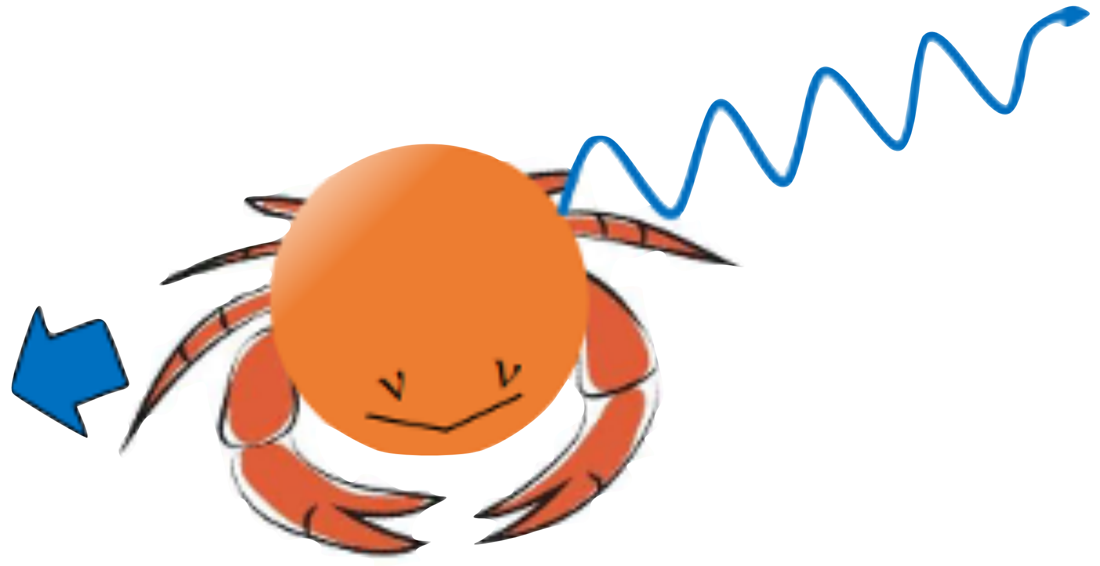
TAUP XICHANG

First results from the CRAB experiment at the TRIGA Mark-II reactor

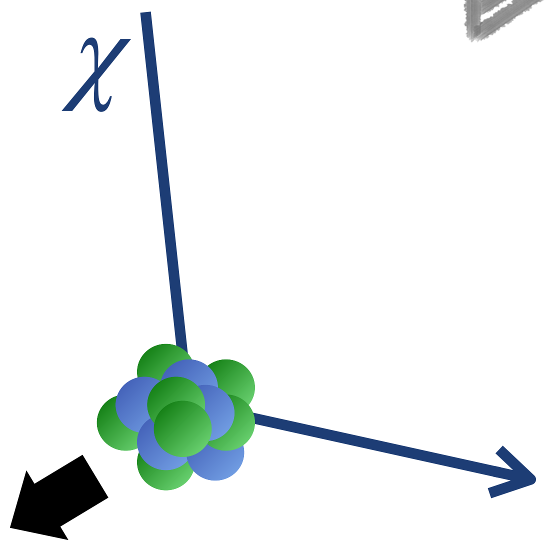
Elisabetta Bossio *on behalf of the CRAB Collaboration*

TAUP 2025, 24-30 Aug 2025, Xichang, China



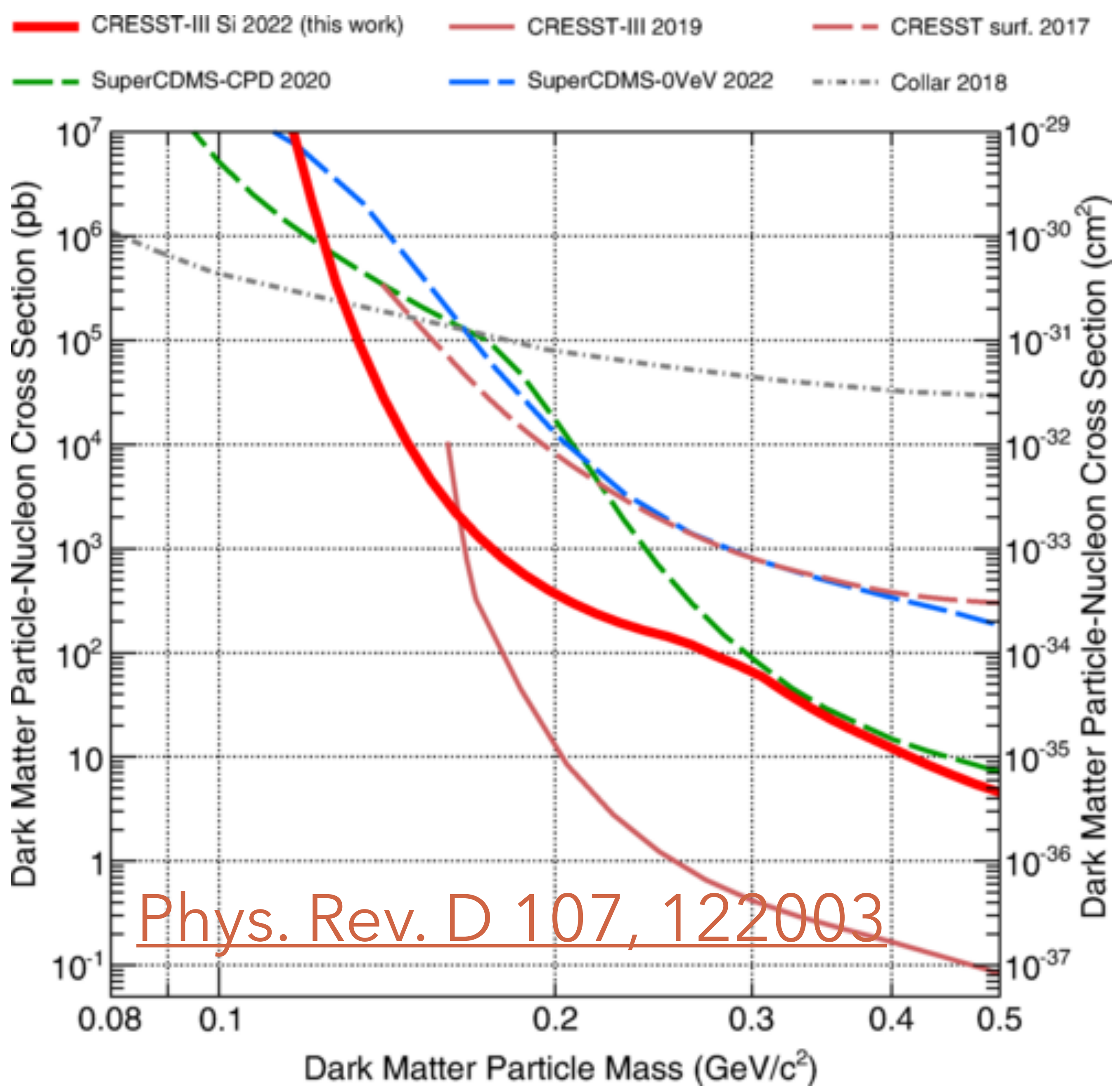
Detection of dark matter and neutrinos

- Tiny (sub-keV) nuclear recoils are at the core of two major research efforts in particle physics:



$$E_{R,max} \sim 2v^2 \frac{m_\chi^2}{M}$$

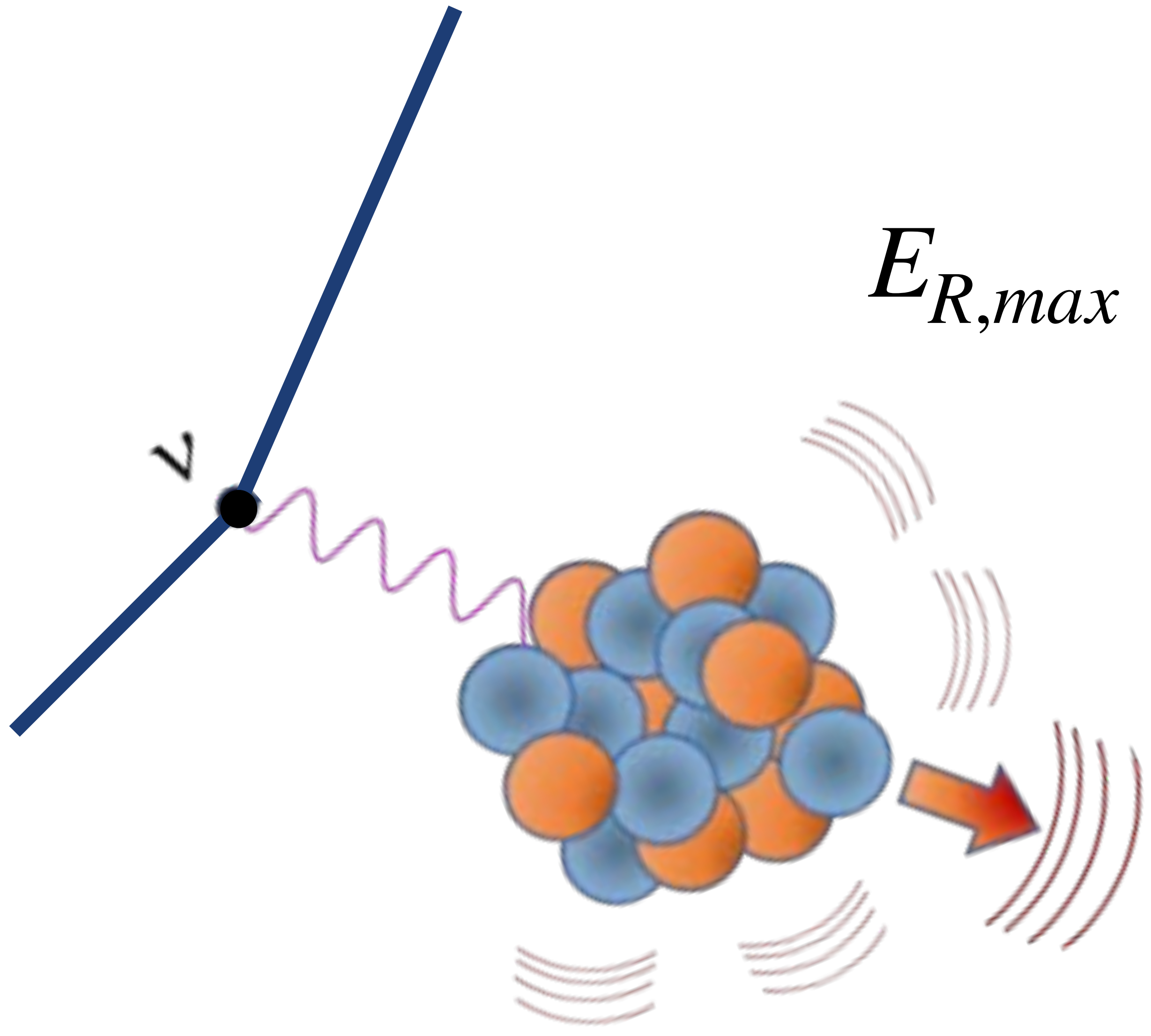
- Low mass Dark Matter direct detection



Phys. Rev. D 107, 122003

- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

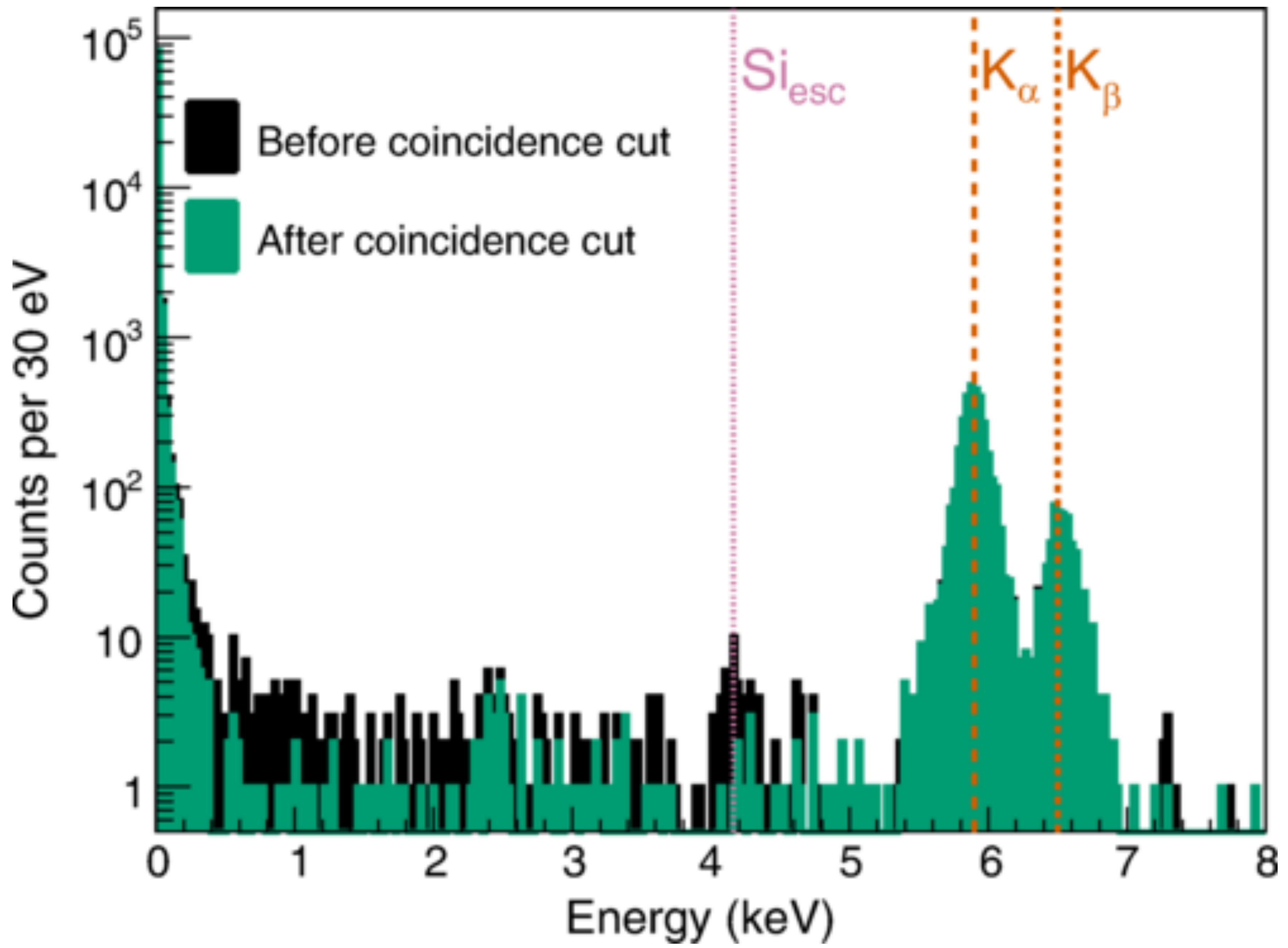
$$E_{R,max} \sim \frac{2E_\nu^2}{M}$$



Energy calibration “state of the art”

- Energy calibration with low energy X-rays and/or LED pulses
- Widely used ^{55}Fe source: K_{α} and K_{β} X-ray lines following electron capture

CRESST 0.35 g Si detector
Phys. Rev. D 107, 122003

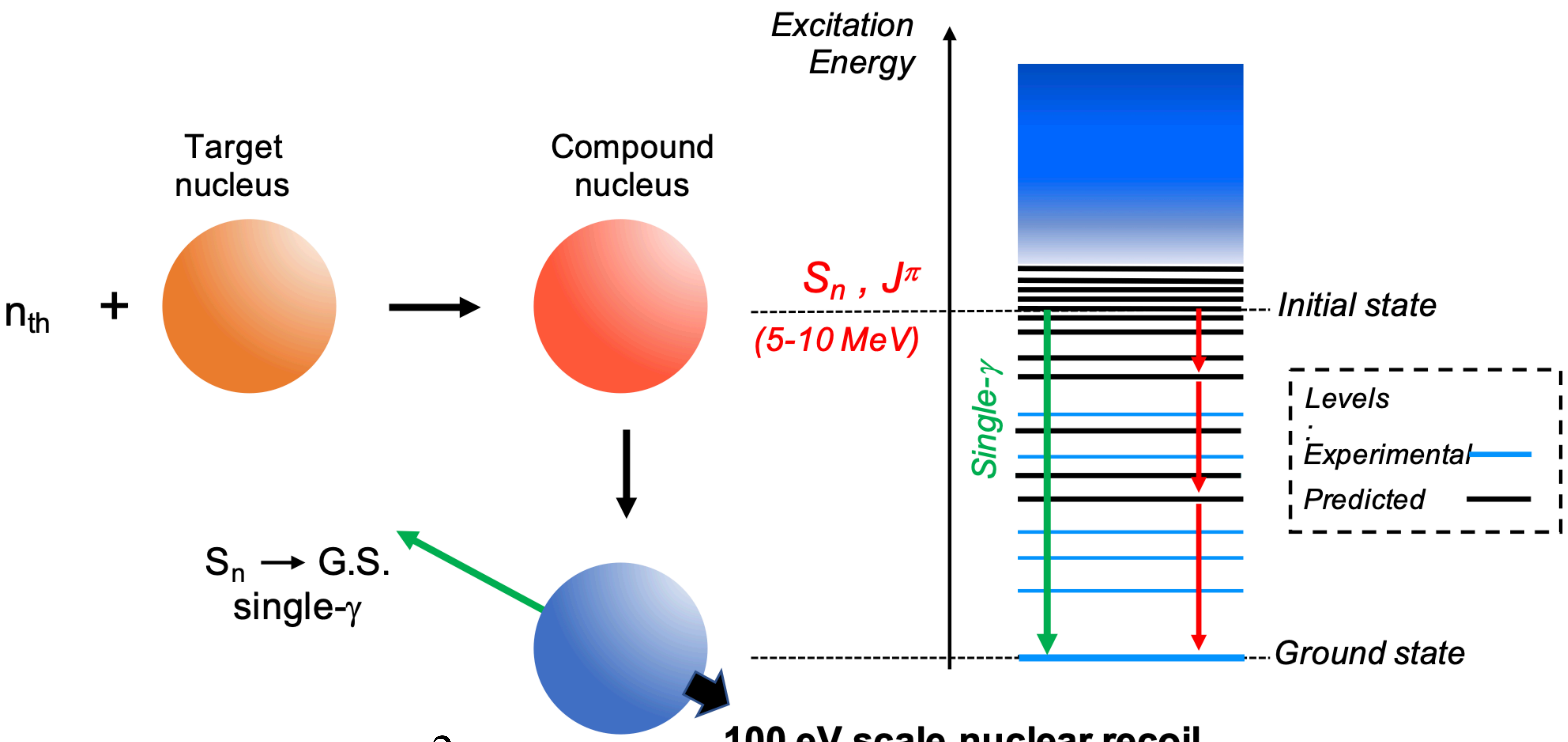


- Extrapolation from keV to sub-keV range: linearity?
- Difference in electron/nuclear recoil response?
- Difference between surface/bulk events?

