# Calibration of nuclear recoils at the 100 eV scale in cryogenic detectors using neutron capture

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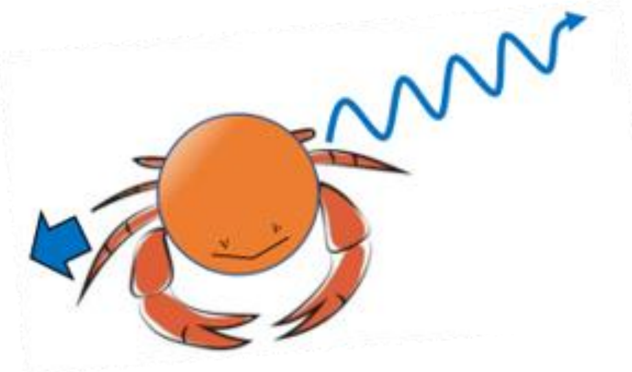
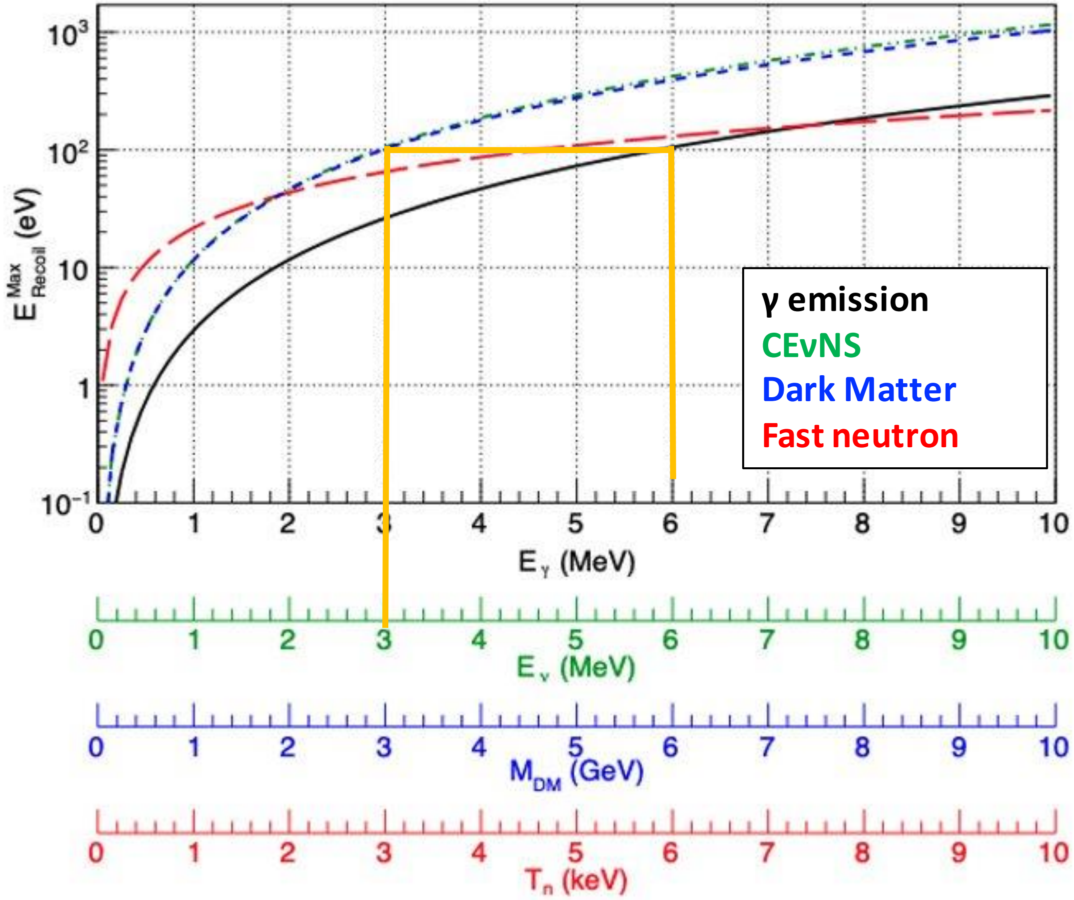
**Magnificent CEvNS – 23 March 2023**
**Munich**



# 100eV nuclear recoils

**Maximal recoil energies for various processes (target = W)**




Sub-keV nuclear recoils are the expected signal for:

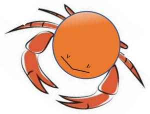
- **CEvNS with MeV neutrinos**
- **Direct detection of low-mass O(GeV) DM**

↓

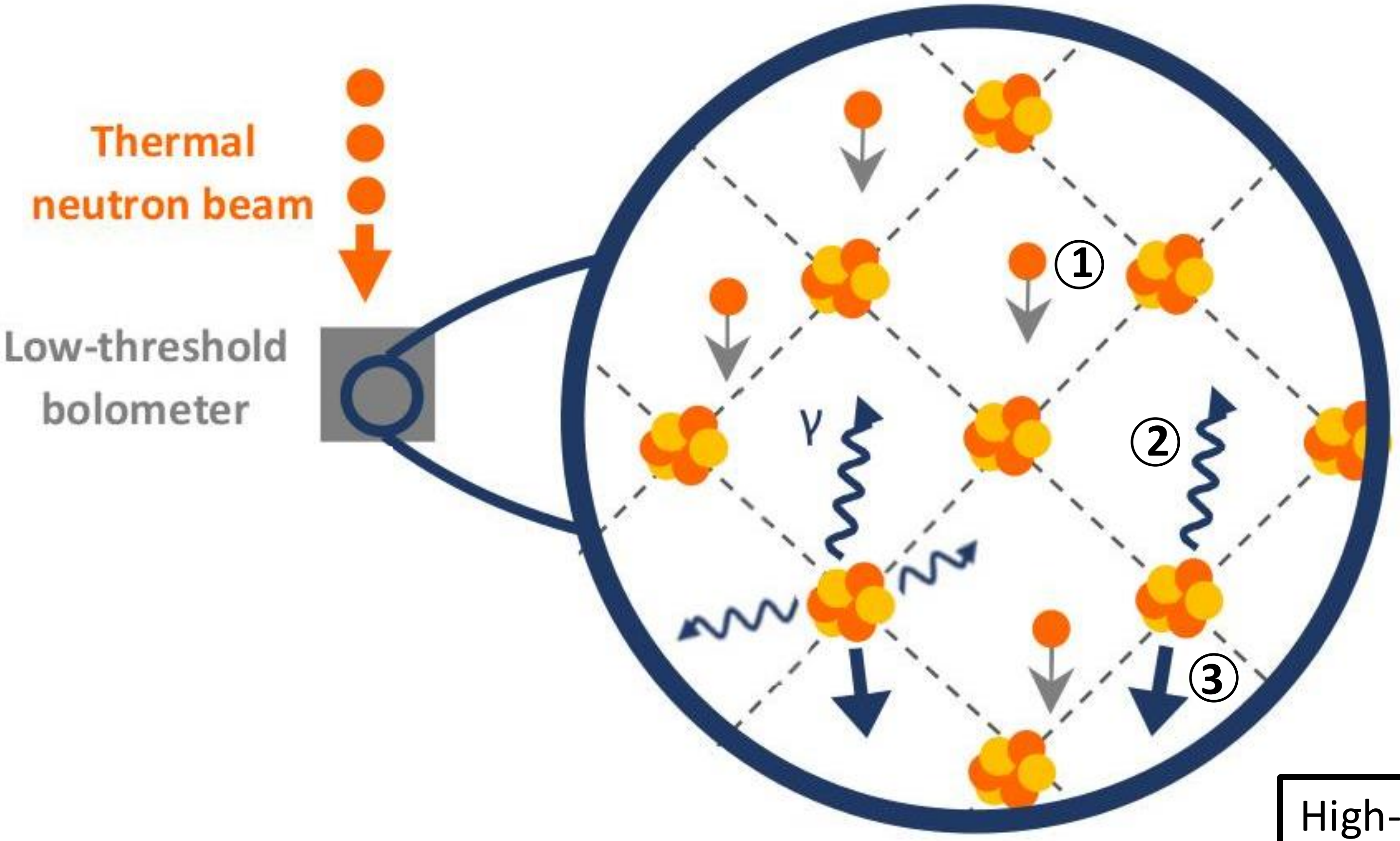
Understanding the sub-keV nuclear recoil signal is crucial for upcoming experiments searching for new physics

Calibrated sub-keV nuclear recoils from:

- **Elastic scattering of keV neutrons**
- **Nuclear recoils following MeV γ emission**



# 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)

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

High-precision & all specifications of physics:

- Pure nuclear recoils
- In the bulk of the detector
- In the sub-keV region

**L. Thulliez, D. Lhuillier et al, 2021, JINST 16 P07032**

# CRAB targets

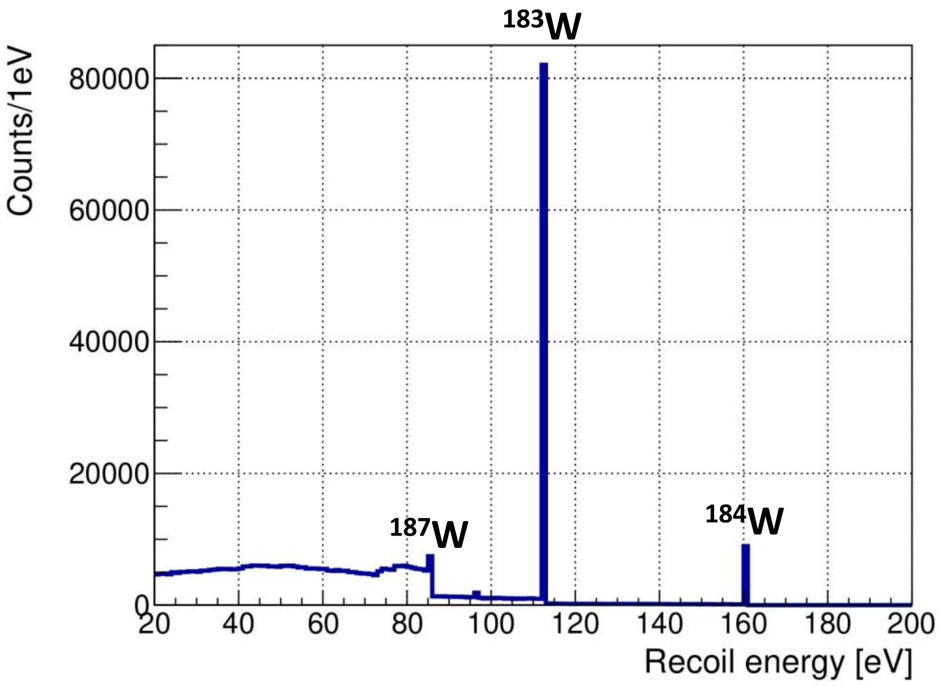
| Cryo-det crystal | Target Isotope | Nuclear Recoil (eV) | F.O.M. (Ab*σ*I) |
|---|---|---|---|
| Ge | $^{70}Ge$<br>$^{74}Ge$ | 416.2<br>303.2 | 122<br>54 |
| Si | $^{28}Si$<br>$^{28}Si$ | 1330<br>989.9 | 36<br>118 |
| $Al_2O_3$ | $^{27}Al$ | 1145 | 616 |
| $CaWO_4$ | $^{182}W$<br>$^{183}W$<br>$^{186}W$ | 112.5<br>160.3<br>85.8 | 7506<br>823<br>281 |

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

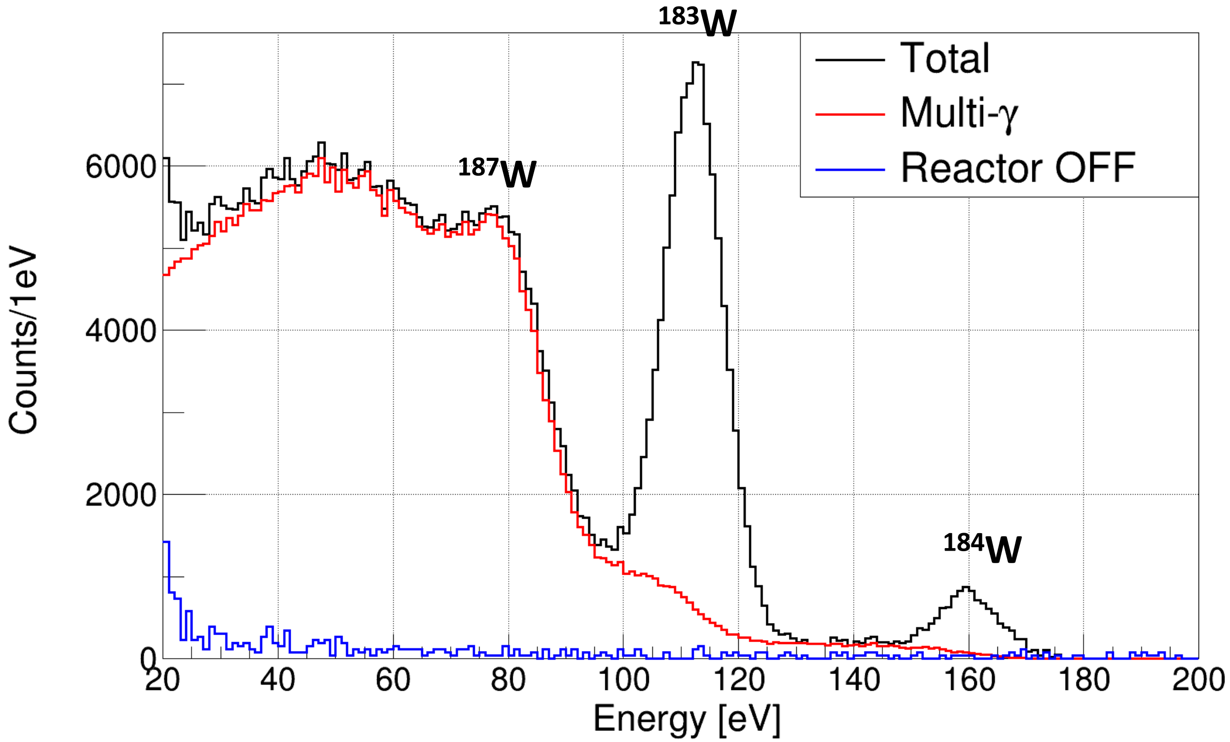
The four main cryodetectors used in the community could be calibrated via CRAB

# CRAB in $CaWO_4$

**Recoil energy spectra for a NUCLEUS $CaWO_4$ detector in a thermal neutron beam from GEANT4+FIFRELIN simulations**




**Without energy resolution**



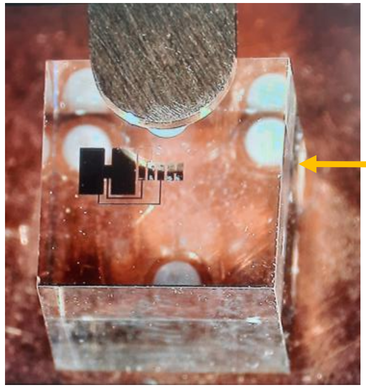

**Energy resolution: σ = 5eV**

Calibration peak @112eV prominent enough for a proof of concept measurement with less favorable background conditions

# Proof of concept : experimental setup

27-30 Jul 2022, TUM

Background data: 18.9h
Source data: 40.2h

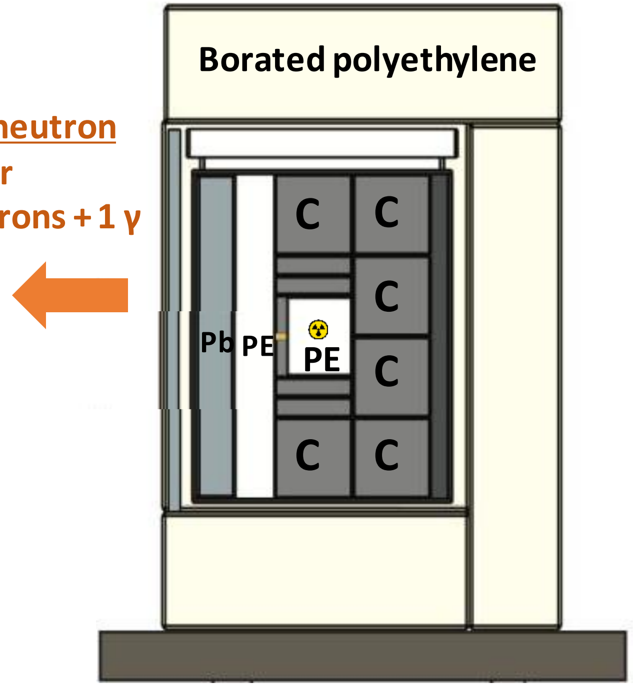


- 0.75g **NUCLEUS** $CaWO_4$ crystal + TES
- Baseline resolution: ~6.5eV
- $^{55}$Fe source for electronic recoil calibration @6keV


