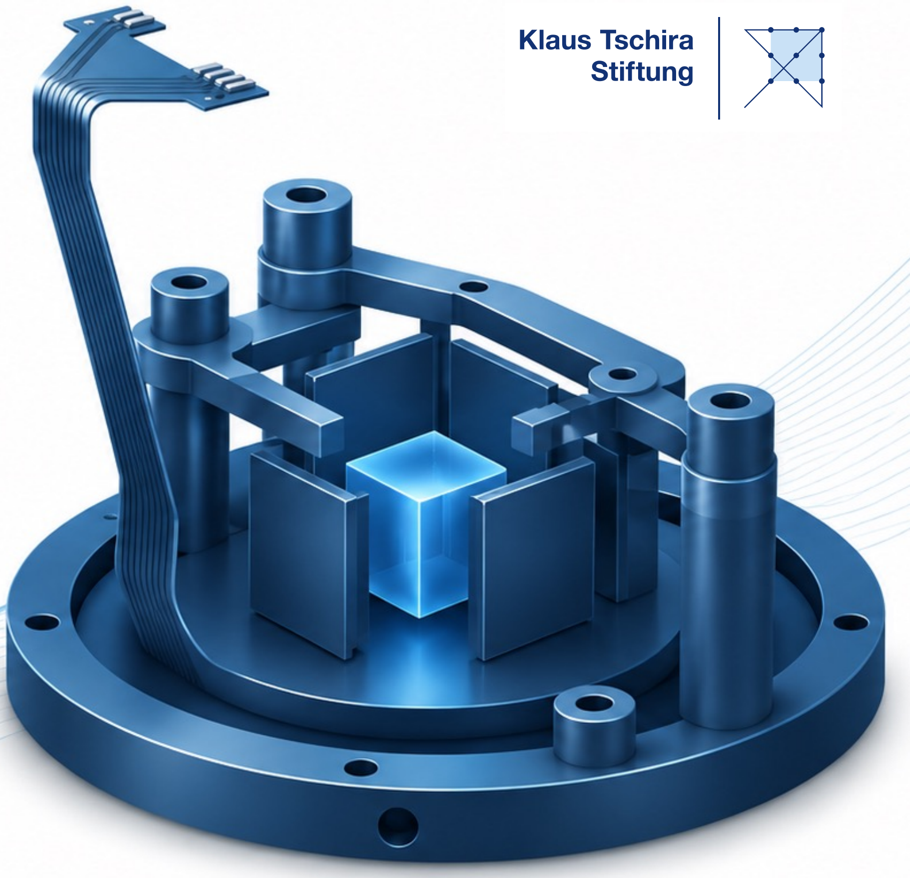
Development of Cryogenic Single-Photon Detectors to Study the Light Output of Sodium Iodide Crystals for Rare Event Searches



Identification of Dark Matter, June 2026

Max-Planck-Institut für Physik

Lutz Ziegele

DAMA/LIBRA Signal

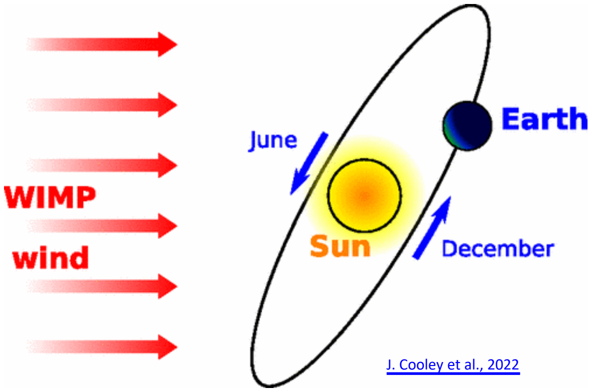
Target material: NaI(Tl)

Detection channel: scintillation light

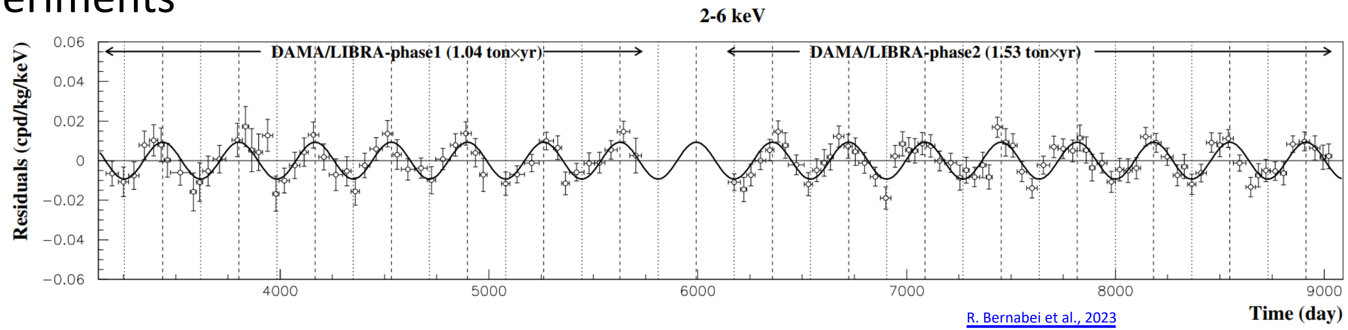
Observation: annual signal modulation compatible with the predicted frequency and phase of a Dark Matter (DM) signal

Statistical significance of observed signal modulation: 13.7σ

Results incompatible with the exclusion results of other experiments



J. Cooley et al., 2022



R. Bernabei et al., 2023

COSINUS Experiment

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

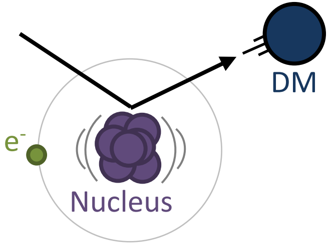
Located at **L**aboratori **N**azionali del **G**ran **S**asso (LNGS) underground laboratory in Italy

Target material: NaI → model independent cross-check of DAMA/LIBRA result

Operates NaI crystals as cryogenic calorimeters at temperatures $\mathcal{O}(15\ \mathrm{mK})$

Observable: nuclear recoils

- Talk by Mariano Cababie on the COSINUS Experiment



Transition Edge Sensor (TES)

COSINUS

COSINUS-TES: tungsten thin film operated in its superconducting phase transition

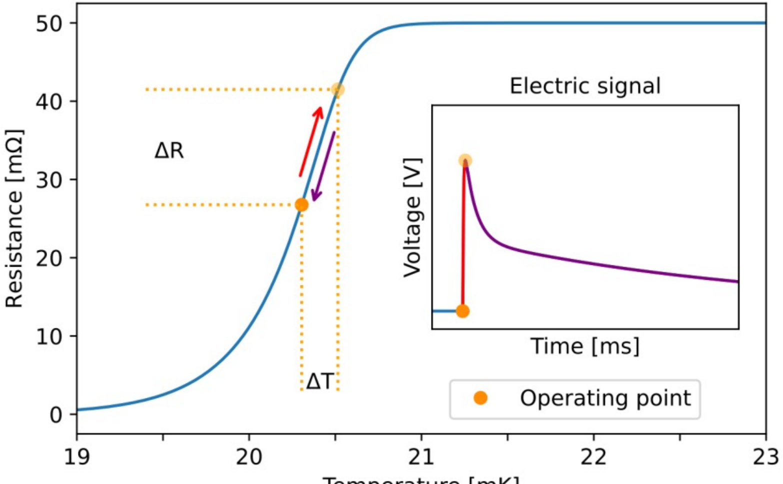
Developed and manufactured by CRESST at Max-Planck-Institut für Physik

CRESST
Cryogenic Rare Event Search with Superconducting Thermometers
CRESST (online: accessed on Dec. 4th, 2025)

Dependence of electrical resistance on temperature

Signal generation process:

1. A particle interaction deposits energy in the absorber
2. Temperature increase in tungsten film $\mathcal{O}(\mu\mathrm{K})$
3. Measureable resistance change $\mathcal{O}(\mathrm{m}\Omega)$
4. Record a pulse-like signal in voltage stream of readout circuit



M. Kellermann, 2025

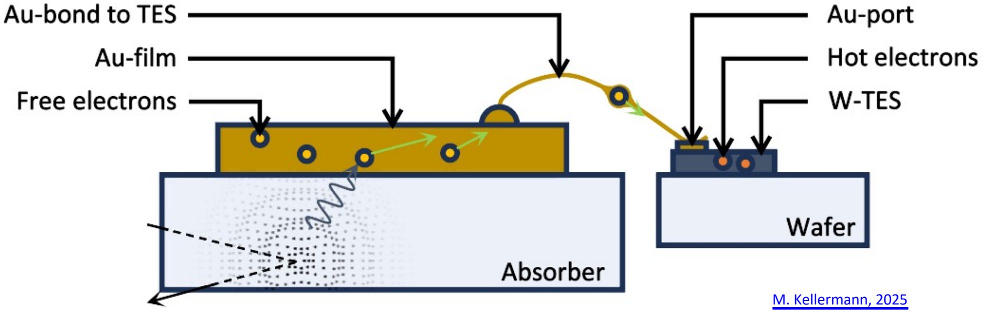
Phonon Signal Detection

NaI crystals: hygroscopic, soft and have a low melting point

➢ Direct TES fabrication onto the crystal surface is not possible using standard protocols

remoTES:

- TES sensor on separate wafer
- Interaction in the absorber generates phonons
- Phonons propagate into deposited metal film on the crystal surface
- Phonons transfer their energy to electrons (electron-phonon coupling)
- Electrons diffuse to the tungsten film of the remoTES → detection of phonon signal



M. Kellermann, 2025

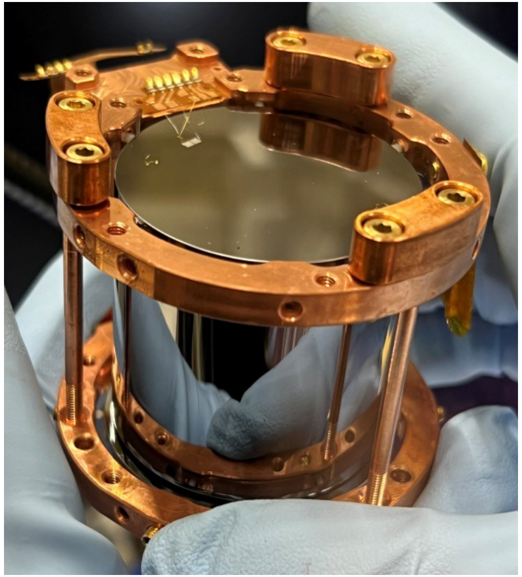
➢ Poster by Martin Stahlberg on optimizations of remoTES sensors

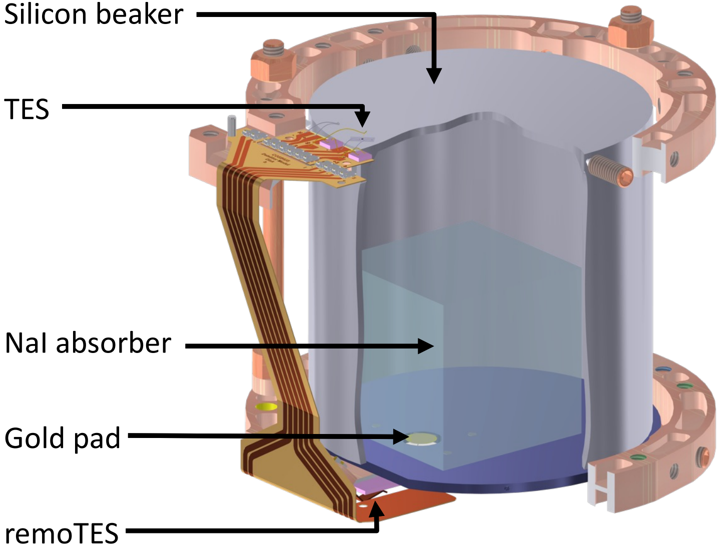
➢ Poster by Kilian Heim on optimization of gold connection from remoTES to absorber

Dual-Channel Readout

NaI crystal equipped with remoTES → phonon signal

TES-equipped silicon beaker surrounding the crystal → scintillation light





M. Kaznacheeva, 2024

Event-by-Event Background Discrimination

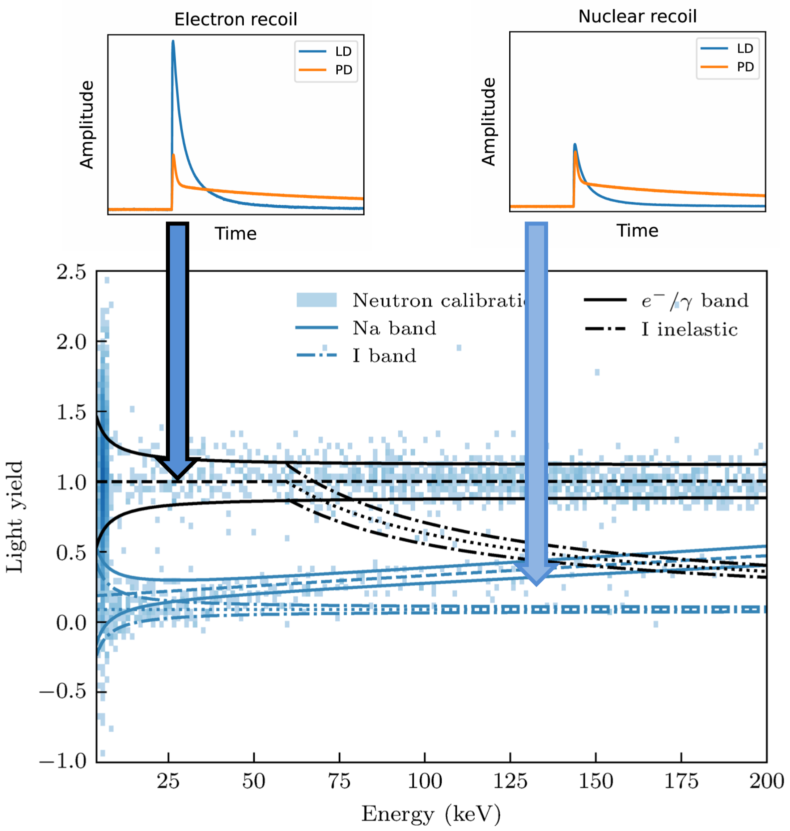
COSINUS

From the amplitude ratio of the two signals electron and nuclear recoils can be discriminated

Light yield: $\mathrm{LY} = \frac{E_{\mathrm{light}}}{E_{\mathrm{phonon}}}$

Nuclear recoil events and electronic interactions accumulate in separate bands

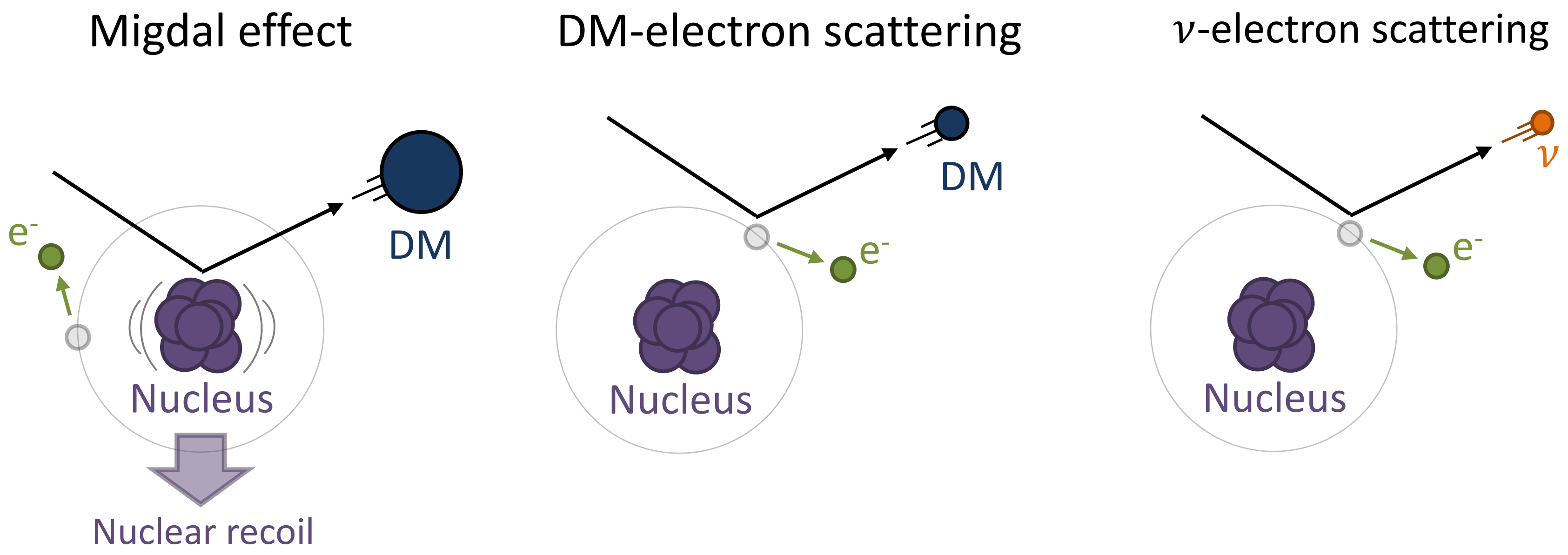
In-situ quenching factor measurement



G. Angloher et al., 2025

0νDES Research Goals

Klaus Tschira Stiftung
0νDES



Interactions cause electronic excitations or ionization

Observable: one or multiple scintillation photons from the following relaxation

OνDES Project

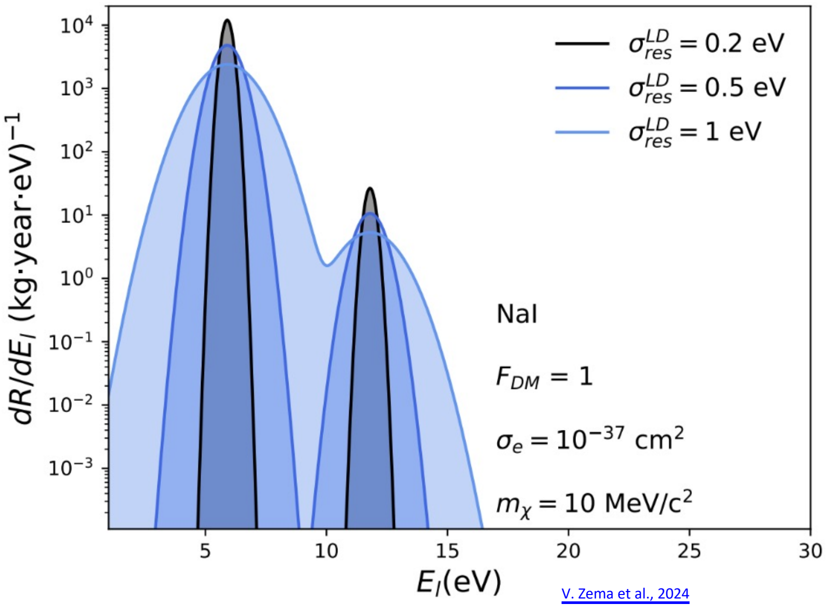
Observatory for **N**eutrino and **D**ark matter **E**lectron **S**cattering (OνDES)

