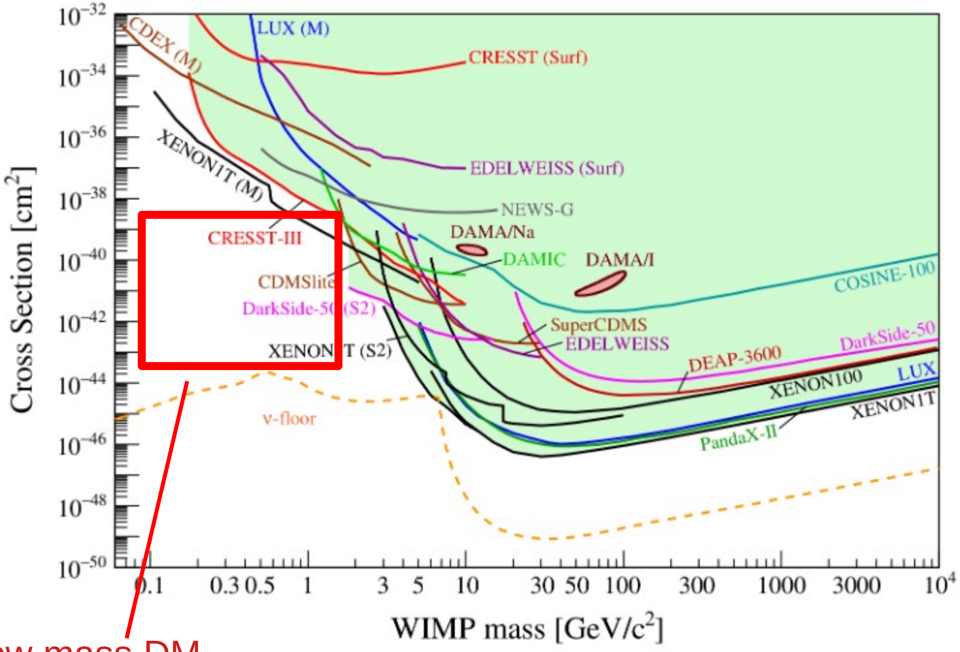
The CRAB project: precise calibration of cryogenic detectors

Romain MARTIN, CRAB collaboration

IRN Neutrino, June 2025

Nuclear recoil : Direct detection of dark matter and neutrinos

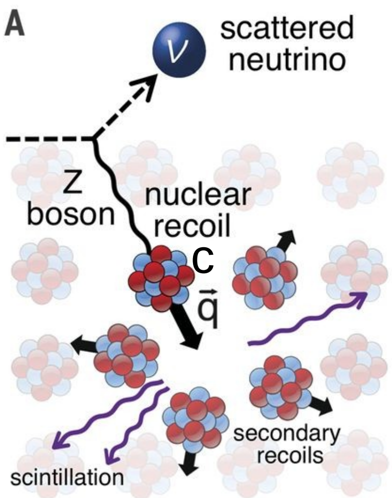
- Experimental signature: Nuclear Recoil (NR)



Low mass DM (sub-keV NR)

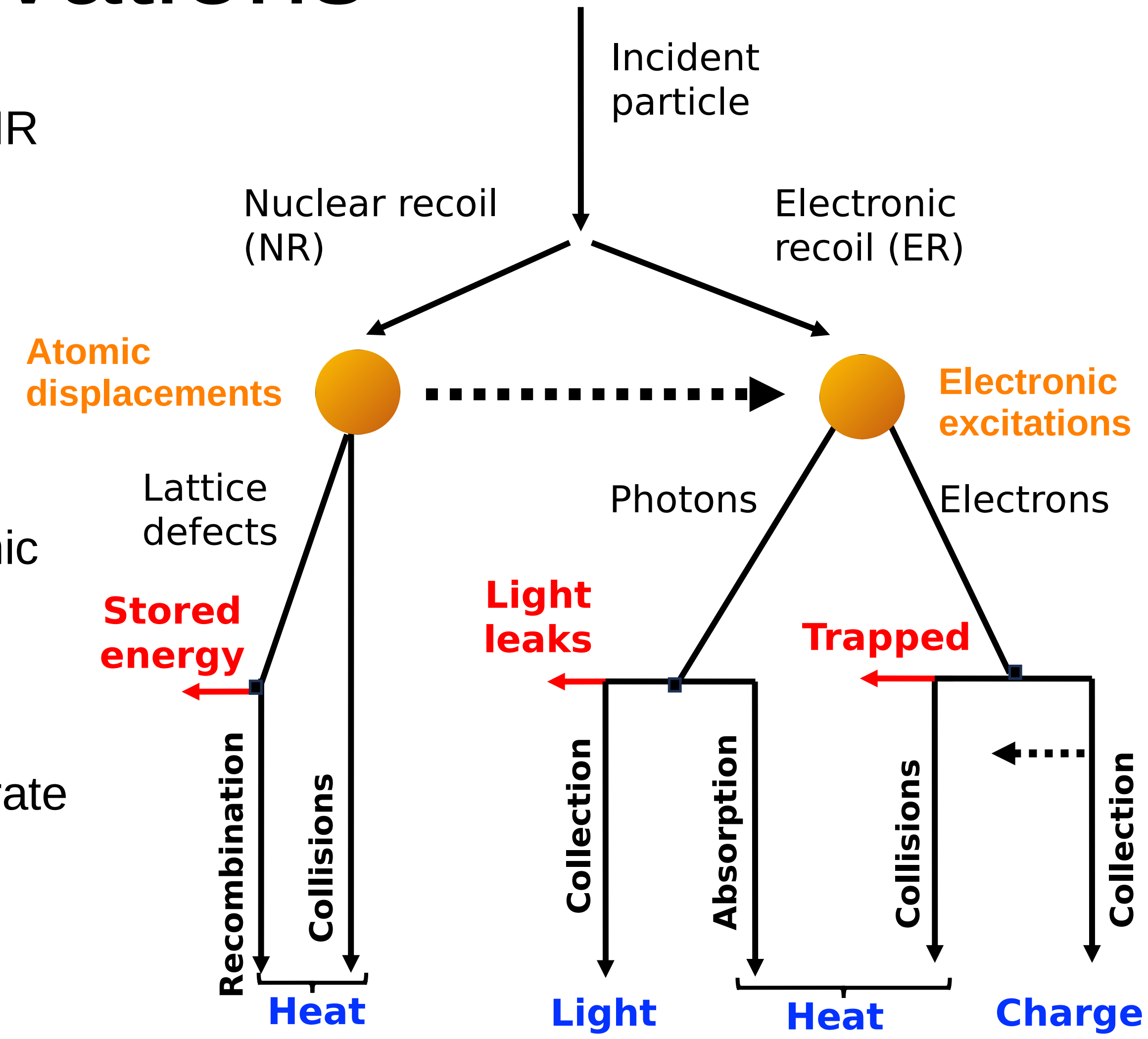
J. Billard *et al.*, *Rep. Prog. Phys.* 85, 056201(2022)

- Coherent Elastic neutrino Nucleus Scattering : ν-floor
  - Low nuclear recoil < 1 keV
  - Irreducible background for DM search
  - Test electroweak sector of SM at low E



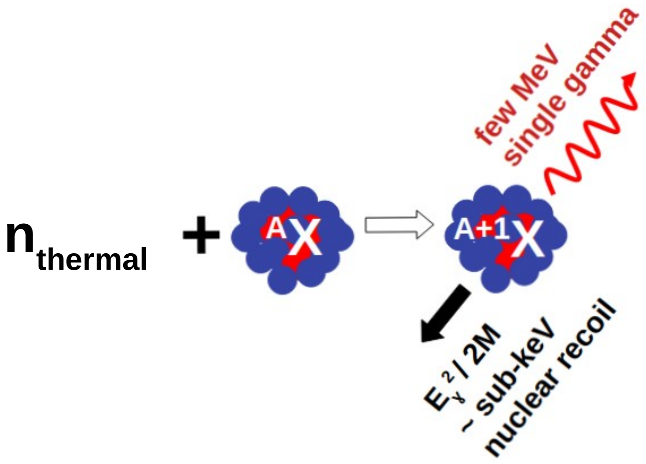
Motivations

- Calibration : detector response to NR
- Standards calibrations : Electronic Recoils (ER)
- Goal: induce low energy NR to mimic signal
- **CRAB** : **C**alibrated **R**ecoil for **A**ccurate **B**olometry



CRAB method

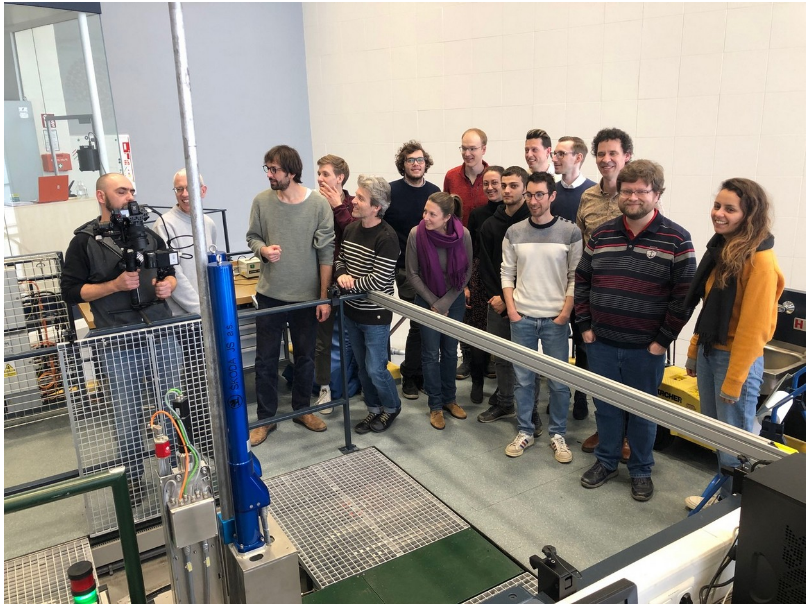
- Radiative thermal neutron capture: ɣ + NR
- NR fixed energy : $E_{NR}=\frac{E_\gamma^2}{2M}$ → Calibration peaks < 1 keV in $CaWO_4$, Al_2O_3, Ge and Si



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

L. Thulliez et al 2021 JINST 16 P07032 : Calibration of nuclear recoils at the 100 eV scale using neutron capture

The CRAB collaboration



~40 peoples, 9 institutes, 4 countries

Promising target for CRAB : $CaWO_4$

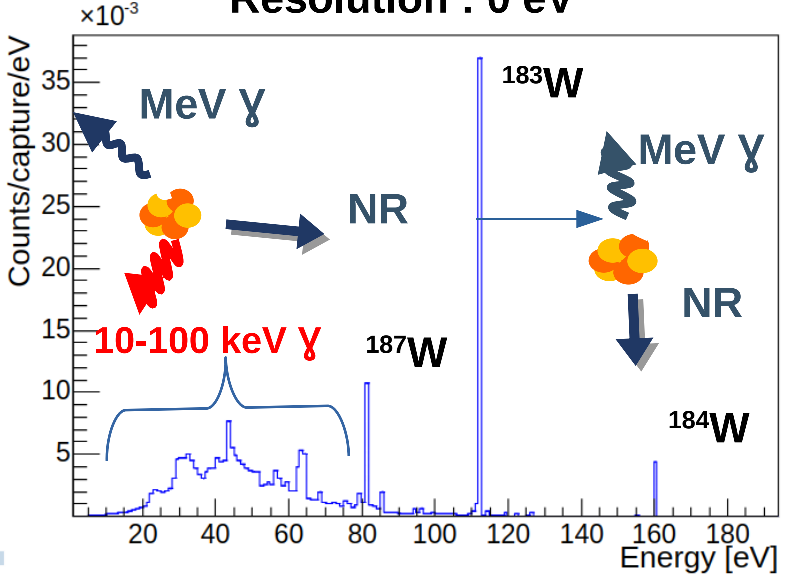
- 3 main natural isotopes of W : ^{186}W, ^{182}W and ^{183}W :

  → peaks at 81, 112 and 160 eV

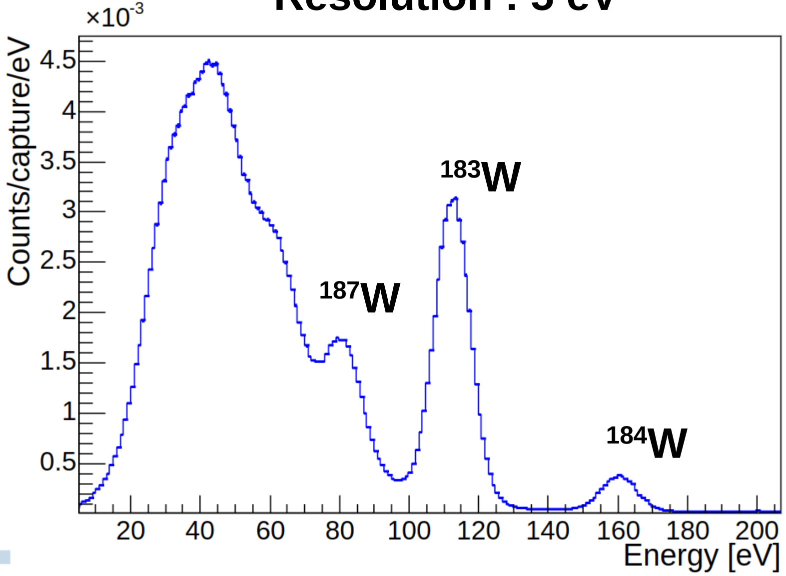
- Multi-ɣ : induce continuum of nuclear recoil
- Intense peak at 112 eV « easy » to detect

