TESSERACT

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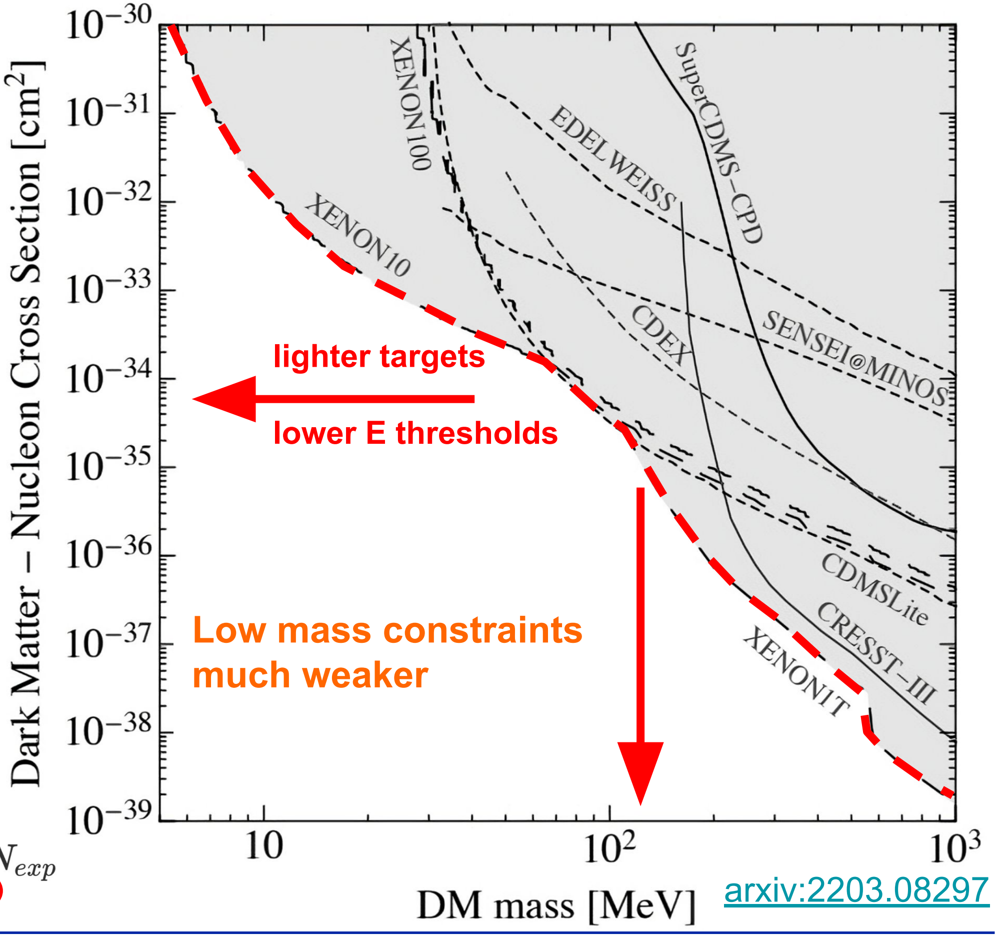
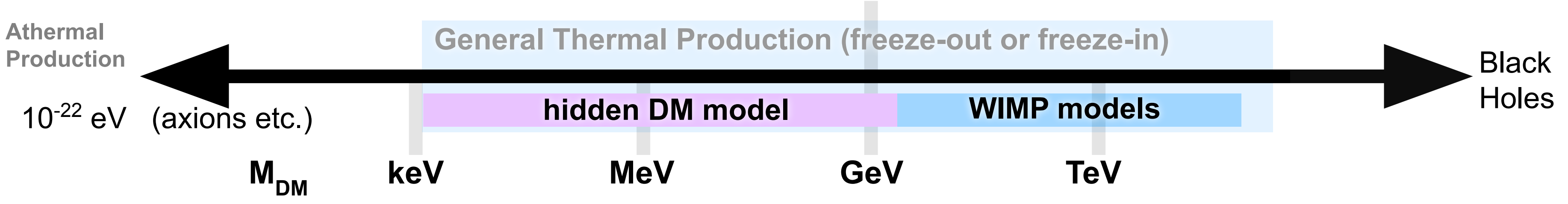
- There is **five times more DM than regular matter**
- **Low-mass DM** (**m_{DM}<m_p**) (LDM) largely unconstrained due to **small energies** transferred in the **DM scattering**
  - LDM consistent with simple thermal production after inflation
- **New Signatures**: electron scatter, nuclear scatter & absorption
- Even **small masses** explore new parameters space: $R = \sigma n_{\rm DM} N_{exp} = \sigma \frac{\rho_{\rm DM}}{m_{\rm DM}} N_{exp}$

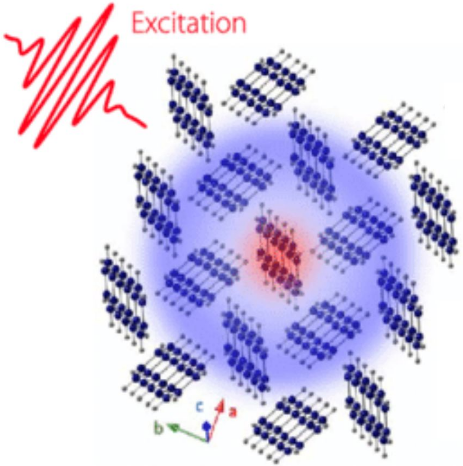


arxiv:2203.08297

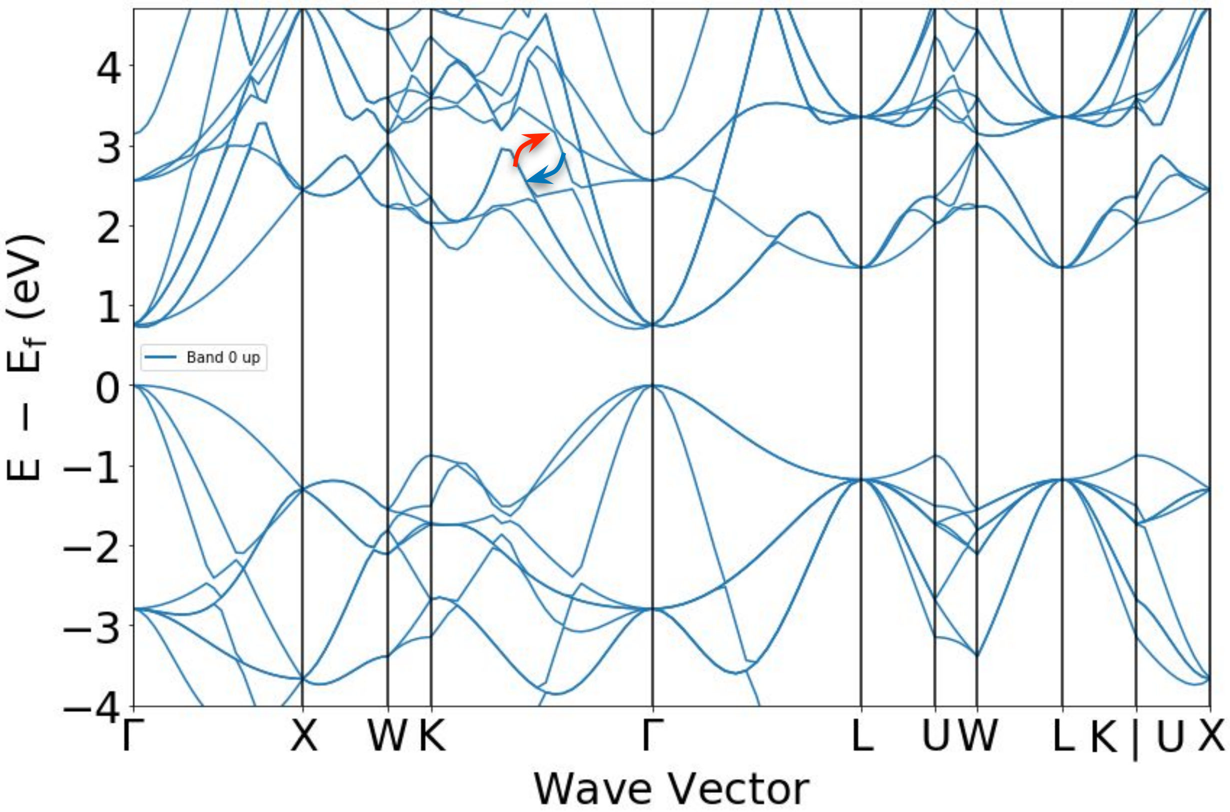


Energy deposit	**~meV**	**~eV**	**~keV**
Primary Signature	**coherent excitation**	**electron recoil**	**nuclear recoil**

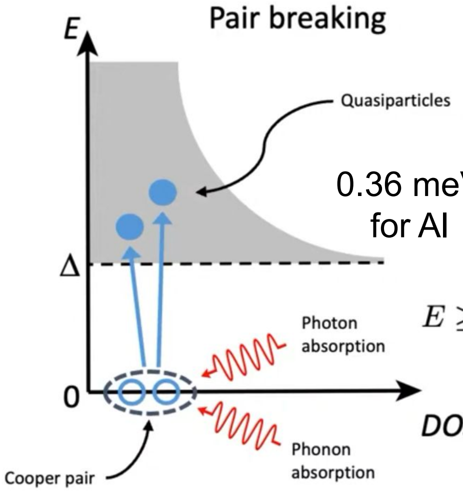
- For sufficiently low masses no ionisation but coherent excitations of the target
- DM wavelength longer than lattice spacing → DM sees material
  - Not a single target will be best (as it is the case for WIMP searches)



- **Condensed matter systems** have a range of gapless and effectively massless modes serving as LDM targets
  - Crystal e^- momentum and energy scales match MeV DM
- However, how do we actually **detect signals below ionisation scale**?



