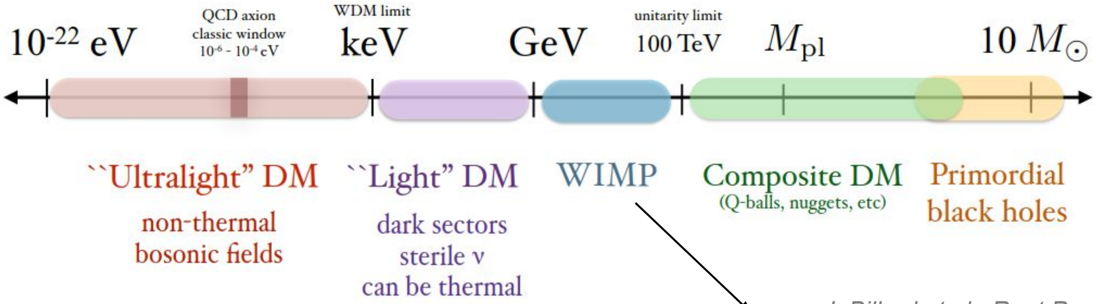
Light DM search with TESSERACT

Paul Vittaz, IP2I - CNRS

Bi-national conference on detectors R&D - 29/11/2025

Motivations

DM candidates : 50 orders of magnitudes in mass



T. Lin

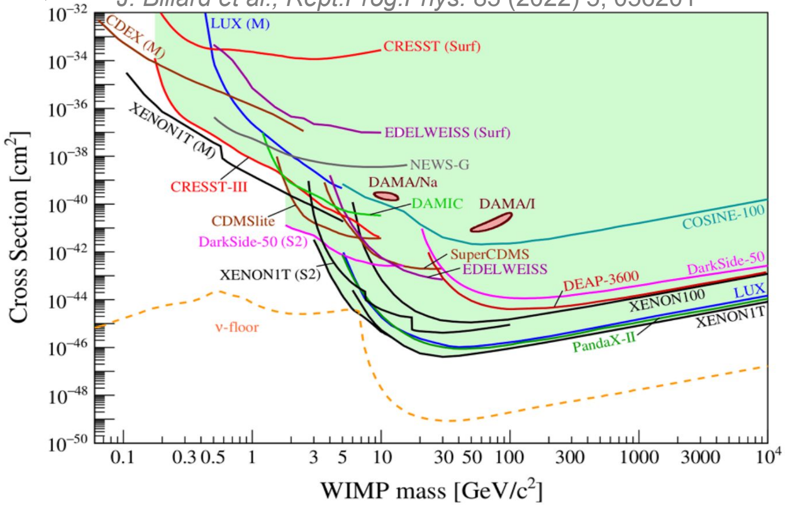
Focus of DM searches for the last decades has been on standard WIMP (10 GeV - TeV)

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 are approaching the neutrino limit

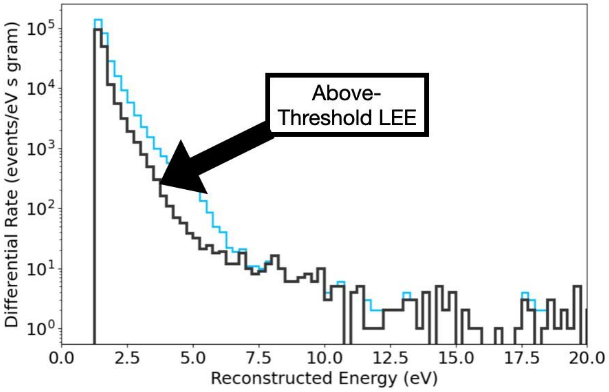
Need for new experiment with broader DM mass range and increased sensitivity to more DM interactions ⇒ use of low threshold cryogenic detectors

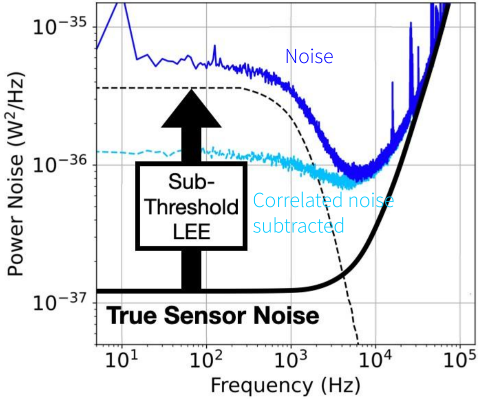
J. Billard et al., *Rept.Prog.Phys.* 85 (2022) 5, 056201



Low Energy Excess

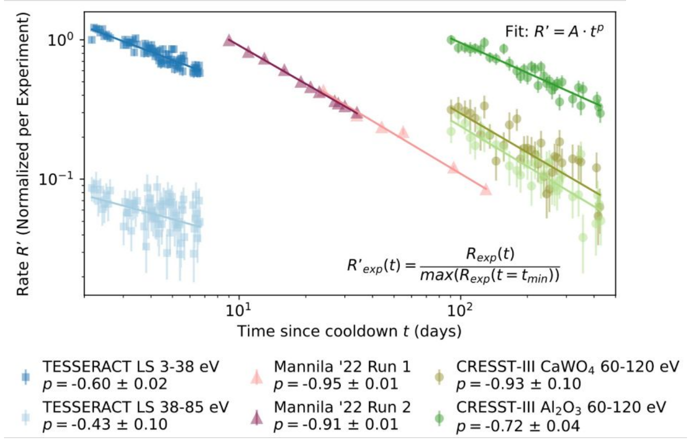
- Currently, all cryogenic experiment which have reached sub keV threshold are seeing a Low Energy Excess (LEE) limiting their DM search (between 10^6 and 10^8 evt/kg/keV/day at 100 eV recoil energy)
- LEE represent both the largely <u>dominating background</u> at the lowest energies **AND** the noise limiting our phonon <u>baseline energy resolution</u>
- LEE characteristics : time dependant, non ionising (“Phonon Only”), dependance with holder/vibrations (?)