The CRAB method

L. Thulliez et al 2021 JINST 16 P07032

CRAB: Calibrated Recoils for Accurate Bolometry



100 eV scale nuclear recoil
for many nuclei: $CaWO_4$, Al_2O_3, Ge, Si

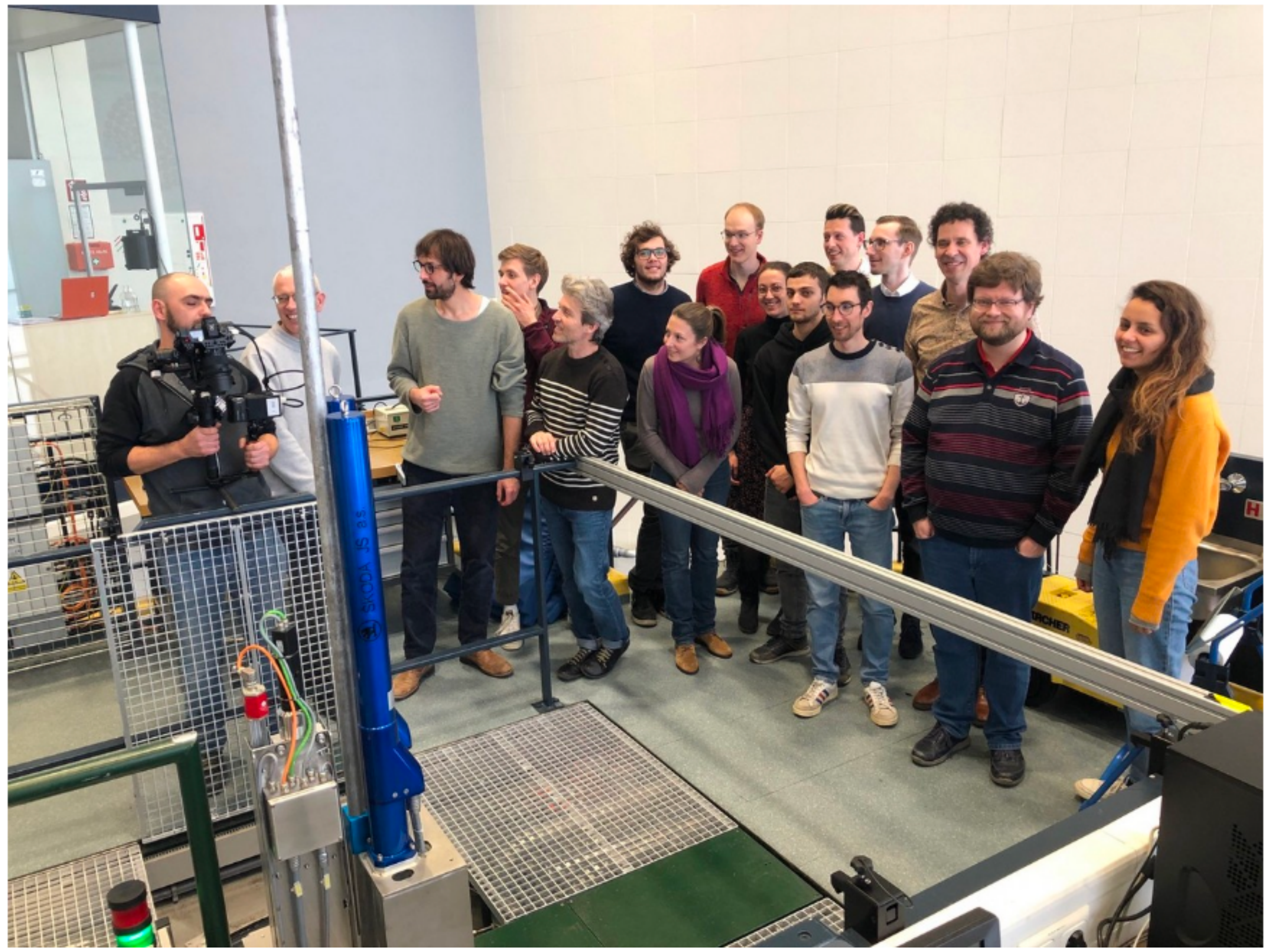
$$E_{NR} = \frac{E_\gamma^2}{2M}$$

The beauty:

- Pure nuclear recoil
- Sub-keV energy
- Uniformly distributed in the detector

The CRAB collaboration

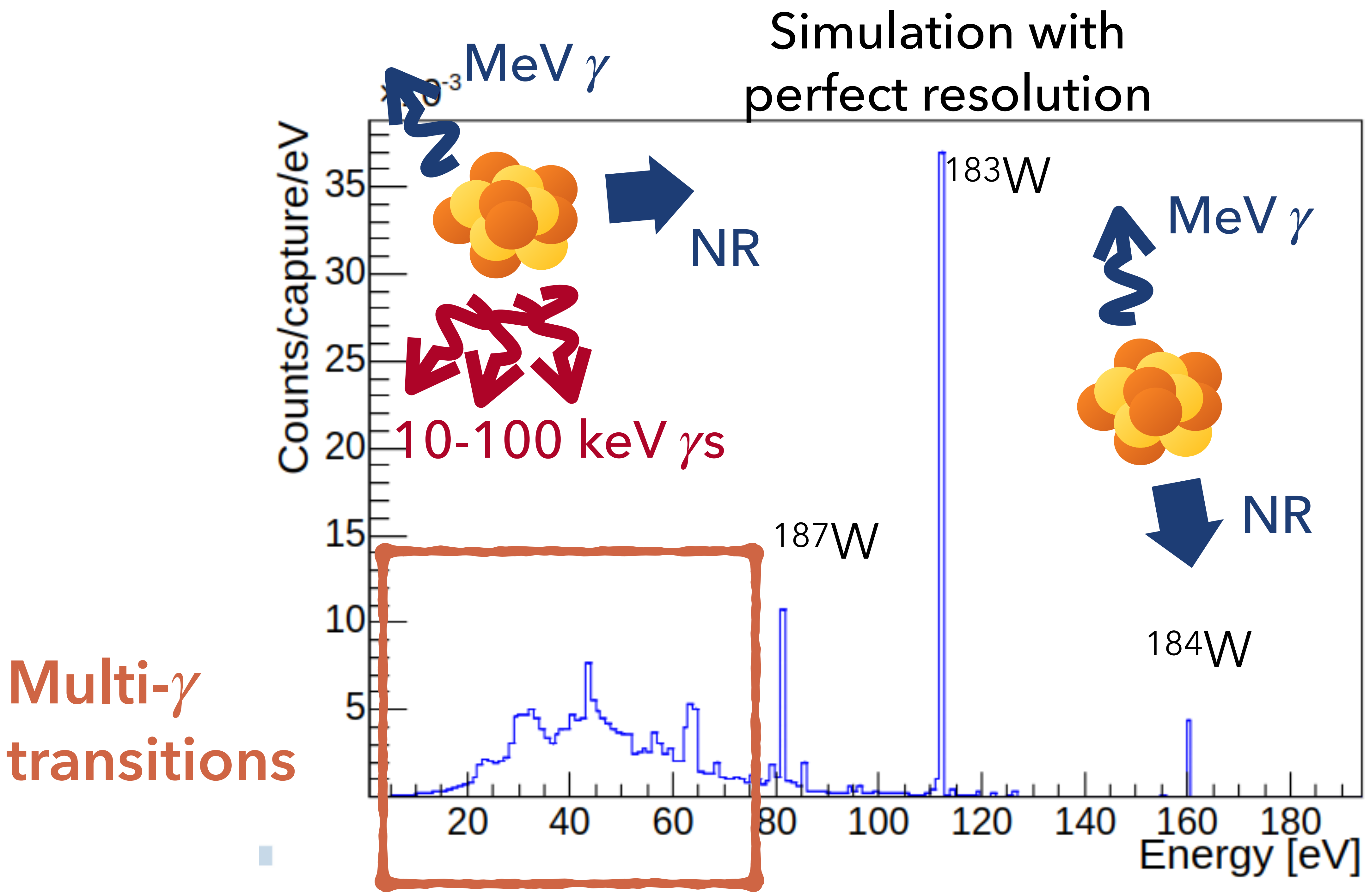
- ~40 people, 9 institutes, 4 countries
- Members from NUCLEUS, RICOCHET, CRESST, TESSERACT collaborations & solid state physicists

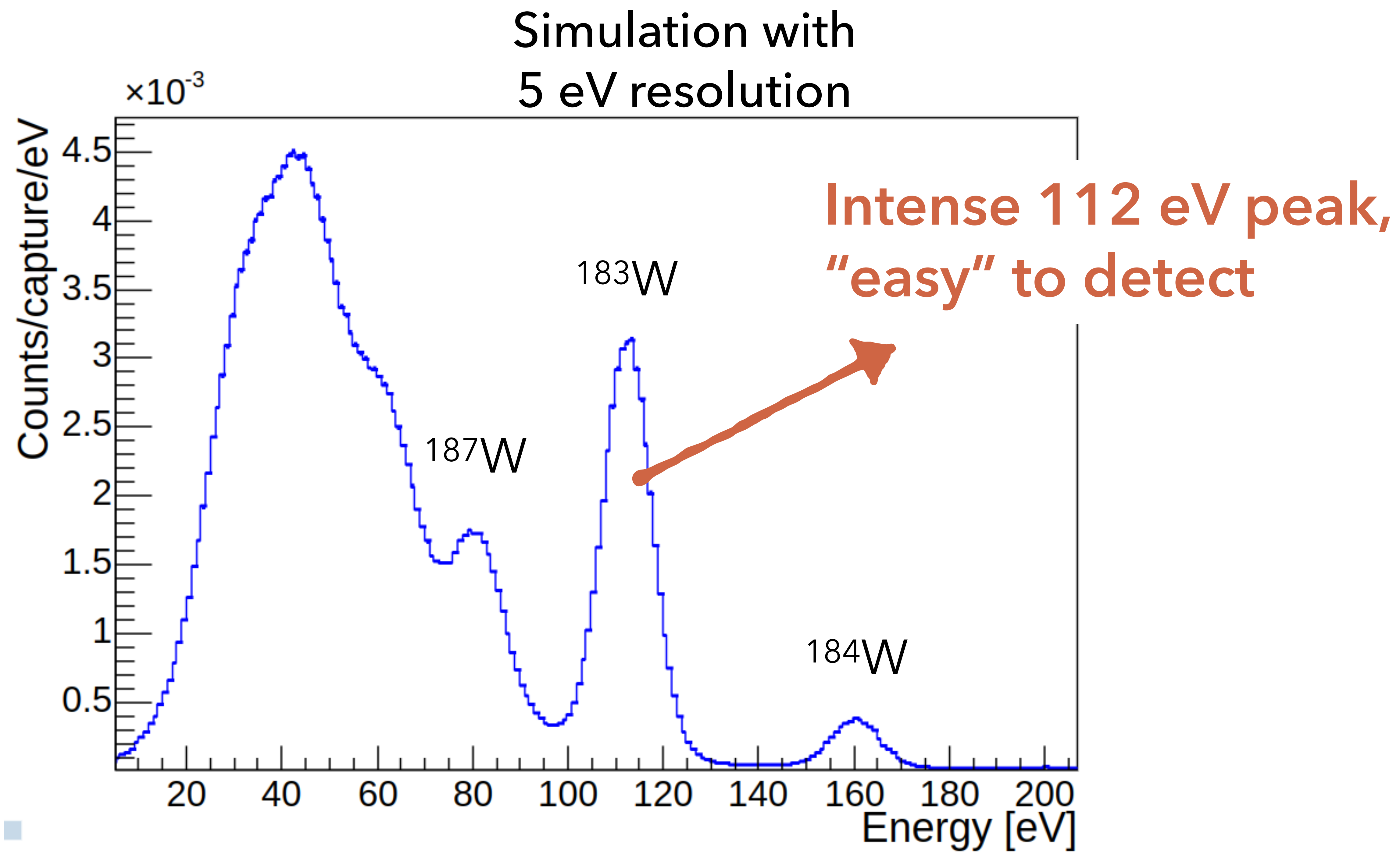


LPSC Grenoble
iP2i Les 2 Infinis Lyon
Max-Planck-Institut für Physik
cea irfu
TU Wien
TUM
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
Sapienza Università di Roma
HEPHY Institut für Hochenergiephysik
INFN

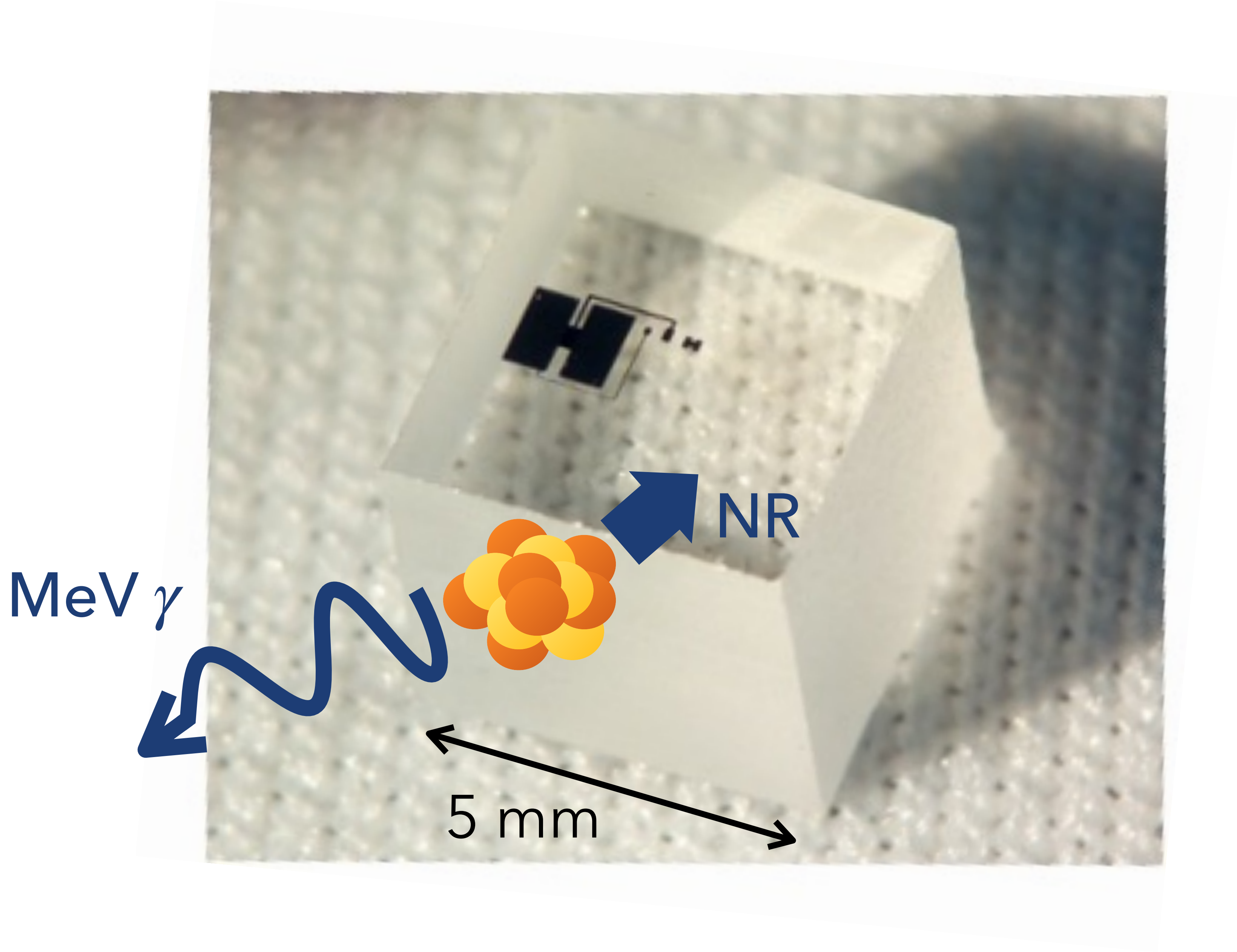
CRAB with $CaWO_4$

- 3 main natural isotopes of W: ^{186}W, ^{182}W, ^{183}W
- Single-γ peaks at 81 eV, 112 eV, 160 eV
- Multi-γ induce a continuum of nuclear recoils





NUCLEUS detectors for CRAB



Nucleus cryogenic detectors:

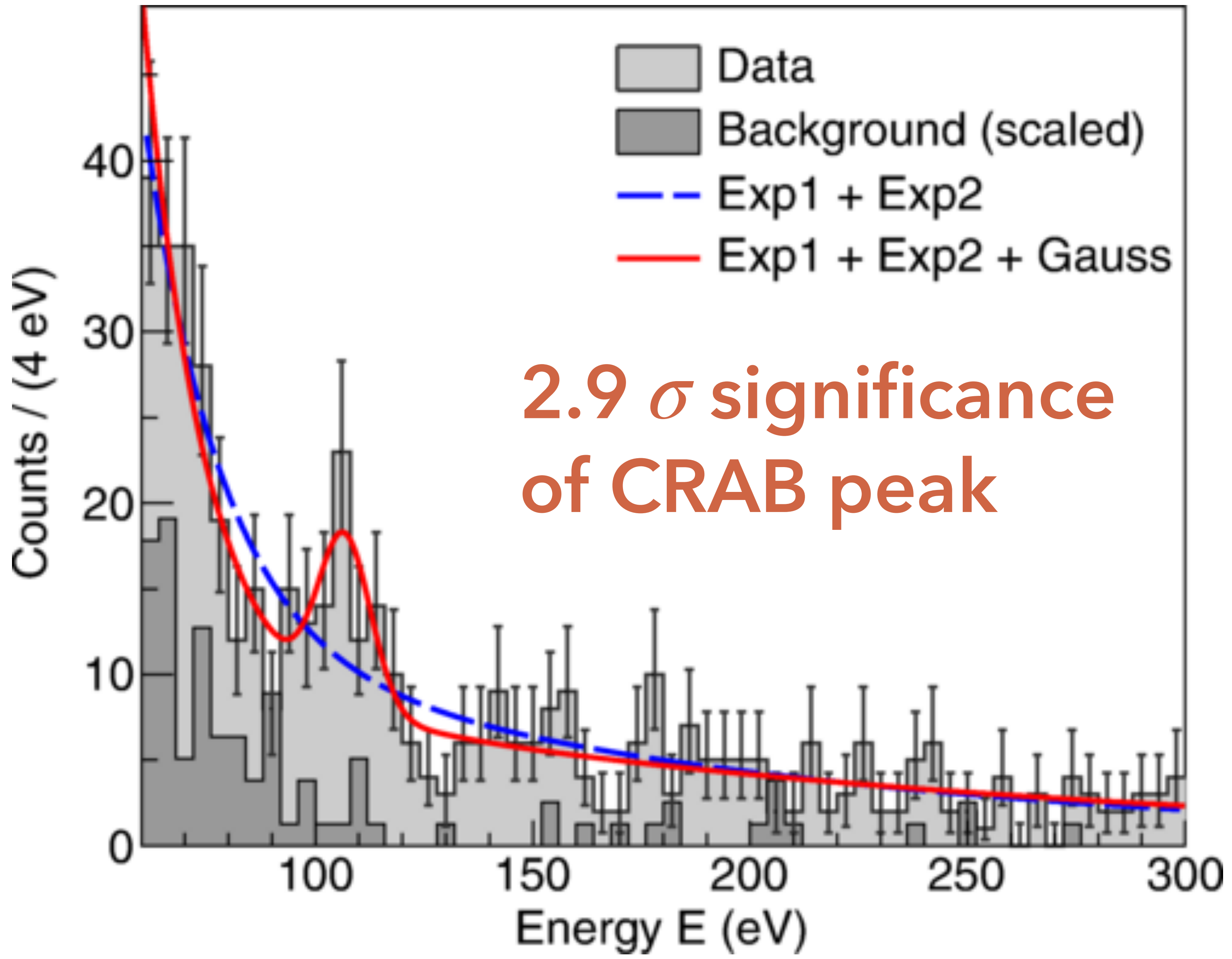
- Single crystal: $CaWO_4$, Al_2O_3, Ge, Si
- Operated at 10 mK
- Read out by Transition Edge Sensor (TES)
- 4 eV resolution achieved
  Phys. Rev. D 96, 022009 (2017)

