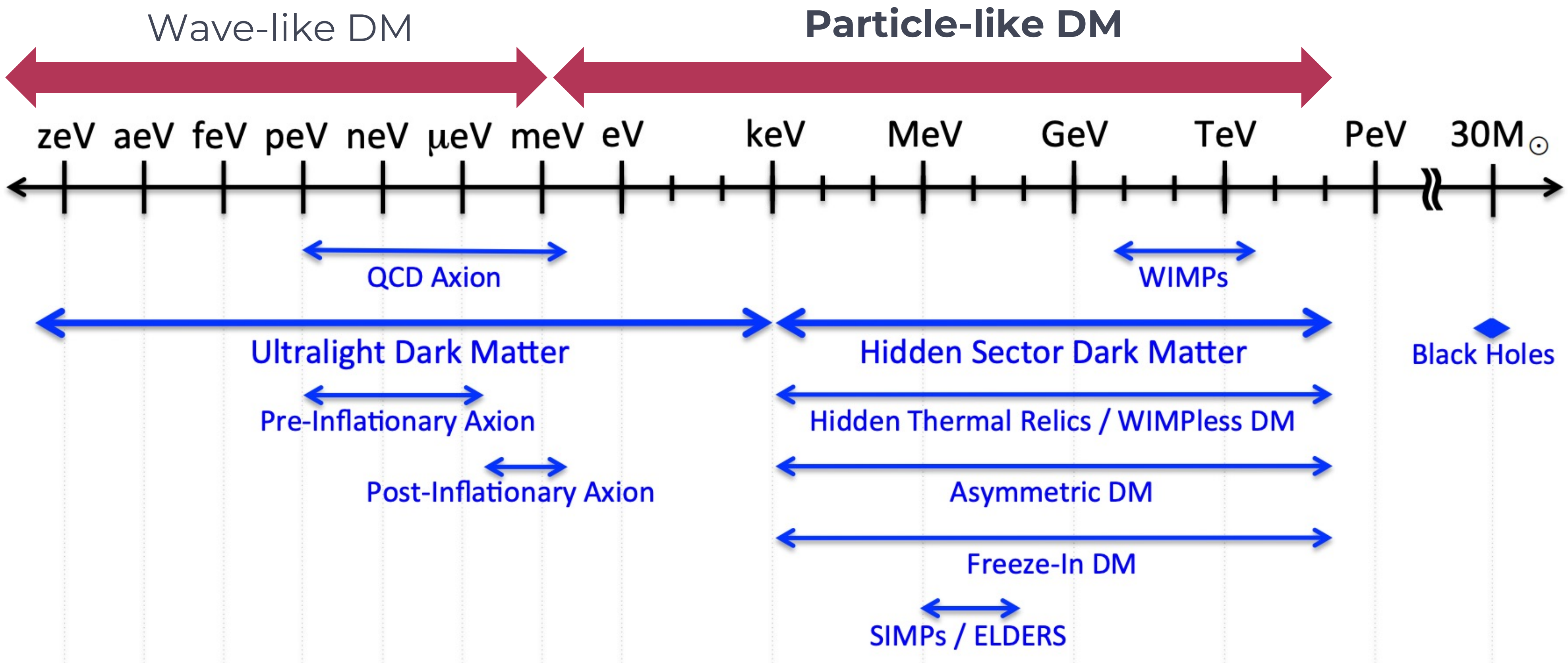
LDMA'25

# Direct-detection of sub-GeV dark matter with cryogenic detectors

~ $\mathcal{O}$(10 mK)

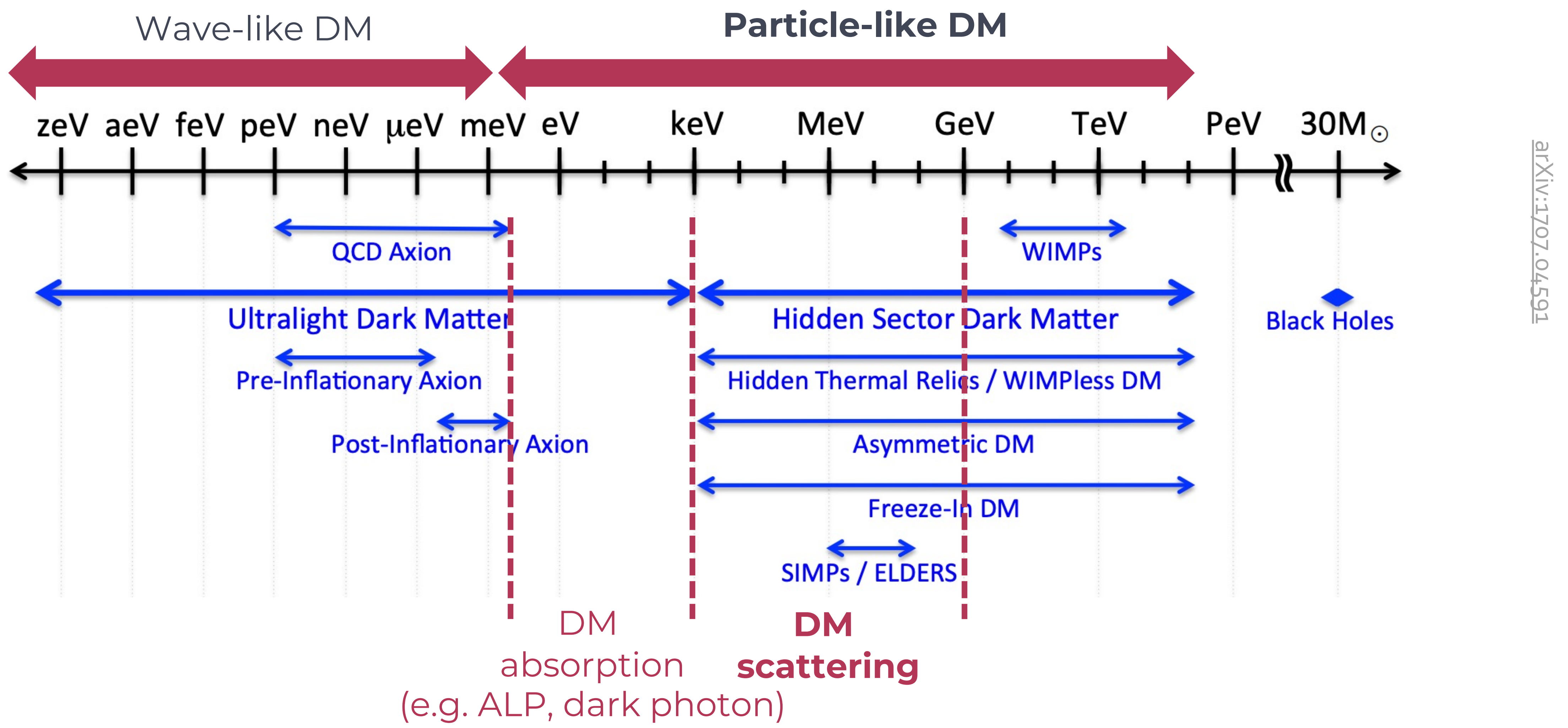
Margarita Kaznacheeva
Technical University of Munich

# Dark Matter candidates




arXiv:1707.04591

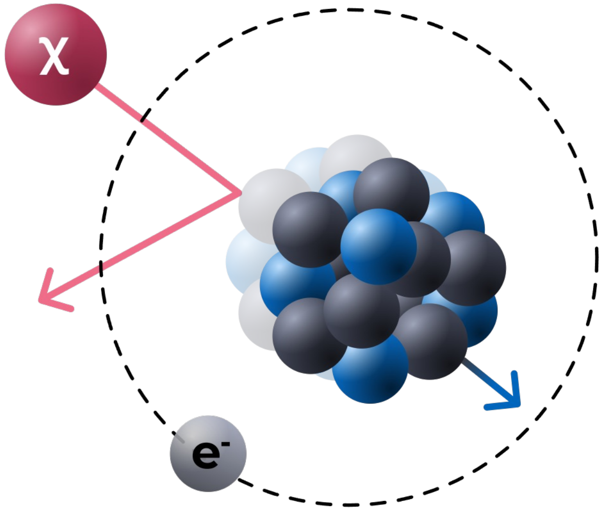
# Sub-GeV DM



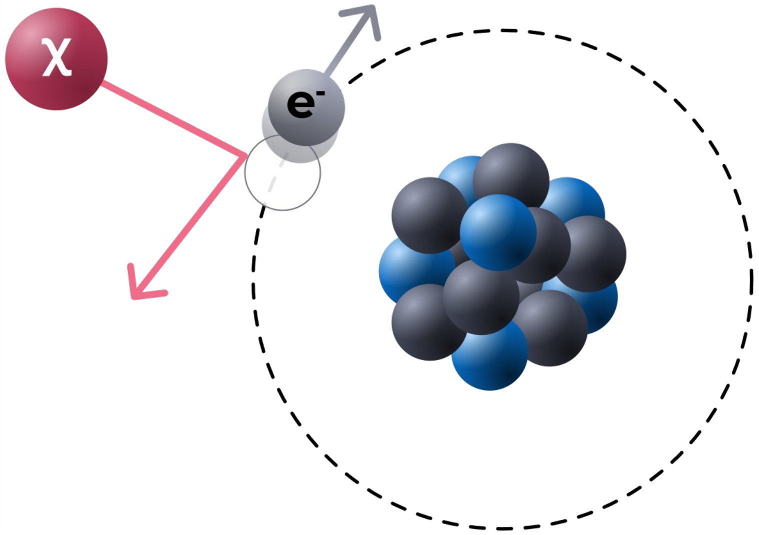
Wave-like DM
Particle-like DM
zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV 30M⊙
QCD Axion
WIMPs
Ultralight Dark Matter
Hidden Sector Dark Matter
Black Holes
Pre-Inflationary Axion
Hidden Thermal Relics / WIMPless DM
Post-Inflationary Axion
Asymmetric DM
Freeze-In DM
SIMPs / ELDERS
DM absorption (e.g. ALP, dark photon)
DM scattering
arXiv:1707.04591

# DM scattering

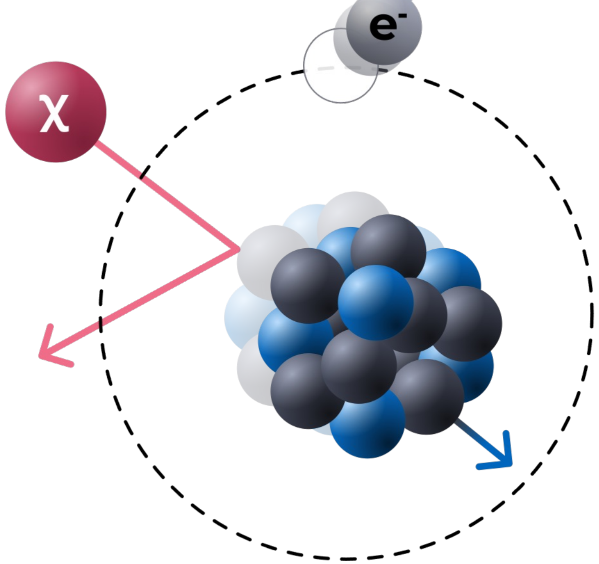
### DM-nucleus scattering




### DM-electron scattering



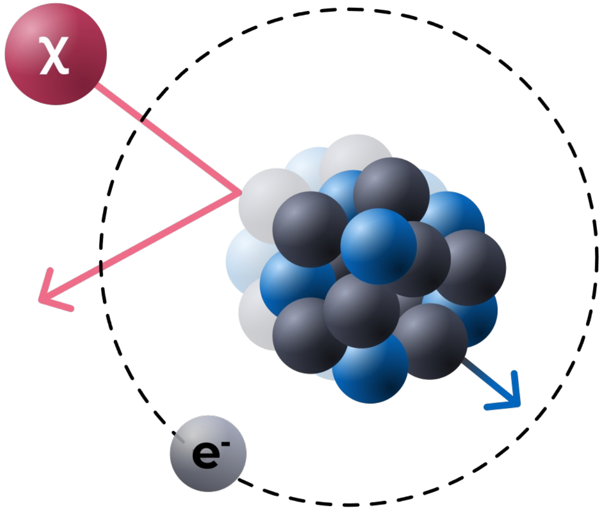

### Migdal effect




Perturbation of the electron cloud → energy transfer $e^-$'s
BUT: suppressed signal rates

# DM scattering

## DM-nucleus scattering

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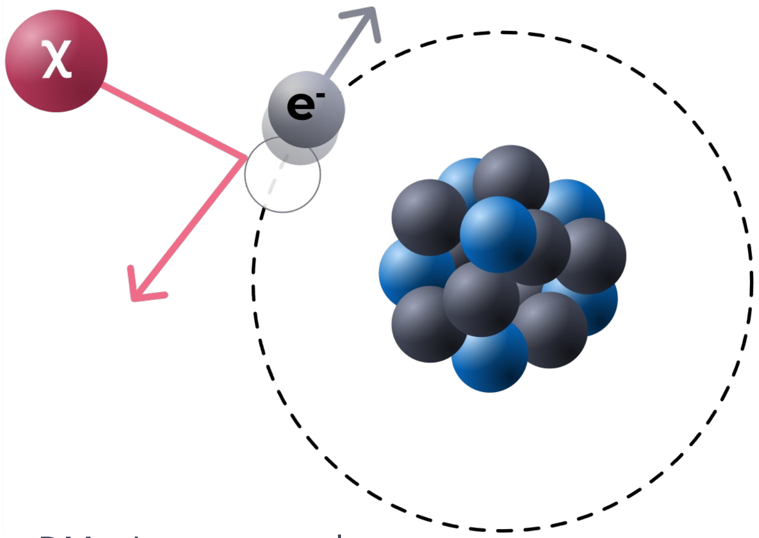
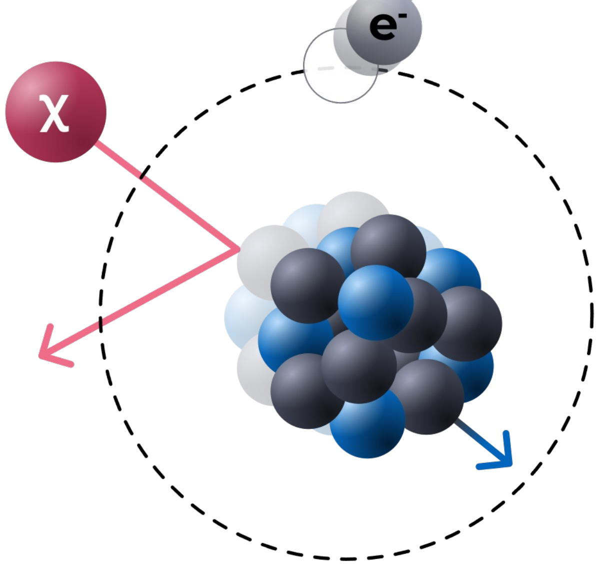



DM-e in cryo crystals:
V. Zema et al. PRD 2024
Y. Kahn,T. Lin Rep. Prog. Phys. 2022
S. Griffin et al. PRD 2020

See talk by
P. Privitera (CCDs, Tue)

## Migdal effect

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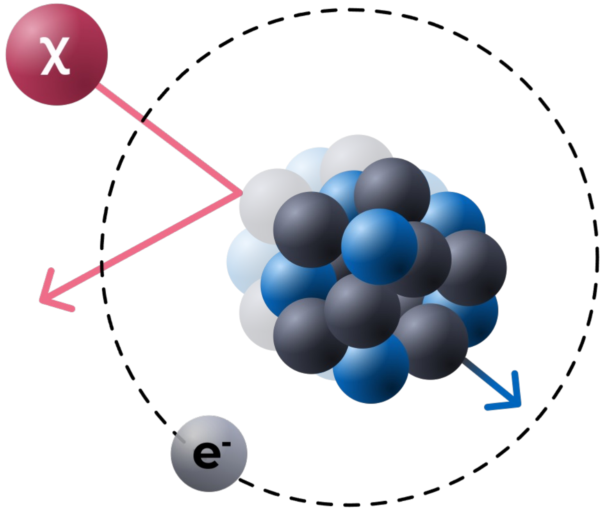
BUT: suppressed signal rates

