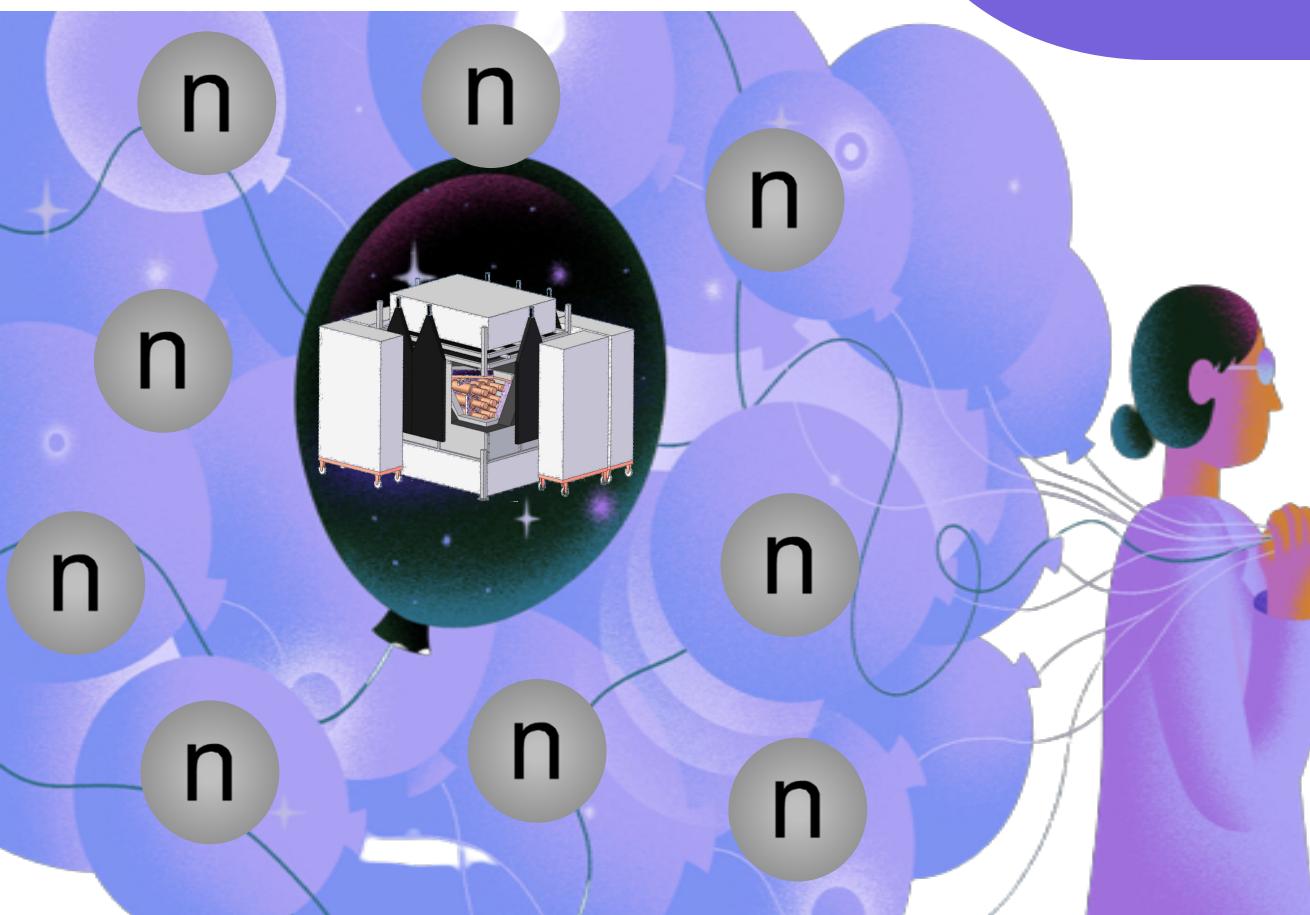




Neutron calibrations in dark matter searches: the ANAIS-112 case

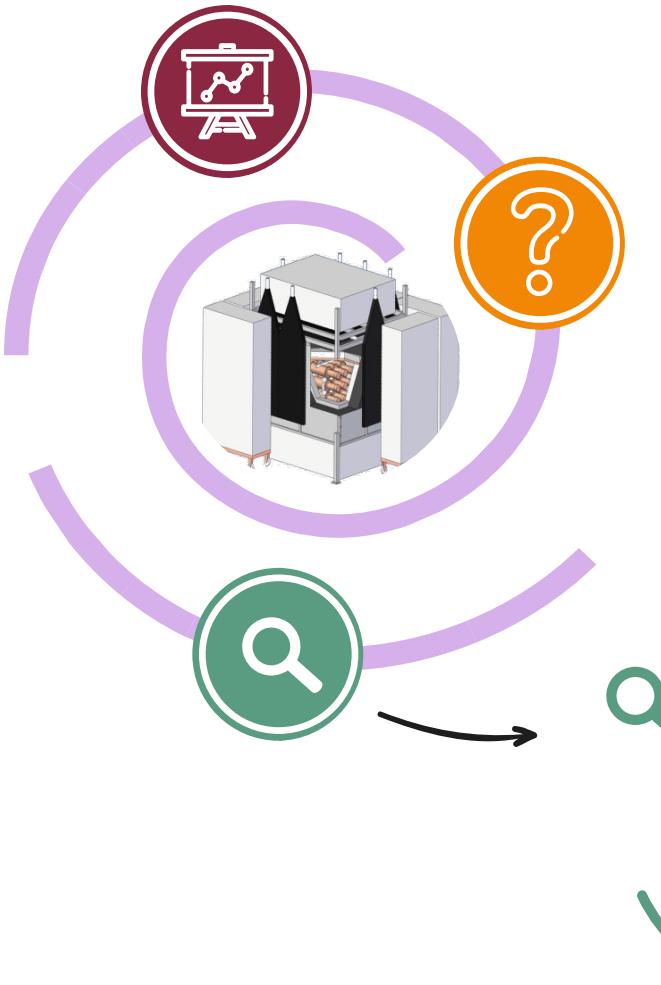
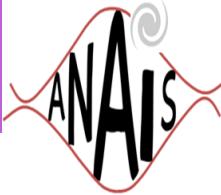


Tamara Pardo on
behalf of the ANAIS research team

J. Amaré, J. Apilluelo, S. Cebrián, D. Cintas, I. Coarasa,
E. García, M. Martínez, M.A. Oliván, Y. Ortigoza,
A.Ortiz de Solórzano, T. Pardo, J. Puimedón,
A. Salinas, M.L. Sarsa, P. Villar

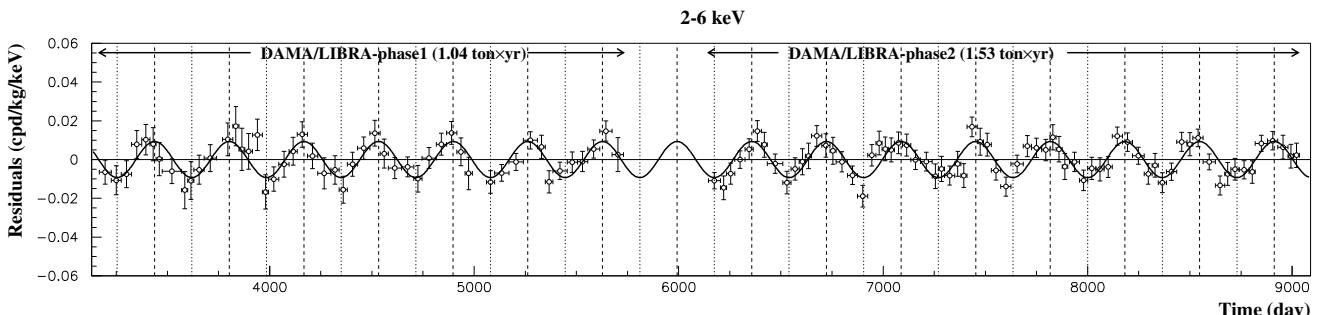
XVII TAUP conference, Vienna
28 August-1 September 2023

THE ANAIS-112 EXPERIMENT



Universe 4, 116 (2018), 1805.10486
Progress in Particle and Nuclear Physics 114 (2020)

DAMA/LIBRA experiment at LNGS uses ~250kg NaI(Tl) as target and it has been taking data for more than 20 years



DAMA/LIBRA data favor the presence of a modulation with proper features at 13.7σ CL in the 2-6 keV & 11.8σ CL in the 1-6 keV

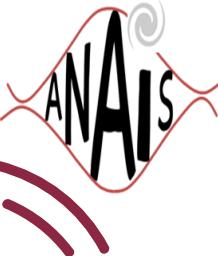
ANAIS' goal is to **confirm or refute** in a model independent way the DAMA/LIBRA positive annual modulation result with the same target and technique (but different experimental approach and environmental conditions) at the Canfranc Underground Laboratory (@Spain) with 112.5 kg of NaI(Tl)

More details on the ANAIS-112 set-up here:



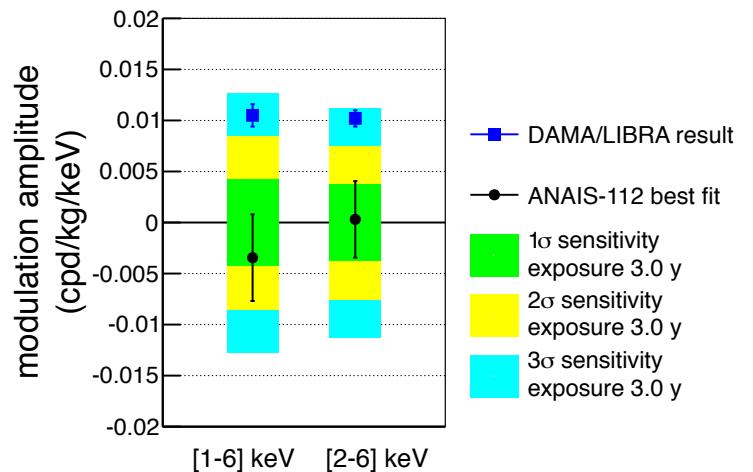
J. Amaré et al., EPJC79 (2019) 228

THE ANAIS-112 EXPERIMENT



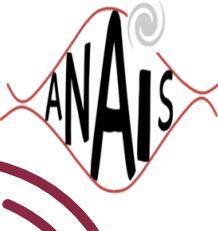
3 years of analyzed data are compatible with absence of modulation and incompatible with DAMA/LIBRA with a sensitiviy $> 2.5\sigma$ in [1-6] & [2-6] keV

J. Amaré et al. Physical Review D 103 (2021) 102005
Phys. Rev. Lett. 123 (2019) 031301

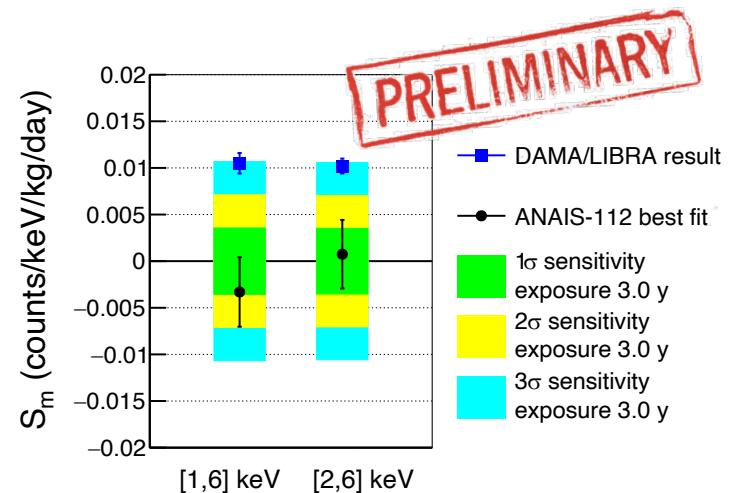


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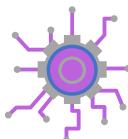
THE ANAIS-112 EXPERIMENT



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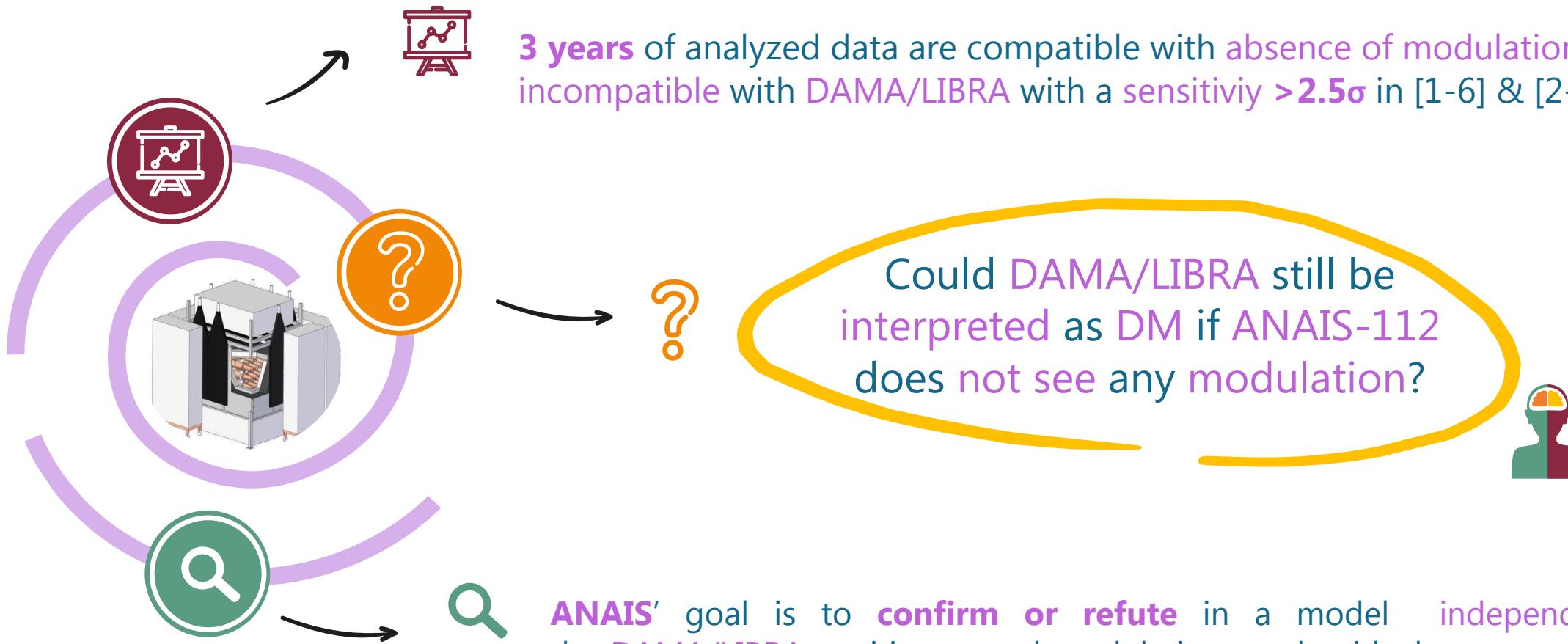
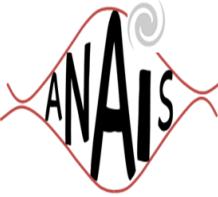
I. Coarasa et al, JCAP11(2022)048
I. Coarasa et al, JCAP06(2023)E01



Wanna know about our latest reanalysis?
Go see I. Coarasa talk!
Parallel DM session #8B (Thursday 16:15)

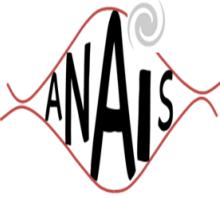
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THE ANAIS-112 EXPERIMENT



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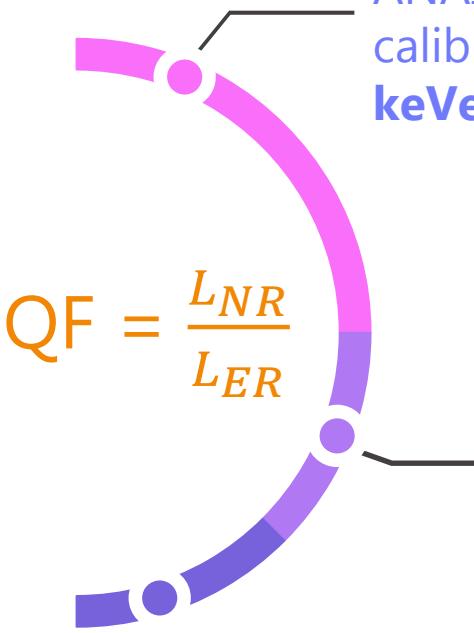
Is it really a direct comparison?



ANALIS & DAMA use the same target material, **NaI(Tl)**, and are calibrated with gamma sources → direct comparison in **keVee(*)**



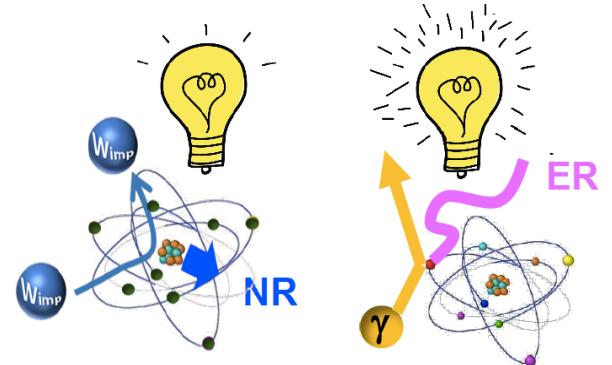
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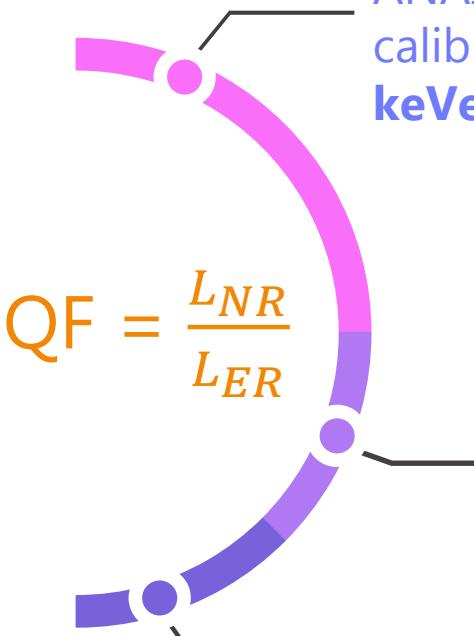
ANALIS & DAMA use the same target material, **NaI(Tl)**, and are calibrated with gamma sources  direct comparison in **keVee**(*)

 (*) keVee: electron-equivalent keV

In a scintillator, an **electron recoil** (ER) produces much more light than a **nuclear recoil** (NR) of the same energy



Is it really a direct comparison?



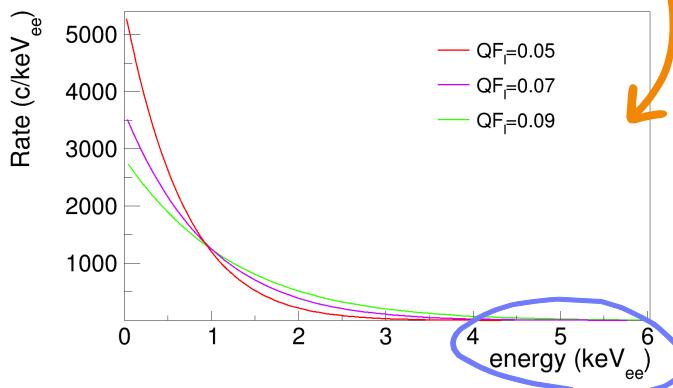
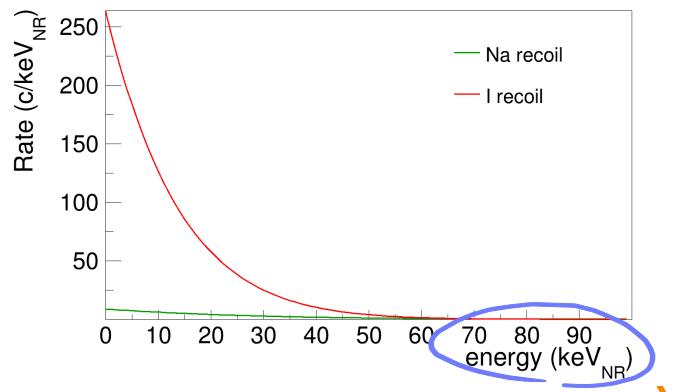
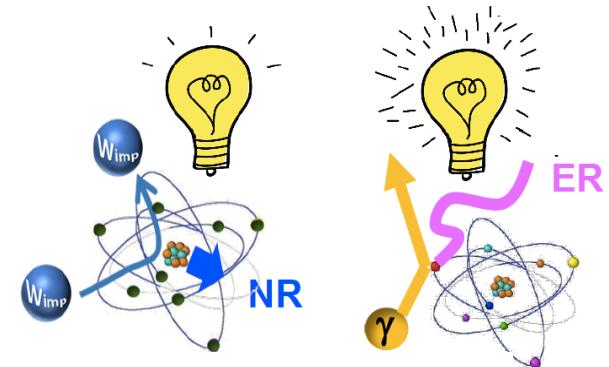
$$QF = \frac{L_{NR}}{L_{ER}}$$

ANAIS & DAMA use the same target material, **NaI(Tl)**, and are calibrated with gamma sources direct comparison in **keVee**(*)

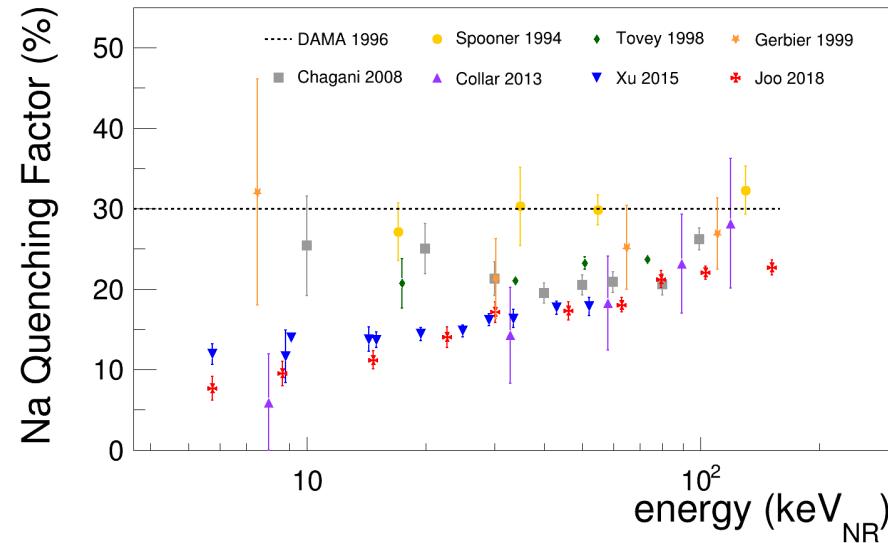


In a scintillator, an **electron recoil (ER)** produces much more light than a **nuclear recoil (NR)** of the same energy

In most of the models, DM is supposed to produce NR
Experiments must be compared in the **NR**-energy scale,
which requires a precise knowledge of the **QFs**



Current status of QF measurements in NaI



A large number of experiments have been performed to measure the QFs of NaI detectors

Still too many uncertainties in the QF values and energy dependences for NaI

$$\begin{aligned} Q_{\text{Na}} \text{ DAMA} &= 0.3 \\ Q_{\text{I}} \text{ DAMA} &= 0.09 \end{aligned}$$

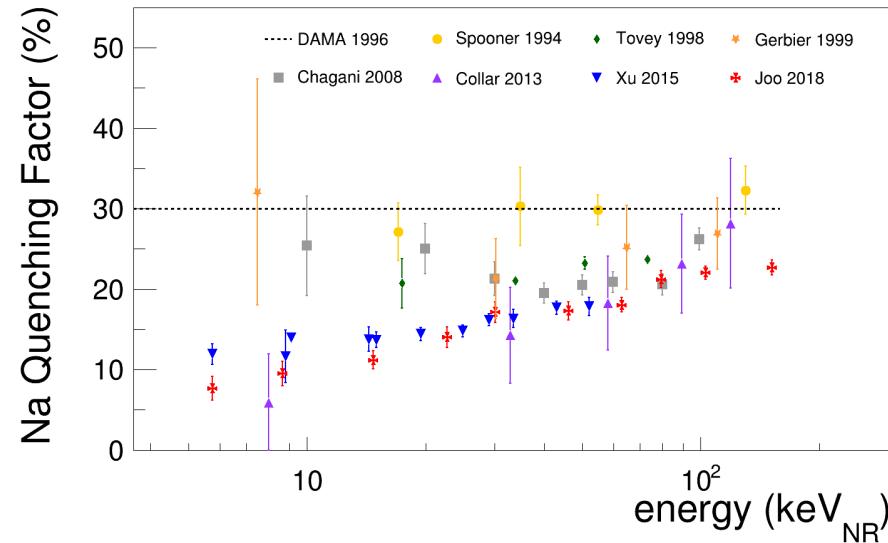
Constant QF?