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

A. Erhart

1 thermal neutron for 2 fast neutrons + 1 γ



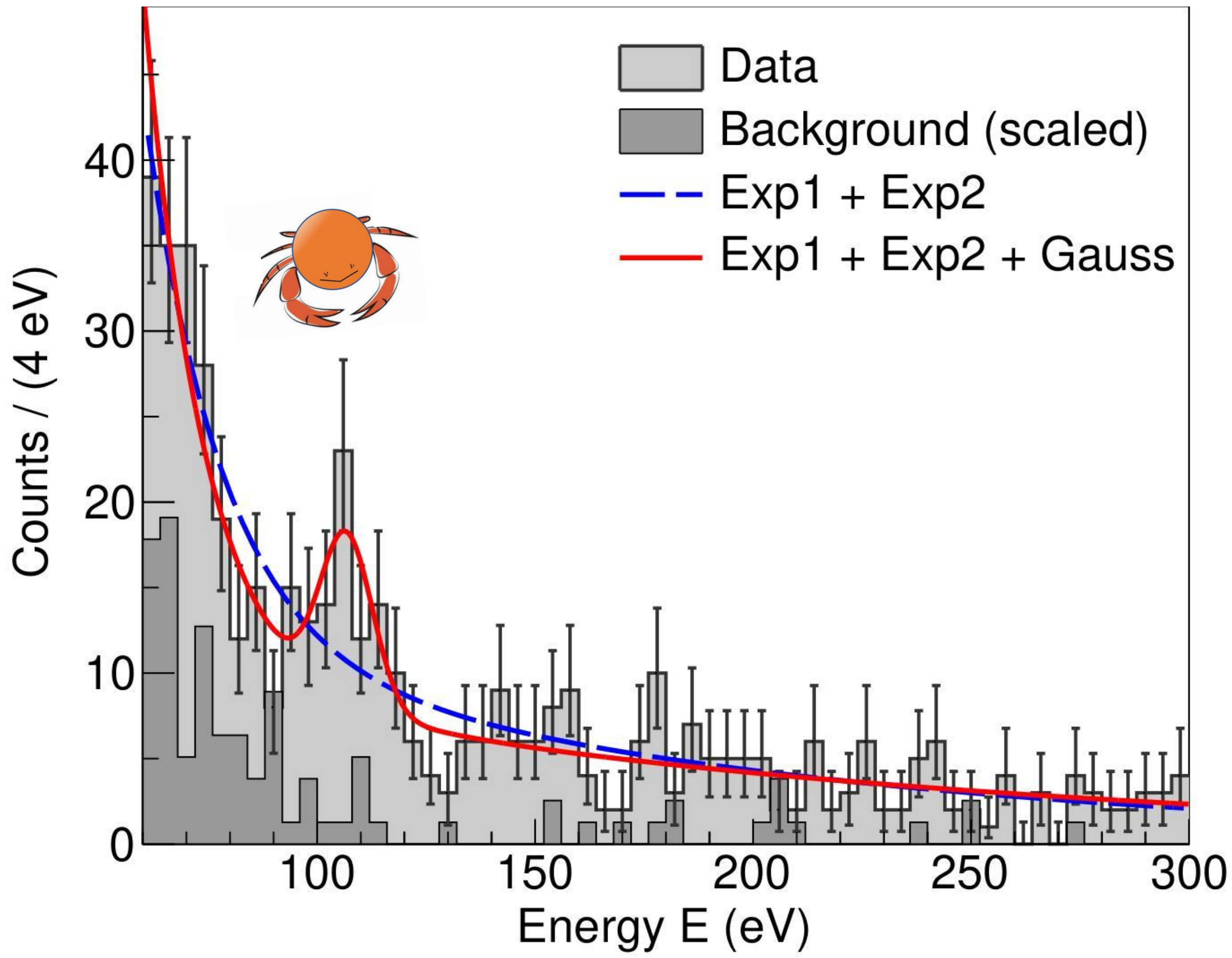

3MBq $^{252}$Cf source

- MeV fission neutrons thermalized by PE
- Fission **γ** attenuated by lead

*Similar measurement on Si: A.N. Villano et al., Phys.Rev.D 105 (2022) 8, 083014*

# Proof of concept : blind peak search

**NUCLEUS/CRAB joined publication**
**arXiv:2211.03631, 2022**




**Delta chi2-test with binned likelihood fits**

Two exponentials

- steep rise @low energy
- Fast neutron scattering

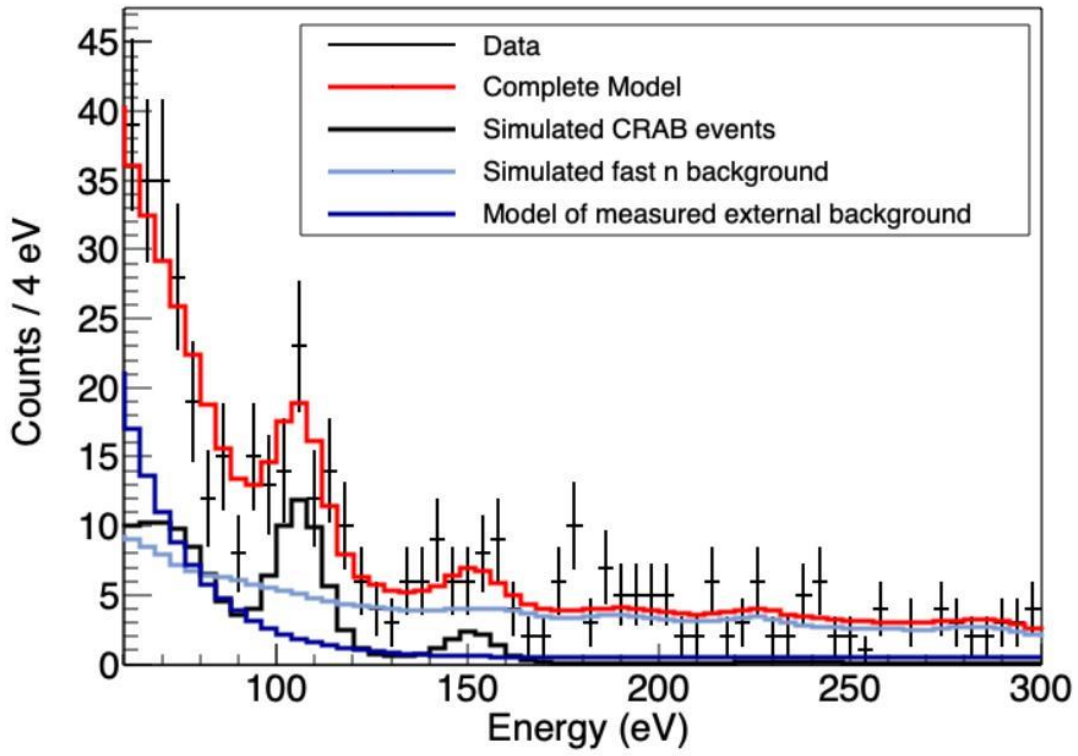
+1 gaussian for the expected peak

**Significance: 3σ** (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**



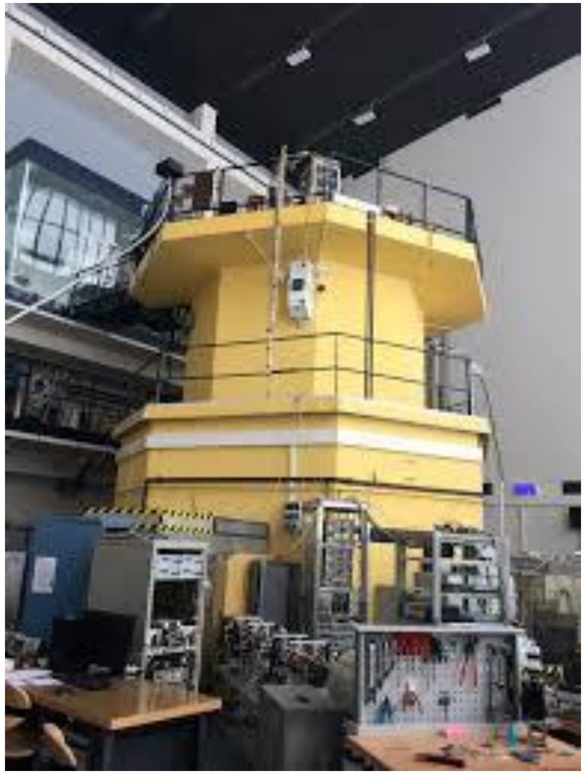

- Two binned likelihood fits of the model on the data, with/without the capture signal

  **Significance: 6σ** (2-sided)

- With the capture signal:
  - Parameter **values fully compatible with blind peak search**
  - $chi^2/ndf = 58.06/58$