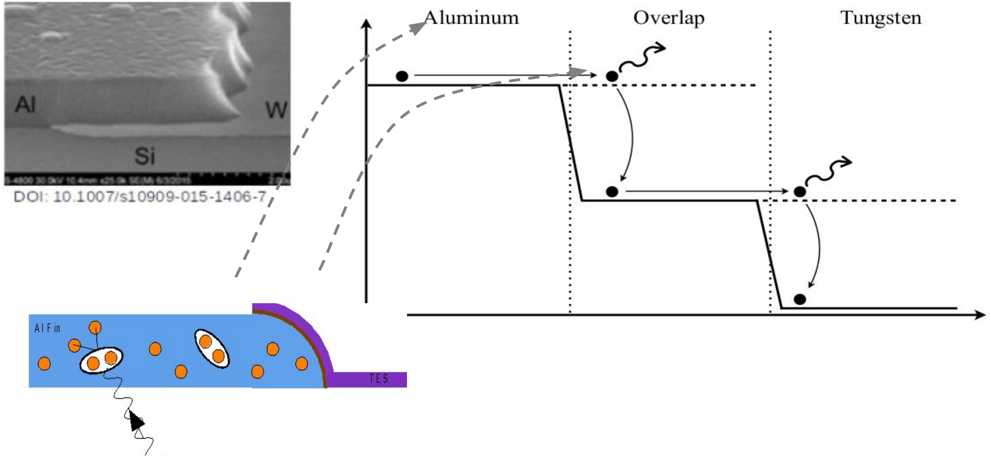
- Instead 'breaking' electrons out of an atom we break 'cooper pairs' (quasiparticles)
- Can measure those using **Transition Edge Sensors** (TES) actings as ultra-sensitive thermistors



0.36 meV
for Al

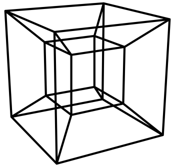
$E \geq 2\Delta$

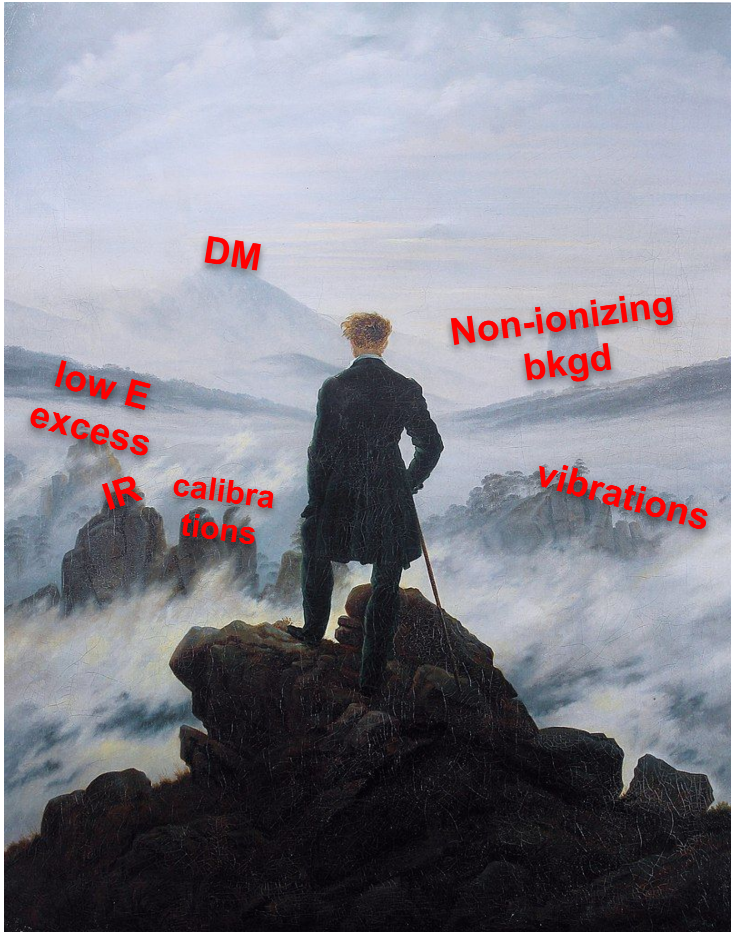
Operate at mK to
keep noise < 'bandgap'



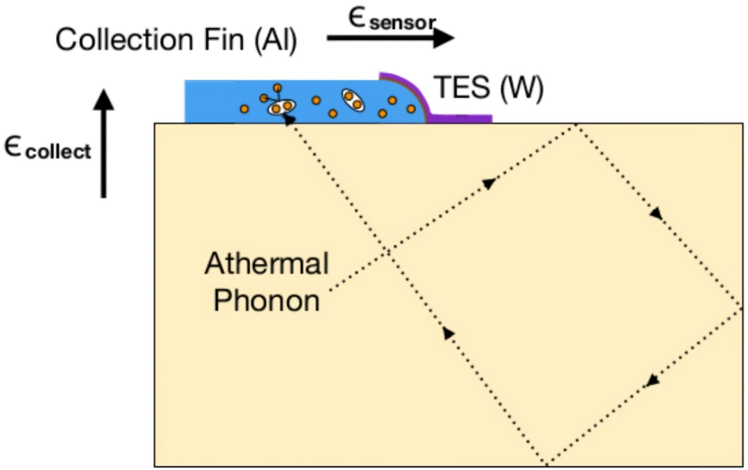
- **Collect athermal phonons** energy in Al fins → **break cooper pairs** in Al → **absorb QP** in TES
- Al fins allow large collection area without the drawback of the heat capacity of a large sensor

- Facing **new landscape**
- **Nuclear backgrounds**: Exists but less significant
  - **γ down-scatter** to low E, can also **induce NR** via Thomas-Delbrück
  - Epithermal **neutrons**
- **Novel backgrounds** due to extreme sensitivity
  - **IR** backgrounds, **parasitic power**, **phonons**, **vibrations**, **transition radiation, crystal defects, metastable solid-state excitations** etc
  - Example: **Low Energy Excess (LEE)** at O(eV) in many experiments
- We know some of the challenges we're facing, but **some cliffs** are likely still **hidden in the fog**
- **TESSERTACT** (Transition Edge Sensors with Sub-eV Resolution And Cryogenic Targets) designed to face this challenge





- Our TES based pixel phonon detectors (PPD) have world leading energy resolution of **273 meV**
    - Operated at **mK temperatures**



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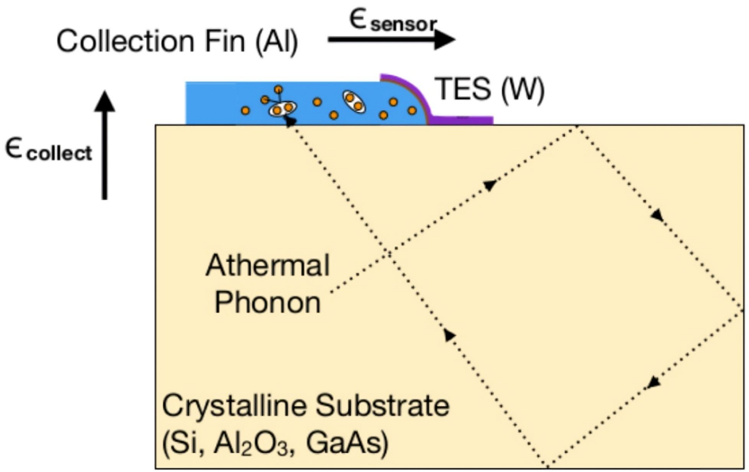
- **Different targets** to **maximise sensitivity to DM** and to obtain **different responses** to backgrounds



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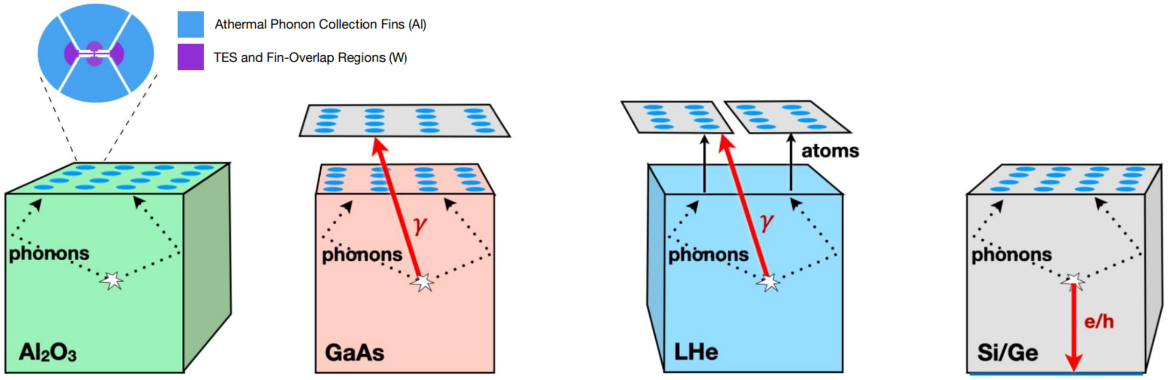
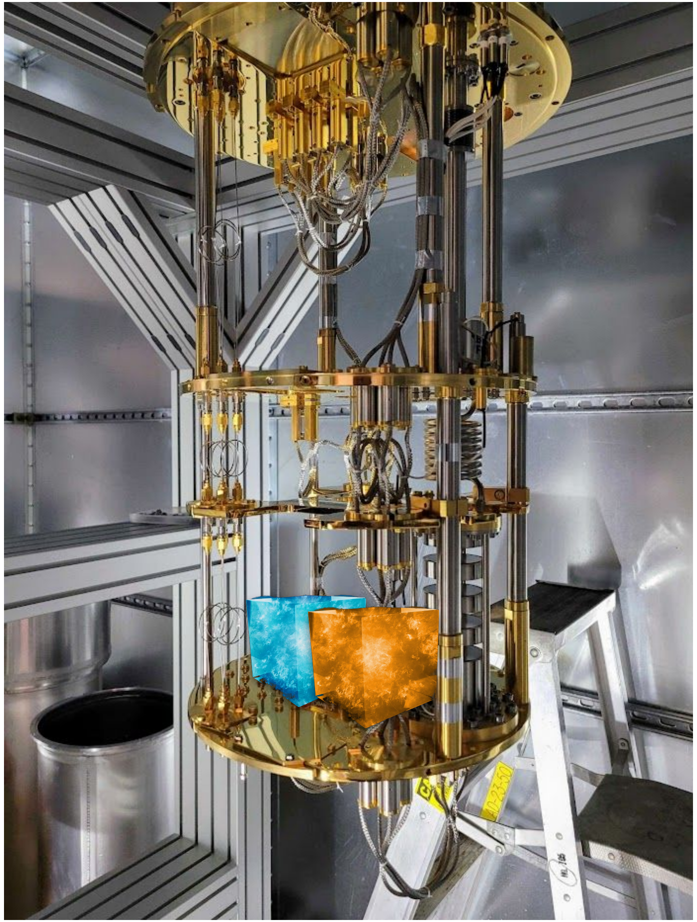
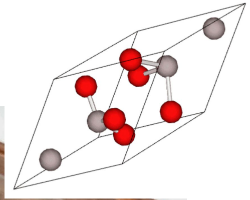
    - Operated at **mK temperatures**
- **Different targets** to **maximise sensitivity to DM** and to obtain **different responses** to backgrounds
- **Multi-target approach** enables us to **identify** and **discriminate** backgrounds and **mitigate** their impact