1



2 Decreasing with energy
QF @ low energies?

Current status of QF measurements in NaI



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Why?

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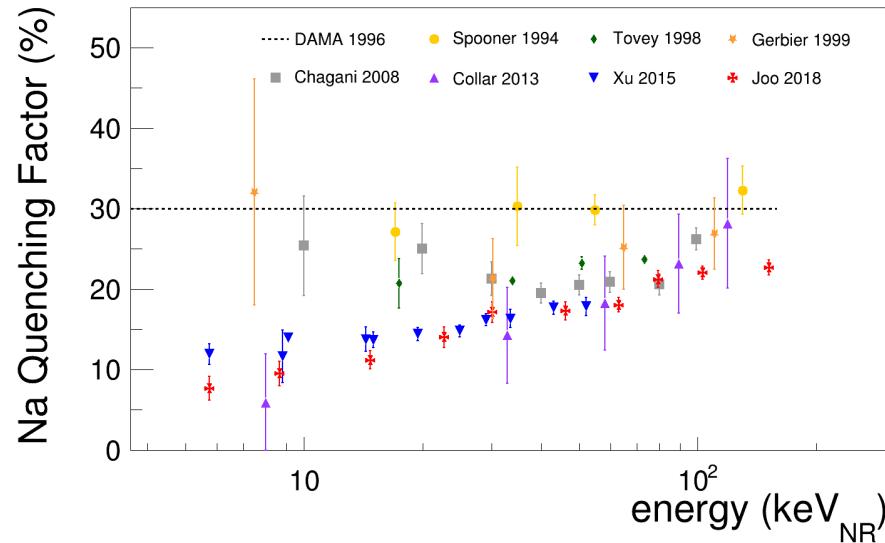
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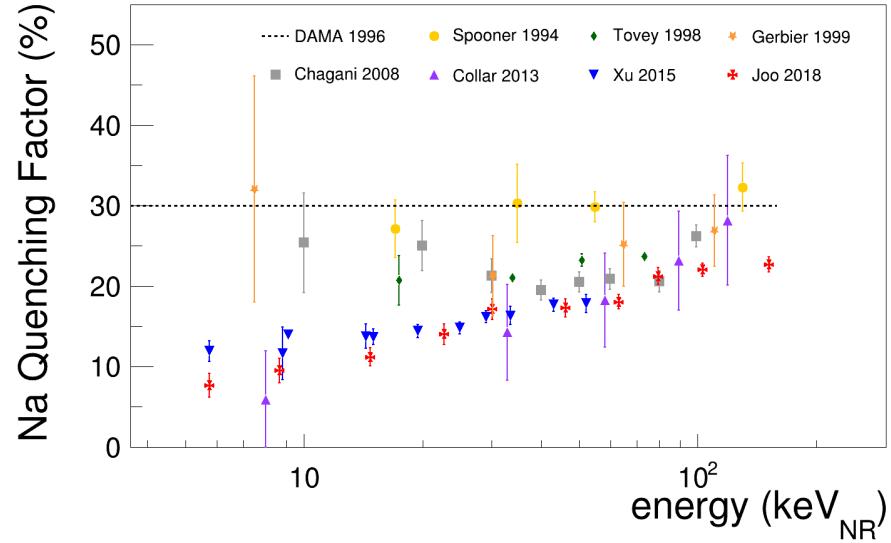
Why?

1

Differences in experimental procedures have introduced systematic differences

QF is an inherent property of NaI(Tl)

Current status of QF measurements in NaI



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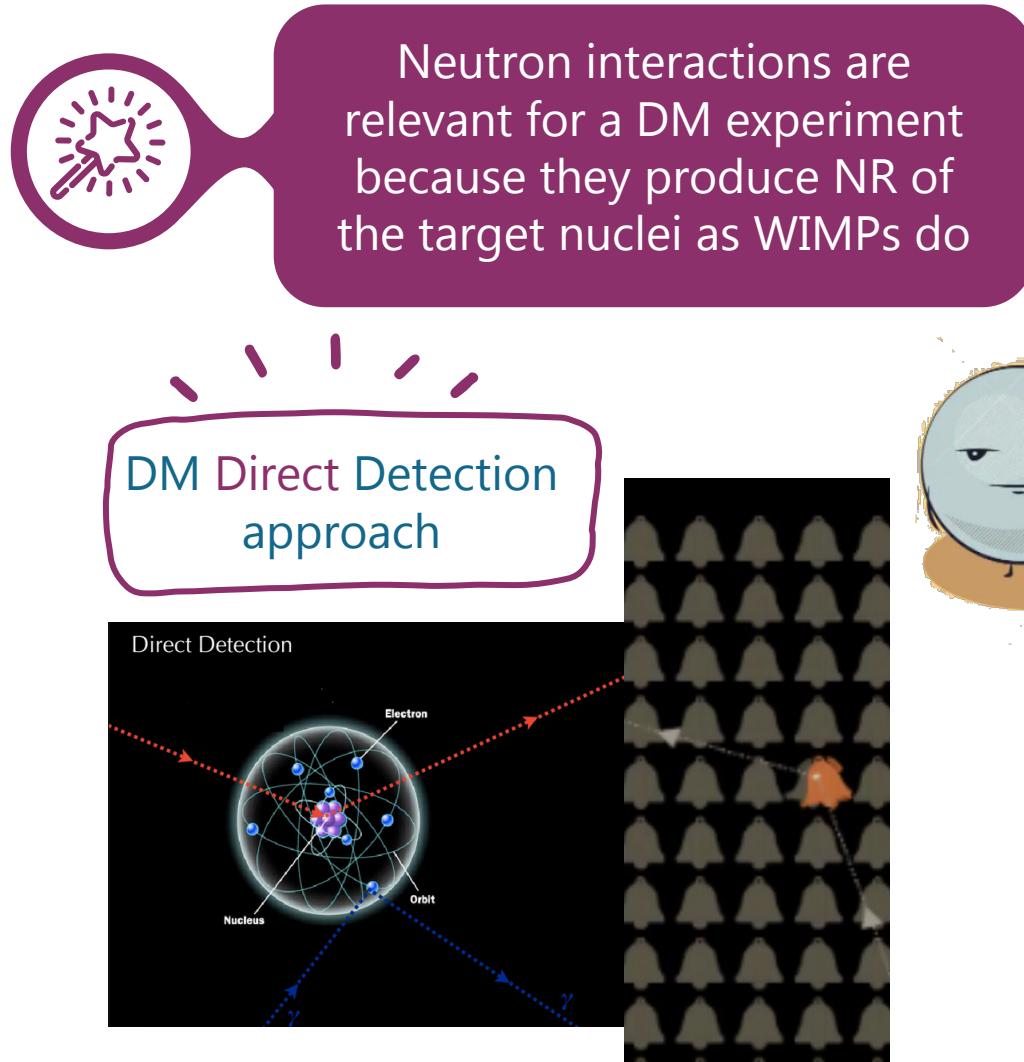
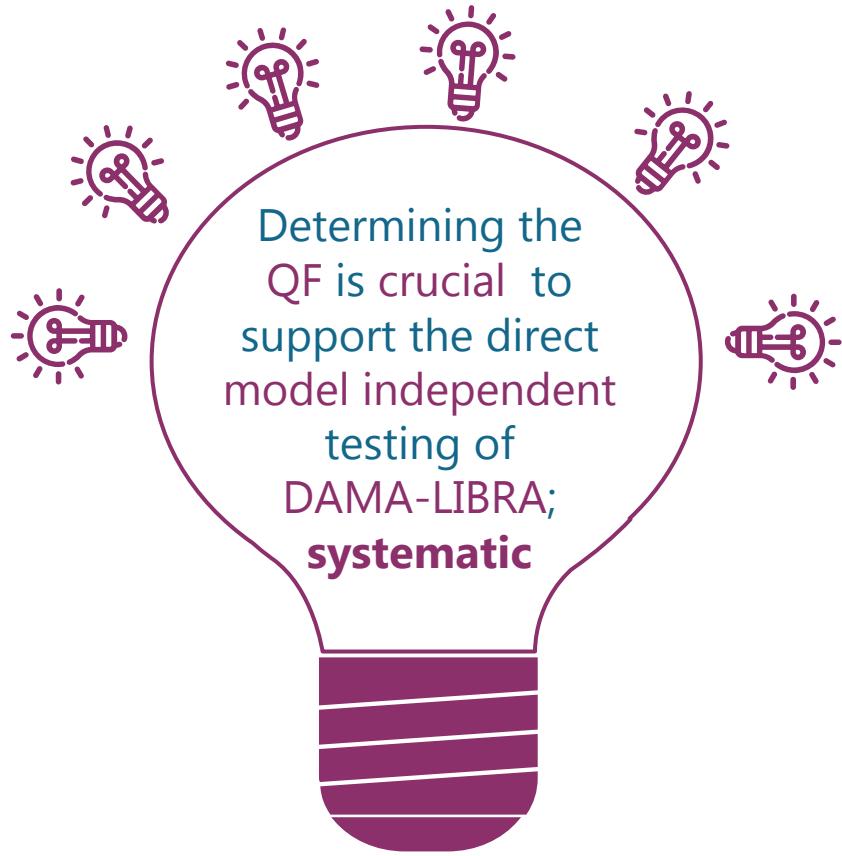
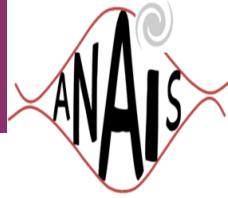
2

QF can vary between individual NaI(Tl) detectors

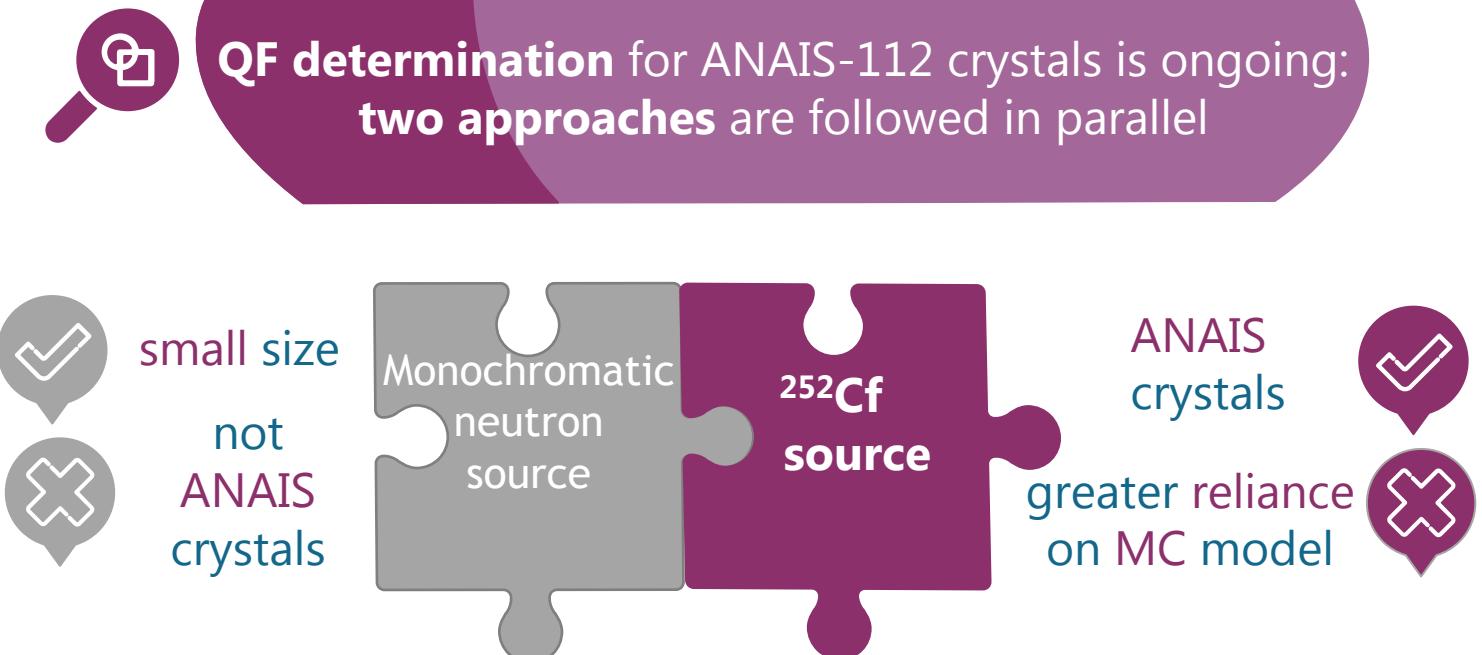
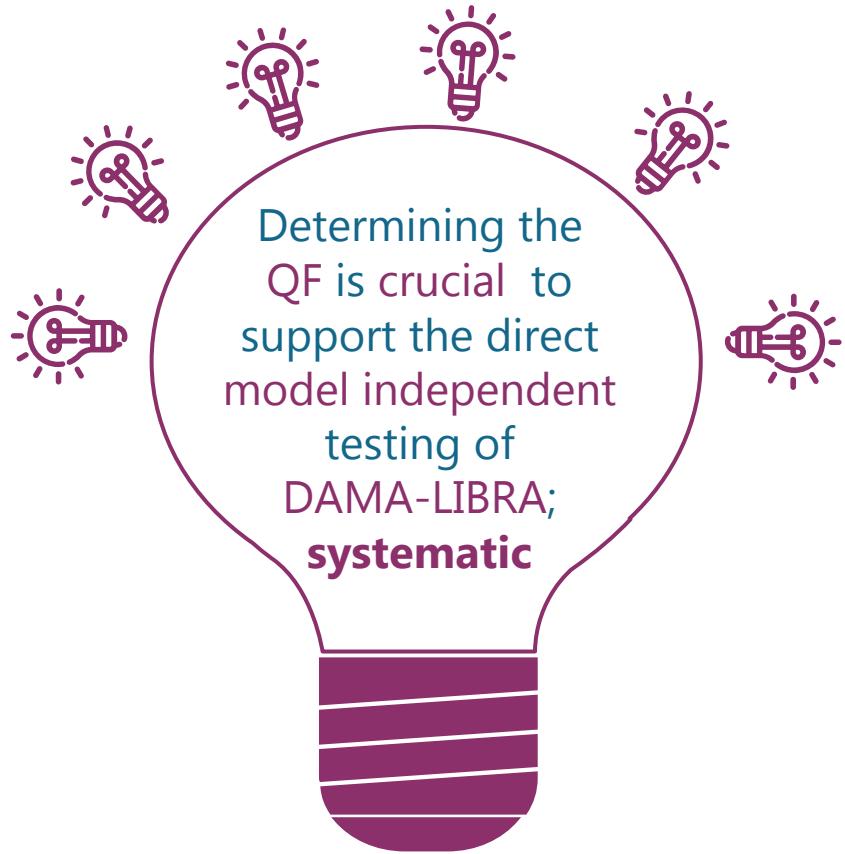
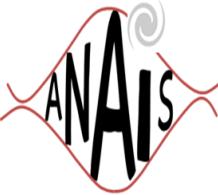
QF is an inherent property of NaI(Tl)

- Impurities
- Doping concentration
- ...

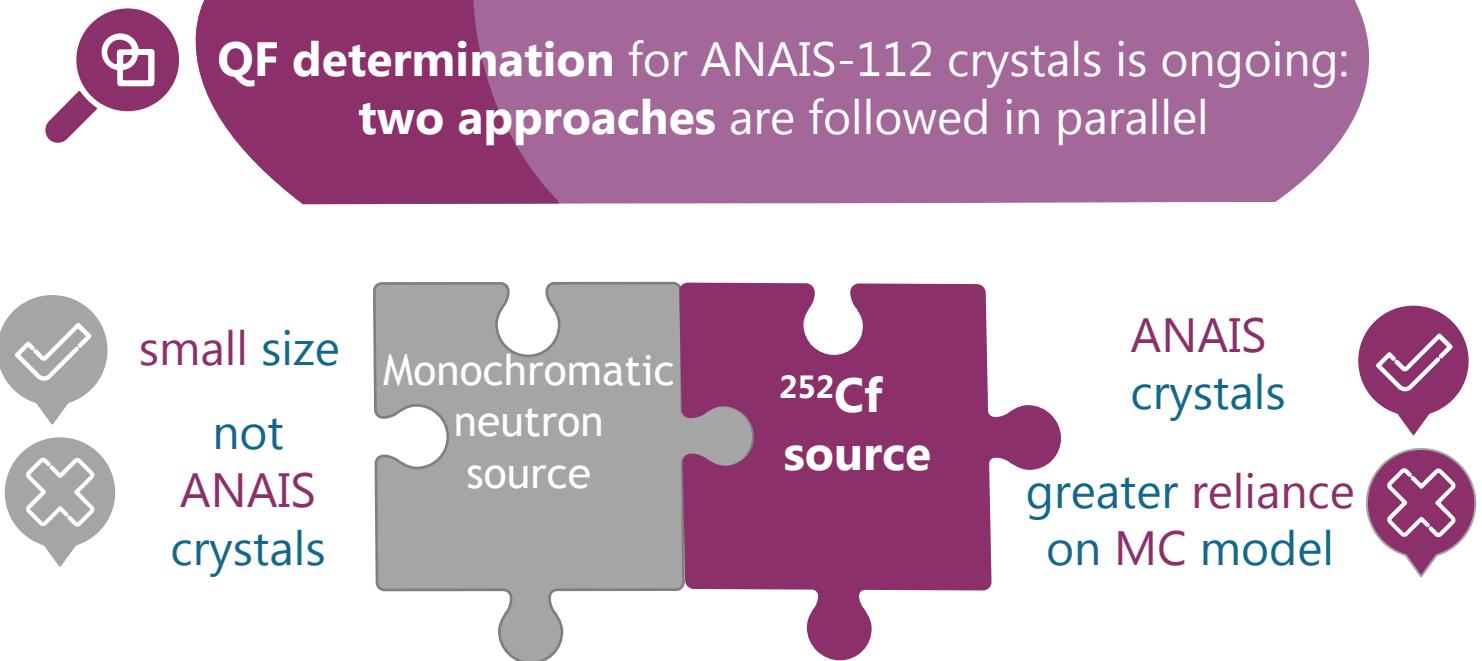
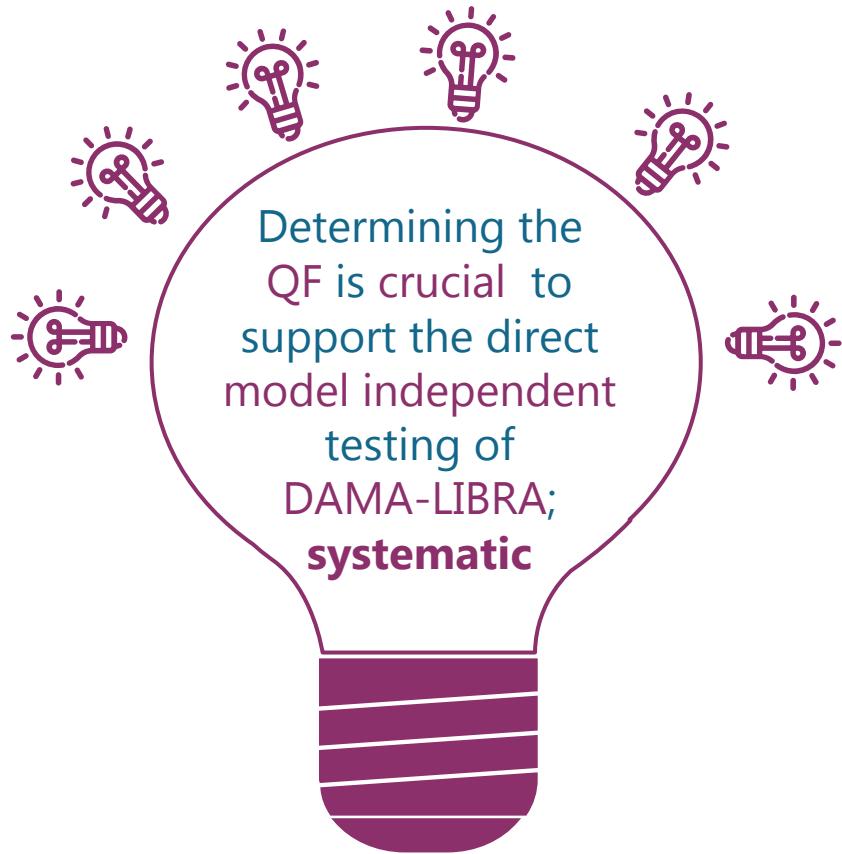
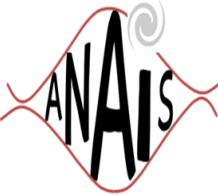
Neutron calibration program



Neutron calibration program



Neutron calibration program

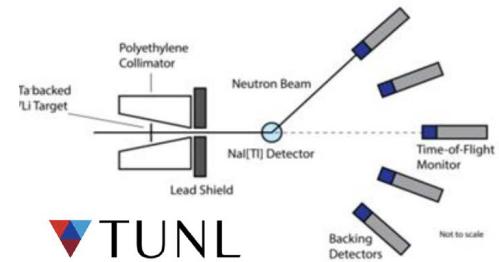
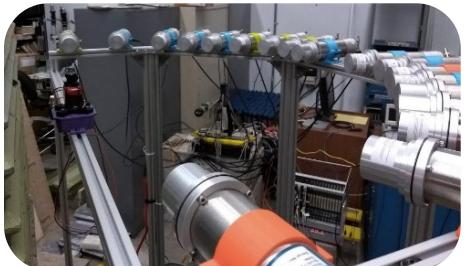
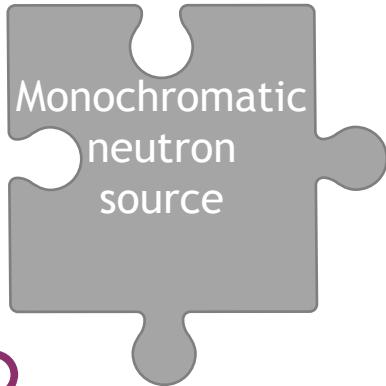
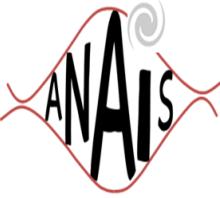


⚠ **Multiple scattering** is one of the most relevant differences



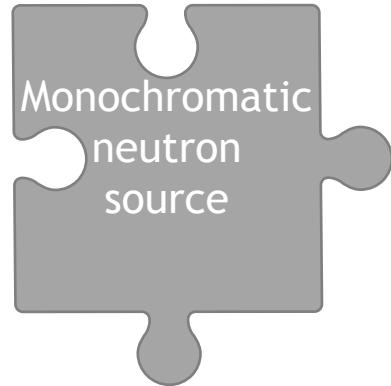
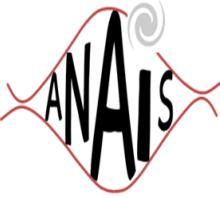
Both approaches are **complementary** and **should be consistent**

Neutron calibration program



In collaboration with Yale (from COSINE collaboration) and Duke researchers @ TUNL

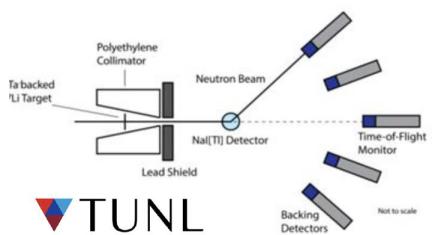
Neutron calibration program



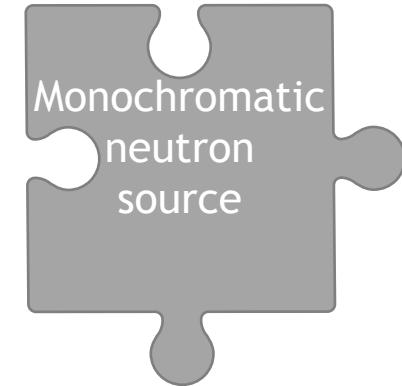
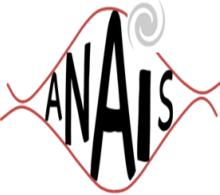
Analysis of
systematic
effects