Simulation

Resolution : 0 eV

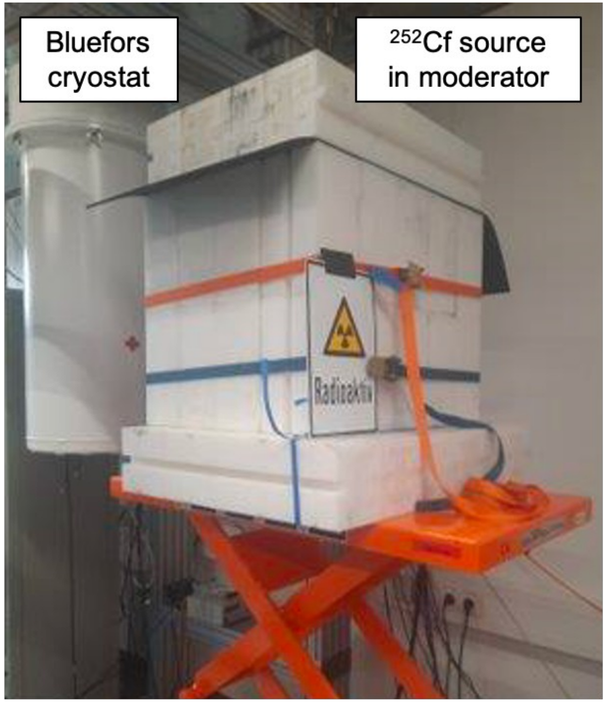


Resolution : 5 eV

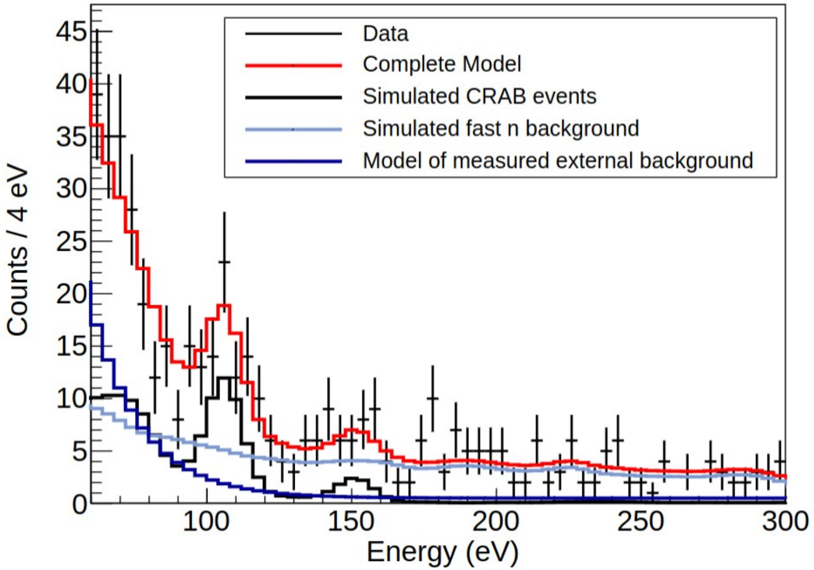


Experimental validation

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



- 112 eV peak detected at 2.9 σ
- Neutron capture events at 6 σ
- Confirmed by CRESST at 6.6 σ
- **CRAB works !**



- Fast neutron background induced by the source prevents high precision measurement

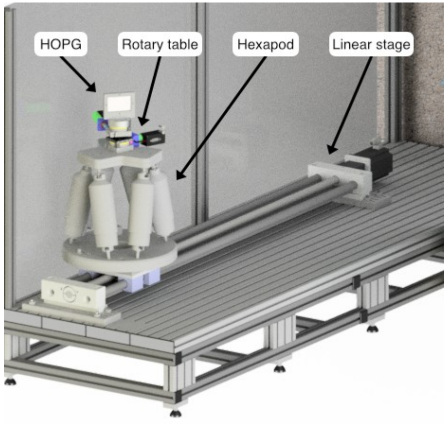
Phase II : Toward high precision

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

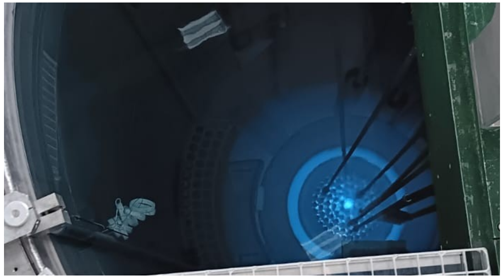
" TRIGA Mark-II reactor in Vienna "

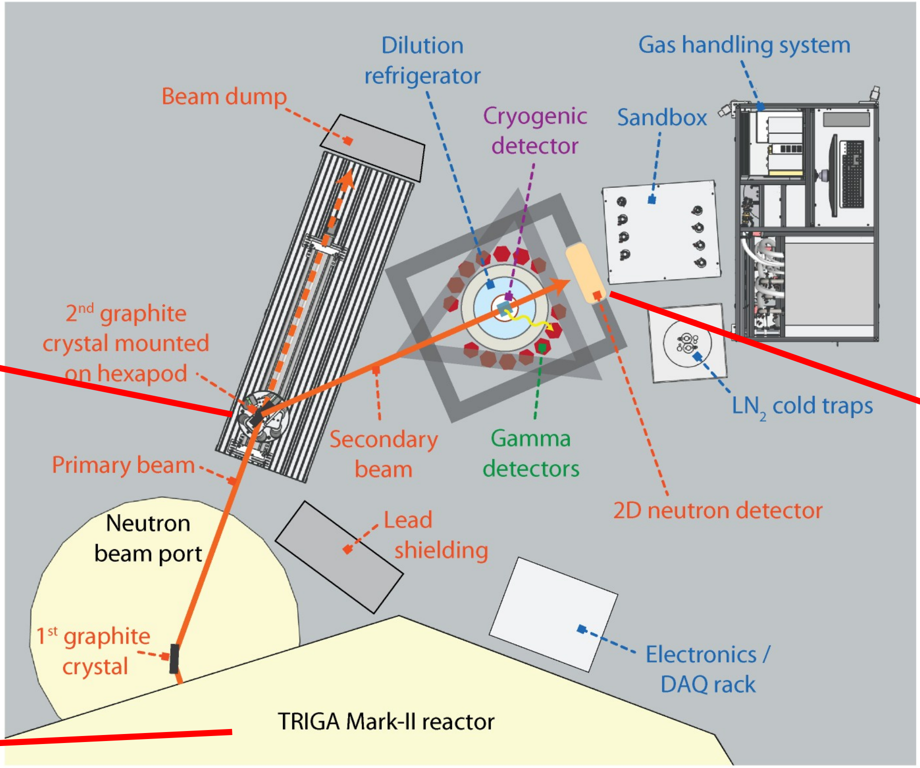
Experimental setup : The neutron beam

Reflective Graphite crystal mounted on hexapod



TRIGA Mark-II reactor

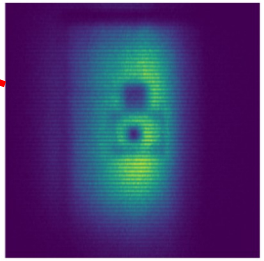


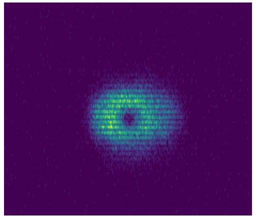


Measured flux :

$\phi_n = 469 \pm 47$ **n/cm²/s**

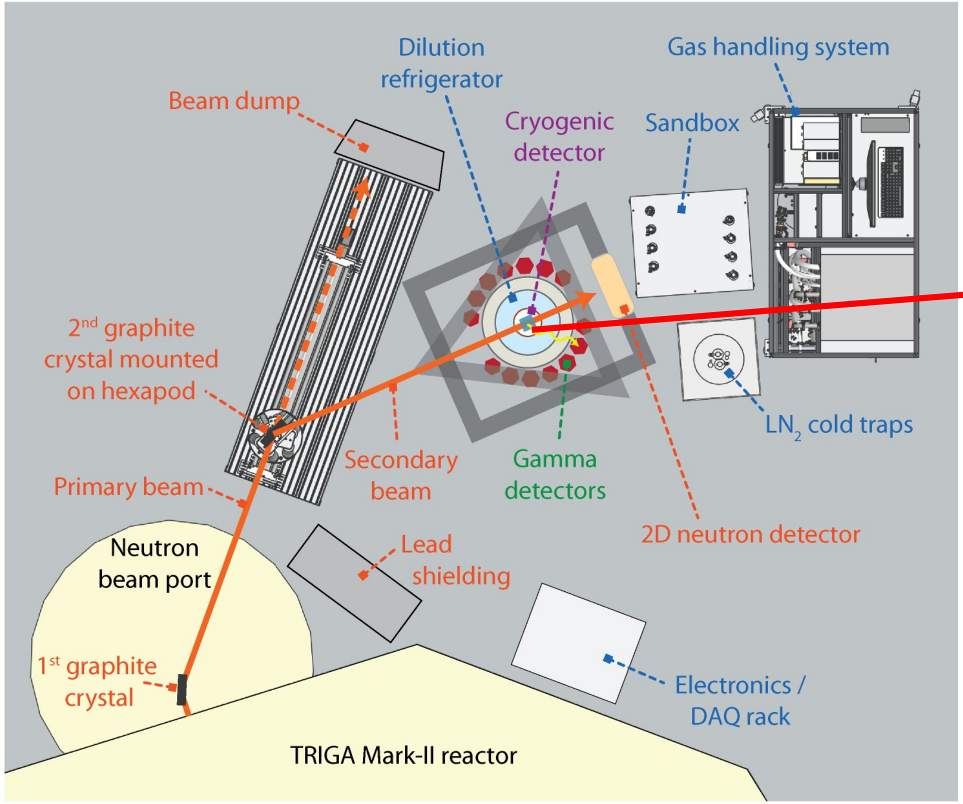
2D neutron detector
(^{3}He filled wire chamber)



