HENSA collaboration at LNGS: characterization of the underground neutron flux

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HENSA
High Efficiency Neutron Spectrometry Array

The HENSA collaboration

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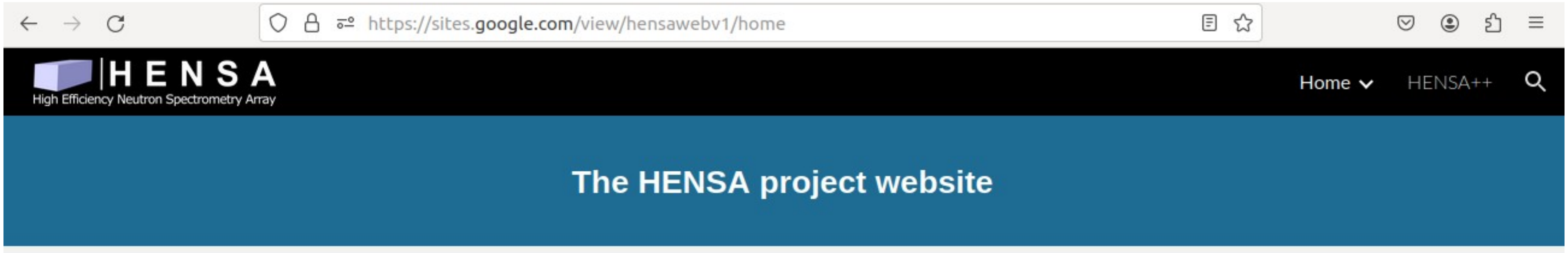

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The HENSA collaboration

HENSA
High Efficiency Neutron Spectrometry Array

***HENSA collaboration** at Laboratori Nazionali del Gran Sasso (LNGS)*

UPC
UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Institut de Tècniques Energètiques

INFN
LNGS

IFIC
INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

UNIVERSIDAD DE GRANADA

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Objectives

HENSA
High Efficiency Neutron Spectrometry Array

Characterization of the underground neutron flux at LNGS

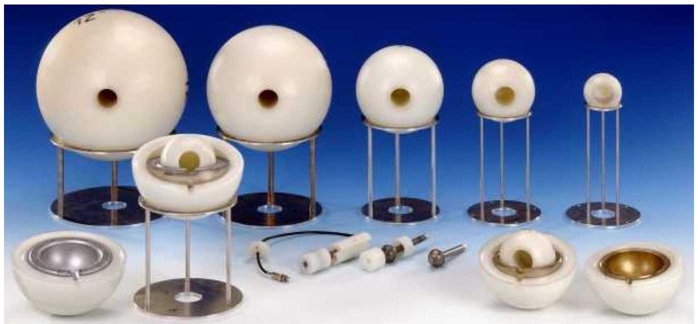
- Absolute magnitude of the neutron flux.
- Energy spectrum.
- Local variations.
- Temporal/seasonal fluctuations.

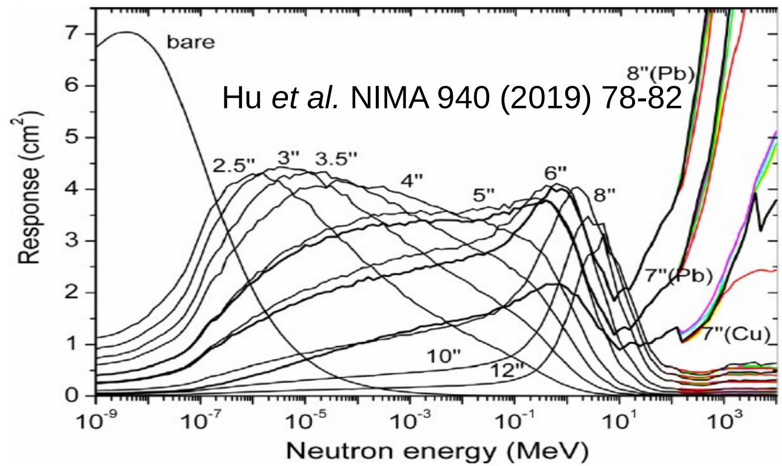
What is HENSA?

HENSA
High Efficiency Neutron Spectrometry Array

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

- Array of moderated proportional neutron counters with variable sizes in order to provide sensitivty at different neutron energies.





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

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

What is HENSA?

HENSA
High Efficiency Neutron Spectrometry Array

It 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).

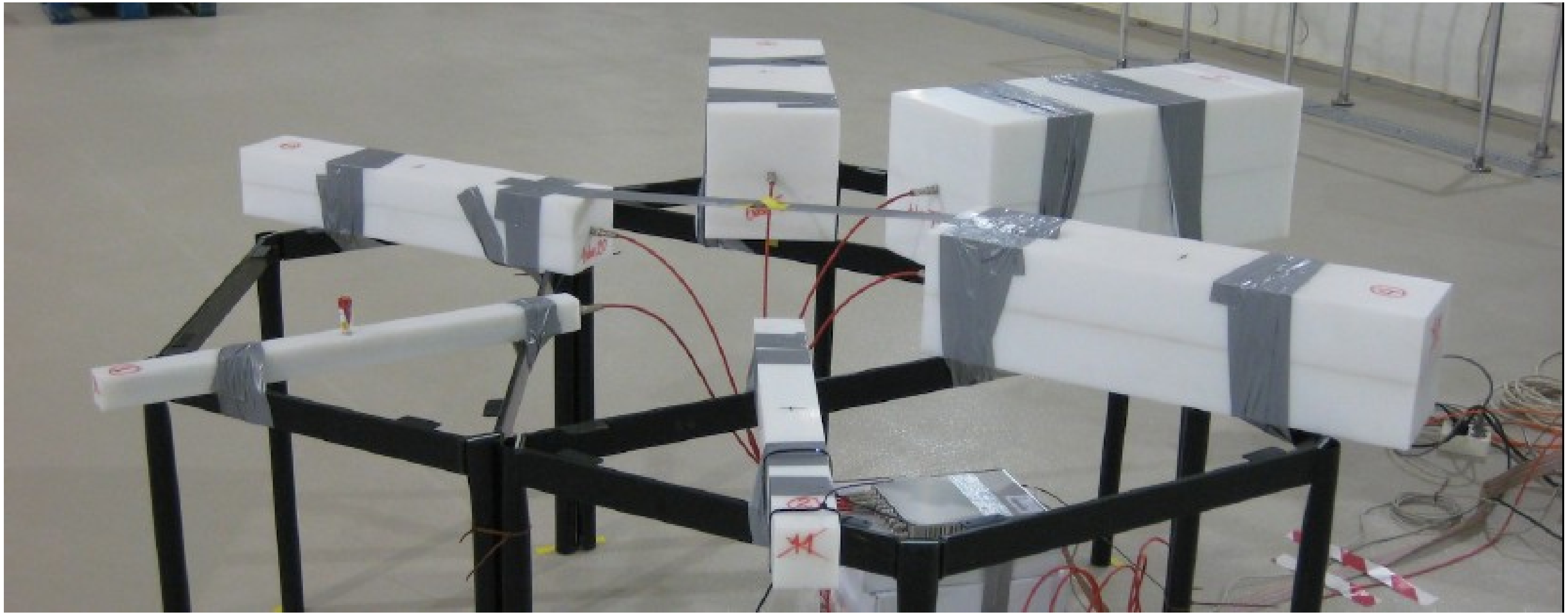
- HENSA is achieved by a topological change in Bonner Spheres in order to benefit from high detection efficiency in cylindrical proportional neutron counters (60 cm active length).

- 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***.

What is HENSA?

HENSA
High Efficiency Neutron Spectrometry Array

Above thermal energies: moderation (HDPE)
First version of the HENSA setup (6 detectors) in 2011



What is HENSA?

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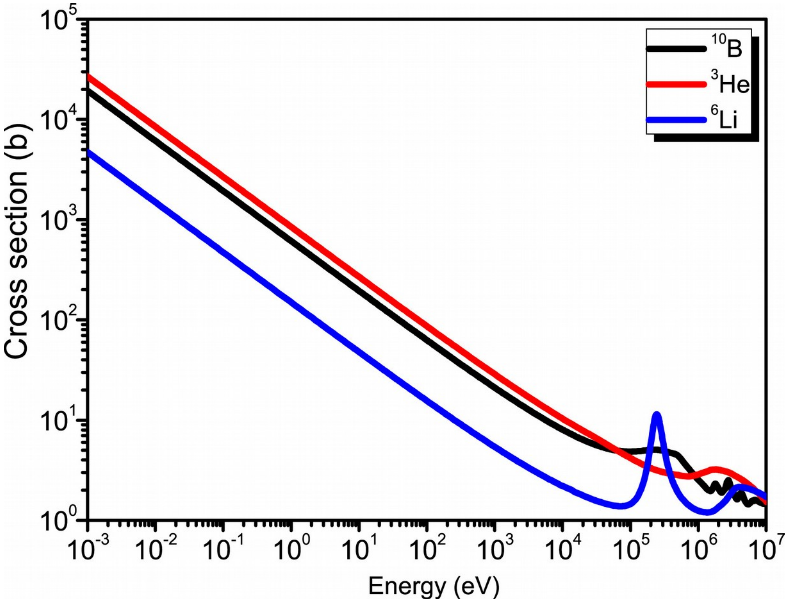
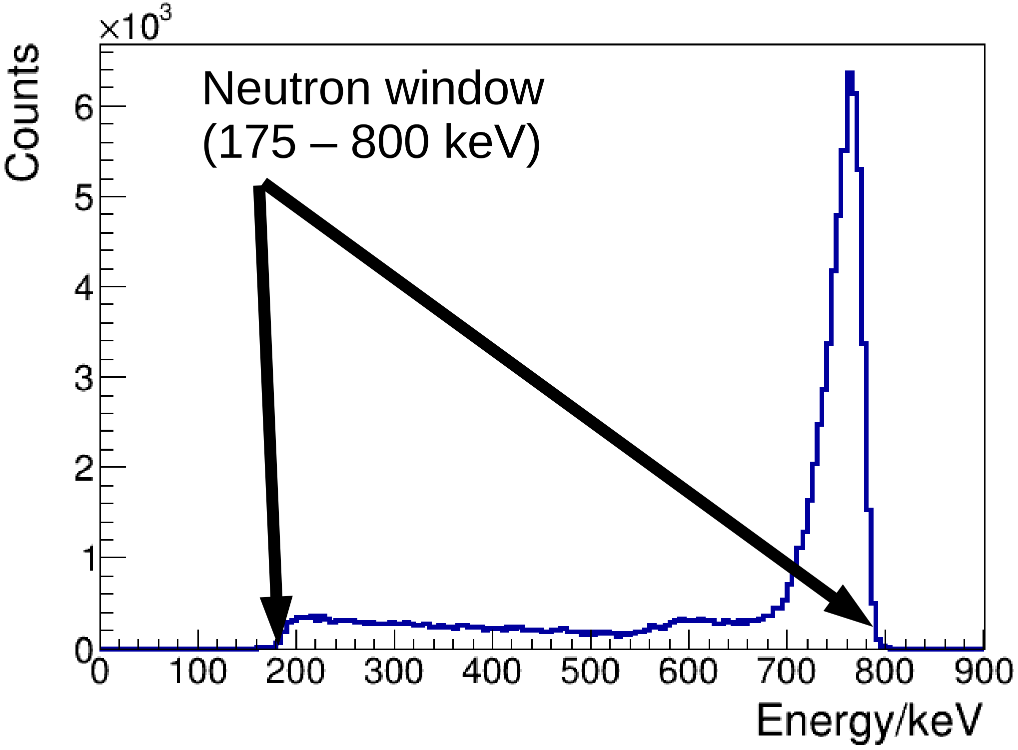
High Efficiency Neutron Spectrometry Array

Neutron detection in He-3 proportional counters

$^{3}He + n \rightarrow {}^{3}H + p + 764\ keV$





What is HENSA?

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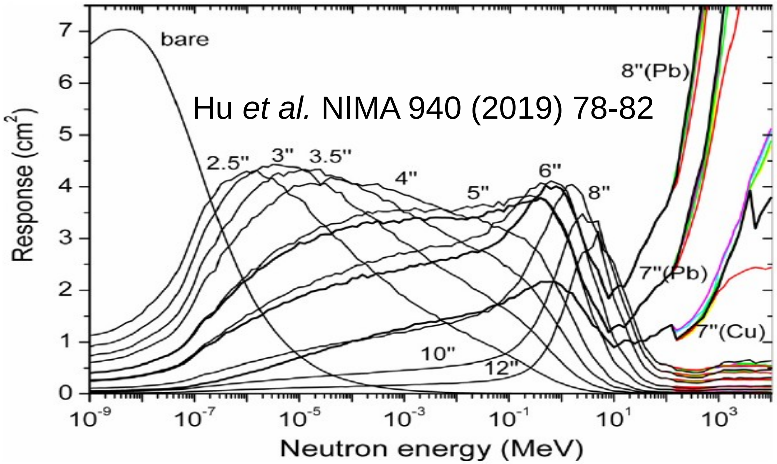
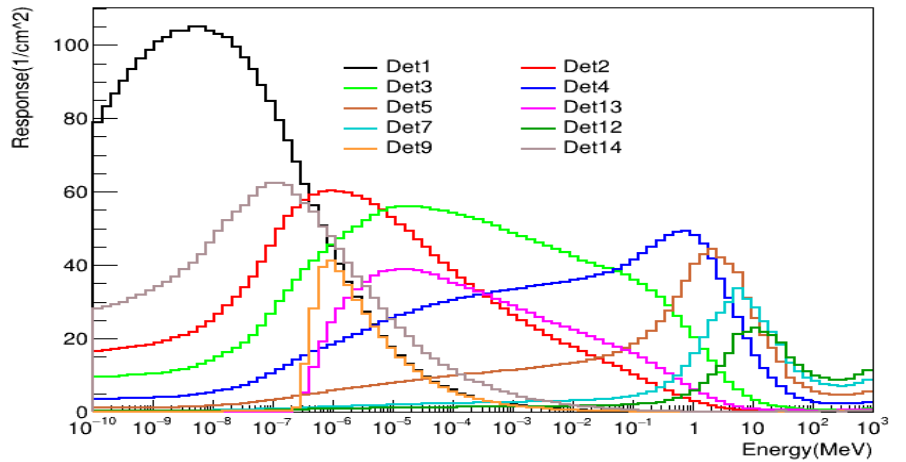
Standard extended Bonner Spheres



HENSA version 2022



HENSA neutron response is **~5-15 times larger** than standard Bonner Spheres systems in the energy range **from thermal up to 20 MeV**.

