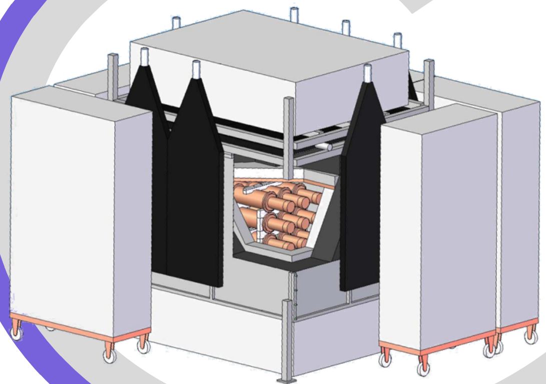
ANAIS–112: updated results on annual modulation with three-year exposure and future prospects

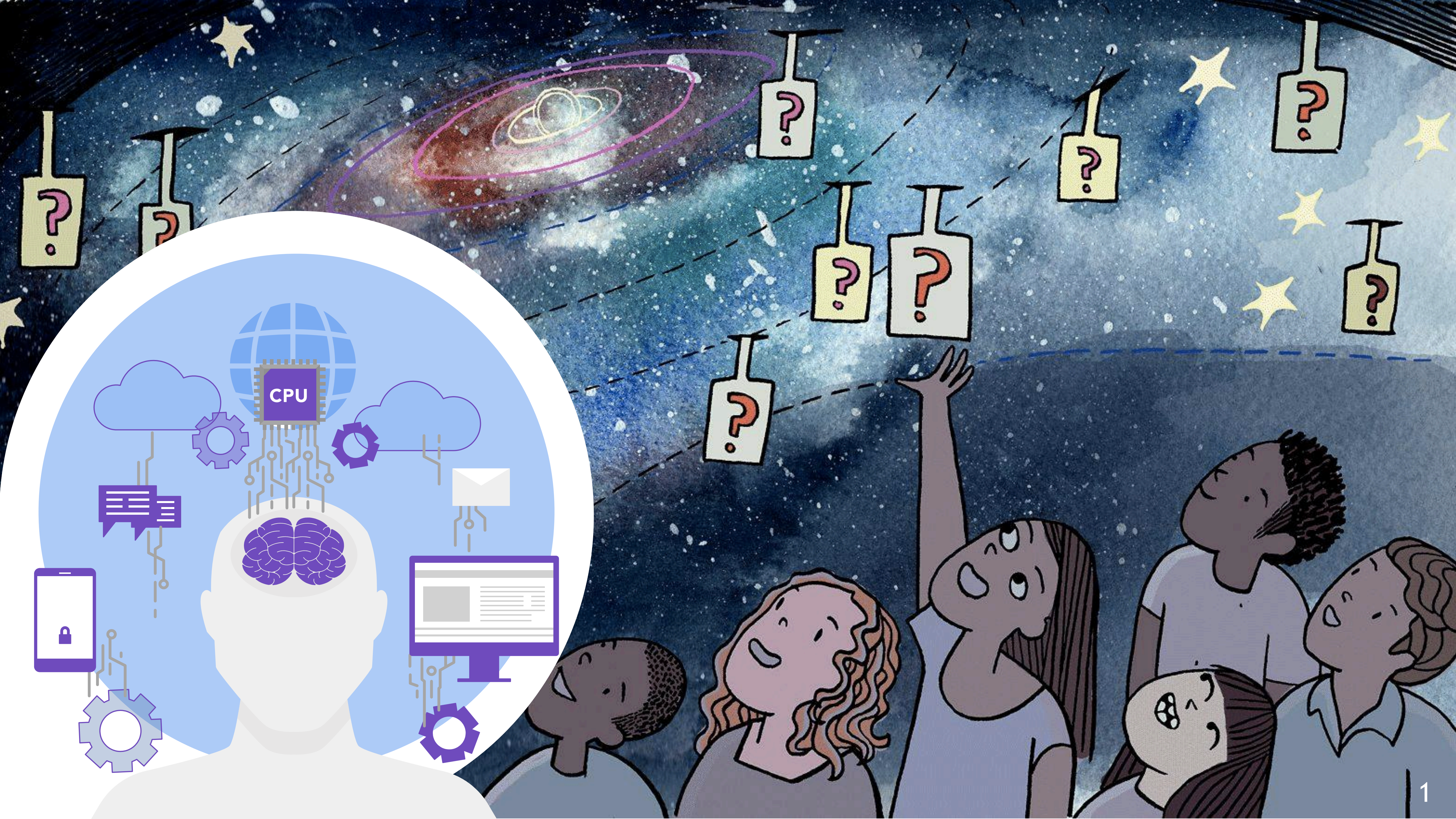


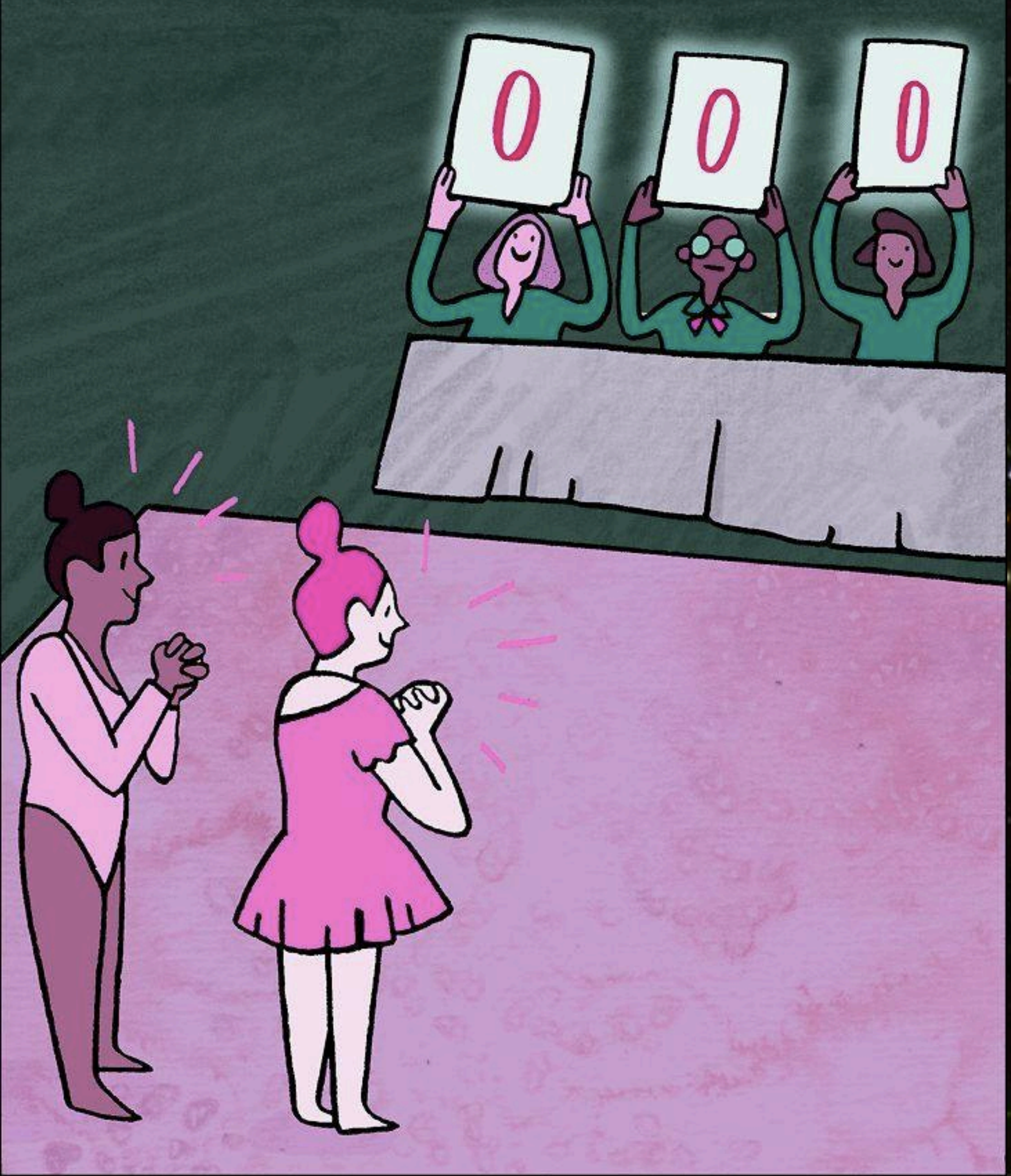
Tamara Pardo on behalf of the ANAIS research team

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

Saturnalia 2023 Workshop, Zaragoza
18 December-21 December 2023

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


CPU

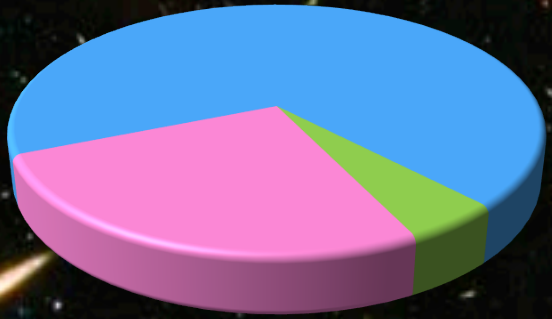


The "recipe" for our Universe

68% Dark Energy

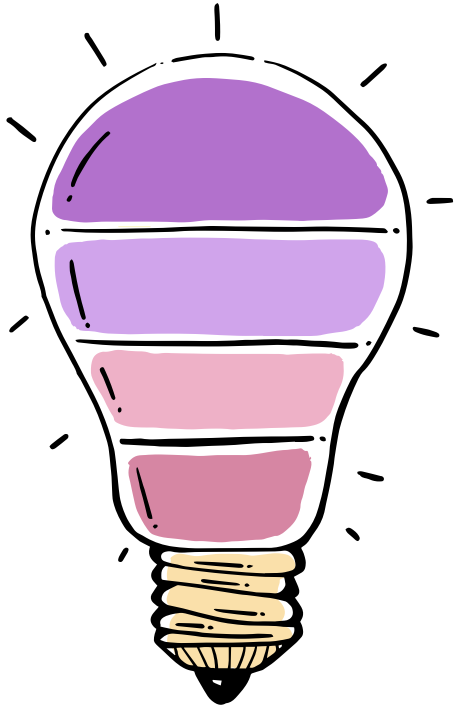
27% Dark Matter

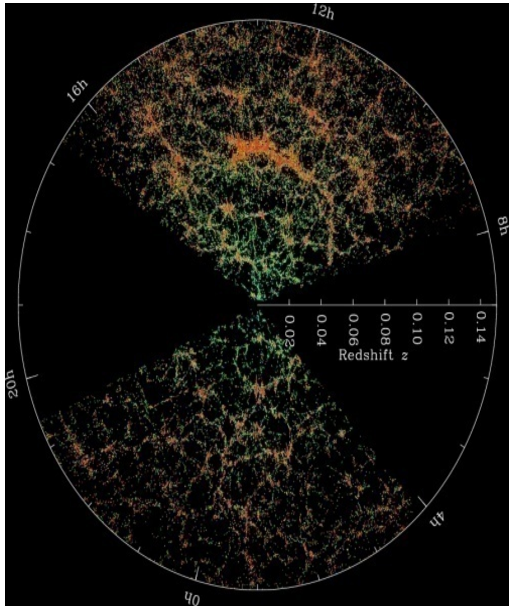
5% Ordinary Matter

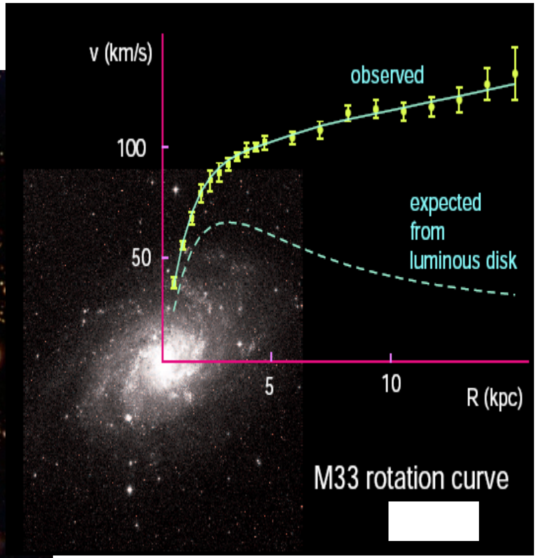


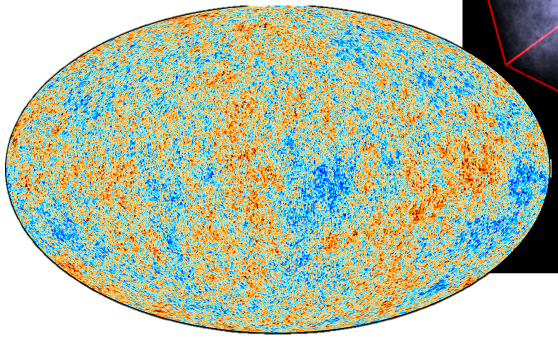
Introduction

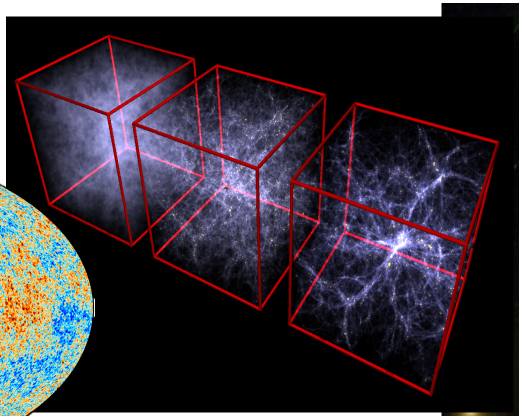
Evidences of Dark Matter come from different experimental observations at various scales and times in the history of the Universe









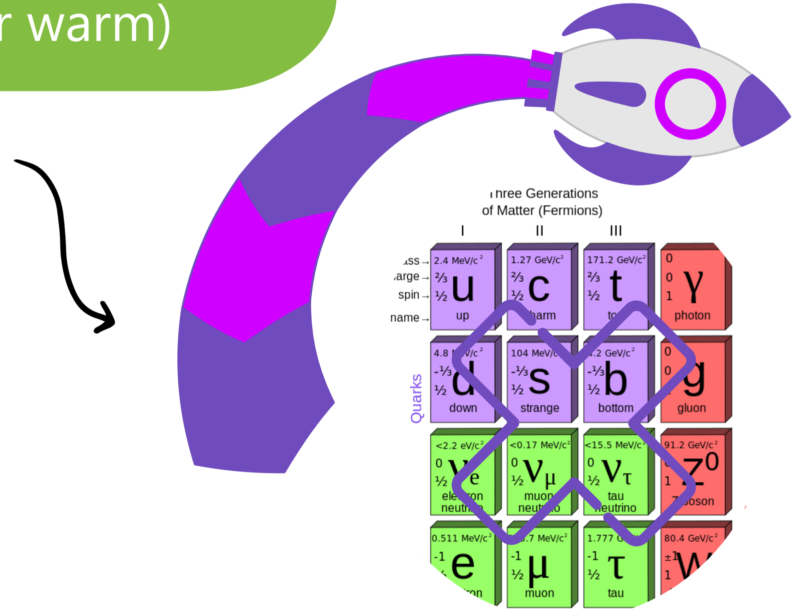


Very weakly interacting
Massive
Able to provide the relic abundance

Lifetime >> Age of the Universe

Non-relativistic (cold or warm)

Non-baryonic



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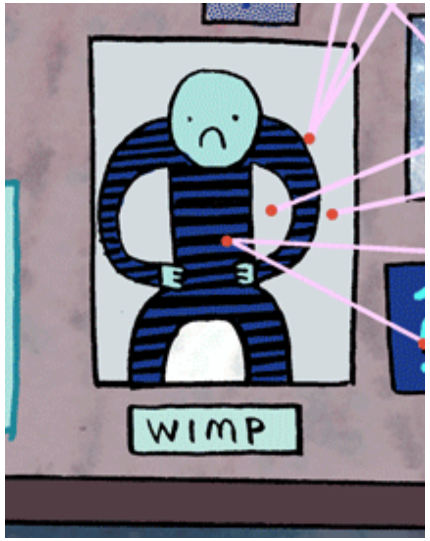
Weakly Interacting Massive Particle



Beyond many other hypothetical DM candidates…


Despite the great international effort, no experiment has found evidence of DM

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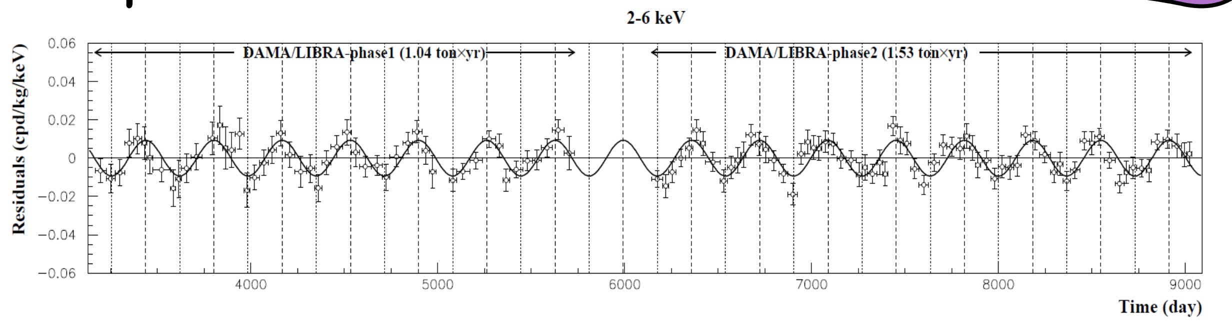
** Except for the DAMA/LIBRA experiment

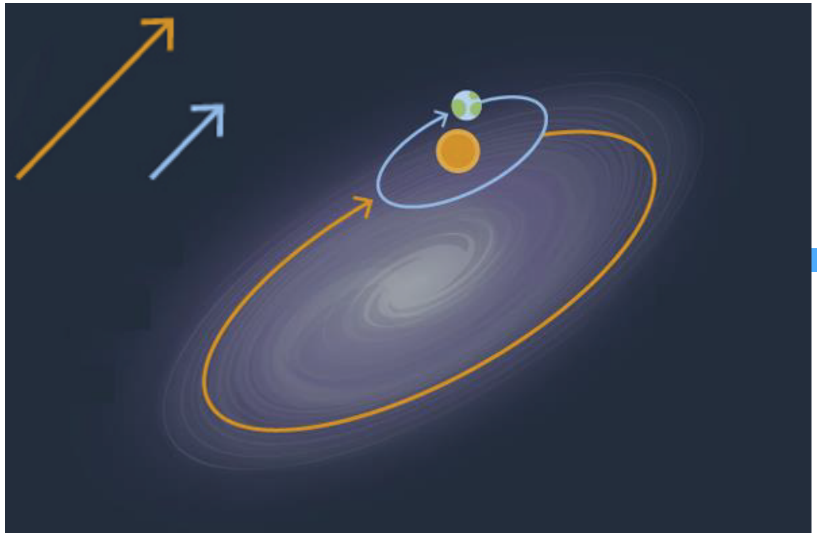
Annual modulation



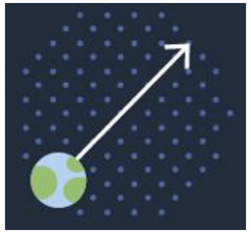
Introduction

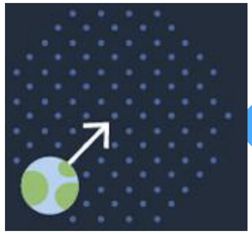
Annual modulation

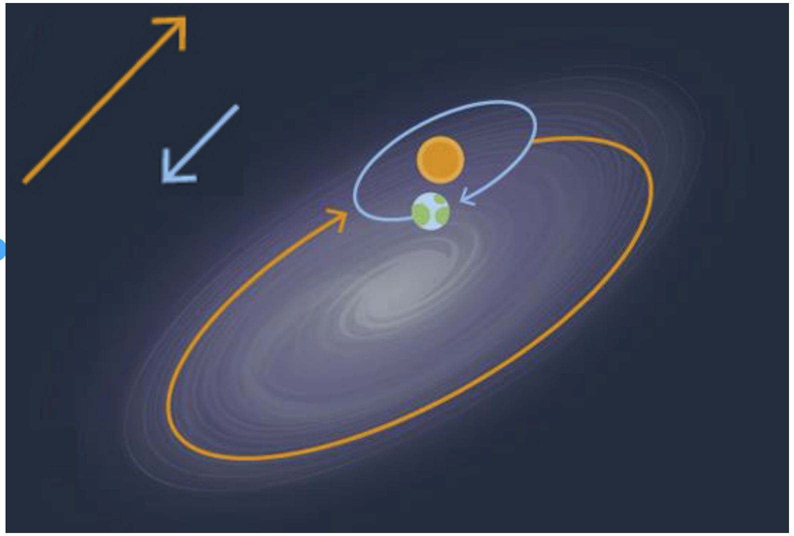
Due to the rotation of the Earth around the Sun, the speed of DM particles in the Milky Way's halo relative to Earth **varies seasonally**, producing an **annual modulation** in the rate of nuclear recoil events in detectors



$v_{\text{Earth-Halo}}$







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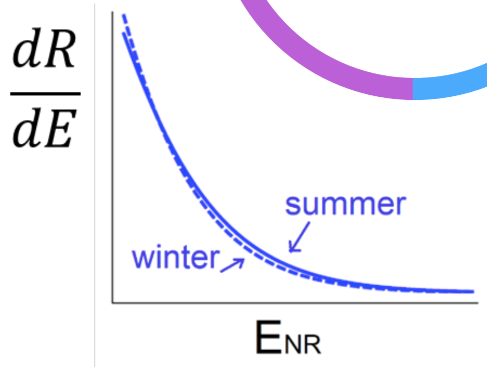
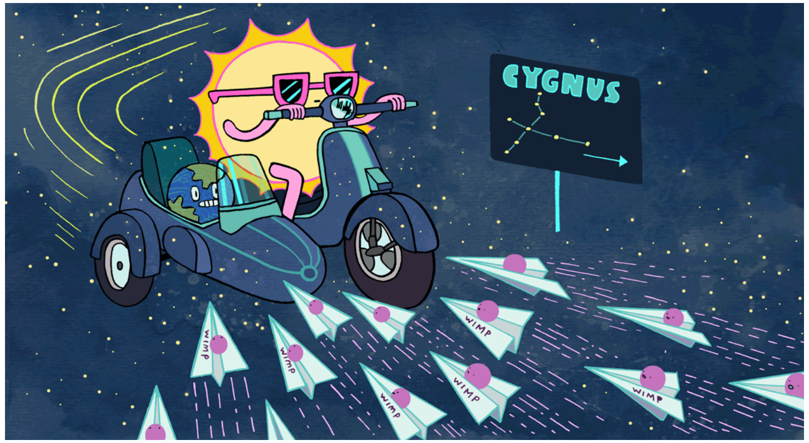
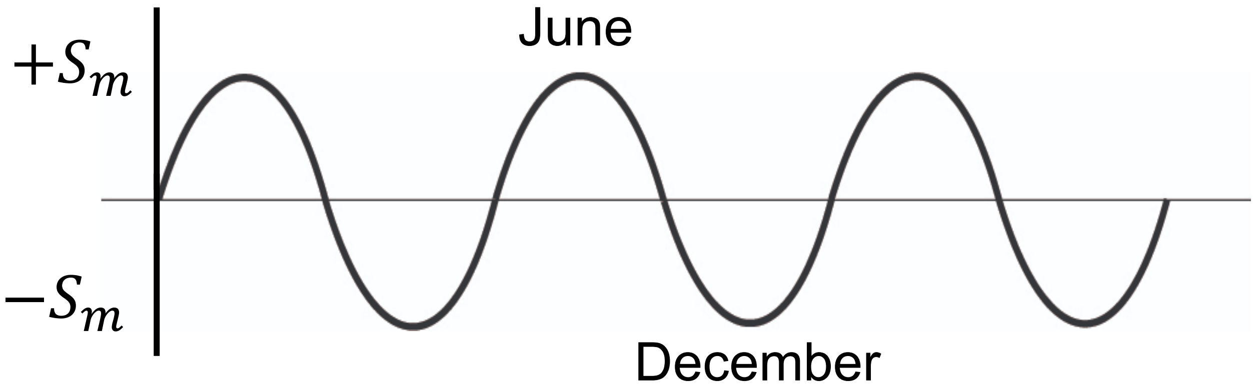




Detection rate would have a cosine behaviour with a yearly period and maximum around June 2nd

Only at low energy

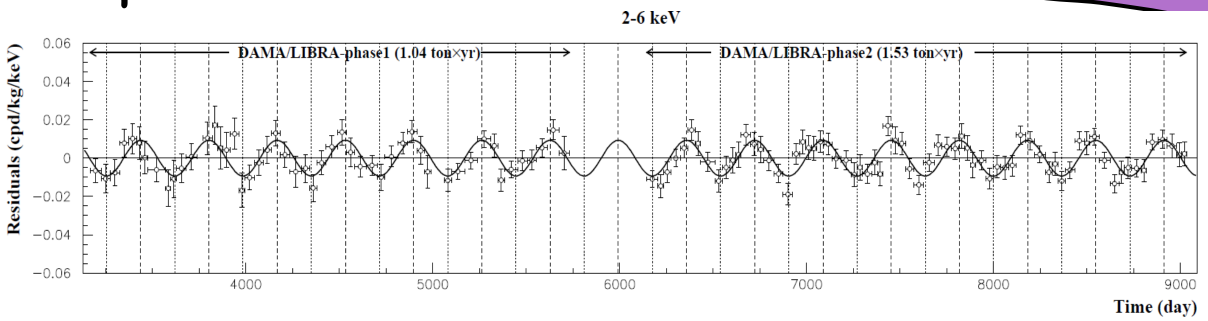
Single-hit events



** Except for the DAMA/LIBRA experiment

Annual modulation

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



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

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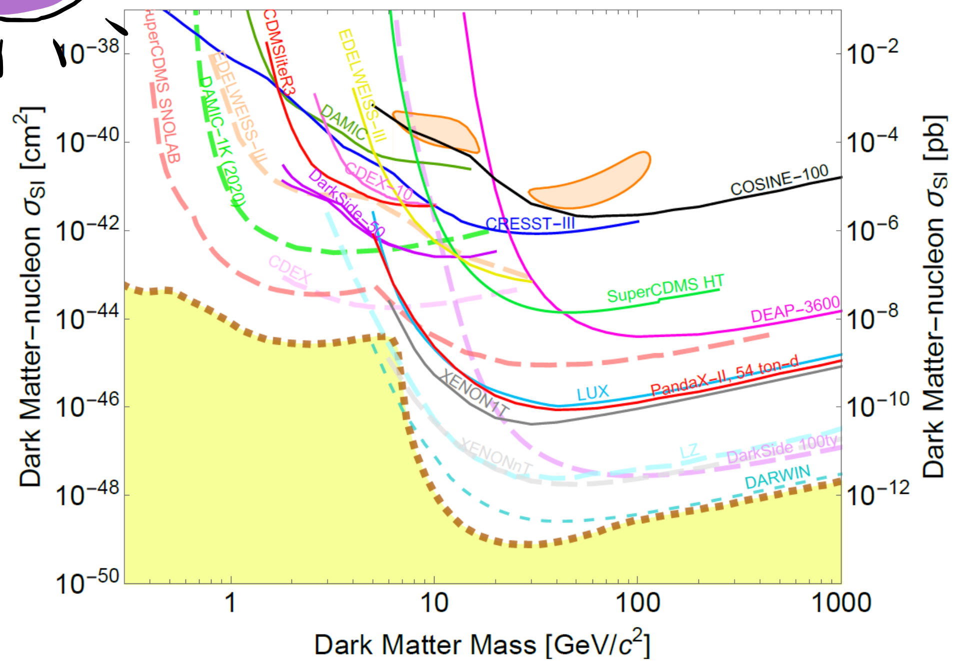

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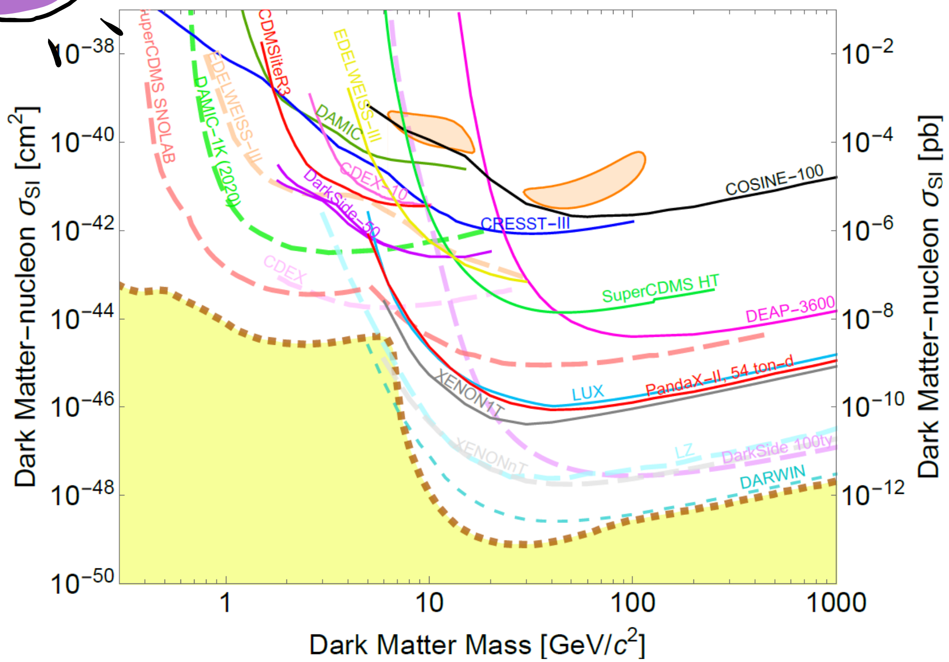

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NEED TO TEST THE DAMA/LIBRA POSITIVE SIGNAL WITH THE SAME TARGET (NaI)

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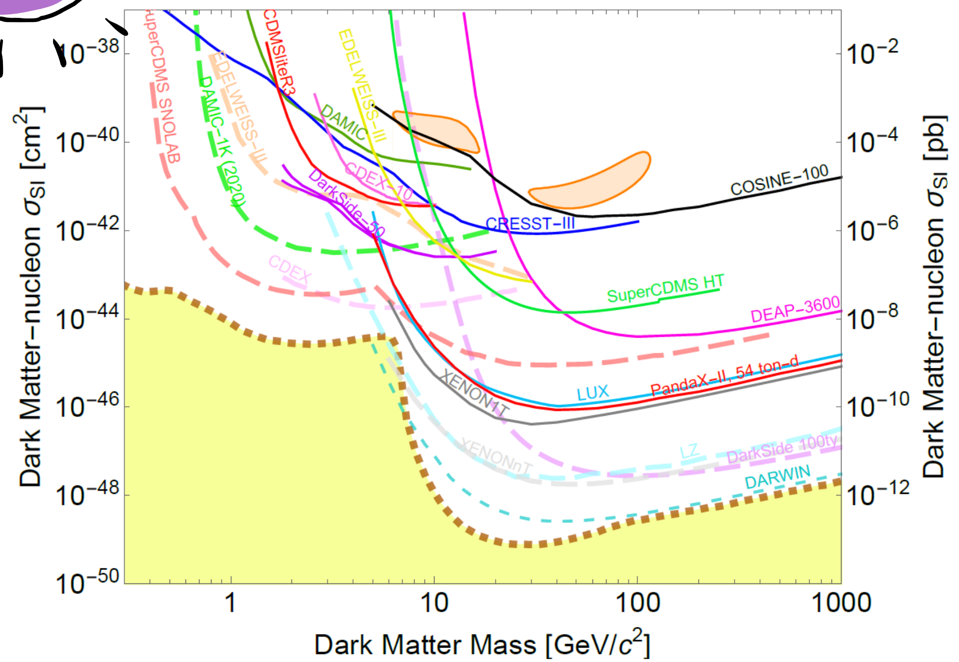

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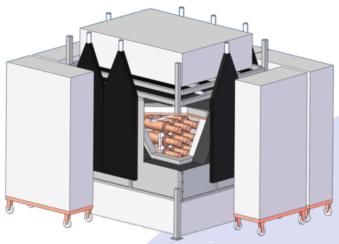
The ANAIS-112 experiment



1 — GOAL

Experimental set-up

2 — Low-energy calibration

Data-taking overview

3 — 3-year annual modulation results

4 — Event selection

5 — 3-year annual modulation with machine learning techniques

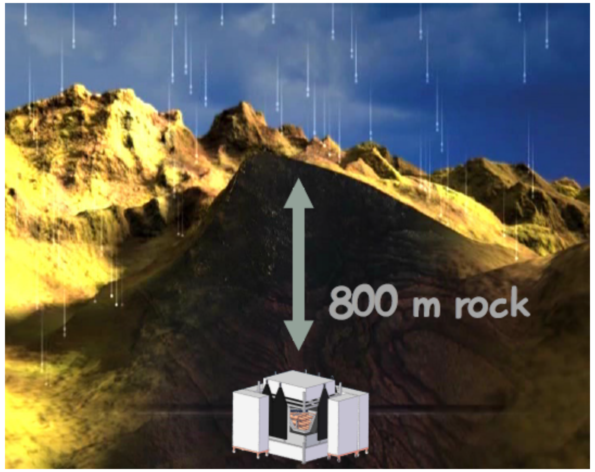
6 — Neutron calibration program → ¿Quenching factor?

