

CPAN 2025

The HENSA project for the characterization of neutron fluxes in underground laboratories

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Objectives

- **Characterization of the temporal evolution of the neutron flux.**
- **Characterization of neutron flux energy spectrum.**
- **Understand the neutron sources.**

The High Efficiency Neutron Spectrometry Array

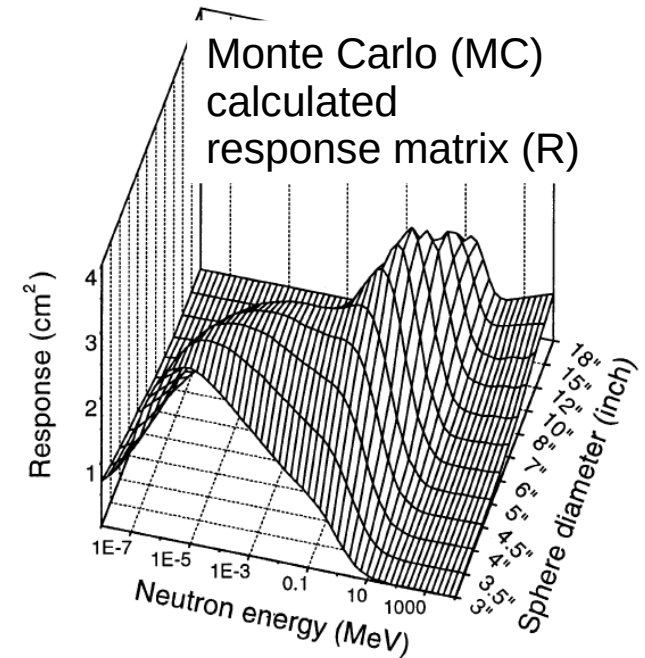
Bonner Spheres neutron spectrometry



Array of moderated neutron proportional counters

$$M_i = \int R_i(E) \phi(E) dE. \quad \Rightarrow \quad M_i = \sum_{j=1}^n R_{ij} \phi_j$$

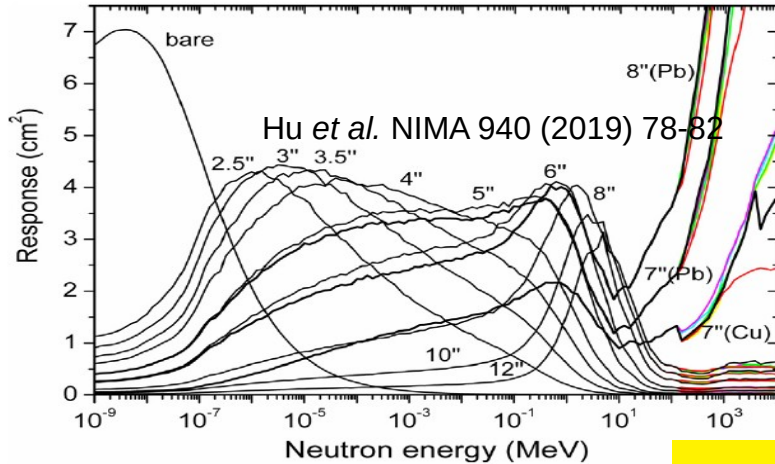
From M and R, we estimate the real spectrum Φ (unfolding)



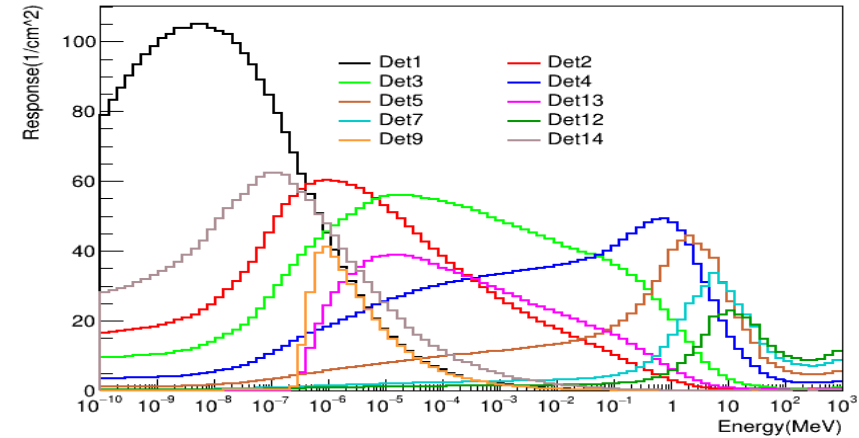
Unfolding typically relies on some preliminary knowledge about the spectrum (prior spectrum)

The High Efficiency Neutron Spectrometry Array

Standard extended Bonner Spheres



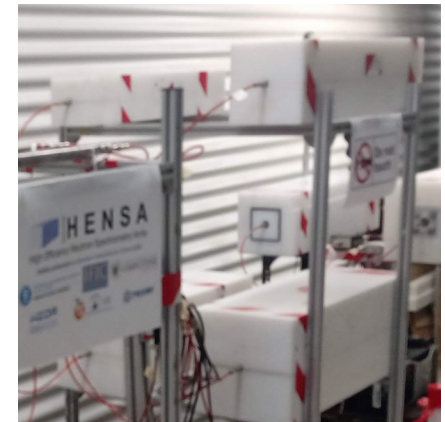
HENSA version 2022



www.hensaproject.org

HENSA neutron response is **~5-15 times larger** than standard Bonner Spheres systems in the energy range from thermal up to 10 GeV.

Use of **larger counters** (^3He) and of moderators (HDPE) with the shape of a rectangular prisms.

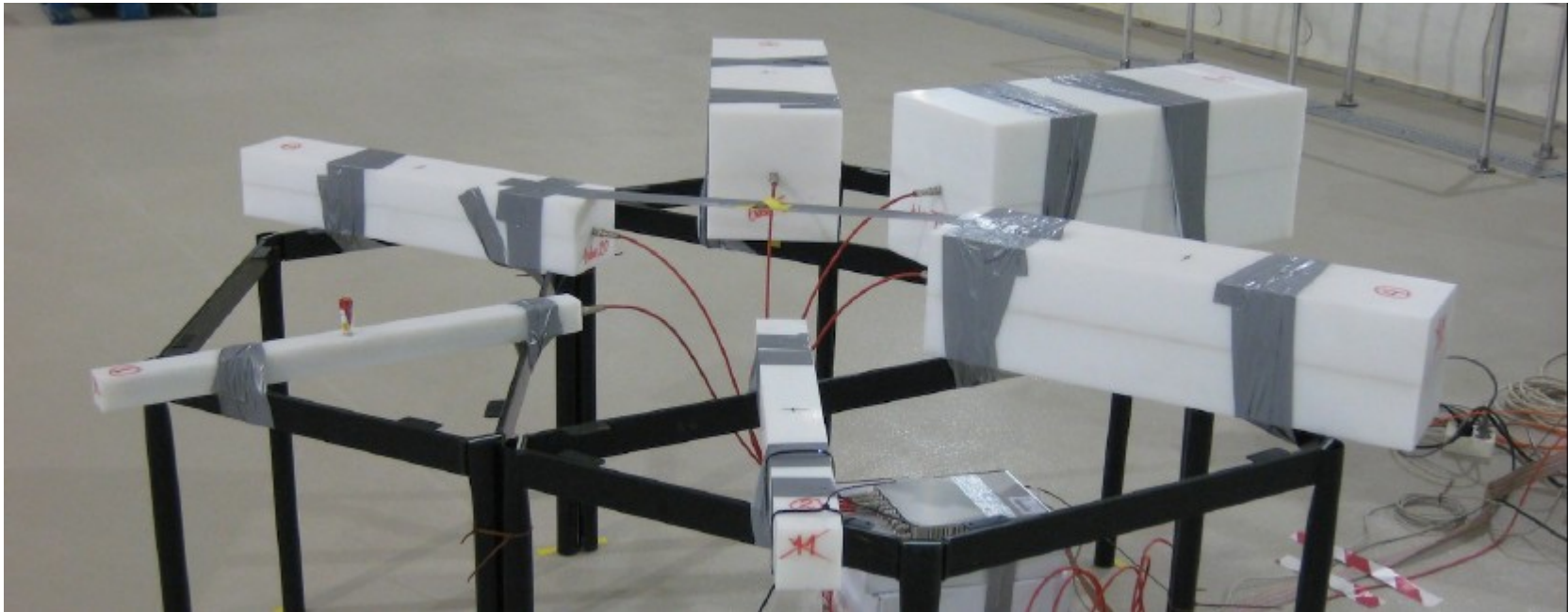


The HENSA project

- HENSA at the Canfranc Underground Laboratory (LSC)
- HENSA for cosmic rays (CR) applications (**CPAN 20/11 @ 10:15**)
- HENSA at the Gran Sasso National Laboratory (LNGS)

The HENSA project

HENSA at LSC-hall A (D. Jordan et al 2013, Astroparticle Physics 42, 1 – 6)



The HENSA project

HENSA at Felsenkeller (M. Grieger et al 2020, Phys. Rev. D 101, 123027)



The HENSA project

HENSA at LSC-hall A (2019 – 2021, S. Orrigo et al 2022, EPJ C 82, 814)



The HENSA project

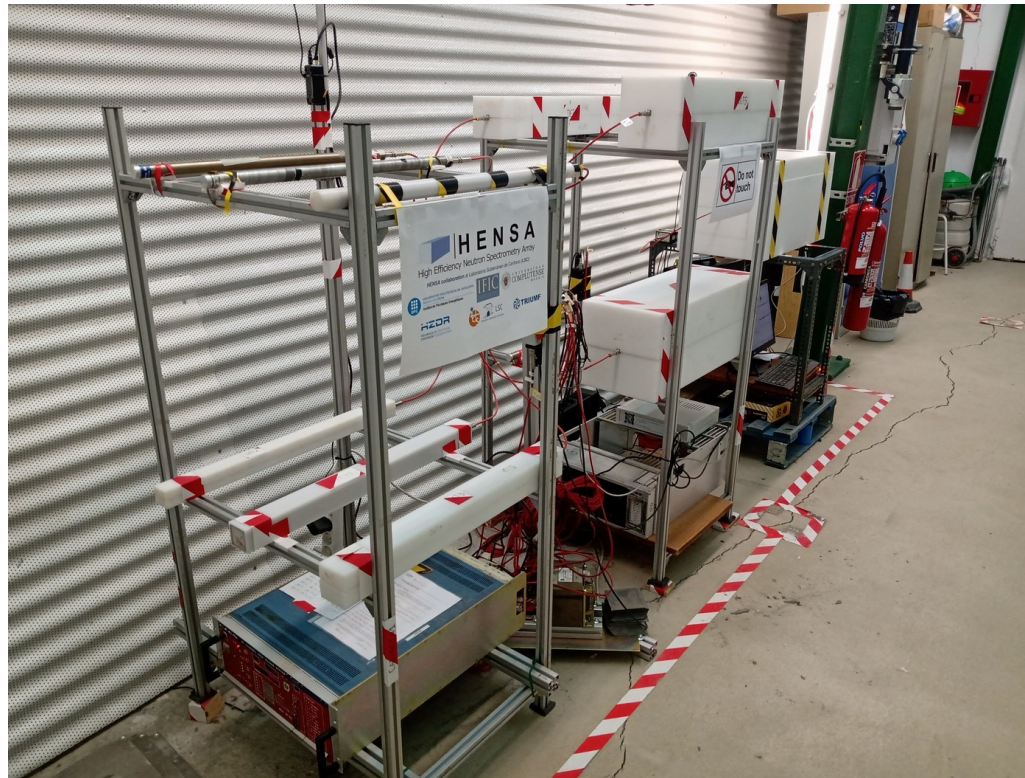
HENSA neutron monitor at LSC-hallA (PhD thesis J. Plaza)



The HENSA project

HENSA at LSC-hallB (2021 - 2025)

**N. Mont-Geli et al/ 2023, PoS 441, 136672
Ph. D. Thesis by N. Mont-Geli (17/11/2025)**



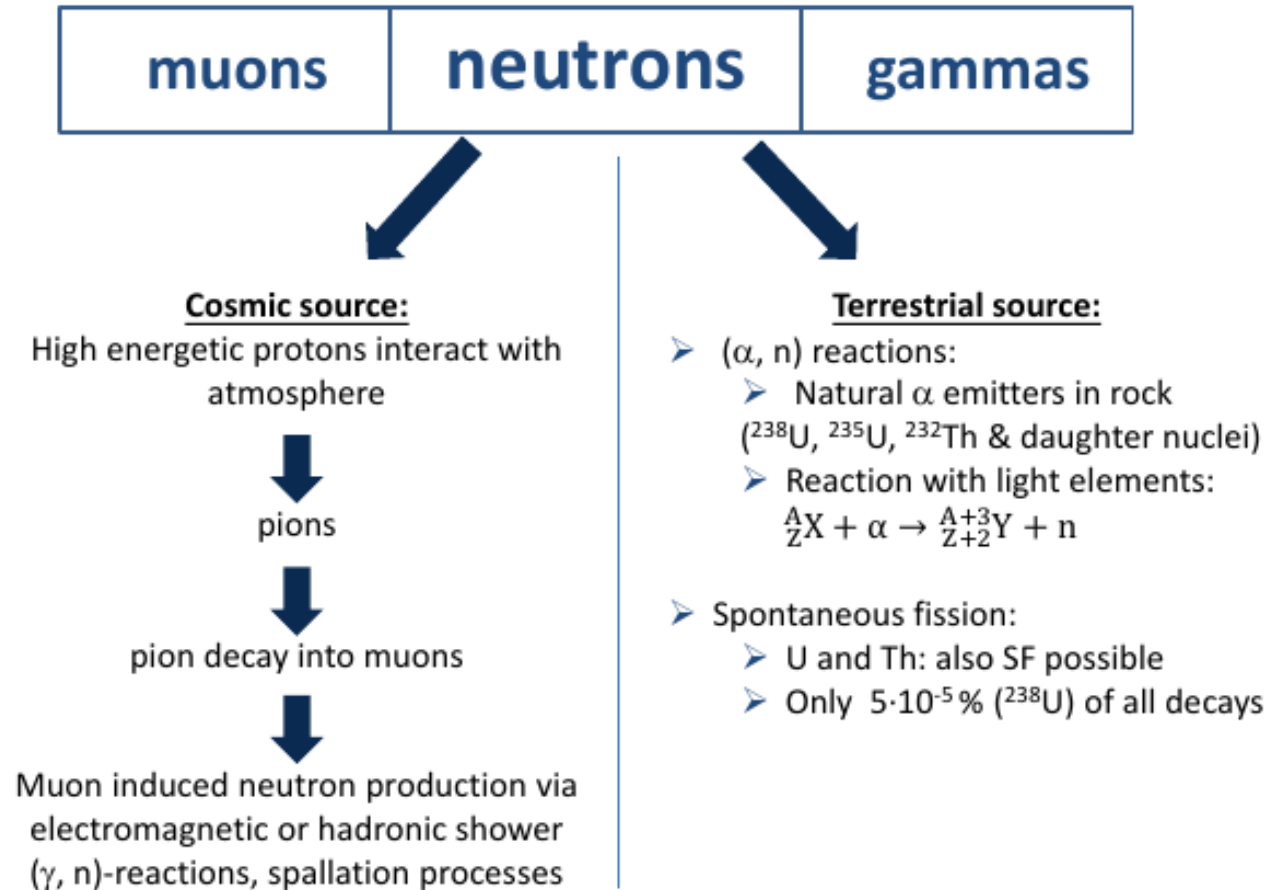
The HENSA project

HENSA at LNGS (2024 - 2025)



Simulations of the neutron flux

Neutron flux in underground laboratories



Monte Carlo simulations of the neutron flux

Monte Carlo FLUKA (v. 4.3.2) calculations used to estimate the neutron flux in Canfranc.

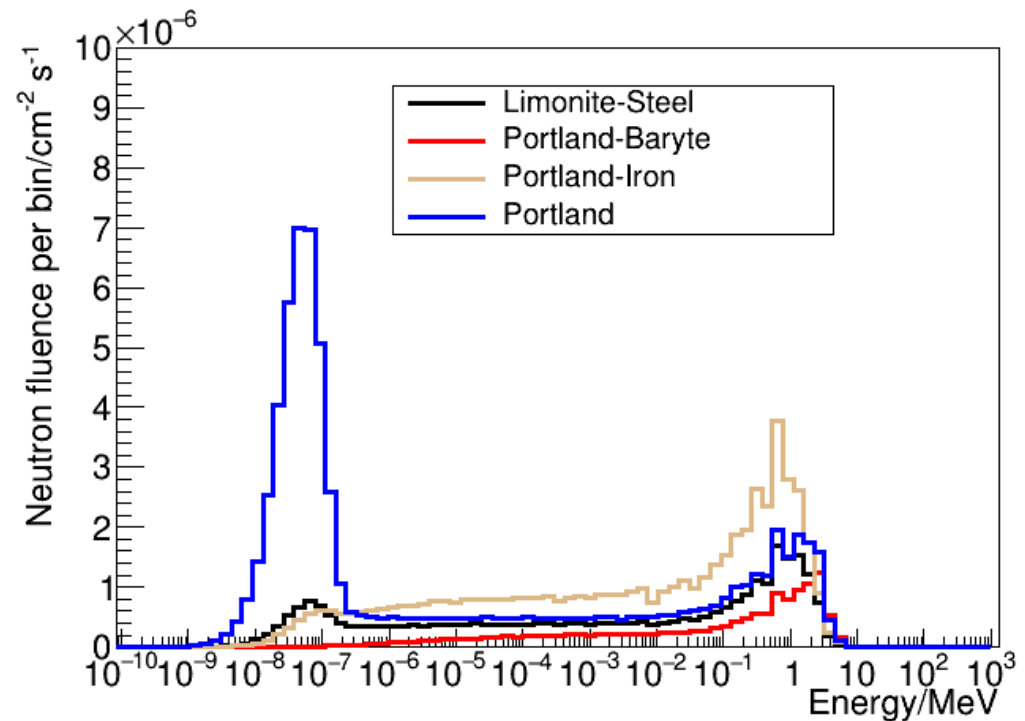
- (α ,n) reactions.
- Spontaneous fission.
- Thermal peak $\sim 4.5 - 6.5 \cdot 10^{-8}$ MeV
- Isolethargic intermediate region
- Fast peak $\sim 0.5 - 3$ MeV (1 MeV P and LS)

Spectra to be used as priors in the unfolding algorithms.