SPICE experiment : arXiv:2505.16092

arXiv: 2503.08859



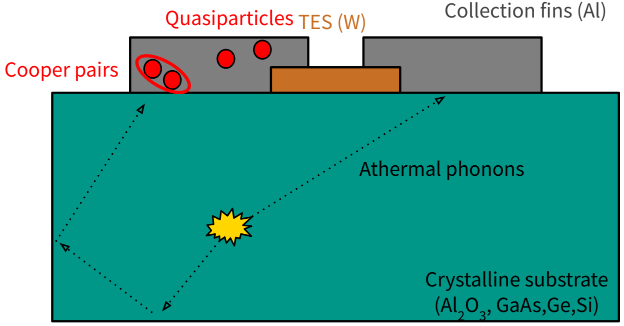
TESSERACT : Proposed experiment at LSM

Transition Edge Sensor with Sub-Ev Resolution And Cryogenic Targets

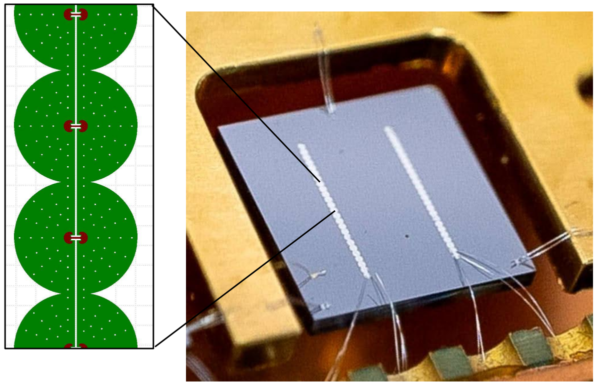
- Target : extend the DM search window from meV to GeV with ultra-low threshold cryogenic detectors, using :
  - sub-eV energy thresholds
  - background rejection capabilities
  - diverse target materials with diverse DM couplings
  - ultra quiet underground cryogenic infrastructure at LSM
- Design driver :
  - find the origin of LEE to mitigate it
  - develop technologies that can reject it

TESSERACT : New generation TES phonon sensors

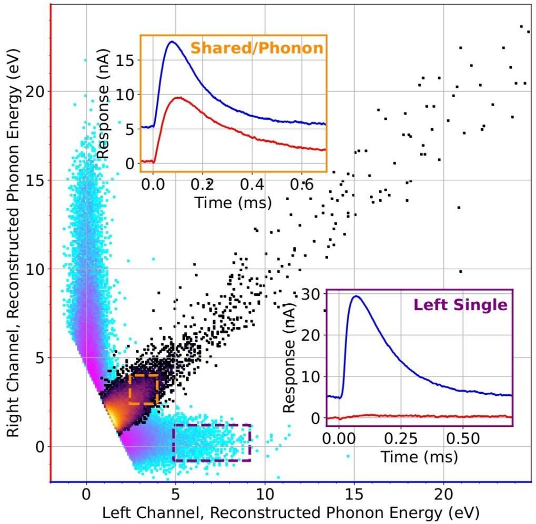
arXiv:2503.03683v2

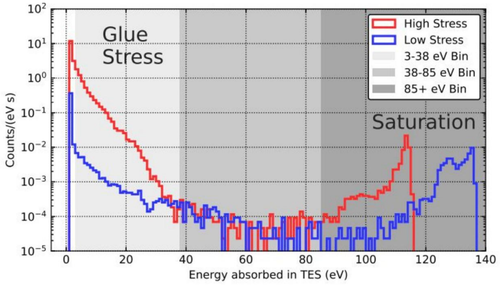


$$\sigma_E \propto V_{det}^{1/2} T_c^3$$



1 cm^2 x 1 mm (Si)

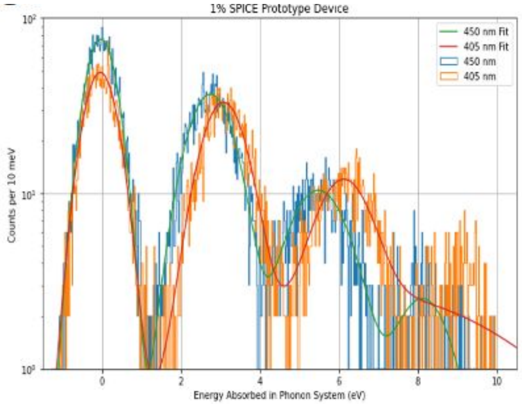


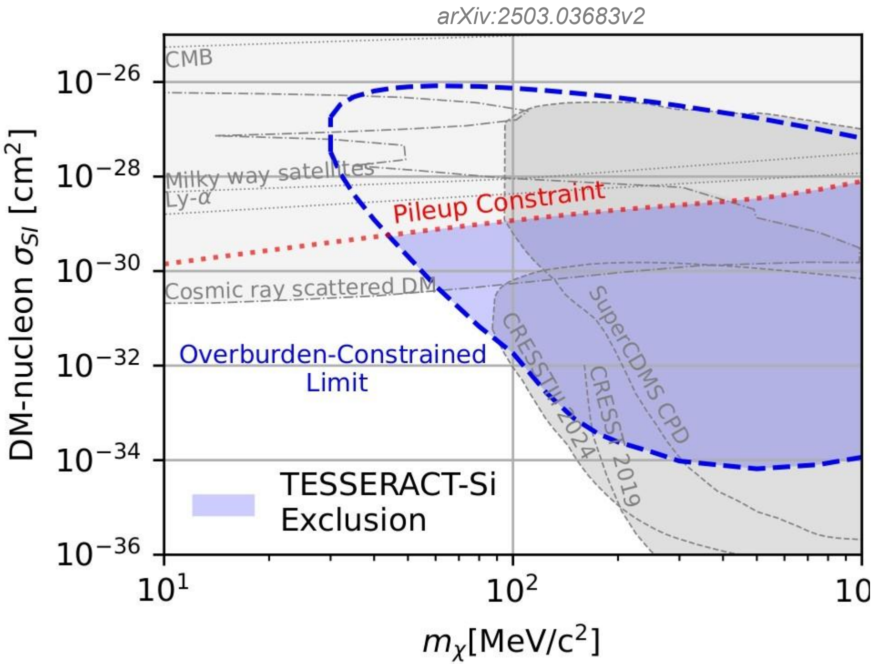


- Need to lower the detector **volume** and the TES critical **temperature** to increase the sensitivity
- LEE mitigation : Low-stress holder ⇒ detector suspended by Al wires
- Background discrimination : Use of two TES channels ⇒ remove sensor stress-induced events (single channel events)

