TESSERACT @ LSM

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

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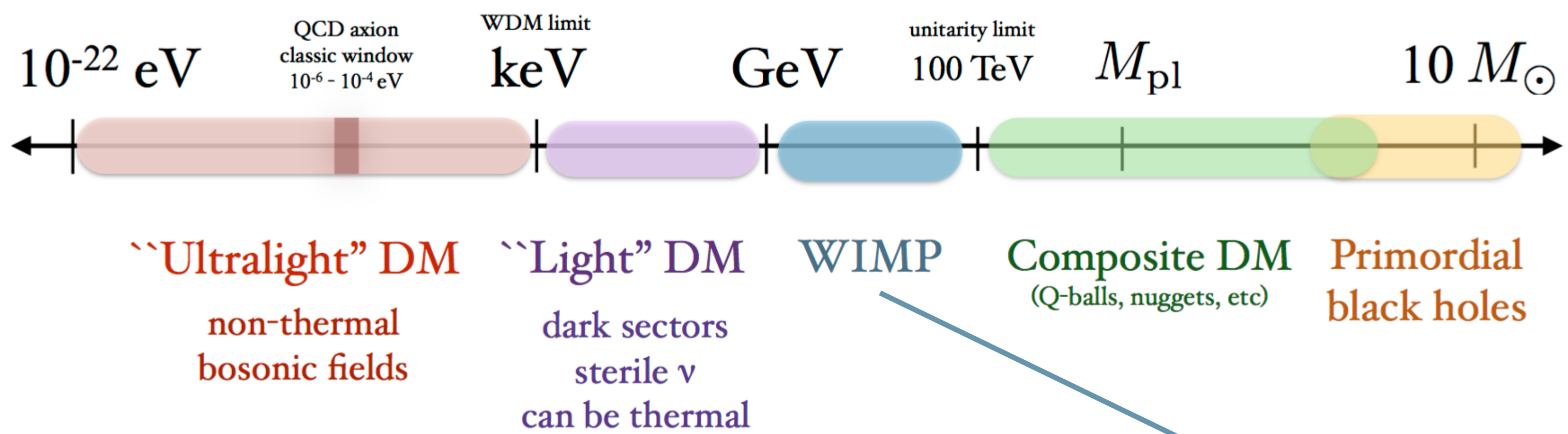
Institut de Physique des 2 Infinis de Lyon / CNRS / Université Lyon 1

GDR DUPhY, June 21st, 2023

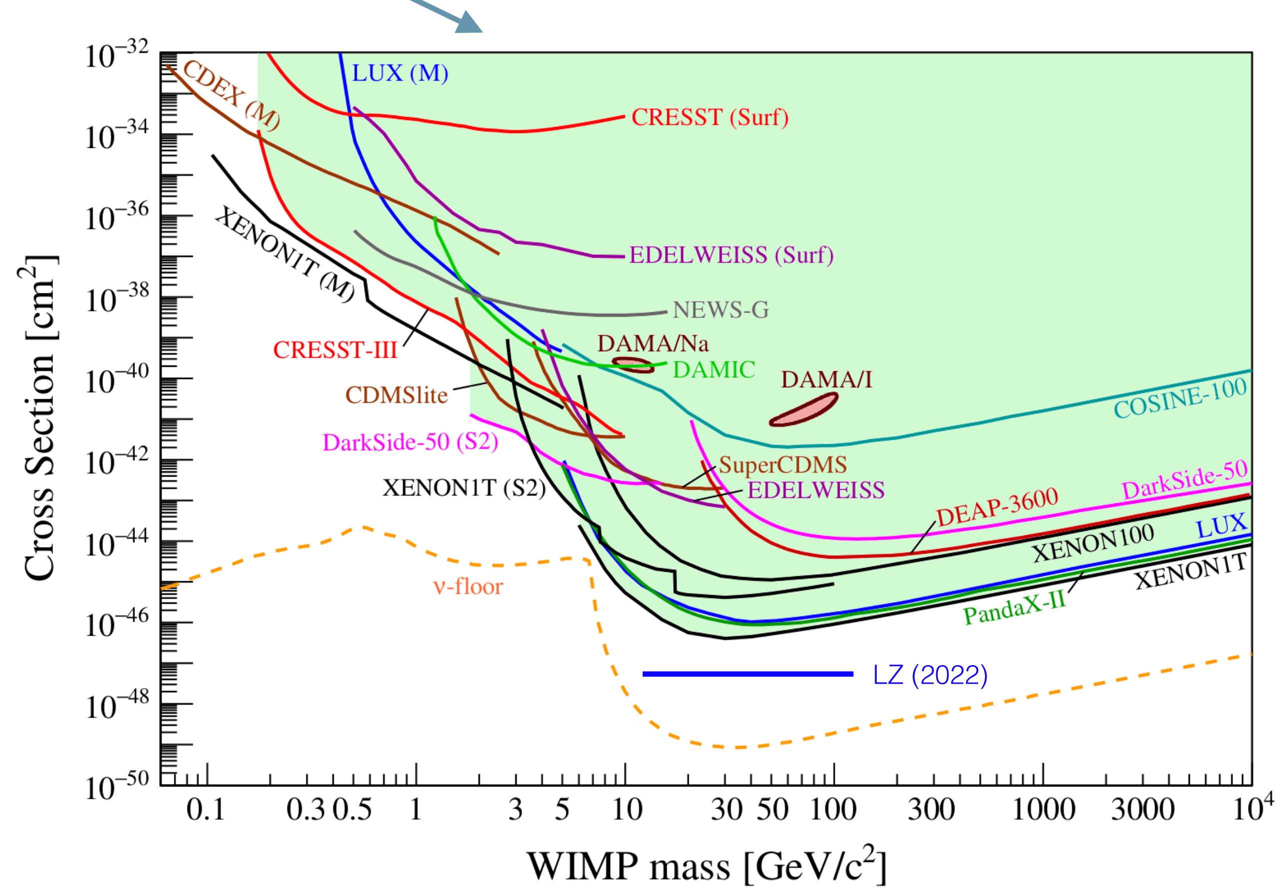
TESSERACT: *Dark Matter candidates*

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

Courtesy: T. Lin

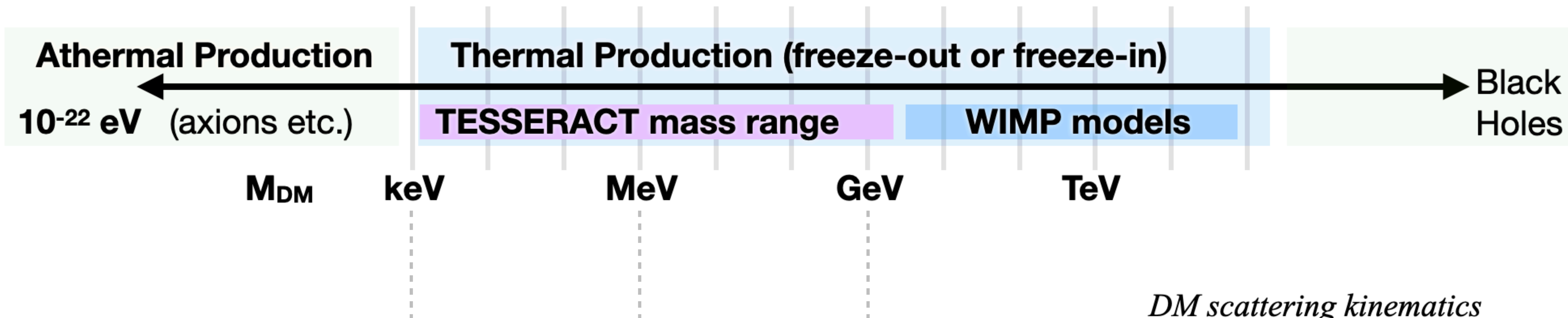


- Focus of DM searches for the last decades has been on axion DM (ueV - meV) and the standard WIMP (10 GeV - TeV)
- The standard WIMP case *« was »* highly motivated thanks to the so-called WIMP miracle and the SUSY predictions
- After few decades, still no DM signal and ongoing or planned ton-scale 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 !***



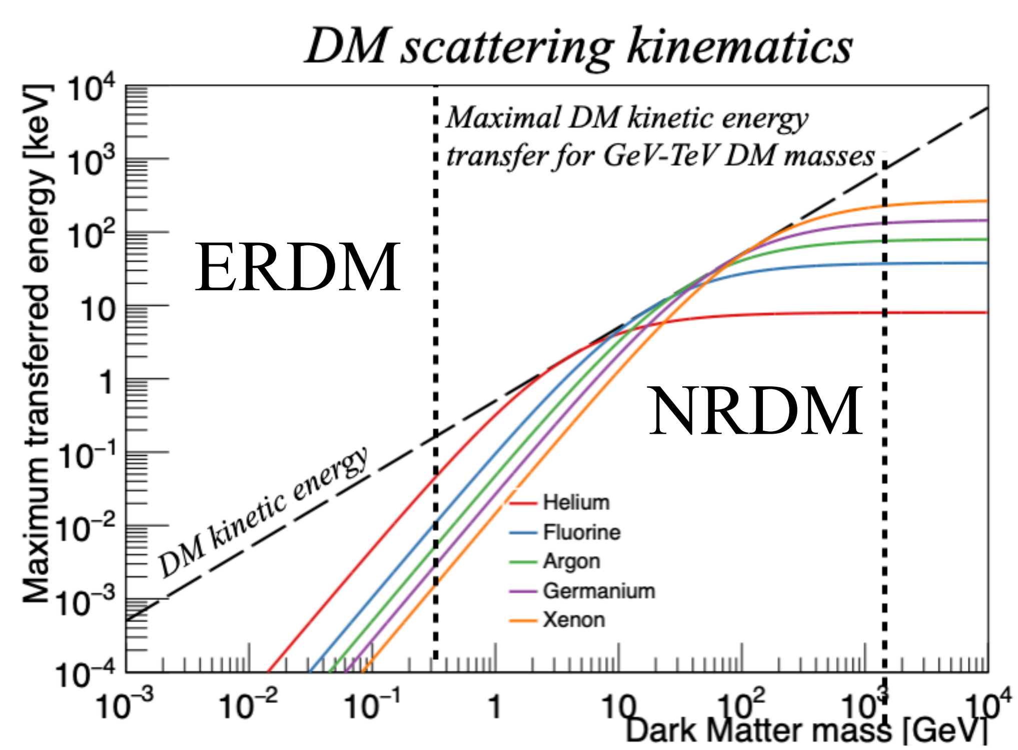
TESSERACT: *keV-GeV « light » Dark Matter*

- 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)

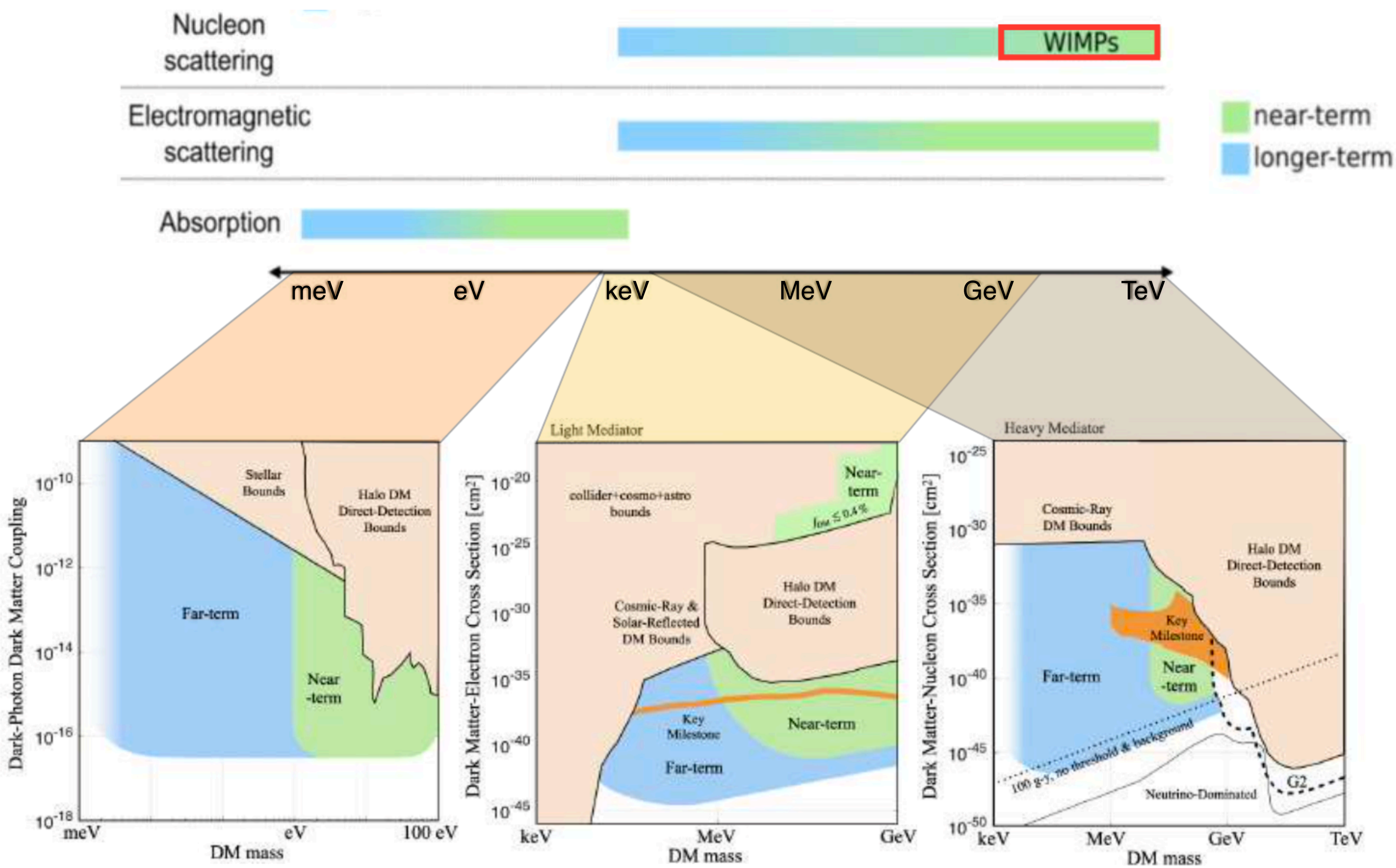


	keV	MeV	GeV
Nuclear recoil end-point:	~neV	~meV	~keV
Electronic recoil end-point:	~meV	~eV	~keV

- 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*

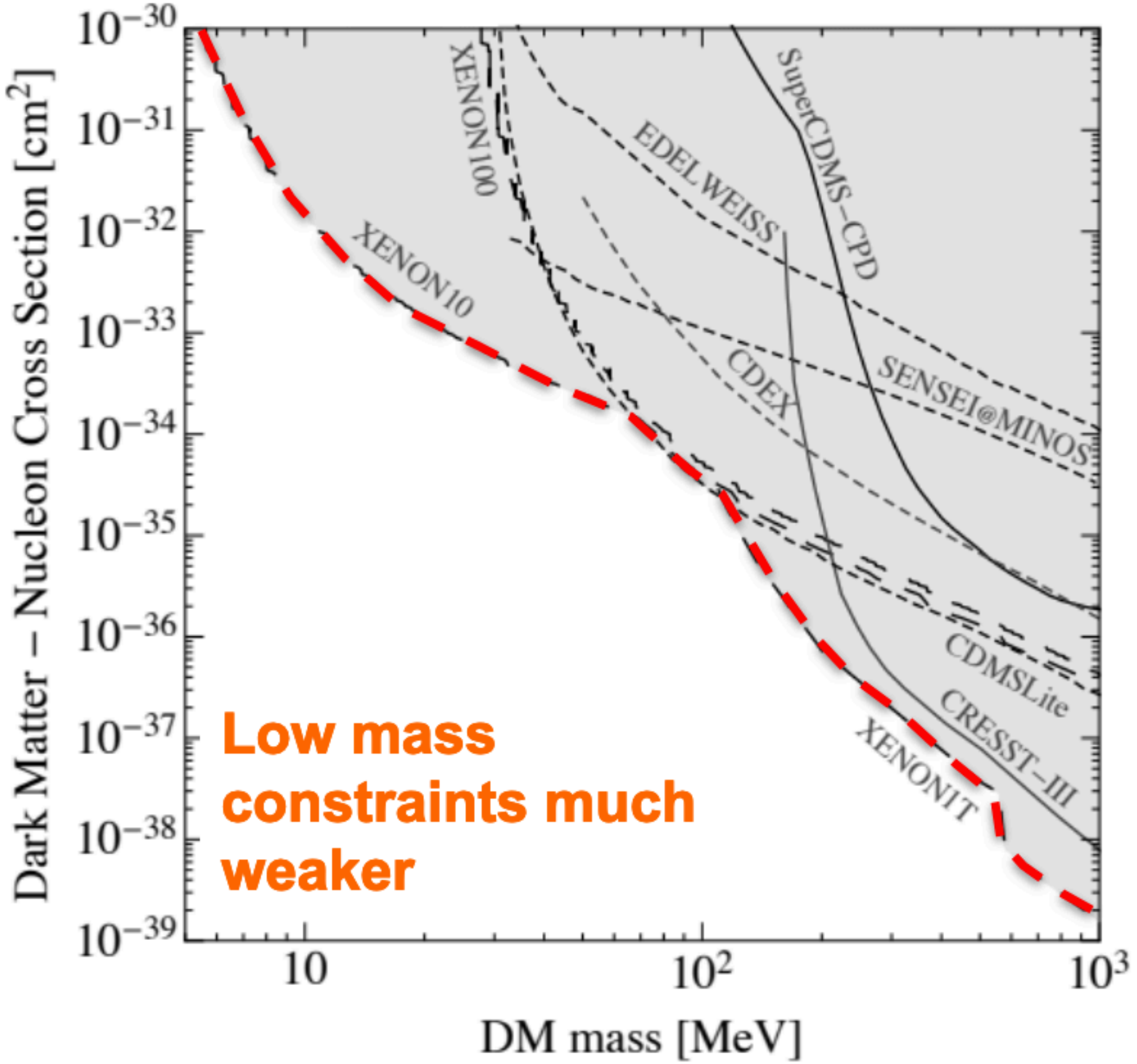


TESSERACT: *Dark Matter search range*



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: *State of the art (NRDM)*



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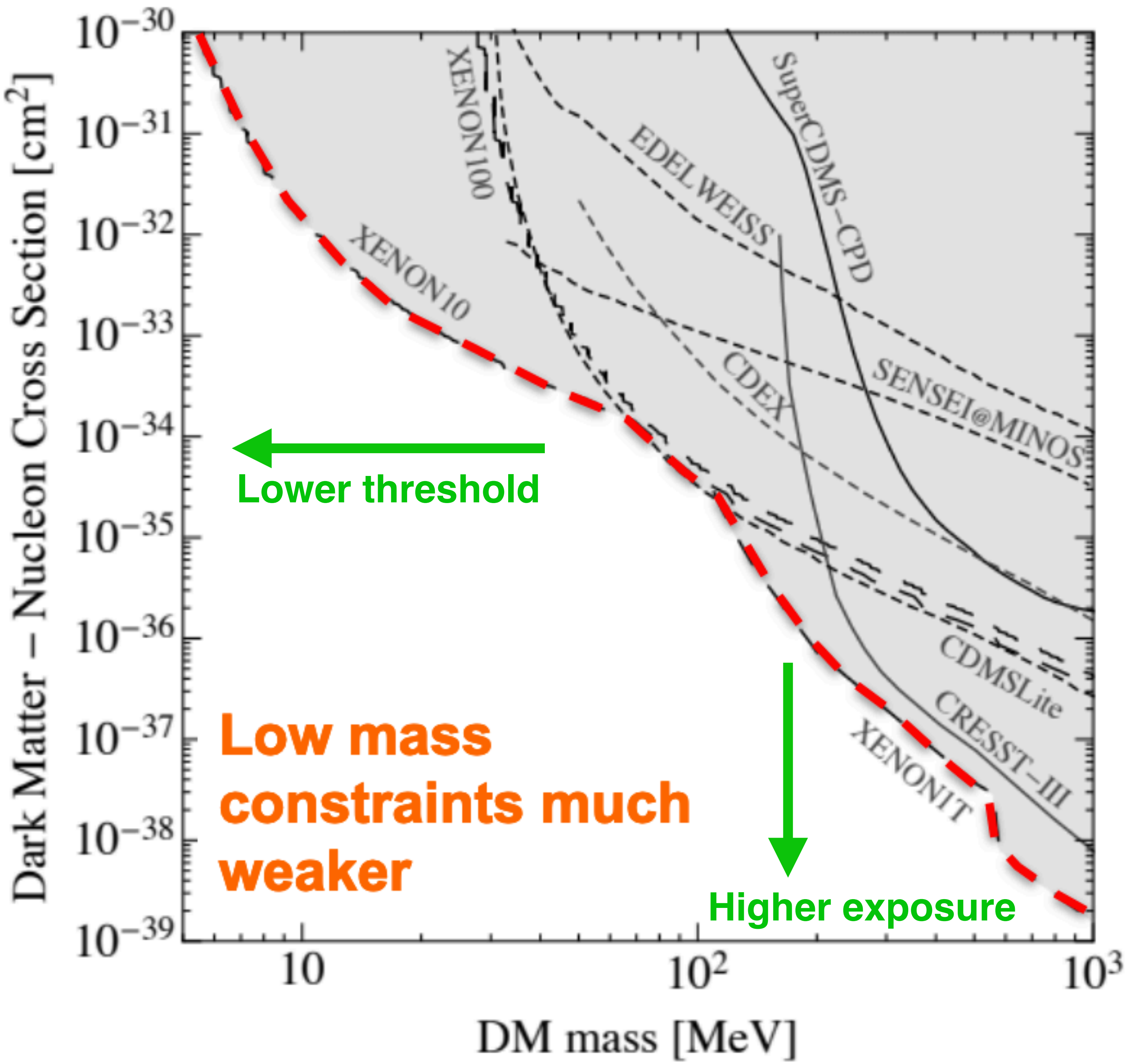

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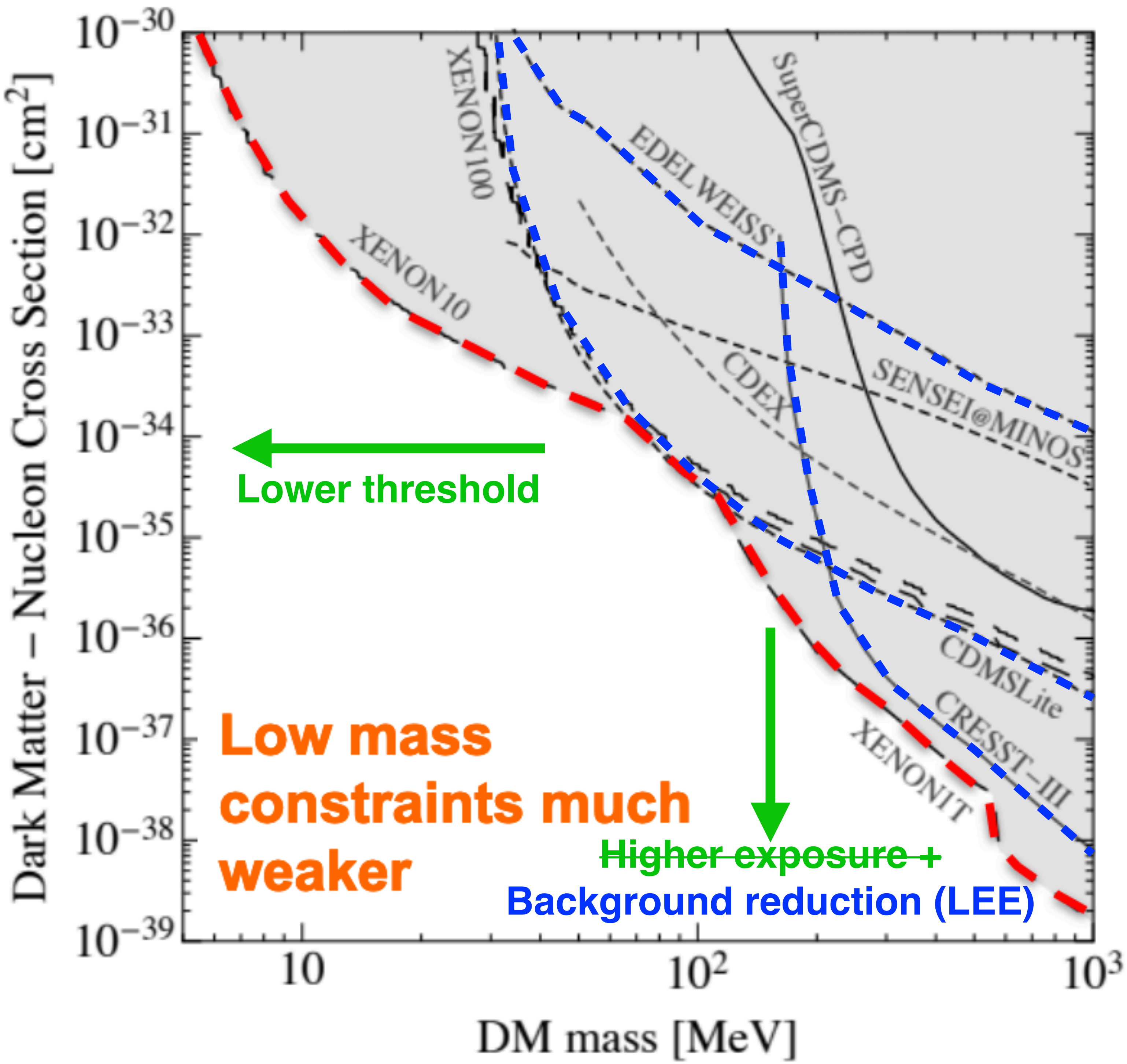
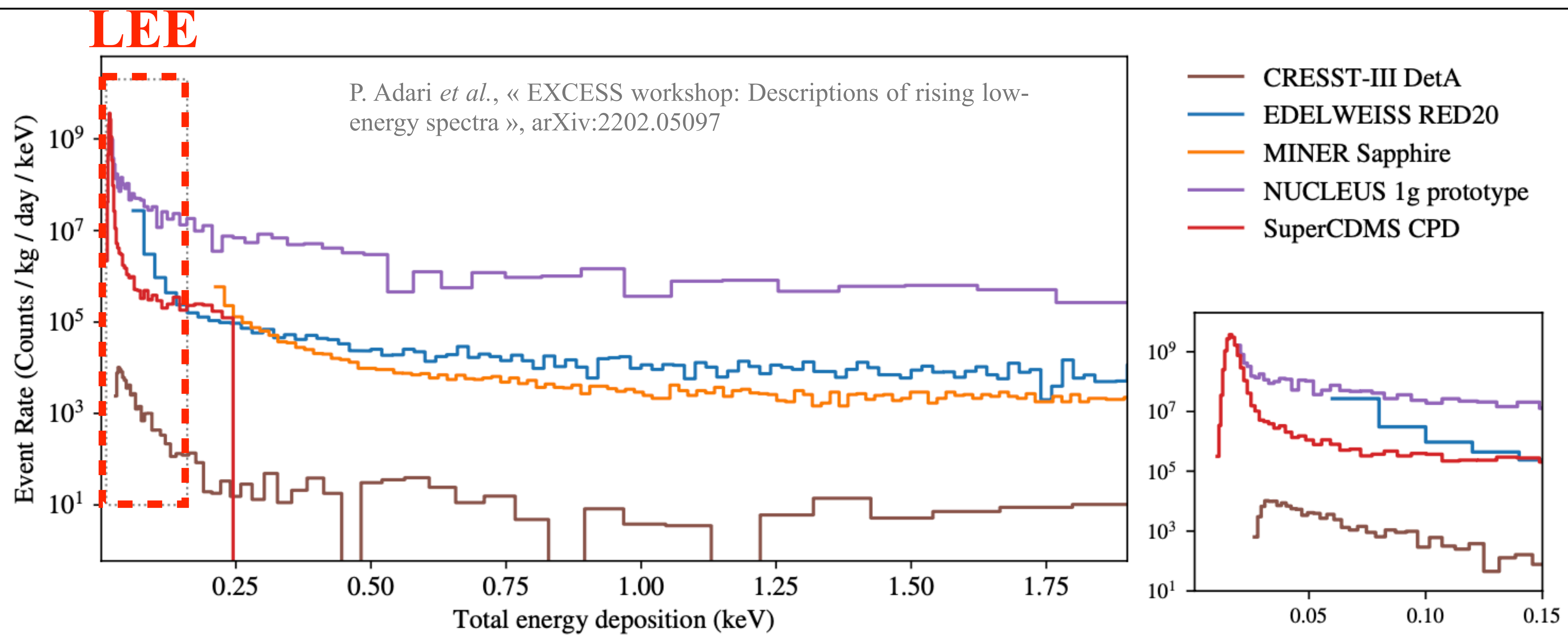


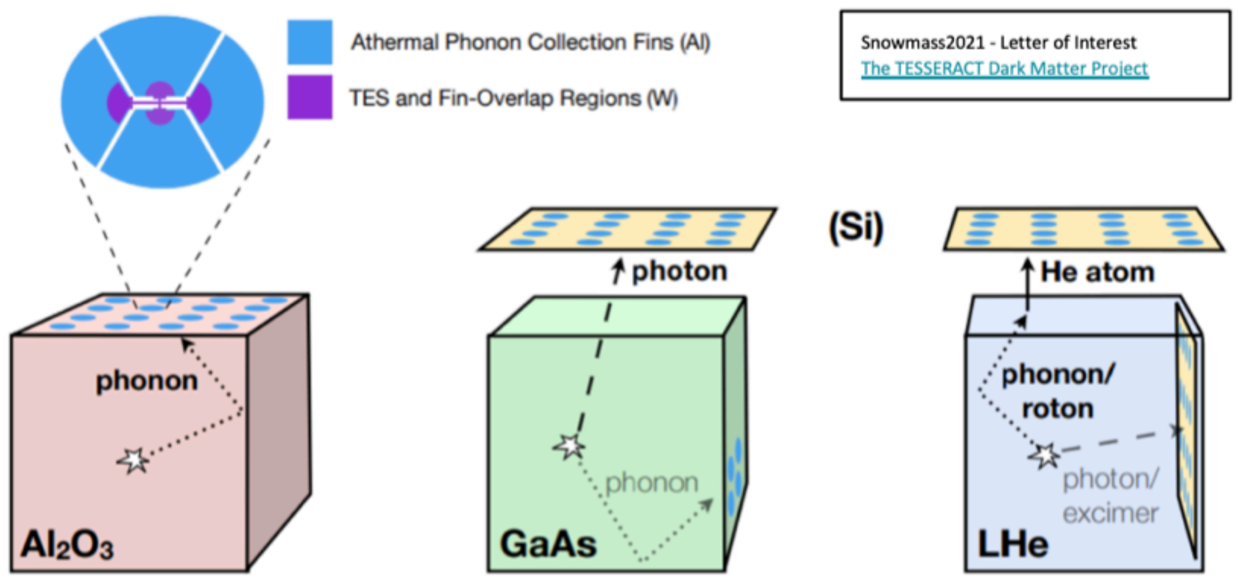
CENNS: *Cryogenic experiments — Low-E excess !*



- Currently, all cryogenic experiments which have reached sub-100 eV thresholds are seeing such an excess
- **This excess is nowadays fully acknowledge by the international community** and a dedicated workshop has been created to exchange ideas and results with experimentalists and theorists (https://indico.cern.ch/event/1013203/)
- Characteristics: time dependent, non-ionising, independent of sites, dependence with holding techniques (?)
- **Design driver of TESSERACT: Chose methods to reject LEE**

TESSERACT: *Proposal experiment at LSM*

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**

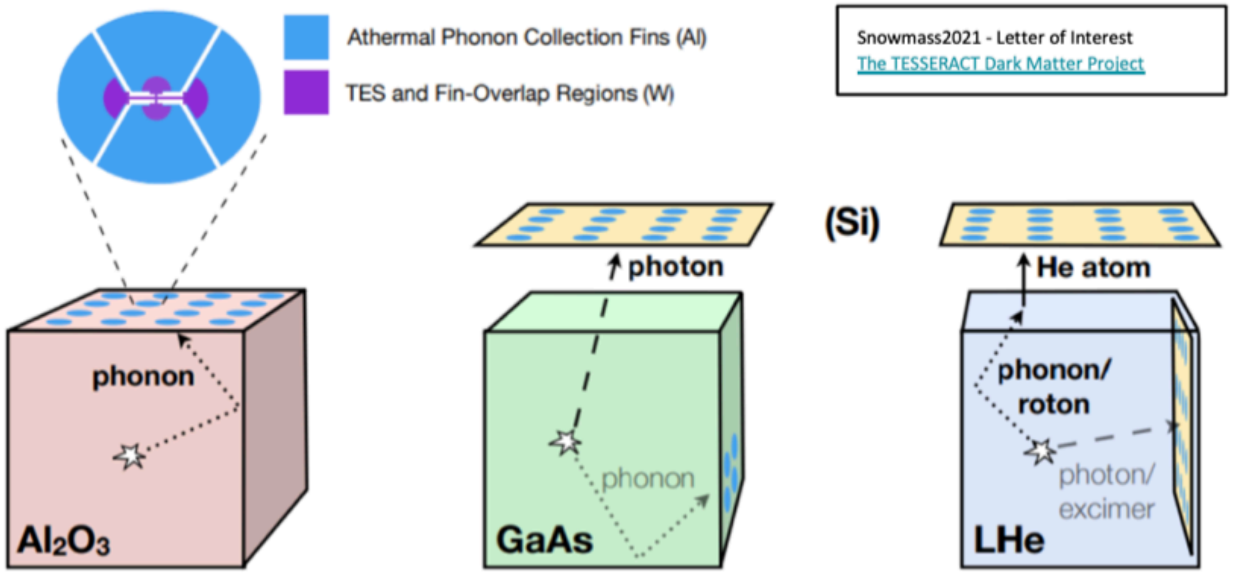
Berkeley Lab · Berkeley University of California · Caltech · Florida State · Texas A&M University · University of Michigan · Argonne National Laboratory · UMass Amherst

TESSERACT: *Proposal experiment at LSM*

TESSERACT

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets

Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project



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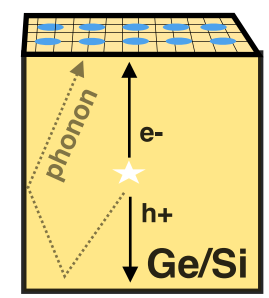
TESSERACT @ LSM



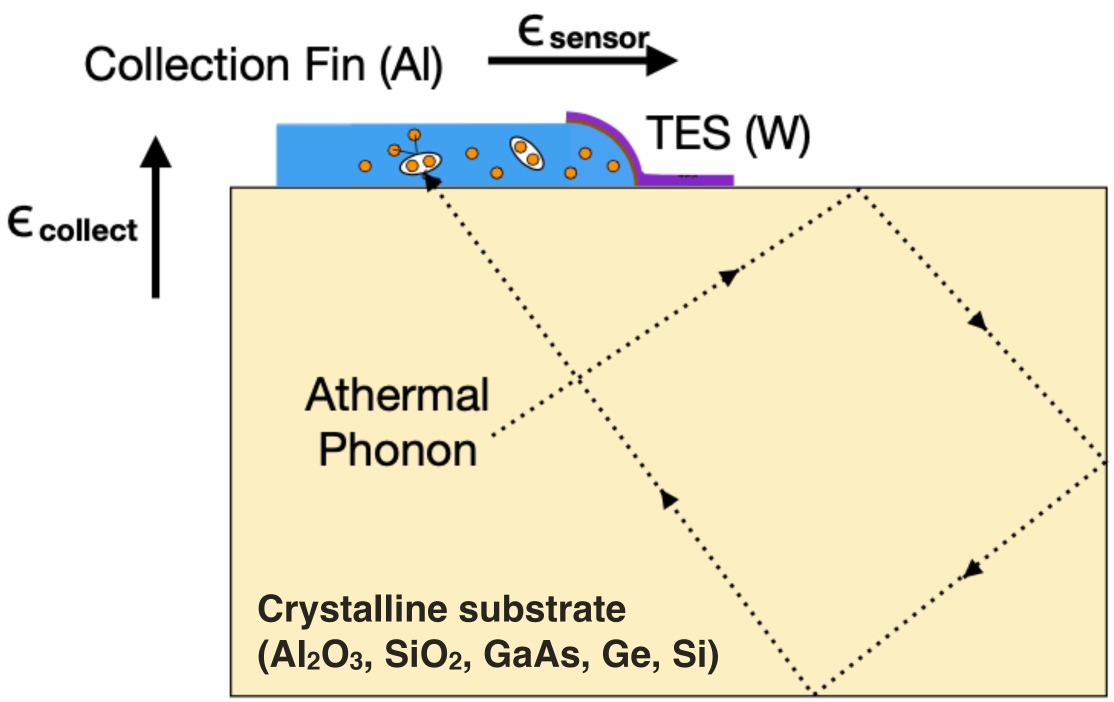
LSM

- 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**

iP2i Les 2 Infinis Lyon, IJCLab Irène Joliot-Curie, LPSC Grenoble

TESSERACT: *New generation TES phonon sensors*

TES based athermal phonon sensor technology:

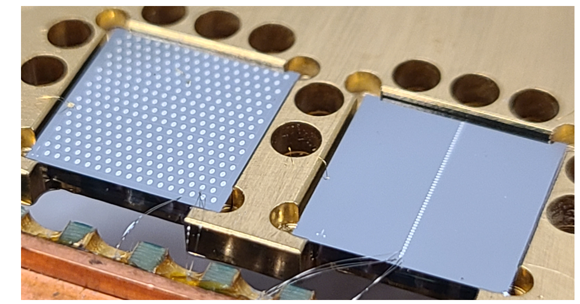


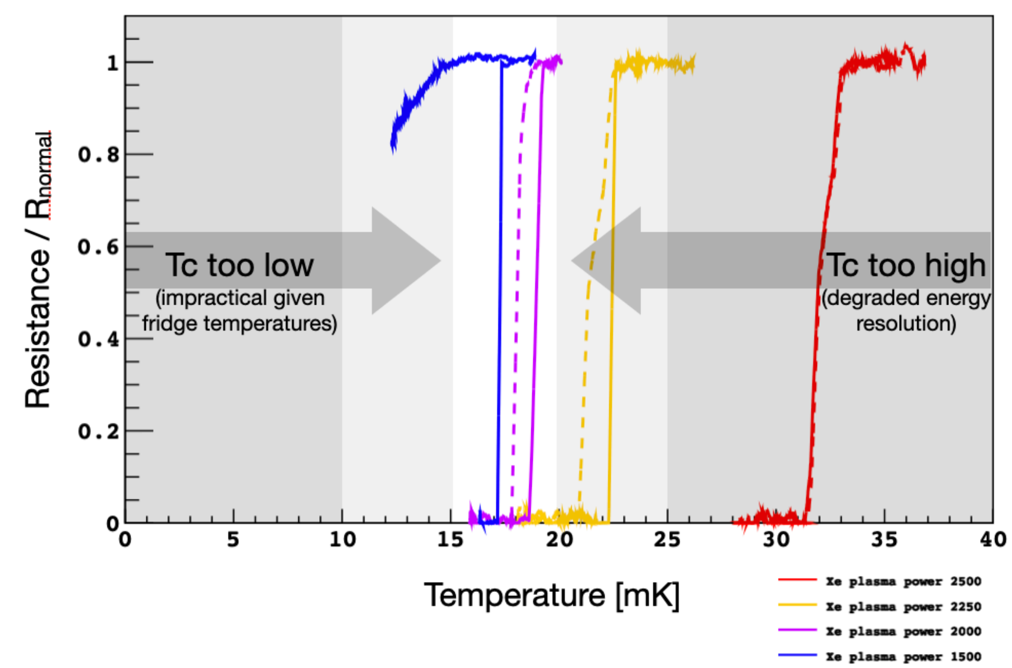
$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

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

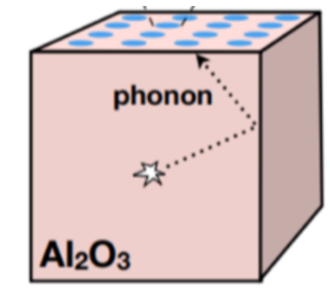
Energy threshold decreases with detector mass

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



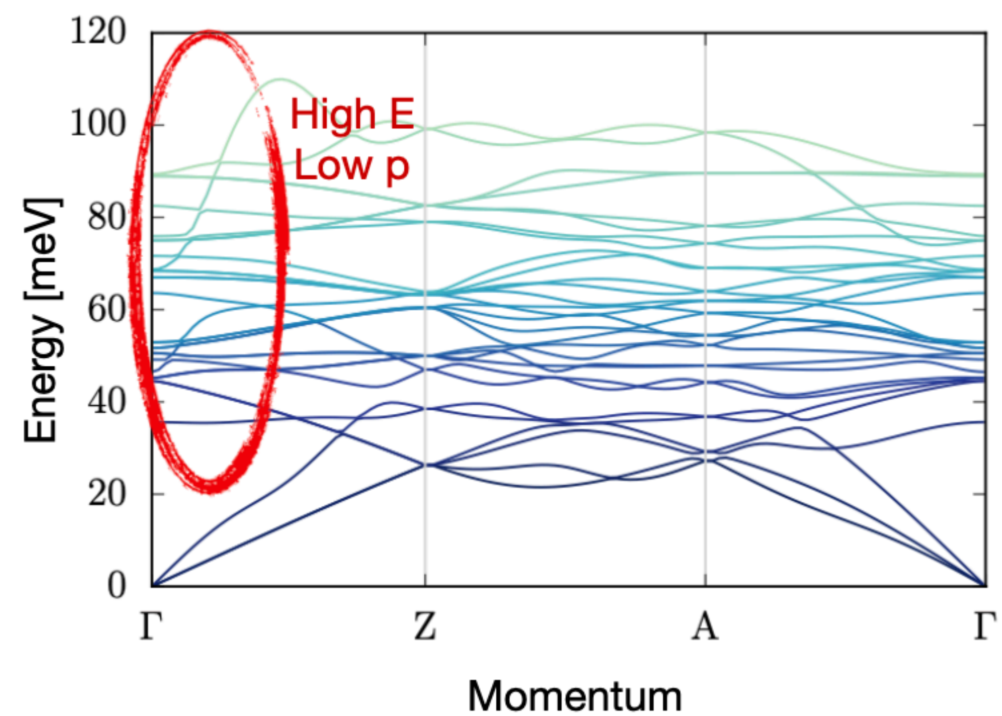
TESSERACT: *SPICE*

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

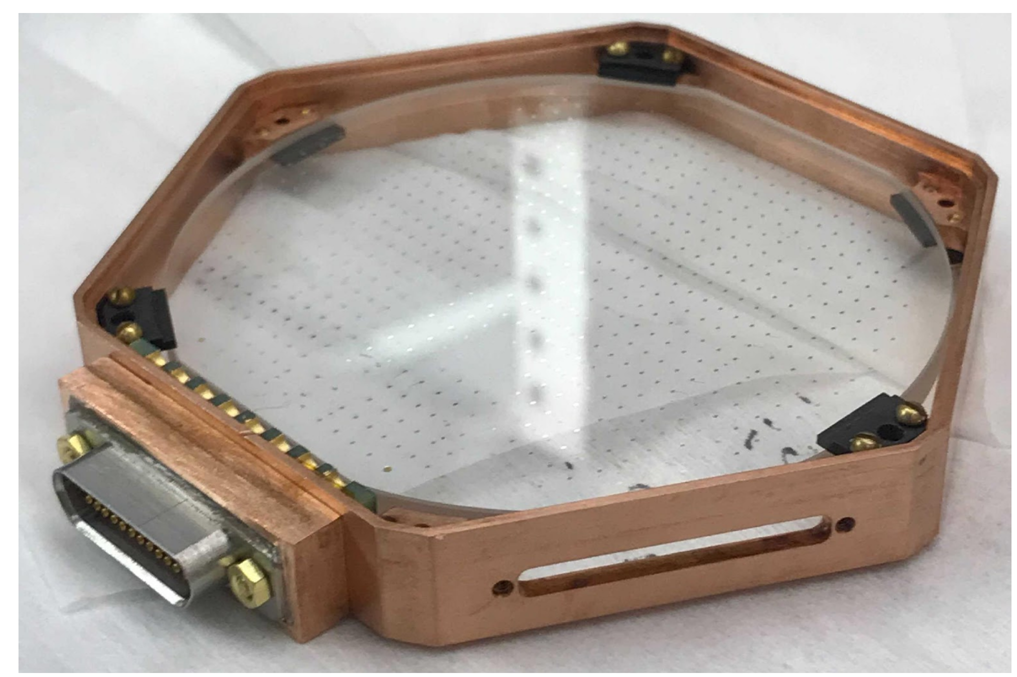
Optical phonons are kinematically well-matched to low-mass dark matter (similar effective mass)



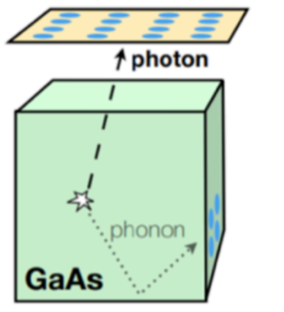
2. Sapphire is a polar crystal
(couples well to E&M-like inputs)

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

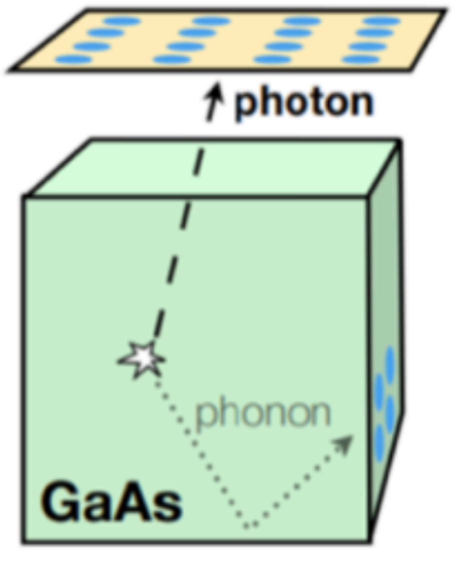
Possibility to extend further down to 100-meV (eV) DM masses thanks to absorption on phonon (electron)

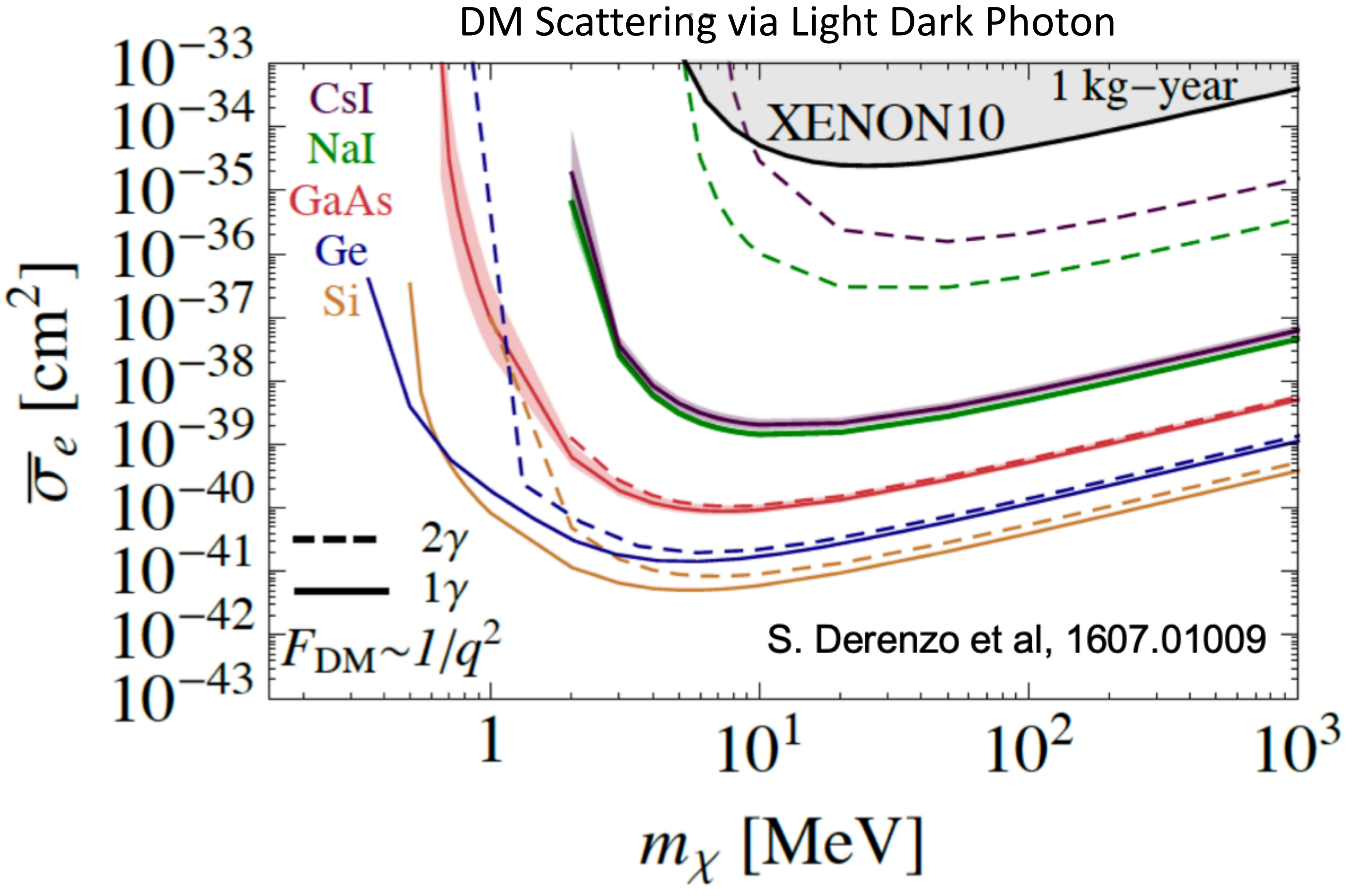


TESSERACT: *SPICE*



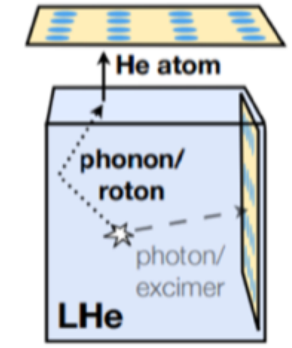
<u>S</u>ub-eV <u>P</u>olar <u>I</u>nteractions <u>C</u>ryogenic <u>E</u>xperiment: GaAs



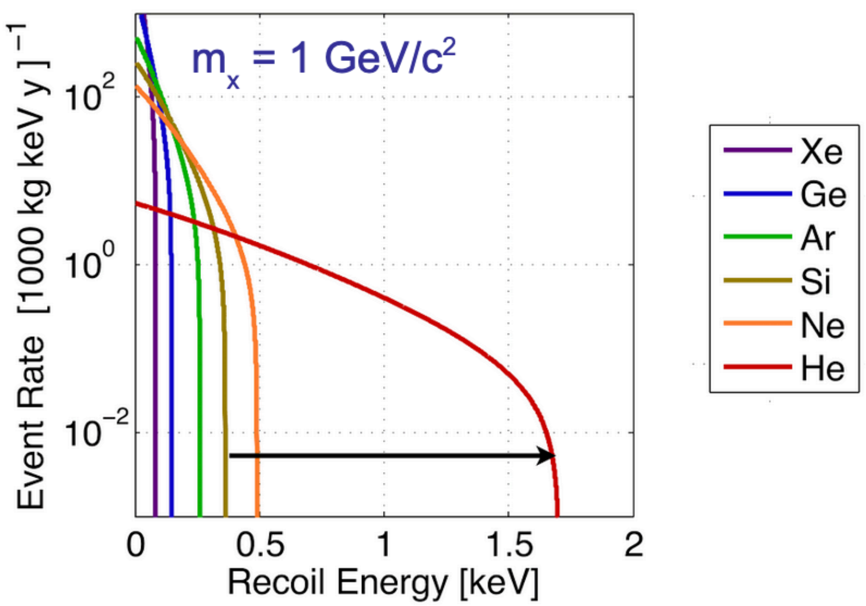


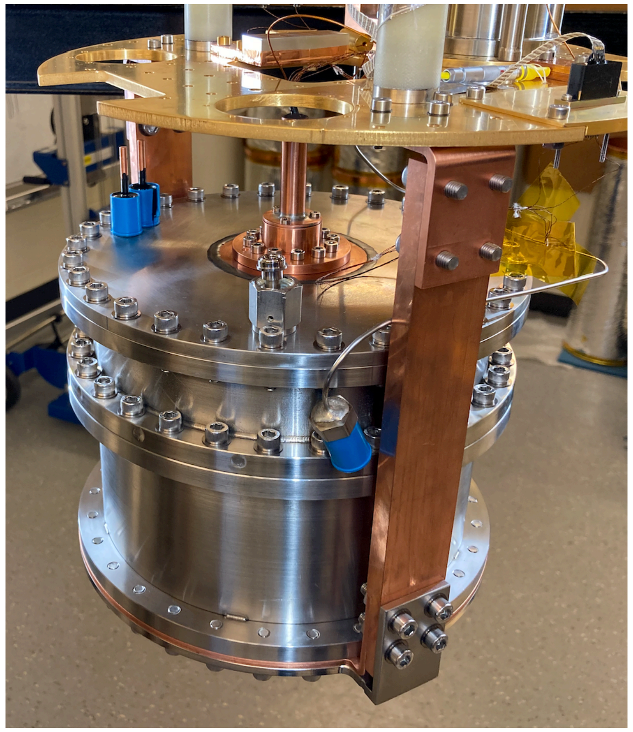
- GaAs has very high scintillation yield (125 ph/keV, *arxiv:1904.09362*), PID from heat/light readout down to 100 eV
- GaAs has a similar ERDM sensitivity than Ge/Si and similarly allows for **control of the backgrounds**:
  - photon:phonon ratio depends on the recoiling particle type: NR/ER discrimination
  - photon/phonon coïncidence in two separate sensors: instrumental background rejection

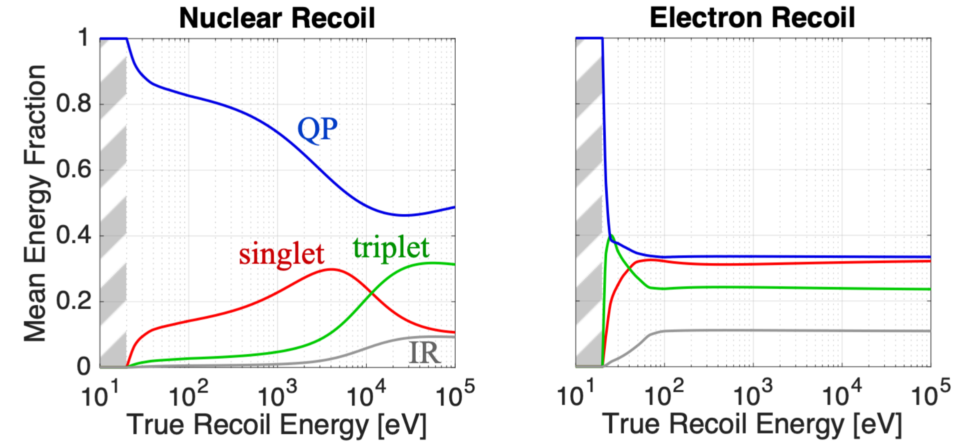
TESSERACT: *HeRALD*

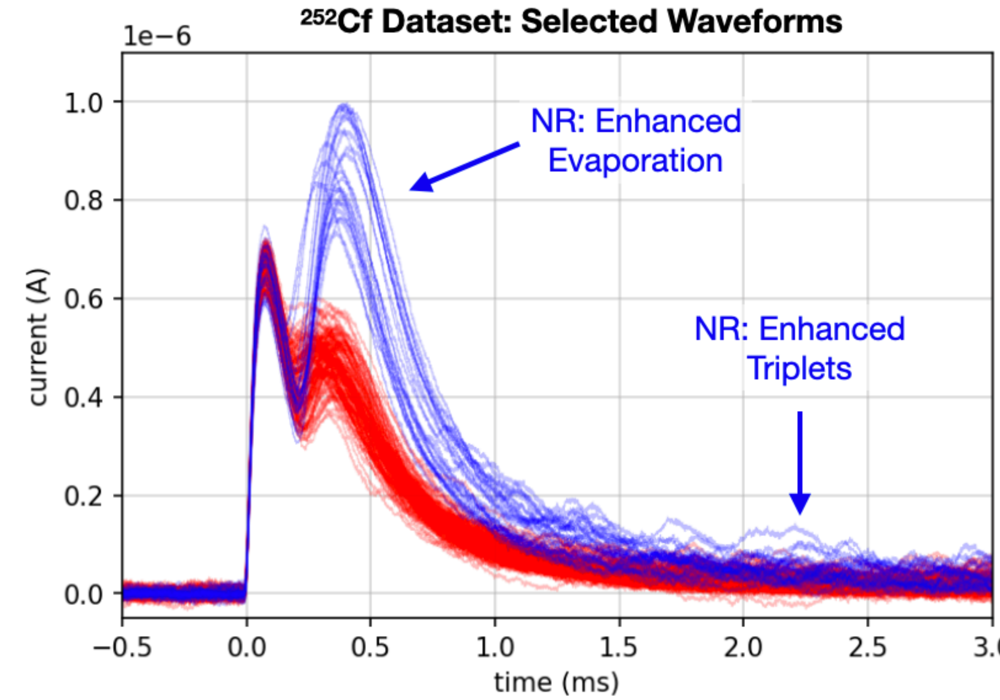


<u>He</u>lium <u>R</u>oton <u>A</u>pparatus for <u>L</u>ight <u>D</u>ark matter





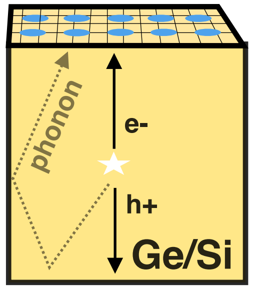




- Well kinetically matched to GeV-scale DM
- Easy to purify, intrinsically radio pure
- Monolithic and scalable
- LHe cell operated at 20-50 mK with wafer-like cryogenic detectors with TES suspended in vacuum
  - UV/IR photons and **He atoms** from qp induced evaporation
- ***First evidence of ER/NR discrimination @ 10 keV***
- **Segmented sensors to reject LEE from coincidences**

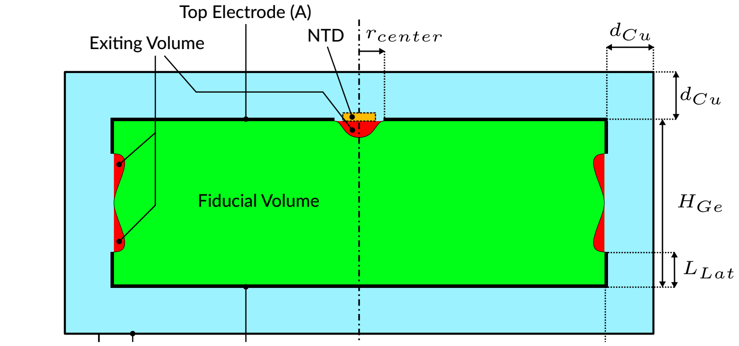
First experimental results !

TESSERACT: *Ge/Si semiconductors*



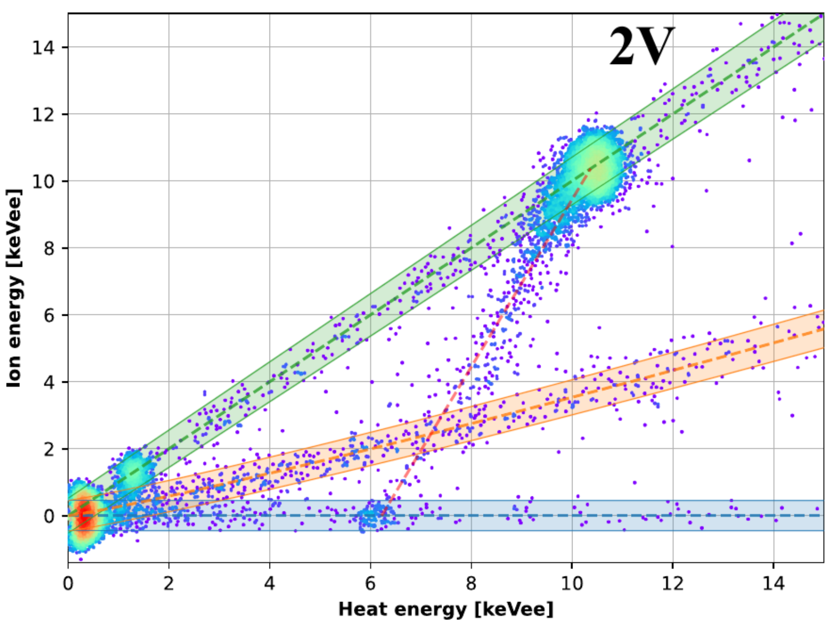
Low-Voltage ***approach for optimal particle identification (Ricochet style bolometers)***

PL 38



- Incomplete charge coll. **< 10%**
- Fiducial volume: **98.6 %**
- Surface event rejection: **NO**
- Total capacitance: **15 pF**

JFET EDW elec.: Heat 30 eV, **Ion. 220 eVee** (RMS)



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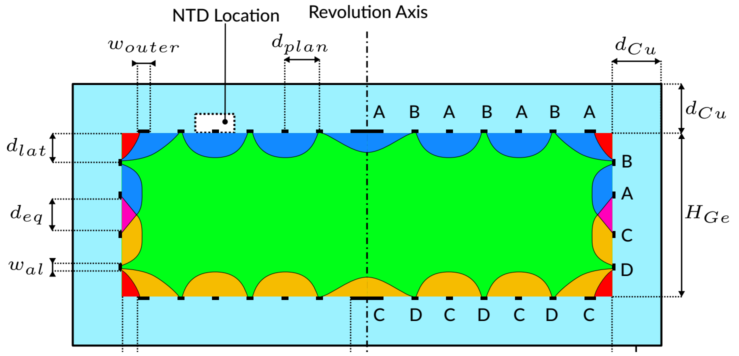
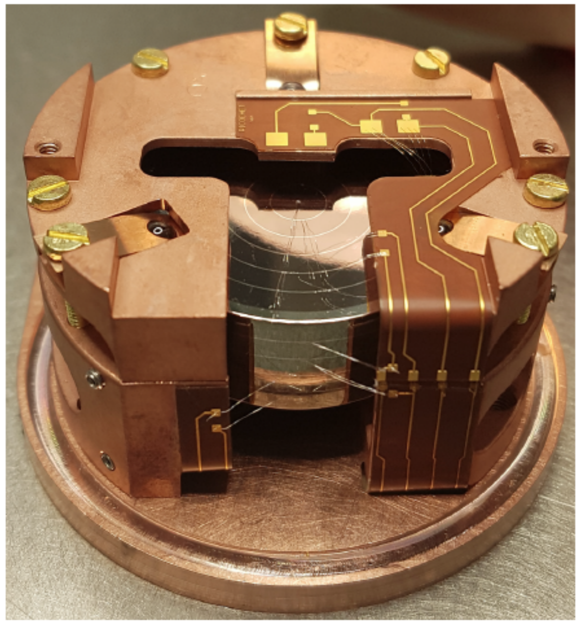
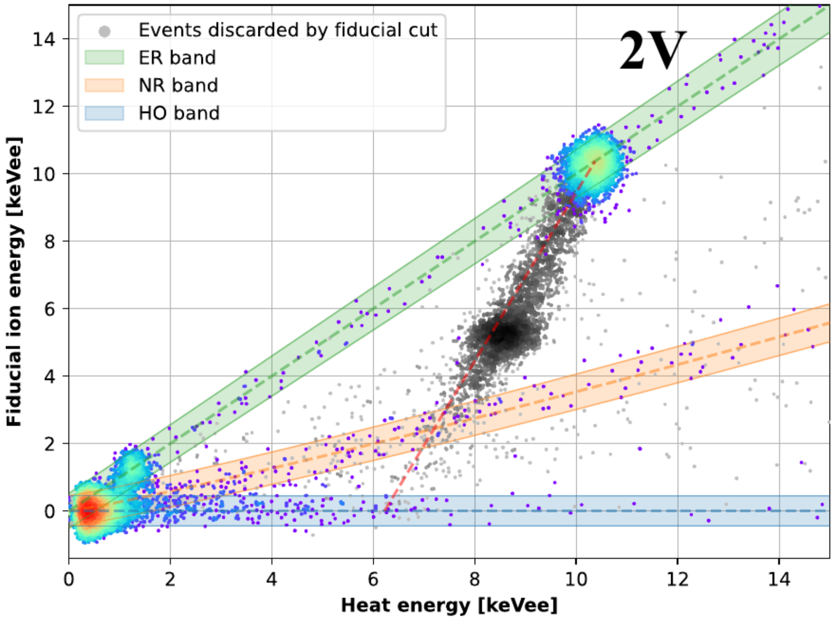


- Incomplete charge coll. **< 1%**
- Fiducial volume: **62 %**
- Surface event rejection: **YES**
- Total capacitance: **18 pF**

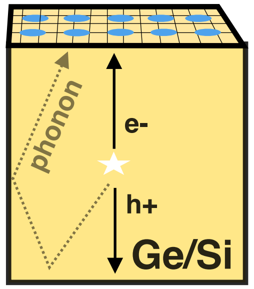
Salagnac & al: arXiv:2111.12438





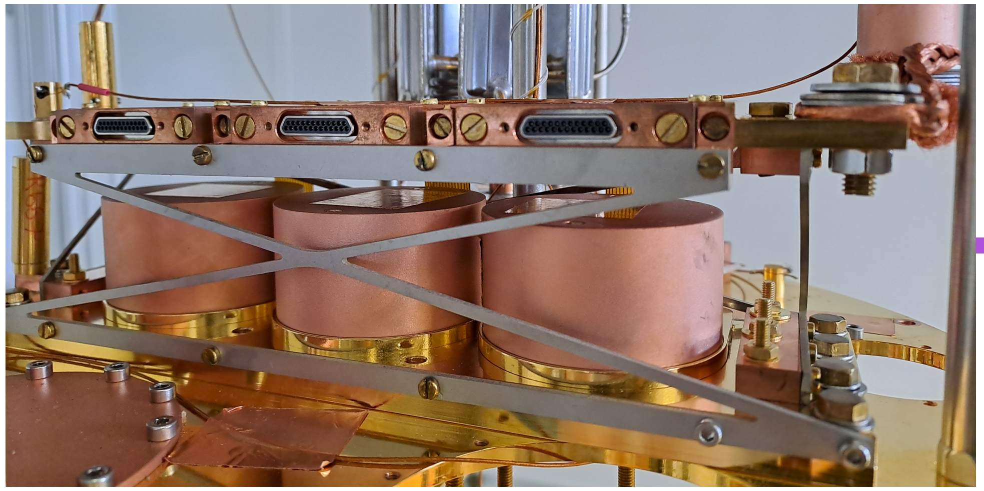
- ***First results with Ricochet-CryoCube HEMT-based electronics upcoming…***

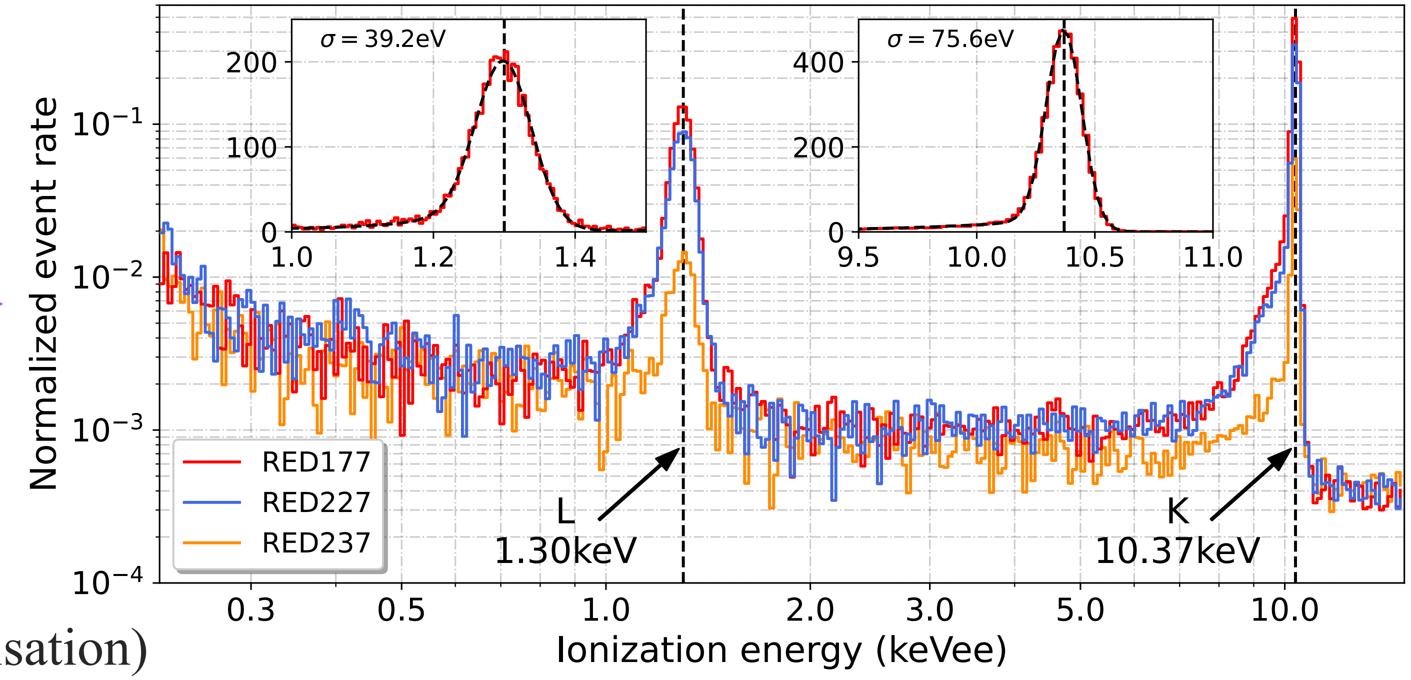
TESSERACT: *Ge/Si semiconductors*



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

Ricochet coll., *arXiv:2306.00166*





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

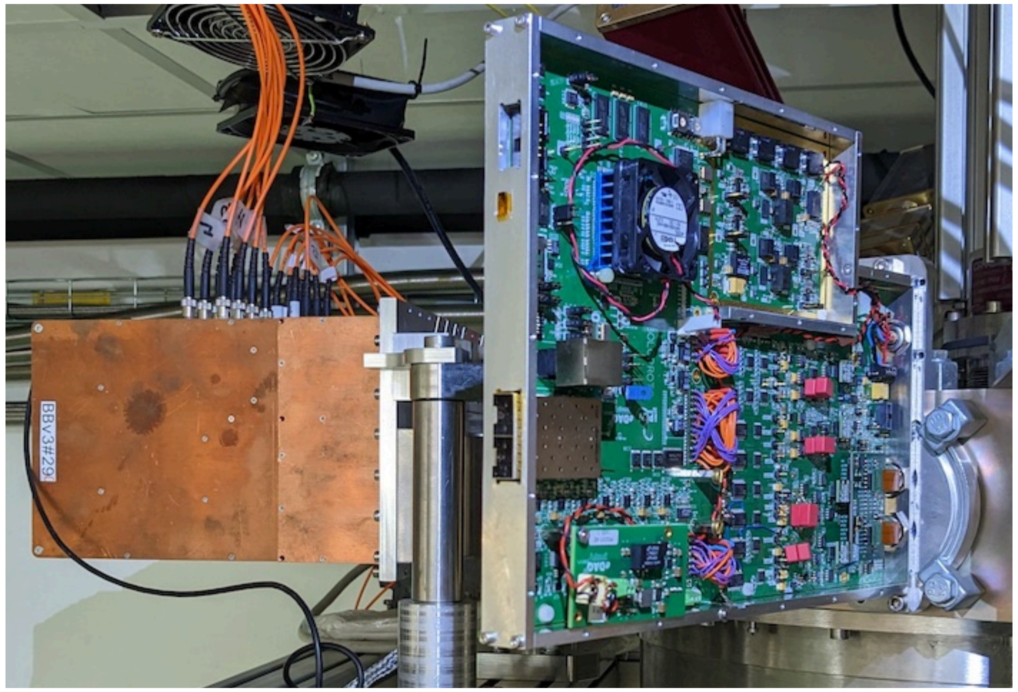
CryoCube array: 1K stage (HEMT elec.) and 10 mK (det.)

Achieved:

- **Heat: 17 - 30 eV (RMS)**
- **Ionisation: 30 eVee (RMS) => Major Breakthrough**

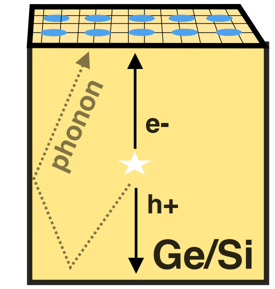
For TESSERACT:

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

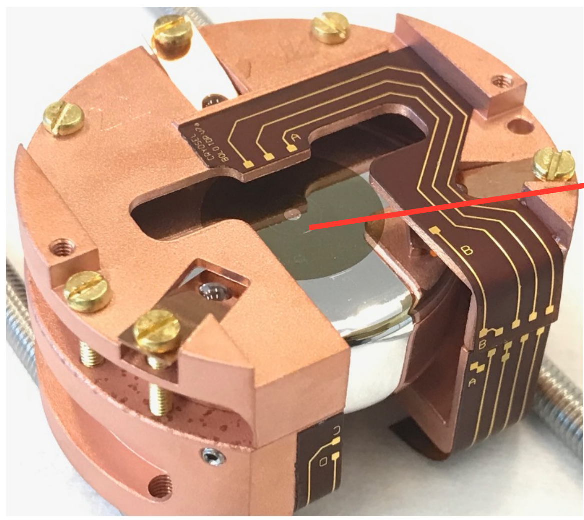


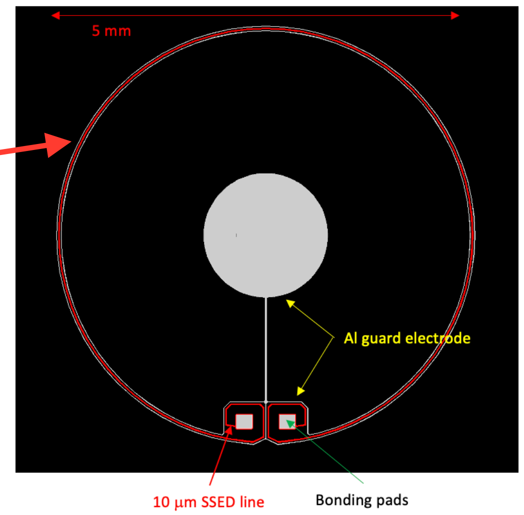
Dual heat/ionization upcoming with new Ricochet elec.

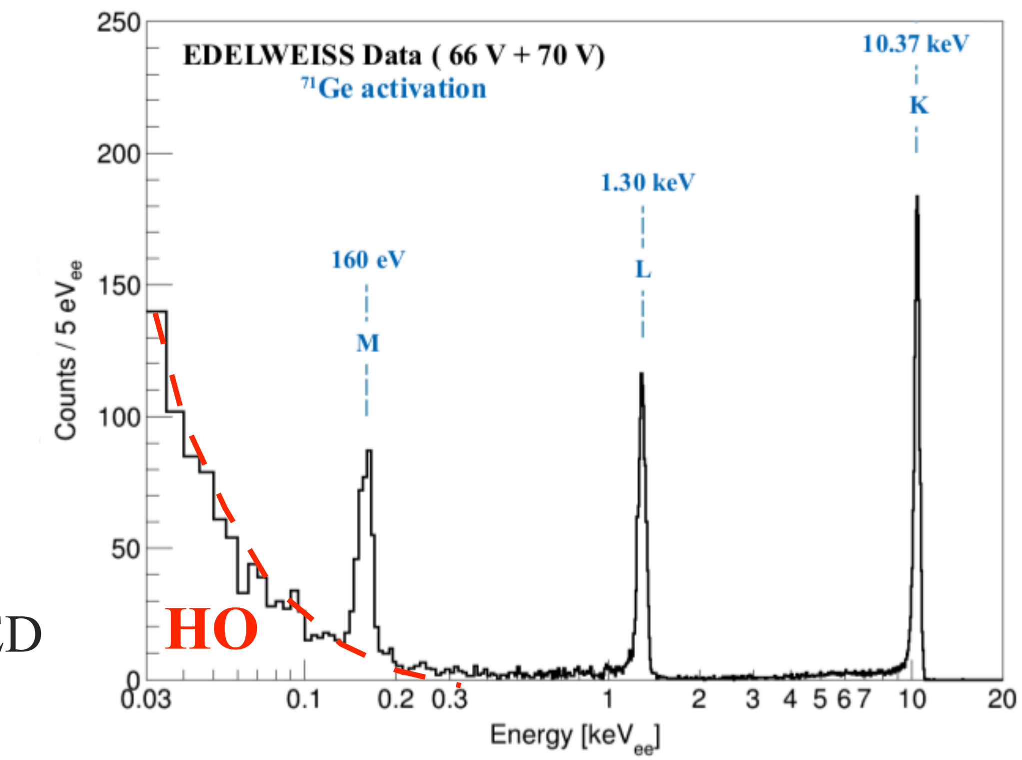
TESSERACT: *Ge/Si semiconductors*



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







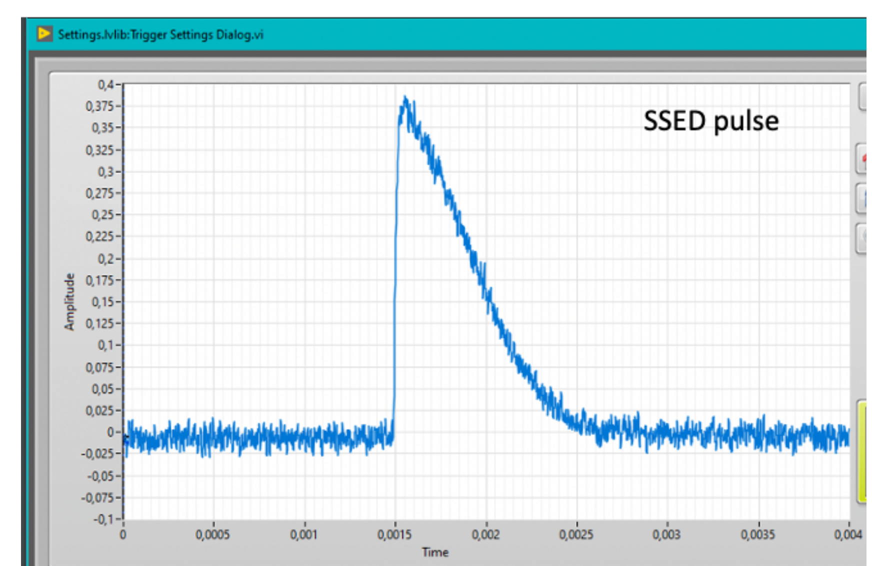
CRYOSEL performance goals: 100 V bias + single e-h sensitivity + SSED Heat Only tagging efficiency > 1000

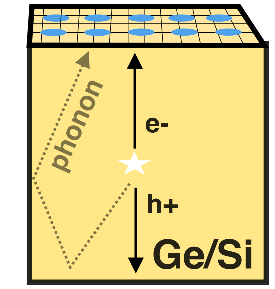
First R&D results:

- 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*
- ***See Elsa Guy presentation for more details***

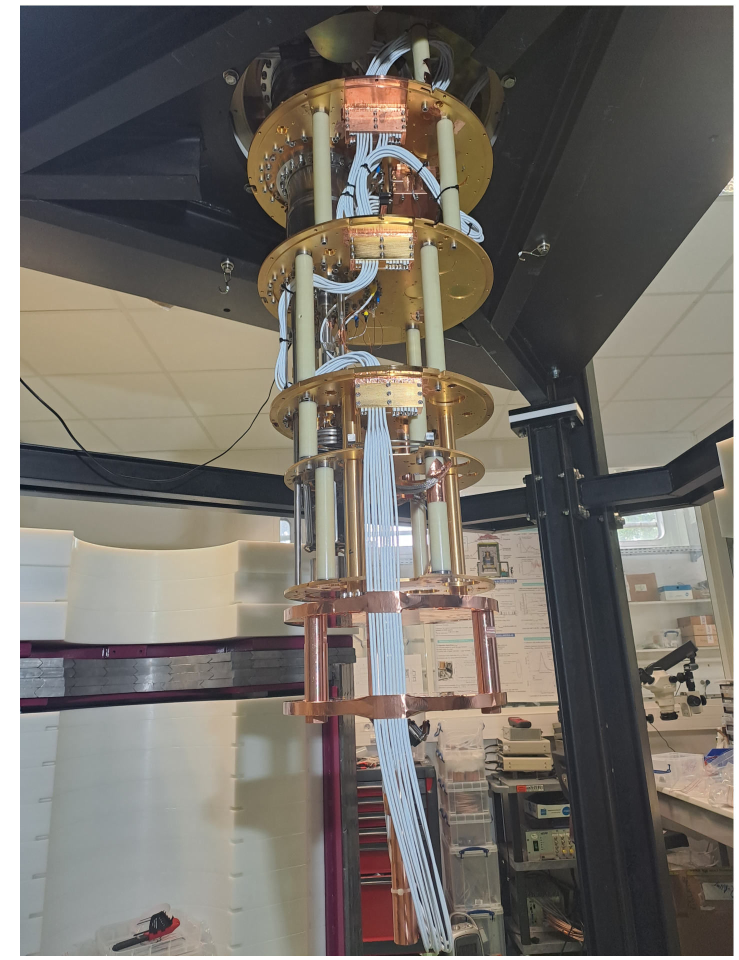
For TESSERACT:

- 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***





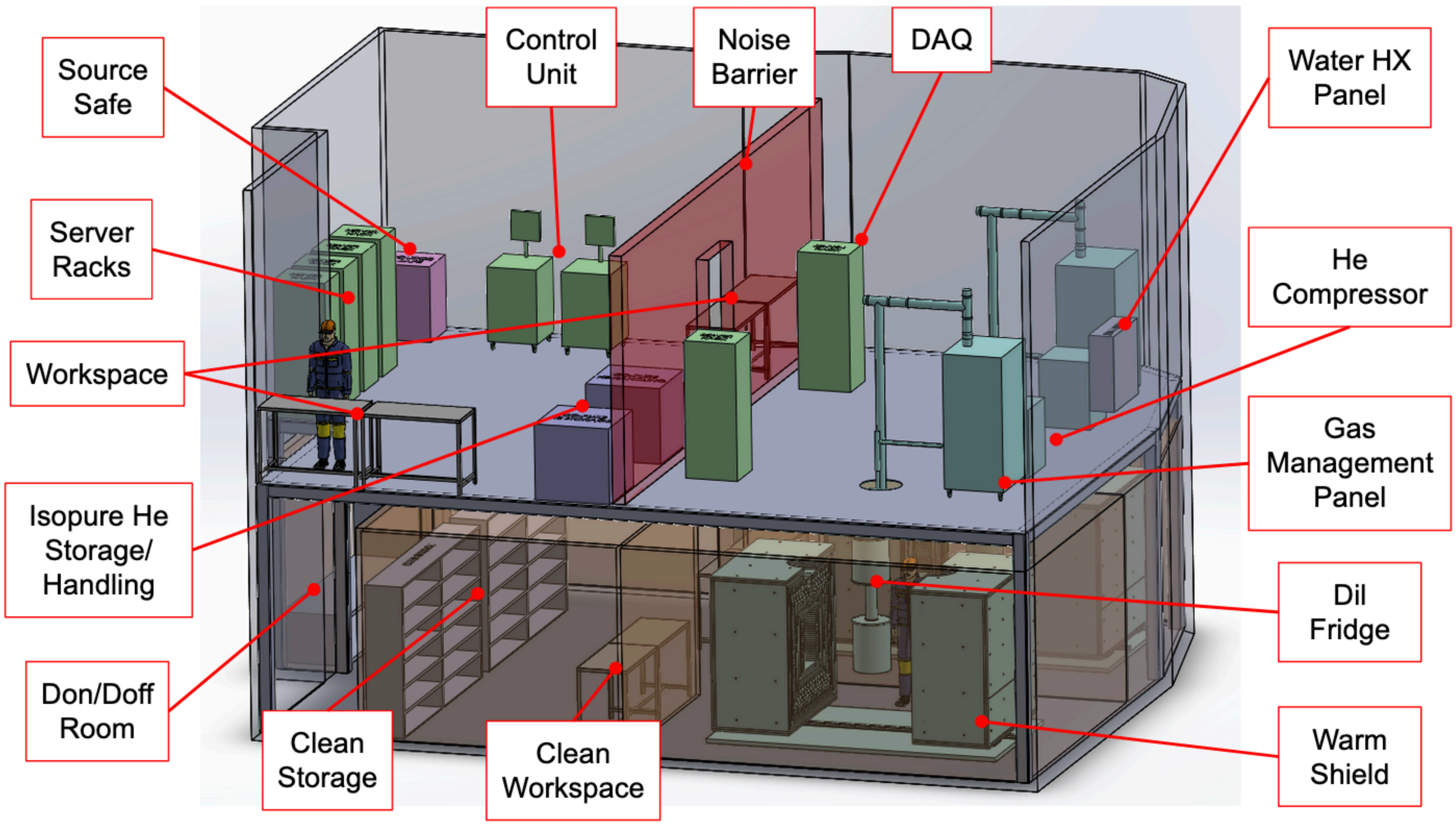
TESSERACT: *Ge/Si semiconductors*



- **CRYORED cryogenic platform in Lyon (IP2I)**
  - *to support Ricochet, TESSERACT, … R&D programs and detector fabrication and testing*
- Validation of the Ricochet cryostat: cryogenic and vibration performances (**done**)
- Validation of the cold inner shielding: Pb, PE, and Cu layers + cryogenic muon veto (**done**)
- Integration of the cold cabling, electronics and cryogenic detectors (**ongoing**)

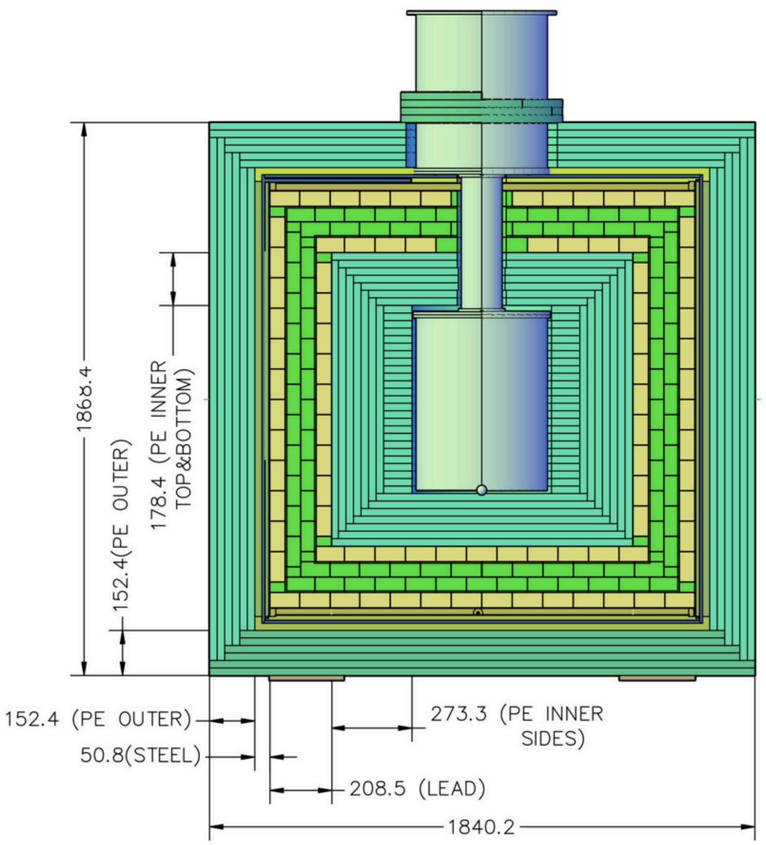
- **Ricochet cryostat will go to ILL by end-2023 and be replaced by a new cryostat dedicated to CRYORED**

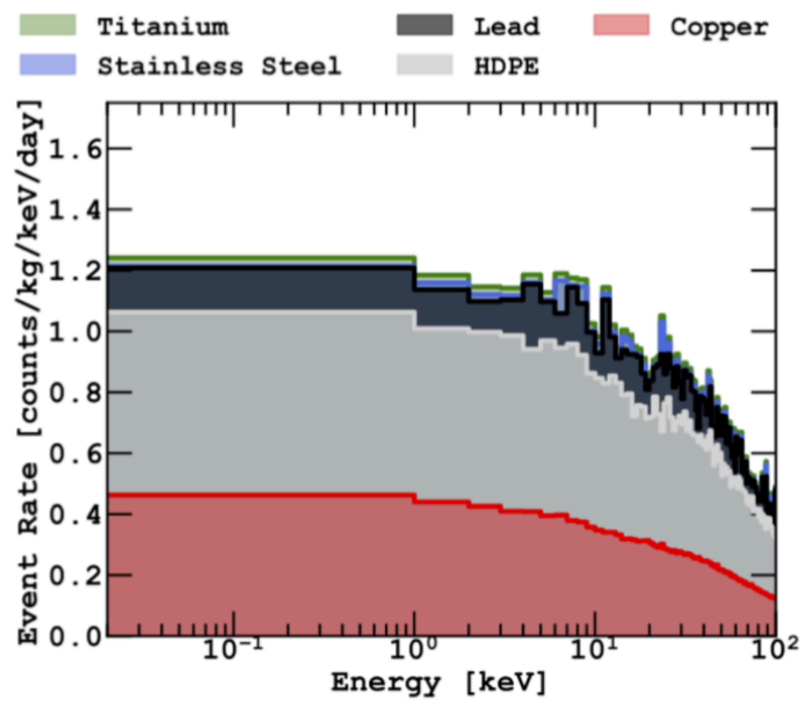
TESSERACT: *Proposal for an installation at LSM*

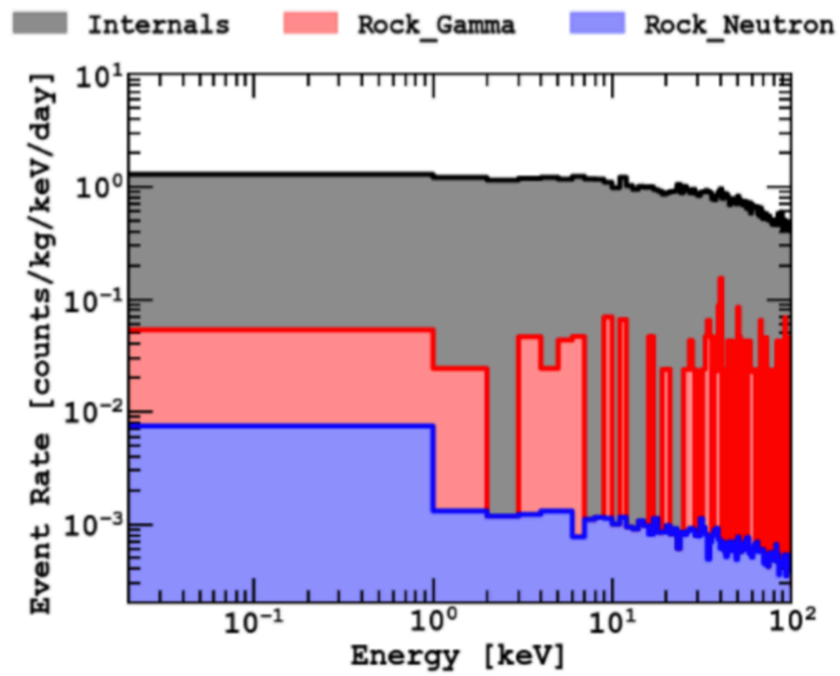


- Potential TESSERACT layout in Modane accommodating the BINGO cryostat in the former EDW space
  - Work ongoing between US and IN2P3 TESSERACT partners
- Ideally two cryostats would be needed tom combine short (R&D) and long (DM search) cycles simultaneously
- Significant emphasis on vibrational and EM noise suppression
- Integration of dedicated low energy NR and ER calibration sources

TESSERACT: *Proposal for an installation at LSM*



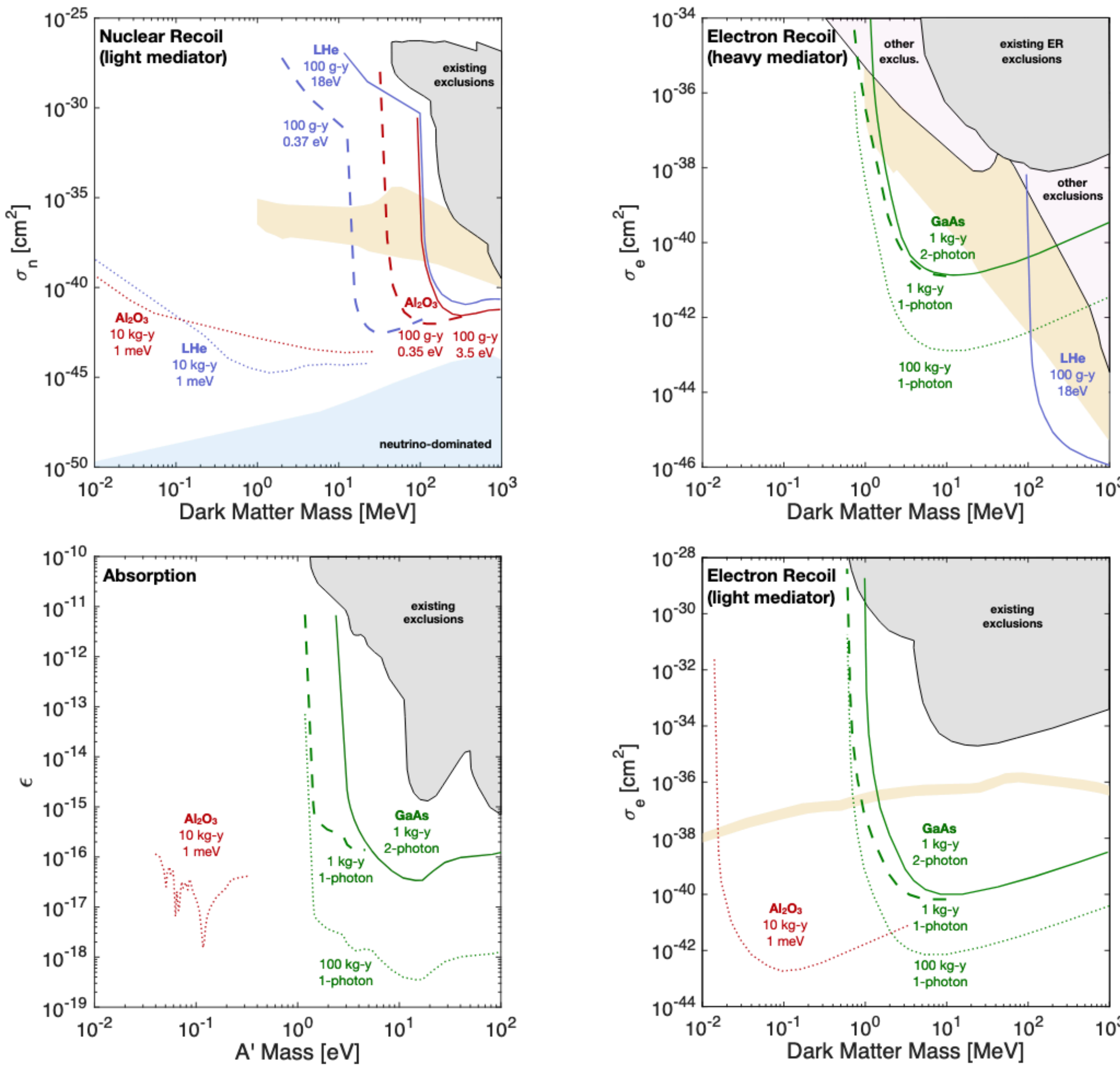




- The shielding design has converged on a compact lead/polyethylene approach with a neck to avoid internal cryogenic passive layers of shielding
  - **Shielding design nearing completion and being quoted**
- Simulation based on **rock composition & density** of the Homestake mine
- Internal backgrounds 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

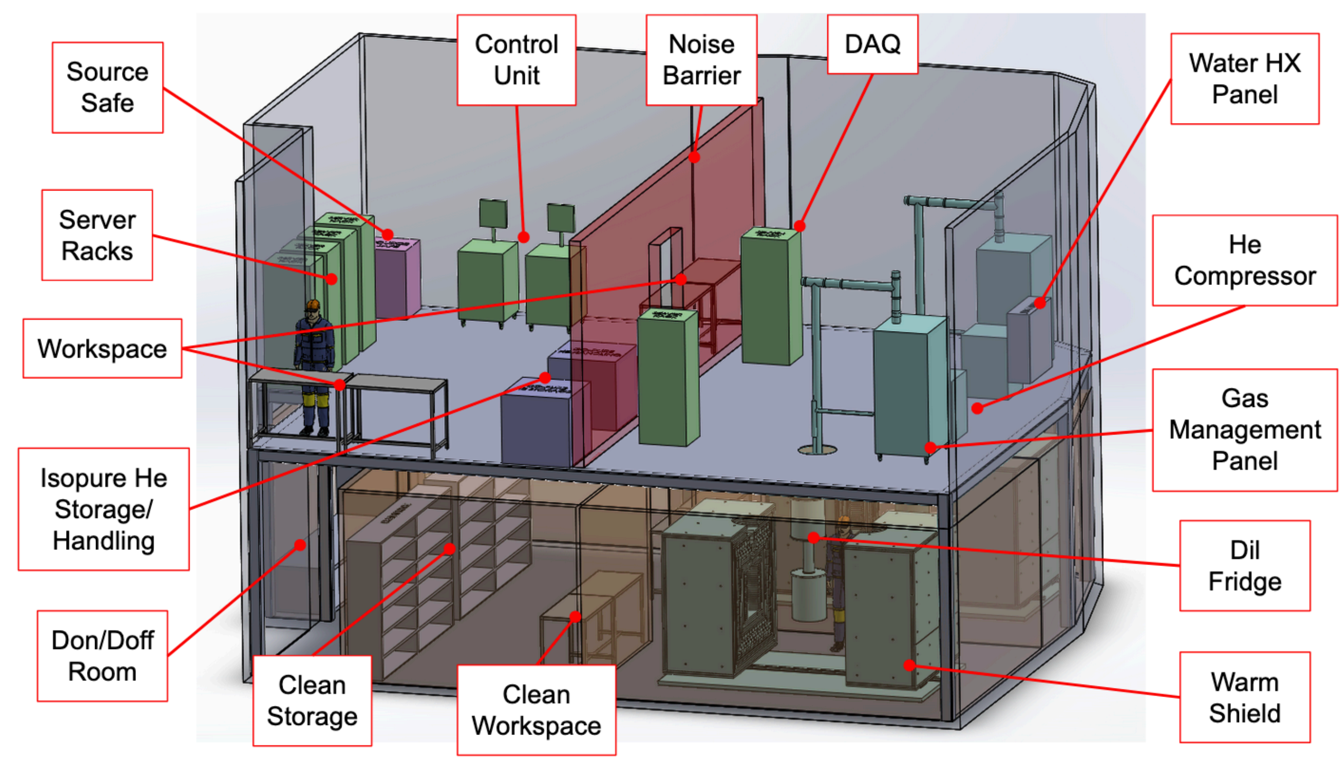
Ge/Si sensitivities under calculations

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**

- Ongoing discussions with IN2P3 to start a TESSERACT master project by the summer 2023
- Green light from the DOE for a TESSERACT collaboration with US and IN2P3 partners (LPSC/LSM, IP2I, IJClab) and possibly additional CNRS labs
  - One IN2P3 TESSERACT postdoc position at LPSC
  - One IN2P3 international PhD thesis grant at IP2I to start in the Fall 2023 ***(NEW !)***
- Actively looking for fundings to start building TESSERACT at LSM by the horizon 2026



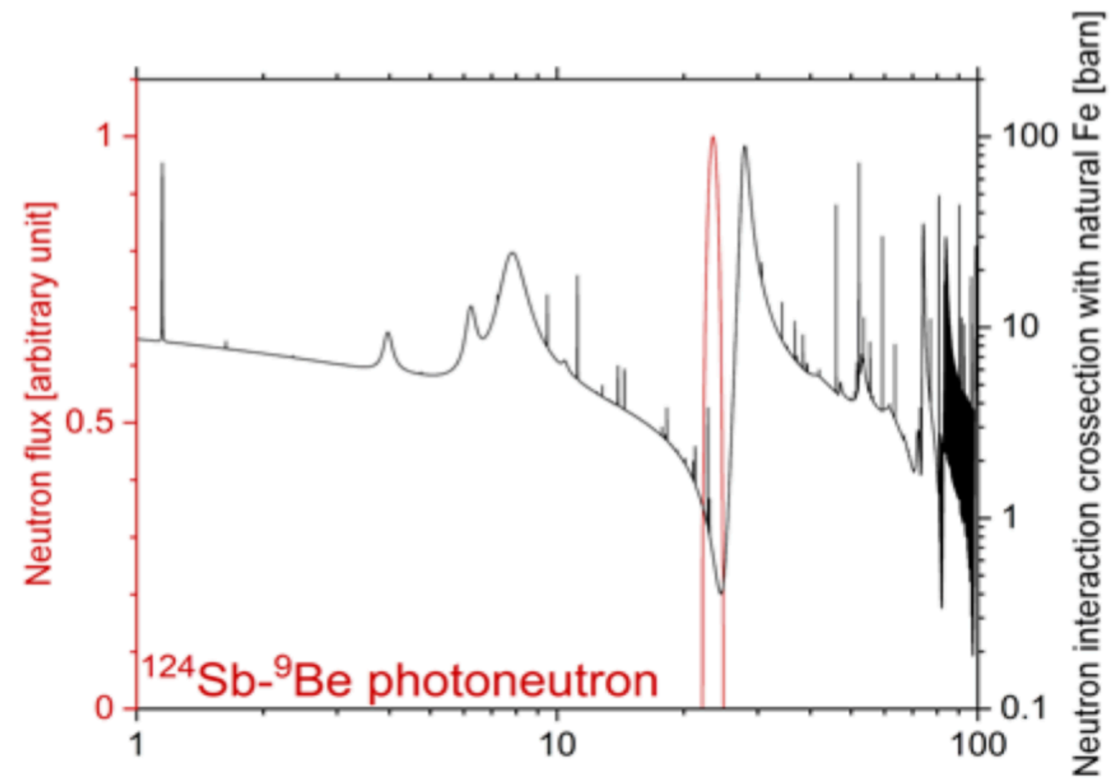
- Potential layout in Modane

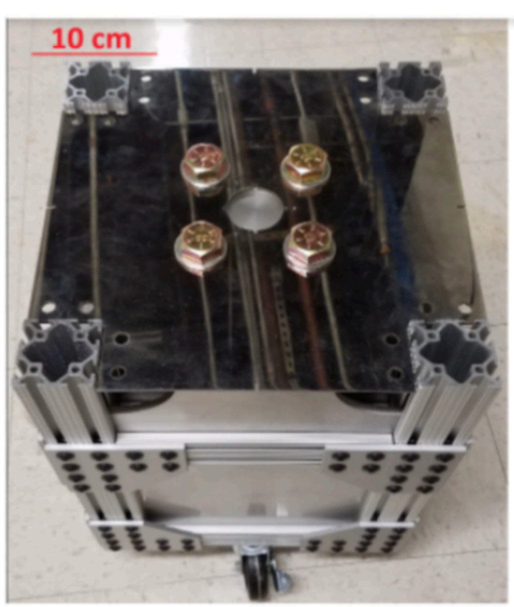
Back up

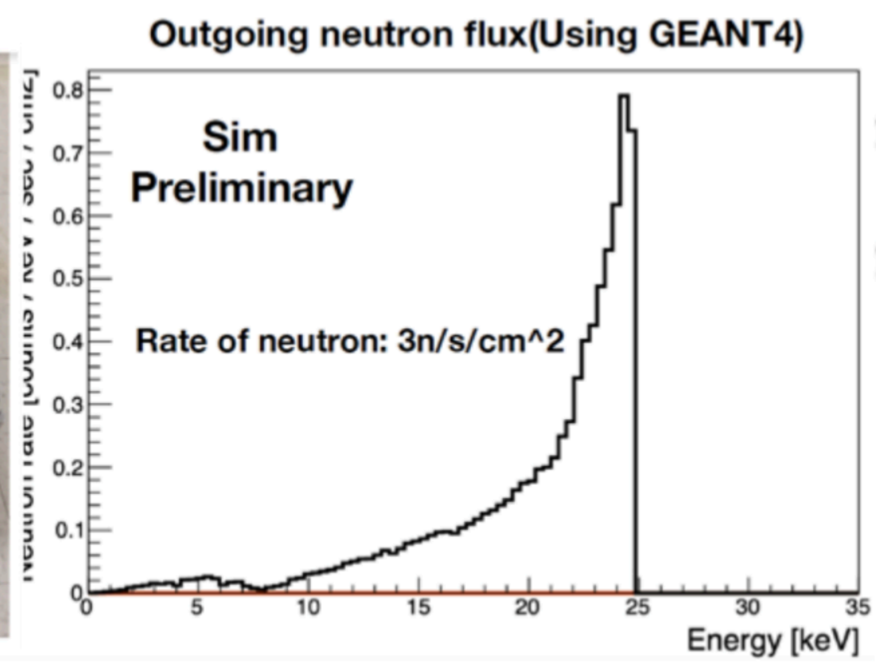
TESSERACT: *Energy calibration*

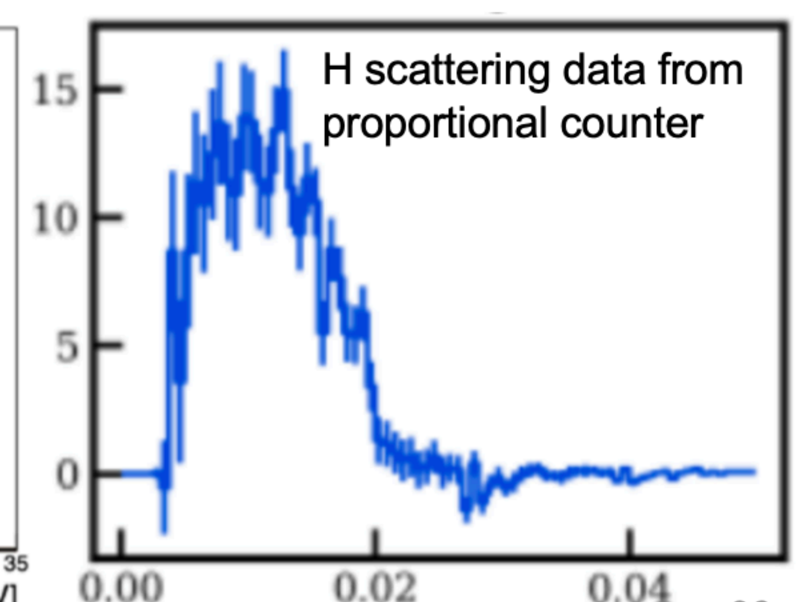
Dedicated low energy and mono-energetic neutron source

- 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

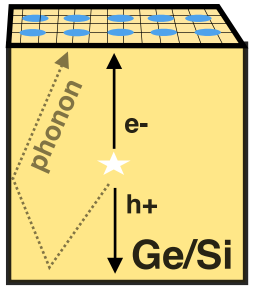




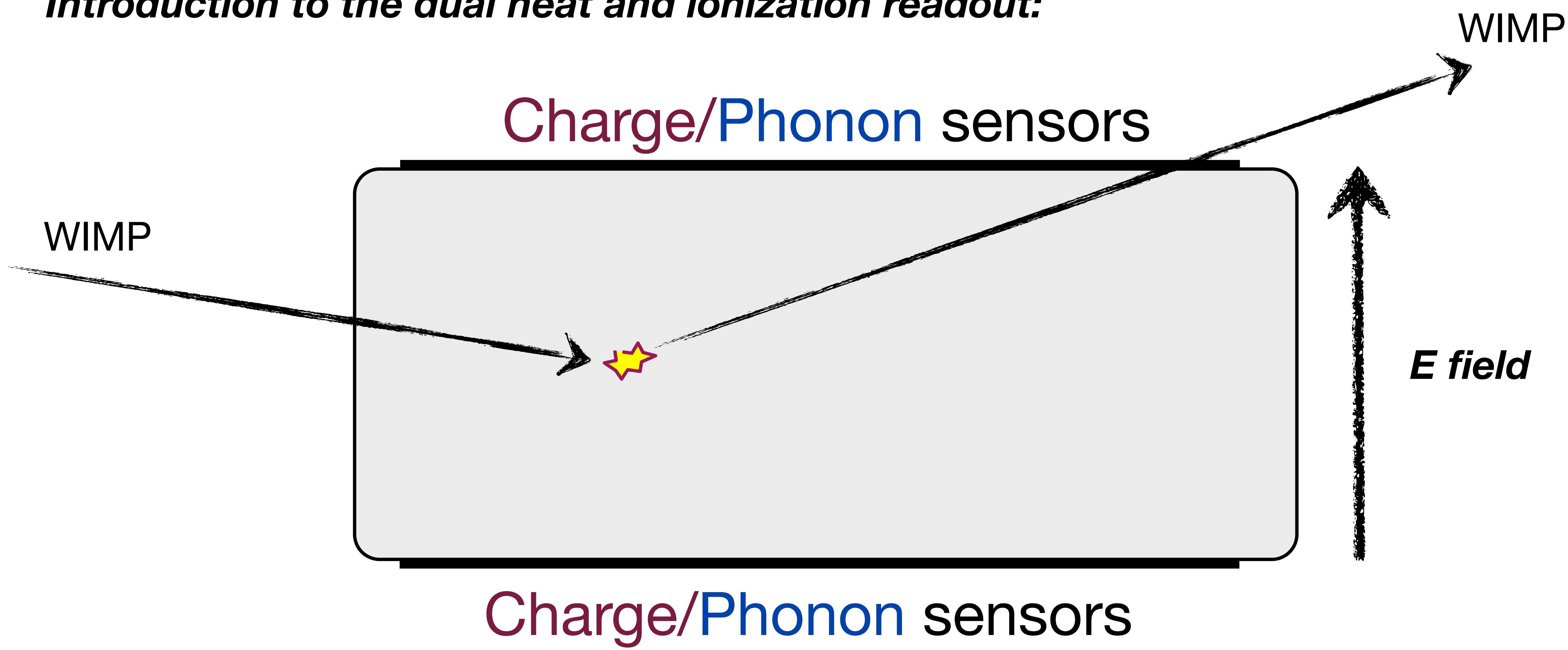




TESSERACT: *Ge/Si semiconductors*



Introduction to the dual heat and ionization readout:



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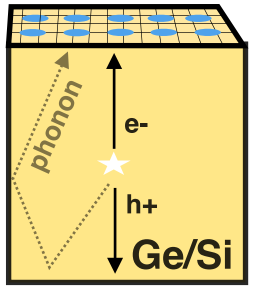

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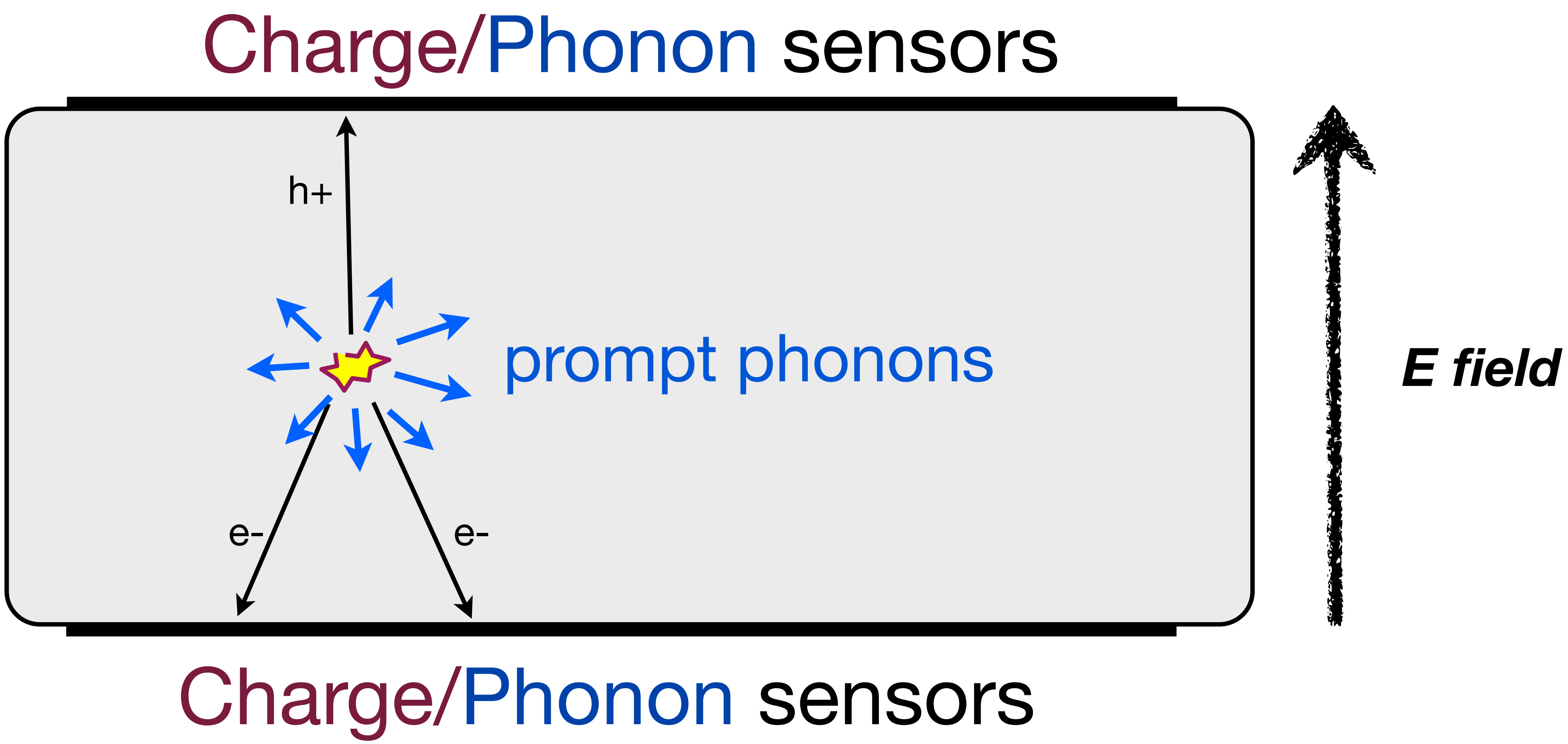

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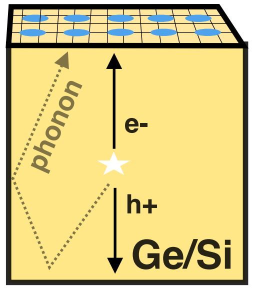

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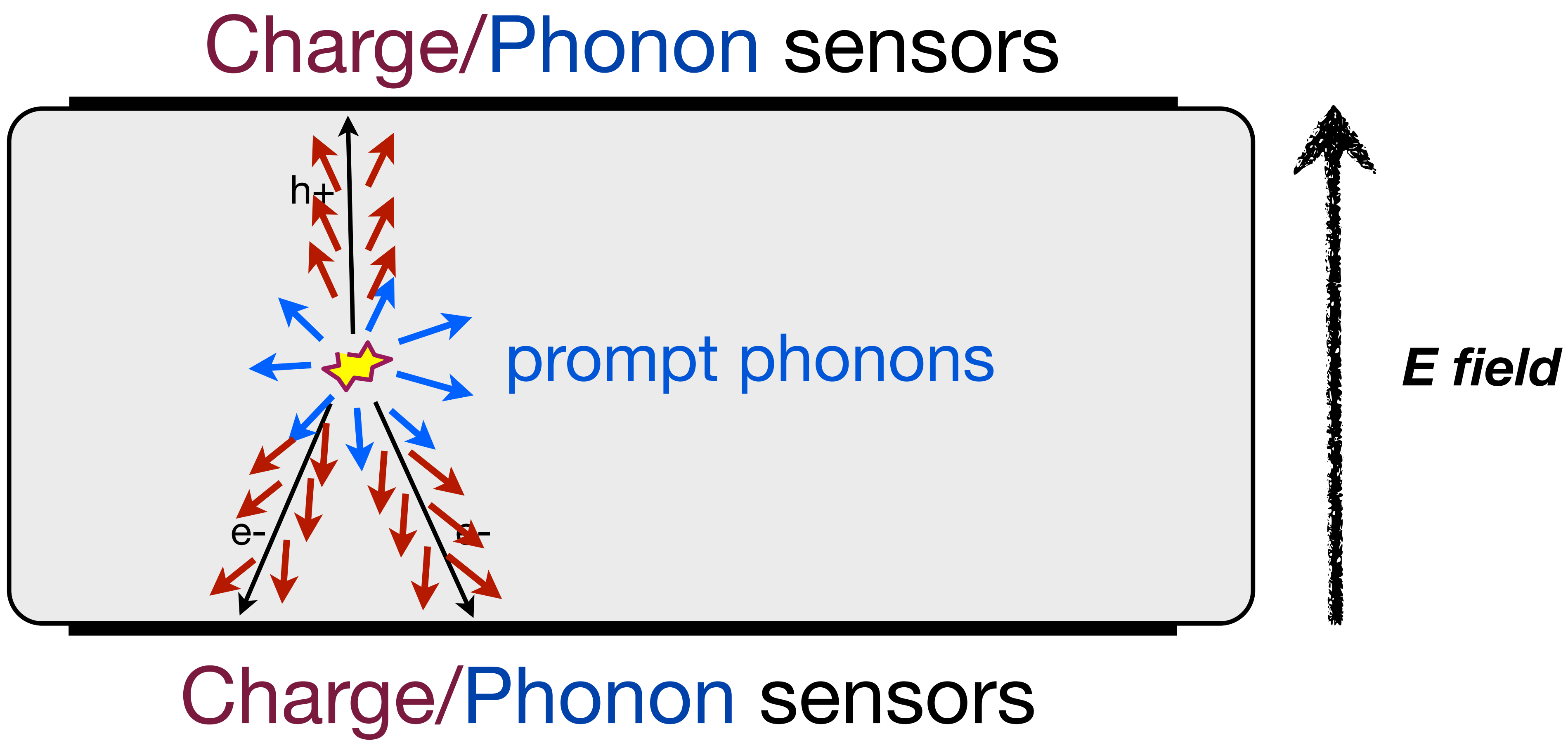
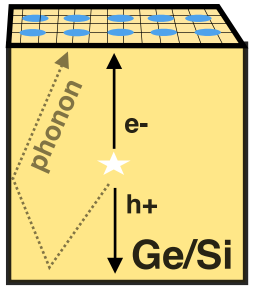


$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + \frac{1}{3\ eV} E_{ion} \Delta V$$

TESSERACT: *Ge/Si semiconductors*



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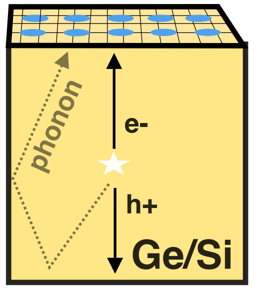

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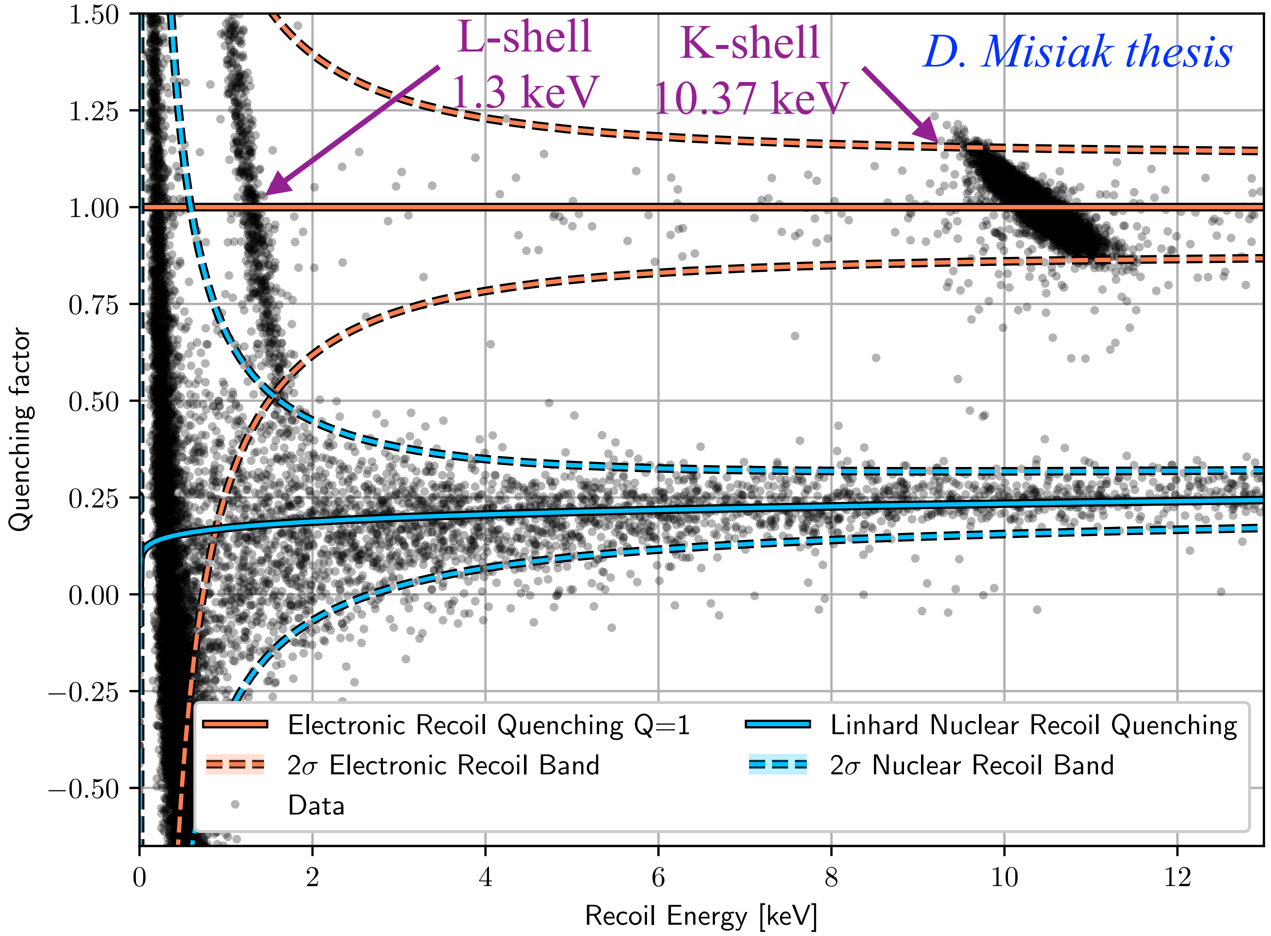
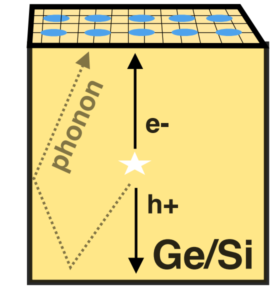
Low Voltage mode

Part. ID + Fid



TESSERACT: *Ge/Si semiconductors*



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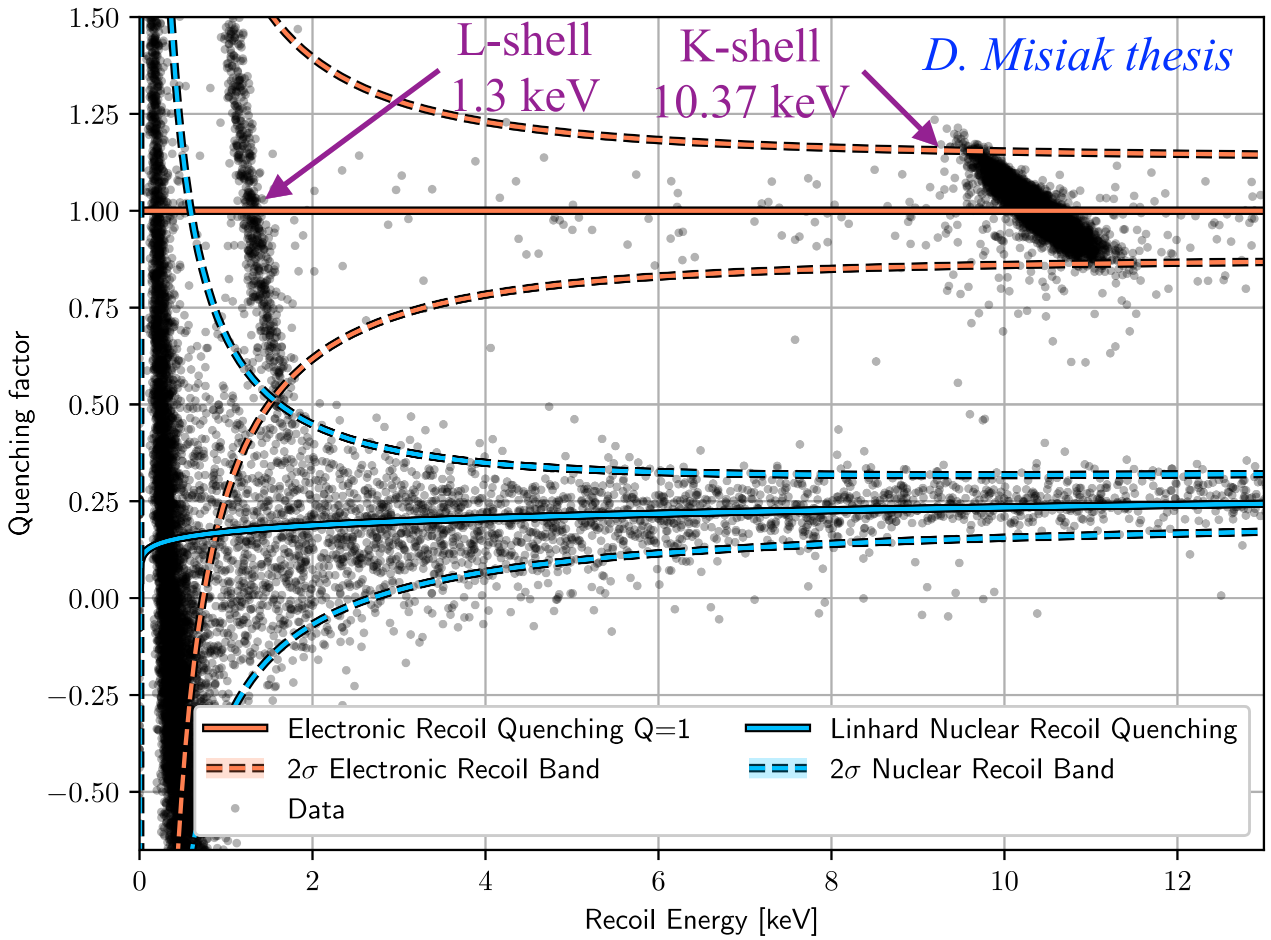
$$= E_{recoil} + \frac{1}{3\ eV} E_{ion} \Delta V$$

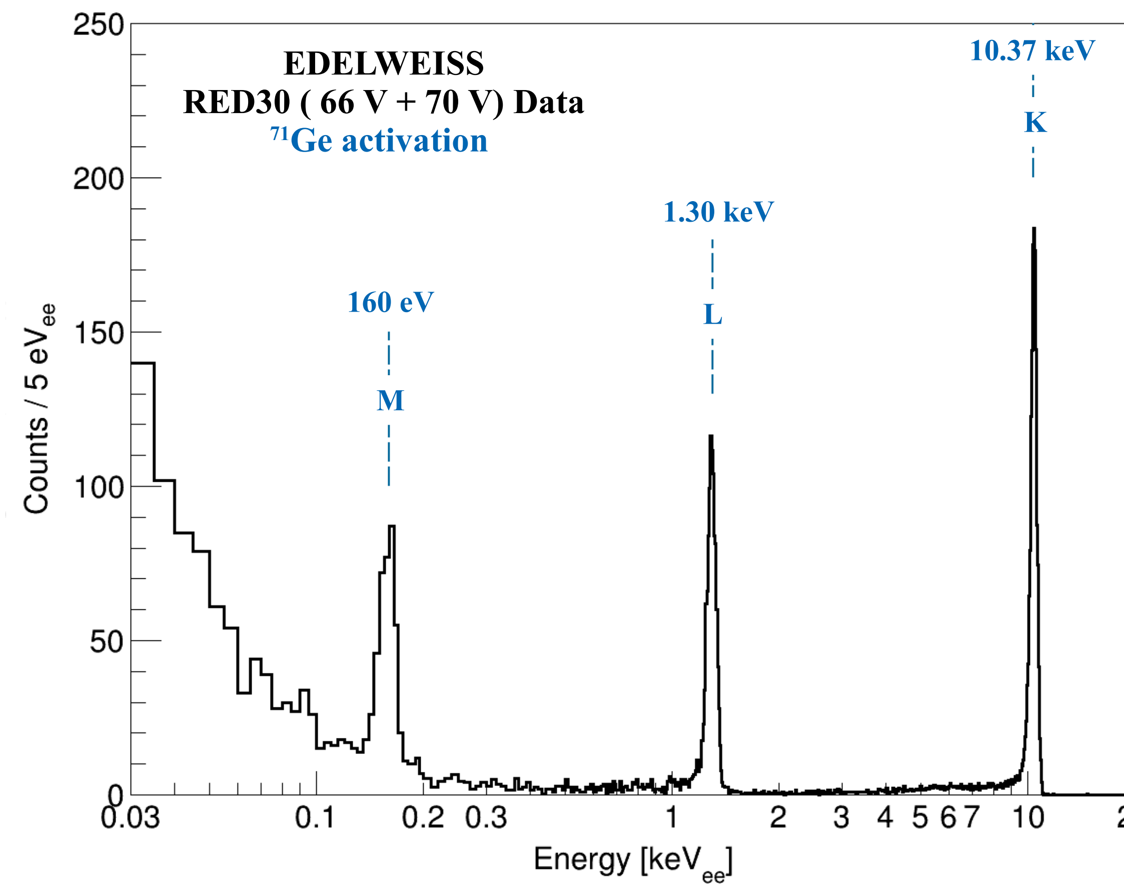
Low Voltage mode

Part. ID + Fid

High Voltage mode

single e/h - No PID





Q. Arnaud et al., Phys. Rev. Lett. 125 (2020)