See talk by
C. McCabe (Wed)

# DM scattering

## DM-nucleus scattering

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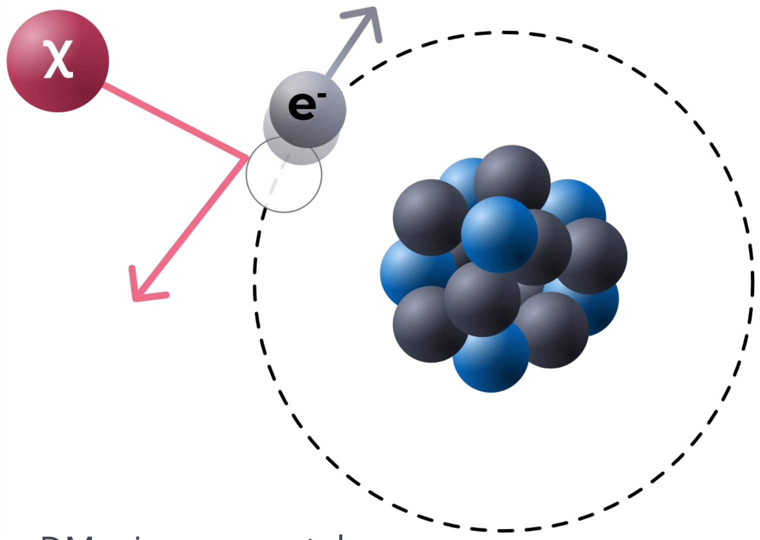


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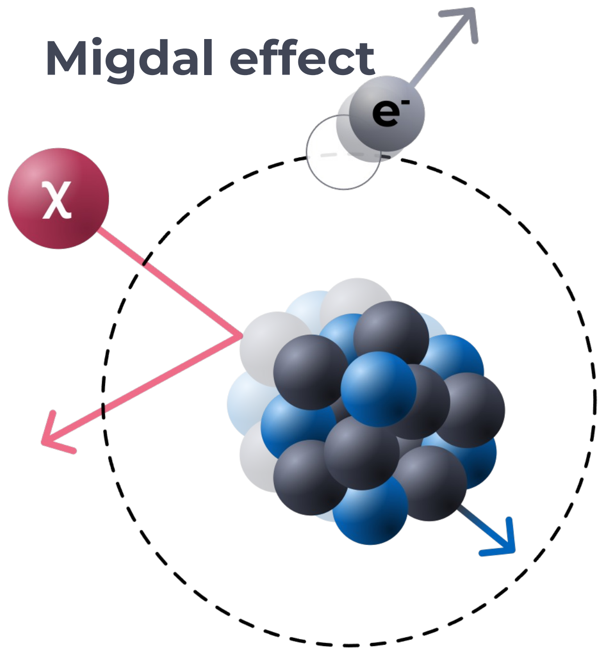
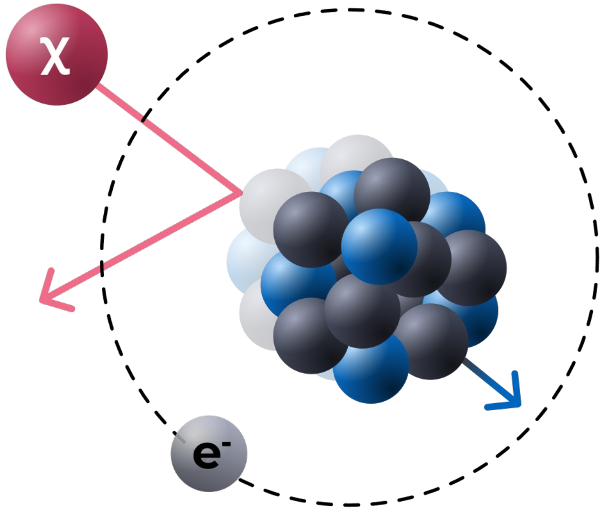



Perturbation of the electron cloud → energy transfer $e^-$'s
BUT: suppressed signal rates

See talk by
C. McCabe (Wed)

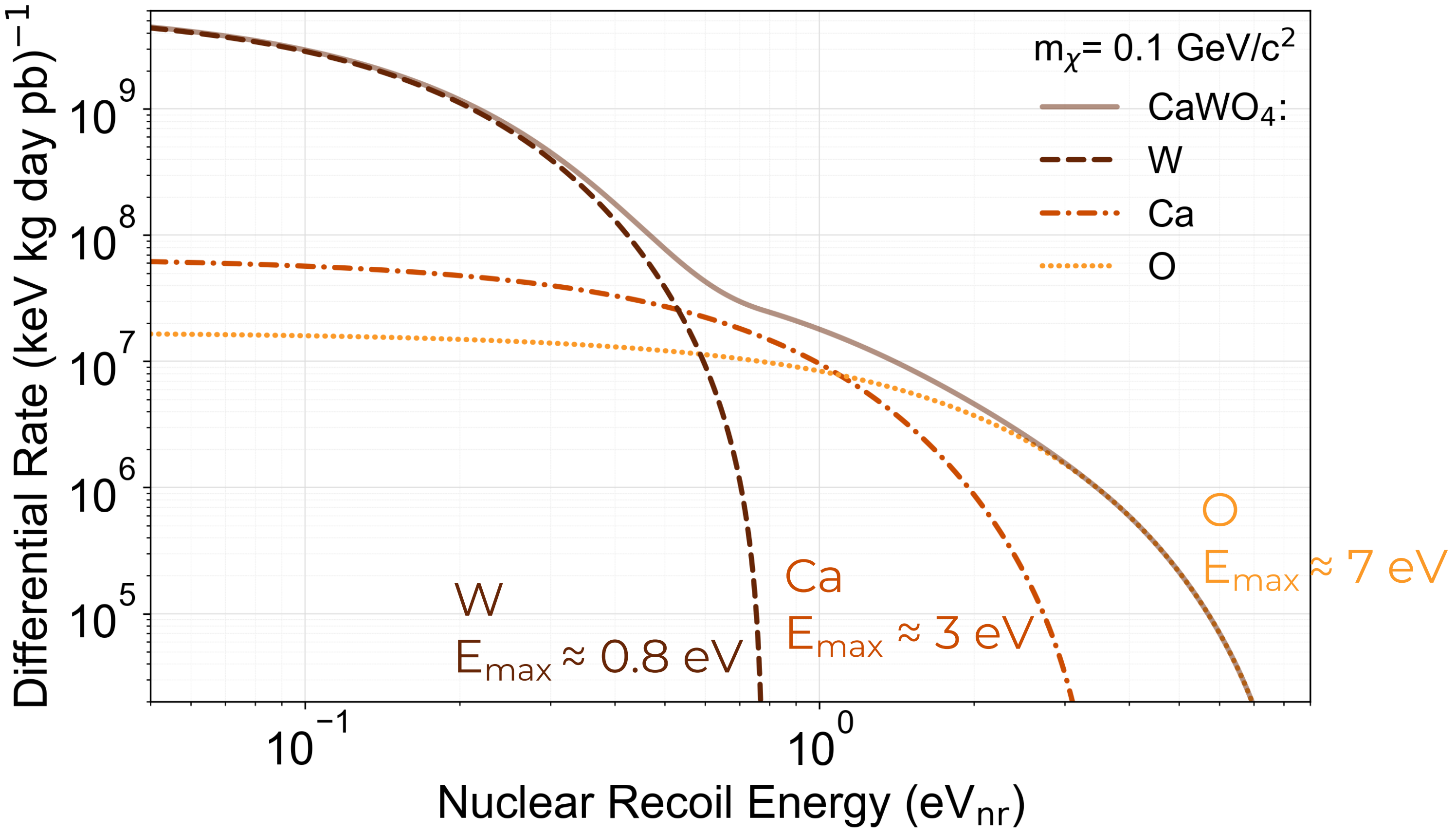
# DM-nucleus scattering

Elastic DM-nucleus scattering



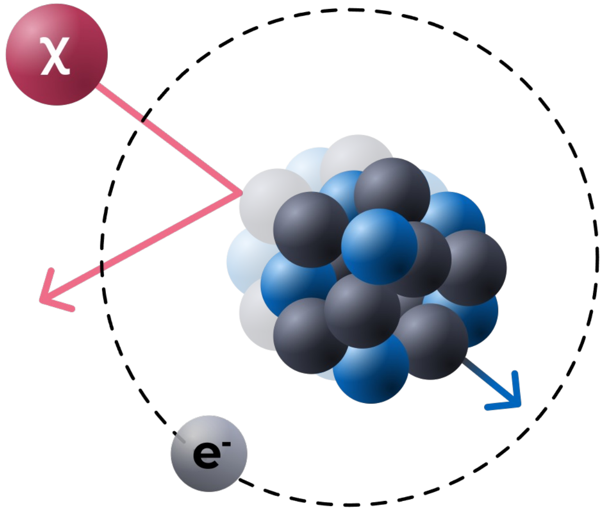

**Light materials are beneficial for light DM**

Lighter target materials → higher recoil energy



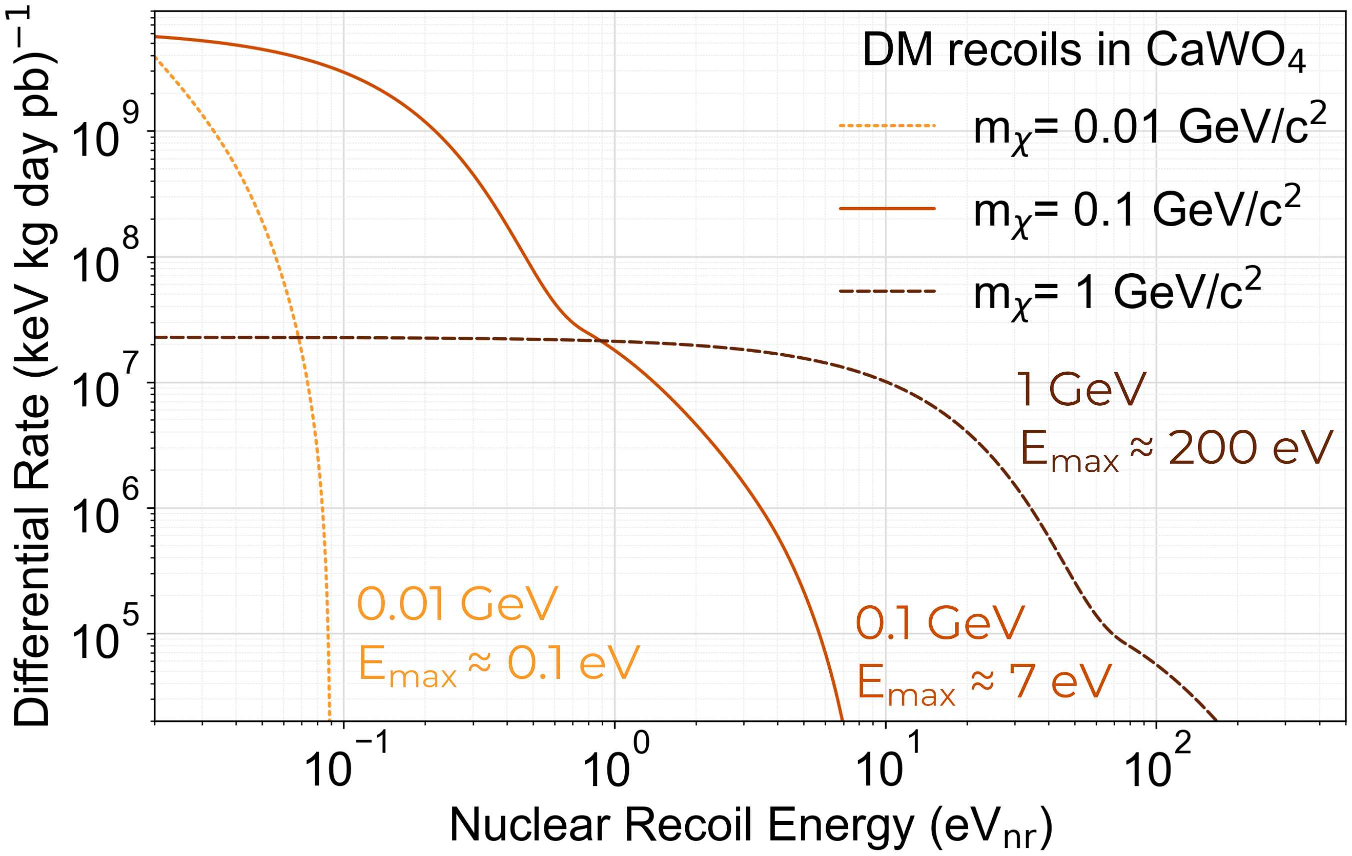
# DM-nucleus scattering

Elastic DM-nucleus scattering

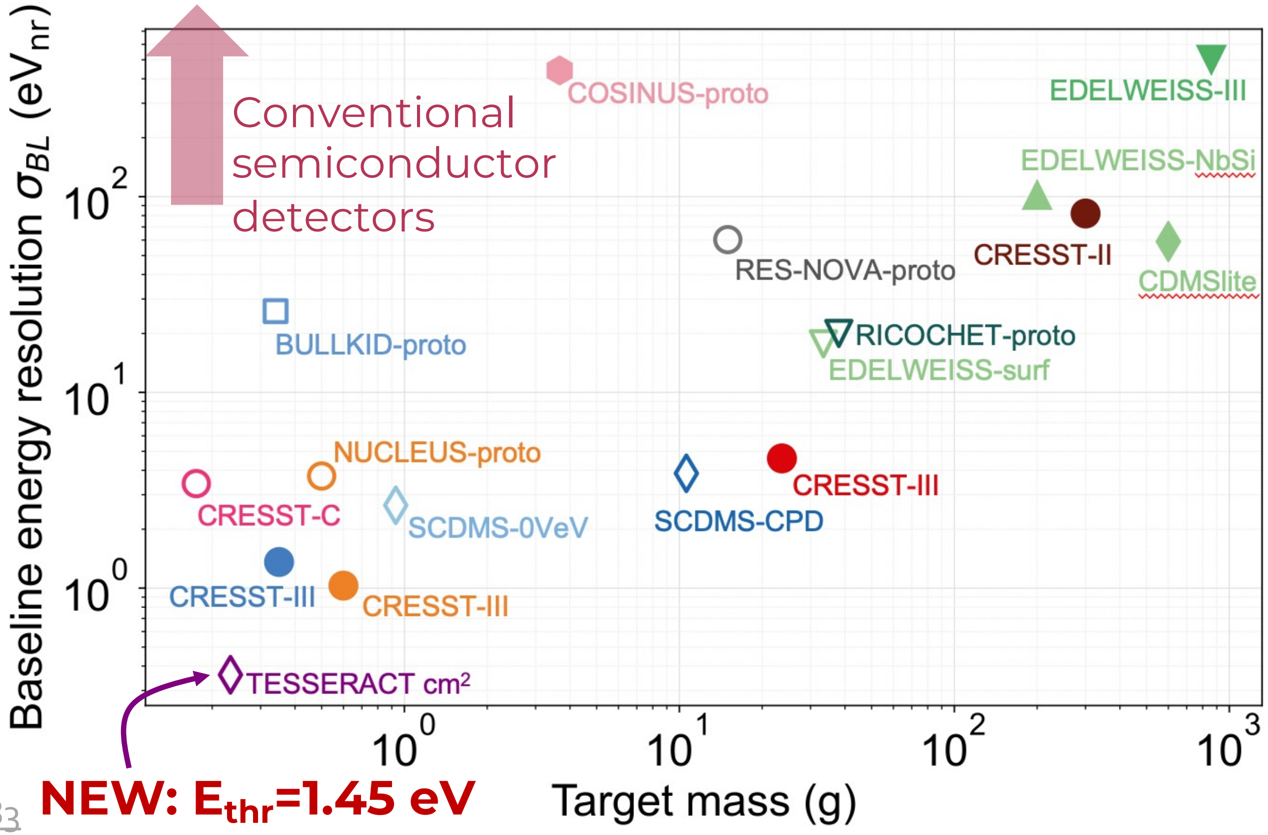



**Thresholds of $\mathcal{O}$(10 eV) and lower are required**

Lighter DM particle → smaller recoil energy



# Main advantage: performance




MK, K. Shäffner, J. of Adv. Instr. in Science (2024)

