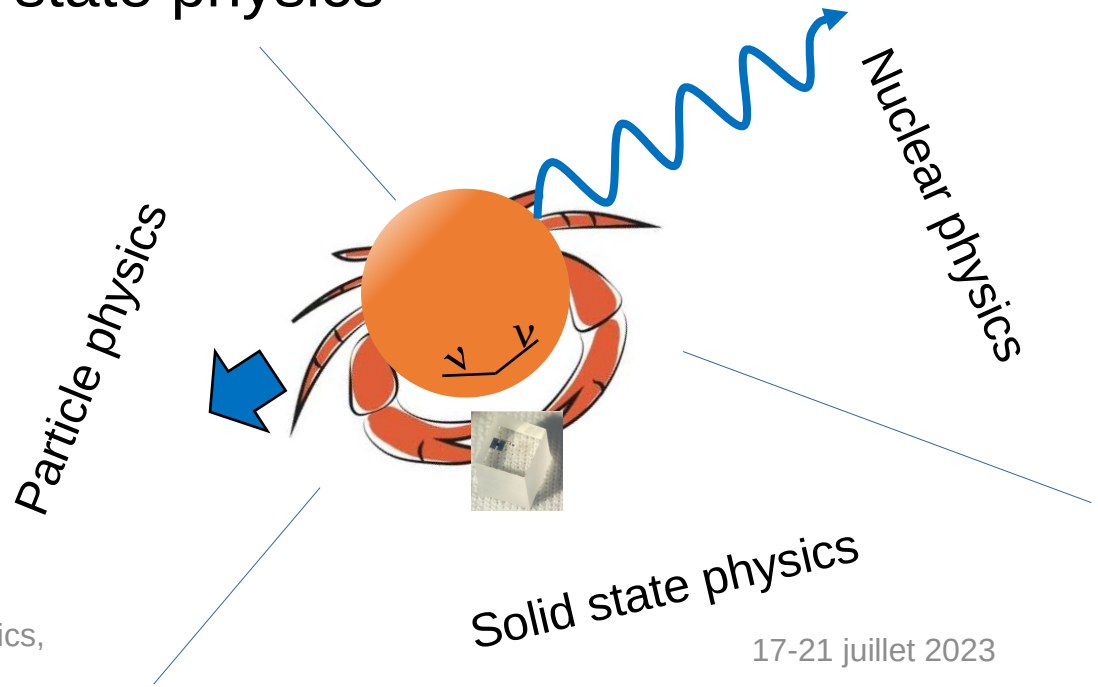
CRAB (**C**alibrated **R**ecoils for **A**ccurate **B**olometry at the 100 eV scale) on the shore of particle, nuclear and solid state physics

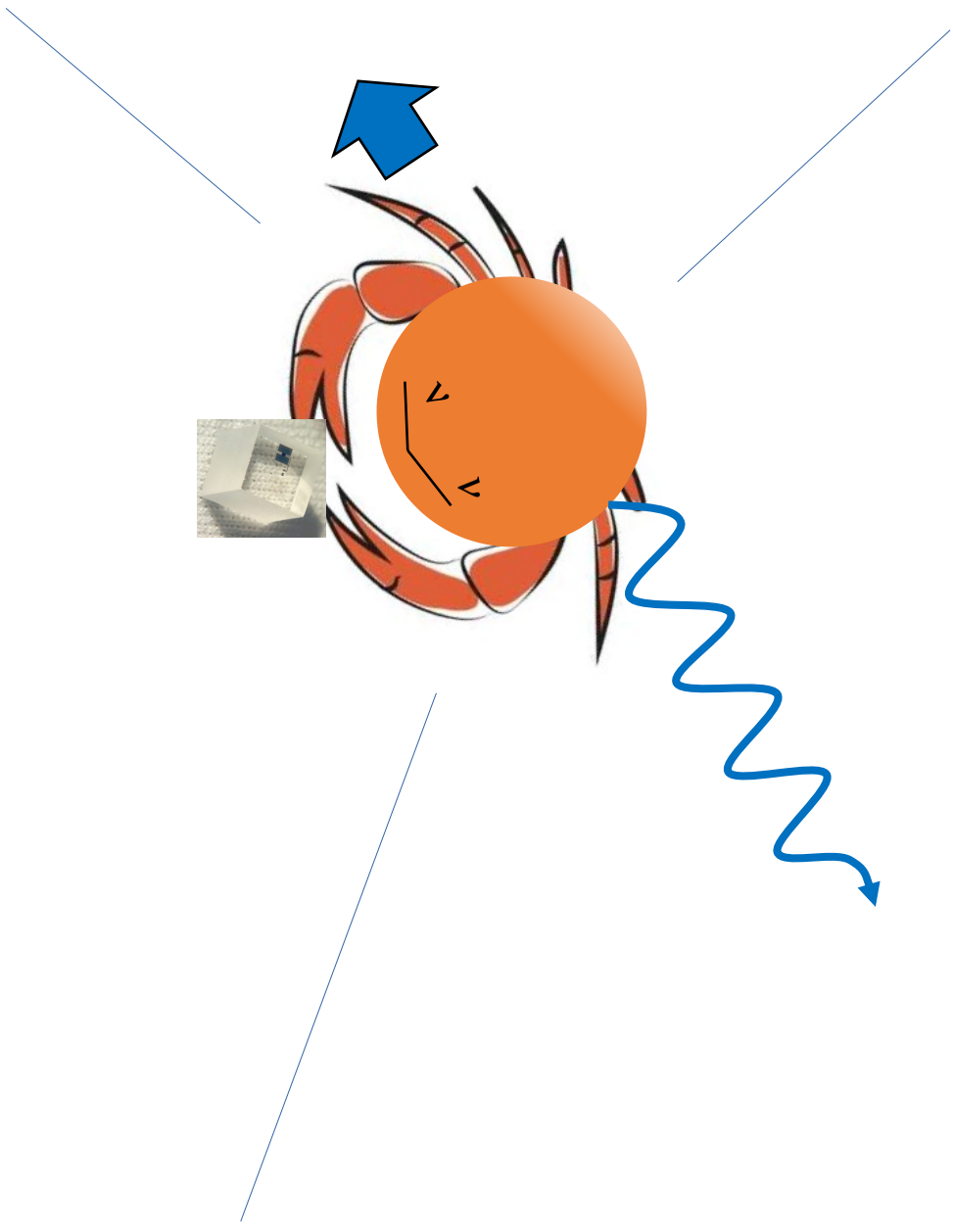
L. Thulliez on behalf of the CRAB collaboration

CEA-Saclay/DRF/Irfu/DPhN

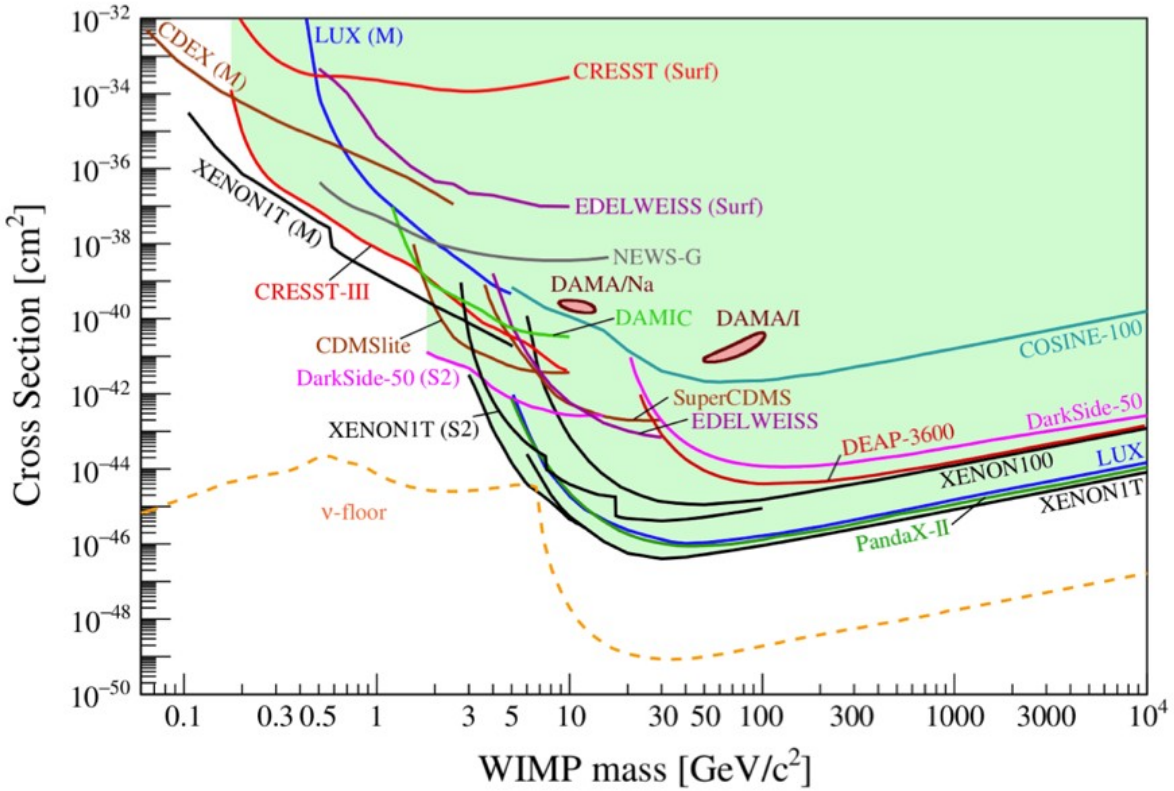
loic.thulliez@cea.fr



Particle physics



NEW PHYSICS WITH DARK MATTER ?



Direct Detection of Dark Matter APPEC Committee Report (2021)

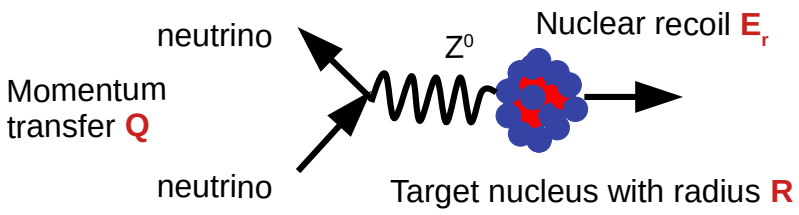
- Moving to lower mass range
  ⇒ detection of sub-keV nuclear recoil energy

- Sensitivity in large mass range approaching the neutrino-floor limit

COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING (CEvNS)

- Proposed by D. Z. Freedman in 1974 [1]
- First detected by COHERENT in 2017 [2]
- Not sensitive to neutrino flavors

- *test SM (θ_W, etc)*
- *test BSM physics*
  (neutrino magnetic moment, non-standard interaction, etc)
- *Measure nuclear form factor (neutron skin)*
- *Nuclear reactor monitoring*

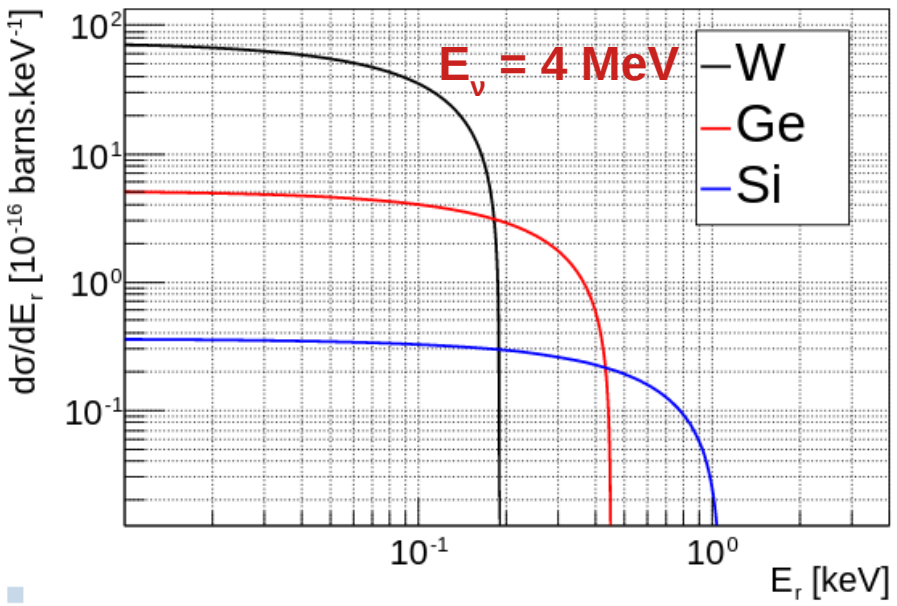


$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi}\left[N - Z\left(1 - 4\sin^2\theta_W\right)\right]^2 F^2\left(Q^2\right) M\left(1 - \frac{ME_r}{2E_\nu^2}\right)$$

Weak nuclear charge
$\sin^2(\theta_W)$~0,231
→ N^2

Nuclear form factor
Full coherency QR<1
Fulfill for E_ν < 30 MeV
→ 1

Kinematics



Reactor anti-neutrinos induce sub-keV energy
⇒ real challenge from the detector side
→ good energy resolution ~ few eV
→ low energy threshold ~ few 10 eV

Examples :
RICOCHET @ILL [3]
NUCLEUS @Chooz nuclear power plant [4]

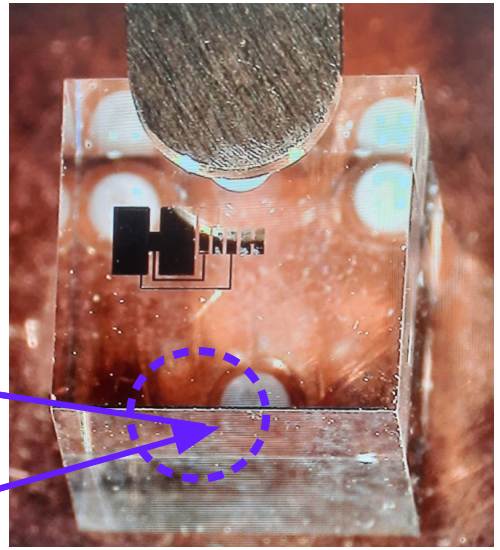
[1] Freedman, Phys. Rev. D, 9, 5, 1974 [2] Akimov et al., Science, 357, 6356, 2017 [3] J. Billard et al., J. Phys. G, 44, 10 (2017) [4] R. Strauss et al., Eur. Phys. J., C77:506, 2017

HOW TO DETECT LOW ENERGY NUCLEAR RECOILS ?

