TESSERACT

TESSERACT @ LSM

A new generation light DM search cryogenic experiment in Modane

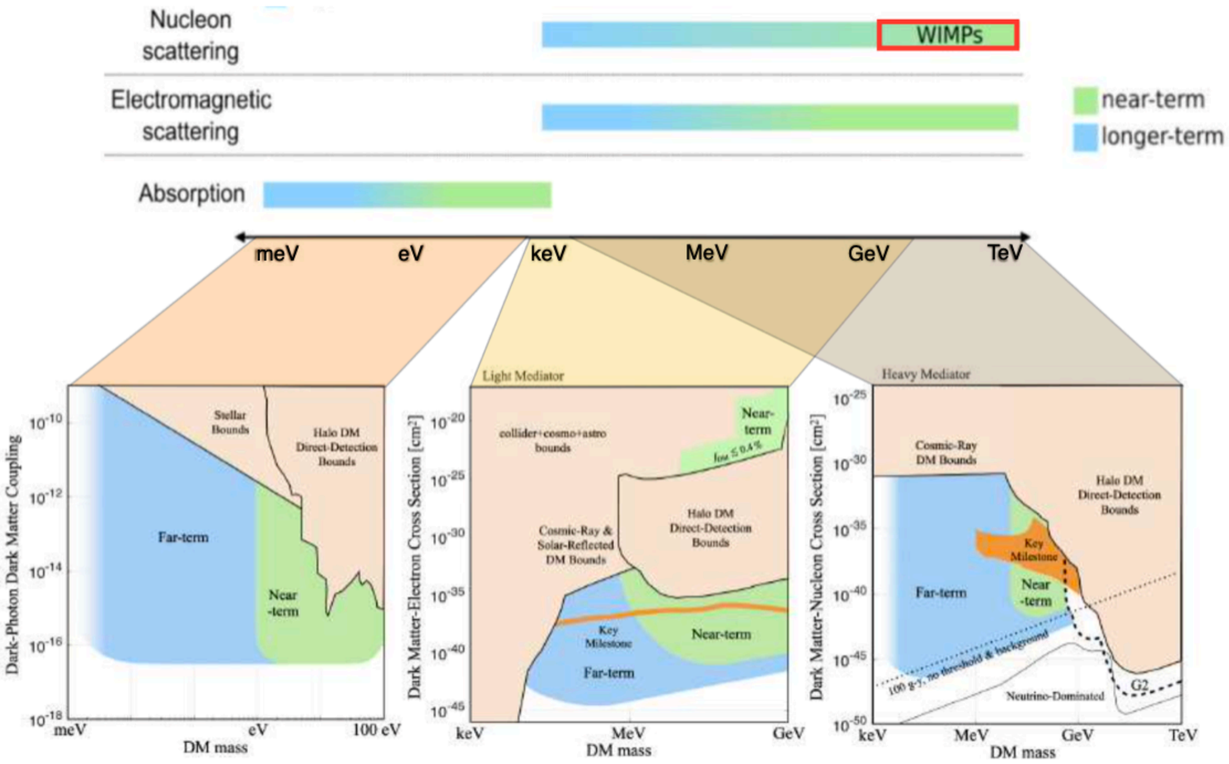
J. Billard (IP2I)
on Behalf of the TESSERACT collaboration

Dark Matter Symposium
November 4th, 2025

TESSERACT@LSM: Introduction

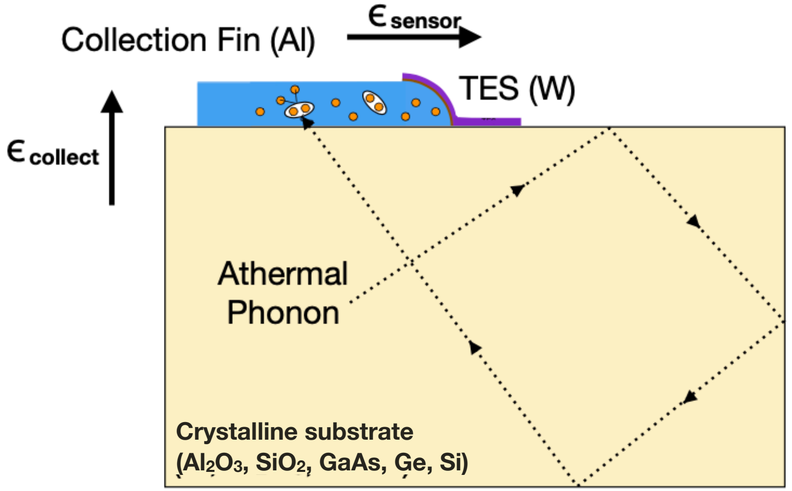
TESSERACT aims at extending the direct dark matter mass range from meV-to-GeV using phonon mediated cryogenic detectors with:

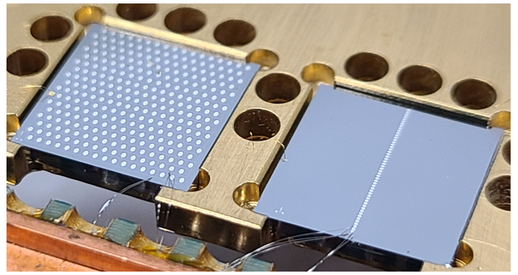
1. sub-eV energy thresholds
2. background rejection capabilities
3. diverse target materials with diverse DM couplings
4. ultra quiet underground cryogenic infrastructure at LSM

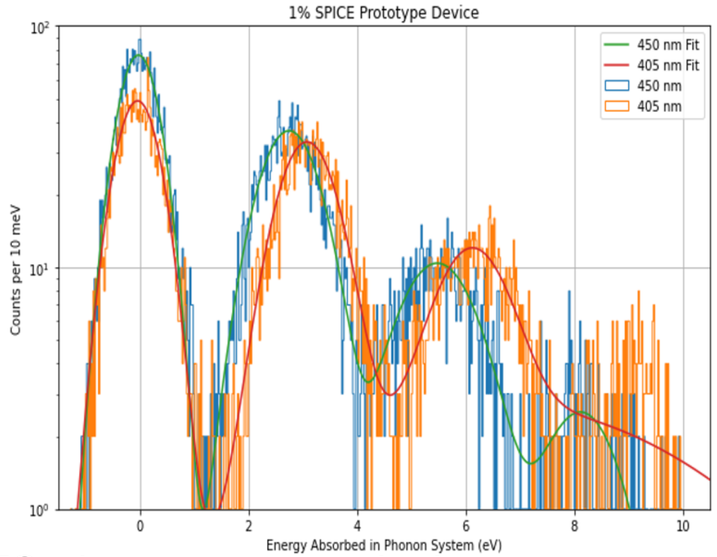


TESSERACT@LSM: TES phonon sensors

TES based athermal phonon sensor technology:







$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

$$\sigma_E \propto V_{det}^{1/2} T_c^3$$

Energy threshold decreases with detector mass

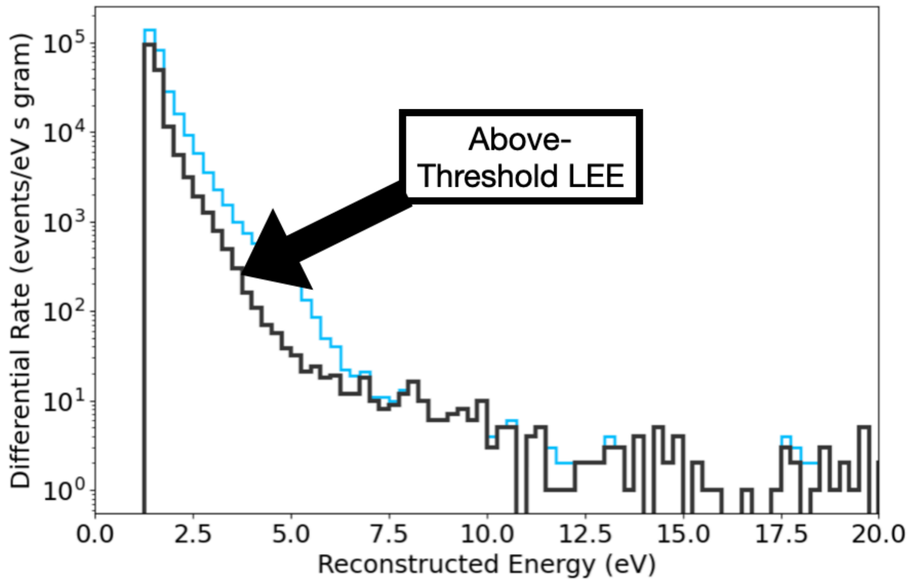
Energy threshold decreases very quickly with Tc

