Light DM search with TESSERACT

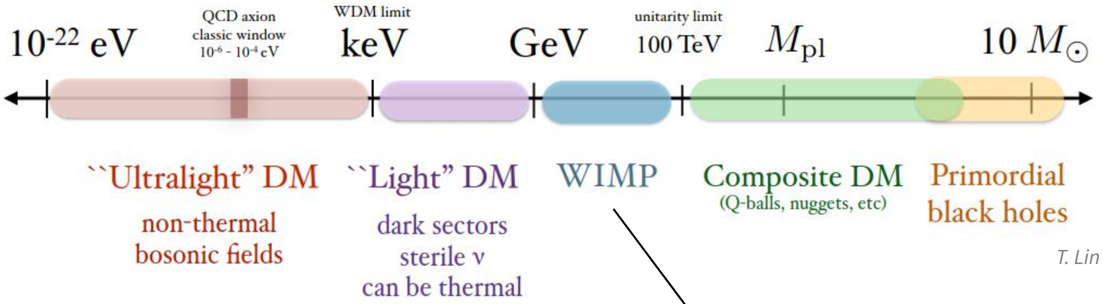
Paul Vittaz, 2nd year PhD student

GDR DUPhy - 09/10/2024

Motivations

50 orders of magnitudes in mass

DM Candidates



T. Lin

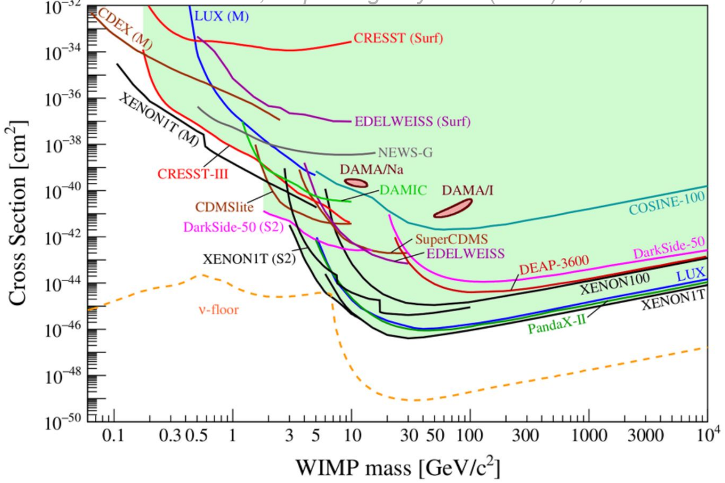
Focus of DM searches for the last decades has been on axion DM (ueV - meV) and standard WIMP (10 GeV - TeV)

The standard WIMP case was highly motivated thanks to the so-called WIMP miracle and the SUSY prediction

After few decades, still no DM signal and ongoing or planned ton-scale experiment (LZ, XENON-nT, DarkSide-20k, DARWIN, ARGO, …) are approaching the neutrino limit

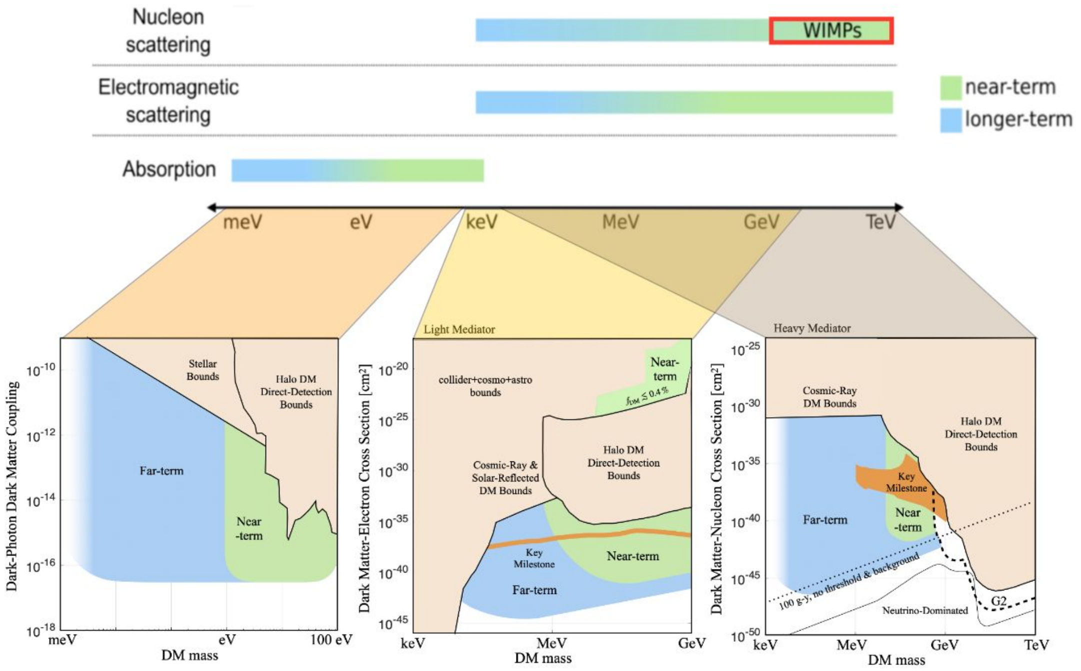
Need for new experiment with broader DM mass range and increased sensitivity to more DM interactions

J. Billard et al., Rept.Prog.Phys. 85 (2022) 5, 056201



Motivations

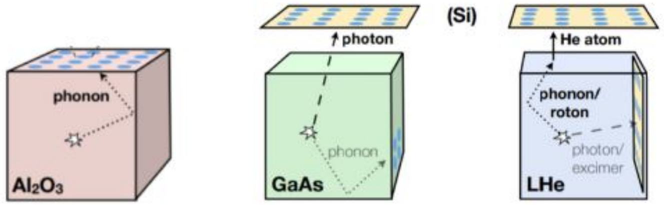
DM search range



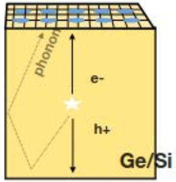
TESSERACT : Extending the Dark Matter mass search window from meV to GeV with ultra-low threshold cryogenic detectors with multiple targets and particle identification capabilities