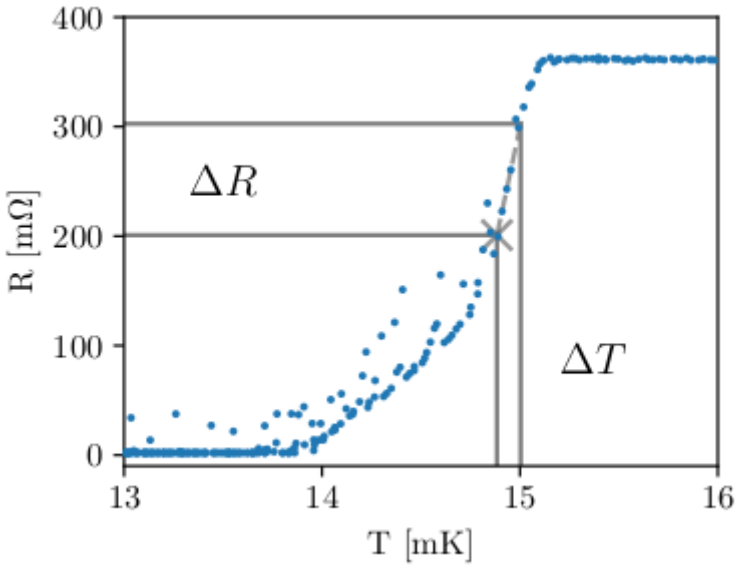
Use of **cryogenic detector** operated at **few mK**

Crysostat Bluefors LD400

Neutrino / DM

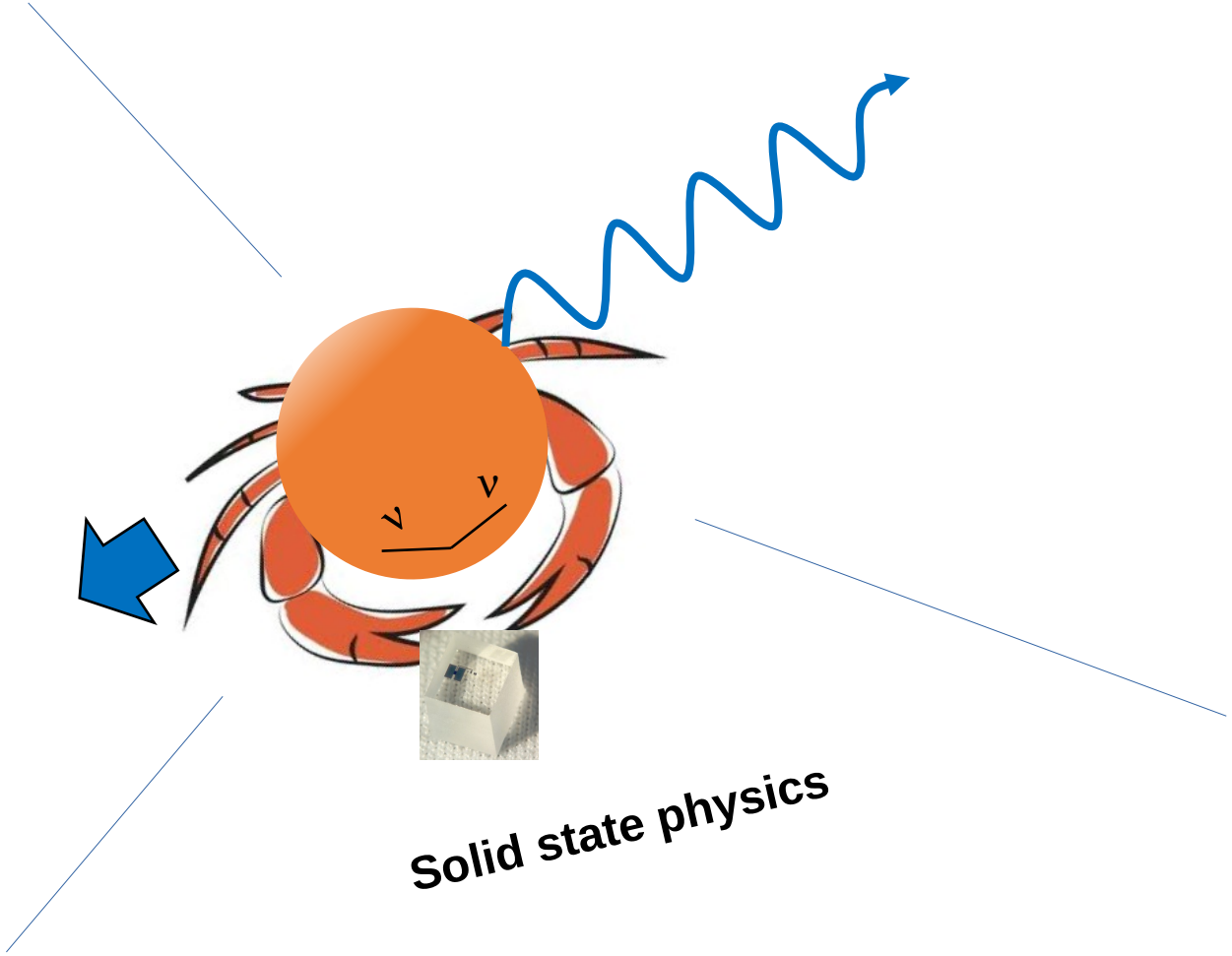


CaWO4 5x5x5 mm³ ***NUCLEUS cryogenic detector***
E_{th}=50 eV σ(E)=6 eV [1]



TES resistance as a function of temperature [2]

[1] H. Abele. et al., Phys. Rev. Lett. 130, 211802 (2023)
[2] J. Rothe thesis 2020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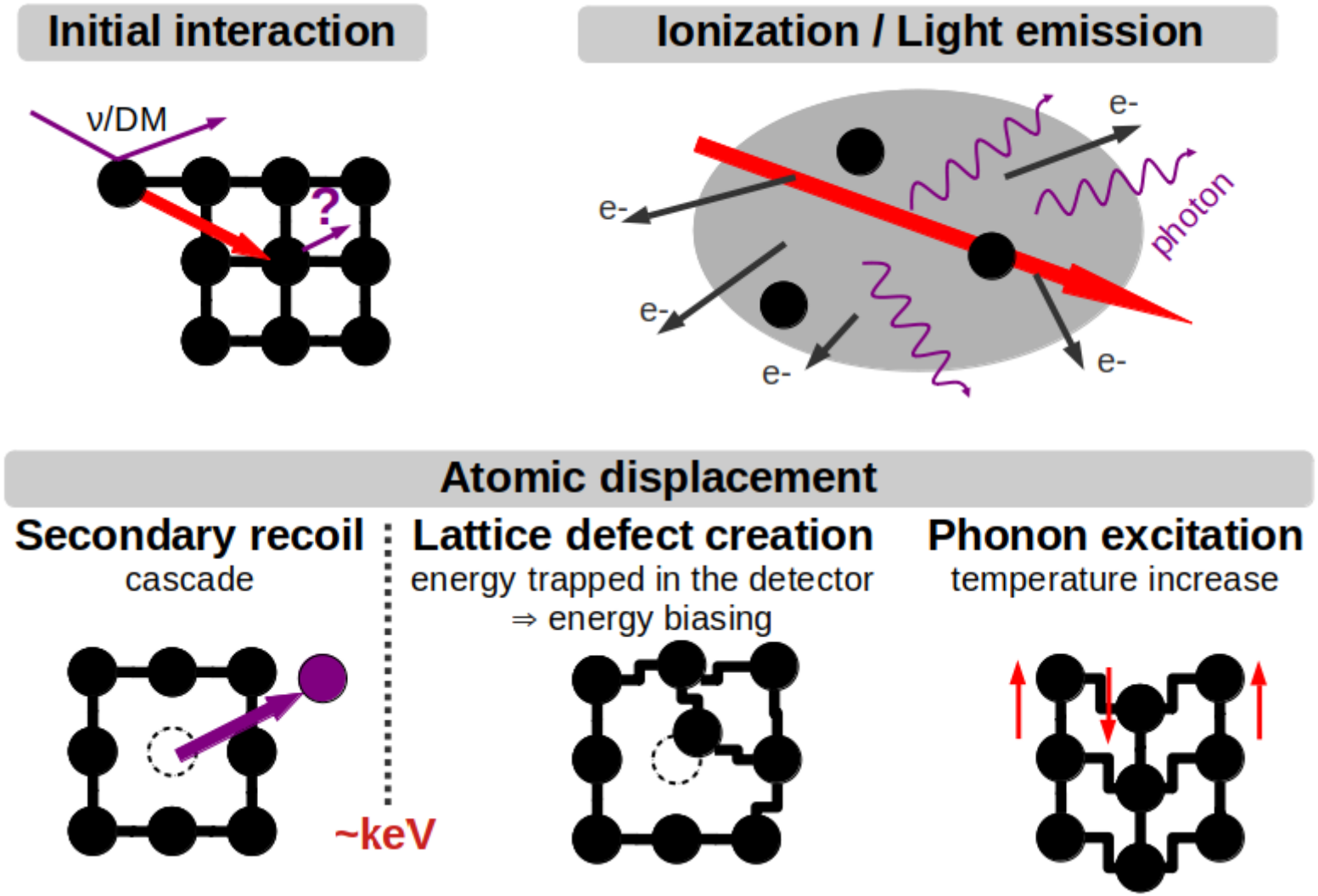
Solid state physics

WHAT HAPPEN AFTER A PRIMARY RECOIL IN THE DETECTOR ?

Complex solid state physics to understand for precise measurements



→ Quenching factor k below 1 keV ?

$k = E_{nr}^{ioni}/E_{e-}^{ioni}$

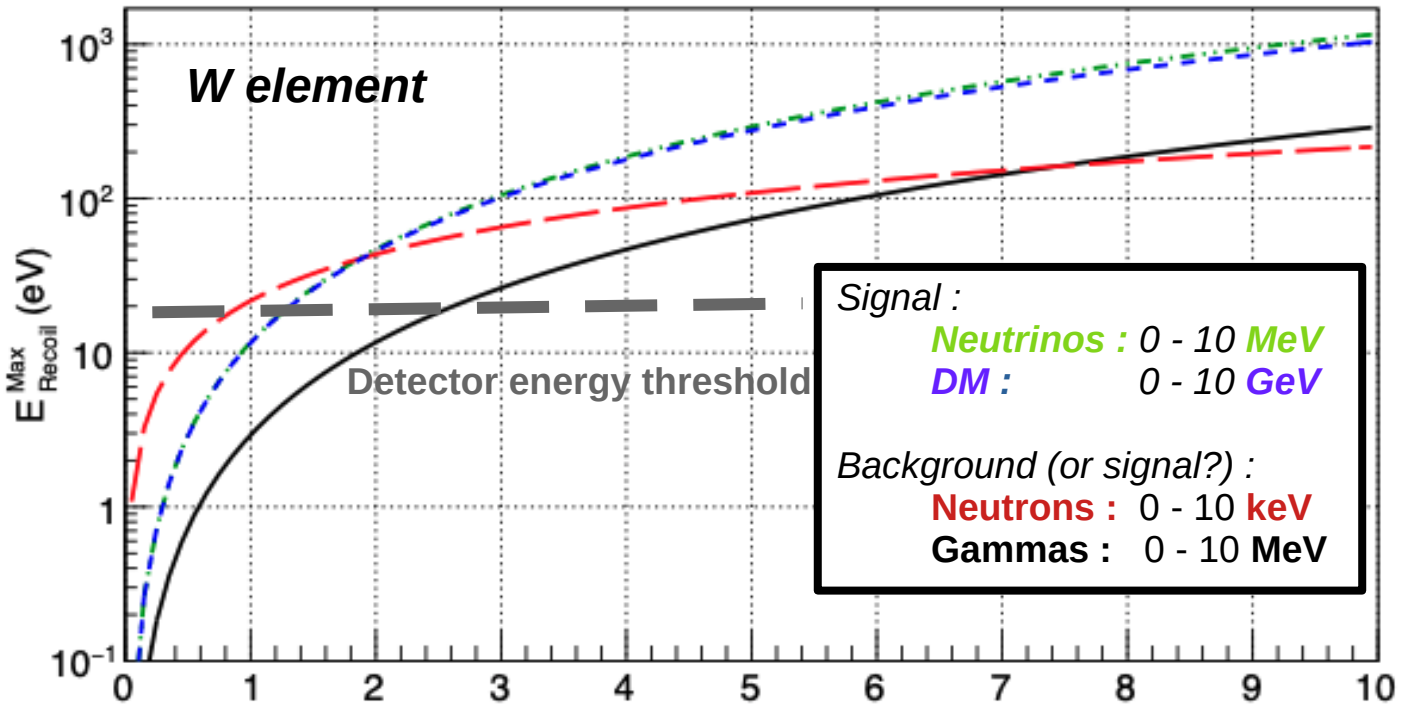
→ Impact of energy stored in lattice defect when reaching 100 eV scale ?

⇒ linearity study

NEED SUB-keV CALIBRATION METHODS

State-of-the-art calibration techniques :

- mainly electron recoils for *in-situ* calibration with LED [1], XRF source BUT surface calibration
- alphas BUT surface calibration
- epithermal/fast neutrons produced at accelerator AND limited by TOF and angular precisions



What about thermal neutrons ?

