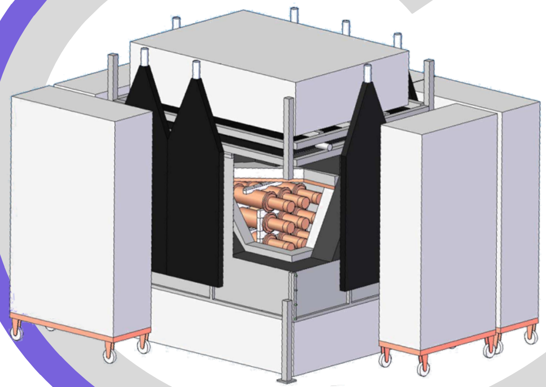
GEANT4 simulations within the ANAIS-112 experiment data analysis procedures



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

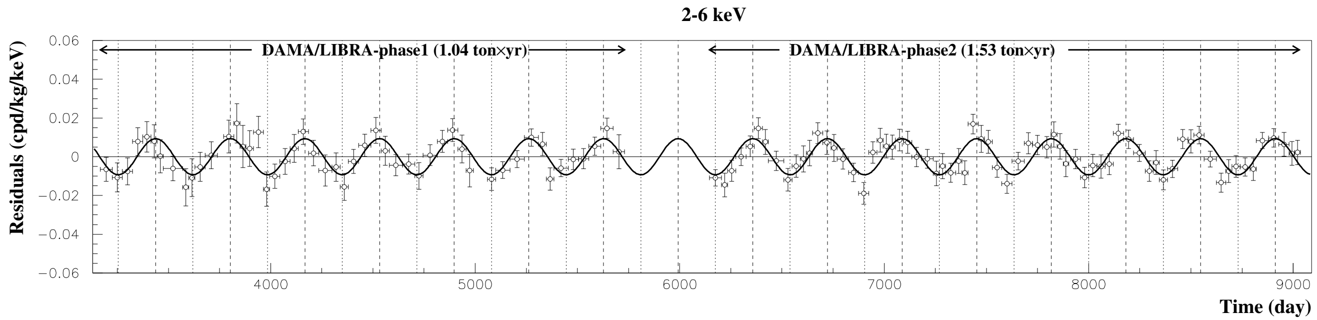
Vienna Workshop on Simulations (VIEWS 2024)
25 April-27 April 2024

MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA Fondo Social Europeo
CAPA
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza
MultiDark
Multimessenger Approach for Dark Matter Detection
Universidad Zaragoza

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 with a total exposure of 2.86 ton x year



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**

not compatible with the results of other much sensitive experiments assuming general halo/interaction models

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)

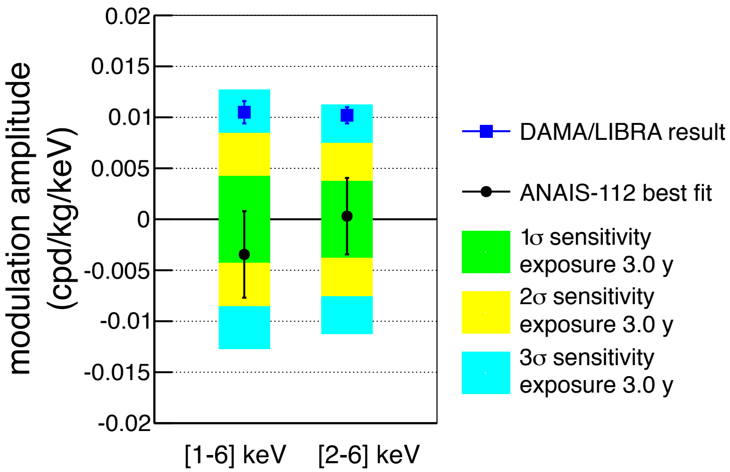
More details on the ANAIS-112 set-up here:

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 **>2.5σ** 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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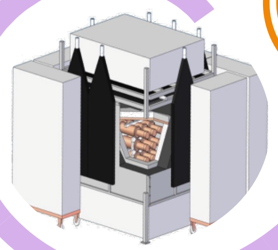
The ANAIS-112 experiment



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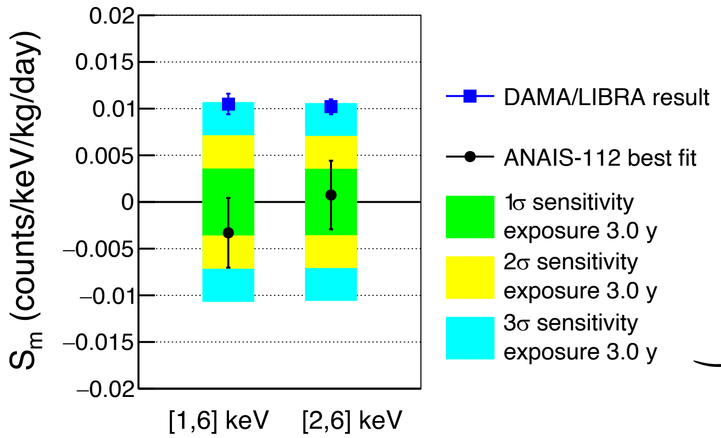


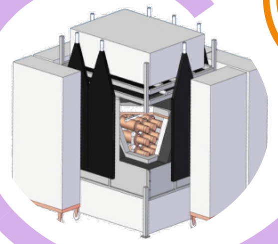
Best fit **incompatible with DAMA/LIBRA** at 3.9(2.8)σ for [1-6] ([2-6]) keV

Sensitivity with 3 years data: 2.9σ for [1-6] and [2-6] keV

Reanalysis of three-year exposure using machine learning techniques recently released !!

I. Coarasa et al, JCAP11(2022)048
I. Coarasa et al, JCAP06(2023)E01
Soon in arxiv !!

The ANAIS-112 experiment



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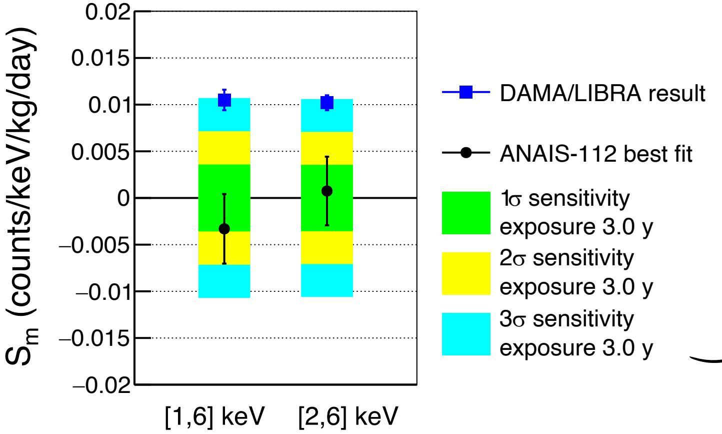

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I. Coarasa et al, JCAP06(2023)E01
Soon in arxiv !!

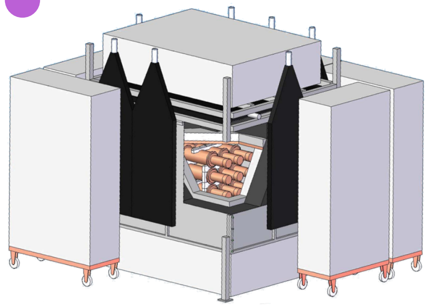
5σ sensitivity at reach in late 2025 !!

The ANAIS-112 experiment

Quenching factor

Background model

Optical simulations

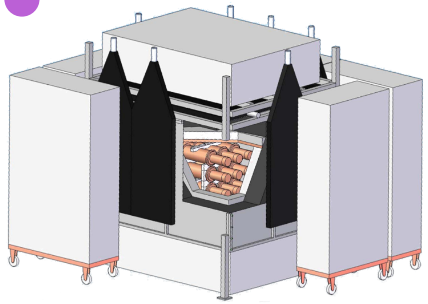


Data analysis @ANAIS-112

The ANAIS-112 experiment

GEANT4
A SIMULATION TOOLKIT

Background model



Data analysis
@ANAIS-112

The ANAIS-112 background model

Detailed Geant4 MC simulation for each detector including

- External components screening with HPGe at LSC
- Internal activity directly assessed: 40K, 210Pb
- Cosmogenic activity: short-lived Te and I isotopes, 3H, 22Na, 109Cd, 113Sn

J. Amaré et al., EPJC79 (2019) 412

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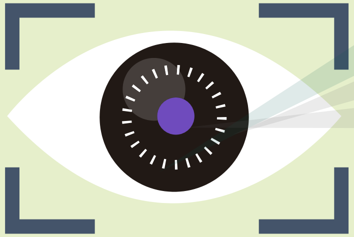

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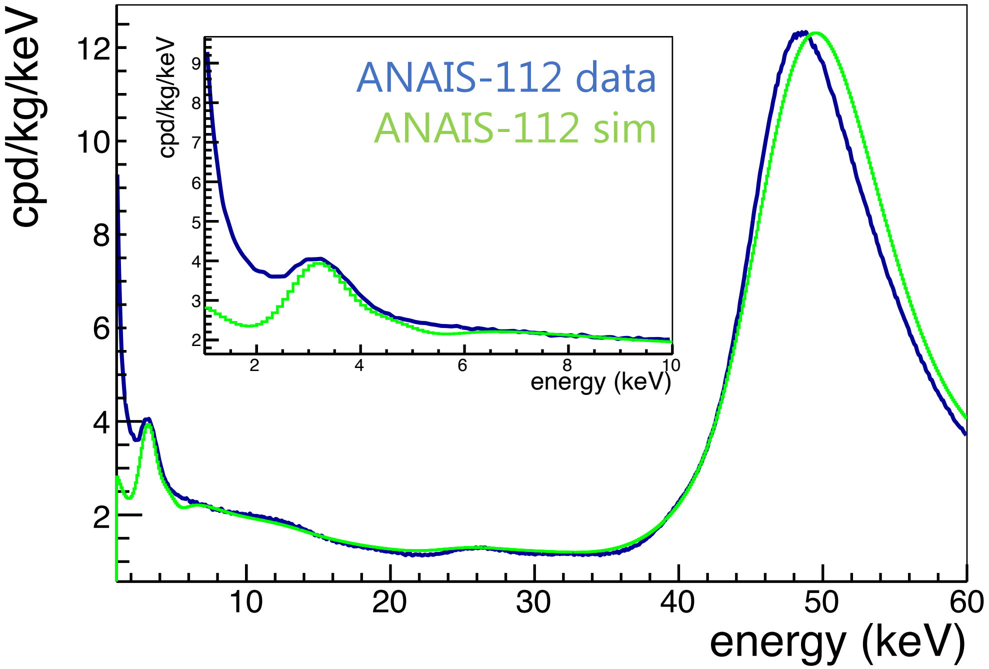

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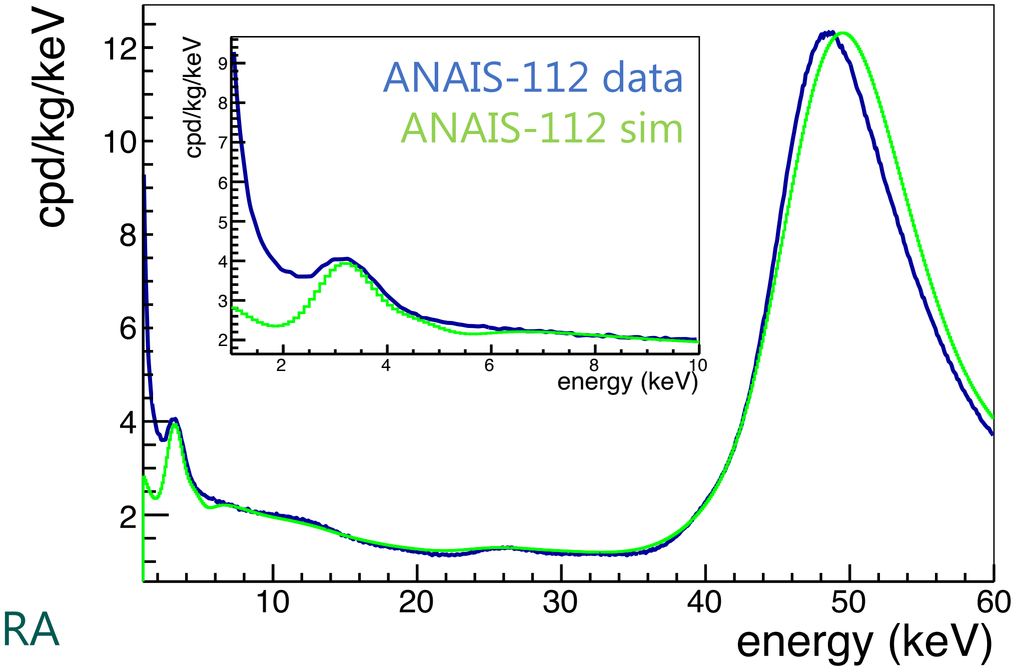
At very low energy, main contribution to background from internal contamination @NaI(Tl) crystal:

- 40K and 22Na peaks (12% and 2%)
- 210Pb (bulk+surface) (**32.5%**)
- 3H (26.5%)

> higher than DAMA/LIBRA



The ANAIS-112 background model

Detailed Geant4 MC simulation for each detector including

J. Amaré et al., EPJC79 (2019) 412

Robust overall agreement

Strong discrepancy in [1-2] keV

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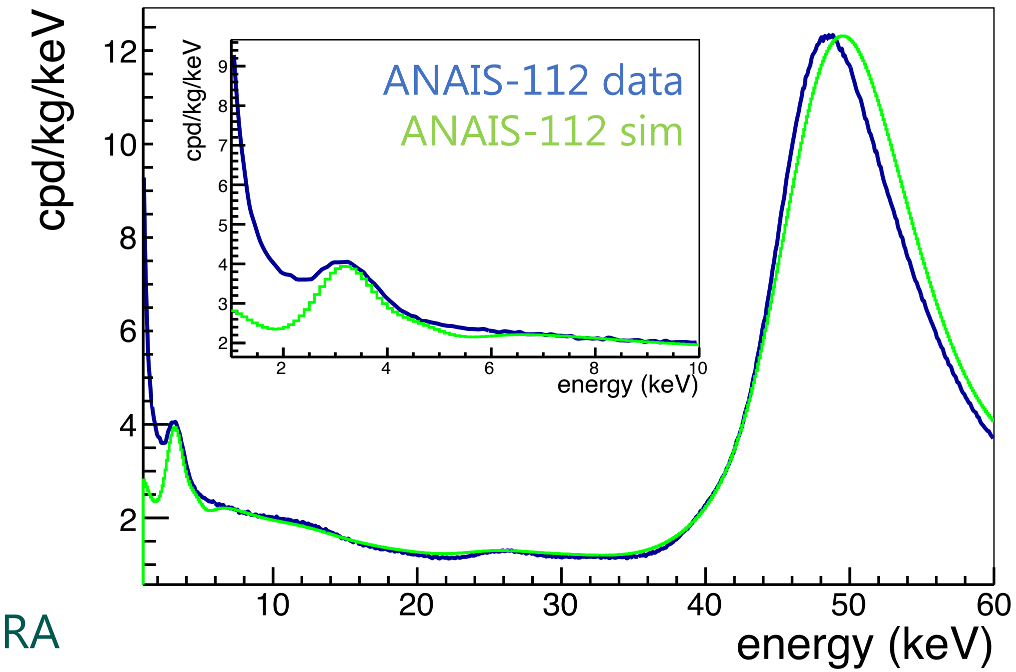
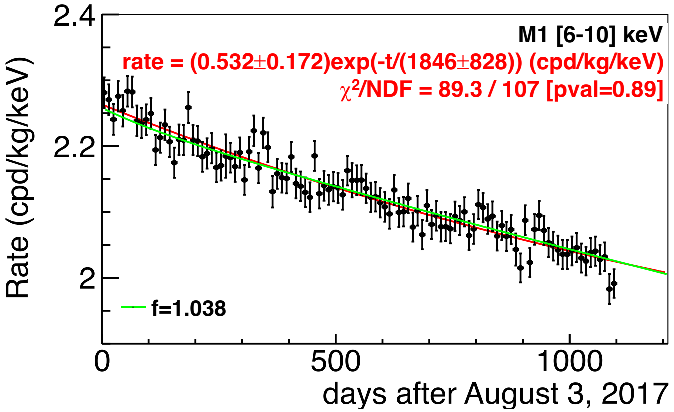
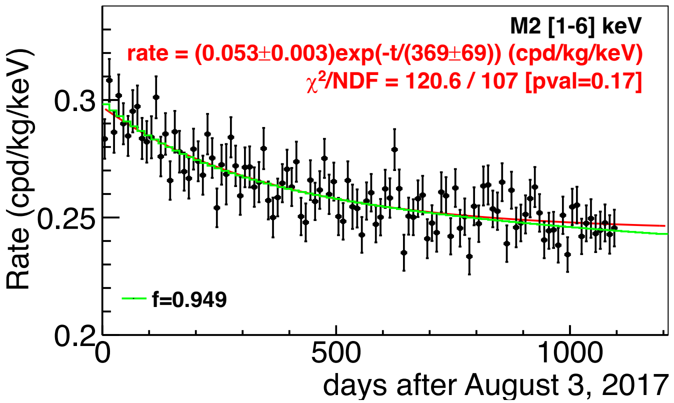


The ANAIS-112 background model

Cosmogenic isotopes and 210Pb are decaying…

Our model predicts **time evolution** of the background detector by detector and reproduce satisfactorily the time evolution inside and outside the ROI





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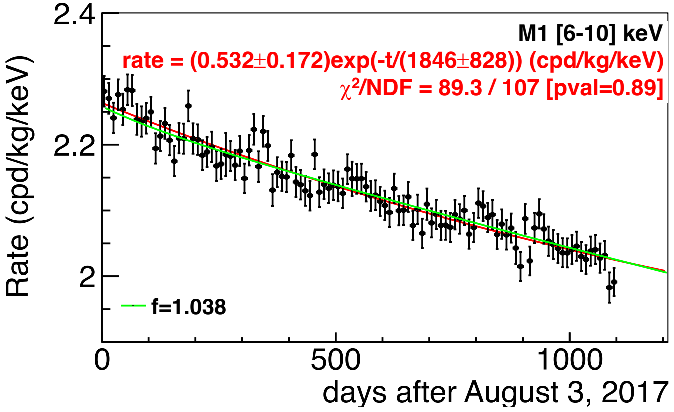
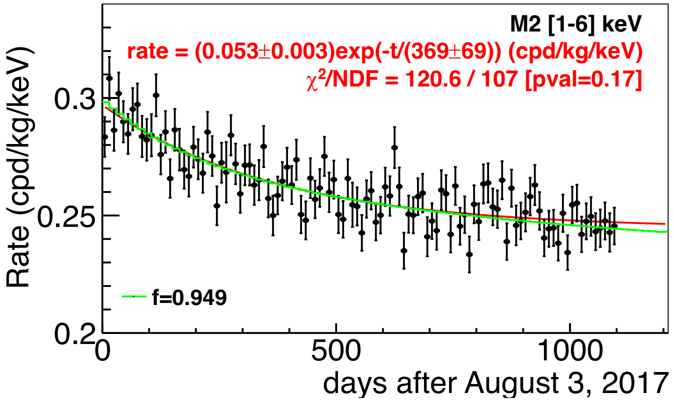




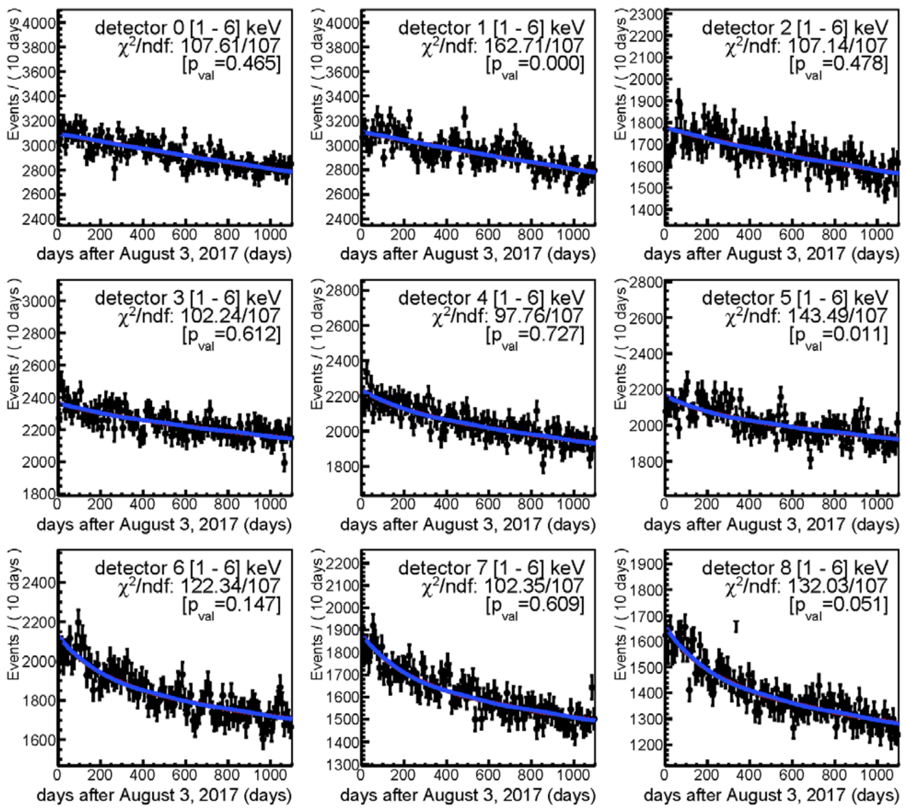
MC model is used in the annual modulation analysis

$$\mu_{i,d} = [R_{0,d}(1 + f_d \phi^{MC}_{bkg,d}(t_i)) + S_m cos(\omega(t_i - t_0))] M_d \Delta E \Delta t,$$

Null hyp χ^2/ndf: 1075.81/972 [p_{val}=0.011]

Mod hyp χ^2/ndf: 1075.15/971 [p_{val}=0.011]

S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)



The ANAIS-112 background model

In order to perform the annual modulation analysis corresponding to **six-year exposure**, a series of improvements are being implemented

WORK IN PROGRESS

We are revisiting the ANAIS-112 Geant4 model NEW!