= **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

# CRAB with pure thermal neutron beam

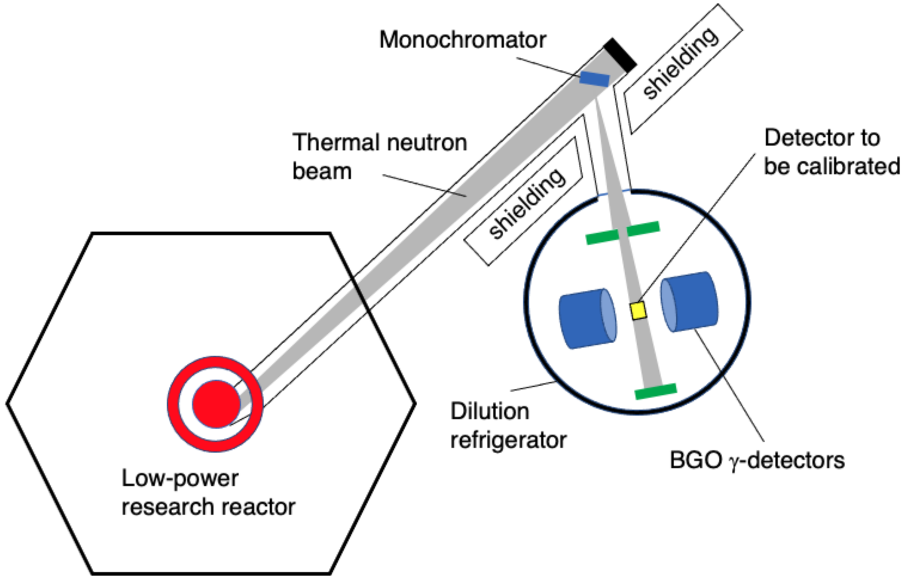


250kW TRIGA Mark-II nuclear reactor, TU-Wien

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

--> high-precision and full use of the method potential

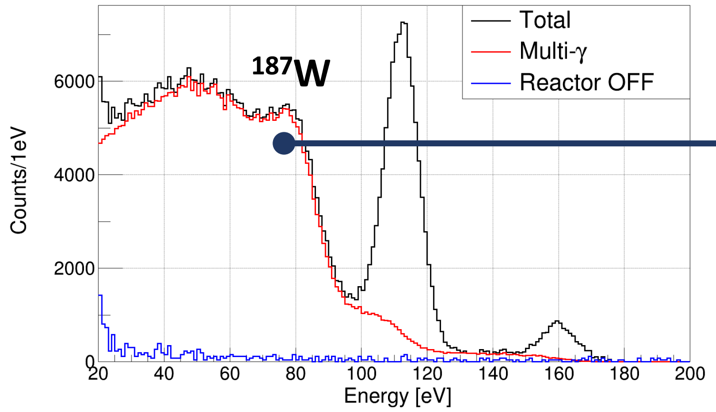
**Foreseen experimental setup**

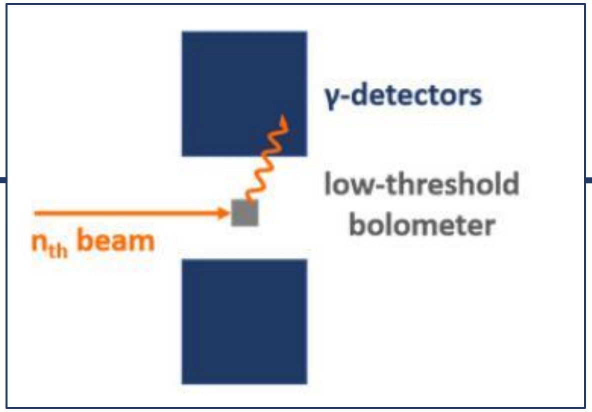



Beamline being prepared by TU-Wien
10-1000 n/s/cm²

# γ-cryodetector coincidence

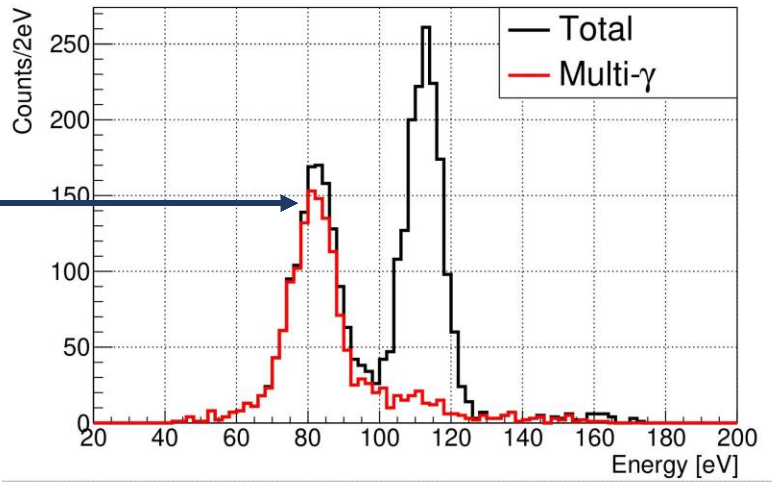
$CaWO_4$




With coincidence

$\mathbf{E_\gamma = 5.47 \pm 0.20\ MeV}$




Third calibration peak @85eV

Detailed description of **γ** cascades using FIFRELIN
[O. Litaize et al., Eur. Phys. J. A (2015) 51: 177]

Rejection of multi-**γ** continuum

**γ**-detection solution under study:

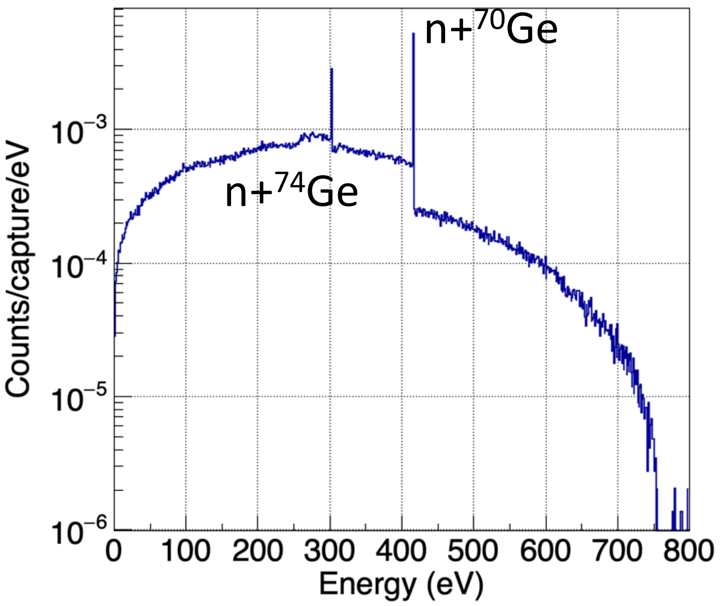
- BGO detectors in cryostat
- Larger segmented **γ**-detectors outside the cryostat

**Extend the method :**

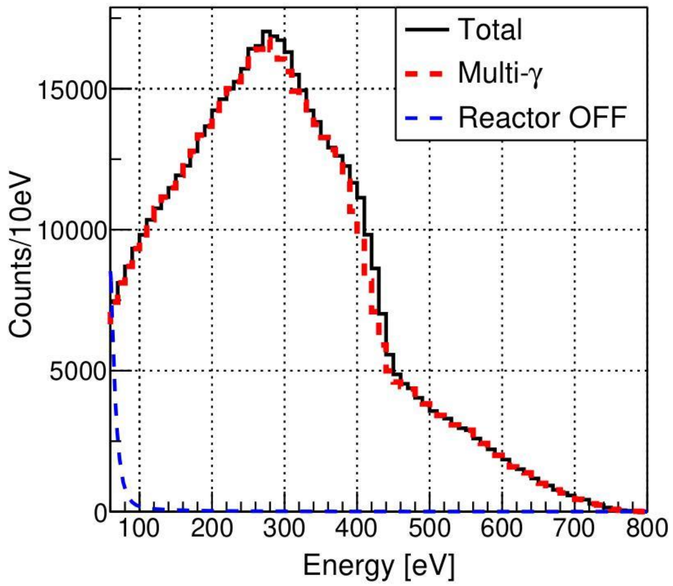
- Directionality studies (well-defined recoil direction)
- Additional calibration features
  - Linearity studies with the three W peaks
  - Other materials

# Germanium cryo-detector

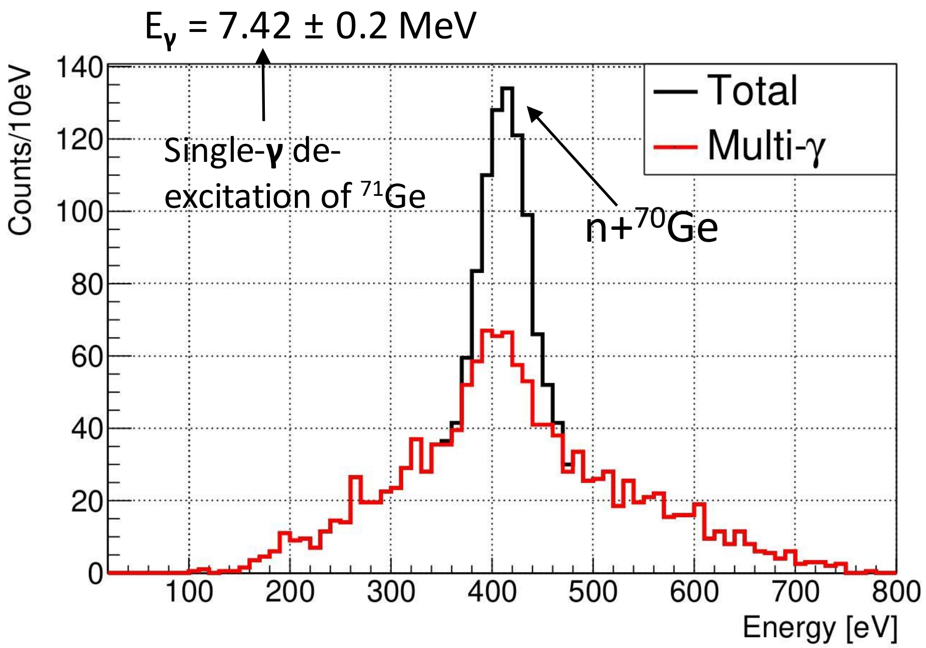
No resolution effect




With 20eV resolution




With resolution and **γ**-tagging




EDELWEISS (2cm length cube) cryodetector

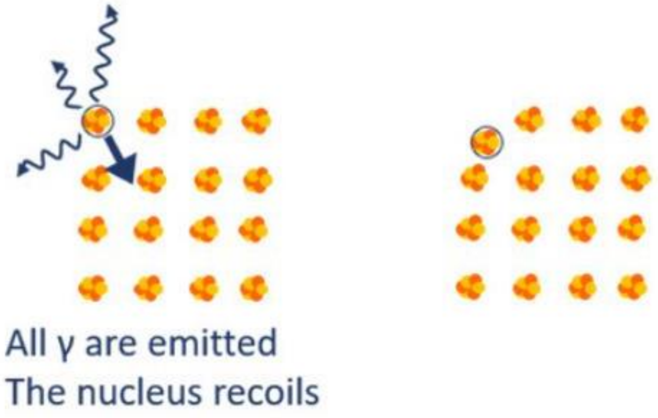
E. Armengaud et al. Phys. Rev. D, 99:082003, 4 2019

- Calibration peak @416eV
- Ionization should still be accessible --> could provide a NR/ER quenching measurement in a high-quenching region
- Further calibration perspectives using timing...

