XIX TAUP CONFERENCE

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

Nil Mont-Geli

Institut de Tècniques Energètiques
Universitat Politècnica de Catalunya
nil.mont@upc.edu

Ariel Tarifeño-Saldivia

Instituto de Física Corpuscular
C.S.I.C – Universidad de Valencia
atarisal@ific.uv.es

HENSA
High Efficiency Neutron Spectrometry Array

UPC
UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Institut de Tècniques Energètiques

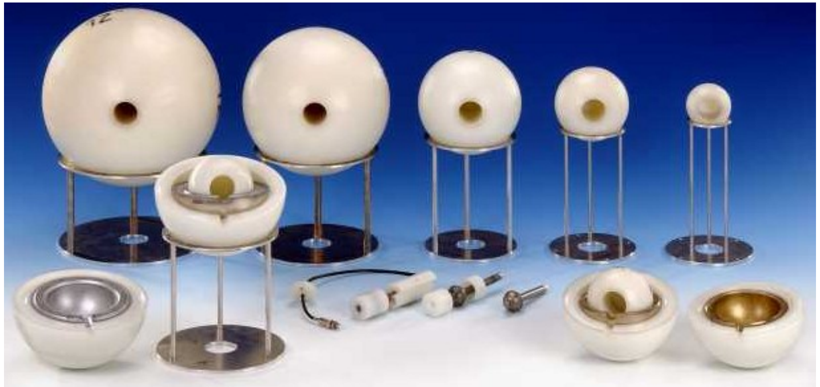
IFIC
INSTITUT DE FÍSICA CORPUSCULAR

Objectives

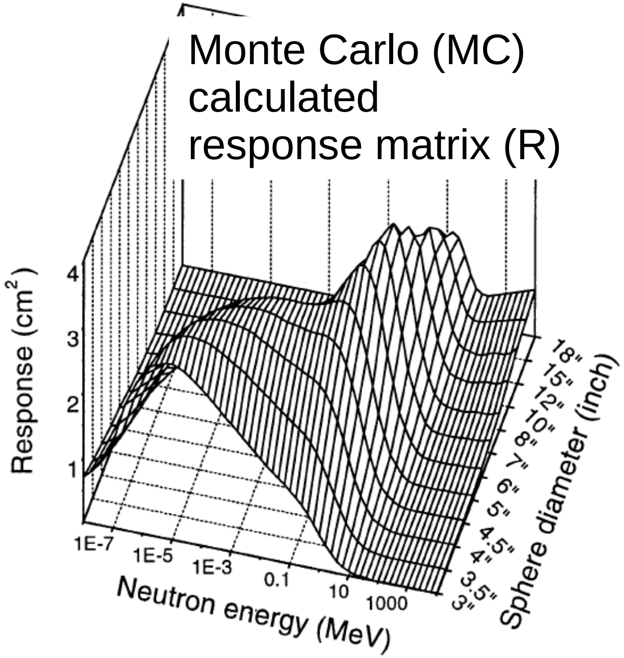
- Characterization of the temporal evolution of the neutron flux.
- Characterization of neutron flux energy spectrum.
- Understand the neutron sources.

The High Efficiency Neutron Spectrometry Array

Bonner Spheres neutron spectrometry



Array of moderated neutron proportional counters



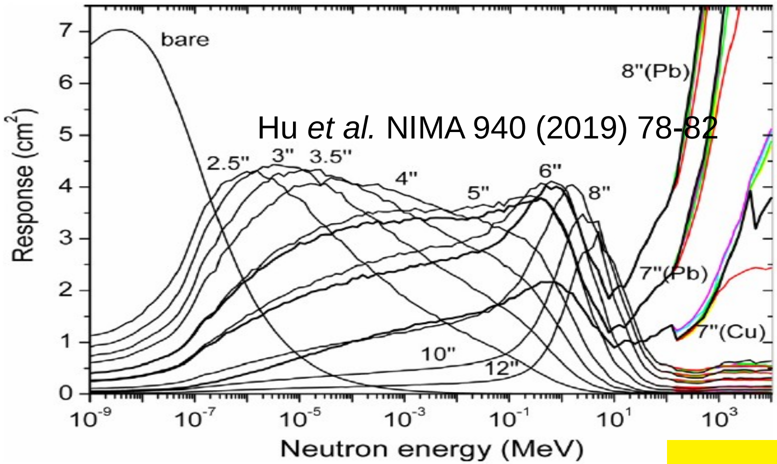
$$M_i = \int R_i(E)\phi(E)\,\mathrm{d}E. \quad \Rightarrow \quad M_i = \sum_{j=1}^{n} R_{ij}\phi_j$$

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

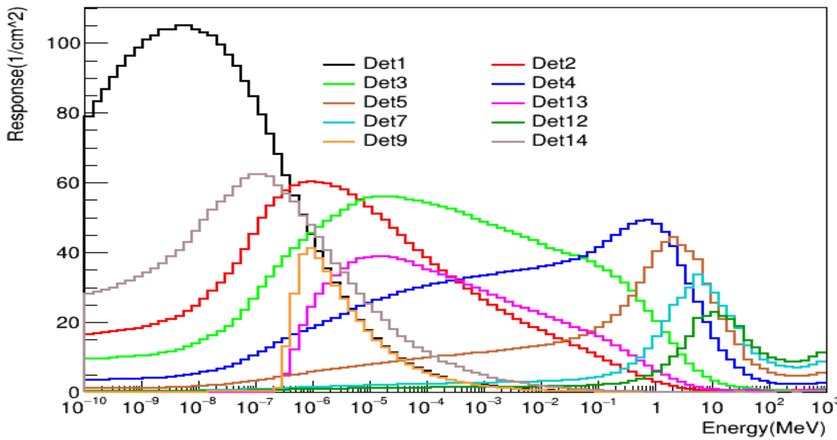
Unfolding typically relies on some preliminary knowledge about the spectrum (prior spectrum)

The High Efficiency Neutron Spectrometry Array

Standard extended Bonner Spheres



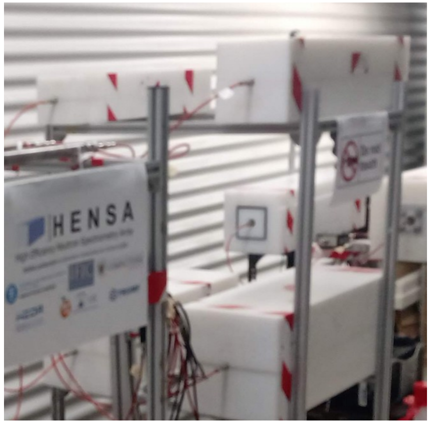
HENSA version 2022



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 <u>moderators</u> (HDPE) with the shape of a rectangular prisms.



The HENSA project

- HENSA at the Canfranc Underground Laboratory (LSC)
- HENSA for cosmic rays (CR) applications (HENSA++)
- HENSA at the Gran Sasso National Laboratory (LNGS)

The HENSA project

- Short-term measurement at LSC (empty hall A):
  D. Jordan et *al* 2013, Astroparticle Physics 42, 1 – 6
  Corrigendum: **D. Jordan et *al* 2020, Astroparticle Physics 118, 102372**

- Measurement at Felsenkeller:
  M. Grieger et *al* 2020, Phys. Rev. D 101, 123027

- Long-term campaign in hall A of the LSC (October 2019 – March 2021):
  S. Orrigo et *al* 2022, European Physics Journal C 82, 814

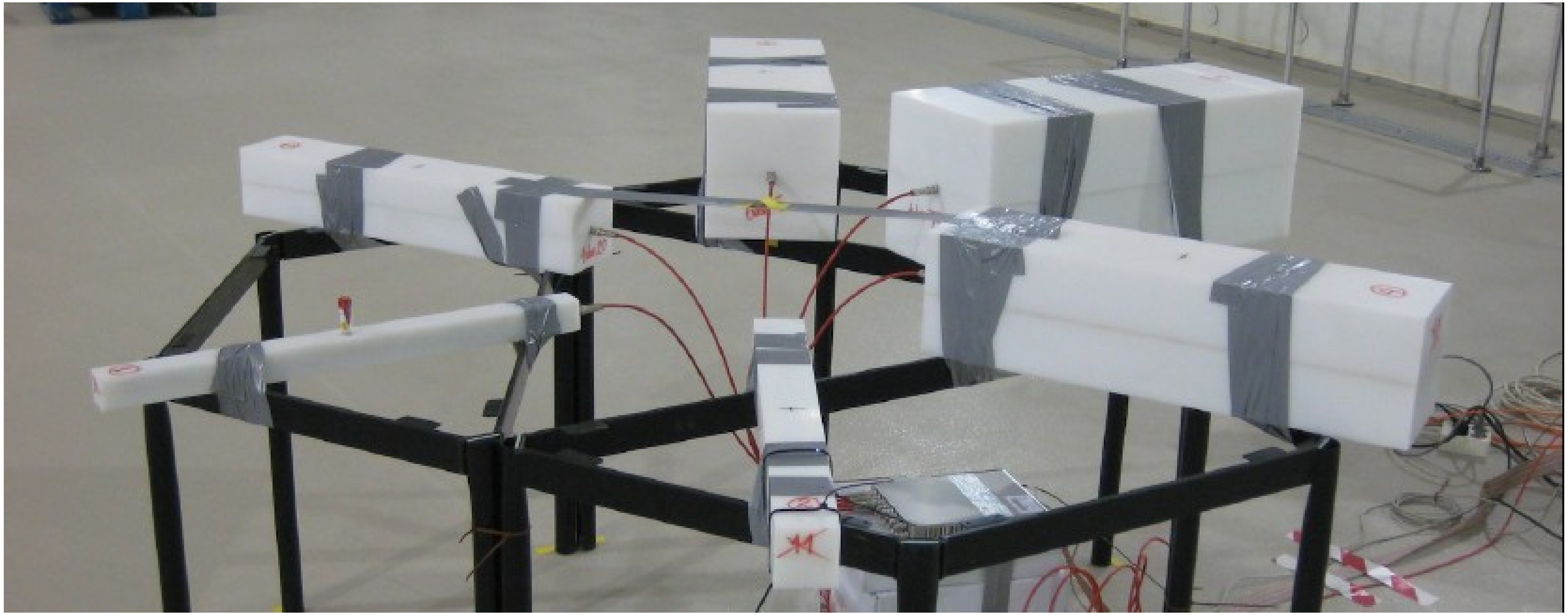
- Cosmic rays campaign (July - August and October 2020).

- Long-term campaign in hall B of the LSC (since March 2021): **THIS TALK**
  N. Mont-Geli et *al* 2021, Journal of Physics: Conference Series 2156, 012223
  N. Mont-Geli et *al* 2023, Proceedings of Science 441, 136672
  Ph. D. Thesis byN. Mont-Geli (expected: Oct/Nov 2025)

- Continuous monitoring with a reduced setup (4 detectors) in hall A:
  Ph. D. Thesis by J. Plaza (CIEMAT)

The HENSA project

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



The HENSA project

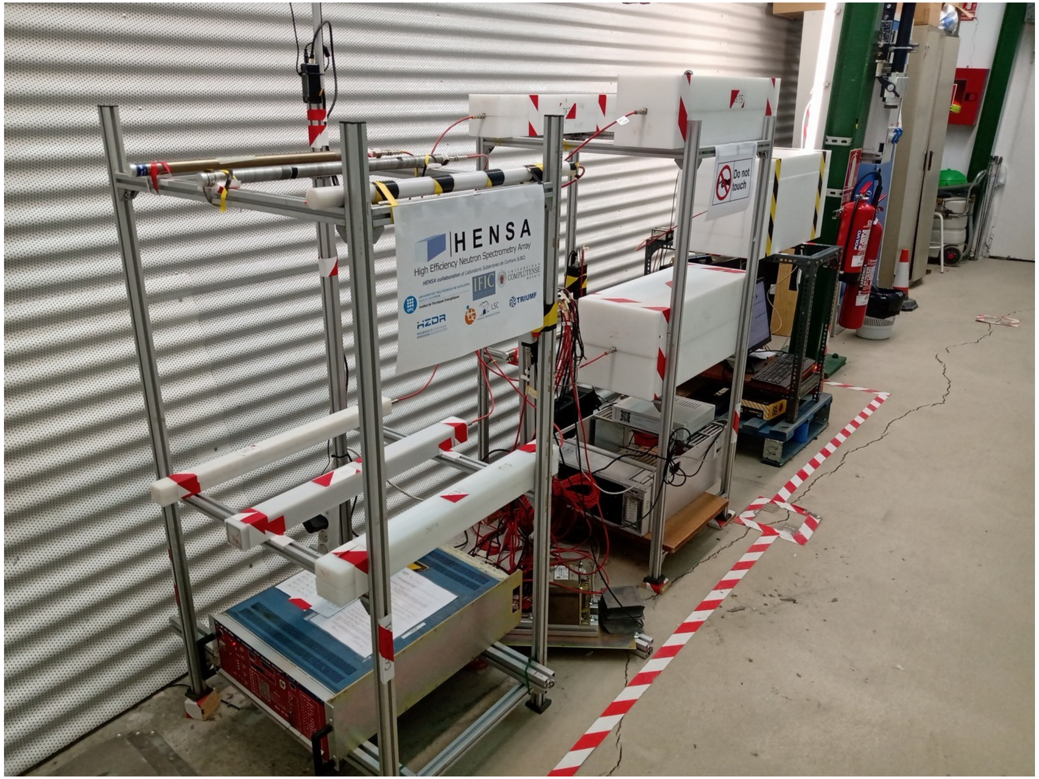
HENSA at Felsenkeller (M. Grieger et *al* 2020, Phys. Rev. D 101, 123027)

The HENSA project

HENSA at LSC-hall A (2019 - 2021)

The HENSA project

HENSA at LSC-hallB (2021 - 2025)



The HENSA project

HENSA at LNGS (2024 - 2025)

Simulations of the neutron flux

Neutron flux in underground laboratories

muons	neutrons	gammas

Cosmic source:

High energetic protons interact with atmosphere

↓

pions

↓

pion decay into muons

↓

Muon induced neutron production via electromagnetic or hadronic shower (γ, n)-reactions, spallation processes

Terrestrial source:

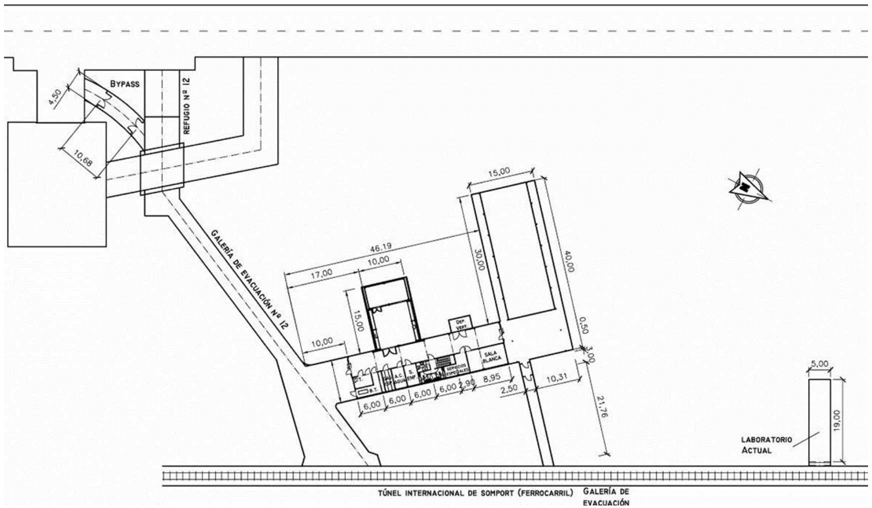
- (α, n) reactions:
  - Natural α emitters in rock (^{238}U, ^{235}U, ^{232}Th & daughter nuclei)
  - Reaction with light elements:
    $^{A}_{Z}X + \alpha \rightarrow {}^{A+3}_{Z+2}Y + n$
- Spontaneous fission:
  - U and Th: also SF possible
  - Only $5 \cdot 10^{-5}$ % (^{238}U) of all decays