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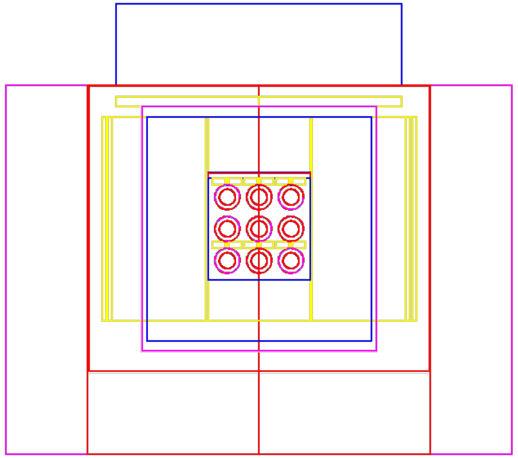
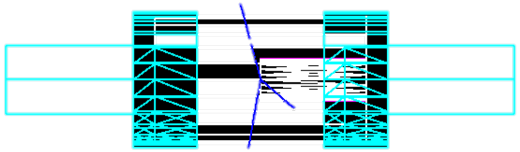
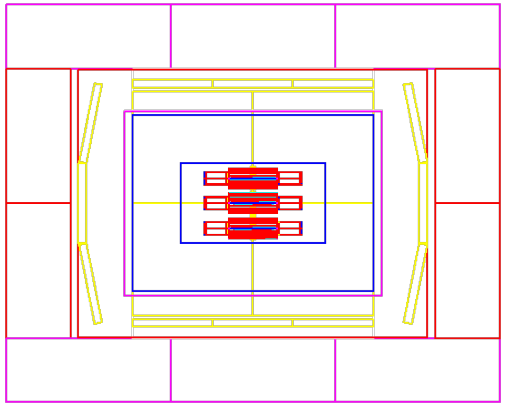


- 3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules + PMTs
- 30 cm lead
- Anti-Radon box
- 40 cm PE/water
- 16 anti-muon vetoes



Cd109 calibration source



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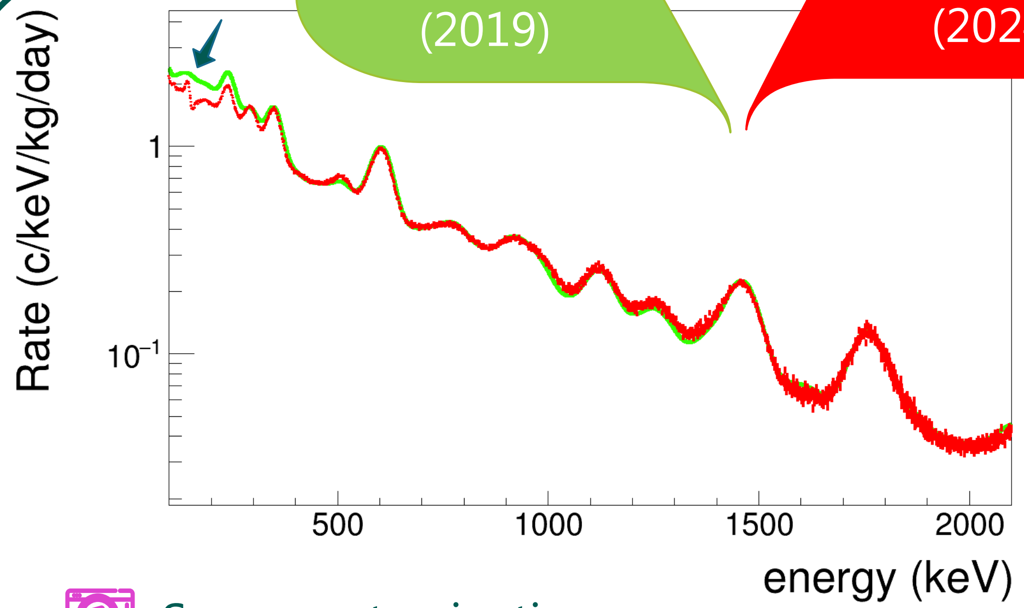
Geant4 version has been updated (physics models, decay schemes···)

geant4-v9.4.1 (2019)

geant4-v10.7.0 (2024)



Same contaminations

Differences in [100-300] keV caused by the contribution from natural chains @PMTs

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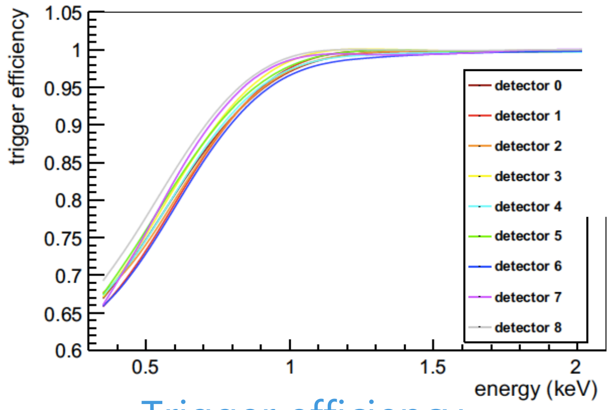
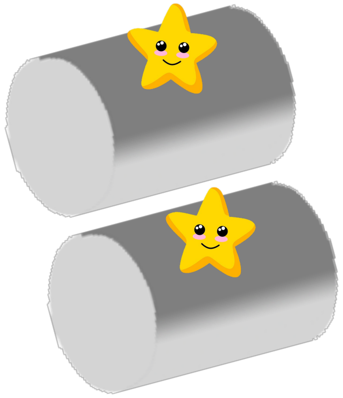
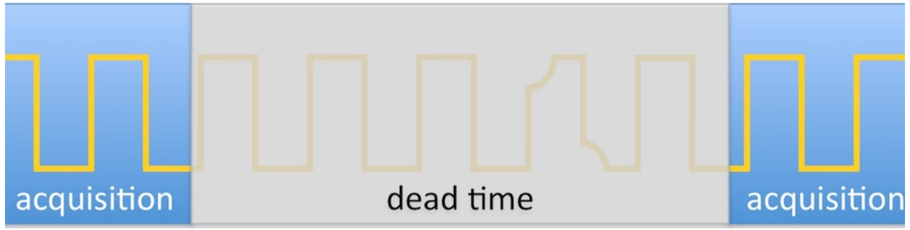


Trigger efficiency



Coincidence definition



ANAIS t_{integW} = 1μs / ANAIS dead time = 4.5 ms

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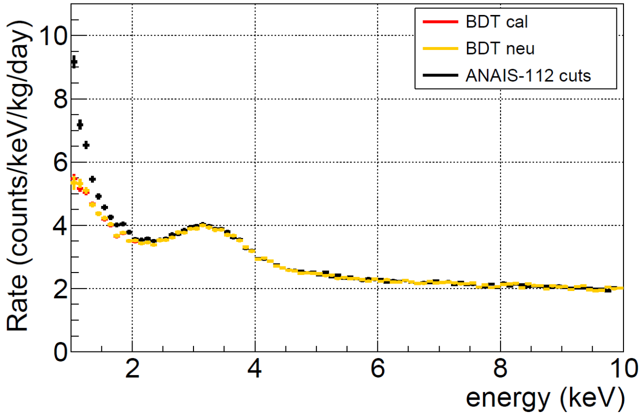
- Better experimental input

New filtering protocol based on machine learning techniques



~ 18% background reduction in [1-2] keV

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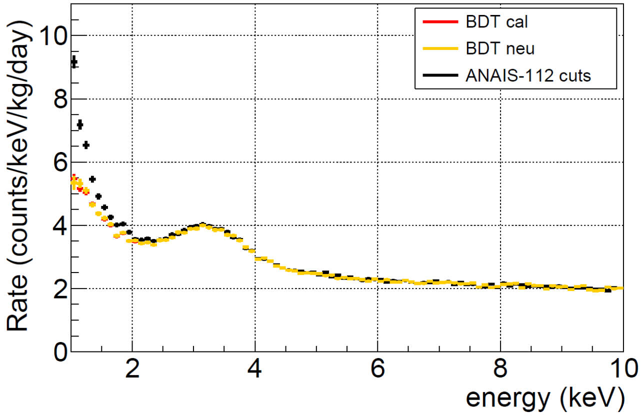

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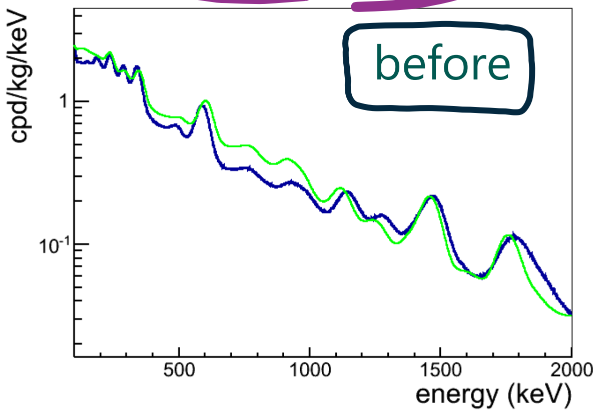
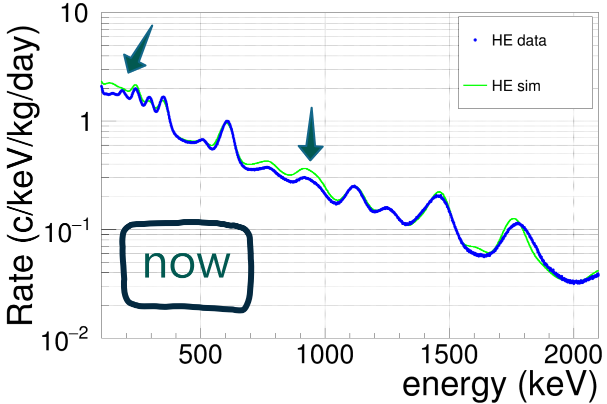
Enhancement of the calibration strategy (LE, ME & **HE**)





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Multiparametric fit to the different components @ANAIS background

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WORK IN PROGRESS

Contributions → pdfs

9 crystals ($K40$, $Pb210$, $Th232$, $U238$, $U235$, $H3$, $Na22$, $Cd109$, $Sn113$, I's, Te's)

18 PMTs ($K40$, $Ra226$, $Th232$, $U238$, $U235$)

Others: 9 Cu housing, 18 SiPads, 18 Quartz windows ($K40$, $Ra226$, $Th232$, $U238$)
+ Air inside the shielding ($Rn222$)
+ Roman Lead ($Pb210$)

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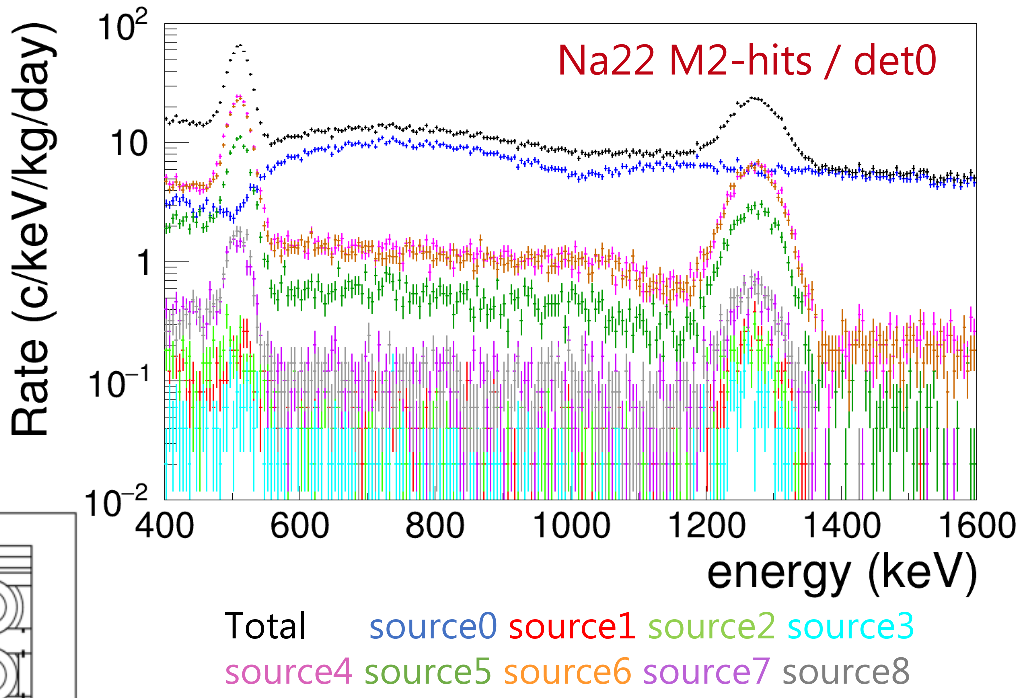
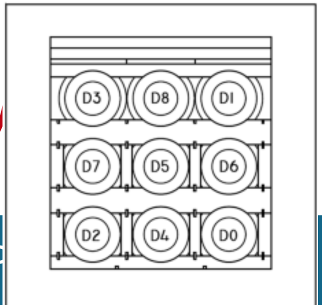
Pdf for each det is built taking into account the contribution from itself and from other sources





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Need to valorate degenerations and feasibility !!

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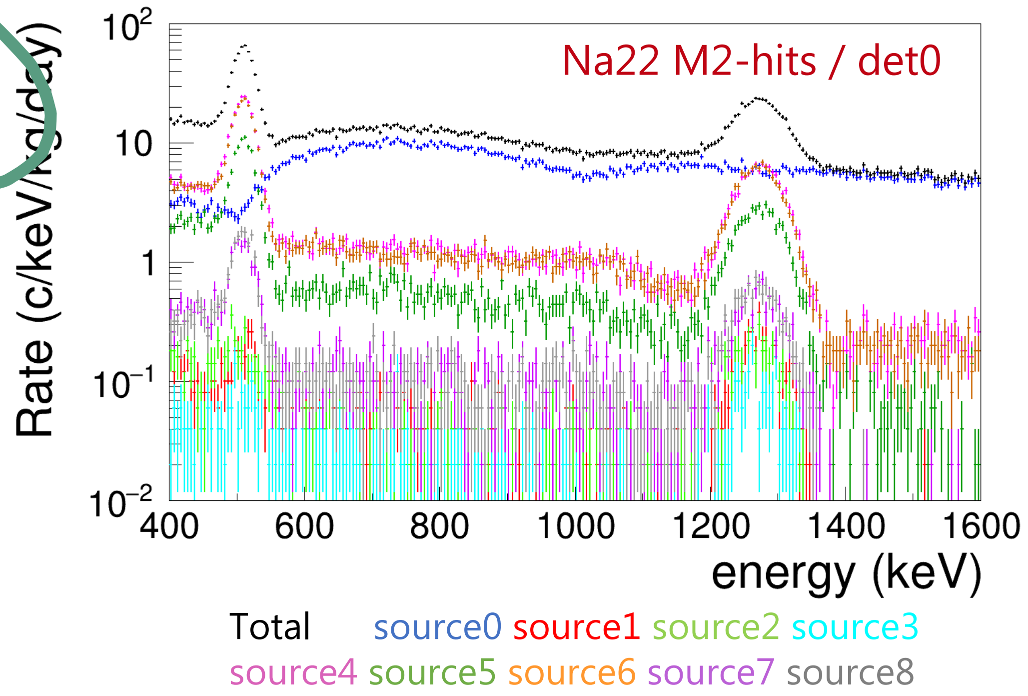
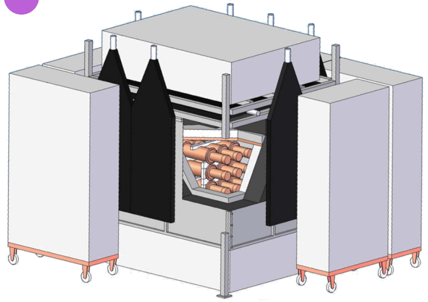


The ANAIS-112 experiment

Quenching factor

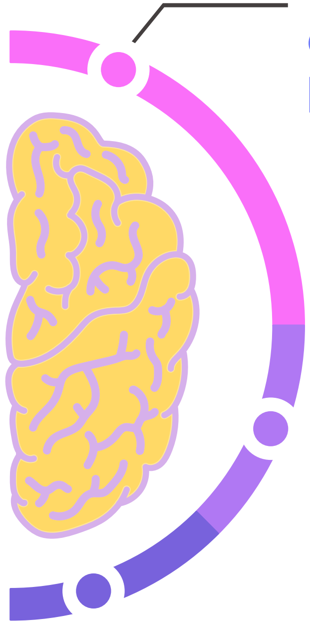
GEANT4
A SIMULATION TOOLKIT

Background model



Data analysis
@ANAIS-112

Can DAMA/LIBRA result be directly compared to ANAIS result?



