NMDB Meeting 2025: Cosmic Ray studies with Neutron Detectors
Athens Neutron Monitor Station _ANeMoS 25th anniversary
Athens, 19-21 March 2025

HENSA
High Efficiency Neutron Spectrometry Array

HENSA++
Space weather & Dosimetry

Measurement of Cosmic-ray Neutrons with a High Efficiency Spectrometer

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www.hensaproject.org

- **Neutron spectrometry with moderated thermal counters**
- **The Bonner's Spheres Spectrometer (BSS)**
- **High efficiency BSS systems**
- **The HENSA project**
- **Previous activities with cosmic-ray neutrons**
- **HENSA++: status and perspectives**

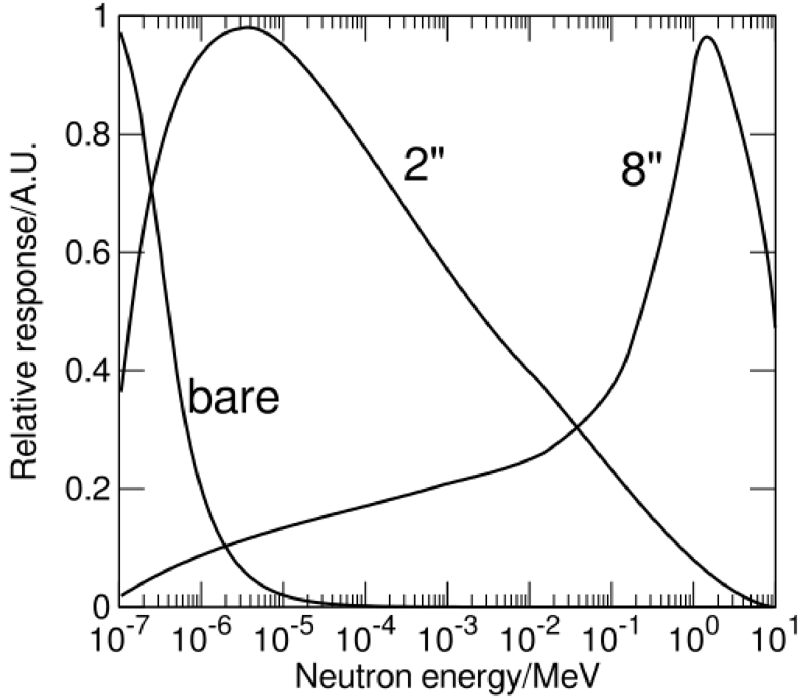
Neutron detection based on moderated thermal sensors

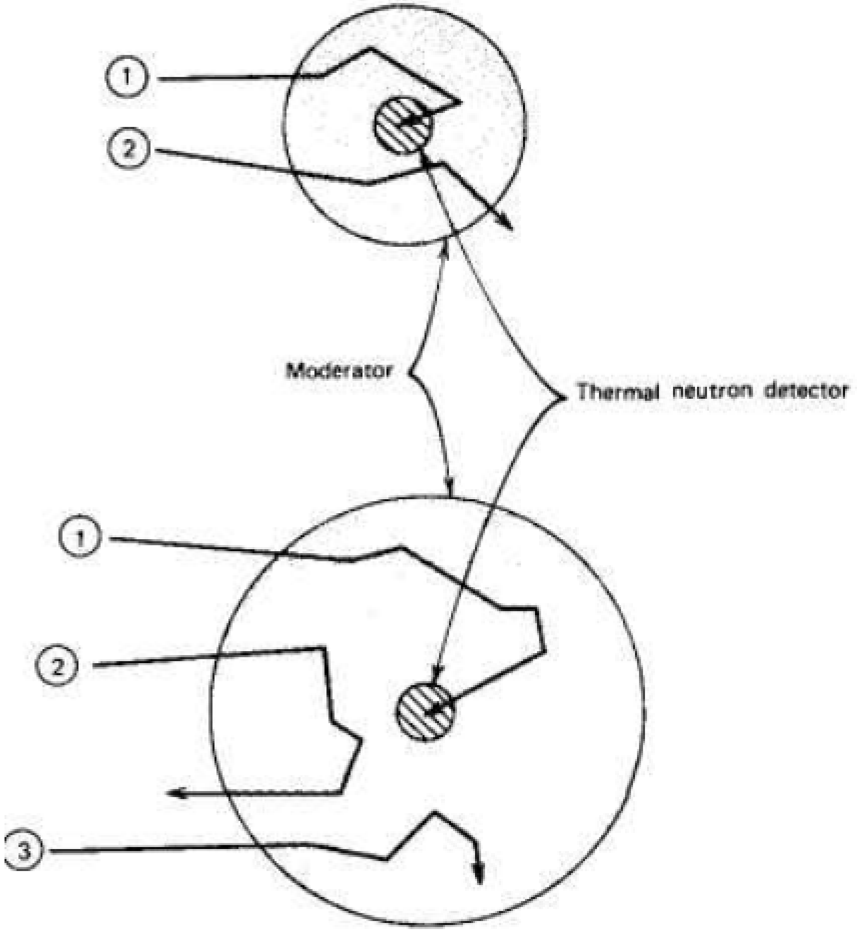
Detector response depends on:

- Moderator material: HDPE (H2O, graphite, etc)
  - ➔ scattering cross section
- Moderator geometry:
  - ➔ size or "effective thickness"

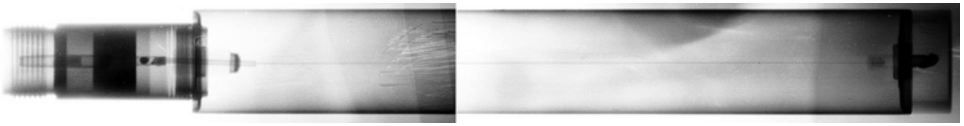
- Neutron energy:
  - ➔ Simple moderator: meV – 20 MeV
  - ➔ Moderator+multipliers: meV - GeV's

- Thermal sensors: 3He, BF3, 6LiI(Eu) scintillator
  - ➔ Cross section
  - ➔ Size





G. Knoll, Radiation detection and measurement, 3rd ed.



Detection reaction:

$$^{3}He + n \rightarrow {}^{3}H + p \quad Q=0.764\ MeV$$

High Thermal cross section: **5330 barns!!!**

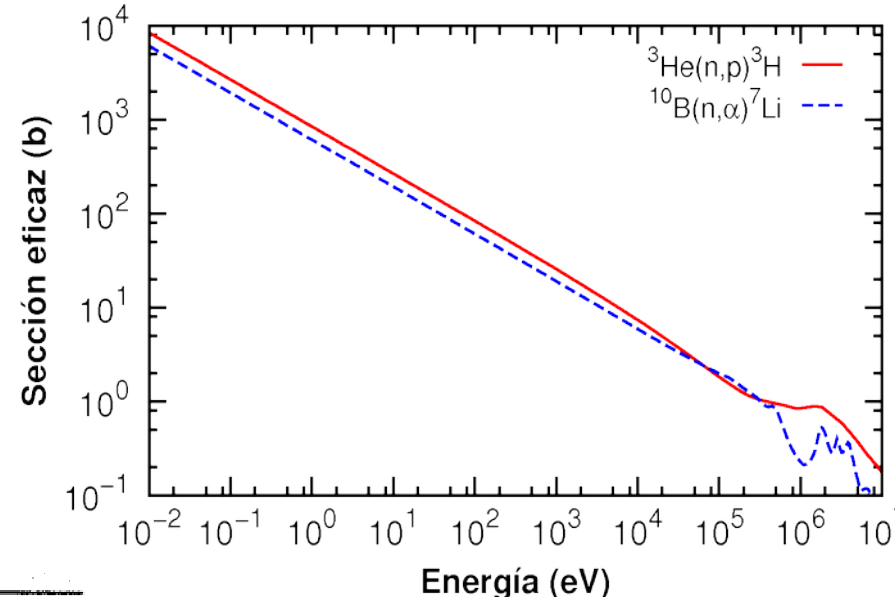


Table 13-1. Neutron and gamma-ray interaction probabilities in typical gas proportional counters and scintillators

Thermal Detectors	Interaction Probability: Thermal Neutron	Interaction Probability: 1-MeV Gamma Ray
^{3}He (2.5 cm diam, 4 atm)	0.77	0.0001
Ar (2.5 cm diam, 2 atm)	0.0	0.0005
BF_3 (5.0 cm diam, 0.66 atm)	0.29	0.0006
Al tube wall (0.8 mm)	0.0	0.014

Fast Detectors	Interaction Probability: 1-MeV Neutron	Interaction Probability: 1-MeV Gamma Ray
^{4}He (5.0 cm diam, 18 atm)	0.01	0.001
Al tube wall (0.8 mm)	0.0	0.014
Scintillator (5.0 cm thick)	0.78	0.26

*Extracted from Neutron Detectors, T. W. Crane and M. P. Baker

- These neutron counters are gaseous ionization detectors that use 3He as converting gas.
- Due to the **high thermal capture cross section**, 3He filled counters have a high neutron sensitivity.
- For non-thermal neutrons, the high efficiency can be exploited by using moderators.
- In addition, the l**ow gamma-ray sensitivity** makes these detectors very attractive for neutron spectroscopy (Bonner spheres) and dosimetry.

NUCLEAR INSTRUMENTS AND METHODS **9** (1960) 1–12; NORTH-HOLLAND PUBLISHING CO.

6LiI(Eu) scintillator
+
Moderator spheres
2”-12” diam.

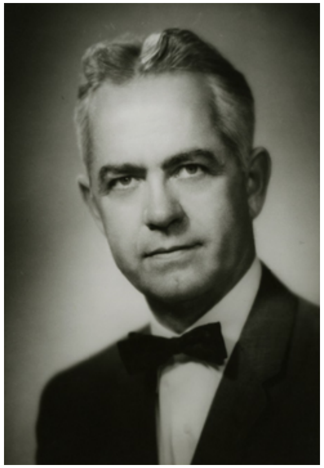
A NEW TYPE OF NEUTRON SPECTROMETER†

RICHARD L BRAMBLETT, RONALD I. EWING and T. W. BONNER

The Rice University, Houston Texas

Received 4 July 1960

Neutrons are detected in a small Li^{6}I(Eu) scintillator placed at the center of polyethylene moderating spheres with sizes ranging from 2 to 12 inches in diameter The efficiency of this neutron counter has been experimentally determined using monoenergetic neutrons from thermal energies to 15 MeV The counter has excellent energy sensitivity from 0 1 to 2 MeV and is particularly useful for determining the shapes of continuous neutron spectra The pronounced difference in the efficiencies for the five sizes of spheres which have been calibrated provides a basis for accurate neutron energy determination The good γ ray discrimination of the counter allows it to be used with a radium-beryllium neutron source Neutron spectra from a variety of sources have been determined with this counter These include the two groups of neutrons from the $C^{14}(p,n)N^{14}$ reaction, the evaporation spectrum of the neutrons from the reaction $Rh^{103}(p,n)Pd^{103}$, the energy spectra of inelastically scattered neutrons, and the neutron spectrum from the scattering of fast neutrons by the floor and walls of a building

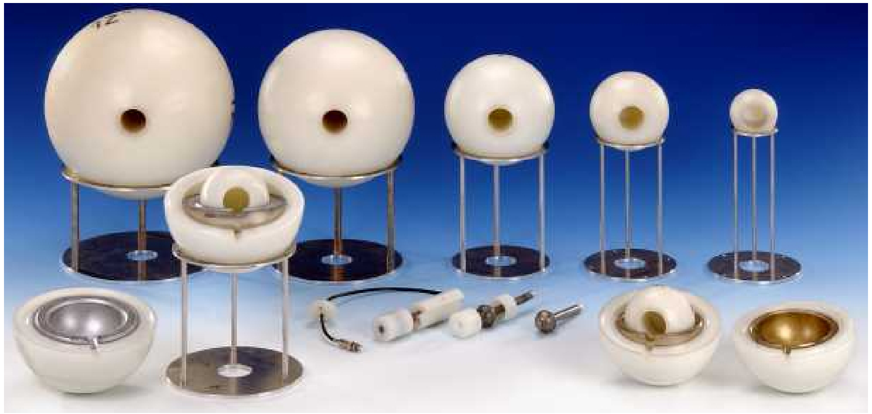


The Bonner Spheres neutron Spectrometer (BSS)