# CRAB 2 : timing effects

**Prompt hypothesis**

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

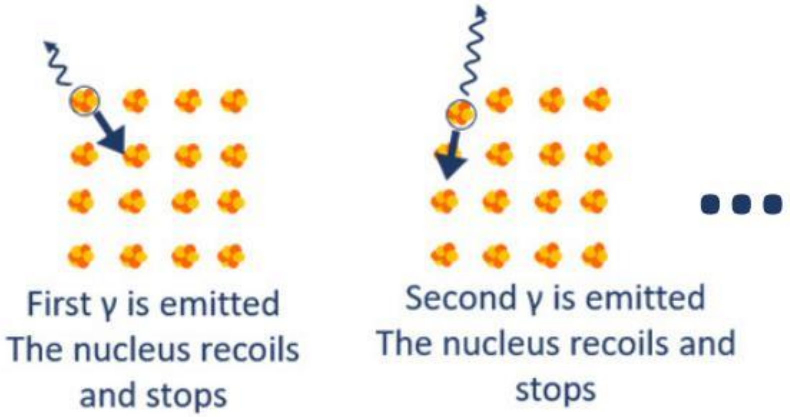



$$E_{recoil} = \left(\sum_\gamma \vec{p}_\gamma\right)^2 / 2M_{nucleus}$$

Continuum of possible recoil energies

**Slow hypothesis**

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




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

**Unique** recoil energy value per cascade

**FIFRELIN** coupled to **IRADINA** (Binary Collision Approximation code) to simulate in-flight **γ** emission

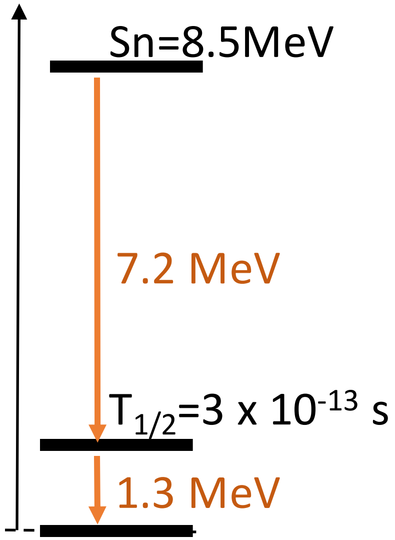
C. Borschel, C. Ronning/Nucl. Instrum. Methods B 269 (2011) 2133

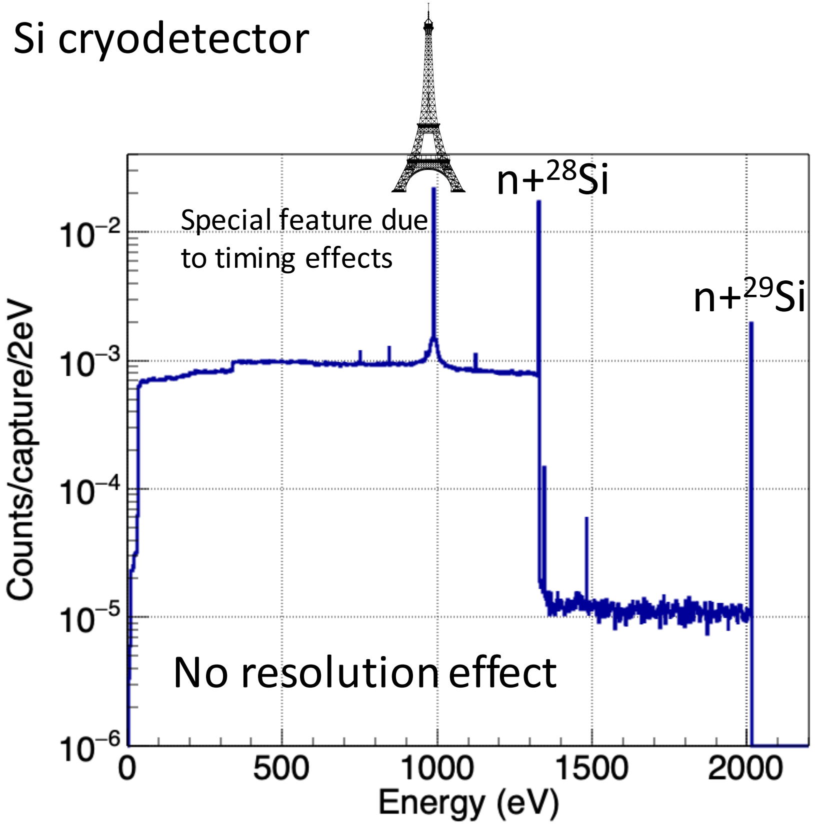
- Timing changes the energy deposited in the bolometer
- Single-γ calibration peaks are not affected

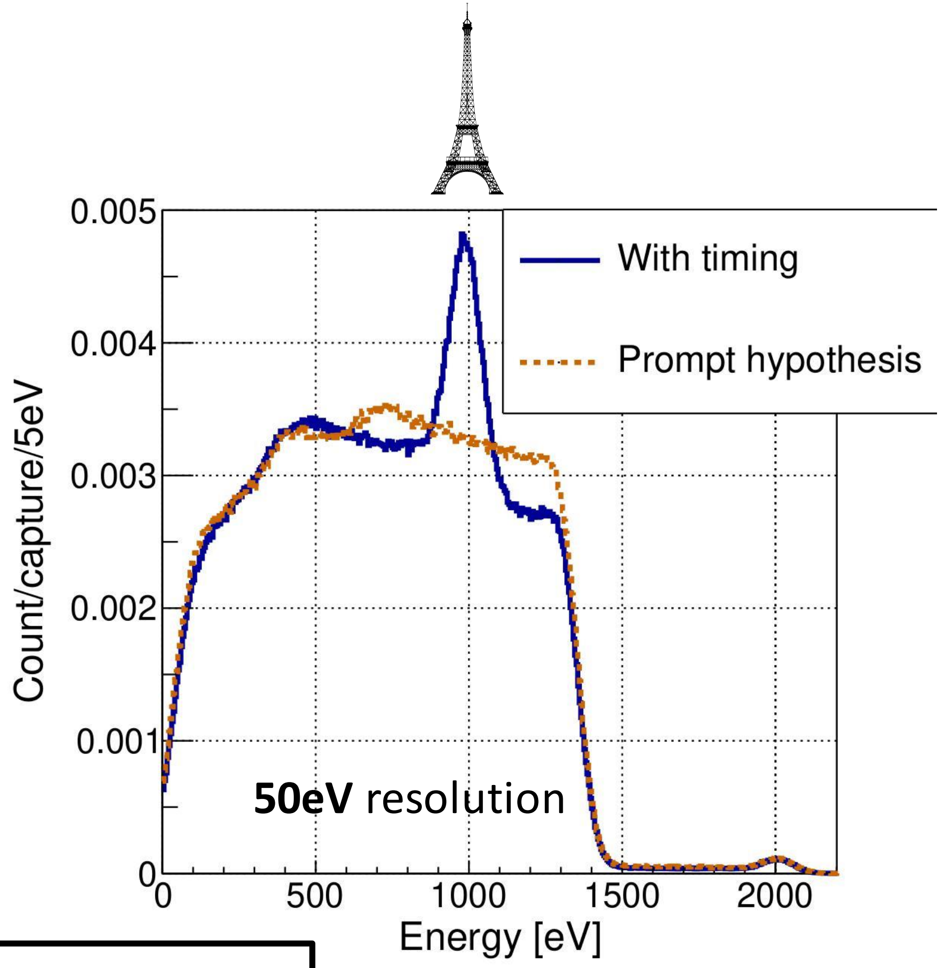
Similar study: *K. Harris, et al., arXiv:2302.02044, 2023*

# Timing effects in Silicon

Recoil energy spectra in a Si cryodetector




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

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

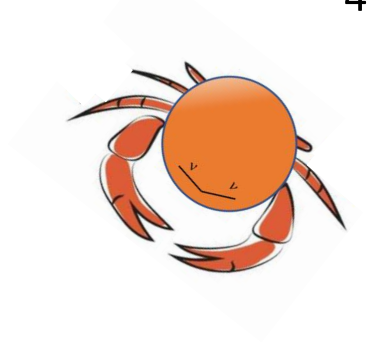
**Calibration feature**

- Present only when in-flight **γ**-emission is considered
- Detector with larger mass (and lower E resolution) can compensate for the low $\sigma_{capture}$

# Conclusion

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

- Proof of concept with portable thermal neutron source and NUCLEUS $CaWO_4$
  - **3σ** significance for 112eV peak from single-**γ** de-excitation of $n + {}^{182}W$
  - **6σ** significance for the contribution of CRAB events
  - In-situ calibration for cryodetectors



- High-precision measurements to come in Phase 2
  - pure thermal neutron beam
  - **γ**-tagging and timing effects: additional calibration features
    - extension to Ge, Si, $Al_2O_3$
    - Linearity, directionality studies, ...

