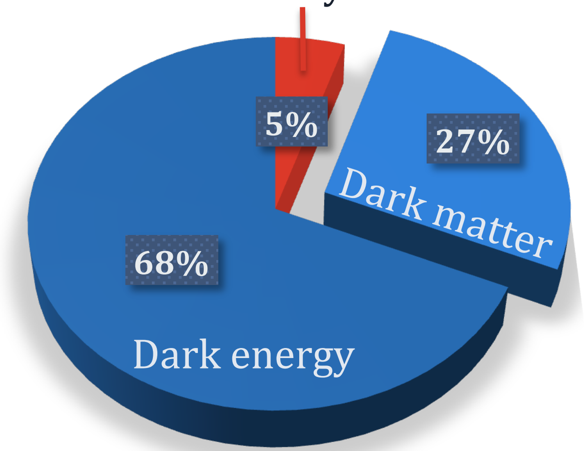
Annual Modulation Searches for Dark Matter with NaI Detectors: Status, Challenges, and Recent Advances

Florian Reindl
TU Wien & MBI Vienna

Les Rencontres de Noirmoutier
June 05, 2026

Dark Matter

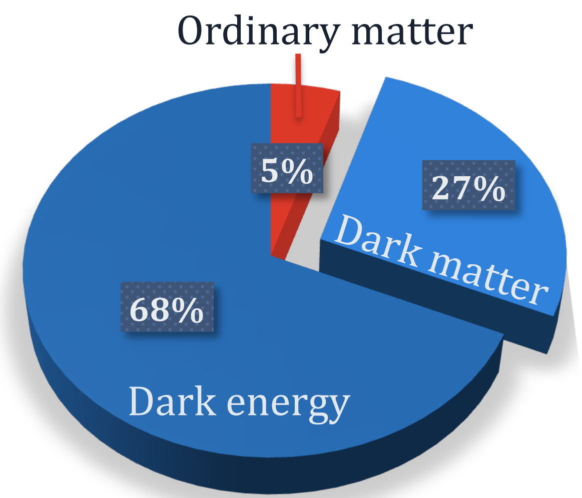
DM exists



Planck 2018 - A&A 641 (2020)

Dark Matter

DM exists



Planck 2018 - A&A 641 (2020)

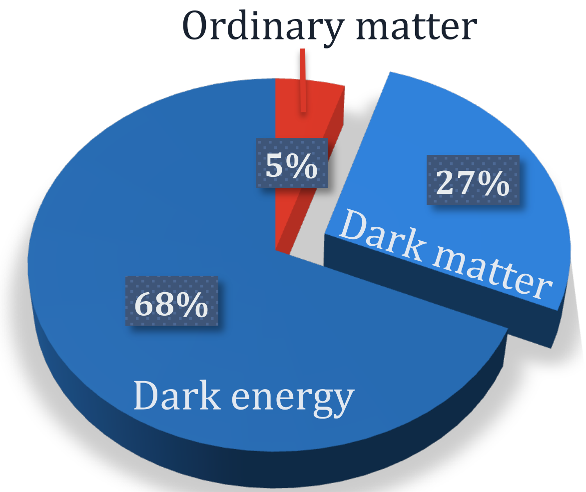
DM is beyond the Standard Model

Standard Model Plus Set

https://www.particlezoo.net/products/standard-model-plus

Dark Matter

DM exists



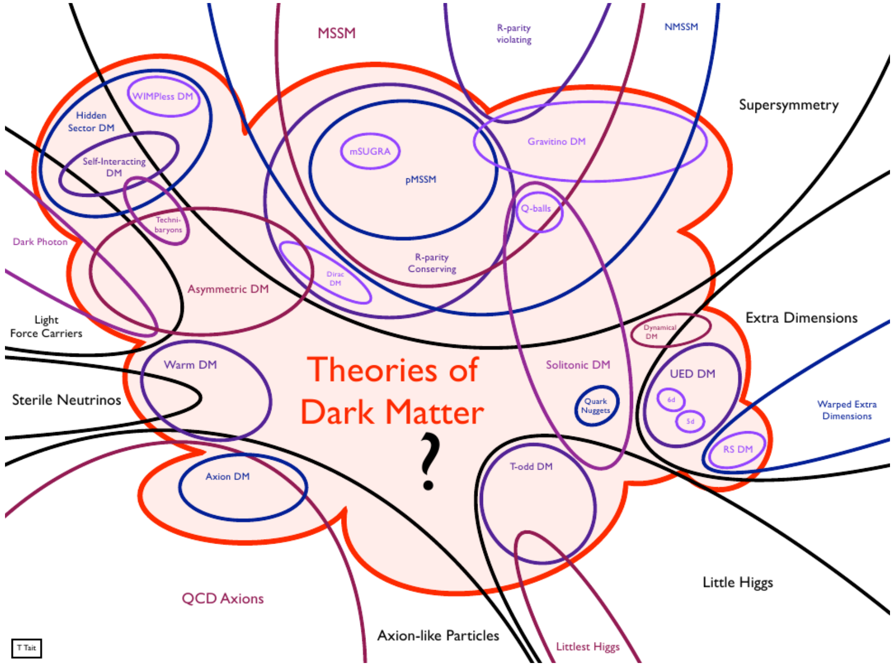
Planck 2018 - A&A 641 (2020)

DM is beyond the Standard Model

Standard Model Plus Set

https://www.particlezoo.net/products/standard-model-plus

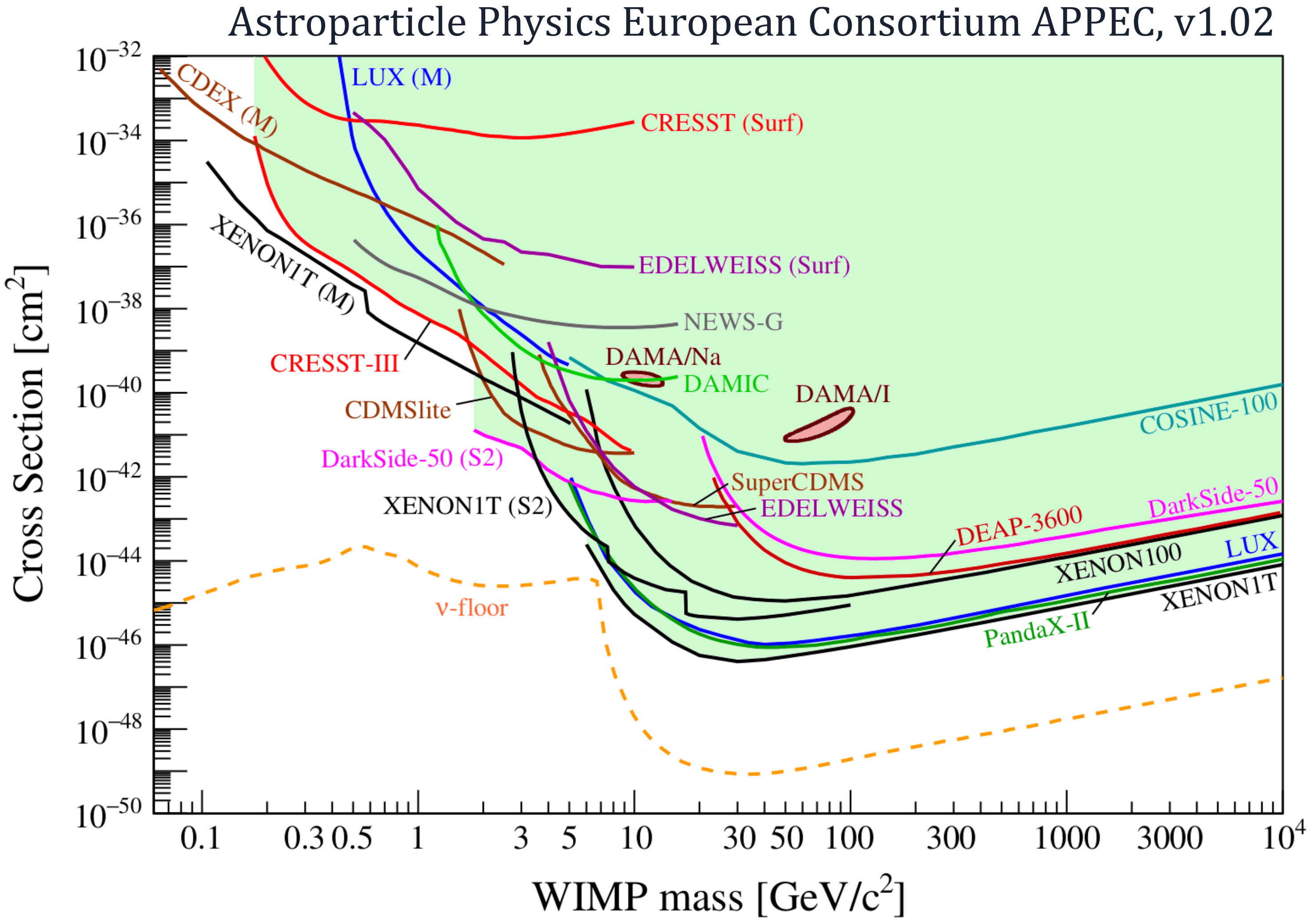
What is DM ?????



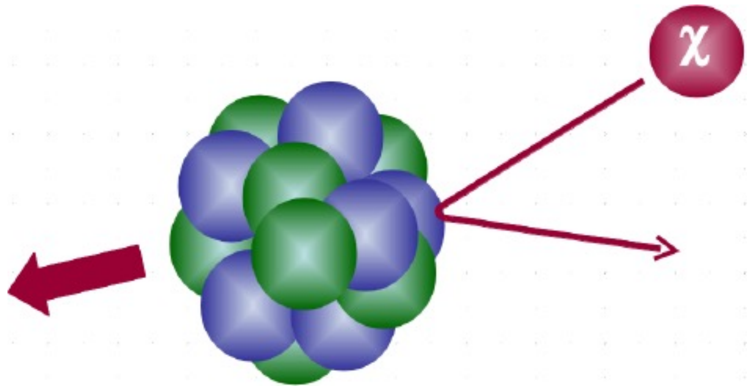
T. Tait at UCLA DM 2016

How to detect it????

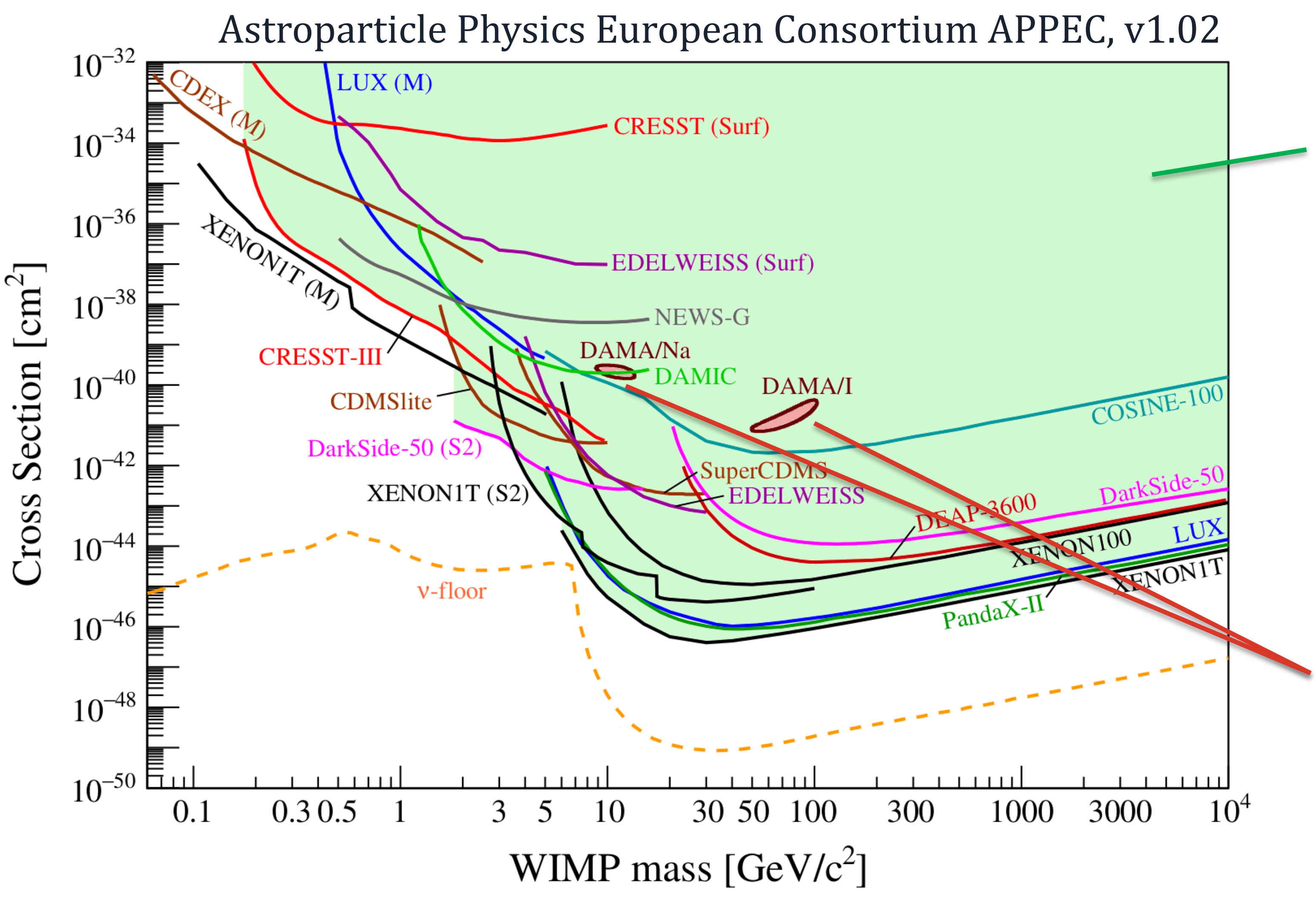
Direct Dark Matter Detection Landscape



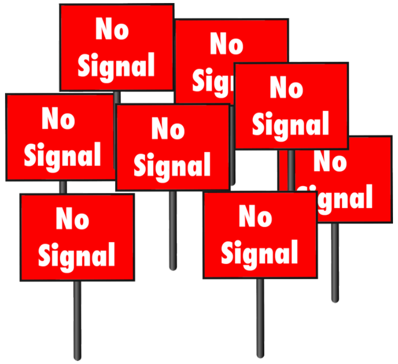
Standard scenario:
elastic DM-nucleus scattering
+ Standard Halo Model



Direct Dark Matter Detection Landscape



Excluded area



Positive evidence reported by DAMA

DAMA vs. Scientific Age and Time

F. Kahlhöfer, IDM2022

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?

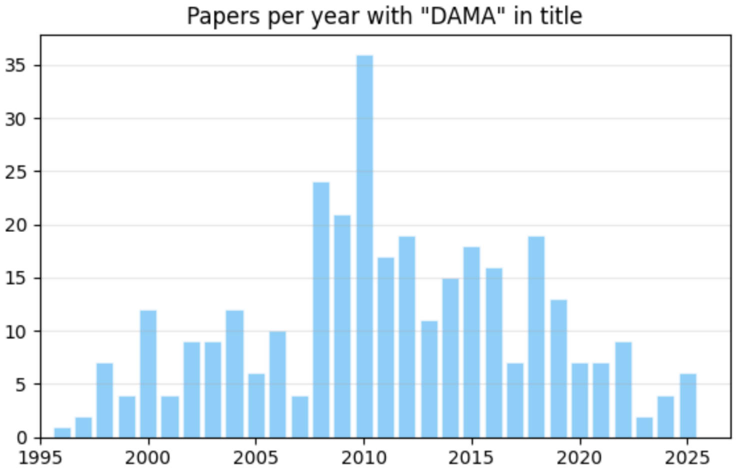
DAMA vs. Scientific Age and Time

F. Kahlhöfer, IDM2022

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?



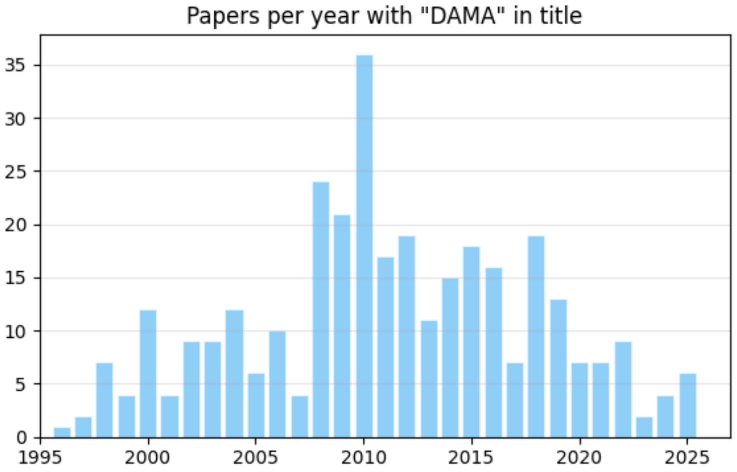
DAMA vs. Scientific Age and Time

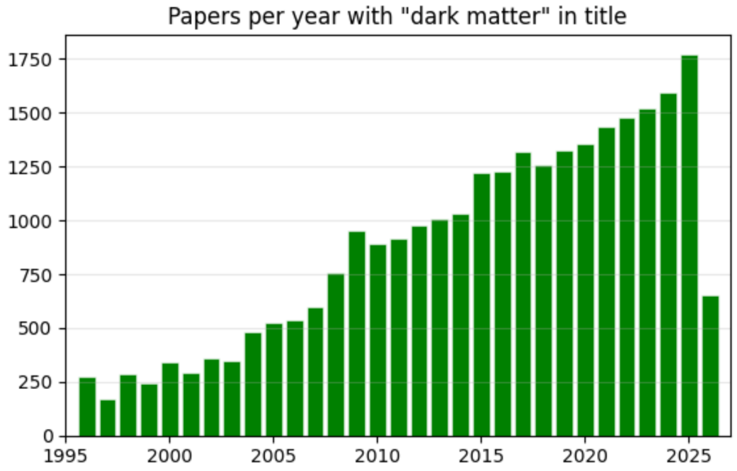
F. Kahlhöfer, IDM2022

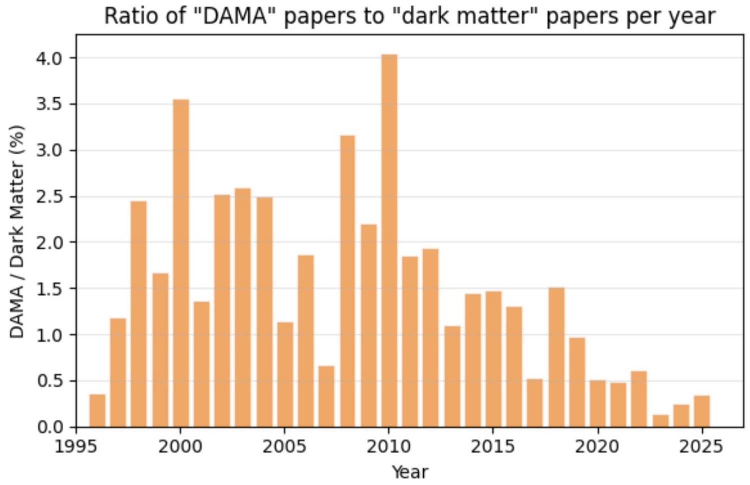
Professor:
Ahh, those were the good old days, when we were still excited about DAMA. I was there, you know?

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

Grad student:
What is DAMA?

