TESSERACT

Detection of Light-Mass and Ultralight Dark Matter Particles with the TESSERACT Experiment

Dan McKinsey - LBNL and UC Berkeley

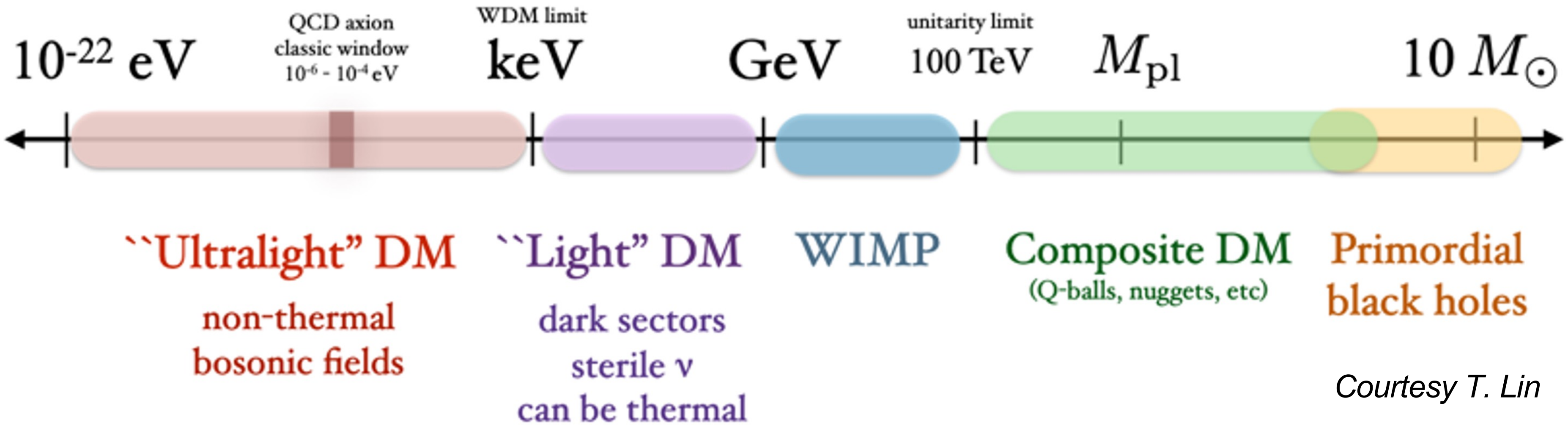
20th Patras Workshop on Axions, WIMPs, and WISPs

Sept. 25, 2025

TESSERACT - A New Experiment to Detect Light and Ultralight Dark Matter

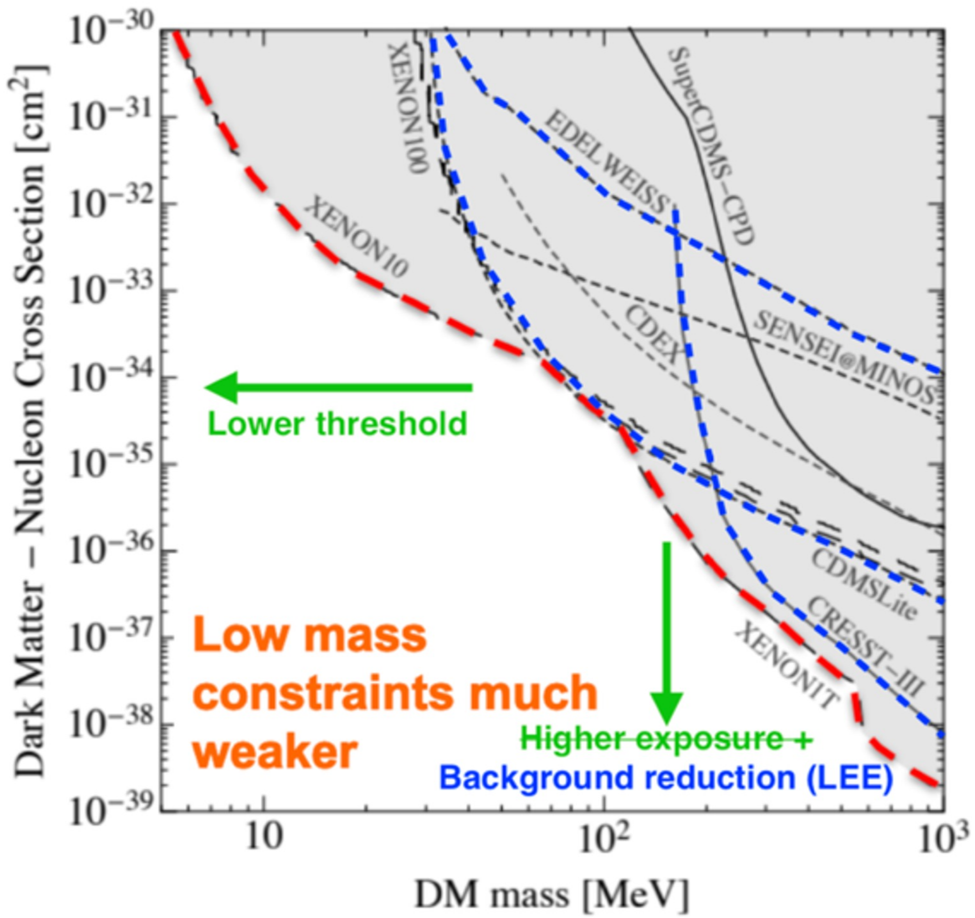
We don’t know the dark matter particle mass; many possibilities exist

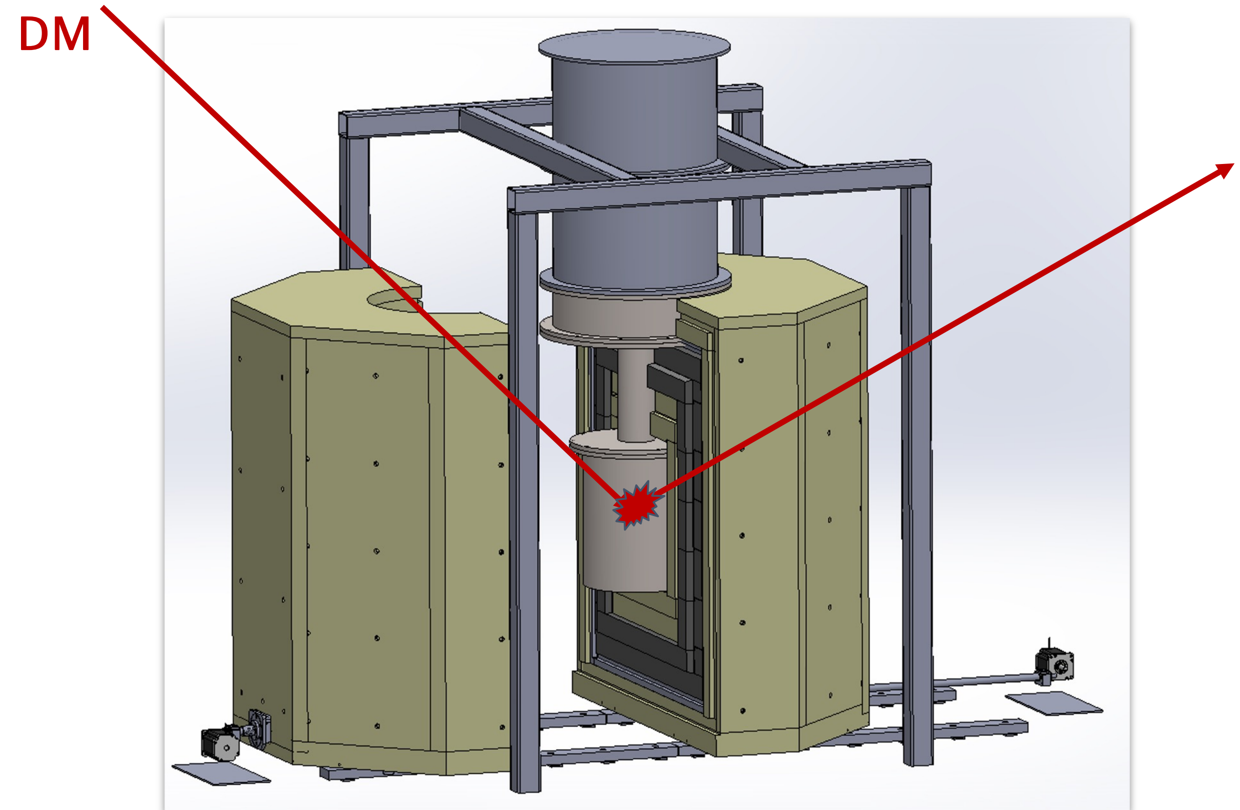
TESSERACT is sensitive to bosonic dark matter absorption in the meV to keV mass range (“ultralight DM”), and to Electronic Recoil (ER) and Nuclear Recoil (NR) scattering in the keV to GeV mass range (”Light DM”)