# Back-up slides

# 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) | $E_\gamma$ (keV) | Nuclear Recoil (eV) |
|---|---|---|---|---|
| Ge | $^{70}Ge$<br>$^{74}Ge$ | 122<br>54 | 7416<br>6506 | 416.2<br>303.2 |
| Si | $^{28}Si$<br>$^{28}Si$ | 36<br>118 | 8473<br>7199+1273 | 1330<br>989.9 |
| $Al_2O_3$ | $^{27}Al$ | 616 | 7725 | 1145 |
| $CaWO_4$ | $^{182}W$<br>$^{183}W$<br>$^{186}W$ | 7506<br>823<br>281 | 6191<br>7411<br>5467 | 112.5<br>160.3<br>85.8 |

**Within reach of ionization channel Quenching studies**

**Interesting cases of 2γ transitions**

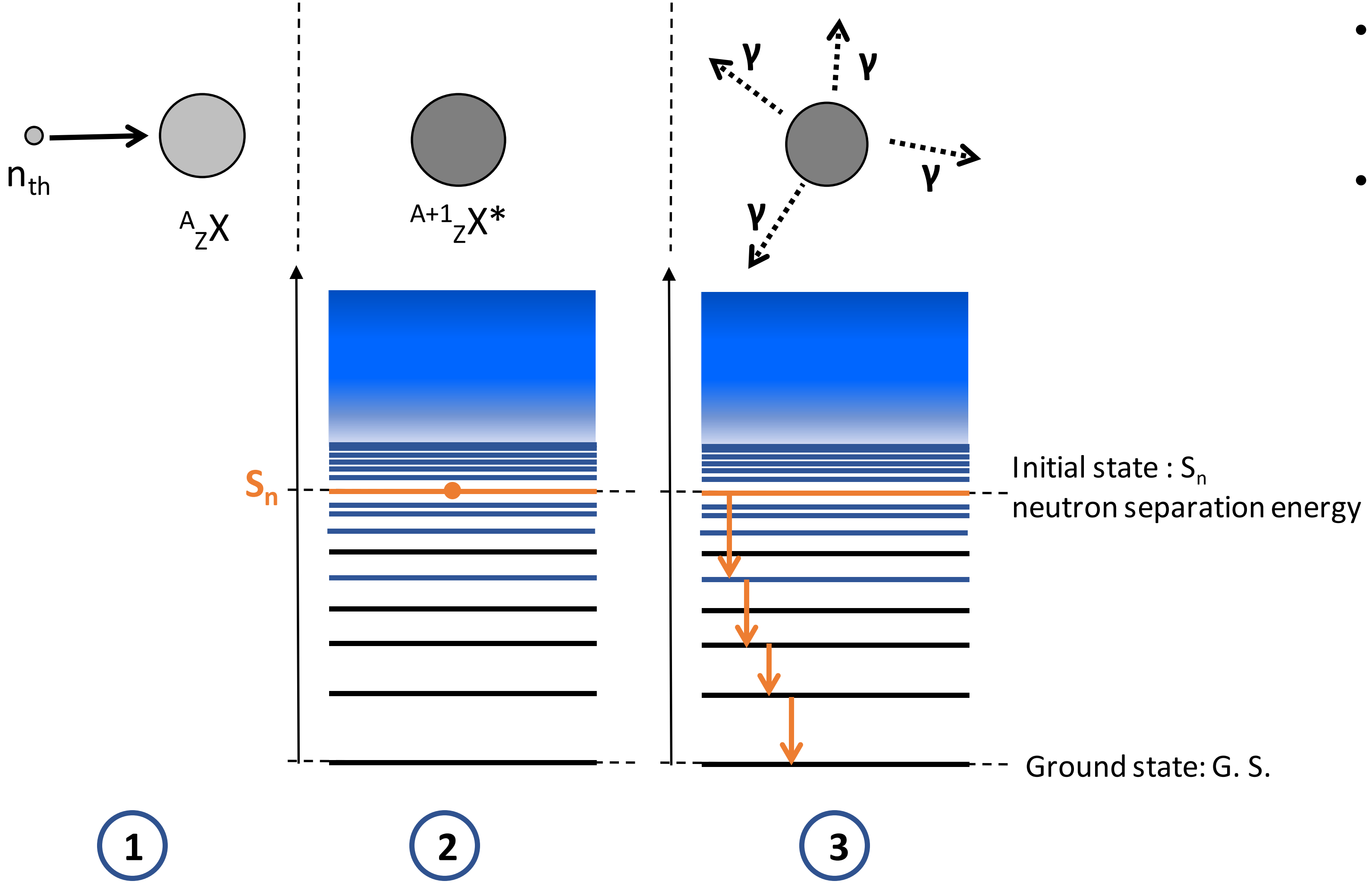
**Strongest single-γ transition**

**Large F.O.M**
**3 peaks -> Linearity study**

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

# 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.

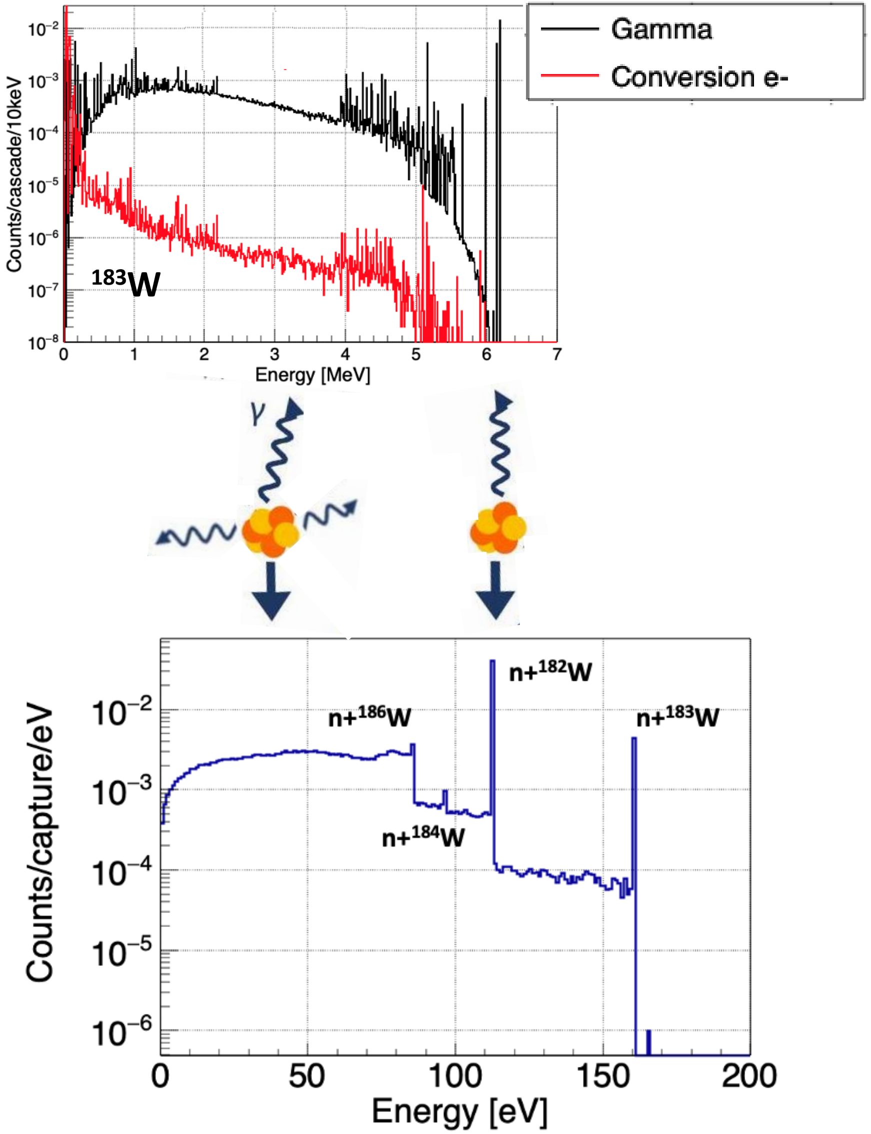
# Accurate description of the recoil spectrum

- 1**γ** de-excitations : calibration peak

- Multi **γ** de-excitations : recoil energy depends on **γ** energies and relative directions
  --> recoil energy continuum

- **FIFRELIN:** fine predictions of de-excitation cascades [O. Litaize et al., Eur. Phys. J. A (2015) 51: 177]