TESSERACT : New generation TES phonon sensors

Proof of concept : 1st DM limit from above-ground detector



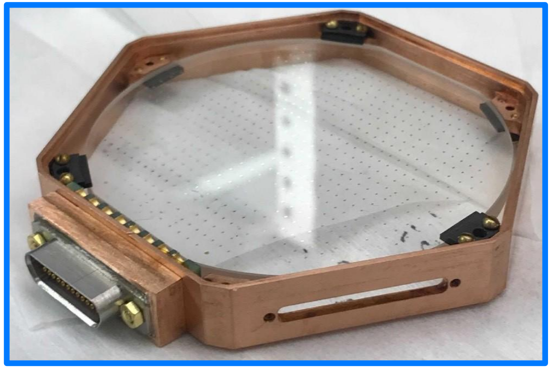


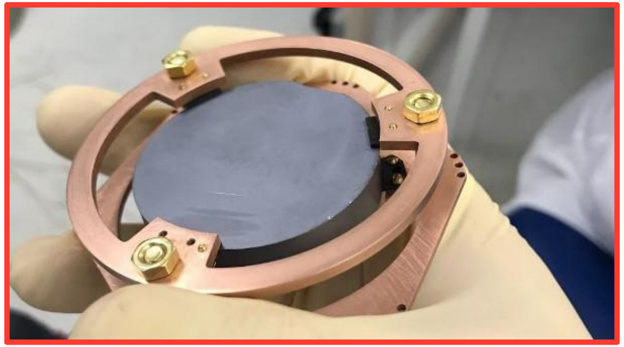
- World leading 258.5 meV baseline resolution leading to eV-scale threshold already achieved with a 0.2 g Si detector and T = 50 mK : *arXiv:2505.16092v2*
- Dark Matter limit published : *arXiv:2503.03683v2*
- Targeted Tc around 15-20 mK recently achieved

SPICE (Sub-eV Polar Interaction Cryogenic Experiment)

Sapphire (Al_2O_3):

- Sapphire supports many optical phonon modes (~ 100 meV)
- 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
- *LEE mitigation :* Use of two TES-channels to suppress sensor induced LEE

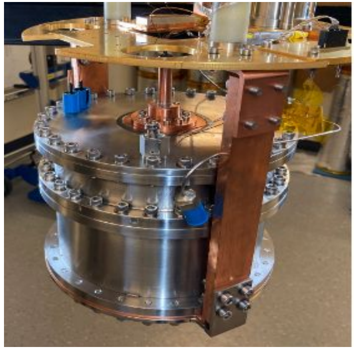




GaAs:

- Polar crystal & bandgap well matched to kinematic region of low mass DM
- Background discrimination using phonon/photon ratio
- *LEE mitigation :* Photon-phonon coincidence

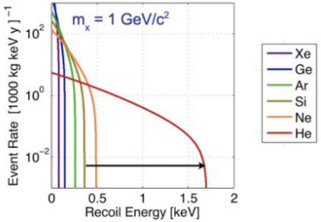
HeRALD (Helium Roton Apparatus for Light Dark Matter)

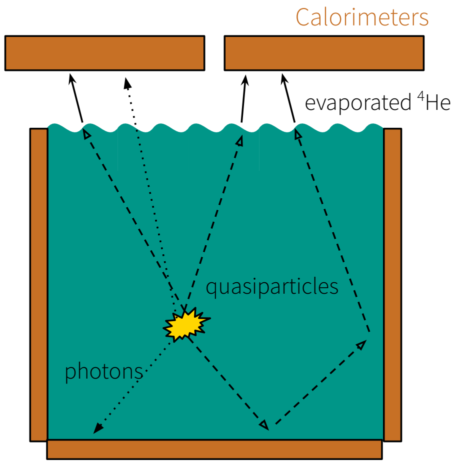


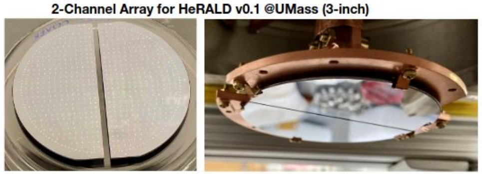
R. Anthony-Petersen et al., arXiv:2307.11877

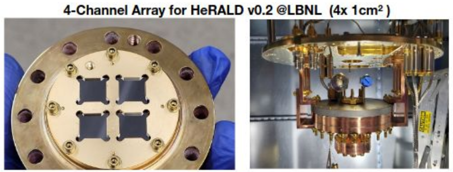
Target : Liquid He

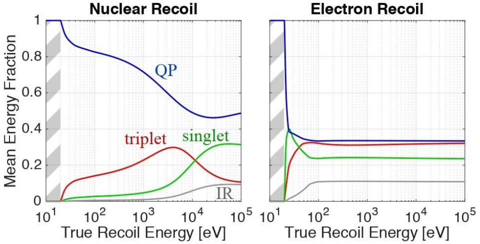
- Light material ⇒ better kinematic matching with LDM
- Extremely radiopure
- No internal stress nor dislocation (LEE source ?)
- Superfluid ⇒ no vibrational coupling with the environment (another LEE source ?)
- Several signal channels ⇒ particle identification through pulse shape discrimination
- *LEE mitigation :* multichannel evaporation readout to reject LEE via coincidences