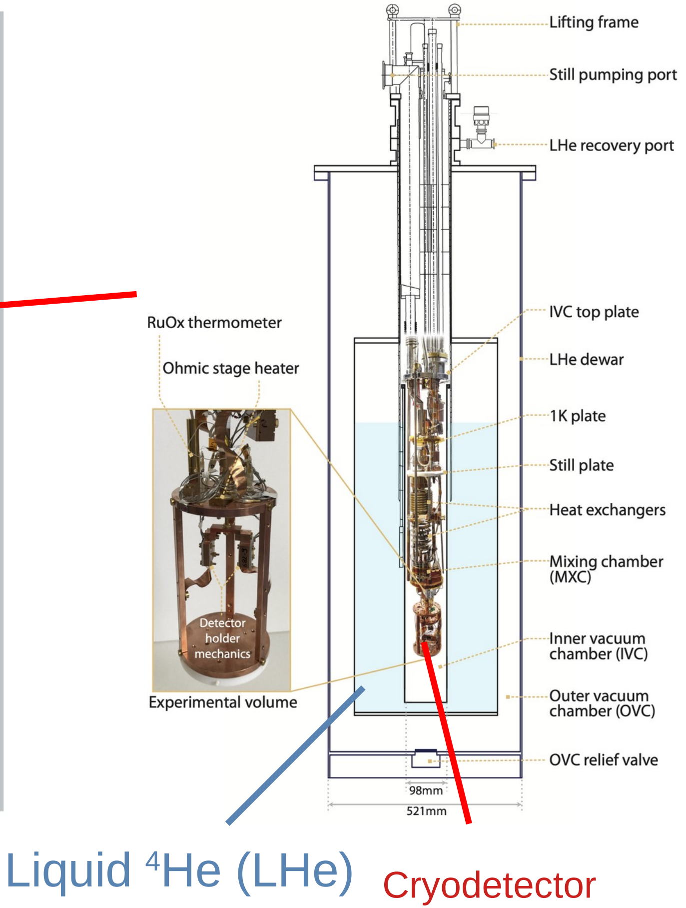


Collimated beam

Experimental setup : The cryostat

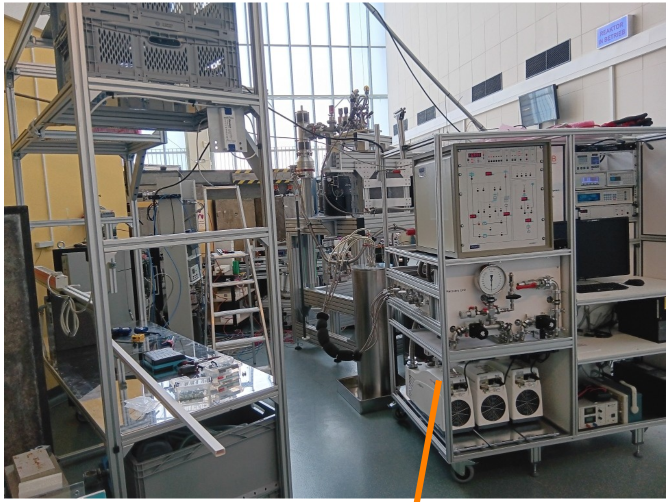


Wet dilution refrigerator

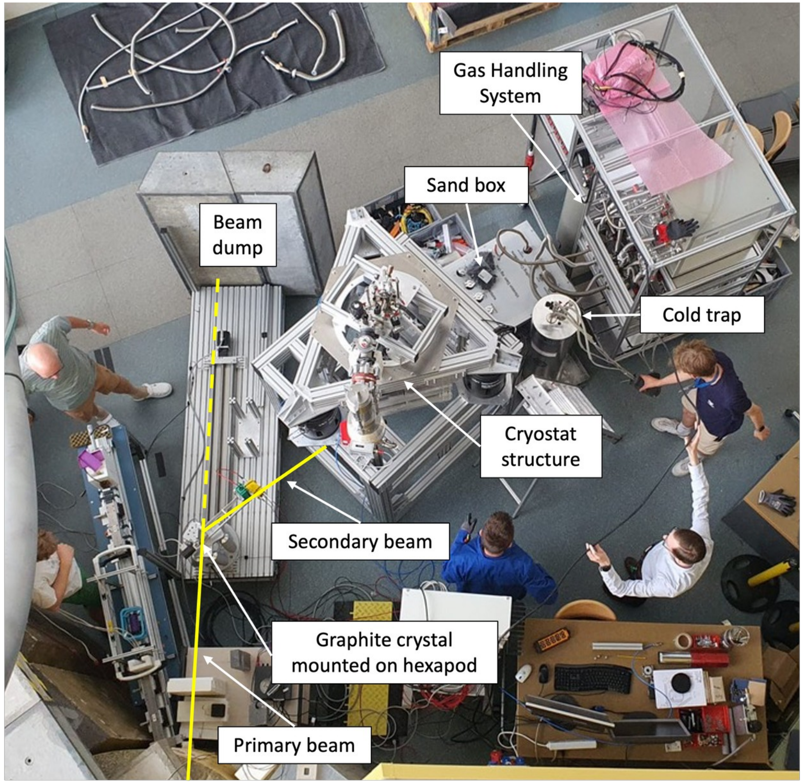


Installation : summer 2024

Support structure

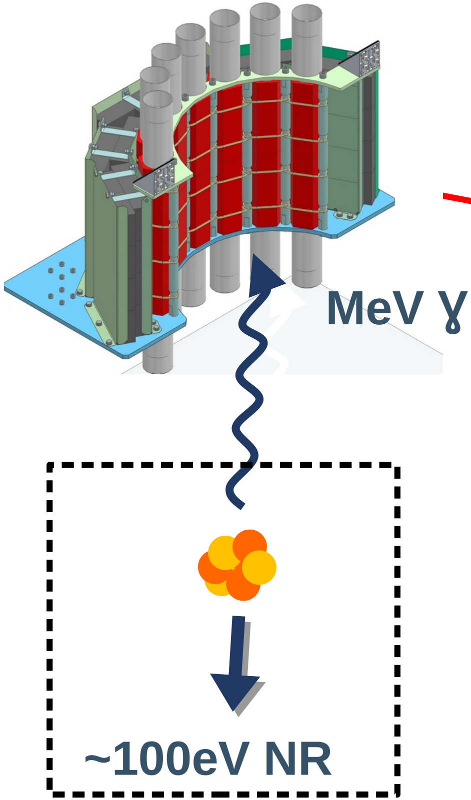


Gas Handling System

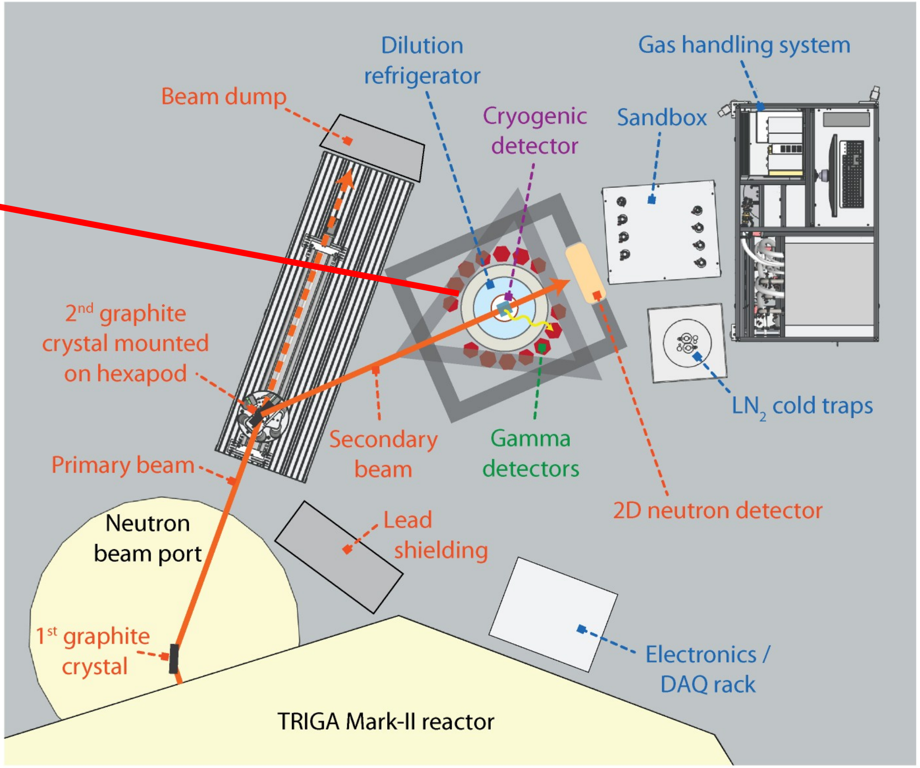


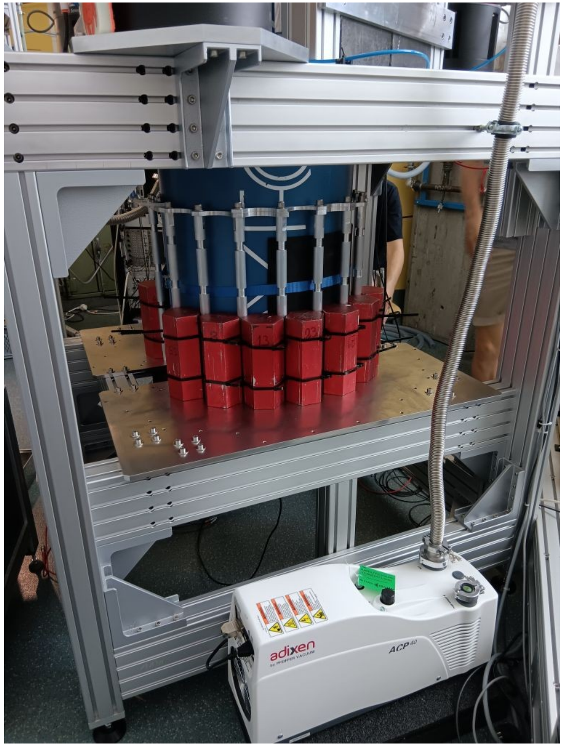
Experimental setup : The ɣ-detectors

BaF_2 detector array



Cryodetector

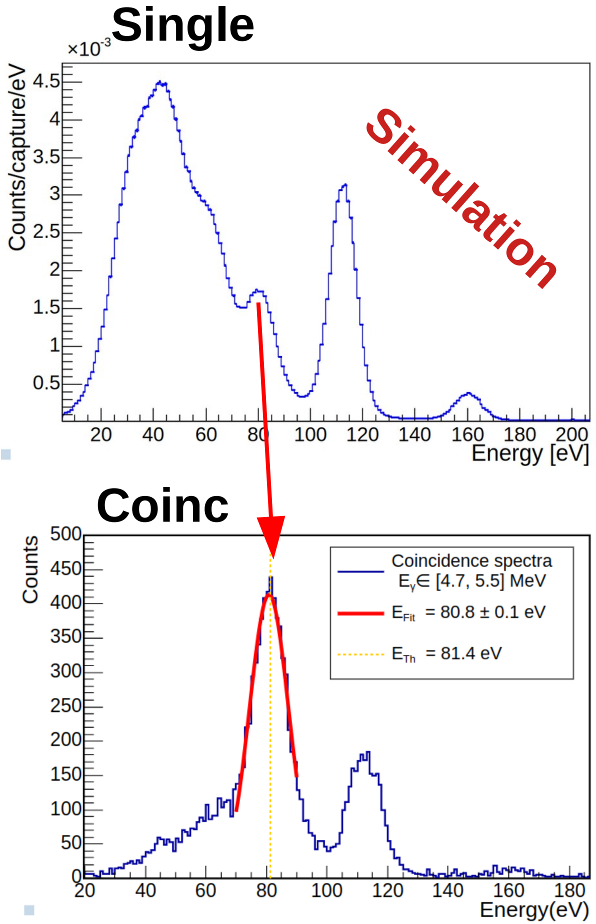




- Tag NR in Time, Energy and Direction

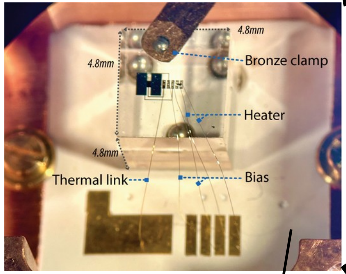
Coincidence ɣ-NR

- Detection of NR in coincidence with the ɣ reduces multi-ɣ background
- Relax constraint on energy resolution
- Extension to more target material (Germanium)

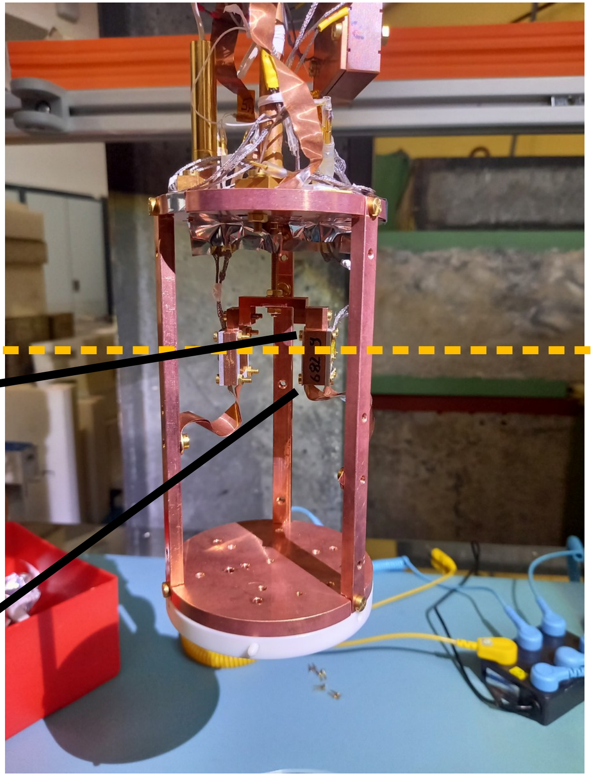


Cryodetector signal

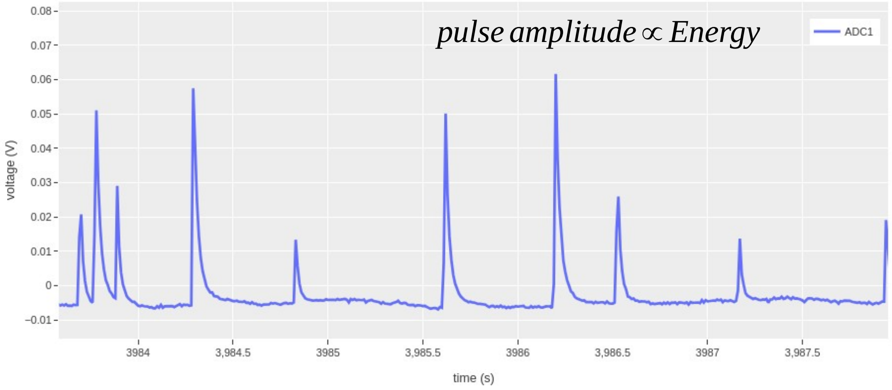
n-beam



Aluminium PCB



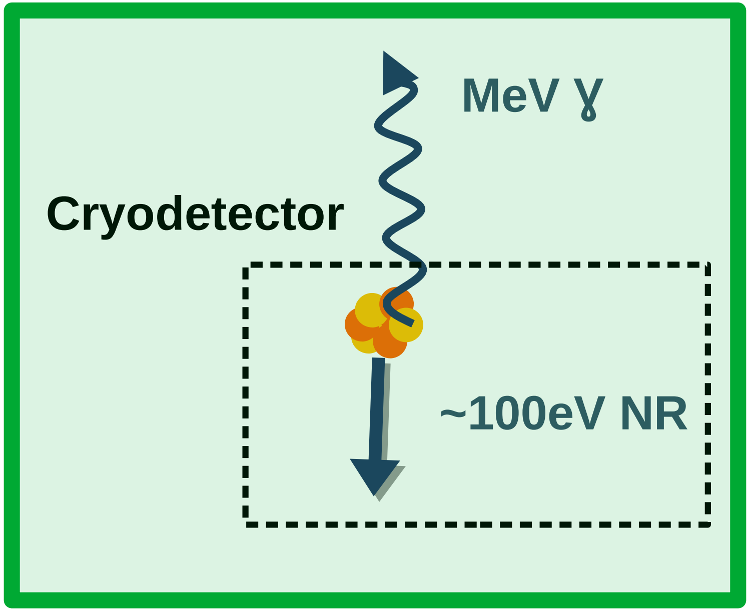
Stream with pulses :



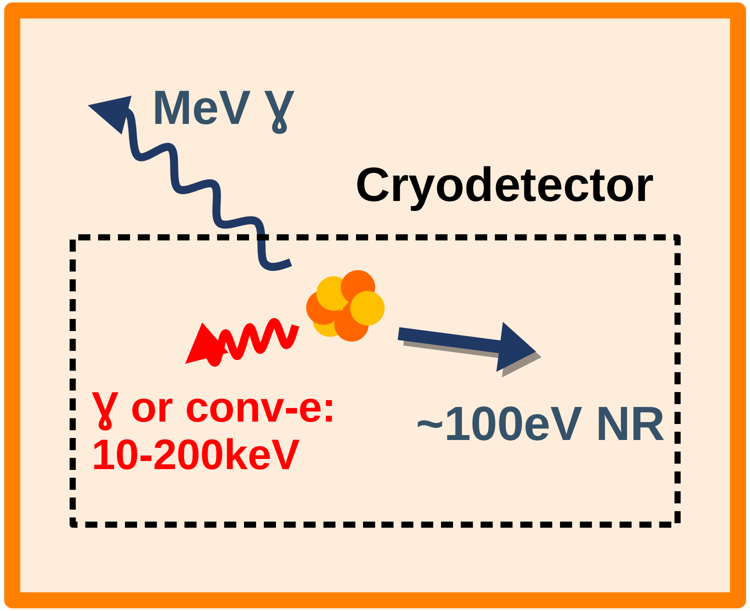
- Continuous stream
- Offline analysis

Current status

We want :



We have so far :



