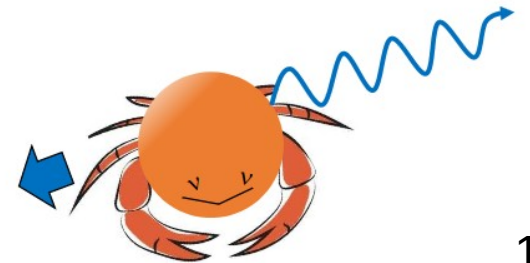


Cryogenics detectors for sub-keV nuclear recoils detection: motivations and calibration

LPSC seminar – Romain MARTIN

11/06/2026



Outline

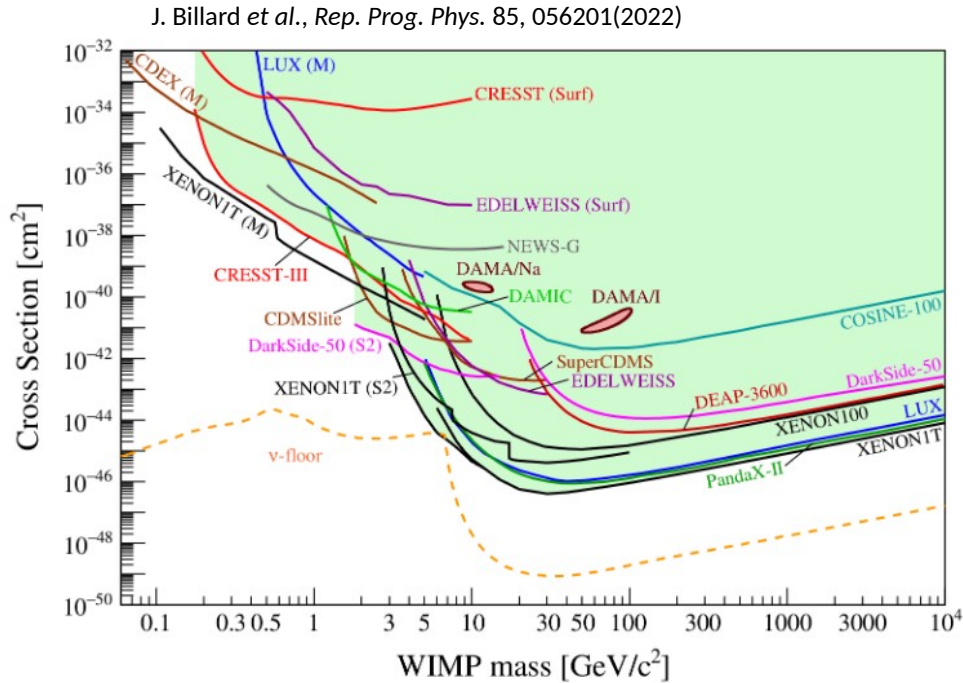
I. Motivations

II. Cryogenic detector for sub-keV NR detection

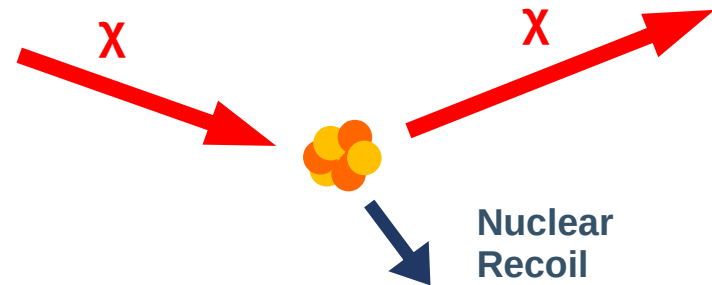
III. Calibration with the CRAB method

IV. Presentation of CRAB phase II

The Mystery of Dark Matter (DM)

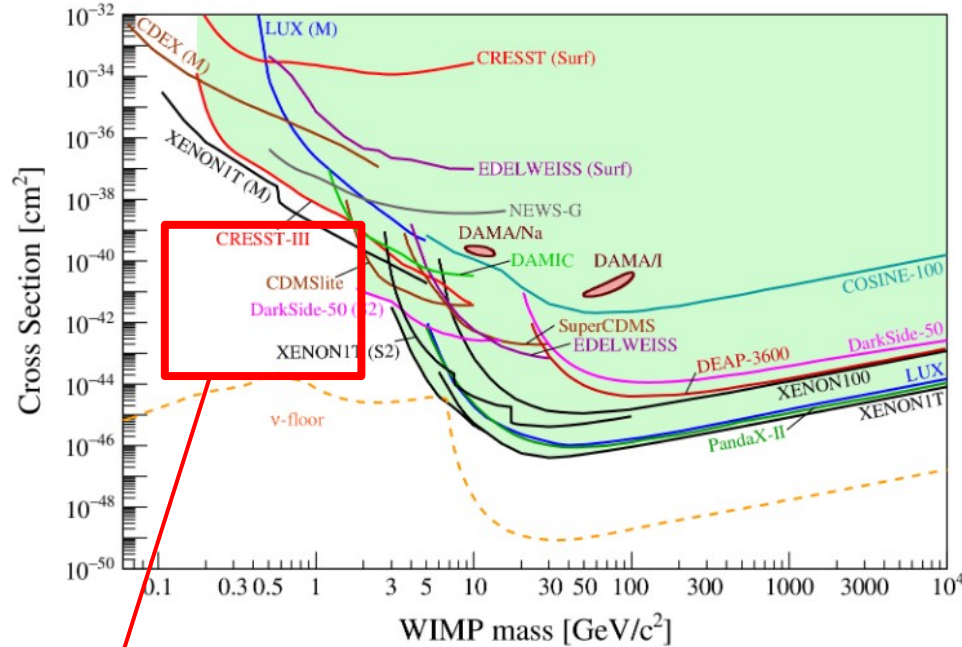


- Gravitational evidence for DM
- Direct detection: elastic scattering on matter
→ Nuclear Recoil (NR)



The Mystery of Dark Matter (DM)

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



- Gravitational evidence for DM
- Direct detection: elastic scattering on matter
→ Nuclear Recoil (NR)
- No DM detected → probing lower masses

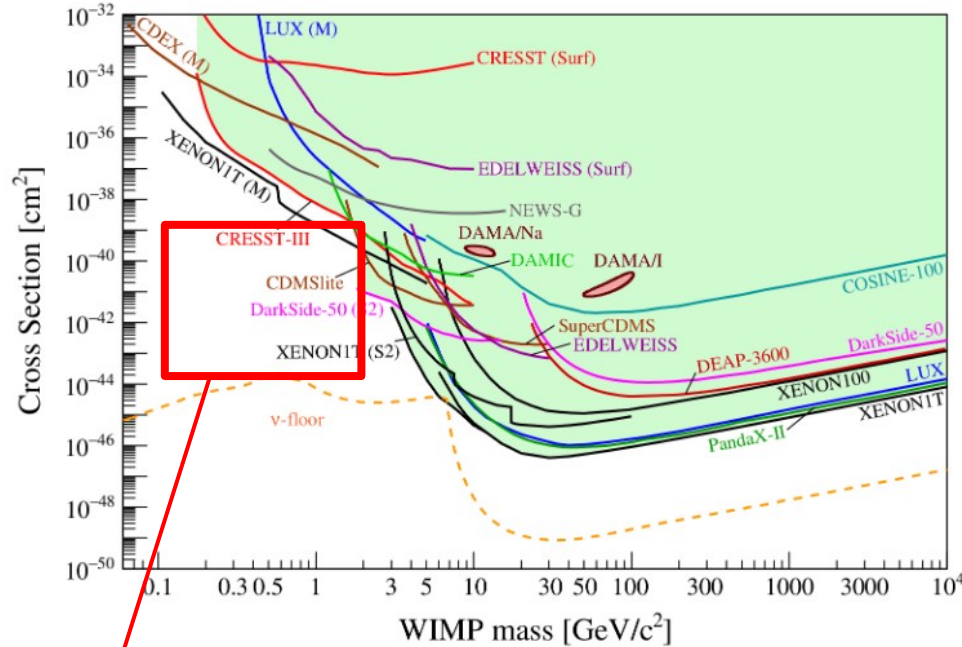
Low mass DM



Sub-keV NR !

The Mystery of Dark Matter (DM)

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



Low mass DM → Sub-keV NR !

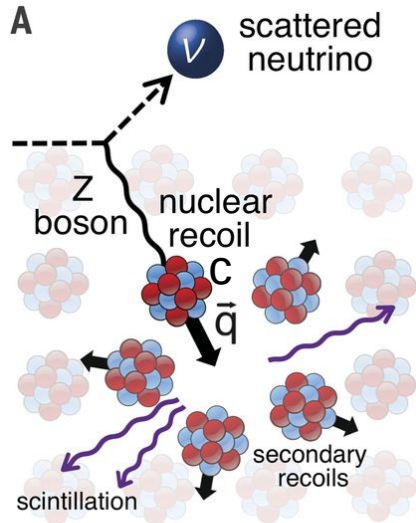
- Gravitational evidence for DM
- Direct detection: elastic scattering on matter
→ Nuclear Recoil (NR)
- No DM detected → probing lower masses
- Background : Coherent Elastic neutrino Nucleus Scattering (CEvNS) : **v-floor**

CEvNS process

- Suggested by Freedman in 1973 and detected by COHERENT in 2017
- CEvNS cross section enhanced for low energy neutrino: coherent regime
 - Low momentum transfer
 - Sub-keV NR

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{4\pi} Q_W^2 \left(1 - \frac{E_R}{E_R^{\max}}\right) \propto N^2$$

$$Q_W = N - Z(1 - 4\sin^2\theta_W) \approx N$$



CEvNS enhanced for heavy target materials

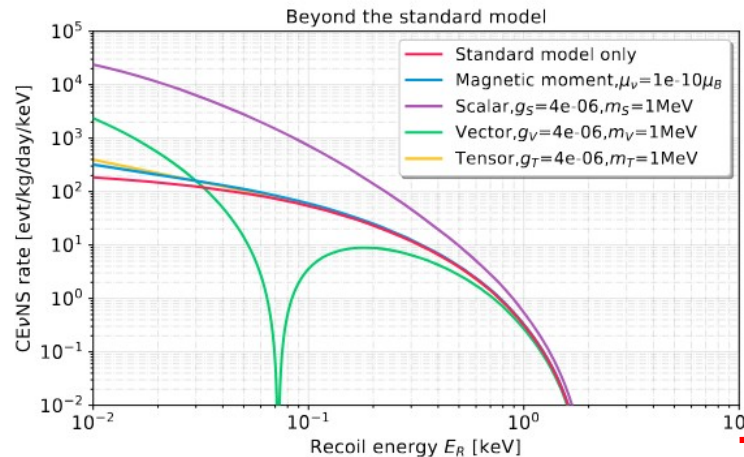
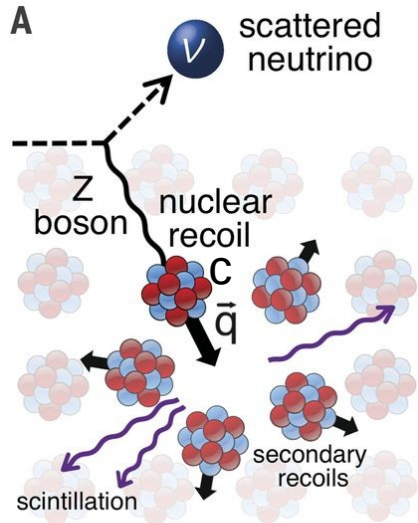
Sub-keV NR !