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

(*) keVee: electron-equivalent keV

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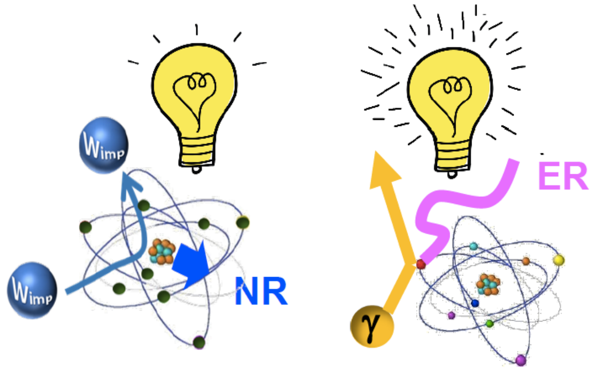

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$$QF = \frac{L_{NR}}{L_{ER}}$$

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

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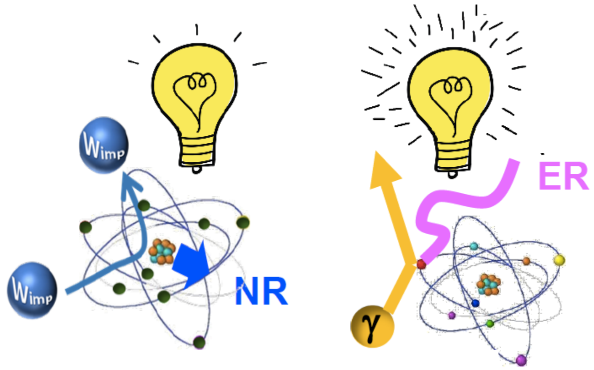
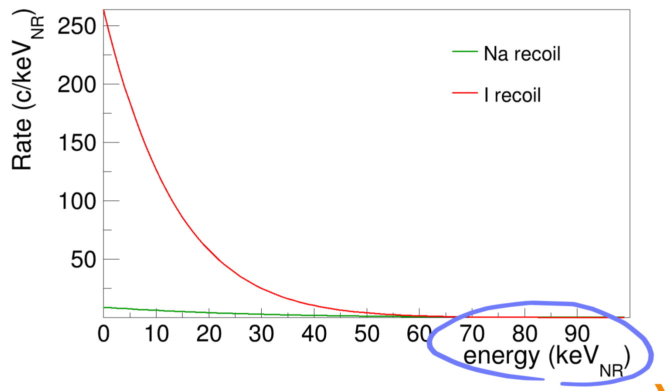


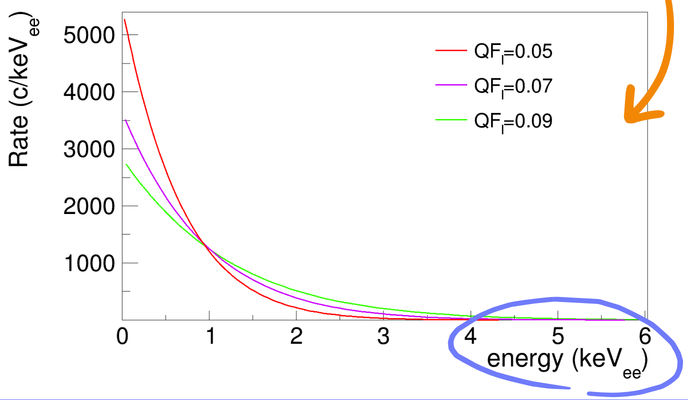
$$QF = \frac{L_{NR}}{L_{ER}}$$

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**





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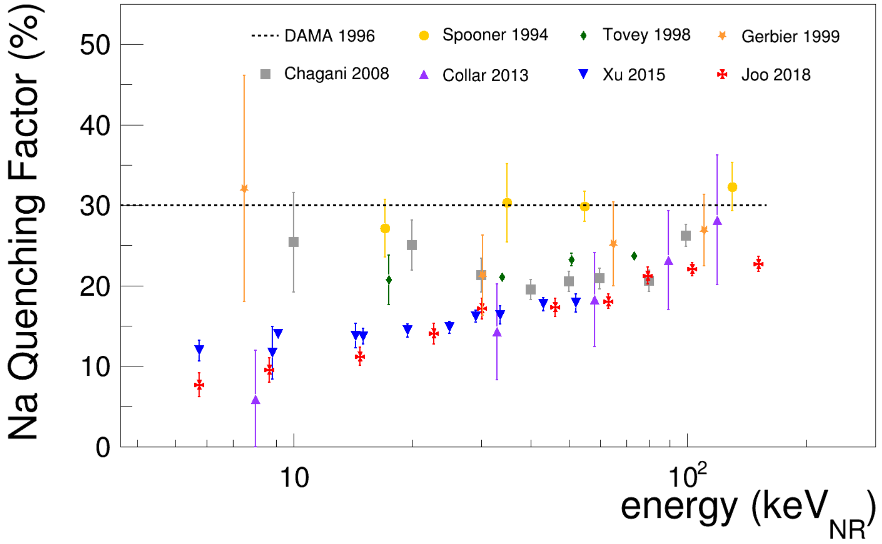


$QF_{Na,DAMA} = 0.3$

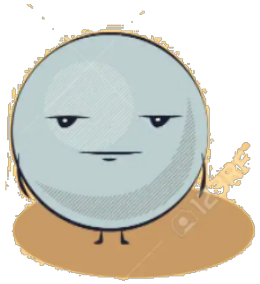
$QF_{I,DAMA} = 0.09$

Constant QF? 1

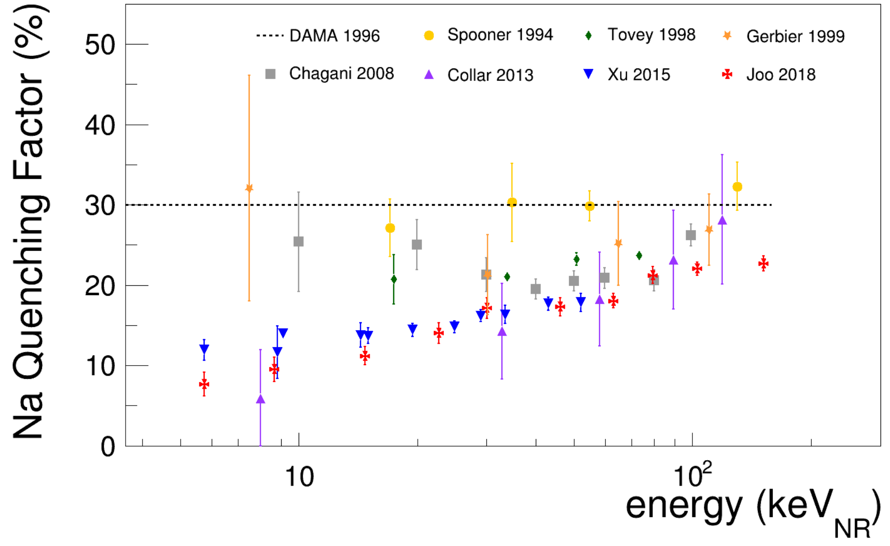
2 Decreasing with energy QF @ low energies?

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

Determining the QF is crucial to support the direct model independent testing of DAMA-LIBRA; **systematic**



Neutron interactions are relevant for a DM experiment because they produce NR of the target nuclei as WIMPs do



$QF_{Na,DAMA} = 0.3$

$QF_{I,DAMA} = 0.09$

Constant QF? 1

2 Decreasing with energy QF @ low energies?

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

Can DAMA/LIBRA result be directly compared to ANAIS result?

Determining the QF is crucial to support the direct model independent testing of DAMA-LIBRA; **systematic**

QF determination for ANAIS-112 crystals is ongoing: **two approaches** are followed in parallel

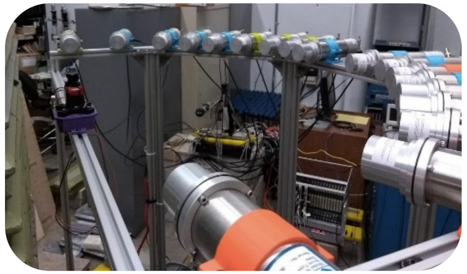
	Monochromatic neutron source	**^{252}Cf source**	
✔	small size	ANAIS crystals	✔
✘	not ANAIS crystals	greater reliance on MC model	✘

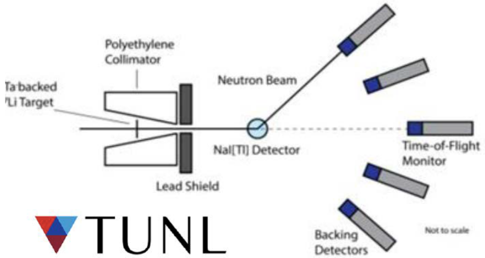
Multiple scattering is one of the most relevant differences

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

Neutron calibration program

Monochromatic neutron source





TUNL
Triangle Universities Nuclear Laboratory

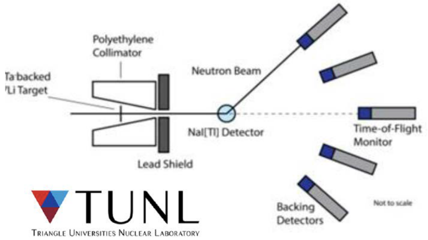
In collaboration with Yale (from COSINE collaboration) and Duke researchers @ TUNL

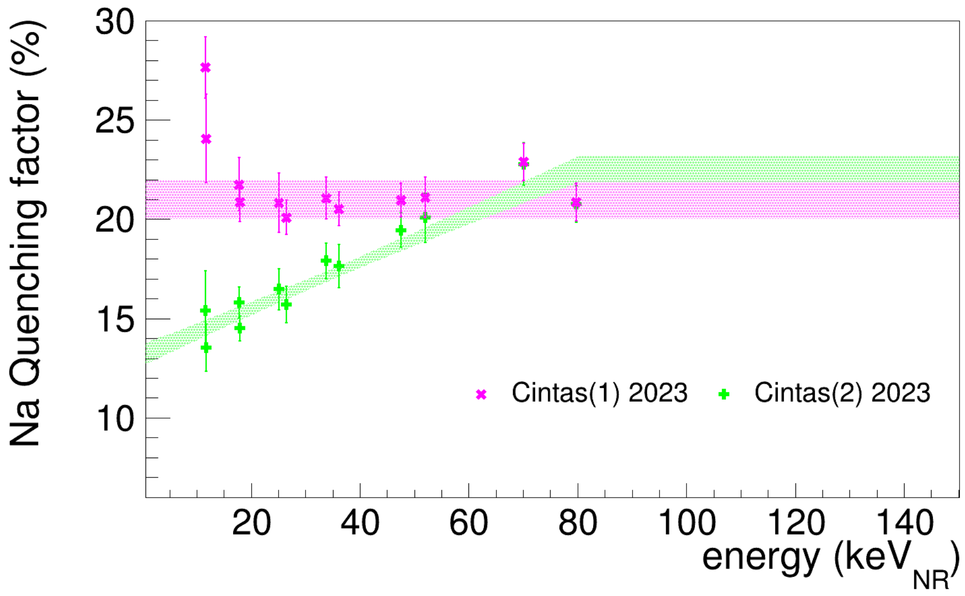
Neutron calibration program

Monochromatic neutron source

Analysis of **systematic** effects

3 different **energy calibrations**





The Na-QF derived from the different energy calibrations considered are not compatible

2 Decreasing with energy **QFNa(E)** @ low energies?

1 **QFNacte** = (21.2 ± 0.8) %

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

arXiv:2402.12480

Neutron calibration program

Monochromatic neutron source

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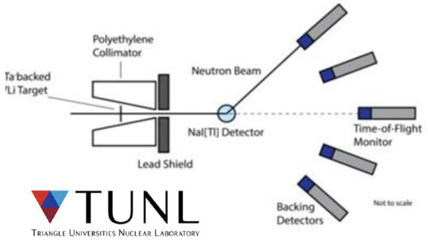

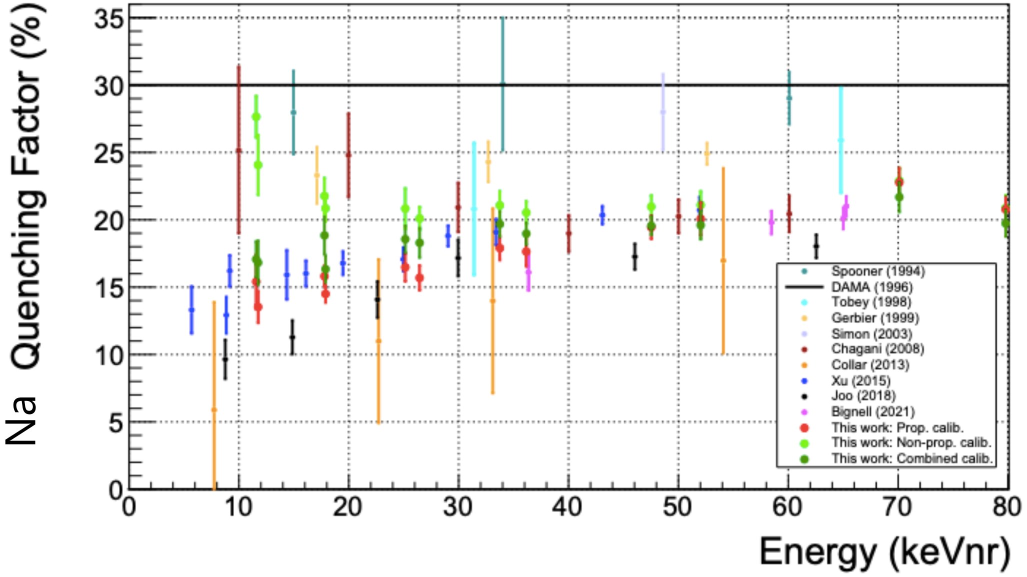

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Fully compatible results among the different cyrstals tested. Dispersion compatible with previous measurements

Systematics play a relevant role in the comparison of results

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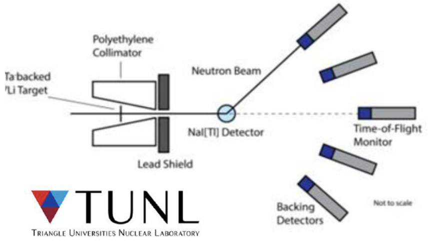
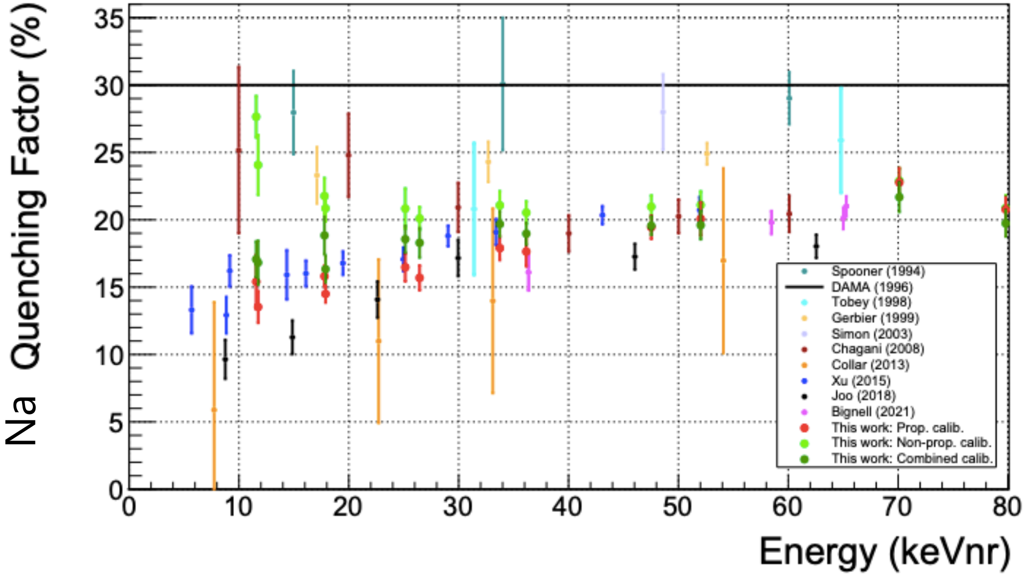
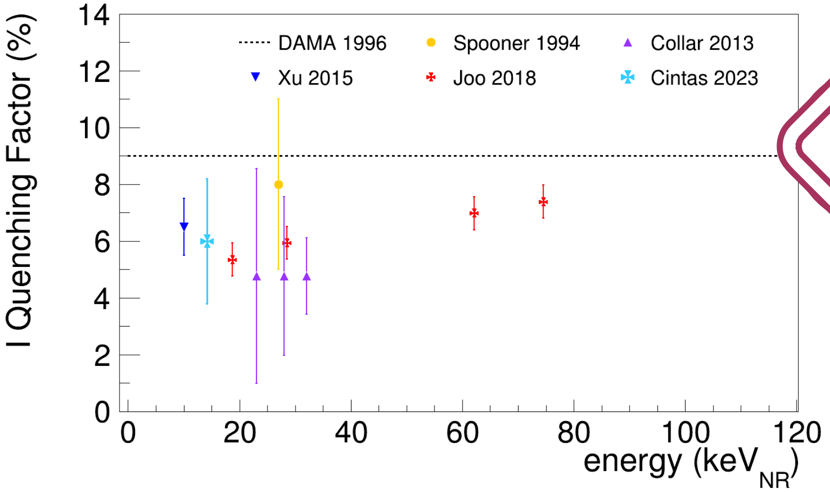






The Na-QF derived from the different energy calibrations considered are not compatible

Fully compatible results among the different cyrstals tested. Dispersion compatible with previous measurements

Systematics play a relevant role in the comparison of results

I

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

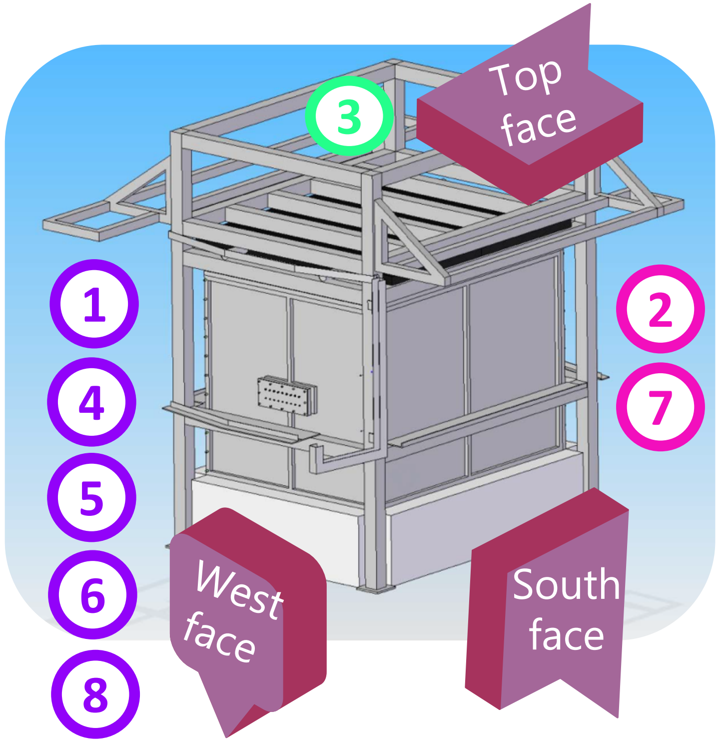
D. Cintas. *New strategies to improve the sensitivity of the ANAIS-112 experiment at the Canfranc Underground Laboratory*. PhD Thesis. Universidad de Zaragoza, 2023

arXiv:2402.12480

Neutron calibration program

^{252}Cf source

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



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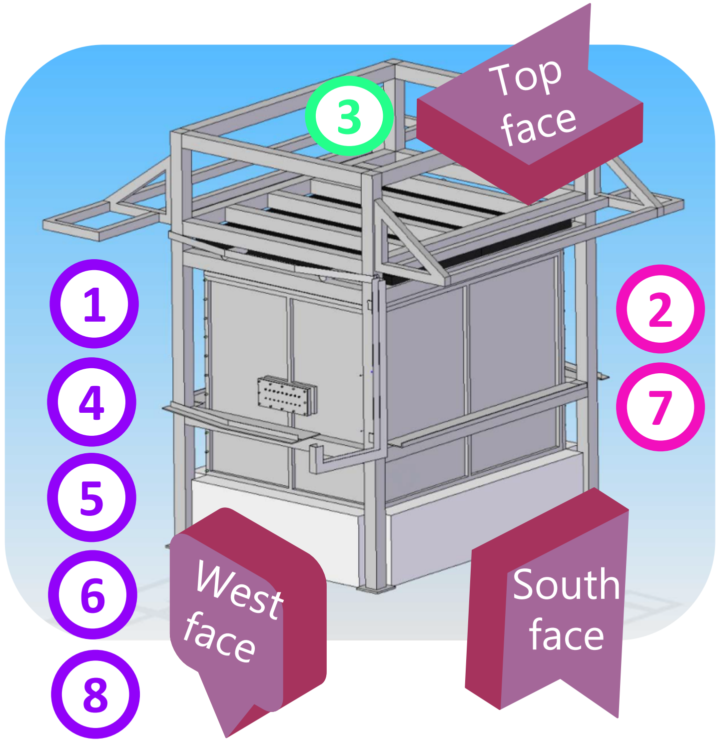
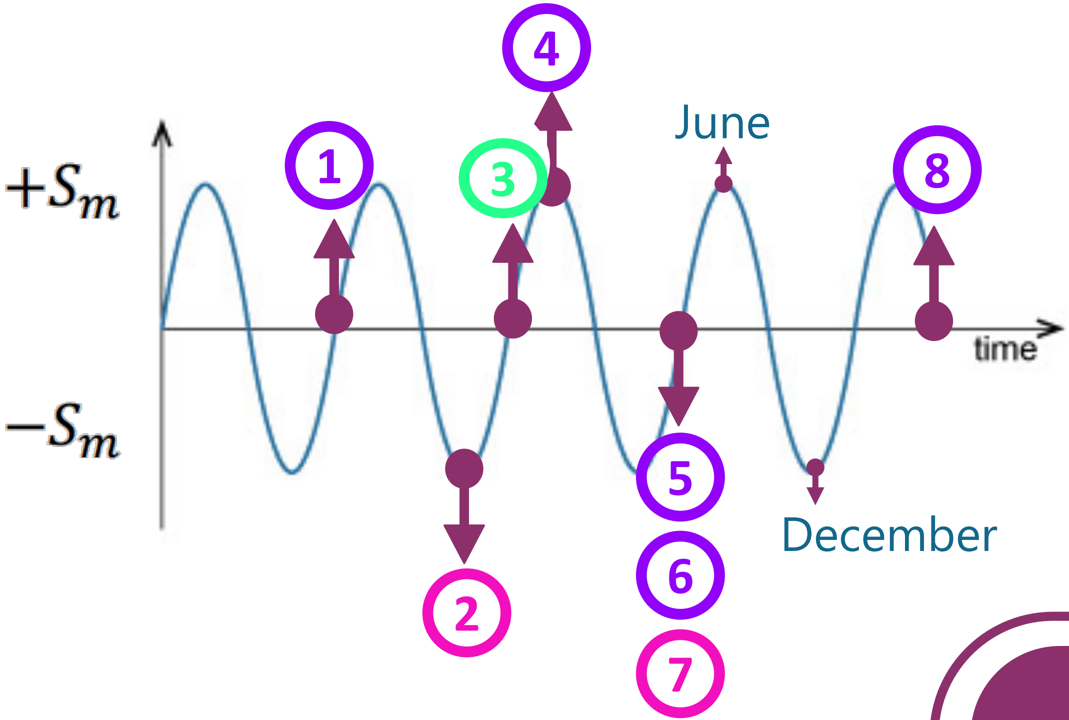




On-site neutron calibrations can be an important cross-check!!