Courtesy T. Lin

Dark Matter Nuclear Recoils: Future Directions

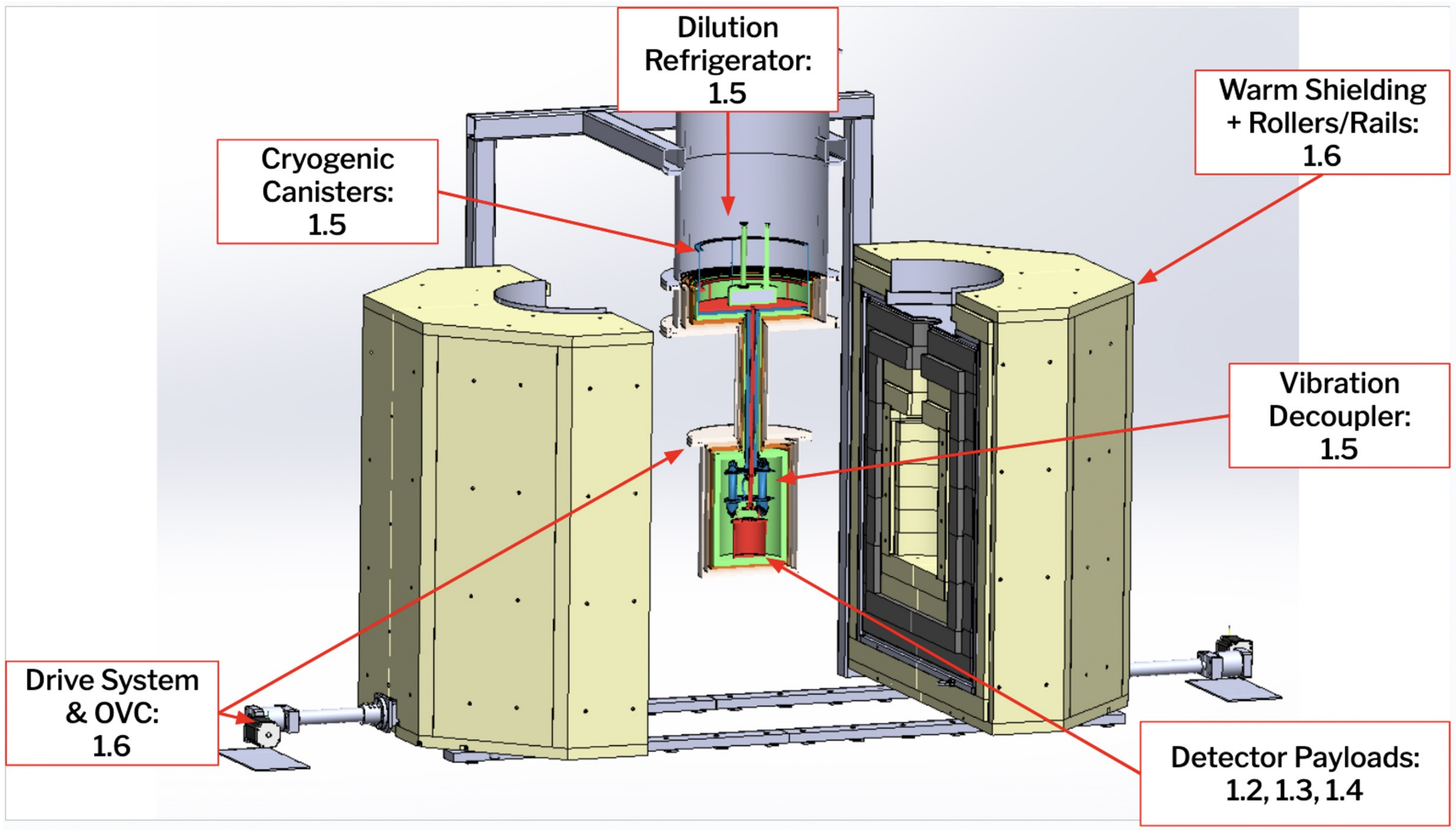


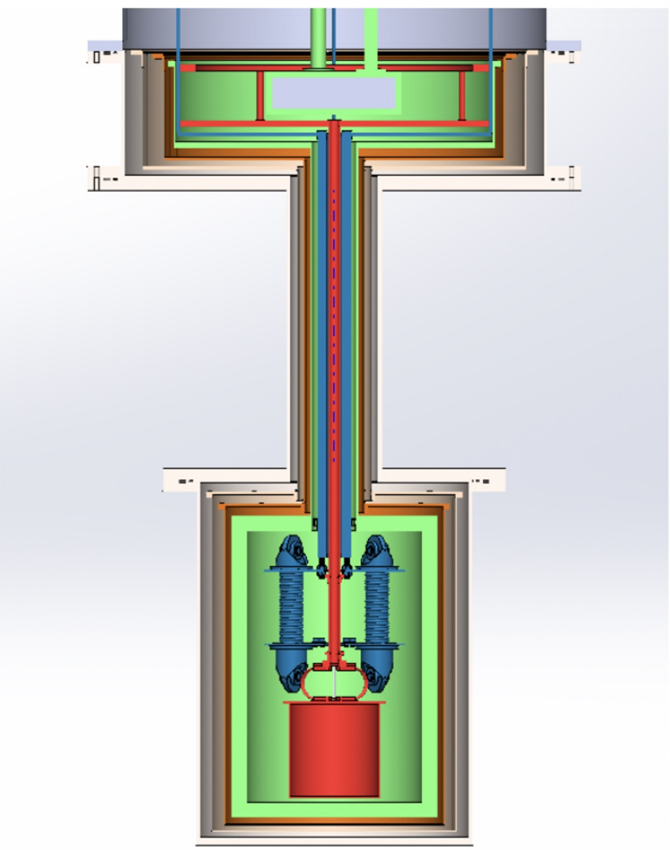


- **Exposure**: Rate scales inversely with dark matter mass $R = \sigma n_{\mathrm{DM}} N_{exp} = \sigma \frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}} N_{exp}$
- Compare ton scale LXe with gram scale low mass DM experiments

TESSERACT Overview

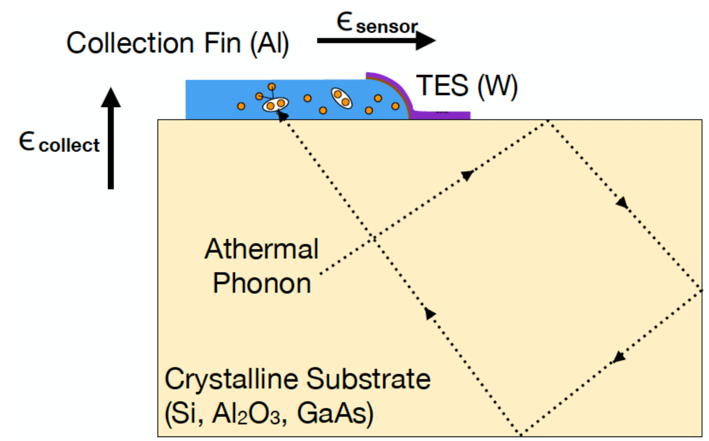
TESSERACT is designed for flexibility and straightforward detector replacement, with a common infrastructure of shielding, cryostat, vibrational decoupler, cold electronics, and DAQ.



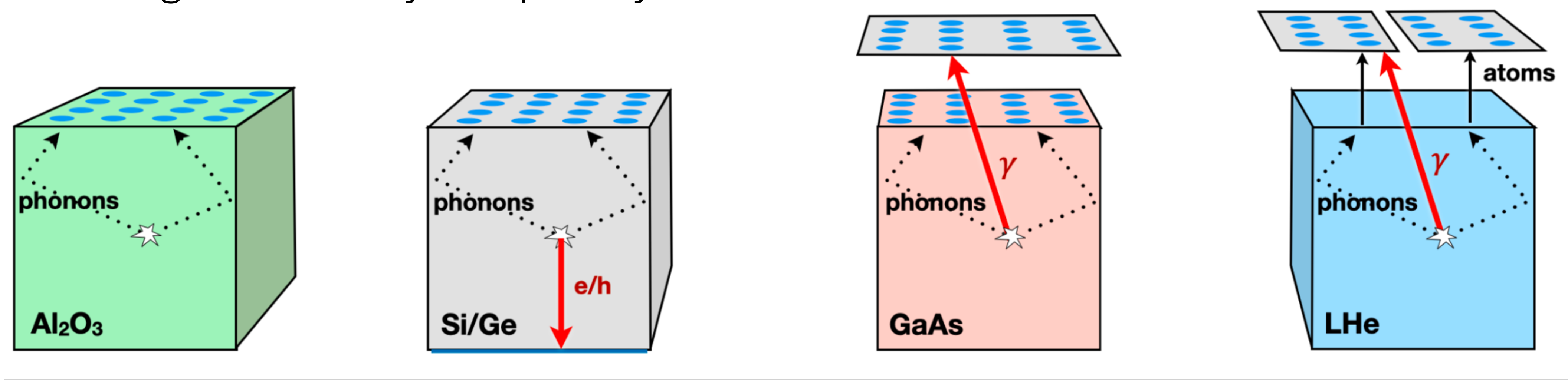


TESSERACT Overview

TESSERACT has existing detectors with world-leading energy resolution that can provide interesting science as soon as they can get underground in a low-background, cryogenic setup.

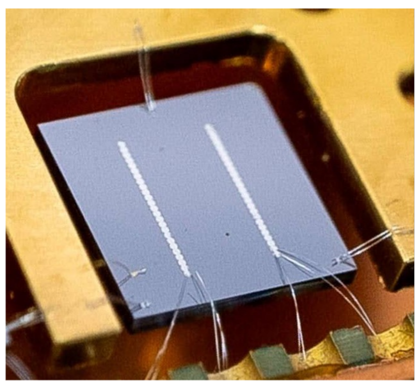


The Si/Ge, GaAs, and LHe technologies all benefit from multiple signal types and requiring coincidence across readout pixels, allowing strong reduction of instrumental and radioactive backgrounds. Al2O3 benefits from dark matter-lattice coupling, enhancing its sensitivity at especially low dark matter masses.



