ANAIS-112 annual modulation results and prospects to test DAMA/LIBRA beyond 3σ

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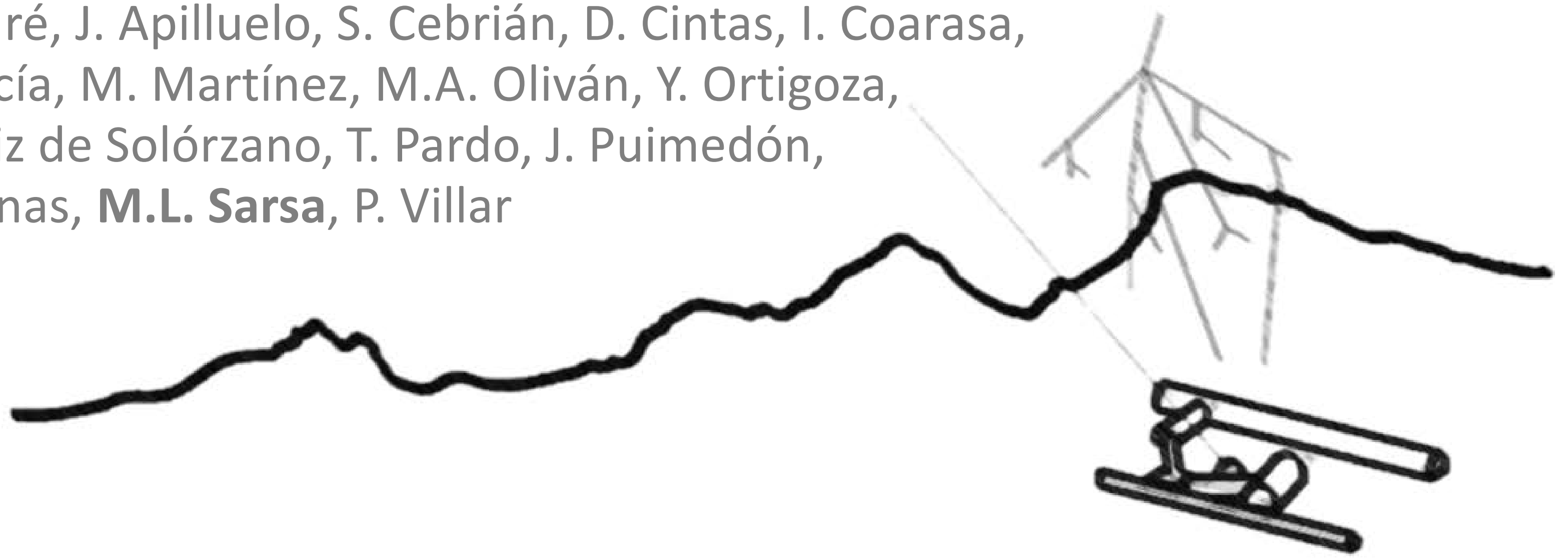


MultiDark
Multimessenger Approach for Dark Matter Detection

Universidad Zaragoza

LSC
Laboratorio Subterráneo de Canfranc

ANAIS

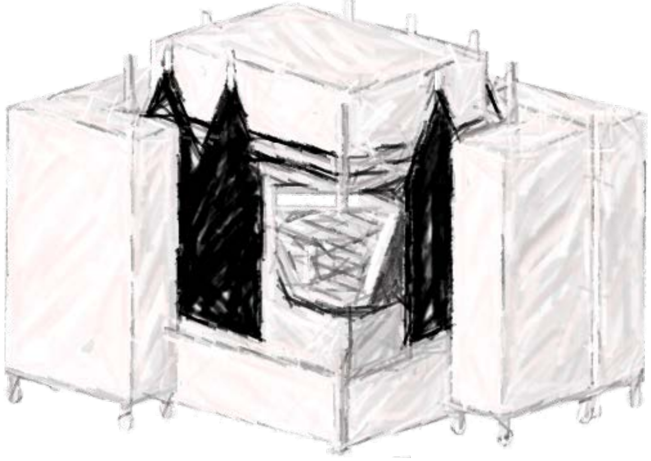
IDM 2022

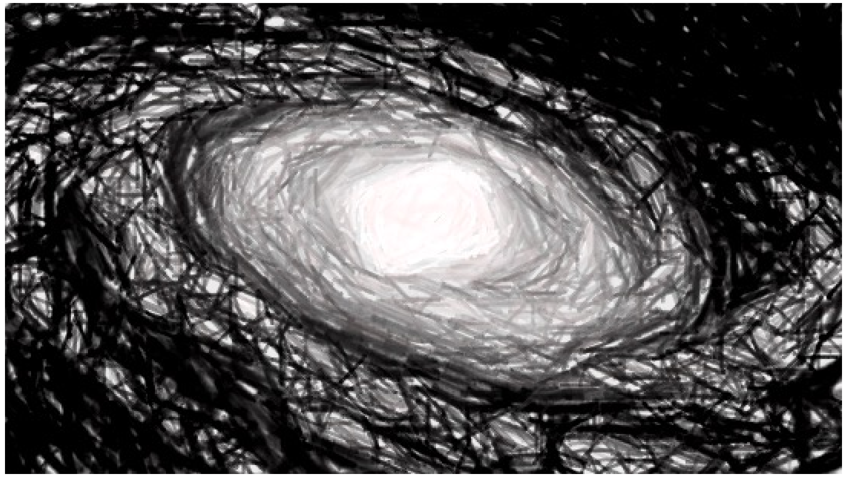
14th International Conference on Identification of Dark Matter

18-22 July 2022
Vienna, Austria

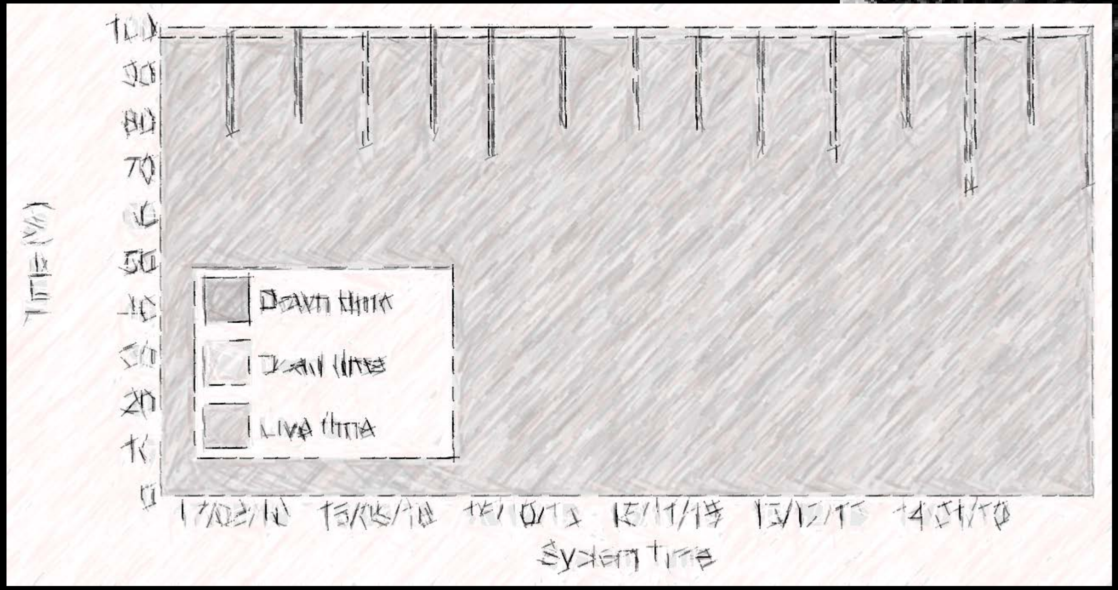
CAPA
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

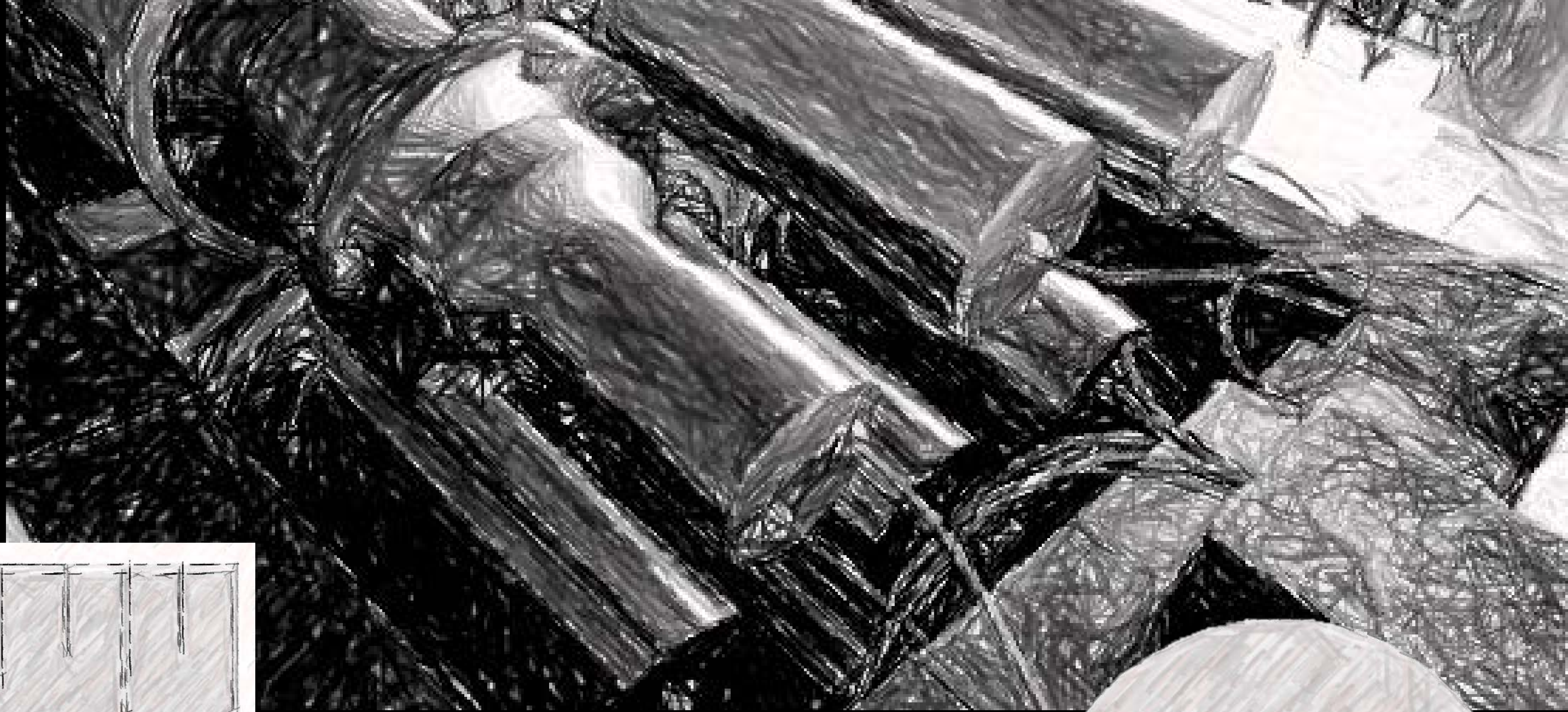
Outline





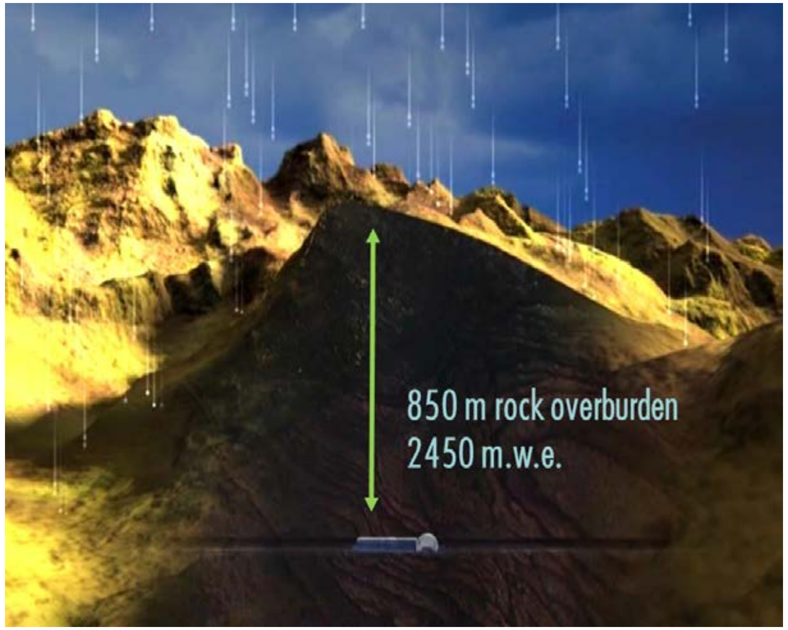
- **ANAIS-112 experimental set-up and performance**
- **Neutron calibration program of ANAIS-112 detectors**
- **New ANAIS-112 event selection protocol using Machine Learning techniques**
- **ANAIS-112 three years annual modulation re-analysis and update of ANAIS-112 sensitivity prospects**
- **Summary and Outlook**

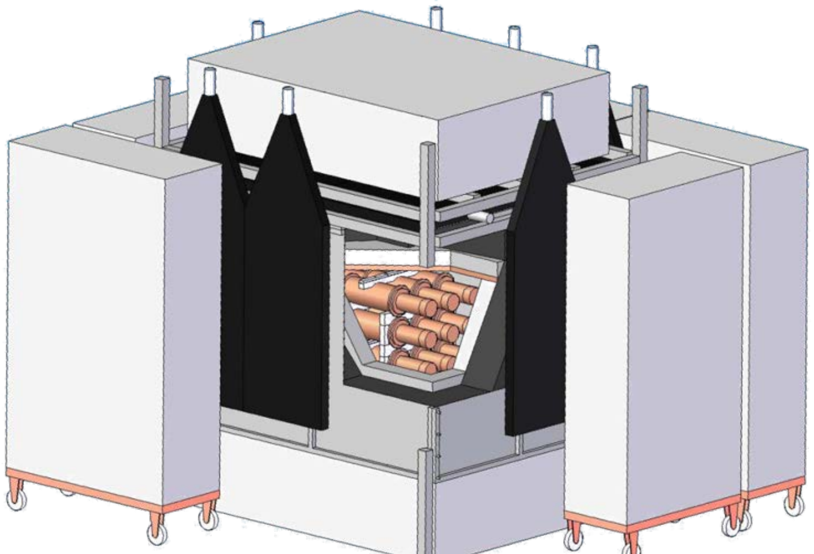




ANAIS-112 experimental set-up and performance

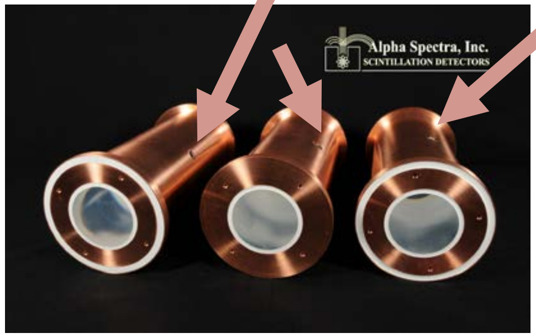
Annual modulation with NaI Scintillators





- Confirmation of DAMA-LIBRA modulation signal -> **same target and technique** / **different** experimental approach / **different** environmental conditions affecting **systematics**
- **At Canfranc Underground Laboratory, SPAIN taking data since August 2017**
- 3x3 matrix of 12.5 kg cylindrical modules = **112.5 kg of active mass** grown @ Alpha Spectra, Inc.
- HE PMTs coupled at LSC clean room

Annual modulation with NaI Scintillators

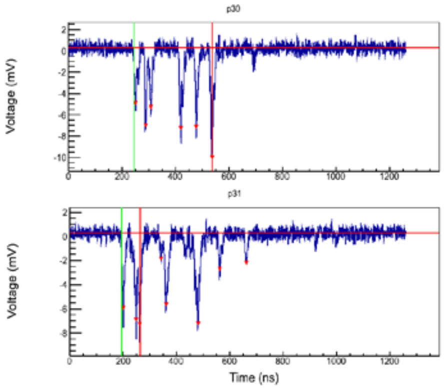


RELEVANT EXPERIMENTAL FEATURES

Mylar windows built-in allowing for calibration at LE with ^{109}Cd sources

Excellent light collection in all the nine modules, at the level of 15 p.e./keV

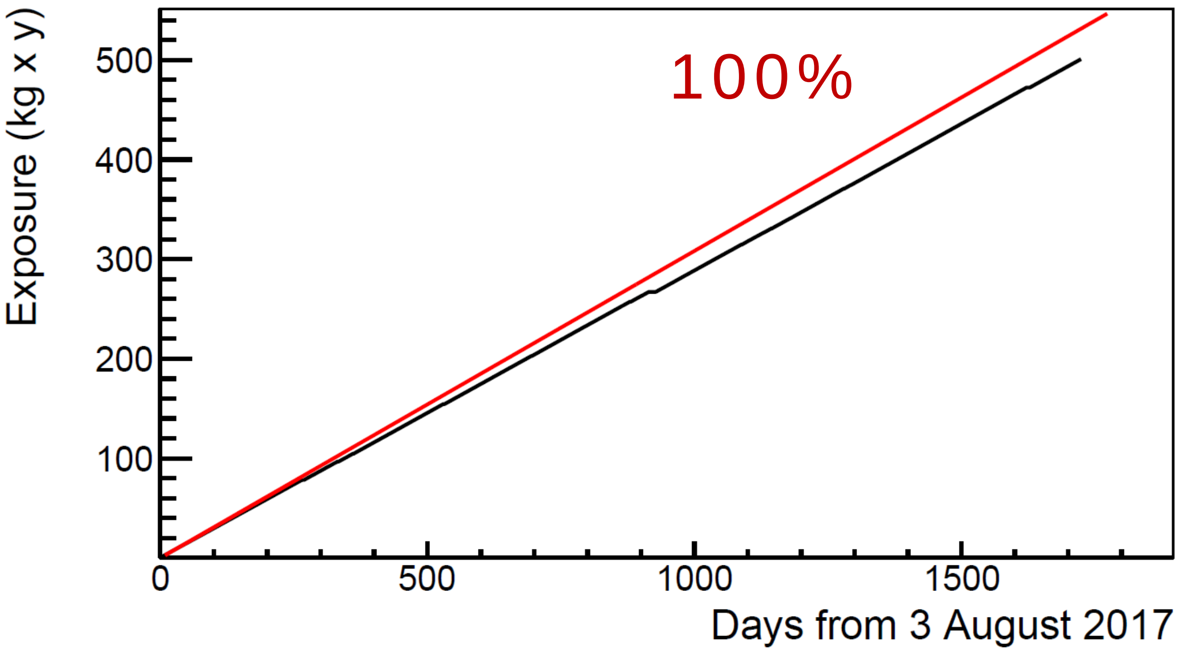
Active muon veto system (16 plastic scintillators)



Individual PMT signals digitized and fully processed (**14 bits / 2 GS/s**), trigger at p.e. level for each PMT + Logical AND coincidence in 200ns window

Robust / low noise / tested with previous prototypes

The ANAIS-112 Dark Matter Run started on August 3, 2017



524.44 kg x y @ June 7, 2022

ANAIS-112 accumulated exposure

Time period	Accumulated Live Time	Live Time (%)	Down Time (%)	Dead Time (%)
08/03/2017-07/31/2018	341.722 days	94.5	2.6	2.9
08/01/2018-08/28/2019	374.302 days	95.6	2.4	2.1
08/29/2019-08/13/2020	333.791 days	95.2	2.5	2.3
08/13/2020-08/18/2021	354.667 days	95.9	1.7	2.4
08/19/2021-06/07/2022	297.022 days	95.0	3.2	1.9
TOTAL LIVE	**1701.504 days**			
TOTAL	**1766.25 days**			