Results on the quenching factor

Our aim

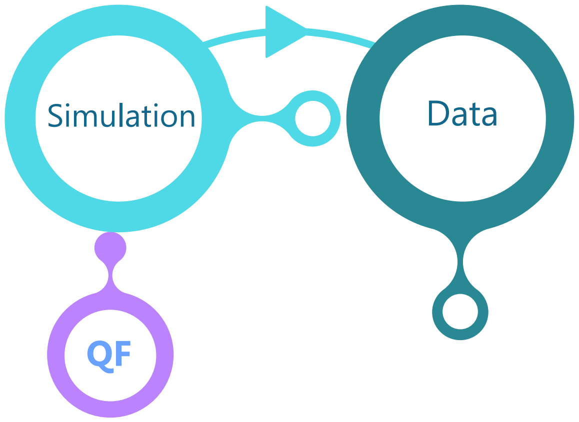
Determine the **QF** for **our crystals** by a precise quantitative comparison between measurement and simulation

Results on the quenching factor

Our aim

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

Modeling the Na-QF and I-QF for Na and I recoils is an essential input for these simulations



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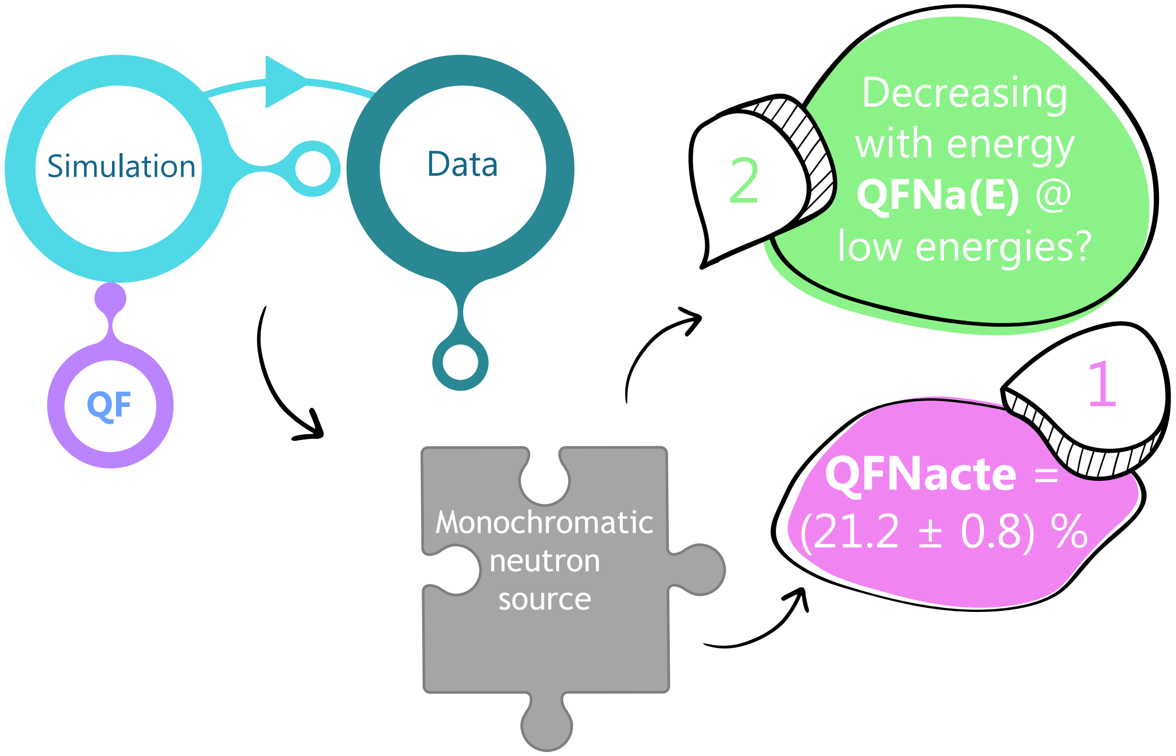

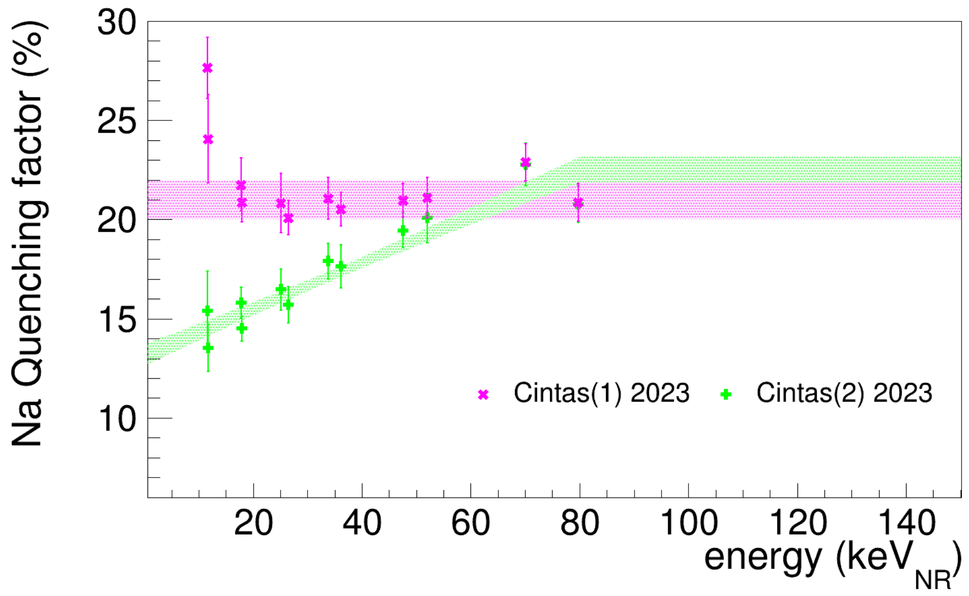

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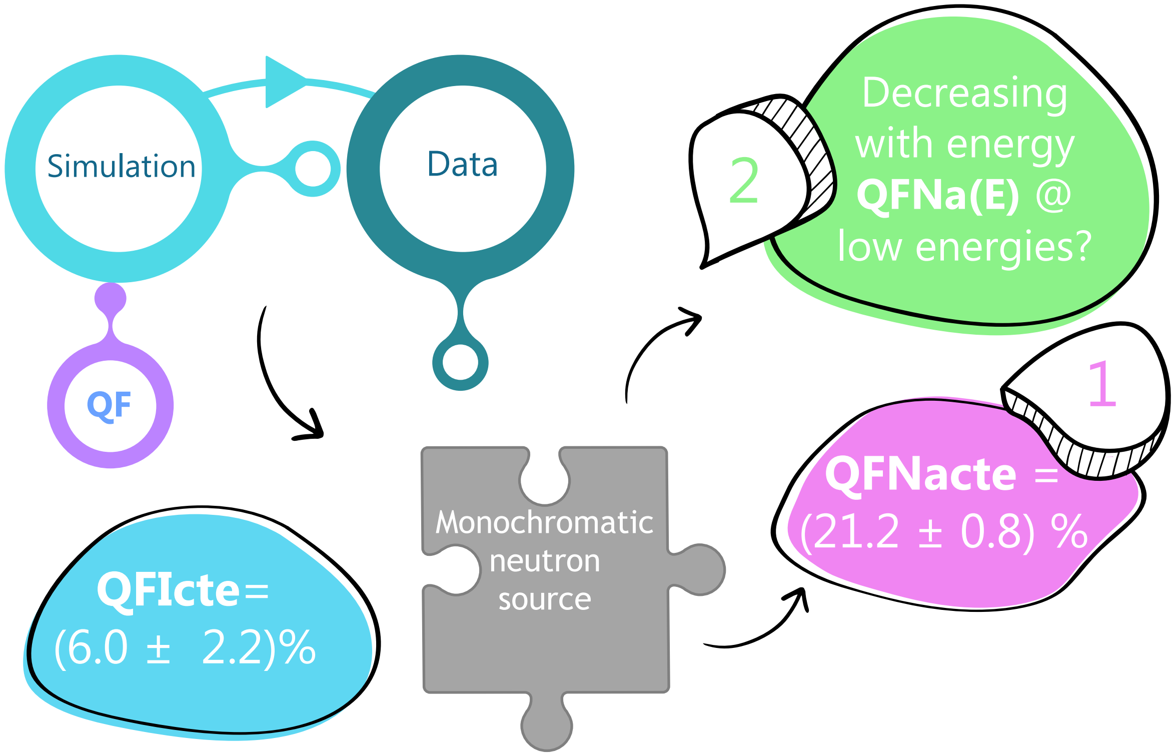

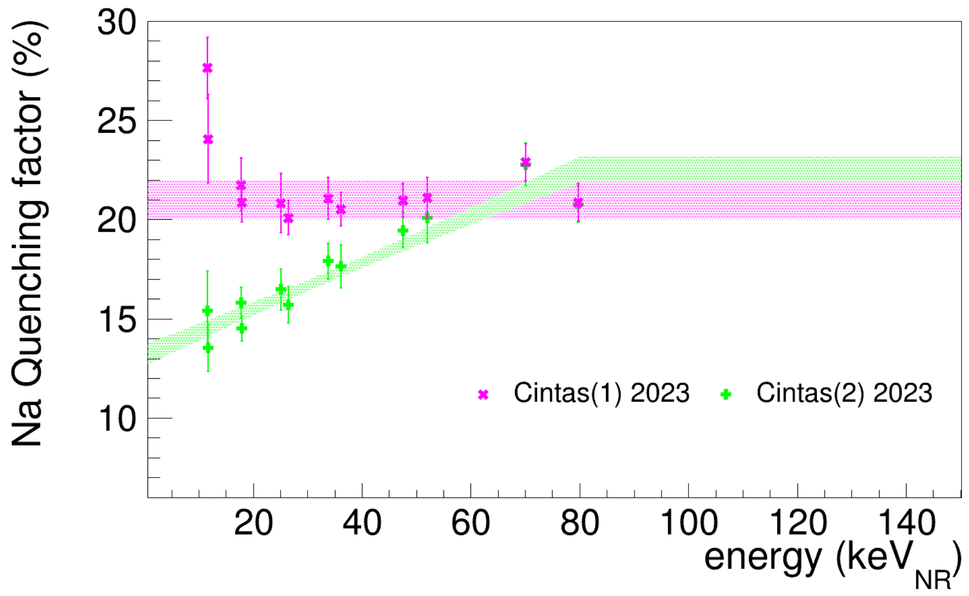

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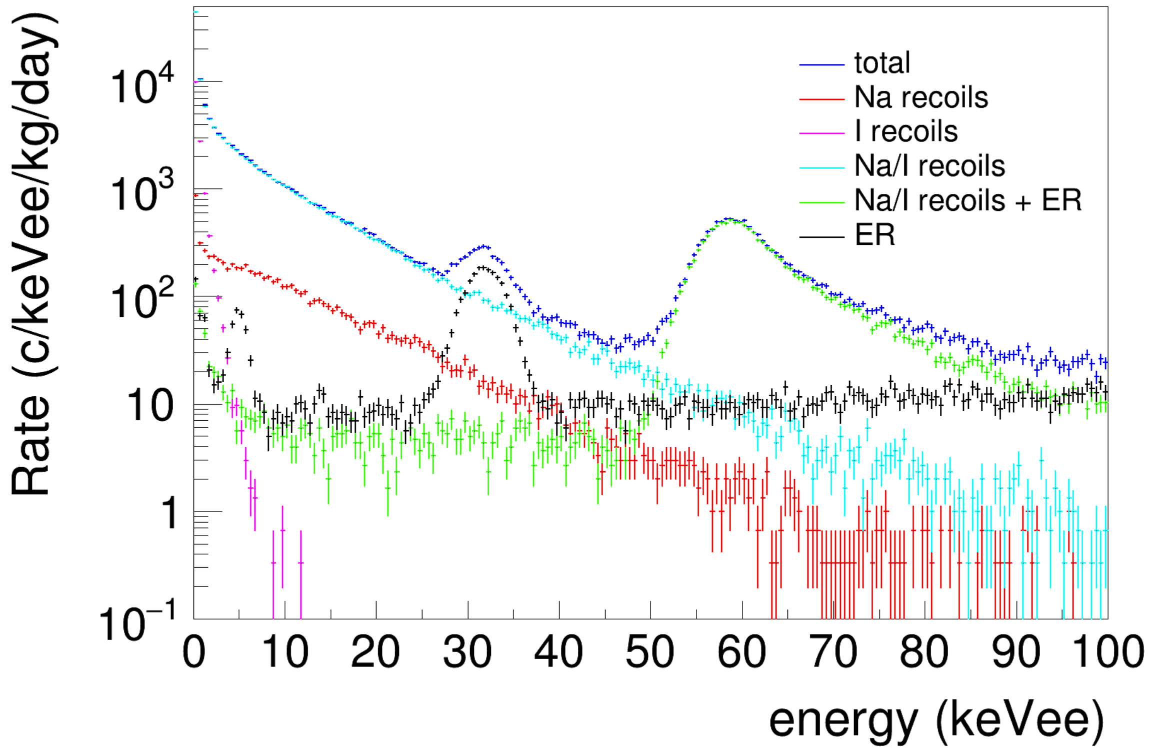


$E_{ee} = QF \times E_{NR}$

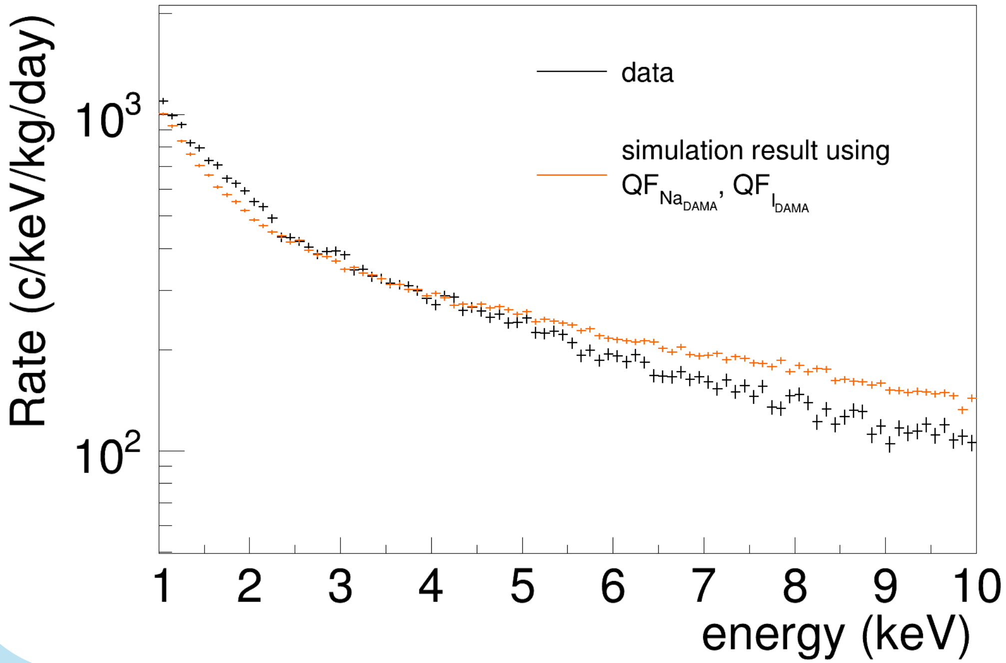
Large ANAIS-112 crystals exposed to fast neutrons show rates at low energy dominated by **multiple scattering**

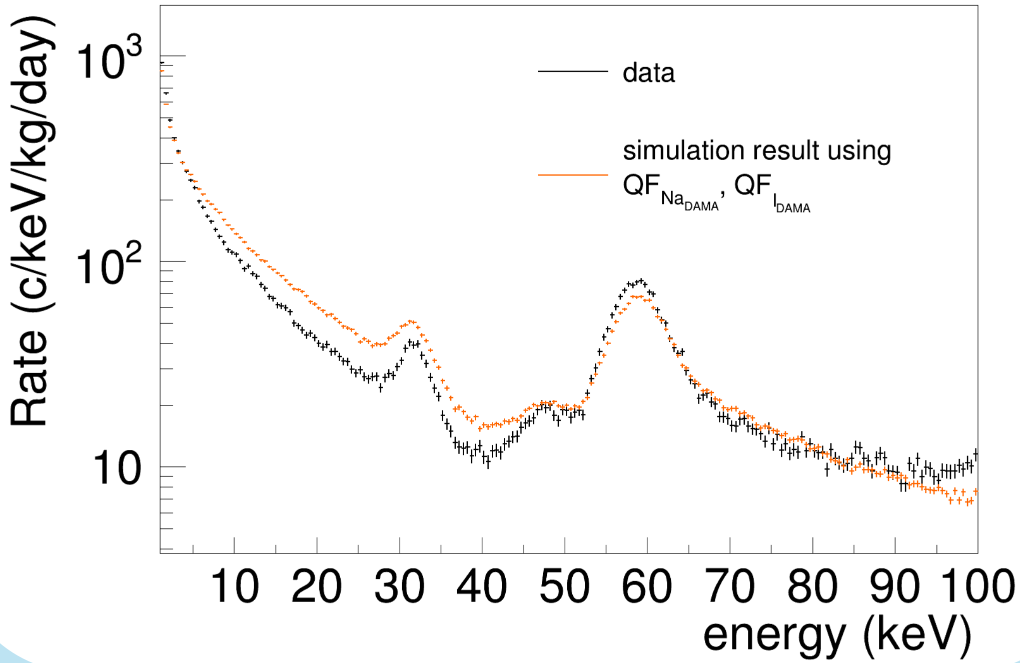
Nuclear recoils produced by the elastic scattering of the neutrons are dominant are dominant up to 50 keVee

