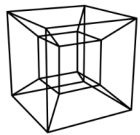


Status of the TESSERACT Experiment

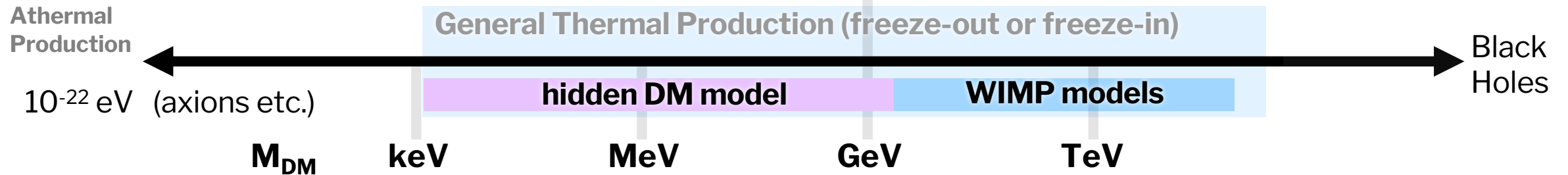


Dan McKinsey
UC Berkeley and LBNL
for the TESSERACT Collaboration
June 4, 2026



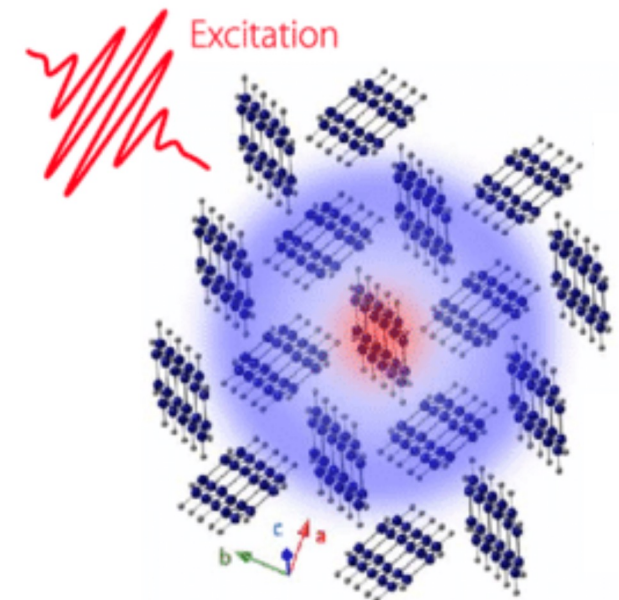


Light Mass DM



Energy deposit	~meV			~eV	~keV
Primary Signature	coherent excitation			electron recoil	nuclear recoil

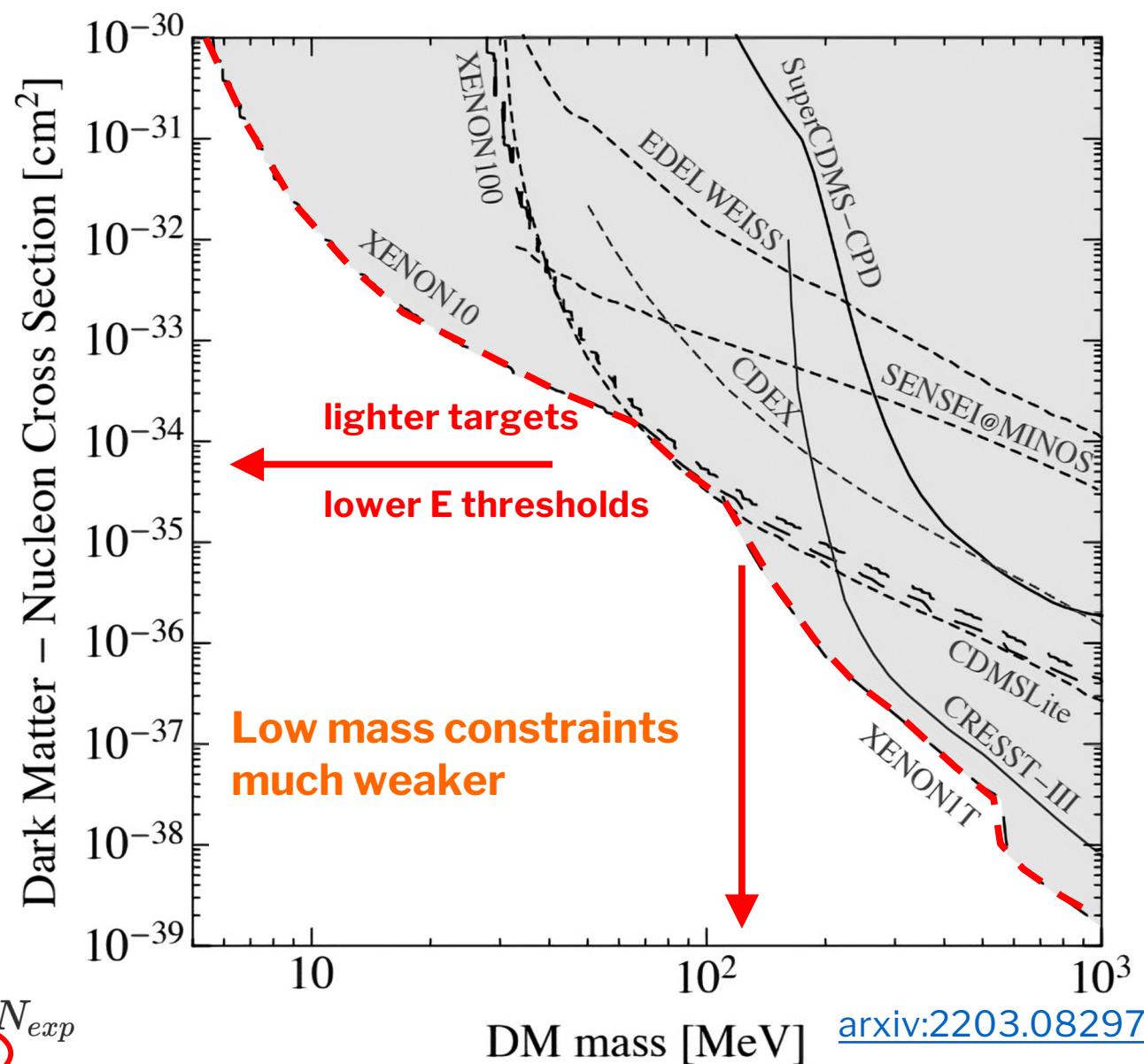
- For sufficiently low masses, no ionization but coherent excitations of the target
- DM wavelength longer than lattice spacing → DM sees material
 - Not a single target will be best (as it is the case for WIMP searches)



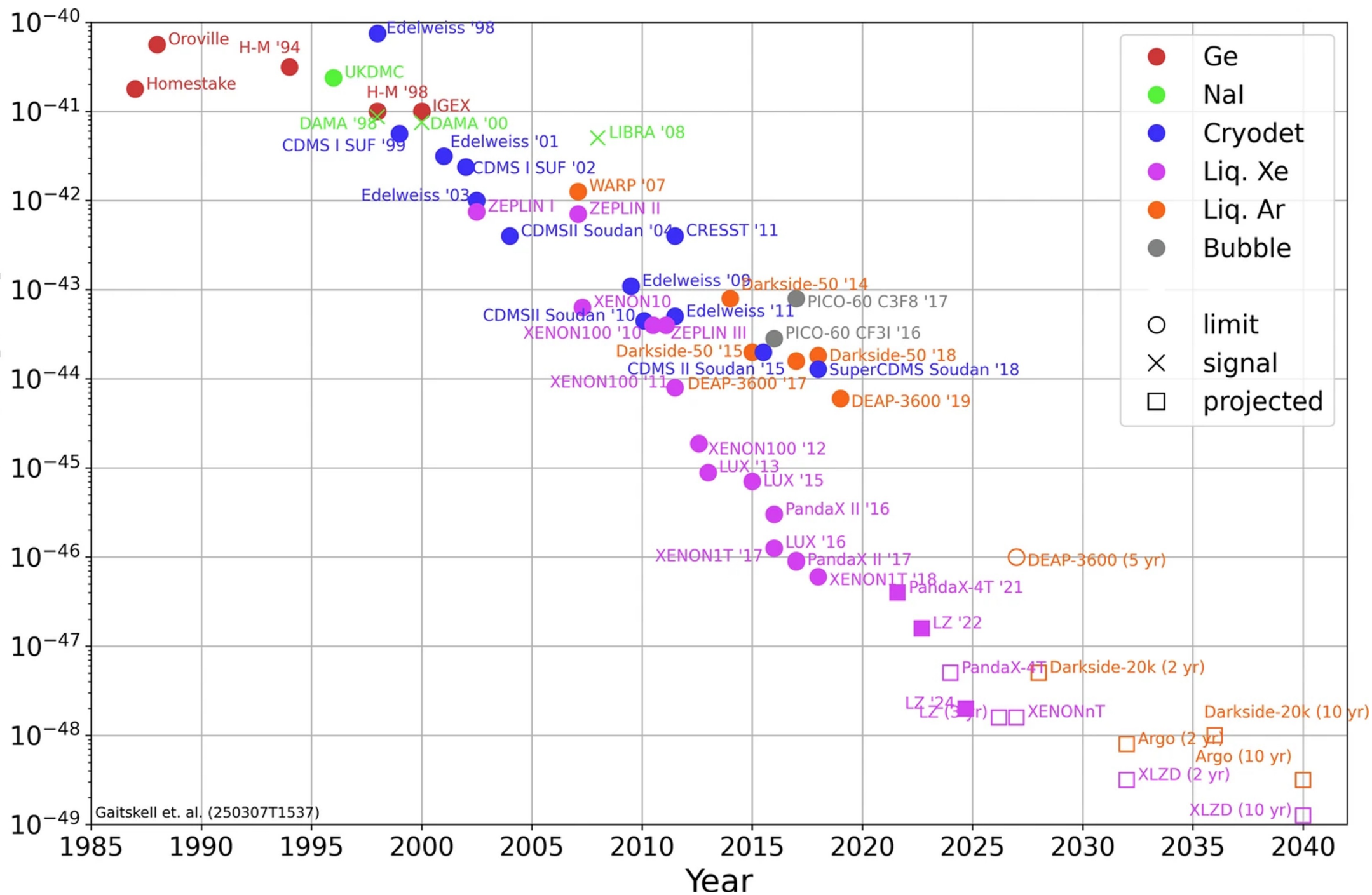
Light Mass Dark Matter

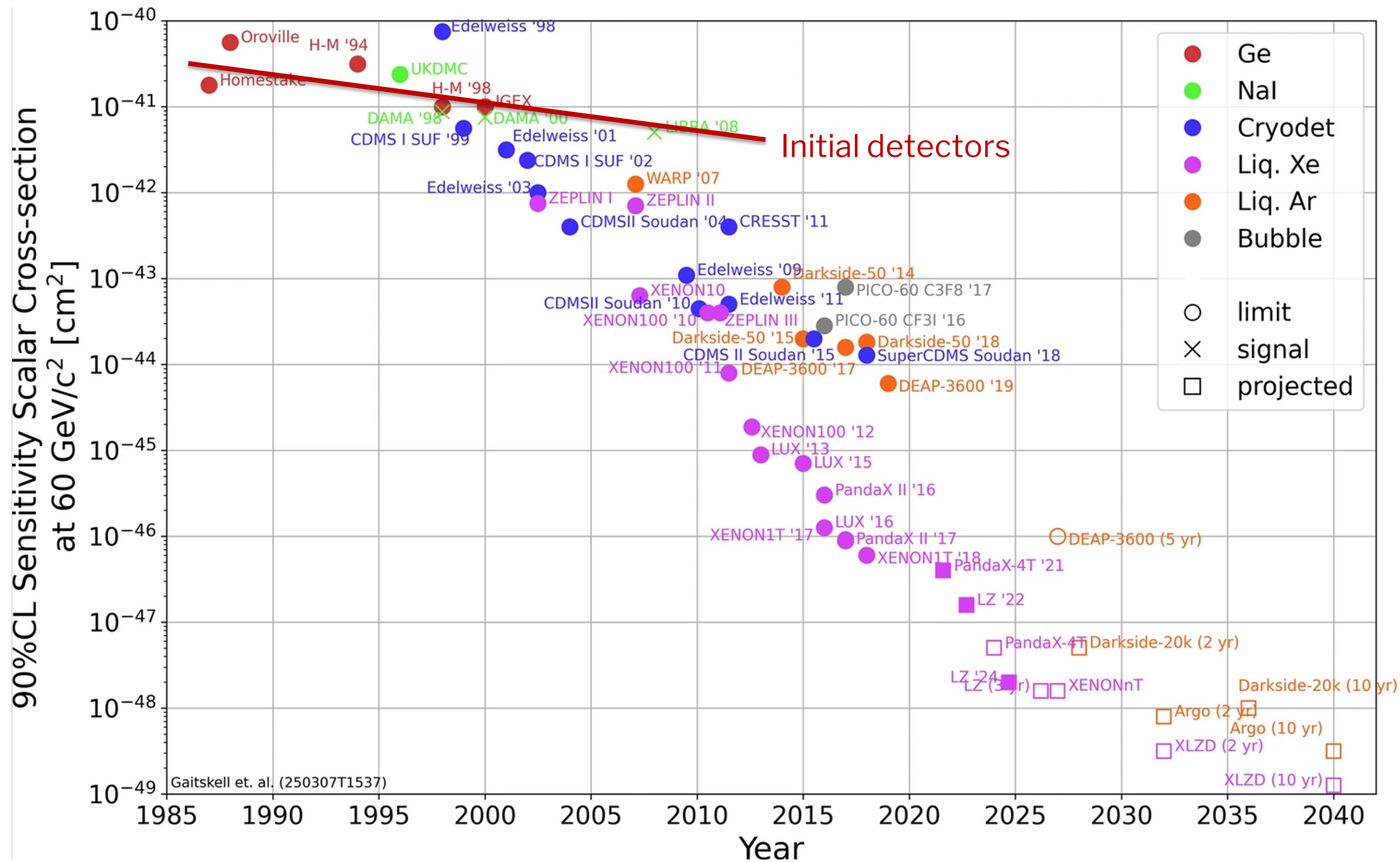
- There is **five times more DM than regular matter**
- **Light-mass DM** ($m_{\text{DM}} < m_p$) (LDM) largely unconstrained due to **small energies** transferred in the **DM scattering**
 - LDM consistent with simple thermal production after inflation
- **New Signatures:** electron scatters, nuclear scatters & absorption
- Even **small target masses** explore new parameter space:

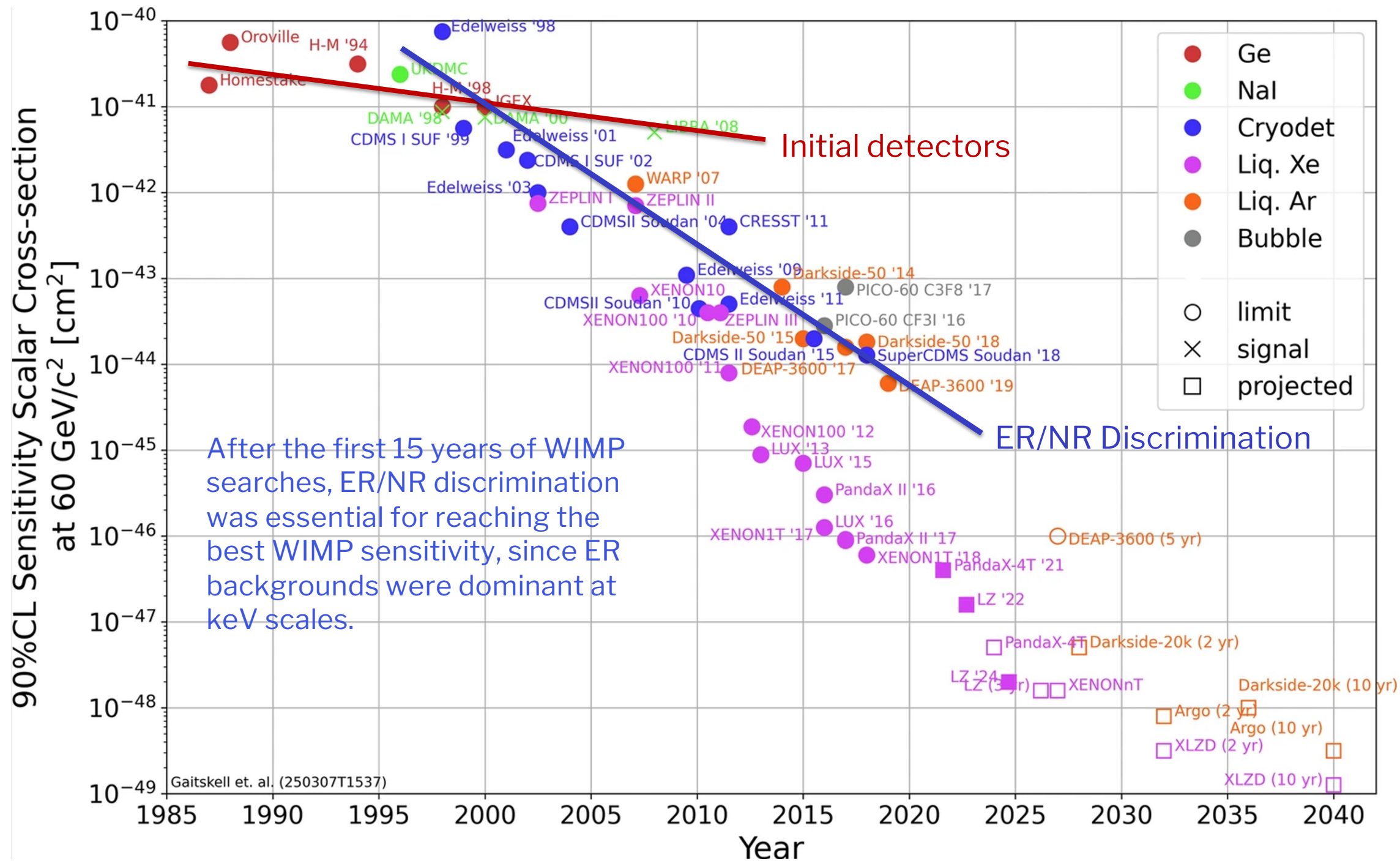
$$R = \sigma n_{\text{DM}} N_{\text{exp}} = \sigma \frac{\rho_{\text{DM}}}{m_{\text{DM}}} N_{\text{exp}}$$

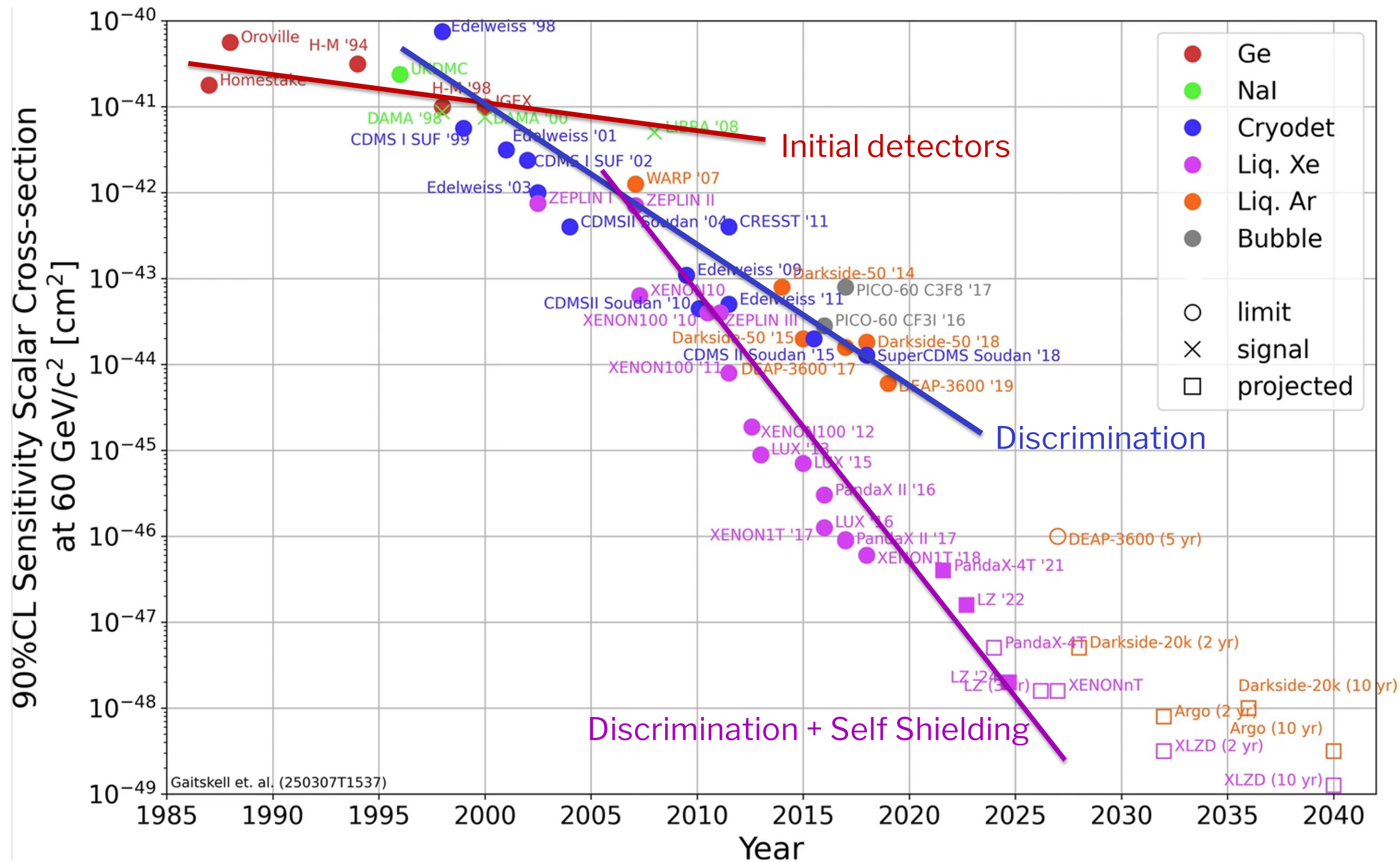


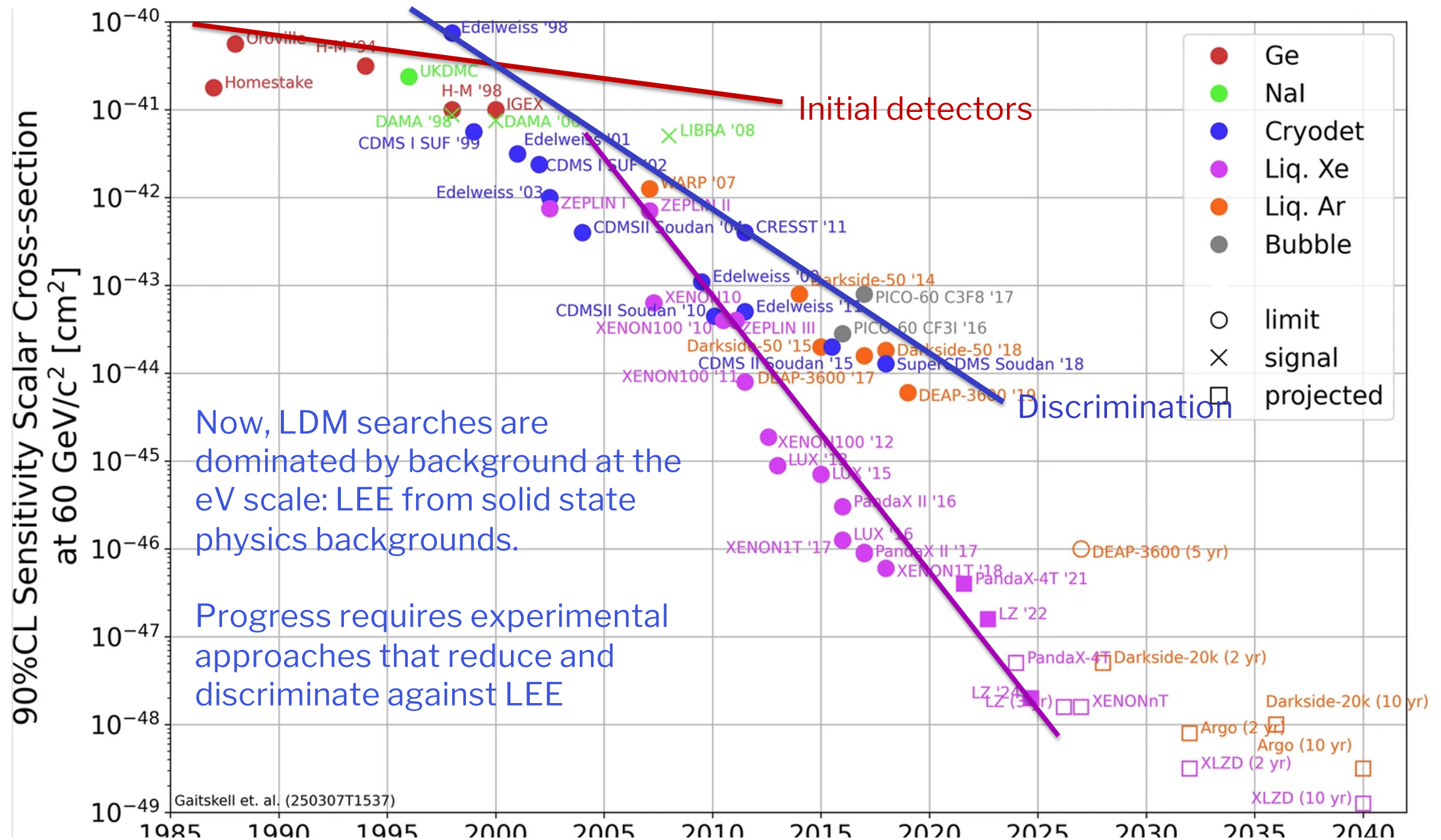
90%CL Sensitivity Scalar Cross-section
at 60 GeV/c² [cm²]

