COSINUS

HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

Dark matter search with cryogenic sodium iodide detectors

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Dark Matter Direct Detection

Relic dark matter particle scattering off detector material nuclei.

Expected differential recoil rate:

$$\frac{dR}{dE_{\mathrm{nr}}} = \frac{\rho_0 M}{m_N m_\chi} \int_{v_{\min}}^{v_{esc}} v f(v) \frac{d\sigma}{dE_{\mathrm{nr}}} dv$$

galactic escape velocity

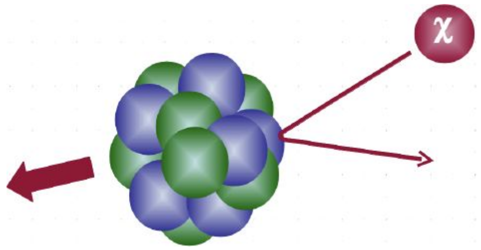
velocity distribution

minimal velocity to produce a recoil above E_R

DM-nucleon cross section ~ A^2 , ~ form factor

Astro physics: Velocity distribution, escape velocity

Particle physics: Form factor, energy threshold, detector material, dark matter mass



Dark Matter Direct Detection

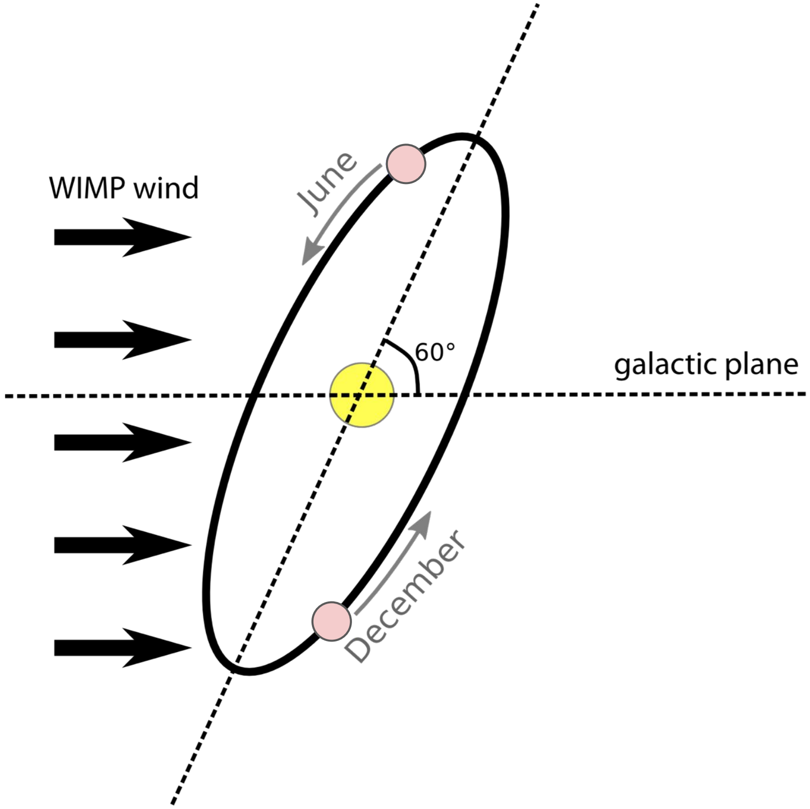
Movement of the earth w.r.t. the sun introduces an annual modulation in the expected signal:

$$S(t) = B(t) + S_0 + S_m \cos\left[\omega(t - t_0)\right]$$

B(t) … Background

S_0 … Constant signal share

S_m … Modulating signal share (~ 0.05 S_0)*



*J. Billard et al. (2021), arXiv:2104.07634, p. 21

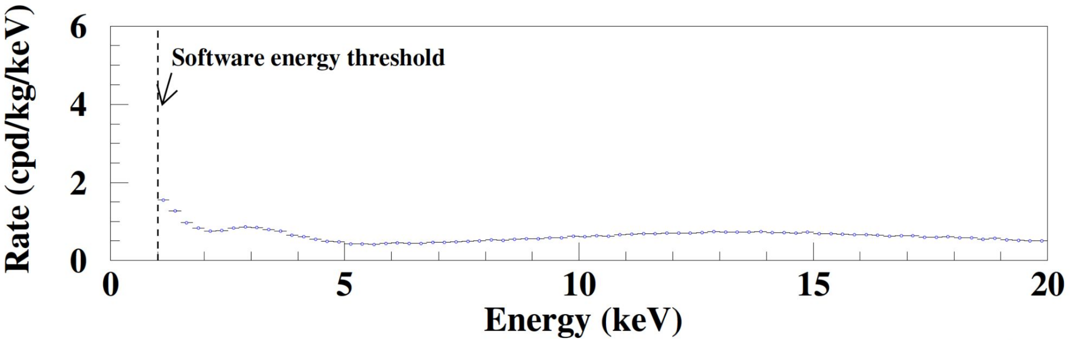
The DAMA/LIBRA results

Observation of positive evidence for the presence of dark matter particles via *annual modulation*.

Target: 250 kg sodium iodide NaI(Tl) crystals.

Location	LNGS
Material	250 kg NaI(Tl)
Signal(s)	Light (PMTs)
Particle Discrimination	no
Energy Threshold	1keVee
Data taking	since 1996