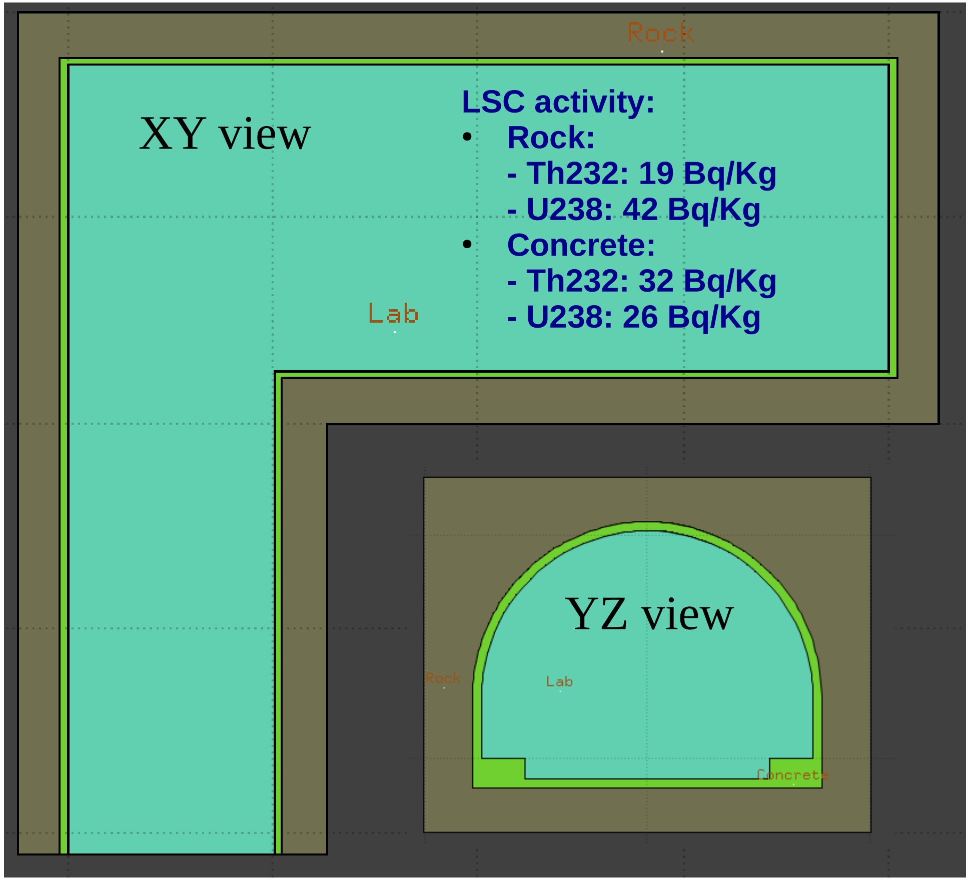
Monte Carlo simulations of the neutron flux

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

- 15 x 40 m^2 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

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

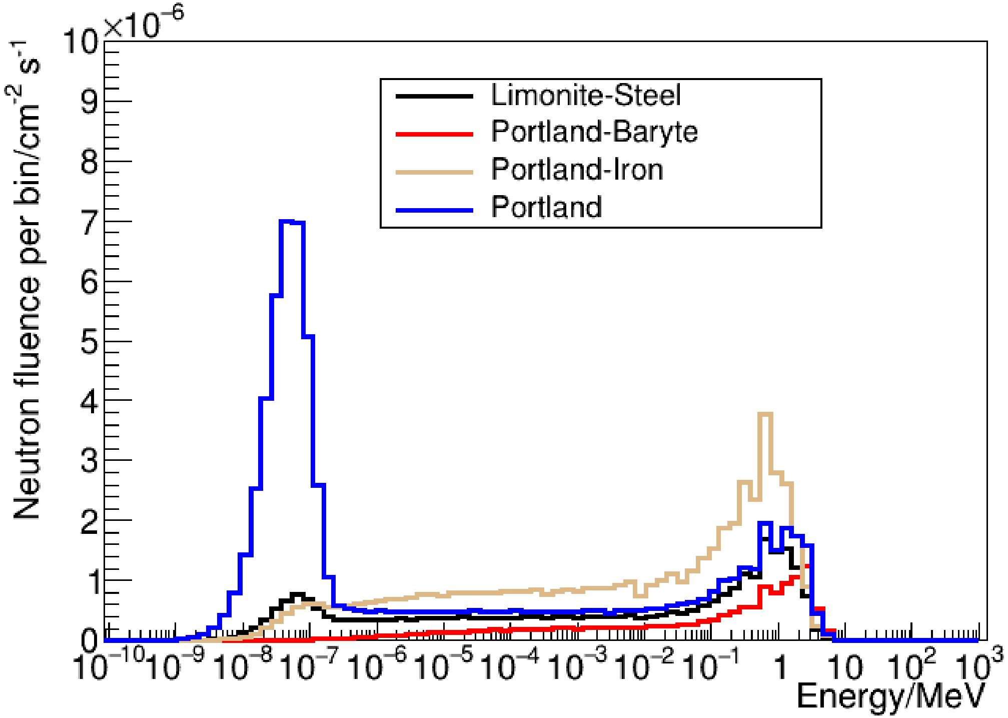
- (α,n) reactions.
- Spontaneous fission.

- Thermal peak ~ 4.5 – 6.5 · 10^{-8} MeV
- Isolethargic intermediate region
- Fast peak ~ 0.5 – 3 MeV (1 MeV P and LS)

<u>Spectra to be used as priors in the unfolding algorithms.</u>

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)

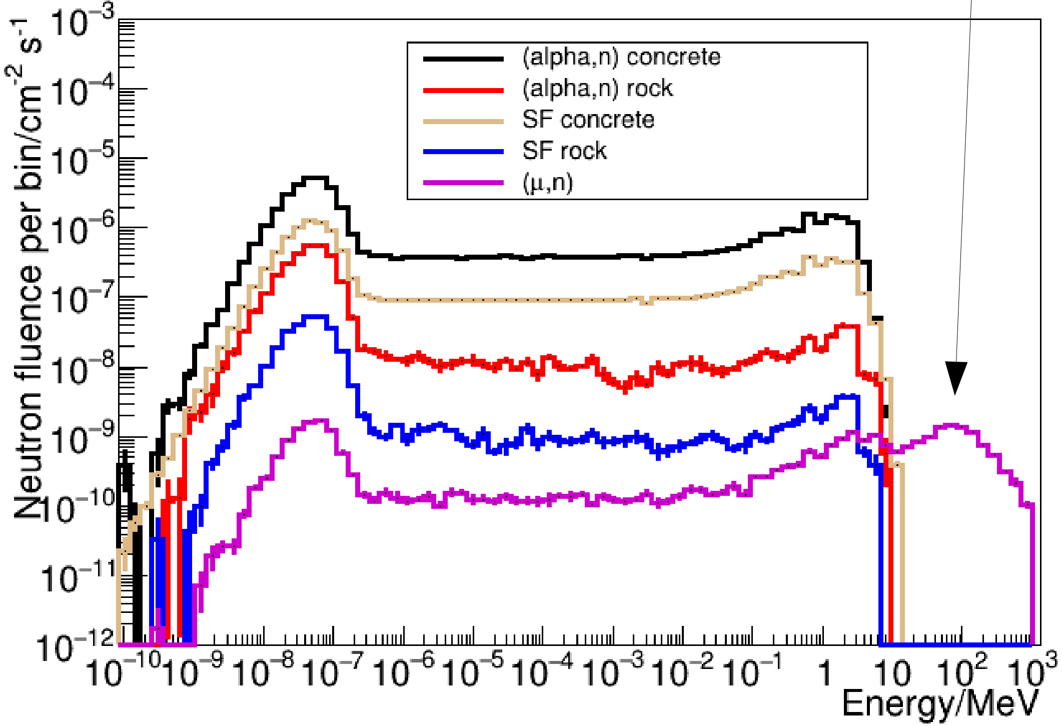
- (α,n) reactions.
- Spontaneous fission.
- **Muon-induced neutrons**

- Thermal peak ~ 4.5 – 6.5 · 10^{-8} MeV
- Isolethargic intermediate region
- Fast peak ~ 0.5 – 3 MeV (1 MeV P and LS)
- HE peak ~ 50 MeV

- **Muons contribution*: 0.03%.**
  **Preliminary estimation*

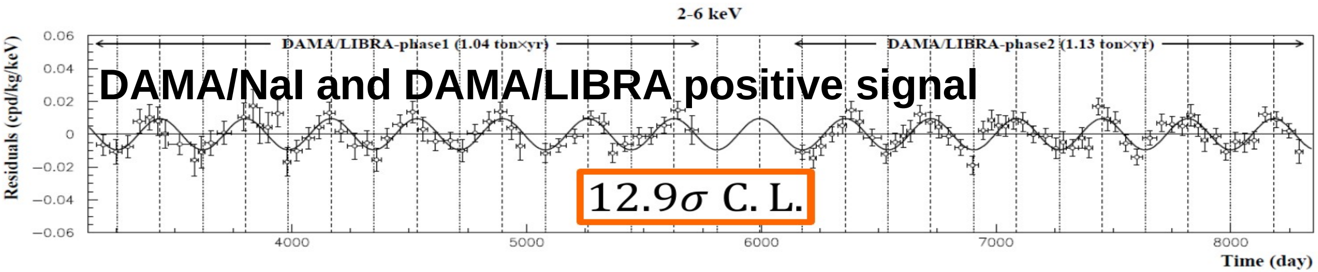
Based in the work by M. Grieger at Felsenkeller:
M. Grieger et al 2020, Phys. Rev. D 101, 123027

not feasible with HENSA



HENSA in hall B of the LSC

Physical case (ANAIS - 112)



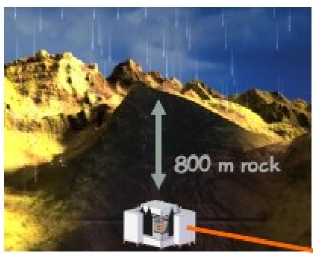
See talks by M Martinez (ANAIS) on:

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

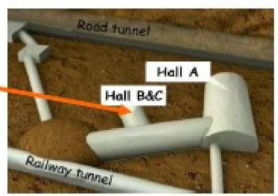
Goal

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)

Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza



LSC
Laboratorio Subterráneo de Canfranc



Experimental goals

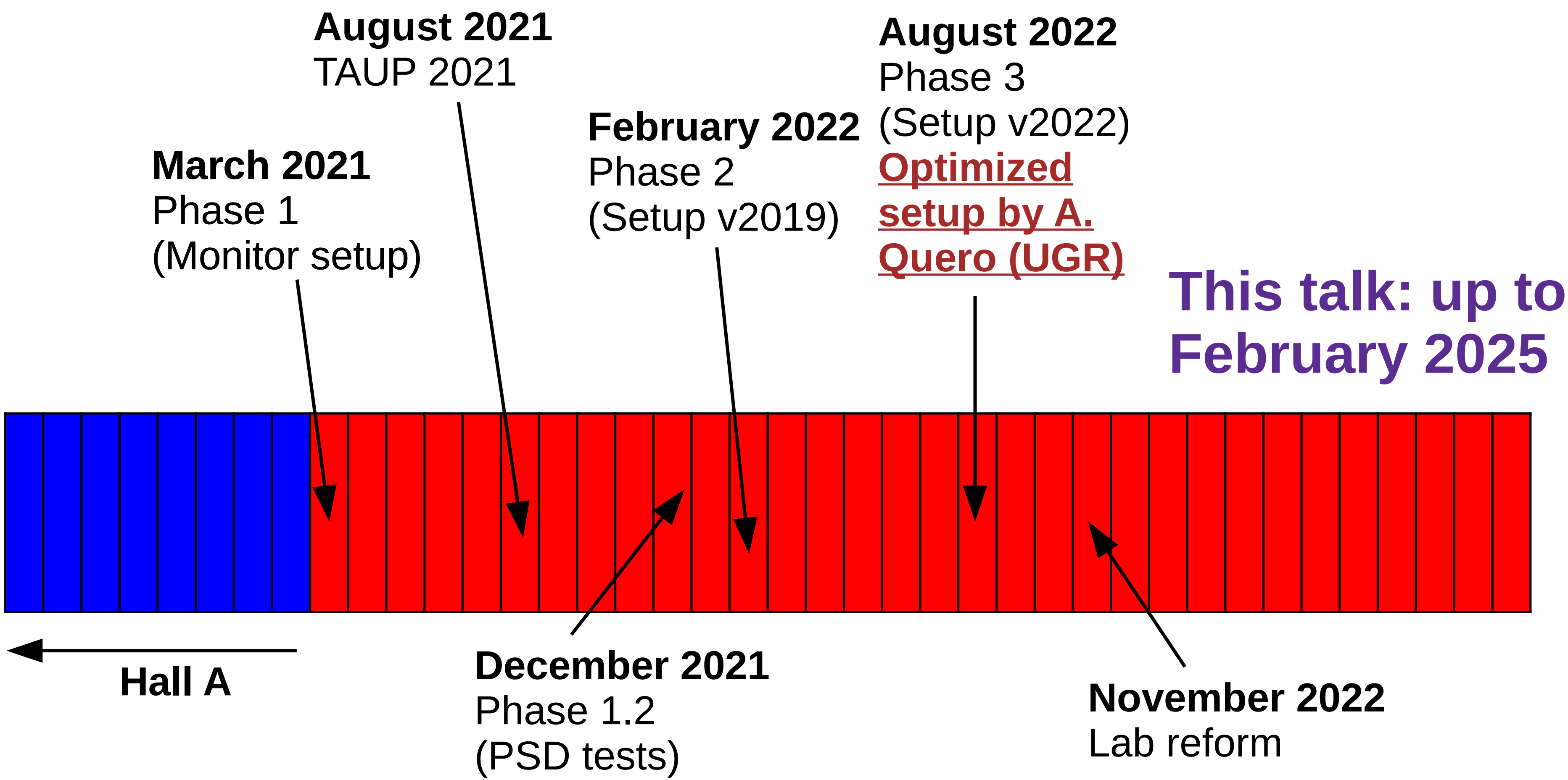
- Energy **threshold** at 1 keV_{ee}
- **Background** level below 10 keV_{ee} at a few $cpd/kg/keV_{ee}$
- Very **stable** operation conditions

Courtesy ANAIS team

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.