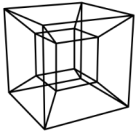








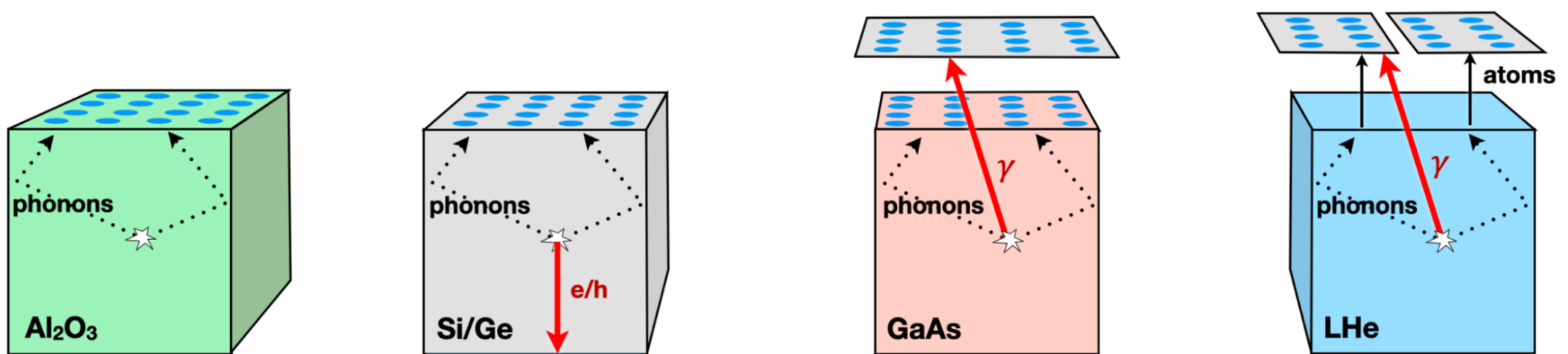
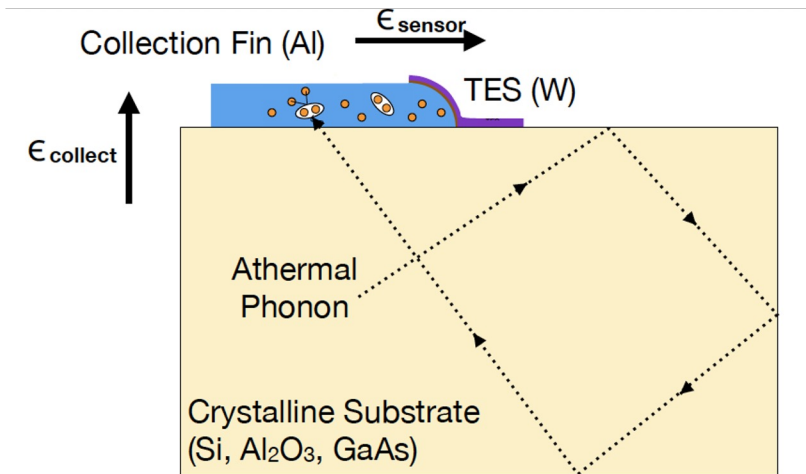


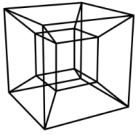


TESSERACT Overview

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.

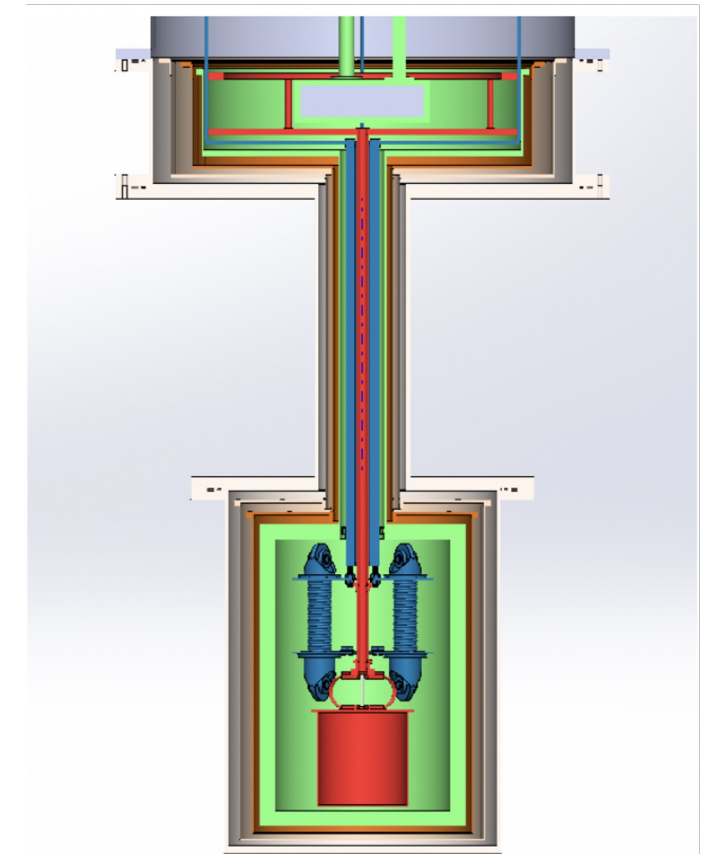
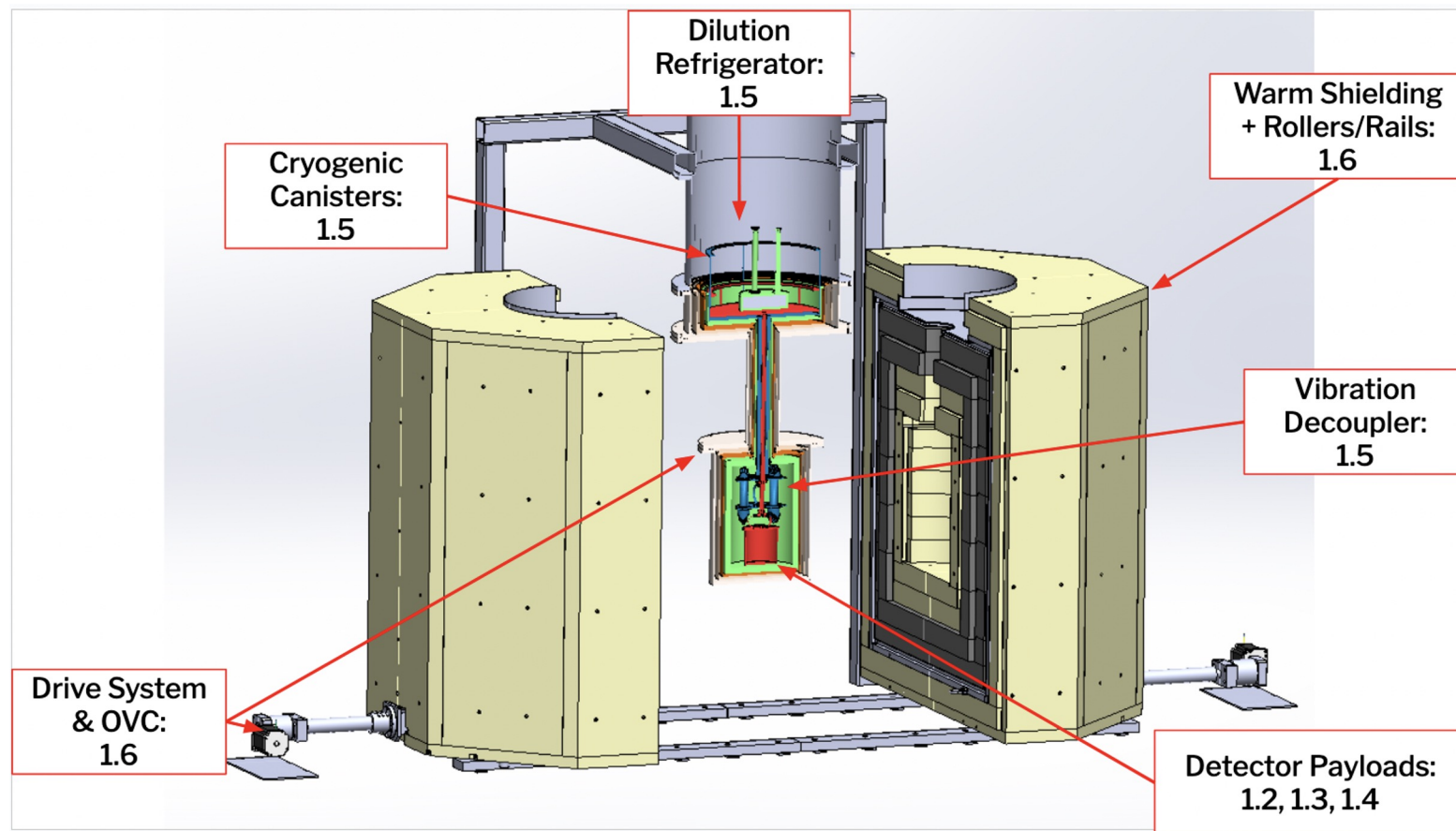
The Si/Ge, GaAs, and LHe technologies all benefit from **multiple signal types and requiring coincidence across readout pixels**, allowing **strong reduction of instrumental and radioactive backgrounds**. Al₂O₃ benefits from **dark matter-lattice coupling**, enhancing its sensitivity at especially low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

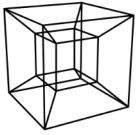




TESSERACT Overview

TESSERACT is designed for flexibility and straightforward detector replacement, with a common infrastructure of shielding, cryostat, dilution refrigerator, vibrational decoupler, cold electronics, and DAQ. There will be 2 identical setups, each installed in a deep underground laboratory (LSM).

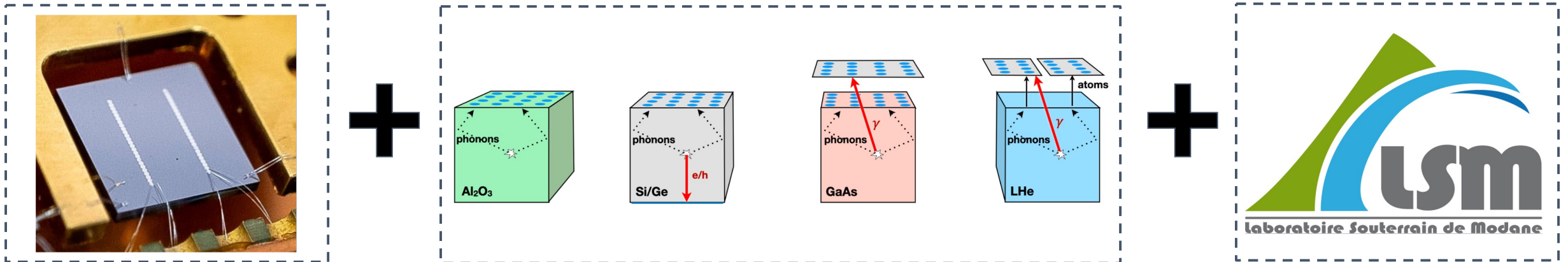


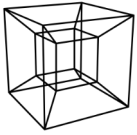


TESSERACT Overview

Three ingredients will make TESSERACT successful:

1. Low-threshold, background-reduced sensors
2. Optimized, complementary dark matter targets/modules
3. Long-term, low-background, underground searches





TESSERACT Collaboration

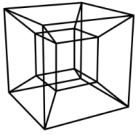
TESSERACT = Transition-Edge Sensors with Sub-eV
Resolution And Cryogenic Targets

- Direct search for light-mass and ultralight dark matter
- Multiple target materials with identical readout (transition edge sensors and SQUID amplifiers)
- Capability to search for dark matter particles with mass in the 100 meV to 1 GeV range.



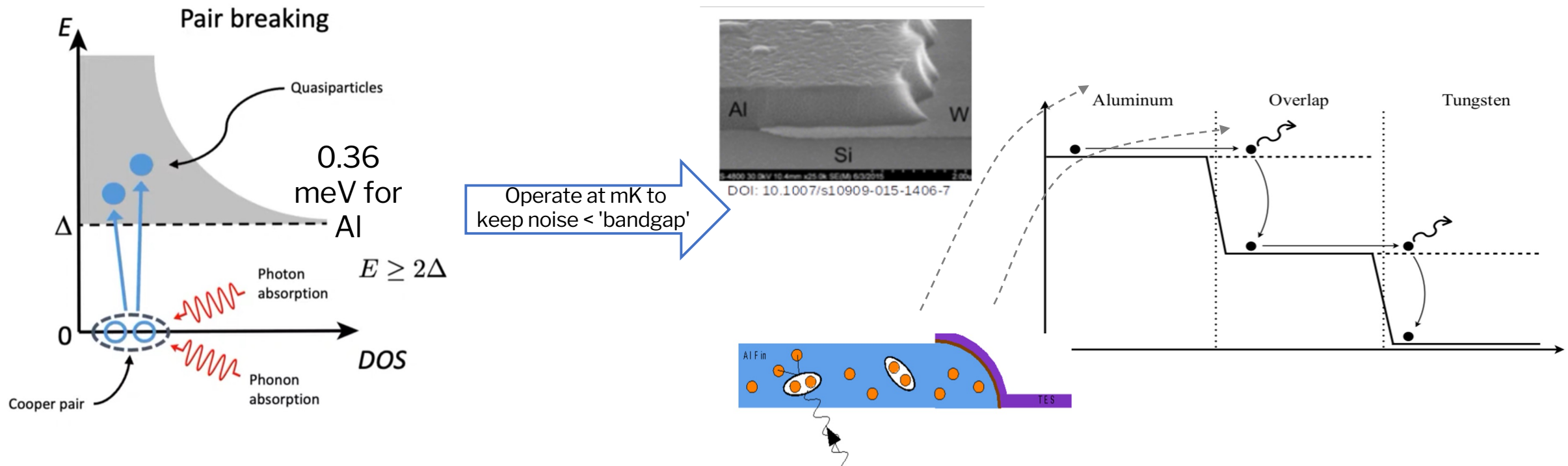
TESSERACT includes over 60 scientists, researchers, engineers, project managers, postdocs, and graduate students, from 12 institutions in the US, France, and Switzerland.



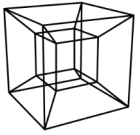


W TES

- Instead of 'breaking' electrons out of an atom we break 'cooper pairs' (quasiparticles)
- Can measure those using **Transition Edge Sensors** (TES) acting as ultra-sensitive thermistors

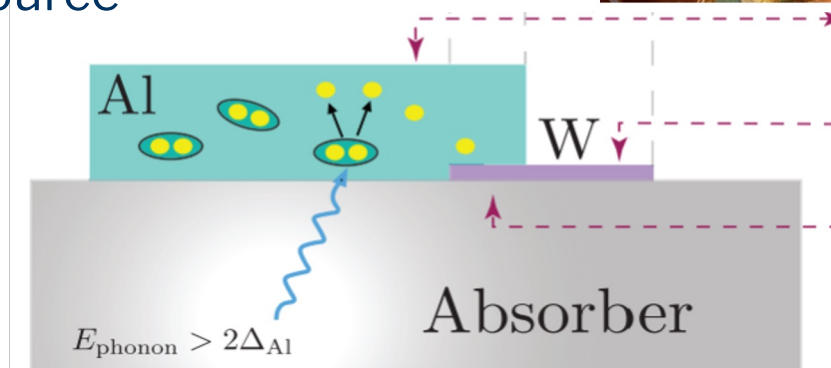
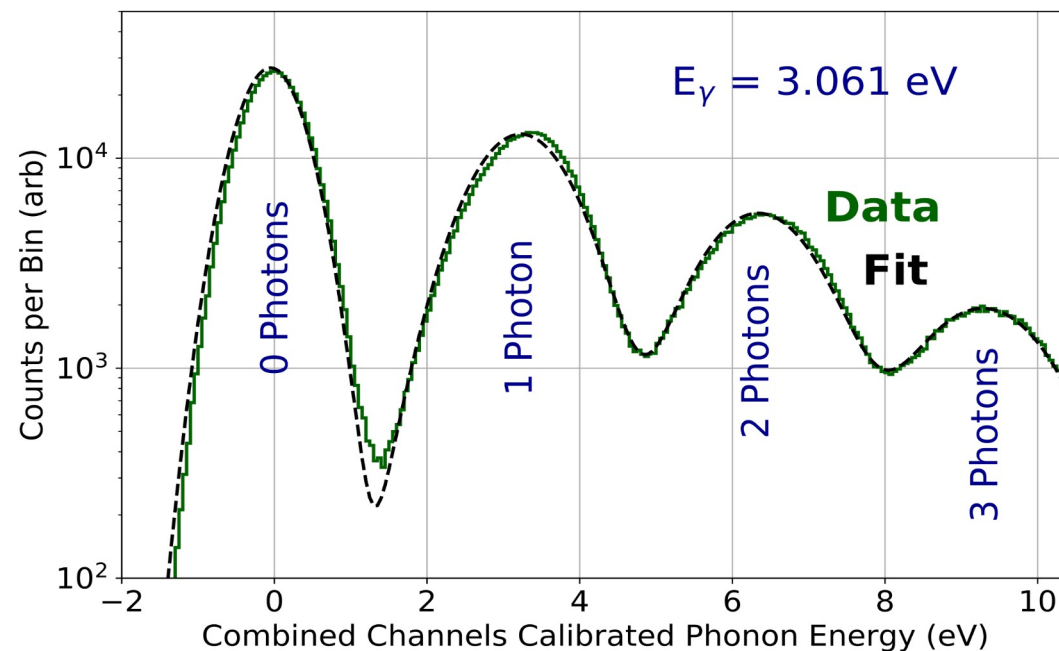
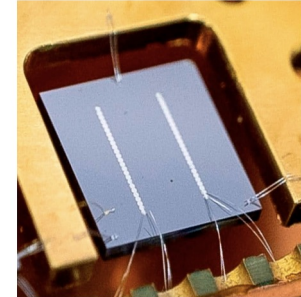


- **Collect athermal phonons** energy in Al fins → **break cooper pairs** in Al → **absorb QP** in TES
- Al fins allow large collection area without the drawback of the heat capacity of a large sensor



TESSERACT Sensor R&D

- W Transition-edge-sensors, with $T_c = 48$ mK
- 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: **$361.5 \pm .4$ meV** from photon source

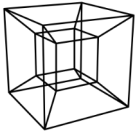


$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G (\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect} \epsilon_{sensor}}$$

$$\sigma_E \propto \underbrace{V_{det}^{1/2}}_{\text{Energy threshold improves with decreasing TES mass}} \underbrace{T_c^3}_{\text{Energy threshold improves very quickly with decreasing } T_c}$$

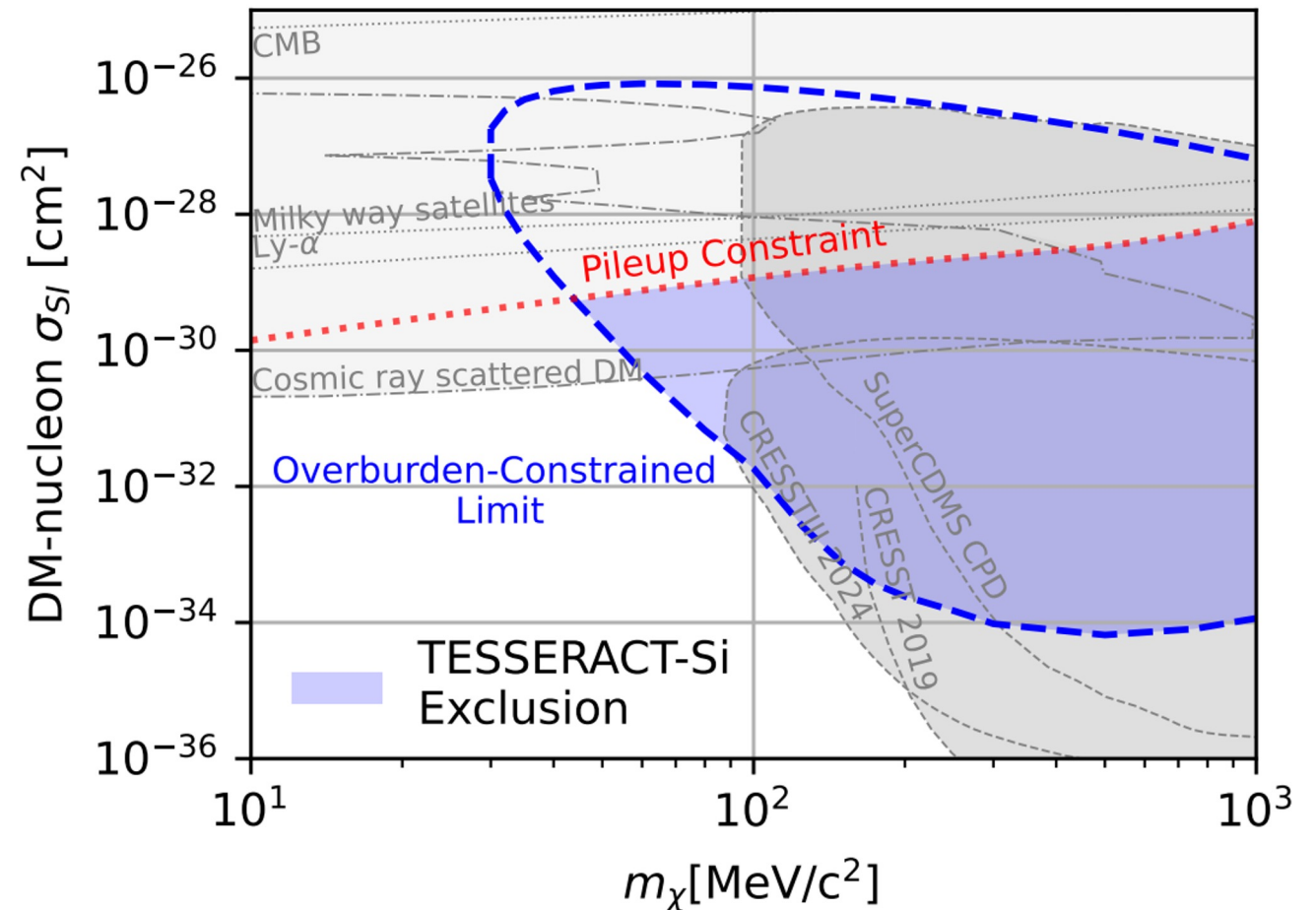
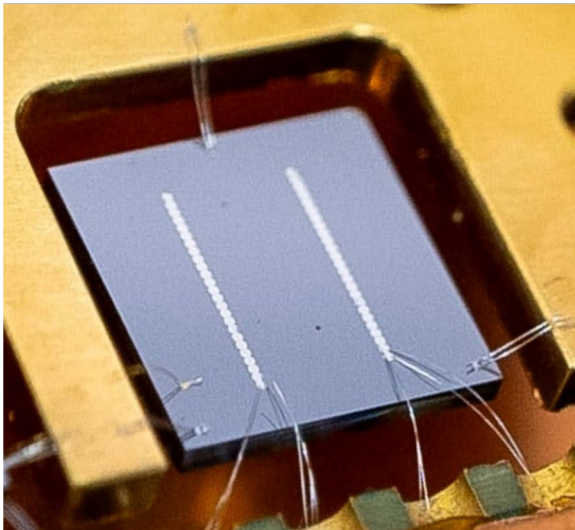
Energy threshold improves with decreasing TES mass