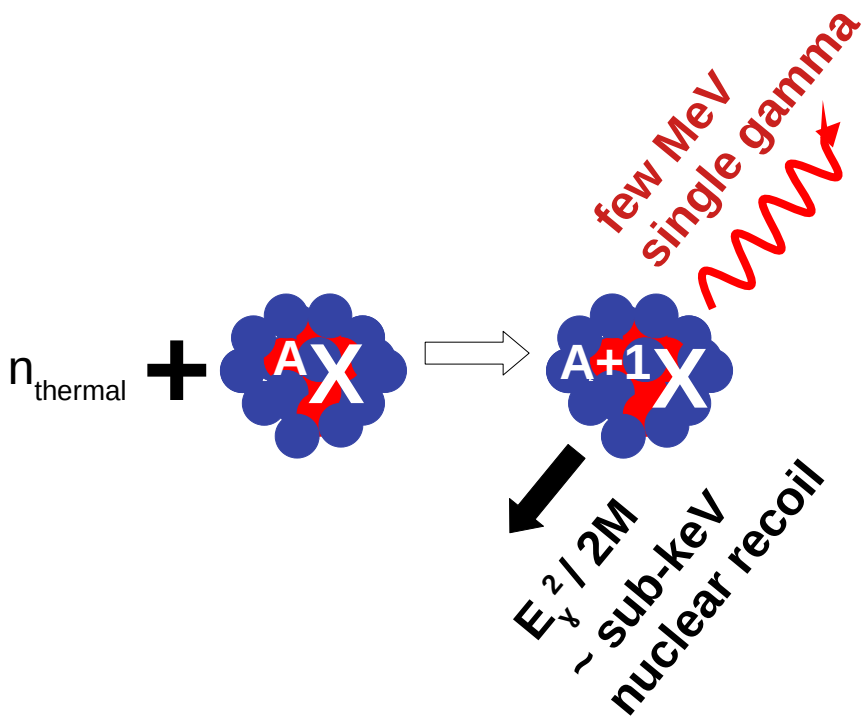
- gammas from (n,ɣ) reaction

First indirect measurement by Jones and Kramer [2]

[1] L. Cardini et al., Eur. Phys. J. C 81 (2021) 7, 636.
[2] K.W. Jones and H.W. Kraner, Phys. Rev. A, 11 4, 1975

CRAB METHOD [1]

Thermal (~25meV) neutron radiative capture



The high-energy gamma leaves the cm scale detector without energy deposition

Advantages

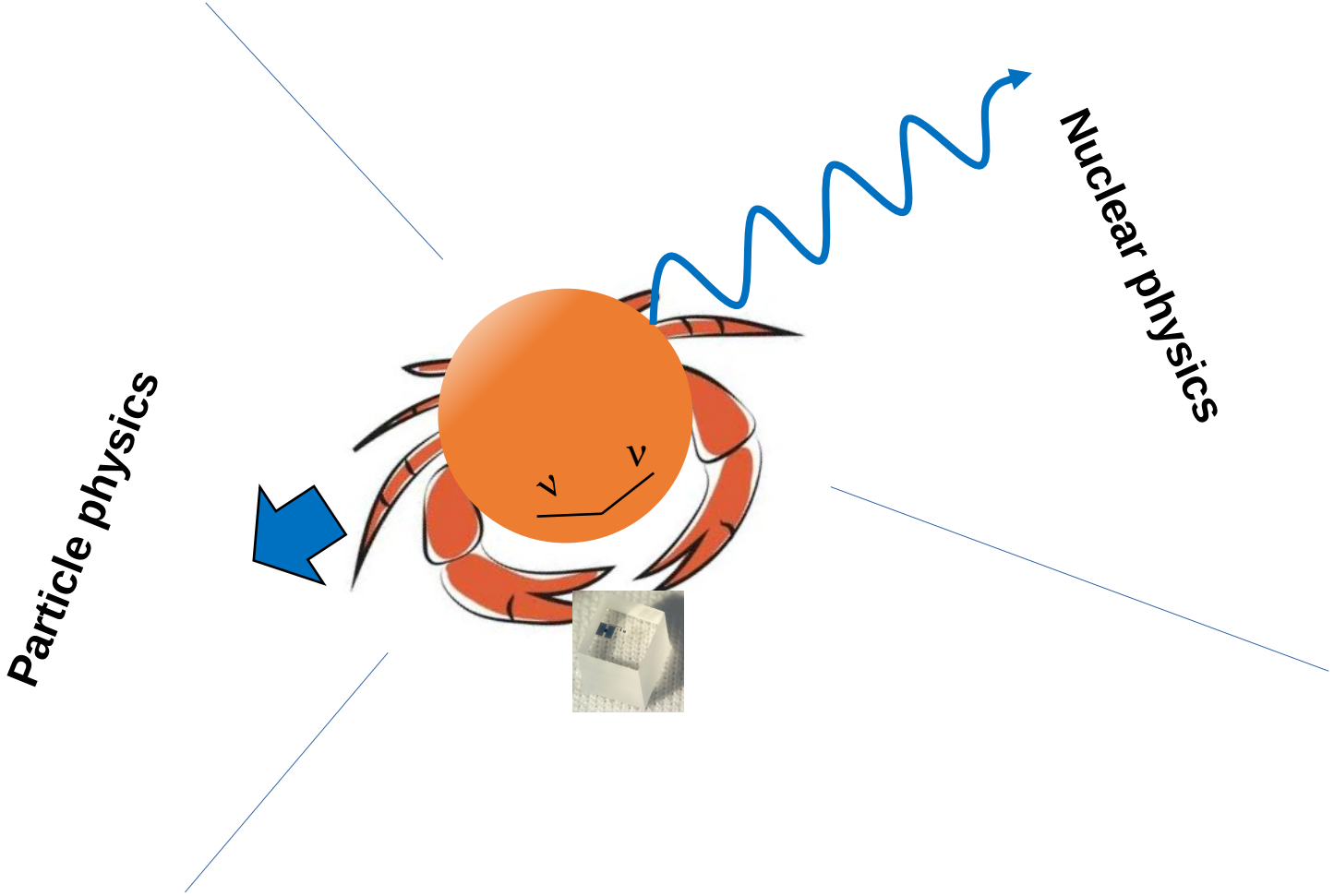
- Pure nuclear recoil ⇒ mimic the neutrino/DM signal
- Allows to probe the whole bolometer
- Accuracy ⇒ well defined peak

However non-trivial nucleus de-excitation to simulate

- transition probability from S_n to GS ?
  ⇒ signal intensity
- multi-gamma/electron cascade ?
  ⇒ background evaluation in the ROI
  ⇒ dead-time (typical response time of ~ms for cryogenic detectors)

[1] L. Thulliez, D. Lhuillier et al., Calibration of nuclear recoils at the 100 eV scale using neutron capture, JINST, 16, 7 (2021)

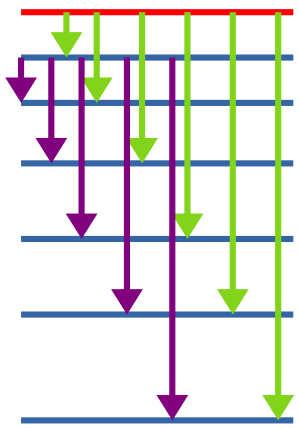
THE CRAB METHOD
WHERE PARTICLE AND NUCLEAR PHYSICS MEET



FIFRELIN SIMULATION

Fission fragment de-excitation code developed at CEA-Cadarache [1]

Step 1 → x_{EGAF}



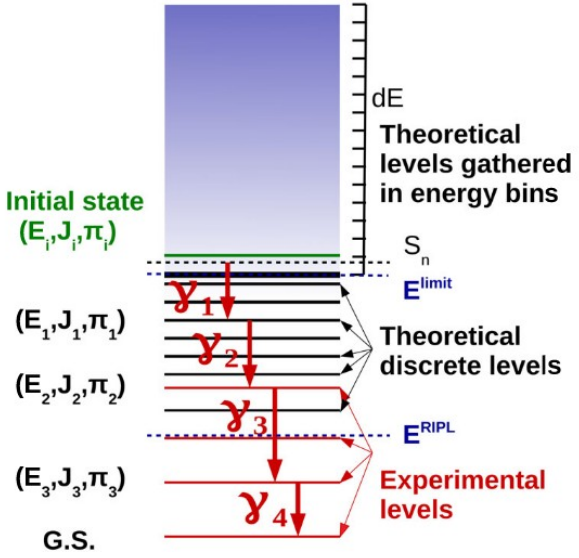
⇒ known level scheme (only few levels)
⇒ known transition probabilities

For light nuclei the level scheme is complete x_{EGAF}=1
→ Aluminium, Silicon

EGAF, ENSDF, RIPL3 databases are key ingredients
Gamma spectroscopy is important for particle physics !

+

Step 2 → (1 - x_{EGAF})



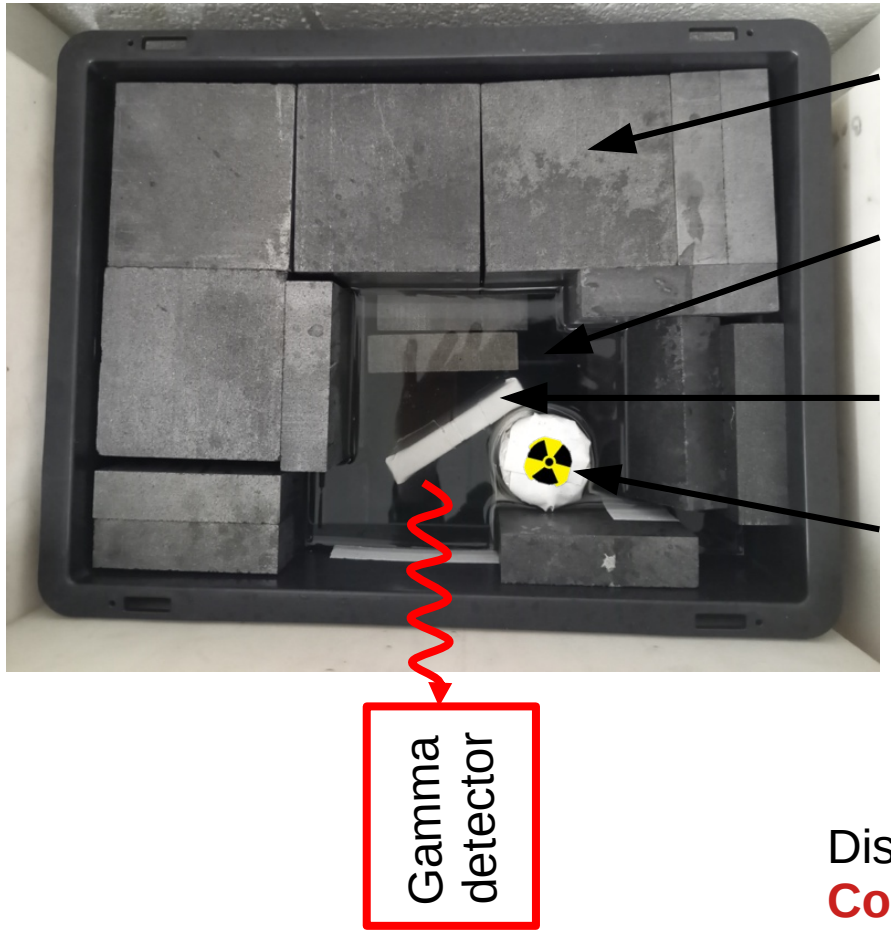
For heavy nuclei too many levels !
⇒ need theoretical models
→ level density (CGCM, HFB)
→ radiative strength function (EGLO, QRPA)
→ electron conversion coefficient (BrICC)

⇒ Model uncertainties taken into account by sampling many different level schemes.

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

FIFRELIN VALIDATIONS – HOME MADE HIGH ENERGY GAMMA SOURCE

Already validated in the STEREO experiment on Gd isotopes *[1,2]*

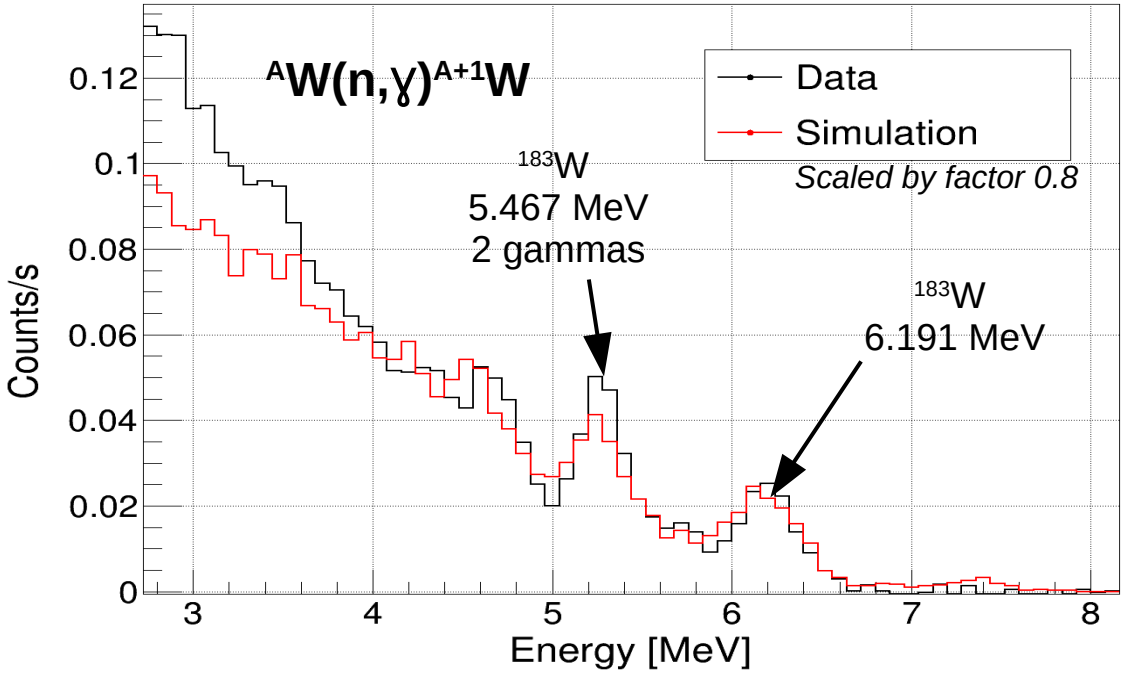


Graphite
reflector

Water
moderator

Target
(W, Ni, Fe, etc)

Neutron source
^{252}Cf



Discrepancies between data and MC **less than 20 % for W isotopes**

Confirmation of the FIFRELIN predictions : position and intensities of the S_n gamma line from tungsten.

