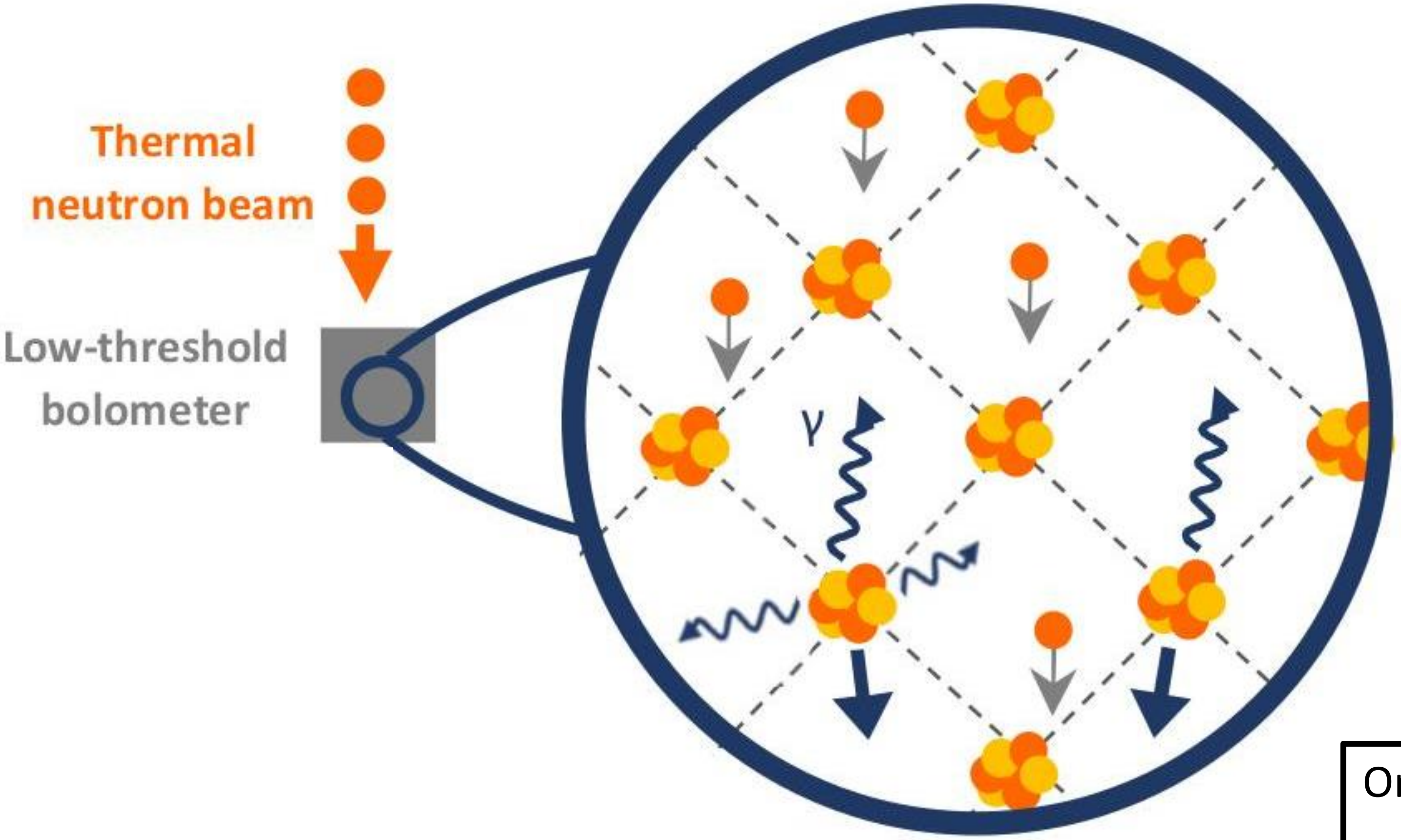
Calibration of cryo detectors at the 100eV scale

Gabrielle Soum-Sidikov, CRAB collaboration
CEA Saclay

IRN Neutrino – 17 Nov 2022

CRAB calibration method



1. Thermal neutron capture

2. Emission of a single- **γ** with energy S_n ~ 5-8MeV
Leaves the cm-size detector without energy deposition

3. Well-defined recoil energy (two-body kinematics)

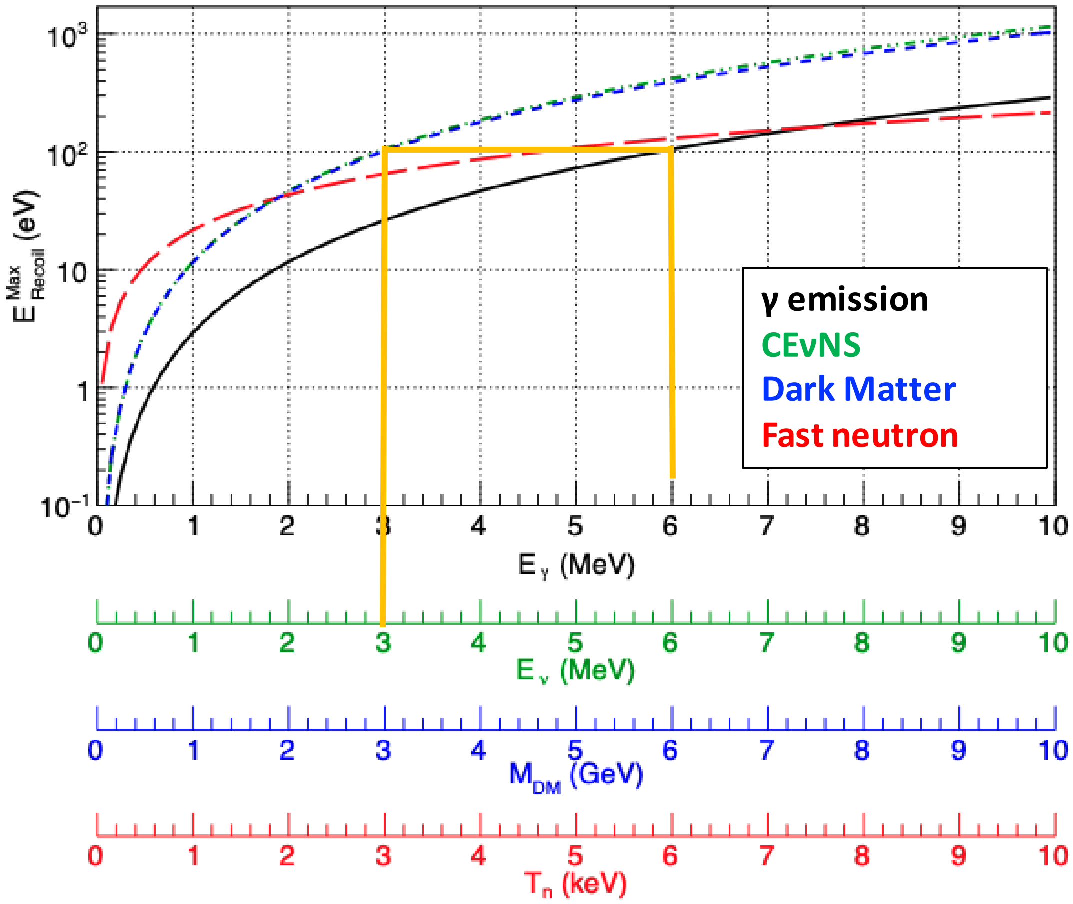
$$\frac{E_\gamma^2}{2Mc^2} \sim 100\text{eV-}1\text{keV}$$

Only method combining:
- Pure nuclear recoils
- In the bulk of the detector
- In the sub-keV region

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

100eV nuclear recoils

Maximal recoil energies for various processes (target = W)



Equivalent kinematics for several neutral particles :

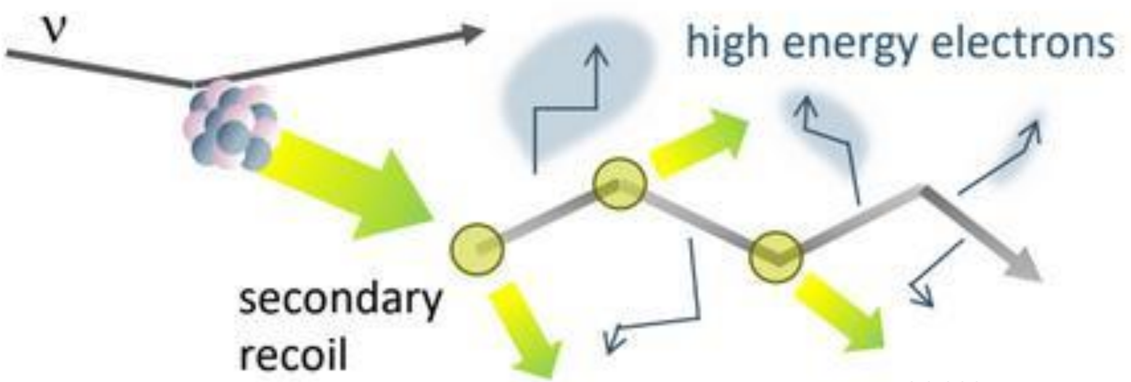
- **Nuclear recoils following n_{th} capture**
- **CevNS with MeV neutrinos**
- **Direct detection of low-mass O(GeV) DM**

↓

Understanding the sub-keV nuclear recoil signal is crucial for upcoming experiments searching for new physics

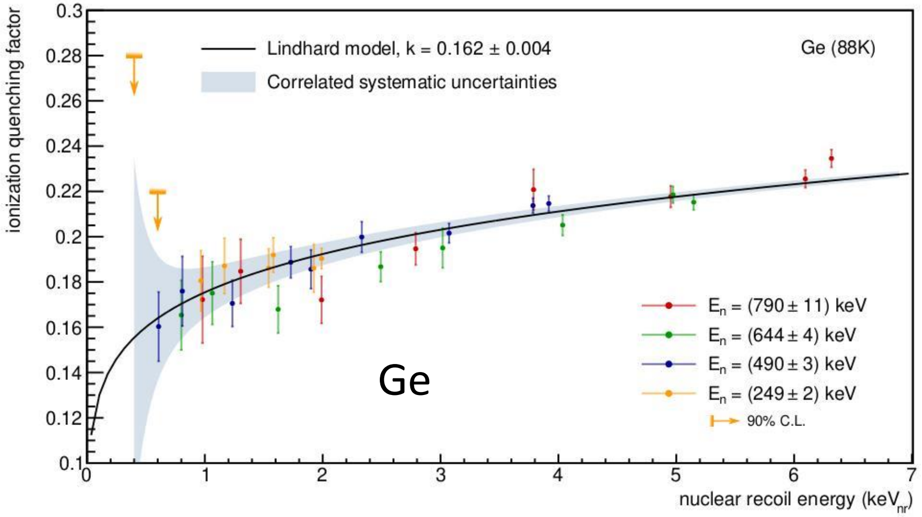
Complex physics of energy dissipation

- **Four channels** for energy deposition in detectors:
    - Ionization
    - Scintillation
    - Phonons
    - Creation of defects



V. Wagner

- **Distribution of the energy** in the different channels depends on:
    - Nature of incident particle
    - Energy of incident particle
    - Material of detector