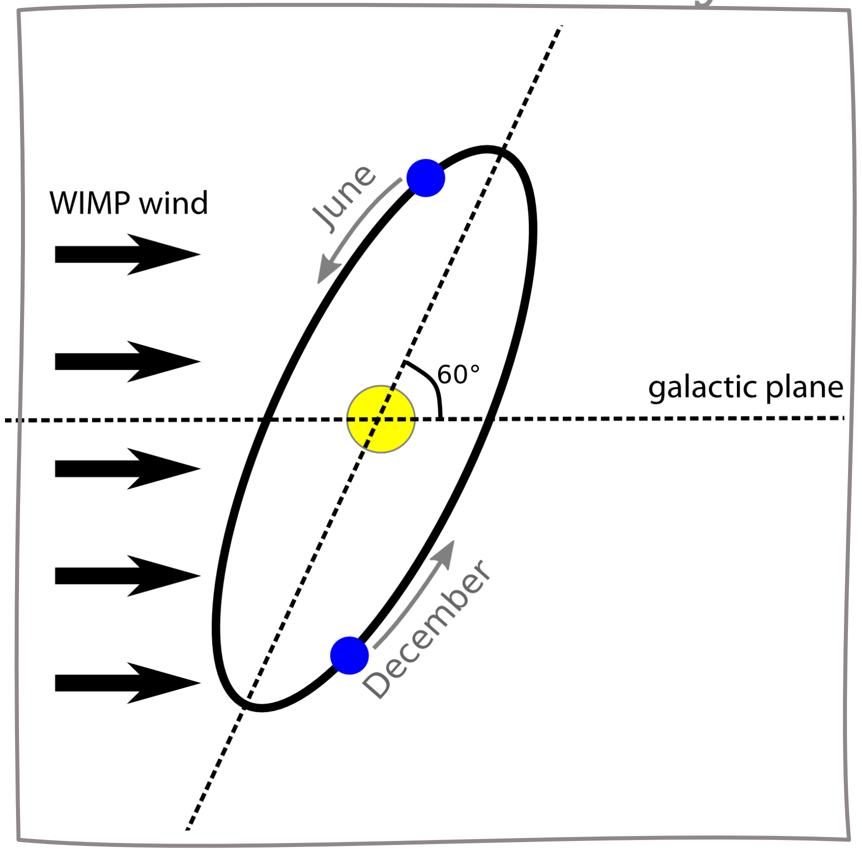






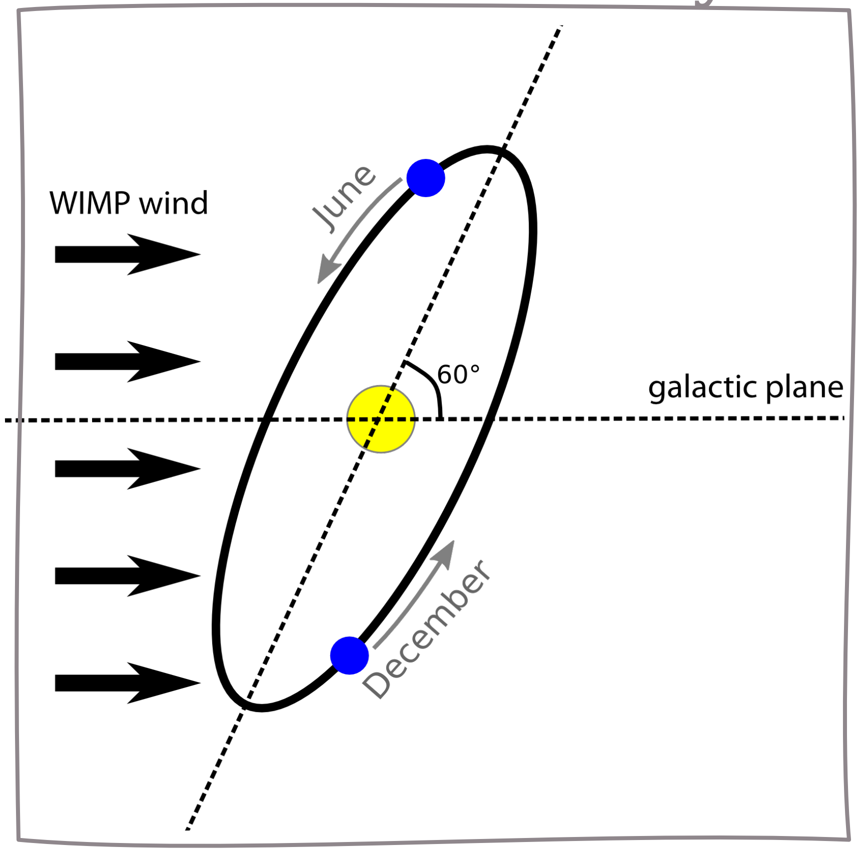
Annual Modulation

Relative velocity

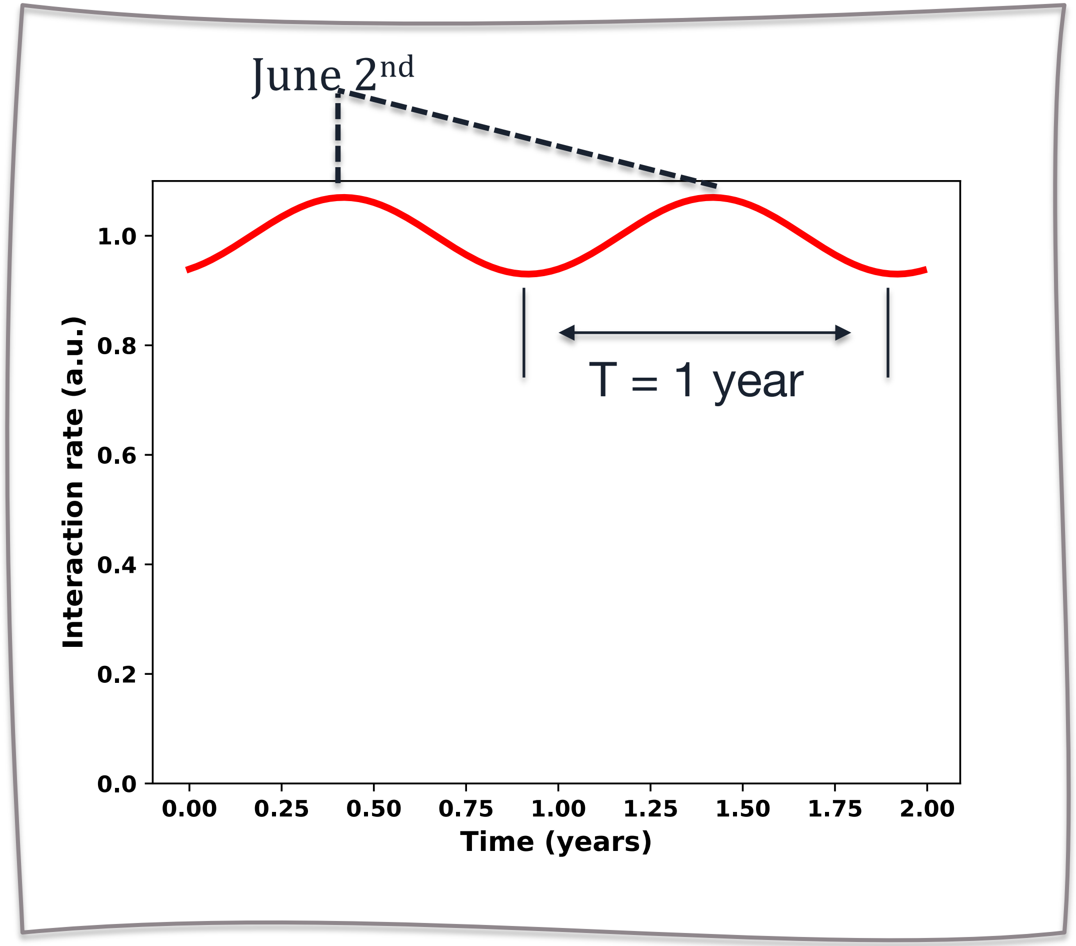


Annual Modulation

Relative velocity



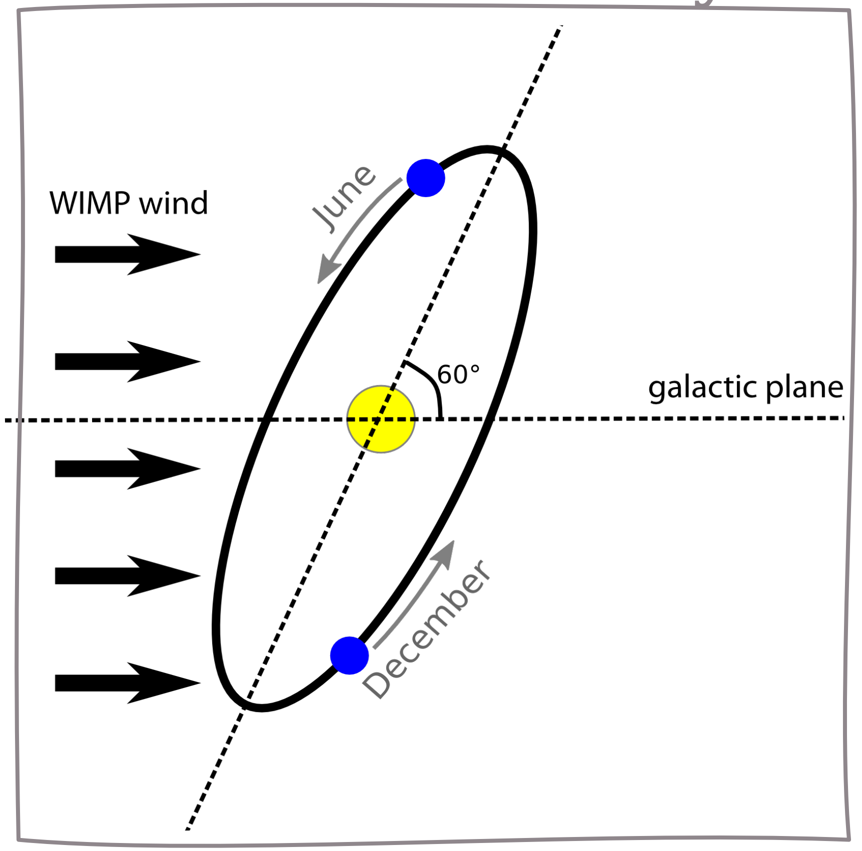
DM interaction rate in detector

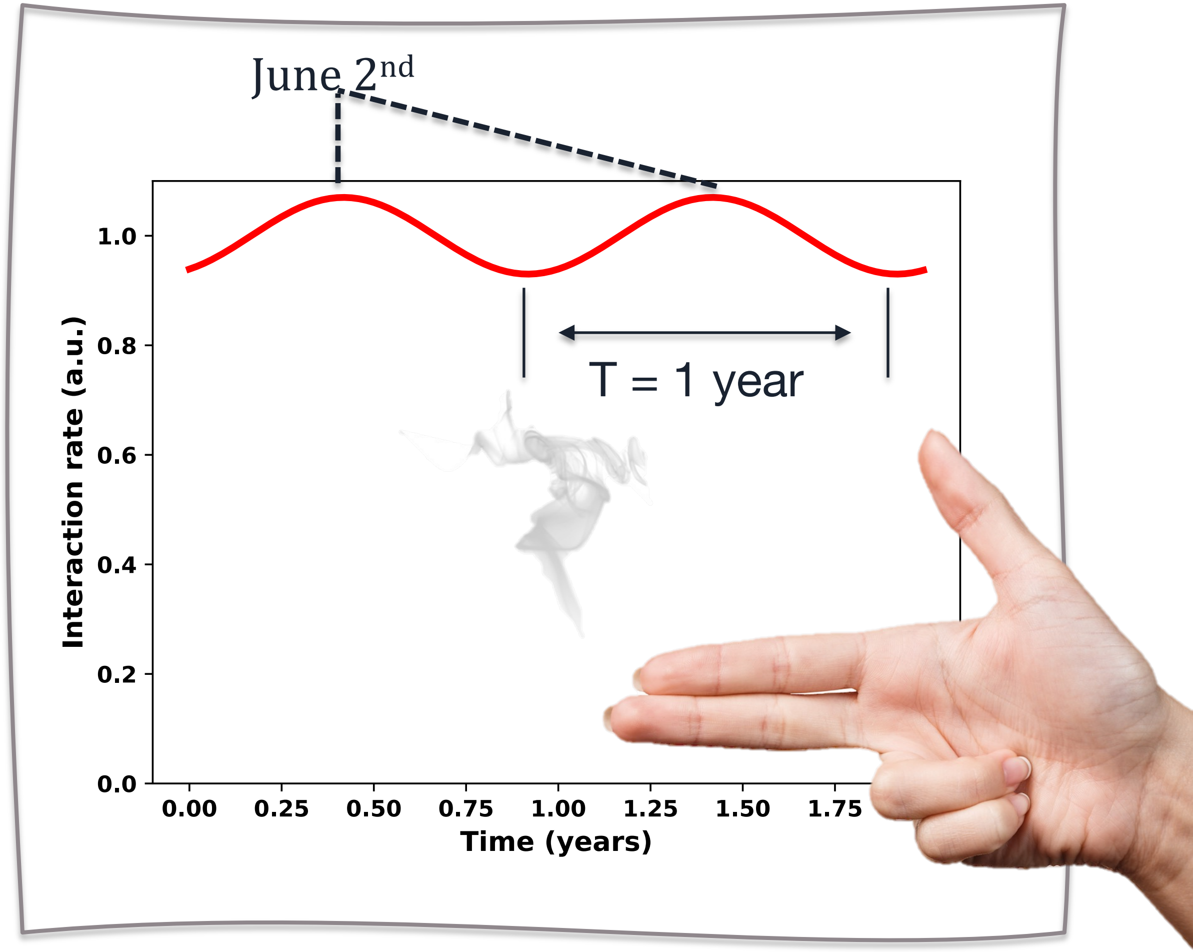


Annual Modulation

DM interaction rate in detector

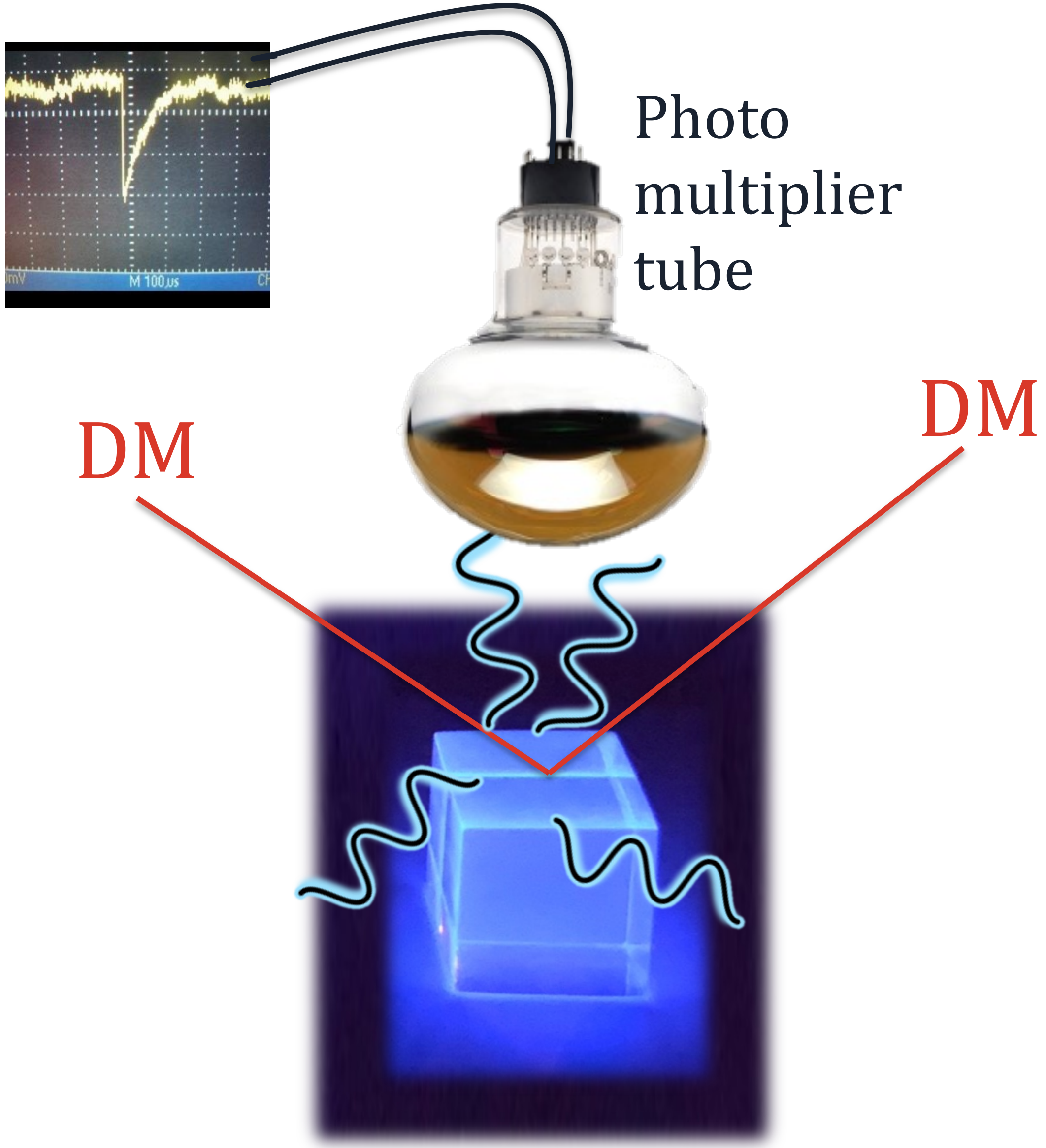
Relative velocity





The smoking gun evidence?

DAMA – Working Principle

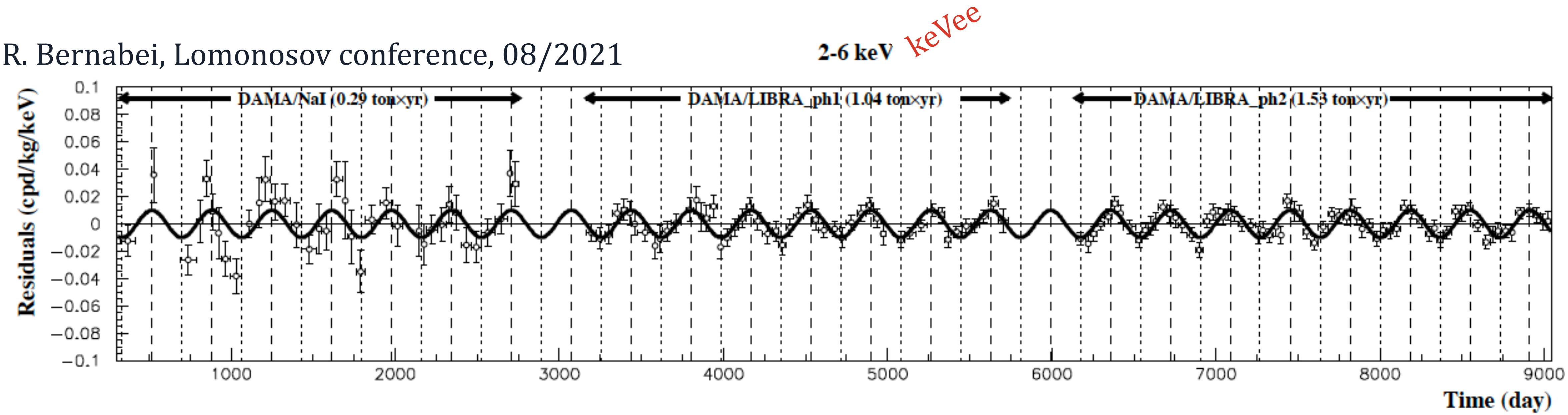


NaI(Tl) crystal

Single channel: scintillation light
→ Electron-equivalent energy scale
→ No event-by-event discrimination between electron recoils and nuclear recoils off Na and I

DAMA/LIBRA Modulation Signal
Time Distribution

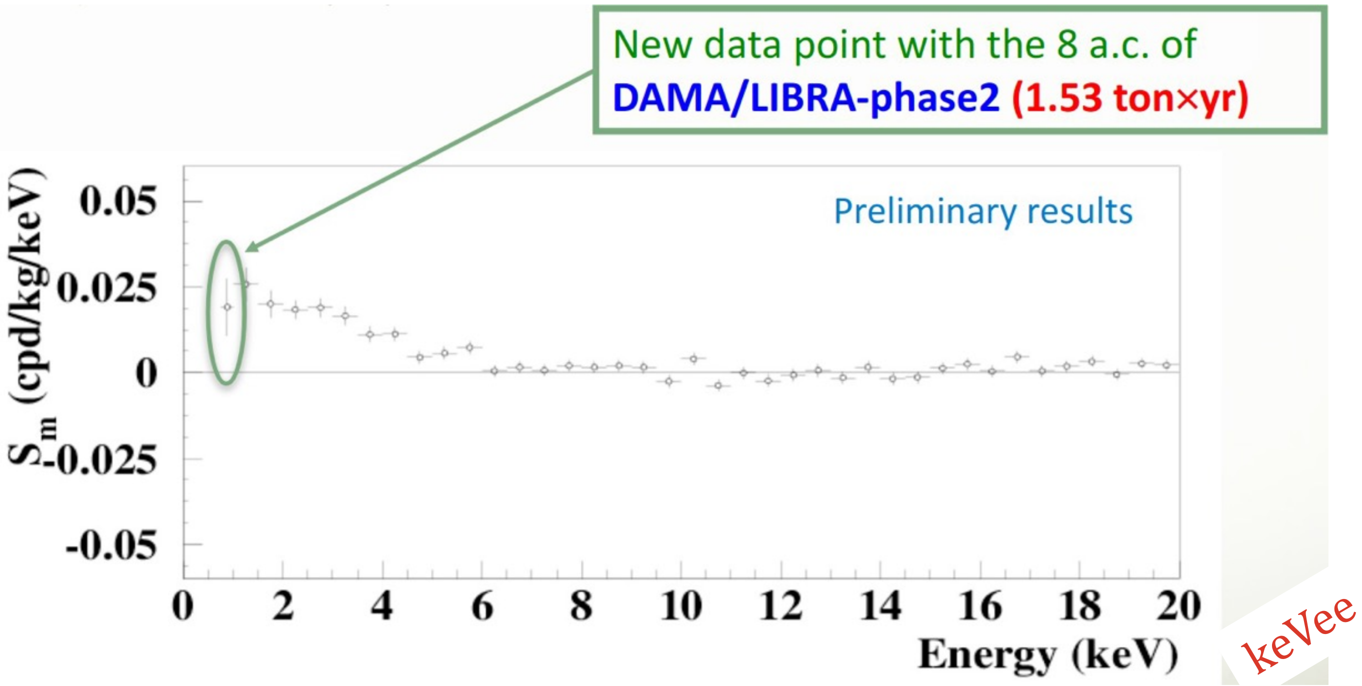
R. Bernabei, Lomonosov conference, 08/2021



2-6 keV_{ee} (=electron equivalent)

~25 years of data, 2.86 tonne years exposure, 13.7σ statistical significance

DAMA/LIBRA – Phase 2



P. Belli, UCLA Dark Matter 04/2023

2010:
new PMTs with higher Q.E.
→ 1 keV_{ee} software threshold
(later lowered to 0.75 keV_{ee})

2021 - 2024:
new electronics and digitizers
→ 0.5 keV_{ee} software threshold
→ data taking 12/2021 – 12/2024

DAMA/LIBRA finished data taking and is decommissioned → results from 0.5 keV_{ee} data expected for late 2025

A Dark Matter Signal?

Statistics: 13.7σ ✓

Period: (0.99834 ± 0.00067) years* ✓

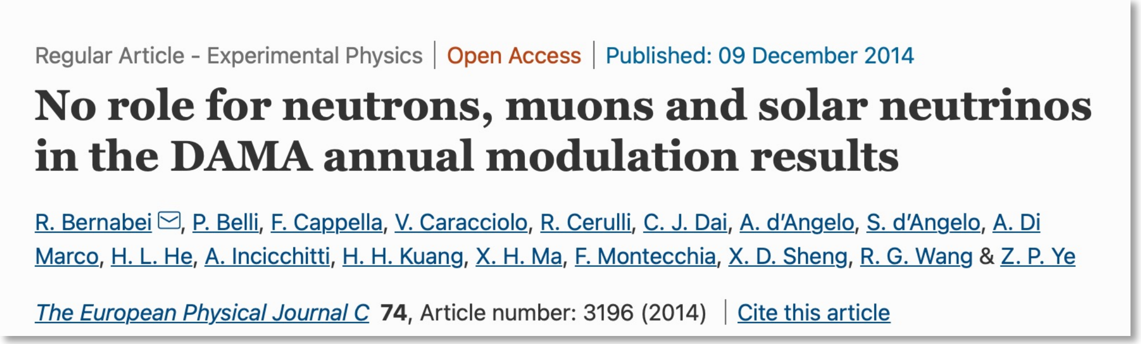
Phase: 22th May +/- 4 days* ✓

(cosine peaking June 2nd)

Convincing non-DM explanation ✗

*in (2-6)keVee interval

Non-Dark Matter Explanations for DAMA

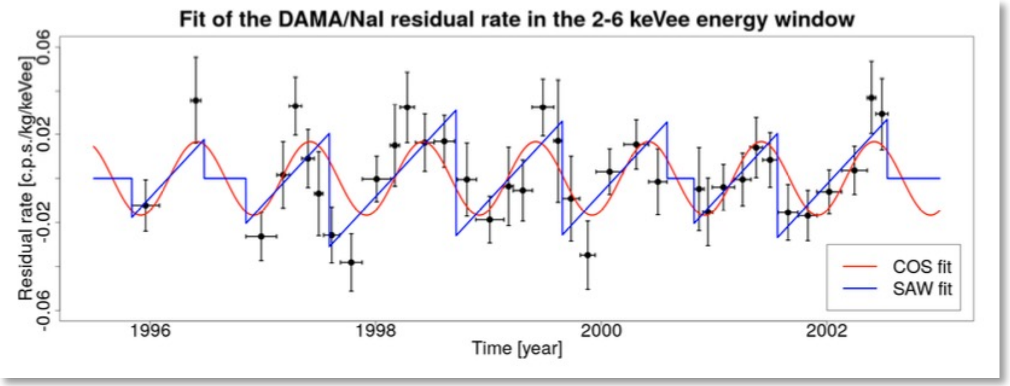

Regular Article - Experimental Physics | Open Access | Published: 09 December 2014

No role for neutrons, muons and solar neutrinos in the DAMA annual modulation results

R. Bernabei, P. Belli, F. Cappella, V. Caracciolo, R. Cerulli, C. J. Dai, A. d'Angelo, S. d'Angelo, A. Di Marco, H. L. He, A. Incicchitti, H. H. Kuang, X. H. Ma, F. Montecchia, X. D. Sheng, R. G. Wang & Z. P. Ye

The European Physical Journal C **74**, Article number: 3196 (2014) | Cite this article

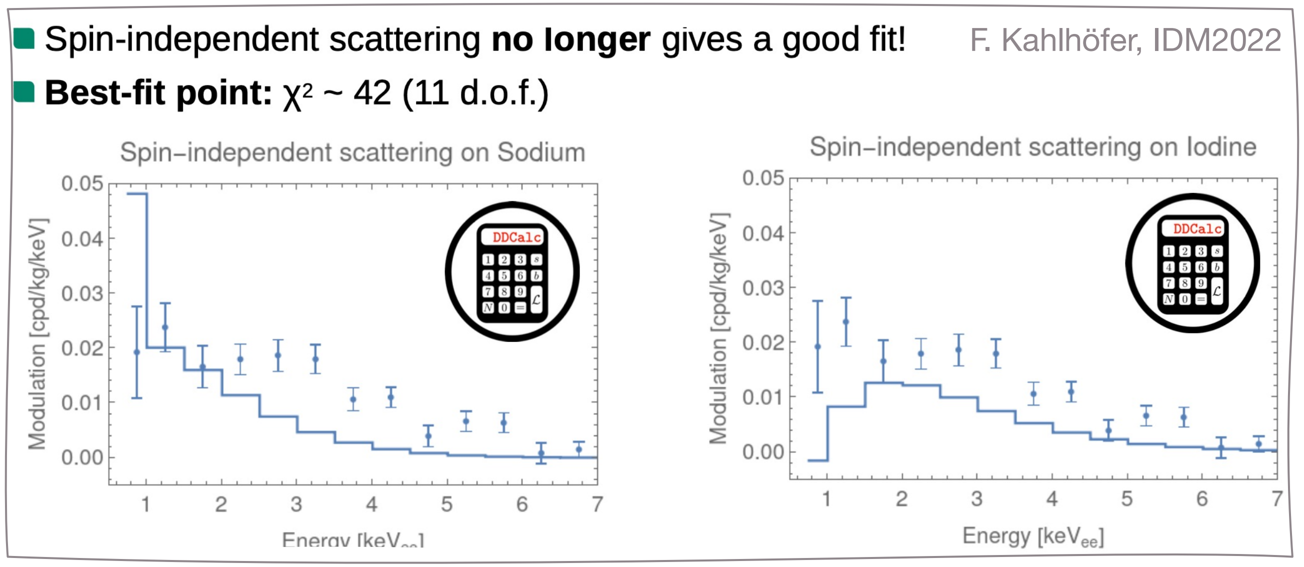
- Muons
- Muon-induced neutrons
- Neutrinos
- He in PMTs
- Analysis method
- …



arXiv:2003.03340, JCAP04, 2020
arXiv:2002.00459, JHEP, 2020

- arXiv search for "DAMA" in the title: 179 results
- Inspirehep for "DAMA" in the title: 331 results

A Dark Matter Signal?



Statistics: 13.7σ ✓

Period: (0.99834 ± 0.00067) years* ✓

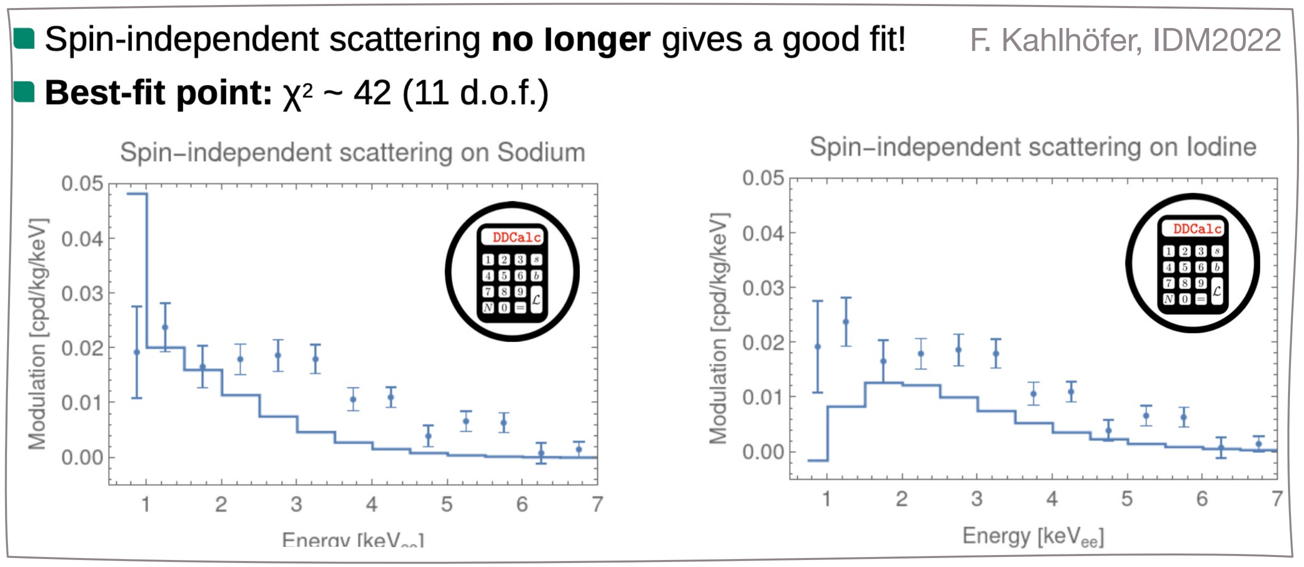
Phase: 22th May +/- 4 days* ✓

(cosine peaking June 2nd)

Convincing non-DM explanation ✗

*in (2-6)keVee interval

A Dark Matter Signal?



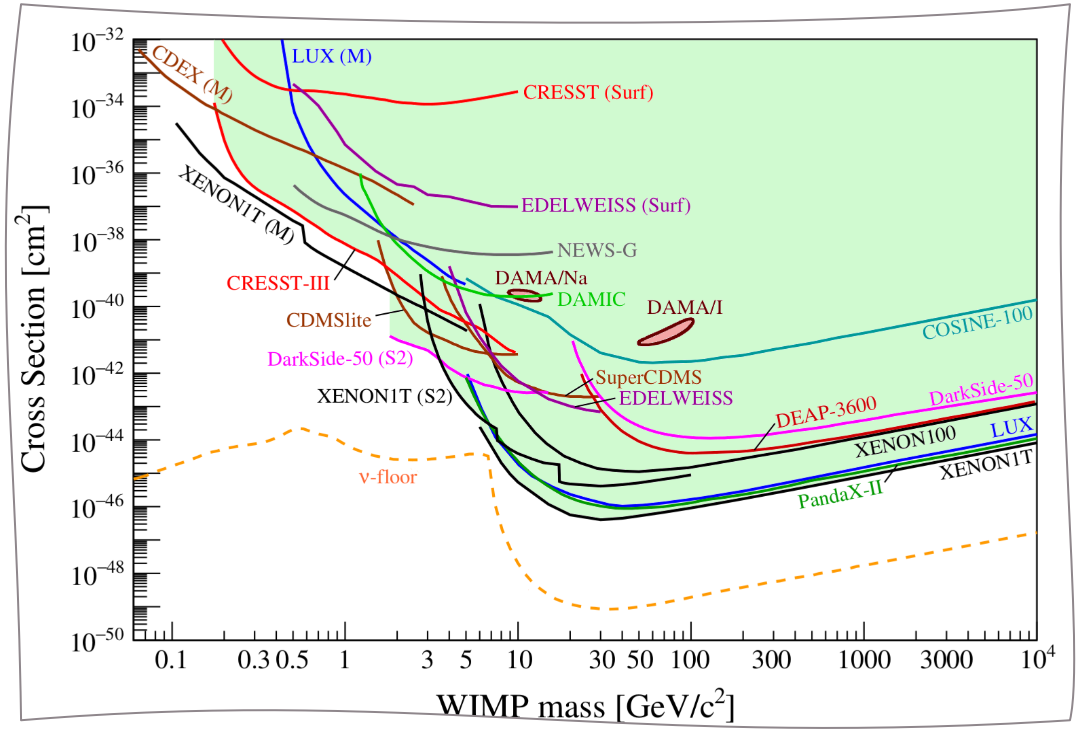
Statistics: 13.7σ ✓

Period: (0.99834 ± 0.00067) years* ✓

Phase: 22$^{\text{th}}$ May +/- 4 days* ✓

(cosine peaking June 2$^{\text{nd}}$)

Convincing non-DM explanation ✗



*in (2-6)keVee interval

What are the Unknowns?

galactic escape velocity

velocity distribution

WIMP-nucleon cross section

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

minimal velocity to produce a recoil above E_R

~ A^2

~ form factor

What are the Unknowns?

