COSINUS
An update on the experiment

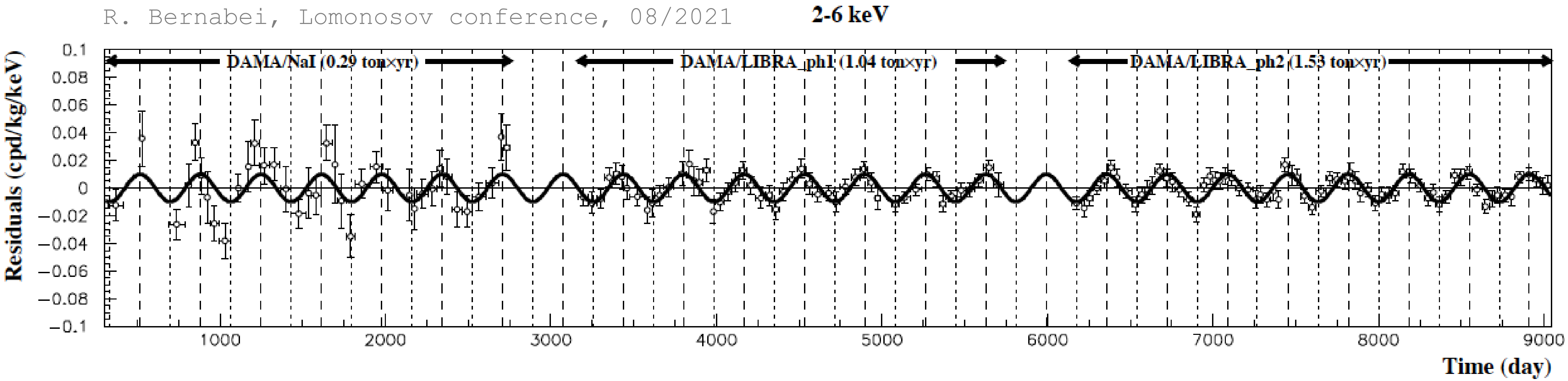
Clemens Dittmar
on behalf of the COSINUS Collaboration

Lake Louise Winter Institute

4th March 2025

DAMA/LIBRA

R. Bernabei, Lomonosov conference, 08/2021



Total exposure: 2.86 tonne years
Statistical significance: 13.7 σ
Energy region: 2-6 keV_{ee}
Period: 0.99834 ± 0.00067 years
t_0= 152.5 day ~ 2. June

No model independent confirmation by other experiments yet!

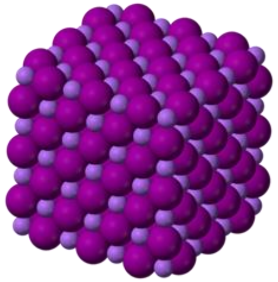
- Different target materials -> model dependent
- Crystal Purity -> higher background
- Statistics -> ongoing
- Energy Threshold -> difficult to archive with NaI
- Quenching Factor -> still uncertain

How will COSINUS do it?

Cryogenic **O**bservatory for **SI**gnatures seen in **N**ext-generation **U**nderground **S**earches

COSINUS

- Same target material
  - Operated as low-temperature scintillating calorimeter



NaI

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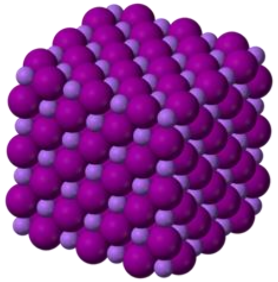
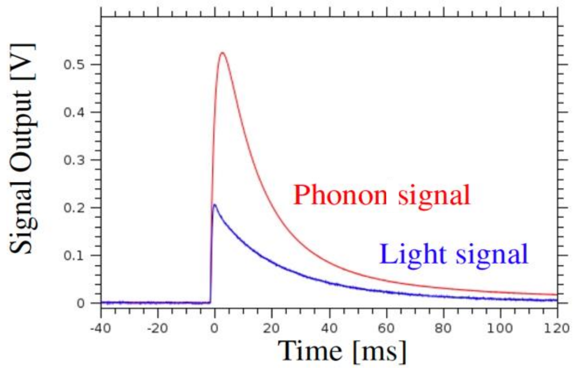
  - First NaI experiment with photon and phonon channel
  - No need of QF knowledge but intrinsic QF measurement for free



NaI



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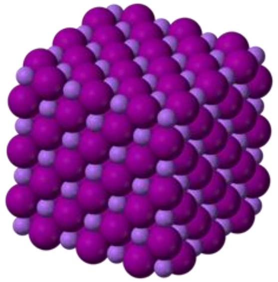
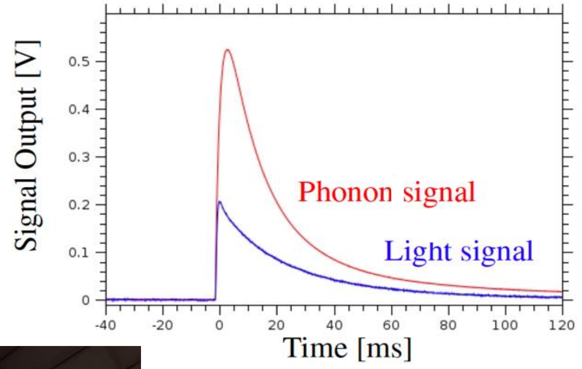
  - Same underground lab as DAMA/LIBRA (LNGS) + active muon veto
  - High radiopure crystals



NaI



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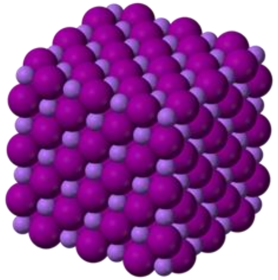
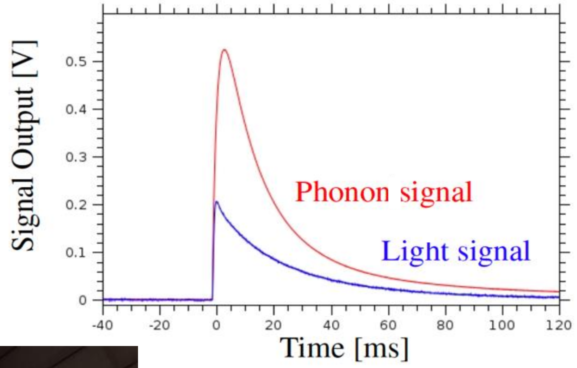


NaI



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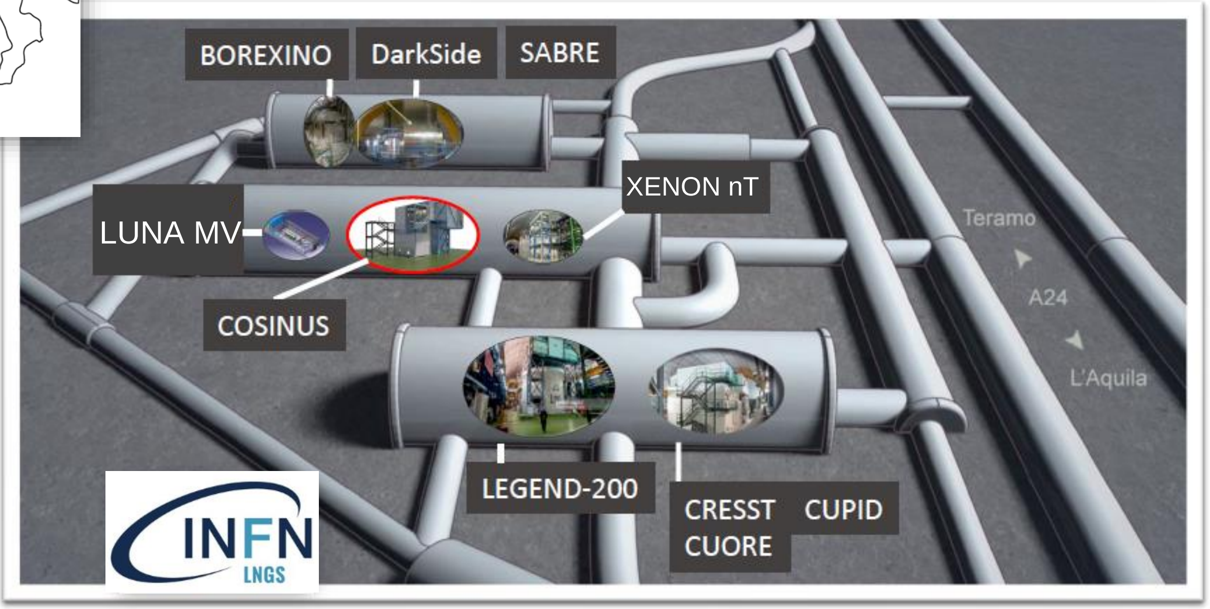
- Rarte search instead of modulation
  - Test DAMA/LIBRA in a single annual cycle

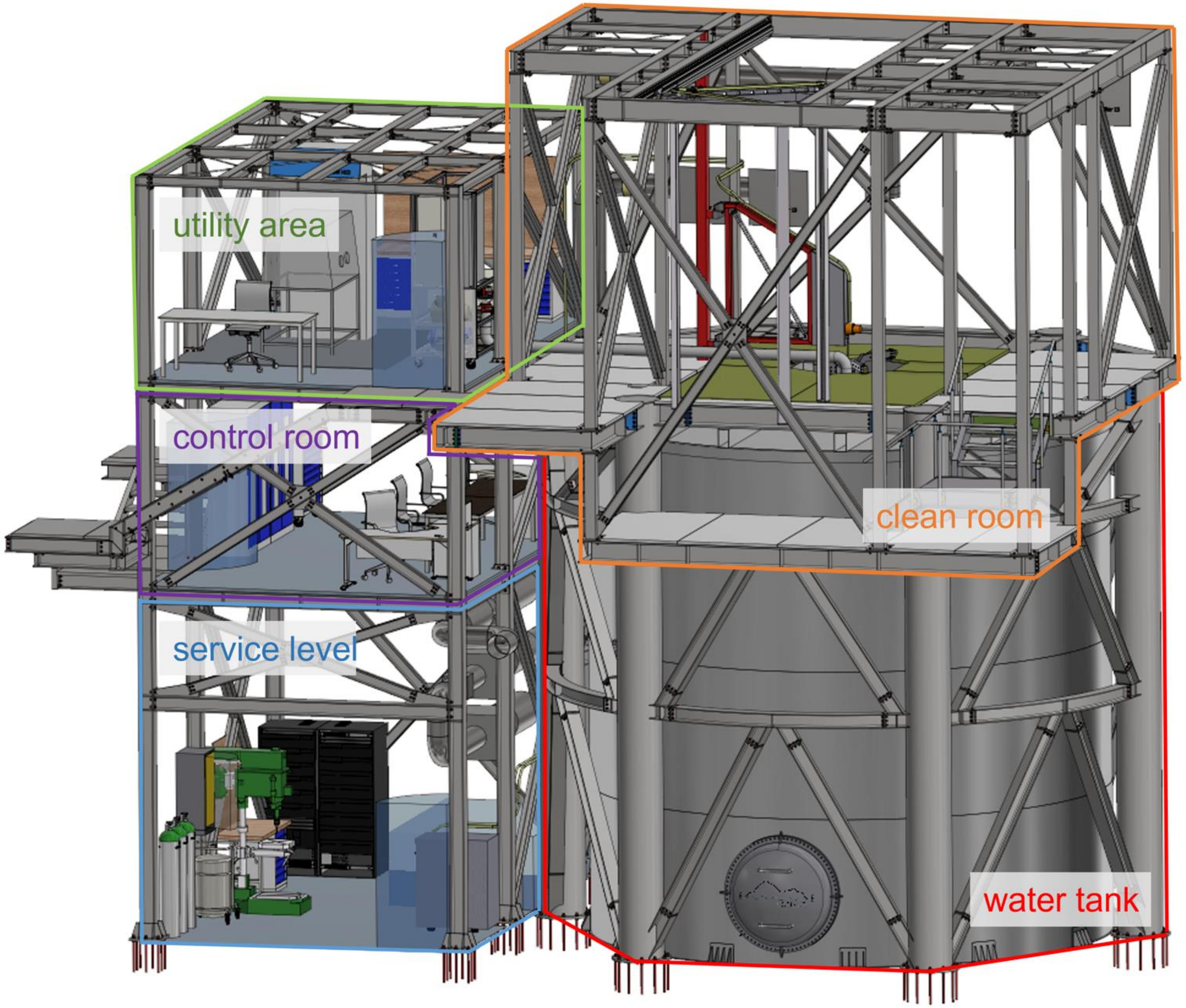
$$S_m \leq \bar{R}$$

COSINUS experimental site

- Laboratori Nazionali del Gran Sasso (LNGS)
- COSINUS is located in hall B
- 1400m rock ~ 3600m w.e



COSINUS setup overview



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

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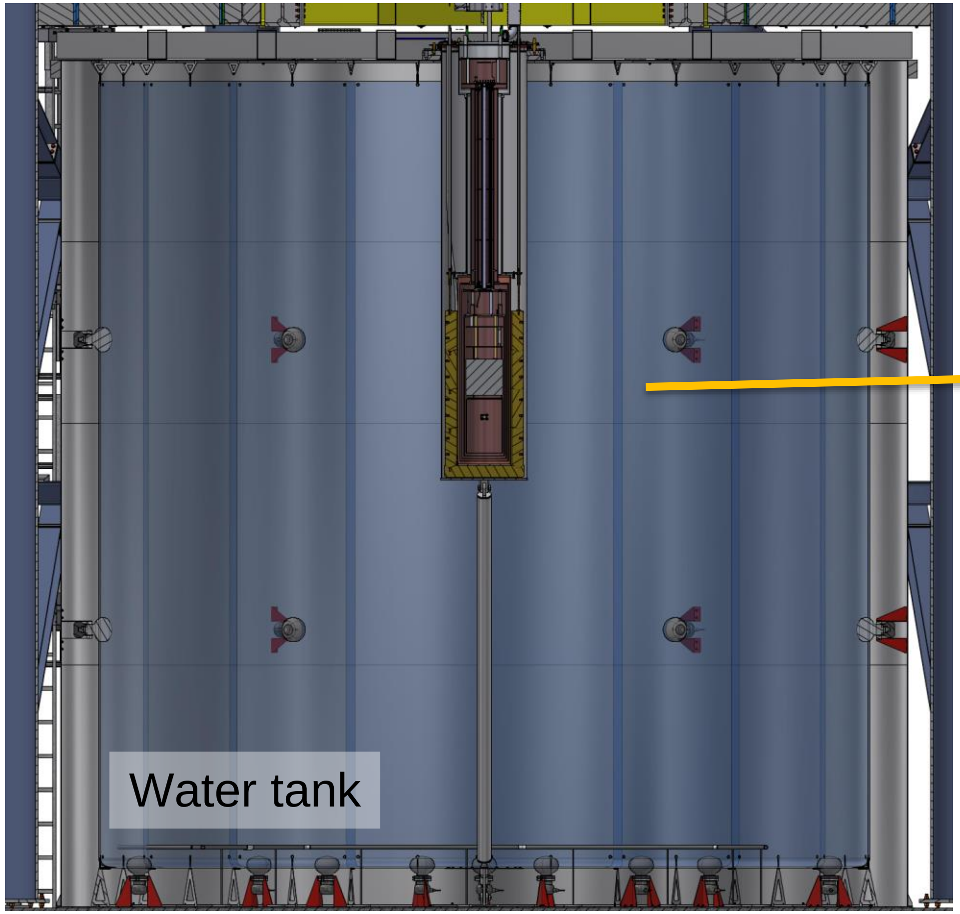
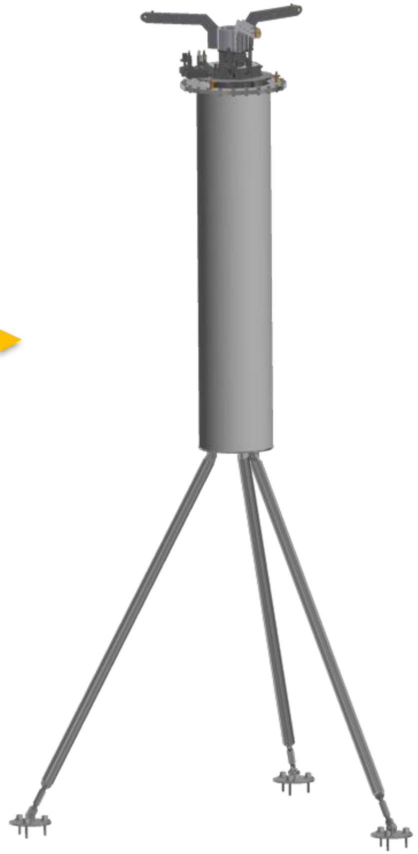


Dry-well supported by tripod



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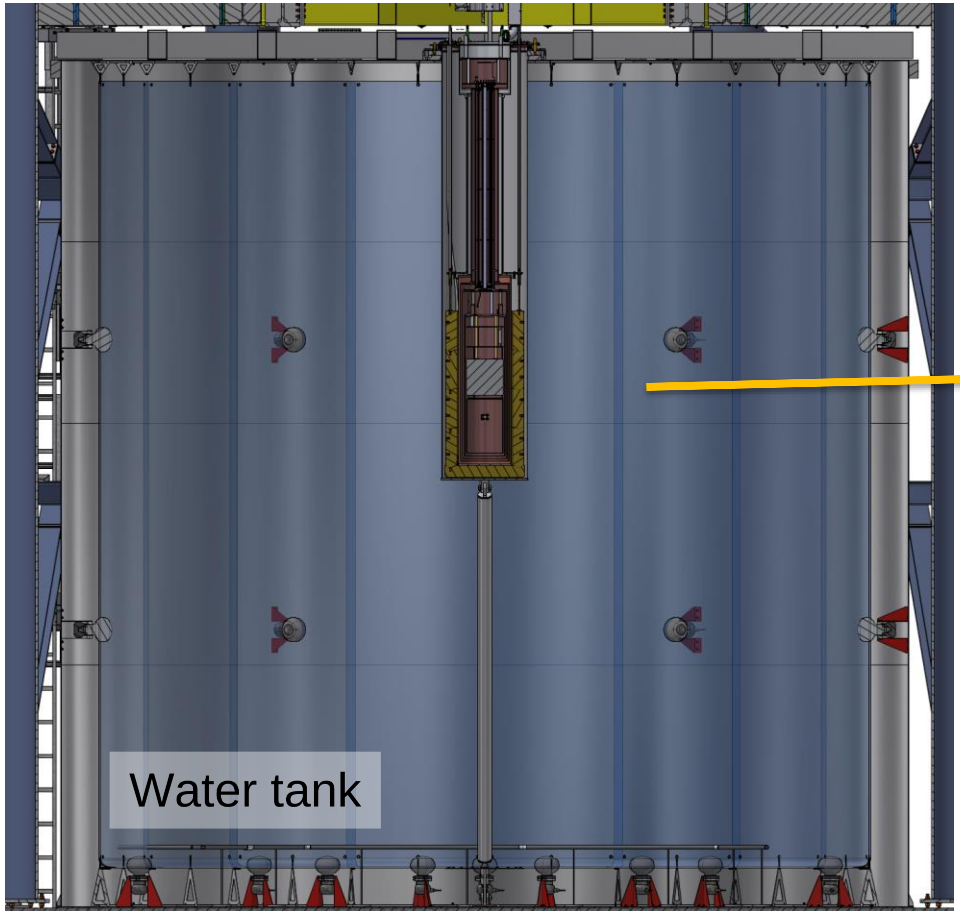