TESSERACT Overview

Three ingredients will make TESSERACT successful:
1. World-leading, background-reduced sensors
2. Optimized, complementary dark matter targets/modules
3. Long-term, low-background, underground searches



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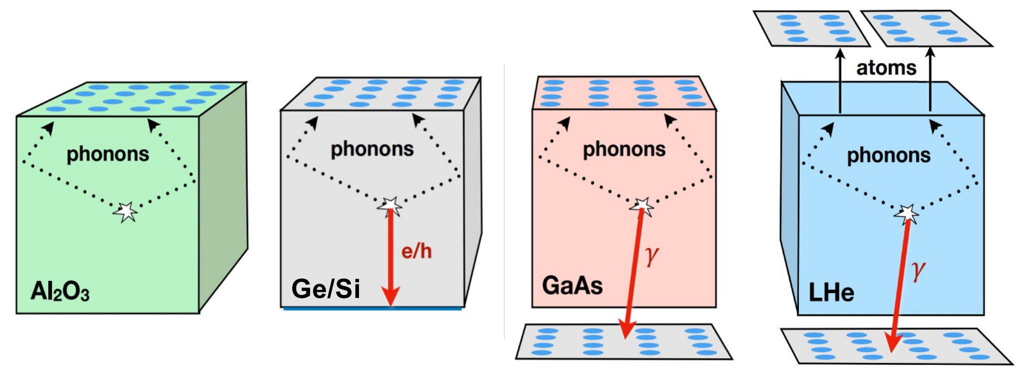

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LSM
Laboratoire Souterrain de Modane

Collaborating Institutions

TESSERACT includes over 60 scientists, researchers, engineers, project managers, postdocs, and graduate students, from 12 institutions in the US, France, and Switzerland.

BERKELEY LAB Bringing Science Solutions to the World

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TEXAS A&M UNIVERSITY

FLORIDA STATE UNIVERSITY

University of Zurich UZH

UNIVERSITY OF MICHIGAN

TESSERACT project

Science goal: Direct detection of particle-like sub-GeV dark matter

- Sensitive to a wide variety of dark matter interaction modes: DM-electron scattering, DM-nuclear scattering, and DM absorption

Technology and Strategy:

- Athermal phonon readout with Transition Edge Sensors for fast signals, decreased noise
- Shared engineering on shielding design, cryostat, vibrational isolation, electromagnetic interference, TES readout electronics, data storage and processing.
- Multiple targets. Sapphire and Gallium arsenide (SPICE), Superfluid helium (HeRALD), plus French technologies based on Ge and Si.
- Strong emphasis on detector coincidence and discrimination techniques to reduce backgrounds
- One detector type operated at a time, to avoid extra backgrounds
- Two identical setups of the shielding, cryostat, and electronics for operational flexibility and the ability to let one detector type run to collect more exposure, while still testing other detectors.
- Shared analysis tools and a single, cohesive analysis team across detector technologies

Schedule:

- Project planning stage: FY2020-FY2025 (completed)
- Project phase: FY2025-FY2028 (current)
- Operations phase: FY2029-FY2031

TESSERACT Overview

TESSERACT has existing detectors with world-leading energy resolution that can provide interesting science as soon as they can get underground in a low-background, cryogenic setup.

TESSERACT has chosen an underground site: The Laboratoire Souterraine de Modane (LSM), located under the Alps at the French/Italian border. CNRS/IN2P3 has also committed laboratory space for both setups at LSM.

The CNRS IN2P3 is allocating equipment, postdocs/theses, and permanent staff working on the project

Switzerland (SNF) is supporting TESSERACT research.

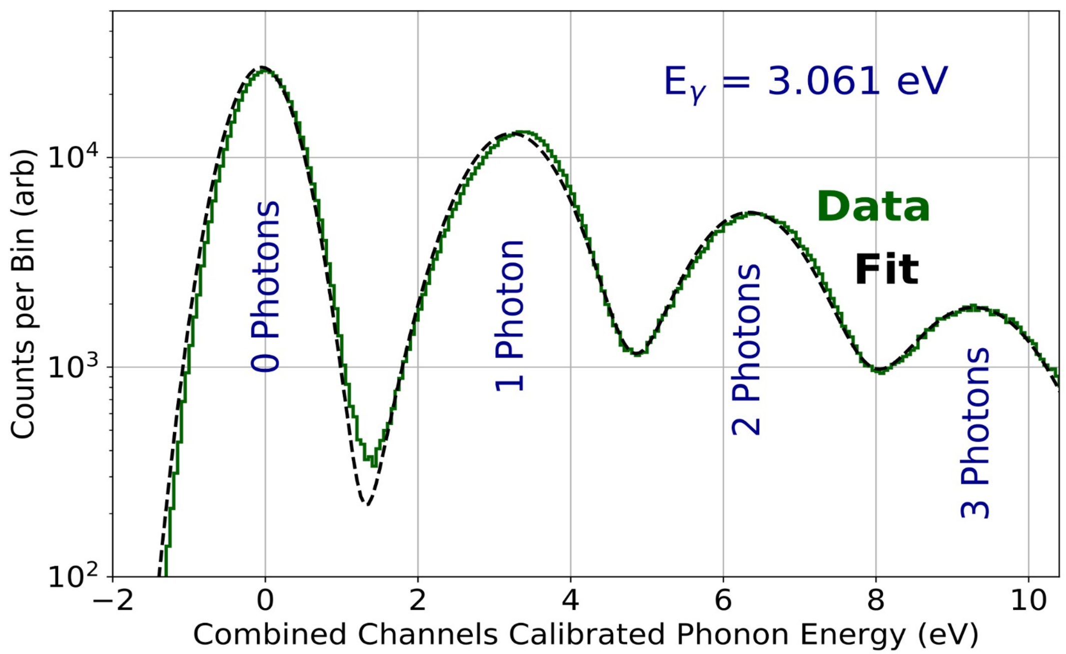
May 9, 2024: DOE announces TESSERACT to be the first new small project in DM physics.

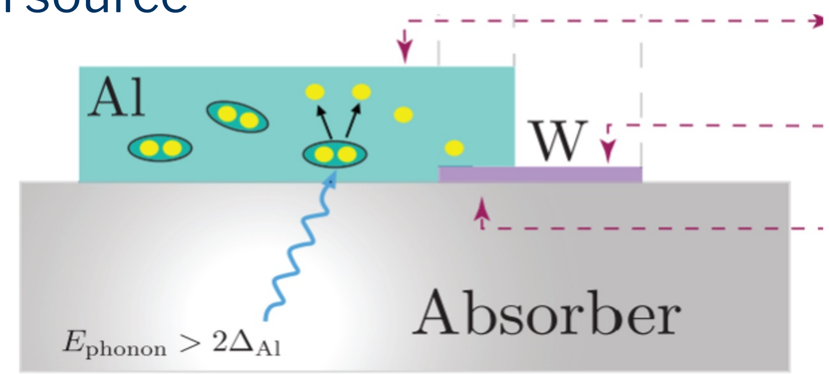
In June 2025 TESSERACT held a Director's Review (PD-1/3a).

In July 2025 we held a DOE gateway review, shepherding TESSERACT into the Project phase, with approval to start purchasing major equipment.

TESSERACT Sensors

- W Transition-edge-sensors
- DM scatters in absorber, producing athermal phonons
- Athermal phonon break cooper pairs in large area Al
- Broken cooper pairs thermalize in W (biased in superconducting transition)
- Optimized for resolution: **361.5 ± .4 meV** from photon source





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

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

Energy threshold decreases very quickly with T_C

Energy threshold decreases with TES mass

Instrumental Backgrounds

Low-temperature detectors see an excess of backgrounds at low energies (LEE)

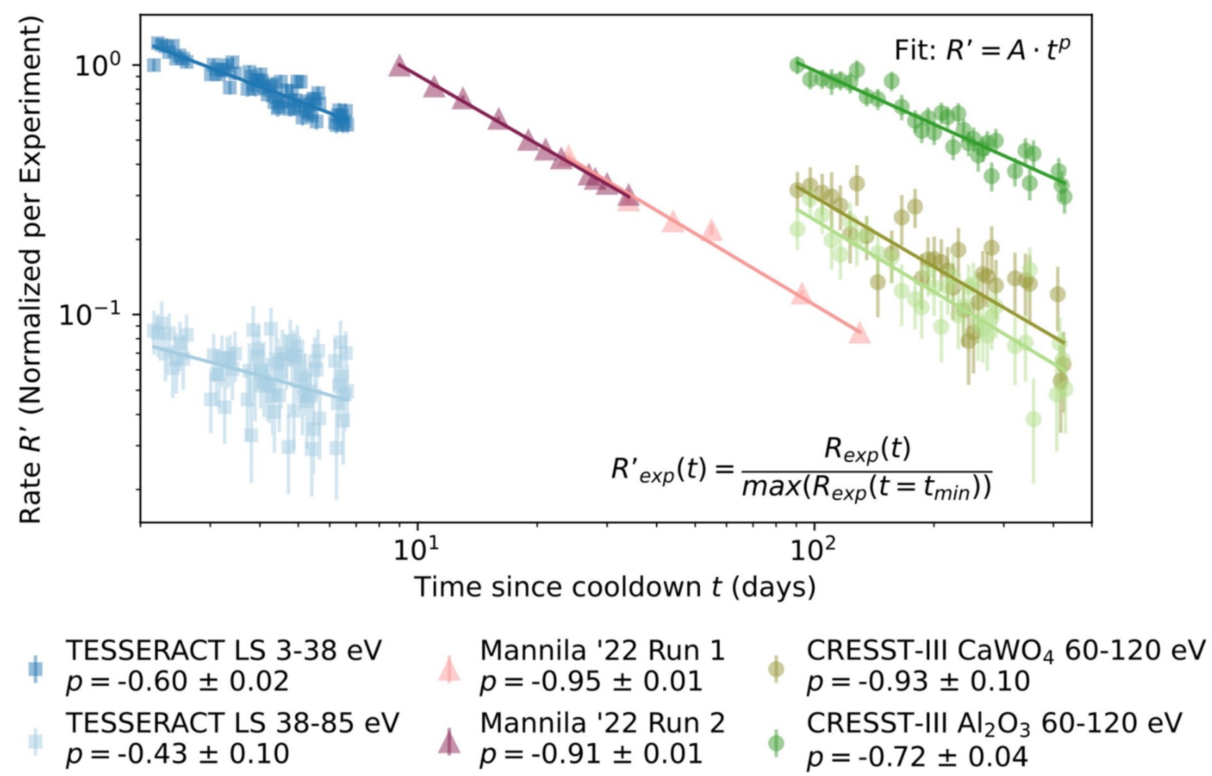
What do we know?

- It's not DM: rate is time-dependent

What impact does this have on our science goals?

- Above threshold: LEE is a background, limiting DM searches at lower cross-sections
- Sub-threshold: LEE adds extra noise. Limiting DM searches at lower masses

arXiv: 2503.08859



Instrumental Backgrounds

Extensive R&D toward mitigating LEE from 3 sources:

1) Mounting Scheme (stress)

Hang by wire-bonds > Gluing

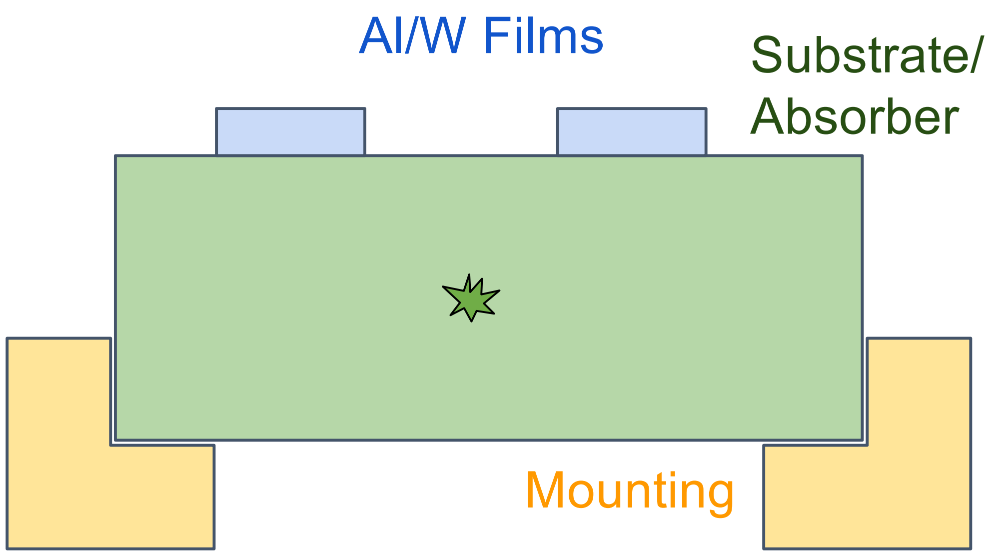
2) Al/W Films

Require coincidence between 2 independent sensor films

3) Substrate volume

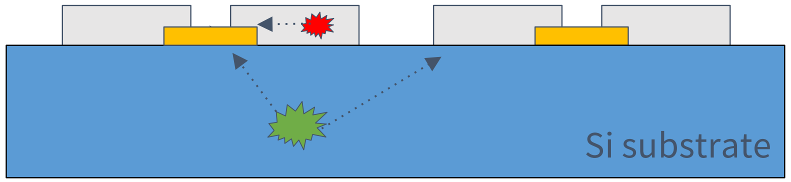
Active area of research

Rate ~ substrate volume

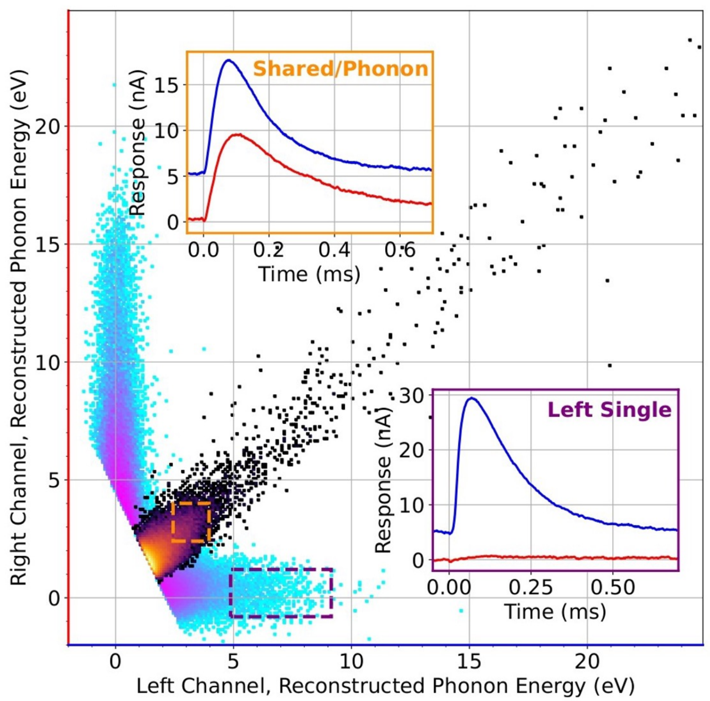


LEE Discrimination and Mitigation

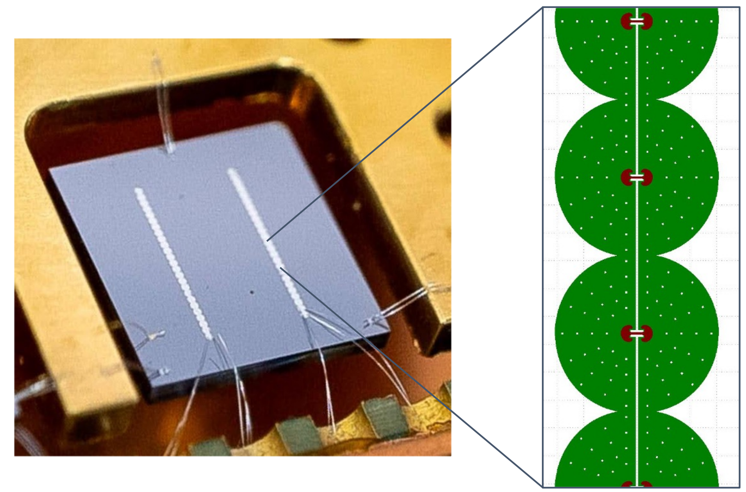
LEE Discrimination: selection of events shared between 2 channels:

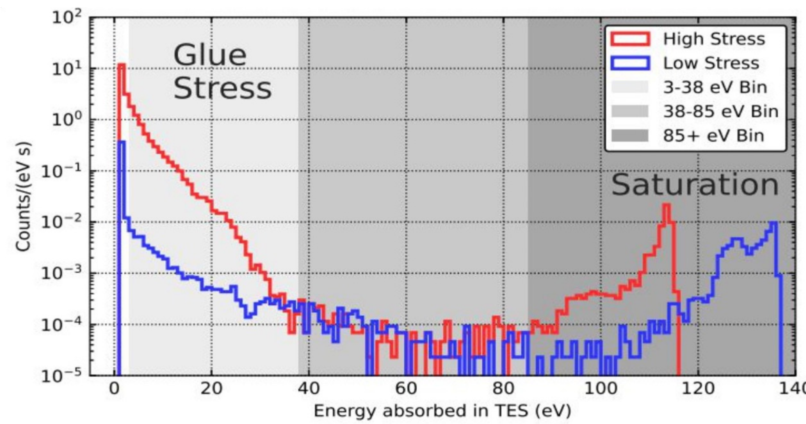


arXiv:2503.03683v2



LEE mitigation : Si substrate suspended with Al wires ⇒ suppress a stress induced LEE source from the holder

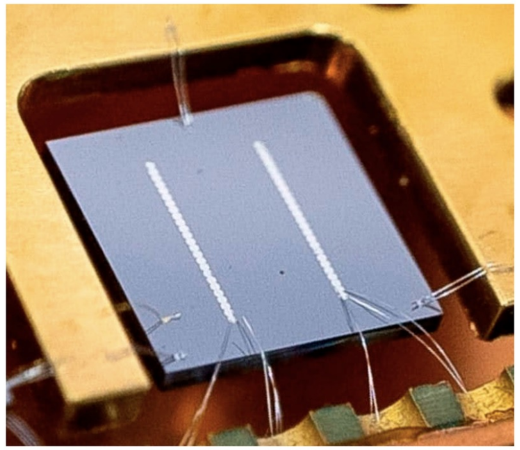




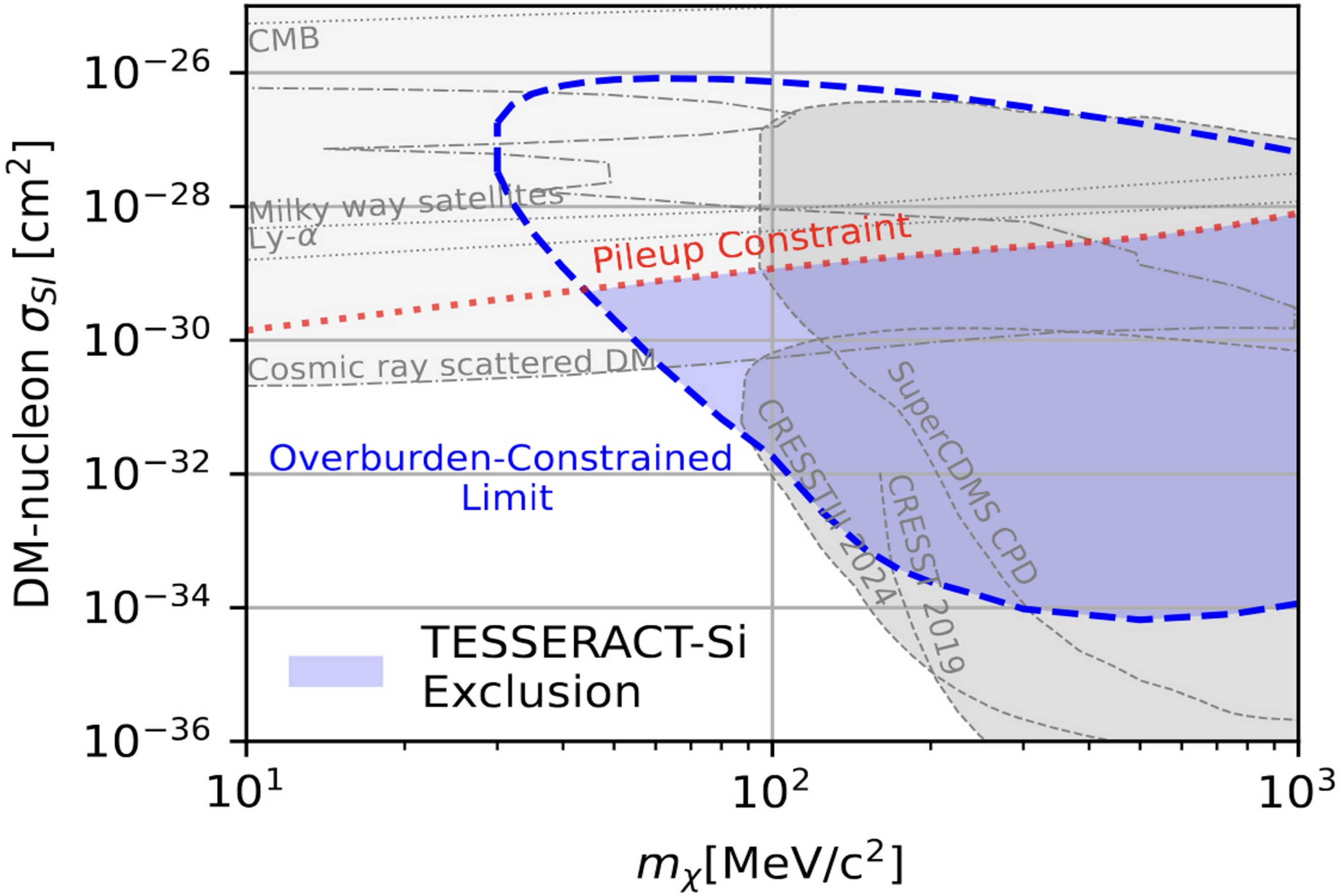
TESSERACT Has Already Produced New DM Science

Because TESSERACT energy thresholds are especially low, even very small detectors operated at the surface can probe new dark matter parameter space.

Here is a new TESSERACT result, using a 0.23 g silicon detector, like we would use for one of the readout pixels for HeRALD.
361.5 ± .4 meV photon resolution



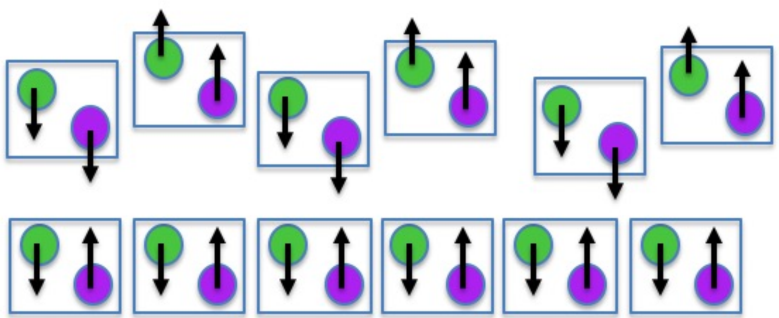
TESSERACT Collaboration,
https://arxiv.org/pdf/2503.03683
Now accepted to Physical Review Letters

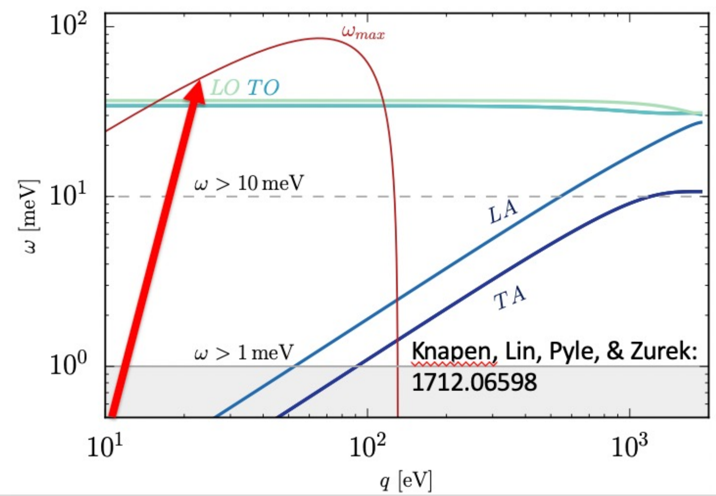


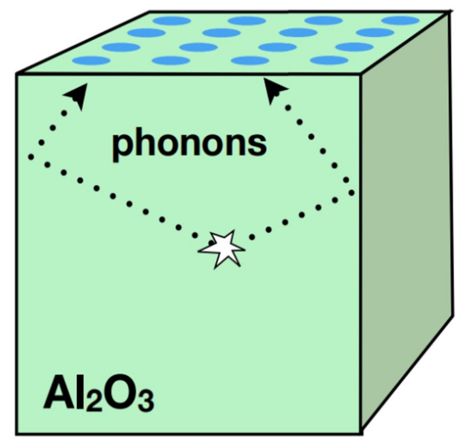
Sapphire Target

Coherent excitations:

- Vibrational energy scale in crystals is O(100 meV)
- For dark matter masses < 100 MeV, we can't use the simplifying approximation that the nucleus is free.
- DM scatters coherently with the entire crystal, producing a single phonon.
- The kinematics of optical phonon production are favorable; due to their gapped nature, all of the kinetic energy of the DM can potentially be used for phonon creation.
- Optical phonons modulate the electric dipole in polar crystals, so they have strong couplings to IR photons, and thus by extension, all DM models that interact through a kinematically mixed dark photon.







- 1 detection channel: Phonons (sensors on sapphire)
- Polar crystal => phonon modes couple to dark photon
- Status: First sensors have been fabricated!

Gallium Arsenide Target

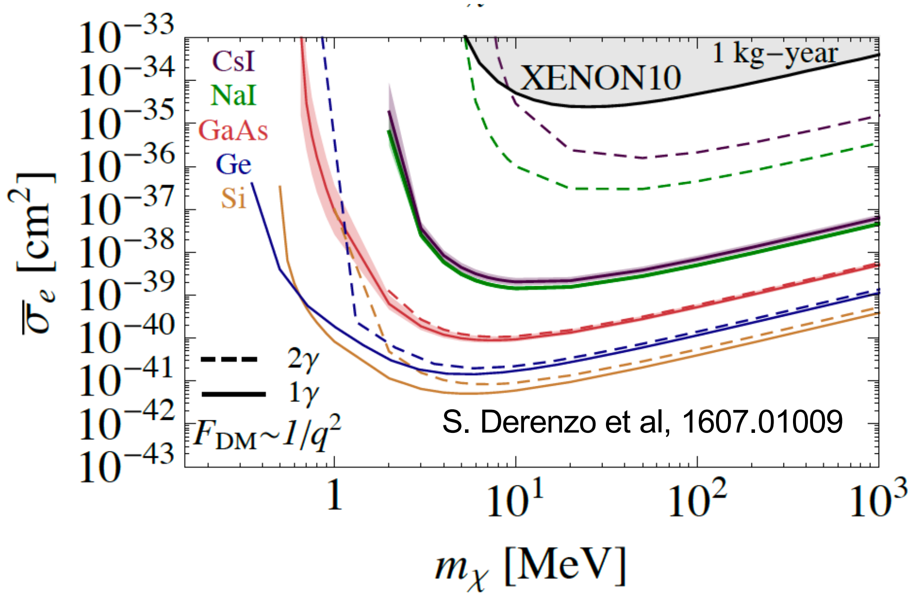
Low bandgaps:

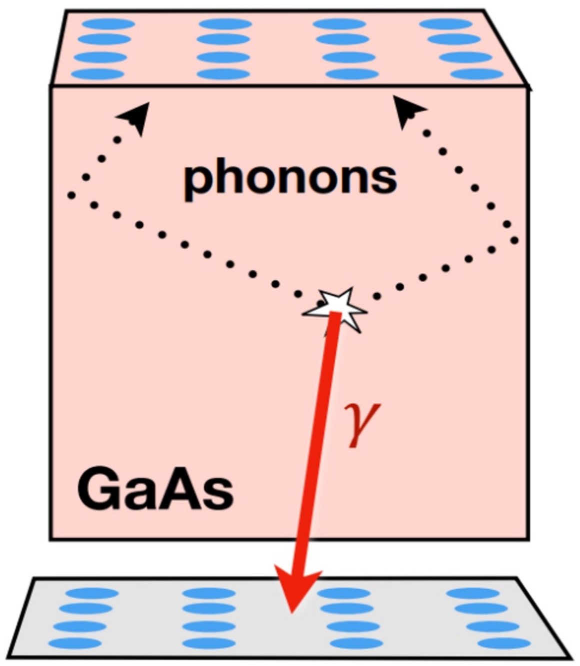
- Just as with optical phonons, the gapped nature of an electronic excitations in semiconductors allows them to maximally extract kinetic energy when scattering with or absorbing DM.
- Due to a strong rate dependence upon energy, low bandgap semiconductors like Ge, Si (SENSEI and SuperCDMS HV), and GaAs (SPICE) are the preferred target candidates.

With GaAs one can collect both photons and phonons!

Can allow background rejection through phonon/photon ratio

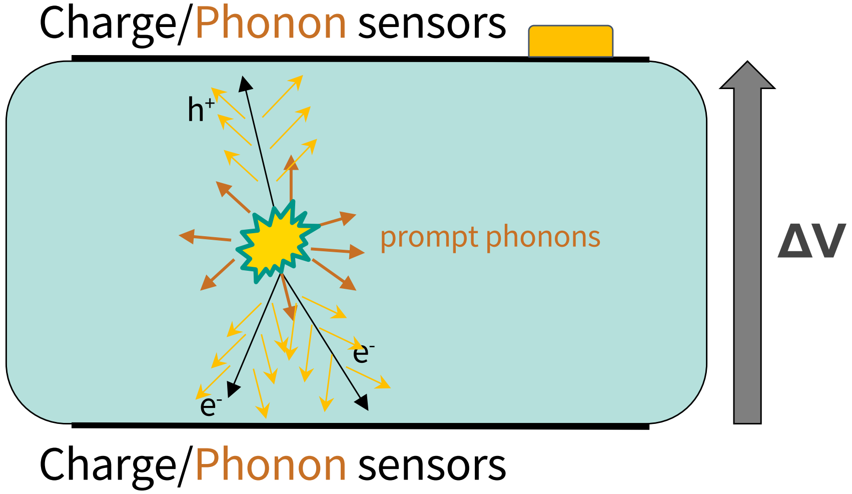
Status: First sensors have been fabricated!

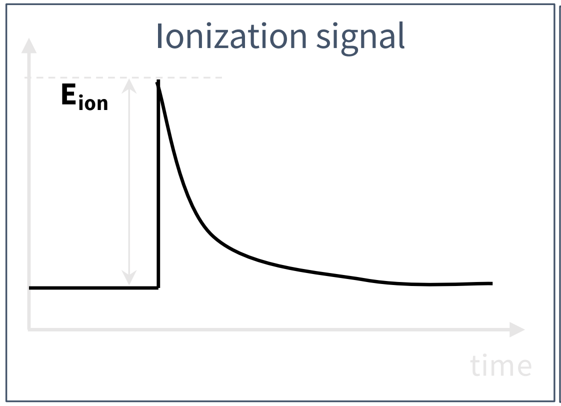


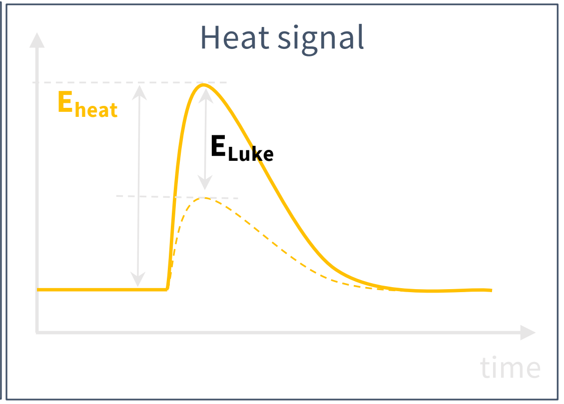


Si/Ge Target

Based on EDELWEISS and Ricochet expertise







$$E_{heat} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + E_{ion}\,\Delta V/\varepsilon_{eh}$$

- Two channels : heat and ionization
- Luke boost ⇒ additional phonons proportional to ΔV

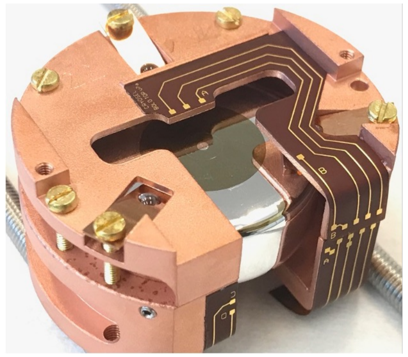
Two working modes : Low Voltage (LV) and High Voltage (HV)

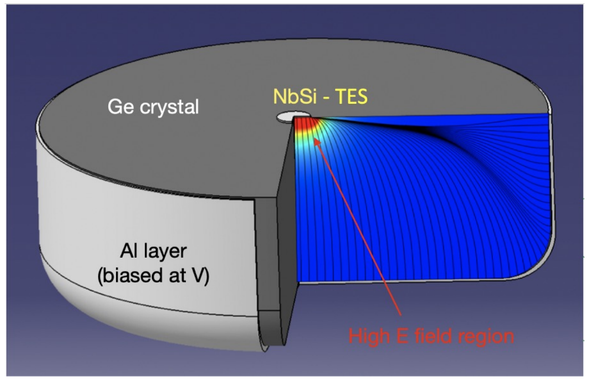
Si/Ge Target

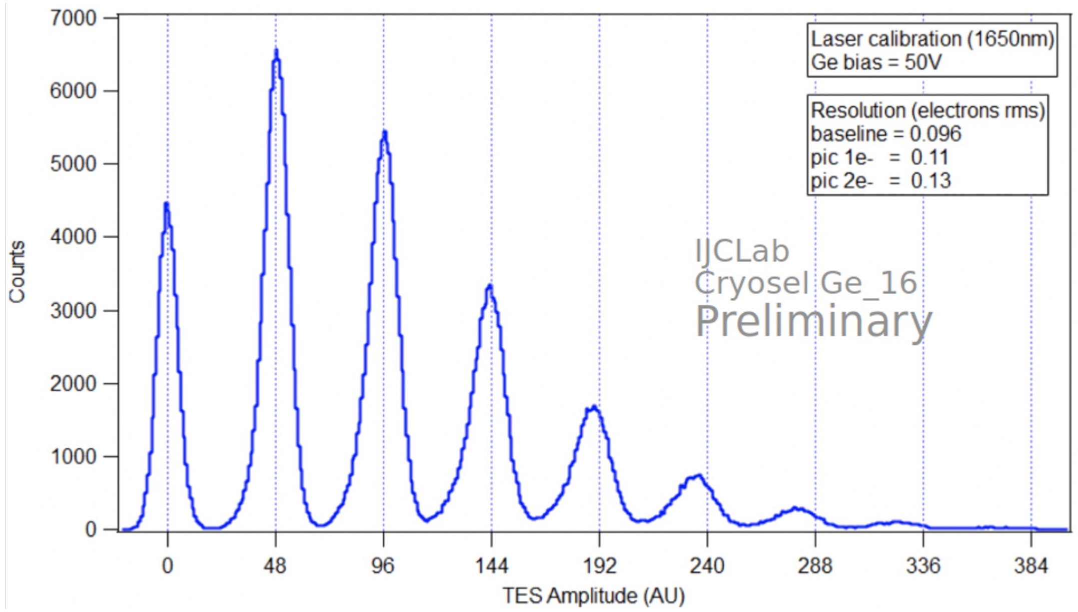
High-Voltage approach for optimal ERDM sensitivity

$E_{heat} = E_{recoil} + E_{ion}\ \Delta V/\varepsilon_{eh}$

$E_{heat} \simeq E_{ion}\ \Delta V/\varepsilon_{eh}$ (HV)







First observation of a single-electron sensitivity in a massive (40g) Ge cryogenic detector !

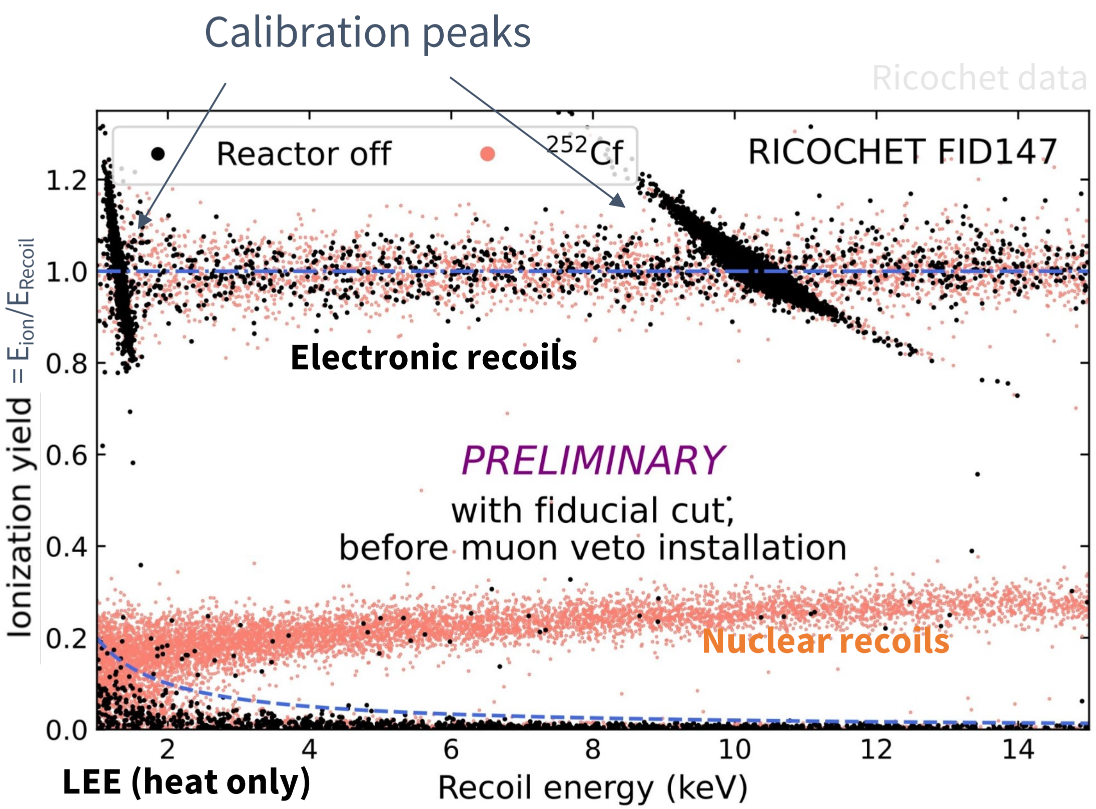
- Low-imp. TES and SQUID readout : **0.1 electron/hole (RMS)**

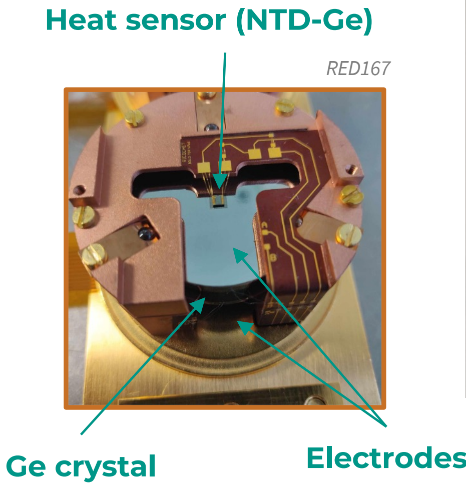
For TESSERACT :

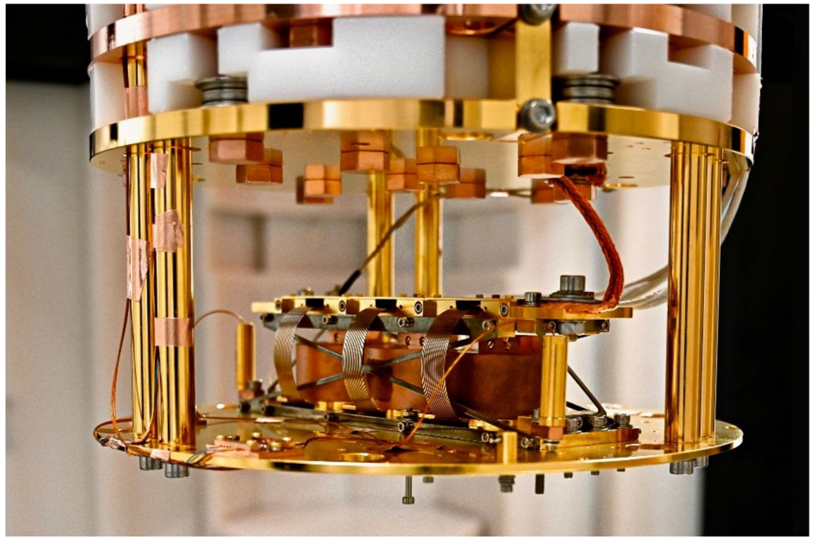
- High control of IR backgrounds and charge leakage
- LEE discrimination down to single e/h pair
- **Exquisite sensitivities to ERDM with LEE discrimination**

Si/Ge Target

Low-Voltage approach for optimal NRDM sensitivity







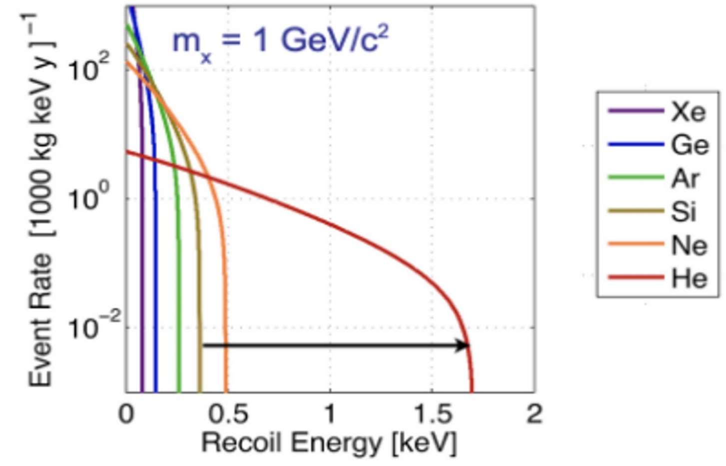
Ricochet Mini-Cryocube

- Double readout heat/ionization ⇒ particle identification
- LEE are non ionizing ⇒ improving the charge resolution is of major importance

Superfluid Helium Target (HeRALD)

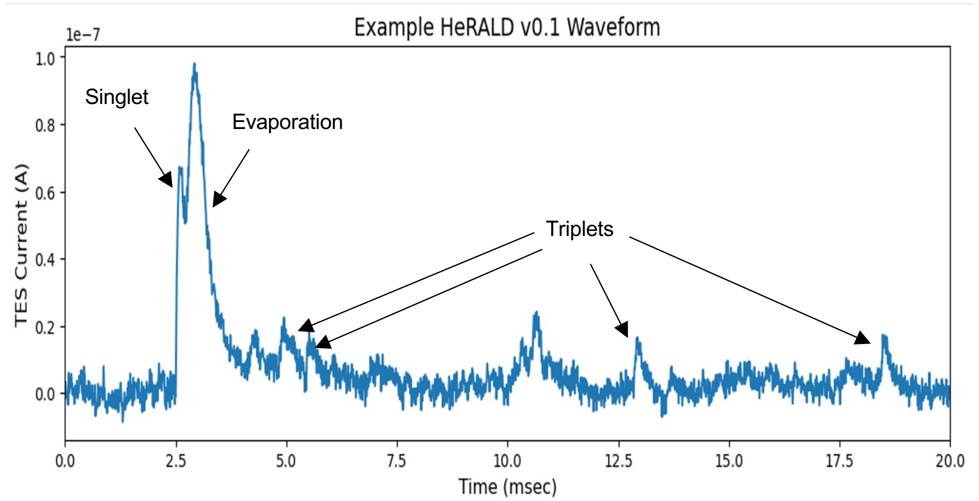
Target : Liquid He

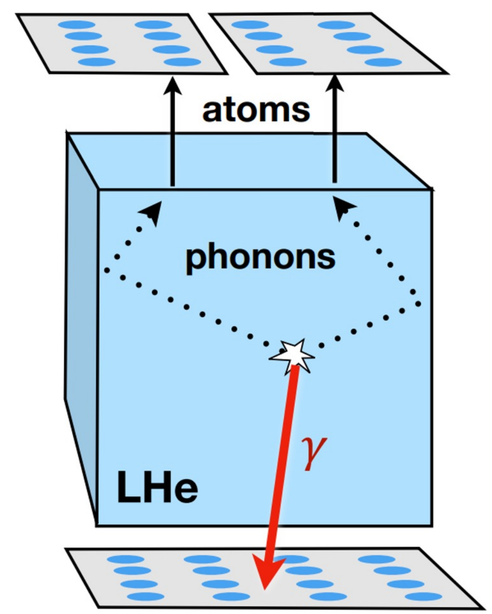
- Light material ⇒ better kinematic matching with LDM
- Extremely radiopure
- No internal stress nor dislocation (LEE source ?)
- Superfluid ⇒ no vibrational coupling with the environment (another LEE source ?)