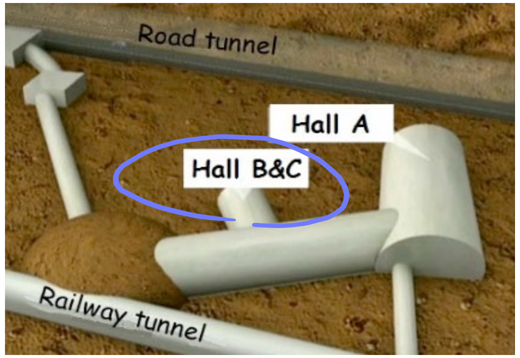
7 — ANAIS+

The ANAIS-112 experiment

1

ANAIS' goal (*Annual Modulation with NaI Scintillators*) 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





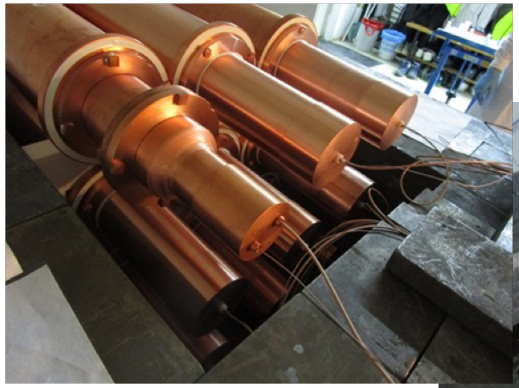
At **Canfranc Underground Laboratory**, @ SPAIN (2450 m.w.e.)

- → Energy **threshold** at 1 keV_{ee}
- → **Background** level below 10 keV_{ee} at a few $cpd/kg/keV_{ee}$
- → Very **stable** operation conditions
- → Large **exposure**

The ANAIS-112 experiment

1 Experimental set-up

- 9 ultrapure NaI(Tl) cylindrical crystals 12.5 kg (**112.5 kg of active mass**)
- Coupled to 2 Hamamatsu PMTs with high QE (~40%)
- Encapsulated in OFE copper
- Mylar window allows external calibration
- Outstanding light collection of ~15 phe/keV
- 30 cm lead
- Tight box preventing Radon entrance
- 40 cm PE/water
- 16 plastic scintillators acting as muon veto system



2 Low-energy calibration

➔ We explore same energy regions than DAMA/LIBRA for better comparison: [1-6] keVee & [2-6] keVee

(*) keVee: electron-equivalent keV

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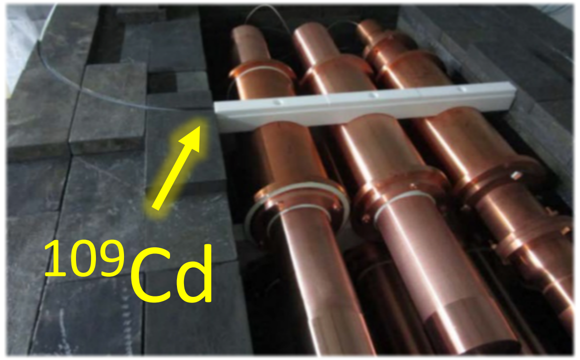
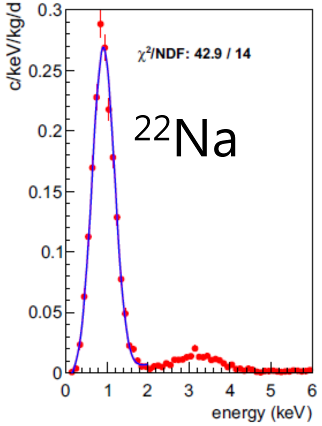
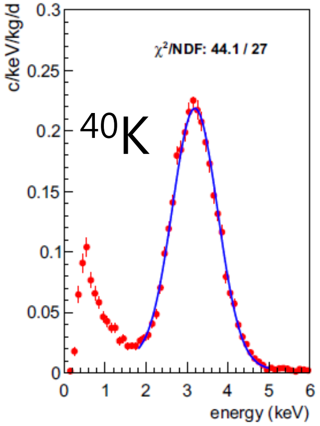
- ➔ We explore same energy regions than DAMA/LIBRA for better comparison: [1-6] keVee & [2-6] keVee
- ➔ Current ANAIS-112 ROI calibration (1-6 keVee) relies on electron recoils populations
    - ➔ Periodical external calibration using ^{109}Cd (11.9, 22.6 and 88.0 keVee)
    - ➔ Internal bulk contaminants ^{22}Na (0.9 keVee) and ^{40}K (3.2 keVee) using whole statistics







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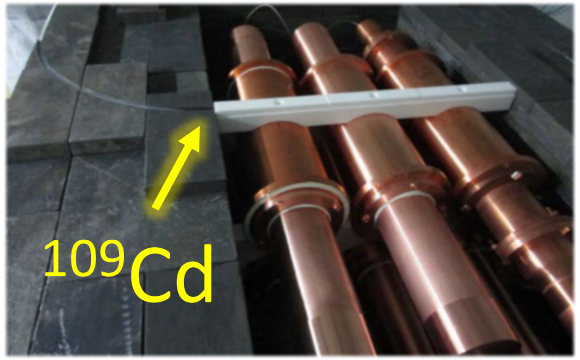
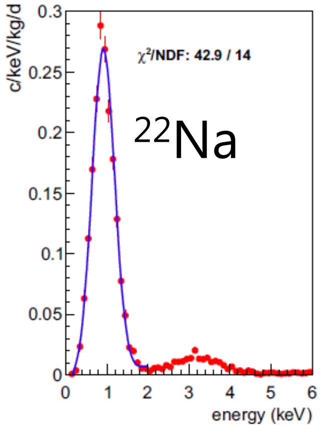
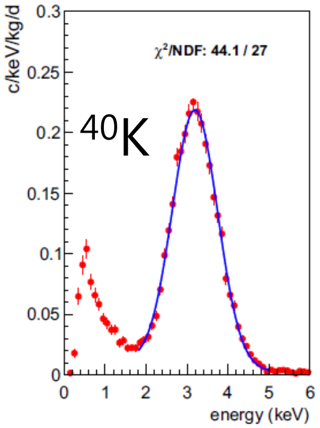
ANAIS & DAMA are calibrated with gamma sources -> direct comparison in **keVee(*)**







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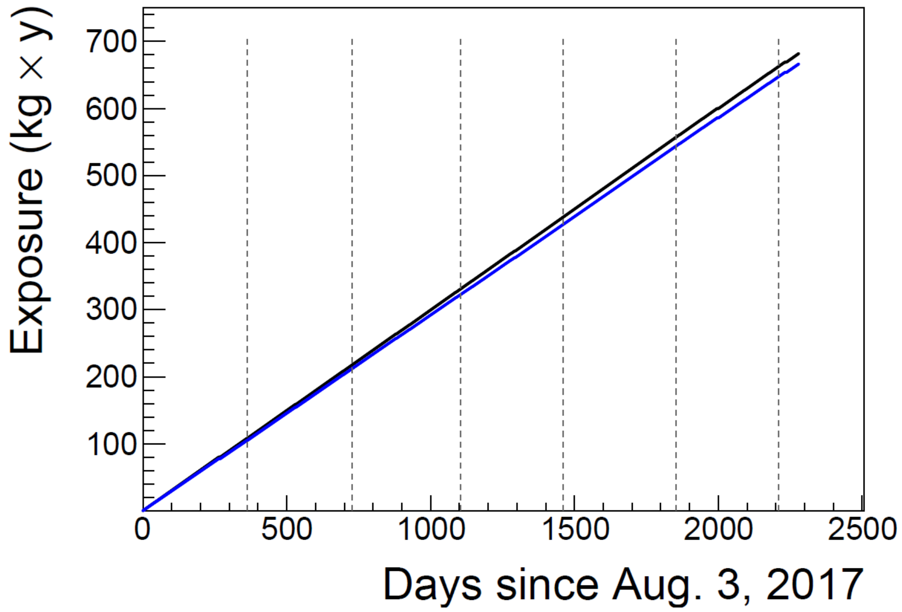
The ANAIS-112 experiment

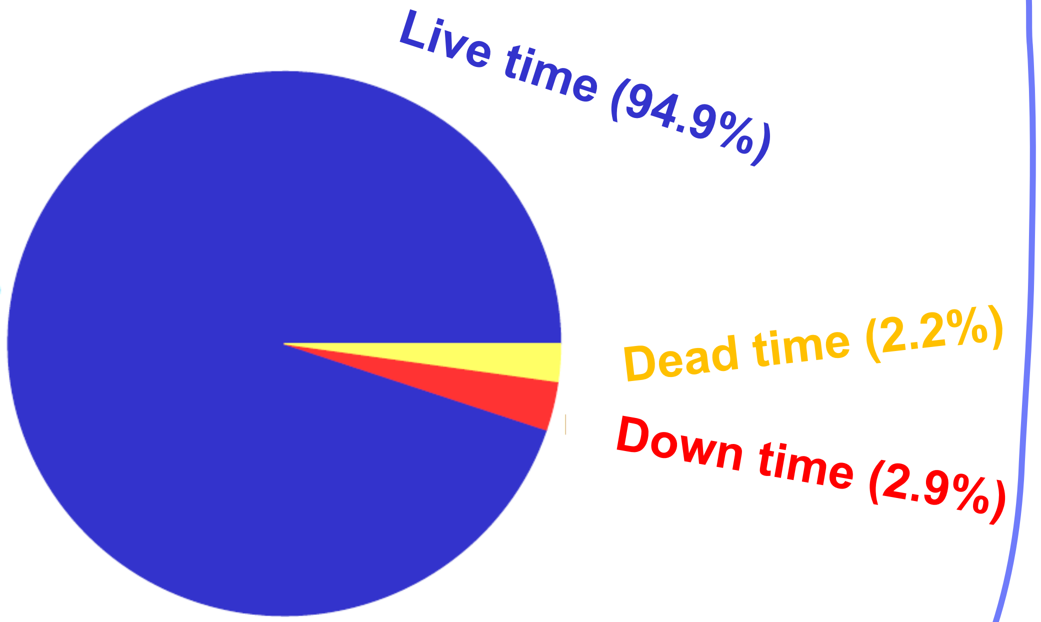
2 Data-taking overview

➔ The ANAIS – 112 dark matter run started on **August 3, 2017**



ANAIS–112 accumulated exposure

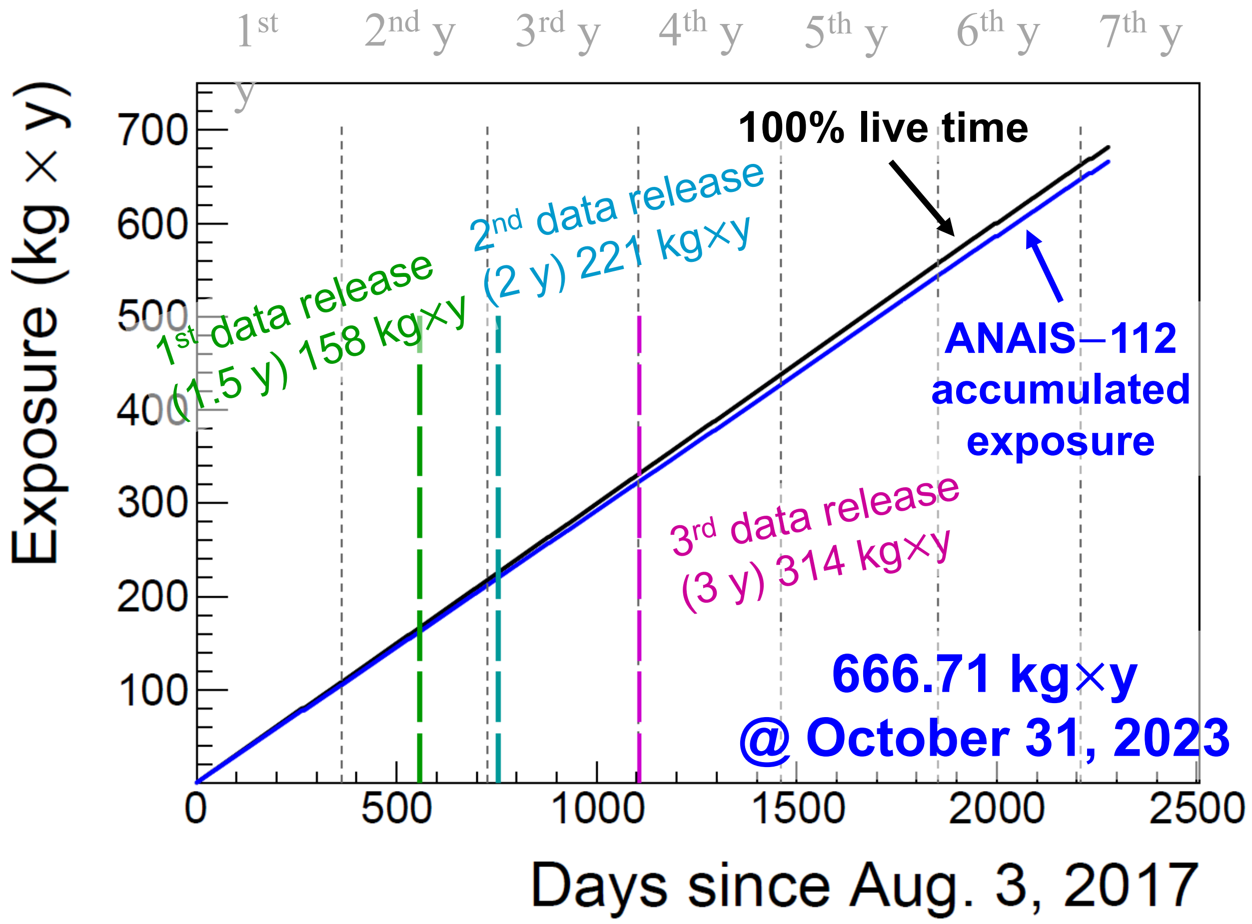
666.71 kg×y
@ October 31, 2023



➔ Six-year exposure has already been completed this August with about **95%** of live time

The ANAIS-112 experiment

3 Annual modulation results



ANAIS−112 modulation results:

- 1.5 y: Phys. Rev. Lett. 123, 031301 (2019)
- 2 y: J. Phys. Conf. Ser. 1468, 012014 (2020)
- 3 y: Phys. Rev. D 103, 102005 (2021)

The ANAIS-112 experiment

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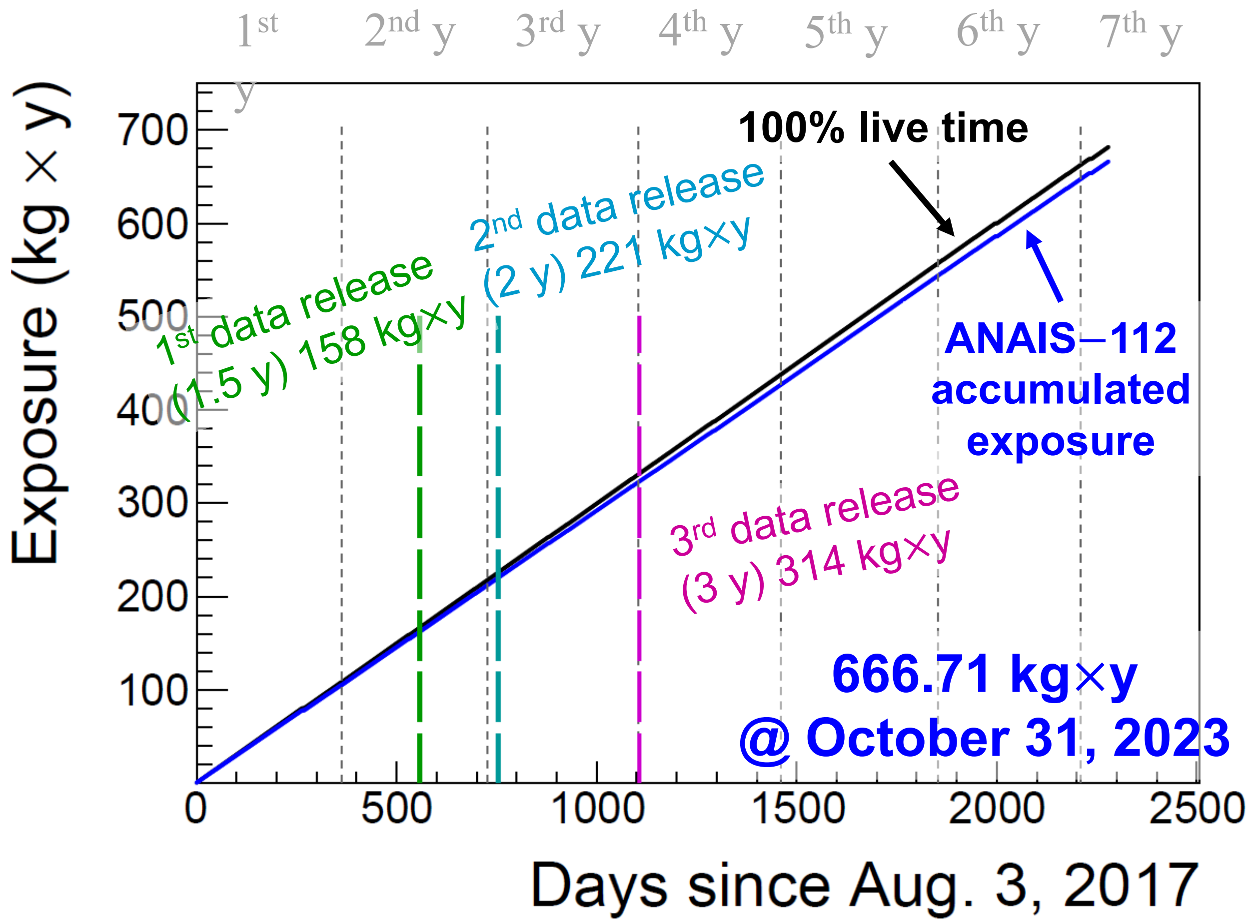

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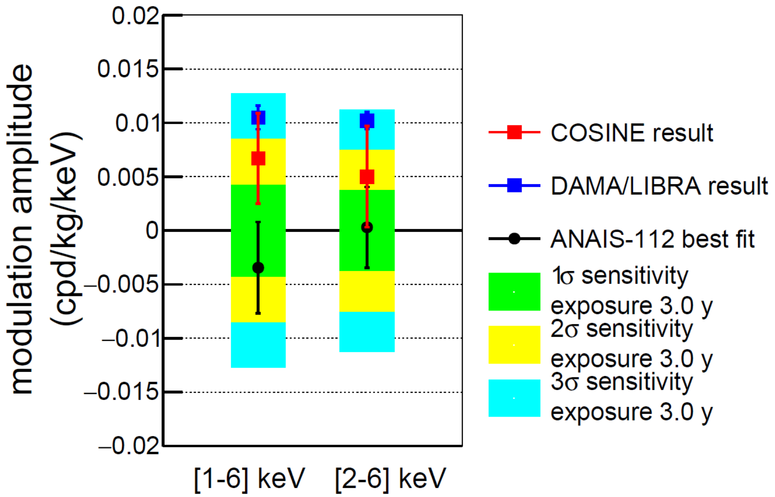
- 3 y: Phys. Rev. D 103, 102005 (2021)

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

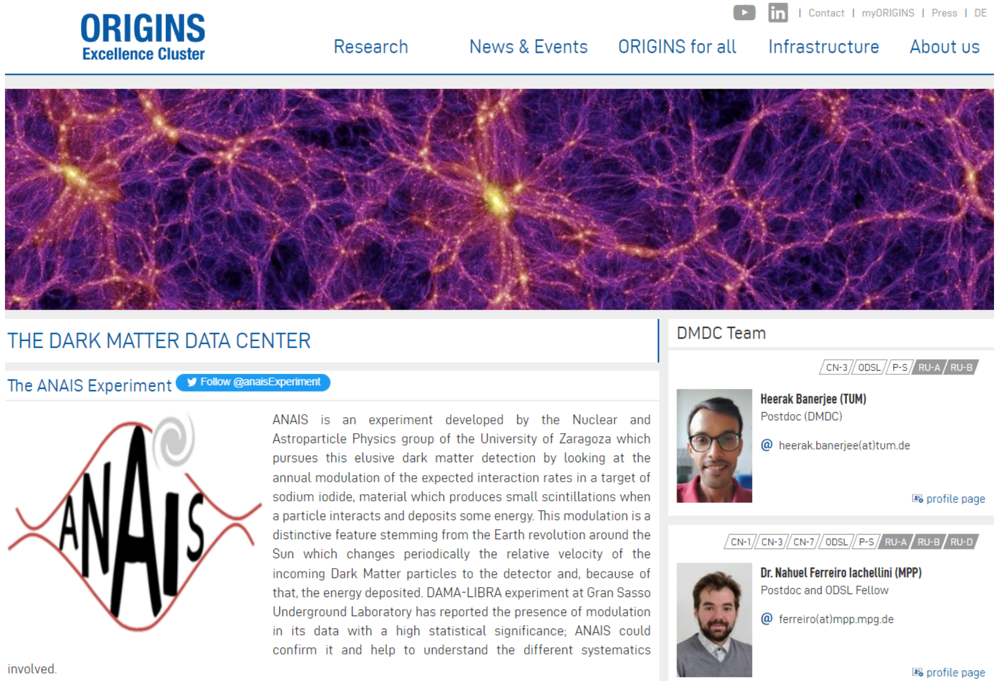


The ANAIS-112 experiment

3 Annual modulation results

➔ Thanks to the support of the **Dark Matter Data Center**, funded by the ORIGINS excellence cluster, ANAIS–112 three-year data are freely available for downloading

https://www.origins-cluster.de/odsl/dark-matter-data-center/available-datasets/anais



ANAIS-112 Three Year

Detector Module	ANAIS-112
Material	NaI(Tl)
Technology	3 × 3 Array of NaI(Tl) scintillating crystals D0-D8 using two Photo Multiplier Tubes (PMTs) each to detect scintillation light signal.
Fiducial Mass	12.5 Kg each. Total 112.5 Kg
Total Live Time	1013.83 days **Sec III of PhysRevD.103.102005 misquotes this as 1018.6 days. The last bin, bin 111, live time: 4.74 days, was not considered for the analysis in this publication.)
Threshold	1 keV (Electron equivalent energy. All energies are in keVee, aliased by keV)
Acceptance Region	1-6 keV and 2-6 keV
Average Resolution	$\sigma = (-0.008 \pm 0.001) + (0.378 \pm 0.002) \times \sqrt{E(keV)}$

ANAIS provides a JuPyter Notebook with examples of how to plot the data in these datasets and to run the RooFit macro for fitting the data.
Launch a Binder session with the notebook preloaded: launch binder

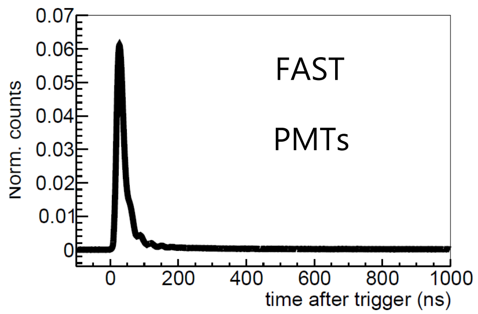
Download full repository as tar.gz: GitLab

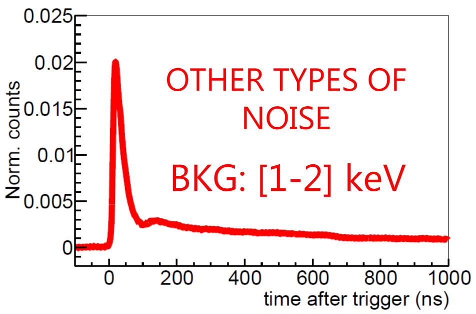
If you use this dataset, please cite:
PhysRevD.103.102005
arXiv:2103.01175 [astro-ph.IM]

Resources **Visualize**

4 Event selection

➔ Trigger rate in the ROI dominated by non-bulk scintillation events





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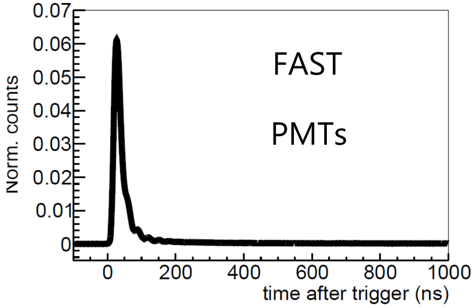
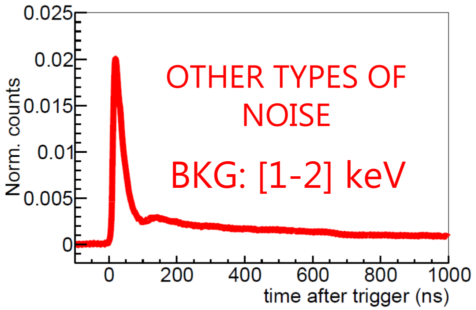
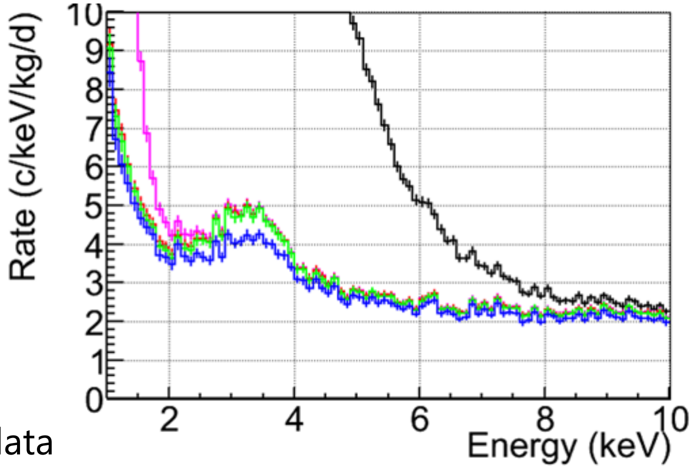
➔ Filtering protocols based on pulse shape and asymmetry