For Portland concrete:

- **Concrete contribution: 94%.**
- **Rock contribution: 6%.**

Based in the work by M. Grieger at Felsenkeller:
M. Grieger et al 2020, Phys. Rev. D 101, 123027



Monte Carlo simulations of the neutron flux

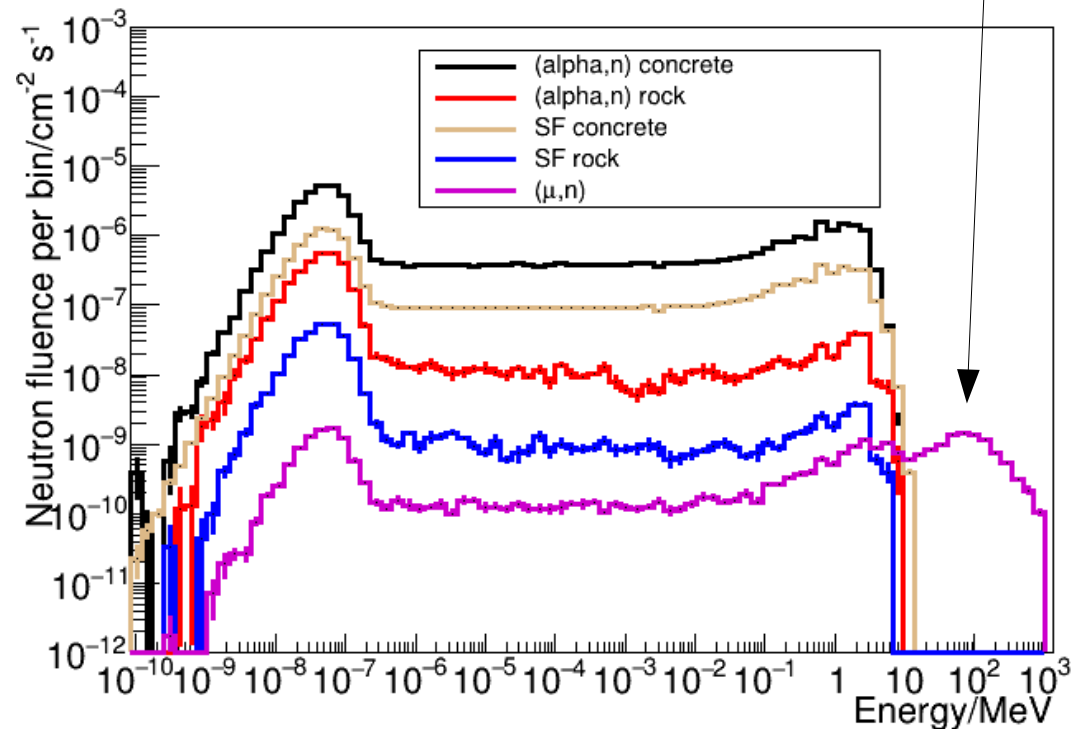
Monte Carlo FLUKA (v. 4.3.2) calculations used to estimate the neutron flux in Canfranc.

(ex: Portland concrete)

- (α, n) reactions.
- Spontaneous fission.
- **Muon-induced neutrons**
- Thermal peak $\sim 4.5 - 6.5 \cdot 10^{-8}$ MeV
- Isolethargic intermediate region
- Fast peak $\sim 0.5 - 3$ MeV (1 MeV P and LS)
- HE peak ~ 50 MeV
- **Muons contribution*: 0.03%.**
*Preliminary estimation

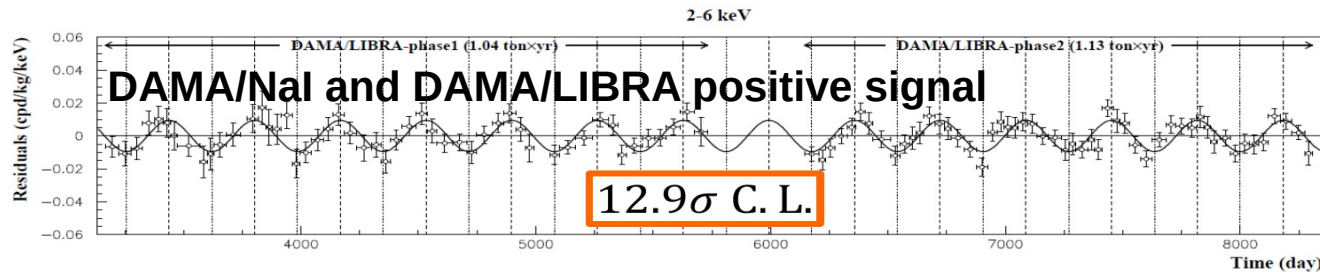
Based in the work by M. Grieger at Felsenkeller:
M. Grieger et al 2020, Phys. Rev. D 101, 123027

**not feasible
with HENSA**



HENSA in hall B of the LSC

Physical case (ANAIS - 112)



See talks by M Martinez (ANAIS) on:

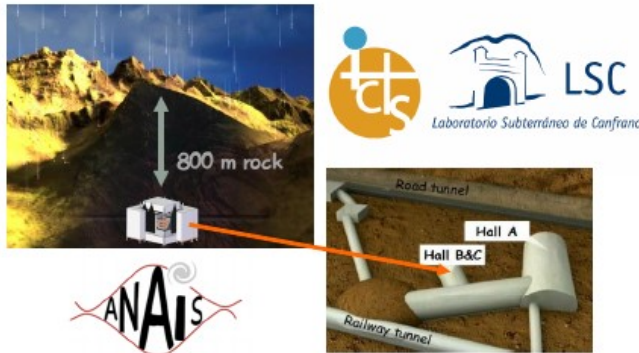
- 25 Aug, 18:00
- 27 Aug, 16:20

Goal

ANAIS (*Annual modulation with NaI(Tl) scintillators*) intends to provide a **model independent** test of the signal reported by DAMA/LIBRA, using the **same target and technique** at the **Canfranc Underground Laboratory** (Spain)



CAPA Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza



Experimental goals

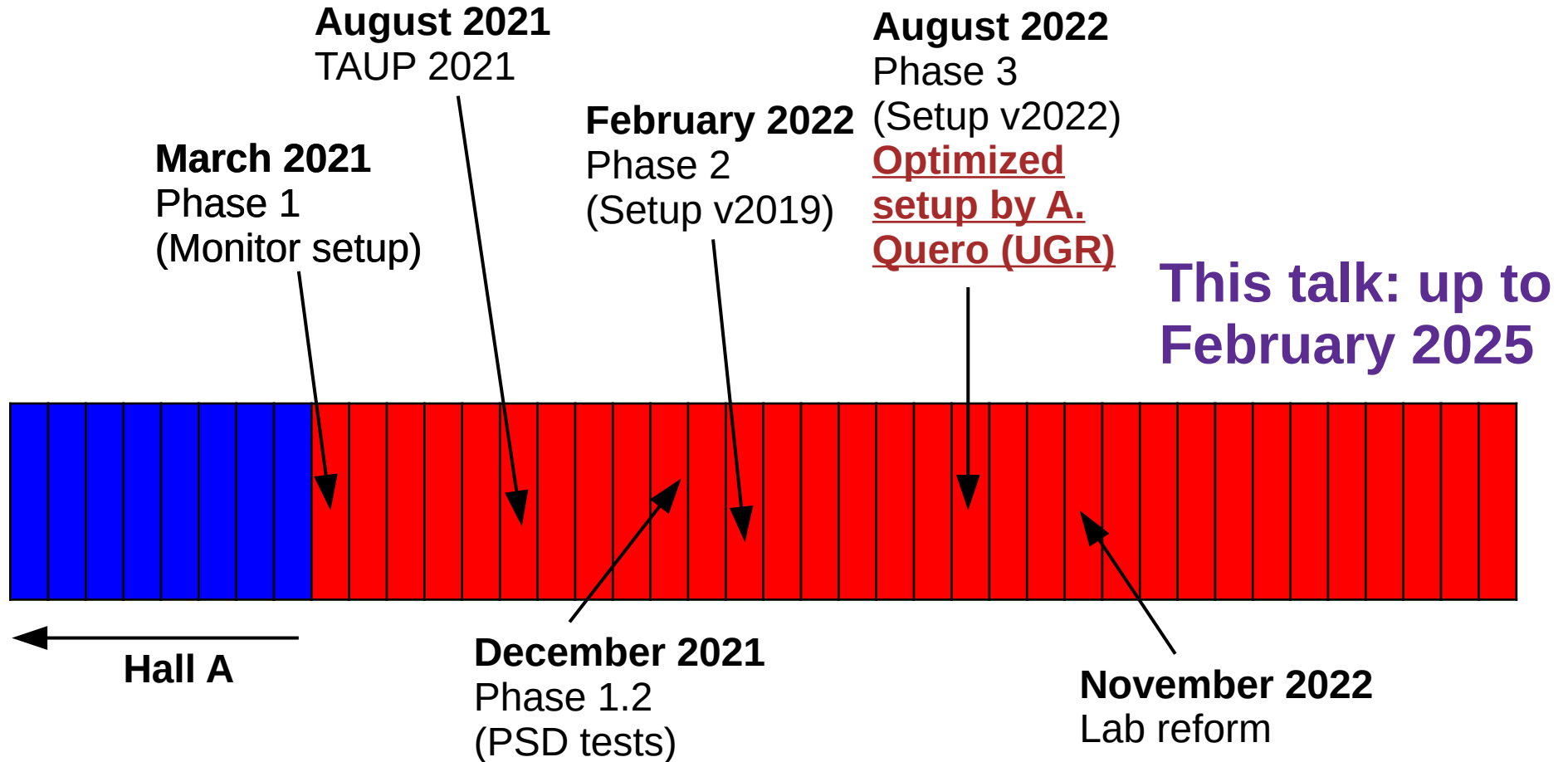
- Energy **threshold** at 1 keV_{ee}
- **Background** level below 10 keV_{ee} at a few cpd/kg/keV_{ee}
- Very **stable** operation conditions

For ANAIS is **relevant** the measurement of:

- I) total **neutron flux** and spectral distribution at LSC (Hall B).
- II) Possible **long-term variations** of the neutron flux. Required in order to set a limit on the corresponding effect in ANAIS background and annual modulation analysis.

Courtesy ANAIS team

Experimental campaign in hall B



Response matrix (v 2019)

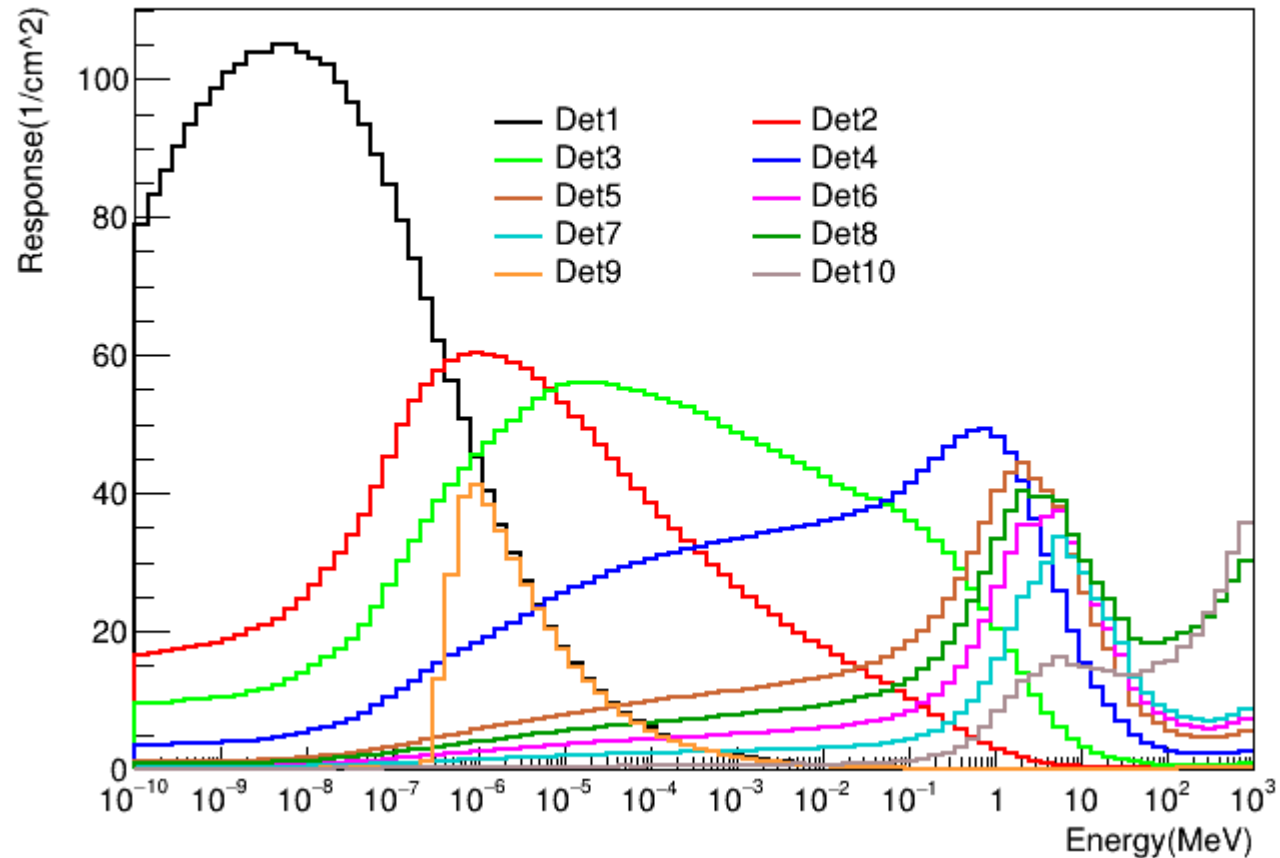
Version 2019

Monte Carlo calculations using Particle Counter, code based on Geant 4.

No cross-talk.

**Particle
Counter**

<https://www.particlecounter.net>



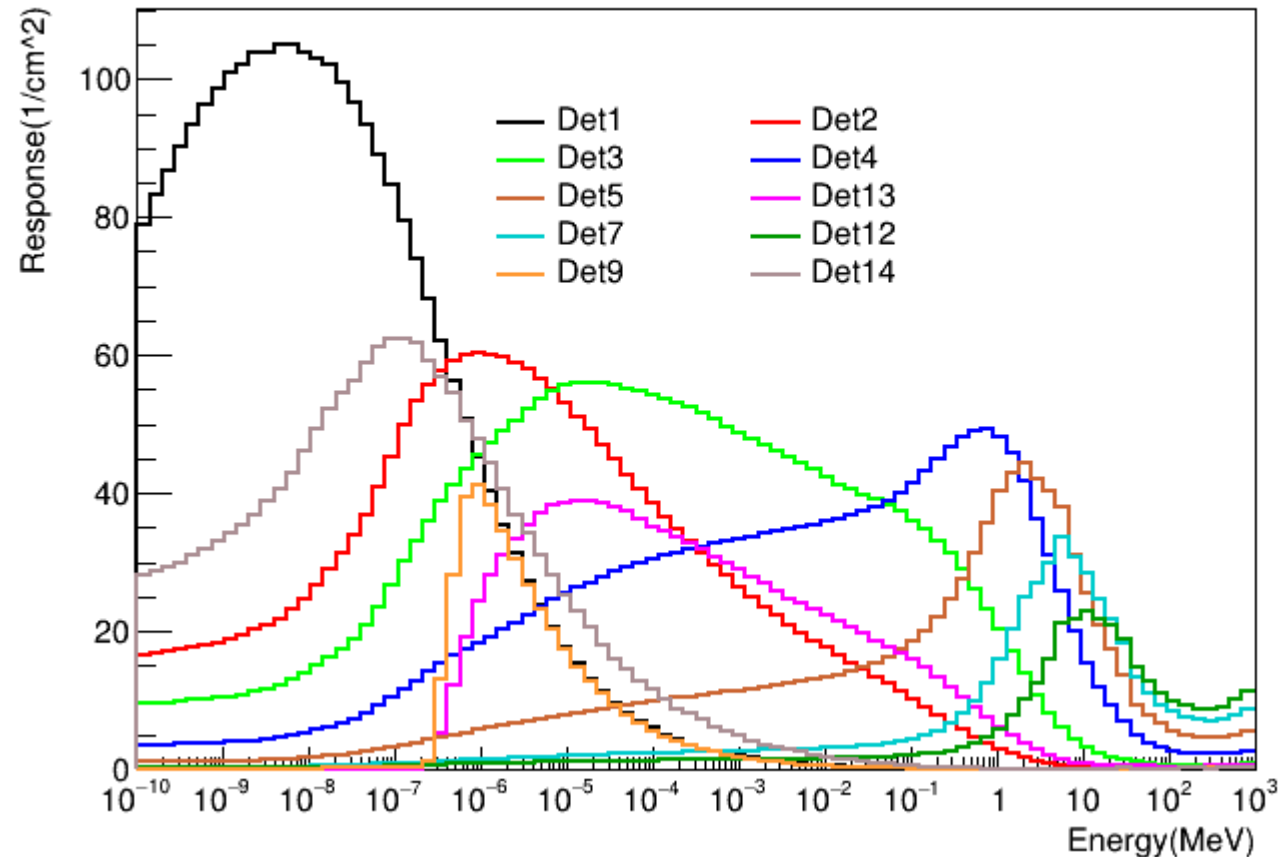
Response matrix (v 2022)

Version 2022

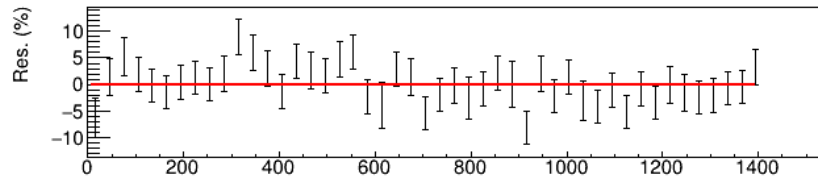
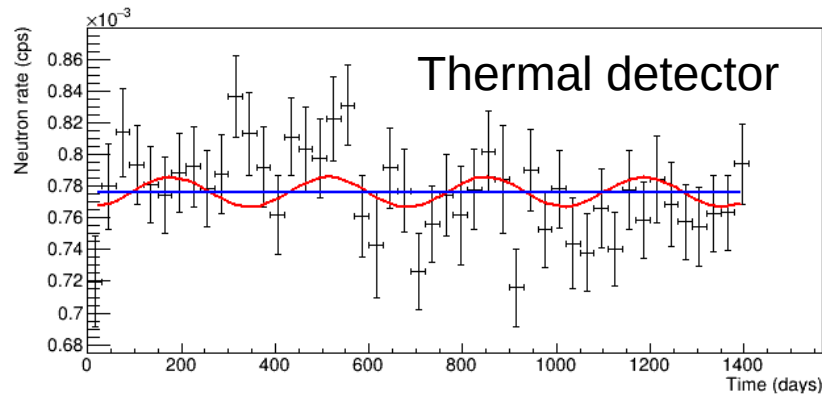
New design with improved spectral resolution by **A. Quero (UGR)**.