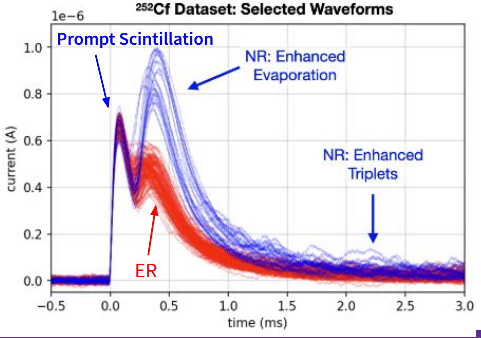






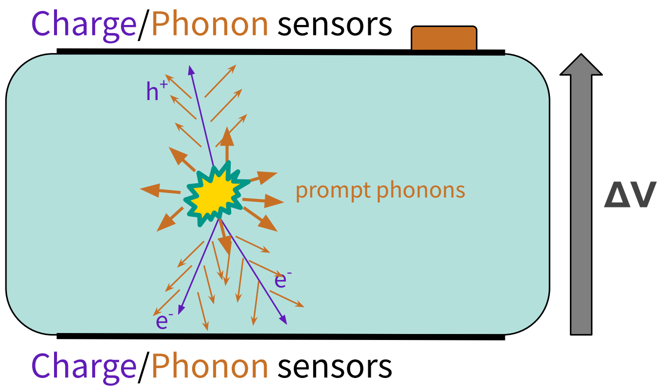


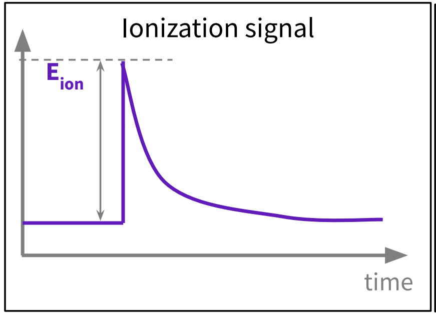


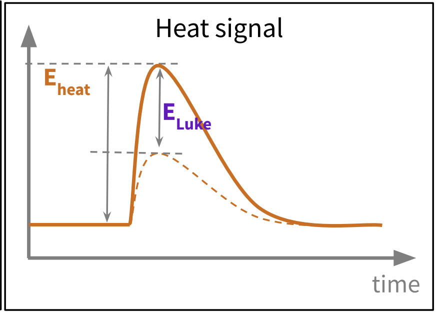


Ge/Si semiconductors

Based on EDELWEISS and Ricochet expertise







$$E_{heat} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + E_{ion}\,\Delta V/\varepsilon_{eh}$$

- Two channels : heat and ionization
- Luke boost ⇒ additional phonons proportional to ΔV

⇓

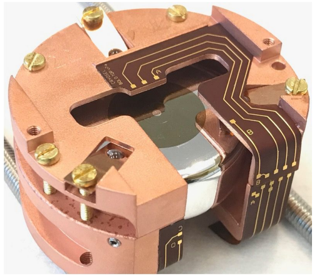
Two working modes : High Voltage (HV) and Low Voltage (LV)

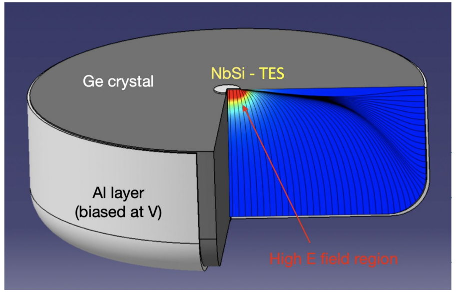
Ge/Si semiconductors HV

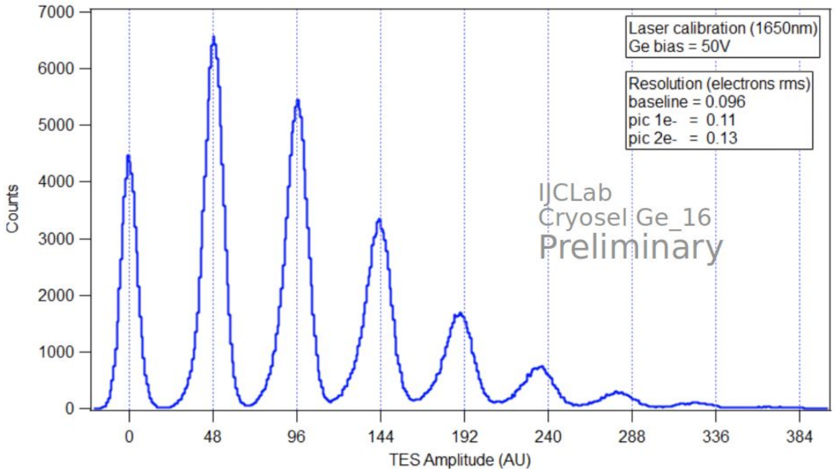
High-Voltage approach for optimal ERDM sensitivity

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

$E_{heat} \simeq E_{ion}\ \Delta V/\varepsilon_{eh}$ (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 :

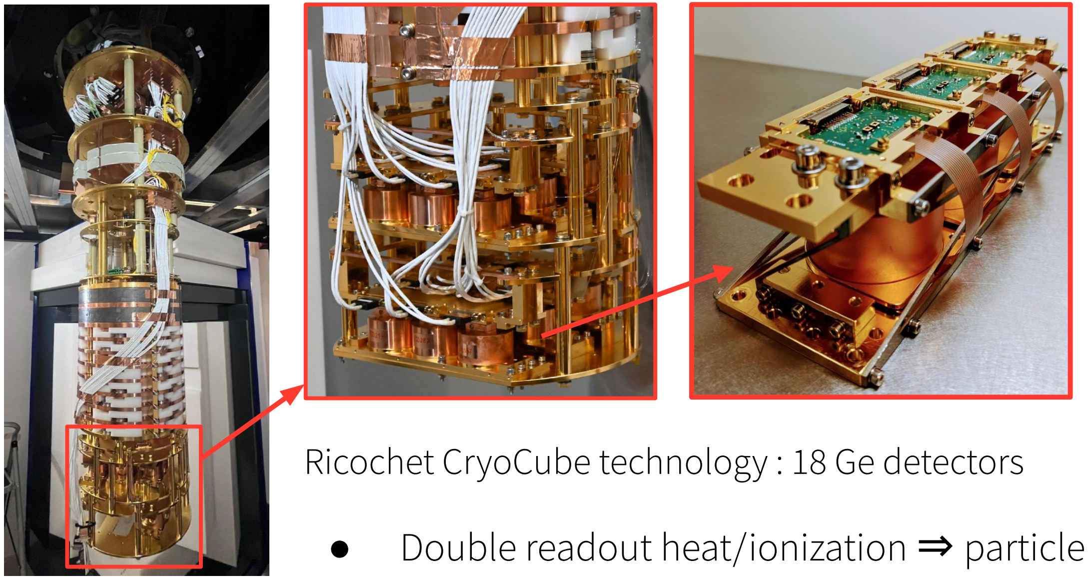
- High control of IR backgrounds and charge leakage
- LEE discrimination down to single e/h pair
- **Exquisite sensitivities to ERDM with LEE discrimination**