Results on the quenching factor

Comparison between **data** and simulation with **DAMA/LIBRA QFs**

Q_{Na} DAMA = 0.3
Q_I DAMA = 0.09





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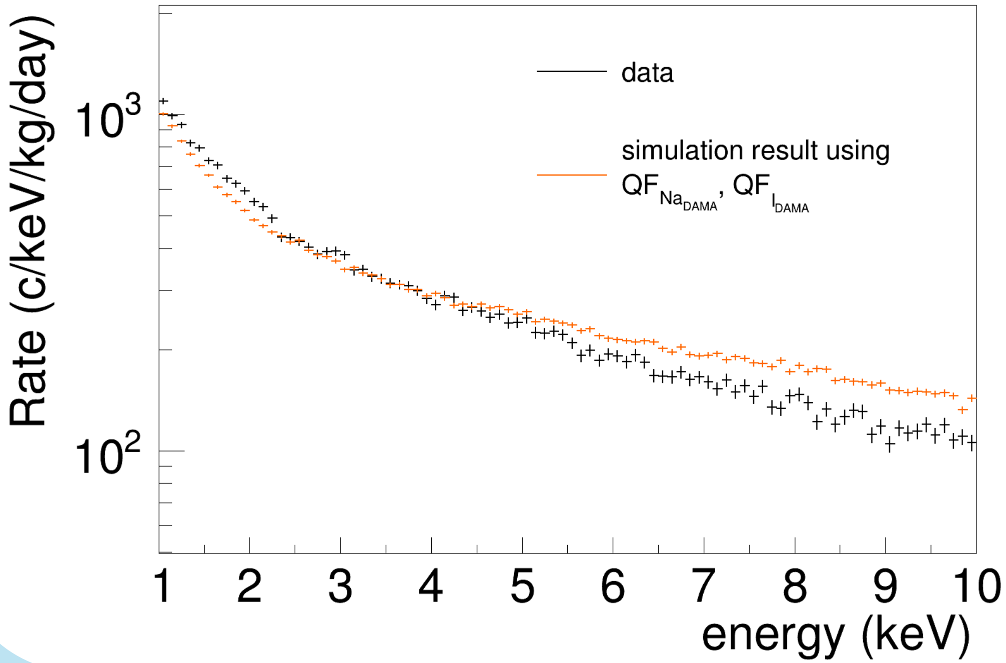
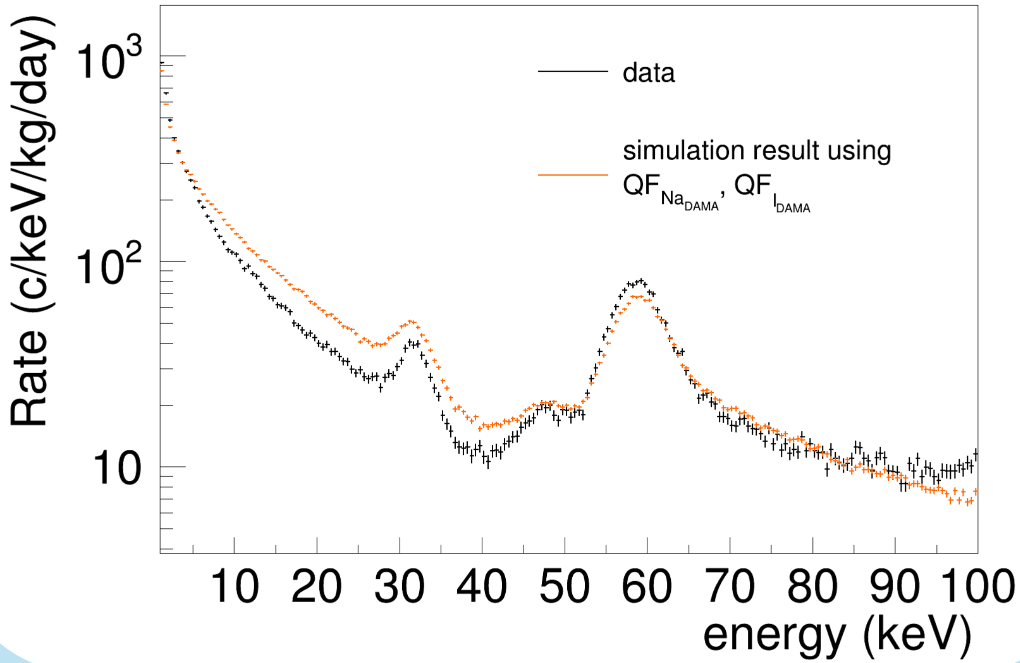
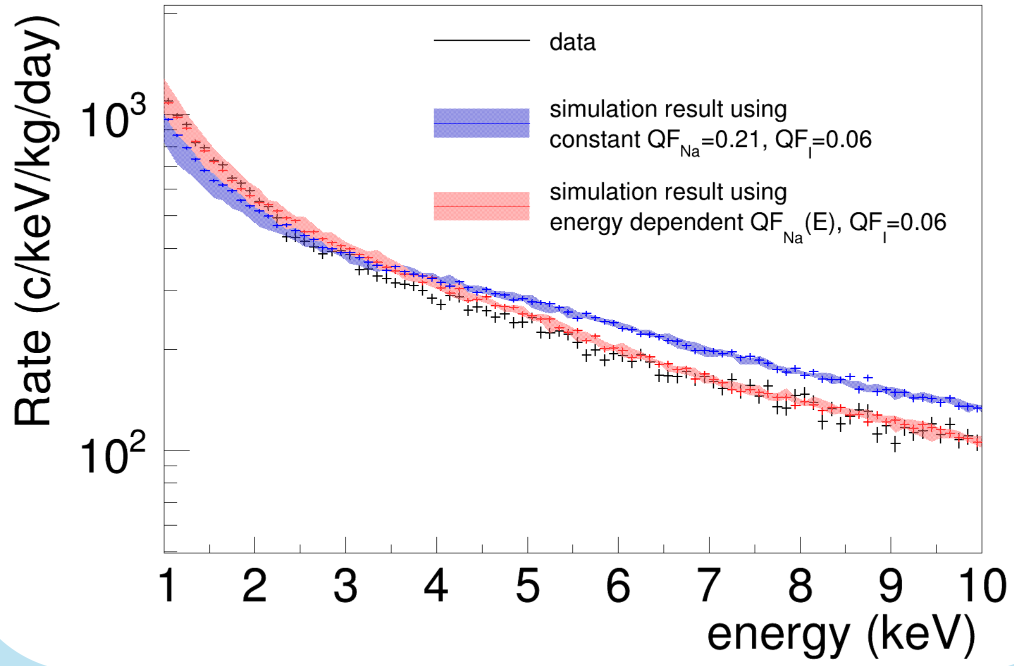


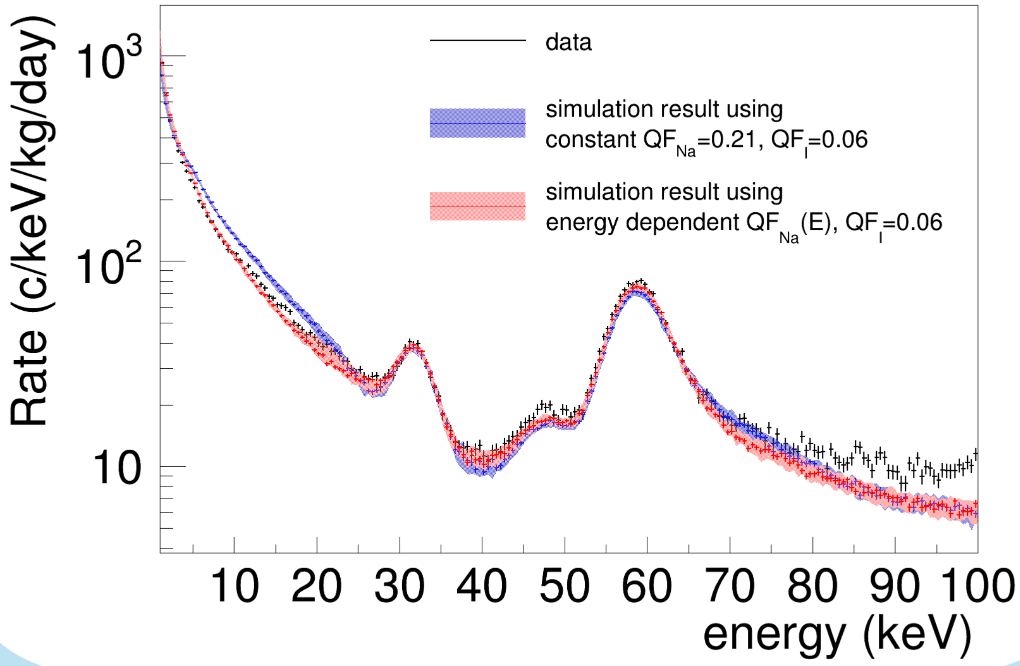


DAMA/LIBRA QFs are **not compatible** with our data

Results on the quenching factor

Comparison between **data** and simulation with **QFNa(E)** and **QFNacte**



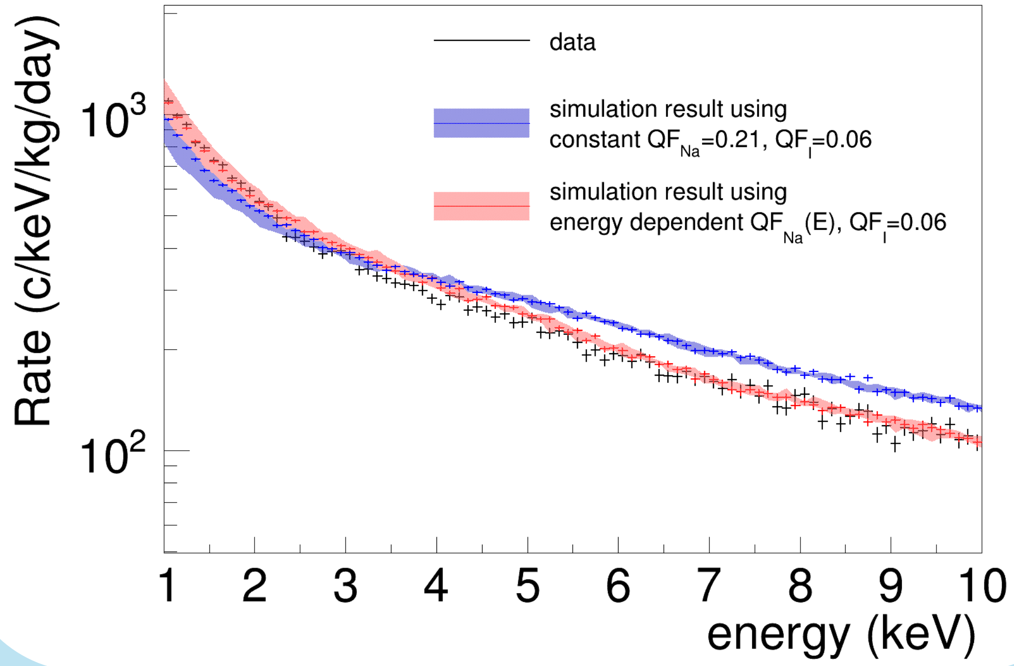


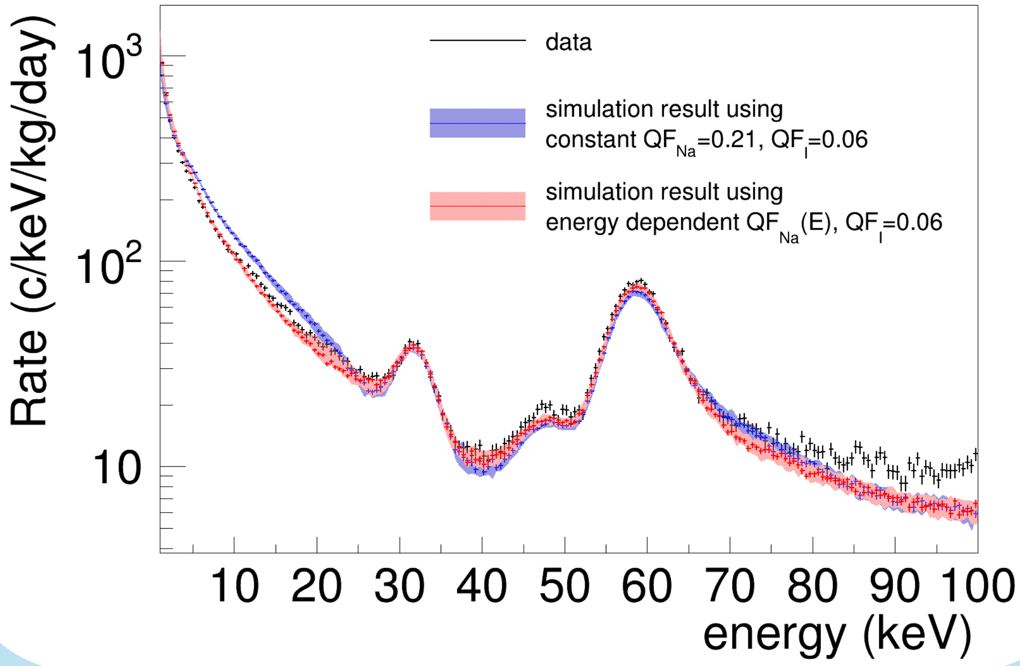
Results on the quenching factor

Comparison between **data** and simulation with **QFNa(E)** and **QFNacte**

Very goog agreement !!
Fitting has **not** been **attempted** (yet)!

WORK IN PROGRESS





QFNa(E) provides a robust **agreement**

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

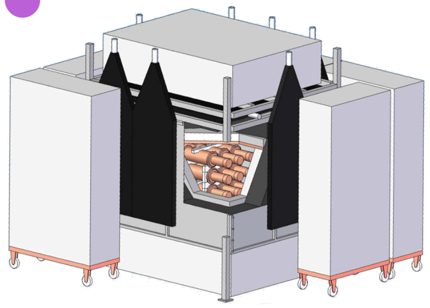
The ANAIS-112 experiment

Quenching factor

GEANT4
A SIMULATION TOOLKIT

Background model

Optical simulations



Data analysis
@ANAIS-112

The ANAIS-112 optical simulations

Optical processes play a fundamental role in the building of the detector signal

The ANAIS-112 optical simulations

Optical processes play a fundamental role in the building of the detector signal

Understand the pulse shape characteristics of light signals with different origin

The ANAIS-112 optical simulations

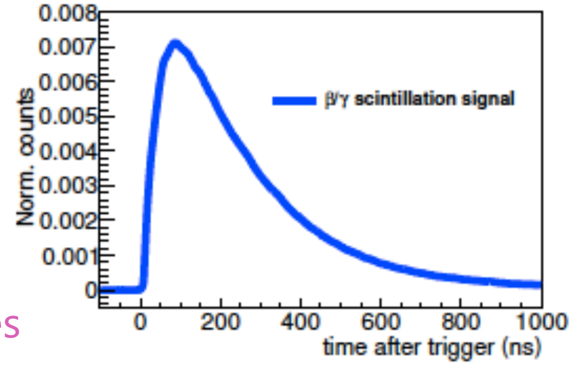
Optical processes play a fundamental role in the building of the detector signal

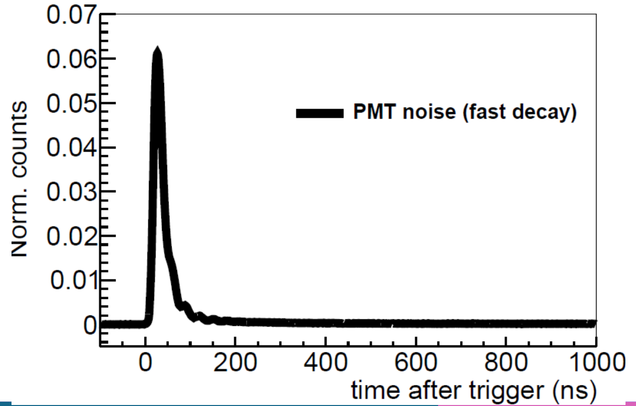
Understand the pulse shape characteristics of light signals with different origin

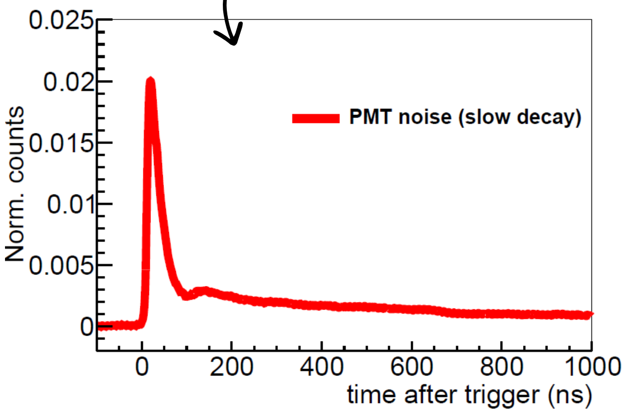
- total trigger rate dominated by non-bulk scintillation events
- anomalous events passing all the filtering protocols
- light collection efficiency and spatial dependences

anomalous scintillation events…

Average pulses

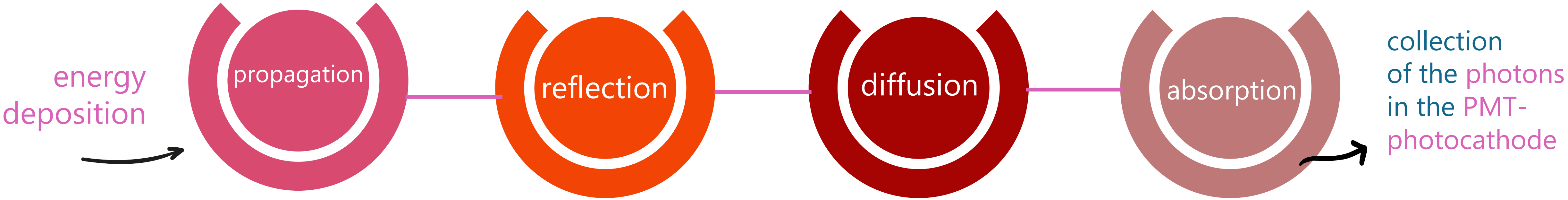






The ANAIS-112 optical simulations

A MC simulation using the unified optical model of GEANT4 package has been developed and it is being applied for simulating the detector response to specific components of the background



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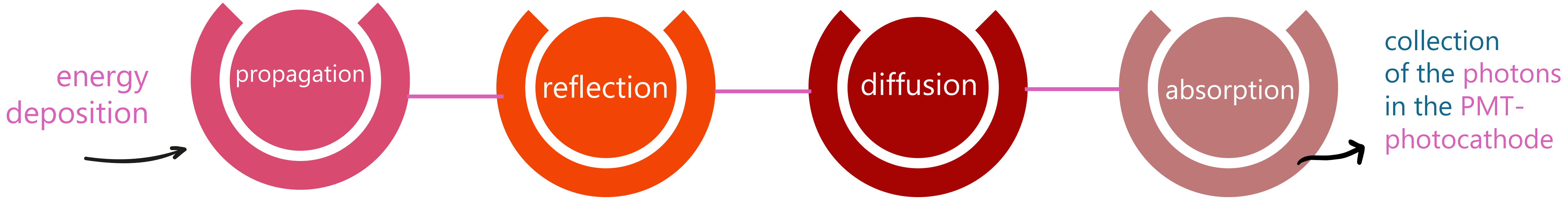
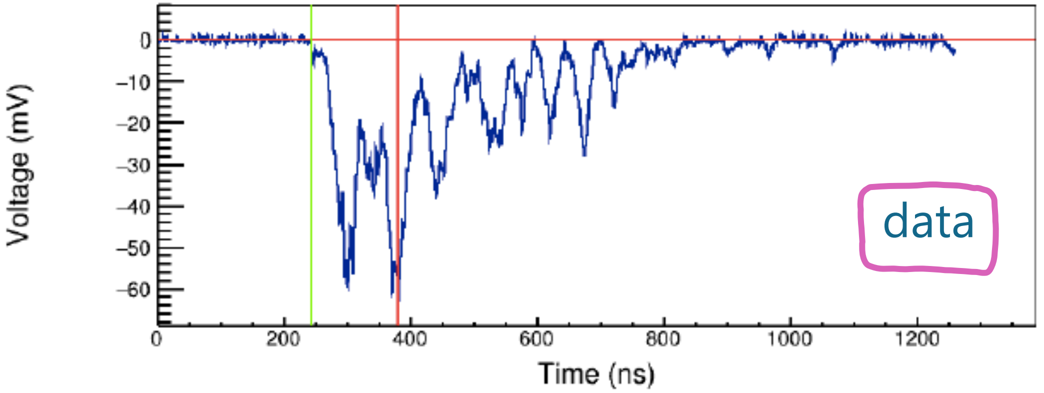
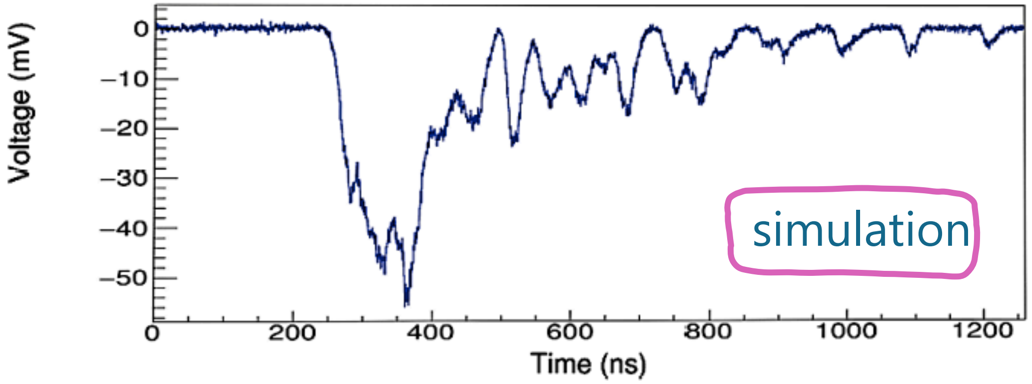


By including the LC and the SER of the ANAIS-112 PMTs, the detector output signals are also obtained, allowing to apply the same analysis as in ANAIS (P1, μ, npeaks variables···)





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A MC simulation using the unified optical model of GEANT4 package has been developed and it is being applied for simulating the detector response to specific components of the background

Some results have been obtained (ongoing)

Cherenkov emission reasonably reproduces the total trigger rate

Contribution of Rn222 to the blank trigger rate variations

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

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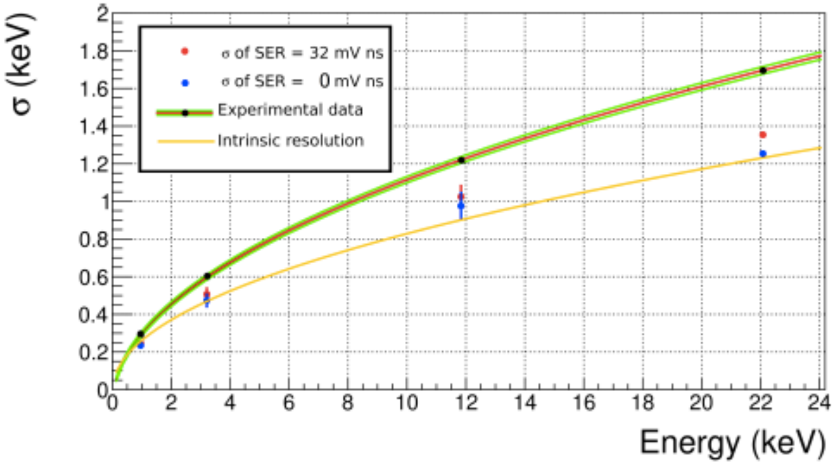

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The ANAIS-112 optical simulations

A MC simulation using the unified optical model of GEANT4 package has been developed and it is being applied for simulating the detector response to specific components of the background

Some results have been obtained (ongoing)

Better description of the PMT geometry and the optical properties of the detector components

WORK IN PROGRESS

Cherenkov emission reasonably reproduces the total trigger rate

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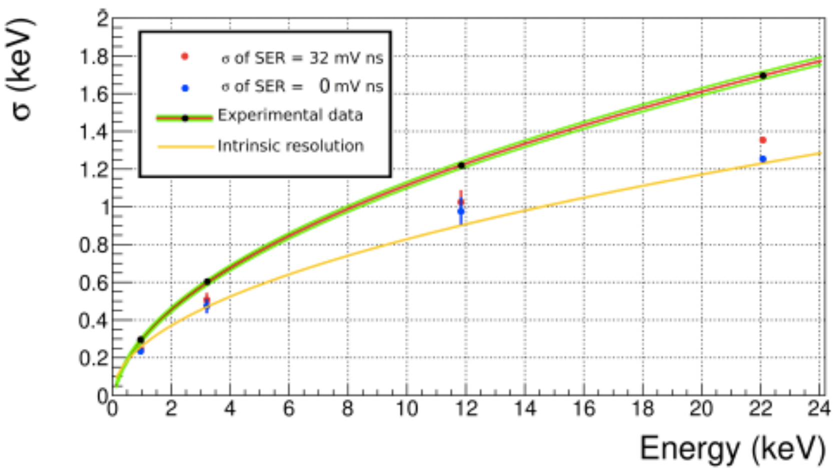

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TO SUM UP

Currently, many efforts trying to provide an **independent confirmation** of DAMA/LIBRA signal with the same target. ANAIS−112 and COSINE−100 in data-taking. ANAIS−112 is taking data in stable condition at LSC since 3rd August 2017 with excellent performances. Up to now it has accumulated more than **660 kg×y exposure**.