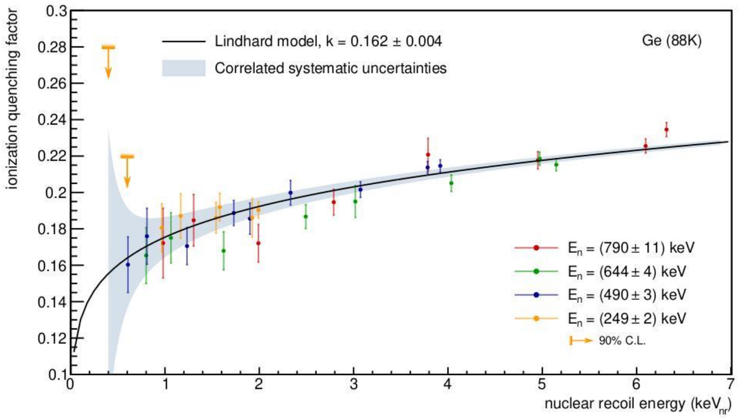
A.Bonhomme et al. Eur.Phys.J.C 82 (2022) 9, 815

Quenching factor: ratio of ionization energy produced by NR/ER

Complex physics of energy dissipation

CRAB

nuclear recoil energy	target
400-600eV	Germanium
100eV	$CaWO_4$



A.Bonhomme et al. Eur.Phys.J.C 82 (2022) 9, 815

- Lindhard model for quenching factor in the keV region
- Need for more measurements in the sub-keV region

Only active channels:

- Phonons → Detected energy
- Defects creation → Lost energy

No energy dissipation model

Difference between ER and NR scales to be studied

Need for direct NR calibration in the sub-keV region

Courtesy of D. Lhuillier

CRAB targets

Suitable candidates have
- High natural abundance
- Large neutron capture cross-section
- High branching ratio for single-**γ** transition

Cryo-det crystal	Target Isotope	F.O.M. (Ab*σ*I)	S_n (keV)	Nuclear Recoil (eV)
$CaWO_4$	^{182}W	7506	6191	112.5
	^{183}W	823	7411	160.3
	^{186}W	281	5467	85.8
Ge	^{70}Ge	122	7416	416.2
	^{74}Ge	54	6506	303.2
Al_2O_3	^{27}Al	616	7725	1145
Si	^{28}Si	36	8473	1330
	^{28}Si	118	7199+1273	989.9

Large F.O.M
Linearity study

Within reach of ionization channel
Quenching studies

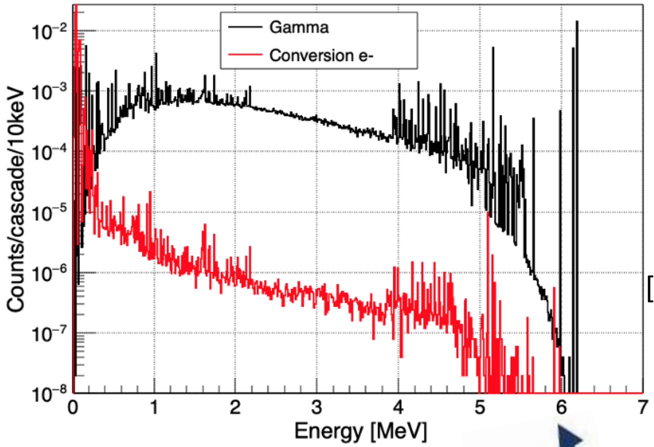
Strongest single-γ transition

Interesting cases of 2γ transitions

The four main cryodetectors used in the community could be calibrated via CRAB

CRAB in $CaWO_4$

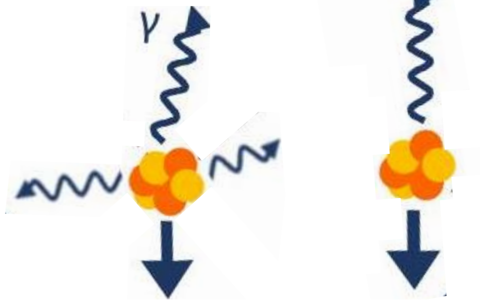
- **1γ** de-excitations : calibration peak
- Multi **γ** de-excitations : recoil energy depends on **γ** energies and relative directions
  --> recoil energy continuum
- Lower energy **γ** and conversion electrons can saturate the detector with energy deposition above 1keV
  --> limit the acceptable neutron flux
  --> no direct impact on calibration peaks



^{183}W de-excitation spectrum, from FIFRELIN

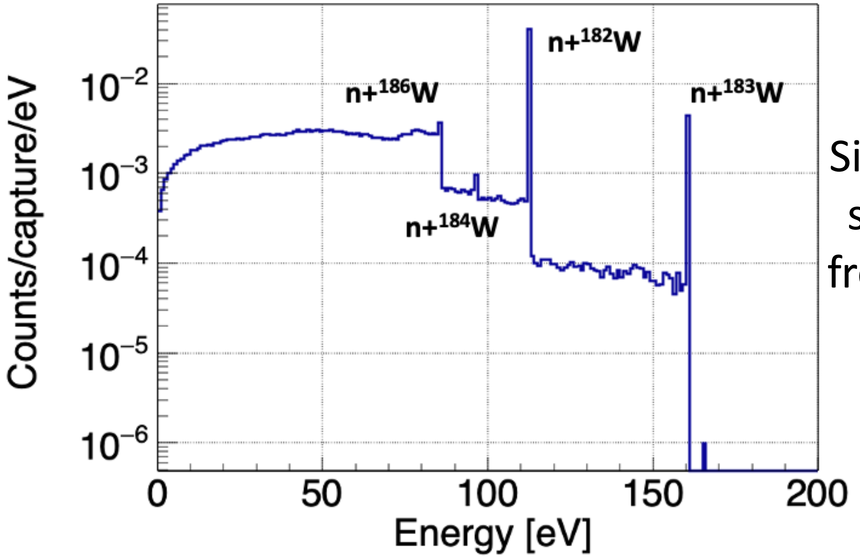
See A. Chalil's talk

[O. Litaize et al., Eur. Phys. J. A (2015) 51: 177]



1γ de-excitation : Sn=6.2MeV

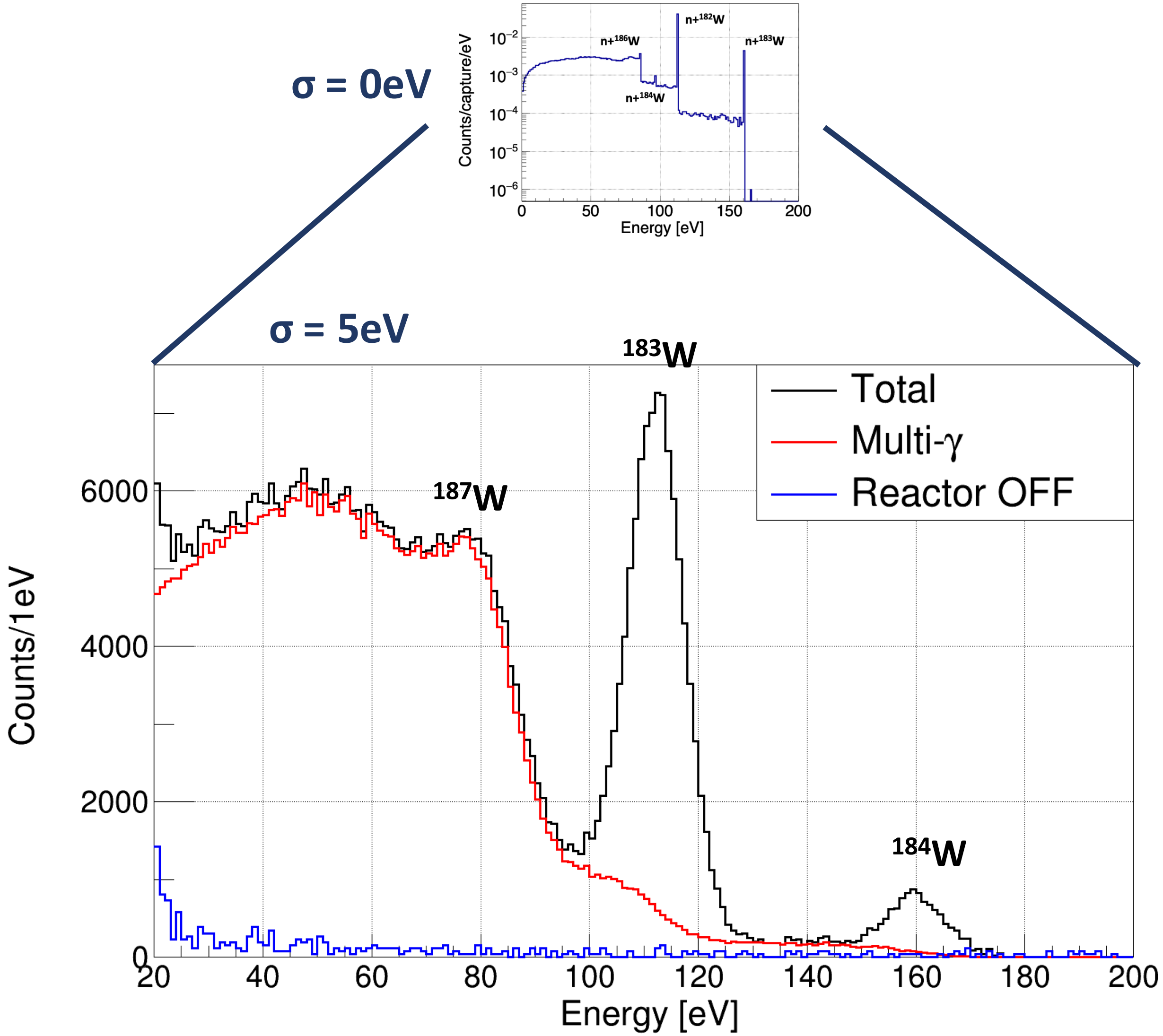
112eV recoil



Simulated recoil energy spectrum, for $CaWO_4$ from GEANT4+FIFRELIN

CRAB in $CaWO_4$

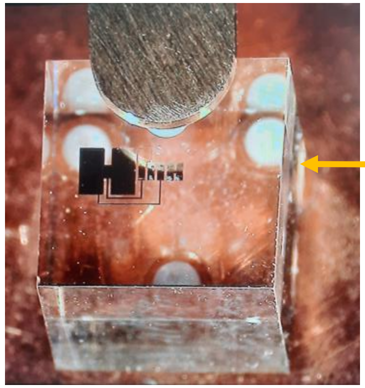
- Two calibration peaks @112eV and @160eV
- A third peak burried in the multi-**γ** continuum



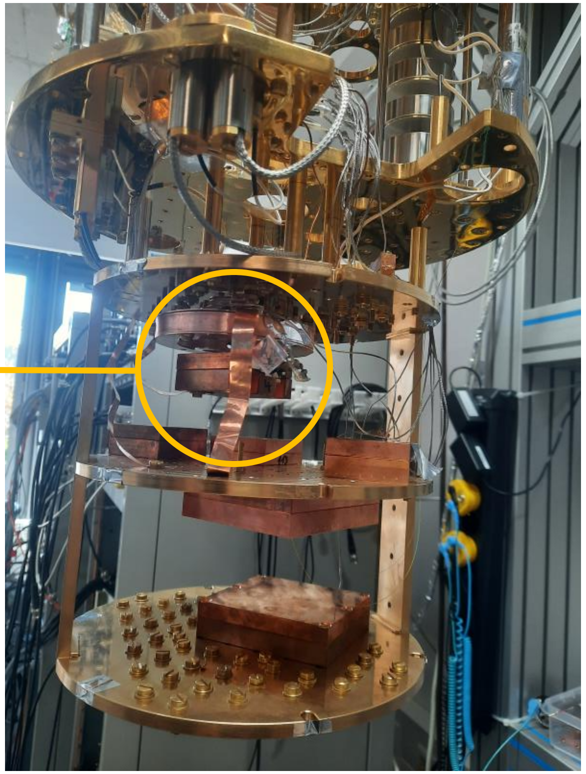
Recoil energy spectrum for $CaWO_4$ from GEANT4+FIFRELIN simulations