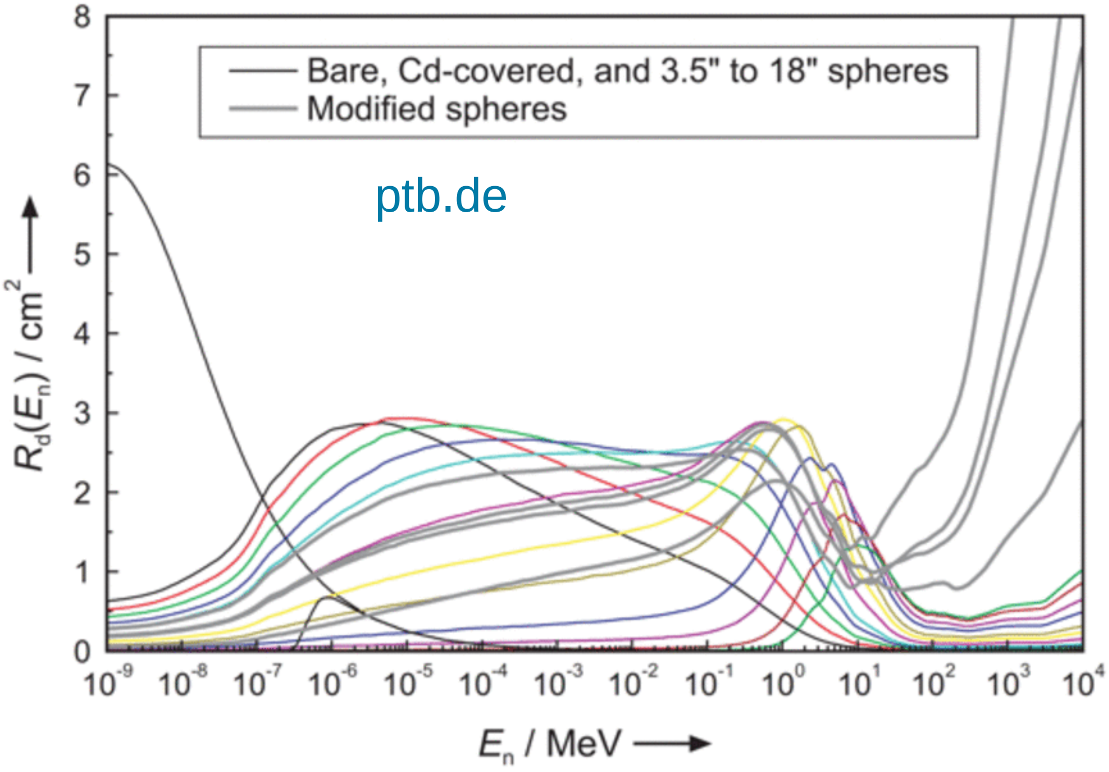
- **BSS are among the most known and widespread technique for neutron spectrometry.**

- **Material:**
  - Moderator: HDPE (other options: paraffin wax, water,...)
  - Neutron filters: Cd foils
  - **Extended energy range** BSS use neutron multipliers (Pb, Cu, W, ...)

- **Thermal sensor:**
  - Active systems: 3He tubes (BF3 tubes, 6LiI(Eu) scintillators)
  - Passive systems: Activation foils (Au, Dy, ….), TLD-pairs 700/600

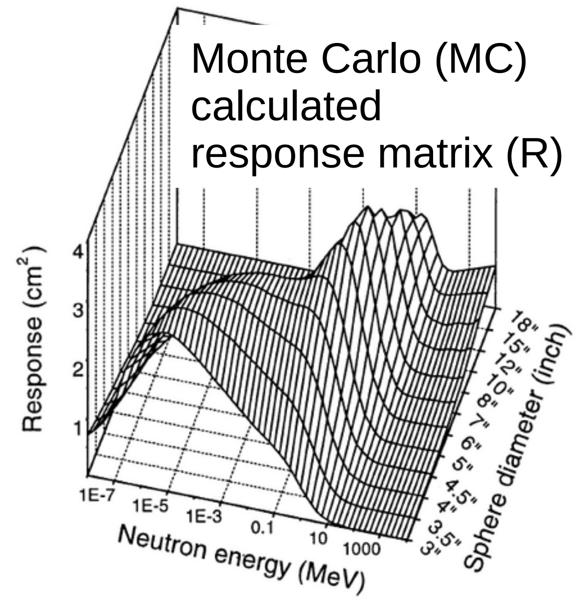


NEMUS (PTB)



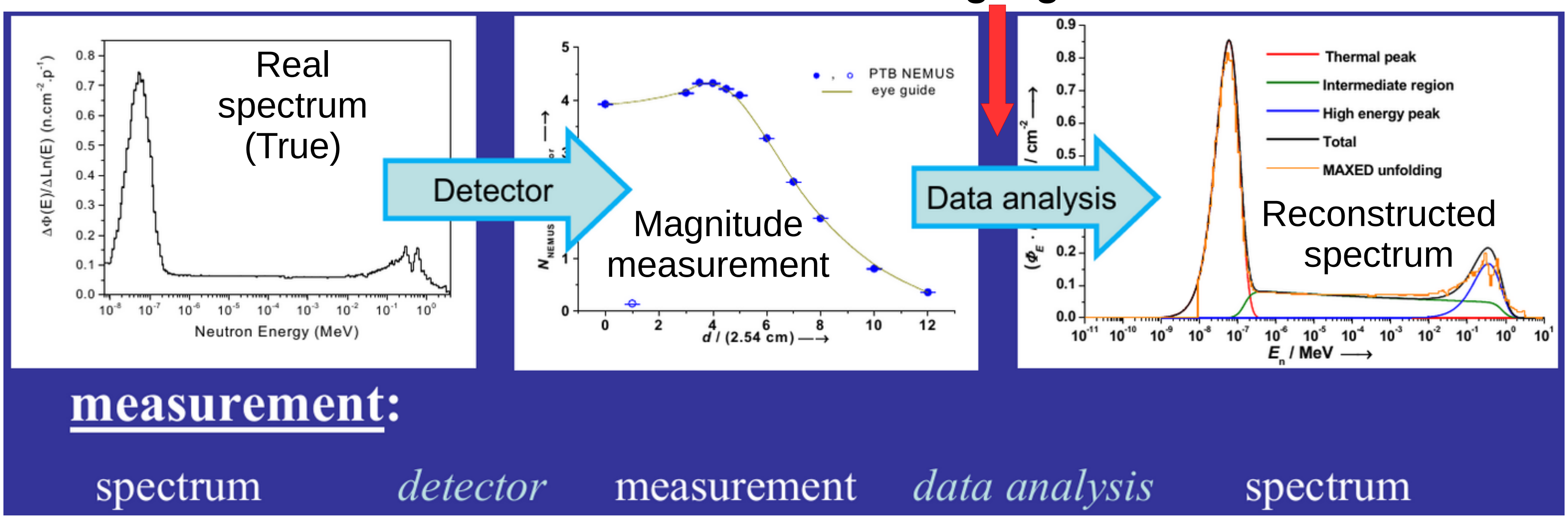
The Bonner Spheres neutron Spectrometer (BSS)

- **Number of detectors:** Typically 5 up to 16 spheres → ***ill-posed linear inverse problem*!**
  - Nasty connection with unfolding!
- **Detector responses:** calculated by using general purpose Monte Carlo codes. Requires:
  - Satisfactory geometrical model of the detector
  - High Precision nuclear data for neutron transport
  - Validation
- **Energy spectrum reconstruction (unfolding):** requires
  - A-priori information (again MC calcs!)
  - An unfolding algorithm
  - A well-trained user



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

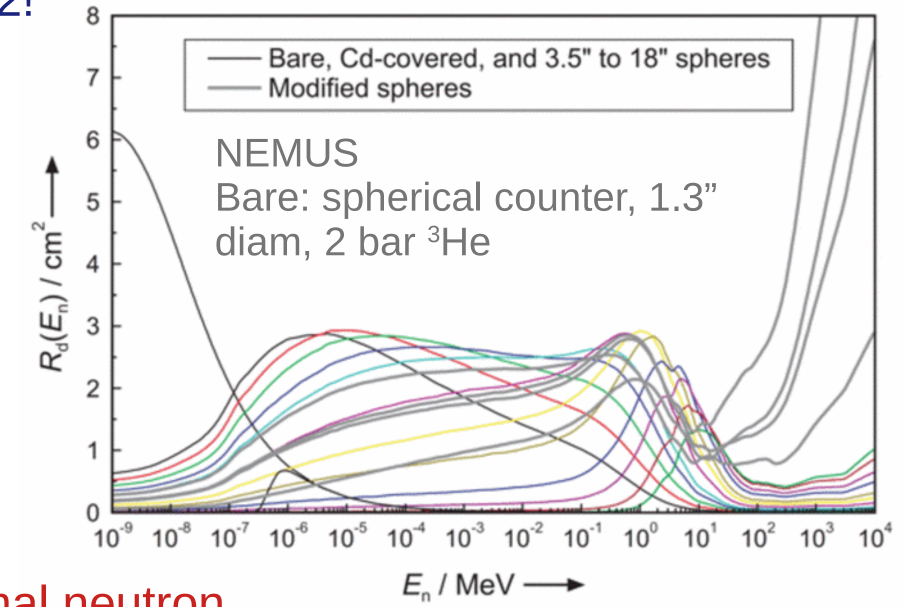
Unfolding algorithm



Main applications:

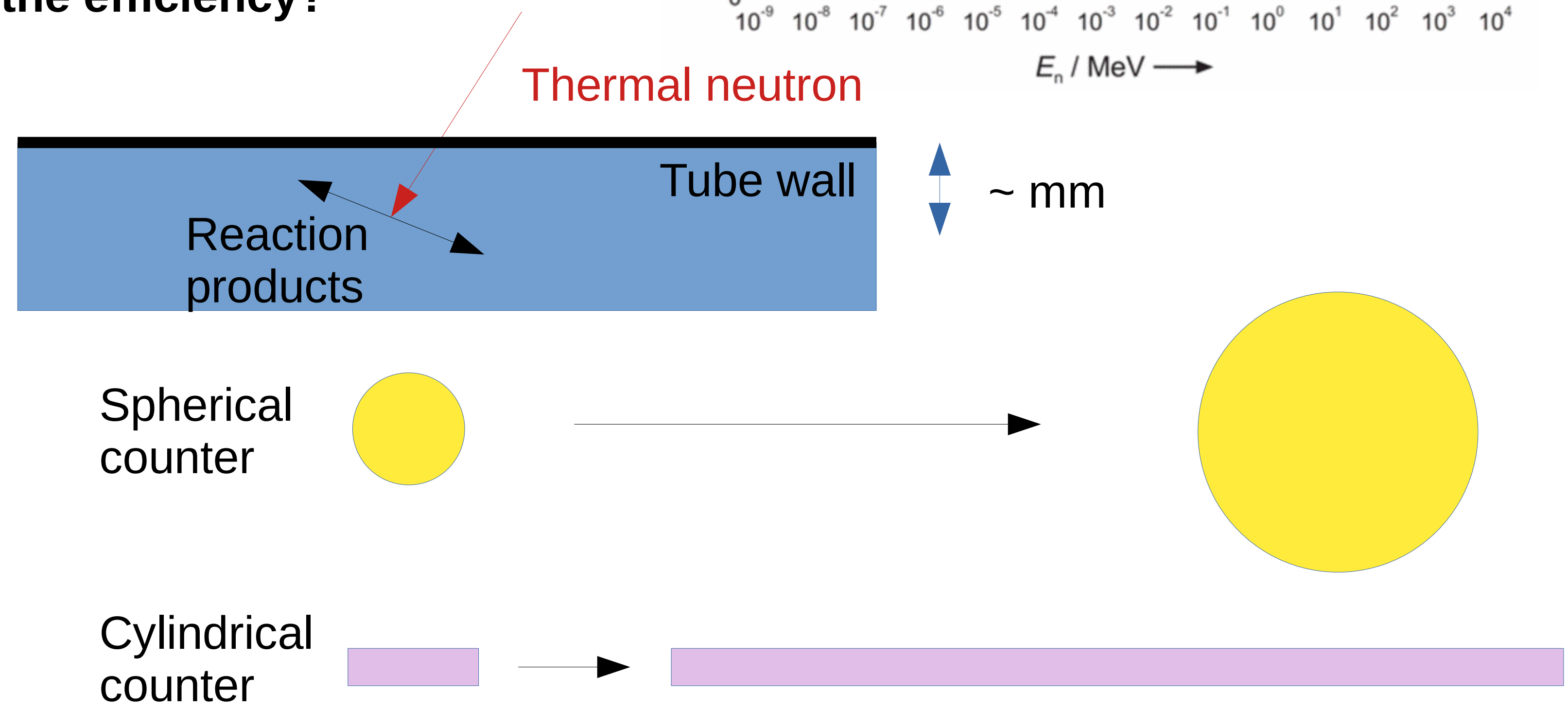
- Environmental dosimetry
- Cosmic rays and space weather
- Nuclear safeguard
- Underground physics

Conventional BSS systems provides responses of just a few cm2!



