TESSERACT @ LSM

A proposal for a new generation light DM search cryogenic experiment in Modane

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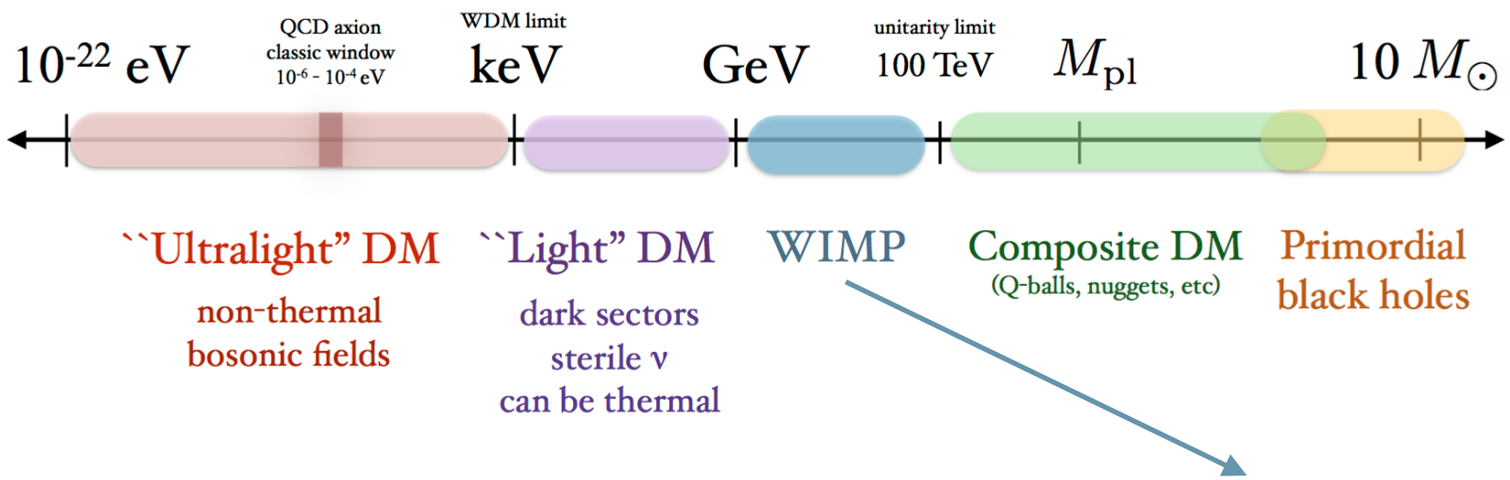
GDR DUPhY, October 20th, 2022

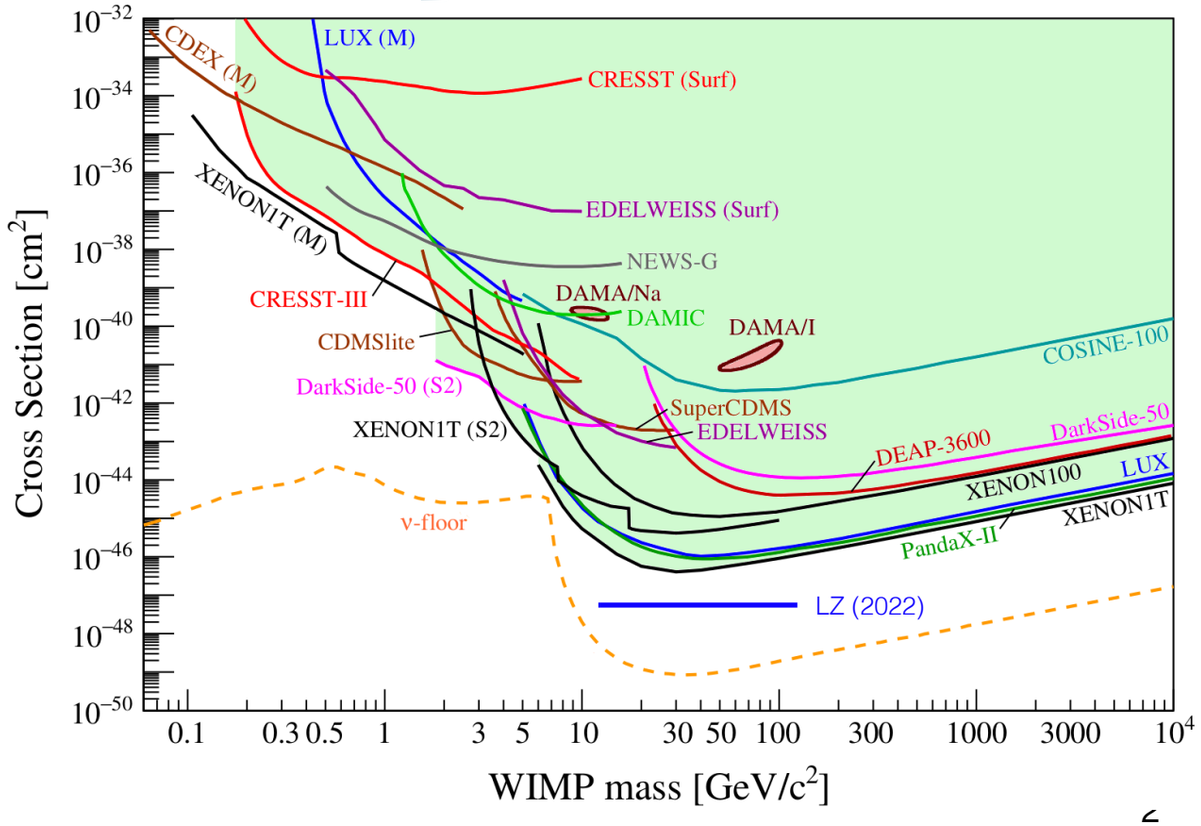
TESSERACT: *Dark Matter candidates*

Dark matter candidate: *About 50 orders of magnitude in mass (assuming it is an elementary particle)*

Courtesy: T. Lin

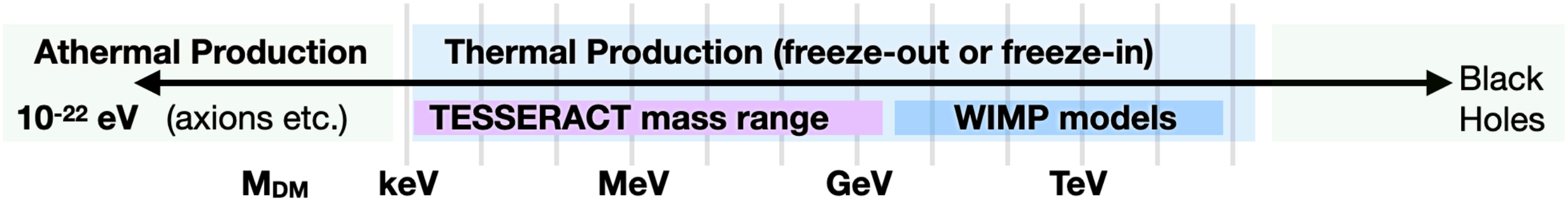


- Focus of DM searches for the last decades has been on axion DM (ueV - meV) and the standard WIMP (10 GeV - TeV)
- The standard WIMP case *« was »* highly motivated thanks to the so-called WIMP miracle and the SUSY predictions
- After few decades, still no DM signal and ongoing or planned ton-scale experiments (LZ, XENON-nT, DarkSide-20k, DARWIN, ARGO,…) are approaching the neutrino limit
- ***Need for new experiments with broader DM mass range and increased sensitivity to more DM interactions !***



TESSERACT: *keV-GeV « light » Dark Matter*

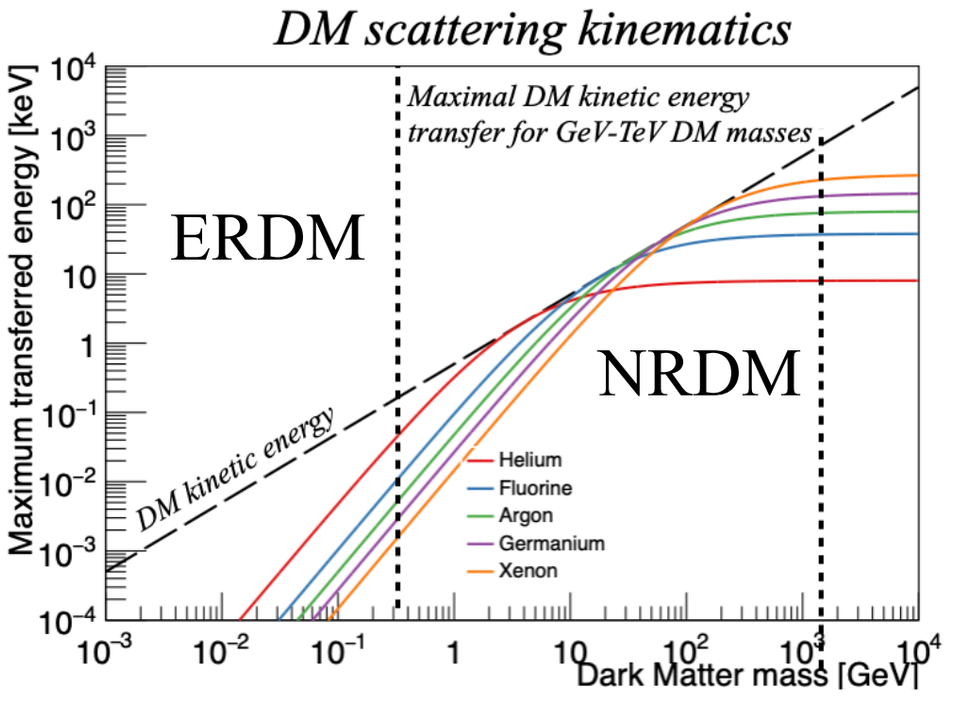
- Consistent with simple thermal production after inflation (like other massive particles)
- Typically requires a new force mediator too, not just the DM particle.
- Direct detection searches via electron scattering (ERDM) or nuclear scattering (NRDM)