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

HENSA before LNGS

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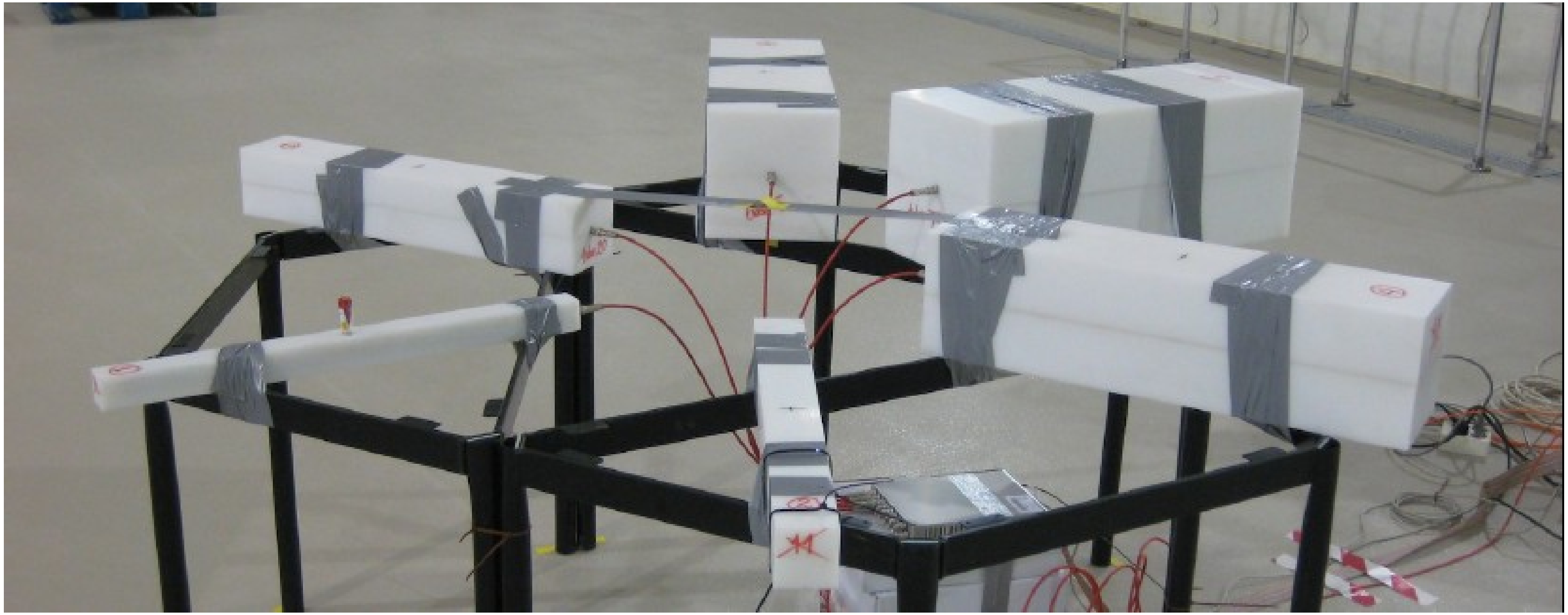
HENSA at LSC (first measurement in hall A)

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

Corrigendum: D. Jordan et *al* 2020, Astroparticle Physics 118, 102372



HENSA before LNGS

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

HENSA before LNGS

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

HENSA before LNGS

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Long-term measurement at LSC (hall A)

S. E. A. Orrigo *et al* 2021, J. Phys.: Conf. Ser. 2156, 012169

S. E. A. Orrigo *et al* 2022, European Physics Journal C 82, 814

HENSA before LNGS

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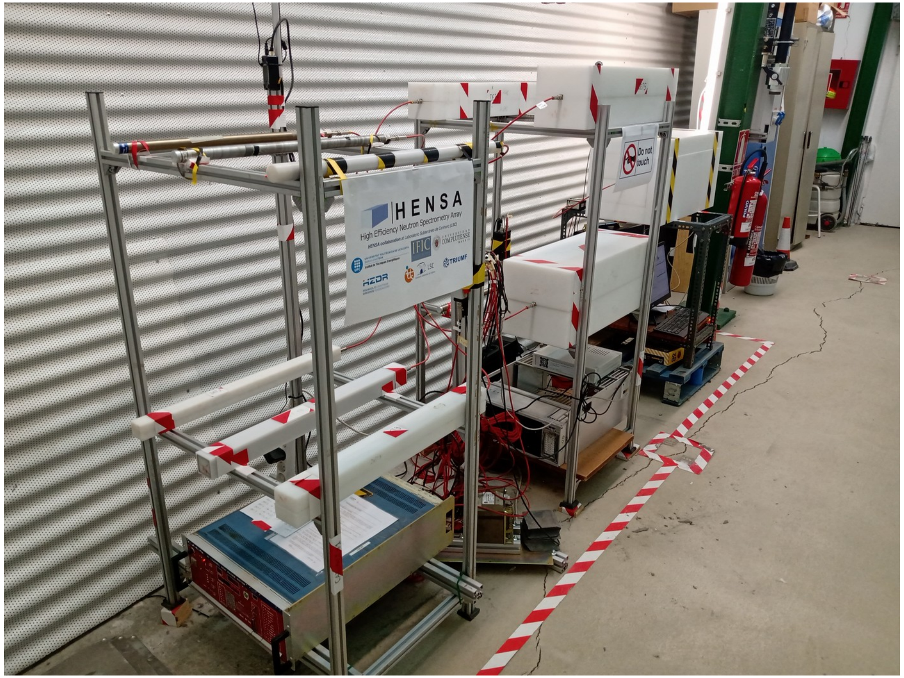
Long-term measurement at LSC (hall B)

N. Mont-Geli *et al* 2021, J. Phys.: Conf. Ser. 2156, 01223

N. Mont-Geli *et al* 2023, Proceedings of Science 441, 312



HENSA before LNGS

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HENSA for CR (in 2020 and since 2023/2024)

HENSA at LSC

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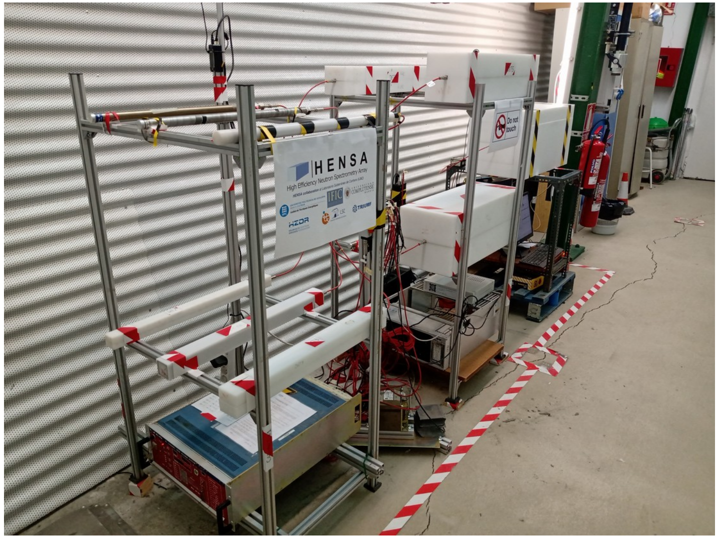
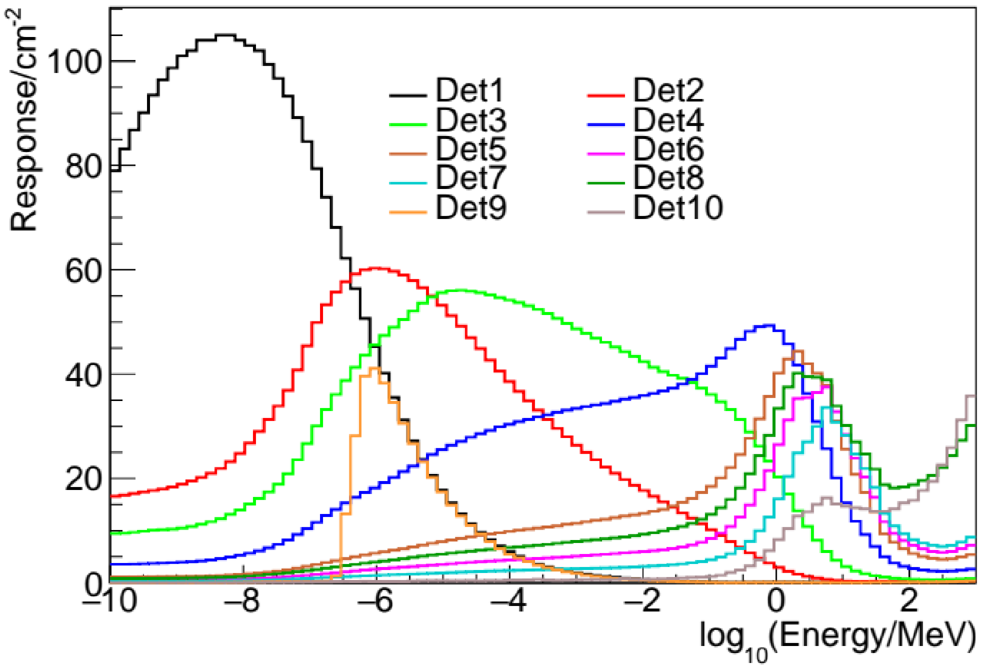
Long-term measurements in halls A and B

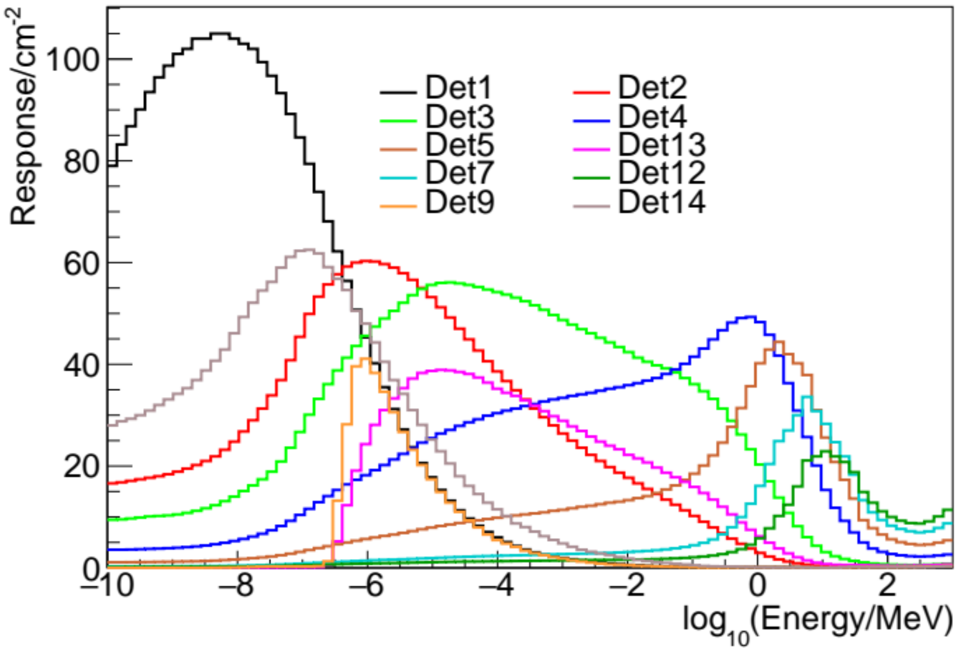
Two setups:

- HENSA-v2019 (hall A, October 2019 – March 2021).
- HENSA-v2019 (hall B, February 2022 – August 2022).
- HENSA-v2022 (hall B, since August 2022) – **Better spectral resolution**



Responses


Response/cm^-2
100
80
60
40
20
0
−10
−8
−6
−4
−2
0
2
log10(Energy/MeV)
Det1
Det2
Det3
Det4
Det5
Det6
Det7
Det8
Det9
Det10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Det1
Det2
Det3
Det4
Det5
Det13
Det7
Det12
Det9
Det14

HENSA at LSC

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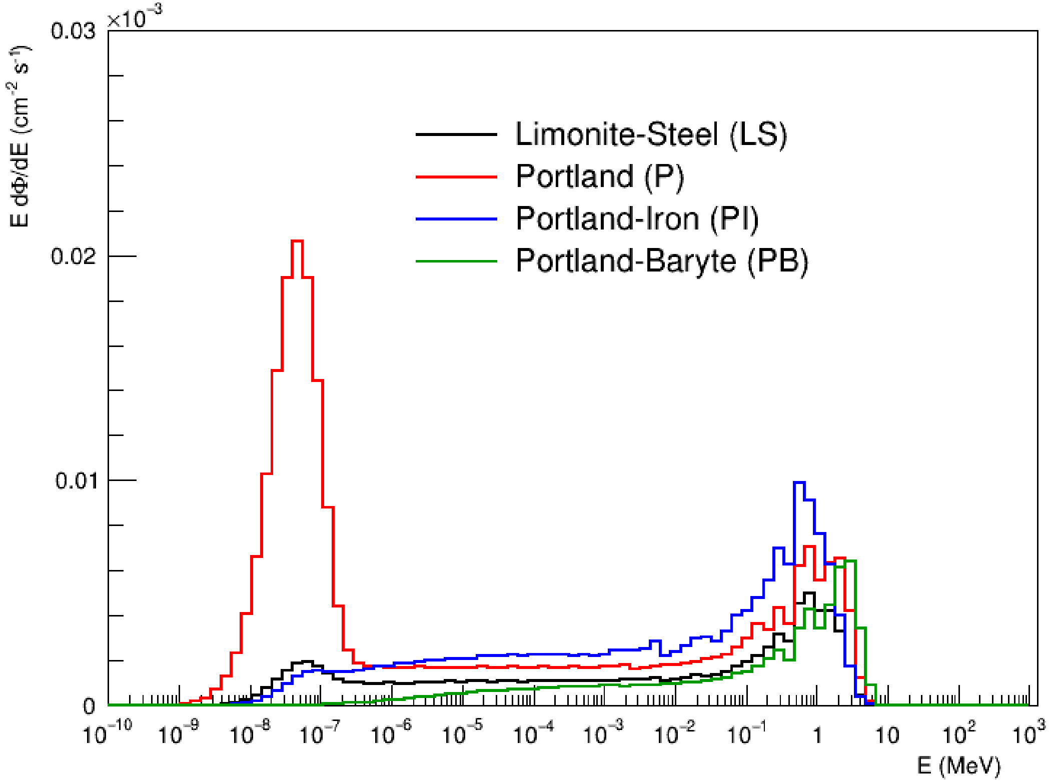
Neutron source in hall A

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

- **(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
HE peak ~ 50 MeV

Concrete contribution: 94%
Rock contribution: 6%
Muons contribution: 0.03%



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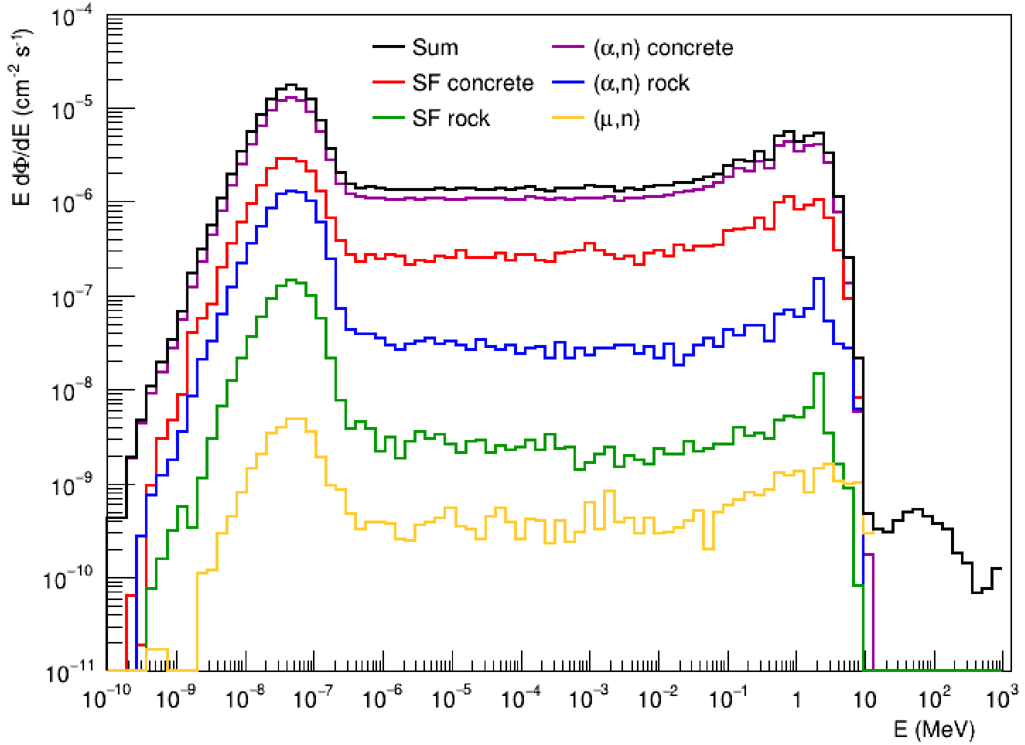

Energy spectrum

Unfolding algorithms:

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

- Bayesian method: **S. Agostini, NIM A 362 (1995) 487**
  - Computational implementation 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)**

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

HENSA at LSC

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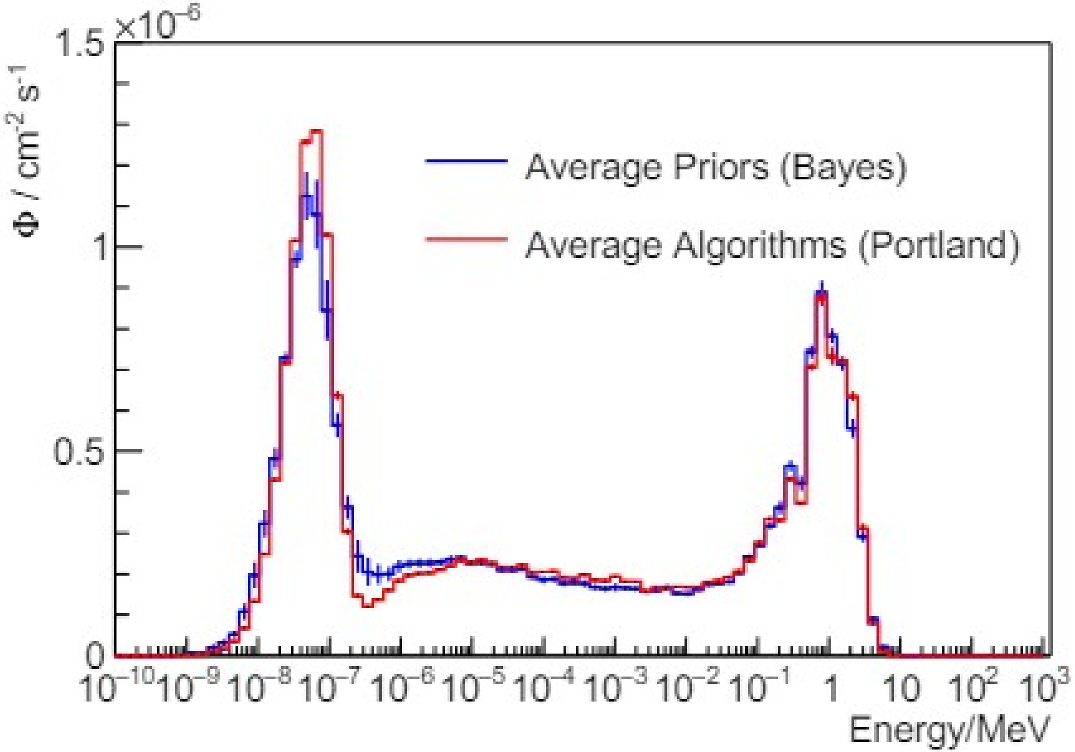
Energy spectrum (hall B)



N. Mont-Geli *et al* 2023, Proceedings of Science 441, 312

HENSA at LNGS

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- **Setup assembled in hall A from 17 to 20 April 2024.**
- **Acquisition started on 20 April 2024.**

HENSA at LNGS

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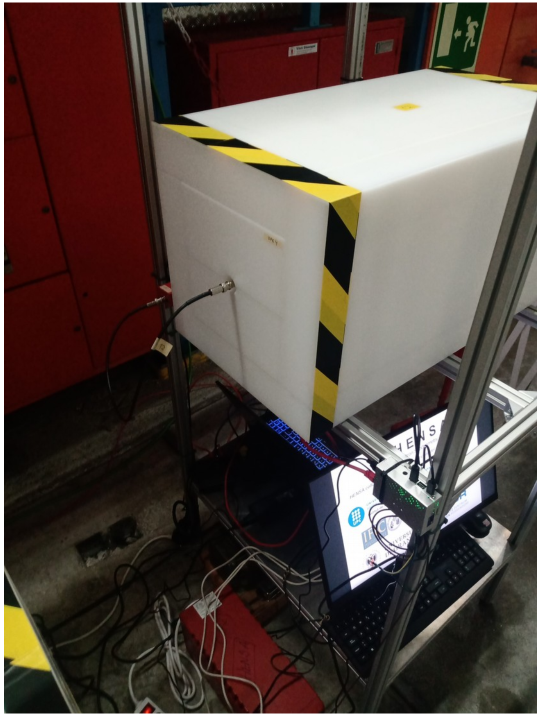
- 10 He-3 thermal neutron counters (2.54 cm diameter, 60 cm length)
- HDPE shielding with variable sizes (HDPE thickness from 32 to 380 mm)



HENSA at LNGS

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Current HENSA plans at LNGS

- Short measurements (2 – 4 months) at different locations:
  - Hall A, since late April 2024.
  - Inside the new STELLA facility (begin in mid-July until late September/October).
  - Other locations: hall B, hall C.
- Long-term monitorization of the neutron flux (minimum 1 year).
  - Location to be decided.

Status of the neutron data at LNGS

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)

Status of the neutron data at LNGS

I have compiled ten different previous works related with neutrons (1985 – 2019).

Only two works provides a “complete” spectrum (from thermal to fast energies):

- Belli (1989) using a HENSA-like setup (but no unfolding) in hall A.
- Arneodo (1999) direct energy measurement (proton recoil) in hall C.

Moreover, discrepancies between measurements. Example in hall A:

- Fast flux (cm^-2 s^-1):
  - Belli (1989): 0.32(14) E-6 (contribution above 2.5 MeV)
  - Aleskan (1989): 0.78(4)E-6 (only above 3 MeV)
  - Cribier (1995): 0.09(6)E-6 (only above 2.5 MeV)