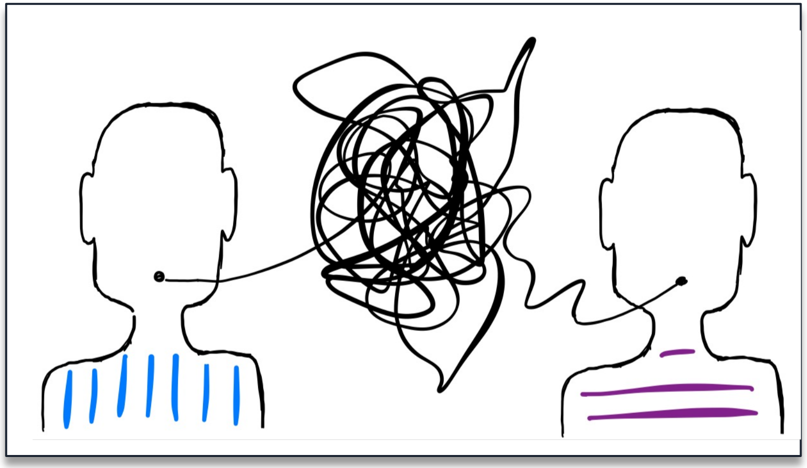
galactic escape velocity — velocity distribution — WIMP-nucleon cross section

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

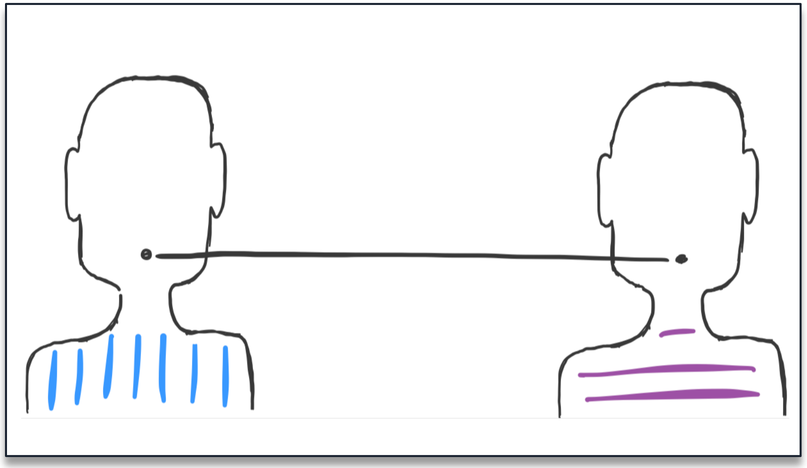
minimal velocity to produce a recoil above E_R

~ A^2
~ form factor

Different targets



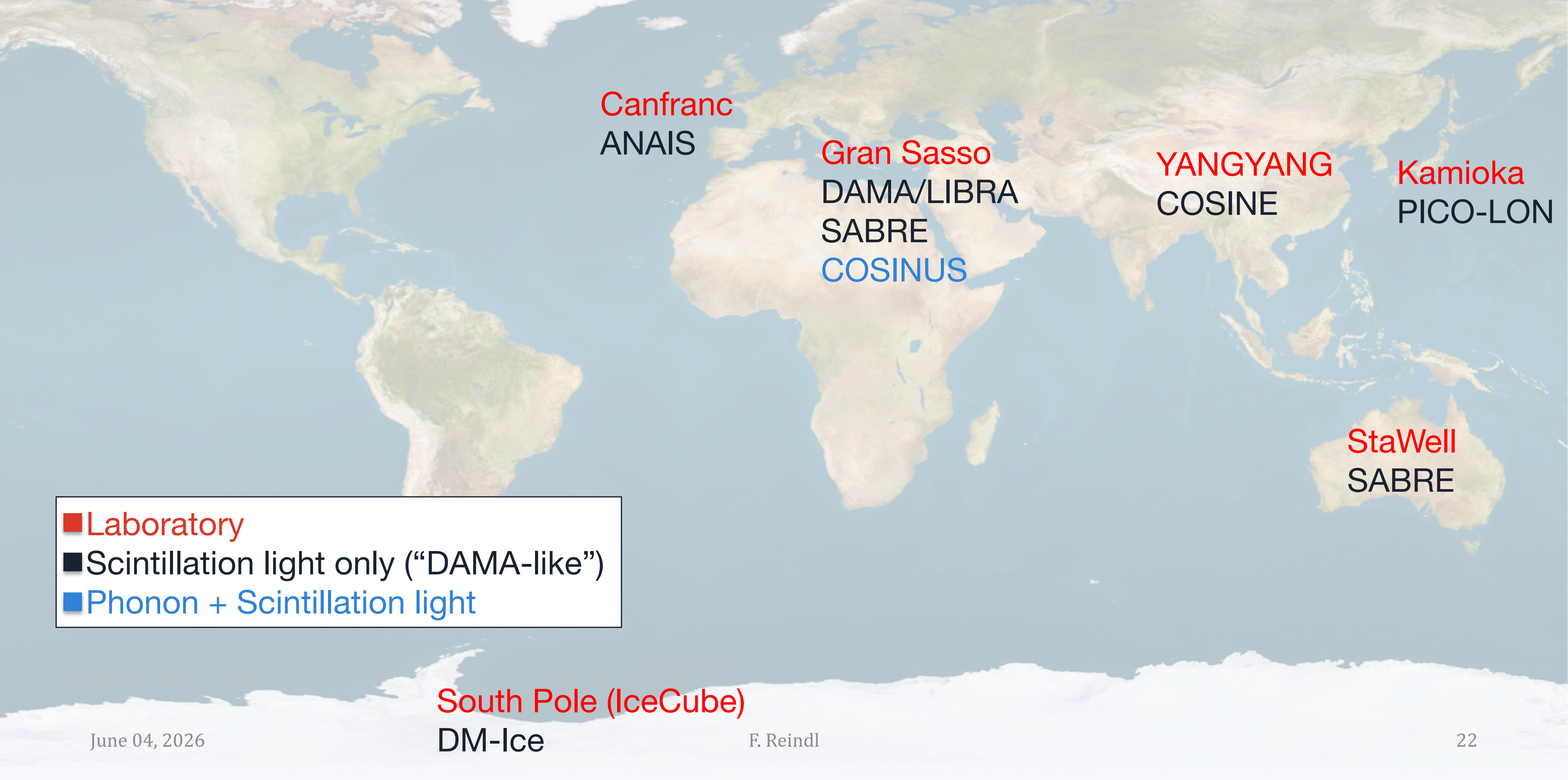
Same target



→Astroparticle Physics European Consortium (APPEC) Recommendation:

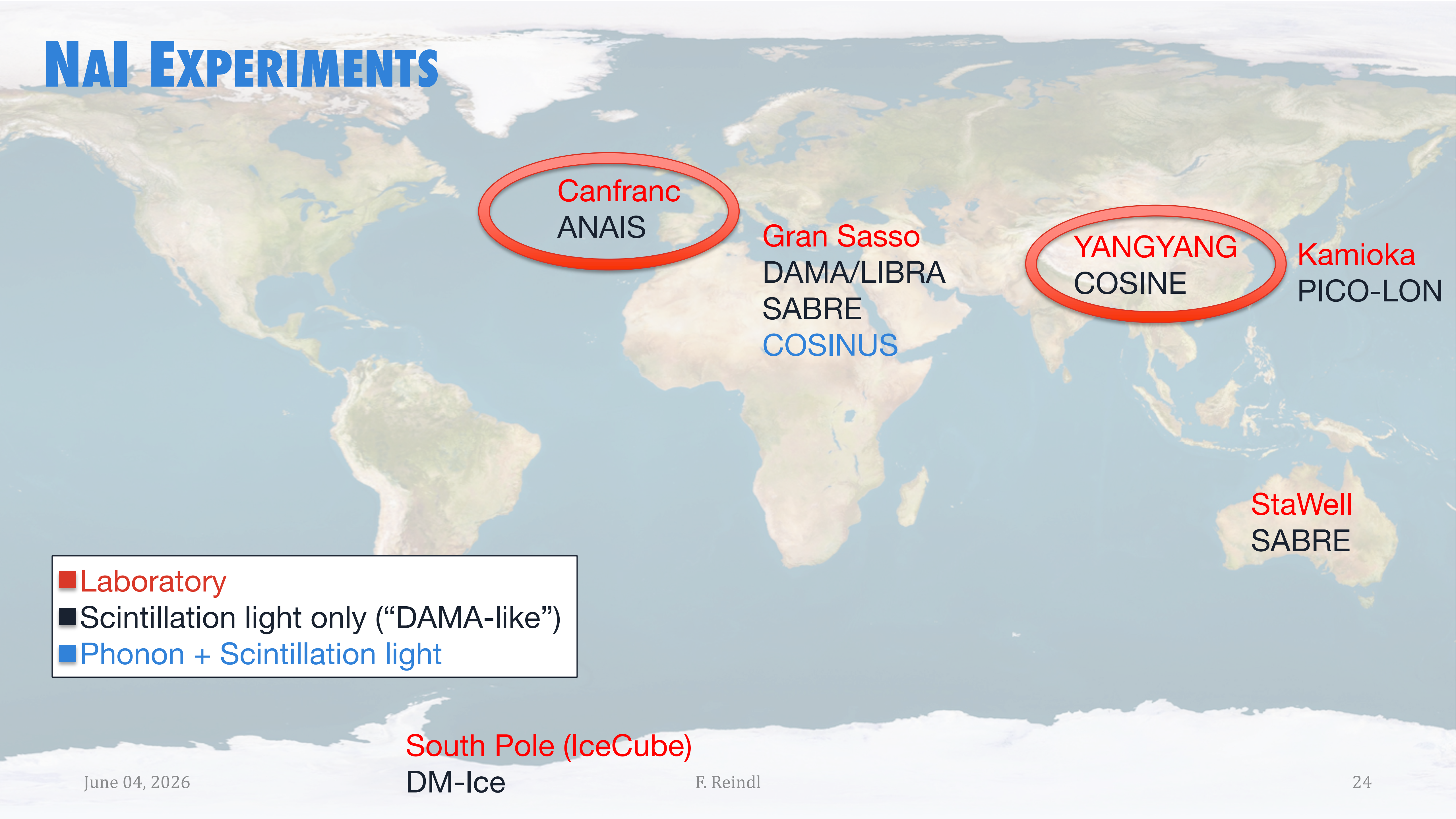
“The long-standing claim from DAMA/LIBRA […] needs to be independently verified using the same target material.”

NaI Experiments

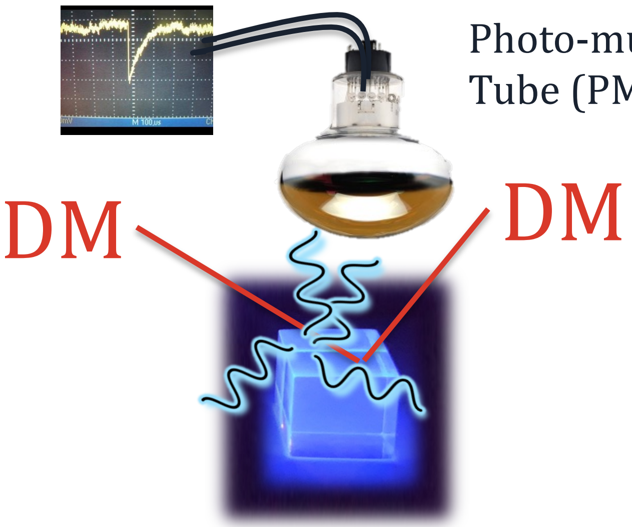


NaI Experiments

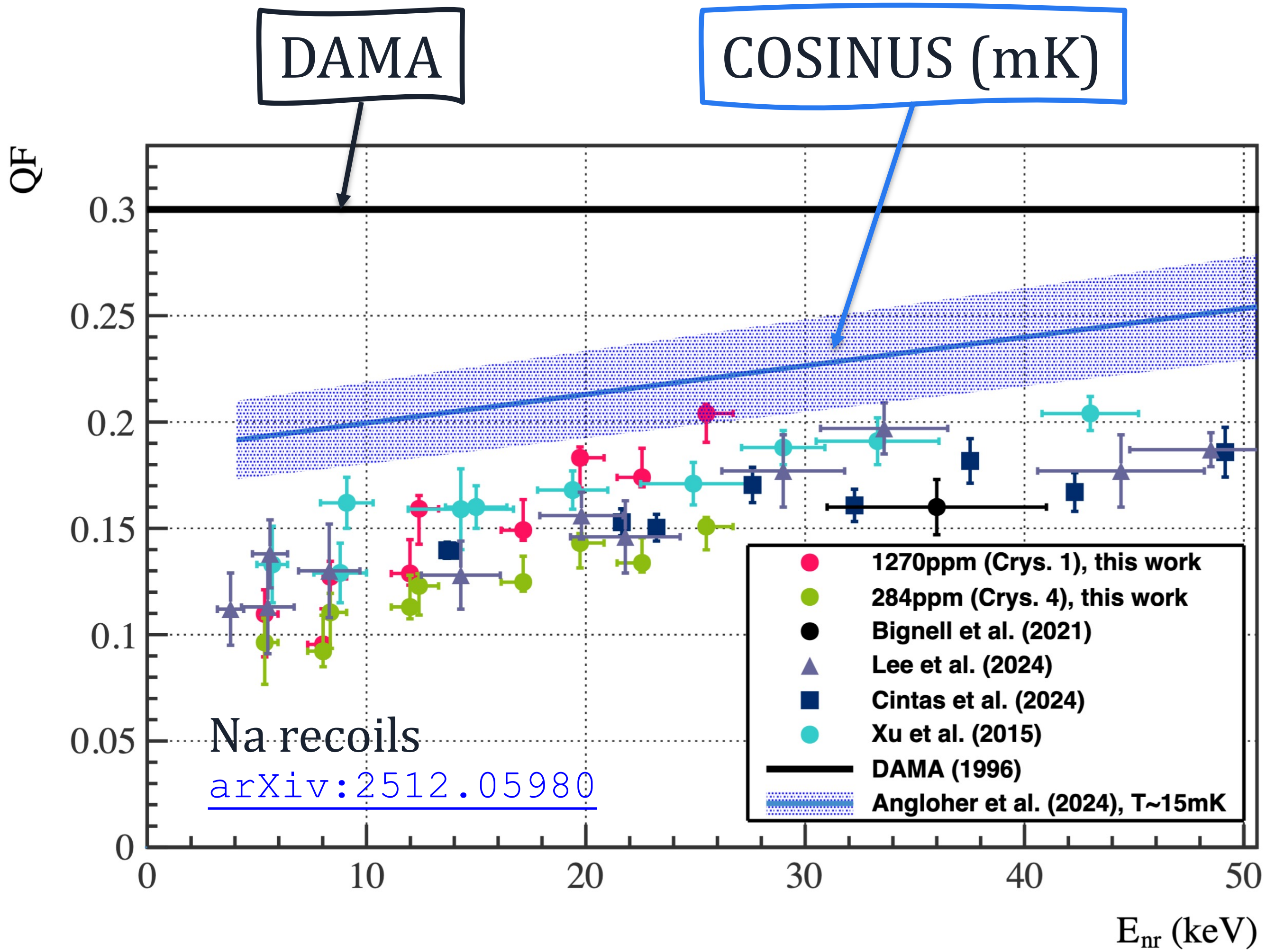
NaI Experiments



DAMA(-LIKE) SETUPS



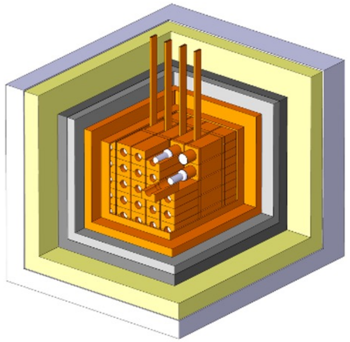
Scintillation light only!
→ Electron-equivalent energy scale



Quenching factors are uncertain
→Uncertainty on nuclear recoil energy scale

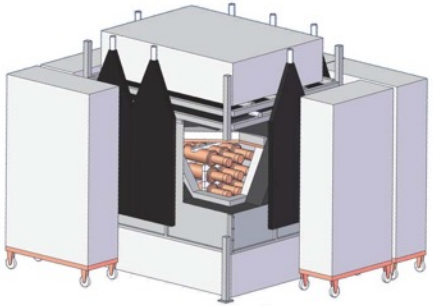
Experiment Comparison

DAMA/LIBRA



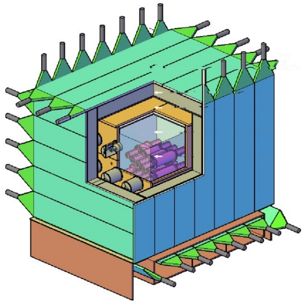
- LNGS - Italy
- Mass: 250 kg
- Bckg.: ~1 dru
- Threshold: 0.5 keV_{ee}
- Data taking: 1997 – 2024

ANAIS-112



- LSC - Spain
- 112.5 kg NaI
- Bckg.: ~2 – 4 dru
- Threshold: ~ 1 keV_{ee}
- Data taking: 2017 – 2026

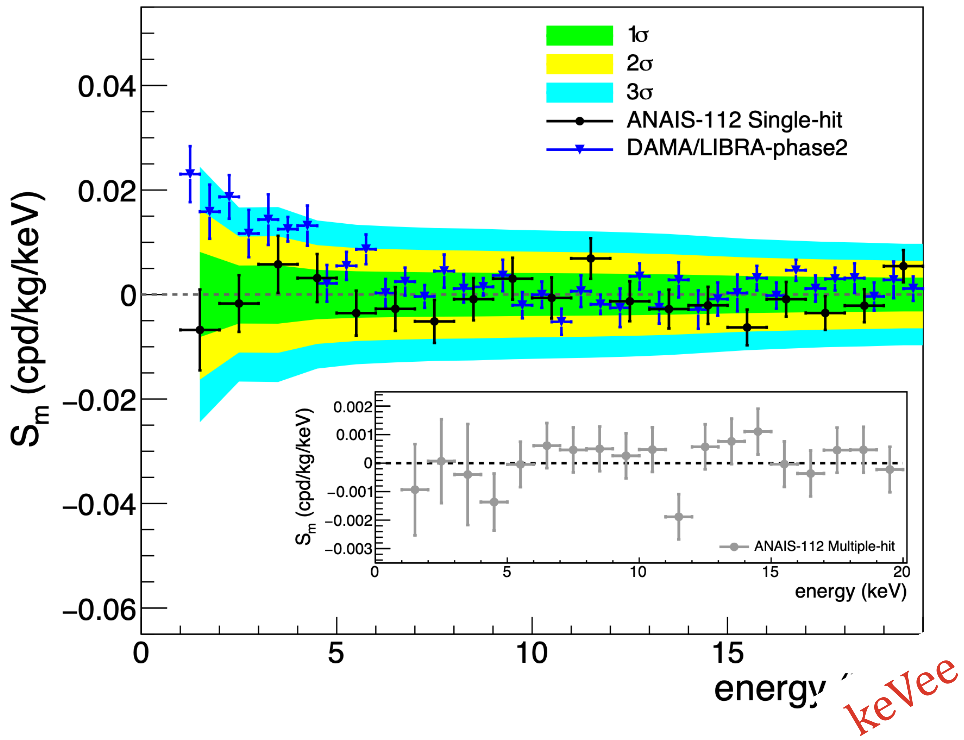
COSINE-100



- Y2L - South Korea
- 106 kg NaI
- Bckg.: ~2 – 5 dru
- Threshold: 0.49 keV_{ee}
- Data taking: 2016 - 2023