R. Bernabei et al. (2018), DOI: 10.15407/jnpae2018.04.307



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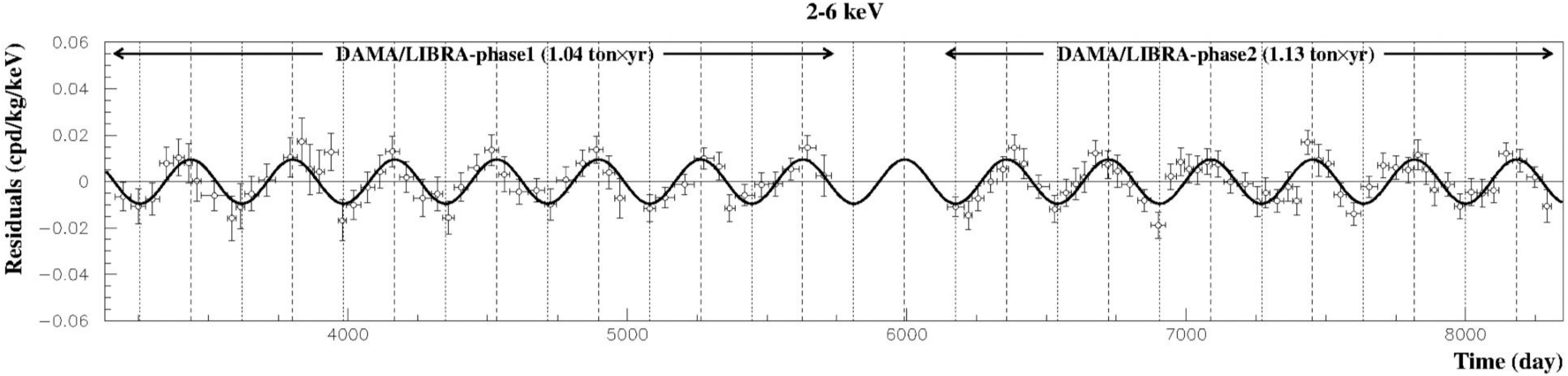
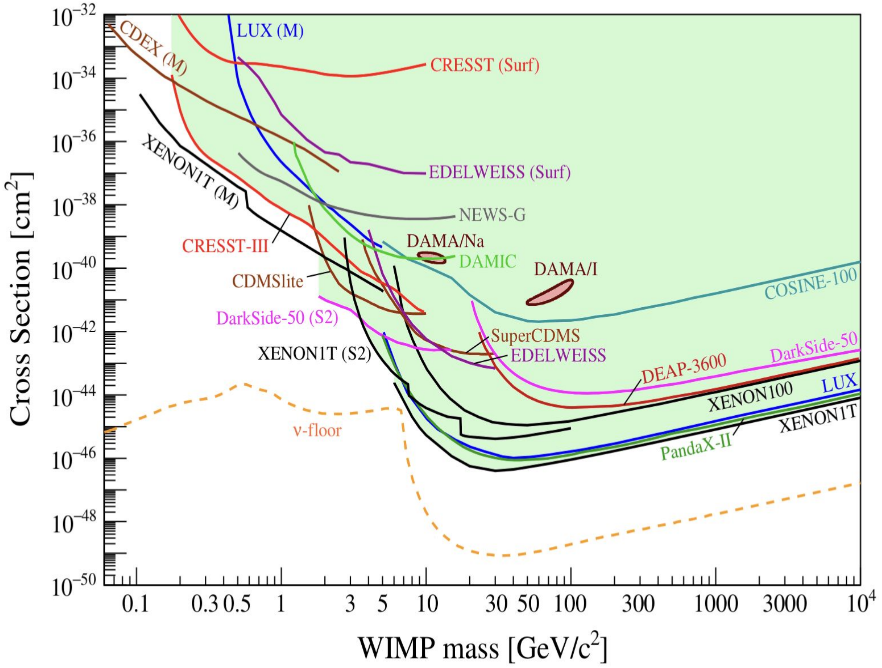


Modulation Amplitude: S_m= (0.0103±0.0008) /(keV×kg×day)

Exposure: 2.46 t×year over 20 annual cycles in 2-6 keV

***C.L.:* 12.9 σ**

Dark Matter Landscape



J. Billard et al. (2021), arXiv:2104.07634, p. 27

Other experiments with NaI targets:

Anais. J. Amare et al., Phys. Rev. D 103, 102005 (2021)

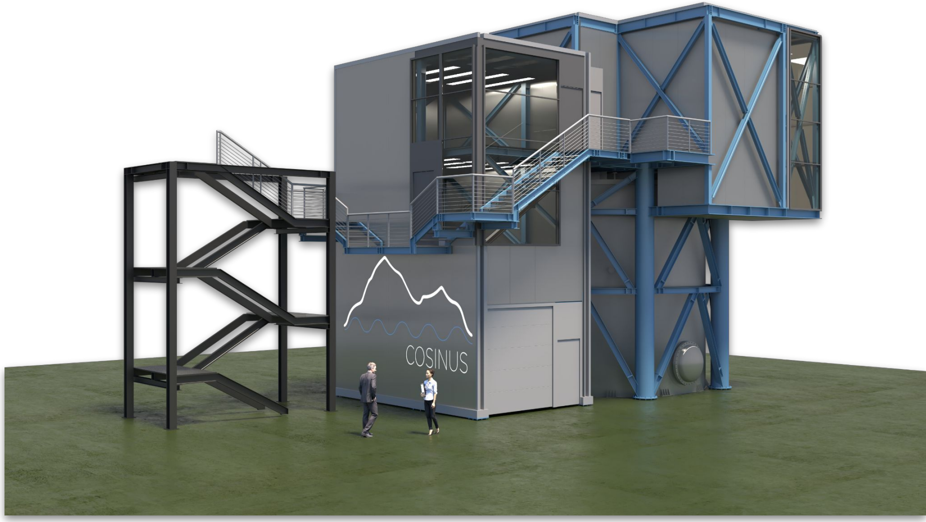
Sabre. M. Antonello et al., Eur. Phys. J. C (2019) 79: 363

Cosine. G. Adhikari et al., Phys. Rev. Lett. 123, 031302 (2019)

… all of them measure scintillation light, but no total energy deposition.

The COSINUS Experiment

- *Two channel approach (heat, light):* In-situ measurement of nuclear energy scale.
- NaI as target material: Immune against *material dependence.*
- Operation as *cryogenic detector*: <1 keV nuclear recoil energy threshold.



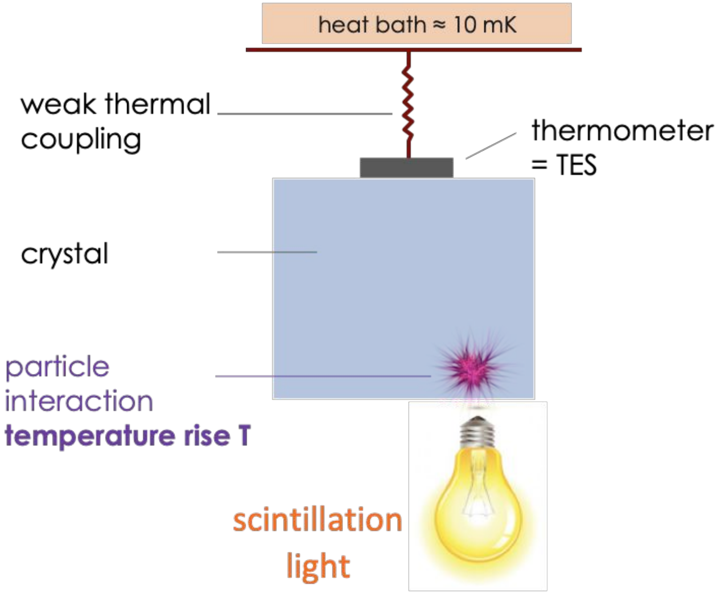
Cryogenic Calorimeters

Small scintillating crystals (~50 g), operated at *cryogenic temperatures* (~10-20 mK).

