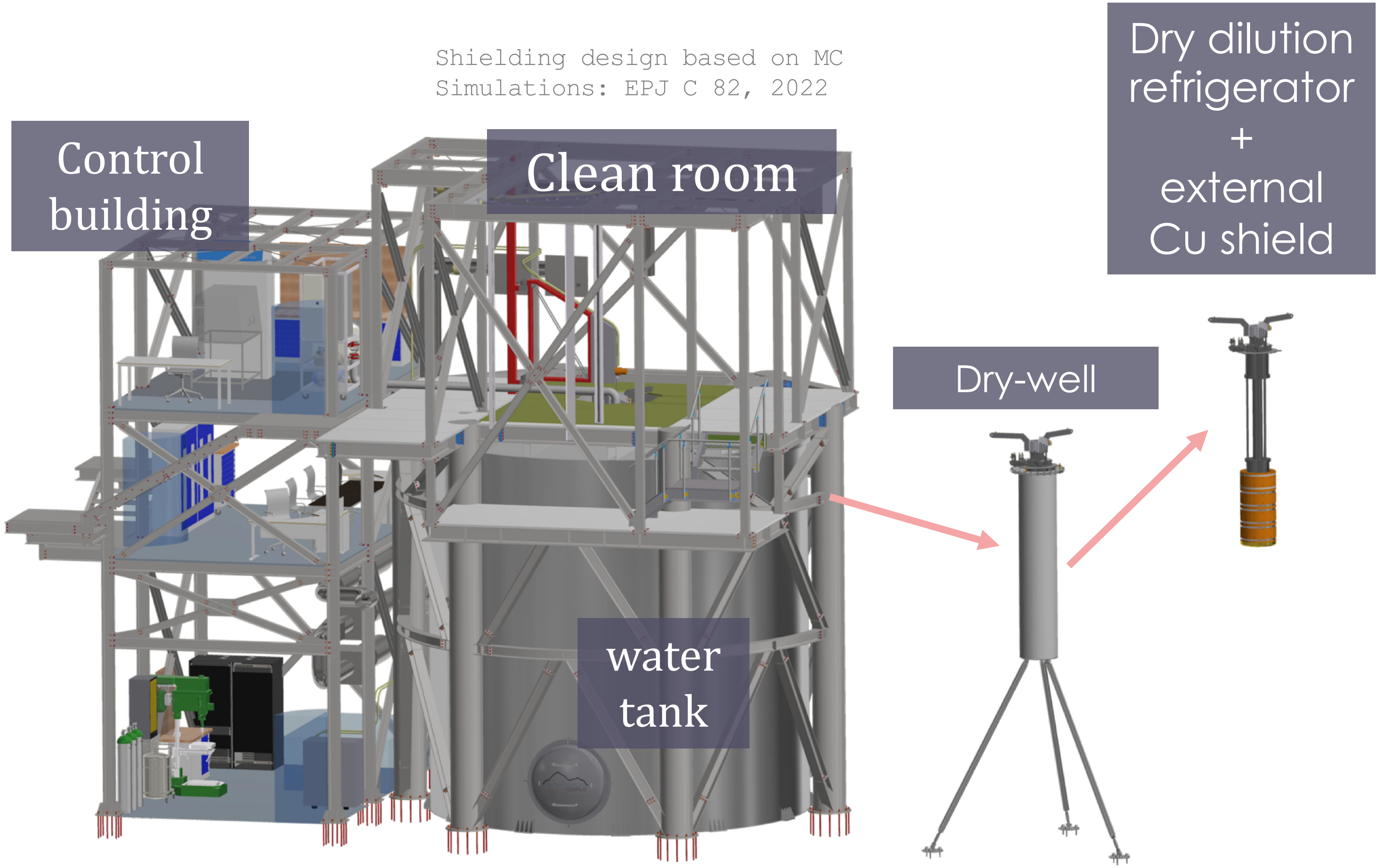
COSINUS experimental site



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

COSINUS experimental site and facility

Shielding design based on MC Simulations: EPJ C 82, 2022

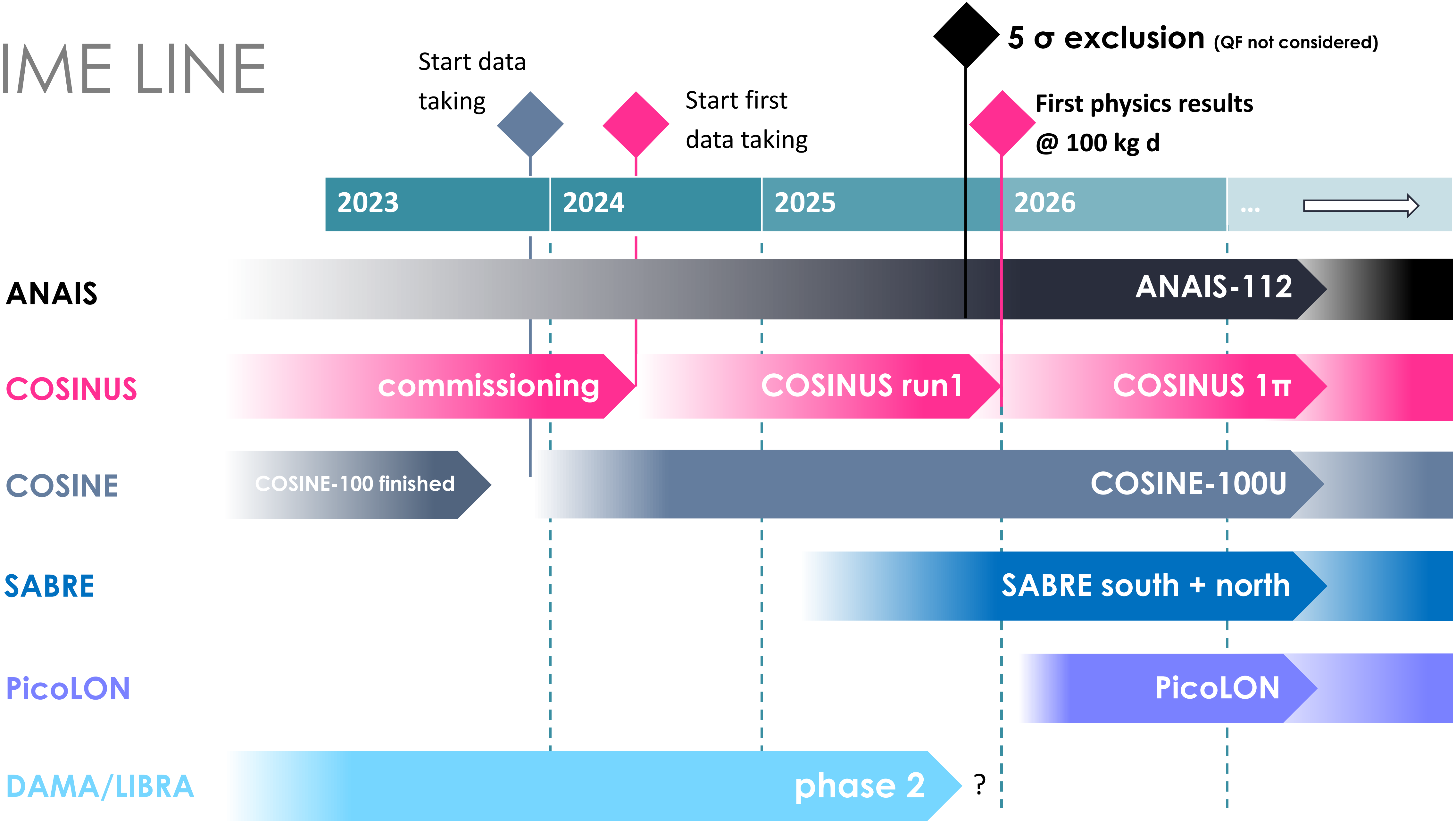


COSINUS experimental facility

view from COSINUS to XENONnT 2023

COSINUS facility completed in Aug, 2023

TIME LINE



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

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 2024

In the year ~2028

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

Professor PostDocs Grad students

In the year ~2028

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?


THANK YOU FOR YOUR ATTENTION
@Maurizio Verdecchia Photography

EXTRA MATERIAL

DARK MATTER RATE

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

galactic
escape velocity

velocity
distribution

DM-nucleus
cross-section

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

minimal velocity to
produce a recoil
of energy E_r

$\sim A^2$
$\sim$ form factor

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:

$$\bar{R} \geq S$$

COSINUS

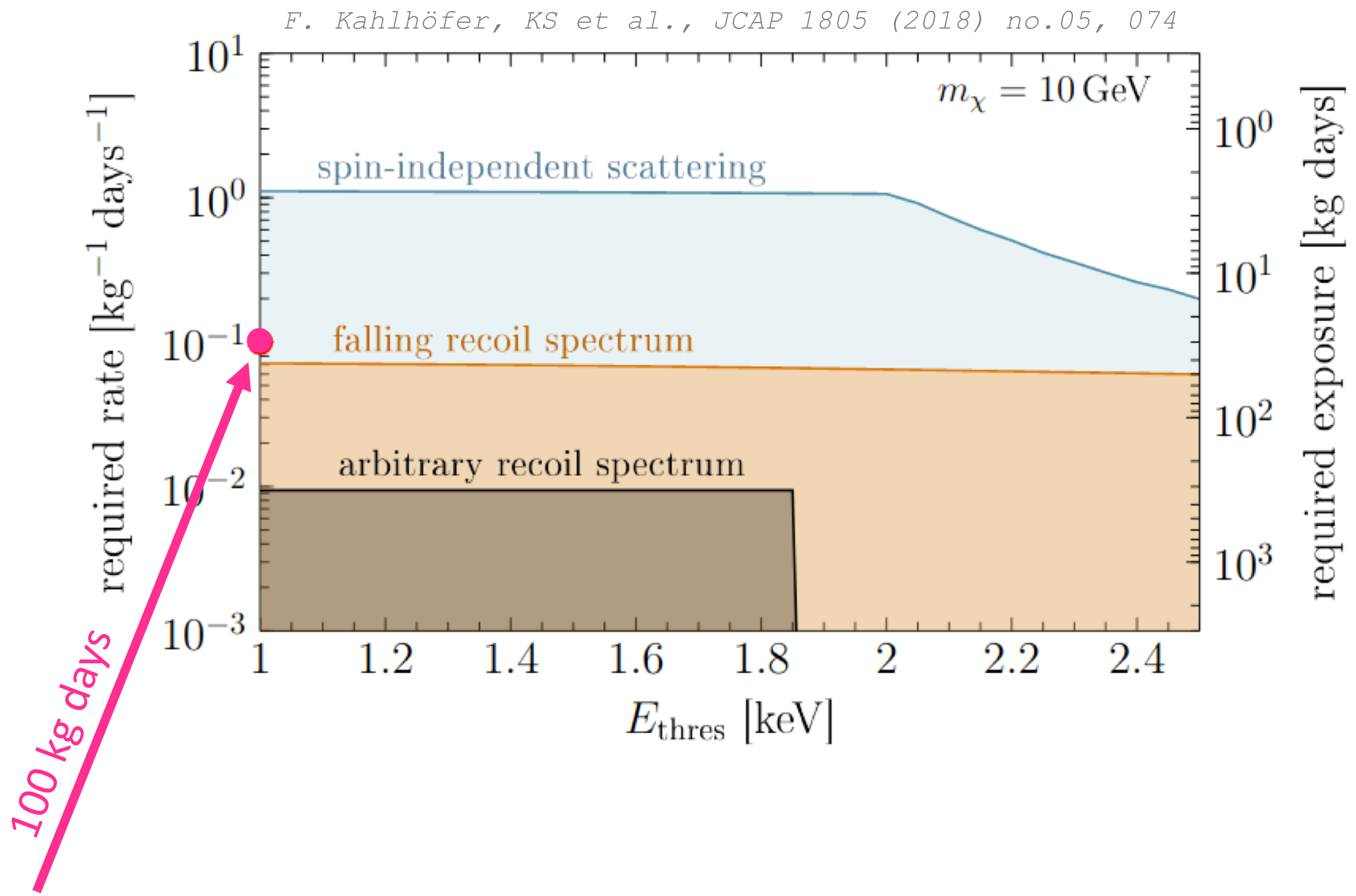
Mean rate $\bar{R} = \frac{1}{2}\,[R(t = \text{June } 1^{st}) + R(t = \text{Dec. } 1^{st})]$

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

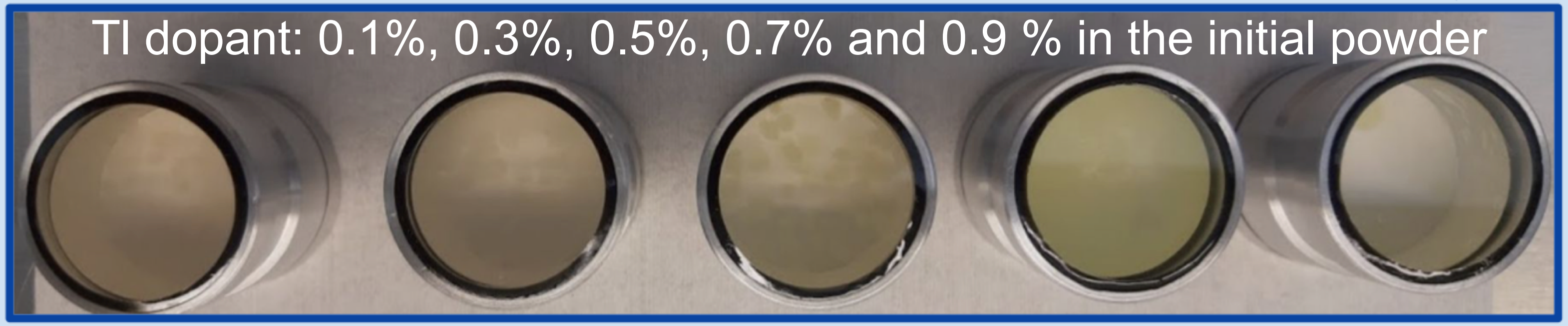
Outlook: Cut and count only → make use of spectral information for potentially stronger bounds

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)