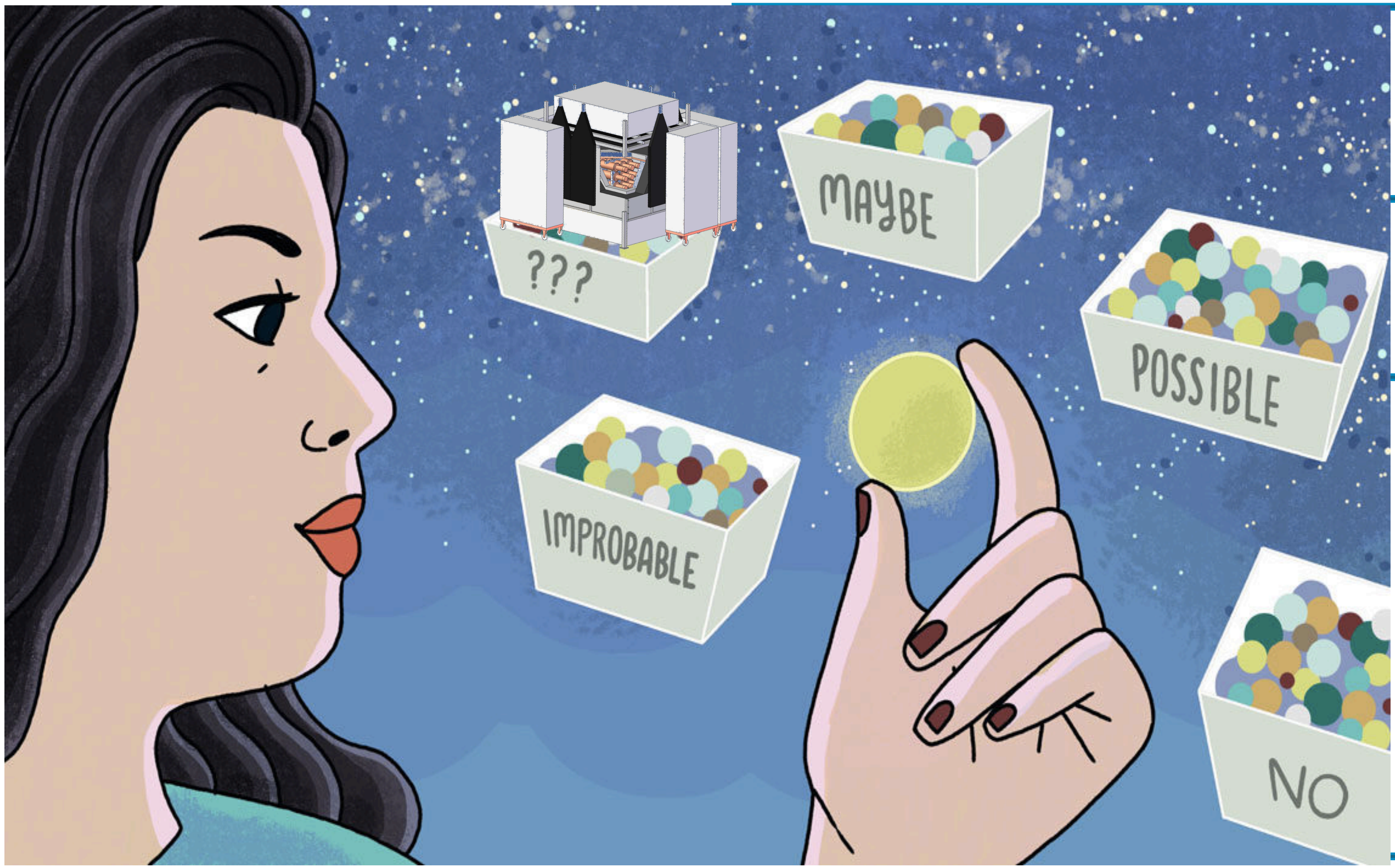
Sensitivity improved with machine-learning techniques. **ANAIS−112 observes no modulation and discards DAMA/LIBRA DM interpretation with $\sim 3\sigma$ sensitivity** in [1-6] keV ([2-6] keV). **For the first time, a direct test (i.e. model independent) of DAMA is at reach with $>3\sigma$ sensitivity. 5σ sensitivity in late 2025.**

The **Geant4** package is a toolkit used in several analyses performed within the ANAIS-112 experiment: background modeling, quenching factor estimation, and optical simulations. The background model of the full ANAIS-112 experiment is currently under revision and upgrading. Regarding QF, **QFNa(E)** provides a robust agreement and seems to be favoured over constant QF when comparing data and simulations. Furthemore, a MC simulation using the unified optical model of GEANT4 package has been developed.

ANAIS-112 annual modulation analysis corresponding to **six-year exposure** is **underway**.
New results will be released soon !!

Stay Tuned!

Thank you for your attention! ? ? ?



Tamara Pardo on behalf of the ANAIS research team

Vienna Workshop on Simulations (VIEWS 2024)
25 April-27 April 2024

CAPA Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

https://gifna.unizar.es/anais/

Unanswered questions?
tpardo@unizar.es

MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA Fondo Social Europeo
AGENCIA ESTATAL DE INVESTIGACIÓN
This research is founded by MCIN/AEI/10.13039/501100011033 under grant PID2019-104374GB-I00

Neutron calibration program

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

^{252}Cf source

cross-check !!

Monochromatic neutron source

^{252}Cf source

Calibrations

1 — Non-prop	2 — Prop
Ba133	I127
6.6, 30.8, 35.1 keV	57.6 keV

Neutron calibration program

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

Non-prop | Prop

1 — Calibrations — 2

cross-check !!

Monochromatic neutron source

^{252}Cf source

1 (Non-prop)	2 (Prop)
Ba133 6.6, 30.8, 35.1 keV	I127 57.6 keV
22Na & 40K + neutrons (0.9 & 3.2 keV) + (31.8 & 57.6 keV)	

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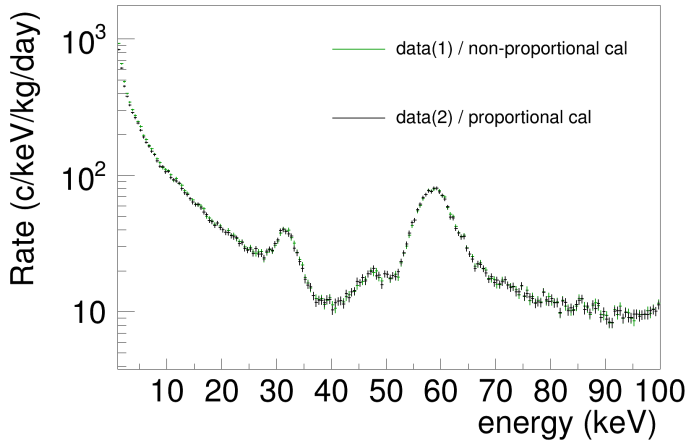

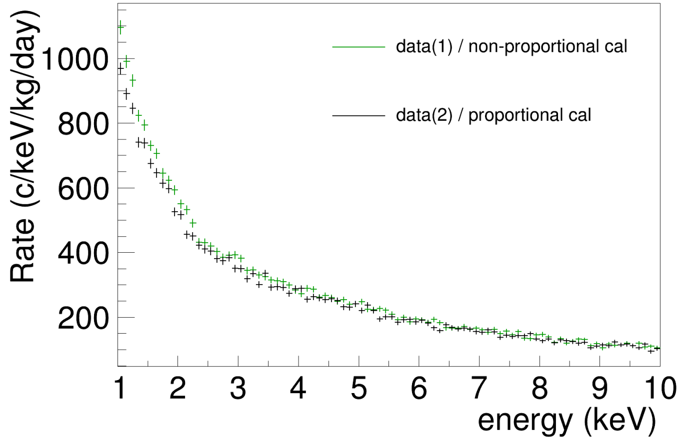

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^{252}Cf source

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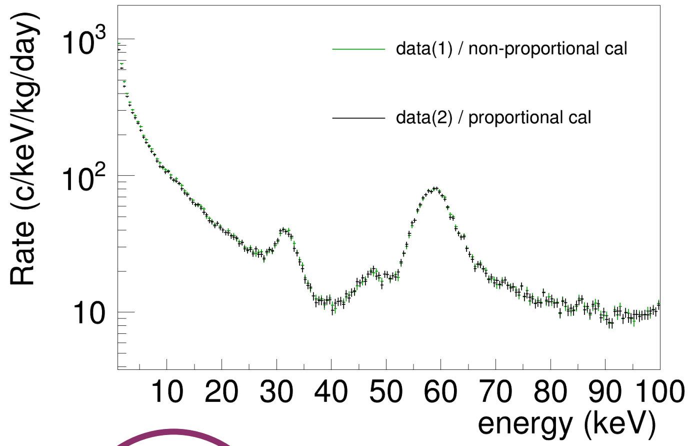
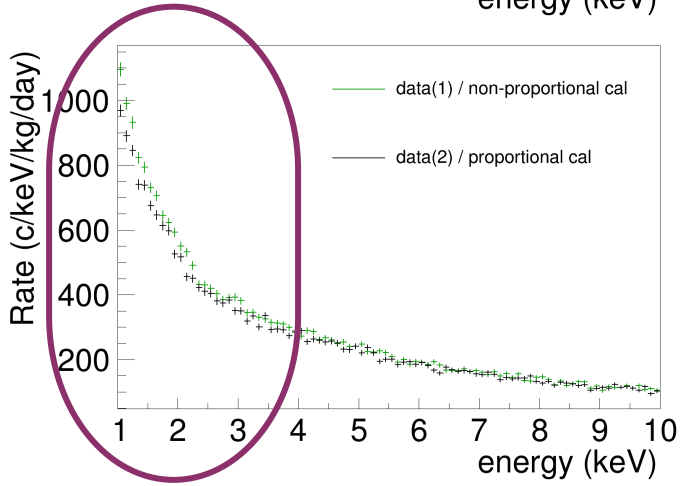