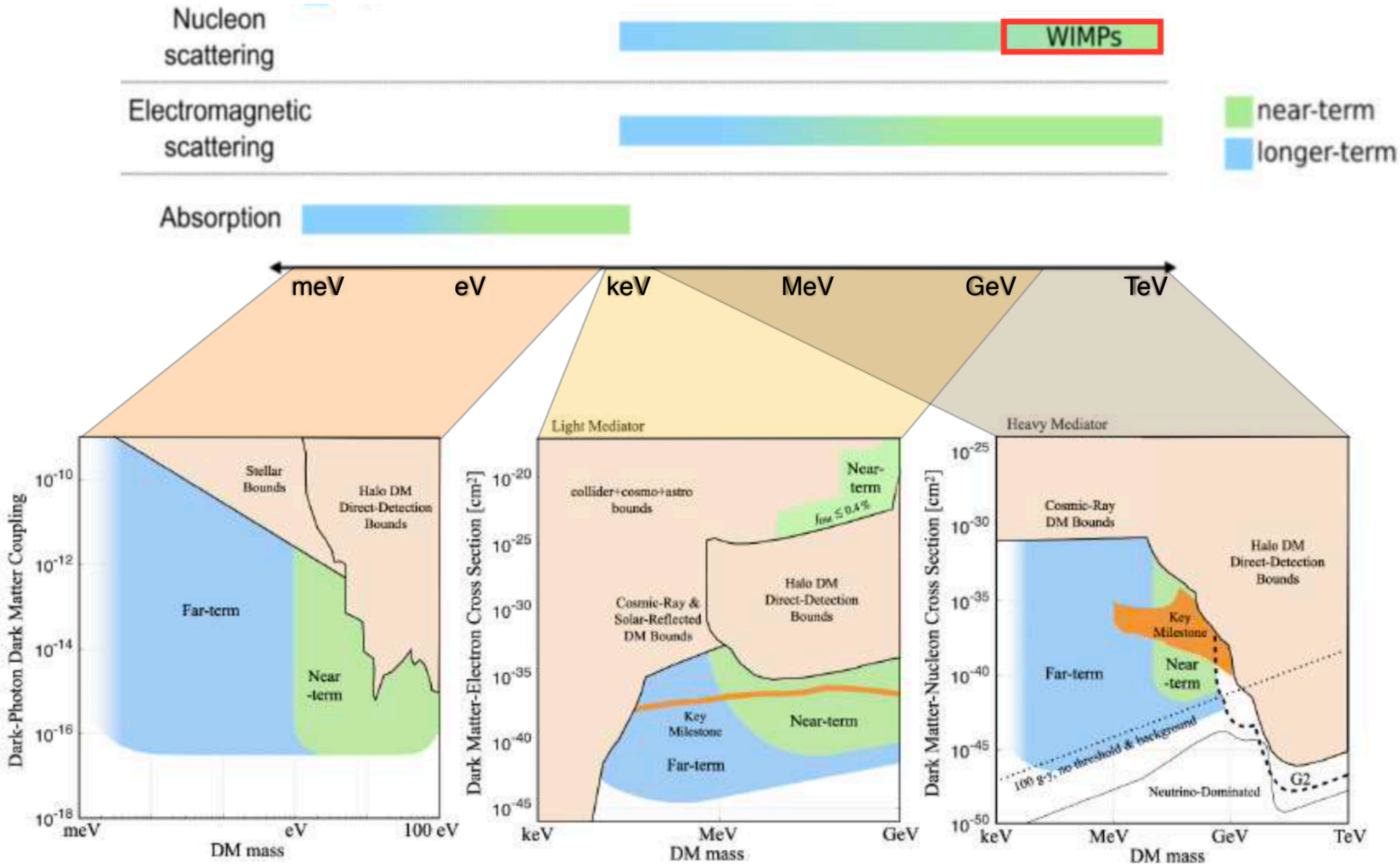
Nuclear recoil end-point: ~neV ~meV ~keV

Electronic recoil end-point: ~meV ~eV ~keV

- eV-scale thresholds already demonstrated
- meV-scale threshold under intense R&D
- **Bonus**: Extend the DM search window to ultra-light DM (10meV-scale masses) *thanks to DM absorption on electron/phonons*



TESSERACT: *Dark Matter interaction type*

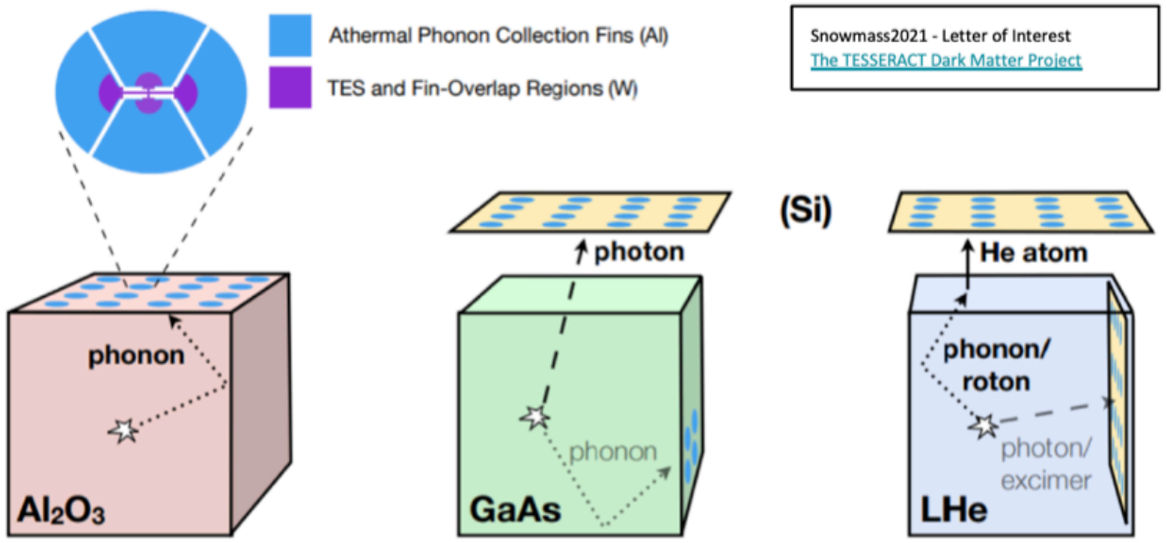


TESSERACT: Extending the Dark Matter mass search window from meV-to-GeV with ultra low-threshold cryogenic detectors with multiple targets and particle identification capabilities

TESSERACT: *Proposal experiment at LSM*

TESSERACT

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets



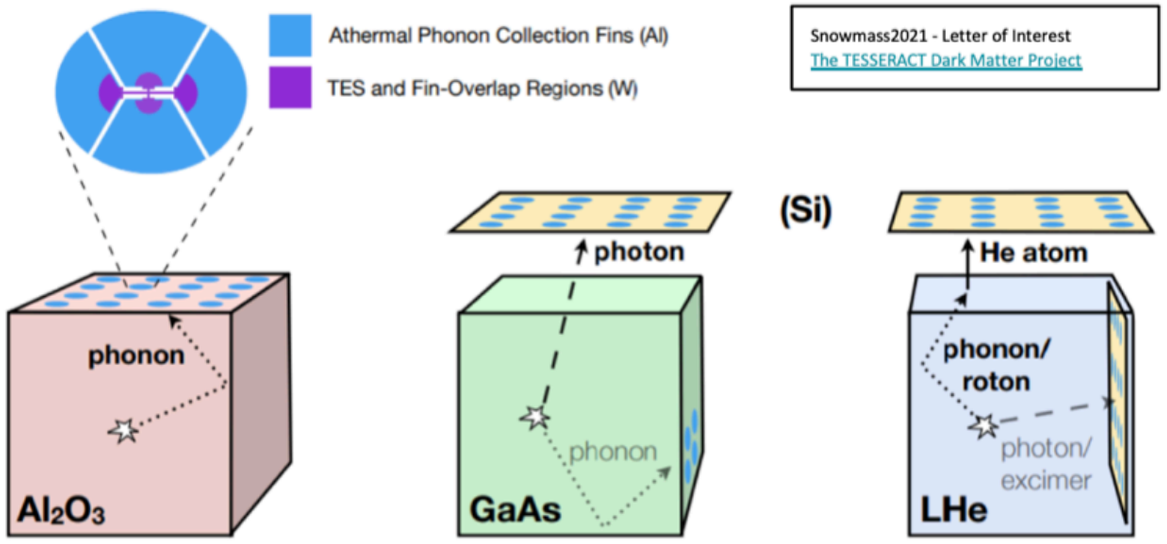
- DOE Funding for R&D and project development began in June 2020 (Dark Matter New Initiative)
- One experimental design, and different target materials with complementary DM sensitivity, all using TES
- Includes SPICE (Al_2O_3 and GaAs) and HeRALD (LHe)
- ~40 people from 8 institutions
- **Actively searching for an underground lab**

Berkeley Lab · Berkeley · Caltech · Florida State · Texas A&M · Michigan · Argonne National Laboratory · UMass Amherst

TESSERACT: *Proposal experiment at LSM*

TESSERACT

***T**ransition **E**dge **S**ensors with **S**ub-**E**v **R**esolution **A**nd **C**ryogenic **T**argets*



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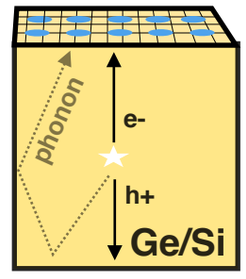
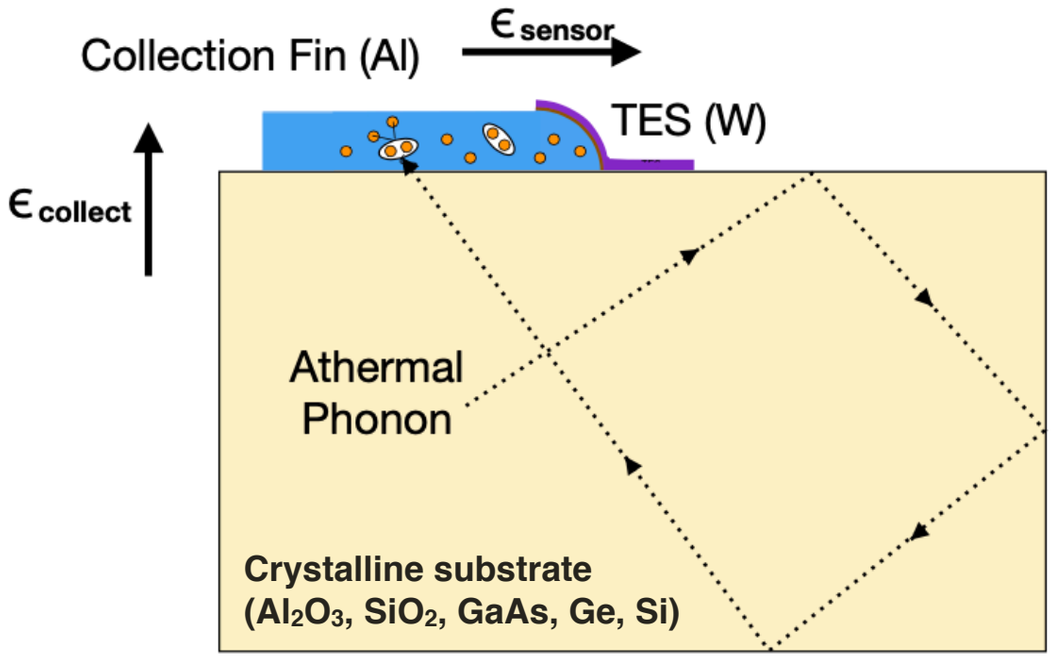
TESSERACT @ LSM