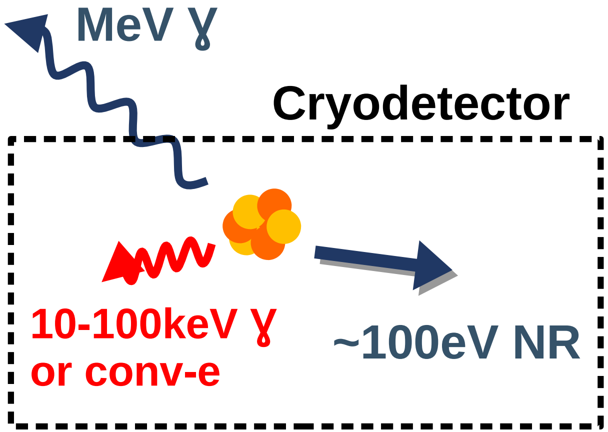
Challenging energy resolution <10 eV not achieved in Vienna yet

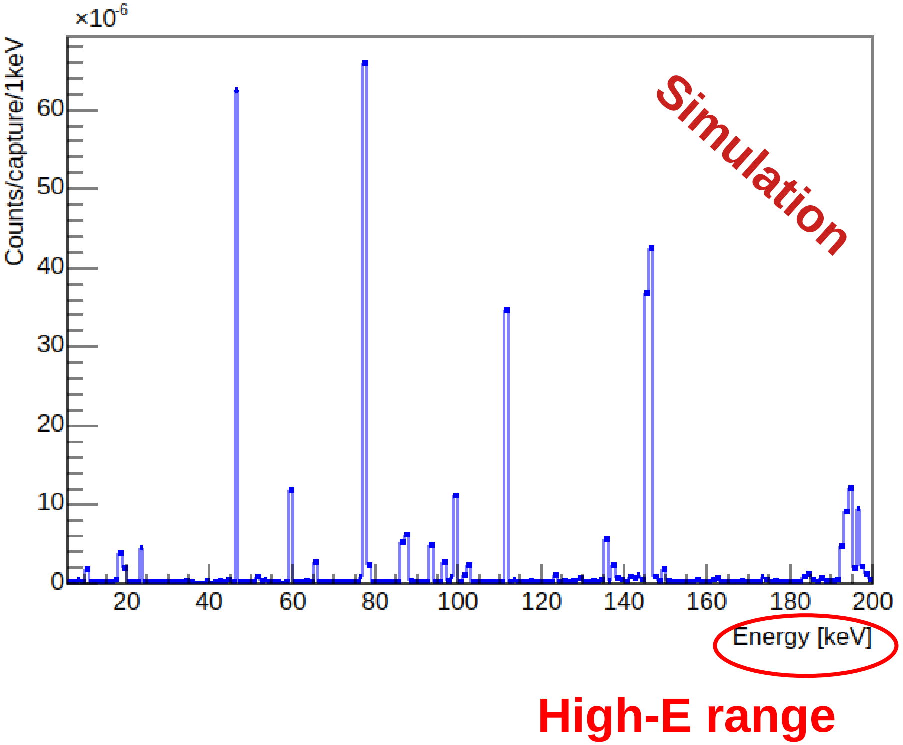
Degraded energy resolution : 20 eV (E_{thr} = 100 eV)

Unexpected very low gain in a $CaWO_4$ cube operation

High energy CRAB events from multi-ɣ cascades

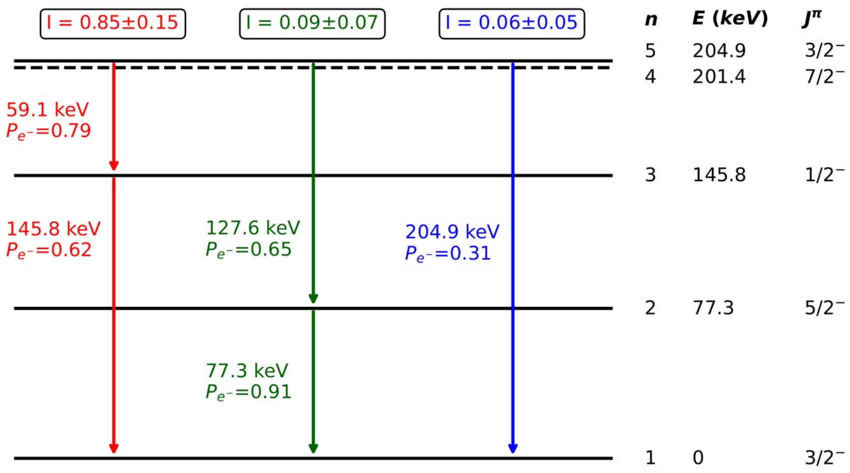
- 0.7g $CaWO_4$ cube :
  - Monitor high energy event (~10-200 keV) induce by de-excitation cascades (2/3 of the events)
    - Low energy ɣ
    - Conversion electron

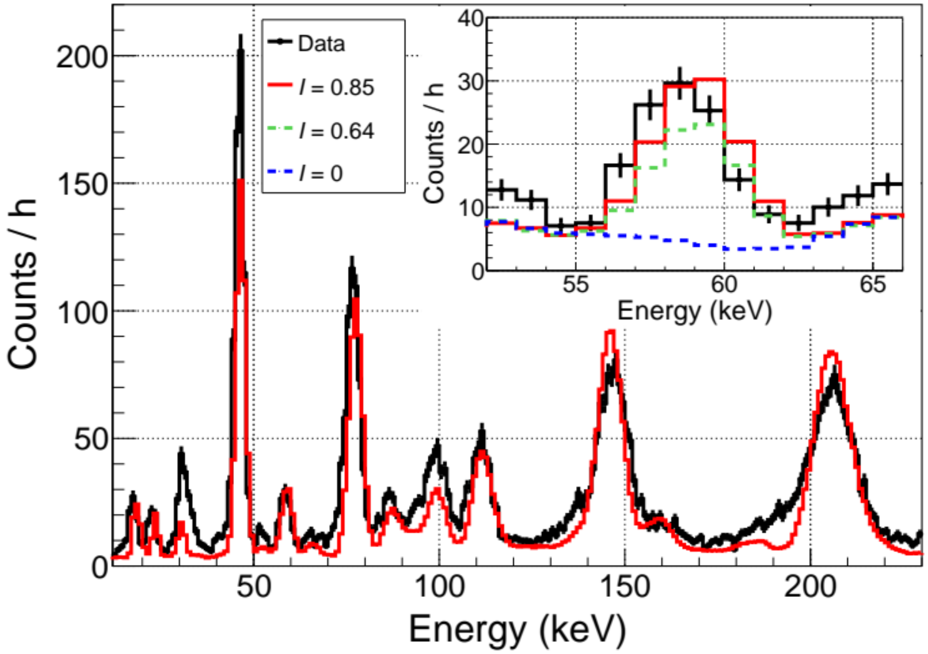




Results : energy spectrum

- Data show electron conversion lines
- Good agreement data/simulation after update of the ^{187}W decay scheme!
- **New input for nuclear database !**





Results : Rate time evolution

- High energy event (>20 keV)
- Method : fit on the data a model with several contributions
- 3 normalization parameters :

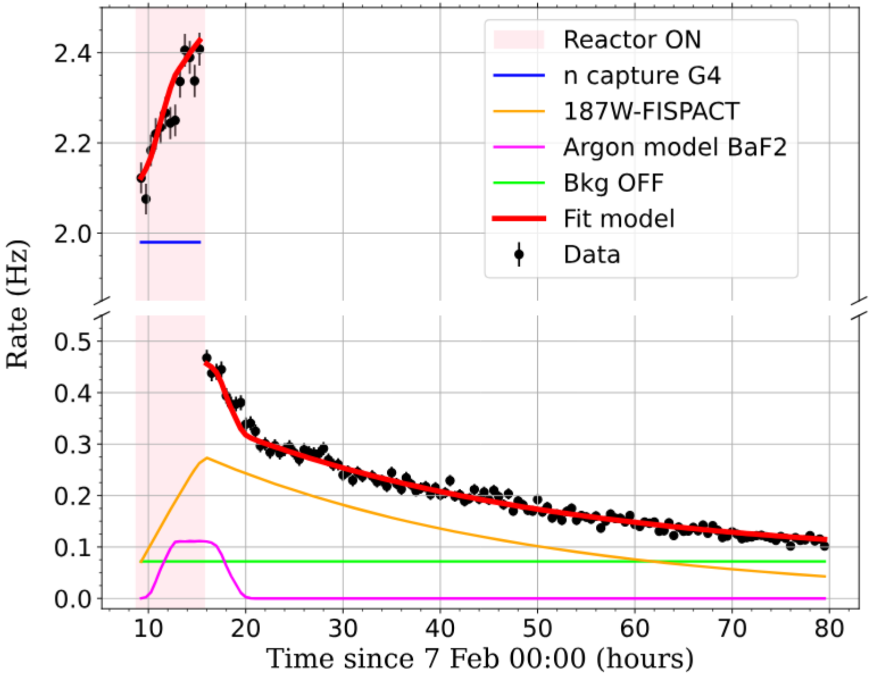
ϕ_n , N_{OFF} , A_{Argon}

Beam induced events

^{187}W activation

Ambiant radioactivity

Argon activation



- Fitted neutron flux : $\phi_n = 442 \pm 2$ n/cm²/s

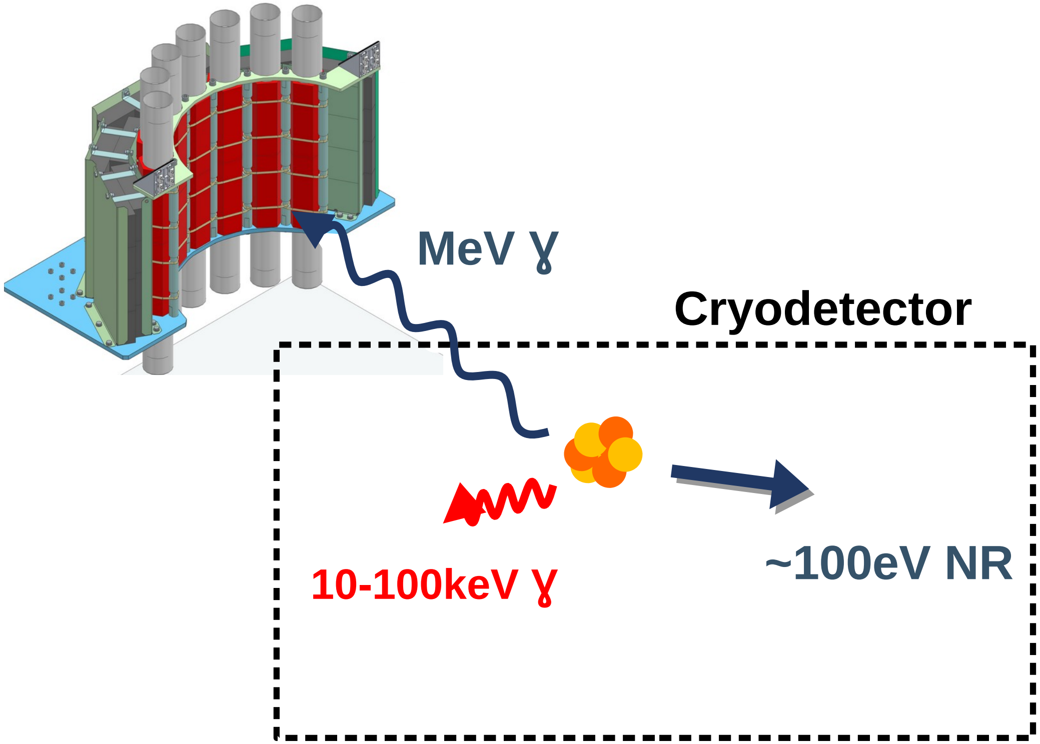
  → Measured $\phi_n = 469 \pm 47$ n/cm²/s

- Excellent data/model agreement

  → validation of our understanding of signal and background components

Coincidence ɣ-cryodetector

- Time difference between events in cryodetector and ɣ-detector
- Flat background : accidental coincidence
- Coincidence peak shifted by 580 µs due to readout delay

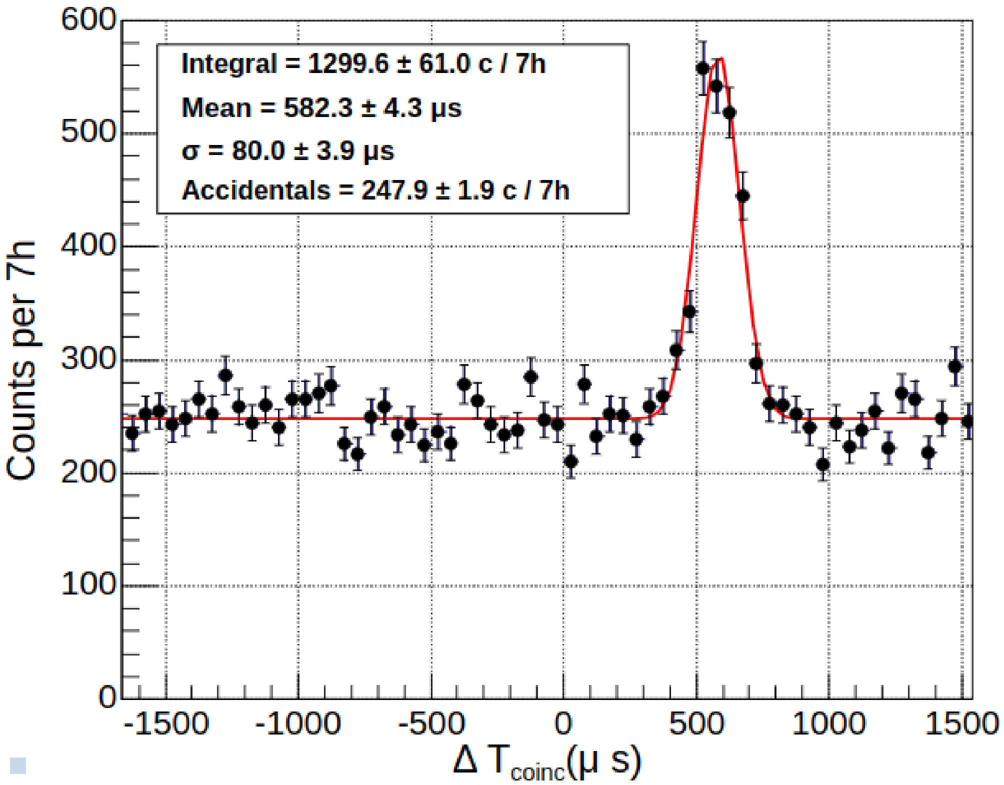


https://arxiv.org/pdf/2505.15227

Submited to EPJC

Coincidence γ-cryodetector

- Time difference between events in cryodetector and γ-detector
- Flat background : accidental coincidence
- Coincidence peak shifted by 580 μs due to readout delay