Experimental campaign in hall B



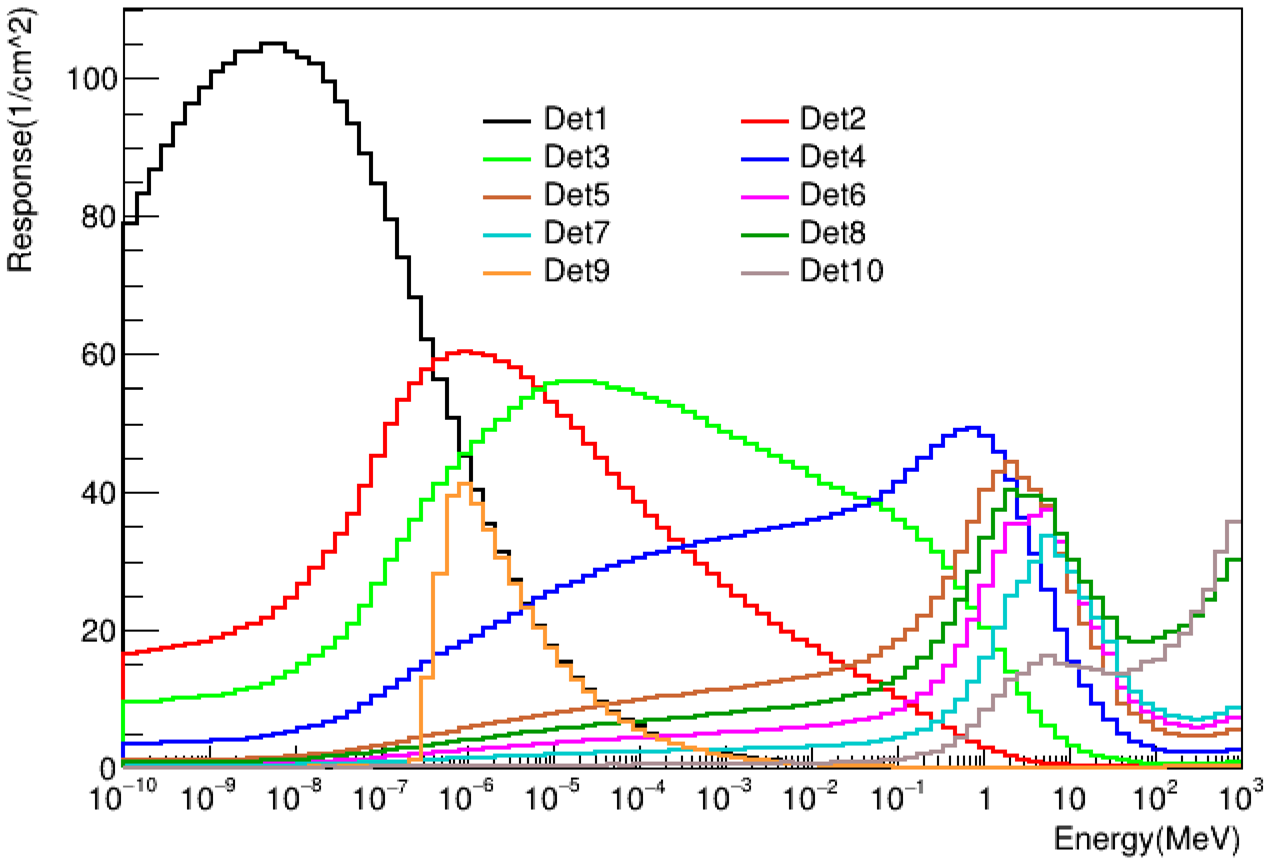
Response matrix (v 2019)

Version 2019

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

No cross-talk.

https://www.particlecounter.net

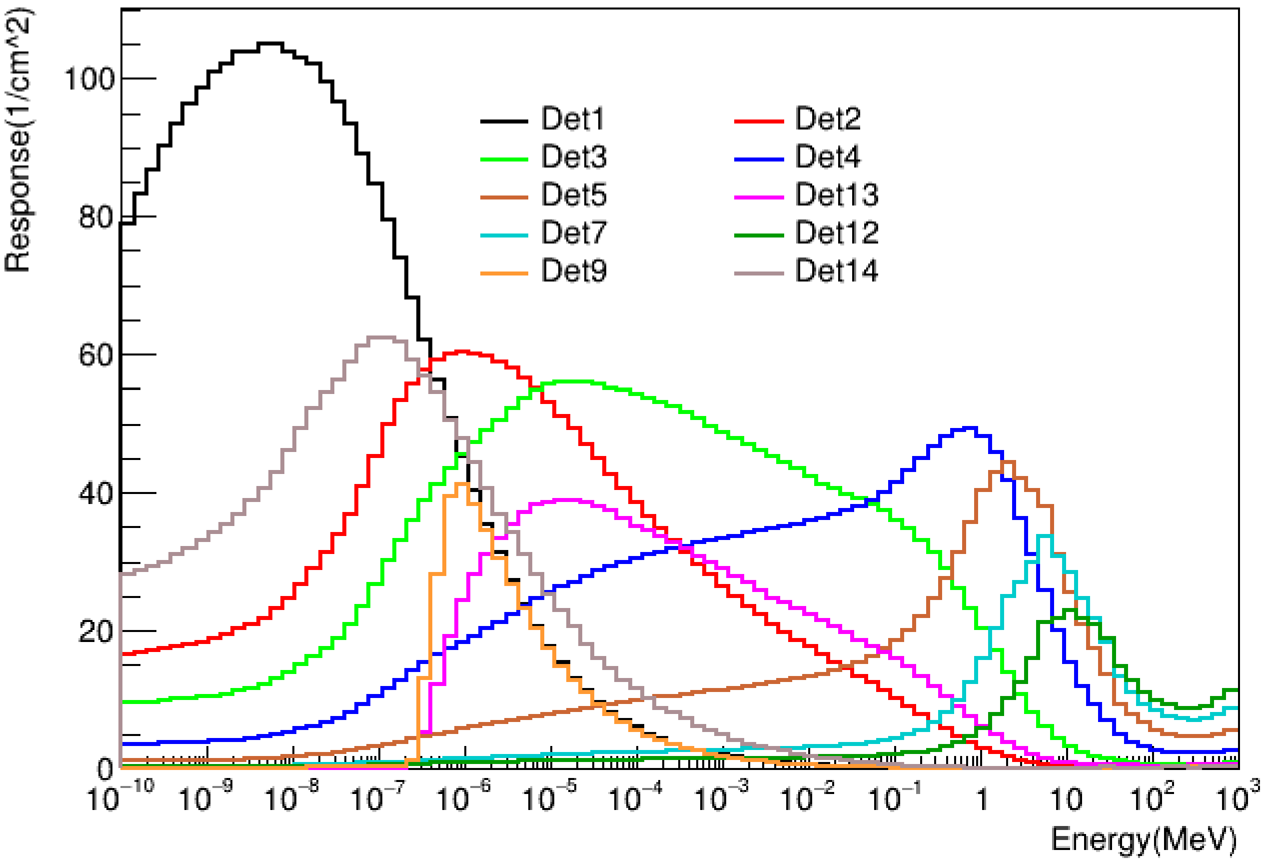


Response matrix (v 2022)

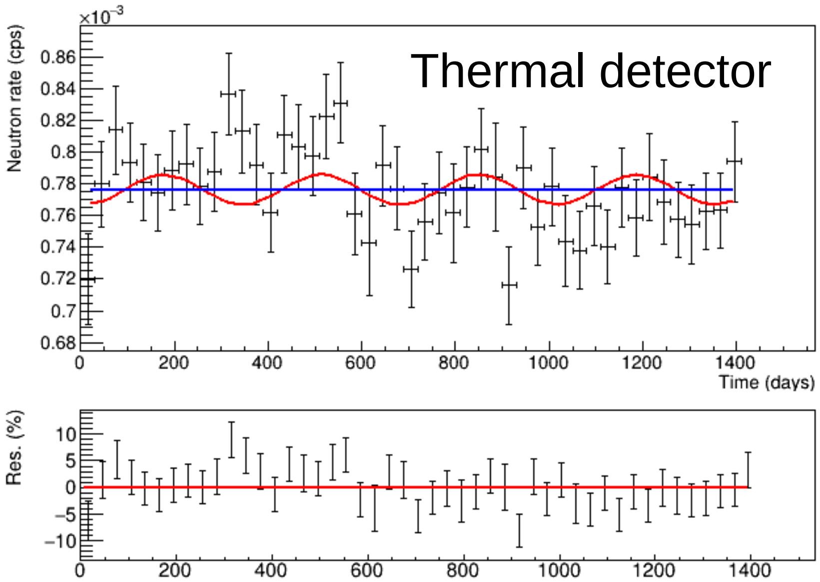
Version 2022

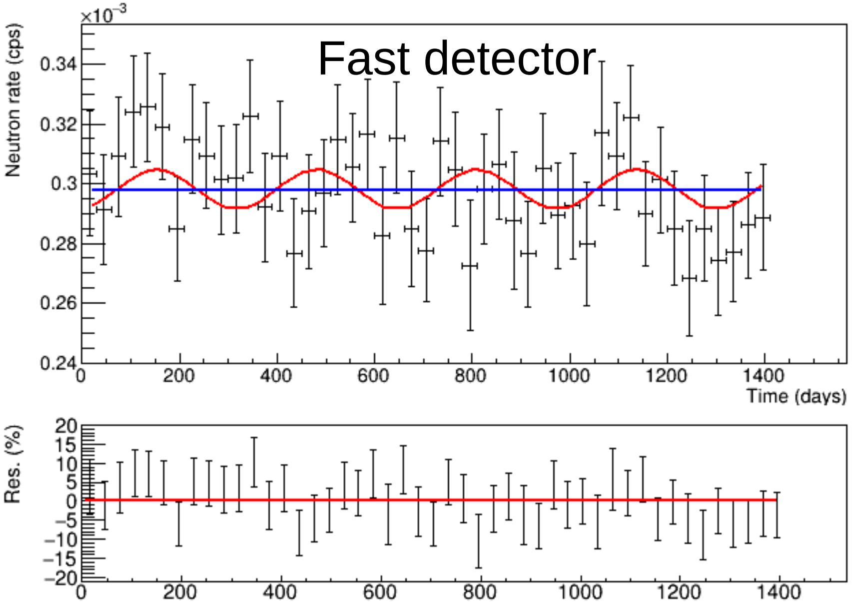
New design with improved spectral resolution by **A. Quero (UGR)**.

https://www.particlecounter.net



Neutron counting rates





Rel. Amp. ~ x.x%
Unc. ~ 2.7%

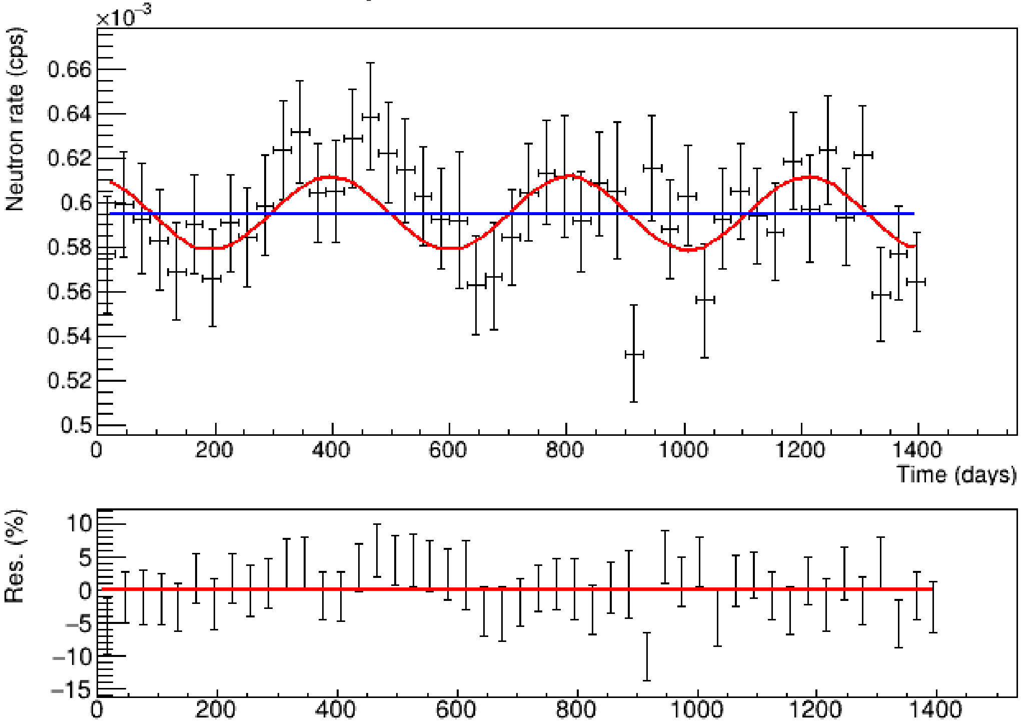
Rel. Amp. ~ 2.2%
Unc. ~ 4.8%

Fit chi-square (per degree of freedom):
Thermal: 1.05 (**line**), 1.10 (**oscilation**)
Fast: 0.52 (**line**), 0.62 (**oscilation**)

Line: f'(t) = E
Oscillation: f(t) = A·sin(Bt+C)+D

Neutron counting rates

Epithermal detector



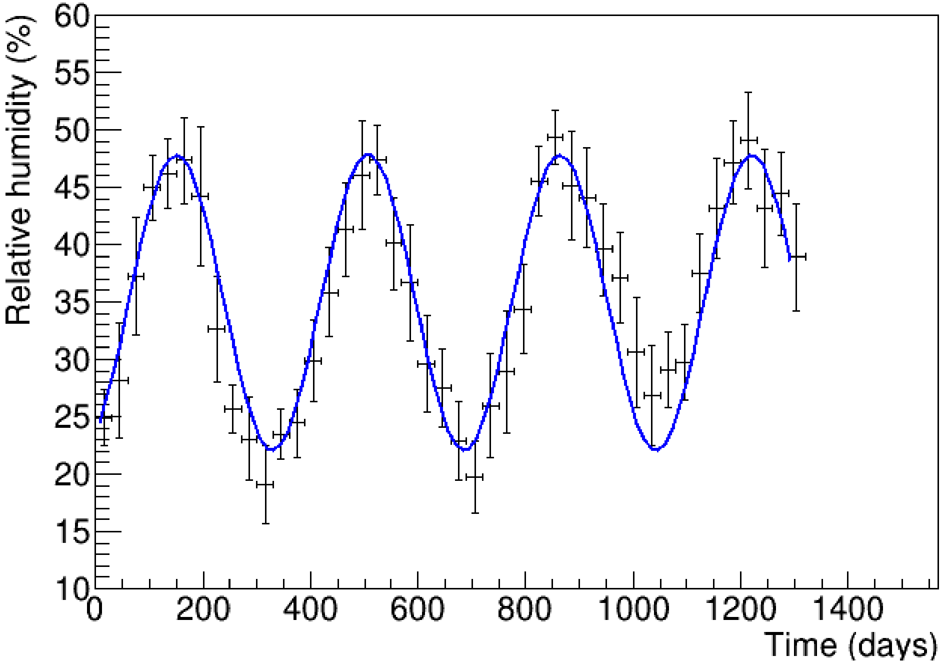
Fit chi-square (per degree of freedom):
0.70 (**line**), 0.93 (**oscilation**)

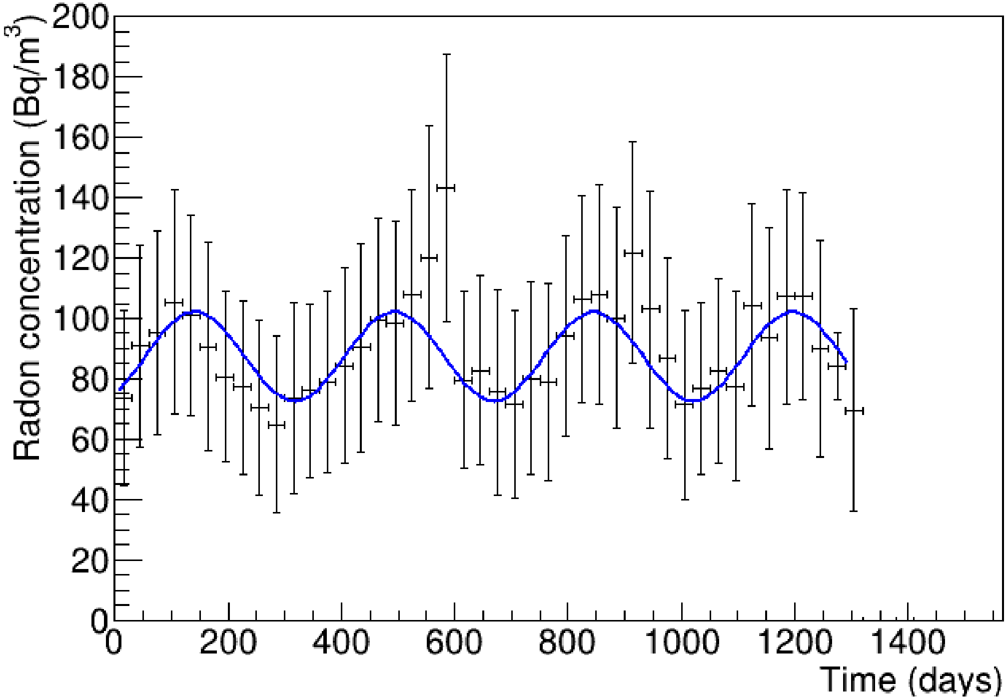
Rel. Amp. ~ 2.8%
Unc. ~ 3.1%

Line: f'(t) = E
Oscillation: f(t) = A·sin(Bt+C)+D

See for the evolution in hall A:
S. Orrigo et al 2022, European Physics Journal C 82, 814