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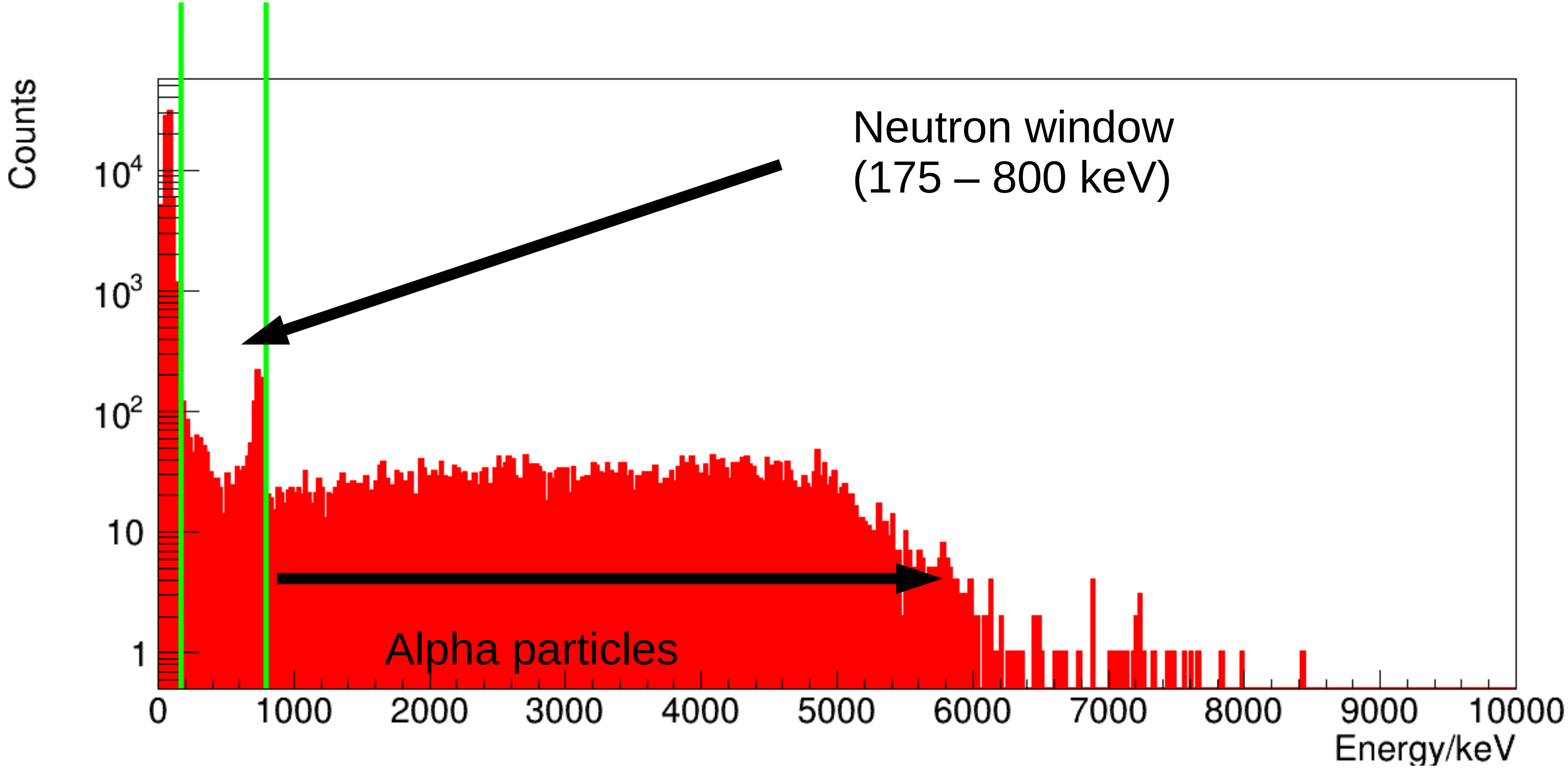
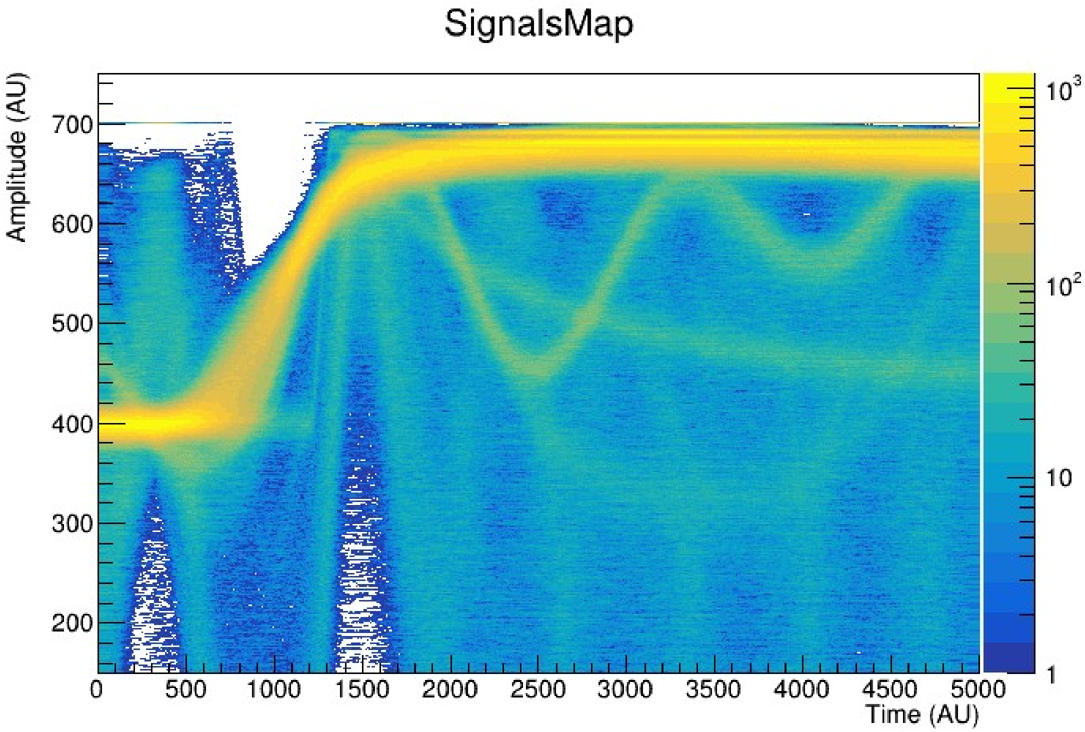
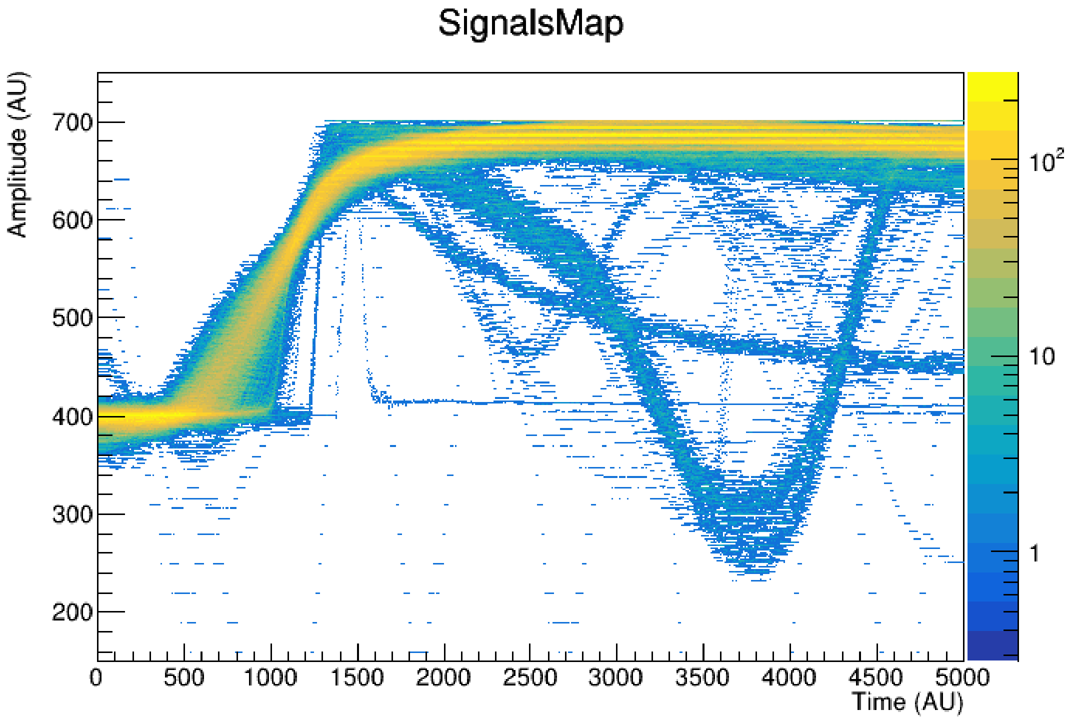
Pulse-height spectrum (neutron events overlaped with other contributions)



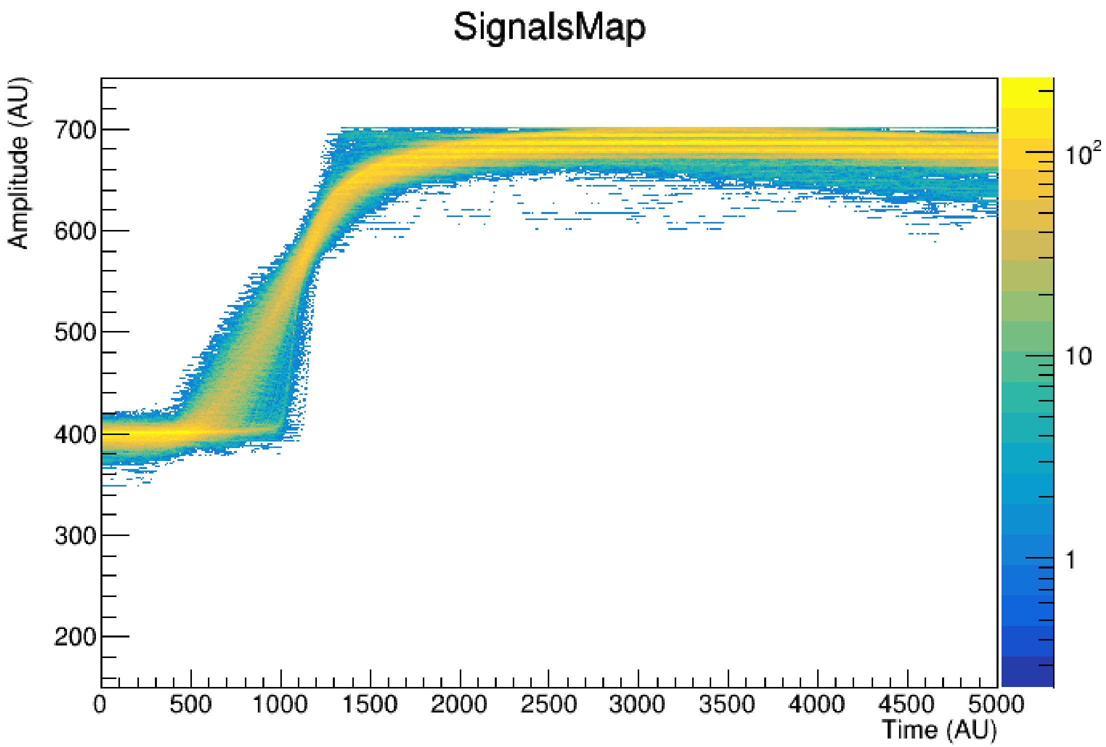
All signals (from 0 to 1000 keV)



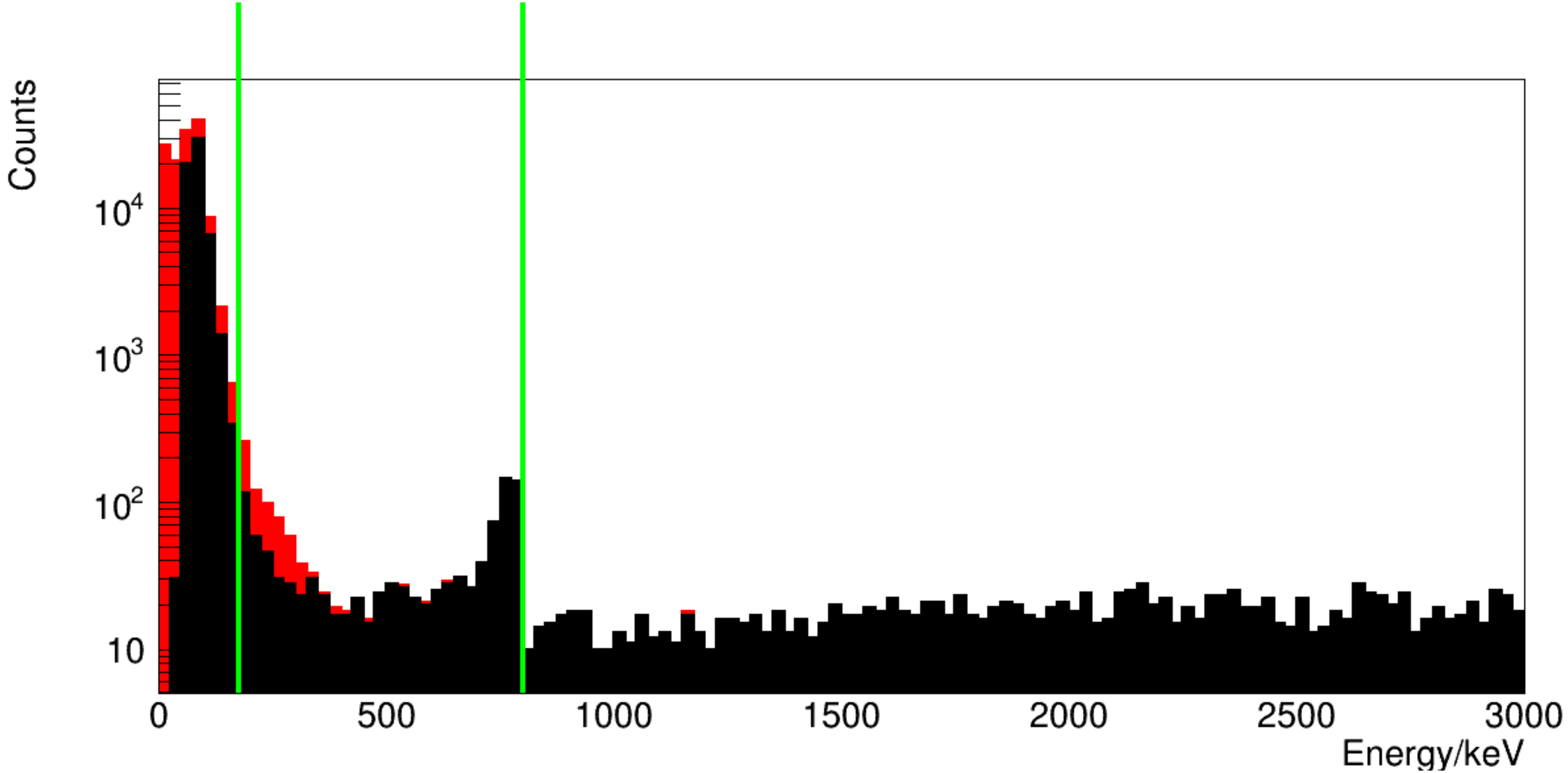
All signals (from 100 to 1000 keV)



Pulse Shape Discrimination (noise filter)

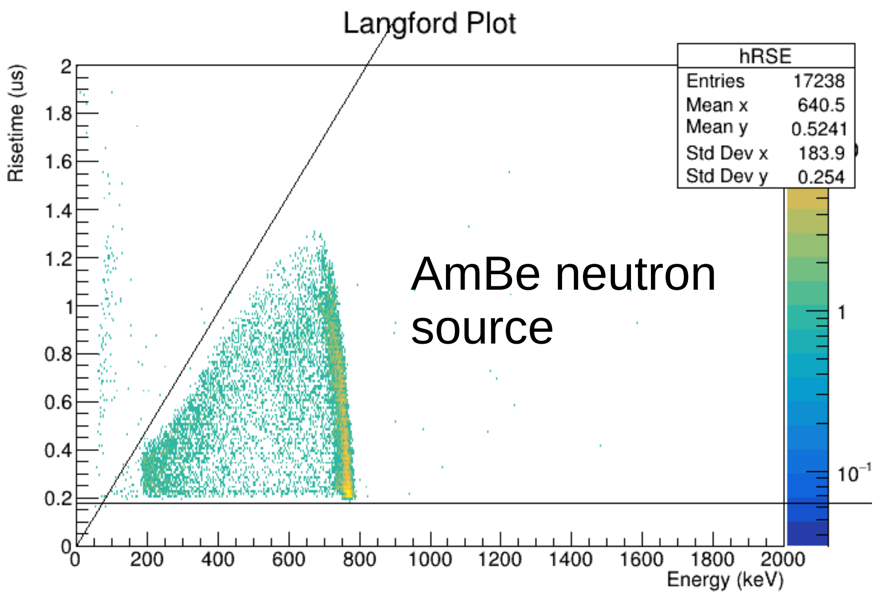


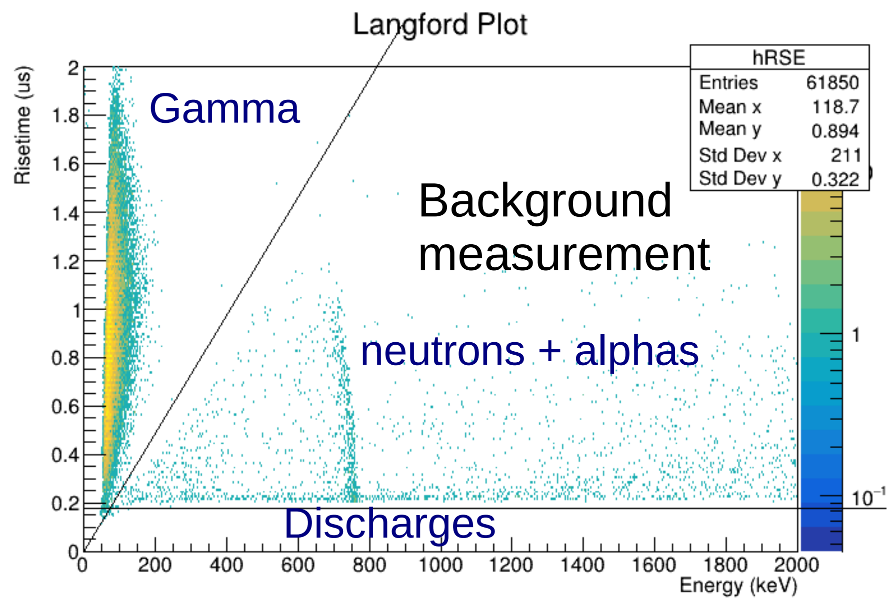
Pulse Shape Discrimination (noise filter)



Pulse Shape Discrimination (gamma rays and “fast” discharges filter)

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





HENSA in Hall A

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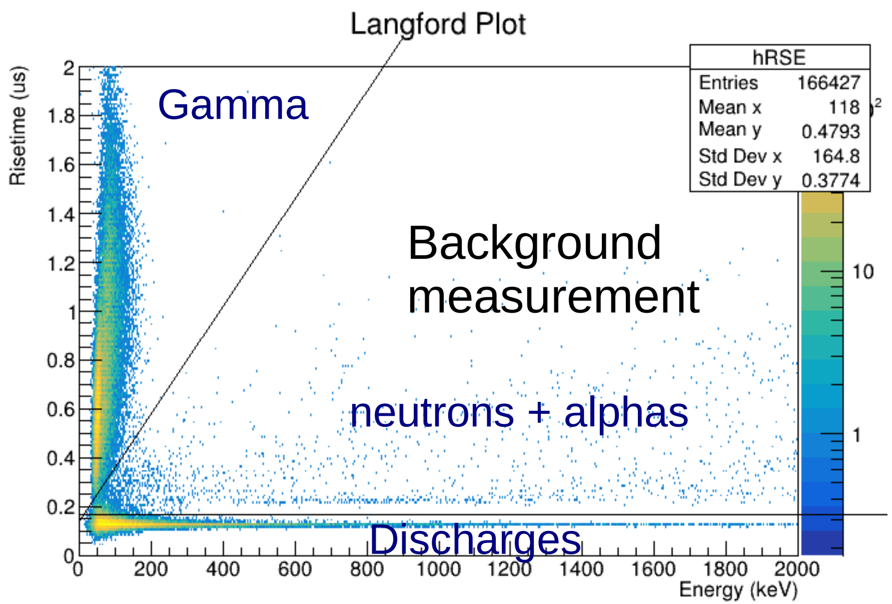
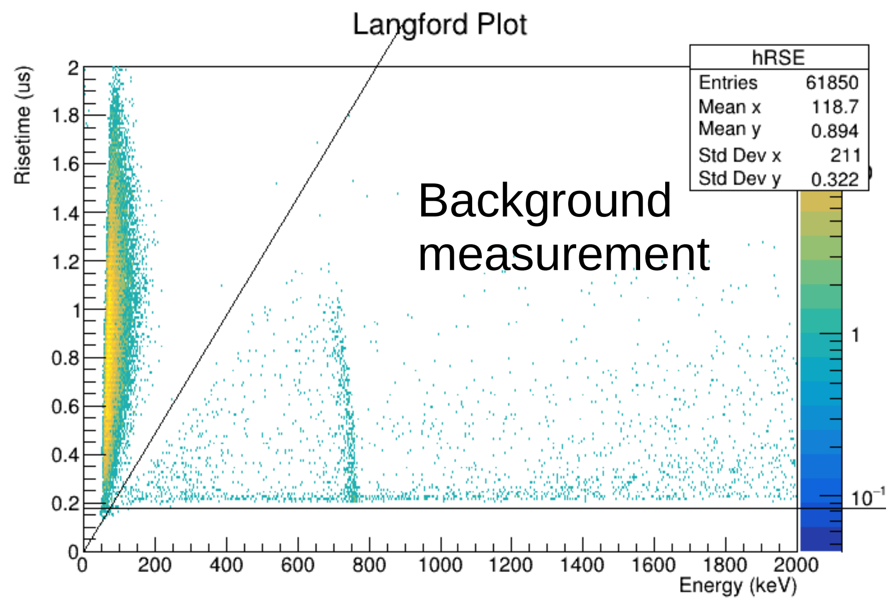
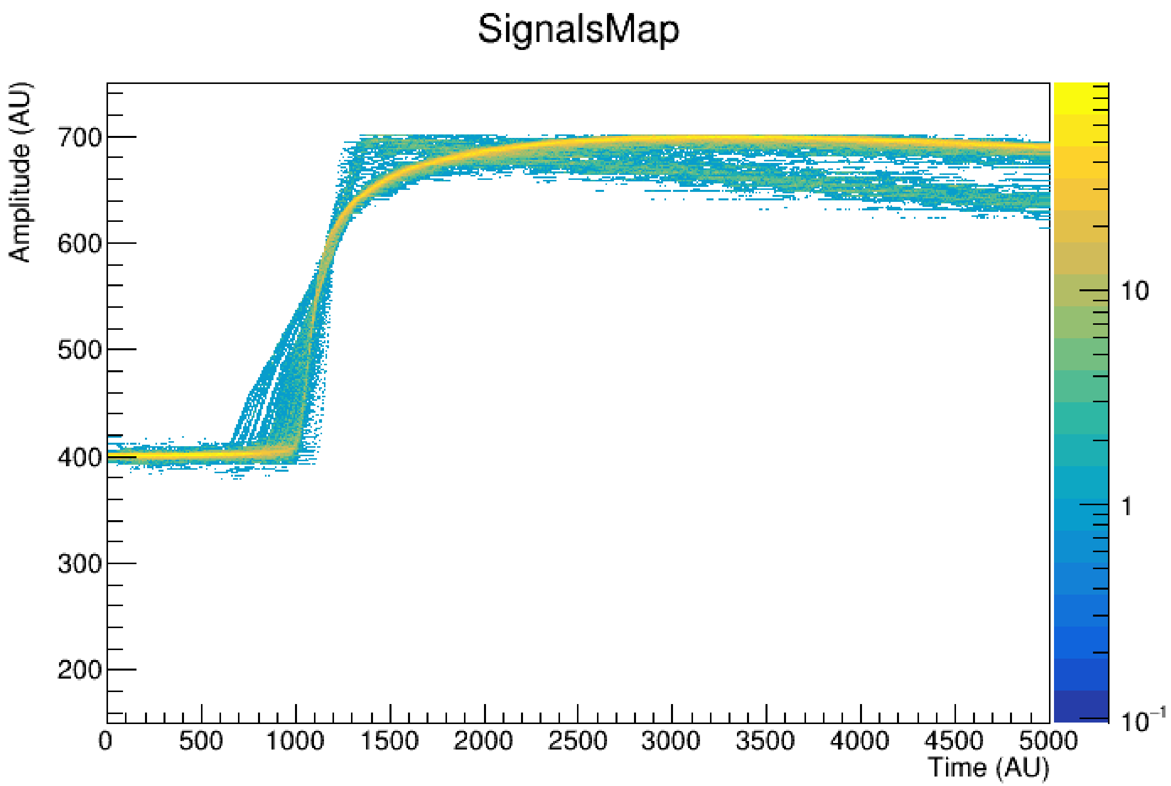
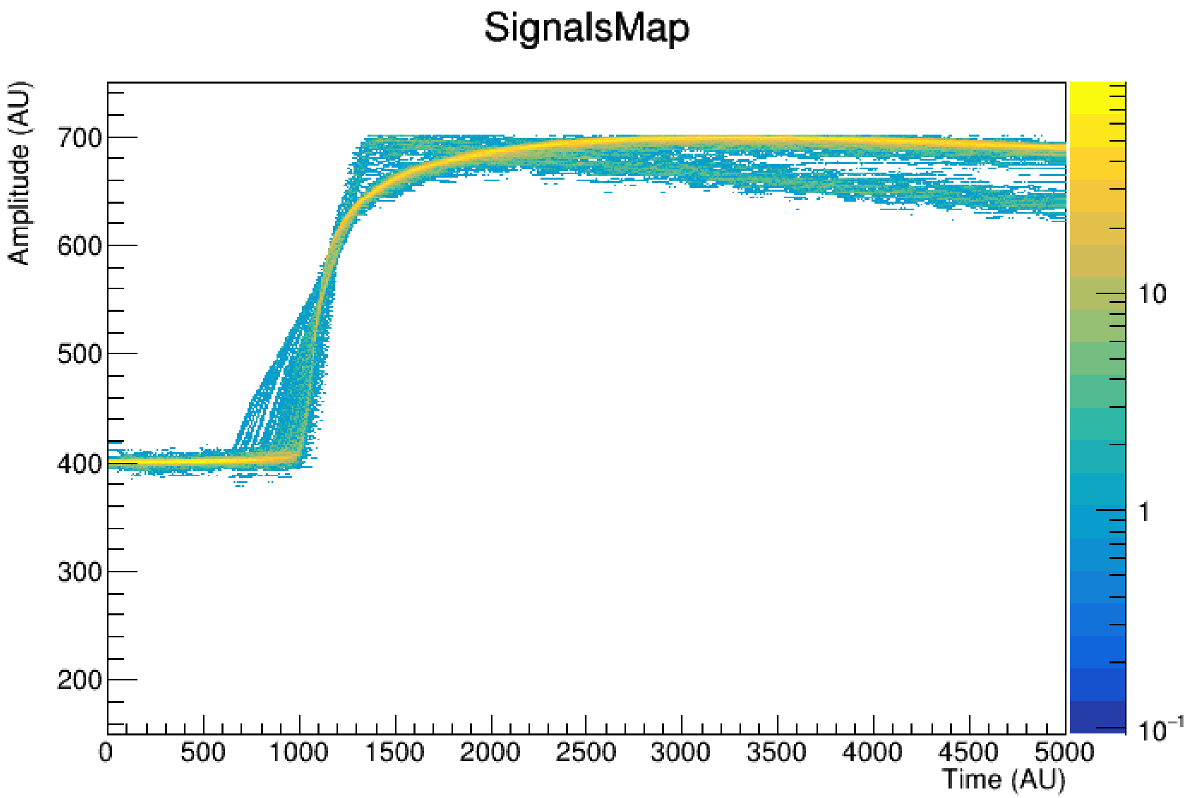




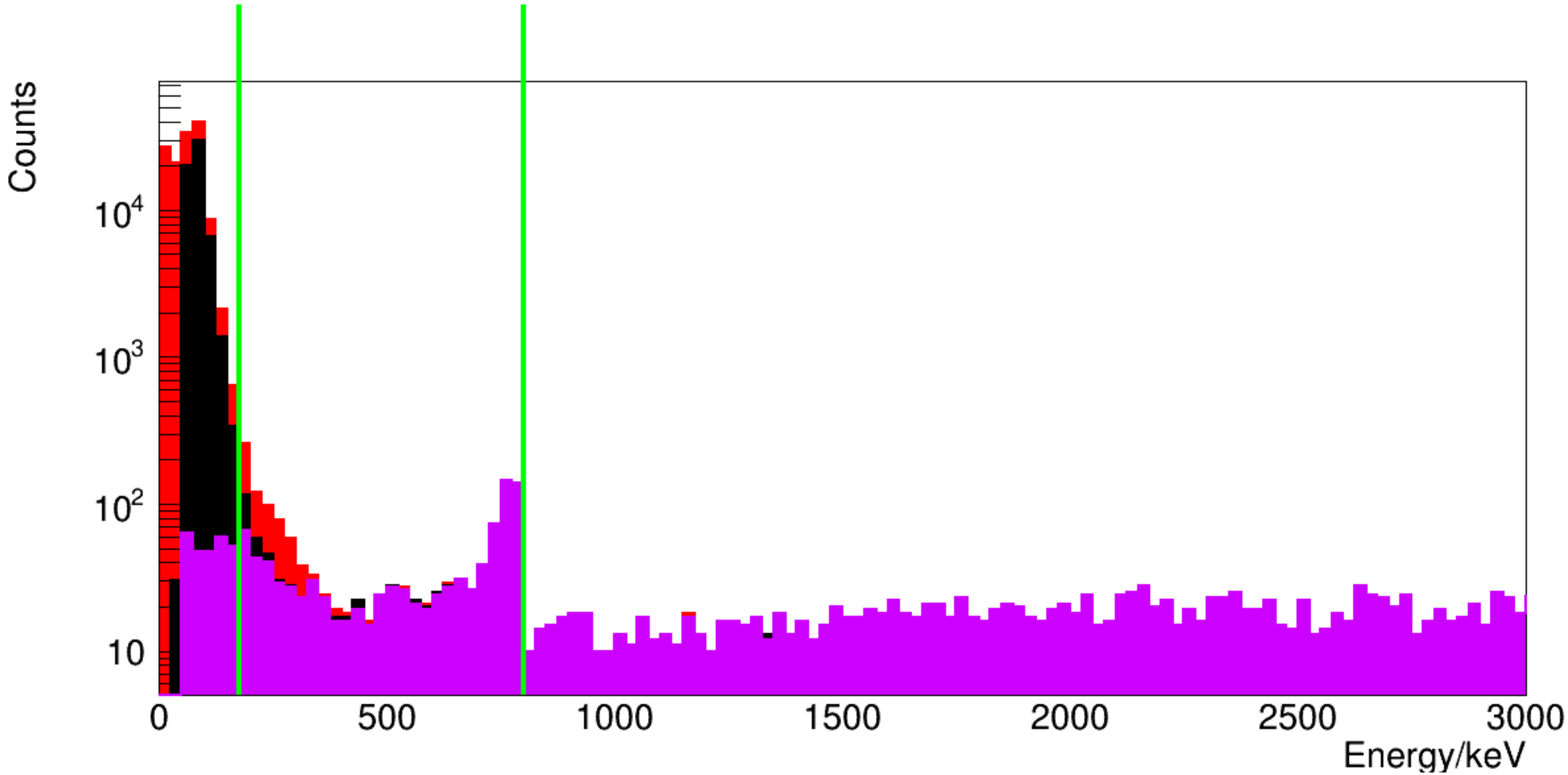
Pulse Shape Discrimination (Gamma filter)



Pulse Shape Discrimination (Langford filter)



Pulse Shape Discrimination (noise + Langford filter)



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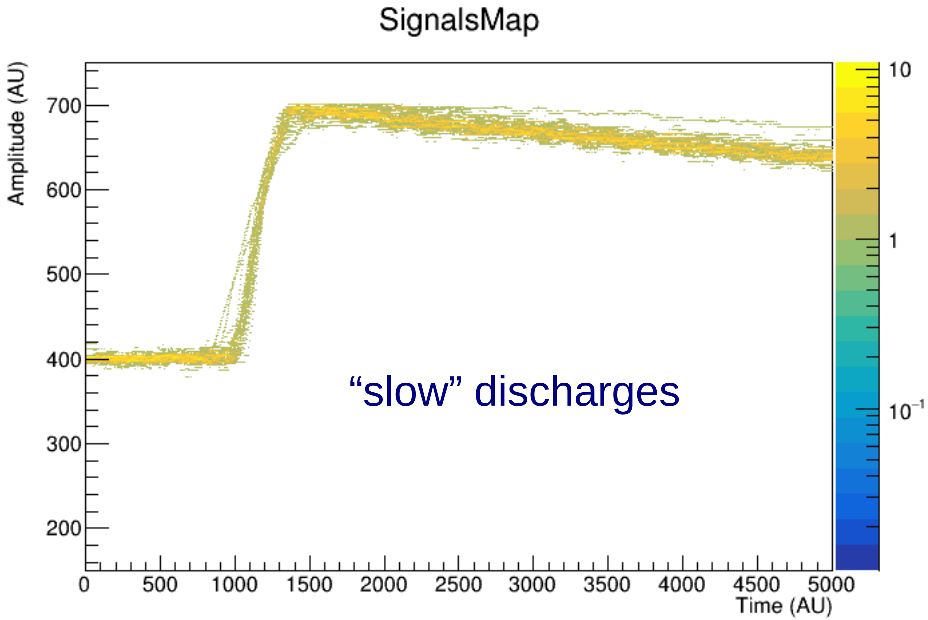
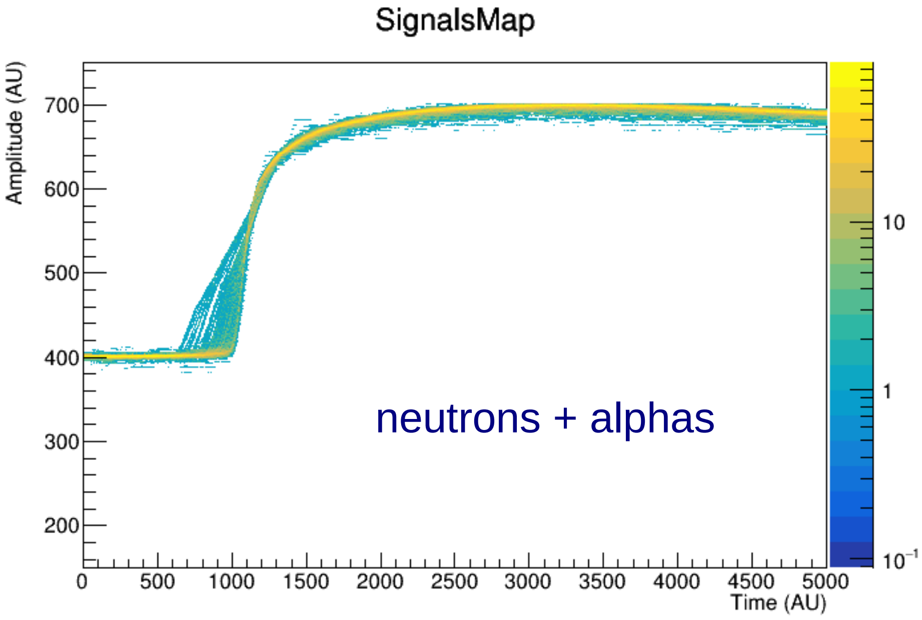
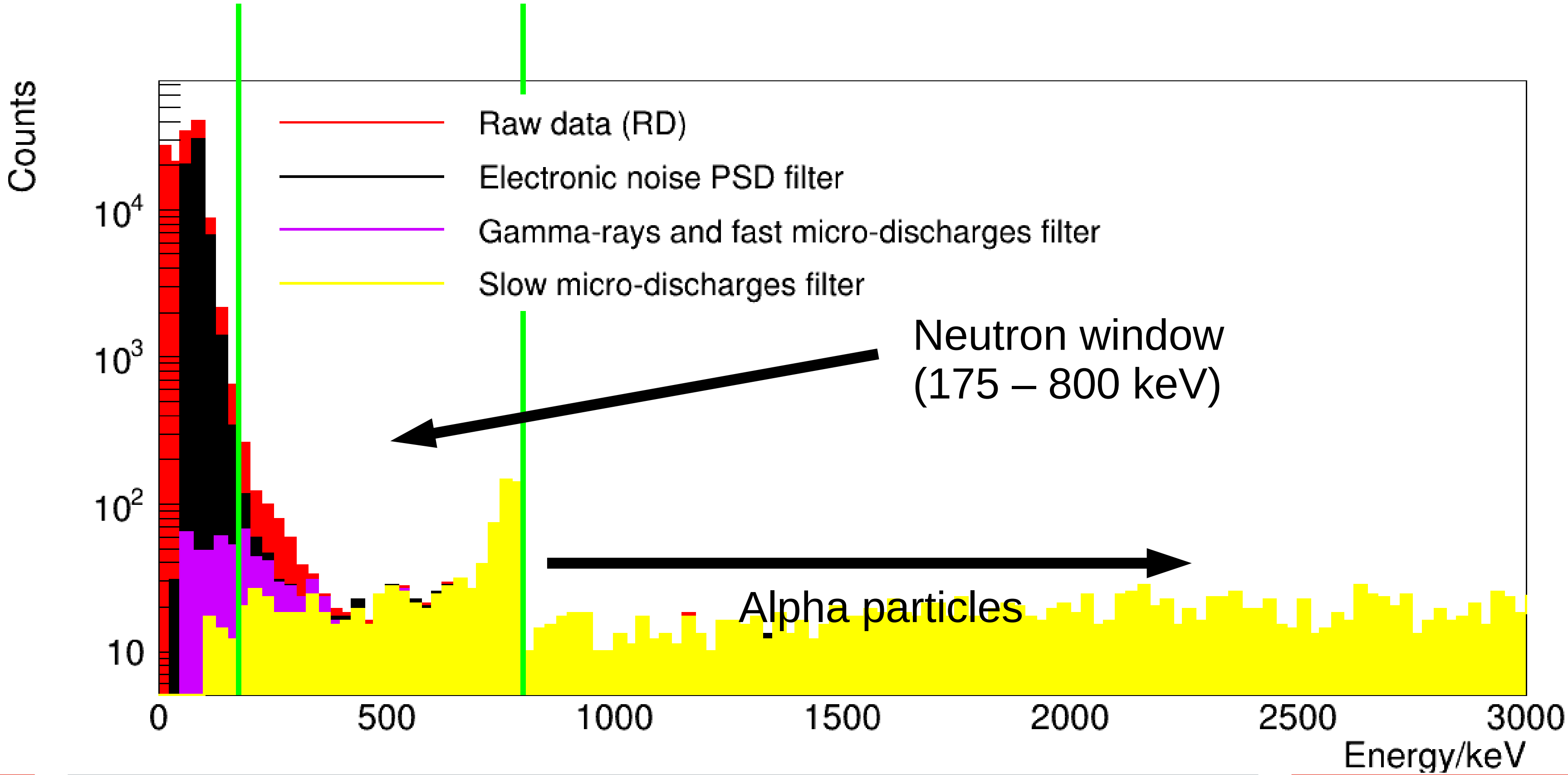
Pulse Shape Discrimination (“slow” discharges filter)

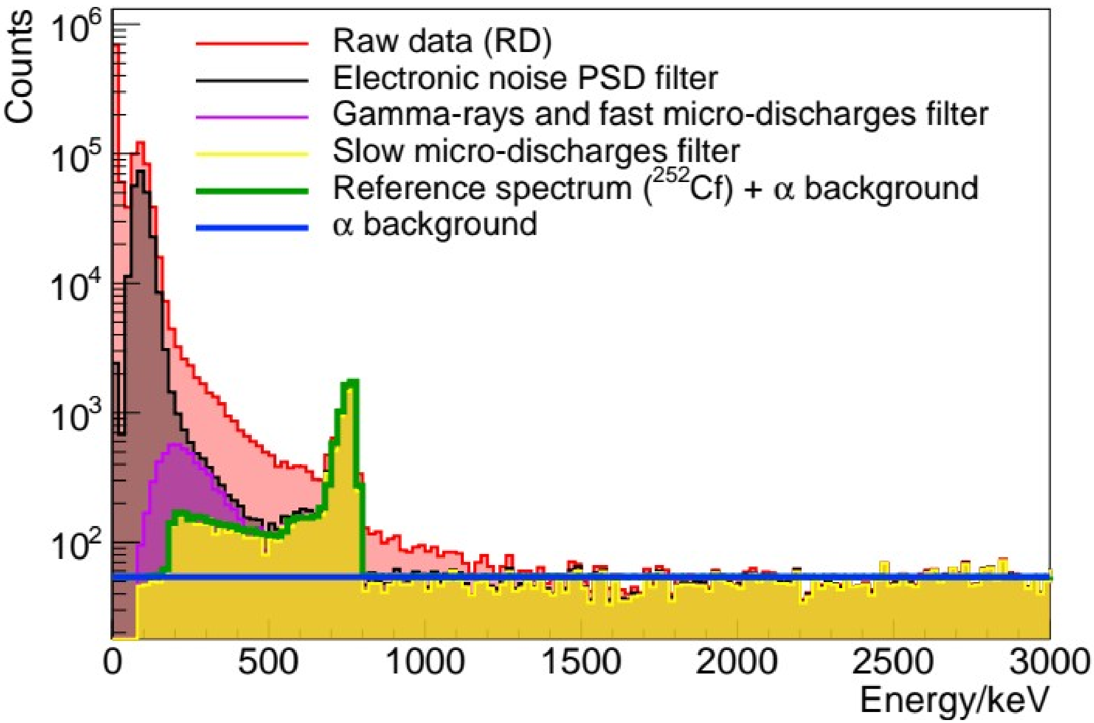




Pulse-height spectrum (+ PSD)



Pulse-height spectrum at LSC
(comparison with a pure 252Cf neutron spectrum)



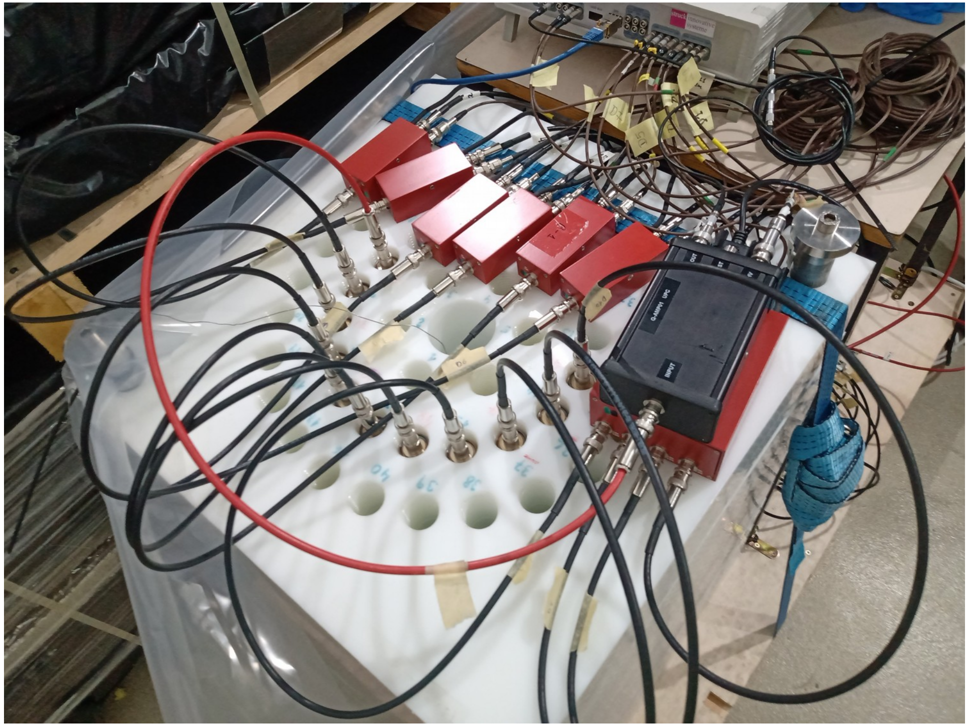
Characterization of the alpha background

Characterization of the intrinsic backgroud at Canfranc (LSC, Aug 23 – Feb 24)

- Counters completely covered with cadmium.
- Embedded in a HDPE shielding.

The result is that all neutron are absorbed before reaching the ^{3}He.

No neutrons are detected.



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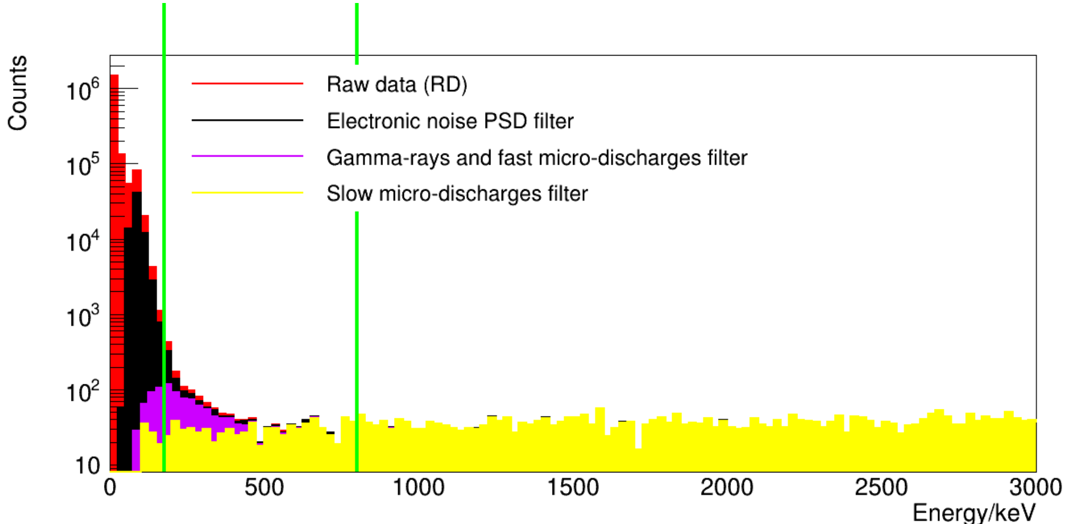

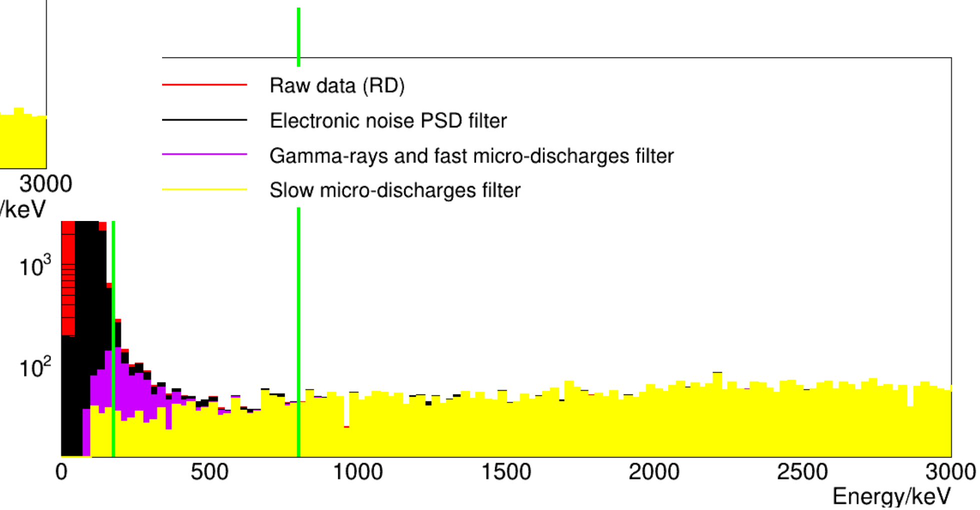

HENSA in Hall A

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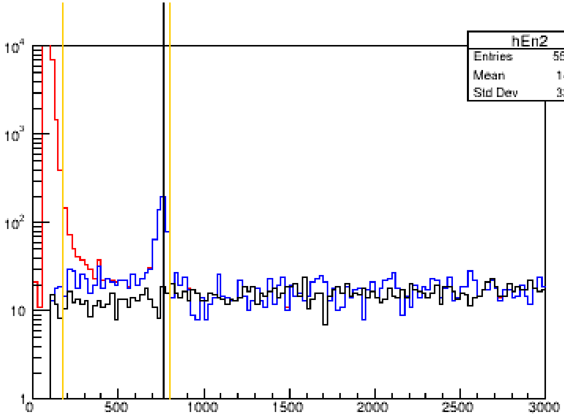
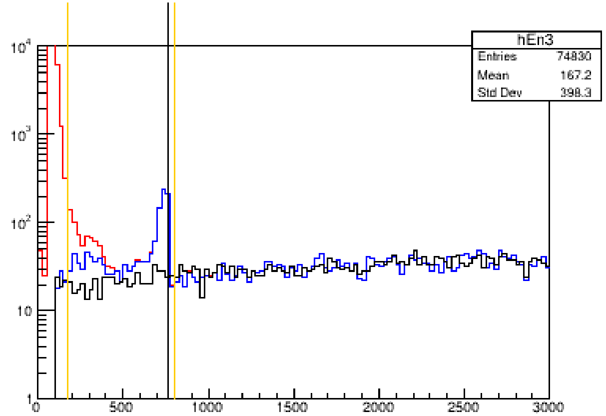
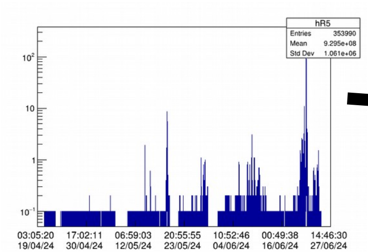
Substraction of the alpha background

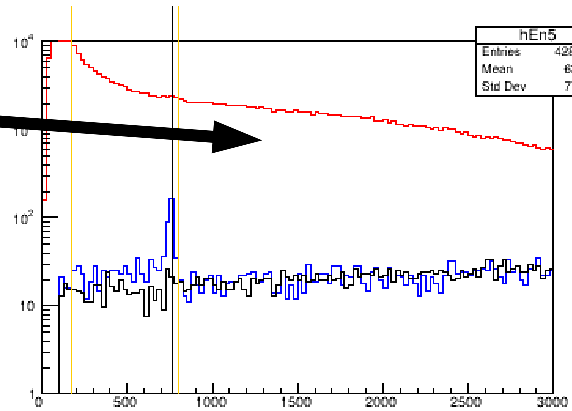
The alpha background is our main limitation!

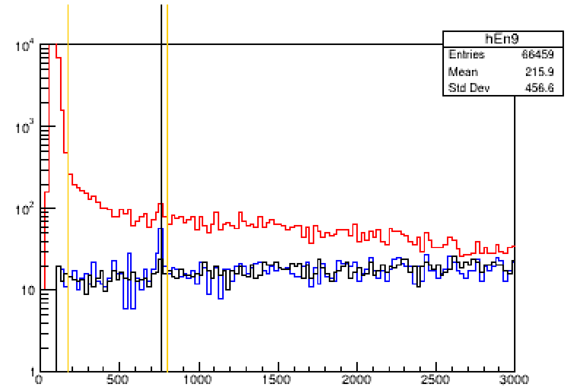




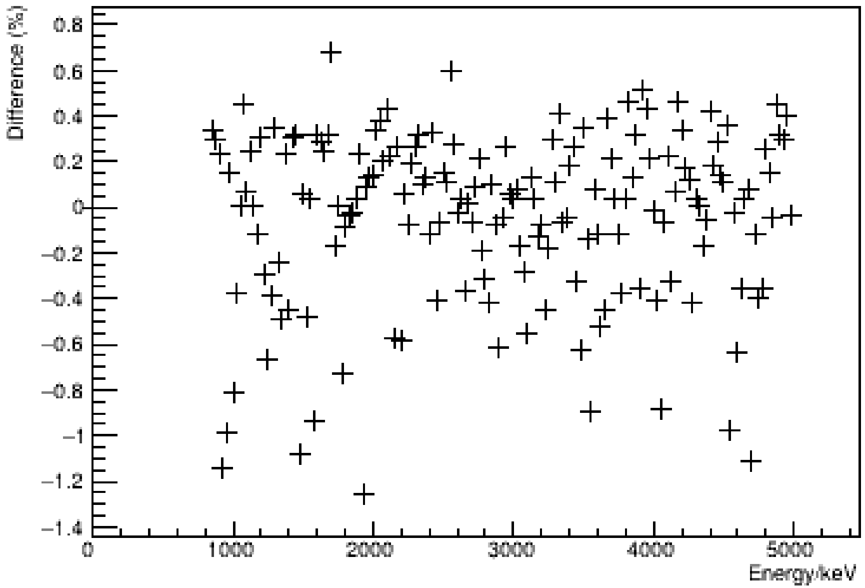


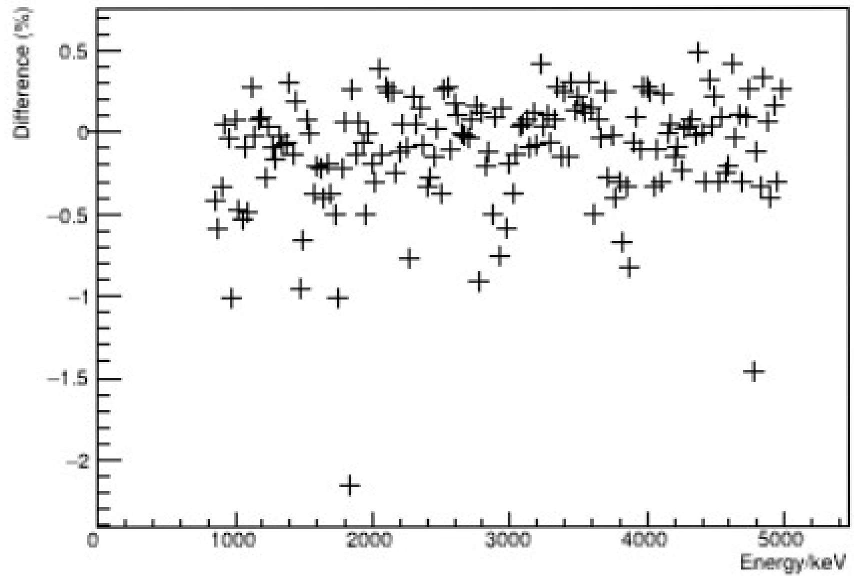
High micro-discharges rate periods (max: ~ 200 cpm)





Substraction of the alpha background (residuals)





HENSA in Hall A

HENSA
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Substraction of the alpha background (counting time: 59 days)

Detector	Rate (cps)	Error (cps)	Error
1	1.38E-04	7.31E-06	5.3%
2	1.48E-04	7.37E-06	5.0%
3	1.76E-04	8.55E-06	4.9%
4	1.42E-04	7.47E-06	5.3%
5	1.12E-04	6.82E-06	6.1%
7	4.51E-05	5.87E-06	13.0%
9	1.33E-05	5.30E-06	39.9%
12	1.67E-05	5.38E-06	32.3%
13	6.97E-05	6.15E-06	8.8%
14	1.25E-04	7.13E-06	5.7%

Substraction of the alpha background (counting time: 59 days)