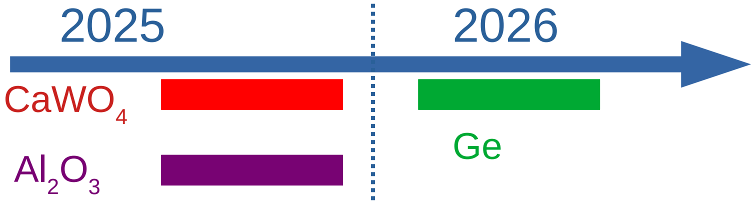


https://arxiv.org/pdf/2505.15227

Submited to EPJC

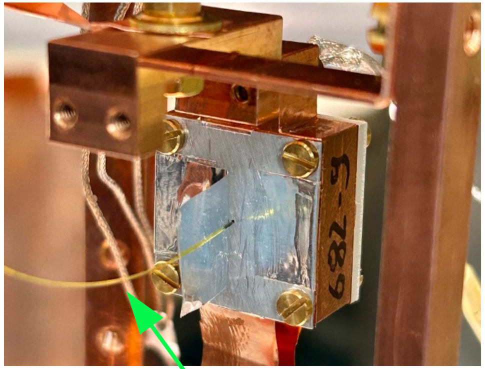
Perspectives : Hardware improvement

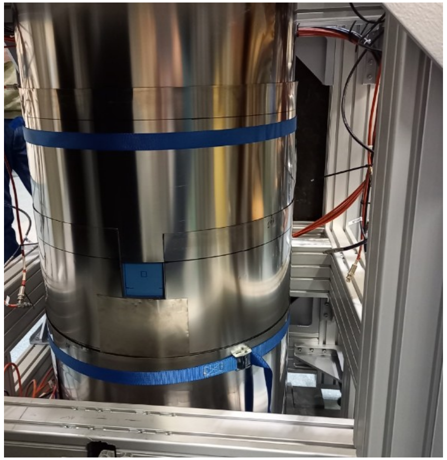
- Reach better energy resolution
    - Electronic noise reduction
    - µ-metal shielding
- LED system
- Next cool down : July 2025



LED calibration

- ER calibration from light pulse
- Detector response different from ER to NR
- Inter-calib ER/NR

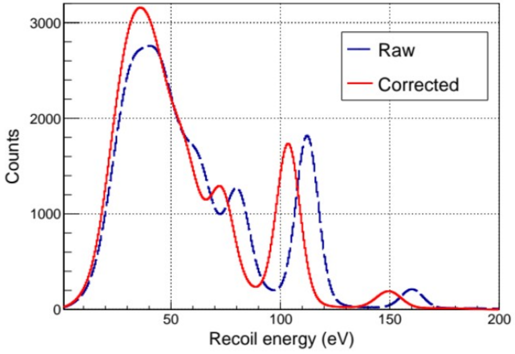




$CaWO_4$: Insight to crystal defect

- Stored energy in crystal defects induced by NR
- July-December 2025 : Probe crystal defect creation in $CaWO_4$ with CRAB
- Lead to spectral distortion that should be taken into account for CEvNS and low mass DM spectra

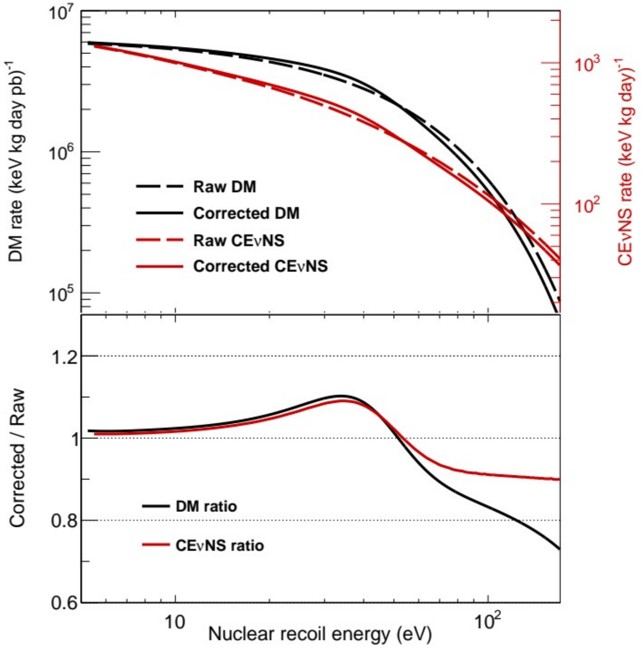
Impact in CRAB spectrum :



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)

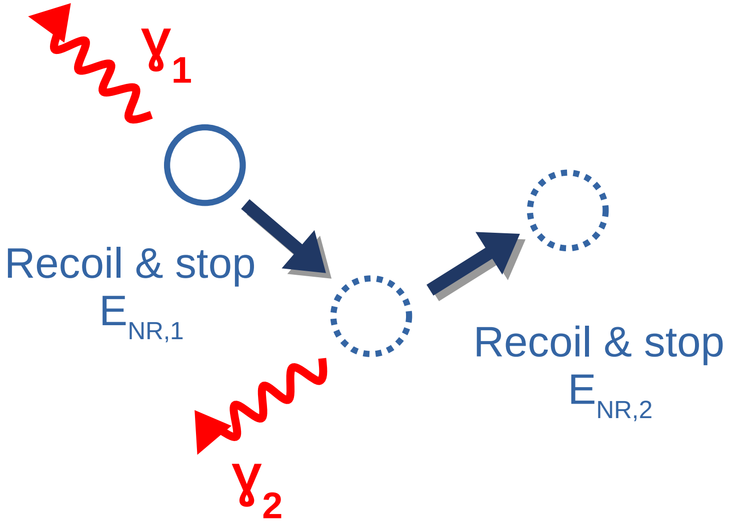
Impact in CEvNS/DM spectra :

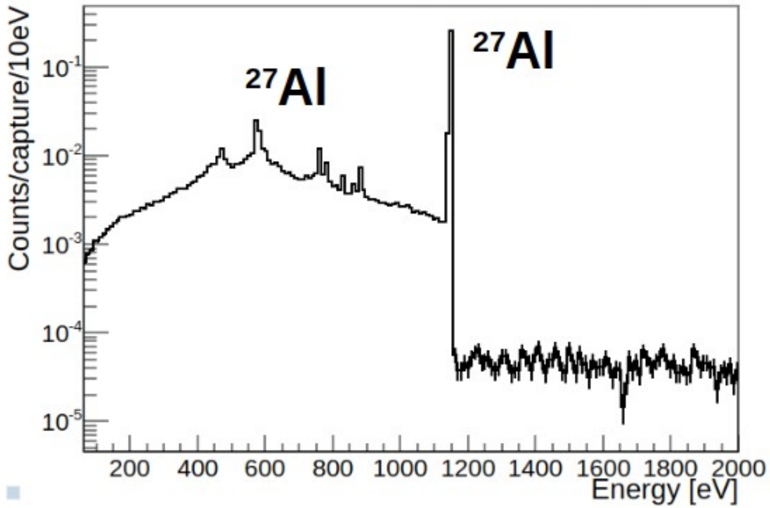


PRD, 2025, 111 (8), pp.085021.

Al_2O_3 : Multi-ɣ cascade's timing

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





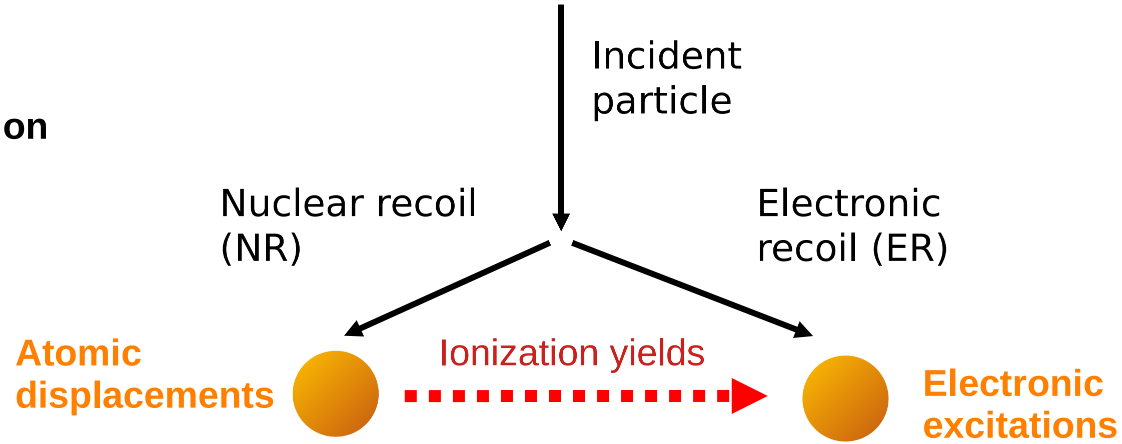
$$E_{tot} = E_{NR,1} + E_{NR,2}$$

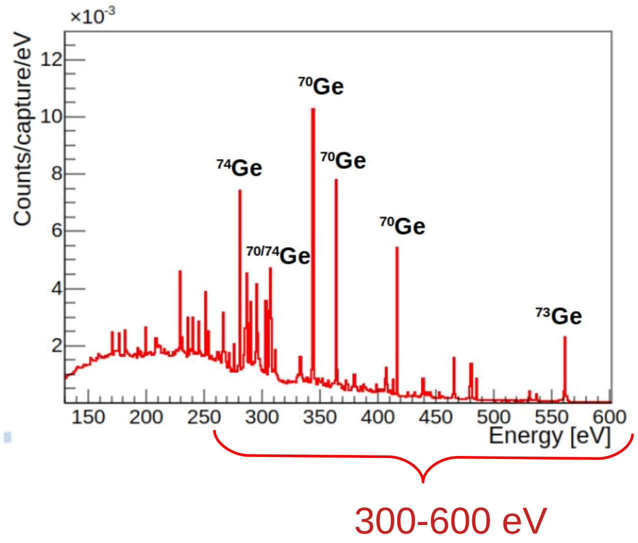
→Additionnal calibration peak at fixed energy

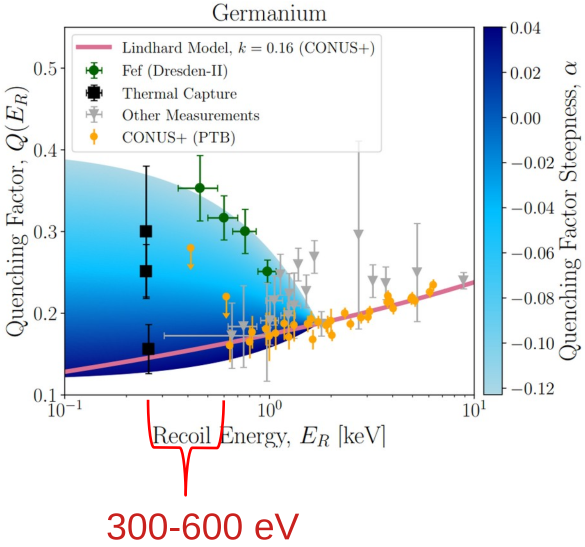
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.108.072009

Extension to Germanium

- Preparation of a **double readout heat/ionization Germanium detector** from TESSERACT and RICOCHET
- Quenching factor study : Crucial for particle identification
- Implementation in the CRAB setup in 2026