- ➢ Employing TES-based cryogenic scintillating calorimeters for DM, neutrino and Migdal investigations

Expected signal from electronic recoils:

1. Electrons get excited or ionized
2. Emission of one or multiple photons with energies of the material-specific band gap
3. Distinct peaks in low-energy light spectrum

NaI band gap (at $T \sim 15$ mK): $(3 - 6)$ eV



V. Zema et al., 2024

OνDES Project

Klaus Tschira Stiftung

OνDES

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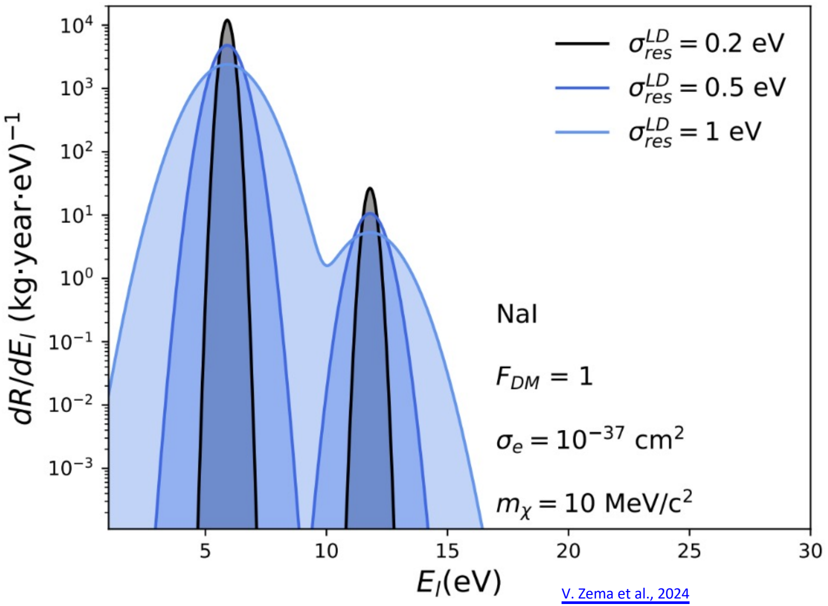
LD requirements:

- eV/sub-eV resolution to resolve peaks
- High light collection efficiency



V. Zema et al., 2024

Technical Implementation

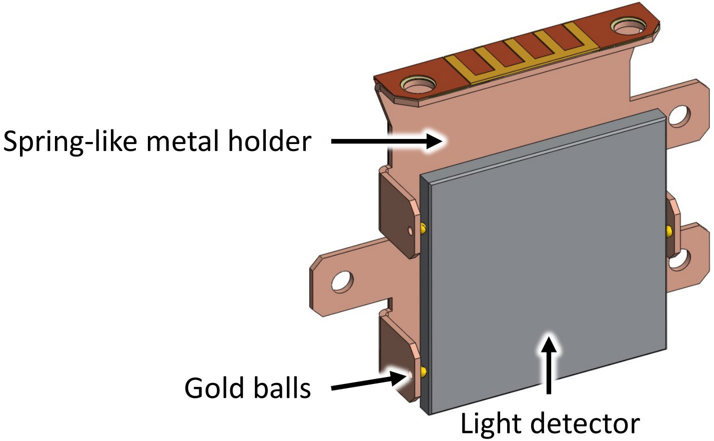
COSINUS

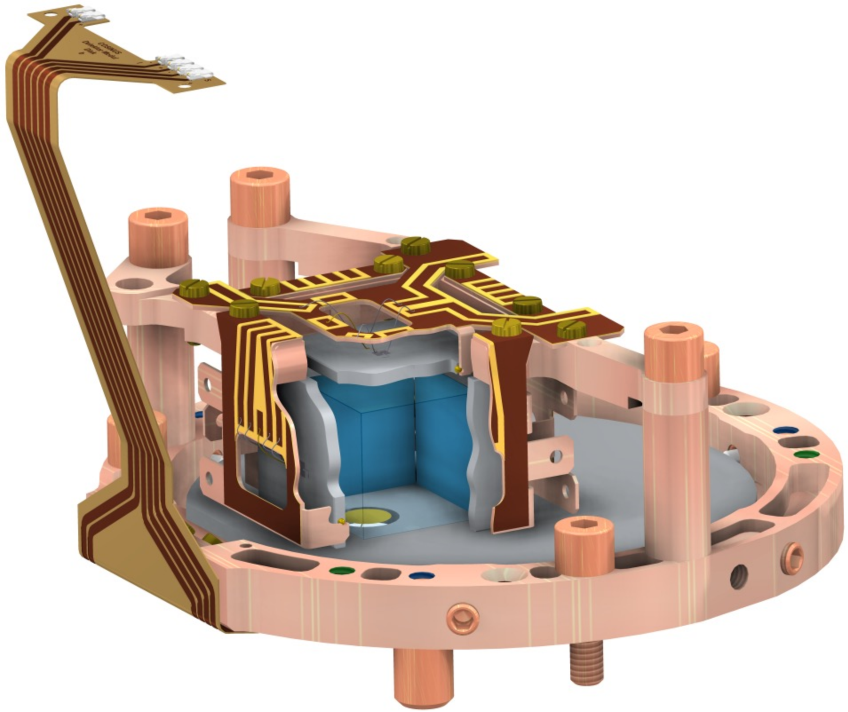
Based on detector concept proposed by [V. Zema et al. (2024)]

"NaIM" module consisting of:

- $1\times$ NaI crystal: $(10\times10\times10)\ \mathrm{mm}^3$
- $5\times$ Si light detectors: $(12\times12\times1)\ \mathrm{mm}^3$

Low-stress mounting of light detectors:





Proof-of-Principle Prototype

COSINUS

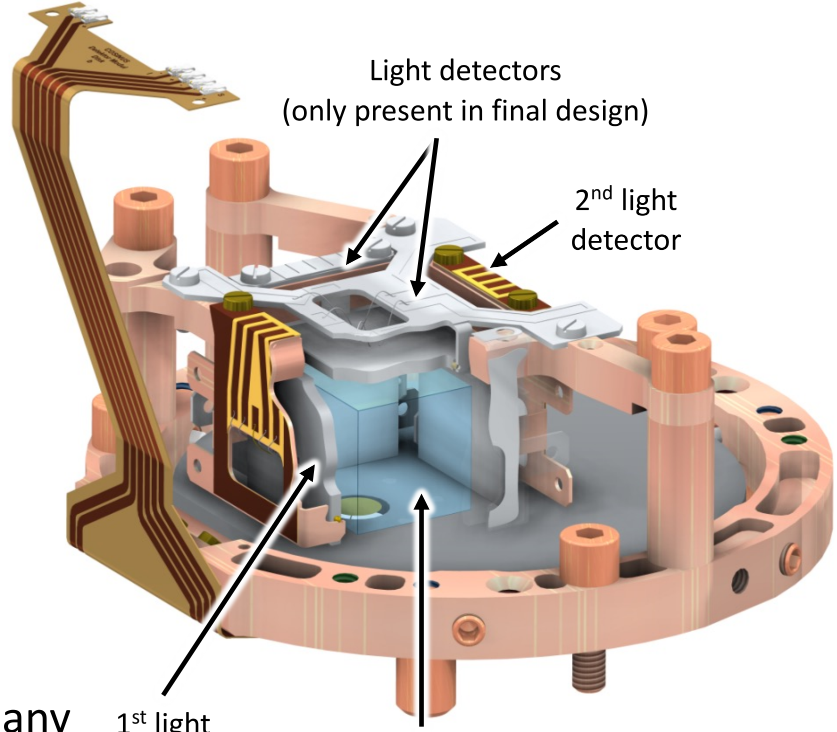
Proof-of-principle prototype:

- 1 x NaI crystal: $(10\times10\times10)\ \mathrm{mm}^3$
- 2 x Silicon On Sapphire (SOS)
  light detectors: $(12\times12\times0.4)\ \mathrm{mm}^3$
- 3 x ^{55}Fe calibration sources

Sensors manufactured by the CRESST group
at Max-Planck-Institut für Physik

- One light detector being a CRESST-III spare detector for RUN37 ([Low Temp Phys 193, 1160-1166 (2018)])

Measured in COSINUS above-ground cryostat at
Max-Planck-Institut für Physik in Garching, Germany



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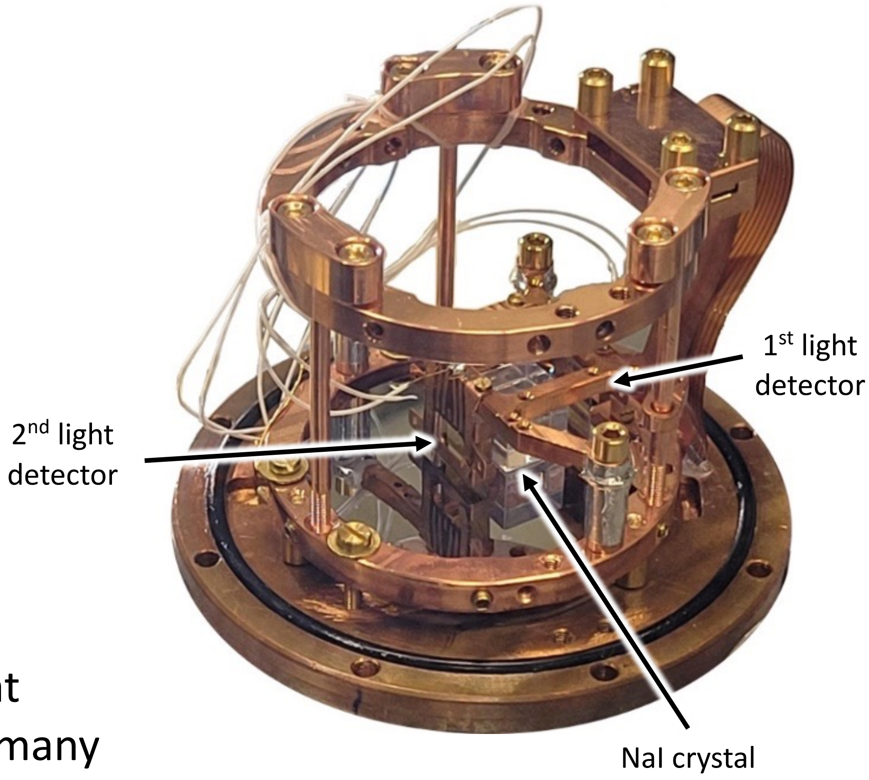
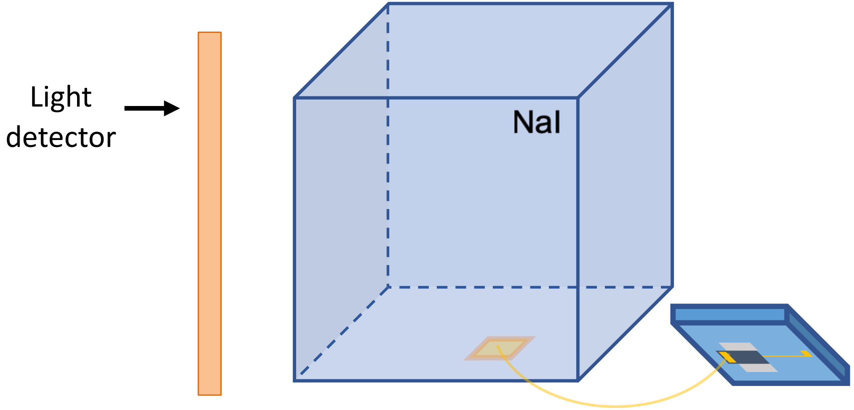


Expected Signal in Prototype

^{55}Fe calibration sources: dominant emission line at $5.9\ \mathrm{keV}$



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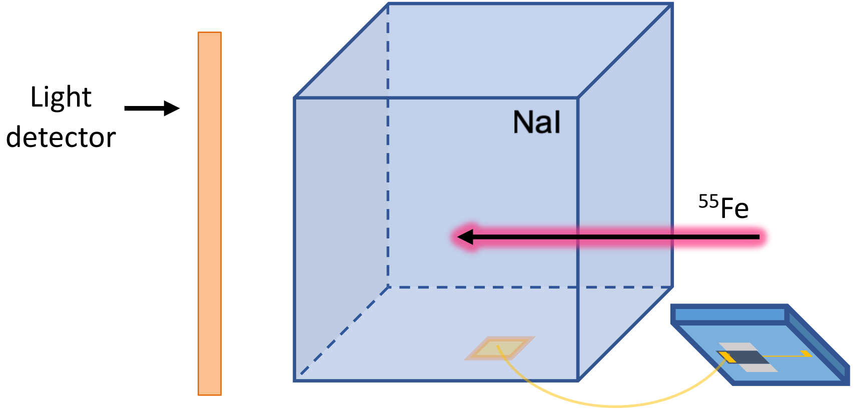

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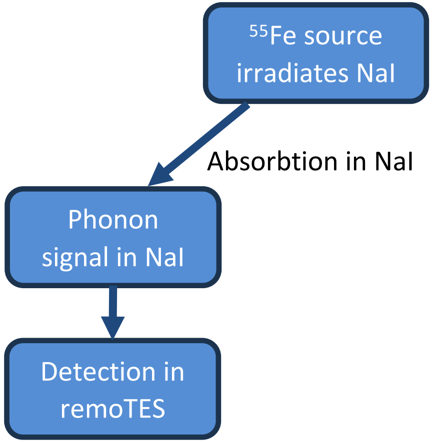
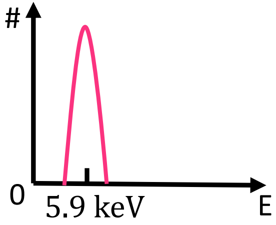
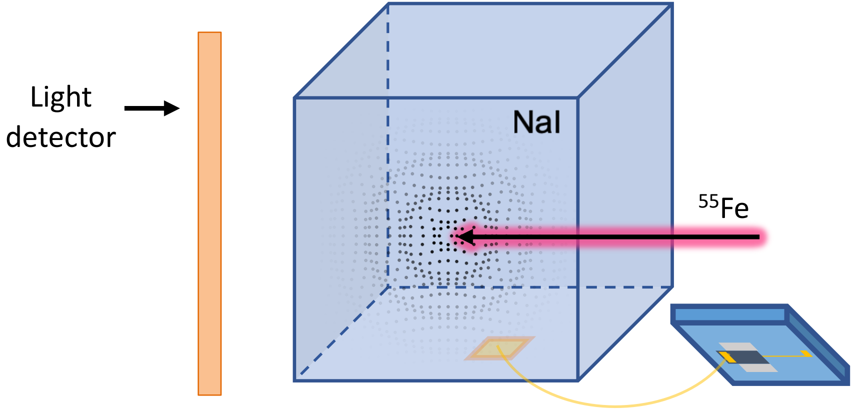


NaI phonon spectrum





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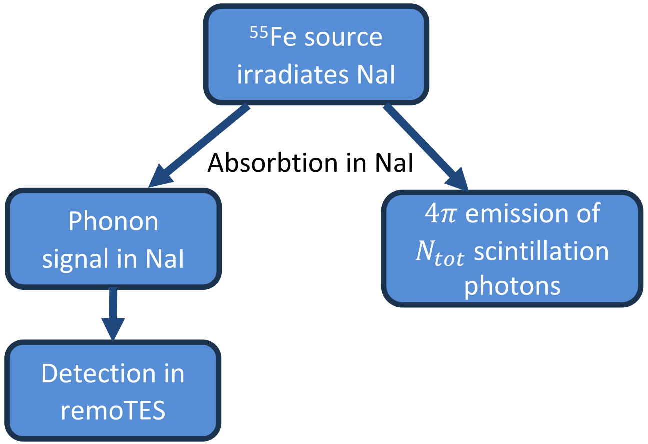

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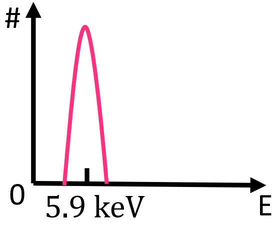

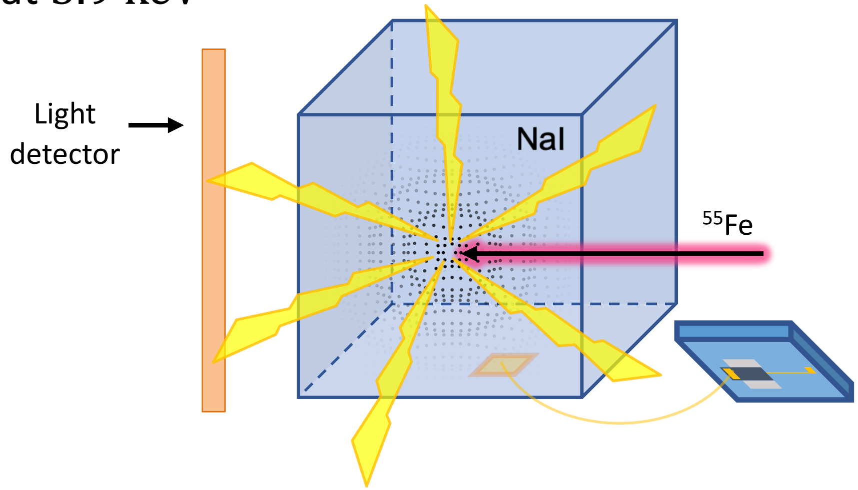

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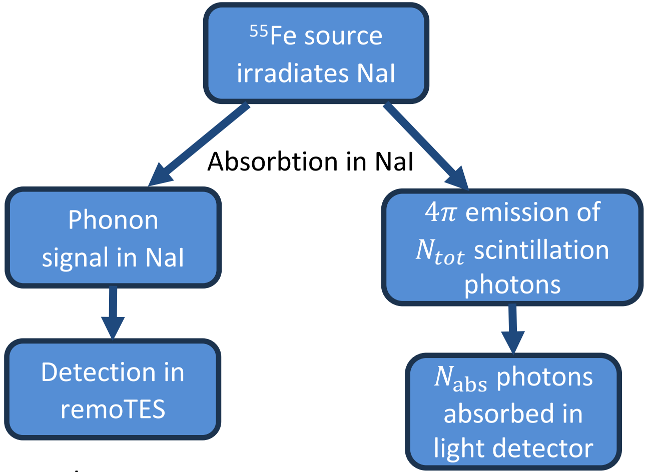
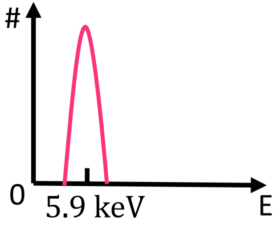
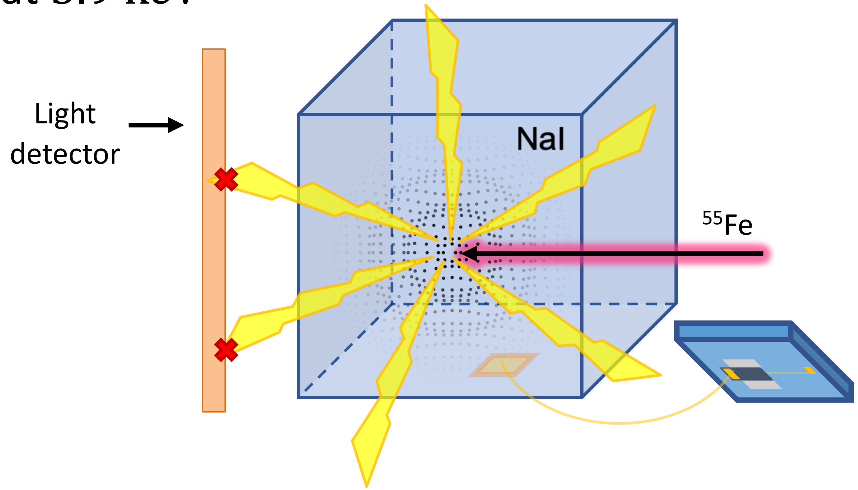


NaI phonon spectrum





Expected Signal in Prototype

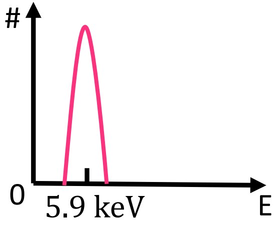
^{55}Fe calibration sources: dominant emission line at 5.9 keV

^{55}Fe source irradiates NaI

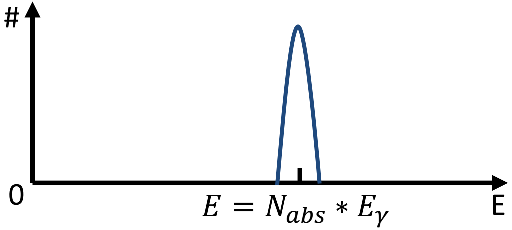
Absorbtion in NaI

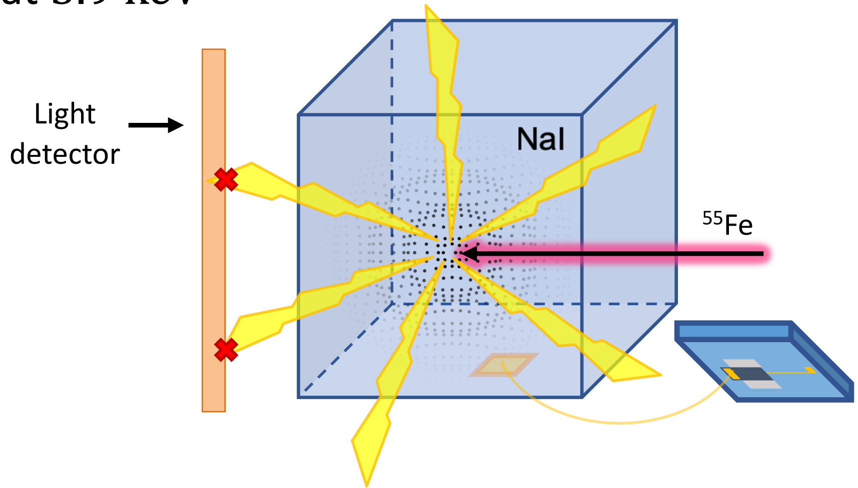
- Phonon signal in NaI → Detection in remoTES
- 4π emission of N_{tot} scintillation photons → N_{abs} photons absorbed in light detector → Peak in light spectrum $E = N_{abs} * E_\gamma$

NaI phonon spectrum



Spectrum in one light detector



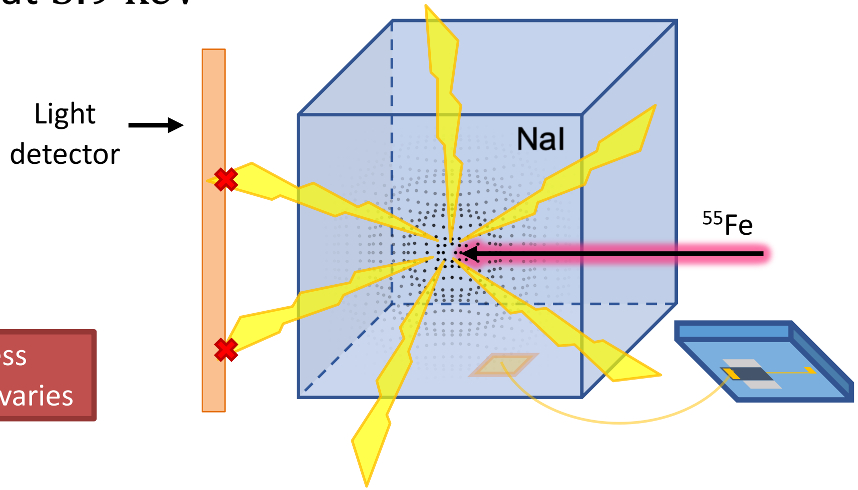


Expected Signal in Prototype

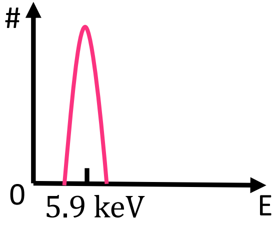
^{55}Fe calibration sources: dominant emission line at 5.9 keV

- ^{55}Fe source irradiates NaI
  - Absorbtion in NaI
  - Phonon signal in NaI → Detection in remoTES
  - 4π emission of N_{tot} scintillation photons **!** → N_{abs} photons absorbed in light detector **!** → Peak in light spectrum $E = N_{abs} * E_\gamma$

Statistical process
➢ Photon number varies



NaI phonon spectrum



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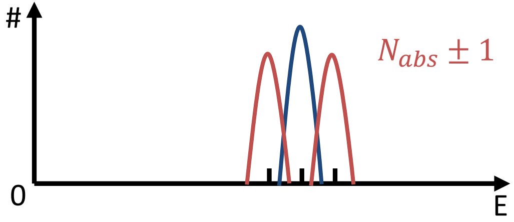

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Absorbtion in NaI

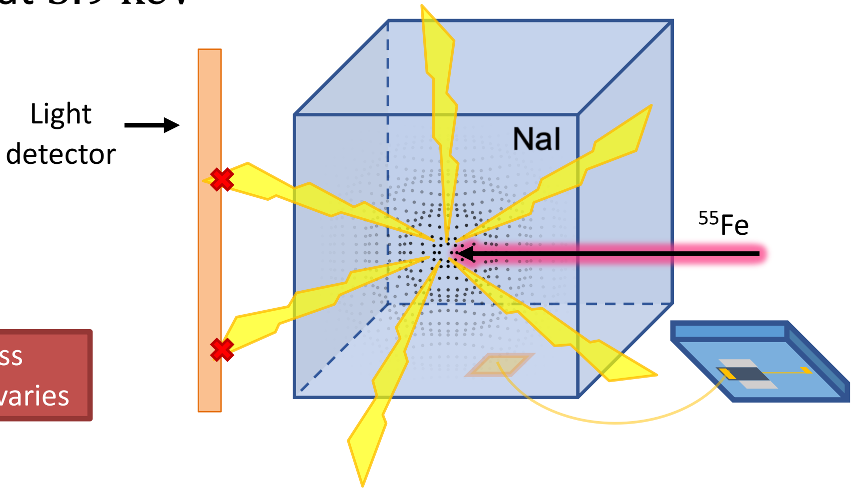
Phonon signal in NaI

Detection in remoTES

4π emission of N_{tot} scintillation photons

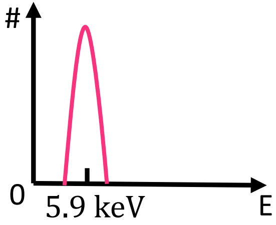
N_{abs} photons absorbed in light detector

Peak in light spectrum $E = N_{abs} * E_\gamma$

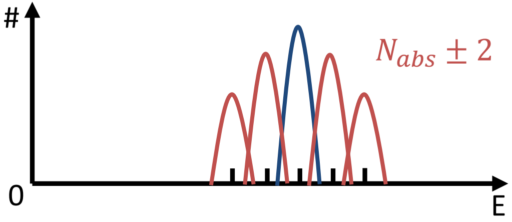


Statistical process
➢ Photon number varies

NaI phonon spectrum



Spectrum in one light detector



➢ Resulting total spectrum is a **Poissonian distribution**

Expected Signal in Prototype

COSINUS

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^{55}Fe source irradiates NaI

Absorbtion in NaI

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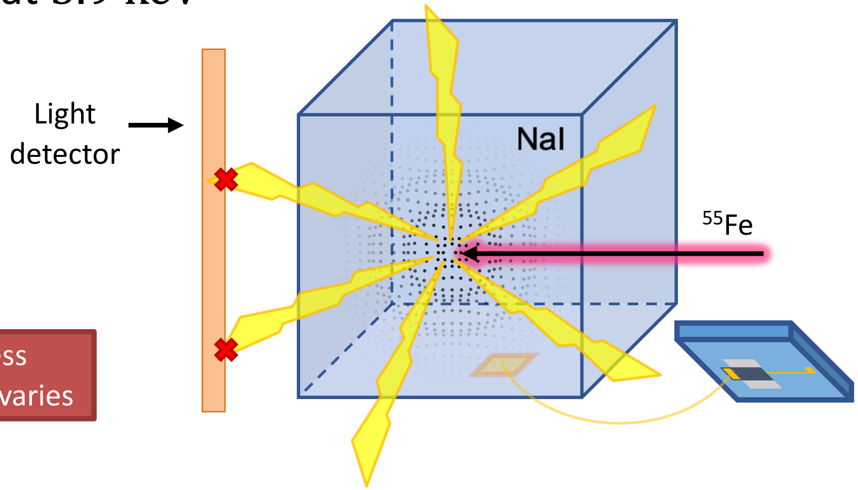

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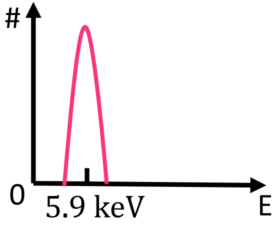
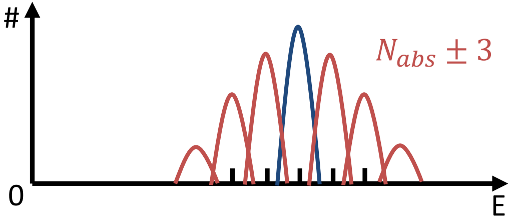


Spectrum in one light detector



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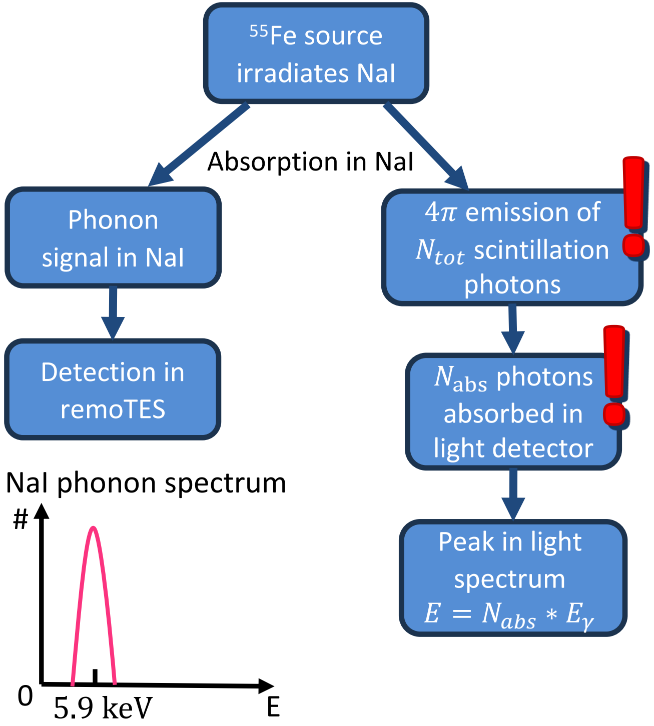
Expected Signal in Prototype

^{55}Fe calibration sources: dominant emission line at 5.9 keV



Statistical process
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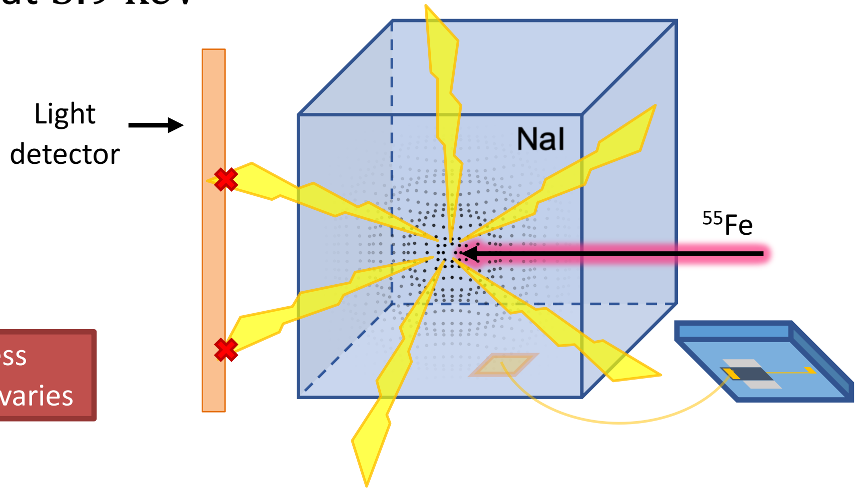

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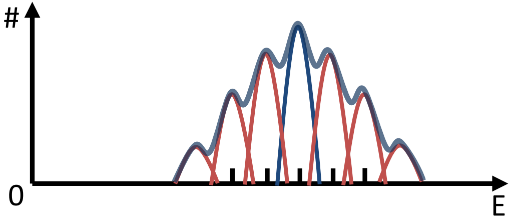


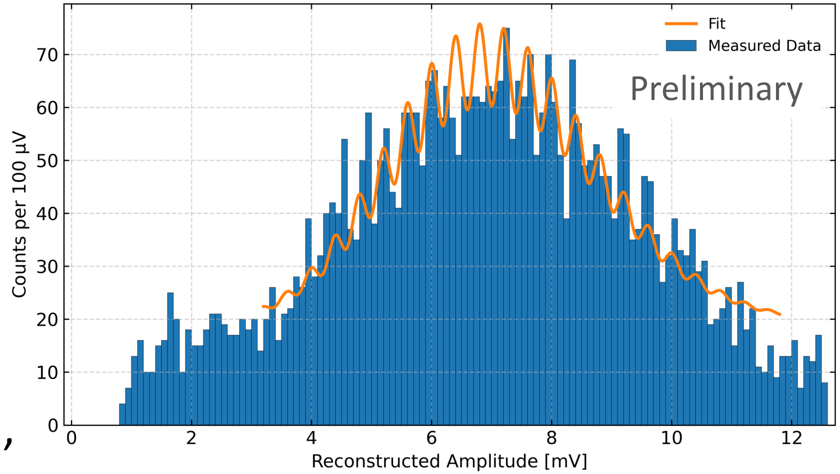
➢ Resulting total spectrum is a **Poissonian distribution**

Prototype Measurement

Indications of Poisson-like peaks and single-photon sensitivity observed

- Required resolution: $\mathcal{O}(1\ \mathrm{eV})$

Low-energy spectrum measured in one light detector



Remaining uncertainty from low statistics and non reliable energy calibration at eV-scale

Next:

- Long-term low-background run planned at the COSINUS underground facility
- Underground operation expected to improve performance (B-field compensation, low background)
- Multiple light detectors improve background rejection
- LED system under development for low-energy calibration

- Talk by Philipp Schreiner on details of single photon analysis

Summary and Outlook

The developed NaIM detector module enables:

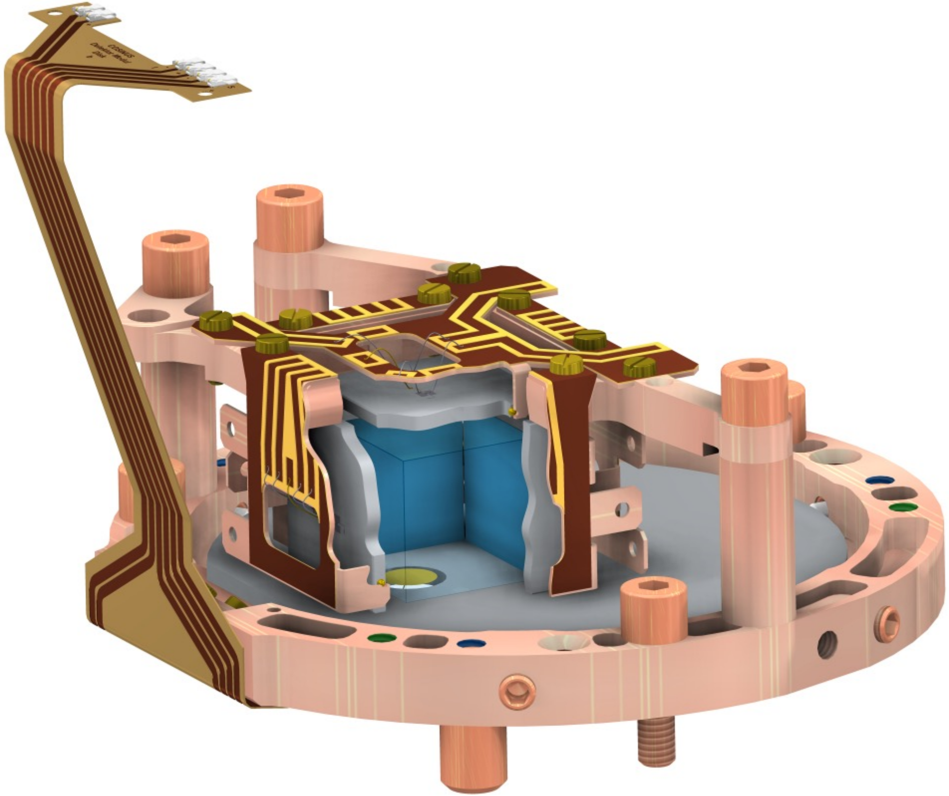
- Precision studies of NaI light yield and quenching factors at low energies
- Investigations of electronic excitations in cryogenic scintillating calorimeters

The proof-of-principle prototype meets the target performance goals

Next:

- Assembly of the full module for the low-background COSINUS-1π Run1 data taking starting within 2026
- LED-based energy calibration at MPP and later at LNGS
- For OνDES: scaling up both the number of sub-eV light detectors, including the readout concept, and the NaI crystal mass

Thank you for your attention!



Identification of Dark Matter, June 2026

Max-Planck-Institut für Physik

Lutz Ziegele

COSINUS Strategy

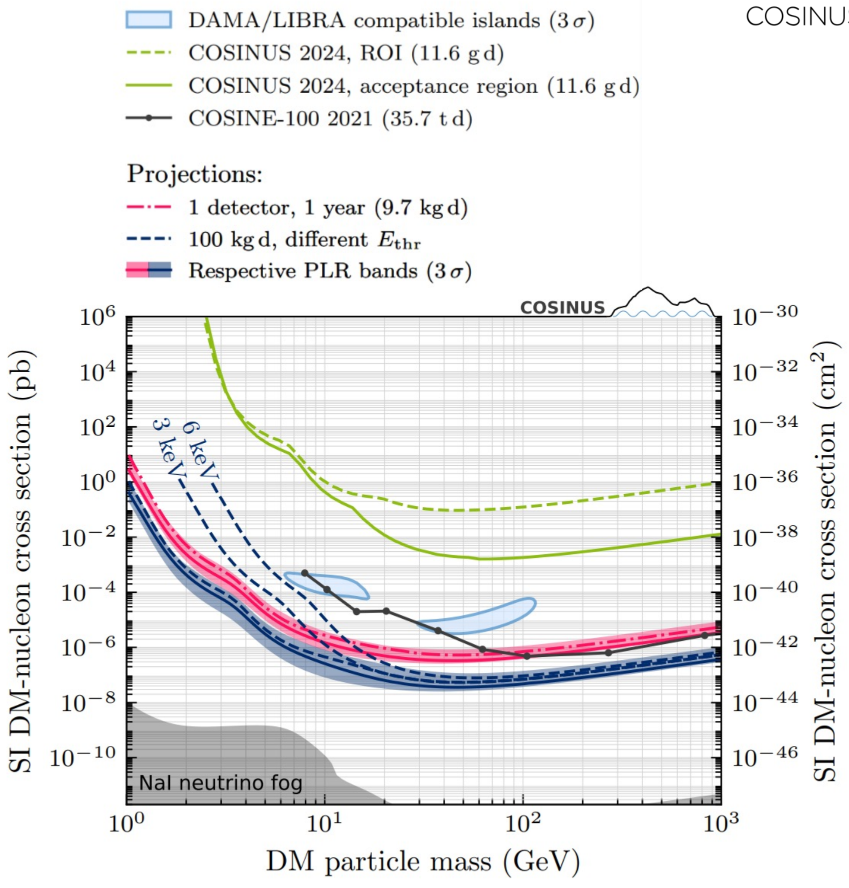
Goal: cross check the hypothesis that the DAMA/LIBRA signal is caused by DM-nuclear scattering

COSINUS-1π Run 1:

- 100 kg·days of exposure
- 8 detector modules, 34.8 g NaI each
- Cross check standard scenario (robust even with a 6 keV threshold)
- Start constraining more general scenarios (e.g monotonous recoil spectra)

COSINUS-1π Run 2:

- Model-independent test assuming DM–nucleus scattering
- 1000 kg·days of exposure
- 24 detector modules (30 – 100) g NaI each



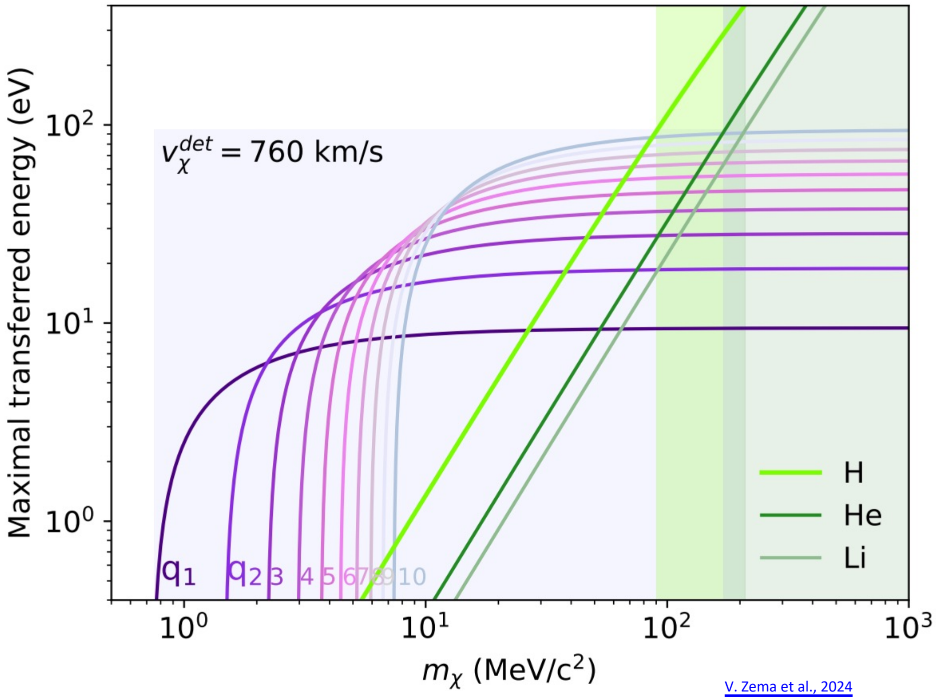
G. Angloher et al., 2025

DM-Electron Scattering Compared to Nuclear Scattering

COSINUS

Maximum recoil energy in DM-electron scattering as a function of the DM mass for different transferred momenta q_i for $i = 1, \ldots, 10$

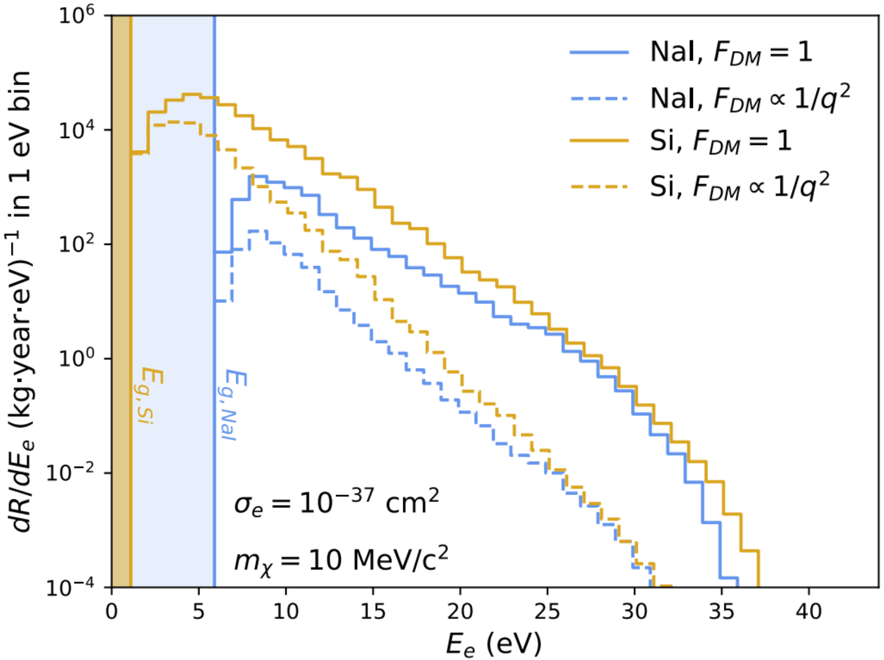
The maximal nuclear recoil energy for DM-nuclei elastic scattering for three light targets, H, He, and ^{6}Li is shown for comparison



V. Zema et al., 2024

DM-Electron Scattering Differential Rate

Differential DM-electron interaction rate per 1 eV bin and kg year in NaI (blue) and Si (yellow), for $\sigma_e = 10^{-37}\ \mathrm{cm}^2, m_\chi = 10\ \mathrm{MeV/c}^2$, and for the energy gap $E_g = 5.9$ eV and (blue vertical line) and 1.1 eV (yellow vertical line), respectively. The differential rate for $F_{\mathrm{DM}} = 1$ is depicted with solid lines, while the one for $F_{\mathrm{DM}} = \left(\frac{\alpha m_e}{q}\right)^2$ is depicted with dashed lines.



V. Zema et al., 2024

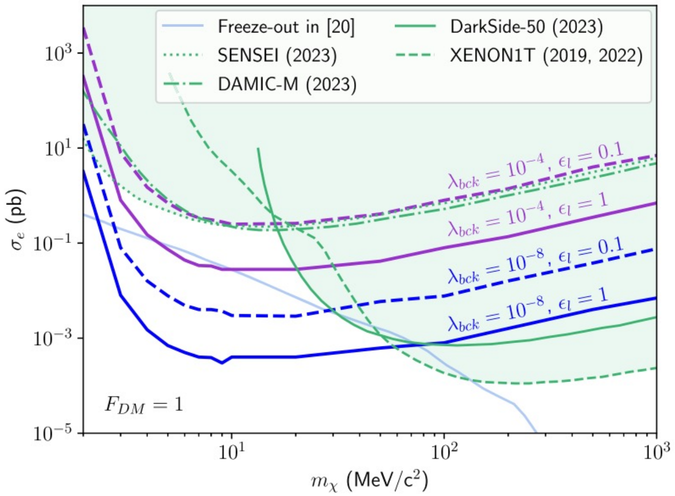
Projected Sensitivity for DM-Electron Searches with NaI

Assumed exposure: 1 kg · year

Scintillation light detection efficiency: $\epsilon_l = 0.1$ (dashed lines), $\epsilon_l = 1$ (solid lines)

Background suppression: $\lambda_{bck} = 10^{-4}$ (purple), $\lambda_{bck} = 10^{-8}$ (blue)

$F_{DM}(q) \sim 1$ for heavy mediators ($m_{med} \gg \alpha m_e$)



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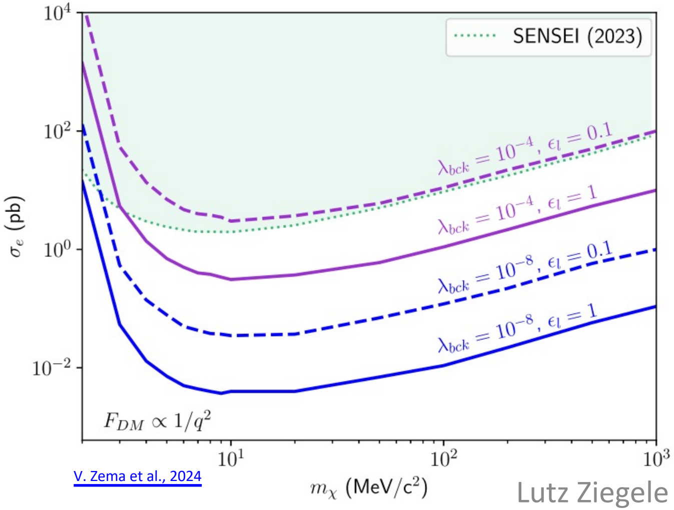

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Low Energy Excess (LEE) Background

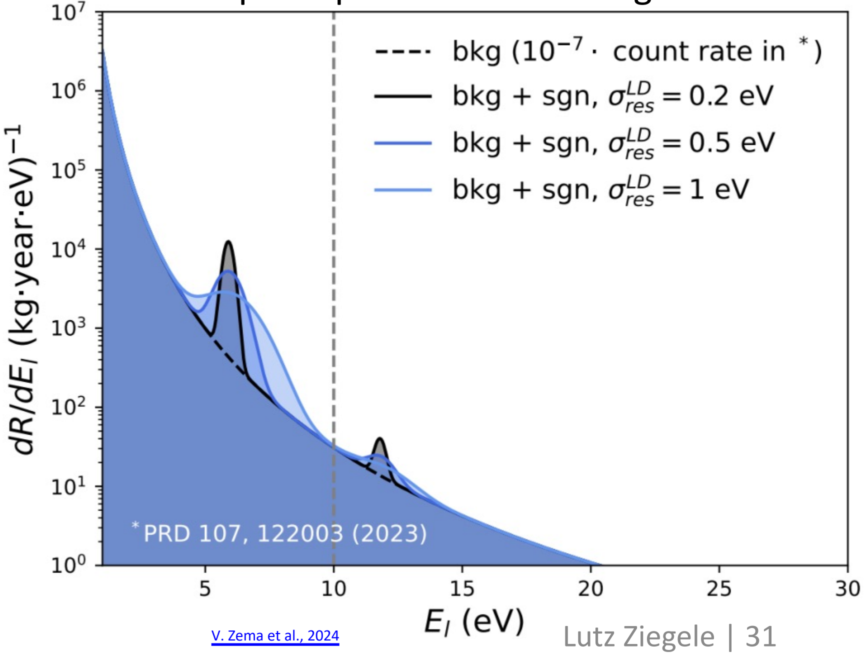
COSINUS

Excess of events observed in many cryogenic experiments below energies of few 100 eV with a rising spectrum towards lower energies

Dominant background for investigations of electronic excitations in cryogenic scintillating calorimeters

Depicted is the LEE detected by CRESST-III with a silicon wafer of $10\ \mathrm{eV}$ energy threshold suppressed by a factor 10^{-7} and extrapolated below $10\ \mathrm{eV}$

Expected signal from DM-electron scattering superimposed on LEE background



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Low Energy Excess in Prototype

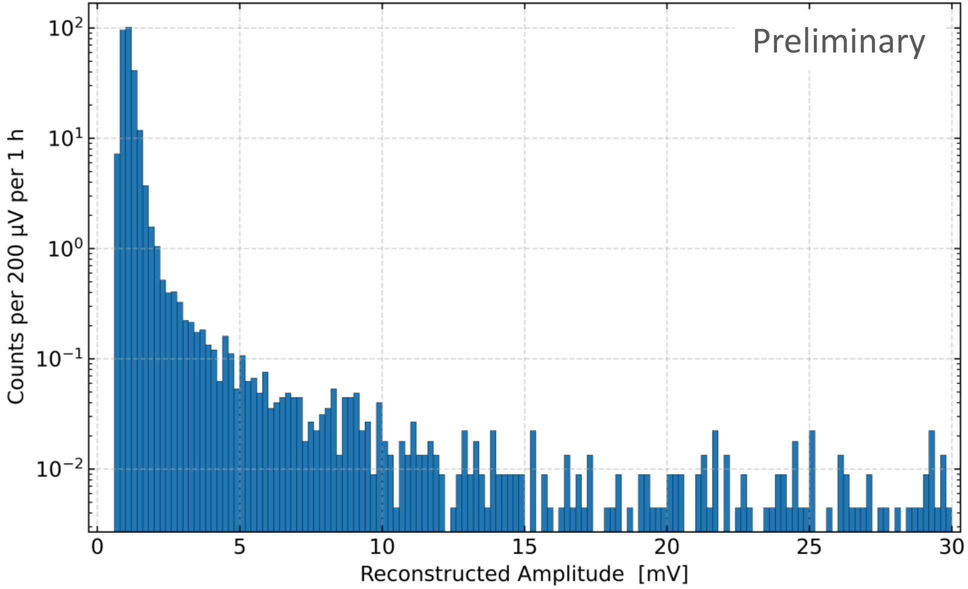
COSINUS

Extracted Low Energy Excess (LEE) spectrum of one light detector in the proof-of-principle measurement

Shape matches observations of other experiments

Investigation of the effect of the novel LD mounting concept on LEE is ongoing

The unreliable energy conversion makes LEE comparisons difficult



Fit Parameters for the Low-Energy Light Spectrum

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Fitted photon energy matches the expected photon energy: $(3 - 6)$ eV

Fit parameter	Fit value
Energy of a single scintillation photon	(400.2 ± 0.9) µV
Scintillation light yield	$(1.19 \pm 0.01) \cdot 10^{-3}$
Constant background	(19 ± 1) Counts
Global scaling factor	$(182 \pm 8) \cdot 10^{-3}$
K_β-fraction (fixed)	0.142857
Baseline resolution (fixed)	143.1 µV
Resolution scaling factor C_{lin} (fixed)	$1.4 \cdot 10^{-3}$

Low-energy spectrum measured in one light detector