Energy threshold improves very quickly with decreasing T_c



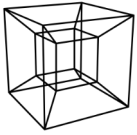
First TESSERACT DM Result

- Due to our very low energy thresholds, even very small masses can obtain new DM results
- **First TESSERACT DM** result using 0.23g Si detector and 361 +/- 5 meV resolution
- 1.5 eV analysis threshold!
- Surface-level data, limited by LEE
- Will further improve with more mass, better discrimination, **going underground**



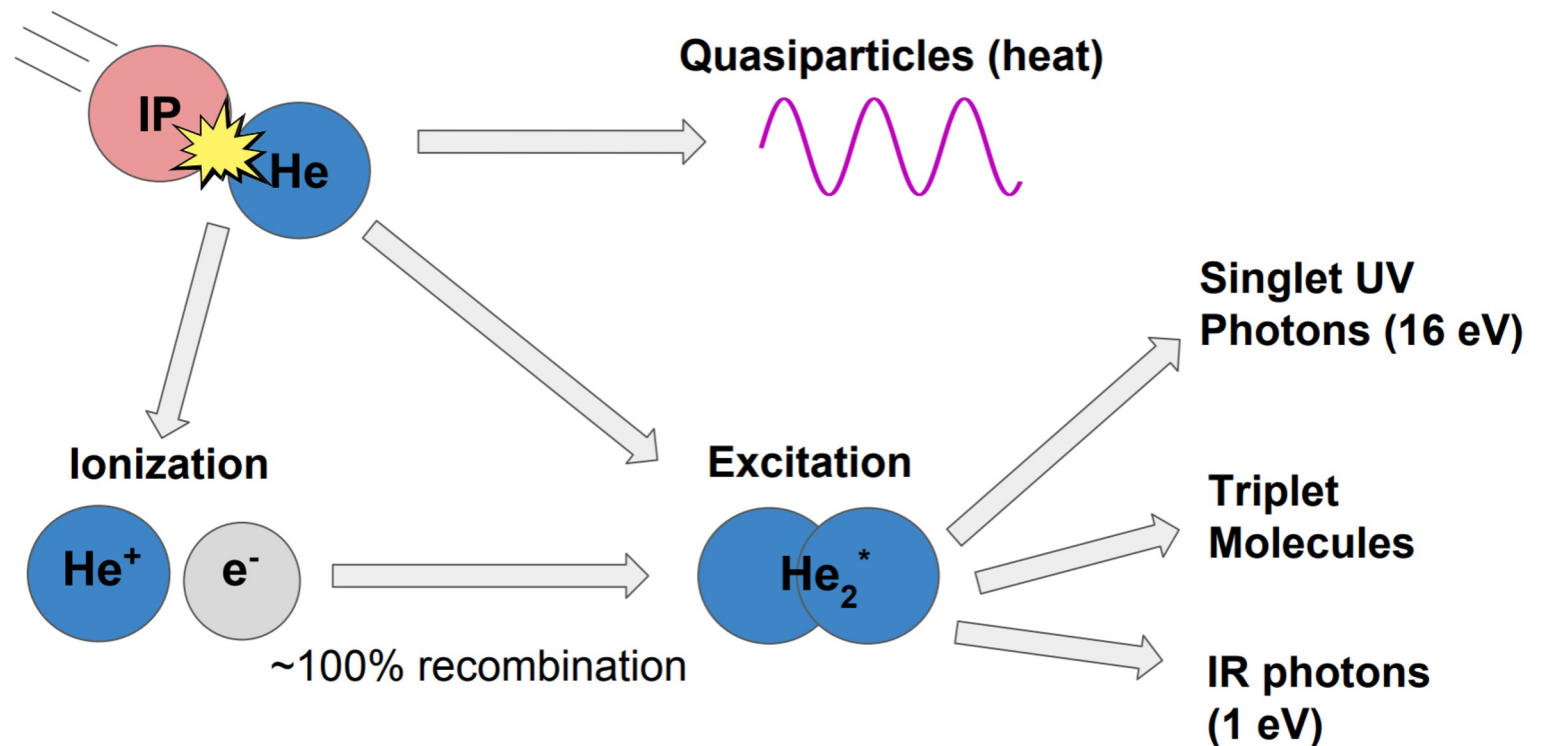
Phys. Rev. Lett. 135, 161002

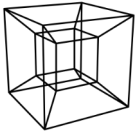
[arXiv.org:2503.03683](https://arxiv.org/abs/2503.03683)



Superfluid ^4He

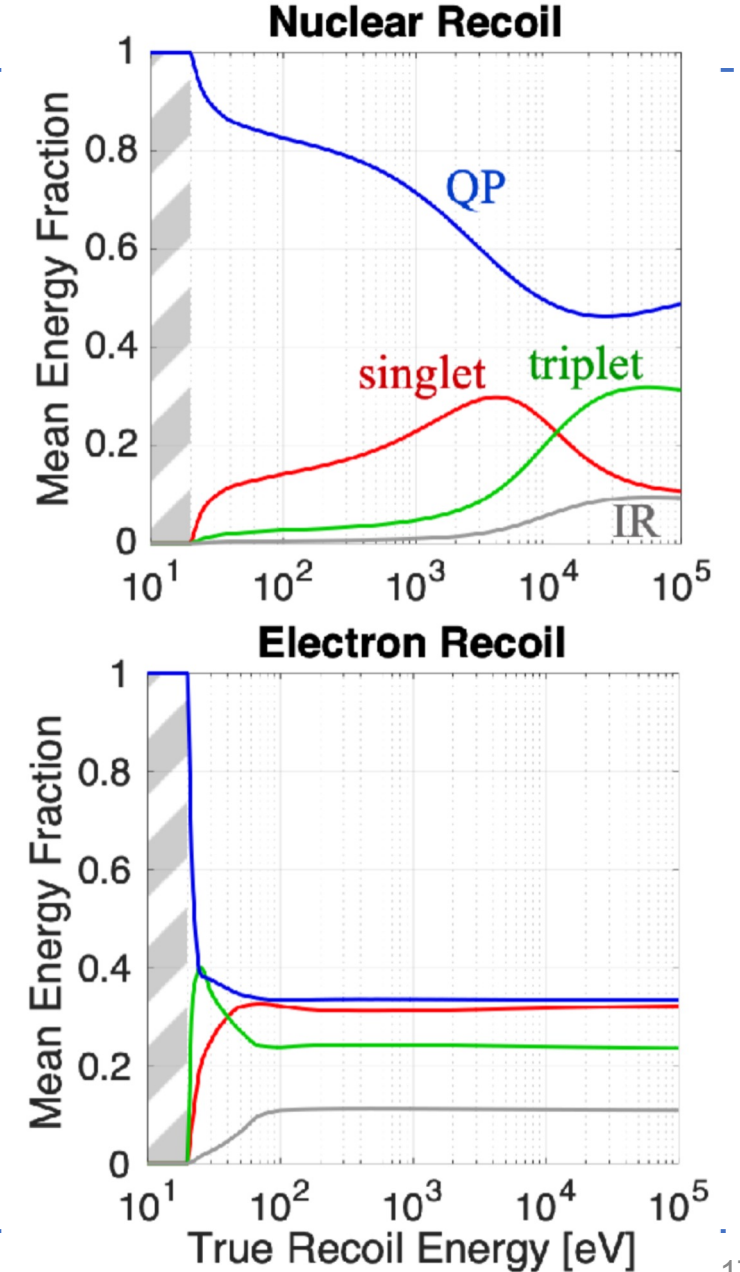
- **Heat leads to quasiparticles** (phonons and rotons) ballistically propagating through the detector below 100 mK
- **Atomic excitations**
 - Excimer states resulting in **VUV** and **IR** photons with characteristic lifetimes
 - Not unlike scintillation light in LXe

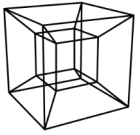




Superfluid ^4He

- **Above 20 eV:**
 - Significant fraction of recoil energy goes into excimers
 - Estimate fraction directly from measured atomic excitation cross sections.
 - So far ER and NR calibrations agree with expectation ([arXiv:1810.06283](https://arxiv.org/abs/1810.06283))
- **Below 20 eV:**
 - All recoil energy appears as phonons and rotons (Hard cutoff of electronic excitation)
 - Compton scattering backgrounds highly suppressed
- If the goal is $E < 20$ eV recoils, then dimers can act as a veto, tagging $E > 20$ eV recoils





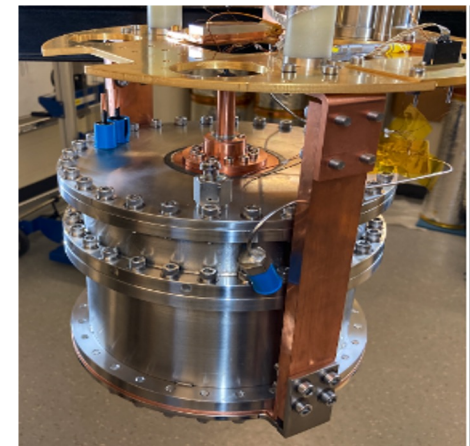
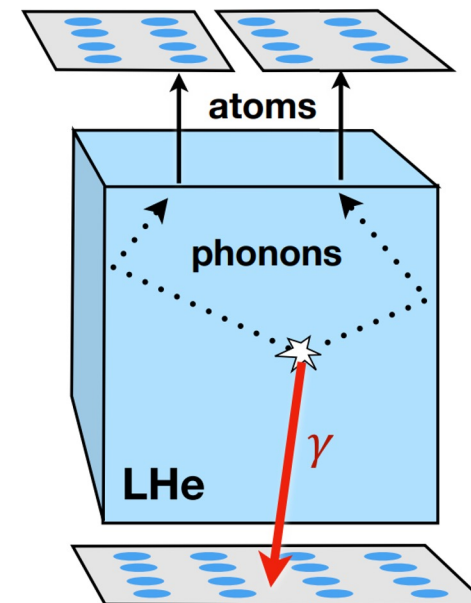
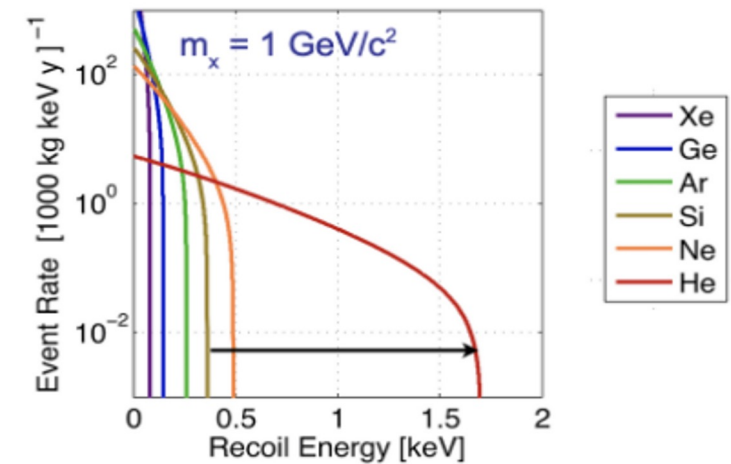
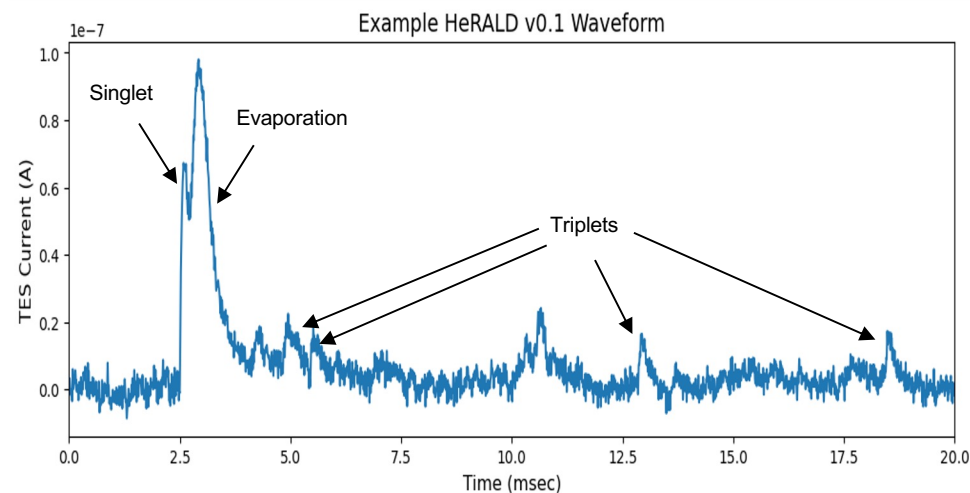
Superfluid Helium Target

Target : **Liquid He**

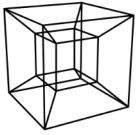
- Light material $\Rightarrow$ better kinematic matching with LDM
- Extremely radiopure
- No solid state physics or chemistry!
- No internal stress nor dislocation (LEE source ?)
- Superfluid $\Rightarrow$ no vibrational coupling with the environment

Several signal channels :

- quasiparticles (phonon/rotons)
- singlet excimers $\Rightarrow$ short lived, emits 15.5 eV photon
- triplet excimers $\Rightarrow$ long lived, ballistic

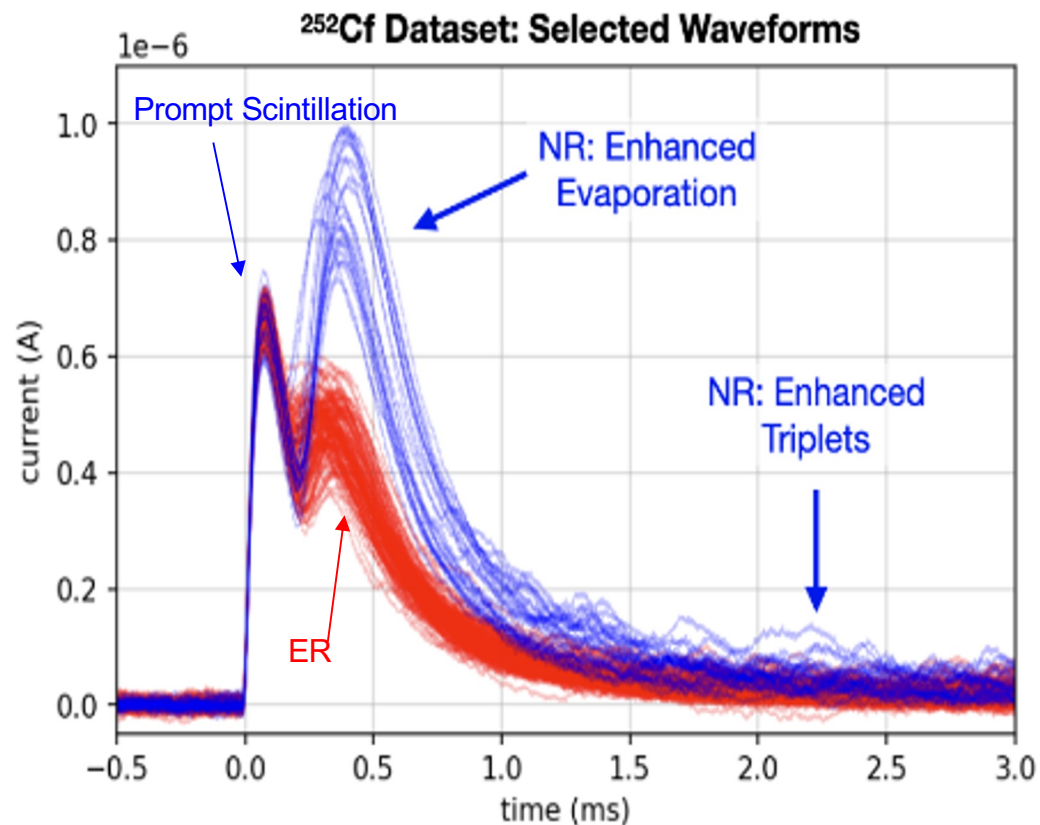


R. Anthony-Petersen et al.,
arXiv:2307.11877



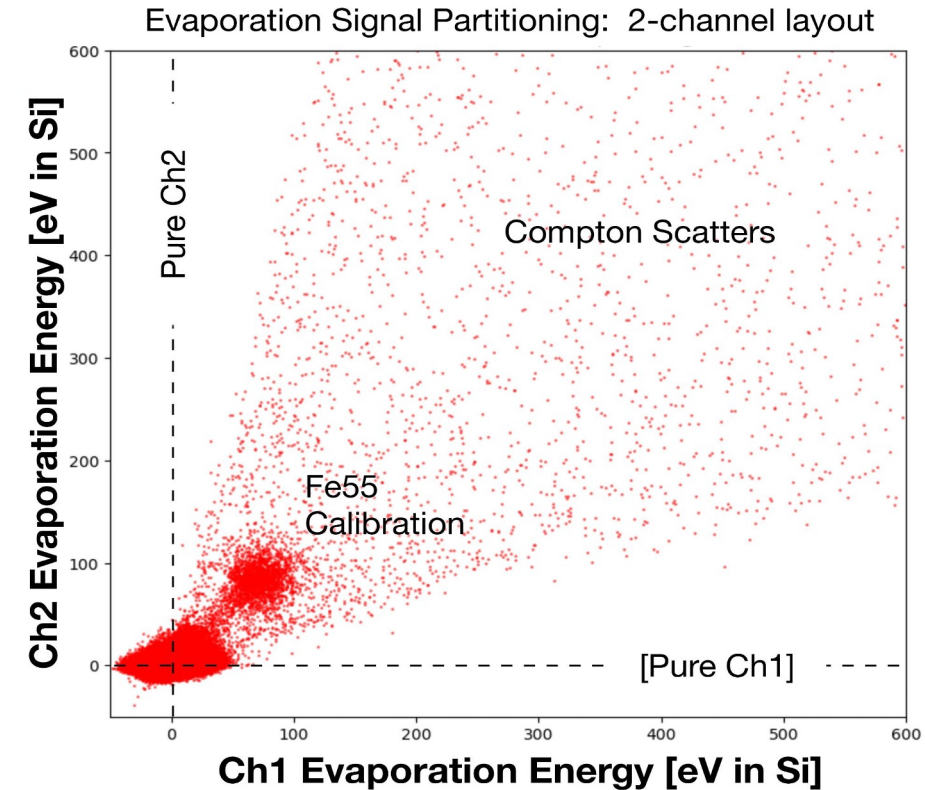
Superfluid Helium Target

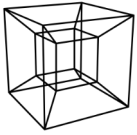
Particle identification thanks to pulse shape discrimination



LEE mitigation strategy:

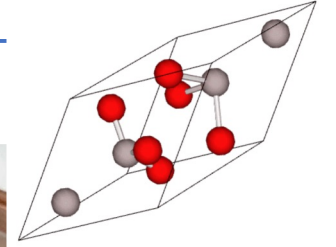
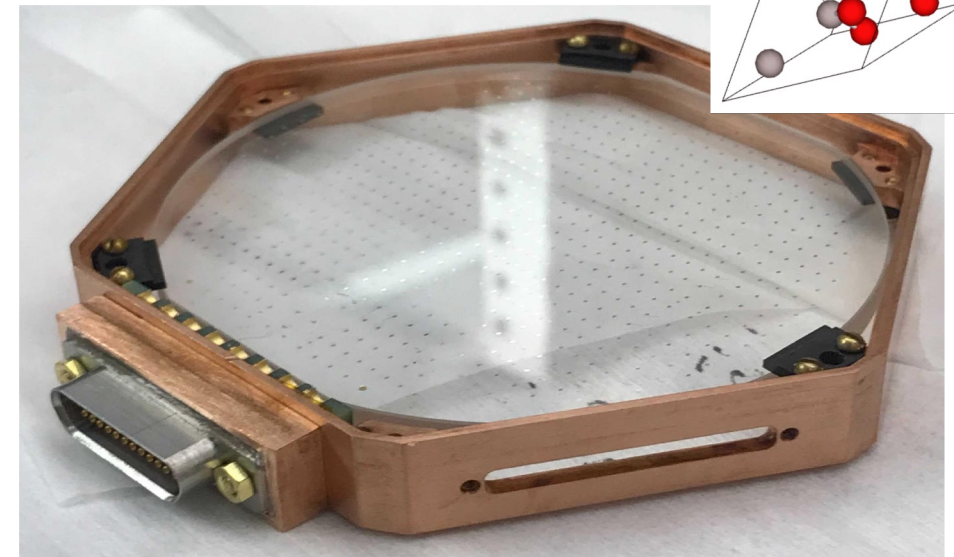
- Several channels above the vacuum
 - Events in calorimeters (LEE) $\Rightarrow$ single channel
 - Events in ^4He $\Rightarrow$ multiple channels



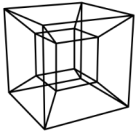


Solid State Detectors

- **Sapphire** (Al_2O_3):
 - **Sapphire** supports many optical phonon modes.
 - **Optical phonons** kinematically well-matched to low-mass DM $\rightarrow$ effective energy transfer
 - Coupling to E&M-like inputs due to electric dipole $\rightarrow$ **dark photon sensitivity**
 - TES coincidence requirement to reduce LEE