**Particle
Counter**

<https://www.particlecounter.net>



Neutron counting rates

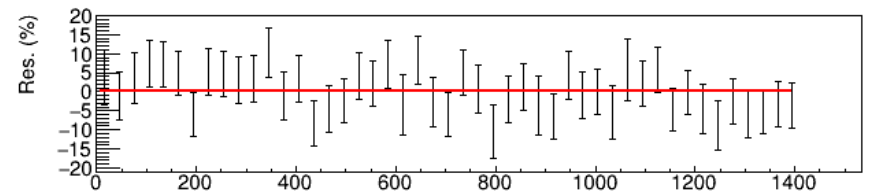
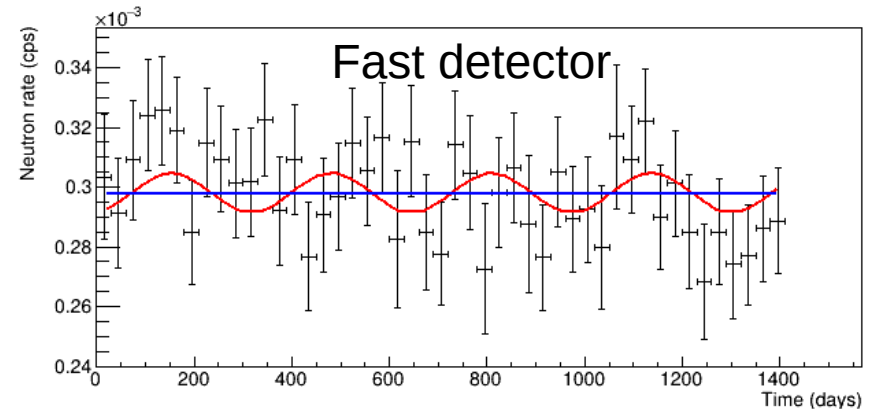


Rel. Amp. $\sim 1.2\%$
Unc. $\sim 2.7\%$

Fit chi-square (per degree of freedom):

Thermal: 1.05 (**line**), 1.10 (**oscillation**)

Fast: 0.52 (**line**), 0.62 (**oscillation**)



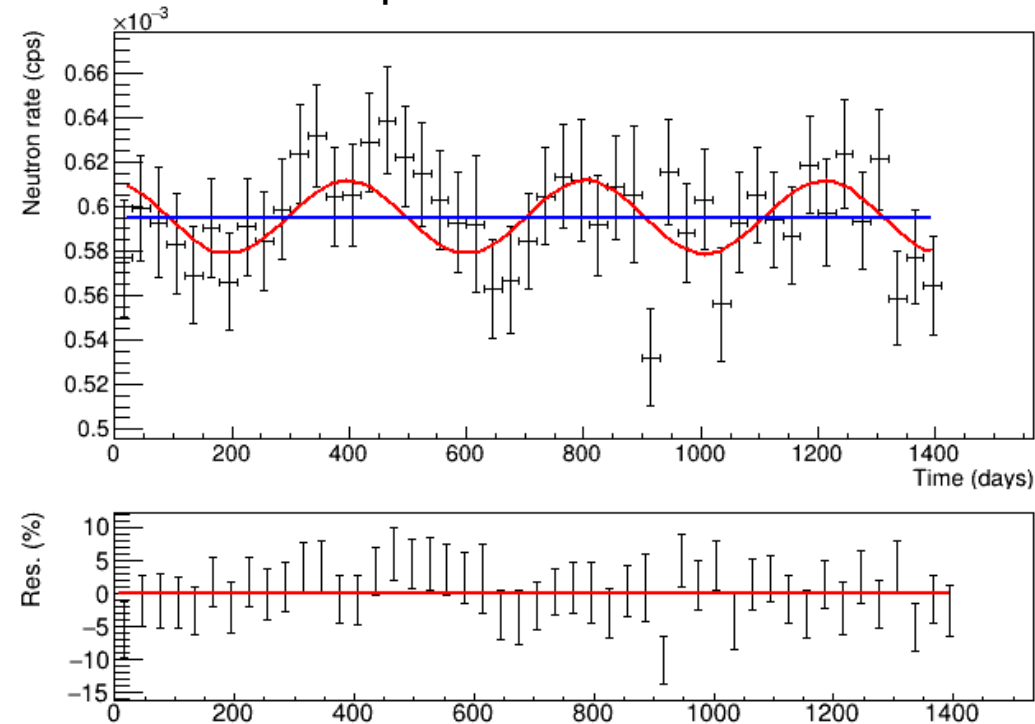
Rel. Amp. $\sim 2.2\%$
Unc. $\sim 4.8\%$

Line: $f'(t) = E$

Oscillation: $f(t) = A \cdot \sin(Bt+C)+D$

Neutron counting rates

Epithermal detector



Fit chi-square (per degree of freedom):
0.70 (**line**), 0.93 (**oscillation**)

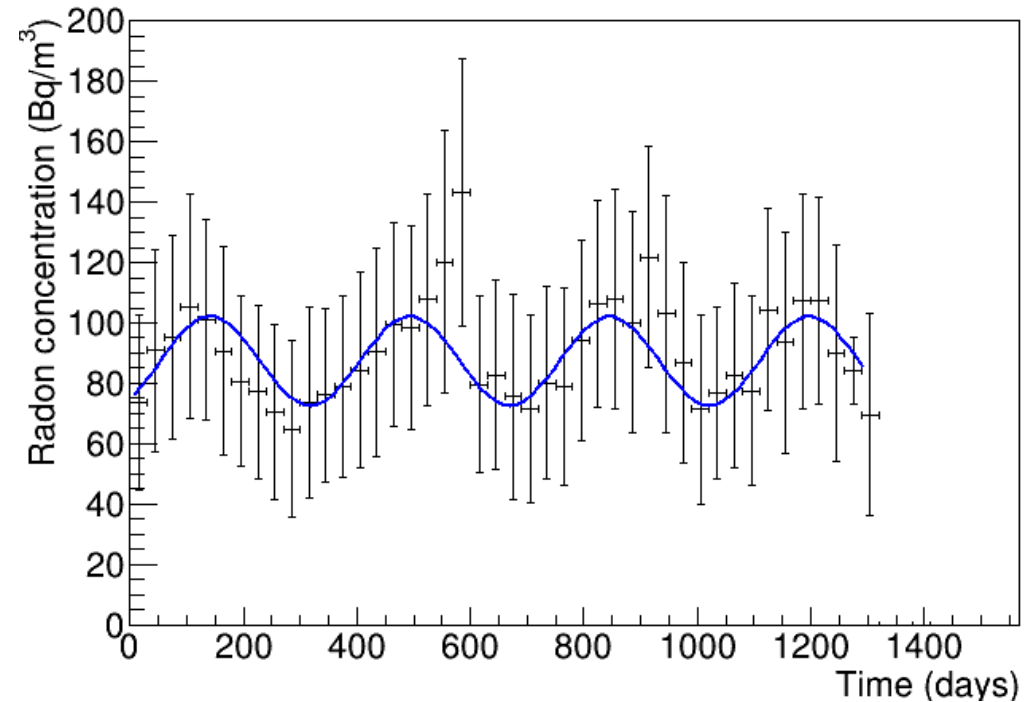
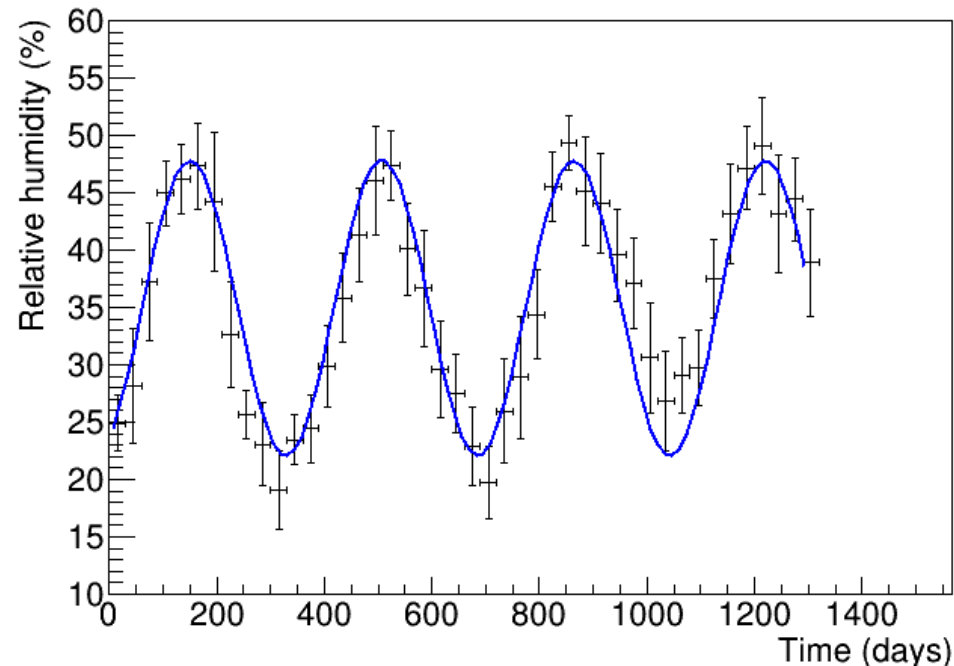
Rel. Amp. $\sim 2.8\%$

Unc. $\sim 3.1\%$

Line: $f'(t) = E$

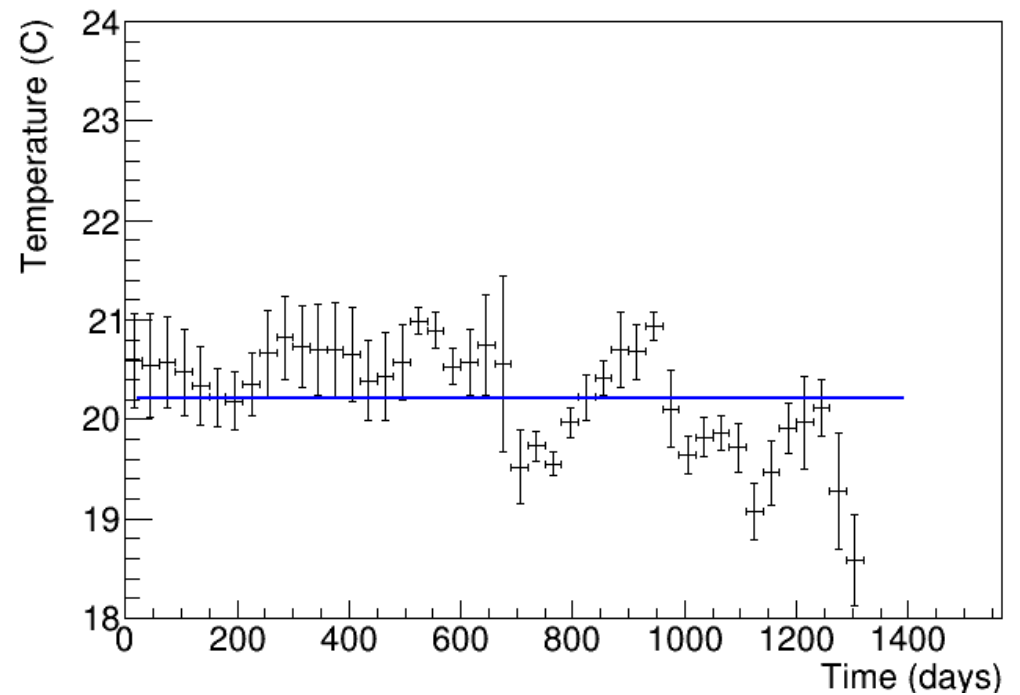
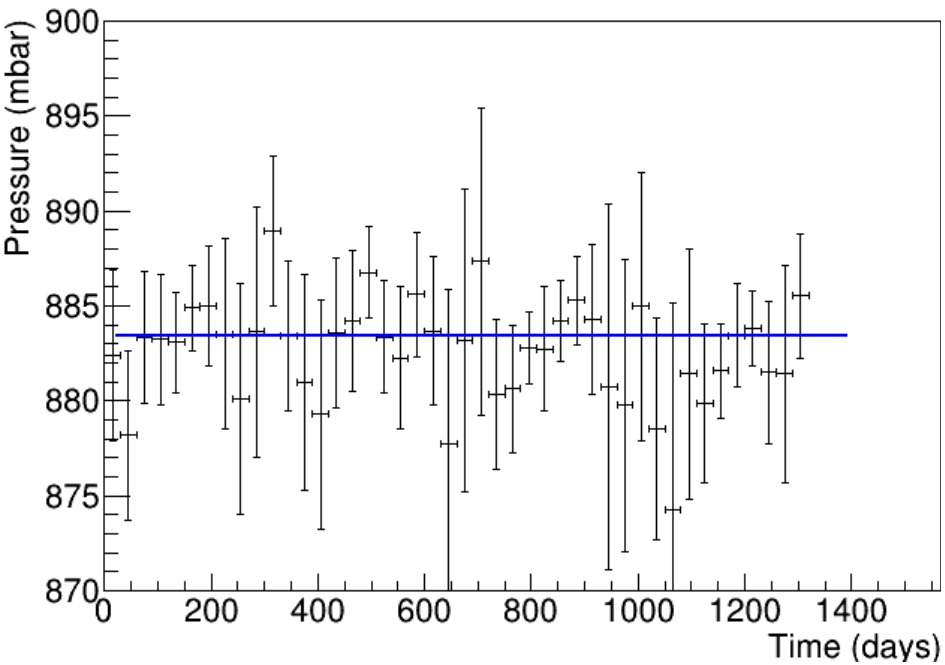
Oscillation: $f(t) = A \cdot \sin(Bt+C)+D$

Environmental variables

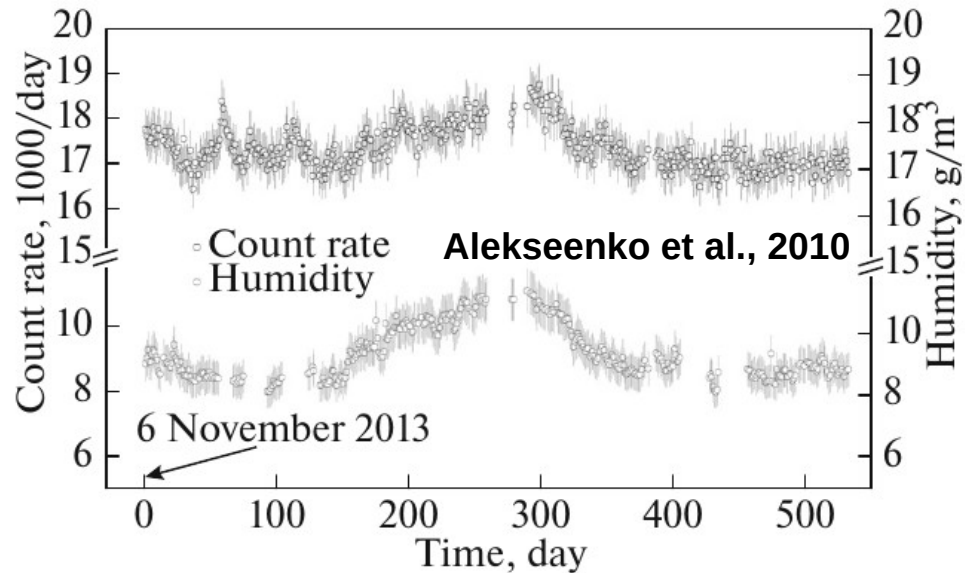


Humidity-radon correlation factor: 0.85

Environmental variables



Rates vs water content in air (relative humidity)



**What
happens at
LSC?**

Aleksenko et al., 2010, Journal of Physics Conferences Series 203, 012045

- 2% relative amplitude fluctuation in the humidity correlated thermal rates at BNO

Aleksenko et al., 2017, Physics of Particles and Nuclei 48, 34 - 37

5% relative amplitude fluctuation in the humidity correlated thermal rates at DULB-4900

Rates vs water content in air (relative humidity)

**No
correlation**

Det.	ρ	Det.	ρ
1	0.12	5	0.15
2	0.27	13	-0.005
3	0.01	7	-0.02
4	-0.04	12	-0.13
5	0.15	14	0.05

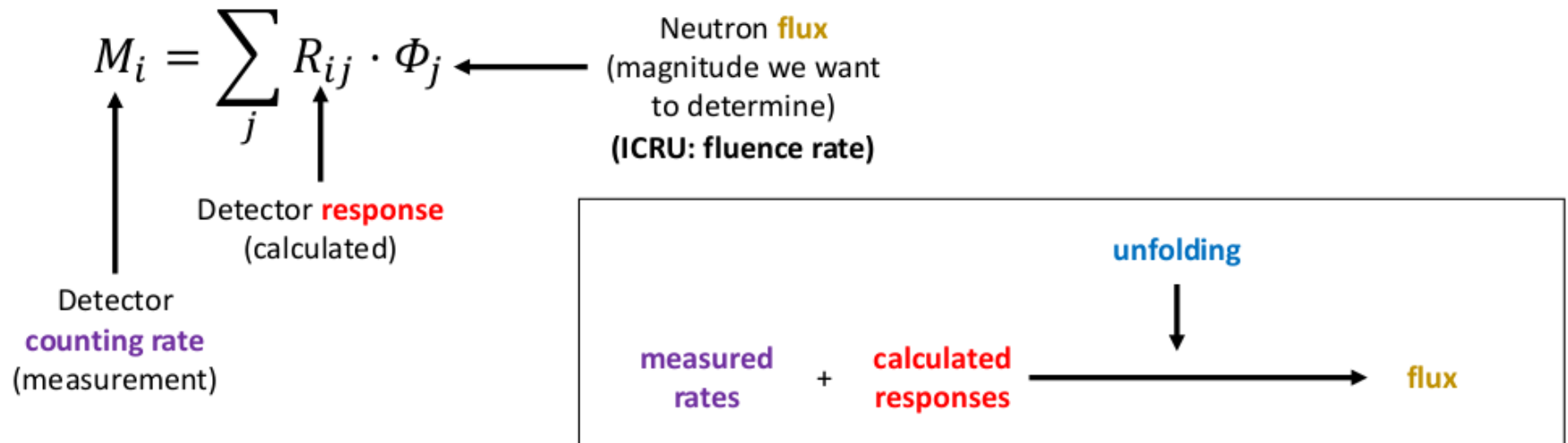
Table 5.5: Pearson correlation coefficients between the relative humidity and each detector of HENSA (ρ). See text for more details.