Standard analysis



Raw data
NaI scintillation time behaviour / biparametric cut
Npeaks>4 at both PMTs
More than 1s after a muon
Single Hits

The ANAIS-112 experiment

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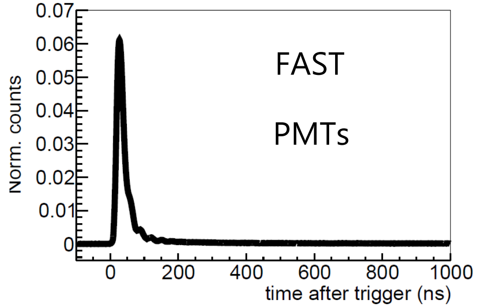

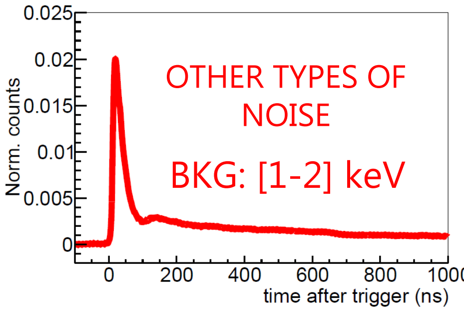

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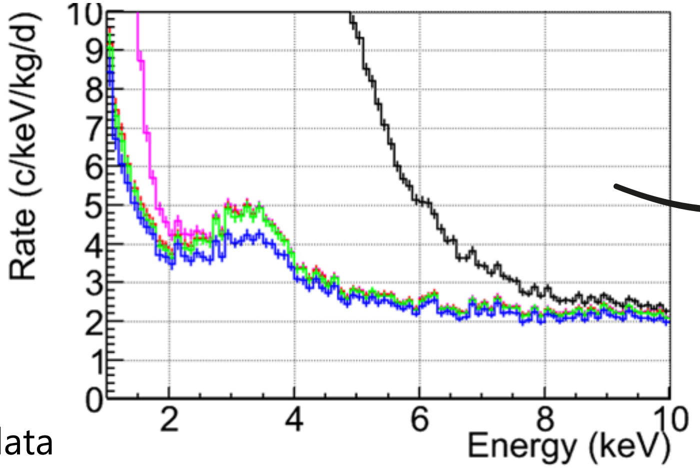

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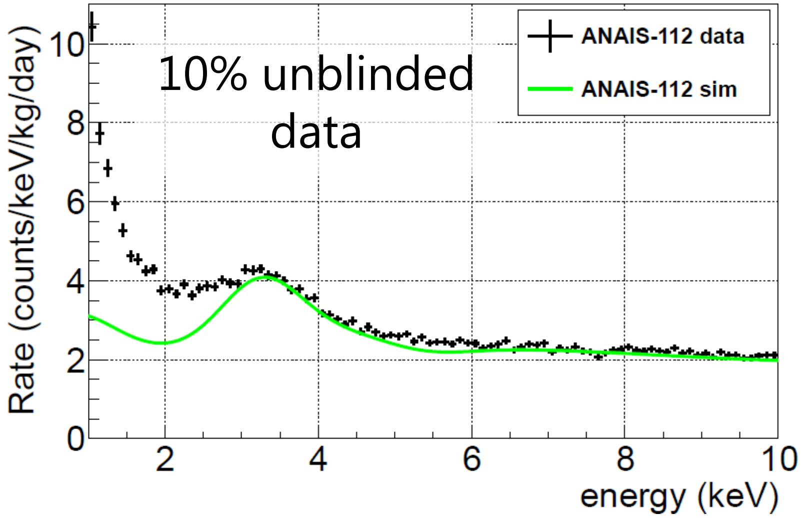

Comparing with MC background model…
Strong discrepancy in [1-2] keV

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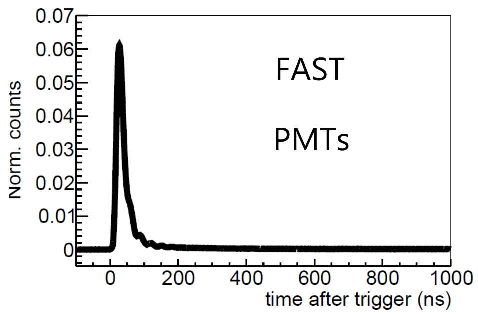

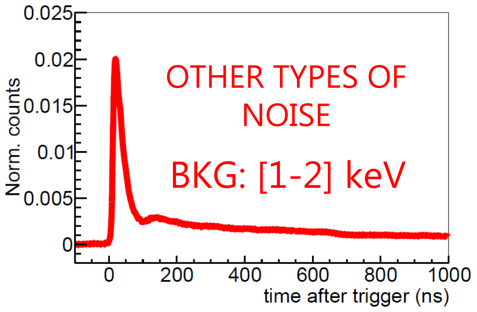

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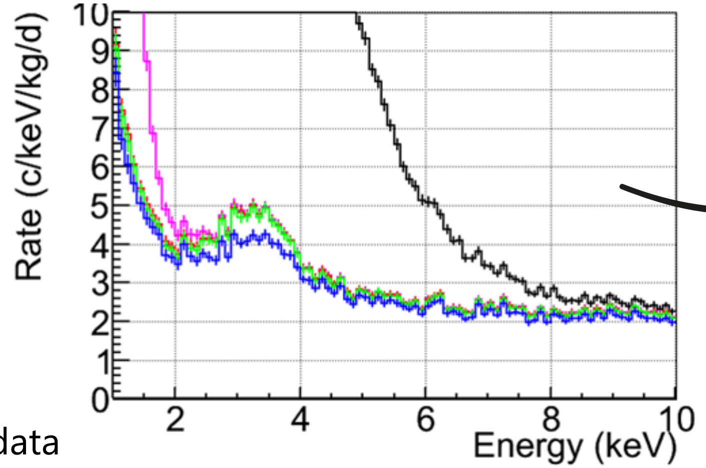

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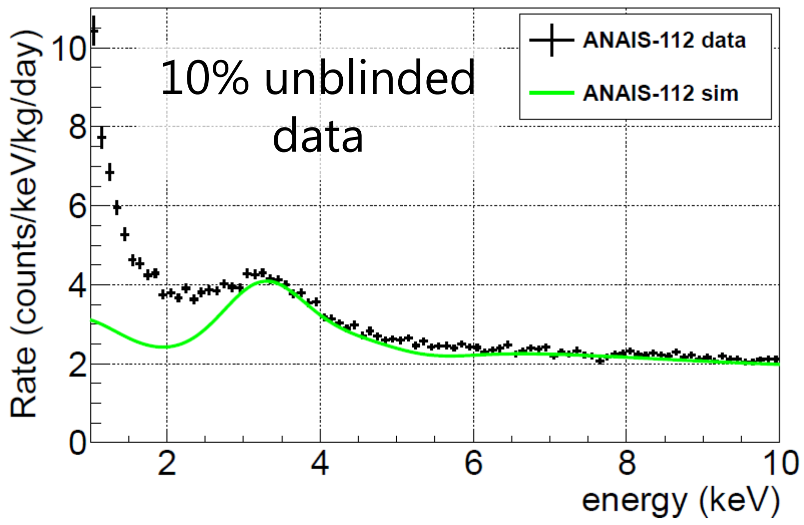


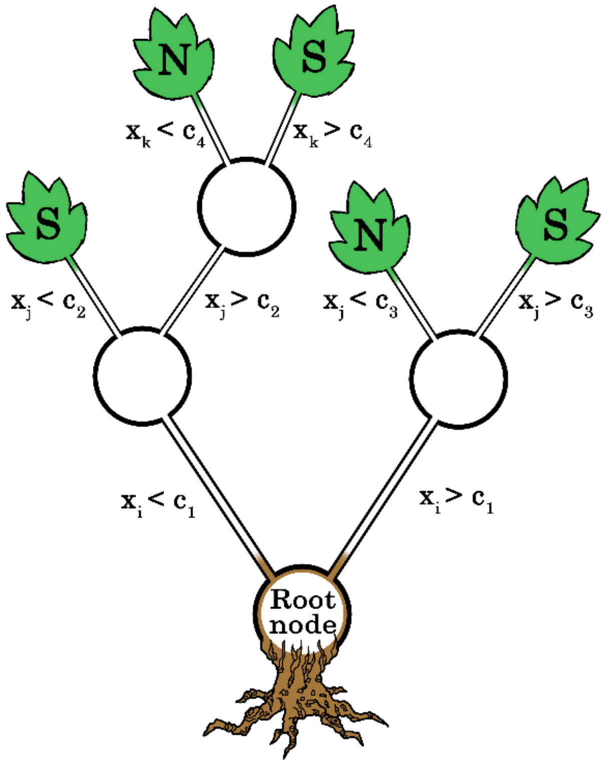
Comparing with MC background model…
Strong discrepancy in [1-2] keV

Machine-learning technique to improve noise rejection in [1-2] keV

5 3-year annual modulation with machine learning

Improving ANAIS-112 sensitivity to DAMA/LIBRA signal with machine learning techniques, I. Coarasa et al, JCAP11(2022)048
JCAP06(2023)E01

- ➔ Event selection based on Boosted Decision Trees (BDT)
- ➔ Multivariate analysis (15 parameters used for classification)



The ANAIS-112 experiment

5 3-year annual modulation with machine learning

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JCAP06(2023)E01

➔ Event selection based on Boosted Decision Trees (BDT)

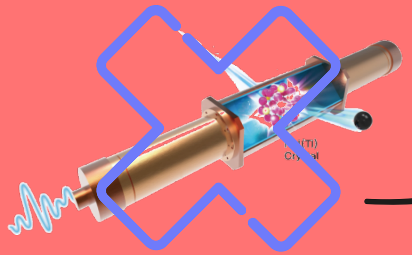
➔ Multivariate analysis (15 parameters used for classification)

➔ Training populations:

SIGNAL EVENTS:

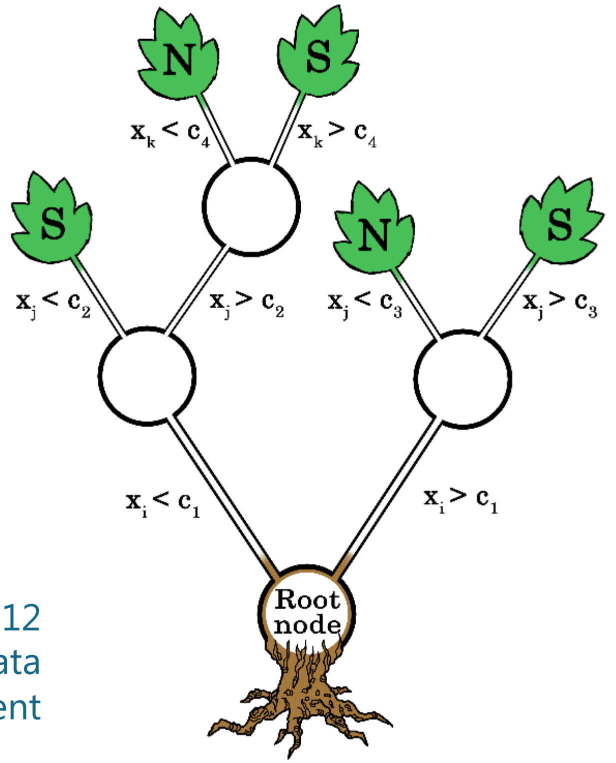
Neutron calibrations

NOISE EVENTS:



"Blank module"

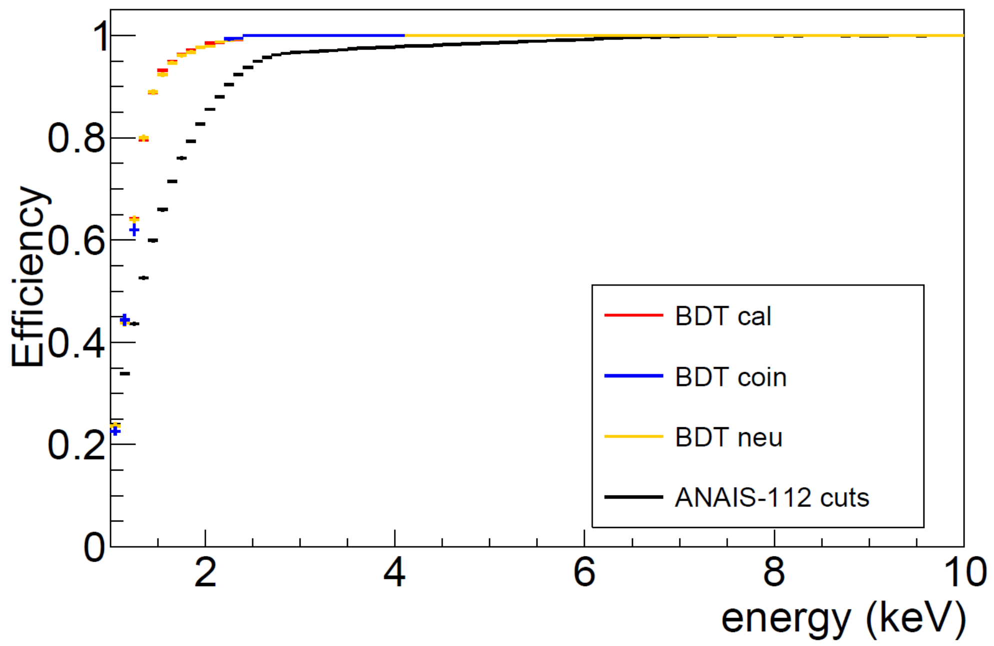
Since 2018, a Blank module (similar to ANAIS−112 modules, but without NaI(Tl) crystal) is taking data with the same DAQ, but in an independent shielding close to ANAIS−112



The ANAIS-112 experiment

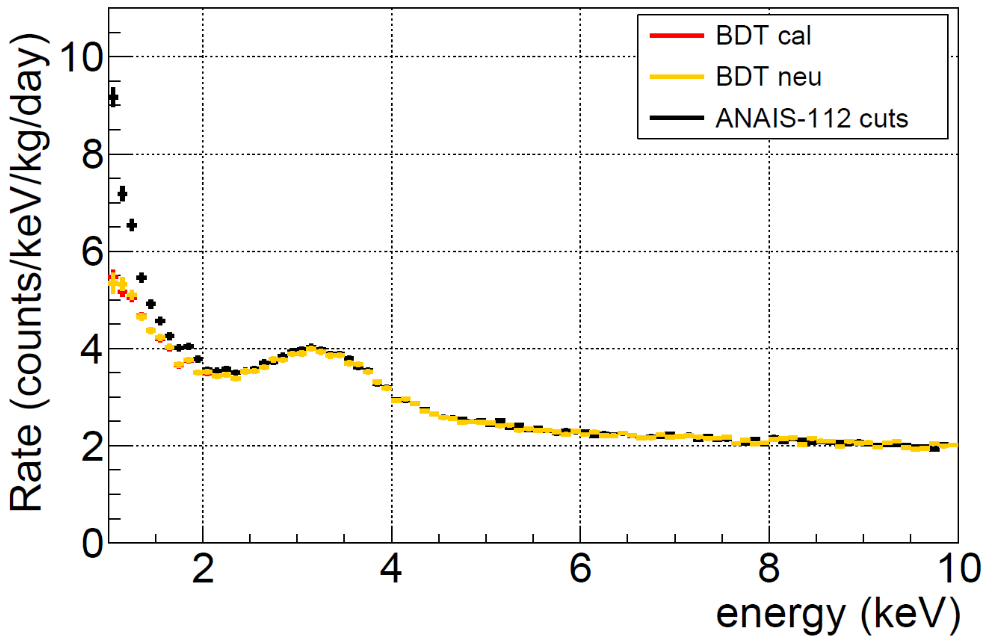
5 3-year annual modulation with machine learning

Acceptance efficiency



➔ ~ 30% improvement in efficiency in [1-2] keV

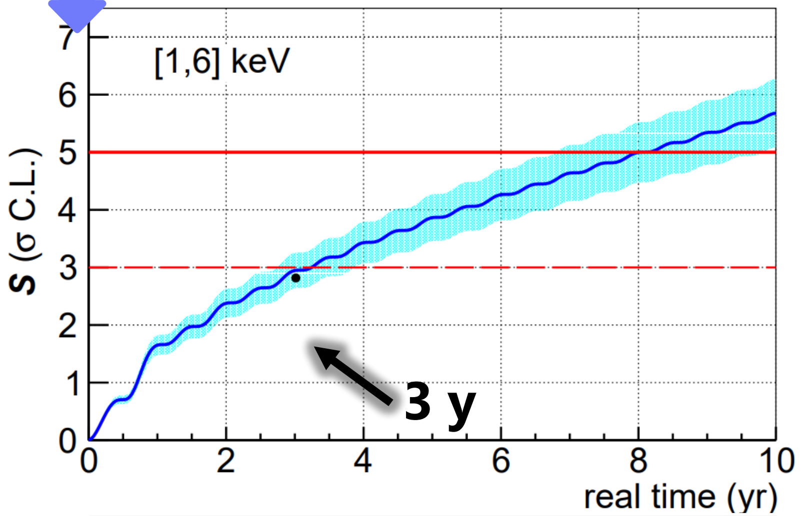
Efficiency-corrected background

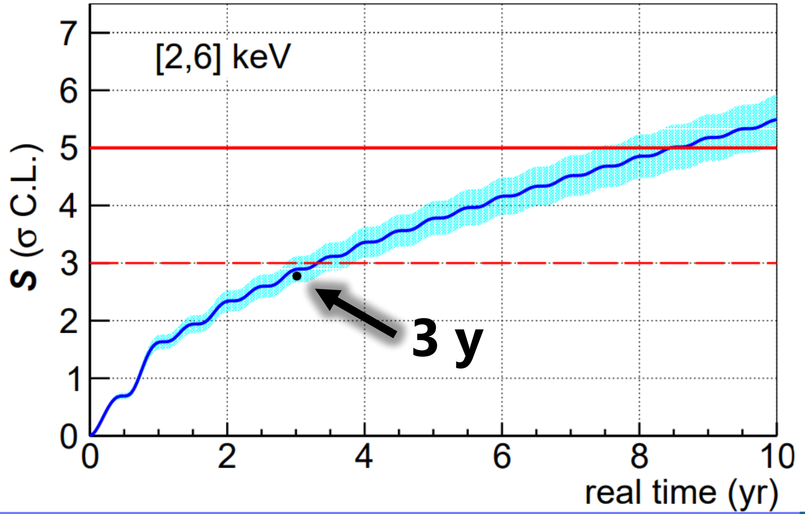


➔ ~ 18% background reduction in [1-2] keV

➔ The excess in [1-2] keV wrt MC model still present

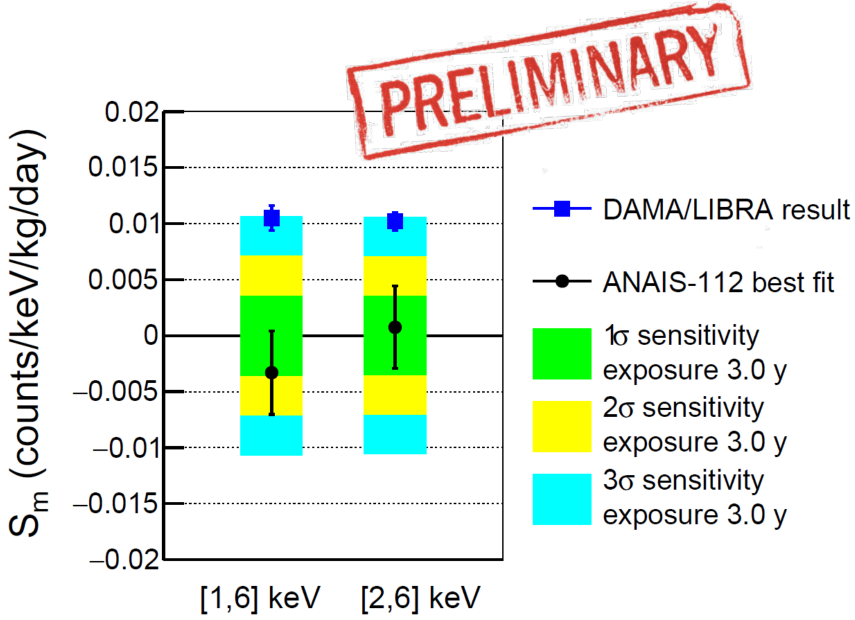
5 3-year annual modulation with machine learning





Best fit modulation amplitudes **compatible with zero** at $\sim 1\sigma$

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

5σ sensitivity at reach in late 2025 !!

More data is required to solve this puzzle
··· and to guarantee model independency···

arXiv:2311.03392
TAUP2023. To be published in PoS

Is it really a model independent test?

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

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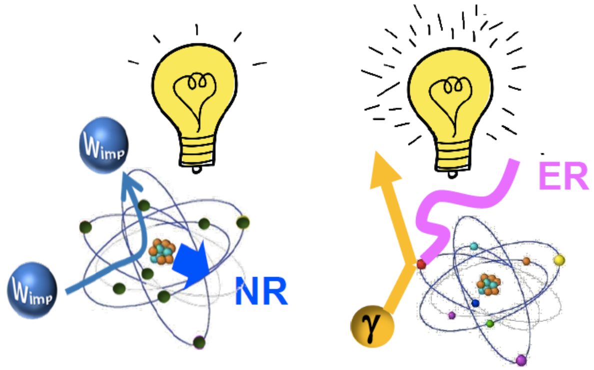
In a scintillator, an **electron recoil** (ER) produces much more light than a **nuclear recoil** (NR) of the same energy -> QF



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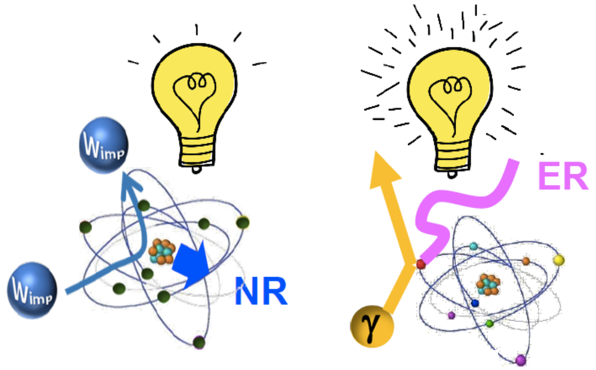

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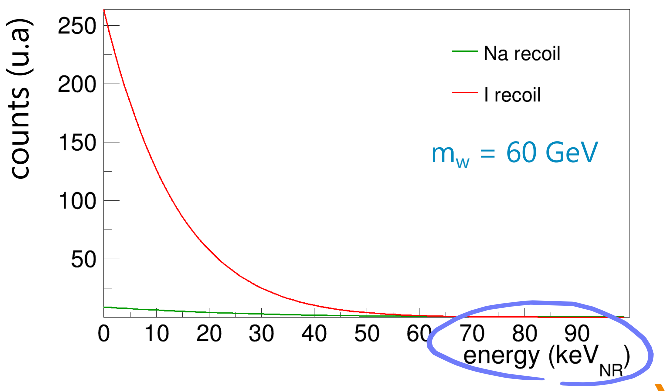
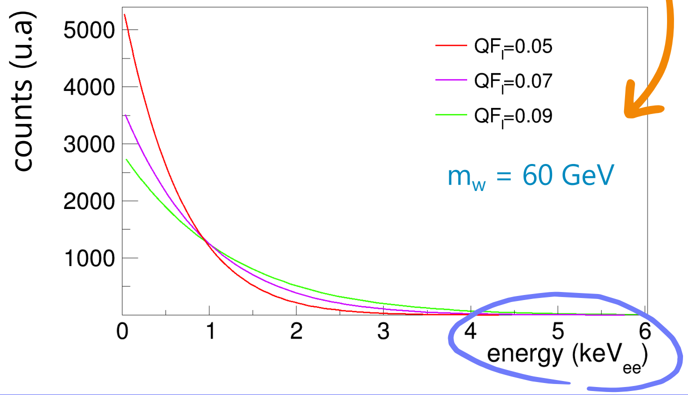
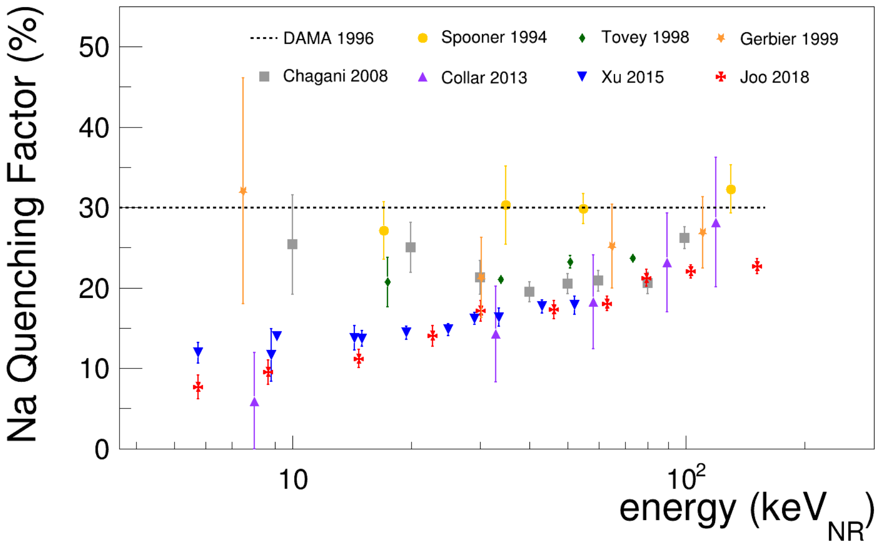


In most of the models, DM is supposed to produce NR

→ Experiments must be compared in the **NR**-energy scale, which requires a precise knowledge of the **QFs**



Current status of QF measurements in NaI



Q_{Na} DAMA = 0.3
Q_I DAMA = 0.09

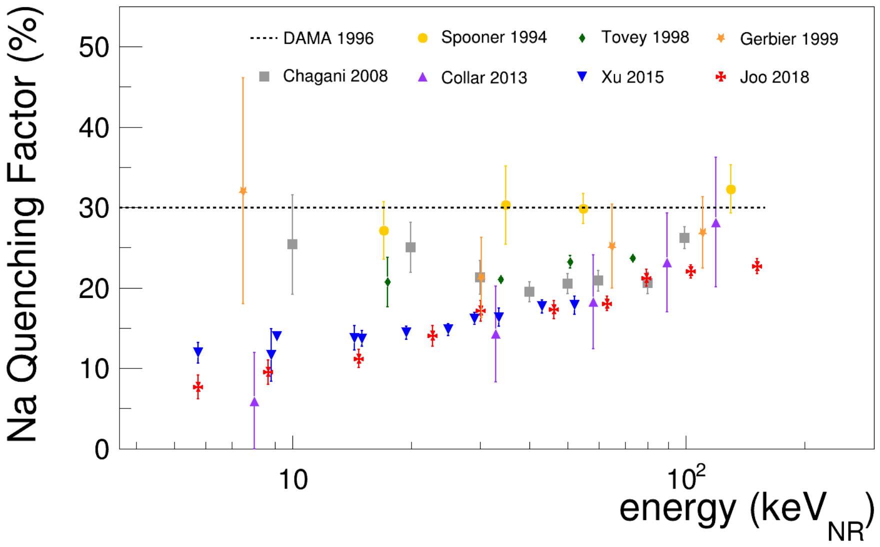
Constant QF? 1

2 Decreasing with energy QF @ low energies?

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

Current status of QF measurements in NaI



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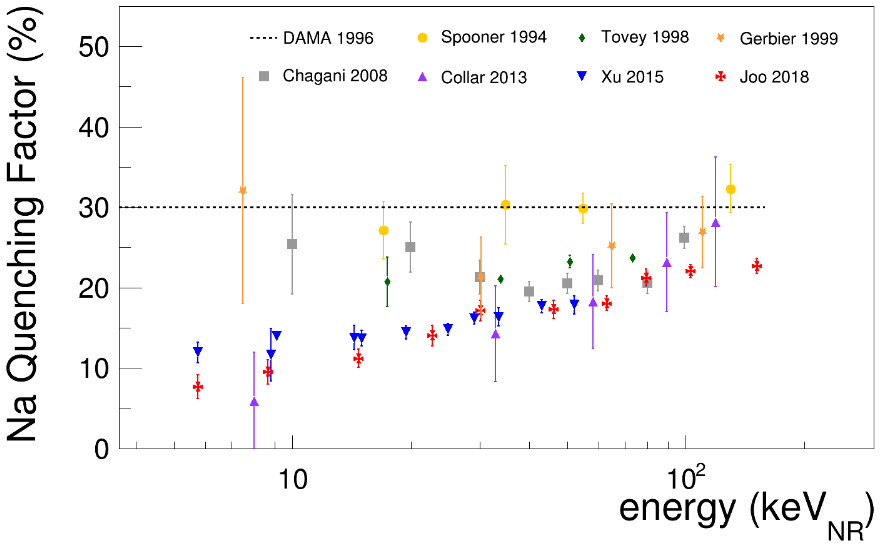

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Differences in **experimental procedures** have introduced systematic differences

QF is an **inherent** property of NaI(Tl)