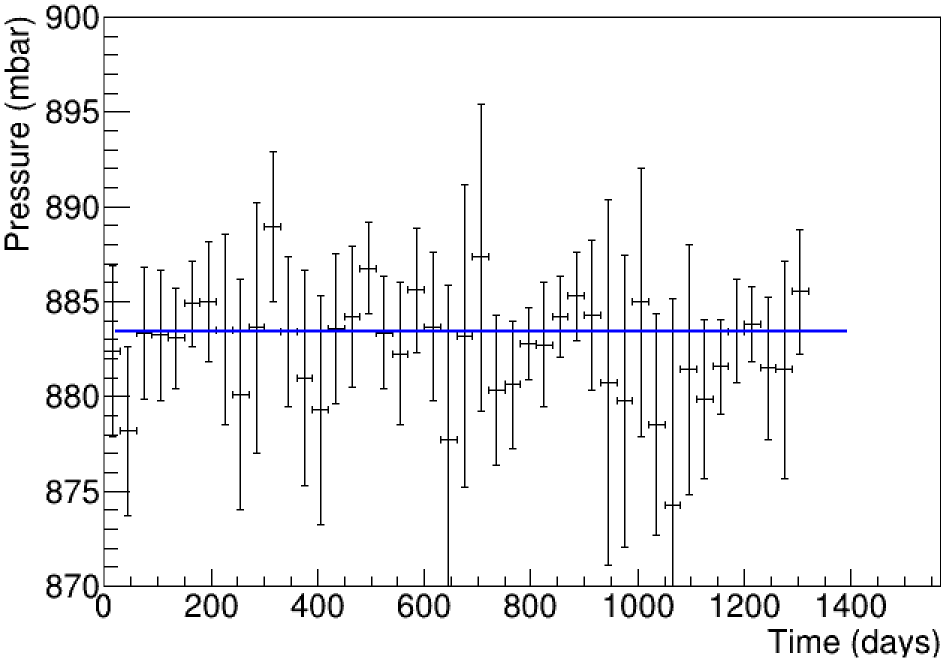
Environmental variables

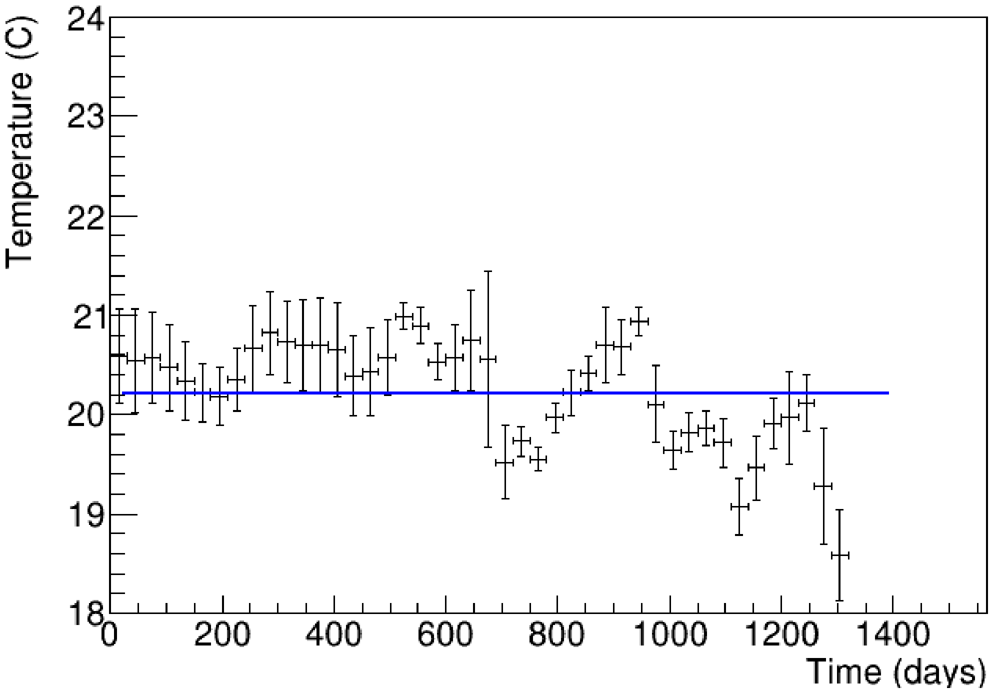




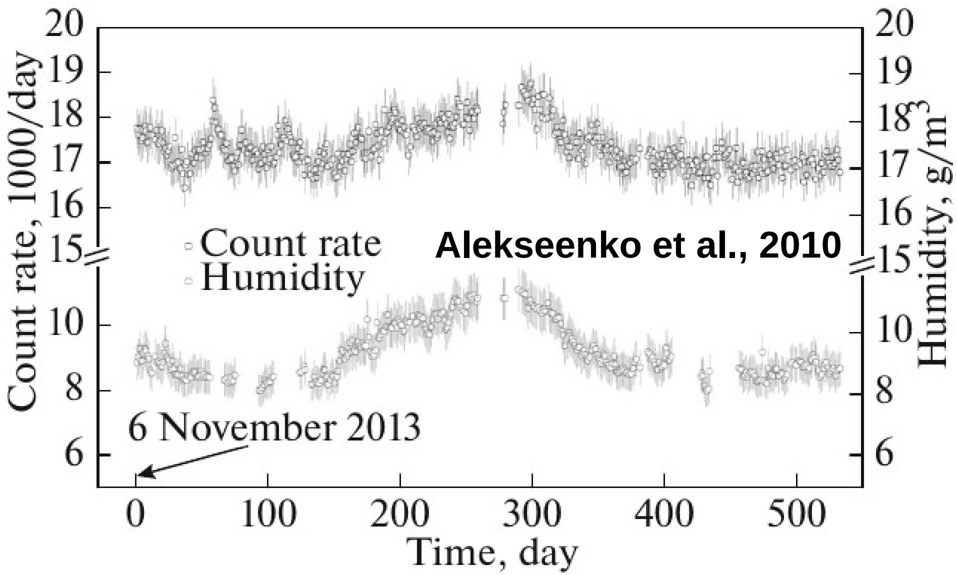
Humidity-radon correlation factor: 0.85

Environmental variables





Rates vs water content in air (relative humidity)



What happens at LSC?

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

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

Alekseenko 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 between the relative humidity and each detector of HENSA (ρ). See text for more details.

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

Spectra reconstruction

Unfolding algorithms

- Bayesian method: **S. Agostini, NIM A 362 (1995) 487**
  - Computational implementation (BAYES) by J.L Tain (IFIC) and D. Cano-Ott (CIEMAT).

- GRAVEL and MAXED implemented in UMG package version 3.3 (free-distributed by PTB).
  - MAXED: **M. Reginatto et al., NIM A 476 (2002) 242**
  - GRAVEL: **M. Matzke, Report PTB-N-19 (1994)**

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

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

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

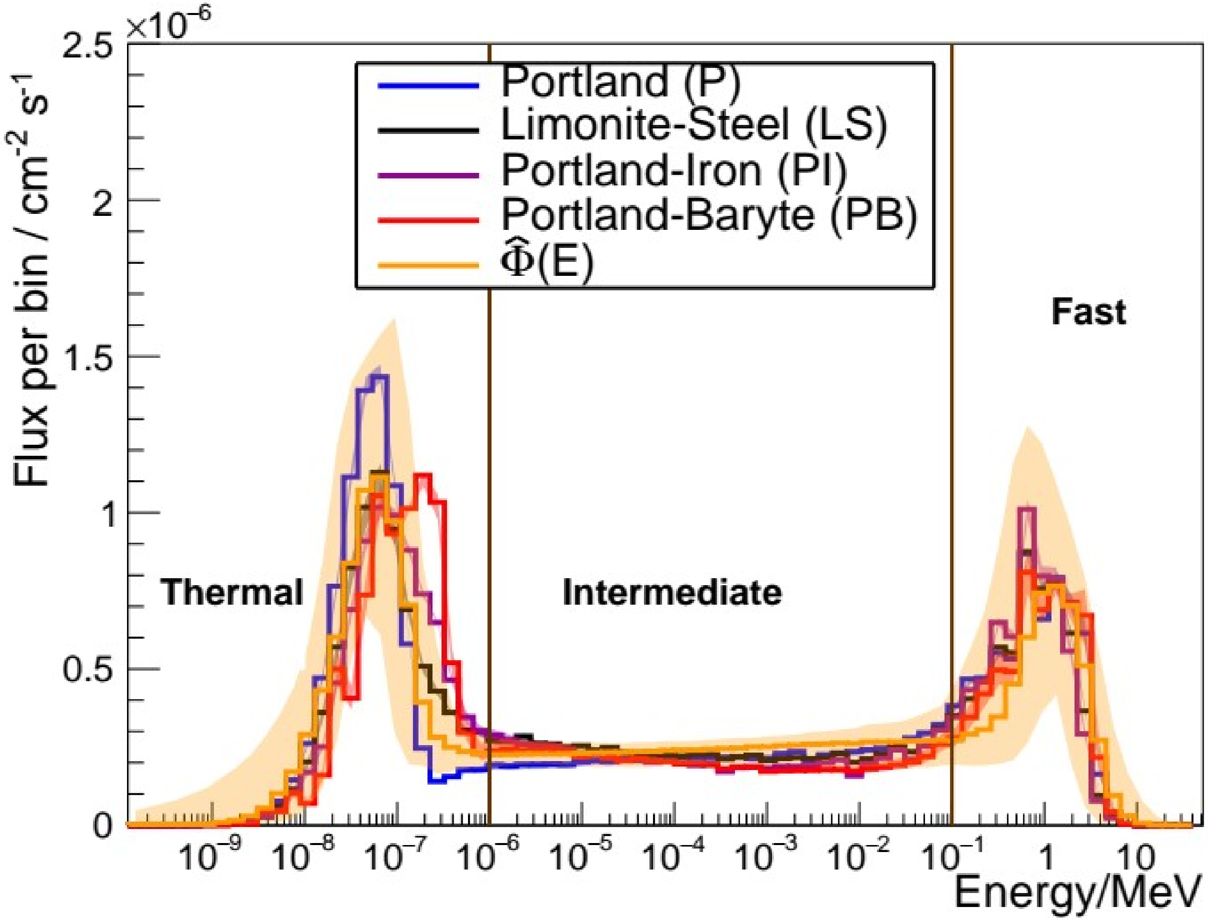
The POU method

- Developed by the HENSA collaboration, specially A. Quero (UGR), A. Lallena (UGR), M. Pallàs (UPC), J.L. Tain (IFIC) and A. Tarifeño-Saldivia (IFIC).

A. Quero, PhD thesis, UGR, expected 2026

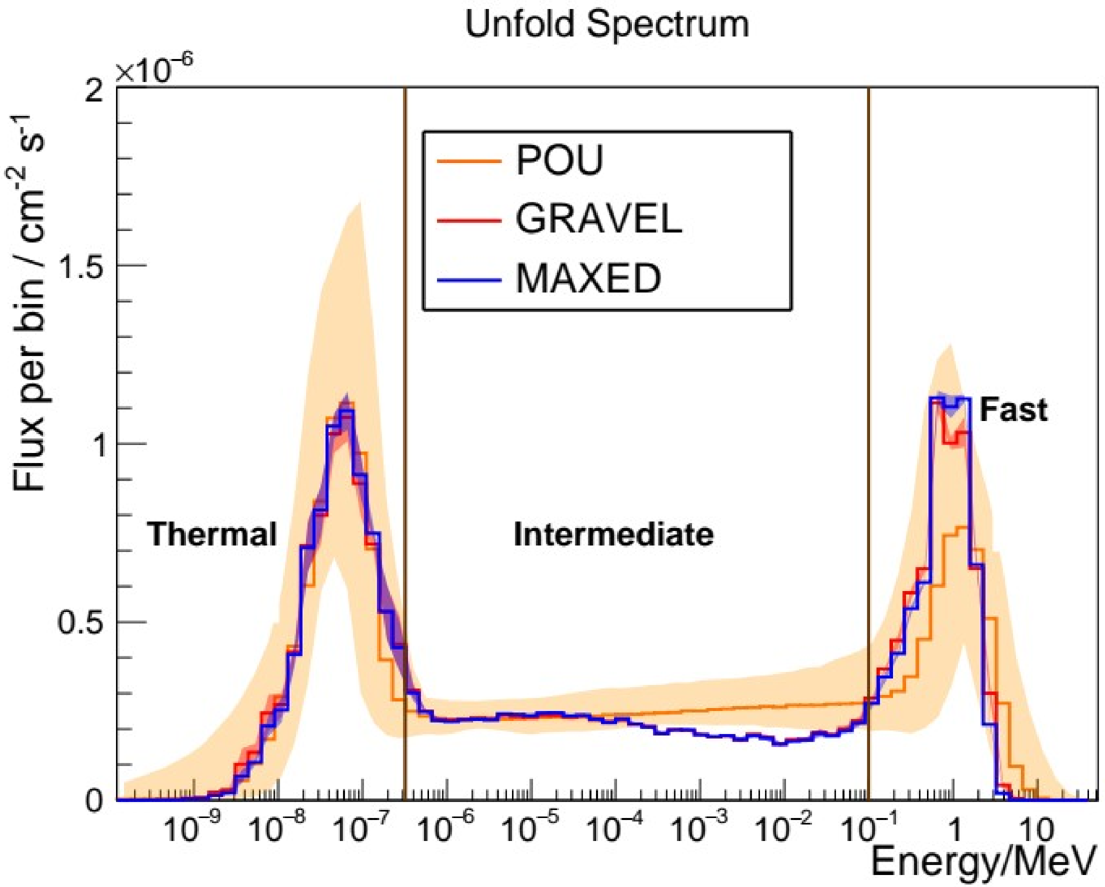
- Based on BAYES.
- Parametric spectrum to define multiple (10^3 – 10^4) priors.
- All intermediate solutions that are accepted (that is, are with consistent with the measured rates) are used to construct the definitive solution.
- Result: for each bin content we have a distribution of fluence that is used to extract the median value (solution bin content). The uncertaintes are treated as confidence intervals.
- **Allows to quantify the systematics due to the use of a priori information.**