Note that the HENSA monthly uncertainties are of the same order than the BNO and DULB-4900 modulations (2 – 5%)

Spectra reconstruction

Unfolding algorithms

Unfolding consists on extracting the **flux magnitude and energy distribution** from the measured **rates** and the **response**.



- Many different unfolding algorithms exist. In this work: **MAXED, GRAVEL, POU**.

- All three are based on the use of a priori information.
(an educated guess of the spectrum)

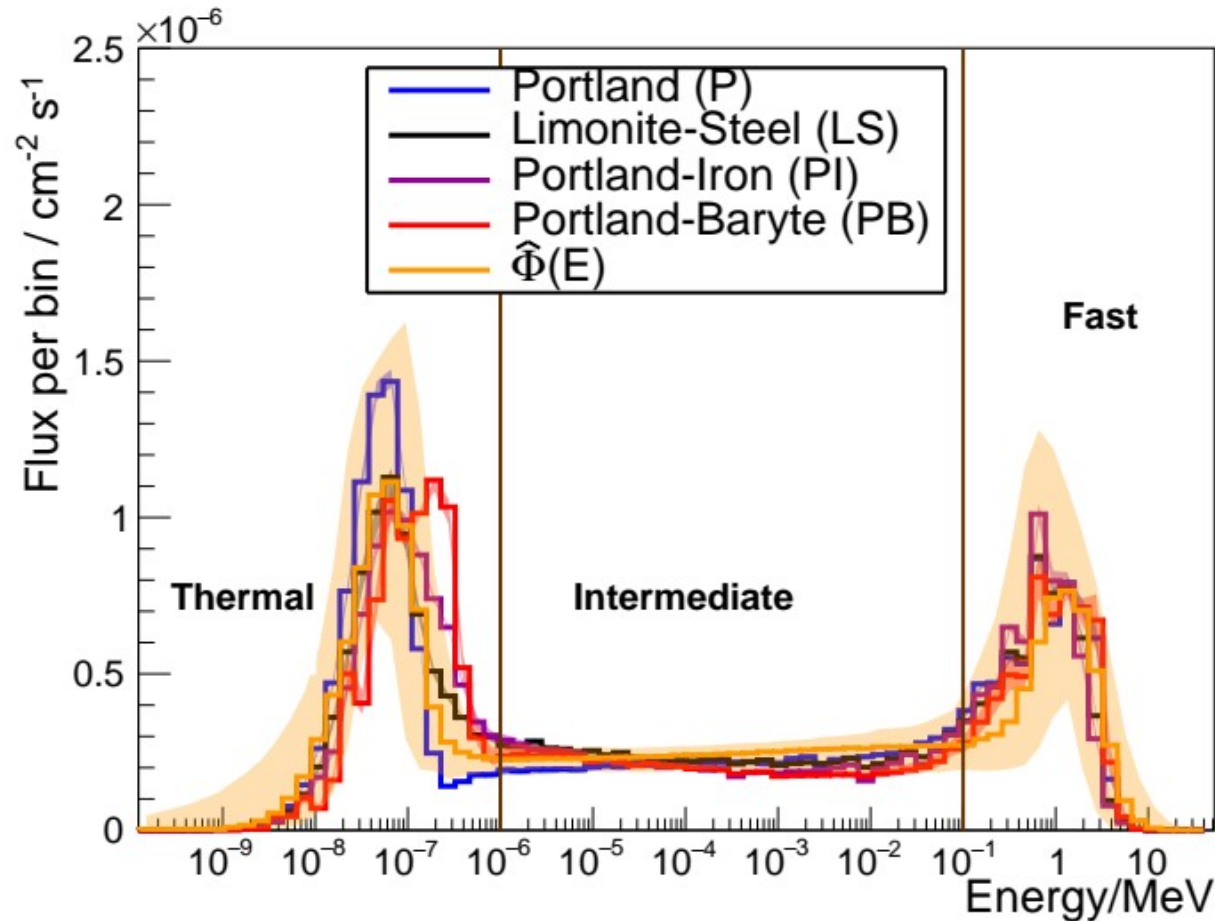
- **Results depend on the a priori information!**
 - Realistic estimations (MC).

POU: developed in the context of the HENSA collaboration by **A. Quero and others** (M. Pallàs, J.L. Tain, A. Tarifeño, A. Lallena).

MAXED and **GRAVEL** are freely distributed as the UMG 3.3 packaged through the NEA Computer Program System.

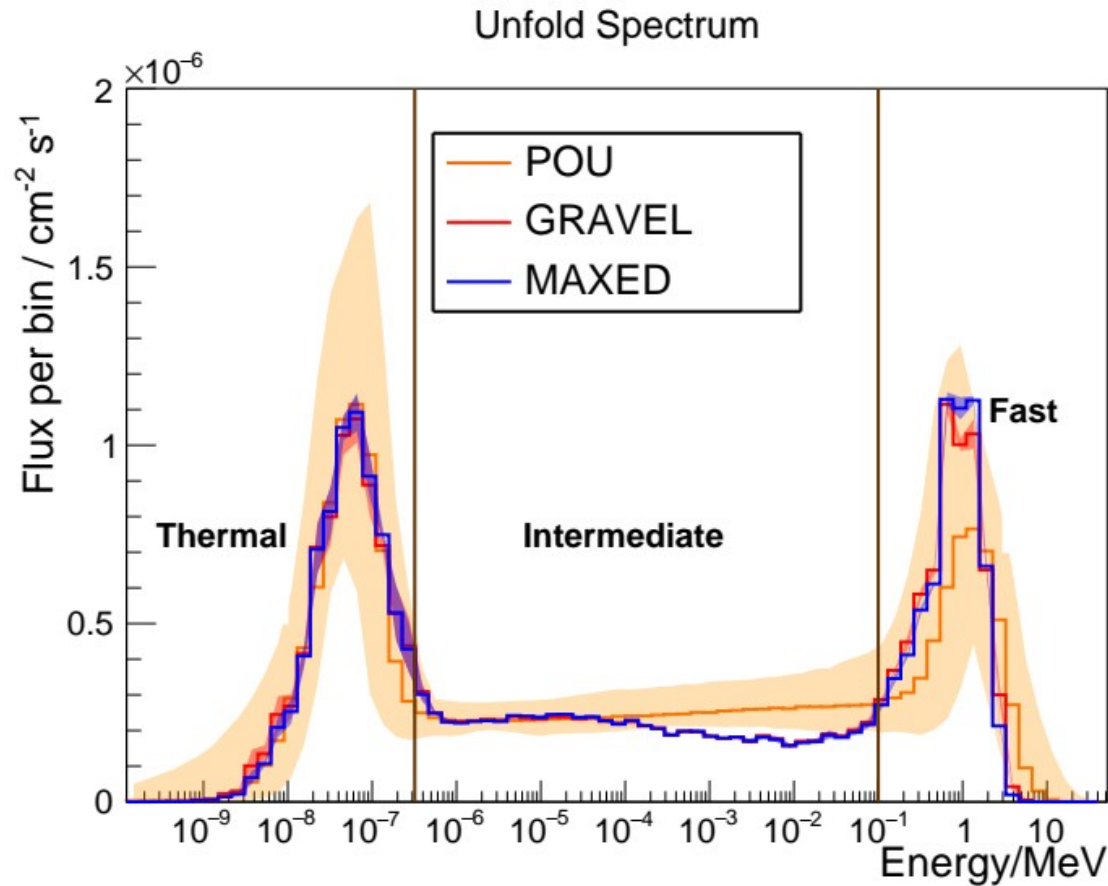
21

Unfolded neutron flux at LSC



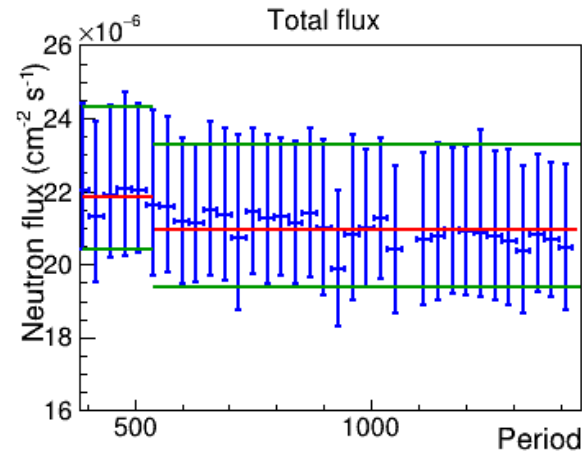
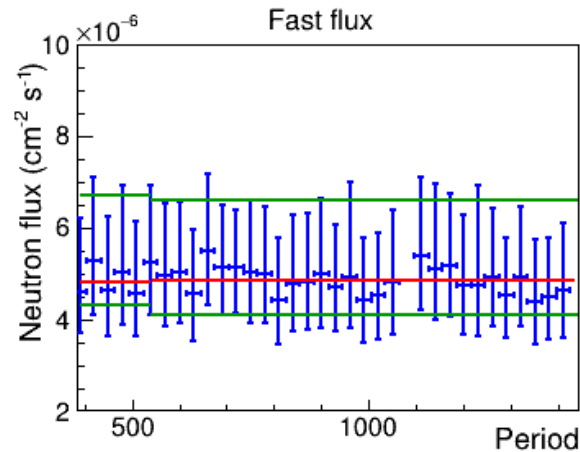
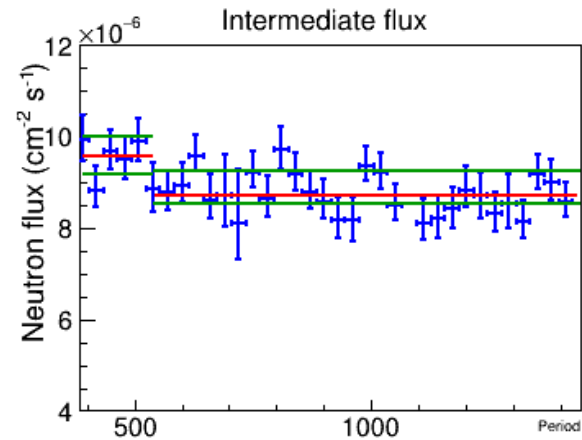
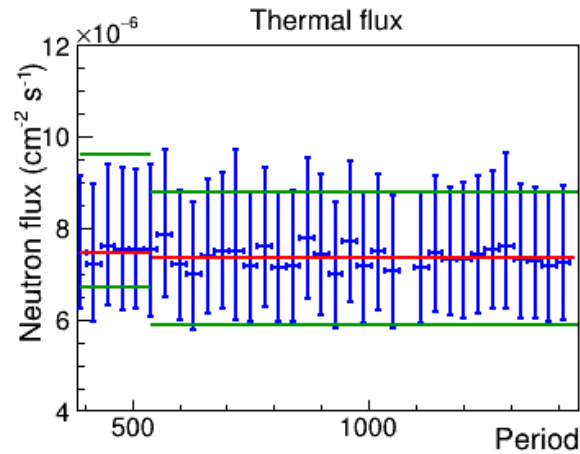
10% total uncertainty
due to the the prior
systematics

Unfolded neutron flux at LSC



Evolution of the neutron flux

Evolution of the neutron flux



Evolution of the neutron flux

Energy region	χ^2/ndf	χ'^2/ndf	$T = 2\pi/C$	A/D
Thermal	0.015	0.016	246(126) days	1.02 %
Intermediate	1.03	1.10	313(23) days	3.96%
Fast	0.029	0.040	383(46) days	2.69%
Total	0.041	0.047	340(83) days	1.43%

Table 5.8: χ^2 divided by the number of degrees of freedom (ndf) when fitting a sinusoidal function or a linear constant flux to the neutron rates data of HENSA. T is the period in days of the sinusoidal function and A/D is the relative amplitude of the oscillation.

Energy region	Quotient (B/A)
Thermal (0 MeV - $3.2 \cdot 10^{-7}$ MeV)	2.27(44)
Intermediate ($3.2 \cdot 10^{-7}$ MeV - 0.1 MeV)	1.37(6)
Fast (0.1 MeV - 20 MeV)	0.98(25)
Total flux (0 MeV - 20 MeV)	1.43(14)

Table 5.9: Quotients between the neutron fluxes in the thermal, intermediate and fast energy regions in halls A and B. See text for more details.

Impact of the neutron flux on the background of ANAIS-112

Impact on the background of ANAIS-112

V. Impact of neutrons on ANAIS-112



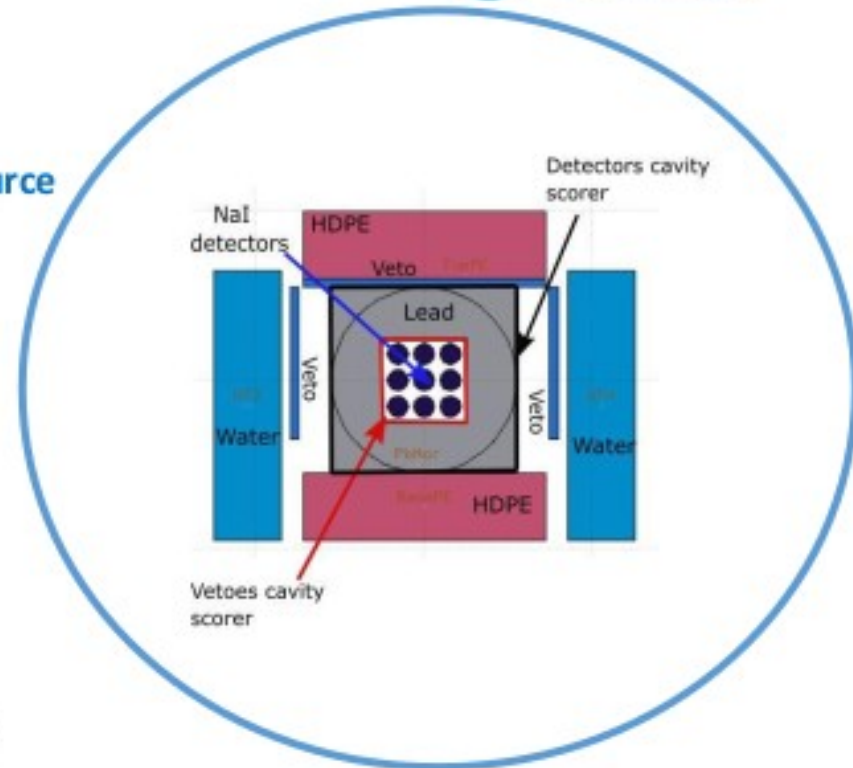
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measurement
by HENSA

neutron source

Contribution of neutrons to the total background is of 0.08% - 1% (at maximum). This **is negligible**.