A particle recoil in the crystal produces *heat* and *scintillation light*.

Amount of emitted light depends on particle type: *Light quenching*.

Sensitive *thermometers (TES - transition edge sensors)* measure the temperature of the detector crystal.



Cryogenic Calorimeters

Original detector concept developed by the CRESST collaboration!

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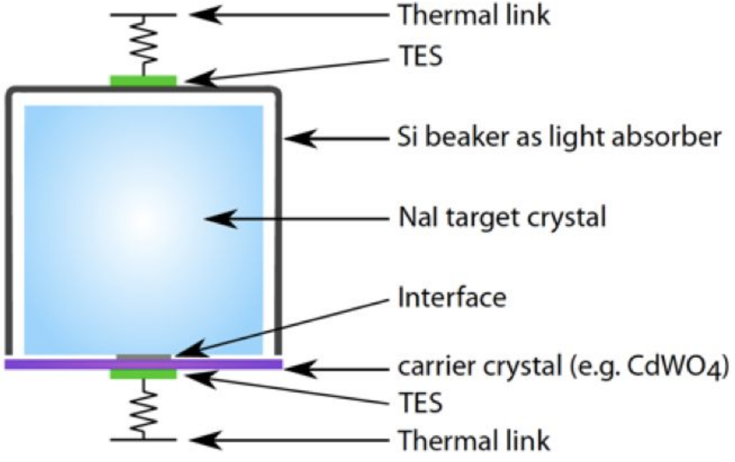

Cryogenic Calorimeters

Light Yield: Light Energy / Phonon Energy

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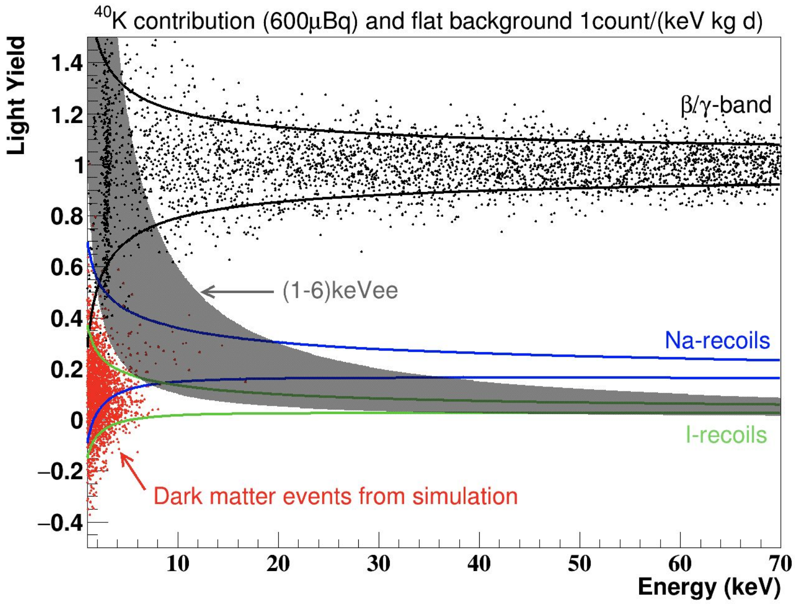


G. Angloher et al. (2016), DOI: 10.1140/epjc/s10052-016-4278-3

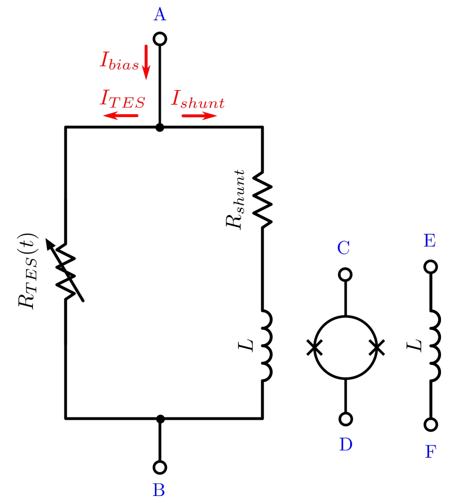
Superconducting Thermometers

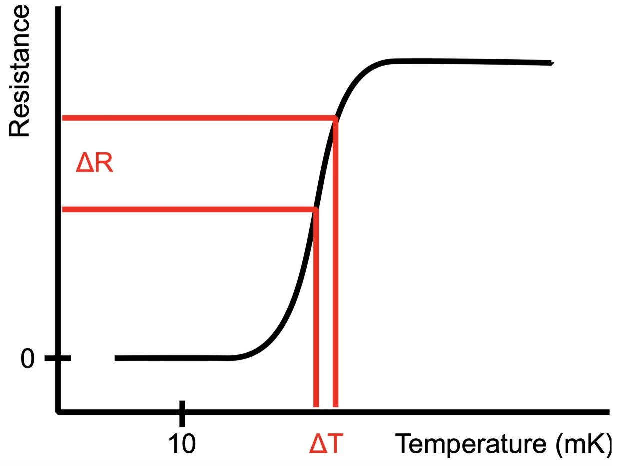
A *Transition Edge Sensor* (TES) measures the temperature of the detector crystal.

A small increase in temperature produces a large increase in resistance.

The changing electrical current is run through a coil, inducing a magnetic field change.

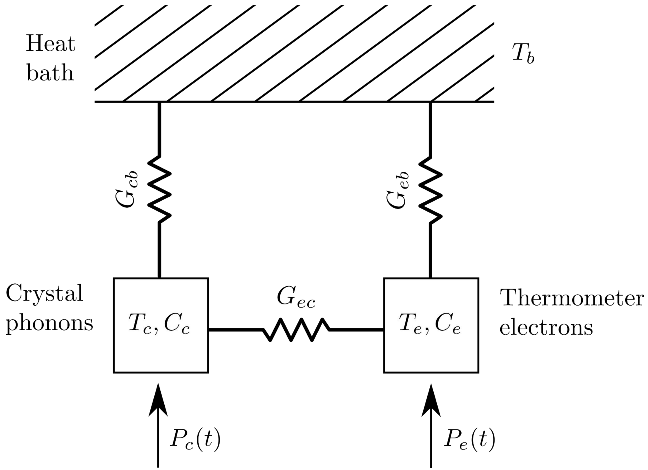
The field is measured by a SQUID amplifier, producing a voltage signal.