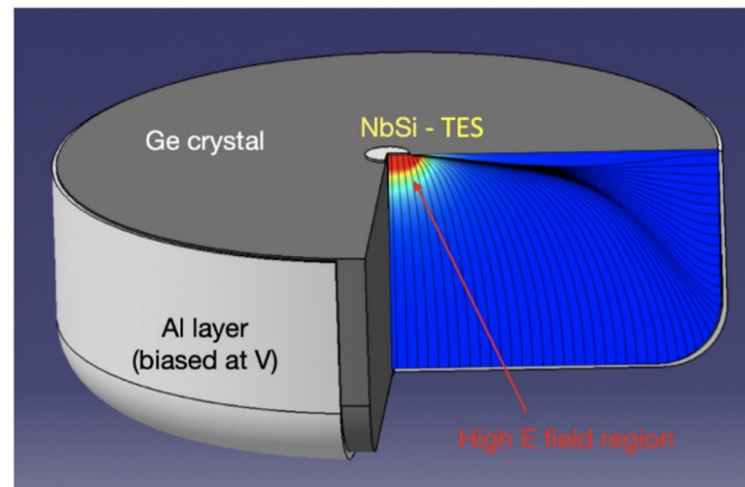
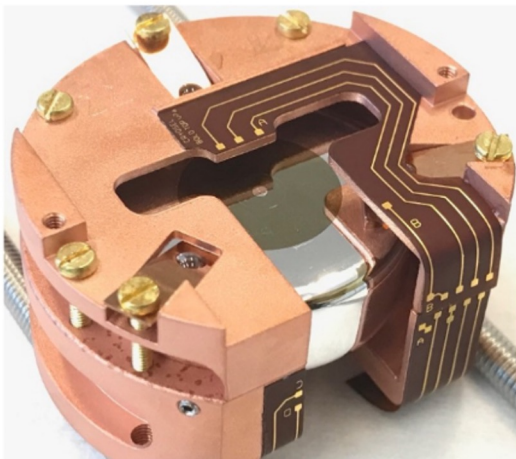
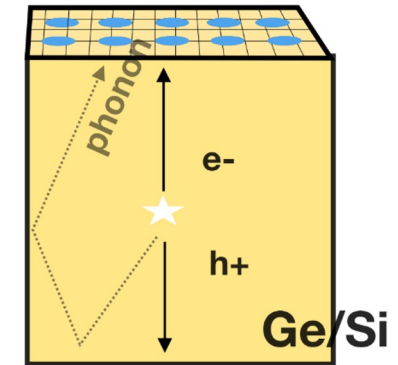


- **GaAs:**
 - **Polar crystal & bandgap** well matched to kinematic region of low mass DM
 - **Background discrimination** using phonon/photon ratio
 - Photon-photon and phonon-phonon coincidence can reduce instrumental bkgds
 - **High light yield** (125 ph/keV, 1904.09362)



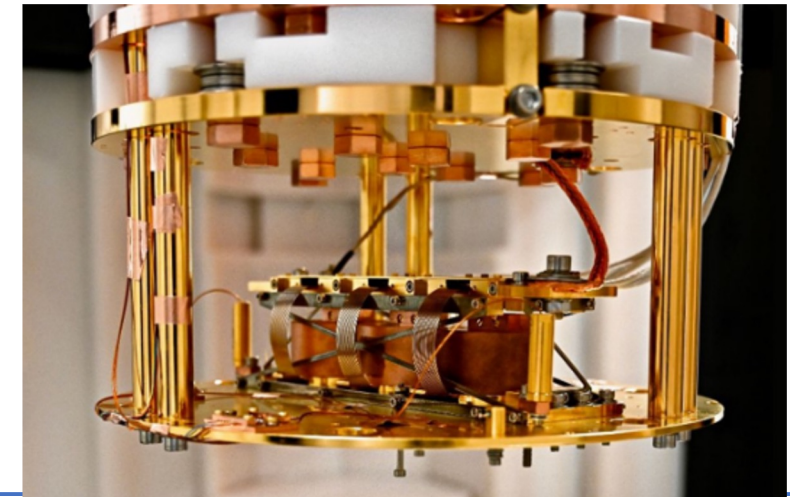
Si/Ge Targets

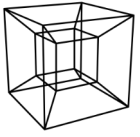
- Ge/Si semiconducting bolometers similar to Edelweiss in low voltage mode
- Two channels: Heat & Ionization
 - Luke boost → Additional photons proportional to ΔV
- Can operate either in low or high voltage mode:
 - HV: Very good ER sensitivity with LEE discrimination
 - LV: Very good NR sensitivity with NR/ER and LEE discrimination
- Ongoing R&D, discussed yesterday by Juliette Blé



D. McKinsey

TESSERACT

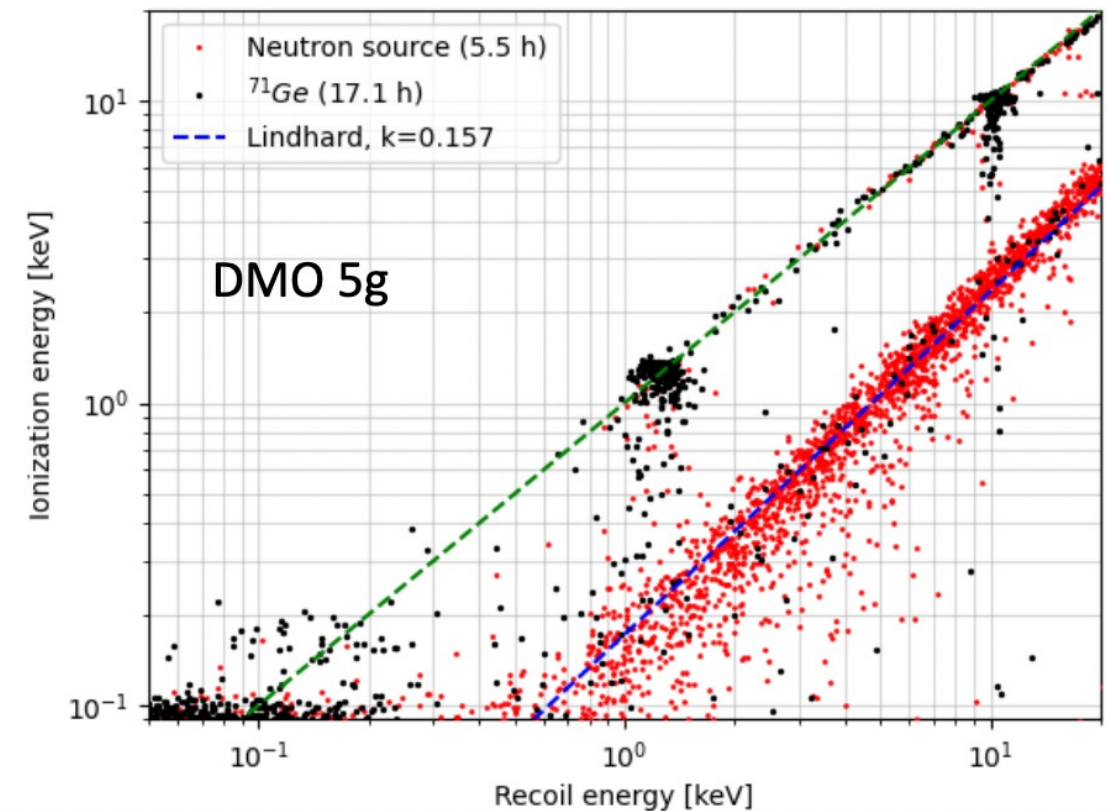
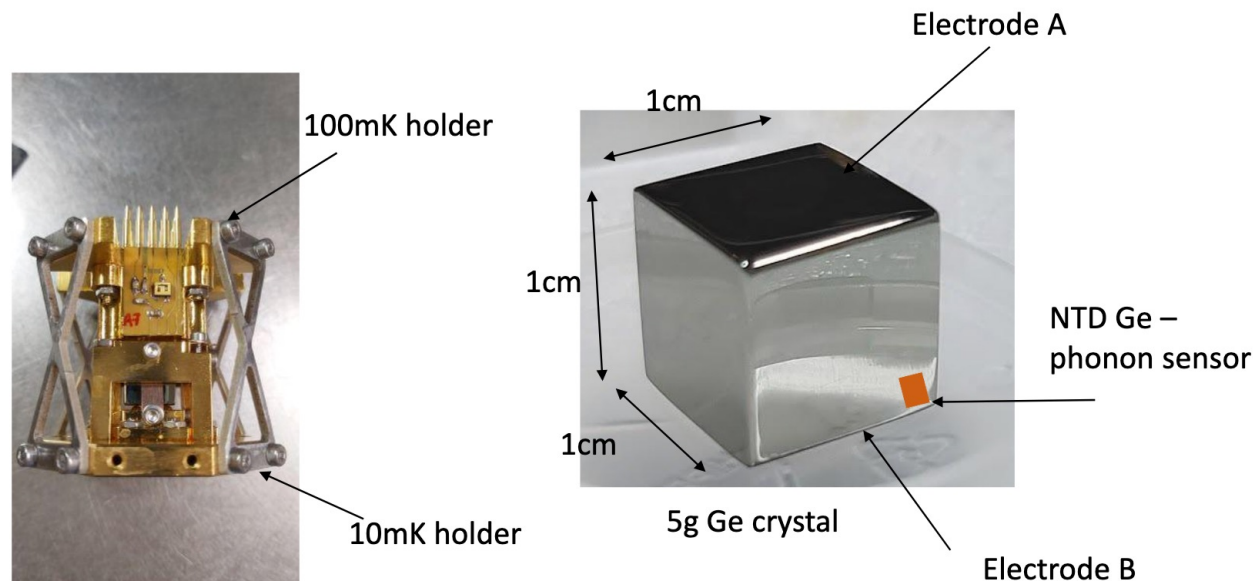


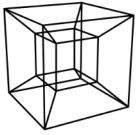


Si/Ge Target

Low-Voltage approach for optimal NRDM sensitivity

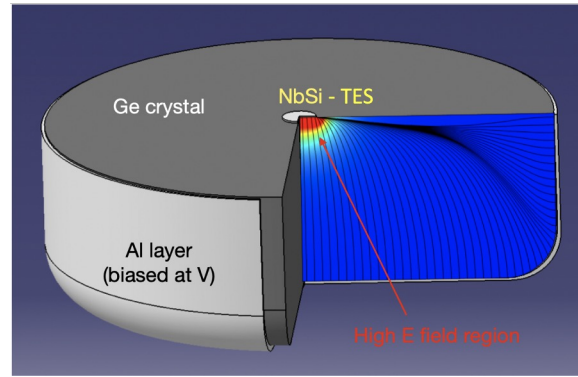
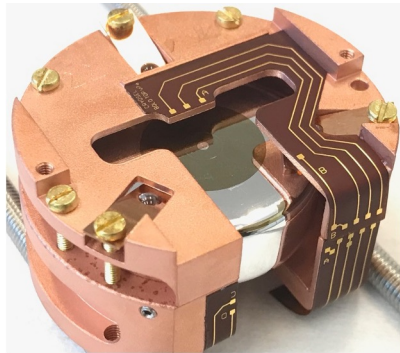
- Double readout heat/ionization $\Rightarrow$ particle identification
- LEE are non-ionizing $\Rightarrow$ improving the charge resolution is of major importance
- Tesseract Ge LV first prototype (5 g) performance:
- Ionization resolution ~ 22 eVee
- Phonon resolution ~ 20 eVph
- Clear identification of NR/ER bands





Si/Ge Target

High-Voltage approach for optimal ERDM sensitivity



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

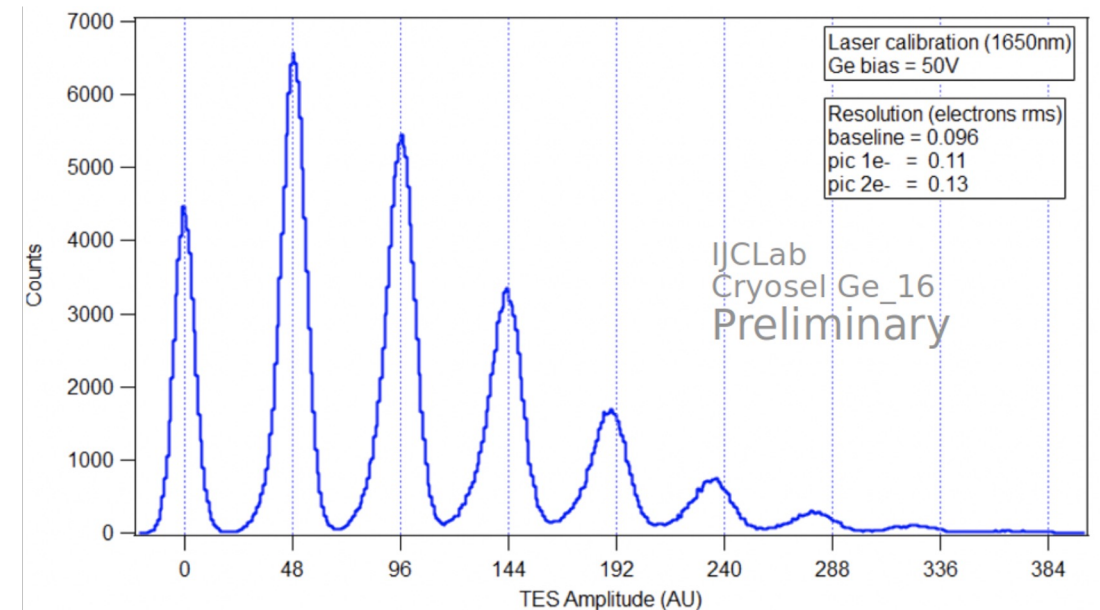
$$E_{\text{heat}} \approx E_{\text{ion}} \Delta V / \epsilon_{\text{eh}} \text{ (HV)}$$

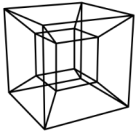
First observation of a single-electron sensitivity in a massive (40g) Ge cryogenic detector !

- 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**





Instrumental Backgrounds

Extensive R&D toward mitigating LEE from 3 sources:

1) Mounting Scheme (stress)

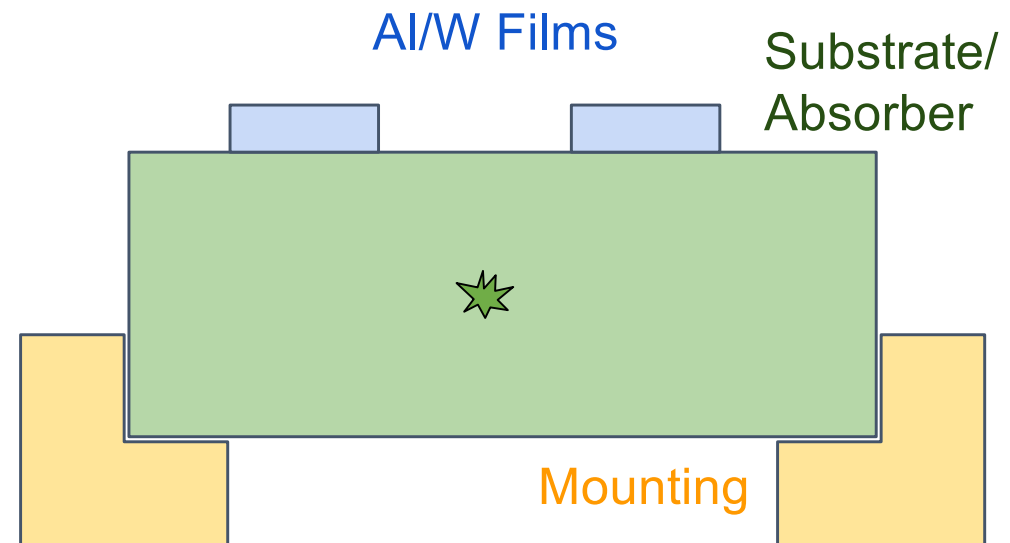
Hang by wire-bonds > Gluing

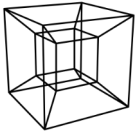
2) Al/W Films

Require coincidence between 2 independent sensor films

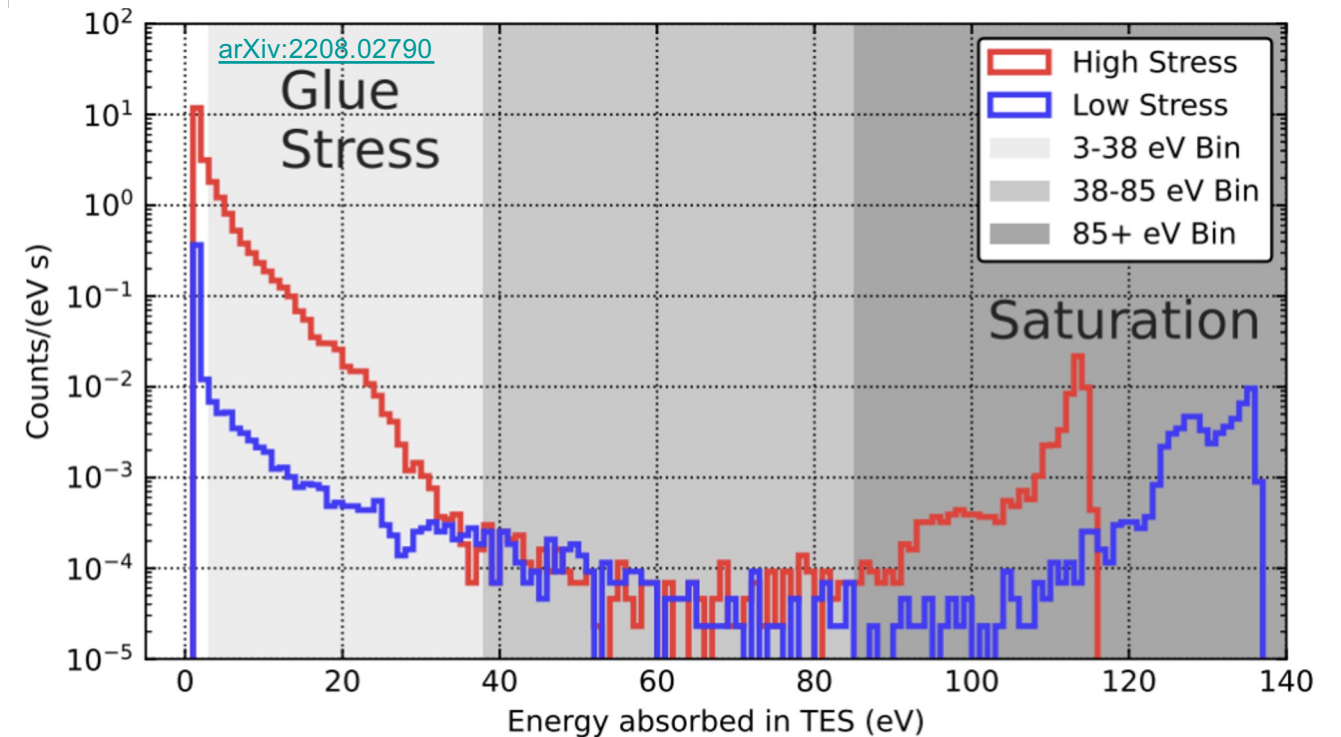
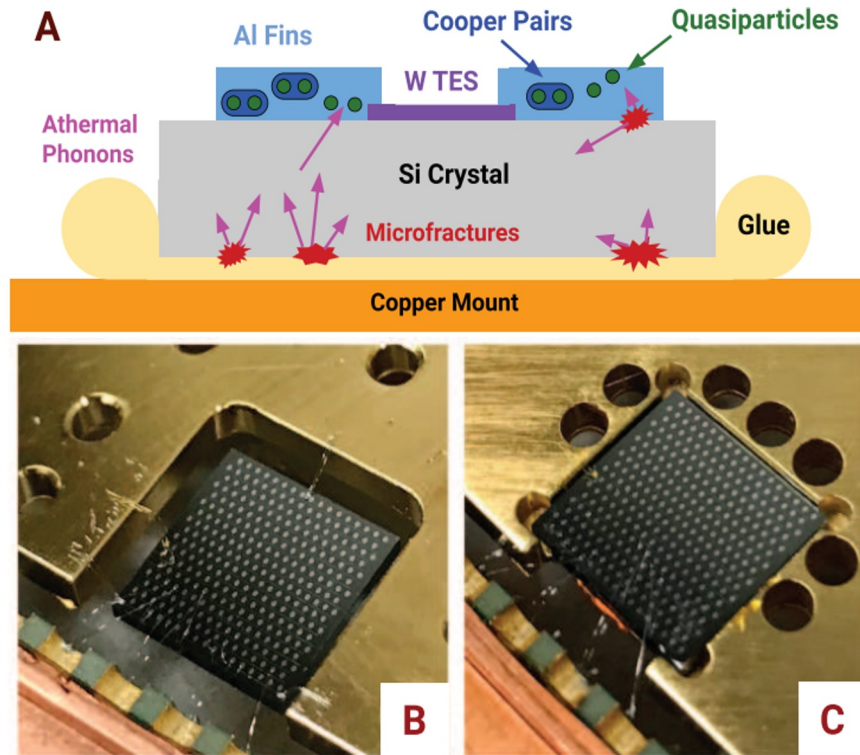
3) Substrate volume