We will show **non-proportional** calibration

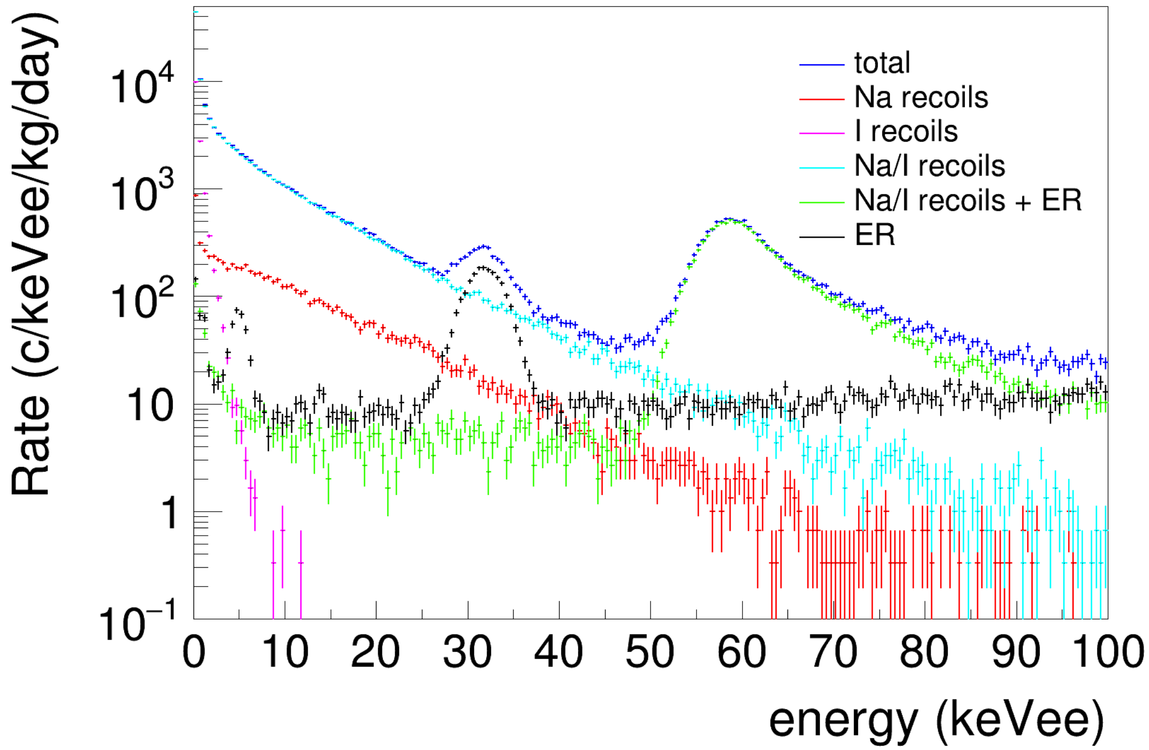
Bulk calibration

Results on the quenching factor

Our aim

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

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

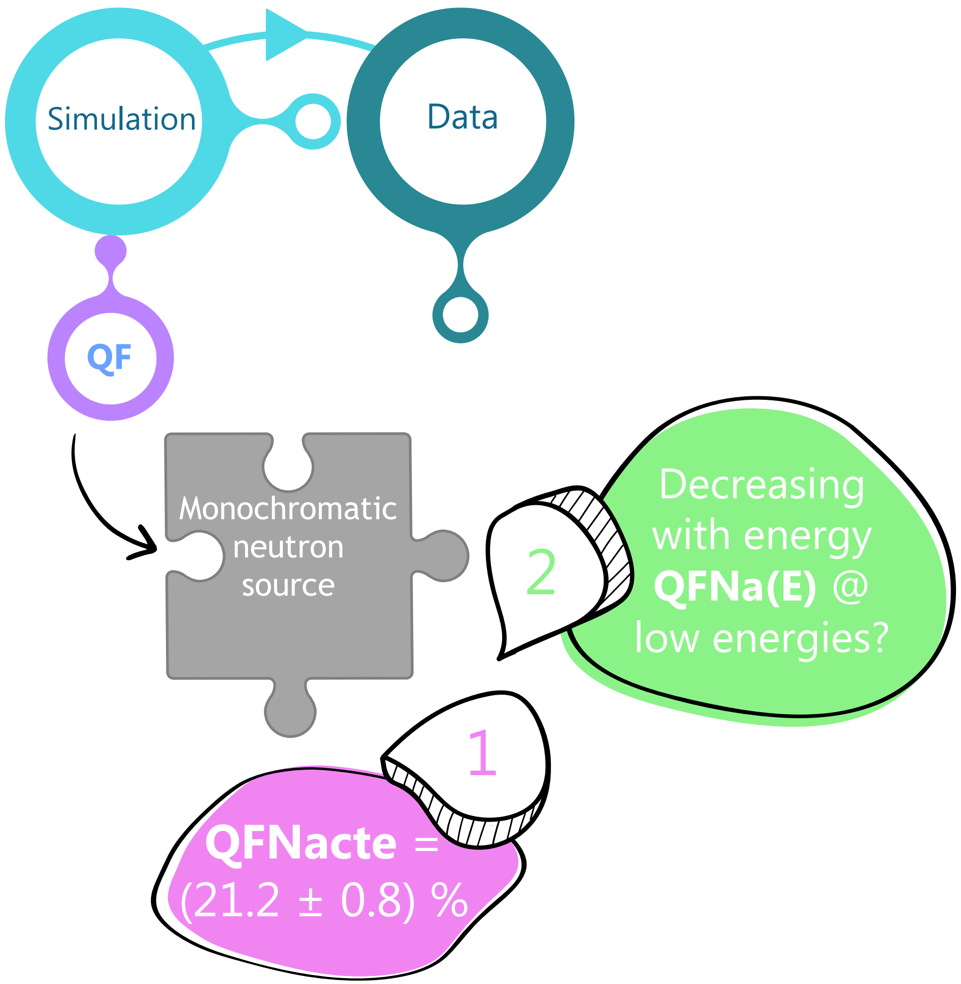


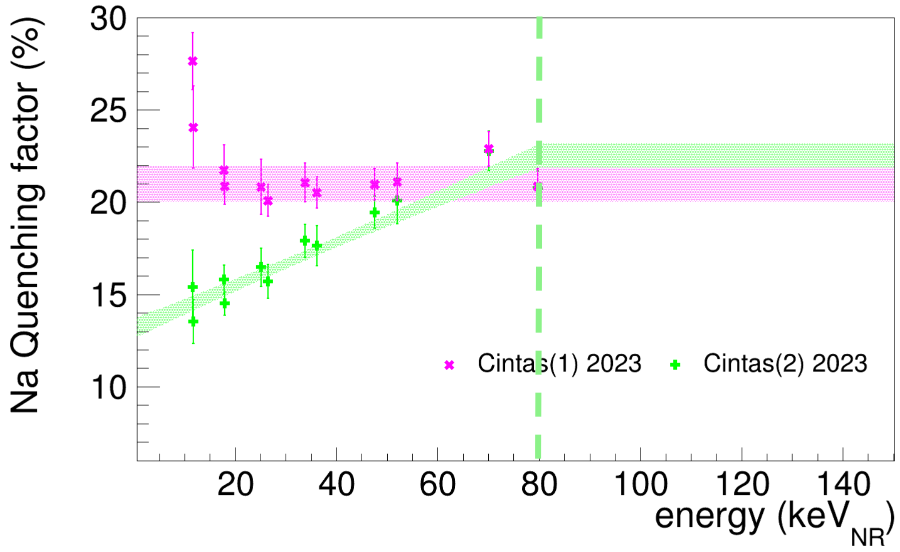
$$E_{ee} = QF \times E_{NR}$$

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

Nuclear recoils are dominant up to 50 keVee

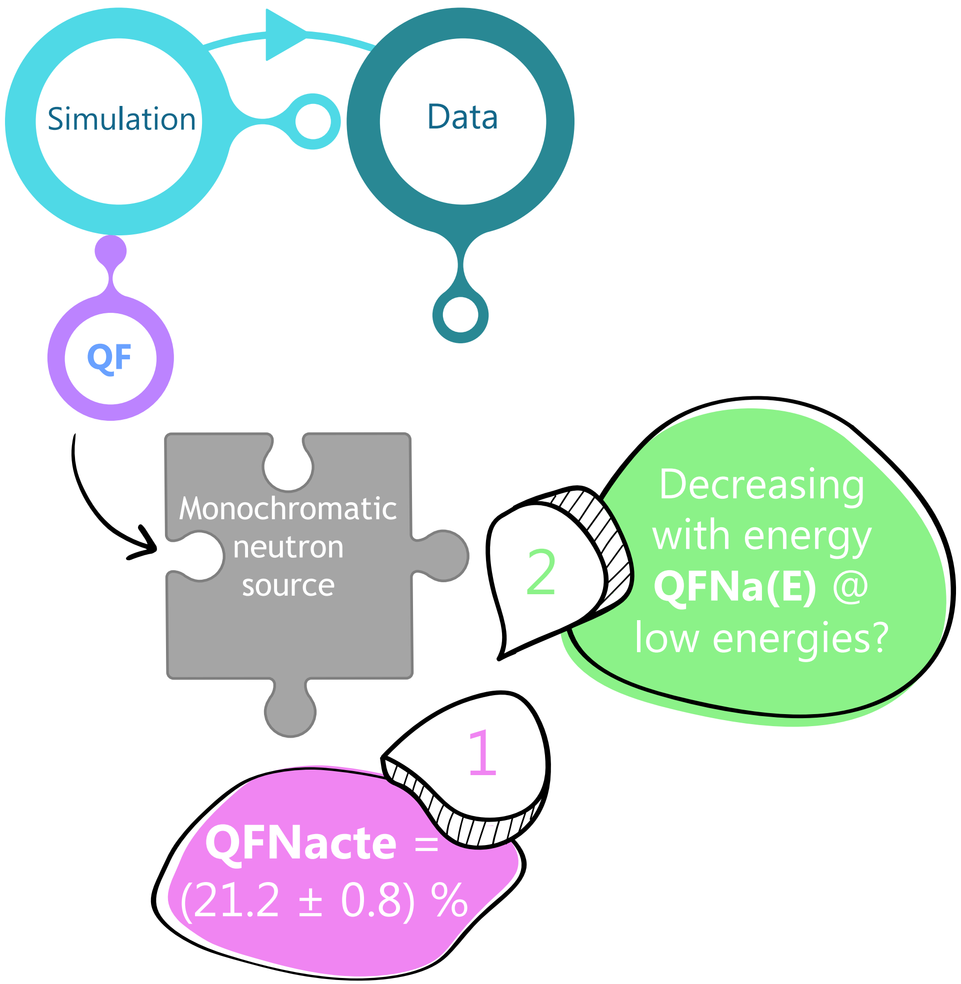
Results on the quenching factor

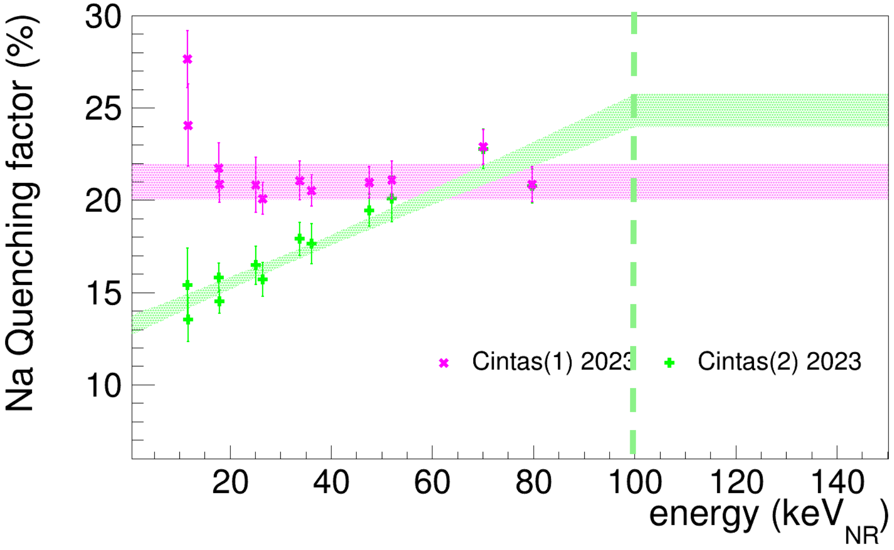




Uncertainty in QFNa(E) modelling

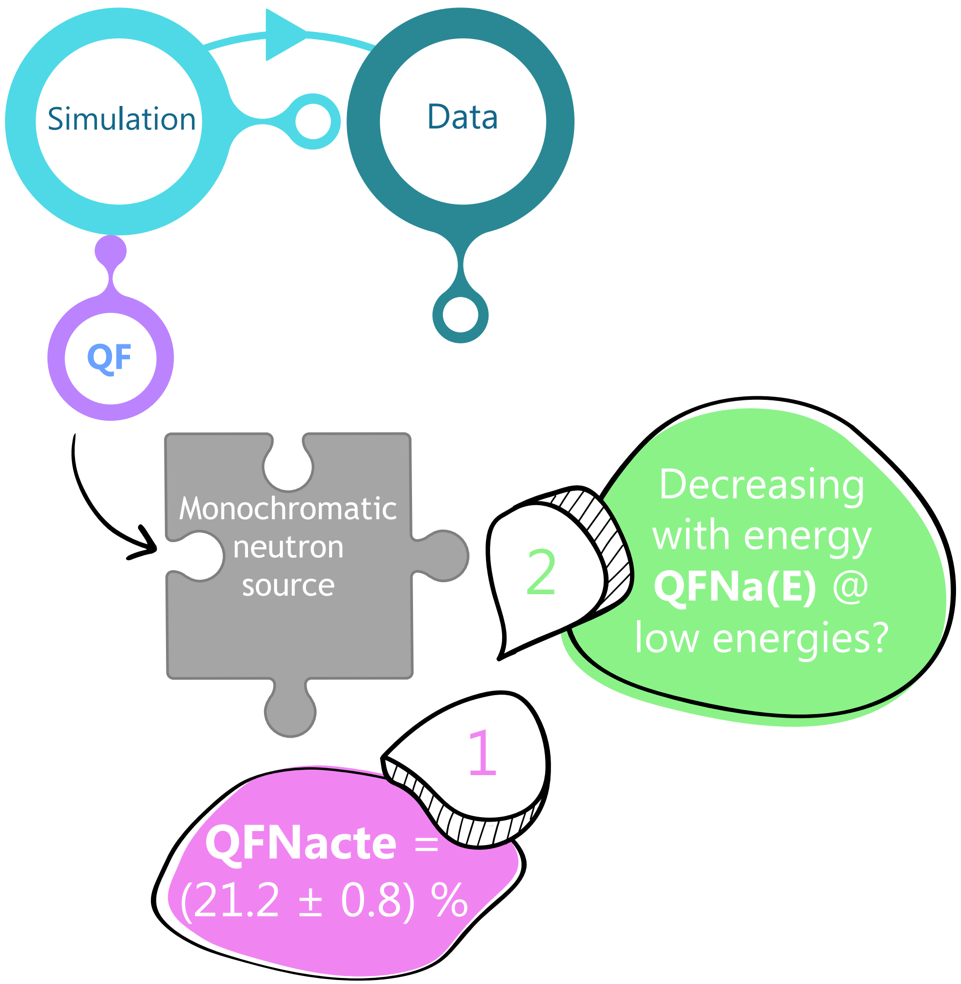
Results on the quenching factor

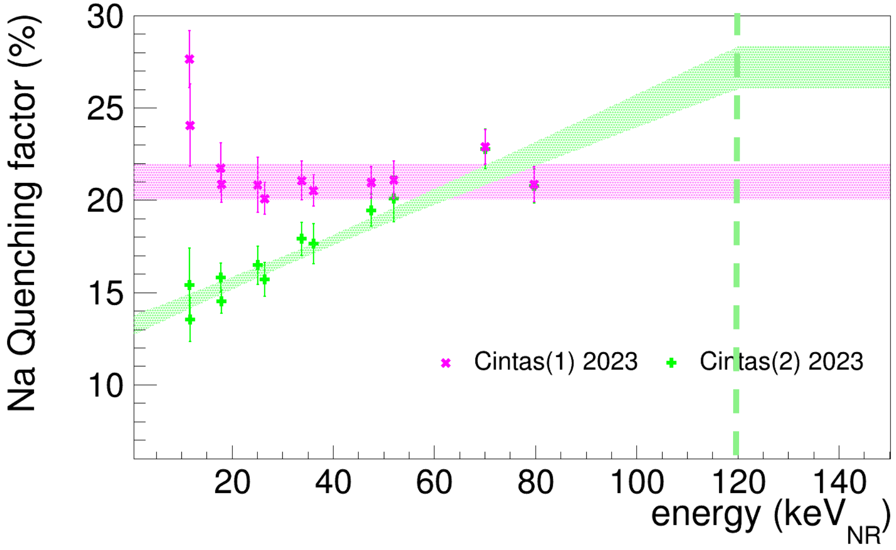




Uncertainty in QFNa(E) modelling

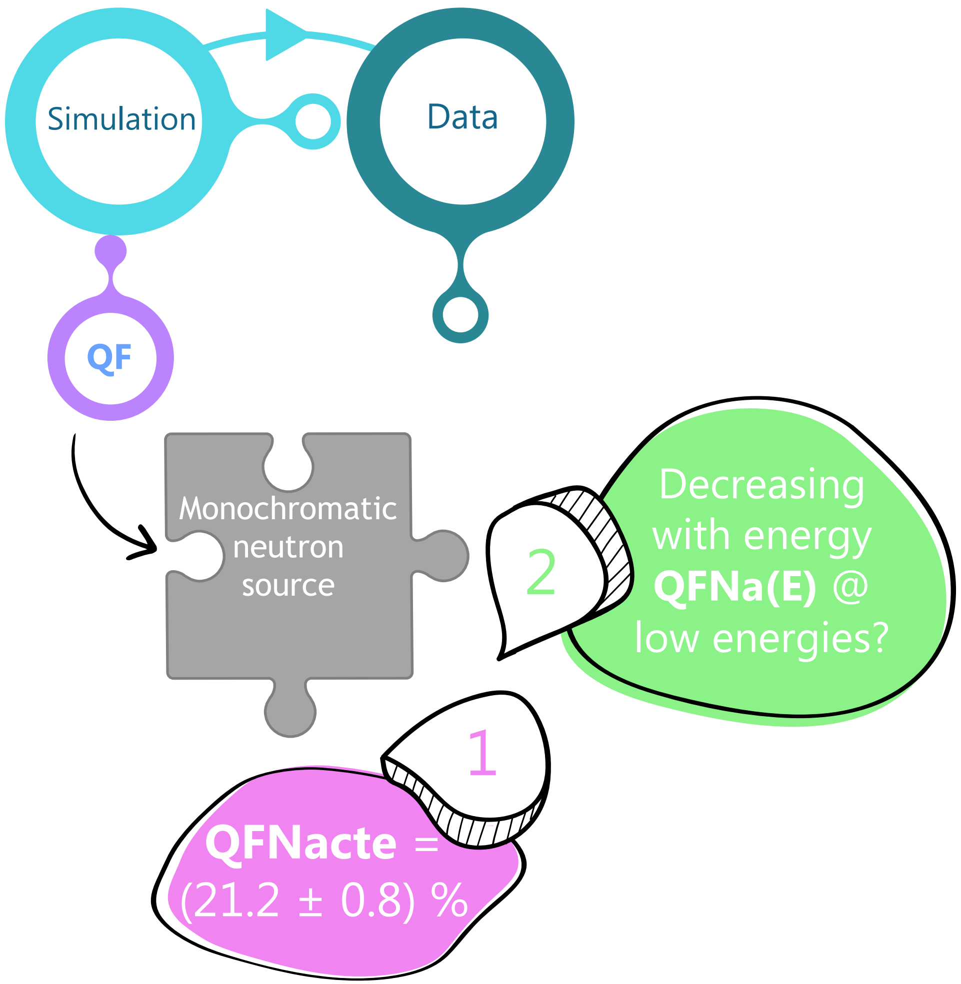
Results on the quenching factor

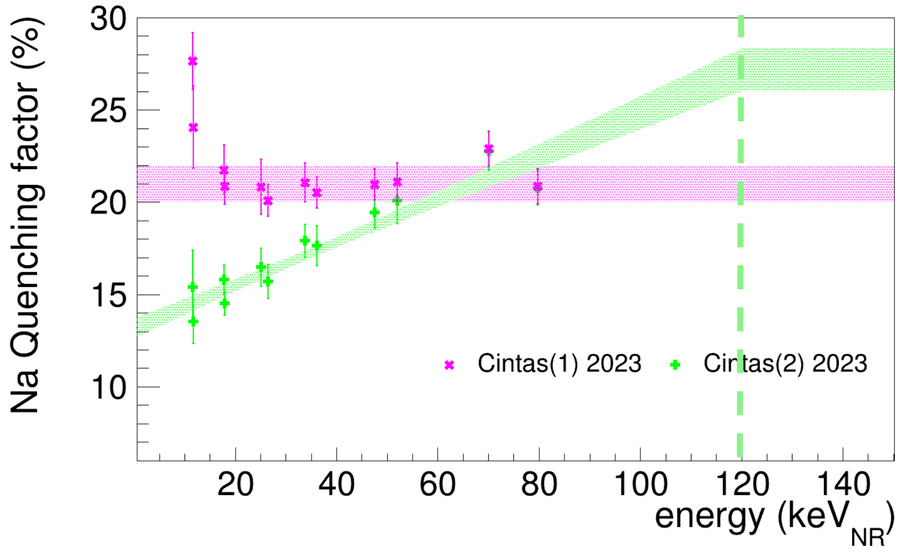




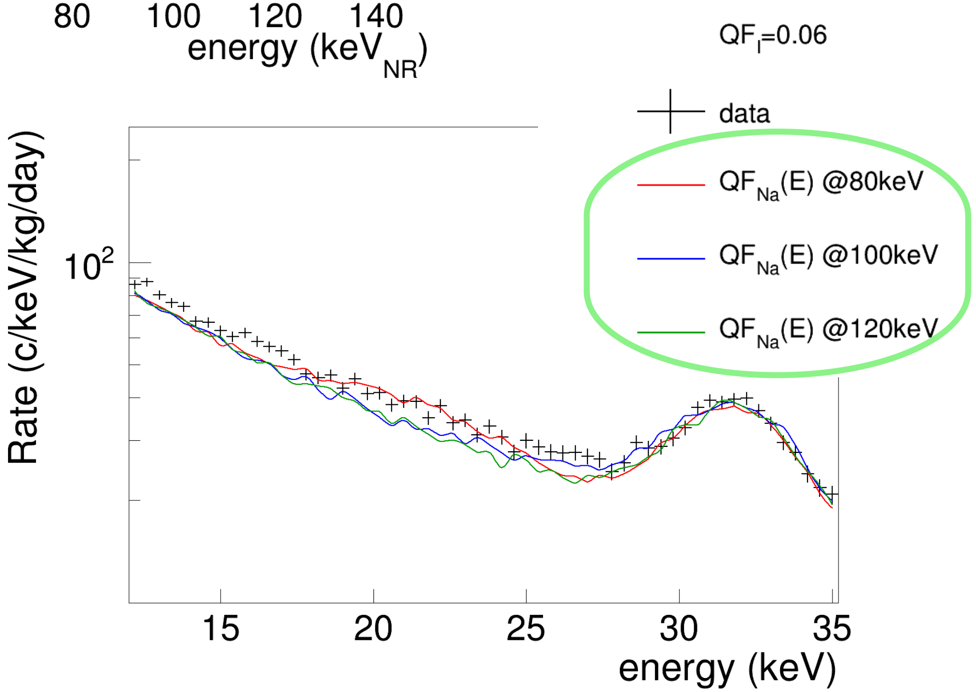
Uncertainty in QFNa(E) modelling

Results on the quenching factor

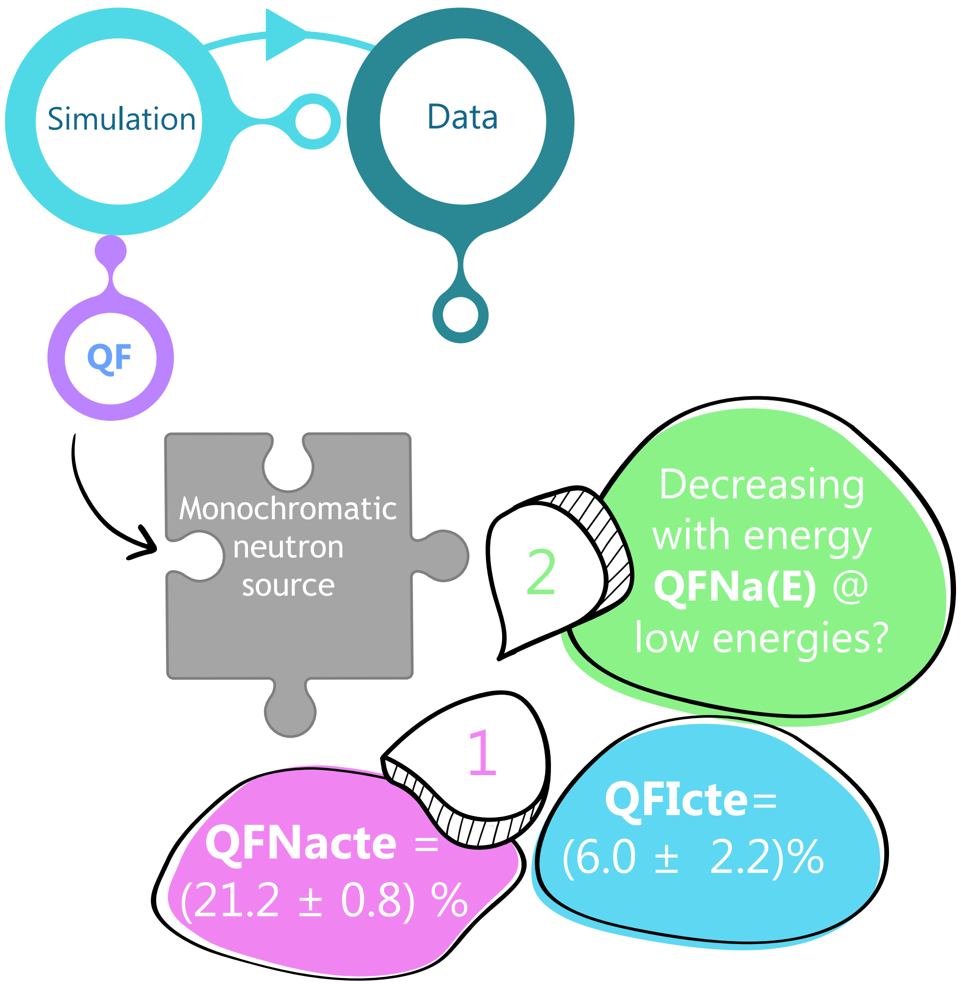


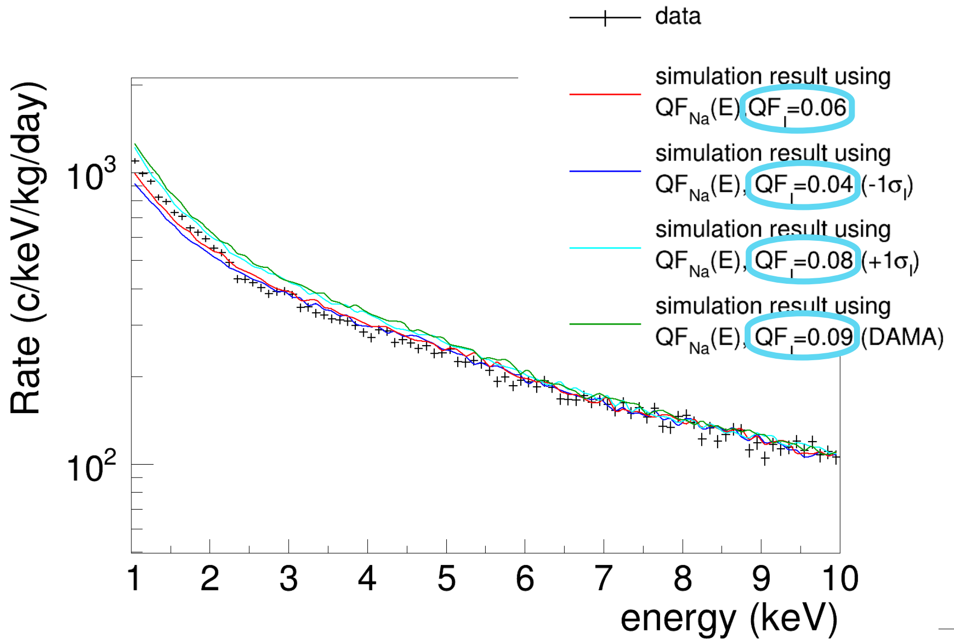


Uncertainty in QFNa(E) modelling

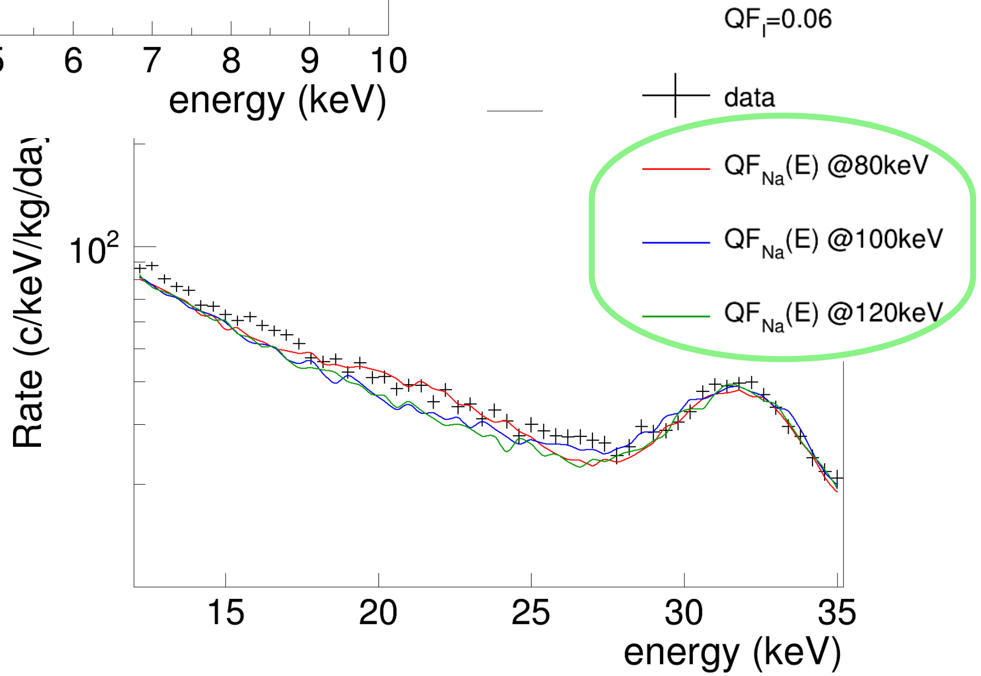


Results on the quenching factor





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

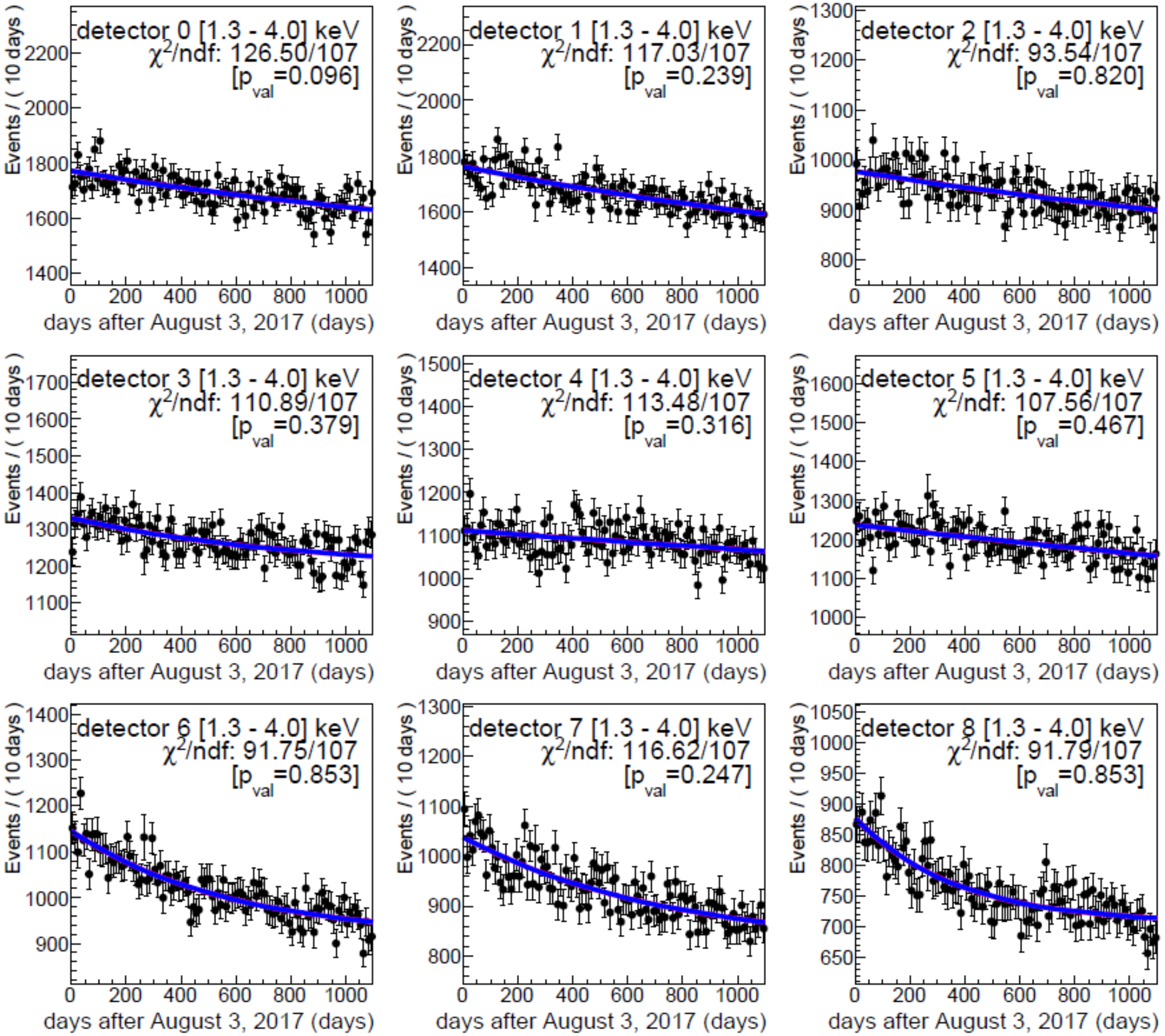


3-year annual modulation analysis in 1.3 – 4 keV

Null hyp χ^2/ndf: 968.31/963 [p_{val}=0.446]

Mod hyp χ^2/ndf: 968.16/962 [p_{val}=0.438]

S_m = (-0.0019 ± 0.0050) (cpd/kg/keV)



Preliminary

Supposing:

- ➔ $Q_{Na} = 0.30$ in DAMA/LIBRA
- ➔ $Q_{Na} = 0.20$ in ANAIS−112

DAMA [2 – 6] keV ⟶ ANAIS [1.3 – 4] keV

Best fit modulation amplitude $S_m = (-0.0019 \pm 0.0050)$ counts/keV/kg/day **compatible with zero** at 1σ

Best fit **incompatible with DAMA/LIBRA** at 2.4σ