F. Pröbst et al., J. Low Temp. Phys. 100, 69 (1995)

Detector Response Model

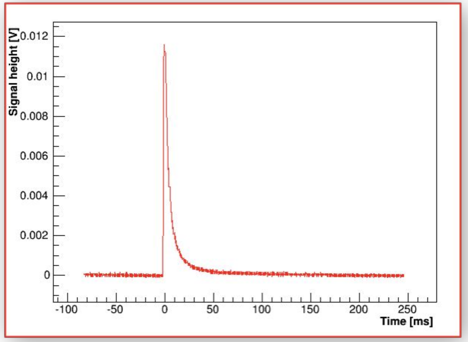


Equivalent thermal circuit of the detector components provides matrix-valued differential equation for all temperatures:

$$C_i \frac{dT_i}{dt} + G_{ib}(T_i - T_b) + \sum_j G_{ji}(T_j - T_i) = P_i$$

Solution for thermometer temperature after *particle recoil* in the crystal:

$$\Delta T_e(t) = \Theta(t)\left[A_n\left(\mathrm{e}^{-t/\tau_n} - \mathrm{e}^{-t/\tau_{in}}\right) + A_t\left(\mathrm{e}^{-t/\tau_t} - \mathrm{e}^{-t/\tau_n}\right)\right]$$

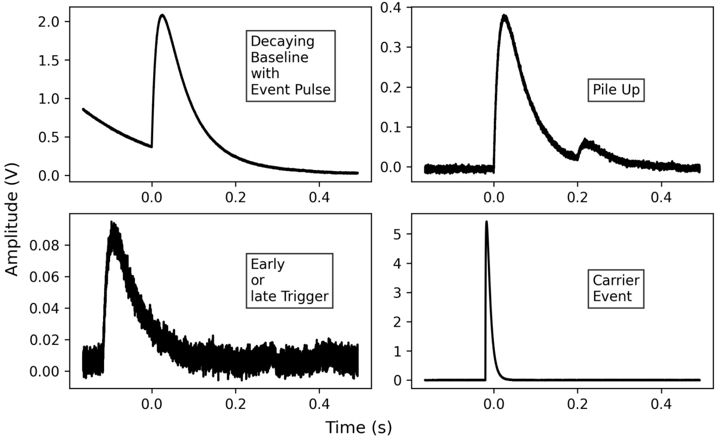


Analysis Methods

Continuous data taking enables offline triggering and various simulation methods.

Two independent software packages for validation:

- CAT (Cryogenic Analysis Tools): ROOT/C++-based standard analysis.
- Cait (Cryogenic Artificial Intelligence Tools): Open Source Python Package for machine learning-based raw data analysis.



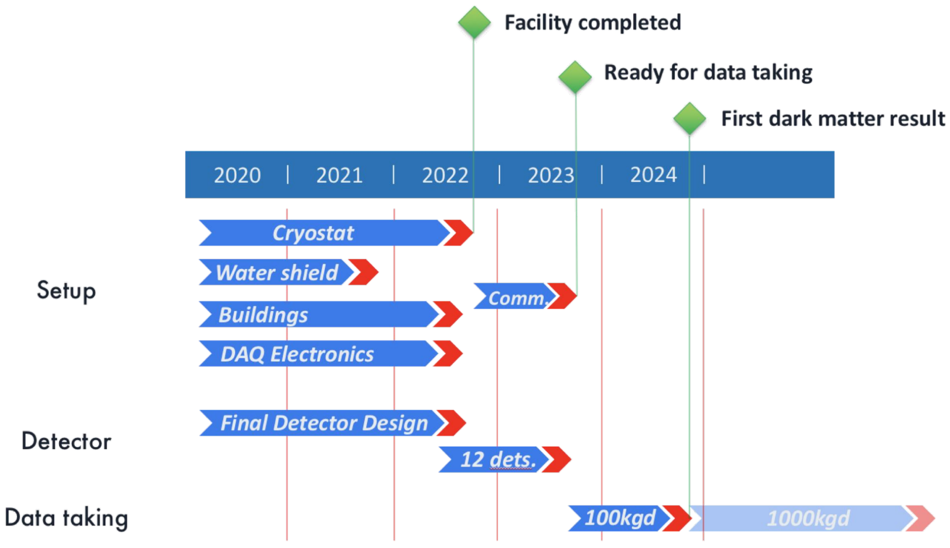
F. Wagner (2021), DOI: 10.5281/zenodo.5091416

cait

Time Scale

COSINUS – 1π (2022-2025)
Exclude or confirm nuclear recoil origin of DAMA, independent of dark matter halo, for any interaction of dark matter with nuclei.

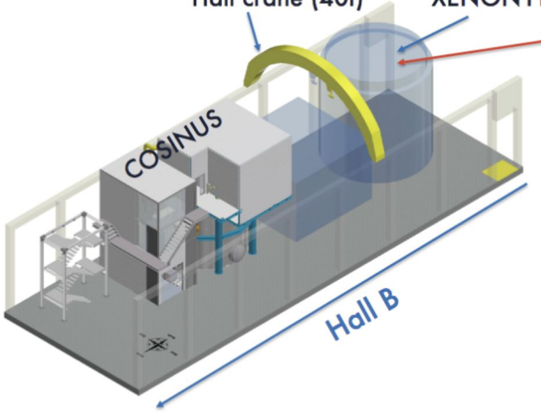
COSINUS – 2π (≥2026)
Investigate annual modulation signature with COSINUS.

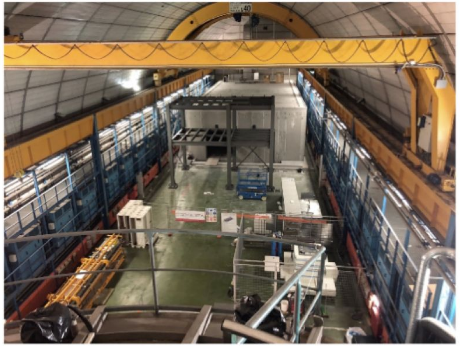


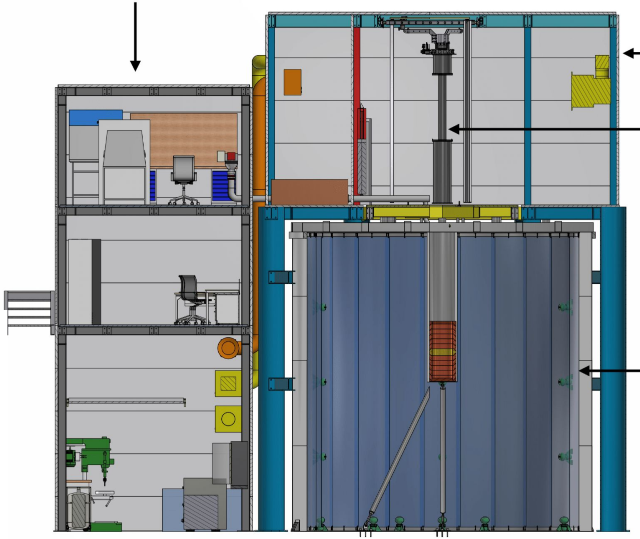
"It has been evaluated that if COSINUS excludes a DM scattering rate of about 0.01 events/(kg×day), with an energy threshold of 1.8keV, it will rule out the explanations of DAMA/LIBRA in terms of DM scattering off sodium and/or iodine." - 2021 APPEC Committee Report