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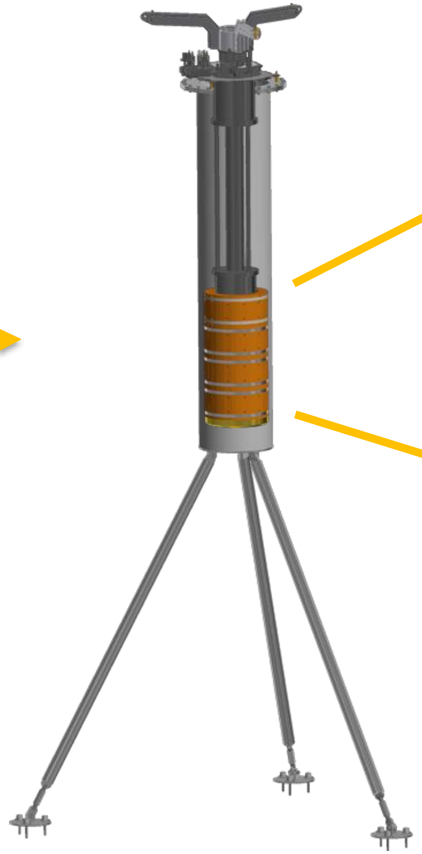

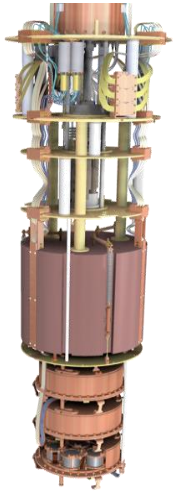

Dry dilution refrigerator
+ external Cu shield

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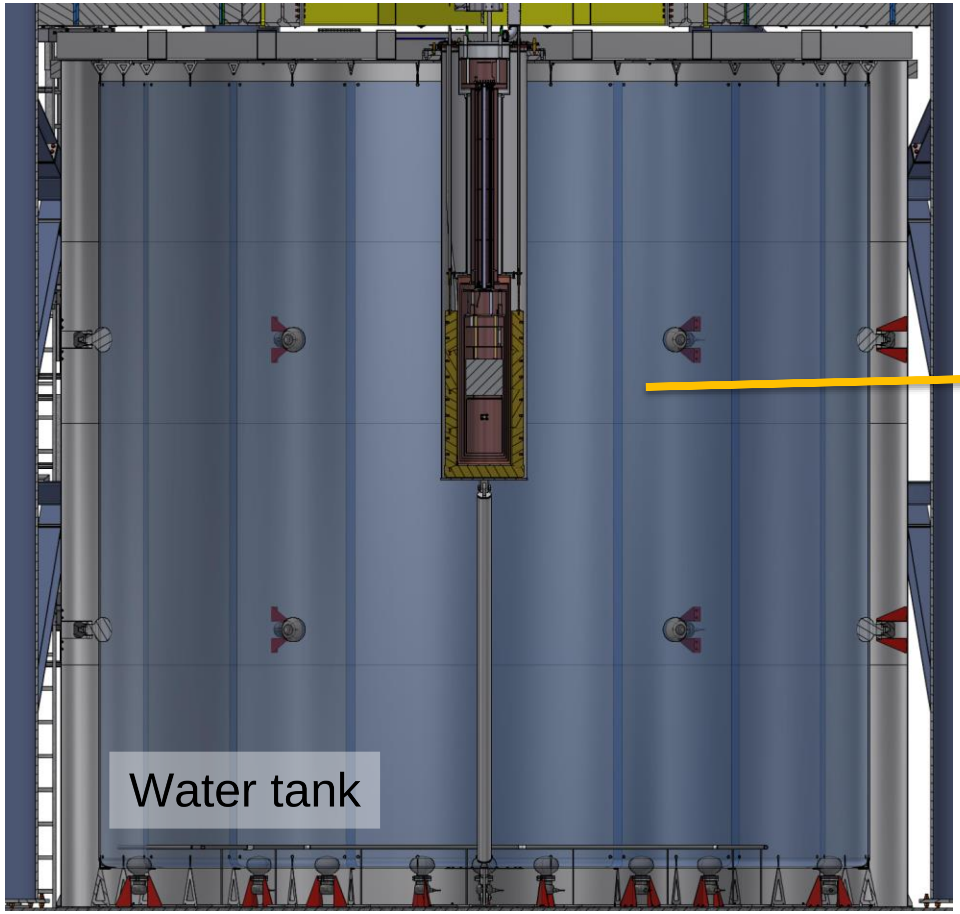

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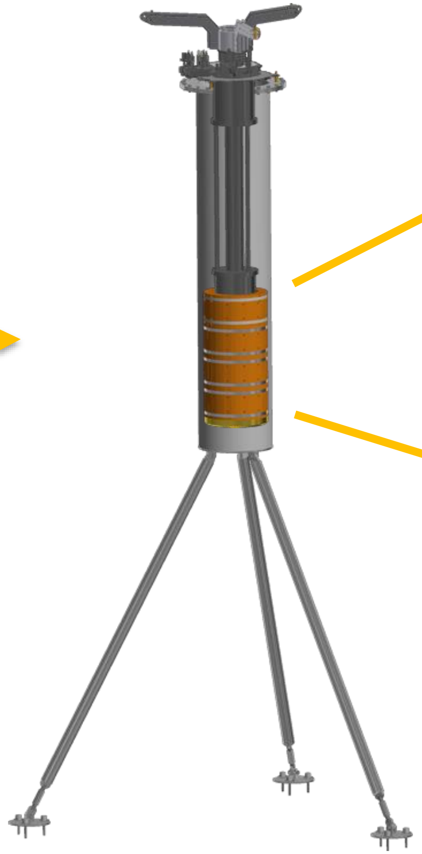

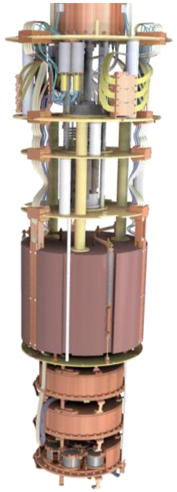

3 Boxes with 8 Detector Modules each

Dry dilution refrigerator
+ external Cu shield

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

Milestones:

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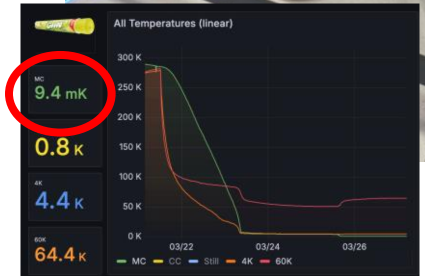
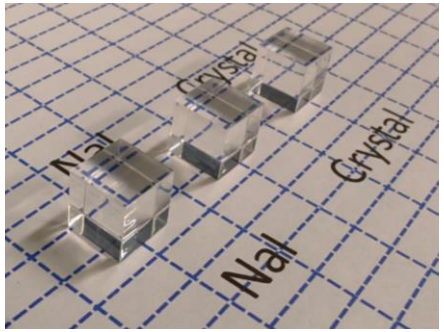
Dry dilution refrigerator



COSINUS setup

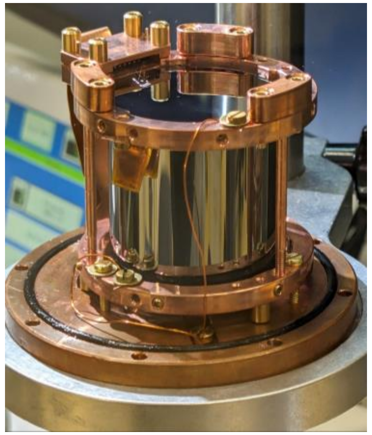
Muon veto installation

Radiopure NaI crystals

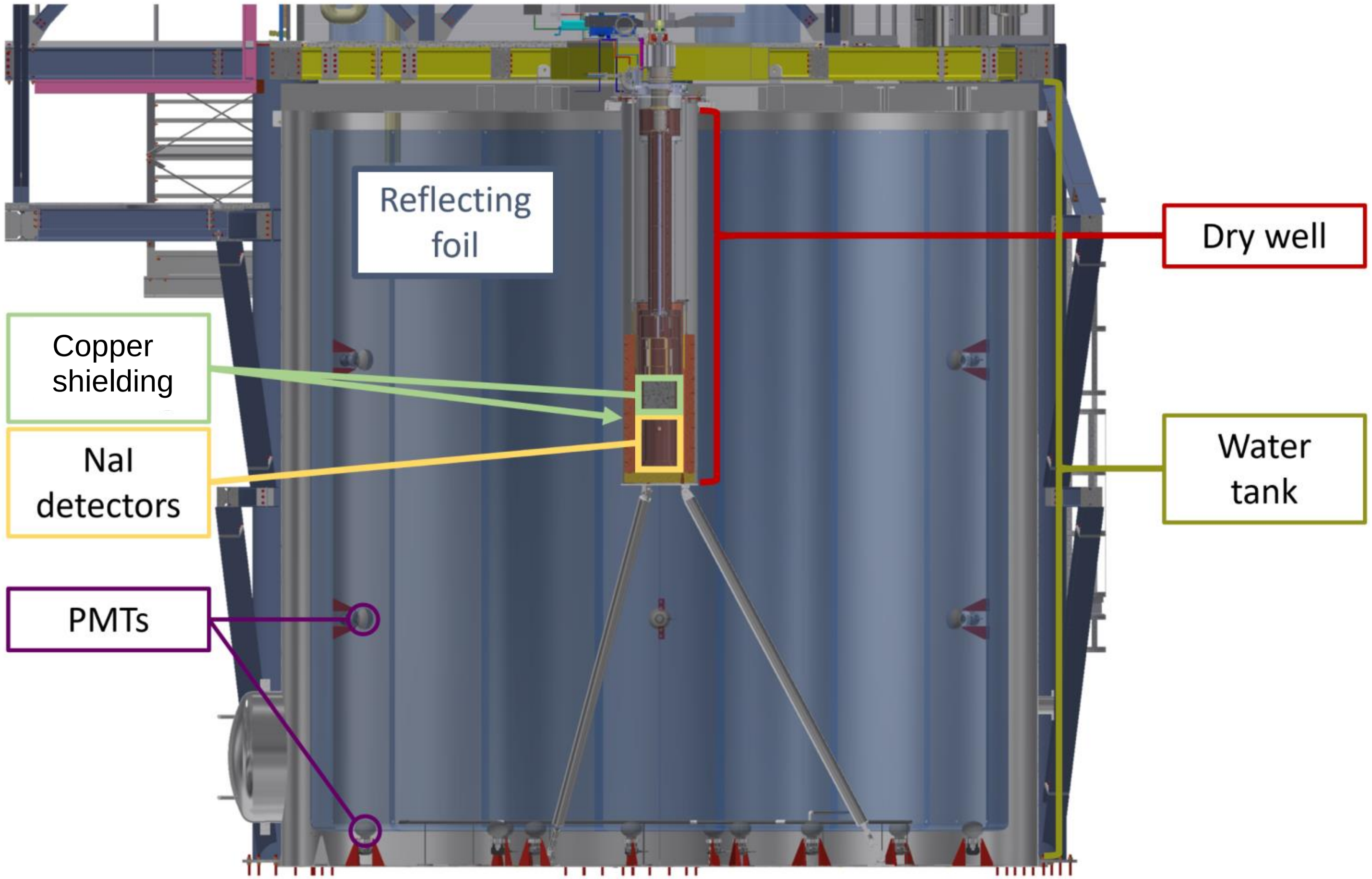


Servers for DAQ

Final tests



Water cherenkov muon veto

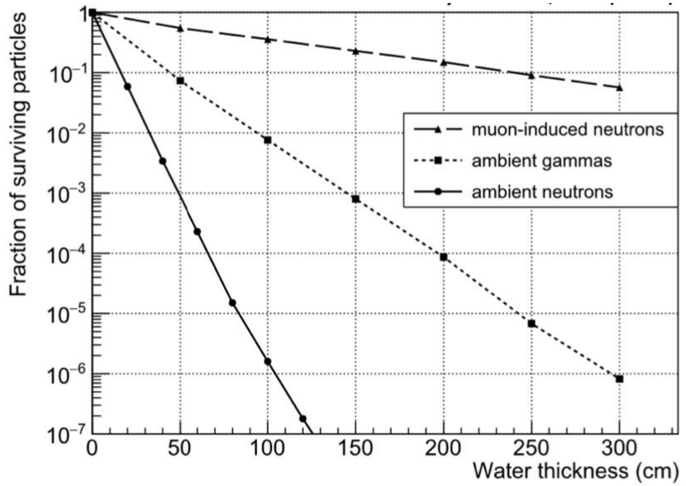


G.Angloher et al, 2024, NeutrinoFS, 2409.09109

- 269 m³ Water
- 30 PMTs - 8-inch R5912-30 from Hamamatsu
- Tyvek (1082D) - Used as reflector in experiments e.g. Super Kamiokande and Juno
- Total ~ 1 Muon/s (MV)

Rate of cosmogenic neutrons in NaI:

- no veto: ~ 3 counts yr^{-1}
- with veto: < 0.05 counts yr^{-1}



G. Angloher et al., 2022, s10052-022-10184-5

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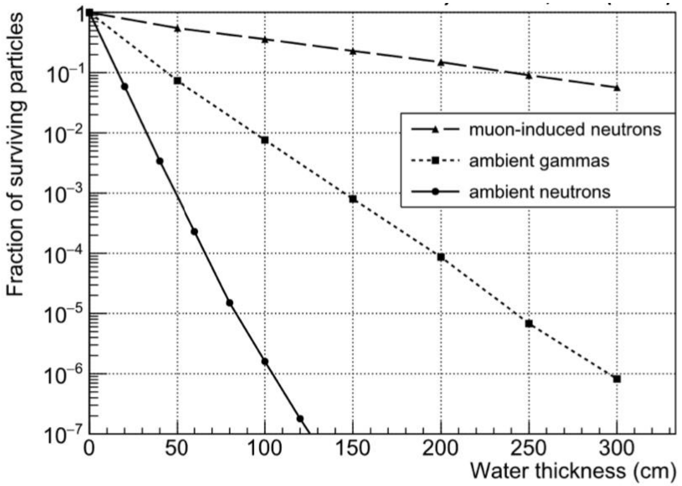

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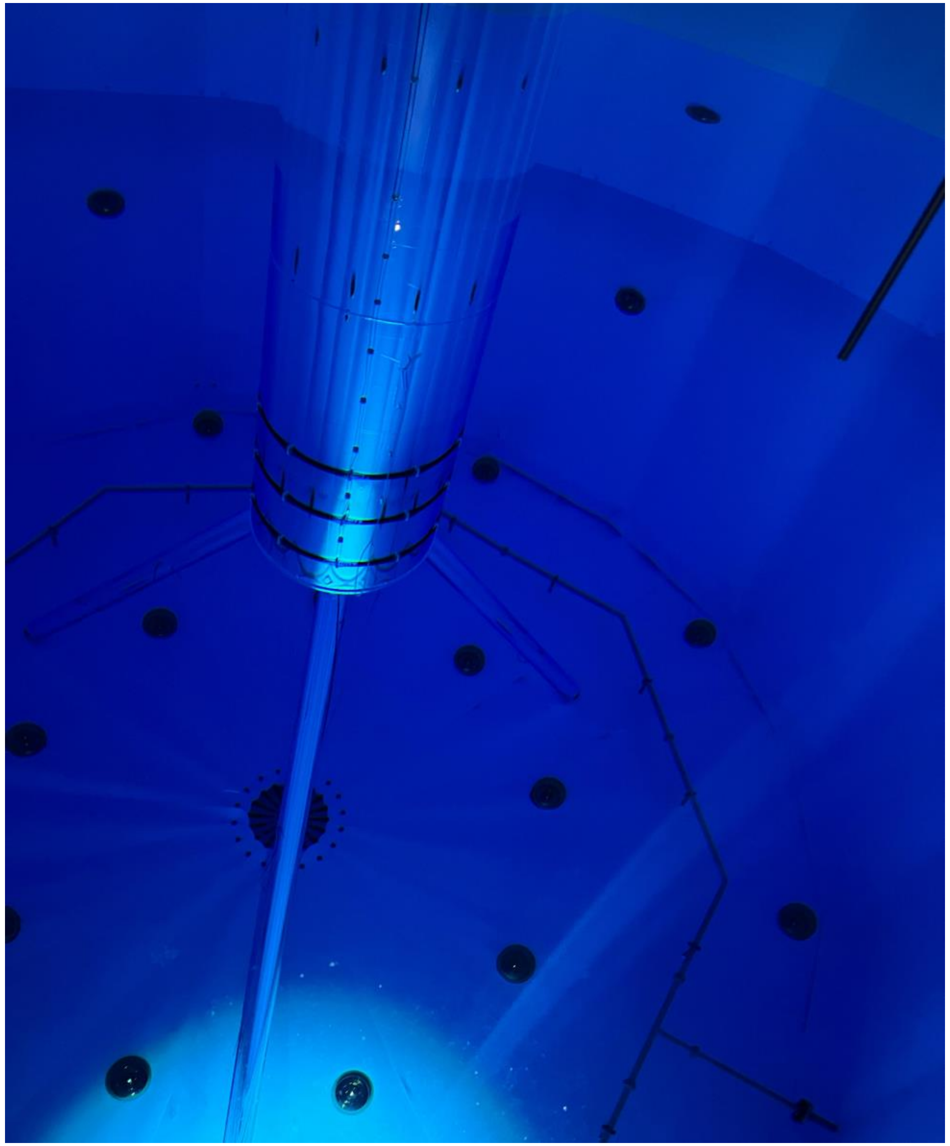
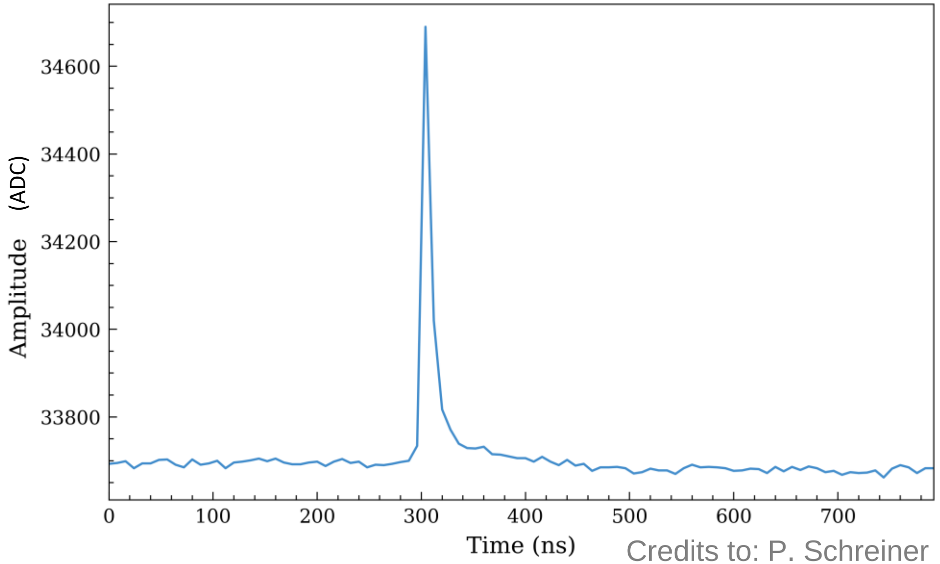
Water Cherenkov Muon Veto



Filled since February and DAQ is running!