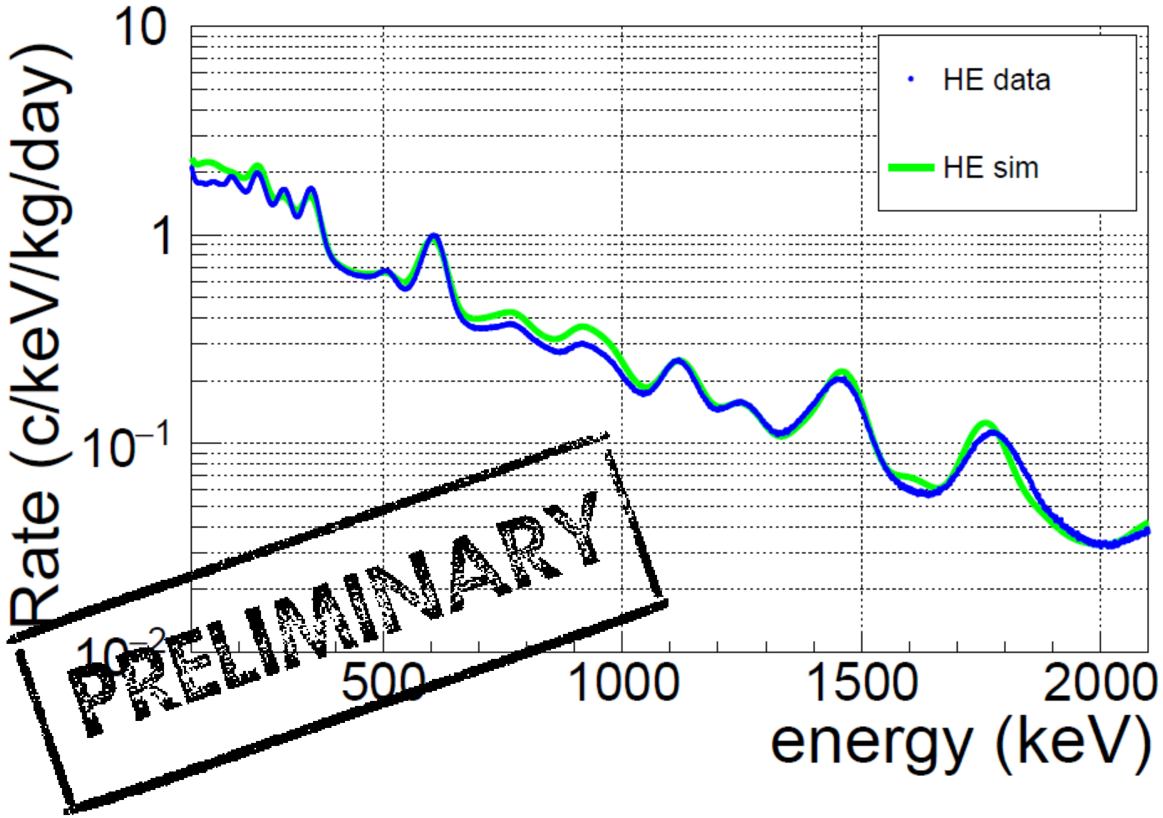
Five-year exposure will be completed by August 2022 with about 95% of live time

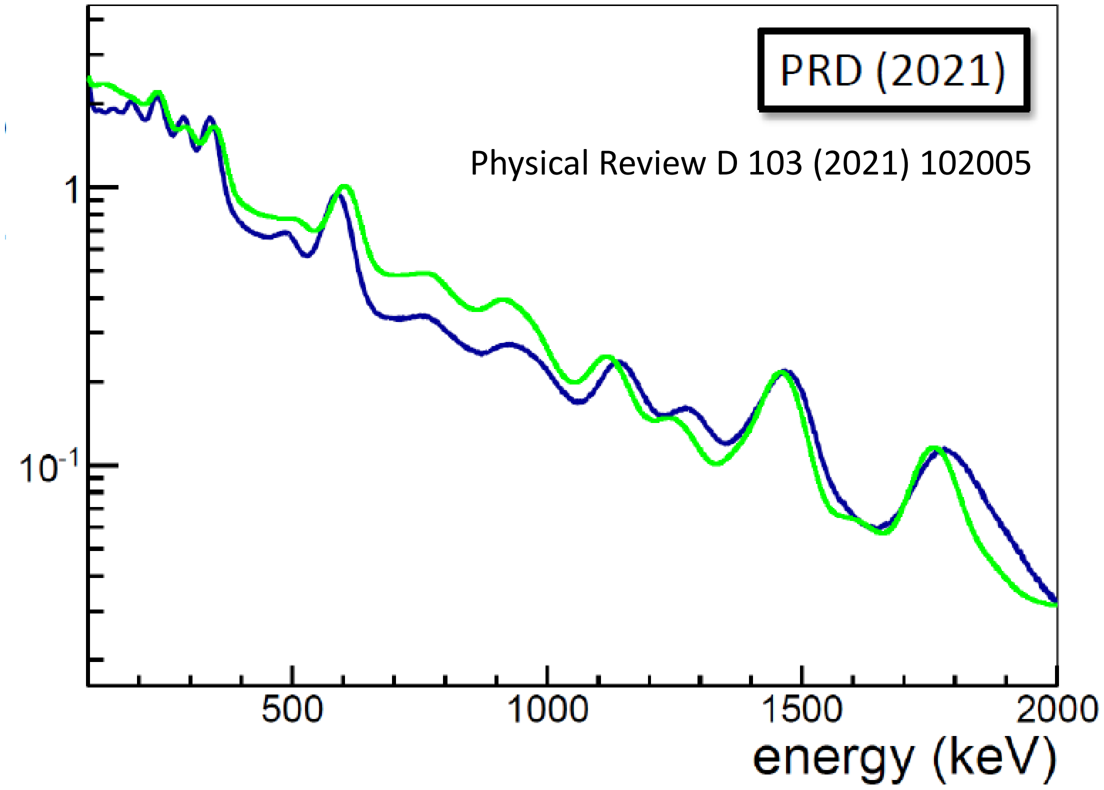
ANAIS-112 Duty Cycle

Calibration @ HE (above 100 keV)

Improvement of the estimate of energy above 100 keV by better linearizing the pulse area – QDC relation for each module (using Chebyshev' polynomials +pol1 +pol2 instead of a logistic function) and calibrating quadratically with background lines

IMPROVEMENT IN MATCHING THE MC SIMULATED BACKGROUND

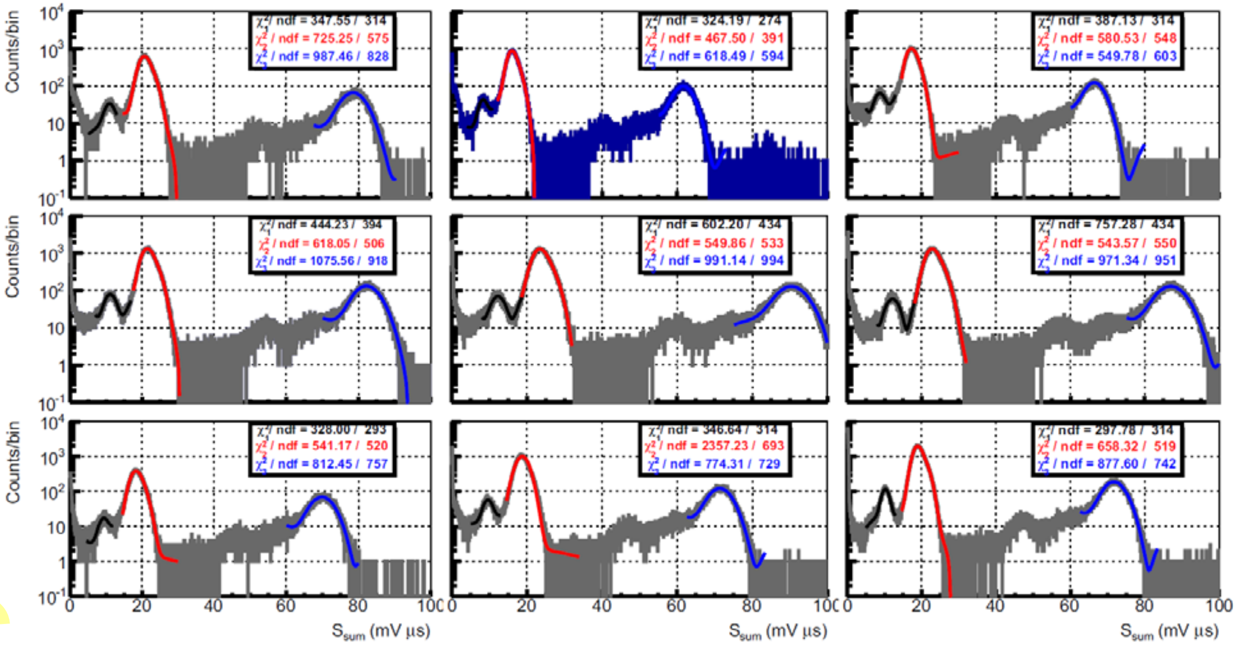




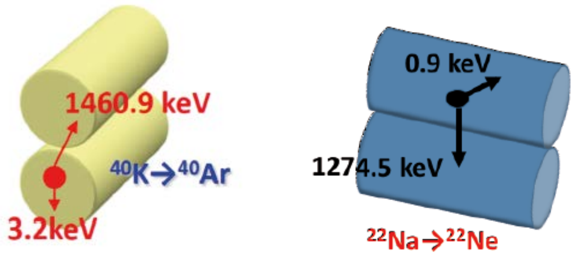
Calibrating the ROI with high accuracy

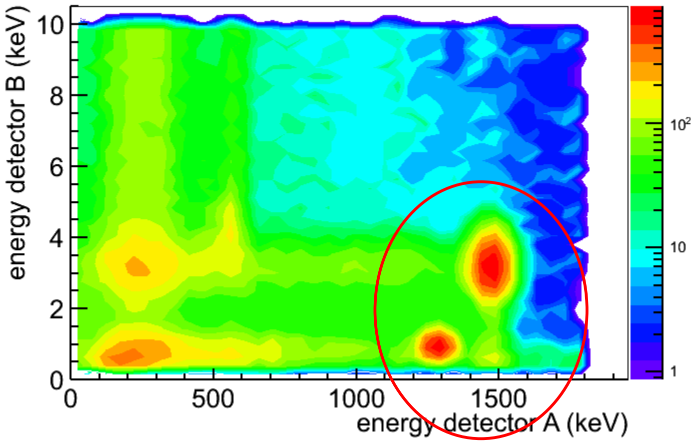
Two calibration steps:

- periodical external calibration using ^{109}Cd (**88.0, 22.6 and 11.9 keV**) to correct gain drifts every two weeks
- ^{40}K and ^{22}Na internal contamination background lines (**3.2 and 0.9 keV**) identified by coincidences with HE gammas every 1.5 months



88.0 keV (blue)
22.6 keV (red)
11.9 keV (black)





3.2 and 0.87 keV

ROI calibrated with 22.6, 11.9, 3.2 and 0.9 keV

ANAIS-112 Low Energy Calibration

Calibrating the ROI with high accuracy

Two calibration steps:

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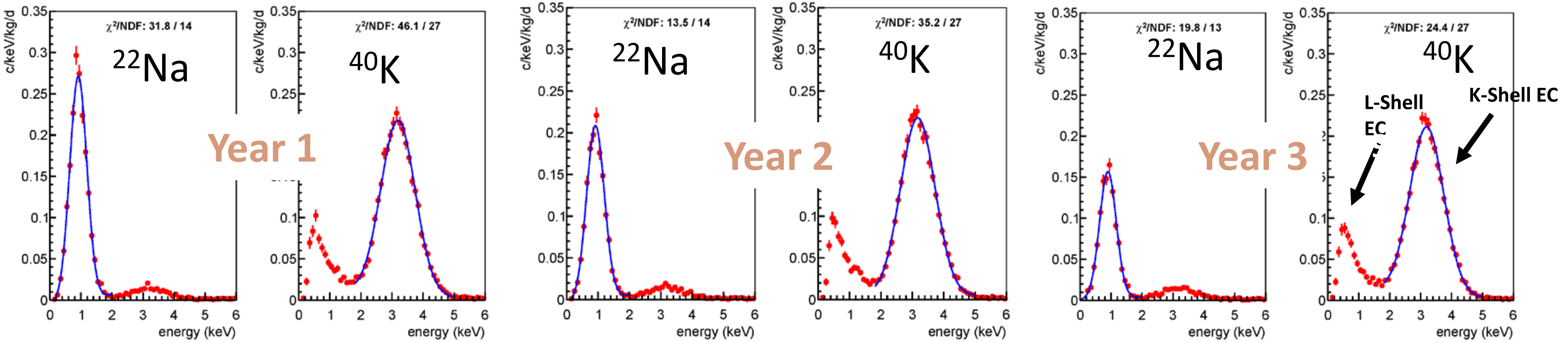
- ^{40}K and ^{22}Na internal contamination background lines (**3.2 and 0.9 keV**) identified by coincidences with HE gammas every 1.5 months

ROBUST CALIBRATION AT LOW ENERGY checked by ^{40}K and ^{22}Na peaks mean values and non-degradation of energy resolution in the analysed period

Clear demonstration of triggering below 1 keV

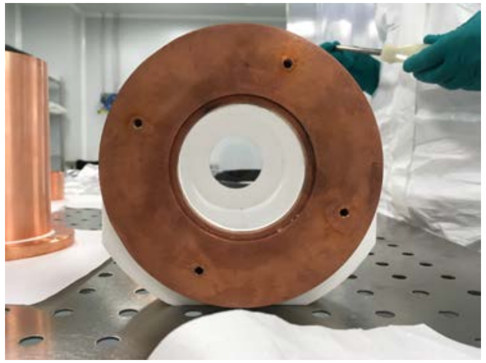


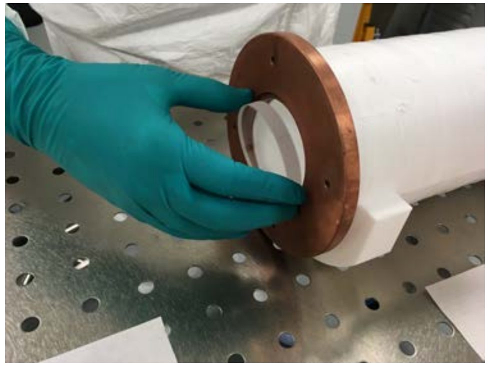
ANAIS-112 BLANK module

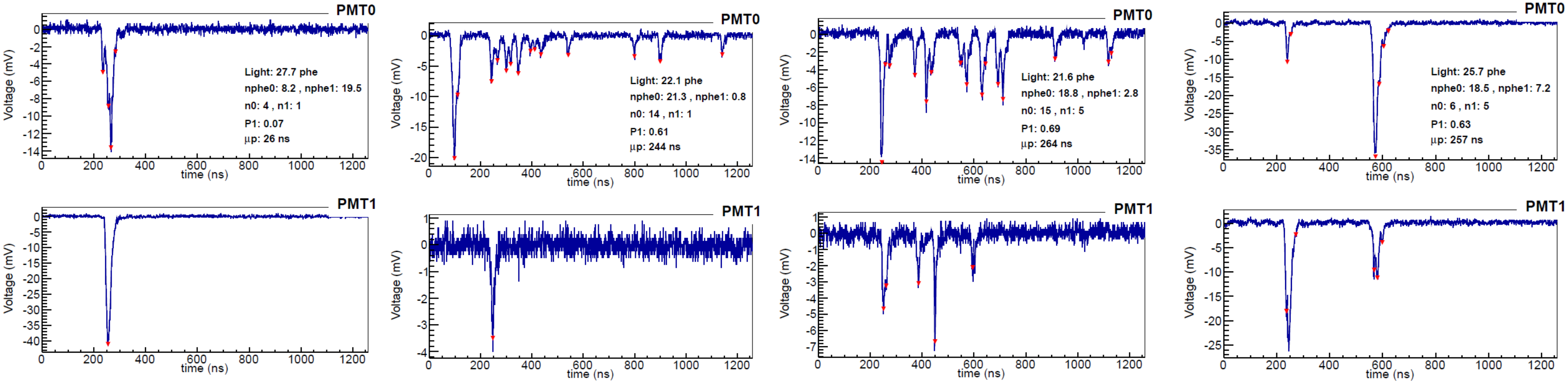
In 2018 a BLANK module was commissioned for taking data in similar conditions to ANAIS-112 modules

similar size, housing and PMTs, without NaI(Tl) crystal

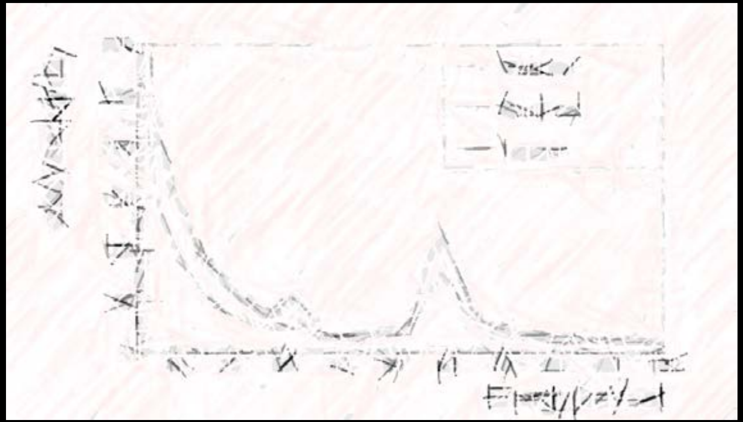
same DAQ, independent shielding close to ANAIS-112

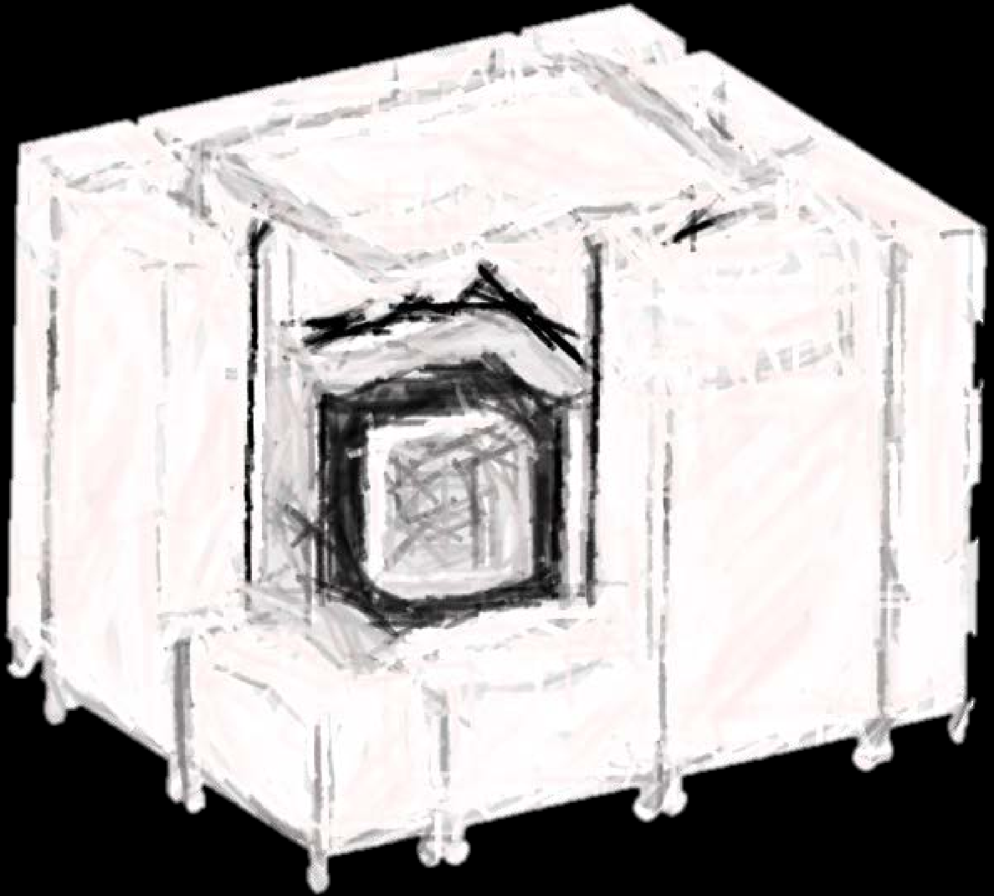






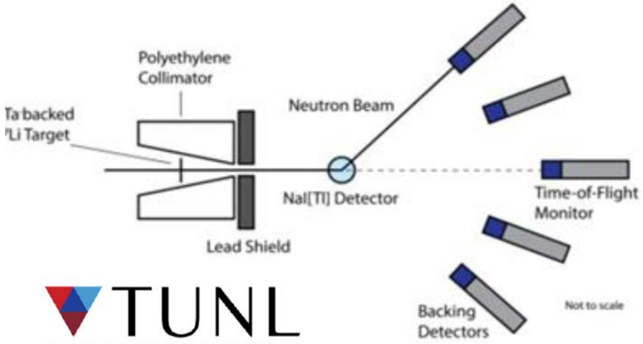
ANAIS-112 neutron calibration program





UNCERTAINTIES IN SCINTILLATION QUENCHING FACTORS ARE A RELEVANT SYSTEMATIC EFFECT for the comparison between DAMA/LIBRA and ANAIS