J. Billard et al. (2021), arXiv:2104.07634, p. 27
F. Kahlhöfer et al., JCAP 1805 (2018) no.05, 074

Setup @ LNGS


Hall crane (40t)
XENON1T
Picture taken from here in direction of hall B
COSINUS
Hall B




three level building
service level
cryostat
water tank

G. Angloher et al. (2021), arXiv:2106.07390

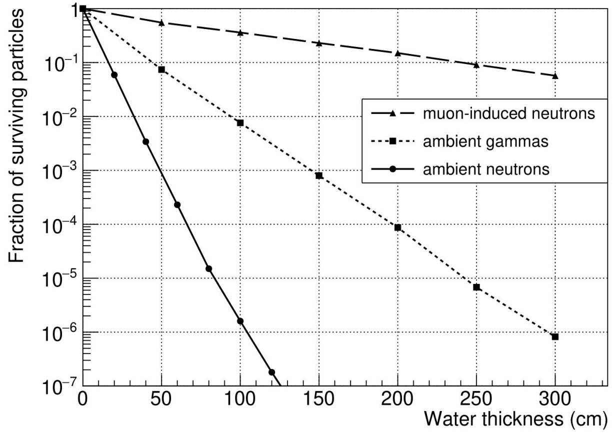
Setup @ LNGS

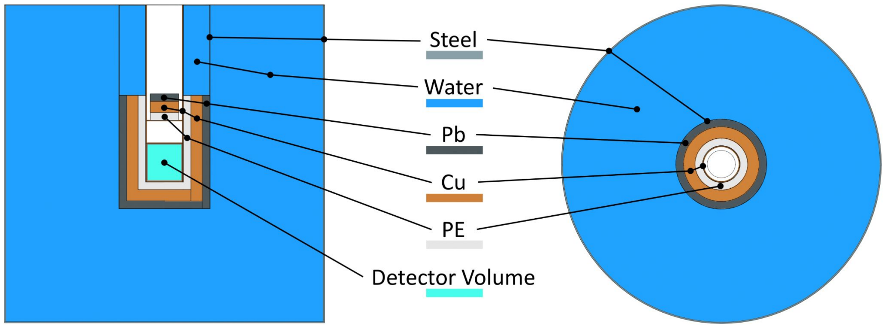
Construction @ LNGS (3600 mwe), starting 2021.

A PMT-equipped water tank acts as passive shielding and active veto.

Result of simulation studies:

- Cylindrical water tank, 7 m height and diameter.
- 8 cm Cu.
- No lead (Pb) layer: Water provides enough shielding against gammas, less muon-induced events in Cu.
- No polyethylen (PE) layer: Contaminations could cause additional neutrons.





Baseline Design

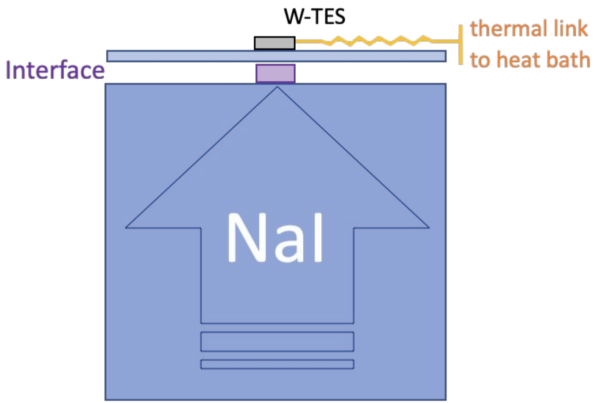
Measurement at LNGS (2017).

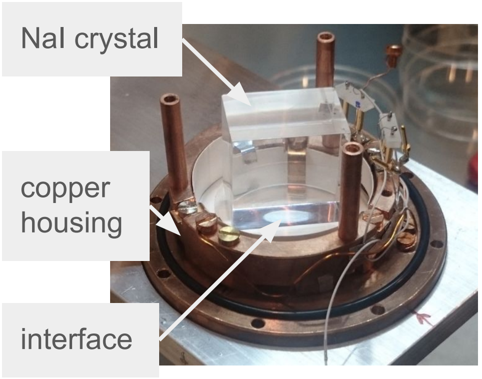
66 g NaI crystal, 1.32 kg days exposure.

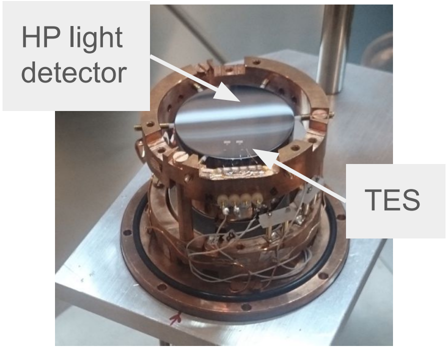
^{241}Am source (~60 keV).

Beaker-shaped light detector (Si).

Three thermal components: Absorber crystal, thermometer and carrier crystal.







F. Reindl et al., J. Phys. Conf. Ser. 1342 012099 (2020)
Schäffner, K. et al. J Low Temp Phys (2018)

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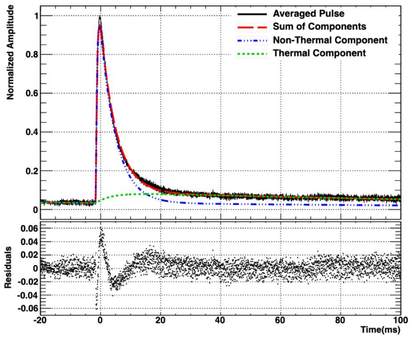
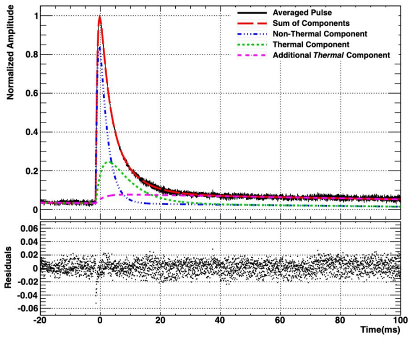
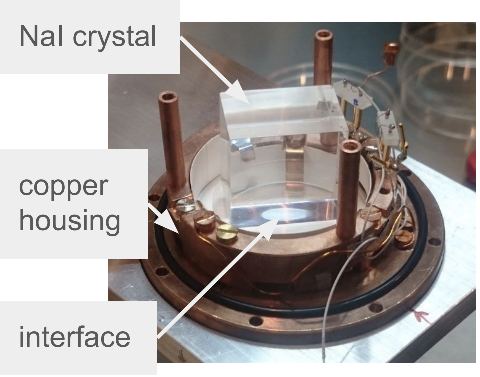
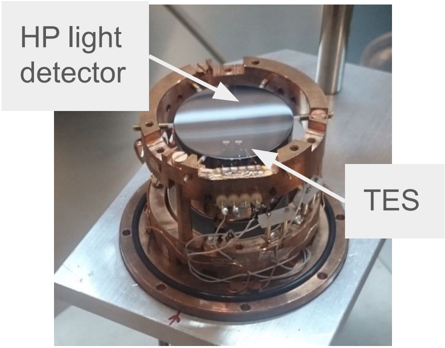