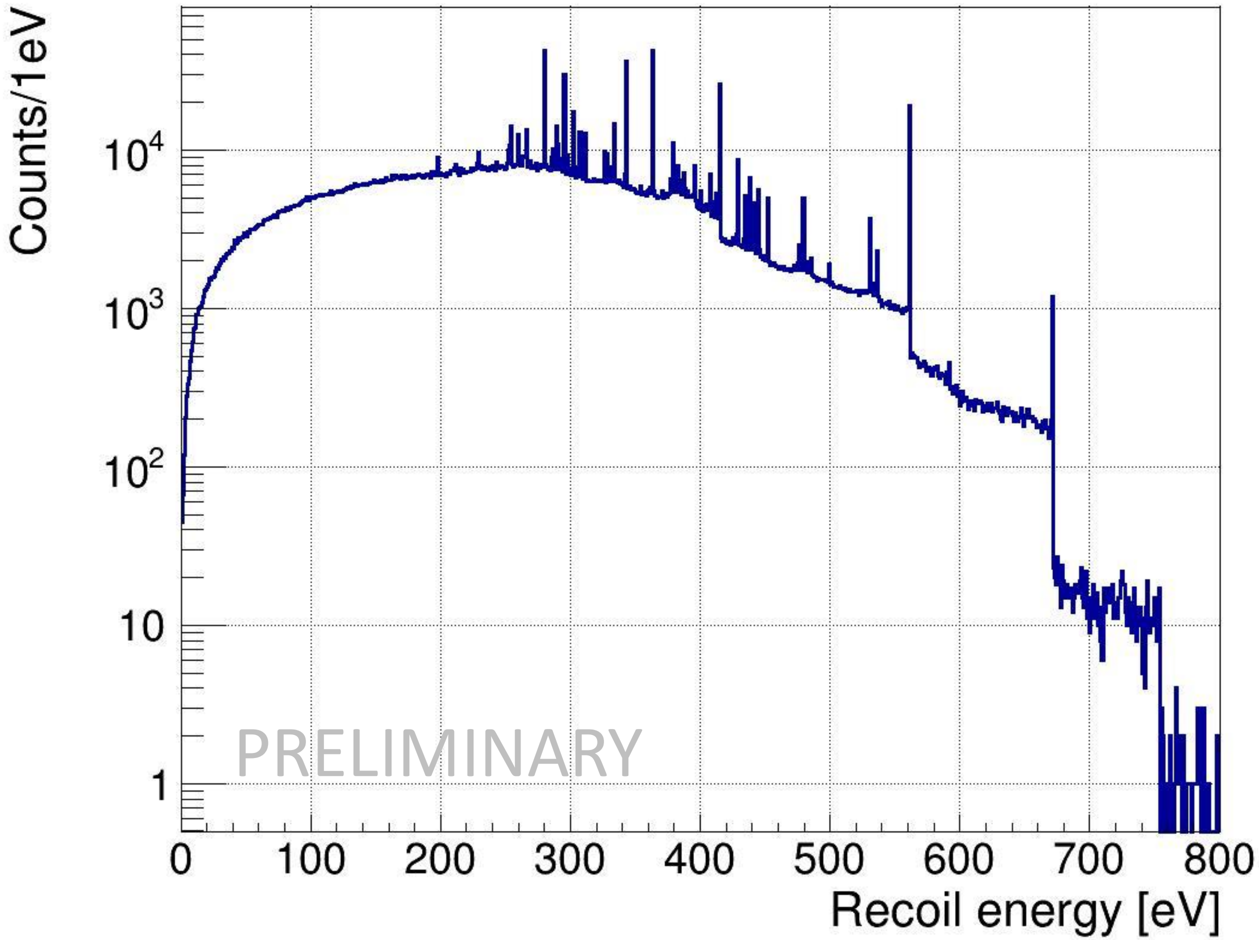
- Lower energy **γ** and conversion electrons can saturate the detector with energy deposition above 1keV
  --> limit the acceptable neutron flux
  --> no direct impact on calibration peaks



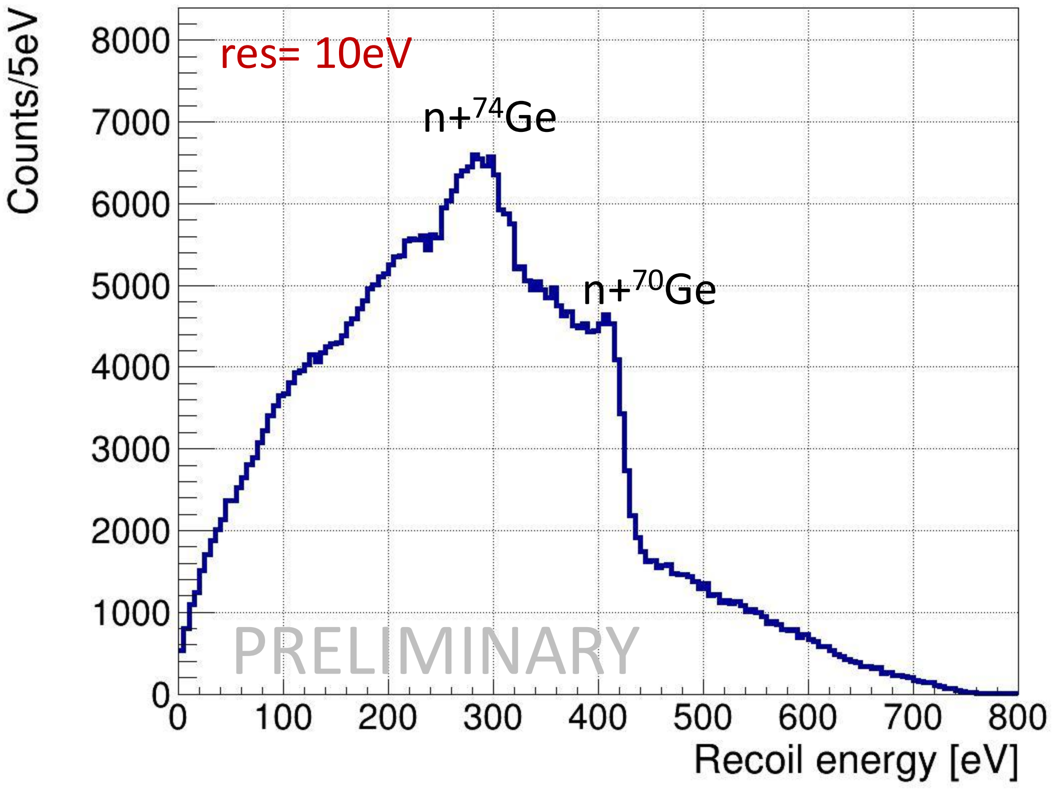

Simulation, GEANT4+FIFRELIN

# Timing effects in Germanium

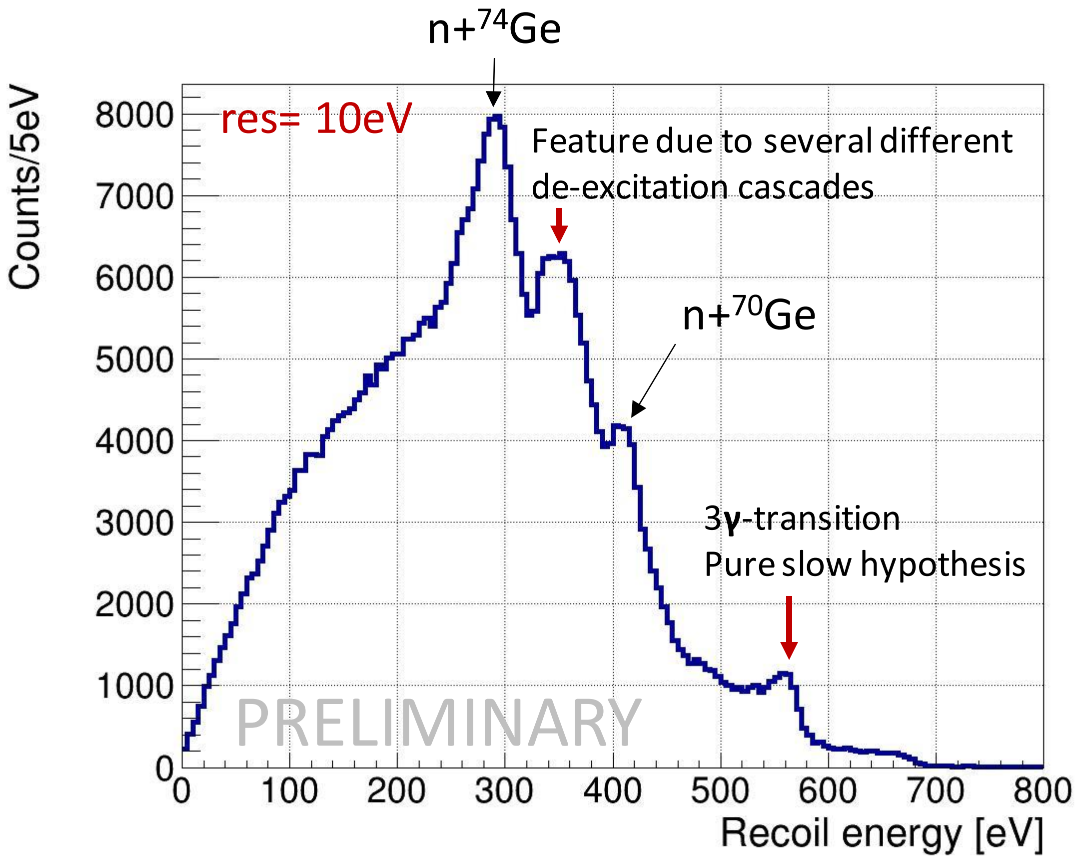
**In-flight γ**-emission
No resolution effect