Credits to: P. Schreiner

Neutrino flux sensitivity to supernova

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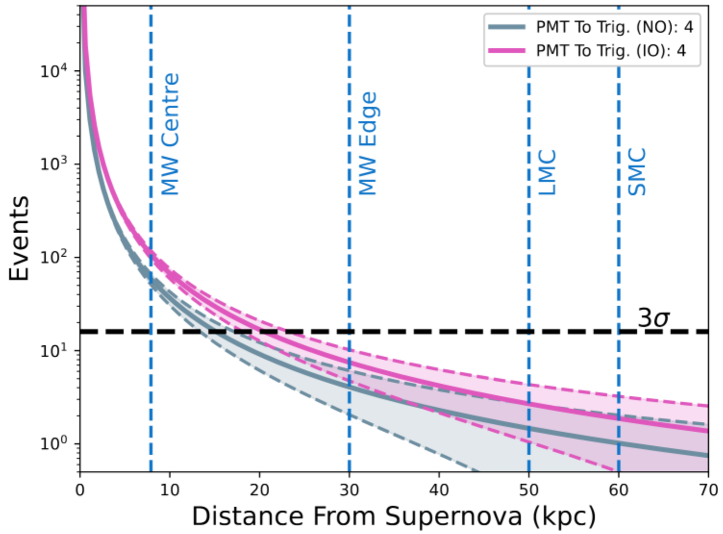
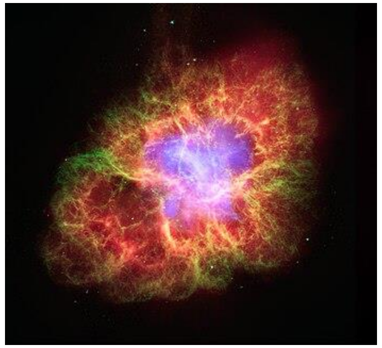
Muon Veto:

- Supernova near the Milky Way Center (10 kpc)
  - ~60 measurable event
- 3σ sensitivity to supernovae up to 22 kpc
  - ~10 measurable events
- Larges channel (Inverse Beta-Decay): $\overline{\nu}_e$

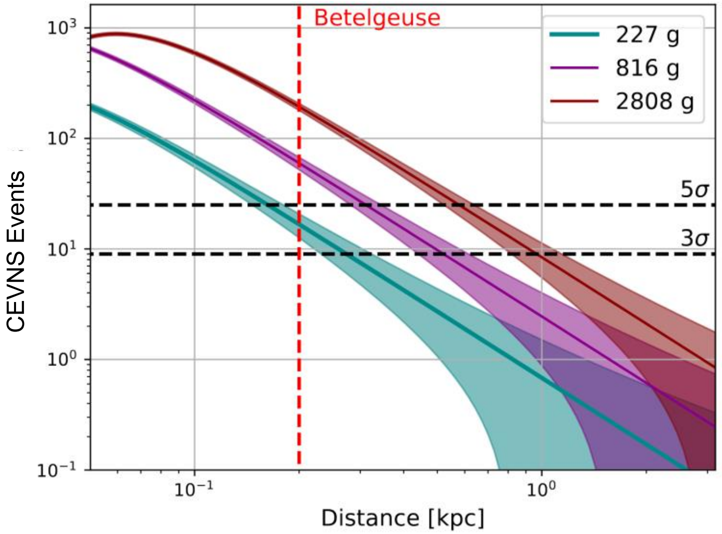




Crystals:

- Sensitive to the Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) against Na and I nuclei
  - ν_e, ν_μ and ν_τ
- Identify close supernovae within 1 kpc without pileup

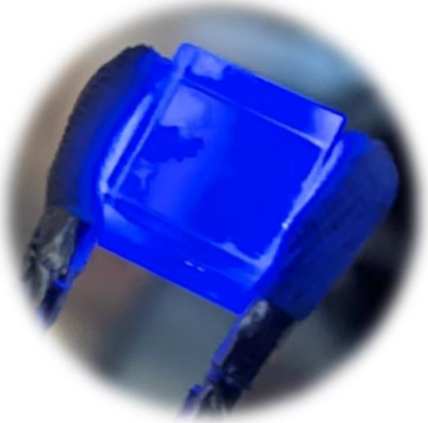
G.Angloher et al, 2024, NeutrinoFS, 2409.09109



- Calculation for SN1987A - like Supernova
- Next close Supernova is Betelgeuse which is located at 200 pc
- $\sim 3 \times 10^{53}$ ergs of neutrinos will be emitted within ~ 10 s

Sodium Iodide

- Same target material (undoped) as DAMA/LIBRA
- 21x21x21 mm^3 ~ 34g crystal
- Scintillating – Photon Signal
- Extremely hygroscopic !
- Extremely soft !



Sodium Iodide + remoTES design

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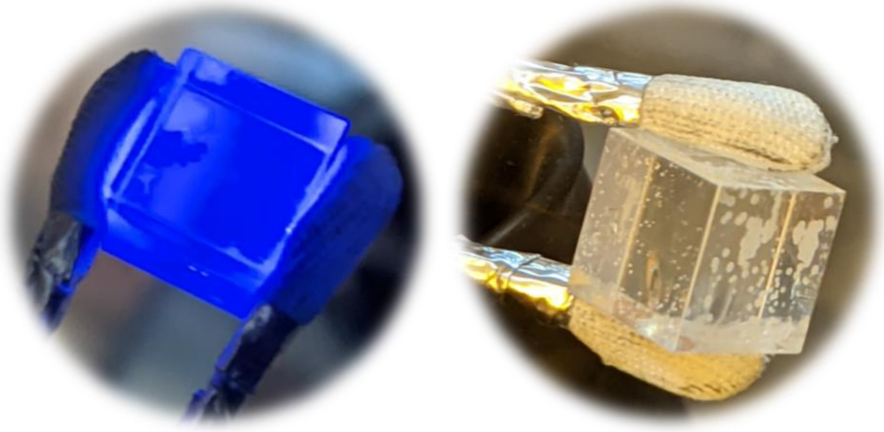
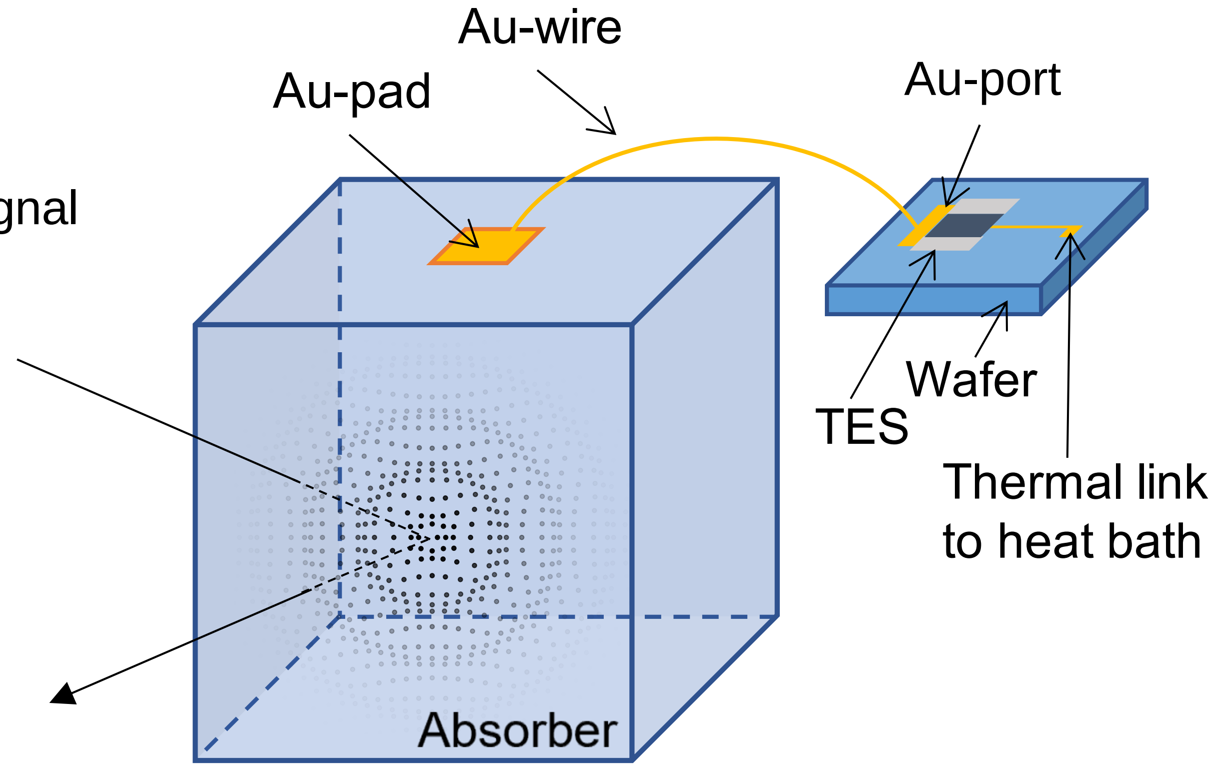
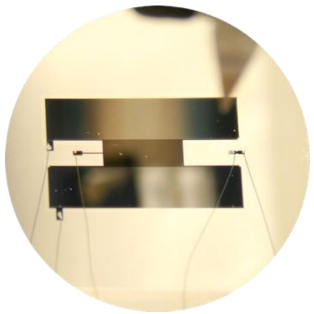


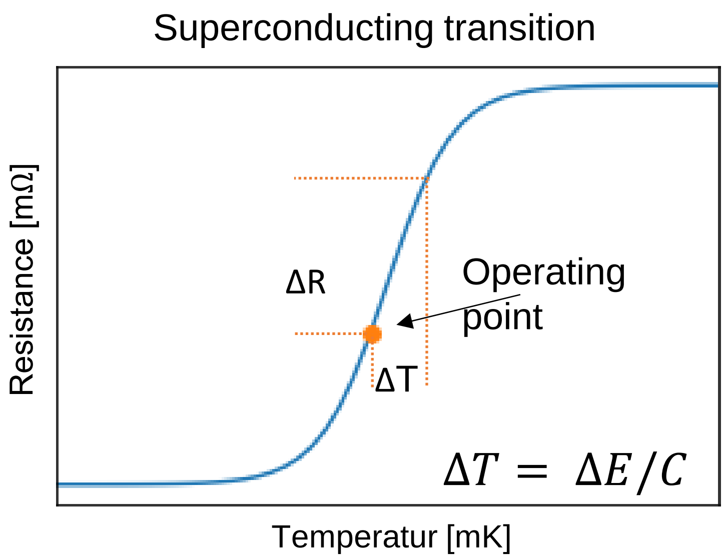
To get phonon signal



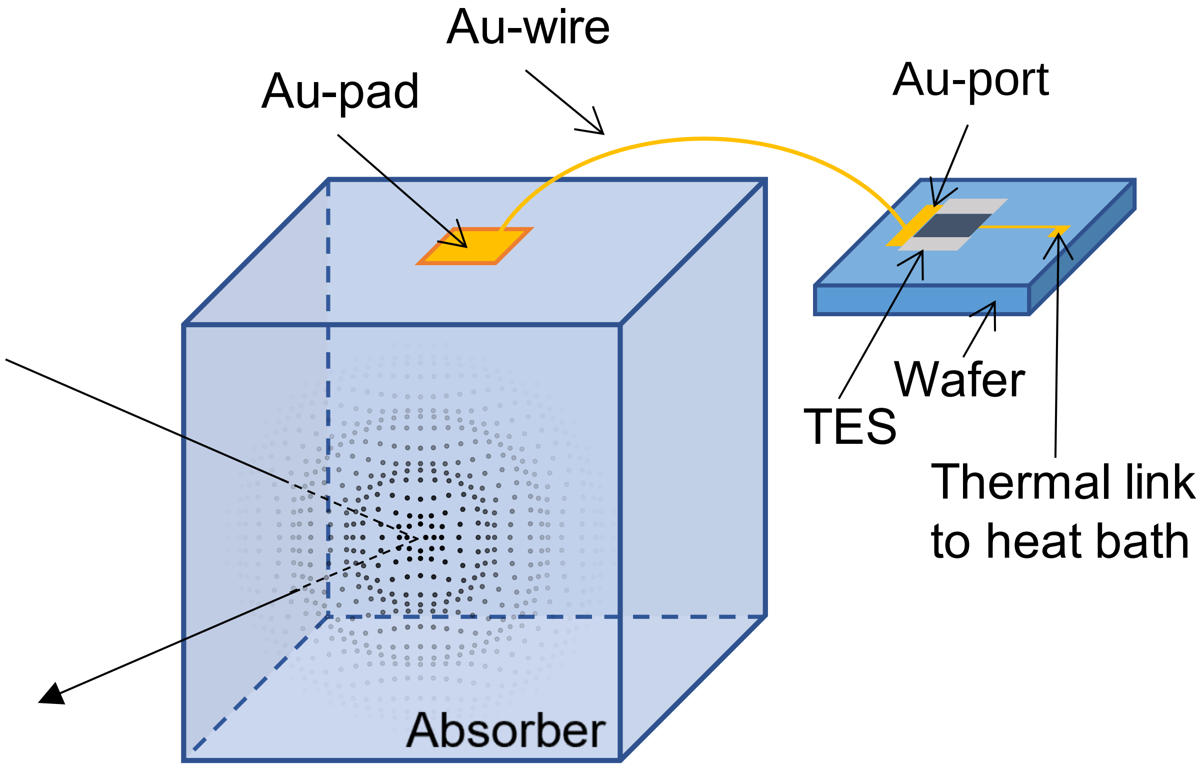
G. Angloher et al. 2024, PhysRevD.110.043010

Transition Edge Sensors (TES)





- Technology from CRESST
- Measures µK-temperature differences
- Energy deposition
  -> Change in temperature -> Change in resistance
- Electrical readout using "superconducting quantum interference devices" (SQUIDs) as amplifiers



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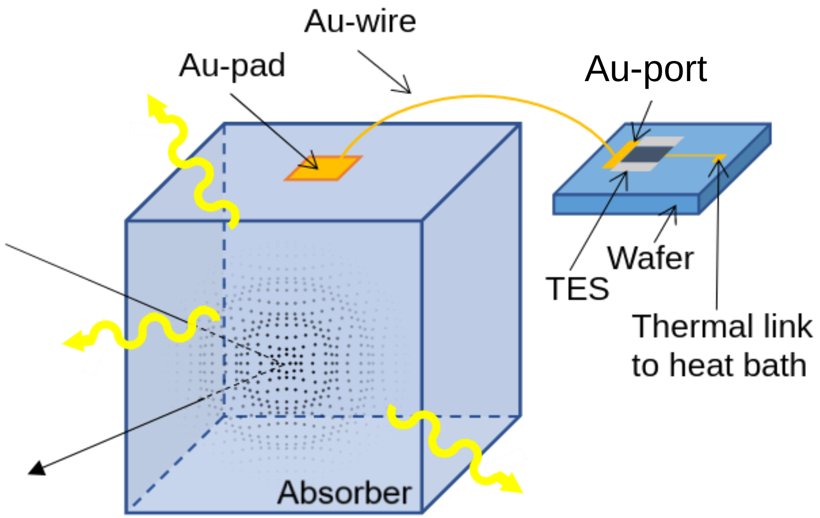
Photon and phonon channel

- Si-beaker for active surrounding of the crystal



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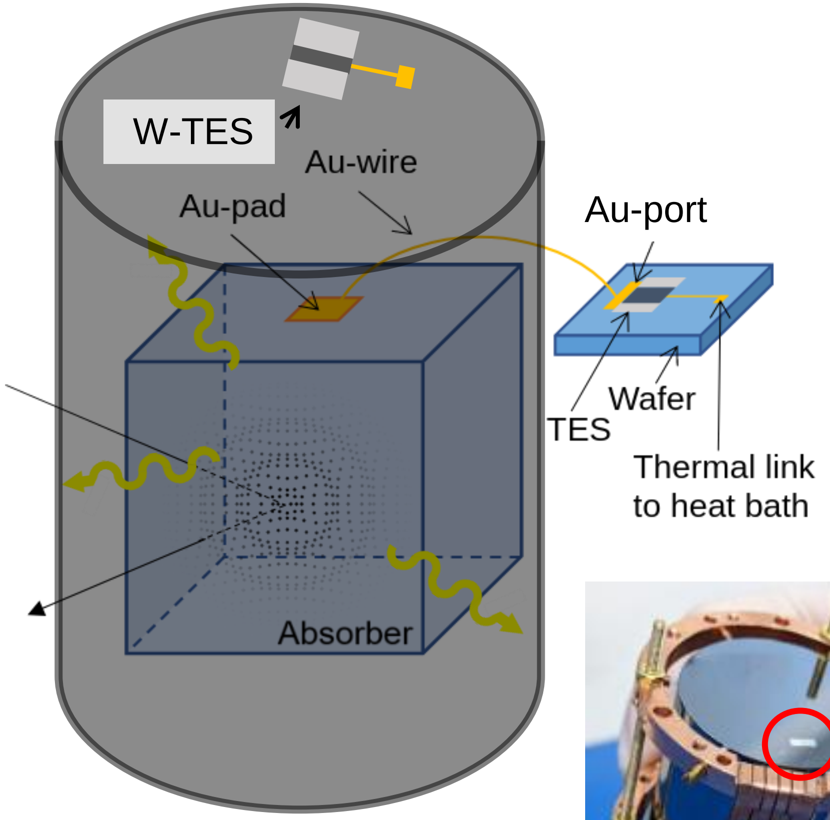