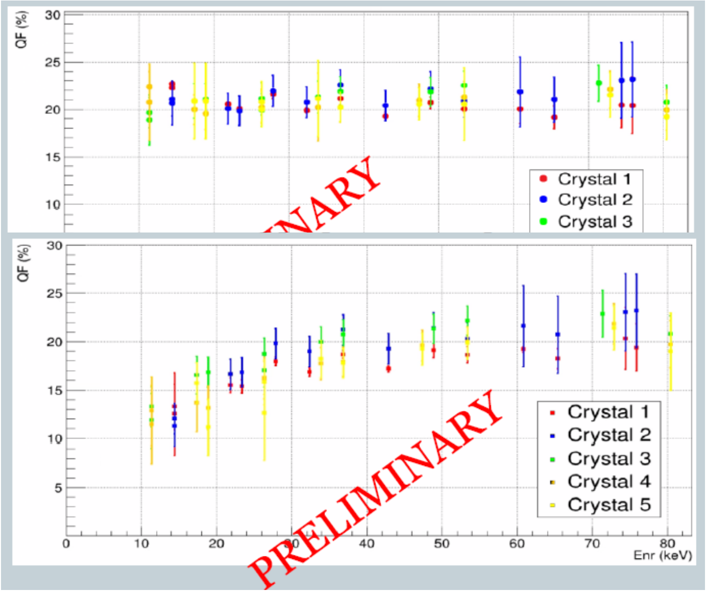
Na - QF derived using different methods and different calibration procedures do not agree. Dependences on the crystal properties can not be discarded



TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

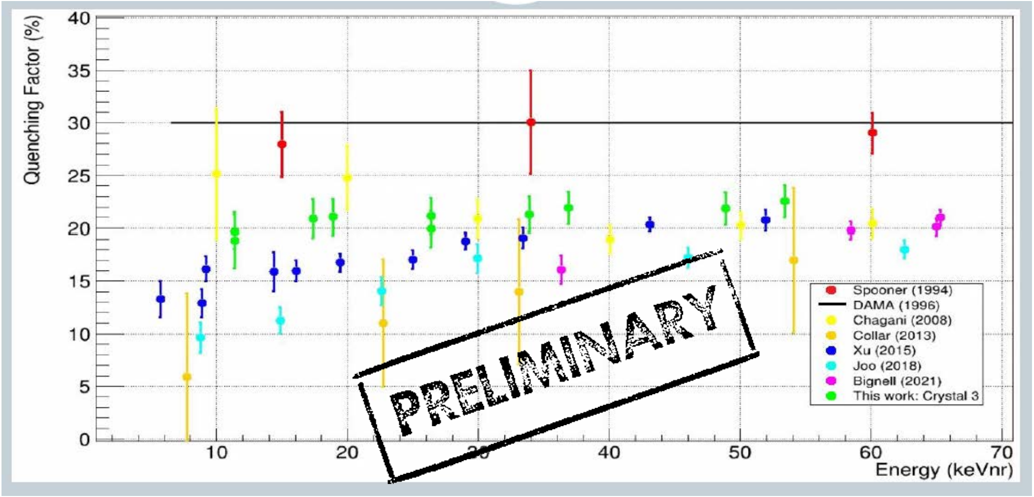
Five small AS crystals
Collaboration between Yale, Duke and Zaragoza
Measurements in 2018 @TUNL

Our best (preliminary) estimate for Na-QF in NaI(Tl)-AS crystals is 20%



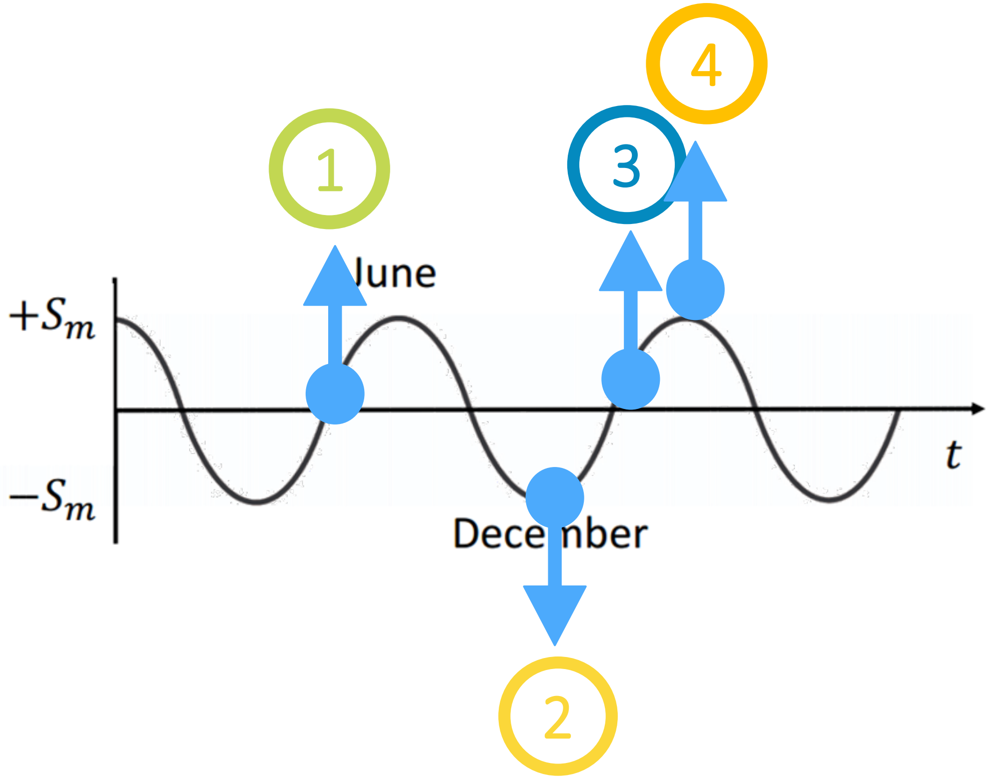
Linearizing response in energy using ^{133}Ba data

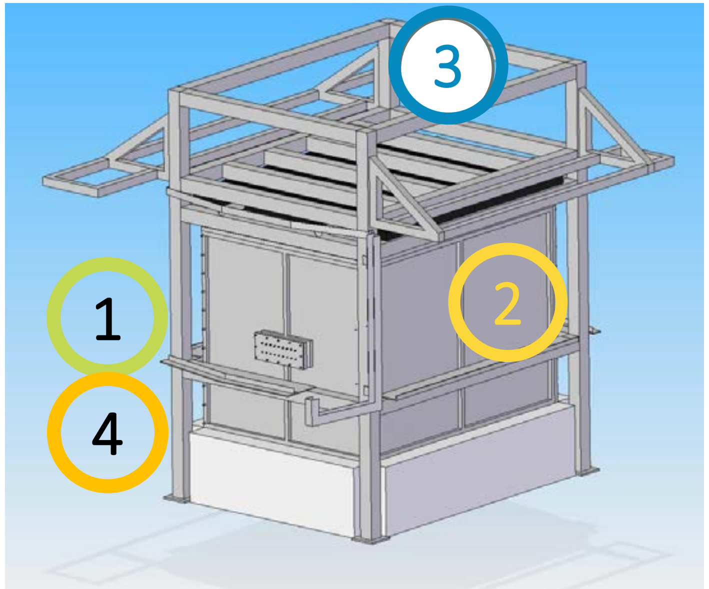
Assuming proportional response using 57.6 keV energy deposition



"onsite" neutron calibrations with the full ANAIS-112 set-up

Four calibration runs since April 2021 using ^{252}Cf neutron source at different positions in the ANAIS-112 set-up



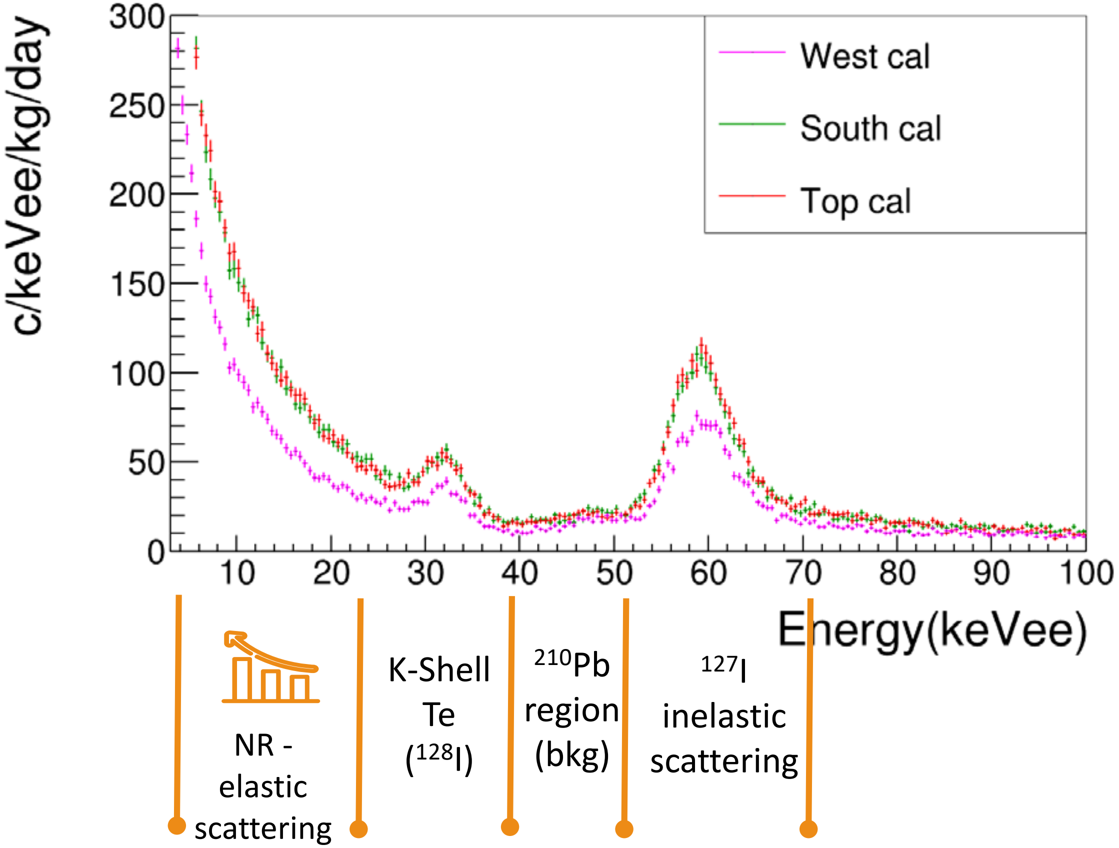


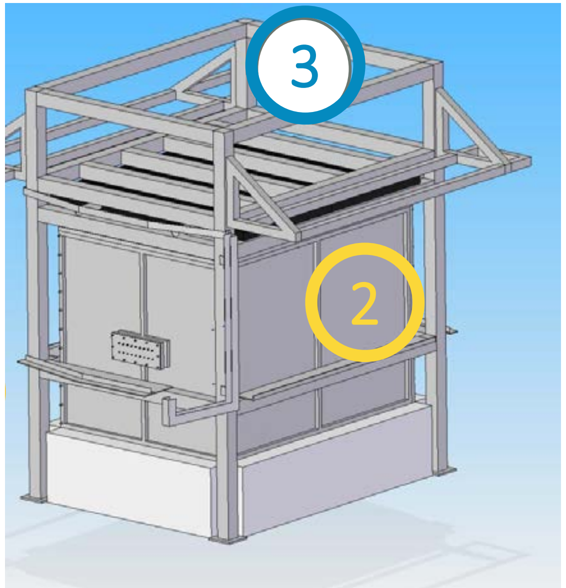
Neutrons produce many "bulk scintillation events" at very low energy

- We have a large population of events for training our new ML analysis and checking efficiency stability
- We expect to derive some information on QF by comparing simulations and measurements

"onsite" neutron calibrations with the full ANAIS-112 set-up

Four calibration runs since April 2021 using ^{252}Cf neutron source at different positions in the ANAIS-112 set-up





Neutrons produce many "bulk scintillation events" at very low energy

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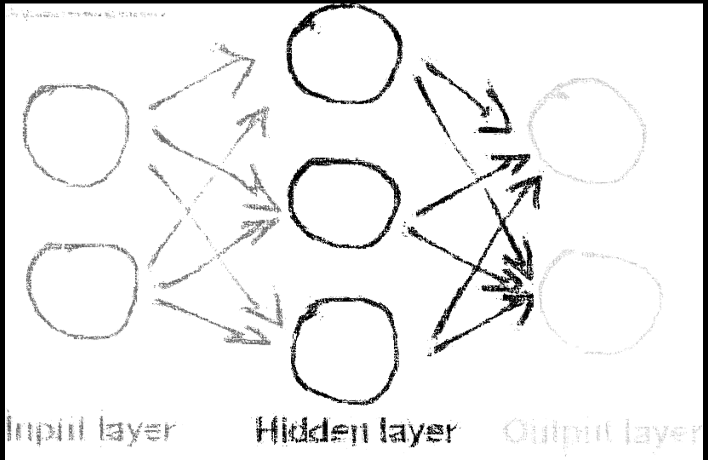
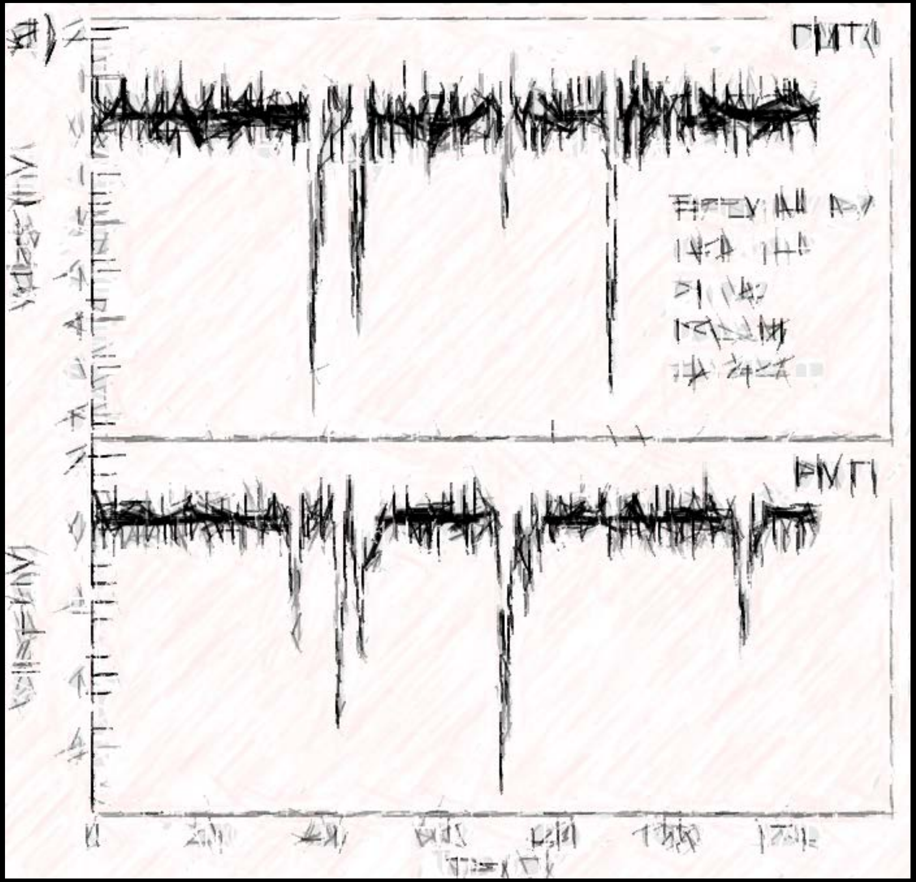
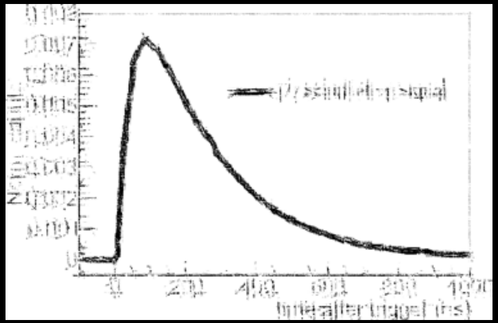
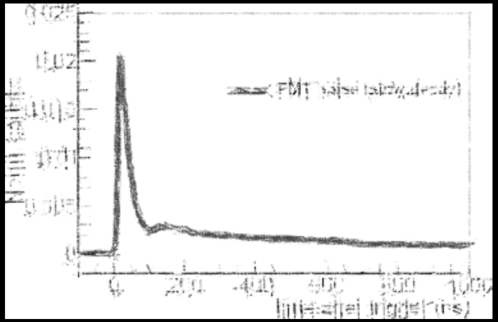
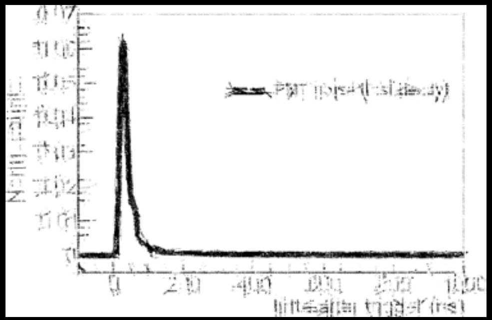
New ANAIS-112 event selection protocol using Machine Learning techniques





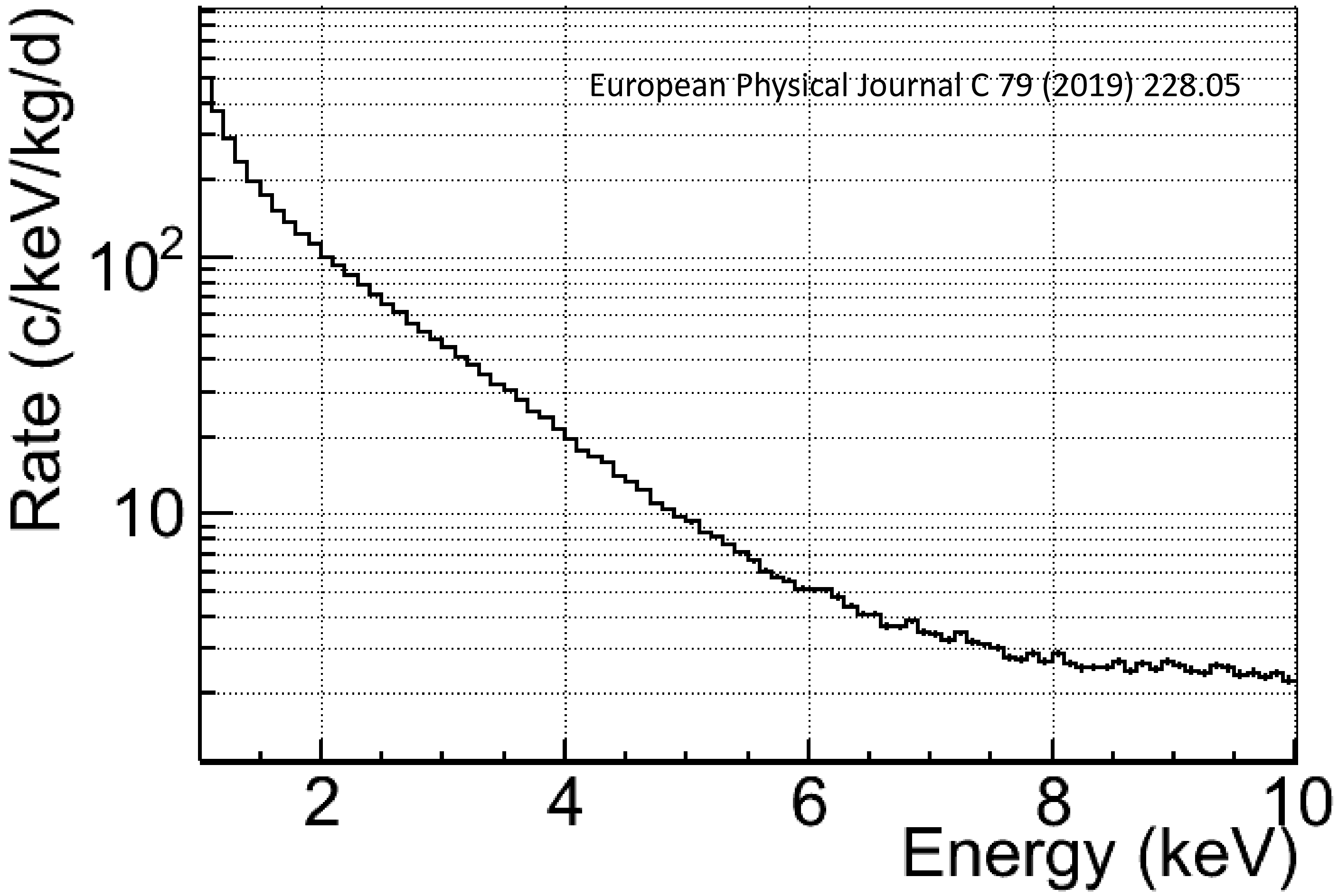






ANAIS-112 event selection for the three-year analysis (PRD 2021)