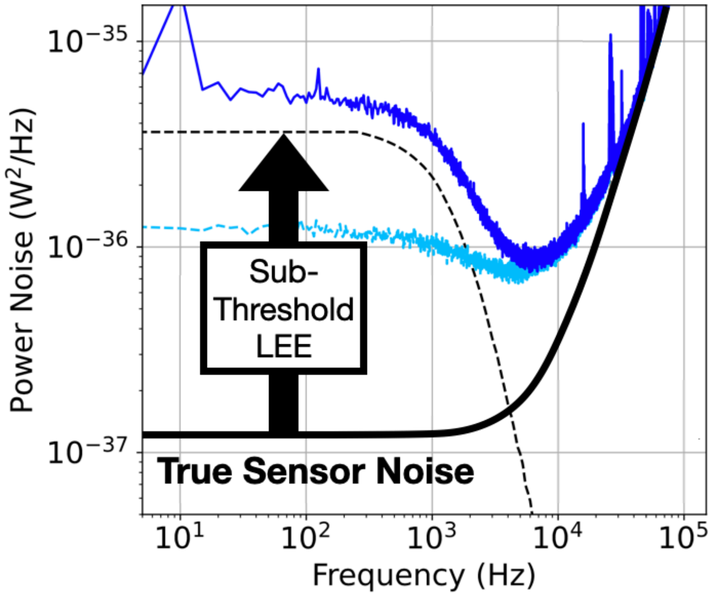
- Intense R&D efforts to optimize TES phonon sensor design:
  - Match TES and phonon collection bandwidths, Tc, and TES volume
- **273 meV (RMS) leading to eV-scale threshold already achieved** with a 0.2g Si detector and Tc = 50 mK
- Targeted Tc around 15-20 mK recently achieved

  ~100 meV threshold achievable on 1 cm³ crystals
- **BUT …**

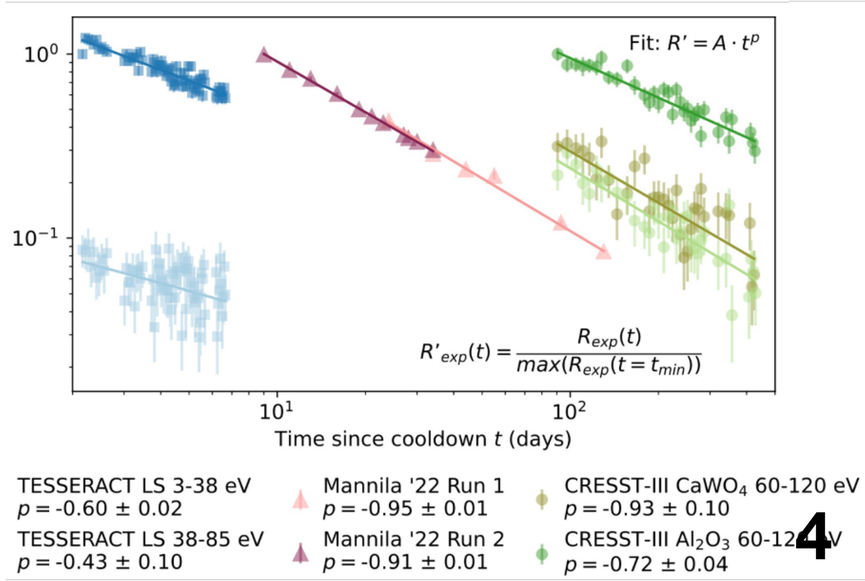
TESSERACT@LSM: Low-E excess

- Observation of a strong Low Energy Excess of events in **ALL** low-threshold cryogenic experiments limiting their DM sensitivity
- The LEE is both the largely dominating background at the lowest energies **AND** limiting our phonon baseline energy resolution !
- LEE characteristics: **time dependent**, **non-ionising**, and mostly independent of sites
- Design driver of TESSERACT: *1) find the origin of the LEE to mitigate it*, and *2) develop detector technologies that can reject it*
- Possible connection to anomalously short coherence time in Q-bits seeing high **decreasing over time** quasiparticle density

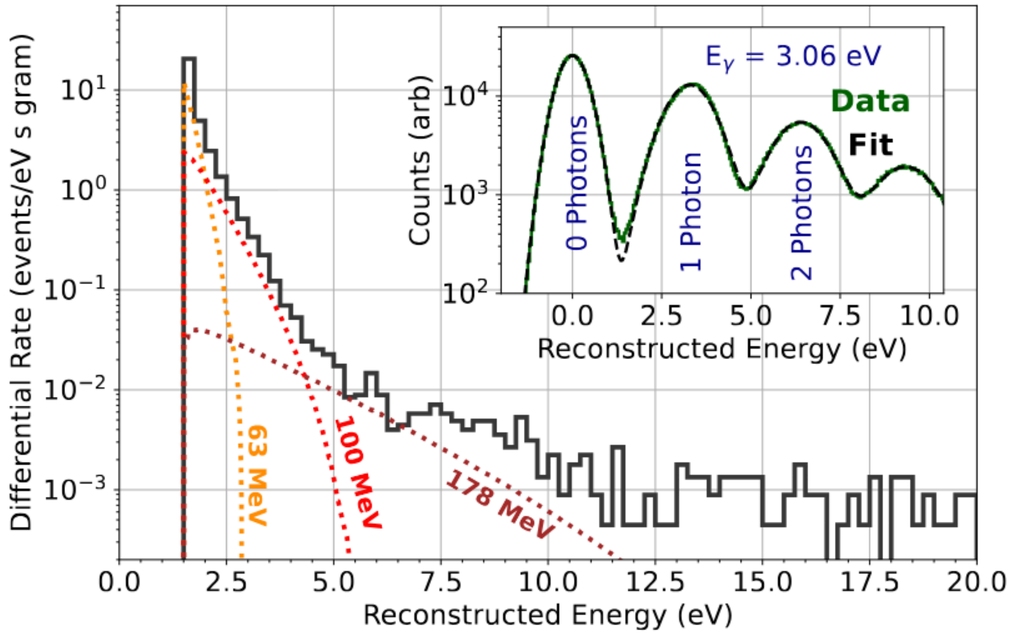


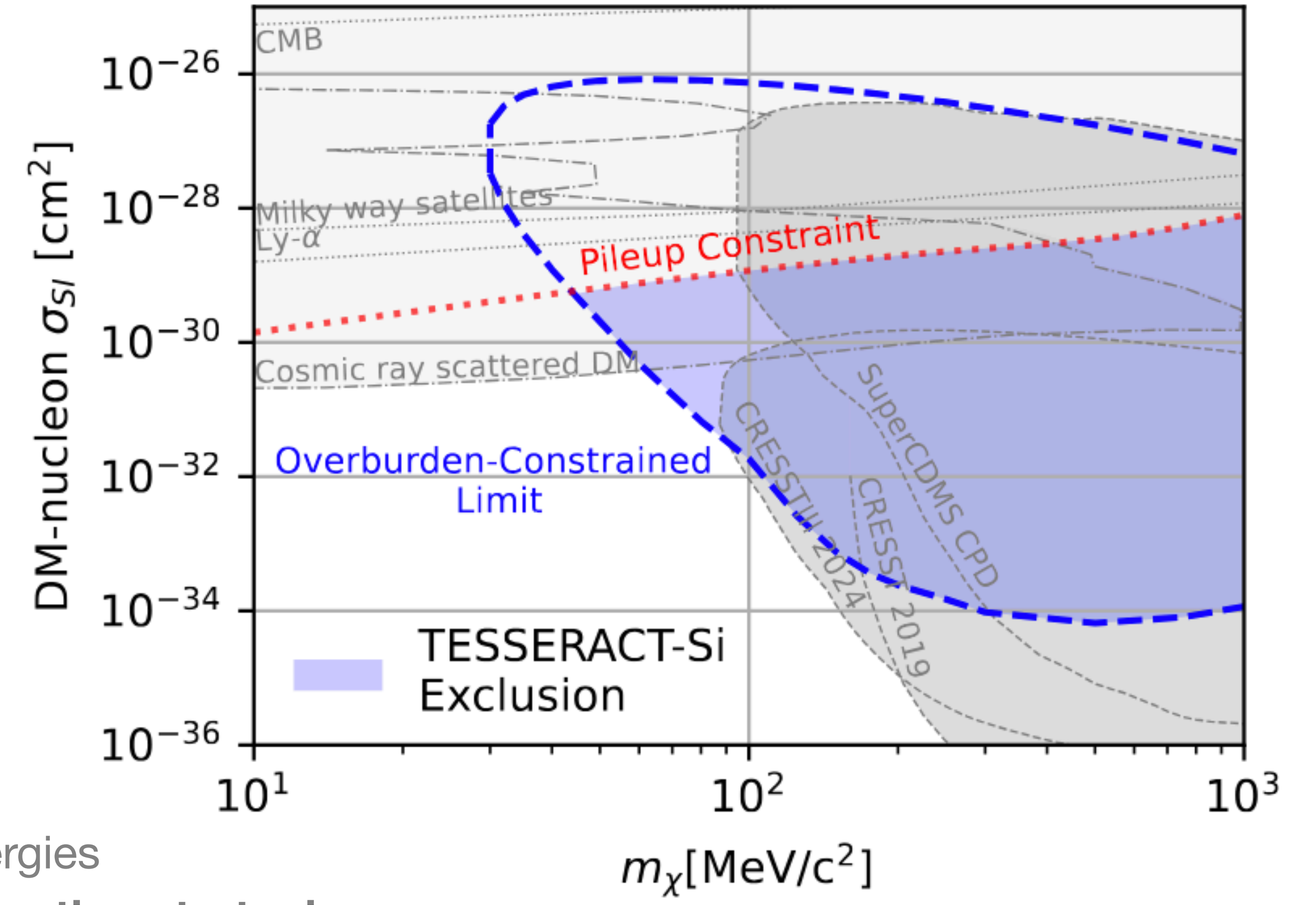


arXiv: 2503.08859



TESSERACT@LSM: First surface DM search

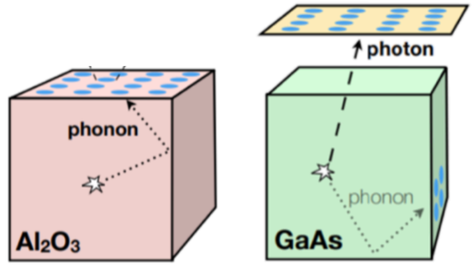




First TESSERACT DM limit — arXiv:2503.03683

- World-leading 1.45 eV energy threshold !
- Leading between 44 MeV and 87 MeV
- Limited by the overwhelming LEE at the lowest energies
  - **Need LEE discrimination techniques and mitigation strategies**