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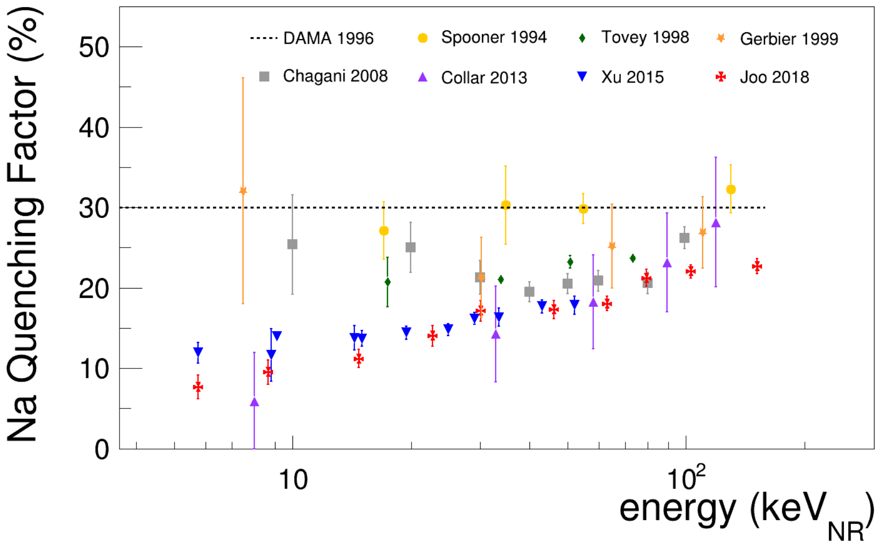

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Constant QF? 1

2 Decreasing with energy QF @ low energies?

1 Differences in **experimental procedures** have introduced systematic differences

QF is an **inherent** property of NaI(Tl)

2 QF can **vary** between individual NaI(Tl) detectors

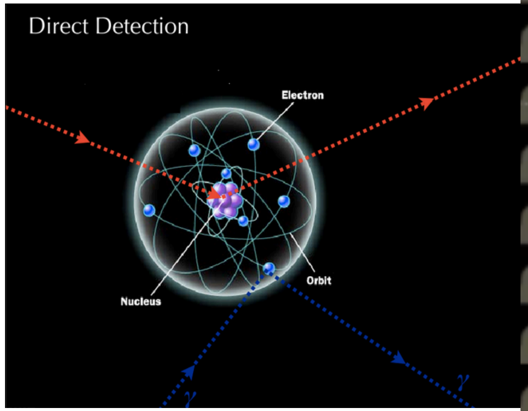
- Impurities
- Doping concentration
- …

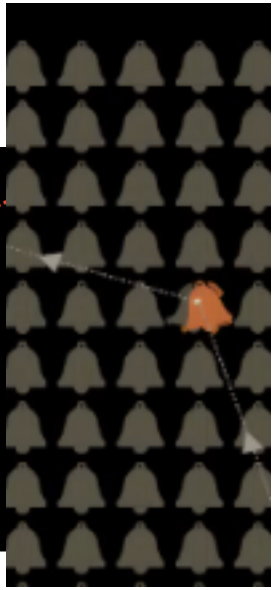
Neutron calibration program

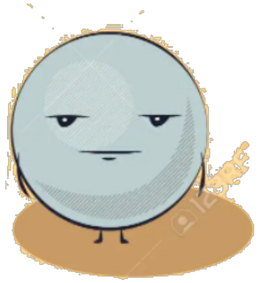
Determining the QF is crucial to support the direct model independent testing of DAMA-LIBRA; **systematic**

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

DM Direct Detection approach







Neutron calibration program

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

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

Neutron calibration program

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

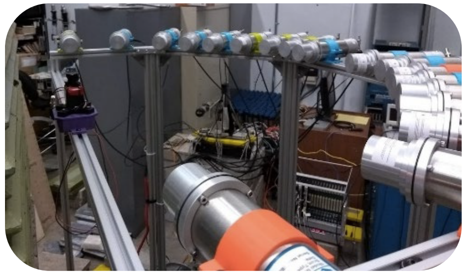
small size	Monochromatic neutron source	^{252}**Cf source**	ANAIS crystals
not ANAIS crystals			greater reliance on MC model

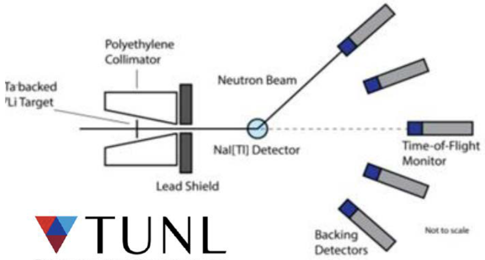
Multiple scattering is one of the most relevant differences

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

Neutron calibration program

Monochromatic neutron source





TUNL
Triangle Universities Nuclear Laboratory

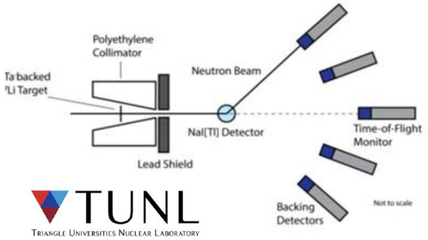
In collaboration with Yale (from COSINE collaboration) and Duke researchers @ TUNL

Neutron calibration program

Monochromatic neutron source

Analysis of **systematic** effects

2 different linear **energy calibrations**



Neutron calibration program

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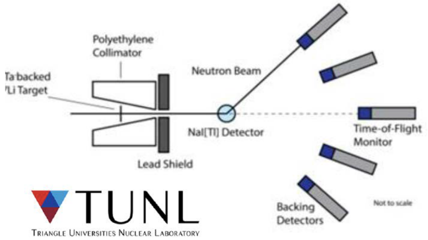
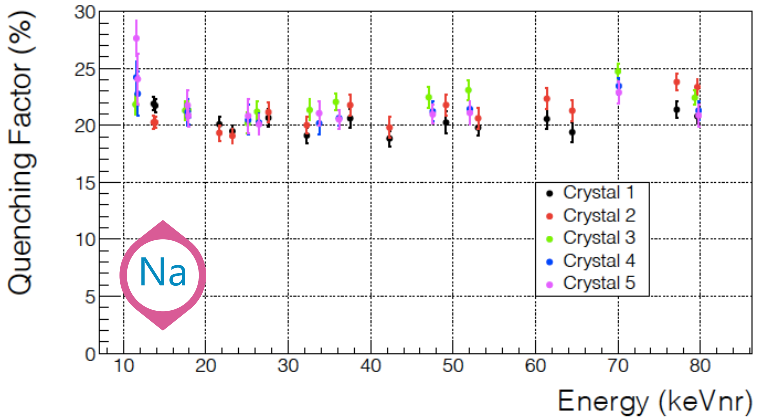


133Ba

1 Non-proportional

6.6, 30.8, 35.1 keV



No clear dependence with energy

QFNa =(21.2 ± 0.8) %

Neutron calibration program

Monochromatic neutron source

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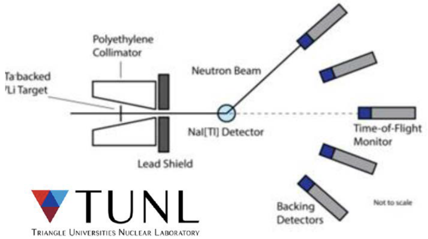

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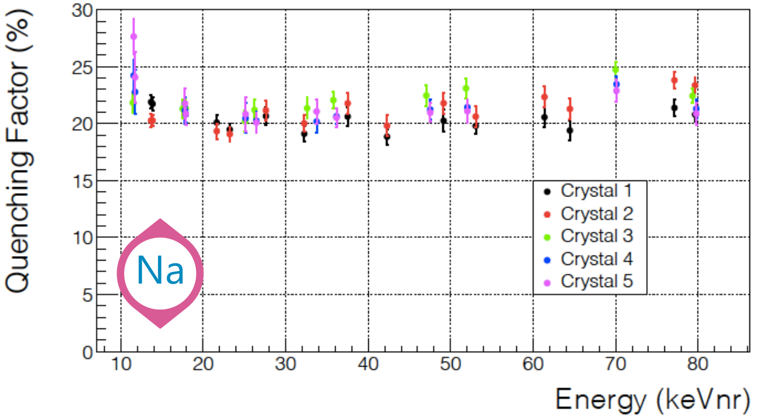

No clear dependence with energy

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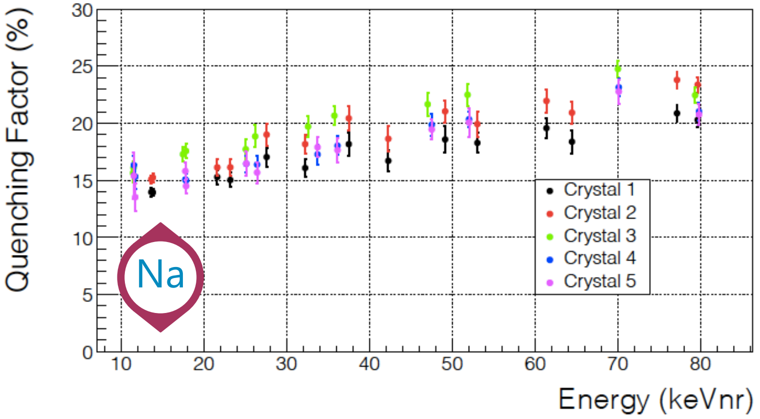
127I

2 Proportional

57.6 keV inelastic peak



Decreasing with energy QFNa @low energies

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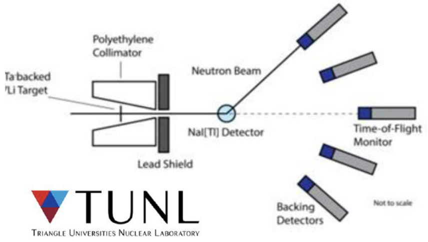

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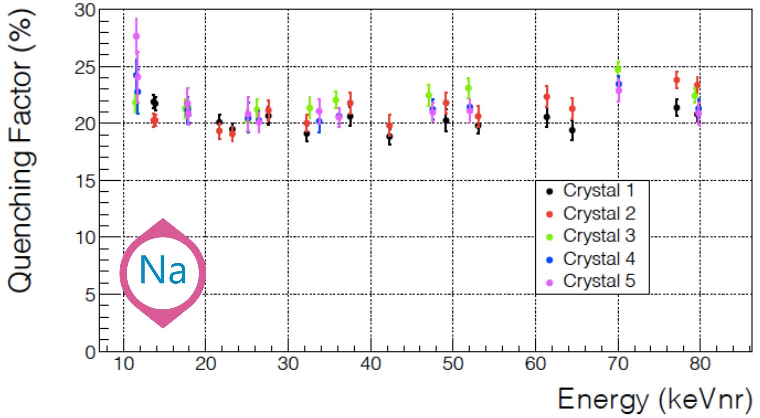

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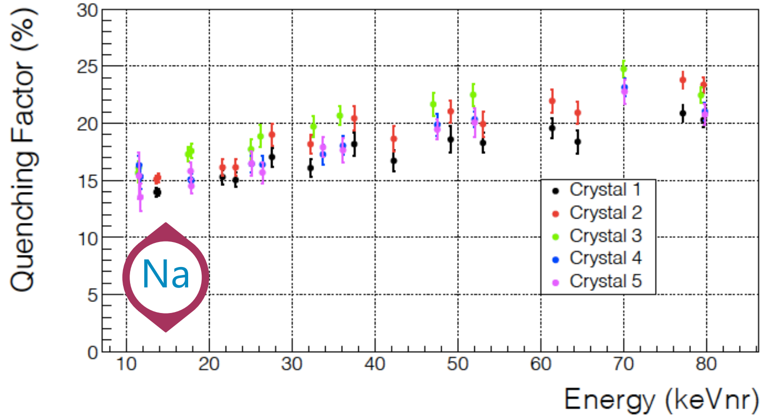


Decreasing with energy QFNa @low energies

Compatible values for the 5 crystals

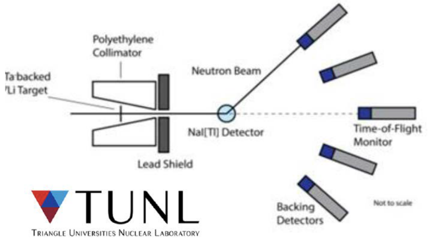
Both procedures are **not compatible** among them <50 keV

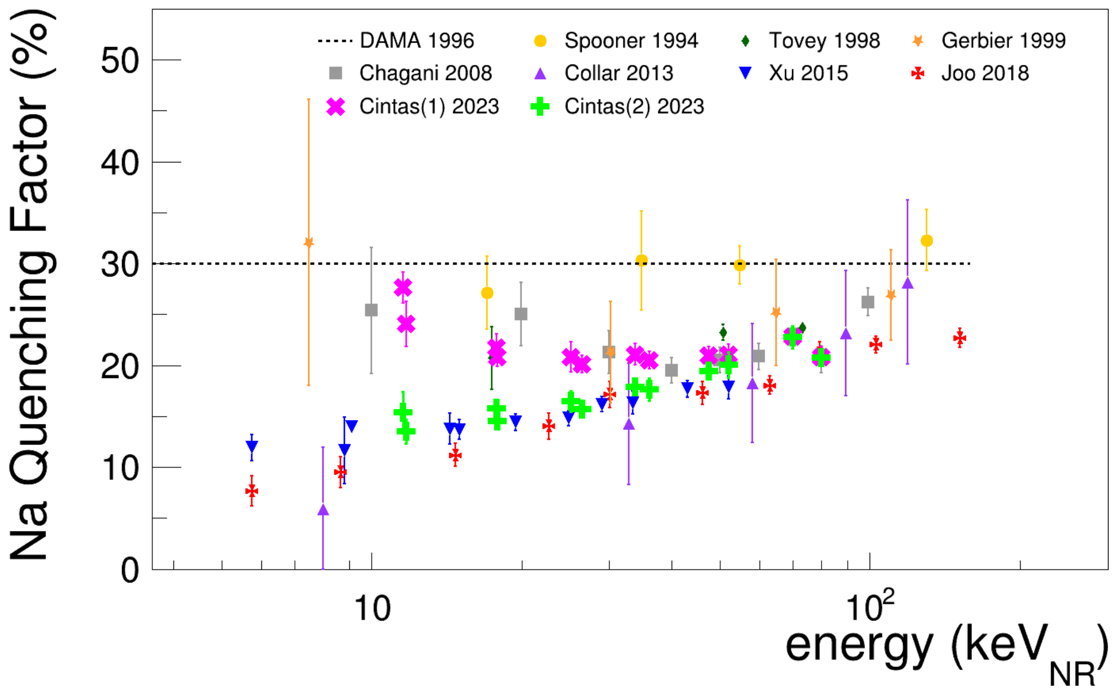
Neutron calibration program

Monochromatic neutron source

Analysis of **systematic** effects

2 different linear **energy calibrations**





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

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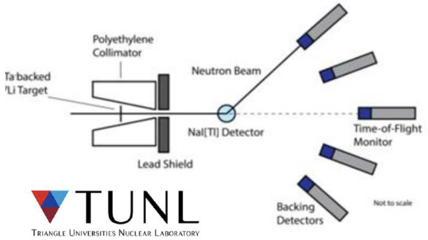

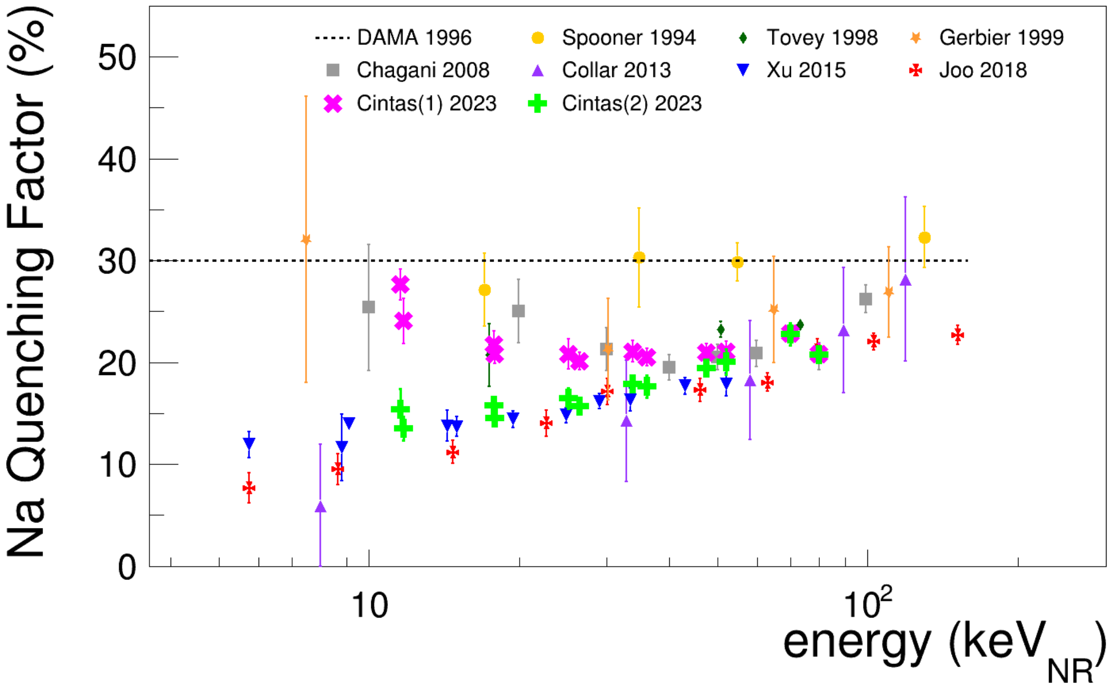

Fully **compatible** with previous measurements

Both procedures are **not compatible** among them

Systematics play a relevant role in the comparison of results

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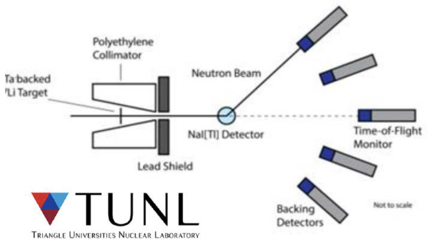

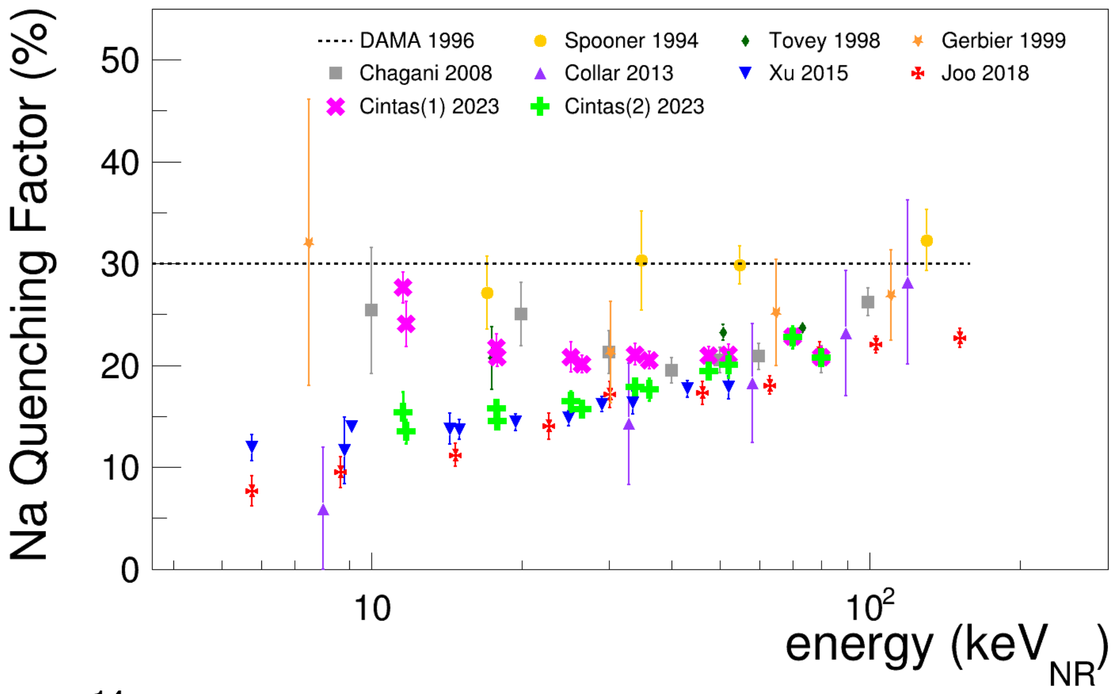

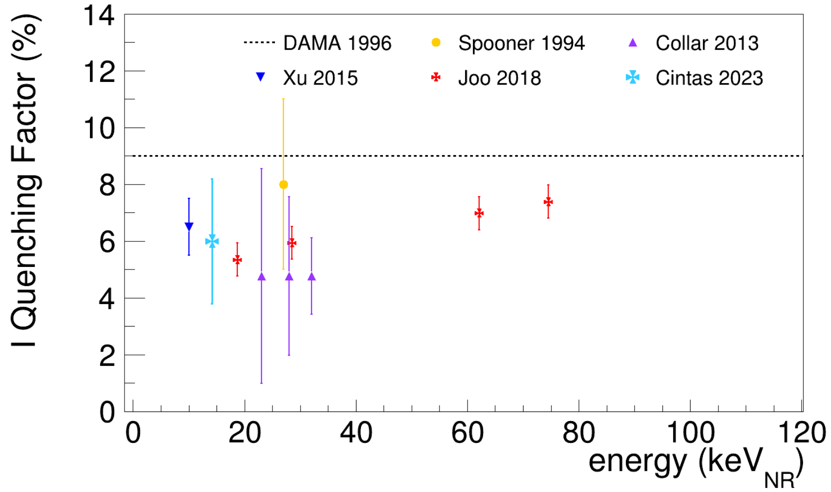

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Systematics play a relevant role in the comparison of results

I

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

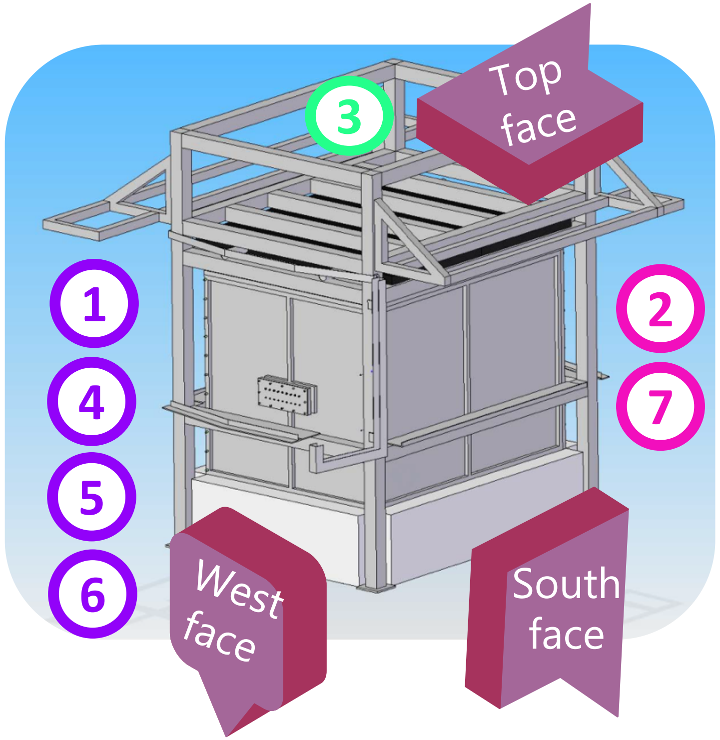
D. Cintas et al 2021 J. Phys.: Conf. Ser. 2156 012065

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

^{252}Cf source

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



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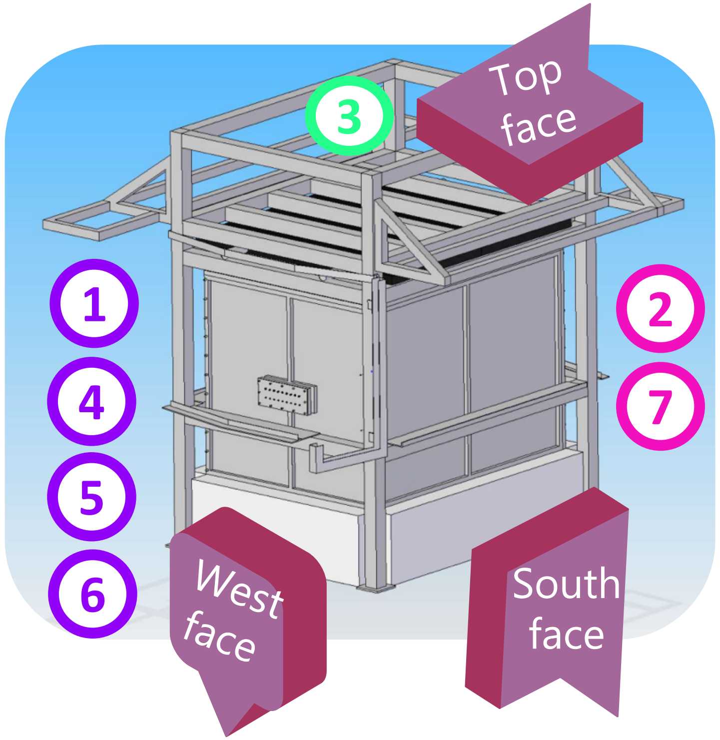

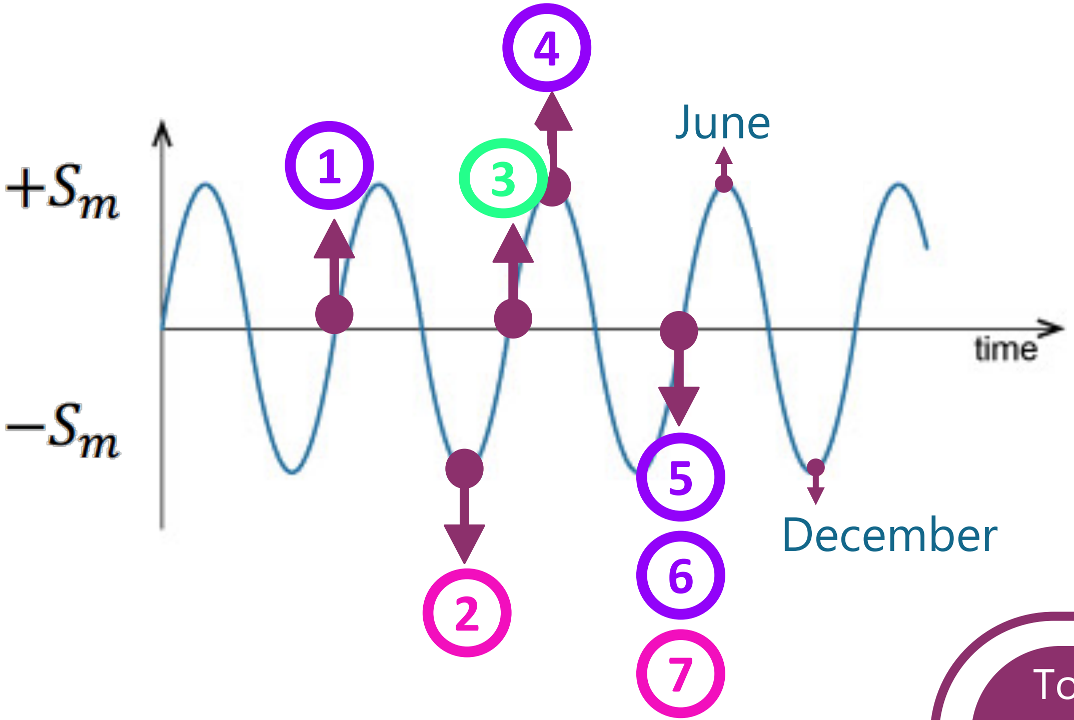

...