Unfolded neutron flux at LSC



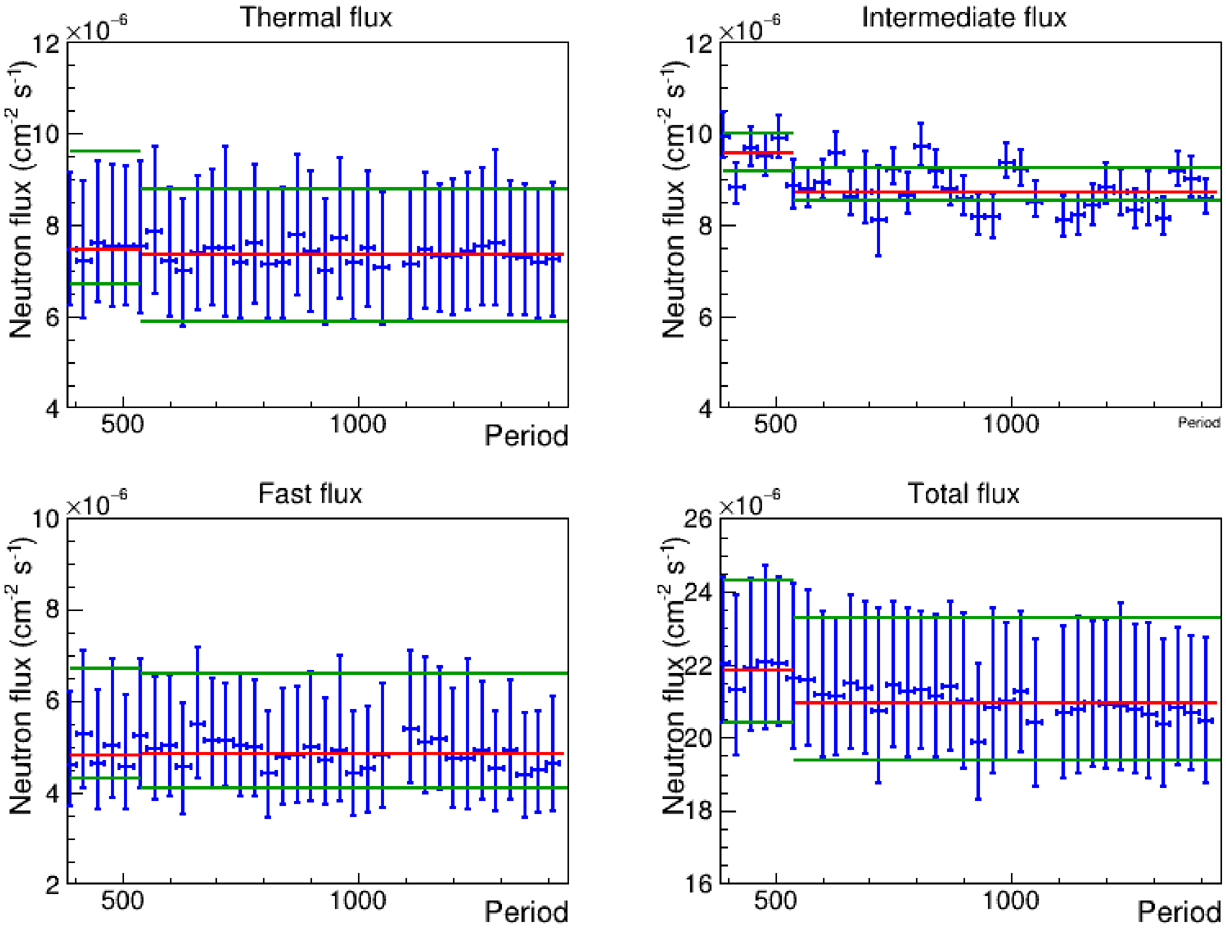
10% total uncertainty due to the the prior systematics

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.

See for the evolution in hall A:
S. Orrigo et al 2022, European Physics Journal C 82, 814

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

Impact on the background of ANAIS-112

Monte Carlo calculations are carried out to assess the impact of the underground neutron flux at LSC on the background of the ANAIS-112 setup.

The flux measured by HENSA is used as input in a neutron transport simulation through the shielding of ANAIS-112.

PRELIMINARY RESULTS

The neutron contribution to the total ANAIS-112 background found to be of **about 0.08% - 1%**

In collaboration with T. Pardo, PhD thesis, 2025

HENSA at LNGS

HENSA at LNGS: overview

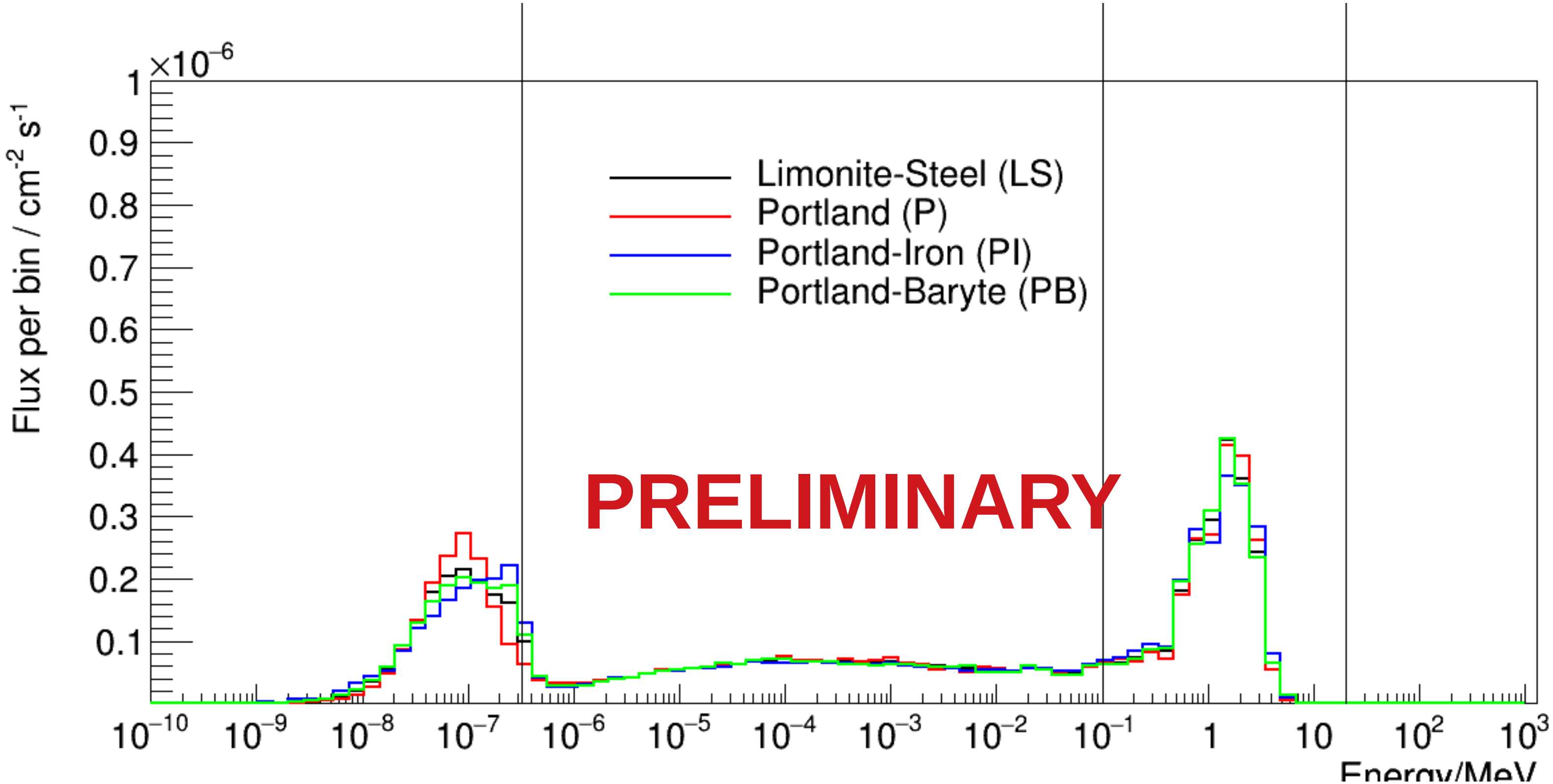
Current status of HENSA at LNGS

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

Spectral resolution (→ Belli (1989))

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)

HENSA at LNGS: preliminary results in hall A



Belli (1989)	2.99(10) [< 1 keV]	0.81(8) [> 1 keV]
HENSA	2.90(5) [< 1 keV]	2.94(3) [> 1 keV]

Concluding remarks

- **Characterization of the temporal evolution of the neutron flux.**
  - The **counting rates are stable within the statistical uncertainties**.
  - Results compatible with a constant flux. **Modulation, if exist, smaller than 3%**.
  - **No correlation with meteorological variables found**.
- **Characterization of neutron flux energy spectrum.**
  - Since August 2022, an optimized setup is being used.
  - Different methods and priors converges to the same results.
  - POU method to assess the systematics.
  - Neutron flux at LSC.
    - Neutron flux in hall A: **16.6(2) · 10^{-6} cm^{-2} s^{-1}** (S. Orrigo et al EPJ C 82, 2022)
    - Neutron flux in hall B: **21.1(+2.2)(-1.7) · 10^{-6} cm^{-2} s^{-1}**
    - **Impact on the bakcground of ANAIS-112 found to be negligible**
  - **Preliminary** neutron flux in hall A of the LNGS: **5.9 · 10^{-6} cm^{-2} s^{-1}**

- **Understand the neutron sources.**
  - MC calculations to **estimate the contribution of each neutron source** to the total flux.
  - Calculated spectra used as prior information in the unfolding algorithms.

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).

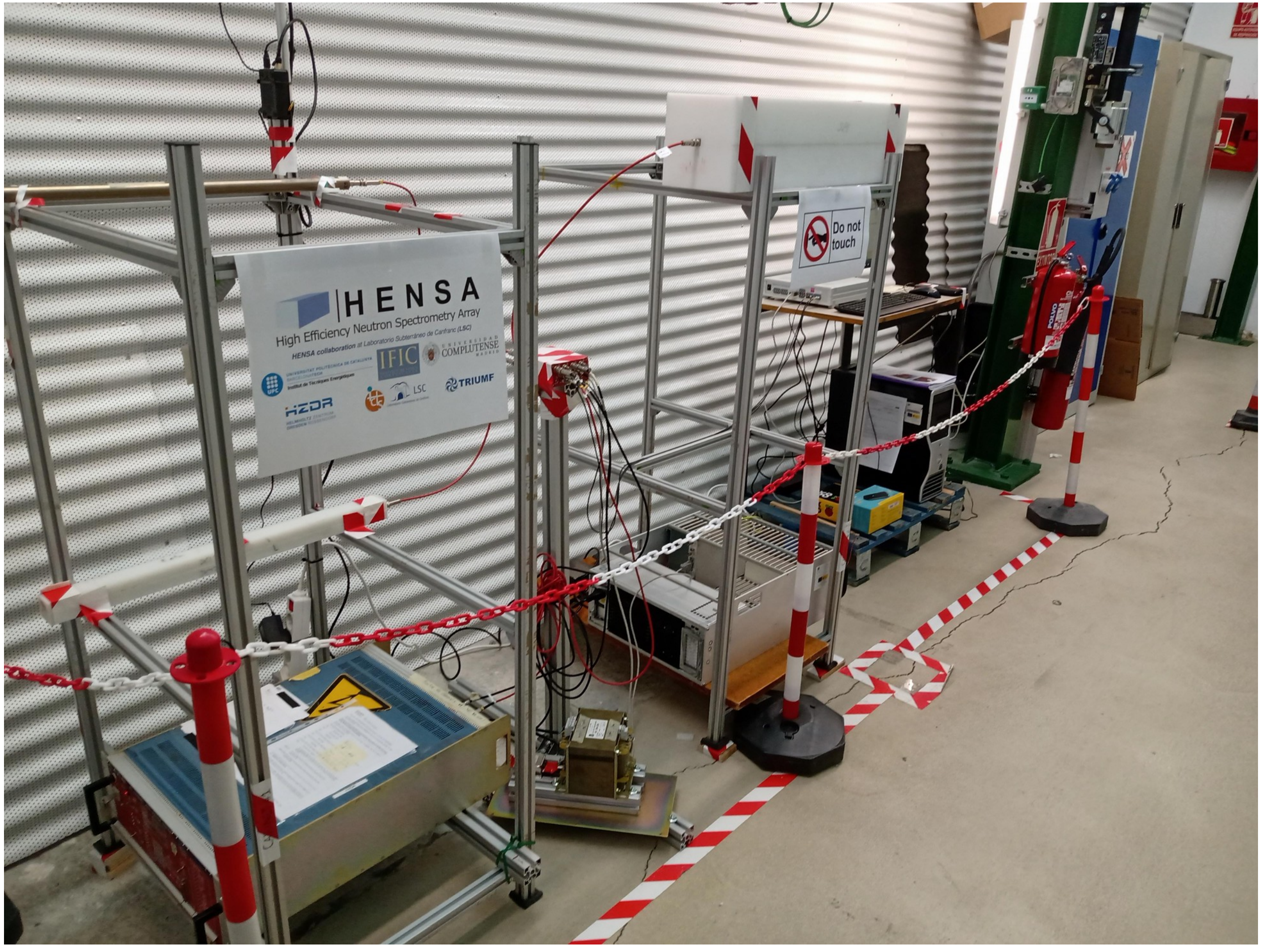
We acknowledge the support of the Generalitat Valenciana Grant No. PROMETEO/2019/007.

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.

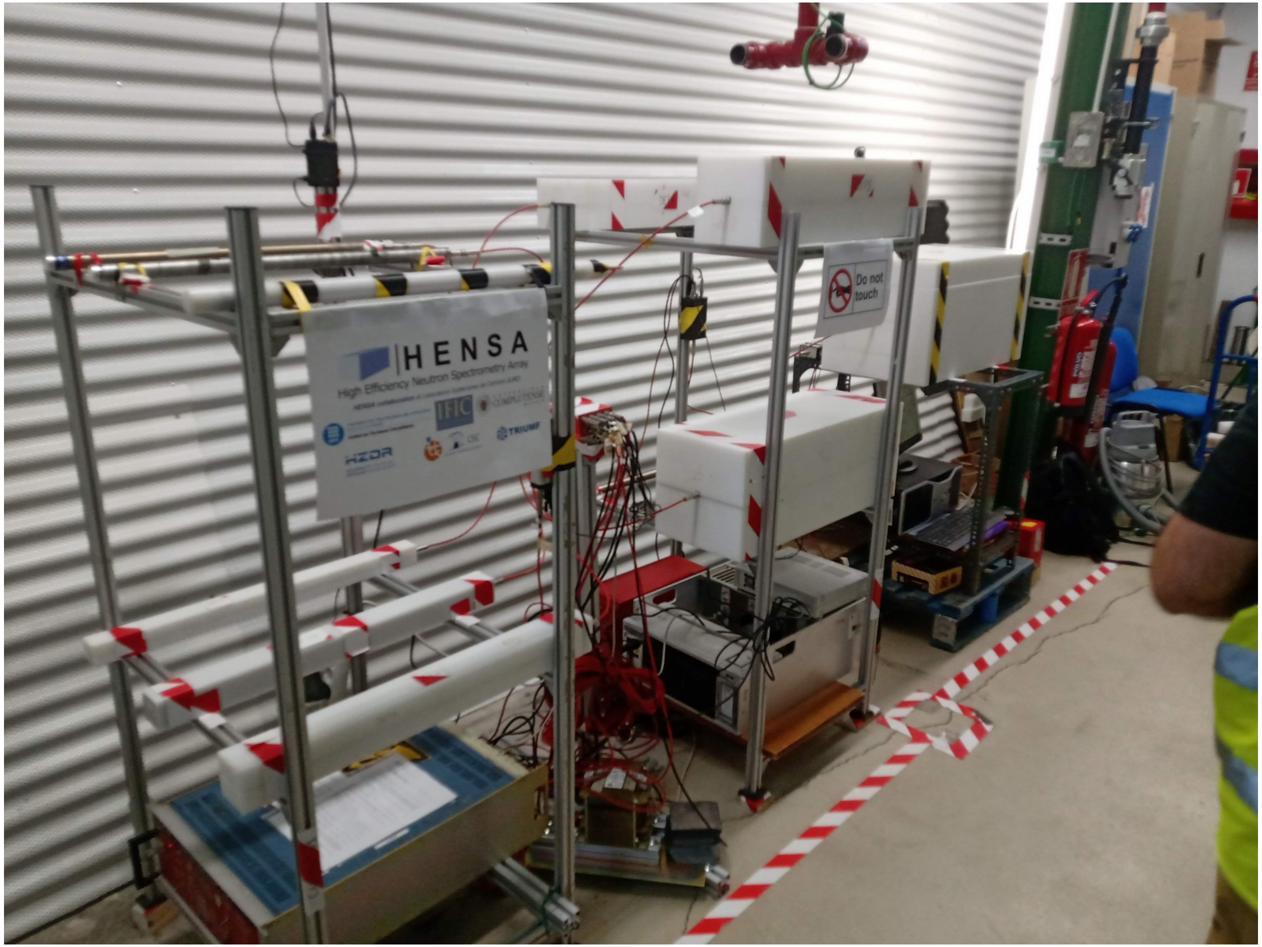
Backup slides

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-facilites/#

Underground neutrons

Spectral resolution

(as far as I know!)