Proof of concept : experimental setup

27-30 Jul 2022, TUM



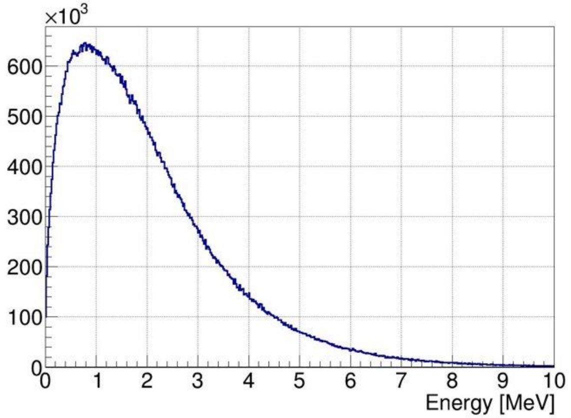
- 0.75g **NUCLEUS** $CaWO_4$ crystal + TES
- Baseline resolution: ~6.5eV
- Copper holder + sapphire balls for contact
- ^{55}Fe source for electronic recoil calibration @6keV



Two-stage spiral spring decoupling between assembly and detector holder

Portable neutron source near a dry cryostat (<7mK) @ TUM

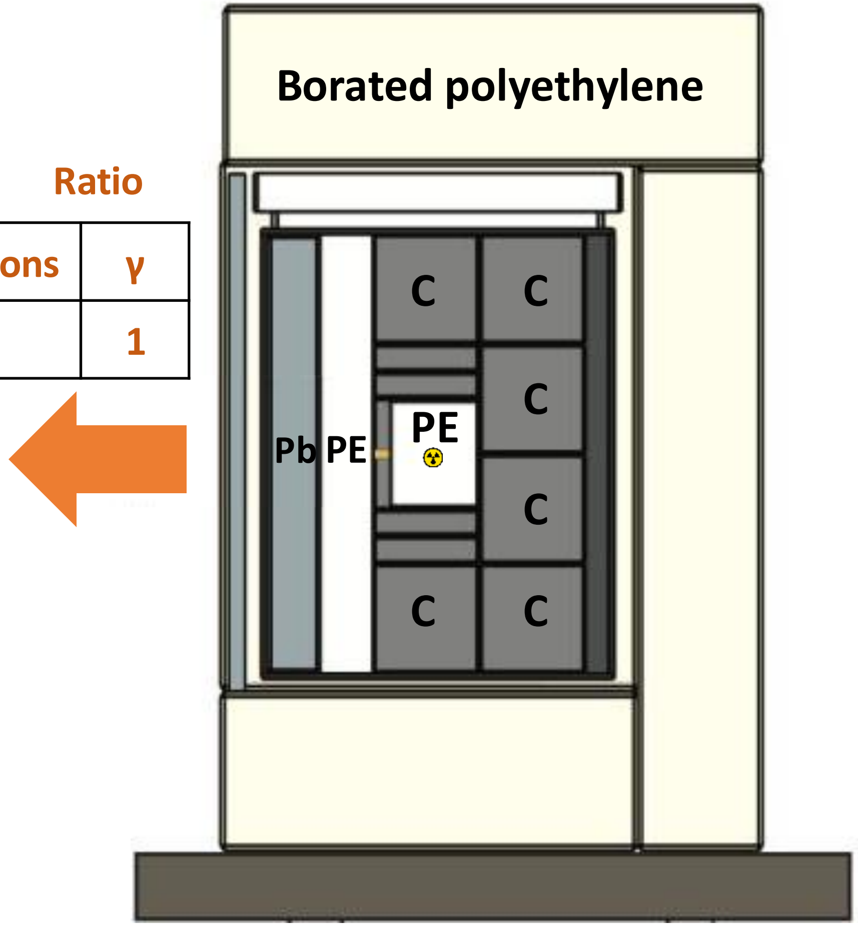
Proof of concept : portable neutron source



n-spectrum (from FIFRELIN) for ^{252}Cf

Ratio

Thermal neutrons	**Fast neutrons**	**γ**
1	**2**	**1**



A. Erhart

From ^{252}Cf:

- Thermalize fast neutrons:
  enable captures + avoid scattering in the ROI
- Attenuate fission **γ**:
  protect cryodetector counting rate and pileup

Proof of concept : blind peak search

NUCLEUS/CRAB joined publication
8 Nov 2022
arXiv:2211.03631

Background data: 18.9h
Source data: 40.2h

Delta chi2-test

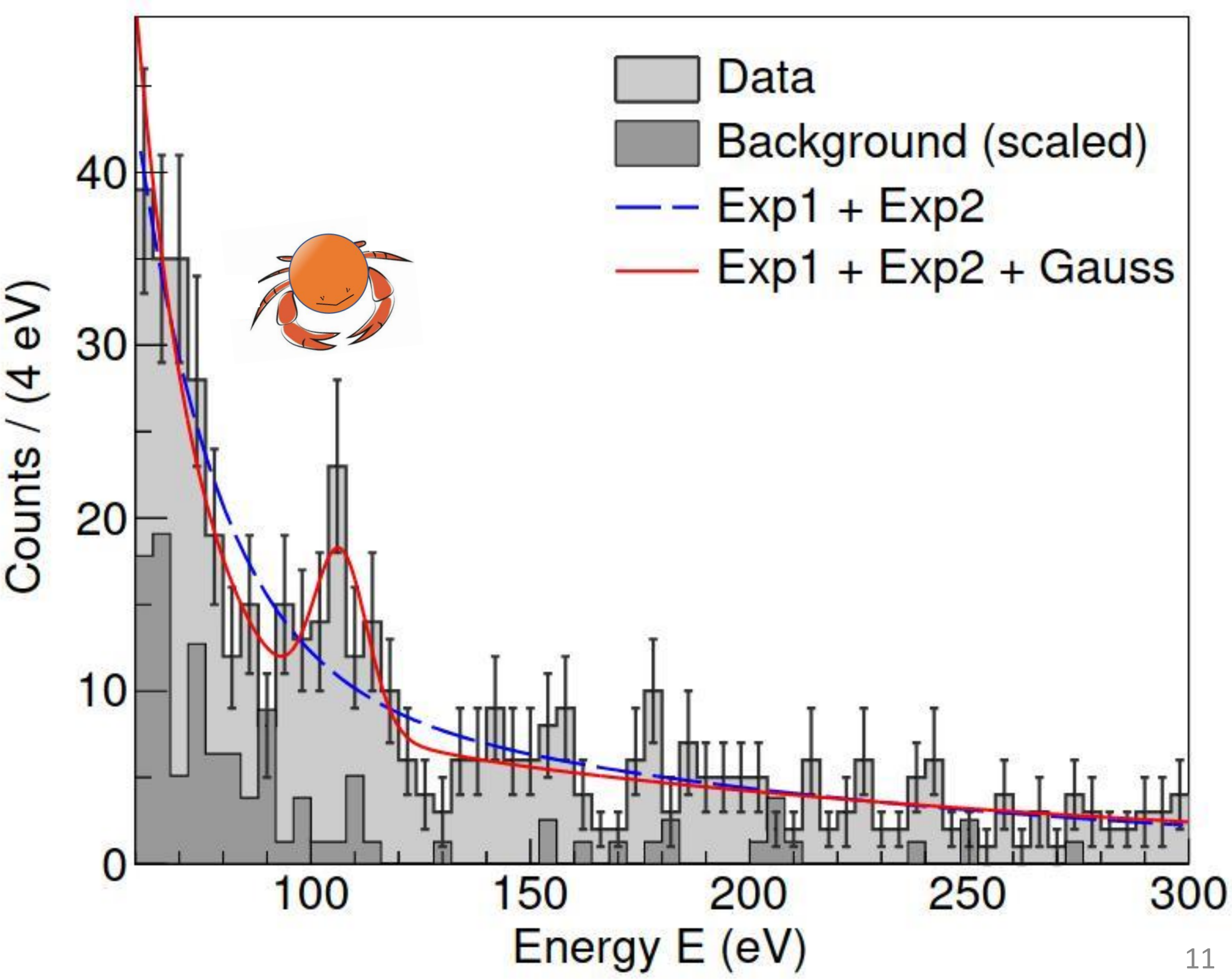
Two exponentials

- steep rise @low energy
- Fast neutron scattering

+1 gaussian for the expected peak

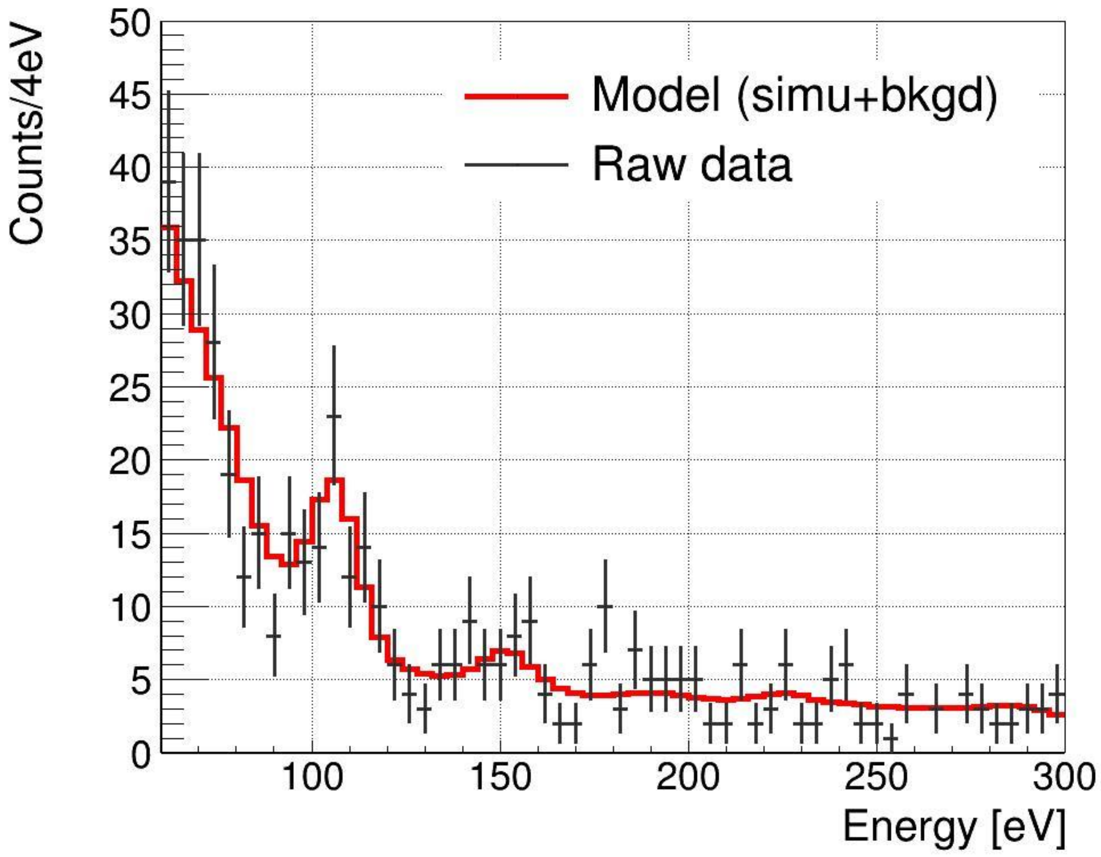
Significance: 3.1σ (2-sided)

