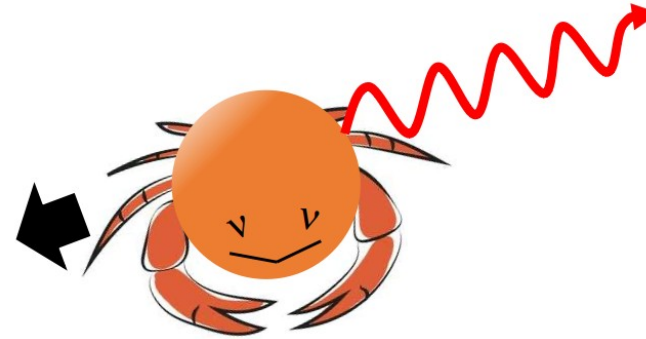




irfu



First experimental study of the startpoint of ^{28}Al β^- decay with the CRAB facility

Corentin Doutre, PhD student - CEA Saclay/DRF/IRFU/DPhN - corentin.doutre@cea.fr

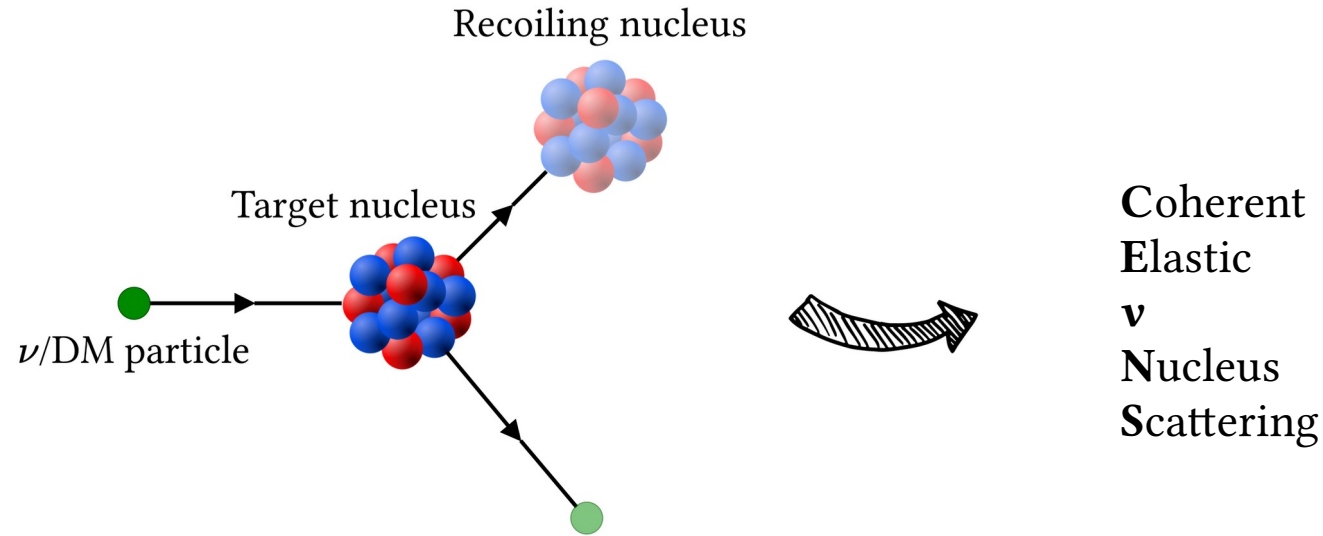
ESNT Workshop – 24/09/2026



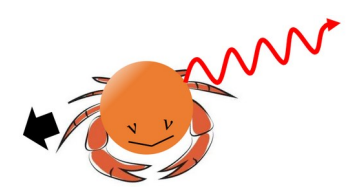
Marietta Blau
Institute for
Particle Physics



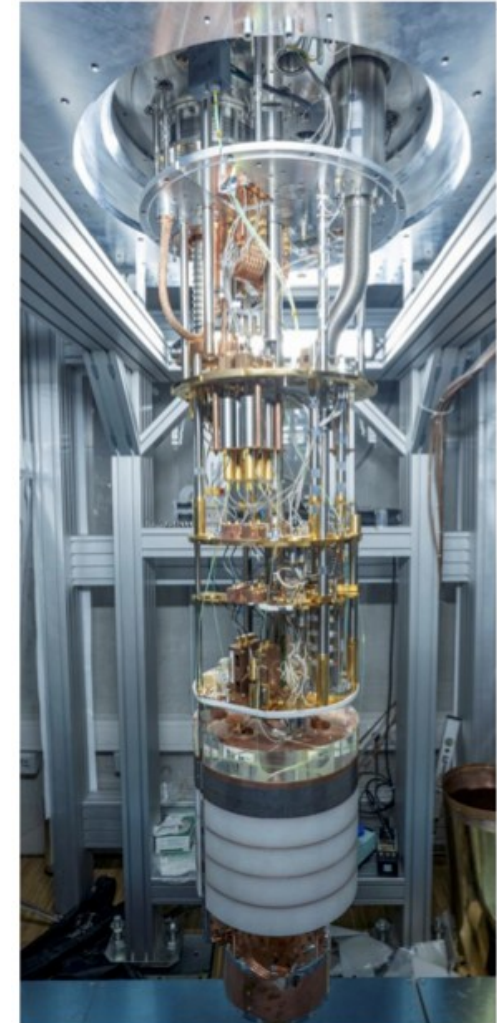
Low-energy nuclear recoils



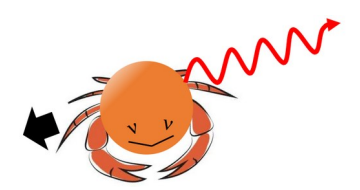
- NUCLEUS experiment (DPhP/DPhN)
 - look for CEvNS with reactor anti- ν at Chooz power plant in France
 - **test the Standard Model at very low energy**
- Detection is very challenging
 - **signal = nuclear recoil in [100 - 1000] eV range**
- **Need precise characterization of the detector response to sub-keV nuclear recoils**



Nucleus's cryostat

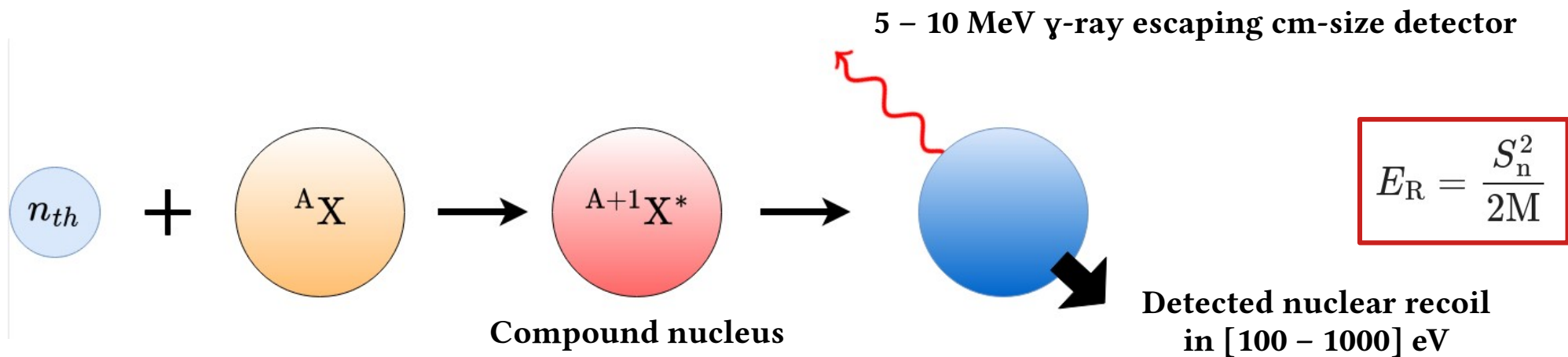


CRAB calibration method



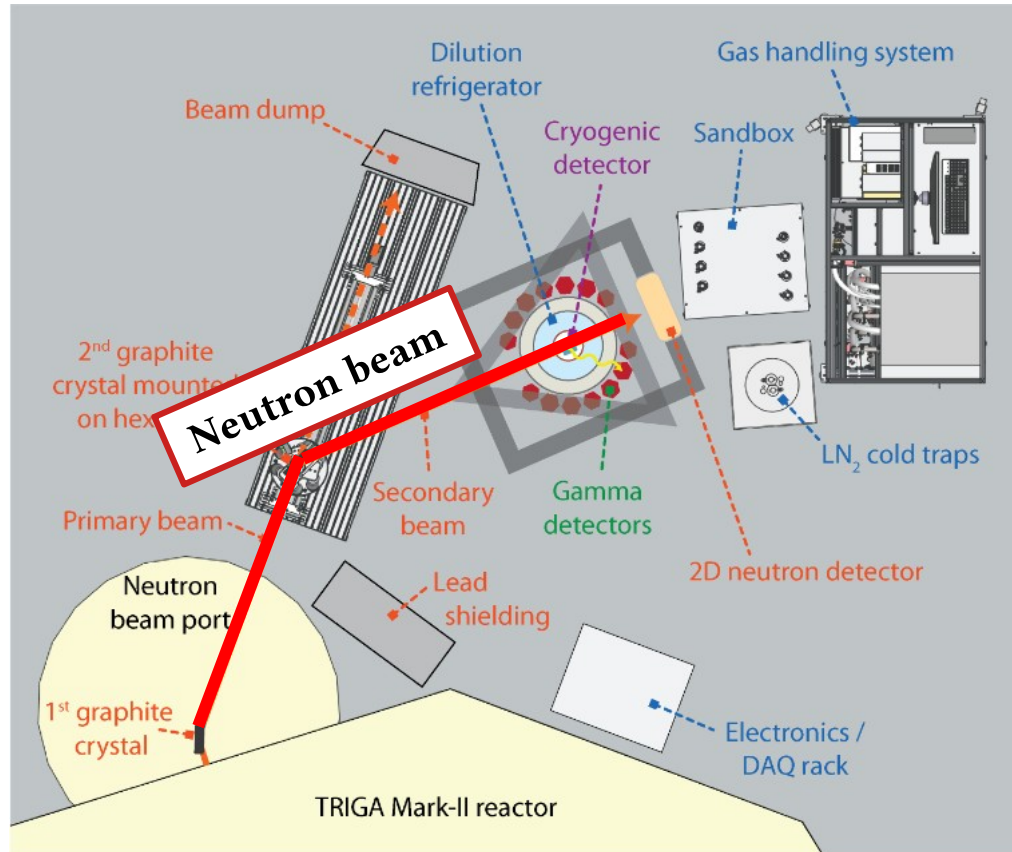
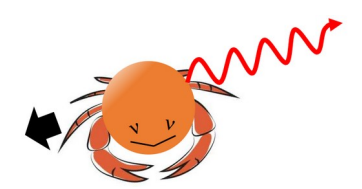
Calibration
Recoil for
Accurate
Bolometry

- CRAB = **ONLY** method that :
 - **Induces pure nuclear recoils**
 - **Probes the whole detector volume**
 - **Scans the [100 – 1000] eV energy range**

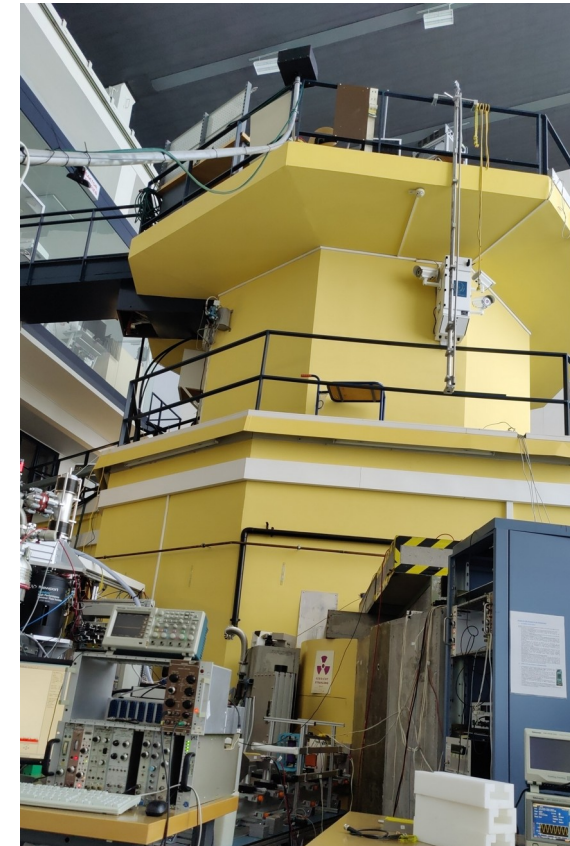


→ Suitable for most of the detectors used in the CEvNS/DM communities (CaWO₄, Al₂O₃, Ge, Si)

Experimental setup : neutron source

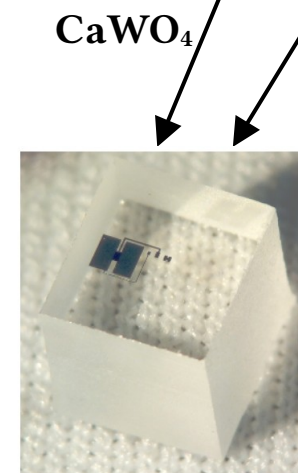
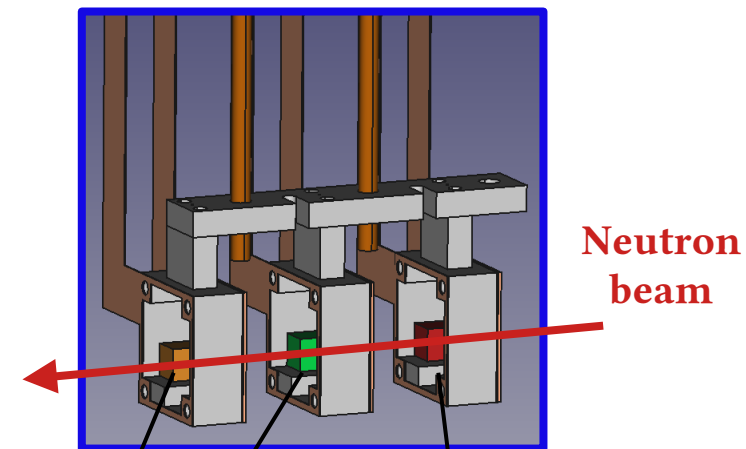
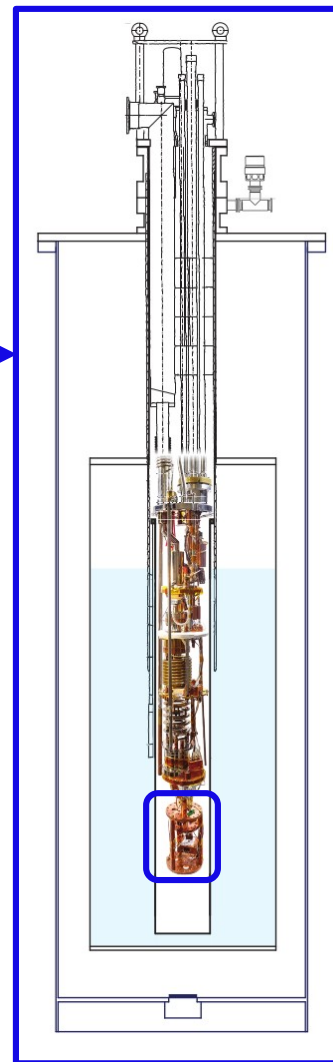
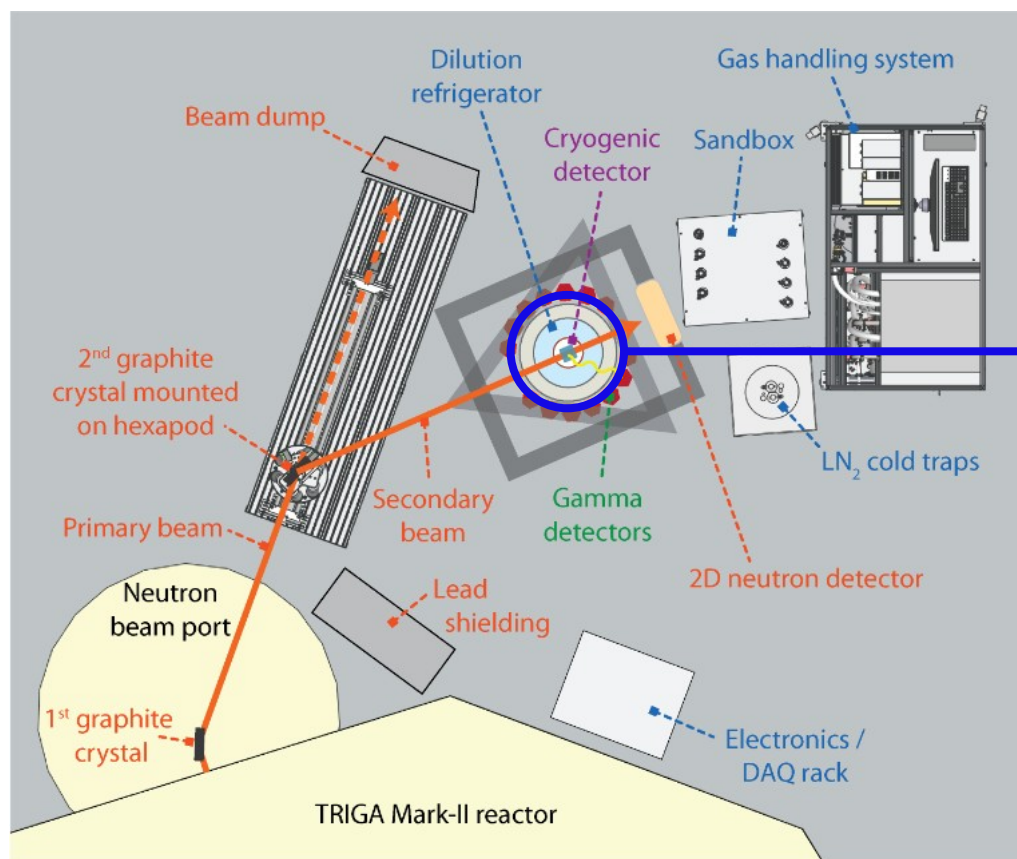


- **Collimated beam of thermal neutrons** from TRIGA Mark-II research reactor (250 kW)



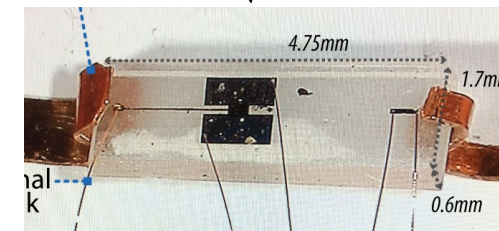
Experimental setup : cryostat

→ Wet dilution cryostat with base temperature < 10 mK



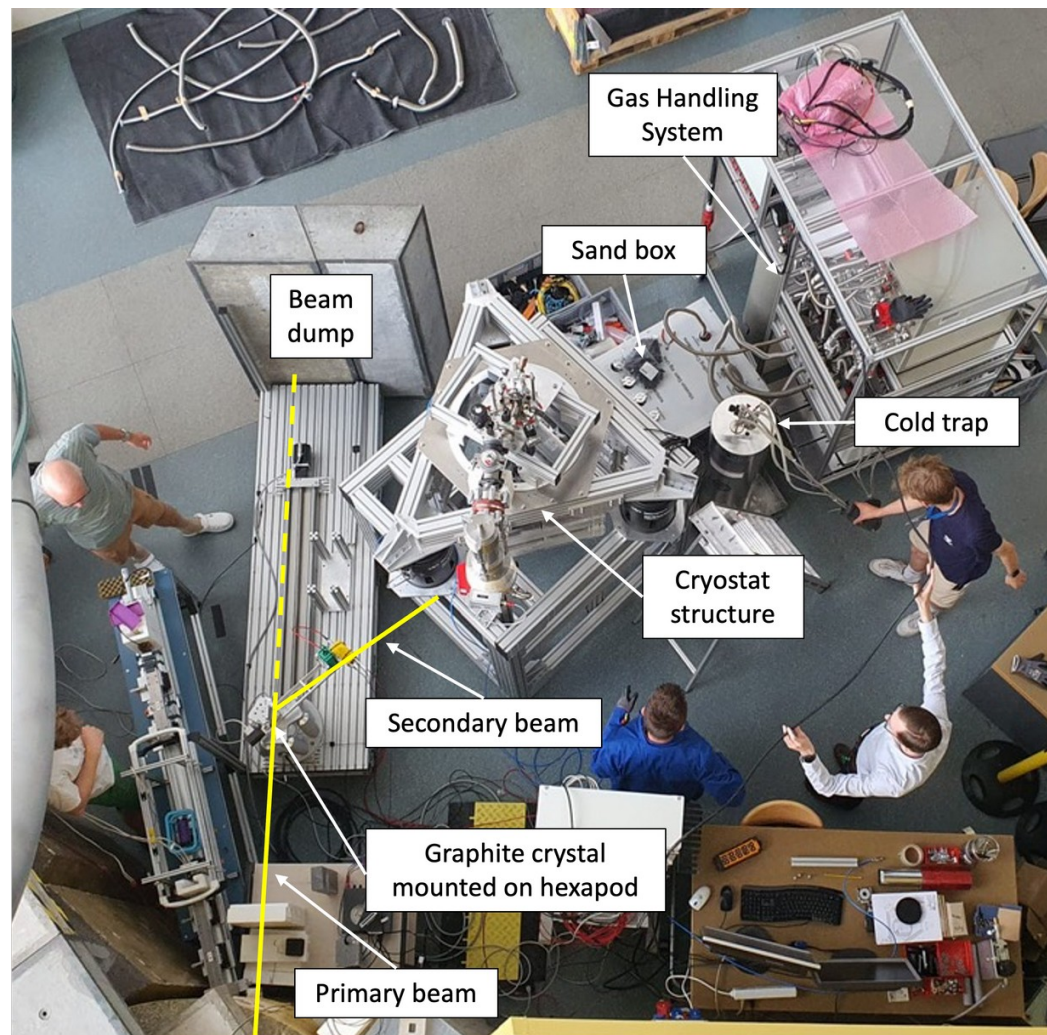
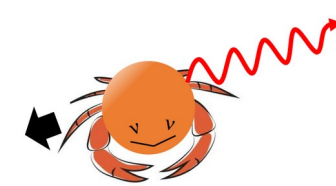
5×5×5 mm³

CaWO₄: 0.67 g, Al₂O₃: 0.5 g

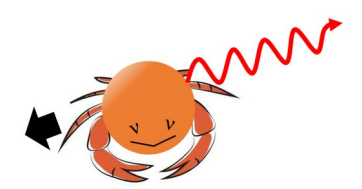


4.75×1.7×0.6 mm³
0.03 g

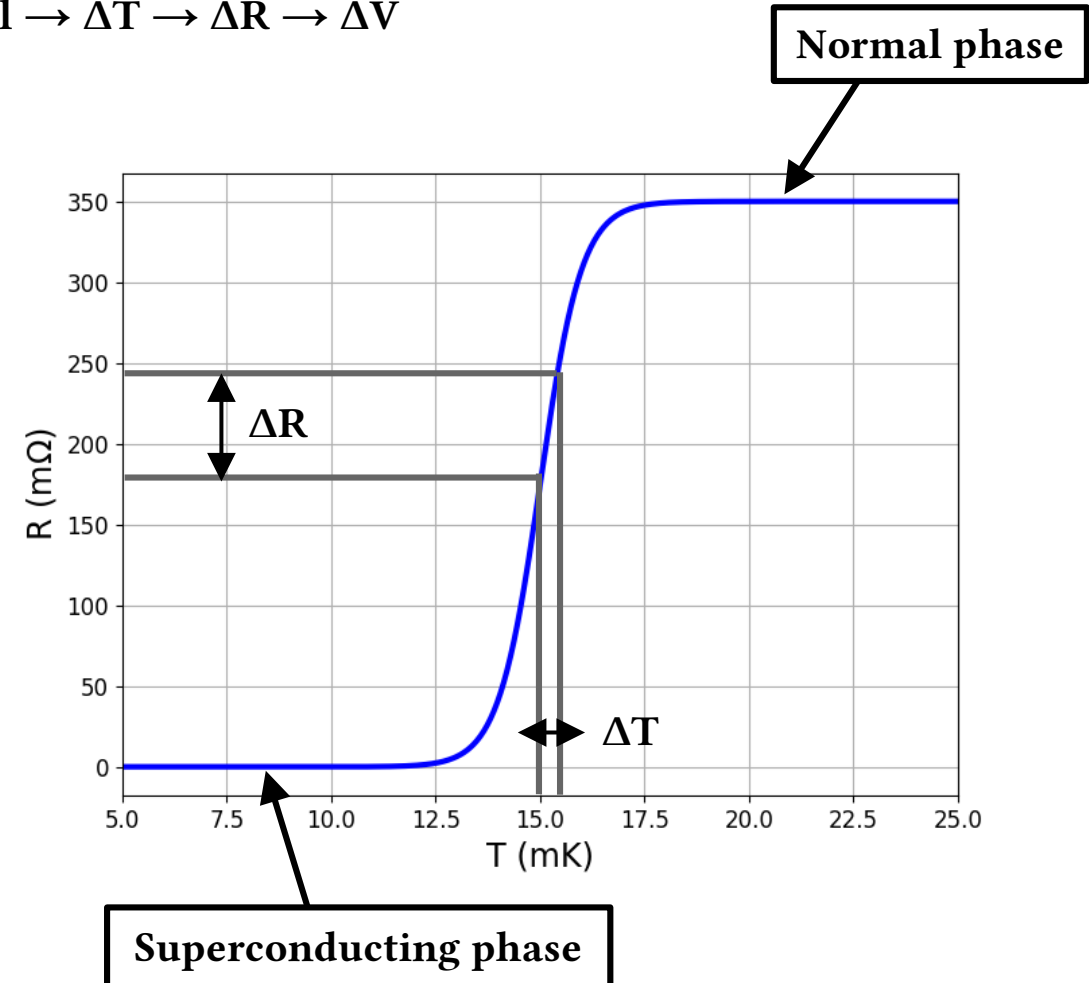
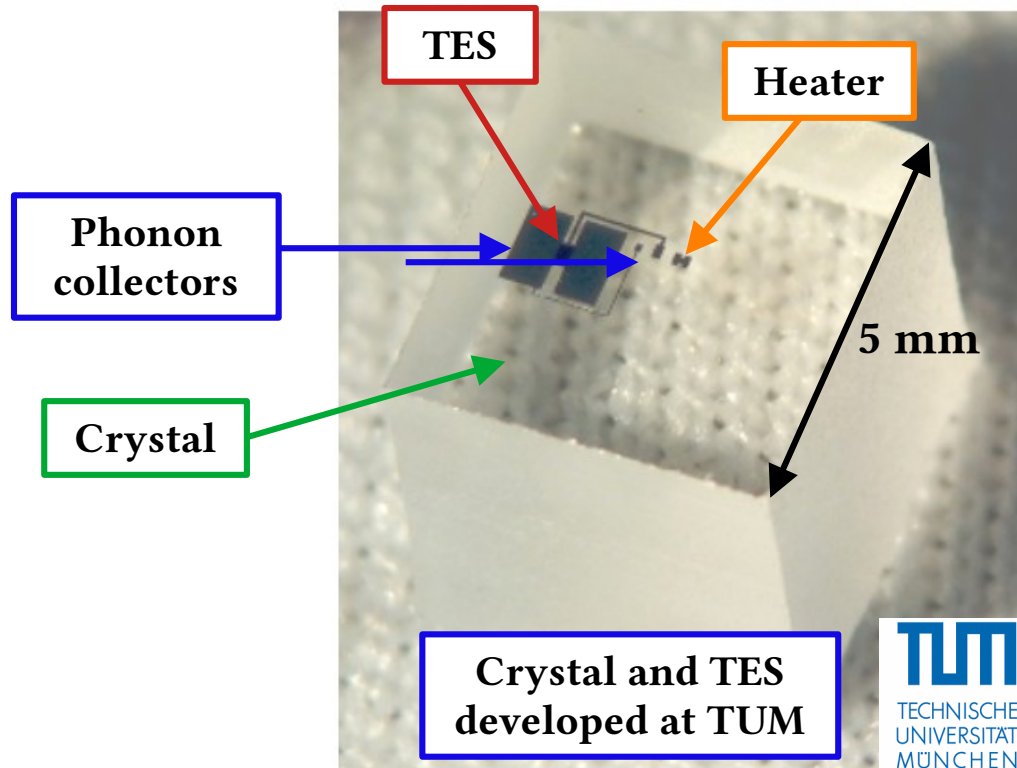
Top view from the setup



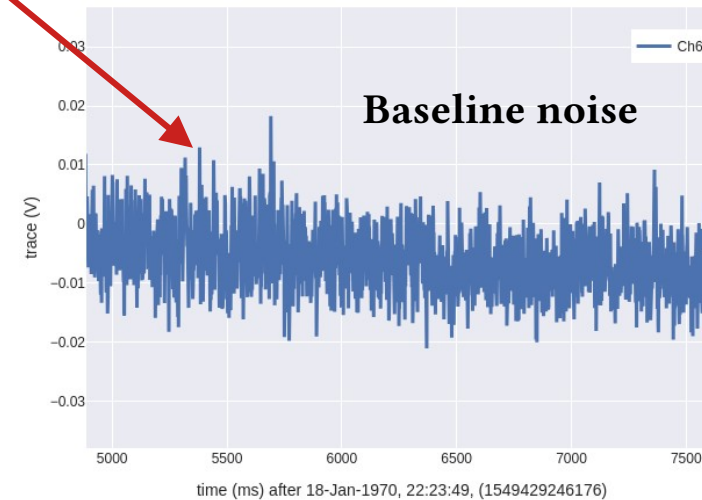
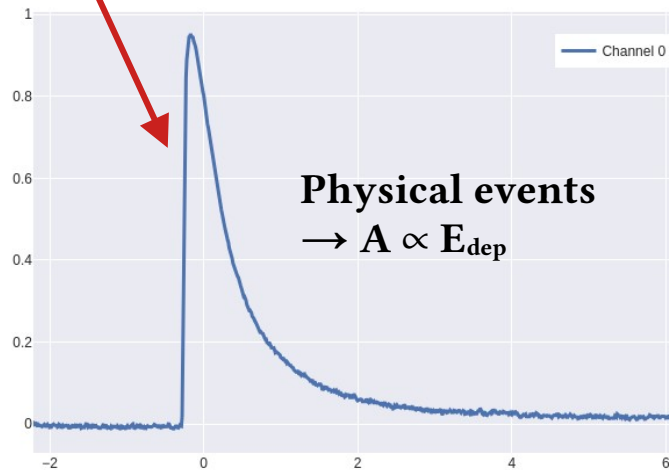
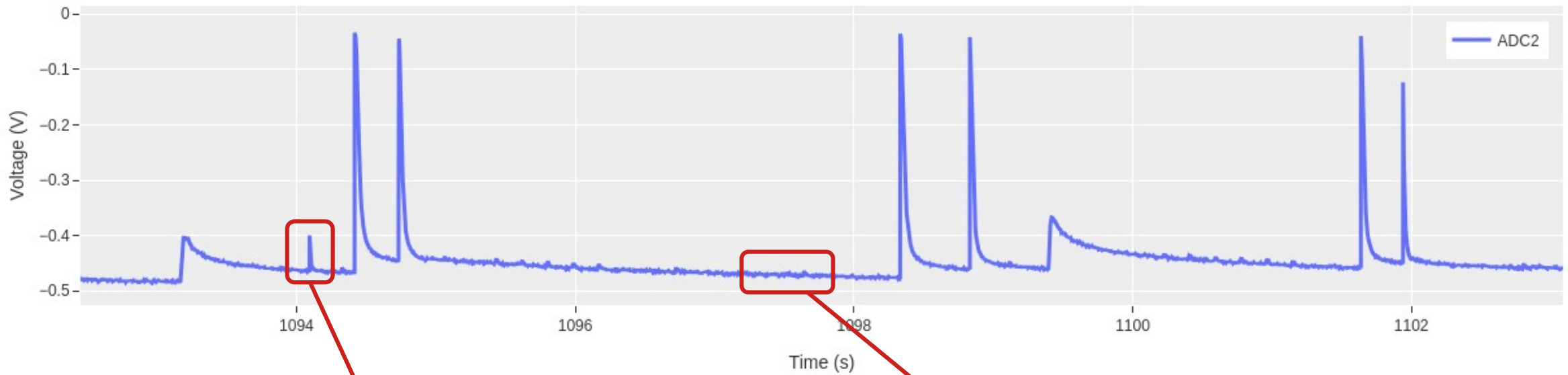
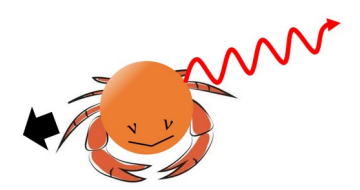
Cryogenic detector with Transition Edge Sensor



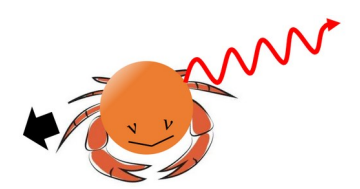
- Gram-scale bolometer cooled down to ~ 10 mK $\rightarrow$ **20 eV energy threshold and few eV resolution**
- Energy deposition in the absorber via **phonon channel** $\rightarrow \Delta T \rightarrow \Delta R \rightarrow \Delta V$



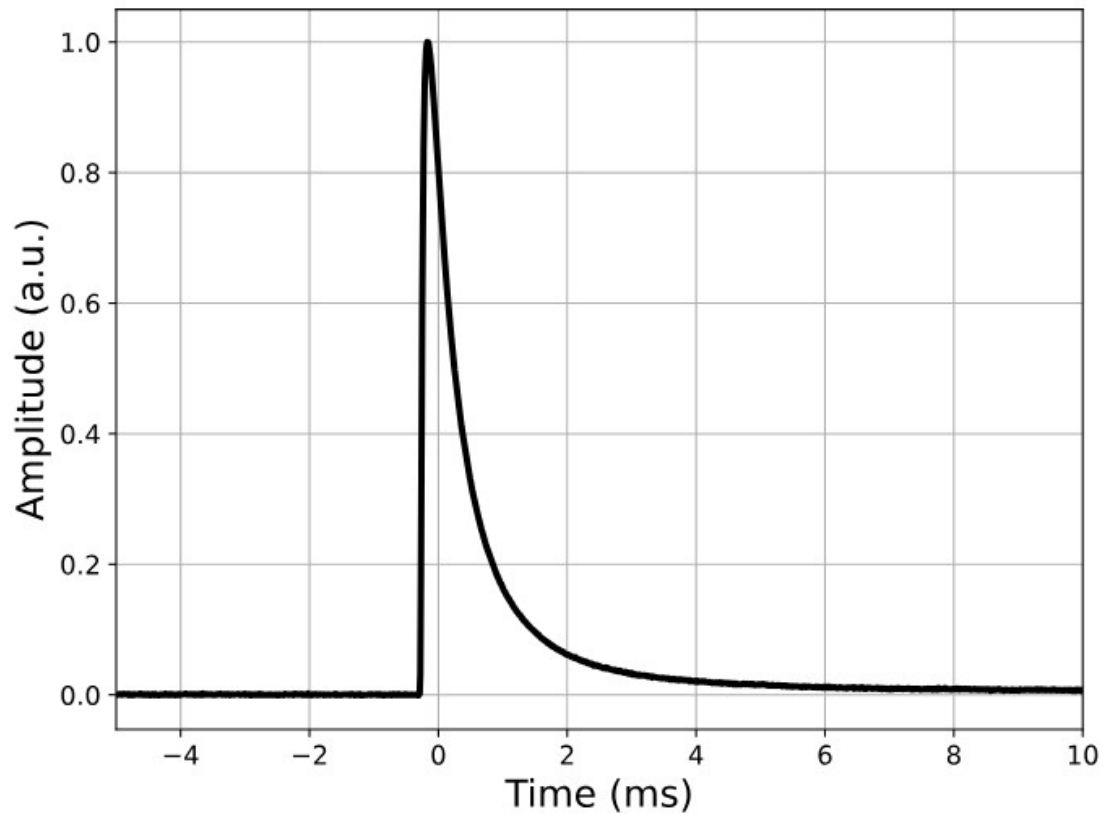
Cryogenic data processing – Data stream



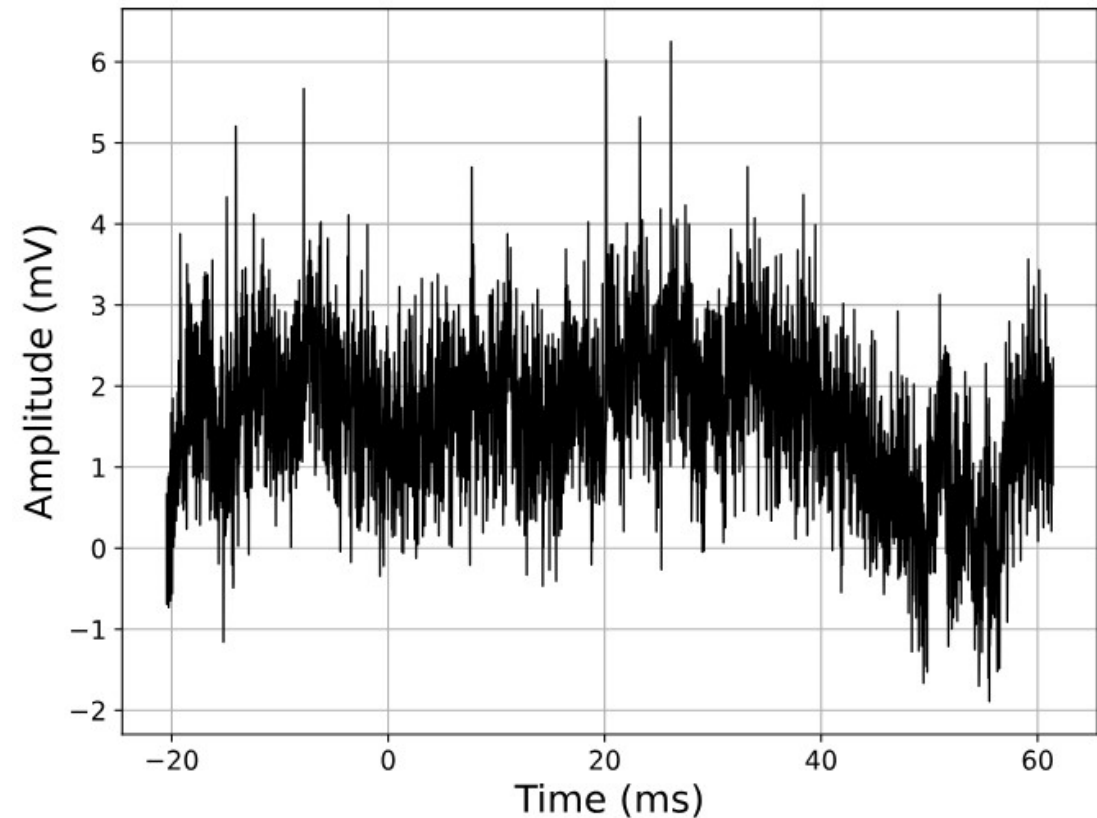
Cryogenic data processing – Time domain



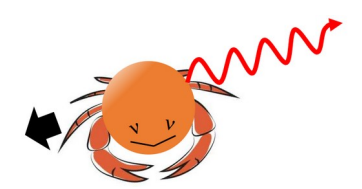
- Construction of a **Standard Event (SEV)** from a collection of non-saturated pulses



- Collection of **clean noise traces** (without artefacts)

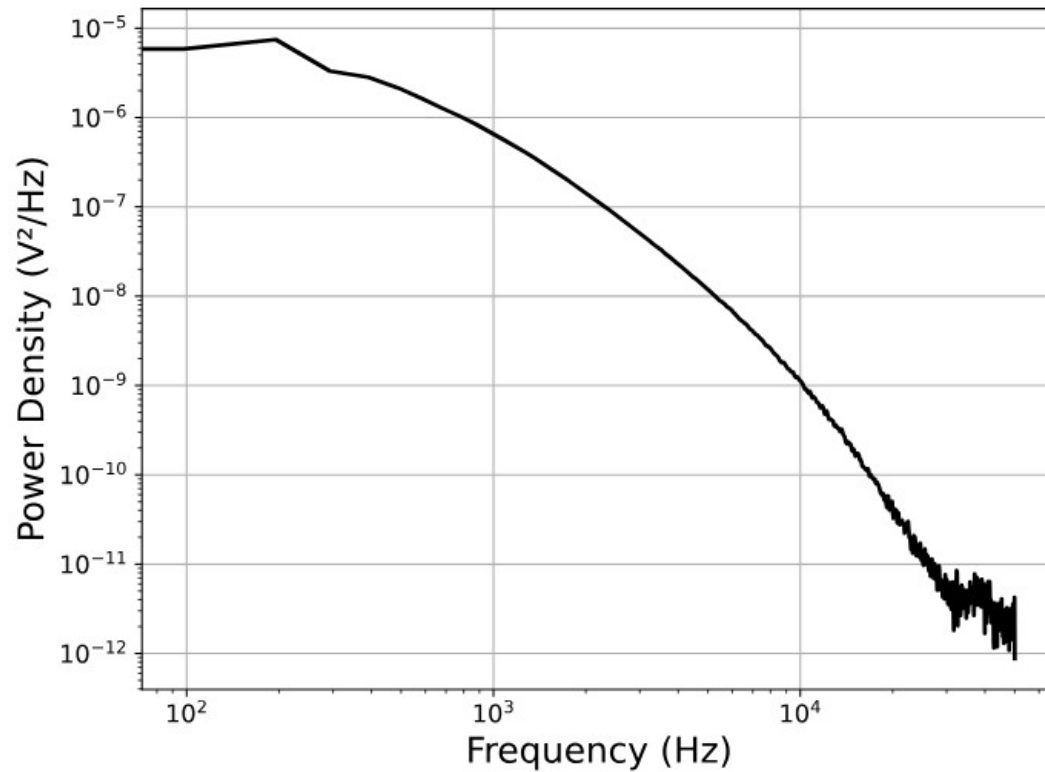


Cryogenic data processing – Frequency domain

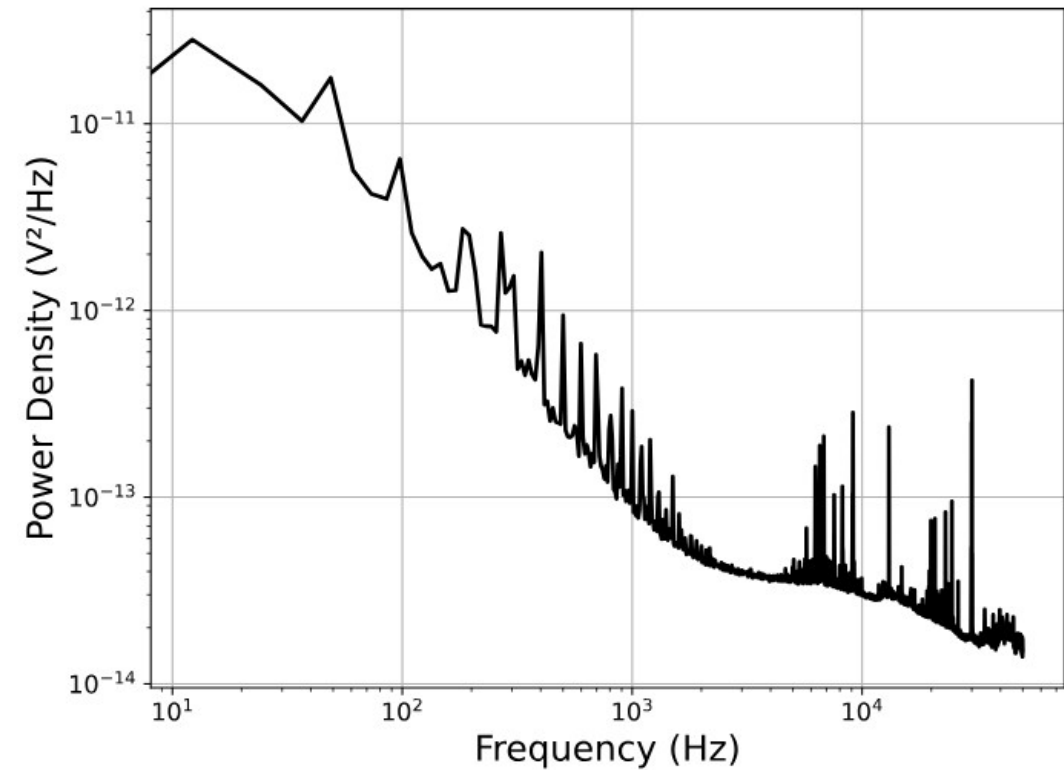


- Fourier analysis of SEV and noise traces

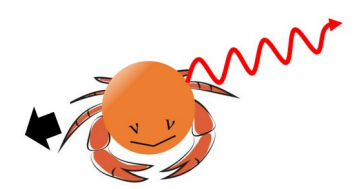
→ Standard Event



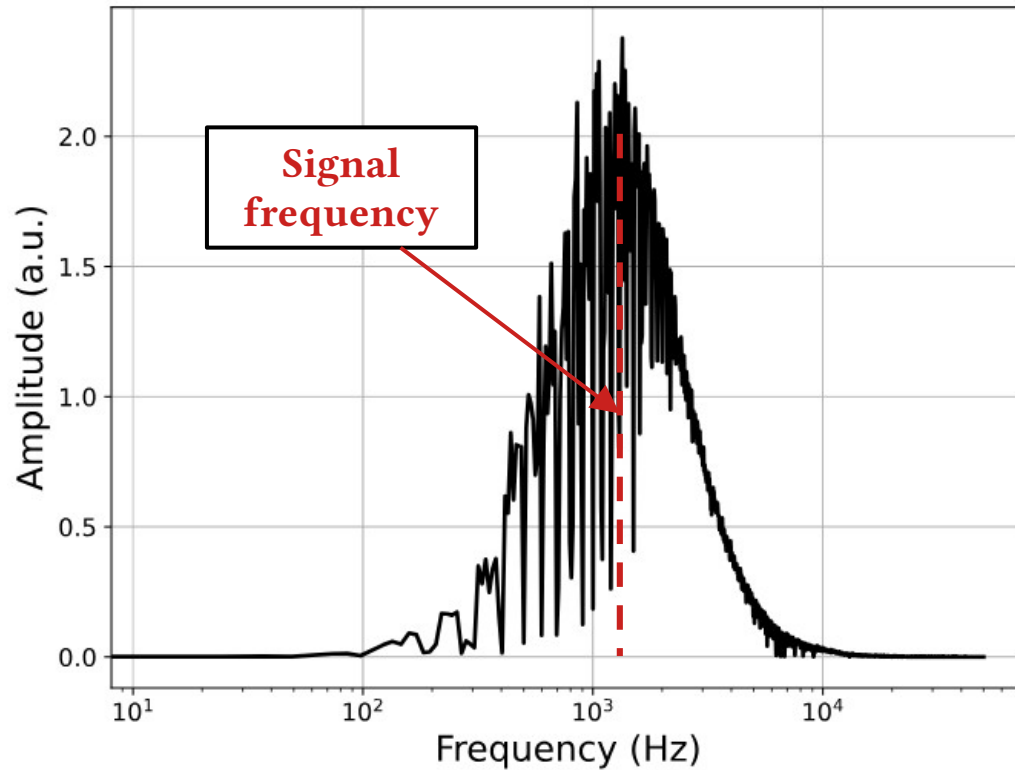
→ Noise Power Spectrum



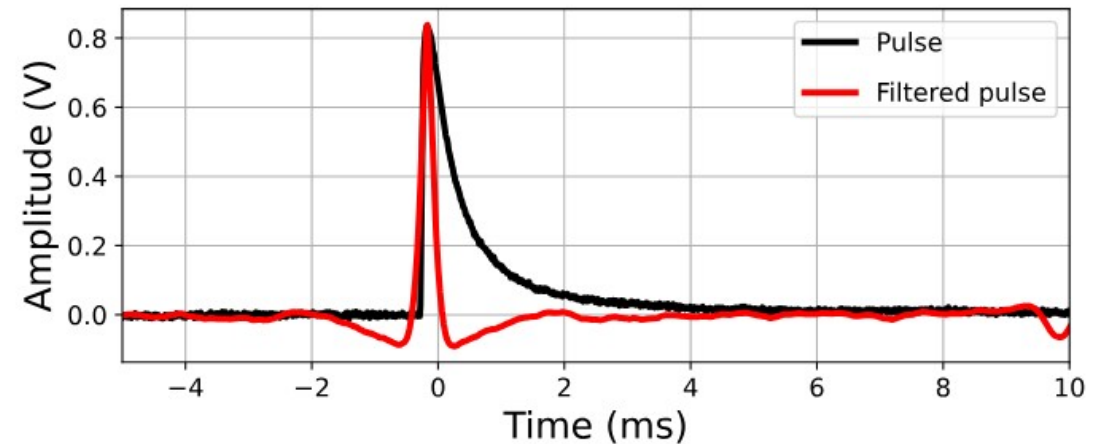
Cryogenic data processing – Optimal Filter analysis



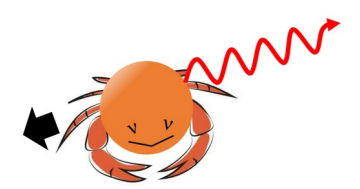
Transfer function of Optimal Filter



- Construction of an **Optimal Filter (OF)**
 - increase signal-to-noise ratio
 - lower the threshold
 - better energy resolution
 - robust estimation of the pulse amplitude

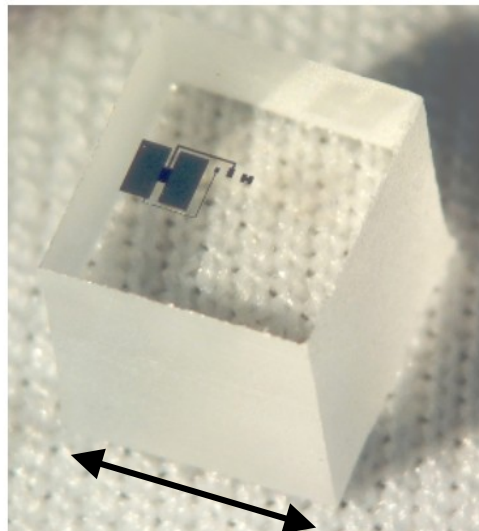


Nuclear recoil spectrum in Al_2O_3

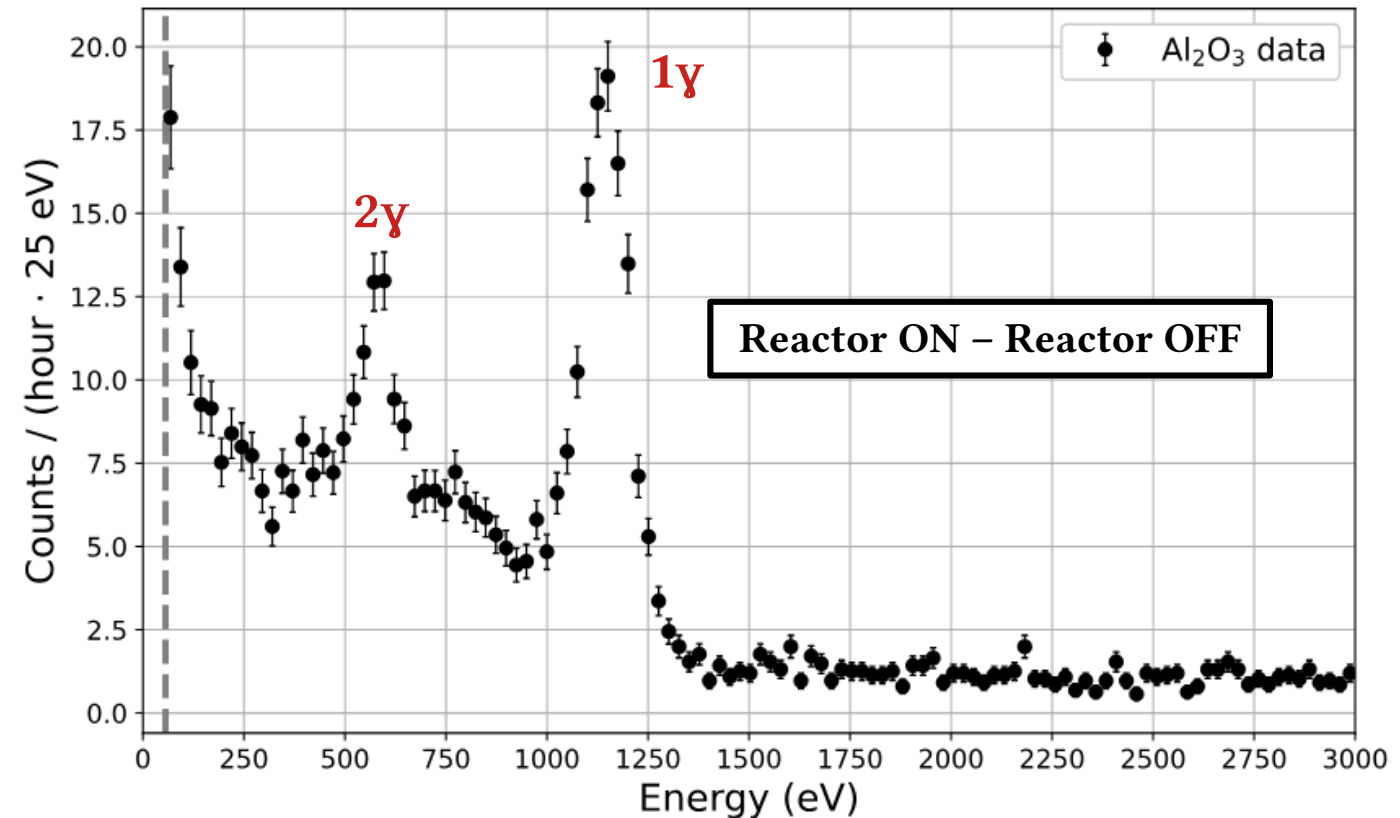
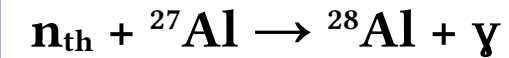


- 25 h of stable data with a $5 \cdot 5 \cdot 5 \text{ mm}^3$ Al_2O_3 cryodetector
- Excellent baseline resolution :
 - $\sigma_{\text{BR}} = 5.5 \text{ eV}$
 - analysis threshold = 56 eV

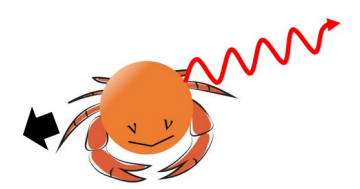
Al_2O_3 cube



5 mm



Timing effects in Al_2O_3



Phys. Rev. D 108, 072009

- Timing effects = interplay between
 - emission time of γ -rays in the nuclear deexcitation cascade
 - duration of the nuclear recoil in matter

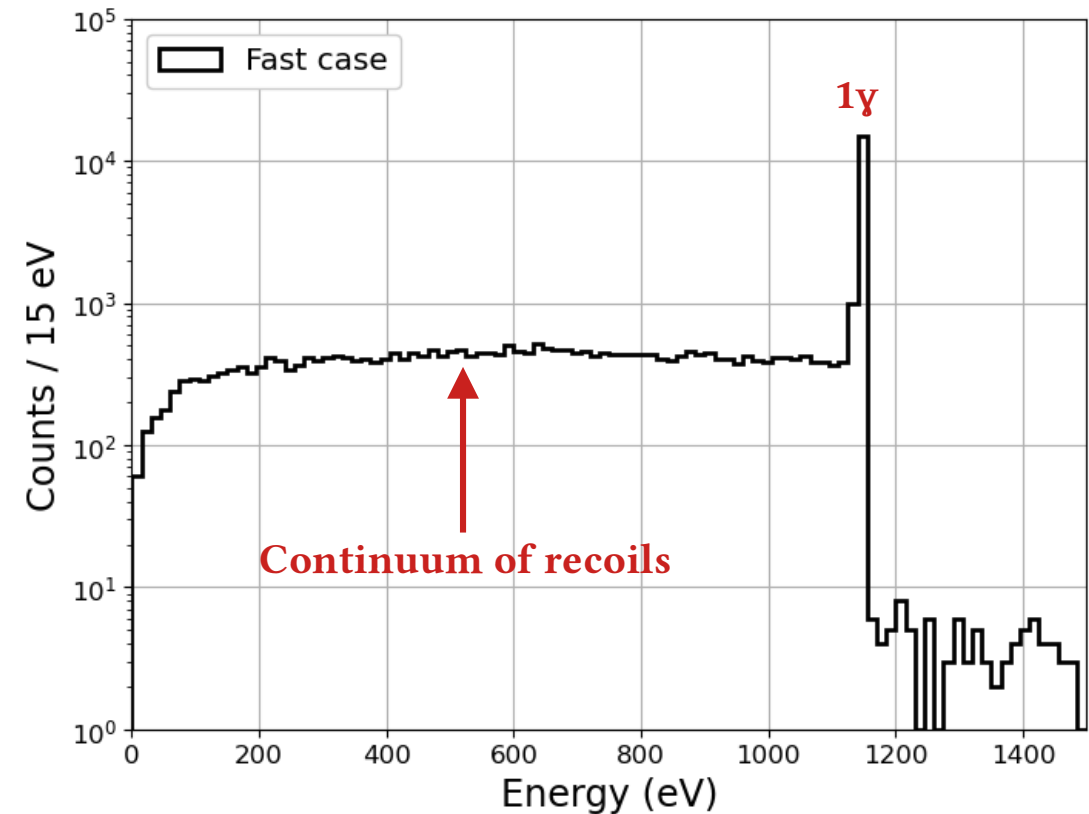


$$E_R = \frac{E_{\gamma_1}^2 + E_{\gamma_2}^2 + 2 \cos(\theta) \cdot E_{\gamma_1} E_{\gamma_2}}{2M}$$

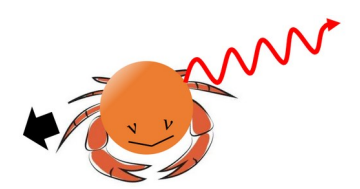
All γ are emitted
The nucleus recoils

→ FAST : E_{dep} depends on γ -rays direction

No energy resolution

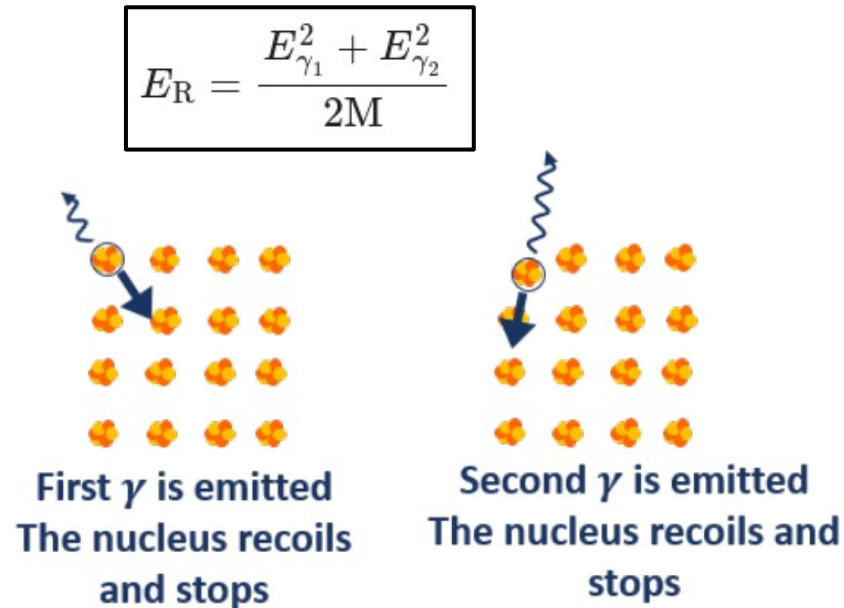


Timing effects in Al_2O_3



Phys. Rev. D 108, 072009

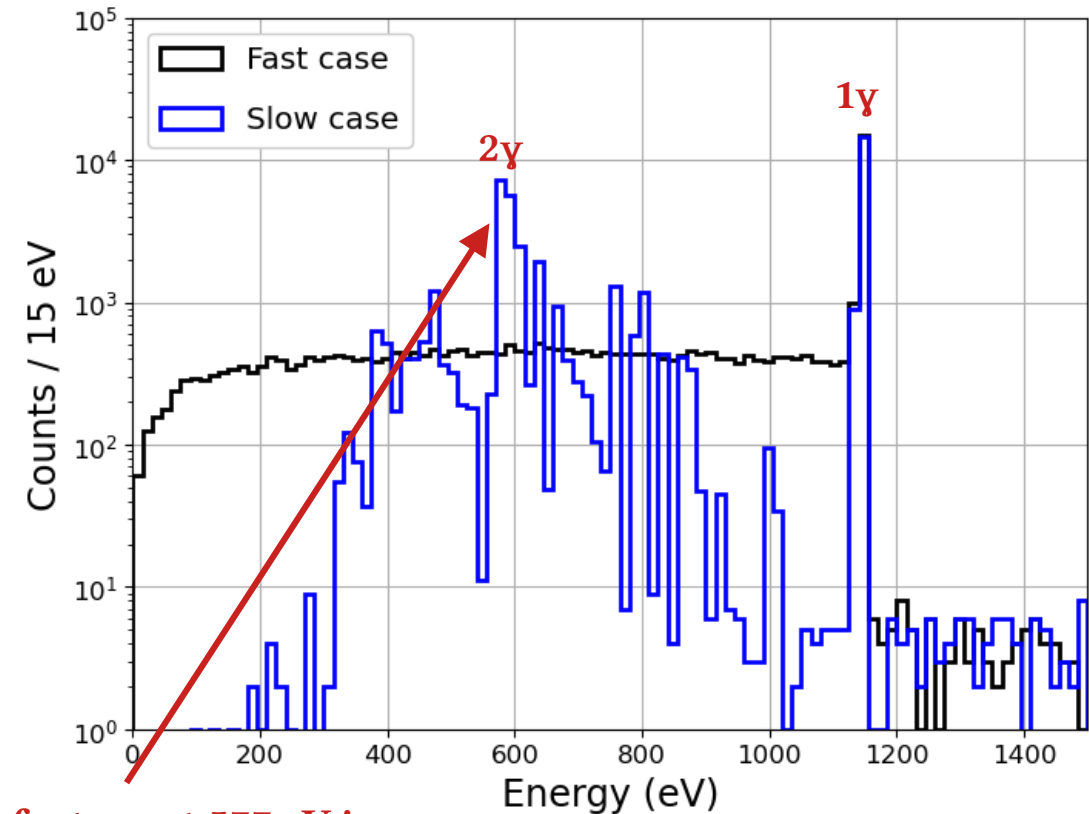
- Timing effects = interplay between
 - emission time of γ -rays in the nuclear deexcitation cascade
 - duration of the nuclear recoil in matter



$$E_R = \frac{E_{\gamma_1}^2 + E_{\gamma_2}^2}{2M}$$

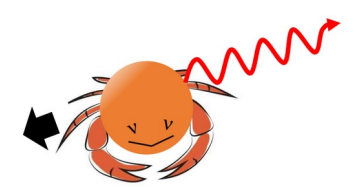
→ SLOW : E_{dep} is fixed

No energy resolution



New calibration feature at 577 eV !

Timing effects in Al_2O_3

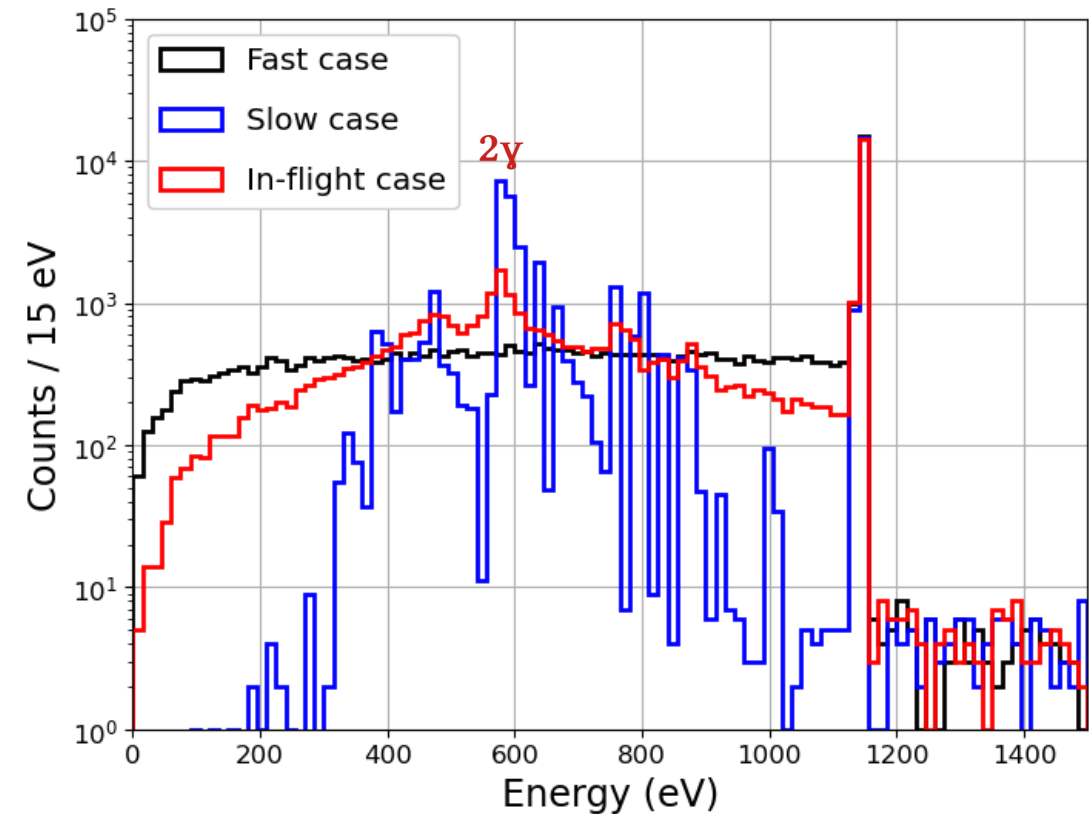


Both phenomena are in the $10^{-14}/10^{-13}$ s order !

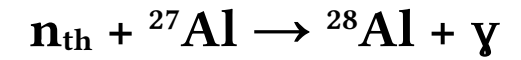
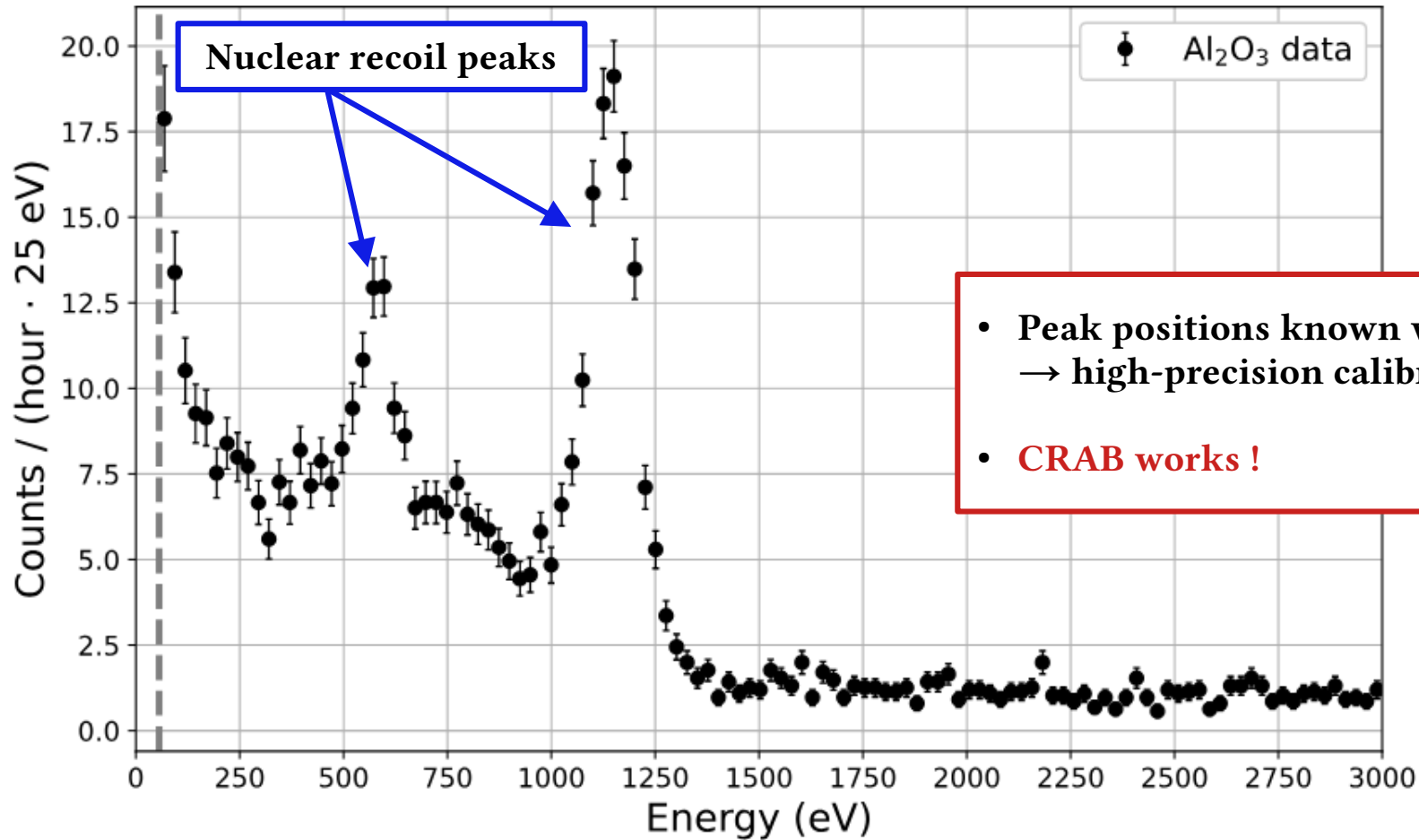
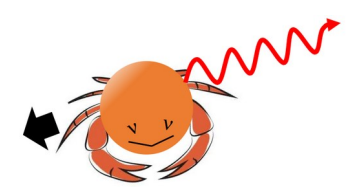


Intermediate between Prompt and Slow = IN FLIGHT

- Very sensitive to nuclear level halflife and recoil modeling
 - Simulation package couples :
 - **Fifrelin** : nuclear deexcitation following neutron capture
 - **Iradina** : atomic displacement cascade following nuclear recoil
- = **FIFRADINA code**

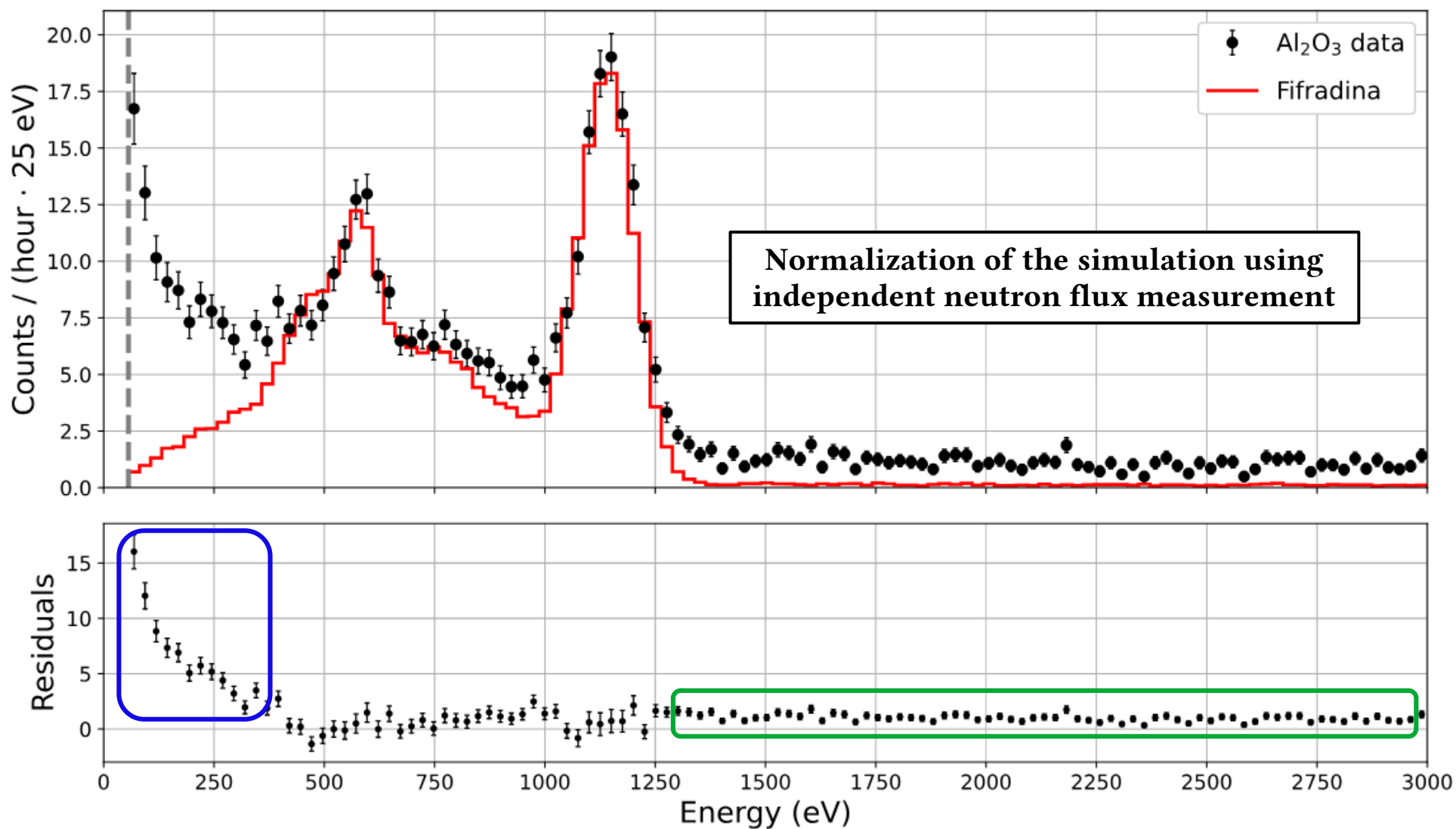
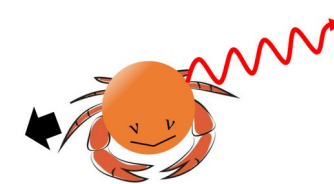


High-precision calibration

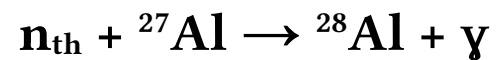
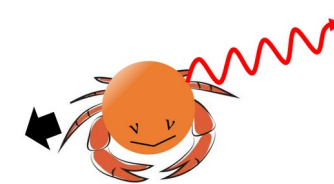


- Peak positions known with < 1 % error
→ high-precision calibration to nuclear recoils
- **CRAB works !**

Comparison with simulation

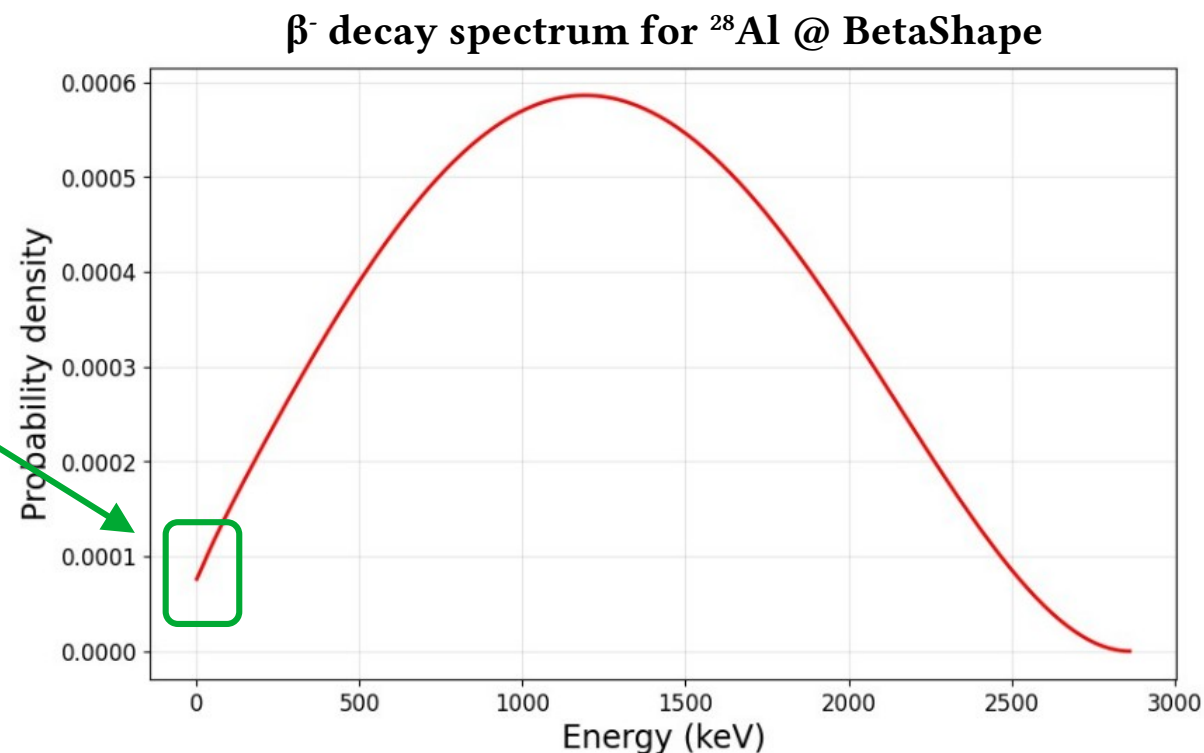


β^- decay of ^{28}Al

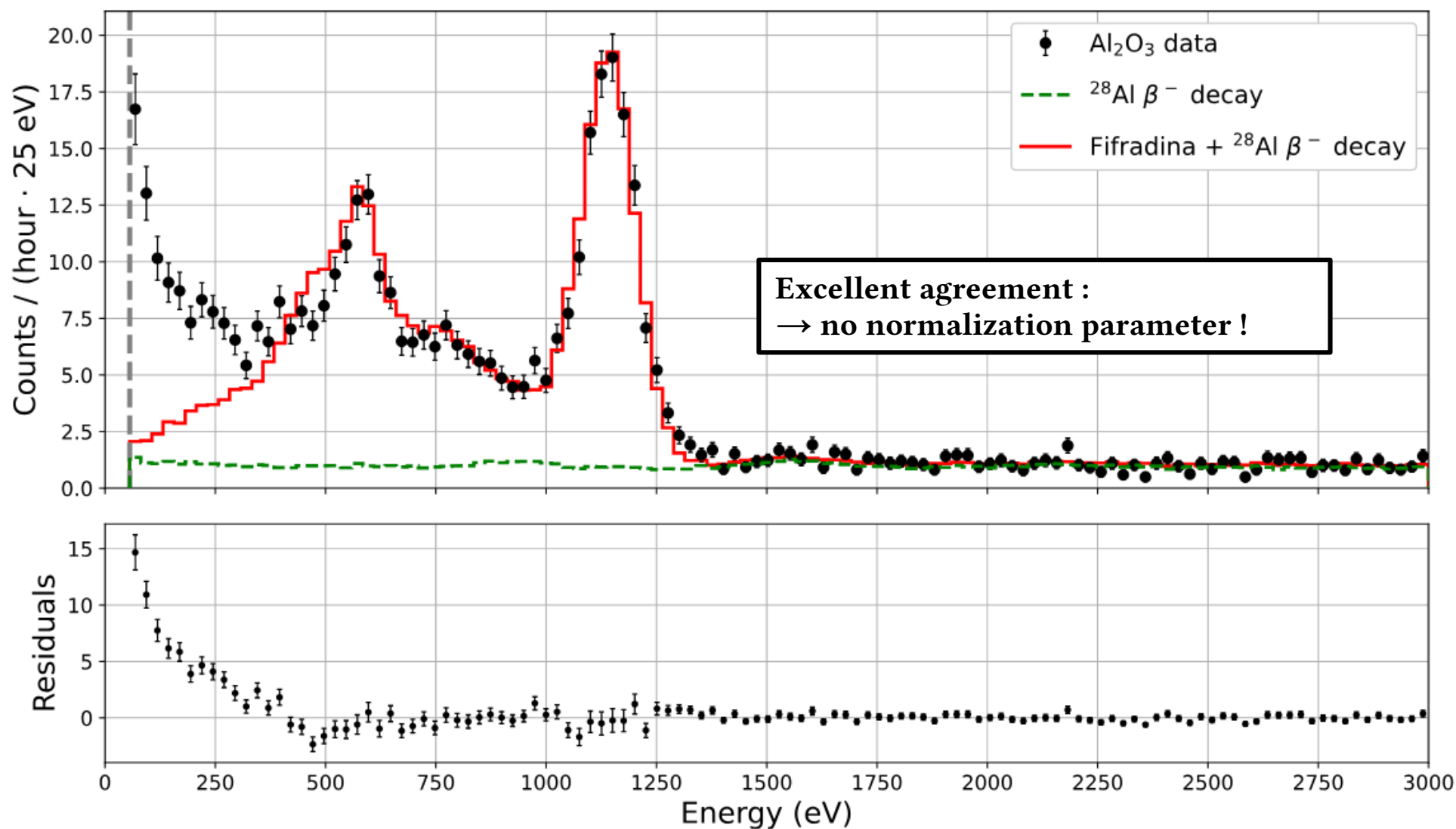
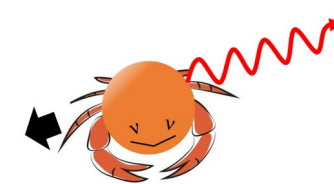


${}^{28}\text{Al}$ = β^- emitter ($T_{1/2} = 2.2$ min)

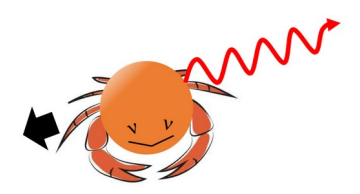
CRAB Region Of Interest = 1st bin !
→ Geant4 simulation to obtain β contribution



Comparison with simulation



β^- decay of ^{28}Al : Startpoint

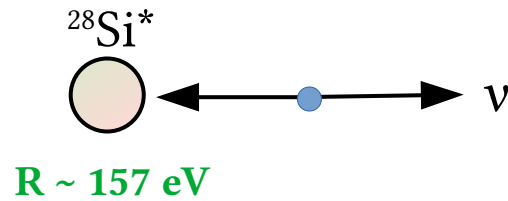


^{28}Al = β^- emitter ($T_{1/2} = 2.2$ min)

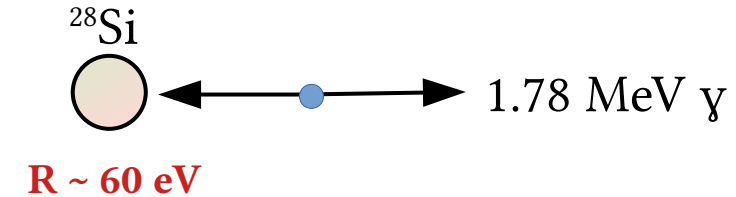


($T_{1/2} = 0.5$ ps)

- At startpoint : $E_\beta \rightarrow 0$ eV
 $\rightarrow ^{28}\text{Si}$ and ν are back-to-back

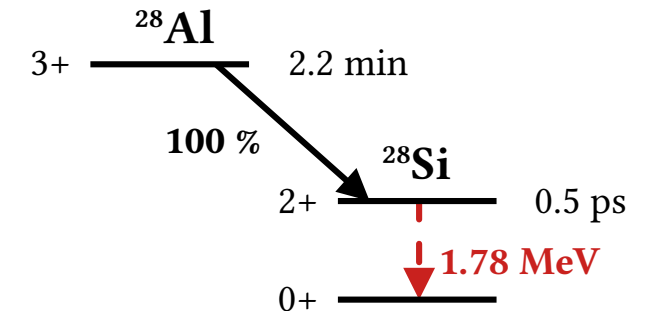


- Deexcitation from ^{28}Si : $2+ \rightarrow 0+$

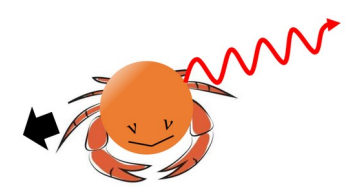


$\rightarrow$ Secondary nuclear recoils measured in the crystal !

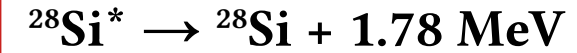
Slow timing case : $(E_R + E_\beta)$ spectrum should start with a **step at $157 + 60 = 217$ eV**



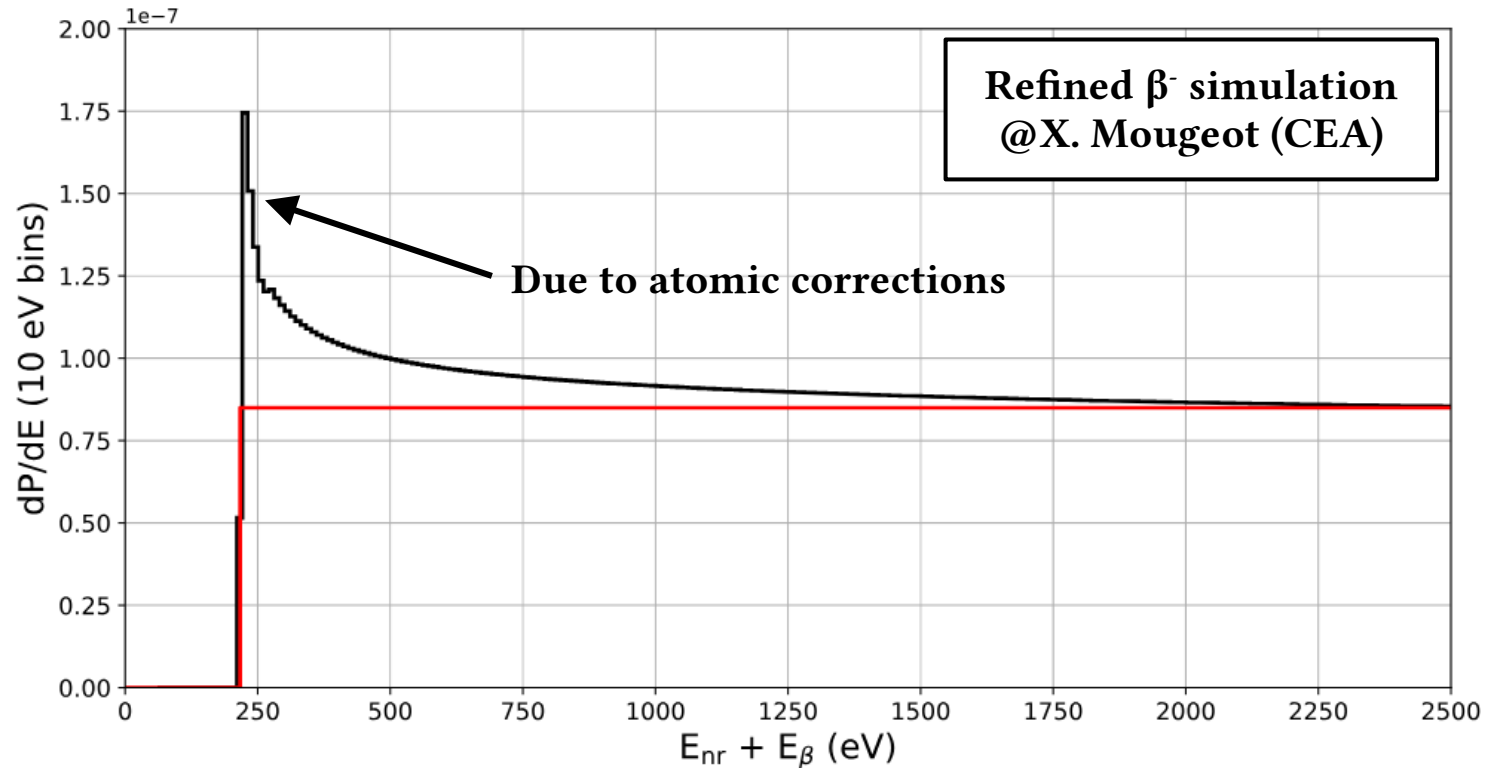
β^- decay of ^{28}Al : Startpoint



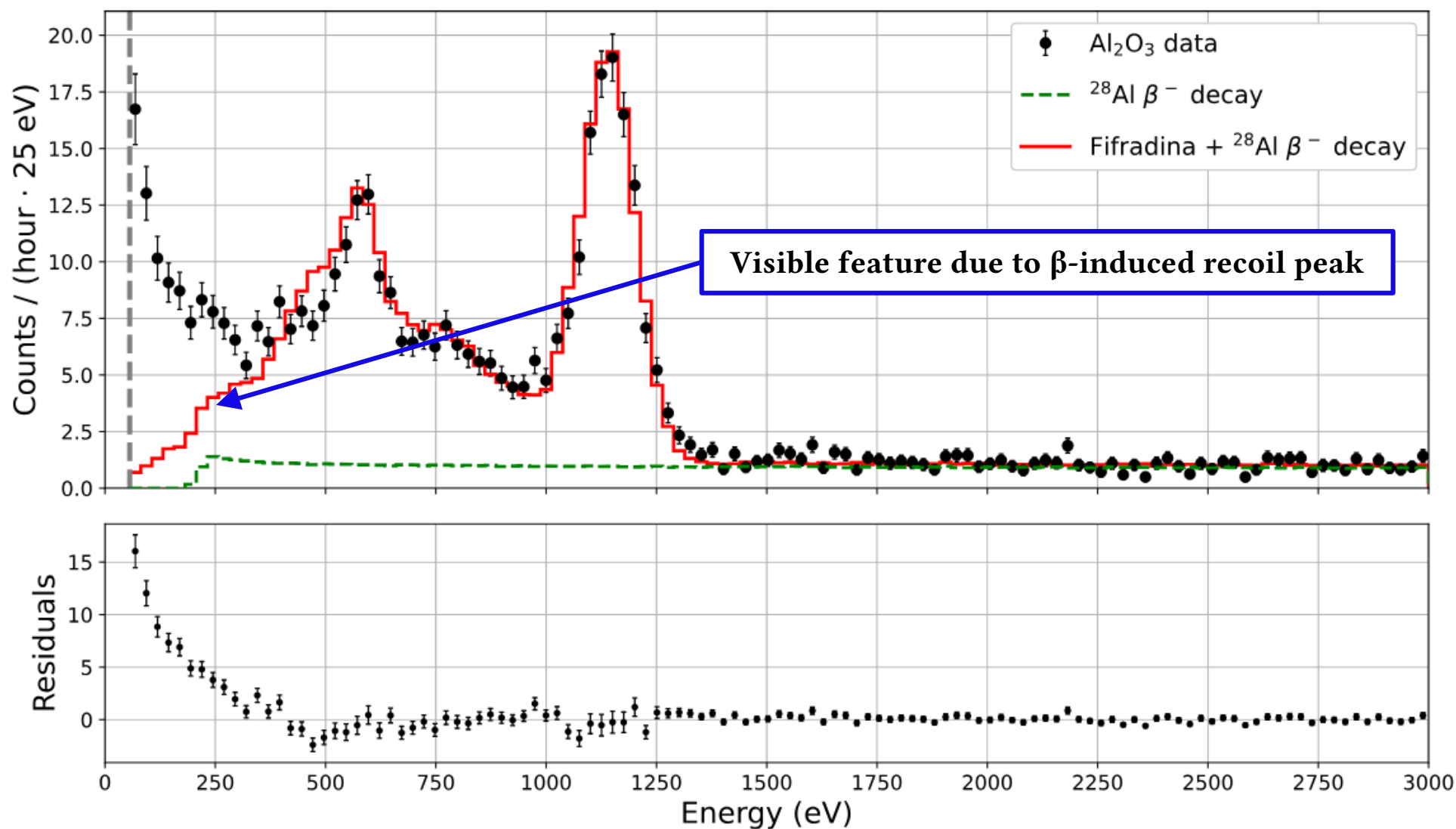
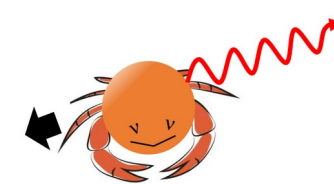
^{28}Al = β^- emitter ($T_{1/2} = 2.2$ min)



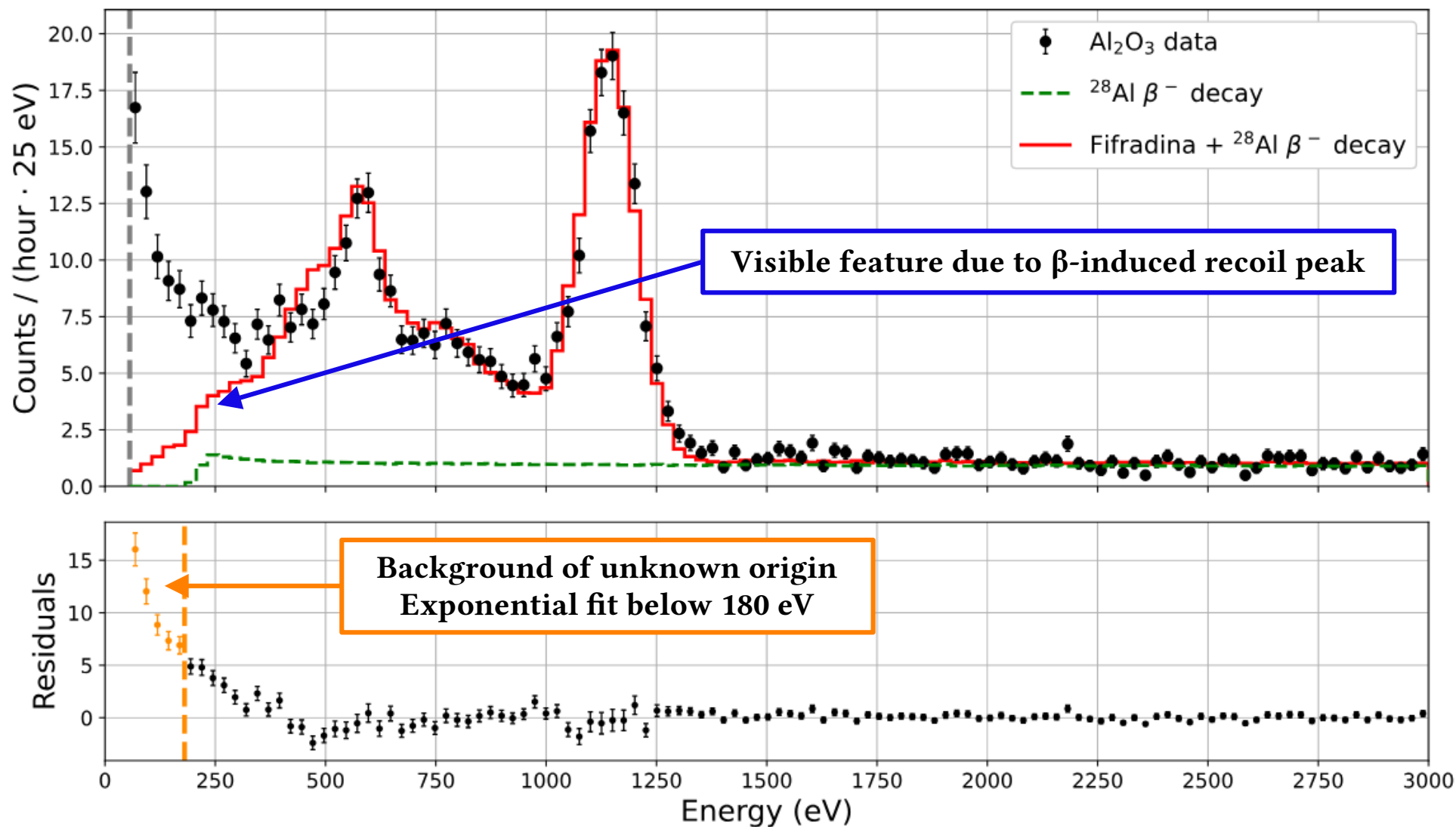
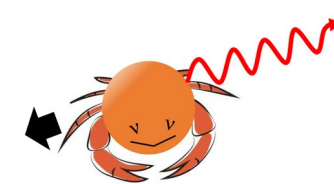
($T_{1/2} = 0.5$ ps)



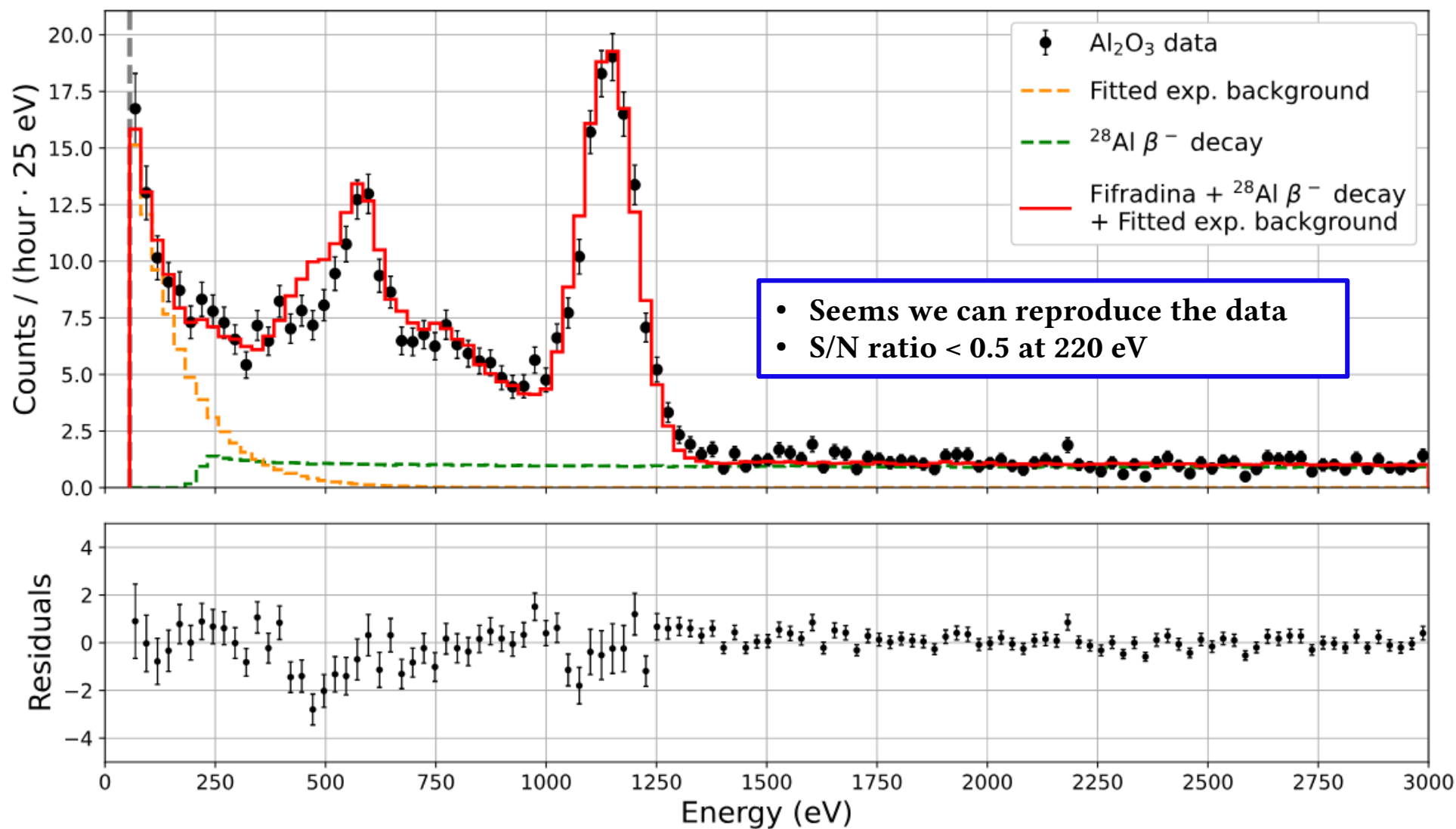
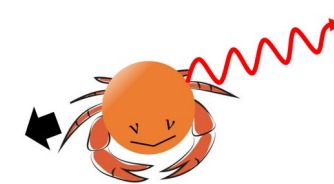
Comparison with simulation



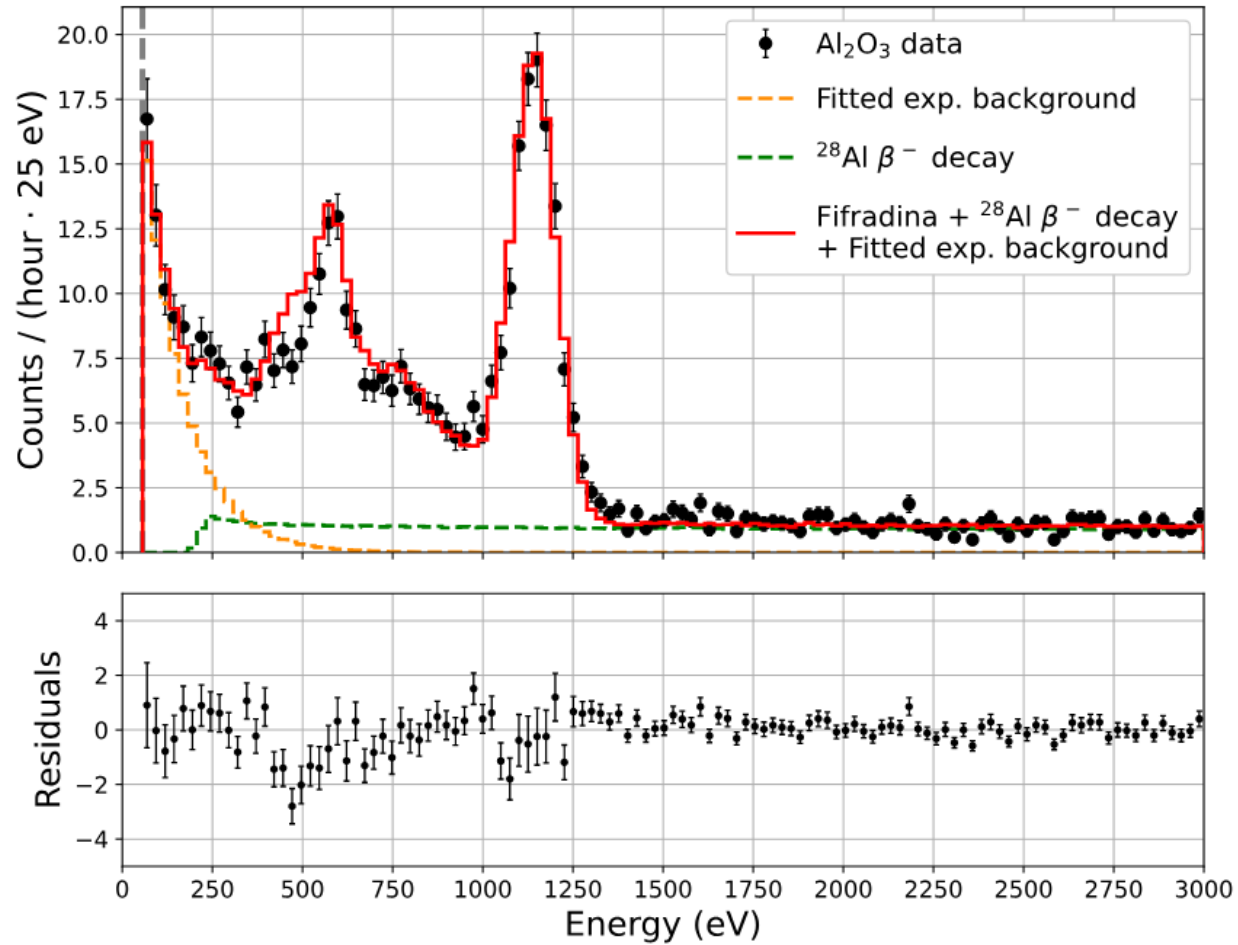
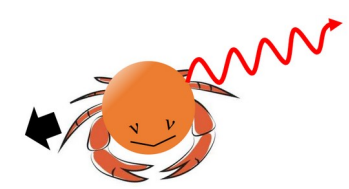
Comparison with simulation



Comparison with simulation

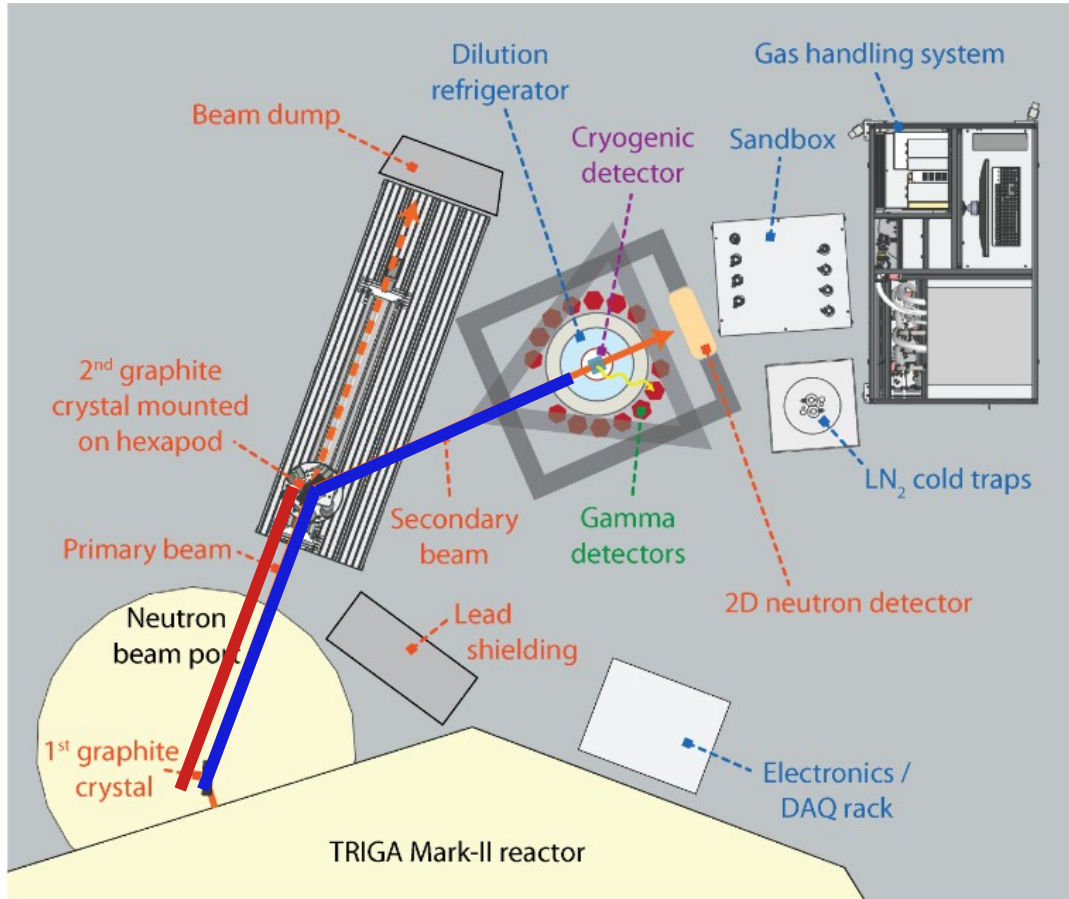


Perspectives



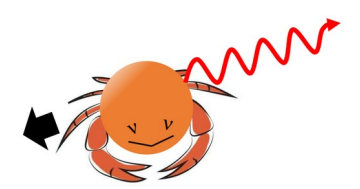
- New Al_2O_3 detector with 10x faster response time
 - improved energy resolution
 - less pile-up
- More statistics
 - this data = only 25 hours
 - will count 4x more !

Perspectives



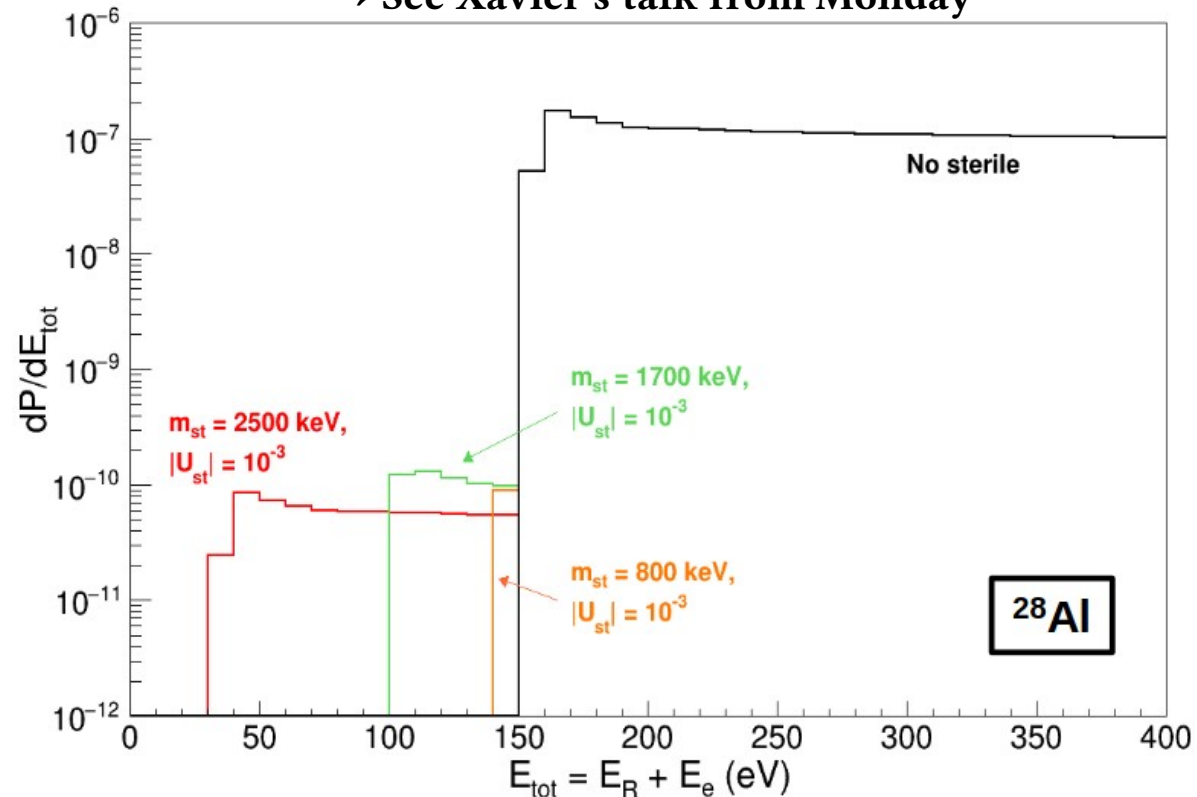
- New Al_2O_3 detector with 10x faster response time
→ improved energy resolution
→ less pile-up
- More statistics
→ this data = only 25 hours
→ will count 4x more !
- Possible explanation : exponential background is reactor/beam-related
→ reactor-related : block the beam at 2nd reflector
→ beam-related : hide the detector by collimating

Sensitivity to massive sterile neutrinos



- Open question
→ β^- decay changes ^{28}Al in ^{28}Si , which have different electronic shells. Does atomic relaxation happen ? Which energy ? Shift of the startpoint ? We should see this radiation in our detector.

→ See Xavier's talk from Monday



→ <https://doi.org/10.48550/arXiv.2606.15014>

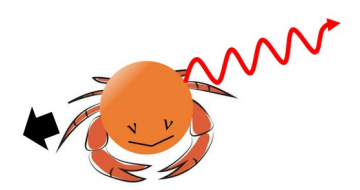
Ultralow-Energy Measurements using the Startpoint of β Decays

D. Kodroff^{1,*} and M.R. Williams^{1,†}

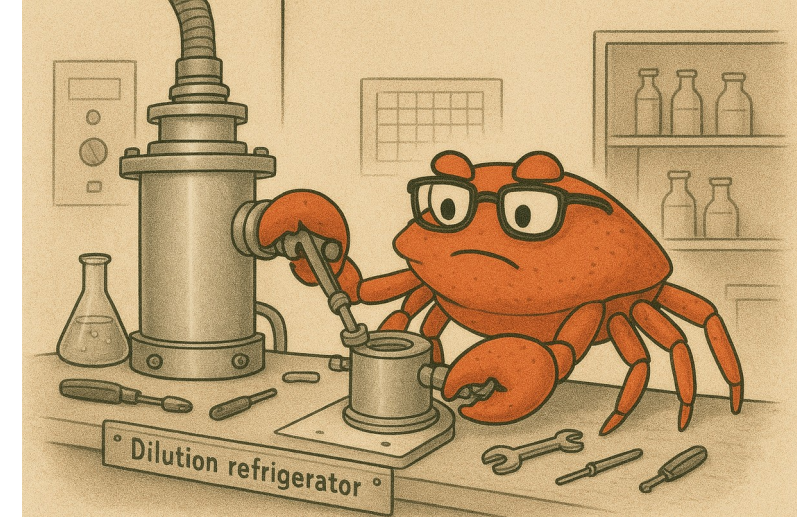
¹Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA 94720-8099, USA

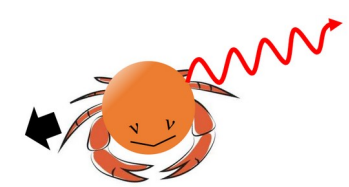
- **Mixing with a potential massive sterile neutrino**
→ shift of the startpoint to lower energy
→ lower plateau amplitude
- **Difficult measurement**
→ very low threshold ...
→ need a huge statistics

Conclusion



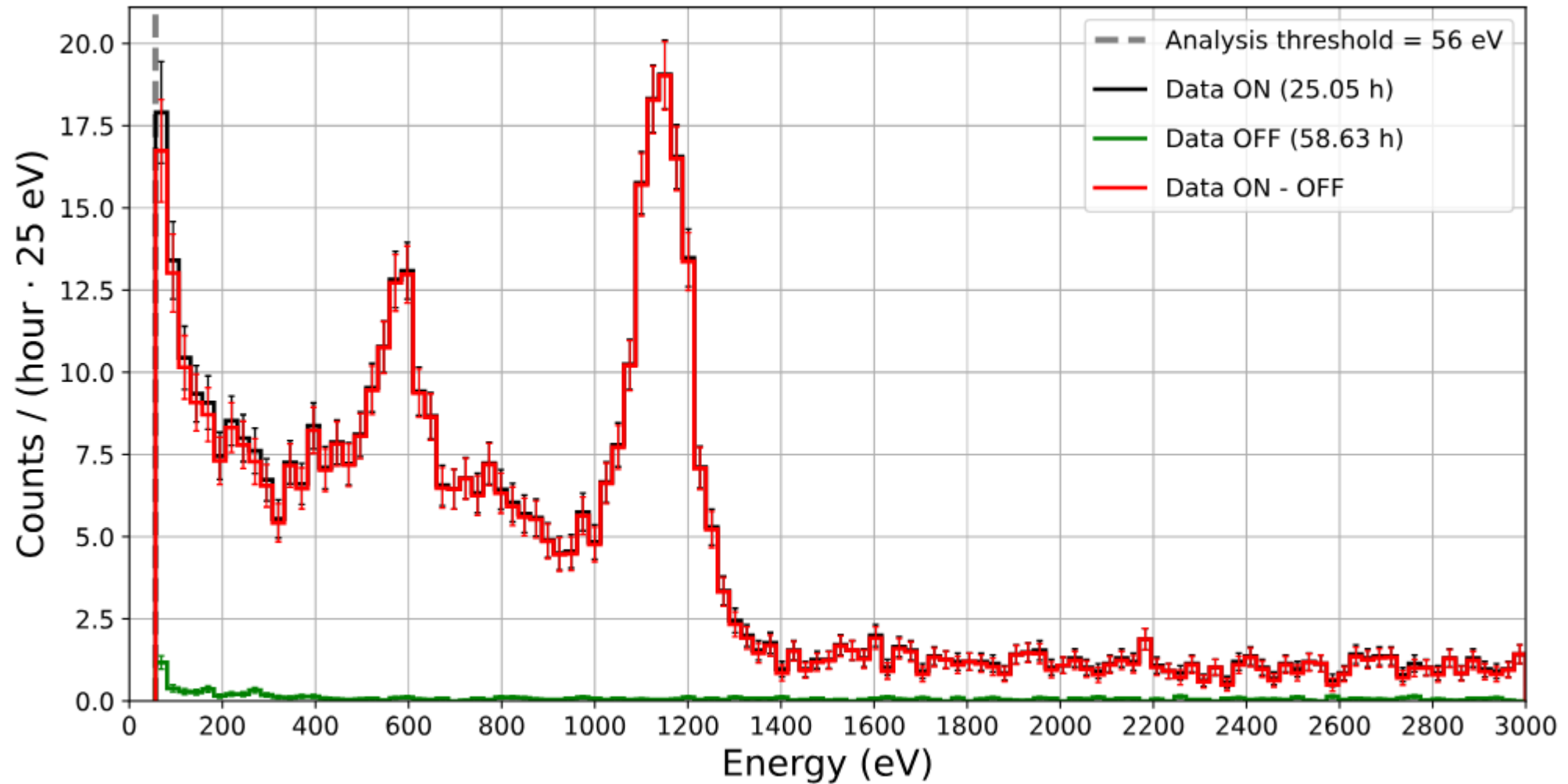
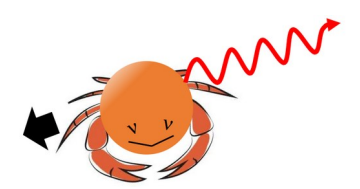
- **CRAB = unique calibration method for CEvNS/DM experiments**
 - high precision characterization of the detector response to nuclear recoils
 - unique dedicated facility in Vienna cryostat coupled with a pure collimated beam of thermal neutrons
- **Observation of nuclear recoil peaks in 2 materials with sub-percent precision**
 - 577 and 1144 eV in Al_2O_3
 - 112 and 160 eV in CaWO_4 (not showed in this talk)
- **Potential first hints for starpoint of ^{28}Al β^- decay spectrum**
 - new measurement in a few weeks with a new Al_2O_3 detector !
 - Stay tuned !



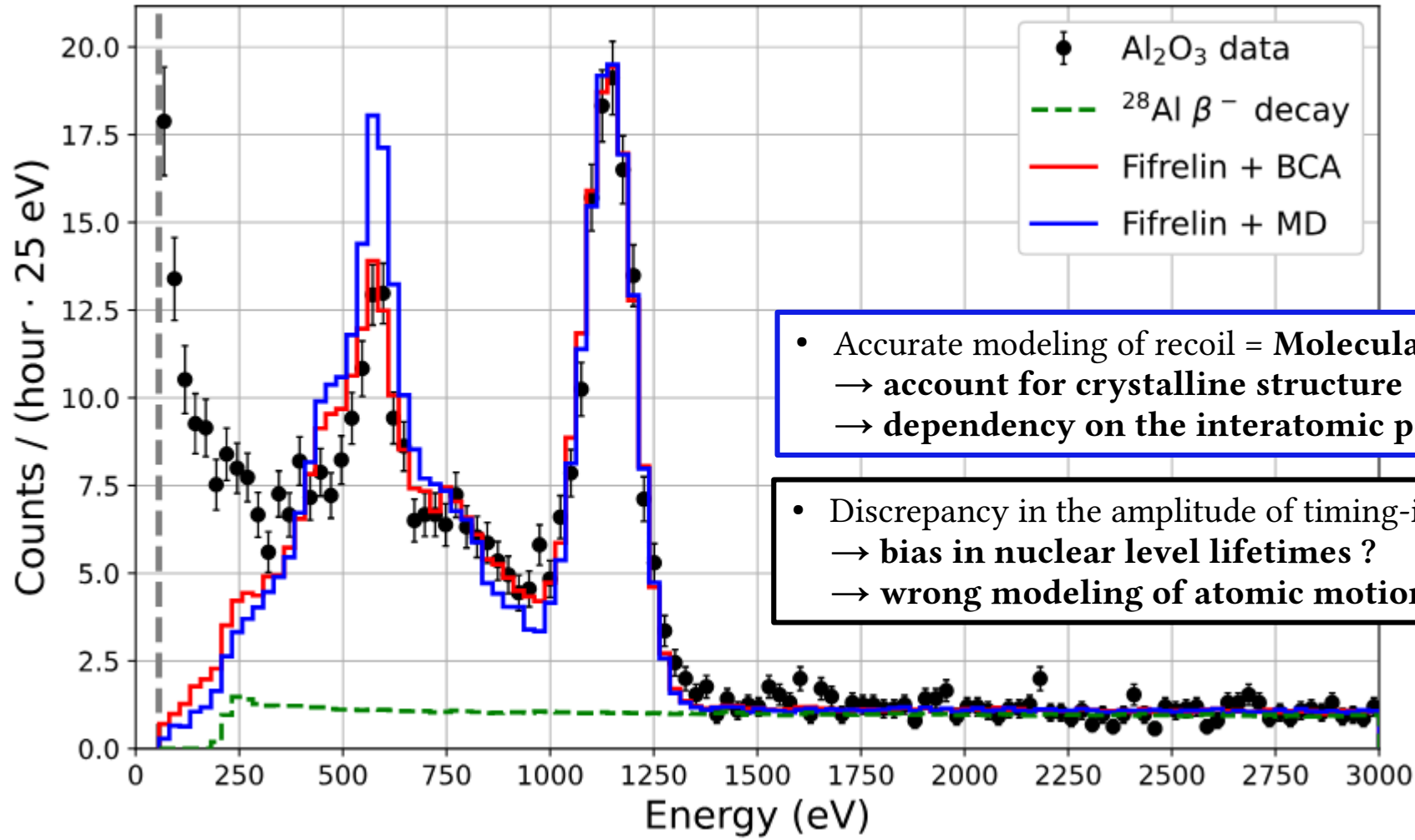
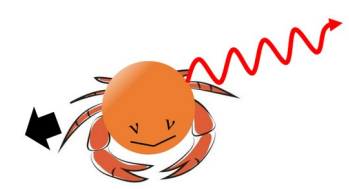


Thank you for your attention !

Reactor ON – Reactor OFF



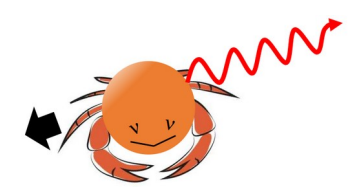
BCA vs Molecular Dynamics



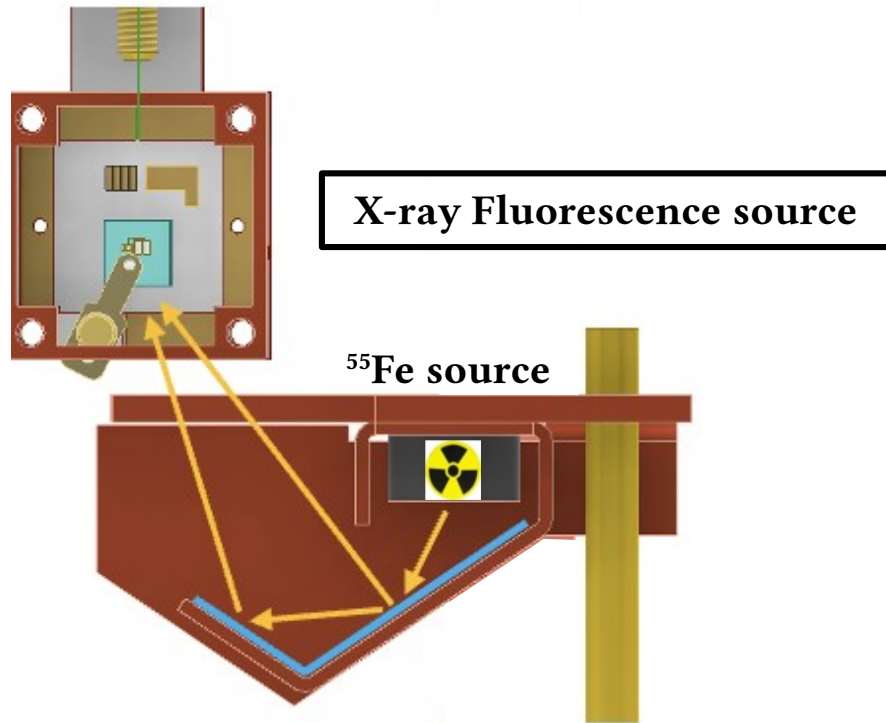
- Accurate modeling of recoil = **Molecular Dynamics (MD)**
 - **account for crystalline structure**
 - **dependency on the interatomic potential**

- Discrepancy in the amplitude of timing-induced peak
 - **bias in nuclear level lifetimes ?**
 - **wrong modeling of atomic motion ?**

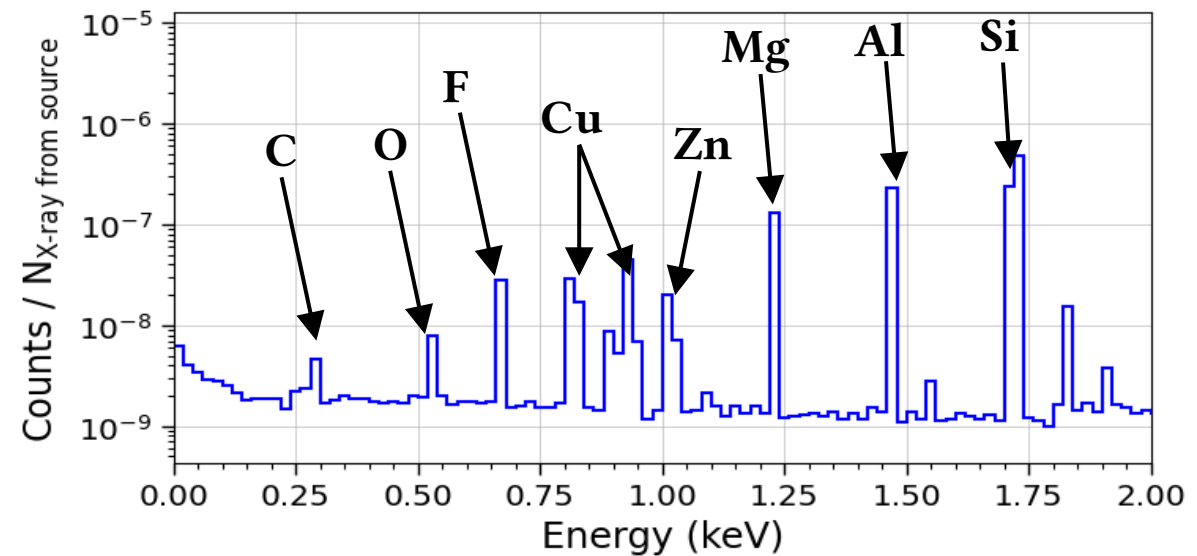
Nuclear/electronic inter-calibration



- **Simultaneous measurement of nuclear/electronic calibration lines below 2 keV**
 - unique sensitivity to crystal defects creation
 - relative scaling of the nuclear and electronic lines

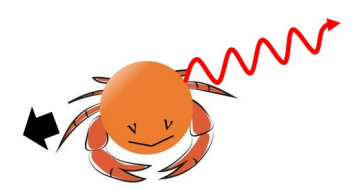


Lower Z means lower X-ray energy AND lower fluorescence yield !

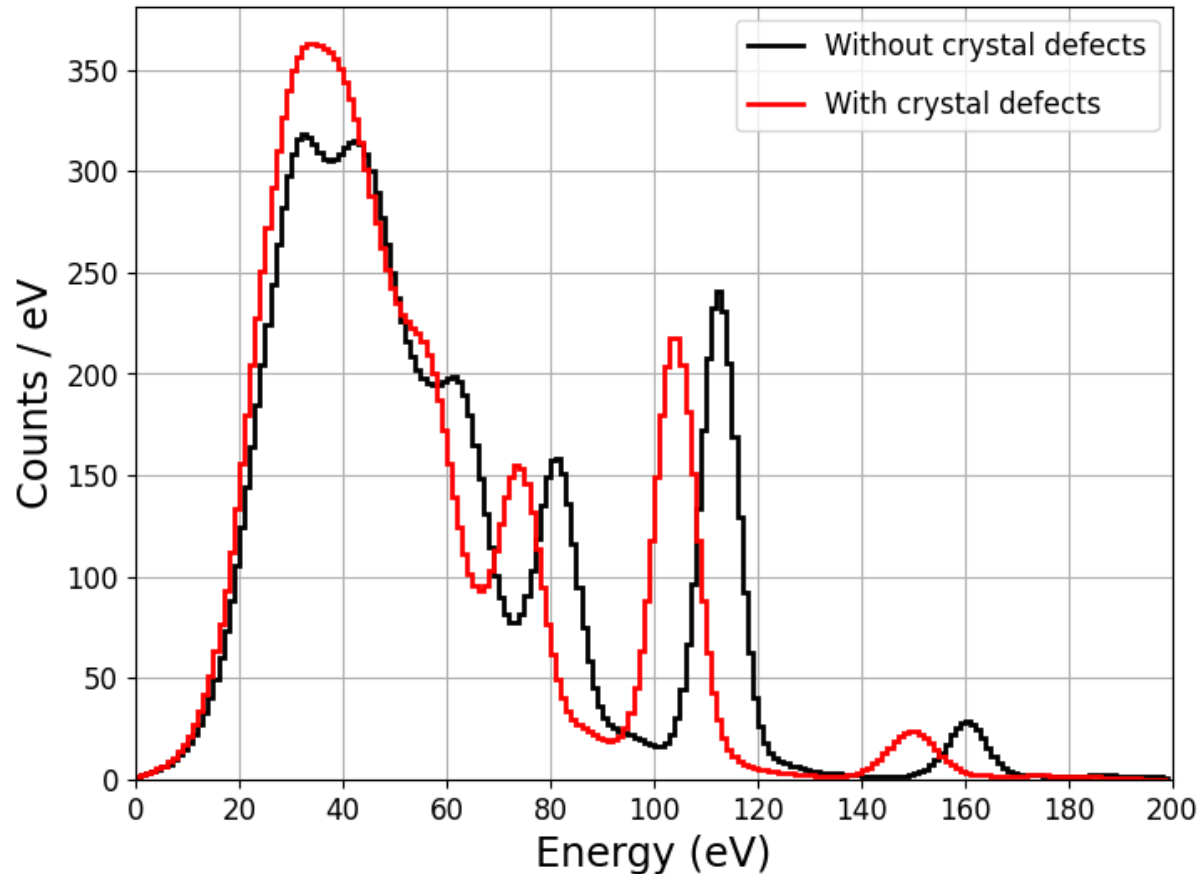


**CRAB calibration portability in
other experimental sites**

Impact of crystal defects in CaWO_4



**Prediction of CaWO_4 wafer recoil spectrum
with and without considering crystal defects**



Nuclear recoil → access to RED energy scale

Electronic recoil → access to BLACK energy scale

**→ comparison of nuclear AND electronic recoil lines
= more sensitive way to study crystal defects**