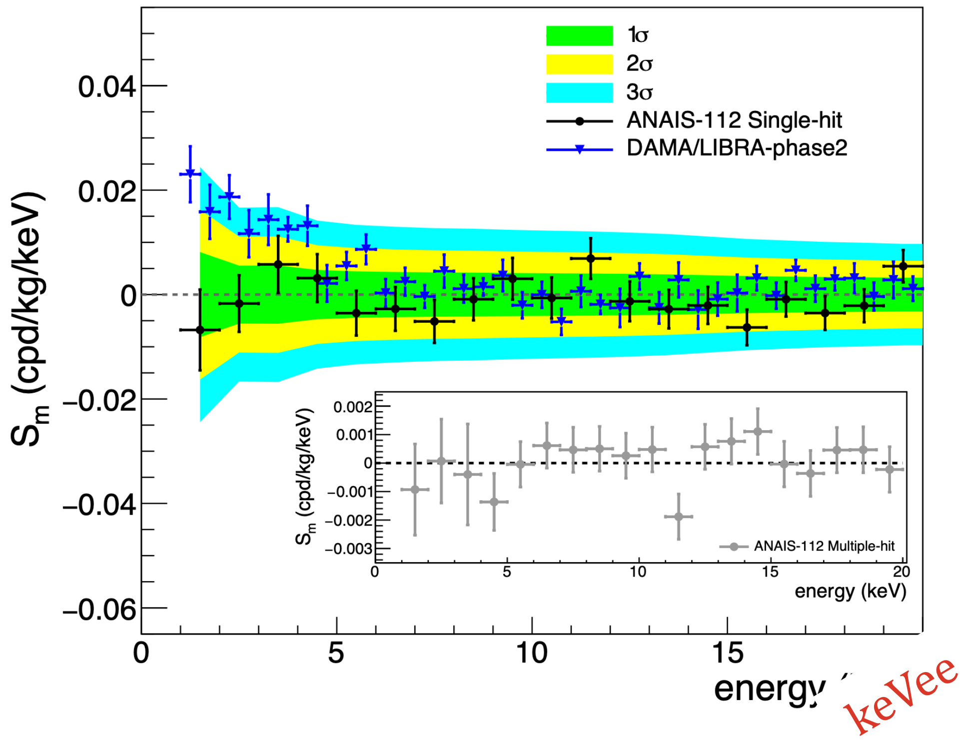
ANAIS – 6 years Data

arXiv:2502.01542, PRL135, 2025

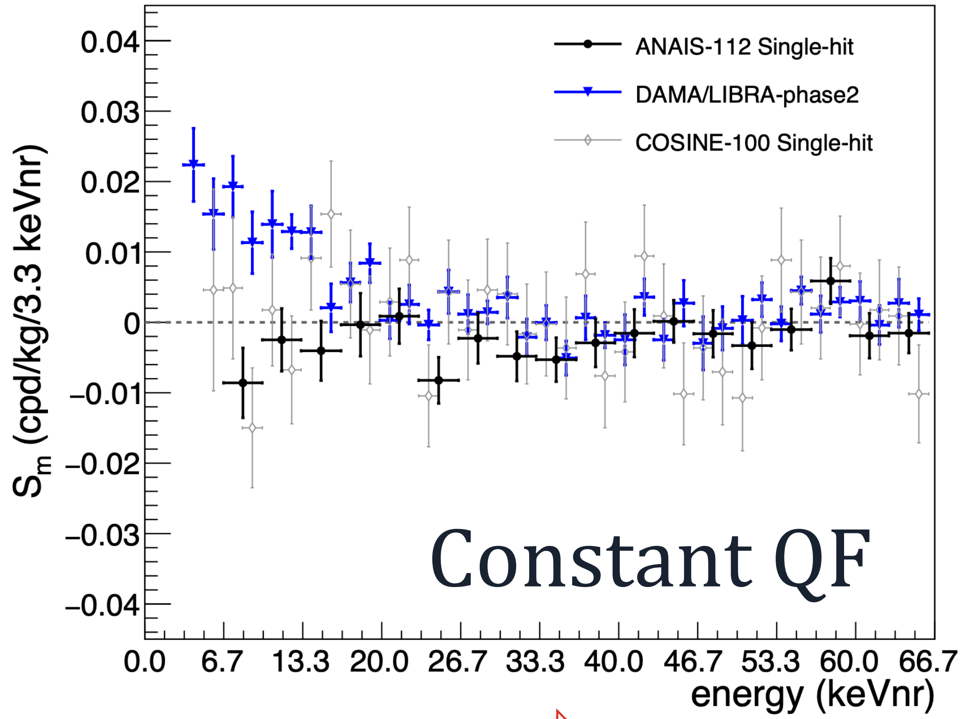


ANAIS – 6 years Data – Conversion keVee → keVnr

arXiv:2502.01542, PRL135, 2025



arXiv:2502.01542, PRL135, 2025



$QF_{ANAIS} = 0.2$

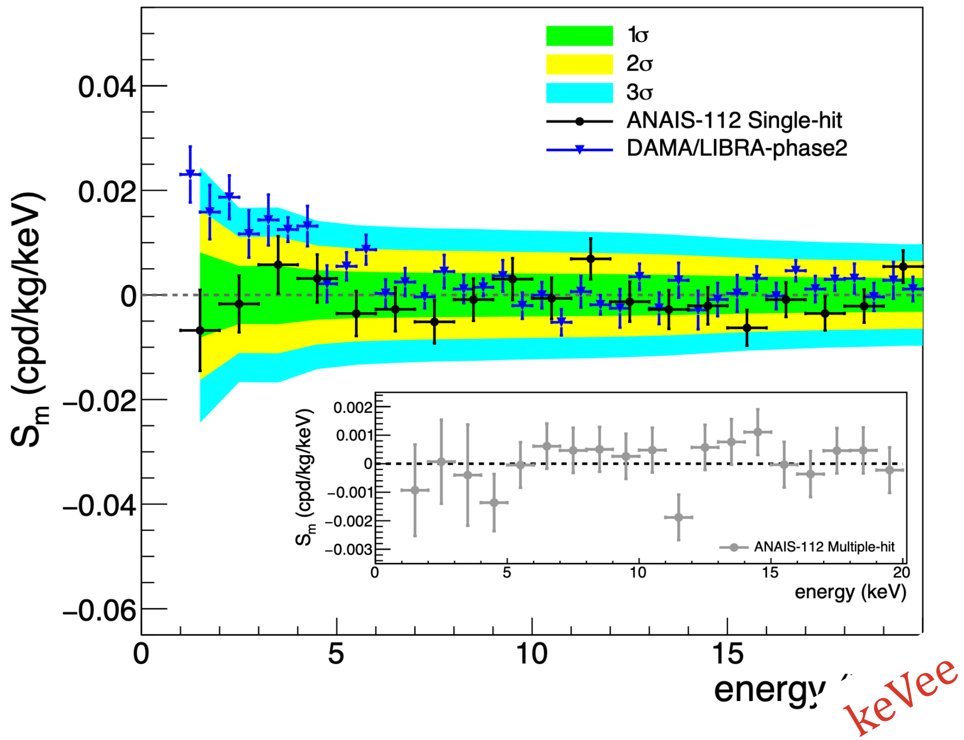
$QF_{DAMA} = 0.3$

[2-6] keVee → ANAIS: [10-30] keVnr

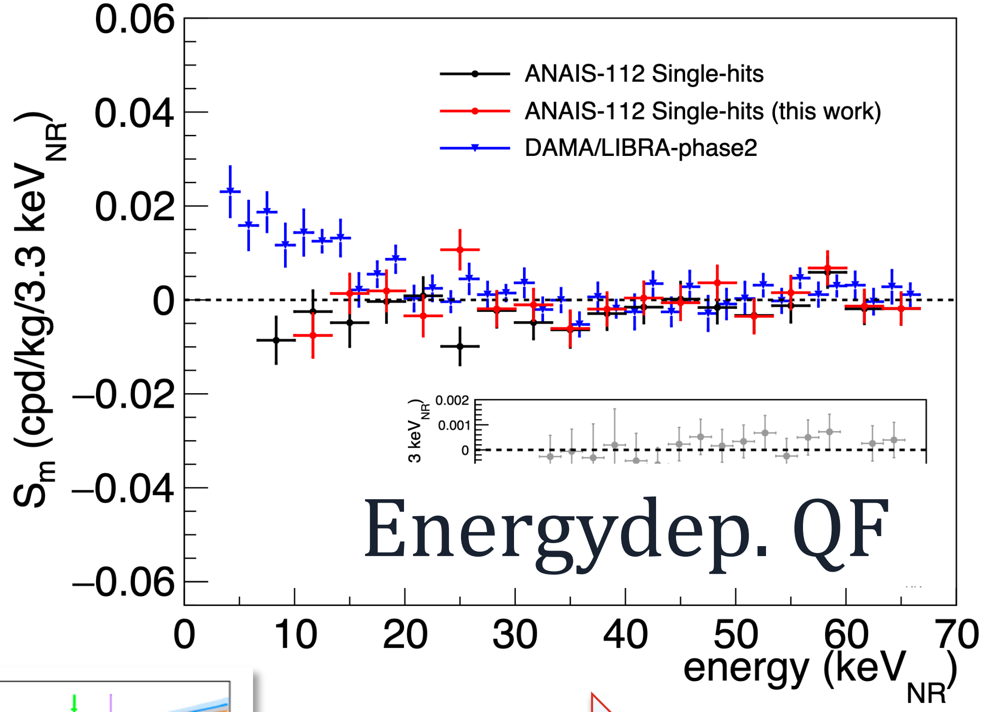
[2-6] keVee → DAMA: [6.7-20] keVnr

ANAIS – 6 years Data – Conversion keVee → keVnr

arXiv:2502.01542, PRL135, 2025

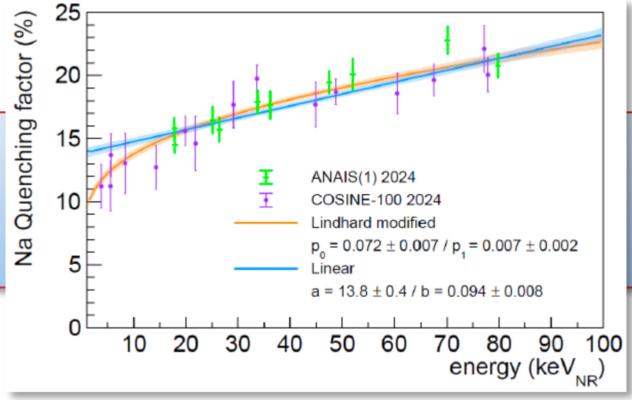


arXiv:2510.19469, PhD T. Pardo



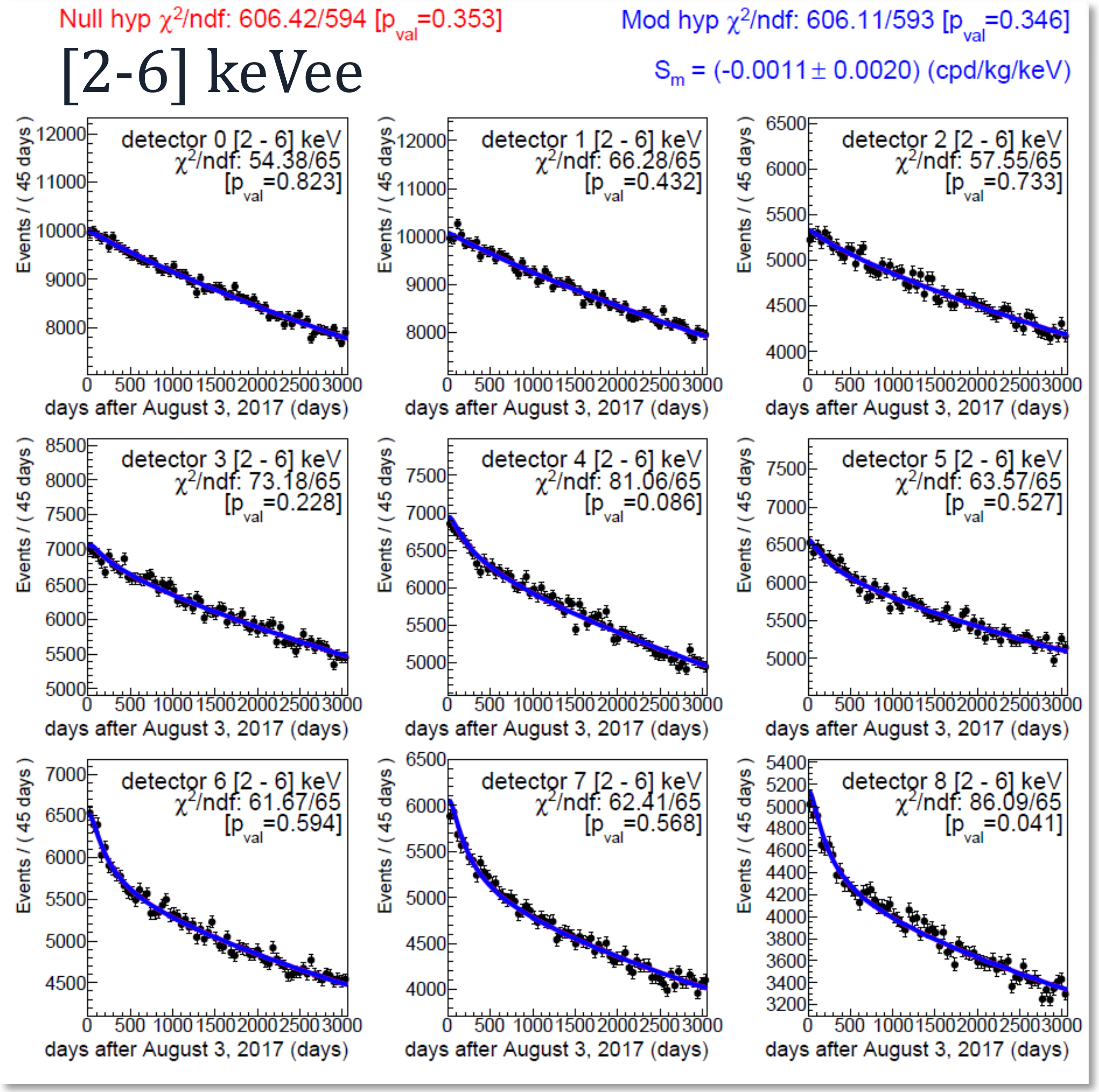
~~$QF_{ANAIS} = 0.2$~~

$QF_{DAMA} = 0.3$



NEW ANAIS: 8 YEARS DATA

PRELIMINARY

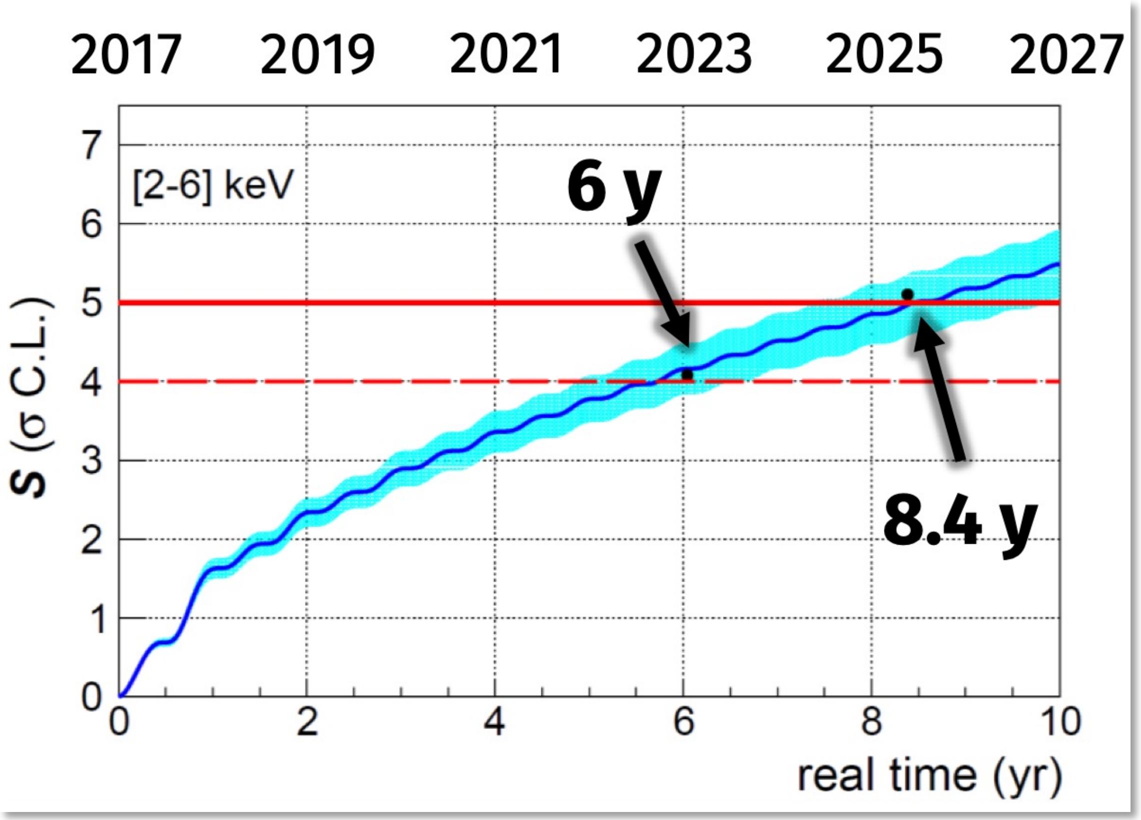


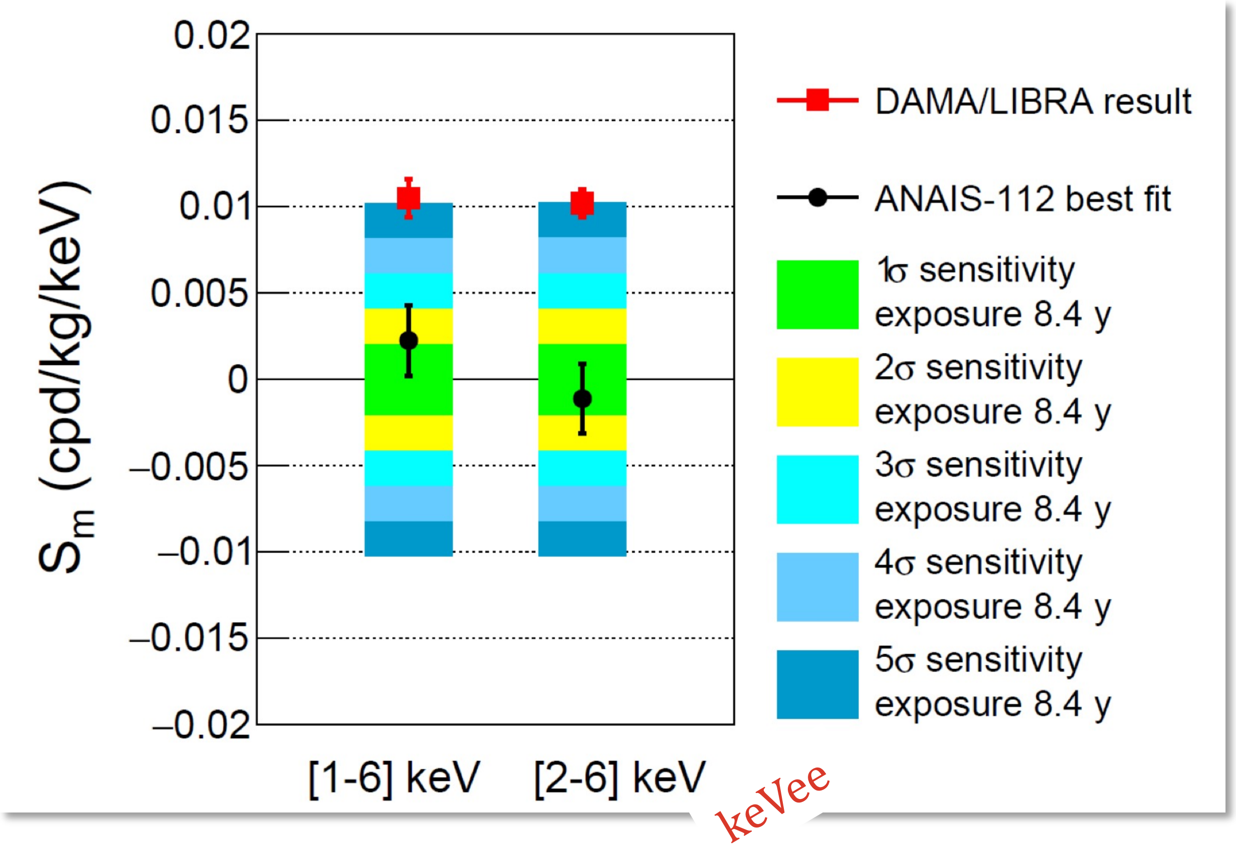
Exposure	872 kg years
Rate	(1.4 – 4.4) counts/(keV kg day)
Modulation Amplitude S_m	(-0.0011 ± 0.0020) counts/(keV kg day)

NEW ANAIS: 8 YEARS DATA

I. Coarasa, IDM2026

[2-6] keVee

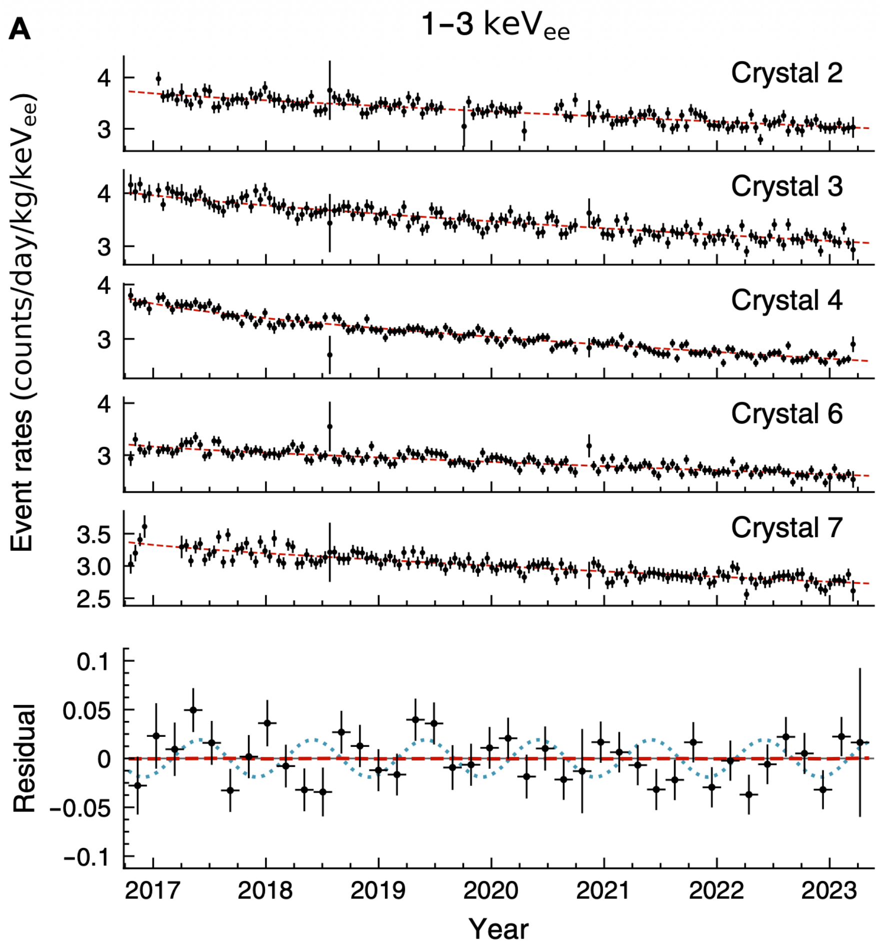




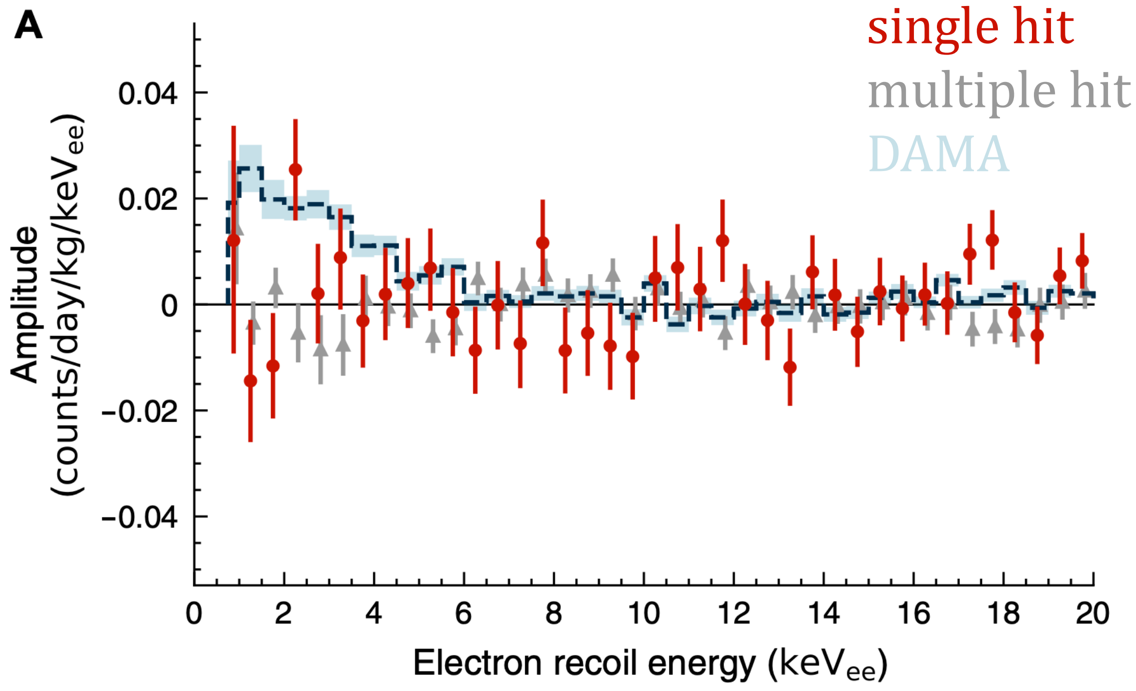
5 σ DAMA test

COSINE-100: 6 years Data

arXiv:2409.13226, SciAdv, 2025



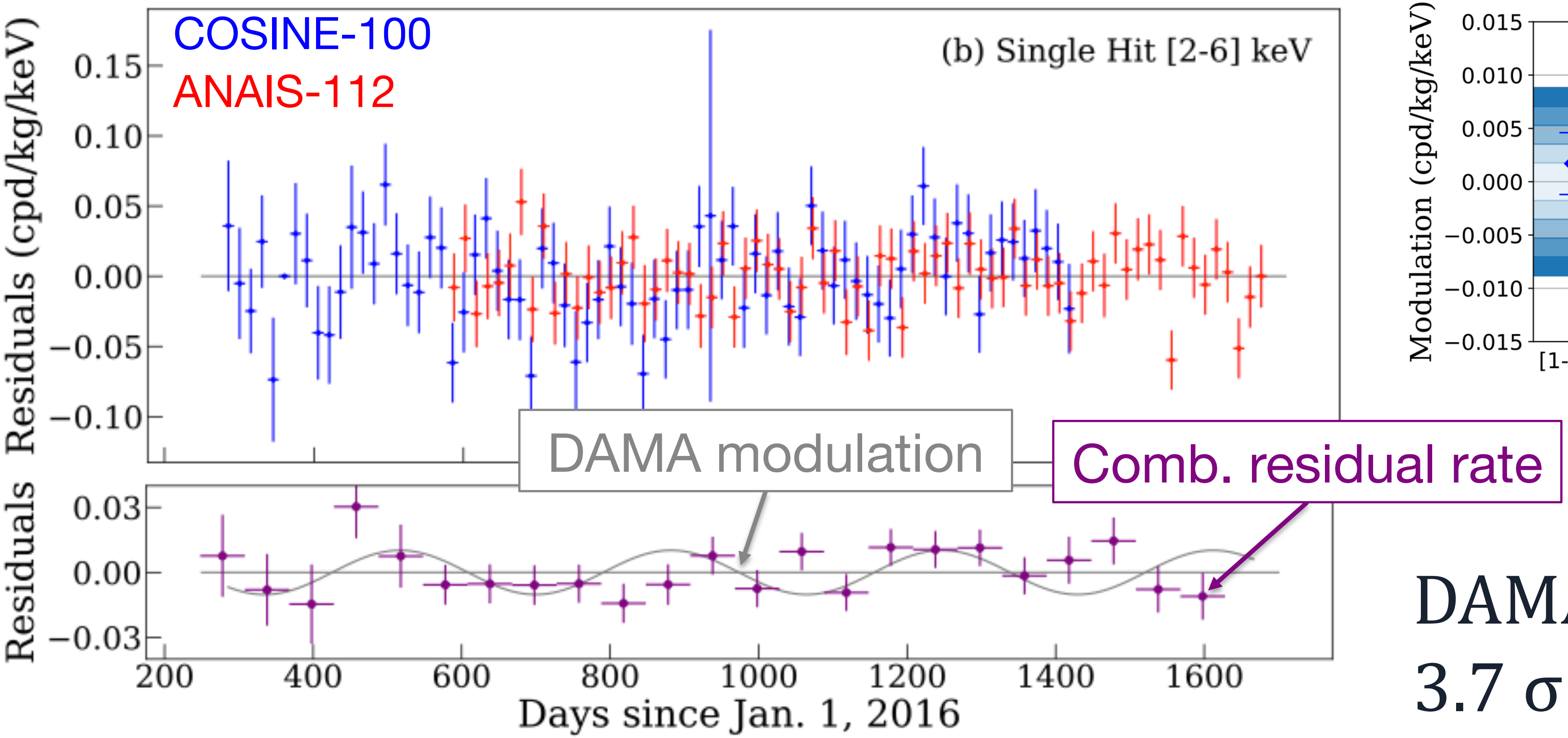
arXiv:2409.13226, SciAdv, 2025

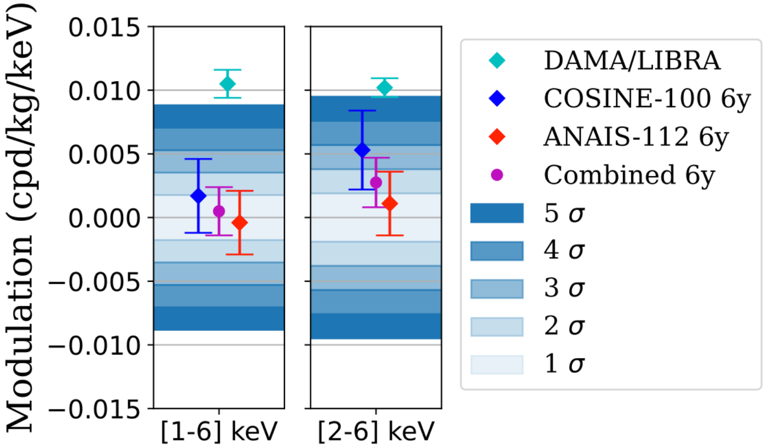


DAMA exclusion:
3.6 σ for (1-3) keVee

COSINE and ANAIS: Combination of 3 year Cata Sets

arXiv:2503.19559, PRL 135 2025





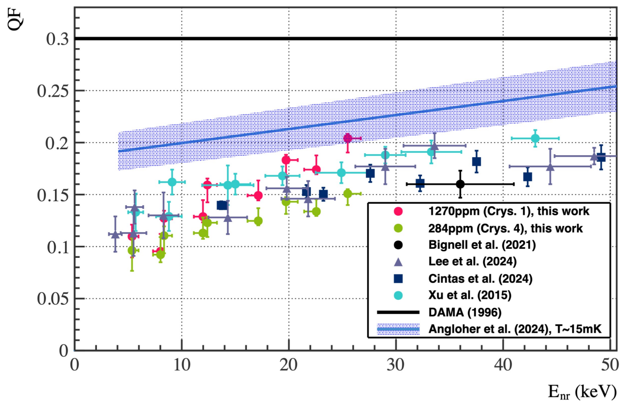
DAMA exclusion:
3.7 σ for (1-6) keVee
2.6 σ for (2-6) keVee

NaI Scintillation Detector Landscape

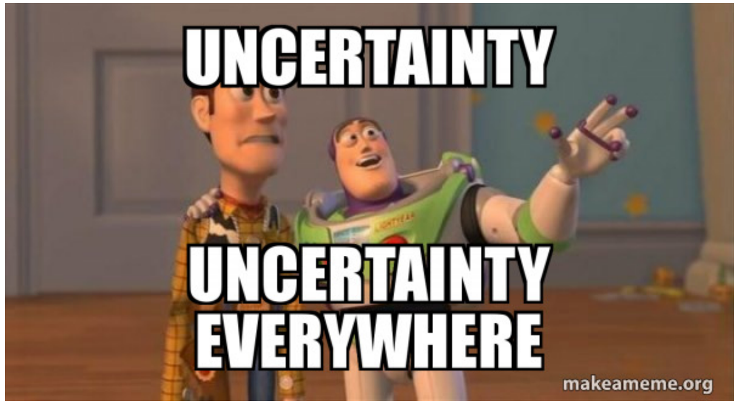
- Experiments more and more constrain DAMA/LIBRA

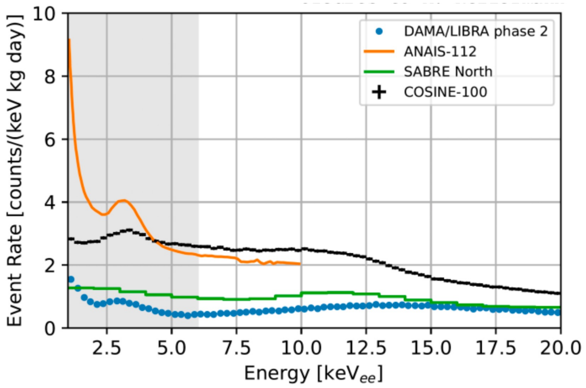
- Uncertainties remain, on quenching, calibration, efficiencies, ...