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

Laboratory (country)	Overburden m.w.e	Neutron flux (10^{-6} cm^{-2} 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] [13]	2400	- -	- -	13.8±1.4 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] [5]	3600	1.08±0.2 0.32±0.10	2.94±0.03 -	- -
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

Institute of Energy Technologies - Technical University of Catalonia (INTE – UPC)
N. Mont-Geli, G. Cortés, M. Pallàs, F. Calviño, A. De Blas, R. Garcia, B. Brusasco
Instituto de Física Corpuscular (IFIC, CSIC – UV)
A. Tarifeño-Saldivia, S.E.A. Orrigo, J.L. Tain, E. Nacher, J. Agramunt, A. Algora
University of Granada
A. Quero-Ballesteros, A. Lallena
Universidad Complutense de Madrid (UCM)
L.M. Fraile
Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
D. Bemmerer, M. Grieger
TRIUMF
I. Dillman
Centro de Astropartículas y Física de Altas Energías – University of Zaragoza (CAPA) (ANAIS team)
J. Amaré, S. Cebrián, D. Cintas, I. Coarasa, E. García, M. Martínez, Y. Ortigoza, A. Ortiz de Solórzano, J. Puimedón, 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
High Efficiency Neutron Spectrometry Array

HENSA experimental setup

- Ten neutron detectors.
  - **60 cm active length cylindrical** ^{3}He-filled <u>neutron proportional counters</u> 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

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.

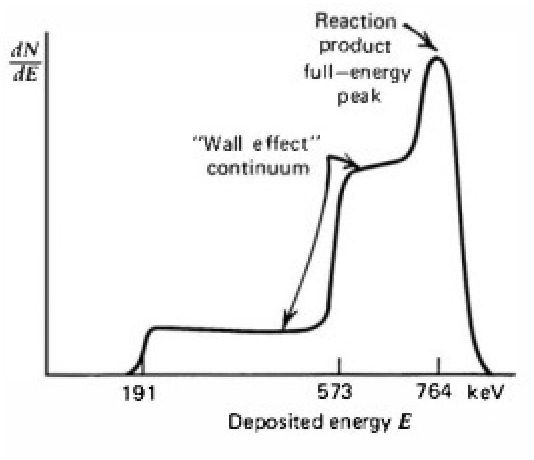
Based in the work by M. Grieger (HZDR) at Felsenkeller:
M. Grieger et al 2020, Phys. Rev. D 101, 123027

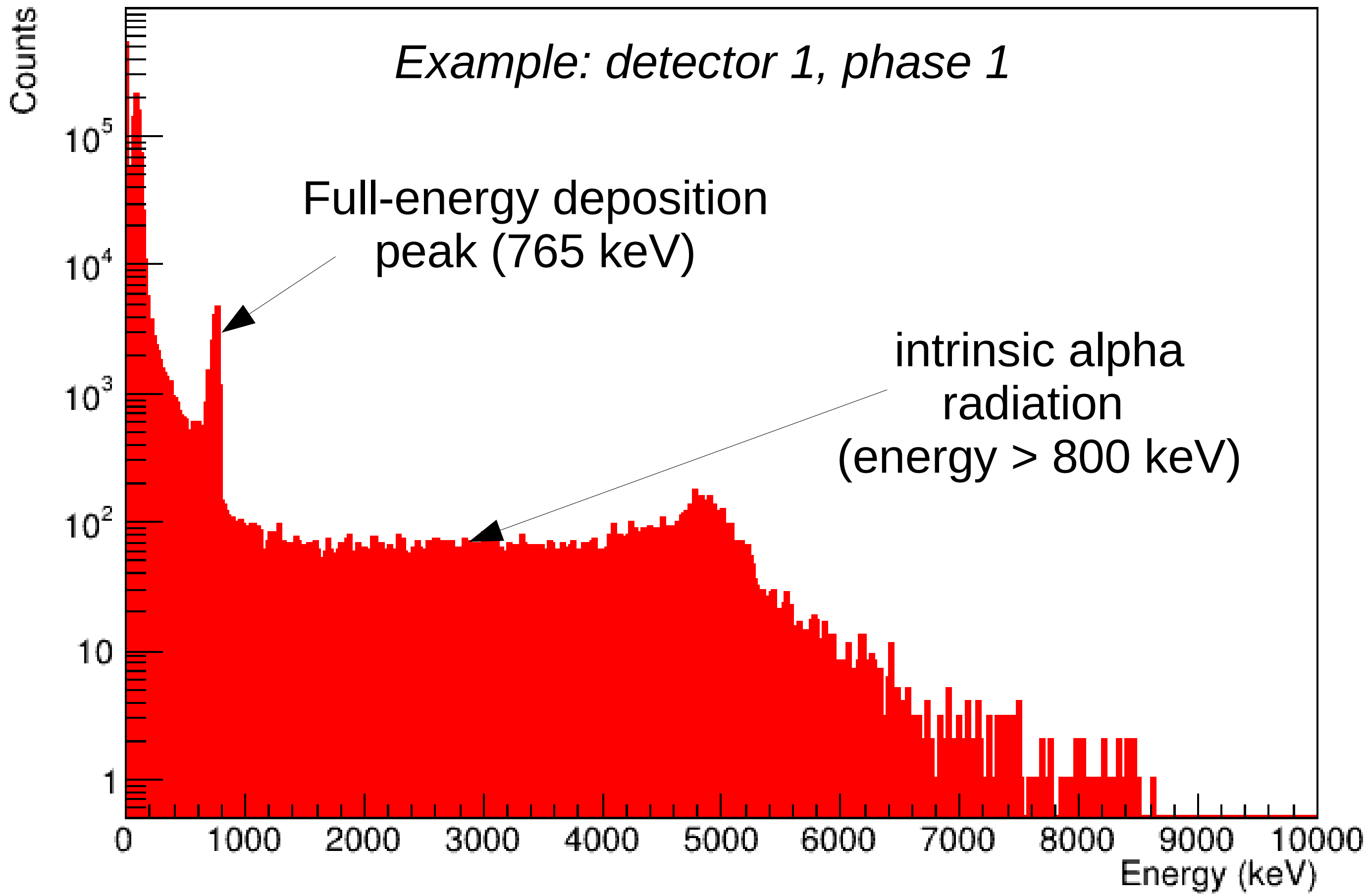
^{3}He counter energy deposition spectrum (event amplitude)

Raw data

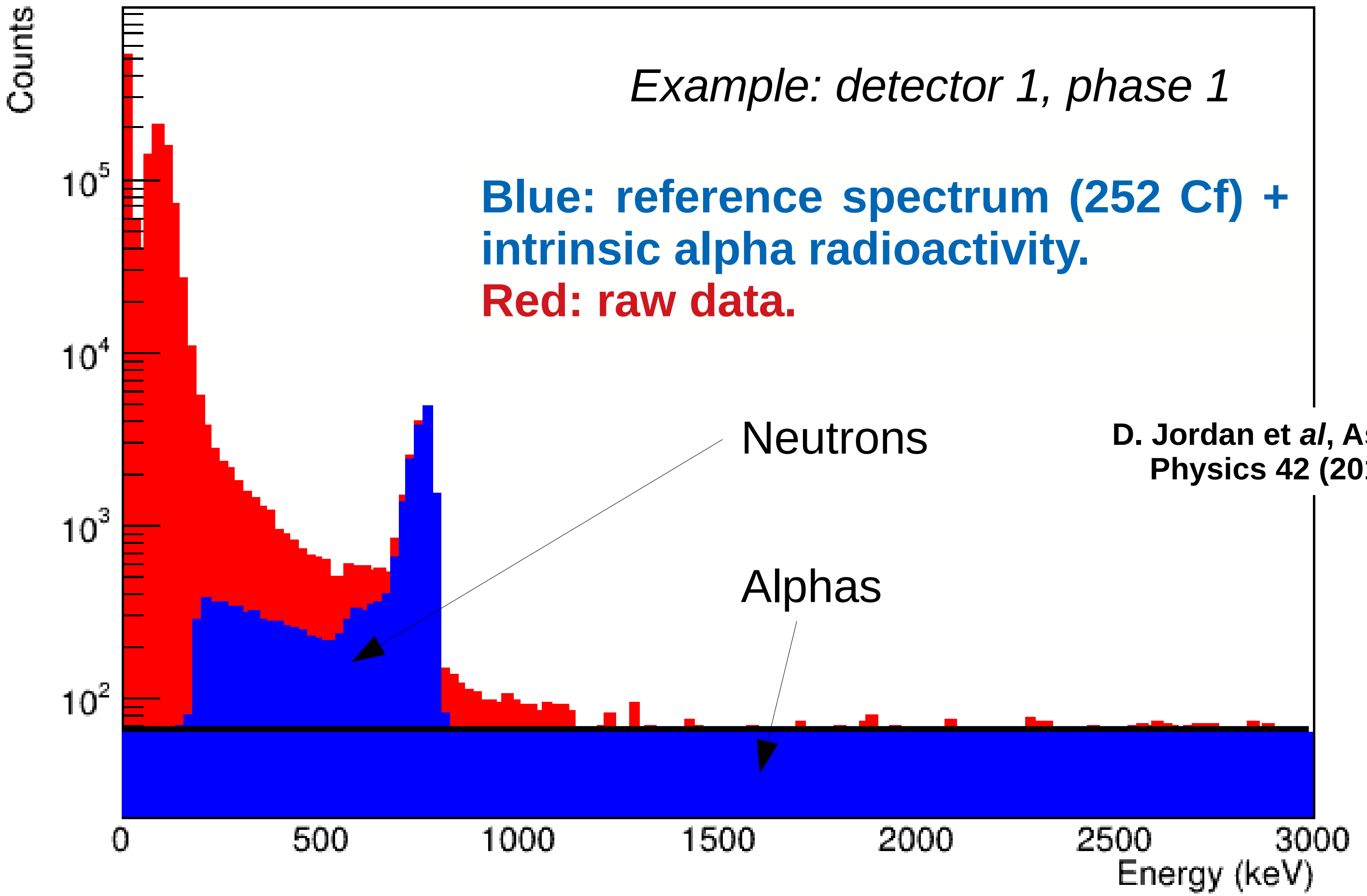
3He + n → p + t + 765 keV

Theoretical amplitude spectrum
(G. Knoll, 2010 edition)



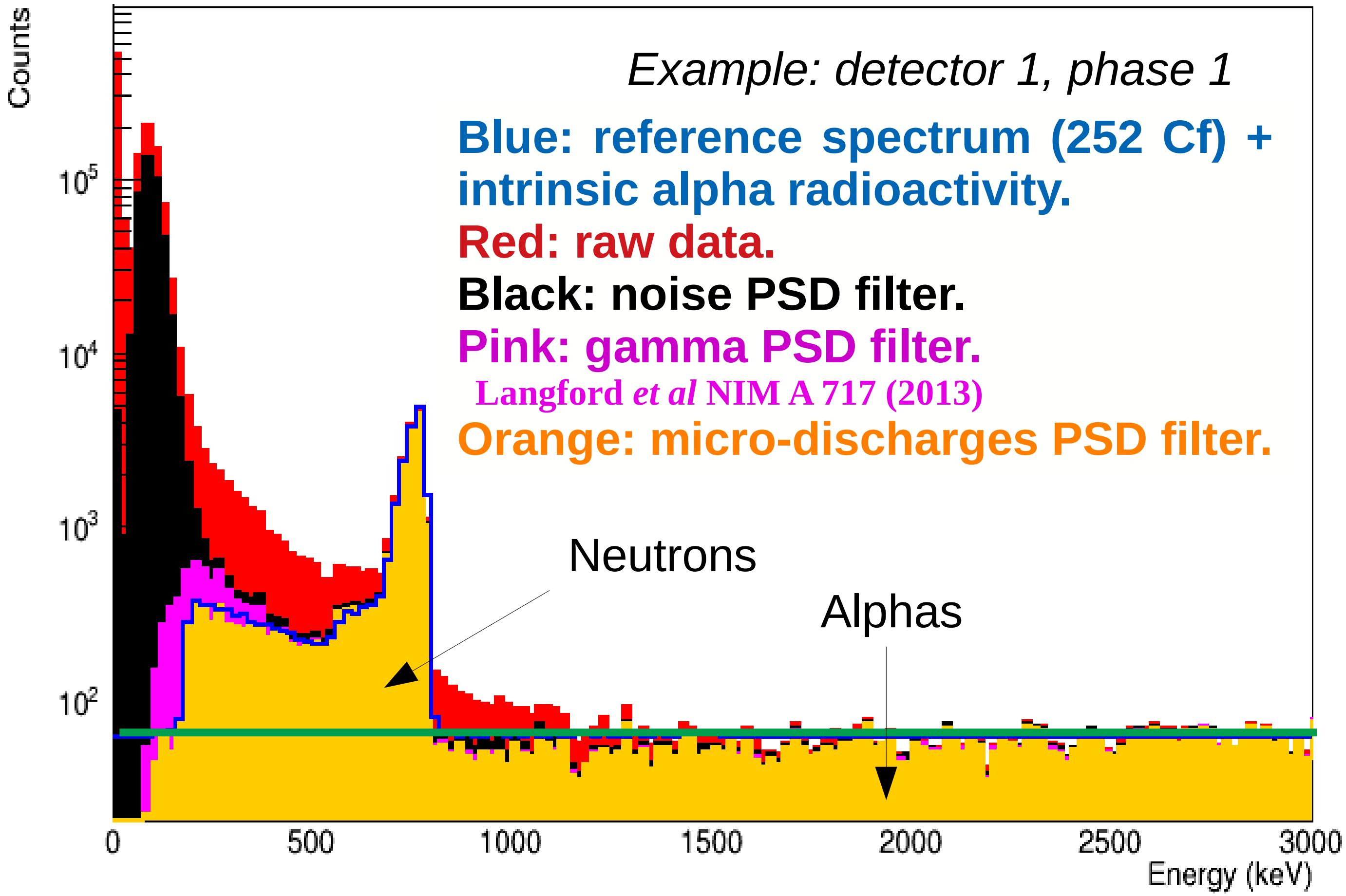


Neutron contribution: reference spectrum method



D. Jordan et *al*, Astroparticle Physics 42 (2013), 1 – 6

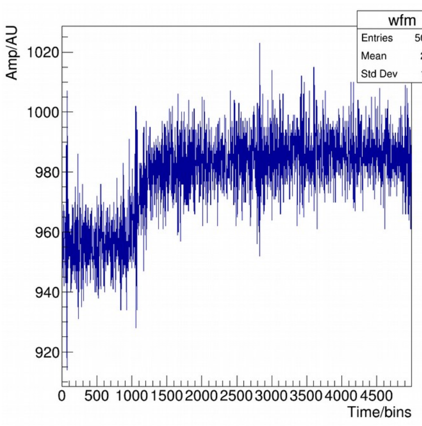
Neutron contribution: PSD



PSD: noise "filter"