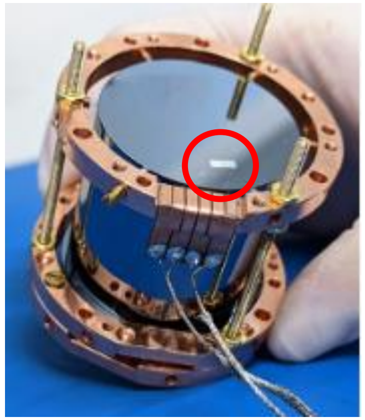

Photon and phonon channel

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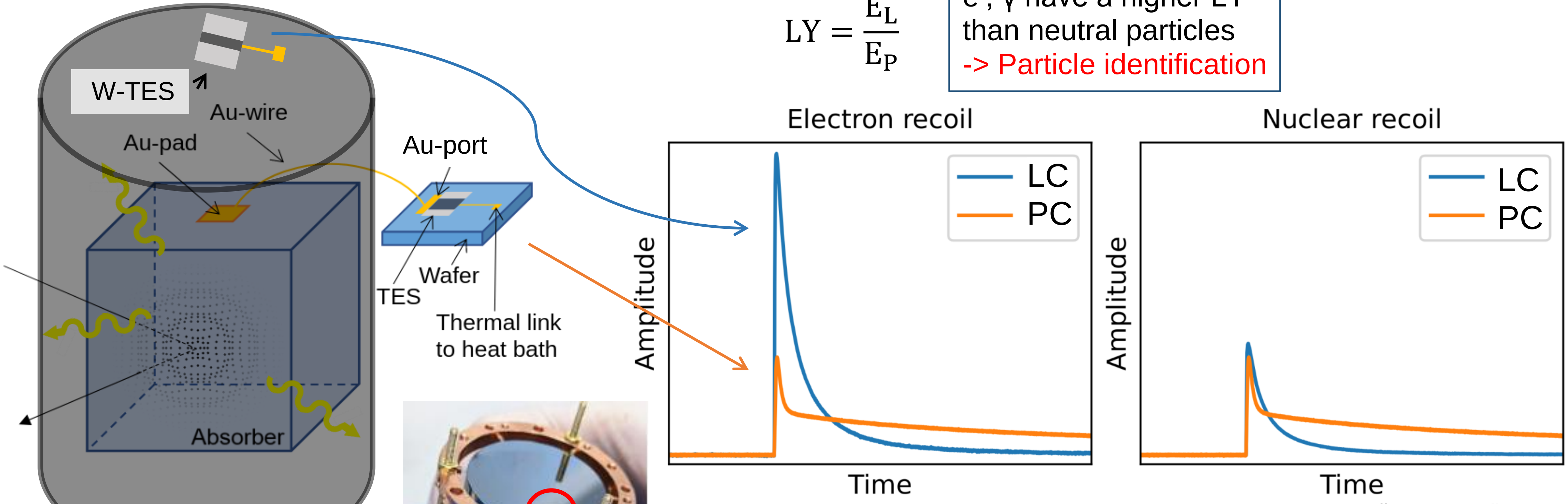
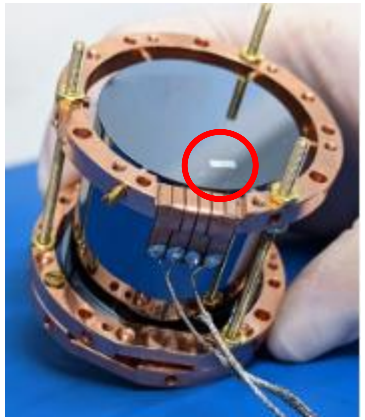
$$LY = \frac{E_L}{E_P}$$

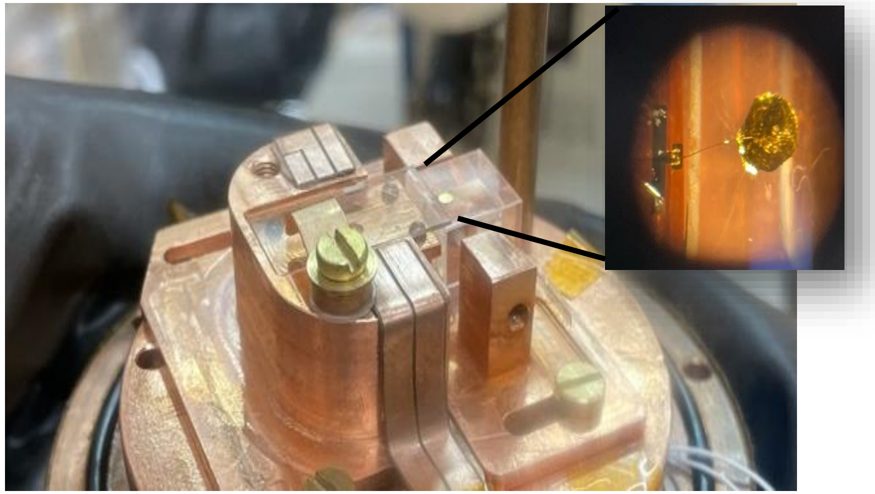
e⁻, γ have a higher LY than neutral particles
-> Particle identification





Credits to: M. Kellermann

Particle identification in a NaI-based detector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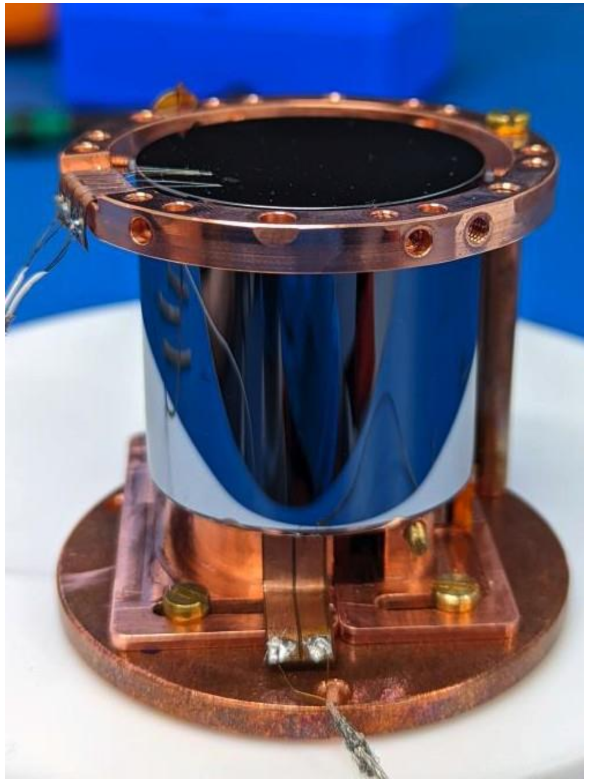
NaI-remoTES – June 2022

- dimensions: 10x10x10 mm^3 ~ 4 g
- Au-foil glued with epoxy
- Au-pad size: 4 mm^2

Measurement carried out at the test facility of CRESST @ LNGS



Particle identification in a NaI-based detector

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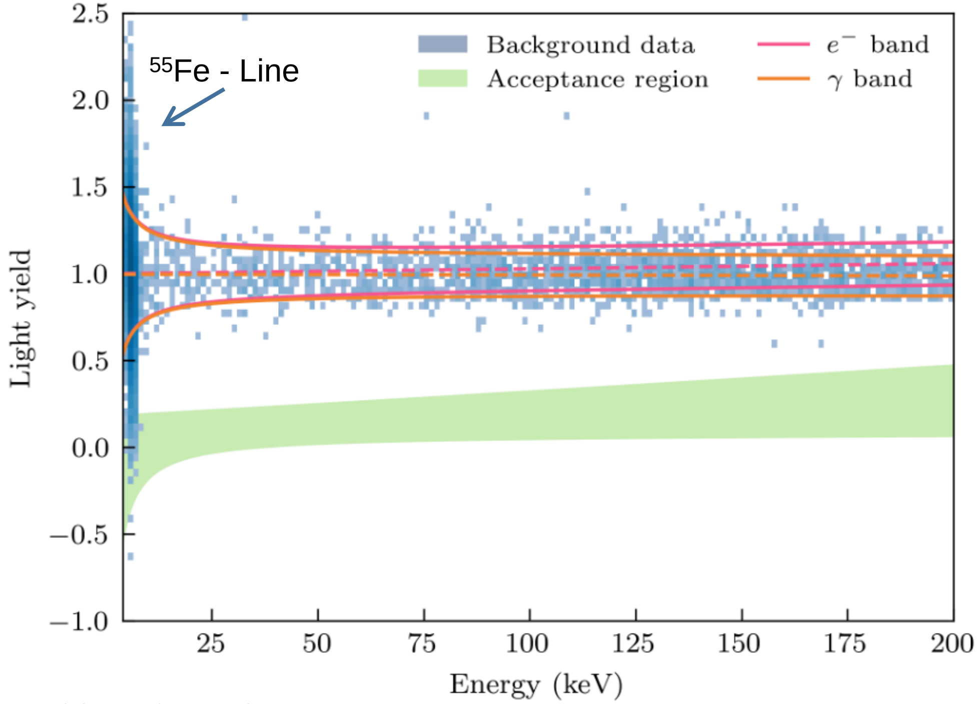
Background Data



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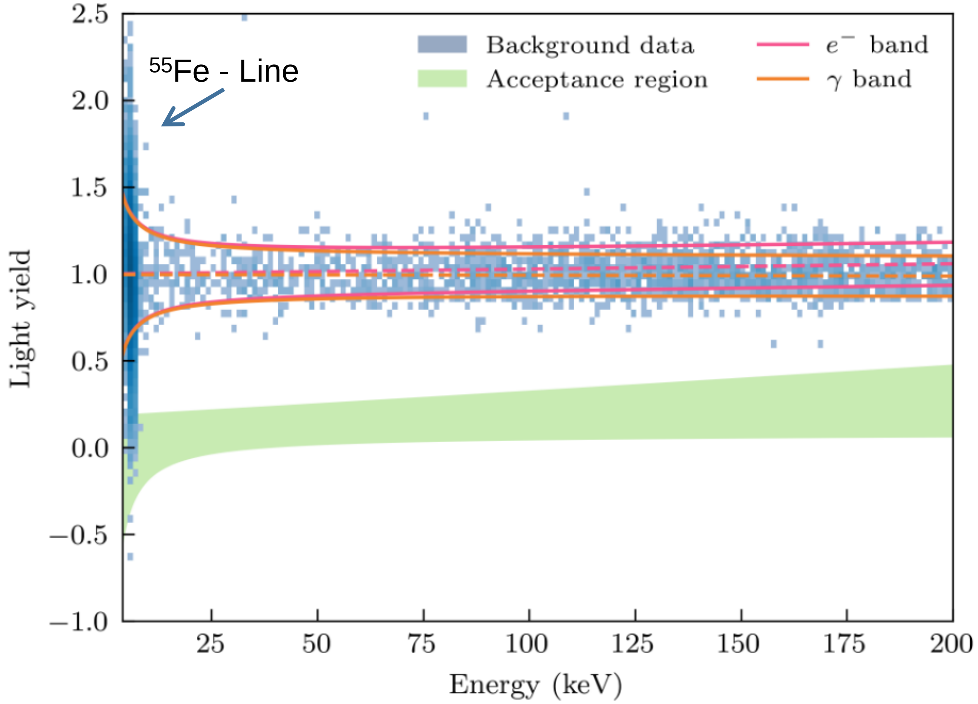

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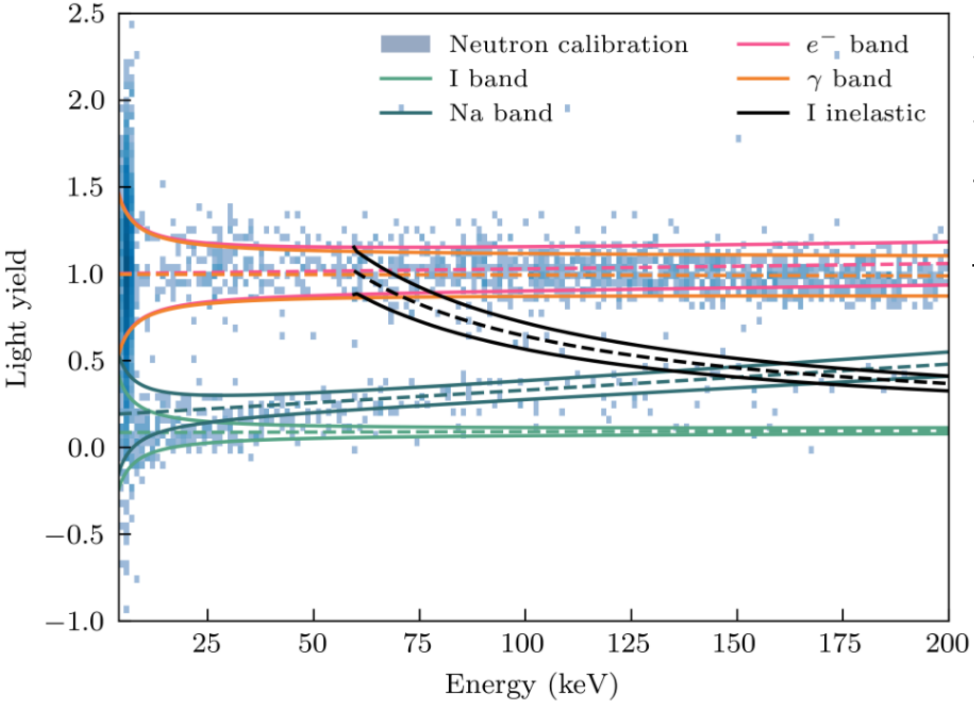
Neutron Data



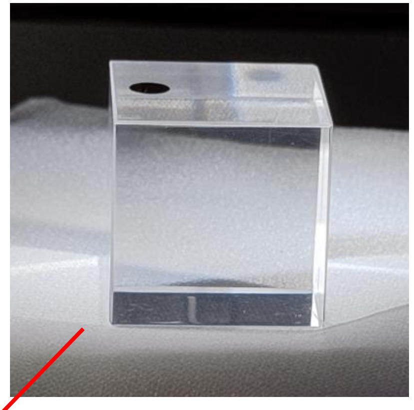
- σ_{NaI} = 0.441 +/- 0.11 keV
- $\sigma_{LD\text{-}direct}$ = 23.87 +/- 0.55 eV
- **E_{thr} = 4 keV Analysis Threshold**

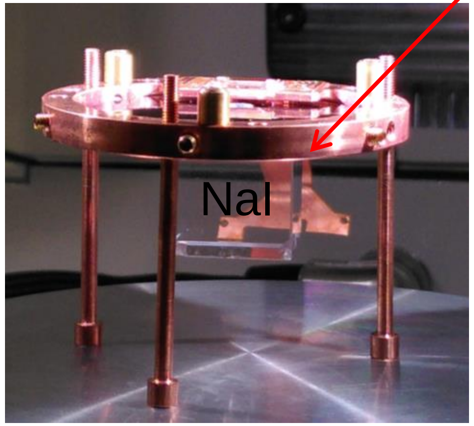
Measurement carried out at the test facility of CRESST @ LNGS

Tests with Detector Module

Modification:

- Dimensions: 21x21x21 mm^3 ~ 34 g
- Au-pad evaporated - 4 mm^2
- Thickness ~ μm
- Glued on Silicon-disc





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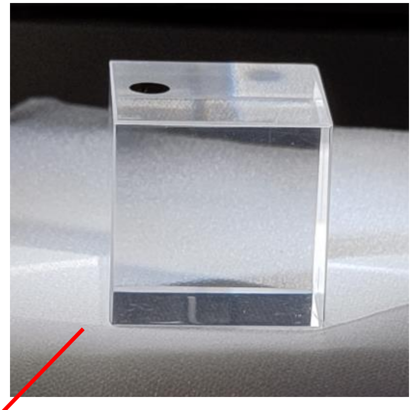
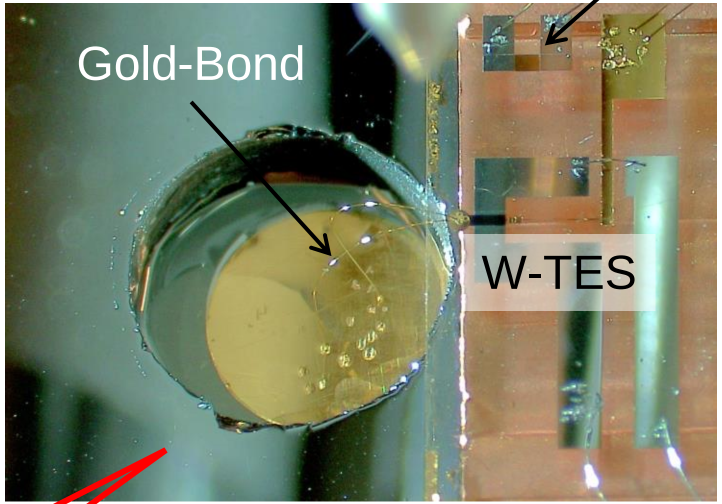
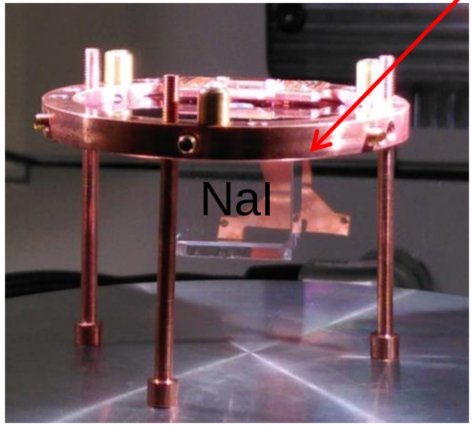
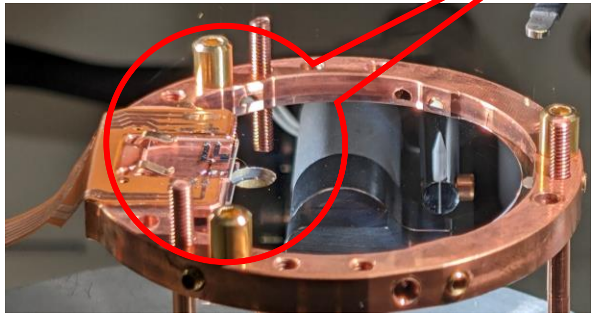


Heater for Test-Pulses and operating point







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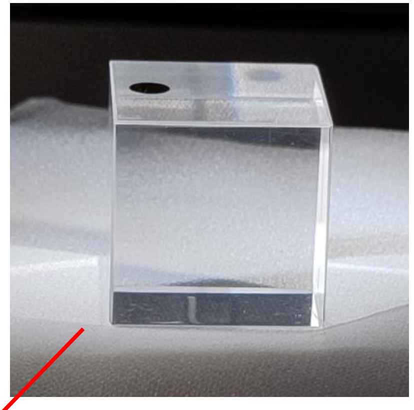