Raw data below 10 keV are dominated by non-bulk scintillation events

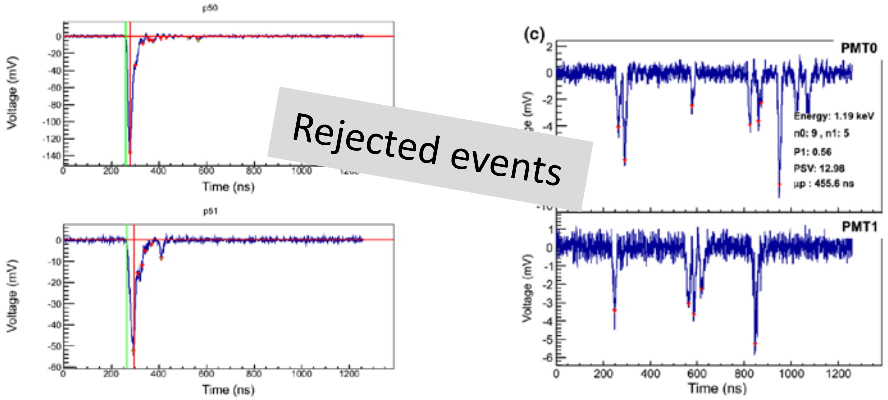


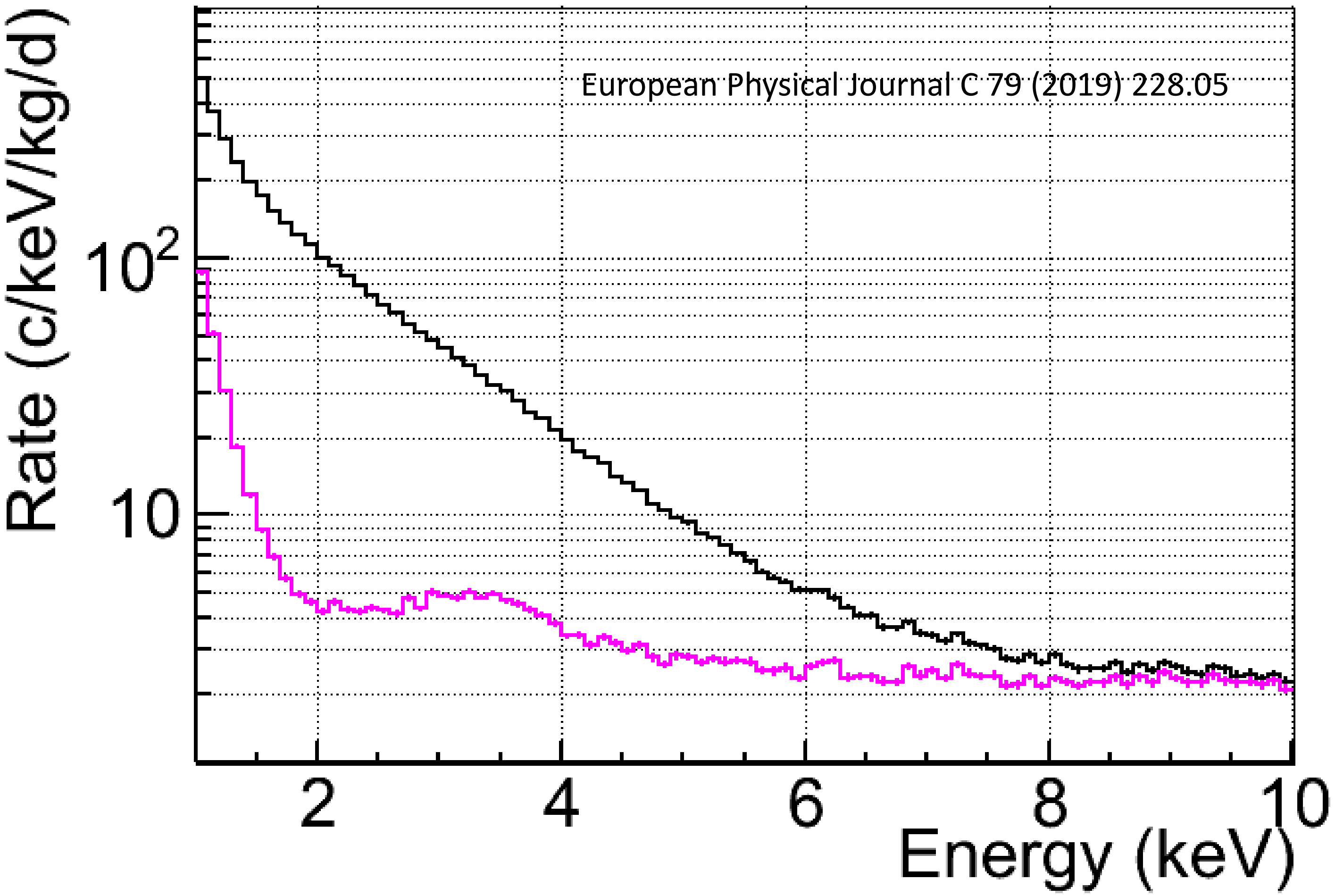
10 % data unblinded background @ ROI (random distribution)

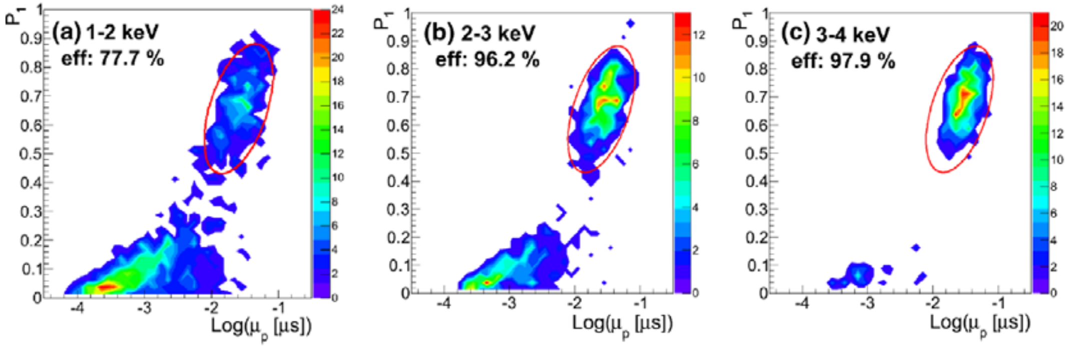
ANAIS-112 Event Selection for PRD21

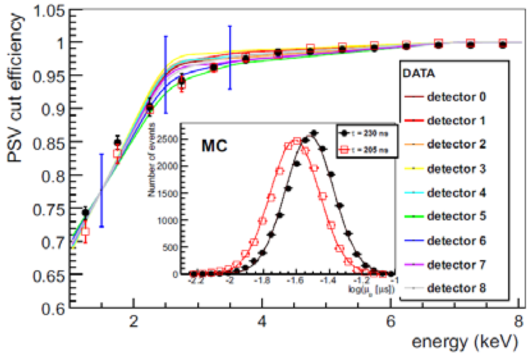
PULSE SHAPE cut to properly select events with pulse shapes from NaI(Tl) scintillation

$$P_1 = \frac{\int_{100\,ns}^{600\,ns} A(t)dt}{\int_{0}^{600\,ns} A(t)dt} \qquad \mu_p = \frac{\sum A_p t_p}{\sum A_p}$$



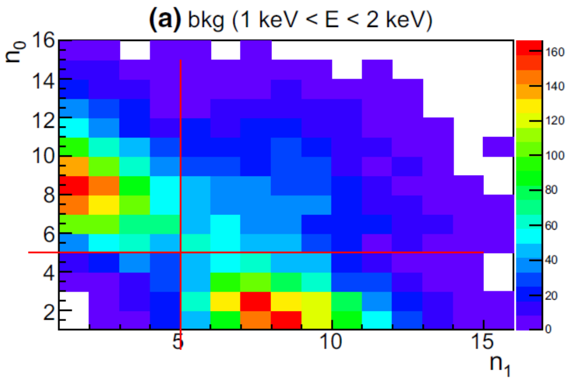




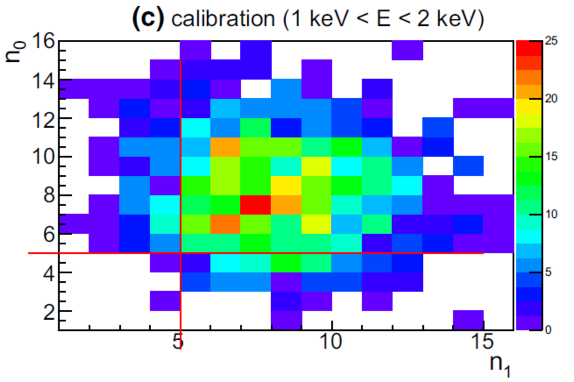


Efficiency determined from ^{22}Na and ^{40}K events

Asymmetric events rejection
(E<2keV):
Requirement on number of peaks >4 at each PMT

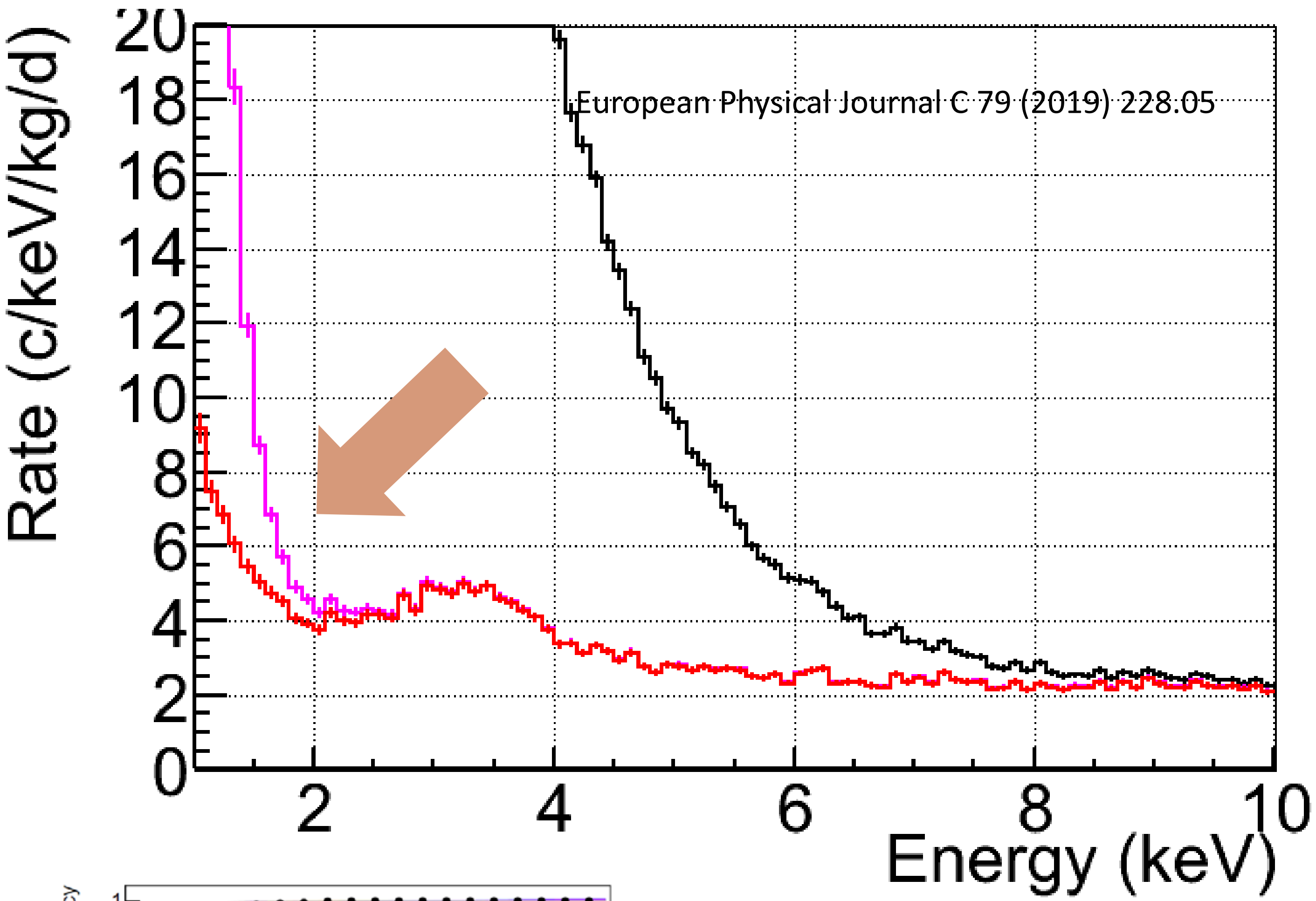


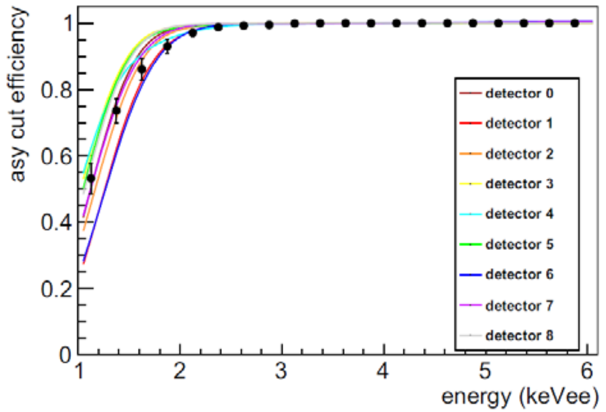
BKG

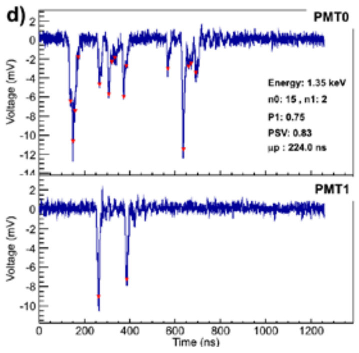


CAL

Efficiency determined from Cd calibration evts



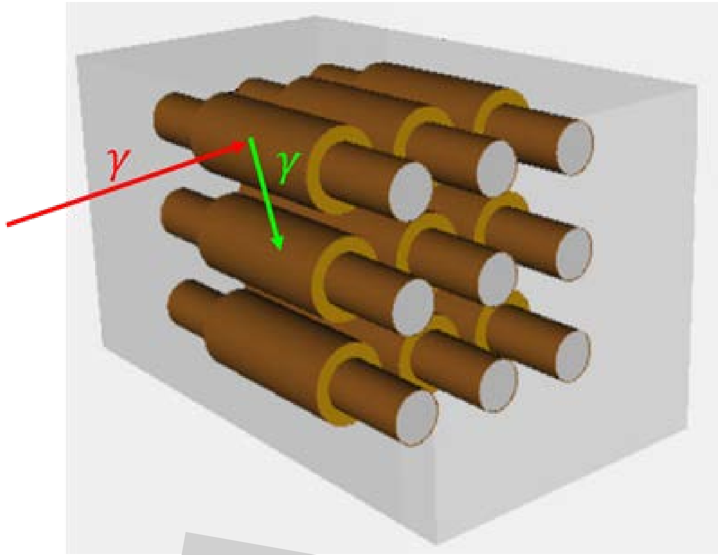




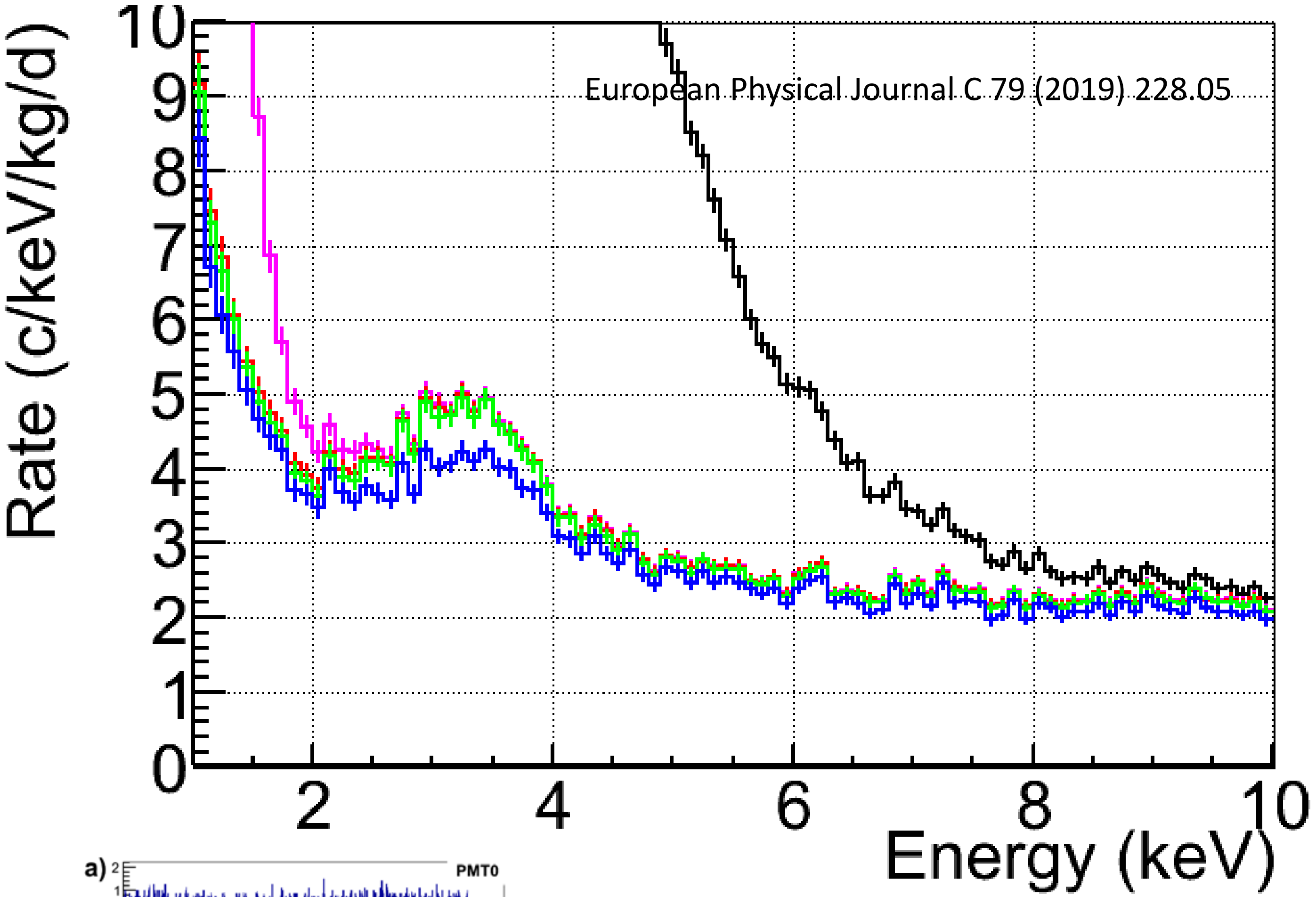
Rejected event

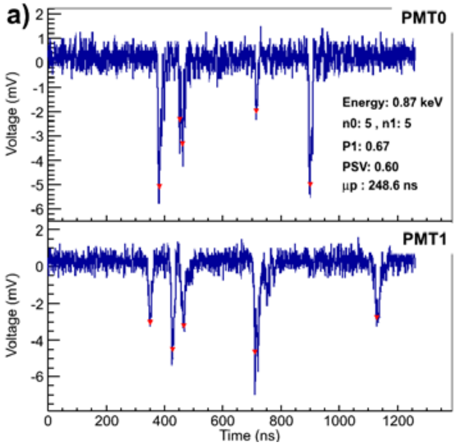
Events arriving more than 1 second after a muon