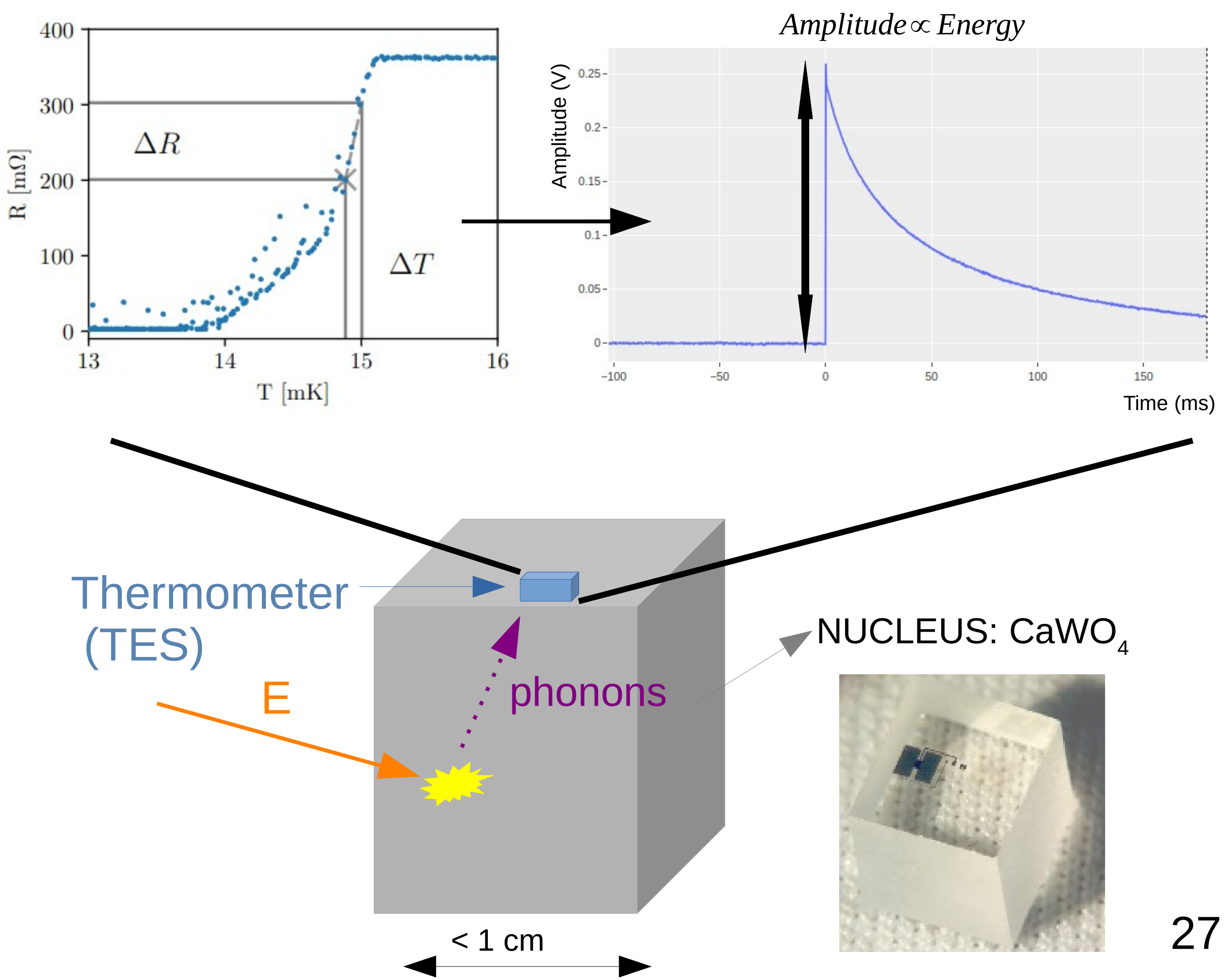


Thank you for your attention !

Back up

NR detection in cryodetector

- Calorimeter: NR induce heat measured by phonon collection
- TES operated at normal-supra transition (15 mK)
- Goal: induce low energy NR to mimic signal
- **CRAB** : **C**alibrated **R**ecoil for **A**ccurate **B**olometry



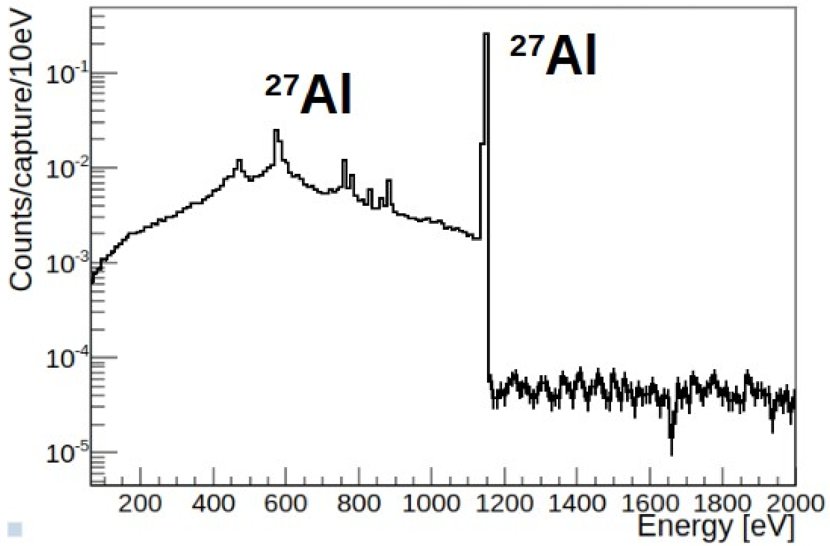
Detector material		**Target nucleus**		**Compound nucleus**				
Formula & Size (mm)	$\Sigma_{(n,\gamma)}$ (cm^{-1})	Isotope	$P_{capture}$ (%)	I_γ (%)	E_γ (MeV)	Half-life (ps)	E_r (eV)	FoM ($\times 10^4$)
Al2O3 $5 \times 5 \times 5$	1.10×10^{-2}	^{27}Al	99.89	6.90 11.73	4.133 ↪ 3.560	- 0.03	571.0	0.89
		^{27}Al	99.89	0.56 46.08	3.825 ↪ 3.902	- 0.19	572.0	0.28
		^{27}Al	99.89	3.12 78.06	3.849 ↪ 3.876	- 0.02	572.0	2.68
		^{27}Al	99.89	0.87 40.65	3.789 ↪ 3.936	- 0.02	572.0	0.39
		^{27}Al	99.89	0.73 37.17	4.015 ↪ 3.705	- 0.19	573.0	0.30
		^{27}Al	99.89	6.90 59.27	4.134 ↪ 3.902	- 0.03	575.0	4.49
		^{27}Al	99.89	6.80 87.72	4.260 ↪ 3.466	- 0.04	578.0	6.55
		^{27}Al	99.89	3.39 100	7.693 ↪ 0.031	- 2070	1135.7	3.72
		^{27}Al	99.89	26.81	7.724	-	1144.8	29.46
Si $10 \times 10 \times 20$	8.23×10^{-3}	^{28}Si	94.60	7.10 100	7.200 ↪1.273	- 0.29	990.4	5.53
		^{28}Si	94.60	2.17	8.474	-	1330.1	1.69
		^{29}Si	3.38	6.73	10.609	-	2016.0	0.19

Detector material		Target nucleus		Compound nucleus				
Formula & Size (mm)	$\Sigma_{(n,\gamma)}$ (cm^{-1})	Isotope	$P_{capture}$ (%)	I_γ (%)	E_γ (MeV)	Half-life (ps)	E_r (eV)	FoM ($\times 10^4$)
Ge $10 \times 10 \times 10$	9.76×10^{-2}	^{74}Ge	8.58	11.75 98.52	6.253 ↪0.253	- 1.36 (W)	280.6	9.69
		^{70}Ge	28.30	5.30 78.65	6.117 ↪1.299	- 0.4	296.0	11.51
		^{74}Ge	8.58	2.83	6.506	-	303.2	2.37
		^{70}Ge	28.30	2.62 77.31	6.276 ↪1.139	- 4.00	307.9	5.59
		^{70}Ge	28.30	4.80 95.44	6.708 ↪0.708	- $<$10.70	344.3	12.65
		^{70}Ge	28.30	3.83 99.30	6.916 ↪0.500	- 0.18 (W)	363.9	10.50
		^{70}Ge	28.30	1.95	7.416	-	416.2	5.39
		^{73}Ge	51.55	1.02 99.95 99.86	8.732 ↪0.868 ↪0.596	- 1.53 12.14	561.8	5.12
CaWO4 $4.8 \times 4.8 \times 4.8$	2.37×10^{-1}	^{186}W	58.11	7.42 27.73	5.262 ↪0.205	- 2.6 (W)	79.6	28.34
		^{182}W	29.01	5.24 52.3	5.165 ↪1.026	- -	81.3	18.84
		^{186}W	58.11	5.26 38.21	5.321 ↪0.146	- 7.1 (W)	81.4	27.68
		^{186}W	58.11	0.26	5.467	-	85.8	3.58
		^{182}W	29.01	13.94	6.191	-	112.5	95.84
		^{183}W	7.62	5.83	7.411	-	160.3	10.53

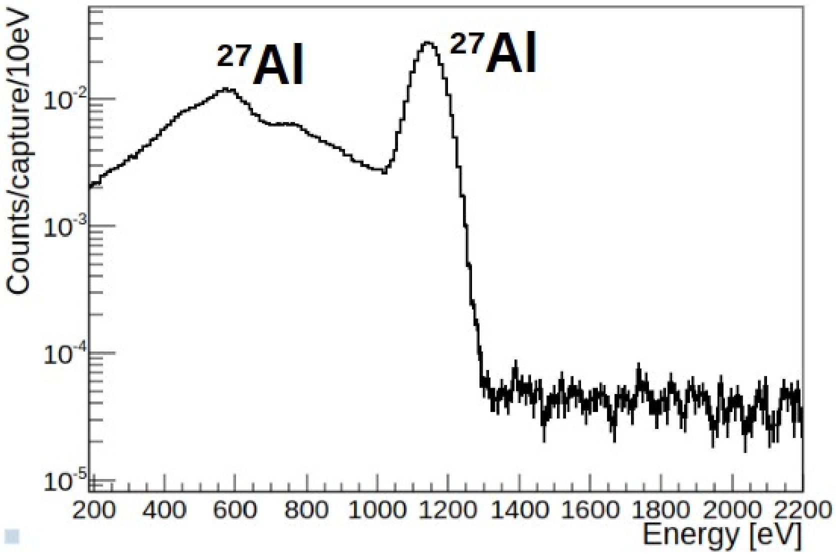
CRAB in Al_2O_3

- Isotope ^{27}Al : Intense peak at 1140 eV
- Additionnal structure at 570 eV from a 2 ɣ transition (slow)