- Adding **Ge/Si** semiconductors with TES (heat) and electrodes (ion) readout
- Benefit from EDW+Ricochet Ge bolometer expertise and low-background cryogenic setup
- Ongoing discussions with IN2P3 Ricochet and EDW partners (LPSC, IJCLab, IP2I)
- **Actively looking for a future cryogenic DM experiment**

TESSERACT: *New generation TES phonon sensors*

TES based athermal phonon sensor technology:

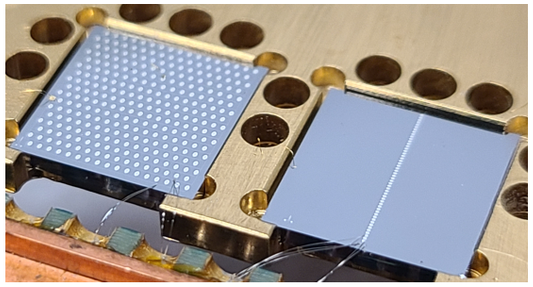


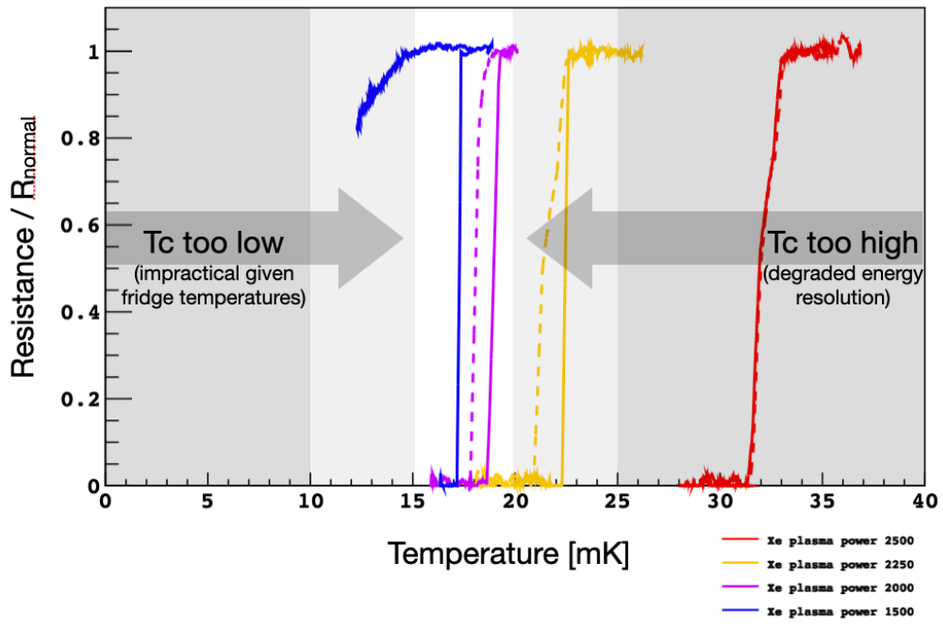
$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

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

Energy threshold decreases with detector mass

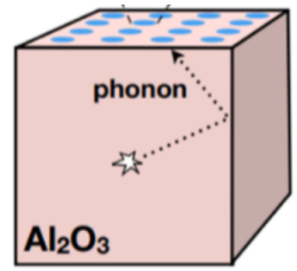
Energy threshold decreases **very quickly** with Tc





- 3.5 eV (RMS) already achieved with a 10g Si detector and Tc = 41 mK
- Targeted Tc around 15-20 mK recently achieved !
  - **~100 meV threshold achievable**
- **Next challenge:** parasitic power (vibrations, EMI, IR photons) needs to be <aW to fully reach TES sensitivity

TESSERACT: *SPICE*

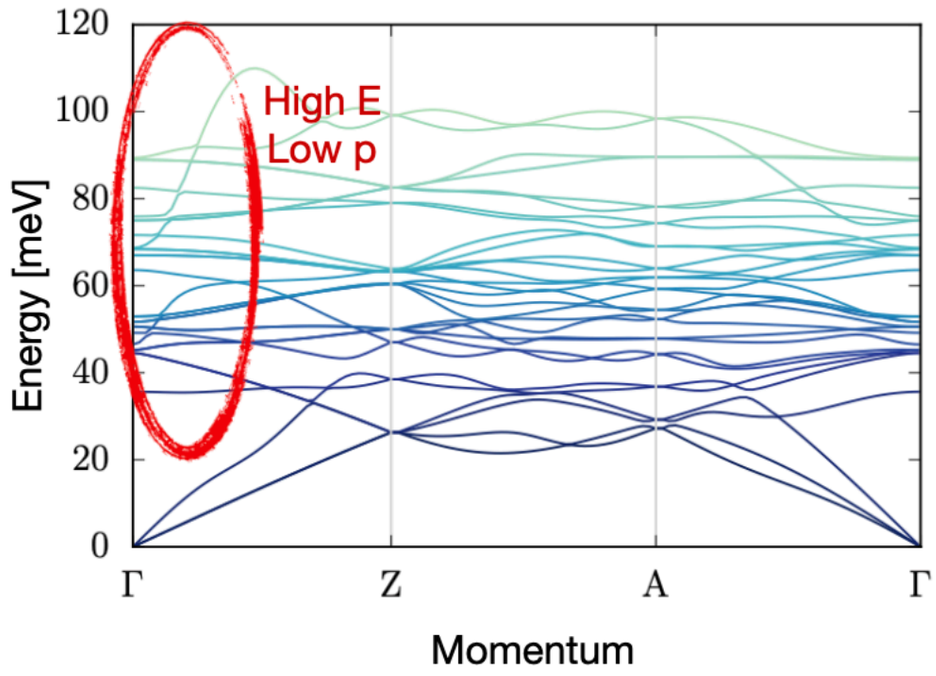


Sub-eV Polar Interactions Cryogenic Experiment: ***Al_2O_3***

1. Sapphire supports many optical phonon modes.
(phonons with a high energy:momentum ratio)

Instead thinking about 'kicking an atom' we now think about recoiling off the lattice, and 'exciting a phonon'.

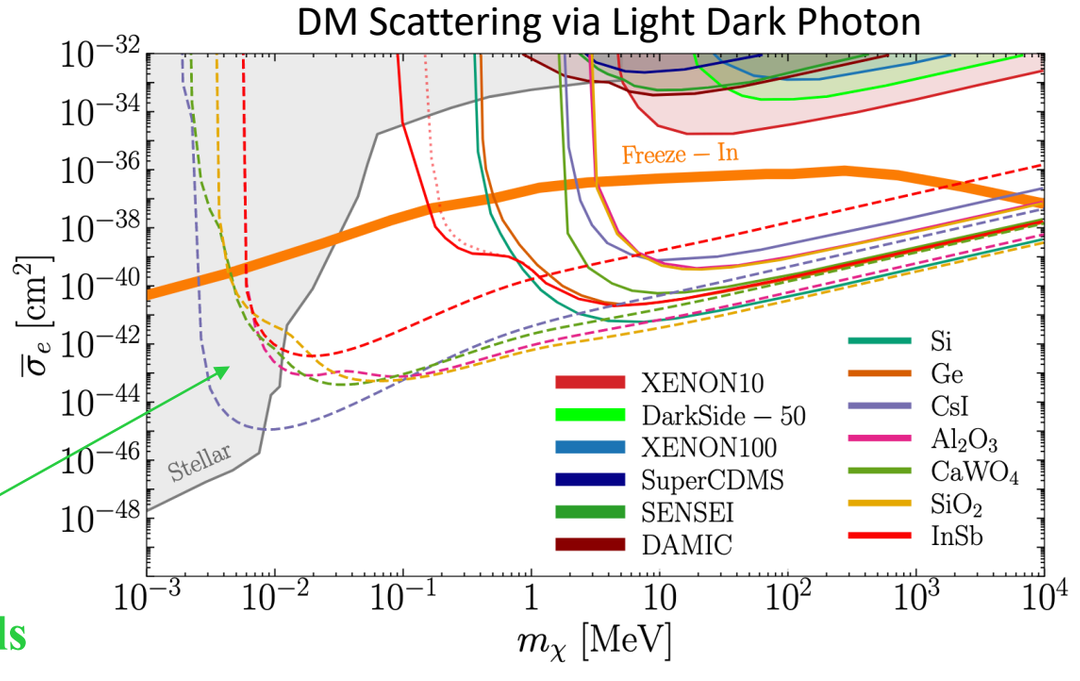
Optical phonons are kinematically well-matched to low-mass dark matter (similar effective mass)



2. Sapphire is a polar crystal
(couples well to E&M-like inputs)

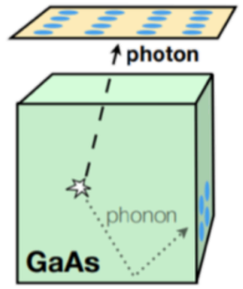
Allows to extend DM scattering searches via light dark photon down to keV masses **not accessible** to any other target materials

Possibility to extend further down to 100-meV (eV) DM masses thanks to absorption on phonon (electron)