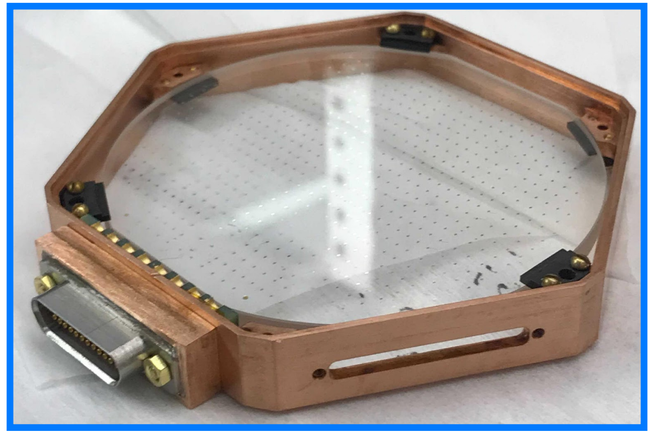
TESSERACT@LSM: SPICE

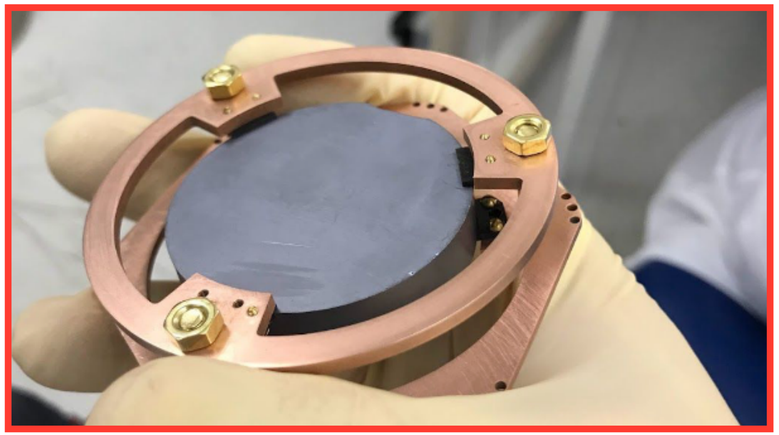


Sub-eV Polar Interactions Cryogenic Experiment

Sapphire (Al_2O_3):

- Sapphire supports many optical phonon modes (~100 meV).
- Optical phonons kinematically well-matched to low-mass DM → effective energy transfer
- Coupling to E&M-like inputs due to electric dipole → dark photon sensitivity
- *LEE mitigation:* Use of two TES-channels to suppress sensor induced LEE



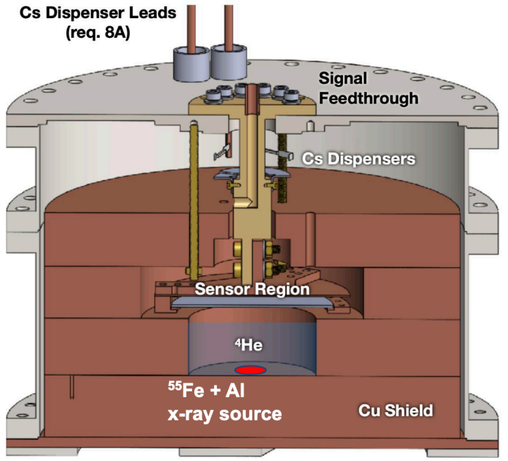


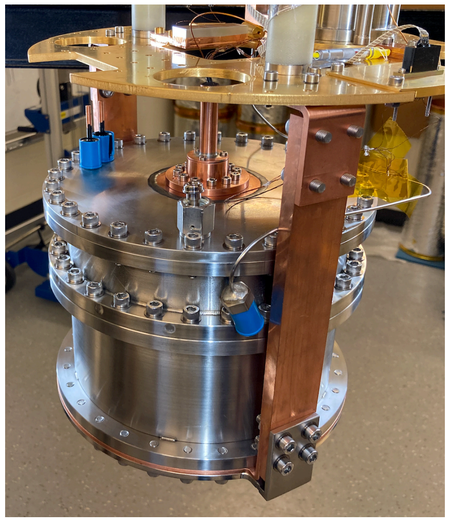
GaAs:

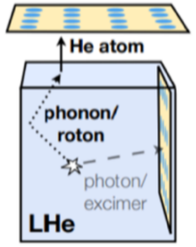
- Polar crystal & bandgap well matched to kinematic region of low mass DM
- Background discrimination using phonon/photon ratio
- *LEE mitigation:* phonon-photon and coincidence

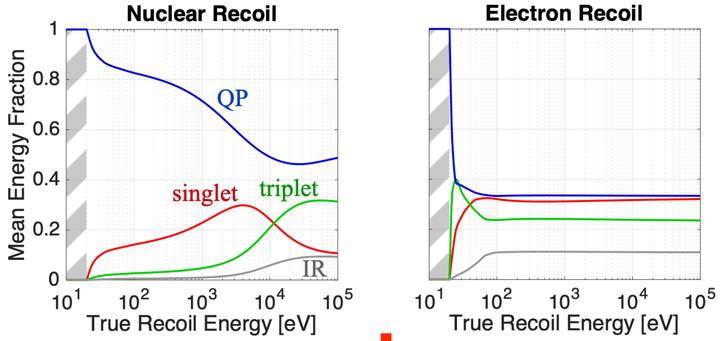
TESSERACT@LSM: HeRALD

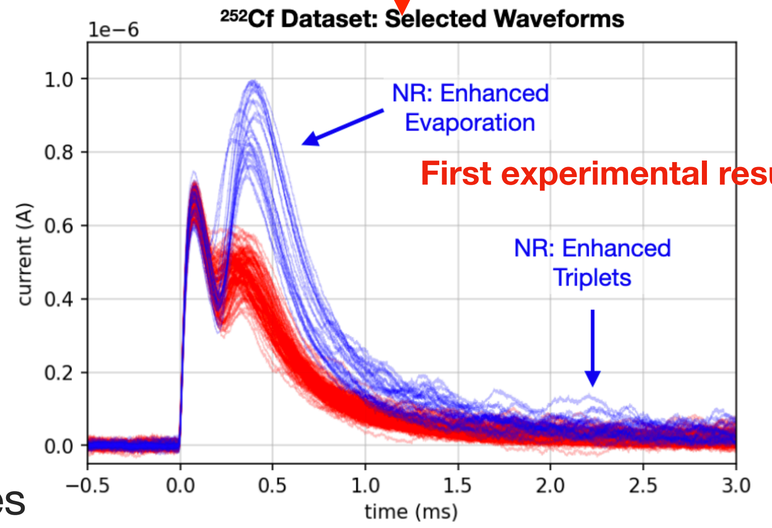
Helium Roton Apparatus for Light Dark matter











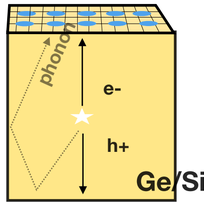
- Well kinetically matched to GeV-scale DM
- Easy to purify, intrinsically radio pure
- LHe cell operated at 20-50 mK with wafer-like cryogenic detectors with TES suspended in vacuum
  - UV/IR photons and **He atoms** from qp induced evaporation
- **First evidence of ER/NR discrimination @10 keV**
- **Already achieved ~170 eV threshold on He recoils (300 MeV DM)**
- *LEE mitigation:* multi-channel evaporation readout to reject LEE via coincidences