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

Accepted



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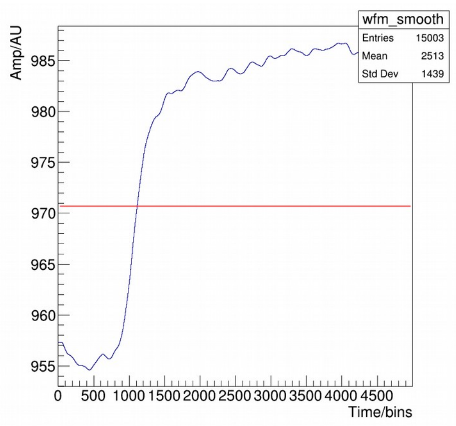
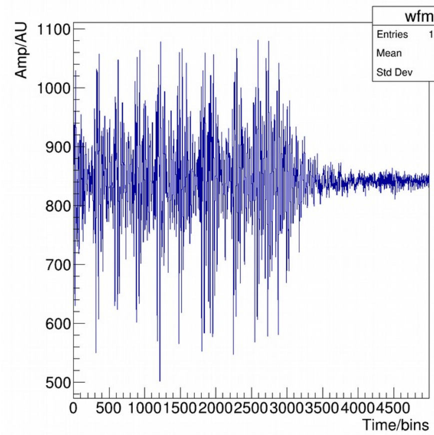


Smoothed

Rejected



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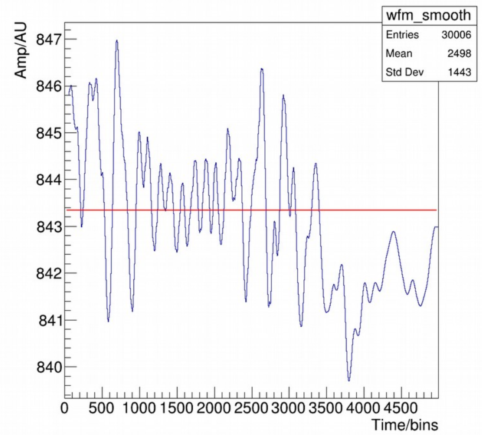
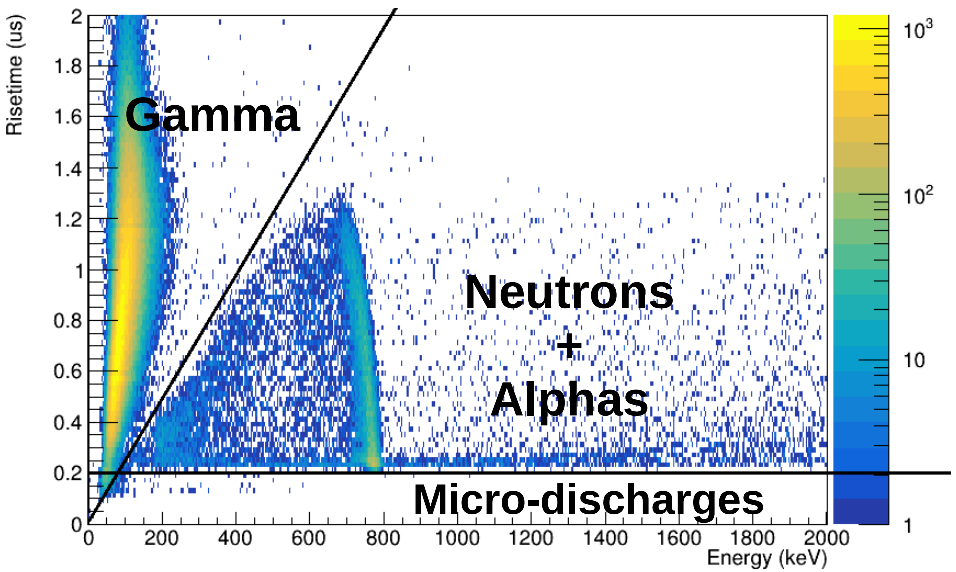
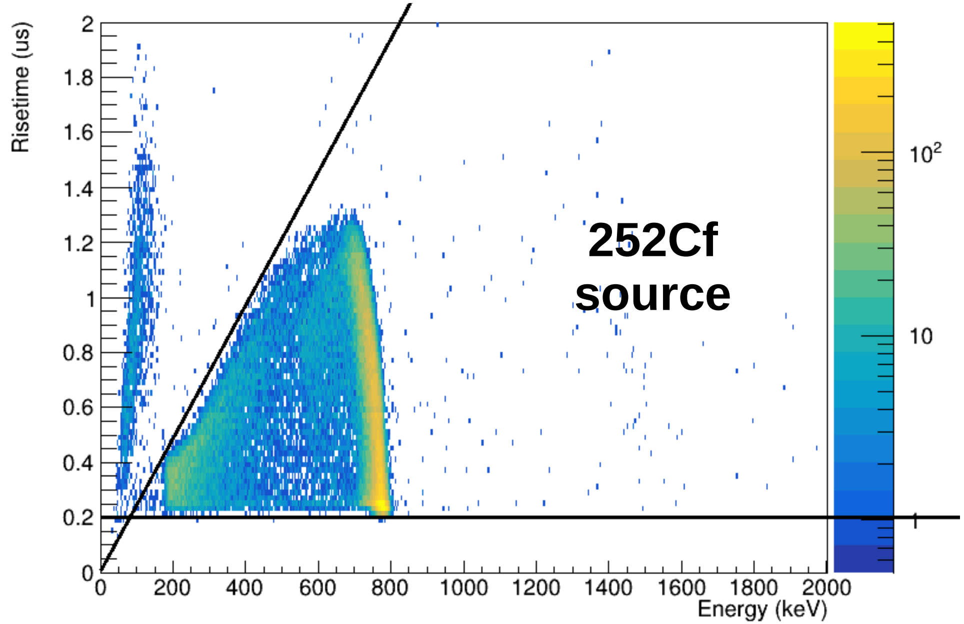


Smoothed

PSD: gamma-neutron discrimination

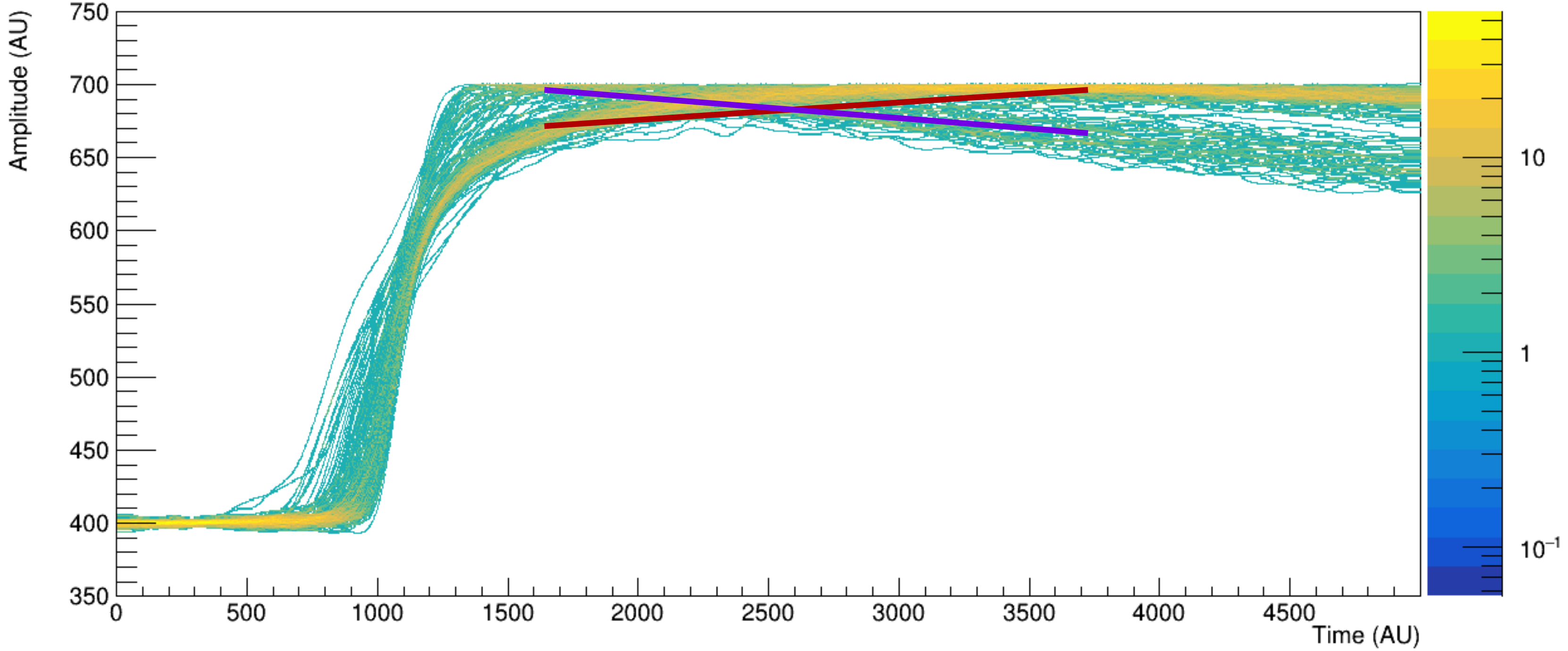
A filter based on the the risetime differences: Langford *et al* NIM A **717** (2013)





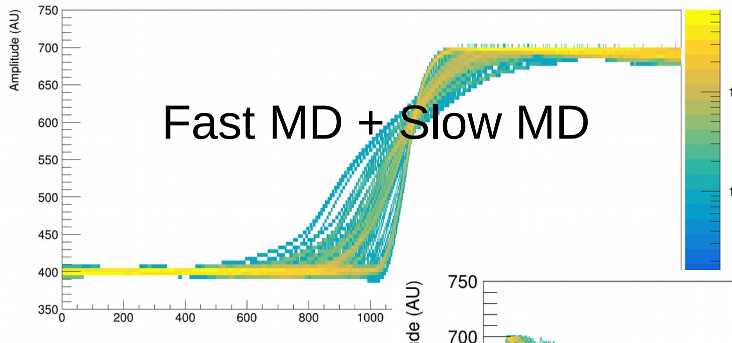
PSD: slow micro-discharges “filter”

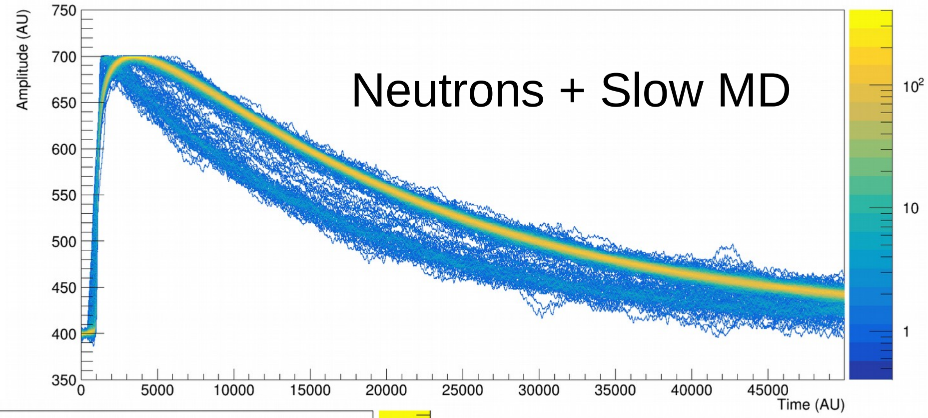
A filter based on the decay shape.

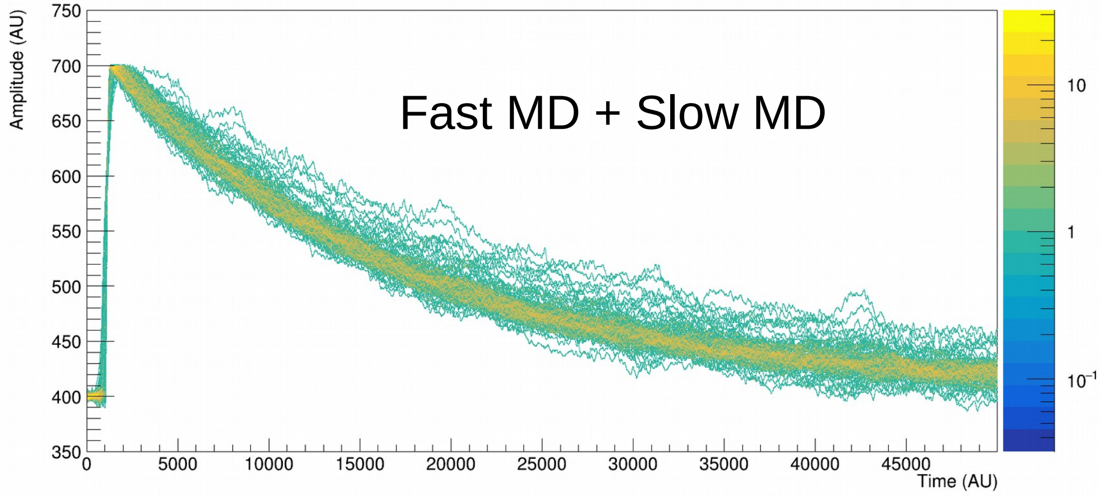


PSD: slow and fast micro-discharges

Different risetime, same decay

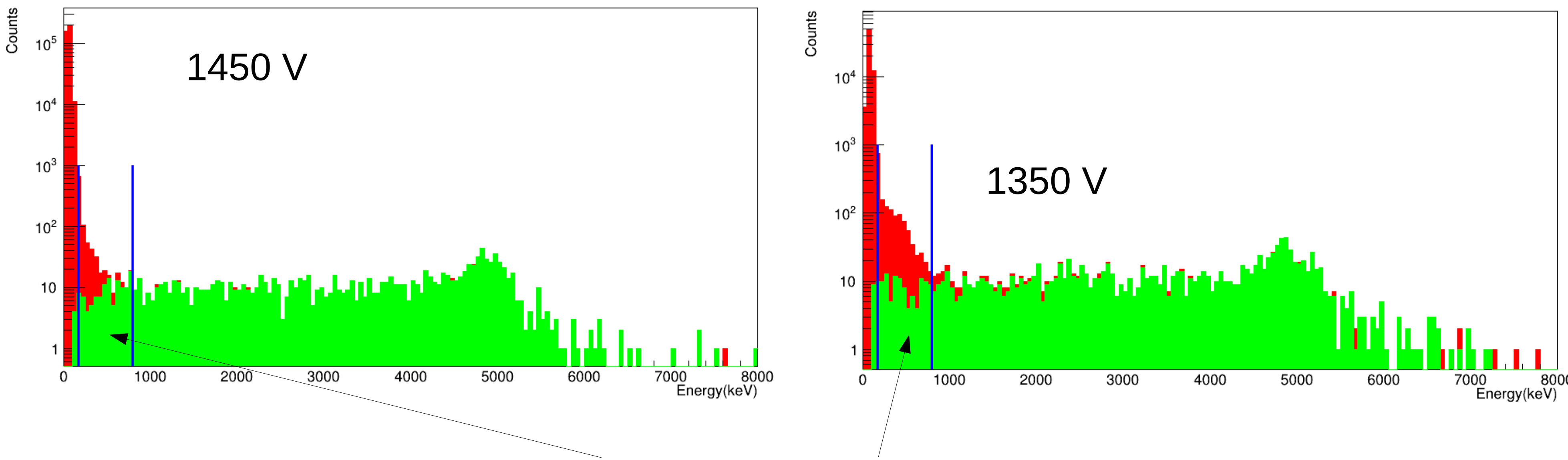




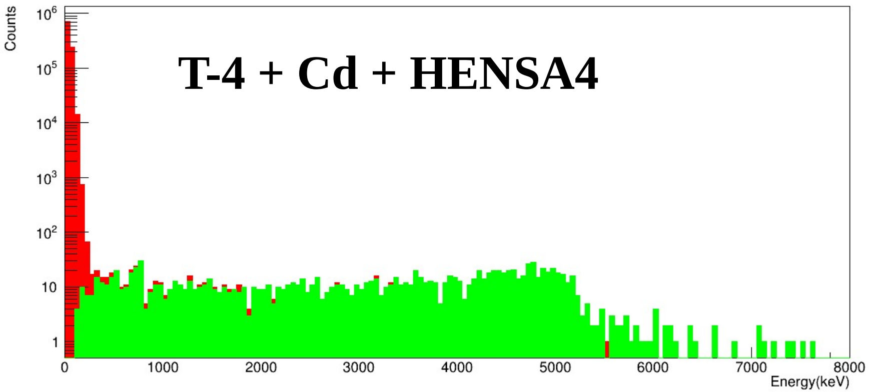


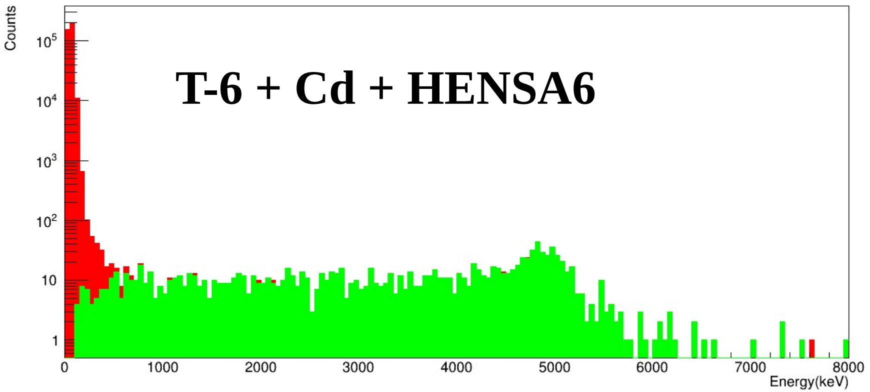
Validation of the alpha background hypothesis