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

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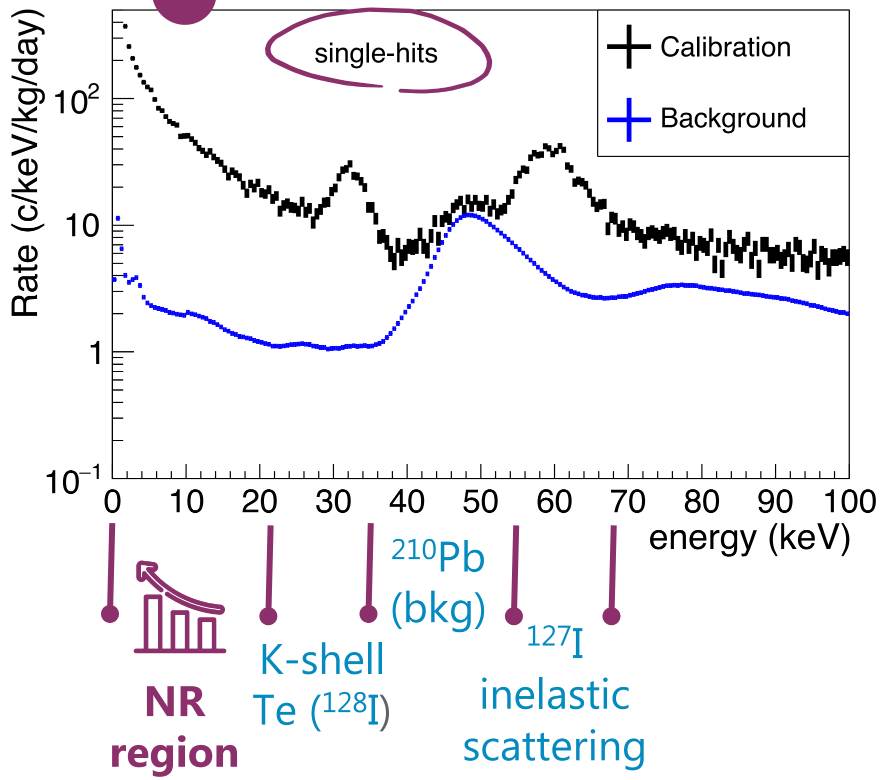

- clean population of **bulk** scintillation events
- large number of events in the ROI ([1-6] keV)

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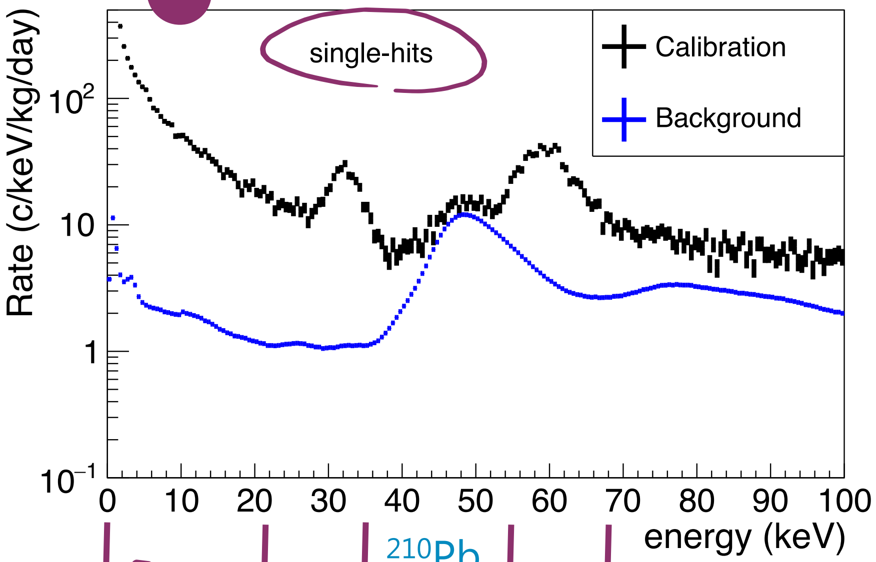

NR region

K-shell Te (^{128}I)

^{210}Pb (bkg)

^{127}I inelastic scattering

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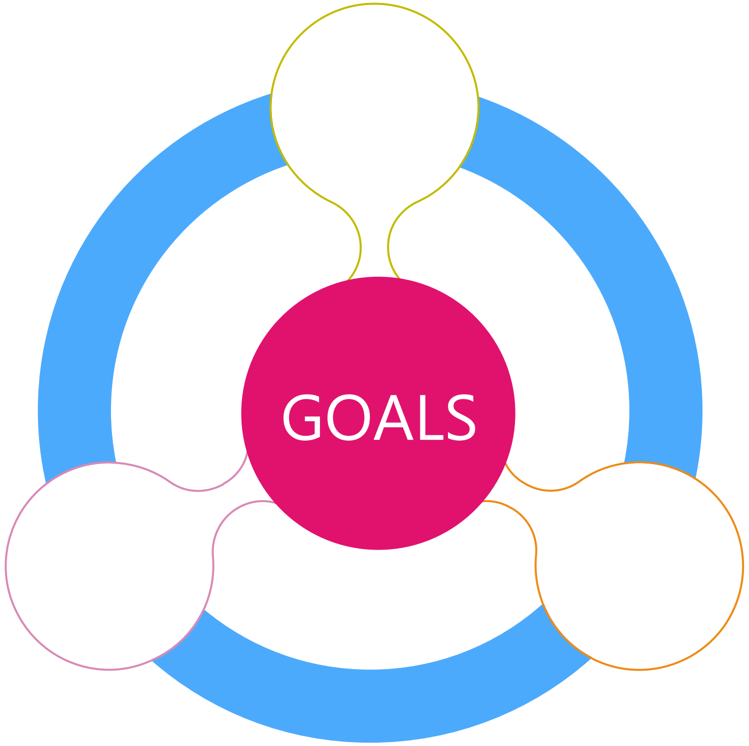

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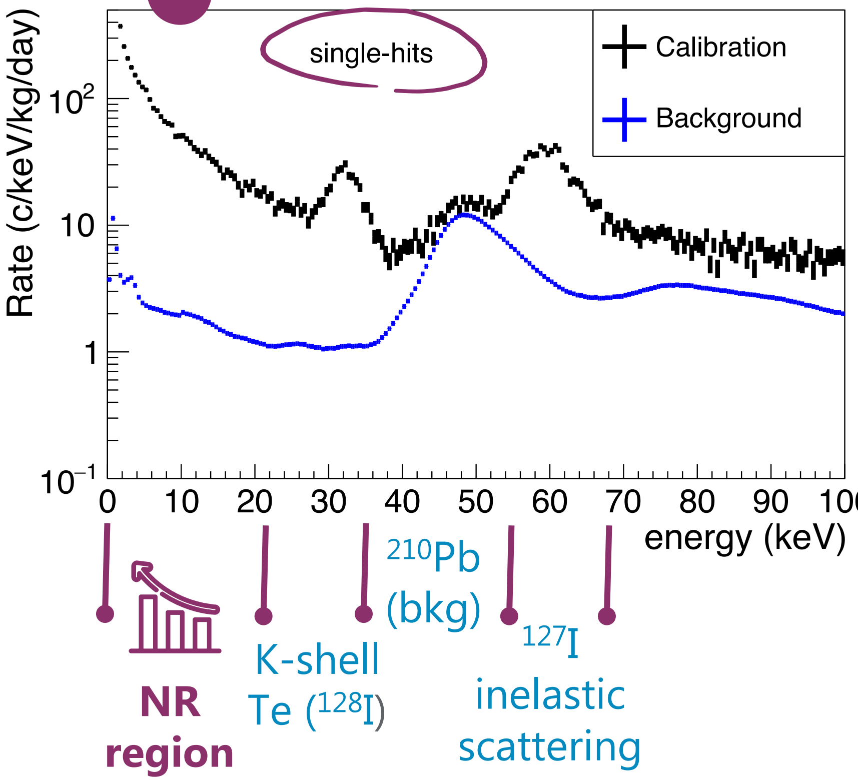

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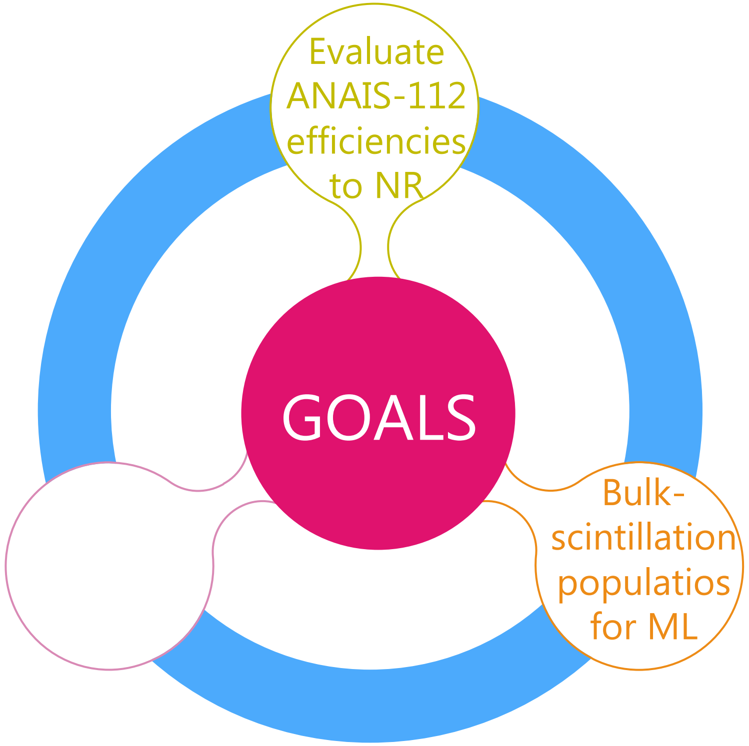

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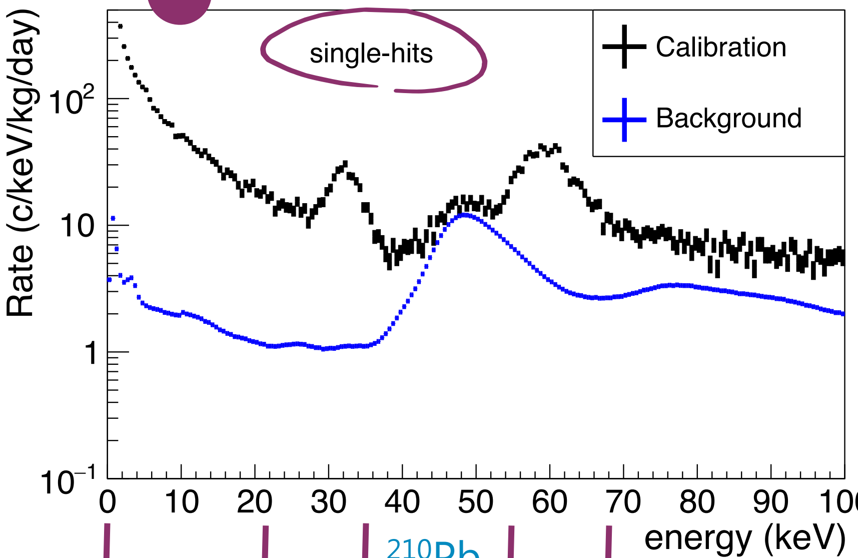

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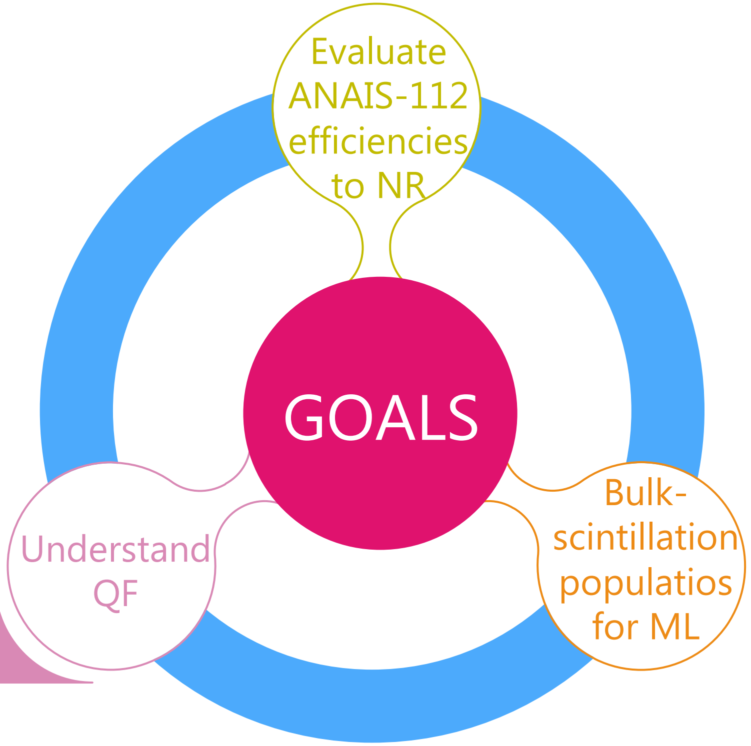
On-site neutron calibrations can be an important cross-check!!



Results on the quenching factor

Our aim

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

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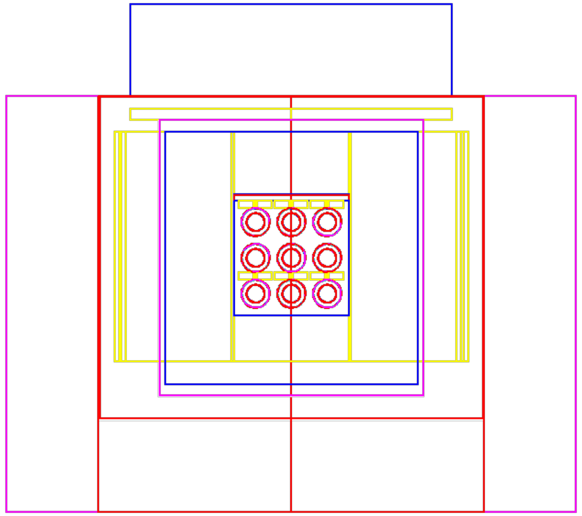
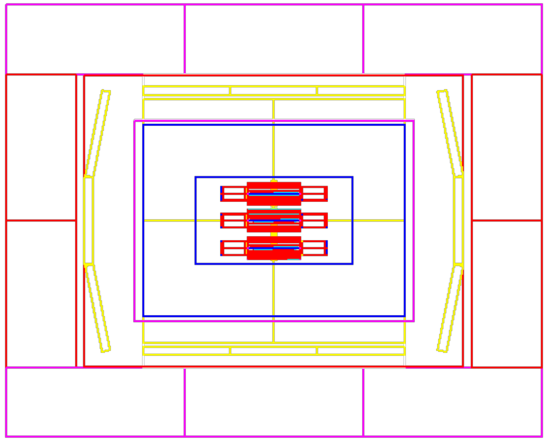
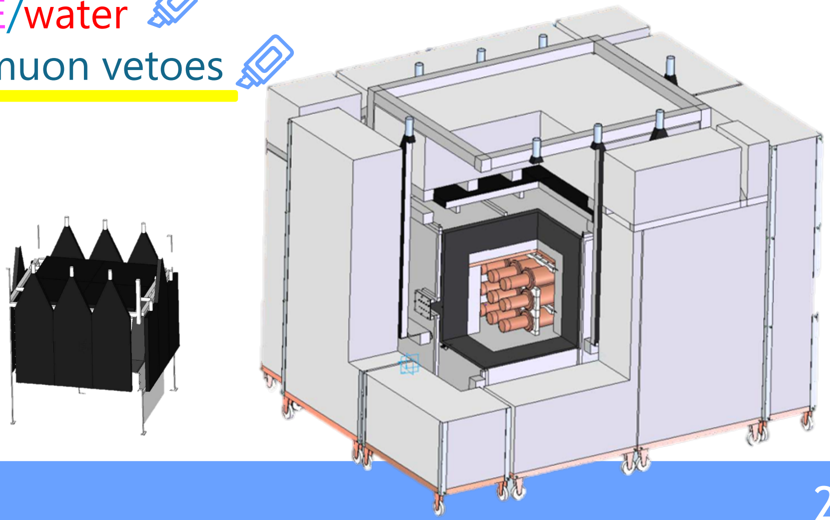
The ANAIS-112 Geant4 model has been extended for simulating the neutron calibration

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



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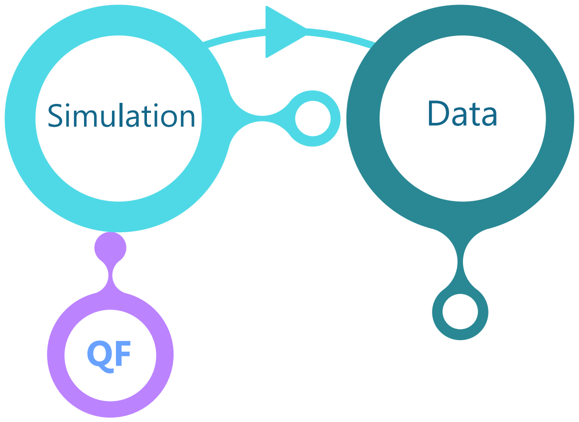

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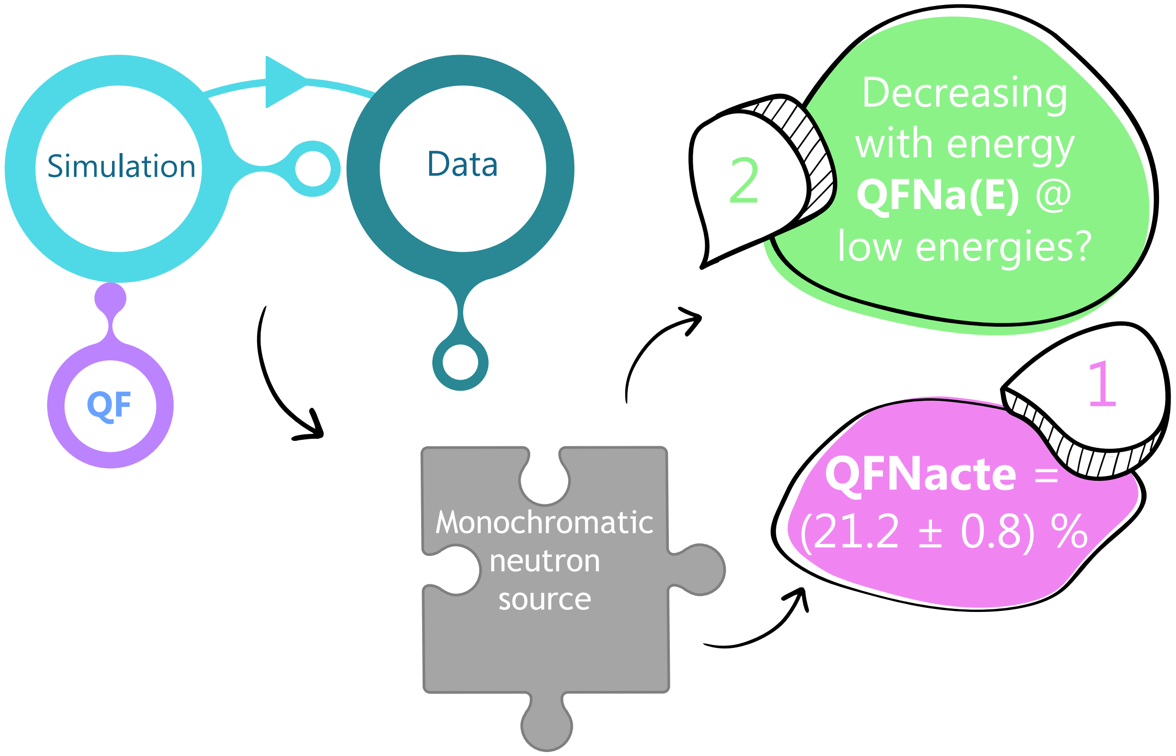

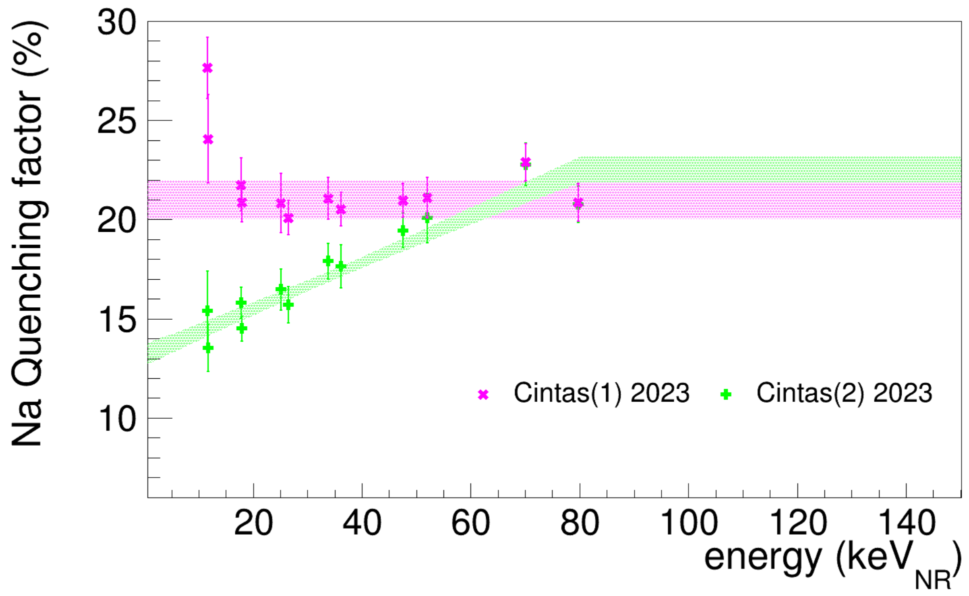

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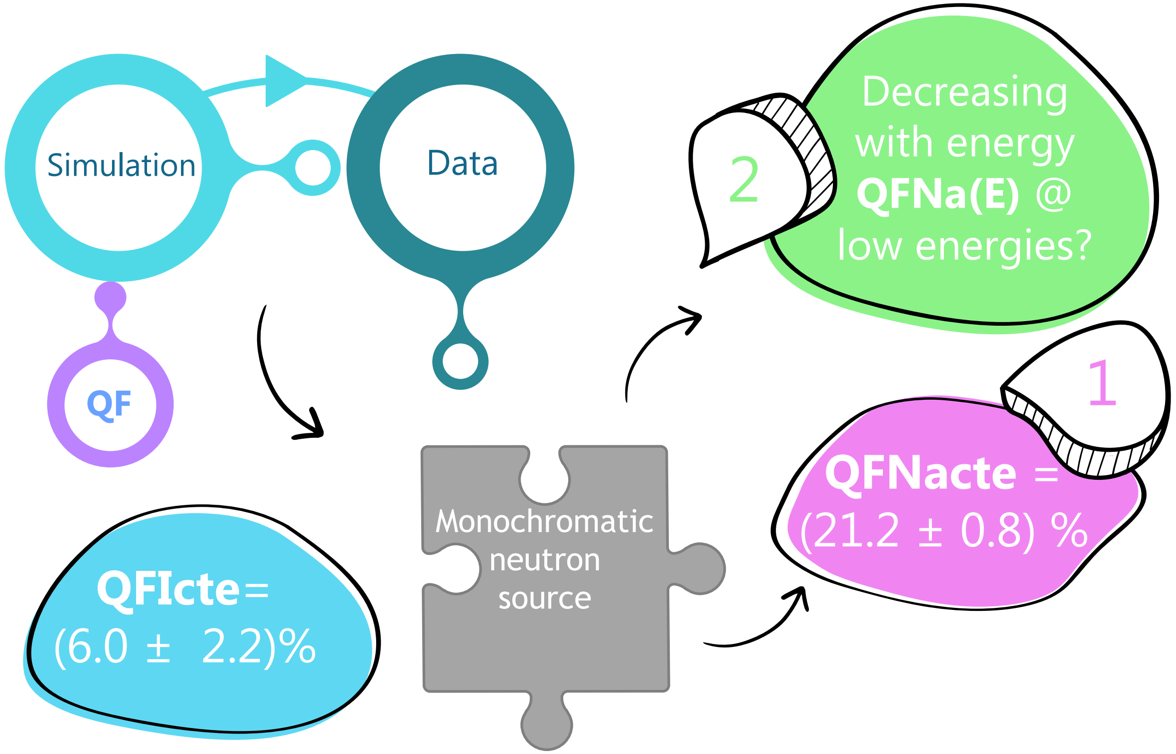
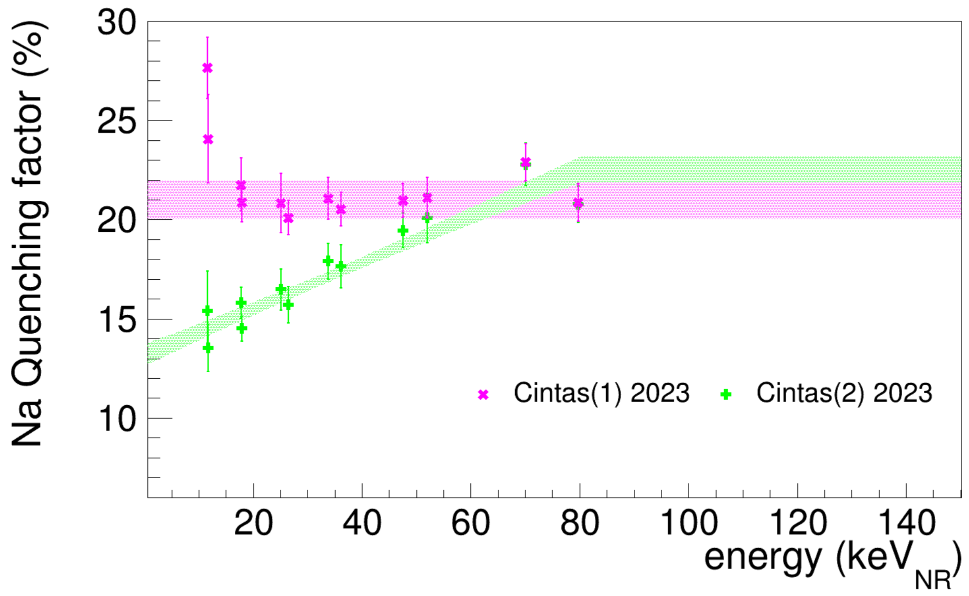
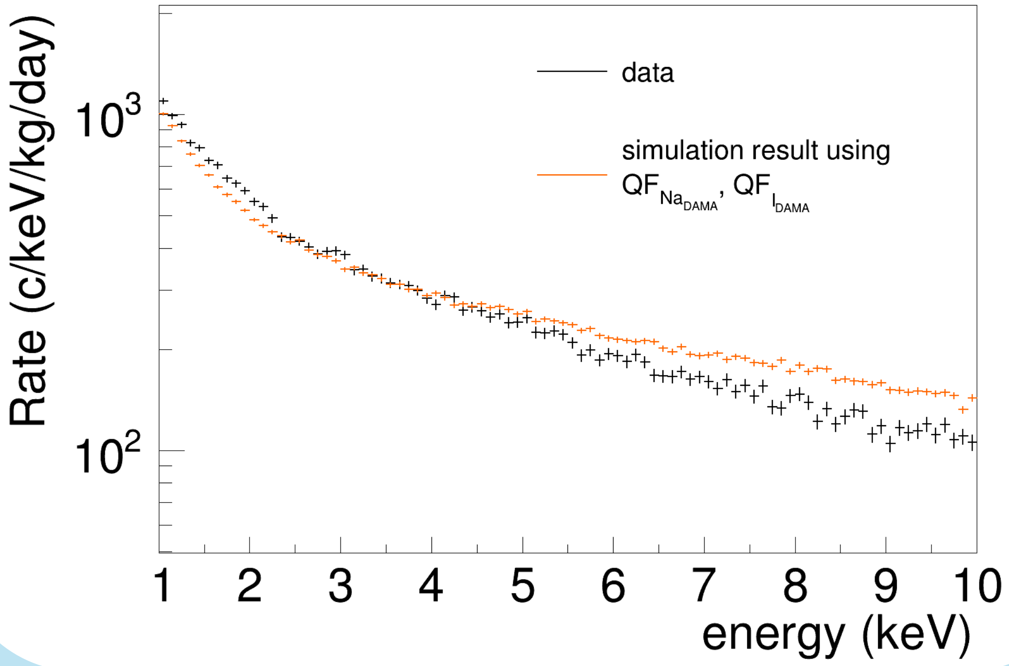
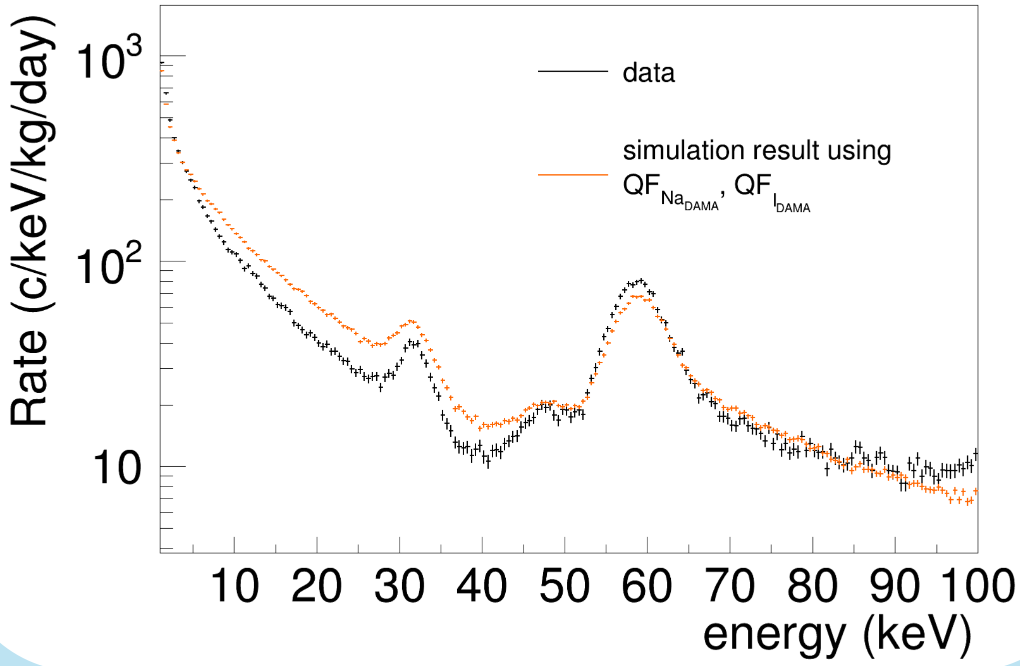