Work in collaboration with Tamara Carrasco (UNIZAR)



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HENSA at LNGS

HENSA at LNGS: overview

Current status of HENSA at LNGS

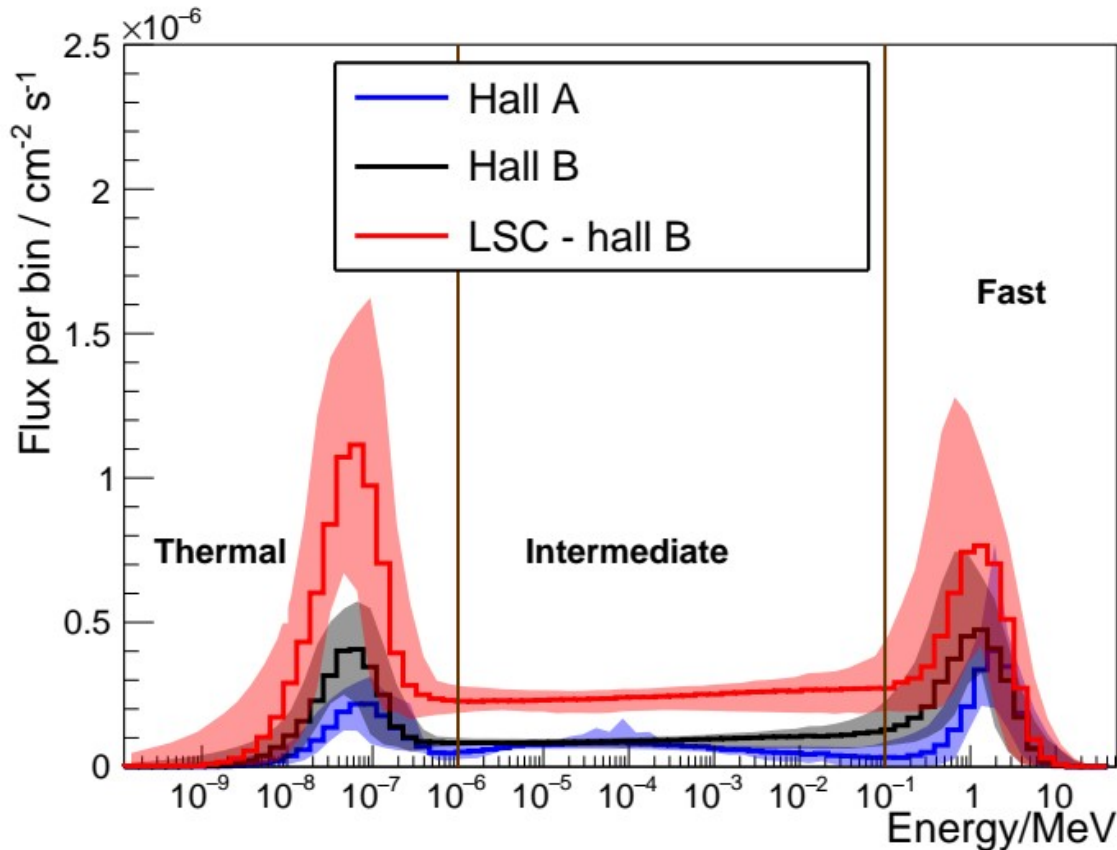
- Hall A: April 2024 – July 2024.
- Inside the new STELLA facility: July 2024 – November 2024.
- Hall B: since November 2024

Work	Hall	Technique
Belli (1989)	A	BF3 counters + variable size moderators (Spec.)
Aleskan (1989)	A	Li-6 scintillator (> 3 MeV)
Arneodo (1999)	C	Proton recoil scintillation detector (Spec.)
Belloti (1985)	B	3He counters, bare + 1 paraffin (thermal and fast)
Debicki (2009)	?	3He bare counters (thermal)
Cribier (1995)	A	CaNO3 radiochemical detector (> 2.5 MeV)
Rindi (1888)	?	3He counters, bare + paraffin + bare and cd
Best (2016)	No hall	3He bare counters (thermal)
Debicki (2018)	(same 2009)	3He counters + long counter for fast neutrons
Bruno (2019)	A (LVD)	Liquid scintillators (above 10 MeV)

**Spectral
resolution**



HENSA at LNGS: preliminary results



Hall A ($10^{-6} \text{ cm}^{-2} \text{s}^{-1}$):

- Thermal: $1.62(+0.30, -0.25)$
- Intermediate: $2.00(+0.17, -0.13)$
- Fast: $1.88(+0.56, -0.39)$
- Total: $5.50(+0.66, -0.48)$

Hall B ($10^{-6} \text{ cm}^{-2} \text{s}^{-1}$):

- Thermal: $2.94(+0.53, -0.43)$
- Intermediate: $3.06(+0.18, -0.17)$
- Fast: $3.08(+0.76, -0.54)$
- Total: $9.08(+0.95, -0.72)$

Unfolded spectra

Hall B ($10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$):

- Thermal: $2.94(+0.53, -0.43)$
- Fast: $3.08(+0.76, -0.54)$

Belloti (1985), hall B:

- Thermal: $5.3(9) \cdot 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$
- Fast: $3.0(8) \cdot 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$

Hall A ($10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$):

- Below 1 keV: $3.03(+0.33, -0.26)$
- **Above 1 keV: $2.46(+0.56, -0.40)$**
- Total: $5.50(+0.66, -0.48)$

Belli (1989), hall A:

- Below 1 keV: $2.99(10)$
- **Above 1 keV: $0.81(8)$**
- Total: $3.80(33)$

Concluding remarks

- **Characterization of the temporal evolution of the neutron flux at LSC**
 - The **counting rates are stable within the statistical uncertainties.**
 - Results compatible with a constant flux. **Modulation, if exist, smaller than 2-5%.**
 - **No correlation with meteorological variables found.**
- **HENSA activities at LSC.**
 - **Impact of neutrons on the bakcground of ANAIS-112 found to be negligible**
 - Expected: short-term measurements in hall A with the new version of the spectrometer.
- **HENSA activities at LNGS.**
 - Expected to finish a one-year long campaing in hall B.
 - Expected: HENSA will stay at LNGS for one more year at least.

Acknowledgements

This work was supported by the Spanish MICINN Grants No. PID2019-104714GB-C21, PID2019-104714GB-C22, FPA2017-83946-C2-1-P and FPA2017-83946-C2-2-P and PID2022-138297NB-C22 (MCIU/AEI/FEDER).

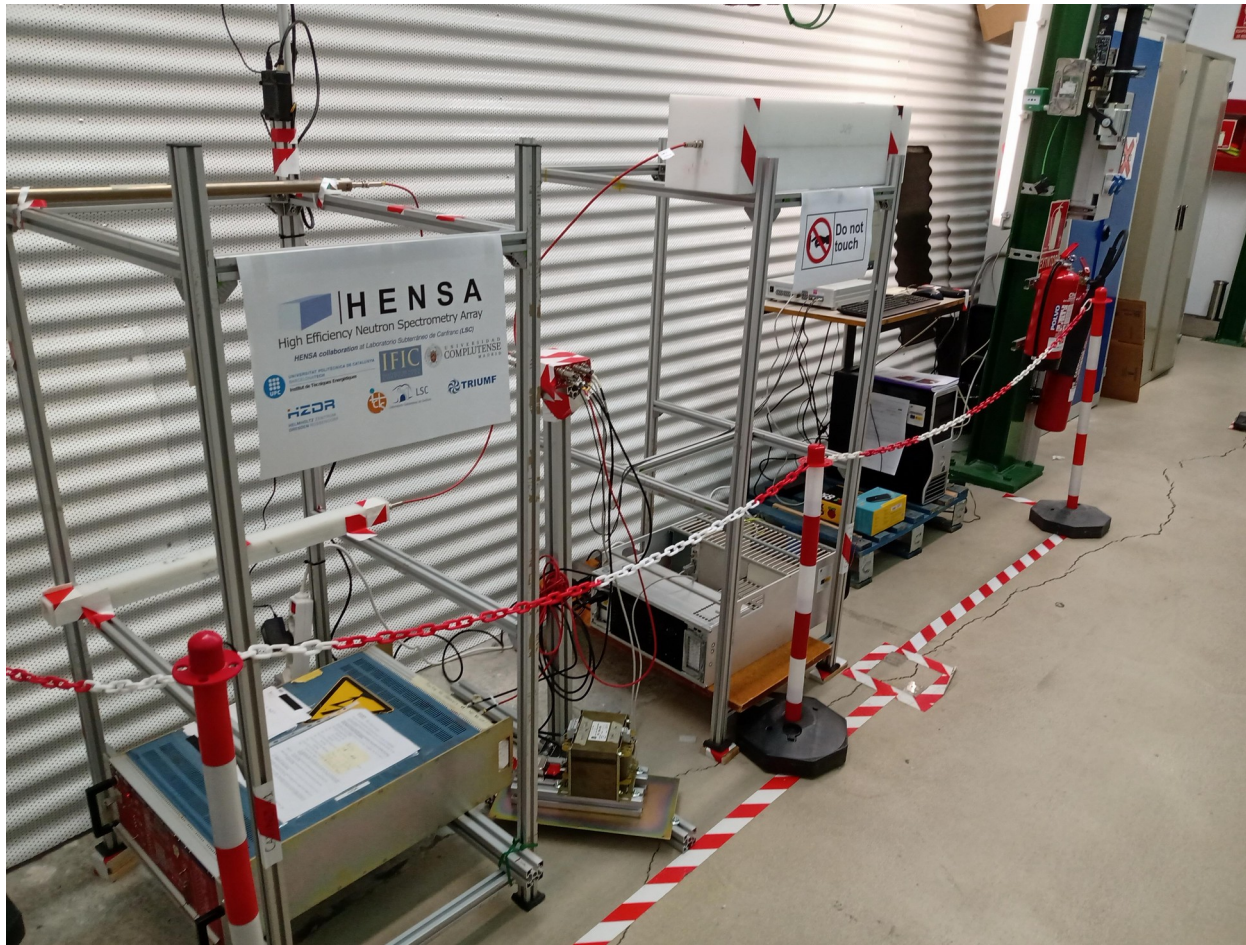
We acknowledge the support of the Generalitat Valenciana Grant No. PROMETEO/2019/007.

L.M.F. acknowledges support from the project No. RTI2018-098868-B-I00.

We are grateful to Laboratorio Subterráneo de Canfranc for hosting the HENSA spectrometer, for the support received by the LSC personnel during the measurement campaign in Hall A and for providing us with the environmental data.

Backup slides

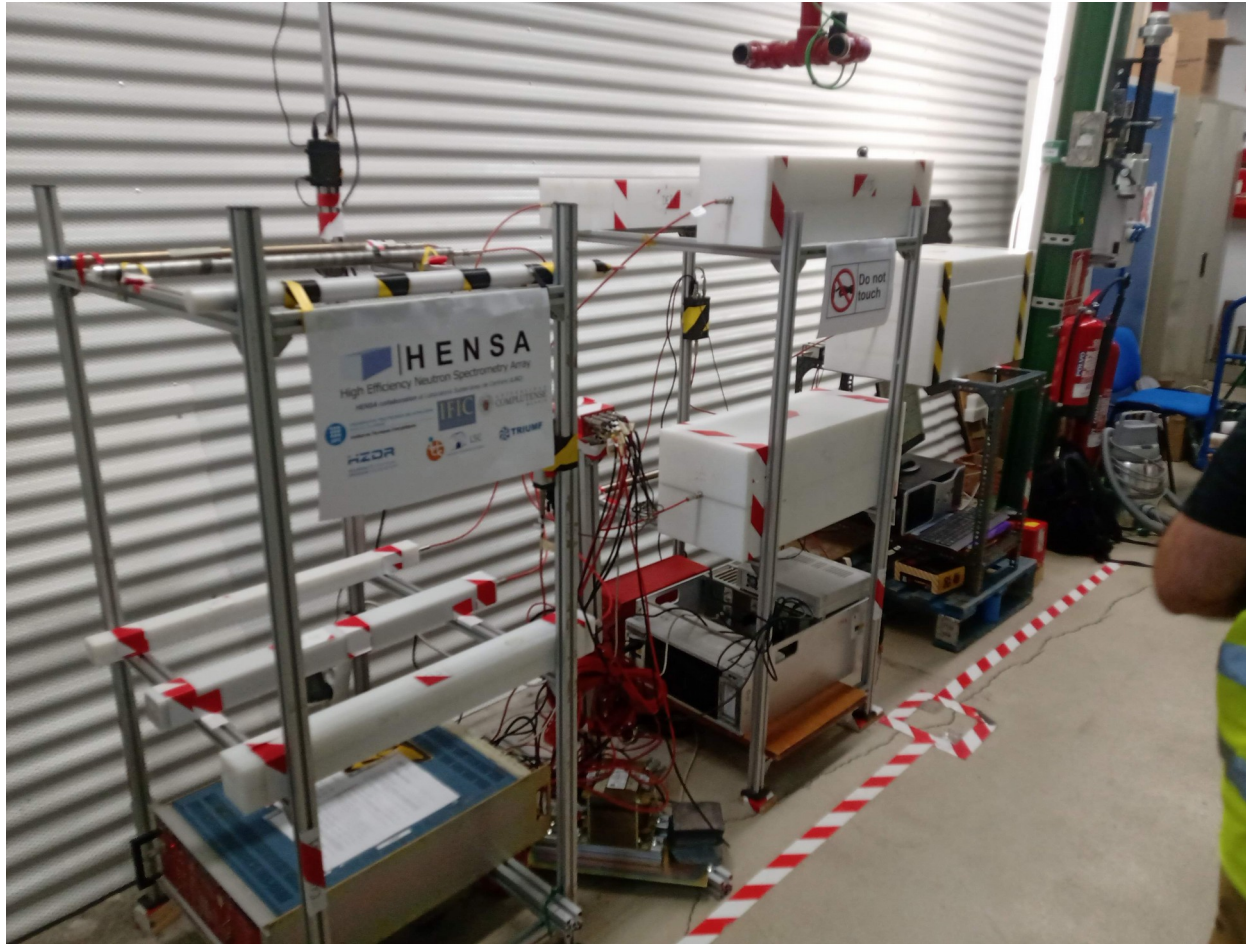
Experimental setup in phase 1 (monitor)



Experimental setup in phase 2 (v 2019)



Experimental setup in phase 3 (v 2022)



The Canfranc Underground Laboratory (LSC)

The Canfranc Underground Laboratory (LSC) is located under Mount Tobazo in the Aragonese Pyrenees (Spain).

- Three experimental halls (A, B and C).
- 2450 mwe (meters water equivalent) depth.
- Underground research: nuclear physics, dark matter, neutrino physics, geology, biology, cryogenics



<https://lsc-canfranc.es/en/photo-gallery-of-the-facilities/#>



Underground neutrons

Spectral resolution

(as far as I know!)

(the quality of the energy resolutions varies, at LNGS, for example, very poor, 1989 measurement)!

Laboratory (country)	Overburden m.w.e	Neutron flux ($10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$)		
		Thermal	Fast	Total
WIPP (USA) [5]	1585	<0.06	-	-
Yang Yang (Korea) [10]	2000	24.2±2.2	0.8	-
Soudan (USA) [5]	2090	0.70±0.11	-	-
LSC (Spain) [11, 12]	2400	-	-	13.8±1.4
[13]		-	-	16.2±0.2
Kamioka (Japan) [14]	2700	7.88	3.88	23.5±2.2
BUL (UK) [15]	2800	1.72±0.69	-	-
LNGS (Italy) [16]	3600	1.08±0.2	2.94±0.03	-
[5]		0.32±0.10	-	-
Pyhäsalmi (Finland) [17]	4100	-	-	17.3±0.1
SURF (USA) ¹ [5]	4300	9.9±1.1	-	-
		8.1±0.9	-	-
		1.7±0.2	-	-
BNO (Russia) [18]	4600	-	0.65±0.21	-
LSM (France) [19]	4800	1.6±0.1	4±1	-
SNOLAB (Canada) [20]	6010	0.047	0.046	-
CJPL (China) [21]	6720	7.03±1.81	3.63±2.77	26.9±10.2

Table 1.1: Underground laboratories in the world and neutron fluxes measured before the contributions of this work. ¹: measurements in different locations.

List of authors

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D. Bemmerer, M. Grieger

TRIUMF

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T. Pardo, M.L. Sarsa

CIEMAT

D. Cano-Ott, T. Martínez, J. Plaza

LNGS

M. Laubenstein, C. Giano, R. Cerrono

The High Efficiency Neutron Spectrometry Array

HENSA is a high efficiency neutron detection system based on the same principles than Bonner Spheres.