TESSERACT : Proposal experiment at LSM

Transition Edge Sensor with Sub-Ev Resolution And Cryogenic Targets



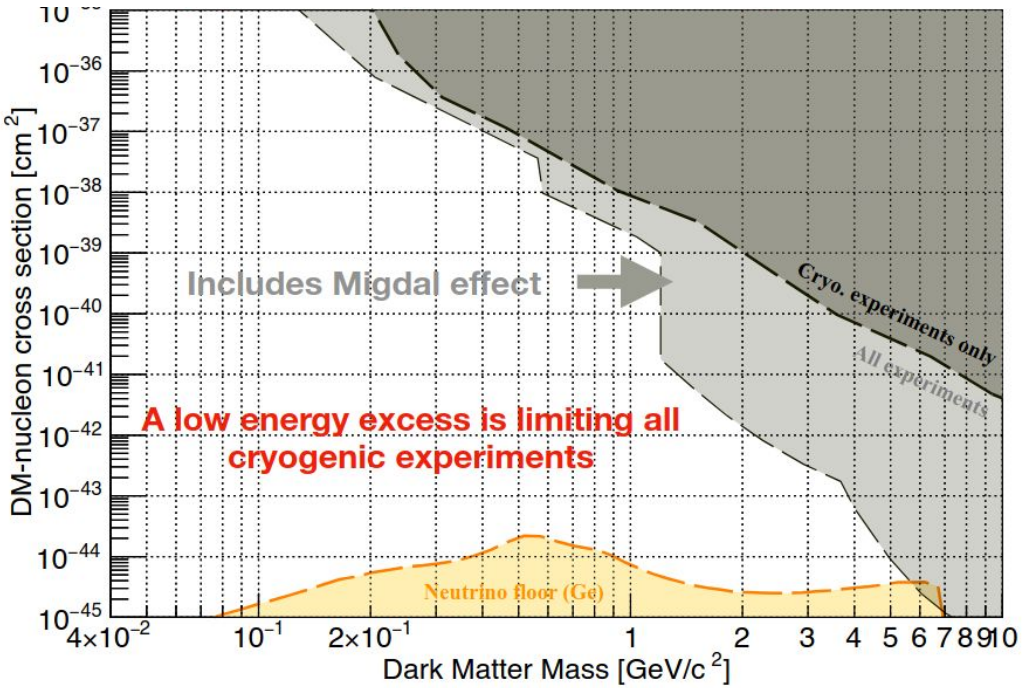
- DOE Funding for R&D and project development began in June 2020 (Dark Matter New Initiative)
- One experimental design, and different target materials with complementary DM sensitivity, all using TES
- Include SPICE (Al_2O_3 and GaAs) and HeRALD (LHe)
- ~ 40 people from 8 institutions



- **RI2 Project TES4DM**
- Benefit from EDELWEISS, Ricochet, CUPID Ge bolometer expertise and low-background cryogenic setup experience to :
  - **Add the French semiconductor Ge bolometer technology to the TESSERACT science program**
  - **Deploy the future TESSERACT experiment at LSM**
- Achieve leading light DM sensitivities on short time scales
- Benefit from exchange of technologies with US partners

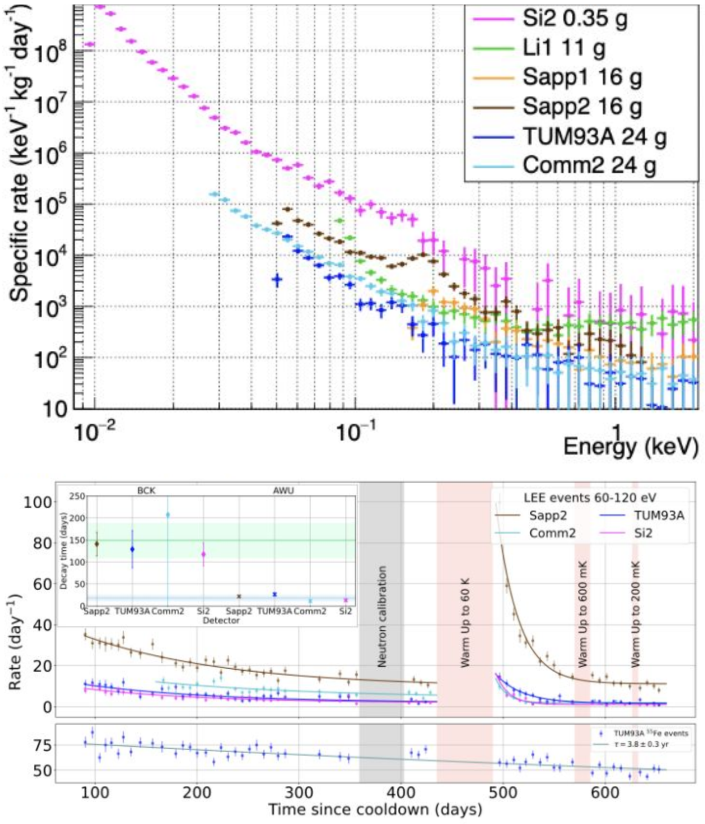
Low-mass NRDM state of the art

Why 100 eV-scale cryogenic DM experiments aren’t leading the sub-GeV search region ?



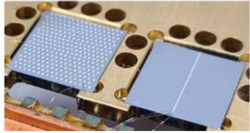
Low Energy Excess

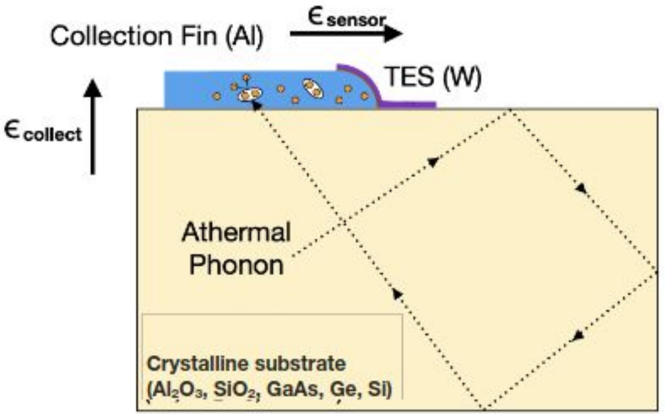
- Currently, all cryogenic experiment which have reached sub eV threshold are seeing such an excess limiting their DM search
- LEE characteristics : time dependant, non ionising (“Heat Only”), mostly independent of sites, dependance with holder/vibrations (?)
- Design driver of TESSERACT :
  - **find the origin of the LEE to mitigate it**
  - **develop technologies that can reject it**



CRESST collaboration, SciPost Phys.Proc. 12 (2023) 013

TESSERACT : New generation TES phonon sensors



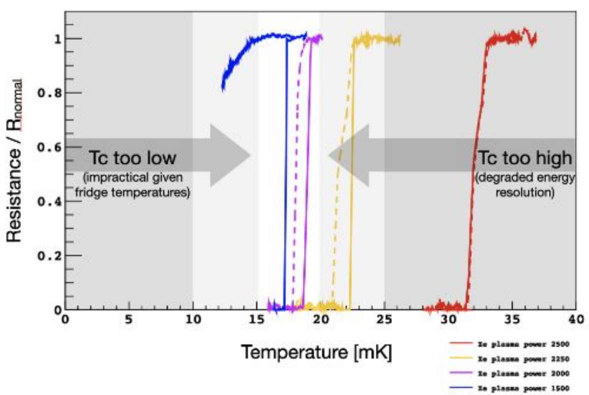


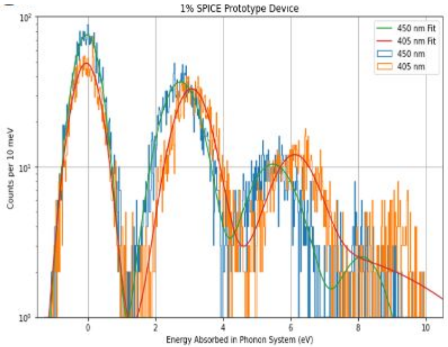
$$\sigma_E \sim \frac{\sqrt{4k_bT_c^2G(\tau_{collect}+\tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

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

Energy threshold decreases with detector mass

Energy threshold decreases very quickly with Tc



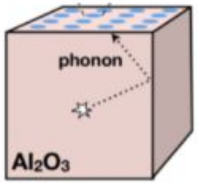


- 273 meV (RMS) leading to eV-scale threshold already achieved with a 0.2 g Si detector and Tc = 50 mK
- Targeted Tc around 15-20 mK recently achieved
  - ~100 meV threshold achievable on 1 cm^3 crystals
- Next challenge : Combining the athermal phonon TES sensor with our electrodes within our Ge/Si detector technology.