Active area of research
Rate $\sim$ substrate volume

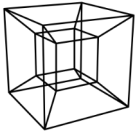




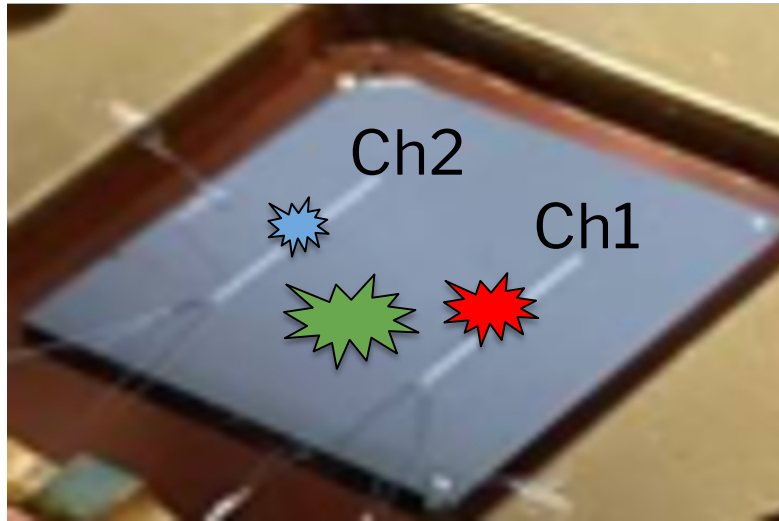
Recent Progress - LEE



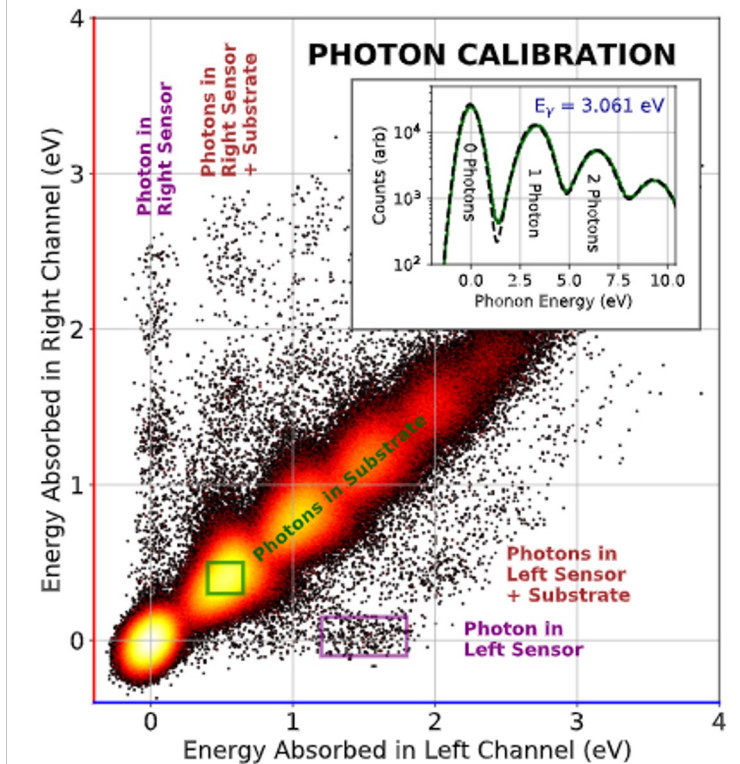
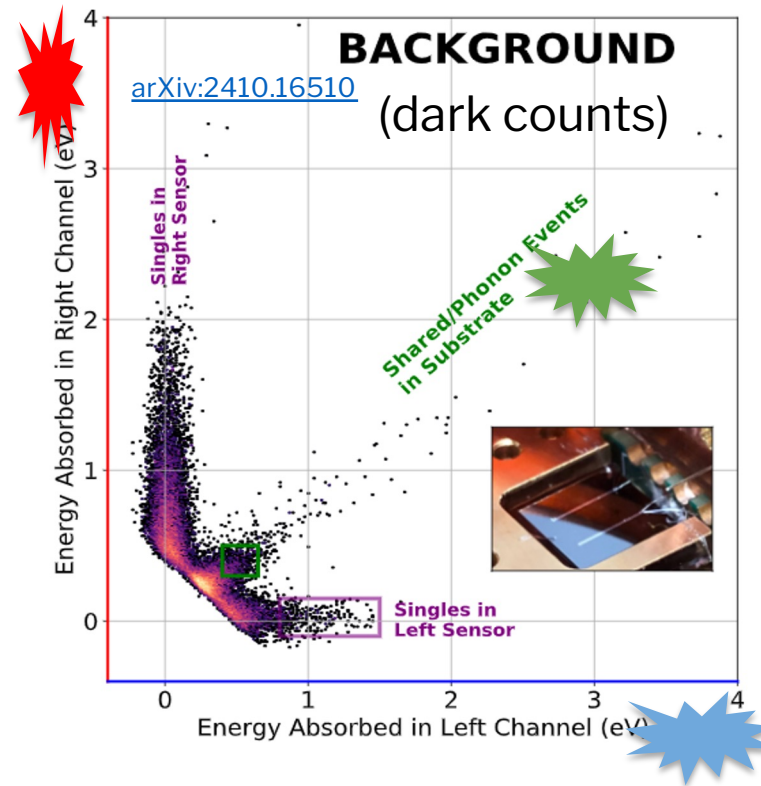
- Two identical detectors, glued vs. suspended from wire bonds
- Measures athermal phonon pulses in substrate
- Successful mitigation of mounting stress
 - Two orders of magnitude difference in rate → stress is major source of LEE



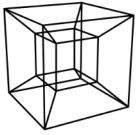
Recent Progress - LEE



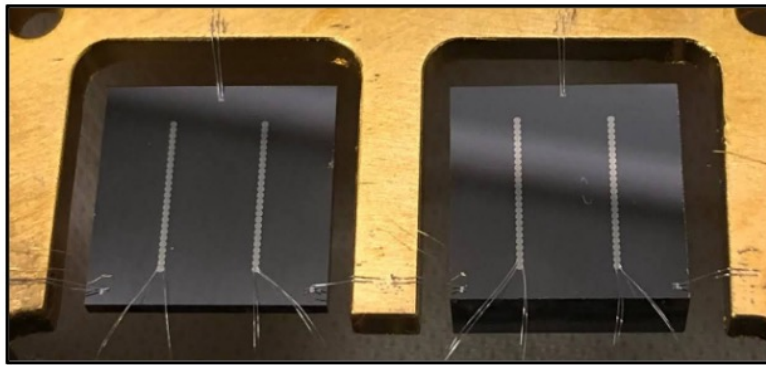
1 cm² 2-channel Si device



- Can use **dual-channel devices** to discriminate LEE events from signal like events
 - Observe single channel events (Al film relaxation) and shared events (bulk substrate phonons)
- Now studying those hypotheses for different sensors geometries → Understanding & mitigation of the LEE will be key to improve resolution

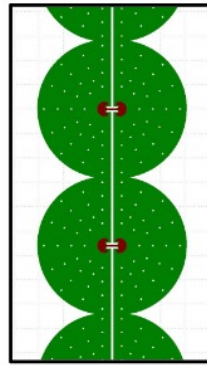


Recent Progress - LEE

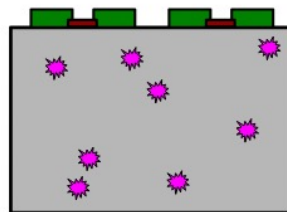


1 mm thick detector

4 mm thick detector



~1x Shared LEE/
Correlated Noise

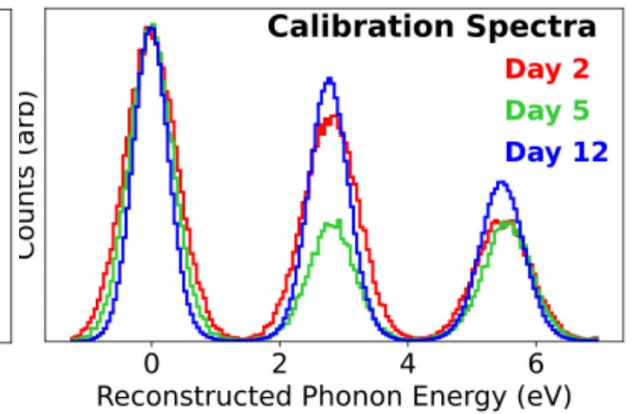
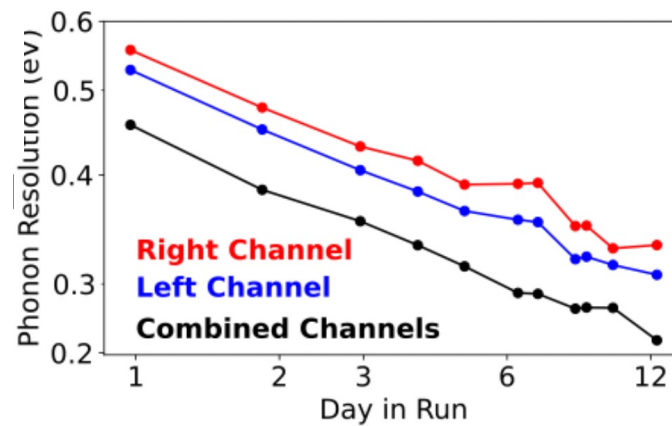
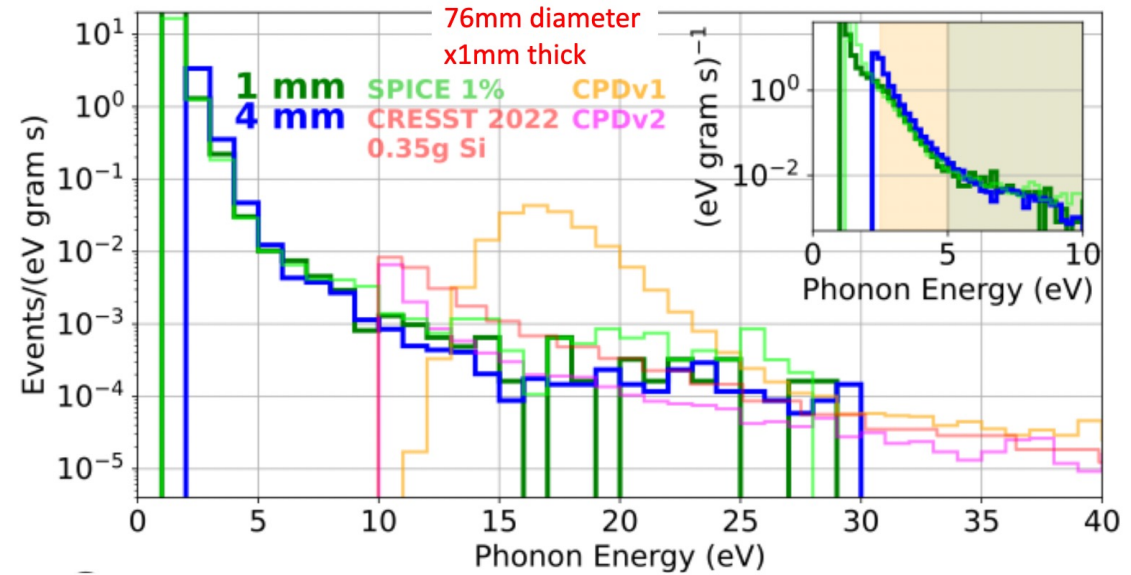


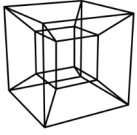
~4x Shared LEE/
Correlated Noise

Aluminum Phonon
Collection Fins
Tungsten TESs
Silicon Detector
Substrate

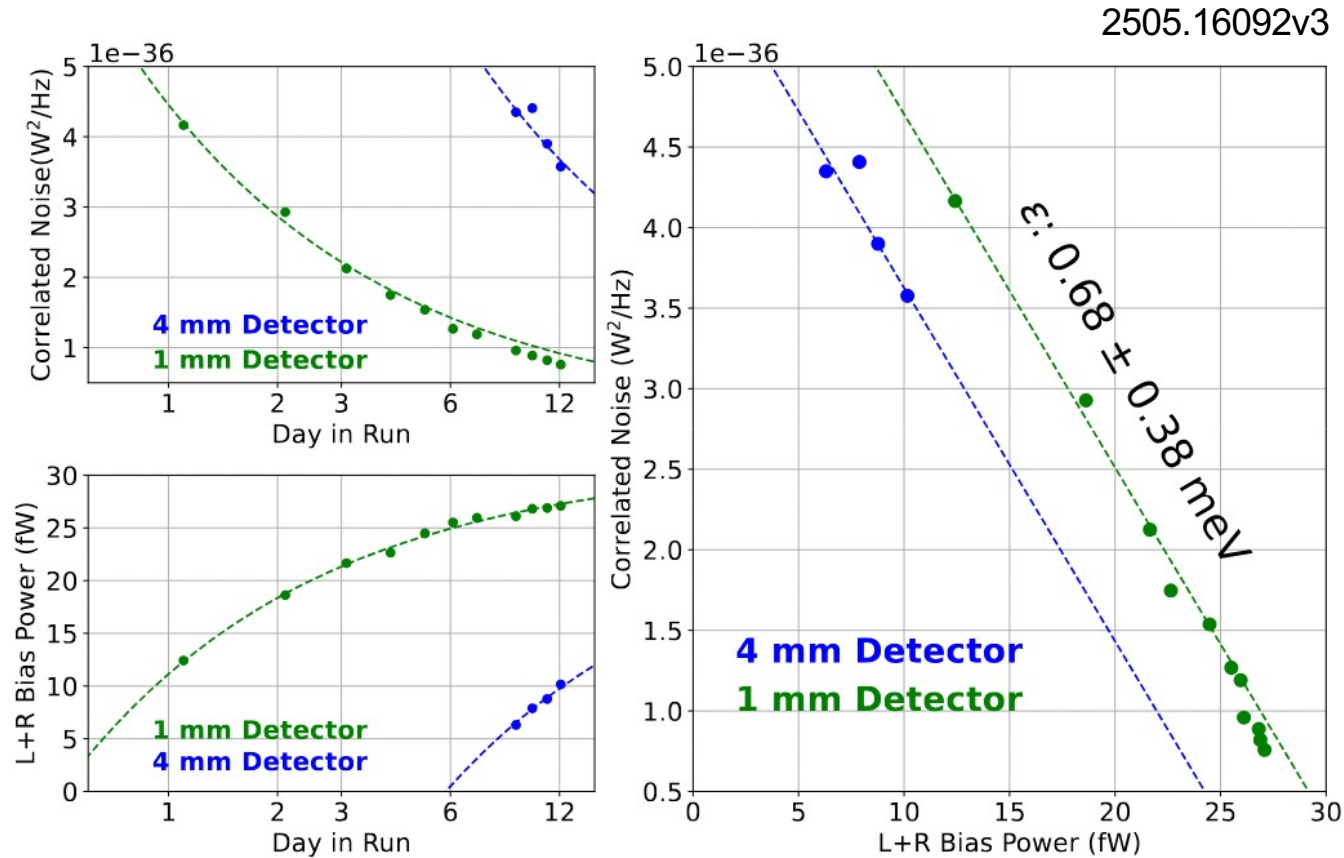
2505.16092v3

- Studies of LEE, comparing 1-mm-thick and 4-mm-thick devices
- Resolution improves over time, reaching 259 meV on Day 12
- Shared event rate is similar in both





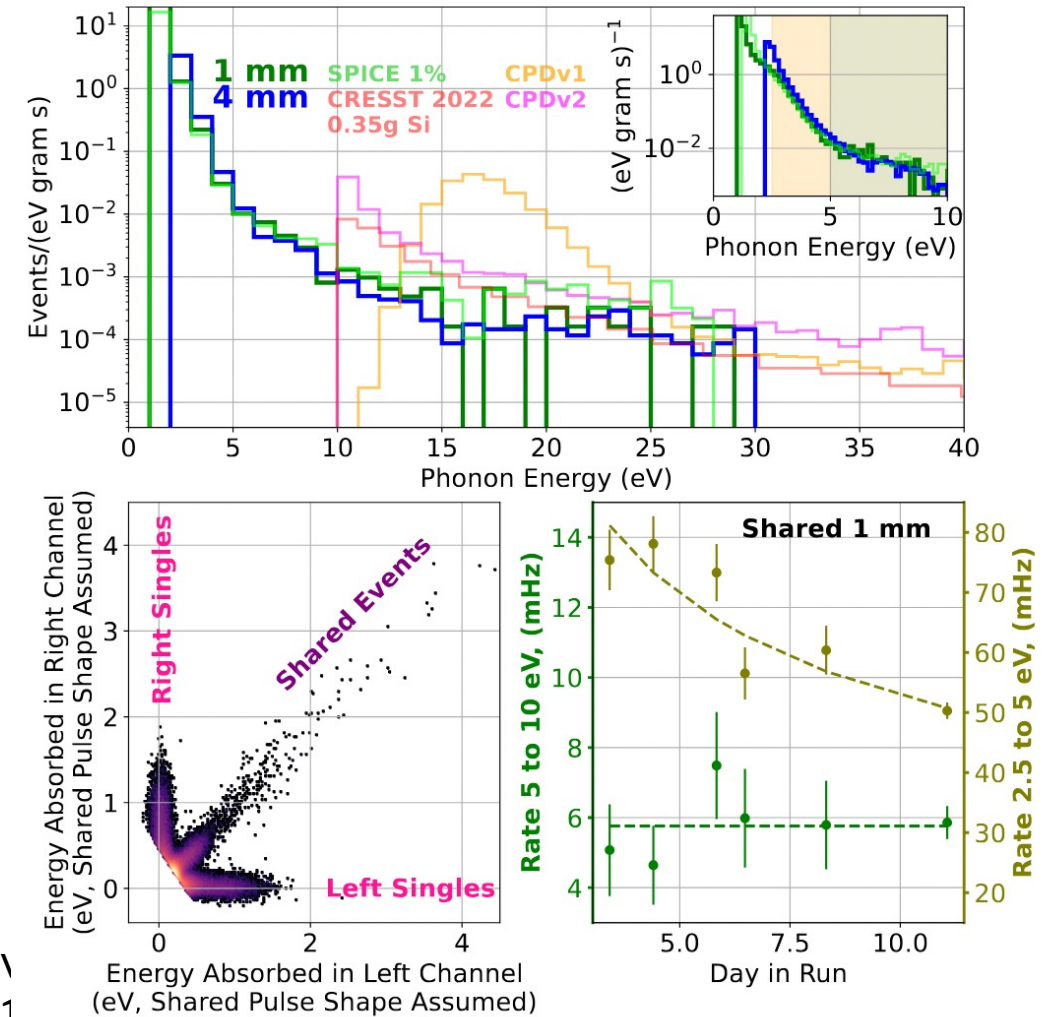
Recent Progress - LEE

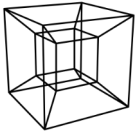


$$P_{1,par} = \epsilon R(t) = \epsilon R_0 t^{-\kappa}$$

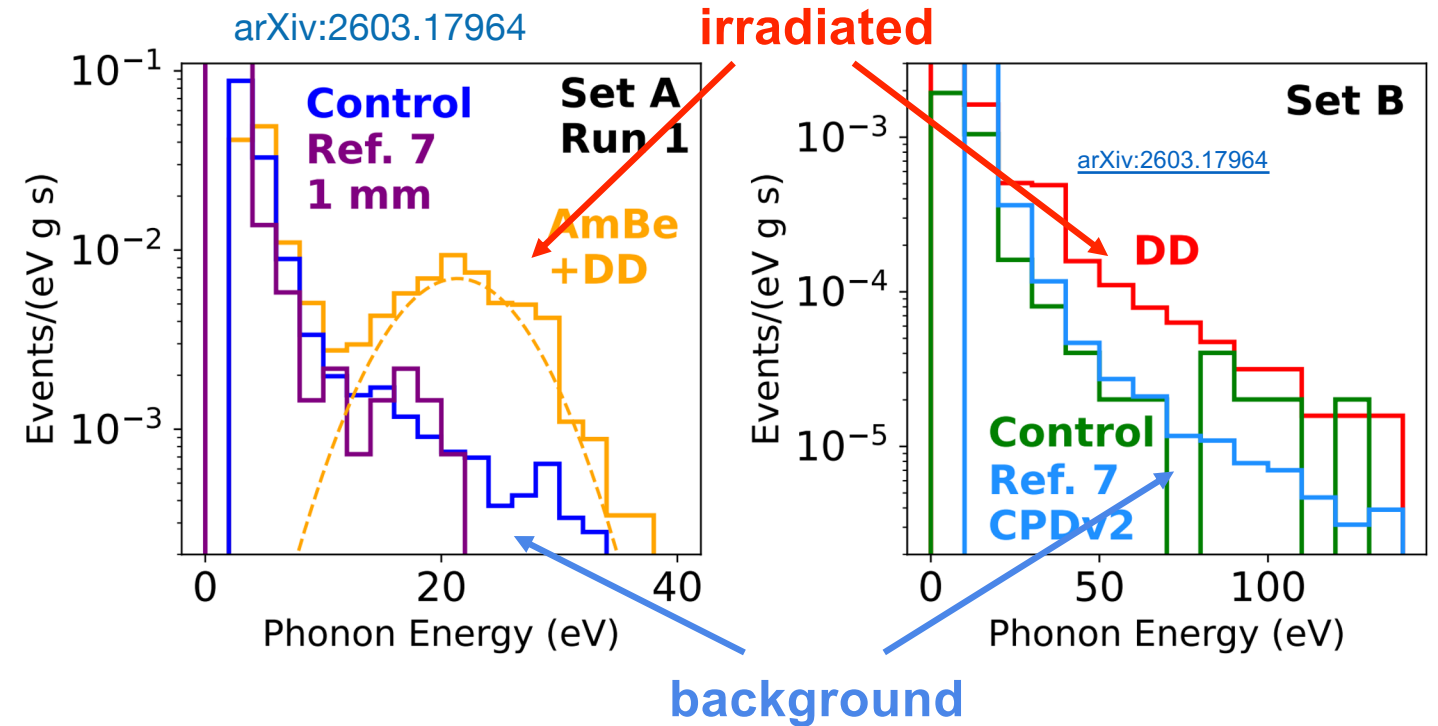
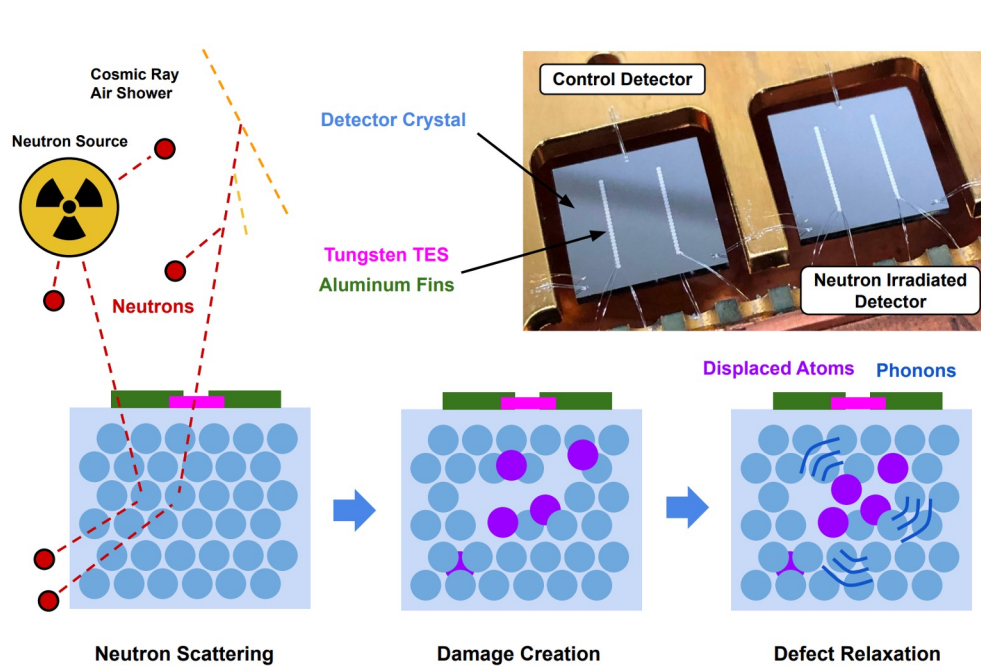
$$\kappa = 0.635 \pm 0.009$$

- Studies of LEE, comparing 1-mm-thick and 4-mm-thick dev
- Resolution improves over time, reaching 259 meV on Day 1
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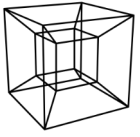




Recent Progress - LEE

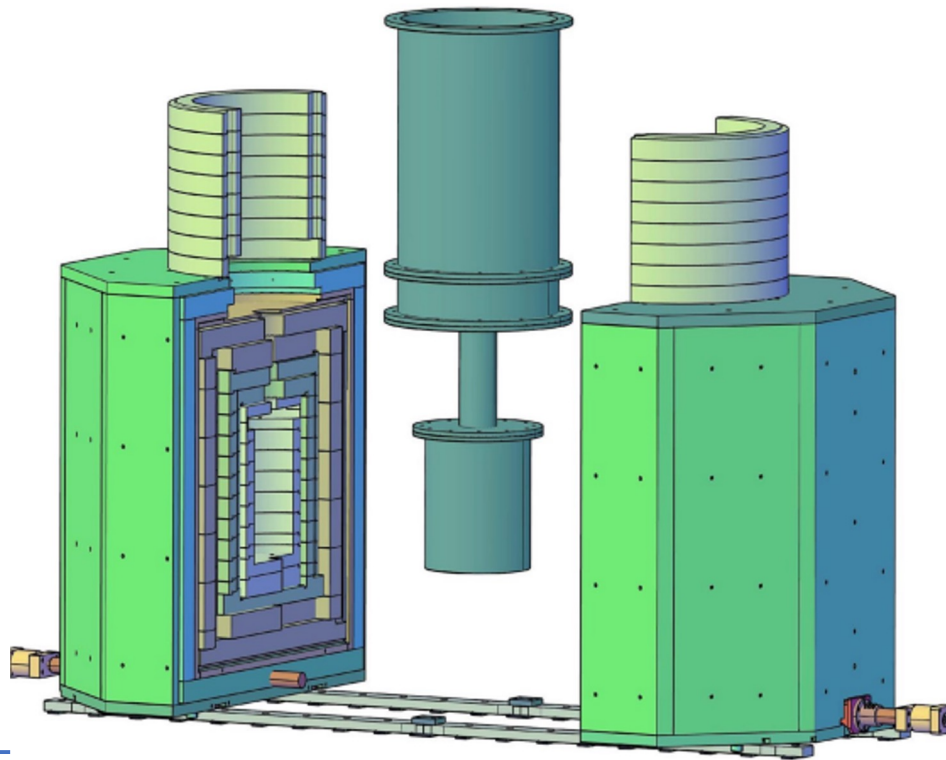


- Hypothesis: Neutron activation cause LEE-type backgrounds via **relaxation of lattice defects**
- Indeed high energy neutrons can create effects days and week after exposure, however:
 - Rate appears subdominant
 - Non-LEE spectral shape & different temp dependencies
 - Observed rate indicates finite but **subdominant** source of LEE