How to increase the efficiency?

Gaseous Thermal Neutron detector

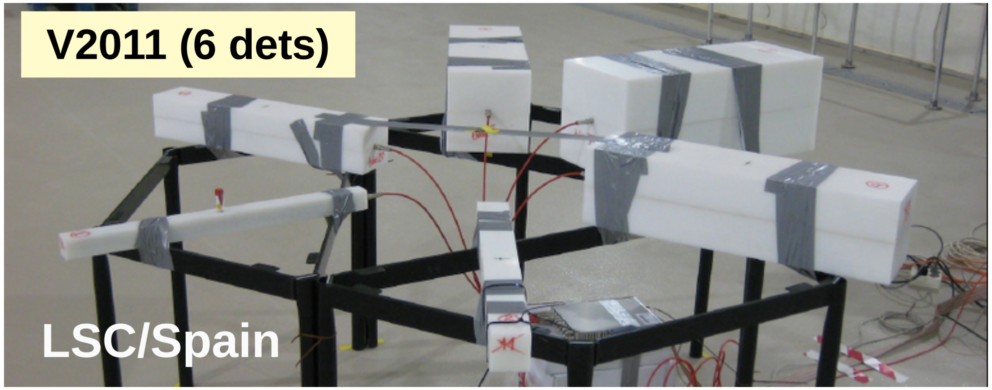


The efficiency is proportional to the active surface instead of the active volume

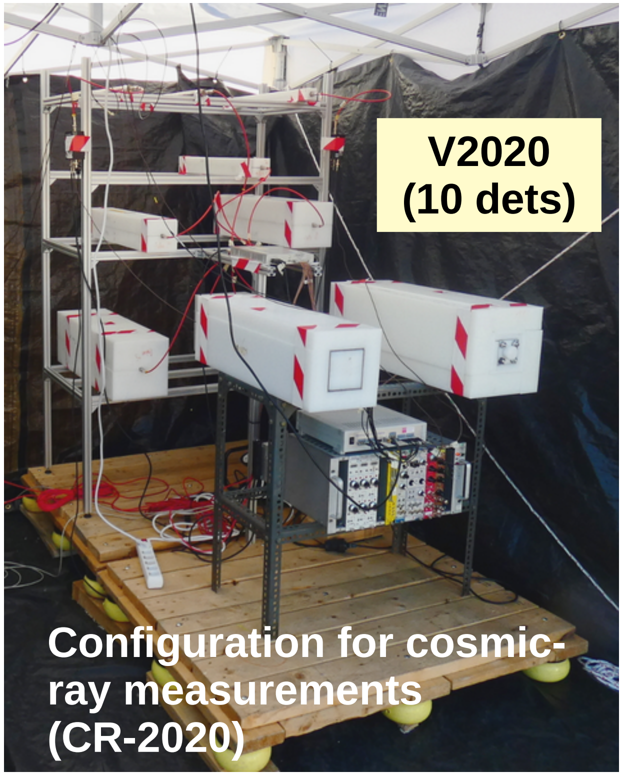
The High Efficiency Neutron Spectrometry Array (HENSA)

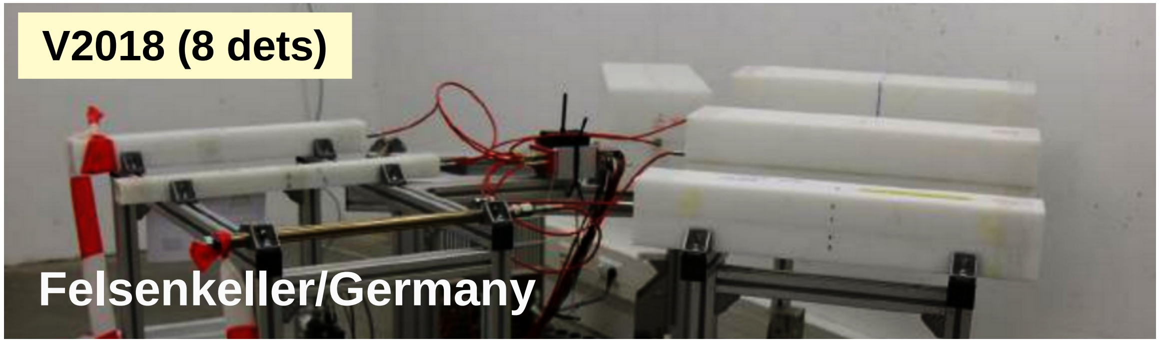
- **HENSA is based on the Bonner Spheres Principle**. Energy sensitivity from thermal to evaporation/high-energy neutrons (depending on the design).

- **Originally proposed in 2011** for underground research (JL Tain, IFIC).



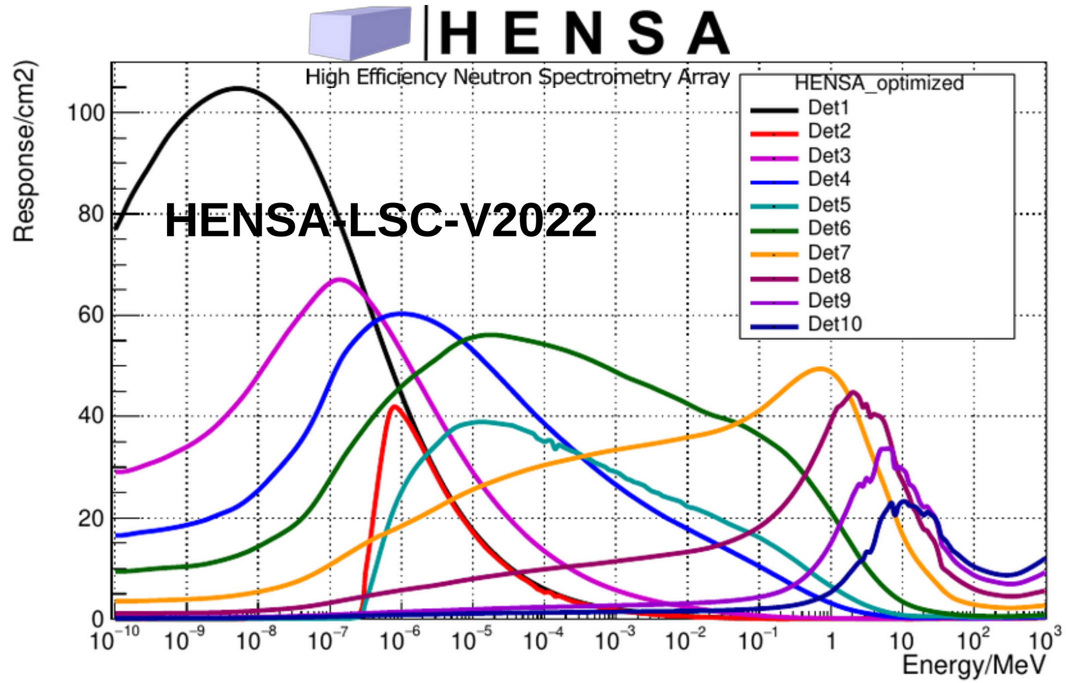
Jordan eta al.
Astr. Phys 42 (2013) 1-6

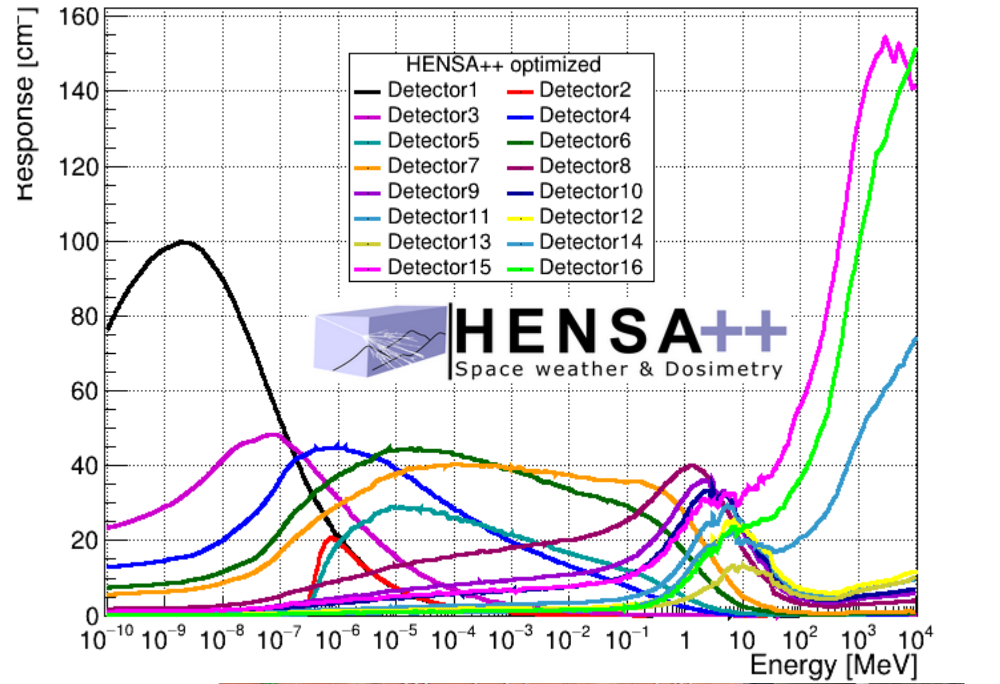


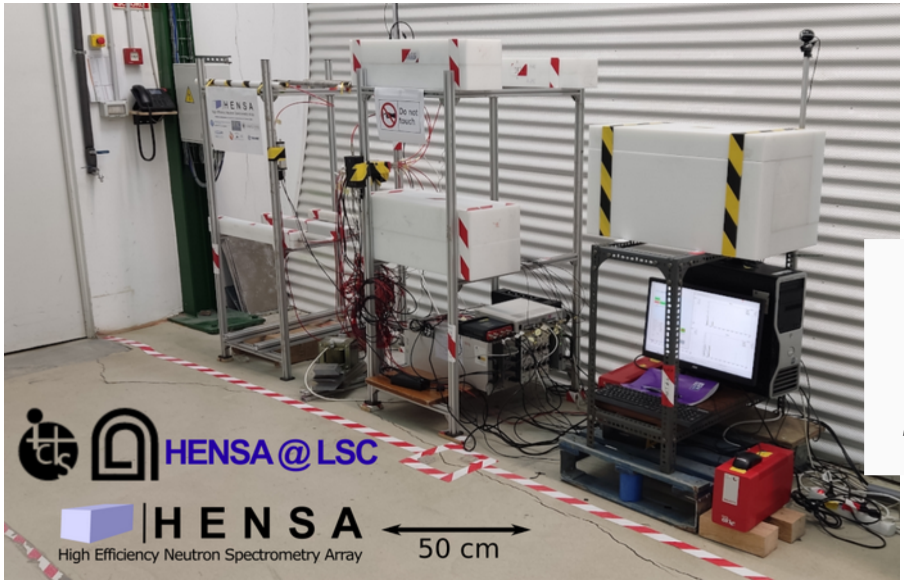


In 2021, the HENSA spectrometer design has been re-optimized in order improved energy resolution for application in underground research and cosmic-ray studies.