CEvNS process

- Suggested by Freedman in 1973 and detected by COHERENT in 2017
- CEvNS cross section enhanced for low energy neutrino: coherent regime
- Probe SM and BSM physics through spectral distortions

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{4\pi} Q_W^2 \left(1 - \frac{E_R}{E_R^{\max}}\right) \propto N^2$$

$$Q_W = N - Z(1 - 4\sin^2\theta_W) \approx N$$

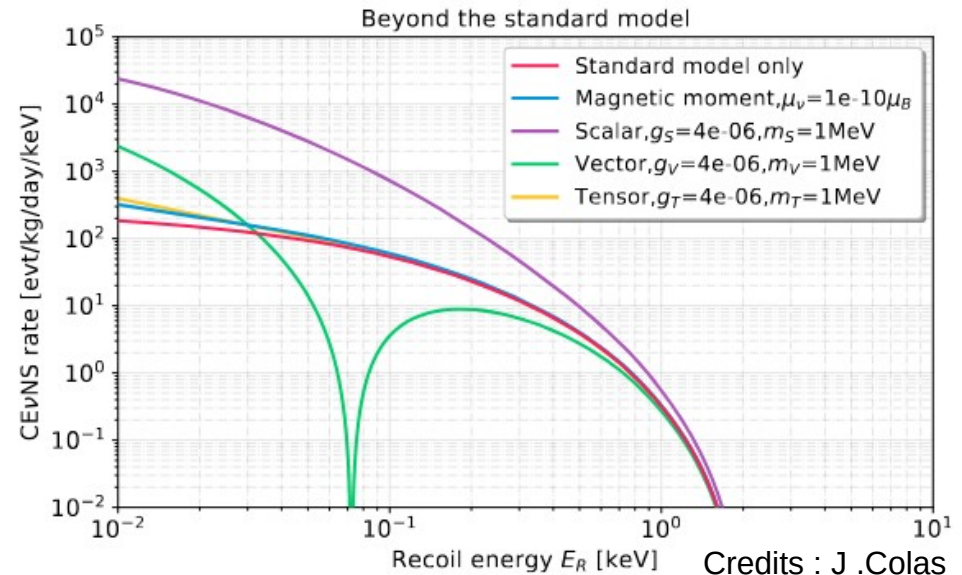


Theoretical spectra

CEvNS detection at reactor

- Reactor → strong source of low energy neutrino (<10 MeV)
- CEvNS rate : few events per day !
- Challenges for CEvNS spectrum measurement:
 - Background mitigation
 - Low energy threshold
 - Precise energy calibration

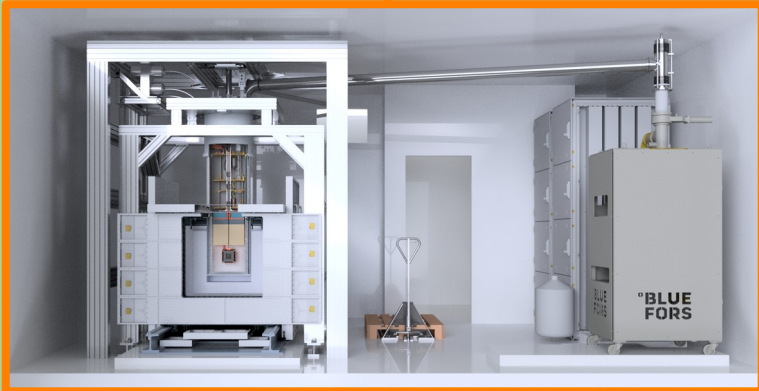
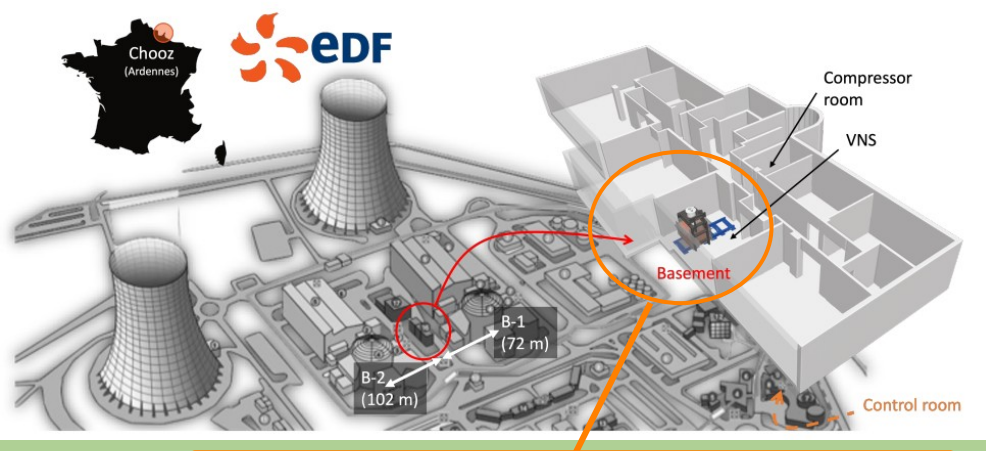
This talk !



On going experiments in France

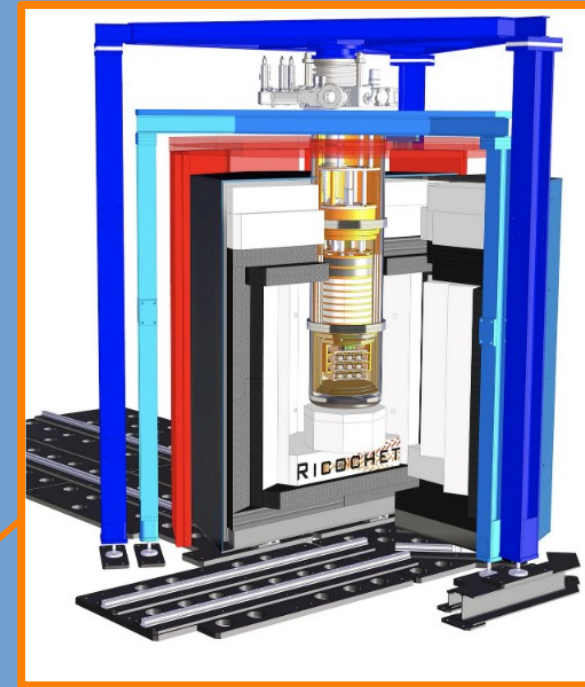
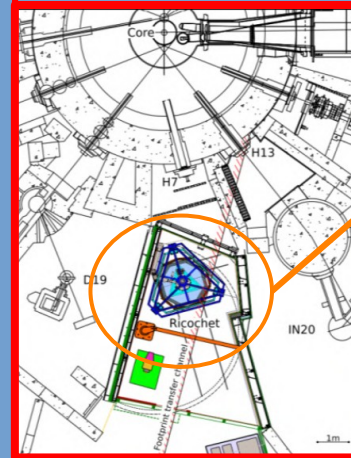
NUCLEUS — Chooz nuclear power plant (EDF)

Target : CaWO_4 Signal : 3 events/week in $[10,100]$ eV with a 10g target



RICOCHET — Institut Laue-Langevin (ILL)

Target : Germanium Signal : 50 events/week in $[50 \text{ eV}, 1 \text{ keV}]$ with a 750g target



Outline

I. Motivations

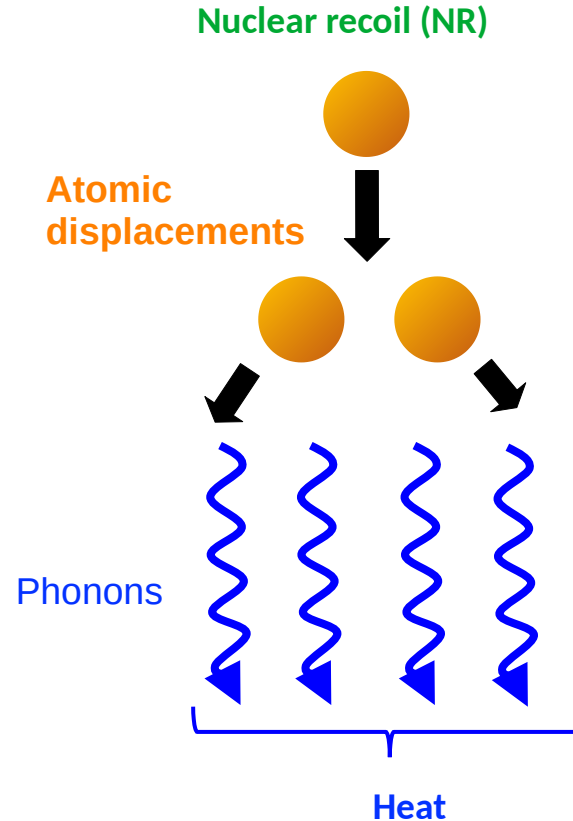
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III. Calibration with the CRAB method

IV. Presentation of CRAB phase II

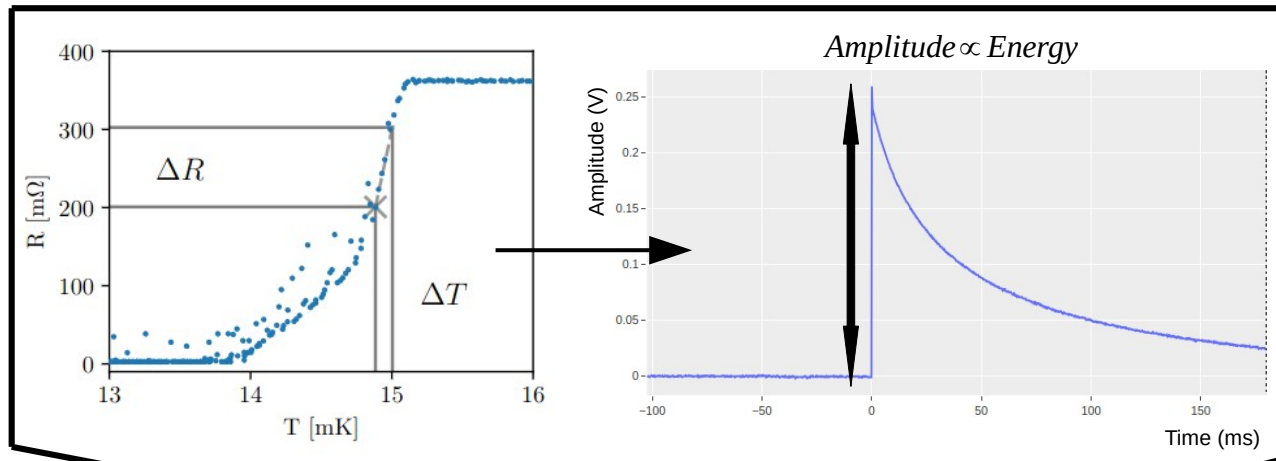
Detection of low energy NR

- Channels of energy deposition :
 - **Heat** : carry most of the energy
- Phonon detector
 - Sensitive to **heat** channel
 - $1 \mu\text{eV}$ to create thermal phonon
 - Good candidate for low NR detection



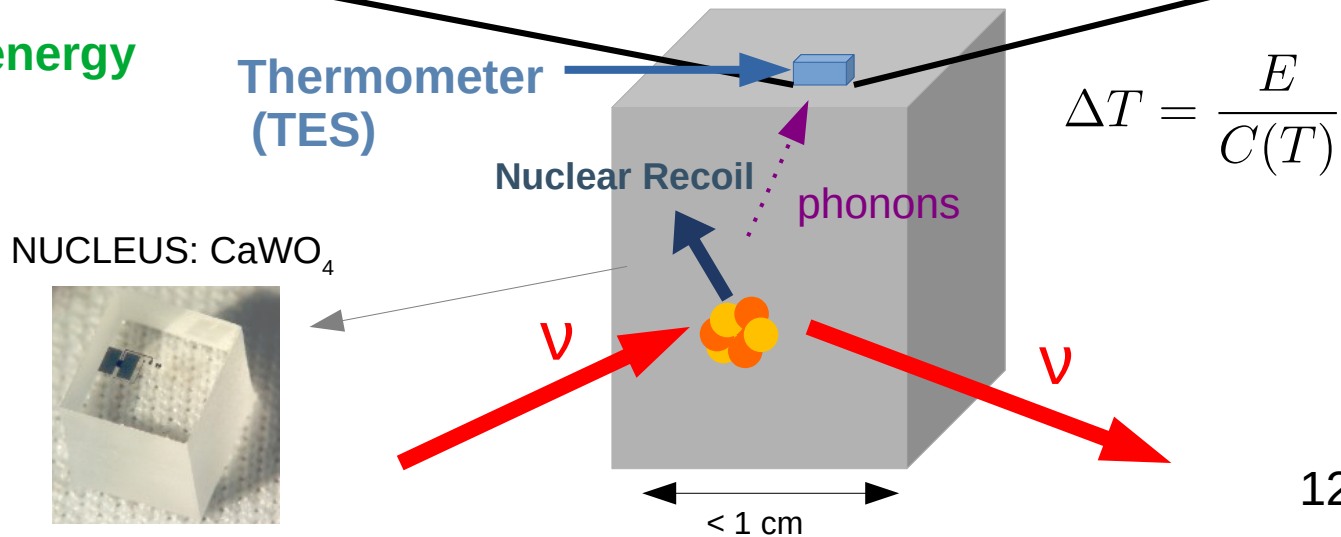
Principle of a calorimeter

- NR induce heat measured by phonon collection
- TES operated at normal-supra transition (15 mK)



✓ Ability to achieve < 10 eV energy resolution \rightarrow desirable for CEvNS detection !