TESSERACT technologies : SPICE

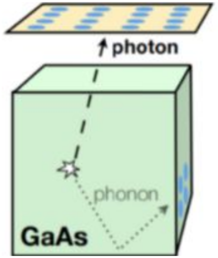
Sub-eV Polar Interaction Cryogenic Experiment :

Al_2O_3 :



- Look for ERDM
- mass range : 100 meV - MeV
- **LEE mitigation method : use of two TES (pulse shape discrimination)**
- No particle identification
- Single Photon sensitivity

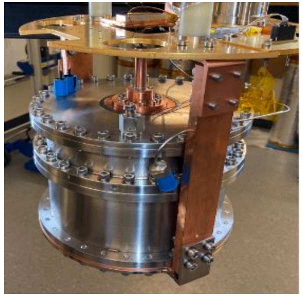
GaAs :



- ERDM and NRDM
- mass range : eV - MeV and MeV - GeV
- **LEE mitigation method : photon / phonon coïncidence in two separate sensors** (~ eV scale)
- Particle identification with dual Photon - Phonon readout (~ 10 eV scale)

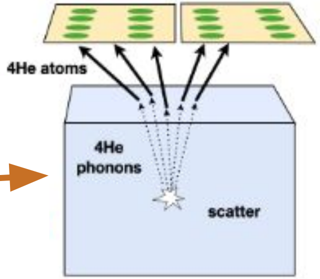
TESSERACT technologies : HeRALD

Helium Roton Apparatus for Light Dark matter

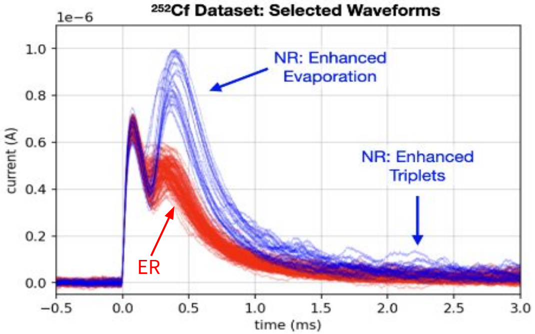


R. Anthony-Petersen et al., arXiv:2307.11877

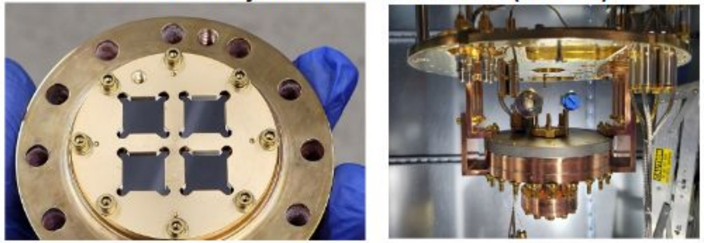
- Target : Liquid He
- NRDM
- Mass range : MeV - GeV
- **LEE mitigation method : multiple ^{4}He/photon detectors**



- Particle identification : Pulse shape discrimination



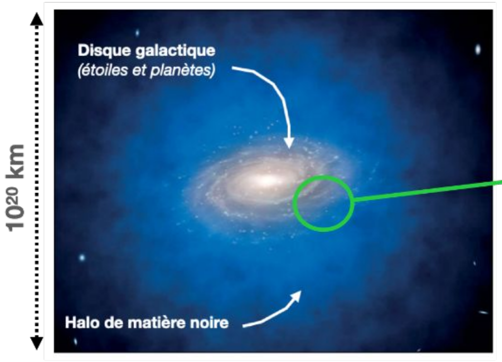
4-Channel Array for HeRALD v0.2 @LBNL (4x 1cm²)

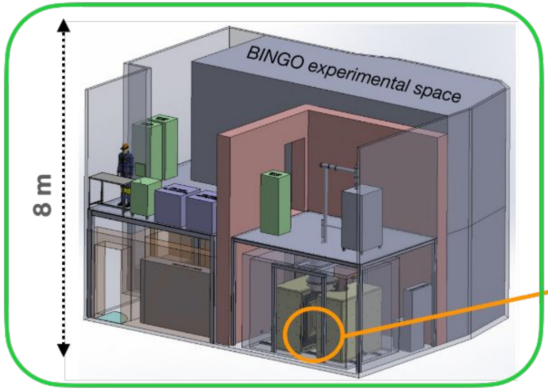


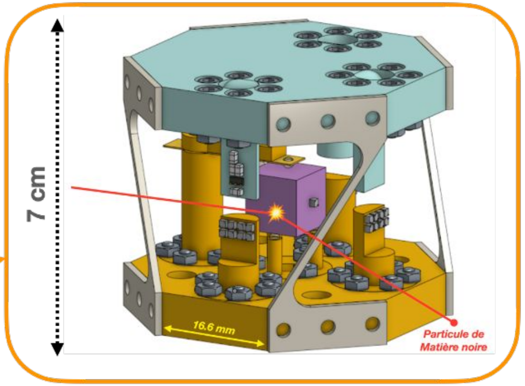
RI2 project: TES4DM

Transition Edge Sensor for Dark Matter - French CNRS contribution to TESSERACT

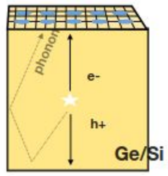
Based on EDELWEISS, RICOCHET and CUPID expertise on Ge/Si bolometers, low background experiments, and rare event searches



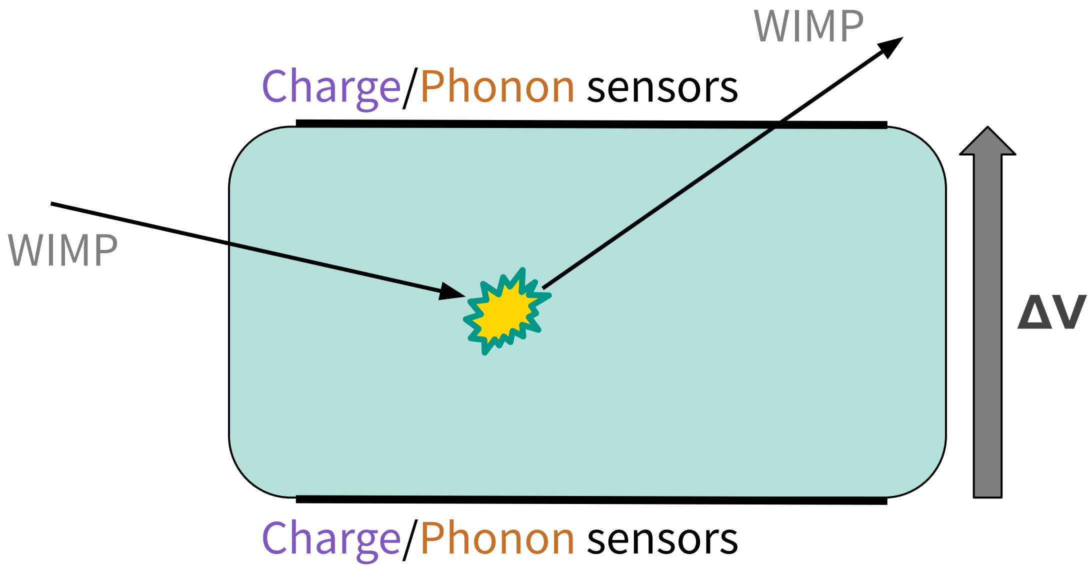




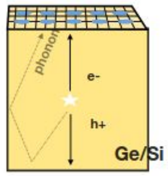
TESSERACT : Ge/Si semiconductors



Dual heat and ionization readout :



TESSERACT : Ge/Si semiconductors



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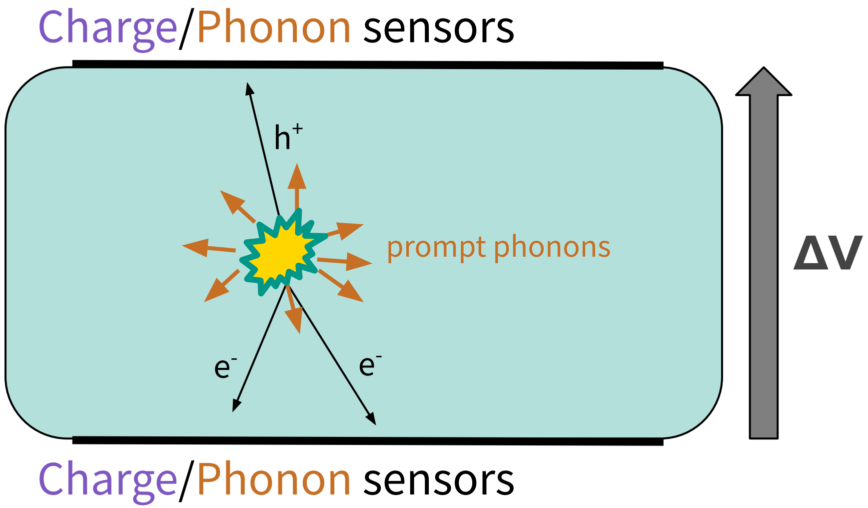
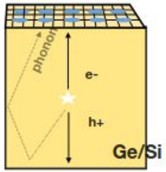
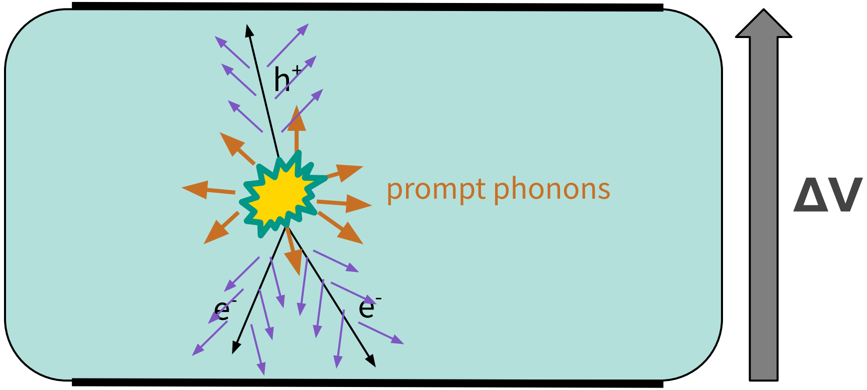


TESSERACT : Ge/Si semiconductors

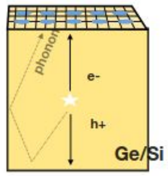


Dual heat and ionization readout :



$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + 1/\omega_{eh}\, E_{ion}\, \Delta V$$

TESSERACT : Ge/Si semiconductors

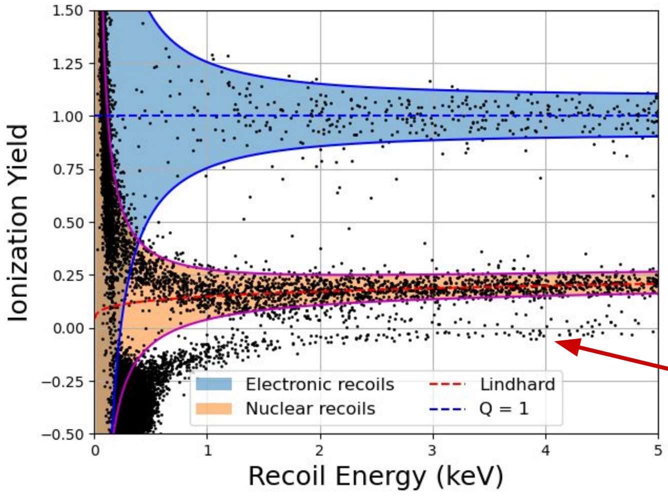


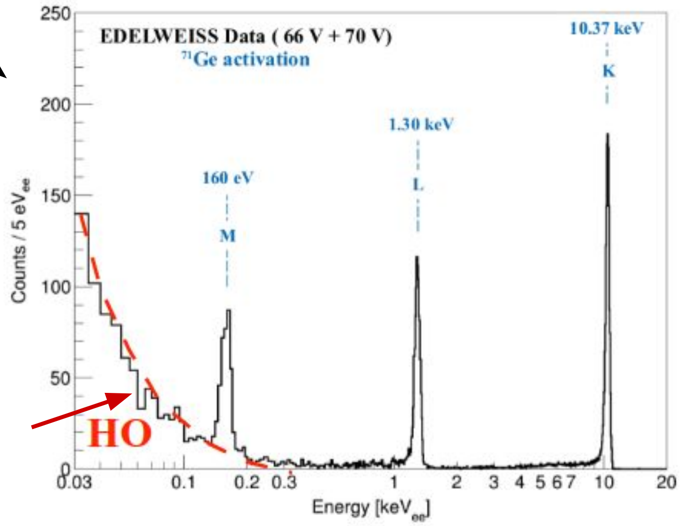
Two working modes

$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + 1/\omega_{eh}\, E_{ion}\, \Delta V$$

Low Voltage mode
Particle ID + Fid

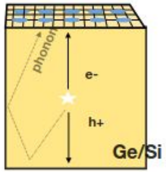
High Voltage mode
no Particle ID - single e/h



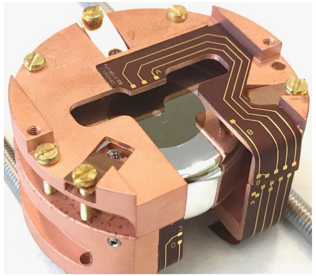


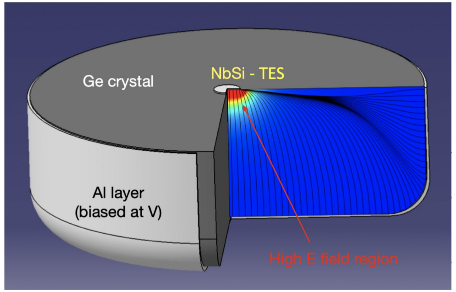
LEE
or HO (Heat Only)

TESSERACT : Ge/Si semiconductors



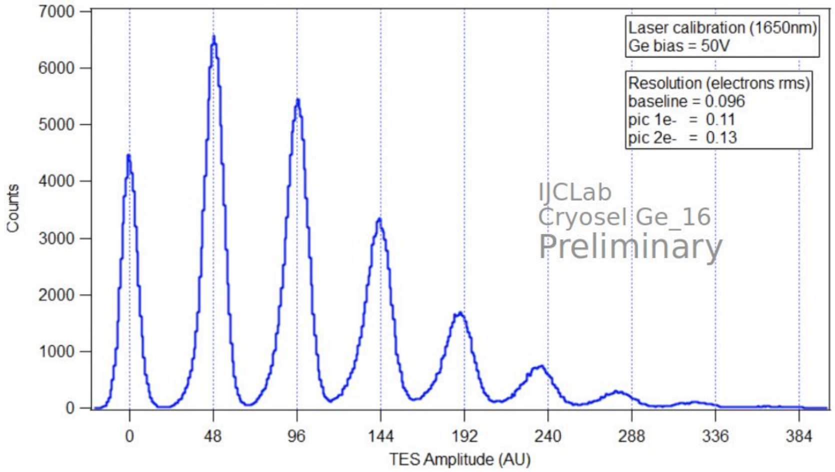
High-Voltage approach for optimal ERDM sensitivity





ANR-CRYOSEL detector R&D :

- 40 g HP-Ge crystal
- Point contact geometry with Luke amplification
- TES for Luke charge read-out
- NTD-Ge sensor for optimal LEE rejection and calibration

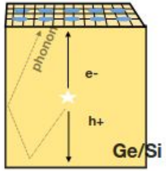


First observation of a single-electron sensitivity in a massive (40g) Ge cryogenic detector !

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

For TESSERACT :

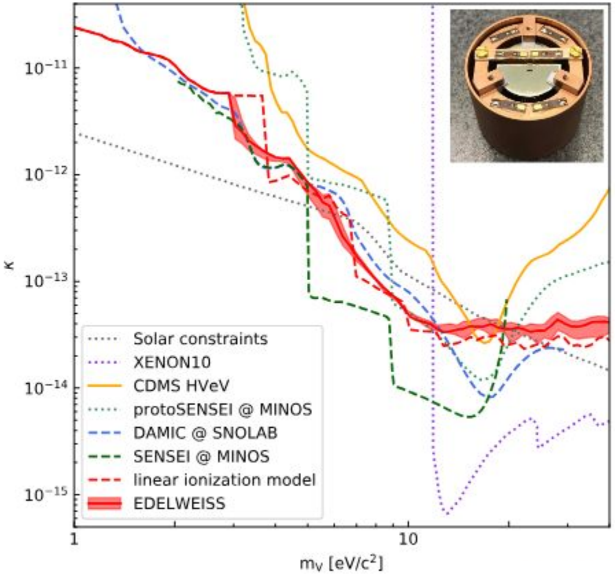
- High control of IR backgrounds and charge leakage
- LEE discrimination down to single e/h pair
- **Exquisite sensitivities to ERDM with LEE discrimination**

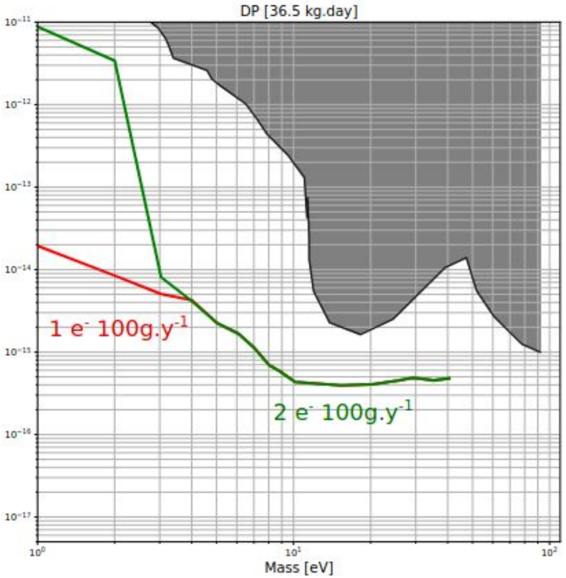


TESSERACT : Ge/Si semiconductors

High-Voltage approach for optimal ERDM sensitivity

EDELWEISS collaboration, PRL 125, 141401 (2020)

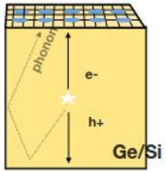




- In 2020 EDELWEISS-III achieved one of the best ERDM sensitivity with sub-electron energy resolution with a 33 g Ge crystal operated at 78 V
- The single-electron technology in TESSERACT will allow to achieve orders of magnitude improved sensitivities

TESSERACT back. model = 10 DRU gamma + other backgrounds from EDW-III

TESSERACT : From RICOCHET to TES4DM



Low-Voltage approach for optimal NRDM sensitivity

Going beyond the Ricochet CryoCube technology

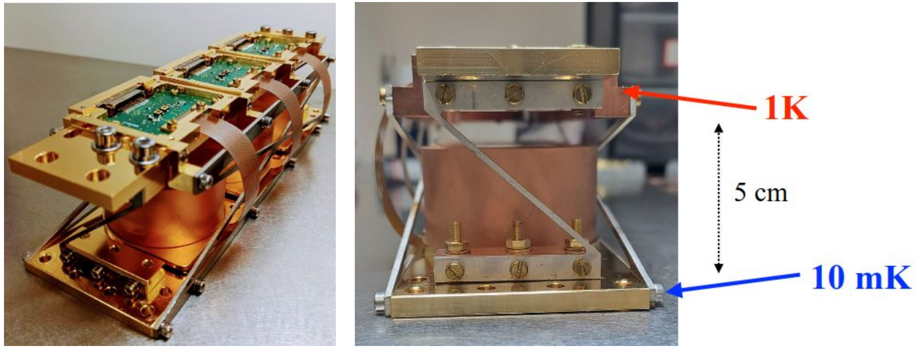
Mini-Cryocube

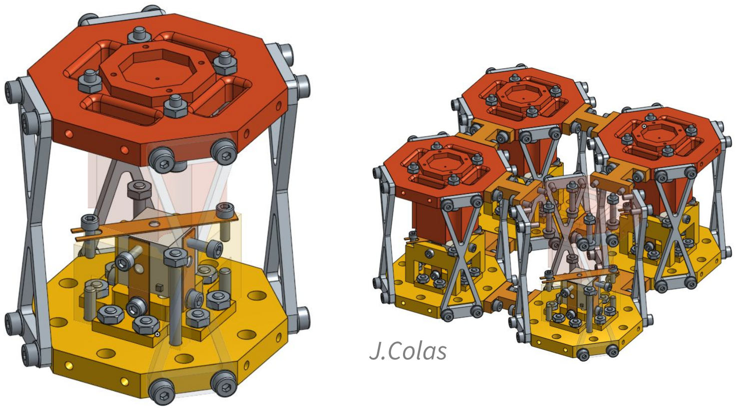
- Phonon sensor : **NTD-Ge**
- Total capacitance **~45 pF**
- σ_{ion} ~**30 - 40 eVee**
- Payload: 3 x **40 g**
- σ_{heat} **~40 eV**

TES4DM

- Phonon sensor : **NTD-Ge ⇒ TES**
- Total capacitance **~5 pF**
- σ_{ion} ~**10 eVee**
- Payload: 4 x **5.35 g**
- σ_{heat} ~**10 eV ⇒ < 1 eV**

Ricochet Coll., Eur. Phys. J. C 84 (2024) 2, 186

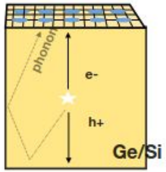


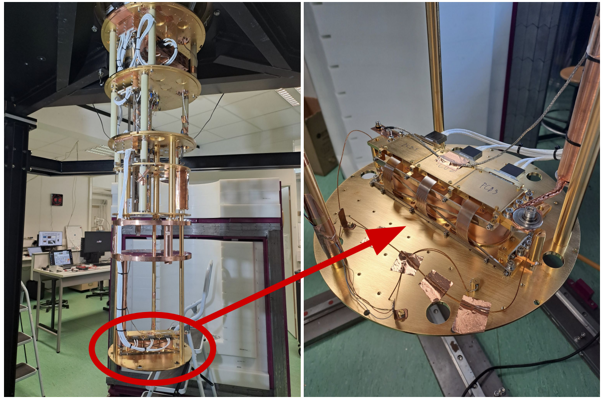


J.Colas

TESSERACT : From RICOCHET to TES4DM

Low-Voltage approach for optimal NRDM sensitivity



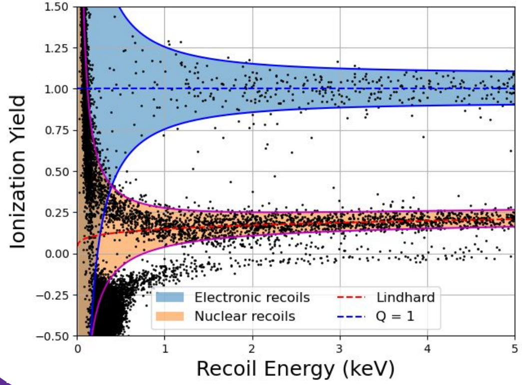


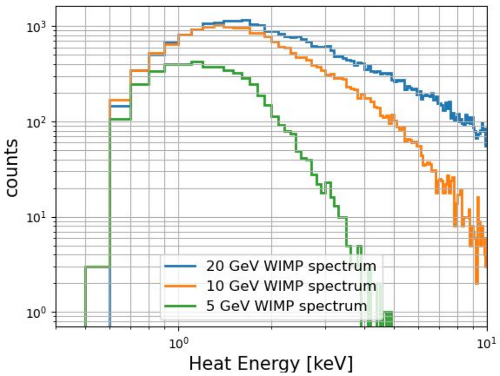
Ricochet @ IP2I

Ricochet Coll., Eur. Phys. J. C 83 (2023) 1, 20

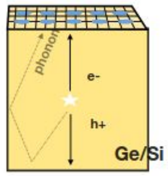
- Mini-CryoCube : 3 bolometers @ 10 mK with HEMT preamplifiers @ 1K only 5 cm above
- Achieved 40eVee and 70 eVph ionization and phonon resolution, respectively
- DM exposure of 200 g.days and neutron calibration with AmBe source

- **Expected TES4DM DM sensitivity : Proof of concept with Ricochet at IP2I**
- Processing and analysis pipeline for TES4DM being developed using Ricochet framework
- DM Limit calculation ongoing with RICOCHET @ IP2I data
- **Next step: estimate the NRDM sensitivity of the future TESSERACT-LV technology with targeted performance**

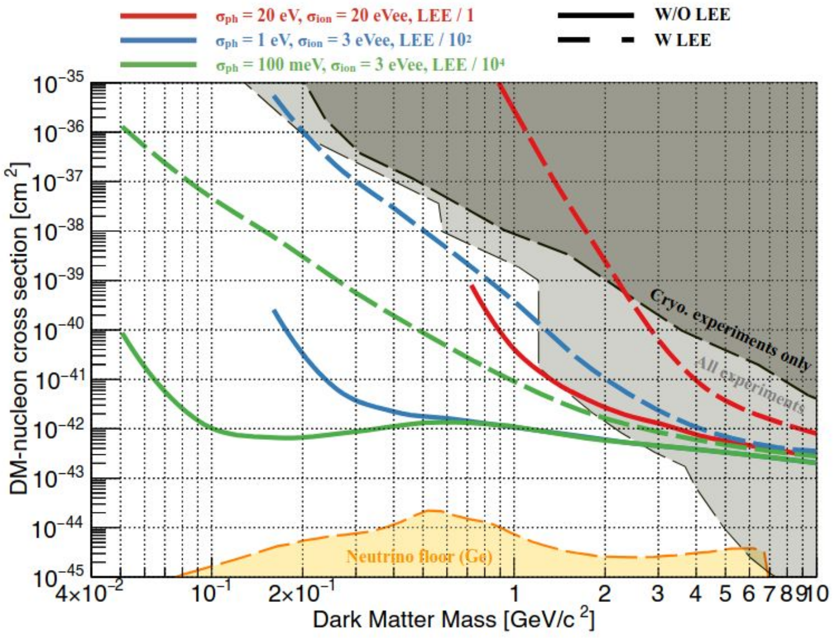




TESSERACT : From RICOCHET to TES4DM



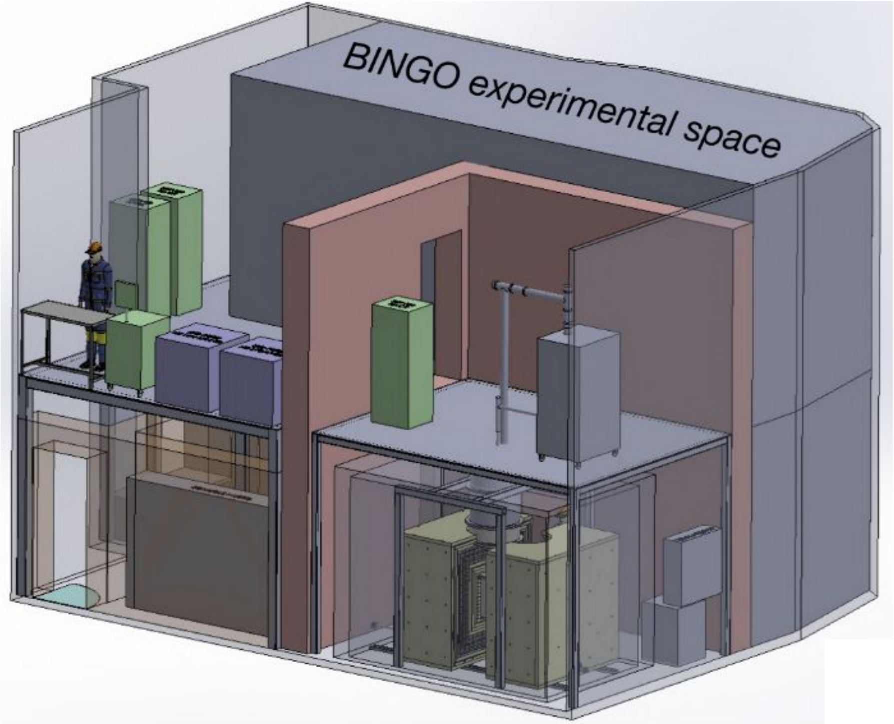
Low-Voltage approach for optimal NRDM sensitivity



The LV technology in TESSERACT will allow to vastly extend the NRDM searches down to 100 MeV with particle ID and LEE rejection in a region of the parameter space inaccessible to non cryogenic experiment

TESSERACT back. model = 10 DRU gamma + other backgrounds from EDW-III

TESSERACT : Proposal for an installation in the *Laboratoire Souterrain de Modane* (LSM)



TESSERACT Integration at LSM

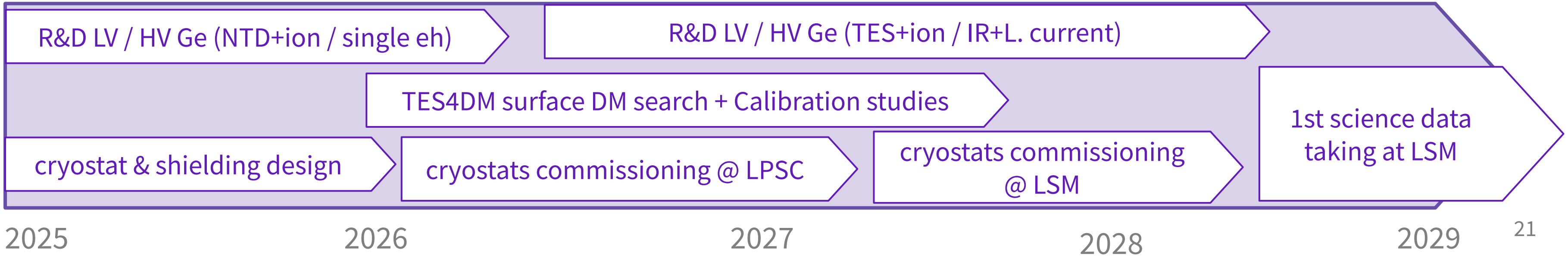
- Two copies of the setup, for enabling both:
  - underground R&D and detector optimisation
  - DM science data taking in parallel
- Targeted background levels of 1 DRU gamma with the possibility to add an active cryogenic veto to further lower the gamma background levels.
- Each detector technologies is designed to achieve major breakthrough in short time scales (few months) hence allowing fast turnarounds
- The two setups will be in LSM between 2027 and 2028

TESSERACT @ LSM

Aim to expand the Dark Matter mass search window from meV to GeV with several different technologies.

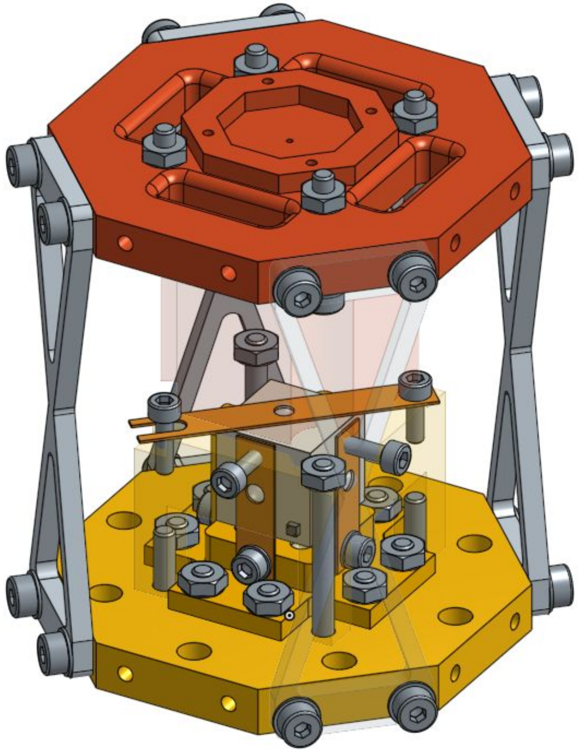
- Different cryogenic targets
- LEE mitigation
- Particle Identification
- Low impedance TES phonon sensors
- LSM ultra-low background environnement

- Ultra-low threshold
- Optimal for both NRDM and ERDM
- Broader DM mass range covering



Thank you for your attention

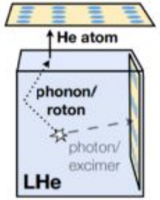
Questions ?