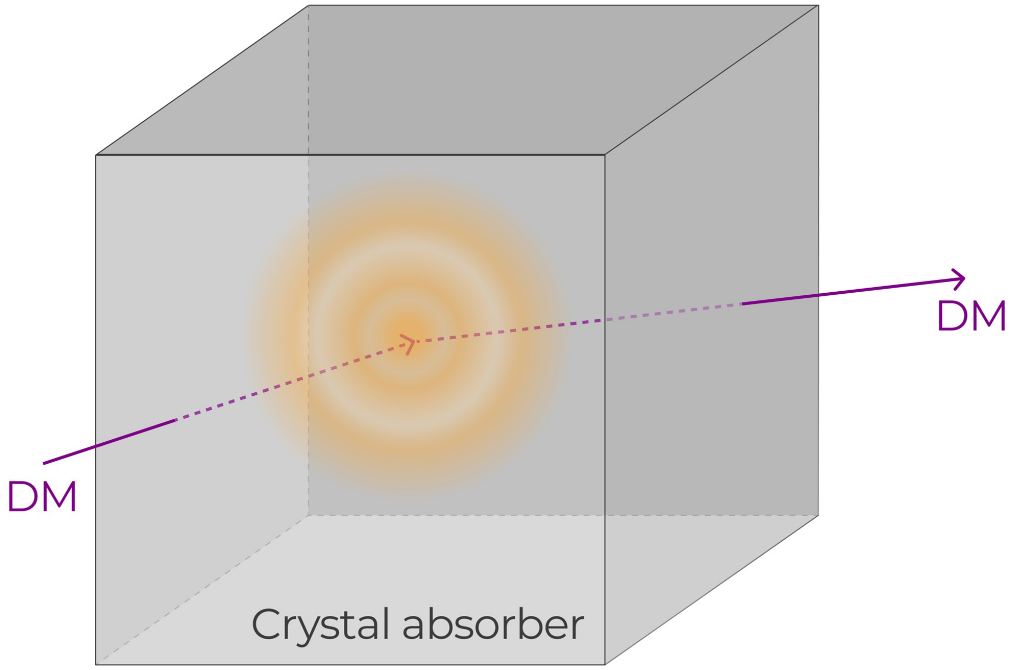
arXiv:2503.03683 **NEW: $E_{thr}$=1.45 eV**

**With cryogenic detectors eV-scale energy thresholds are available!**

# Detection signals

Primary signal:
- Heat / phonons

Secondary signals:
- Ionization
- Scintillation

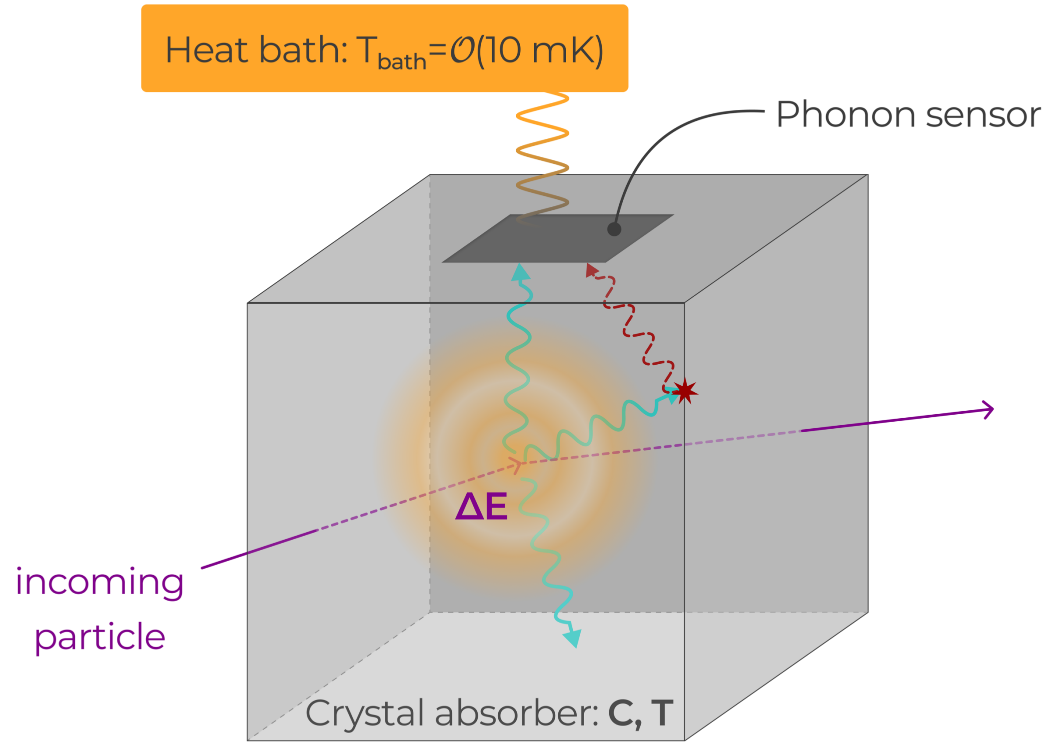



Phonons: precise measurement of (almost) full deposited energy

Available only at cryogenic temperatures

→ **Operation at mK-temperatures**

# Cryogenic phonon detectors

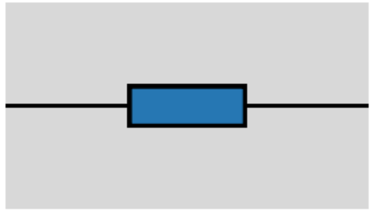



Types of phonon sensors:

DM experiments:

thermal

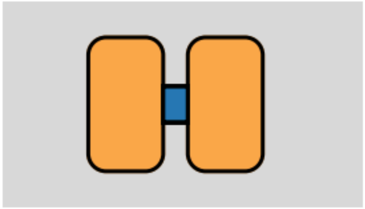
NTD



Resistance — EDELWEISS

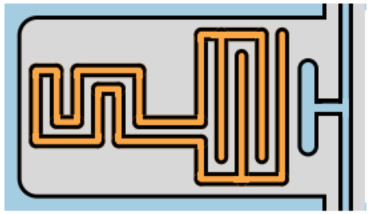
athermal phonons

TES



Resistance — CRESST, SuperCDMS, TESSERACT

KID



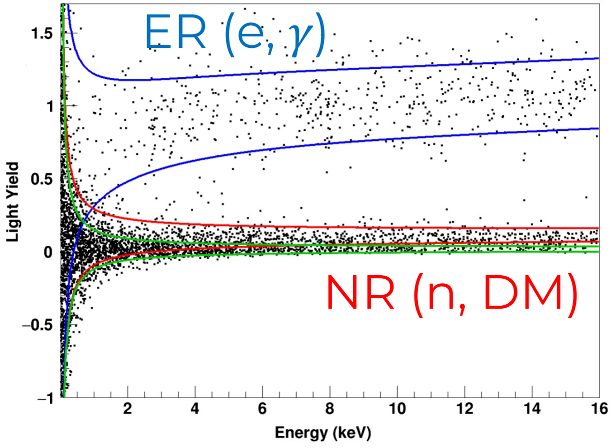
Resonance frequency — BULLKID

+ MMC — Magnetization — DELight

# Background discrimination: scintillation & ionization

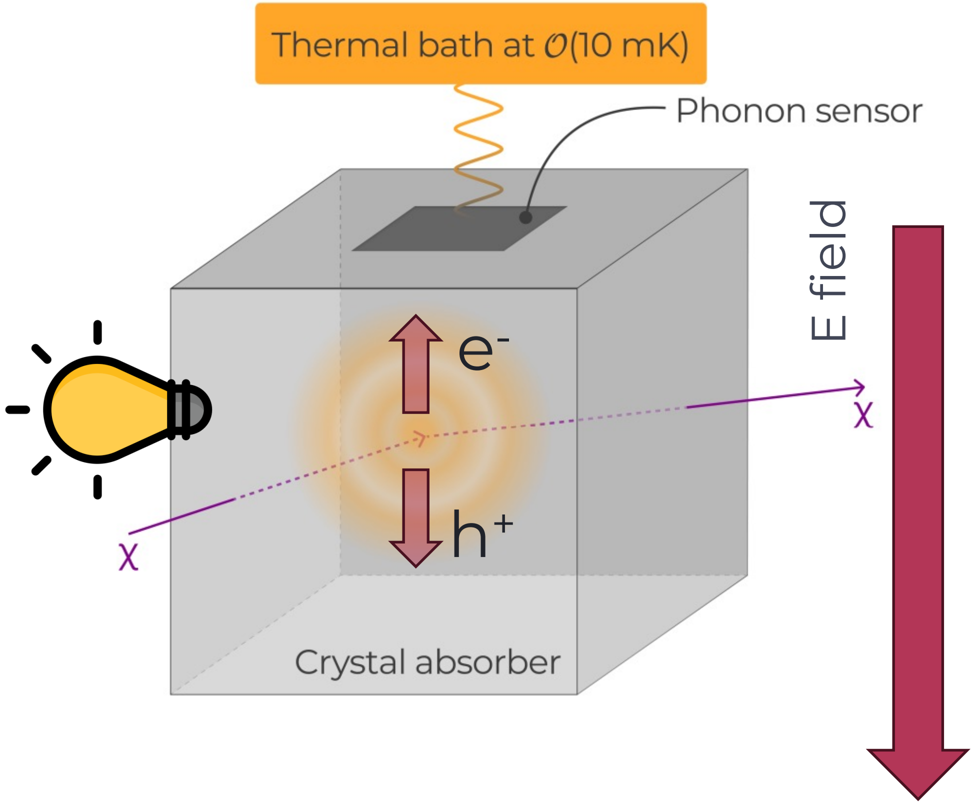
**Phonon + Light**

CRESST-III

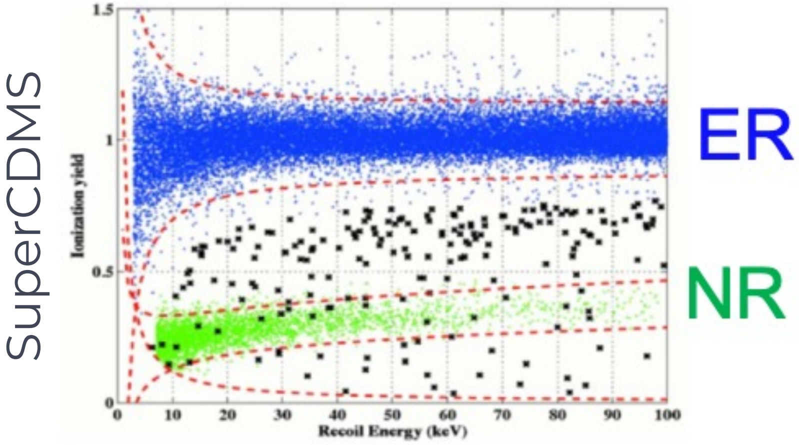


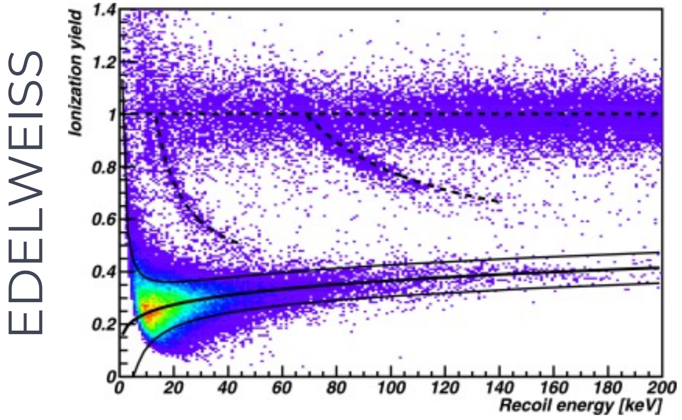

Scintillating material (e.g. $CaWO_4$, NaI)

Phys. Rev. D **100**, 102002




**Phonon + charge**

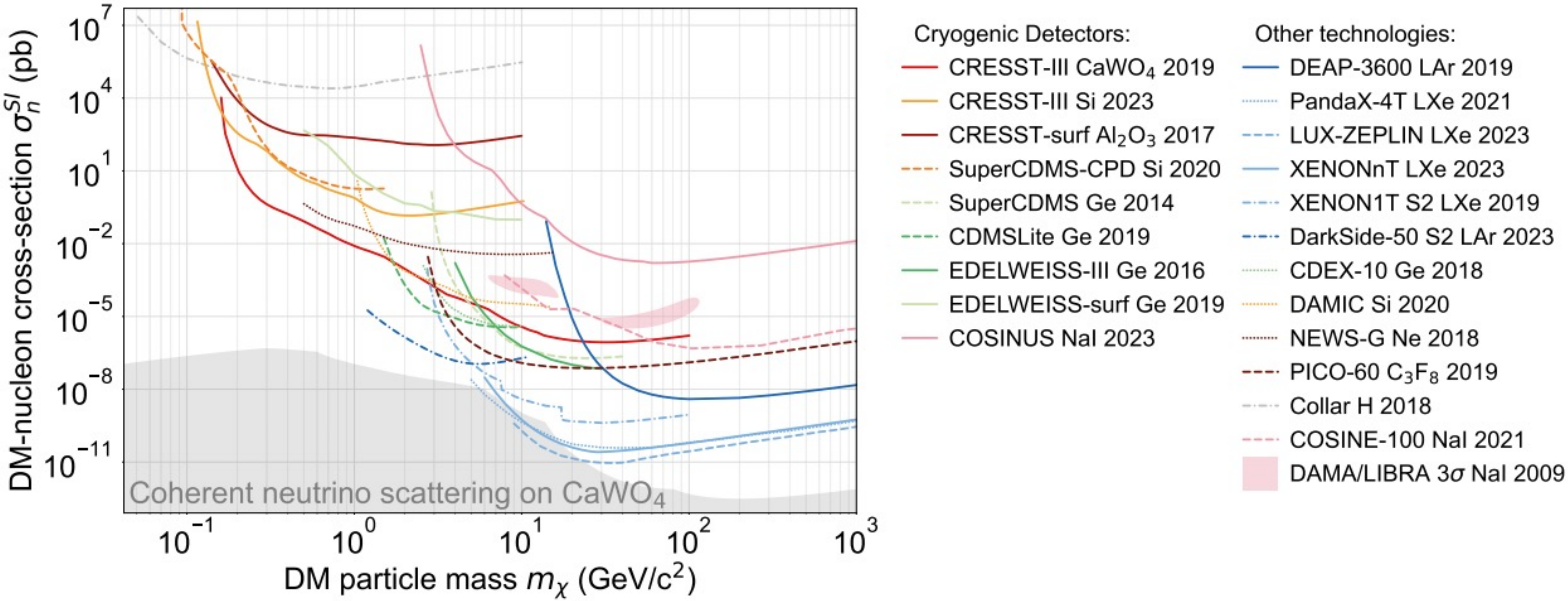



Semiconductor material (e.g. Si, Ge)

EDELWEISS: Phys. Lett. B702,5 (2011)

# DM-nucleus scattering results




MK, K. Shäffner, J. of Adv. Instr. in Science (2024)