— Complex to operate



Ionization detectors

- Channels of energy deposition :

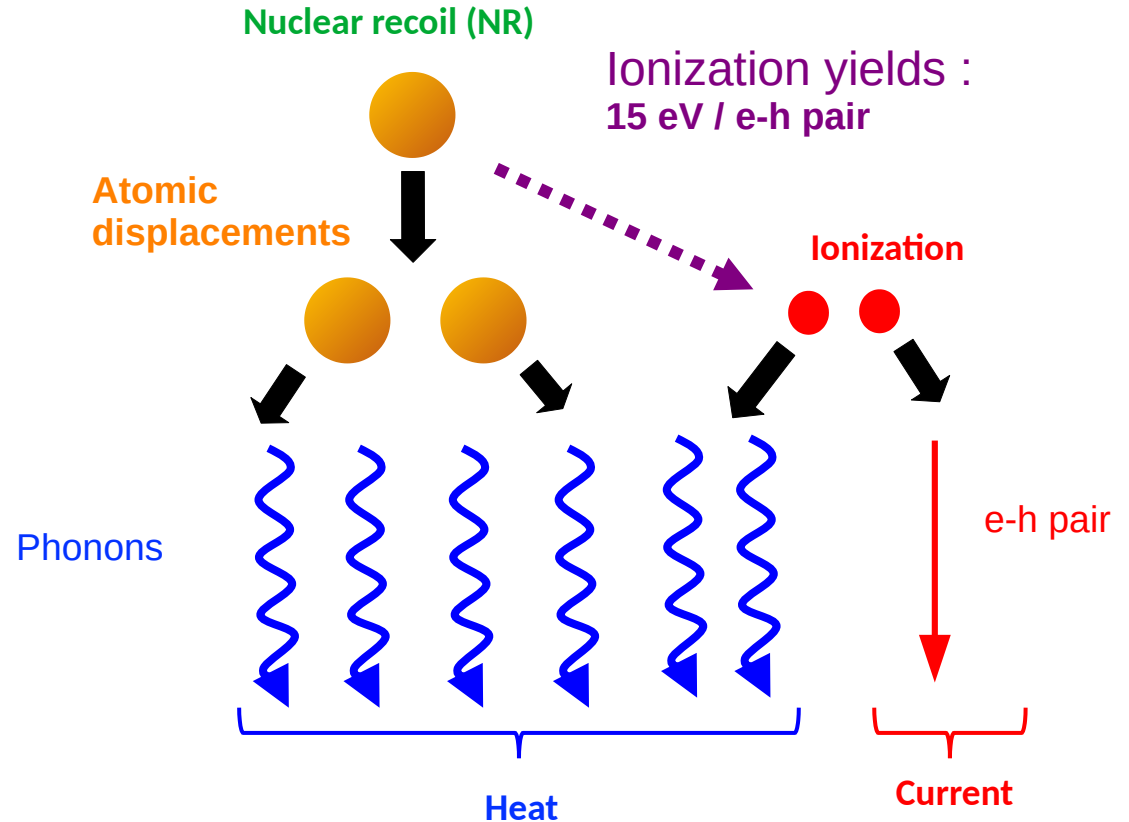
- **Heat** : carry most of the energy

- Phonon detector

- Sensitive to **heat** channel
- $1 \mu\text{eV}$ to create thermal phonon
- Good candidate for low NR detection

- Ionization detector

- Sensitive to **charge** channel
- Limited sensitivity to NR



Ionization detectors

- Channels of energy deposition :

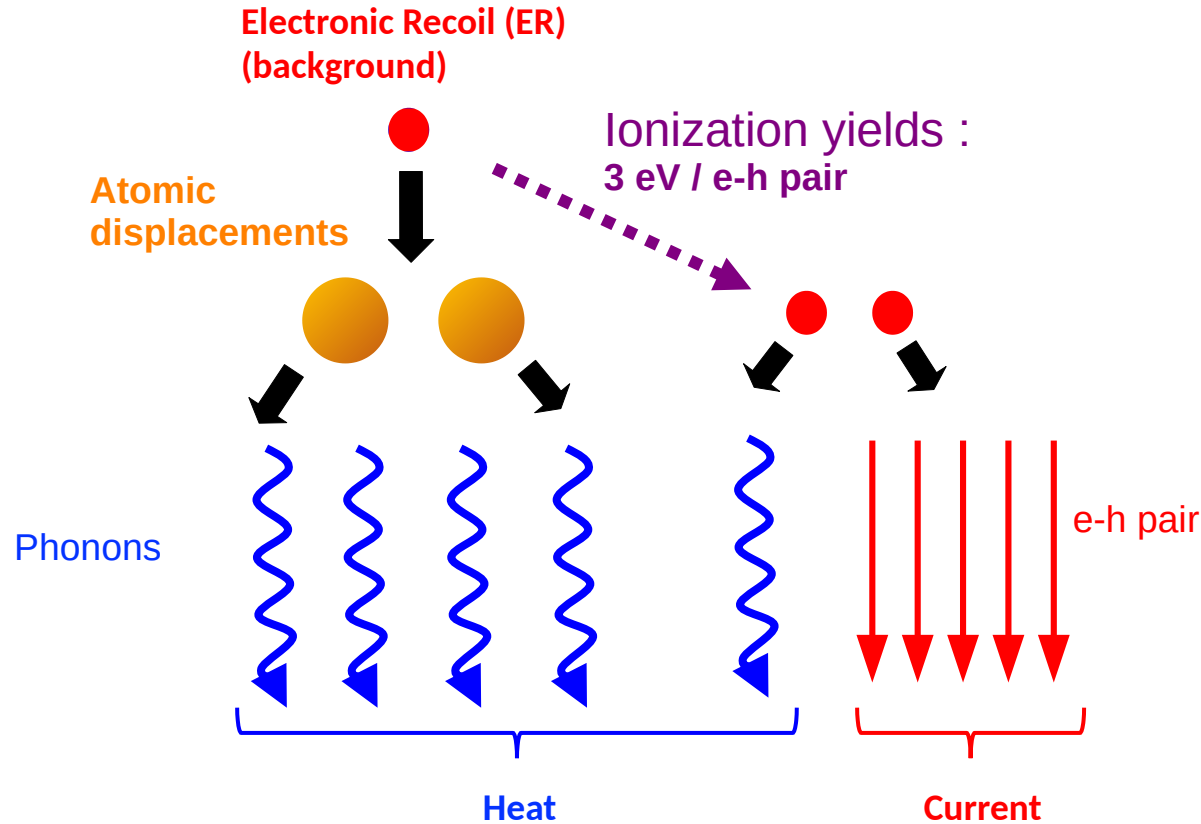
- **Heat** : carry most of the energy

- Phonon detector

- Sensitive to **heat** channel
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- Ionization detector

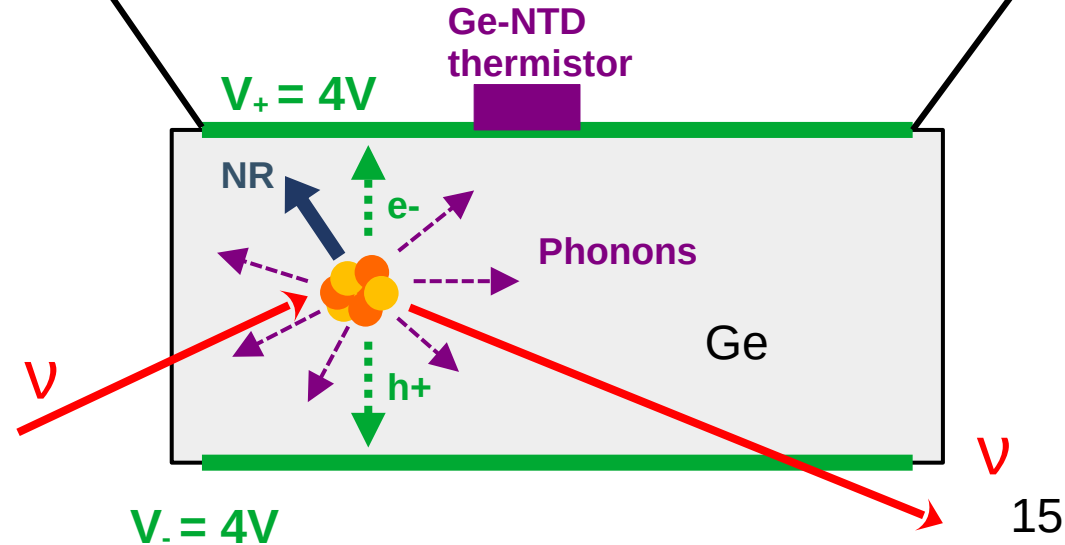
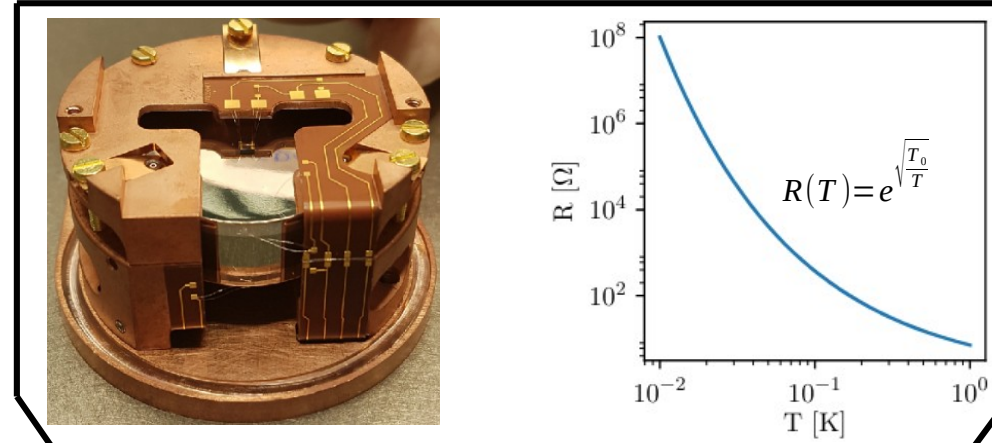
- Sensitive to **charge** channel
- Limited sensitivity to NR
- Allow to detect ER background