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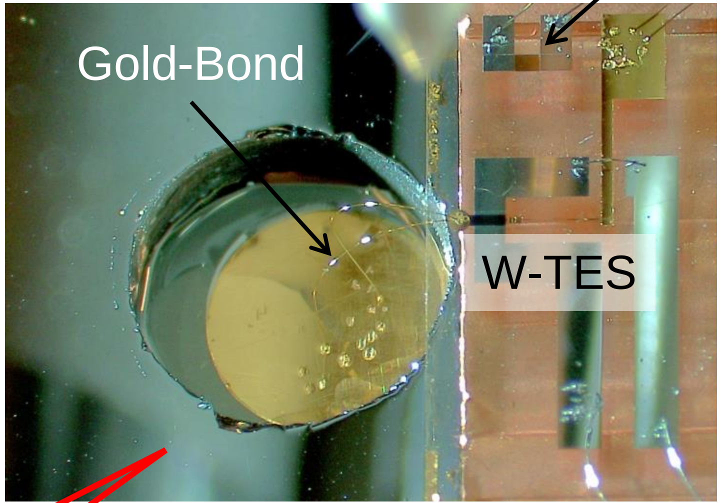
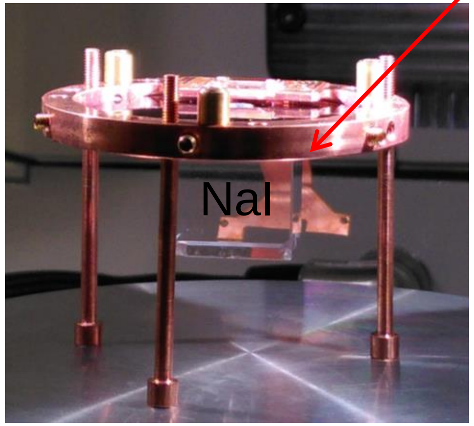
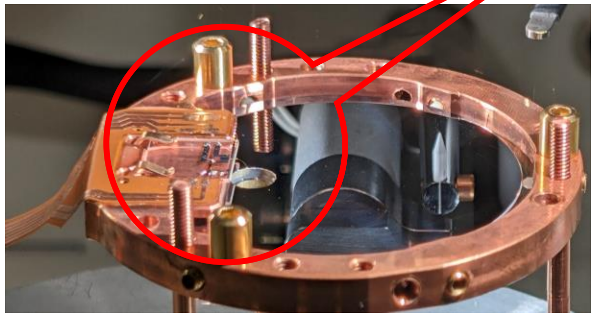
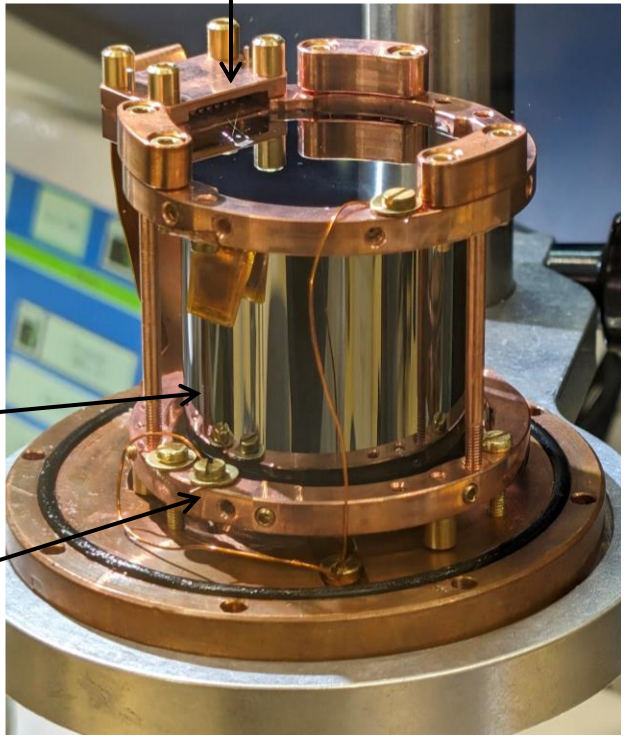


W-TES directly evaporated







Silicon-Beaker

Turned upside down and covered with silicon beaker

Summary & Outlook:

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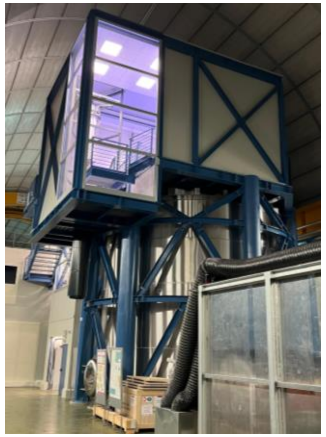

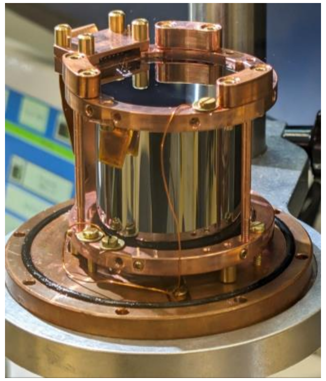

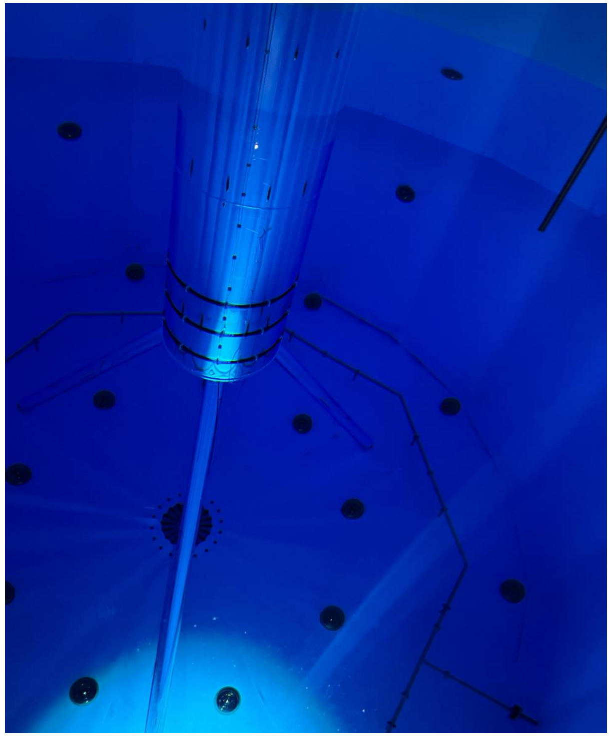

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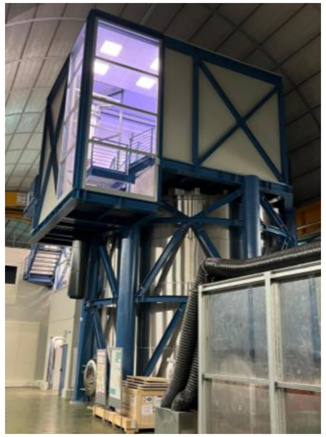
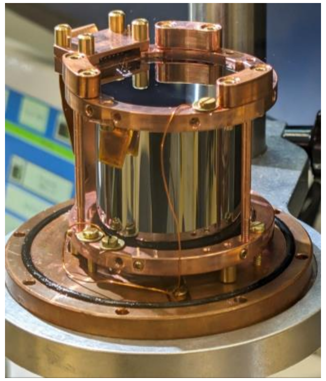
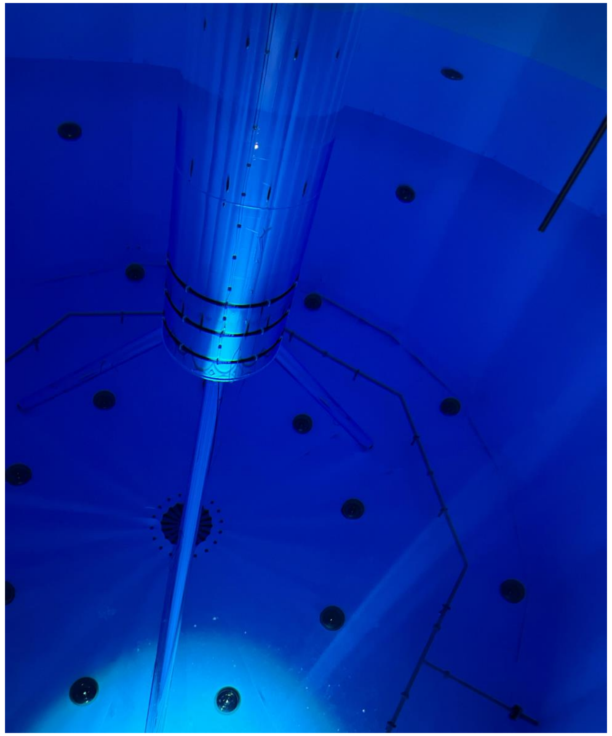
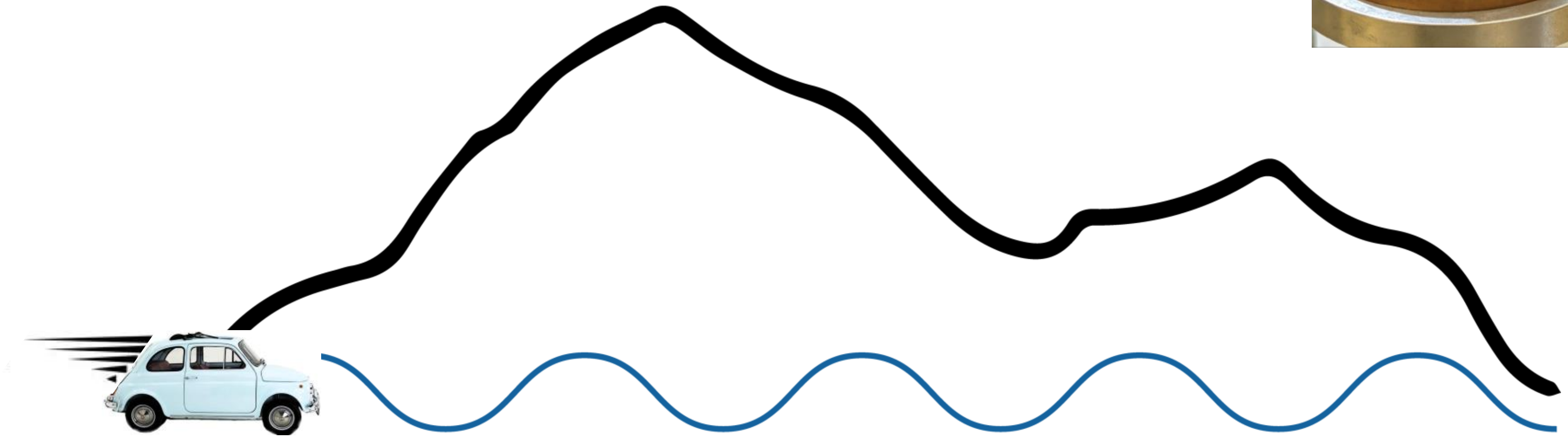






COSINUS



Decoupling

3.2025 →

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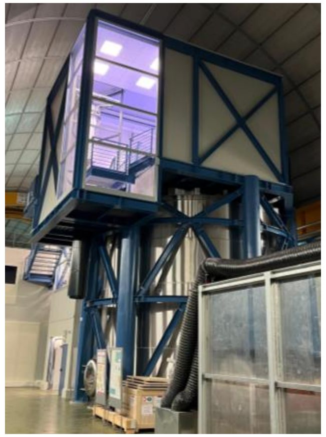

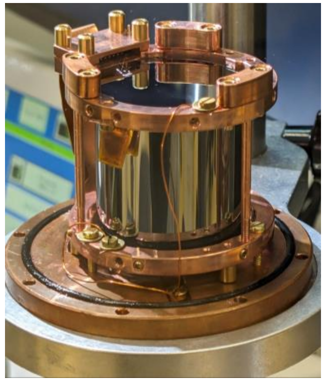

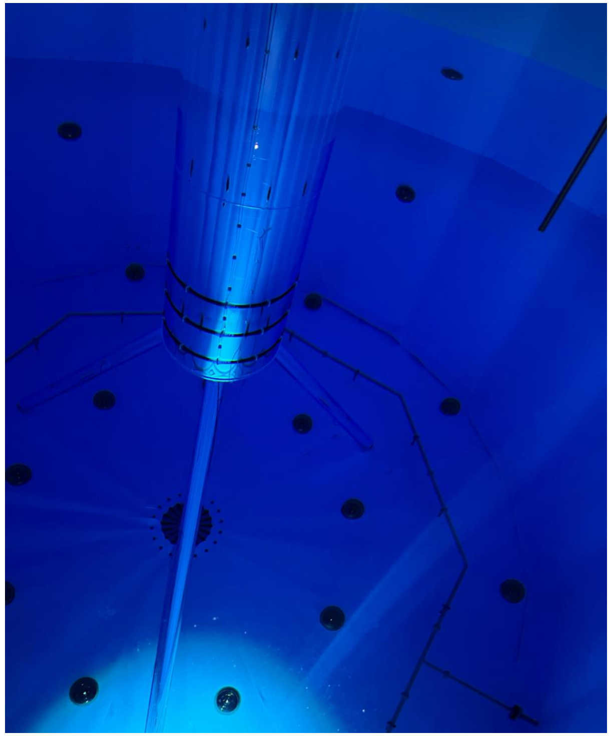

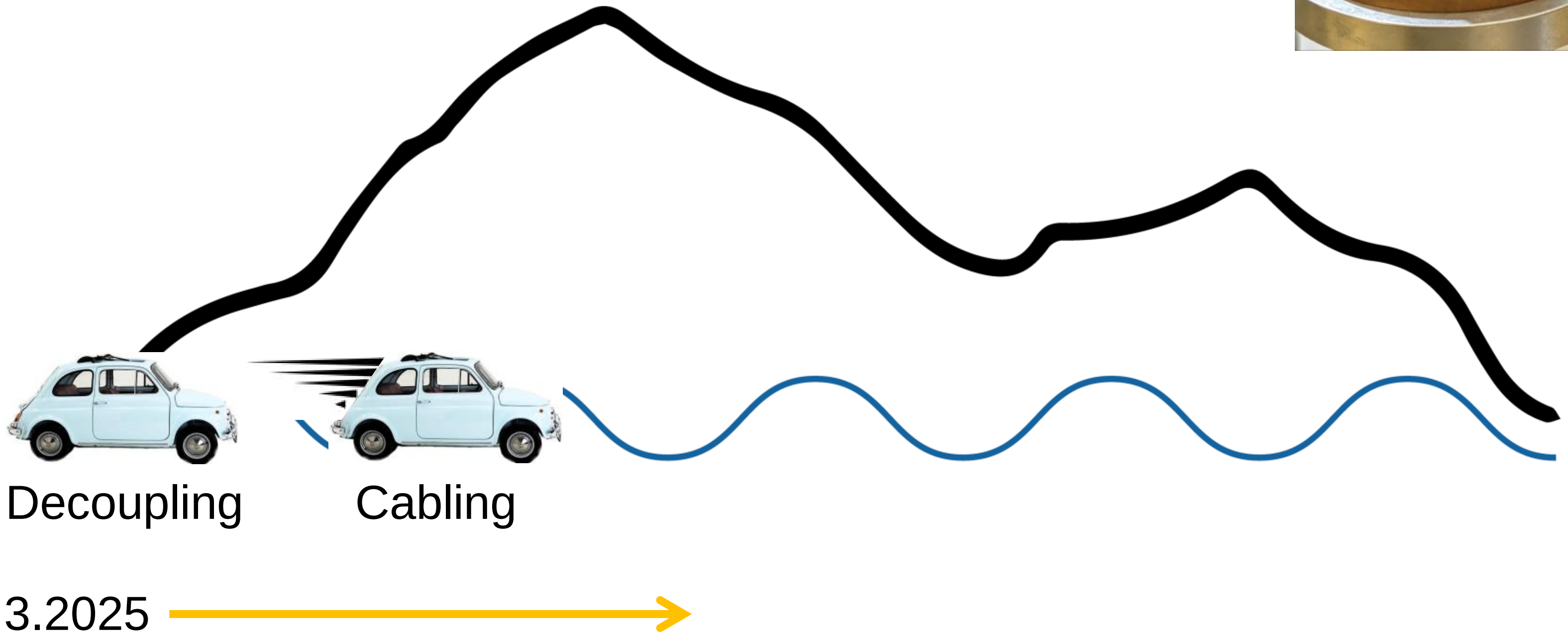

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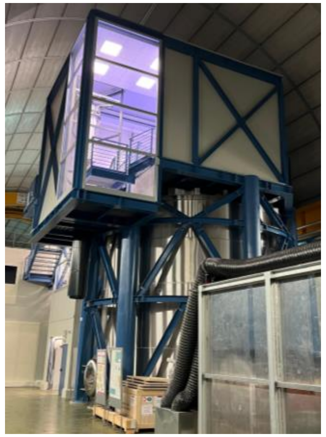

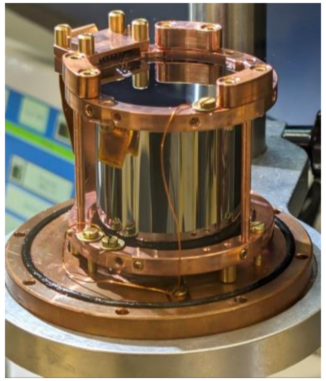

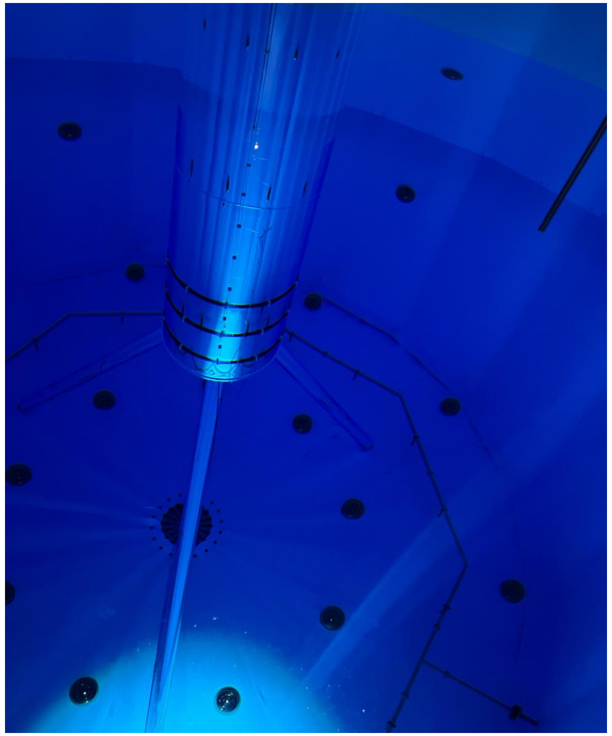

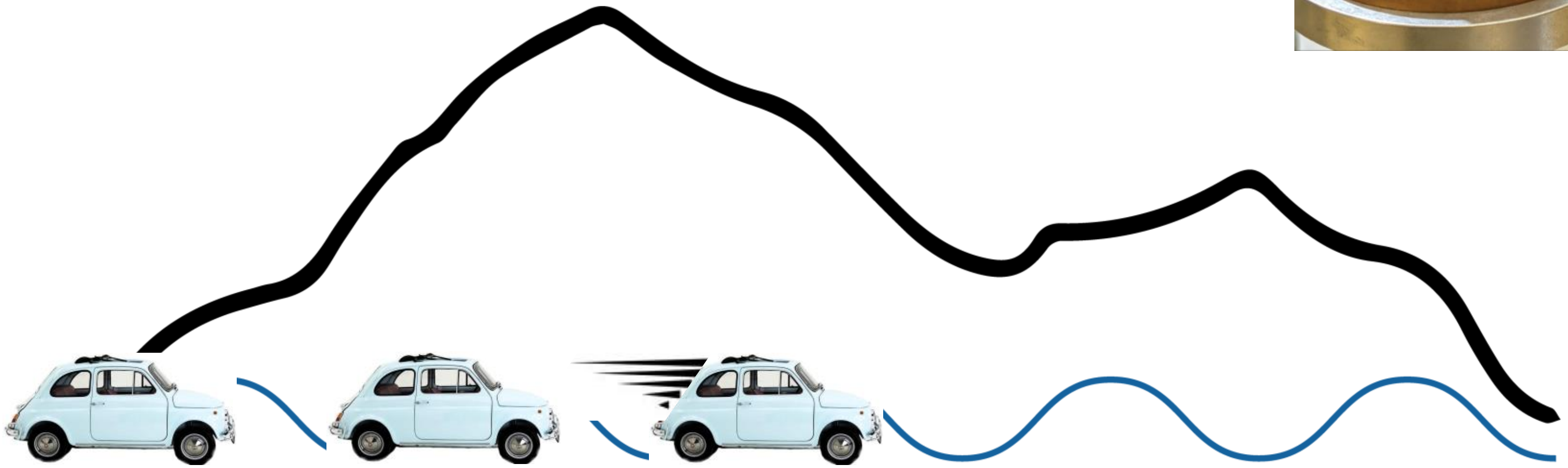

Decoupling Cabling Detector Module

3.2025 → 6.2025

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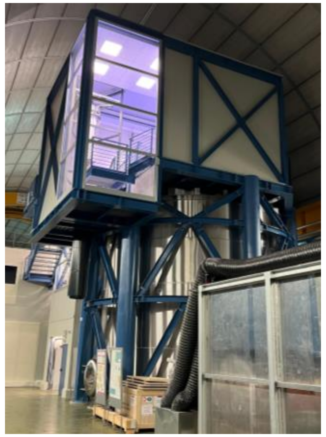