Peak at 106.7 ± 2eV
Std deviation: 6.0 ± 1.5eV



Proof of concept : data vs model

NUCLEUS/CRAB joined publication
arXiv:2211.03631

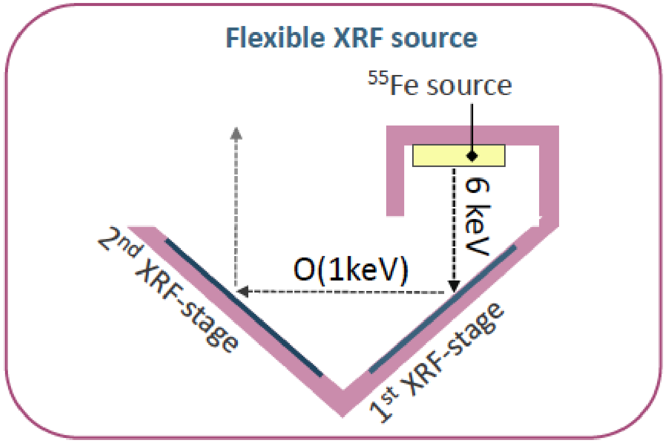


- Model built from MC simulations and fitted bkgd measurements
- Agreement data/model
  chi² = 58.06/58
- Parameters fully compatible with the blind peak search

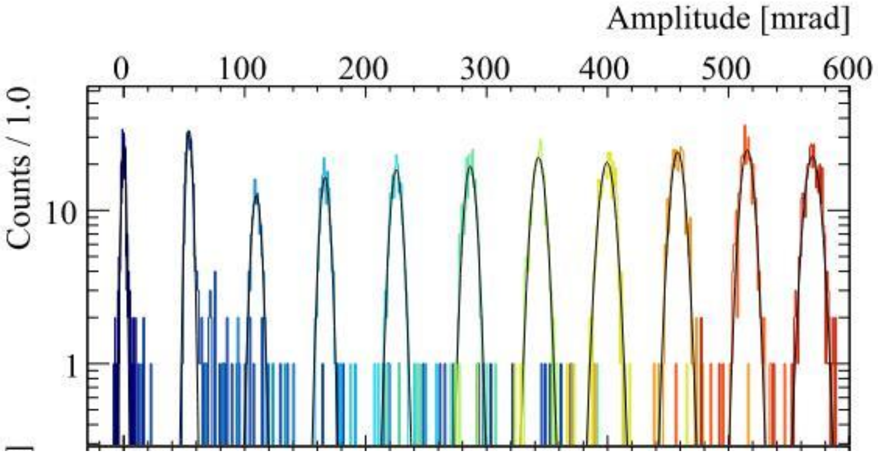
= **1st observation** of neutron-capture-induced peak at 100eV scale, with $CaWO_4$
Demonstration of an **in-situ non-intrusive calibration** for DM and CevNS

Perspectives

- Longer run (more stat), on $CaWO_4$ (access to 160eV peak)
- Run with a NUCLEUS Al_2O_3 cryodetector
- Further electronic recoil calibrations :
  - LED calibration
  - XRF calibration
- More robust energy reconstruction, access to the detector non linearities in the ER response



XRF source with multiple lines
V. Wagner

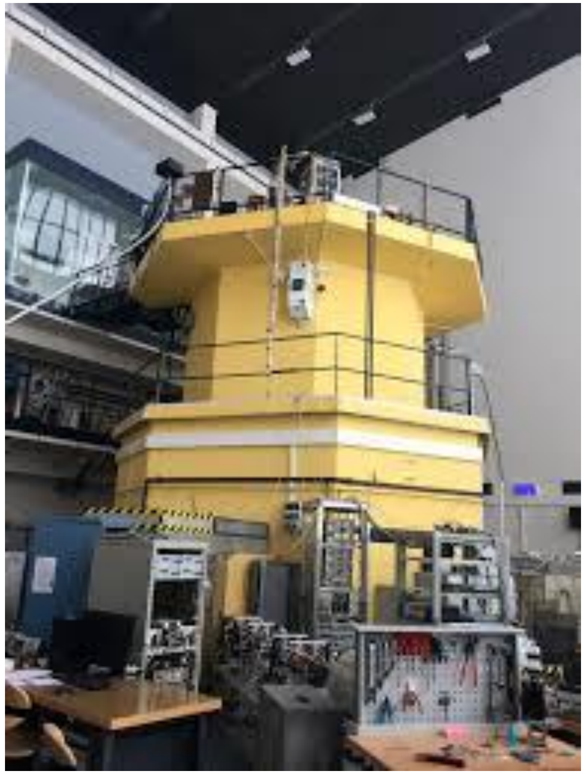


LED calibration scheme with 3.1eV photons

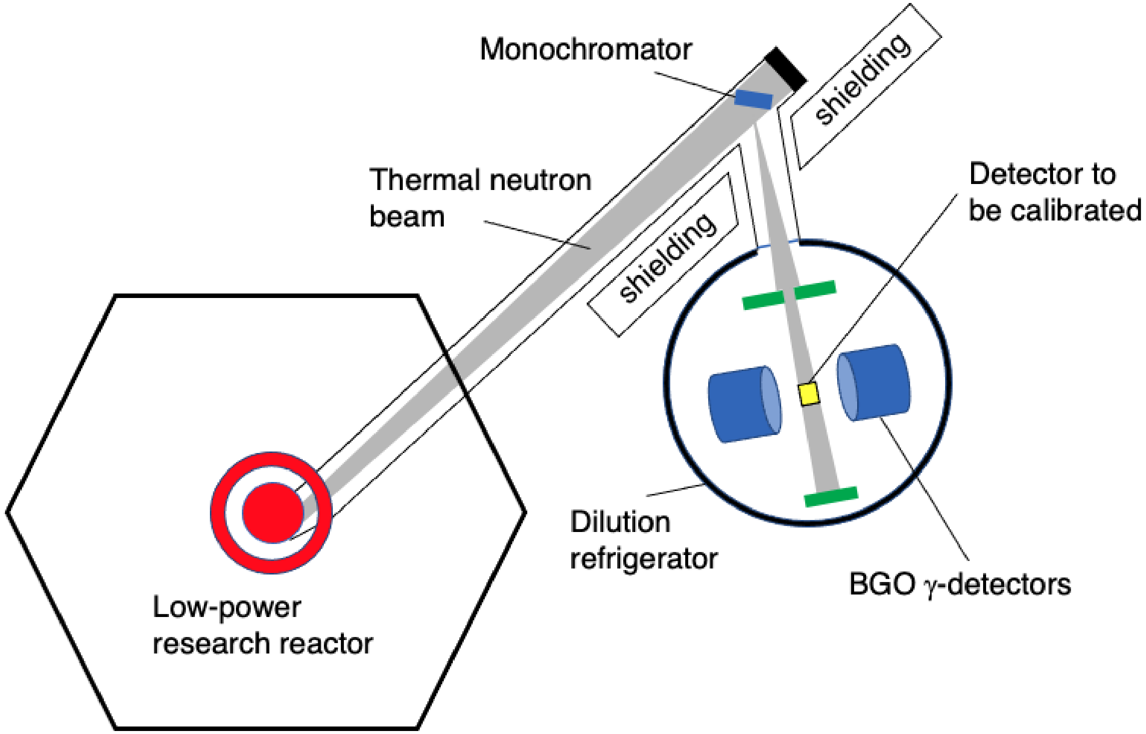
L. Cardini et al., Eur. Phys. J. C 81 (2021) 7, 636.