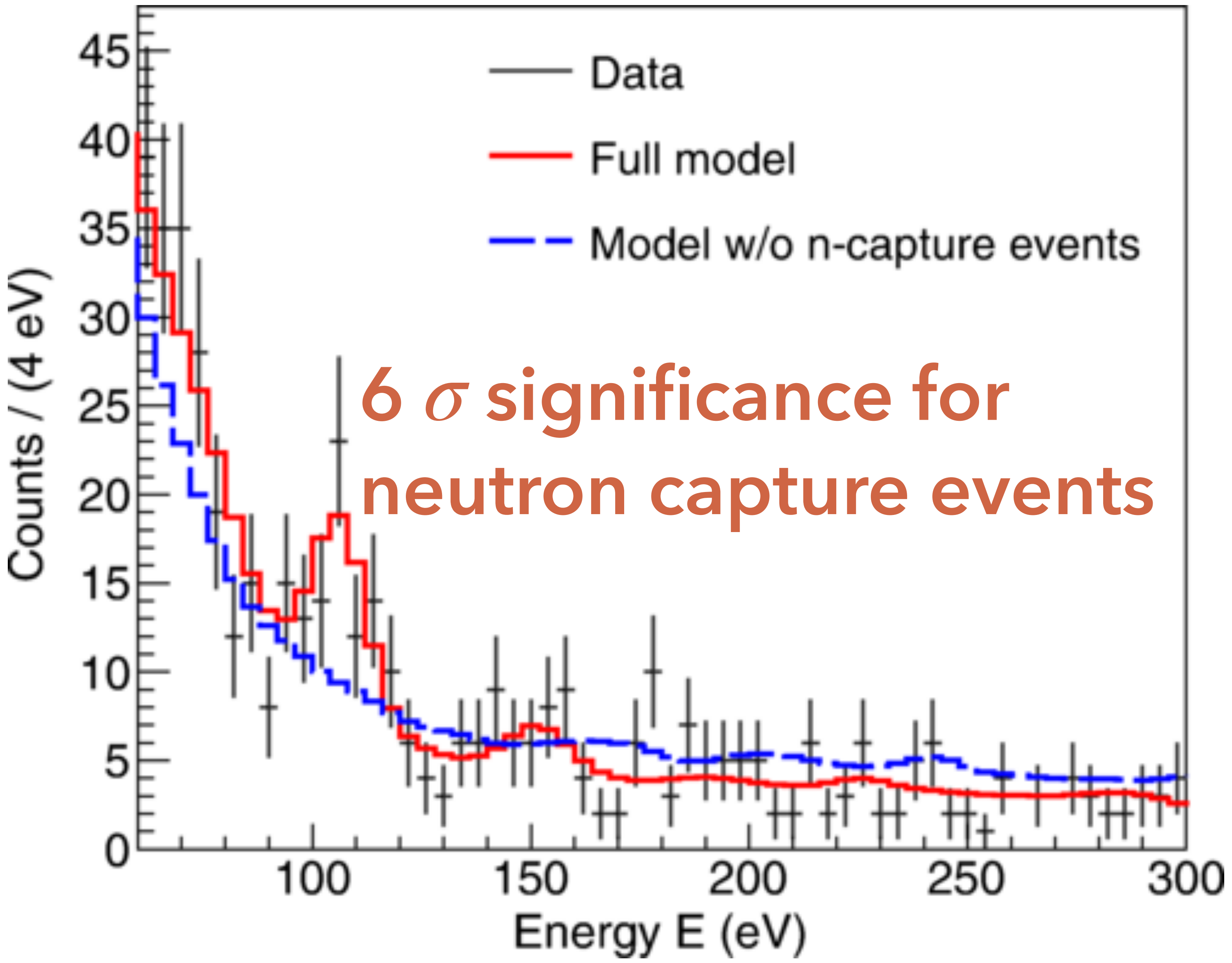
- Small enough that MeV gammas can escape

Proof-of-principle (2022)

- ^{252}Cf neutron source next to NUCLEUS cryostat at the Technical University of Munich
- 0.75 g $CaWO_4$ NUCLEUS detector
- 40.2 h of source data, 18.9 h of background data

Phys Rev Lett 130 211802





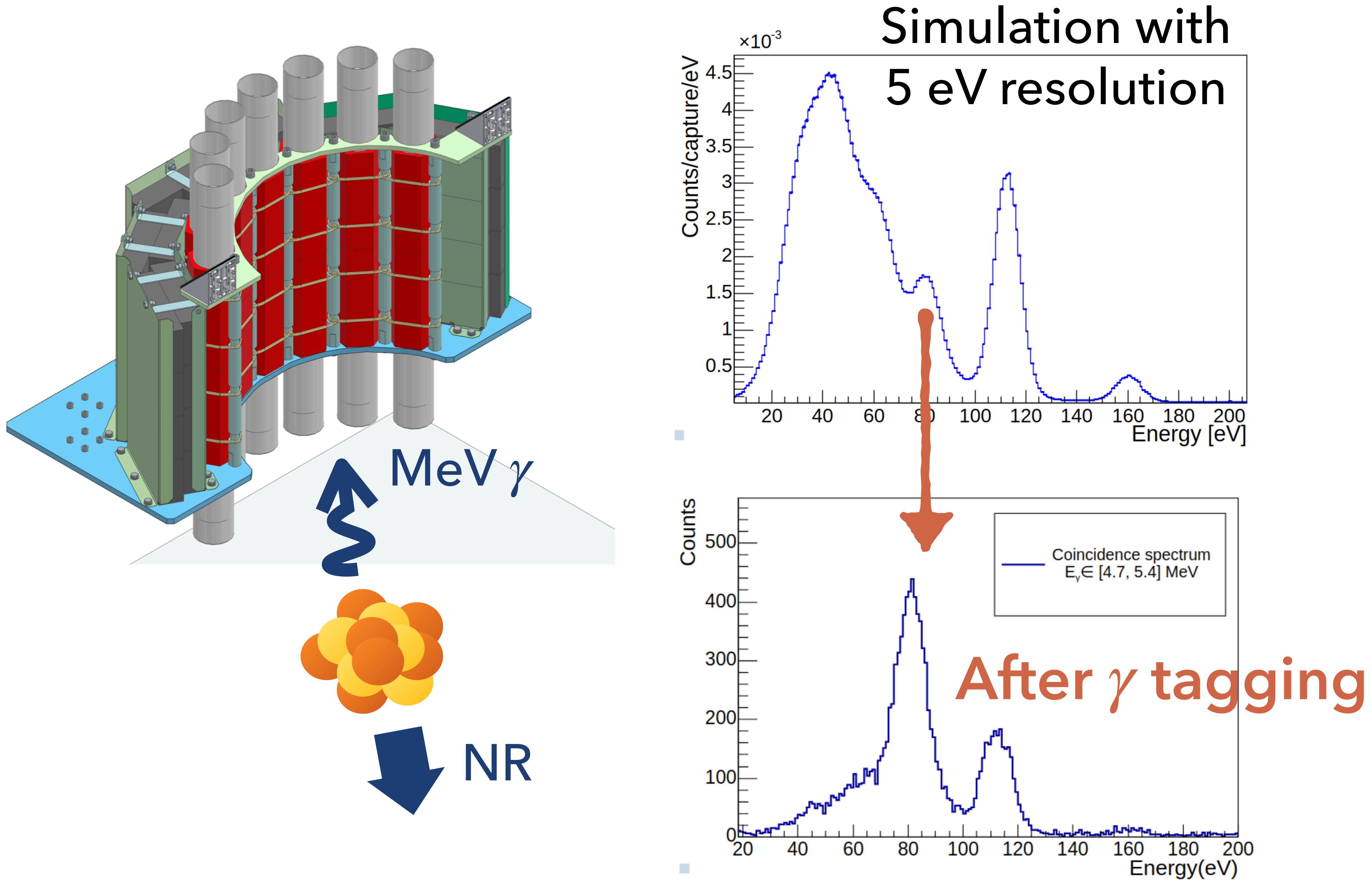
- Later confirmation by CRESST
  Phys. Rev. D 108, 022005
- **Limitation:** fast neutron background induced by the source!

Towards the precision phase

- Use pure thermal neutron beam

→ TRIGA Mark-II reactor at Atominstitut (Vienna)

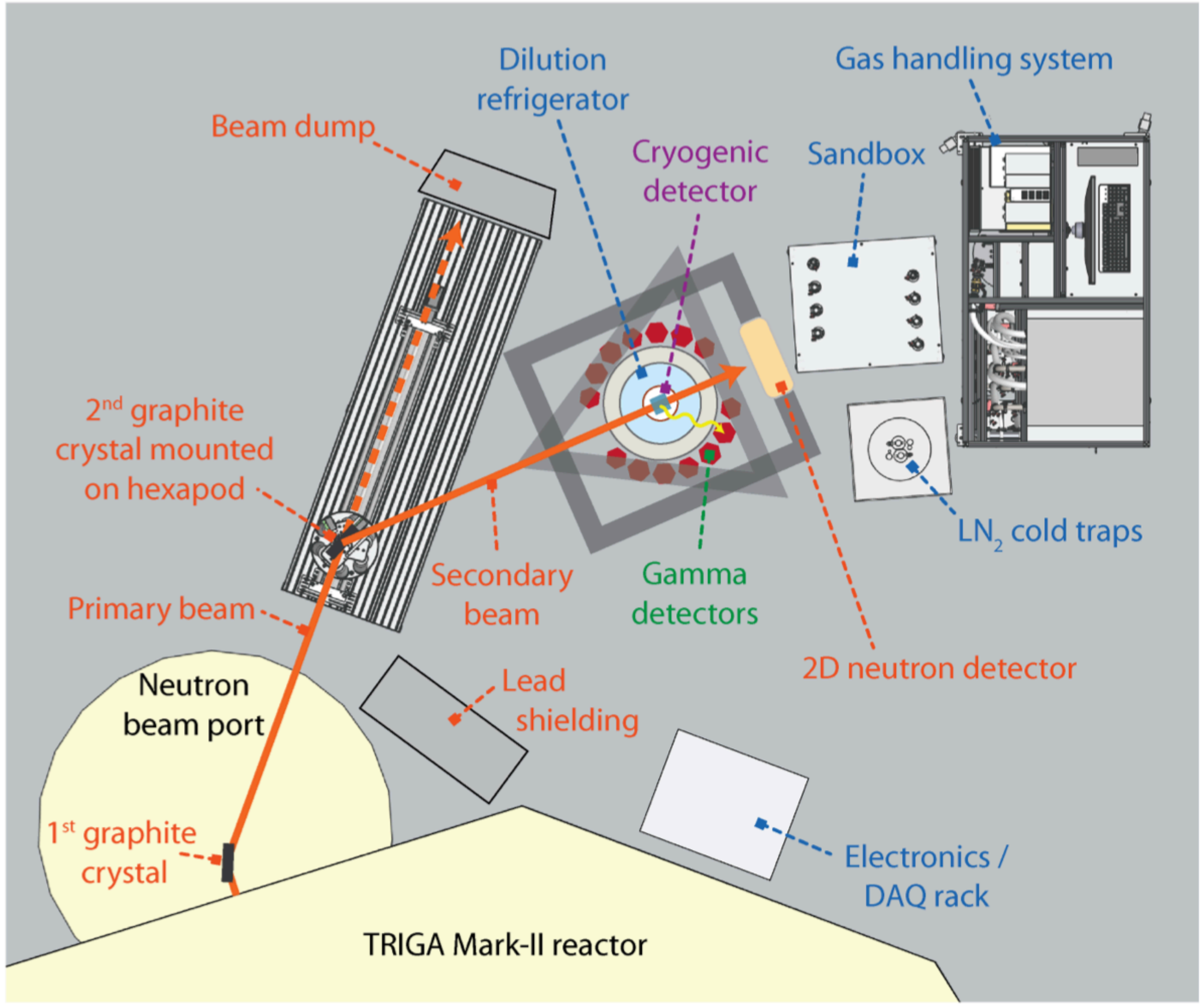
- Tag MeV gammas with dedicated detectors

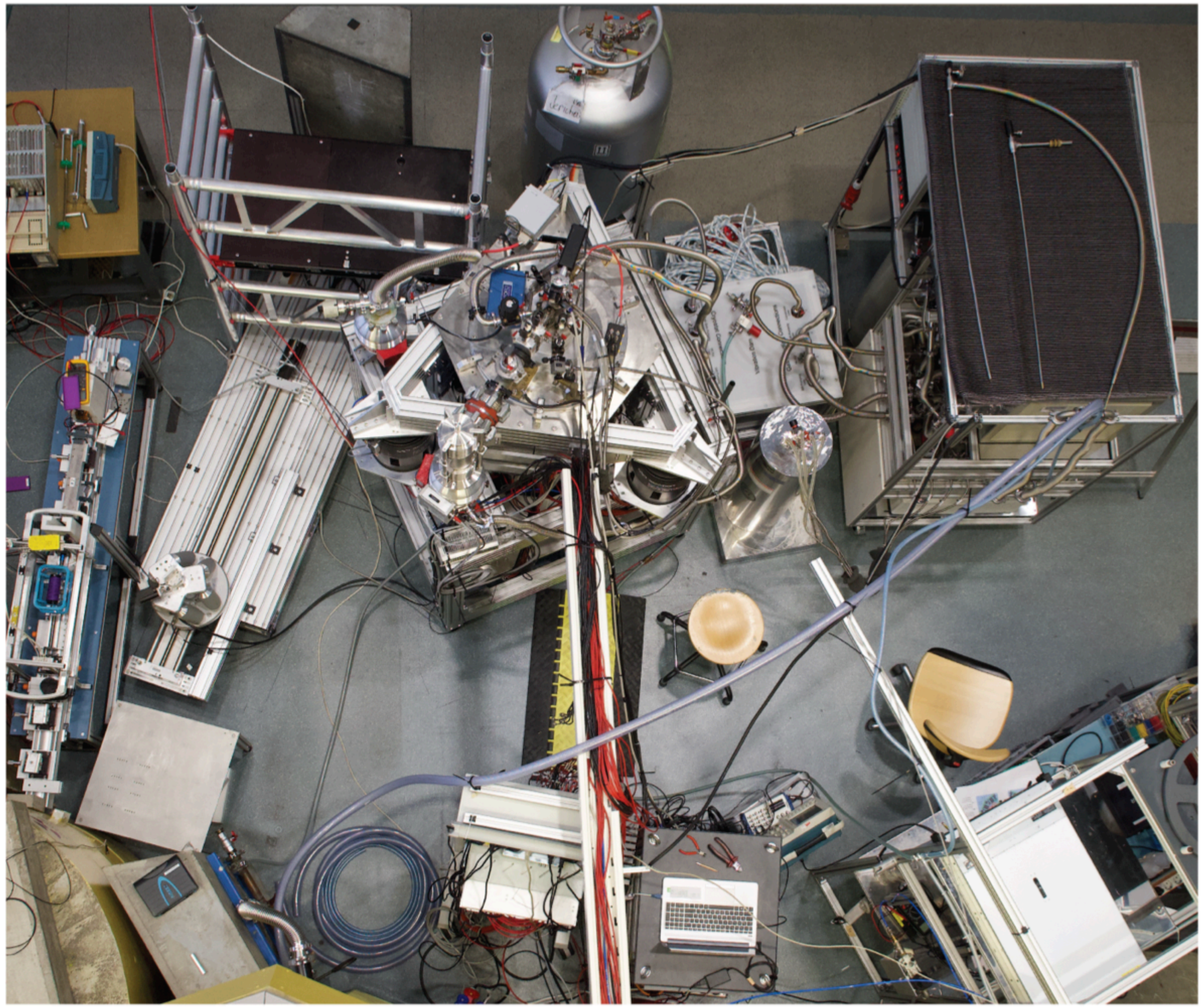


→ BaF_2 detector array

Commissioning in 2024 @TRIGA

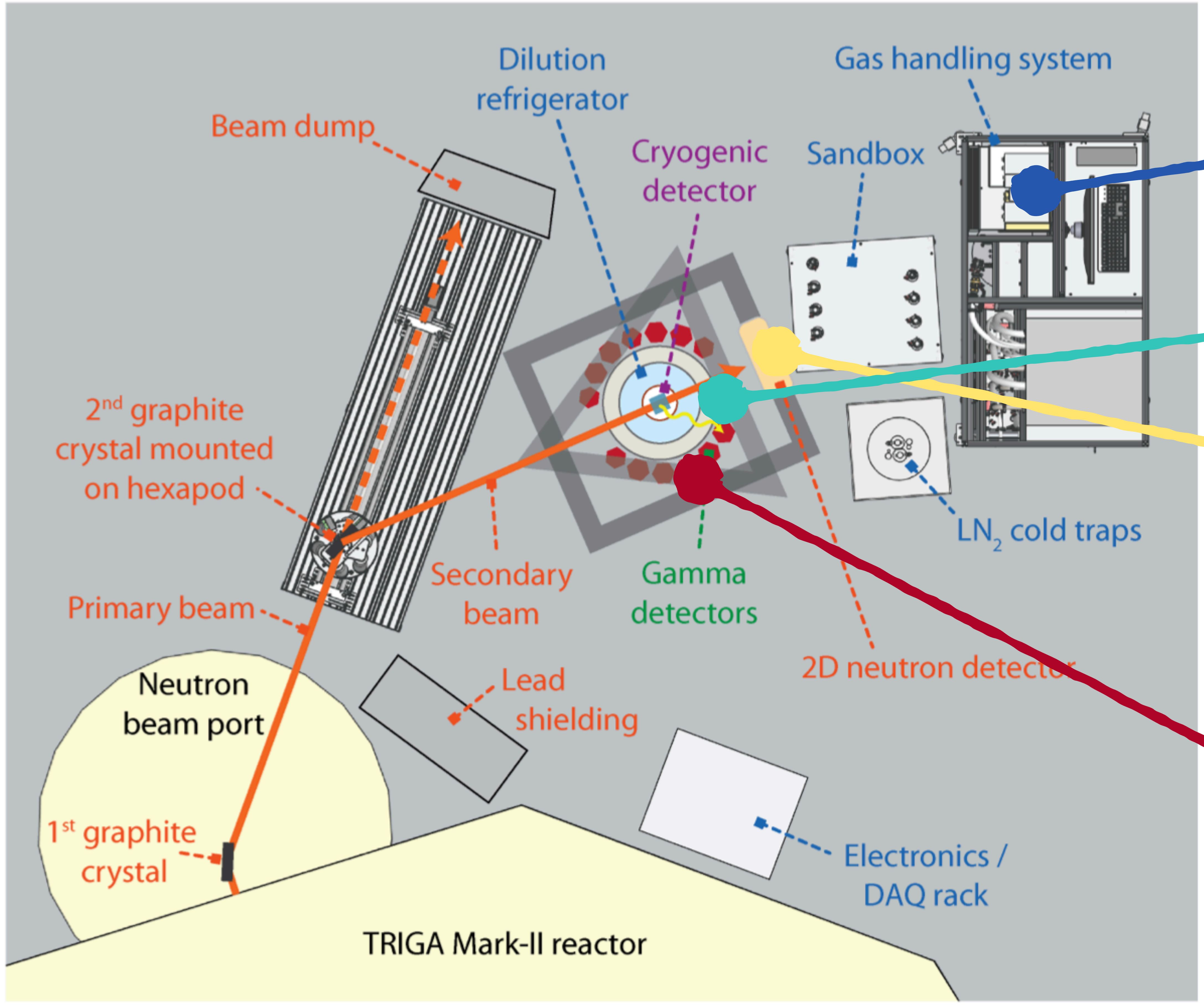
arXiv:2505.15227, accepted by EPJC

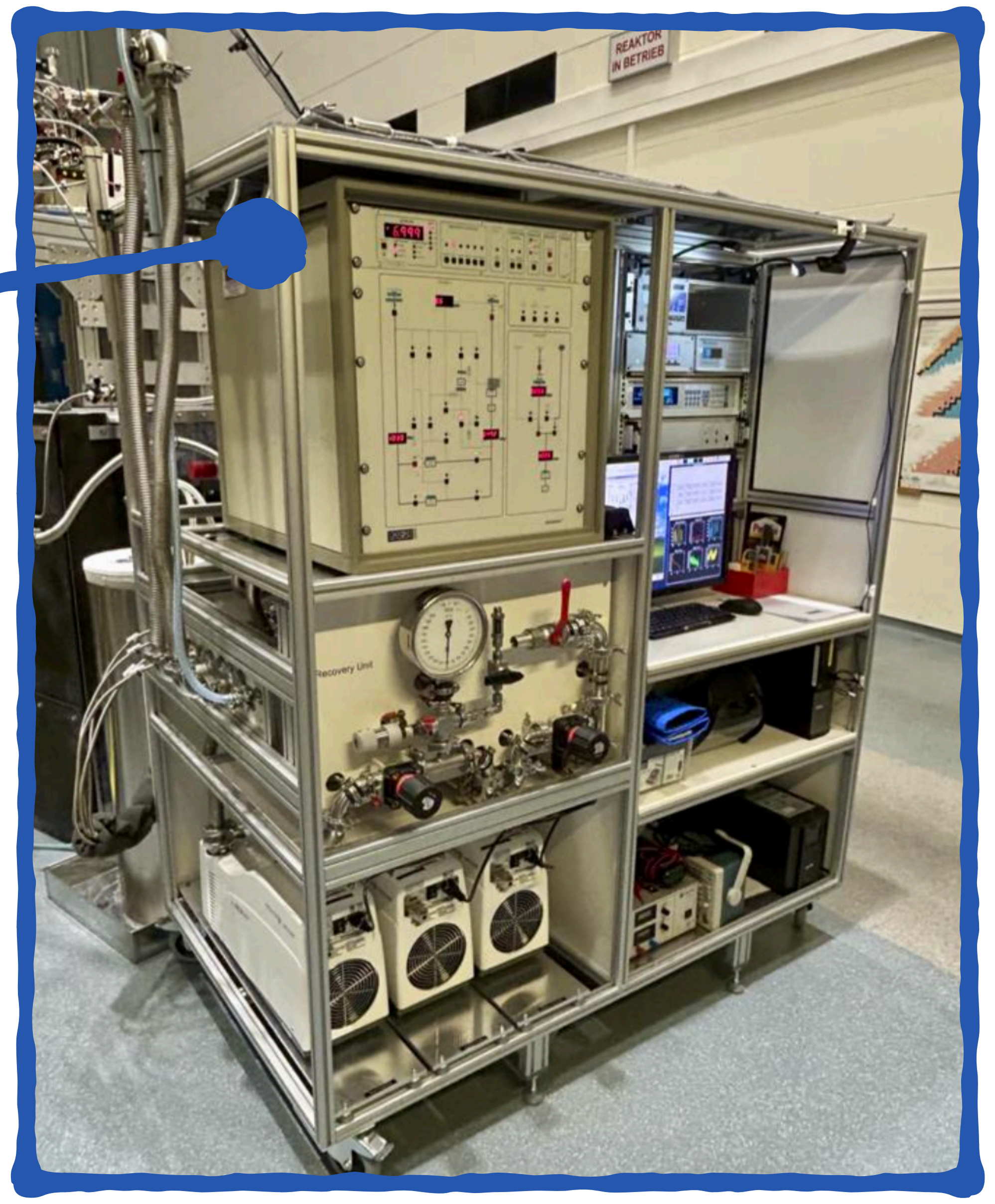


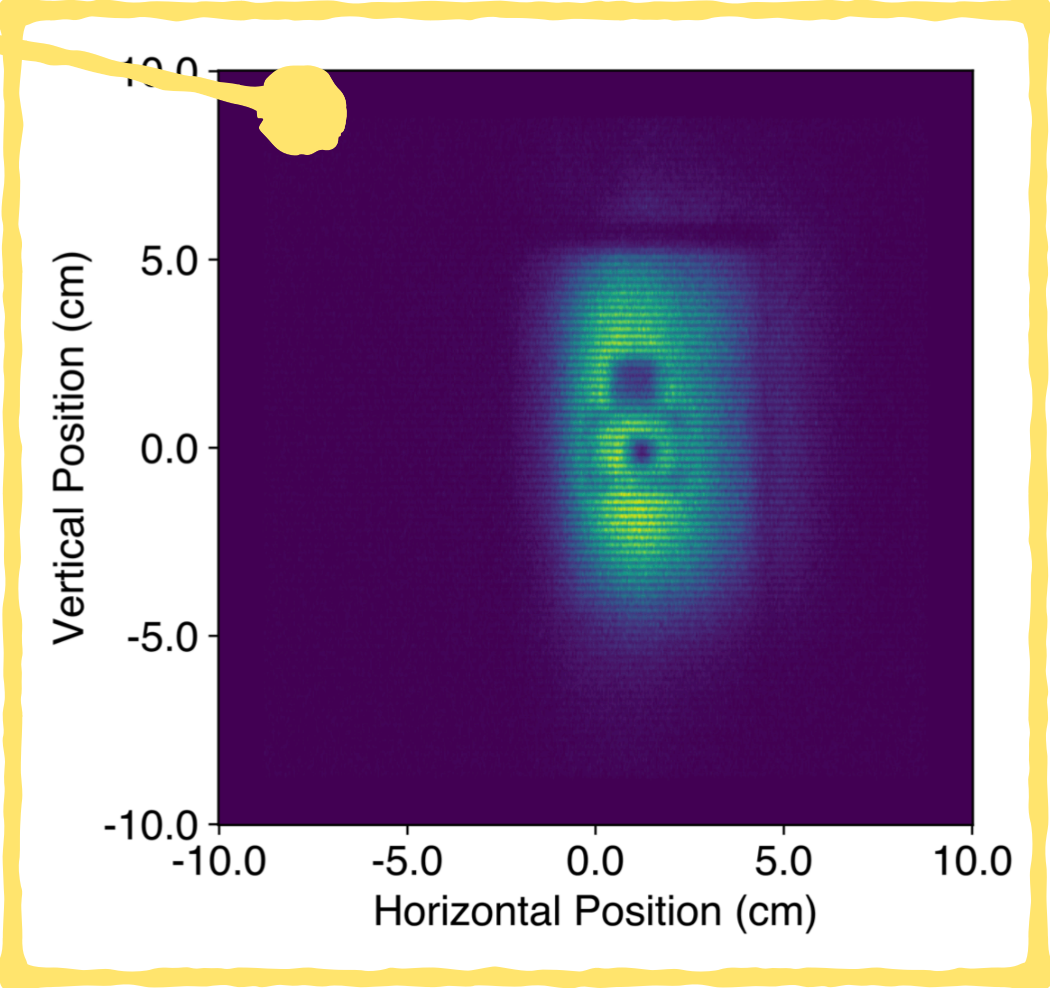


The setup

[arXiv:2505.15227](https://arxiv.org/abs/2505.15227), accepted by EPJC





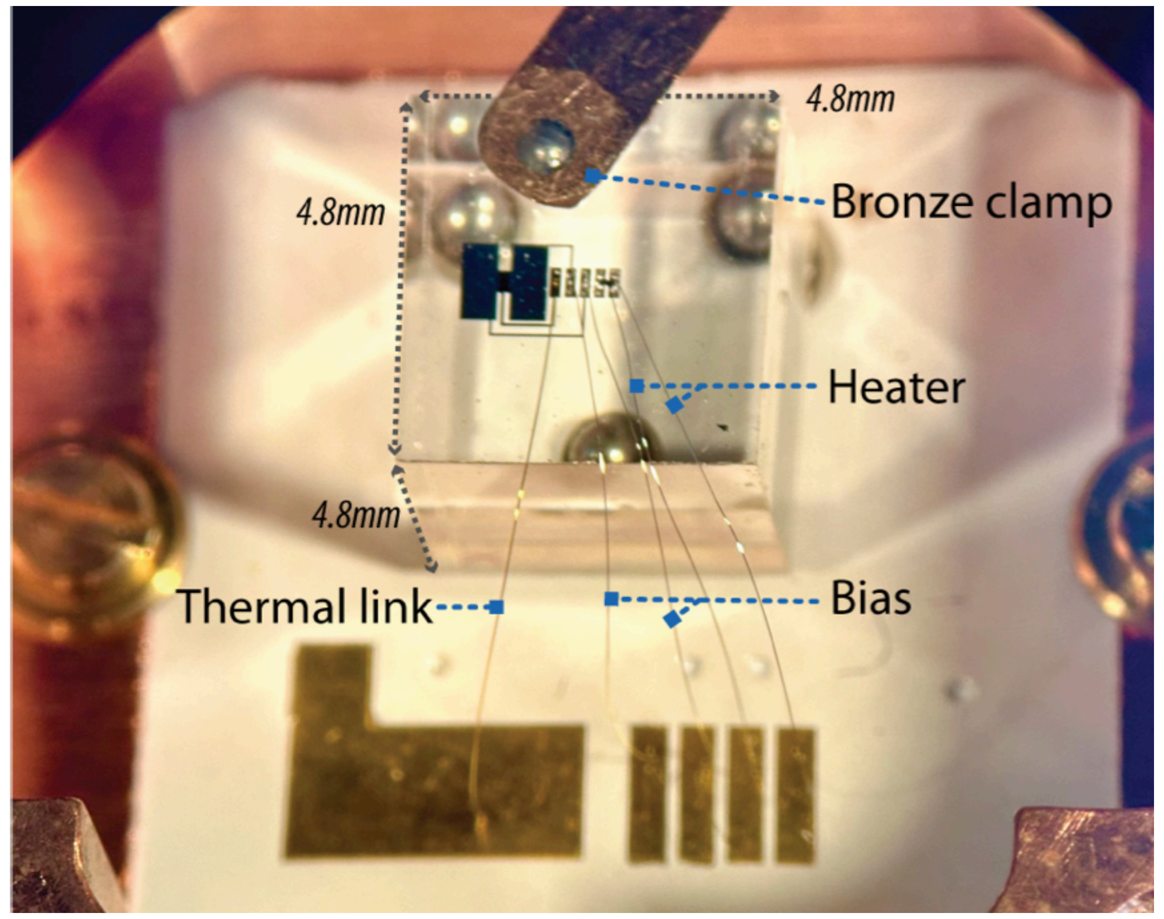


Commissioning results from a $CaWO_4$ detector

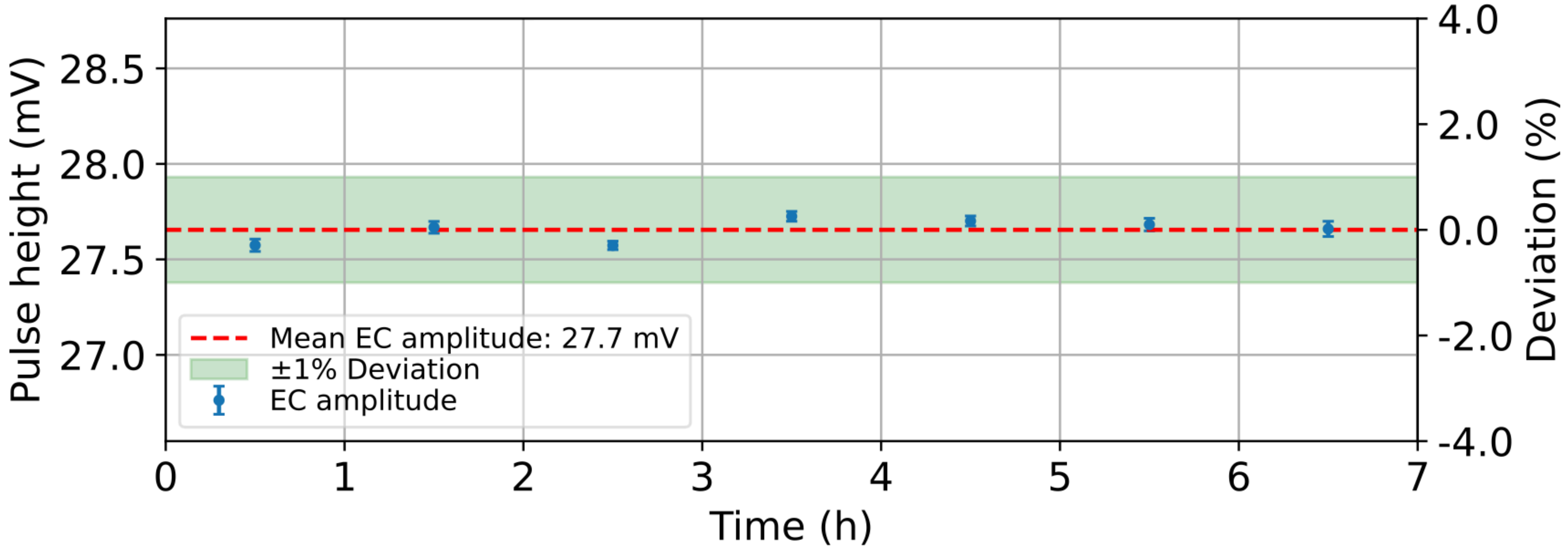
- 0.7 g CaWO4 detector
- Challenging noise condition, baseline resolution >20 eV
- Energy threshold above the CRAB peaks

- But, stable detector operation during beam ON
- And (unintentional) low detector gain
- Unique probe for high-energy counterpart of neutron capture (above 10 keV)

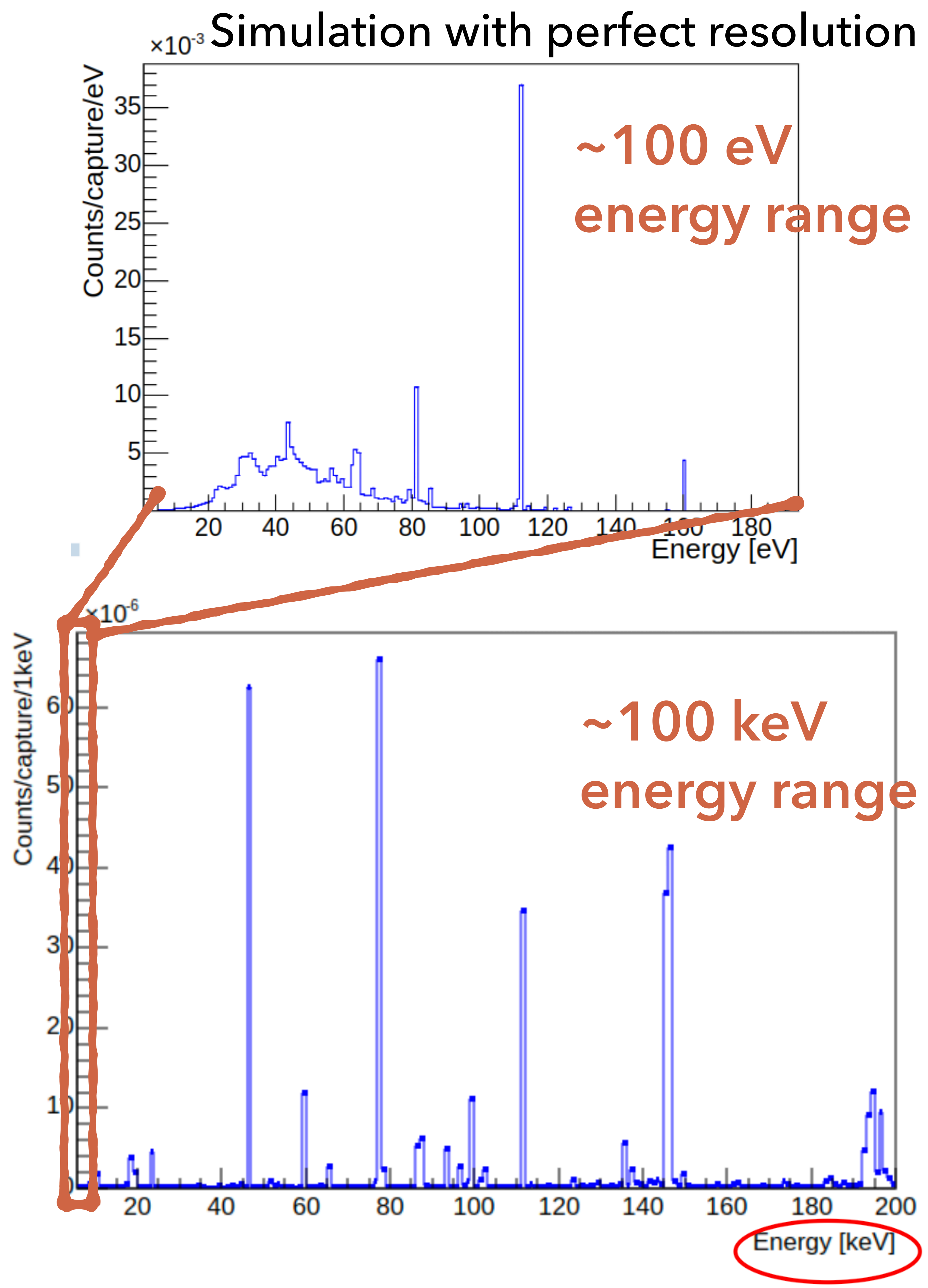
arXiv:2505.15227, accepted by EPJC

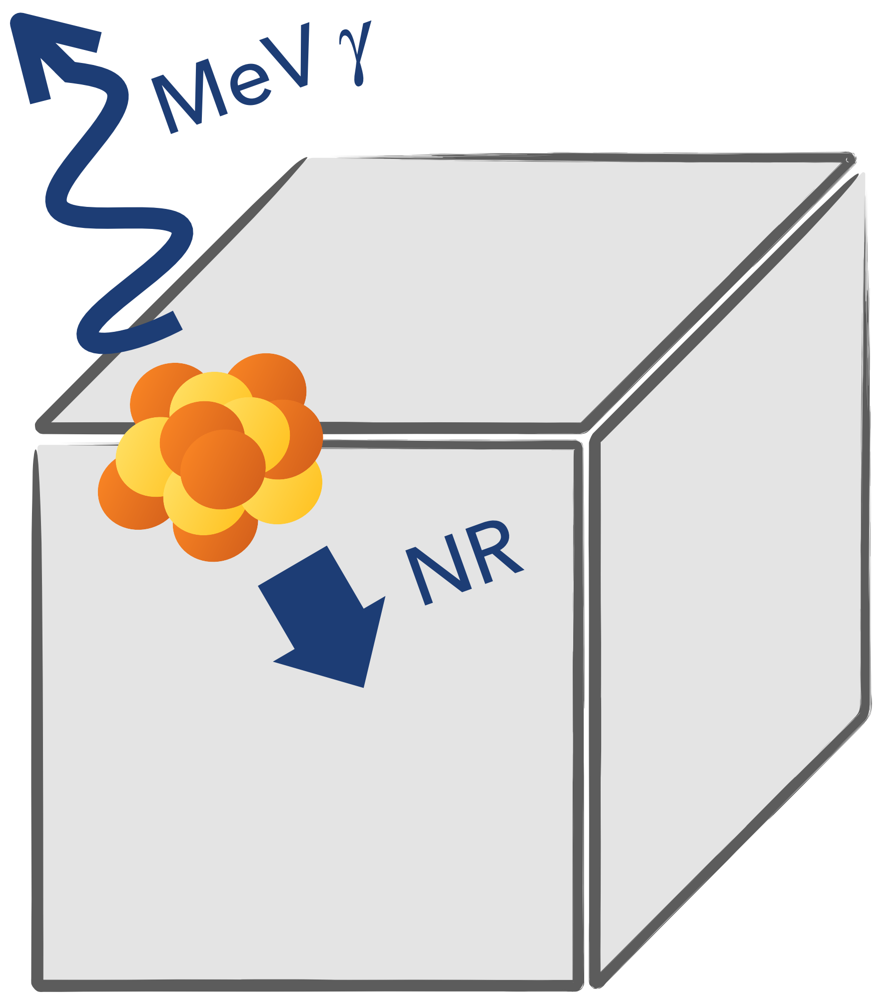


Beam ON, events from 47 keV electron conversion line

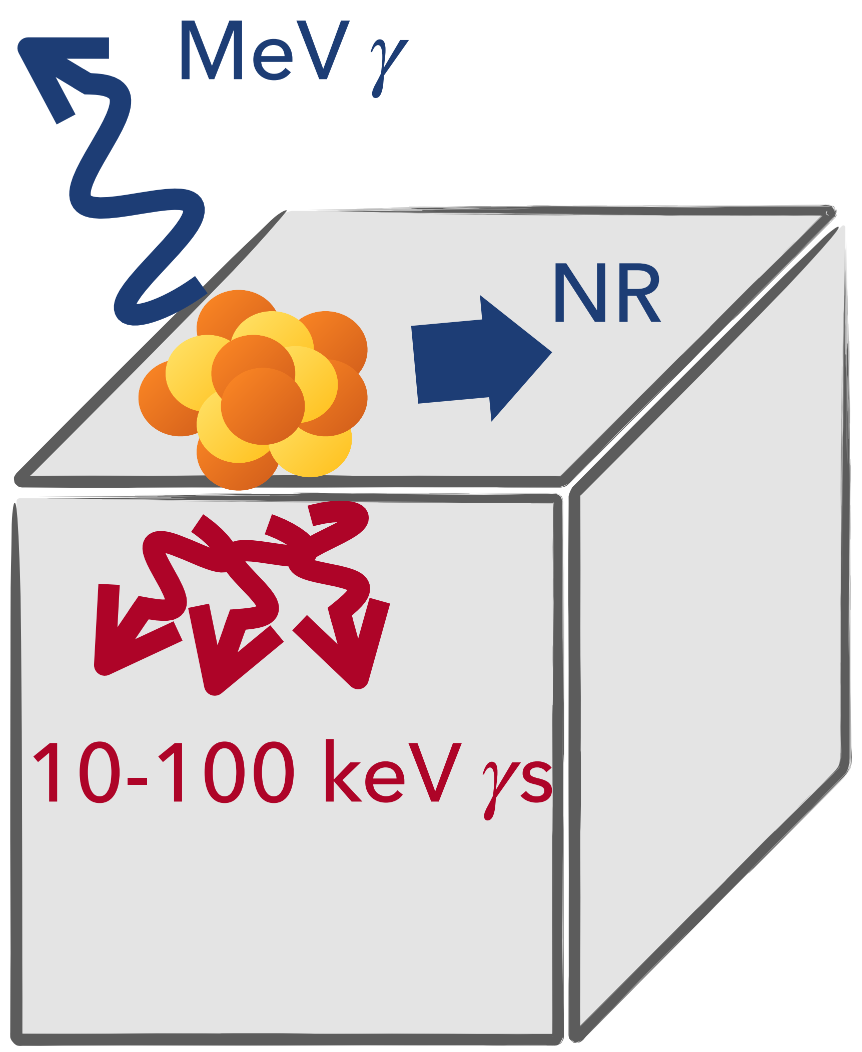


High energy CRAB events from multi-γ cascade





CRAB measurement goal: not accessible yet



High energy events from multi-γ cascade:

- validate signal and background simulations
- validate coincidence detection

Results: time evolution of event rate

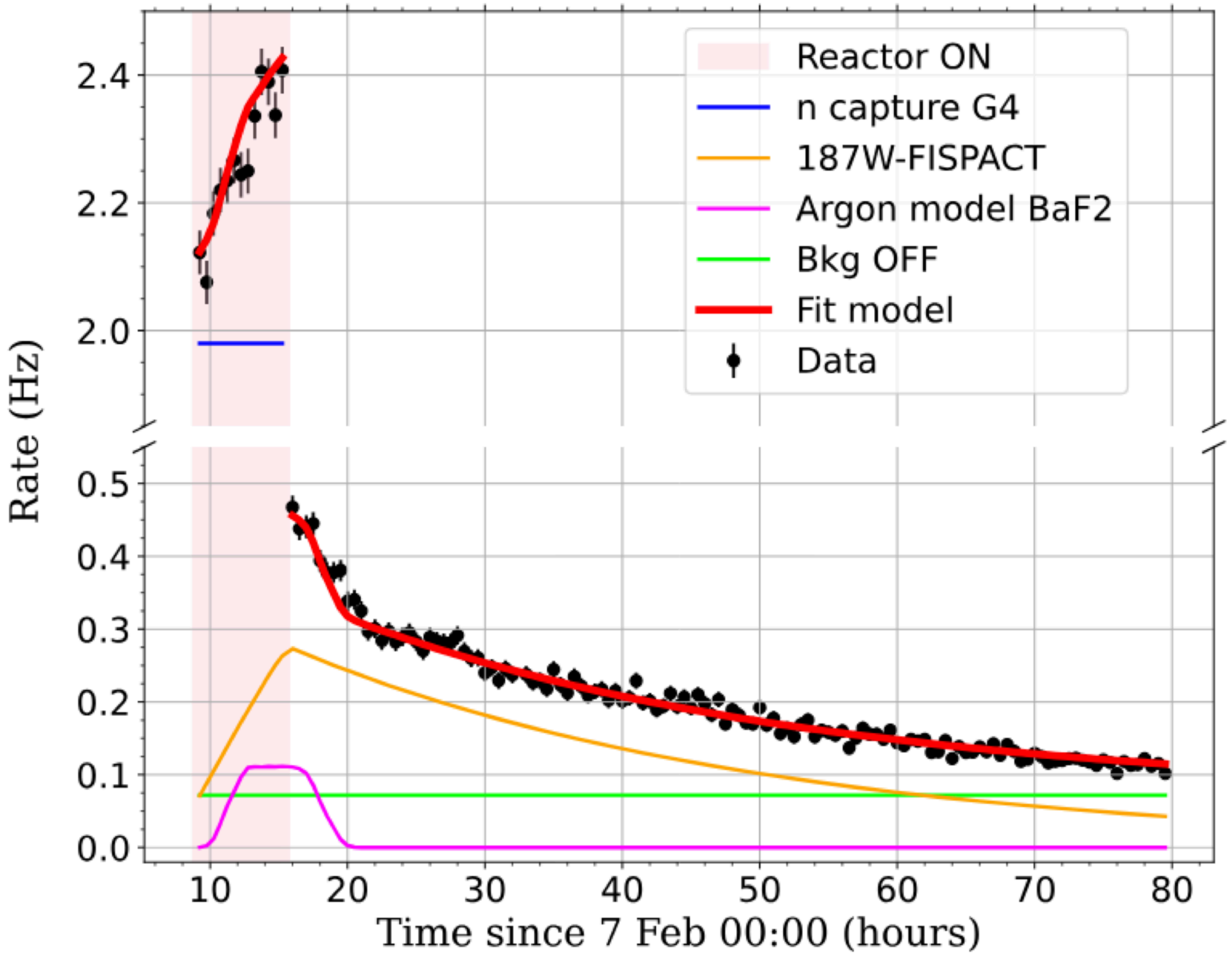
- Rate of events above 20 keV
- Fit with 4 contributions (3 free parameters): neutron capture + decay of ^{187}W (both proportional to the neutron flux), background from ^{41}Ar activation, constant background

Fitted neutron flux: ϕ_n=(442±2) cm^{-2} s^{-1}
Measured : ϕ_n=(469±47) cm^{-2} s^{-1}

- Excellent data/model agreement: validation of our understanding of signal and background components

7h beam ON　　Weekend beam OFF

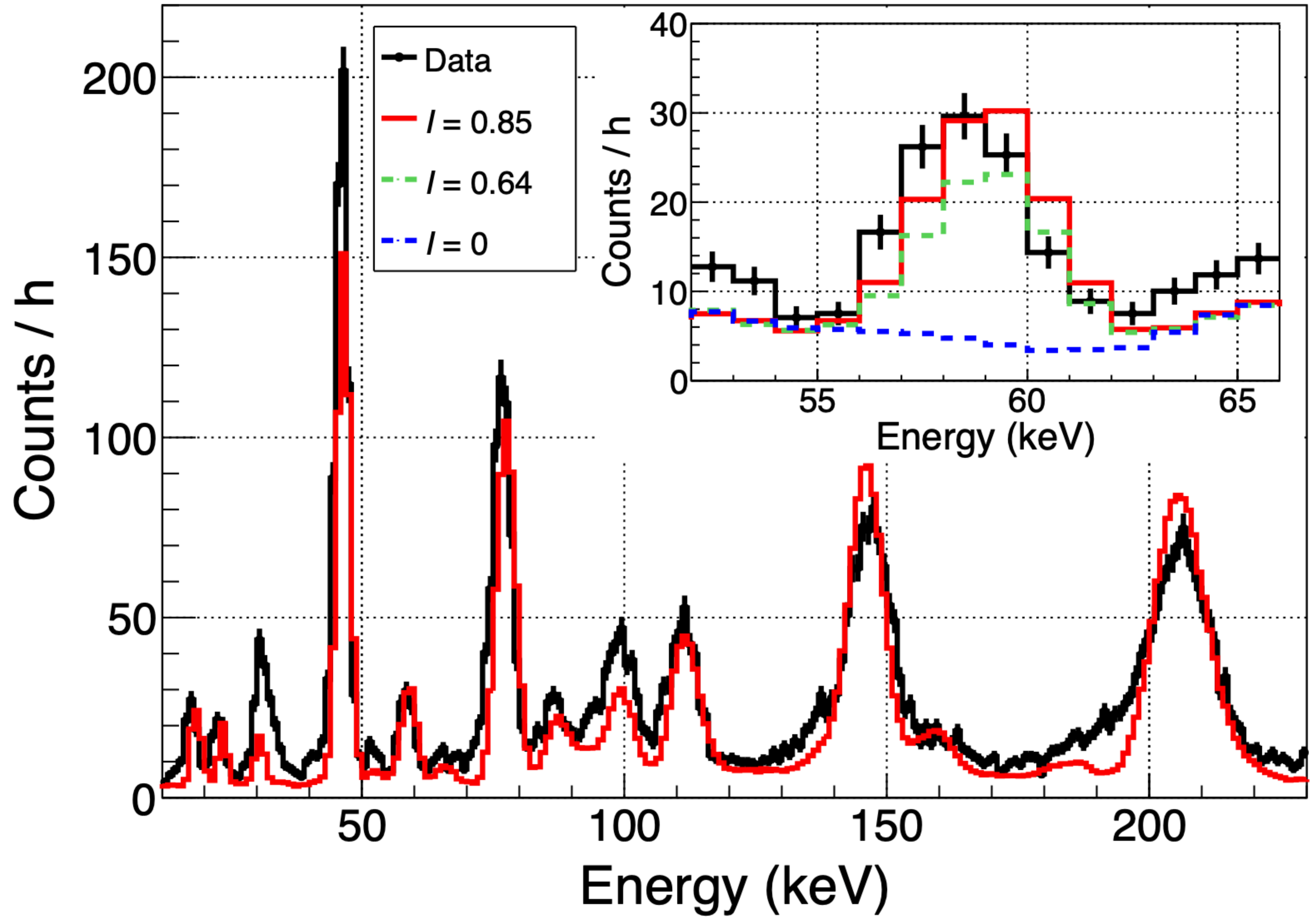
arXiv:2505.15227, accepted by EPJC



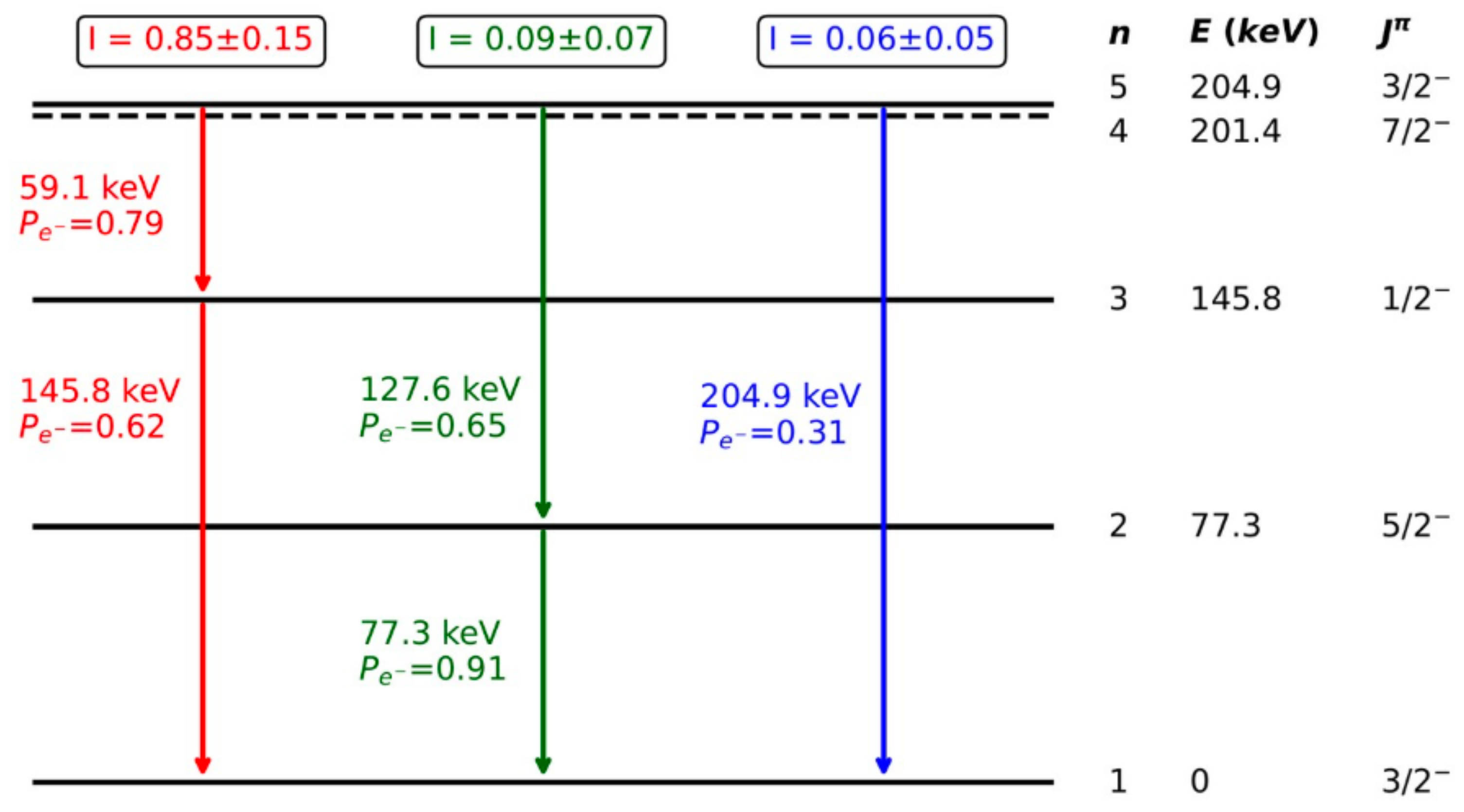
Results: energy spectrum of beam induced events

arXiv:2505.15227, accepted by EPJC

7 h of beam ON data

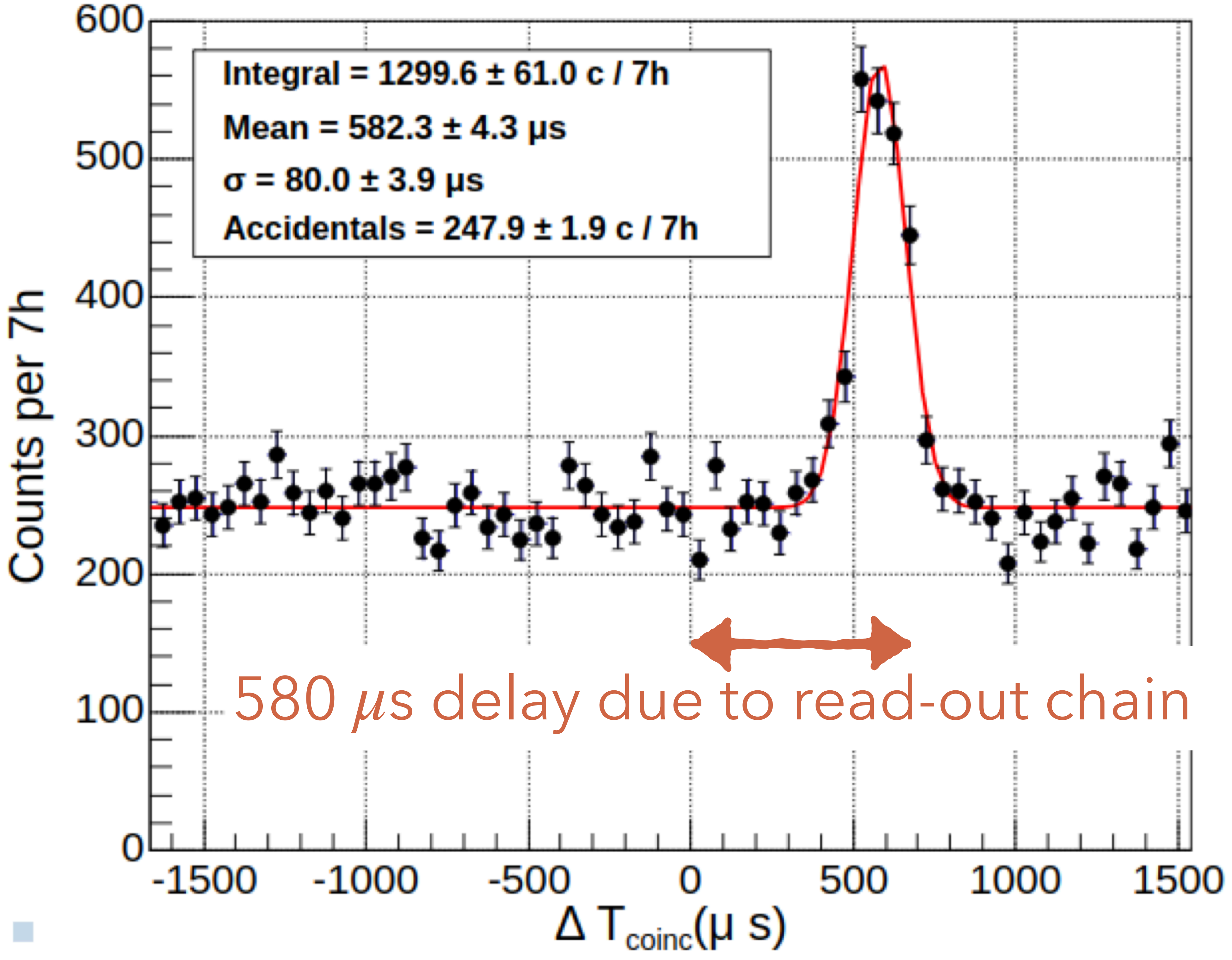


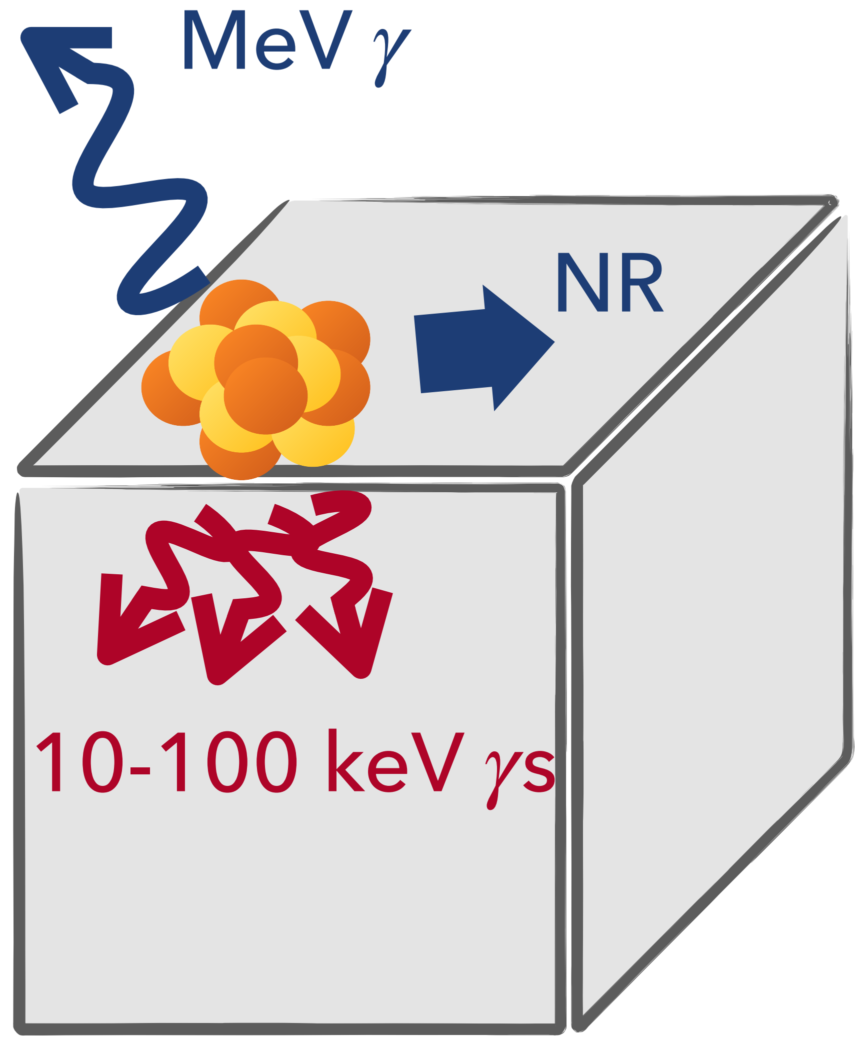
- Beam induced background in $CaWO_4$
- Above 20 keV, several electron conversion lines visible
- Very good agreement between data and simulation
- Update of ^{187}W decay scheme: one peak with missing input in nuclear database



Results: γ-cryodetectors coincidences

- Time difference between events in cryodetectors and γ detectors





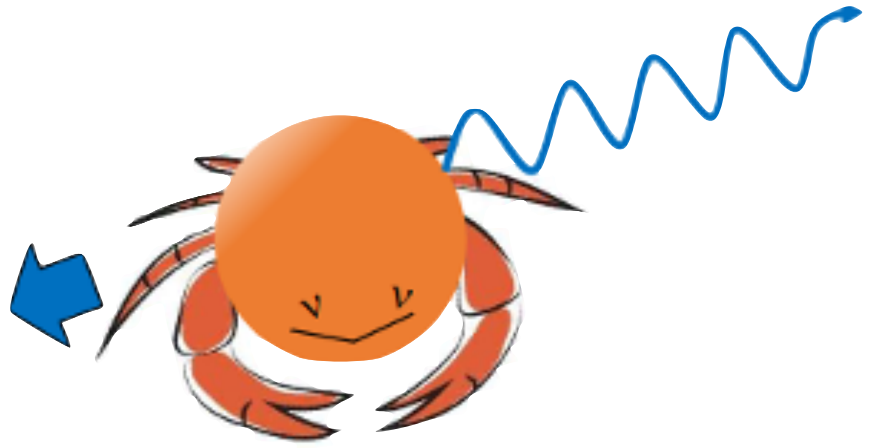
- First observation of neutron-capture induced coincidences!

arXiv:2505.15227, accepted by EPJC

Perspectives: improvements & physics program

- Planned improvements:
  - Improvement of current setup to reach target energy resolution: electronic noise reduction, μ-metal shielding around the cryostat
  - Integration of complementary calibration methods: LED system/XRF source
  - Preparation for implementation of double readout heat/ionization of Ge detectors (TESSERACT/RICOCHET)

2024 — CRAB facility commissioned @TRIGA



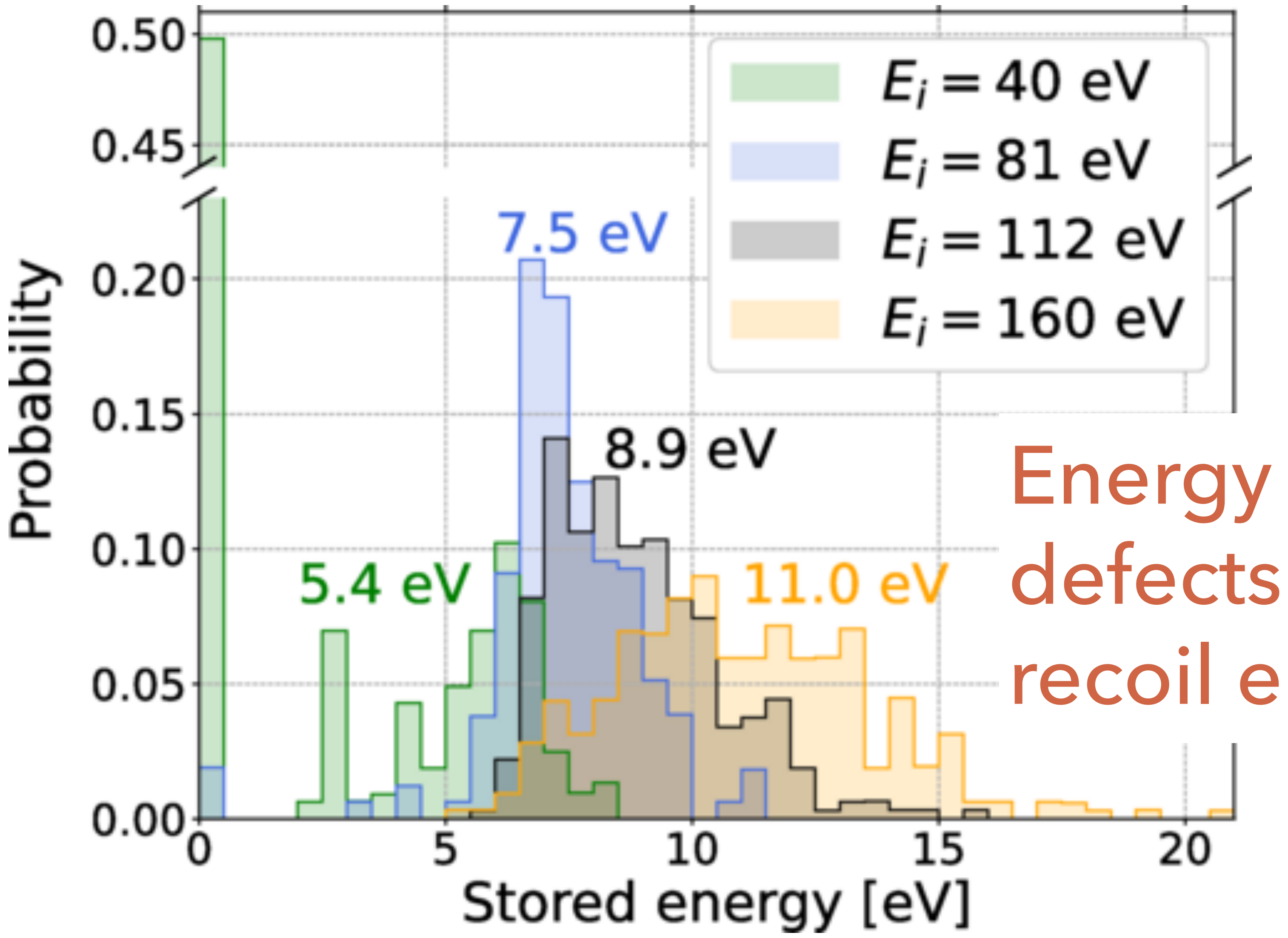
2025 — Experimental program with $CaWO_4$ and Al_2O_3

2026 — Experimental program with Ge

$CaWO_4$: stored energy in crystal defects

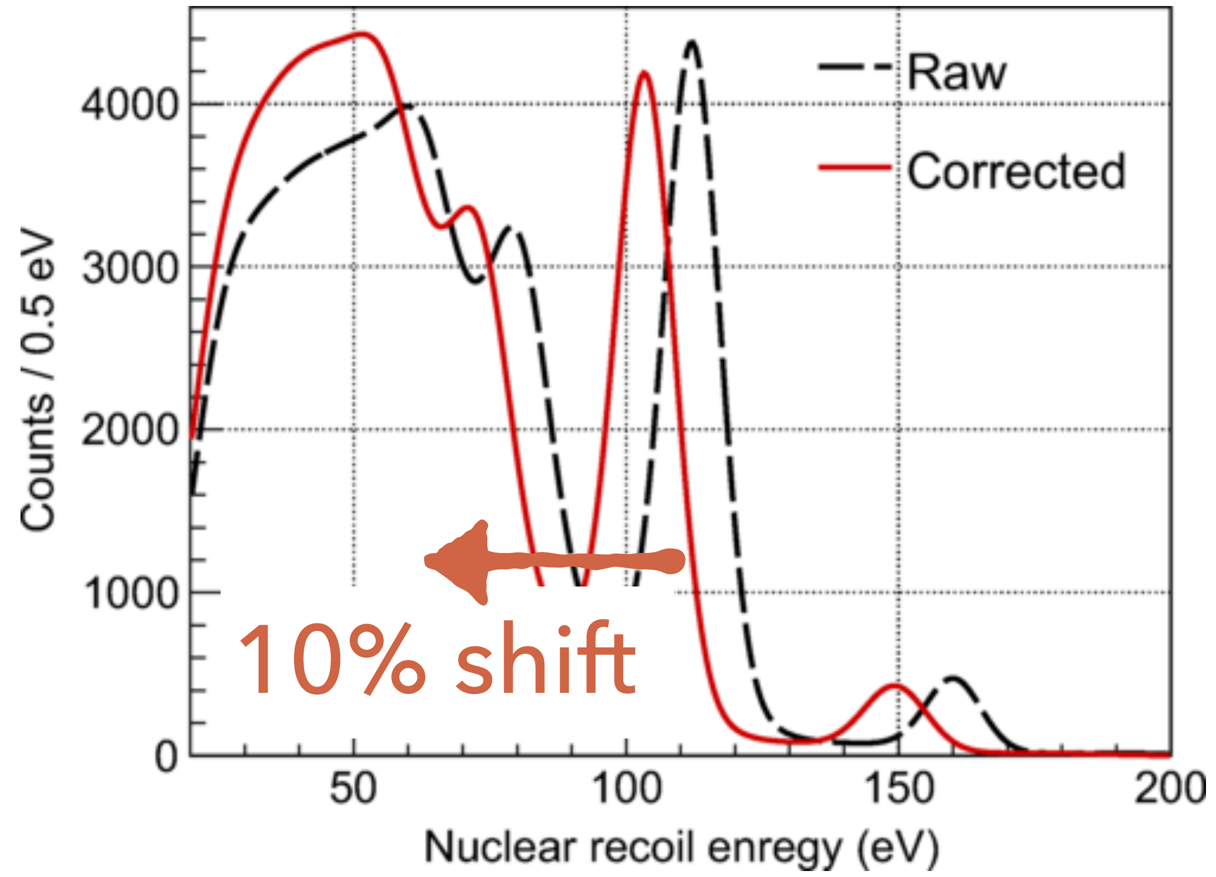
[Phys. Rev. D 111, 085021]

- At low energies, atomic scale material effects become important
- Part of the energy deposited in the target material can be stored in crystal defects created in the process
- Molecular dynamics simulation in $CaWO_4$ with a data driven machine learning interatomic potential to predict Dark Matter and CEvNS spectra

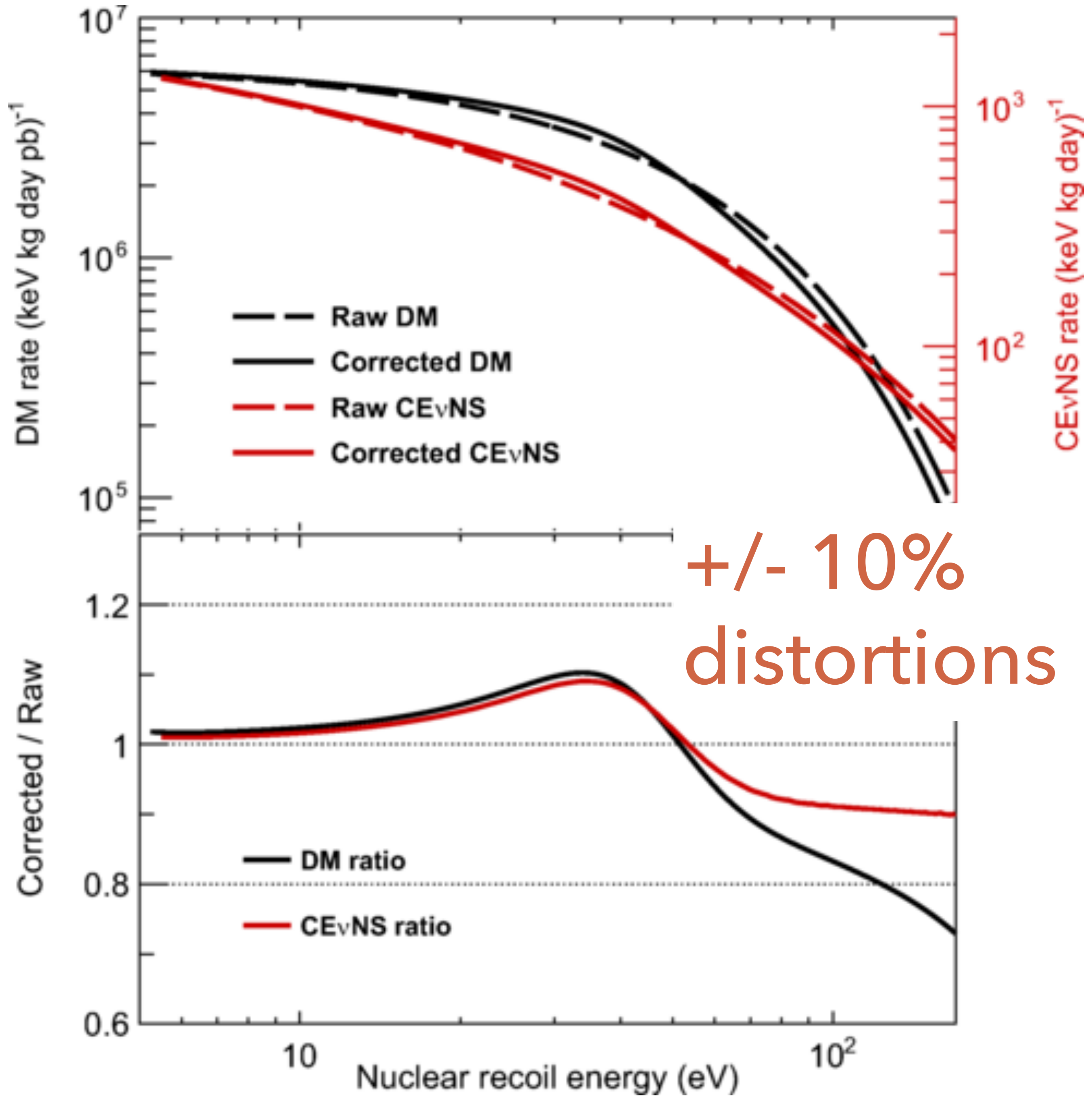


Energy stored in defects for different recoil energies

CRAB spectrum corrected for energy stored in defects



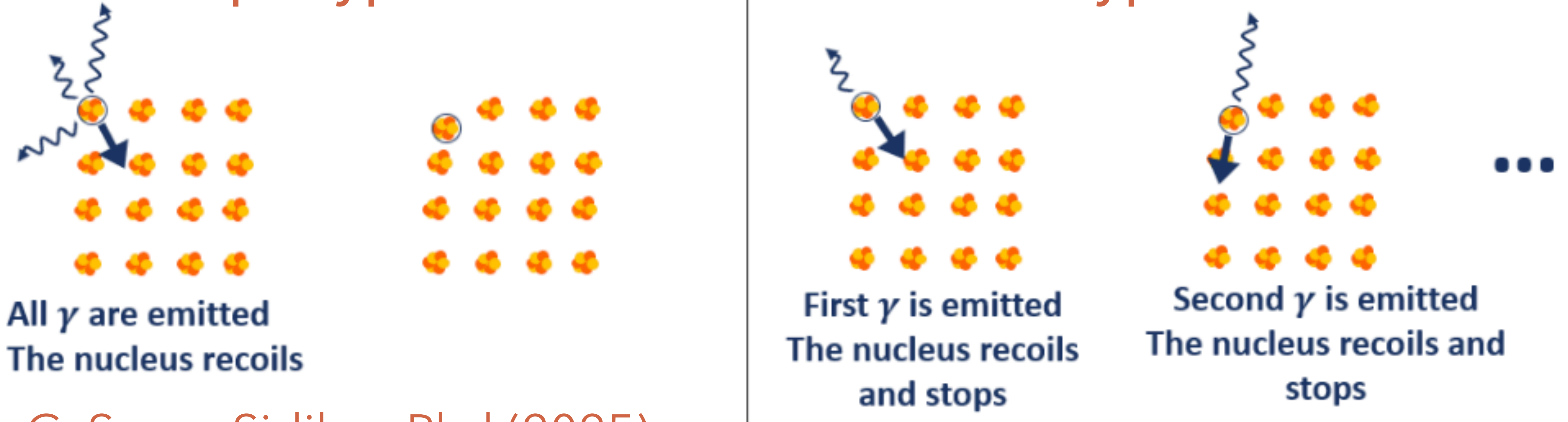
Predicted effect on Dark Matter and CEvNS spectra



Al_2O_3: timing of multi-γ cascade

- The recoil energies in a multi-γ cascade depend on the interplay between the recoil stopping time and the timing of the γ emission

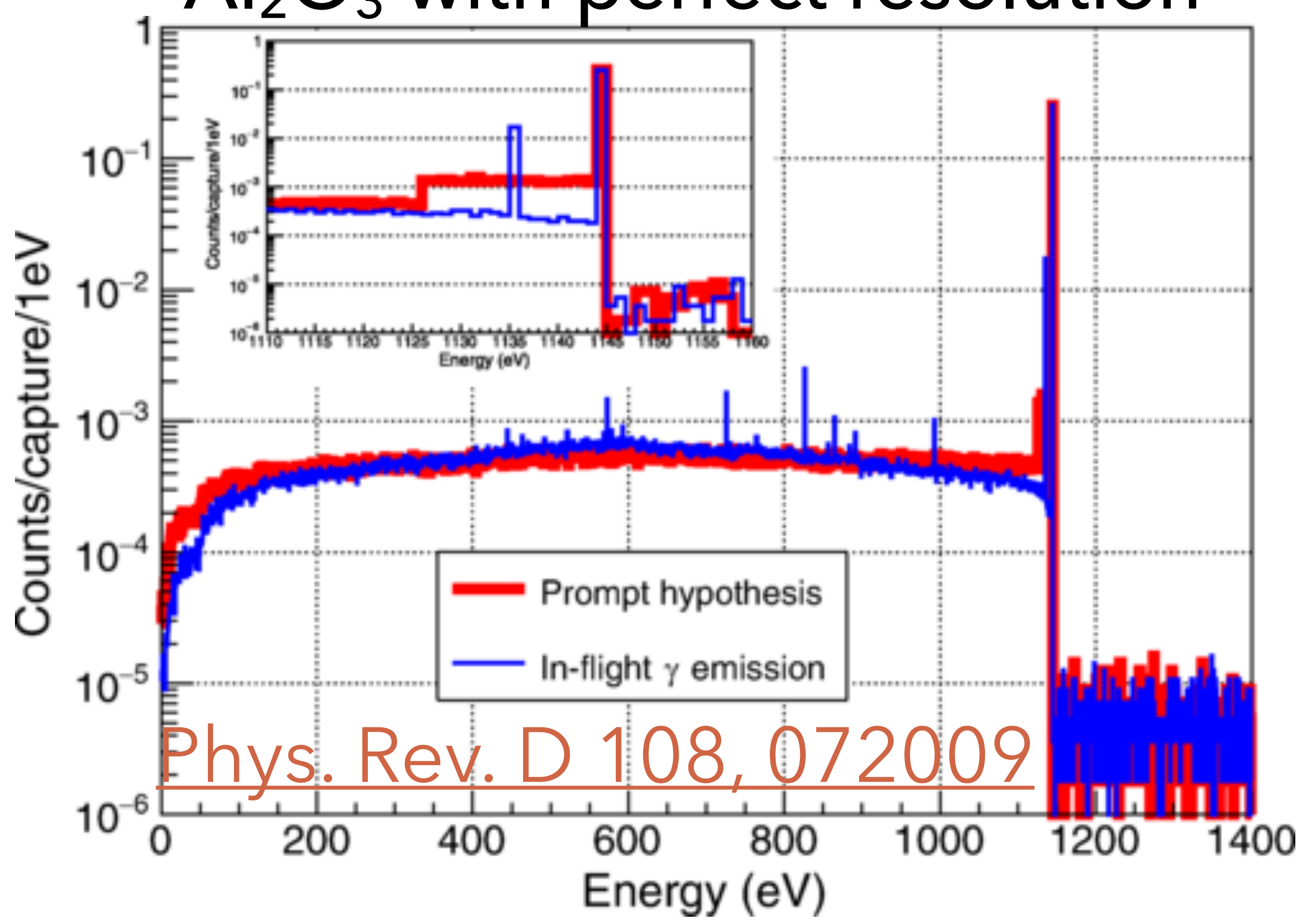
Prompt hypothesis | Slow hypothesis



G. Soum-Sidikov Phd (2025)

- Cascades might fall in one or the other hypothesis (or somewhere in between) depending on the nucleus stopping time and characteristic lifetimes of accessed nuclear levels

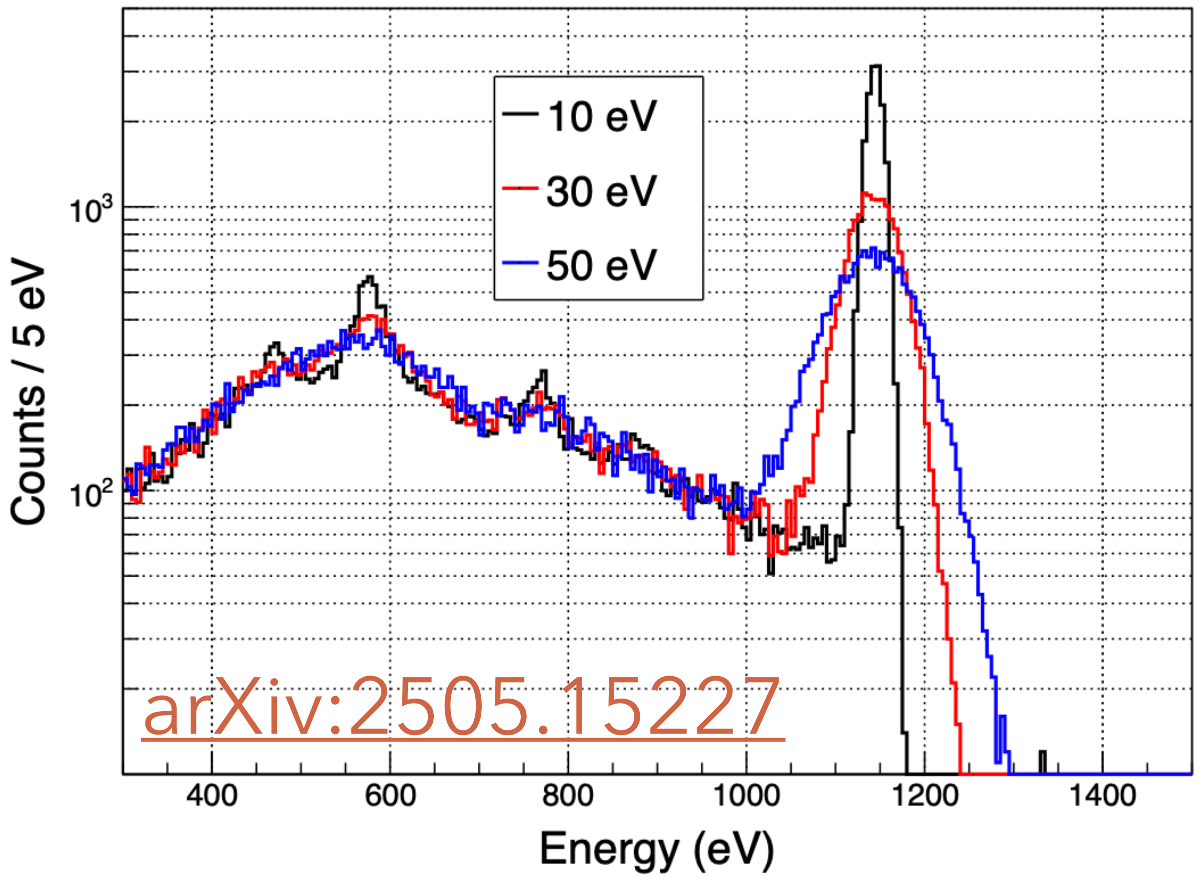
Al_2O_3 with perfect resolution



Phys. Rev. D 108, 072009

Additional peaks at fixed energies when taking into account such timing effects

Al_2O_3 with finite resolution

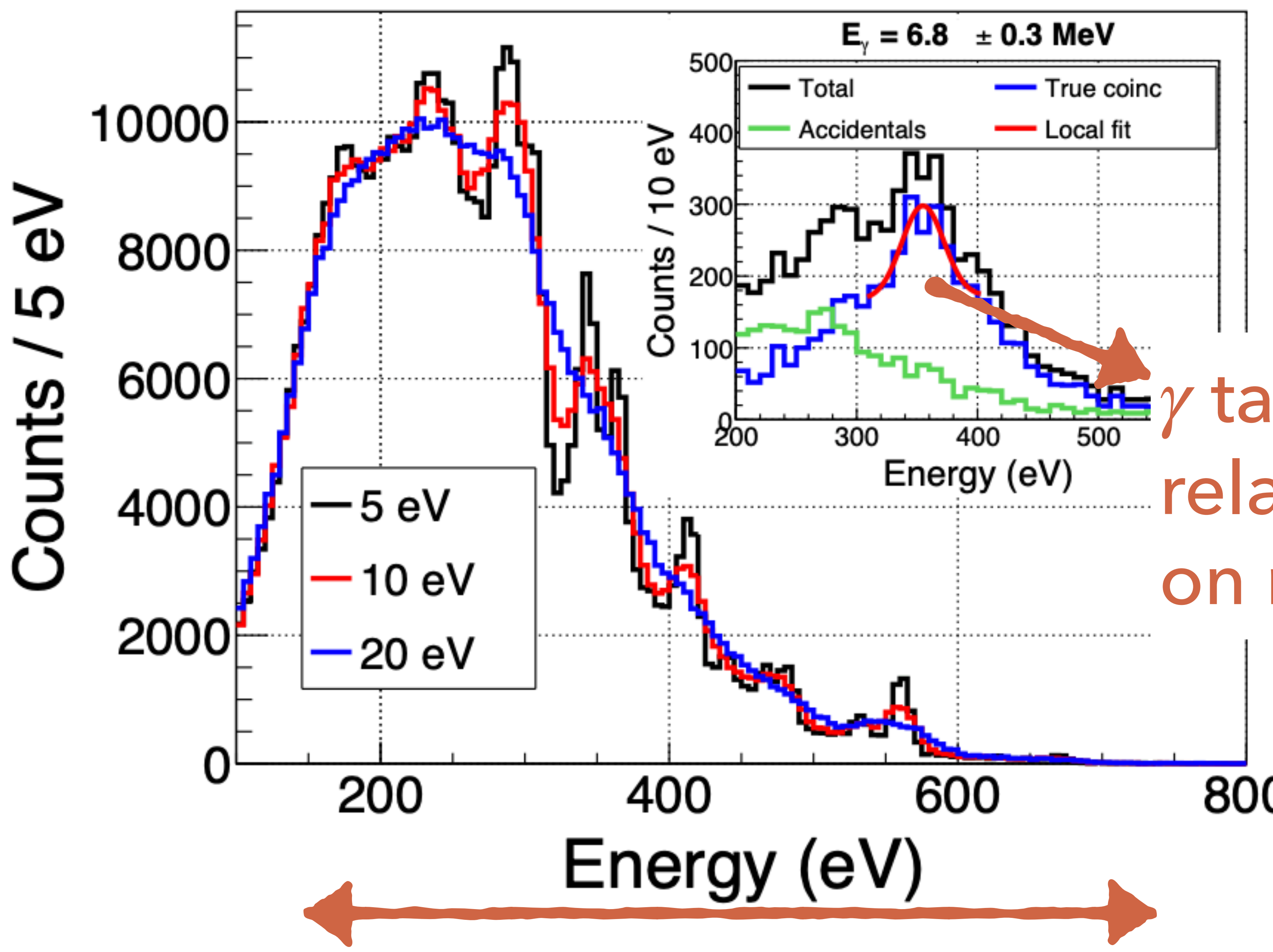


arXiv:2505.15227

Ge: quenching factor at sub-keV

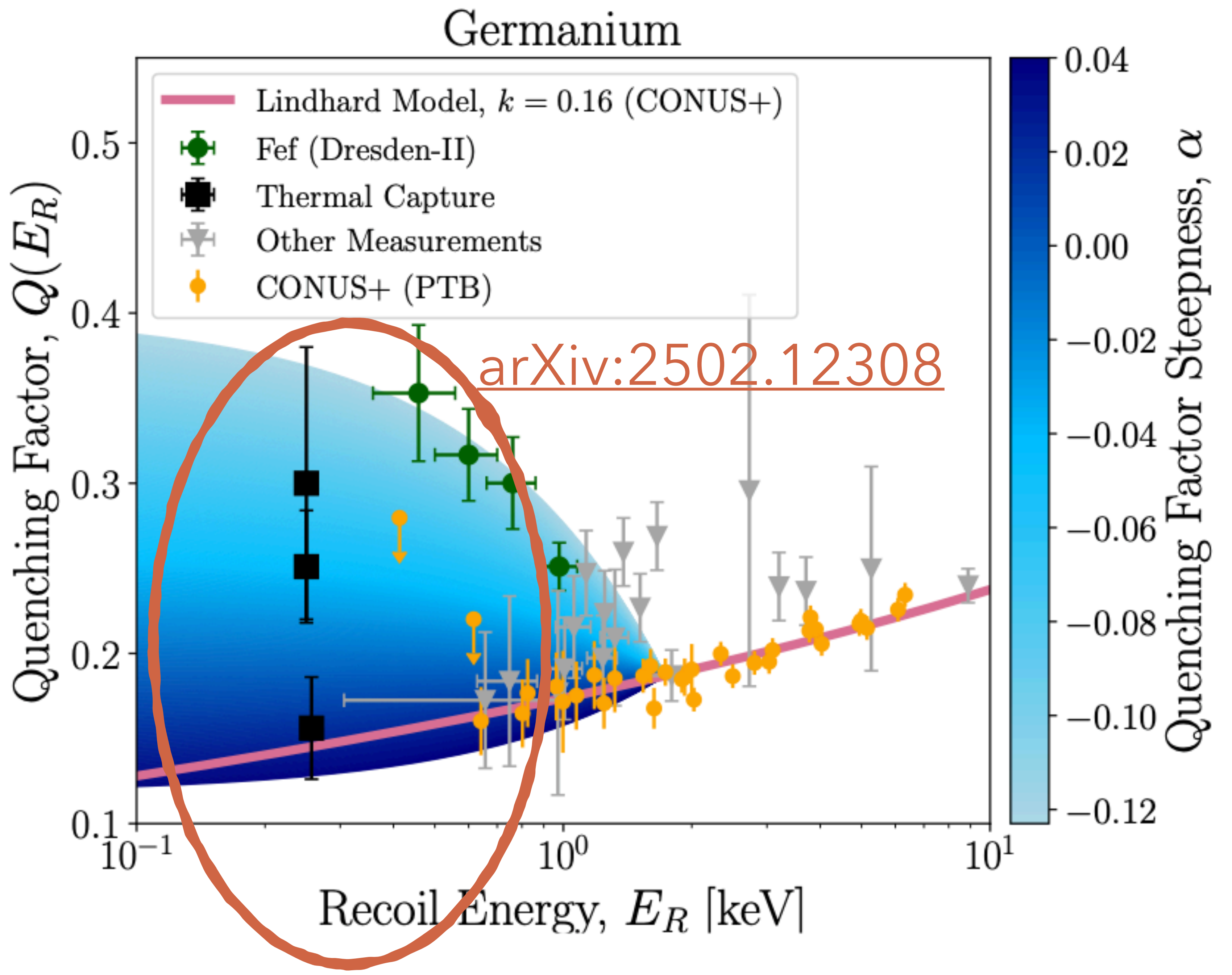
- CRAB measurement with a dual ionization/phonon read out Ge detector (TESSERACT)
- Multiple sub-keV nuclear recoil peaks predicted: study nuclear recoil energy scale and ionization yield (quenching factor, $Q(E_R) = E_{ion}/E_R$)

Resolution is crucial:



100-700 eV

γ tagging to relax constraints on resolution



Quenching factor puzzle

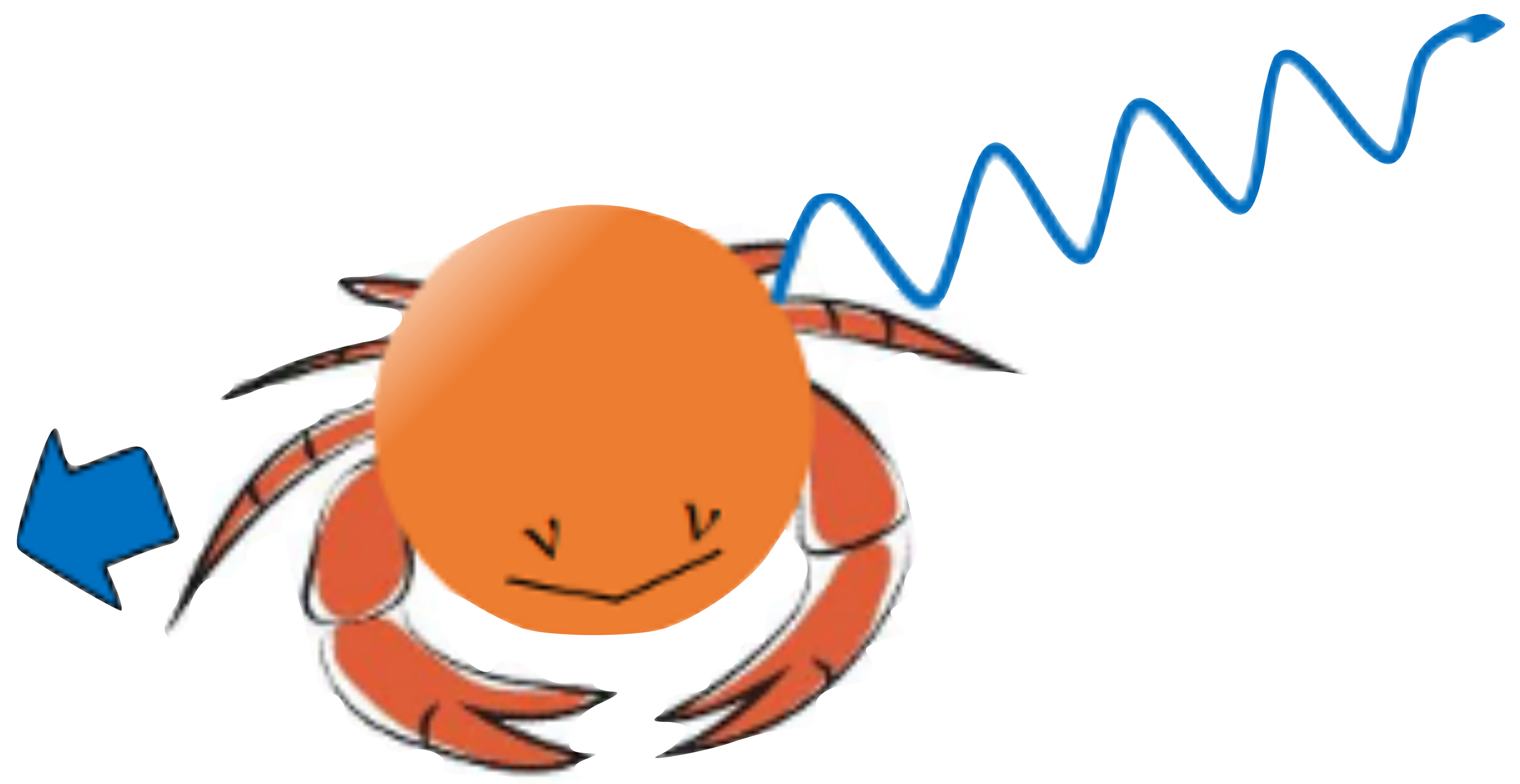
Conclusions

- The CRAB method provides a sub-keV nuclear recoil calibration
- Unique signature equivalent to CEνNS and Dark Matter interactions

- The method was validated with a NUCLEUS detector in 2022
- A new facility for precision studies was commissioned at TRIGA Mark-II reactor in Vienna

- Rich experimental program ahead of us: $CaWO_4$ and Al_2O_3 (2025), Ge (2026), your favourite detector?

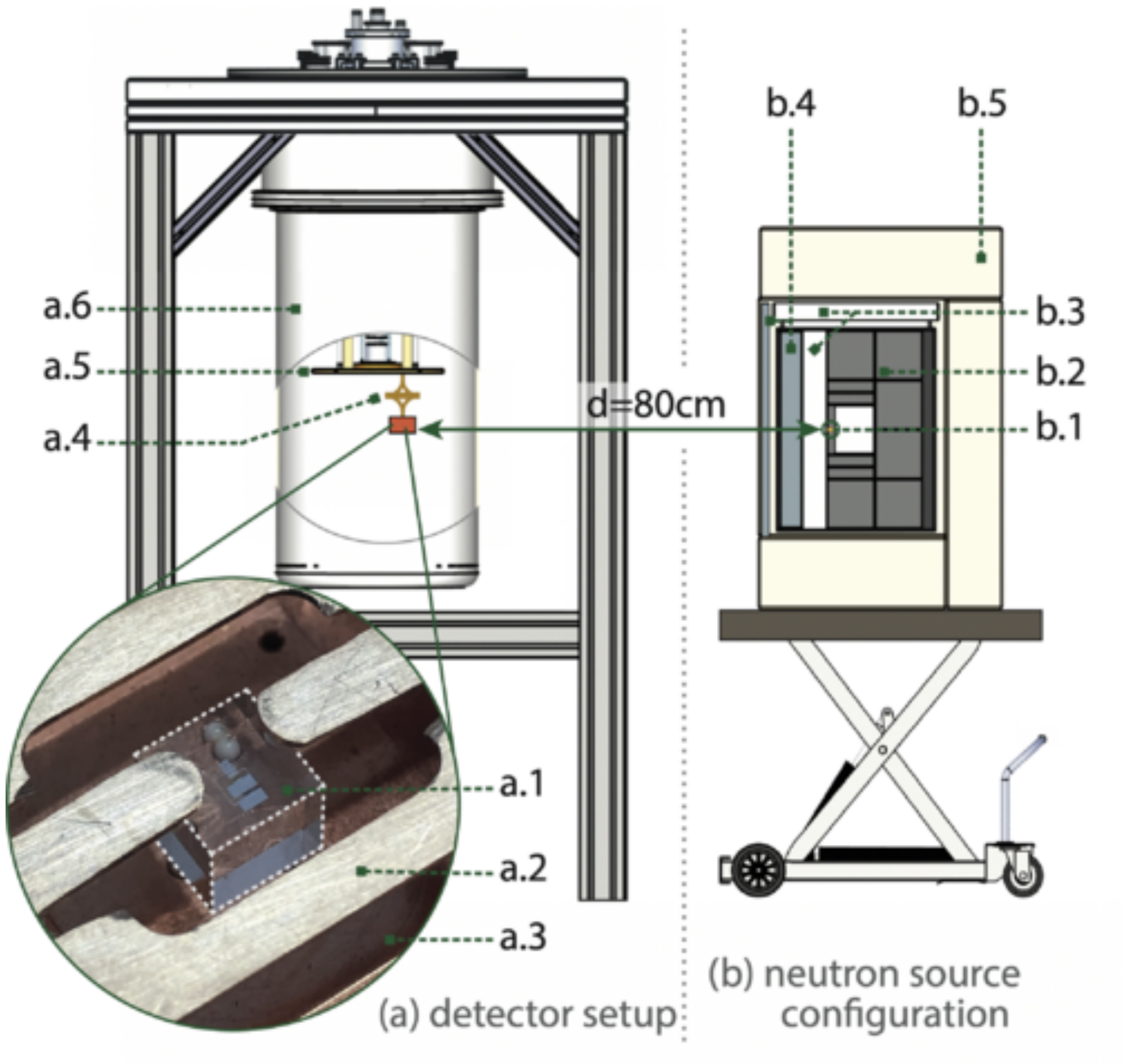
Thank you for your attention!