Heat - ionization detector

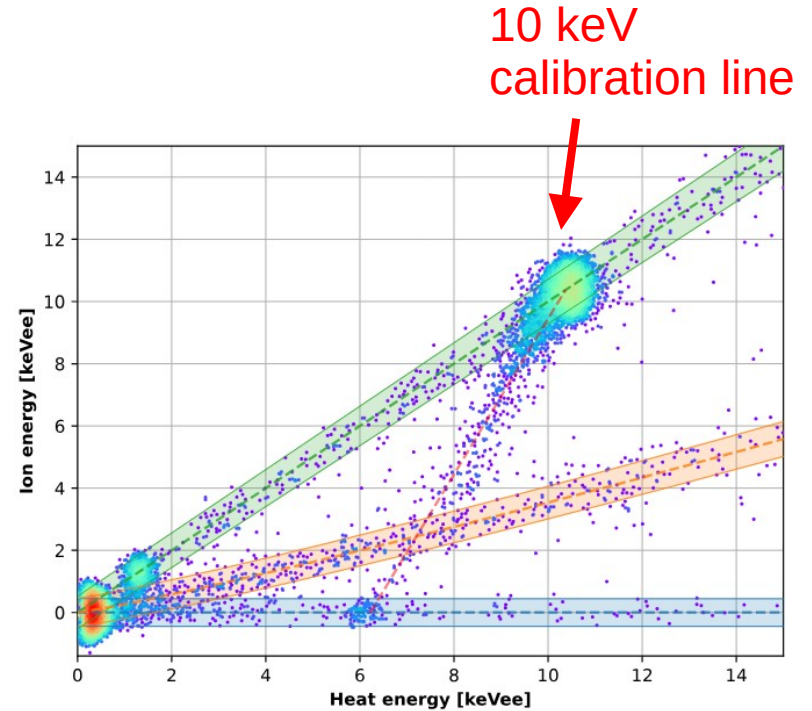
RICOCHET

- Recoil energy dissipated in heat and ionization channels
- Simultaneous **ionization** + **heat** measurement with a Germanium detector
- Thermometer : Neutron Transmuted Doped Germanium



Heat - ionization detector

- Ionization yields depends on recoil type (NR, ER)
 - NR/ER discrimination for background rejection
- Particle identification :
 - **Electronic recoil** : γ , β , X-ray calibration source
 - **Nuclear recoil** : CEvNS signal or neutron
 - **Heat-only** : background



J Low Temp Phys 211 (2023), 398

Outline

I. Motivations

II. Cryogenic detector for sub-keV NR detection

III. Calibration with the CRAB method

IV. Presentation of CRAB phase II

Motivations

- Standards calibrations : Electronic Recoil
 - X rays source, LED
 - Issues : No mono-energetic source of NR
 - Detector response different from NR to ER



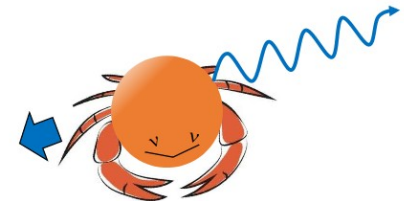
**Extrapolation of ER calibration
for sub-keV NR not reliable !**

Motivations

- Standards calibrations : Electronic Recoil
 - X rays source, LED
 - Issues : No mono-energetic source of NR
 - Detector response different from NR to ER

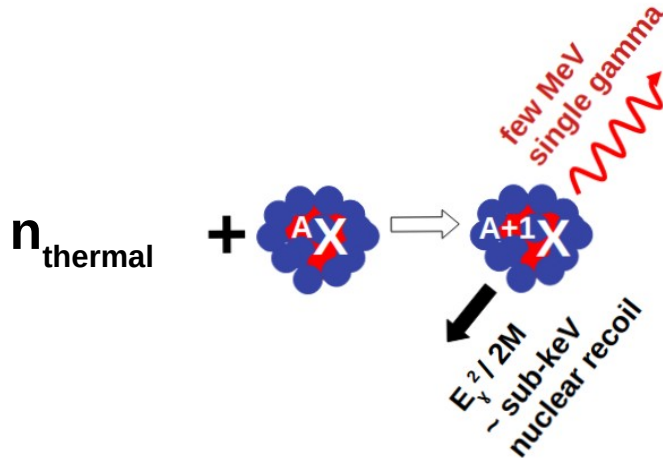
 **Extrapolation of ER calibration for sub-keV NR not reliable !**

- Goal: induce low energy NR to mimic signal
 - calibrate detector response to NR
- **CRAB** : **C**alibrated **R**ecoil for **A**ccurate **B**olometry



CRAB method

- Radiative thermal neutron capture: $\gamma + \text{NR}$
- NR fixed energy : $E_{\text{NR}} = \frac{E_{\gamma}^2}{2M} \rightarrow$ Calibration peaks < 1 keV in CaWO_4 , Al_2O_3 , Ge and Si



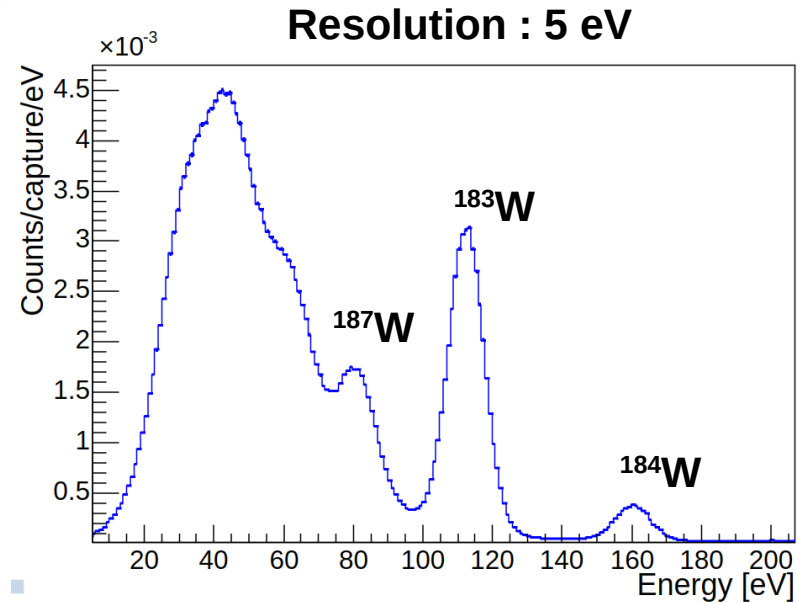
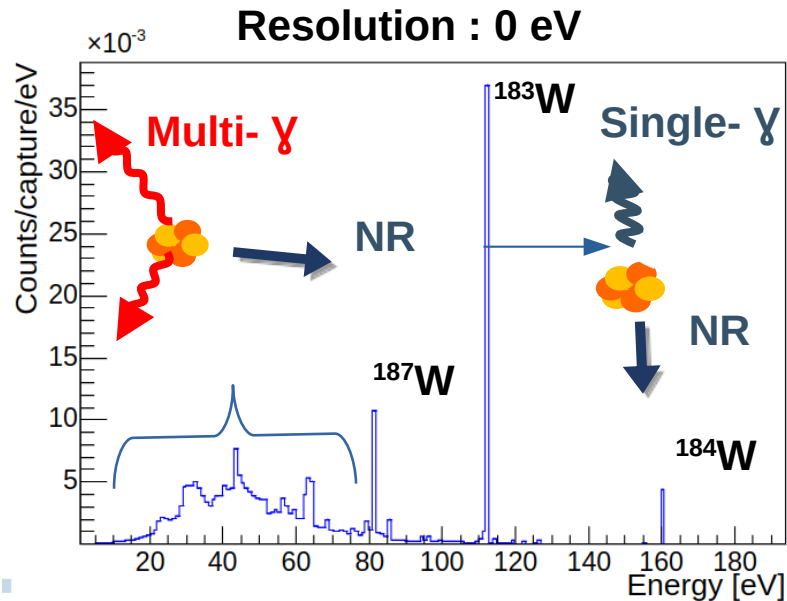
- Pure NR
- Sub-keV range
- Uniformly distributed in the detector

L. Thulliez et al 2021 JINST 16 P07032

Promising target for CRAB : CaWO_4

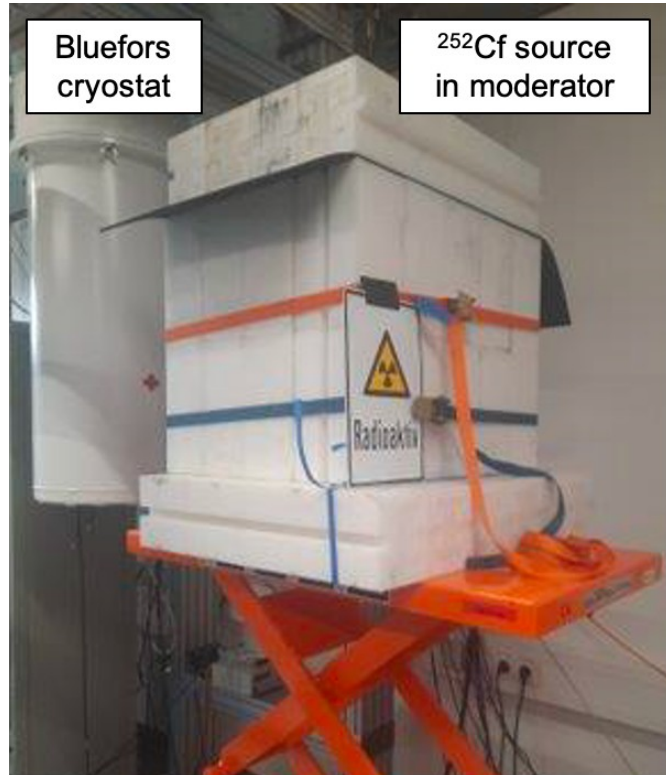
- 3 main natural isotopes of W : ^{186}W , ^{182}W and ^{183}W :
→ peaks at 81, 112 and 160 eV
- Multi- γ : induce continuum of nuclear recoil
- Intense peak at 112 eV « easy » to detect

Simulation

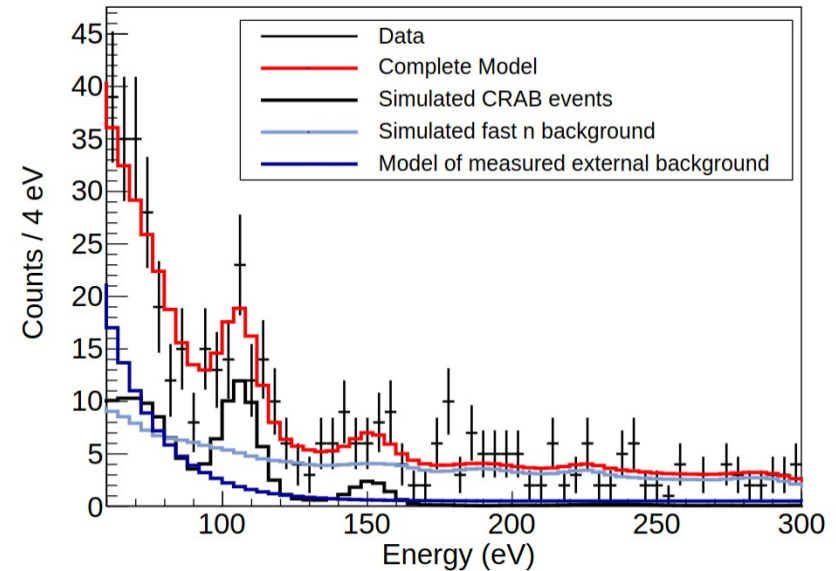


Experimental validation on CaWO_4

- ^{252}Cf neutron source next to the NUCLEUS cryostat in Munich



- 112 eV peak detected at 2.9σ
- **CRAB works !**
- High background level !