[1] H. Almazán et al, Eur. Phys. J. A 55 (2019) 183
[2] H. Almazán et al, Eur. Phys. J. A 59 (2023) 75

STUDIED CRYO-DETECTOR MATERIALS

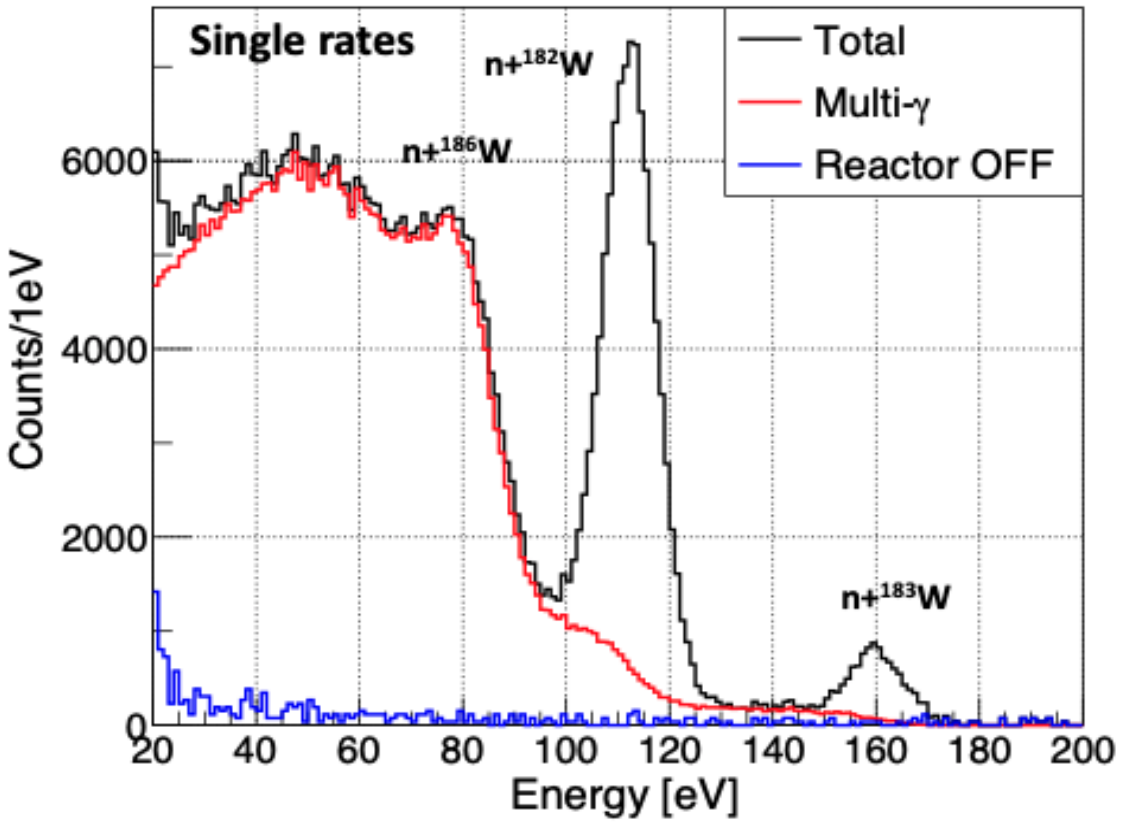
		Nucleus ^{A}X			+ $n_{thermal}$ →	Nucleus ^{A+1}X + g	
Crystal	Isotopes	Nat. ab. [%]	$\sigma_{(n,g)}$ [barn]	I_{g0} [%]	FOM	S_n [keV]	Recoil [eV]
$CaWO_4$ *CRESST* *NUCLEUS*	^{182}W ^{183}W ^{184}W ^{186}W	26.5 14.3 30.6 28.4	20.3 9.9 1.6 37.9	13.9 5.8 1.5 0.3	7478 821 73 323	6191 7411 5754 5467	112.5 160.3 96.1 85.8
Ge *EDELWEISS* *RICOCHET*	^{70}Ge ^{74}Ge	20.5 36.5	3.1 0.5	2.0 2.8	127 51	7416 6506	416.2 303.2
Al_2O_3 *MINER* *NUCLEUS*	^{27}Al	100	0.2	26.8	536	7725	1145
Si *SuperCDMS* *DAMIC SENSEI* *Skipper-CCD* *CONNIE*	^{28}Si ^{29}Si ^{30}Si	92.2 92.2 4.7 3.1	0.2 0.2 0.1 0.1	2.2 7.0 6.7 1.5	41 129 3 0.5	8473 7199+1274 10609 6587	1330 990 2016 752

Keep in mind :

- signal depends on detector resolution (σ)
  ⇒ high resolution needed

PREDICTED NUCLEAR RECOIL SPECTRA – CaWO4

- Geant4 simulation based on TOUCANS [1] + FIFRELIN
- Mono-directionnal thermal neutron beam

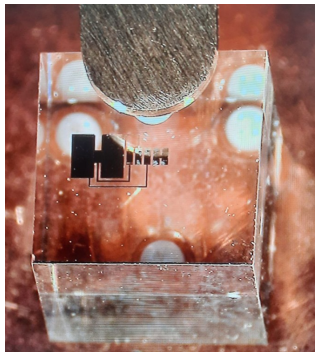


Nuclear recoil spectrum in $CaWO_4$

- One prominent peak at 112 eV
  ⇒ could simply pop-up
- Second small peak at 160 eV
  ⇒ more difficult to get
- Third peak at ~85 eV
  ⇒ burried in multi-γ background
  ⇒ how to recover it ?
  ⇒ wait the end of the talk!

[1] L. Thulliez, B. Mom and E. Dumonteil, Nuclear Inst. and Methods in Physics Research A , 1051 (2023)

FIRST MEASUREMENT CRAB / NUCLEUS COLLABORATIONS



NUCLEUS $CaWO_4$
cryo-detector
E_{th} = 50 eV
σ(E) = 6 eV

Detector in a copper box spring decoupled from cryostat vibration

More copper to thermalize the detector below 100 mK
TES transition ~10 mK

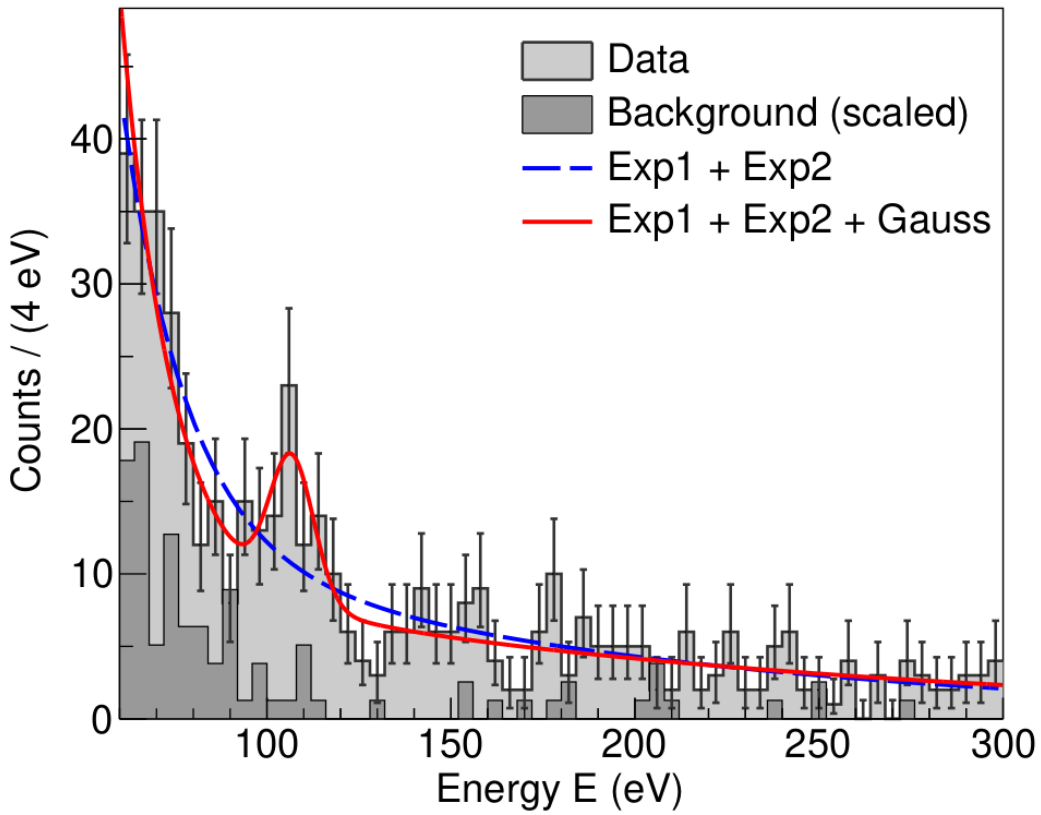
Thermal neutrons produced with a 3.7 MBq ^{252}Cf in a polyethylene and graphite moderator
⇒ 0.25 n_{th}/s on the cryo-detector

FIRST MEASUREMENT – RESULTS

→ Background data lifetime = 18.9 h
→ Source data lifetime = 40.2 h

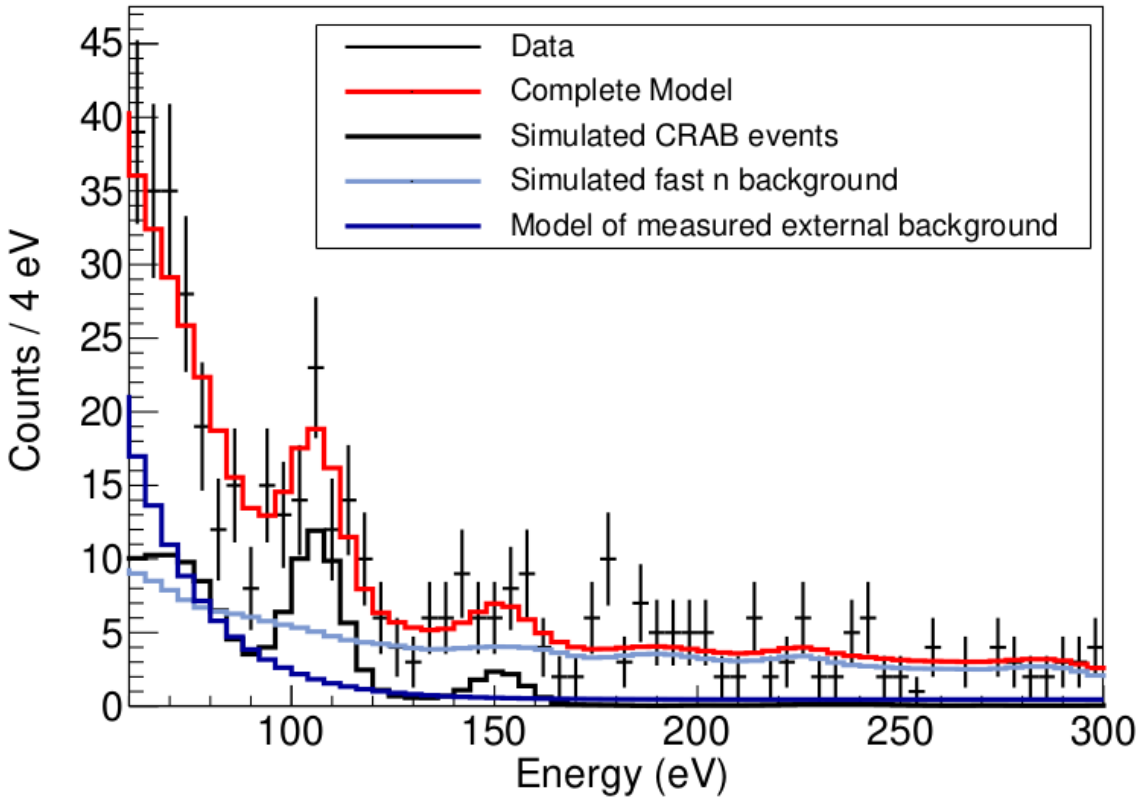
Blind search peak

Test the presence of a peak
Background = 2 exponentials
Signal = gaussian



Presence of a peak
⇒ 3.1σ significance (2-sided)

Test the presence of nuclear recoils from neutron capture
Background = exponential fit to bkgd data
Signal = GEANT4 + FIFRELIN