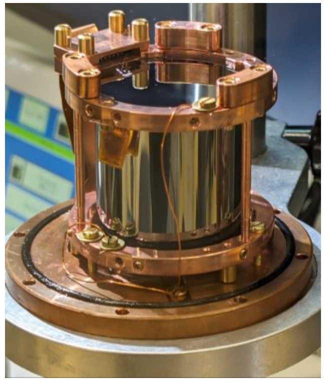

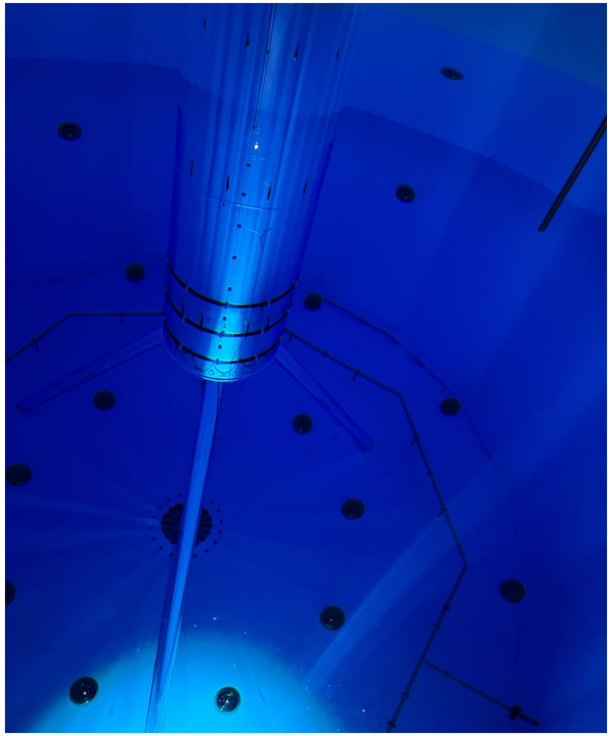

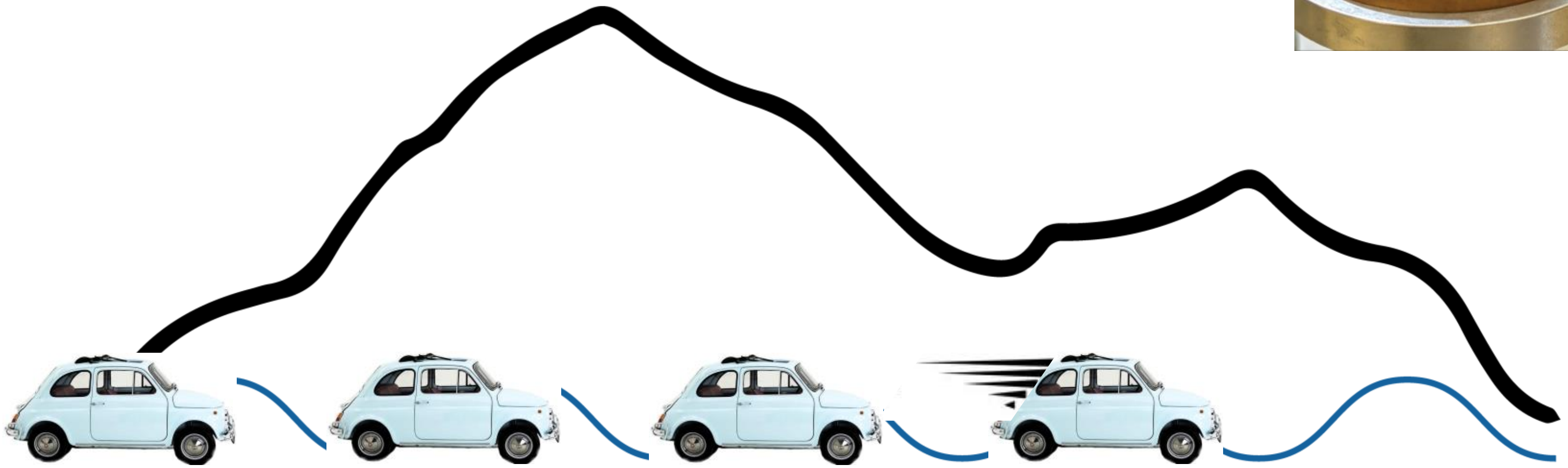

Decoupling Cabling Detector Module Integration

3.2025 → 6.2025 →

Summary & Outlook:

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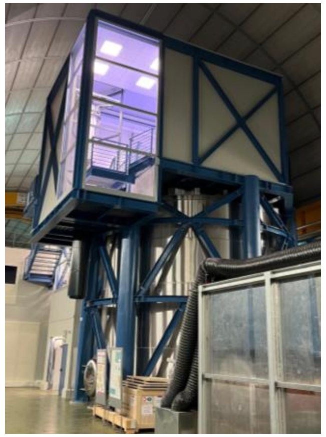
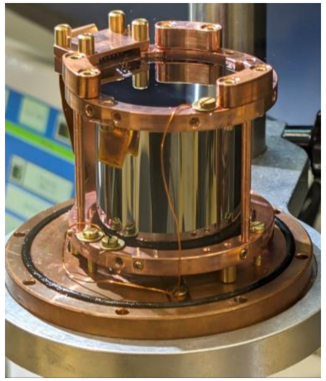
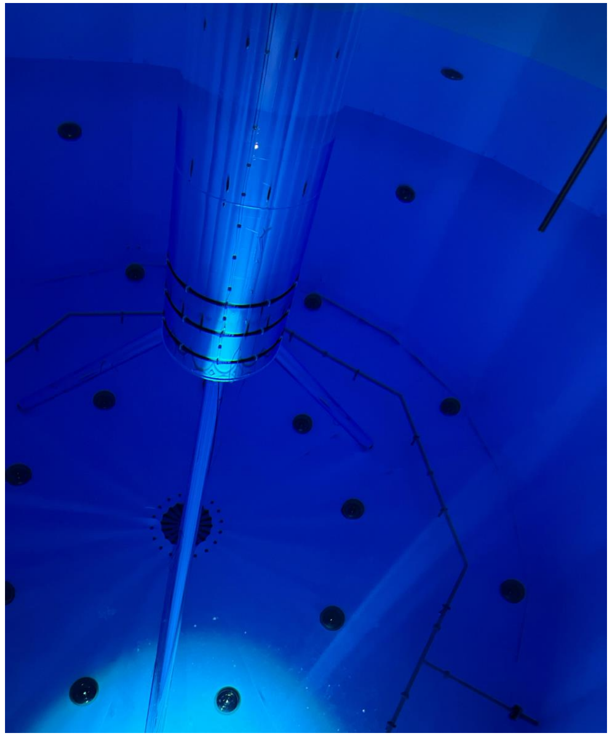
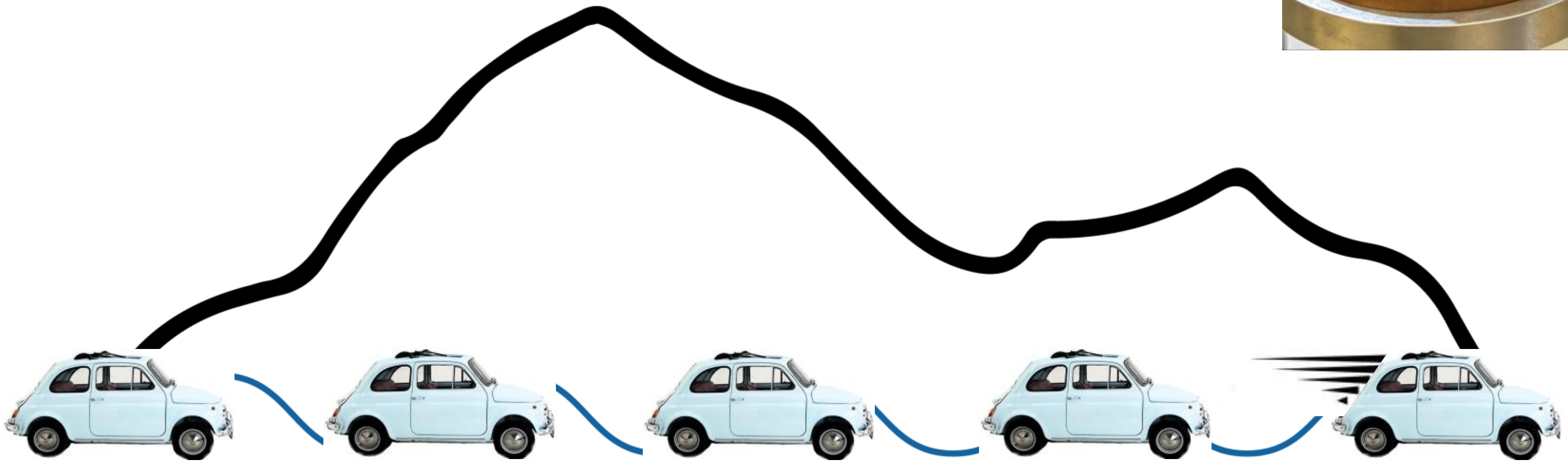
- Particle identification was successfully validated

COSINUS







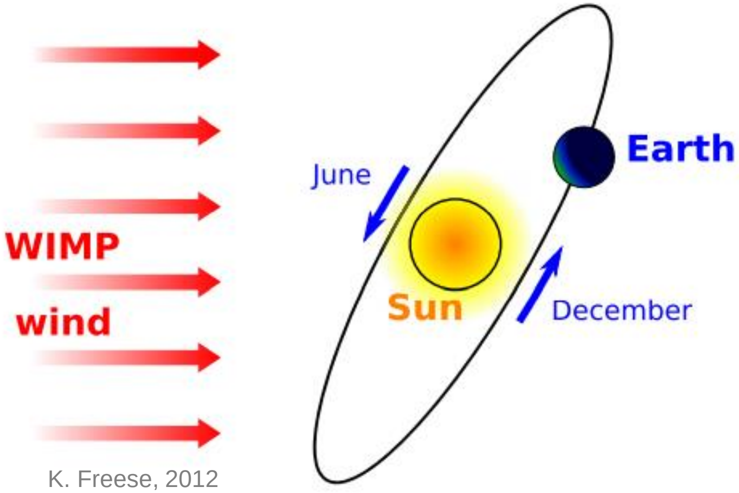


Decoupling | Cabling | Detector Module | Integration | First Run

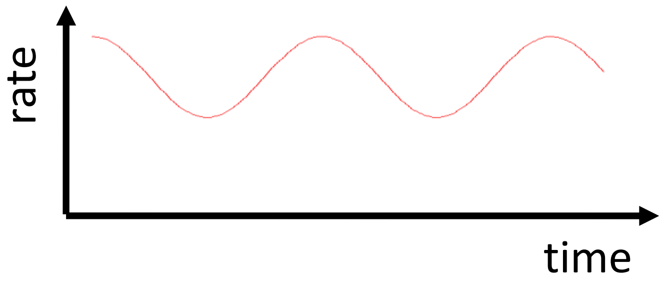
3.2025 → 6.2025 → 10.2025

Thank you!

The annual modulation of dark matter



K. Freese, 2012



- Dark matter (DM) halo around the galaxy
- Particle-like and interacting with standard model particles
- Gravitational and weak force interaction
- Motion of Earth causes a modulation of relative velocities
- Yearly modulation of DM signal

$$\mathbf{v}_{gal}^{det}(t) = \mathbf{v}_{gal}^{\odot} + \mathbf{v}_{\odot}^{det}(t)$$

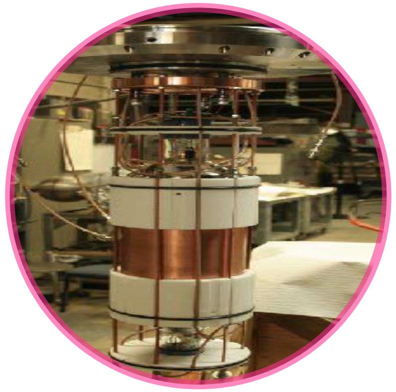
$\rightarrow f(\mathbf{v}_{\chi}^{gal}(t))$ period 1 year

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t-t_0)$$

NaI EXPERIMENTS à la DAMA

*not complete list

COSINUS



DM-Ice

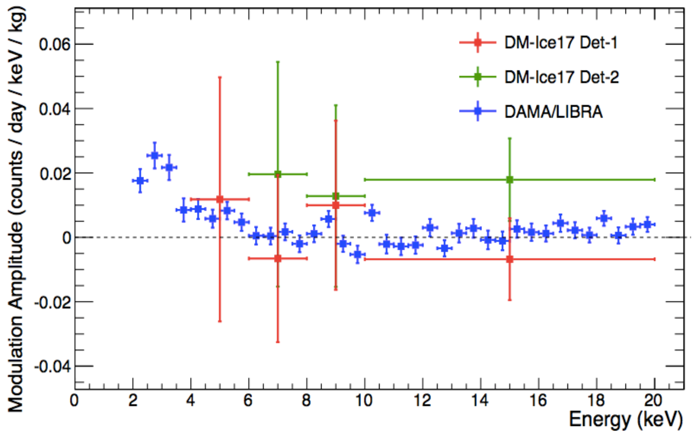
South Pole, 2200 m.w.e of ice
17 kg, 4 keV_{ee}, 3.5 y of data

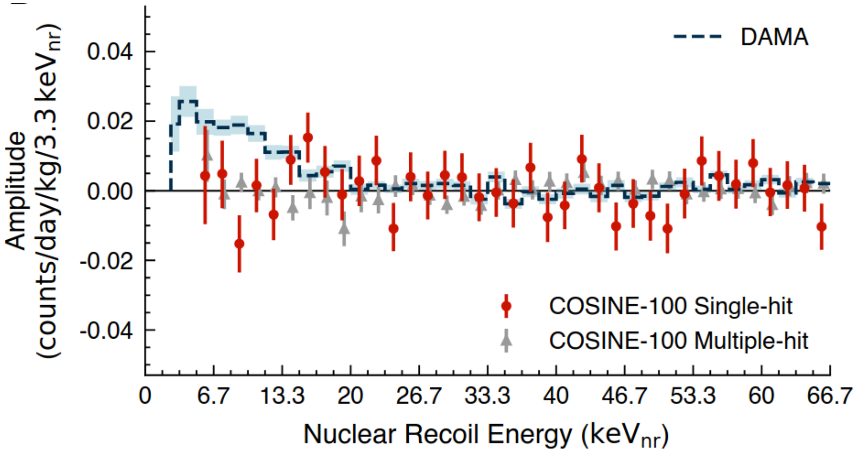
COSINE-100

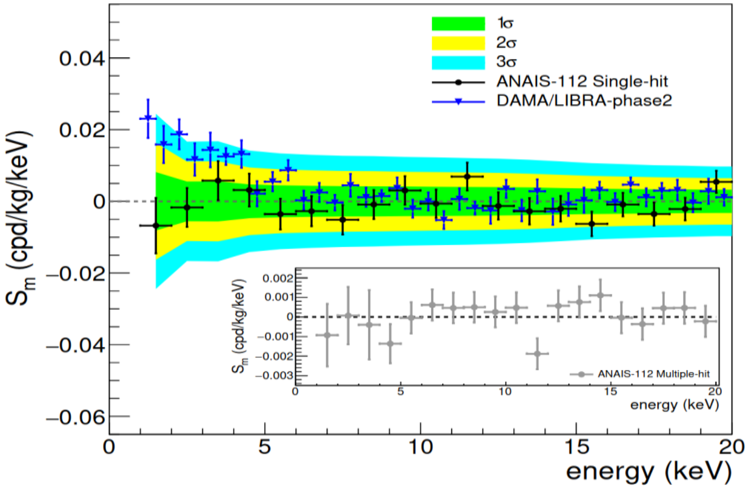
Korea @Y2L, 106 kg, 1 keV_{ee}
6.0 y of data, ~3.6σ

ANAIS-112

Spain @ LSC, 112 kg, <1 keV_{ee}
since 2017, 6 y of data, ~4.2σ







Why a model-independent check is necessary?