CRAB 2 : Experimental setup

- No fast neutrons background
- Counting rate dominated by the CRAB process



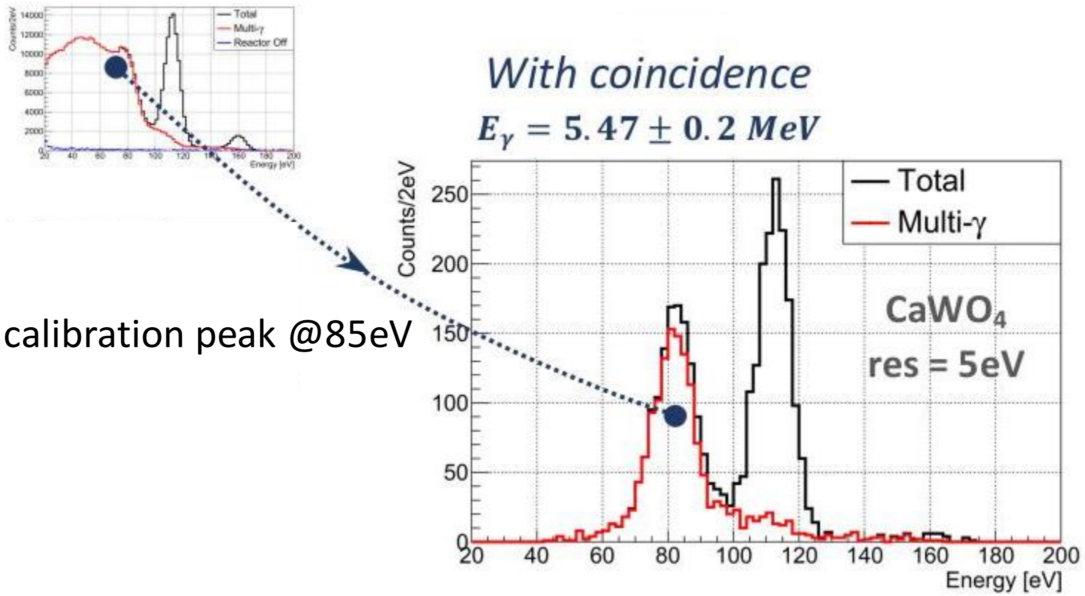
TRIGA Mark-II nuclear reactor
TU-Wien



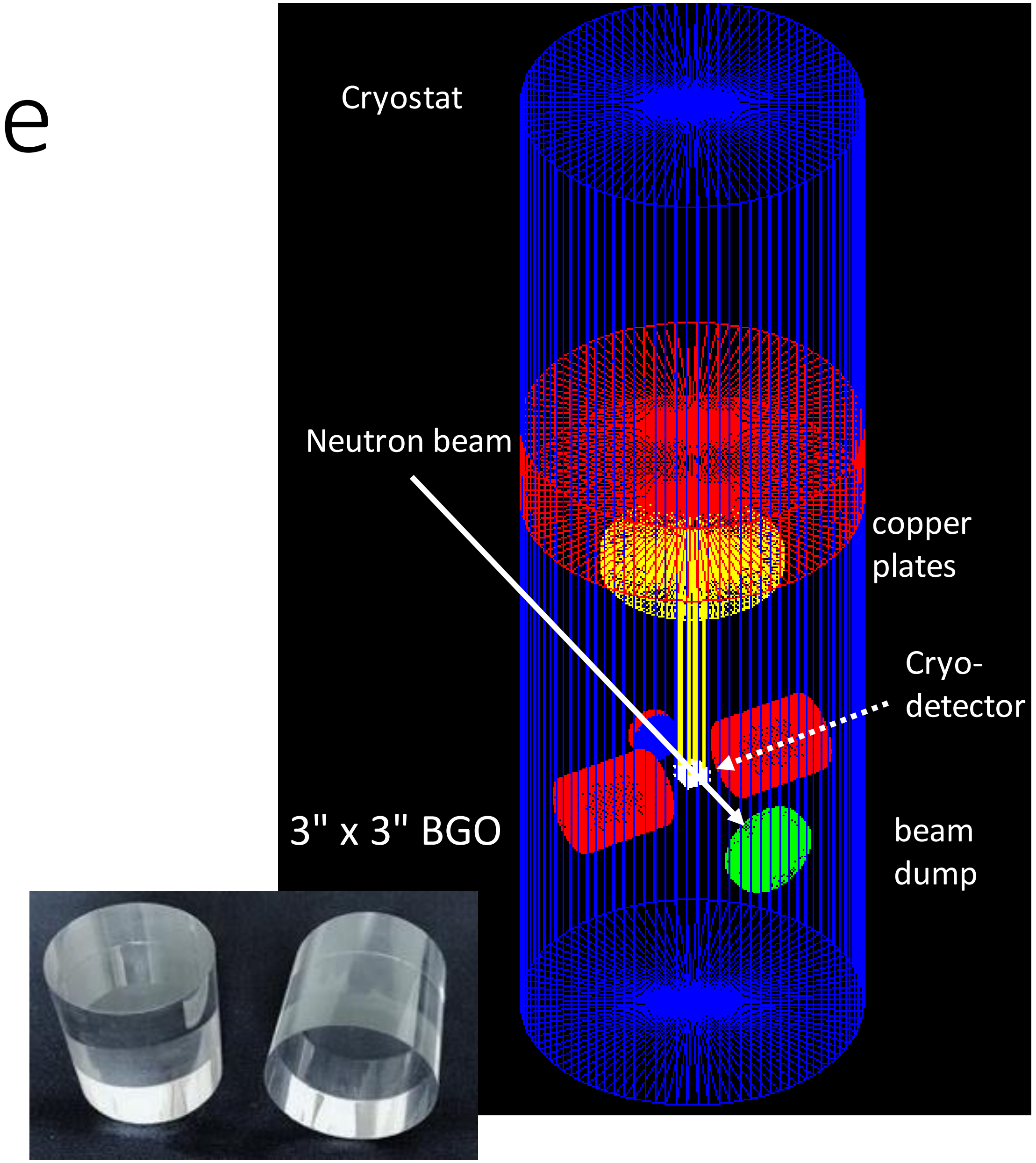
Foreseen CRAB experimental setup

- Beamline has been prepared by TU-Wien
- CRAB measurement planned for **end 2023/early 2024**

γ-cryodetector coincidence



Third calibration peak @85eV



- Rejection of multi-**γ** continuum

- Extend the method :
  - Linearity studies with the three W peaks
  - Lower recoil energy
  - Directionality studies (well-defined recoil direction)
  - Other materials

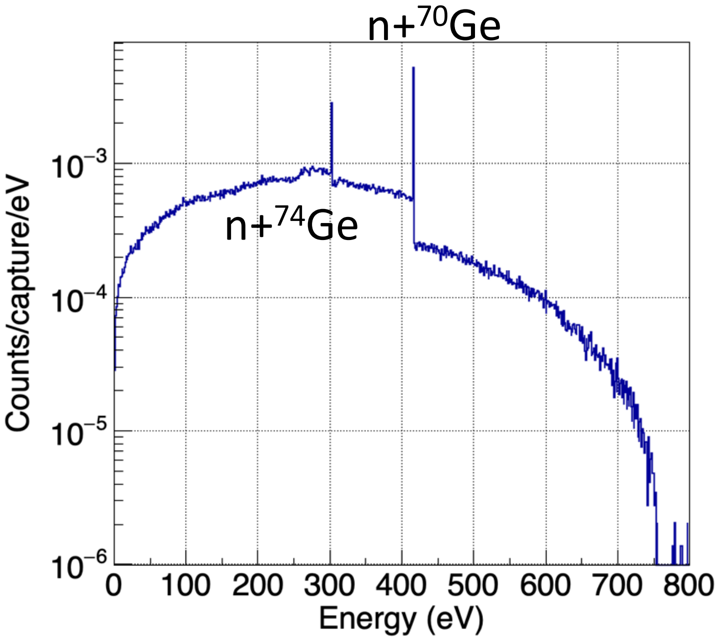
Germanium cryo-detector

EDELWEISS (2cm length cube) cryodetector
Energy resolution: 20eV

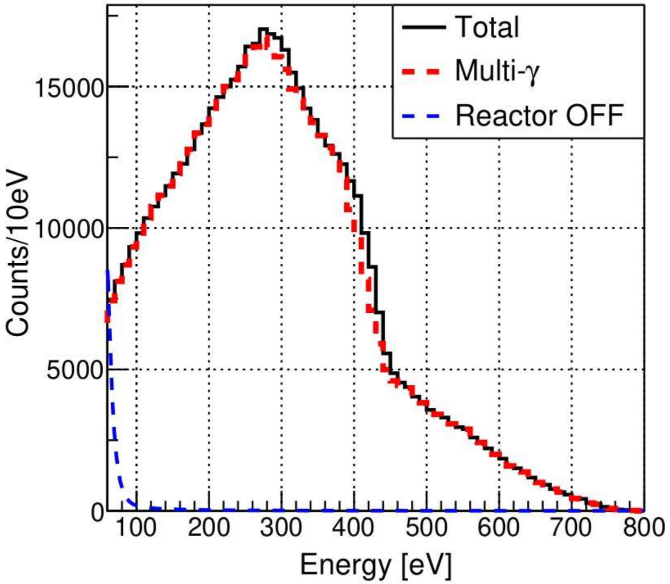
E. Armengaud et al. Phys. Rev. D, 99:082003, 4 2019

- Calibration peak @416eV
- Ionization should still be accessible
  --> could provide a NR/ER quenching measurement in a high-quenching region

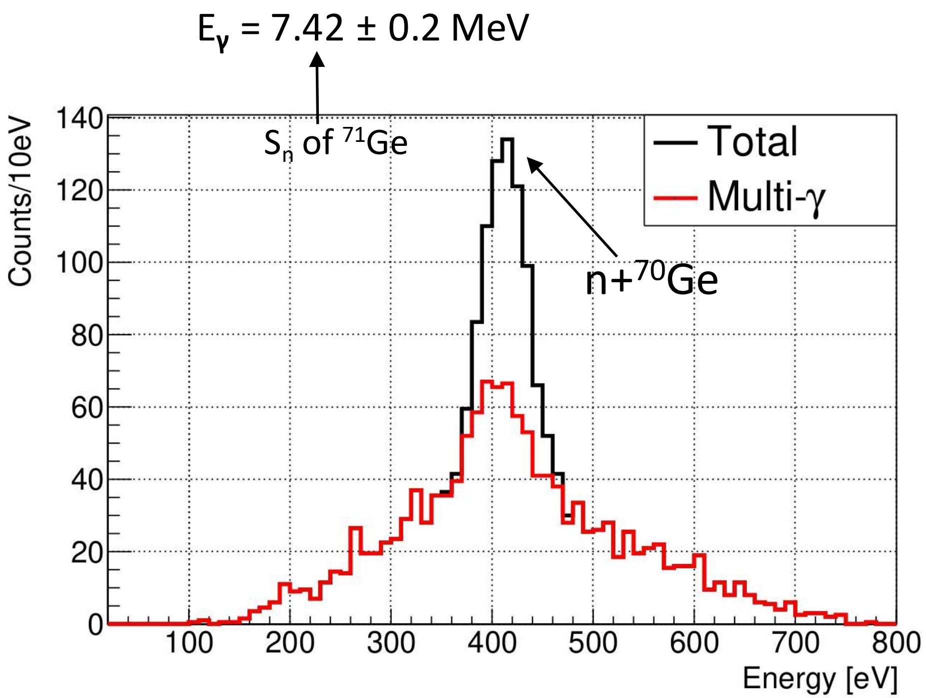
No resolution effect



With resolution



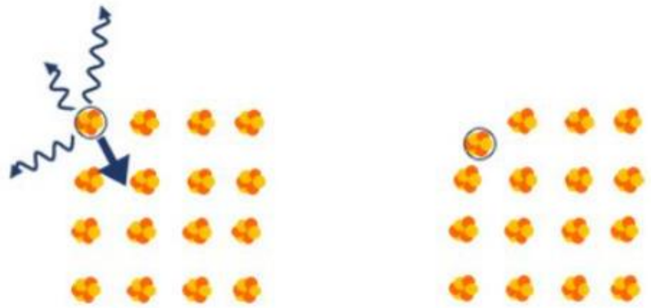
With resolution and **γ**-tagging



CRAB 2 : timing effects

Prompt hypothesis

$\tau_\gamma << \tau_{recoil}$

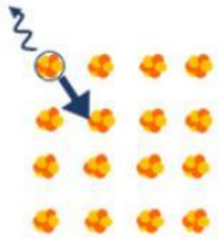


All γ are emitted
The nucleus recoils

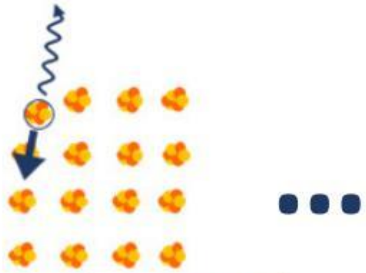
$$\boxed{E_{recoil} = \left(\sum_\gamma \vec{p}_\gamma\right)^2 / 2M_{nucleus}}$$

Slow hypothesis

$\tau_\gamma >> \tau_{recoil}$



First γ is emitted
The nucleus recoils
and stops



Second γ is emitted
The nucleus recoils and
stops

$$\boxed{E_{recoil} = \sum_\gamma p_\gamma^2 / 2M_{nucleus}}$$

FIFRELIN (see A. Chalil's talk) coupled to **IRADINA** (Binary Collision Approximation code) to simulate in-flight **γ** emission

C. Borschel, C. Ronning/Nucl. Instrum. Methods B 269 (2011) 2133

- Timing changes the energy deposited in the bolometer
- Single-γ calibration peaks are not affected

Timing effects in Silicon

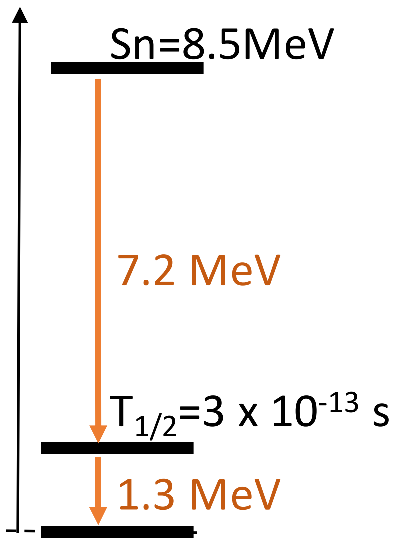
Probable 2**γ**-cascade involving a metastable nuclear level