The Shield & Fridge

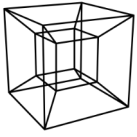
- The **shield consists of layers of PE (2x), Stainless Steel, Lead and Cu**, designed to open/closes rapidly
 - Background (external bkgd + shield) ~ a few DRU
 - Oxford dilution refrigerator with modifications to support ‘dumbbell’ shape of vacuum vessel
- Procurement started of both shield and fridge



D. McKinsey



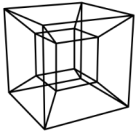
TESSERACT



Commissioning Sites

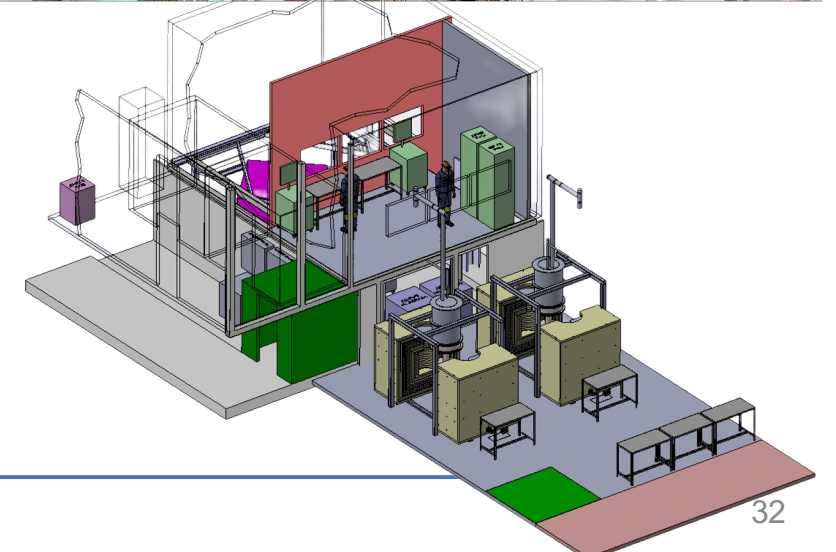
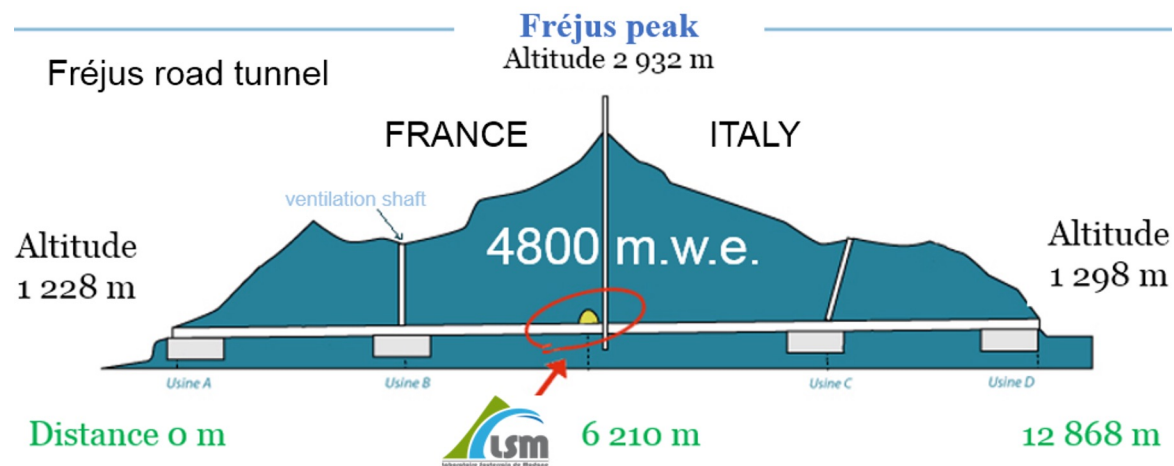
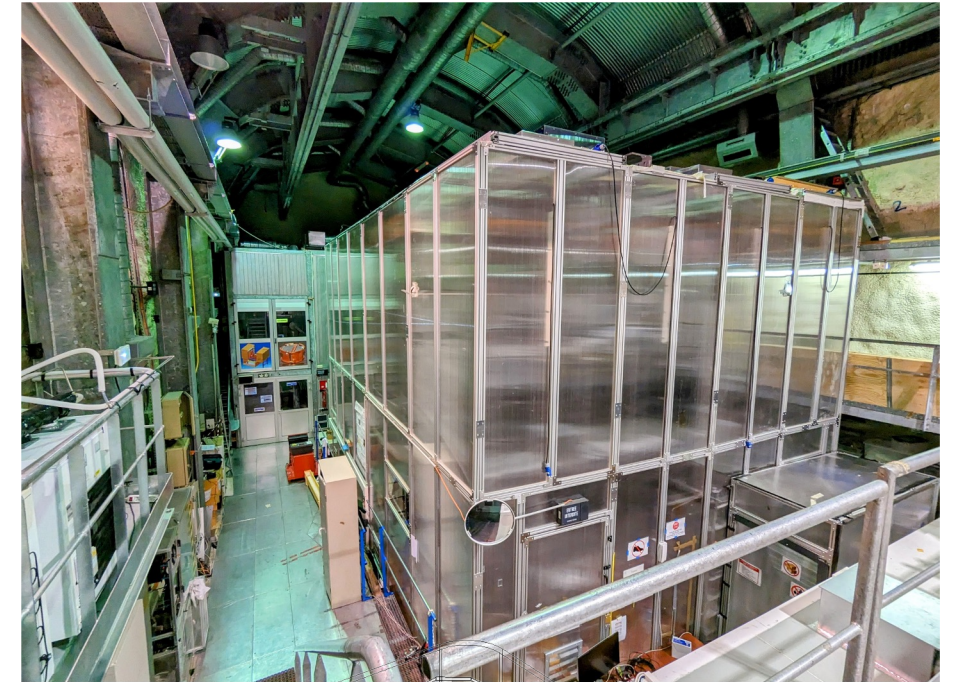
- TESSERACT will have two identical setups (A&B), to be commissioned at LPSC and Berkeley, and then moved underground at LSM
 - New clean room in LPSC for setup A created, space for B identified

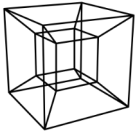




Modane

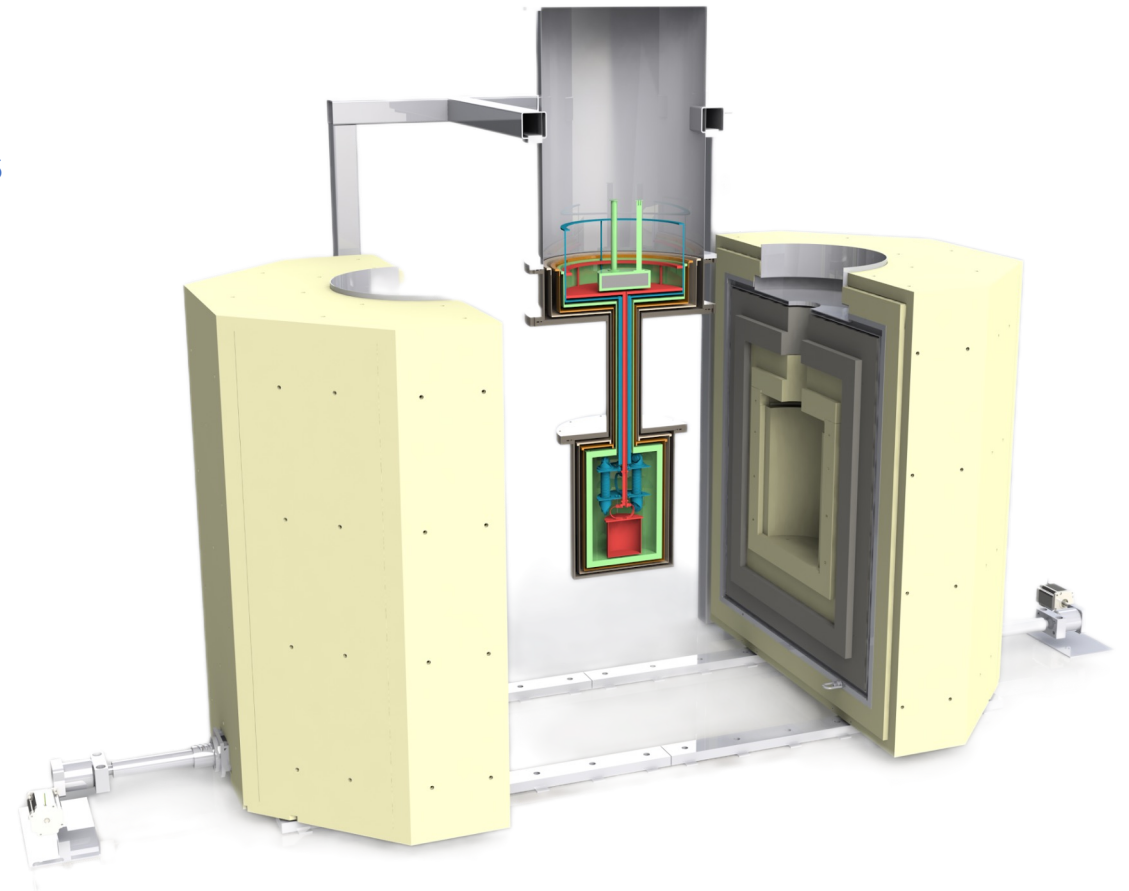
- Both setups to be operated underground at **Modane** (LSM)
- Located in Frejus tunnel between Italy & France (close to Geneva)
 - Deepest European laboratory
 - 4800 m.w.e, $R_n \approx 10\text{-}15 \text{ Bq/m}^3$
- Rich history in **DM & Neutrinos** (Edelweiss & SuperNemo)

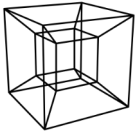




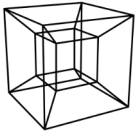
Summary

- **TESSERACT** has state-of-the-art technology for detection of sub-eV events.
 - Multiple target materials allow for exploration of different types of **Dark Matter interactions**
 - **Identification & discrimination of backgrounds** to drive the exploration of this novel regime
 - **Exquisite energy resolution** leads to exploration of new dark matter parameter space at low particle masses.
- **TESSERACT** is a very experienced team supported by US (DOE), France (CNRS) & Switzerland (SNSF)
- **Official project phase started**, infrastructure being developed and construction started
- Planning to move to **Modane in 2028** , with **scientific operations beginning in 2029**

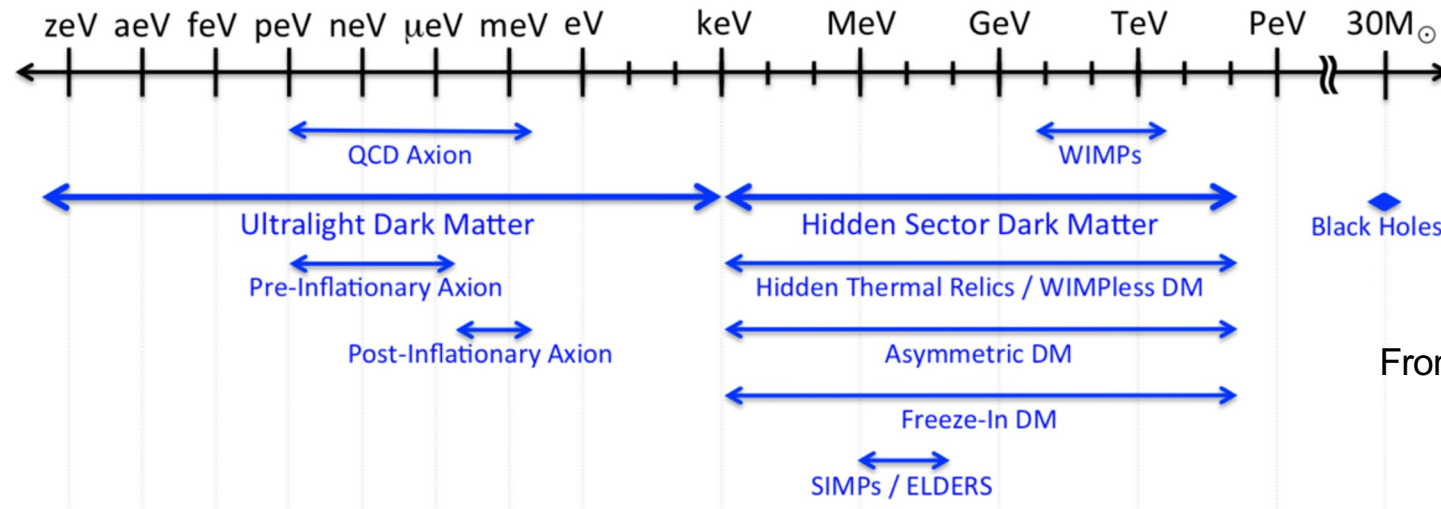




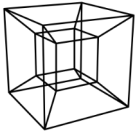
Backup



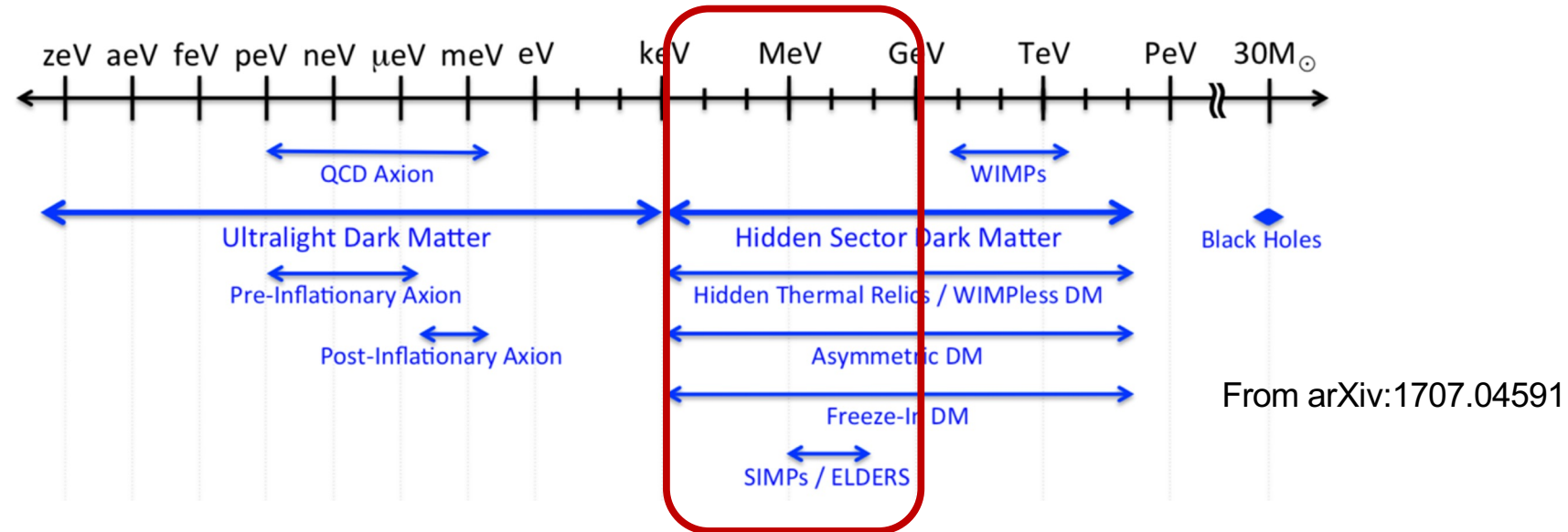
Dark Matter allowable mass range



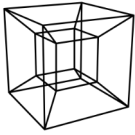
From arXiv:1707.04591



Dark Matter allowable mass range

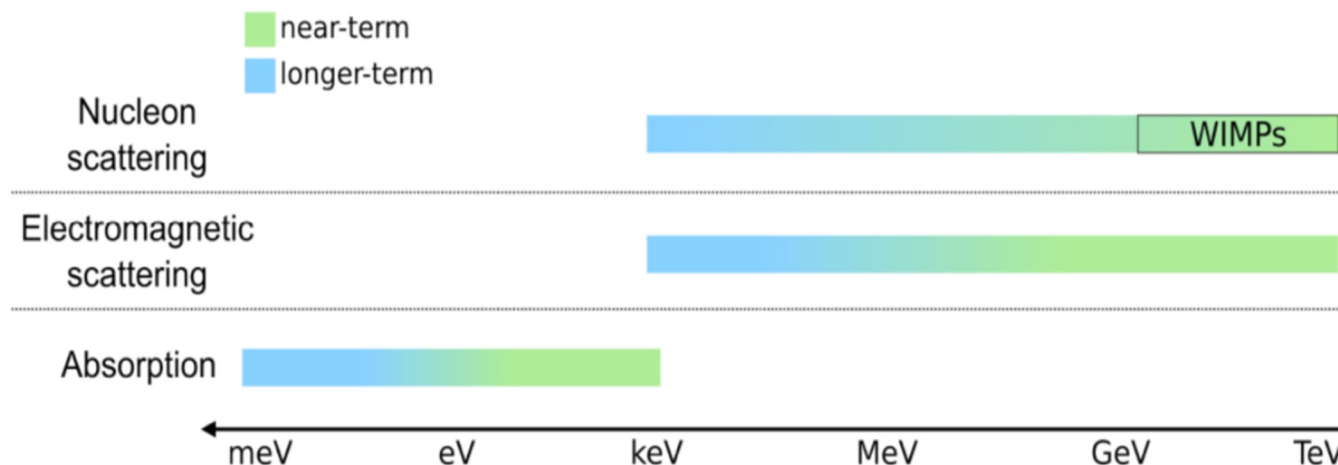


- Unlike WIMPs, composed of particles that interact through the SM weak interactions, the dark matter sector may be instead disconnected from the visible one.
- See summary and references in M. Battaglieri et al., arXiv:1707.04591 .
- General symmetry arguments allow several types of “portal” interaction between generic hidden sectors and the Standard Model, which can be generated by radiative corrections.
- These modest couplings can play a key role in realizing the dark matter abundance, through several possible mechanisms. These include:
 - Determining the DM abundance via **thermal freeze-out** (like in the standard WIMP paradigm)
 - Depleting a thermal component in **Asymmetric DM**
 - Mediating the production of DM from a bath of SM particles in **freeze-in** scenarios
 - Maintaining kinetic equilibrium while hidden-sector dynamics depletes the DM number density (**SIMP/ELDER**)

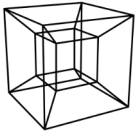


Dark Matter interaction types

- The dark matter theory landscape has evolved in new directions in the last decade, emphasizing the need to probe non-WIMP dark matter candidates with a mass below about 1 GeV.
- Sharp theory targets exist in which dark matter interacts only with baryons or only with leptons, emphasizing the need for experiments that probe dark matter couplings to electrons *and* experiments that probe dark matter couplings to nuclei.
- ER: dark photon mediator or vector coupling predominantly to leptons
- NR: dark photon mediator, vector coupling predominantly to quarks, or scalar coupling