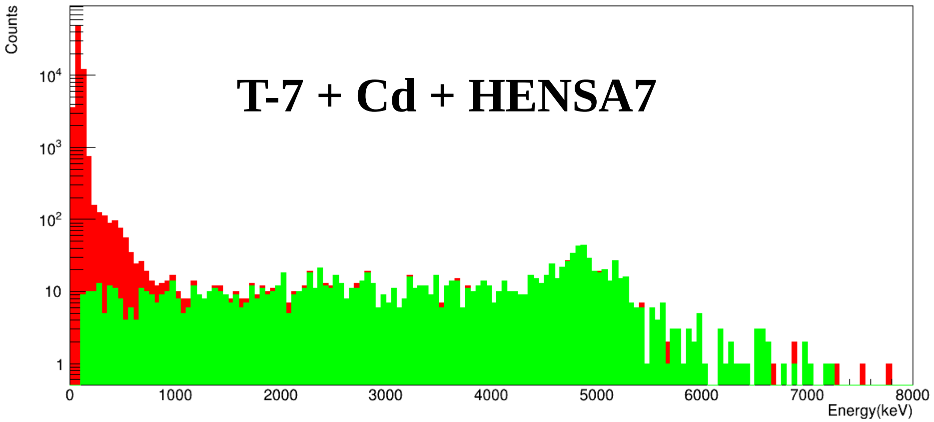
Setup: thermal neutrons counter (T) + Cd (thermal shielding) + HDPE



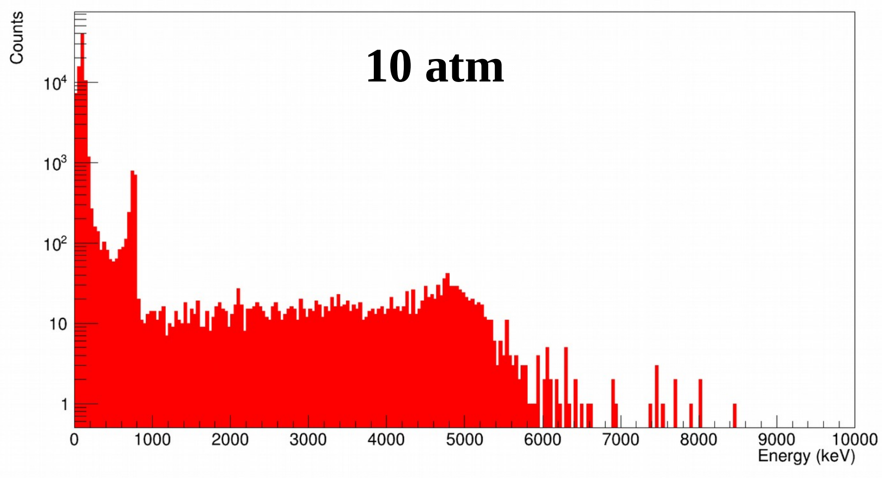
Alpha background

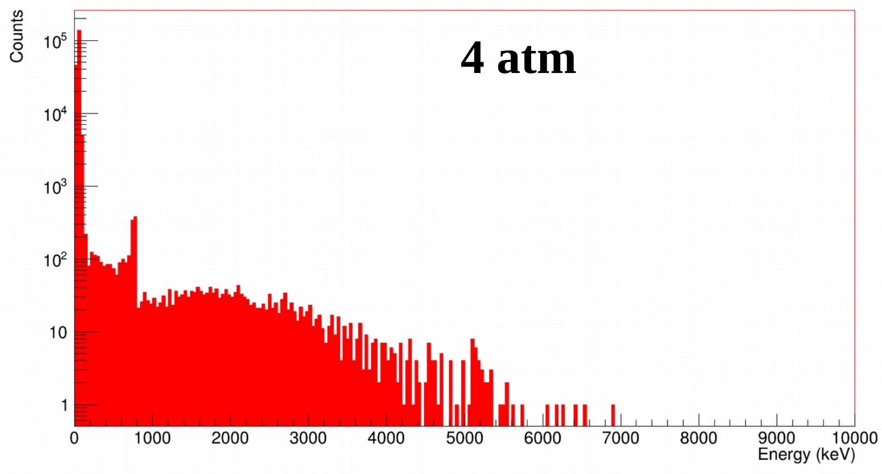


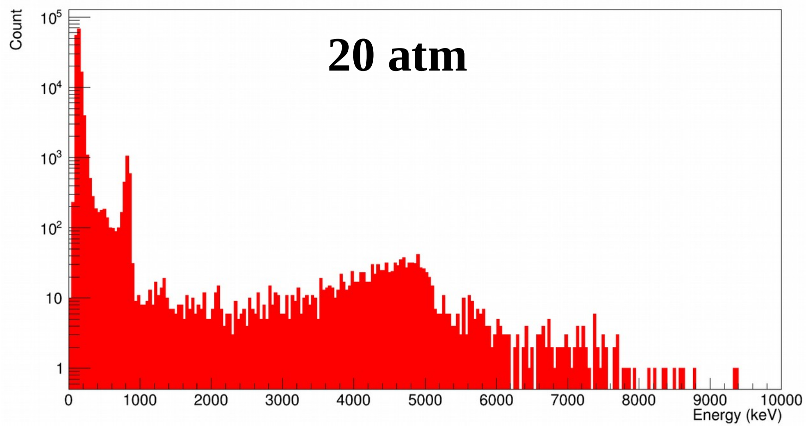




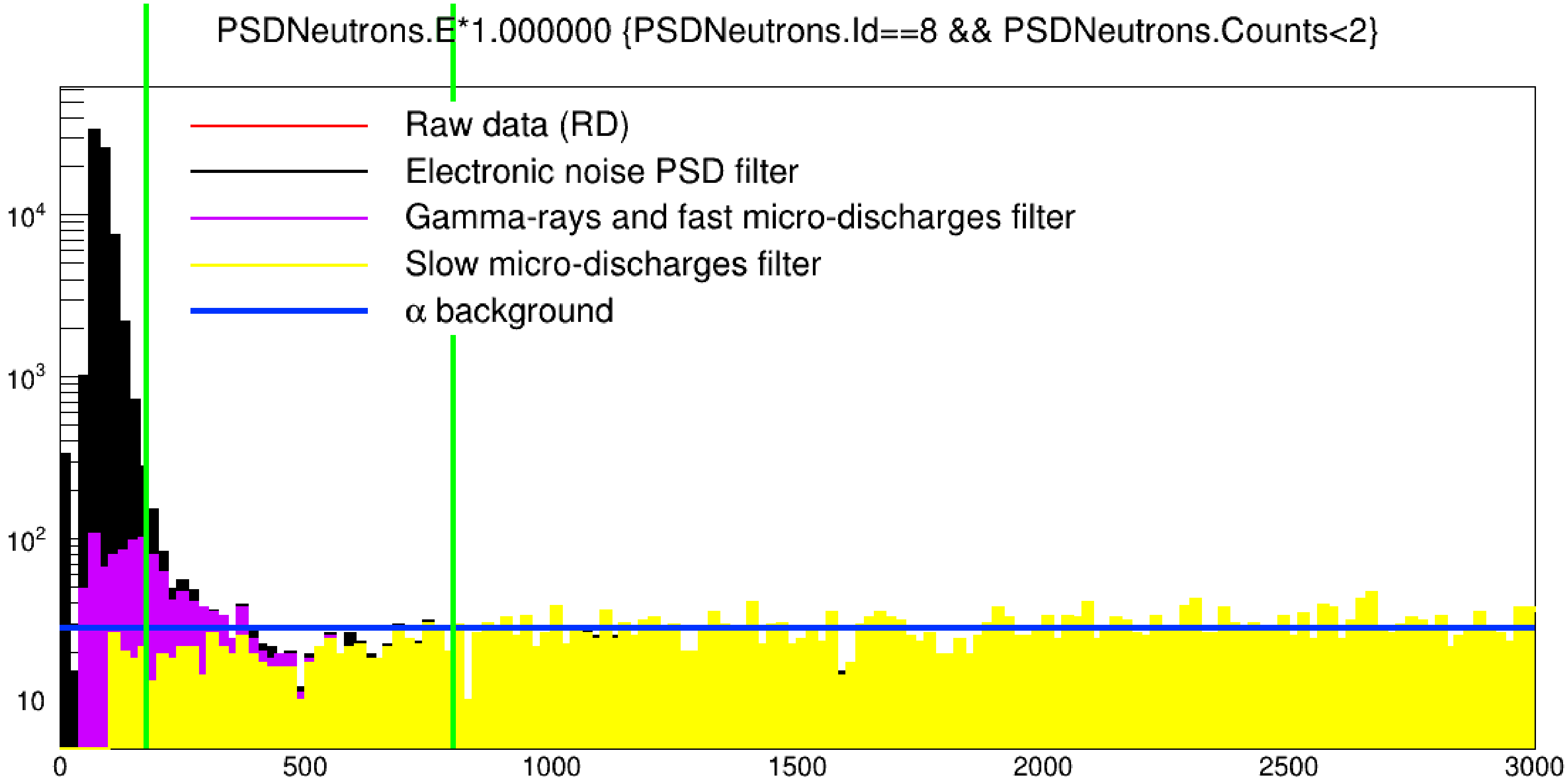
Alpha background







Alpha background



Evolution of the neutron flux

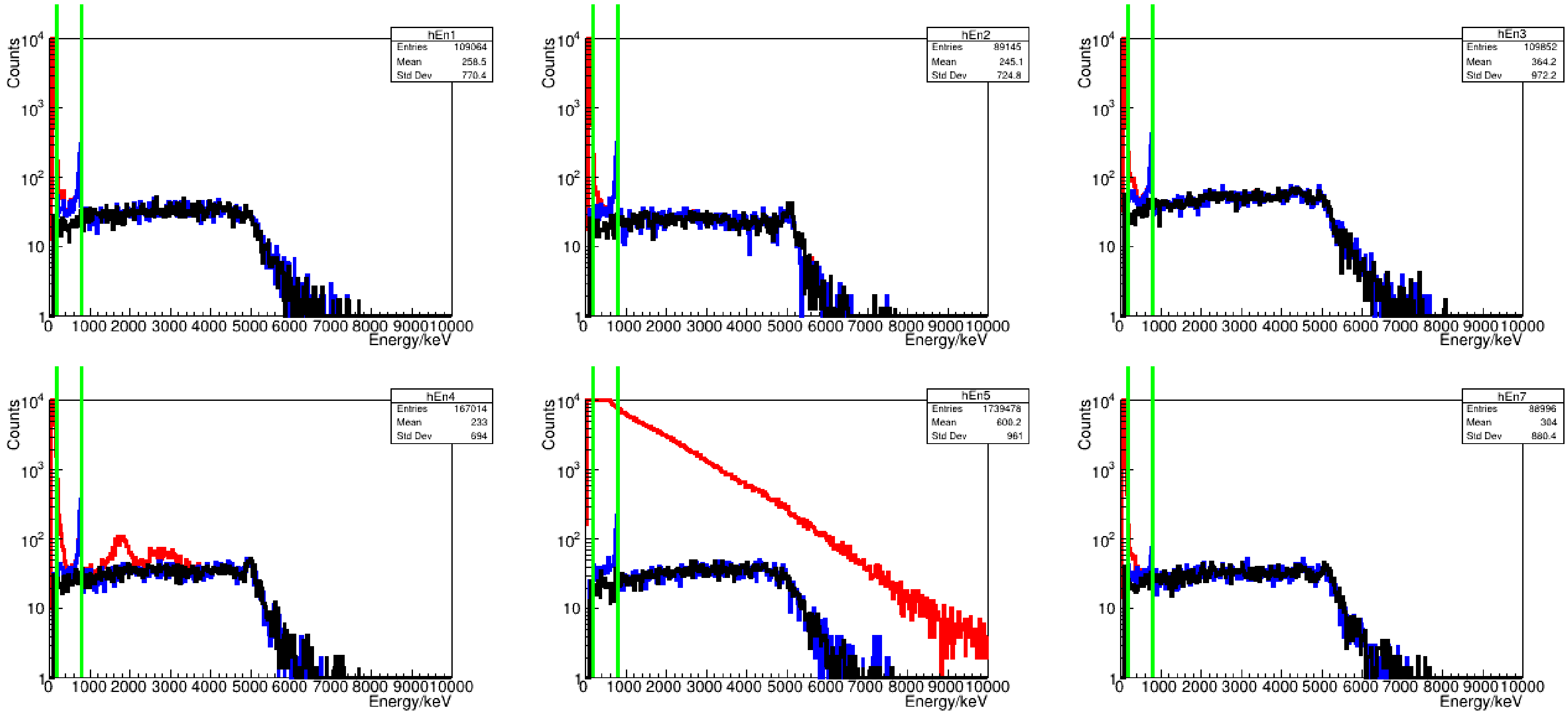
Energy region	χ^2/ndf	χ'^2/ndf	$\mathbf{T = 2\pi/C}$	A/D
Thermal	0.015	0.016	246(126) days	1.02 %
Intermediate	1.03	1.10	313(23) days	3.96%
Fast	0.029	0.040	383(46) days	2.69%
Total	0.041	0.047	340(83) days	1.43%

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.

LNGS


Counts
Energy/keV
hEn1
Entries 109064
Mean 258.5
Std Dev 770.4
hEn2
Entries 89145
Mean 245.1
Std Dev 724.8
hEn3
Entries 109852
Mean 364.2
Std Dev 972.2
hEn4
Entries 167014
Mean 233
Std Dev 694
hEn5
Entries 1739478
Mean 600.2
Std Dev 961
hEn7
Entries 88996
Mean 304
Std Dev 880.4

Neutron counting rates