→ Phys. Rev. Lett. 130, 211802

Phase II : Toward high precision

- CRAB at atominstitut in Vienna
 - Research reactor, $P \sim 250$ kW
 - Collimated and pure thermal n beam



" TRIGA Mark-II reactor in Vienna "

Outline

I. Motivations

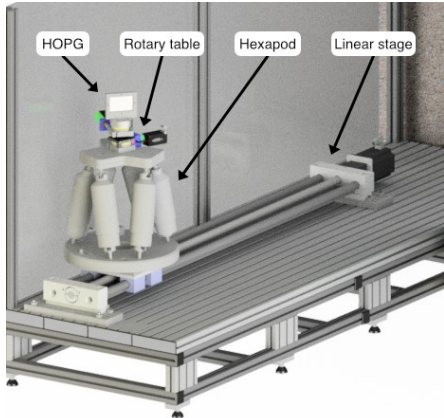
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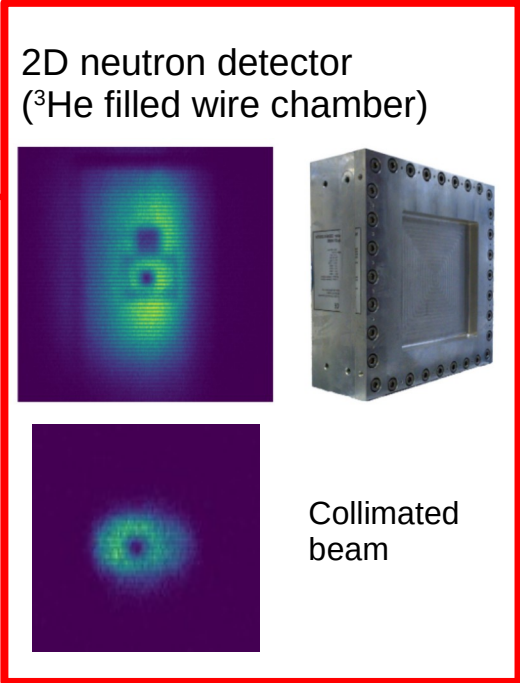
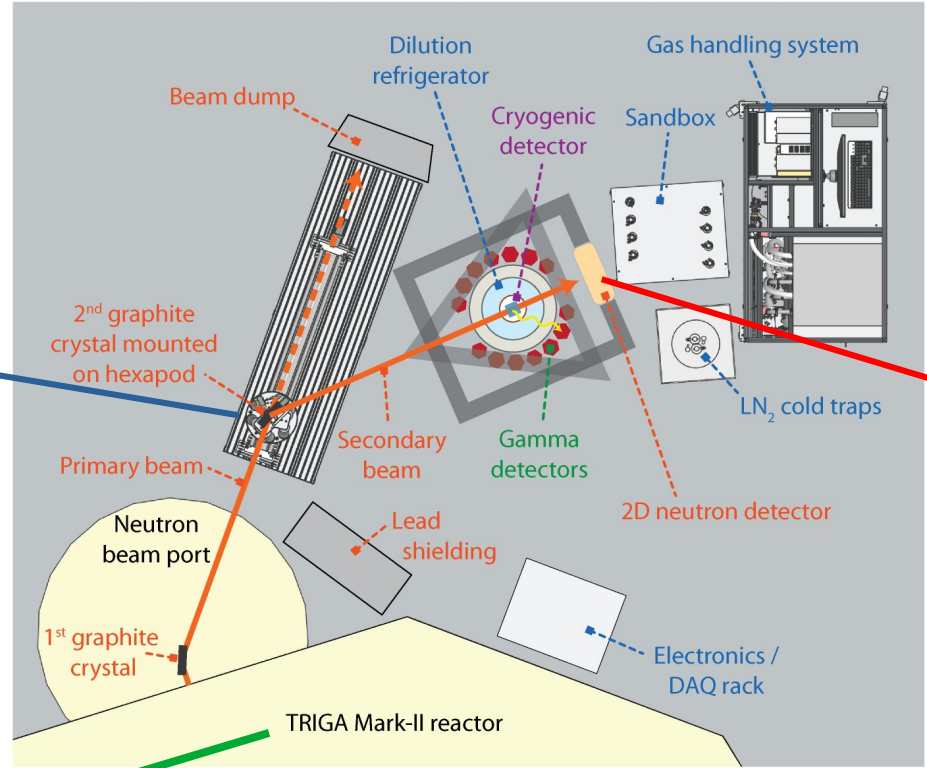
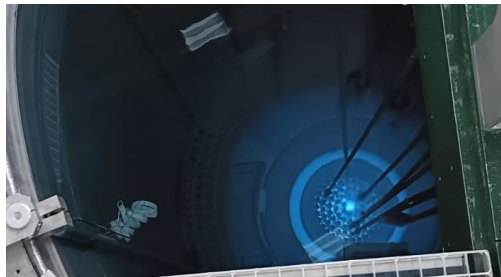
IV. Presentation of CRAB phase II

Experimental setup : The neutron beam

Reflective Graphite crystal mounted on hexapod



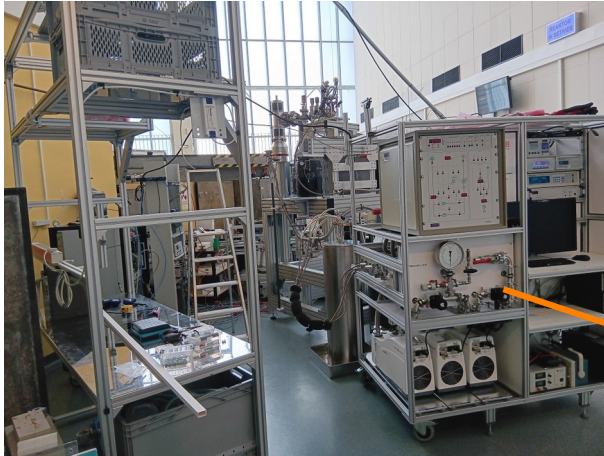
TRIGA Mark-II reactor



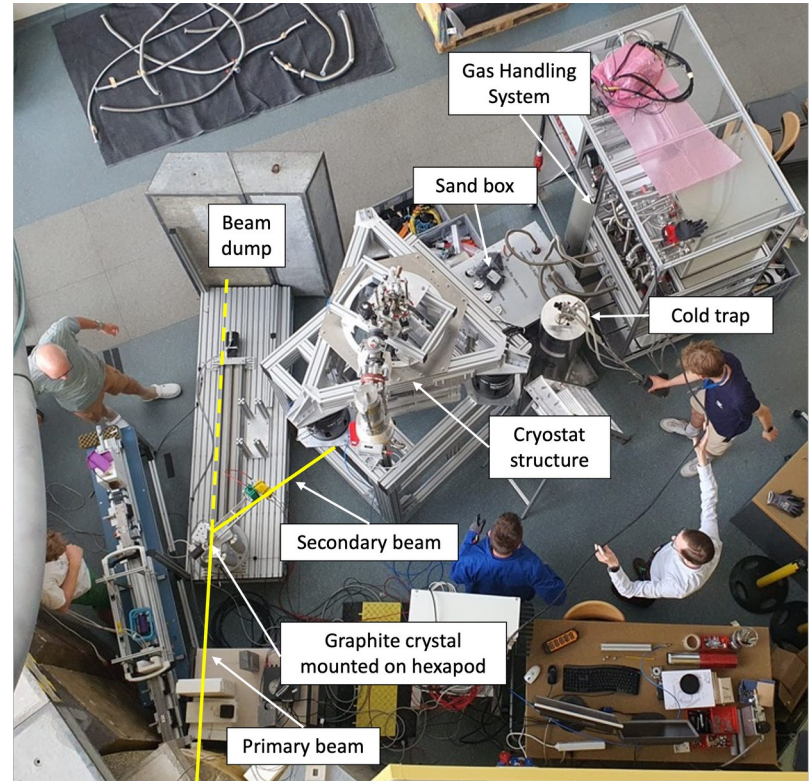
Measured flux :

$$\phi_n = 469 \pm 47 \text{ n/cm}^2/\text{s}$$

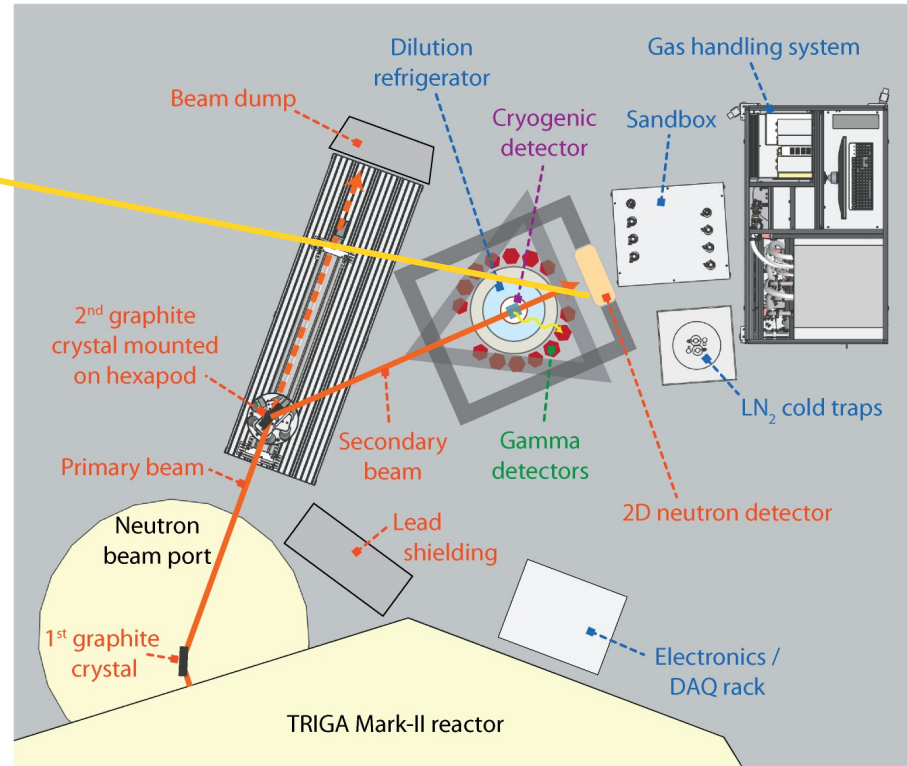
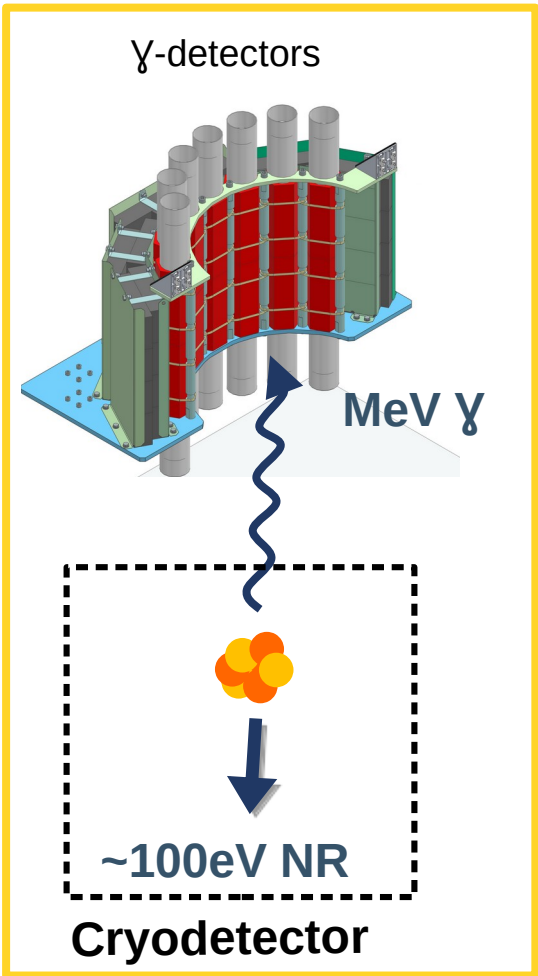
Installation : summer 2024