- In-situ calibrations are very difficult for scintillation-only experiments w/o particle identification

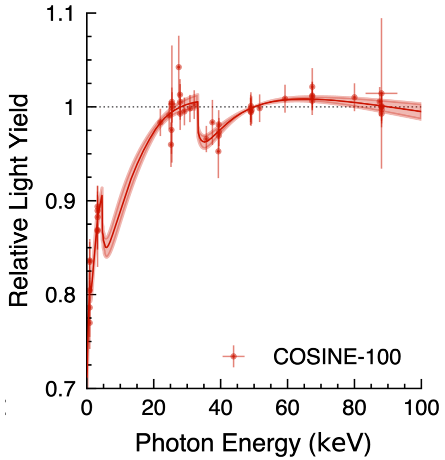


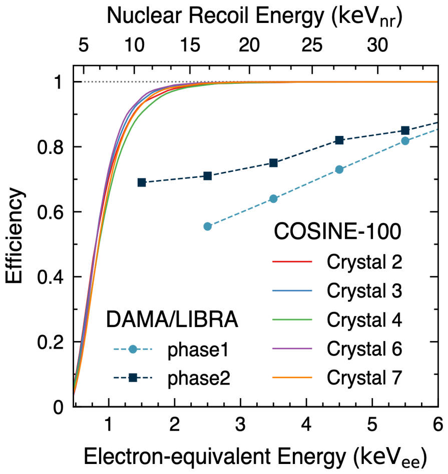
arXiv:2512.05980





M. Kellermann





arXiv:2409.13226, SciAdv, 2025

What's (may be) Coming for NaI Scintillation Detectors

ANAIS+

- PMT → SiPM
- RT → 100K
- Threshold:
  ~ 1 keV_{ee} → 0.5 keVee
- R&D phase

COSINE-100U

- Y2L → Yemilab
- Lower background
- Higher light yield
- Lower temperature
- Data taking:
  started 2025

AND

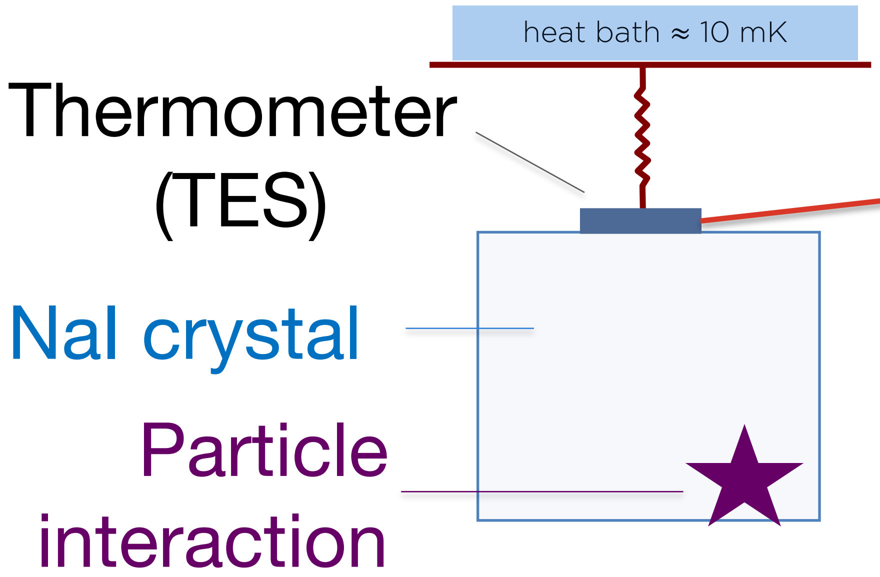
- ASTAROTH
- PICO-LON
- SABRE-North
- SABRE-South
- …

The COSINUS Experiment

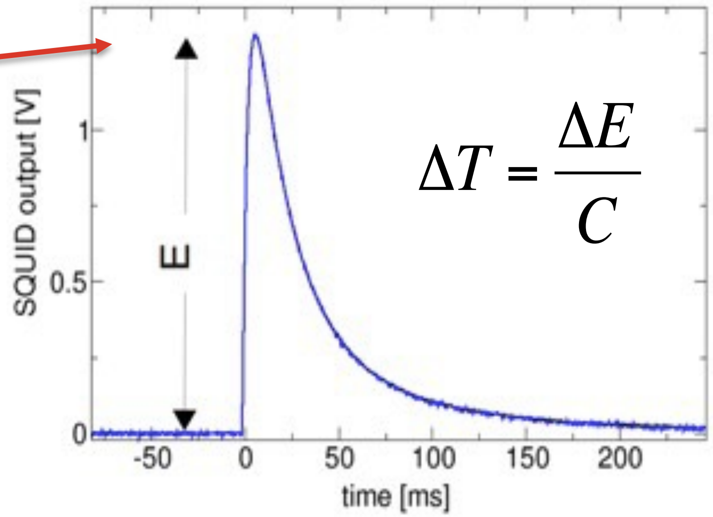
Aims at a model- and material-independent test of DAMA

Novel and unique: operation of NaI as cryogenic detector
→ Low threshold (in particular for nuclear recoils)
→ Precise energy information
→ Signal-only measurement of potential DM signal

CRYOGENIC NaI DETECTOR

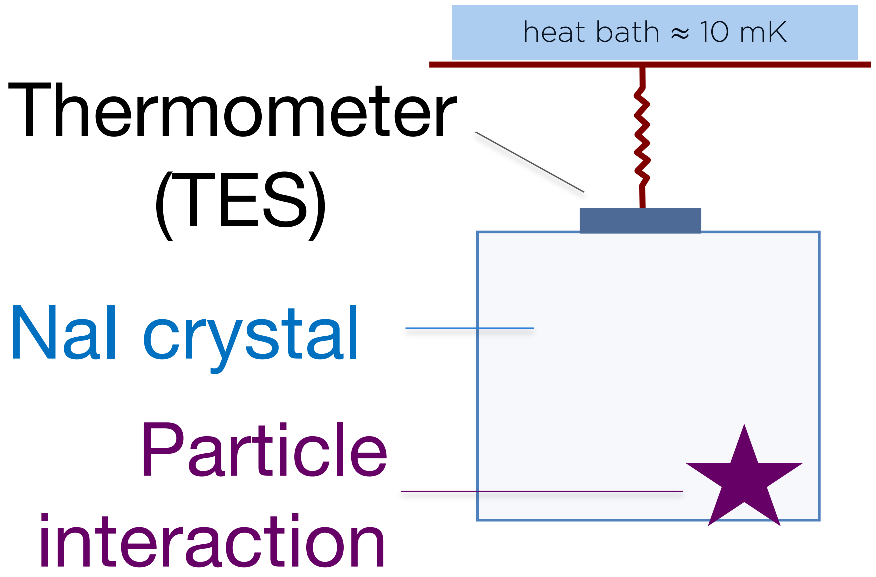


Temperature pulse



$$\Delta T = \frac{\Delta E}{C}$$

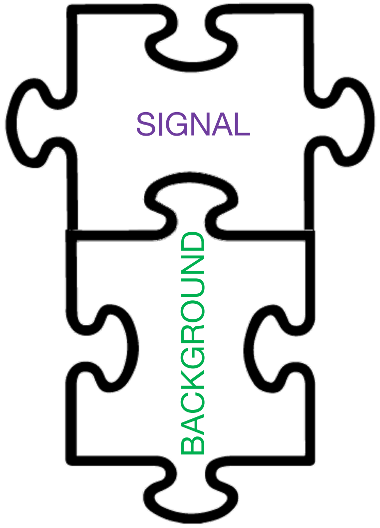
Cryogenic NaI Detector



Phonon signal (~90 %)

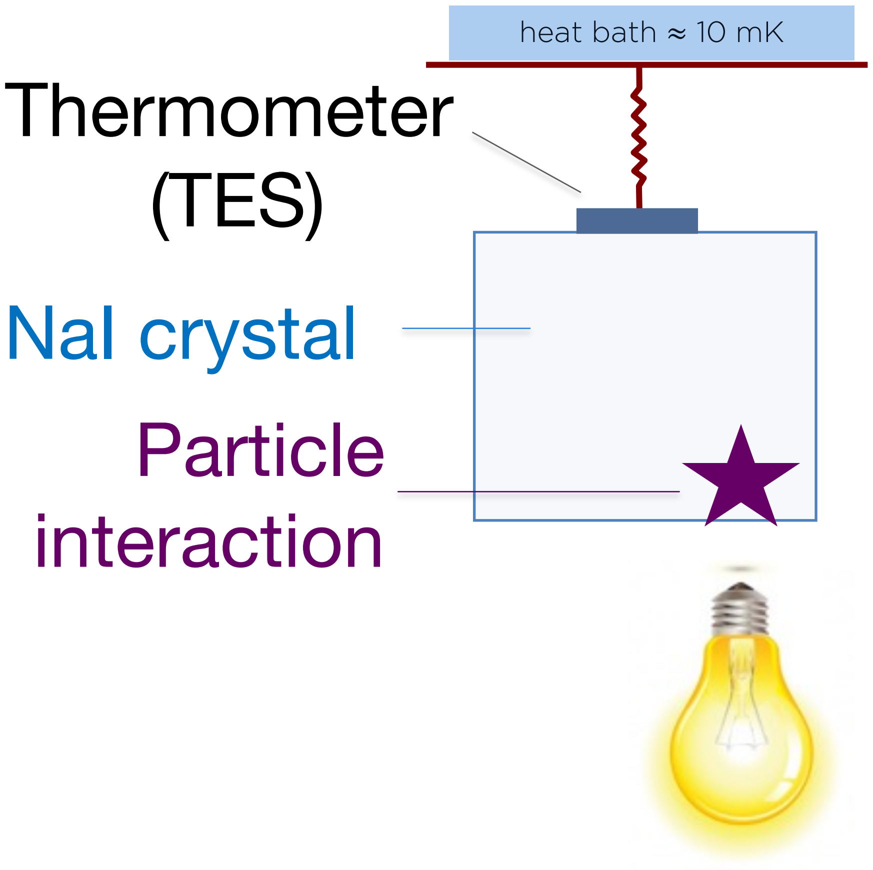
(Almost) independent of particle type

Precise measurement of the deposited energy



SCINTILLATING NaI CALORIMETER

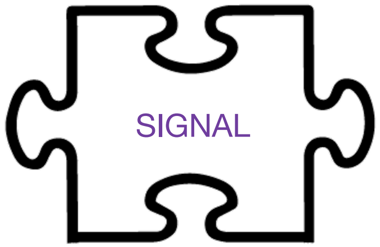
TES-based scintillating calorimeters pioneered by CRESST DM search



Phonon signal (~90 %)

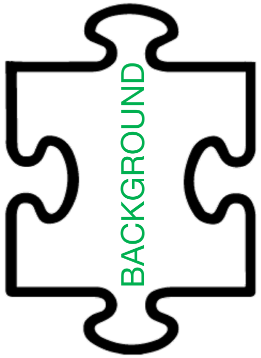
(Almost) independent of particle type

Precise measurement of the deposited energy



Scintillation light (few %)

Particle-type dependent
→ LIGHT QUENCHING



A cryogenic NaI detector is awesome!
Why did it not exist? → Because NaI is not NaICE!

PROBLEM

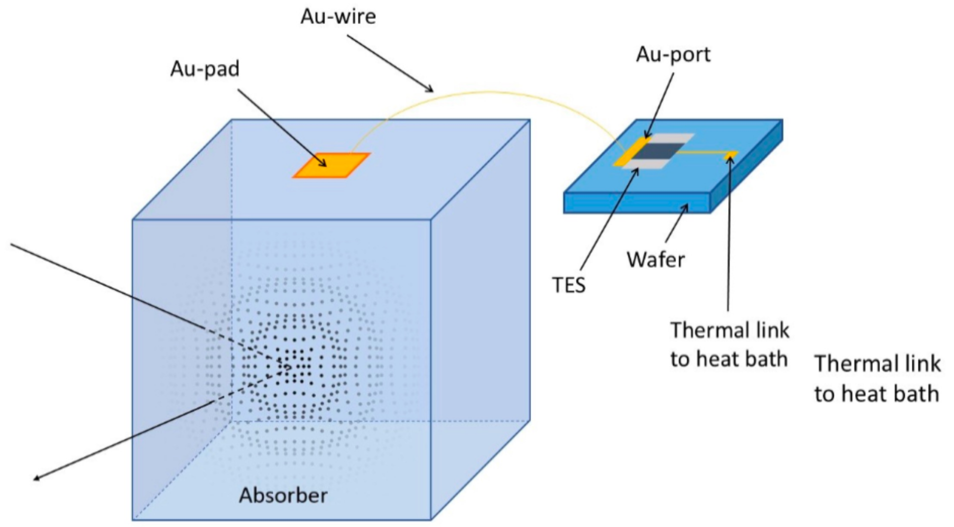
Low Debye temperature

Properties	NaI(pure)	CsI(pure)	$CdWO_4$	$CaWO_4$
Density [g/cm^3]	3.67	4.51	7.9	6.12
Melting point [°C]	661	894	1598	1650
Structure	CsCl	CsCl	Wolframite	Scheelite
λ_{max} at 300 K [nm]	~300	~315	~475	420-425
Hygroscopic	yes	slightly	no	no
Θ_D [K]	169	125	-	335
Photons per keV at 3.4 K	19.5 ±1.0	58.9±5.6	-	-
Mean energy of emitted photon [eV]	3.3	3.9	-	3.14

Small signal amplitudes

SOLUTION

remoTES detector design

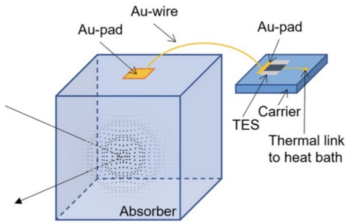


NaI → Au-wire/pad → TES

Phonons couple directly to electron system of Au-pad

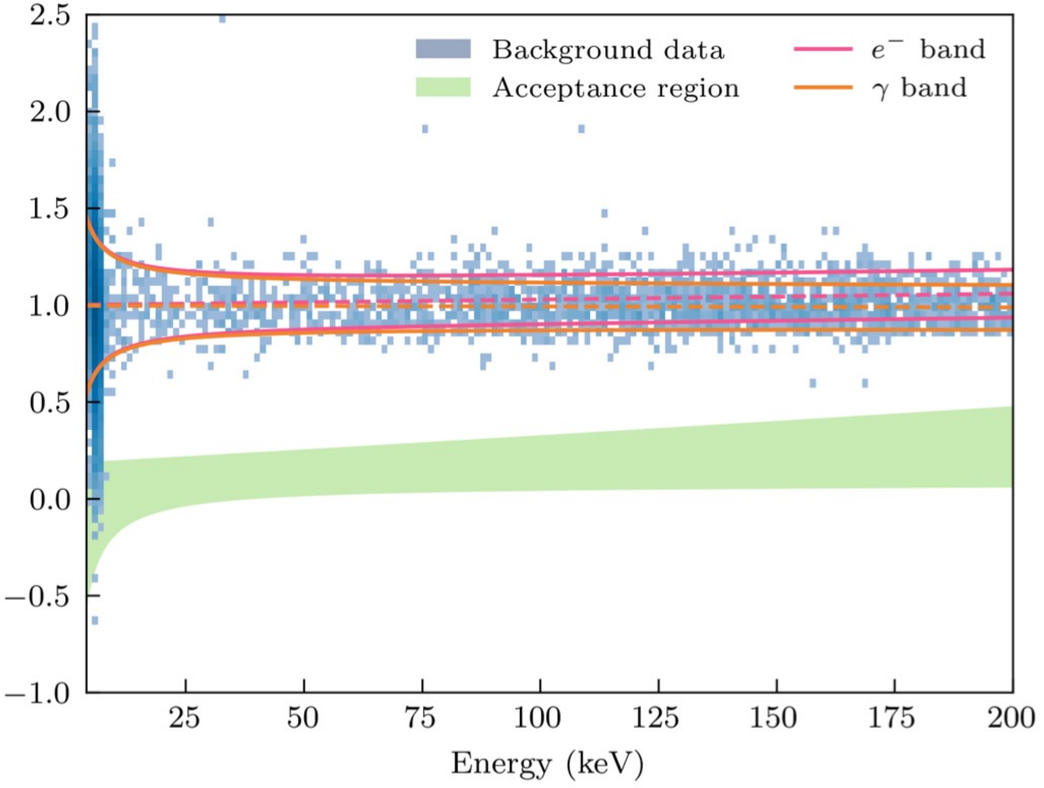
arxiv:2111.00349v1 NIMA, 1045, 2023

remoTES Measurement with NaI Target



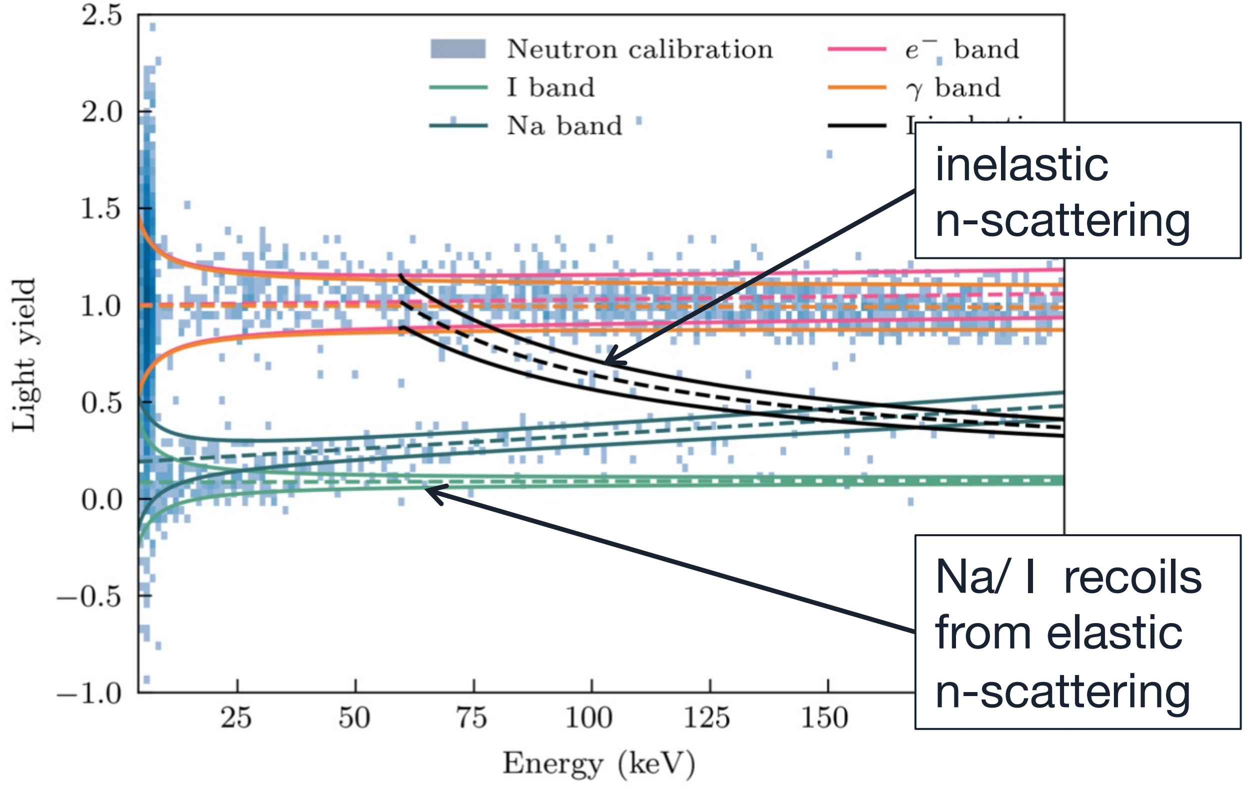
arXiv:2307.11066, PRD 109, 082003
arXiv:2307.11139, PRD 110, 043010

Background data



nuclear recoil threshold: <2 keV

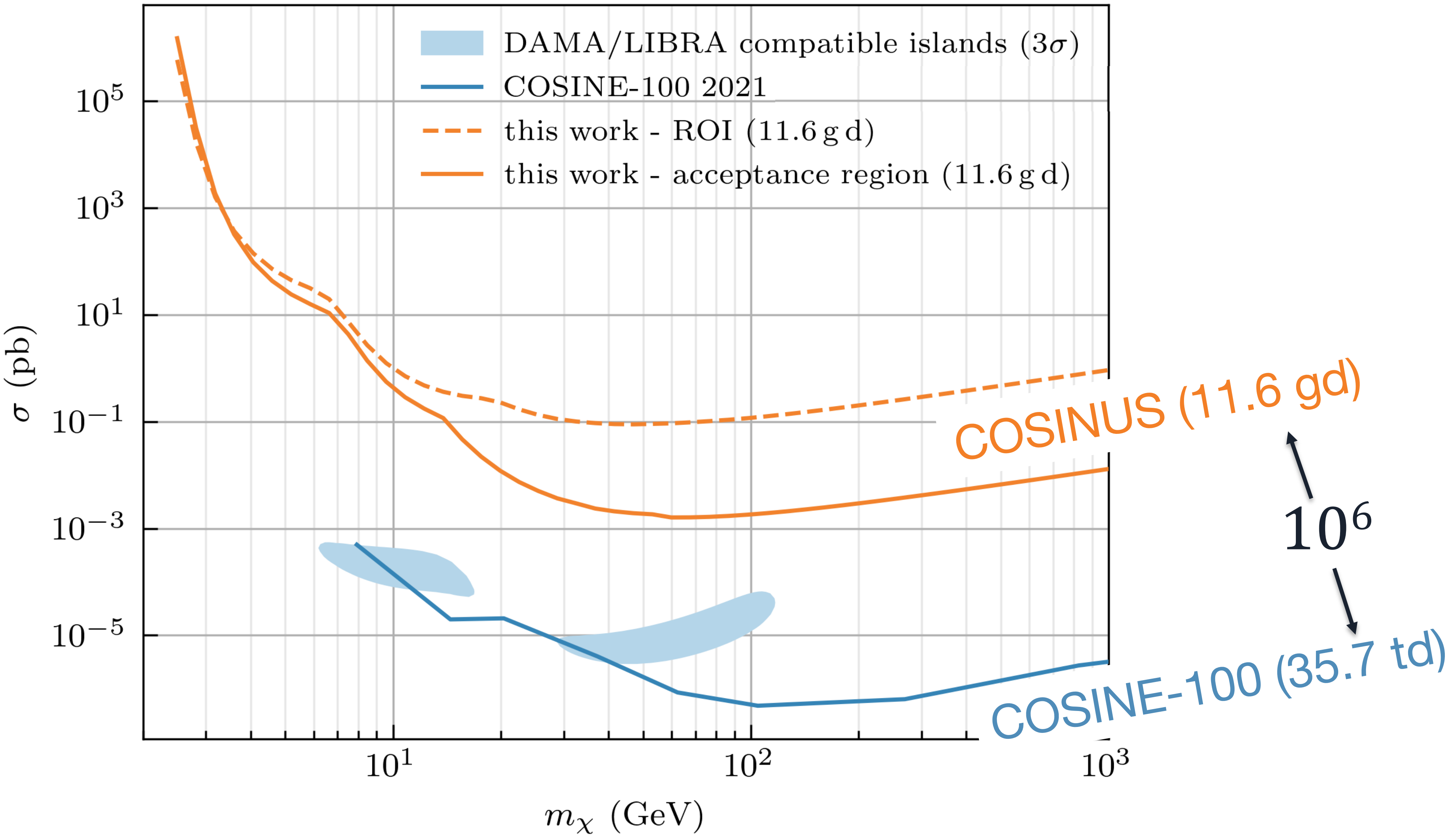
Neutron calibration



first NaI detector with particle identification on event-by-event basis

Measurement: First COSINUS Dark Matter Results

arXiv:2307.11139, PRD 110, 043010

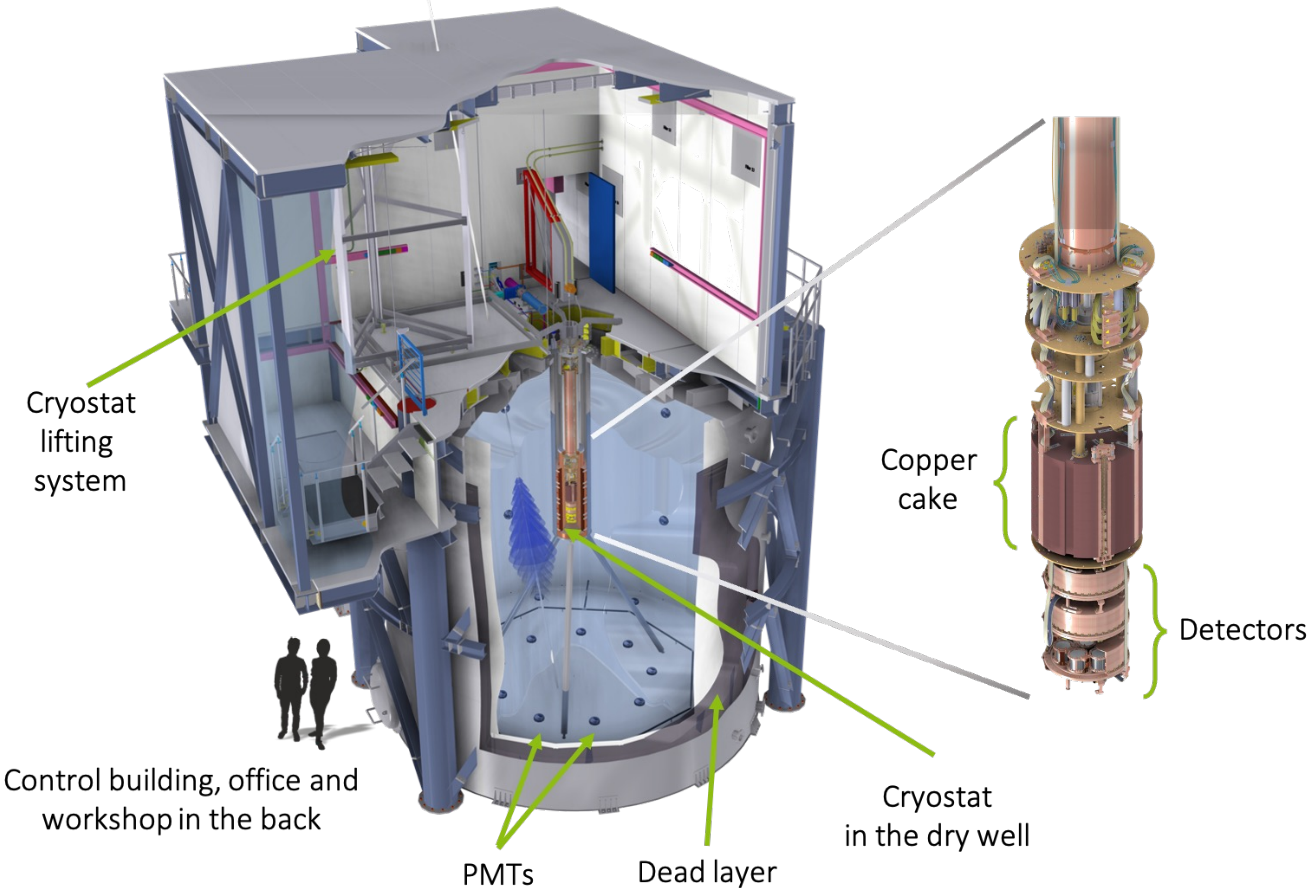


COSINUS Facility at LNGS

arXiv:2106.07390, EPJ-C 82, 248, 2022
arXiv:2406.12870, EPJ-C 84, 551, 2024
arXiv:2507.02429, Nature Comm., 2026