Comparison with **DAMA/LIBRA QFs**

Q_{Na} DAMA = 0.3
Q_I DAMA = 0.09





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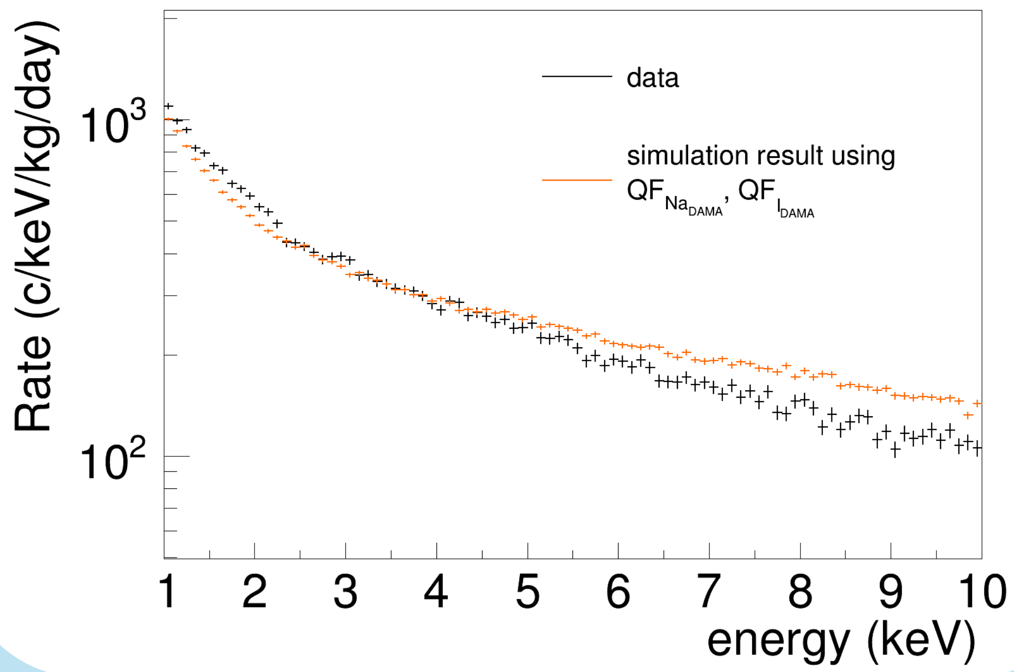
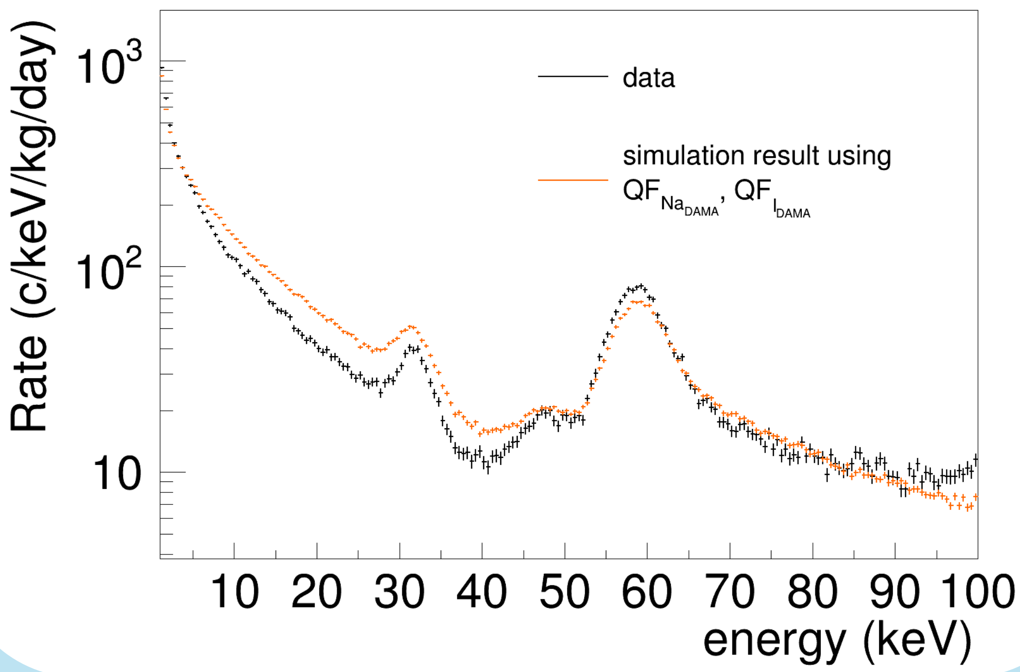
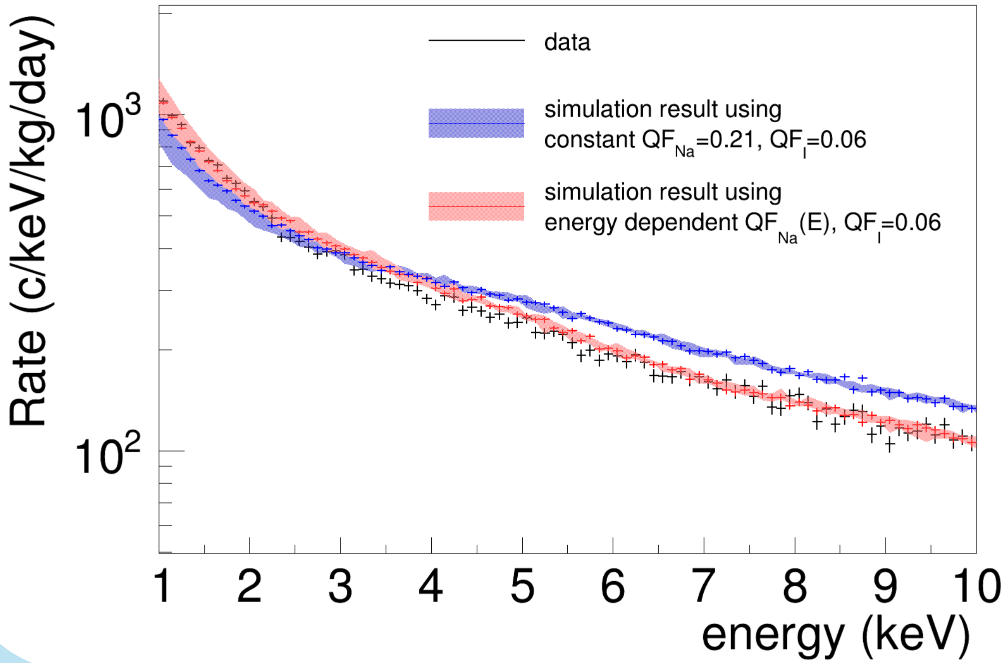


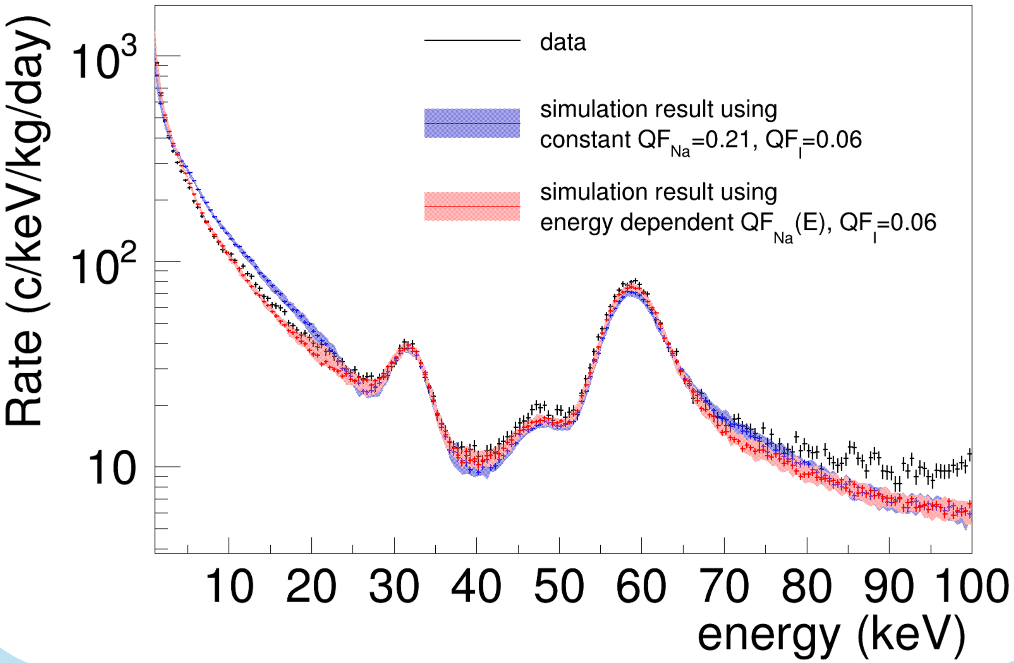


DAMA/LIBRA QFs are **not compatible** with our data

Results on the quenching factor

Comparison between **our QF models**





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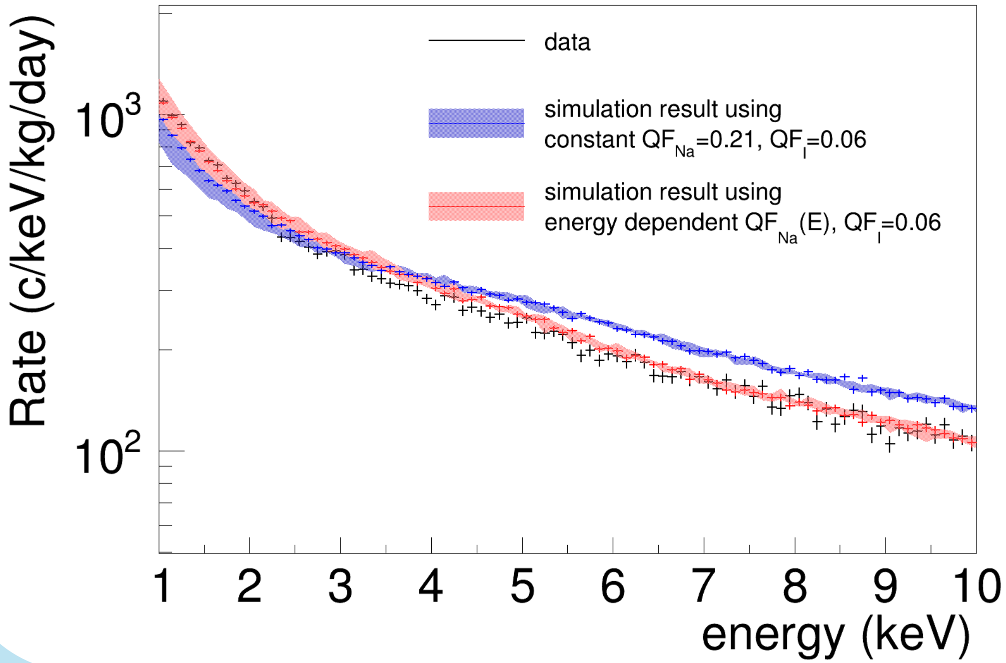

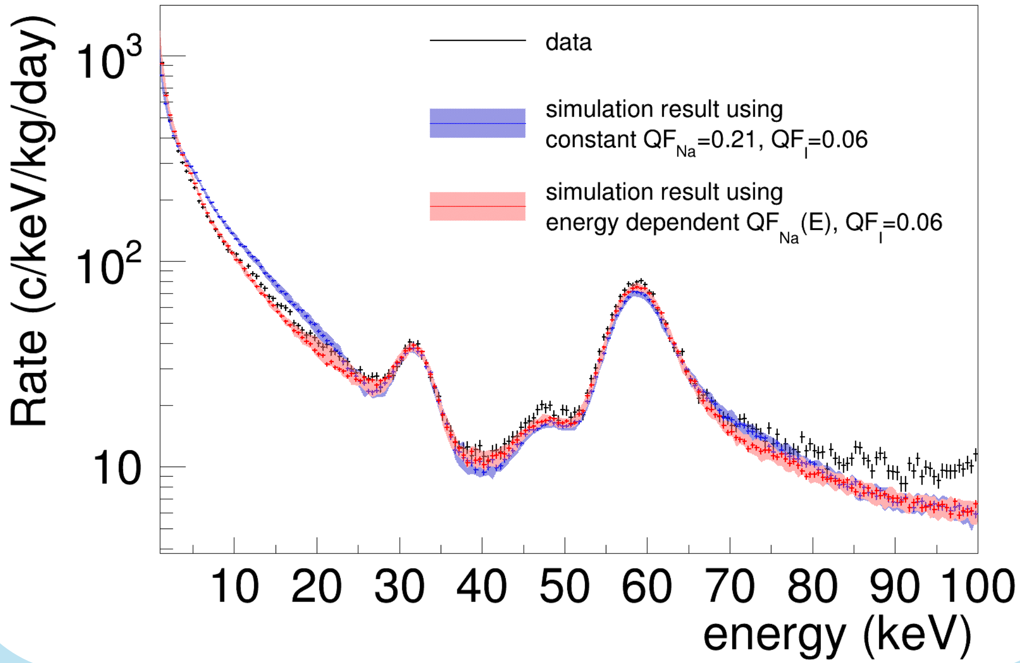

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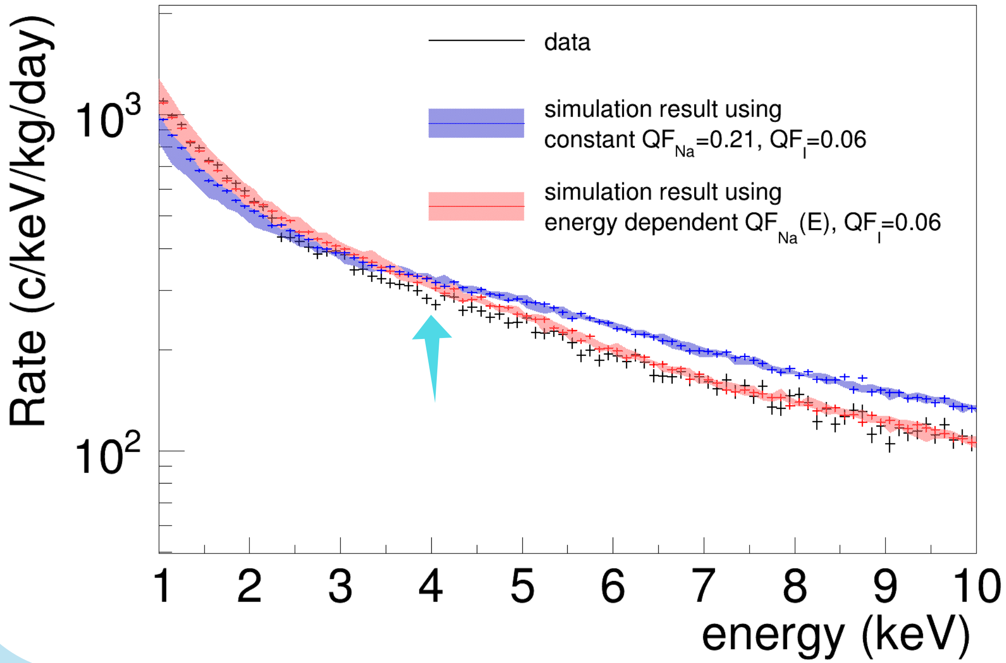

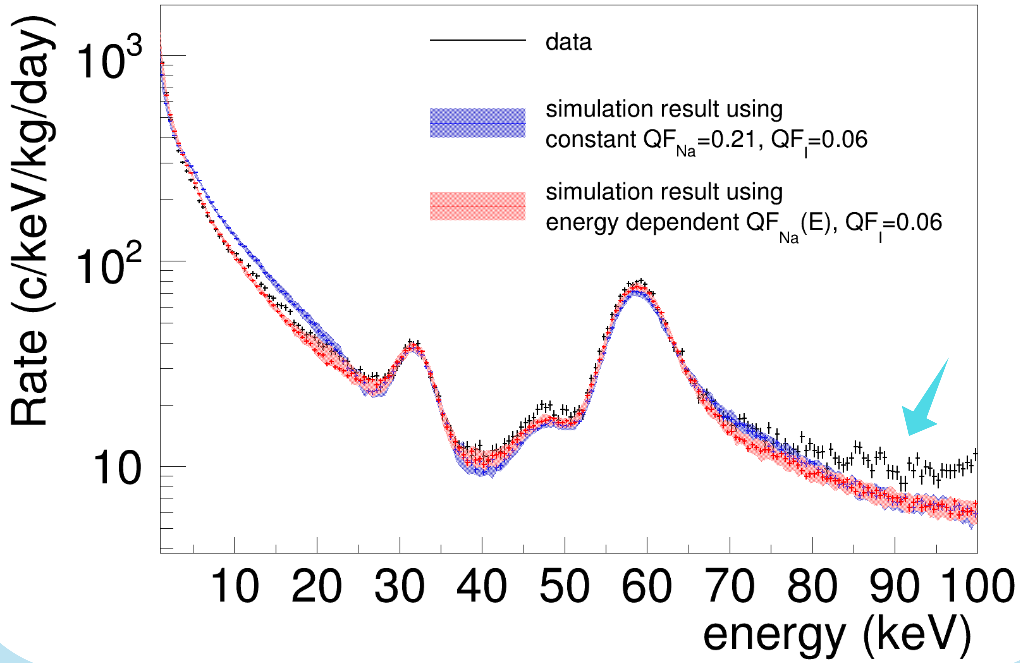

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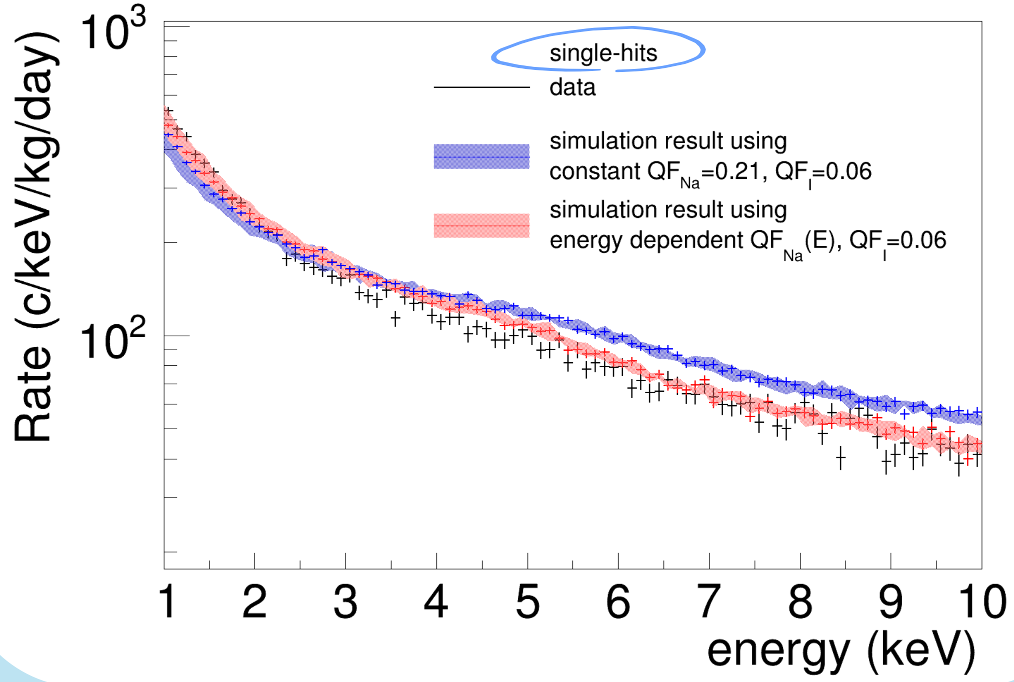

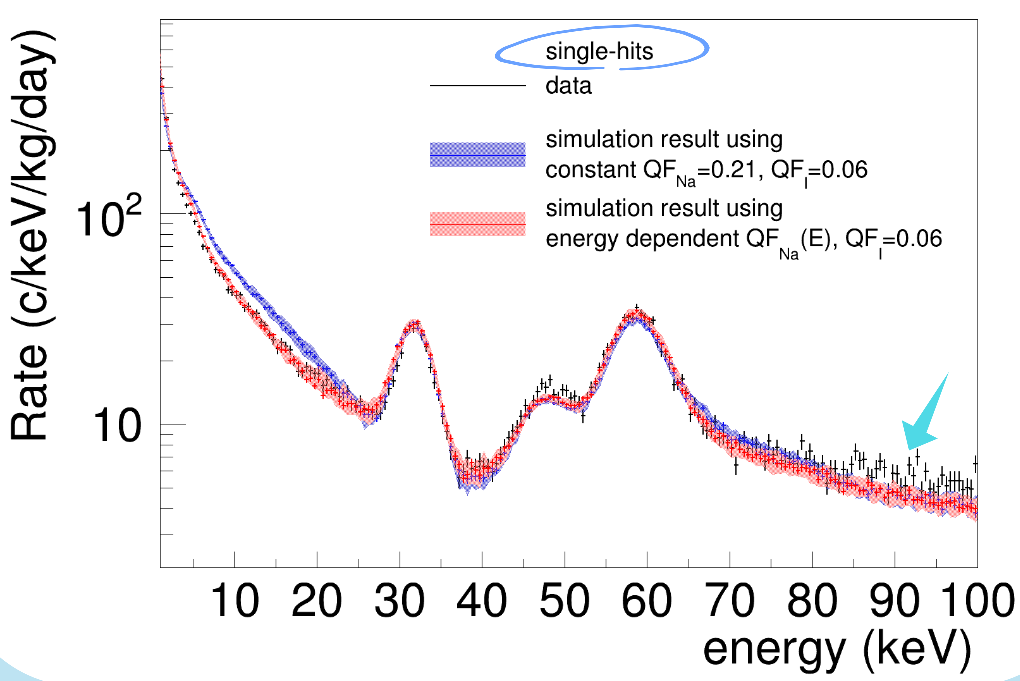

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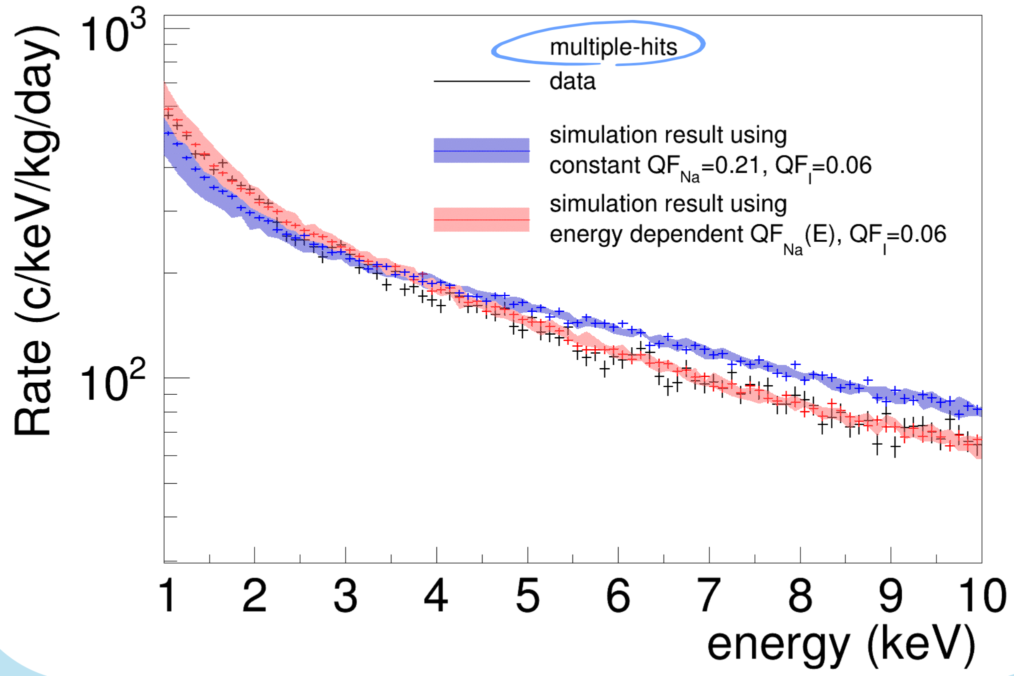
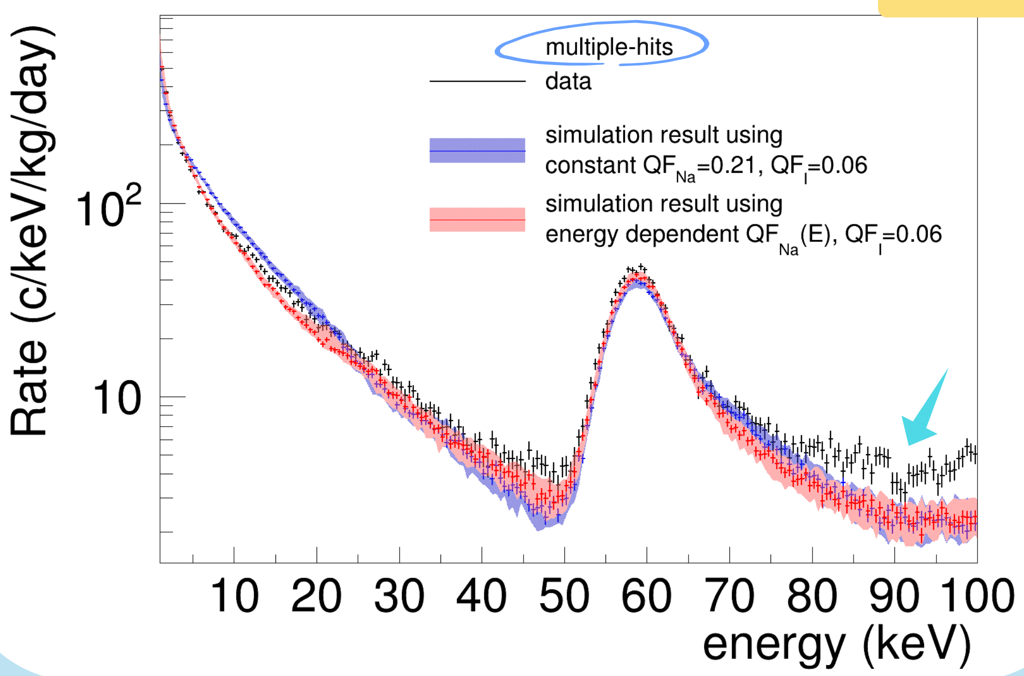
Further investigation is required to better understand multiple-hit events

WORK IN PROGRESS





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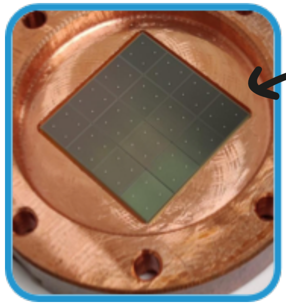

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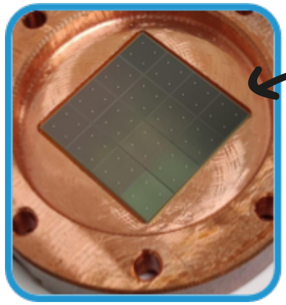

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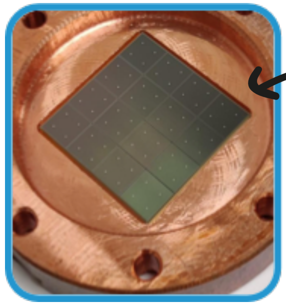

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Studies for the feasibility of this project:

First ANAIS+ prototype analysis

ANAIS+ prototype

- A **prototype** has been built (NaI(Tl) 1'' cube + Hamamatsu SiPMs array + MUSIC readout + optical fiber) and first measurements show the expected behaviour of the SiPMs and NaI(Tl) scintillator with temperature (up to≈ **-40ºC)**

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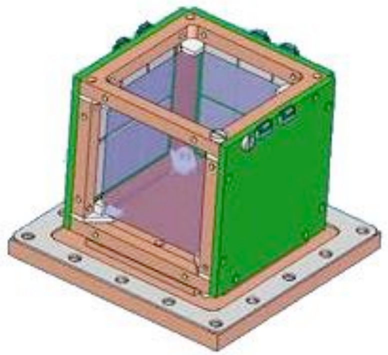
ANAIS+ plans

- A new cooling system will be incorporated, allowing to reduce temperature ≈100 K to explore the properties of NaI – NaI(Tl) + SiPMs down to this temperature

- Assembly of a new prototype, coupling four of the six faces of the NaI cube to SiPMs arrays. As part of a collaboration with the LNGS



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**.

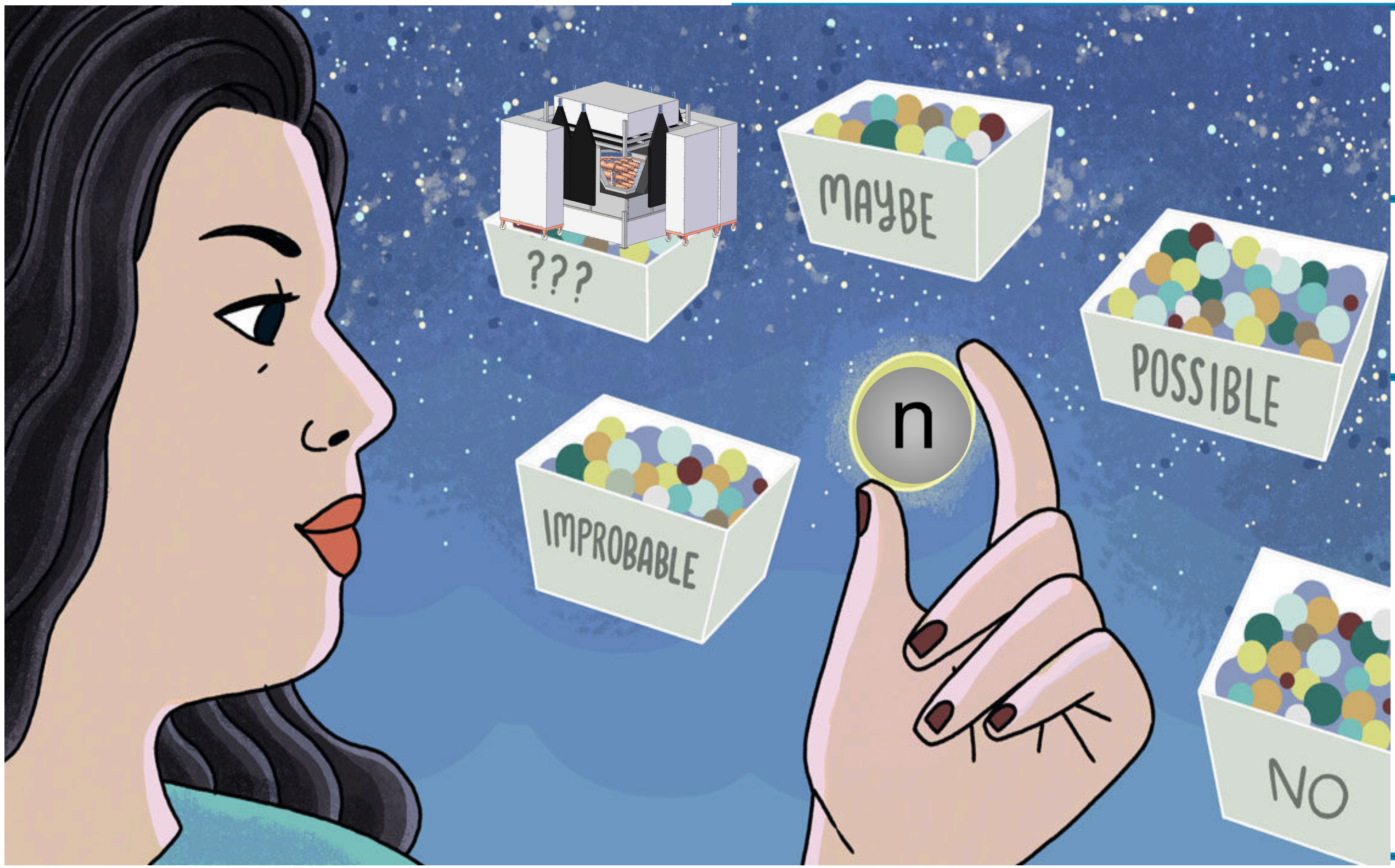
Sensitivity improved with machine-learning techniques. **ANAIS−112 observes no modulation and discards DAMA/LIBRA DM interpretation with $\sim 3\sigma$ sensitivity** in [1-6] keV ([2-6] keV). **For the first time, a direct test (i.e. model independent) of DAMA is at reach with $>3\sigma$ sensitivity.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

Neutron calibrations onsite have been performed using 252Cf 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 proben 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.