Sensitivity with 3 years data: 2σ

Annual modulation with new analysis

Following PRD103(2021)102005

Focus on **model independent** analysis searching for modulation

- In order to better compare with DAMA/LIBRA results
  - use the same energy regions ([1-6] keV, [2-6] keV)
  - Fix period 1 year and phase to June 2nd
- Simultaneous fit of the 9 detectors in 10-day bins. Chi-square minimization: $\chi^2 = \sum_i (n_i - \mu_i)^2/\sigma_i^2$, where the expected number of events μ_i for detector d in time bin i is given by:

$$\mu_{i,d} = \left[R_{0,d}\left(1 + f_d \phi^{MC}_{bkg,d}(t_i)\right) + \boldsymbol{S_m} \cos\left(\omega(t_i - t_0)\right)\right] M_d \Delta E \Delta t$$

Annual modulation with new analysis

Following
PRD103(2021)102005

Focus on **model independent** analysis searching for modulation

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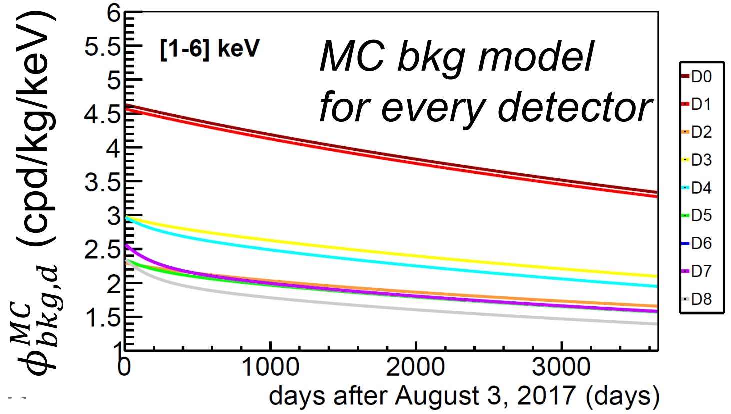
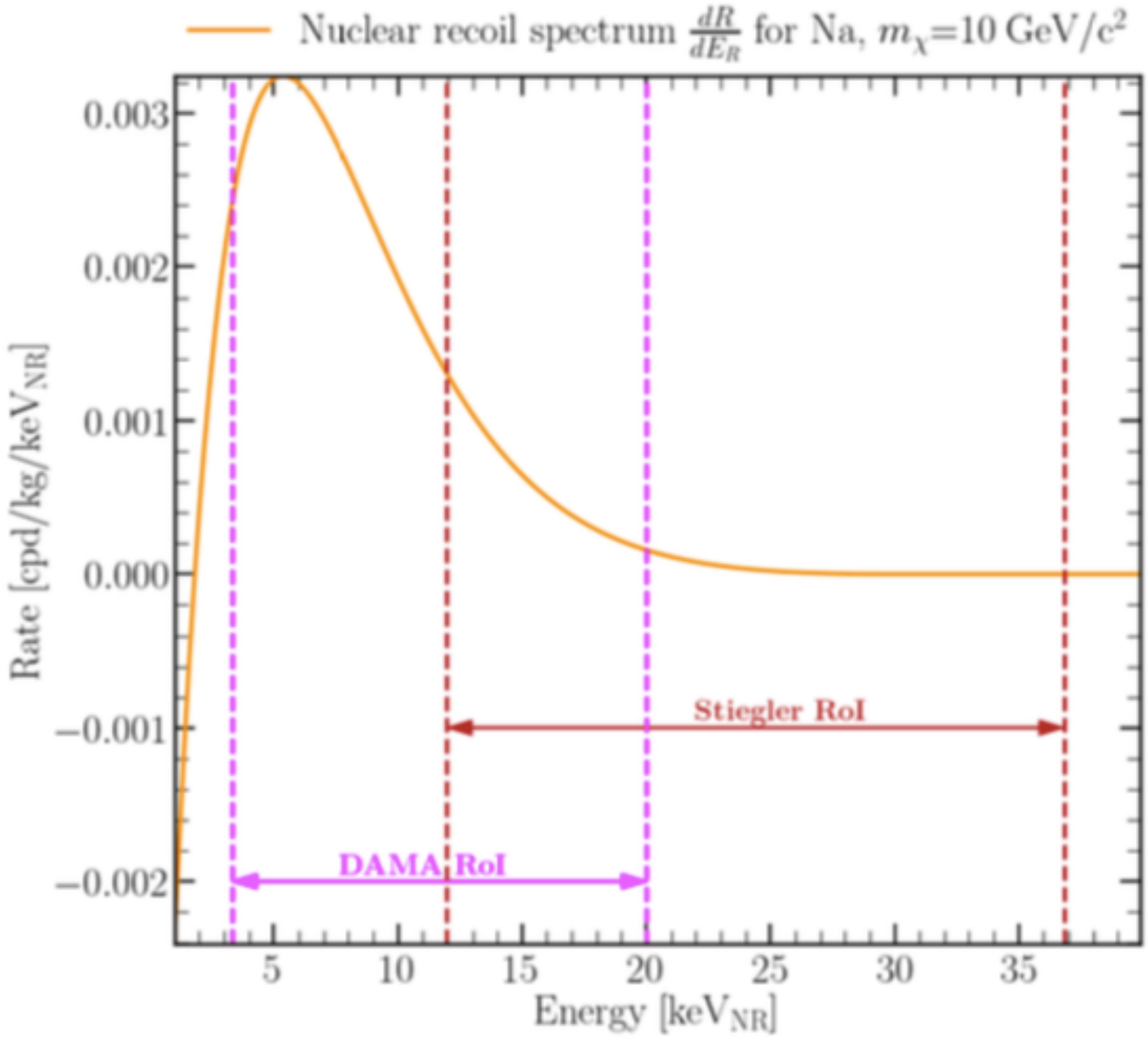
Constant background (long-lived isotopes and residual noise)

Decaying background, modeled by MC

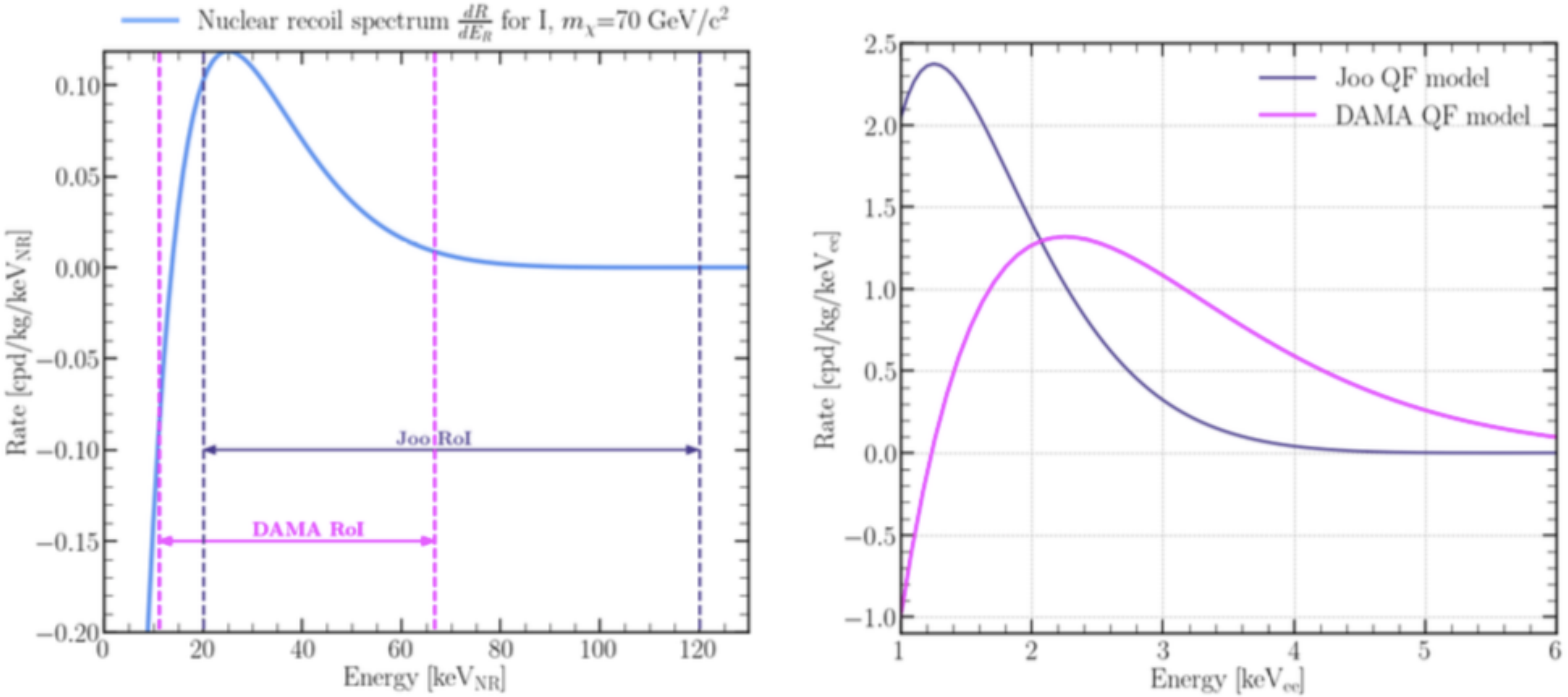
Modulation signal (fixed period and phase)

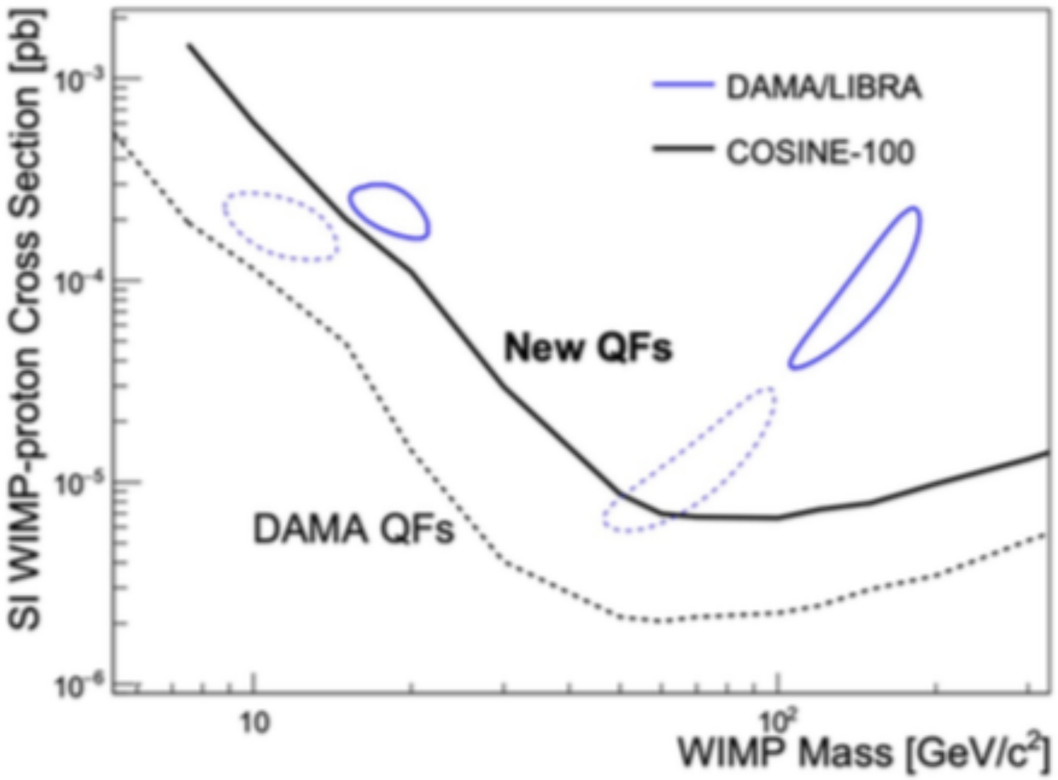


19 free parameters: $R_{0,d}, f_d, S_m$

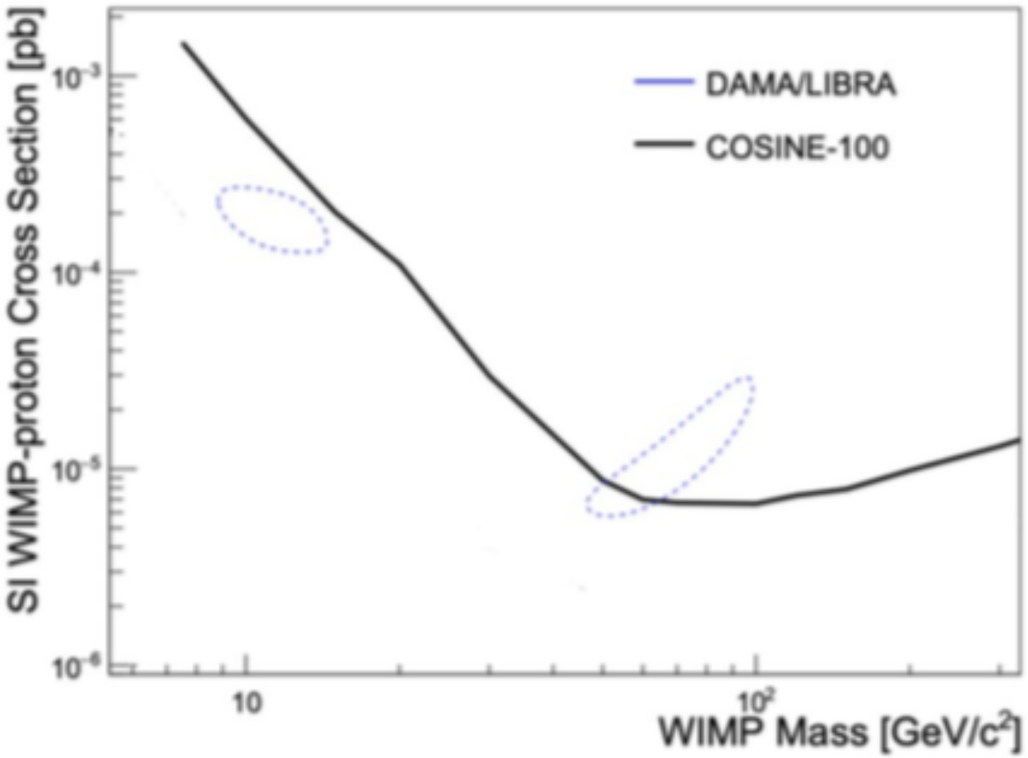


Nuclear recoil spectrum $\frac{dR}{dE_R}$ for Na, m_χ=10 GeV/c^2
Rate [cpd/kg/keV$_{NR}$]
0.003
0.002
0.001
0.000
−0.001
−0.002
Stiegler RoI
DAMA RoI
5
10
15
20
25
30
35
Energy [keV$_{NR}$]


Nuclear recoil spectrum $\frac{dR}{dE_R}$ for I, m_χ=70 GeV/c^2
Joo RoI
DAMA RoI
Rate [cpd/kg/keV$_{NR}$]
Energy [keV$_{NR}$]
Joo QF model
DAMA QF model
Rate [cpd/kg/keV$_{ee}$]
Energy [keV$_{ee}$]



Assuming detectors have the same QF
(either the solid or dotted lines)



Assuming detectors have different QFs