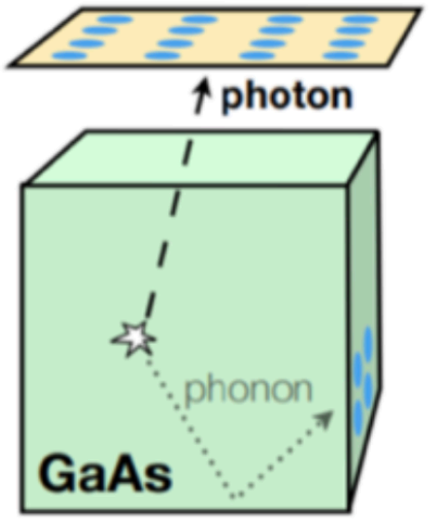


Only polar materials

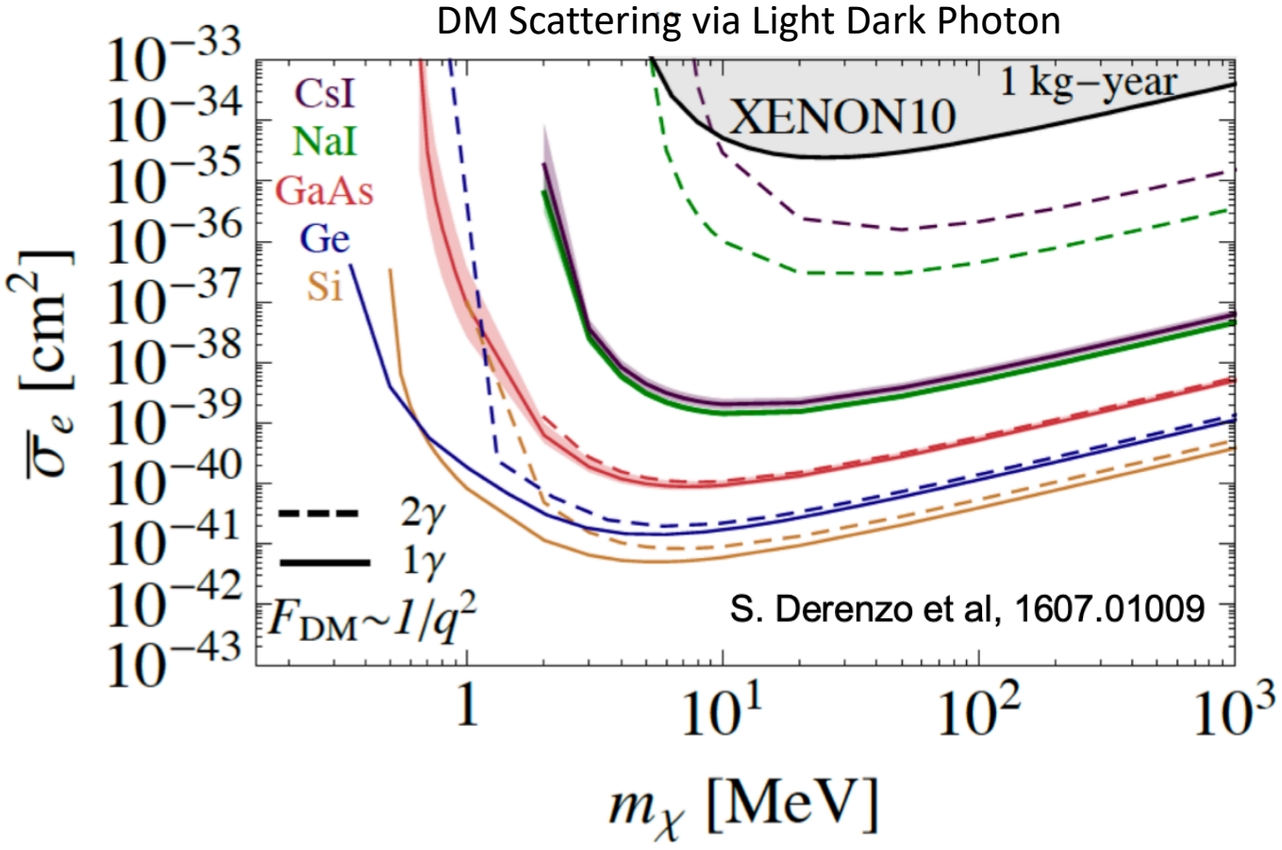
TESSERACT: *SPICE*



***S**ub-eV **P**olar **I**nteractions **C**ryogenic **E**xperiment: GaAs*

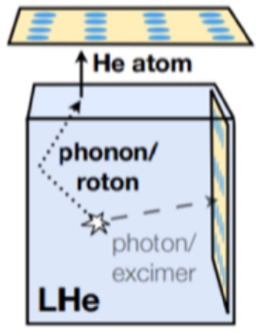


DM Scattering via Light Dark Photon

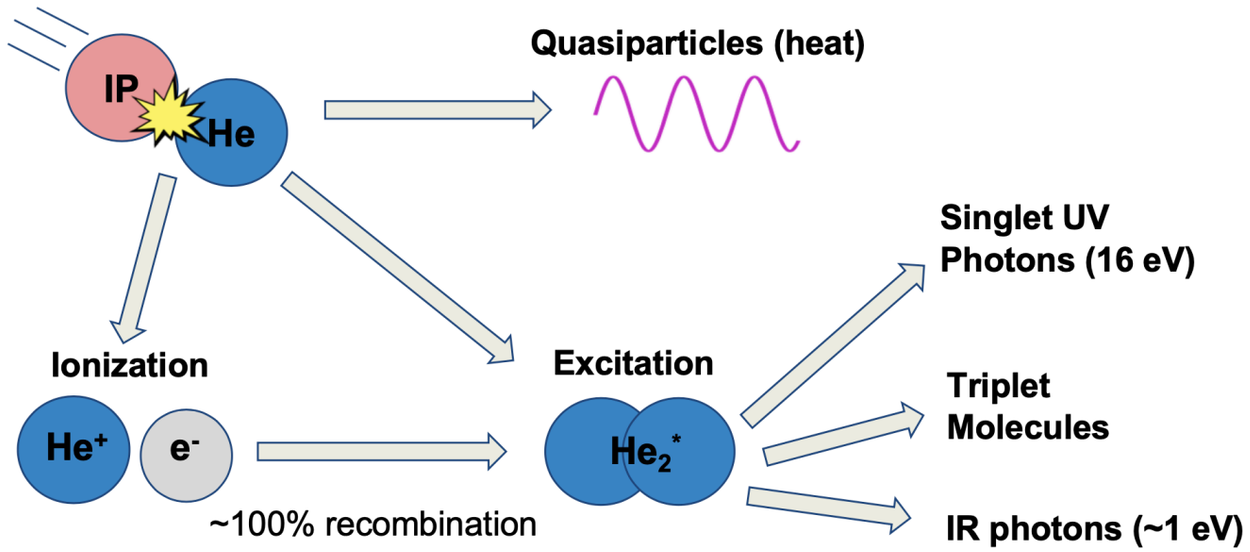


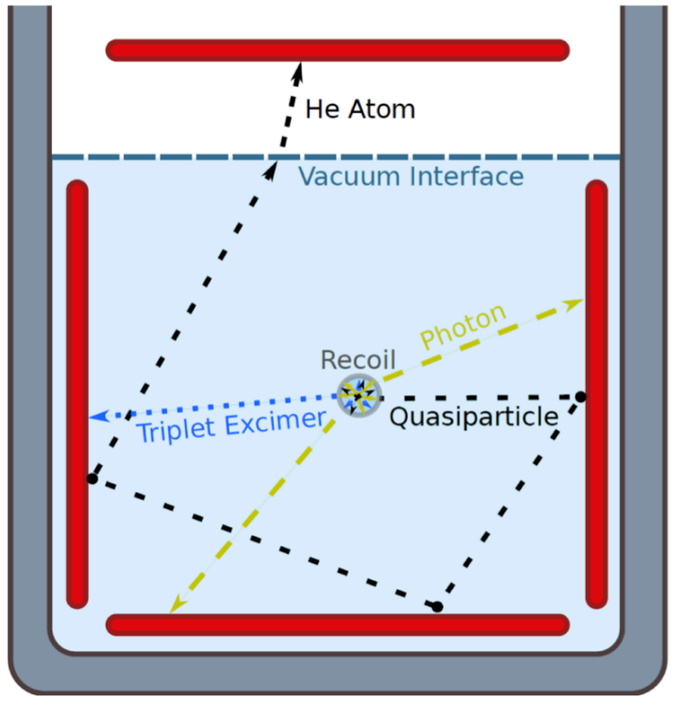
- GaAs has very high scintillation yield, well suited for heat/light dual readout down to 100 eV
- GaAs has a lower ERDM sensitivity than Ge/Si but allows for **control of the backgrounds**:
  - photon:phonon ratio depends on the recoiling particle type: NR/ER discrimination
  - photon/phonon coïncidence in two separate sensors: instrumental background rejection
  - No charge leakage

TESSERACT: *HeRALD*



Helium Roton Apparatus for Light Dark matter





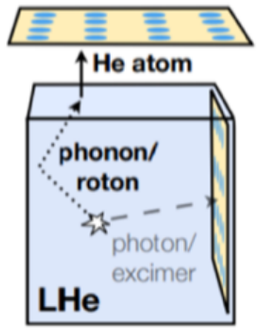
Advantage of He-4:

- Well kinetically matched to GeV-scale DM
- Easy to purify, intrinsically radio pure
- Remains liquid/superfluid down to 0K
- Monolithic and scalable
- Extremely rich signal outputs: scintillation, quasiparticles, triplet excimers and IR photons for **particle identification and fiducialization**
- TES calorimetry for signal readout

HeRALD operation:

- LHe cell operated at 20-50 mK with wafer-like cryogenic detectors with TES
  - Submerged in liquid to detect:
    - **UV photons, triplet molecules, IR photons**
  - Suspended in vacuum to detect:
    - UV/IR photons and **He atoms** from qp induced evaporation (signal gain ~9)
- Segmented sensors allows for **instrumental background rejection** from coincidences