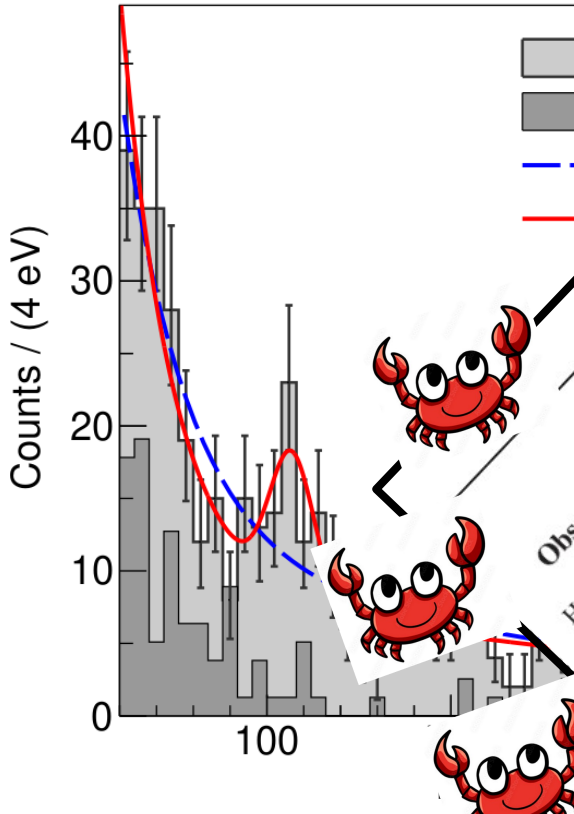


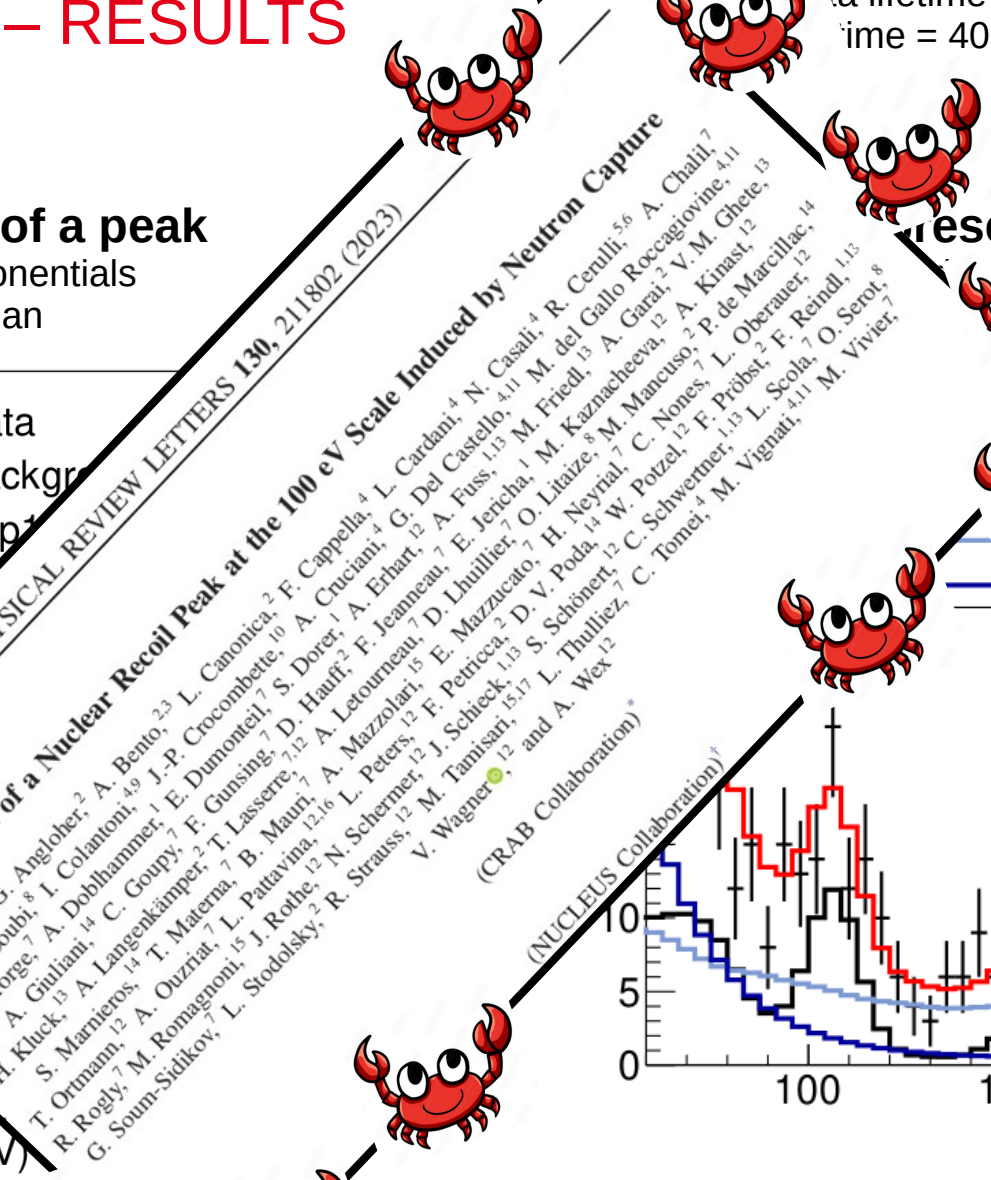
Presence of nuclear recoils from neutron capture
⇒ 6σ significance (2-sided)
⇒ χ^2/NDF = 58.09/59

FIRST MEASUREMENT – RESULTS

Blind search peak

Test the presence of a peak
Background = 2 exponentials
Signal = gaussian




PHYSICAL REVIEW LETTERS 130, 211802 (2023)

Observation of a Nuclear Recoil Peak at the 100 eV Scale Induced by Neutron Capture

H. Abele,[1] G. Angloher,[2] A. Bento,[2,3] L. Canonica,[2] F. Cappella,[4] L. Cardani,[4] N. Casali,[4] R. Cerulli,[5,6] A. Chalil,[7] A. Chebboubi,[8] I. Colantoni,[4,9] J.-P. Crocombette,[10] A. Cruciani,[4] G. Del Castello,[4,11] M. del Gallo Roccagiovine,[4,11] D. Desforge,[7] A. Doblhammer,[1] E. Dumonteil,[7] S. Dorer,[1] A. Erhart,[12] A. Fuss,[1,13] M. Friedl,[13] A. Garai,[2] V.M. Ghete,[13] A. Giuliani,[14] C. Goupy,[7] F. Gunsing,[7] D. Hauff,[2] F. Jeanneau,[7] E. Jericha,[1] M. Kaznacheeva,[12] A. Kinast,[12] H. Kluck,[13] A. Langenkämper,[2] T. Lasserre,[7,12] A. Letourneau,[7] D. Lhuillier,[7] O. Litaize,[8] M. Mancuso,[2] P. de Marcillac,[14] S. Marnieros,[14] T. Materna,[7] B. Mauri,[7] A. Mazzolari,[15] E. Mazzucato,[7] H. Neyrial,[7] C. Nones,[7] L. Oberauer,[12] T. Ortmann,[12] A. Ouzriat,[7] L. Pattavina,[12,16] L. Peters,[12] F. Petricca,[2] D. V. Poda,[14] W. Potzel,[12] F. Pröbst,[2] F. Reindl,[1,13] R. Rogly,[7] M. Romagnoni,[15] J. Rothe,[12] N. Schermer,[12] J. Schieck,[1,13] S. Schönert,[12] C. Schwertner,[1,13] L. Scola,[7] O. Serot,[8] G. Soum-Sidikov,[7] L. Stodolsky,[2] R. Strauss,[12] M. Tamisari,[15,17] L. Thulliez,[7] C. Tomei,[4] M. Vignati,[4,11] M. Vivier,[7] V. Wagner,[12] and A. Wex[12]

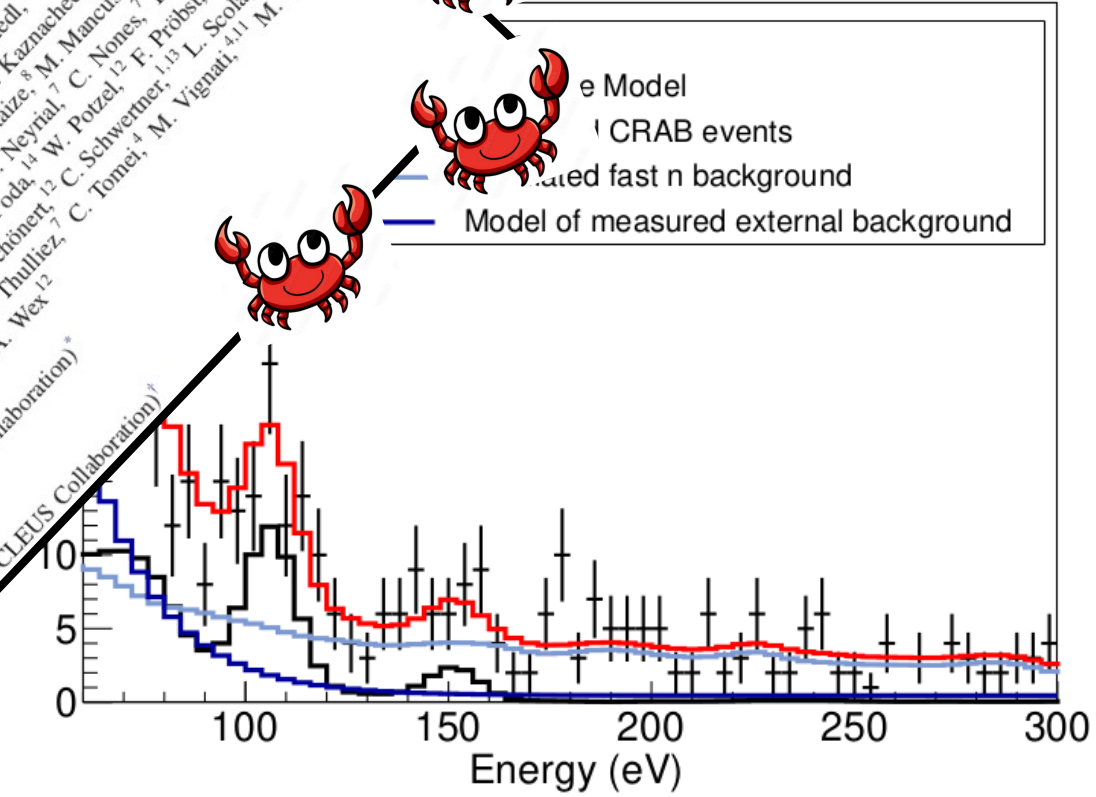
(CRAB Collaboration)*

(NUCLEUS Collaboration)†

Presence of a peak
⇒ 3.1σ significance (2

ta lifetime = 18.9 h
ime = 40.2 h

resence of nuclear recoils
tial fit to bkgd data
FIFRELINBI

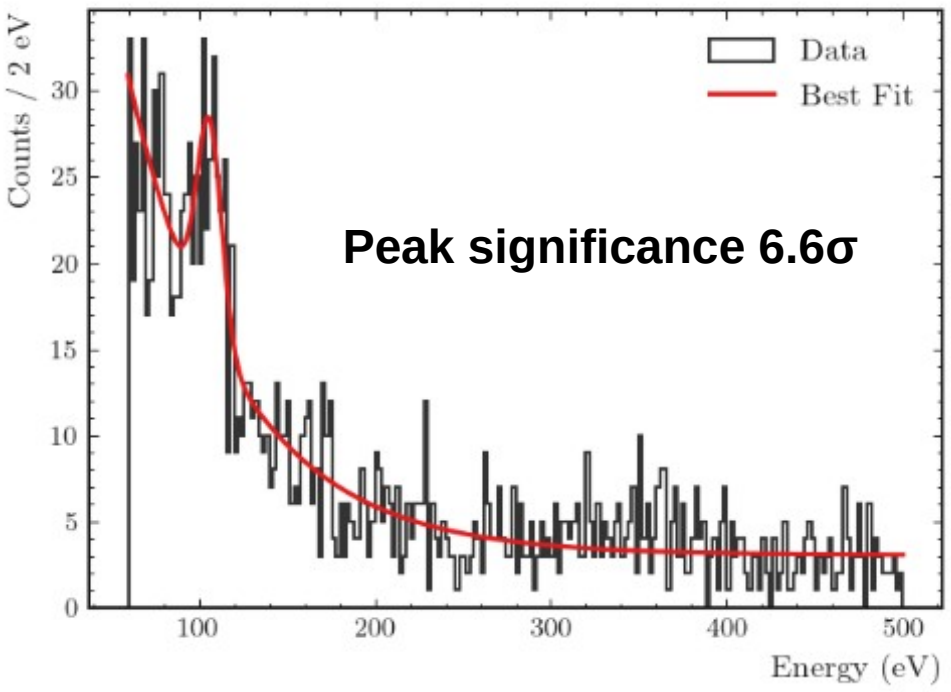


Presence of nuclear recoils
⇒ 6σ significance (2-sided)
⇒ χ^2/NDF = 58.09/59

FIRST MEASUREMENT CONFIRMED BY OTHERS !

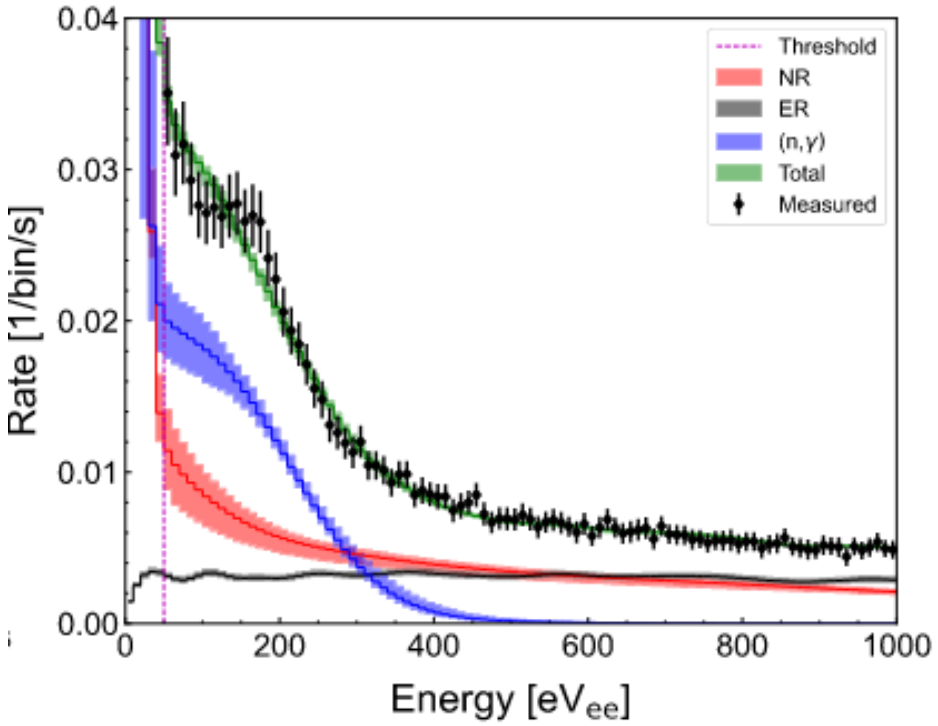
CRESST = dark matter with $CaWO_4$ cryo-detector
→ confirmation of our first CRAB signal with 3 detectors

https://arxiv.org/pdf/2303.15315.pdf
Accepted in Phys. Rev. D in June 2023



Super-CDMS = dark matter with Si cryo-detector
→ presence of nuclear recoils following thermal neutron captures

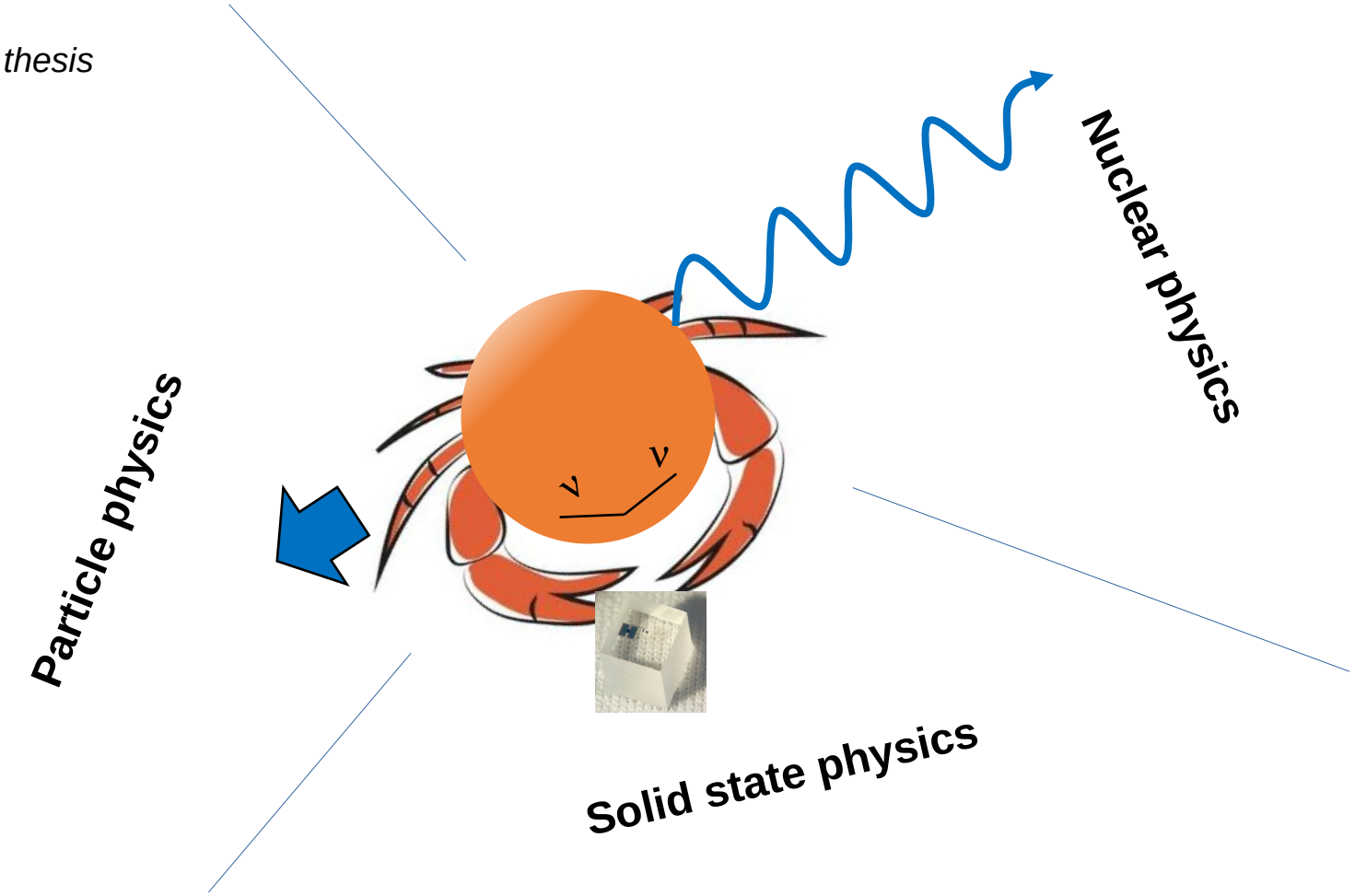
A. N. Villano, Phys. Rev. D, 105, 083014, 2022



CRAB has already a big impact in the dark matter and neutrino communities !

TIMING EFFECT
WHERE NUCLEAR AND SOLID STATE PHYSICS MEET

Gabrielle Soum-Sidikov thesis



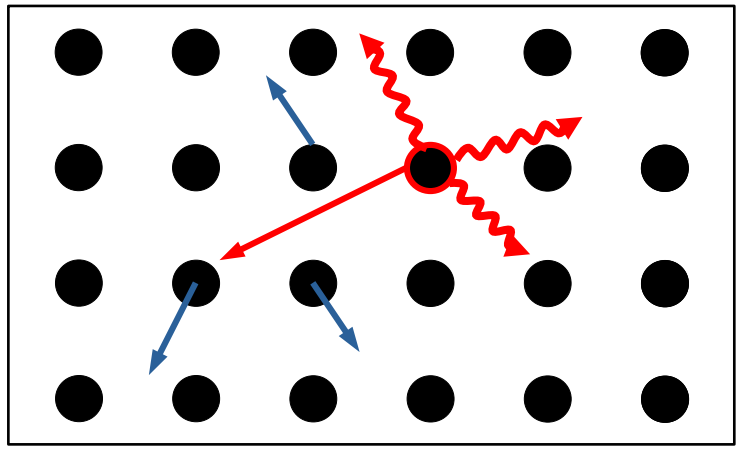
TIMING EFFECT – EXTREME HYPOTHESES

Fast hypothesis

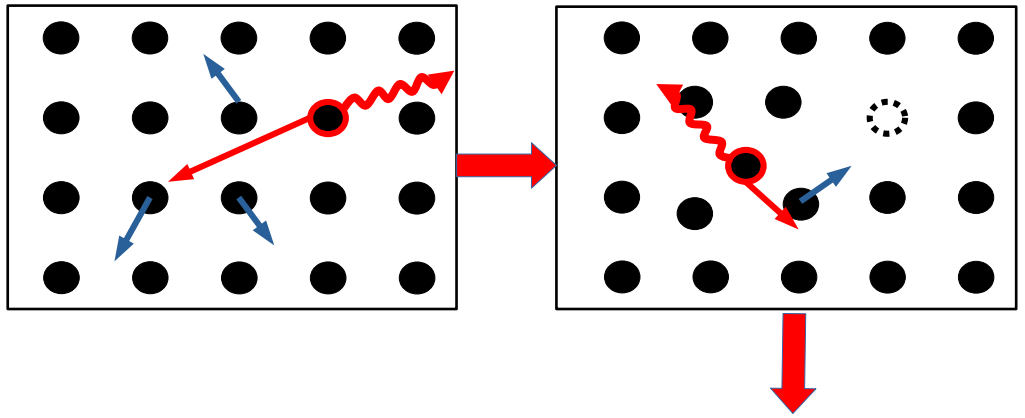
$\tau_{recoil} \gg \tau_{cascade}$ $\quad E_{recoil} = \left(\sum_i \vec{p}_i\right)^2 / 2M$

Slow hypothesis

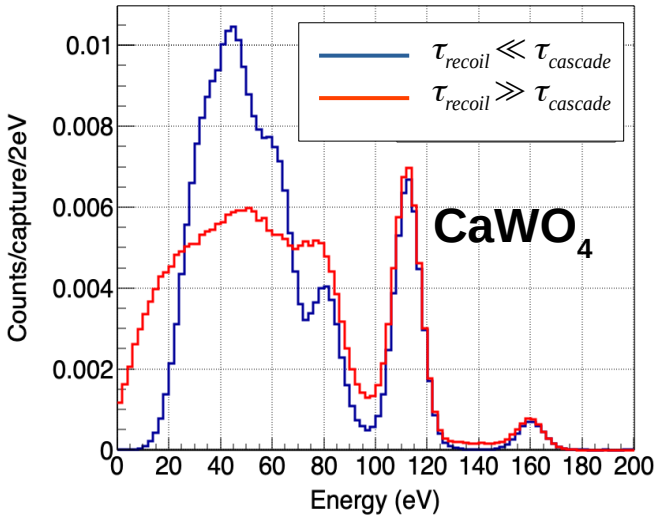
$\tau_{recoil} \ll \tau_{cascade}$ $\quad E_{recoil} = \sum_i E_{recoil,i} = \sum_i p_i^2 / 2M$

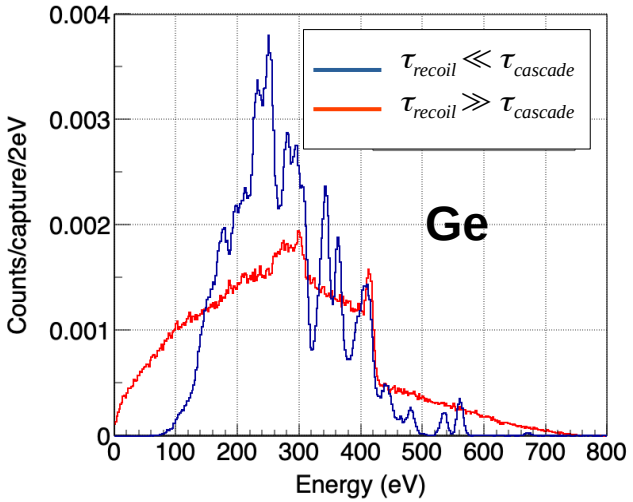


Reality in between ?



etc ...

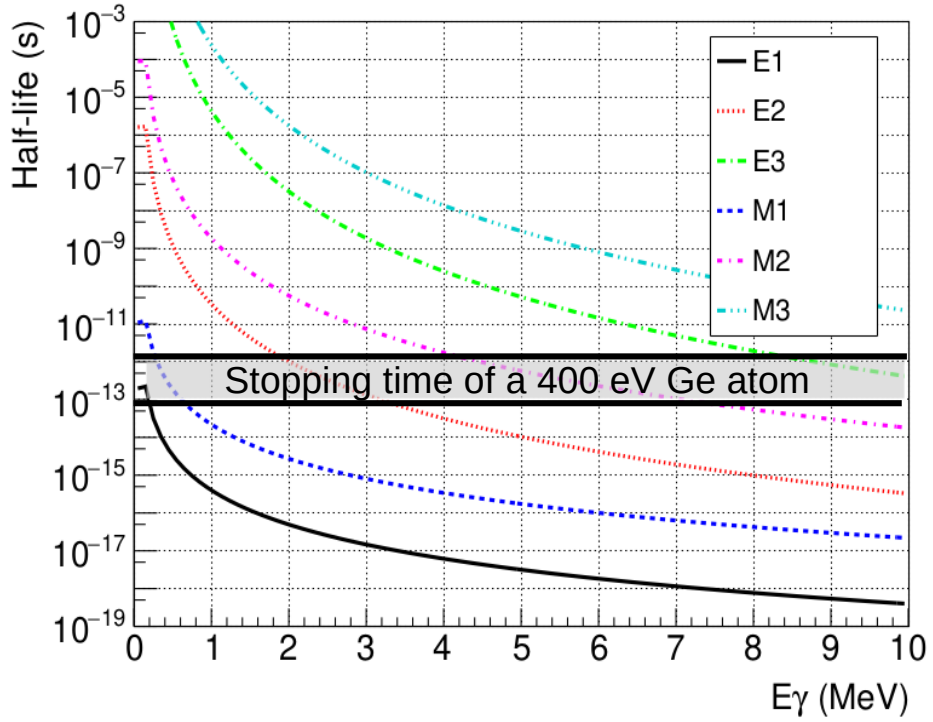




GAMMA TIMING FROM RADIATIVE PARTIAL WIDTH Γ_γ

Γ_γ from Weisskopf estimate

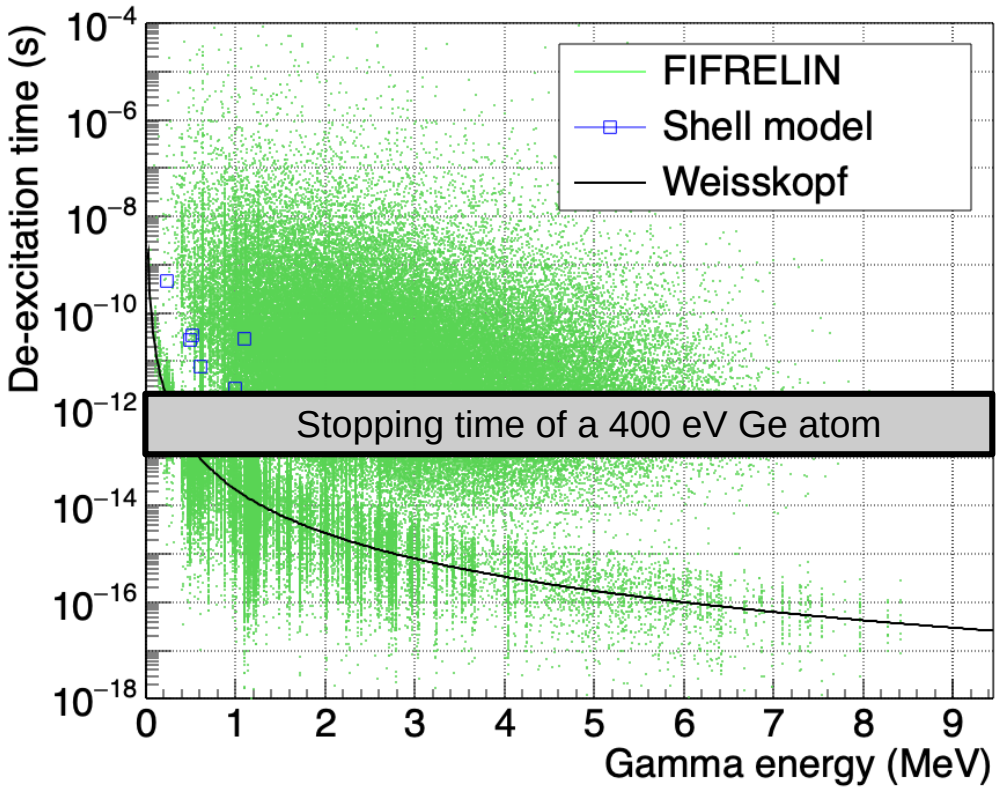
→ single particle approximation



→ known to be inaccurate by a factor ~ 10 – 100

⇒ no collective effects

Γ_γ with collective effect



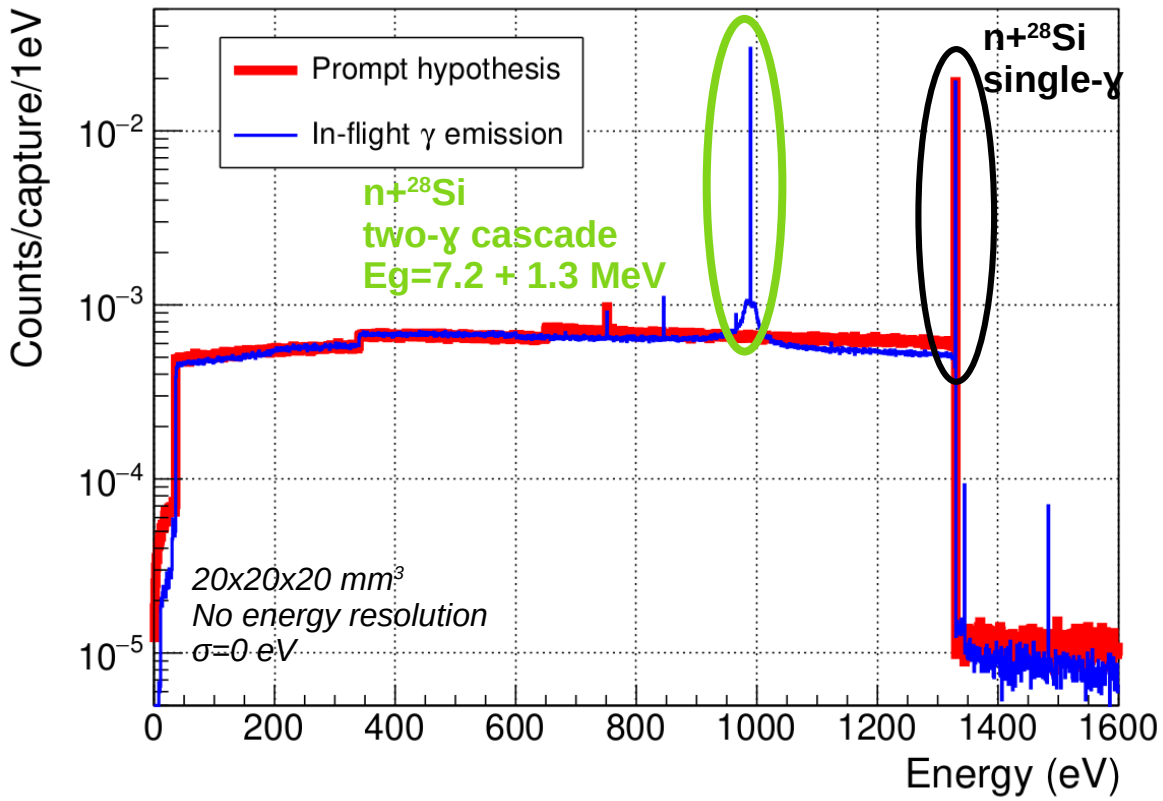
FIFRELIN Γ_γ computed with

- EGLO radiative strength function
- CGCM nuclear level density

} Effective way (parametrisation) to take collective effects into account

Shell model : Kshell code + JUN45 interaction

TIMING EFFECTS – SILICON



Most of the half-live are in the databases (collective effects taken into account)

In-flight gamma emission

⇒ probe nucleus de-excitation time

⇒ probe inter-atomic potentials

⇒ do you remember with GRID at GAMS @ILL [1] ?

Study of collision and γ-cascade times following neutron-capture processes in cryogenic detectors

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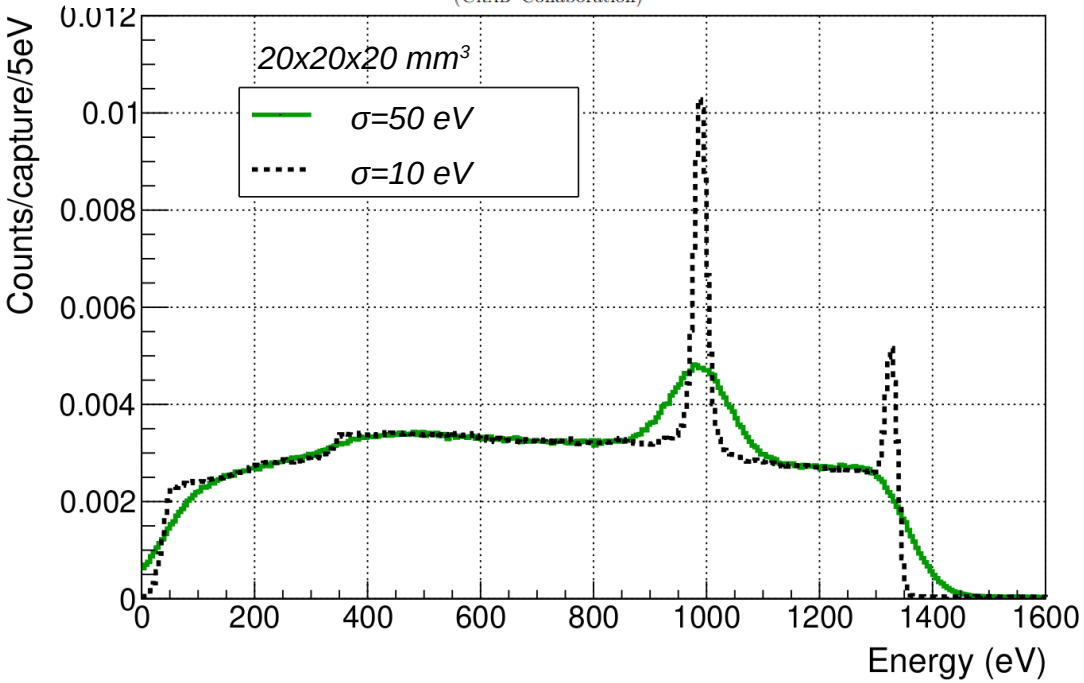
(CRAB Collaboration)



Two-γ cascade robust against poorer energy resolution

[0] G. Soum-Sidikov, Study of collision and γ-cascade times following neutron-capture processes in cryogenic detectors, https://arxiv.org/abs/2305.10139 Submitted to Phys. Rev. D

[1] E. G. Kessler, Nucl. Instrum. Meth. A 457 (2001) 187:202

TIMING EFFECTS – GERMANIUM

Study of collision and γ-cascade times following neutron-capture processes in cryogenic detectors

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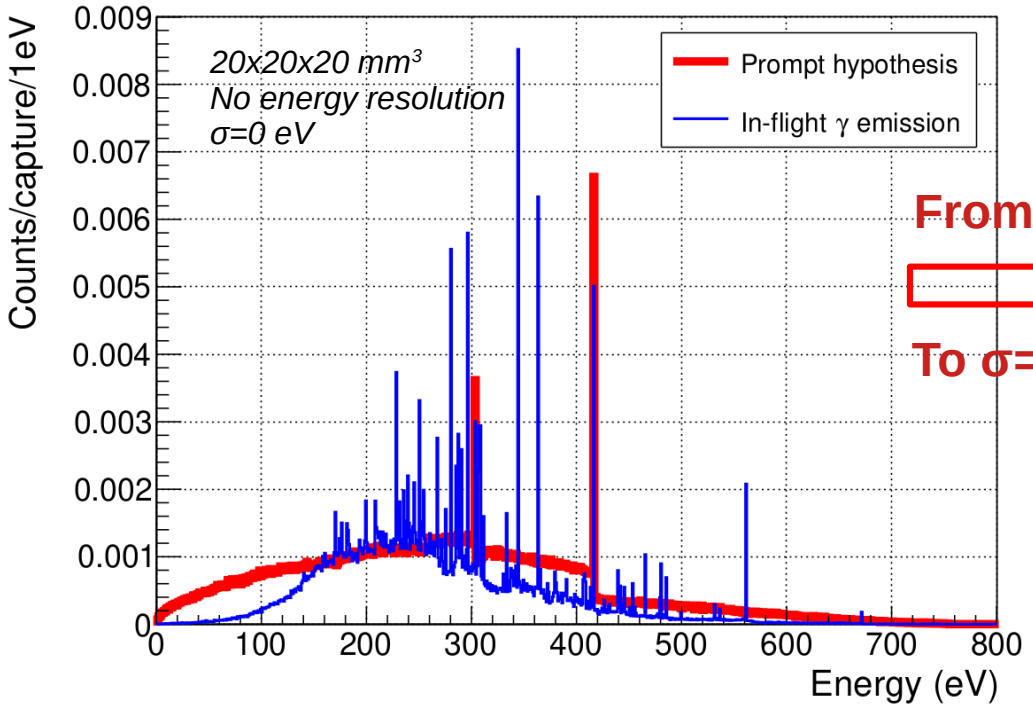
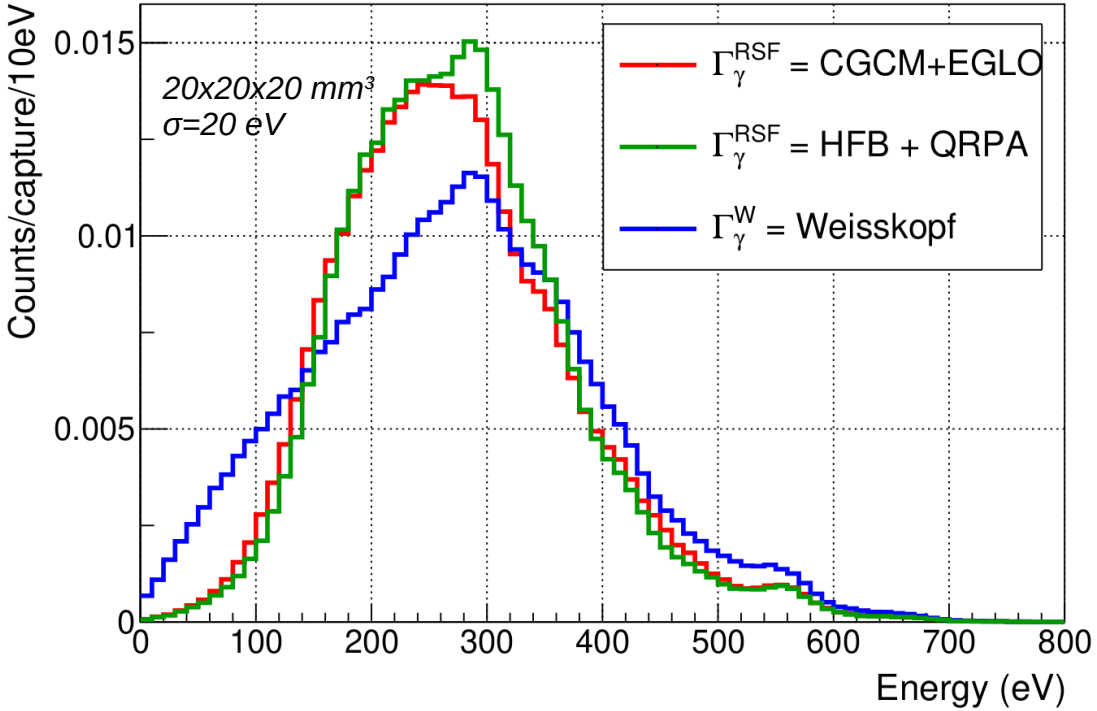


From σ=0 eV

To σ=20 eV



In-flight γ emission ⇒ more calibration peaks

Recoil energy spectrum sensitive to nuclear models !
⇒ could help set constraints on models

Resolution is a critical parameter !

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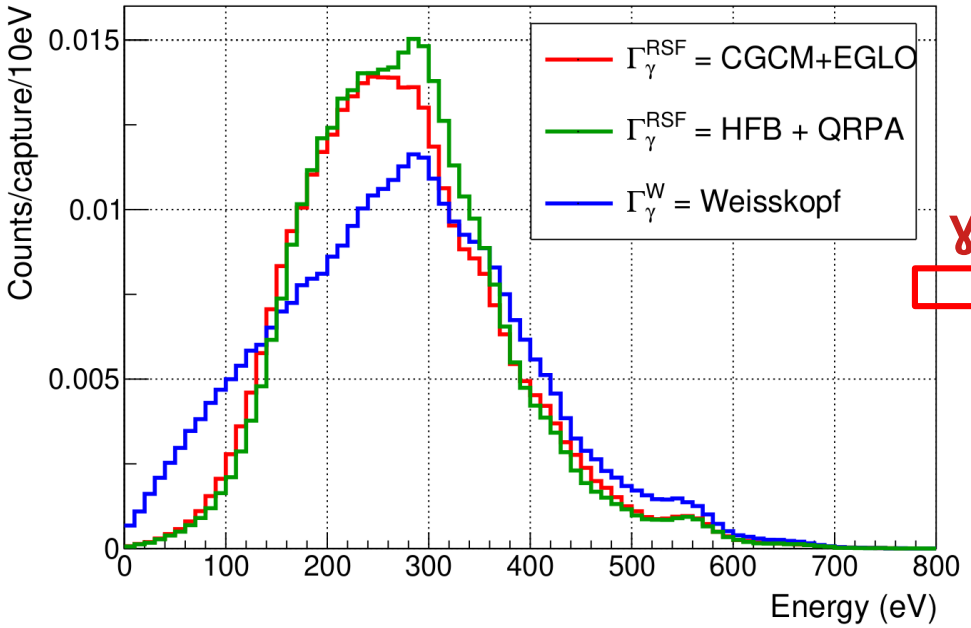
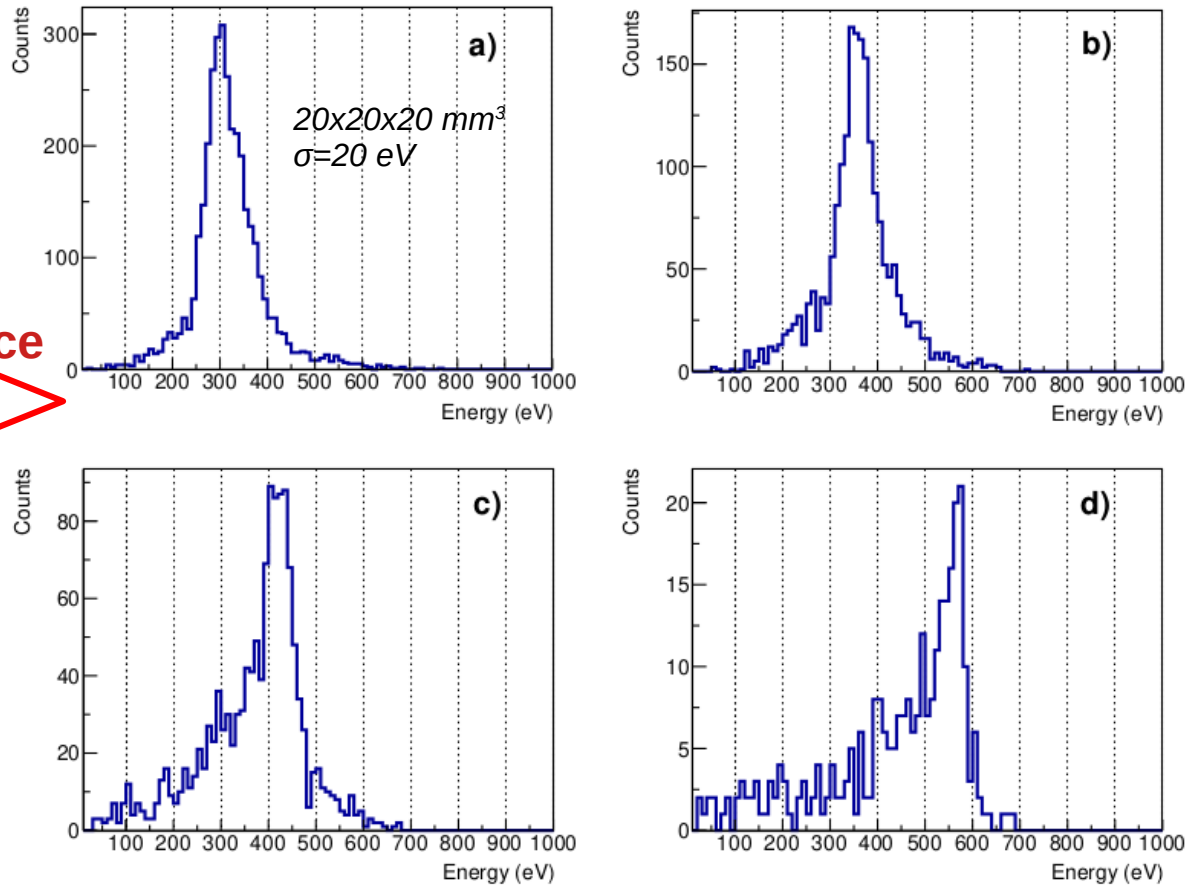


γ-coincidence



Resolution is a critical parameter
BUT gamma coincidence allows to overcome this limitation !

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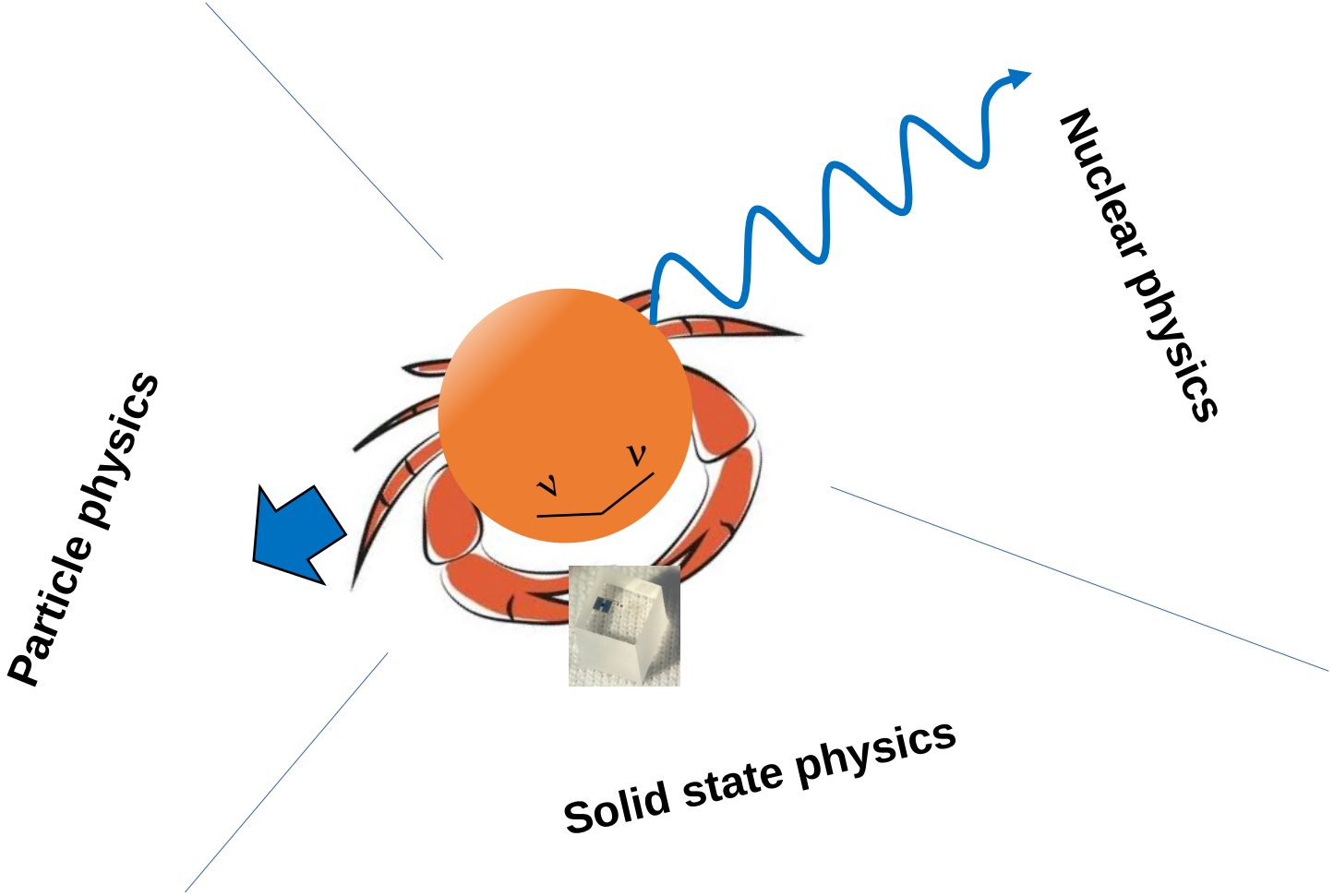
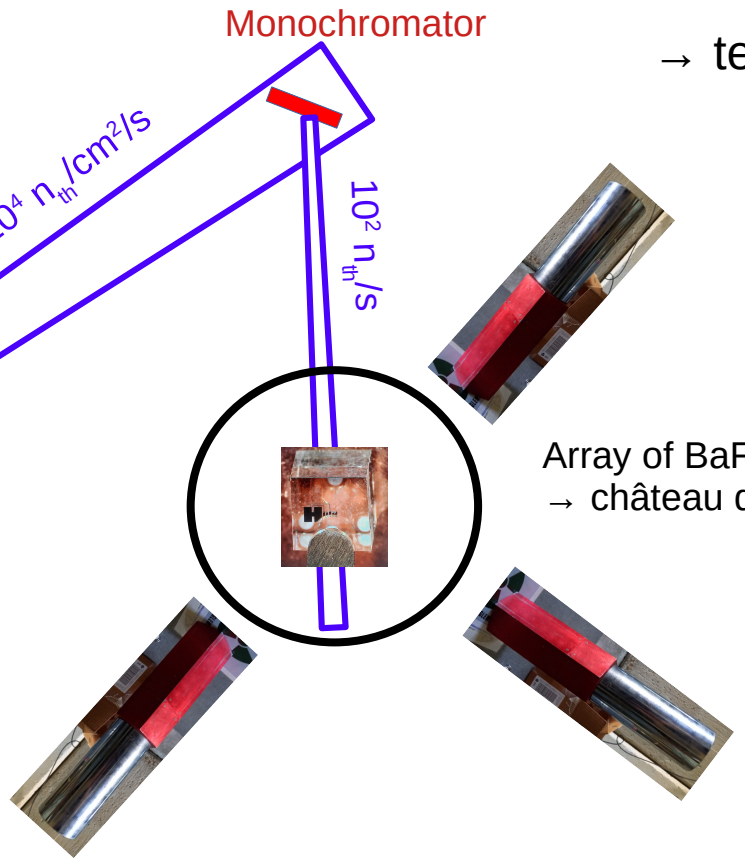
WHAT IS NEXT ?



HIGH PRECISION MEASUREMENTS – SOON IN 2024

Low intensity (~100 n_{th}/s) thermal neutron beam at TRIGA Mark-II nuclear reactor (250 kW) in Vienna

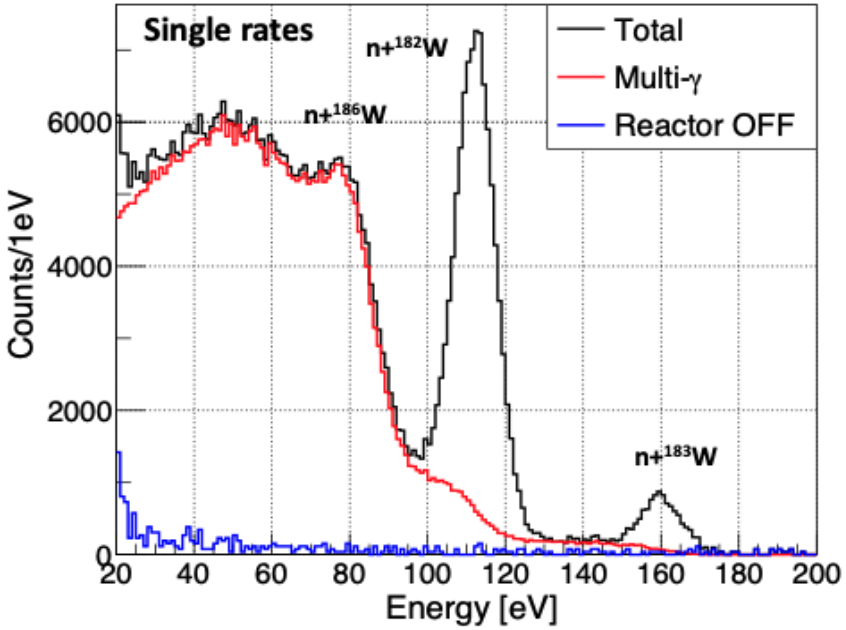


Coincidence between ɣ detectors and cryo-detector
→ increase signal / background ratio
→ get more calibration peaks
⇒ linearity study
→ test directionnality effect

Array of BaF2 gamma detectors
→ château de cristal

DO YOU REMEMBER SLIDE 14 ?

How to get a third peak at ~85 eV from the spectrum below ?



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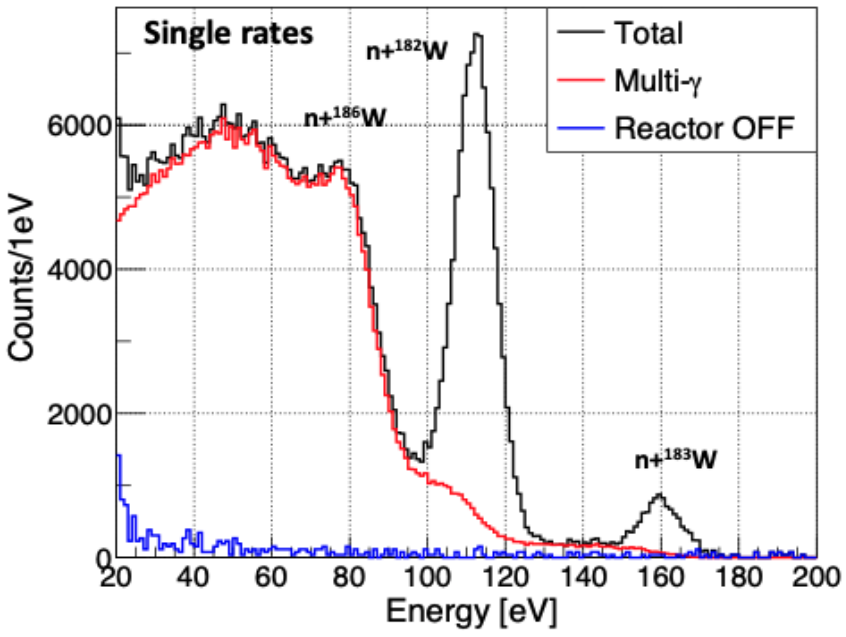
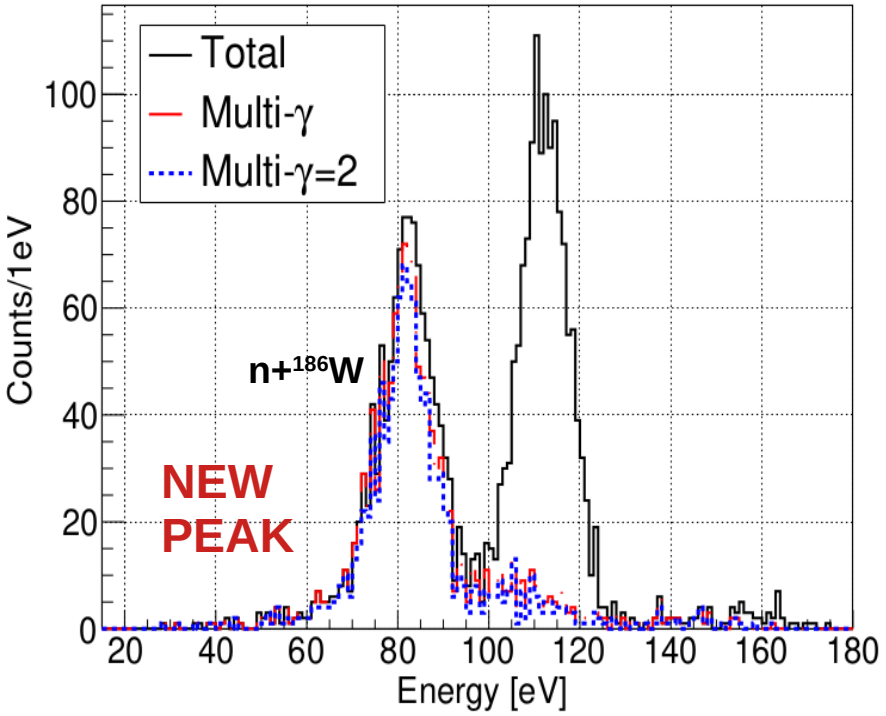


γ-coincidence !



Recoil spetrum after gamma tagging with E_γ=5.5 ±0.2 MeV

γ-tagging is a powerful tool to get a 3rd peak for CaWO4 ⇒ **linearity study** !

CONCLUSION AND PERSPECTIVES

- **CRAB method** promising for a **sub-kev calibration** of the majority of cryo-detector materials in DM/CEvNS communities currently used (**$CaWO_4$**, **Ge**, **Si**, **Al_2O_3**)

- Successfull first measurement with a NUCLEUS $CaWO_4$ and a portable neutron source
  - ⇒ presence of a peak at ~112 eV with 3.1σ significance
    - → Confirmation from independent measurement by the CRESST collaboration with higher significance
  - ⇒ presence of nuclear recoils with 6σ significance

- CRAB with **gamma tagging** is a powerul tool to **increase S/B** and **access lower energy** recoils, study the linearity of the bolometer response and tag the direction of the recoil (directionality)

- CRAB phase 2 / full precision in Vienna in preparation should be performed in 2024
  - ⇒ stay tuned !

THANK YOU

The CRAB collaboration