- Original idea by J.L. Tain (IFIC) in 2010: high efficiency spectrometer with digital acquisition system for CUNA project (Canfranc Underground Nuclear Astrophysics).
- HENSA is achieved by a topological change in Bonner Spheres in order to benefit from high detection efficiency in cylindrical proportional neutron counters.
- HENSA project is a scientific collaboration for the exploitation of the spectrometer. Focus on measurements in *underground laboratories* and *secondary neutrons produced by cosmic-rays*.

www.hensaproject.org

The High Efficiency Neutron Spectrometry Array



HENSA experimental setup

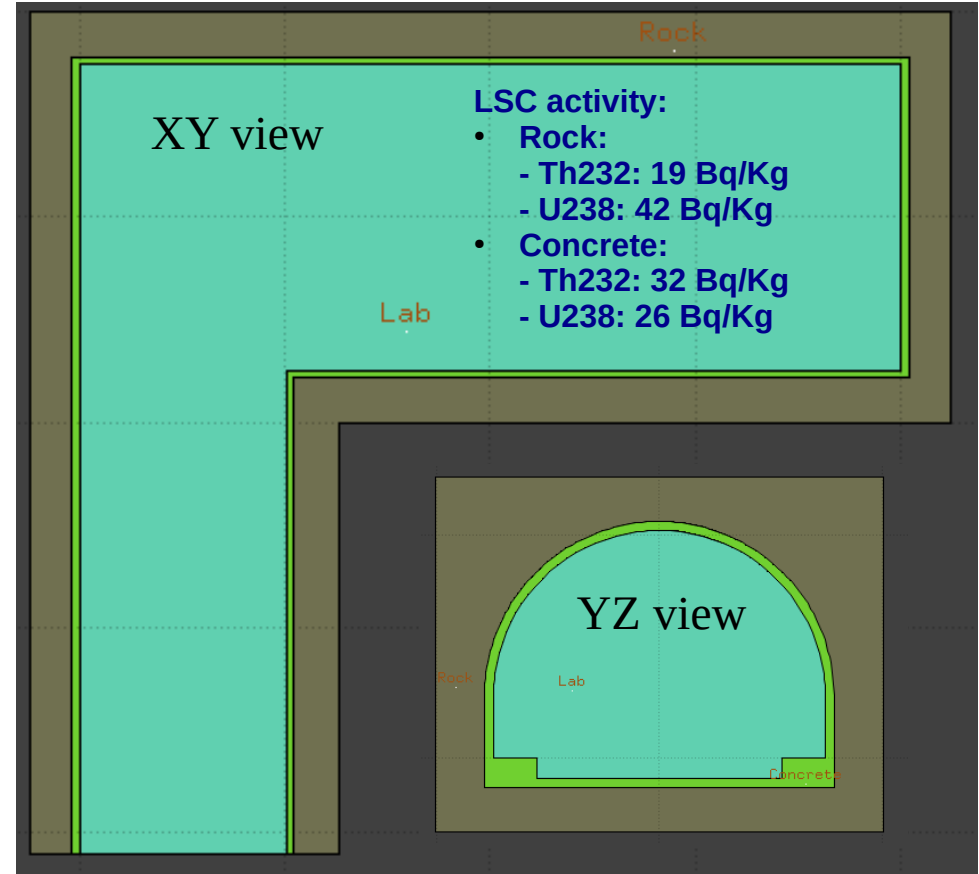
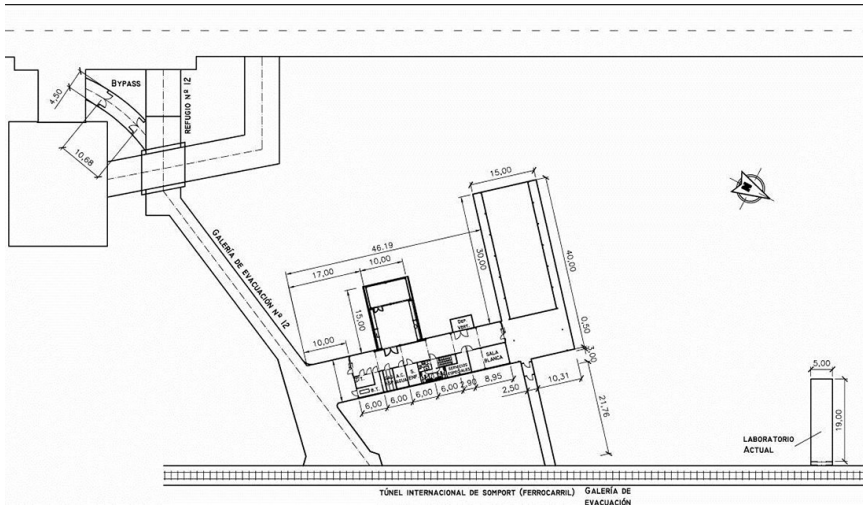
High Efficiency Neutron Spectrometry Array

- Ten neutron detectors.
 - **60 cm active length cylindrical** ^3He -filled neutron proportional counters manufactured by LND (in general, 10 atm gas pressure).
 - Moderators (HDPE, Cd, Pb) with different sizes in order to provide sensitivity in different regions of the neutron flux spectrum (**non-spherical geometries**).
- Electronics:
 - Preamplifiers (CAEN, Canberra, Fast).
 - High Voltage supply (CAEN).
- Data acquisition using a SIS3316 struck digitizer + Gasific software (list mode)

Monte Carlo simulations of the neutron flux

The Canfranc Underground laboratory (**hall A**).

- 15 x 40 m² ground plan.
- ~ 13 m roof altitude.
- Between the rock and the laboratory halls there is a ~40 cm thickness lay of concrete (**concrete walls**).



Monte Carlo simulations of the neutron flux

Three neutron sources are considered

- Muon-induced neutrons.
 - Muon transport, neutron production and neutron transport calculated using FLUKA.
- (α ,n) reactions.
 - Neutron transport calculated using FLUKA, neutron production calculated using specialized codes.
- Spontaneous fission (SF).
 - Neutrons transport using FLUKA, neutron production from experimental measurements.

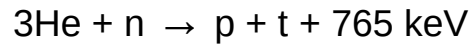
For the (α ,n) reactions and the SF calculations are carried out separately for the neutron production in the mountain rock and in the concrete walls of the laboratory.

Humidity effects not considered.

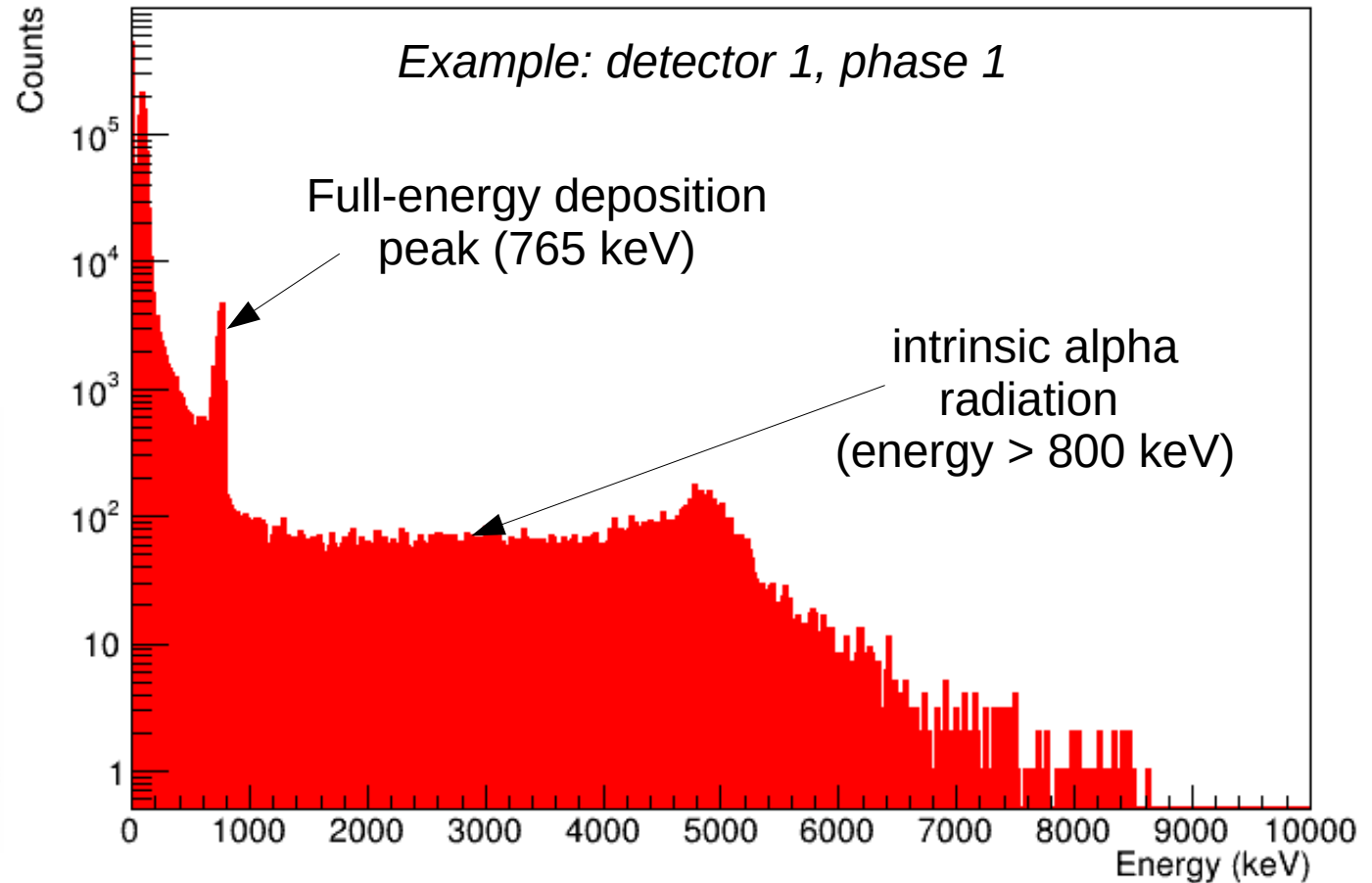
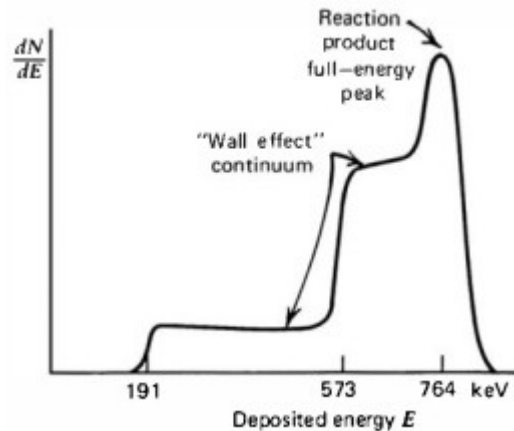
Based in the work by M. Grieger (HZDR) at Felsenkeller:
M. Grieger et al 2020, Phys. Rev. D 101, 123027

^3He counter energy deposition spectrum (event amplitude)

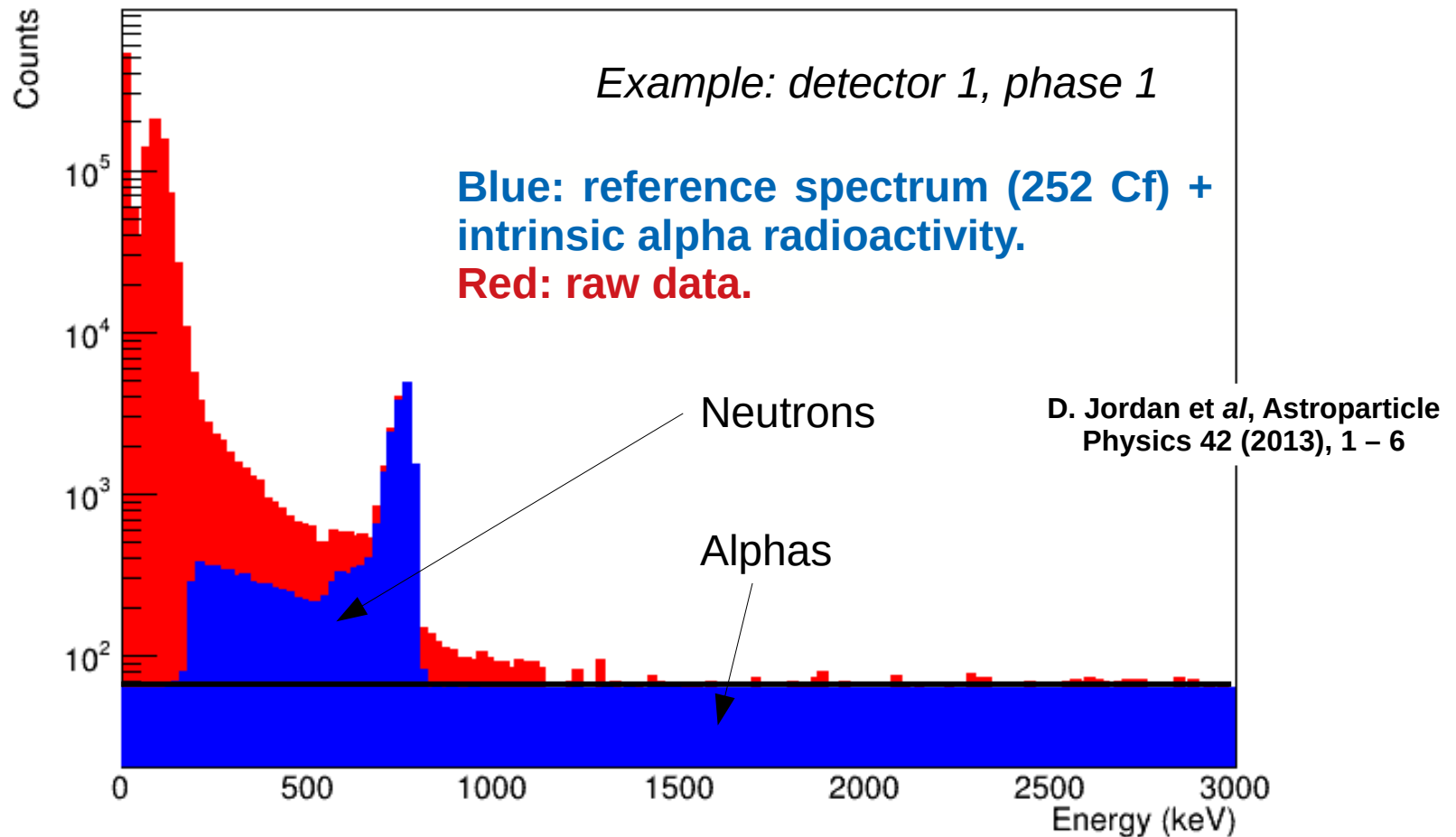
Raw data



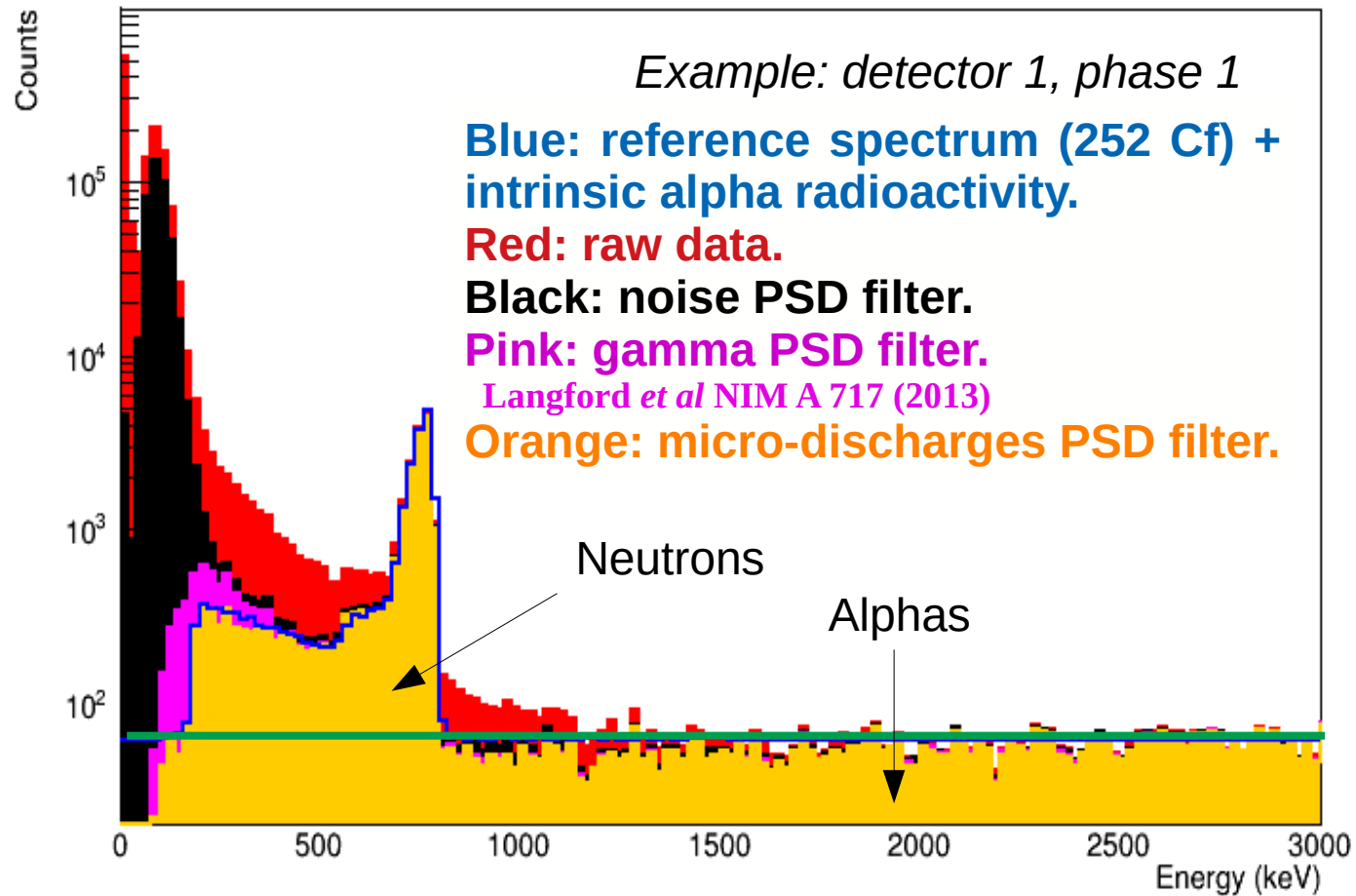
Theoretical amplitude spectrum
(G. Knoll, 2010 edition)



Neutron contribution: reference spectrum method



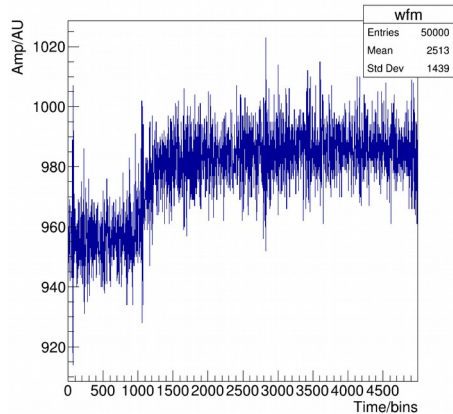
Neutron contribution: PSD



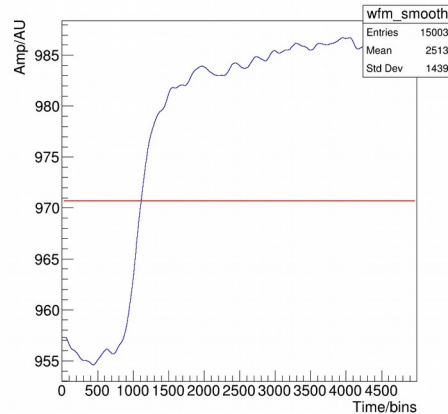
PSD: noise “filter”

A filter based on the oscillatory shape of the noise signals.