F. Reindl et al., J. Phys. Conf. Ser. 1342 012099 (2020)
Schäffner, K. et al. J Low Temp Phys (2018)

Baseline Design

Challenges:

- hygroscopicity
- high Debye temperature
- potassium (K) contamination

Energy Threshold NaI:

8.26 +/- 0.02 keV

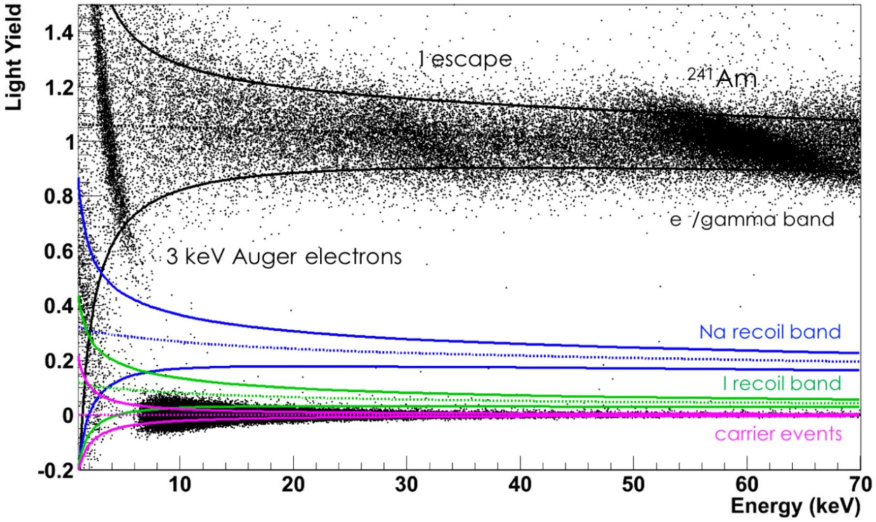
Energy Resolution NaI:

1.1 keV (baseline) - 4.5 keV (60 keV)

Energy Resolution Light:

~0.6 keVee

Pulse shape identification of carrier events.



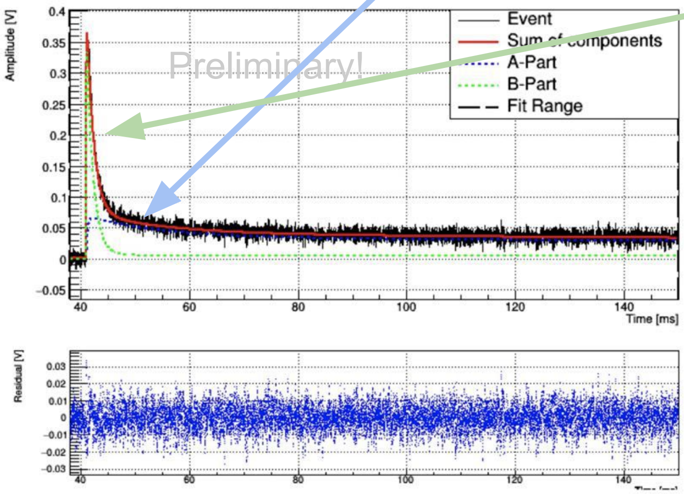
F. Reindl et al., J. Phys. Conf. Ser. 1342 012099 (2020)
Schäffner, K. et al. J Low Temp Phys (2018)

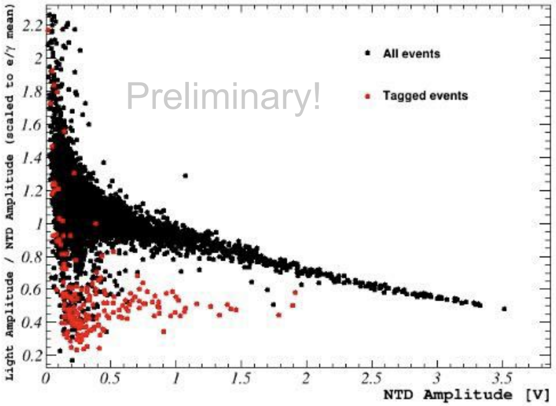
Current developments: Extended Pulse Shape Model

phonon part

light part

$$\Delta T_e(t) = \sum_{i=1}^{3} A_i \left[e^{\lambda_i t} - e^{-t/\tau'_n} \right] + \sum_{i=1}^{3} B_i \left[e^{\lambda_i t} - e^{-t/\tau_\ell} \right]$$





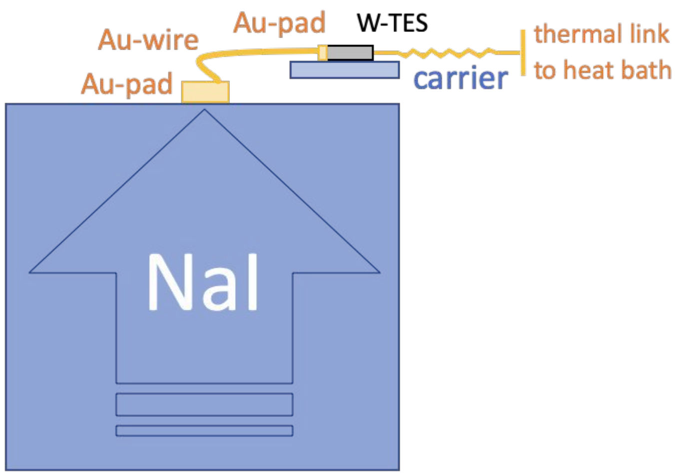
Based on F. Pröbst et al., J. Low Temp. Phys. 100, 69 (1995)
developed by V. Zema, paper in preparation

Current developments: remoTES

remoTES idea first suggested by M. Pyle et al. in 2015, arXiv:1503.01200

NaI has to be exclusively handled in controlled atmosphere:

- avoid the carrier crystal, thus avoid that phonons have to
- pass through another material except of NaI
- avoid the amorphous interface (e.g. glue, grease, oil, …)
- instead: profit from good e-ph coupling of Au



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Results from above-ground test measurements

Absorber material	Au-pad	Au wire	Threshold (eV)
Si	sputtered	glued on pad	*323*
TeO2	foil, glued	2 wedge bonds	*1100*

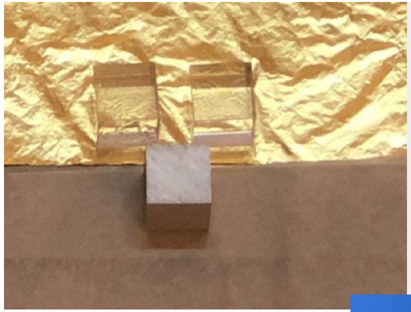
Preliminary!