Checklist to start 100 kg day data taking

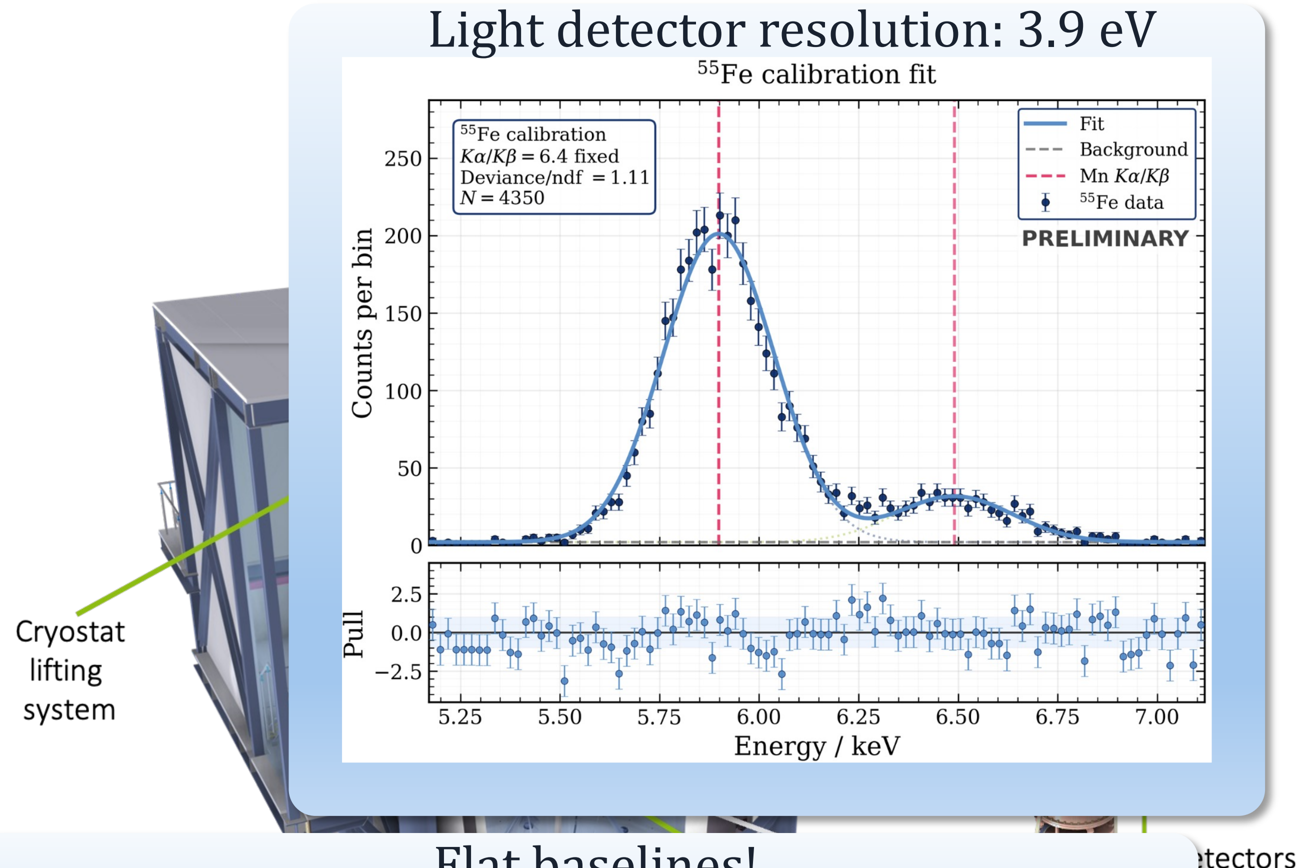
- ☑ 30-PMT water Cherenkov muon veto: working
- ☑ Cryostat: reaches 9mK, runs stably for months
- ☑ Vibration decoupling: working
- ☑ Active magnetic field compensation: working
- ☑ 48-SQUIDs + cabling + DAQ: working
- ☑ Radiopure NaI crystals: available
- ☑ Si-beaker light detectors: available
- ☐ TESs: in production

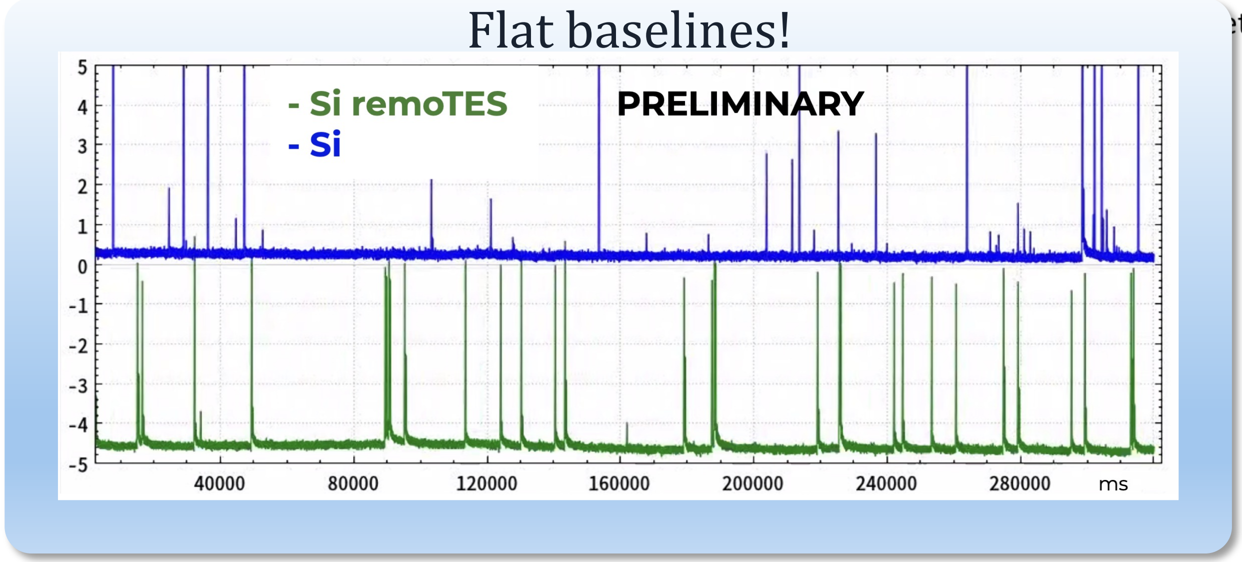


COSINUS Facility at LNGS

Checklist to start 100 kg day data taking

- ☑ 30-PMT water Cherenkov muon veto: working
- ☑ Cryostat: reaches 9mK, runs stably for months
- ☑ Vibration decoupling: working
- ☑ Active magnetic field compensation: working
- ☑ 48-SQUIDs + cabling + DAQ: working
- ☑ Radiopure NaI crystals: available
- ☑ Si-beaker light detectors: available
- ☐ TESs: in production

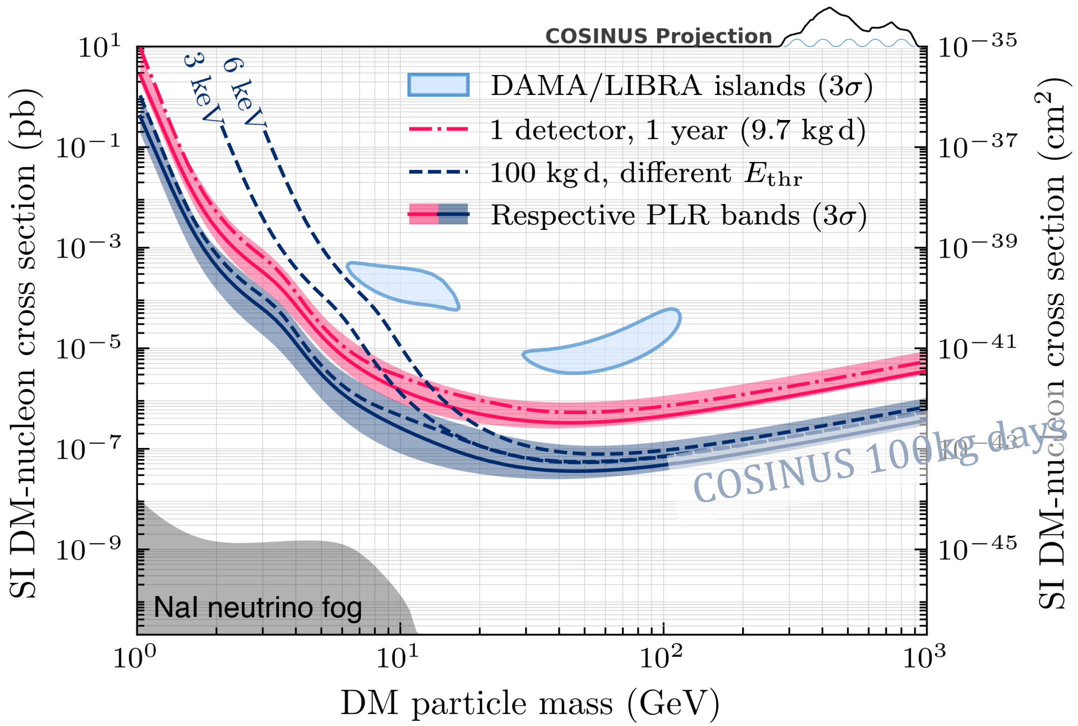




arXiv:1802.10175, JCAP05(2018)074

PHYSICS REACH

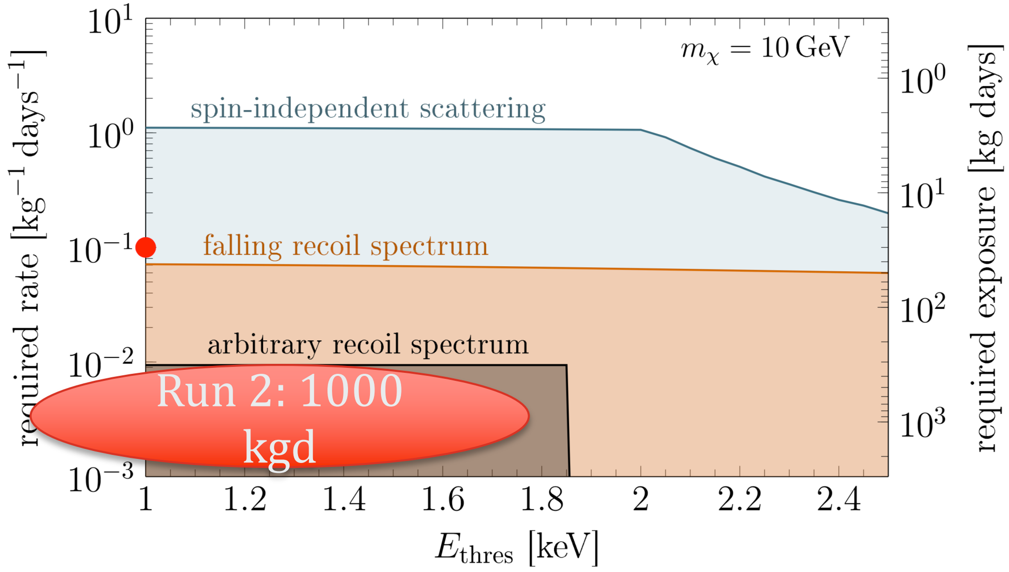
Run 1: 2026-2027



Dark matter results

Run 2: ≥2027

Total rate R ≥ S Modulation amplitude



Final model-independent cross-check

Conclusion

TAUP 1997:

DAMA reports first evidence for an annual modulation signal

Nature news (04/2016):

"This will get resolved," says Frank Calaprice [Princeton, SABRE]

My personal view (10/2018):

This will not take another two decades!

CONCLUSION

TAUP 1997:
DAMA reports first evidence for an annual modulation signal

Nature news (04/2016):
"This will get resolved," says Frank Calaprice [Princeton, SABRE]

My personal view (10/2018):
This will not take another two decades!

My personal view (06/2026)
Yes, but it seems to take one decade from 2018
with data from ANAIS, COSINE, COSINUS, SABRE, ...

NaI DM searches are throwing light on the DAMA/LIBRA DM claim.

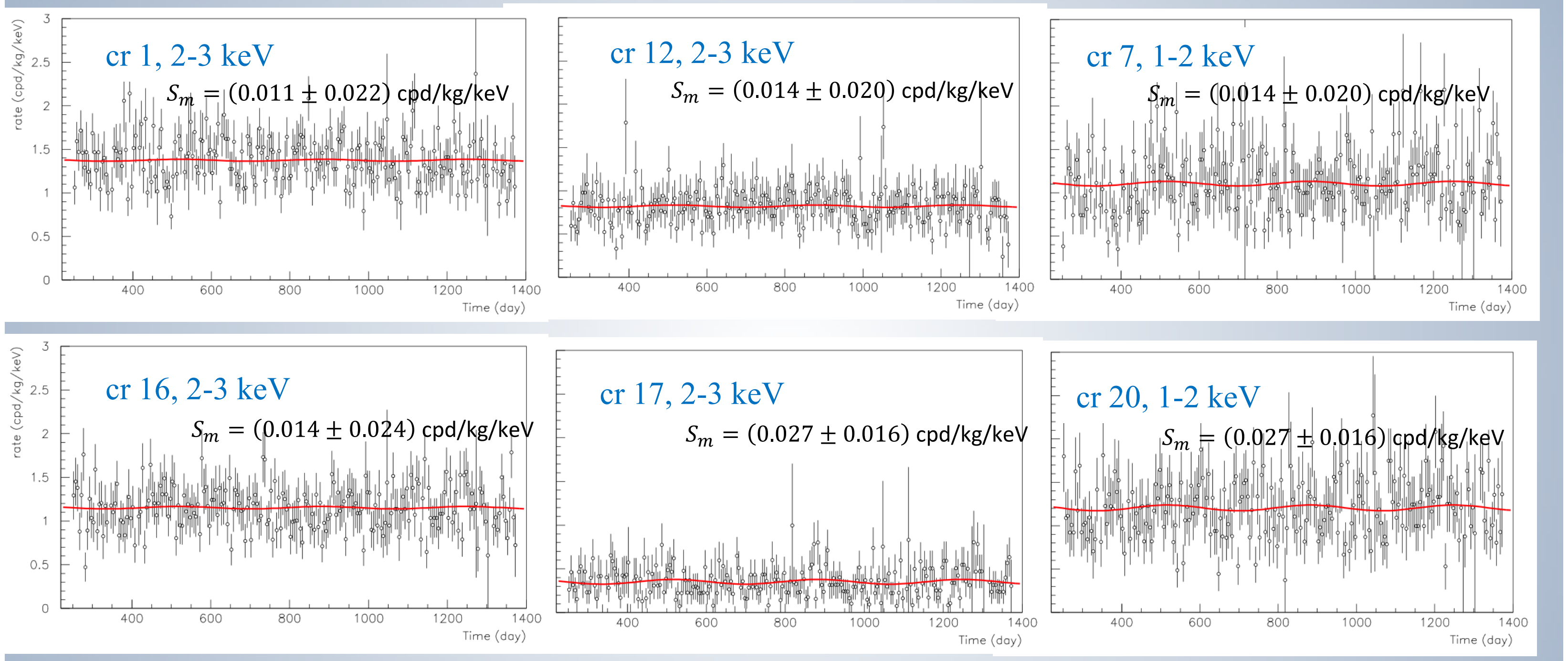
Stay tuned for what they will catch.

Thank you!

Investigation on the rate time dependence

R. Cerulli
IDM2024

The **last three published years** of DAMA/LIBRA–phase2 (in which there was continuity between one year and the next) analysed **considering the same bckg**



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

- Time bin: 5 days
- Red: maxlik analysis on single crystal with common (constant) background

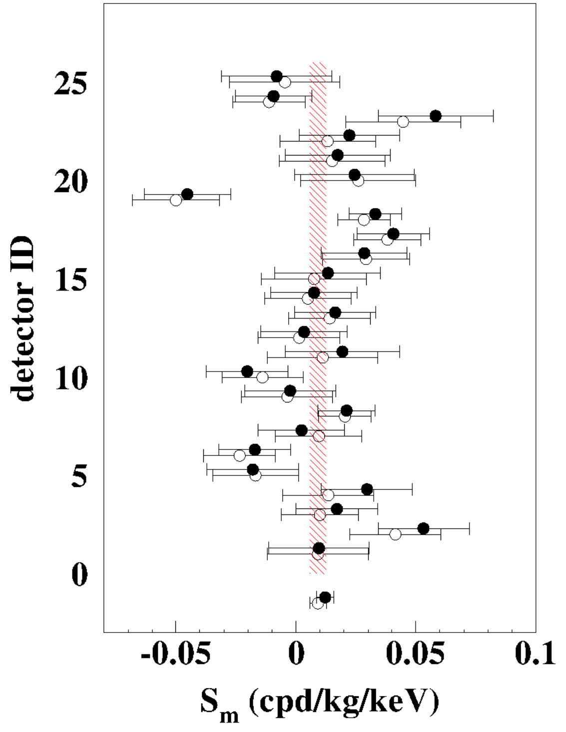
Expected rate over three years: $\boldsymbol{\mu_{ij} = b_j + S_0 + S_m cos[\omega(t_i - t_0)]}$

Investigation on the rate time dependence

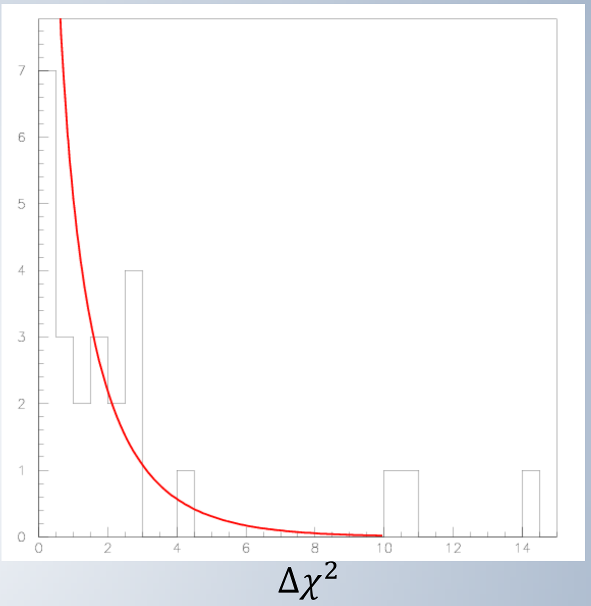
R. Cerulli
IDM2024

A template case: 3-4 keV, 25 crystal, **last three years** of DAMA/LIBRA–phase2 (0.61 ton×yr)

- For each detector the rates are fitted by MaxLik with case **A**: $b + S_m cos$
- Then, with case **B**: $b - a \times time + S_m cos$
- H_0 hypothesis: flat background → case **A**
- Test variable: $\Delta\chi^2 = \chi_A^2 - \chi_B^2$ with dof=1



- Modulation amplitudes, S_m, in the two cases
- Case **A**: open points
- Case **B**: black points
- Mean shift between case **B** an **A** is $\simeq 0.26\sigma$

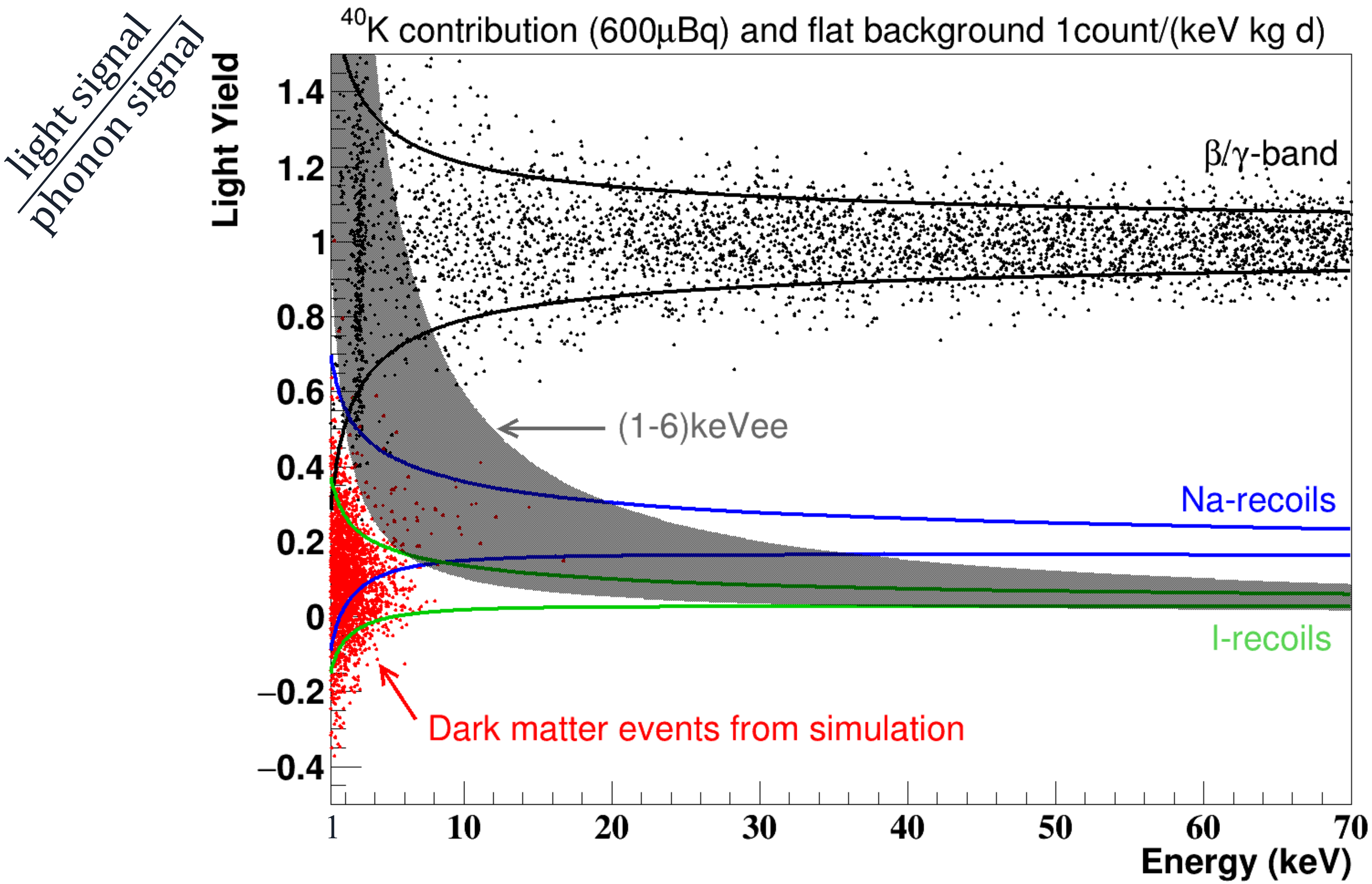


- Plot of $\Delta\chi^2$ for each detector
- It follows a χ^2 distribution with dof=1

There is no need to enable the background slope over time

Simulation (2015)

100 kg-days before cuts
1keV nuclear recoil threshold

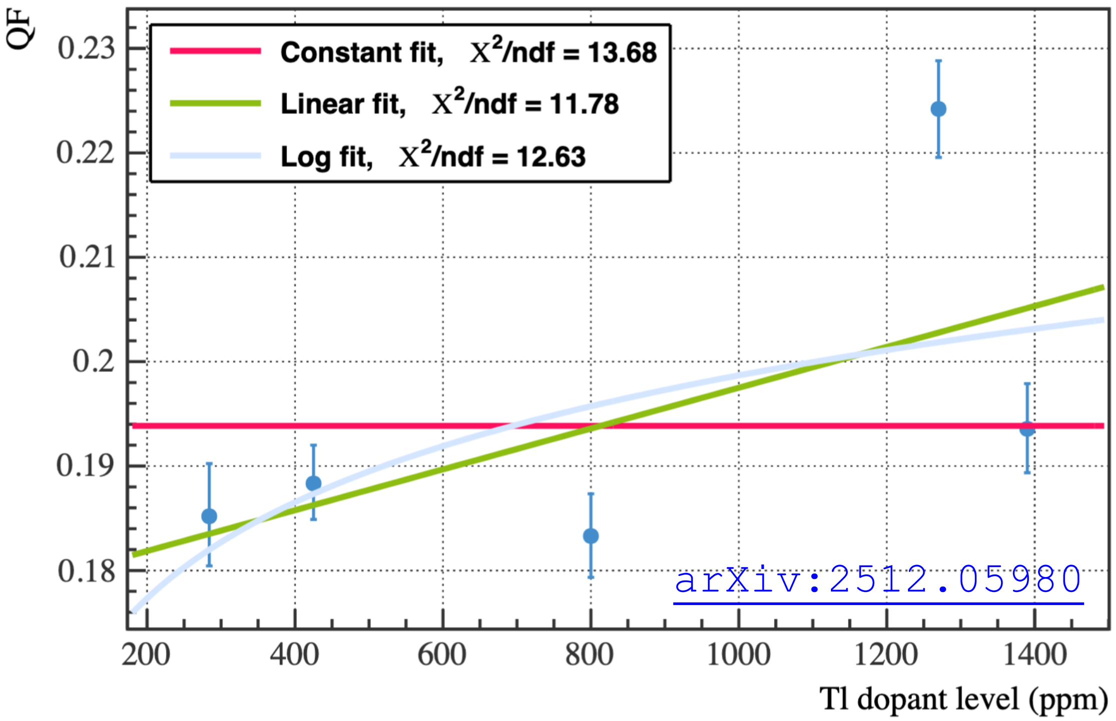


(1-6)keVee = modulation signal in DAMA

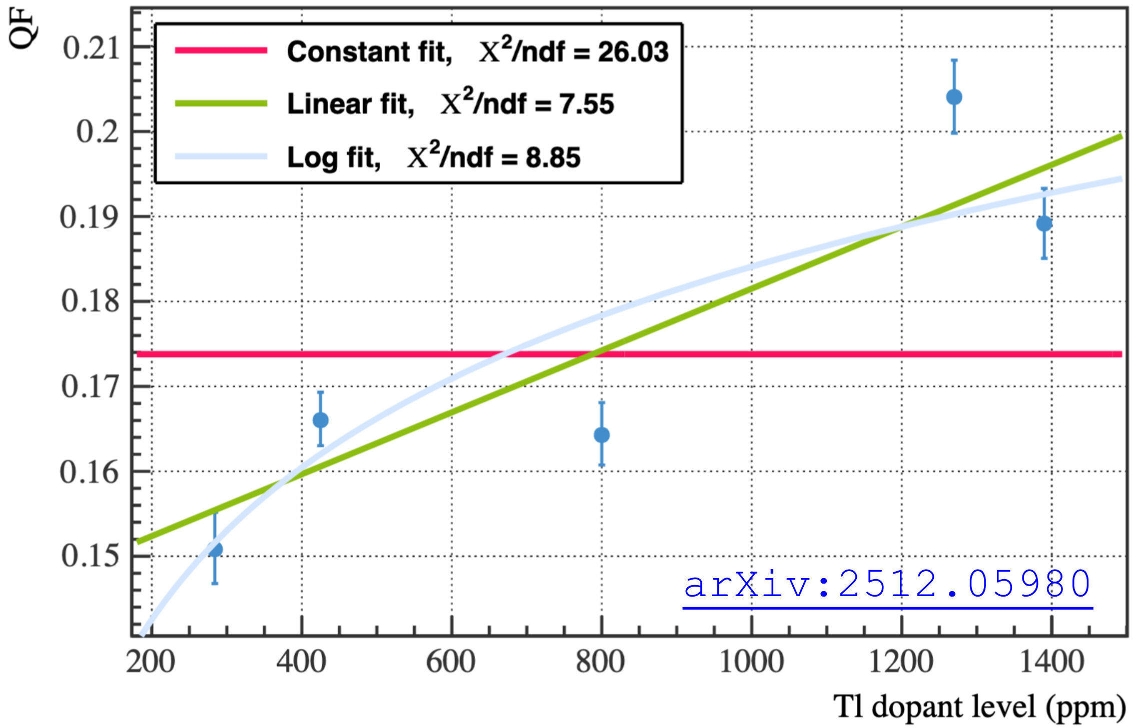
Quenching, Tl-dopant concentration, Calibration

Neutron-Beam Scattering Experiment (Room Temperature)