TESSERACT: *HeRALD*



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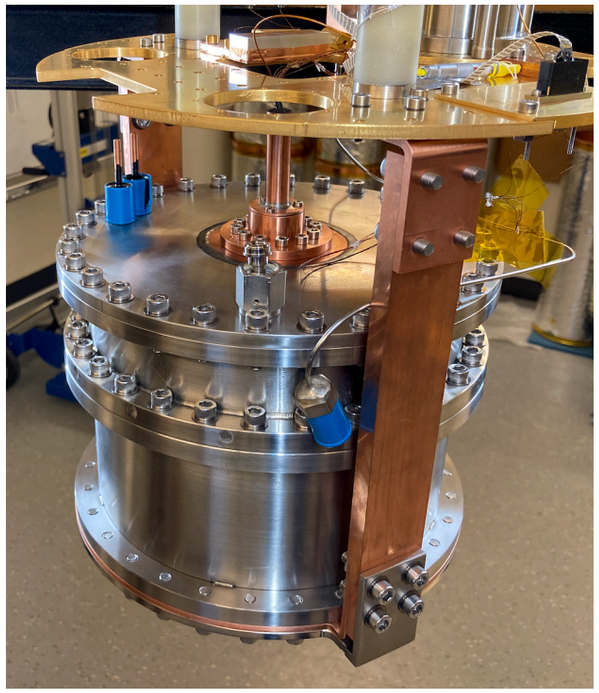
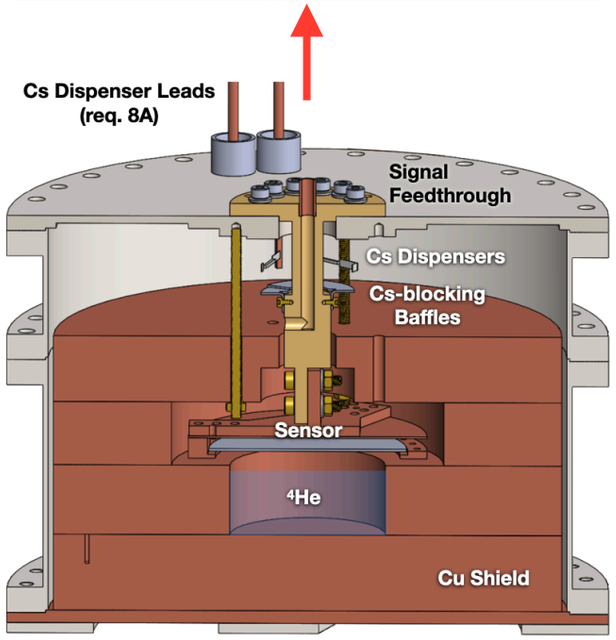
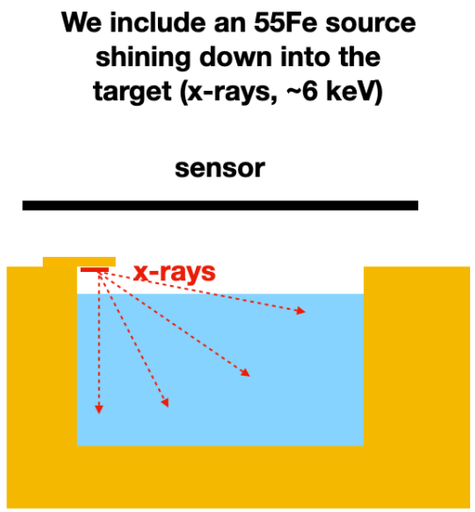
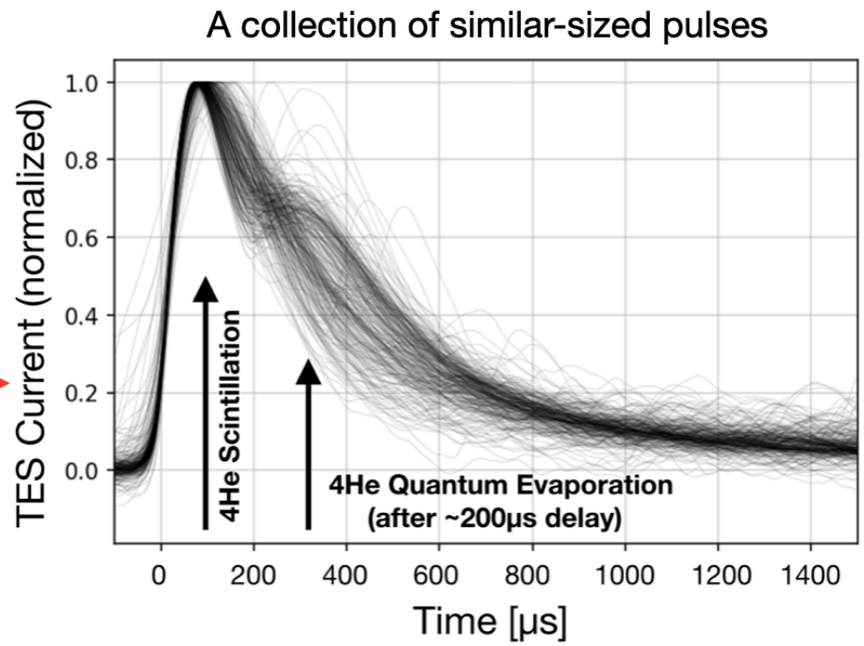


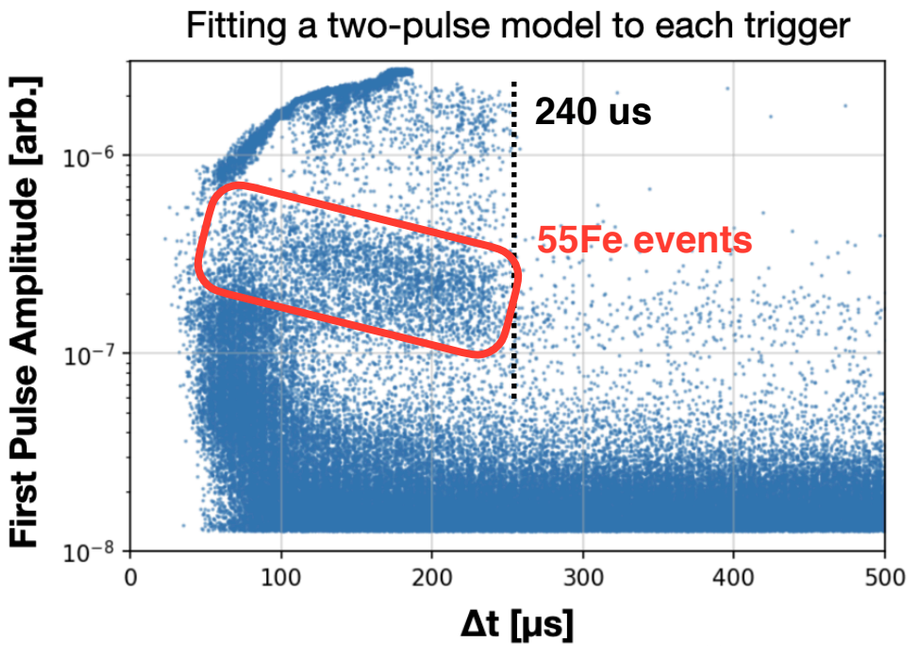




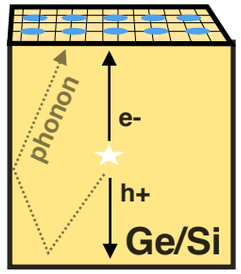


First experimental results !

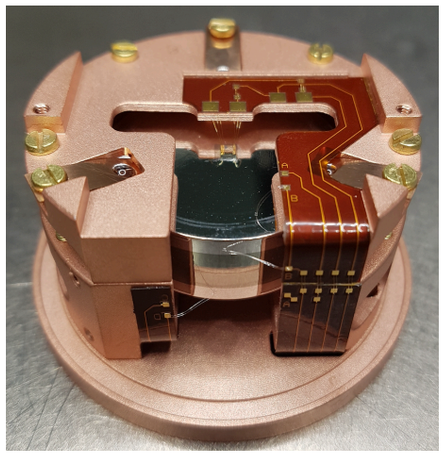
- Clear population of double-pulses at the energies we expect for 55Fe
- Broad distribution in Δt out to a ‘cliff’ of ~240μs (2cm, R+ 100m/s)
- Anti-correlation seen as expected from solid angle (prompt smaller when Δt bigger)
- More data and new exciting results upcoming

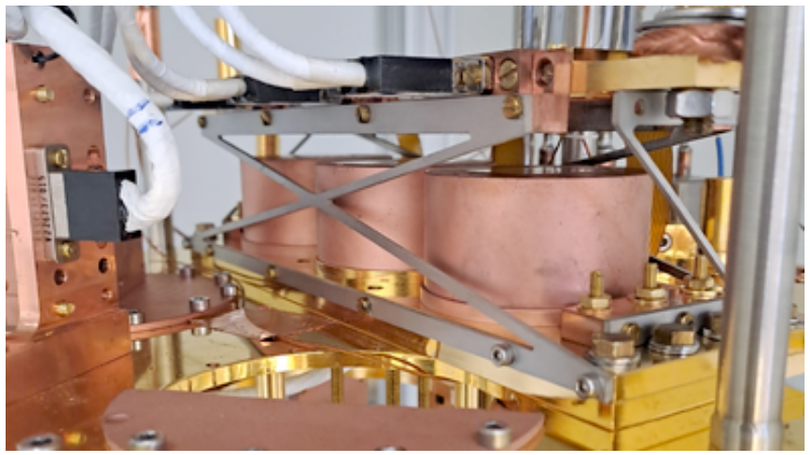


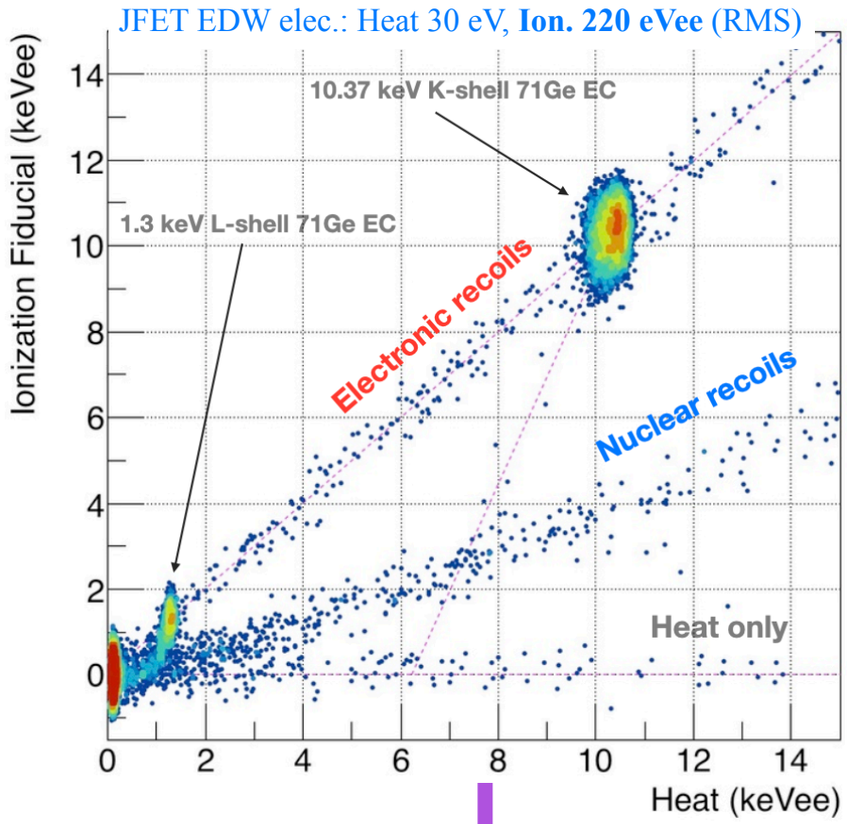
TESSERACT: *Ge/Si semiconductors*



***Low-Voltage* approach for optimal particle identification**







Ricochet resolution goals: 10 eV (heat) + 20 eVee (ionisation)