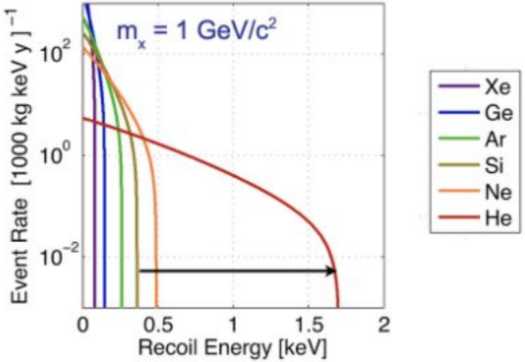


Back-up

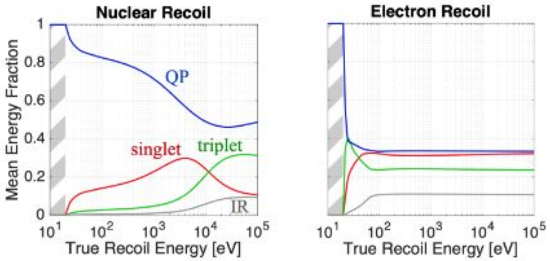
TESSERACT : HeRALD

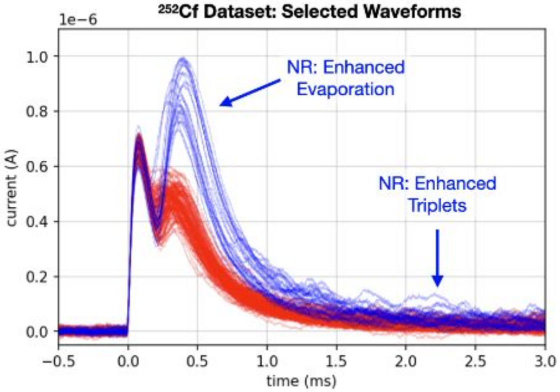
Helium Roton Apparatus for Light Dark matter





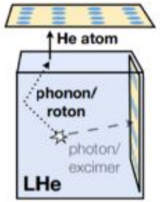
R. Anthony-Petersen et al., arXiv:2307.11877



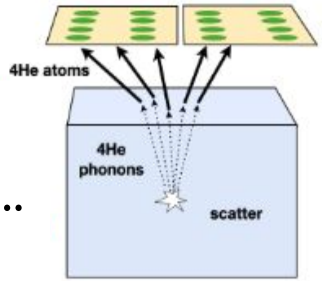


- Well kinetically matched to GeV-scale DM
- Easy to purify, intrinsically radio pure
- Monolithic and scalable
- LHe cell operated at 20-50 mK with wafer-like cryogenic detector with TES suspended in vacuum
  - UV/IR photons and He atoms from qp induced evaporation
- First evidence of ER/NR discrimination at 10 keV
- Already achieved 170 eV threshold on He recoils (300 MeV DM)

TESSERACT : HeRALD



Helium Roton Apparatus for Light Dark matter



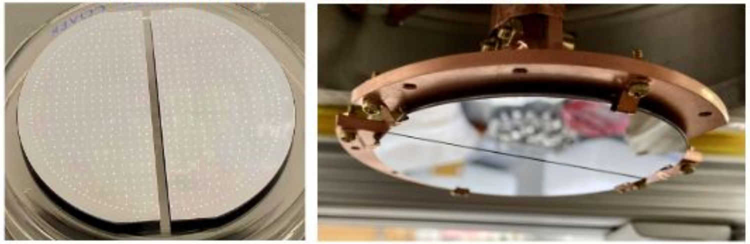
^4He is unique in two ways :

1. **Target material (4He) close to a macroscopic quantum ground state, with no defects, stress …**
   Superfluid ^4He is nearly unique among bulk target materials in this regard
2. **Quantum evaporation allows for robust coincidence-based selection of target events at sub-eV scales**

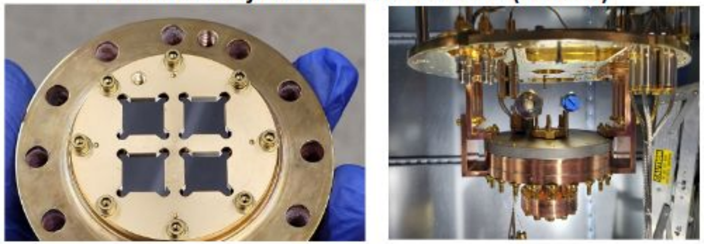
Events in calorimetry :	single-channel (vacuum gaps mean no shared phonons)
Events in ^4He :	always multiple channel (evaporated atoms have large angular spread)

⇒ Near-term HeRALD plans all involve multi-channel evaporation readout and testing the above strategy

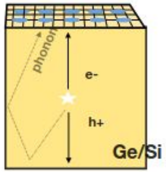
2-Channel Array for HeRALD v0.1 @UMass (3-inch)



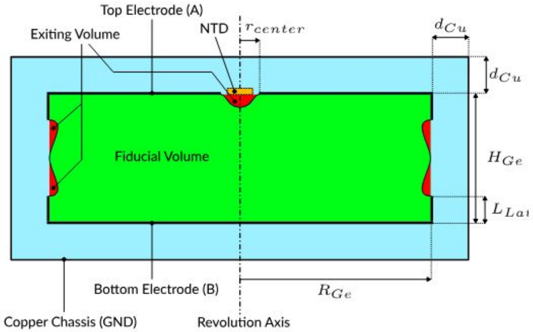
4-Channel Array for HeRALD v0.2 @LBNL (4x 1cm^2)

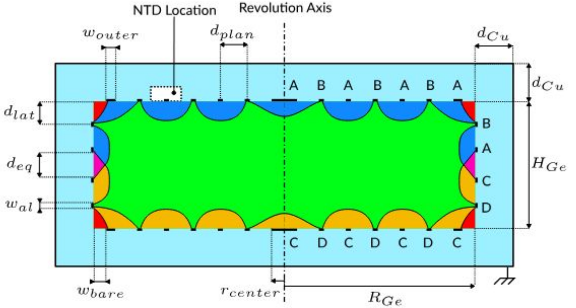


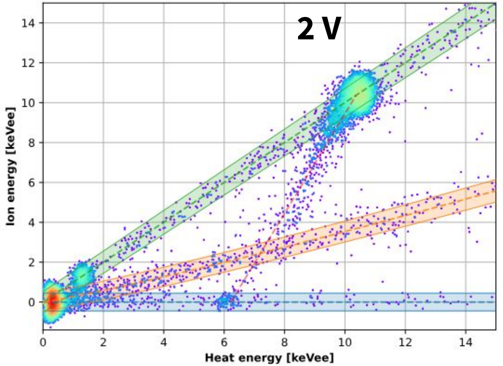
TESSERACT : Ge/Si semiconductors



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







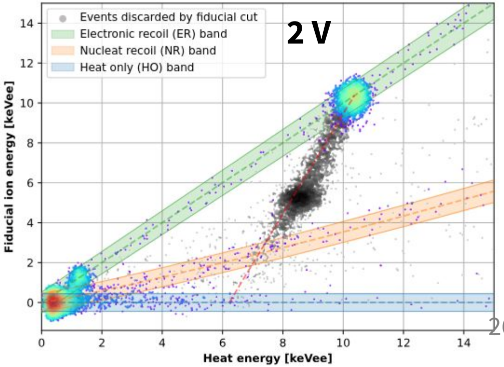
Salagnac & al: arXiv:2111.12438

PL 38

FID 38

- Incomplete charge coll. **< 10 %**
- Fiducial volume : **96 %**
- Surface event rejection : **NO**
- Total capacitance : **15 pF**

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



TESSERACT : Proposal for an installation in the *Laboratoire Souterrain de Modane* (LSM)