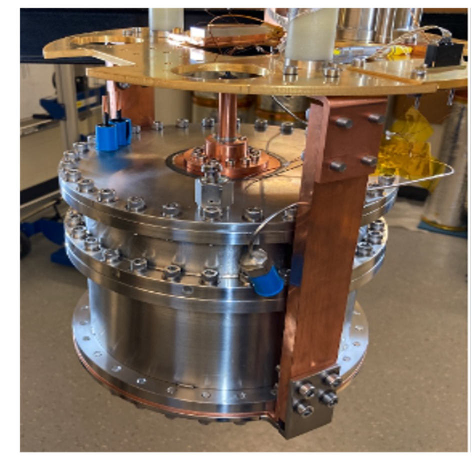


Several signal channels :

- quasiparticles (phonon/roton
- singlet ⇒ short lived, decay to emit a 15.5 eV photon
- triplet ⇒ long lived, ballistic



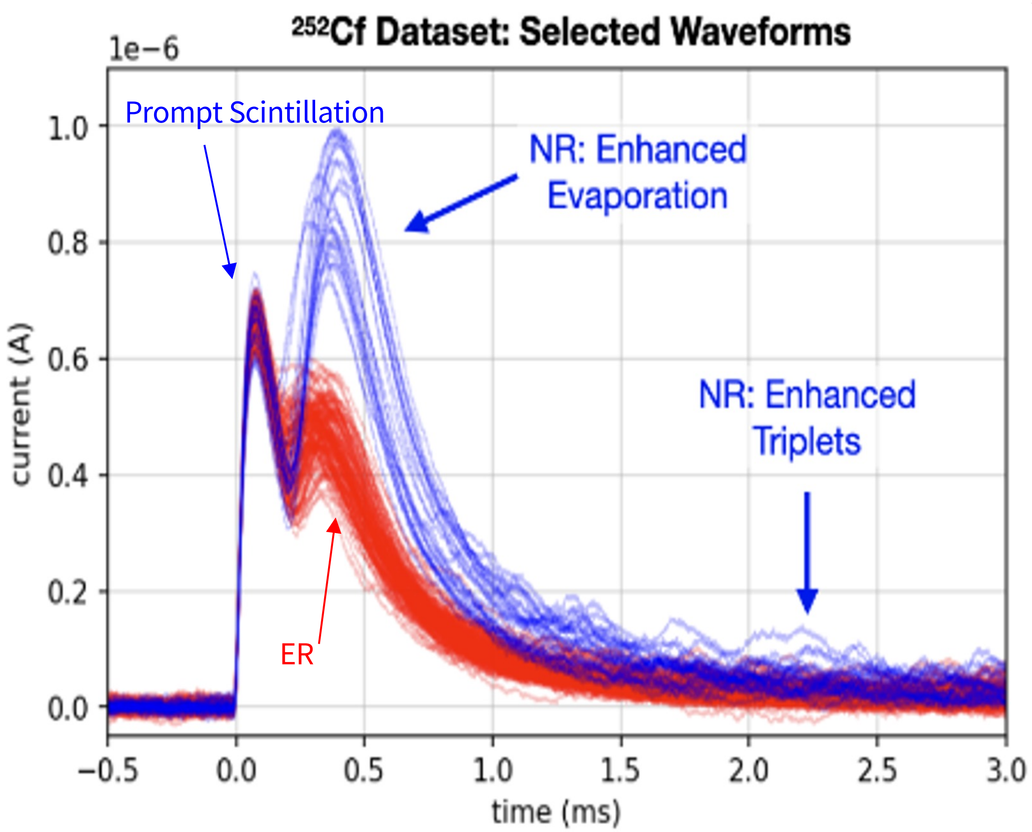




R. Anthony-Petersen et al., arXiv:2307.11877

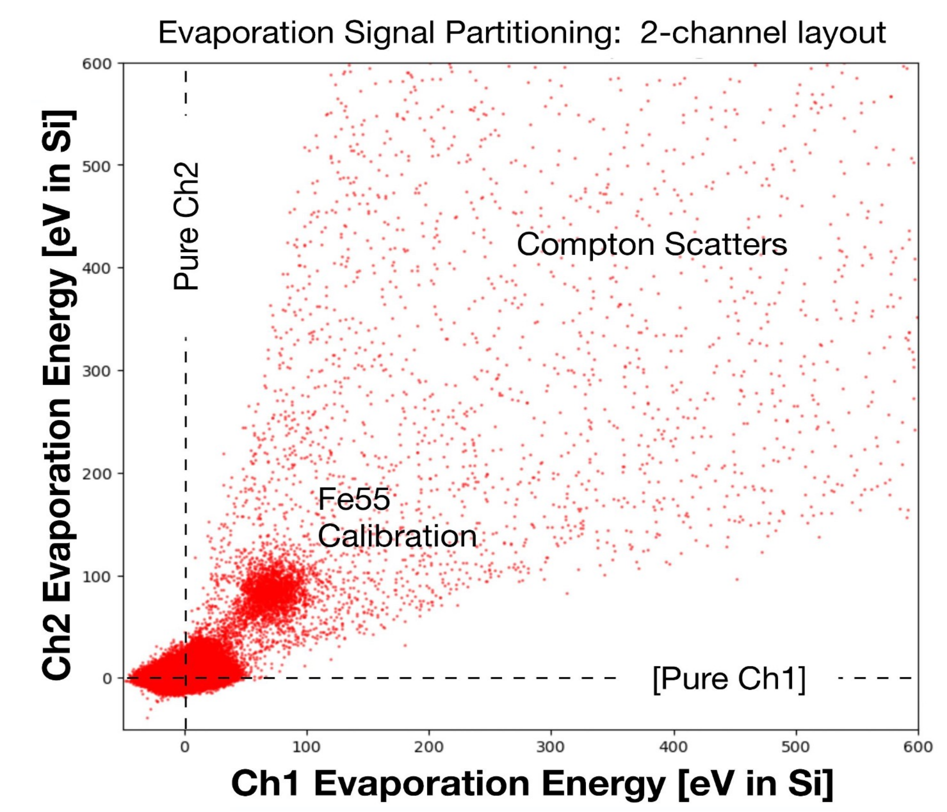
Superfluid Helium Target (HeRALD)

Particle identification thanks to pulse shape discrimination



LEE mitigation strategy:

- Several channels above the vacuum
  - Events in calorimeters (LEE) ⇒ single channel
  - Events in ^{4}He ⇒ multiple channels



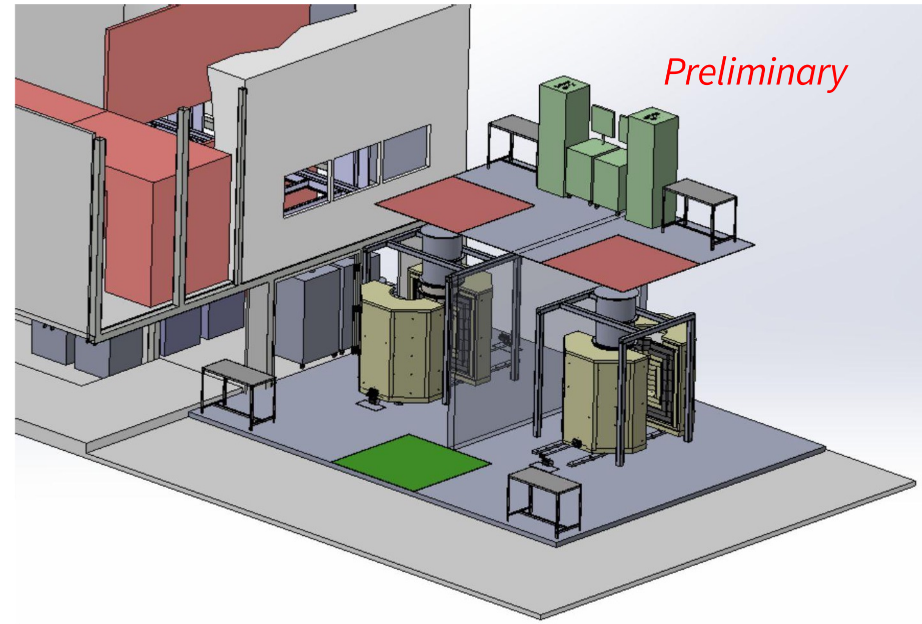
Moving Underground

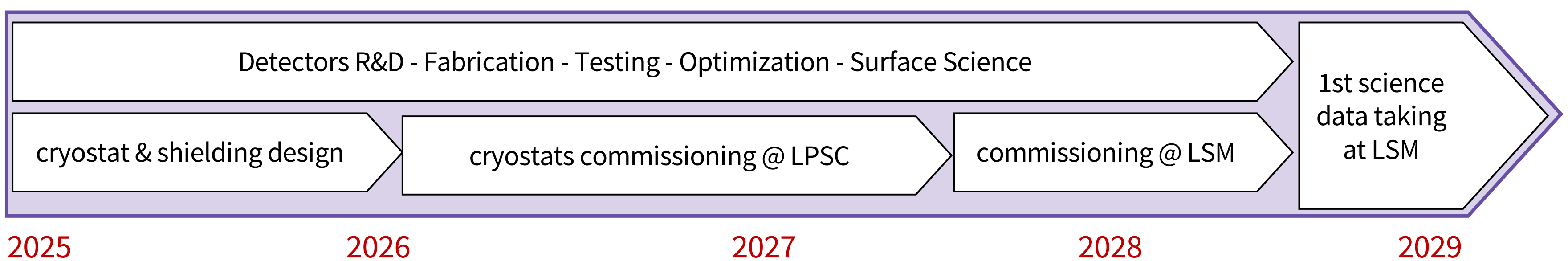
First DM search was background-limited by LEE

This won't be the case for targets with discrimination power

TESSERACT will be moving into Modane underground lab starting in 2028

Target: few-DRU backgrounds
2 dilution fridges
2 DM searches can occur simultaneously





Summary

- TESSERACT has state-of-the-art technology for detection of sub-eV events.
- A strong TESSERACT team has been built, including institutions in the US (DOE-supported), France (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 will lead to improved dark matter sensitivity.
- World-leading energy resolution leads to exploration of new dark matter parameter space at low particle masses. Even small gram-scale detectors can have a big science impact!
- TESSERACT is not trying to improve upon the state-of-the-art in radioactive backgrounds
- R&D focus is shifting toward development of our targets
  - Superfluid He, Al_2O_3, GaAs, Si/Ge
  - Sensor R&D will continue
- Moving to Modane in **2028** for low-background searches

Shielding Scheme