^{133}Ba, 6.6 keV



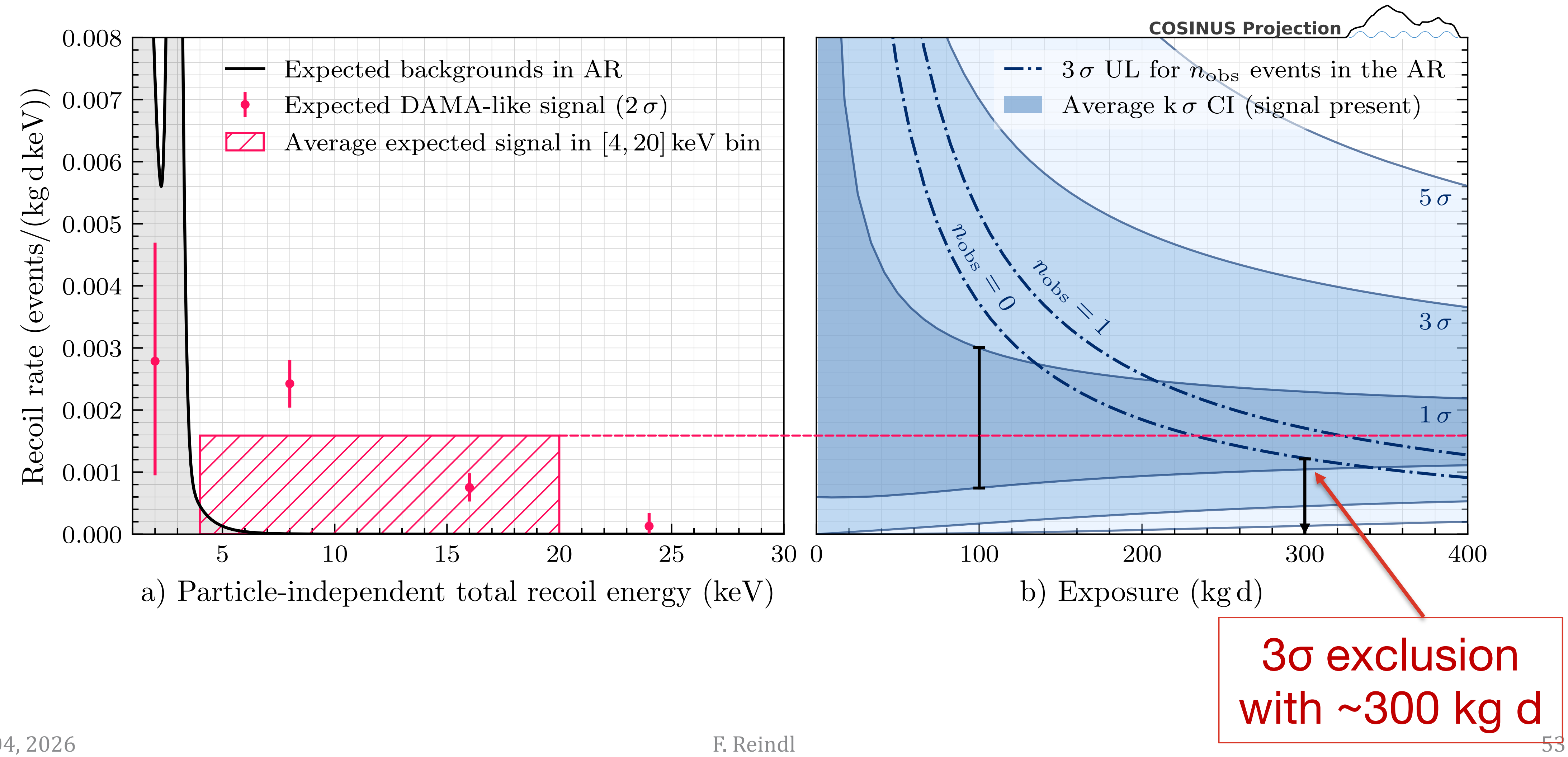
^{241}Am, 59.5 keV

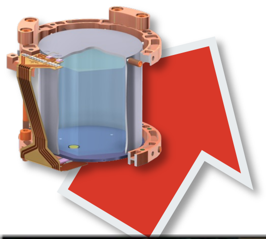


- Lower doping seems to indicate lower QF
- Large systematics due to calibration/PMT non-linearities

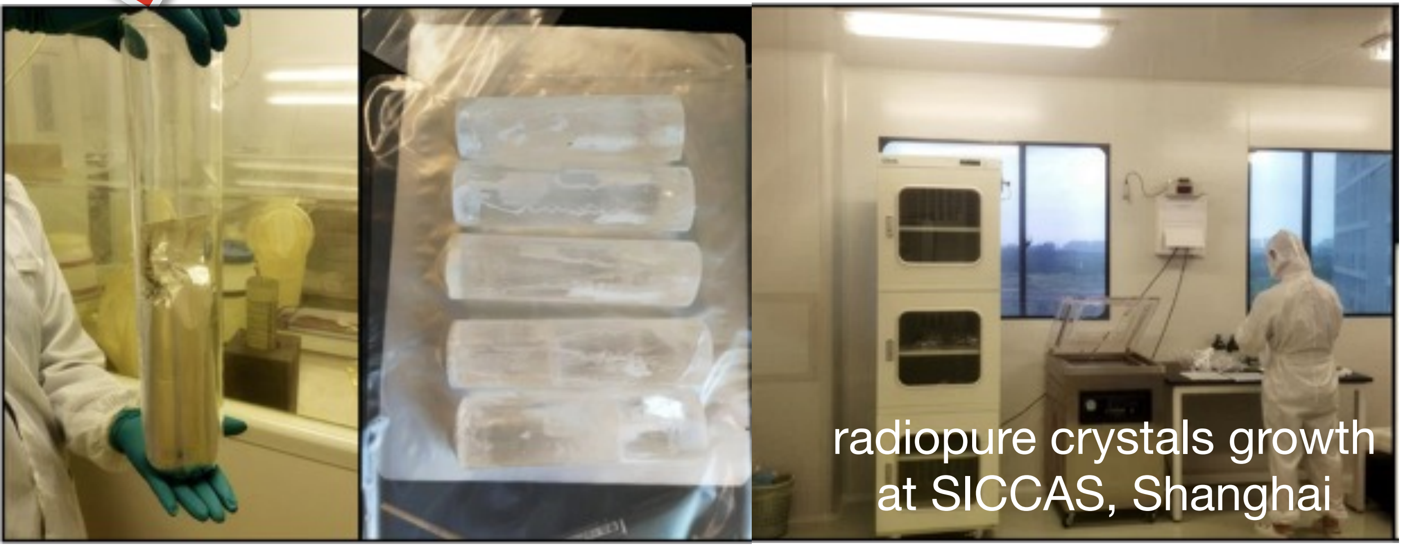
Unfolding the DAMA Spectrum

arXiv:2504.18263, JCAP09, 2025
arXiv:2507.02429, Nature Comm., 2026



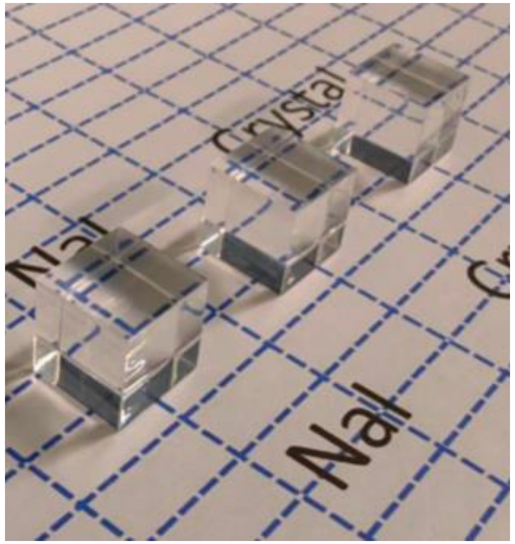


Low-radioactivity Crystals



Zhu, Y. et al, IEEE, 2018

Credit to M. Bharadwaj



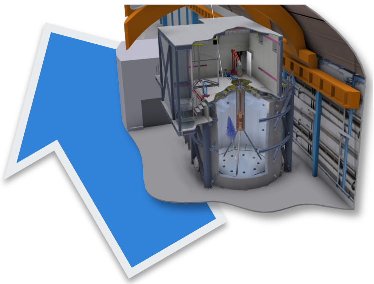
ultrapure “Astrograde” powder from Merck (4ppb of K)

Batch	K	Th	U
Astrograde crystal validation [1]	6-22 ppb	< 1 ppb	< 1 ppb
Astrograde crystals for Run1	< 30 ppb	<10 ppt	< 10 ppt

- first batch of (21x21x21) mm^2 crystals grown, cut and shipped to EU by boat → arrived at LNGS beginning 2025
- additional ingots “on stock” for future larger-size NaI detectors

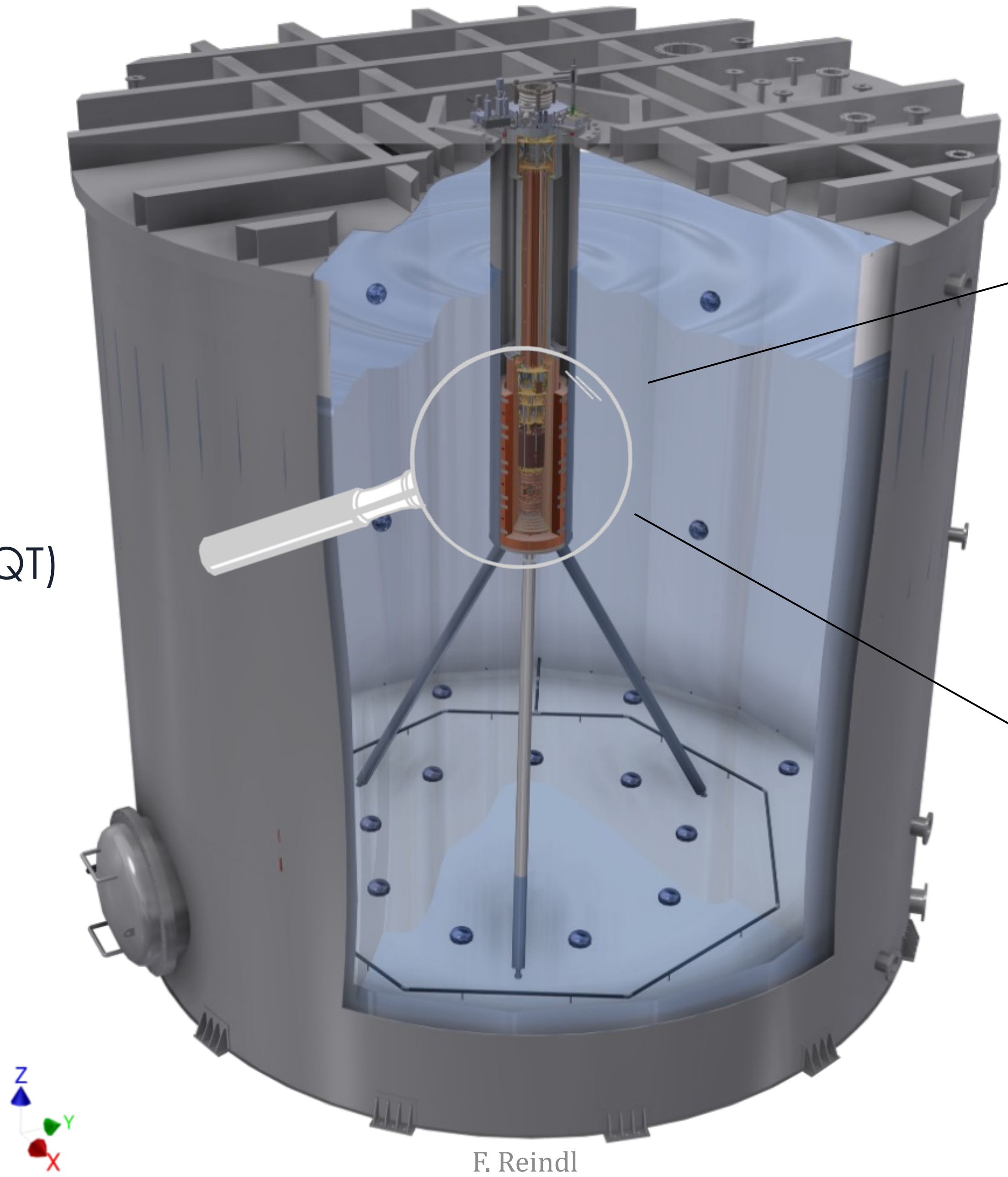
[1] arXiv:2307.11139, PRD 110, 043010

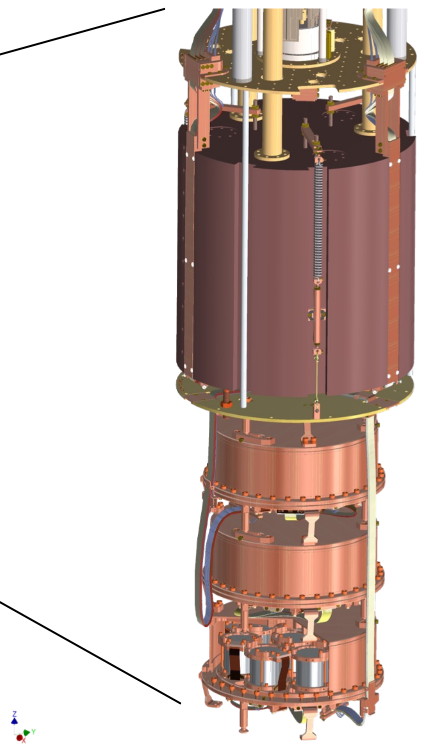
Cryostat



Dry dilution refrigerator to reach 10 mK:

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





CryoConcept
an Air Liquide affiliate

Why Water?

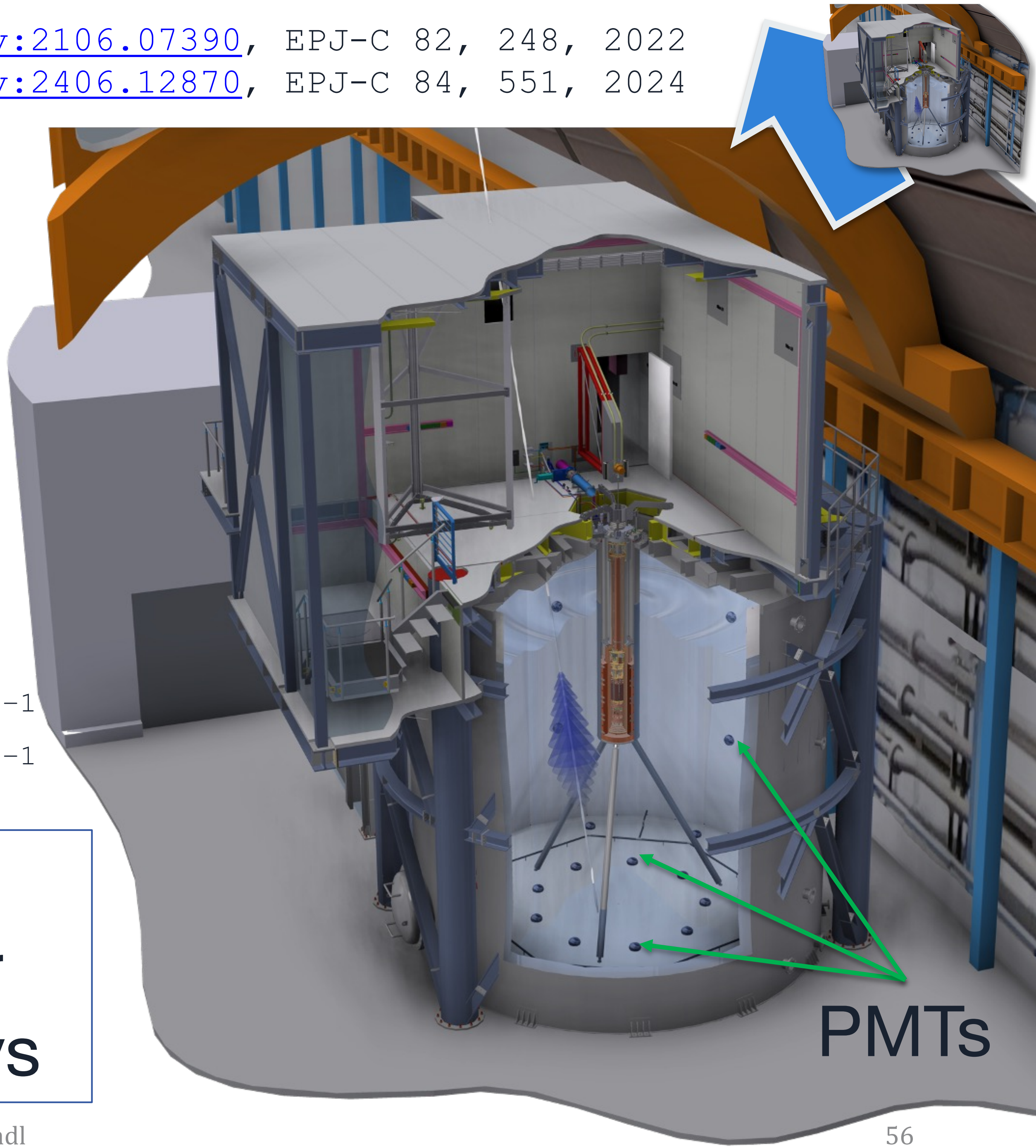
arXiv:2106.07390, EPJ-C 82, 248, 2022
arXiv:2406.12870, EPJ-C 84, 551, 2024

1. Good moderator for neutrons
2. Veto of (cosmogenic) muons via Cherenkov light emitted in water → Instrumentation of water tank with 30PMTs

Rate of cosmogenic neutrons:

```
No veto:      ( 3.5 ± 0.7)  cts kg⁻¹ yr⁻¹
With veto: <(0.30 ± 0.02) cts kg⁻¹ yr⁻¹
```

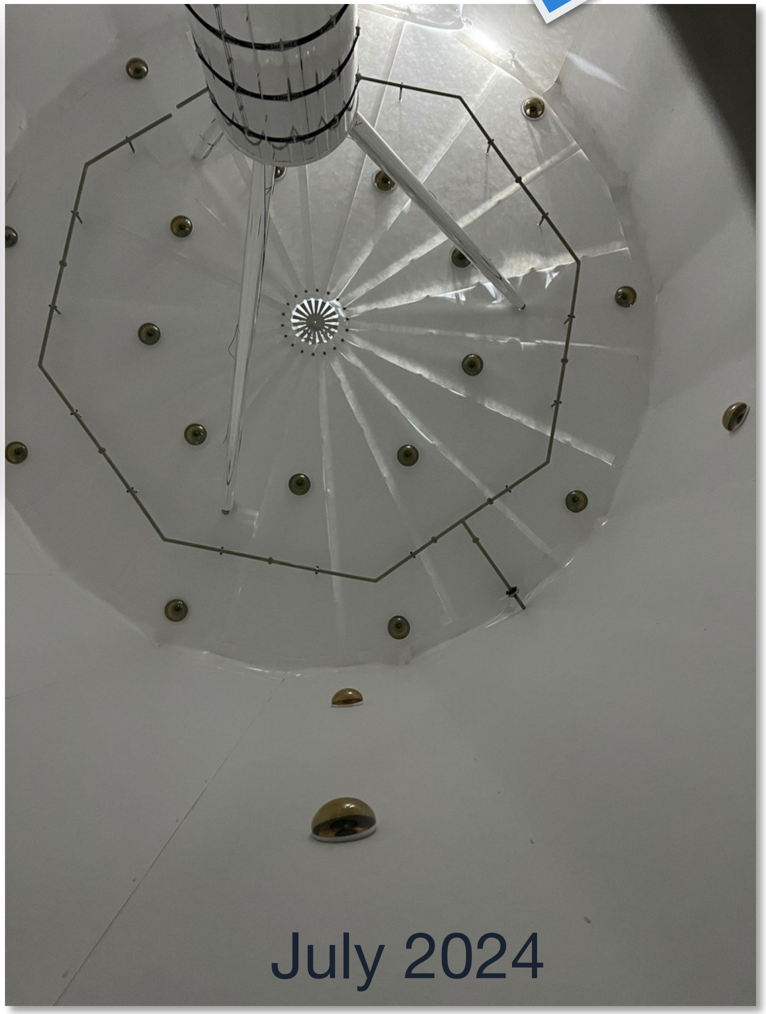
With veto: < 1 expected cosmogenic neutron event for target exposure of 1000 kg days

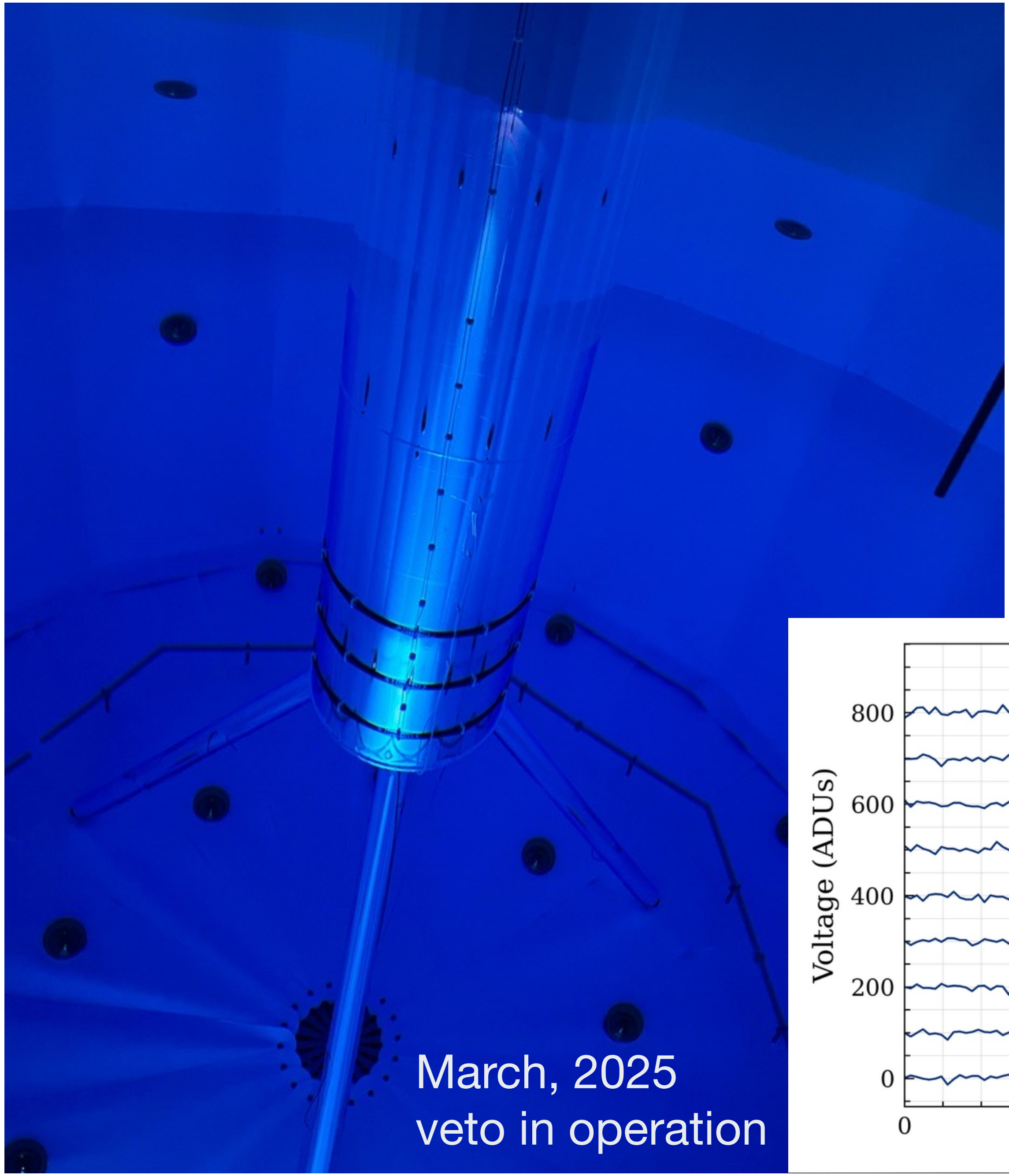


COSINUS Muon Veto

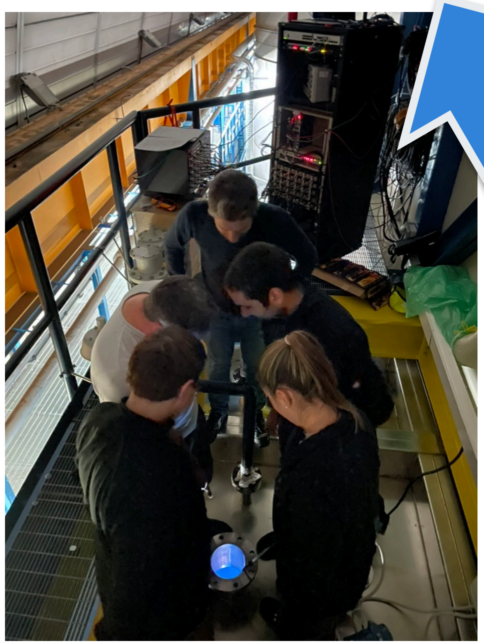
PMT successfully tested above ground at LNGS

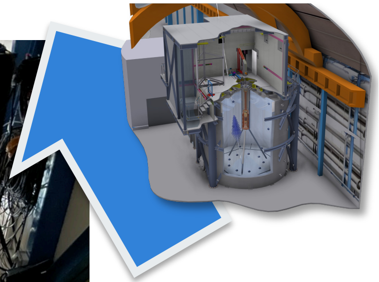
Installation of PMTs and TYVEK curtain (dead layer) in water tank done in July 2024