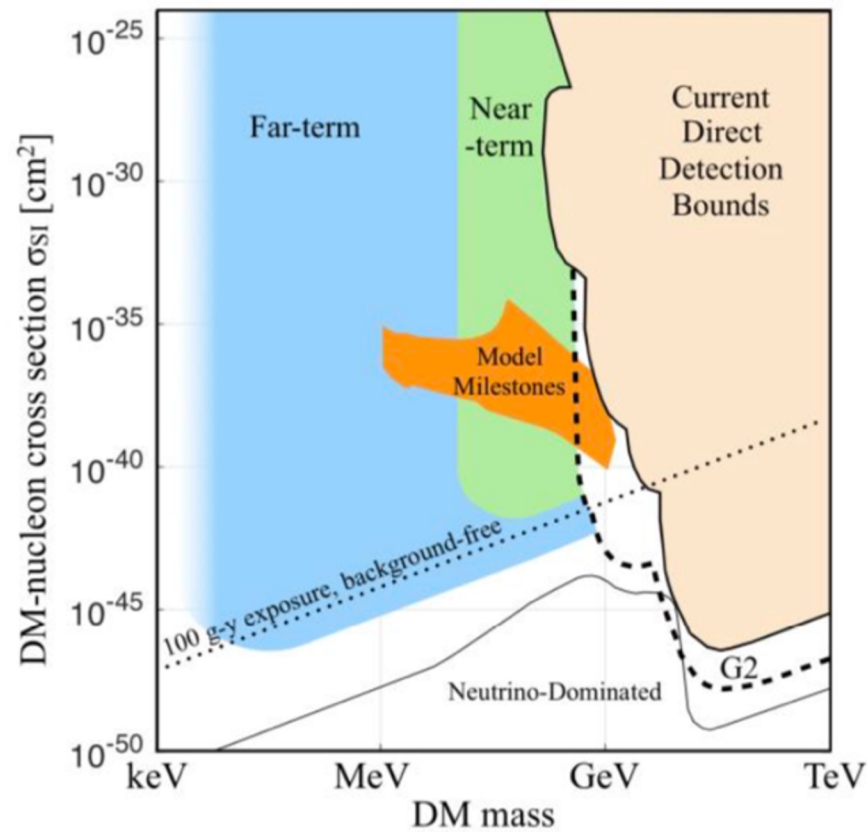


From Basic Research Needs report

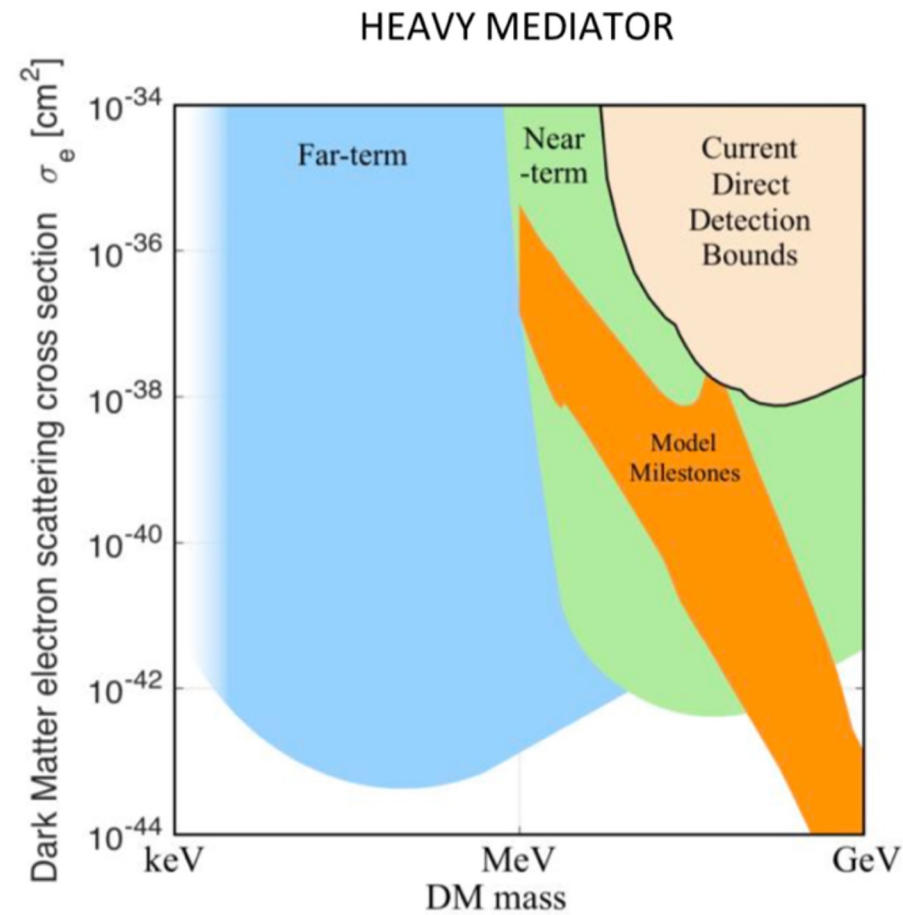


Dark Matter interaction types

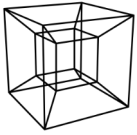
DM - nuclear recoil (NR) interactions



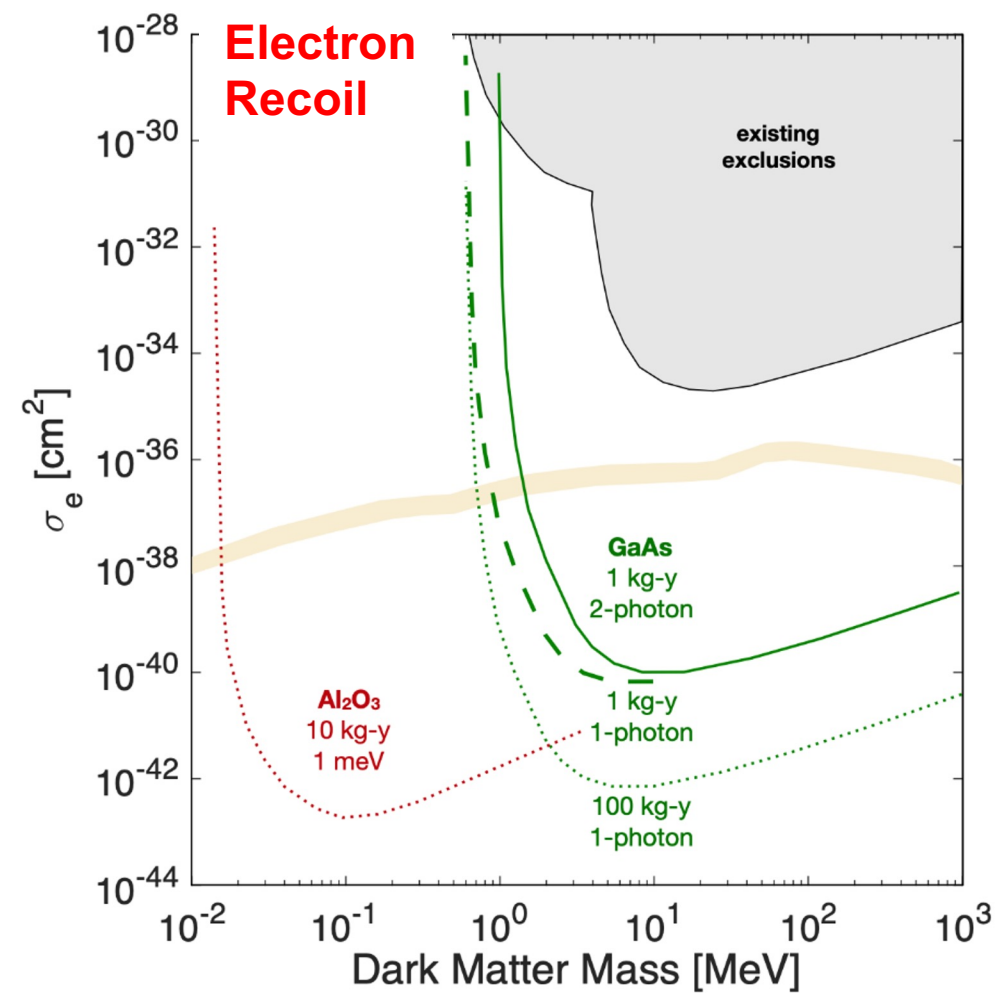
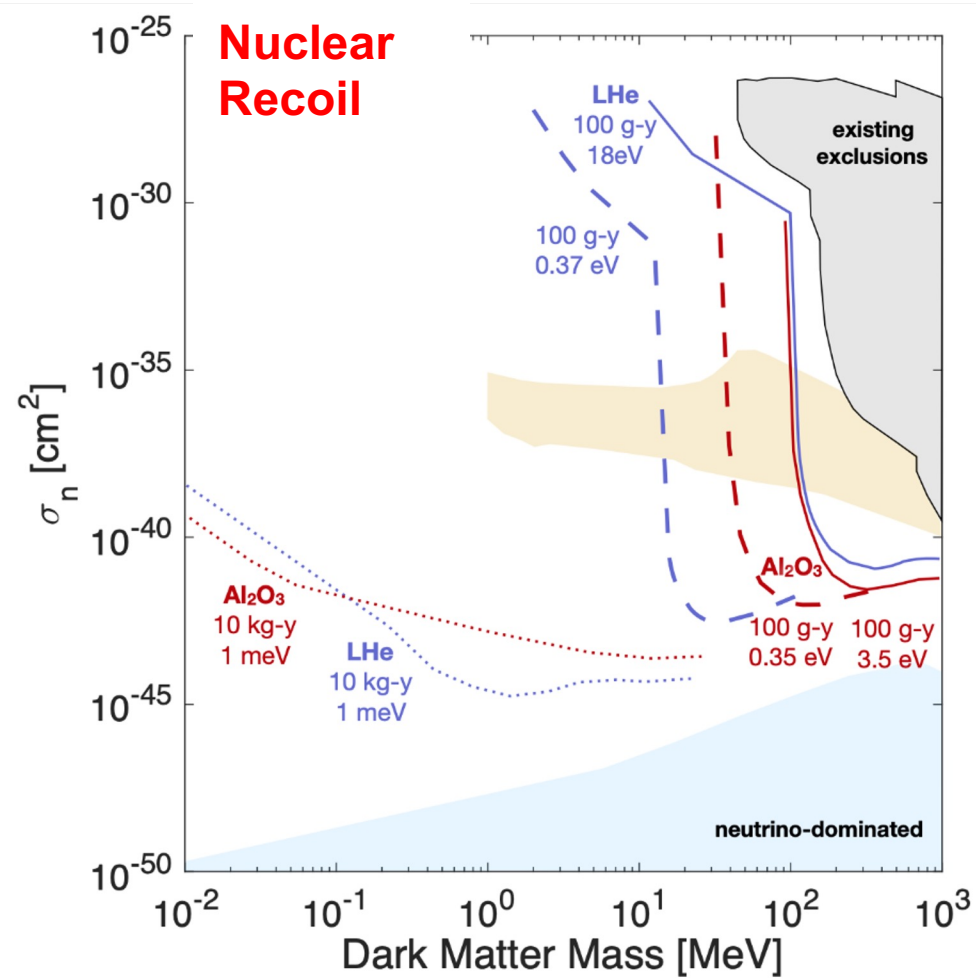
DM - electron recoil (ER) interactions



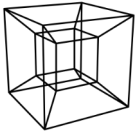
From Dept of Energy Basic Research Needs report



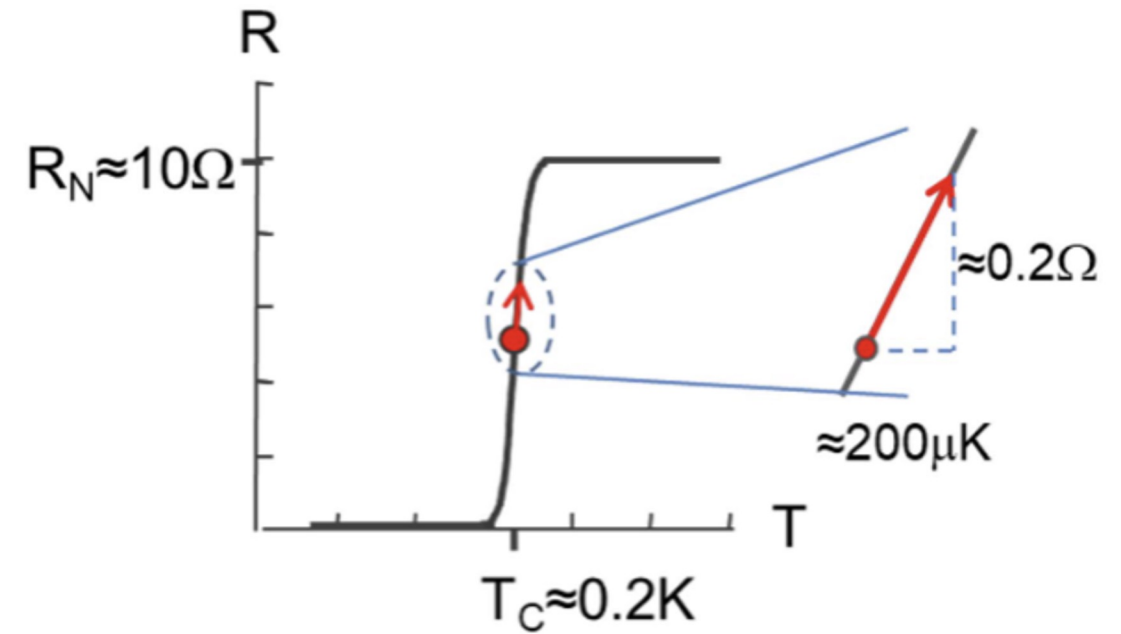
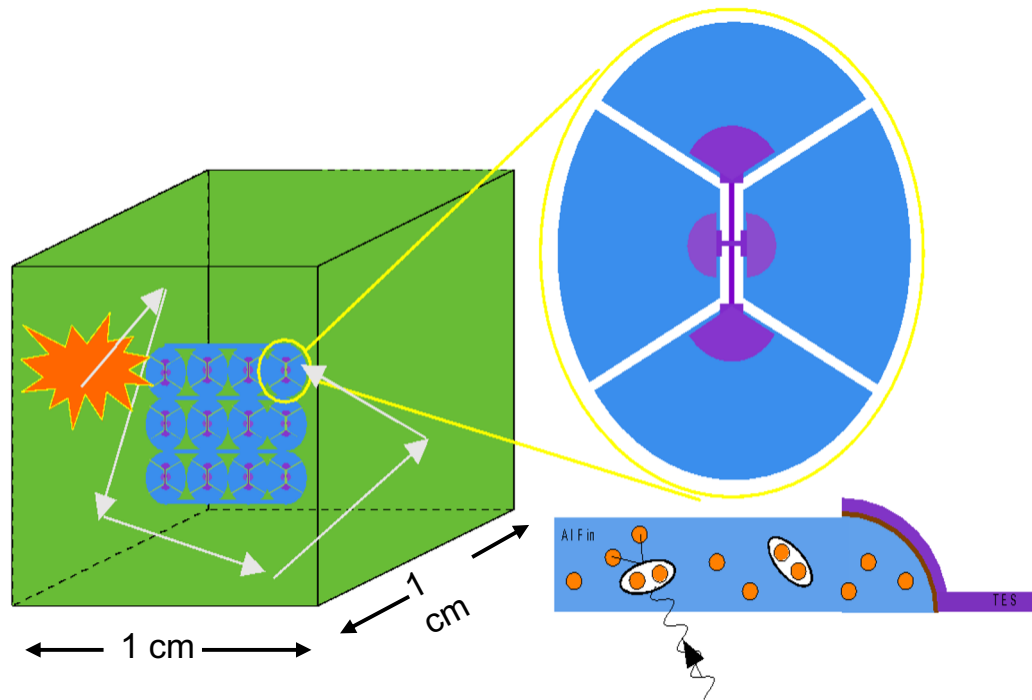
Sensitivity



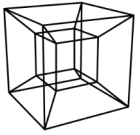
Our approach has a high chance to be the most sensitive low mass DM approach



Athermal Phonon Detectors

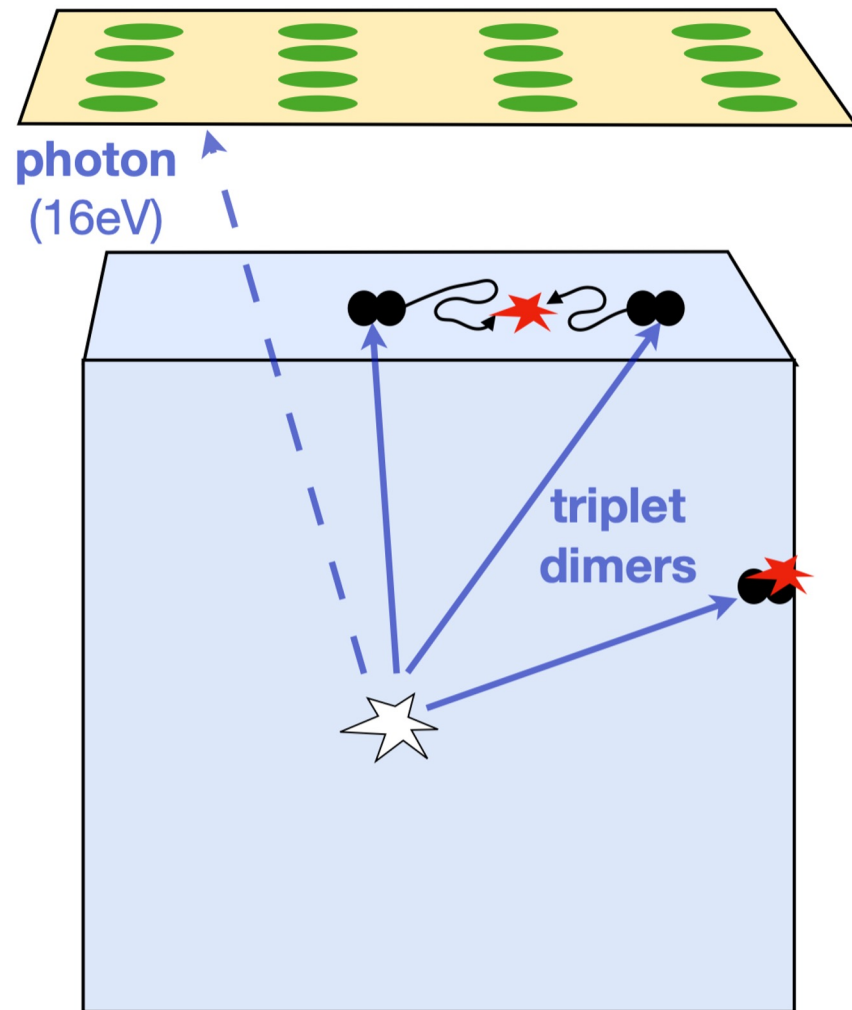


- Read out **athermal phonons** using **Transition Edge Sensors**
- **Readout of all targets identical** except the substrate
- More **DM science** doesn't increase cost significantly!



Superfluid ^4He

TES-based Calorimeter



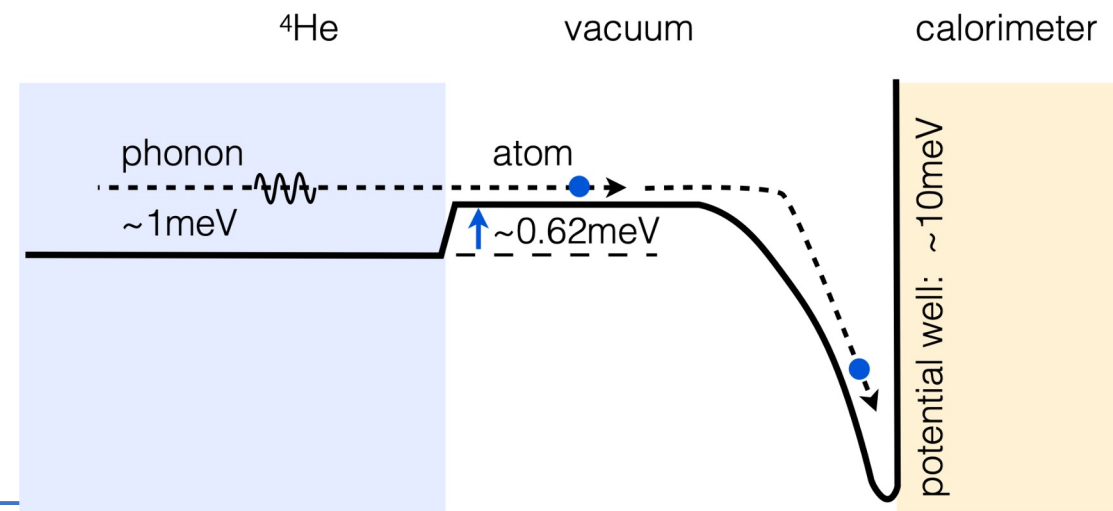
- Atomic Excitations:

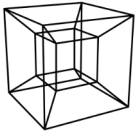
- Singlet dimers: Prompt decay, $E \sim 16$ eV
- Triplet: Quick decay via Penning ionization or very long lifetime (13 s), ballistic propagation

- Position information encoded in signal distributions

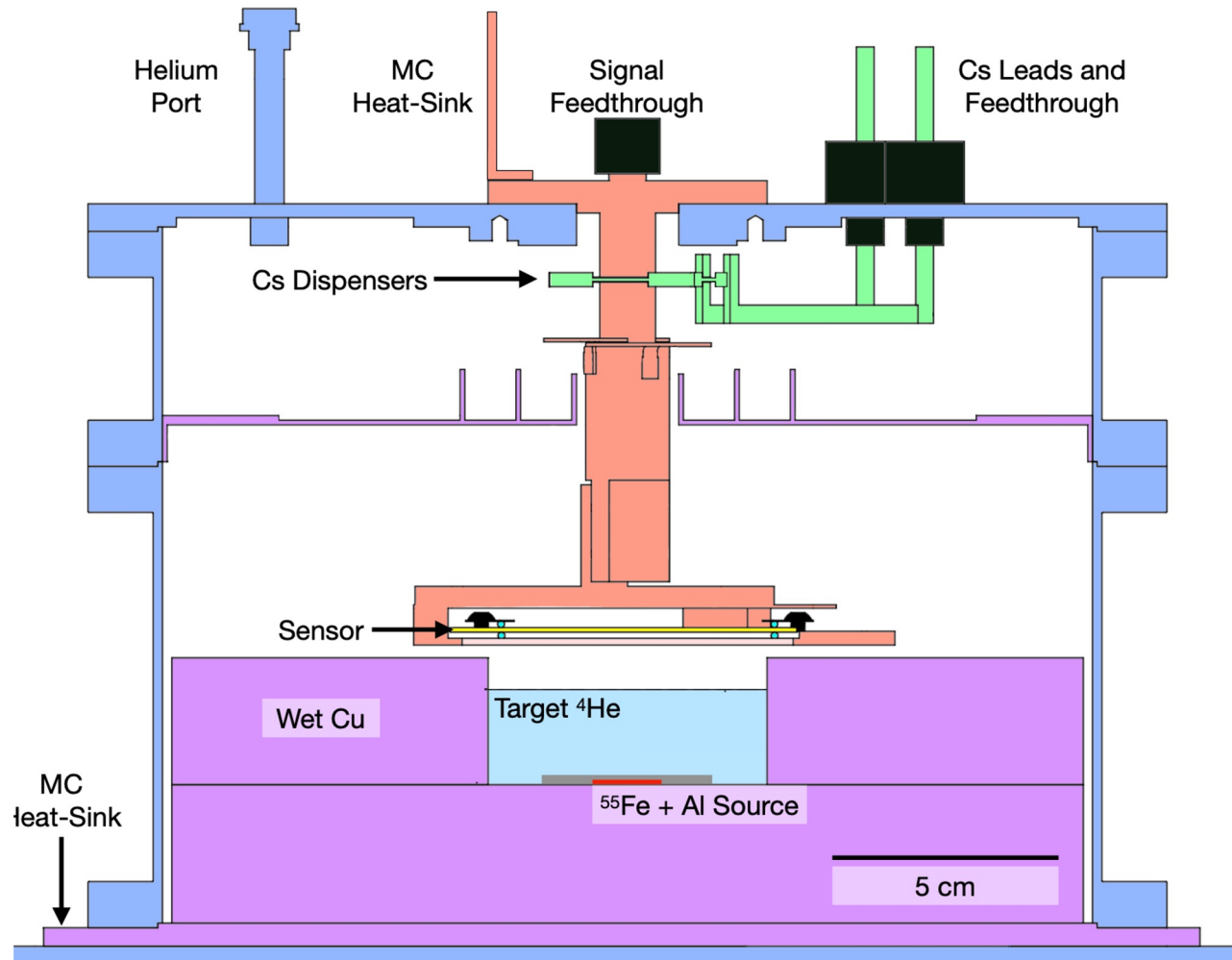
- Quantum Evaporation

- Signal: The adsorption of atoms onto a calorimeter
- Binding energy of ^4He to a typical calorimeter surface: ~ 10 meV
- Signal gain: $\sim 17\times$