2 different
linear **energy**
calibrations

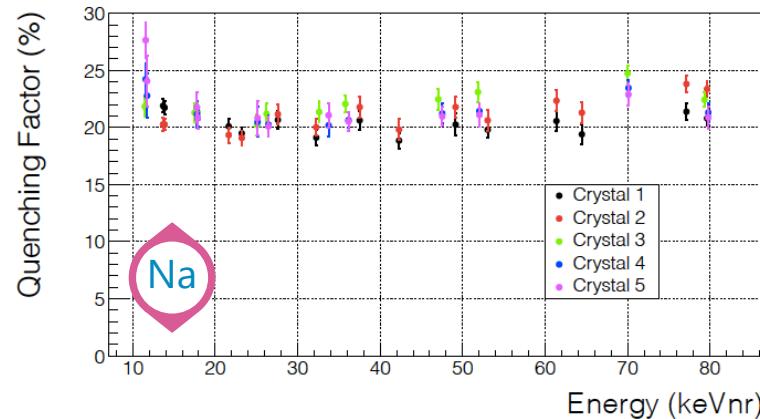
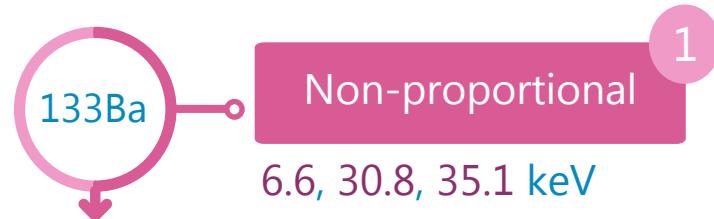
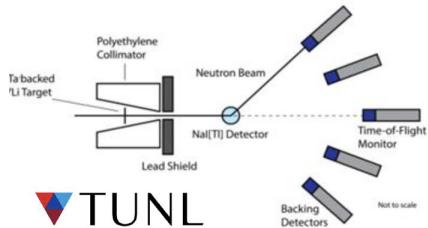


Neutron calibration program



Analysis of systematic effects

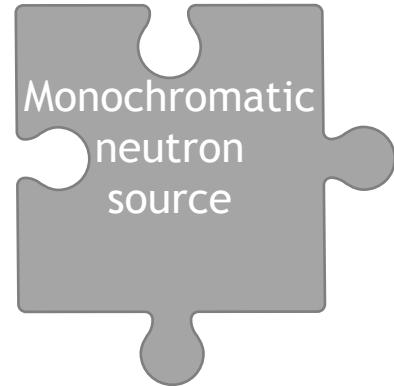
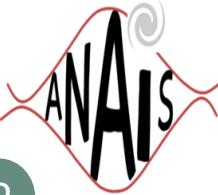
2 different linear energy calibrations



No clear dependence with energy

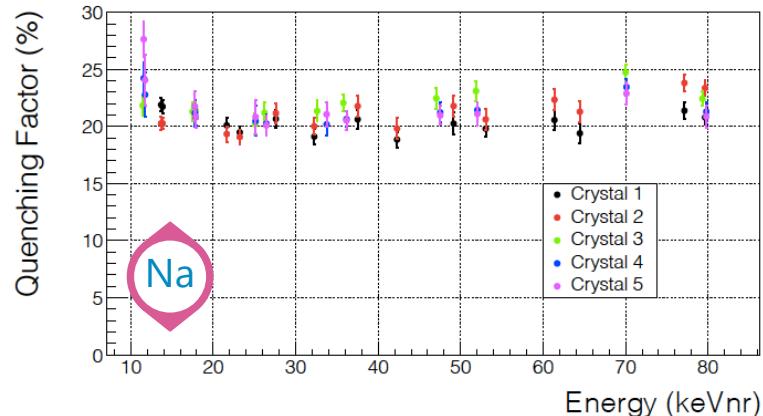
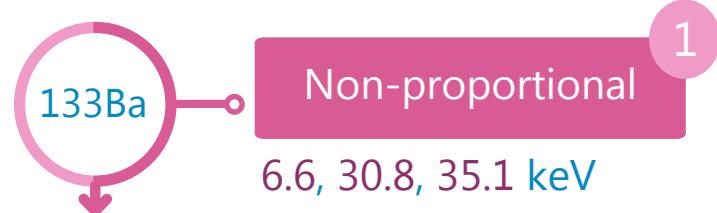
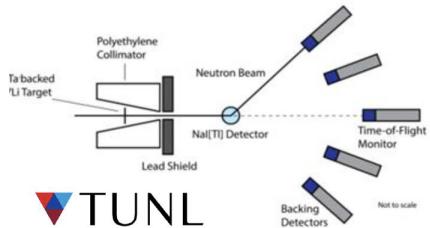
$$QF_{\text{Na}} = (21.2 \pm 0.8) \%$$

Neutron calibration program



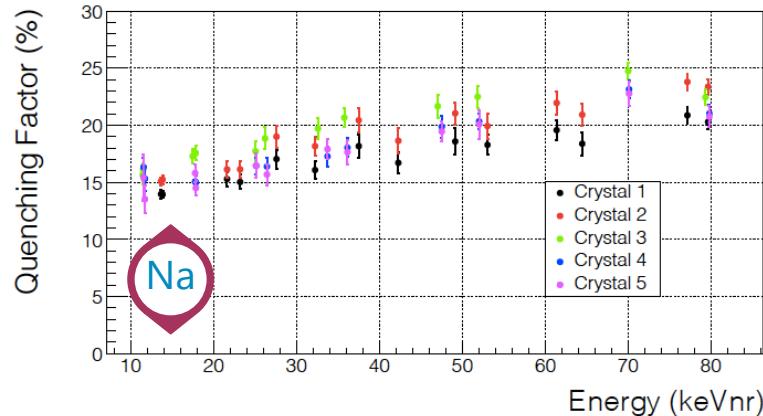
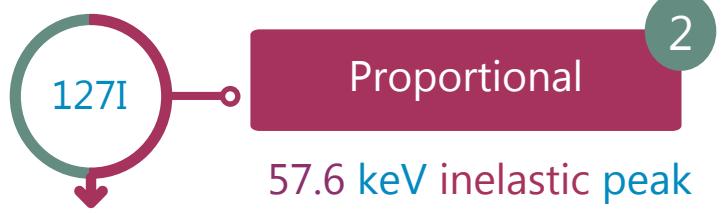
Analysis of systematic effects

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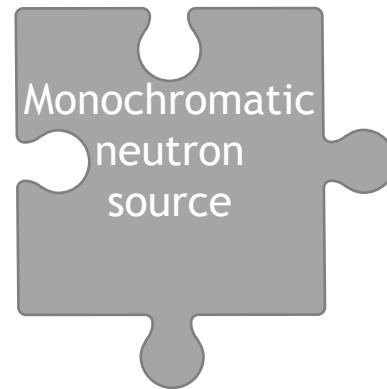
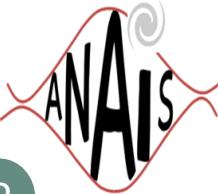
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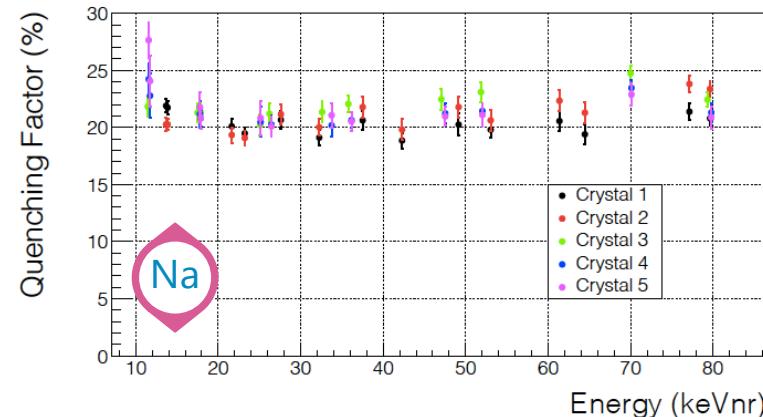
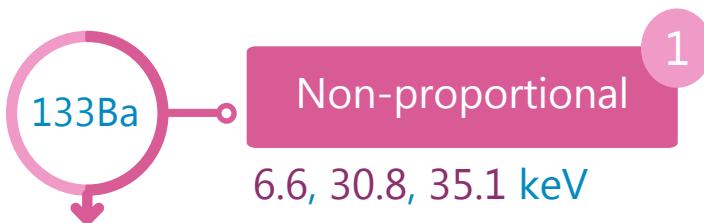
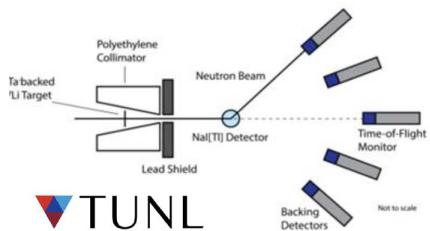
Decreasing with energy QF_{Na} @low energies

Neutron calibration program



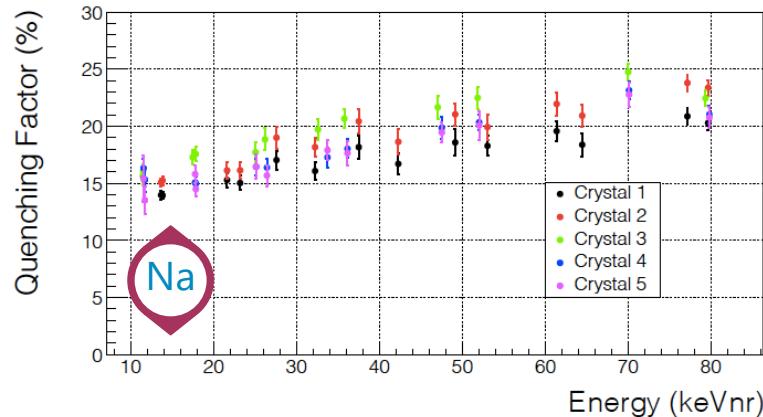
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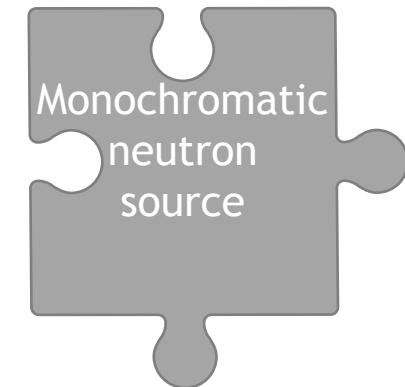
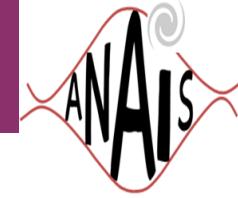
Decreasing with energy QF_{Na} @low energies



Compatible values for the 5 crystals

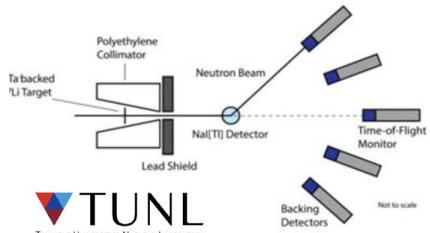
? Both procedures are not compatible among them <50 keV

Neutron calibration program

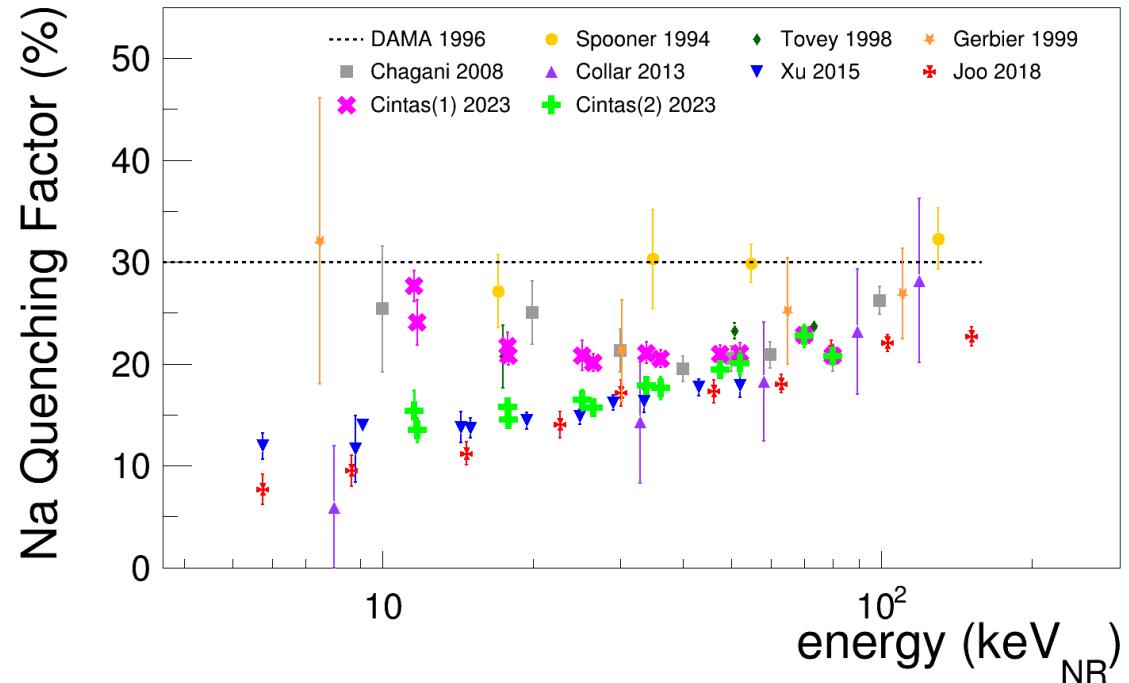


Analysis of systematic effects

2 different linear energy calibrations



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TRIANGLE UNIVERSITIES NUCLEAR LABORATORY



Fully compatible with previous measurements

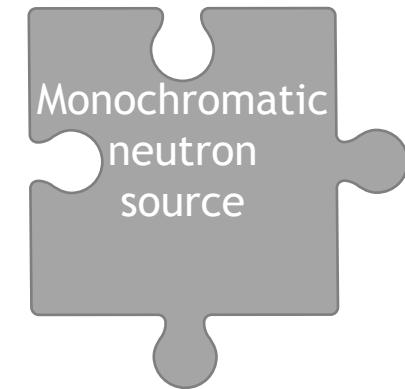
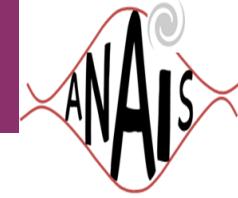


D. Cintas et al 2021 J. Phys.: Conf. Ser. 2156 012065



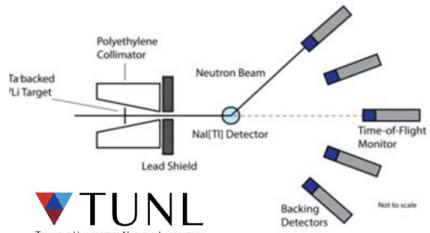
D. Cintas. *New strategies to improve the sensitivity of the ANAIS-112 experiment at the Canfranc Underground Laboratory*. PhD Thesis. Universidad de Zaragoza, 2023

Neutron calibration program

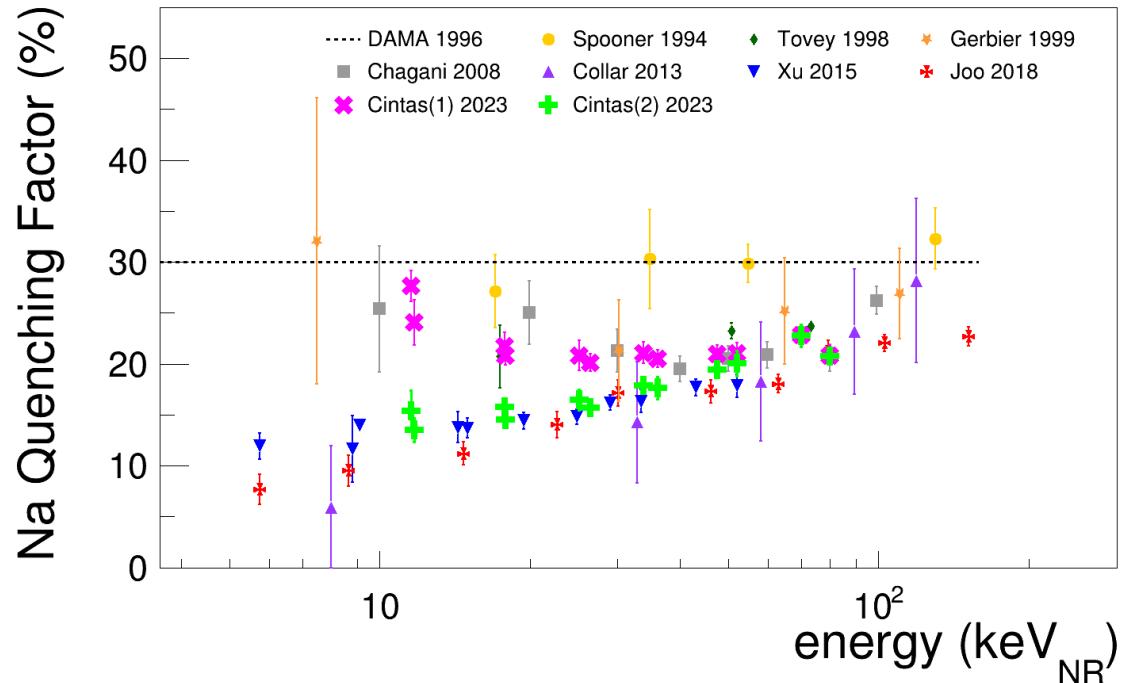


Analysis of systematic effects

2 different linear energy calibrations



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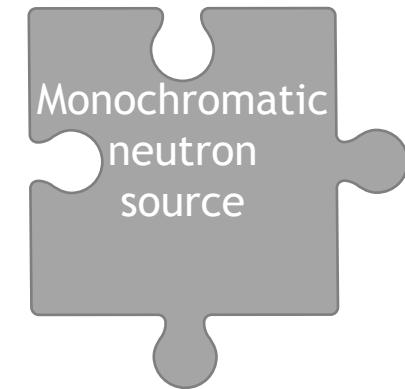
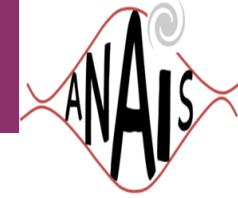


Systematics play a relevant role in the comparison of results

D. Cintas et al 2021 J. Phys.: Conf. Ser. 2156 012065

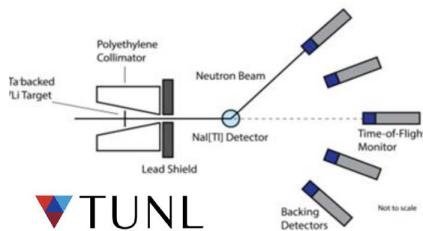
D. Cintas. New strategies to improve the sensitivity of the ANAIS-112 experiment at the Canfranc Underground Laboratory. PhD Thesis. Universidad de Zaragoza, 2023

Neutron calibration program

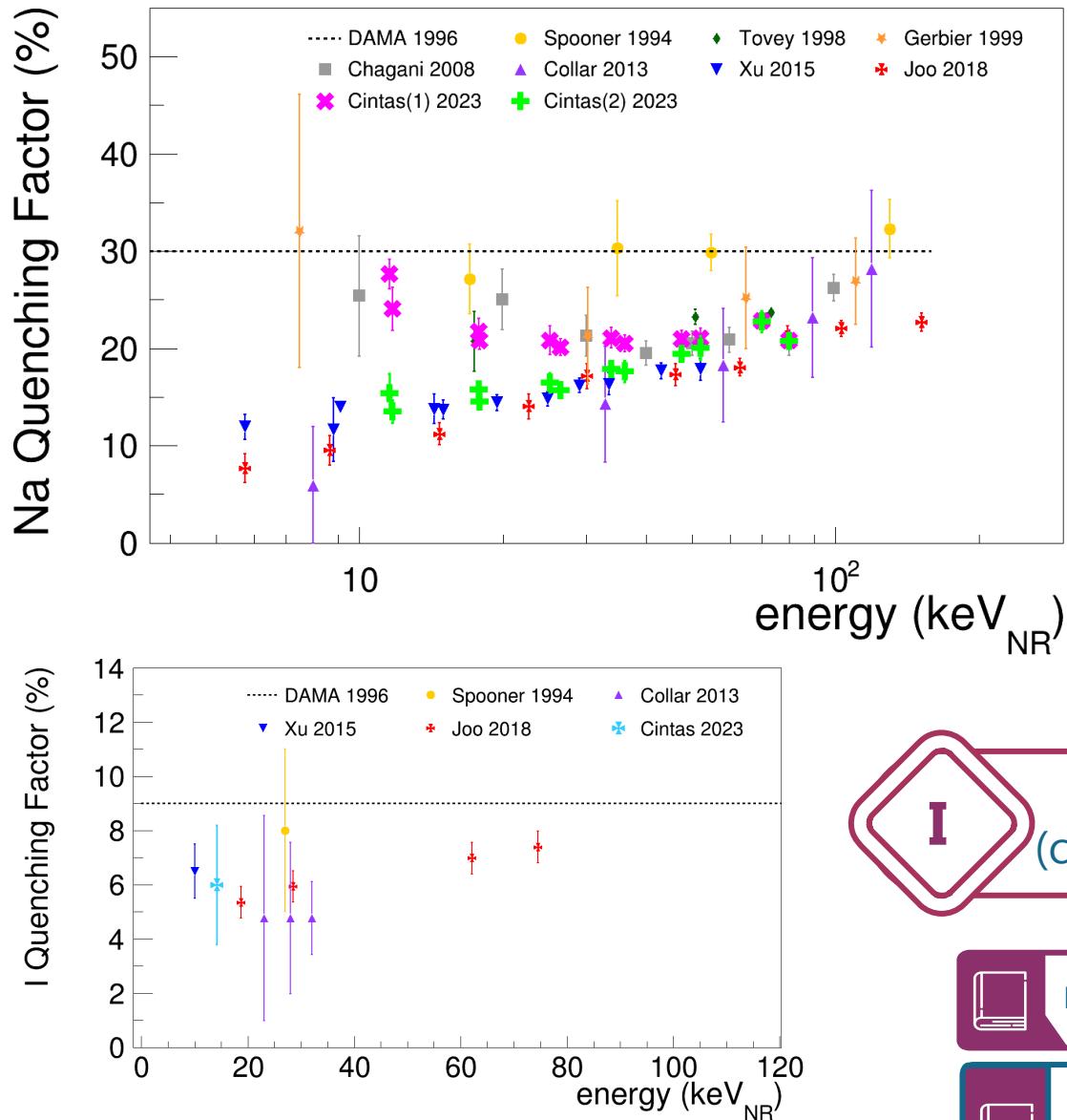


Analysis of systematic effects

2 different linear energy calibrations



TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY



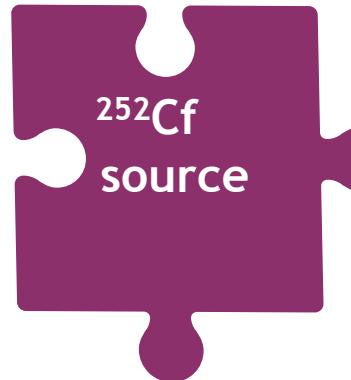
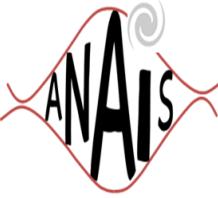
- Monochromatic neutron source
- Analysis of systematic effects
- 2 different linear energy calibrations
- Fully compatible with previous measurements
- Both procedures are not compatible among them
- Systematics play a relevant role in the comparison of results

I **QFI=(6.0 ± 2.2)%**
(combining data from 2 crystals)

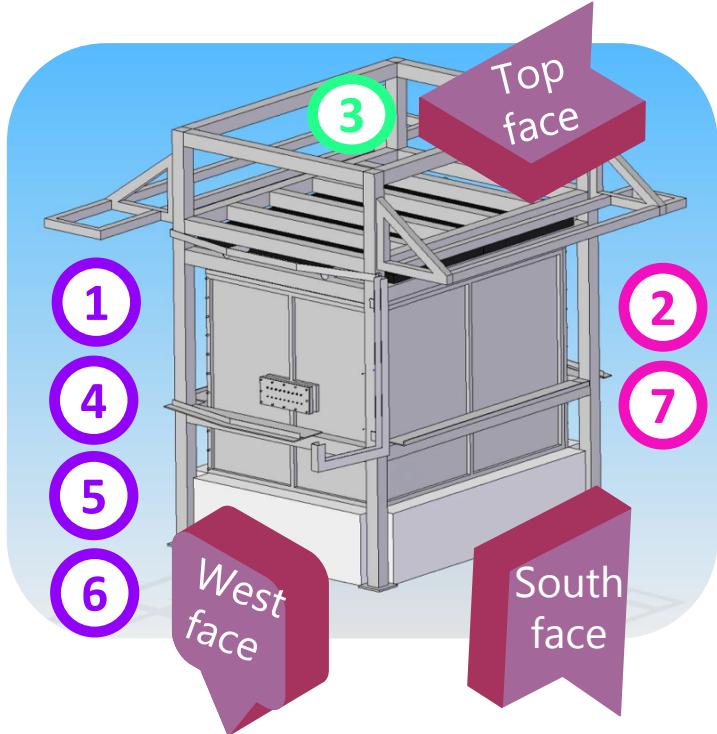
D. Cintas et al 2021 J. Phys.: Conf. Ser. 2156 012065