Accepted

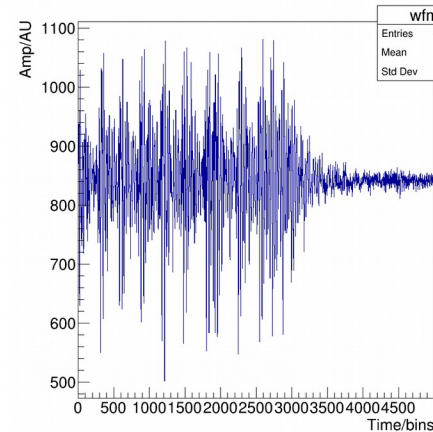


Raw

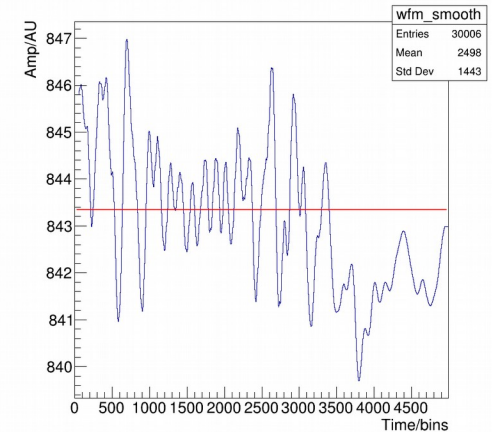


Smoothed

Rejected



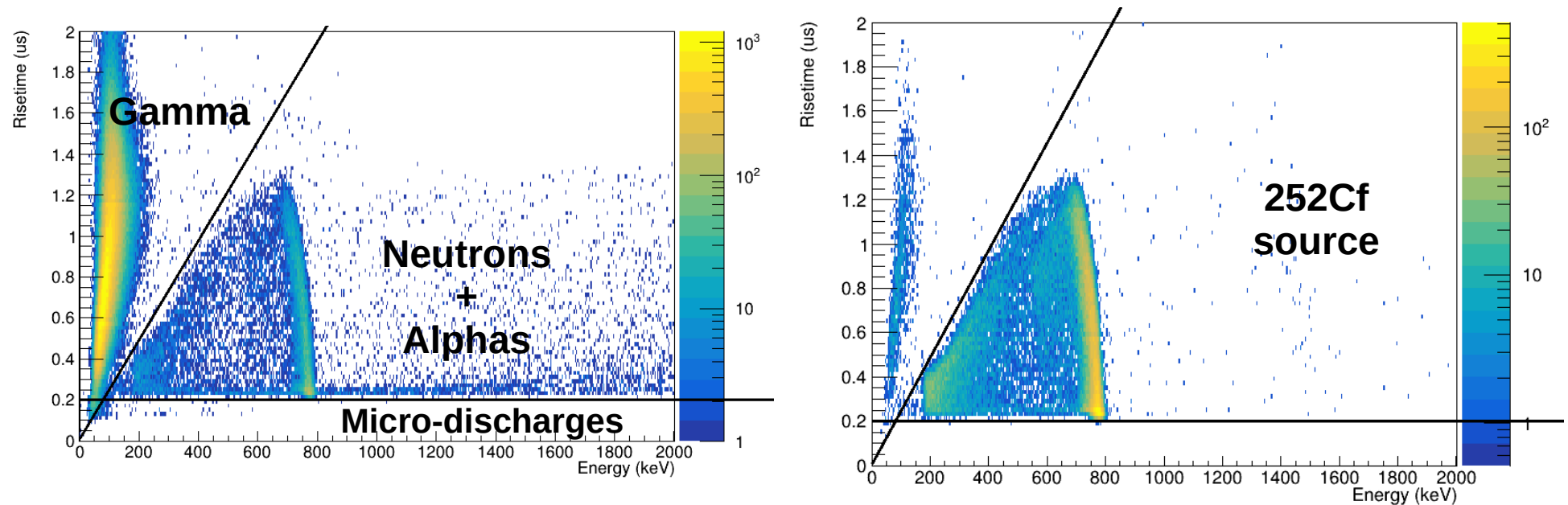
Raw



Smoothed

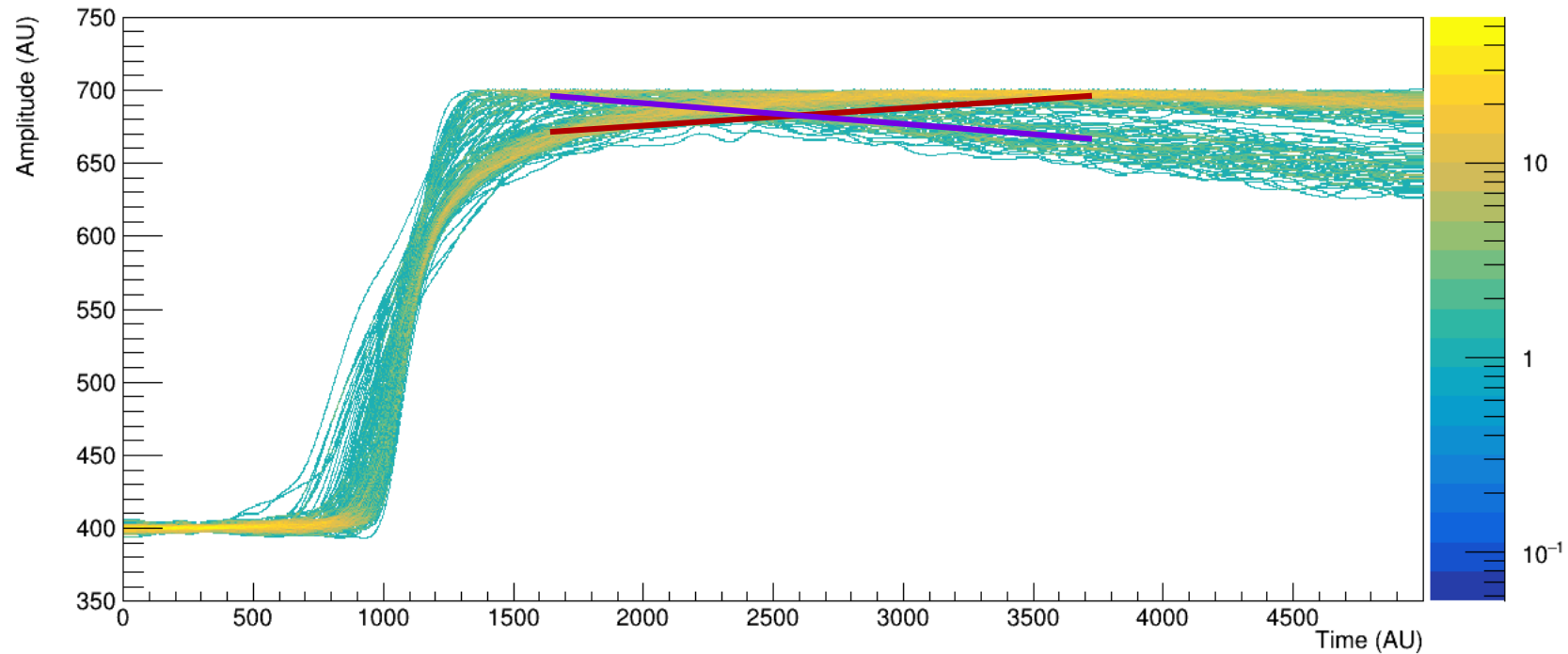
PSD: gamma-neutron discrimination

A filter based on the the risetime differences: Langford *et al* NIM A 717 (2013)



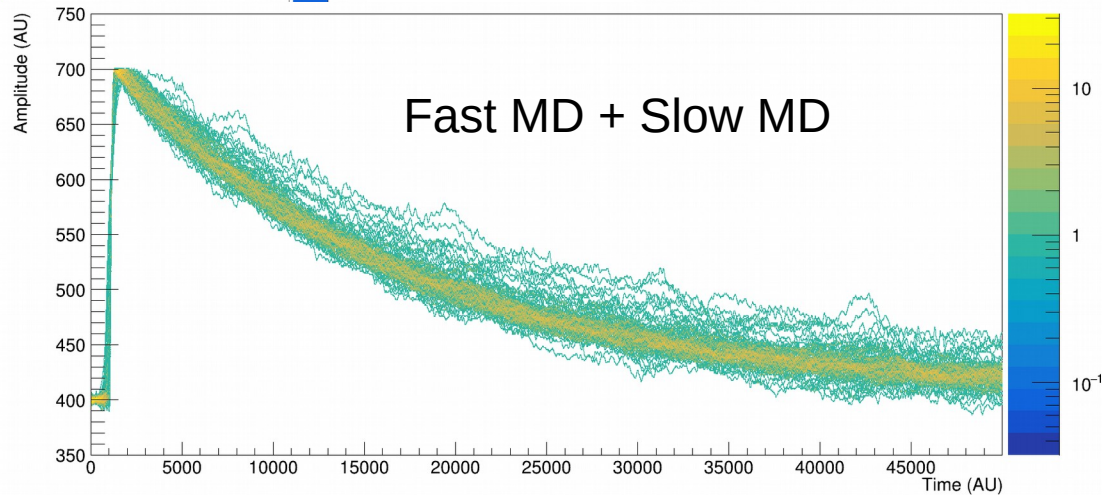
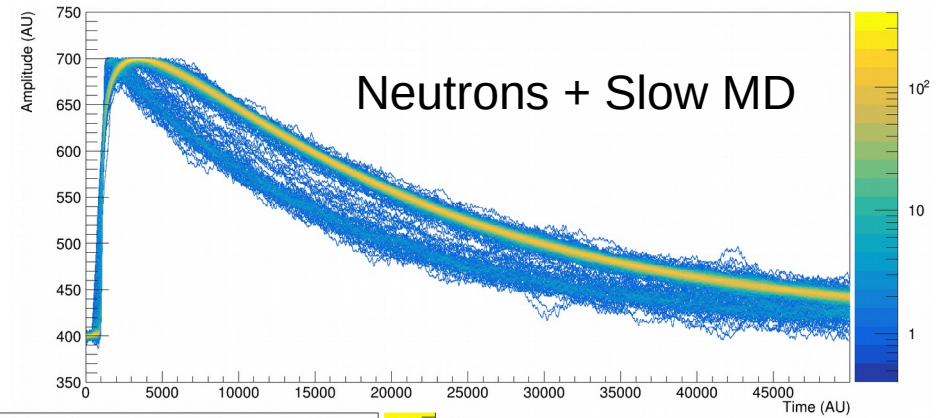
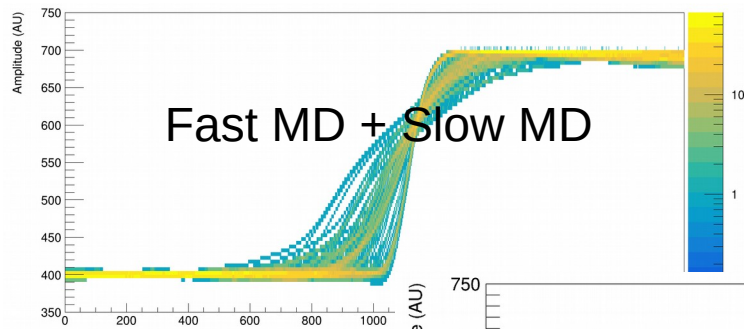
PSD: slow micro-discharges “filter”

A filter based on the decay shape.



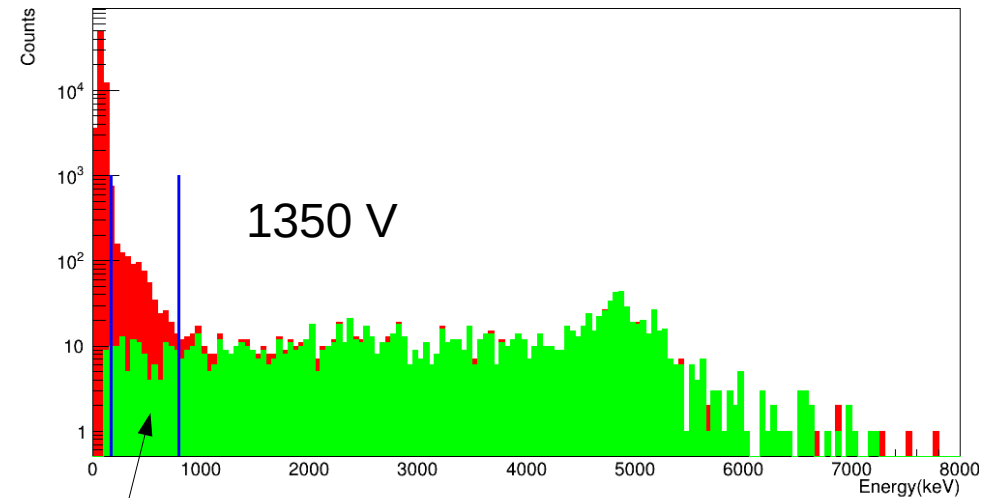
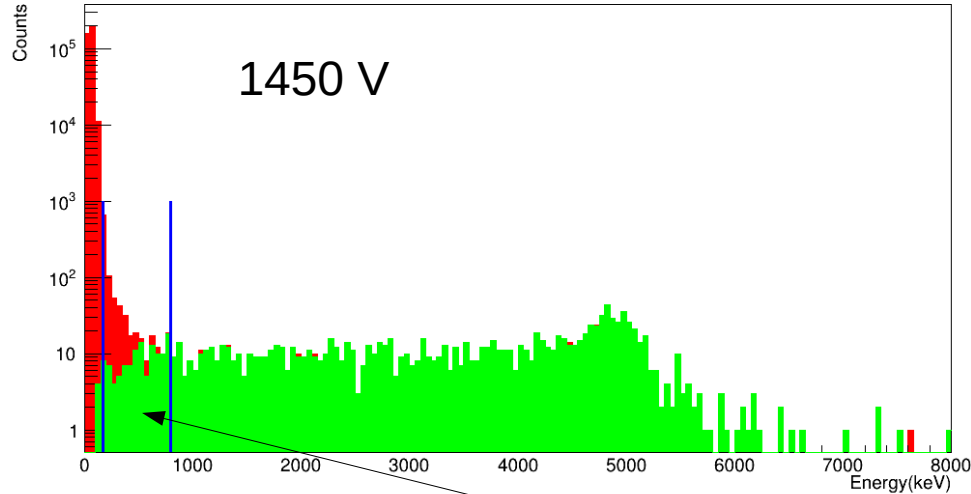
PSD: slow and fast micro-discharges

Different risetime, same decay



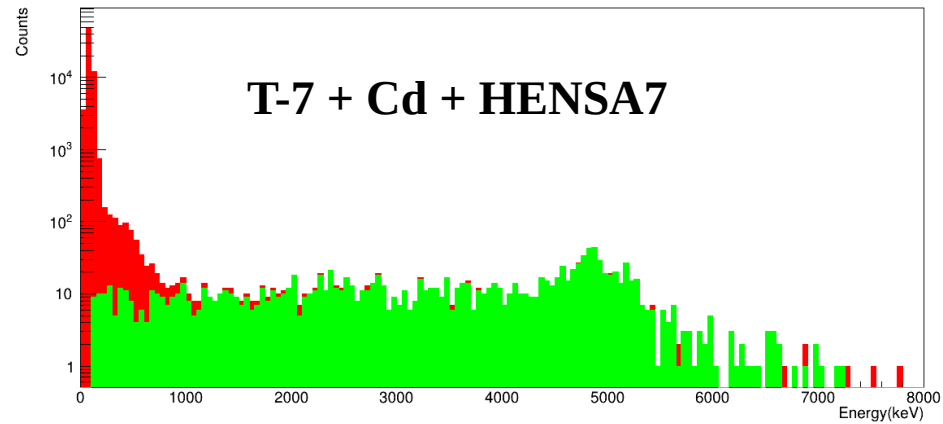
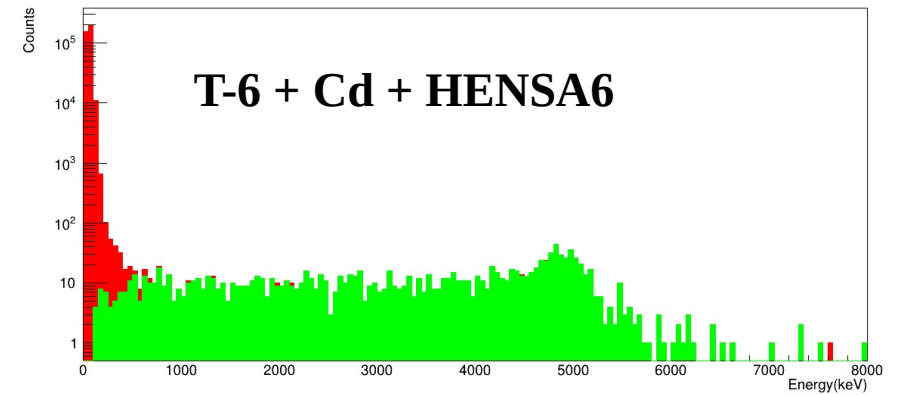
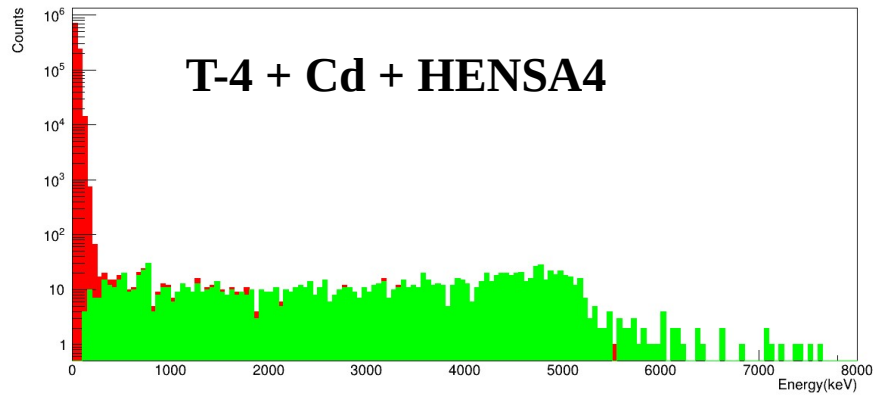
Validation of the alpha background hypothesis