Single Hit events



Rejected events having multiplicity > 1





Accepted event

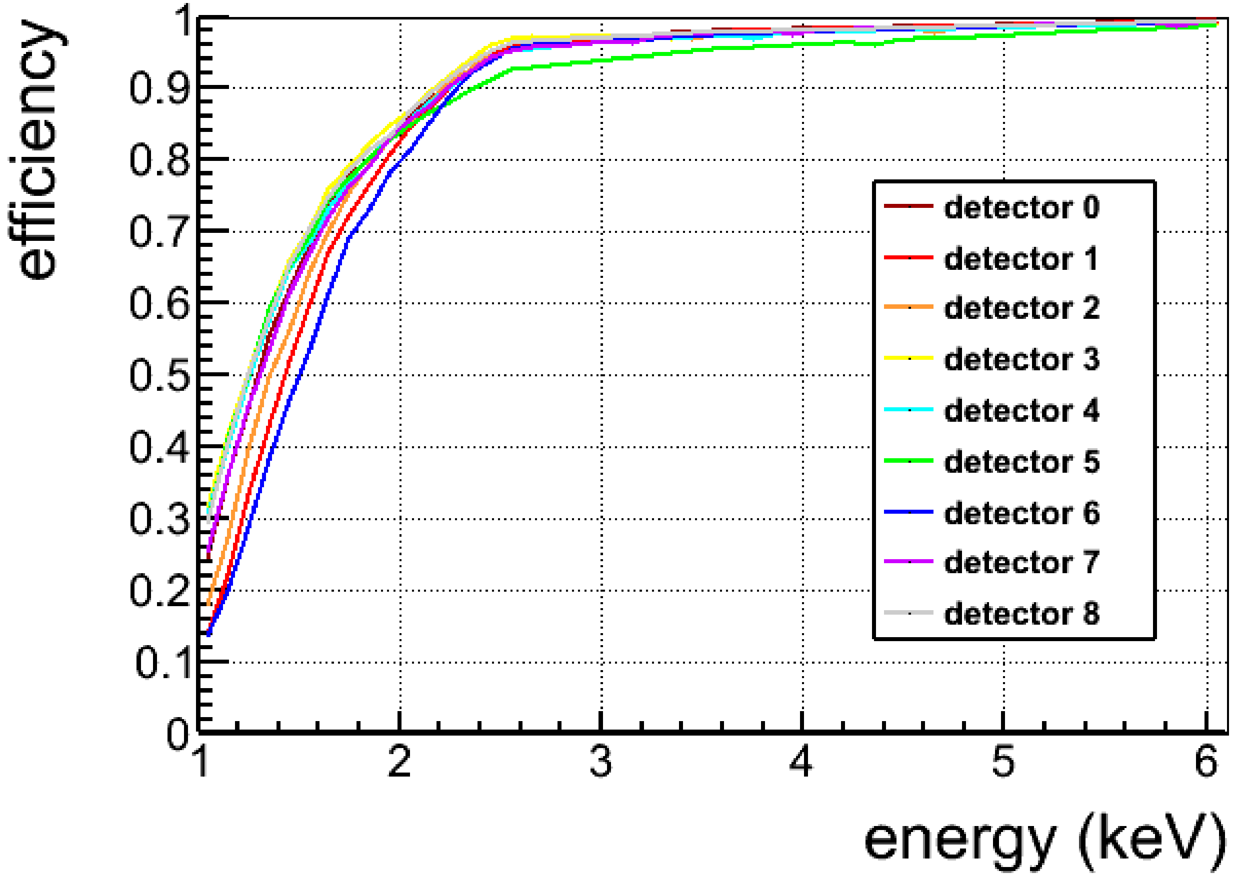
1 keV_{ee}

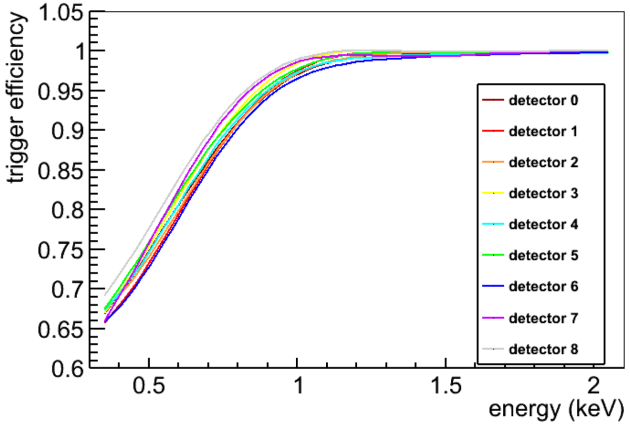
ANAIS-112 Event Selection for PRD21

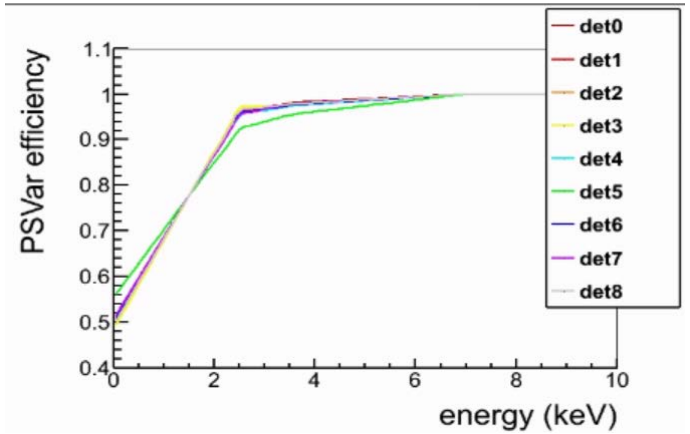
Physical Review D 103 (2021) 102005

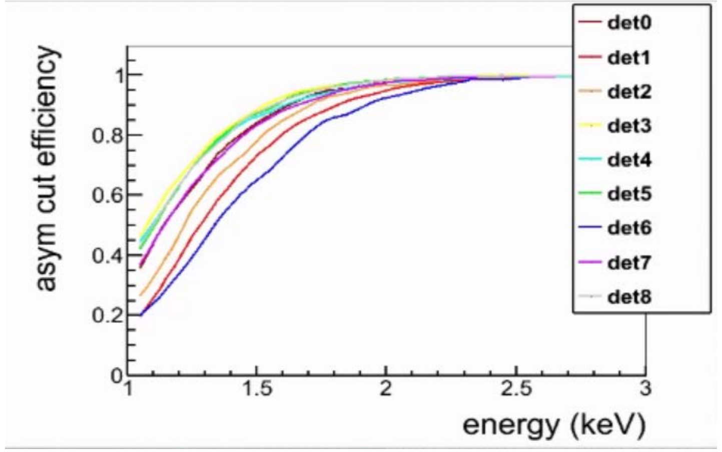
Efficiencies used in PRD21 analysis are calculated with the full statistics detector by detector -> 3 years

$$\varepsilon(E,d) = \varepsilon_{trg}(E,d) \times \varepsilon_{PSA}(E,d) \times \varepsilon_{asy}(E,d),$$









Boosted Decision Tree (BDT) has been trained for events' filtering

NEW ANALYSIS
Following preliminary results in
I. Coarasa *et al* 2021 *J. Phys.: Conf. Ser.* 2156 012036

-Multivariate analysis
-More powerful than standard filtering by combining several variables into one parameter

$$P_1 = \frac{\int_{t=100ns}^{t=600ns} A(t)\,dt}{\int_{t=0ns}^{t=600ns} A(t)\,dt}$$

$$P_2 = \frac{\int_{t=0ns}^{t=50ns} A(t)\,dt}{\int_{t=0ns}^{t=600ns} A(t)\,dt}$$

$$CAP_x = \frac{\int_{0}^{t=x} A(t)\,dt}{\int_{t=0ns}^{t=t_{max}} A(t)\,dt}$$

$$\mu_p = \frac{\sum_i A_i t_i}{\sum_i A_i}$$

$$Asymphe = \frac{n_{phe,0} - n_{phe,1}}{n_{phe,0} + n_{phe,1}}$$

Good events
- **Neutron calibration events from 1 to 2 keV (P1>0.35)**

Noise events
- **Blank module evts (10-28 phe) 80% P1>0.35 and 20% P1<0.35**

PRELIMINARY

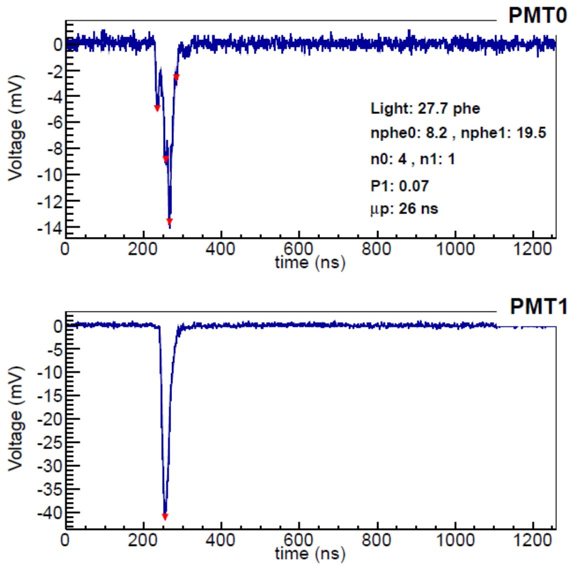
-equilibrated training populations (>30000 evts) and independent from bkg data

-70% used for training
30% used for testing

-CUT defined for every energy bin and detector

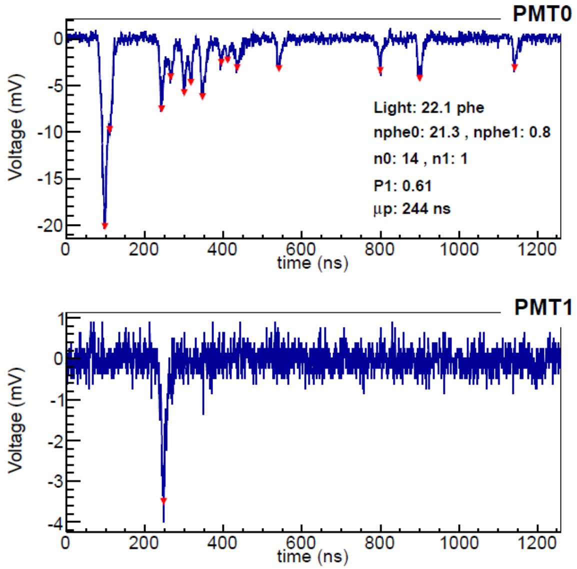
Boosted Decision Tree (BDT) has been trained for events' filtering

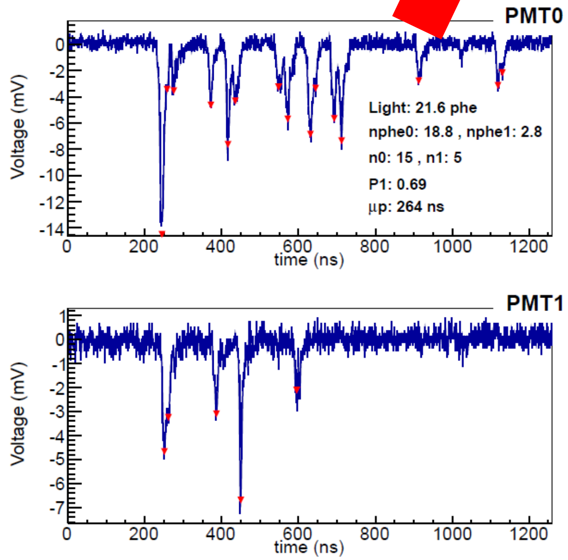
Examples of pulses from blank module selected for the BDT training

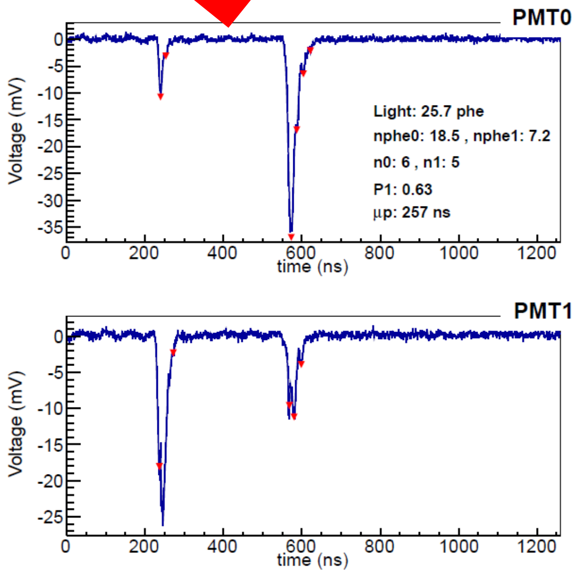


20% P1<0.35

These two passed the previous ANAIS-112 cuts

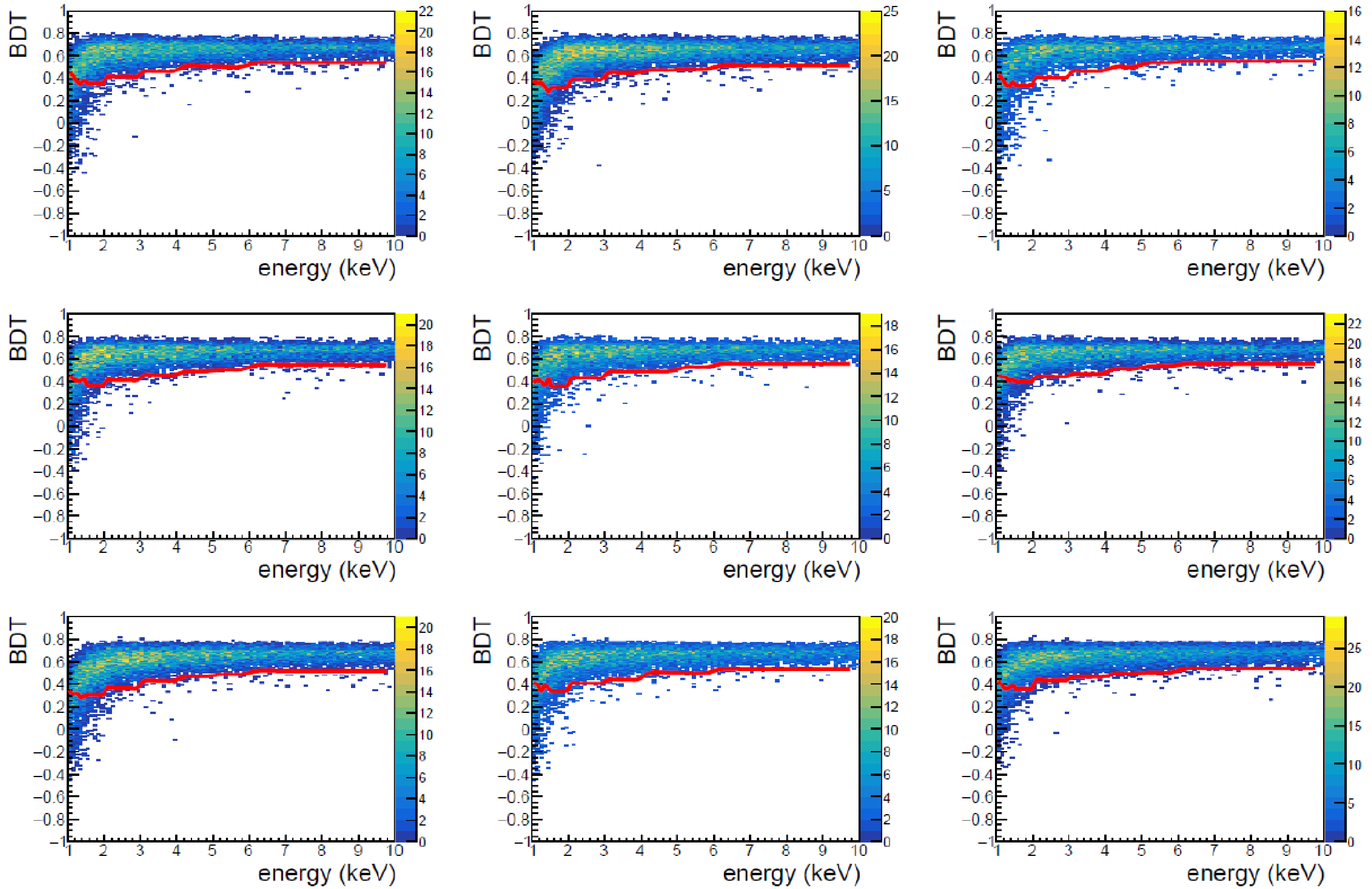






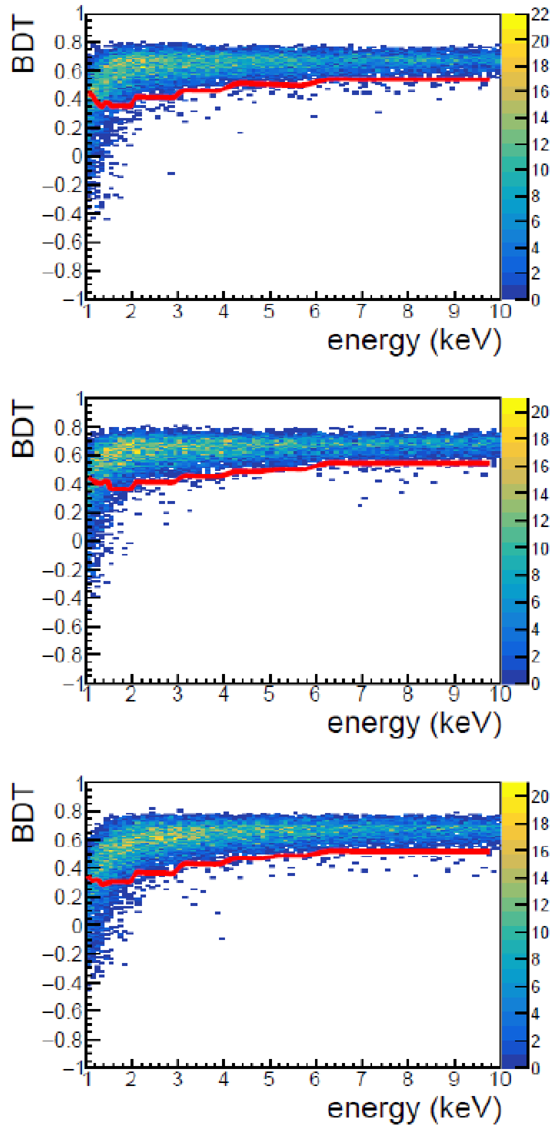
80% P1>0.35

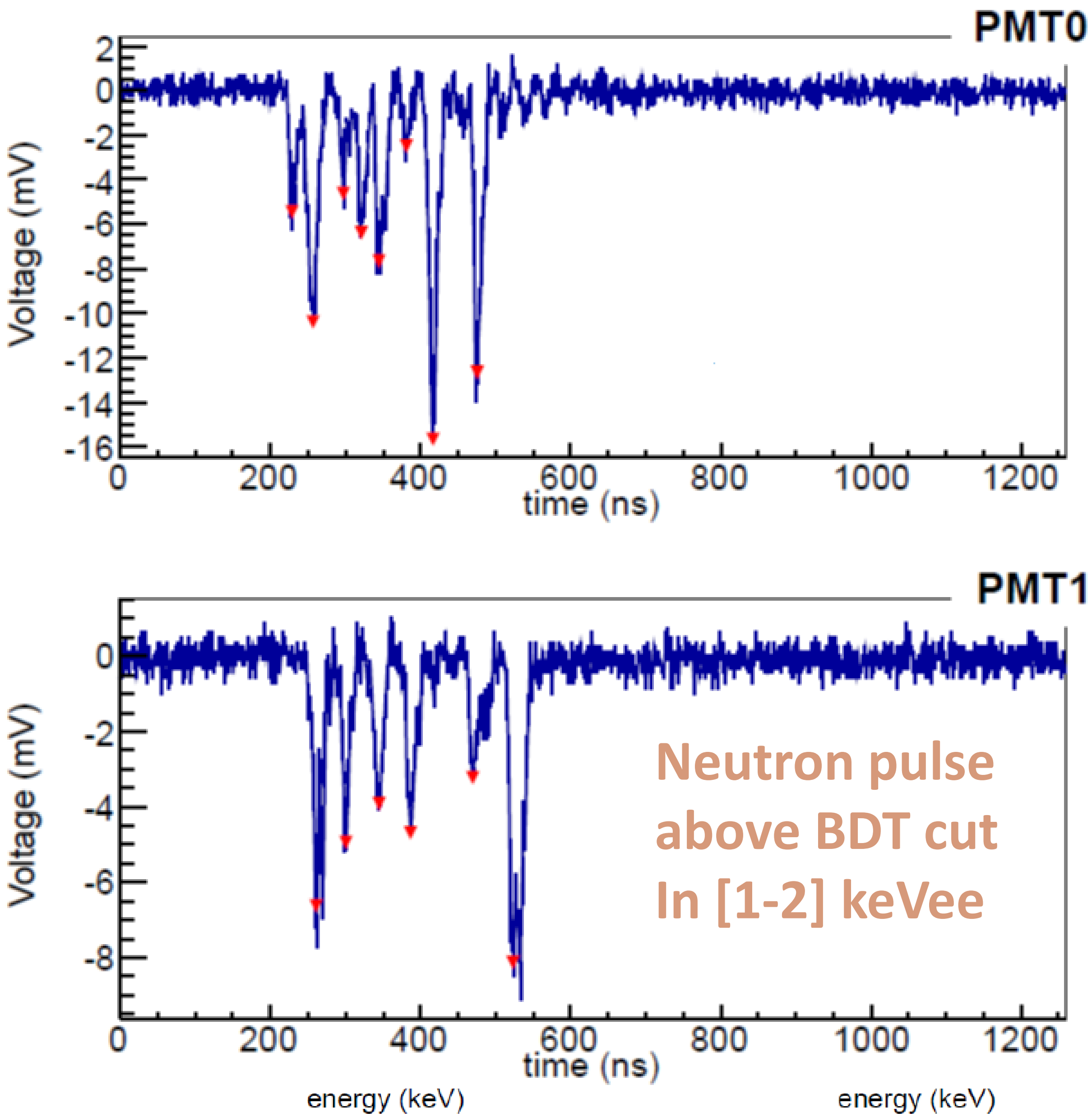
Boosted Decision Tree (BDT) has been trained for events' filtering



CUT on the BDT parameter defined for every energy bin using the neutron population - coincident events