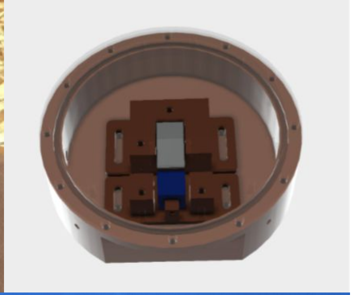
Preliminary!

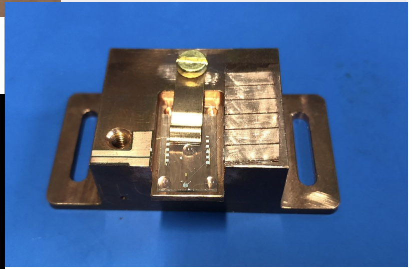
Preliminary!

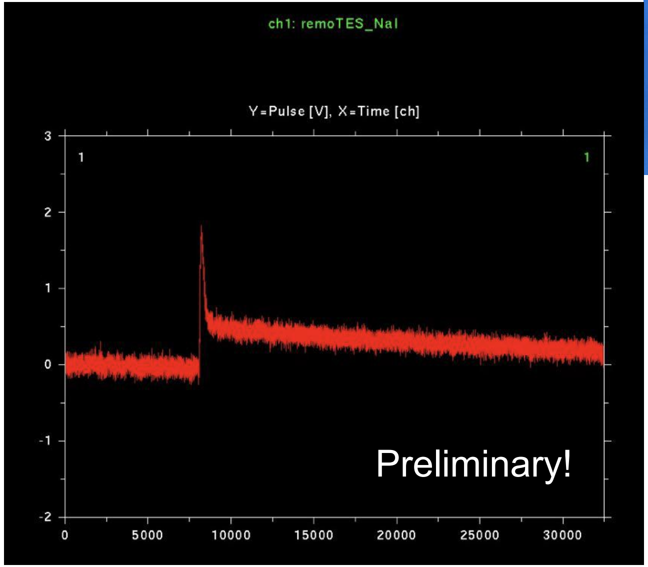
Current developments: remoTES

Measurement of first NaI remo-TES detector is running *this week* in cryo2 of CRESST at MPP.









Todo List for Dark Matter Module

👍 Operate NaI as cryogenic detector.

👍 Beaker-shaped light detector.

👍 Radiopure NaI crystals.

👍 Extended pulse shape model for NaI detector.

🚧 Phonon threshold of 1 keV (current: 8.23 keV).

Prototype measurement results:

G. Angloher et al. JINST 12 P11007 (2017)
F. Reindl et al., J. Phys. Conf. Ser. 1342 012099 (2020)
Schäffner, K. et al. J Low Temp Phys (2018)

Summary

Cosinus provides:

- Particle identification on event-by-event basis,
- Low(er) threshold for nuclear recoils,
- Precise energy information independent of event type,
- Same sensitivity at smaller target mass (~1kg for COSINUS vs. 250kg for DAMA),

… and brings therefore *everything we need to validate the DAMA claim*.

The Collaboration

HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

TU WIEN

MAX-PLANCK-INSTITUT
FÜR PHYSIK

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN
LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

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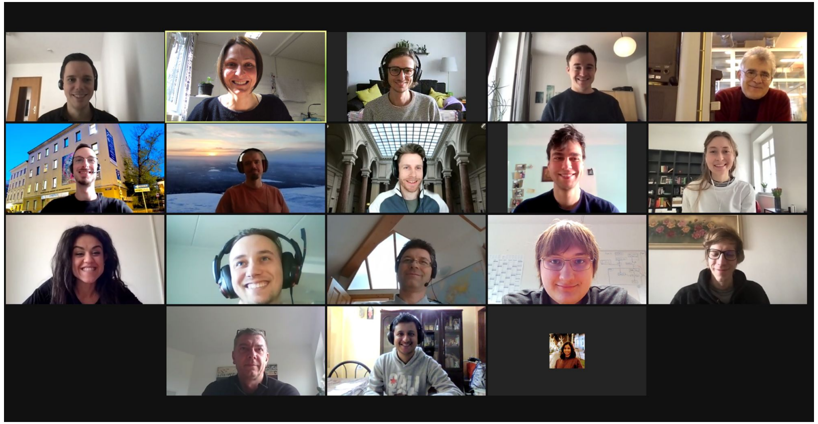


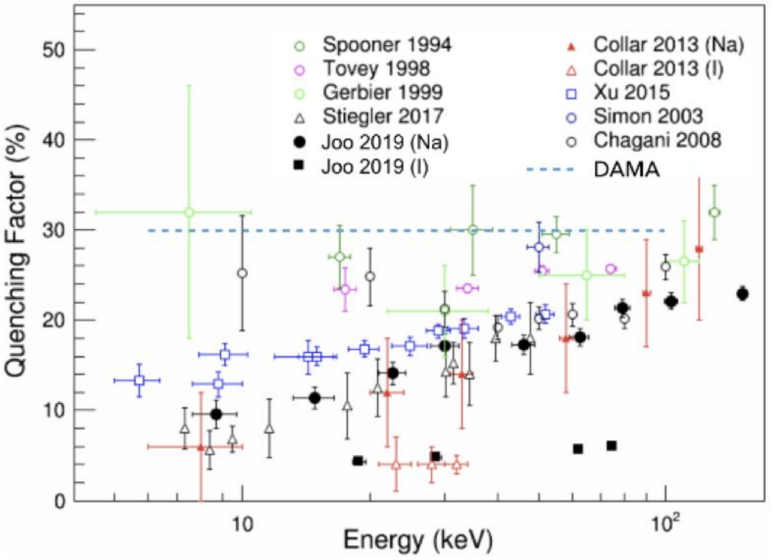
www.cosinus.it

Backup

Quenching Factor Uncertainty

Measurements of quenching factors at room temperature disagree at low energies.