Resolution : 0 eV

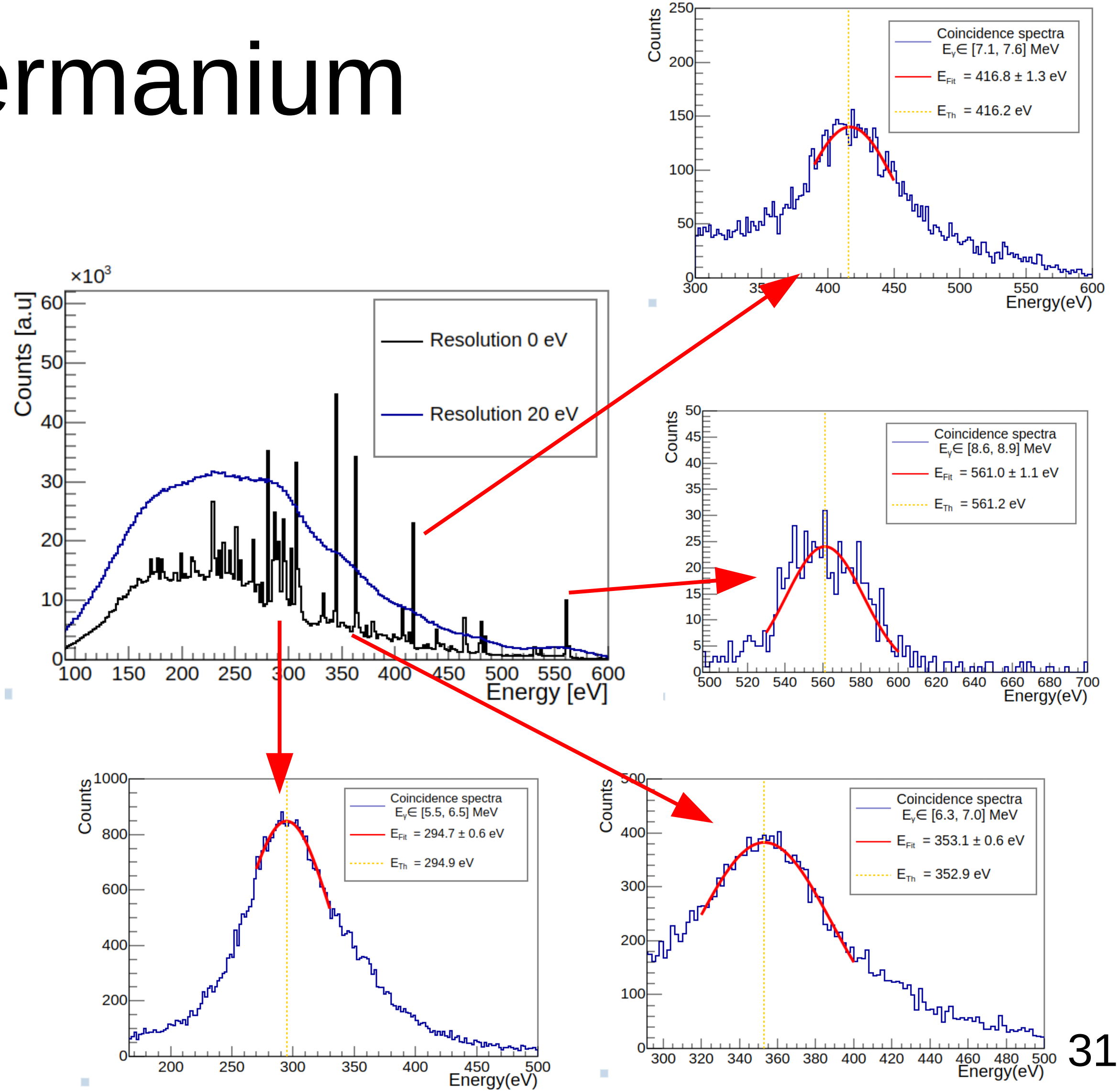


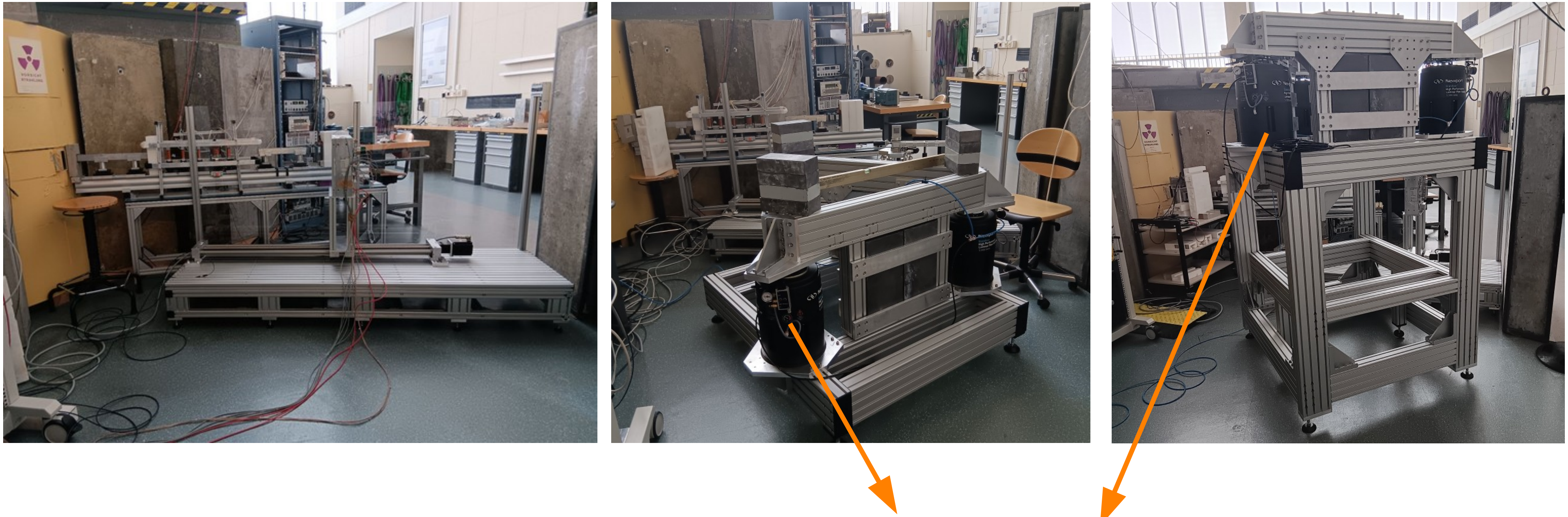
Resolution : 5 eV



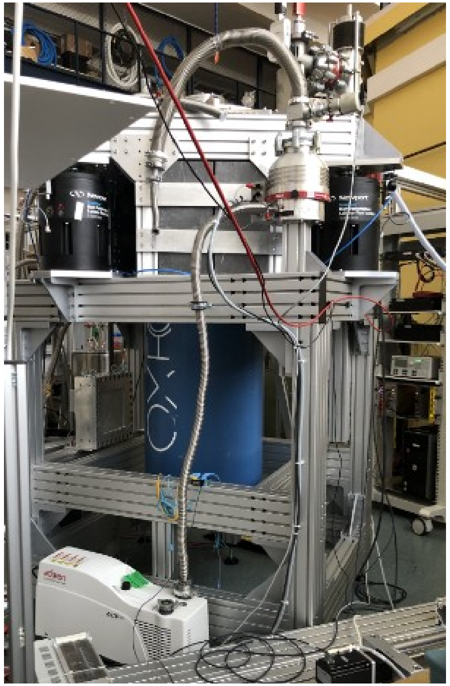
CRAB in Germanium

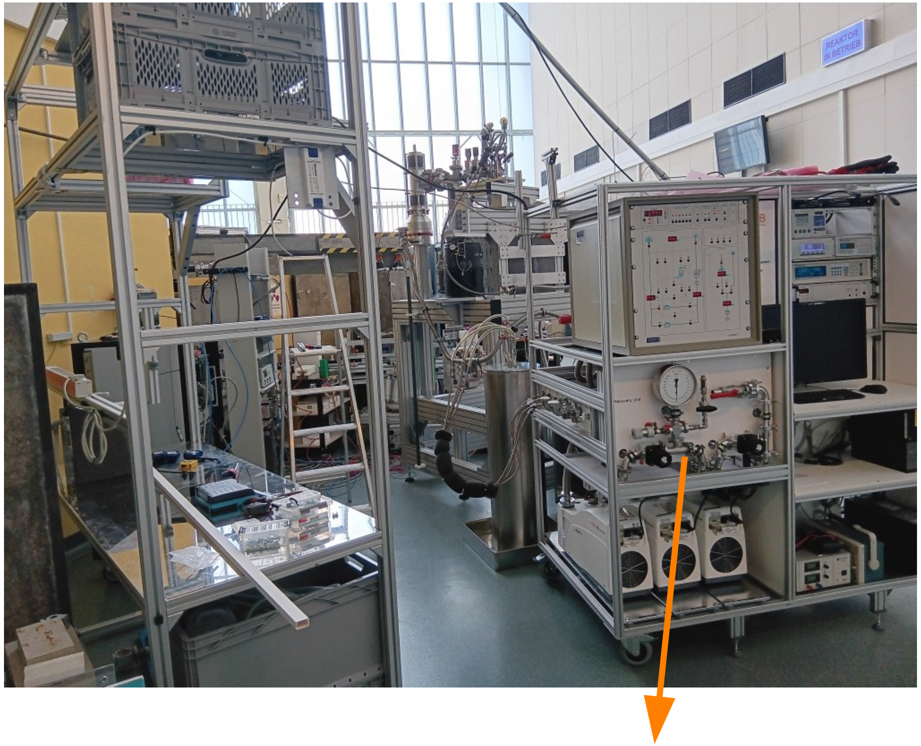
- Several peaks in 200-600 eV from slow multi-ɣ transition
- Smeared out with 20 eV resolution
- Need ɣ-tagging
- Double readout heat-ionization allows to probe the quenching factor



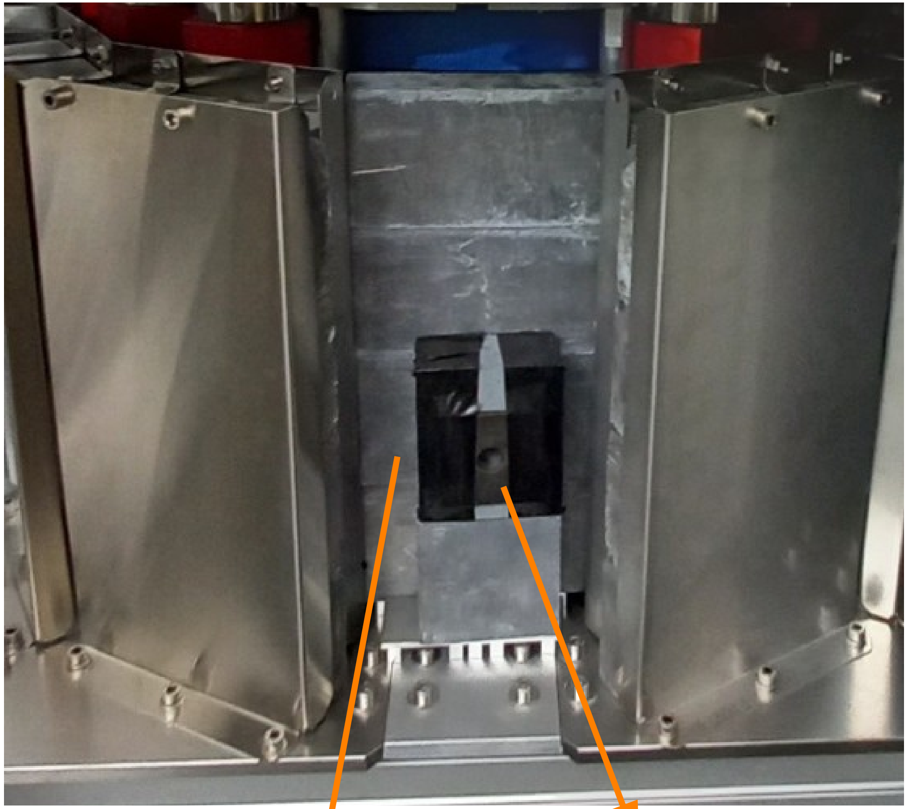


Air dumpers





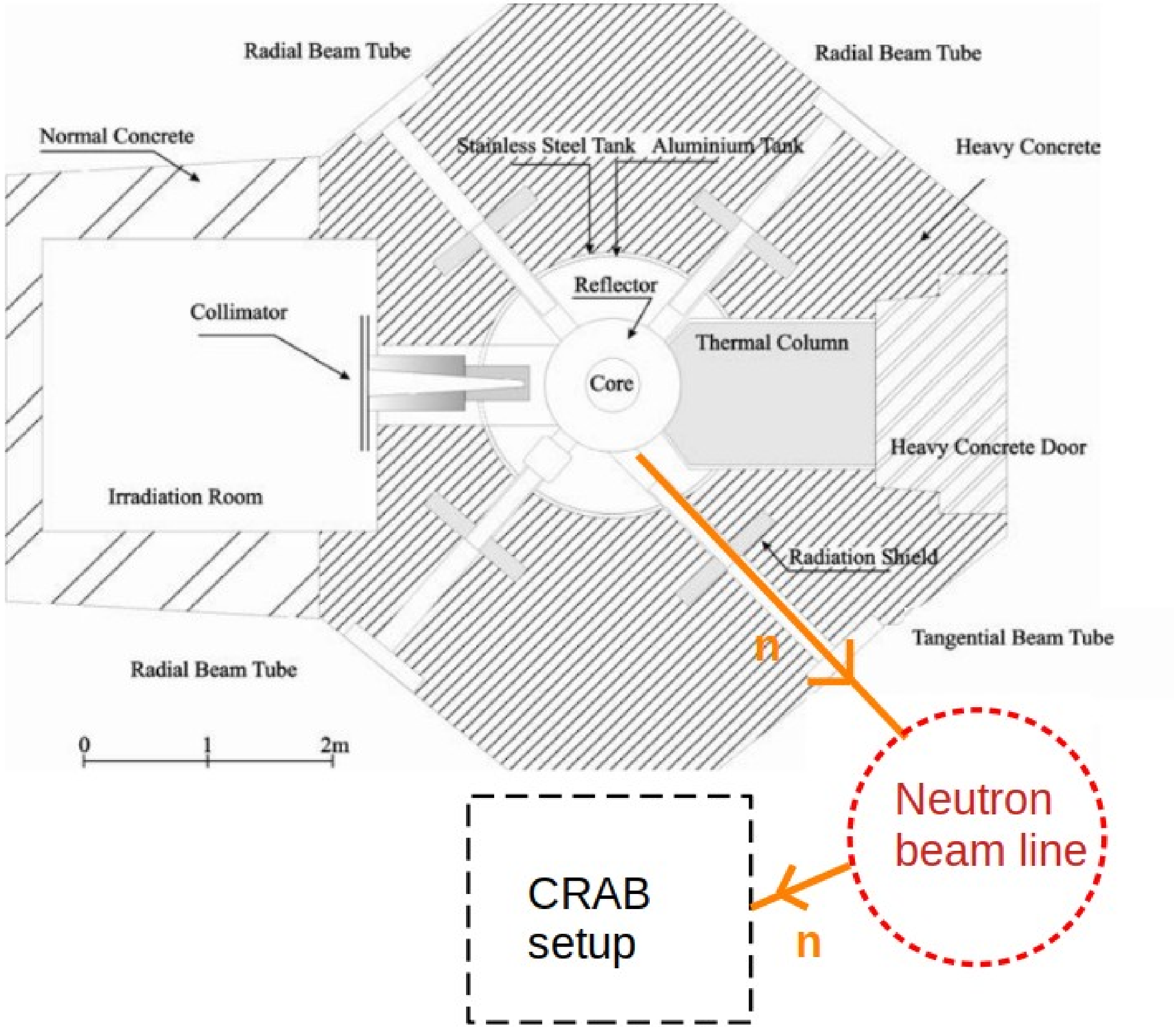
Gas Handling System



Lead

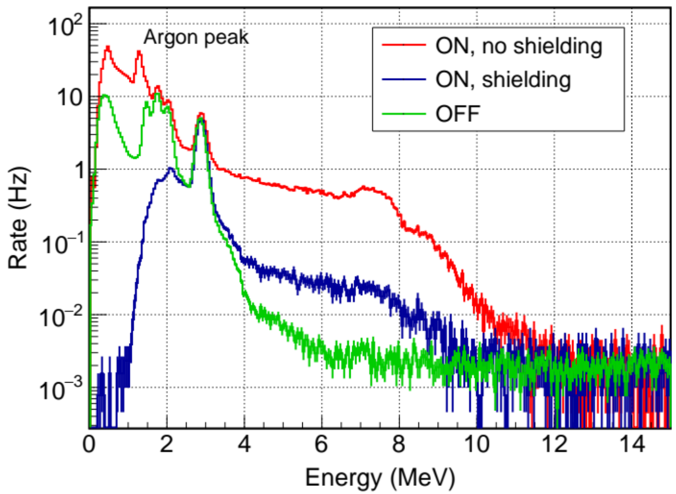
B_4C

Lead wall


Radial Beam Tube
Radial Beam Tube
Normal Concrete
Stainless Steel Tank
Aluminium Tank
Heavy Concrete
Reflector
Collimator
Thermal Column
Core
Heavy Concrete Door
Irradiation Room
Radiation Shield
Tangential Beam Tube
n
Radial Beam Tube
0
1
2m
Neutron beam line
CRAB setup
n

Commissionning BaF2

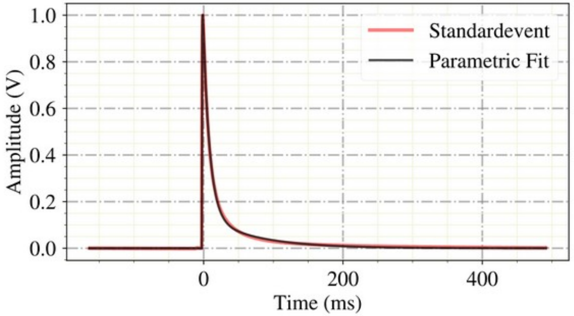
- BaF2 characterisation
  - Energy calibration with radioactive sources
  - Detection efficiency
- On site backgound measurement
  - Characterisation Ɣ+n background source
  - Background mitigation : passive shielding → meet specifications