Boosted Decision Tree (BDT) has been trained for events' filtering





ːUT on the BDT
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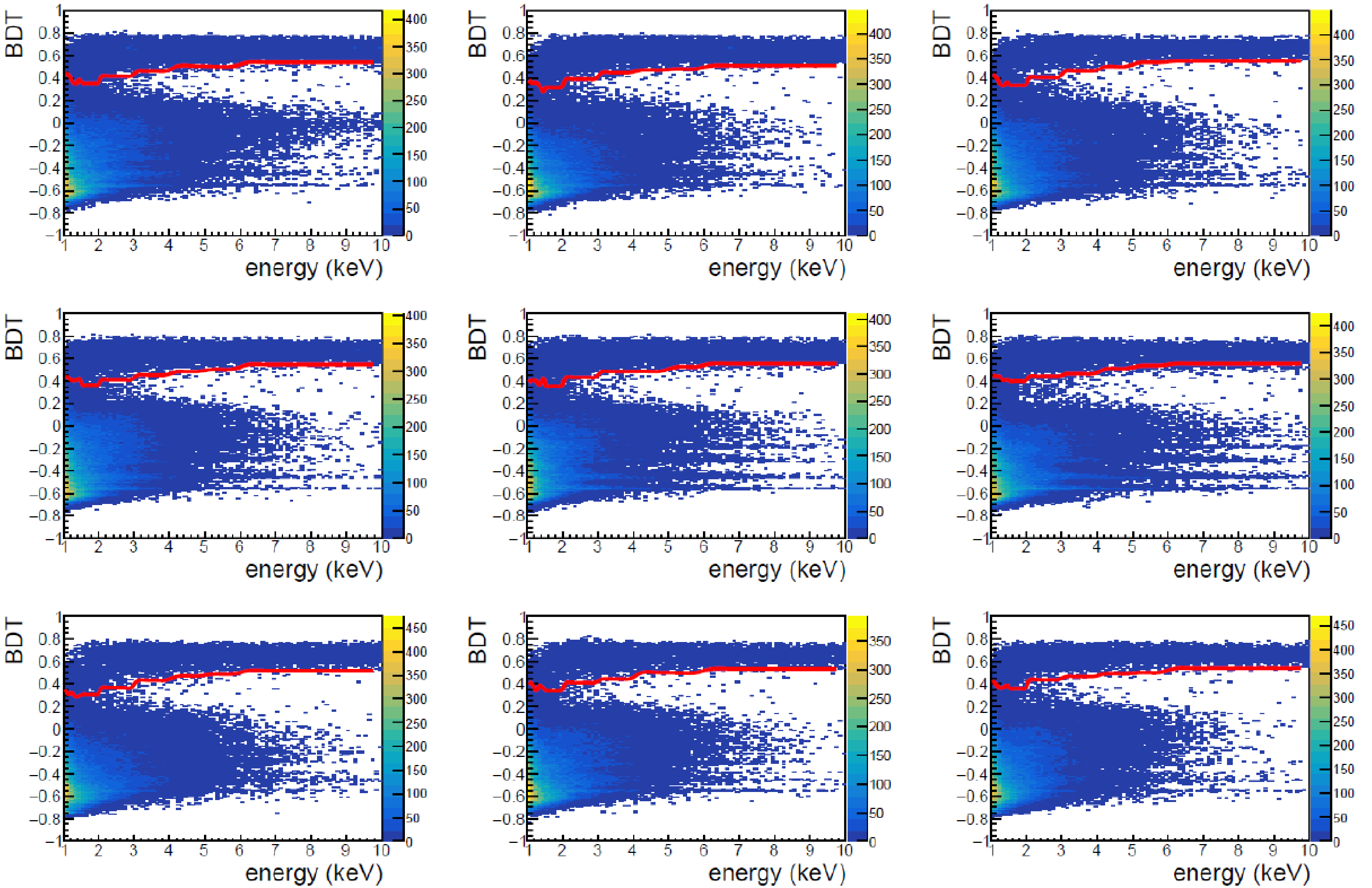
opulation -
oincident events

ANAIS-112 Event Selection using BDTs

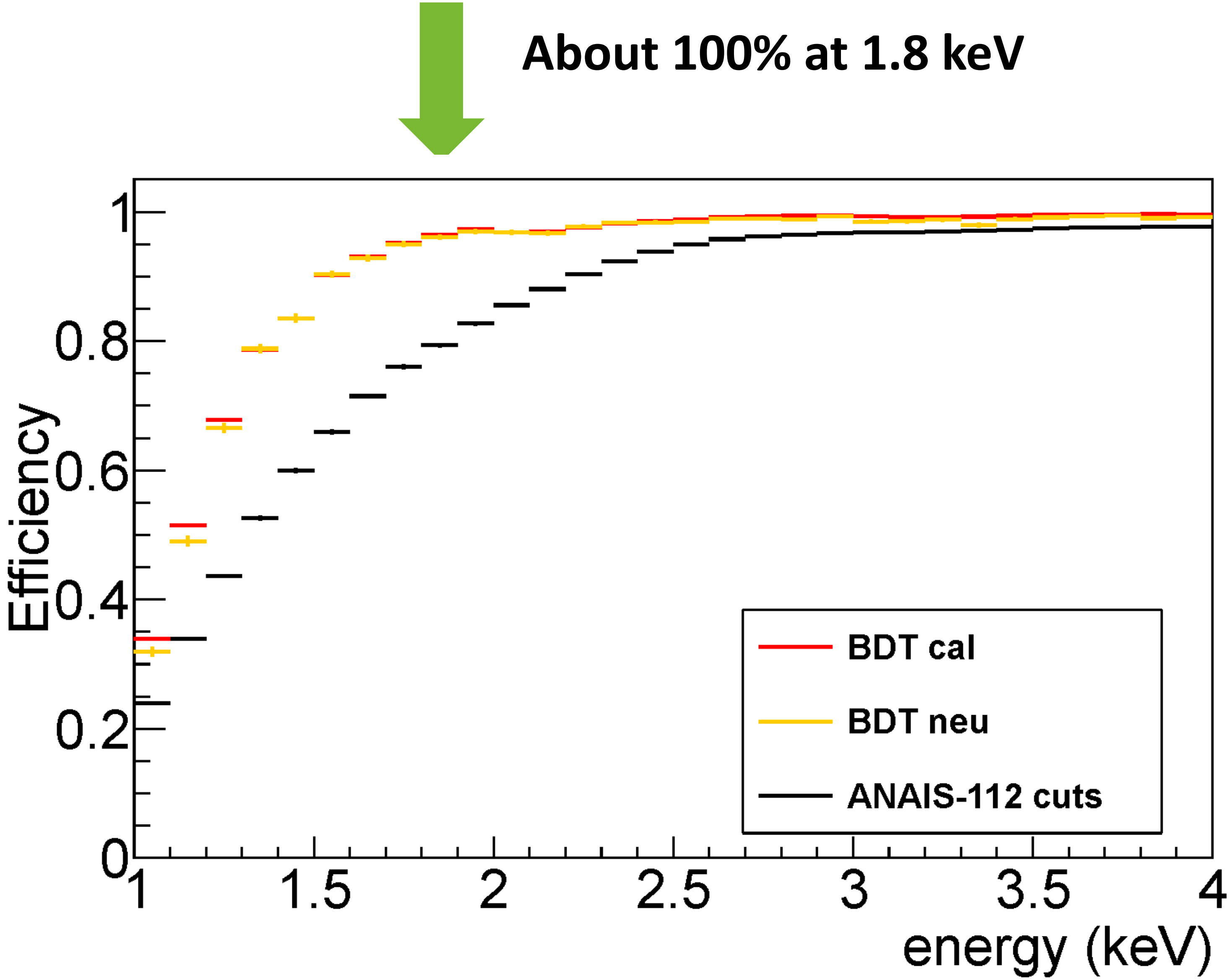
Boosted Decision Tree (BDT) has been trained for events' filtering



CUT on BDT parameter applied to the background (10% events of the first year)

Boosted Decision Tree (BDT) has been trained for events' filtering

About 100% at 1.8 keV



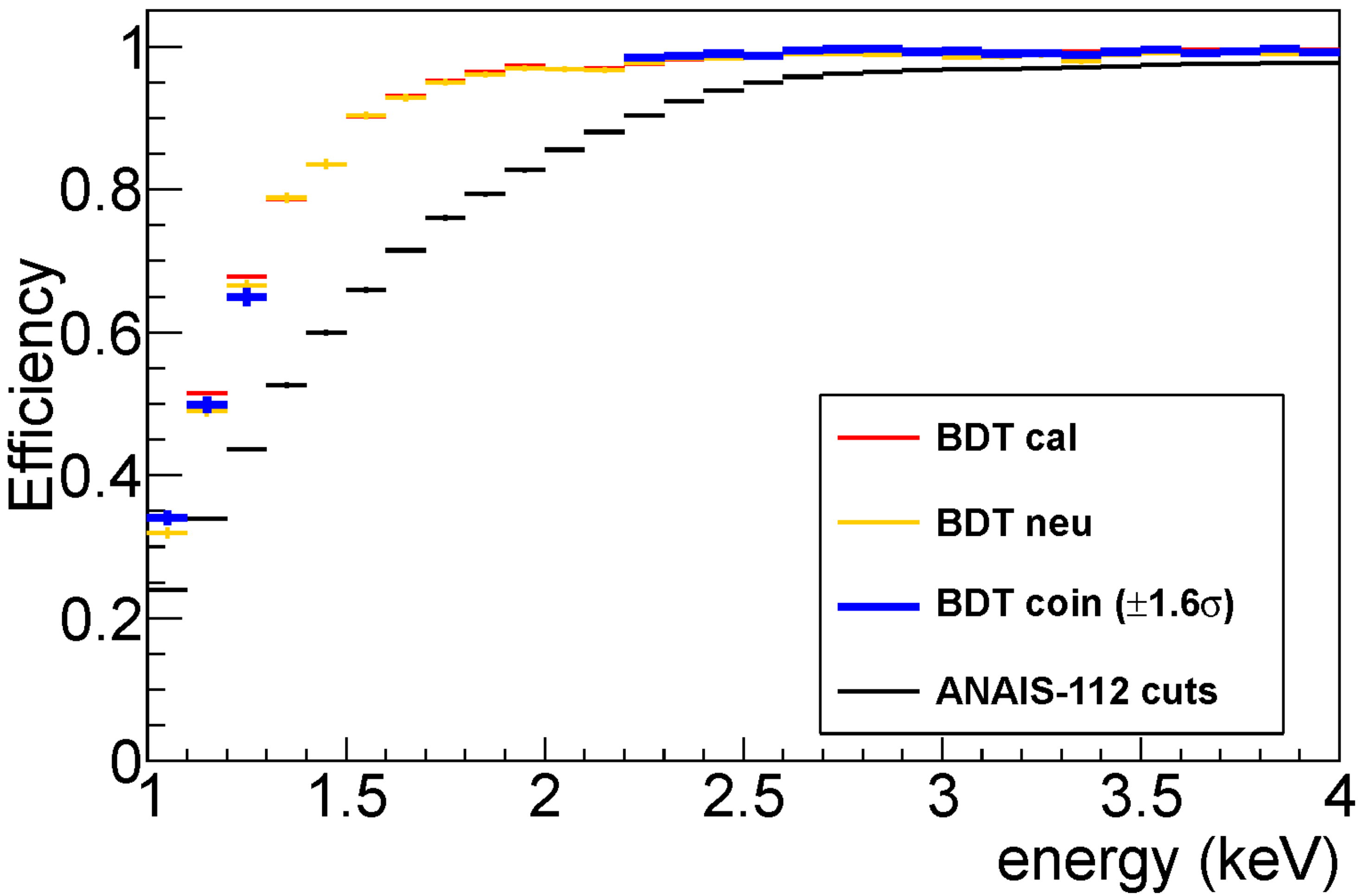
Remarkable improvement in efficiency in the ROI

Efficiencies determined with different populations of scintillation events:
-neutrons
-^{109}Cd events

FULLY COMPATIBLE

Boosted Decision Tree (BDT) has been trained for events' filtering

About 100% at 1.8 keV



Remarkable improvement in efficiency in the ROI

Efficiencies determined with different populations of scintillation events:

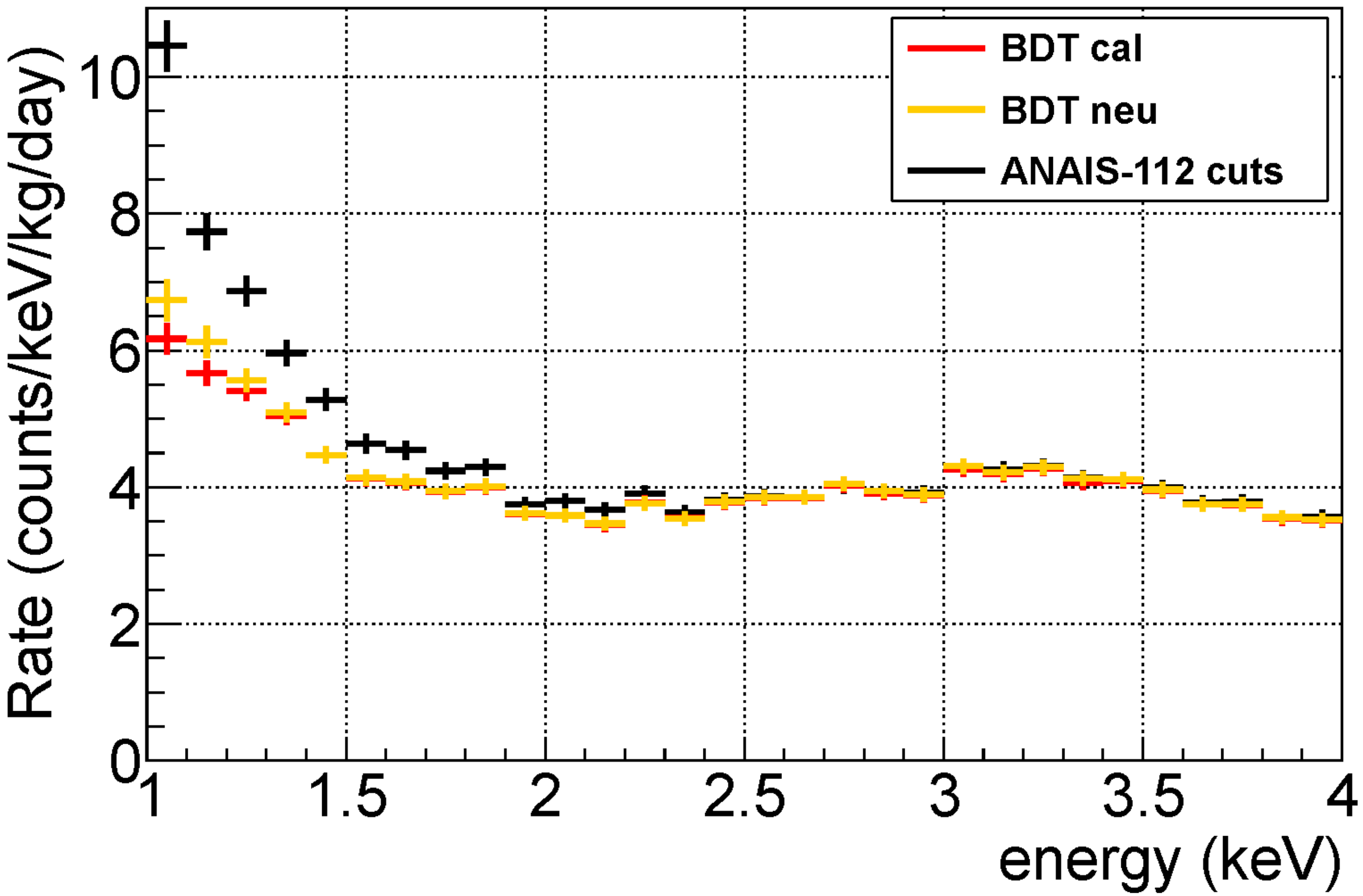
-neutrons

-^{109}Cd events

-^{40}K and ^{22}Na coincident evts

FULLY COMPATIBLE

Boosted Decision Tree (BDT) has been trained for events' filtering



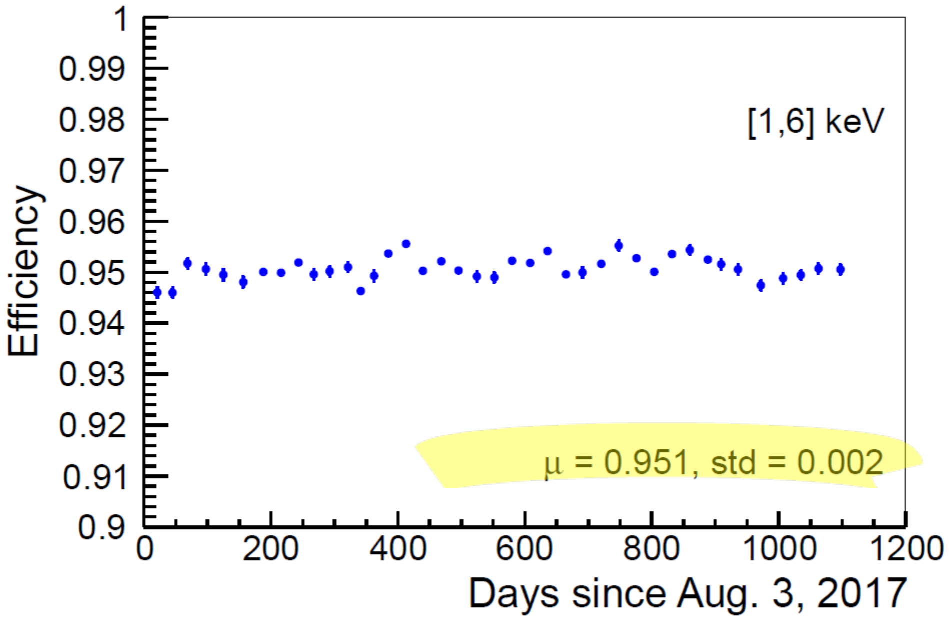
Relevant background reduction

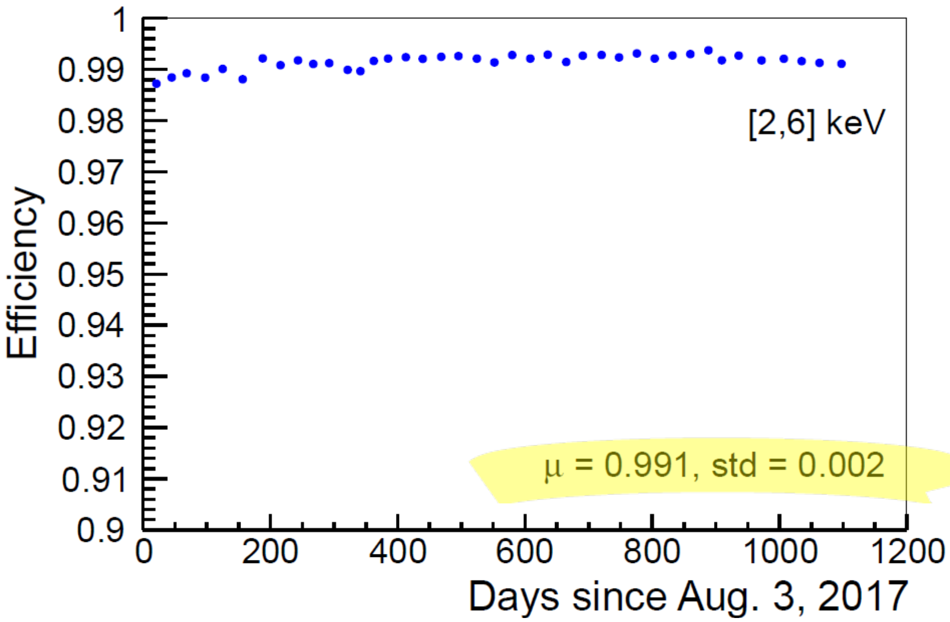
17.2% in [1-2] keV

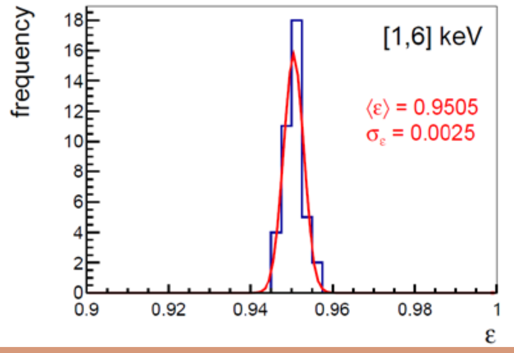
We are working on the reduction of our analysis threshold profiting from the improvement in efficiency achieved by the BDT filtering

Efficiency stability and associated systematic uncertainty

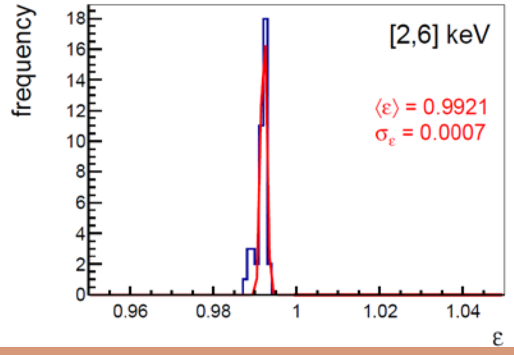
We are working on determining the possible variation in time of the BDT's efficiencies
Using ^{109}Cd data for the first three years with all detectors averaged