HENSA: final instrument designs







MC simulations by the Geant4 application ***ParticleCounter***

Particle Counter

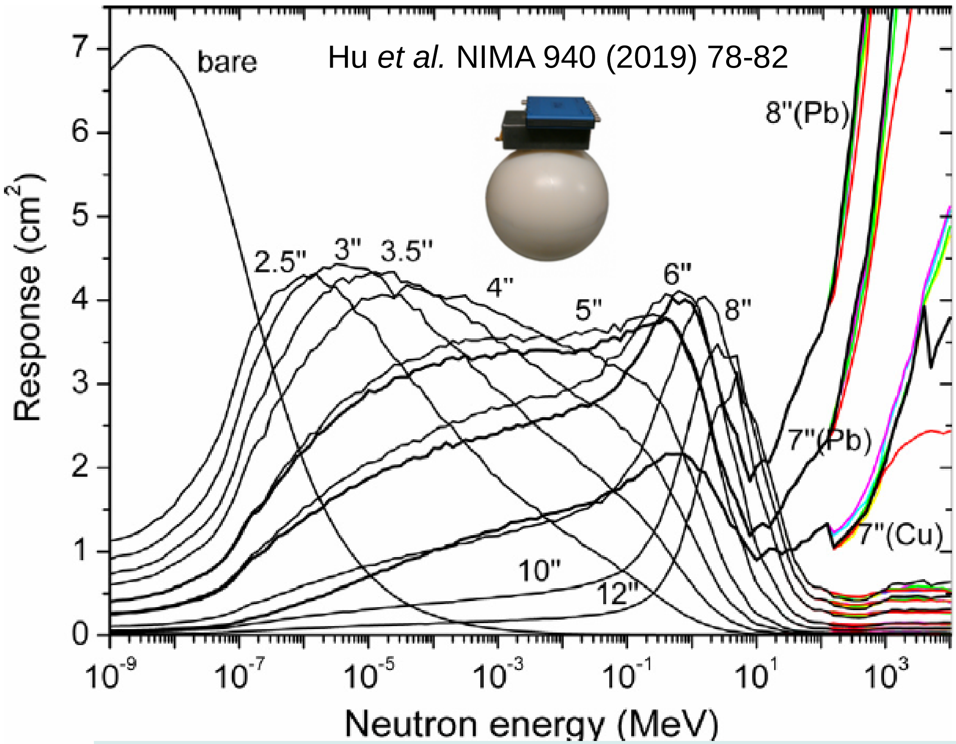
www.particlecounter.net

Underground research
(N. Mont-Geli, PhD thesis, UPC)

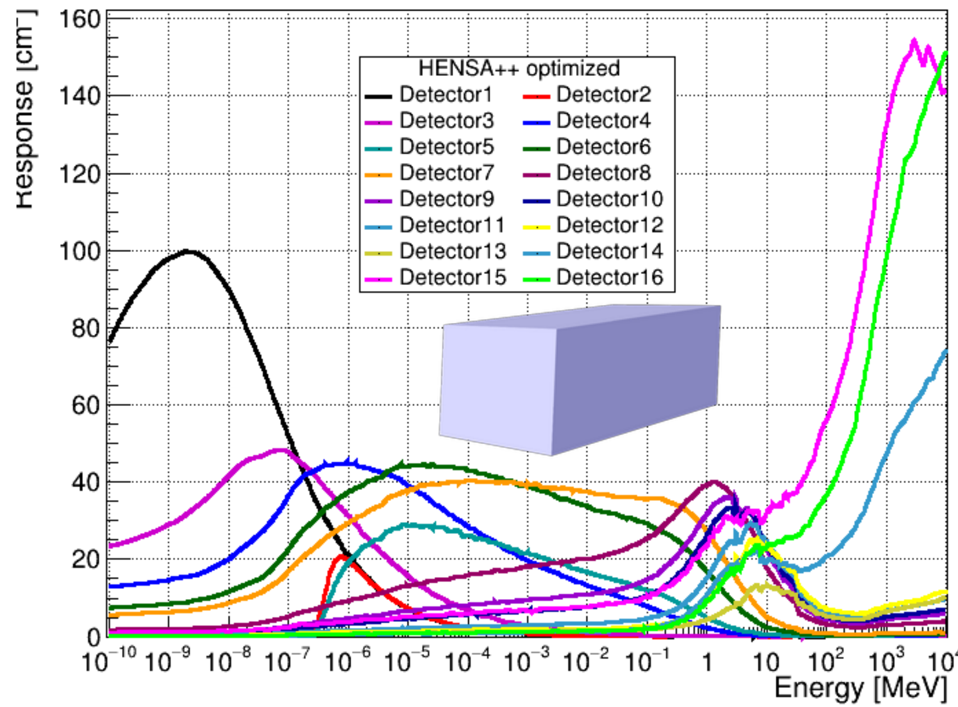
Cosmic-ray studies
(A. Quero , PhD thesis, UGR)

HENSA spectral sensitivity

Standard extended Bonner Spheres



A. Quero, PhD Thesis (UGR)



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

The higher neutron response means:

- Improved precision in low radioactivity or underground facilities.
- Temporal response in the scale of ten of minutes to hours for detecting fluctuations of cosmic-ray neutron flux at ground.

Currently two spectrometer designs: underground facilities & Cosmic-ray neutrons (HENSA++)

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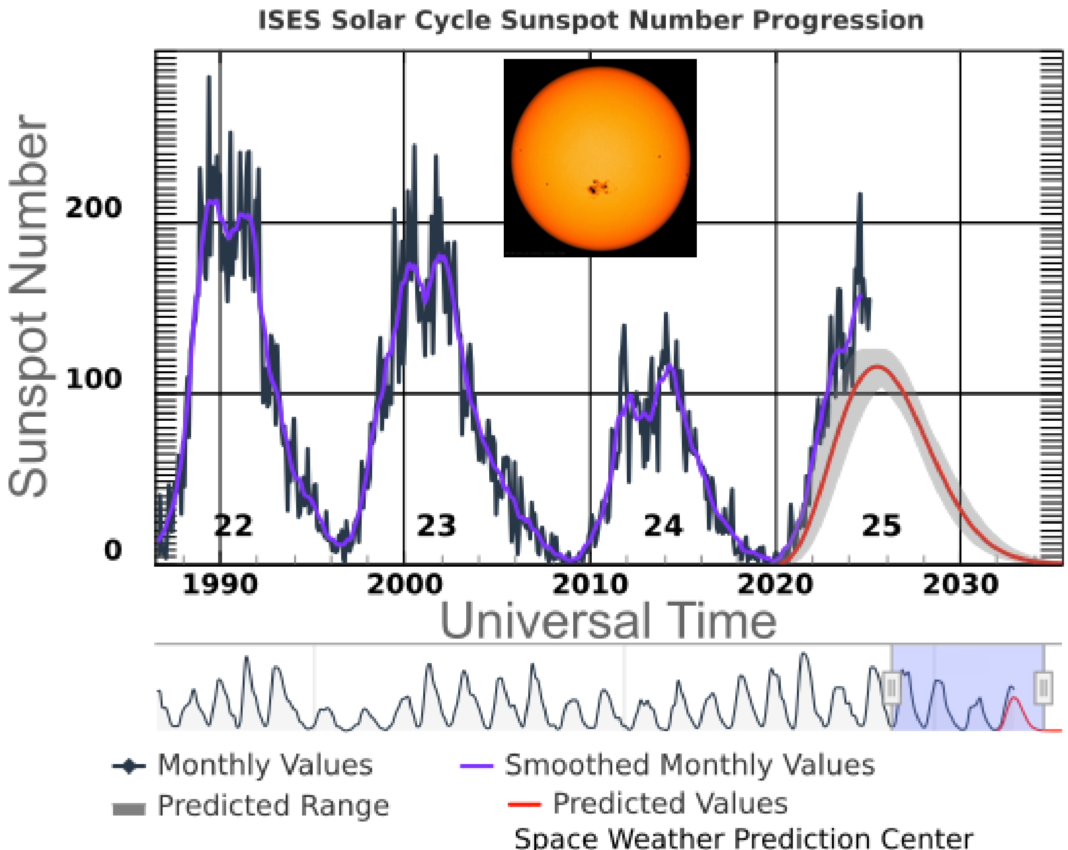
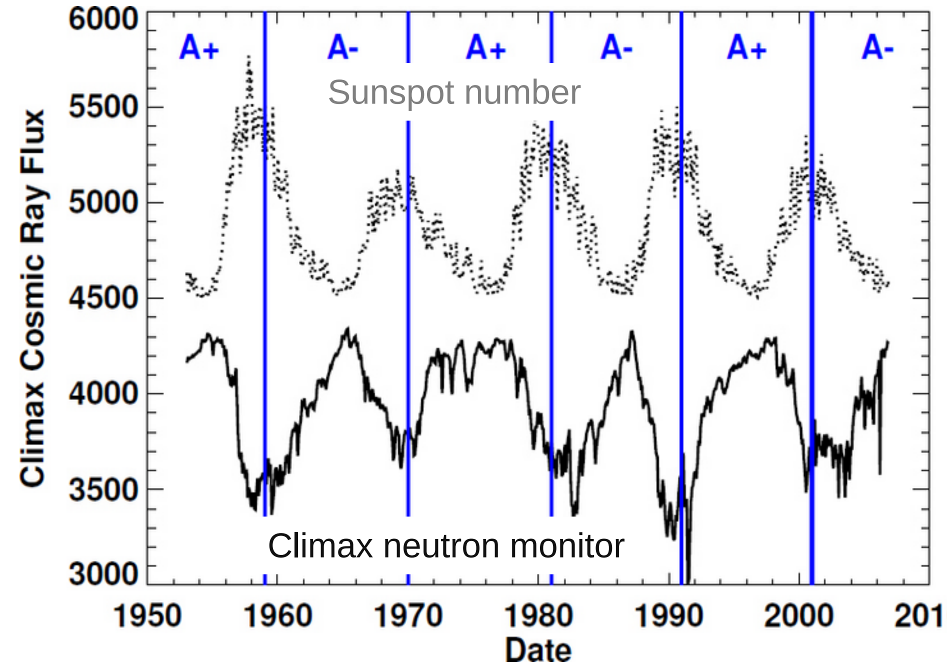
Cosmic-ray neutrons and space weather

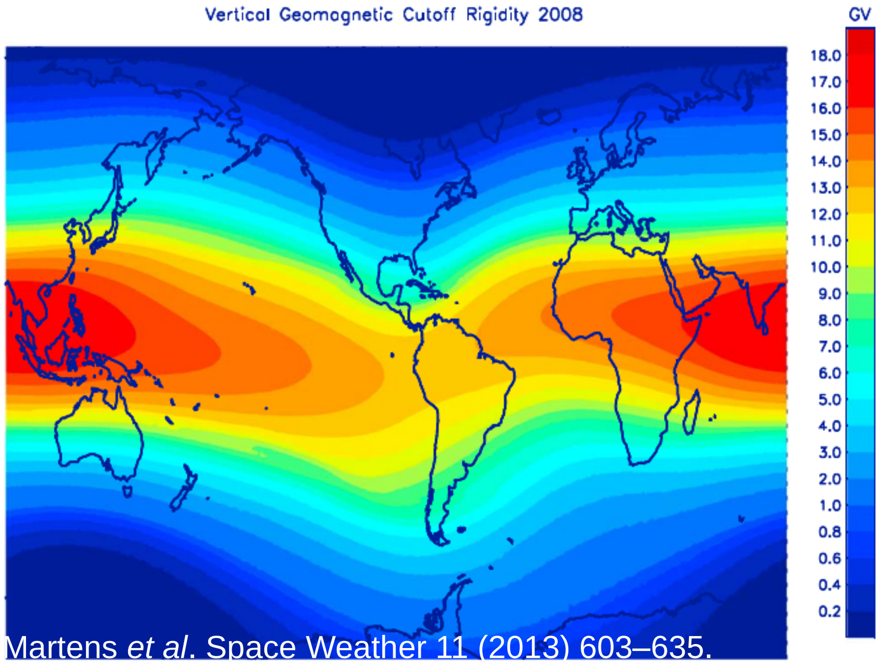


NOAA/NASA forecast for Solar Cycle 25. Maximum solar activity expected for July, 2025 (+/- 8 months). Solar minimum between Cycles 24 and 25 was observed around Dec. 2019 (+/- 6 months).



Neutron background anti-correlation with solar cycle. Cosmic Ray flux from the Climax Neutron Monitor and rescaled Sunspot Number.

Cosmic-ray neutrons in quiet solar conditions



Martens *et al*. Space Weather 11 (2013) 603–635.

Figure 3. Global grid of vertical geomagnetic cutoff rigidities (GV) calculated from charged particle trajectory simulations in the IGRF field for 2008.

Secondary neutrons produced by cosmic rays depends mainly on:
- Solar cycle.
- Geomagnetic cutoff rigidity.
- Altitude.

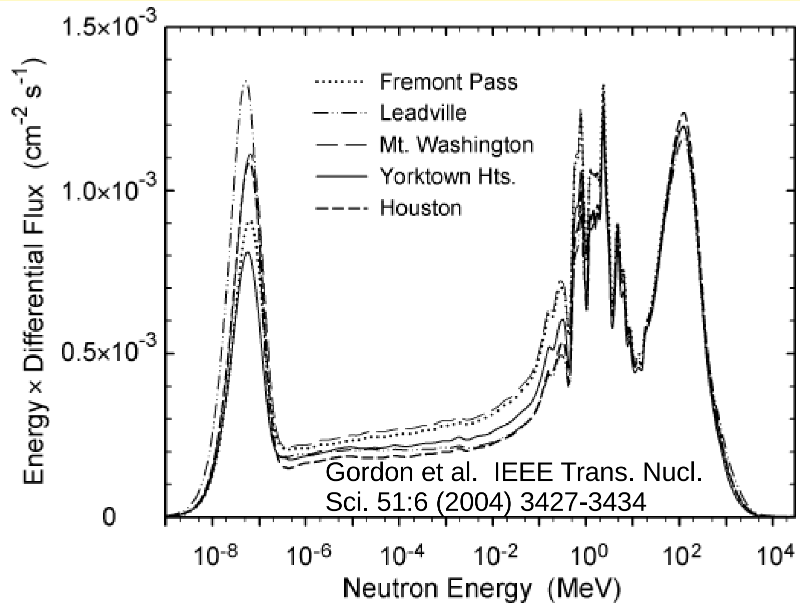
- Peninsular spanish territory covers a range of cosmic rays vertical cutoff rigidity (Rc) values from 5 GV to 9 GV. In Ceuta and Melilla, Rc-values are 9.15 GV and 9.6 GV, respectively. In Canary Islands Rc is ~11.7 GV.
- Thus, the whole spanish territory covers a relatively ample range of Rc-values compared to other larger countries (for instance USA with 1.5 GV < Rc < 4.7 GV).

Analytic models for cosmic-ray neutrons are based on data taken in US ~20 years ago!
- 5 sites, altitude from sea level to 3450 m
- Rc: 2.97 - 4.68 GV
- Solar cycle: Sep/2002-Jun/2003, around peak solar activity cycle 23

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 51, NO. 6, DECEMBER 2004 3427

Measurement of the Flux and Energy Spectrum of Cosmic-Ray Induced Neutrons on the Ground

M. S. Gordon, P. Goldhagen, K. P. Rodbell, T. H. Zabel, H. H. K. Tang, J. M. Clem, and P. Bailey



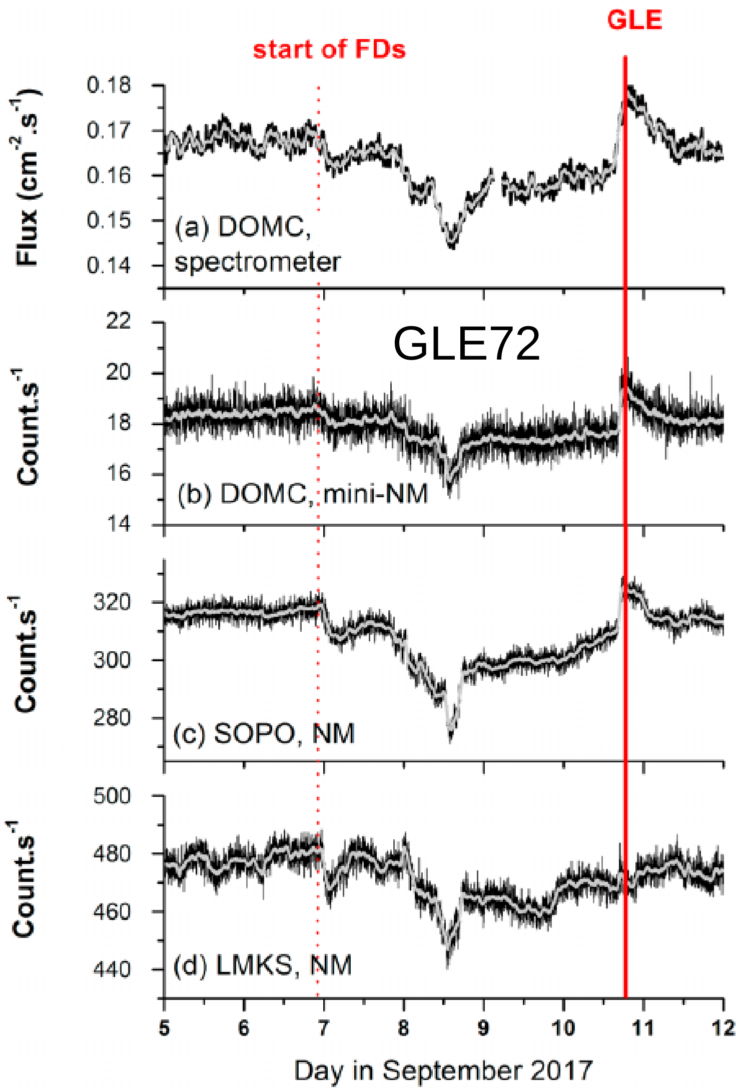
Gordon et al. IEEE Trans. Nucl. Sci. 51:6 (2004) 3427-3434

Cosmic-ray neutron studies with HENSA

GOAL: Study of cosmic-ray neutrons produced during cycle #25 (foreseen for 2022 -2030)

- Continuous monitoring of cosmic-ray neutrons will provide complementary data to NM for cosmic-ray studies.
- Relevant data for dosimetry during Solar Particle Events (FD & GLE).
- Seminal works by *Rühm et al* 2009 (GLE #65) and *Hubert et al* 2019 (GLE #72) with standard Bonner Spheres Spectrometers.
- Study GLE's requires data of neutron flux variations at time scales of 1h or less..

HENSA may provide information for understanding solar event dynamics with spectral resolution and assessment of potential radiation risk at high altitudes.



Hubert et al.J Geo Res: Space Physics, 124 (2019) 661-673

HENSA: cosmic-ray campaign in 2020

HENSA-CR @ 2020
UPC / IFIC / UCM / HZDR

PhD thesis:
N. Mont-Geli (UPC)
A. Quero Ballesteros (UGR)

Spain is a good lab for cosmic-ray neutron studies in pandemic times

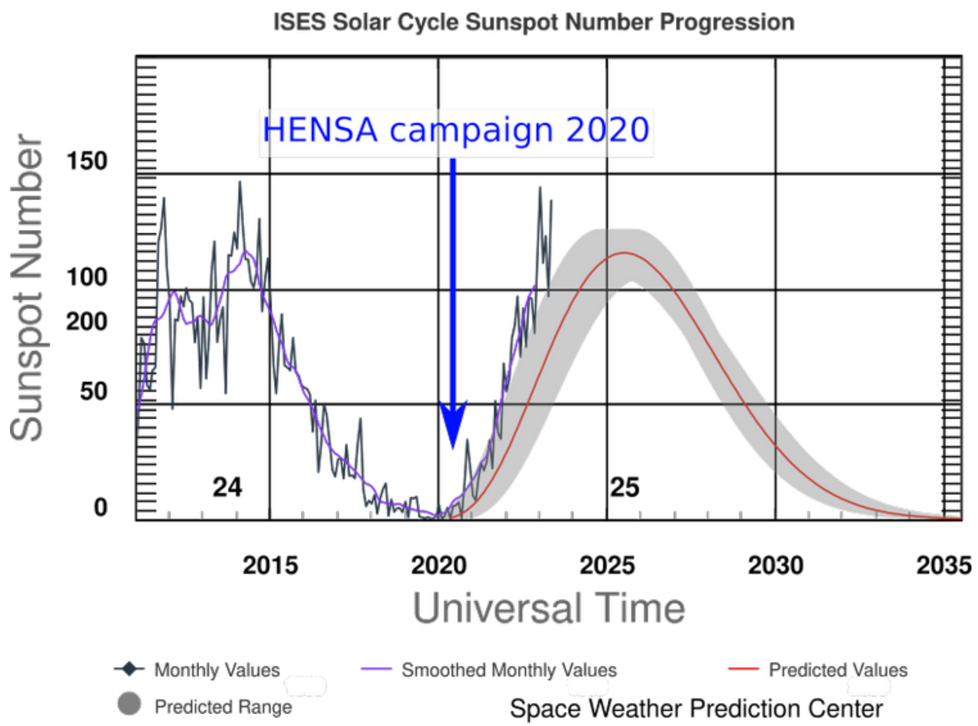
HENSA campaign along the Spanish territory close to the minimum of solar activity (2020, solar cycle #25)

Cosmic ray induced neutron background
- Cosmic ray physics and space weather
- Environmental radiation dosimetry
- Single-event upsets in microelectronics

HENSA
High Efficiency Neutron Spectrometry Array

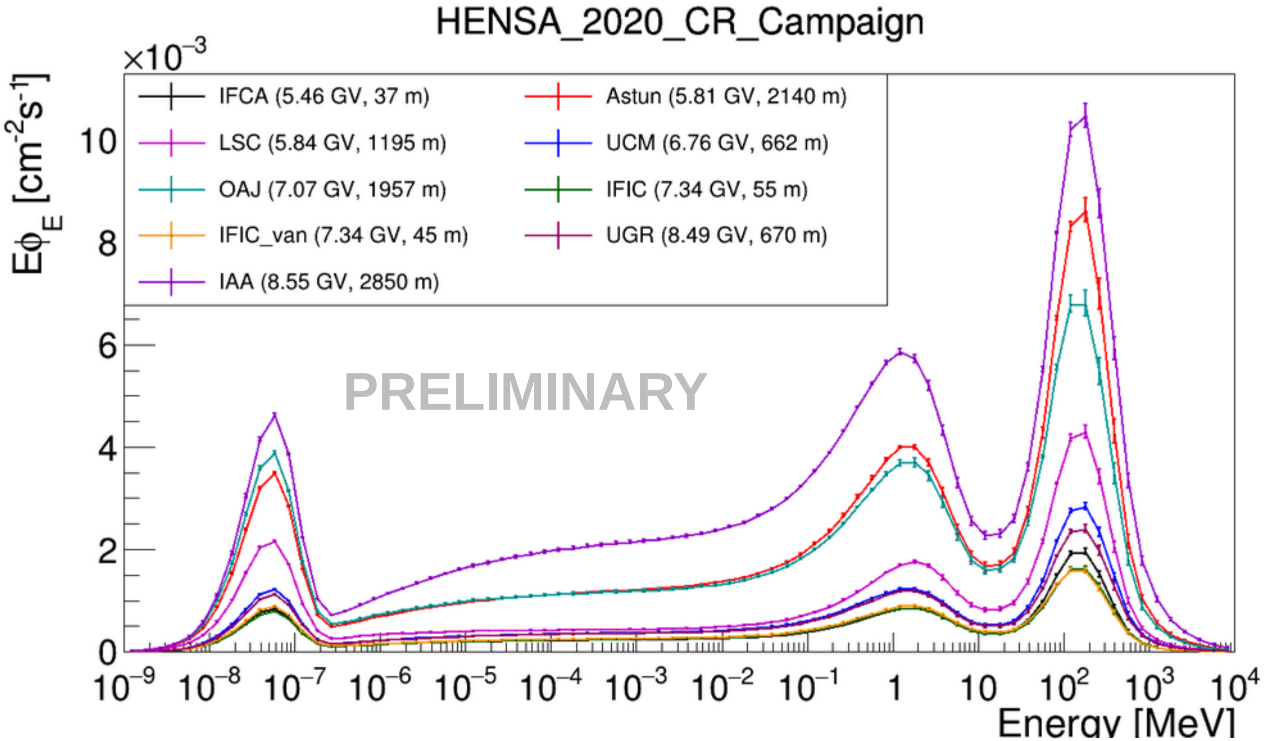
www.hensaproject.org

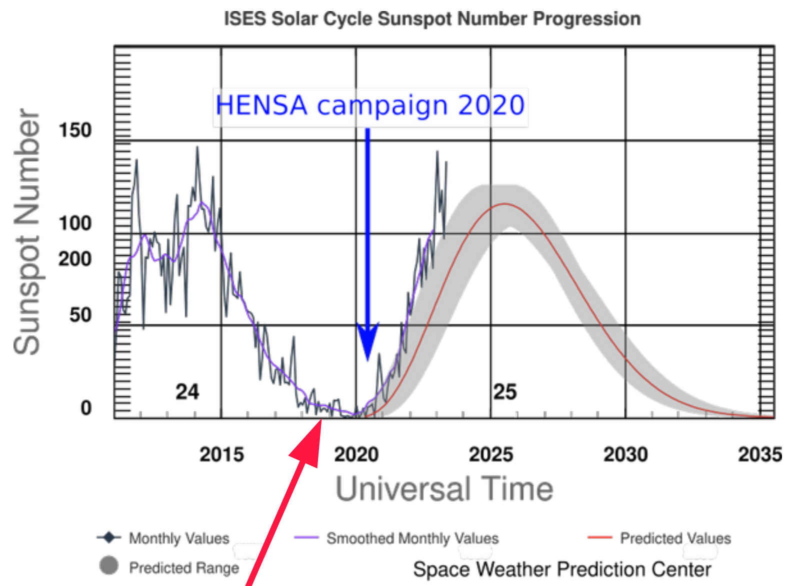
HENSA-CR campaign 2020: description



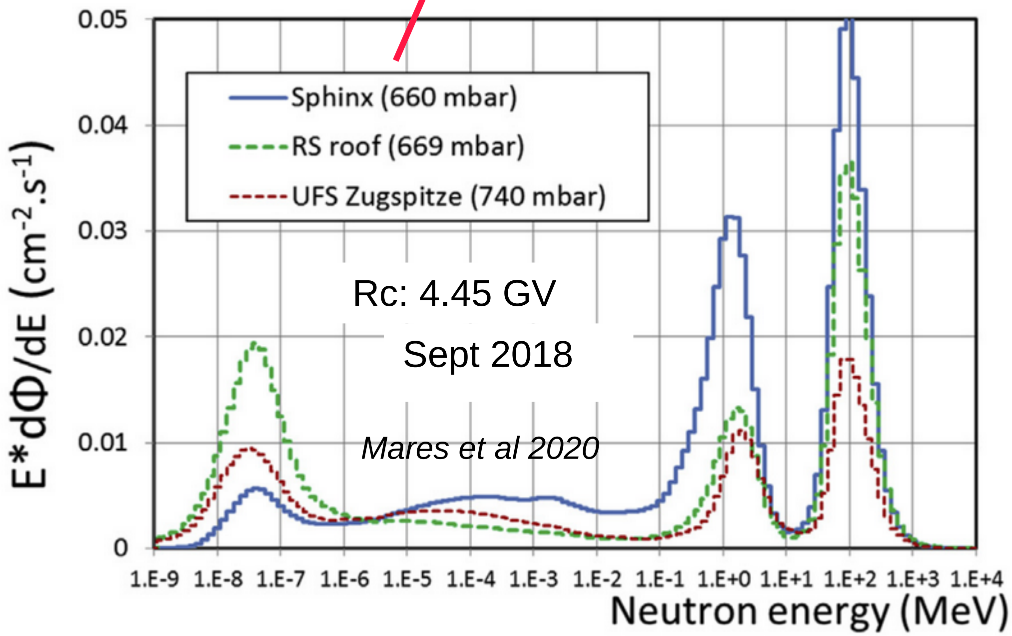
- Dates: July-August, October/November 2020
- 9 weeks of field campaign
- 4000 km in the route
- 9 different sites in Spain
- From sea level up to 2850 m
- Rc: 5.4-8.9 GV (complementary data to Gordon+2004)
- Data acquisition time 2-4 days.

HENSA-CR campaign 2020: results

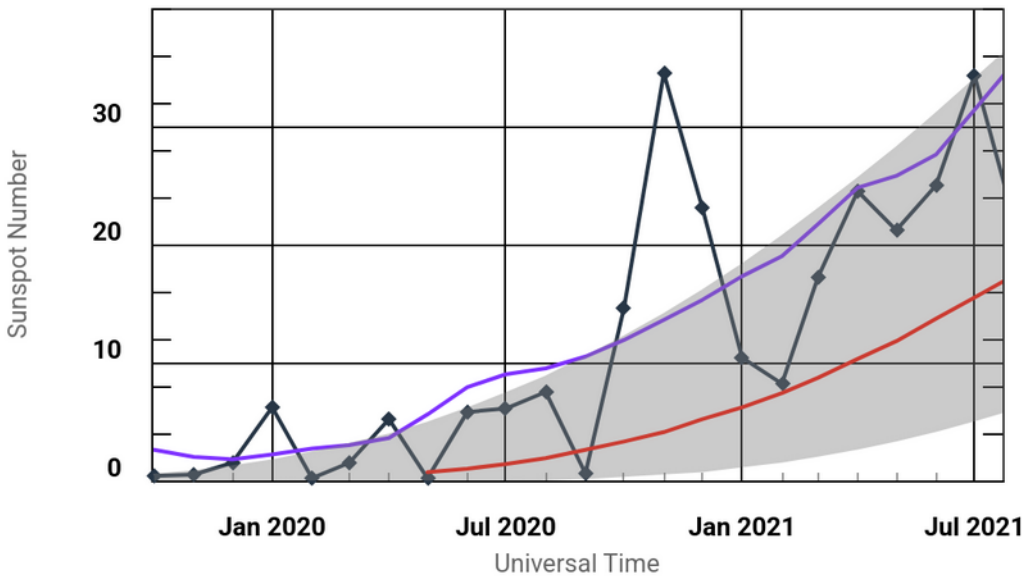




- Confirmed structure and flux magnitude with HENSA
- Confirmed effect of higher sensitivity of HENSA with respect to conventional BSS.
- Over 2000 m altitude, relative uncertainty in count rates at 1h time window is ~2% or less.



Solar modulation corrections



How to normalize our data?

Just an exercise!

- **We can use NM data!**
- Data from 25/07/2020 to 17/11/2020.
- The reference location for us is the measurement at IFIC (13/10/20 - 16/10/20).
- Each NM data is normalized to this period of time (I/Io).
- Corrections are < 1% (as expected).

NM	Rc (GV)	Site	Solar Mod. Correction
BKSN (5.70 GV, 1700 m)	5.46	IFCA	1.002
	5.81	Astun	0.997
	5.84	LSC	0.992
ROME (6.27 GV, 0 m)	6.52	UPC	0.997
	6.76	UCM	1.001
NANM (7.10 GV, 2000 m)	7.07	OAJ	1.001
	7.34	IFIC	1.000
	7.34	IFIC_van	1.000
ATHN (8.53 GV, 260 m)	8.49	UGR	1.000
	8.55	IAA	1.005

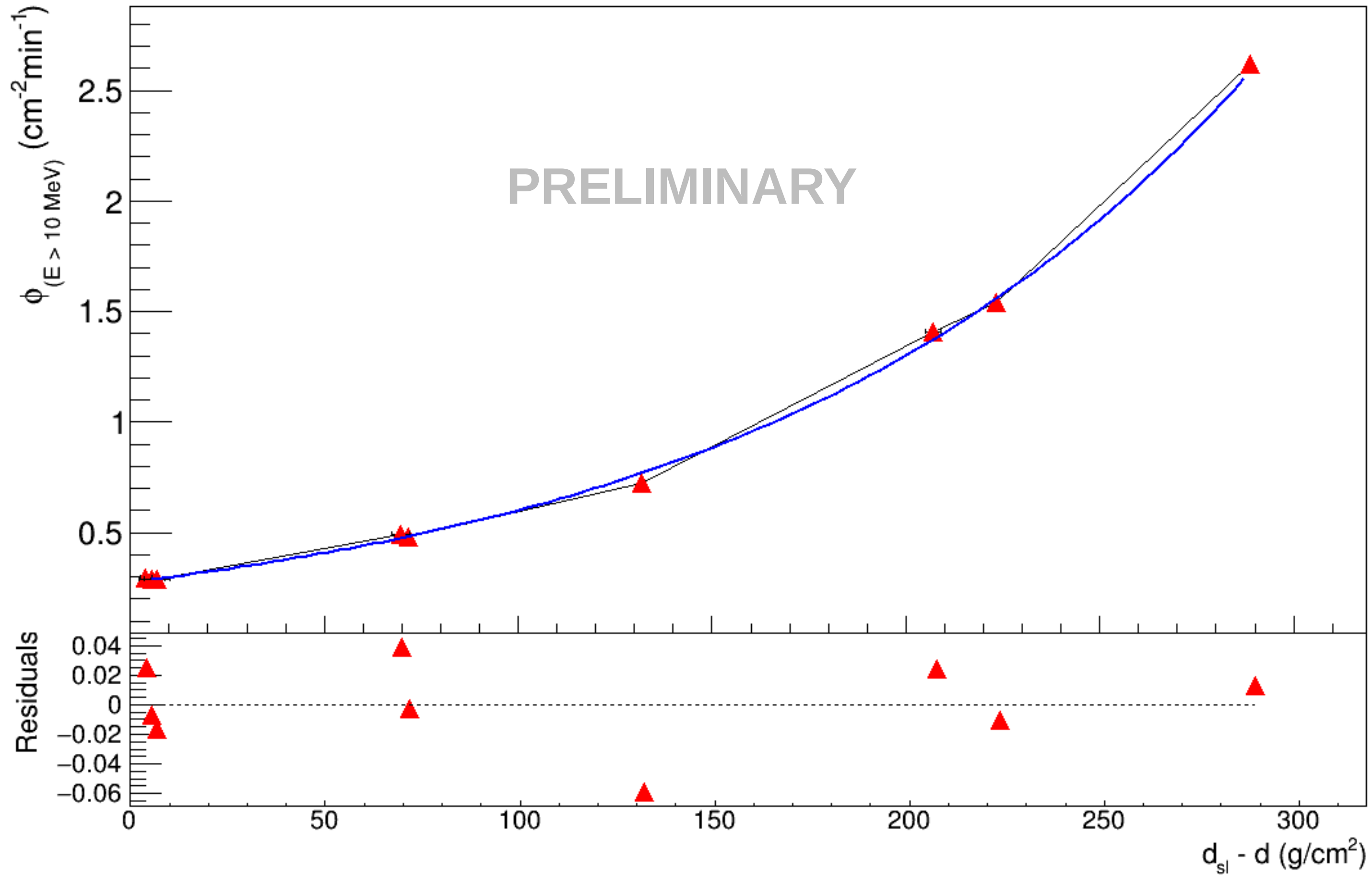
Corrections by altitude

- Data corrected by solar modulation and Rc:

$$F_{\mathrm{BSYD}}(R_c, d, I) = N\left[1 - \exp\left(\frac{-\alpha}{R_c^k}\right)\right]$$

- Then, fitted to the equation:

$$F_{\mathrm{alt}}(d) = \exp\left[\frac{(d_{\mathrm{SL}} - d)}{L_{\mathrm{n}}}\right]$$