# Timing effects in Germanium



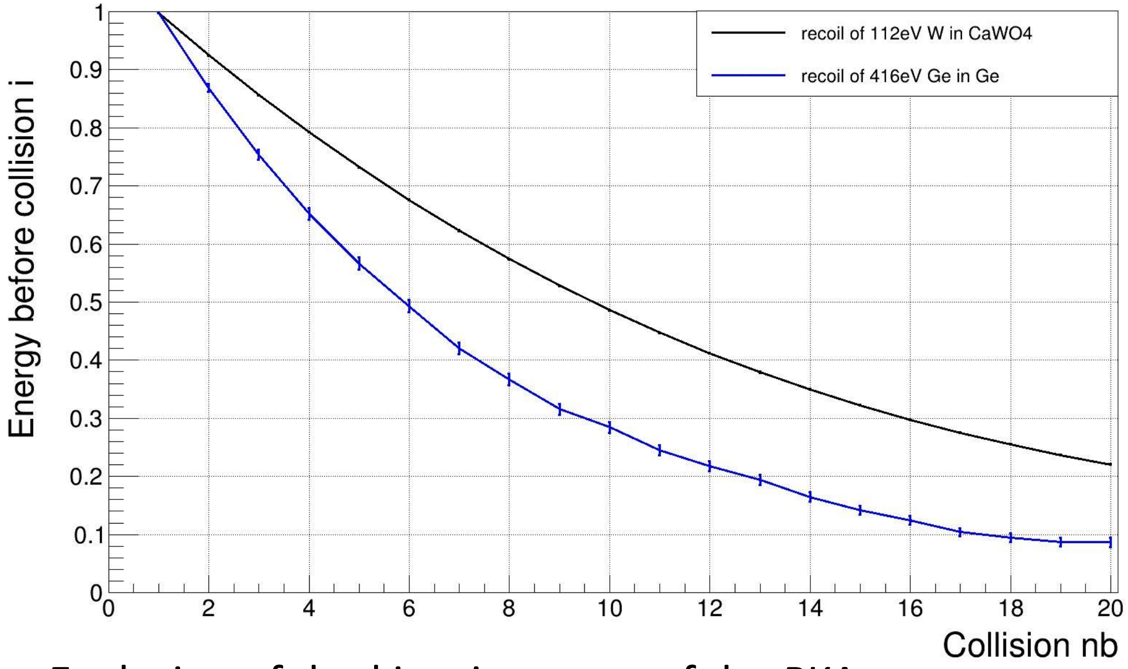

**Prompt hypothesis:** $\tau_\gamma << \tau_{recoil}$



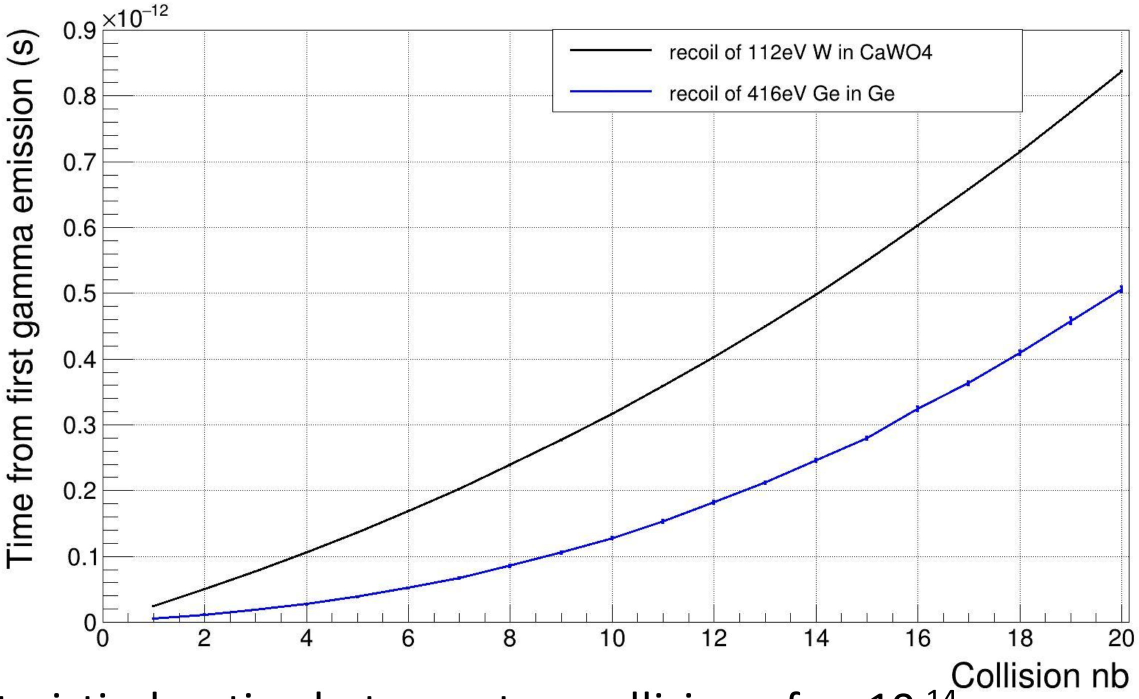

**In-flight γ**-emission

# 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

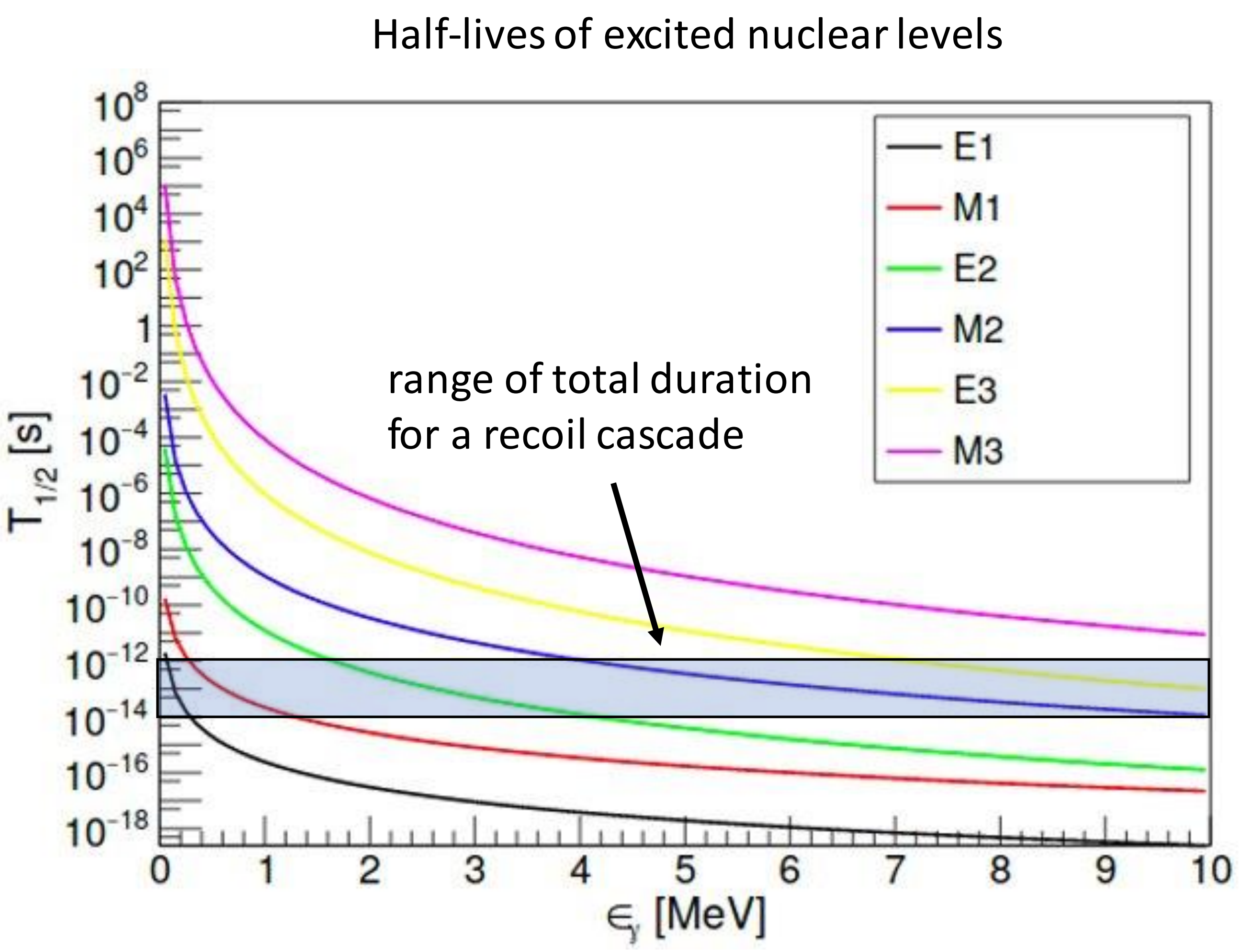



Evolution of the kinetic energy of the PKA, collision after collision
Renormalization to initial recoil energy




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




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