0.5%



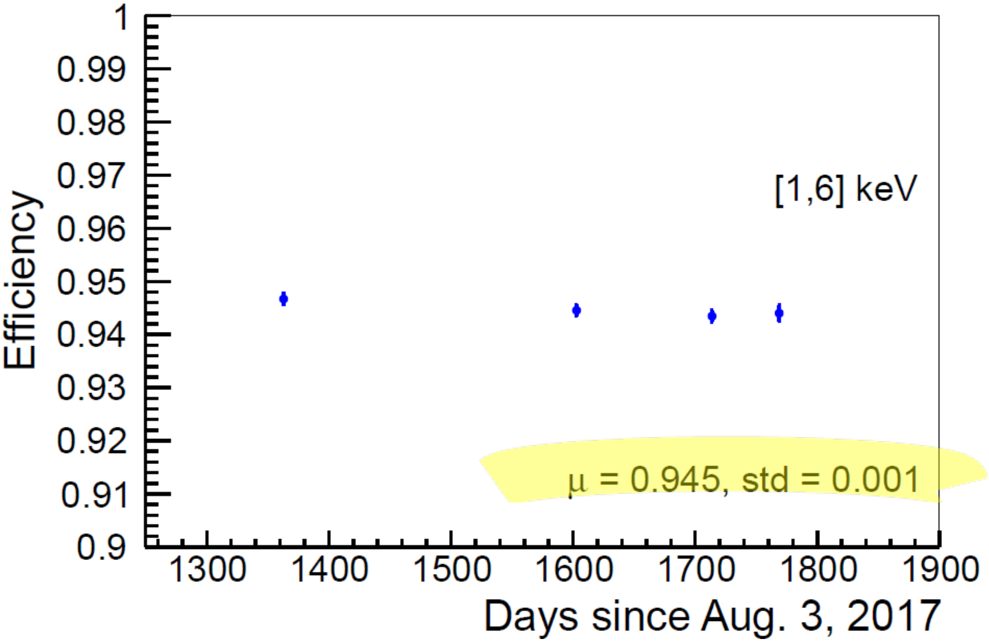
0.33%

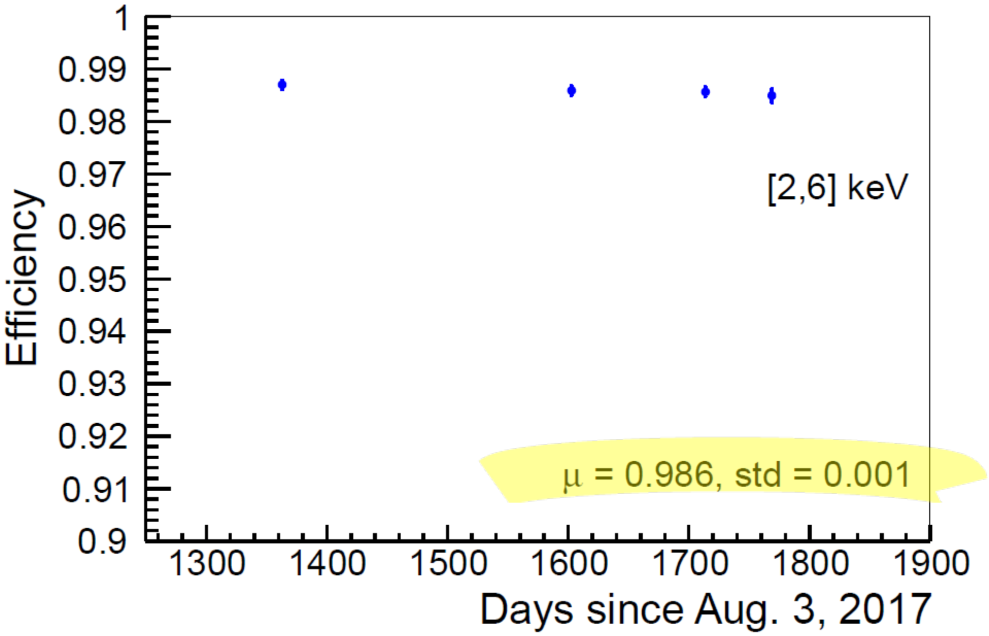
Systematic uncertainty is taken as half the difference between maximum and minimum values

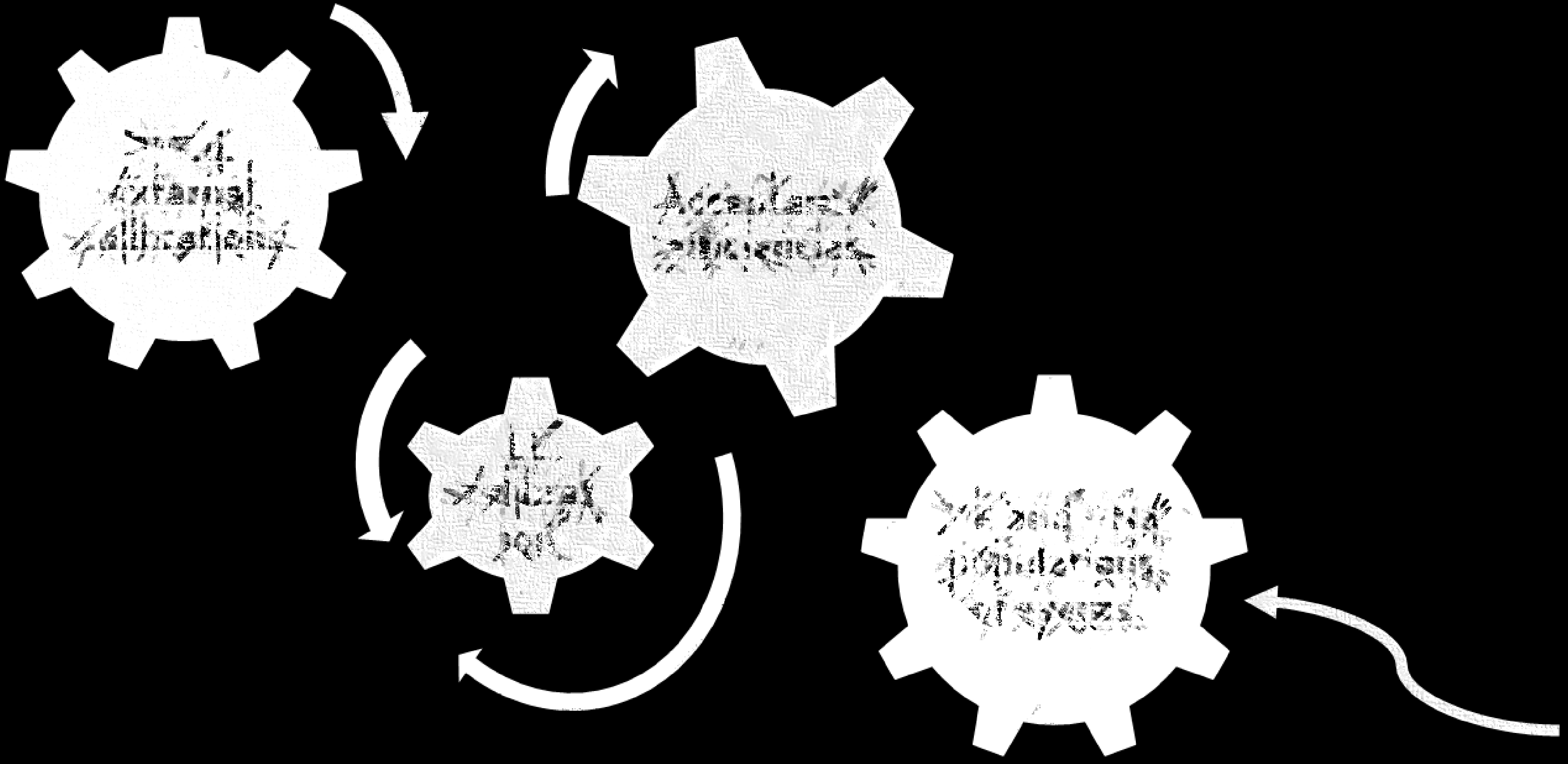
Efficiency stability and associated systematic uncertainty

We are working on determining the possible variation in time of the BDT's efficiencies

Using neutron data (4th-5th years)



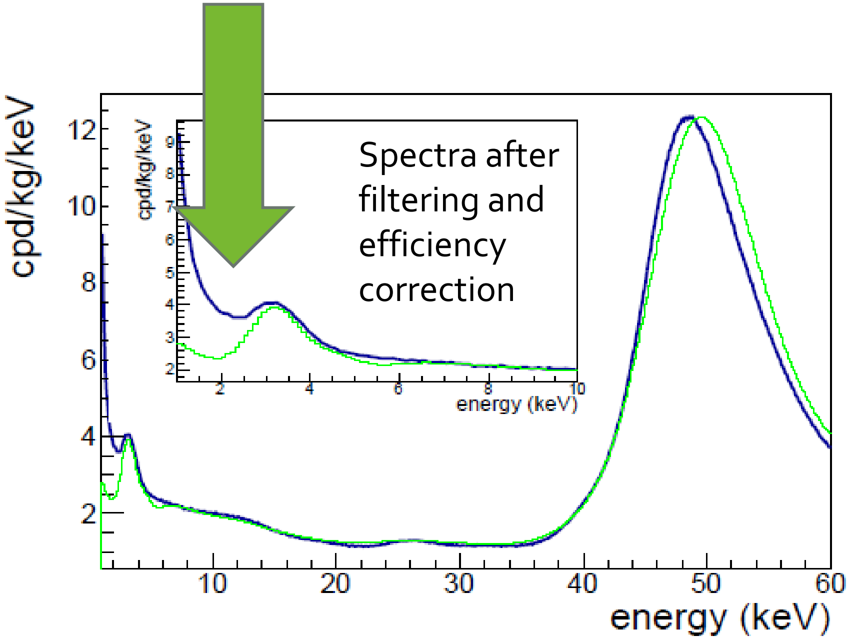




ANAIS-112 annual modulation analysis strategy – DATA BLINDED

Robust background model

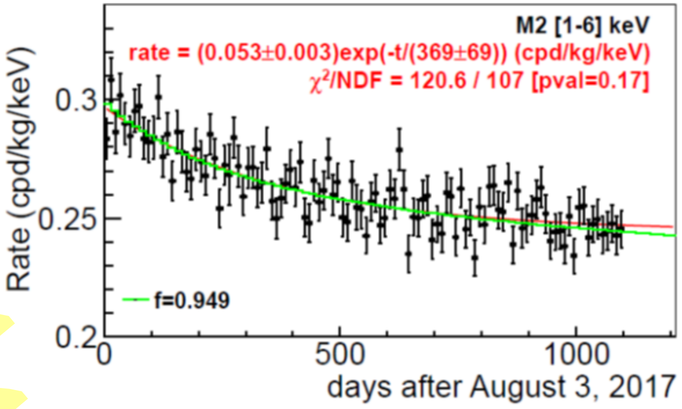
European Physical Journal C 79 (2019) 412.

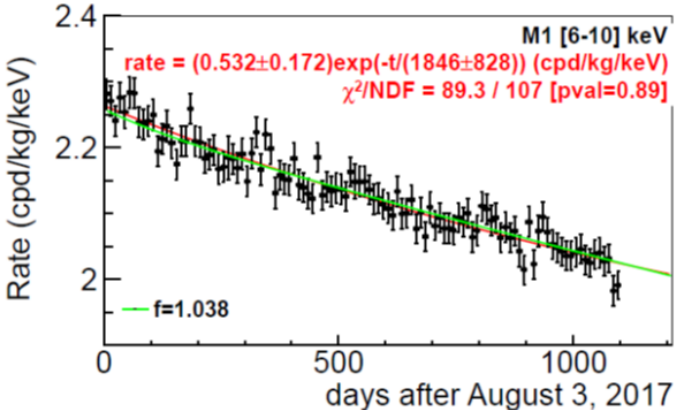


- ROI background dominated by ^{210}Pb, ^{40}K and ^{3}H -> higher than DAMA/LIBRA
- Good agreement in all energy regions, but underestimate in 1-2 keV region
- Background model established before unblinding data

It predicts time evolution of the background detector by detector

It reproduces satisfactorily time evolution outside the ROI and in the ROI for multiple-hit events



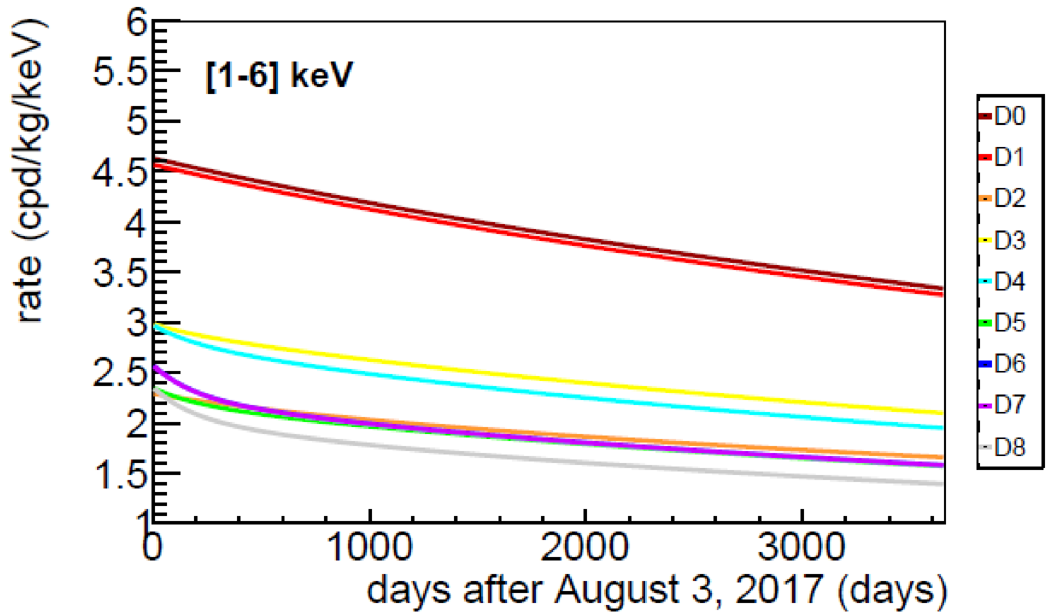


313.95 kg x y (three-year exposure): Annual modulation search

Physical Review D 103 (2021) 102005

Background probability distribution function drawn from ANAIS-112 background model for every detector to account for possible systematic effects related with the different backgrounds and efficiencies of the different modules

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



MODEL INDEPENDENT ANALYSIS

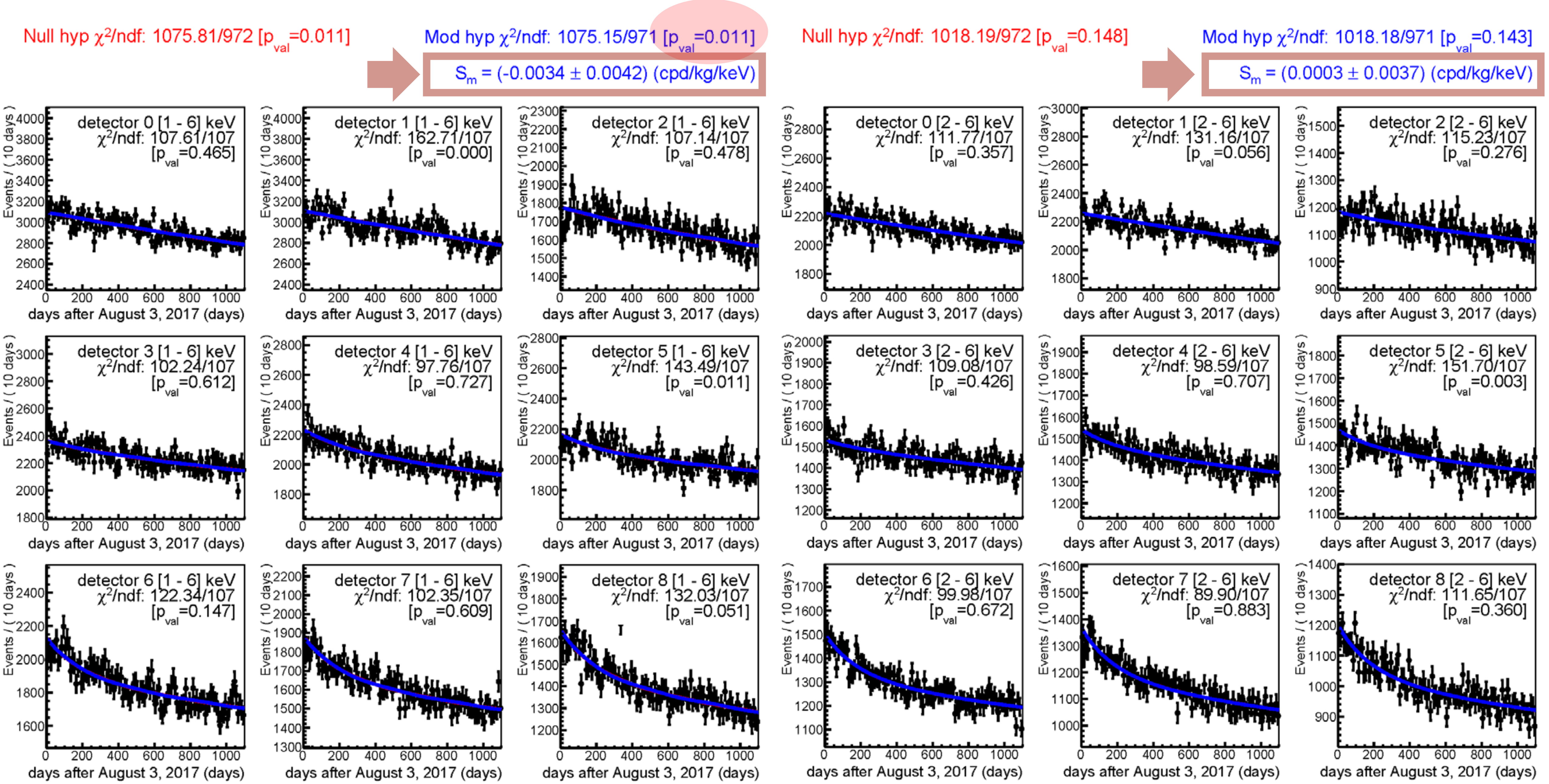
Minimizing:

$$\chi^2 = \sum_{i,d} \frac{(n_{i,d} - \mu_{i,d})^2}{\sigma^2_{i,d}}$$

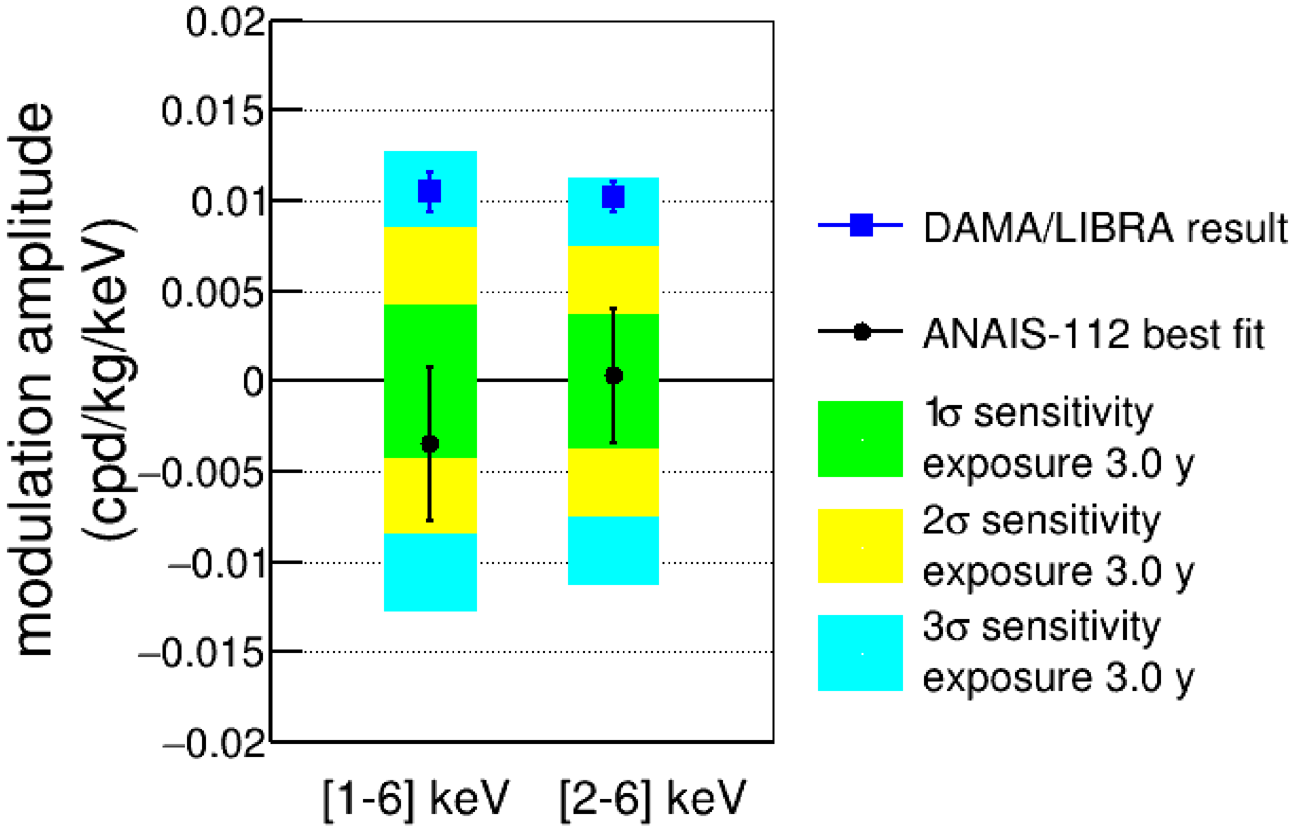
$n_{i,d}$, $\sigma_{i,d}$ are number of events (and Poisson uncertainty) in 10 days bins corrected by live time and efficiency for detector d