D. Cintas. New strategies to improve the sensitivity of the ANAIS-112 experiment at the Canfranc Underground Laboratory. PhD Thesis. Universidad de Zaragoza, 2023

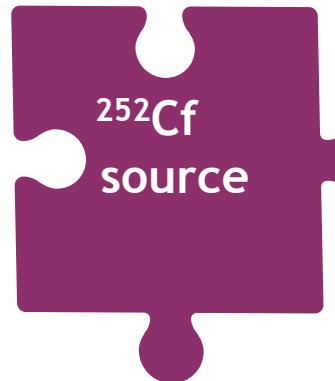
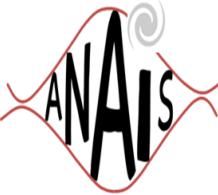
Neutron calibration program



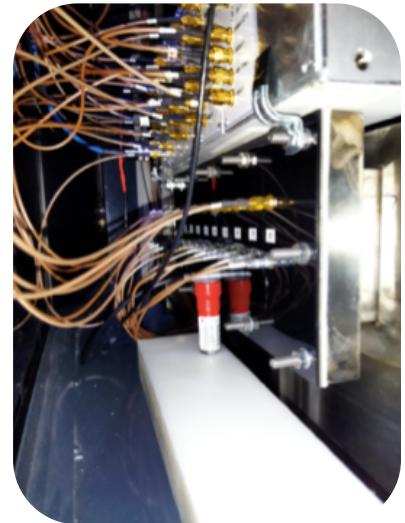
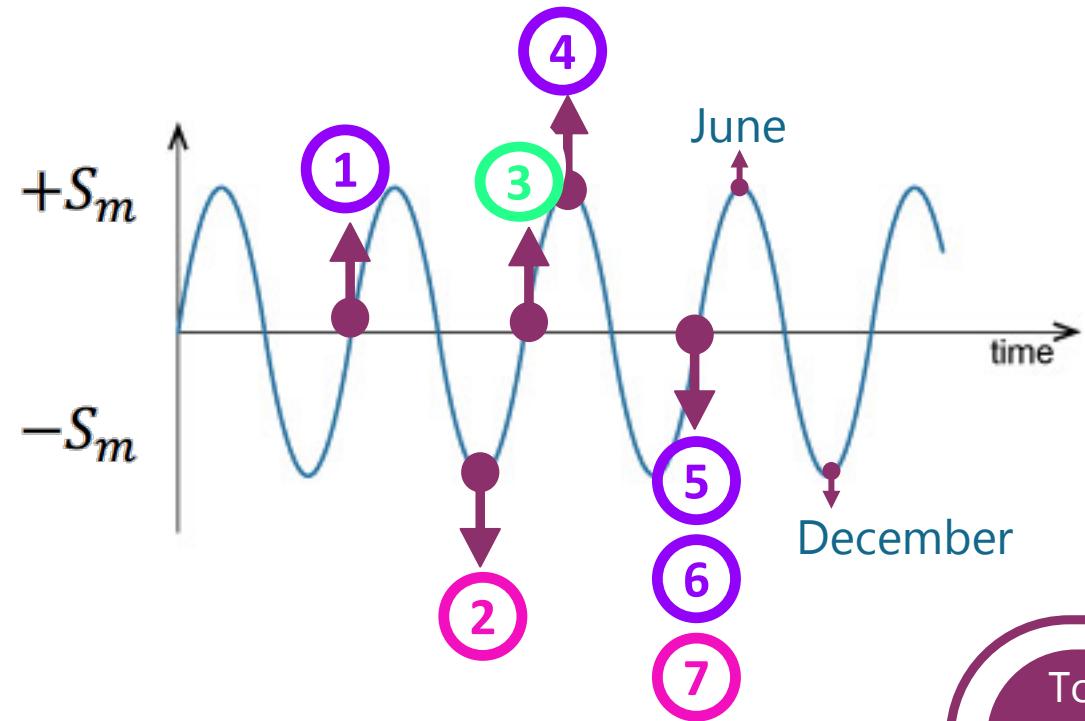
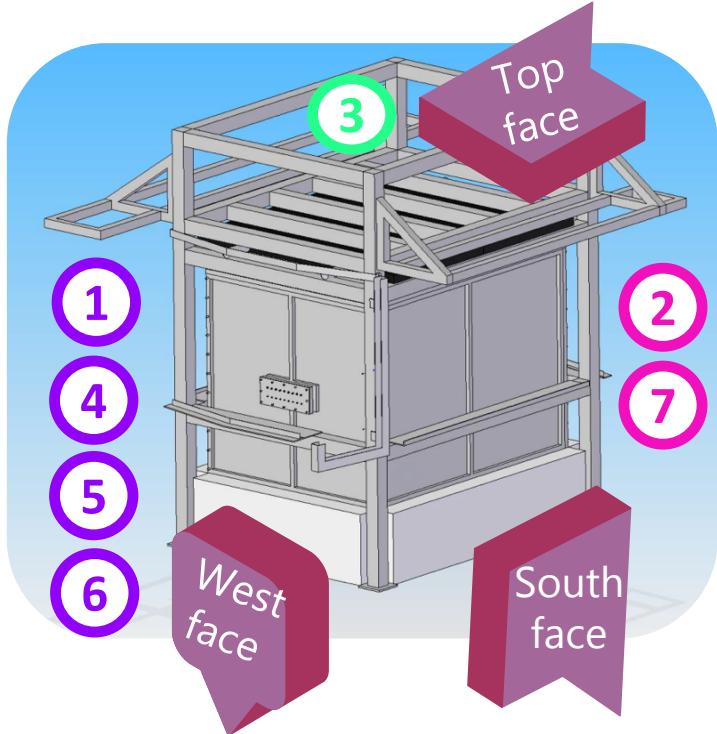
Seven calibration runs since April 2021 using a **^{252}Cf neutron source** at different positions in the **ANAlS-112** set-up



Neutron calibration program

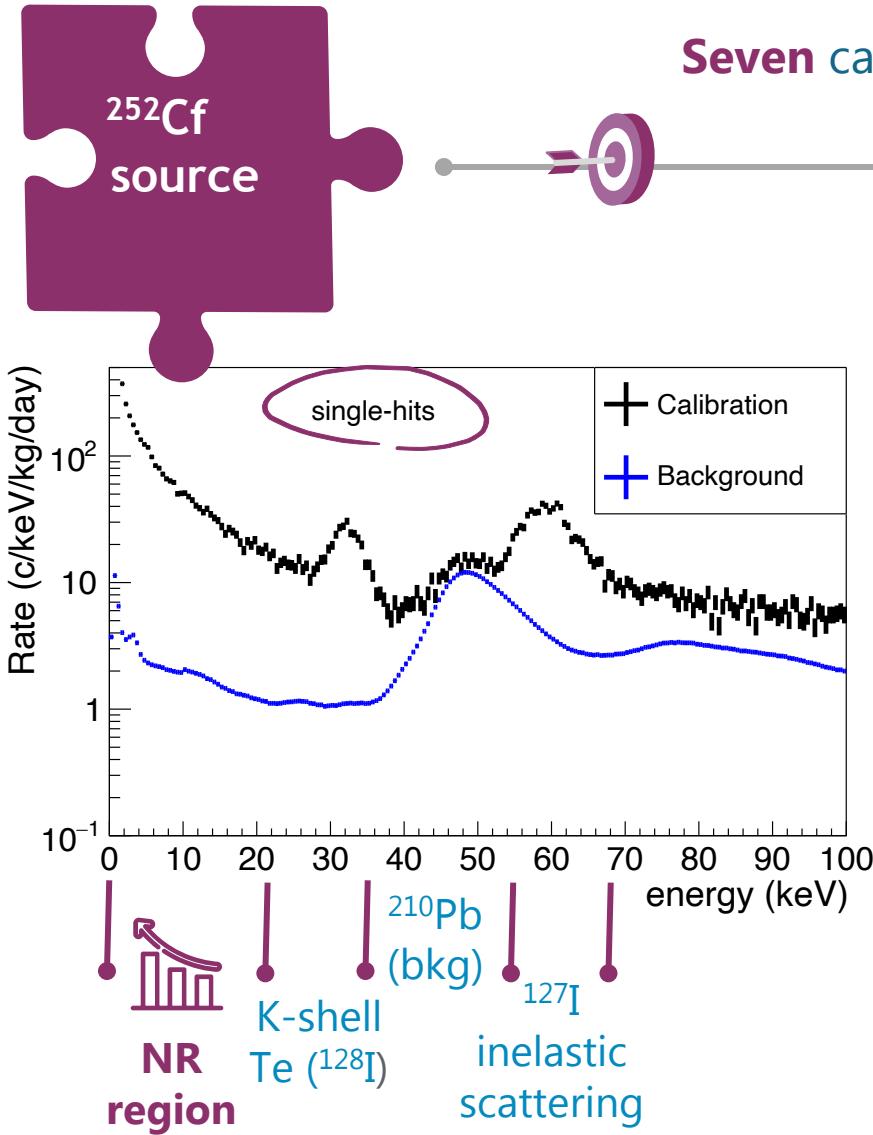


Seven calibration runs since April 2021 using a **252Cf neutron source** at different positions in the **ANALIS-112 set-up**



To evaluate the stability
of the efficiencies for
selecting NR along time

Neutron calibration program

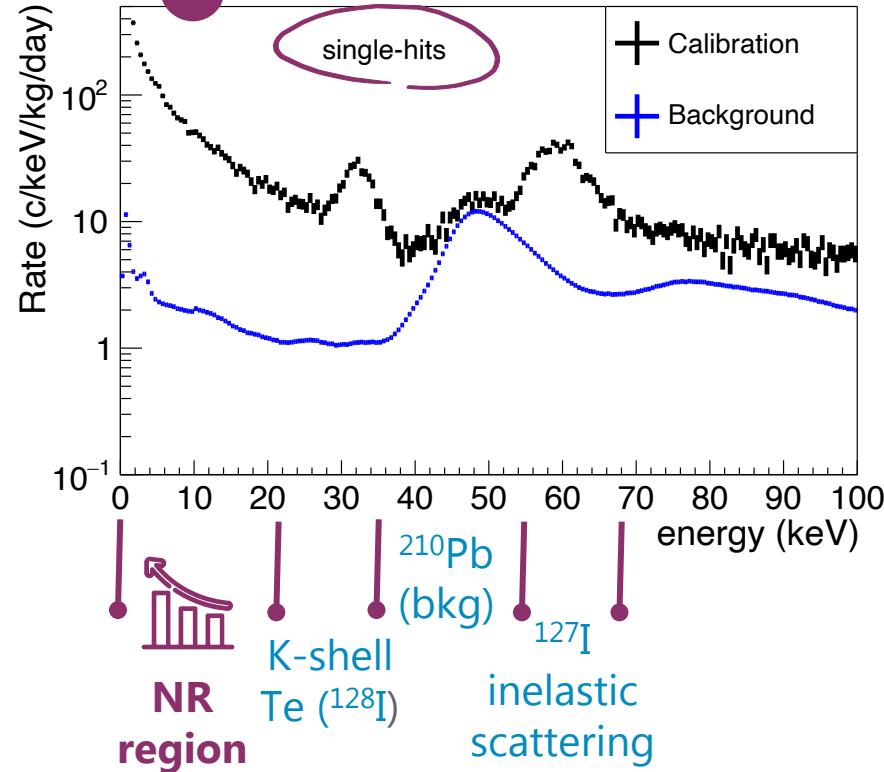
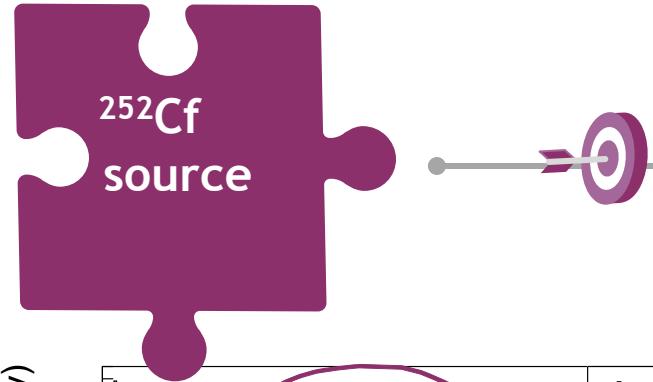


Seven calibration runs since April 2021 using a **^{252}Cf neutron source**
at different positions in the **ANALIS-112** set-up

clean population of **bulk**
scintillation events

large number of events
in the **ROI** ([1-6] keV)

Neutron calibration program



Seven calibration runs since April 2021 using a **252Cf neutron source** at different positions in the **ANALIS-112 set-up**



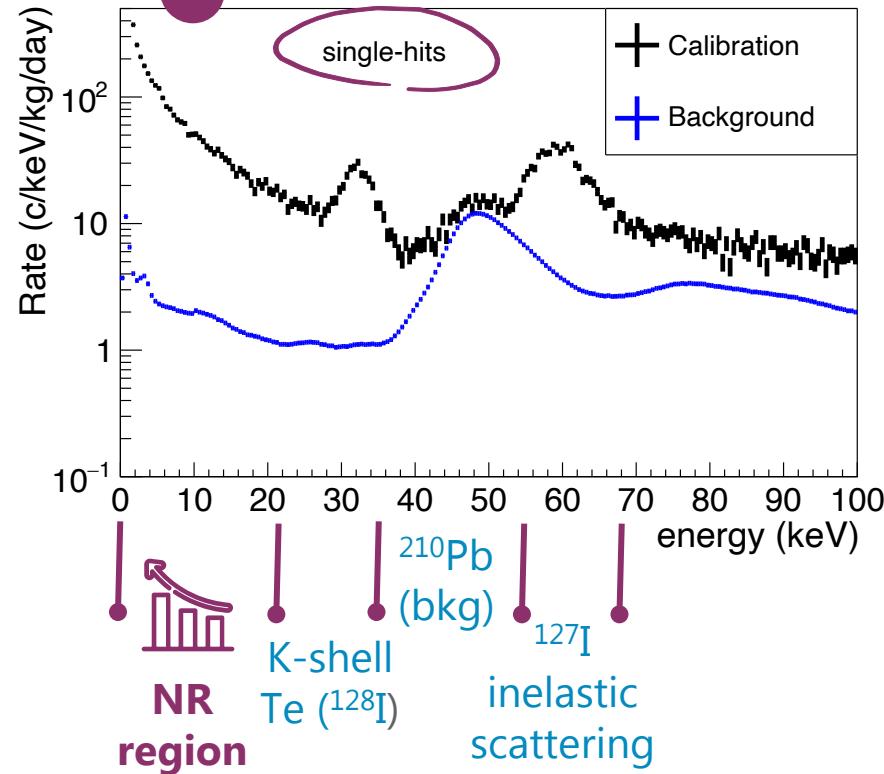
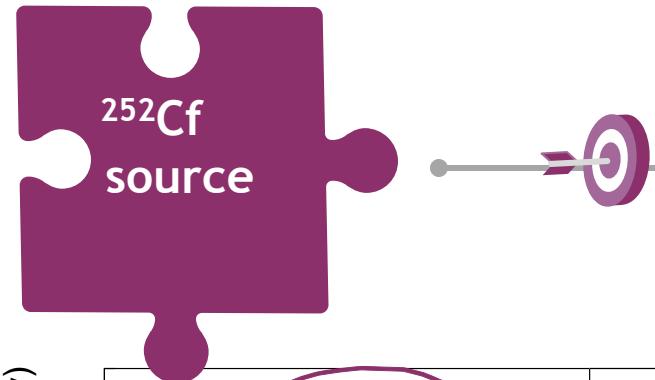
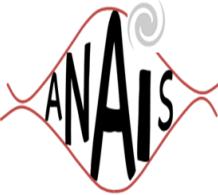
clean population of **bulk** scintillation events



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Neutron calibration program



Seven calibration runs since April 2021 using a **252Cf neutron source** at different positions in the **ANALIS-112 set-up**

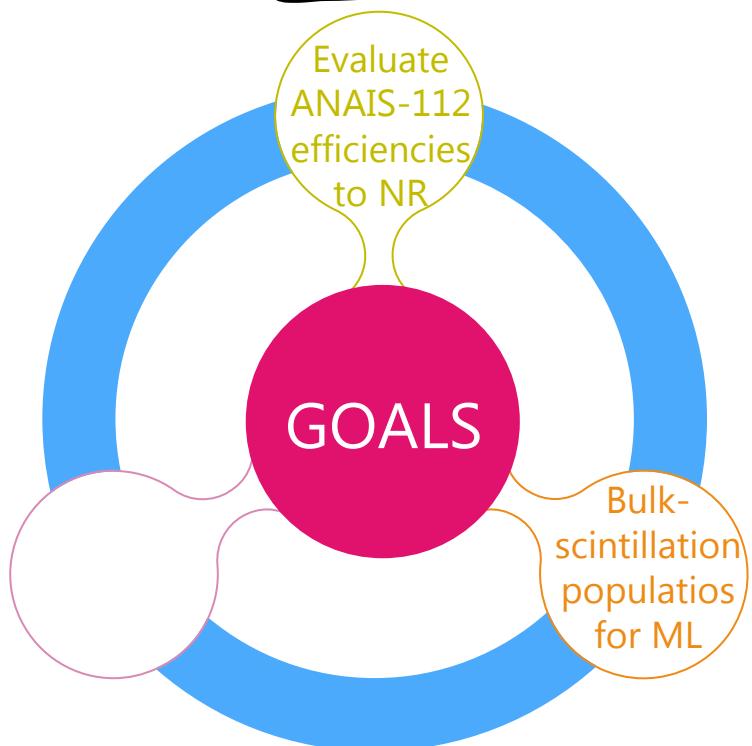


clean population of **bulk** scintillation events

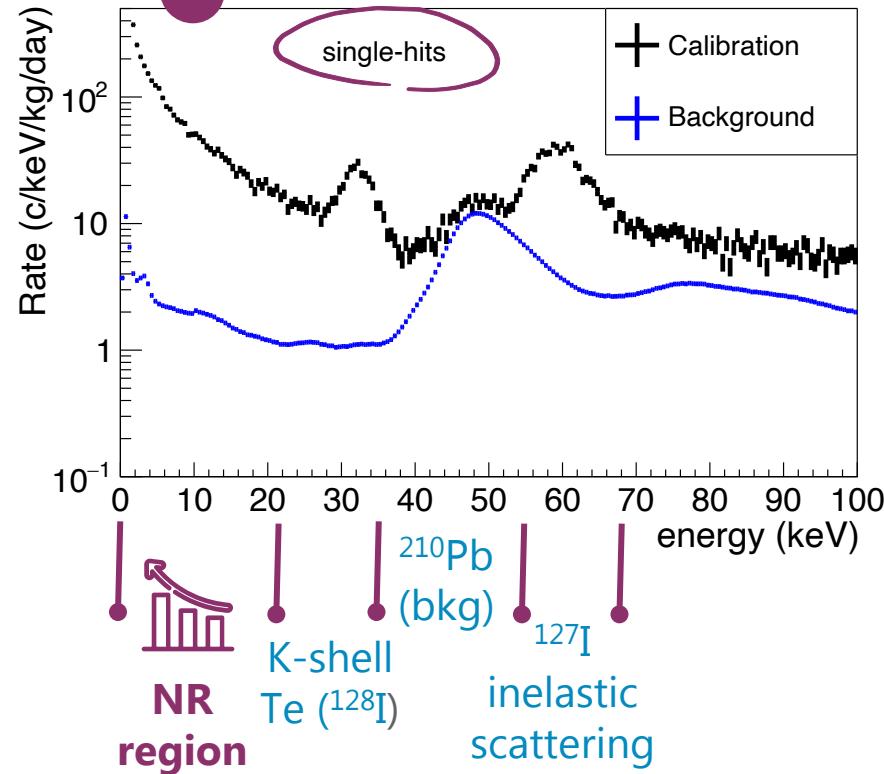
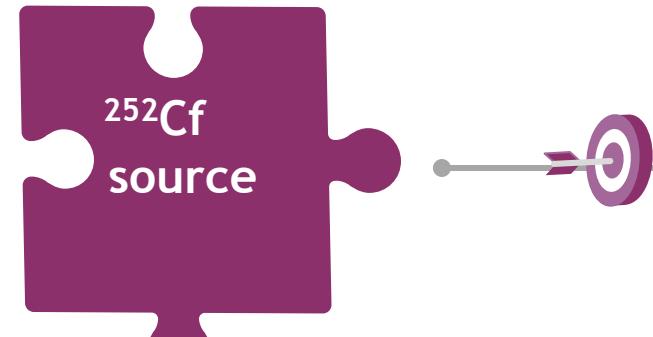
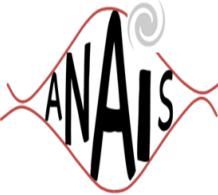


large number of events in the **ROI** ([1-6] keV)

See **I. Coarasa** talk!
Parallel DM session #**8B**
(Thursday 16:15)



Neutron calibration program



Seven calibration runs since April 2021 using a **252Cf neutron source** at different positions in the **ANALIS-112 set-up**



clean population of **bulk** scintillation events

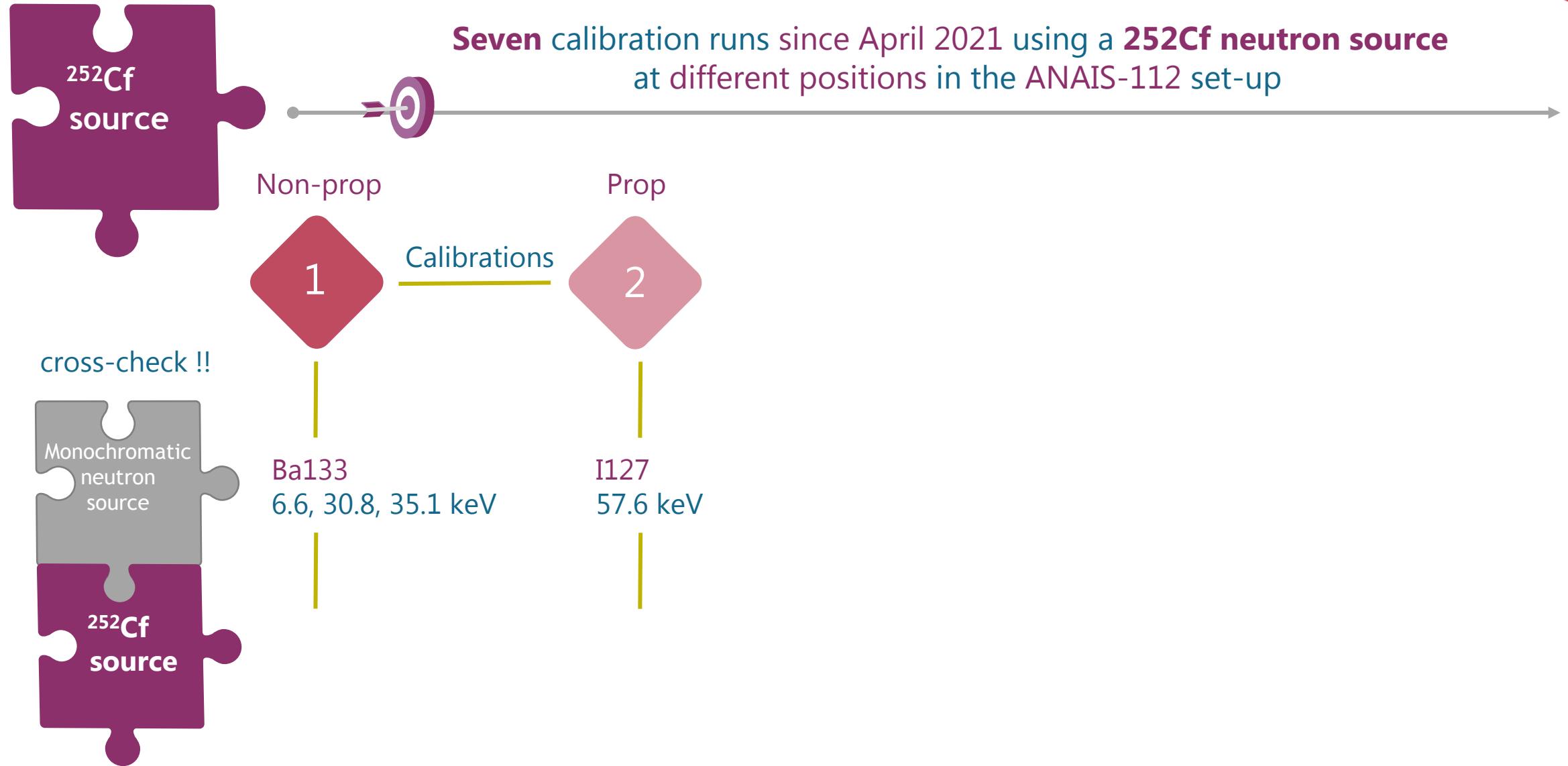


large number of events in the **ROI** ([1-6] keV)