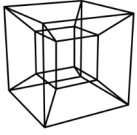




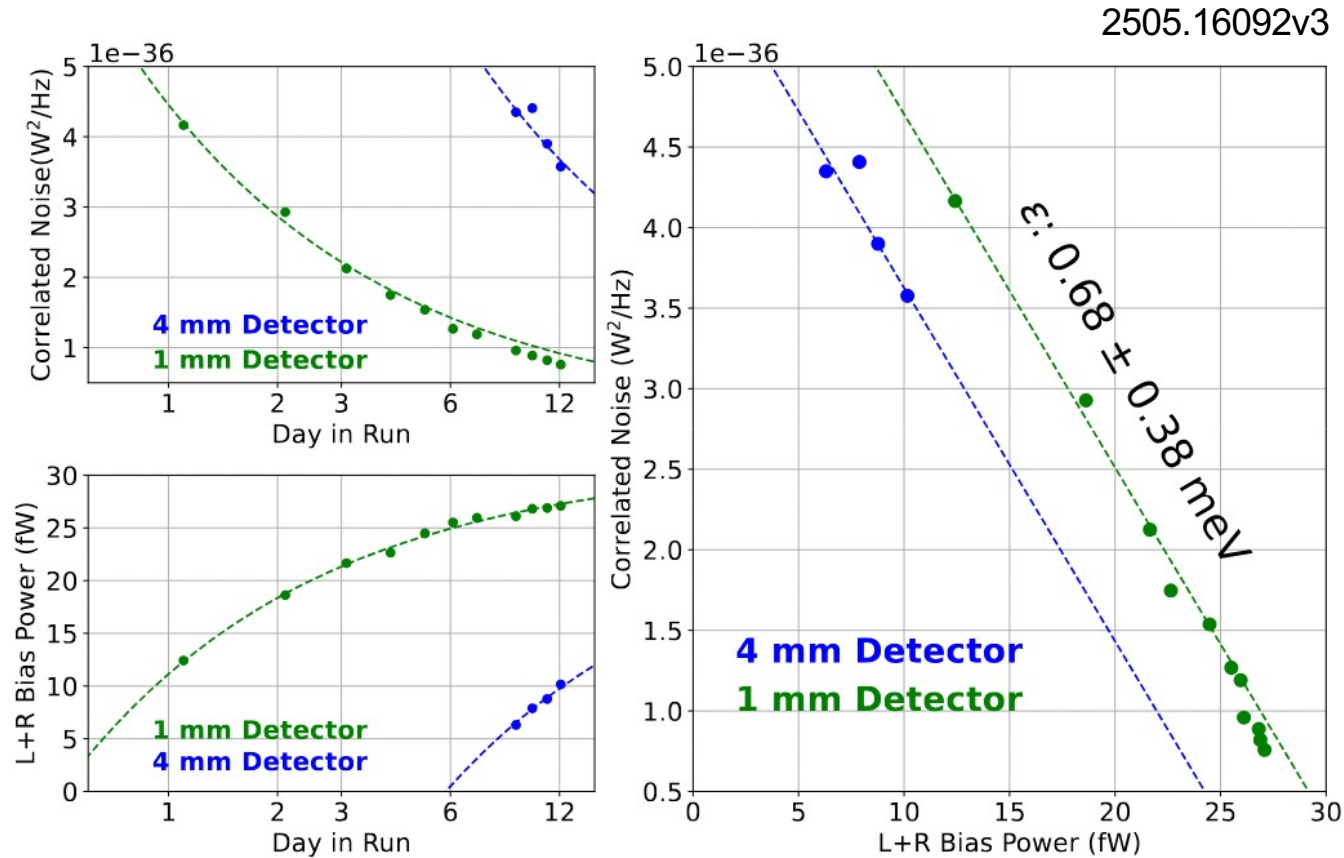
Practical Challenges



- Superfluid He wets all types of surfaces
 - All but cesium and rubidium
- Use Cs barrier to prevent He on sensor
- Very challenging:
 - Must be unoxidized → in-situ deposition in vacuum when chamber is cooled down
 - Evaporation itself requires high temp, large current



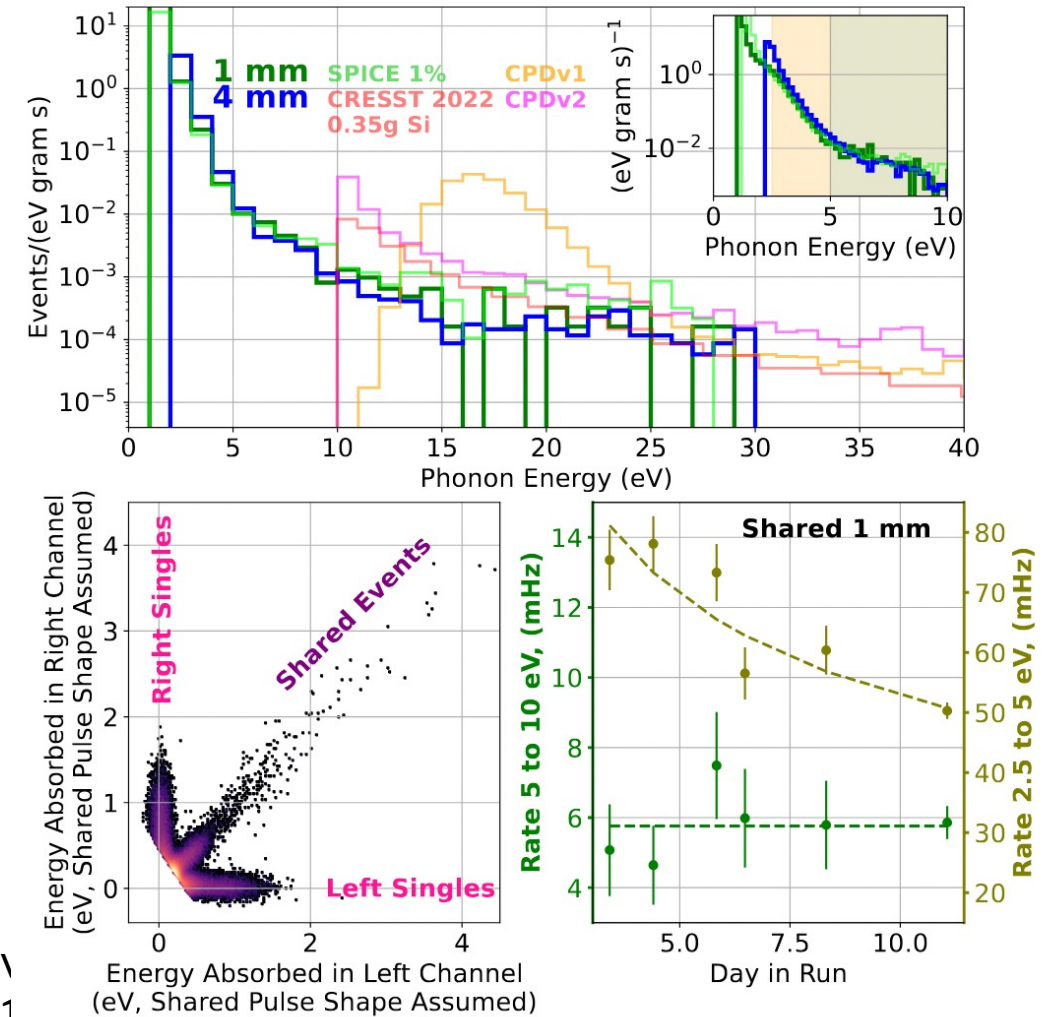
Recent Progress - LEE

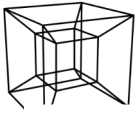


$$P_{1,par} = \epsilon R(t) = \epsilon R_0 t^{-\kappa}$$

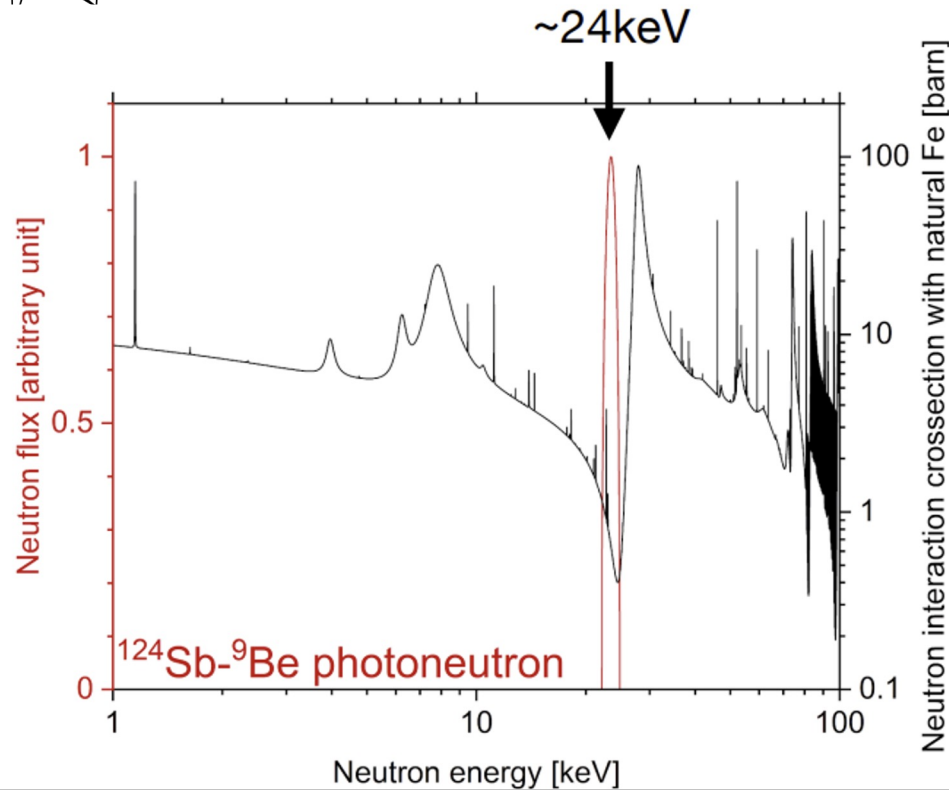
$$\kappa = 0.635 \pm 0.009$$

- Studies of LEE, comparing 1-mm-thick and 4-mm-thick dev
- Resolution improves over time, reaching 259 meV on Day 1
- Shared event rate is similar in both



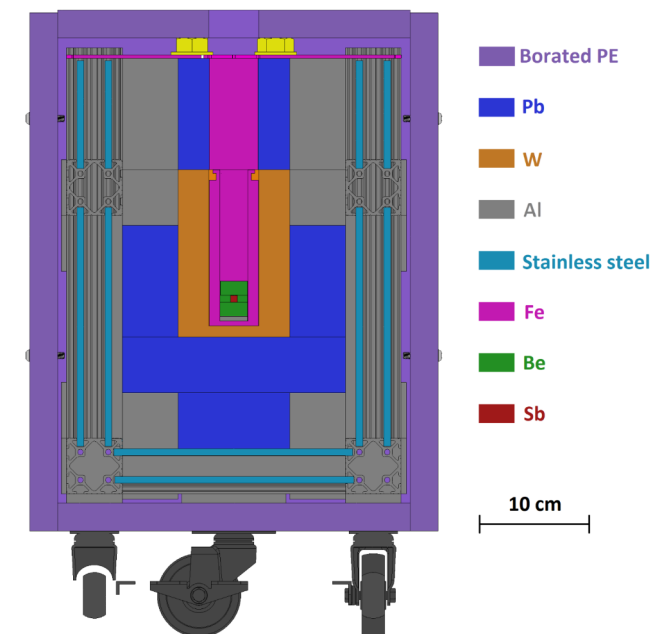


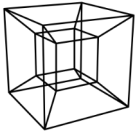
Low NR E calibrations



- Source built & works
- Favorable **n flux**: $\sim 5 \text{ cm}^{-2}\text{s}^{-1}$
- Portable, ideal for **CE ν NS** and **light DM** experiments
- See [arXiv:2302.03869](https://arxiv.org/abs/2302.03869)

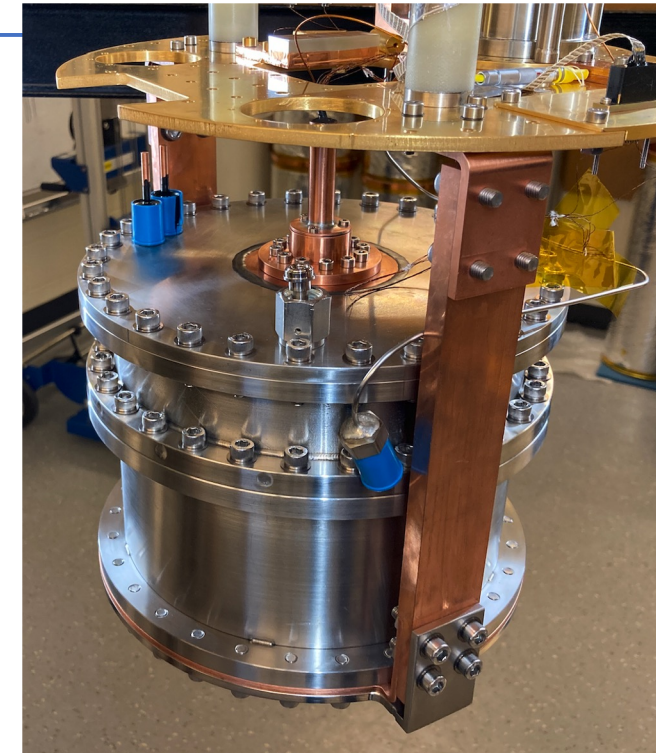
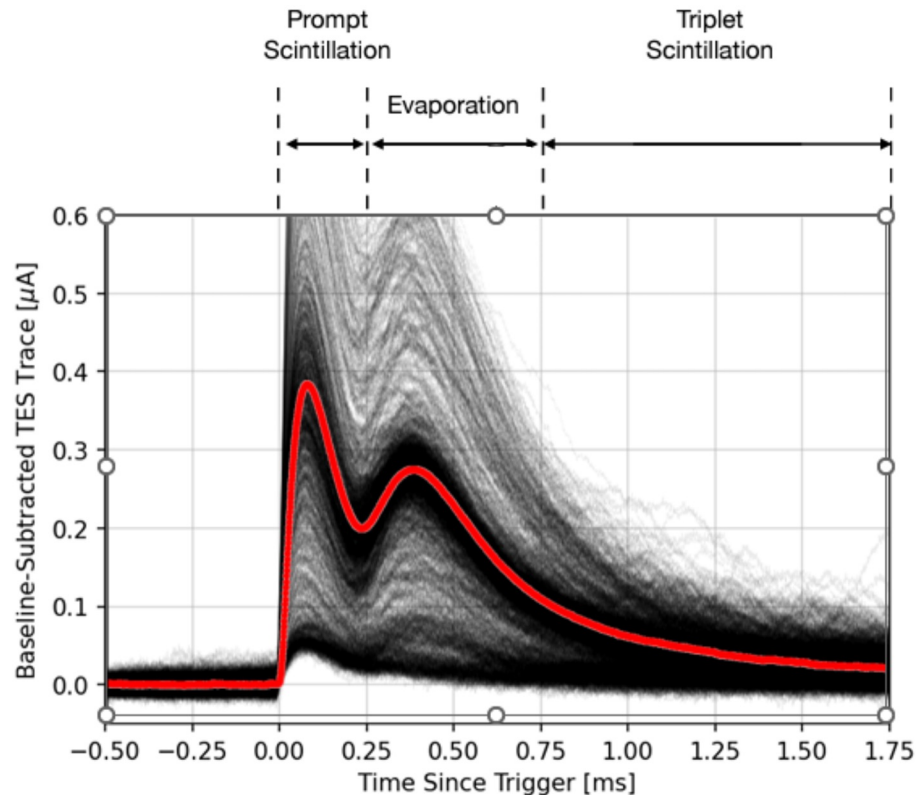
- **SbBe photoneutron + Fe shield**
- Remarkable coincidence:
 - $^{124}\text{Sb}^9\text{Be}$ **neutron energy**: 23.47 keV
 - **Fe n-transmission resonance**: 24.54 keV
- Fe transparent to neutron, serves as collimator and very efficient gamma shield



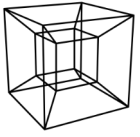


Superfluid Helium Cell

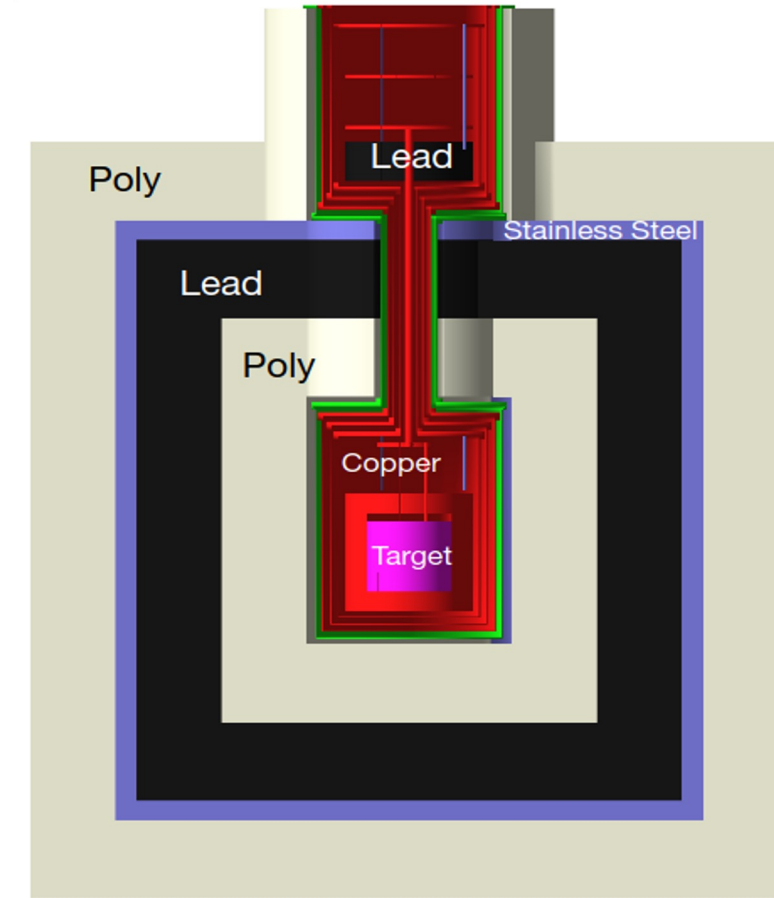
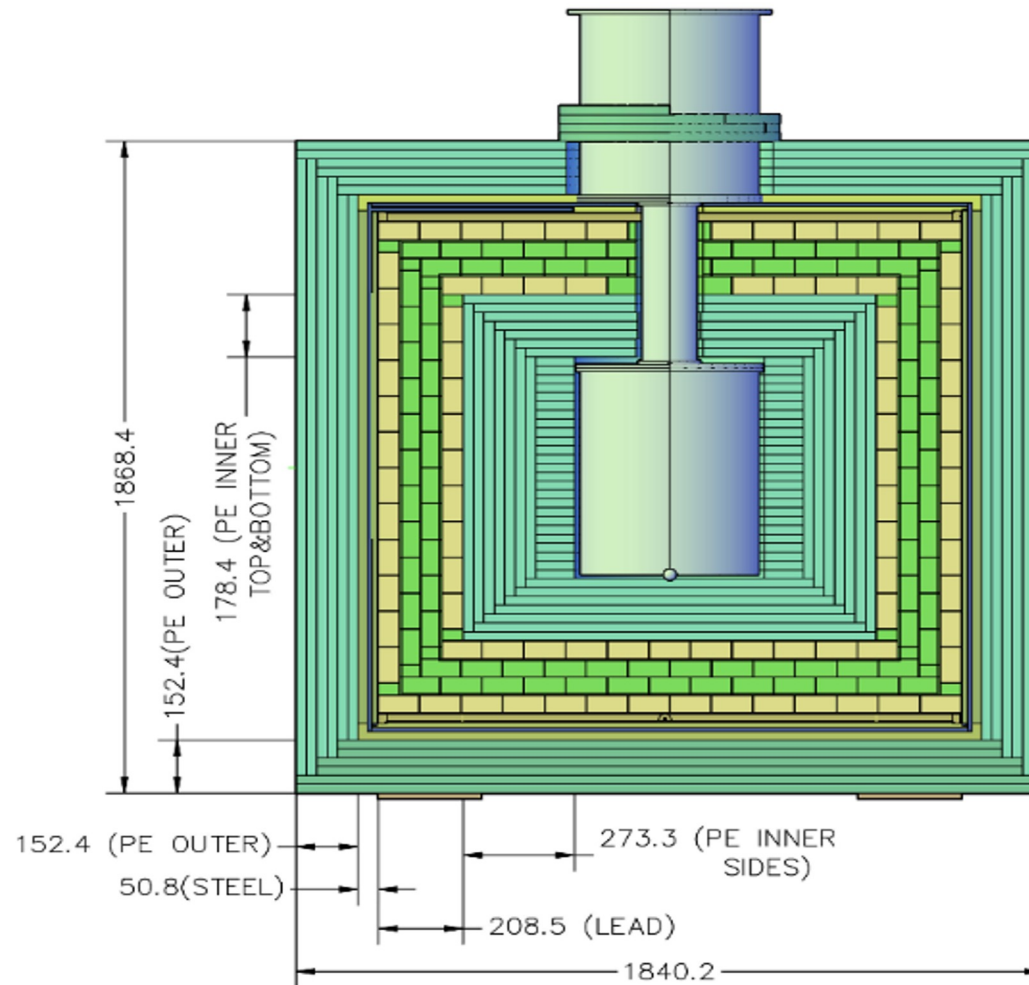
- ^4He is a powerful target:
 - Very radiopure, 33x better NR endpoint w.r.t to LXe
 - No Compton scattering below 19.8 eV
 - UV/IR photons and QP induced evaporation w/ gain

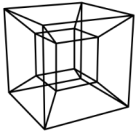


- Read out with dry **TES Si detectors**
- Multiple bgkd discrimination methods & no stress events
- Measured ^4He ER & NR light yield and proof of concept
 - [arXiv:2108.02176](https://arxiv.org/abs/2108.02176), [arXiv:2307.11877](https://arxiv.org/abs/2307.11877)



Shielding Scheme

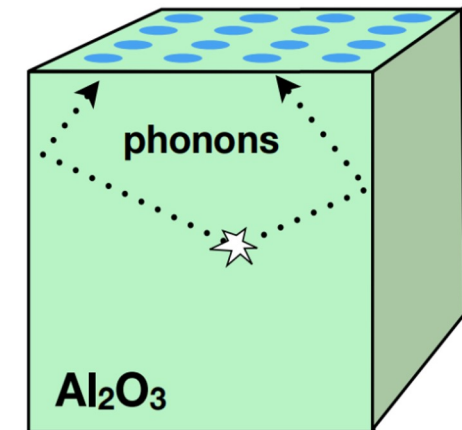
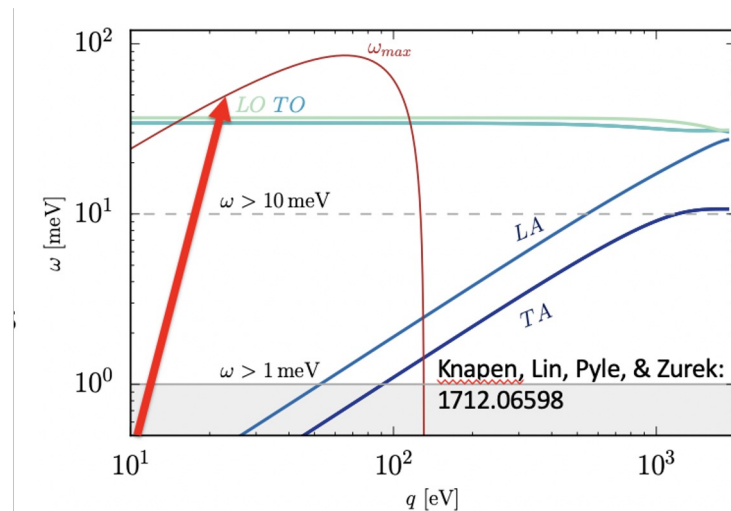
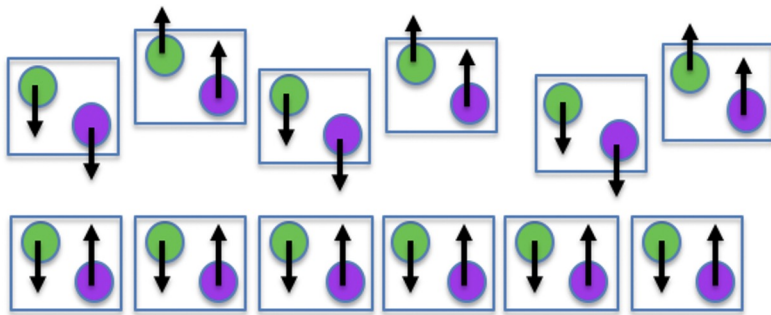




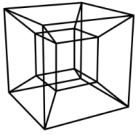
Sapphire Target

Coherent excitations:

- Vibrational energy scale in crystals is $O(100 \text{ meV})$
- For dark matter masses $< 100 \text{ MeV}$, we can't use the simplifying approximation that the nucleus is free.
- DM scatters coherently with the lattice, 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! High light yield (125 ph/keV, 1904.09362)

Can allow background rejection through phonon/photon ratio