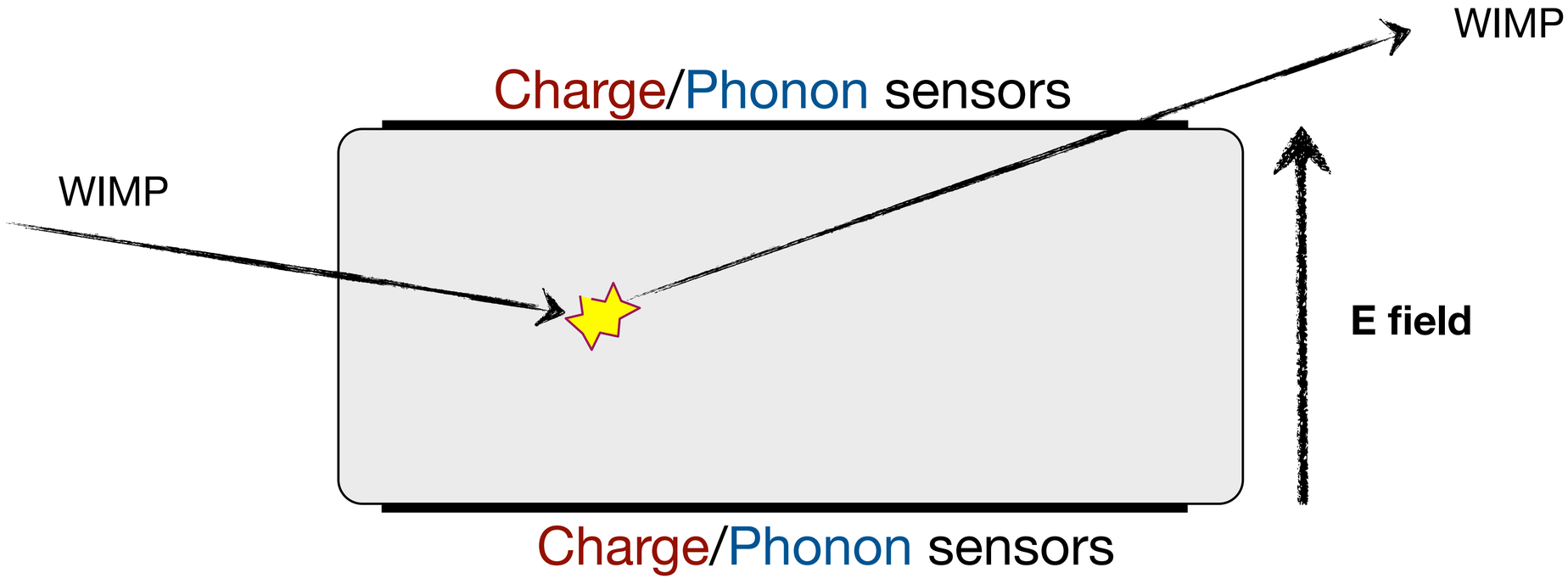
R. Anthony-Petersen et al., arXiv:2307.11877

[see K. Morå's talk on Wednesday]

TESSERACT@LSM: Ge/Si semiconductors

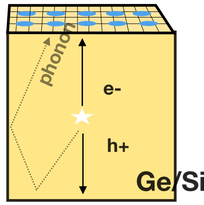
Introduction to the dual heat and ionization readout:

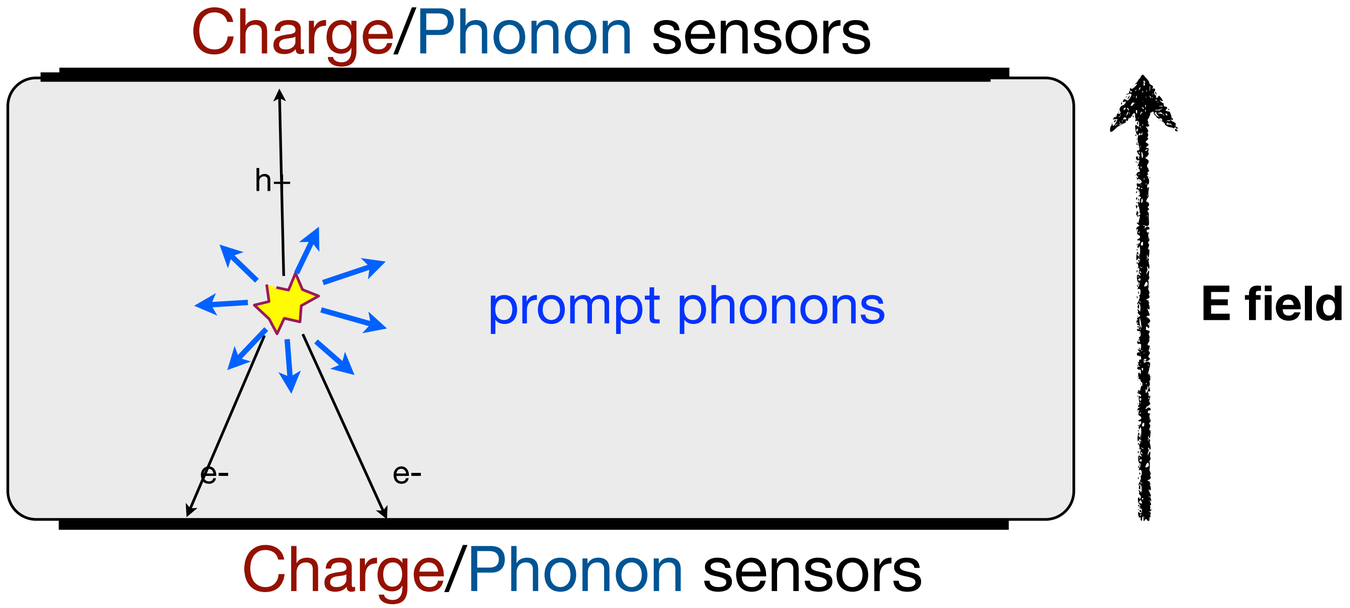




TESSERACT@LSM: Ge/Si semiconductors

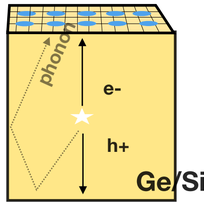
Introduction to the dual heat and ionization readout:

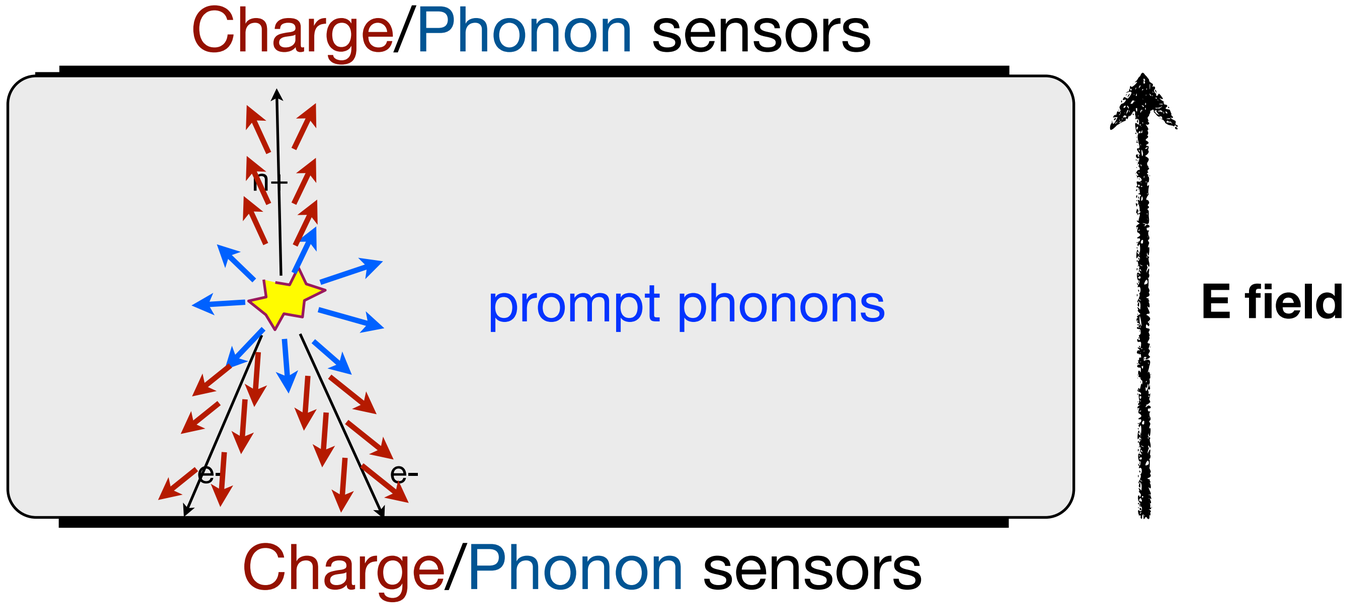




TESSERACT@LSM: Ge/Si semiconductors

Introduction to the dual heat and ionization readout:



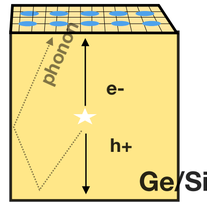


$$E_{total} = E_{recoil} + E_{luke}$$

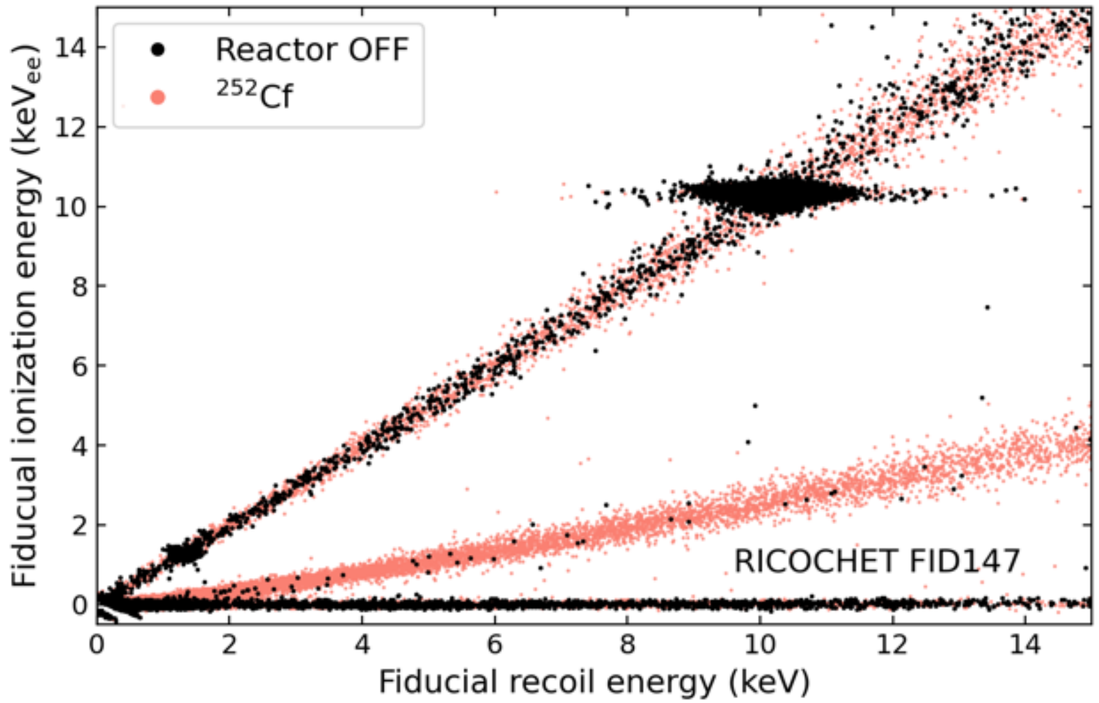
$$= E_{recoil} + \frac{1}{3\,eV} E_{ion}\Delta V$$

TESSERACT@LSM: Ge/Si semiconductors

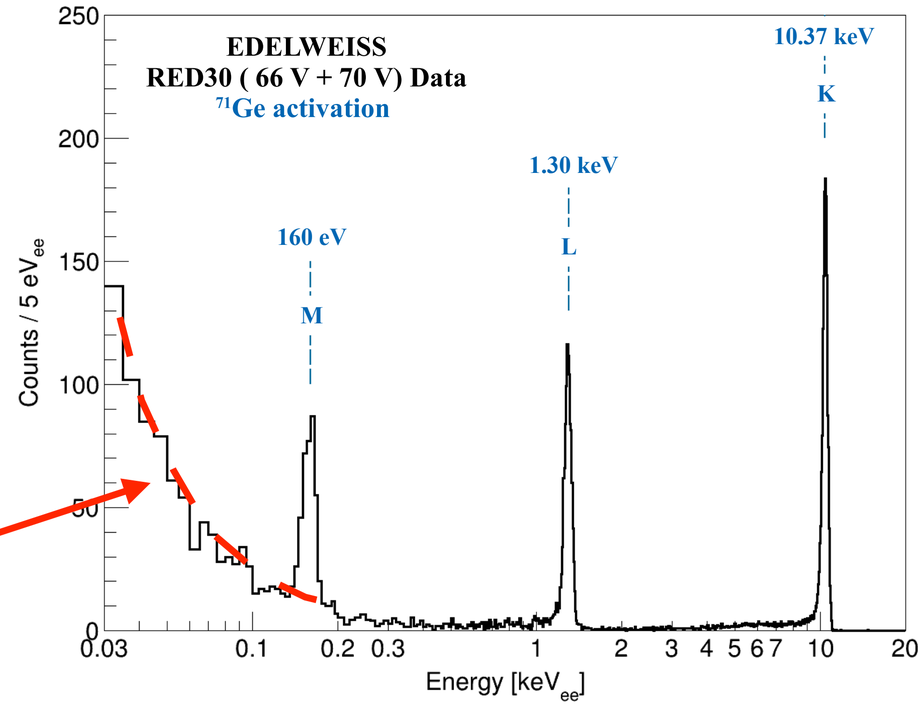
$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\ eV} E_{ion}\Delta V$$



Low Voltage mode
Ideal for NRDM



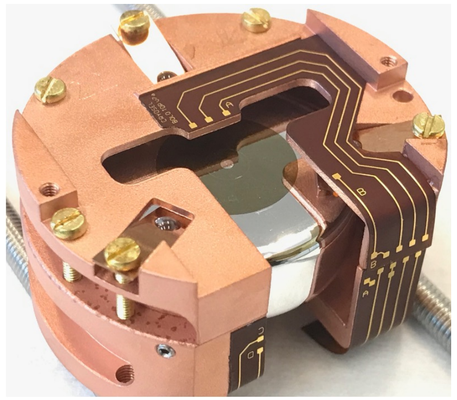
High Voltage mode
Ideal for ERDM

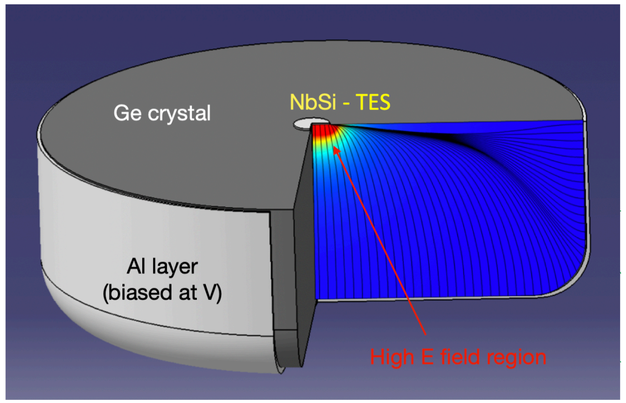


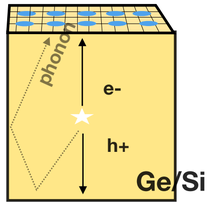
LEE

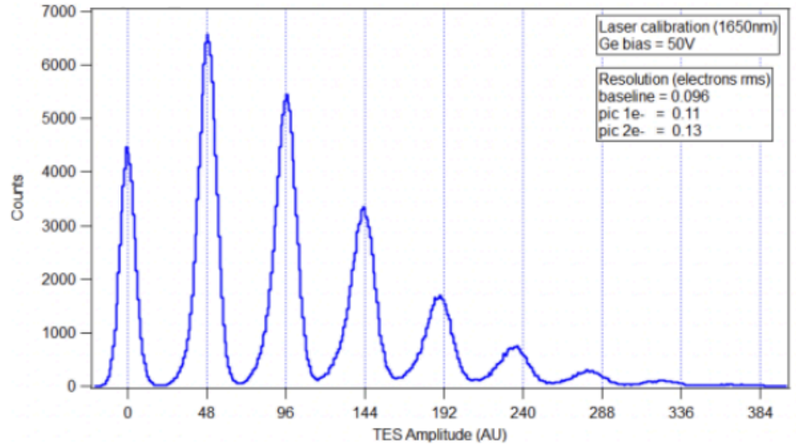
TESSERACT@LSM: Ge/Si semiconductors

High-Voltage approach for optimal ERDM sensitivity



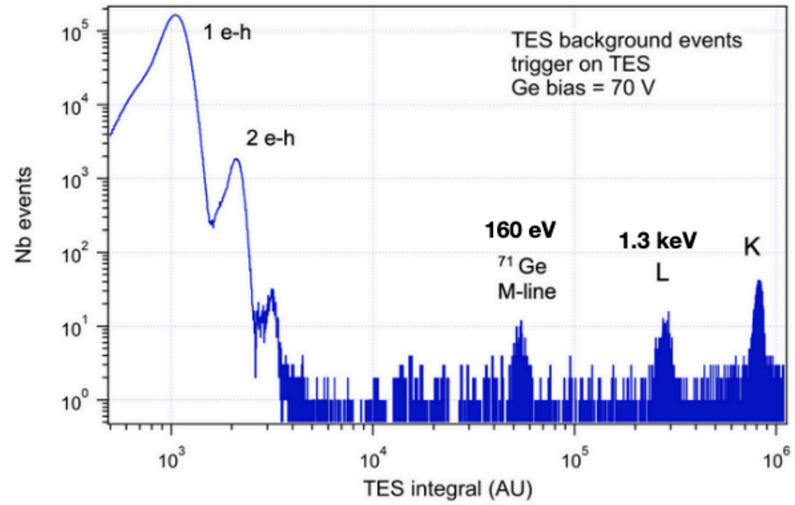






Word leading massive Ge detector with unprecedented single-electron threshold (CryoSEL)

- 40g HPGe crystal with point contact geometry for localised NTL amplification
- Low-imp. TES and SQUID readout : **0.1 electron-hole RMS** @ 50V

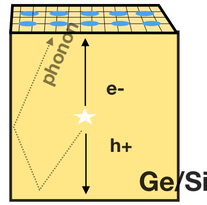


For TESSERACT:

- High control of IR backgrounds and charge leakage
- Exquisite sensitivities to ERDM with LEE discrimination
- **Lowered voltage and dual TES to retrieve some ER/NR discrimination**
- *LEE mitigation:* single-electron sensitivity

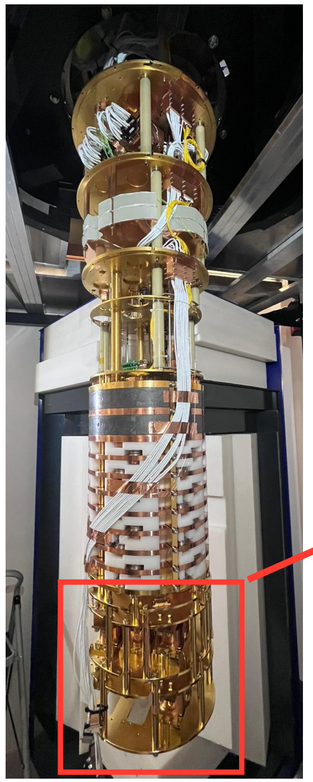
TESSERACT@LSM: Ge/Si semiconductors

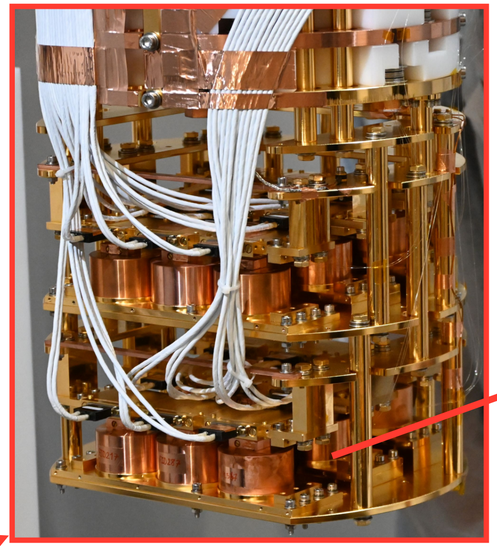
Low-Voltage approach for optimal NRDM sensitivity

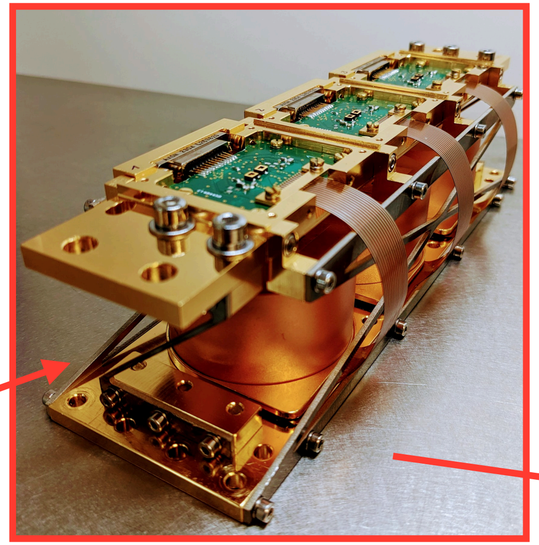


Leveraging the decades of experience and expertise from the **EDELWEISS** experiment in dual phonon-ionisation readout with cryogenic detectors and the now improved **Ricochet** technology

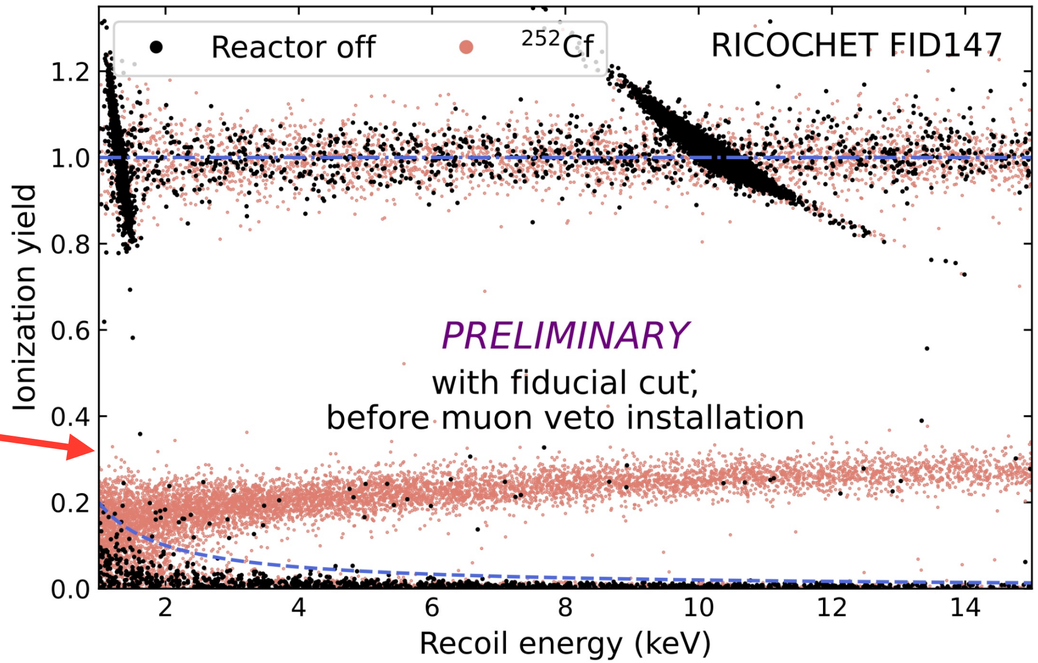
arXiv:2507.22751







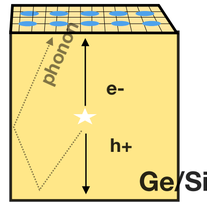
RICOCHET
A Coherent Neutrino Scattering Program



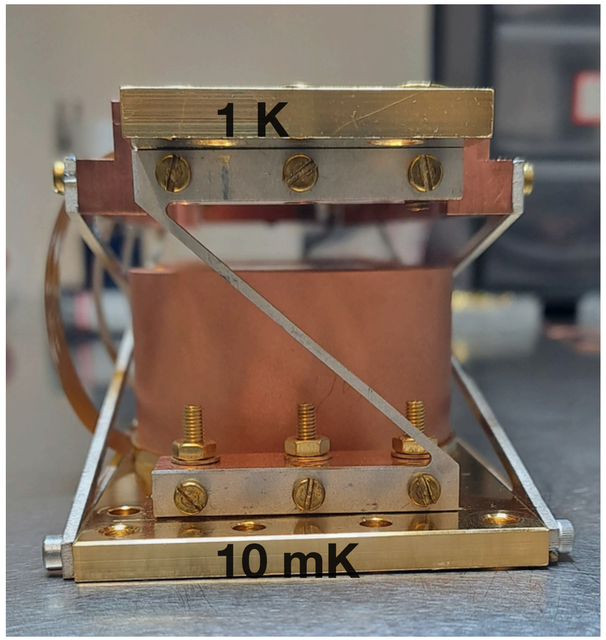
- Ricochet's CryoCube technology *(18 Ge detectors)*:
  - Target crystal and phonon readout at 10 mK
  - HEMT preamplifier for ionization readout at 1 K
- New state of the art in Ge dual readout: **30 eVph and 30 eVee (RMS) @ ILL**
  - Clear ER/NR/LEE discrimination at sub-keV energies: great for CENNS, but not enough for sub-GeV DM

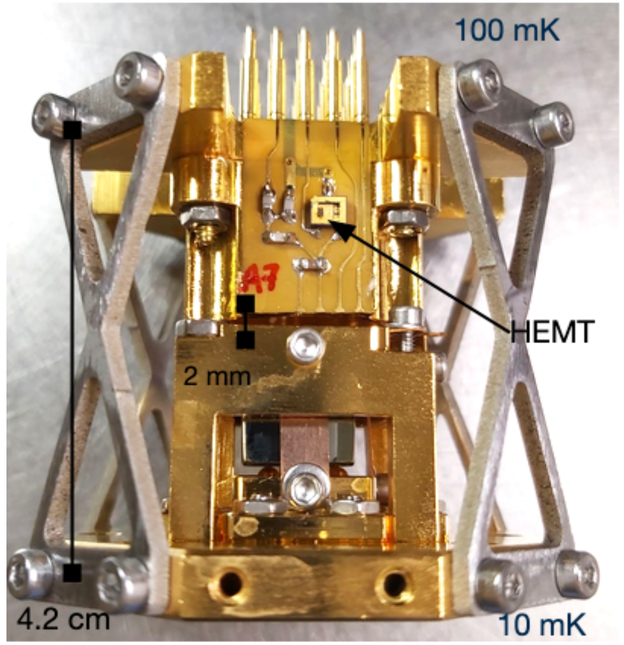
TESSERACT@LSM: Ge/Si semiconductors

Low-Voltage approach for optimal NRDM sensitivity

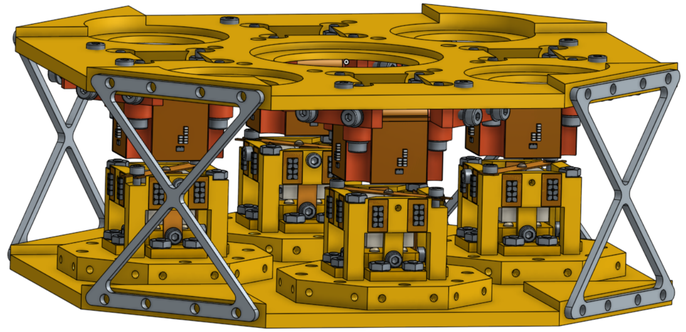


Leveraging the decades of experience and expertise from the **EDELWEISS** experiment in dual phonon-ionisation readout with cryogenic detectors and the now improved **Ricochet** technology





From Ricochet to TESSERACT



For TESSERACT:

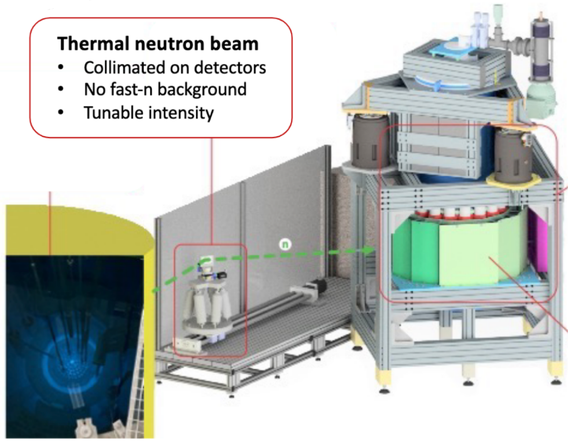
- Phonon sensor: NTD —> TES
- Total capacitance: < 5 pF (max.)
- Total payload: 4 x 5.35 g
- Resolutions:
  - Ionisation (<9 eVee), phonon (100 meV)
- ER/NR discrimination below 100 eVnr
- *LEE mitigation:* coincident charge-phonon signals
- **Need for accurate low-energy NR calibration**

TESSERACT@LSM: Calibration (CRAB)

arXiv:2505.15227

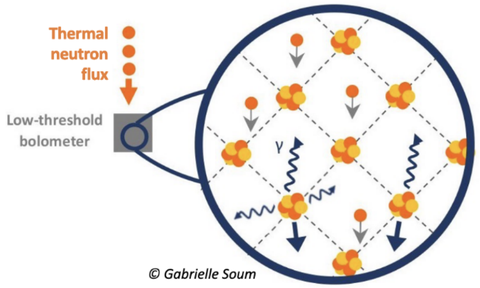
CRAB at TUW

Thermal neutron beam
- Collimated on detectors
- No fast-n background
- Tunable intensity

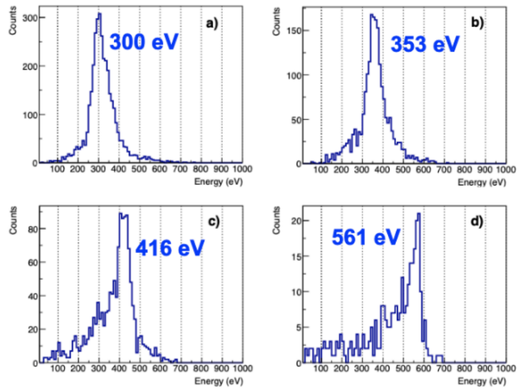


©Sebastian Dorer

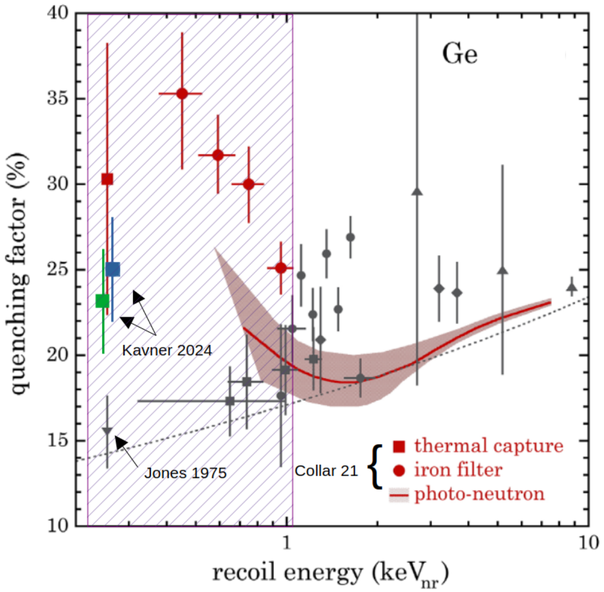
JINST 16 P07032 (2021)



20 eV – recoil-γ coinc



Emission of sub-keV mono-energetic NR following a 5-8 MeV gamma decay from n capture



- **Use of the CRAB thermal neutron beam to look at neutron captured induced single-gamma decays producing mono-energetic NR**
- CRAB/TESSERACT approach will lead to a first dual phonon-ionisation measurement down to 100 eVnr with well identified NR lines in the sub-keVnr energy scale to **accurately measure ionization and phonon quenching at sub-keV energies**
- Will also help understanding lattice defect creation possibly related to LEE

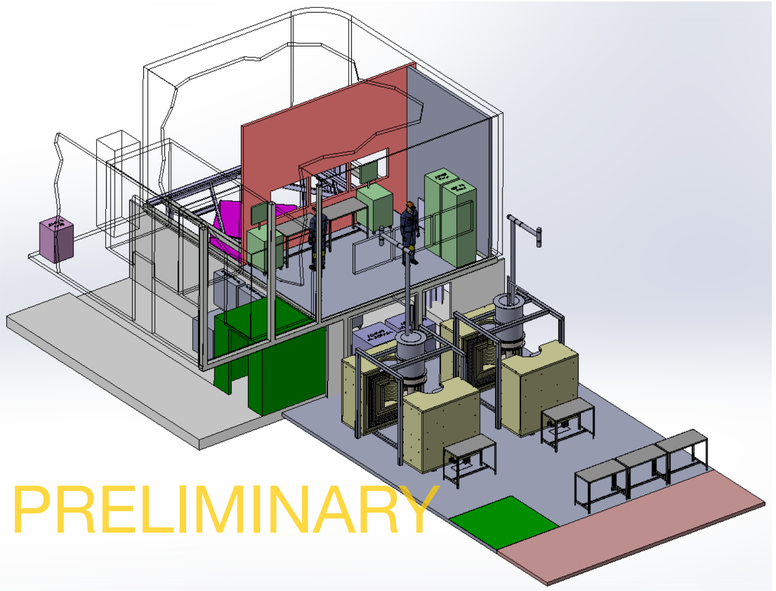
TESSERACT@LSM: Getting ready for LSM

- Two copies of the setup at LSM, for enabling both:
  - underground R&D and detector optimisation
  - DM science data taking in parallel

- Target background levels < 5 evt/kg/keV/day

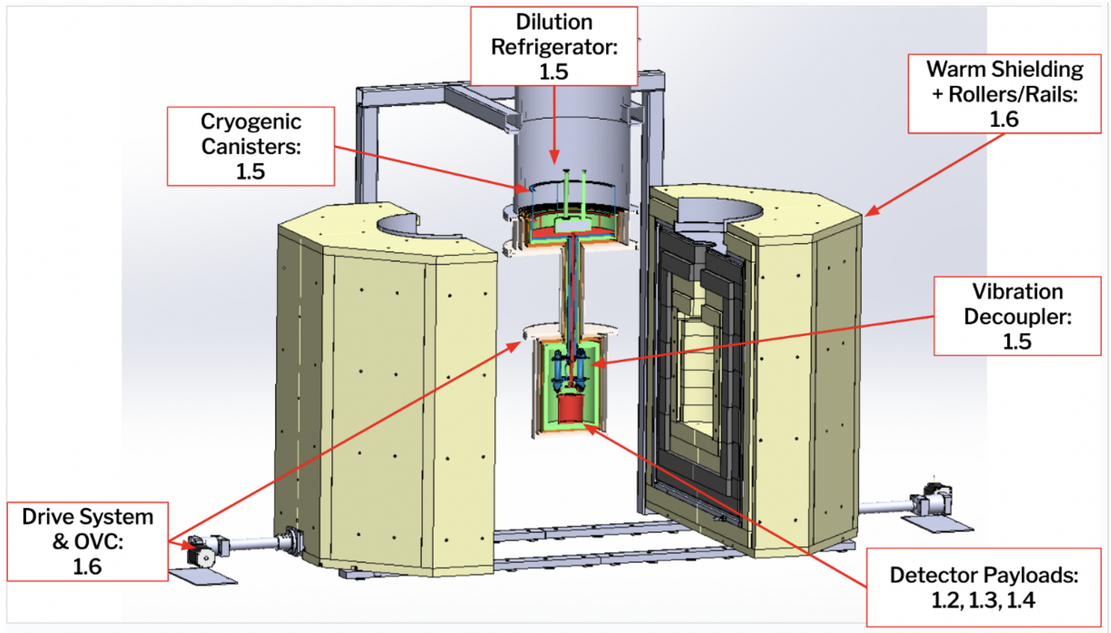
- Each detector technologies is designed to achieve major breakthrough in short time scales (few months) hence allowing fast turnarounds

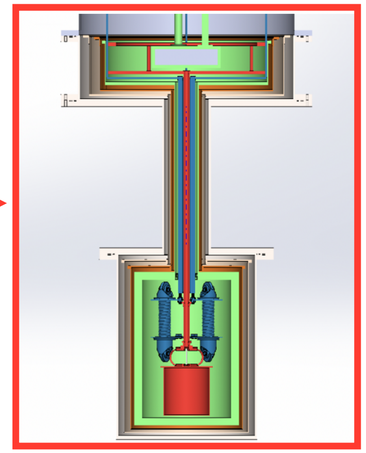
- **Integration at LSM planned in 2028 for first DM science data in 2029**



TESSERACT@LSM: Getting ready for LSM

- TESSERACT is designed for flexibility and straightforward detector replacement, with a common infrastructure of shielding, cryostat, vibrational decoupler, cold electronics, and DAQ.
- Dedicated clean room at LPSC ready to host the first TESSERACT fridge for its surface commissioning including: cryogenics, vibration levels, EMI mitigation, detector integration operation and optimisation, and **surface DM science !**





TESSERACT@LSM: Getting ready for LSM

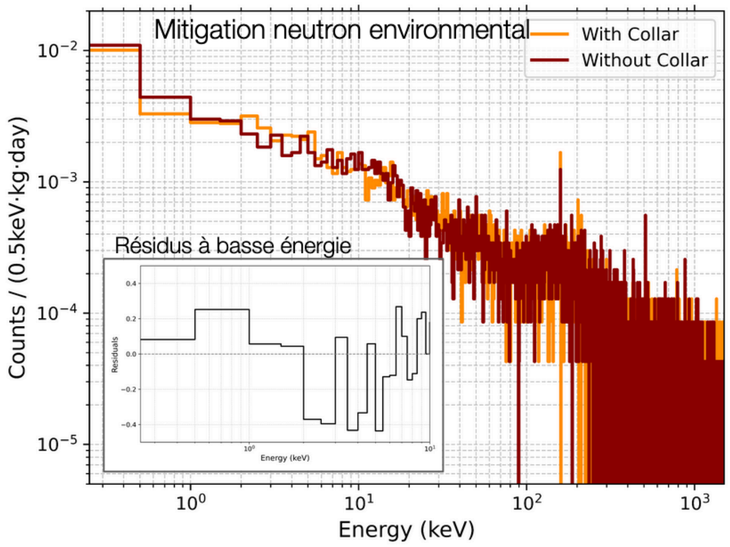
Designed around commercial cryostat and vertical layout.

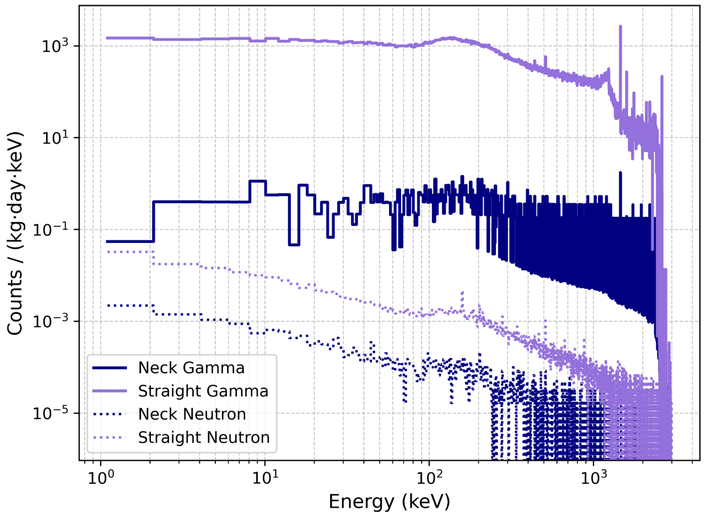
- Narrow ‘neck’ region, with Pb plug above at 1K
- Thick Cu at base temperature surrounds target region.

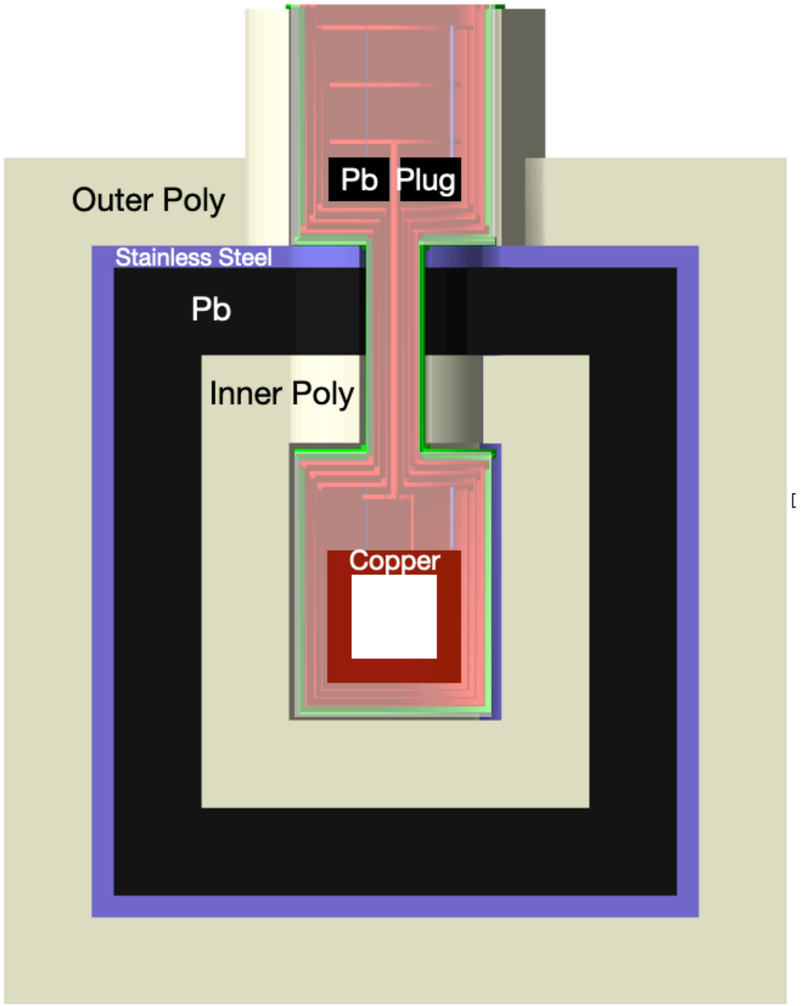
Material screening at LSM ongoing

Simulations predict **~1 DRU (ER)**
<1e-3 DRU (NR)

(possible future upgrade: cold inner veto)

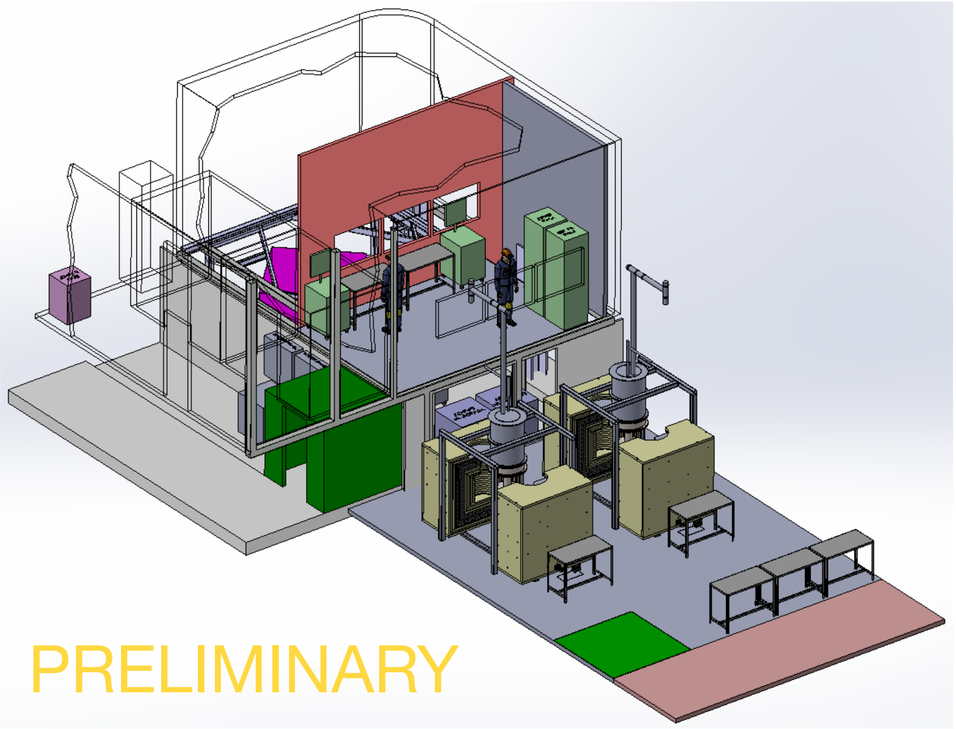


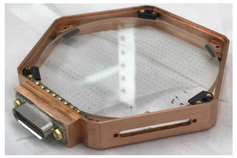
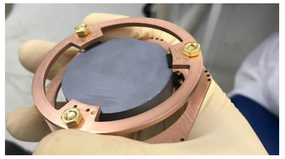
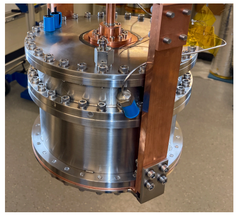
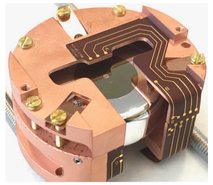
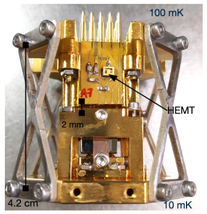




TESSERACT@LSM: Conclusion

- A strong TESSERACT team has been built, including institutions in the US (DOE-supported), France (CNRS/IN2P3-supported), and Switzerland (SNF-supported).
- Following reviews in summer 2025, TESSERACT has moved to the Project phase
- Multiple target materials allow for exploration of different types of interactions and dark matter particle masses.
- Multiple signal channels and coincidence-based background rejection to reject backgrounds, especially the LEE
- Sub-eV phonon energy resolution: Even small gram-scale detectors can have a big science impact!
- Moving to Modane in **2028** for low-background searches starting in **2029**



TESSERACT@LSM

The end