Stay Tuned!

Thank you for your attention! ? ? ?



Tamara Pardo on
behalf of the ANAIS research team

Saturnalia 2023 Workshop, Zaragoza
18 December-21 December 2023

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

^{252}Cf source

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

Non-prop

1

Calibrations

Prop

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Ba133
6.6, 30.8, 35.1 keV

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cross-check !!

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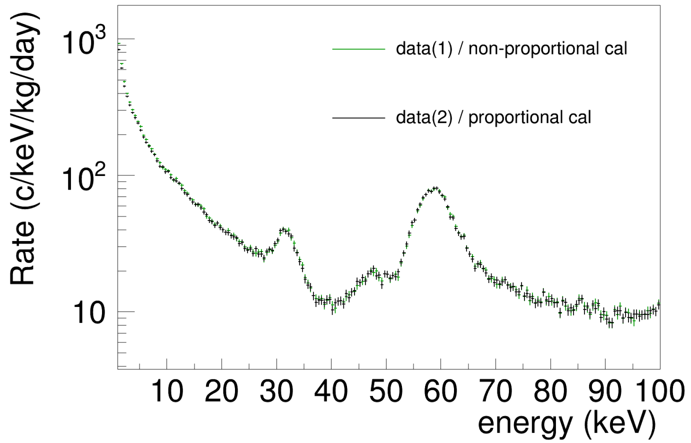

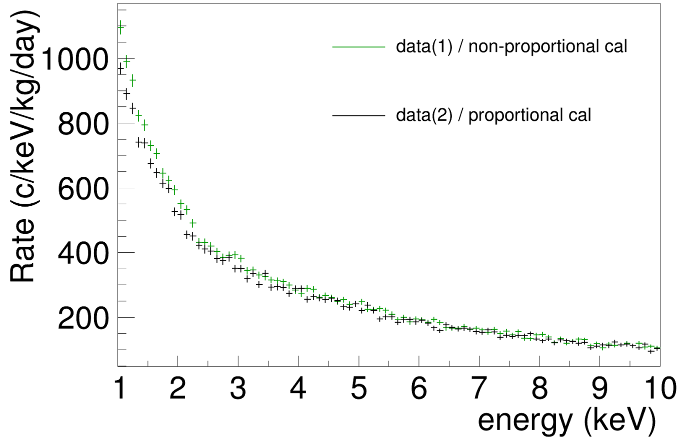

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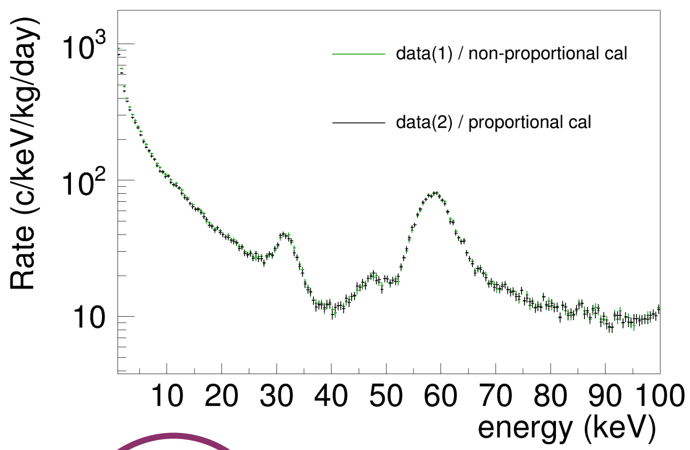

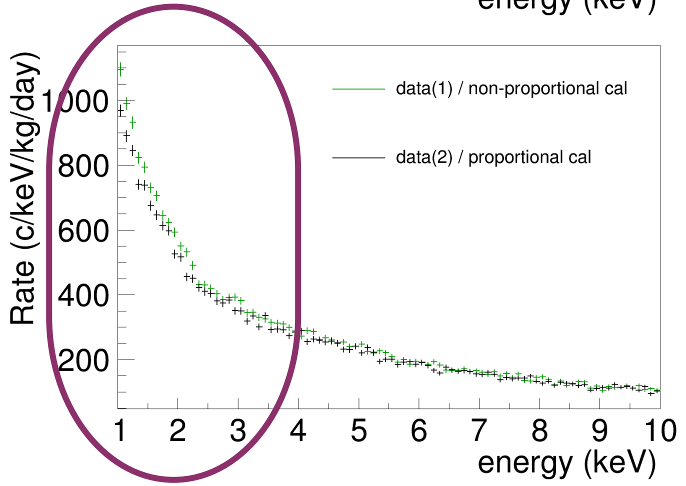

We will show **non-proportional** calibration

Bulk calibration

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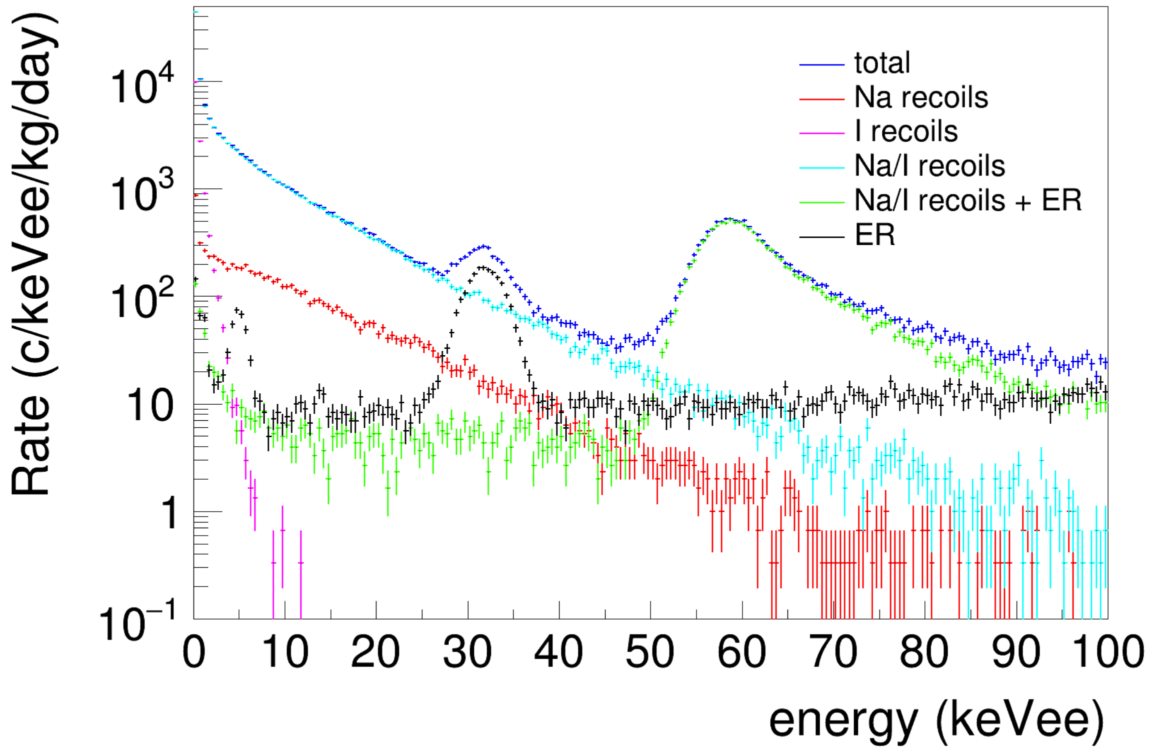
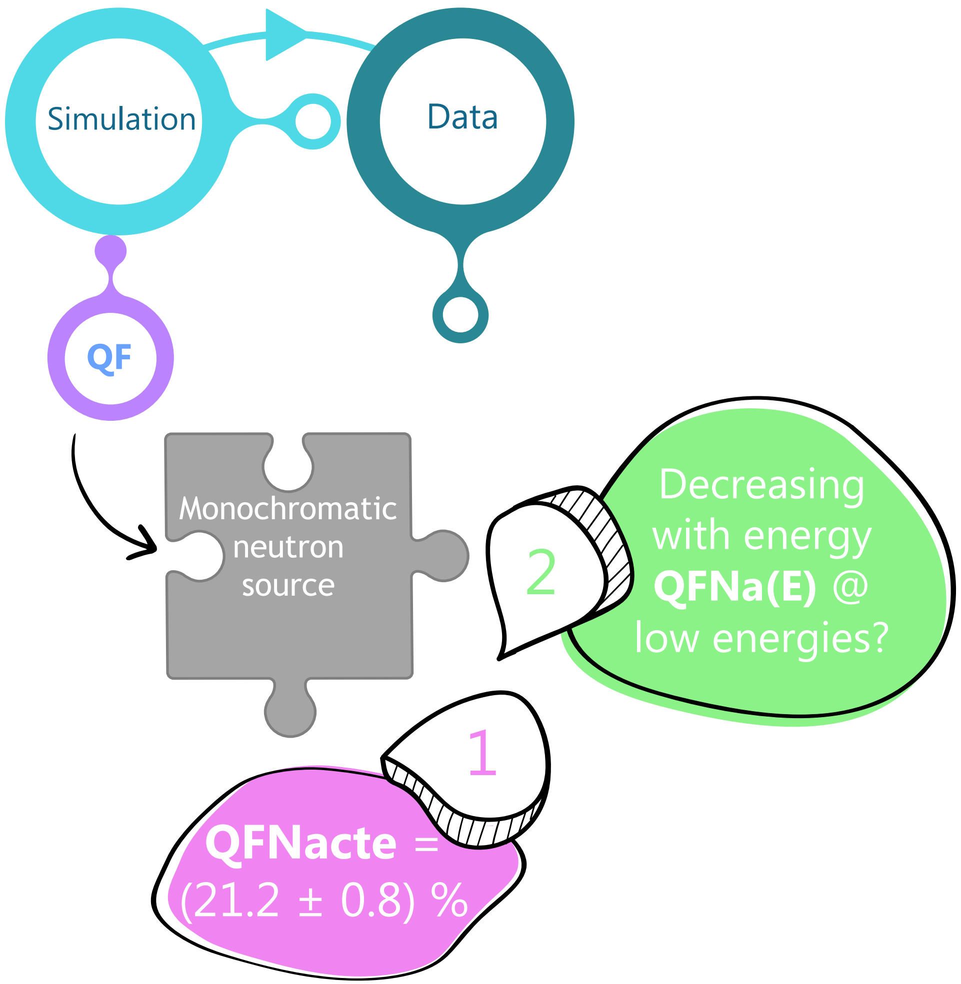


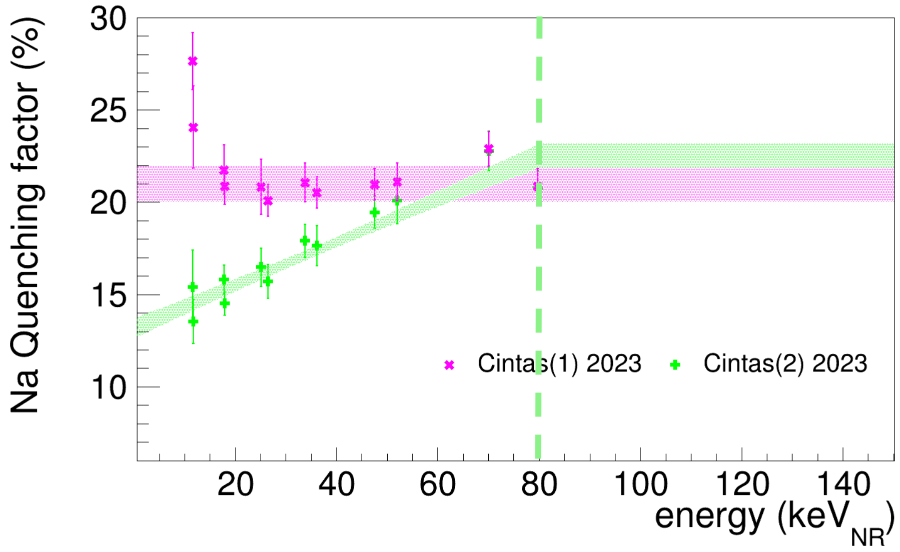
$E_{ee} = QF \times E_{NR}$

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

Nuclear recoils are dominant up to 50 keVee

Results on the quenching factor





Uncertainty in QFNa(E) modelling

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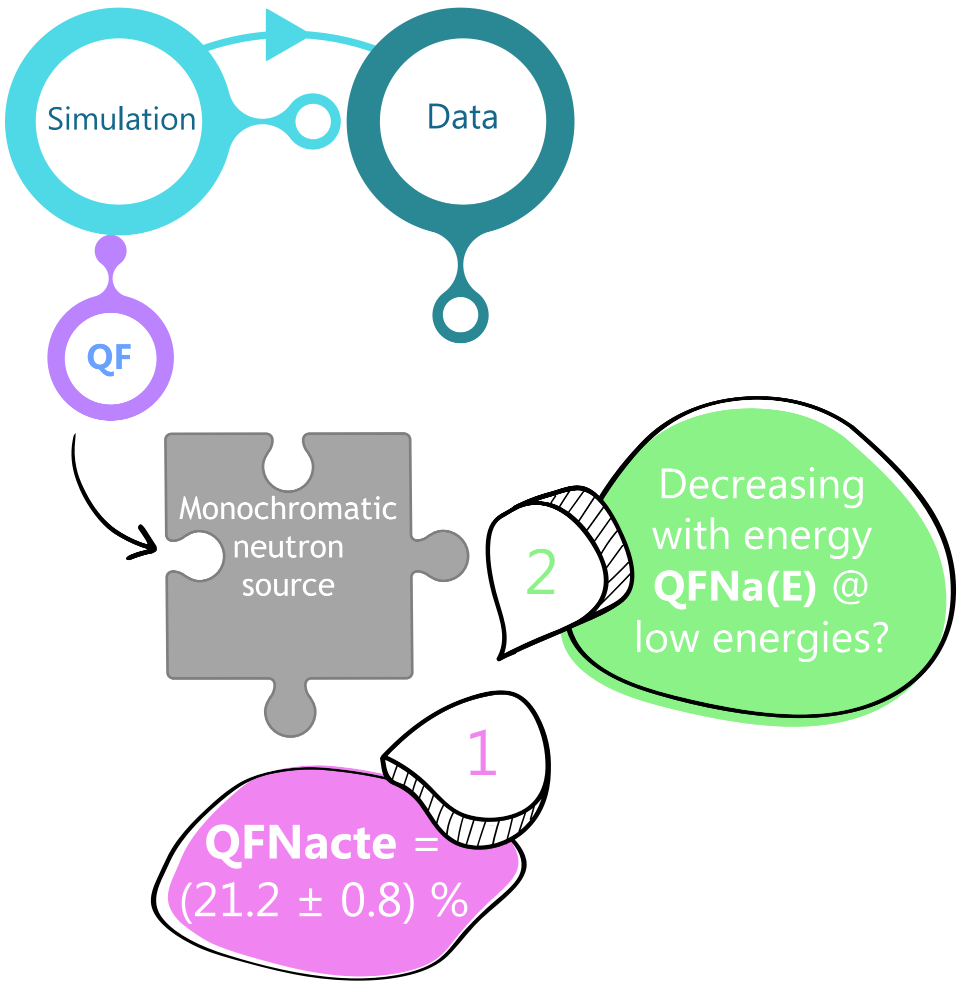

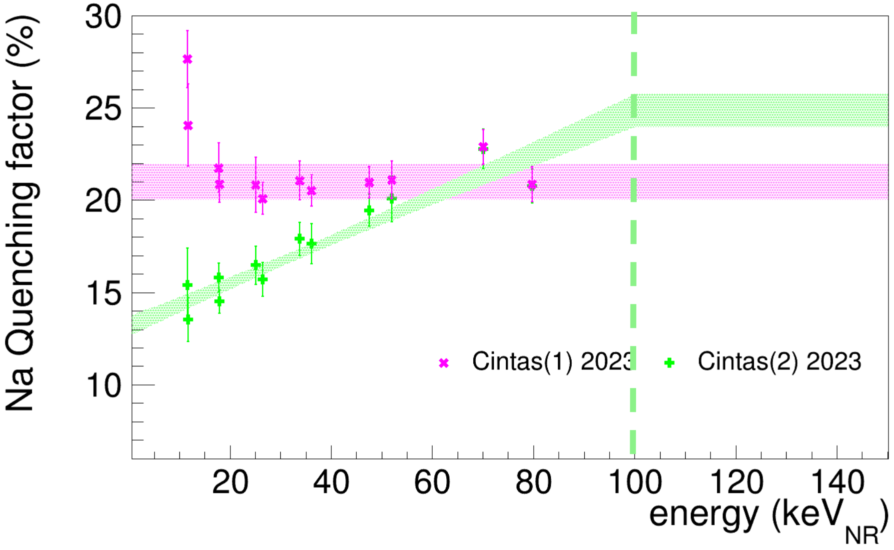

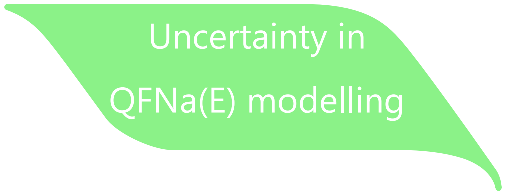

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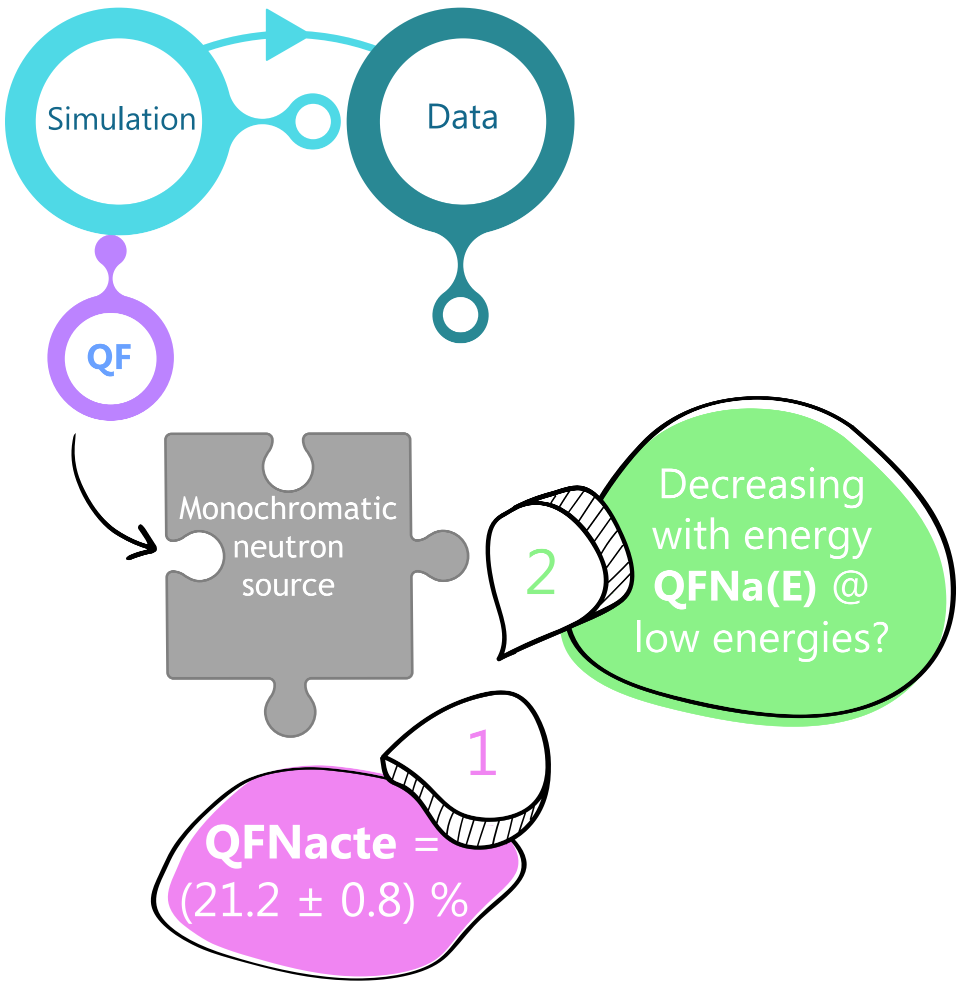

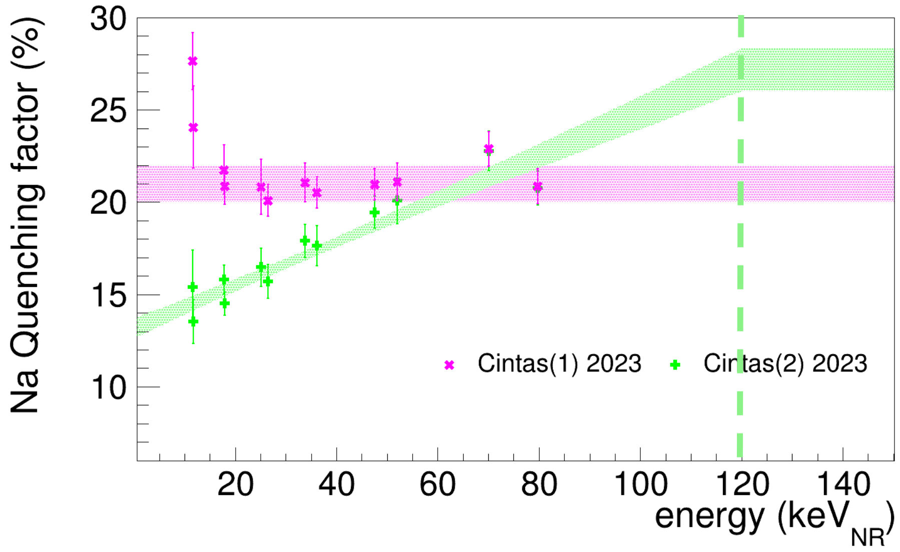

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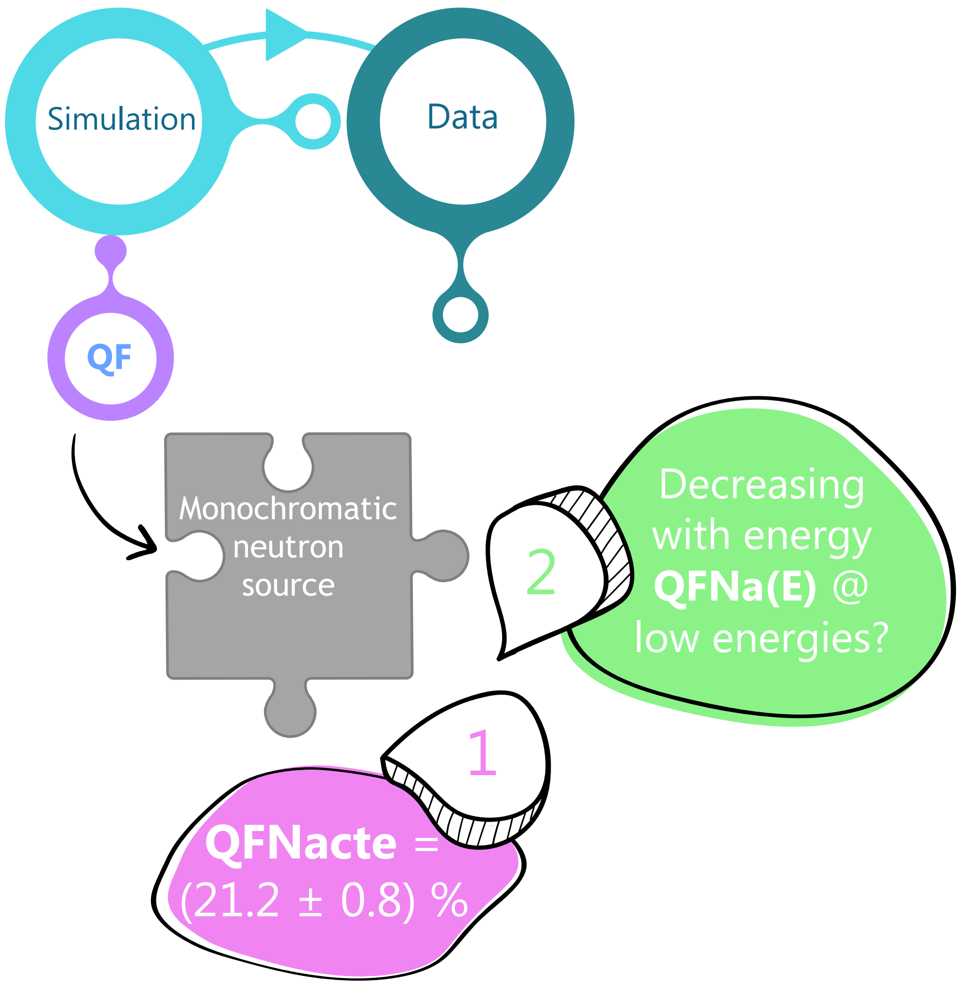

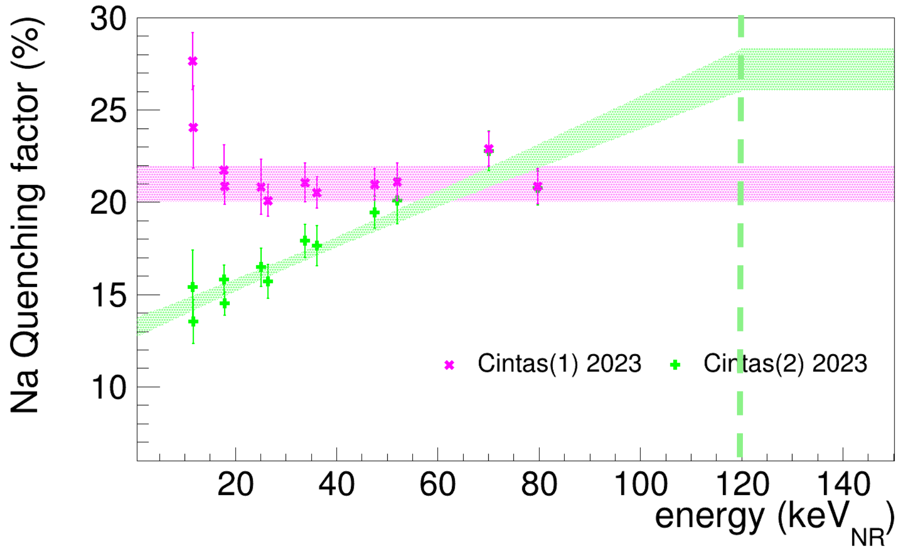

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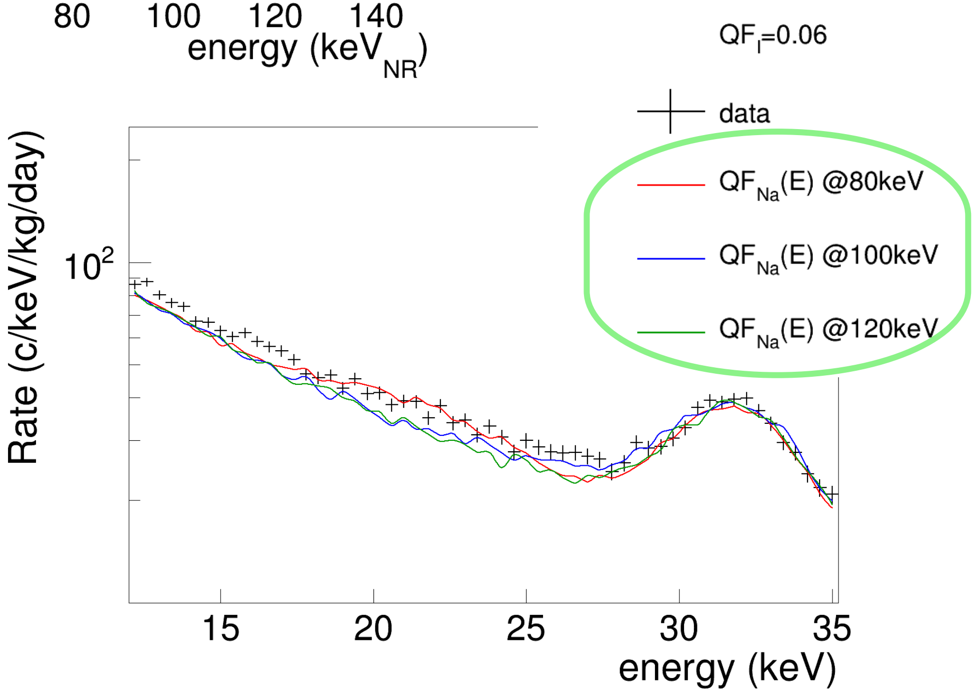

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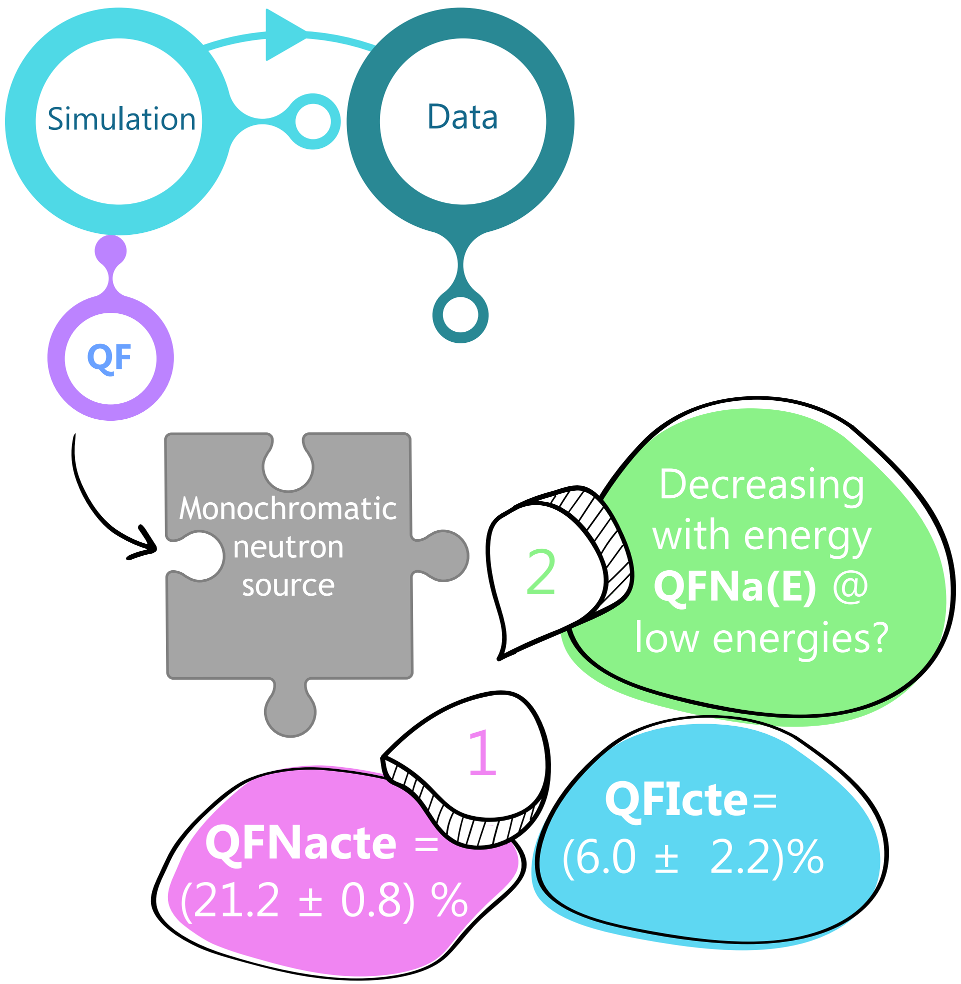
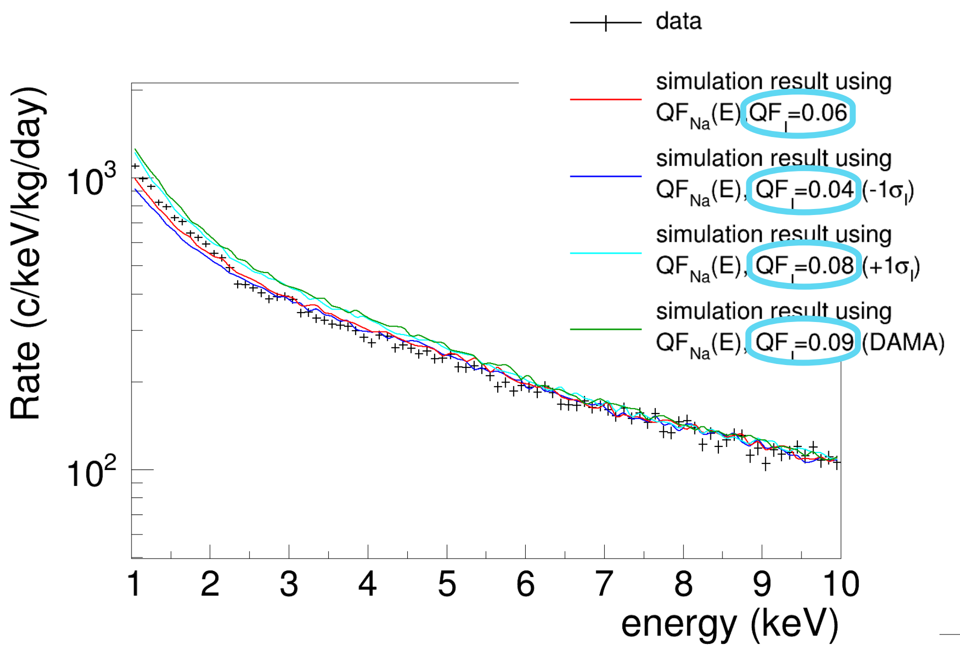
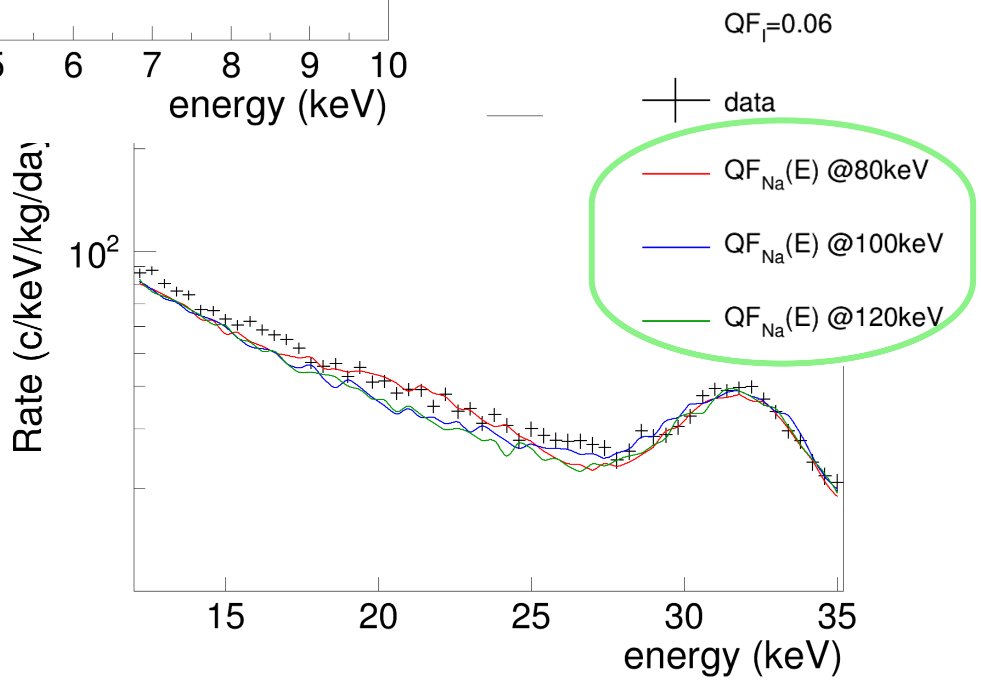
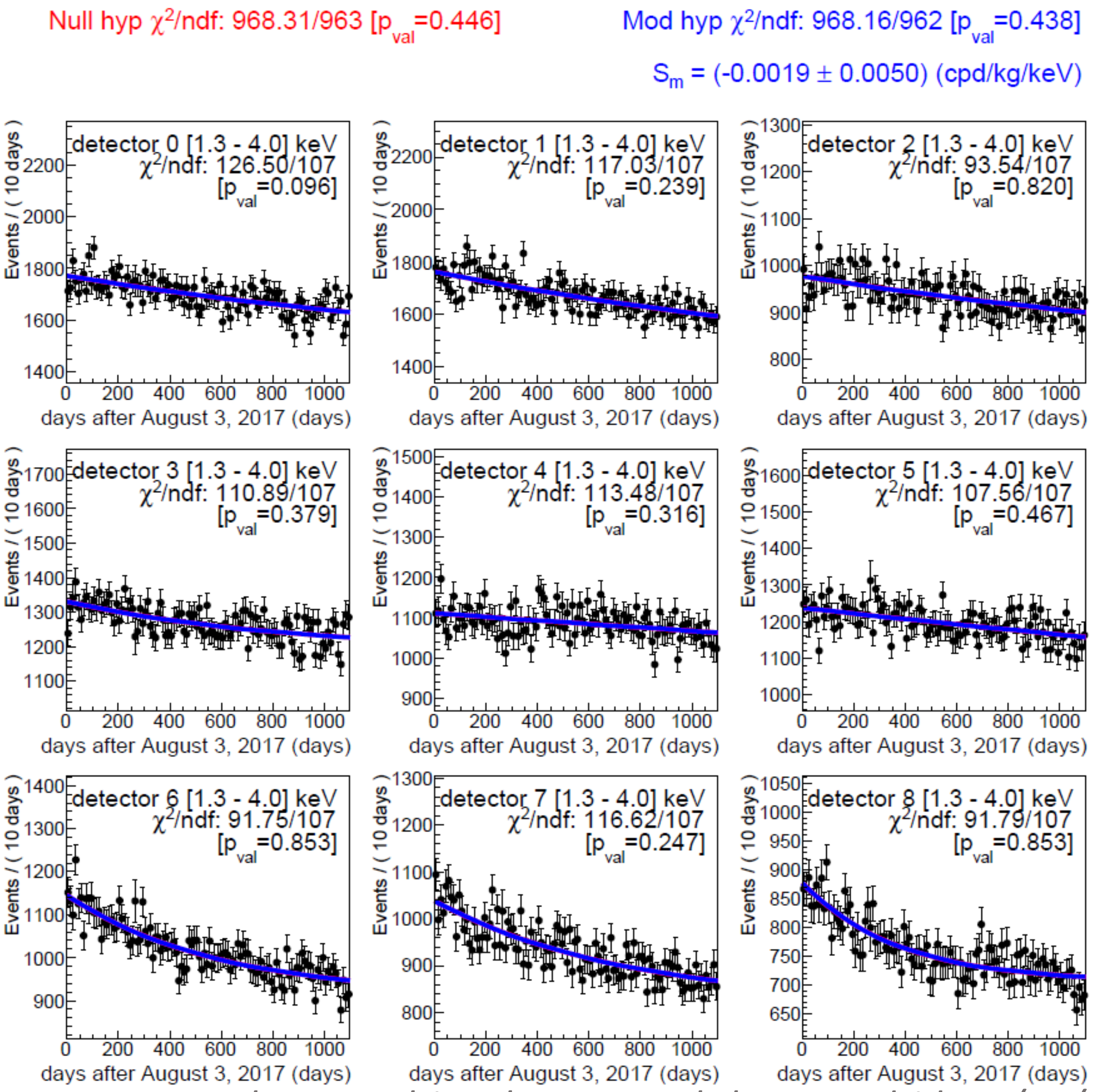




Iodine QF has influence only at very low energies (<10 keVee)



3-year annual modulation analysis in 1.3 – 4 keV



Preliminary

Supposing:

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

DAMA $[2-6]$ keV $\longrightarrow$ 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)
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- 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:

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

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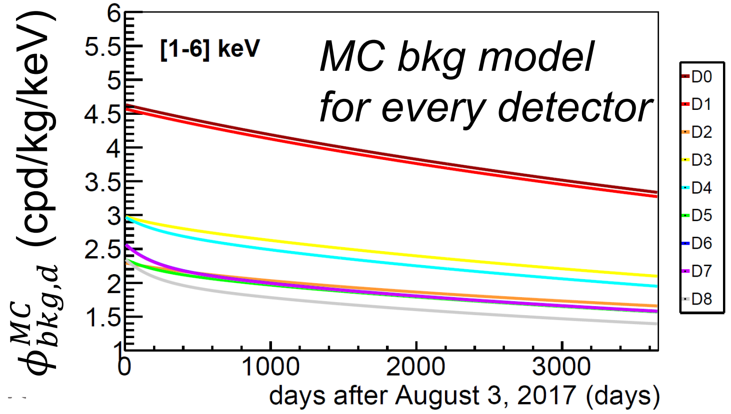
  - Fix period 1 year and phase to June 2nd
- Simultaneous fit of the 9 detectors in 10-day bins. Chi-square minimization: $\chi^2 = \sum_i (n_i - \mu_i)^2/\sigma_i^2$, where the expected number of events μ_i for detector d in time bin i is given by:

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

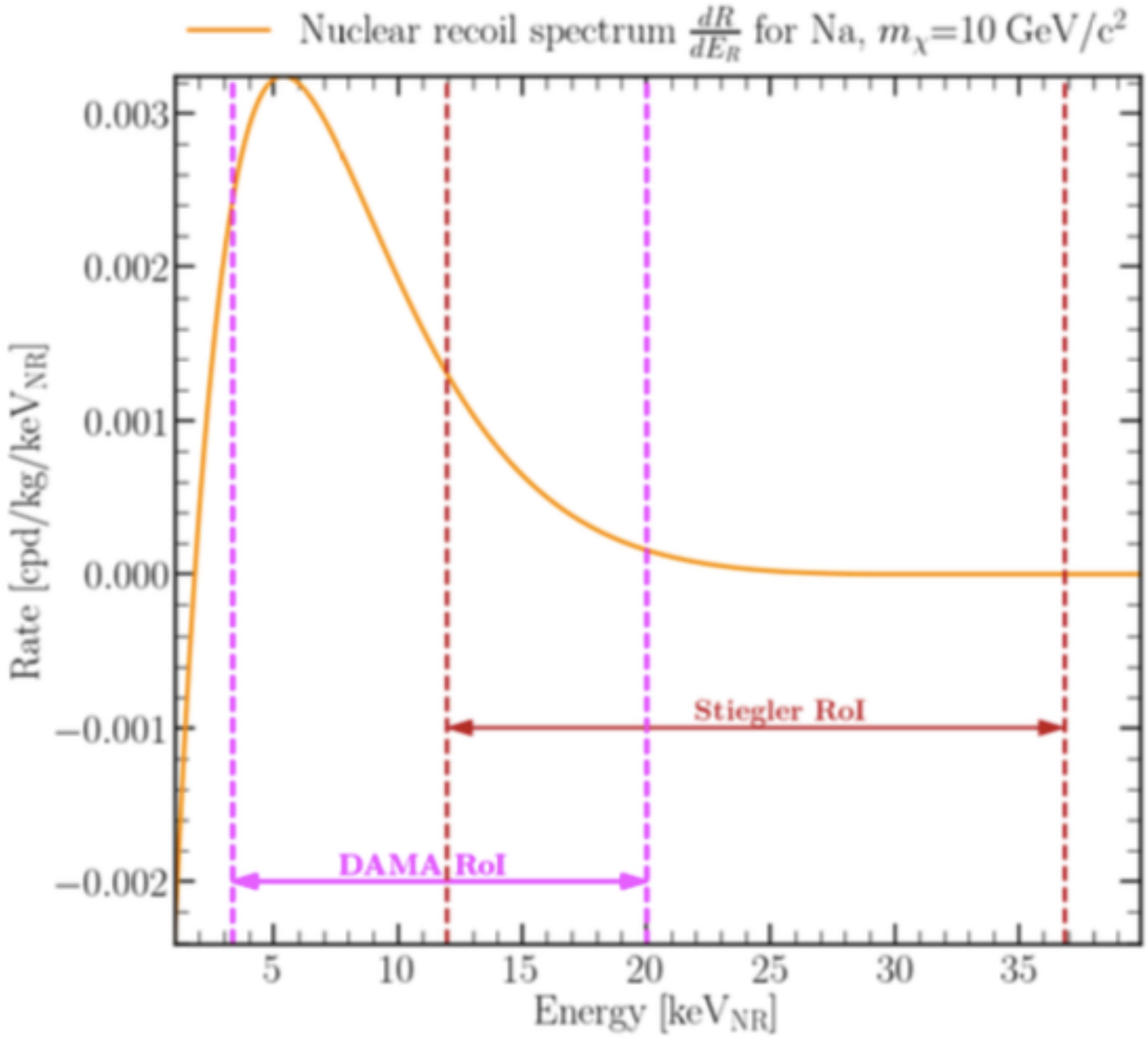
Constant background (long-lived isotopes and residual noise)

Decaying background, modeled by MC

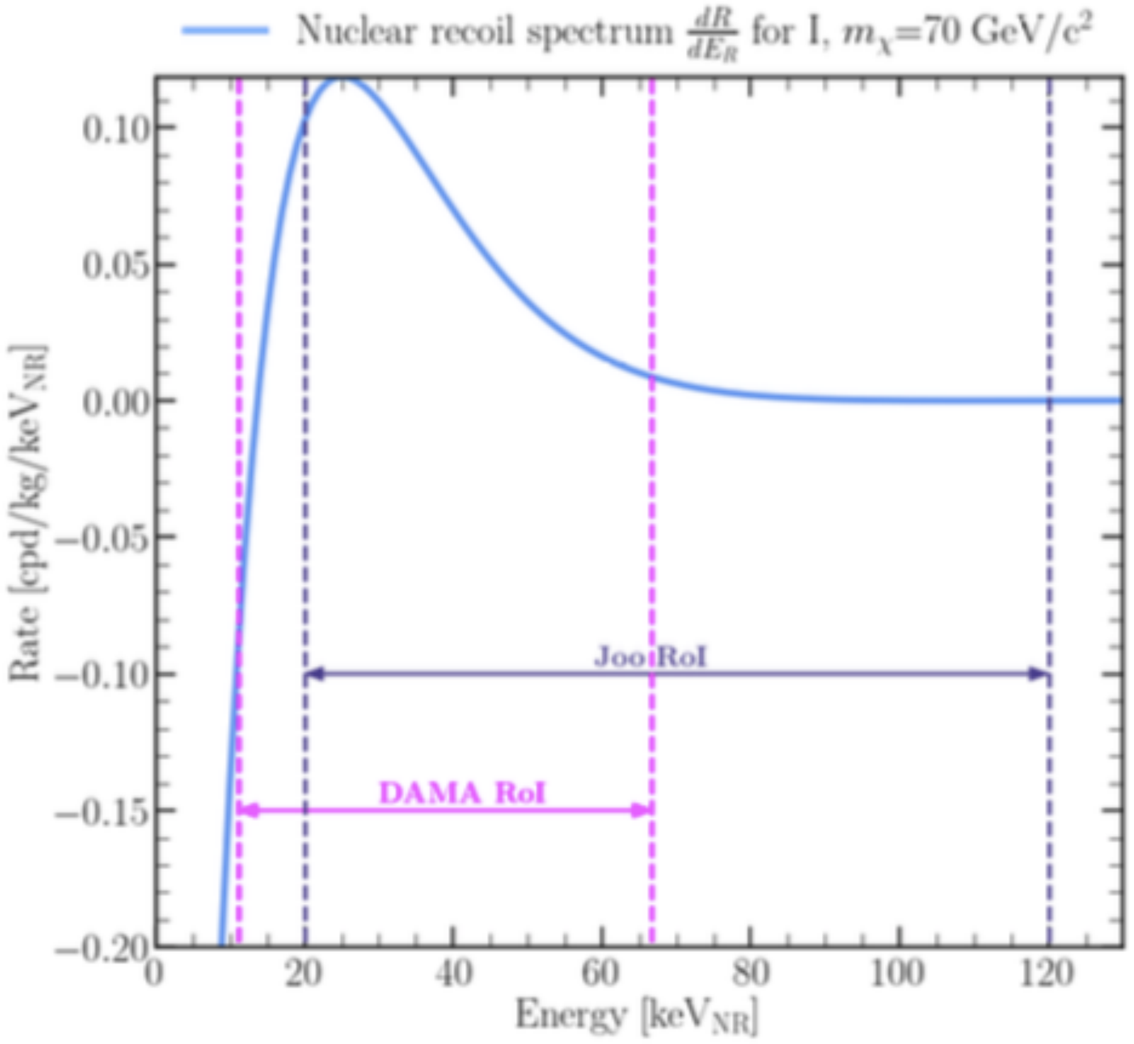
Modulation signal (fixed period and phase)

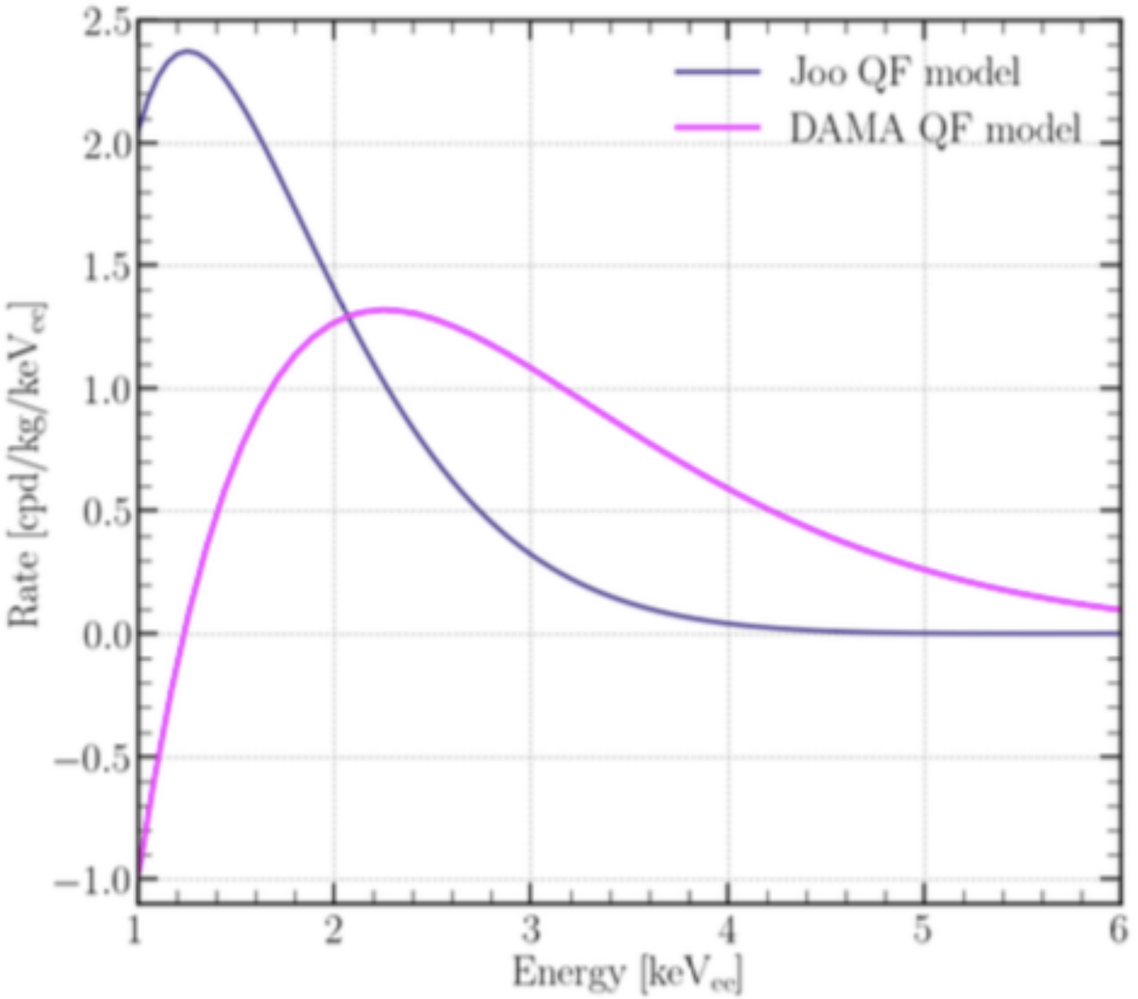


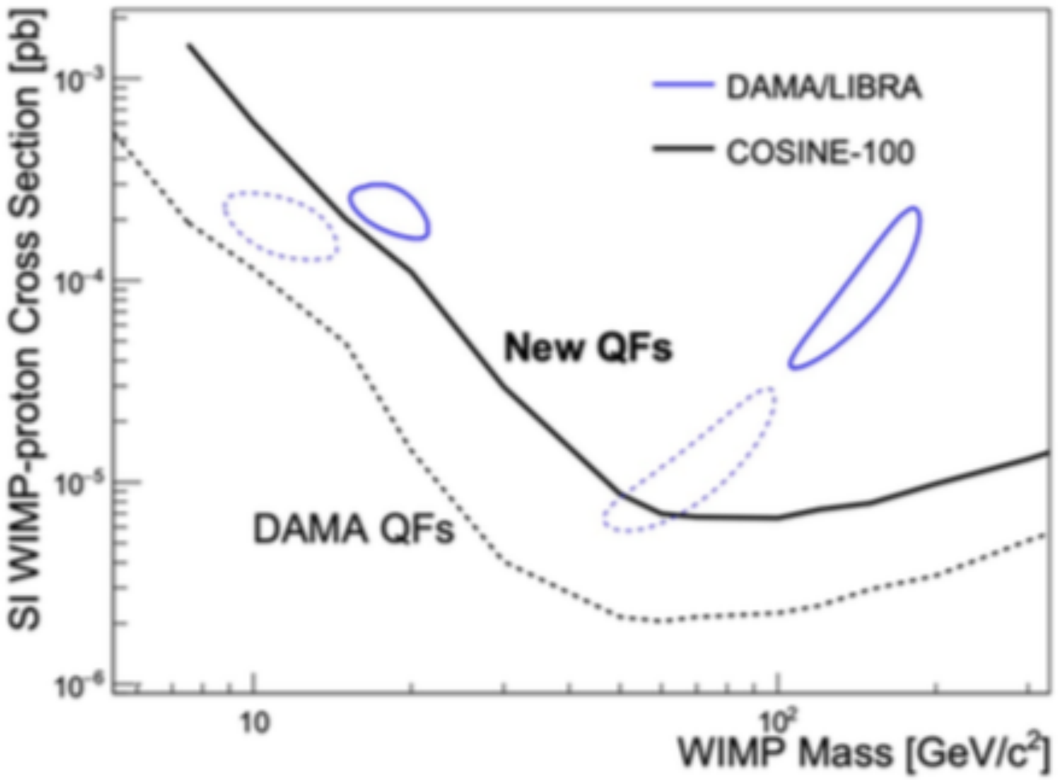
19 free parameters: $R_{0,d}, f_d, S_m$



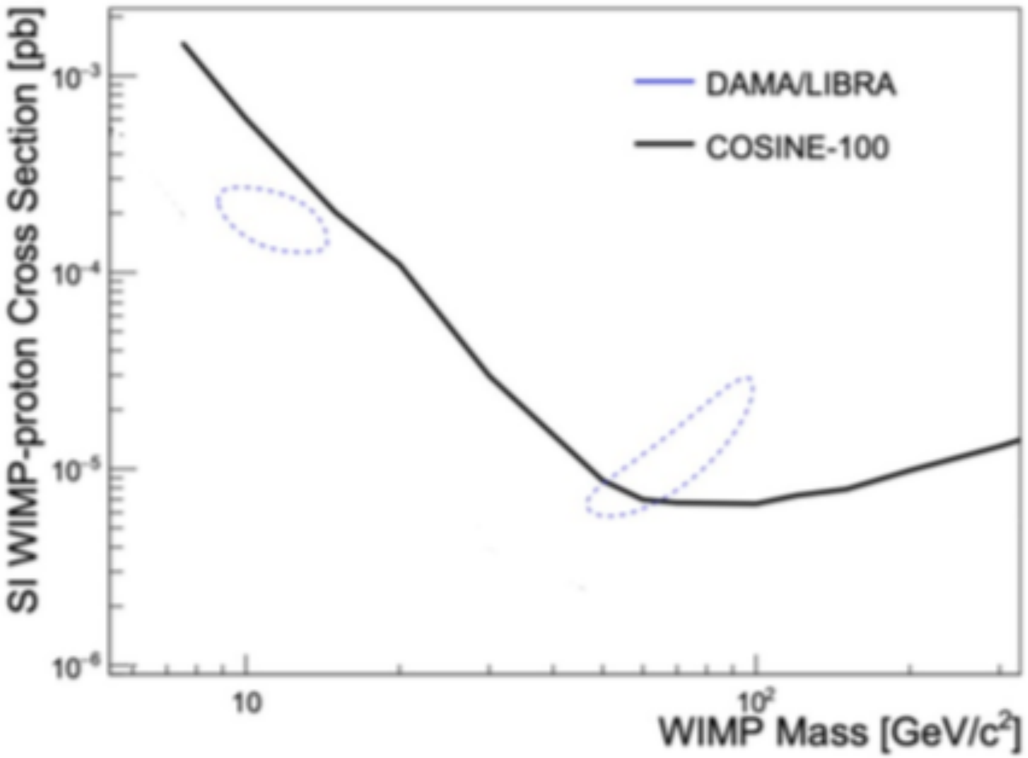
Nuclear recoil spectrum $\frac{dR}{dE_R}$ for Na, m_χ=10 GeV/c^2
Rate [cpd/kg/keV$_{NR}$]
0.003
0.002
0.001
0.000
−0.001
−0.002
Stiegler RoI
DAMA RoI
5
10
15
20
25
30
35
Energy [keV$_{NR}$]


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