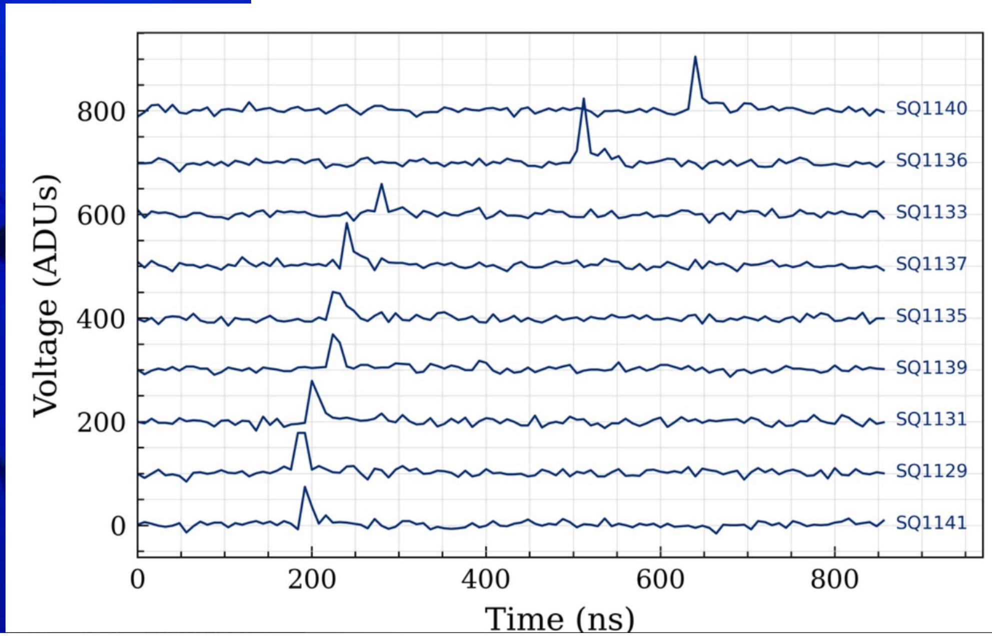


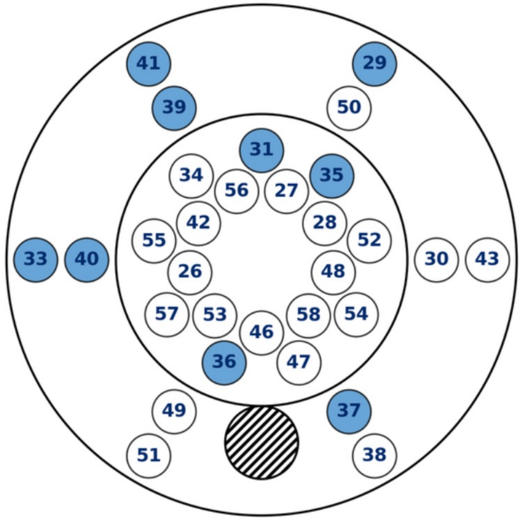


Tank filled in Jan 2025

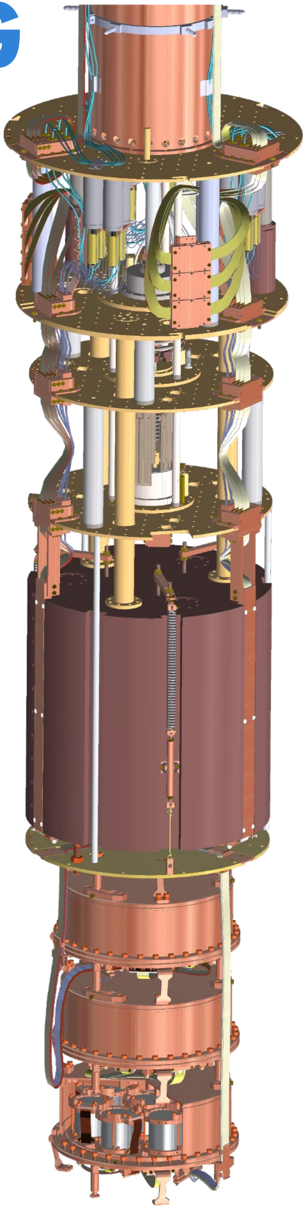






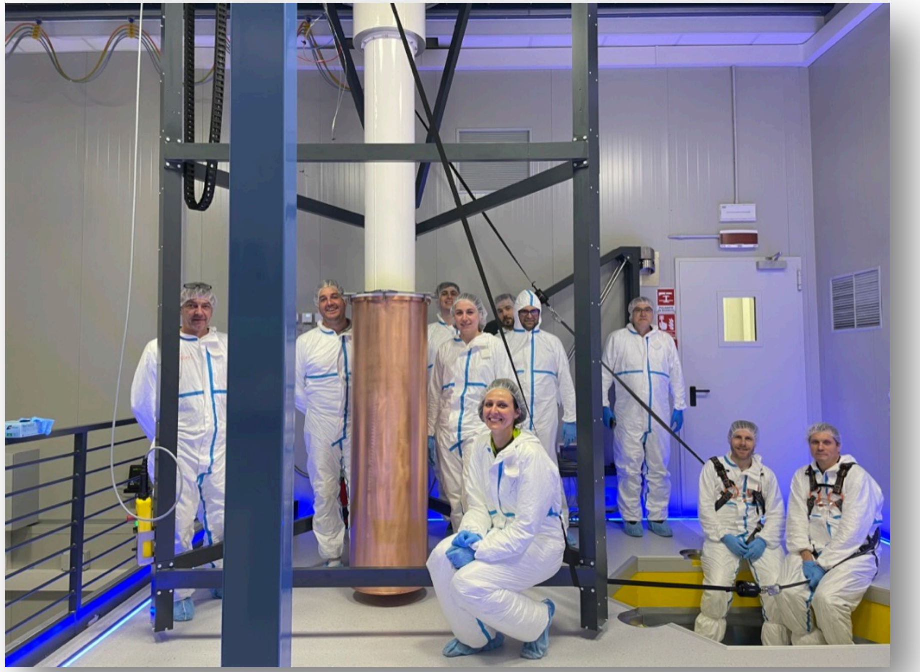


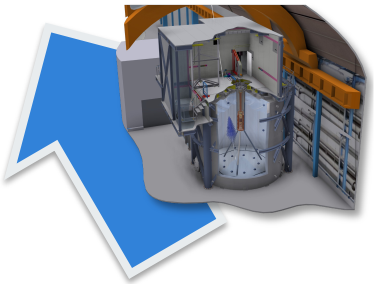
Cryostat Commissioning



Reached 9 mK with Cu-shield (~190 kg) installed

Two long performance runs (3 months and 1 month)





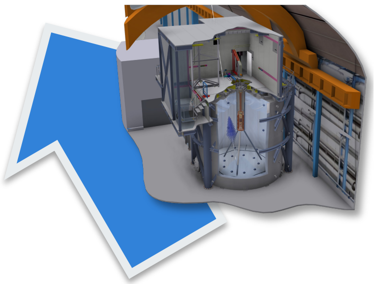
Ultra Quiet Technology (UQT)

All parts of cryostat are centered

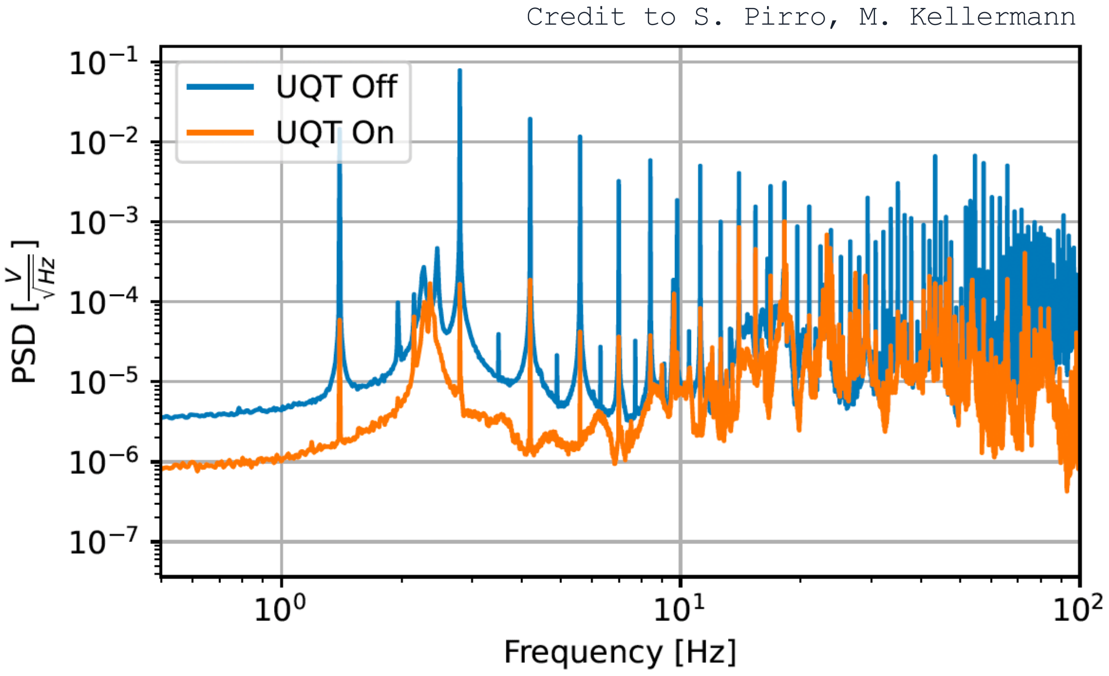
190 kg internal copper shield

Rotary valve of the pulse tube cooler on a separate frame

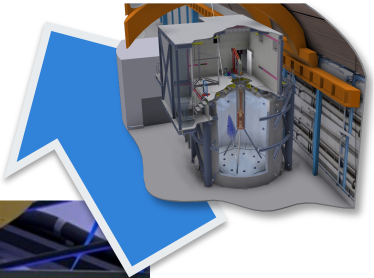
Outer vacuum chamber (OVC) standing on the bottom of the drywell / tank floor via tripod

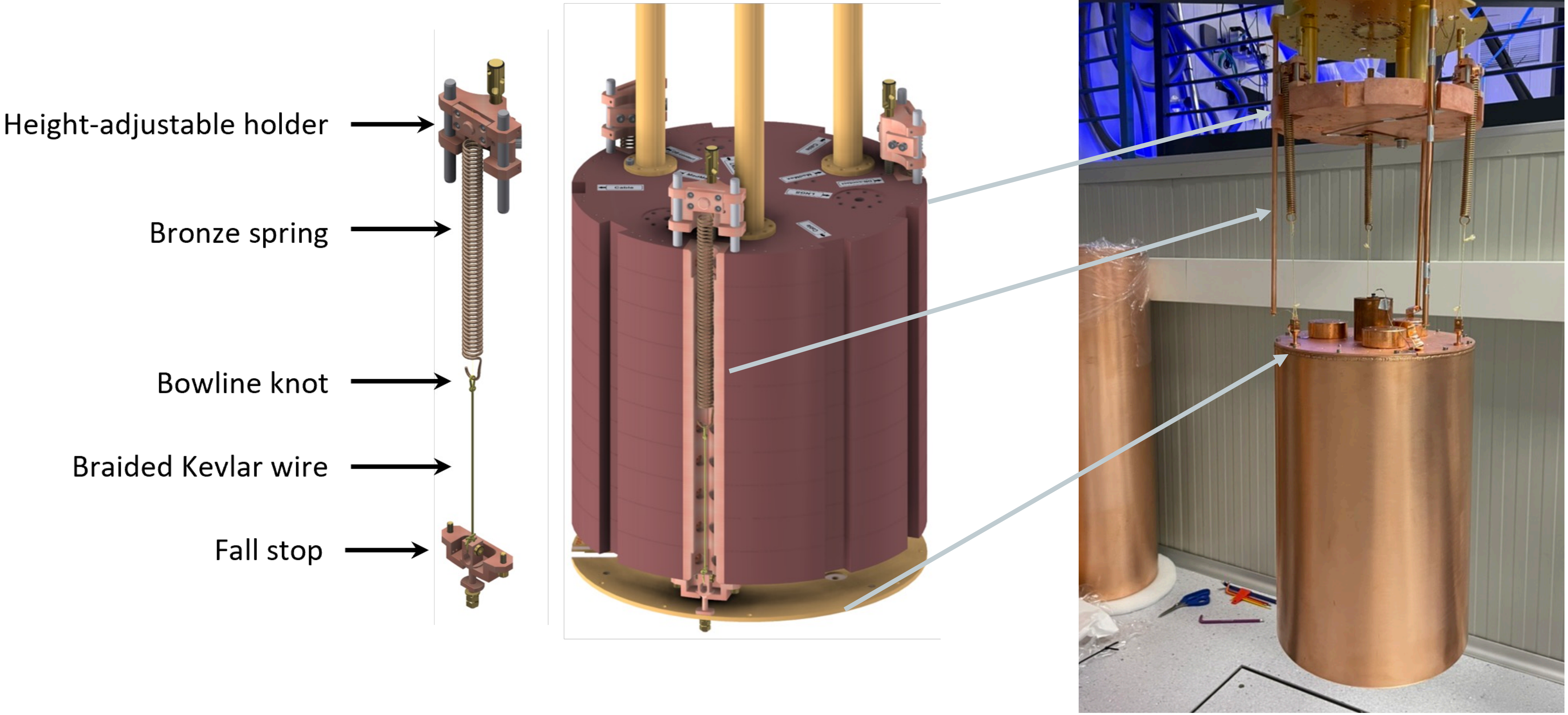


CryoConcept
an Air Liquide affiliate



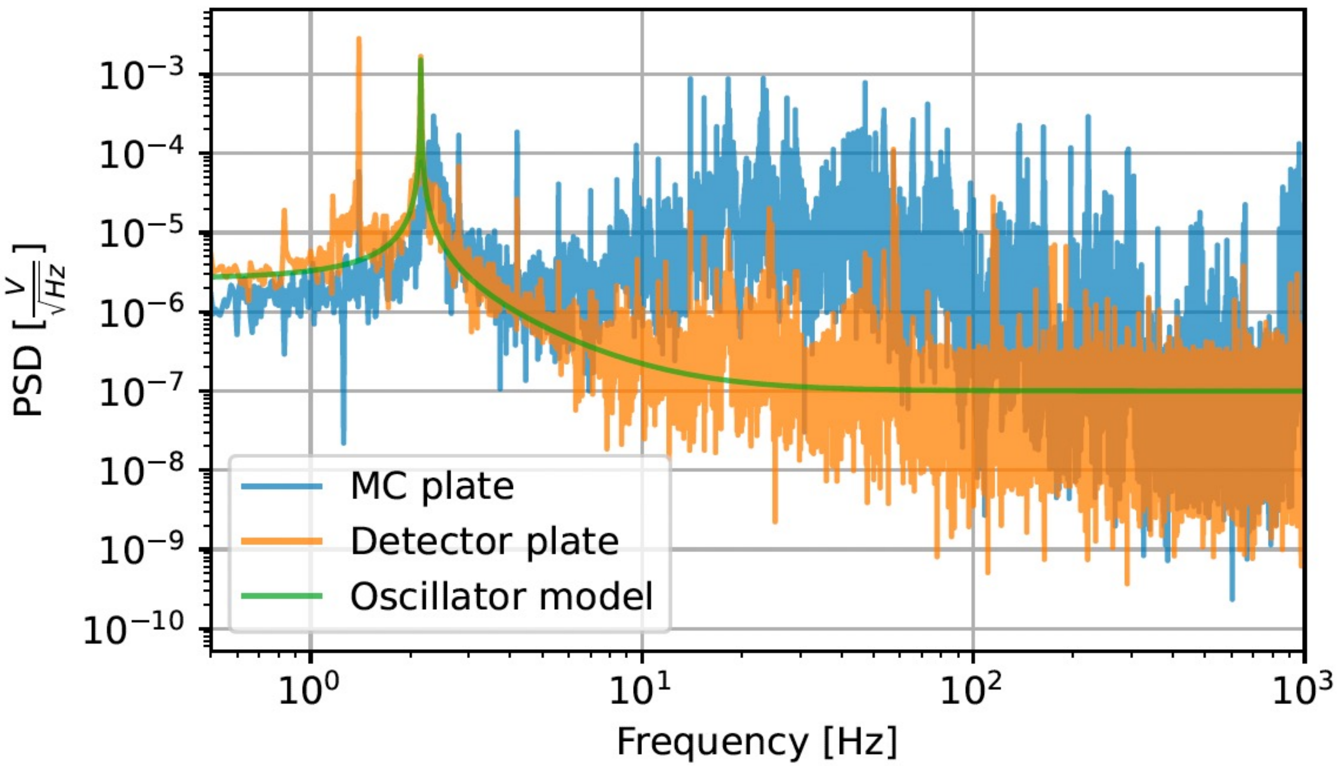
Decoupling System Inside Cryostat

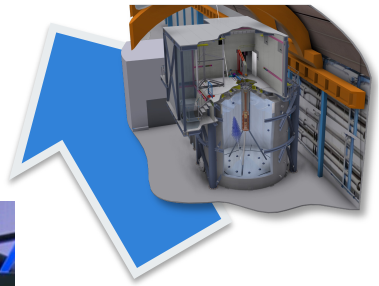




Decoupling System Inside Cryostat

Credit to S. Pirro, M. Kellermann

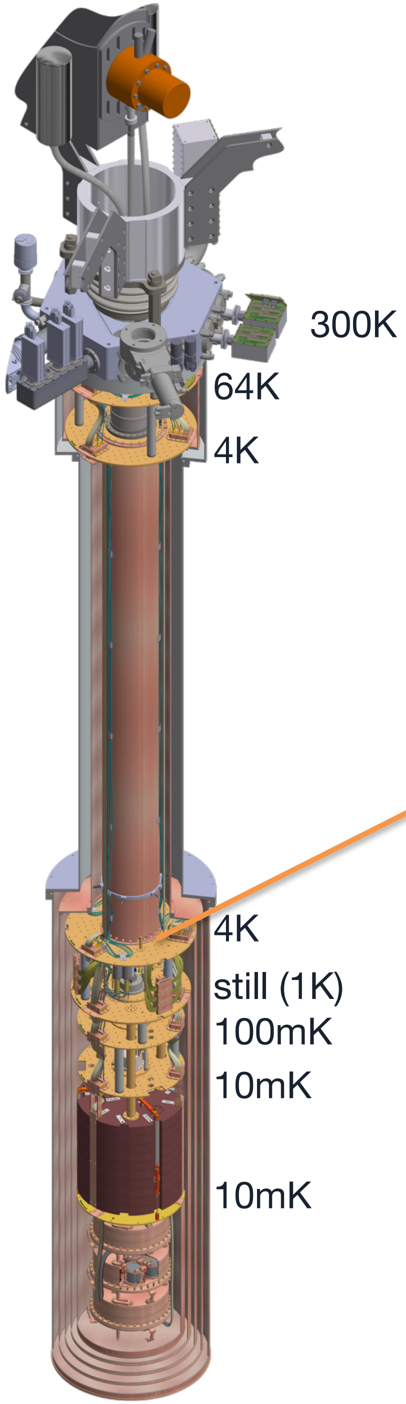


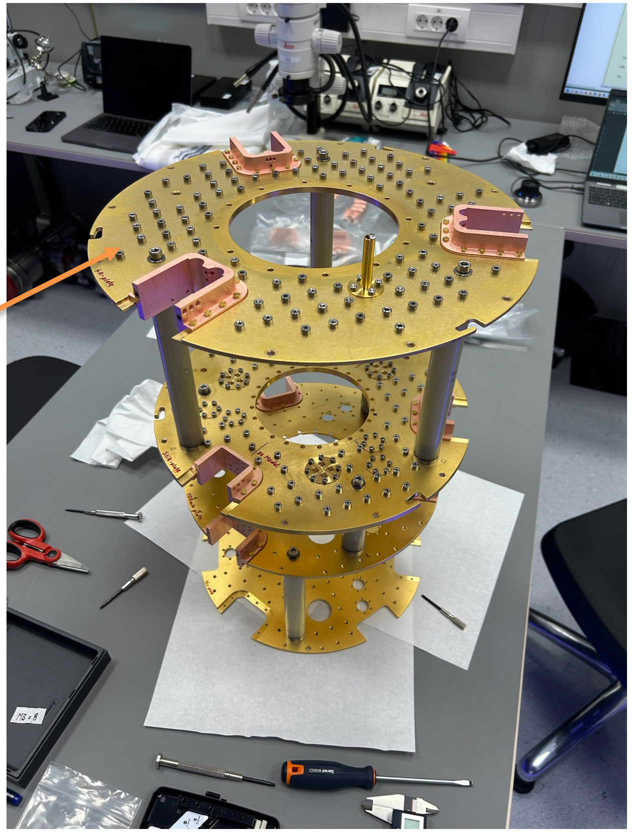


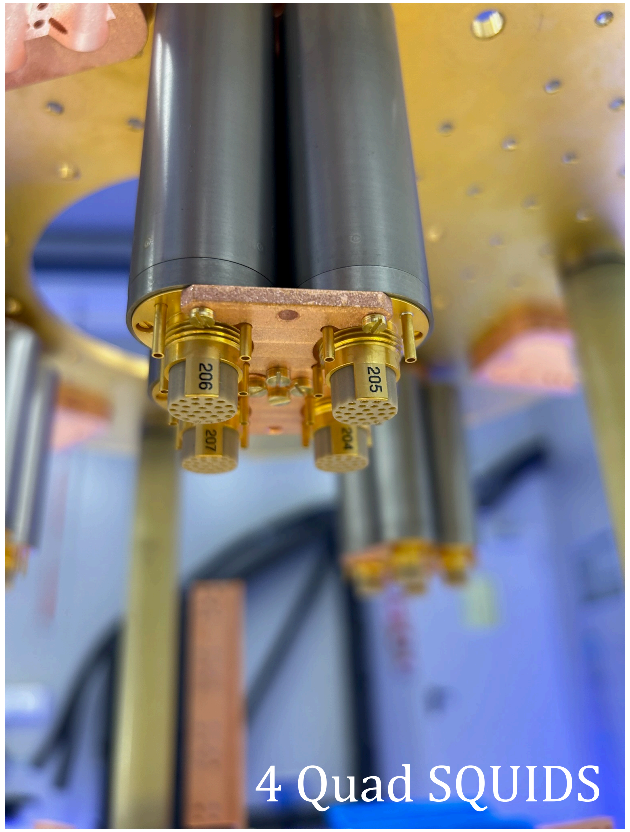
geophone @MC plate

geophone @detector plate

Cabling Installation

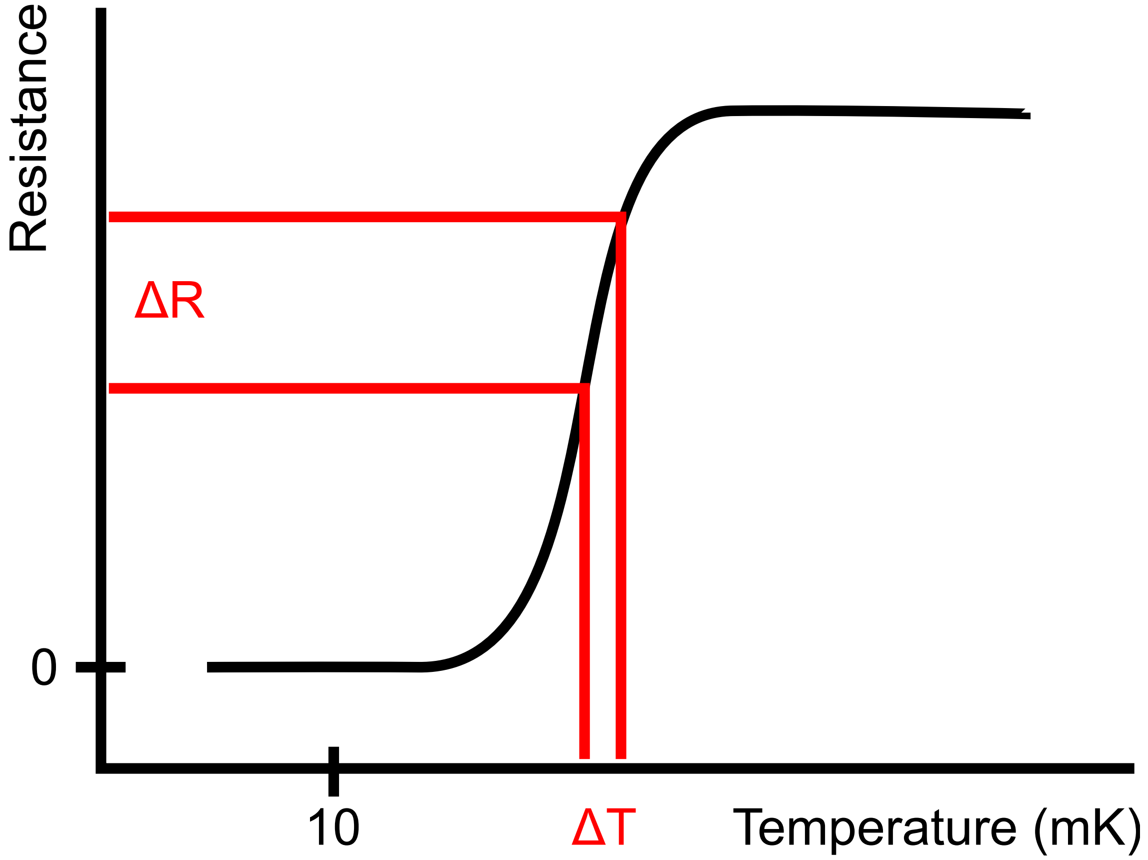






Transition Edge Sensor (TES)
Working Principle

pioneered by CRESST
dark matter search



Energy deposition

~keV

↓

Temperature rise

~μK

↓

Resistance change

~mΩ

Physics Reach – Model Independent

Rate vs. modulation amplitude

Felix Kahlhoefer, FR, et al JCAP05(2018)074

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

COSINUS

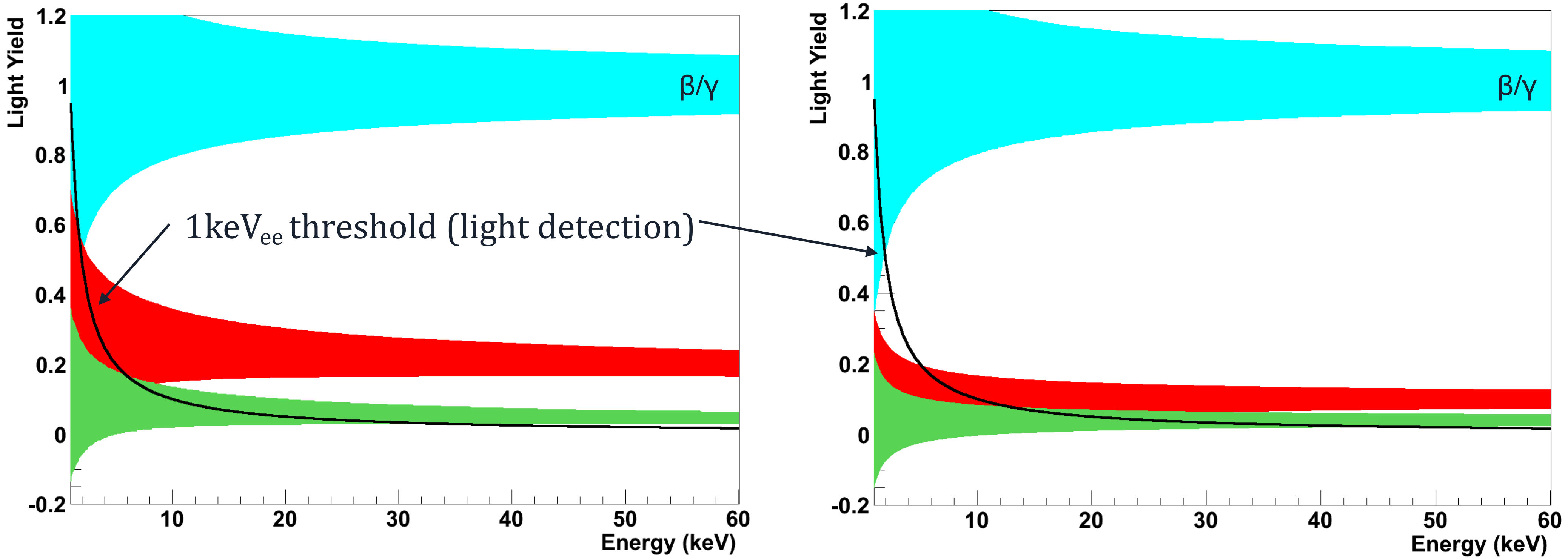
Modulation Amplitude $$S = \frac{1}{2}\left[R(t = \text{June } 1^{st}) - R(t = \text{Dec. } 1^{st})\right]$$

DAMA

Central idea: The modulation amplitude (in a given experiment) cannot exceed the mean rate:

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

Quenching Factors



recoils off Na → factor ~ 0.3

recoils off I → factor ~ 0.1

recoils off Na → factor ~ 0.1

recoils off I → factor ~ 0.04