Ge/Si semiconductors LV

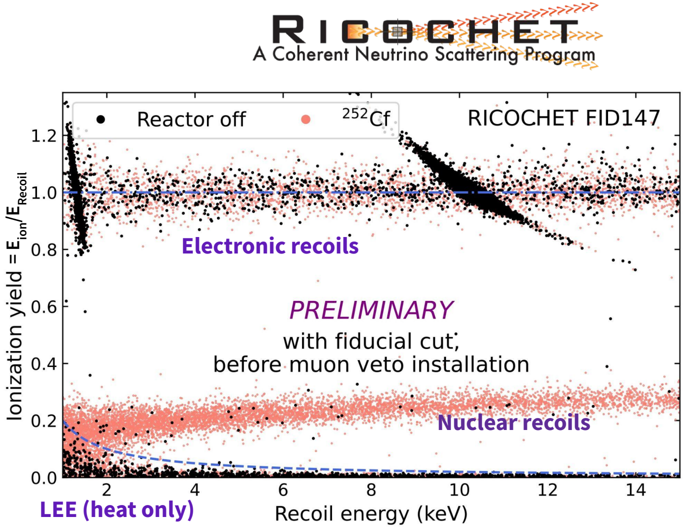
Low-Voltage approach for optimal NRDM sensitivity

Decades of expertise from **EDELWEISS** and **Ricochet** experiments in dual phonon-ionization readout with cryogenic detectors

arXiv:2507.22751



Ricochet CryoCube technology : 18 Ge detectors



- Double readout heat/ionization ⇒ particle identification
- 30 eVph and 30 eVee (RMS) @ ILL
- LEE are non ionizing ⇒ improving the charge resolution is of major importance

Ge/Si semiconductors LV

Low-Voltage approach for optimal NRDM sensitivity

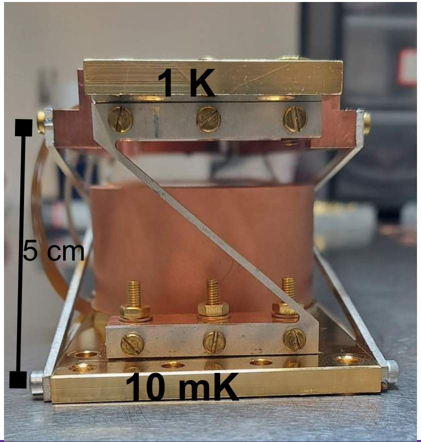
FRAMA FRANCE 2030

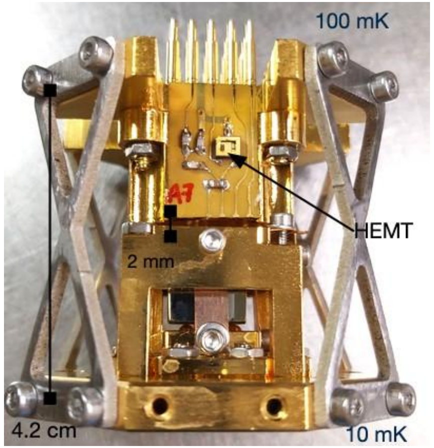
Ricochet Cryocube

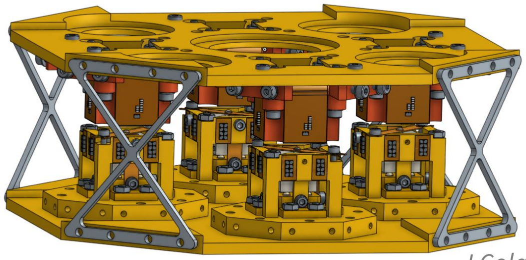
- Looking for : CENNS
- Phonon sensor : NTD-Ge
- Payload: 18 x 40 g
- Total capacitance ~45 pF
- σ_{ion} ~ 30 - 40 eVee
- σ_{heat} ~ 30 eVph

TESSERACT

- Looking for : DM
- Phonon sensor : NTD-Ge ⇒ TES
- Payload: 4 x 5 g (1 cm^3)
- Total capacitance ~5 pF
- σ_{ion} ~ 10 eVee } Projections
- σ_{heat} < 1 eVph } Projections

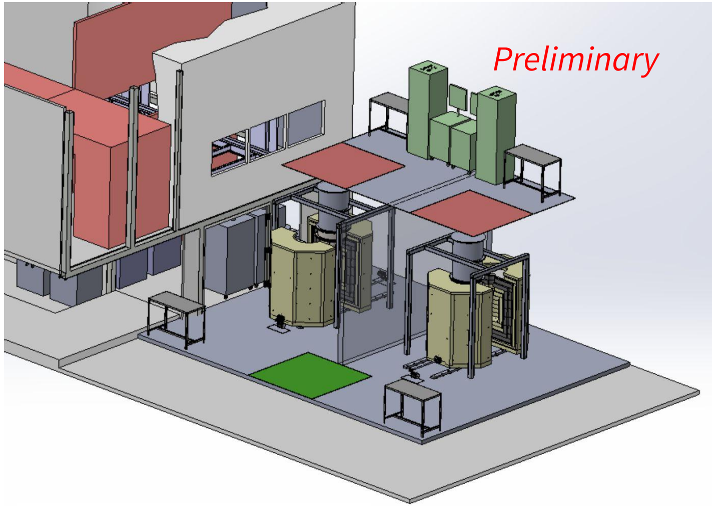






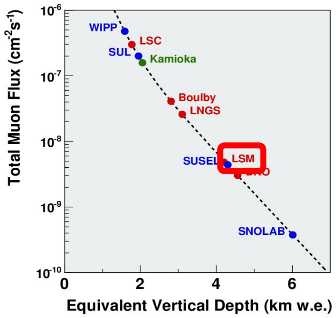
J.Colas

R&D ongoing ...



TESSERACT Integration at LSM

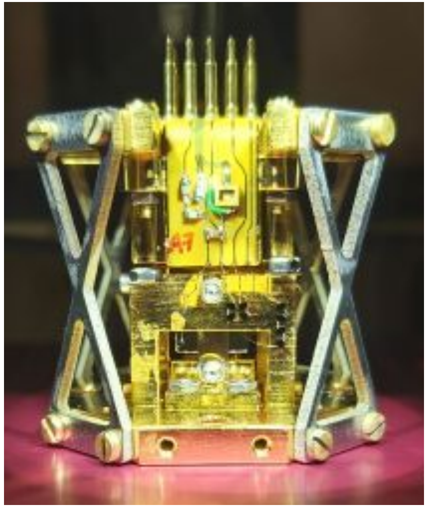
- Two copies of the setup, for enabling both:
    - underground R&D and detector optimisation
    - DM science data taking in parallel
- Each detector technologies is designed to achieve major breakthrough in short time scales (few months) hence allowing fast turnarounds
- Targeted background levels < 5 evt/kg/keV/day
- The two setups will be in LSM between 2028 for first DM science data in 2029



