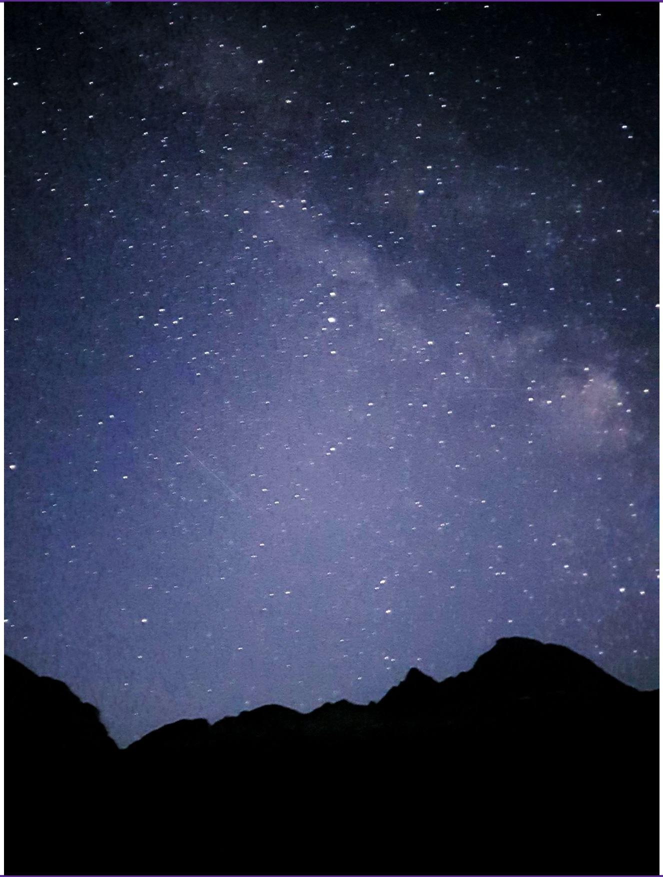
Light Dark Matter search with TESSERACT experiment

Paul Vittaz
supervised by *J. Billard* and *J. Gascon*

PhD days - 17/04/2025

SUMMARY

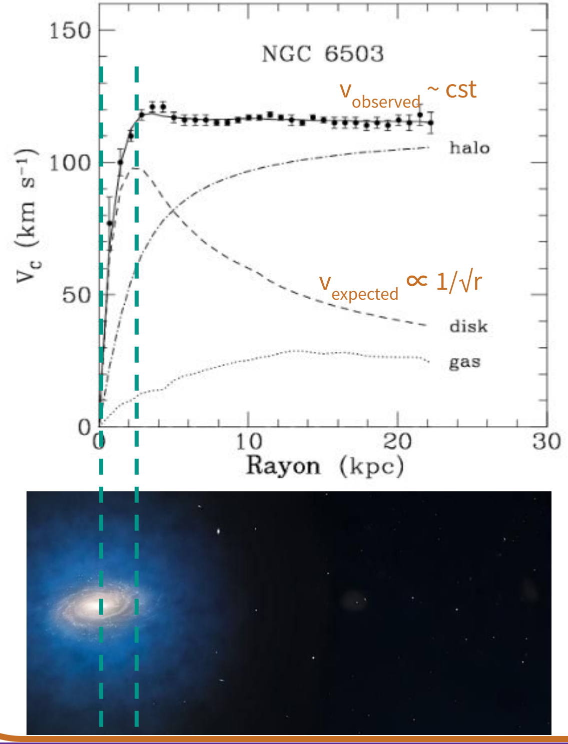
- **Context**
  - The Dark Matter issue
  - Detection strategy
- **TESSERACT Bolometers**
  - Working principle
  - Design (COMSOL)
  - Status
- **Data analysis**
  - Set-up (Ricochet)
  - Simulation & injections
  - Dark matter limit
- **Conclusion**



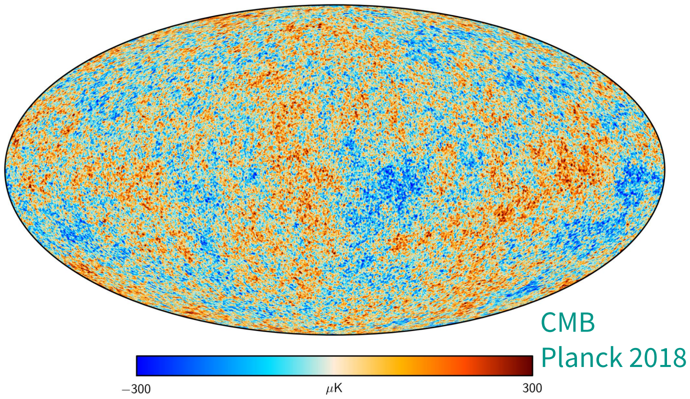
CONTEXT - The Dark Matter issue

Local scale

G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267 (1996) 195-373

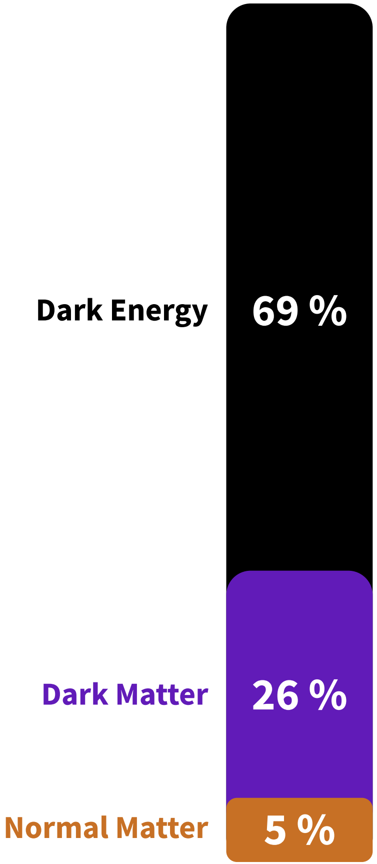


Large scale

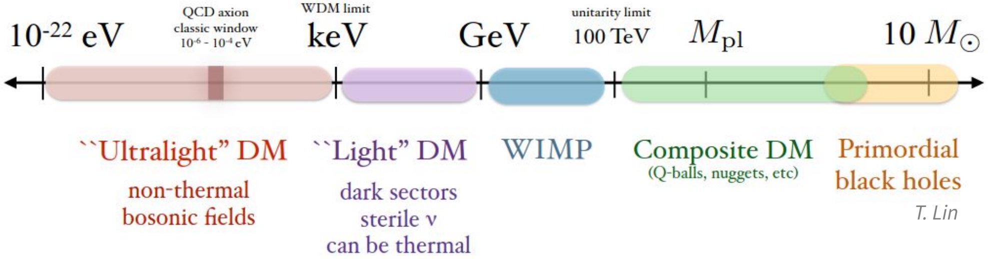


CMB
Planck 2018

Missing mass → **ΛCDM cosmological model**



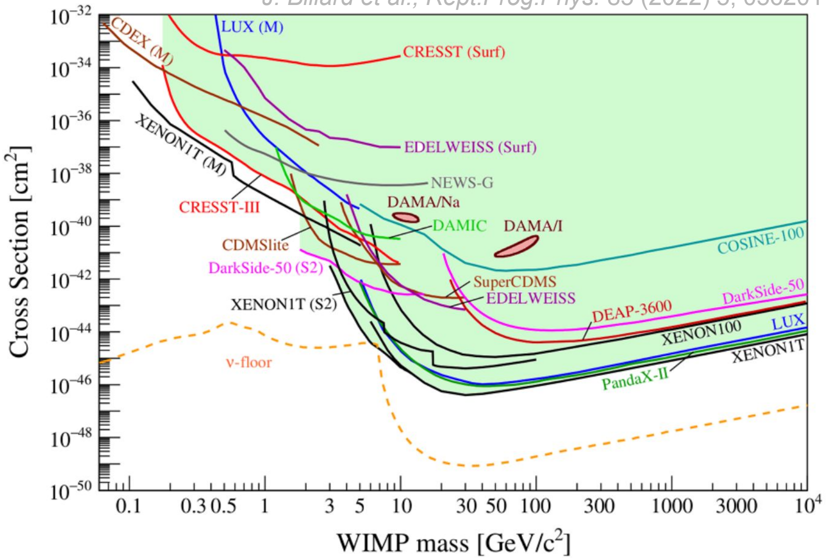
CONTEXT - The Dark Matter issue



T. Lin

50 orders of magnitude in mass

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



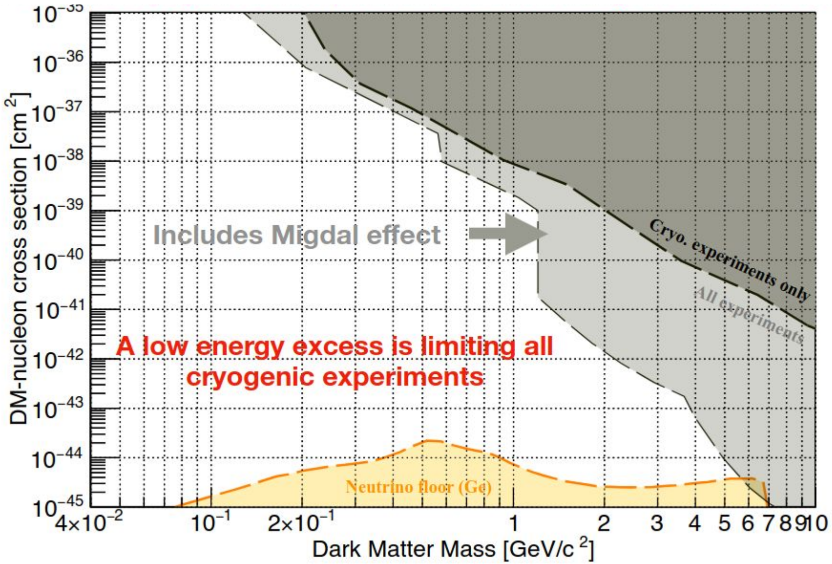
Focus of DM searches for the last decades has been on axion DM (µeV - meV) and standard WIMP (10 GeV - TeV)