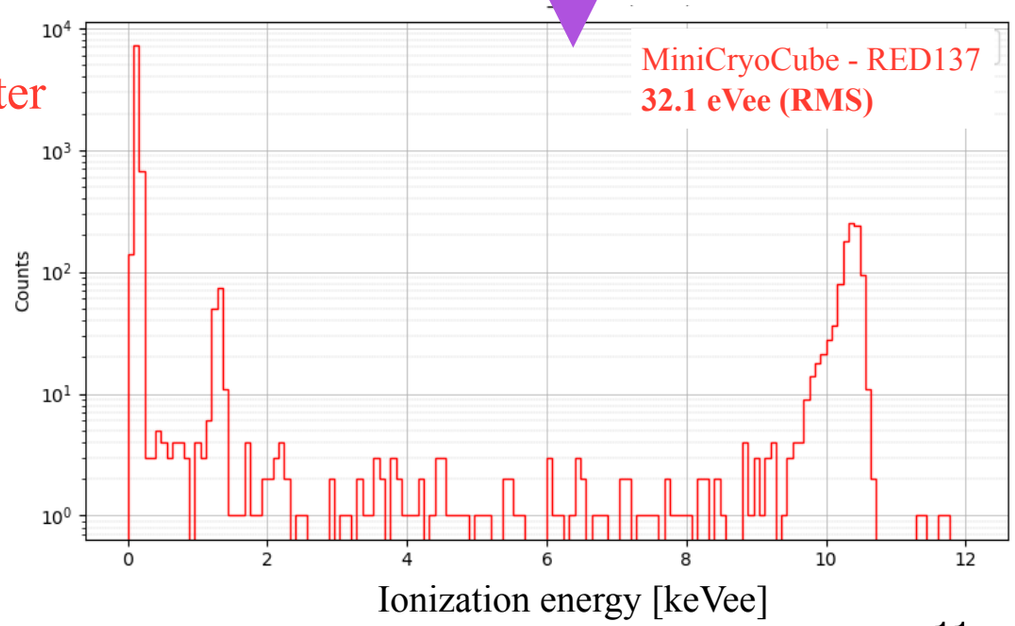
CryoCube array: 1K stage (HEMT elec.) and 10 mK (detectors + elec.)

Achieved:

- **Heat: 17 - 30 eV (RMS)**
- **Ionisation: 32.1 eVee (RMS)** ==> Improvement by ~7, already better than HPGe experiments, but with heat readout in addition !

For TESSERACT:

- Switch to TES for sub-eV heat energy threshold
- Modified geometry for 3-6 eVee (RMS) ionisation resolution
- ER/NR identification down to 10s of eVnr
- Heat Only discrimination down to 50 eVnr
- ***Particularly well suited for low-mass NRDM with PID***



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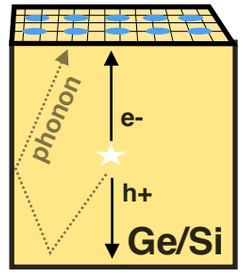
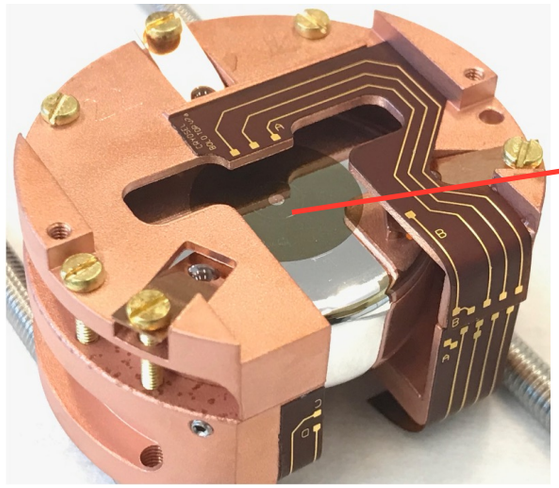
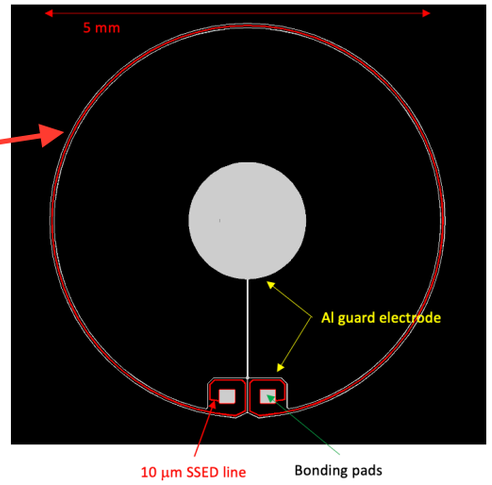
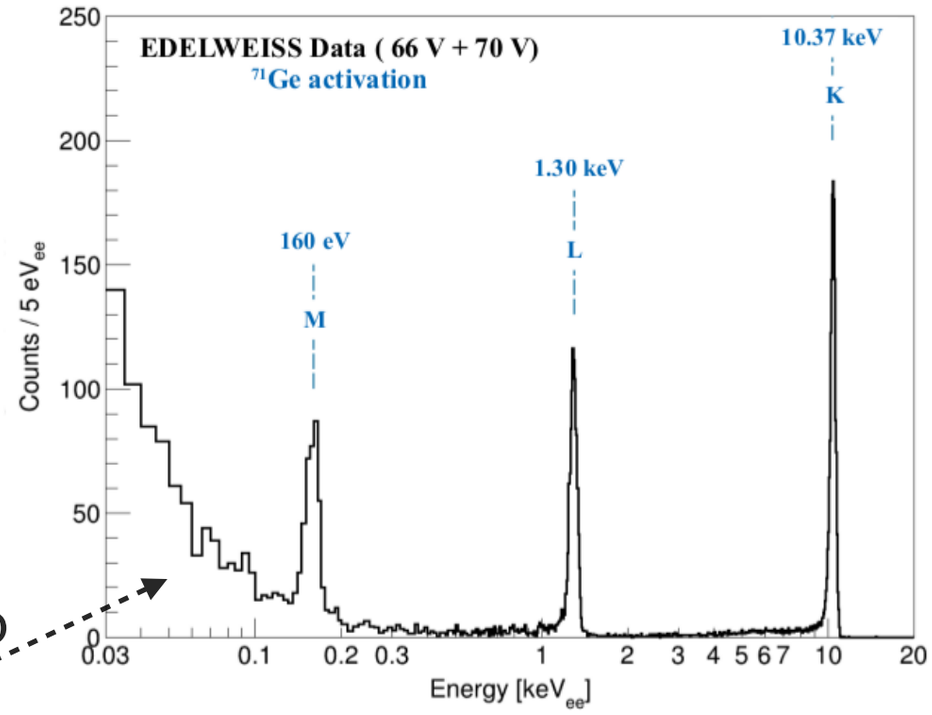


***High-Voltage** approach for optimal ERDM sensitivity*







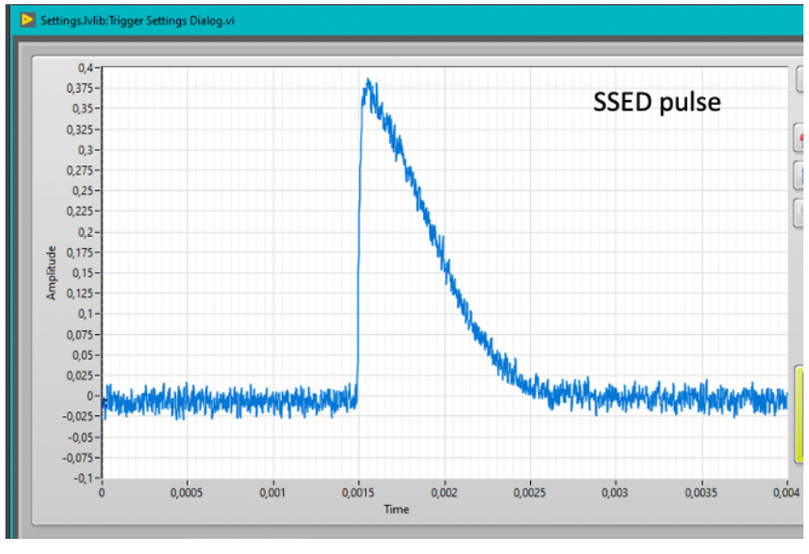
CRYOSEL performance goals: 100 V bias + single e-h sensitivity + SSED
Heat Only tagging efficiency > 1000

First R&D results:

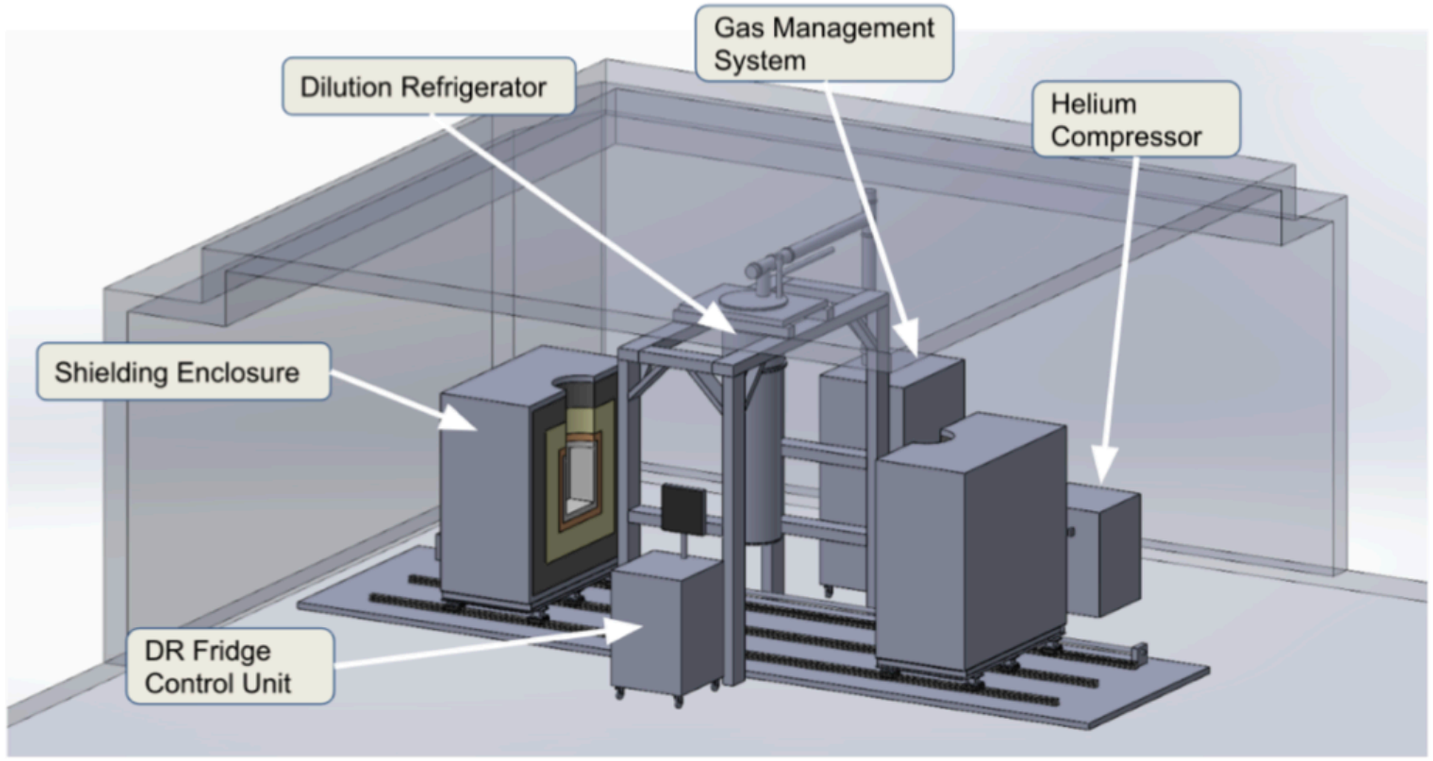
- Stable operation up to 70 V
- Clear pulses from the SSED (NbSi TES) acting as a Heat Only veto
  - *single e-h sensitivity with no sensitivity non ionising events*

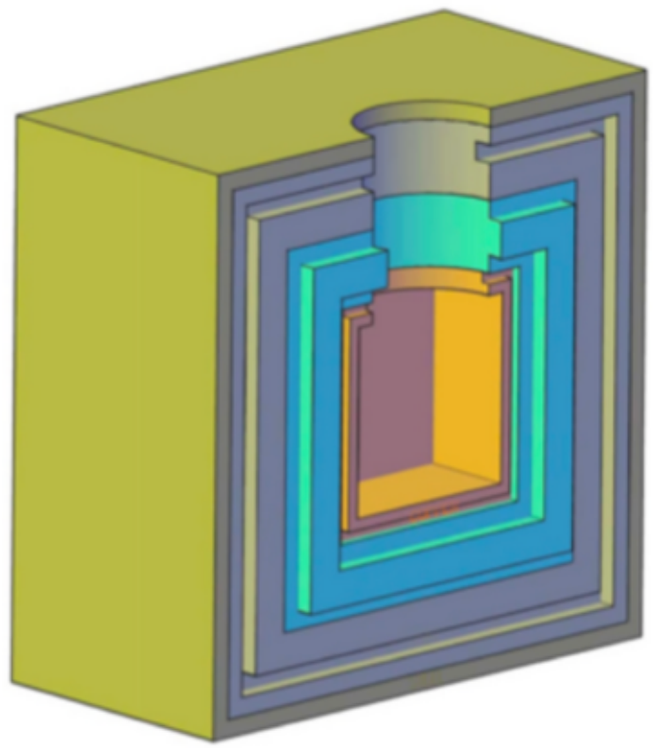
For TESSERACT:

- Switch to low-imp. TES heat sensor for sub-eV heat energy threshold
- High control of IR backgrounds and charge leakage
- Heat Only discrimination down single e-h pair (3 eV)
- ***Exquisite sensitivities to ERDM with Heat Only discrimination***



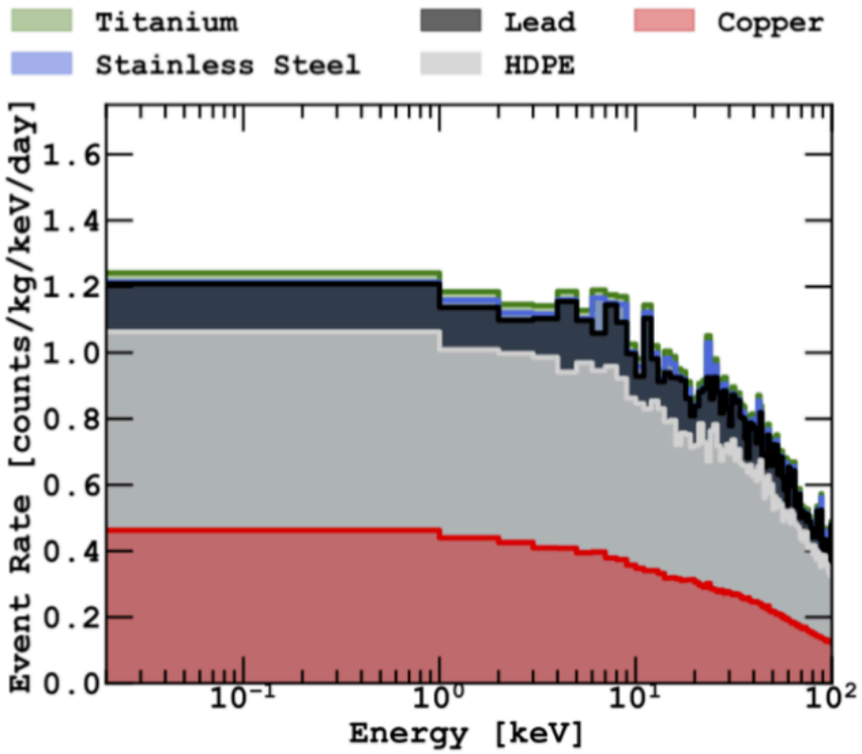
TESSERACT: *Proposal for an installation at LSM*

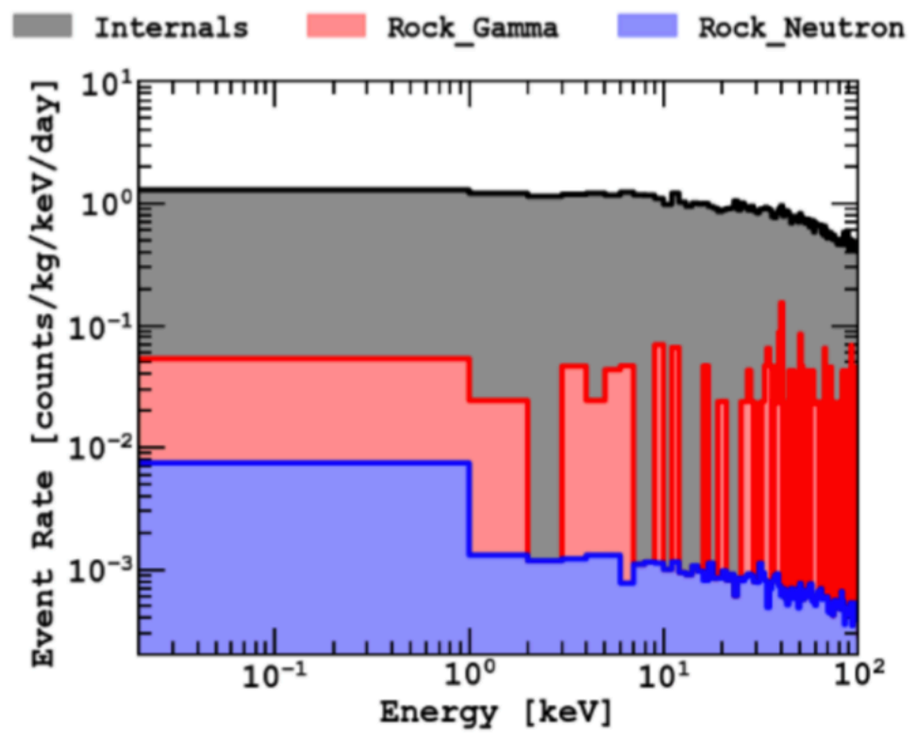




- The experiments will be operated in an underground lab — ***Discussions are just beginning with underground labs***
- The shielding design has converged on a compact lead/polyethylene approach.
  - Shielding will come off on rails so as to enable quick and straightforward access to the cryostat.
  - There will be two copies of the setup, for enabling both 1) underground R&D and detector optimisation, and 2) DM science data taking in parallel
- Significant emphasis on vibrational and EM noise suppression.
- Integration of dedicated low energy NR and ER calibration sources

TESSERACT: *Proposal for an installation at LSM*



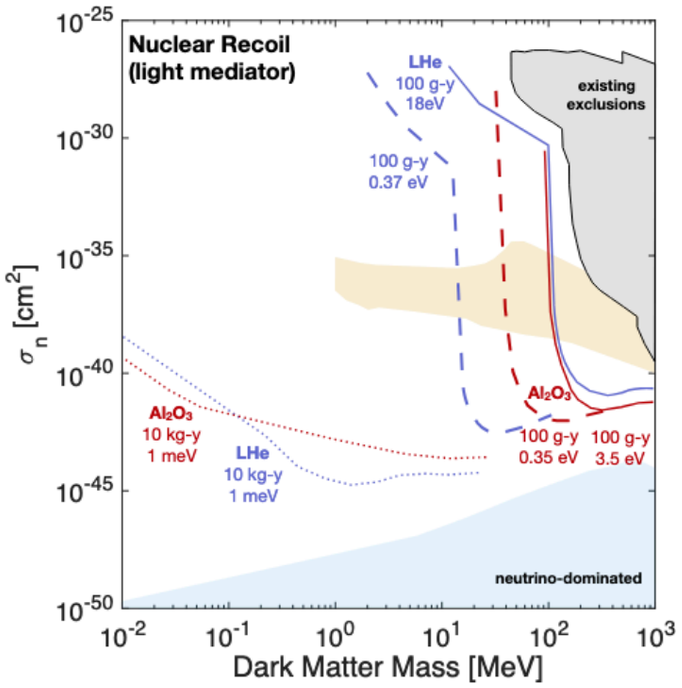


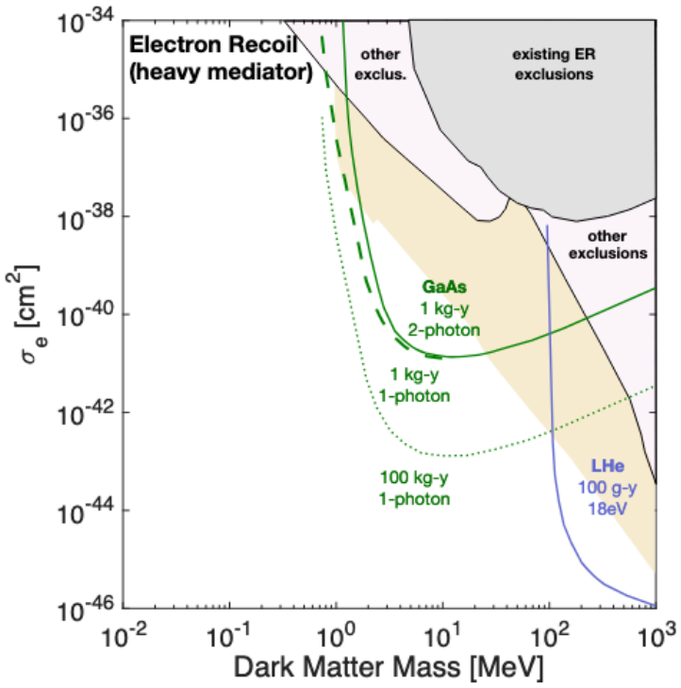
- Simulation based on **rock composition & density** of the Homestake mine
  - Simulated background events for external γ (n) from ^{238}U & ^{232}Th chains
  - Neutrons from (α,n) and spontaneous fission in cavern walls
- Internal backgrounds modelled using **measured activities** in **Ti, SS, Cu & PE** by LZ, SuperCDMS and others
- Total background dominated by internal background with a **total rate of 1.2 DRU at 1 keV**
- Further background reduction possible using event multiplicity and **surrounding cryogenic active vetos**