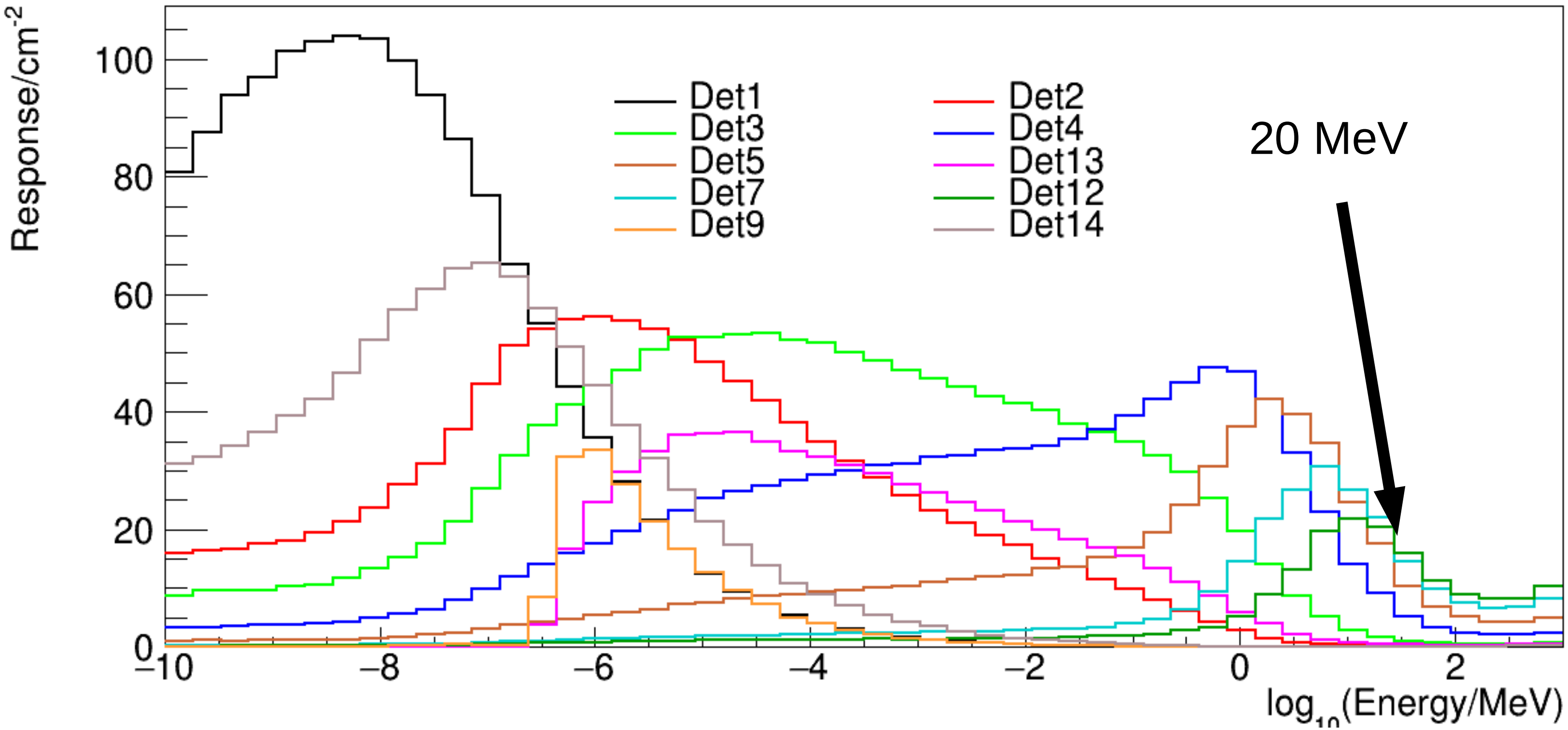
Detector	Rate (cps)	Error (cps)	Error
1	1.38E-04	3.28E-06	2.4%
2	1.48E-04	2.77E-06	1.9%
3	1.76E-04	3.96E-06	2.2%
4	1.42E-04	3.11E-06	2.2%
5	1.12E-04	2.92E-06	2.6%
7	4.51E-05	2.97E-06	6.6%
9	1.33E-05	3.20E-06	24.1%
12	1.67E-05	2.90E-06	17.4%
13	6.97E-05	2.89E-06	4.1%
14	1.25E-04	3.28E-06	2.6%

HENSA in Hall A

HENSA
High Efficiency Neutron Spectrometry Array

Energy spectrum

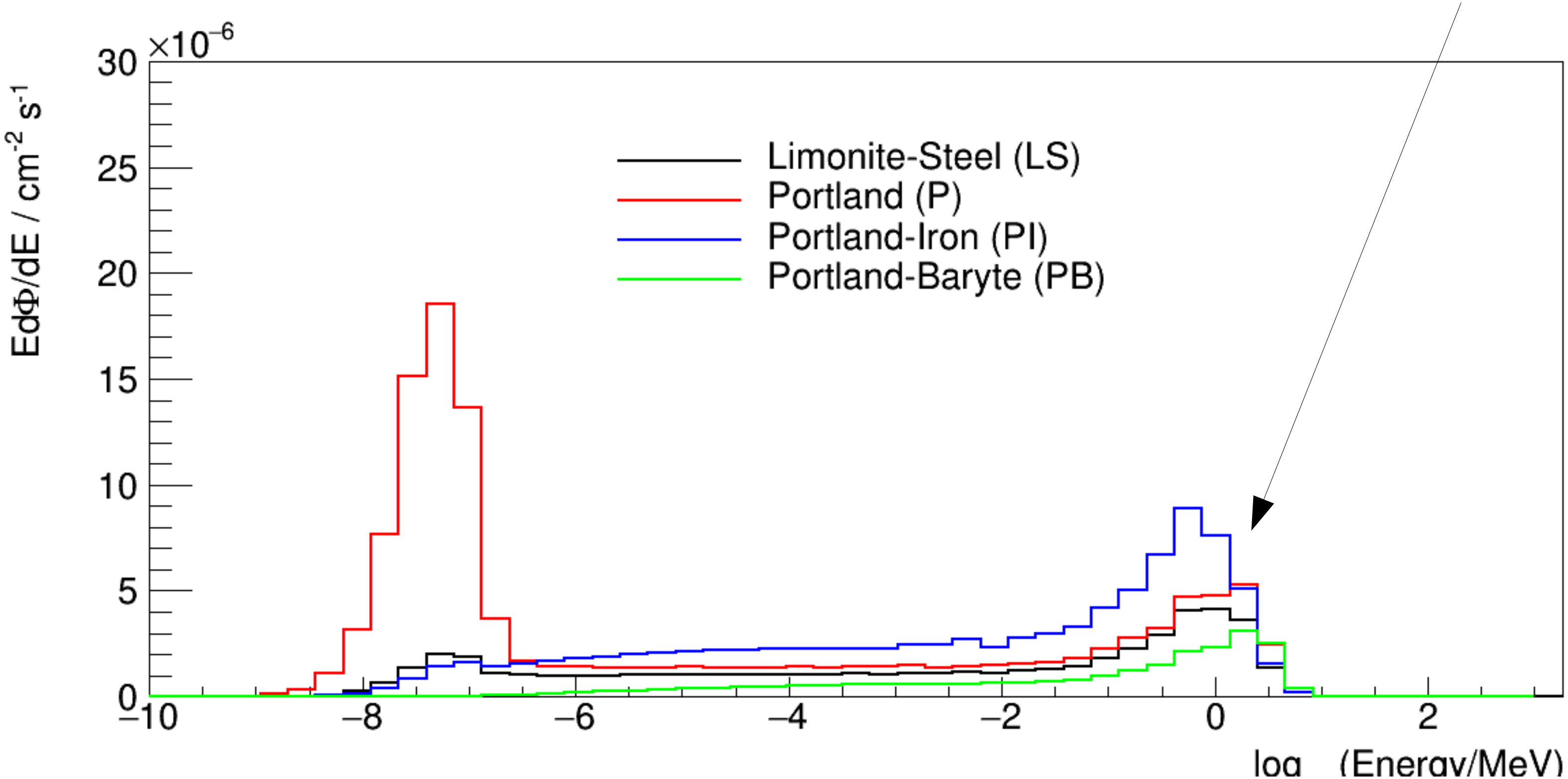
HENSA sensitivty from thermal up to 20 MeV



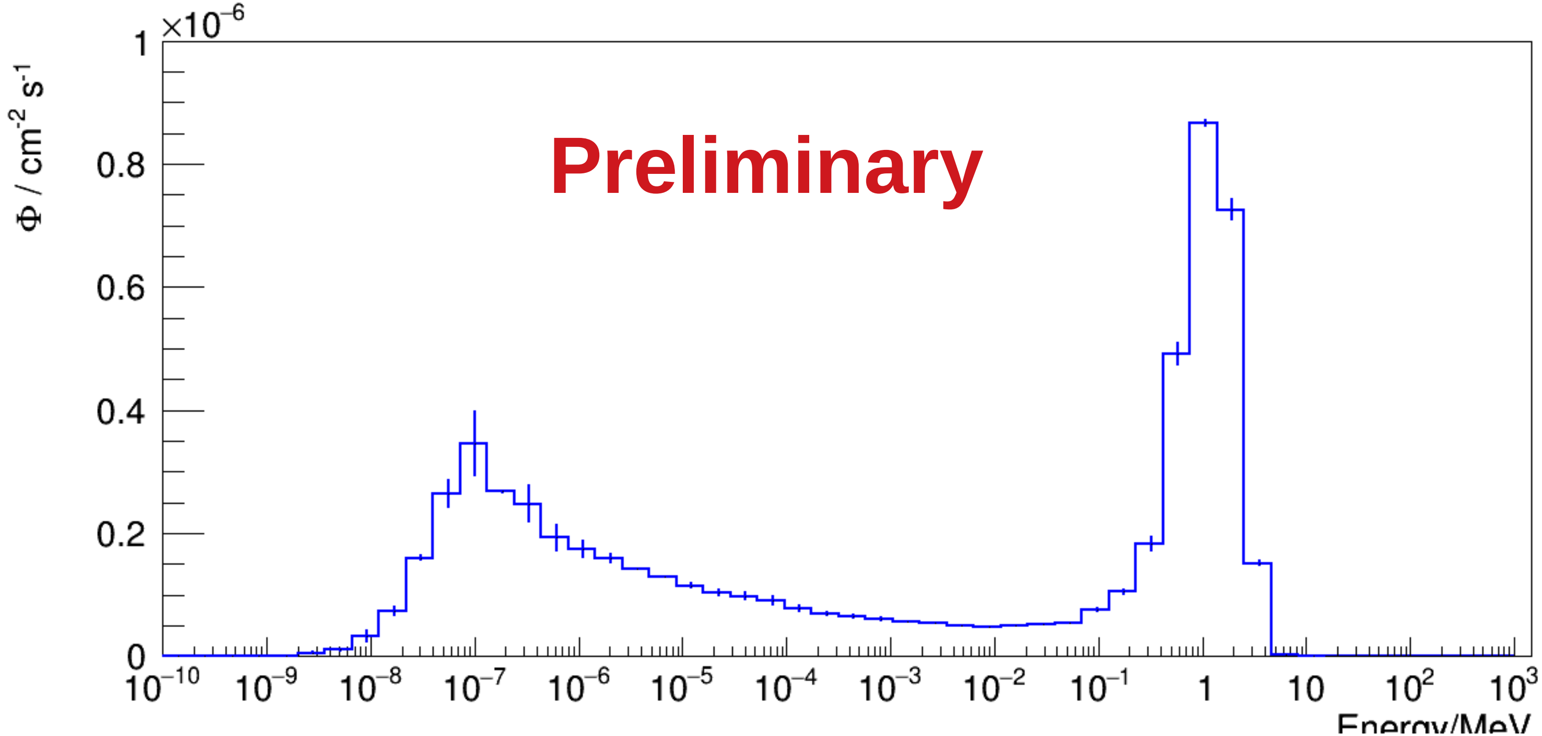
Energy spectrum (up to ~ 20 MeV)

Prior spectra (from Monte Carlo simulations)

0.5 – 3 MeV



Energy spectrum: (average from different priors)



HENSA in Hall A

HENSA
High Efficiency Neutron Spectrometry Array

Neutron flux in hall A (preliminary)

	Thermal	Intermediate	Fast flux	Total flux
LNGS (hall A)	**1.40(6)**	**2.16(5)**	**2.60(3)**	**5.85(8)**
LSC (hall B)	7.45(1)	7.425(7)	5.57(2)	20.45(2)
Belli 1989*	1.08(2)	-	0.86(14)	3.78(26)
*Best (2016)***	*0.320(130)*	-	-	-

*P. Belli et al. (1989): a mesurement of the neutron flux in hall A of the LNGS using an array of 5 large BF3 counters shielde with polyethylene and cadmium. The upper limits for thermal region they used is 0.5e-7 eV.
**Not in hall A, but in the the “interferometer tunnel”

Thermal: 0 < E < 3.2E-7 MeV
Intermediate: 3.2E-7 < E < 0.1 MeV
Fast: 0.1 < E < 20 MeV

About Belli (1989):
Maximum polyethylene shielding was 140 mm. In HENSA is 380 mm.

Summary

HENSA
High Efficiency Neutron Spectrometry Array

- **HENSA is a high efficiency neutron detection system based on the same principle than Bonner Spheres providing sensitivy to neutrons from thermal energies up to MeV.**

- **HENSA has been succesfully used for many years at the Canfranc Underground Laboratory (LSC) in order to characterize the underground neutron flux.**

- **A replica of HENSA has been assembled at LNGS. Firts results have been presented.**

Acknowledgments

HENSA
High Efficiency Neutron Spectrometry Array

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