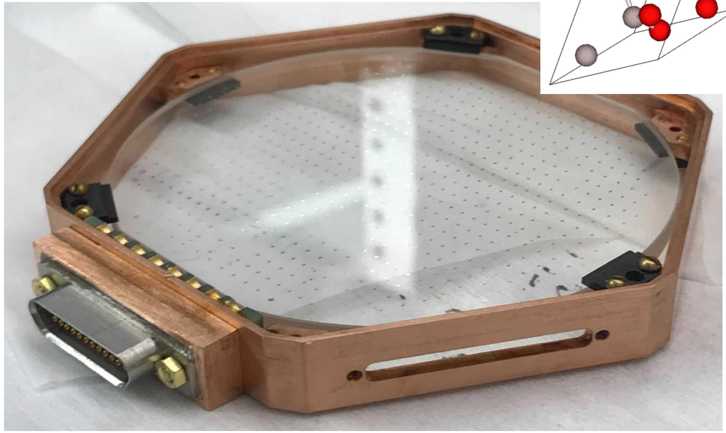
$$\sigma_E \propto V_{\rm det}^{1/2} T_c^3$$

Achieved recently T_c ~15-20 mK
→ ~100 meV threshold achievable on 1 cm^3 crystals



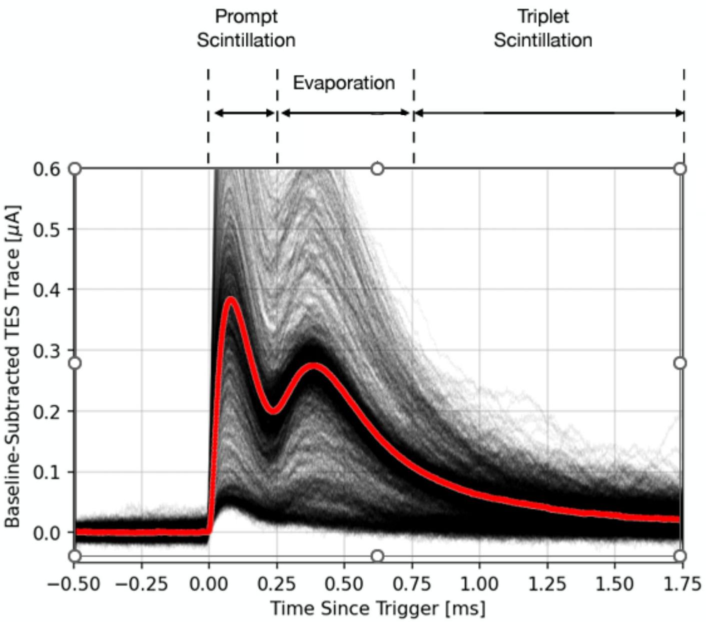


- **Sapphire** (Al_2O_3):
  - **Sapphire** supports many optical phonon modes.
  - **Optical phonons** kinematically well-matched to low-mass DM → effective energy transfer
  - Coupling to E&M-like inputs due to electric dipole → **dark photon sensitivity**
  - Coincidence requirement, no intrinsic LEE suppression



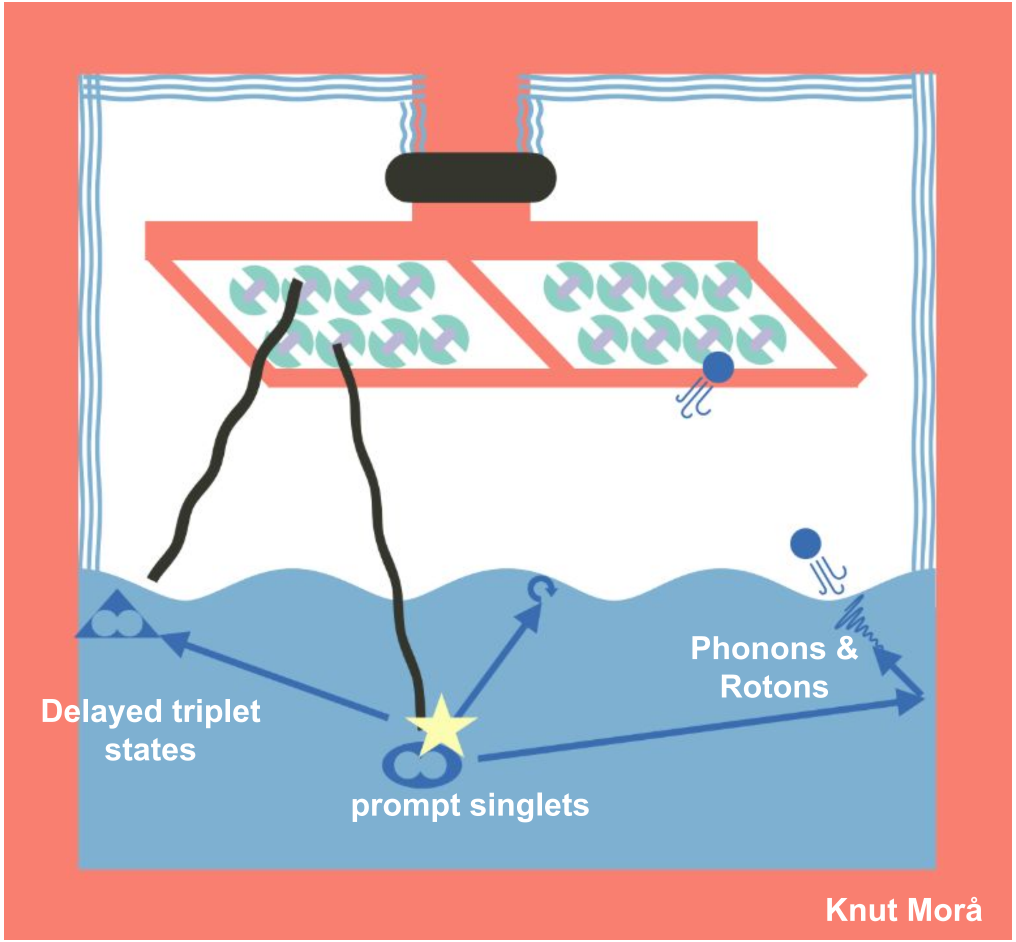
- **GaAs**:
  - **Polar crystal** & **bandgap** well matched to kinematic region of low mass DM
  - **Background discrimination** using phonon/photon ratio
  - Photon-photon and phonon-phonon coincidence can reduce instrumental bkgds

- **^{4}He 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

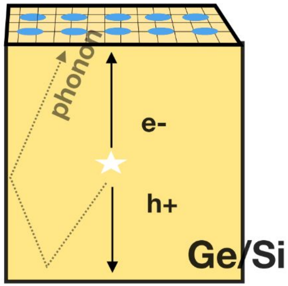


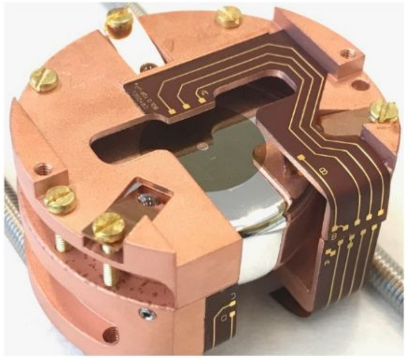
- Read out with dry **TES Si detectors**
- Multiple bgkd discrimination methods & no stress events
- Measured ^{4}He ER &NR light yield and proof of concept
  - arXiv:2108.02176, arXiv:2307.11877

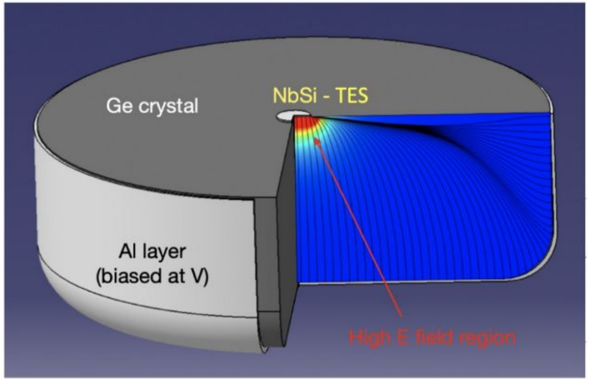
- Interactions in the target create QPs (and, above
- excitons)
    - Prompt dimer scintillation hits the sensors first,
    - Followed by a QP evaporation signal as they hit the surface and knock He atoms up
    - With a long tail of trimer scintillation following

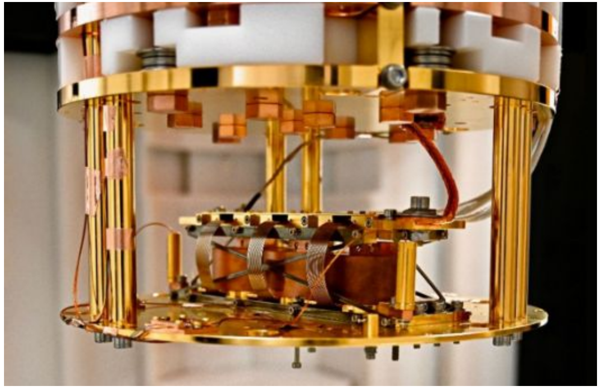


- **CryoCube**: Ge/Si semiconducting bolometers similar to Edelweiss in low voltage mode
- **Two channels:** Heat & Ionization
  - Luke boost → Additional photons prop to ΔV
- Can operate either in low or high voltage mode:
  - **HV**: Very good ER sensitivity with LEE discrimination
  - **LV**: Very good NR sensitivity with PID
- Ongoing R&D

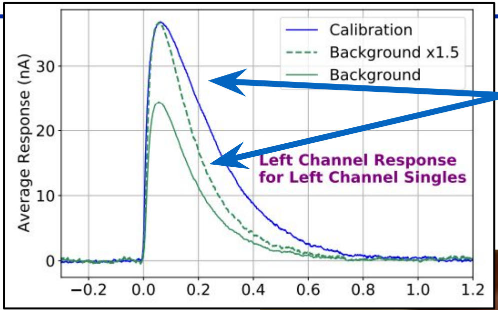




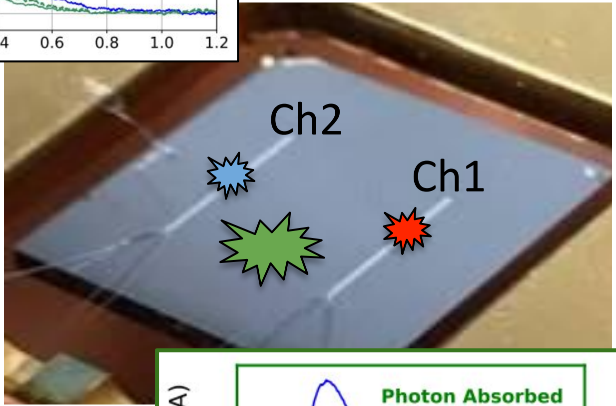




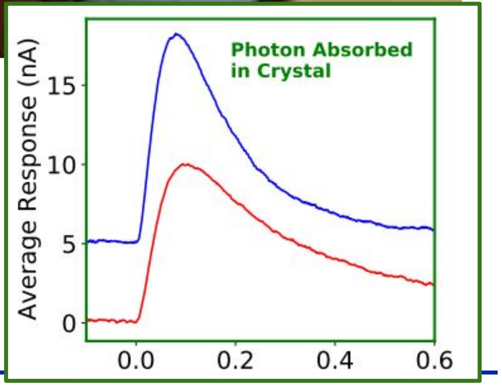
- Using multiple targets improves **background identification & discrimination**
- **Instrumentals and accidentals**:
  - **Coincidence** requirement between sensors & targets (e.g. arXiv:2410.16510)
  - Selecting signals with **arrival time/shape consistent** with **production in target**
- **EM Noise**:
  - **Similar rates and shapes** for different targets
  - **Signal** or **physics events** will have **different rates** and **spectra**
- **Vibration**:
  - **Superfluid He not susceptible** to vibrations



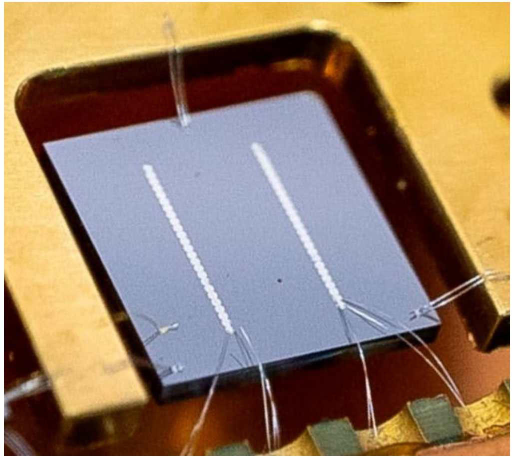
Shape differences singles vs calib

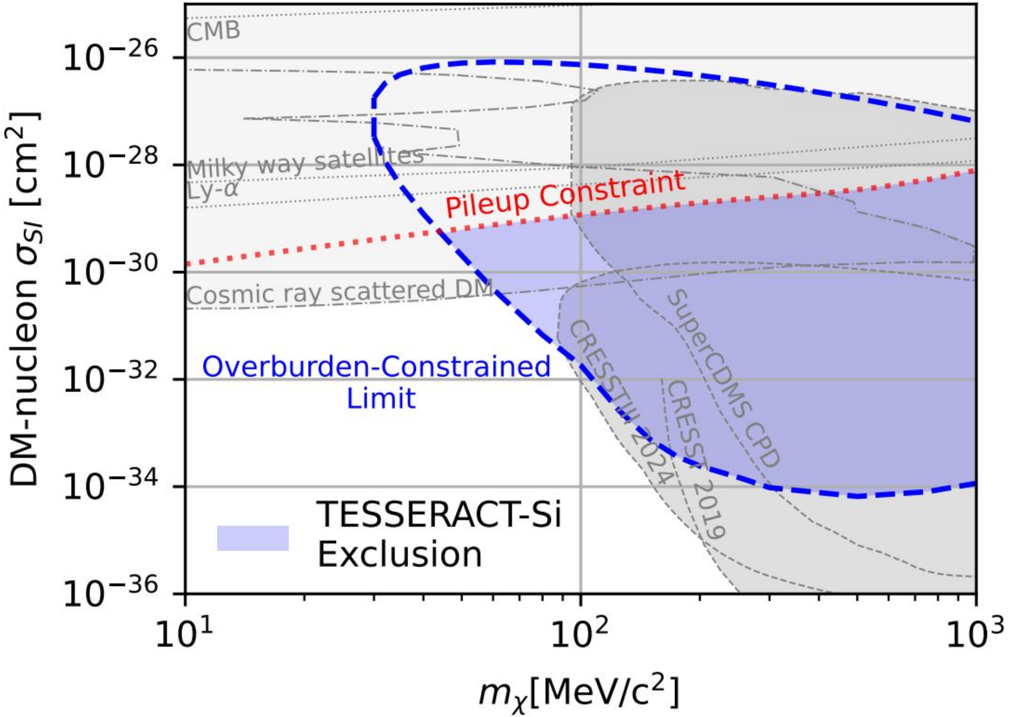


Coincidence for substrate event

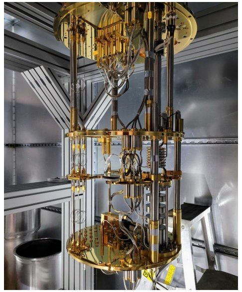


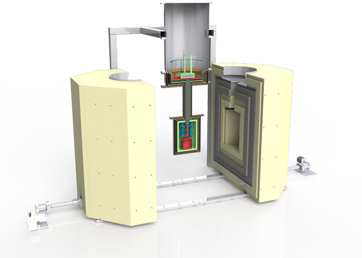
- Due to our very low energy thresholds of even very small masses can obtain new DM results
- **First TESSERACT DM** result using 0.23g SI detector and 361 +/- 5 meV resolution
- Surface-level data, limited by LEE
- Will further improve with more mass, going underground, better discrimination

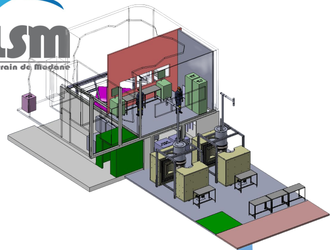




Phys. Rev. Lett. 135, 161002
arXiv.org:2503.03683







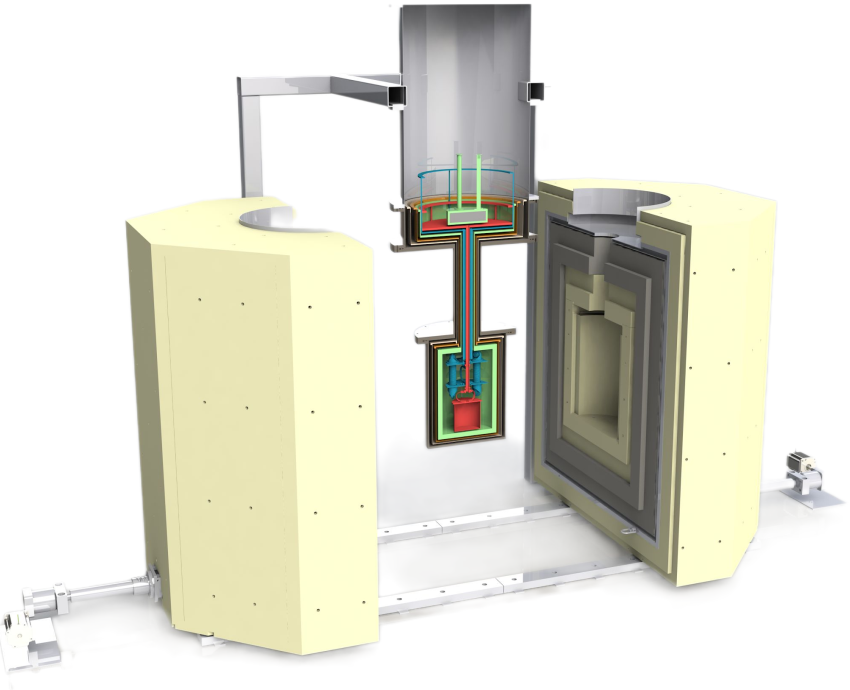
2025 — 2026 — 2027 — 2028 — 2029

- Detector R&D - Fabrication - Testing - Optimization - Surface Science
- Cryostat & Shielding Design
- Surface Cryostat Commissioning
- LSM prep & cryostat integration
- Discovery ?!

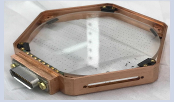
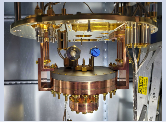
- Surface results still LLE limited, aiming at discriminating power underground at **Modane**
- We are aiming at **two setups running** underground, shielded to a few DRU background
    - Allows for concurrent runnin and R&D.

TESSERACT includes over 60 scientists, researchers, engineers, project managers, postdocs, and graduate students, from 12 institutions supported by the US (DOE), France (IN2PR), and Switzerland (SNF)

- **TESSERACT** has state-of-the-art technology for detection of sub-eV events.
    - Probe **different types of Dark Matter interactions** and a large LDM mass range
    - **Identify & discriminate backgrounds** to drive the exploration of this novel regime
- **TESSERACT** very experienced team supported by DOE, US & Switzerland
- Probing new phase space even in surface runs!
- **Most targets demonstrated** to work, R&D focuses on science-readiness
- **Official project phase started**, infrastructure well developed and construction started
- Planning to move to **Modane in 2028**

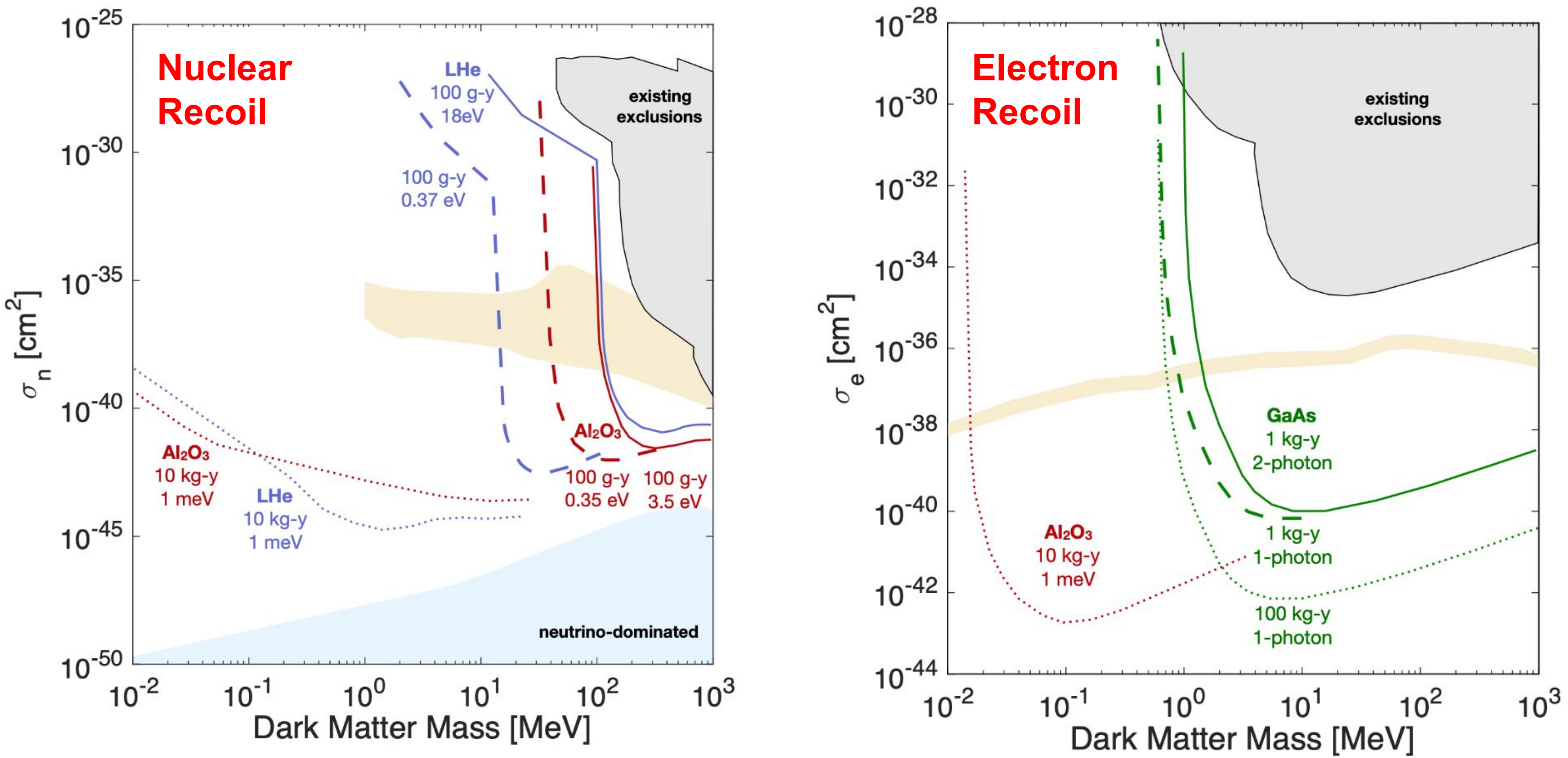


Backup

Target		NRDM	ERDM (> 1 MeV)	ERDM (keV - MeV)	Absorption	Bkgd rejection
Al2O3/SIO2		[green]	[yellow]	[green]	[green]	[grey]
GaAs		[yellow]	[green]	[yellow]	[green]	[green]
Superfluid He		[green]	[grey]	[grey]	[grey]	[green]

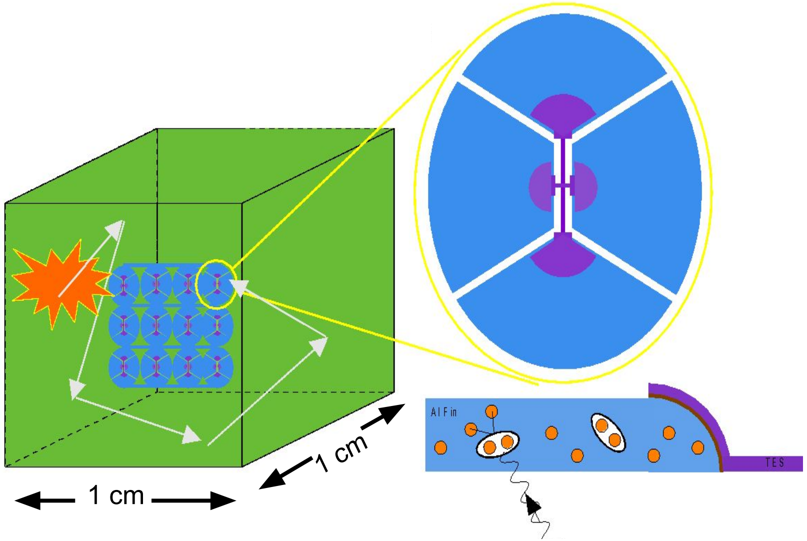
[green] = World-leading sensitivity
[yellow] = Competitive sensitivity

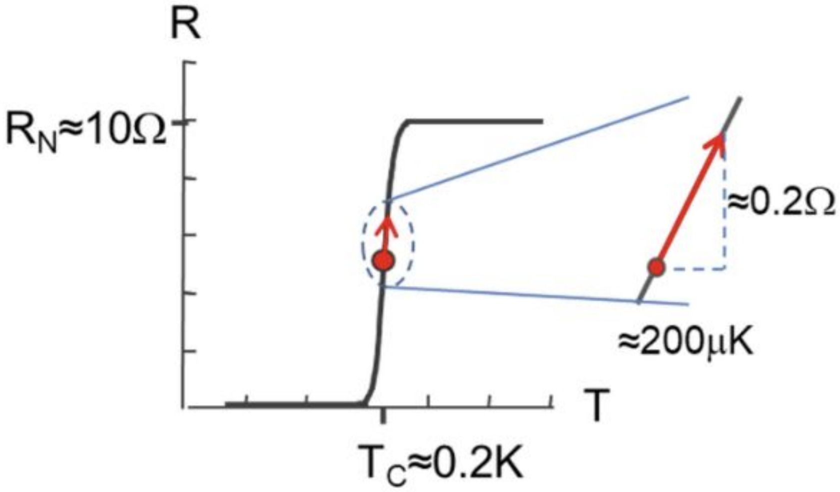
- **Al_2O_3** wide ranging sensitivity.
  One signal (phonon), multiple readouts to reduce instrumental background
- **GaAs** and **superfluid helium**: Advantages in background rejection: multiple signal channels and multi pixel coincidence-based instrumental background rejection
- We already operate **GaAs and Si**, **Sapphire** used with different readout by other experiments



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

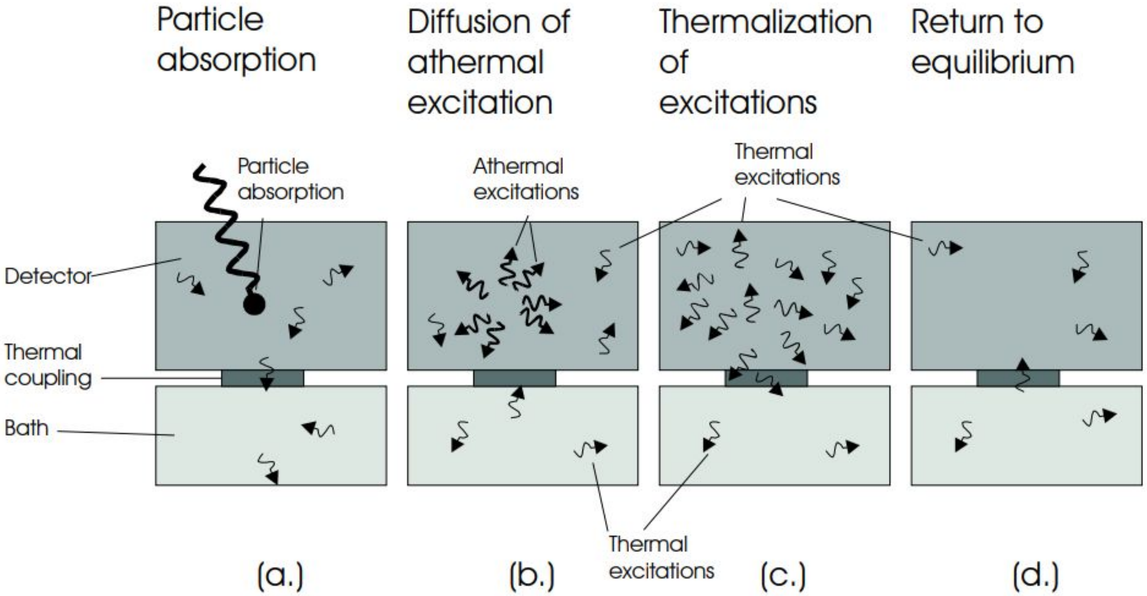
Athermal Photon Detectors





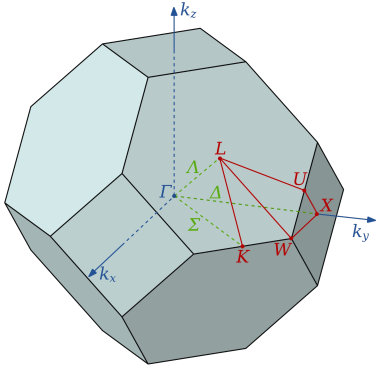
- Read out **athermal phonons** using **Transition Edge Sensors**
- **Readout of all targets identical** except the substrate
- More **DM science doesn’t increase cost** significantly!

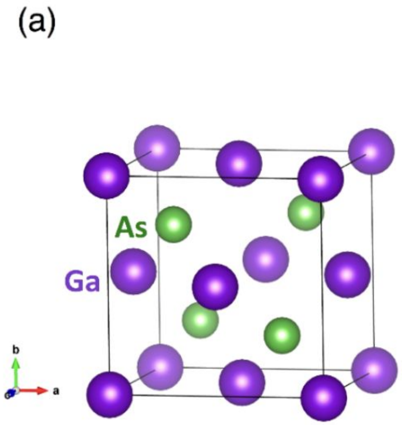
Why Athermal Phonons?

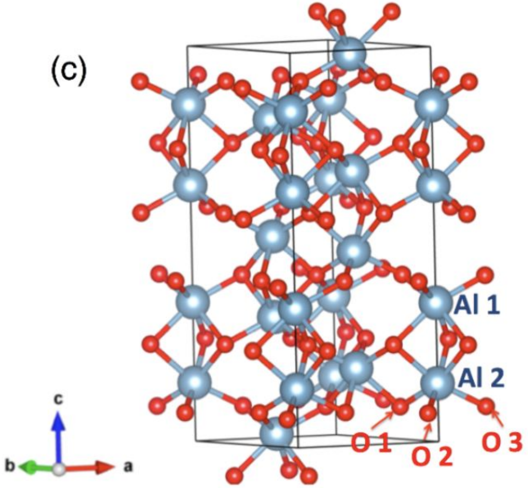


- Sensor based on **athermal phonon** collection will be **more sensitive than any thermal sensor technology** → clearest route available to eventually reach meV-scale thresholds.
  - Decouple the heat capacity of the target and the sensor
  - Provide fast time constants because phonons are detected before they thermalize
- Position information enables fiducialization of the target and to veto surface events

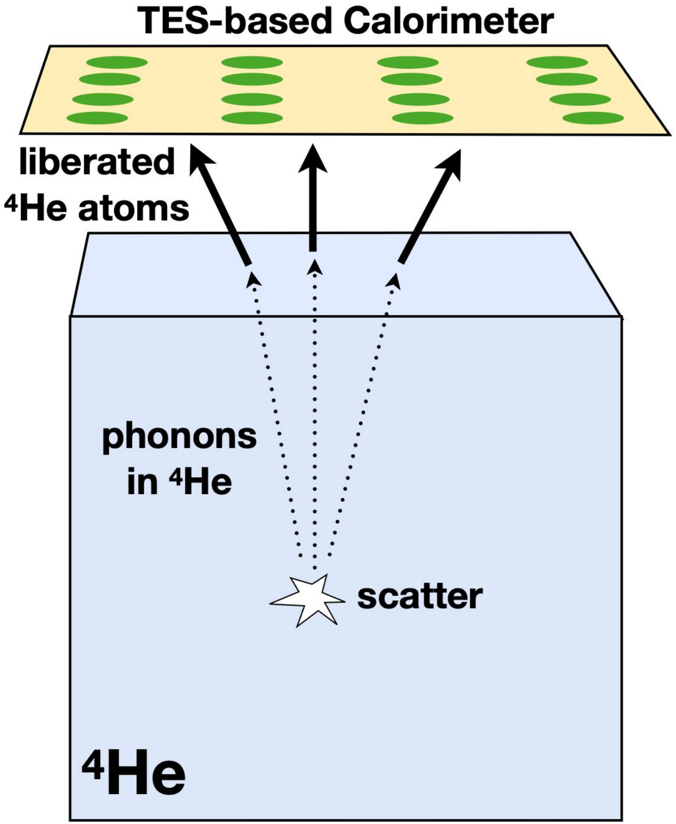
Crystal structure





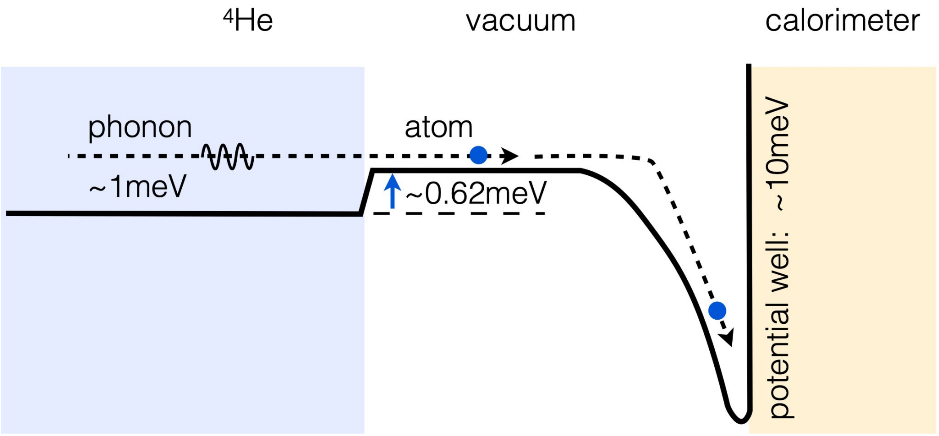


- GaAs and Al2O3 adopt the zincblende (space group F-43m) and sapphire (space group R-3c) structures
- The cubic lattice of GaAs is equivalent in all three crystallographic directions, with all Ga and As atoms in the cell being equivalent. The primitive unit cell in this case is made up of two atoms – one Ga and one As.
- Sapphire's rhombohedral unit cell has inequivalent in-plane and out-of-plane crystal axes. The primitive unit cell of Al2O3 has two copies of five atoms – two Al and three O. These differing Al and O occupy inequivalent symmetry positions in the unit cell and thus have different surrounding chemical environments. Owing to this, the Born effective charges for each of these five atoms can differ since they will have different responses to external perturbations. The calculated Born effective charges for Al2O3 for the inequivalent atoms

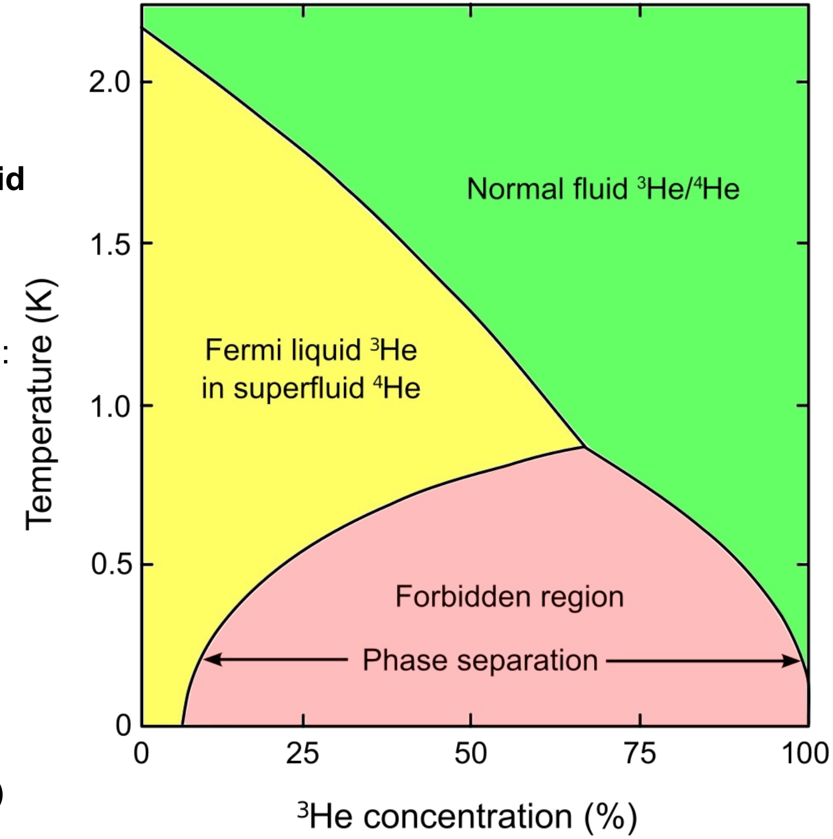


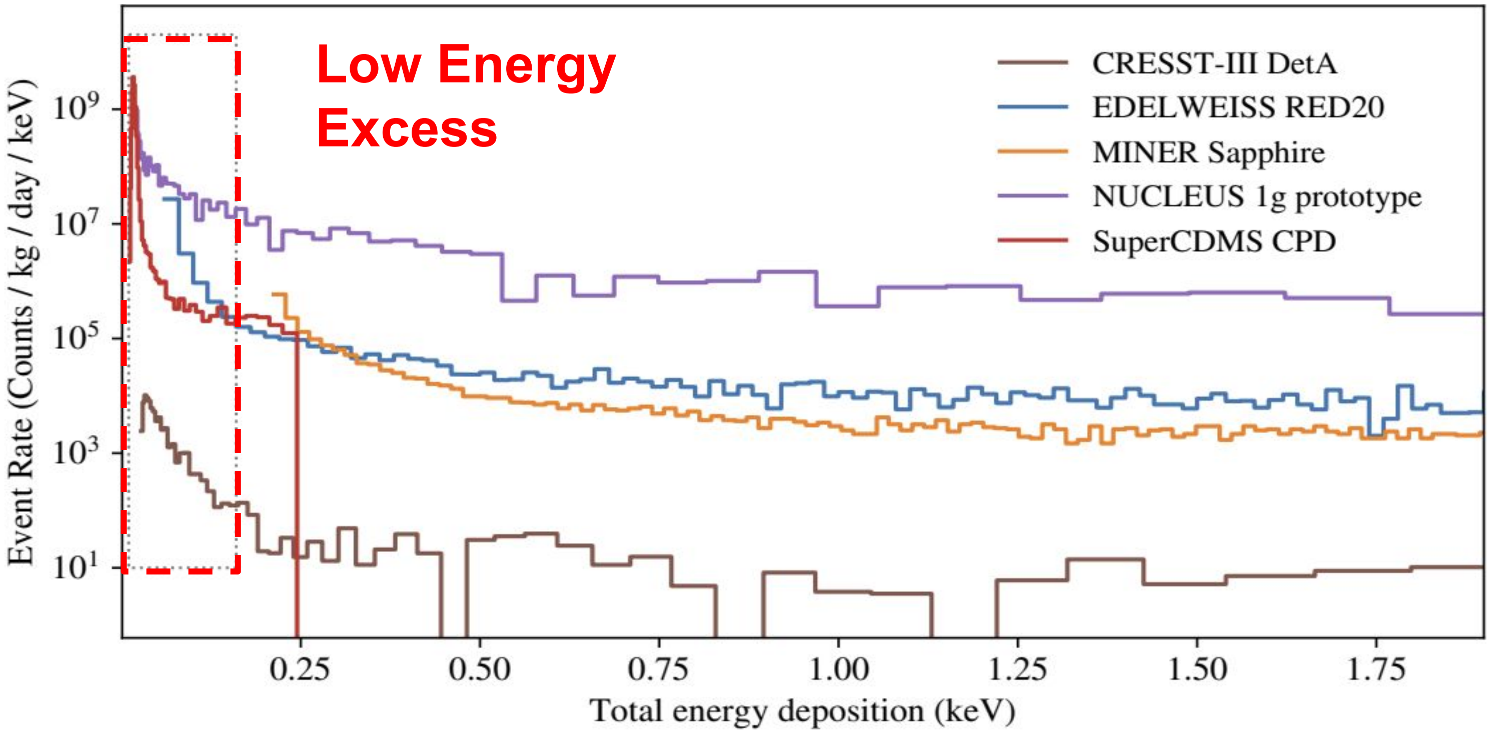
Quantum Evaporation

- Signal: The adsorption of atoms onto a calorimeter
  - Binding energy of ^{4}He to a typical calorimeter surface: ~10 meV
  - Signal gain: ~ 17x



- **Dilution Fridges** (DF), first built in Kamerlingh Onnes Laboratorium in 1964
  - Modern pulse tube cryocoolers enable very efficient devices
  - **^{4}He** is a boson → Bose-Einstein condensation, **superfluid** at about 2.17 Kelvin
  - **^{3}He** is fermion →**not superfluid** in DF
- At about 0.87 K the ^{3}**He/^{4}He mix will separate into two phases**: A **concentrated** (100%) ^{3}He **phase**, ~100% ^{3}He, and **a dilute phase** of 93.4% ^{4}He and 6.6% ^{3}He
  - **Enthalpy of ^{3}He in the dilute phase is larger** than in the concentrated phase
  - Inside the mixing chamber, **the ^{3}He is diluted as it flows from the concentrated phase** through the phase boundary **into the dilute phase**
  - Energy is required to move ^{3}He atoms from the concentrated to the dilute phase (**similar as evaporation**) →**will cool** the dilute phase

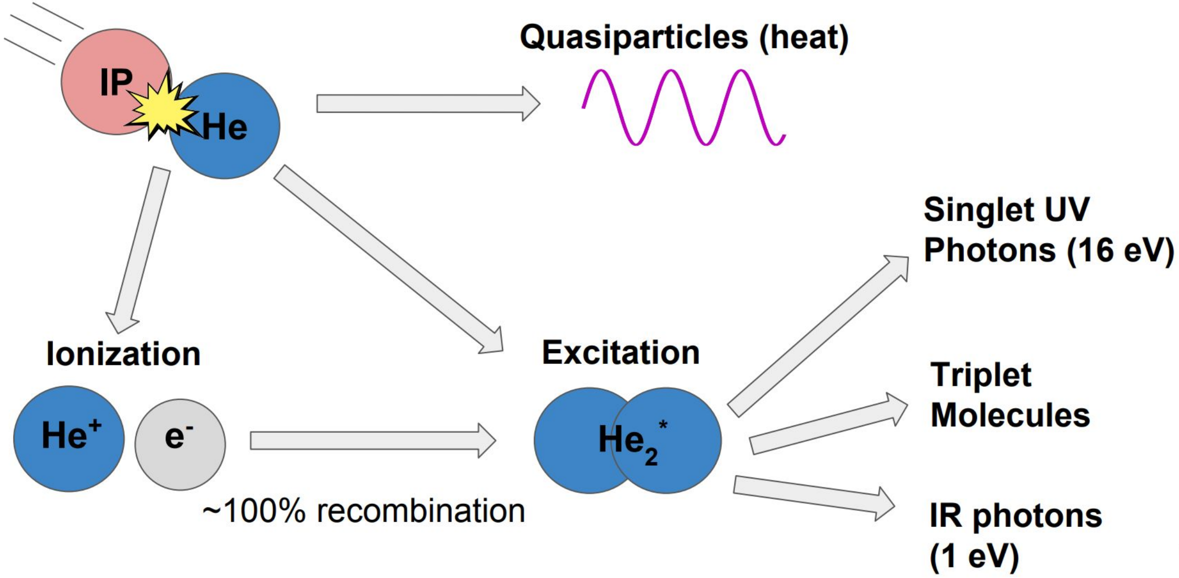




- **Low energy excess** at O(eV) in many experiments: SuperCDMS, Edelweiss, Nucleus, DAMIC, etc
- LEE likely vibrations, but also probably some other components

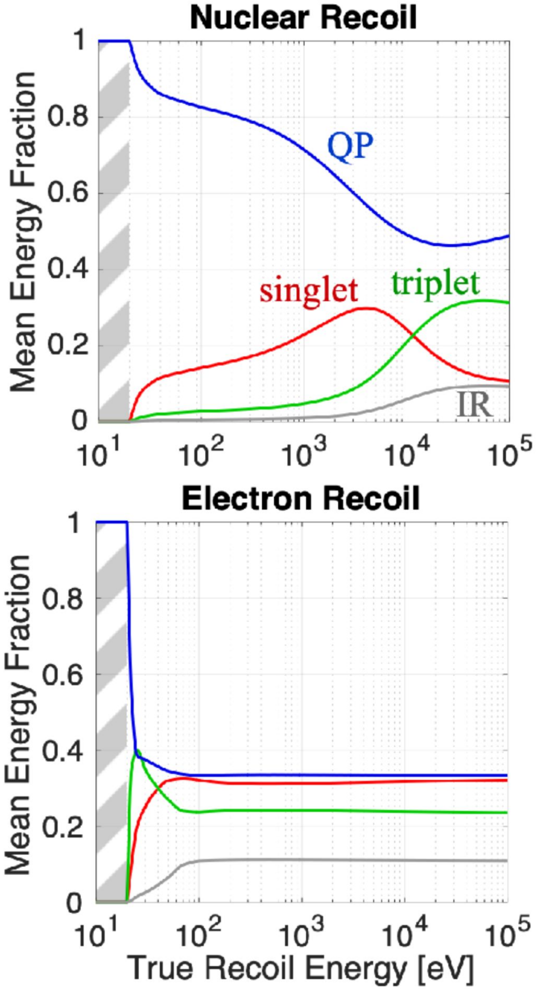
- **Heat leads to quasiparticles** (phonons and rotons) ballistically propagating through the detector below 100 mK

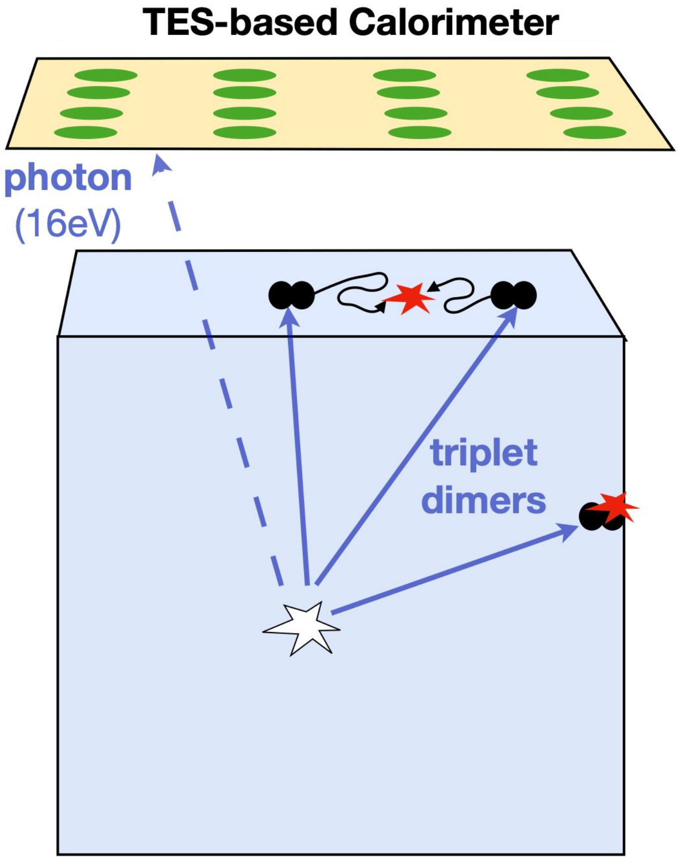
- **Atomic excitations**
    - Excimer states resulting in **VUV** and **IR** photons with characteristic lifetimes
    - Not unlike scintillation light in LXe



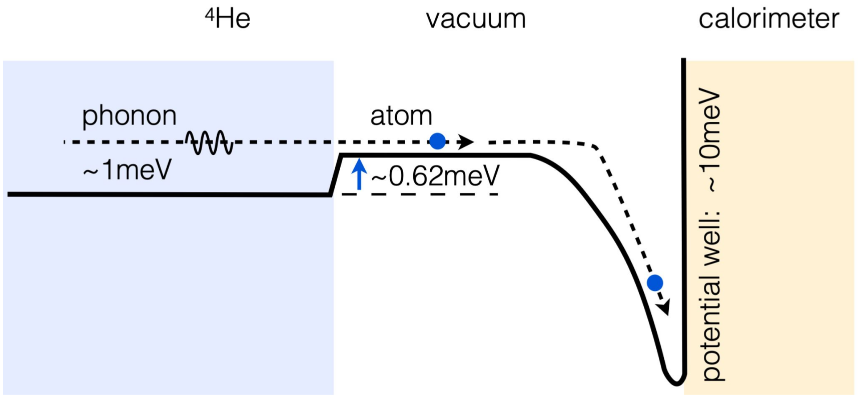
Superfluid ^{4}He

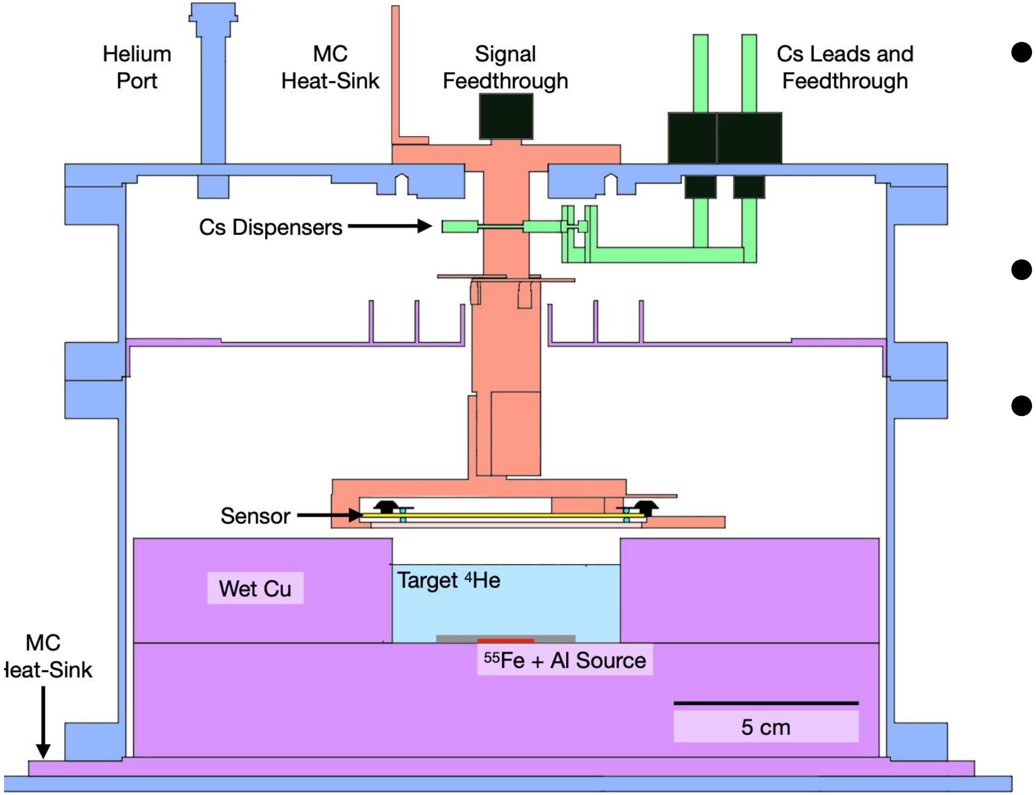
- **Above 20 eV:**
  - Large fraction of recoil energy goes into dimers
  - Estimate fraction directly from measured atomic excitation cross sections.
  - So far ER and NR calibrations agree with expectation (arXiv:1810.06283)
- **Below 20 eV:**
  - All recoil energy appears as phonons (Hard cutoff of 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