DM and target properties | DM interaction model | DM velocity distribution

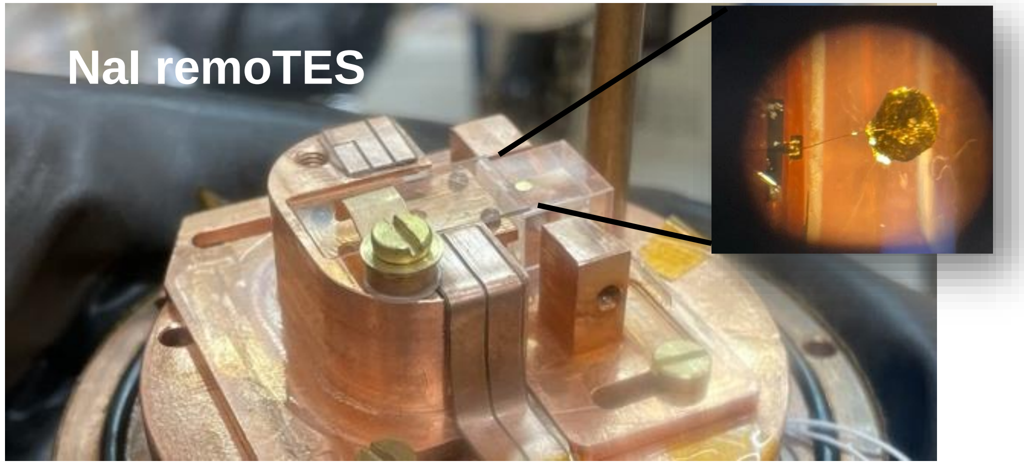
$$\frac{dR}{dE_R} = N_T \frac{\rho}{m_\chi} \frac{\sigma_0 m_T}{2\mu_N^2} \sum_{i,j} \sum_{a,b=0,1} \hat{c}_i^{(a)} \hat{c}_j^{(b)} \left(F_{ij}^{(ab),1}(q) \int \frac{f_{lab}(\vec{v})}{v} d^3v + F_{ij}^{(ab),2}(q) \int v f_{lab}(\vec{v}) d^3v \right).$$

$$\frac{dR}{dE'} = \epsilon(E') \frac{1}{(2\pi)^{1/2}} \int_0^\infty \frac{dR}{dE_R} \frac{dE_R}{dE_{ee}} \frac{1}{\Delta E_{ee}} \exp\left[\frac{-(E' - E_{ee})^2}{2(\Delta E_{ee})^2} \right] dE_{ee}$$

Efficiency/threshold | Number of nuclear recoils | Quenching factor | Resolution

from M.J Zurowski, DSU 2022, Sydney

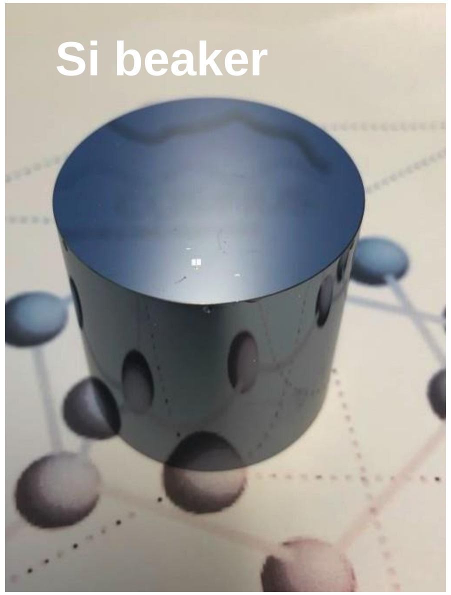
NaI-remoTES – June 2022

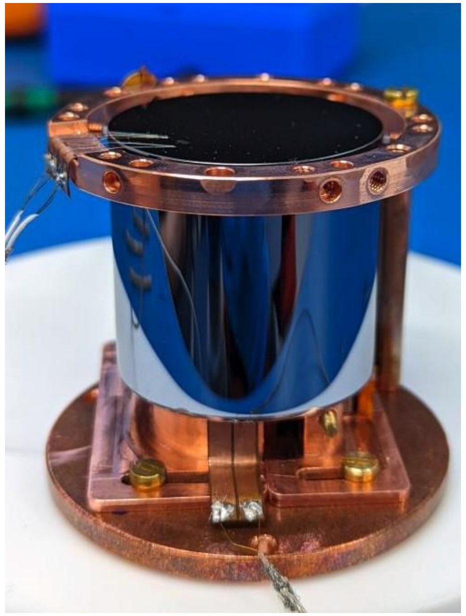


- NaI grown by SICCAS
- dimensions: $10x10x10mm^3$; about 4 g
- Au-foil glued with epoxy
- Au-pad size: 4 mm^2
- TES wafer (Al_2O_3) with W-TES

- Silicon light absorber of beaker-shape
- Dimensions: 40 mm diameter and height, 1 mm thick
- Mass: 15.1 g
- W-TES directly evaporated onto the Si beaker
- TES optimized for light detection

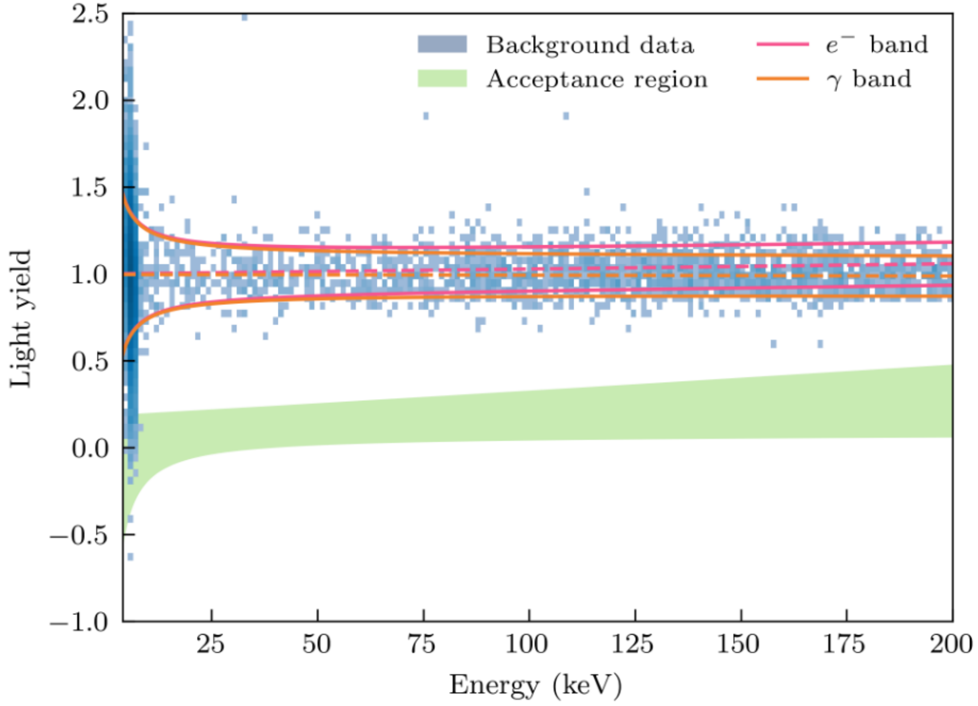
Schäffner et al. 2023, UCLA



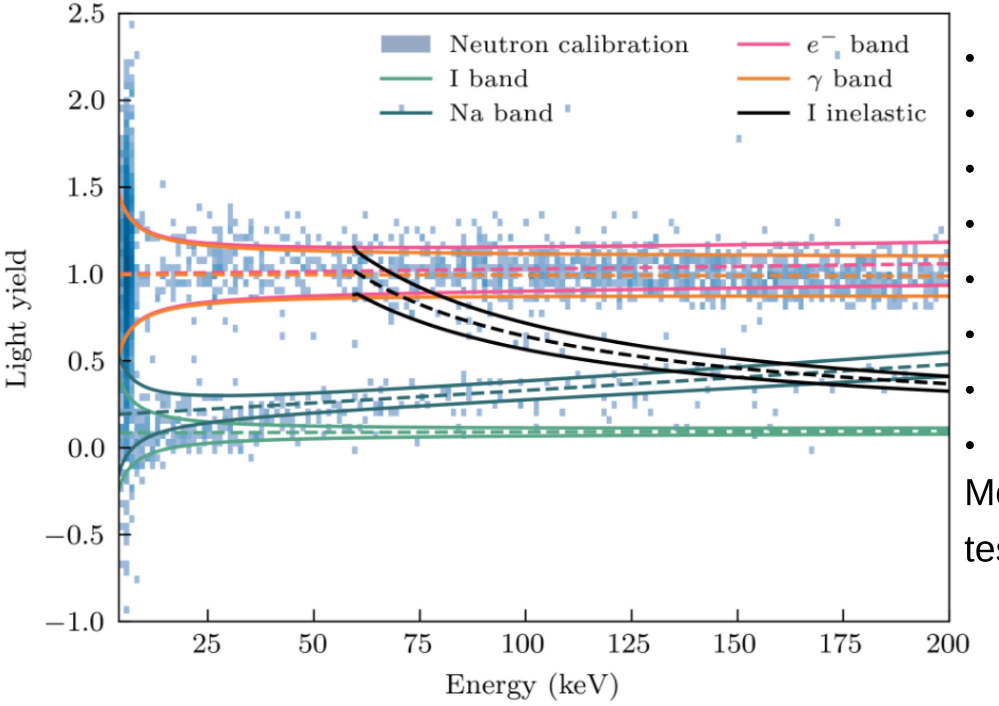


Particle identification in a NaI-based detector

Background Data



Neutron Data



- Background Data 58.07 hours
- σ_{NaI} = 0.441 +/- 0.11 keV
- σ_{LD} = 0.988 +/- 0.052 keV_{ee}
- $\sigma_{LD\text{-}direct}$ = 23.87 +/- 0.55 eV
- Light output NaI: ~ **2.5%**
- Energy calibration with ^{55}Fe & ^{57}Co
- AmBe neutron source 26.0 hours
- **E_{thr} = 4 keV Analysis Threshold**

Measurement carried out at the test facility of CRESST @ LNGS

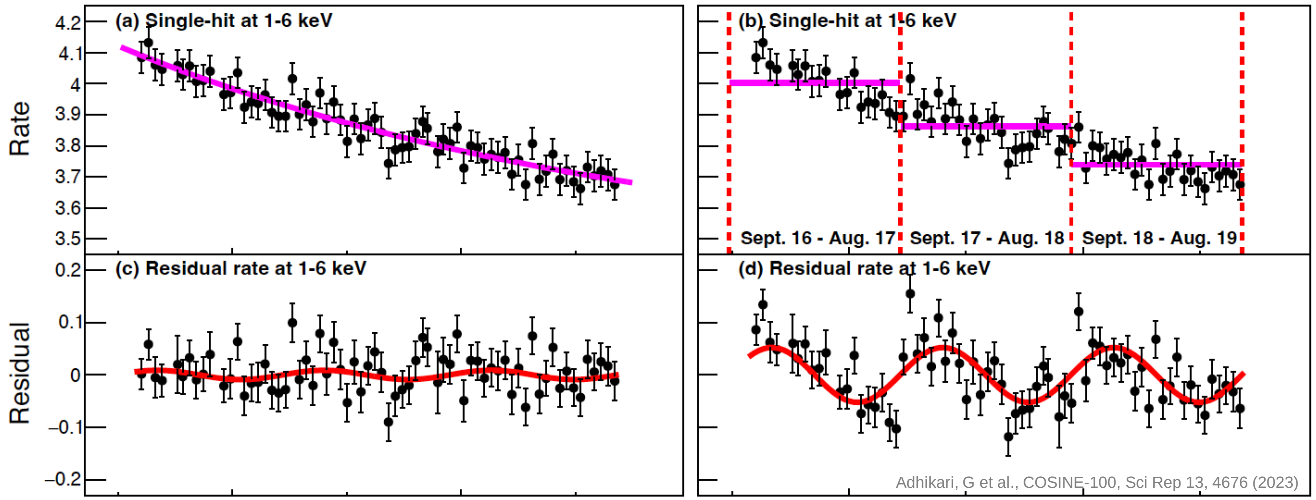
G. Angloher et al. 2024, PhysRevD.110.043010

Background induced modulation effect

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.

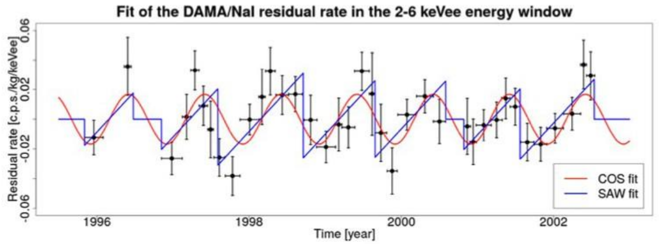
BUT

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

2) wrong by 1pi

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

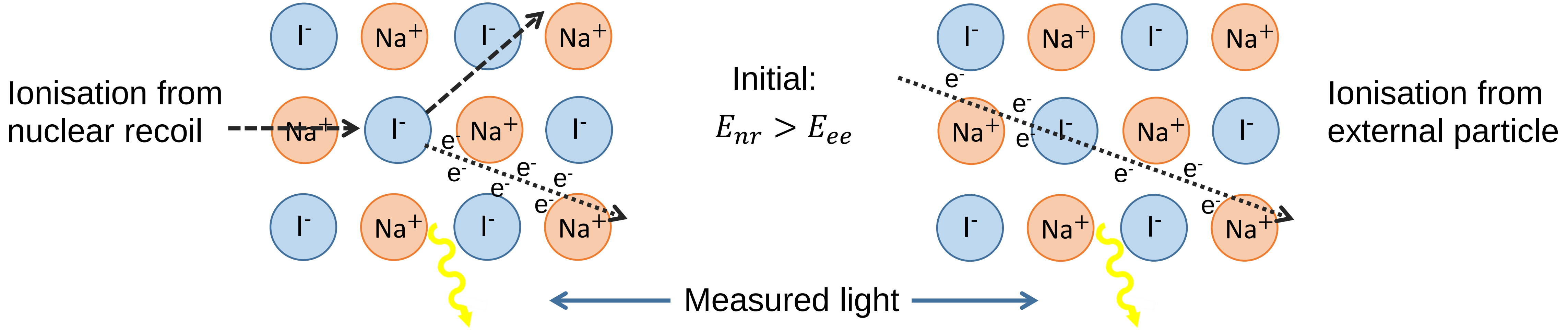
JCAP 04 (2020) 037



Quenching Factor 1

Converts nuclear recoil energy (signal) into electron equivalent energy (used to calibrate detector)

$$\mathrm{QF} = \frac{E_{ee}}{E_{nr}}$$



Motivation:

- Experiment is calibrated with e/γ sources
- QF is determined by calibration with neutron sources
- Conversion to the same energy scale

QF could depend on the :

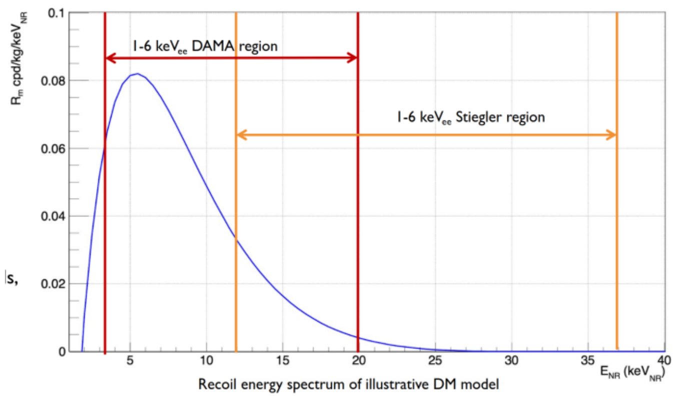
- Optical properties of the crystal
- Growth method
- Tl doping
- Differences in method of measurement

Quenching Factor 2

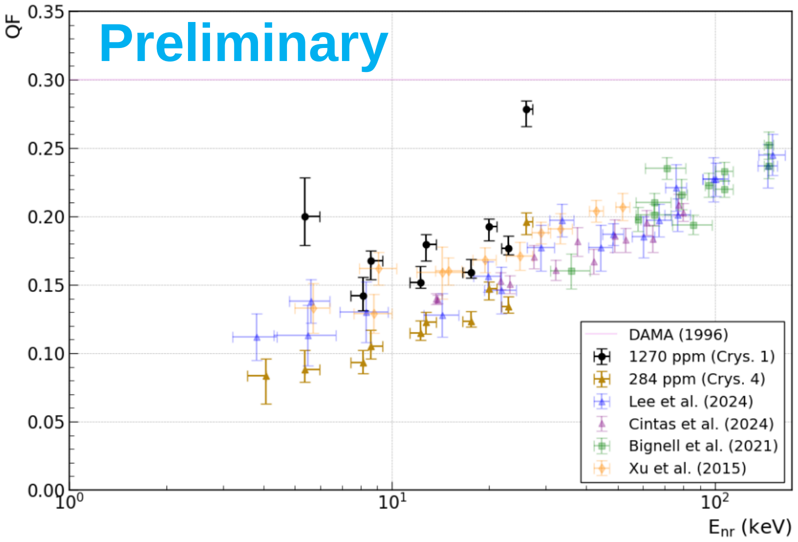
- Electron recoil and nuclear recoil of the same energy produce different intensities of scintillation light within the same target material
- Converts nuclear recoil energy (signal) into electron equivalent energy (used to calibrate detector)

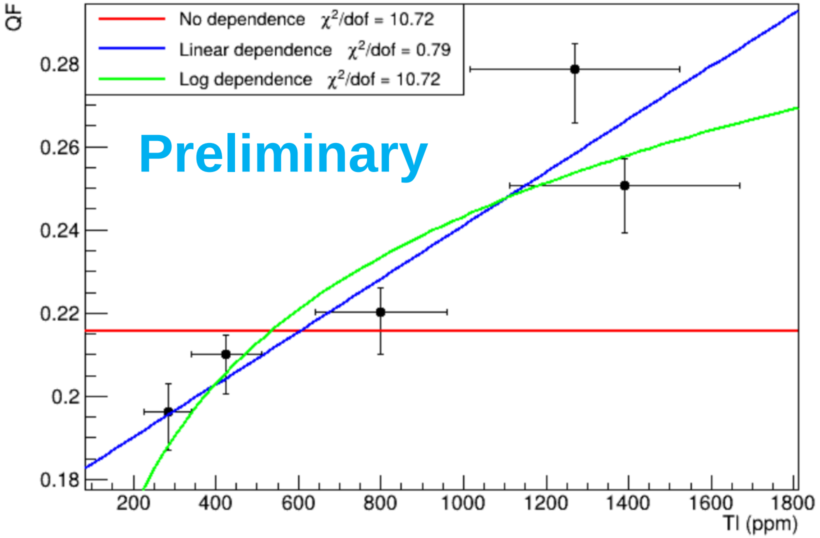
$$\mathrm{QF} = \frac{E_{ee}}{E_{nr}}$$

- Measurements of quenching factor (QF) at room temperature disagree
- Potential dependence on Tl dopant
- Change of QF has a strong impact on observable rate



Plot from M. Zurowski @ IDM 2022



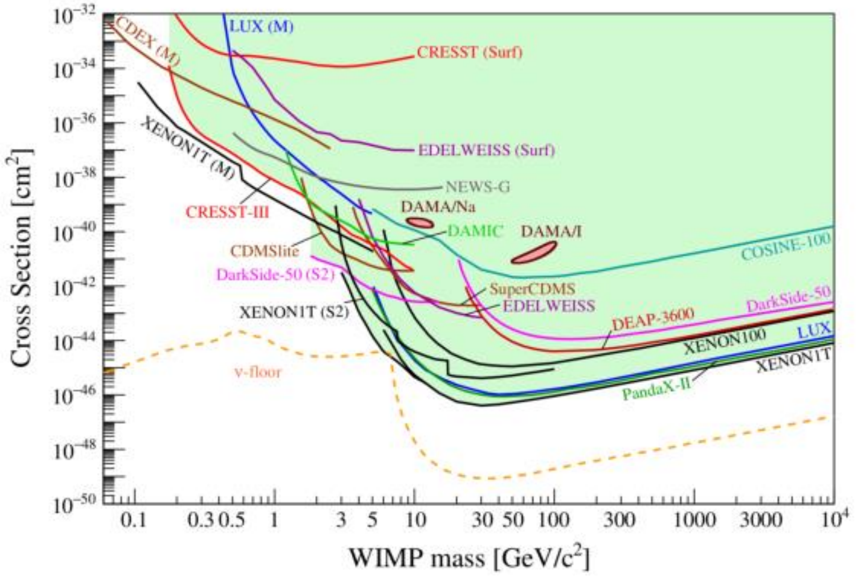


Study of Tl-dopant level on QF @ TUNL facility, Credits to R. Maji

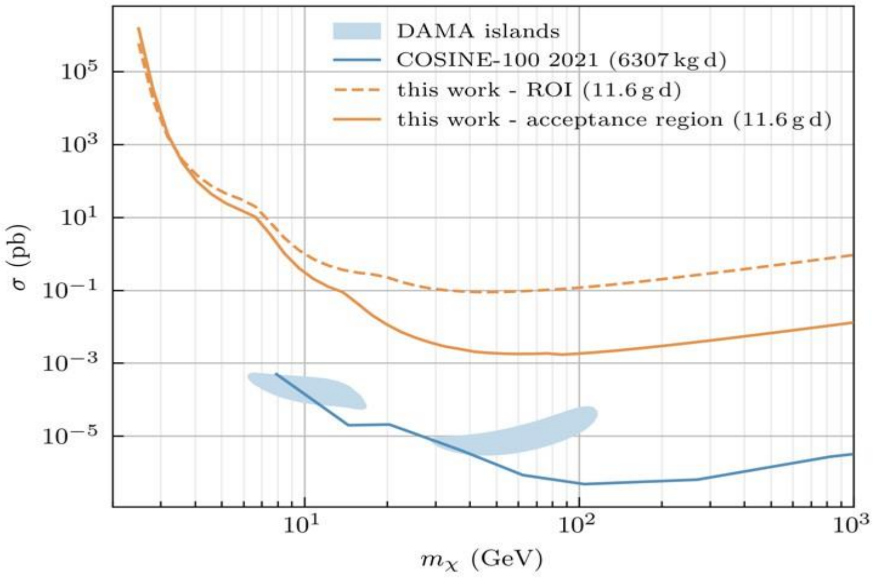
Dark matter limit plot:

COSINUS

COSINUS – FIRST DARK MATTER RESULT



APPEC committee report - Billard, Julien et al , https://cds.cern.ch/record/2764484/plots



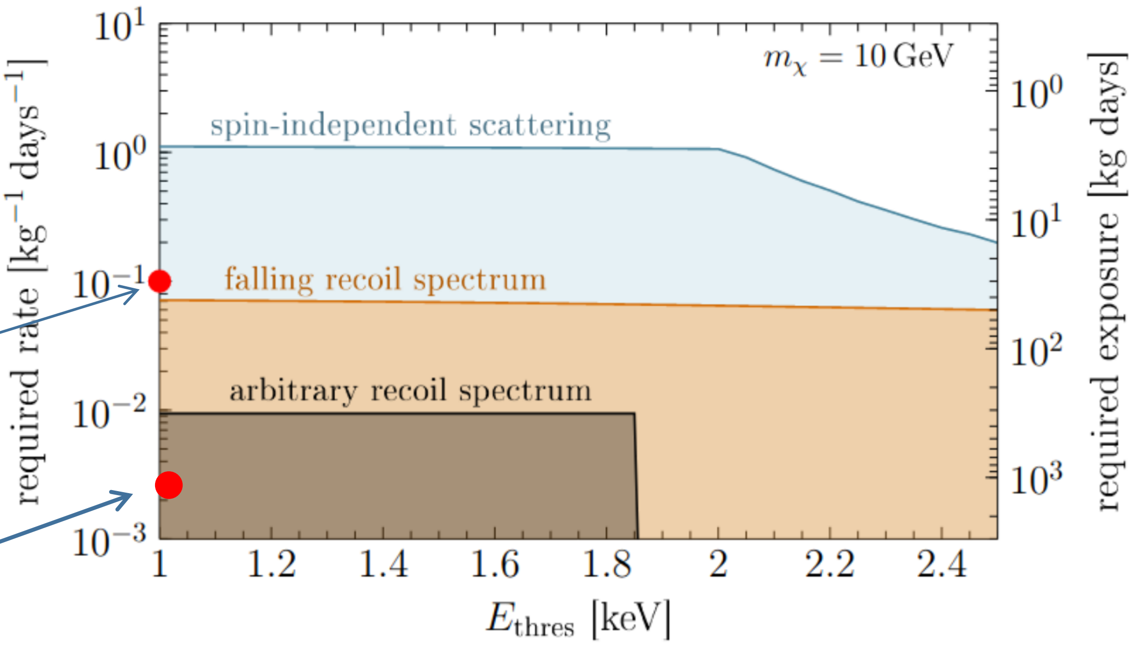
Current status of searches for spin-independent elastic WIMP-nucleus scattering assuming the standard parameters for an isothermal WIMP halo: ρ0=0.3 GeV/cm^3, v0=220 km/s, vesc=544 km/s.

Results labelled "M" were obtained assuming the Migdal effect. Results labelled "Surf" are from experiments not operated underground. The ν-floor shown here for a Ge target is a discovery limit defined as the cross section at which a given experiment has a 90% probability to detect a WIMP with a scattering cross section at ≥3 sigma. It is computed using the assumptions and the methodology described in Billard 2011,Billard 2013, however, it has been extended to very low DM mass range by assuming an unrealistic 1mV threshold below 0.8 GeV/c^2.

Excluded by COSINUS

First COSINUS Run

Second COSINUS Run
with 1000 kg days



RATE vs. MODULATION AMPLITUDE

COSINUS

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

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

COSINUS: $\bar{R} = \frac{1}{2} (R_{max} + R_{min})$

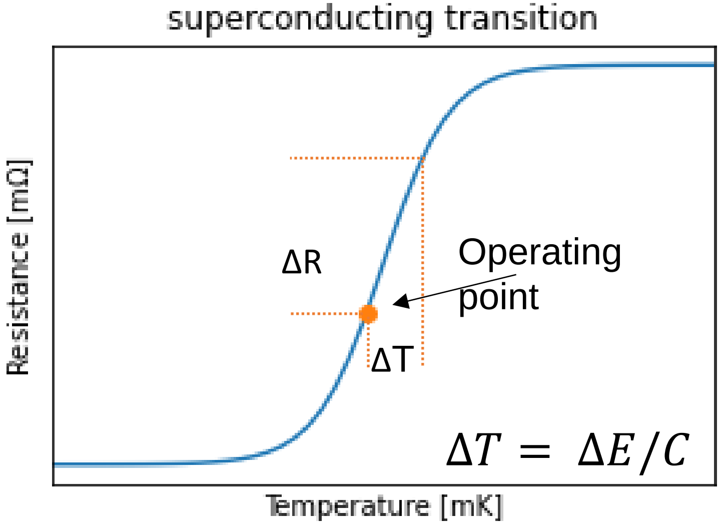
DAMA/LIBRA: $S_m = \frac{1}{2} (R_{max} - R_{min})$

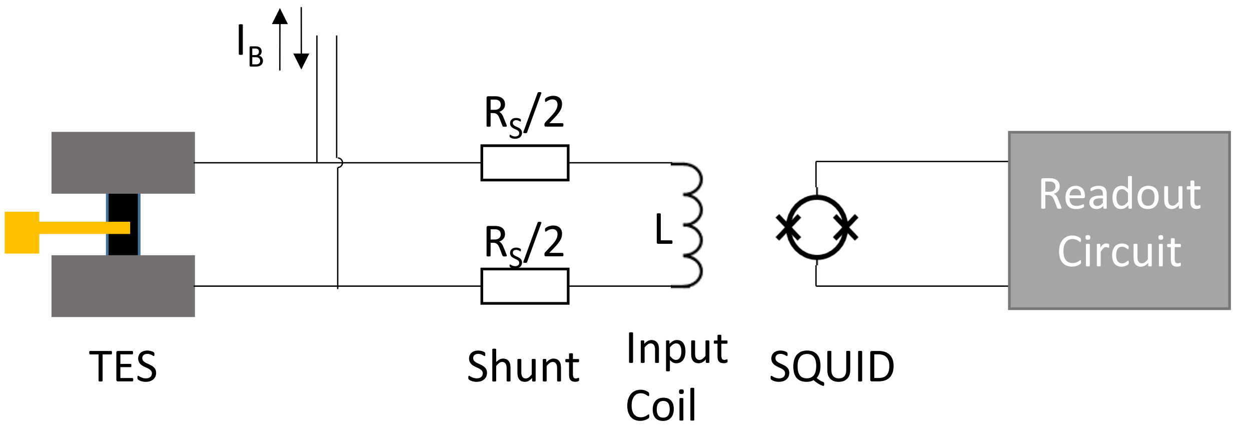
$S_m \leq \bar{R}$

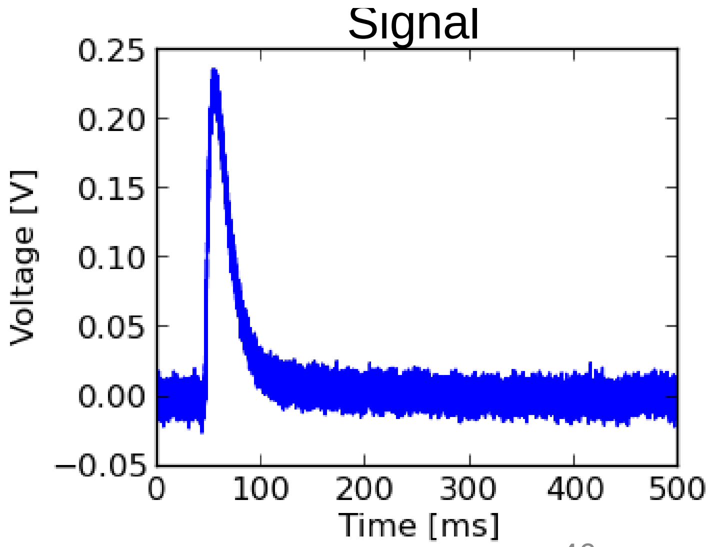
By not measuring any event it disproves a nuclear origin of the signal

Operation of superconducting thermometers

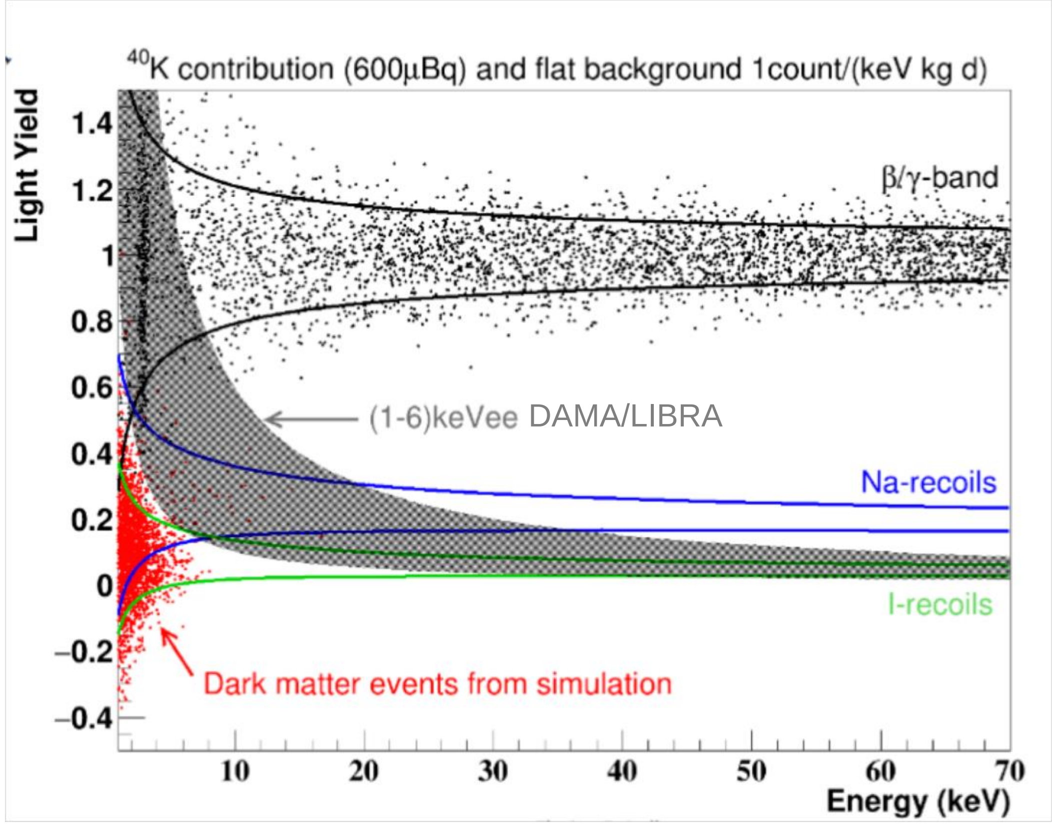
- Measurement of µK-temperature differences with tungsten transition edge sensors (TES)
- Energy deposition leads to change in temperature and thus film resistance
- Electrical readout using "superconducting quantum interference devices" (SQUIDs) as amplifiers

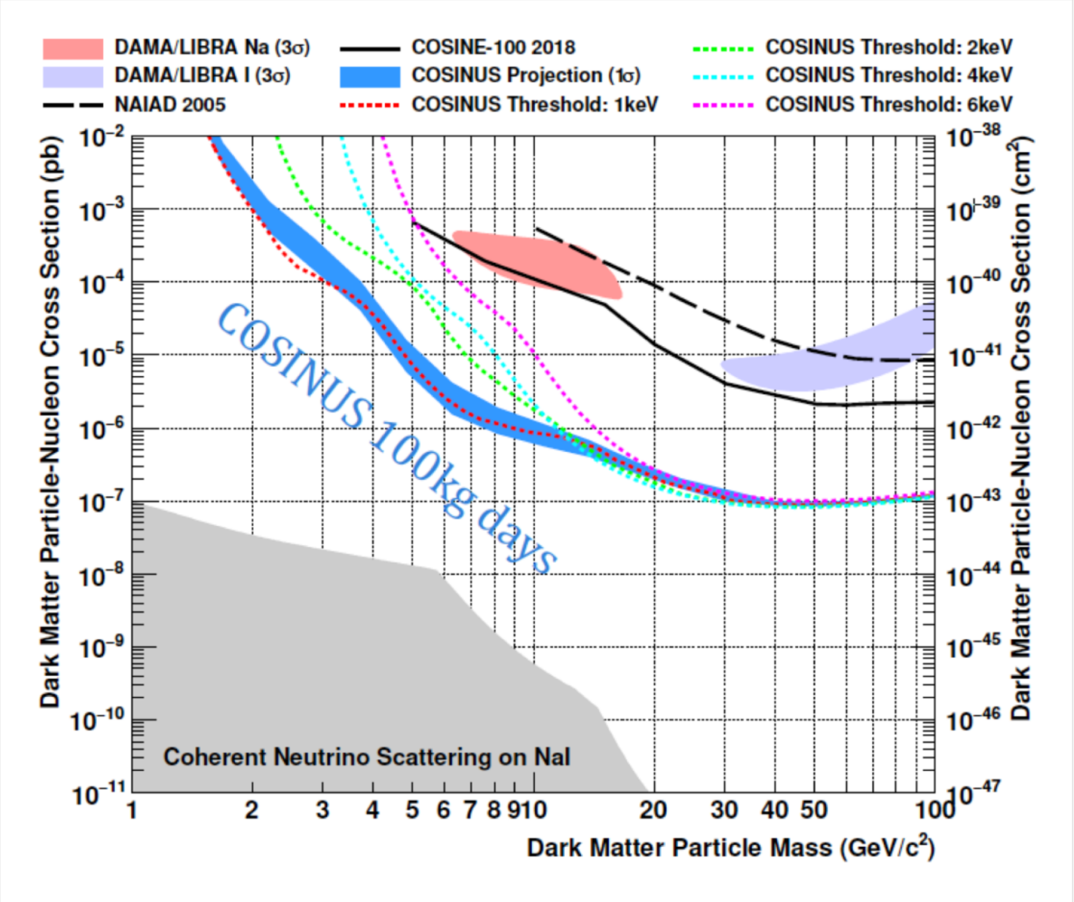






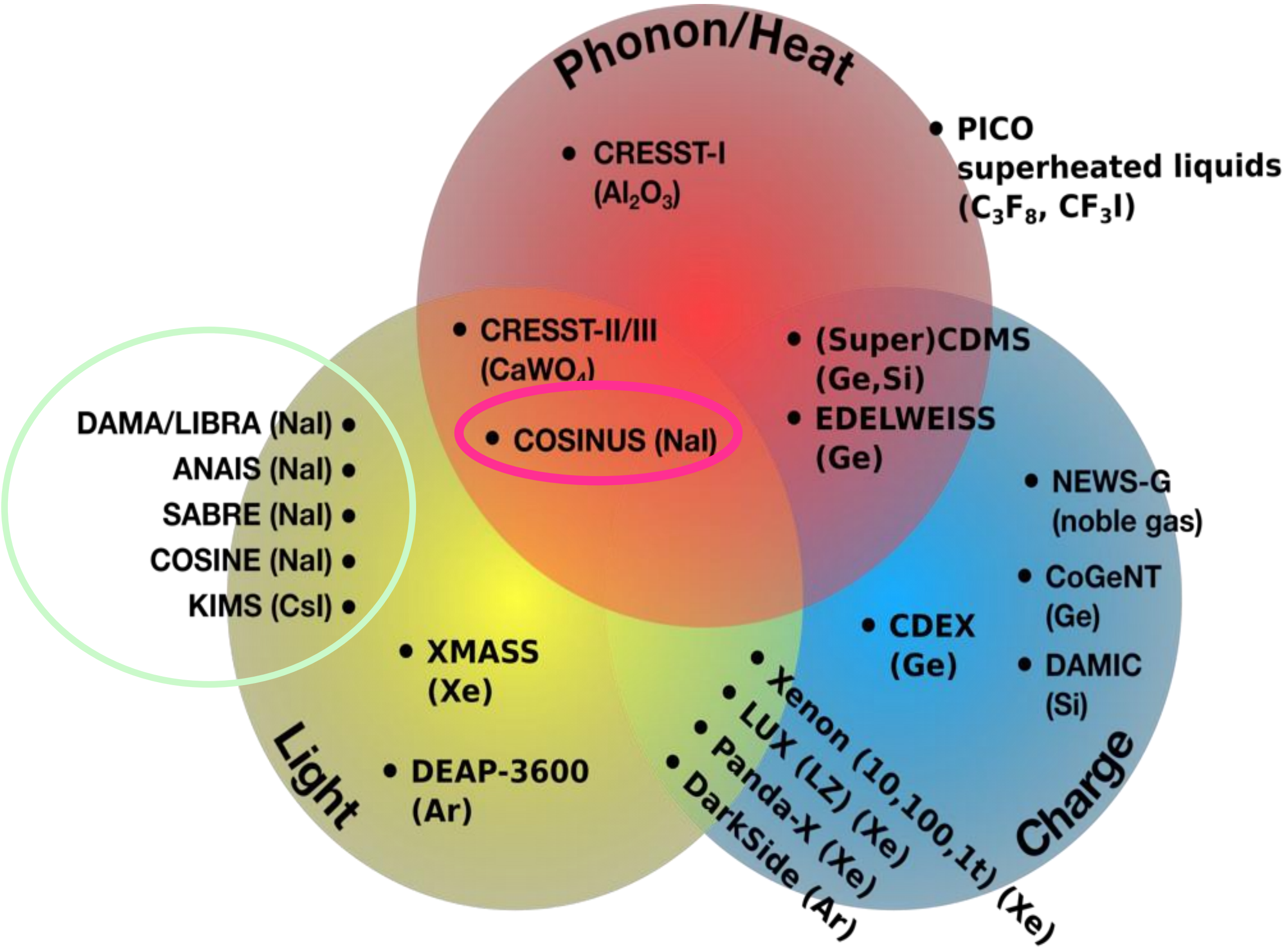
Simulation 100 kg days





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

Experiments:



Credits to: F. Reindl