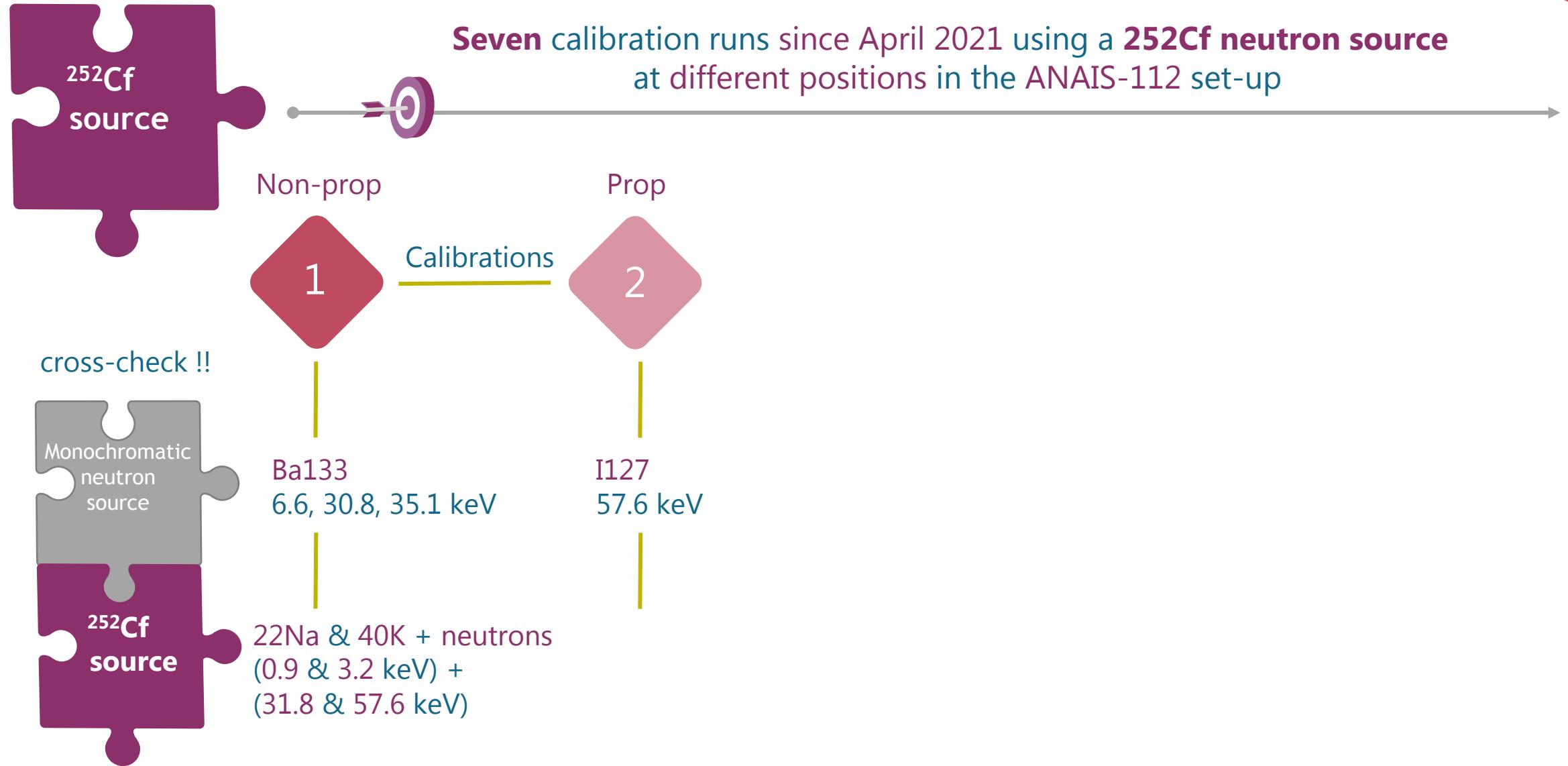
On-site neutron calibrations can be an important cross-check!!



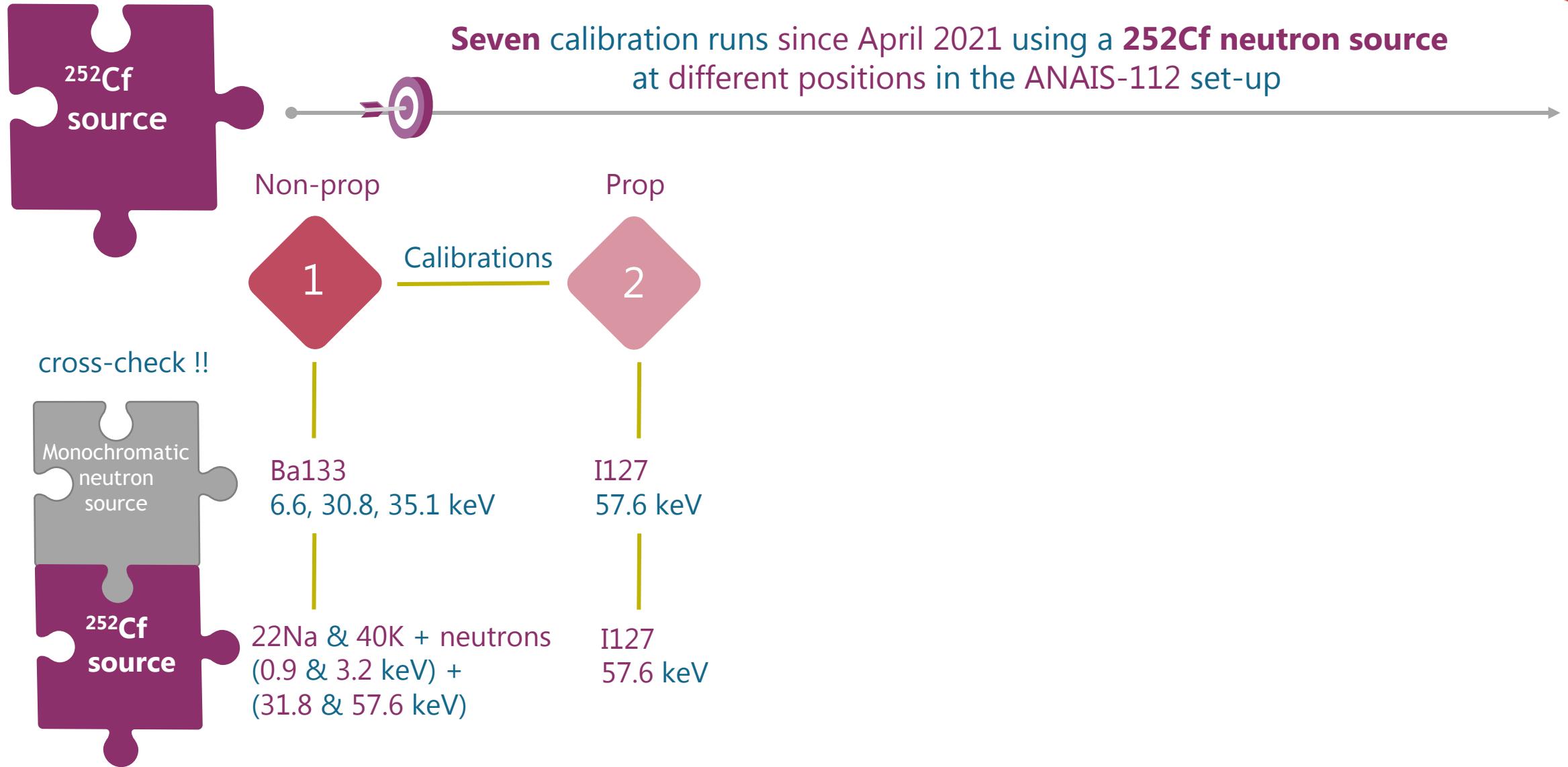
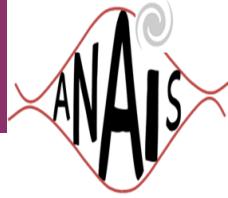
Neutron calibration program



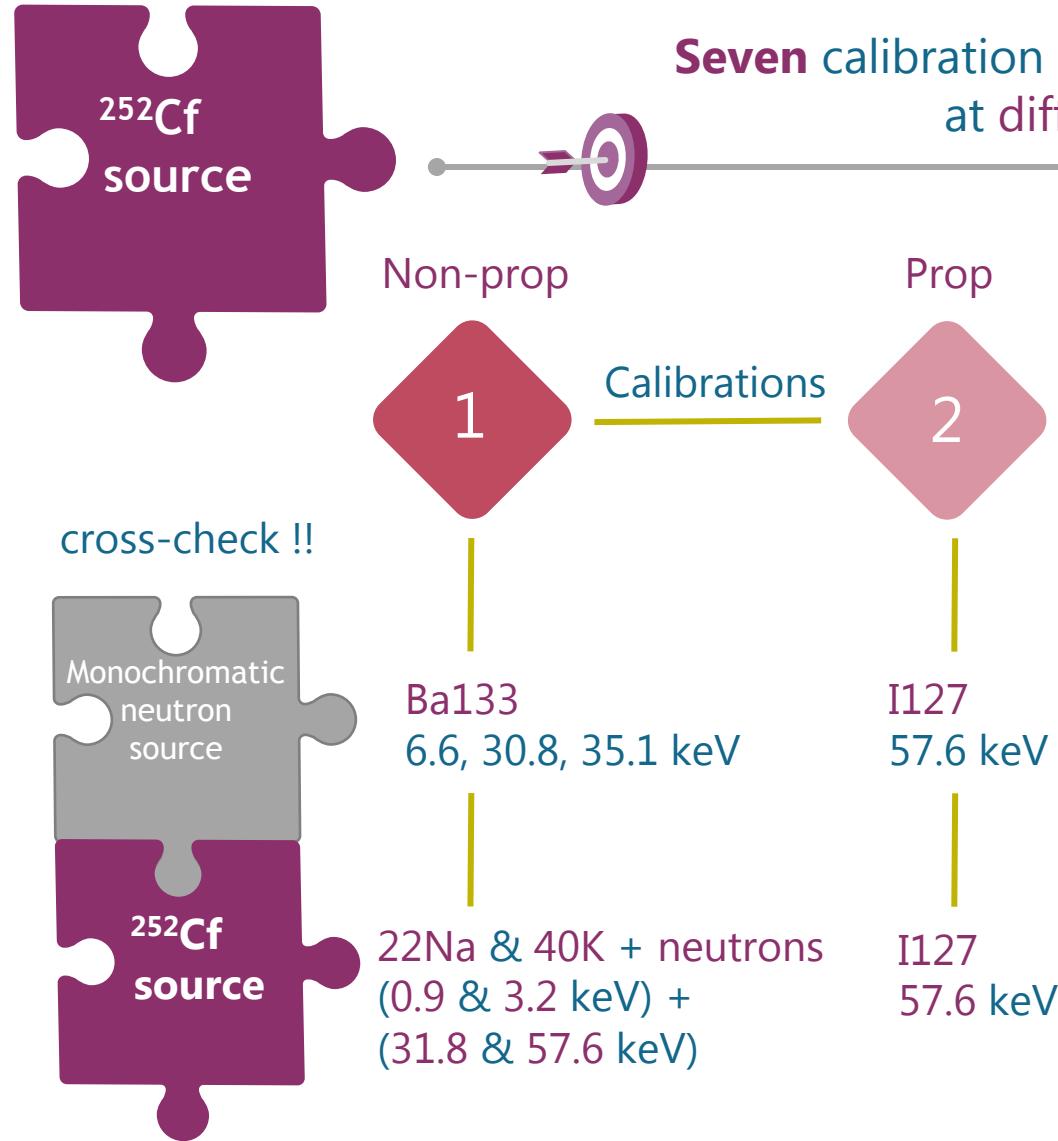
Neutron calibration program



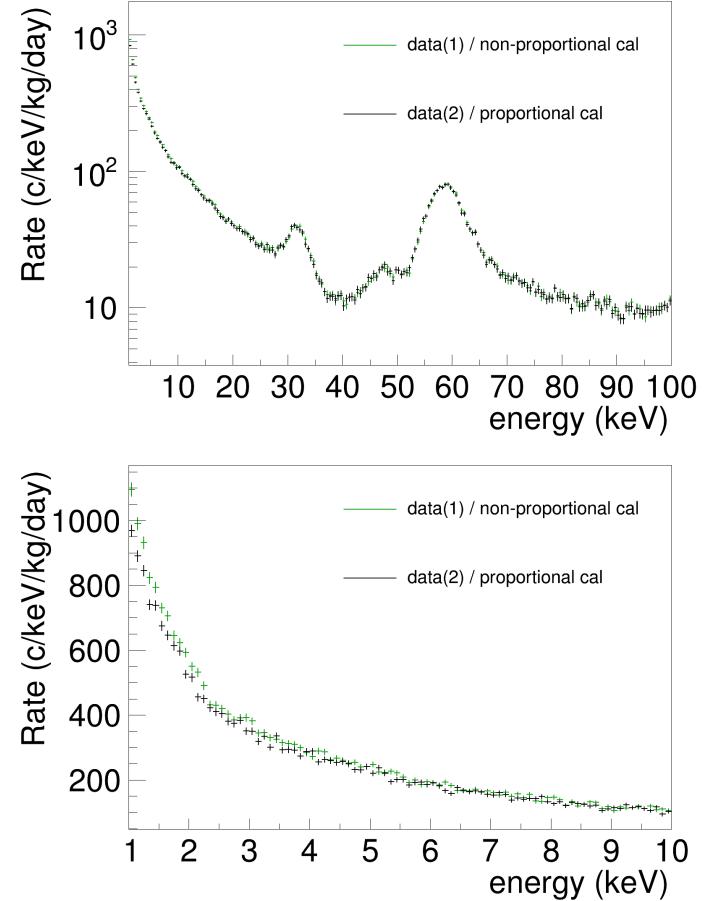
Neutron calibration program



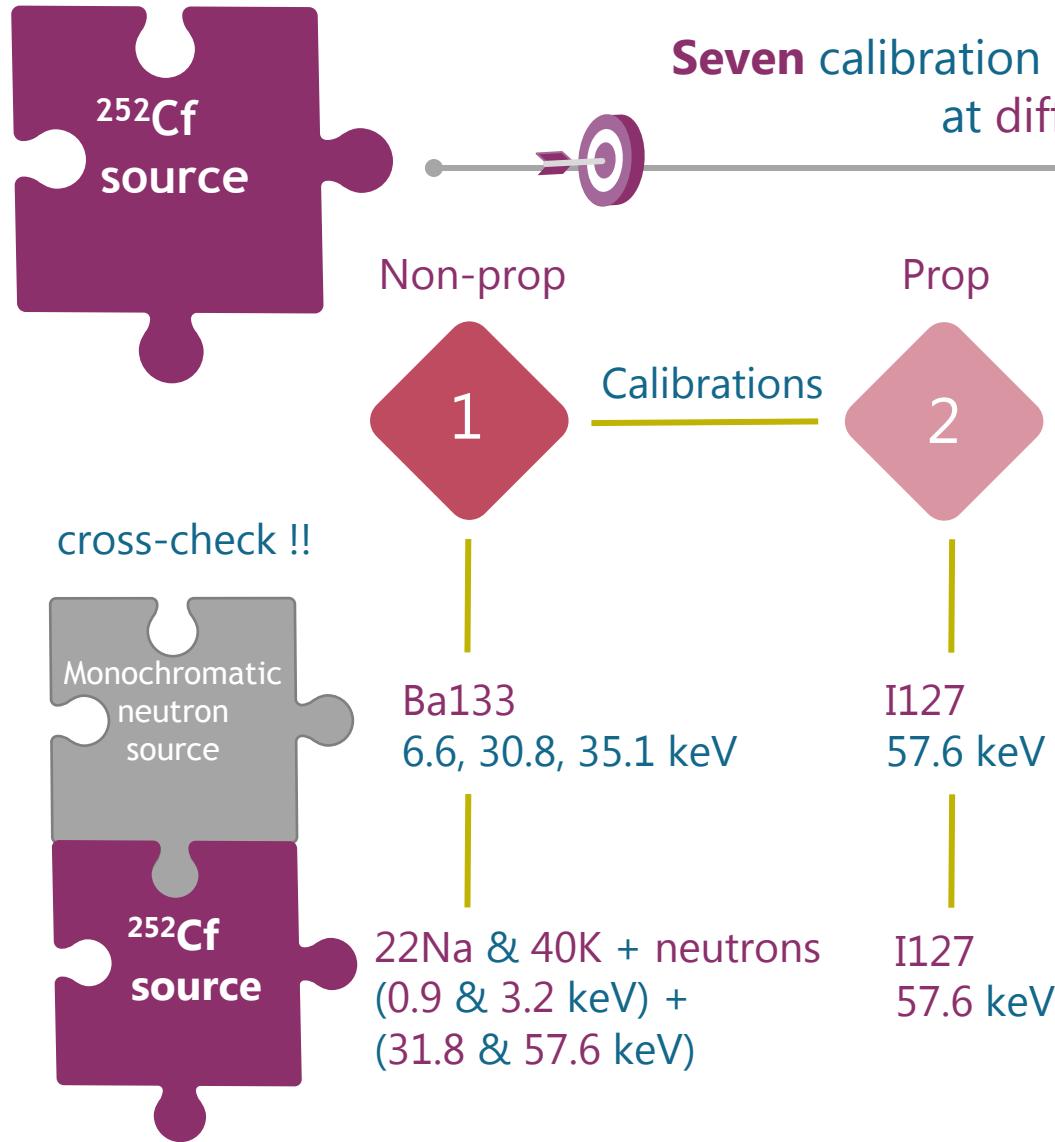
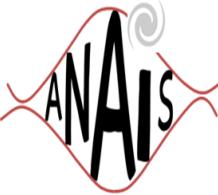
Neutron calibration program



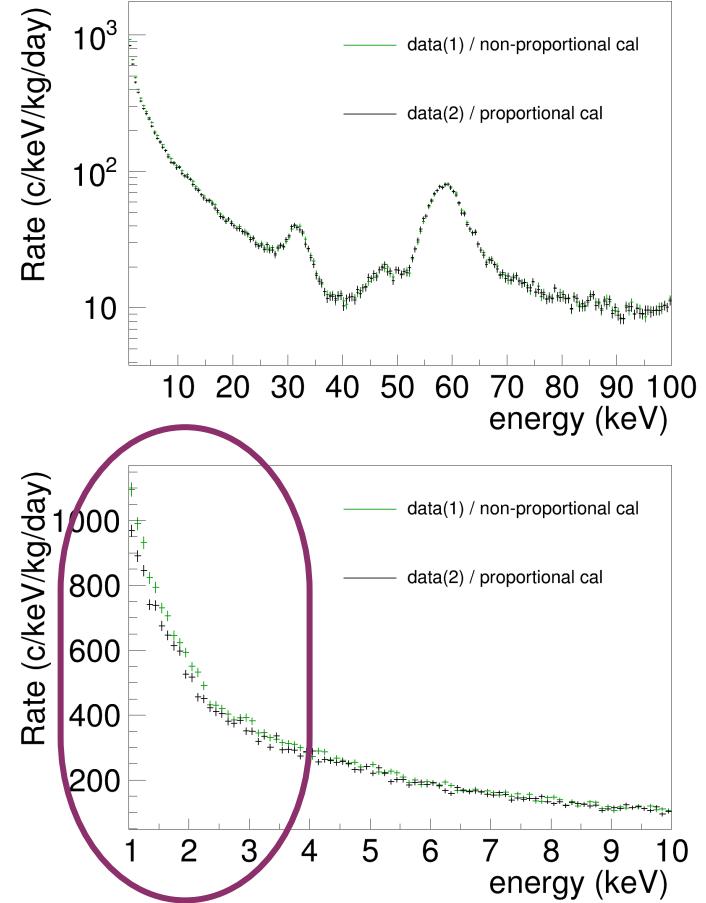
Seven calibration runs since April 2021 using a **252Cf neutron source** at different positions in the **ANALIS-112 set-up**



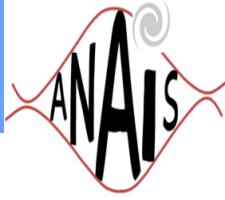
Neutron calibration program



Seven calibration runs since April 2021 using a **252Cf neutron source**
at different positions in the **ANALIS-112 set-up**



Results on the quenching factor

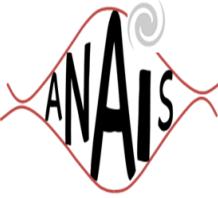


Our aim

Determine the **QF** for **our crystals** by a precise quantitative comparison between **measurement** and **simulation**



Results on the quenching factor



Our aim

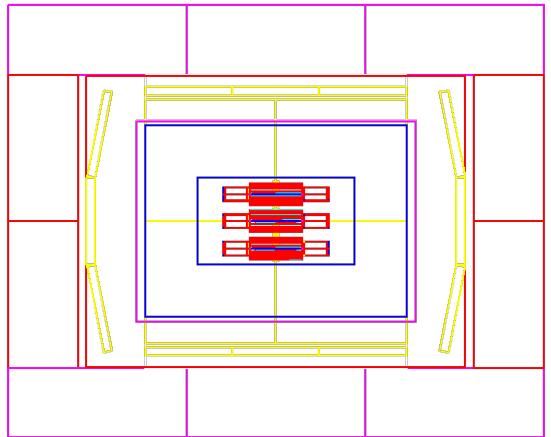
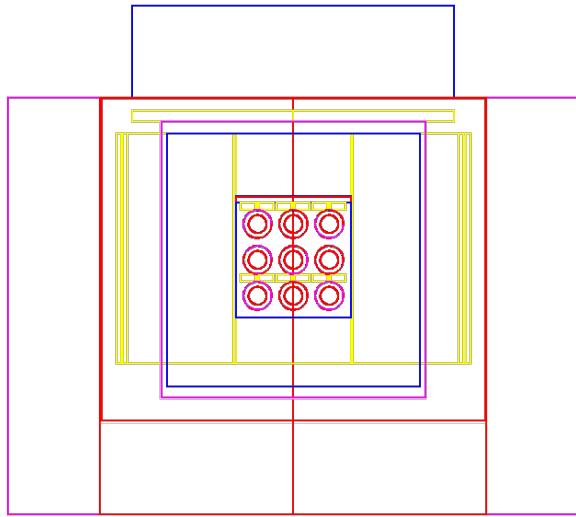
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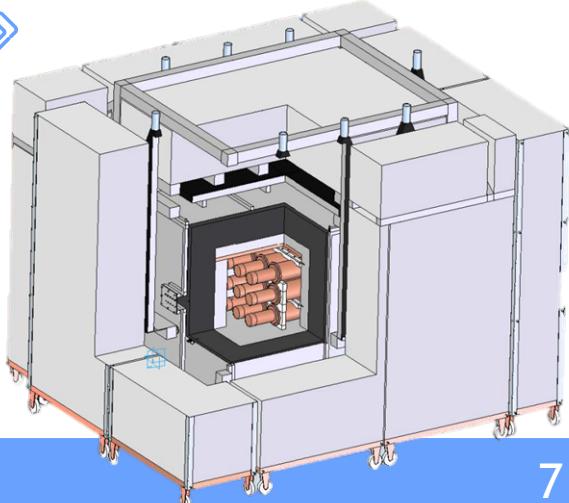
The ANAIS-112 Geant4 model has been extended for simulating the neutron calibration



J. Amaré et al., EPJC79 (2019) 412



- 3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules + PMTs
- 30 cm lead
- Anti-Radon box
- 40 cm PE/water
- 16 anti-muon vetoes