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

CONTEXT - The Dark Matter issue

State of the art of low mass Nuclear Recoil DM search



Low Energy Excess (LEE) is preventing cryogenic DM experiments from leading the sub-GeV search region

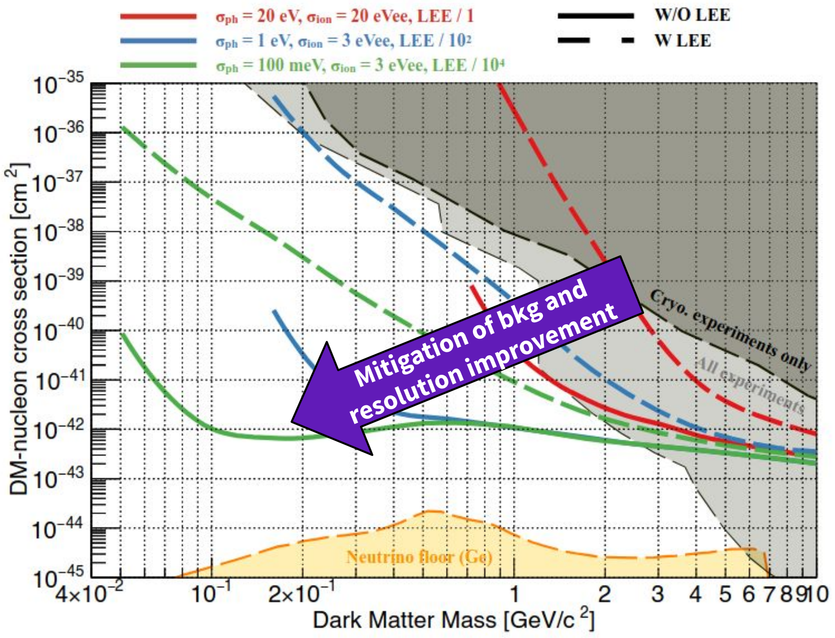
Design driver of **TESSERACT**:

- find the origin of the **LEE** to mitigate it
- develop detector technologies that can reject it

CONTEXT - The Dark Matter issue

TESSERACT projections

Transition Edge Sensor with Sub eV Resolution And Cryogenic Targets



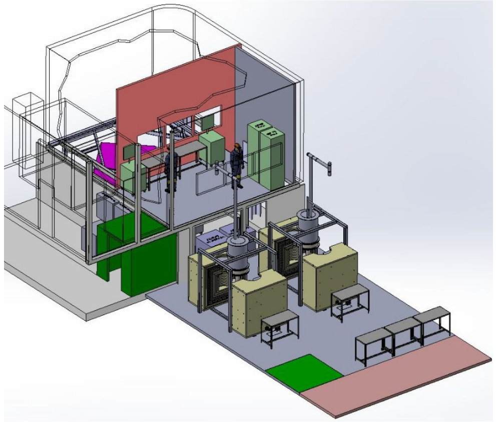
The **TESSERACT** experiment will allow to vastly extend the NRDM searches down to **100 MeV** with **particle ID** and **background rejection** in a region of the parameter space inaccessible to non cryogenic experiment

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

CONTEXT - The Dark Matter issue

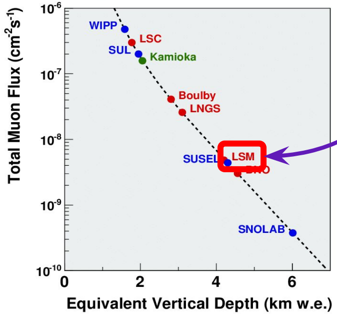
TESSERACT@LSM

Transition Edge Sensor with Sub eV Resolution And Cryogenic Targets



American (SPICE & HeRALD) and French (LV & HV Bolometers) technologies :

- Complementary measurements
- Different strategies of mitigation of the LEE
- Commissioning at LSM in 2028



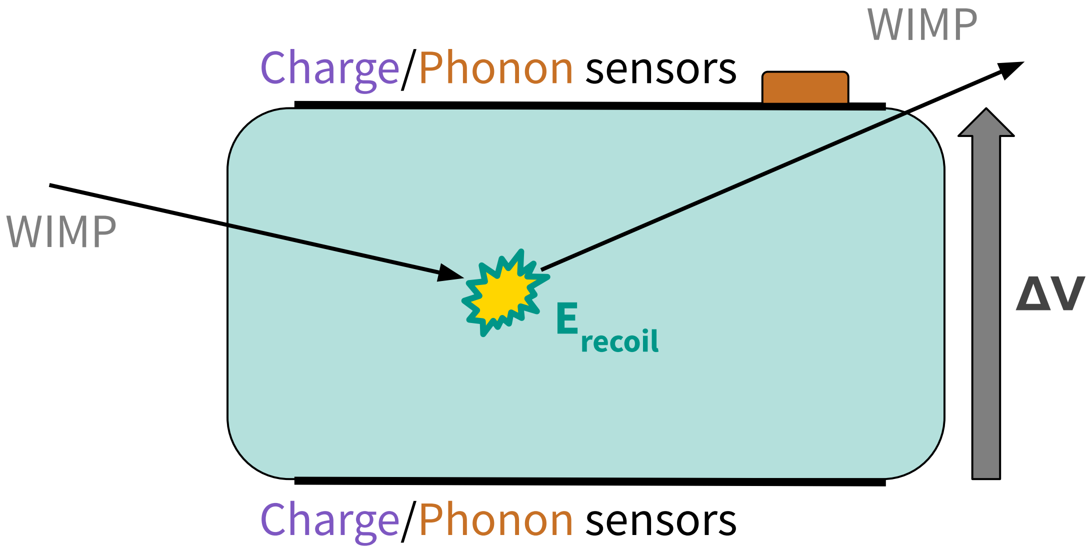
- LSM *(Laboratoire Souterrain de Modane)* : deepest site in Europe, 4800 m.w.e, 5 μ/m^2/day
- Clean room + deradonized air
- PE and lead shielding
- Selection of radiopure materials

TESSERACT bolometers

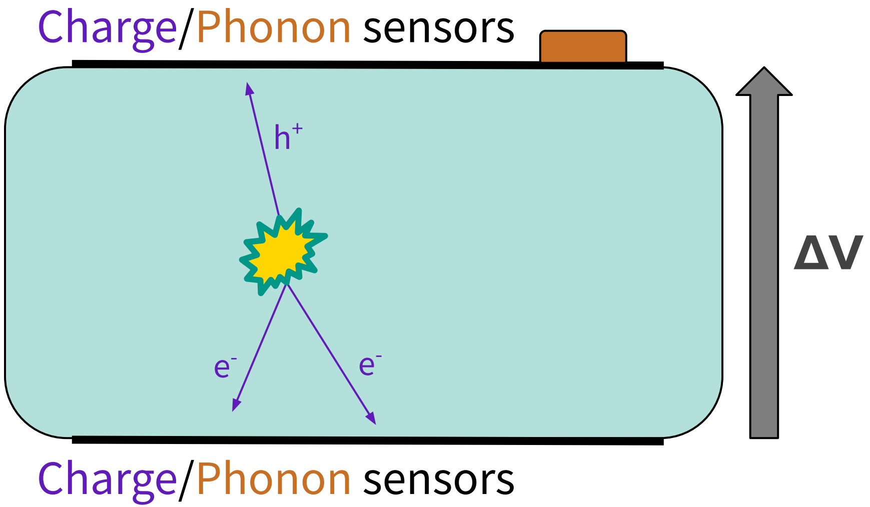
Working principle

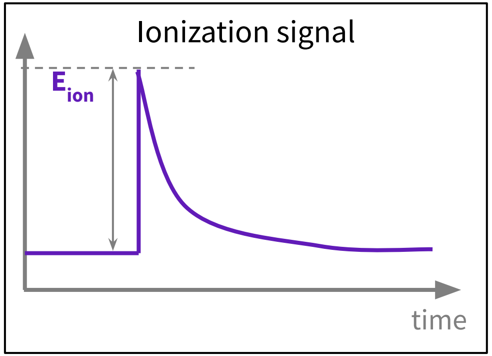
TESSERACT bolometers

Working principle



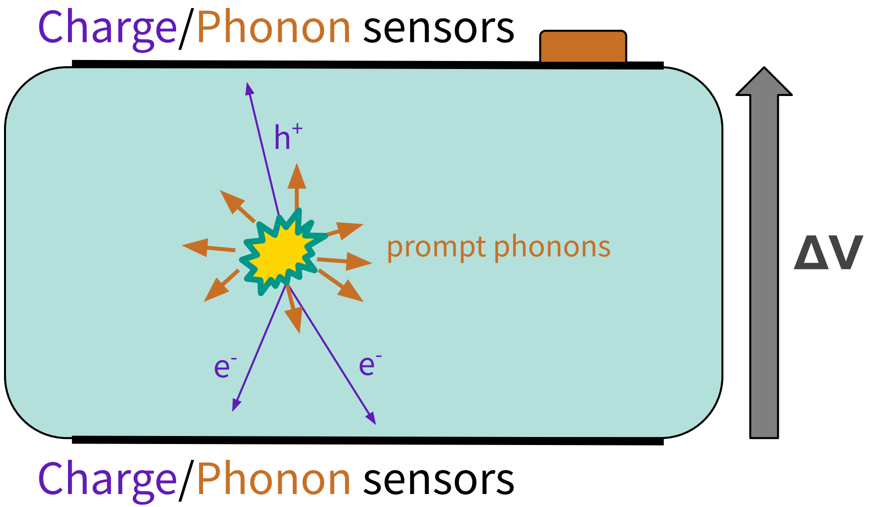
Working principle

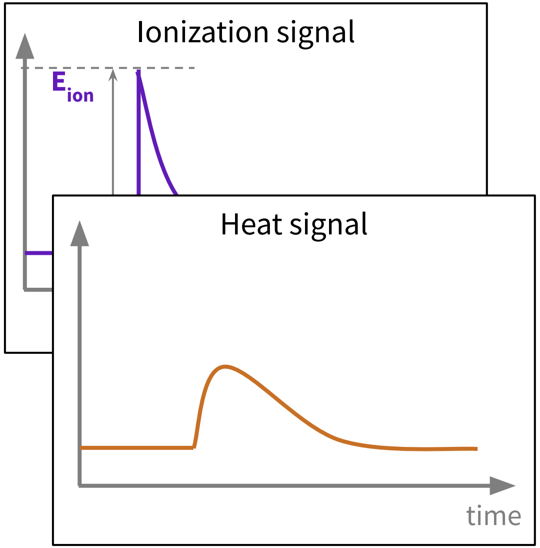




TESSERACT bolometers

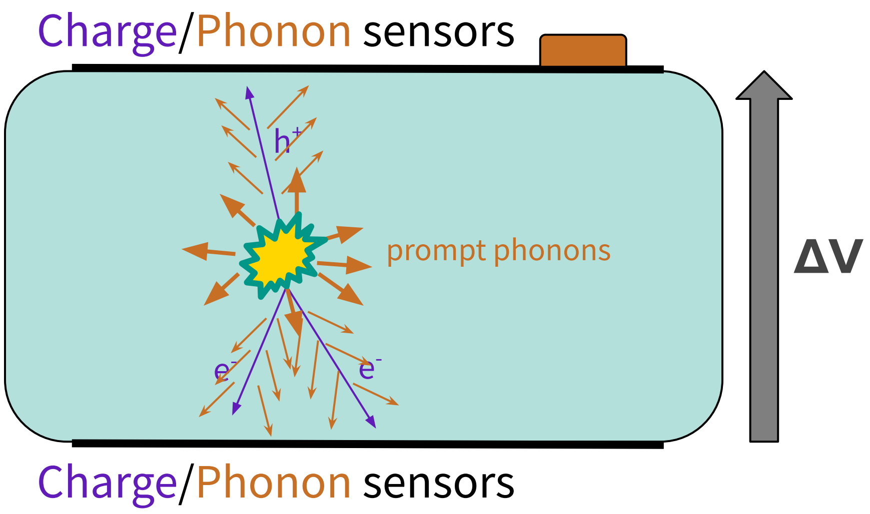
Working principle

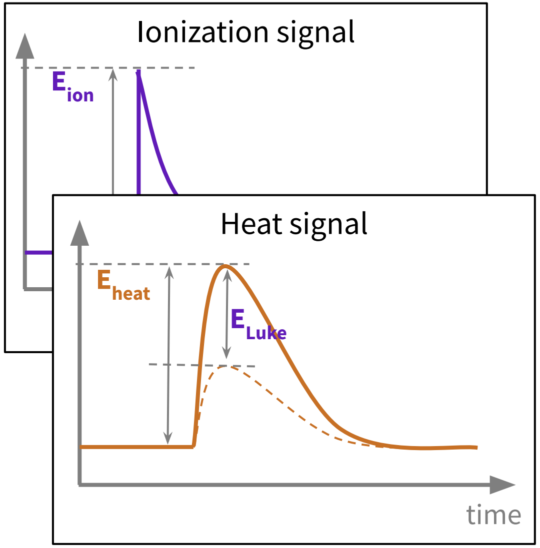




TESSERACT bolometers

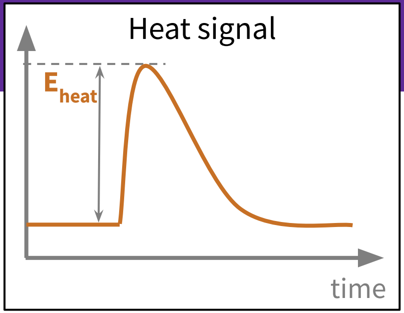
Working principle





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

TESSERACT bolometers



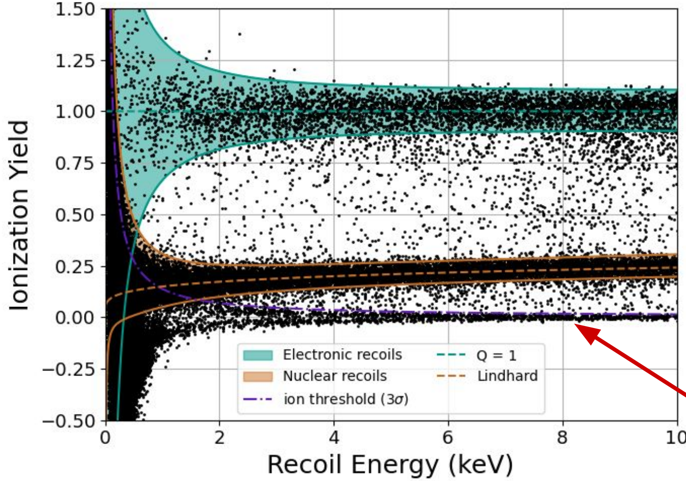
Working principle

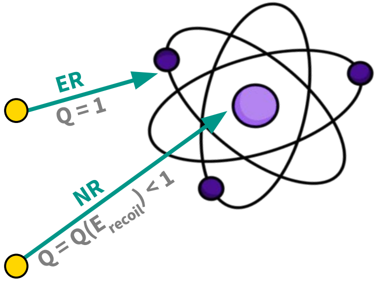
$$E_{heat} = E_{recoil} + E_{luke}$$
$$= E_{recoil}\,(1 + Q\,\Delta V/\varepsilon_{eh})$$

Low Voltage mode
Particle ID + Fid

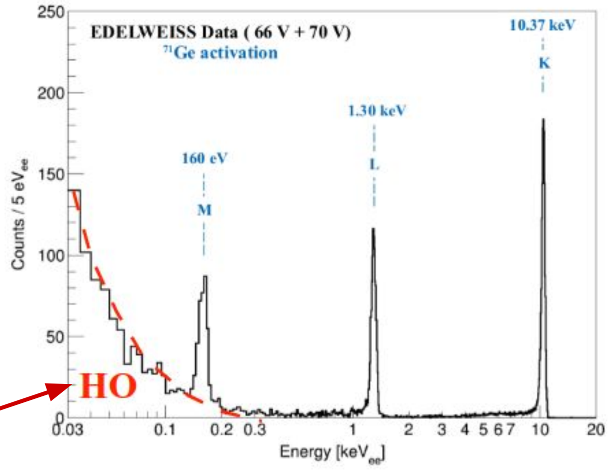
Ionization Yield : $Q = E_{ion} / E_{recoil}$

Ricochet data



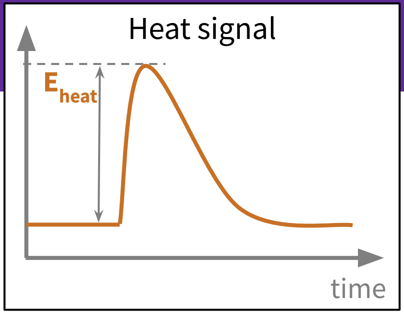


High Voltage mode
no Particle ID - single e/h



Low Energy Excess or HO (Heat Only)

TESSERACT bolometers



Working principle

$$E_{heat} = E_{recoil} + E_{luke}$$
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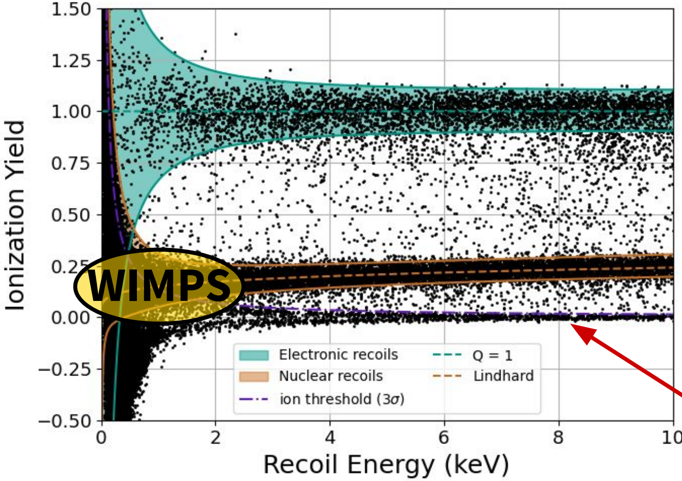

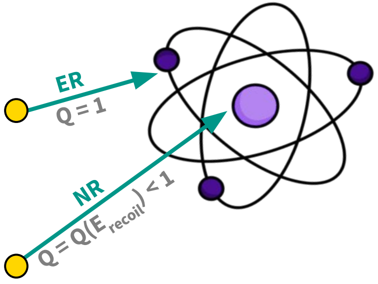

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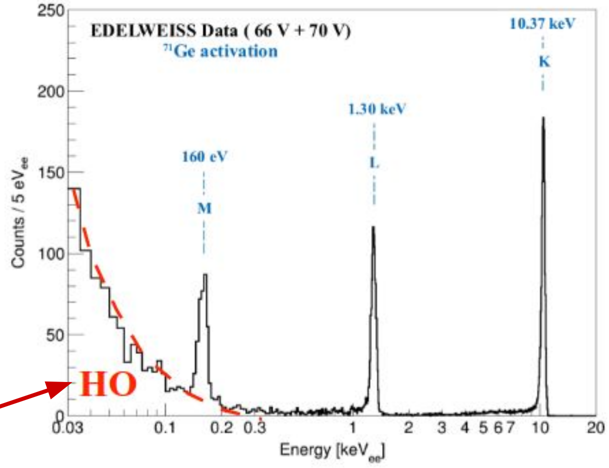


Low Energy Excess or HO (Heat Only)

TESSERACT bolometers

R&D phase : Design drivers

TESSERACT bolometers

From Ricochet to TESSERACT

Going beyond the Ricochet CryoCube technology

RICOCHET Cryocube

- Looking for : **CENNS**
- Phonon sensor : **NTD-Ge**
- Total capacitance **~45 pF**
- Payload: 18 x **40 g**
- σ_{ion} **~30 - 40 eVee**
- σ_{heat} **~40 - 60 eVph**

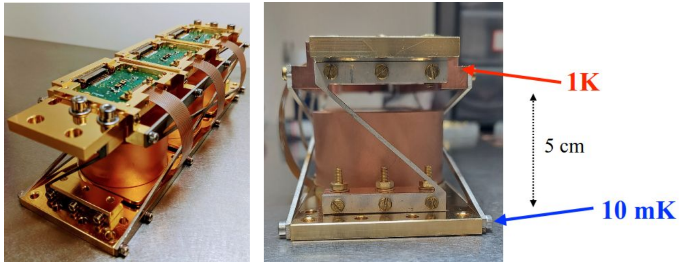
TESSERACT DEMOnstrator (DMO)

- 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**

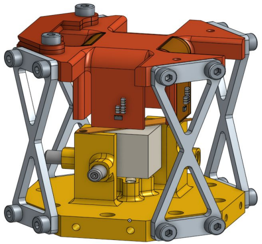
TESSERACT final

- Looking for : **DM**
- Phonon sensor : **TES**
- Total capacitance **~1 pF**
- Payload: 4 x **5.35 g**
- σ_{ion} **<10 eVee**
- σ_{heat} **~0.1 eVph**

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



Mini-Cryocube


J.Colas

DMO

TESSERACT bolometers

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**
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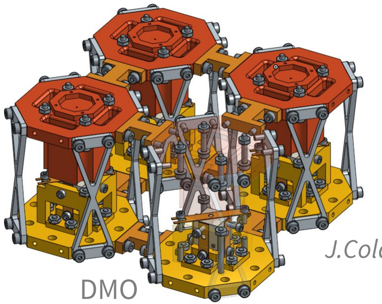
- σ_{heat} **~10 - 20 eVph**

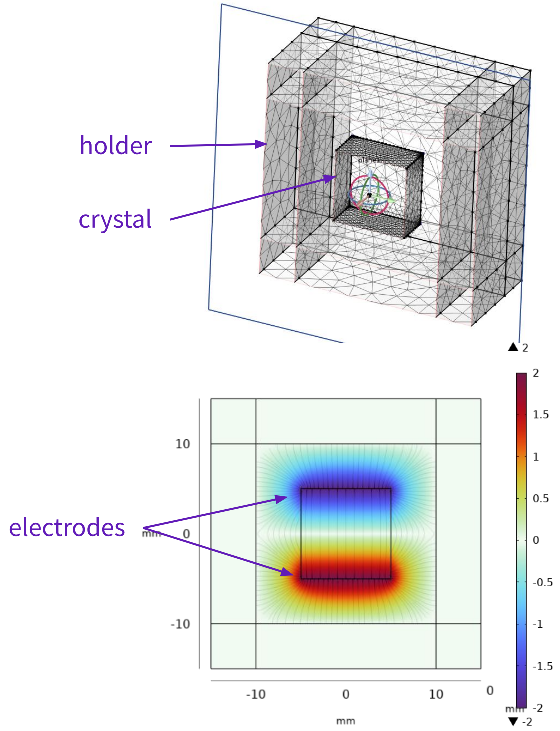


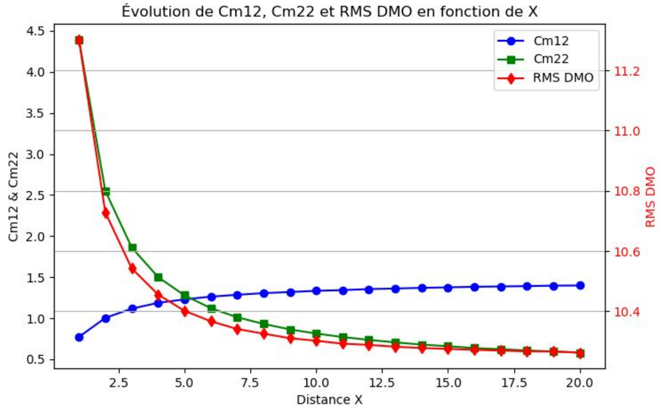
- Reduce the detector volume
- Put the HEMT amplificator at < 1 cm from the electrode
- Optimize the holder, COMSOL driven

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

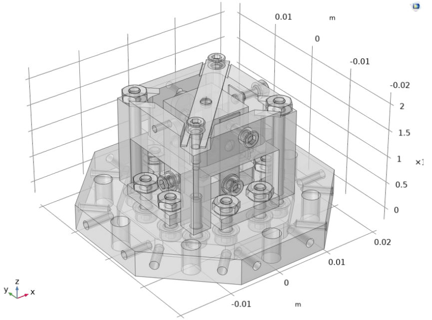
TESSERACT bolometers

DMO Detector Status, COMSOL simulations





Geometry optimization → Reduction of Cm → Better Resolution



Incoming studies :

- Different geometries
- Electrodes shapes
- More accurate holder
- FID detectors

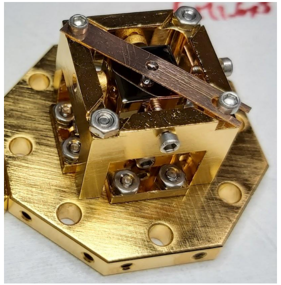
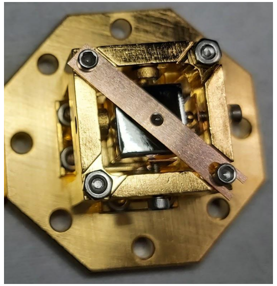
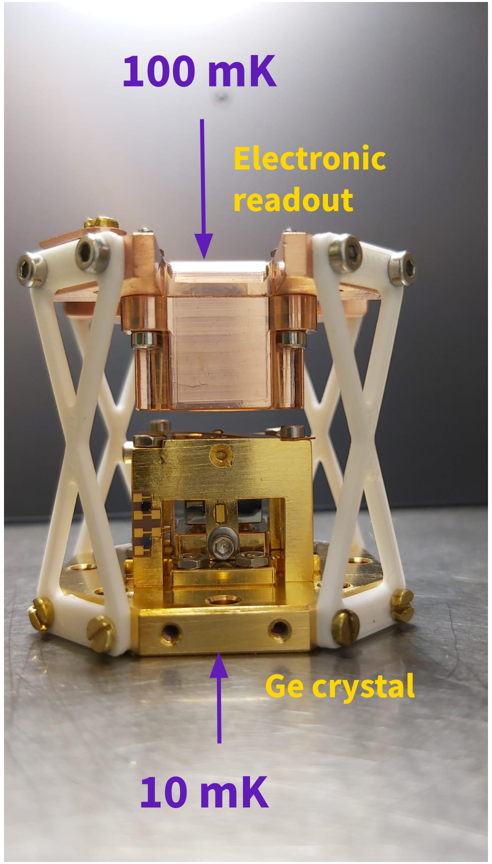
Parameters of interest :

- Mutual Capacitance
- Fiducial volume

TESSERACT bolometers

DMO Detector Status

- 6 Ge crystals :
  - 2 in a DMO holder (V1)
  - 2 set aside for electrode evaporation at INL
  - 2 send to IJCLab for electrodes production
- 2 glued NTDs, no ionization readout for now
- Thermal integration in the cryostat in progress
- Link with the RICOCHET electronic in progress
- 100 mK part of the holder in progress
- Radioactivity measurement of the materials with HPGe detector (LSM) in progress

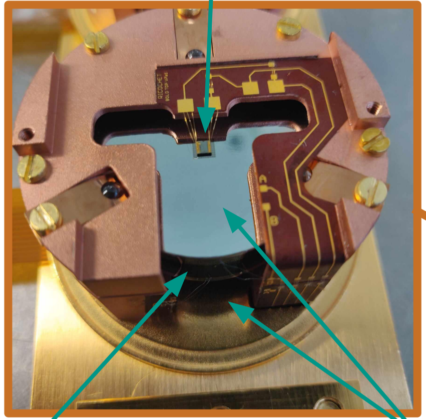
Data analysis, proof of concept

Set up

Set-up - Ricochet detectors

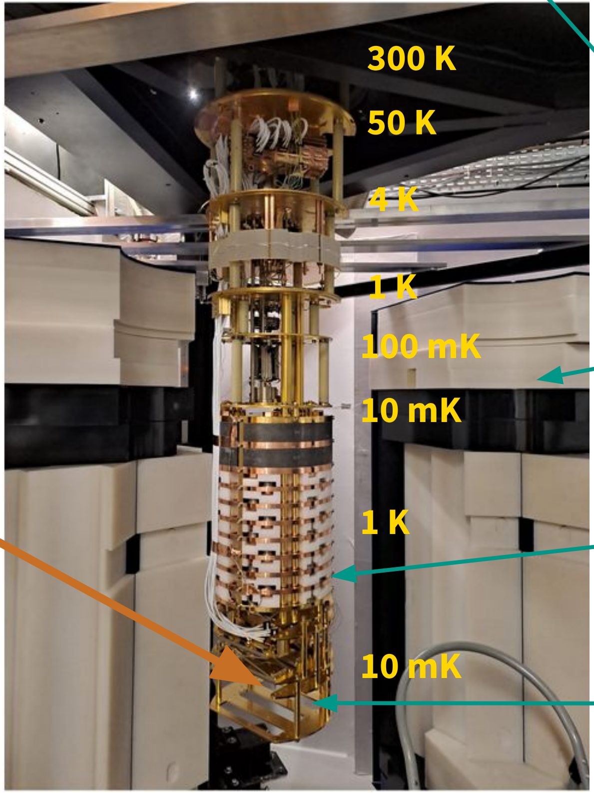
Heat sensor

RED167



Ge crystal

Electrodes



Ricochet Cryostat @ILL

15 meter water equivalent of overburden

External shielding (Lead & Polyethylene)

Internal shielding (Lead & Copper & Polyethylene)

10 mK plate

Data analysis

Set-up - Backgrounds

Reactogenic background

Fast neutrons
Thermal neutrons
High energy gammas
→ from the nuclear reactor and other experiments around Ricochet

Passive shielding

Cosmogenic background

Muons
Neutrons
Gammas
→ from the interaction of cosmic muons with shielding materials

Muon veto & overburden

Radiogenic background

Gammas
Betas
Alphas
Neutrons
→ from the natural radioactivity of the materials near the detectors (^{238}U and ^{232}Th decay chains)

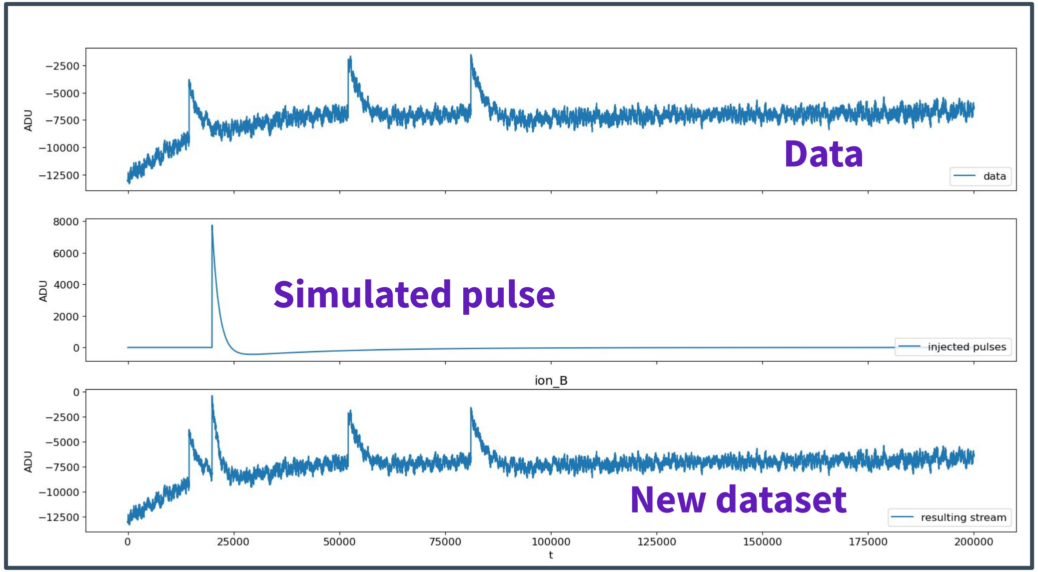
Selection of radiopure materials

Data analysis, proof of concept

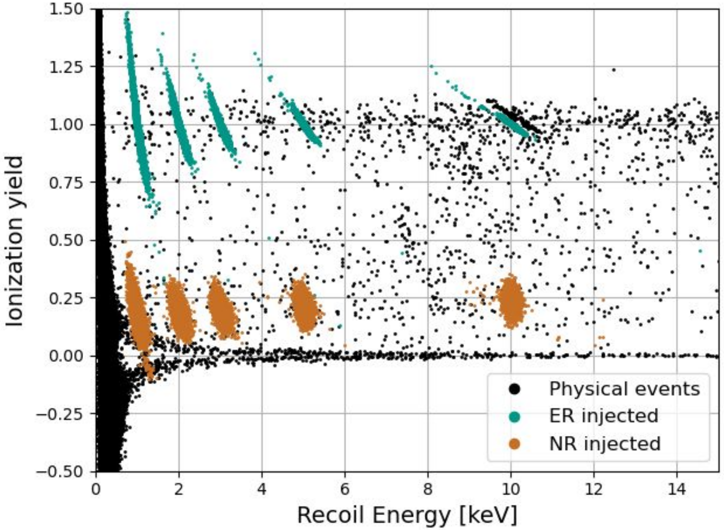
Toward a Dark Matter limit

Data analysis

Simulation and injection

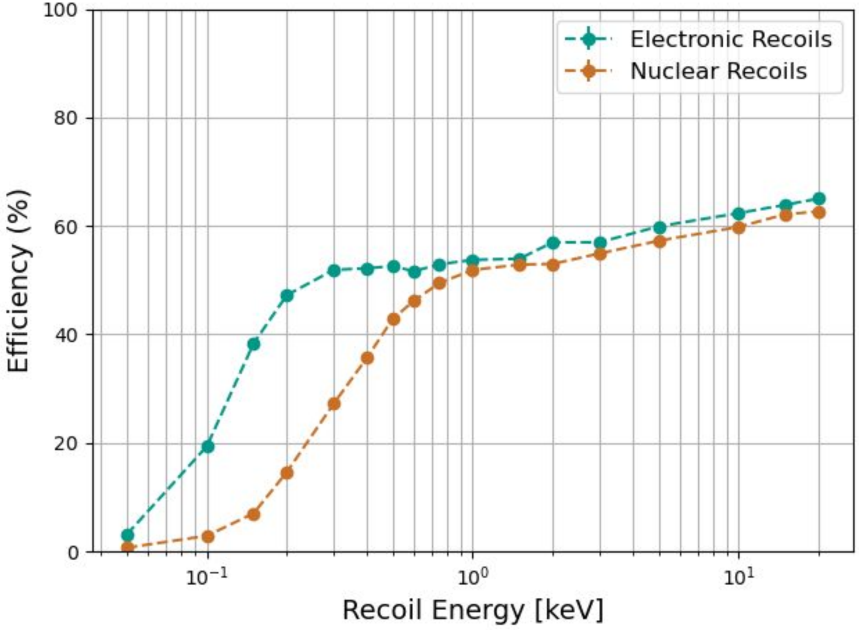


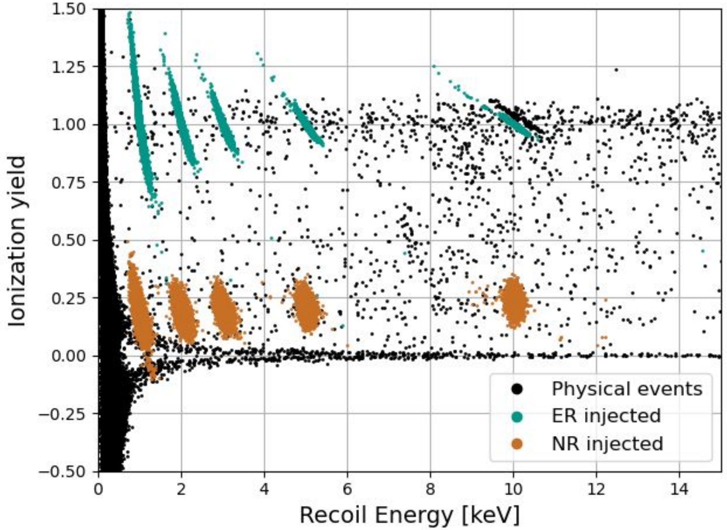
N. Martini



Data analysis

Simulation and injection

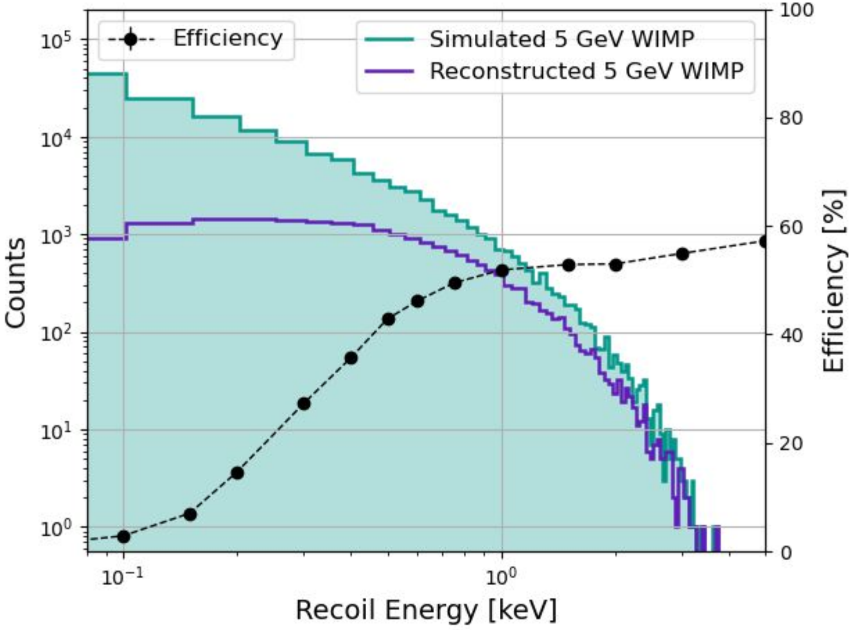


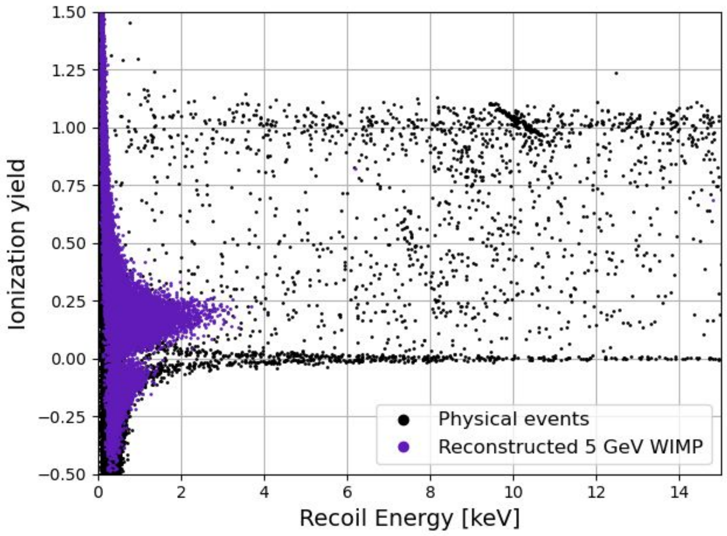


Efficiency = # reconstructed events / # injected events

Data analysis

Simulation and injection

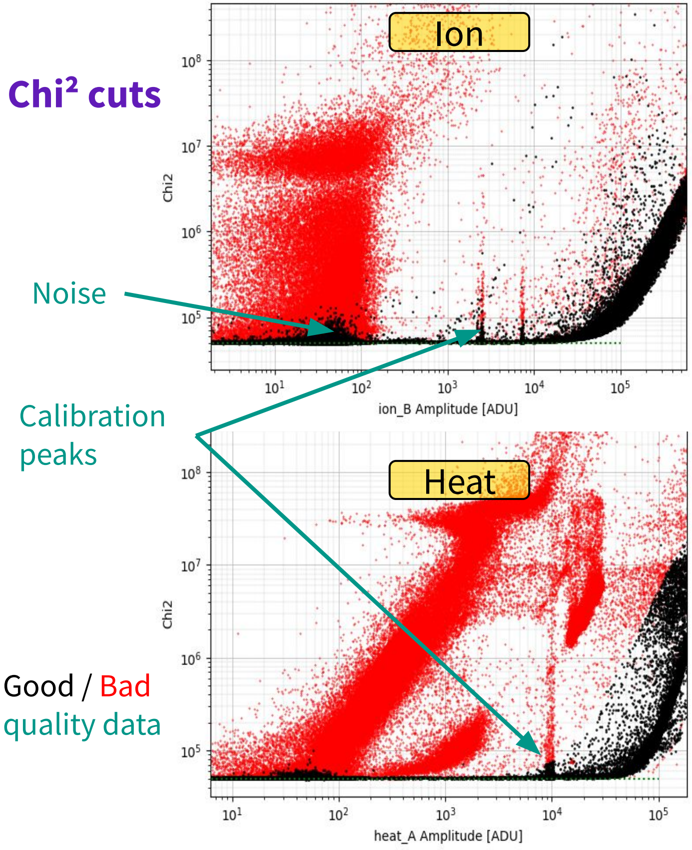




Injection of WIMP spectrum

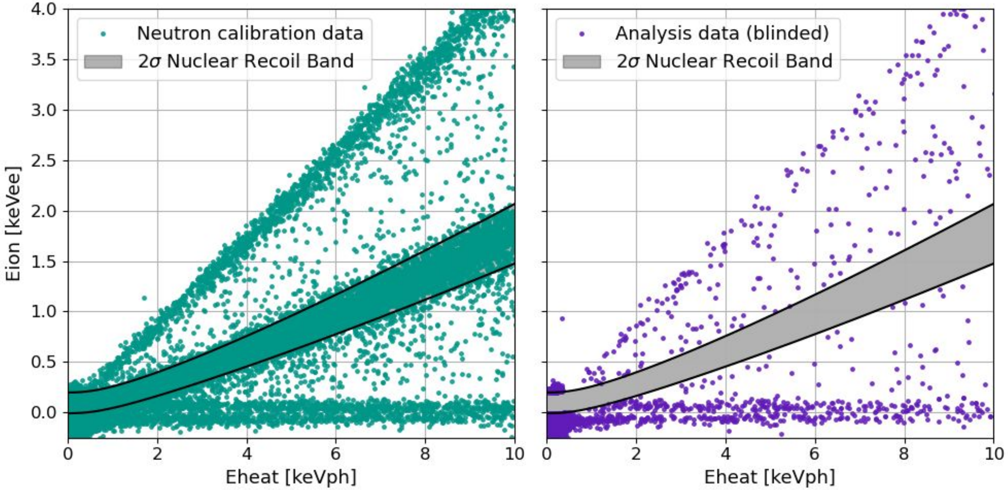
Data analysis

Chi² cuts



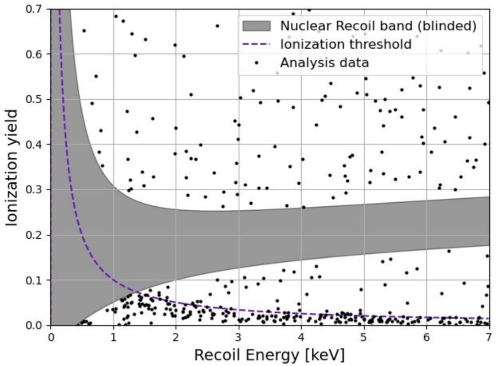
Data Selection

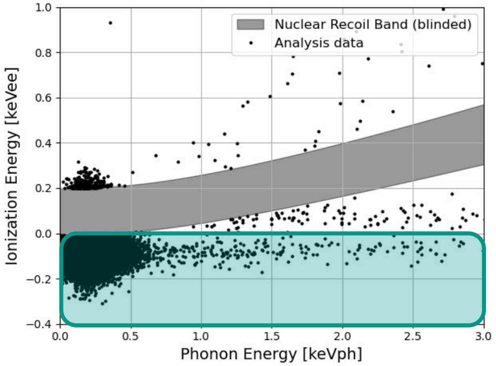
Band cut



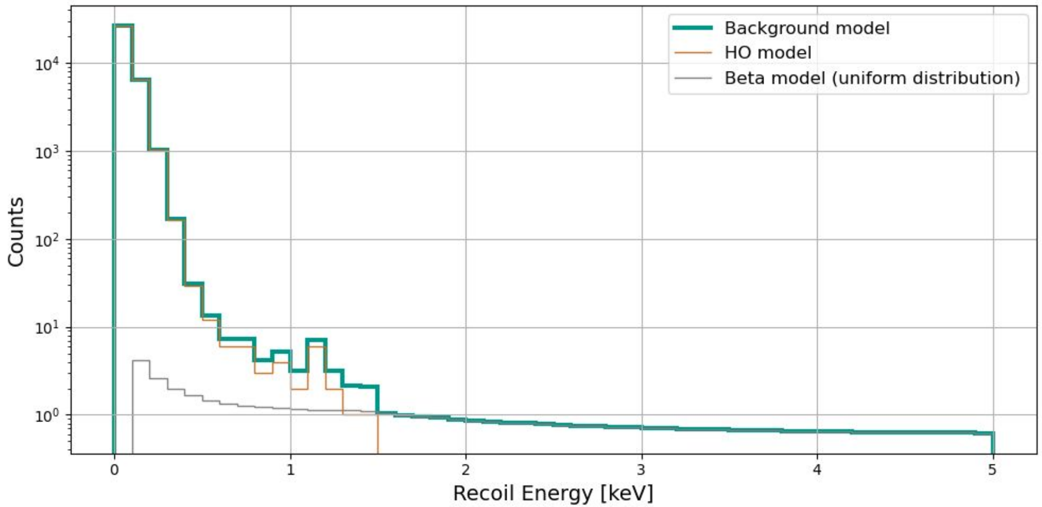
Other cuts : Muon coïncidence, laser events, bad partitions

Background Model





Hypothesis : uniform distribution of beta events in the Q-Er plan

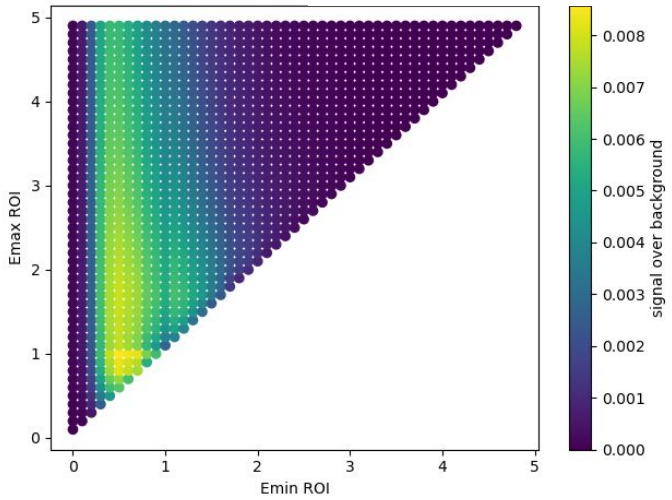


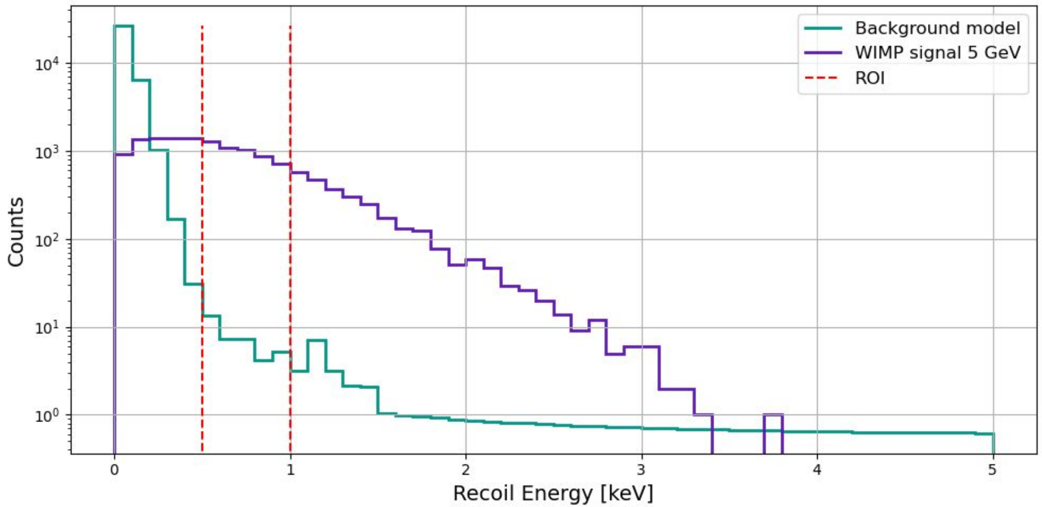
Data analysis

ROI selection

Region Of Interest : best signal over background ratio ⇔ **κ maximum**

$$\kappa = \frac{\varepsilon_s}{\overline{\mu_{90}}} \qquad \overline{\mu_{90}} = \sum_{i=0}^{\infty} \mu_{90}(i) \cdot \frac{e^{-\mu}\mu^i}{i!}$$





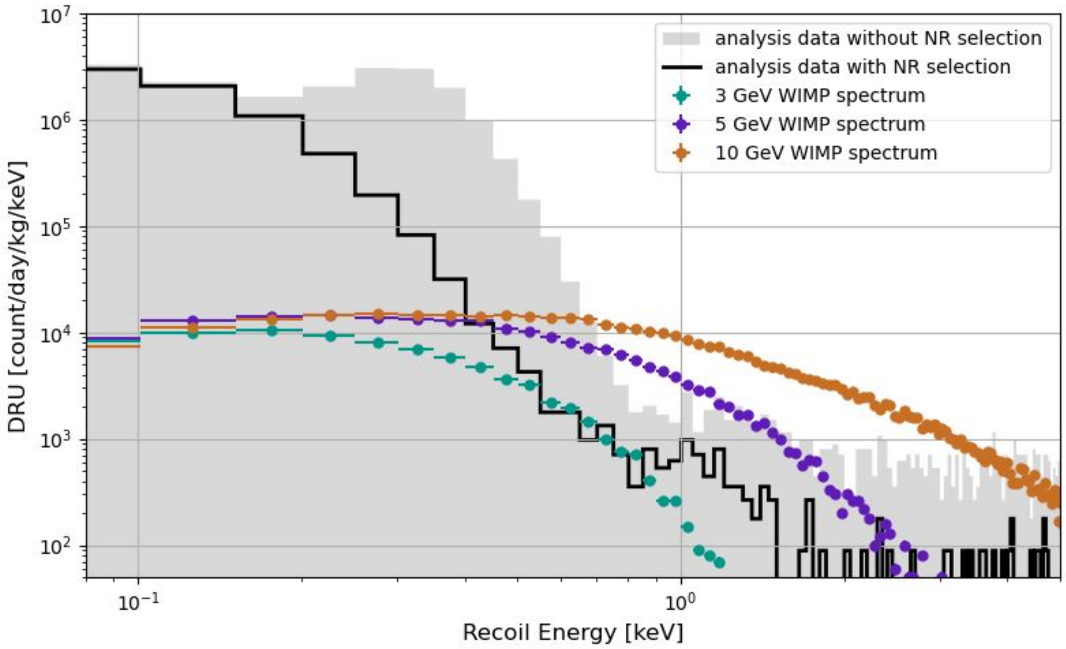
\+ scan over ionization thresholds

Data analysis

Calculation of the DM limit with Poisson statistics

Comparison between the data and WIMP spectrums

Excluded Cross Section (90% CL) $\propto$ (#excluded events in the ROI)



Data analysis

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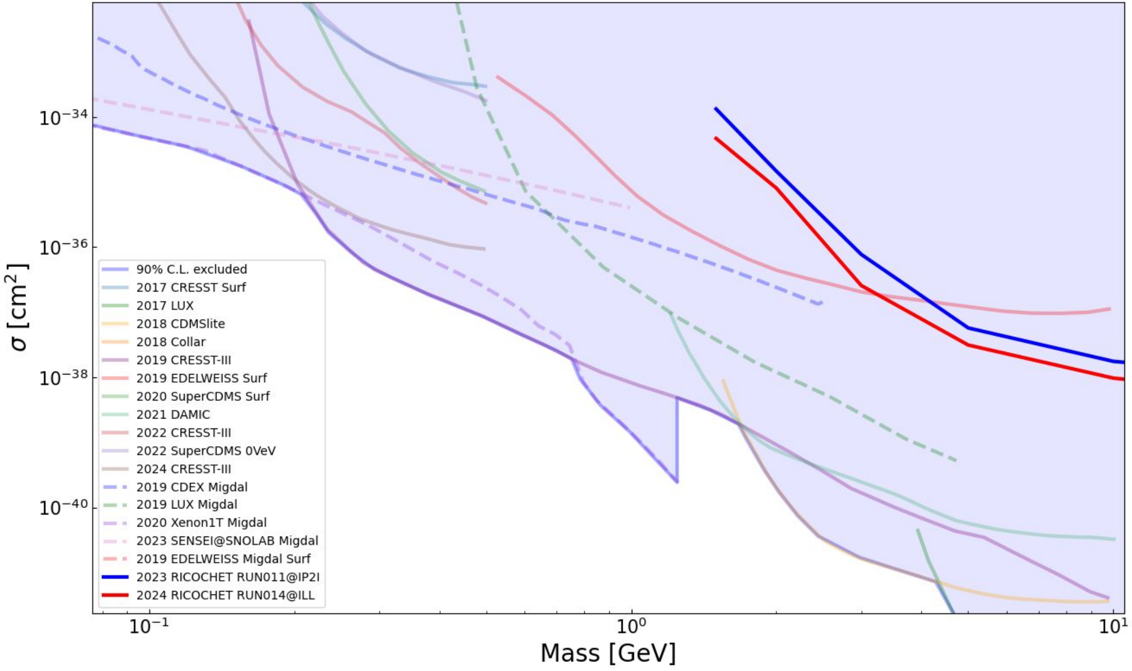
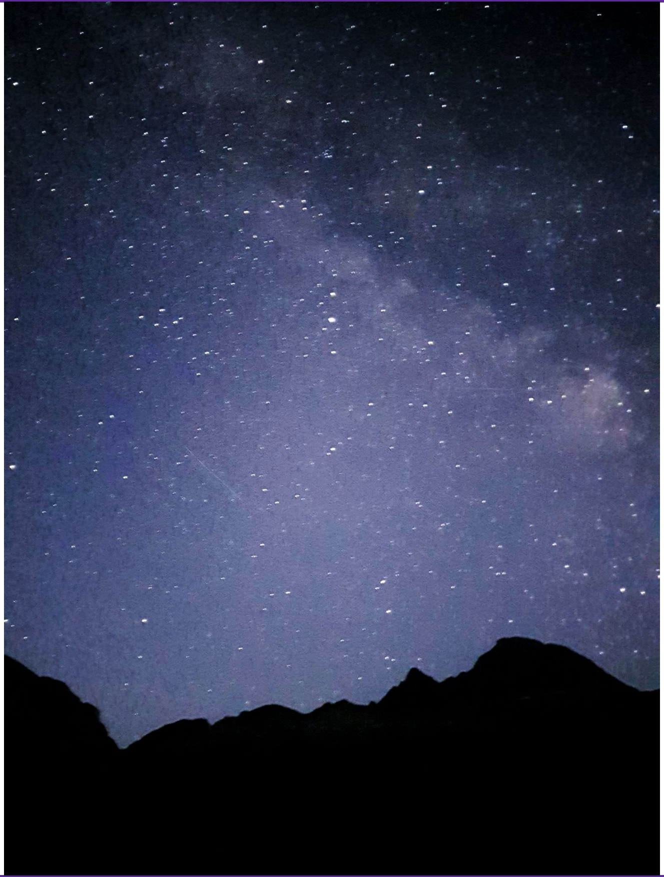


CONCLUSION

Almost done …

CONCLUSION



- Extend the Nuclear Recoil DM search down to 100 MeV
- R&D of the first DMO detectors on going (first data coming soon)
- Simulation for the optimisation of the design of the next versions of the detectors ongoing
- Analysis pipeline tested with Ricochet bolometers (publication in 2025)

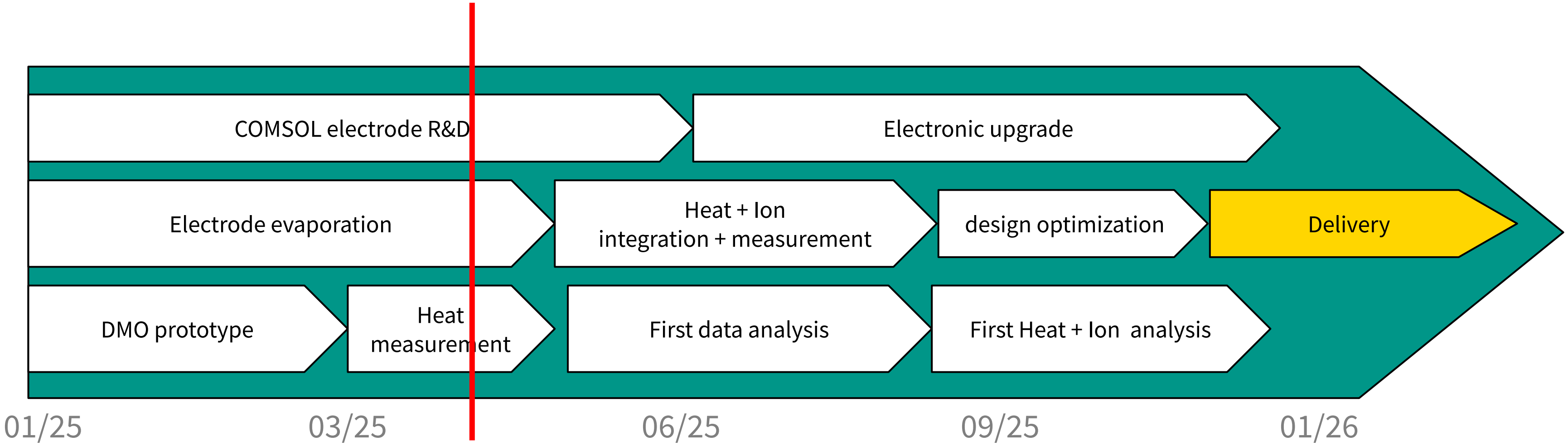
The end

Thanks for listening

Back-up slides

TESSERACT bolometers

DMO Detector planning

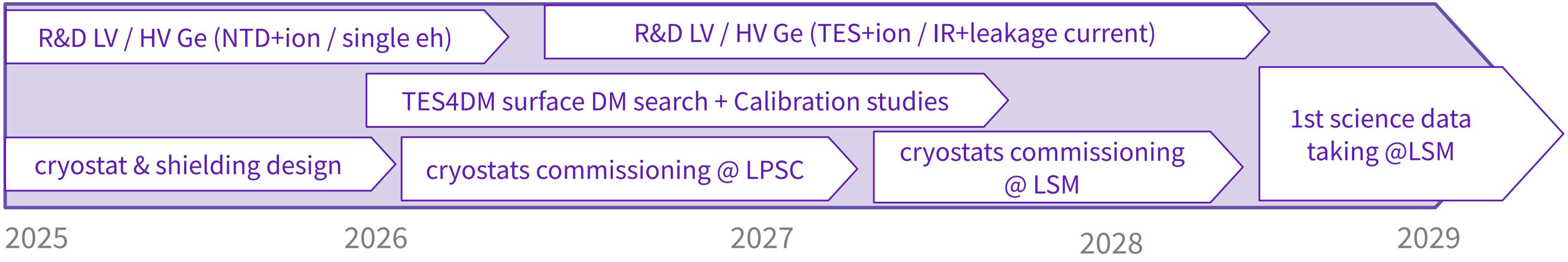


TESSERACT bolometers

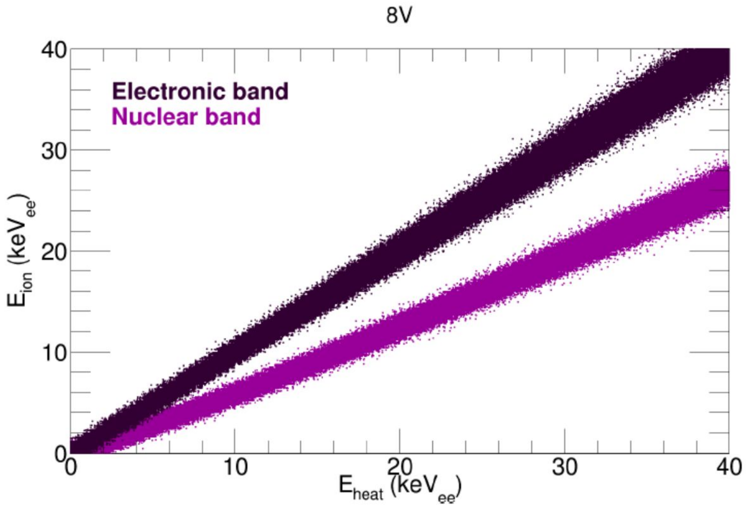
TESSERACT planning, toward a commissioning at Laboratoire Souterrain de Modane

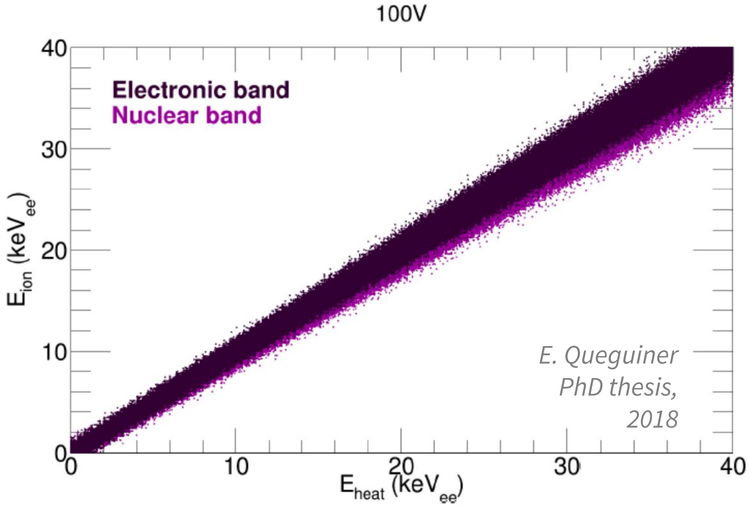
- Different cryogenic targets (French & American technologies)
- LEE mitigation
- Particle Identification
- Low impedance TES phonon sensors
- LSM ultra-low background environnement

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



High Voltage loss of Particle Identification





E. Queguiner PhD thesis, 2018

RUN011@IP2I and RUN014@ILL background comparison