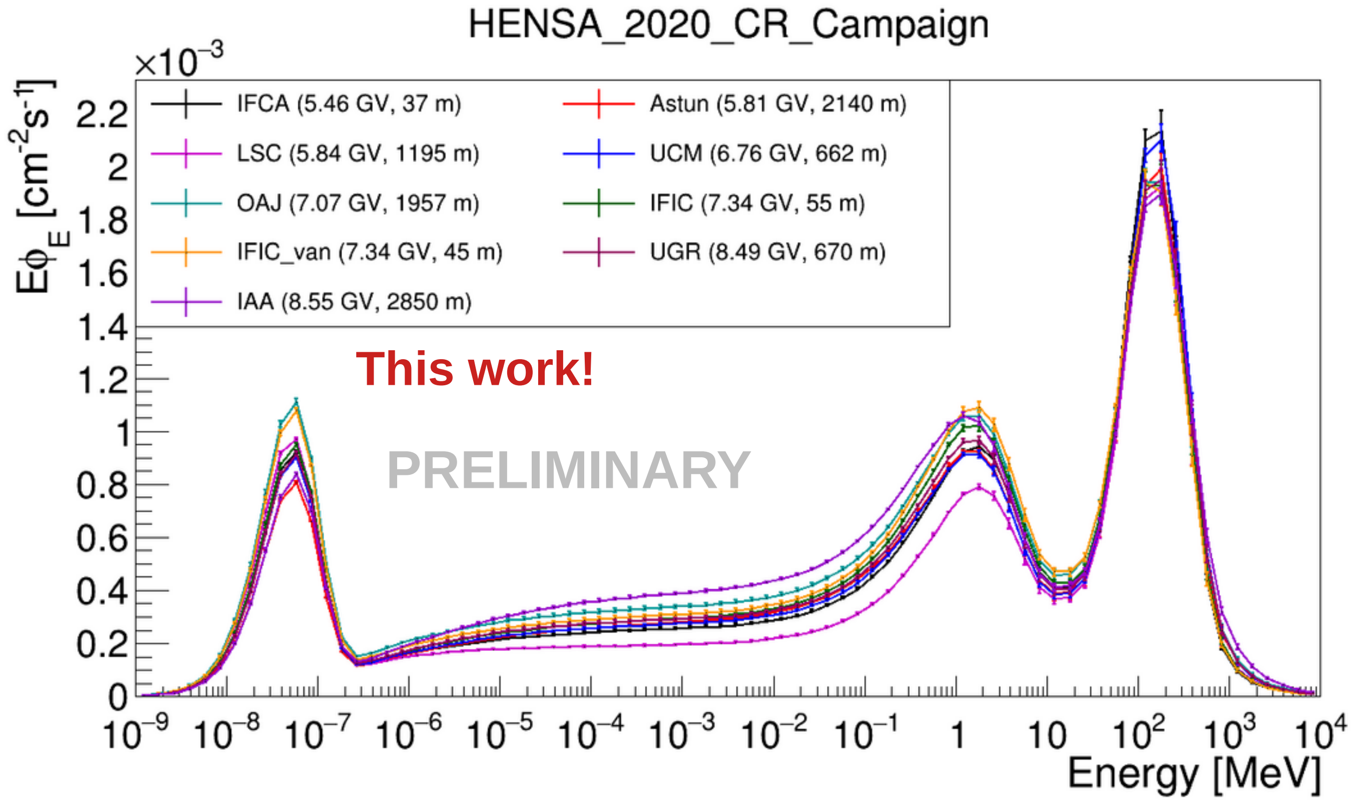


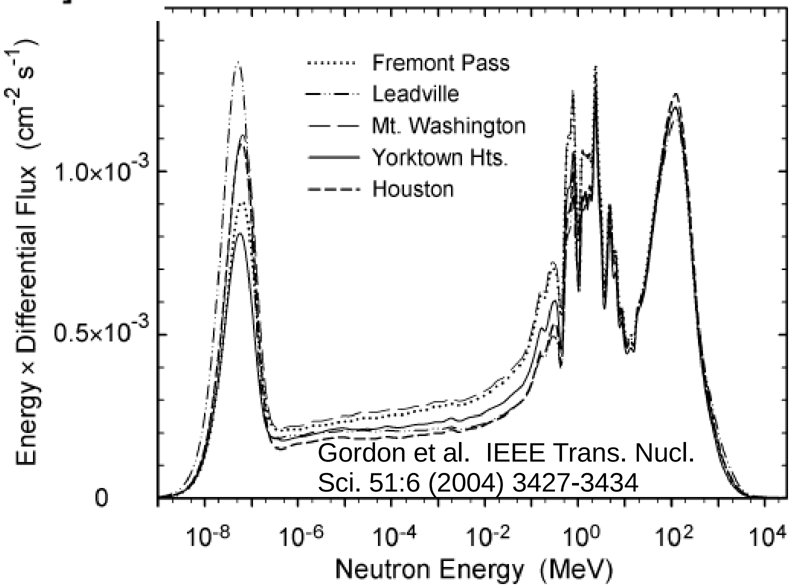
$$\frac{d\phi(E)}{dE} = \frac{d\phi_0(E)}{dE} \cdot F_{\mathrm{alt}}(d) \cdot F_{\mathrm{BSYD}}(R_c, d, I)$$

(Gordon et al. 2004)

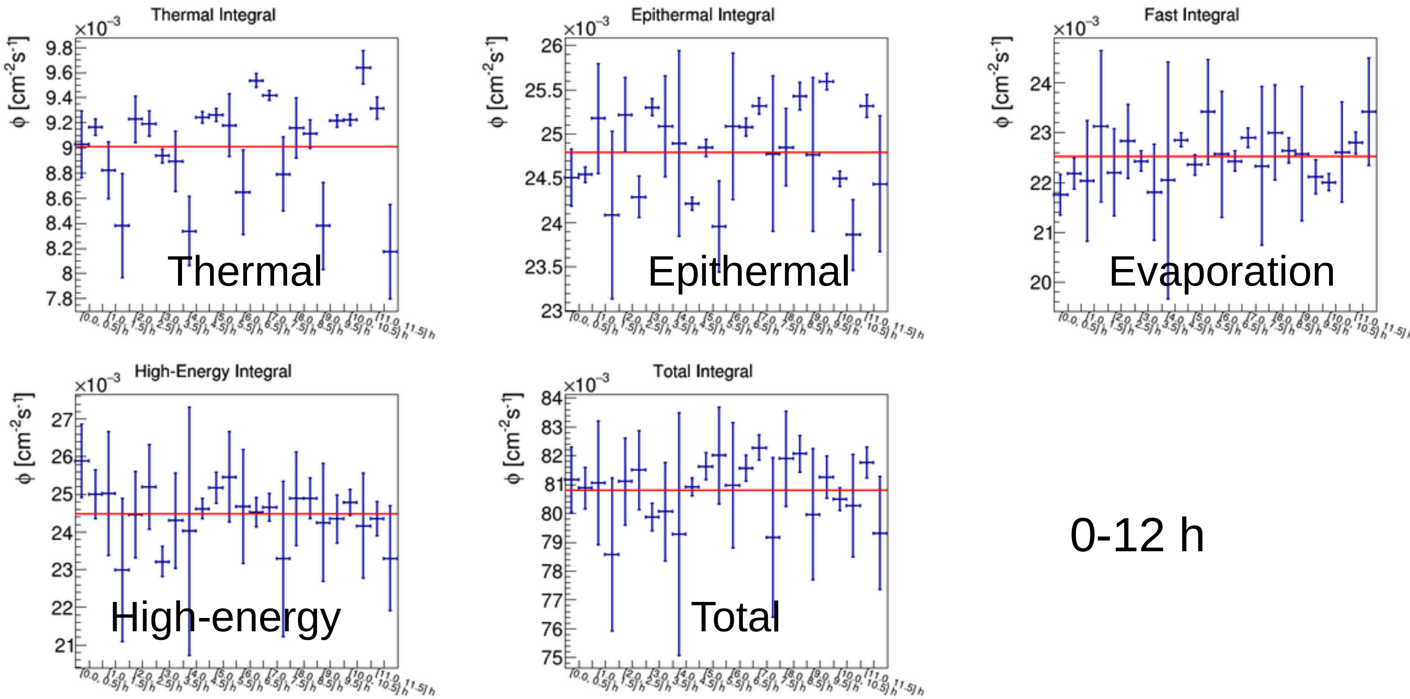
Calculation	Ln (g/cm²)
Gordon et al (2004)	131.3 ± 1.3
This work (2025)	129.5 ± 1.1

Reconstructed spectra corrected by altitude, solar modulation and Rc



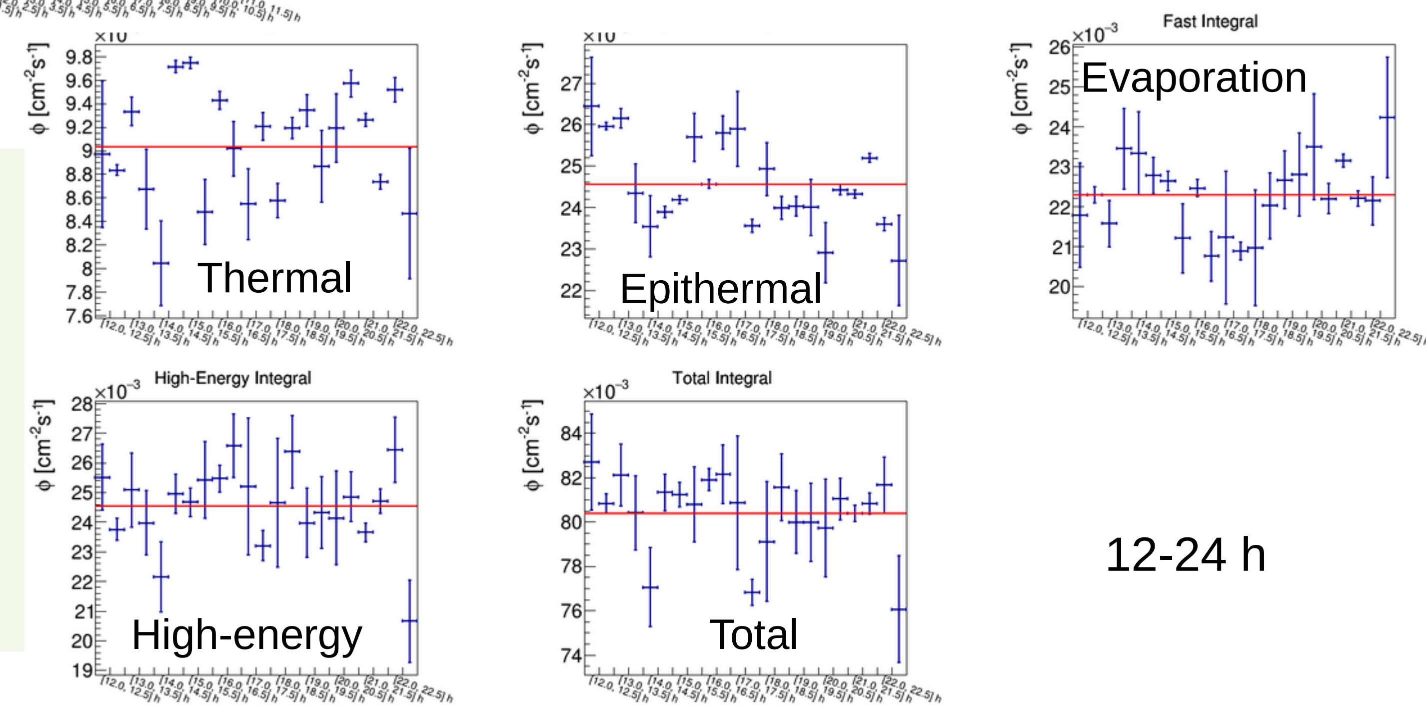


HENSA-CR2020: time resolution for spectral measurements



0-12 h

- Study of the time resolution.
- “Extreme case”: 30 min time base
- Unfolding during 24 h.
- IAA (Sierra Nevada), 8.55 GV, 2850 m.



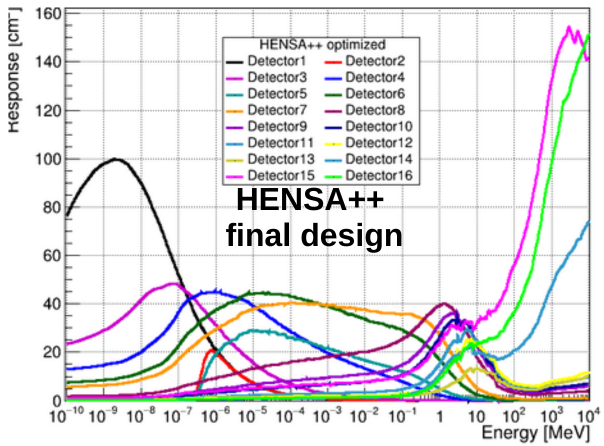
12-24 h

- Confirmed capabilities for spectral reconstruction at “short” period of time (30 min).
- Enables to study Solar Particle Events with neutron spectral resolution

Next step: dedicated HENSA spectrometer to CR applications

High efficiency spectrometer for space weather applications (HENSA++):
- Array of 16 detectors (3He, 4 atm, 60 cm AL) for measurements of cosmic-ray neutrons.
- **Sensitivity from thermal neutrons up to 10 GeV.**
- Focus on monitoring **solar activity** and **environmental radioactivity**.
- System assembled and **commissioning during 2024** (detector array, electronics and auxiliary systems).

Intercomparison activities at different facilities.
- Commissioning phase at OAJ using reduced setup (3 detectors) **Nov/24-Jul/25**.
- Final deployment for **first experimental run planned during summer 2025** at the (***A. Quero, PhD Thesis***).