ω and t_0 are fixed while S_m is set free (modulation hypothesis) or fixed to 0 (non-modulation hypothesis)

ANAIS-112 three year results – annual modulation analysis (PRD2021)



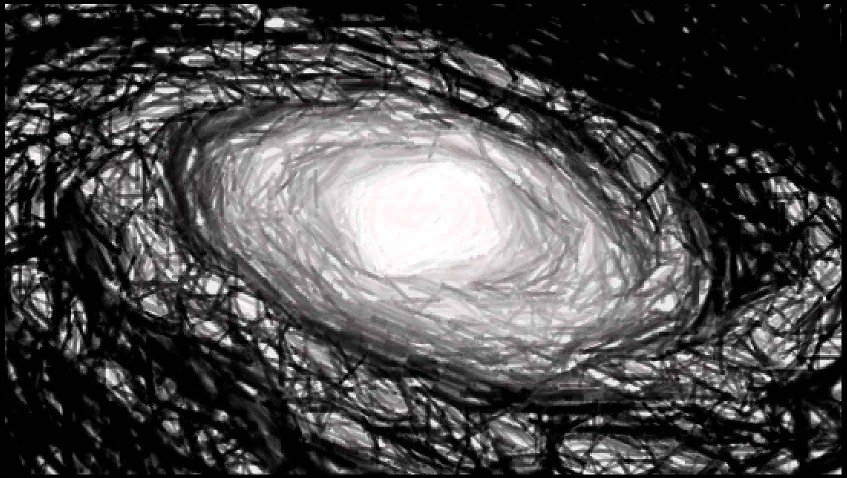
ANAIS-112 three year results – annual modulation analysis (PRD2021)

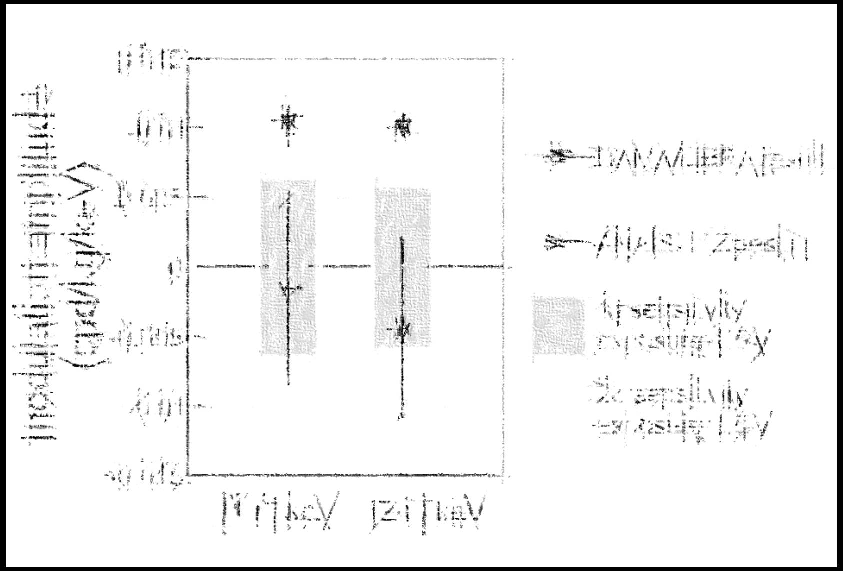


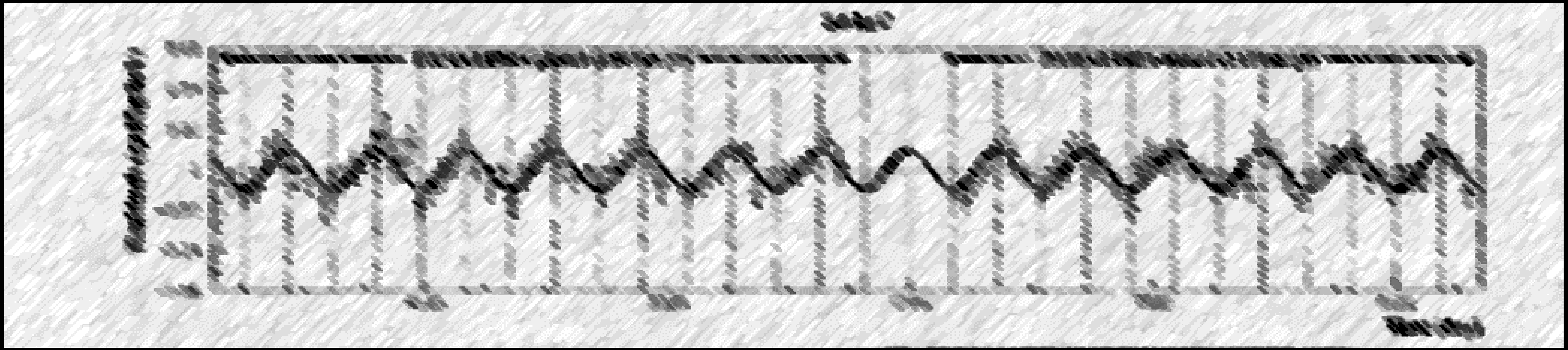
Physical Review D 103 (2021) 102005

- Best fits are incompatible with DAMA/LIBRA result at 3.3 and 2.6 σ in [1-6] and [2-6] keV energy regions
- Sensitivity is at 2.5 and 2.7 σ in [1-6] and [2-6] keV energy regions

ANAIS-112 Three Years Annual Modulation re-analysis







ANAIS-112 three year results – annual modulation re-analysis using BDTs

Null hyp χ^2/ndf: 1010.88/972 [p_{val}=0.188]

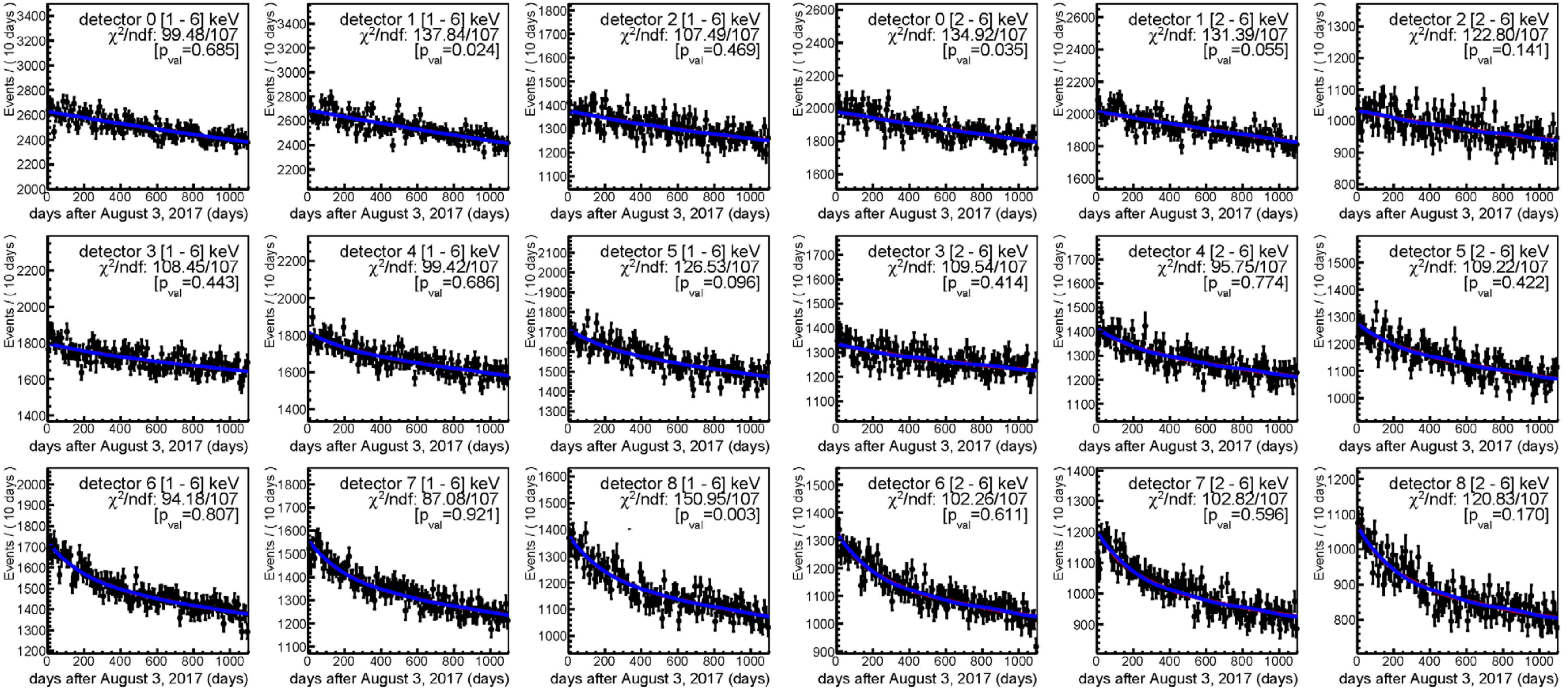
Mod hyp χ^2/ndf: 1010.62/971 [p_{val}=0.183]

S_m = (-0.0016 ± 0.0032) (cpd/kg/keV)

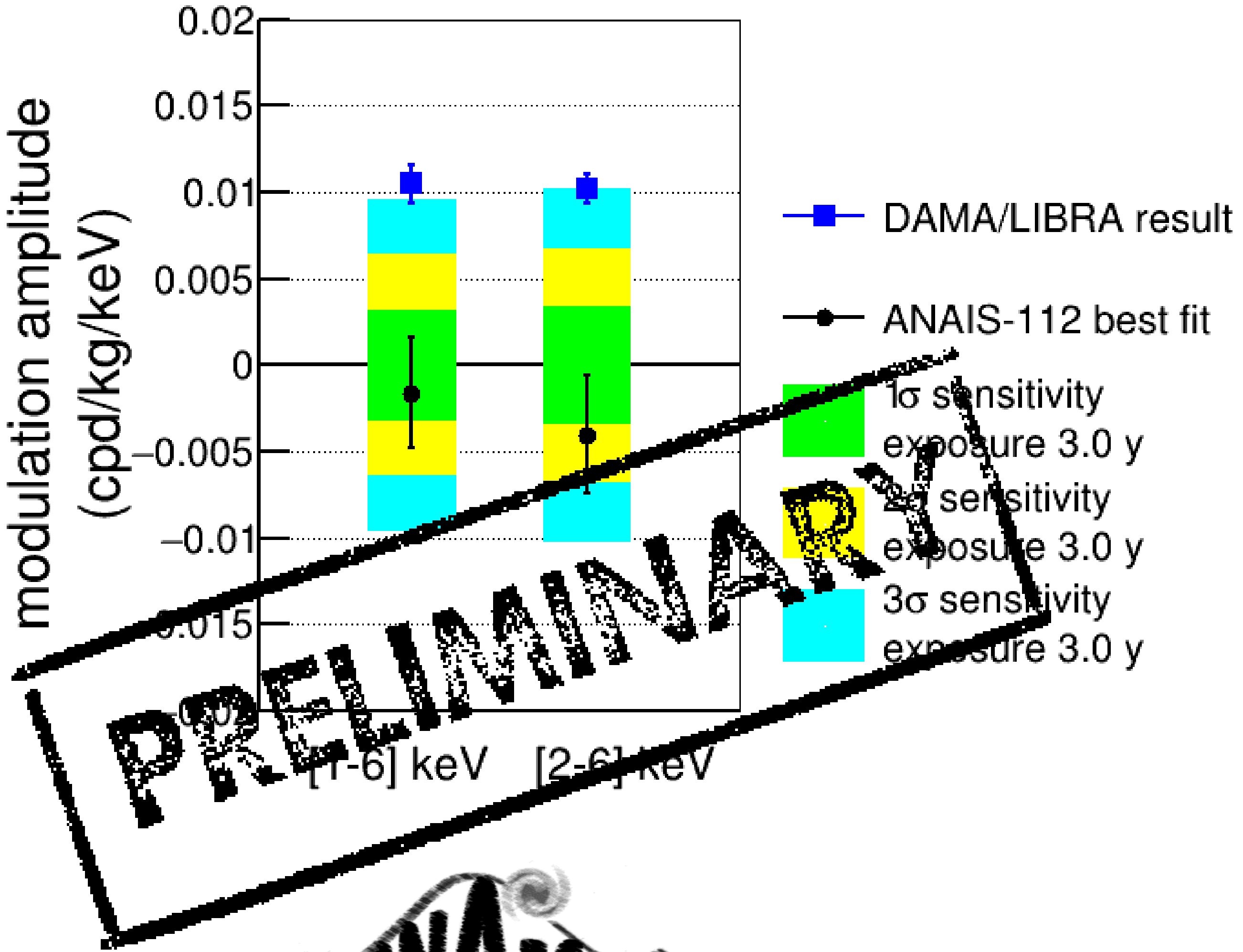
Null hyp χ^2/ndf: 1029.87/972 [p_{val}=0.096]

Mod hyp χ^2/ndf: 1028.50/971 [p_{val}=0.098]

S_m = (-0.0040 ± 0.0034) (cpd/kg/keV)



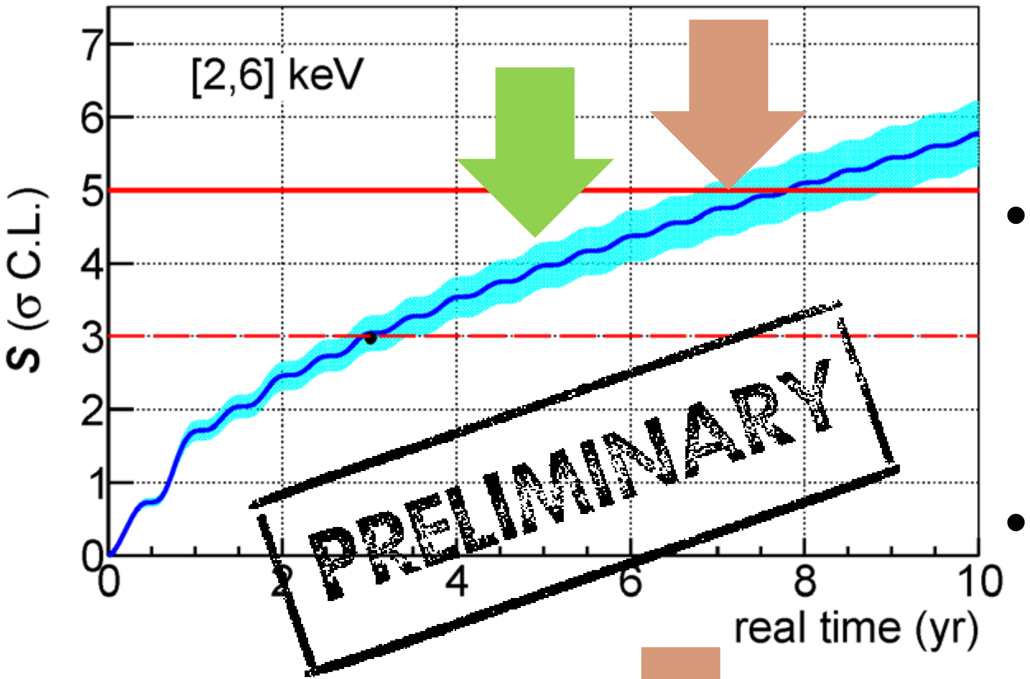
ANAIS-112 three year results – annual modulation re-analysis using BDTs

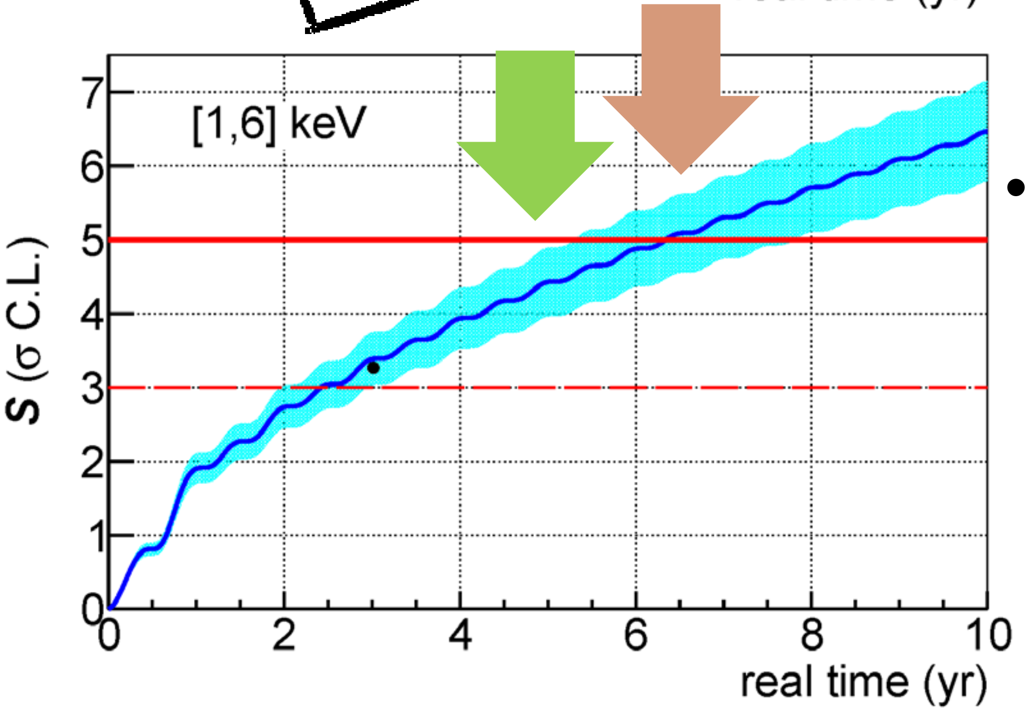


- Best fits are incompatible with DAMA/LIBRA result at 3.8 and 4.2 σ in [1-6] and [2-6] keV energy regions
- Sensitivity is at 3.3 and 3.0 σ in [1-6] and [2-6] keV energy regions

ANAIS-112 annual modulation prospects

European Physical Journal C 79 (2019) 233.

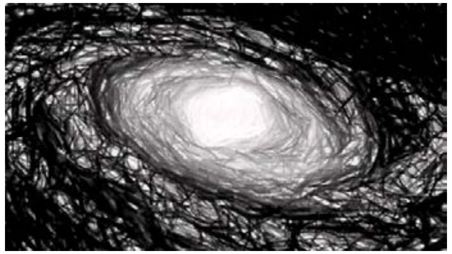




- Our “a priori” sensitivity estimates have been adapted to the new BDT – filtering: IMPROVED background and efficiencies improve our prospects
- Including systematic uncertainty in the efficiency: 0.4% systematic uncertainty quadratically added to the statistical in each energy bin and detector
- We should be at 5σ from DAMA/LIBRA result with two more years of data taking in [1-6] keV region without further analysis improvement

Statistical significance of our result is determined by the standard deviation of the modulation amplitude distribution, σ(Sm)

Summary and Outlook

Summary and Outook

ANAIS-112 data taking is progressing smoothly – almost 5 years !
Improved analysis will be applied by the end of the year to the full exposure

Neutron calibration "onsite" and complementary QF measurements are relevant for understanding systematics -> more coordinated work from the community would be required

Monitoring "onsite" possible modulations of neutron flux, muon flux, radon content in the air, etc.

Three years annual modulation re-analysis almost ready to publish (NO MODULATION OBSERVED WITH 3σ SENSITIVITY)

Testing at 5 sigma is at hand with at least 2 more years of data-taking

Planning to make our data public at The Dark Matter Data Center (ORIGINS cluster) soon

ANAIS

MultiDark
Multimessenger Approach for Dark Matter Detection

Thank you for your attention

LSC
Laboratorio Subterráneo de Canfranc

CAPA
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza