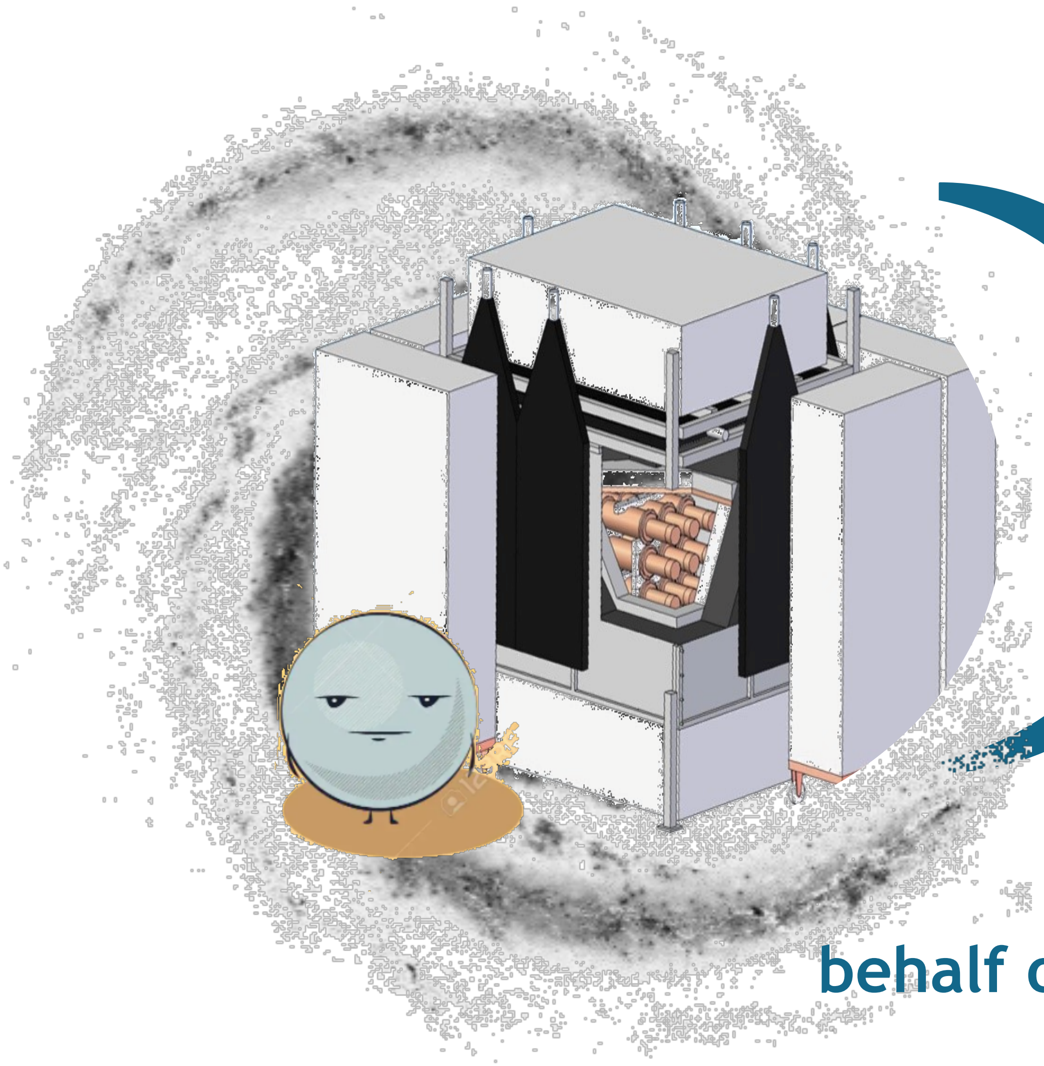


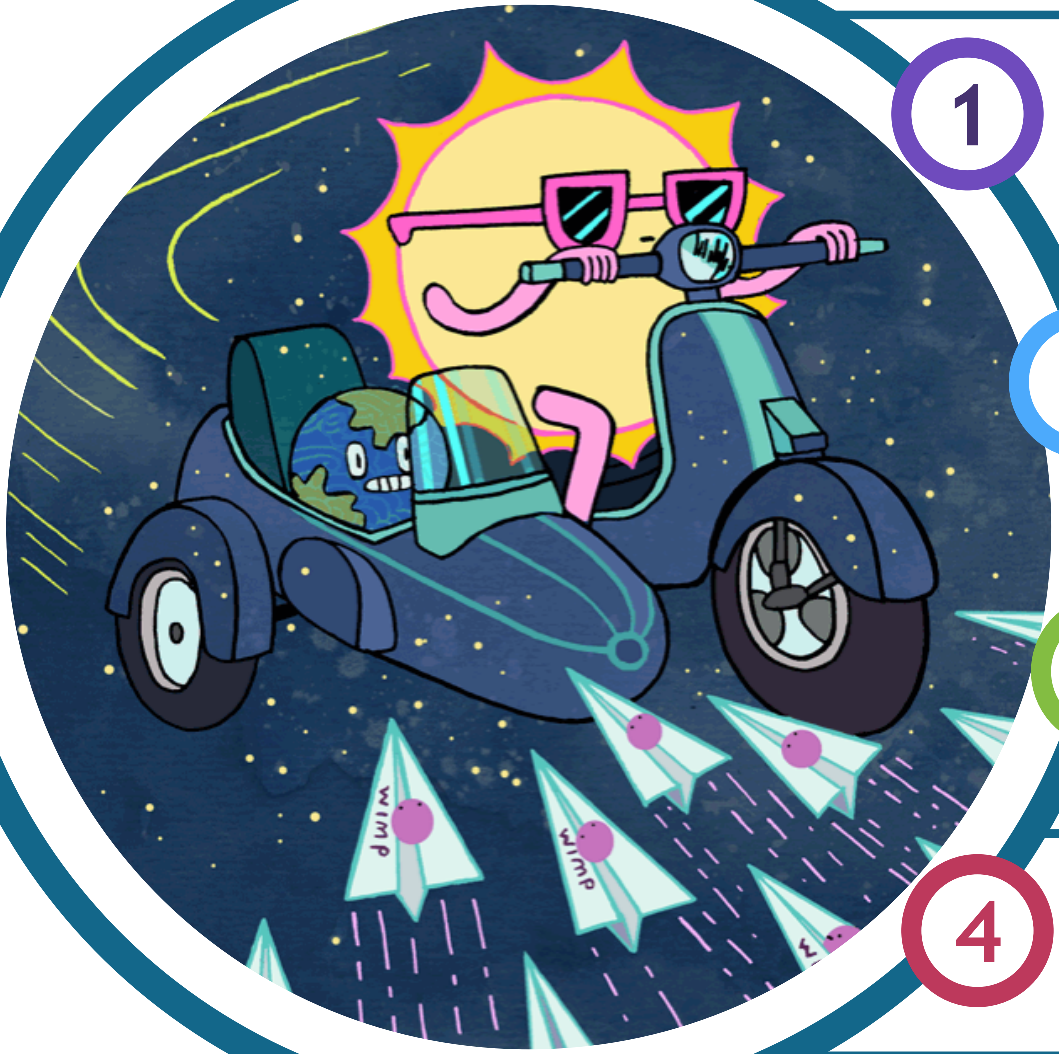
Calibrating the ANAIS-112 experiment with neutrons

Tamara Pardo on behalf of the ANAIS research team

J. Amaré, 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

19TH MULTIDARK CONSOLIDER WORKSHOP
CRISTALERA UAM (MIRAFLORES DE LA SIERRA), MADRID
23-25 MAYO, 2022

MINISTERIO DE CIENCIA E INNOVACIÓN
UNIÓN EUROPEA Fondo Social Europeo El FSE invierte en tu futuro
AGENCIA ESTATAL DE INVESTIGACIÓN
CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza
LSC Laboratorio Subterráneo de Canfranc
MultiDark Multimessenger Approach for Dark Matter Detection



1 STATUS OF THE ANAIS-112 EXPERIMENT

ANAIS-112 three year results – annual modulation analysis

2 NEUTRON CALIBRATION PROGRAM

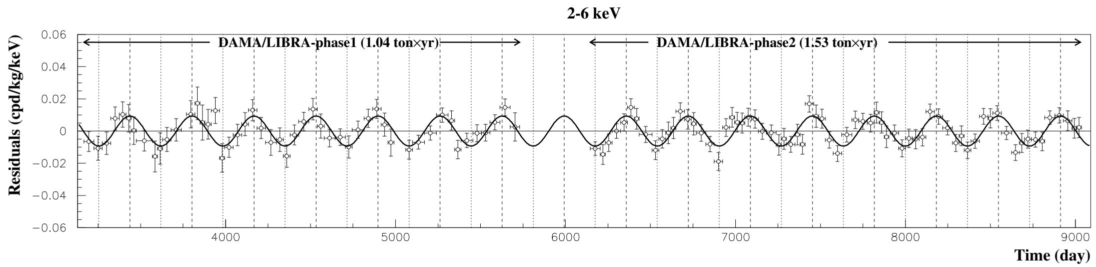
3 ultimate goals

3 RESULTS ON THE QUENCHING FACTOR

Testing different QF models by the comparison between data and simulations

4 CONCLUSIONS

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)



The data of DAMA/LIBRA 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**

Universe 4, 116 (2018), 1805.10486
Progress in Particle and Nuclear Physics 114 (2020)
arXiv:2110.04734

Annual Modulation with NaI Scintillators

STATUS OF THE ANAIS-112 EXPERIMENT

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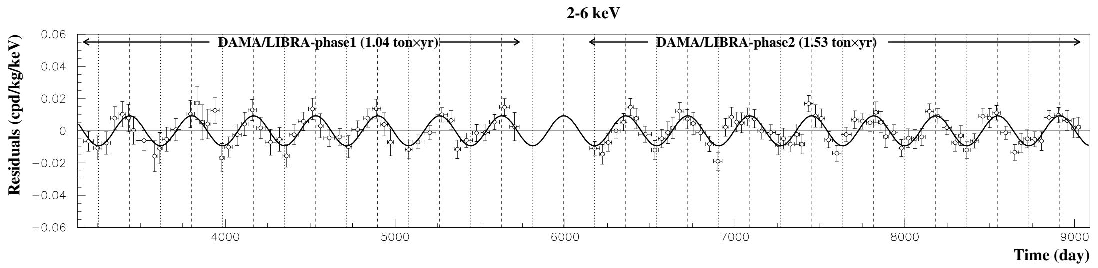

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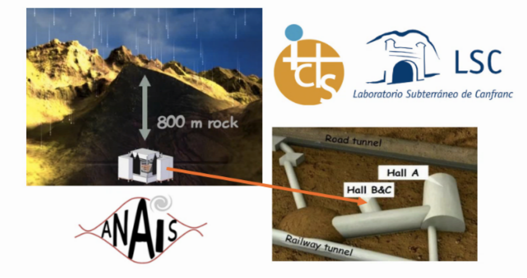
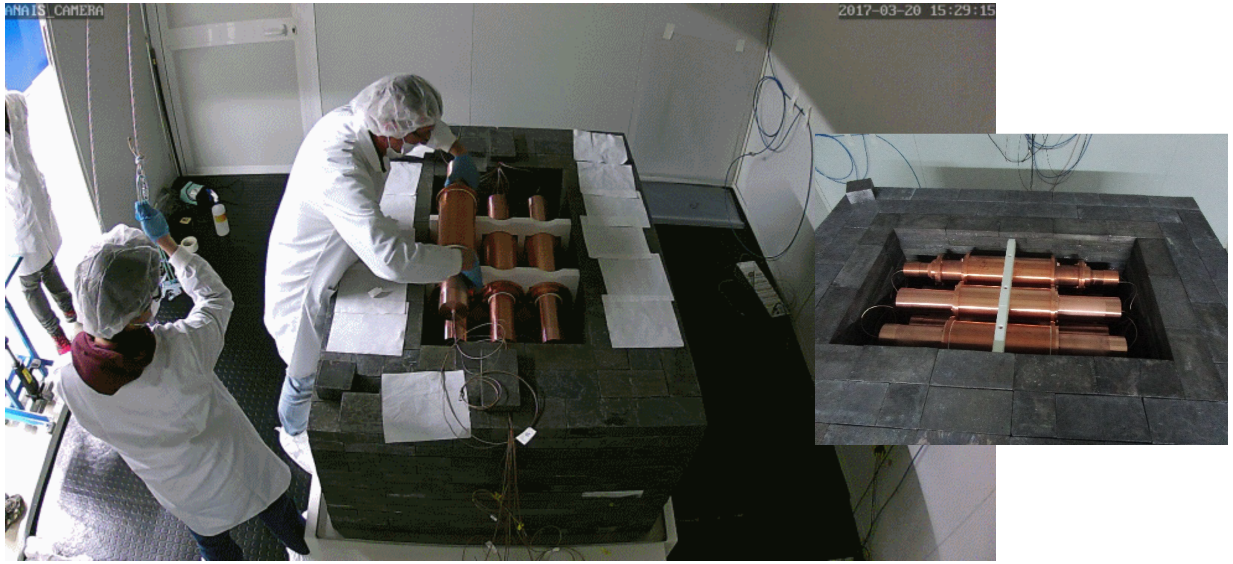


- At **Canfranc Underground Laboratory**, @ SPAIN (2450 m.w.e.)
- Data taking started **3rd August 2017**
- **>4 years** of data-taking with excellent duty cycle, **95% live time**

Annual Modulation with NaI Scintillators

STATUS OF THE ANAIS-112 EXPERIMENT

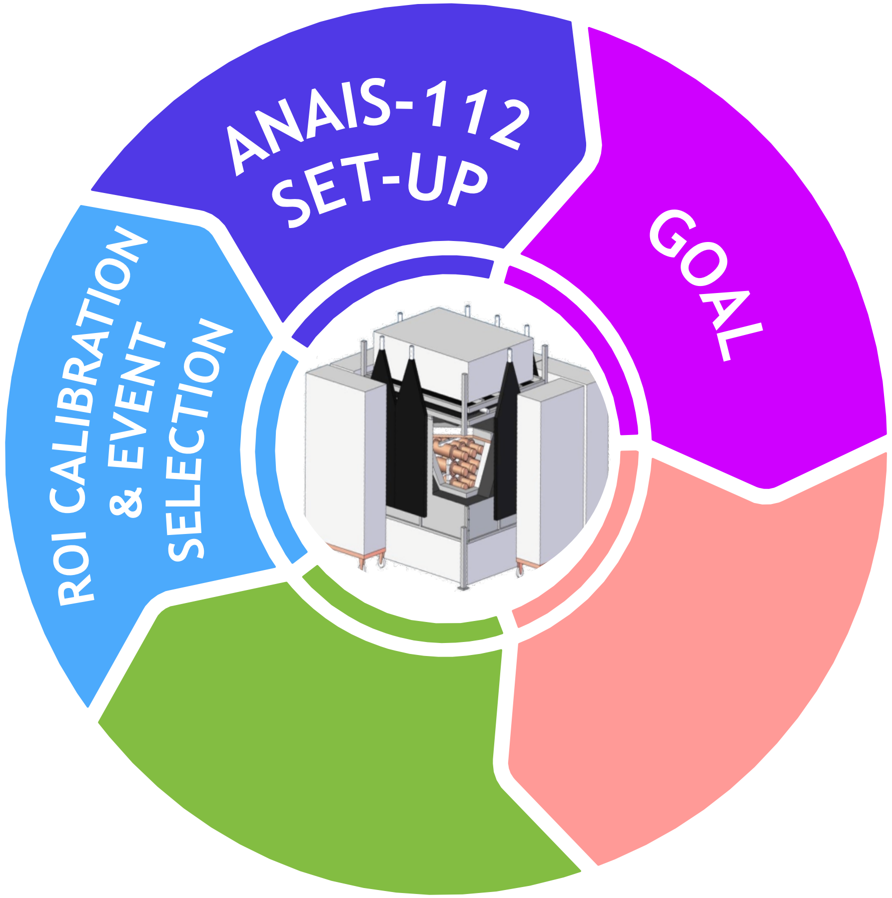


- 3x3 matrix of 12.5 kg **NaI(Tl)** cylindrical modules
- = **112.5 kg** of active mass
- **High QE-PMTs** coupled
- **30 cm lead**
- Tight **box** preventing **Radon** entrance
- **40 cm PE/water**
- **16** plastic scintillators acting as muon **veto** system

STATUS OF THE ANAIS-112 EXPERIMENT

J. Amaré et al., EPJC79 (2019) 228

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



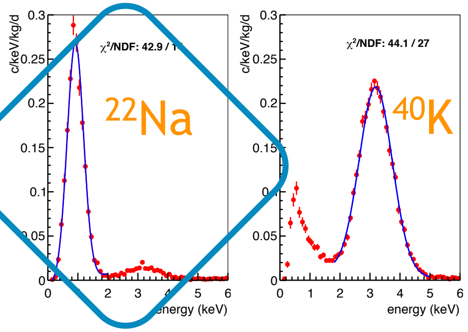
STATUS OF THE ANAIS-112 EXPERIMENT

J. Amaré et al., EPJC79 (2019) 228

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

- Current ANAIS-112 ROI calibration (1-6 keV) relies on electron recoils populations

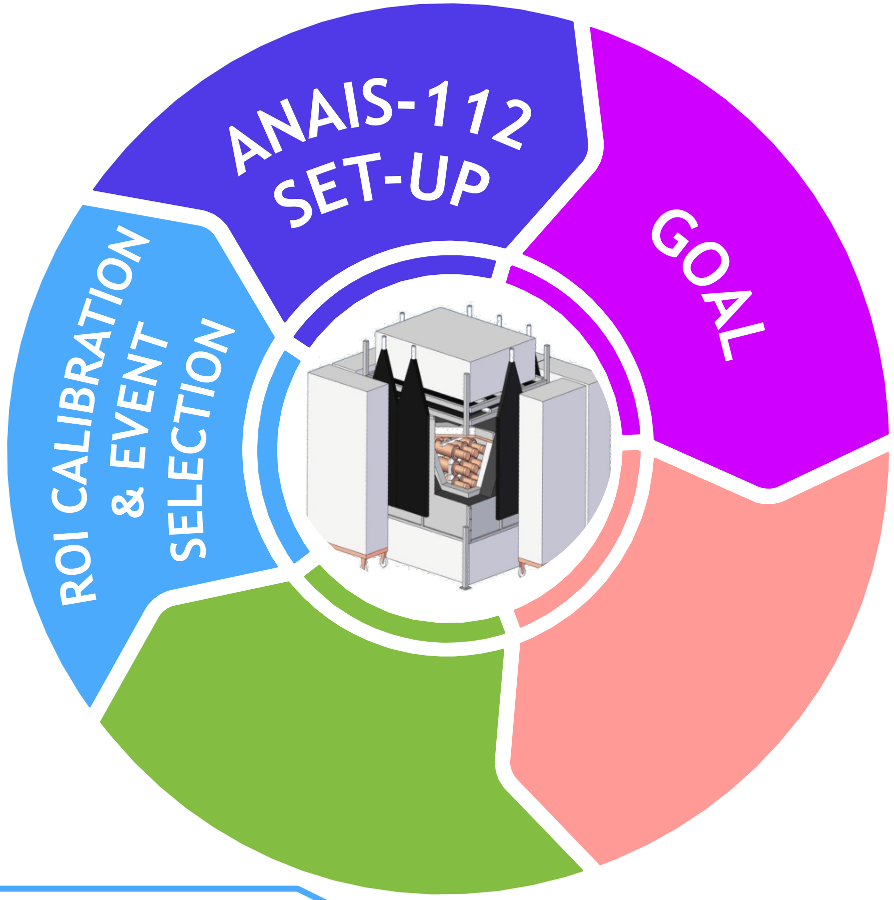
periodical external calibration using ^{109}Cd (11.9 and 22.6 keV) + ^{22}Na (0.87 keV) and ^{40}K (3.20 keV) internal contamination bkg lines



Effectively triggering below 1 keVee

- Both, ANAIS & DAMA/LIBRA spectra, are calibrated with X/γ sources, so are given in keVee(*)

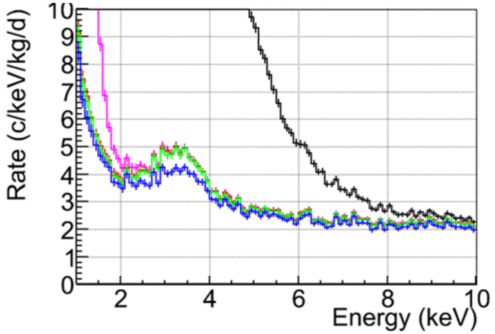
(*) keVee: electron-equivalent keV

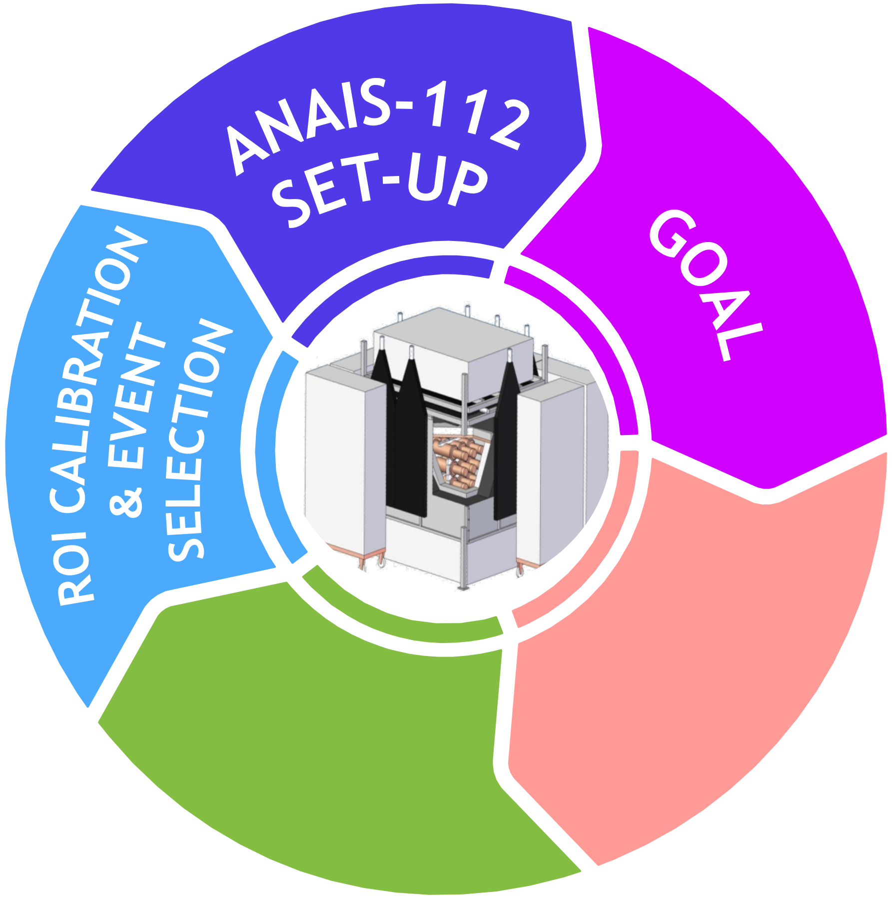


J. Amaré et al., EPJC79 (2019) 228

- **Trigger rate** in the ROI dominated by **non-bulk** scintillation events
- **Filtering protocols** based on **pulse shape** and **asymmetry**

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





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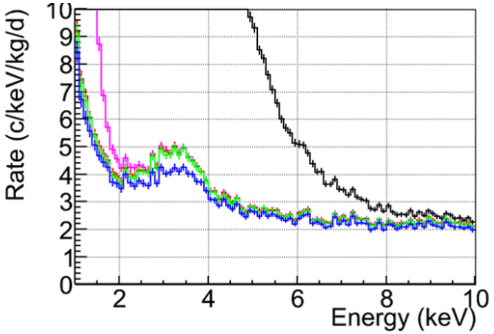
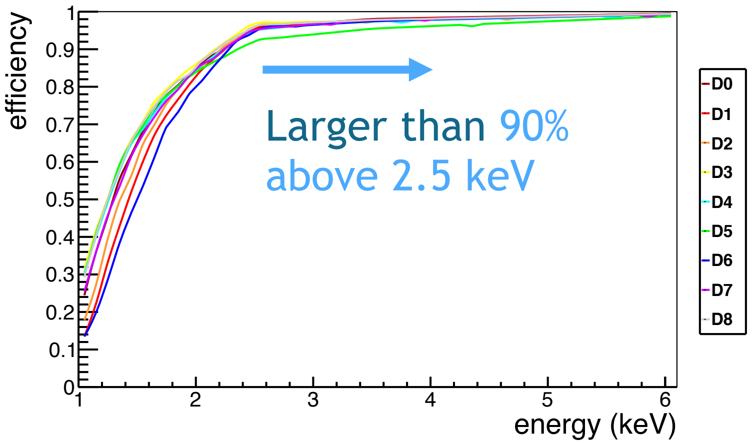
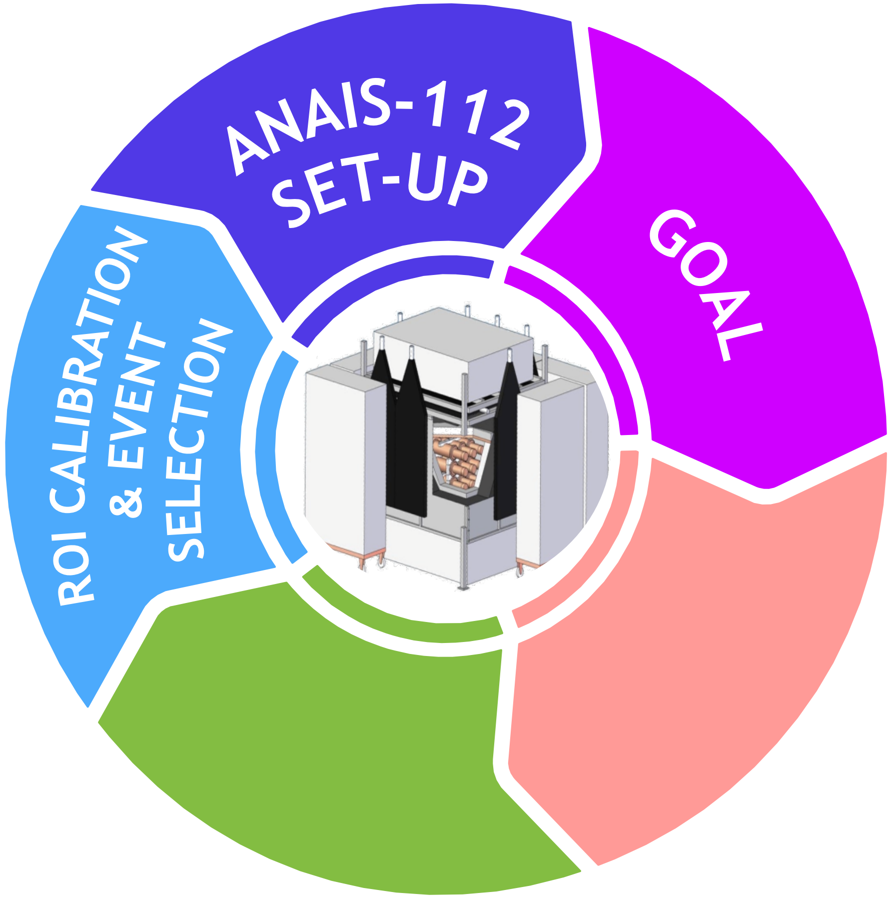




Efficiency calculations are also based on electron recoils populations

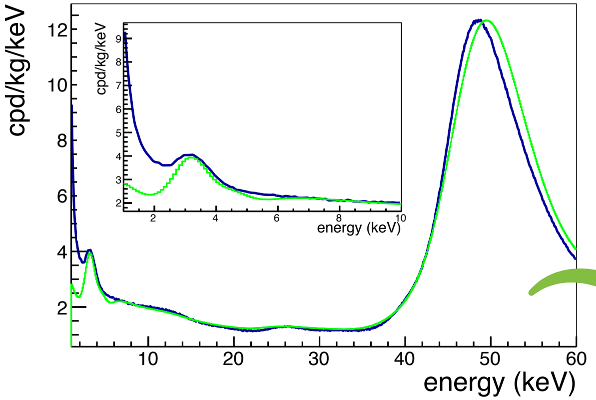
multiplicity -2 events
^{109}Cd calibration



STATUS OF THE ANAIS-112 EXPERIMENT

J. Amaré et al., EPJC79 (2019) 412

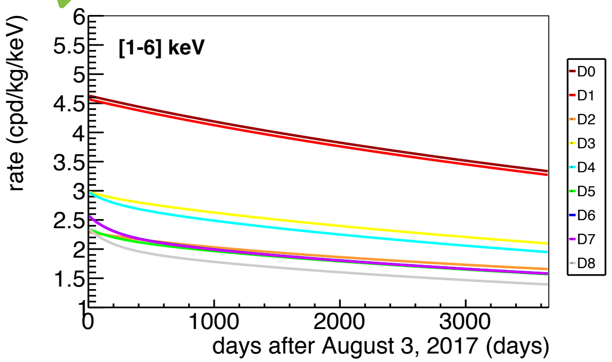
- Good agreement with data above 2 keV
- Strong discrepancy in [1-2] keV



10% unblinded data randomly distributed

ANAIS-112 data
ANAIS-112 MC model

Our model predicts time evolution of the background detector by detector and reproduce satisfactorily the time evolution (also outside the ROI)



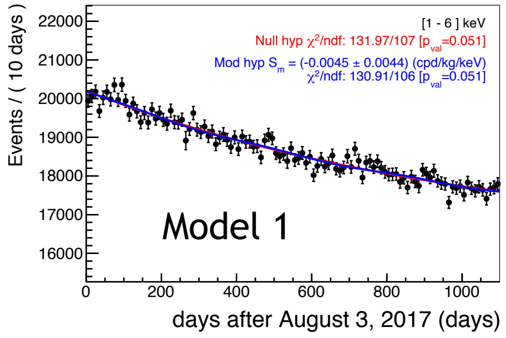
STATUS OF THE ANAIS-112 EXPERIMENT

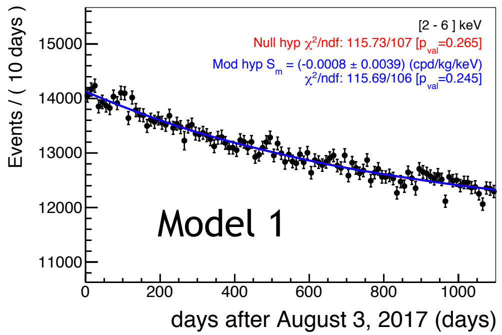
J. Amaré et al. Physical Review D 103 (2021) 102005
Phys. Rev. Lett. 123 (2019) 031301

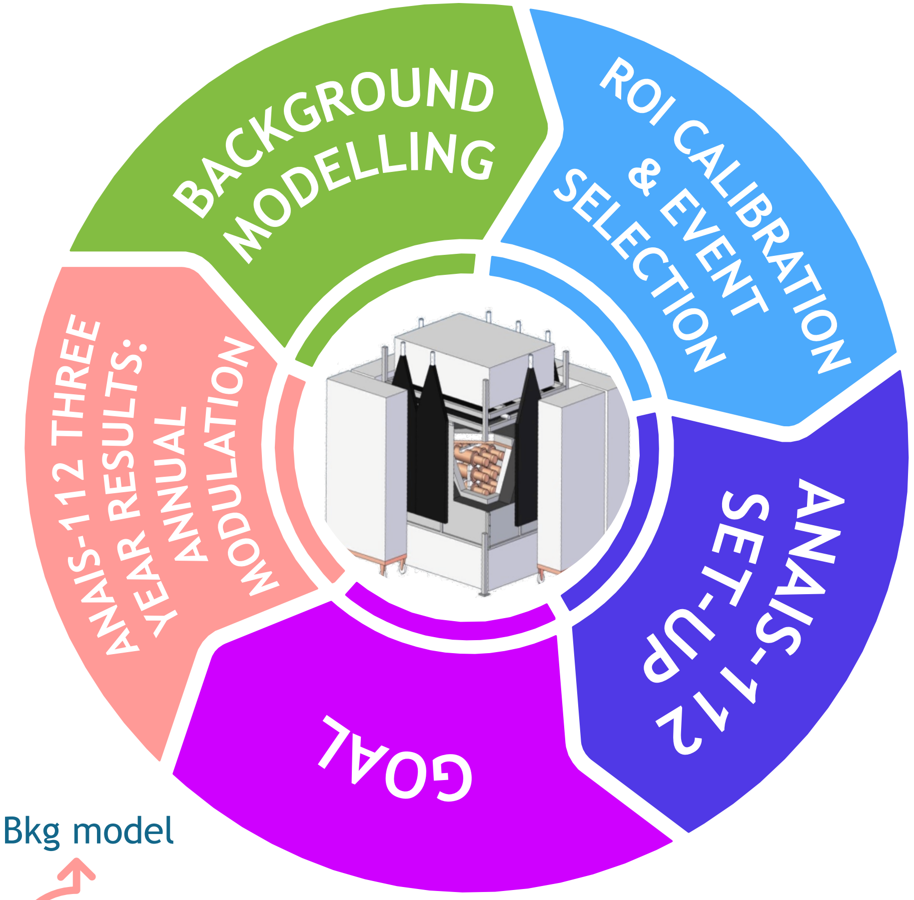
Data support the absence of modulation in both energy regions and for three background models (all of them provide compatible results)

- Model 1: assume exponential decay
- Model 2: Use MC simulation
- Model 3: simultaneous fit using data and bkg model separatedly for every detector -> is taken to quote final result

Energy region	Model	χ^2/NDF null hyp	Nuisance params.	S_m cpd/kg/keV	p value mod	p value null
[1–6] keV	1	132 / 107	3	-0.0045±0.0044	0.051	0.051
	2	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	3	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2–6] keV	1	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	2	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	3	1018 / 972	18	0.0003±0.0037	0.14	0.15



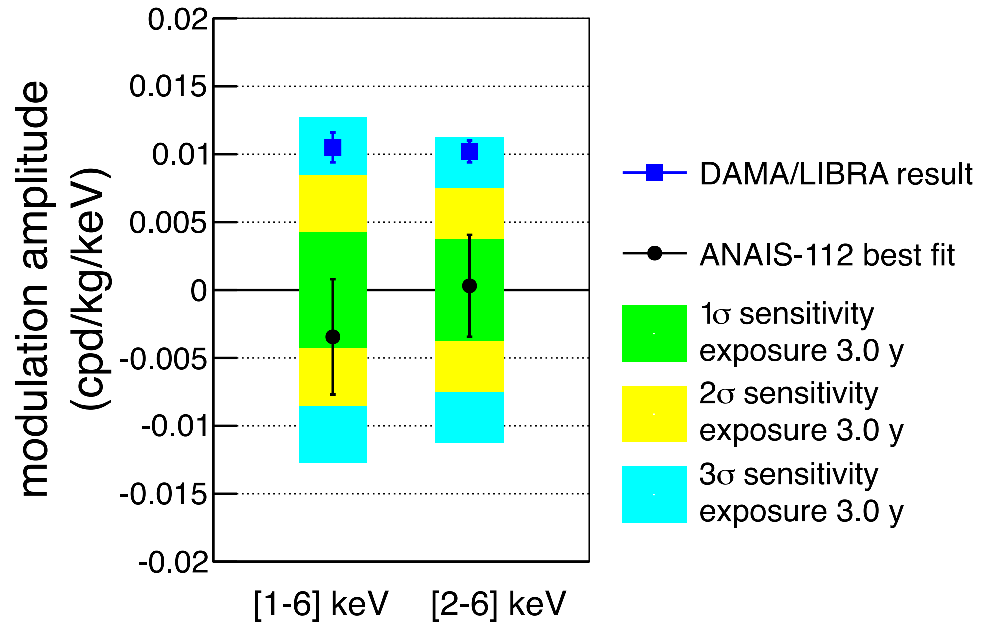




Bkg model

$$\mu_i = [R_0\phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))]M\Delta E\Delta t$$

STATUS OF THE ANAIS-112 EXPERIMENT

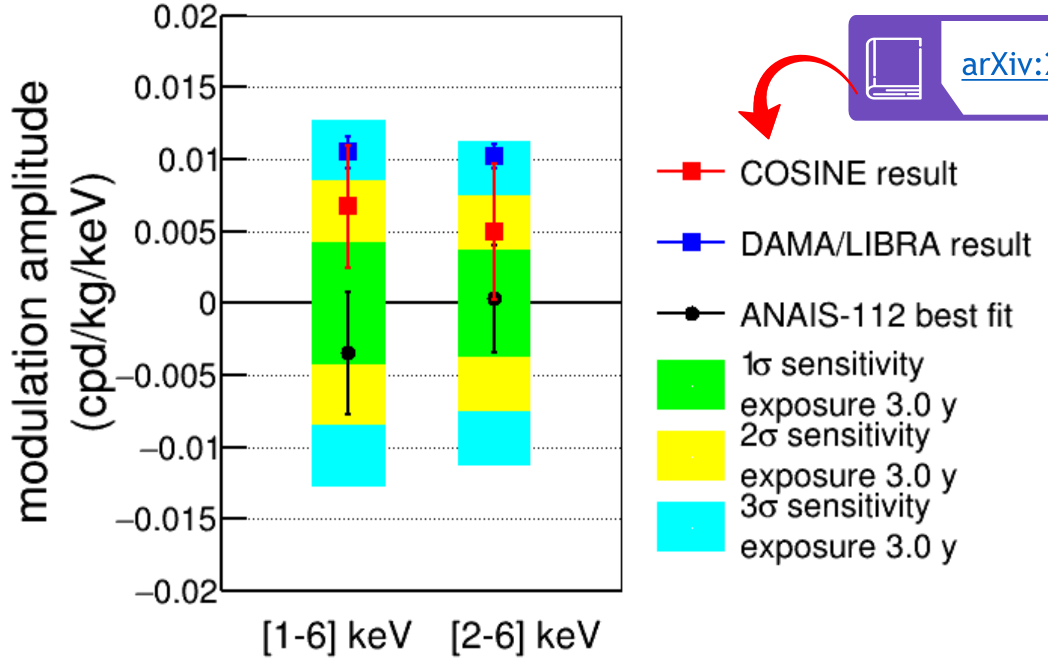


Best fits incompatible with DAMA/LIBRA @ 3.3 (2.6) σ in [1-6] ([2-6]) keV

Sensitivity @ 2.5 (2.7) σ in [1-6] ([2-6]) keV

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

STATUS OF THE ANAIS-112 EXPERIMENT



arXiv:2111.08863

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

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

J. Amaré et al. Physical Review D 103 (2021) 102005
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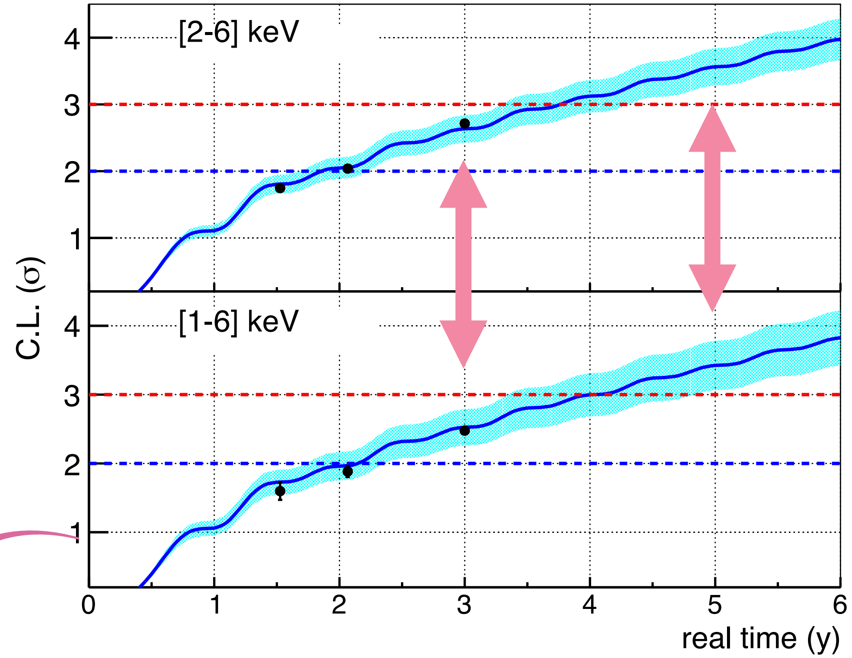
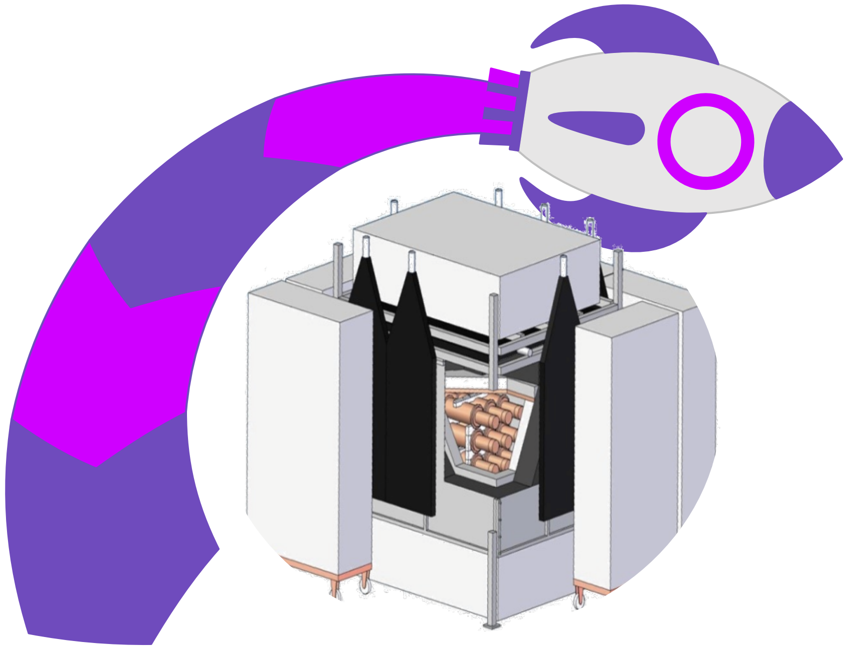


We confirm our sensitivity projections to DAMA/LIBRA result

We should be well at 3σ from DAMA/LIBRA result within the scheduled 5 years of data-taking

I. Coarasa et al., EPJC79 (2019) 233

Beyond current ANAIS-112 procedures…



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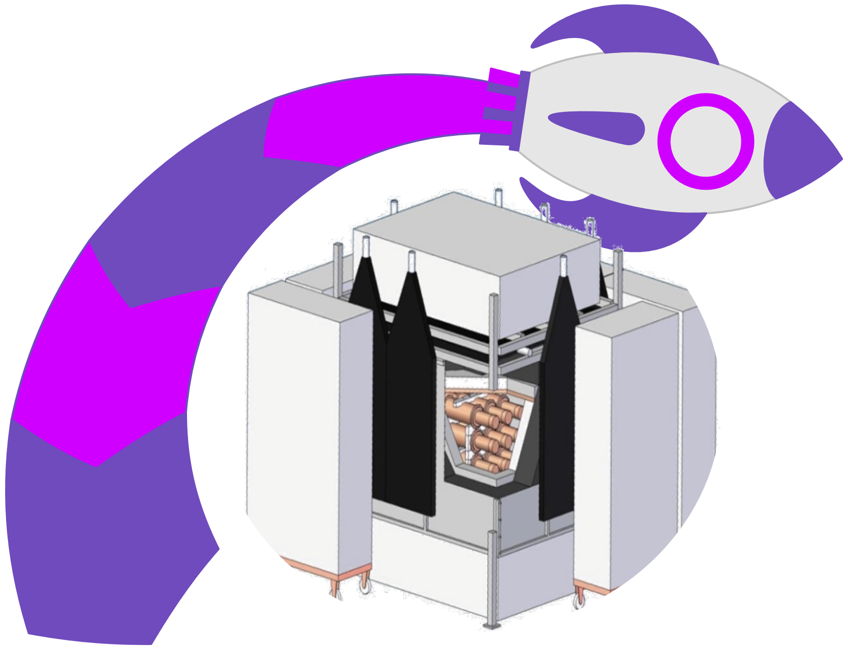
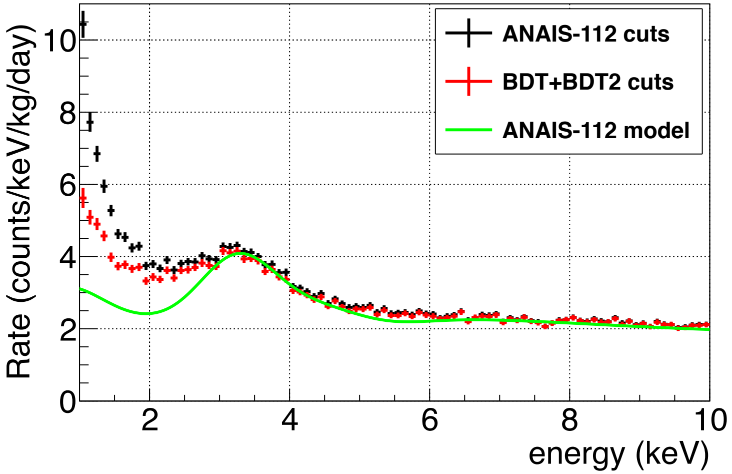


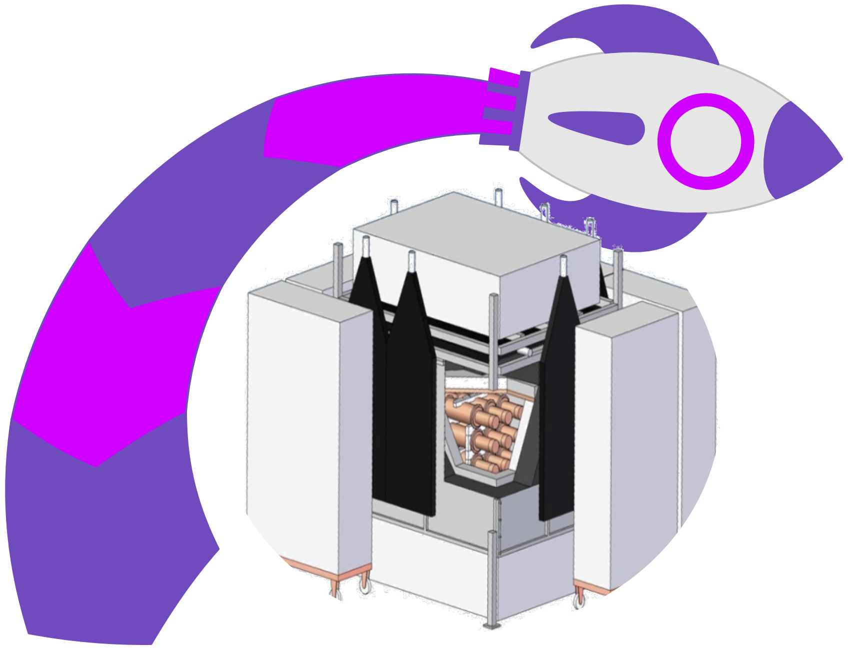
- Development of **machine learning** techniques based on Boosted Decision Tree (BDT) in order to understand the unexplained events <2 keV related with non-bulk scintillation events not rejected



- A background level reduction of 26.5% has been achieved between 1 and 2 keV
- A sensitivity to DAMA/LIBRA result of 4σ in 6 years could be at reach -> very promising!!

I Coarasa et al 2021 J. Phys.: Conf. Ser. **2156** 012036

Beyond current ANAIS-112 procedures…



- Development of **machine learning** techniques based on Boosted Decision Tree (BDT) in order to understand the unexplained events <2 keV related with non-bulk scintillation events not rejected

- Large effort on reducing backgrounds and energy threshold
  - We are testing SiPM – based light readout of Na crystals for operation at 100K
  - We are collaborating to grow ultrapure NaI crystals at LSC in the next future

Is it really a direct comparison?

Could DAMA/LIBRA still be interpreted as DM if ANAIS-112 do not see any modulation?

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Beyond other systematics…

Using same target material → direct comparison in **electron recoil energy (keVee)**

Possible different response of detectors to nuclear recoils?

keV?

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keV?

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

$$\mathbf{QF} = \frac{L_{RN}}{L_{RE}}$$

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

$$QF = \frac{L_{RN}}{L_{RE}}$$

Since the experiments are calibrated with gamma sources, which produce ER,QF is required to convert the energy scale for any NR interpretation

Is it really a direct comparison?

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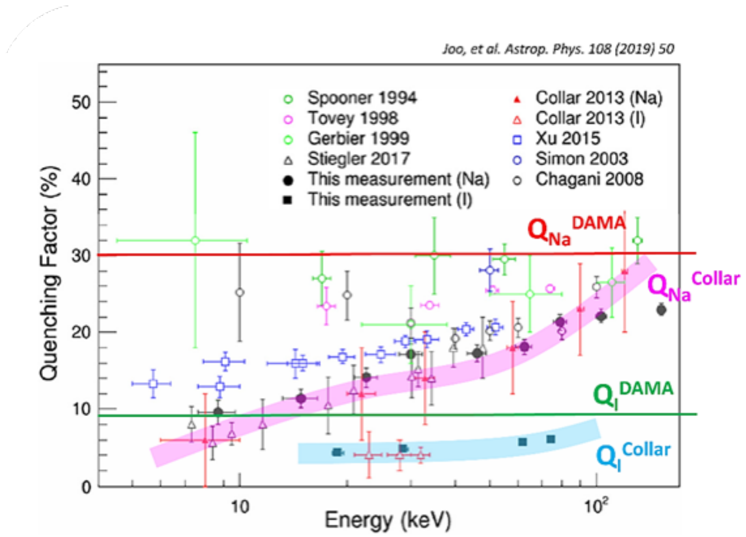
Beyond other systematics…

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



Dependences on:

- crystal properties
- Impurities
- Doping concentration
- ….

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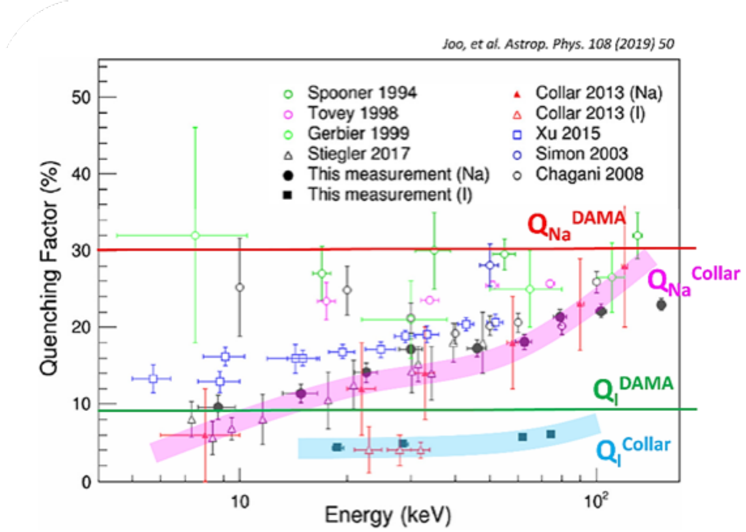


Dependences on:

- crystal properties
- Impurities
- Doping concentration
- ….

Constant QF? 1

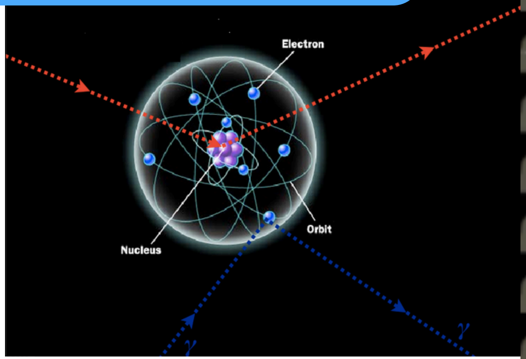
Q_{Na} DAMA = 0.3
Q_{I} DAMA = 0.09

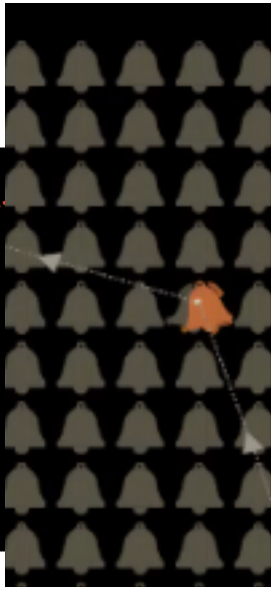
2 Diminishing with energy QF @ low energies?

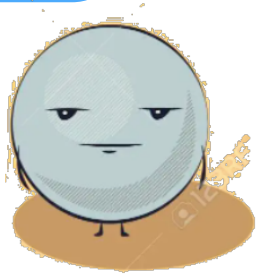
Increasing with energy QF @ low energies? 3

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

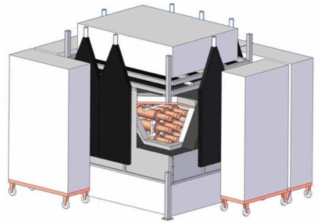
DM Direct Detection approach







NEUTRON CALIBRATION PROGRAM



GOALS

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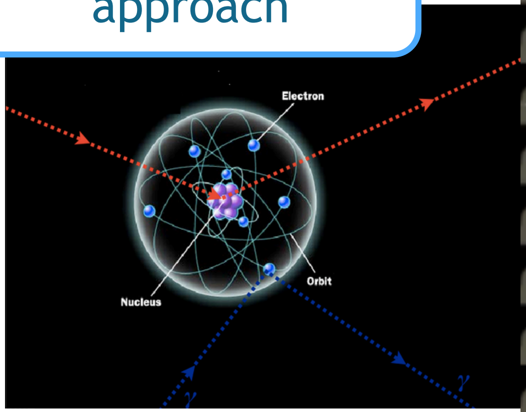

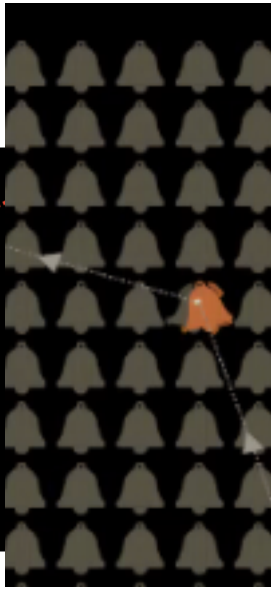

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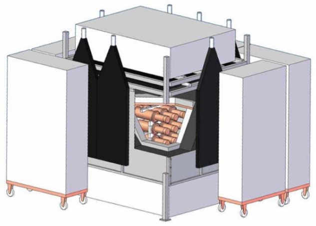
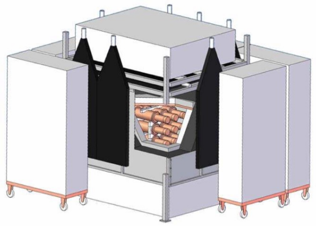


Evaluate ANAIS-112 efficiencies to NR

GOALS

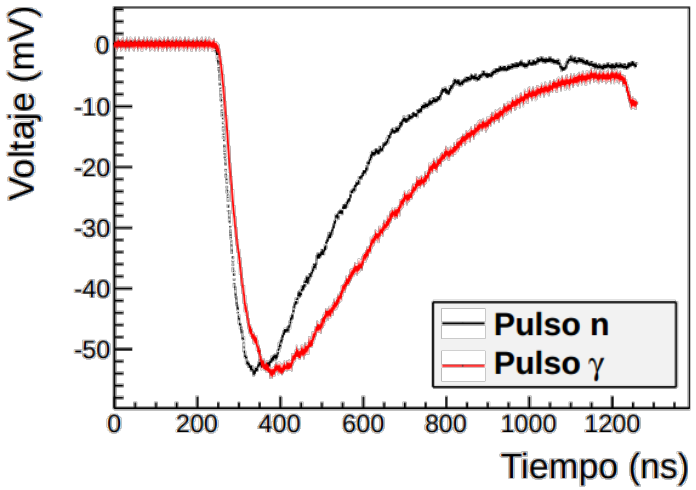
NEUTRON CALIBRATION PROGRAM



Evaluate ANAIS-112 efficiencies to NR

GOALS

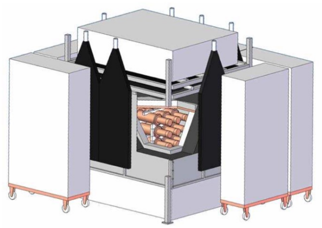
- Our sample population for the current efficiency calculation is originated from ER populations
- For most DM models the expected signal comes from NR
- It is well known that ER and NR feature slightly different scintillations constant in NaI(Tl) at very low energy. NR events in NaI are faster than β/γ ones



τ_γ = 230 ns
τ_n = 205 ns

Work in Progress

NEUTRON CALIBRATION PROGRAM

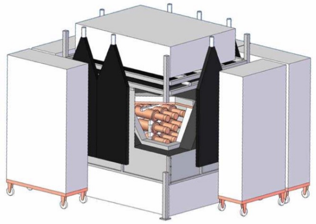


GOALS

Evaluate ANAIS-112 efficiencies to NR

Bulk-scintillation populatios for ML

NEUTRON CALIBRATION PROGRAM



GOALS

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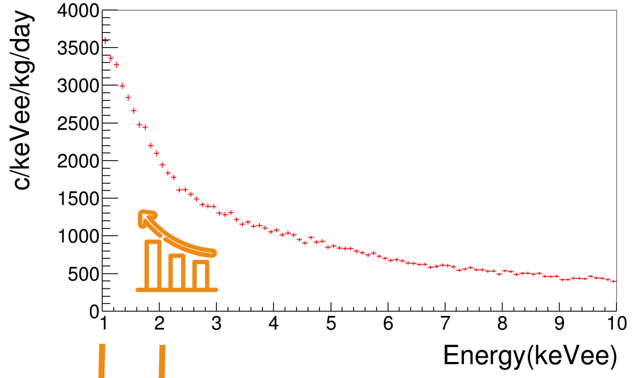


Neutron calibrations provides lots of low energy bulk-scintillation events produced by NR, in particular in [1-2] keV region

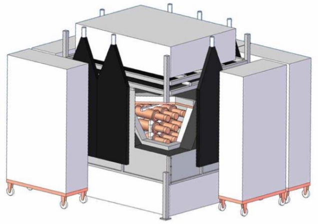
machine learning

Training populations

- Neutron calibrations (signal)
- Blank (noise)

Blank module

NEUTRON CALIBRATION PROGRAM



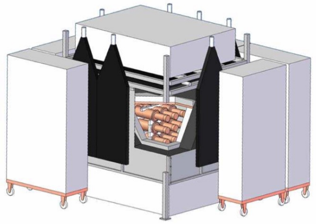
GOALS

Evaluate ANAIS-112 efficiencies to NR

Bulk-scintillation populatios for ML

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

NEUTRON CALIBRATION PROGRAM

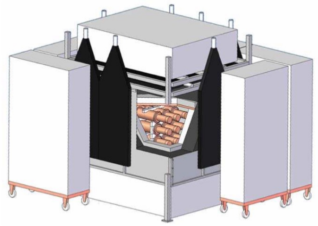


GOALS

- Evaluate ANAIS-112 efficiencies to NR
- Understanding QF
- Bulk-scintillation populatios for ML

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

NEUTRON CALIBRATION PROGRAM



GOALS

- Evaluate ANAIS-112 efficiencies to NR
- Bulk-scintillation populatios for ML
- Understanding QF

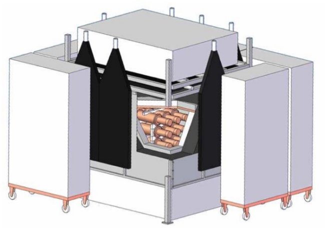
- QF determination for ANAIS-112 crystals is ongoing: two approaches are followed in parallel

Monochromatic neutron source

^{252}Cf source

Both approaches are complementary and should be consistent

NEUTRON CALIBRATION PROGRAM



GOALS

Evaluate ANAIS-112 efficiencies to NR

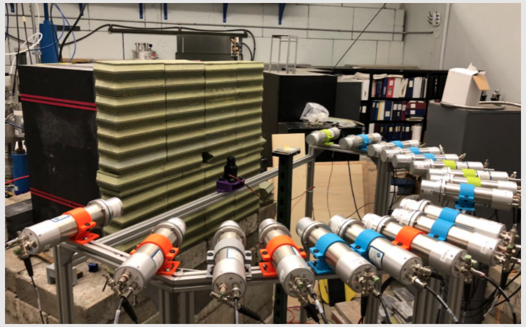
Understanding QF

Bulk-scintillation populatios for ML

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

Monochromatic neutron source

Detection of the scattered neutron at a fixed angle leads the knowledge of the recoil energy



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

PRELIMINARY

- No dependence with energy QF_{Na} = 20.9 ± 0.3%
- Disagreements in QF_{Na} could be attributed to the non-linear response of detectors

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

NEUTRON CALIBRATION PROGRAM

^{252}Cf source

Measurement with a neutron source onsite @LSC has been recently performed with ANAIS-112 set-up

^{252}Cf source

A(t_0) = 10 kBq ; t_0 = August 1, 2016

Fission fragments + n

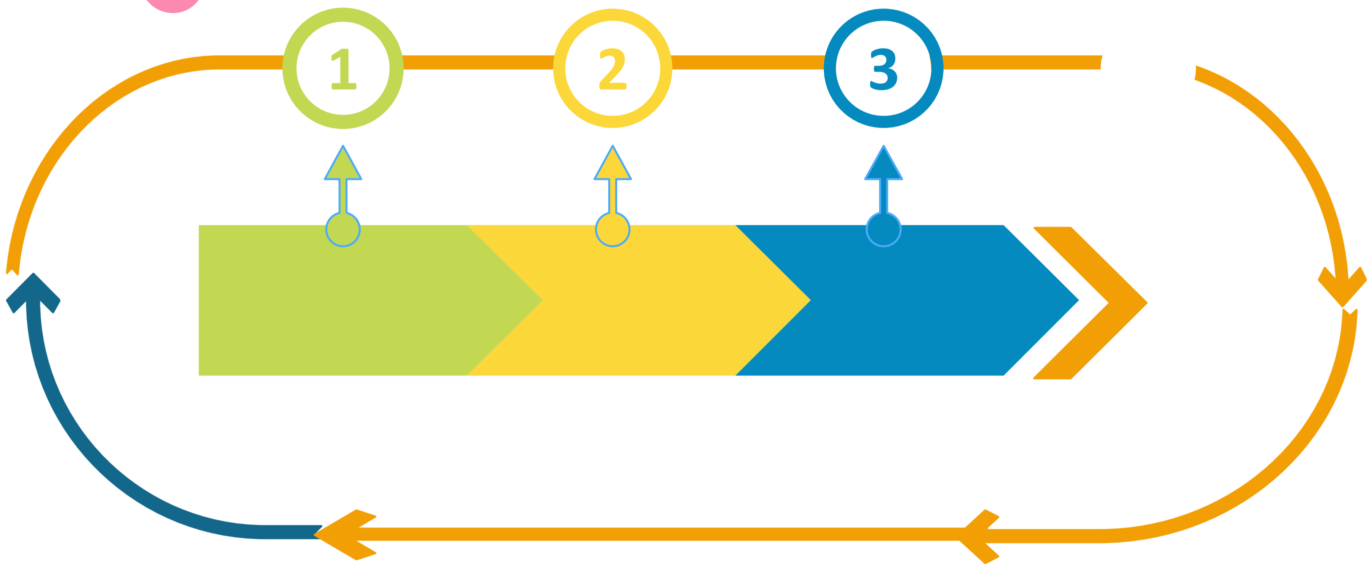
3% EF

^{252}Cf → α → ^{248}Cf → α…

NEUTRON CALIBRATION PROGRAM

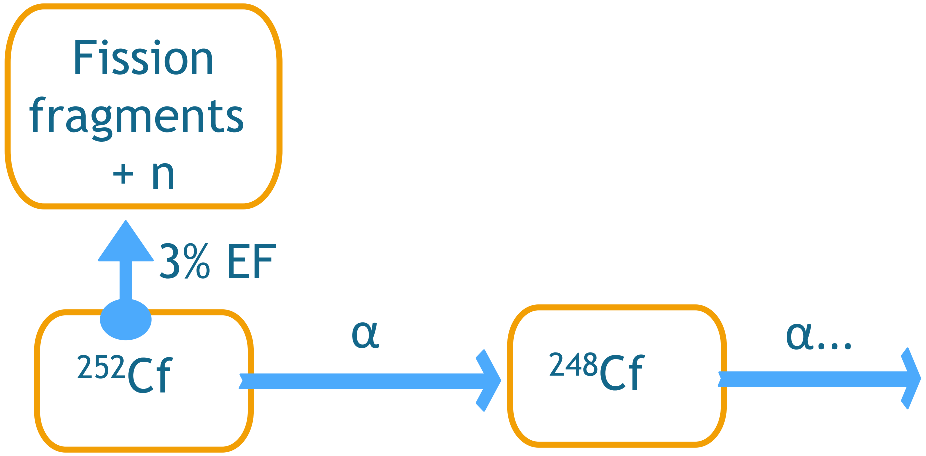
^{252}Cf source

Measurement with a neutron source onsite @LSC has been recently performed with ANAIS-112 set-up



^{252}Cf source

$A(t_0)$ = 10 kBq ; t_0 = August 1, 2016



NEUTRON CALIBRATION PROGRAM

^{252}Cf source

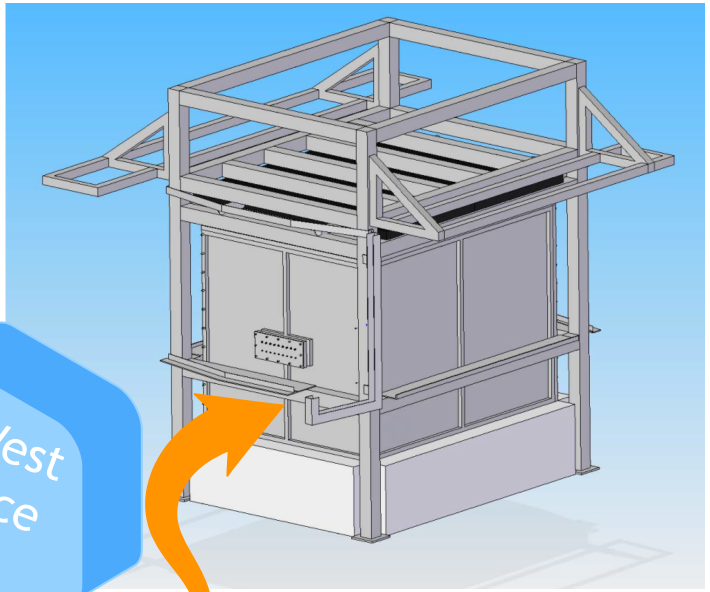
Measurement with a neutron source onsite @LSC has been recently performed with ANAIS-112 set-up

1

2

3

West calibration



West face

April 27, 2021

- Exposure 9.126 kg.day
- Live time: 3.35 h

NEUTRON CALIBRATION PROGRAM

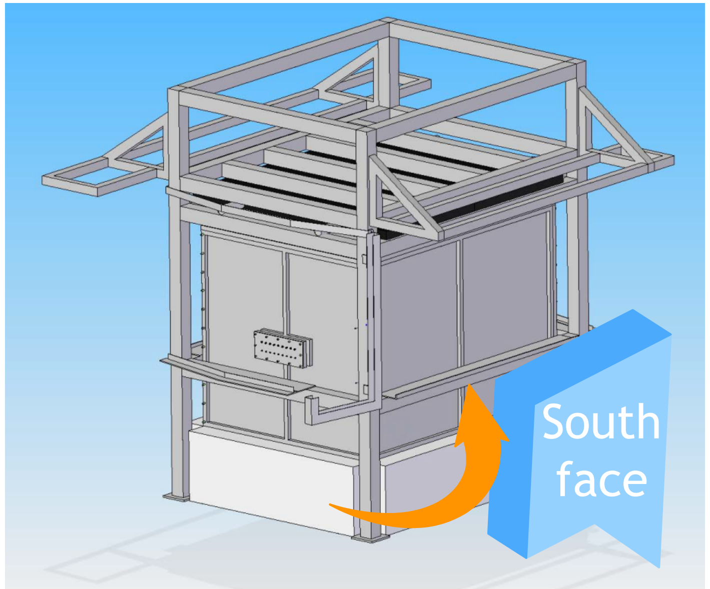
^{252}Cf source

Measurement with a neutron source onsite @LSC has been recently performed with ANAIS-112 set-up

1 — West calibration

2 — South calibration

3



Dec 23, 2021

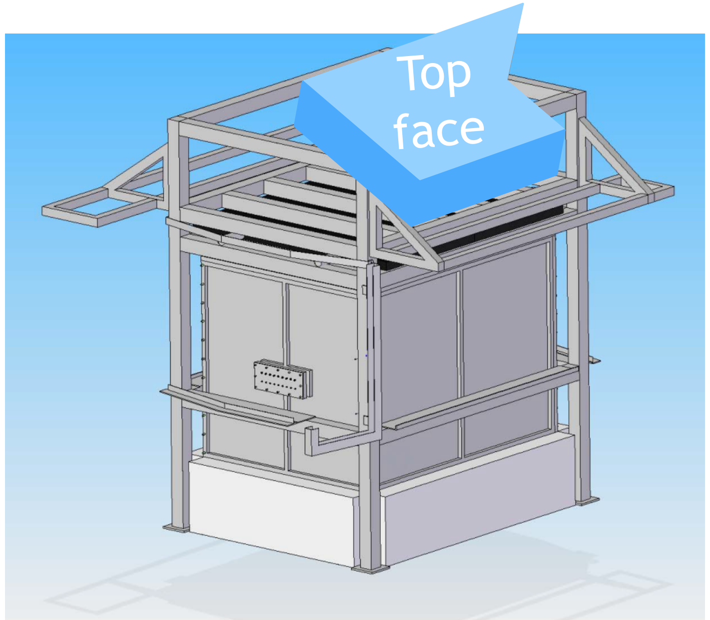
- Exposure 12.036 kg.day
- Live time: 2.57 h

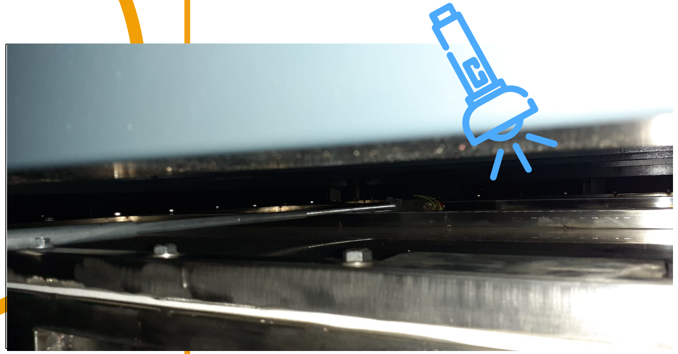
NEUTRON CALIBRATION PROGRAM

^{252}Cf source

Measurement with a neutron source onsite @LSC has been recently performed with ANAIS-112 set-up

1. West calibration
2. South calibration
3. Top calibration





April 13, 2022

- Exposure 12.015 kg.day
- Live time: 2.57 h

NEUTRON CALIBRATION PROGRAM

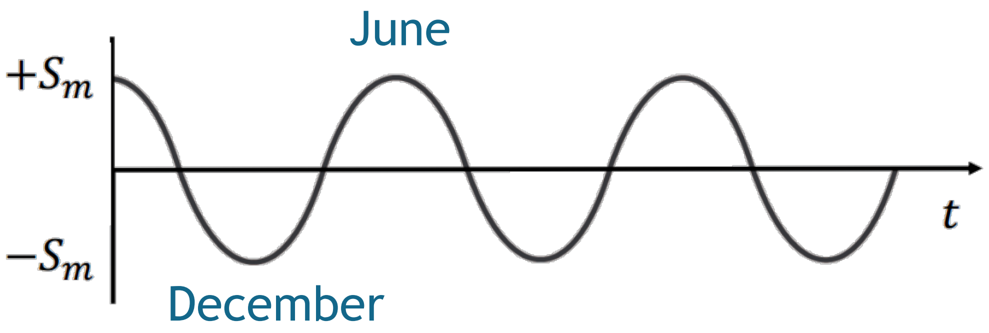
^{252}Cf source

Measurement with a neutron source onsite @LSC has been recently performed with ANAIS-112 set-up

1 — West calibration

2 — South calibration

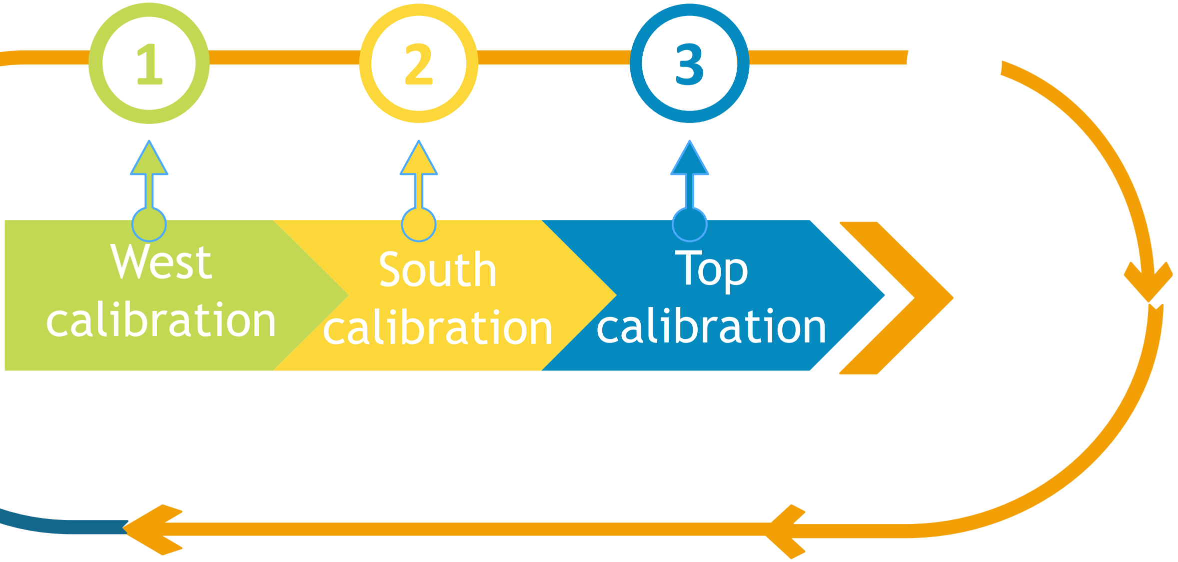
3 — Top calibration

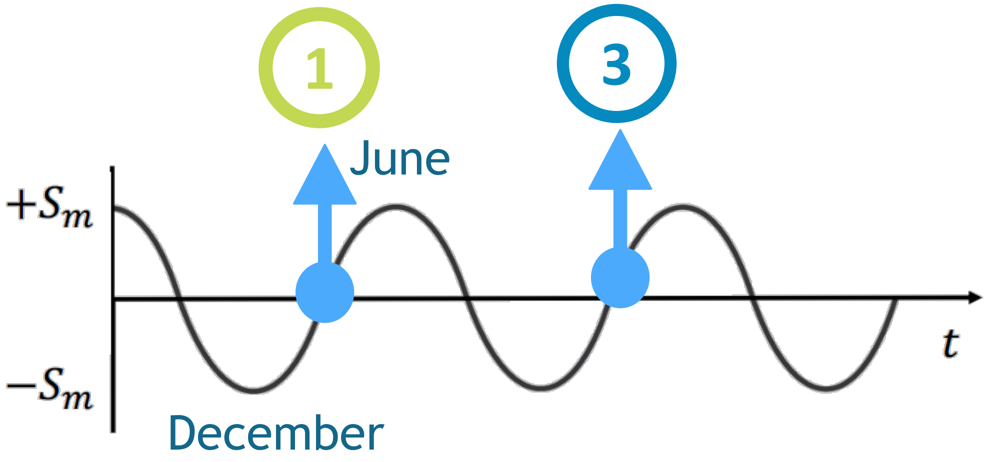


NEUTRON CALIBRATION PROGRAM

^{252}Cf source

Measurement with a neutron source onsite @LSC has been recently performed with ANAIS-112 set-up

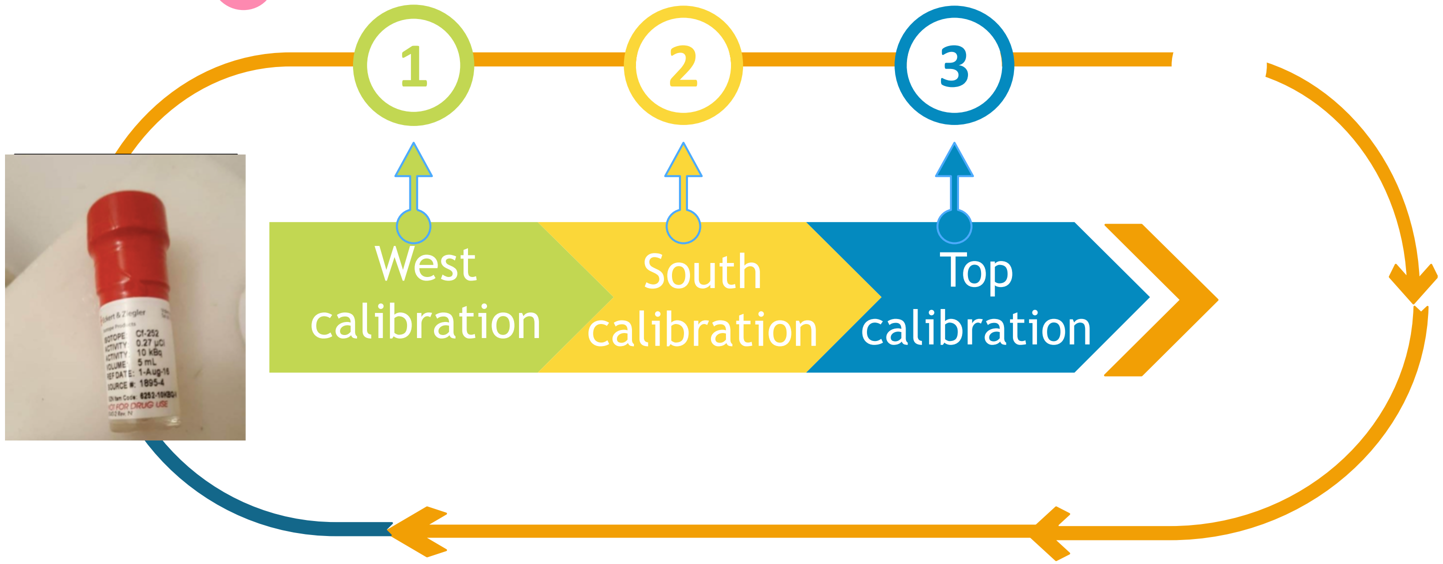


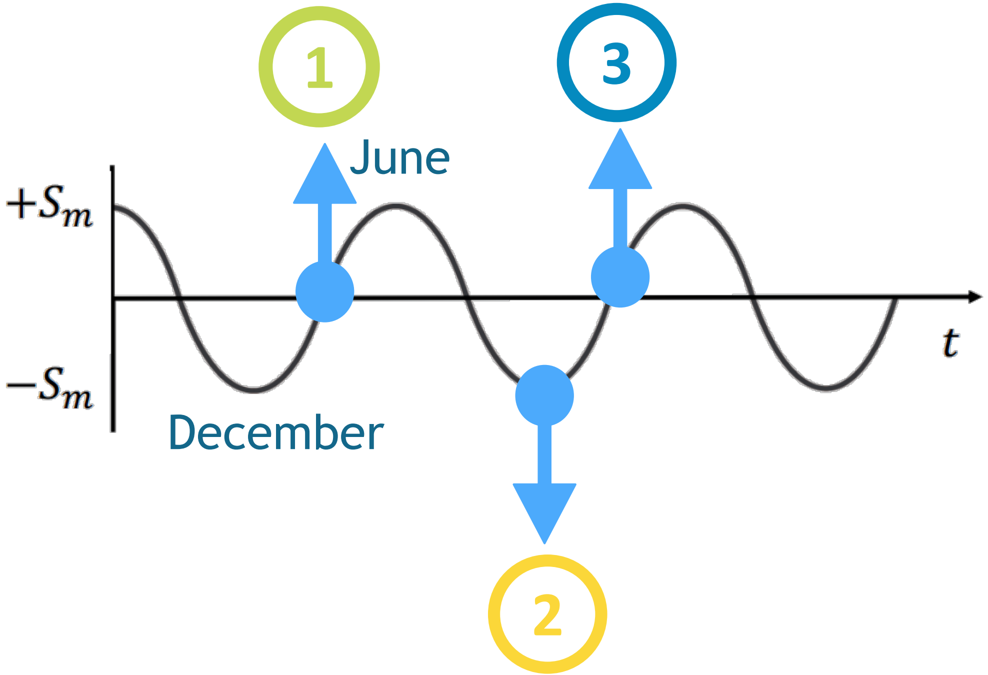


NEUTRON CALIBRATION PROGRAM

^{252}Cf source

Measurement with a neutron source onsite @LSC has been recently performed with ANAIS-112 set-up





NEUTRON CALIBRATION PROGRAM

^{252}Cf source

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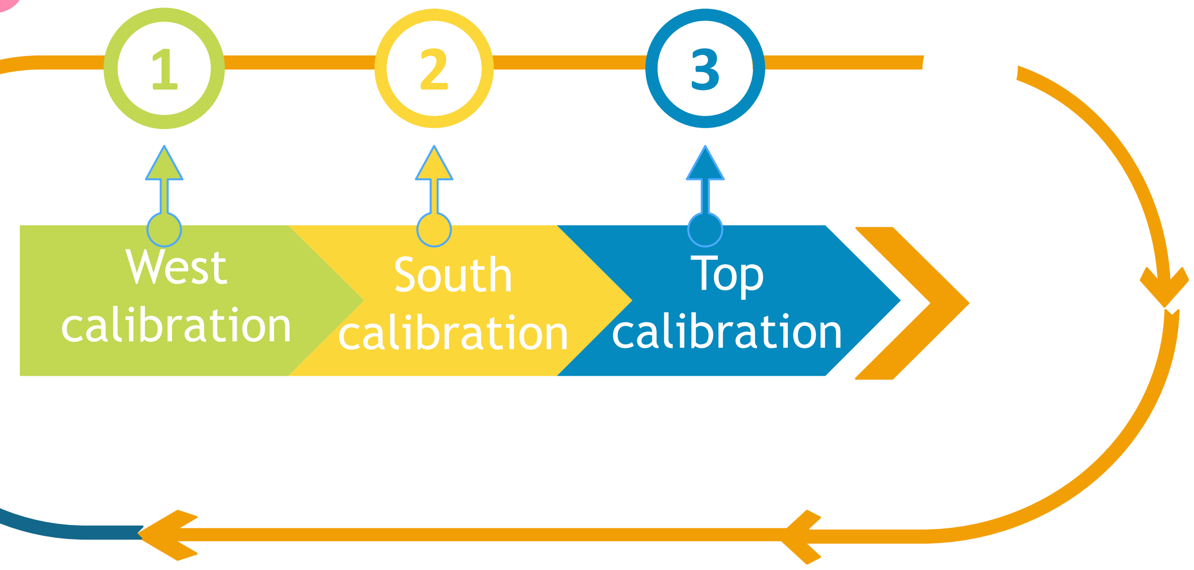
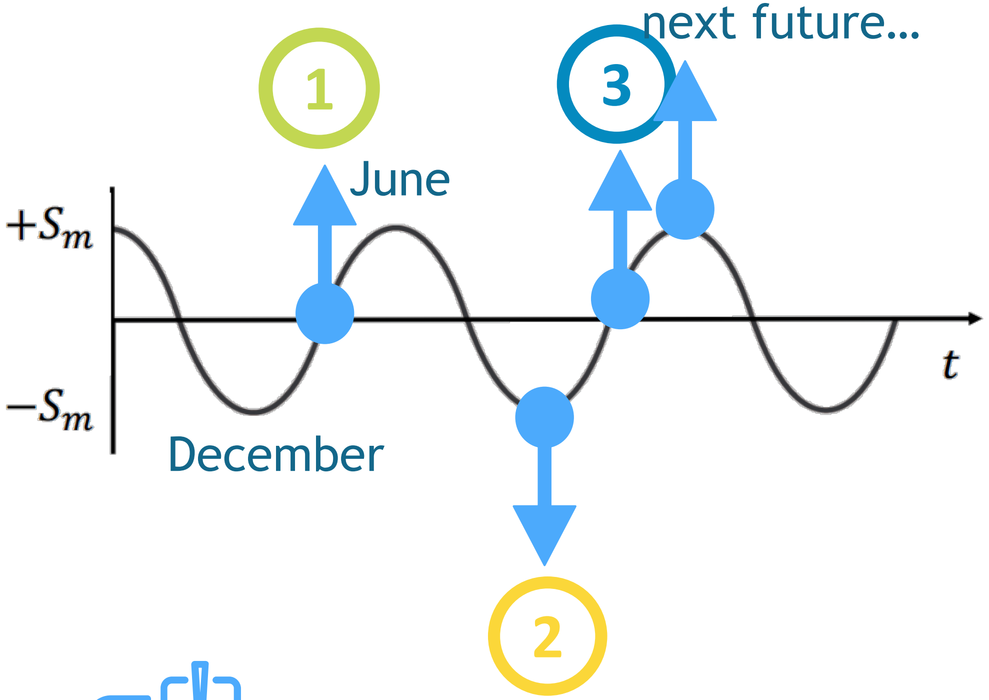
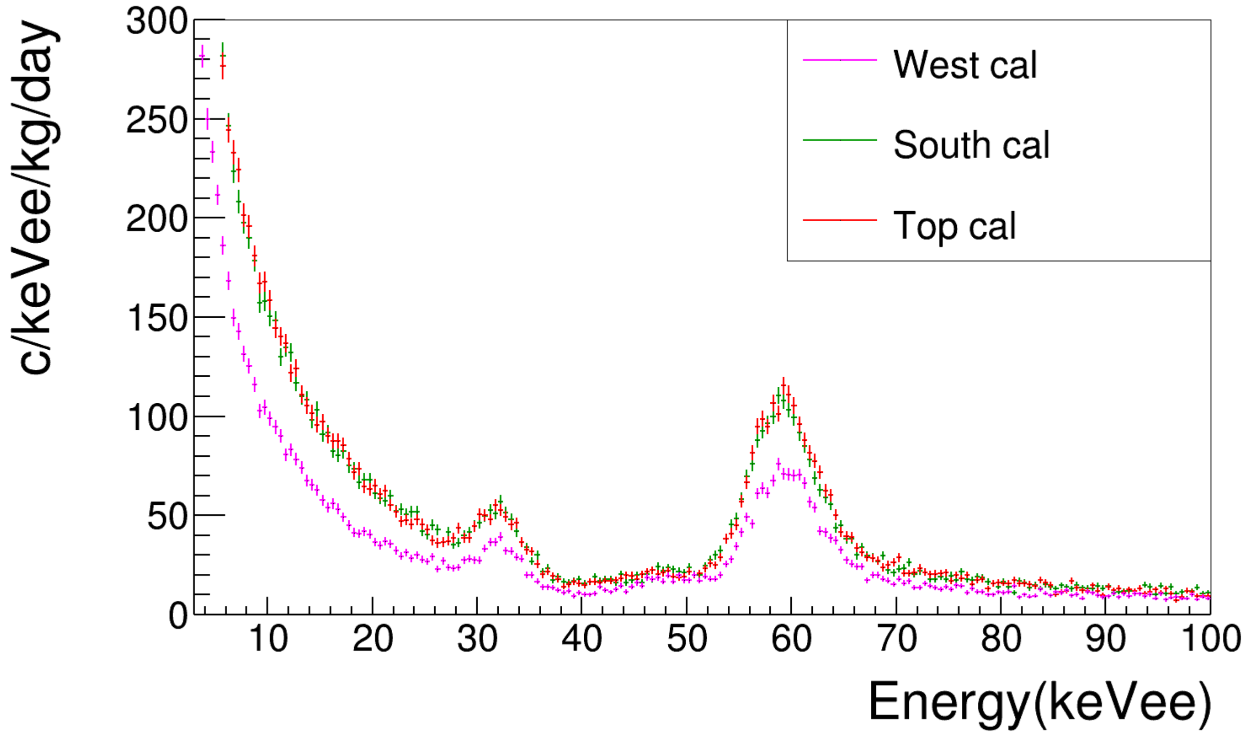


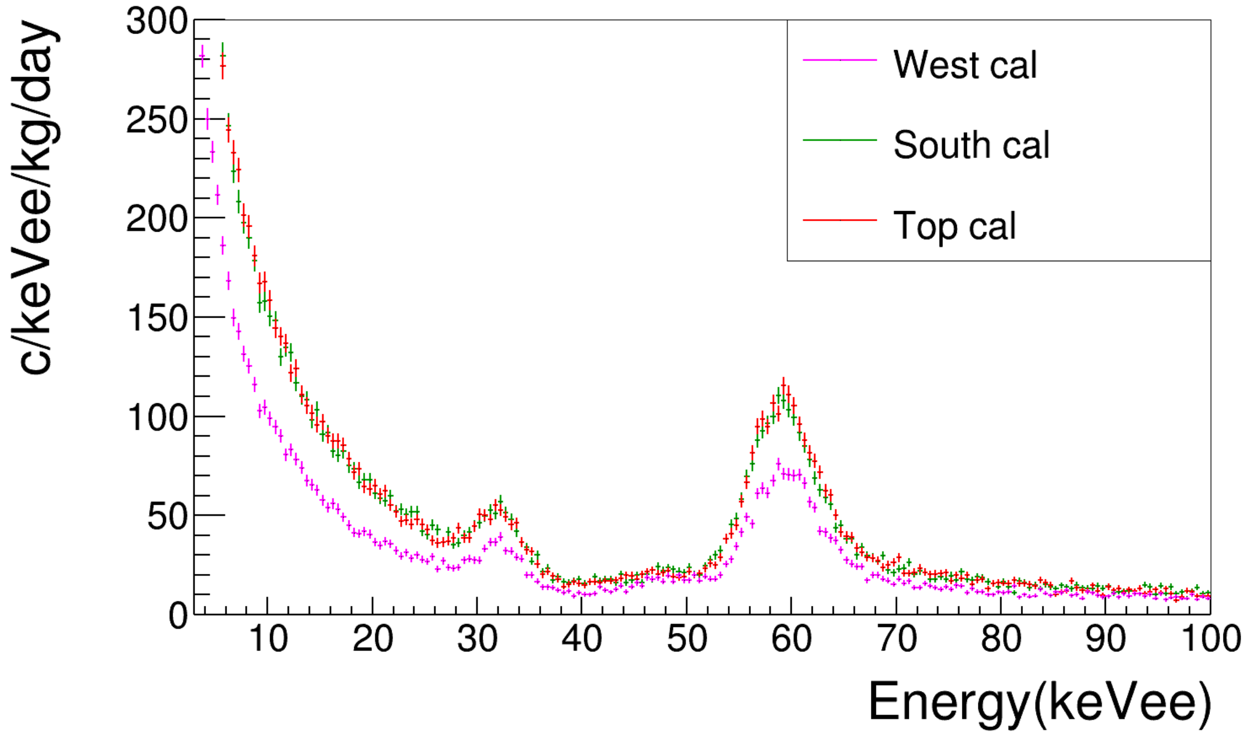


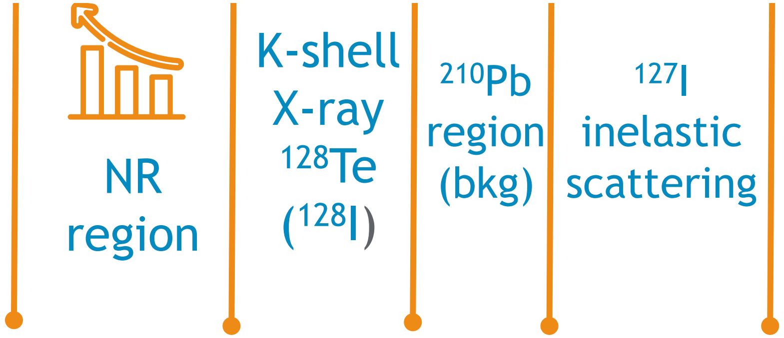
To evaluate the efficiency stability to NR along time

NEUTRON CALIBRATION PROGRAM

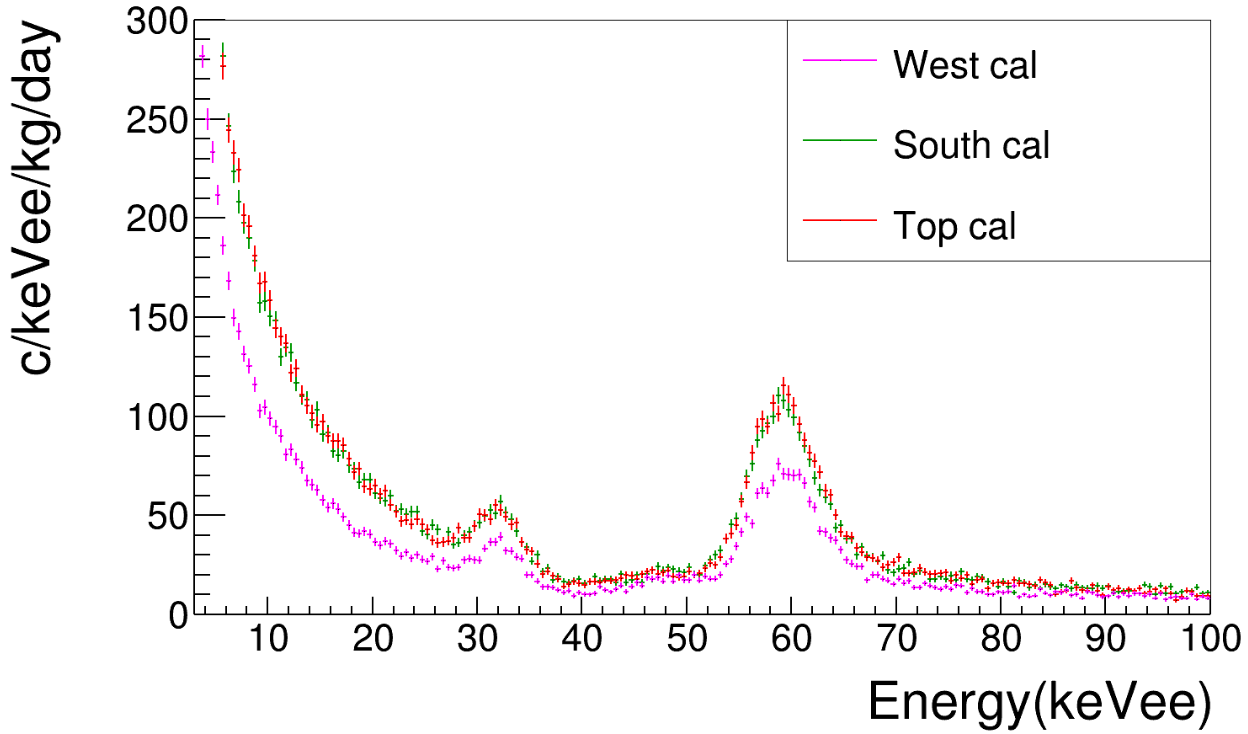


NEUTRON CALIBRATION PROGRAM





NEUTRON CALIBRATION PROGRAM



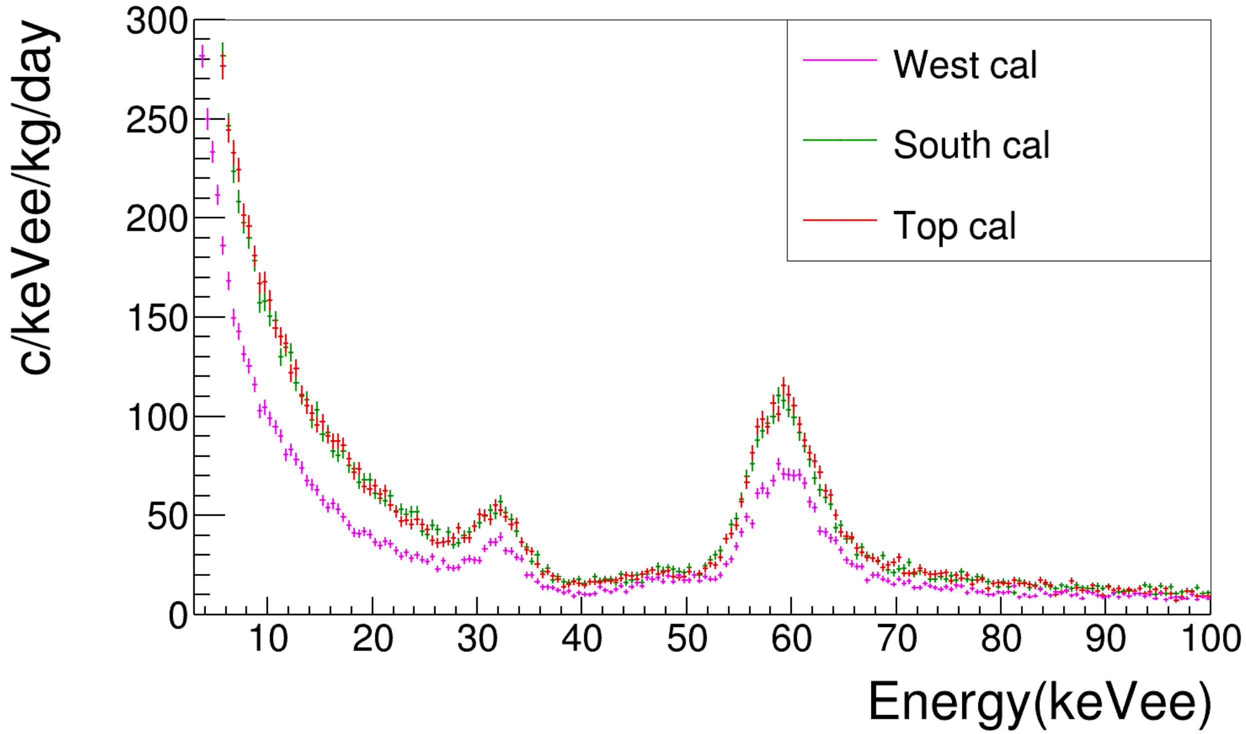
264321 counts @ROI ([1-6] keV)

NR region

K-shell X-ray ^{128}Te (^{128}I)

^{210}Pb region (bkg)

^{127}I inelastic scattering



NR region

K-shell X-ray ^{128}Te (^{128}I)

^{210}Pb region (bkg)

^{127}I inelastic scattering

264321 counts @ROI ([1-6] keV)

@ROI

Neutron cal

~ 34600 counts/h

>15 !!!

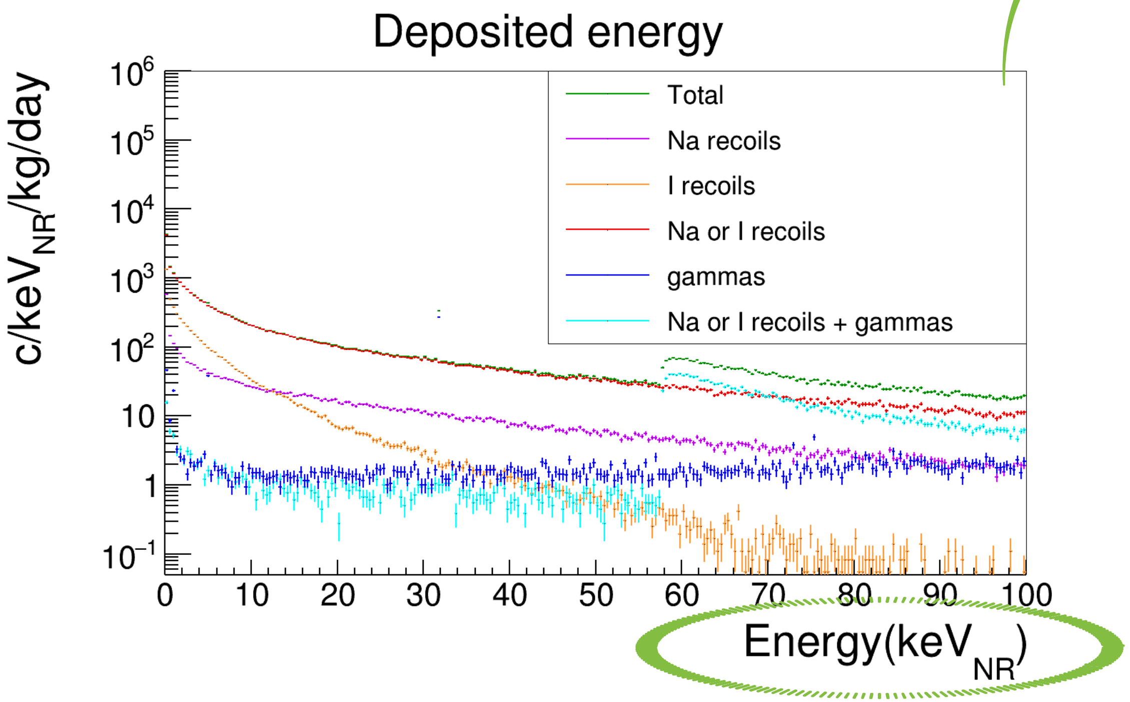
^{109}Cd

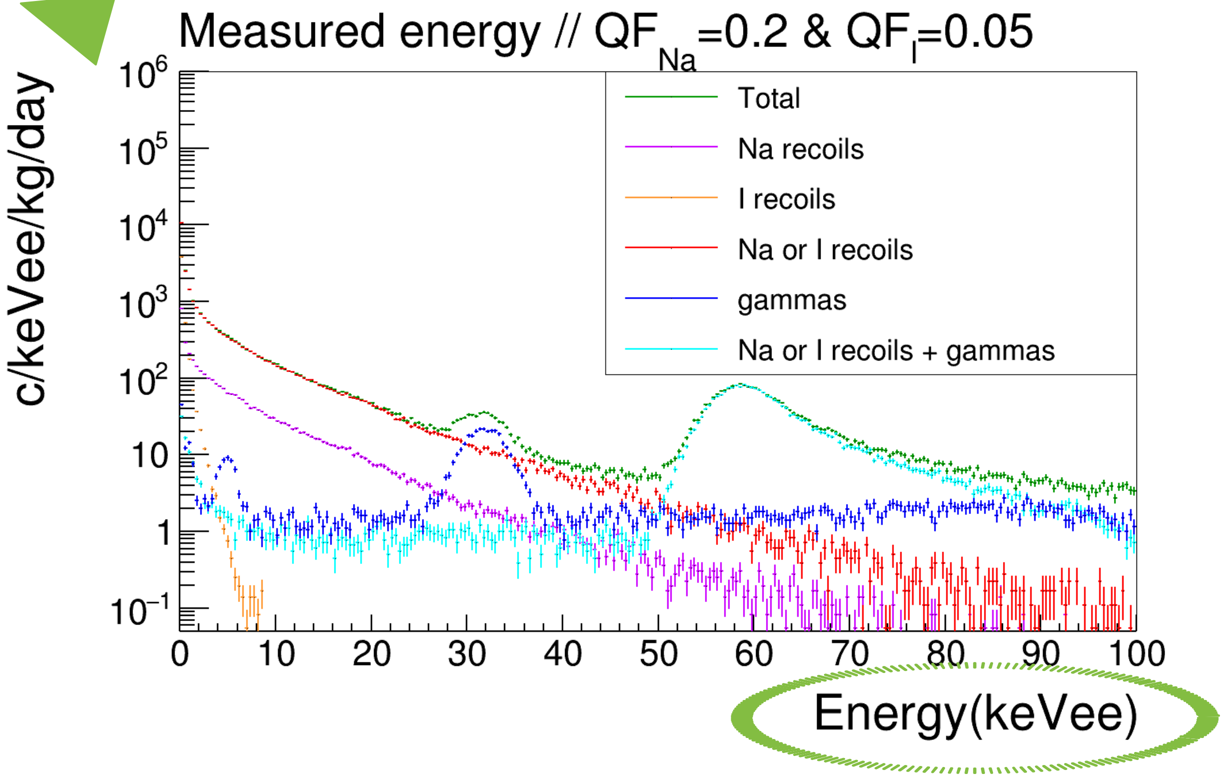
~ 2200 counts/h

RESULTS ON THE QUENCHING FACTOR

Simulation results depending on the QF model

ANAIS-112 resolution

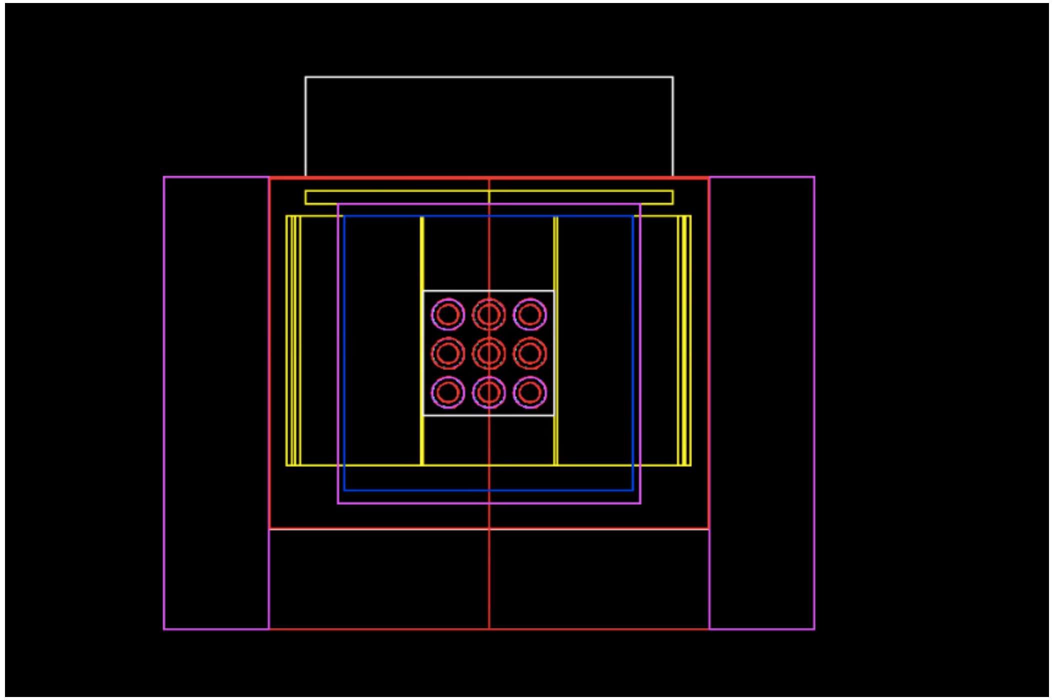


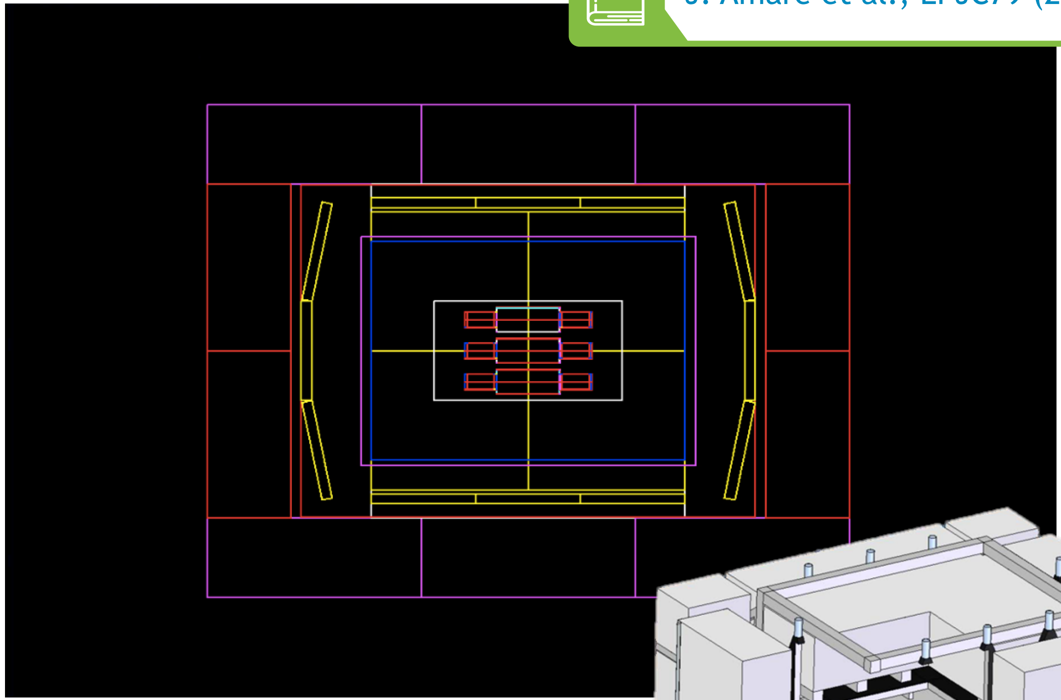


RESULTS ON THE QUENCHING FACTOR

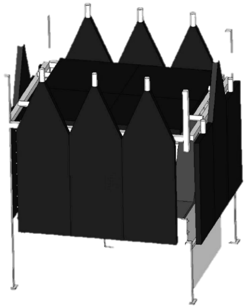
- The ANAIS-112 Geant4 model has been extended for simulating the neutron calibration

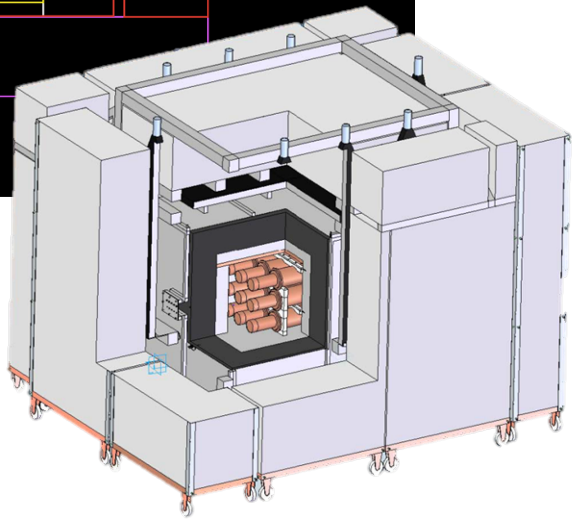
J. Amaré et al., EPJC79 (2019) 412





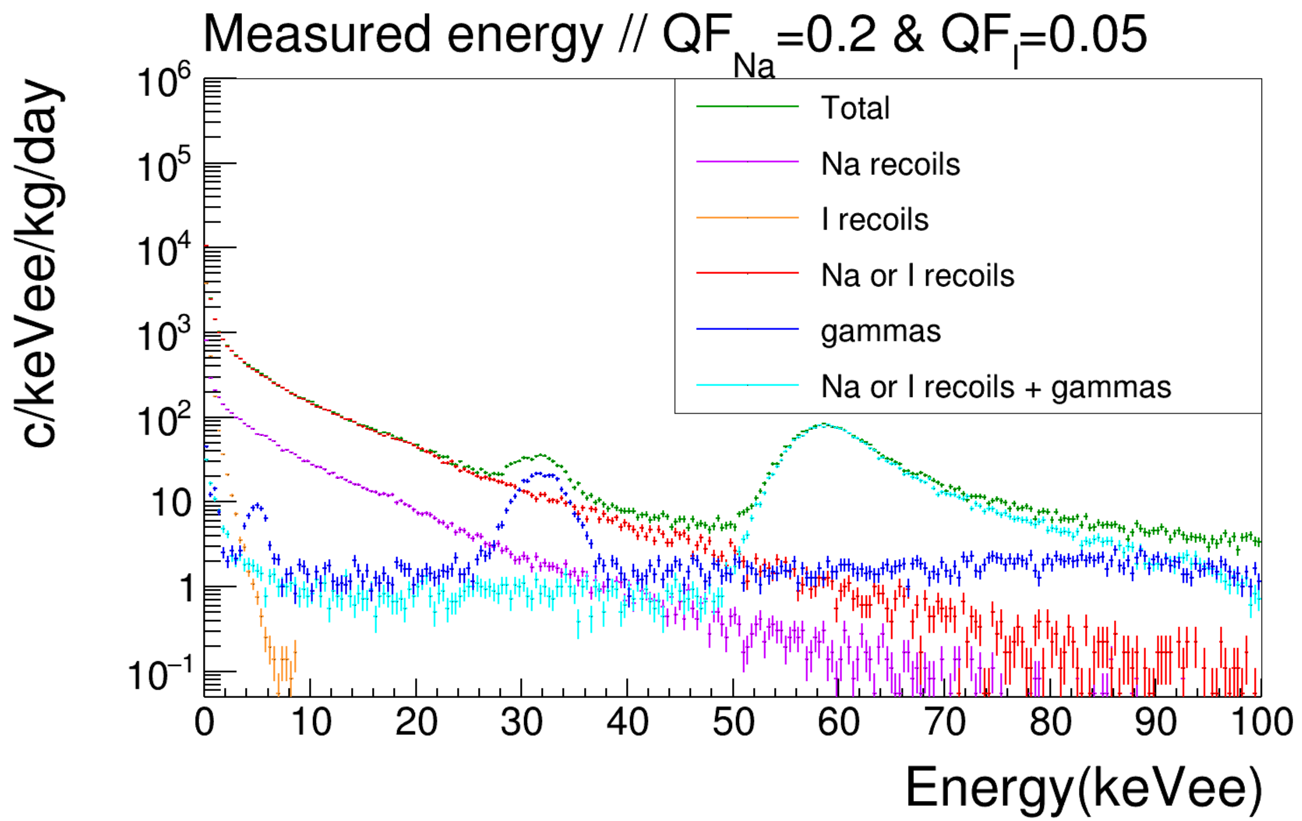
- 3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules + PMTs
- 30 cm lead
- Anti-Radon box
- 40 cm PE/water
- 16 anti-muon vetoes





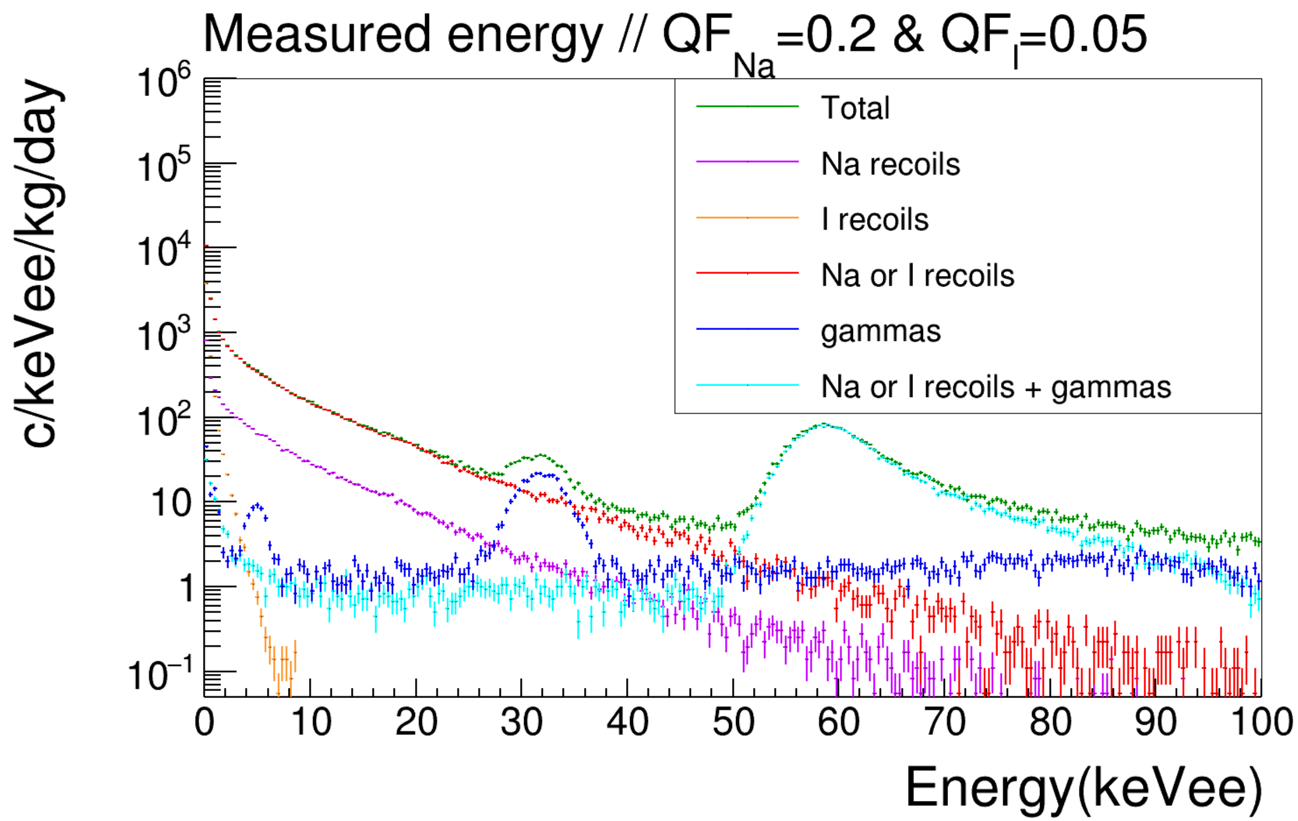
RESULTS ON THE QUENCHING FACTOR

Simulation results depending on the QF model



RESULTS ON THE QUENCHING FACTOR

Simulation results depending on the QF model



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

Nuclear recoils (Na or I) are dominant up to 50 keVee

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

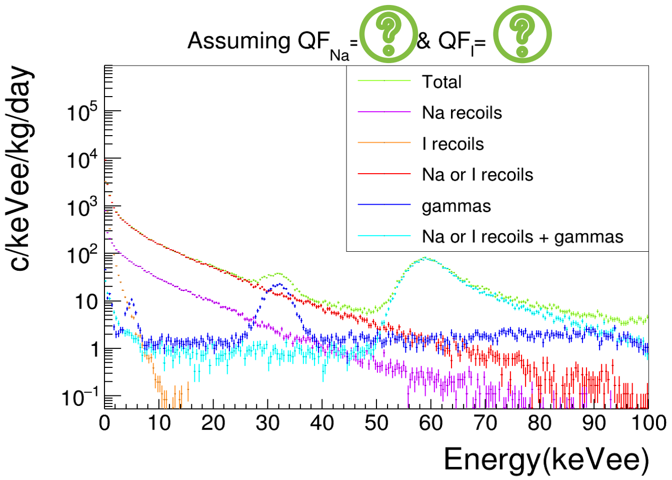
RESULTS ON THE QUENCHING FACTOR

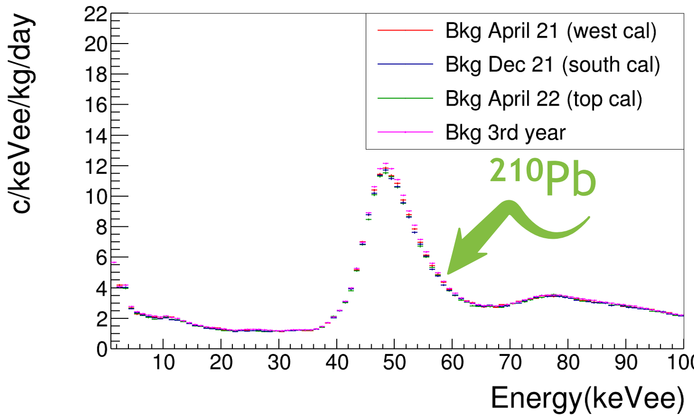
Simulation

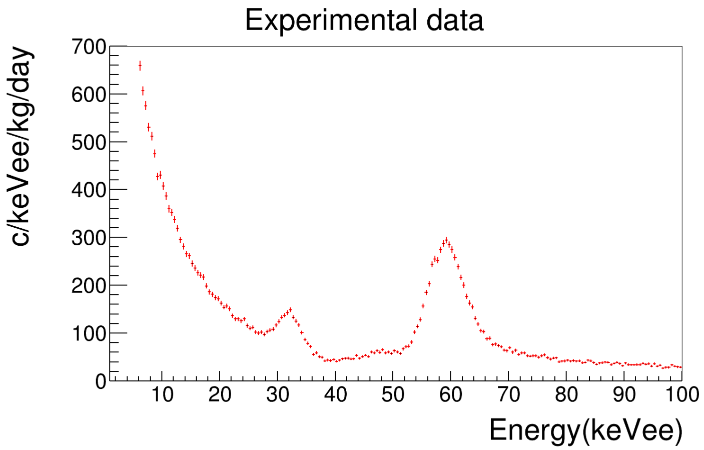
3rd year background

Neutron calibration data

Comparison between data and simulation allows testing different QF models and following a best-fit strategy



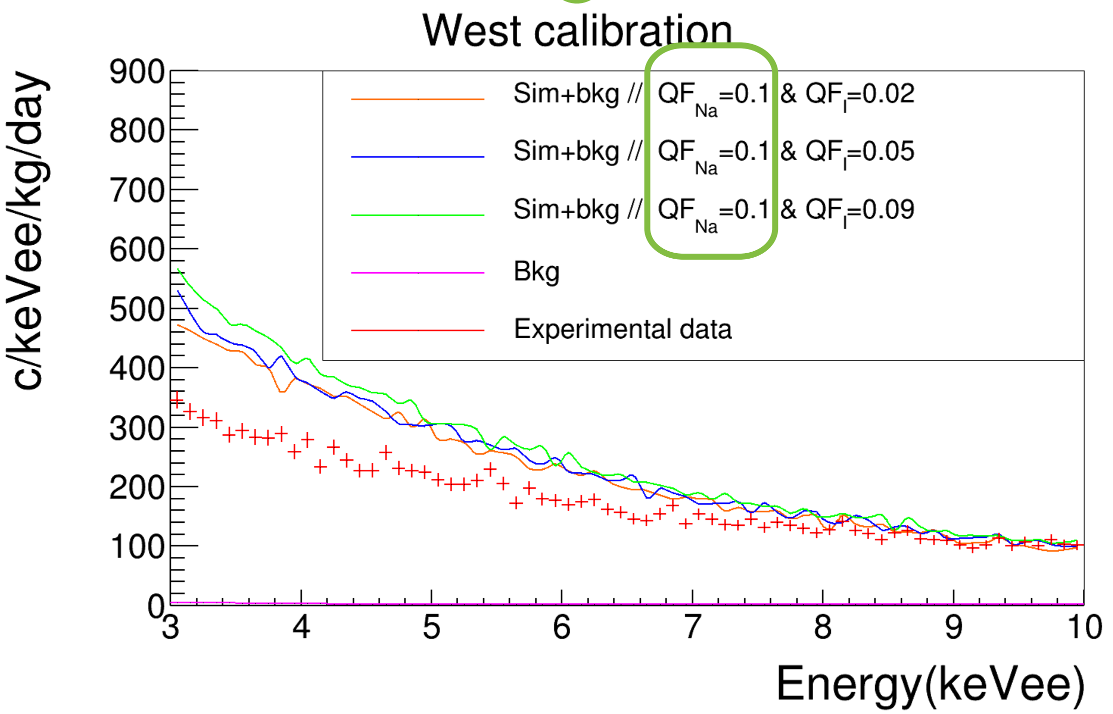


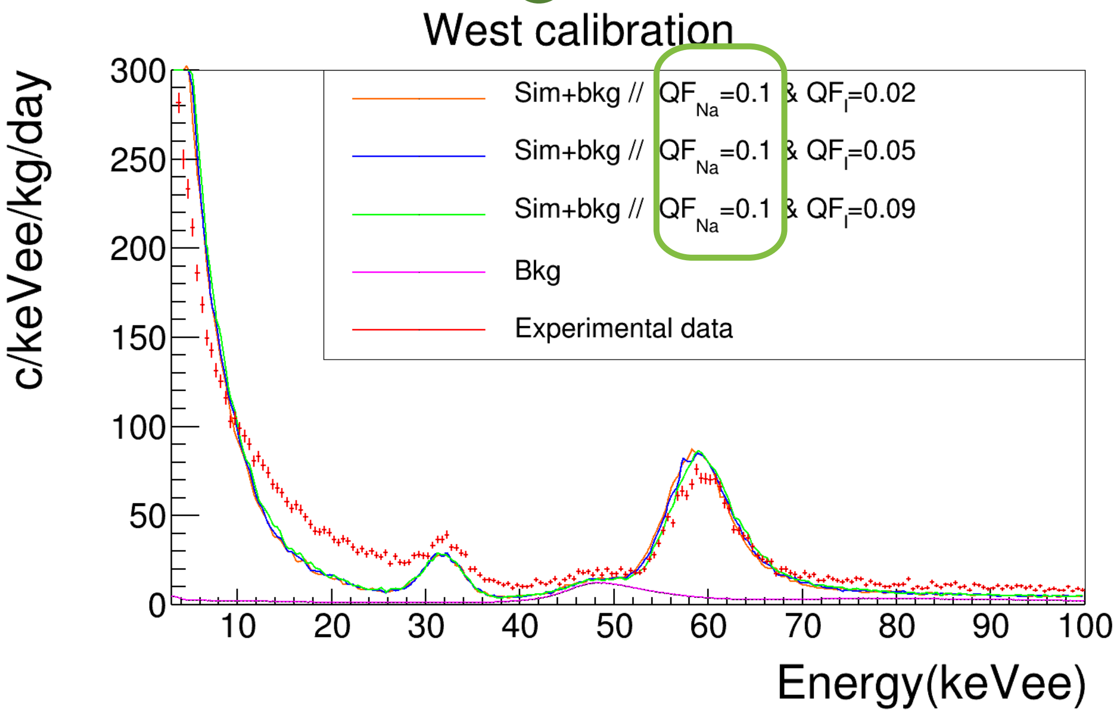


RESULTS ON THE QUENCHING FACTOR

PRELIMINARY

Let's change QF_{Na} !





RESULTS ON THE QUENCHING FACTOR

Let's change QF_{Na} !

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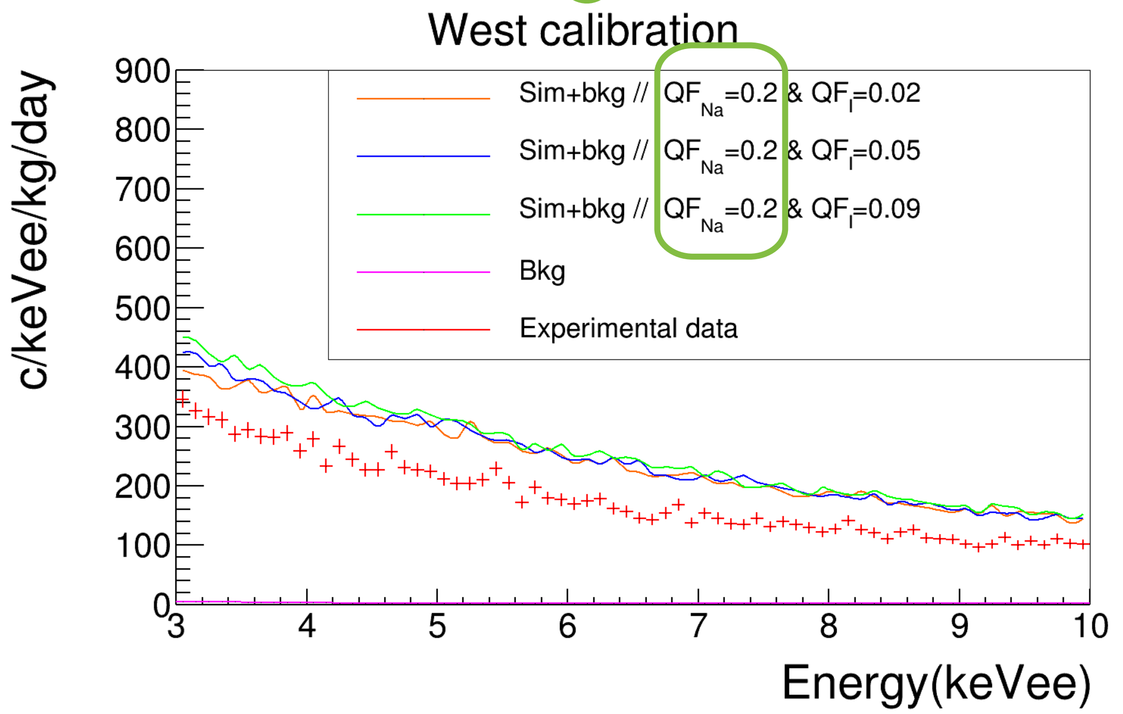

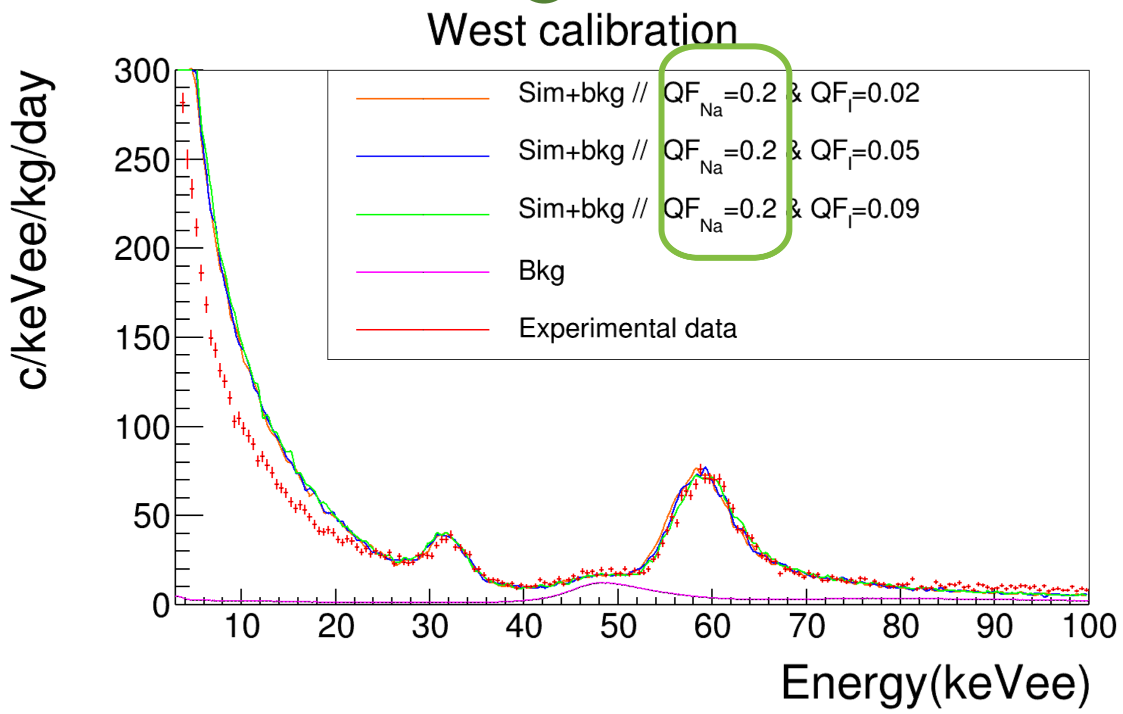

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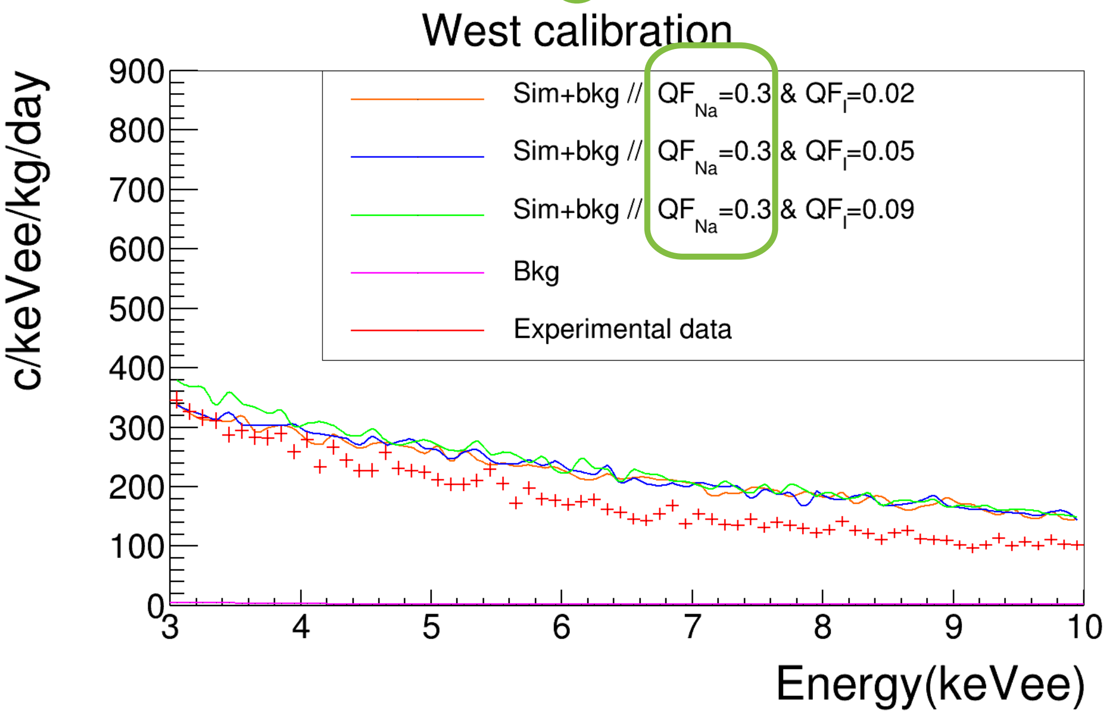
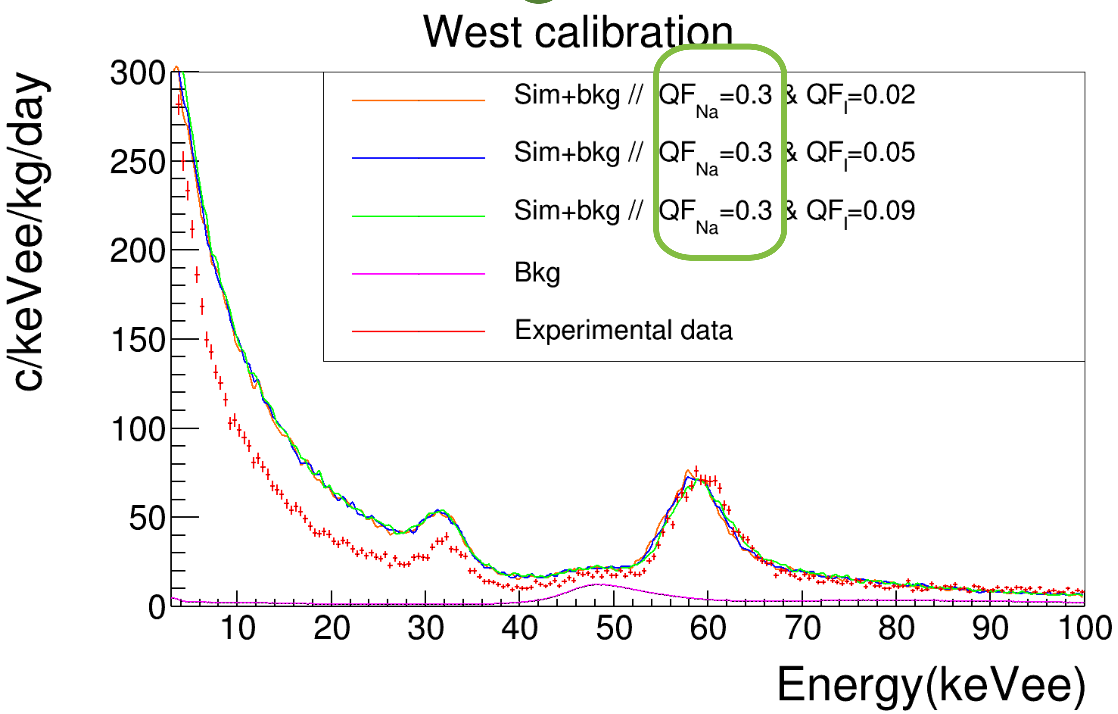
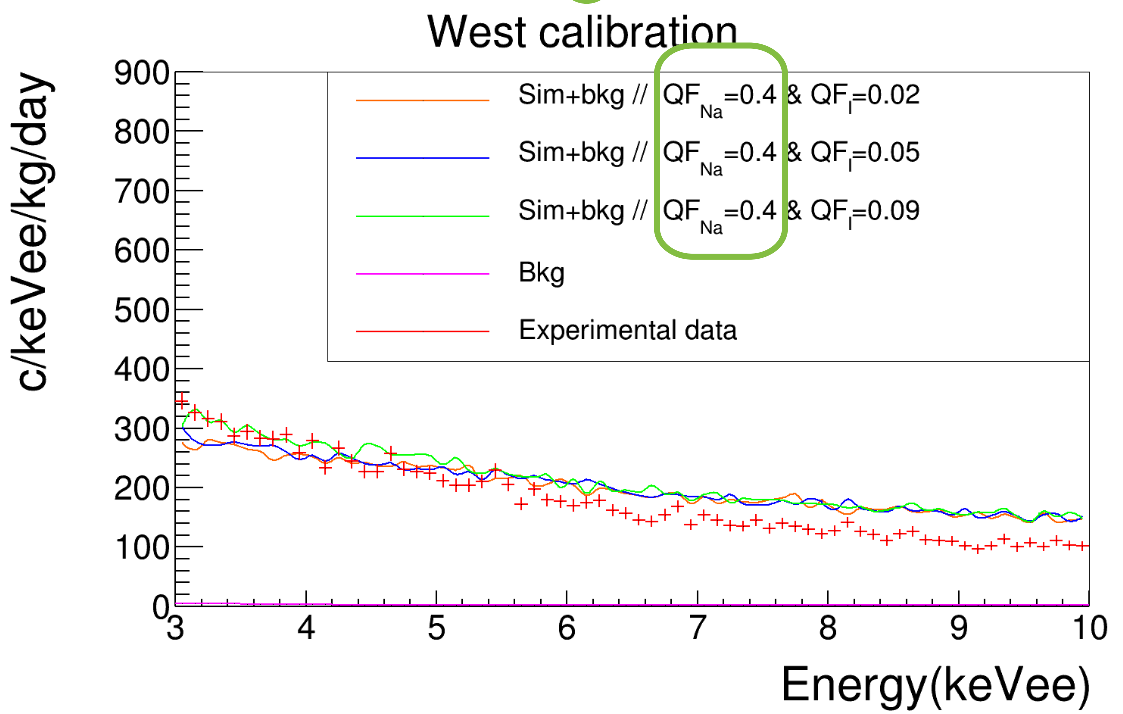
Let's change QF_{Na} !

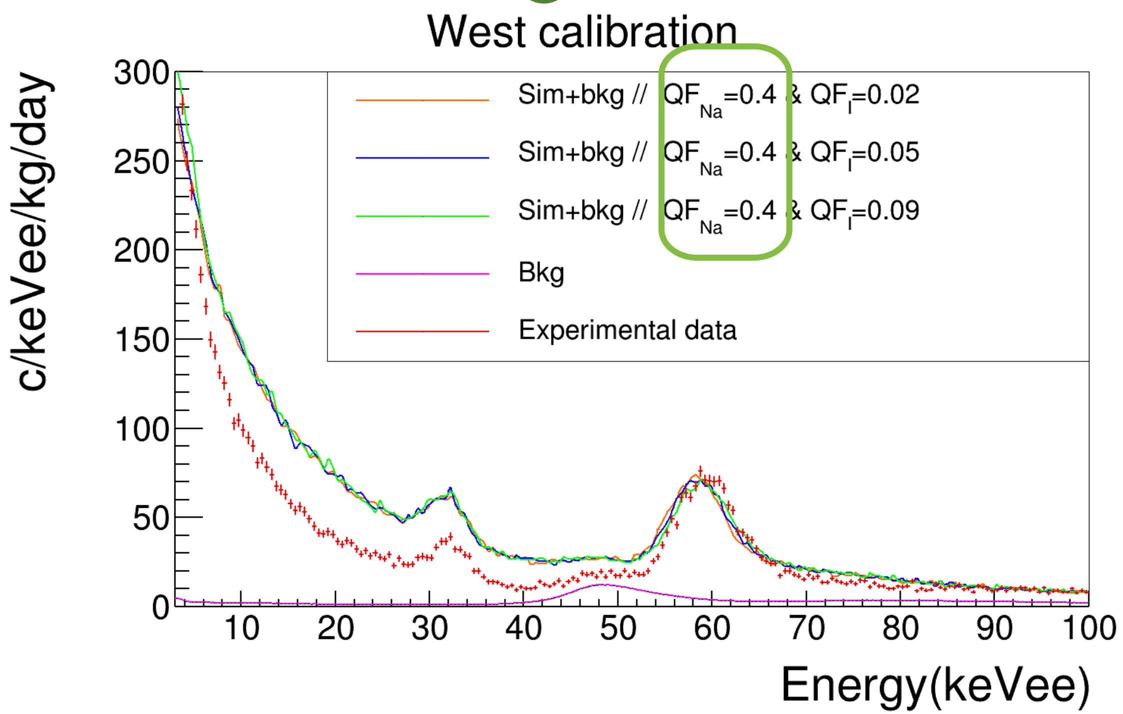




Let's change QF_{Na} !

PRELIMINARY

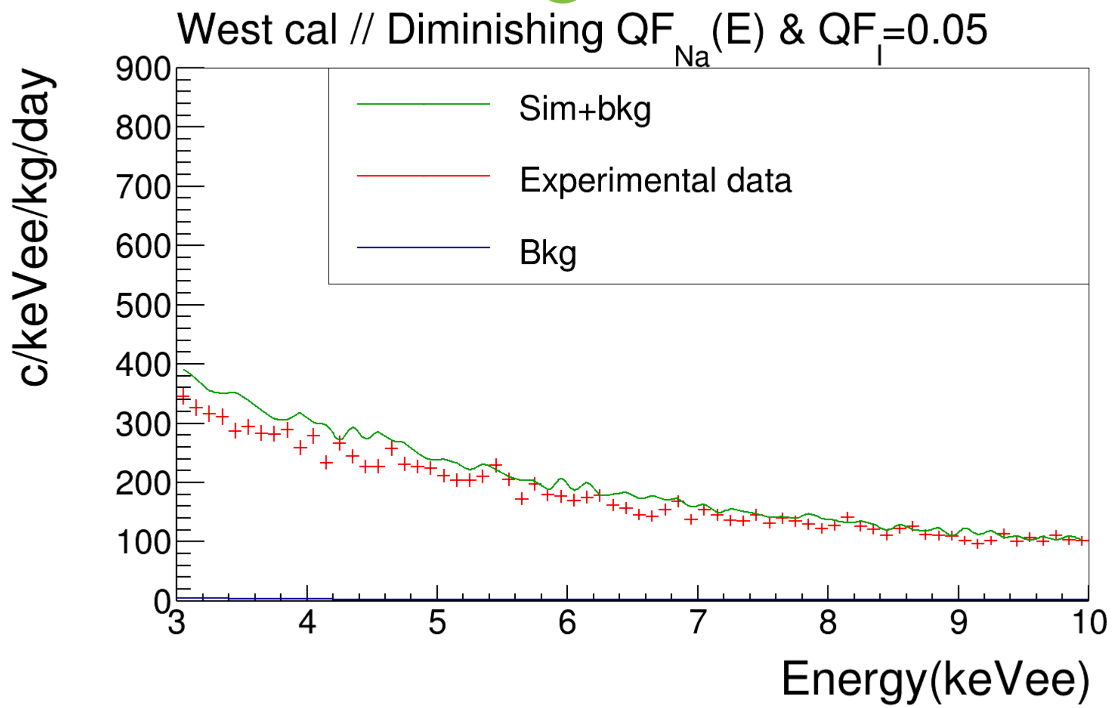


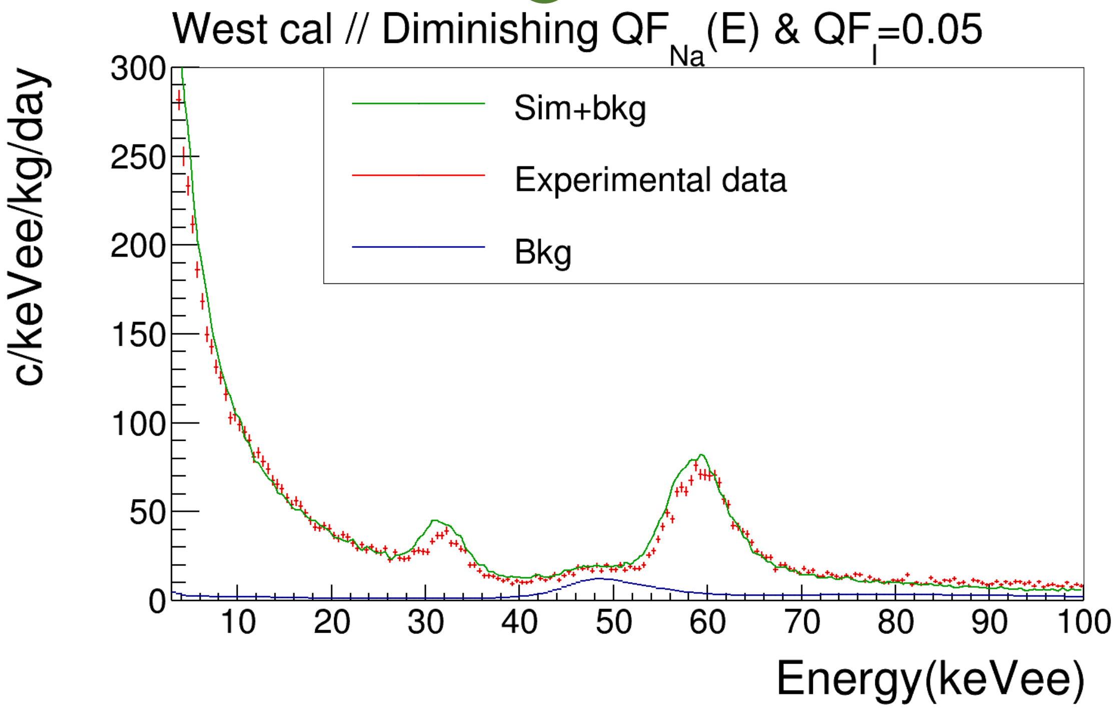


RESULTS ON THE QUENCHING FACTOR

Diminishing with energy QF_{Na} @ low energies !

PRELIMINARY

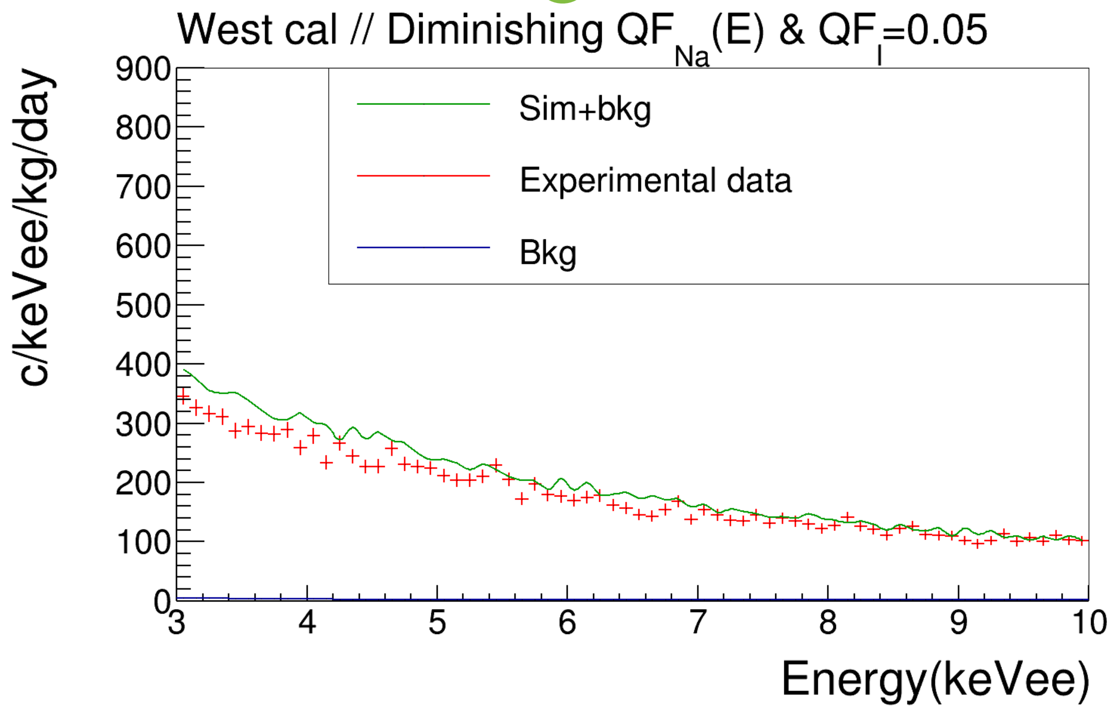


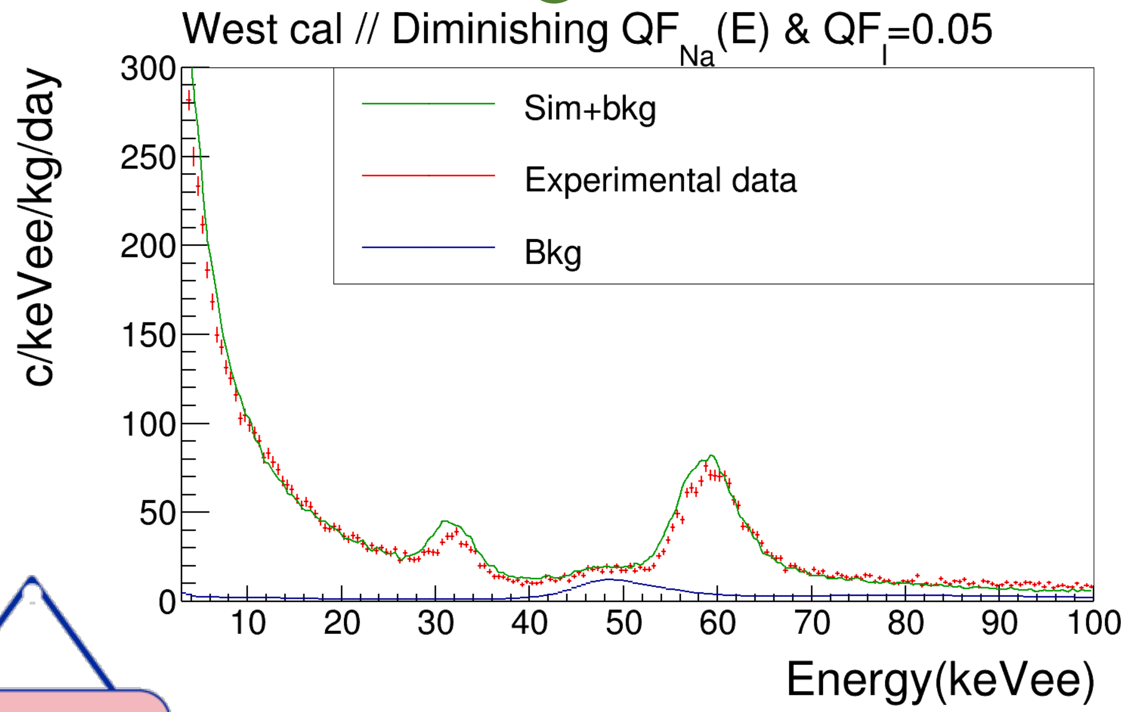


RESULTS ON THE QUENCHING FACTOR

PRELIMINARY

Diminishing with energy QF_{Na} @ low energies !





Work in Progress

RESULTS ON THE QUENCHING FACTOR

PRELIMINARY

1 — Our approach is truly sensitive to the QF

2 — Up to now, we are not able to find a constant QF that really fit our data in all the energy ranges

RESULTS ON THE QUENCHING FACTOR

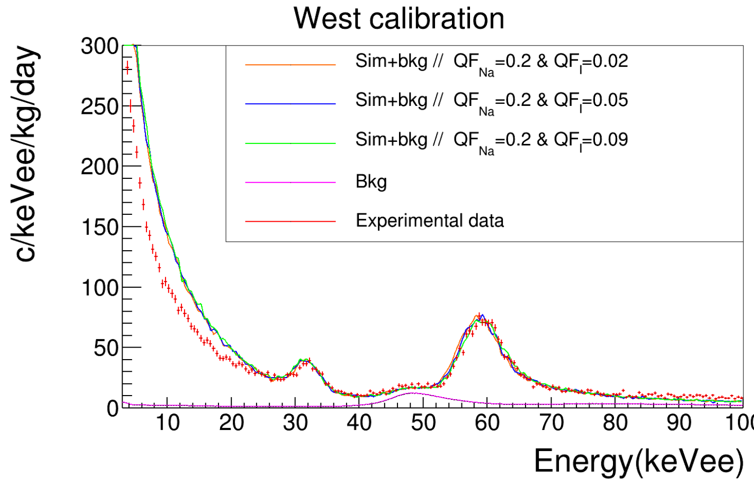
PRELIMINARY

1. Our approach is truly sensitive to the QF

2. Up to now, we are not able to find a constant QF that really fit our data in all the energy ranges

3. QF_{Na}=0.2 seems to be the better fitting constant QF (as obtained @TUNL)

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

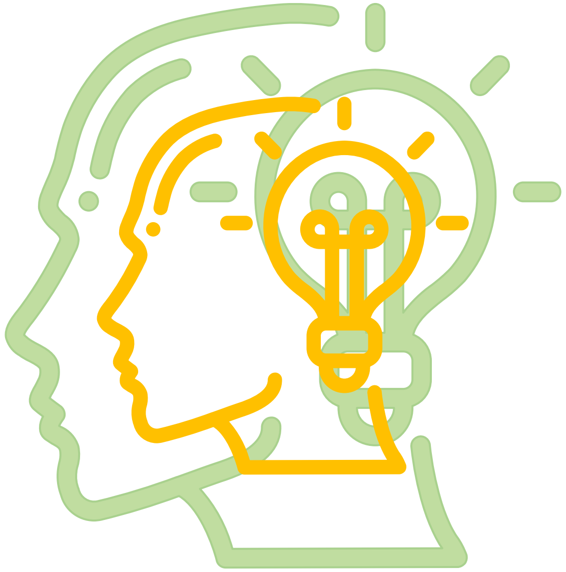


Good agreement above 25 keVee

RESULTS ON THE QUENCHING FACTOR

PRELIMINARY

1. Our approach is truly sensitive to the QF
2. Up to now, we are not able to find a constant QF that really fit our data in all the energy ranges
3. QF_{Na}=0.2 seems to be the better fitting constant QF (as obtained @TUNL)
4. Plans to continue understanding diminishing with energy QF @ low energies and other dependences, and to explore the non proportionality of detectors



CONCLUSIONS

ANAIS-112 is taking data in stable condition @ LSC since 3rd August 2017 with excellent performances.
3 years of analyzed data are compatible with absence of modulation and incompatible with DAMA/LIBRA at 3.3 (2.6)σ in [1-6] ([2-6]) keV. Sensitivity: 2.5σ (2.7σ) in [1-6] ([2-6]) keV.
3σ at reach in 2022 (5 years of measurement)

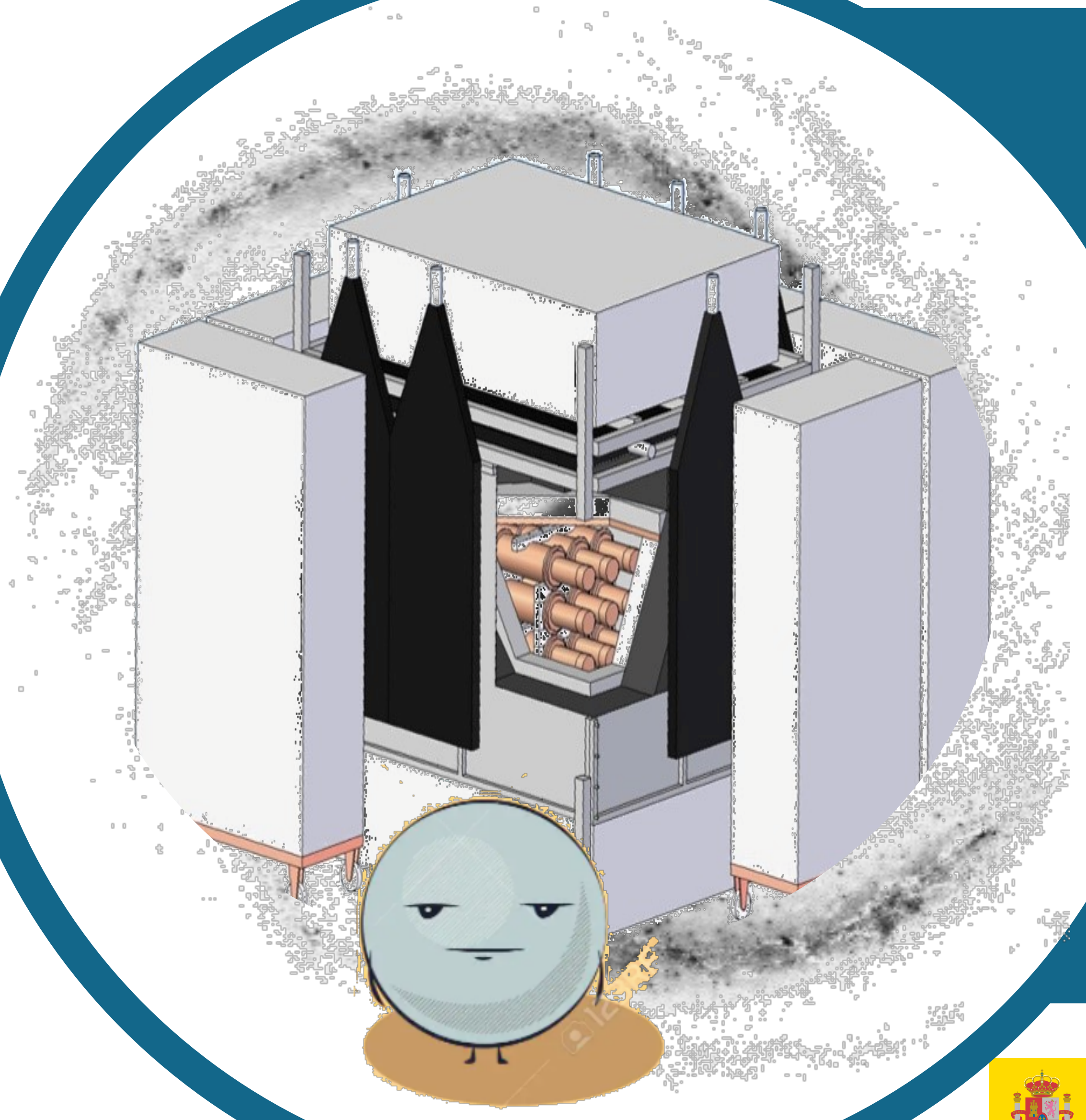
Systematics have to be taken into account for understanding a more than 20 y old-puzzling result: **nuclear recoil energy conversion into visible energy could be different in ANAIS and DAMA/LIBRA detectors!**

We have measured QF @TUNL. Results coming soon. Measurement with a neutron source onsite has been recently performed with ANAIS-112 set-up. Beyond QF understanding, the latter approach will play an important role regarding the evaluation of ANAIS-112 efficiencies to NR and the improvement of filtering protocols with machine learning techniques

Comparison between data and simulation allows following a best-fit strategy. Our simulation is truly sensitive to the QF. However, up to now, we are not able to find a constant QF that really fit our data in all the energy ranges. Plans to include the non proportionality of detectors and to test different QF models. Work is ongoing. Resuts will come soon.

Stay Tuned!

Thank you!



May 23, 2022 @19th Multidark, Madrid

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

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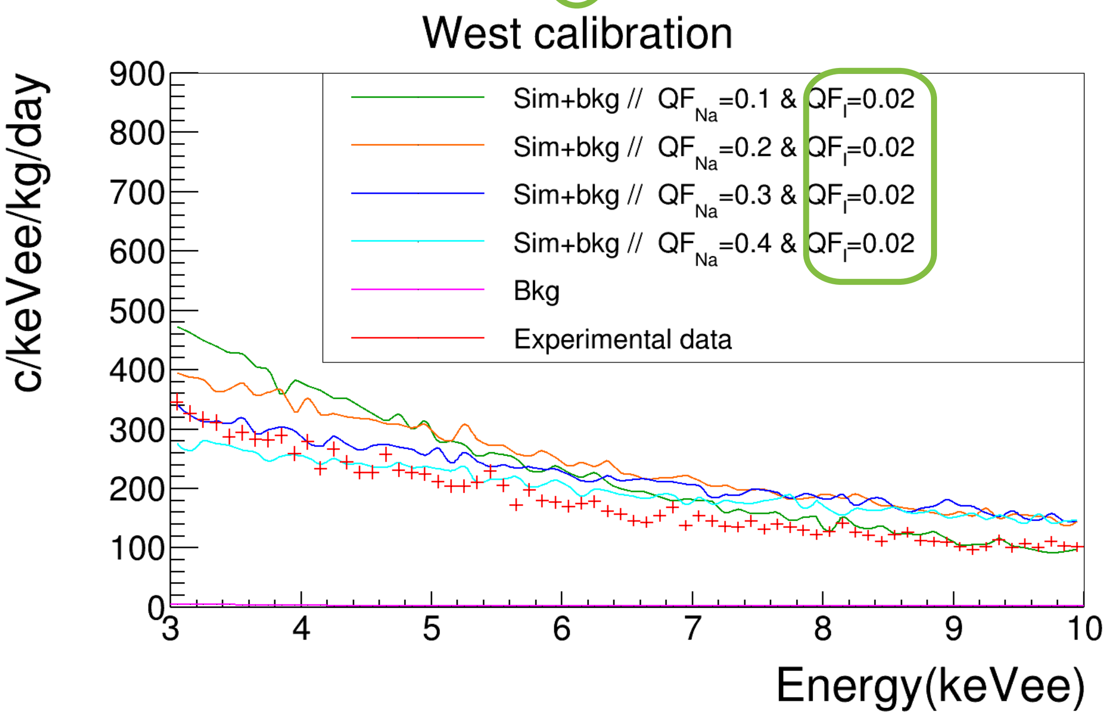
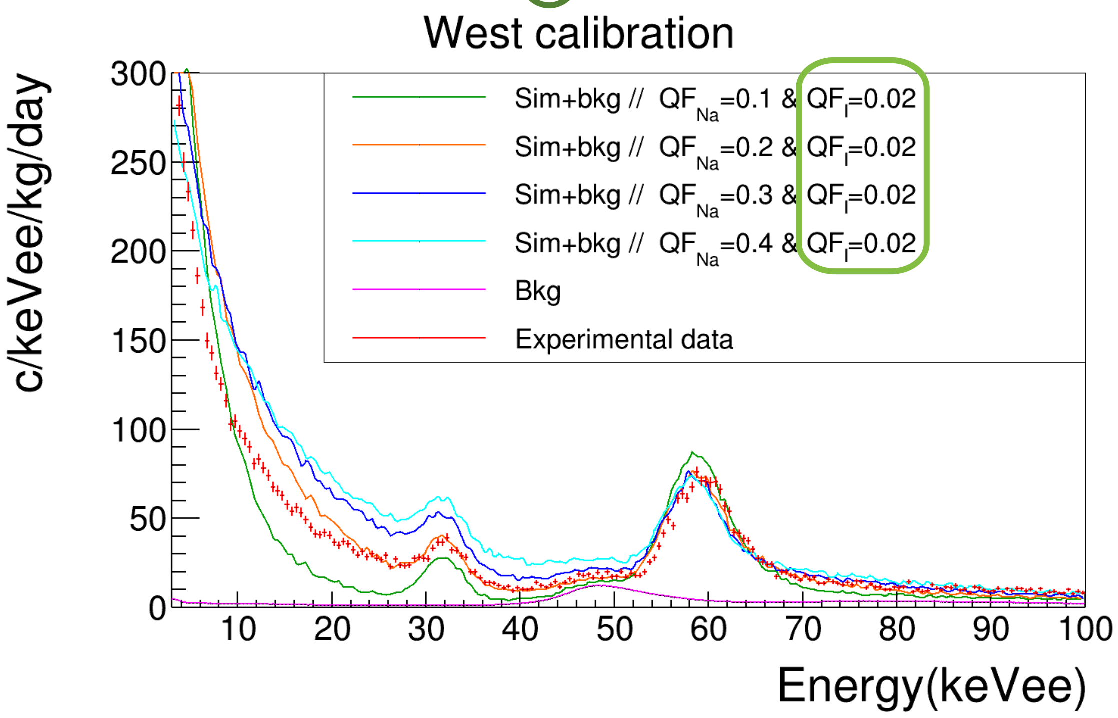
LSC
Laboratorio Subterráneo de Canfranc

MultiDark
Multimessenger Approach for Dark Matter Detection

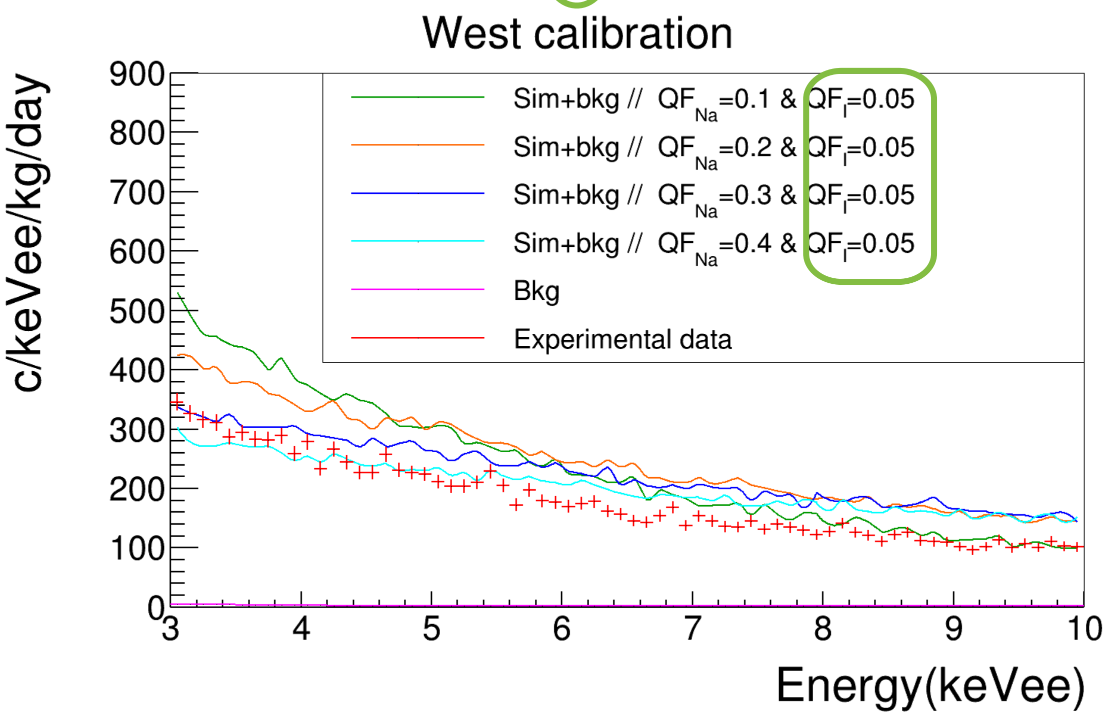
This research is founded by MCIN/AEI/10.13039/501100011033 under grant PID2019-104374GB-I00

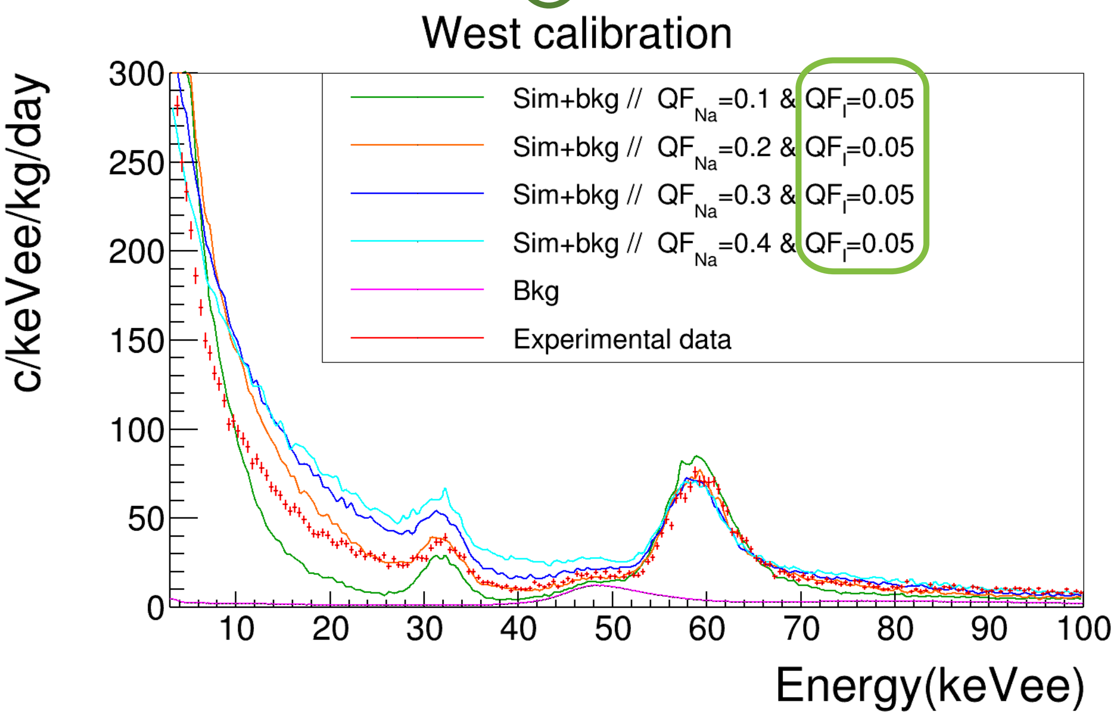
Let's change QF_I !





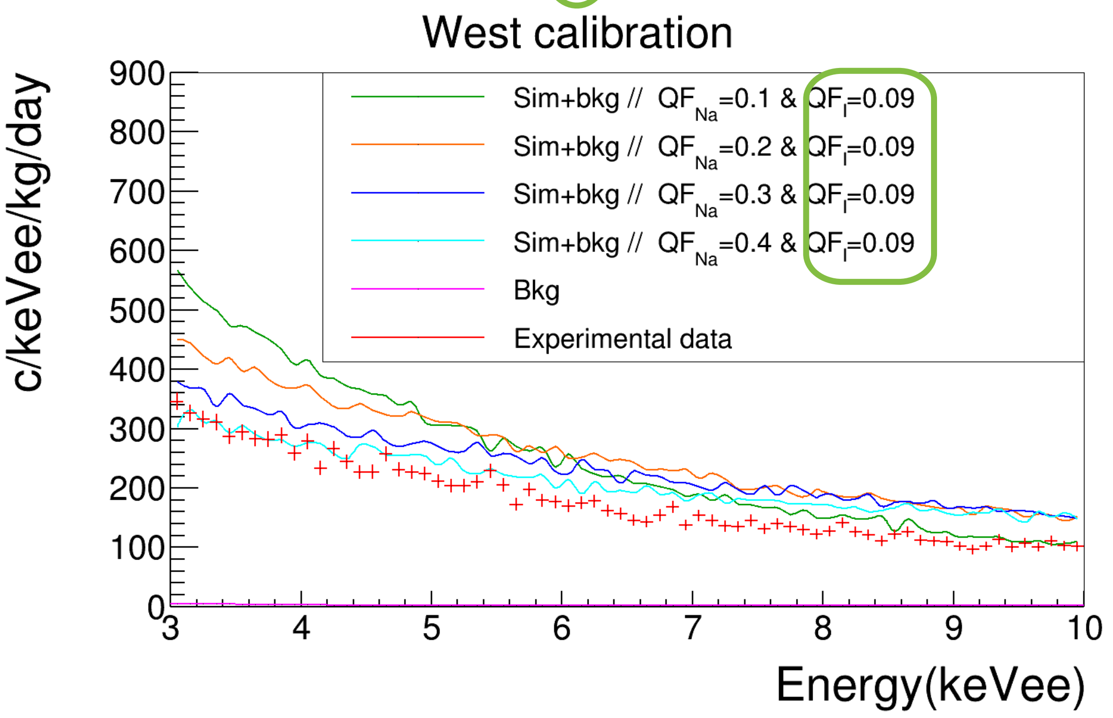
Let's change QF_I !

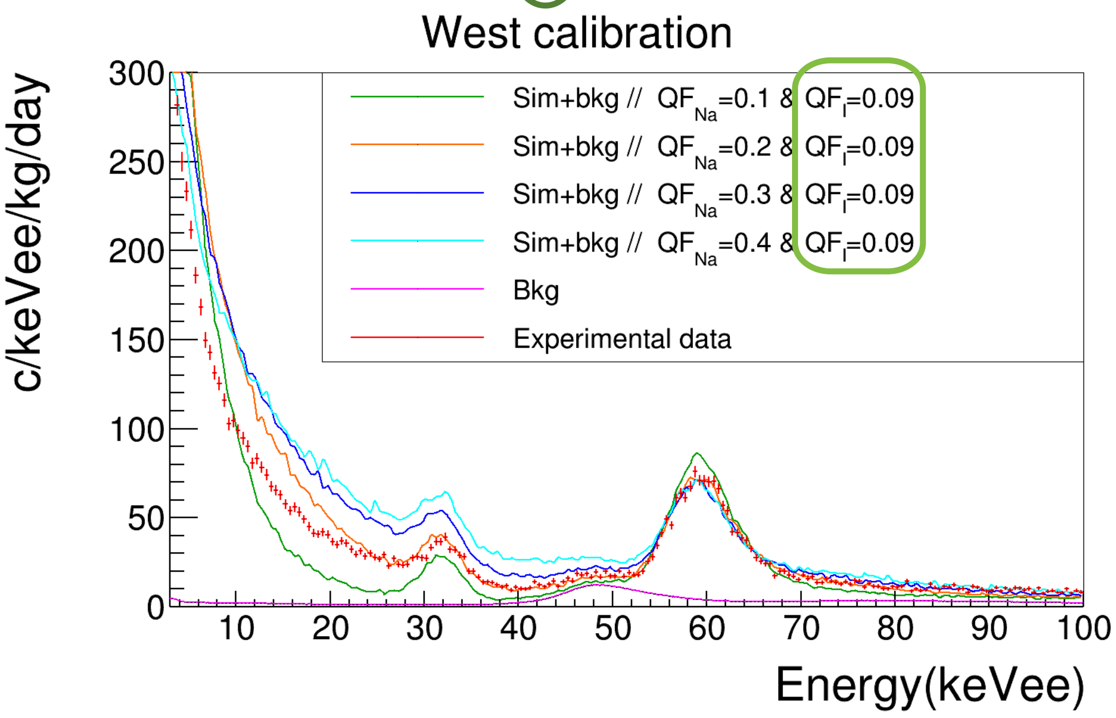




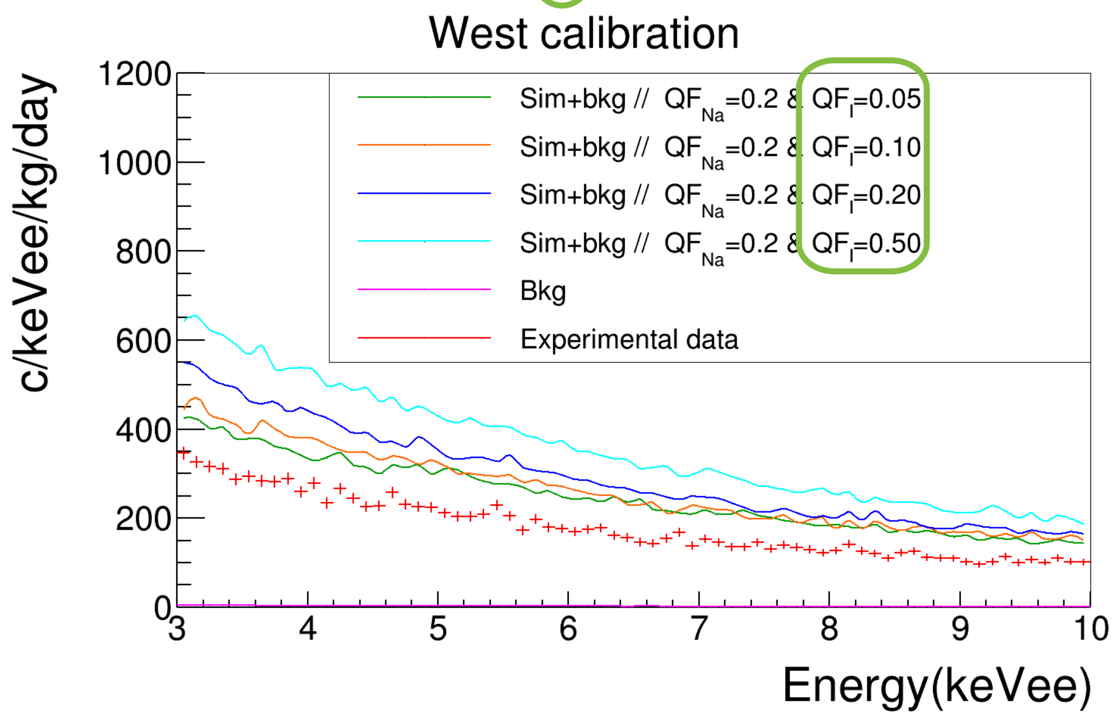
BACKUP SLIDES

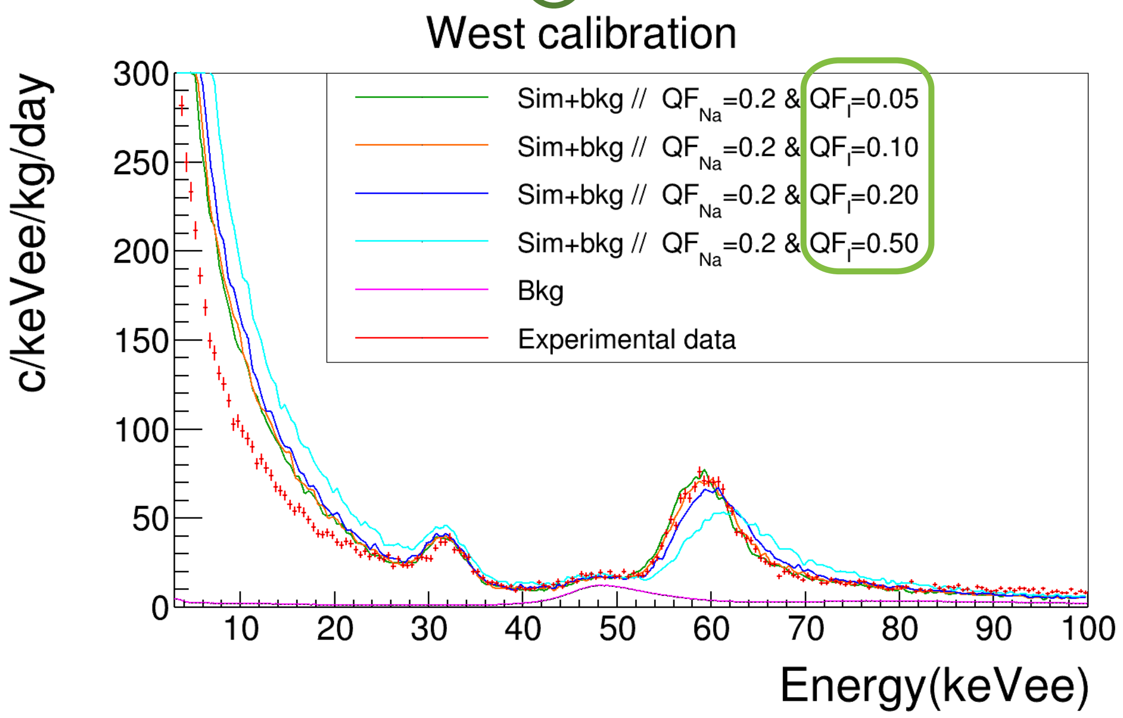
Let's change QF_I !



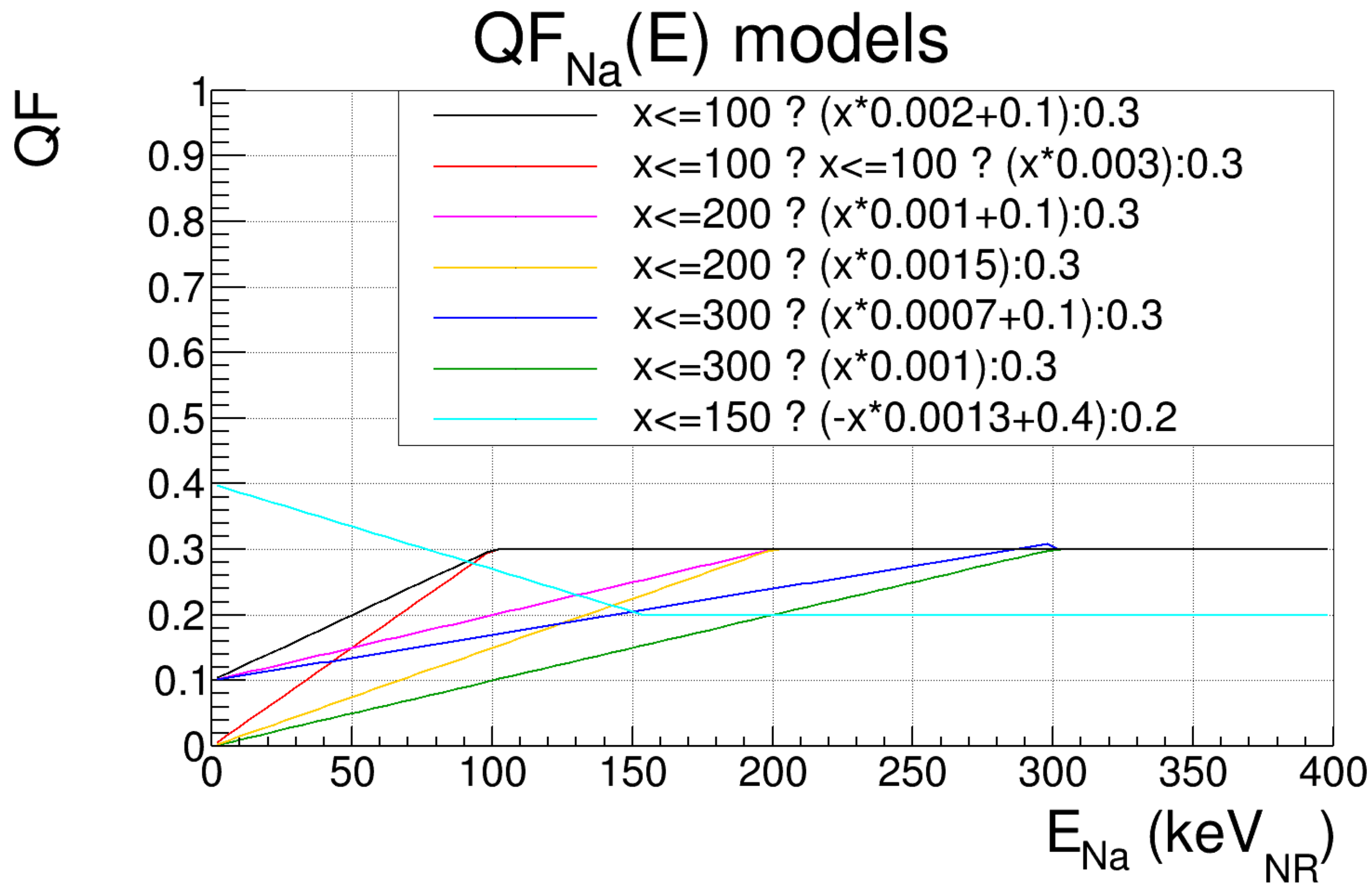


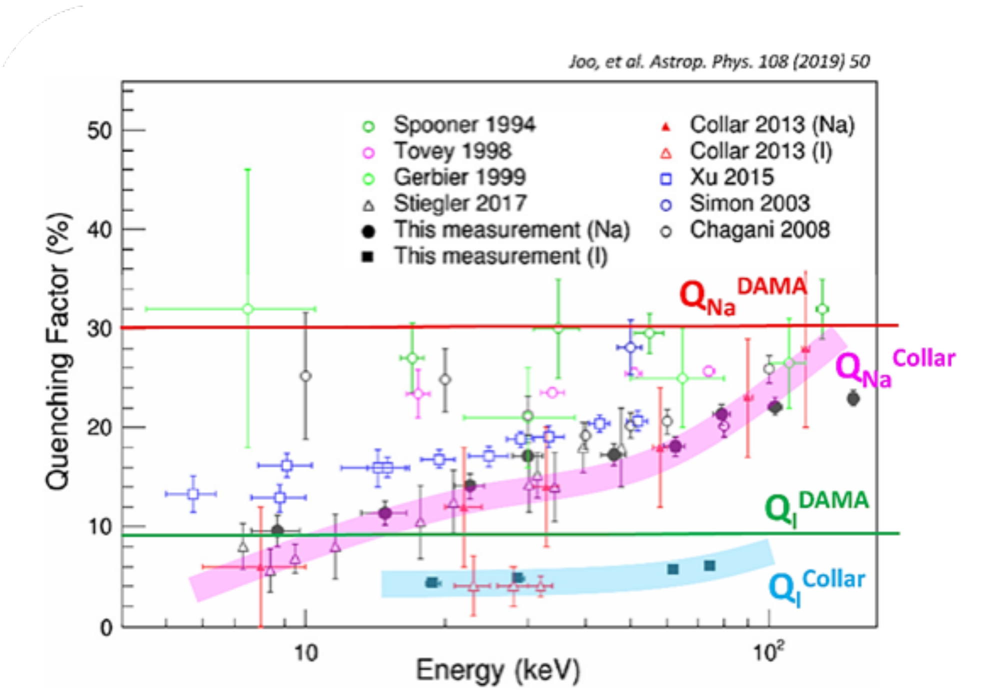
BACKUP SLIDES



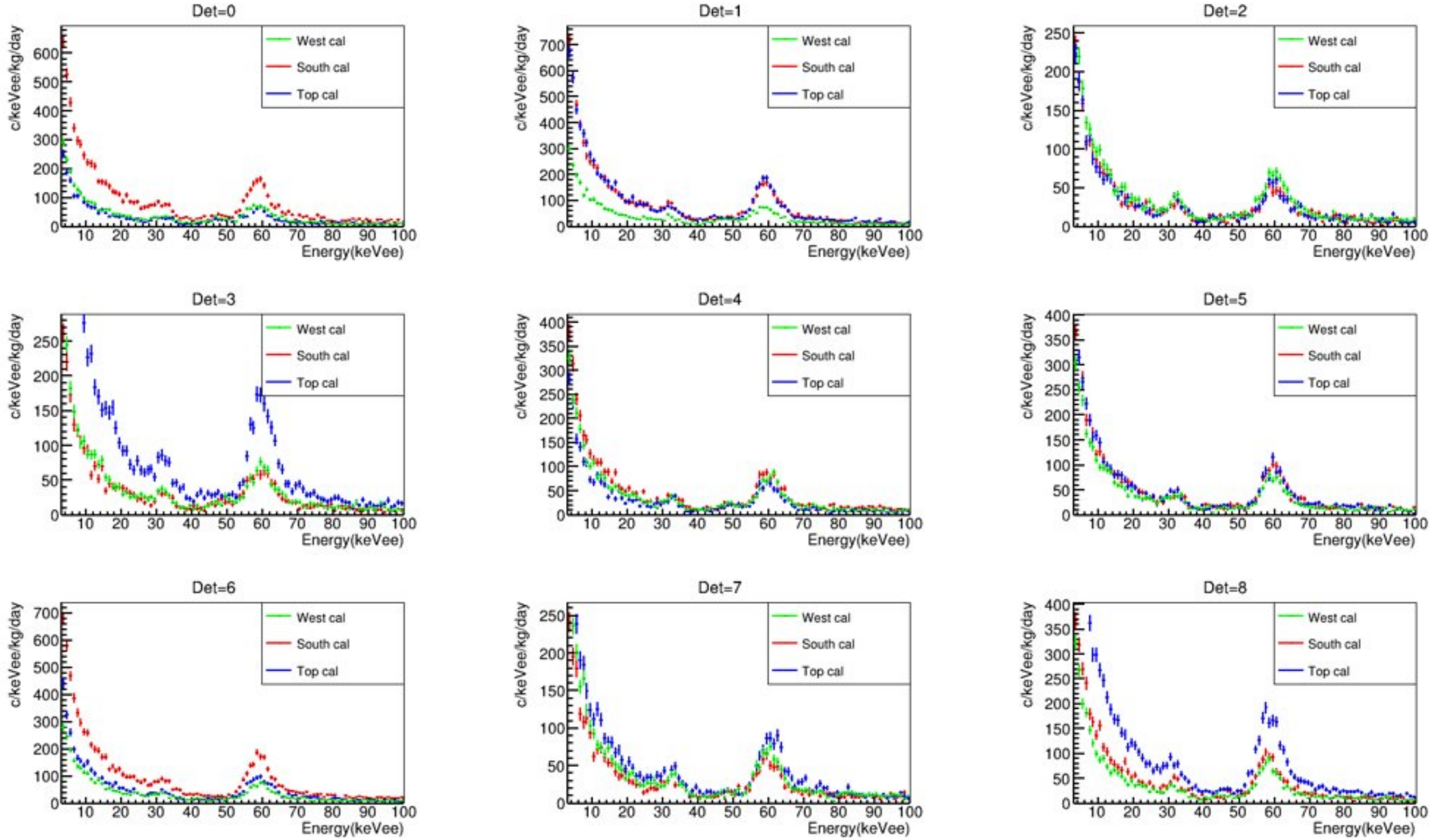


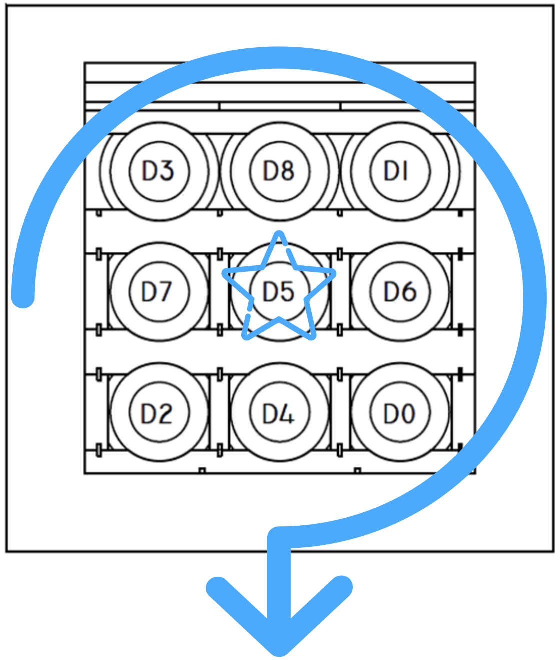
BACKUP SLIDES





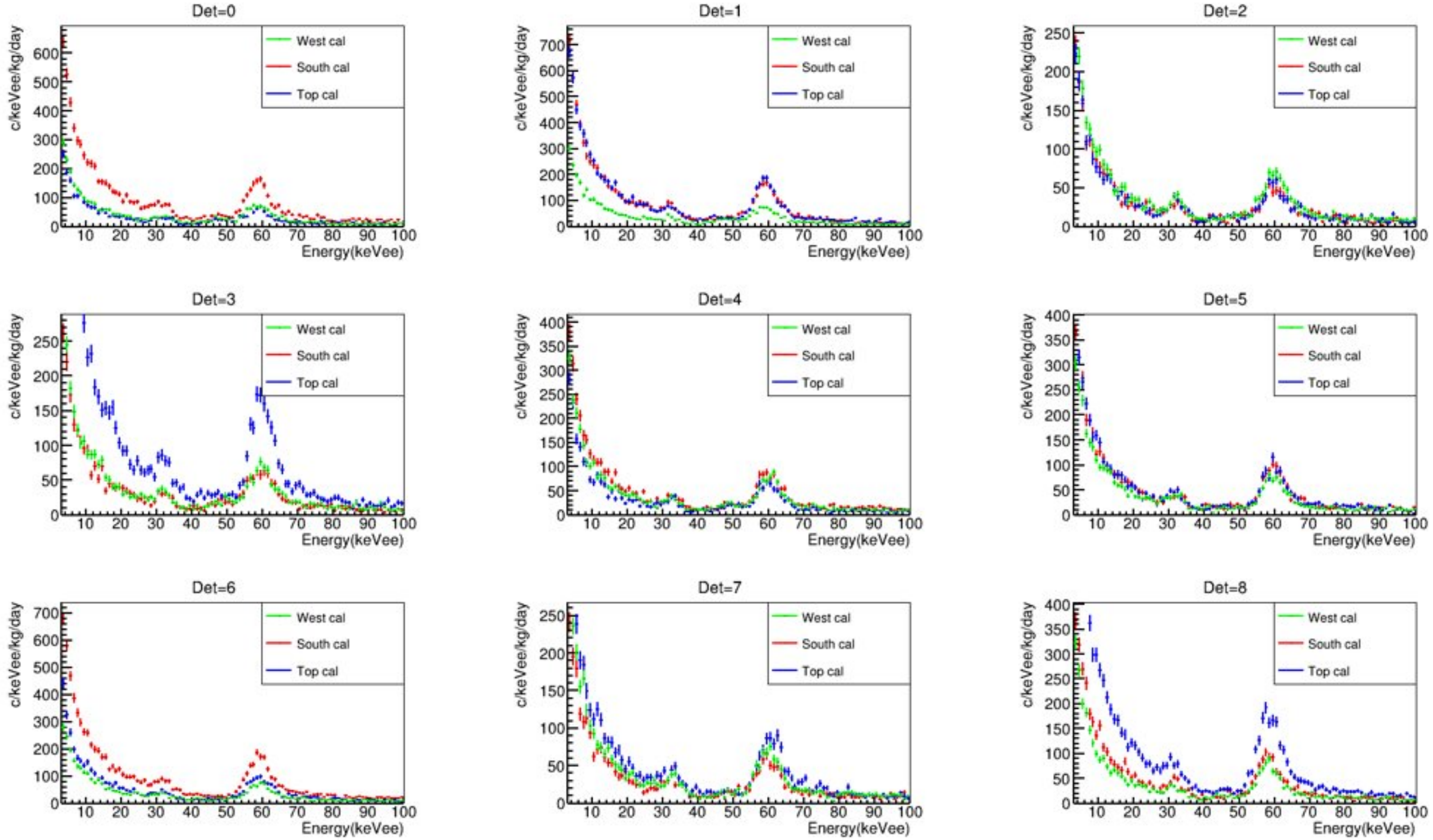
ONSITE NEUTRON CALIBRATION PROGRAM

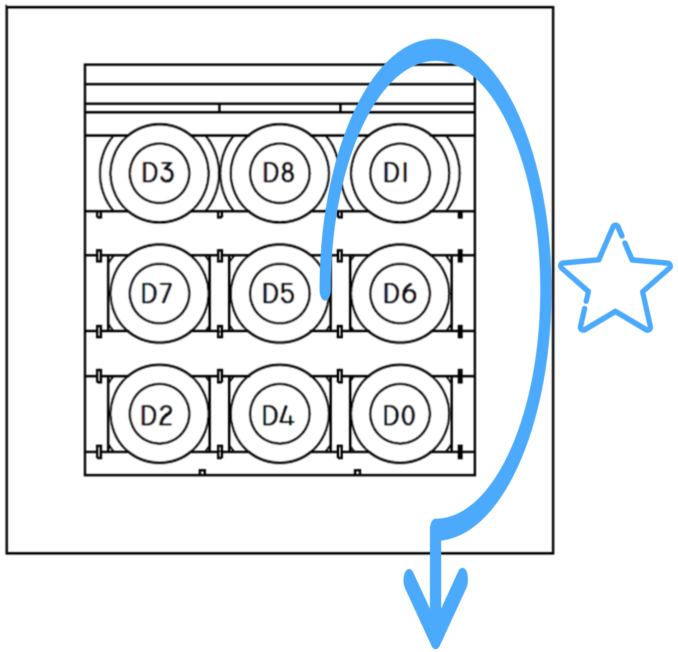




West calibration

ONSITE NEUTRON CALIBRATION PROGRAM





South calibration

ONSITE NEUTRON CALIBRATION PROGRAM