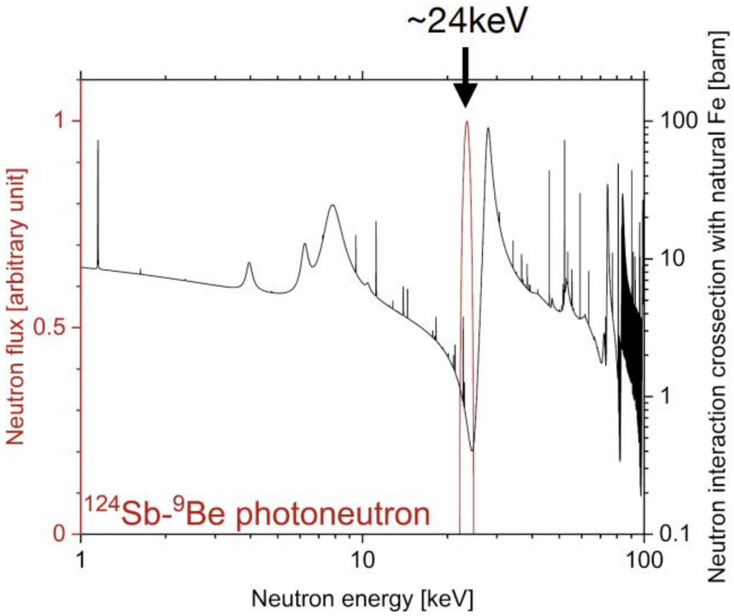


- Atomic Excitations:
  - Singlet dimers: Prompt decay, E~16 eV
  - Triplet: Quick decay via Penning ionization or very long lifetime (13 s), ballistic propagation
- Position information encoded in signal distributions
- Quantum Evaporation
  - Signal: The adsorption of atoms onto a calorimeter
  - Binding energy of 4He to a typical calorimeter surface: ~10 meV
  - Signal gain: ~ 17x

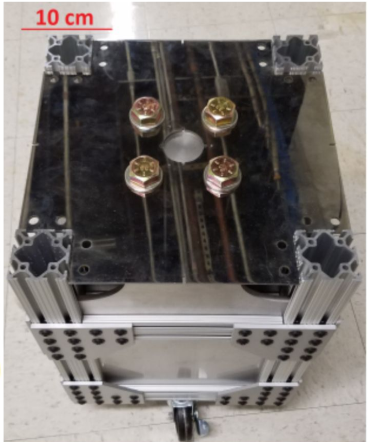


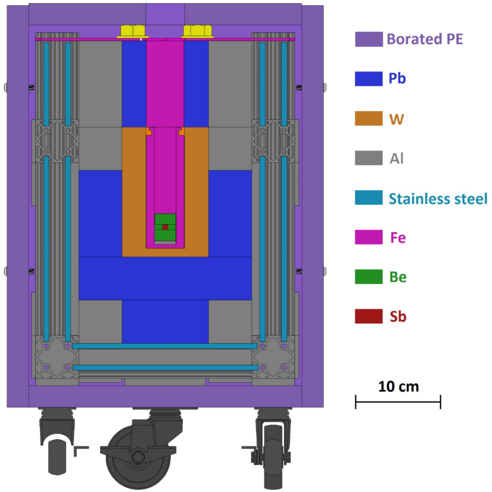


- Superfluid He is wetting all types of surfaces
  - All but **cesium** and rubidium
- Use **Cs barrier to prevent He on sensor**
- **Very challenging**:
  - Must be unoxidized → in-situ deposition in vacuum when chamber is cooled down
  - Evaporation itself requires high temp, large current



- **SbBe photoneutron + Fe** shield
- Remarkable coincidence:
  - ^{124}Sb^{9}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

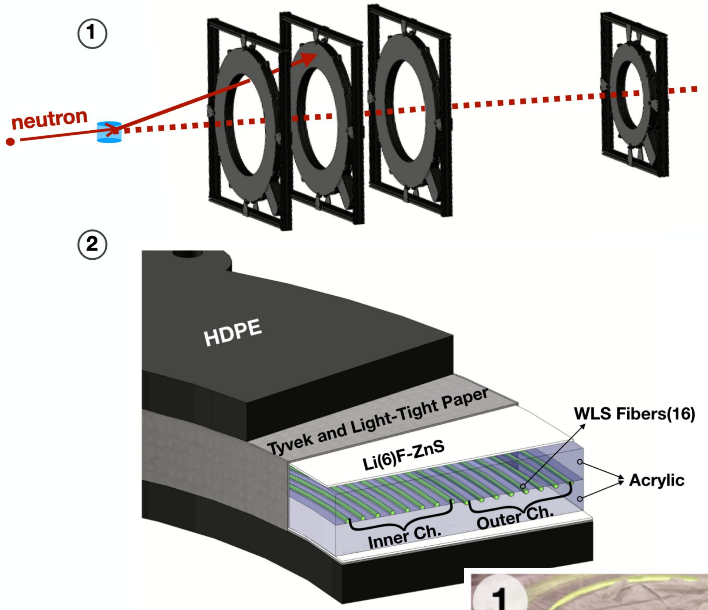


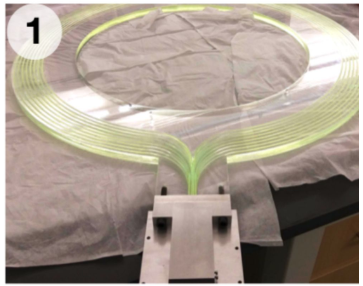


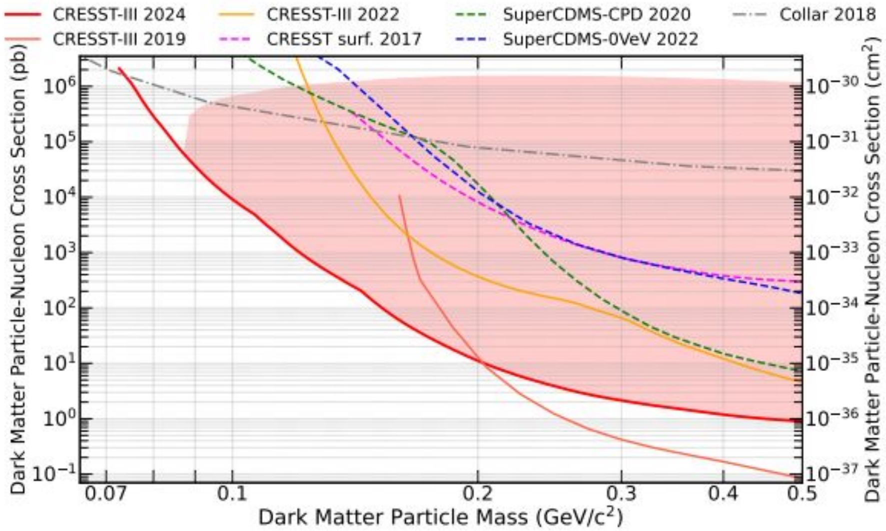
- Source built & works
- Favorable **n flux**: ~5 cm^{-2}s^{-1}
- Portable, ideal for **CEνNS** and **light DM** experiments
- See arXiv:2302.03869

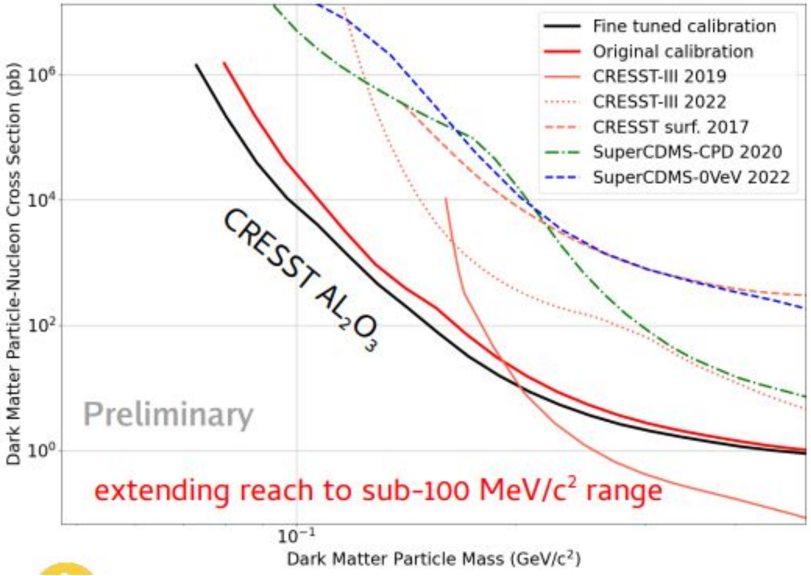
Recent Progress - Calibrations

- Developed a low energy neutron source
  - Scattering of neutron of known energy, tag its scattering angle
- Large arge **keV Neutron backing** detector for low energy NR calibrations
- ^{6}Li + Scintillator + Reflector + WS fiber + SiPM
- Eff: 25% eff. & affordable
- See arXiv:2203.04896









https://arxiv.org/pdf/2405.06527

- Cresst is pursuing many similar avenues, no superfluid helium and TES have lower resolution
- https://indico.cern.ch/event/1199289/contributions/5449631/attachments/2705086/4695850/cresst_kaznacheeva_taup23.pdf