Results on the quenching factor

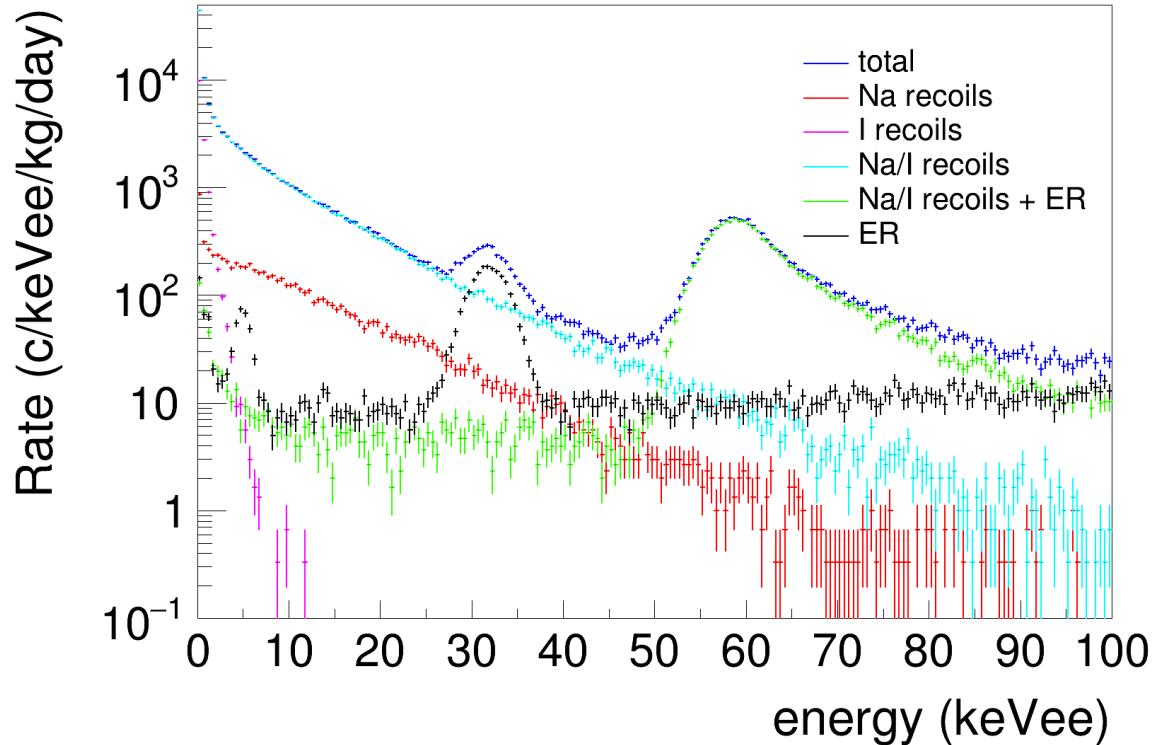


Our aim

Determine the **QF** for **our crystals** by a precise quantitative comparison between **measurement** and **simulation**



The ANALIS-112 Geant4 model has been extended for simulating the neutron calibration



$$E_{ee} = QF \times E_{NR}$$

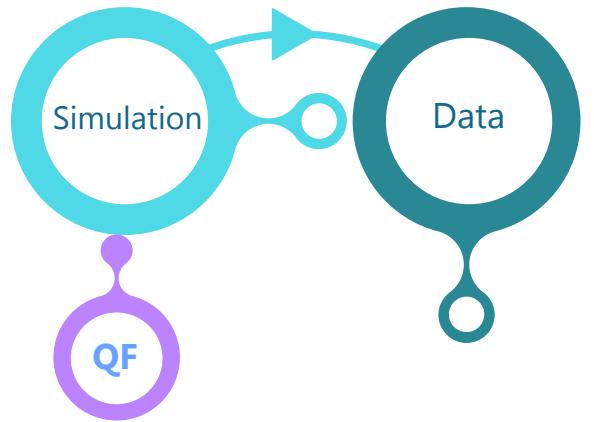
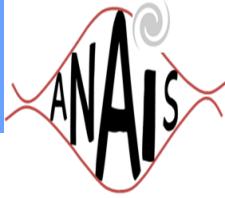


Large ANALIS-112 crystals exposed to fast neutrons show rates at low energy dominated by **multiple scattering**

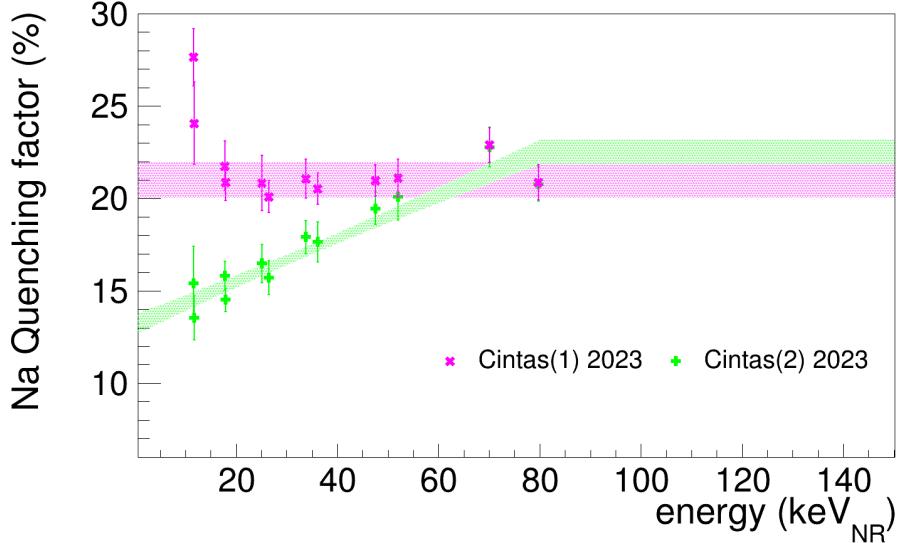
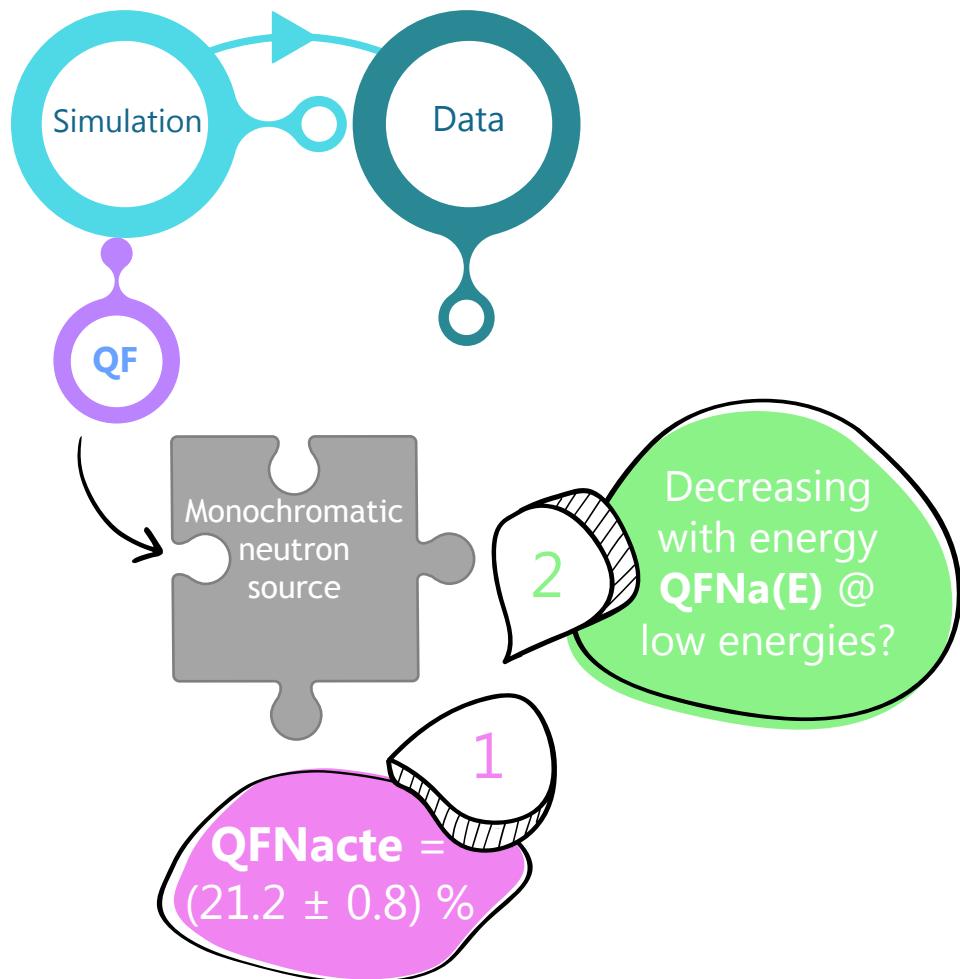


Nuclear recoils are dominant up to 50 keVee

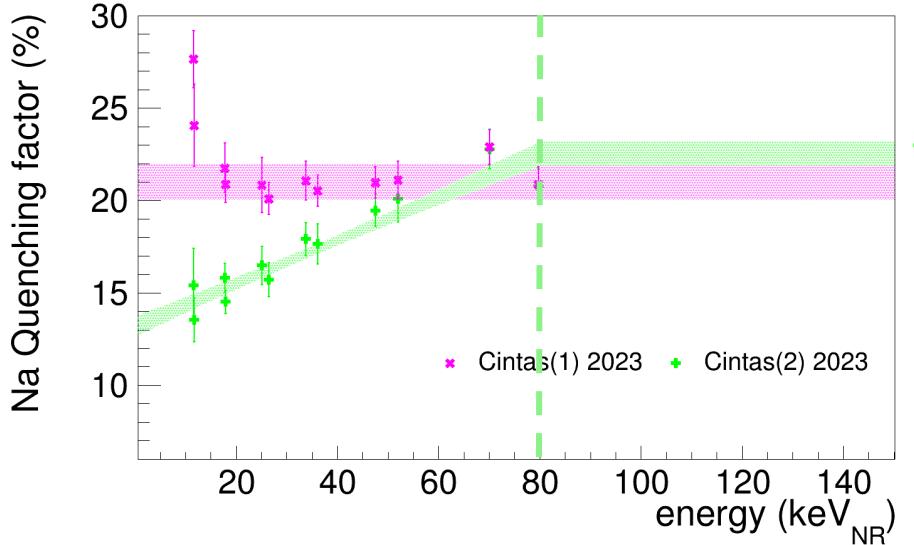
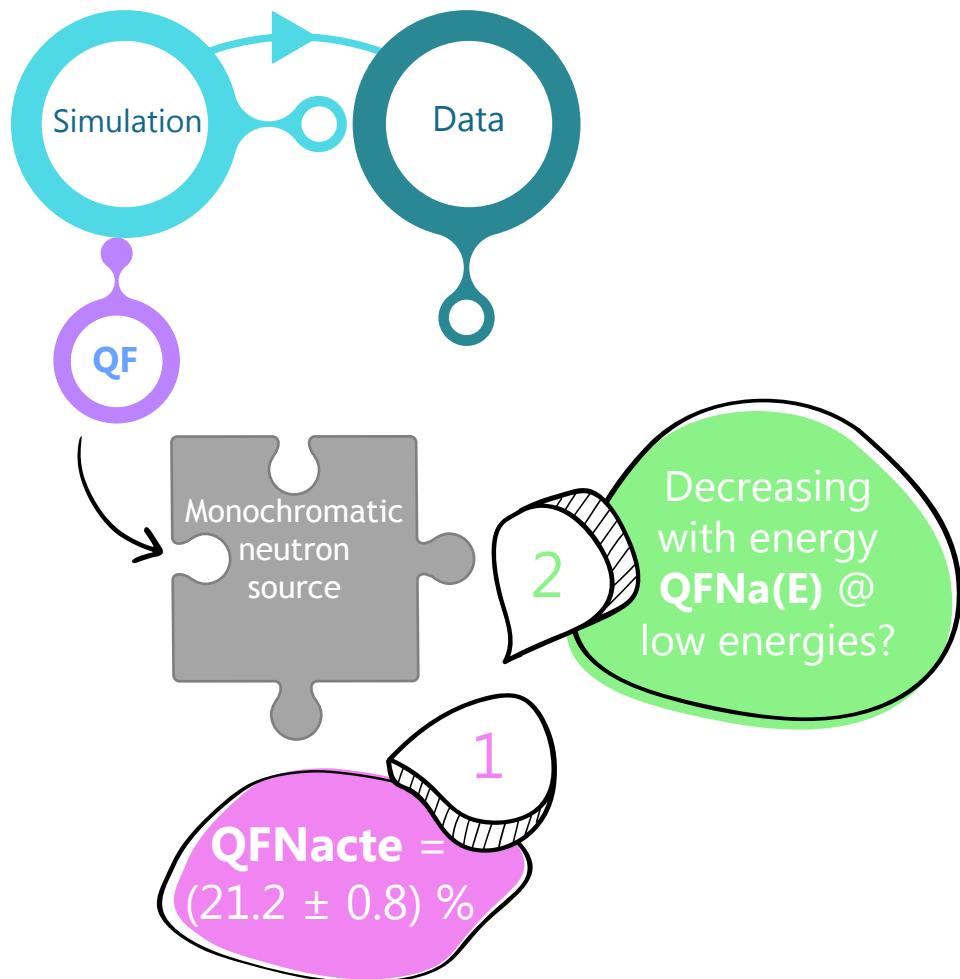
Results on the quenching factor



Results on the quenching factor

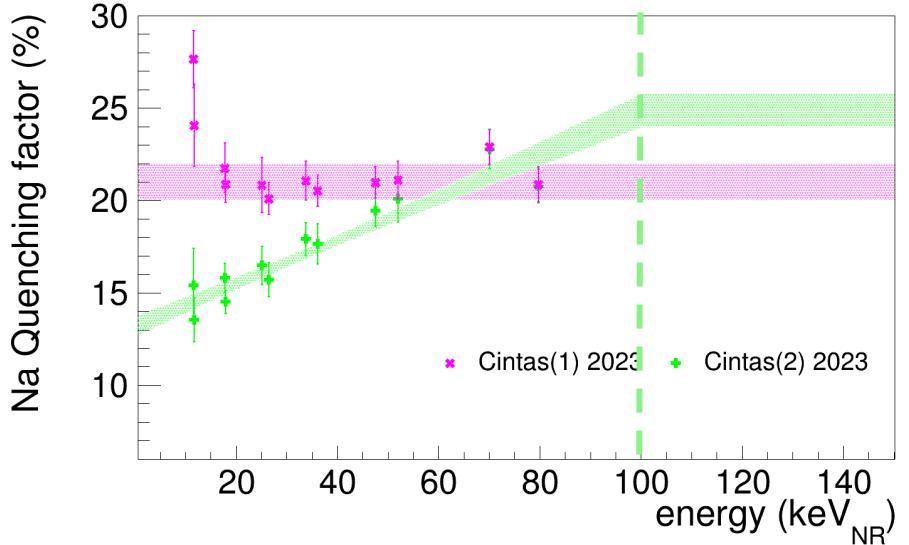
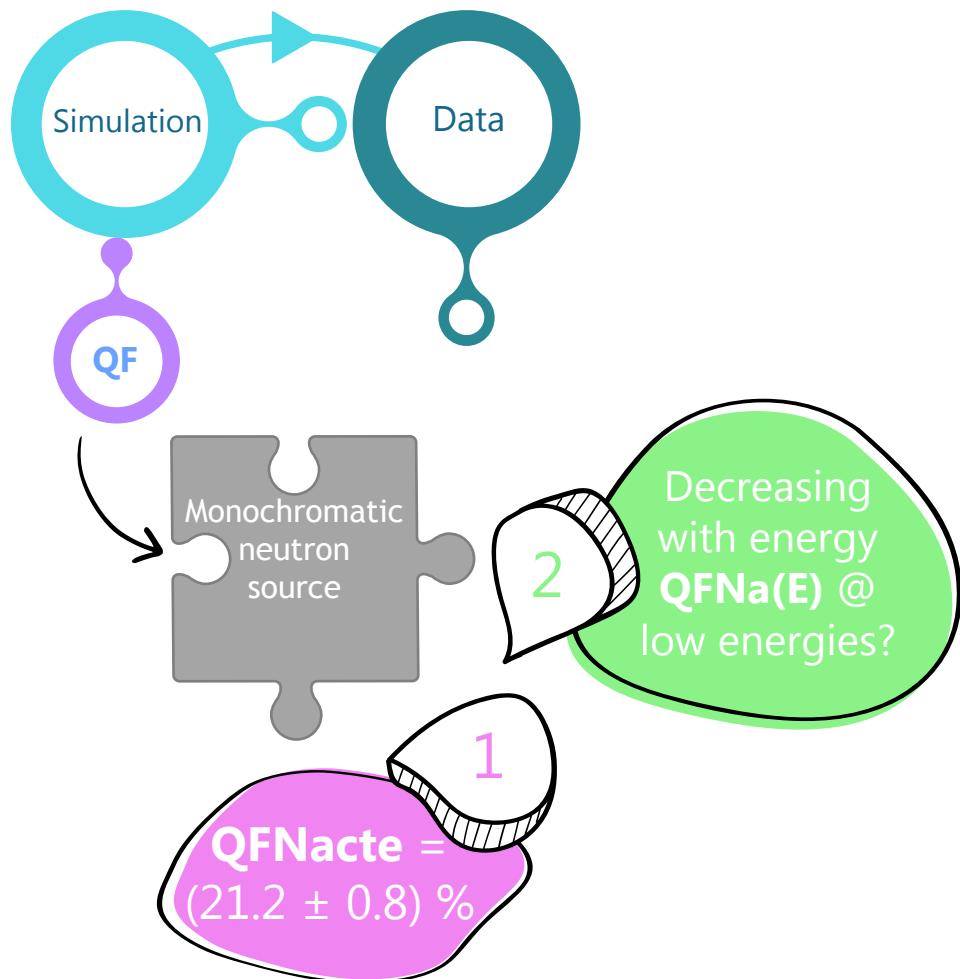


Results on the quenching factor



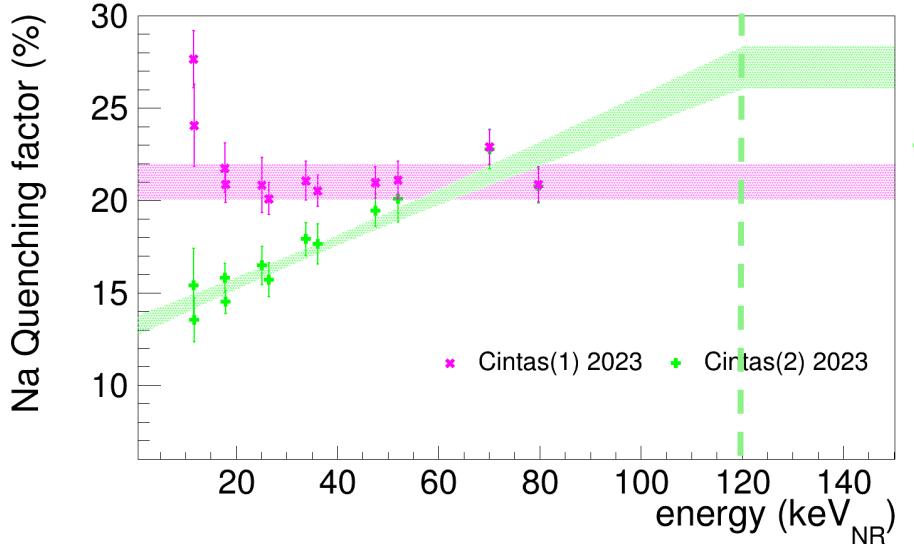
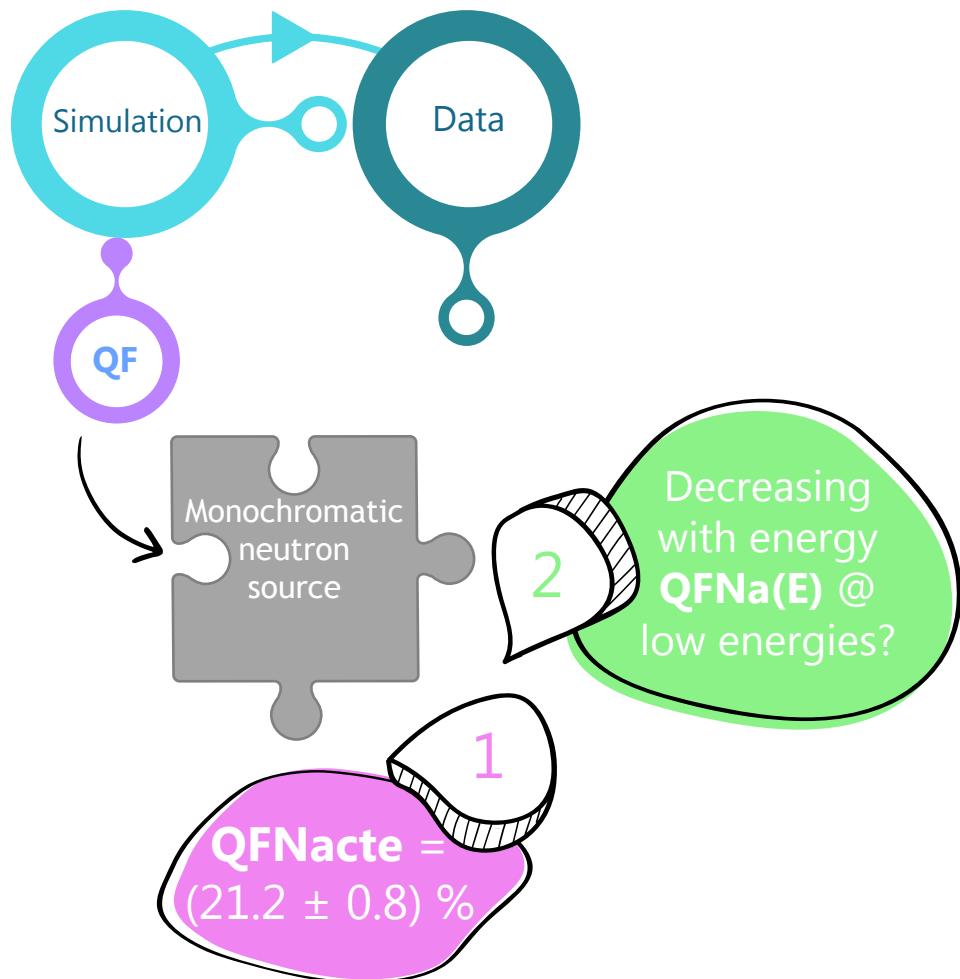
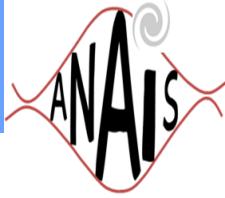
Uncertainty in
QFNa(E) modelling

Results on the quenching factor



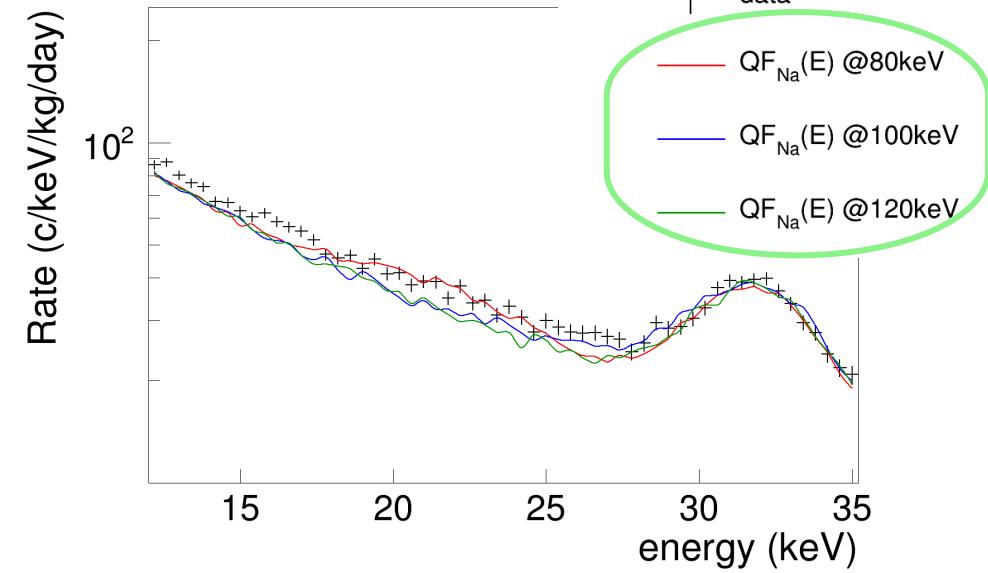
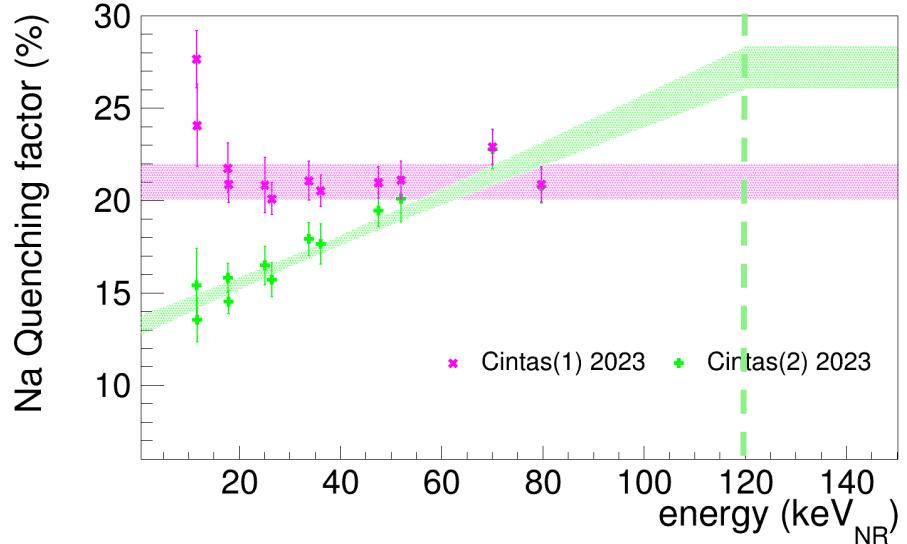
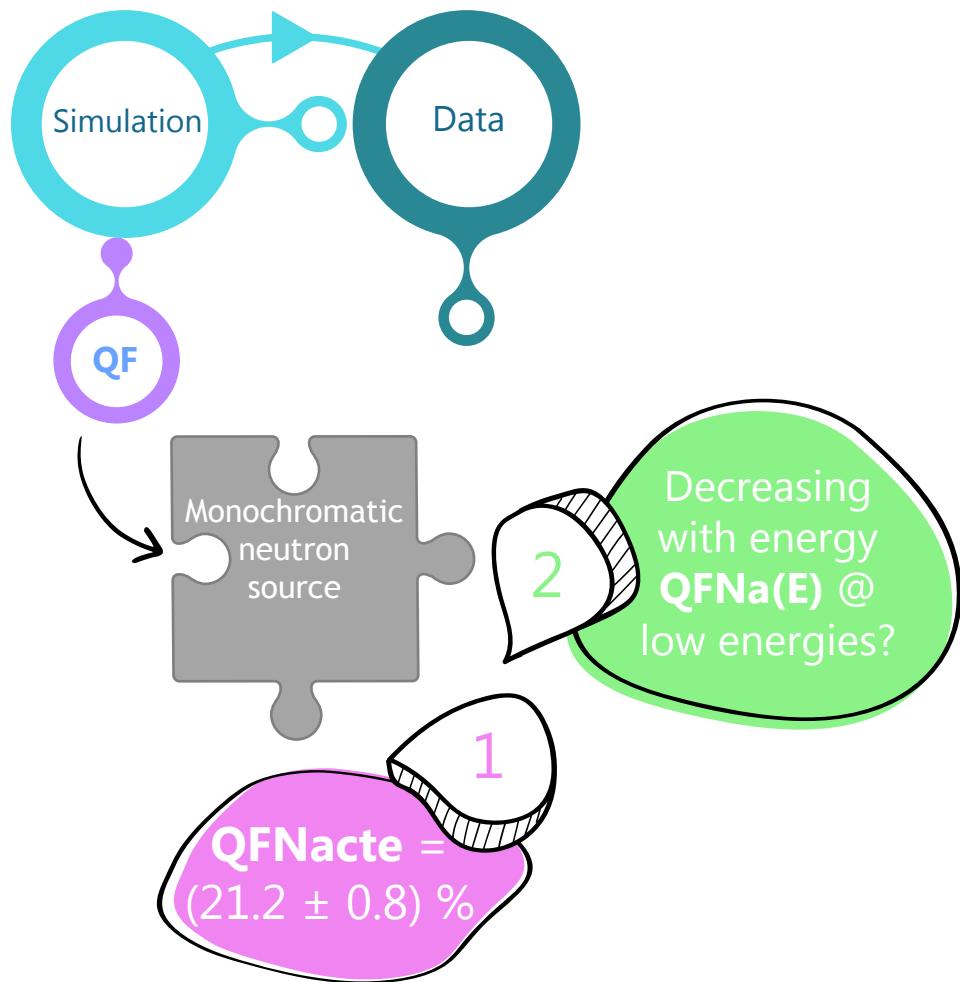
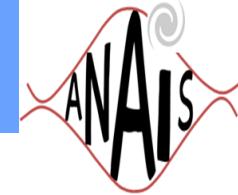
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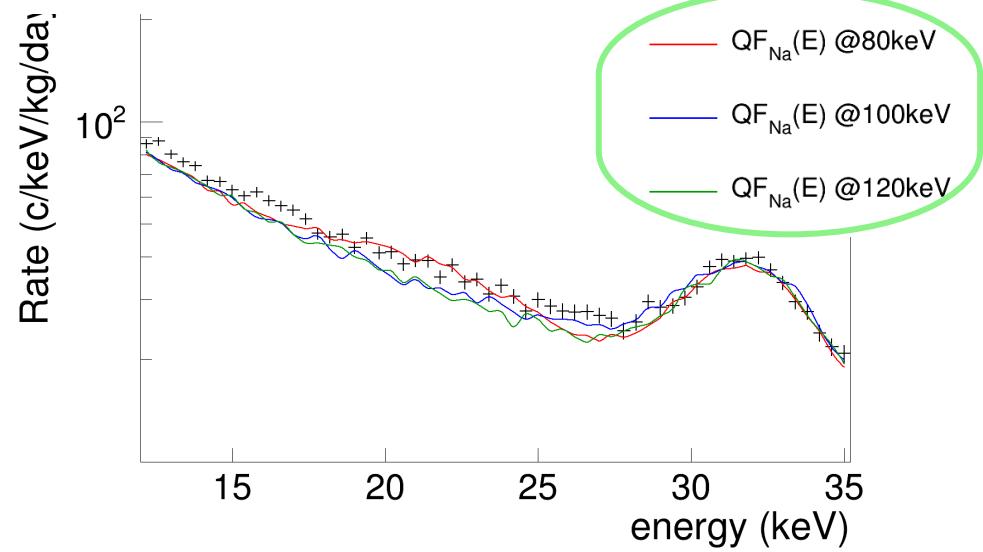
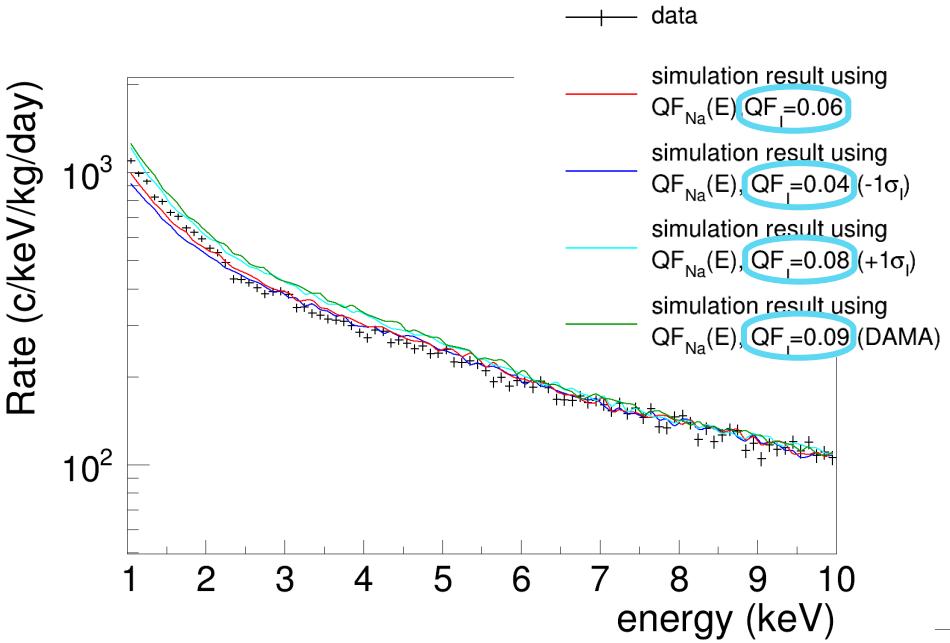
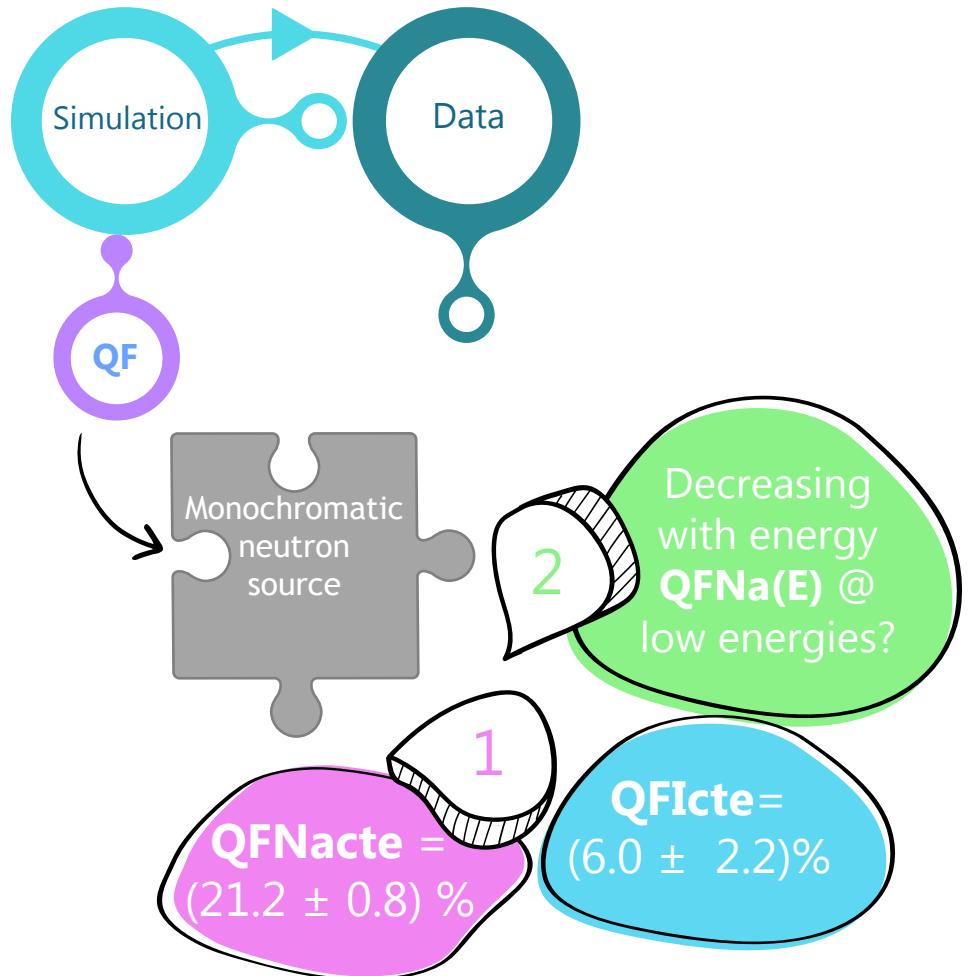


Uncertainty in
QF_{Na(E)} modelling

Results on the quenching factor

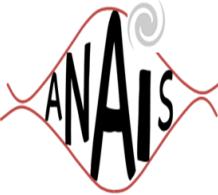


Results on the quenching factor

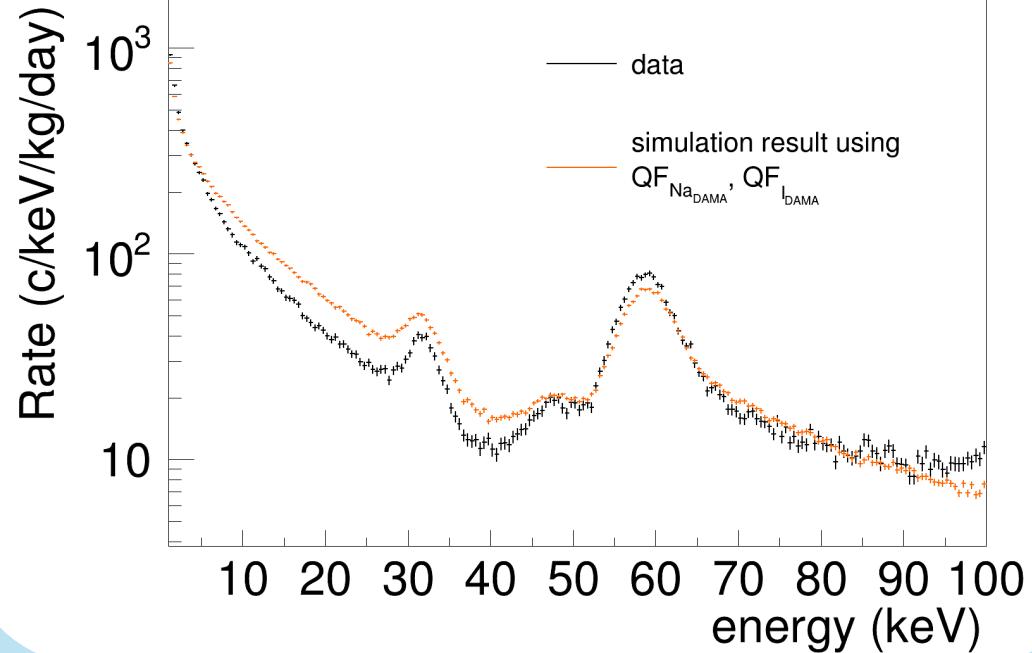
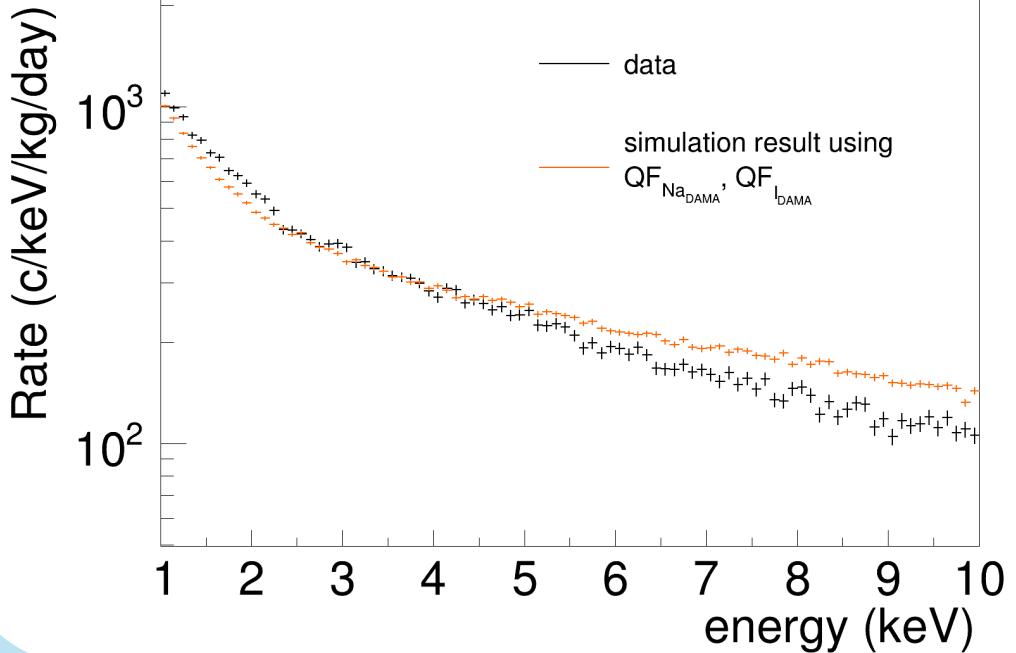


 Iodine QF has influence only at very low energies (<10 keVee)

Results on the quenching factor

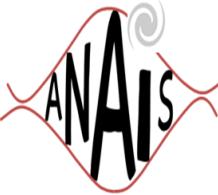


Comparison with DAMA/LIBRA QFs

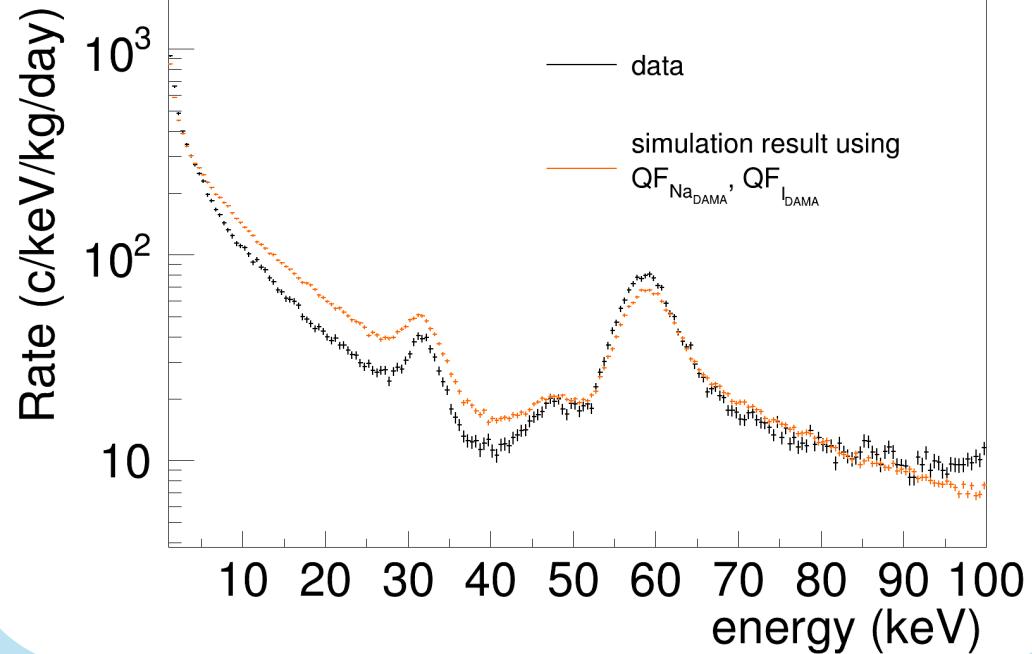
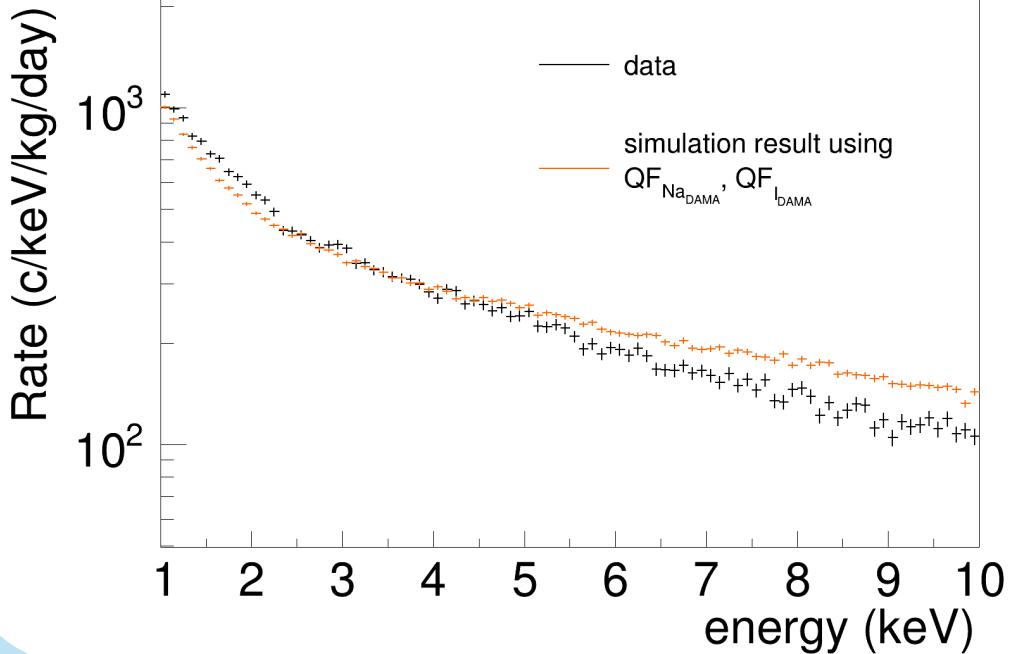


$Q_{Na} \text{ DAMA} = 0.3$
 $Q_I \text{ DAMA} = 0.09$

Results on the quenching factor

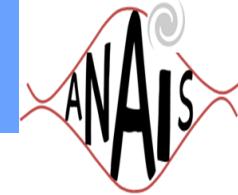


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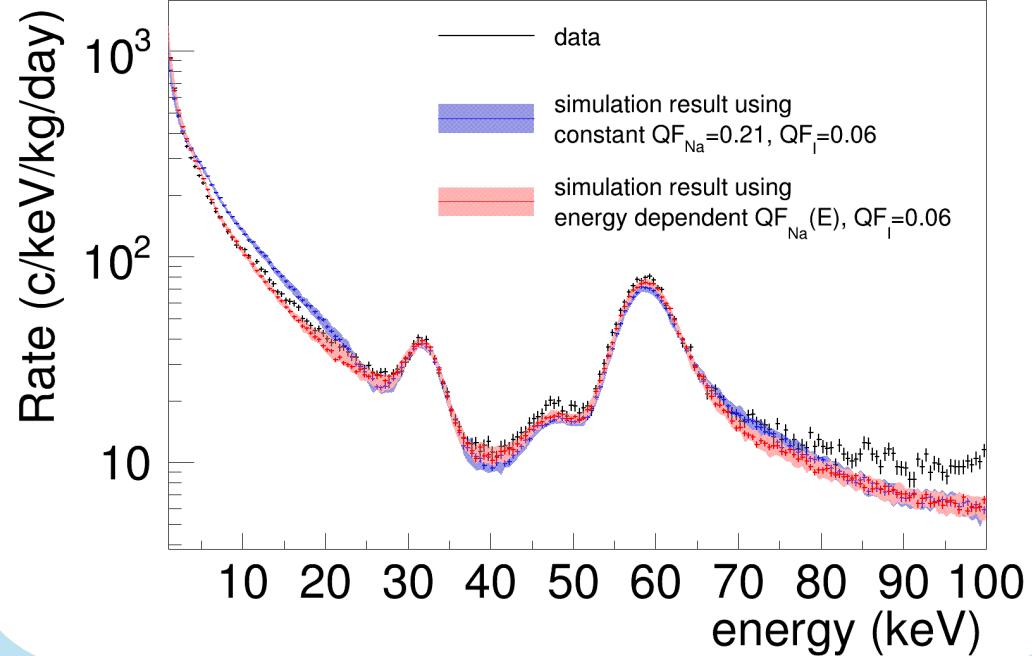
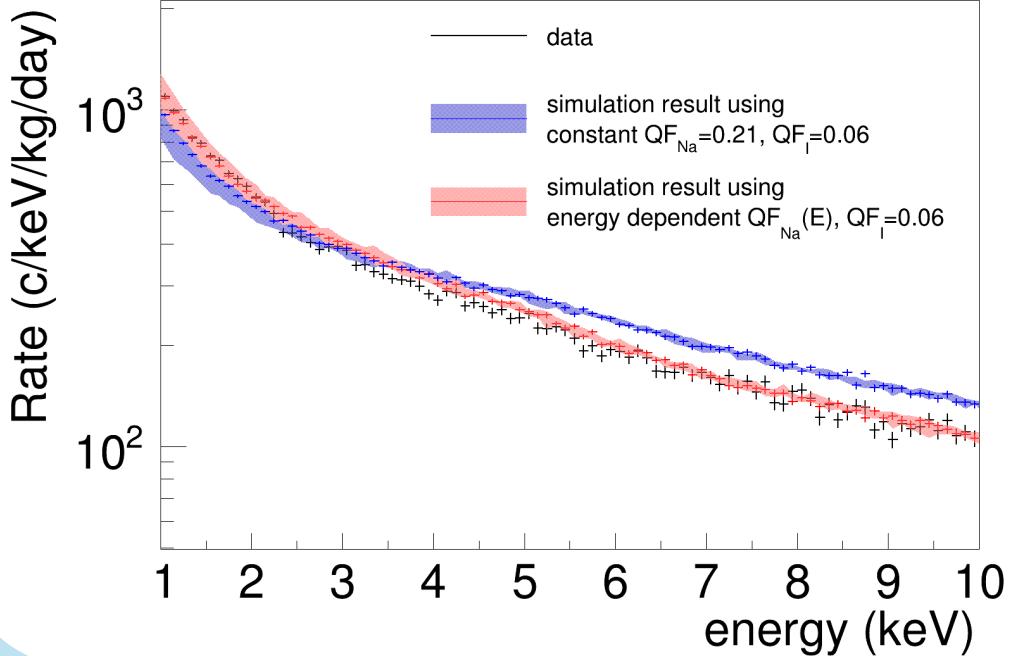


DAMA/LIBRA QFs are **not compatible** with our data

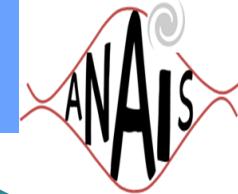
Results on the quenching factor



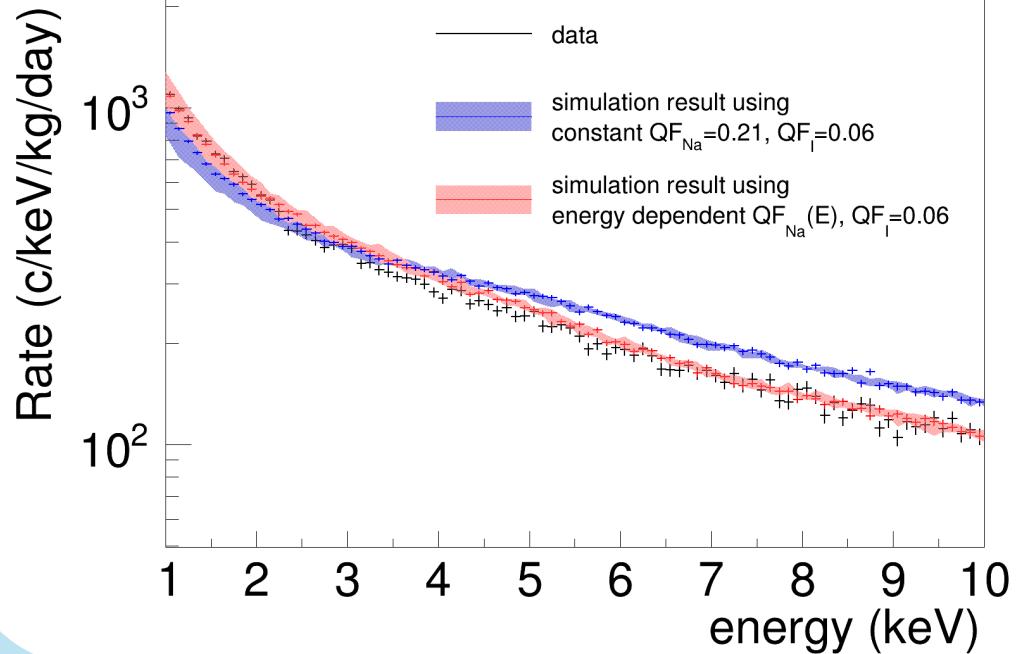
Comparison between our QF models



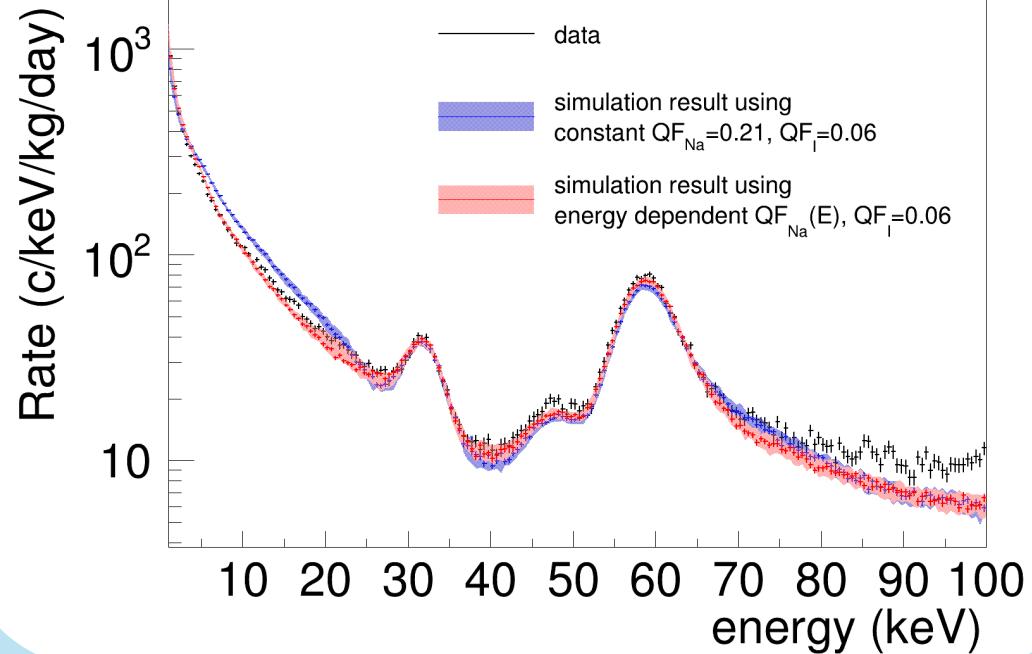
Results on the quenching factor



Comparison between our QF models



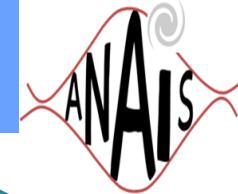
Fitting has not been attempted (yet)!
Spectra normalized only w/ A_{source} and t_{meas} and bkg added



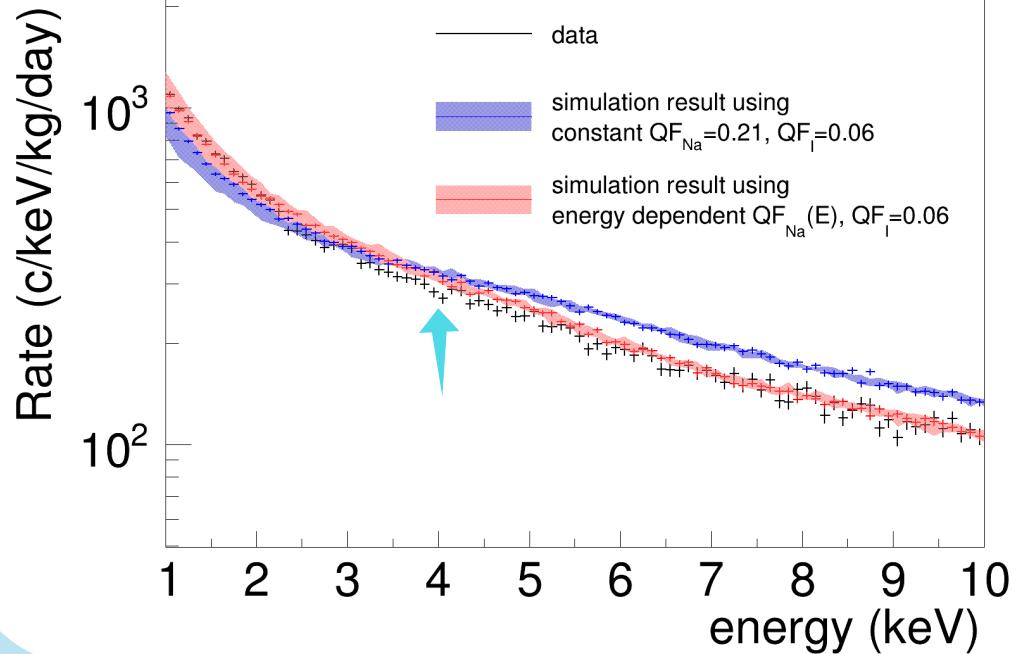
QFNa(E) provides a robust agreement

QFNa(E) seems to be favoured over **QFNacte !!!**

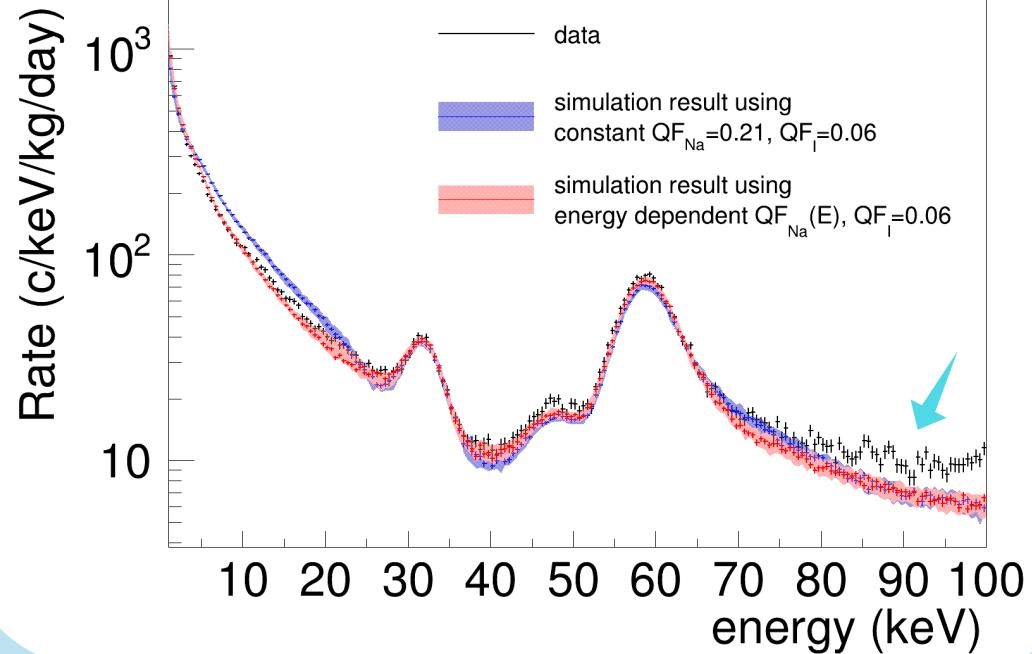
Results on the quenching factor



Comparison between our QF models



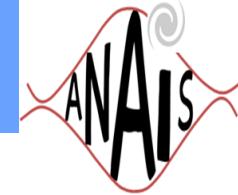
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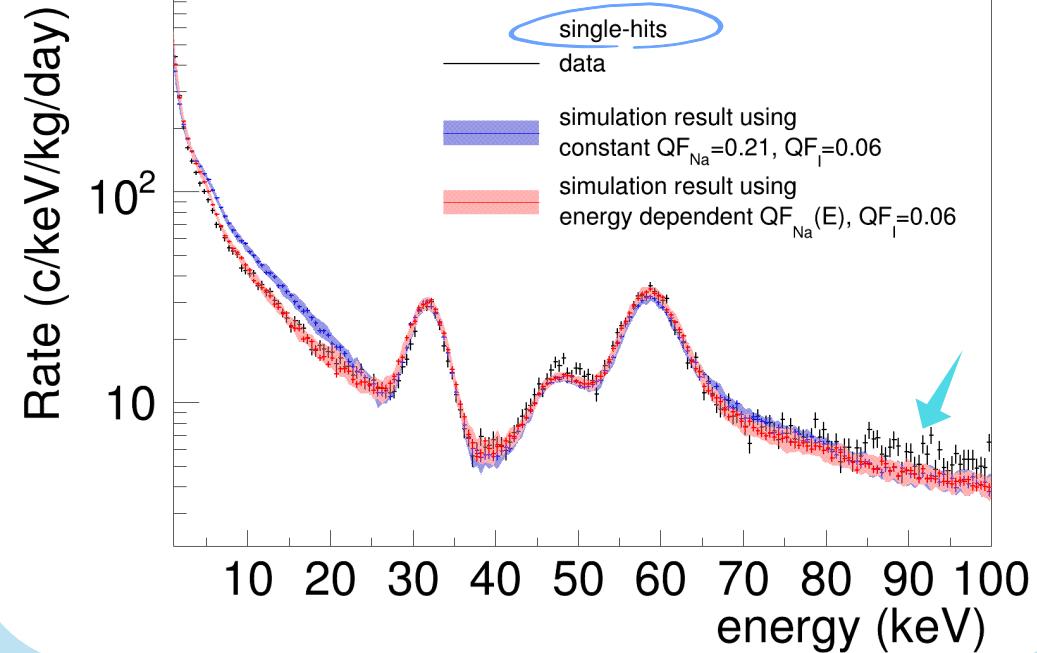
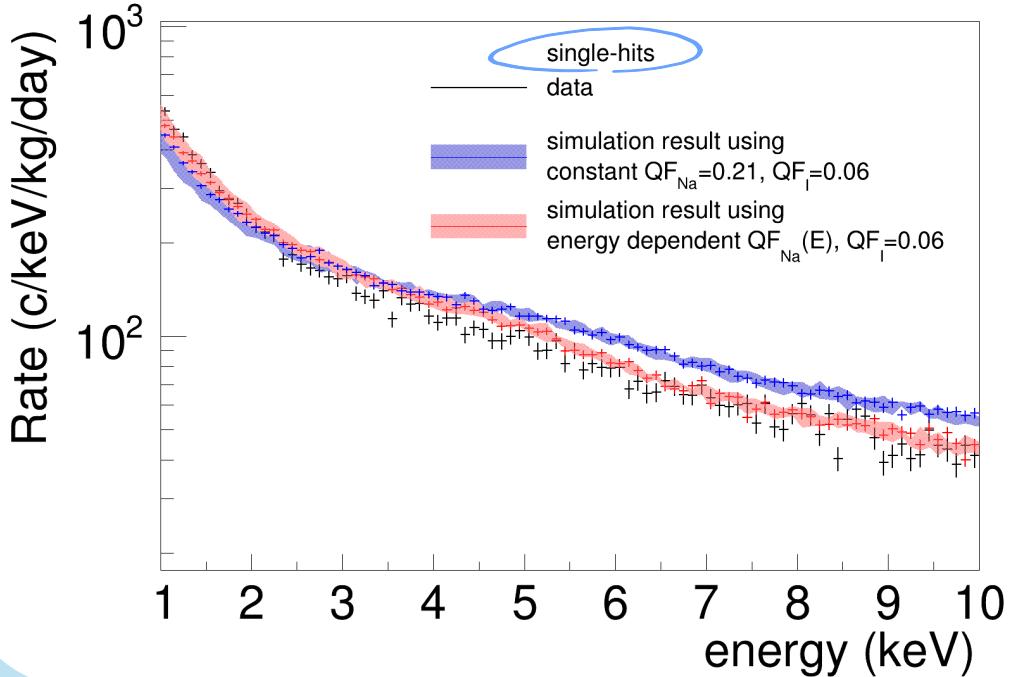
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Results on the quenching factor



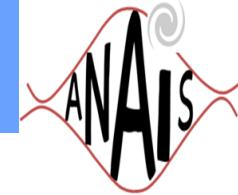
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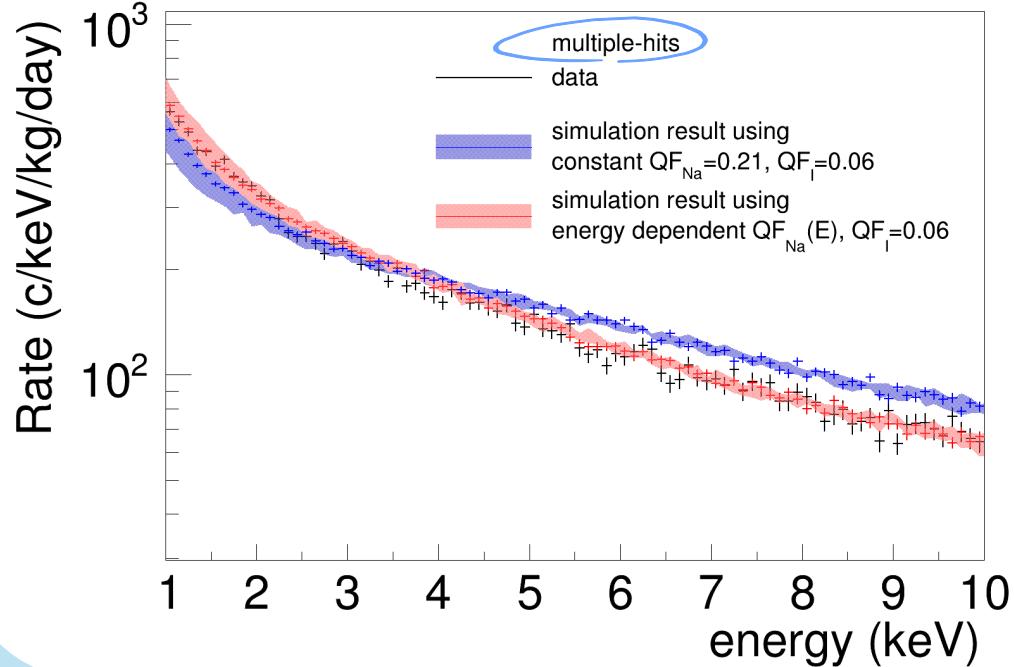
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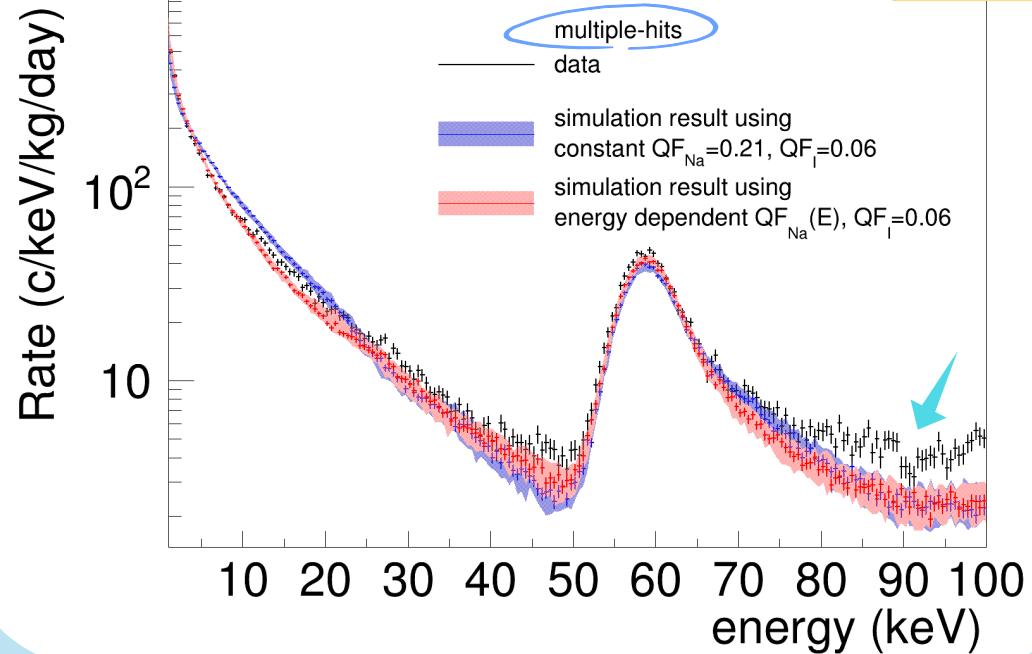
Comparison between our QF models



Further investigation is required to better understand multiple-hit events



WORK IN PROGRESS

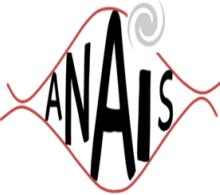


QFNacte provides a robust agreement

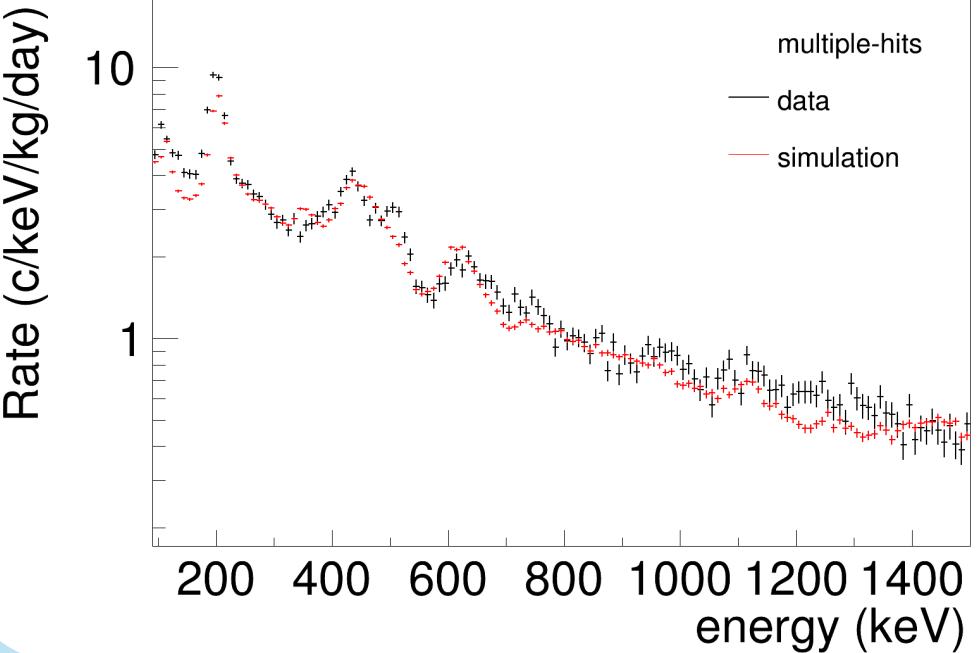
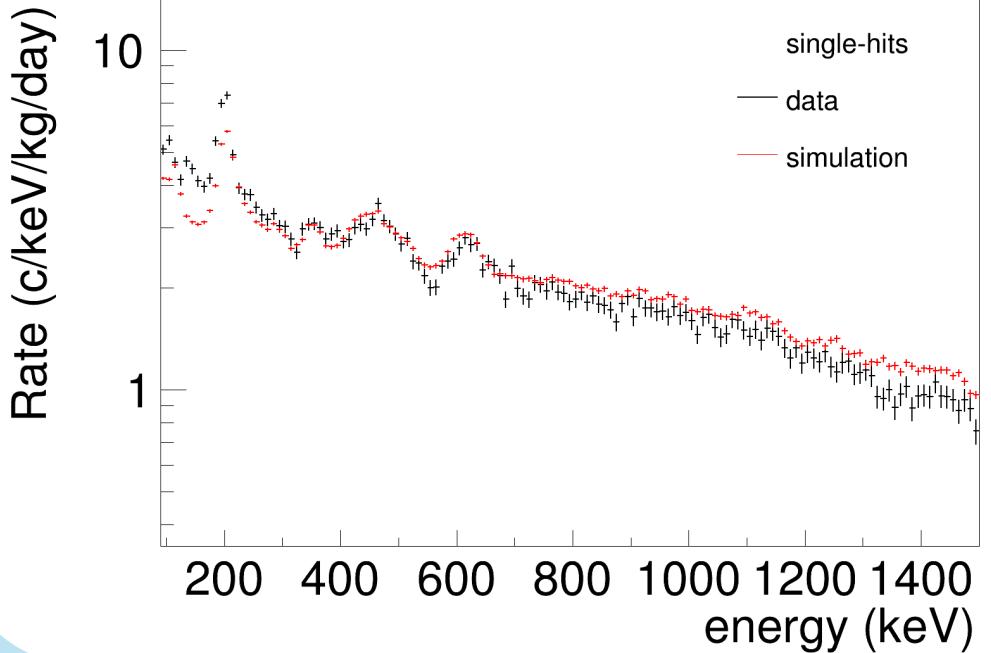


QFNacte seems to be favoured over QFNacte !!!

Results on the quenching factor

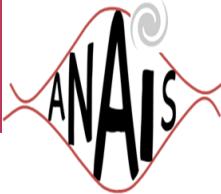


What about HE range?

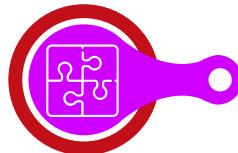


HE spectrum features are qualitatively well reproduced

TO SUM UP



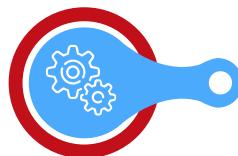
Systematics have to be taken into account for understanding a more than 20 y old-puzzling result: nuclear recoil energy conversion into visible energy could be different in ANALIS and DAMA/LIBRA detectors!



Neutron calibrations onsite have been performed using ^{252}Cf sources at LSC, which are relevant for understanding the unaccounted systematics behind the different QF values and energy dependences for NaI. More coordinated work from the community would be required



Our approach has proven to be truly sensitive to the QF. QFNa(E) provides a robust agreement and seems to be favoured over constant QF. Plans to continue studying other energy dependences and to include the non-proportionality of detectors



Measurements of the QF for ANALIS detectors will be taken into account for the comparison with DAMA/LIBRA results and those from other targets