Setup: thermal neutrons counter (T) + Cd (thermal shielding) + HDPE

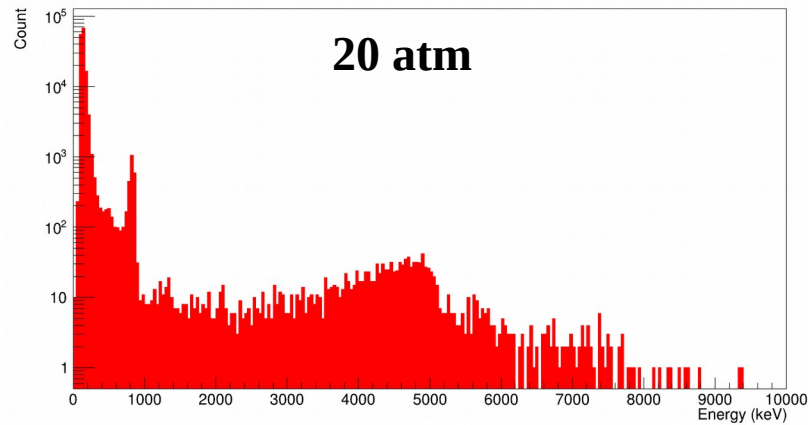
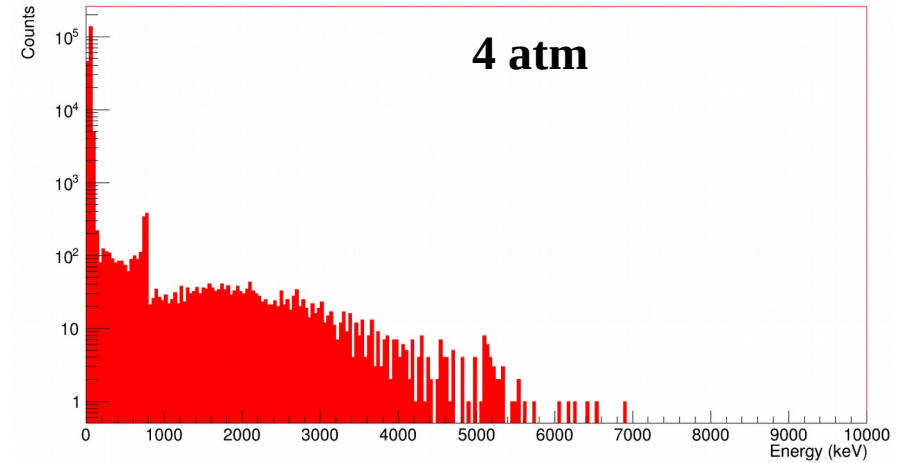
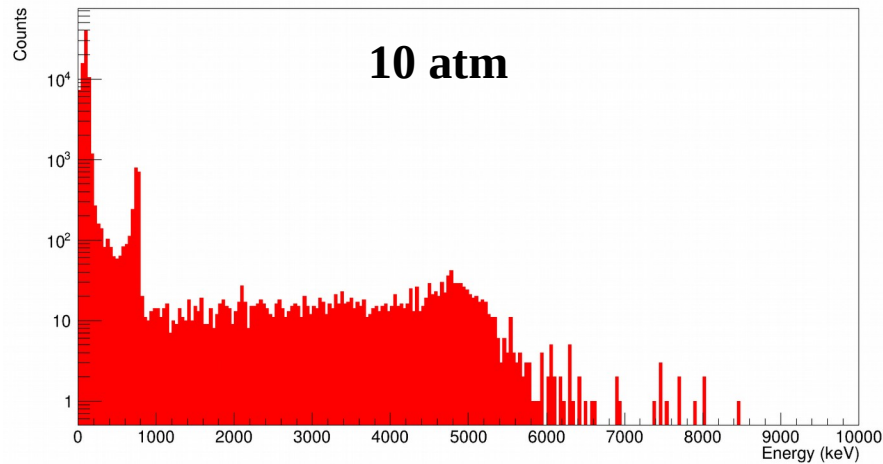


Neutron window (170 – 800 keV)

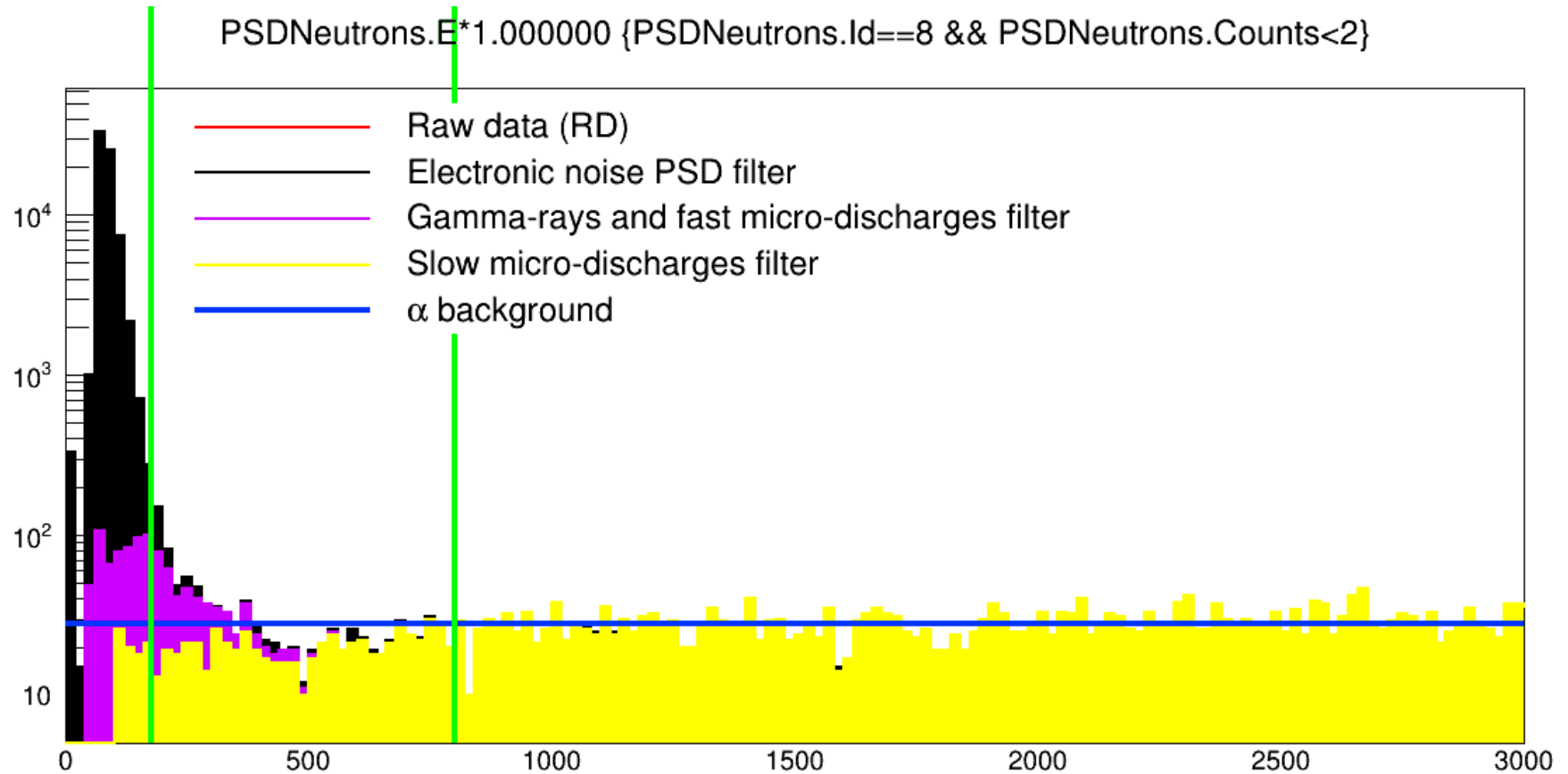
Alpha background

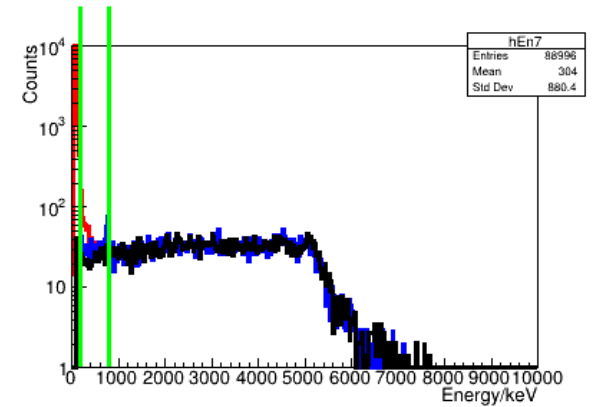
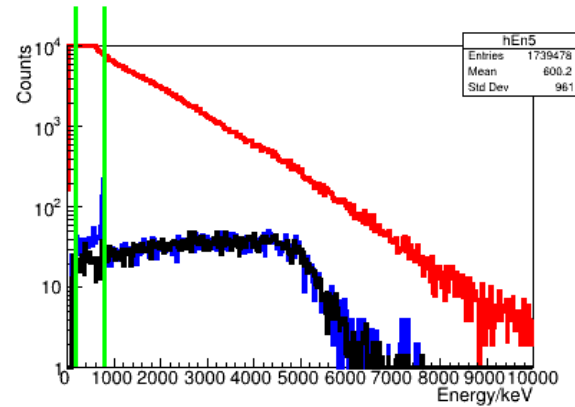
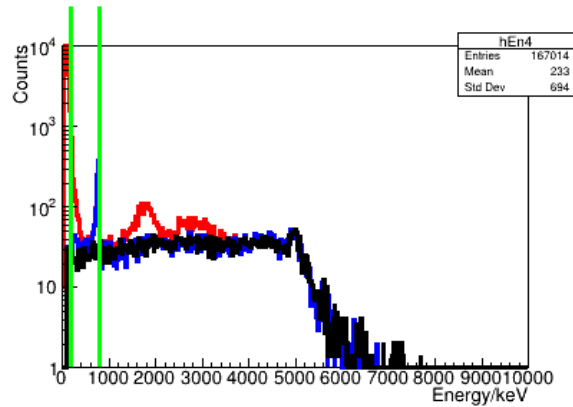
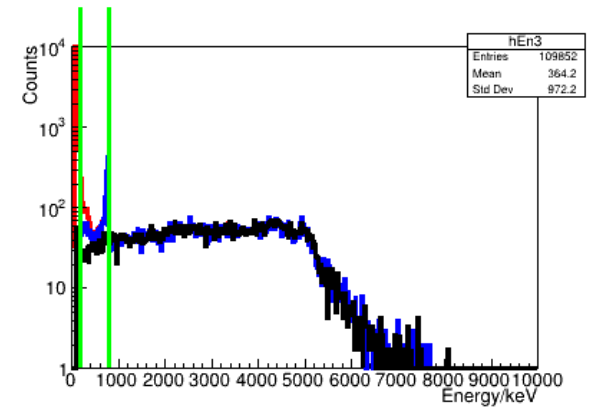
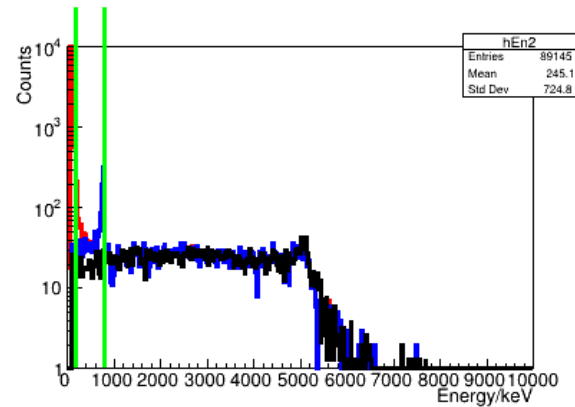
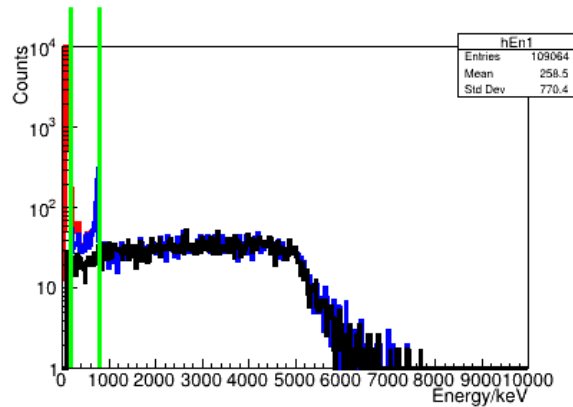


Alpha background

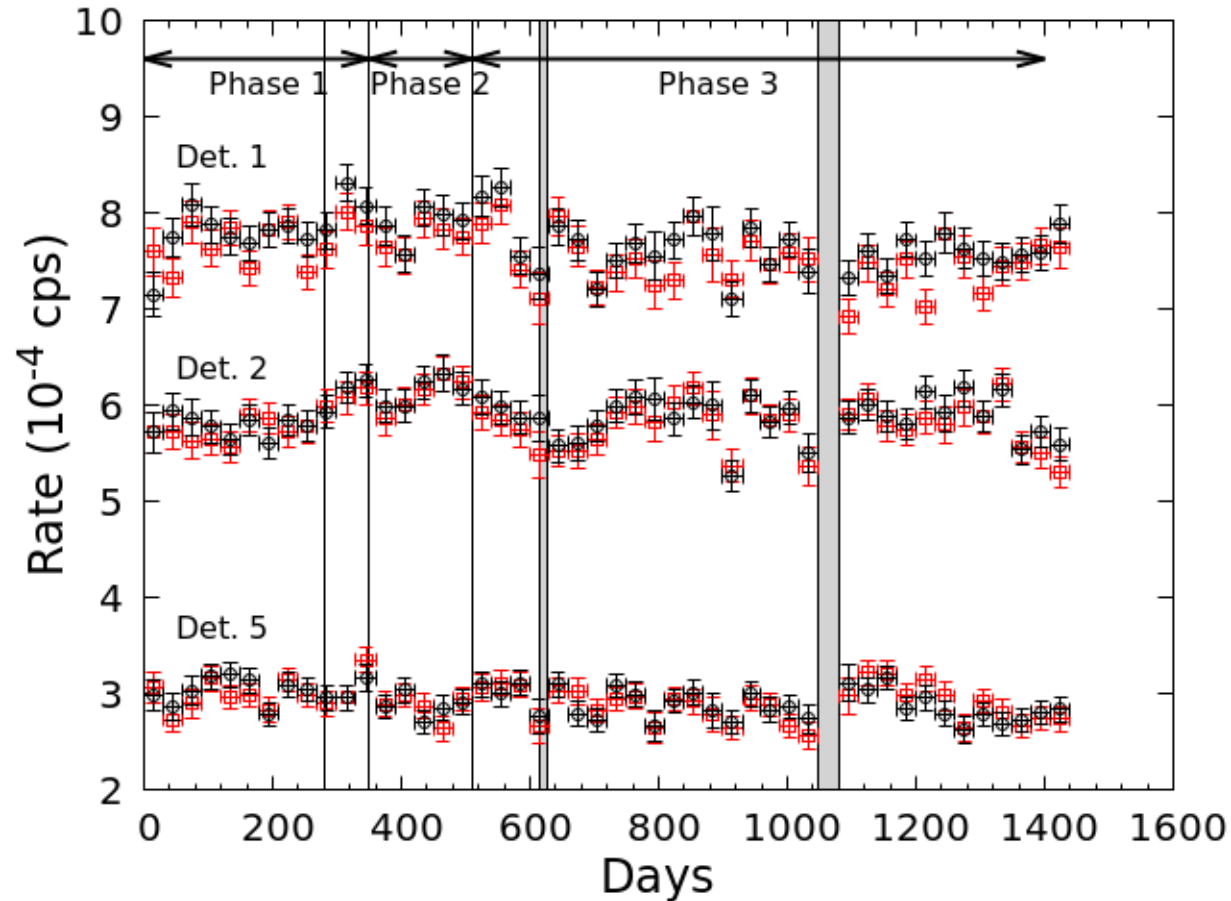


Alpha background





Neutron counting rates



The POU method

- Developed by the HENSA collaboration, specially A. Quero (UGR), A. Lallena (UGR), M. Pallàs (UPC), J.L. Tain (IFIC) and A. Tarifeño-Saldivia (IFIC).
- Based on BAYES.
- Parametric spectrum to define multiple ($10^3 - 10^4$) priors.
- All intermediate solutions that are accepted (that is, are with consistent with the measured rates) are used to construct the definitive solution.
- Result: for each bin content we have a distribution of fluence that is used to extract the median value (solution bin content). The uncertainties are treated as confidence intervals.
- **Allows to quantify the systematics due to the use of a priori information.**

A. Quero, PhD
thesis, UGR,
expected 2026