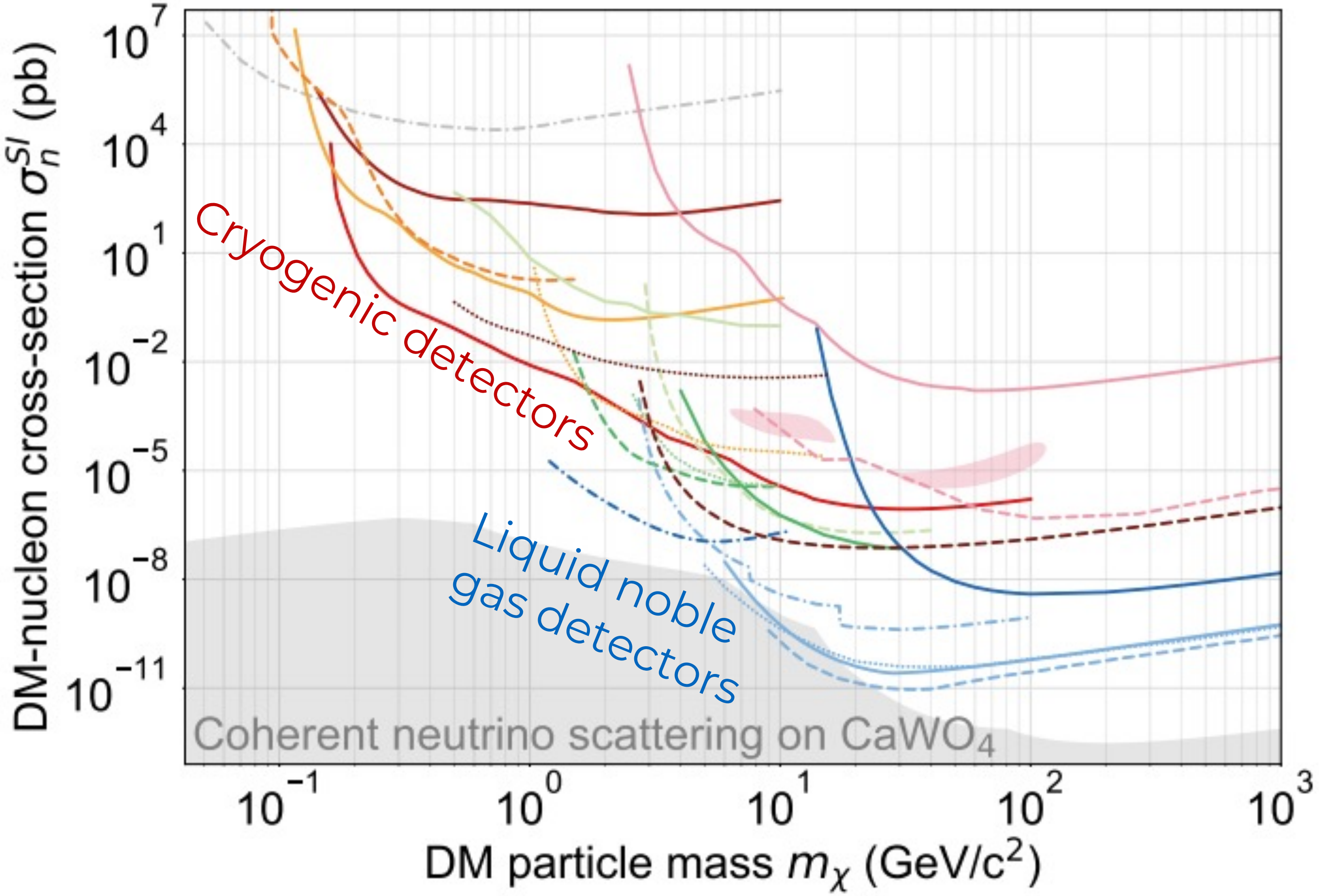
# DM-nucleus scattering results

**≲ 1 GeV**

~ 1 event/ kg-day

- thresholds are pushing the sensitivity

- cryogenic detectors & new technologies




See talk by M. van Uffelen (LAr, Tue)

**≳ 1 GeV**

~ 1 event/ t-year

- exposures are pushing the sensitivity

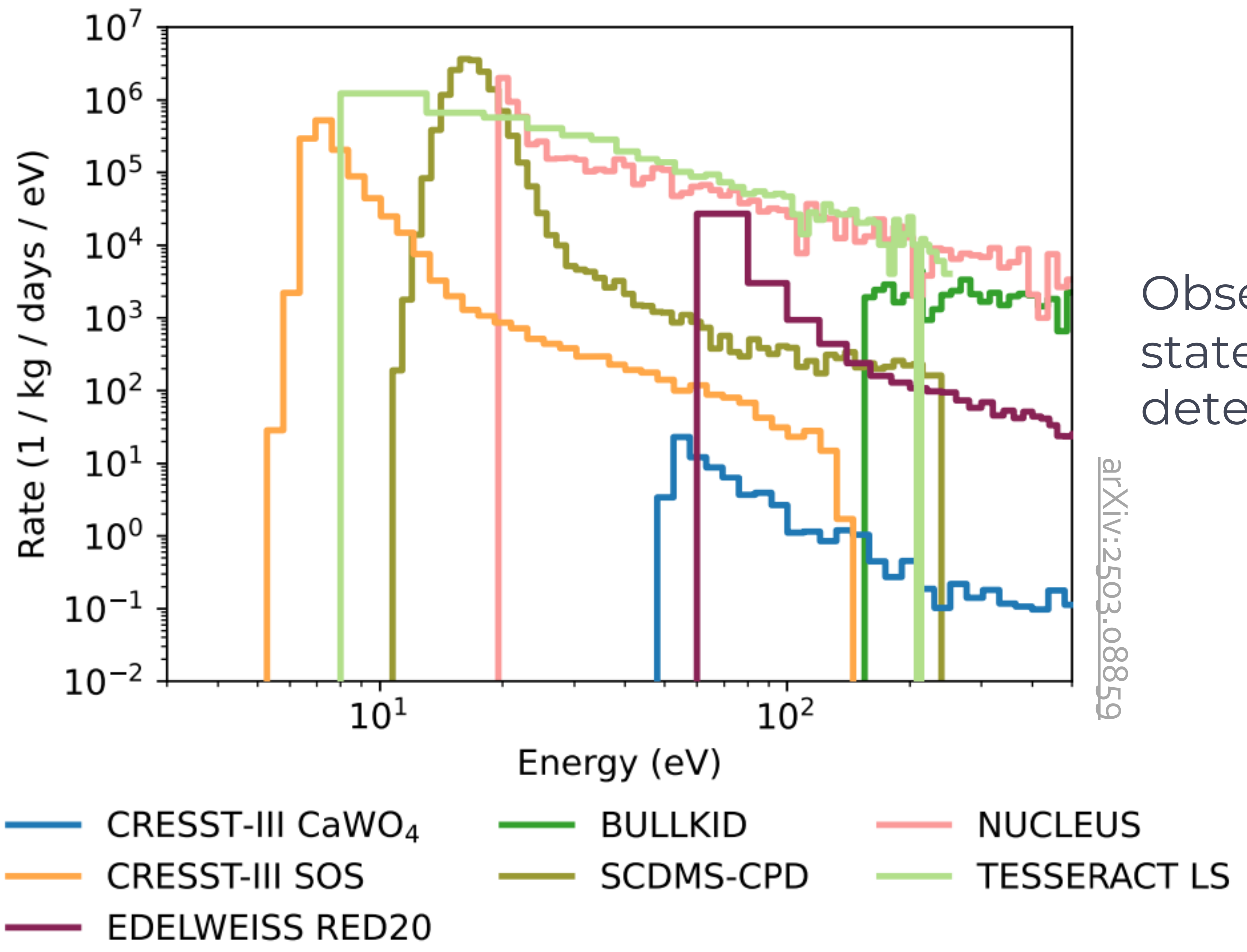
- liquid nobles gas detectors

MK, K. Shäffner, J. of Adv. Instr. in Science (2024)

# Main challenge: Low-Energy Excess (LEE)

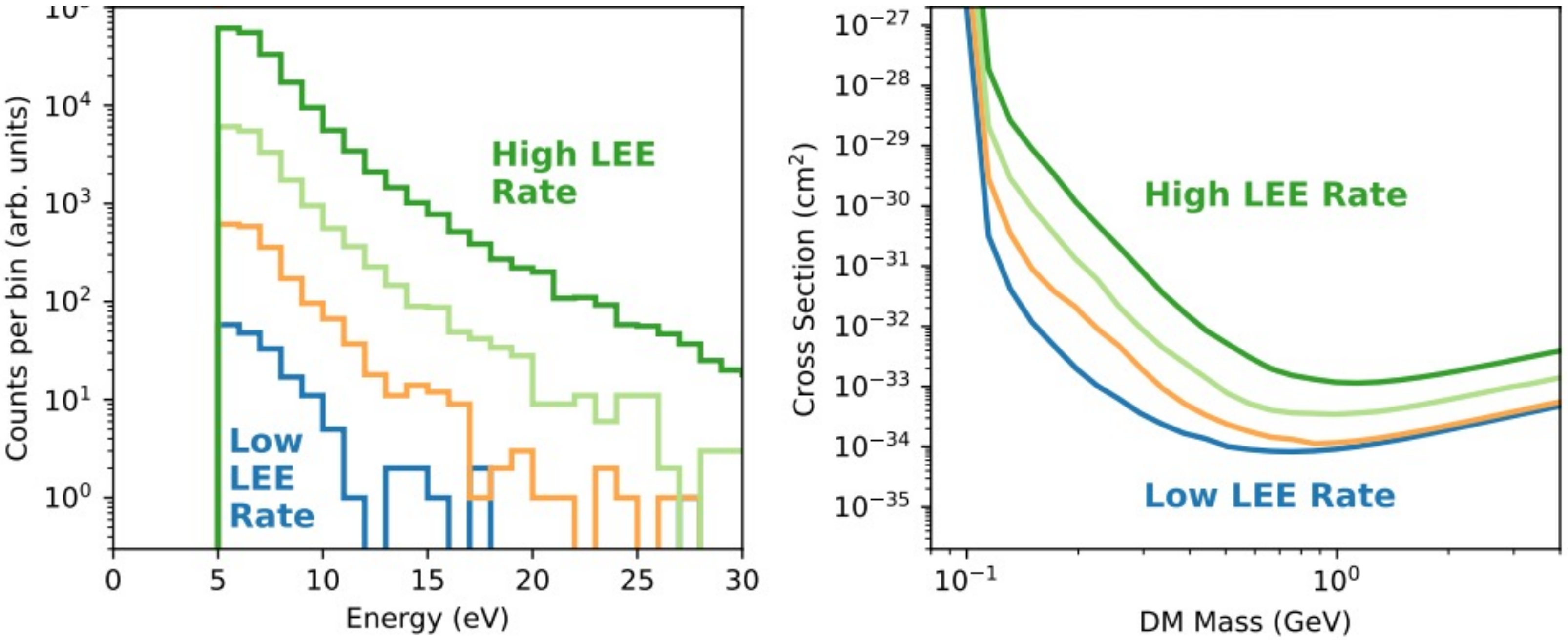
Rise in the measured energy spectra below ~100s eV well above the expected backgrounds

→ **Strong ROI pollution**




Observed in **ALL** solid-state cryogenic detectors below 100 eV

# LEE impact on DM sensitivity

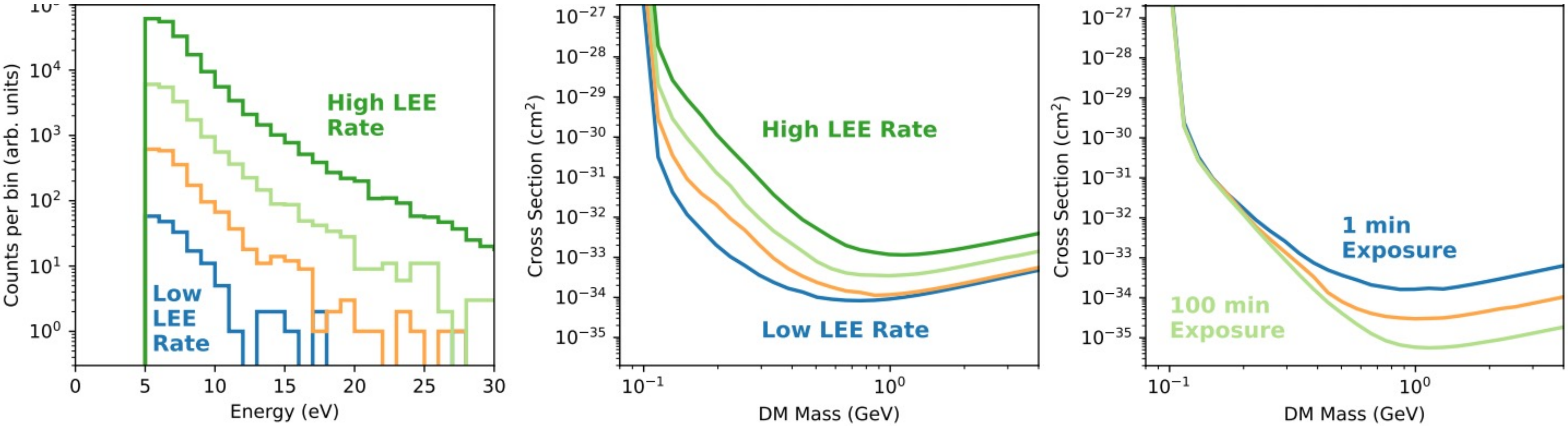



arXiv:2503.08859

**In the LEE presence the DM sensitivity is worsened by orders of magnitude!**

# LEE impact on DM sensitivity

**Exposure increase does not help in the sub-GeV DM regime**

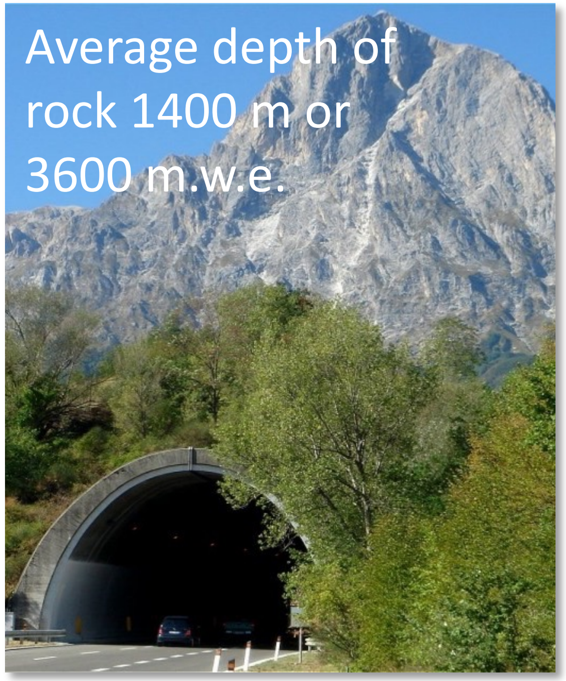



arXiv:2503.08859

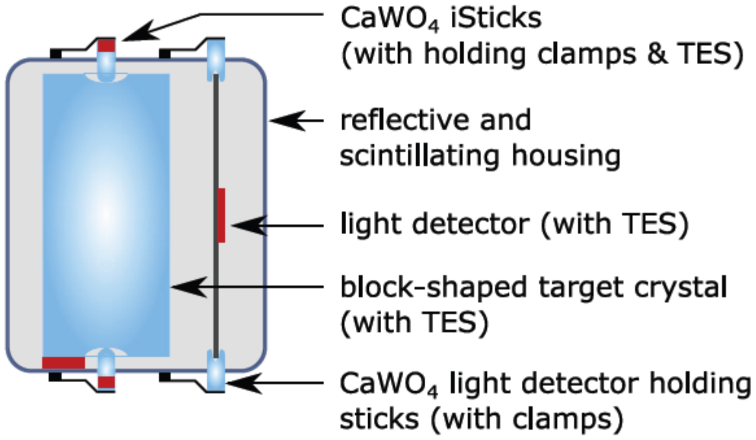
**In the LEE presence the DM sensitivity is worsened by orders of magnitude!**

# Overview of the cryogenic DM experiments

# CRESST-III @ LNGS




Gran Sasso National Laboratory (Italy)



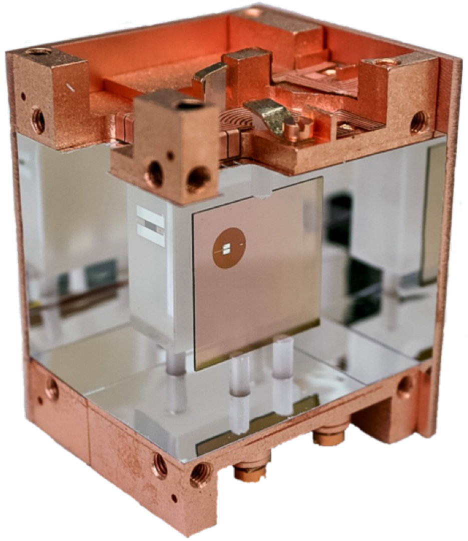

Phys. Rev. D **100**, 102002

**Current status**: Data taking with novel detector designs is currently on-hold – to be resumed in summer 2025.

Two modes:
1. $E_R \gtrsim 1$ keV: phonons + scintillation → particle identification
2. $E_R \lesssim 1$keV: phonons-only, low $E_{thr}$ → **sub-GeV DM with NR** ← primary goal

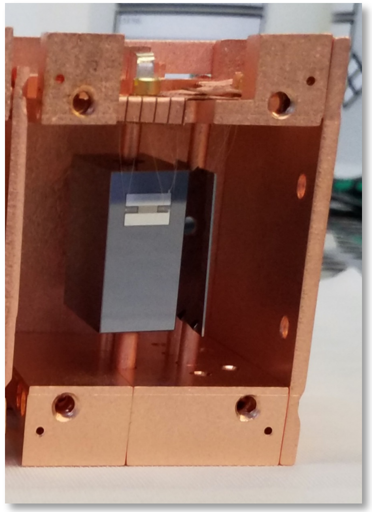
# CRESST-III @ LNGS

W-TES



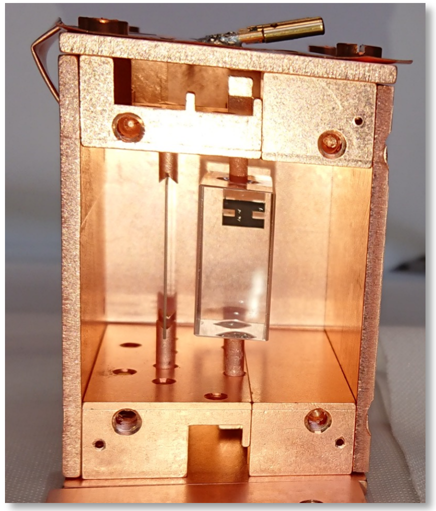


$CaWO_4$: 23.6 g
$E_{th}$= 30.1 $eV_{NR}$



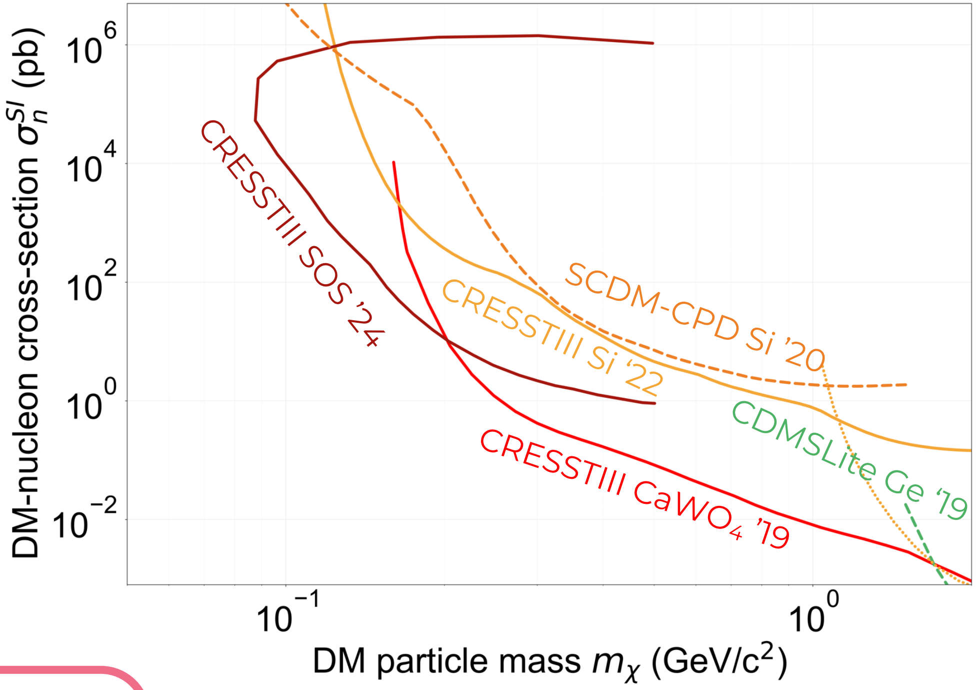


Si wafer: 0.35 g
$E_{th}$= 10.0 $eV_{NR}$





Si-on-$Al_2O_3$ wafer: 0.6 g
$E_{th}$= 6.7 $eV_{NR}$





Large variety of target materials:
$CaWO_4$, Si, $Al_2O_3$

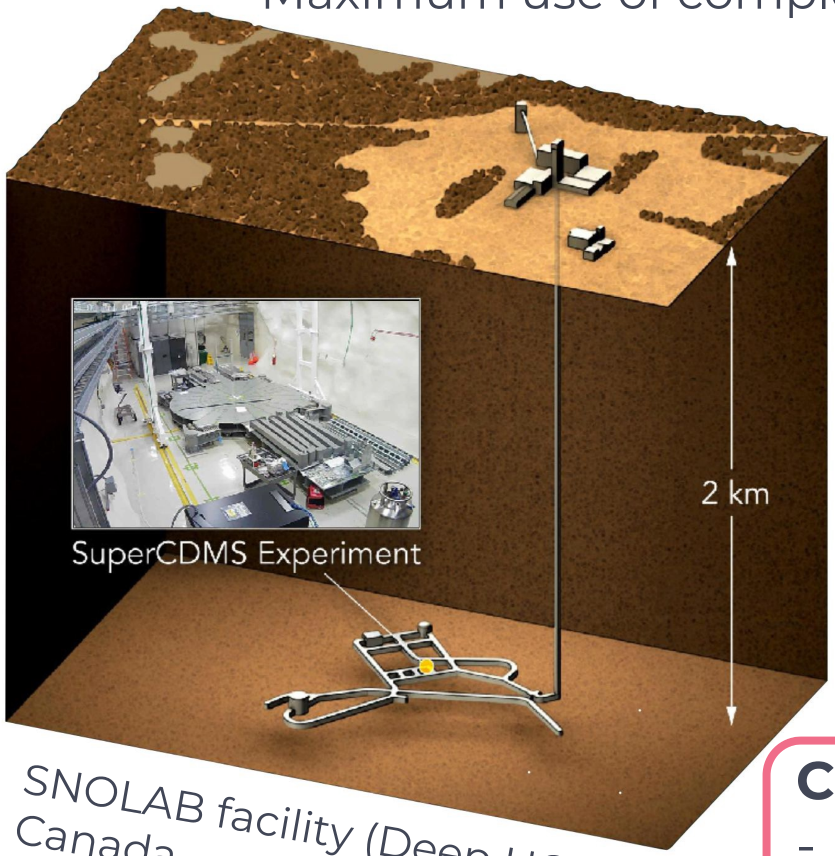
$LiAlO_2$ → enables spin-dependent interaction probes PRD **106**, 092008
C - under development EPJ C **84**, 324 (2024)

**Future upgrade:**
O(100) detectors optimized to sub-GeV DM

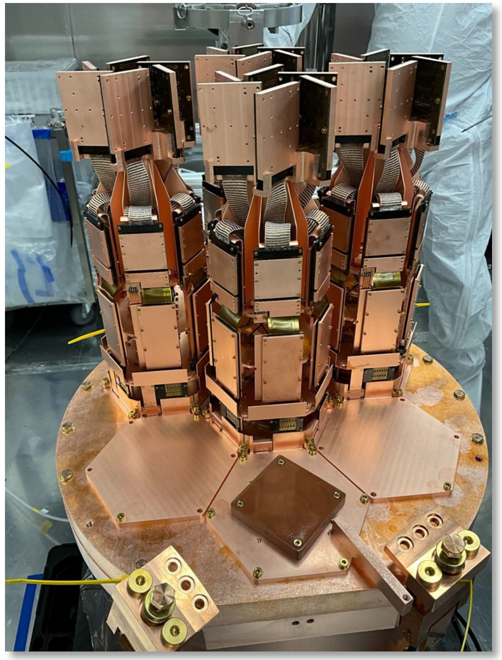
**Best limits for sub-GeV DM-nucleus scattering from ~90 MeV to ~1 GeV**

# SuperCDMS: installation @ SNOLAB

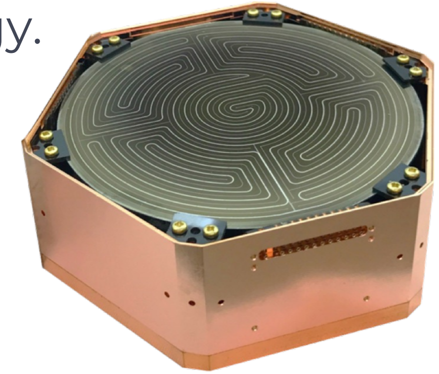
**Goal:** DM NR and ER
Maximum use of complementary detector technology.




SNOLAB facility (Deep UG mine)
Canada

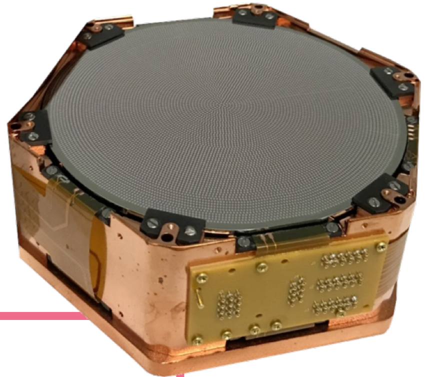


S. Pandey @ UCLA DM 2025



**iZIP detectors:**
Phonons + ionization
$E_{thr}$ ~ 150 $eV_{nr}$
bkg discrimination

W-TES
Ge (1.4 kg)
Si (0.6 kg)



**HV detectors:**
Phonon only
$E_{thr}$ ~ 60 $eV_{nr}$
Amplifies phonon signal
Low thresholds

**Current status:**
- Detector has been tested
- Installation is ongoing

# SuperCDMS: low-threshold efforts

**Goal: searching for the future upgrade options.**

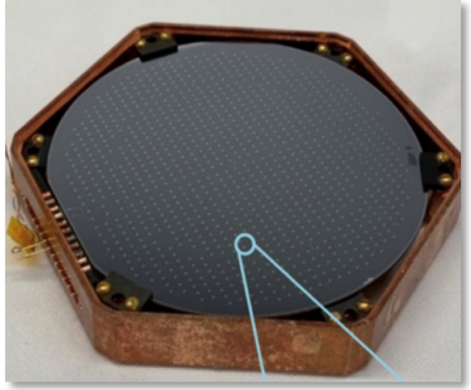
**CPD:**
0V detector
Si wafer of 10.6 g
$E_{thr}$ = 16.3 $eV_{nr}$ Phys. Rev. Lett. 127, 061801

**HVeV:**
Si wafer (1cm² x 4 mm) 1 g
eV scale thresholds
Phys. Rev. D 111, 012006

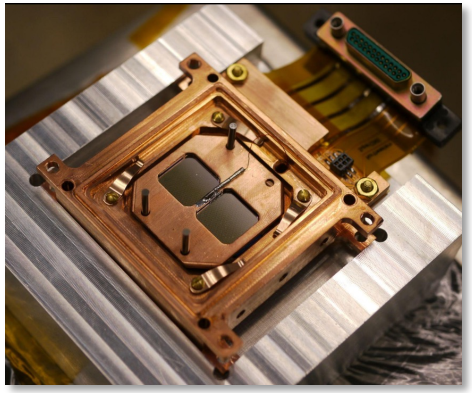
Light-tight copper housings
Attempt to reduce IR bkg
Avoid scintillating materials

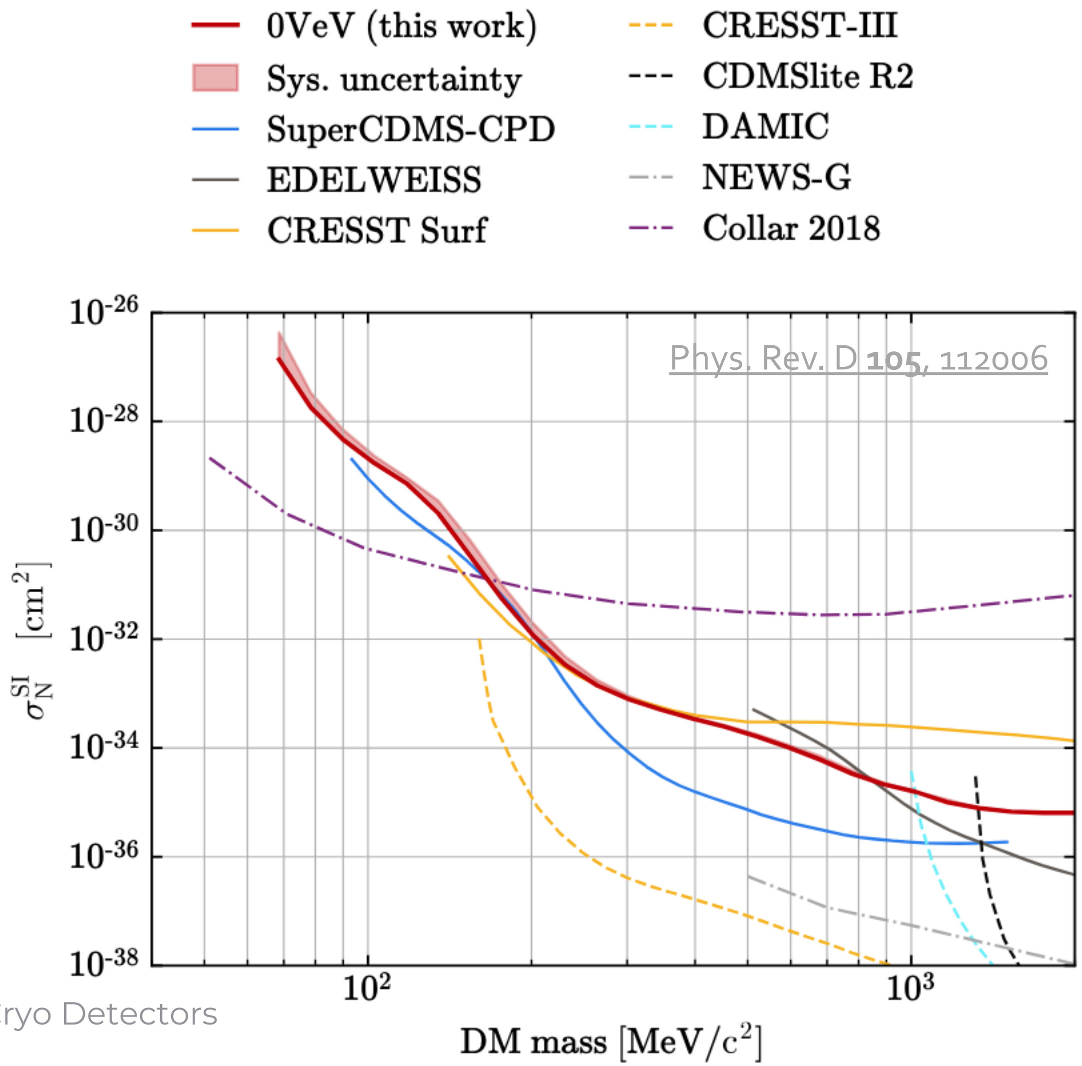
Tests at surface, NEXUS@Fermilab & CUTE@SNOLAB

W-TES



W-TES + E field



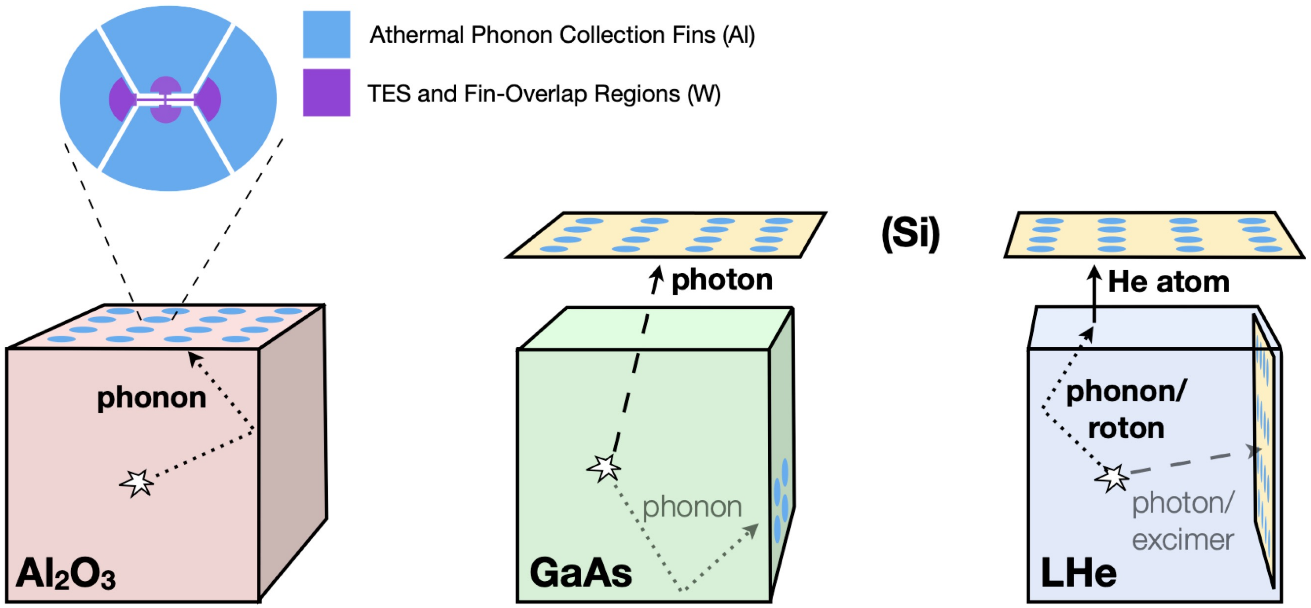


# TESSERACT @ surface

Broad R&D program

**Goals:**

- Light DM probes via various channels
- Sub-eV thresholds
- Diverse target materials
- Complementary approaches for LEE



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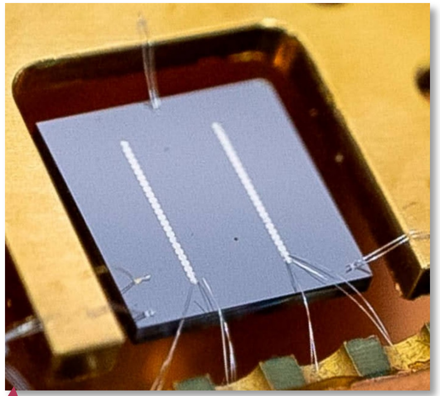
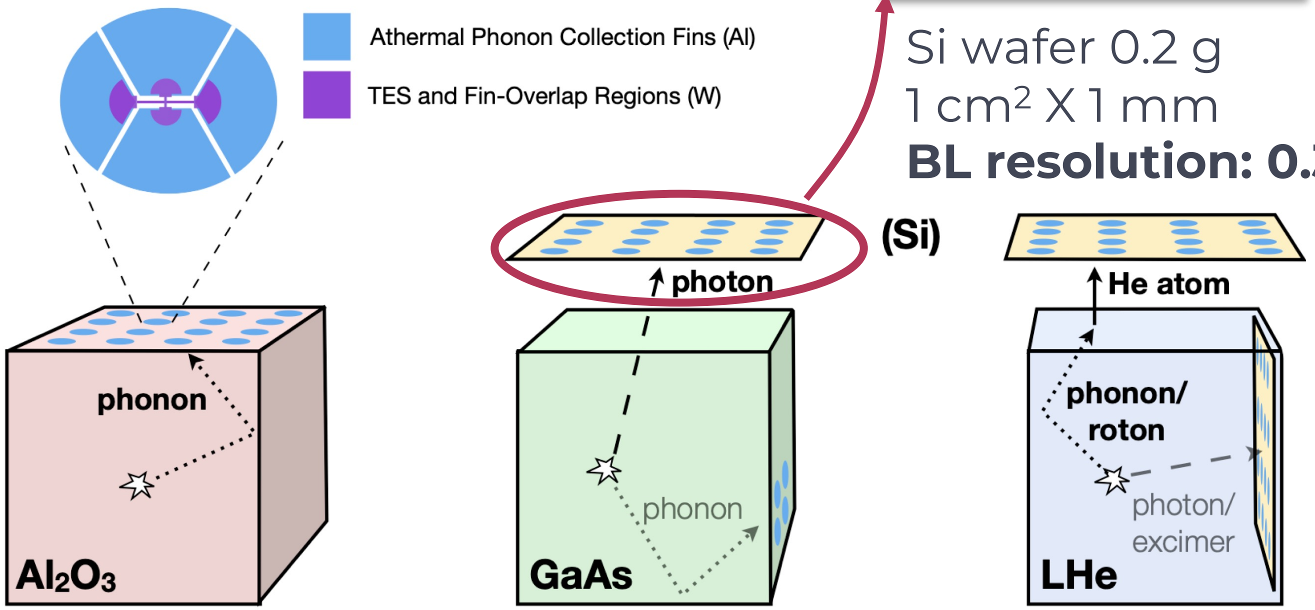


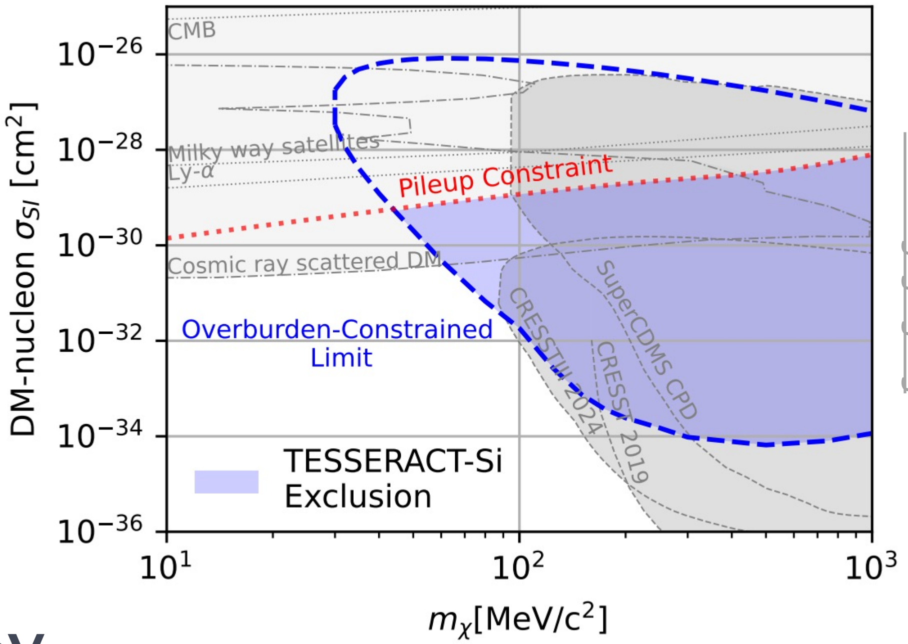
Si wafer 0.2 g

1 cm² X 1 mm

**BL resolution: 0.36 eV**

Appl. Phys. Lett. 126, 102601 (2025)



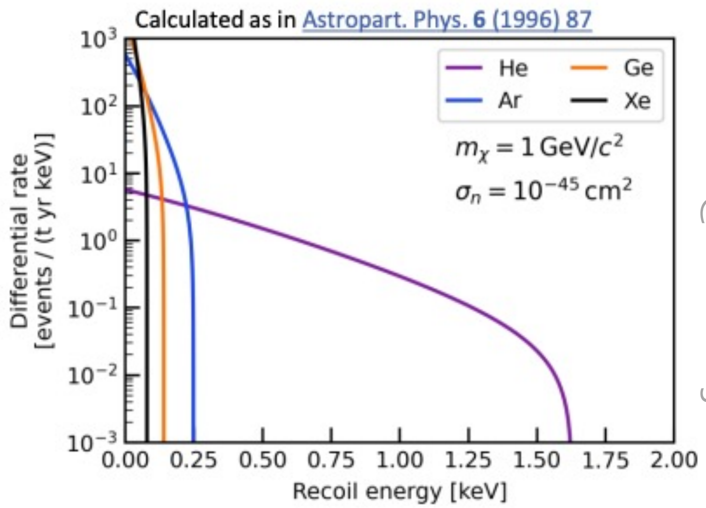

arXiv:2503.03683

**Search down to 44 MeV DM mass**

**Next**: Targeting 2028 for underground installation @Modane (LSM)

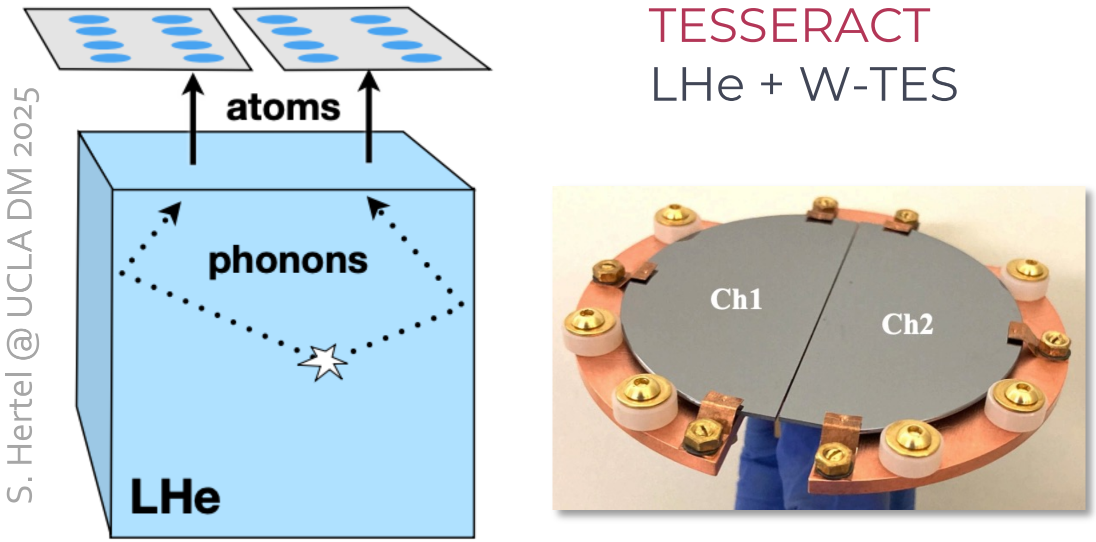
# Superfluid $^4$He target

**$^4$He advantages:**
- Very light nuclei
- Scalability
- Superfluid state
  → no stress-related LEE




F. Toschi @ TAUP 2023

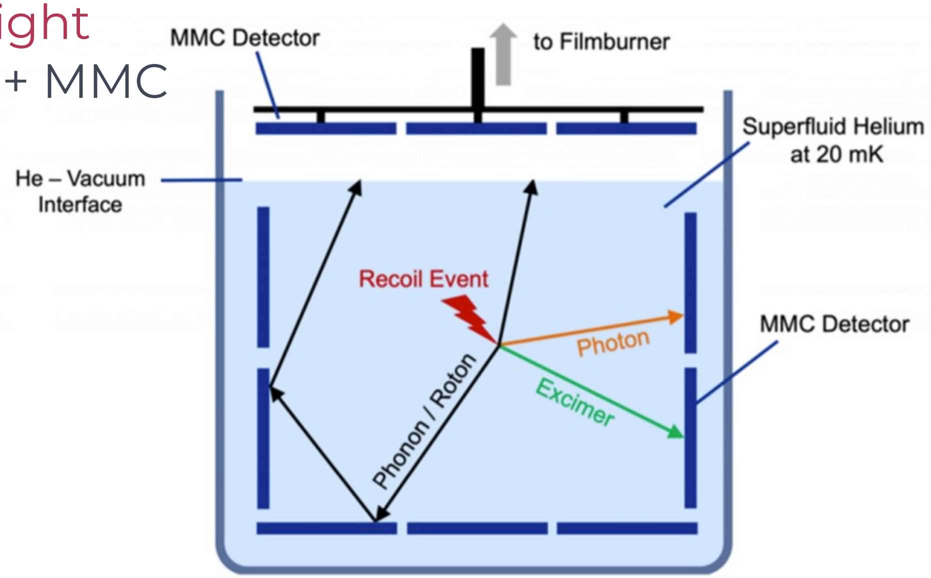
**Development in progress**




S. Hertel @ UCLA DM 2025

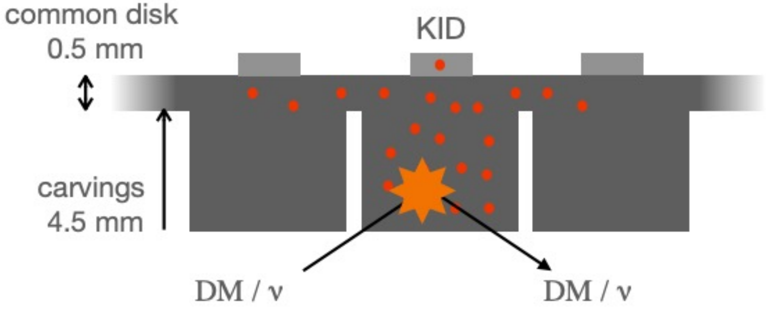
TESSERACT
LHe + W-TES

DELight
LHe + MMC




SciPost Phys. Proc. 12, 016 (2023)

# BULLKID




Si [D. Delicato et al EPJ C 2024]

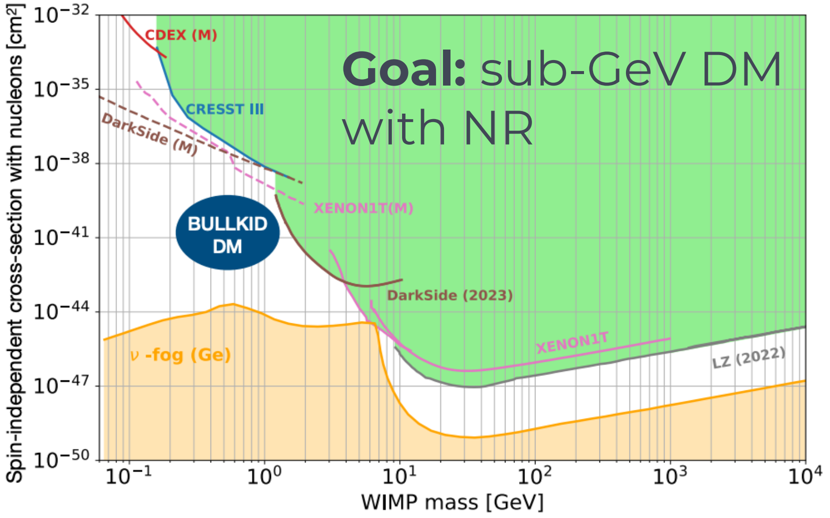
0.34 g x 60 dice = 20 g

$E_{thr}$ = 160 eV

@surface

+ Ge prototype

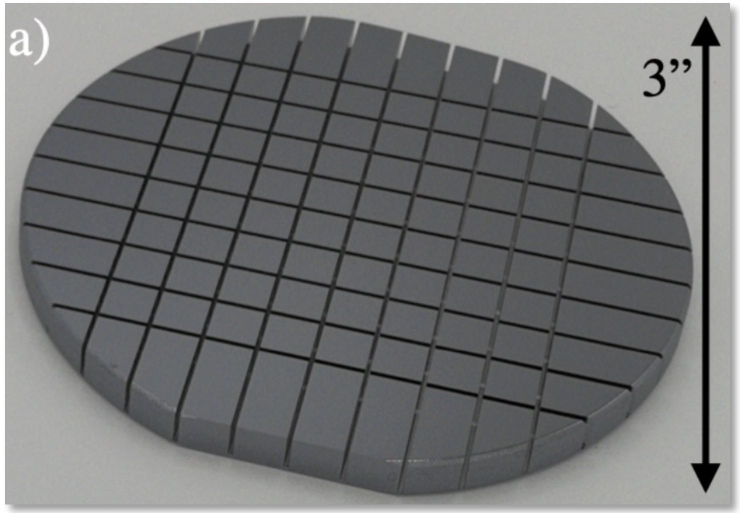
D. Delicato et al: arXiv:2412.07379

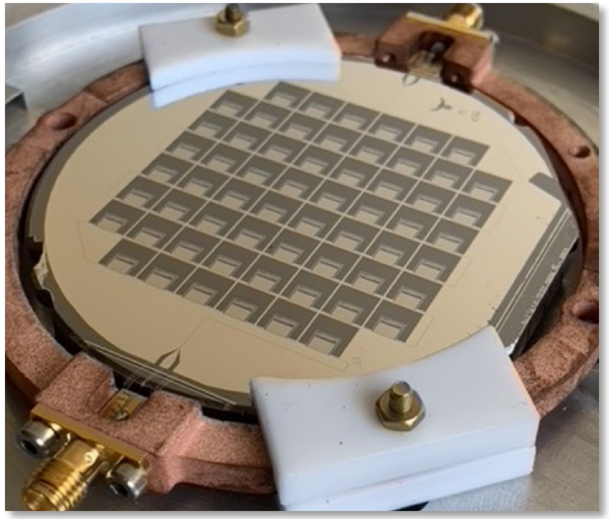



M. Vignati@IDM2024

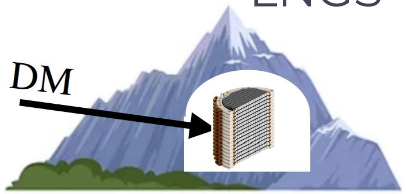
- Monolithic array → Phonon leakage is used to identify the dice with interaction
- Fully multiplexed = single readout line

A. Cruciani, et al, Appl. Phys. Lett. 2022



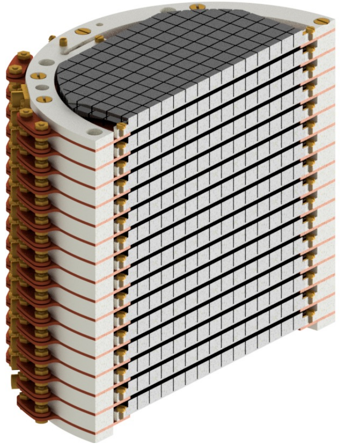



**Next:** BULLKID-DM @ LNGS (2027)




Scalability:
- 800 g of Si
- 2300 detector dice

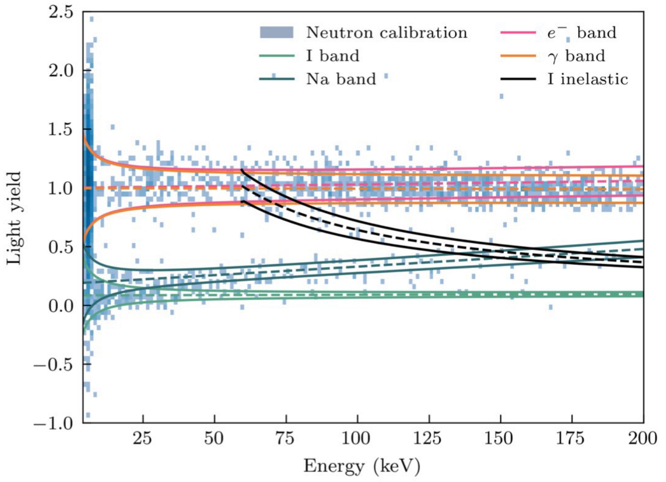
Background:
- fully active
- fiducialization (600 g)



# COSINUS @ LNGS

**DAMA/LIBRA's claim:** positive evidence for the presence of DM particles in the galactic halo via DM annual modulation

**Goal of COSINUS:** model-independent test of DAMA with:
- same material
- signal-to-background discrimination




PRD 110, 043010, 2024

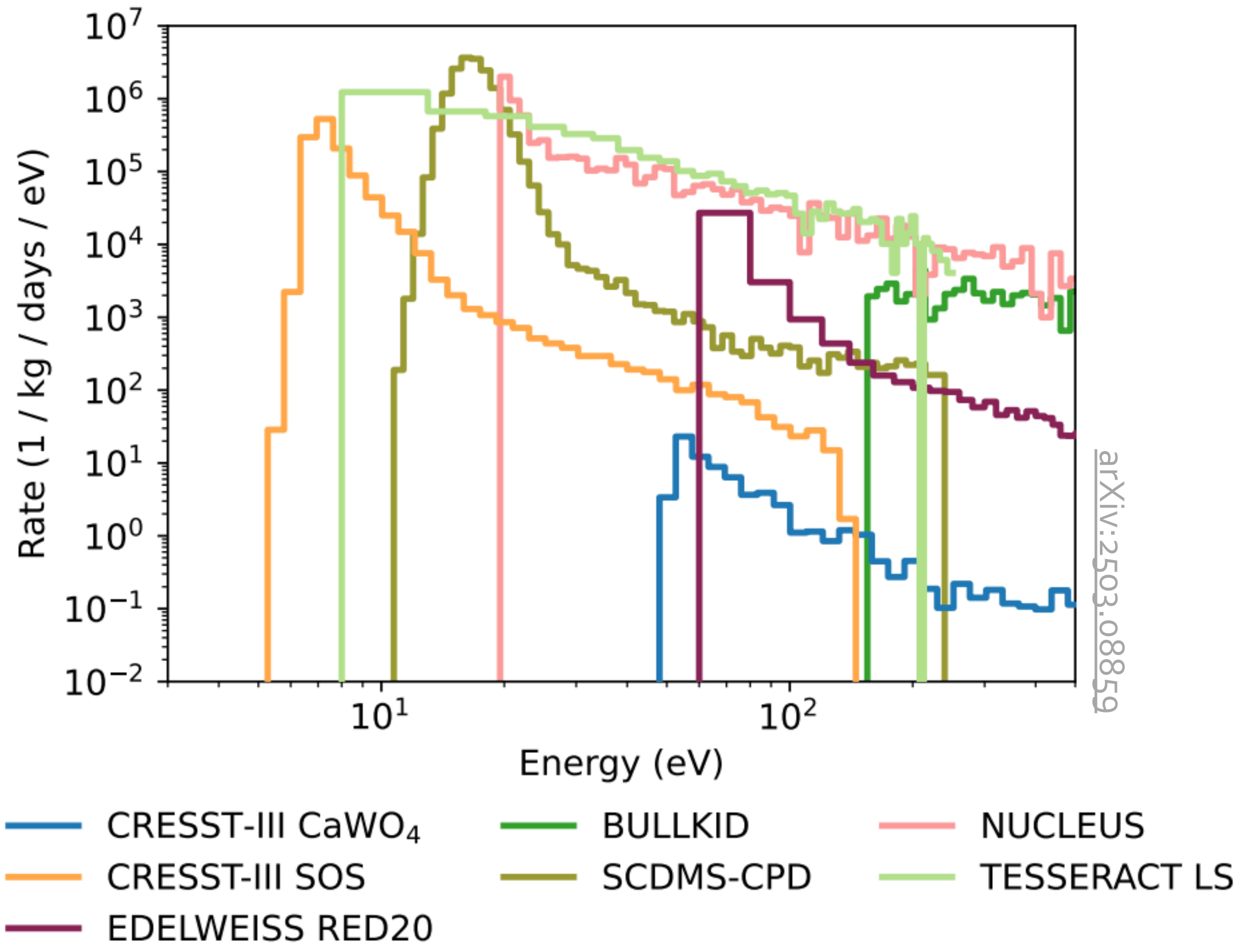
**First data taking is expected to start within 2025**

NIMA 1045, 167532

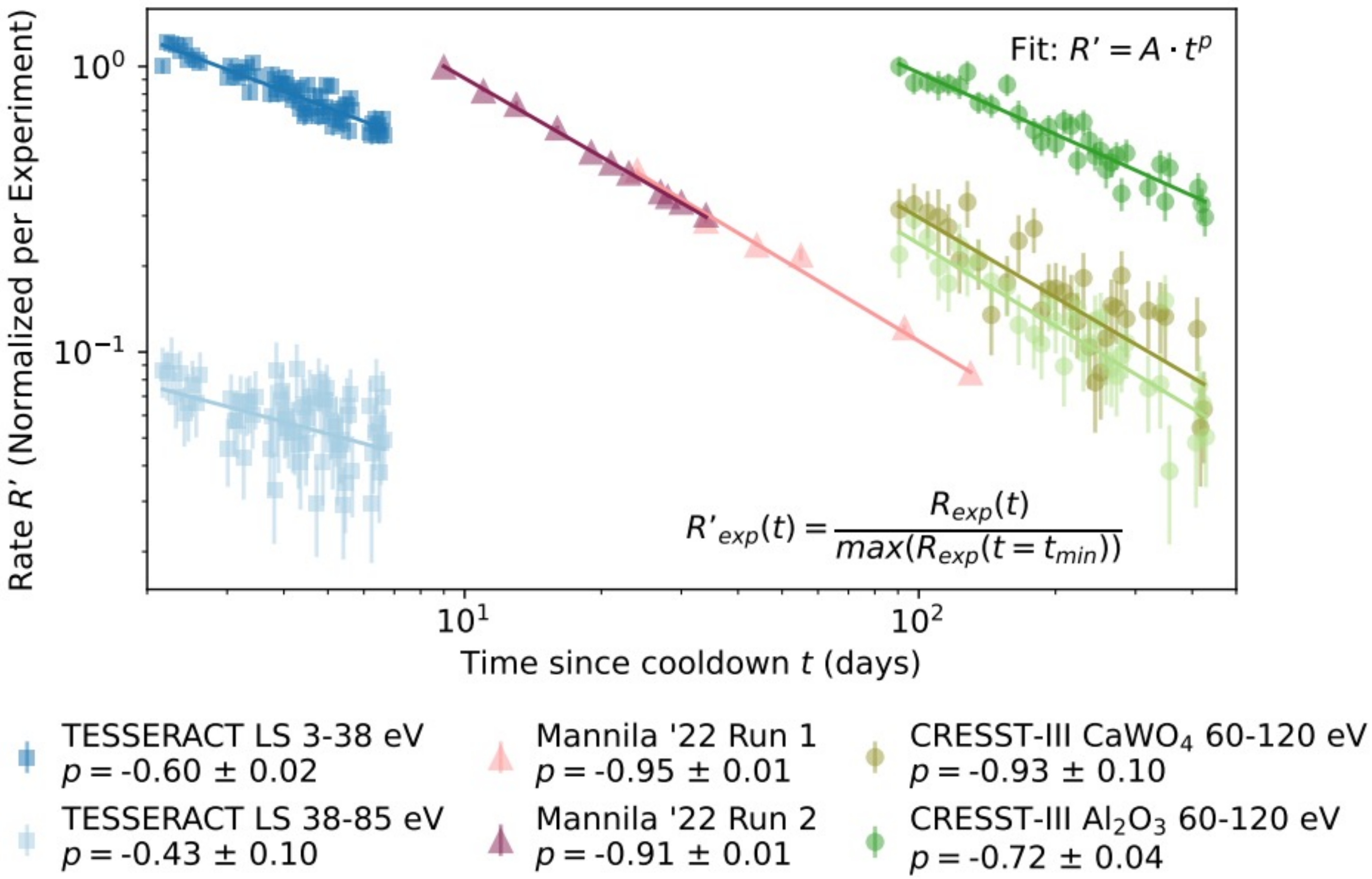
remoTES readout (W-TES on $Al_2O_3$-wafer)
NaI 3.7 g, 1 $cm^3$
Si beaker as a light detector
$\sigma_{BL}$ = 0.441 keV
+Muon veto water tank

New setup at LNGS

# Low-Energy Excess Investigations



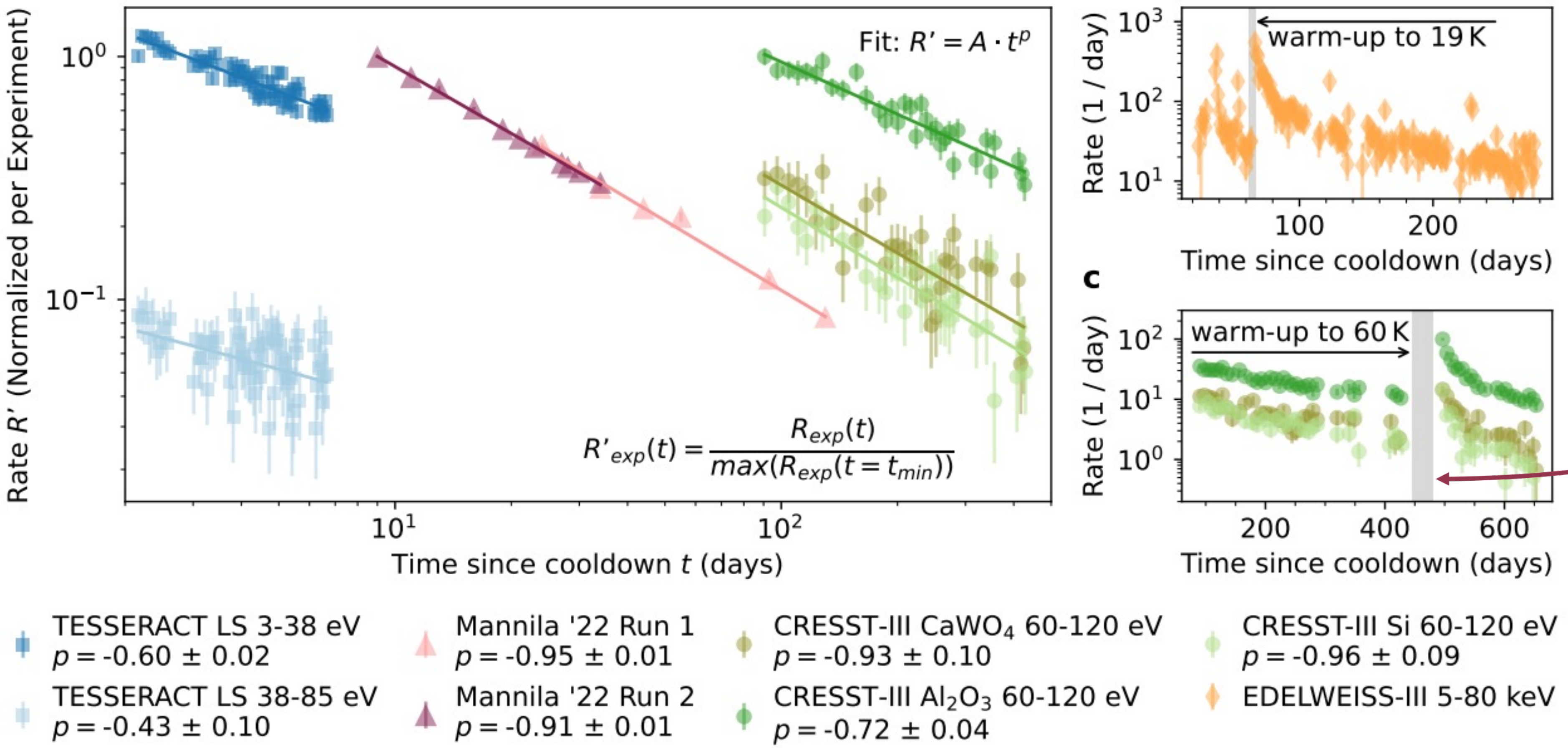
# LEE rate decays with time at cold




arXiv:2503.08859

# LEE rate decays with time at cold

arXiv:2503.08859




Warm-up to tens of K resets the LEE rate

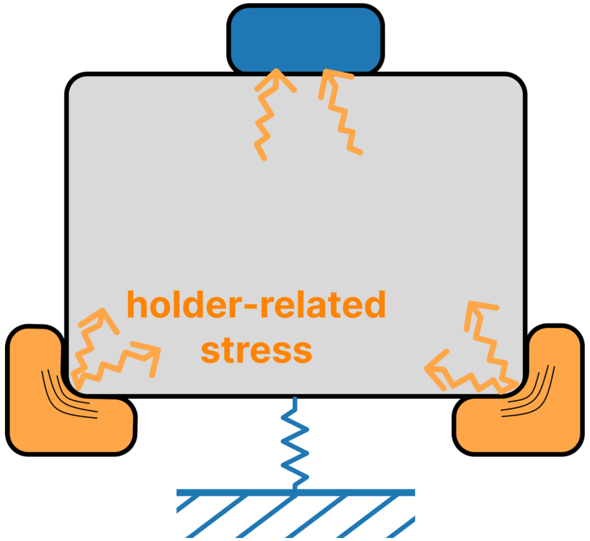
**No particle background**

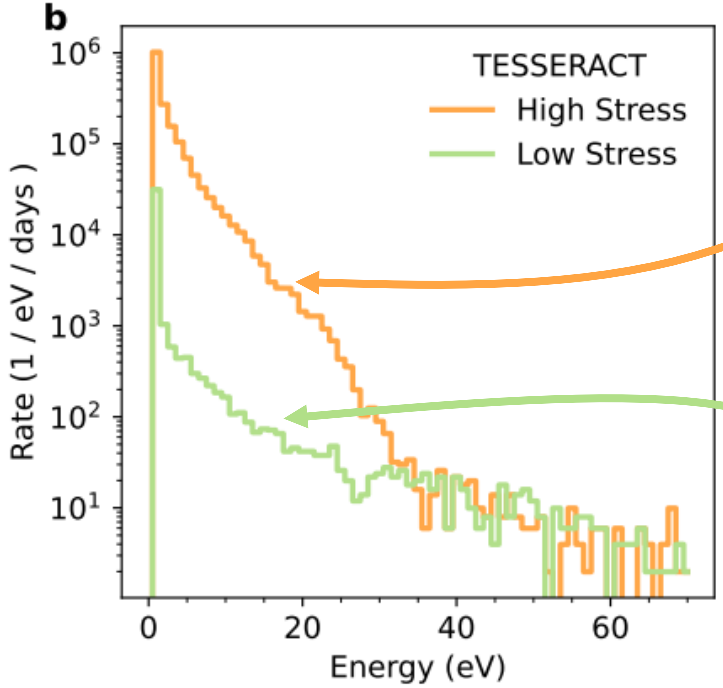
# Possible LEE origin: stress…
# from holding structures

**Stress from the holding can induce excess signals**

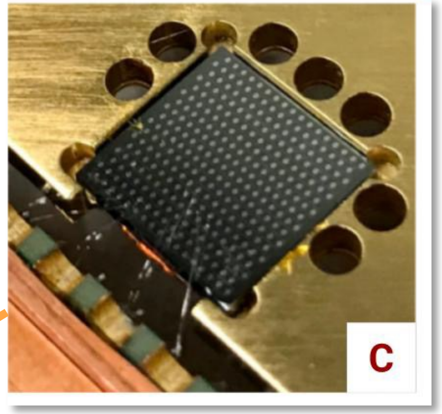
BUT: holding alone is probably insufficient to explain all LEE events

arXiv:2503.08859

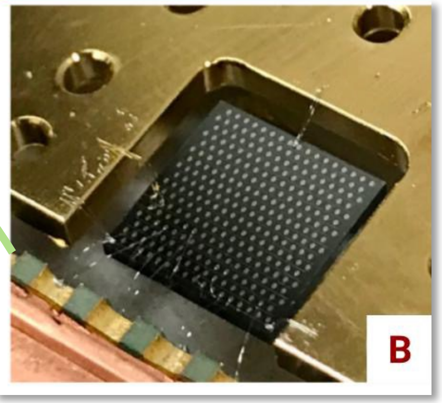



**TESSERACT**




Glued = high stress




Hanging = low stress

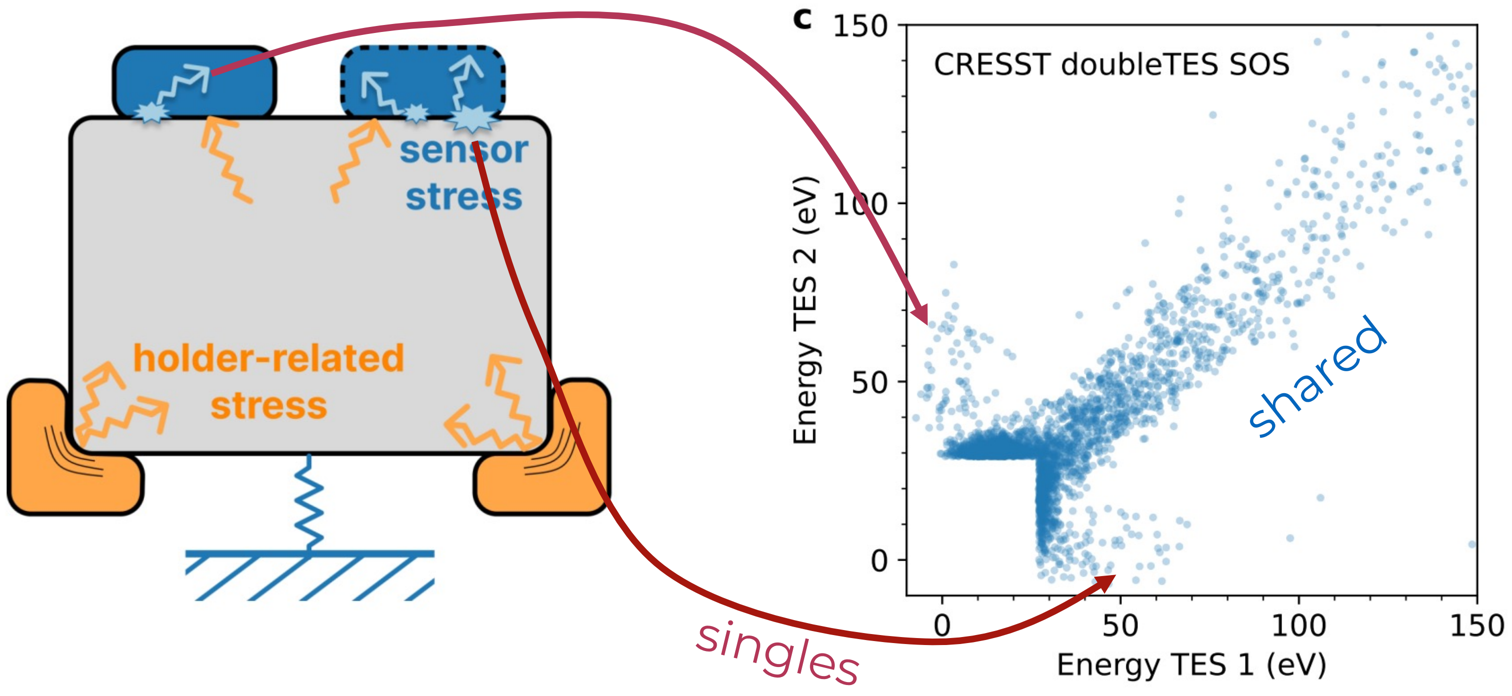
Nat Commun 15, 6444 (2024)

**Mitigation strategies:**

1. Reduce external stress from the holders (CRESST, TESSERACT)
2. Instrumented holders (CRESST)

# Possible LEE origin: stress… from the sensors

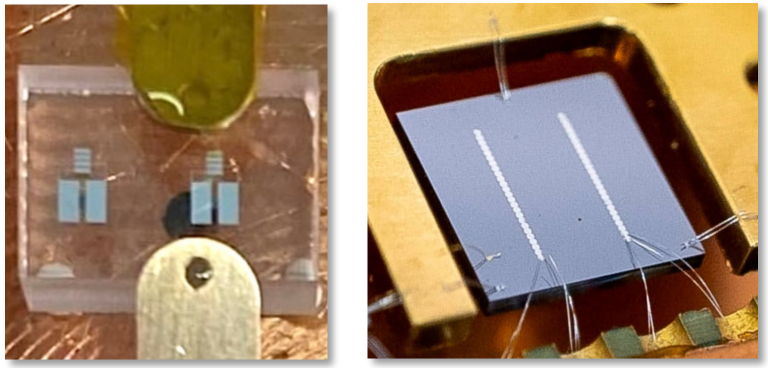
Observation of single (one TES) and shared (two TESs) excess events



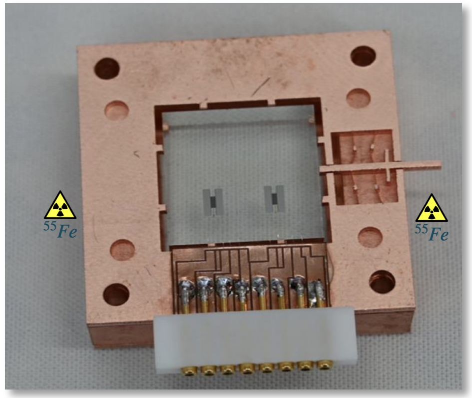

arXiv:2503.08859

→ **LEE has (at least) two components**

MK, PhD Thesis, TUM



Appl. Phys. Lett. 126, 102601 (2025)

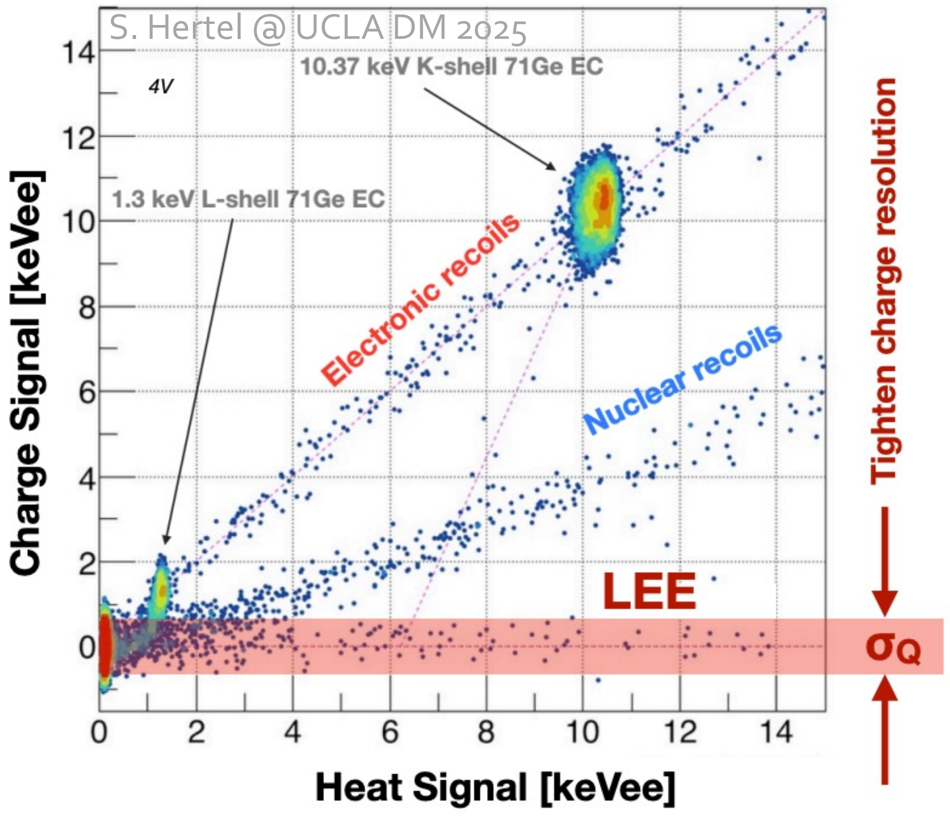



EPJ C (2024) 84: 1001

DoubleTES approach to reject singles:
CRESST
TESSERACT
NUCLEUS

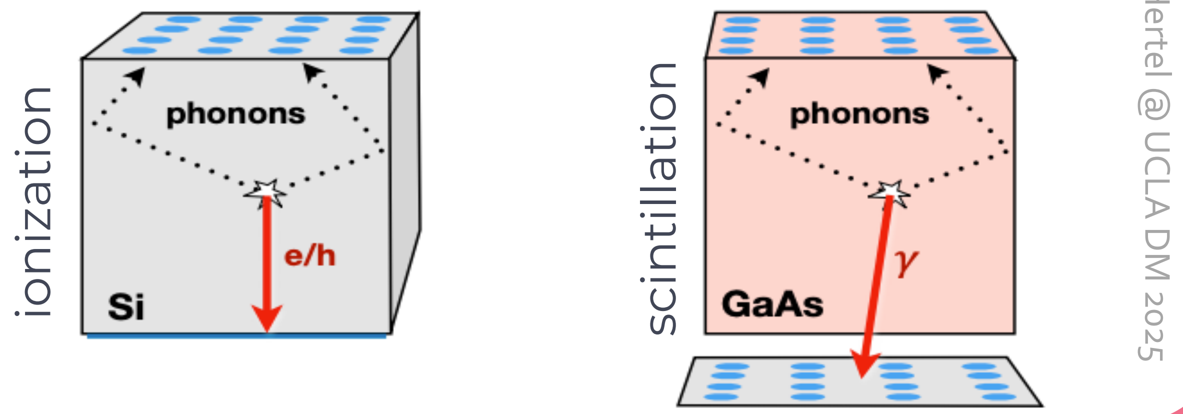
# Phonon excess is not ionizing

**No particle background**



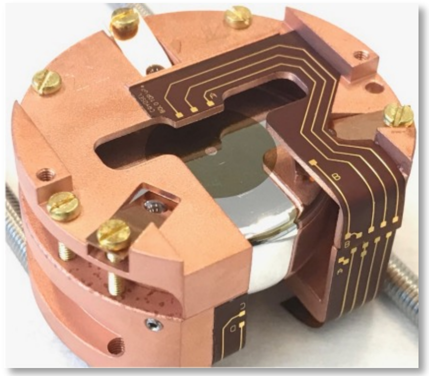

EDELWEISS, Ricochet expertise

TESSERACT: push LEE discrimination threshold down to phonon threshold




Edelweiss CRYOSEL:
40 g Ge HV detectors (200 V)
→ NTD for heat signal
→ identify athermal phonons from phonon heat-only events using the NbSi TES

Phys. Rev. D **108**, 022006



# EXCESS Workshop Initiative

[Publicly available data repository](#)


2023, Vienna

Jun. 2021 (online)
Feb. 2022 (online)
Jul. 2022 (@IDM, Vienna)
Aug. 2023 (@TAUP, Vienna)
Jul. 2024 (@IDM, Rome)

Registration is open!

**Soon:**
**Jun. 2025 (@LTD, Santa Fe)**

**2022**: Joint status report paper from 11 collaborations
*SciPost Phys. Proc (2022).*

**2025**: Review accepted for publication in Volume 75 of the Annual Review of Nuclear and Particle Science
arXiv:2503.08859v1


2022, Vienna

2024, Rome

# Phonon LEE: status

Remarkable similarities between experiments in energy scales and rate time-evolution.

LEE does not have a particle origin and is not ionizing.

LEE has multiple components.

Stress from holders and from the sensors seem to contribute to the LEE.

LEE investigation is currently the main driver of the cryogenic detectors detector development.

Broad R&D programs for:
- identifying LEE origins
- mitigating the LEE rates

# Conclusions

**eV-scale detector thresholds** already enable:
- tens of MeV DM search with NR
- MeV-scale DM with ER

Cryogenic DM detectors gave a start to **coherent elastic neutrino-nucleus scattering experiments**:
- CRESST → NUCLEUS
- EDELWEISS → Ricochet

…

Input to the neutrino fog background.

**Realizing full potential requires mitigation of low-energy backgrounds!**

Broad detector development programs:
- new detector designs
- new sensors
- new materials
- new interactions
- Investigation of the detector response in the eV-range

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**Thank you!**