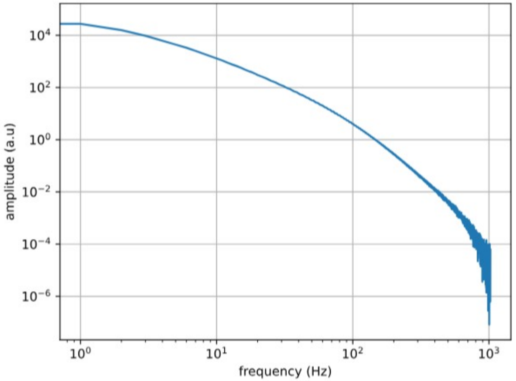


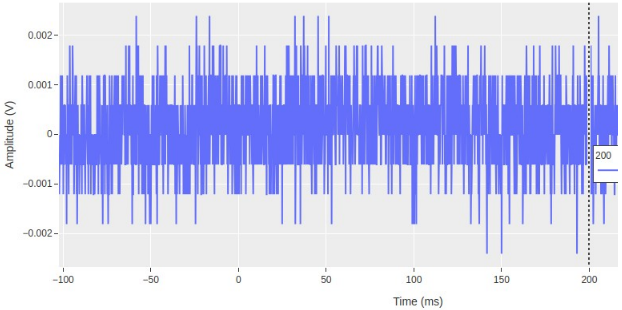
Cryodetector analysis

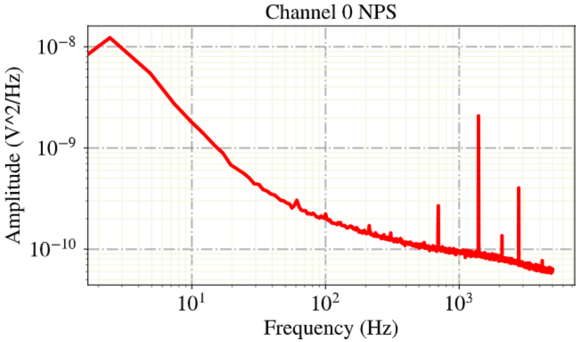
- Software : CAIT developped at HEPHY (Vienna)
- Template pulse to build a standard event (SEV) from physical pulses
- Clean baseline to build the Noise Power Spectrum (NPS)
- Optimum Filter (OF) :
  - Enhance signal frequencies and supress noise frequencies
  - Increase SNR for low threshold sensitivity

Time domain : —TF→ **Frequency domain :**





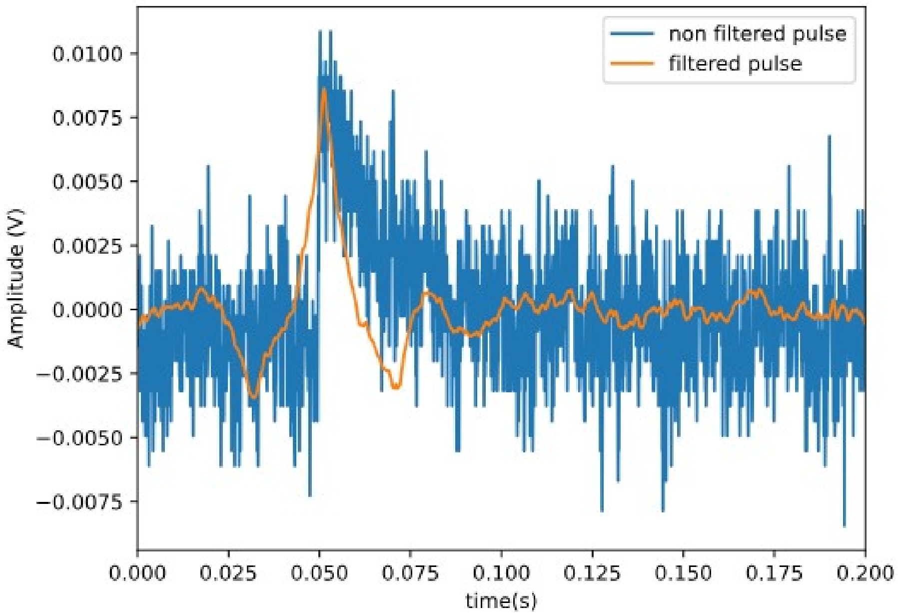




Cryodetector analysis

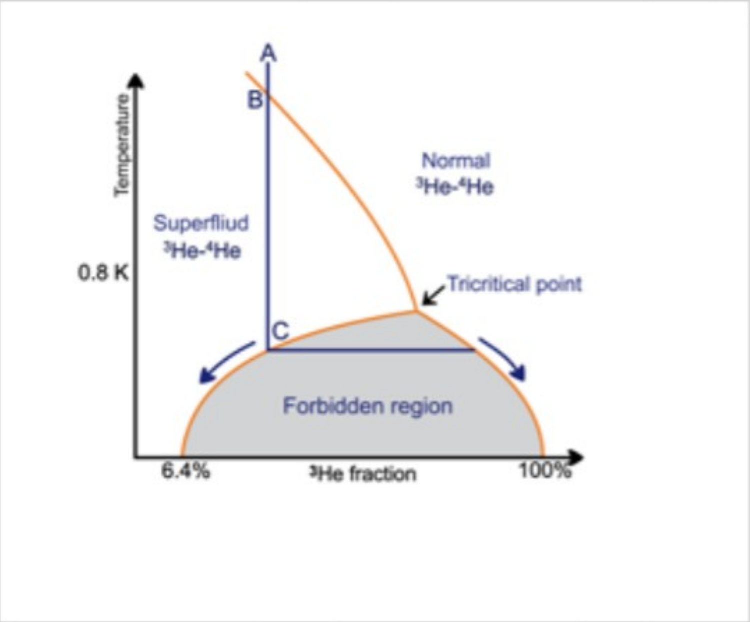
- Filtered pulse amplitude ~ deposited energy
- Used to reconstruct the recoil energy spectra
- Clean cut applied to remove artefacts or pile up
- Energy calibration

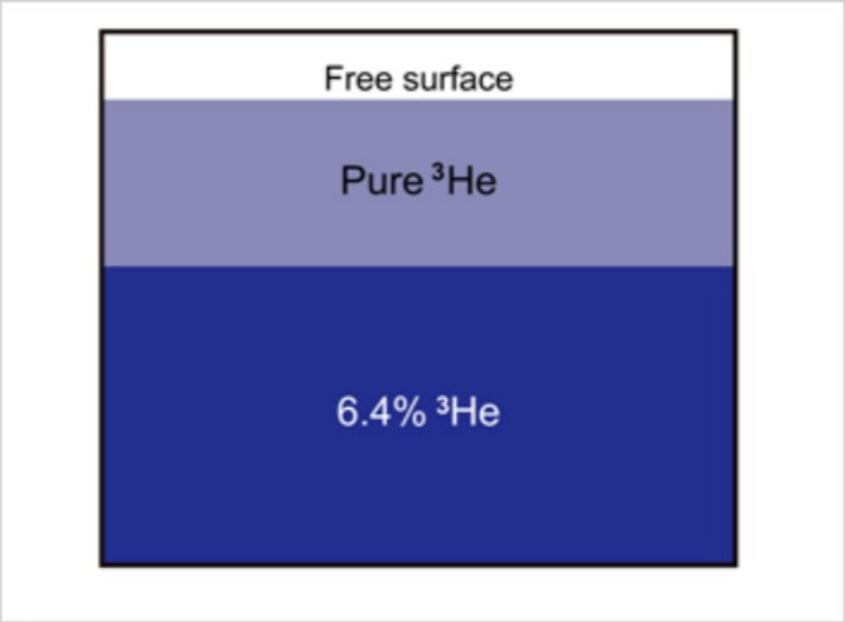
Event : ~200 eV



- Resolution : 8 eV

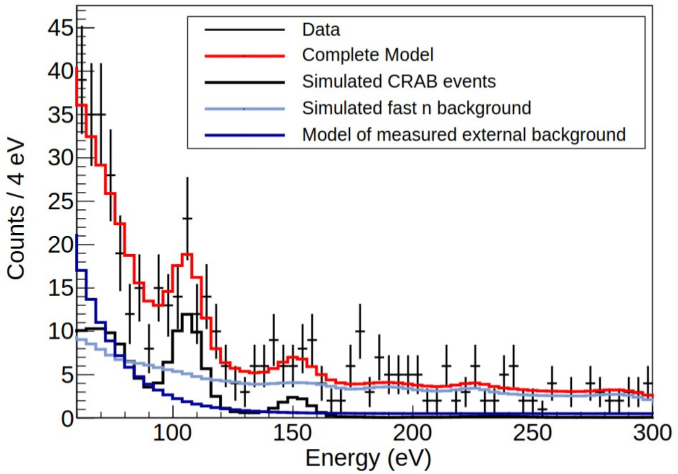
Phase diagram





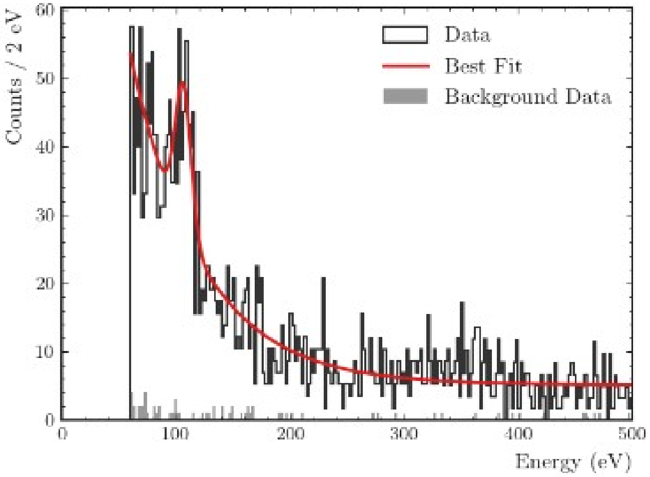
Experimental validation : $CaWO_4$

- 112 eV peak detected at 3 σ significance by the NUCLEUS collaboration and at 6.6 σ by the CRESST collaboration
- First validation of the CRAB method !



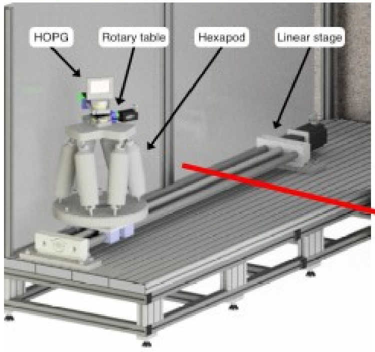
PRL: Observation of a nuclear recoil peak at the 100 eV scale induced by neutron capture (PhysRevLett.130.211802)

PRD: Observation of a low energy nuclear recoil peak in the neutron calibration data of the CRESST-III experiment (Phys. Rev. D 108, 022005)

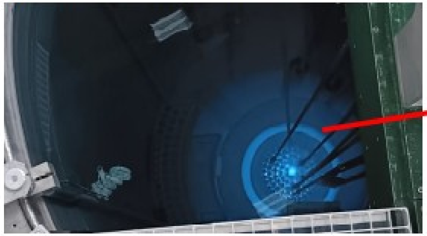


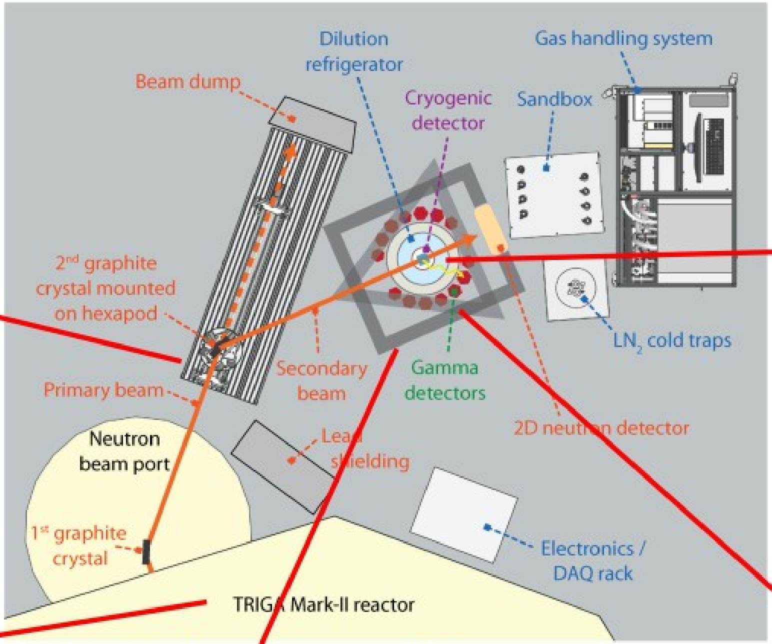
Experimental setup

ii) Reflective Graphite crystal mounted on hexapod

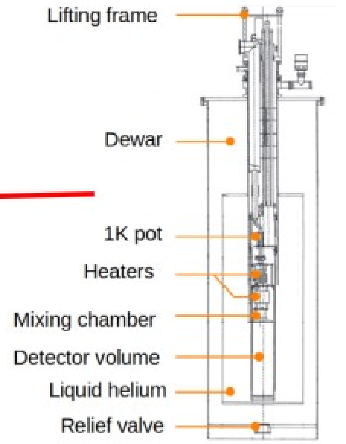


i) TRIGA Mark-II reactor

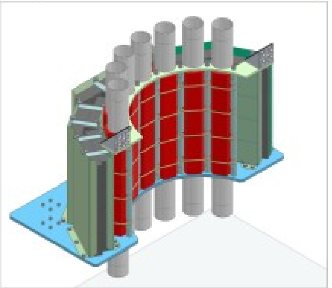




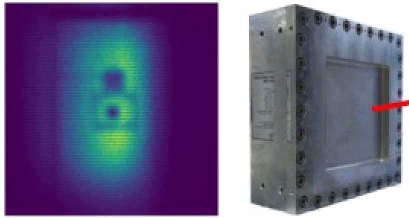
iii) Cryogenic infrastructure



vi) BaF2 detector array



v) 2D neutron detector



iv) Support structure