Backup

CRAB proof-of-principle

- Commercial ^{252}Cf source (3.54 MBq activity)
- Decay by spontaneous fission with 3% BR
- 3.77 neutrons per fission with 1 MeV average energy: to be thermalised down to meV energies
- Other decay channel, by α emission, has no impact
- Neutron moderator carefully designed to maximise thermal neutrons in the direction of the cryostat and minimise fast neutron and γ background (PE, graphite, lead, borated PE)

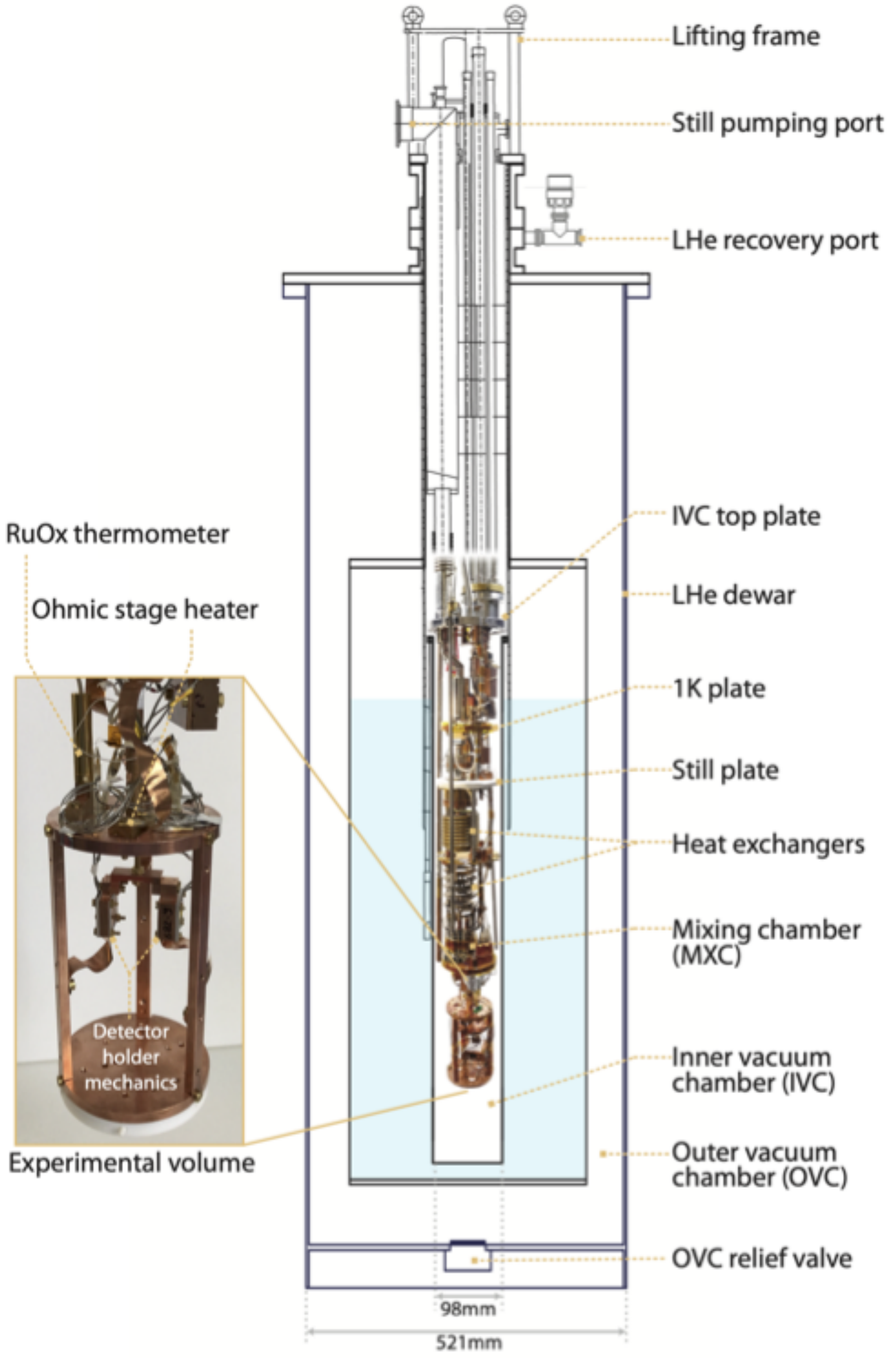


TRIGA Mark-II reactor

- Nominal power of 250 kW_{th}, neutron flux ~ 10^{13} cm^{-2} s^{-1}
- 4 beam lines: CRAB beam line tangential to the core = lower γ and fast neutron background

Wet dilution refrigerator

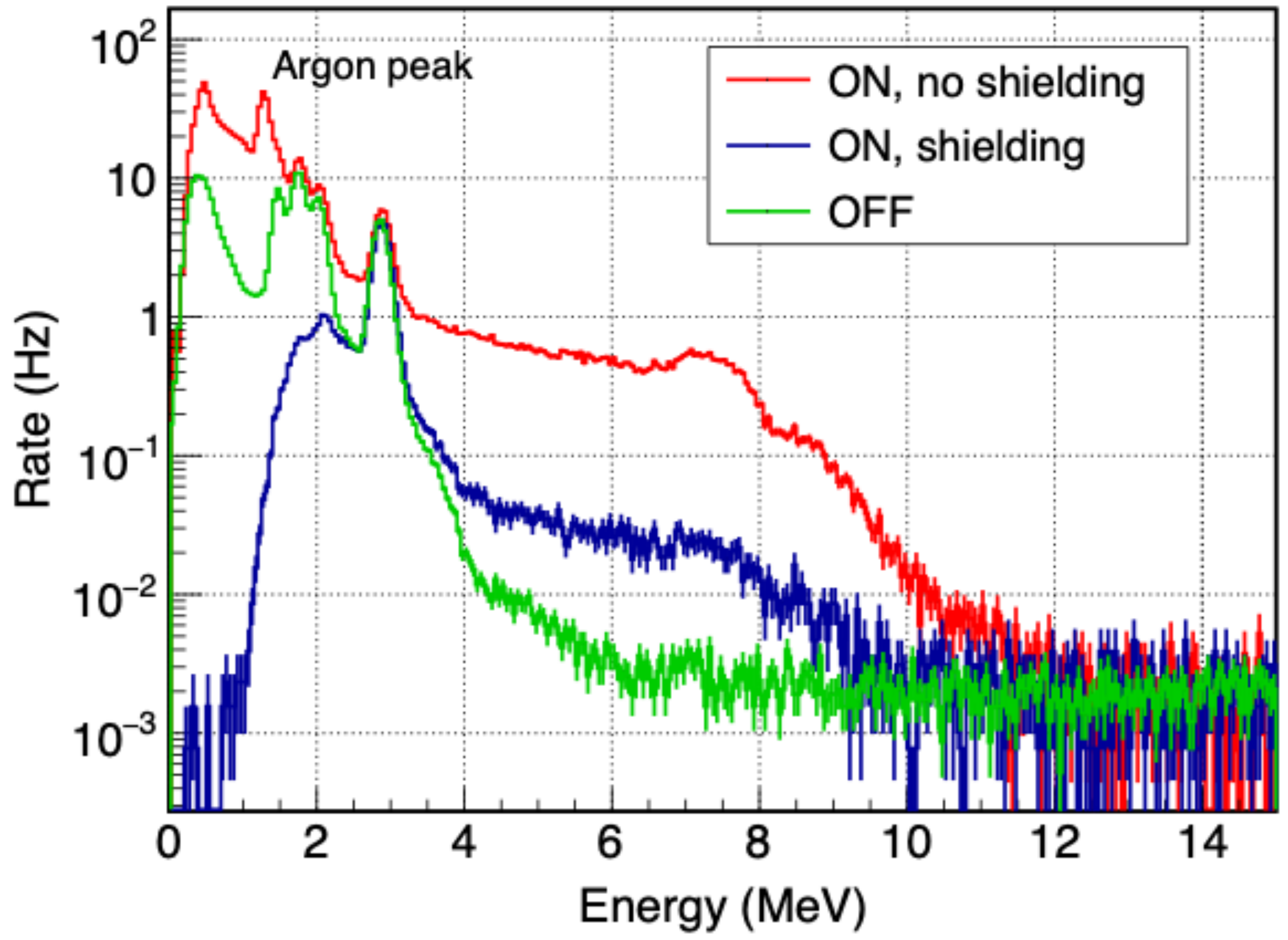
- Wet ^3He-^4He dilution refrigerator Kelvin 100 from Oxford Instruments
- Weekly few-hour long liquid helium refilling
- Several months stable measurements with cryogenic detectors possible
- Cooling power ~140 μW at 100 mK, base temperature < 10 mK
- Optimised or operation of TES based cryogenic detectors, equipped with SQUID readout & optical fibres for LED calibration

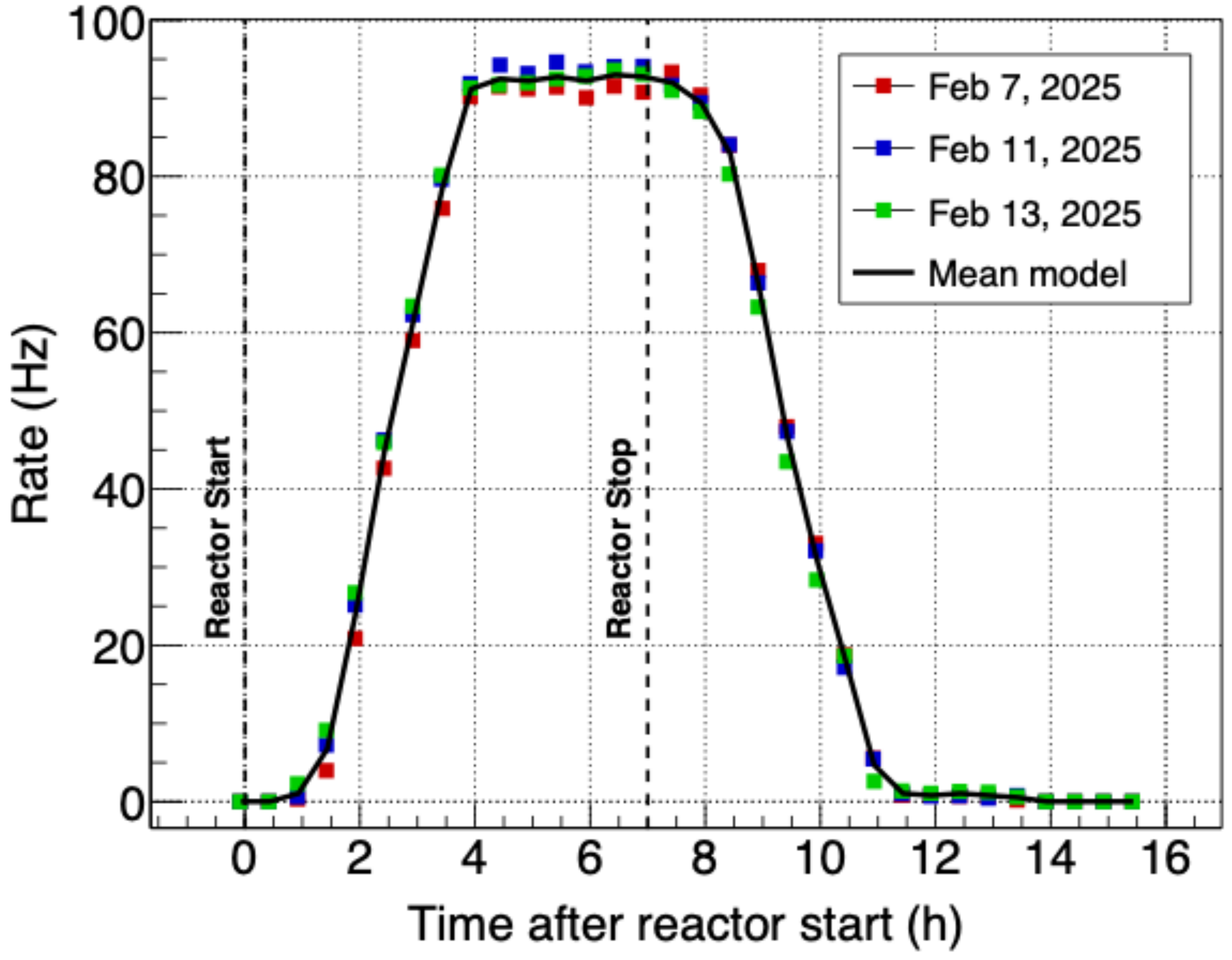


BaF_2 γ detectors

- Energy response characterised with ^{137}Cs, ^{60}Co and Am-Be sources:
  - Linearity better than 1%
  - 2.3% energy resolution at 6.2 MeV
- Very low full peak detection efficiency ~3% at 7 MeV -> we are investigating crystal regeneration to increase the efficiency in the future

Typical energy spectra in BaF_2 detectors



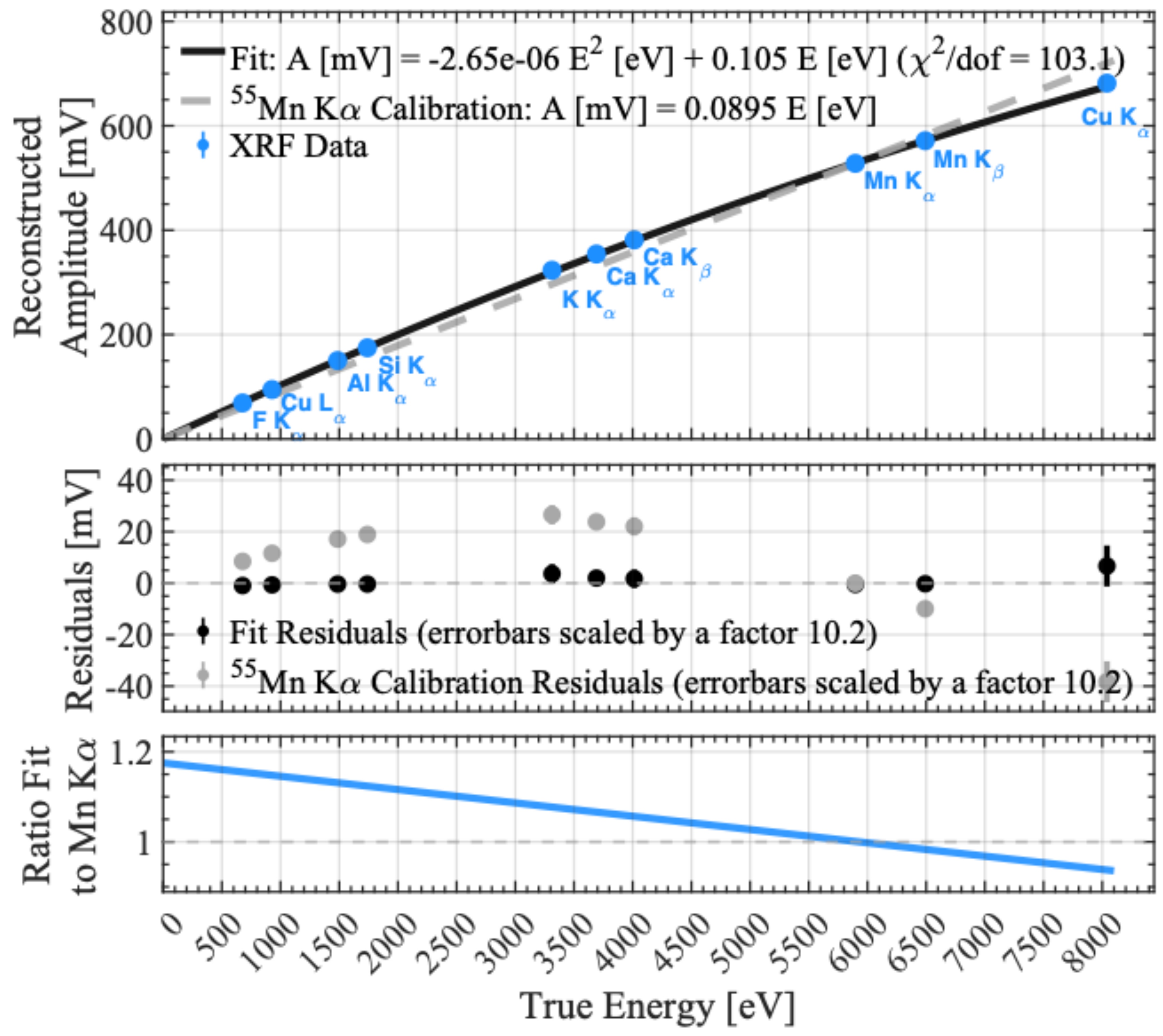


Rate of ^{41}Ar activation line (1.29 MeV) measured in BaF_2 detector

Electron recoil calibration

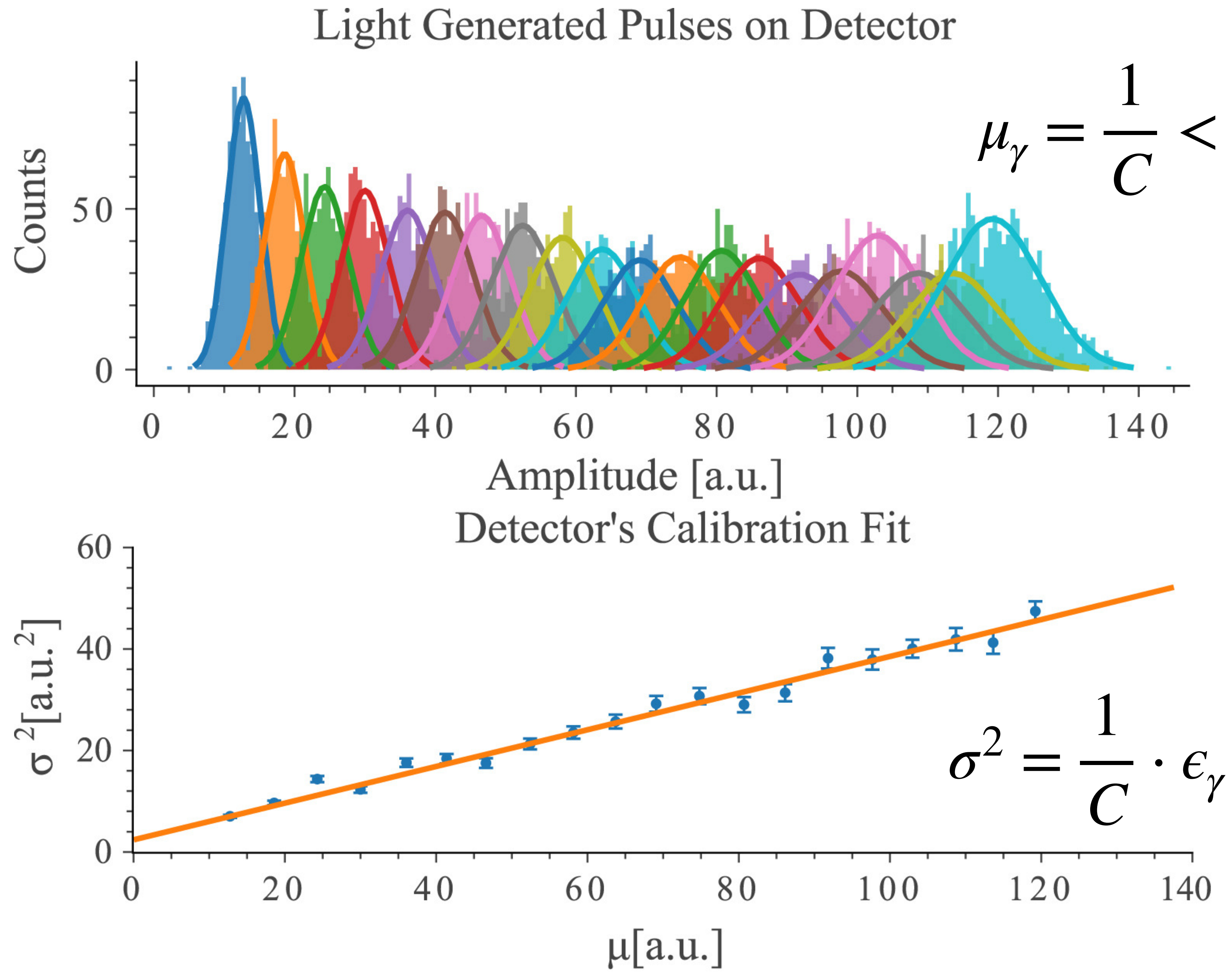
XRF source calibration

arXiv:2505.17686



LED calibration

G. Del Castello, Nucl. Instrum. Methods Phys. Res, Sect. A 1068, 169728 (2024)



$$\mu_\gamma = \frac{1}{C} < N_\gamma > \epsilon_\gamma$$

$$\sigma^2 = \frac{1}{C} \cdot \epsilon_\gamma \cdot \mu_\gamma + \sigma_0^2$$