Special feature

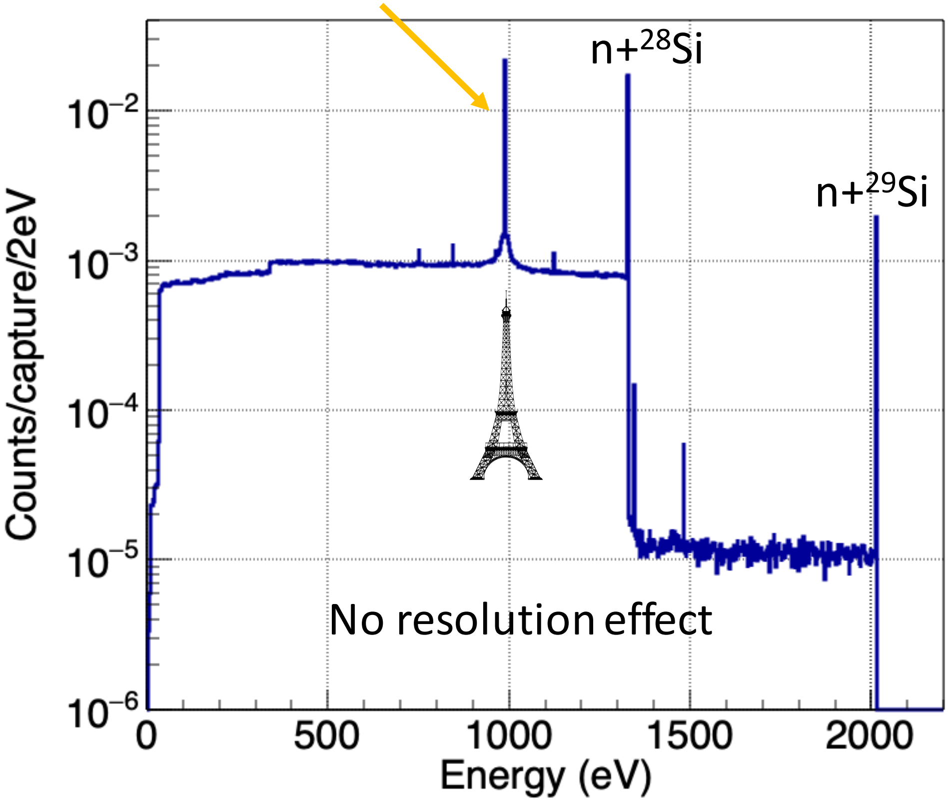
Present only when in-flight **γ**-emission is considered

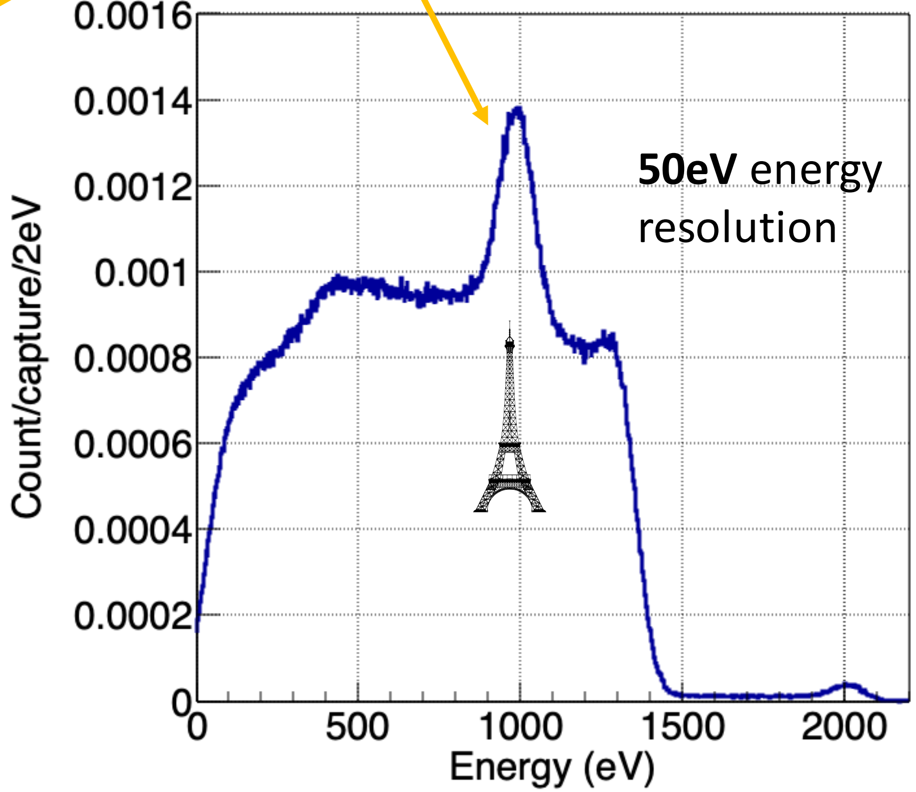
Calibration feature

Sensitive to the interplay between the **γ**-cascade timing and the recoil timing



Typical recoil durations: 10^{-14}-10^{-12}s





Recoil energy spectrum in a Si cryodetector

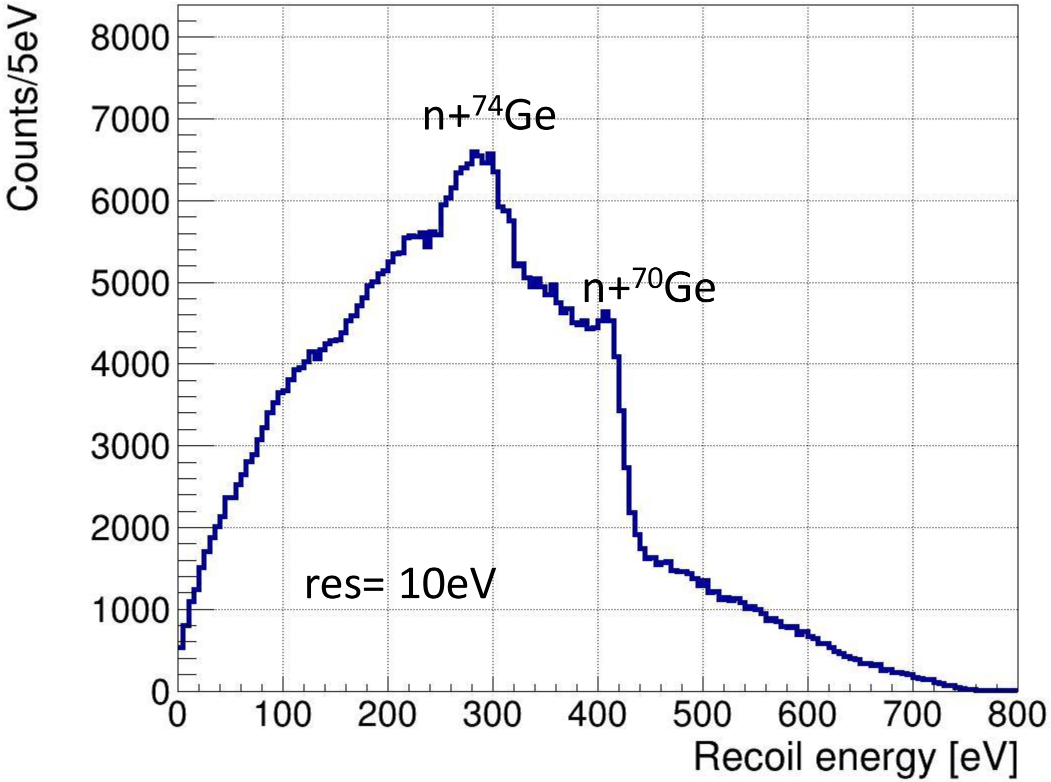
1st experimental evidence: A.N. Villano et al., Phys.Rev.D 105 (2022) 8, 083014

Timing effects in Germanium

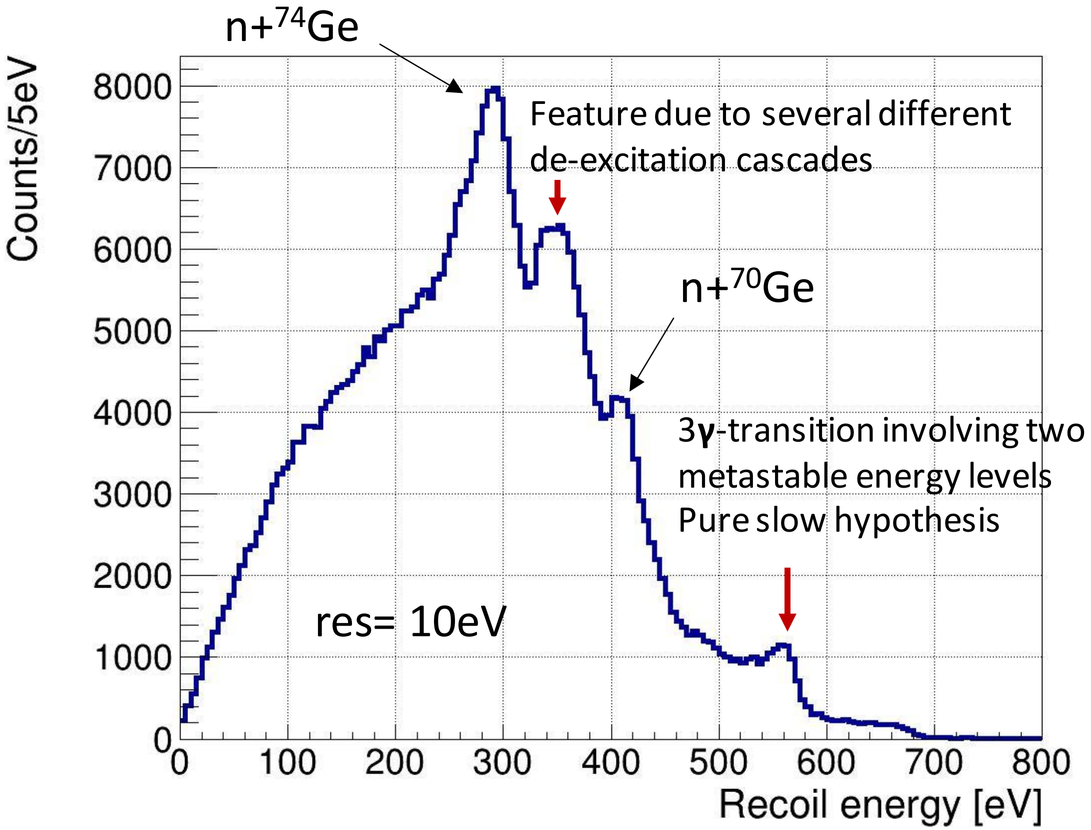
γ-cascade timing from FIFRELIN :

- Experimental
- Weisskopf (Known to be inaccurate)

--> FIFRELIN ongoing development to do better
Intermediate-Z Germanium good study case (see A. Chalil's talk)



Prompt hypothesis: $\tau_\gamma << \tau_{recoil}$

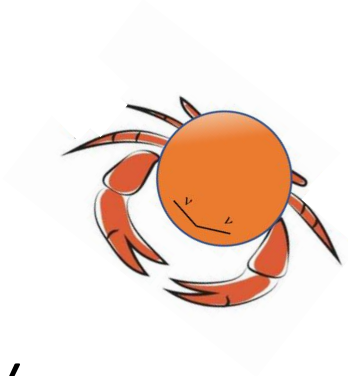


In-flight γ-emission

Conclusion

- CRAB: unique calibration method for the nuclear recoil response of cryodetectors

- First observation of a calibration peak
  - with **3σ** significance
  - Perfect agreement between data and model
  - 112eV recoil due to single-**γ** de-excitation of *n* + ^{182}W

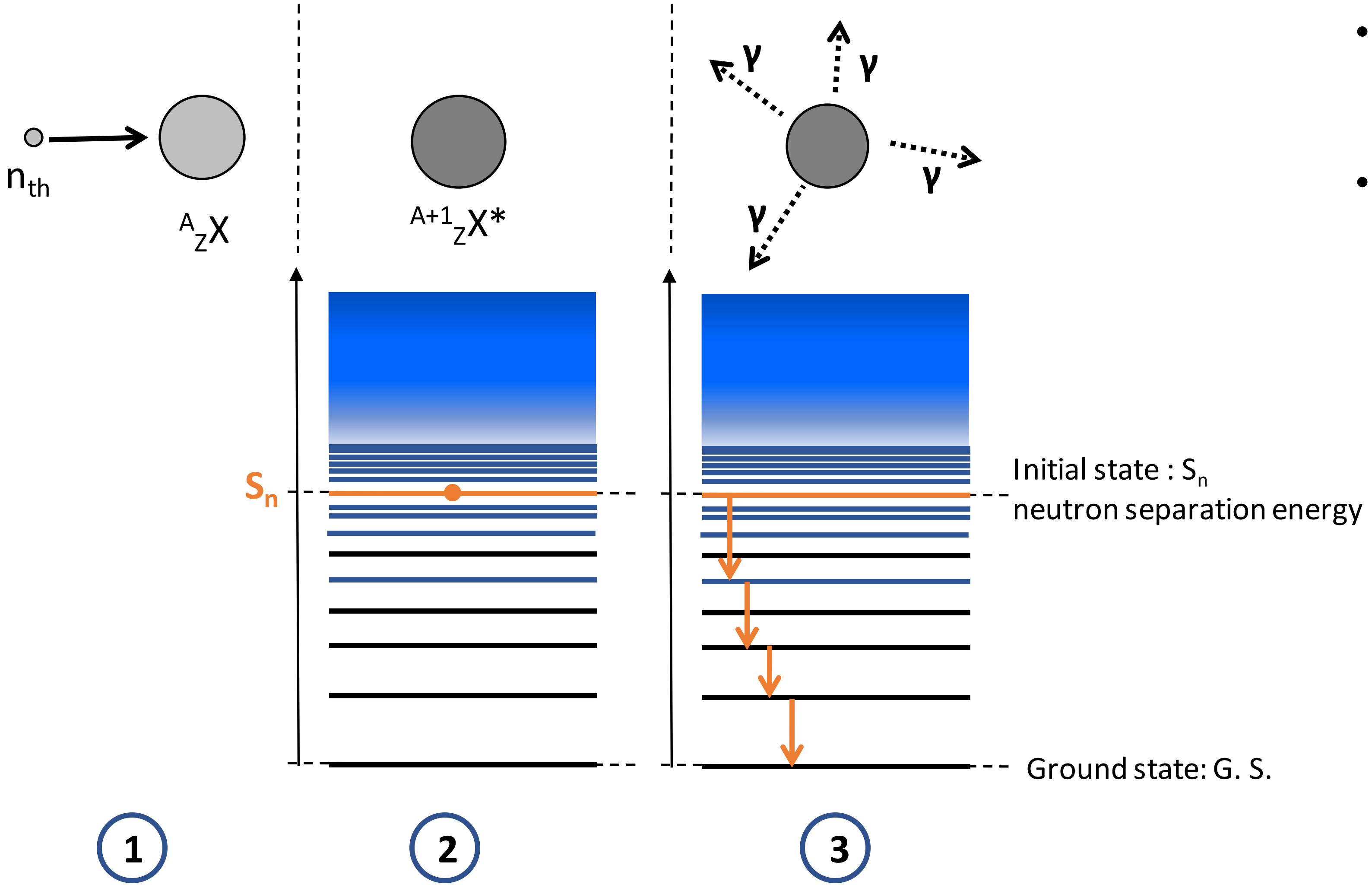


- High-precision measurements to come in Phase 2 (end 2023-early 2024)
  - lower background + higher counting rate in ROI
  - **γ**-tagging: extension to other materials, lower recoil energy
  - timing effects

Back-up slides

CRAB simulations : FIFRELIN

O. Litaize et al., Eur. Phys. J. A 51, 1 (2015)



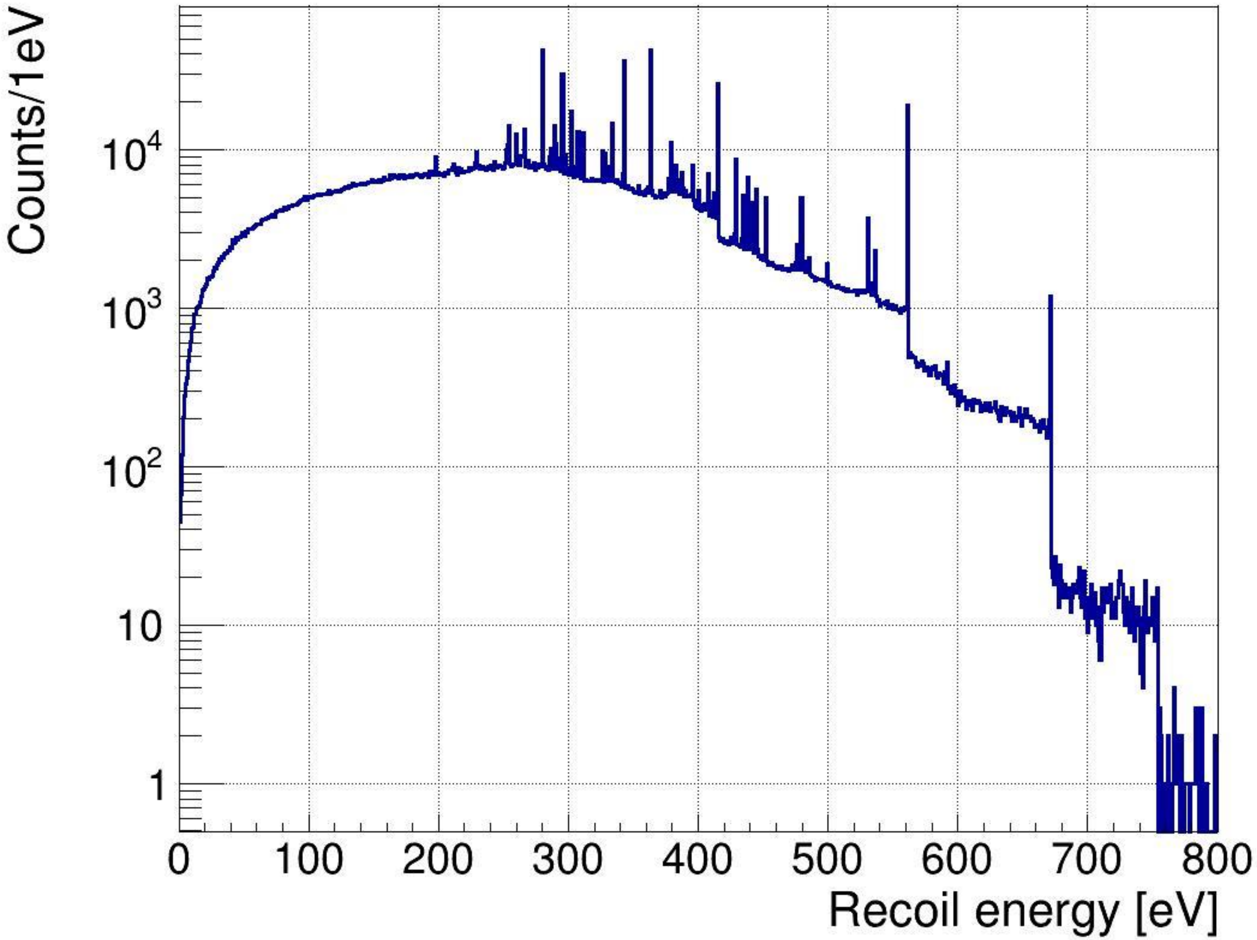
- Developed to model the de-excitation of fission fragments

- FIFRELIN builds the level scheme
  - From evaluated nuclear data
  - Completed with theoretical level density models

1. Following neutron capture, compound nucleus is in a state close to Sn
2. Then de-excitates towards ground state emitting **γ**
3. **FIFRELIN** generates **γ** cascades with a Monte Carlo process from Sn to G.S.

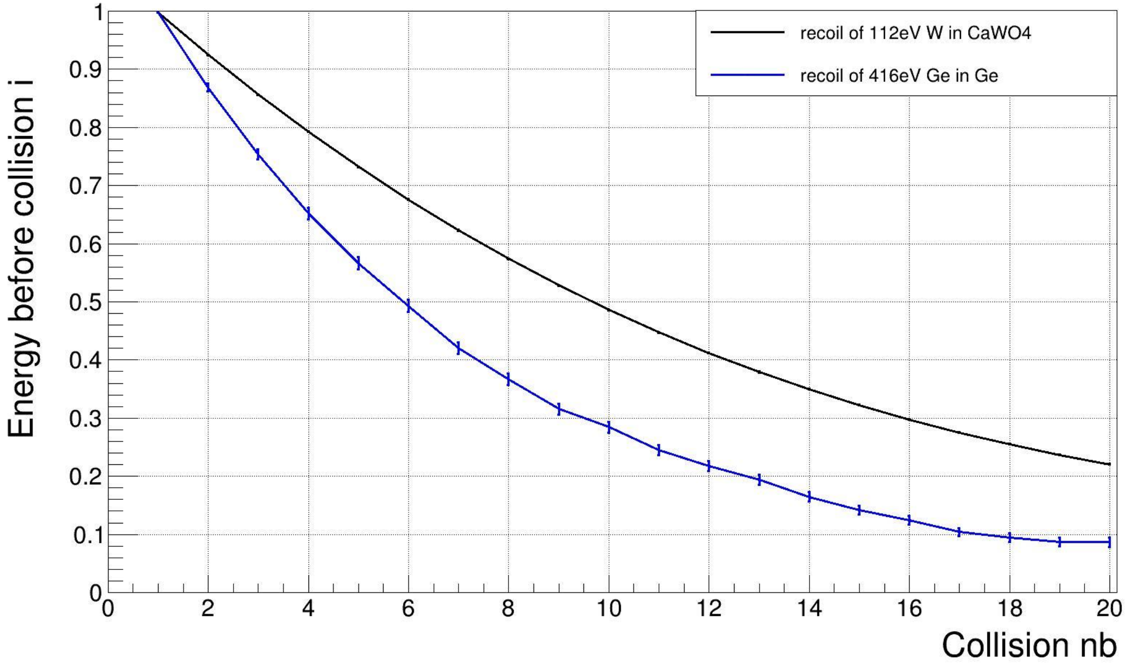
Timing effects in Germanium

In-flight γ-emission
No resolution effect

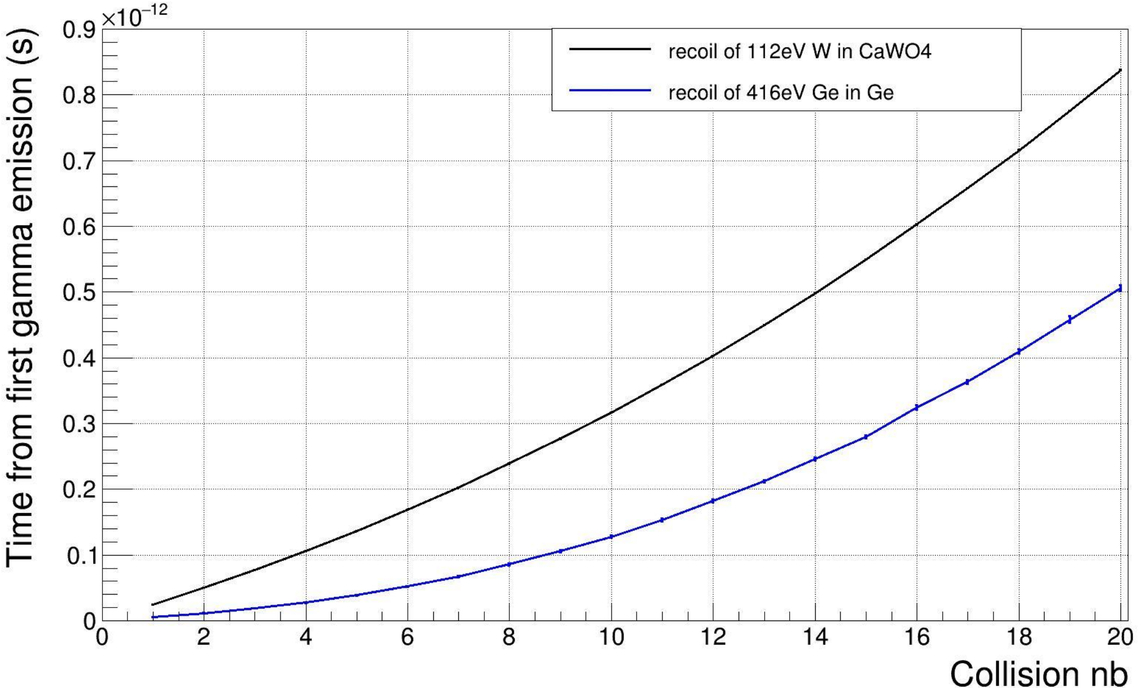


Recoil studies with Iradina

- W recoils with **112eV** in $CaWO_4$
  - W looses less energy in collisions with light elements Ca and O than with W
- Ge recoils with **416eV** in Ge
  - Collides only with similar mass targets



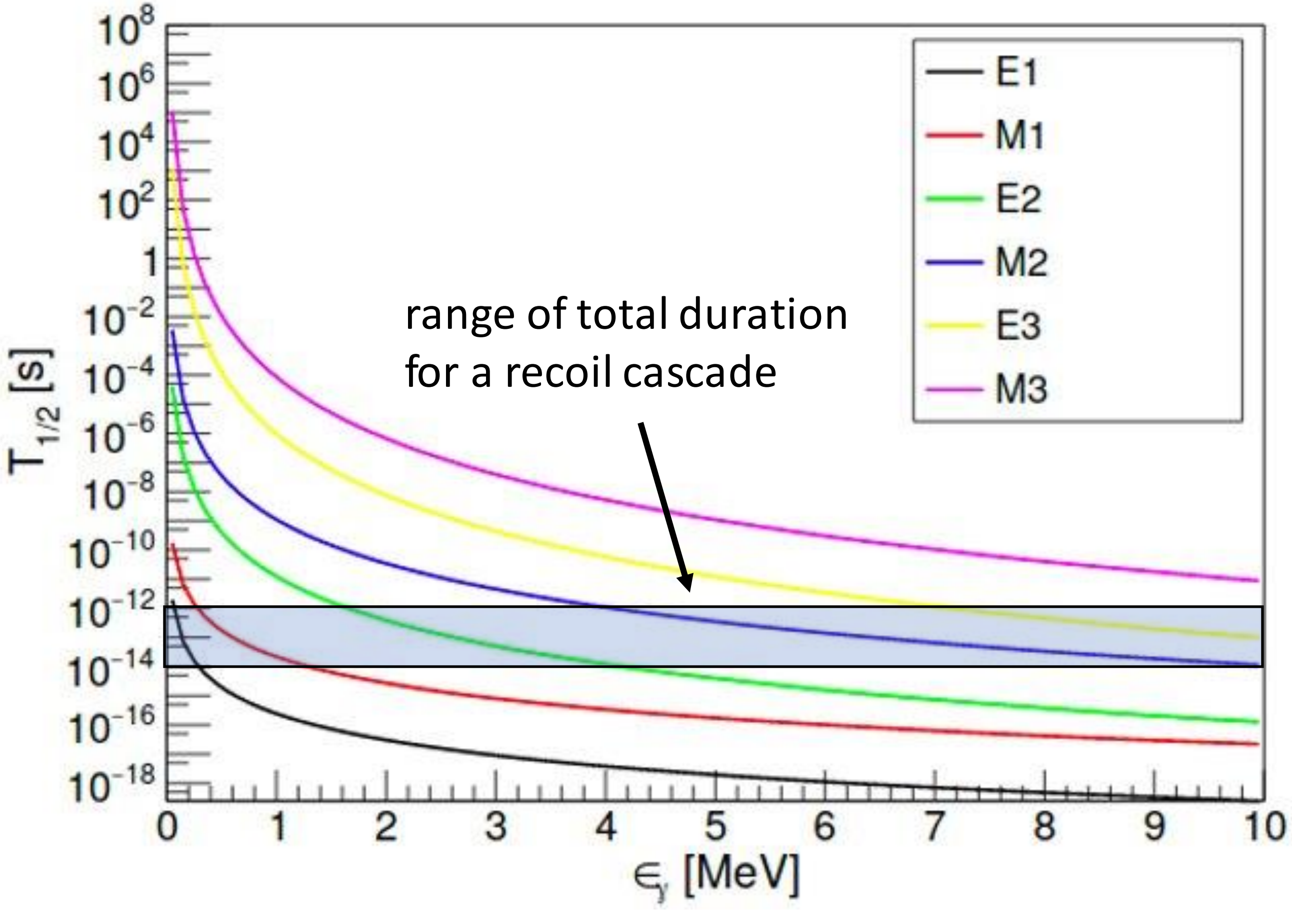
Evolution of the kinetic energy of the PKA, collision after collision
Renormalization to initial recoil energy



Characteristic duration between two collisions: few 10^{-14}s
To be compared to half-lives of nuclear energy levels (next slide)

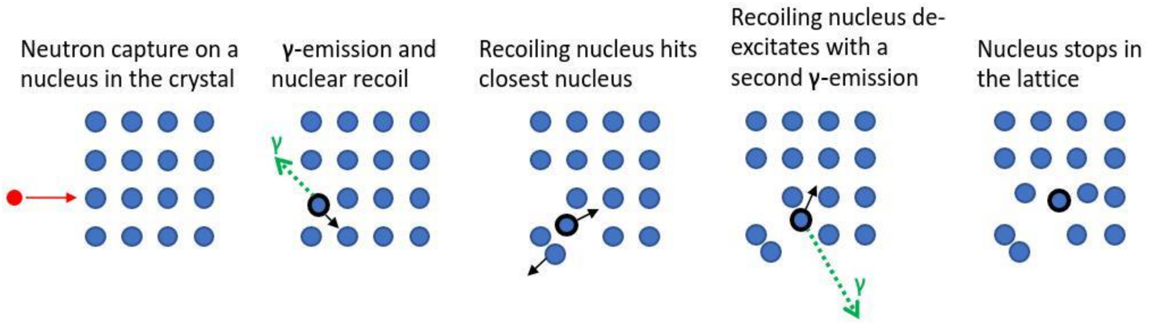
Nuclear level half-lives

Half-lives of excited nuclear levels



range of total duration for a recoil cascade

Low-energy transitions (≤1 MeV) are likely to happen "in-flight", while the nucleus is still recoiling



Neutron capture on a nucleus in the crystal

γ-emission and nuclear recoil

Recoiling nucleus hits closest nucleus

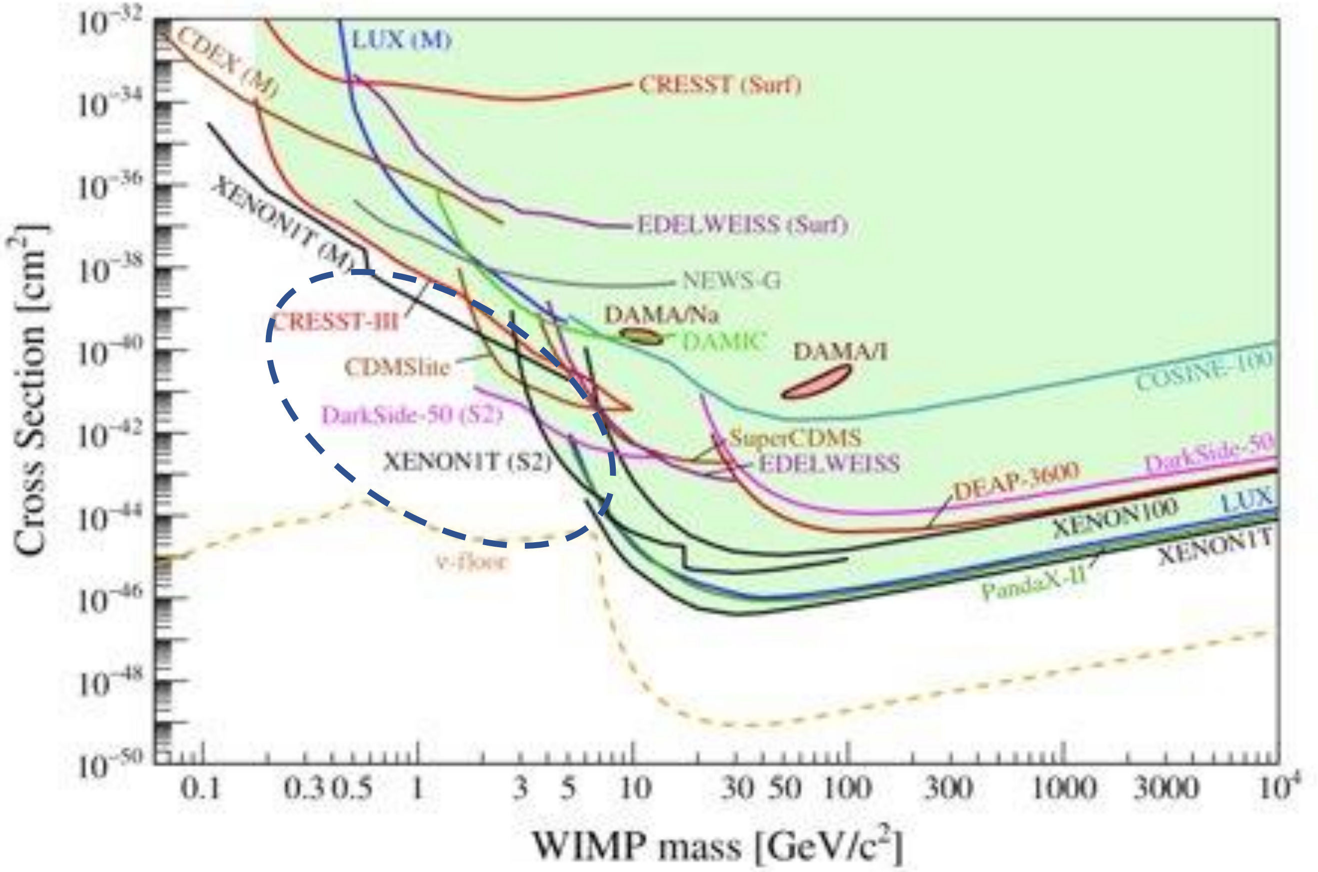
Recoiling nucleus de-excitates with a second γ-emission

Nucleus stops in the lattice

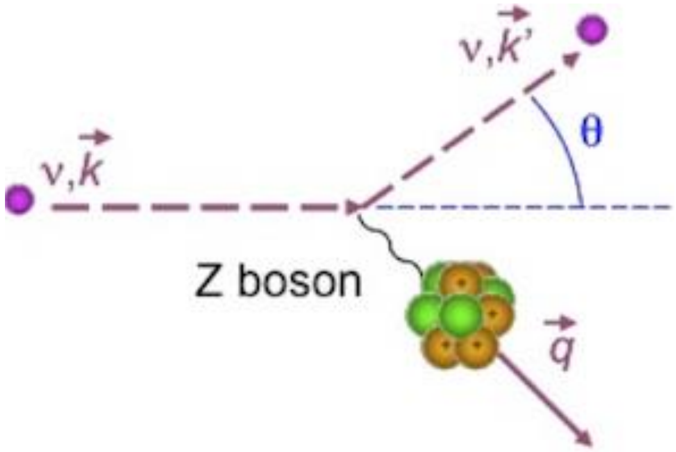
100eV nuclear recoils

Direct detection of light Dark Matter

Direct Detection of Dark Matter -- APPEC Committee Report



Precision measurements with coherent neutrinos/nuclei scattering



Complementary tests of Standard Model

Reactor antineutrinos: several MeV