- ❖ LSM *(Laboratoire Souterrain de Modane)* : deepest site in Europe, 4800 m.w.e, 5 μ/m²/day
- ❖ Clean room + deradonized air
- ❖ PE and lead shielding
- ❖ Selection of radiopure materials

TESSERACT @ LSM

- Different cryogenic targets (Si, Ge, Al_2O_3, GaAs, ^4He) to look for several types of interaction and DM masses
- Multiple signal channels and coincidence-based background rejection to reject LEE and other backgrounds
- Sub-eV phonon energy resolution
- LSM ultra-low background environnement



Detectors R&D - Fabrication - Testing - Optimization

surface DM search + **Calibration studies**

cryostat & shielding **design/ procurement**

cryostat **commissioning @ LPSC**

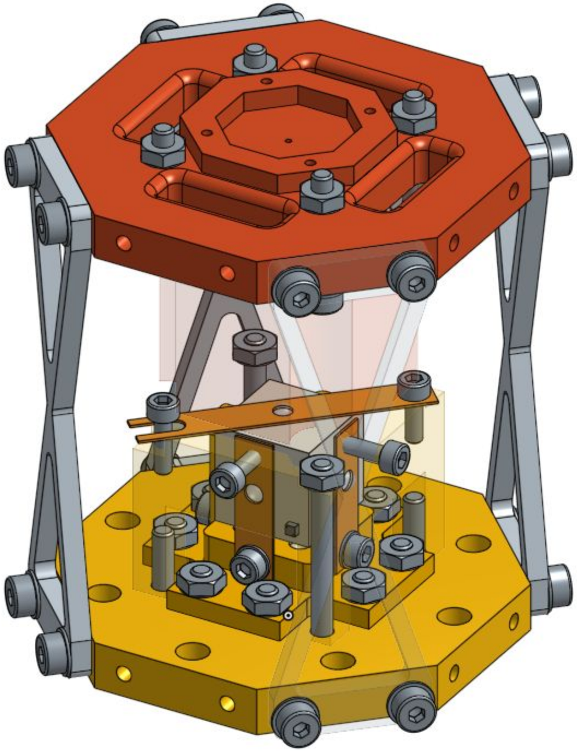
cryostat **Integration @ LSM**

1st science data taking at LSM

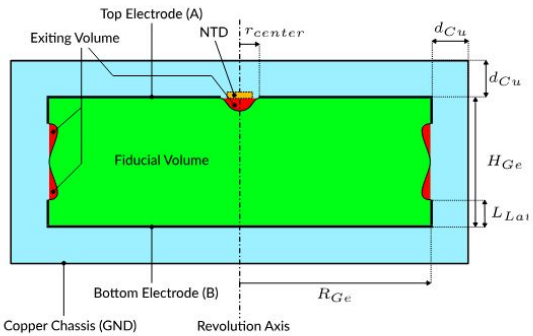
2025 2026 2027 2028 2029

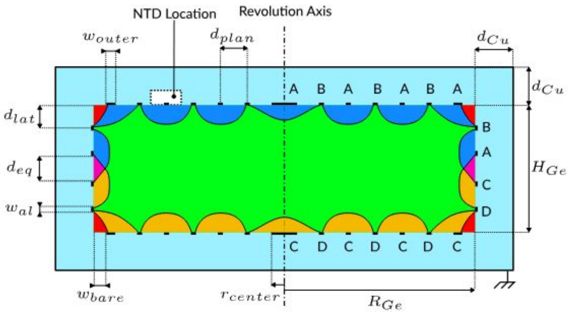
Thank you for your attention

Questions ?

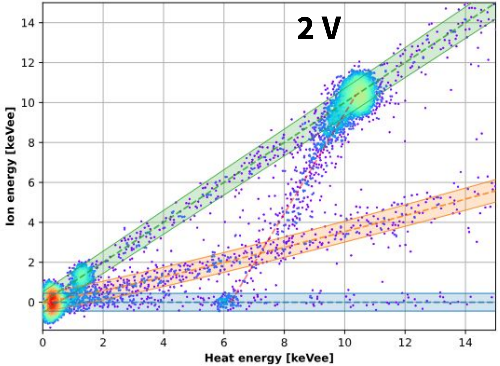


Low-Voltage approach for optimal particle identification (Ricochet style bolometer)



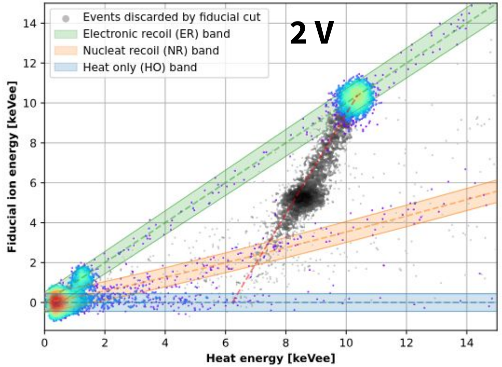


Salagnac & al: arXiv:2111.12438



PL 38

FID 38



PL 38:

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

FID 38:

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

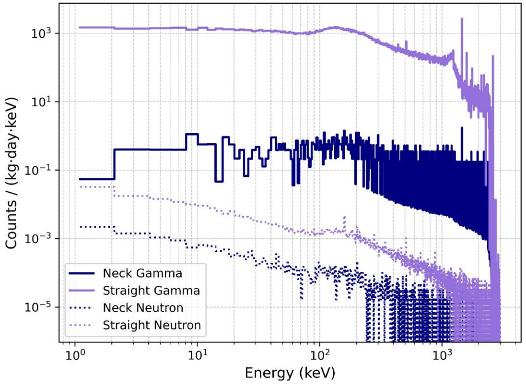
Shielding

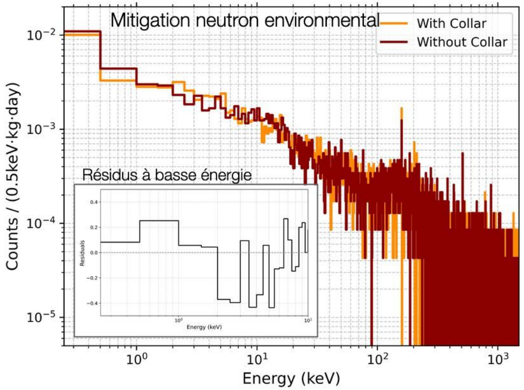
Designed around commercial cryostat and vertical layout.

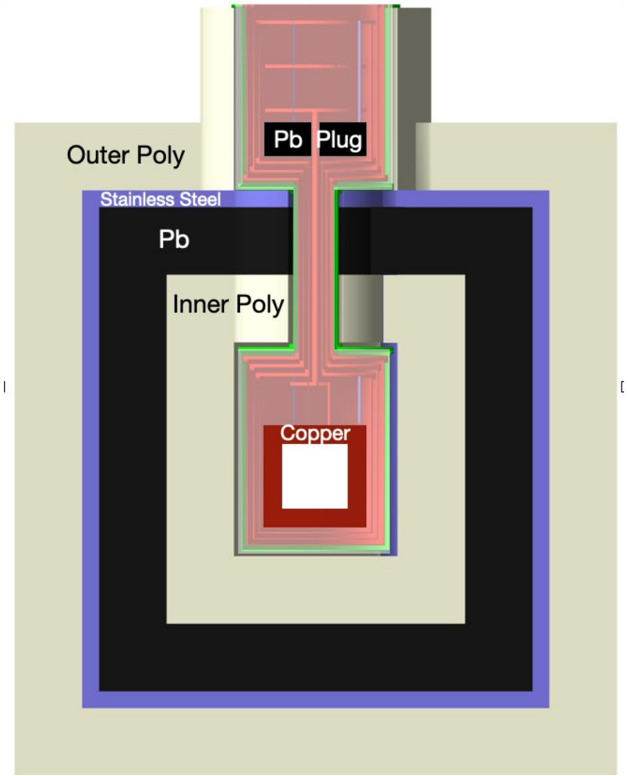
- Narrow 'neck' region, with Pb plug above at 1K
- Thick Cu at base temperature surrounds target region.

Material screening at LSM ongoing

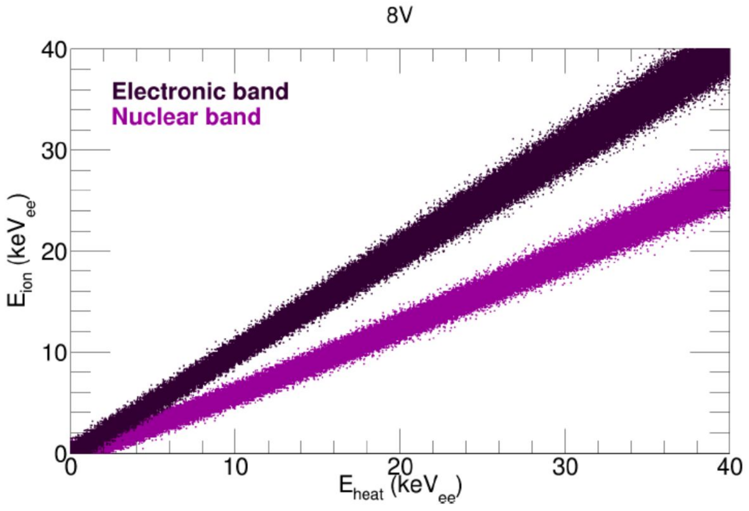
Simulations predict **~1 DRU (ER)**
< 1e-3 DRU (NR)
(possible future upgrade: cold inner veto)

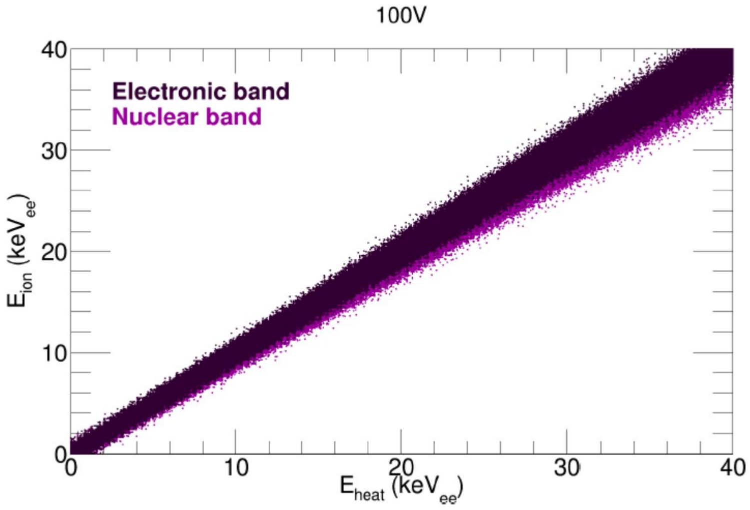






High Voltage loss of Particle Identification

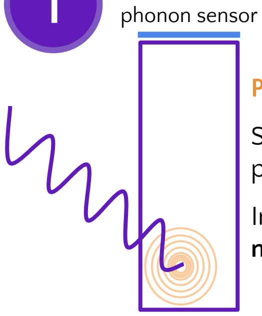




Back-up

Different kinds of phonons and different sensors

1

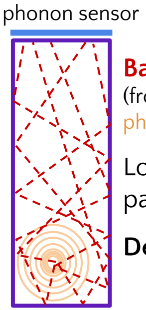


Primary phonons

Short mean free path

In general, **do not reach sensor**

2



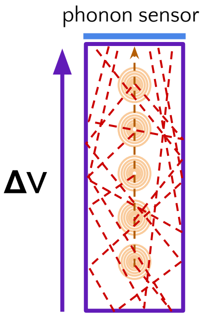
Ballistic phonons
(from decay of primary phonons)

Long mean free path

Detectable in TES

3

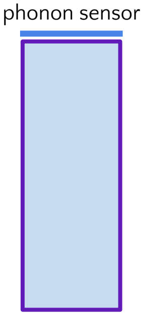
When applying an electric field :



Additional NTL phonons : primary + ballistic production **along field lines**

→ **primaries** at the end of field lines **detectable in TES**

4



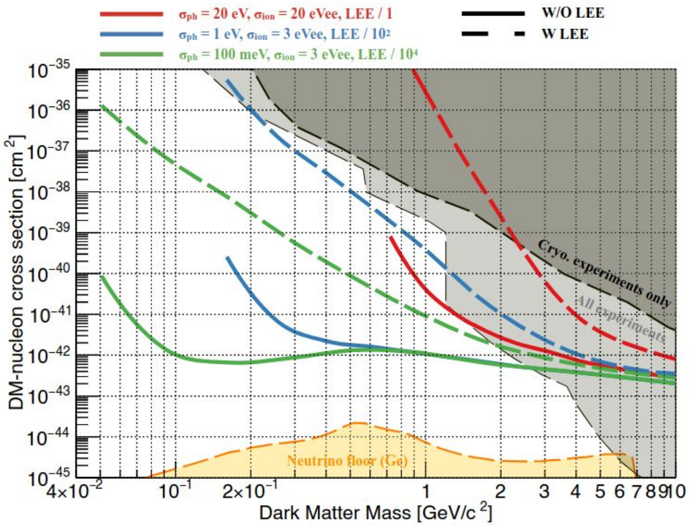
Thermal phonons
(from decay of ballistic phonons)

Detectable in Ge-NTD thermistance (as in RED30)

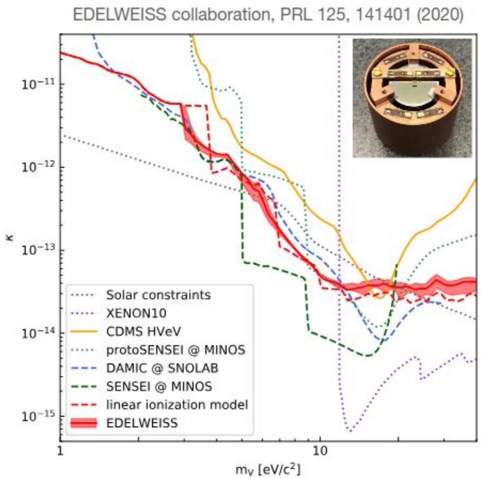
TES sensor

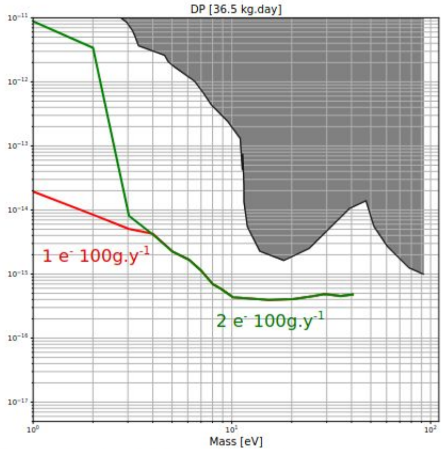
Ge-NTD sensor

Back-up



LV





HV

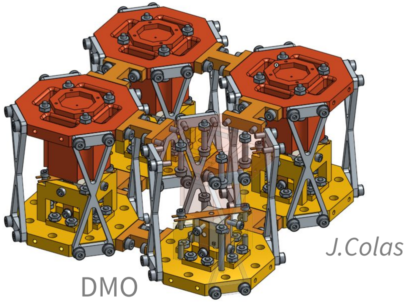
TESSERACT back. model = 10 DRU gamma + other backgrounds from EDW-III

From Ricochet to TESSERACT

Going beyond the Ricochet CryoCube technology

TESSERACT DEMOnstrator (DMO)

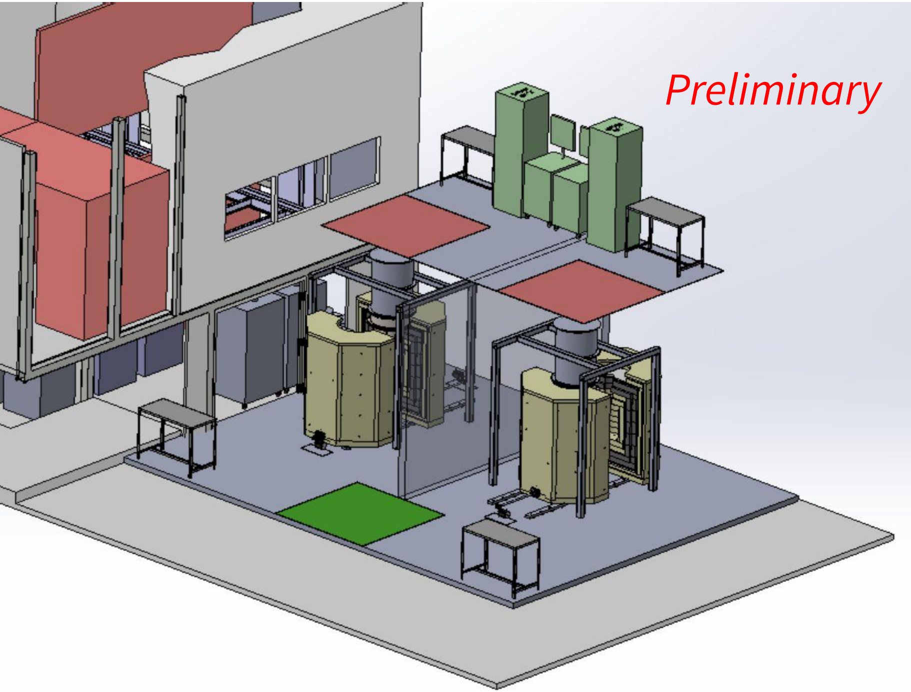
- Looking for : **DM**
- Phonon sensor : **NTD-Ge**
- Total capacitance **~5 pF**
- Payload: 4 x **5.35 g**
- σ_{ion} **10 eVee**
- σ_{heat} **~10 - 20 eVph**



- Reduce the detector volume
- Put the HEMT amplificator at < 1 cm from the electrode
- Optimize the holder, COMSOL driven

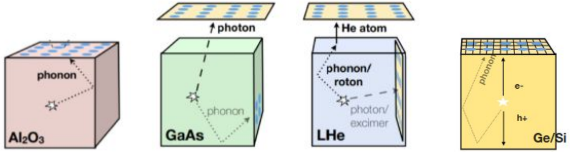
- Reduce the detector volume
- Optimize NTD dimension
- Low microphonic holder

Transition Edge Sensor with Sub-Ev Resolution And Cryogenic Targets



Two cryostats, one experimental design, several targets :

- SPICE (Al_2O_3 and GaAs)
- HeRALD (LHe)
- Ge/Si bolometers



All equipped with new generation TES

Complementary DM sensitivity

Final setup at Laboratoire Souterrain de Modane (2028)