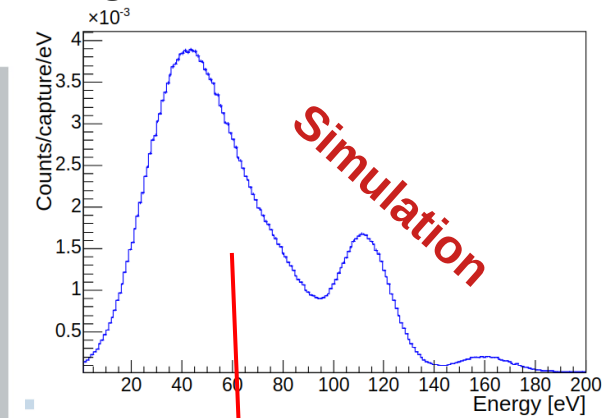
Gas Handling System



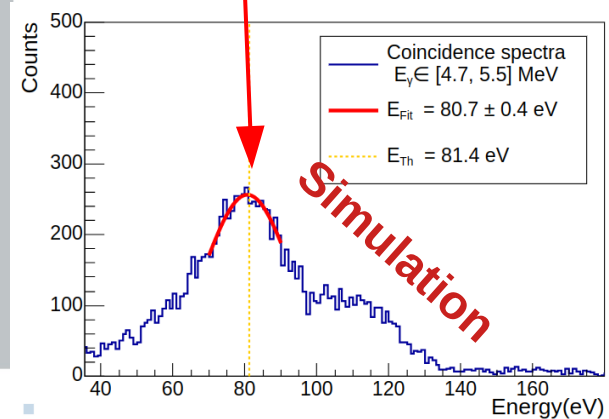
Experimental setup : The γ -detectors



Single : 10 eV resolution



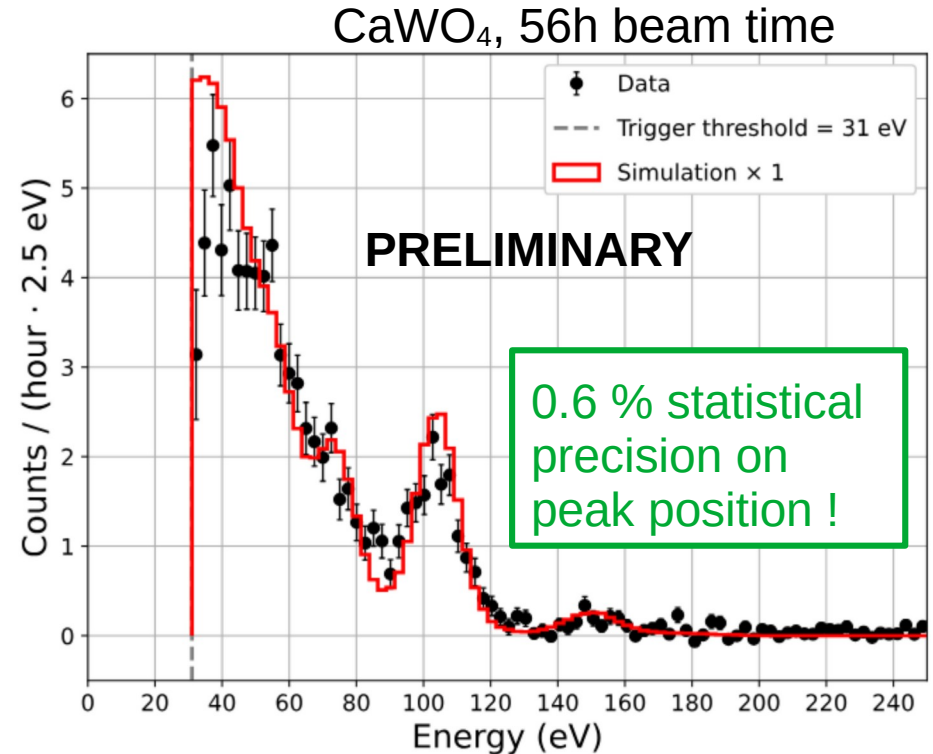
Coinc :



- Tag NR in Time, Energy and Direction

Results in CaWO₄

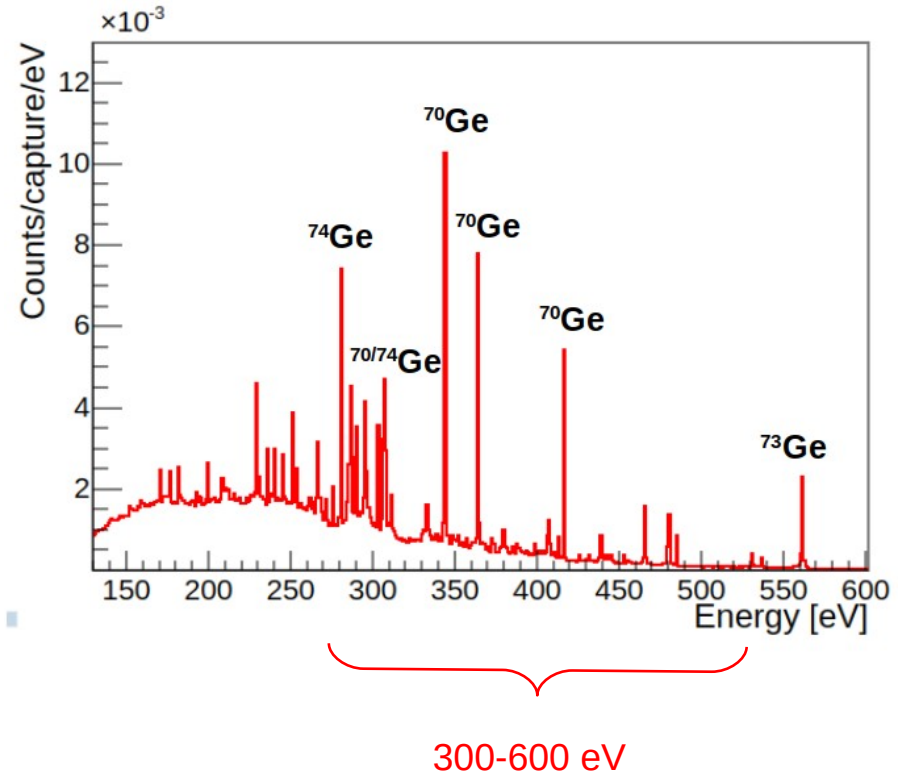
- Excellent agreement with simulated spectrum !
- Peak position shifted to the theoretical value corrected due to energy stored in crystal defects



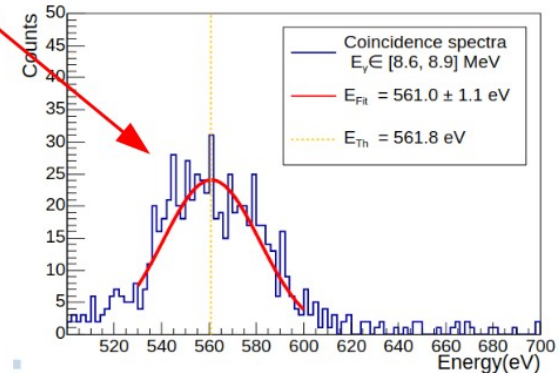
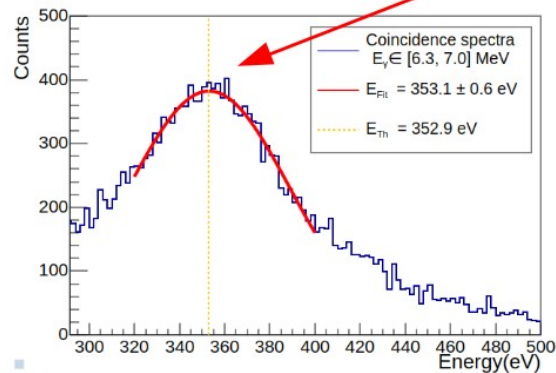
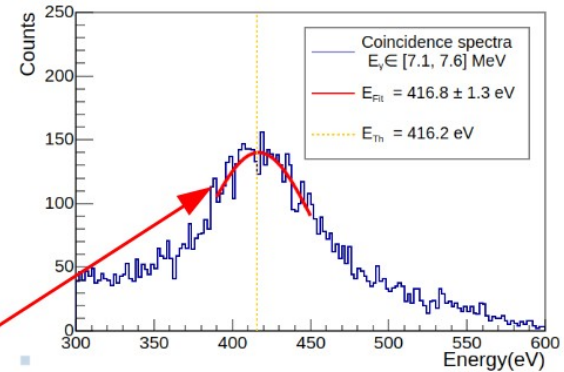
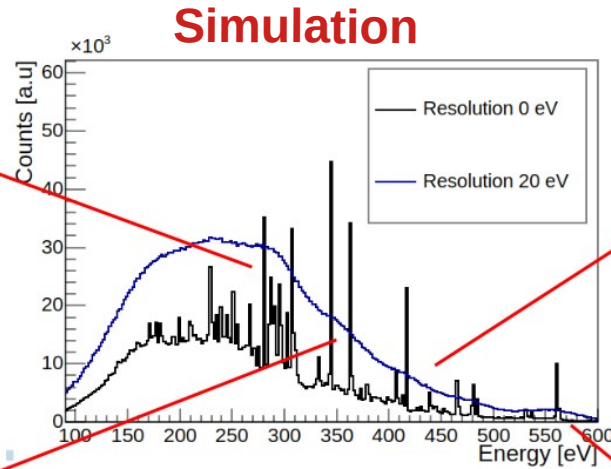
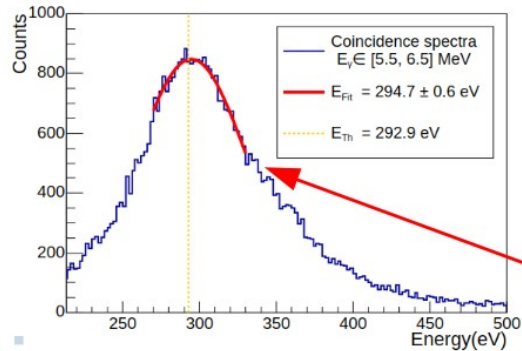
Extension to Germanium

- CRAB in Ge: nuclear-recoil lines in the sub-keV energy range
- Precise determination of nuclear-recoil ionization yields
- Excellent energy resolution highly desirable

Isotope	Primary E_γ (MeV)	Recoils (eV)	Mean recoil (eV)	Fit (eV)	Selection cut (MeV)
^{74}Ge	6.252	280.2			
^{70}Ge	6.117	295.7			
^{74}Ge	6.506	303.2	291.0	298.7 ± 1.6	[6.0,6.5]
^{70}Ge	6.707	344.0			
^{70}Ge	6.916	363.5	354.4	352.0 ± 3.8	[6.7,7.0]
^{70}Ge	7.416	416.2	416.2	418.2 ± 2.9	[7.3,7.6]
^{73}Ge	8.732	561.2	561.2	561.1 ± 4.3	[8.6,8.8]

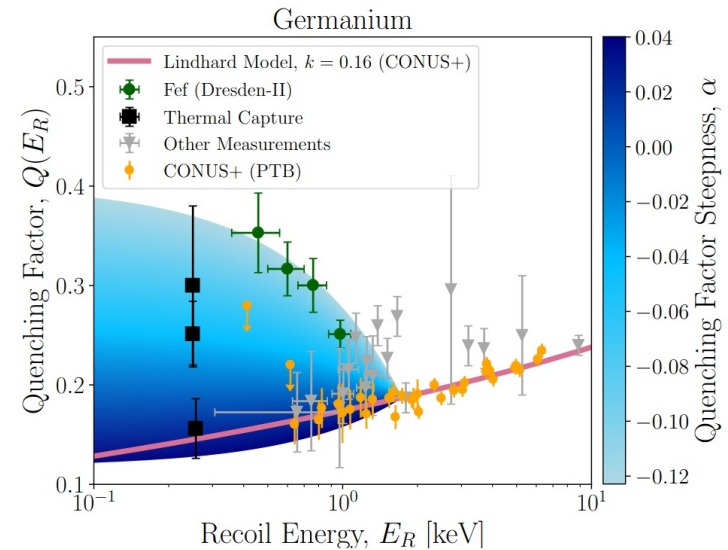


Extracting peak with γ -coincidence



Probe of Ge quenching factor

- Quenching factor : $Q = E_{\text{ion}}/E_{\text{recoil}}$
- Preparation of a **double readout heat/ionization Germanium detector** from TESSERACT → Implementation in the CRAB setup in 2027



Li, Y., Herrera, G. & Huber, P. New physics versus quenching factors in Coherent Neutrino Scattering. *J. High Energy Phys.* 2025, 22 (2025)

Thank you for your attention !

Back up

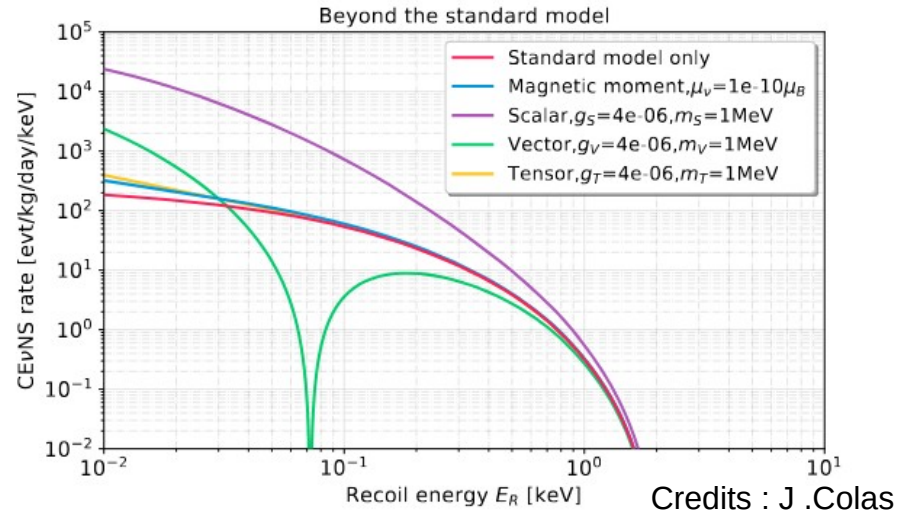
Sensitivity to new physics

- Test SM at low energy
- CEvNS sensitive to weak charge
 - Probe θ_w at low momentum transfer

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 M}{4\pi} Q_W^2 \left(1 - \frac{E_R}{E_R^{\max}}\right) \propto N^2$$

$$Q_W = N - Z(1 - 4\sin^2\theta_w)$$

- New physics :
 - Anormal neutrino magnetic moment
 - Enhance cross section for low recoils
 - New neutrino-quarks coupling
 - Spectrum normalization
 - New light mediator
 - Spectrum distortions



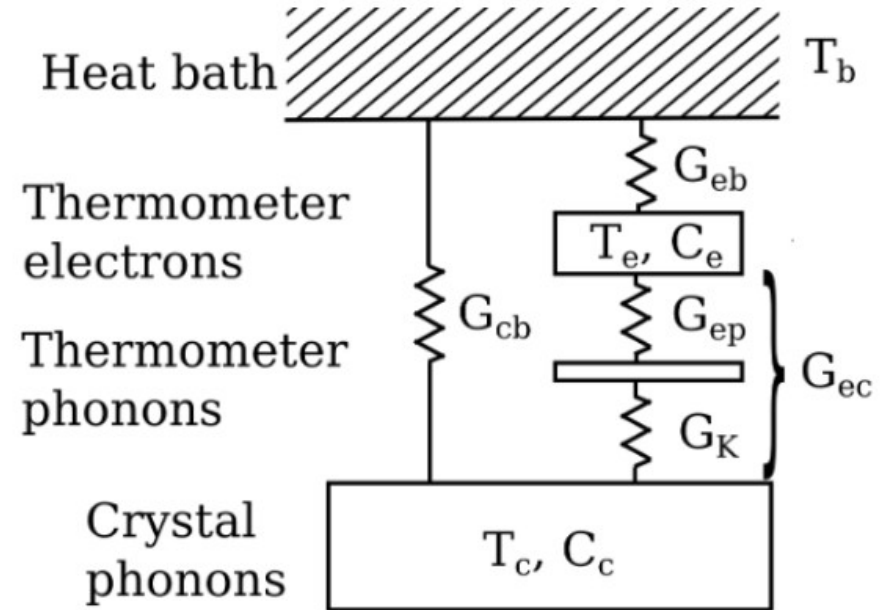
Calorimeter model

$$T(t) = \Theta(t) \left[A_n \left(e^{-\frac{t}{\tau_{in}}} - e^{-\frac{t}{\tau_n}} \right) + A_t \left(e^{-\frac{t}{\tau_t}} - e^{-\frac{t}{\tau_n}} \right) \right]$$

Fast decay time : $\tau_{in} = \frac{C_e}{G_{eb}}$

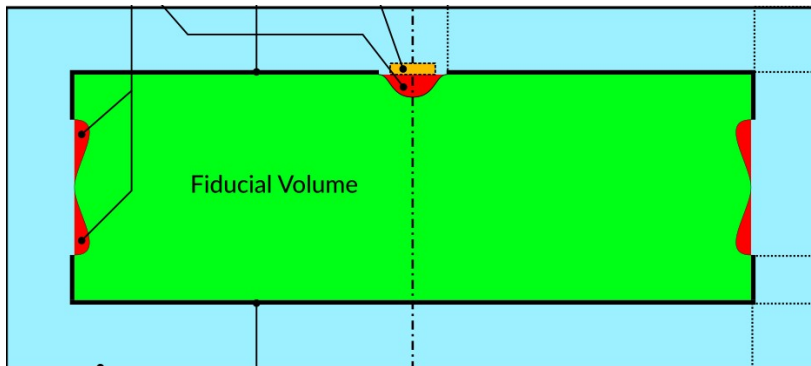
Slow decay time : $\tau_t = \frac{C_c}{G_{ec}}$

Rise time : τ_n



Electrode geometries

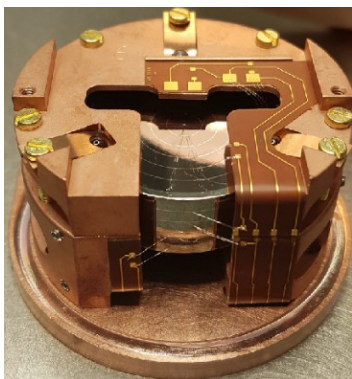
Planar electrodes :



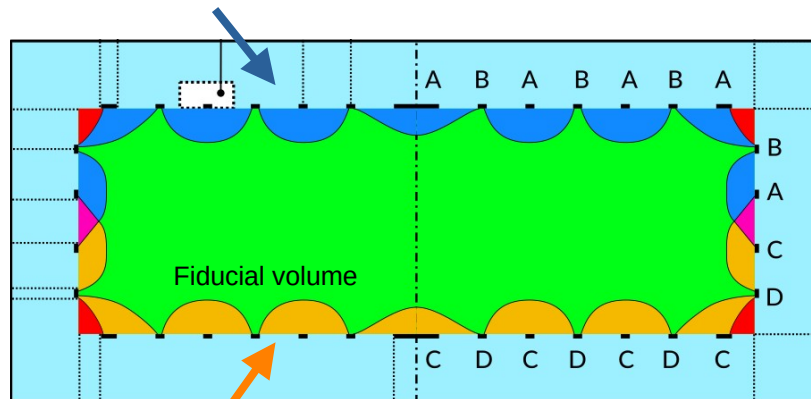
✓ Fiducial volume : 97 %

✗ No surface events rejection

Fully Inter-Digitized (FID) electrodes :



Veto volume



✓ Surface events rejection

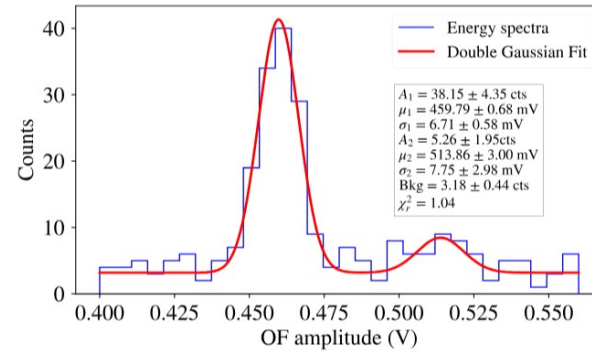
— Fiducial volume : 60 %

Veto volume

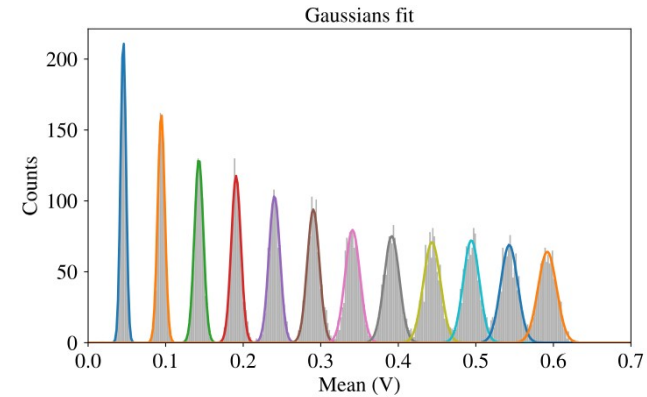
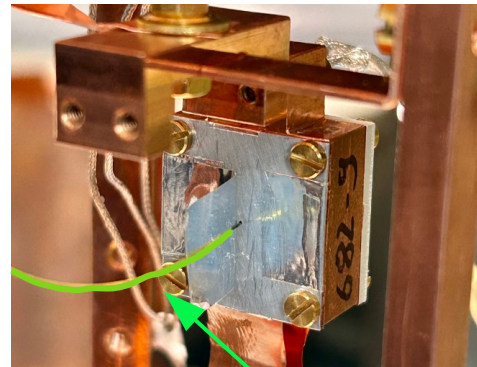
A,C : veto electrodes

Calibration methods

- Copper cosmogenic activation
 - Lines at 8.05 and 8.9 keV



- LED system
 - Photons injection with fixed energy
 - Calibration of electronic recoils



15 % discrepancy between the two calibrations

Optical fiber

LED calibration

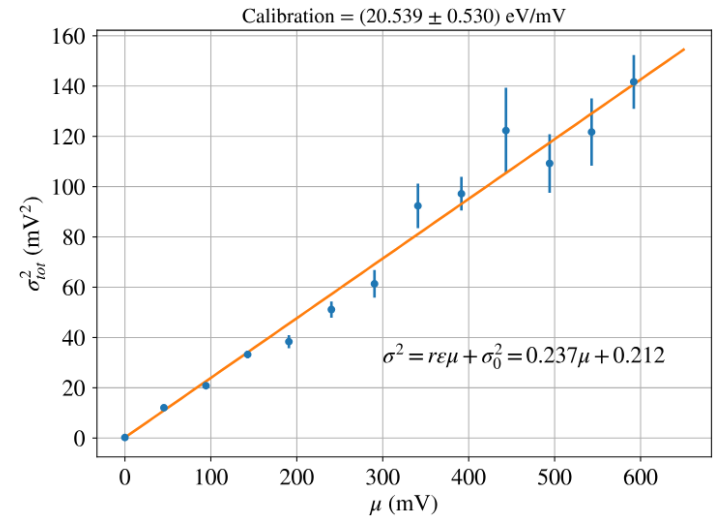
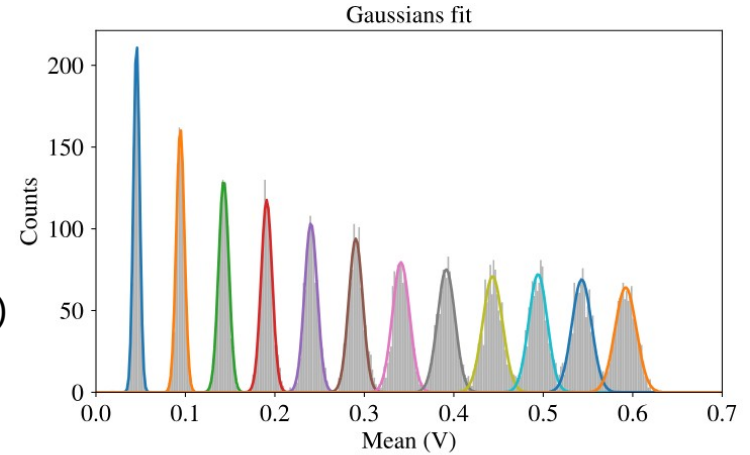
- LED system

- Photons injection with fixed energy ($\lambda = 255 \text{ nm}$, $E = 4.87 \text{ eV}$)

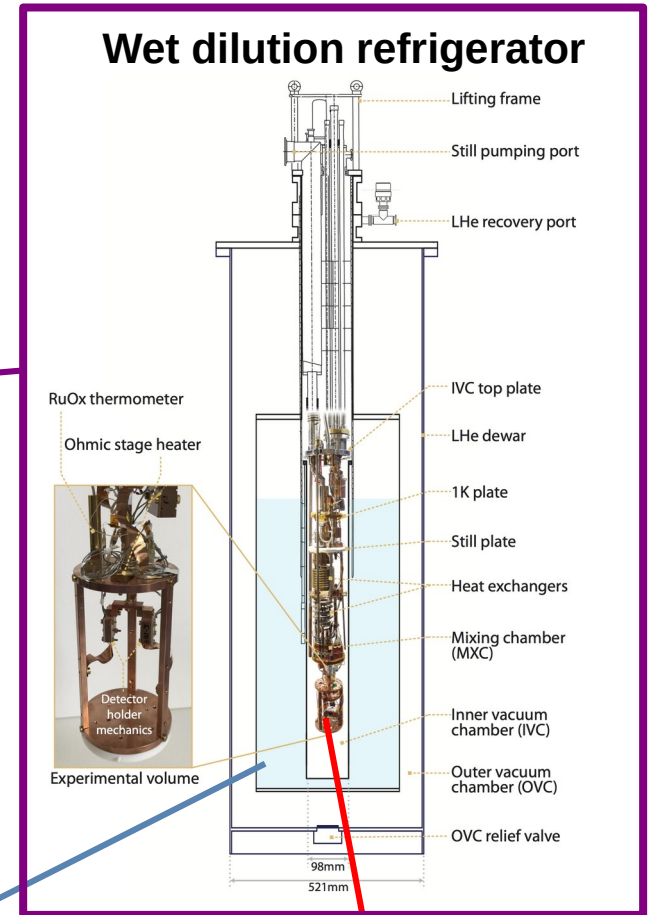
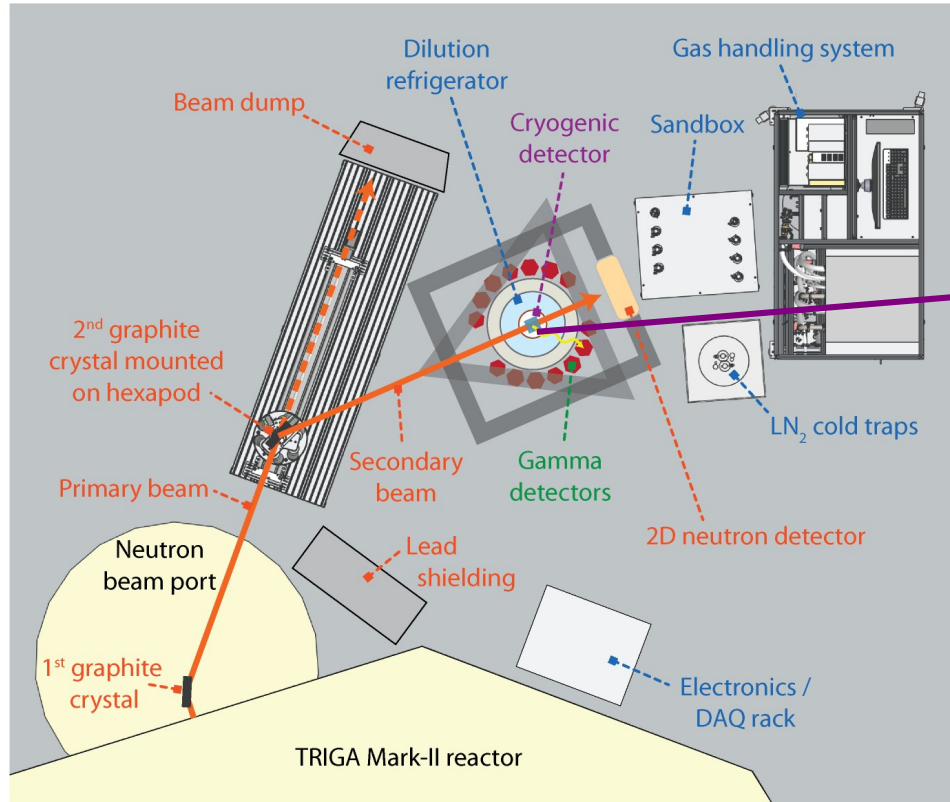
$$\mu = r \langle N_{\text{ph}} \rangle \epsilon_{\text{ph}} \quad \text{Calibration factor}$$

$$\sigma_E^2 = (r \epsilon_{\text{ph}})^2 \langle N_{\text{ph}} \rangle = r \mu \epsilon_{\text{ph}}$$

- Calibration of electronic recoils



Experimental setup : The cryostat



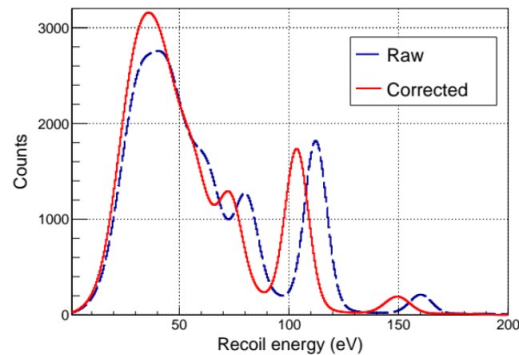
Liquid ⁴He (LHe)

Cryodetector

CaWO₄ : Insight to crystal defect

- Stored energy in crystal defects induced by NR
- July-December 2025 : Probe crystal defect creation in CaWO₄ with CRAB
- Lead to spectral distortion that should be taken into account for CEvNS and low mass DM spectra

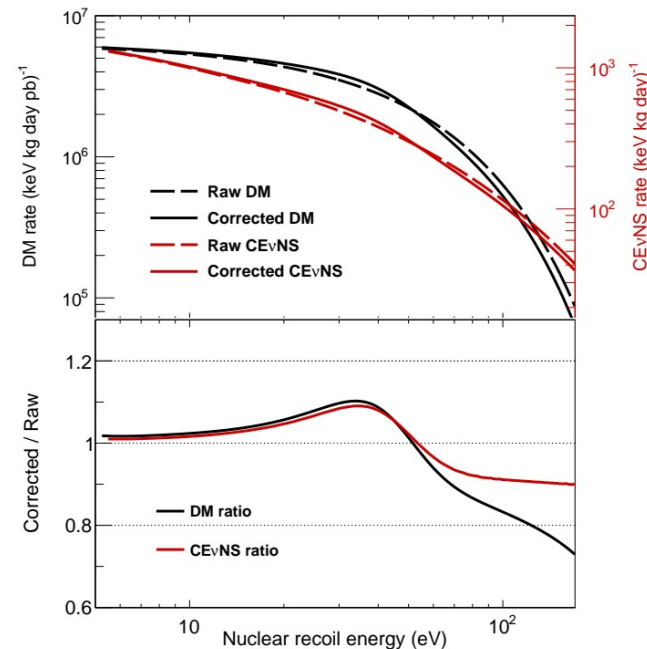
Impact in CRAB spectrum :



Nuclear recoil energy	40 eV	81 eV	112 eV	160 eV
Average energy stored in defects	2.7 eV	7.4 eV	8.9 eV	11.0 eV

Non-linearity
(defect creation thresholds)

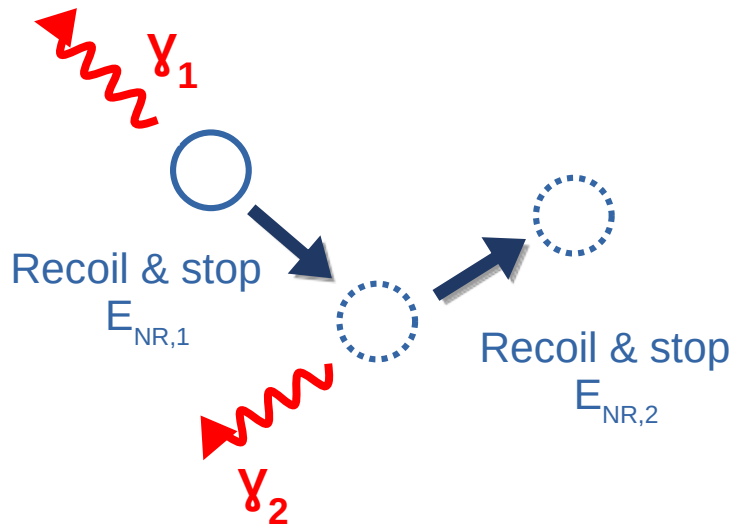
Impact in CEvNS/DM spectra :



PRD, 2025, 111 (8), pp.085021.

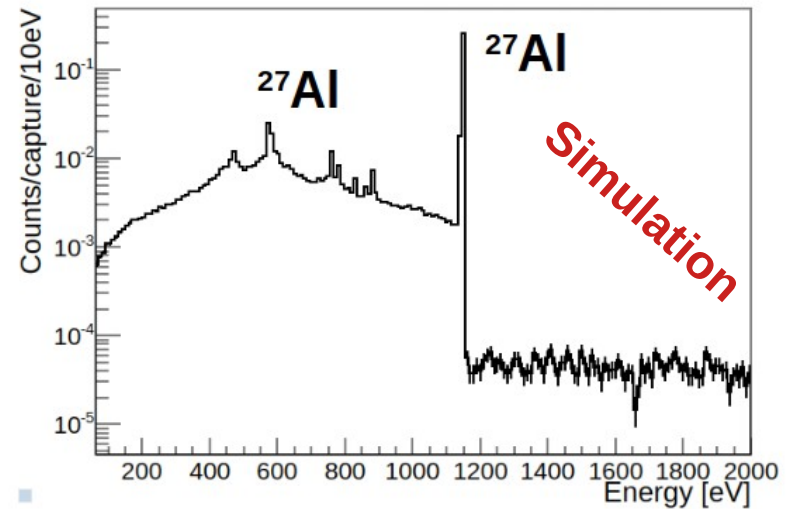
Al_2O_3 : Multi- γ cascade's timing

- Multi- γ : NR energy depends on the cascade's timing
- Al_2O_3 : Probe timing effects between γ and displacement cascades



$$E_{\text{tot}} = E_{\text{NR},1} + E_{\text{NR},2}$$

→ Additional calibration peak at fixed energy



→ Phys. Rev. D 108, 072009

Blind peak search

- Null hypothesis : bkg
- Alternative hypothesis : bkg+signal
- Test statistic :

$$t = -2 \ln \left(\frac{\mathcal{L}_{\text{bkg}}}{\mathcal{L}_{\text{bkg}+\text{signal}}} \right) = 95.7$$

↓ Compared to a $\chi^2(3)$

Peak significances :

-Peak at 196.7 mV : 9.2 σ

-Peak at 107.7 mV : 3.6 σ