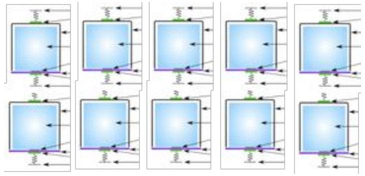
This introduces an uncertainty on the nuclear recoil energy scale.



H. Joo et al., Astropart. Phys. 108 (2019), pp. 50–56

Perspective

Collection of a net exposure of 100kg days, with 10 modules (50g) for 1 year (efficiency 0.5), in a low-background cryogenic facility.



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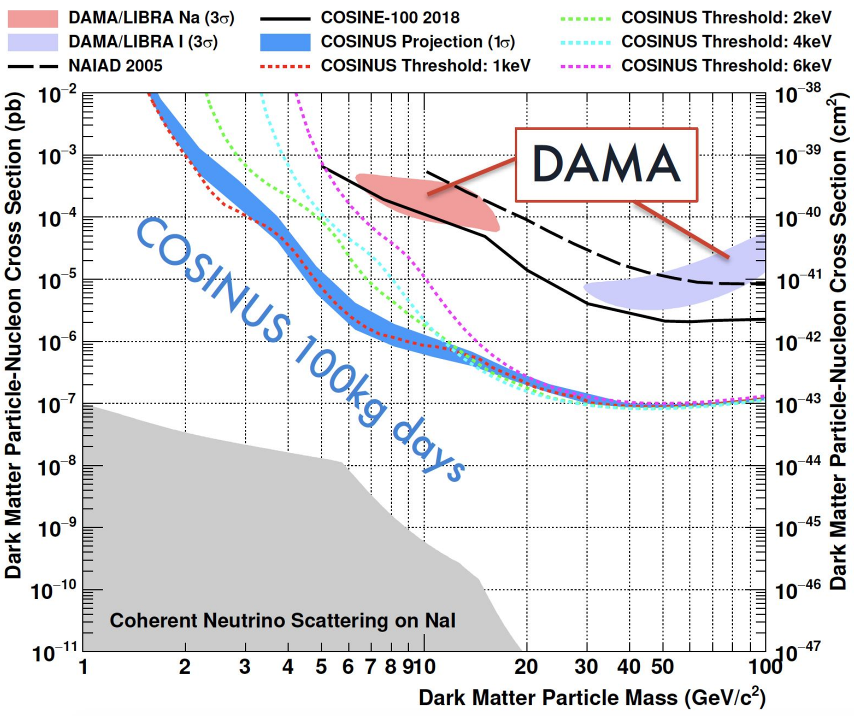
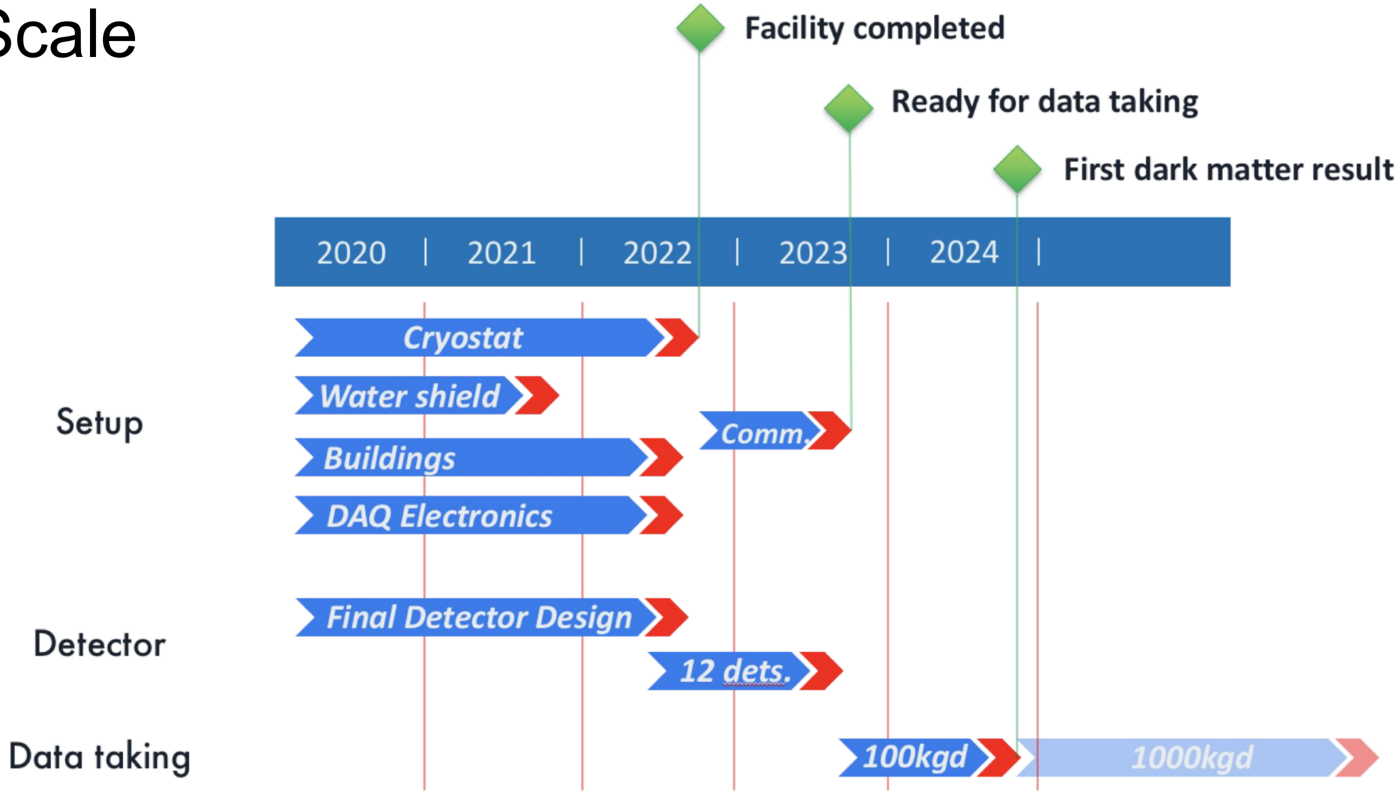


Dark matter exclusion limits for different recoil energy thresholds, under standard scenario assumptions.

Time Scale



Facility completed
Ready for data taking
First dark matter result
2020
2021
2022
2023
2024
Setup
Cryostat
Water shield
Comm.
Buildings
DAQ Electronics
Detector
Final Detector Design
12 dets.
Data taking
100kgd
1000kgd