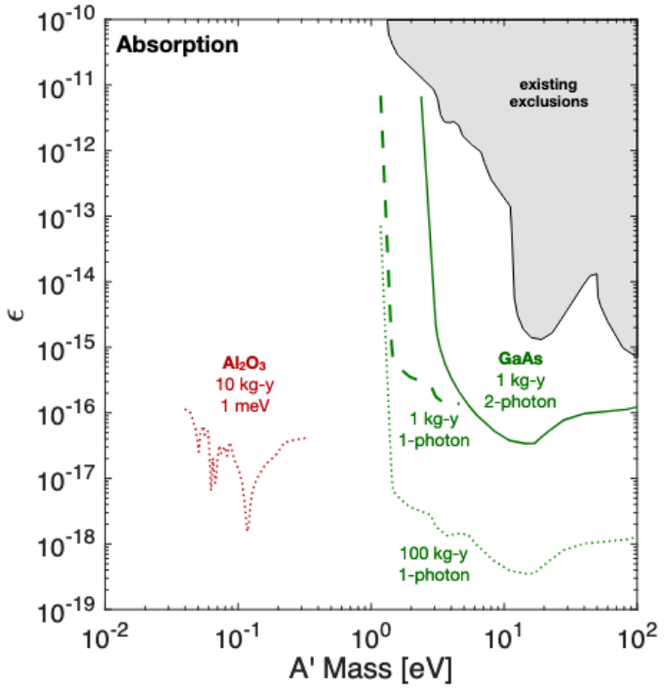
TESSERACT: *Proposal for an installation at LSM*

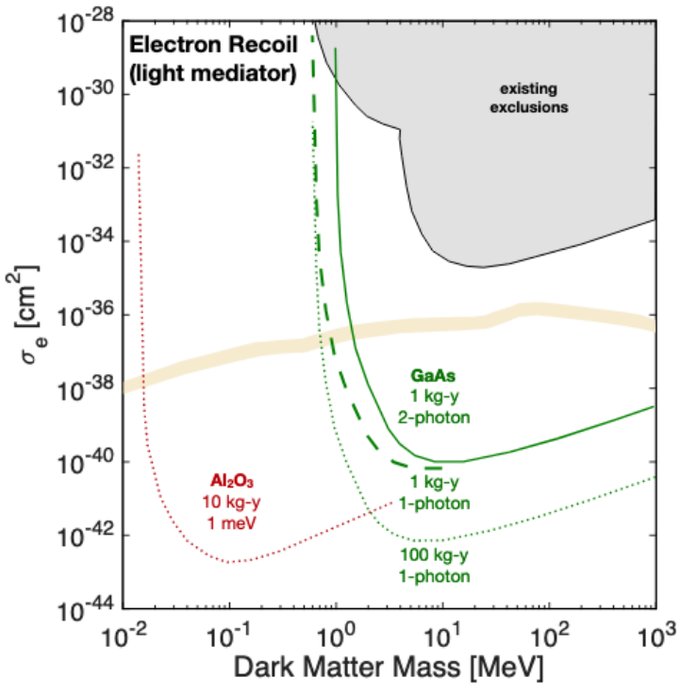
Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project

TES sensitivity:
Solid — Achieved
Dashed — Targeted
Dotted — Ultimate



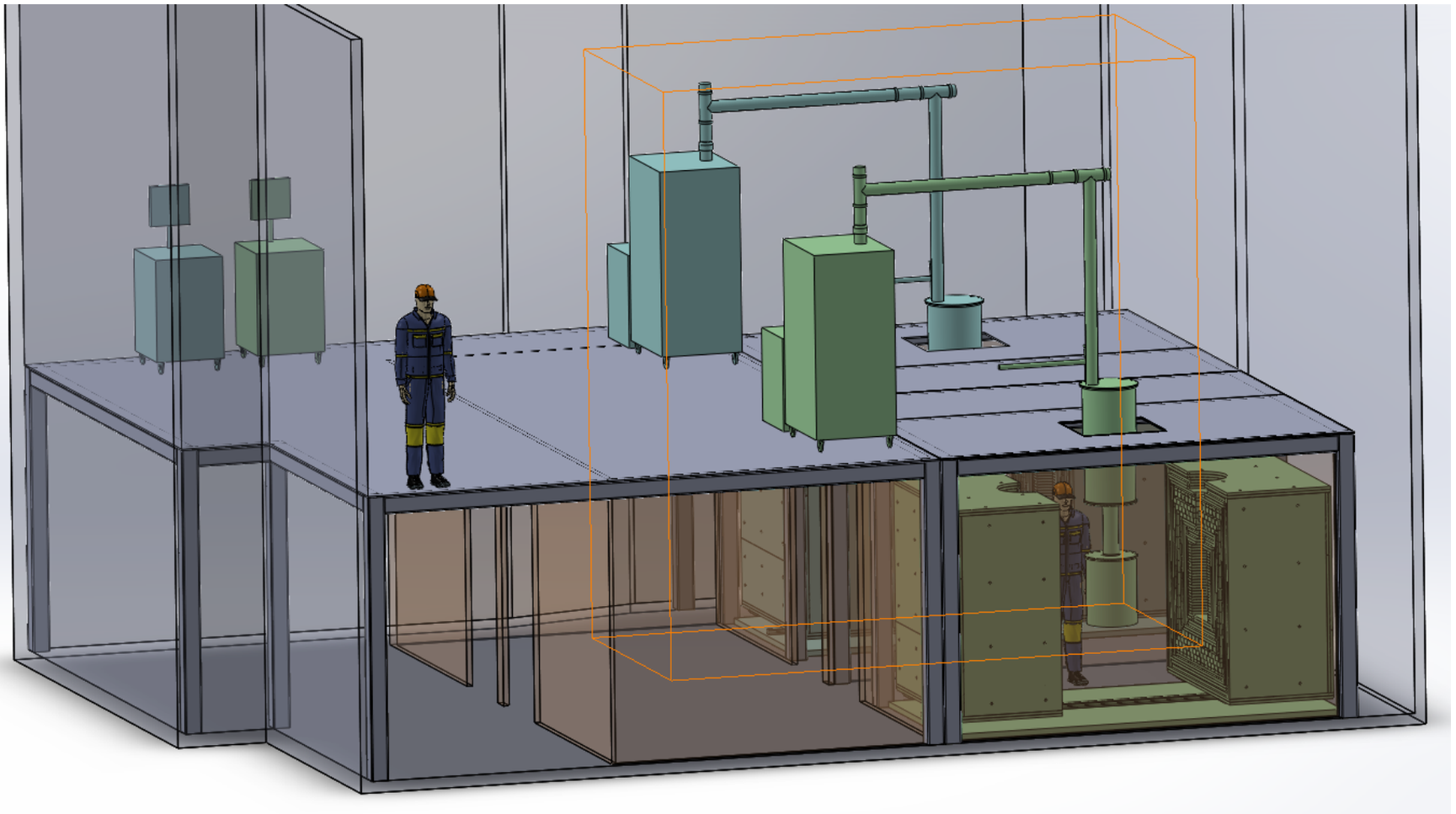


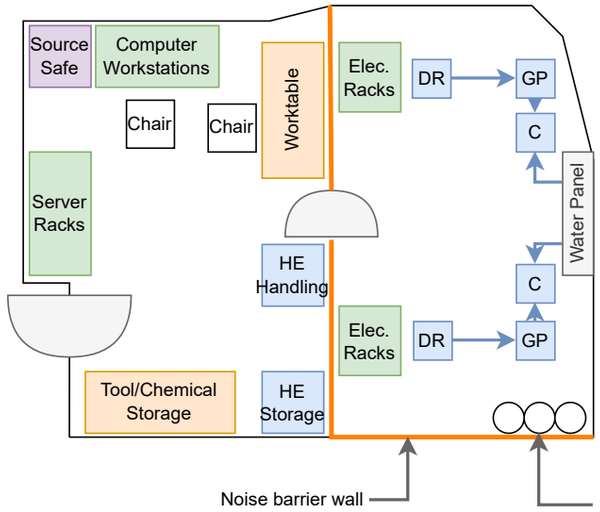


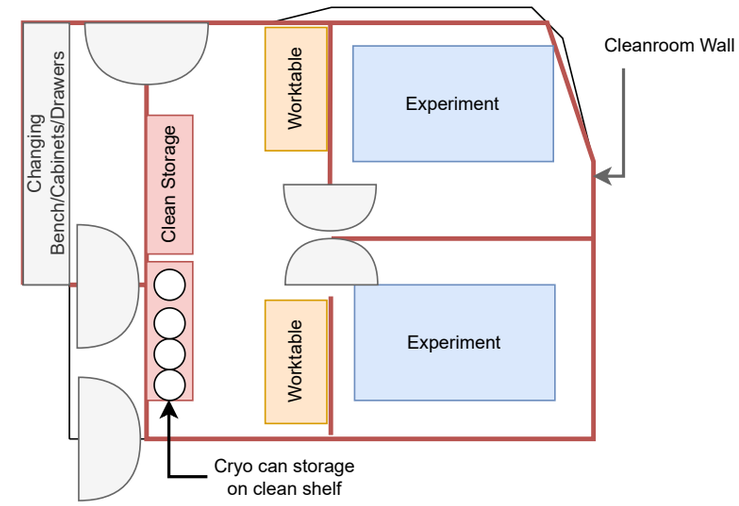


Ge/Si sensitivities under calculations

TESSERACT: *Proposal for an installation at LSM*







TESSERACT@Modane:

Extending the Dark Matter mass search window from meV-to-GeV with **ultra low-threshold cryogenic detectors** with **multiple targets** and **particle identification capabilities** with two identical cryogenic setups installed in the **ultra-low background environment from the LSM**

Back up

TESSERACT: *Energy calibration*

Dedicated low energy and mono-energetic neutron source

- 24 keV photo-neutrons from ^{124}Sb-^{9}Be
- Iron cross-section dip at 24 keV neutrons
- 3-GBq Sb produced at nuclear reactor
- Currently being characterised
- Also the possibility to use a DT generator *à la Ricochet* as the source of primary neutrons to be down-converted
- Compton scattering from 57-Co for low-energy ER calibration