Observatorio Astrofísico de Javalambre

Proyecto: IDIFEDER/2021/002

INSTRUMENTACIÓN AVANZADA EN DETECCIÓN DE NEUTRONES PARA LA VIDA Y EL CLIMA ESPACIAL: HENSA++

Programa Comunitat Valenciana Fondo Europeo de Desarrollo regional (FEDER) 2021 - 2027

Subvención: 260.199,21 €

Beneficiario: CSIC – Instituto de Física Corpuscular

GENERALITAT VALENCIANA Conselleria d'Innovació, Universitats, Ciència i Societat Digital

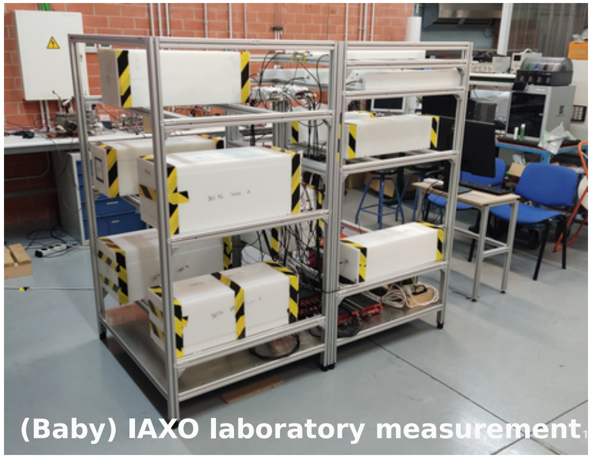
Financiado por la Unión Europea

HENSA++ Space weather & Dosimetry

Commissioning of HENSA++

Spain

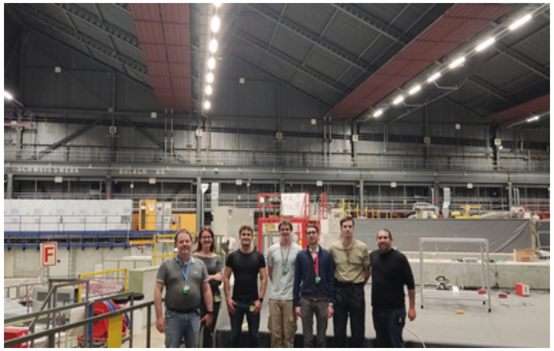
Outdoor measurement: HENSA + (Baby)IAXO team

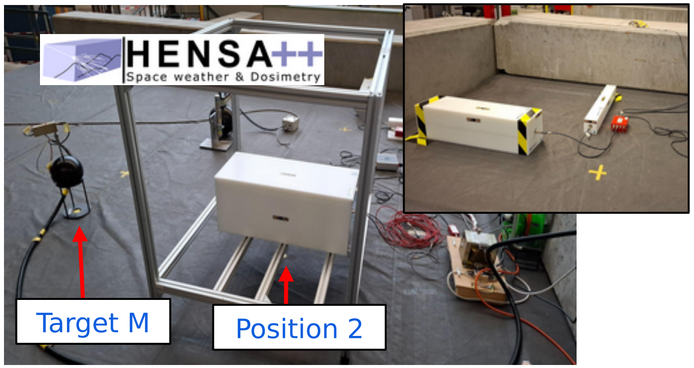


(Baby) IAXO laboratory measurement

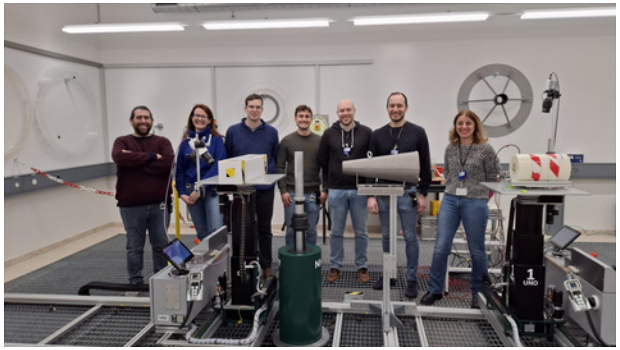
PSI Switzerland

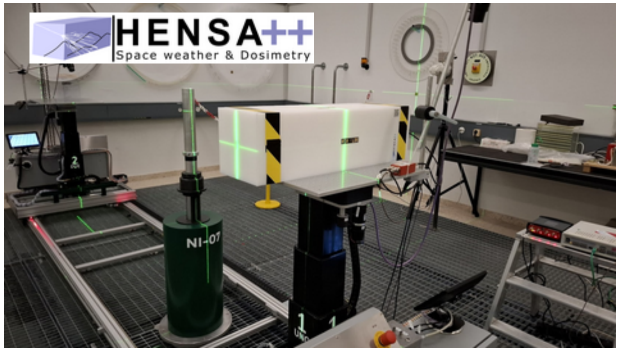
Intercomparison exercise BSS measurements (p-channel, Target M)

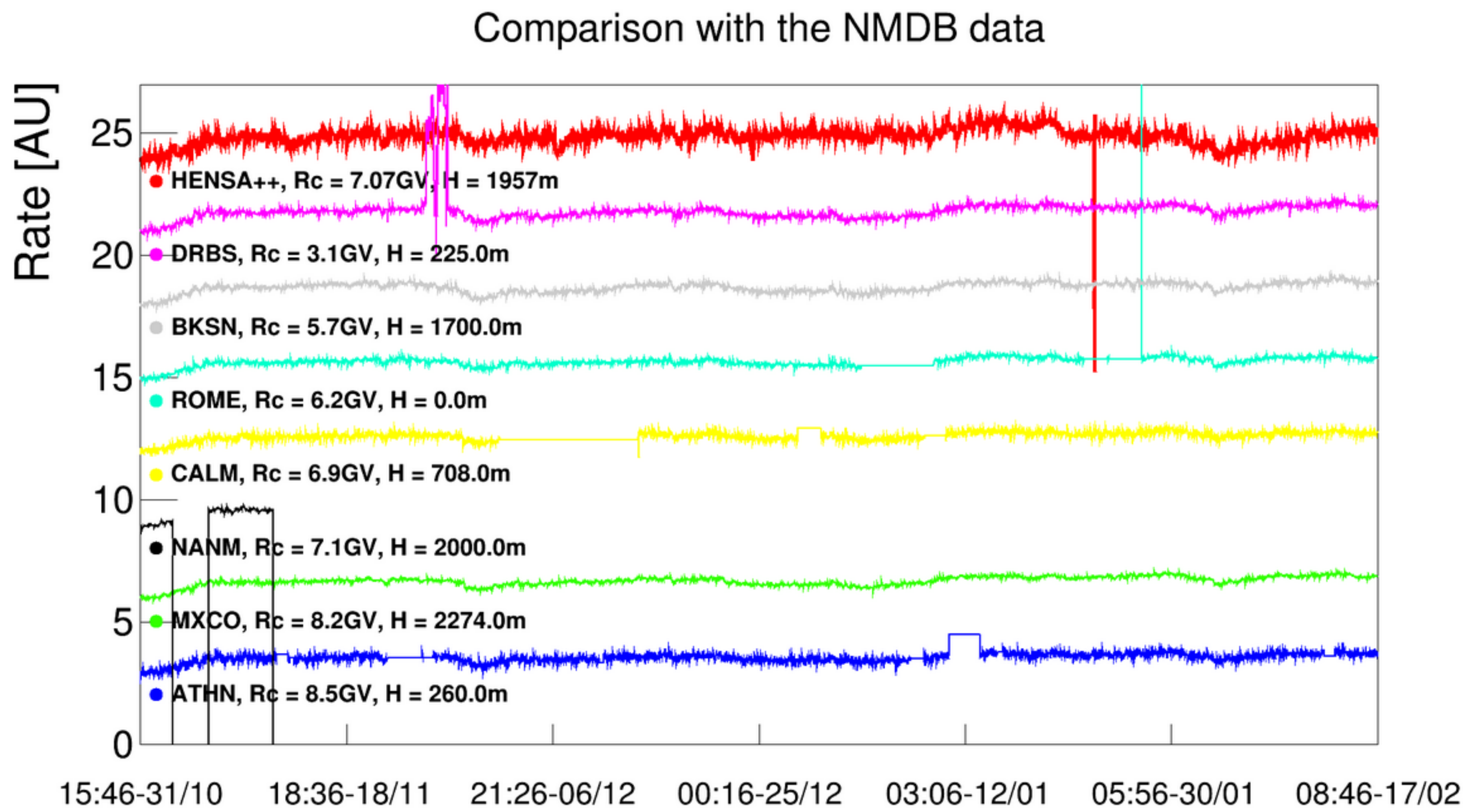




Benchmarking measurements with AmBe source (Calibration laboratory)







- Just 3 detectors!
- Very poor spectral sensitivity.
- Interesting data for dosimetry.

Since Nov/24, HENSA++ is producing bunches of interesting data related to space weather monitoring!

- There are many technical remarks!
- **But the most important ones:**
  - Results from the HENSA-CR2020 campaign will be released this year.
  - There is lot of room for collaboration of HENSA++ with the NM community.
  - Potentially, HENSA++ spectral information can be integrated into the NMDB.
  - What do you think? (how, what and when)

Discussion is welcomed!

PEOPLE

- Instituto de Física Corpuscular (IFIC), CSIC-UV, Spain

A. Tarifeño-Sadivia, J.L. Tain, S.E.A. Orrigo, B. Rubio, E. Nácher.

- Institute of Energy Technologies (UPC)

*F. Calviño, **N. Mont i Geli**, A. Casanovas, G. Cortés, A. De Blas, R. García, **M. Pallàs**, **B. Brusasco**.*

- Universidad Complutense de Madrid (UCM)

*L.M. Fraile, **V. Martínez Nouvillas***

- Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

D. Bemmerer, M. Grieger

HENSA collaboration for cosmic-rays & space weather

- Universidad de Granada

*A. Lallena, **A. Quero***

HENSA collaboration at LSC

- CIEMAT

*D. Cano-ott, T. Martínez, **J. Plaza del Olmo***

- Centro de Astropartículas y Física de Altas Energías

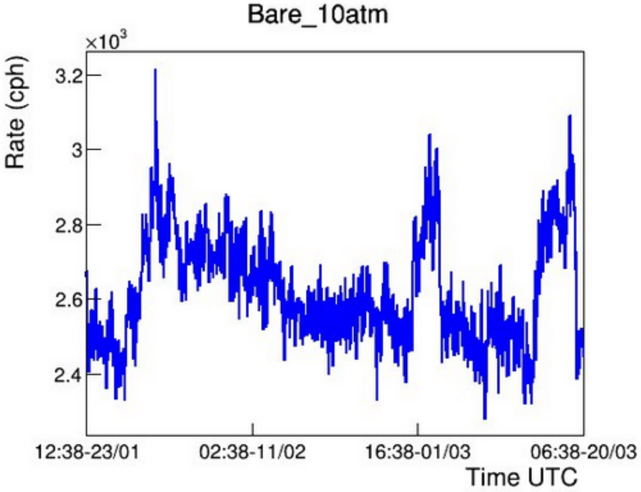
M. Martínez, M.L. Sarsa, A. Ortiz de Solórzano

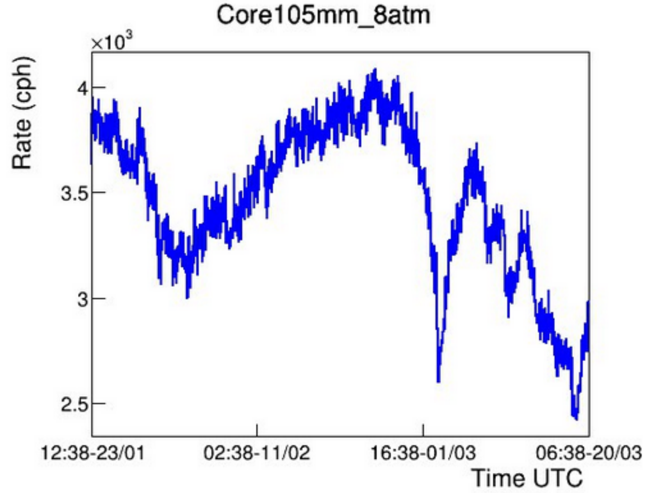
www.hensaproject.org

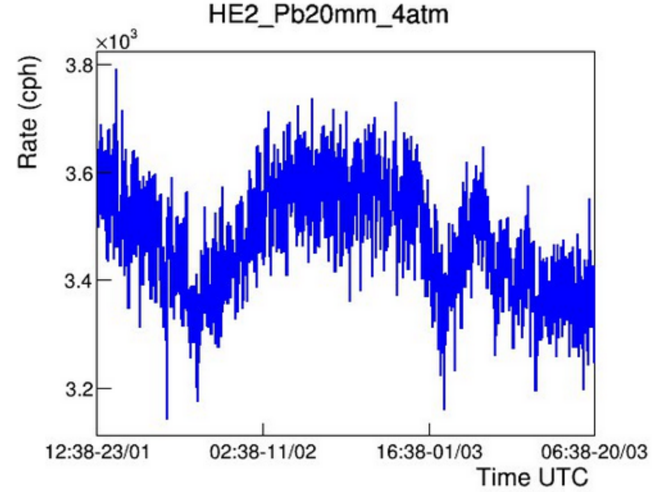
THANKS

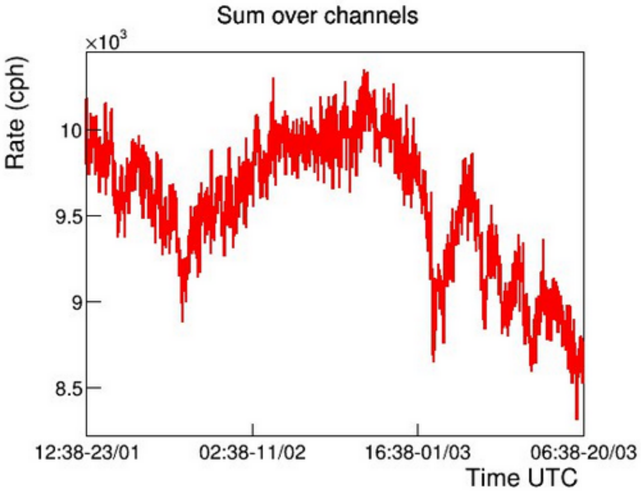
BACKUP SLIDES

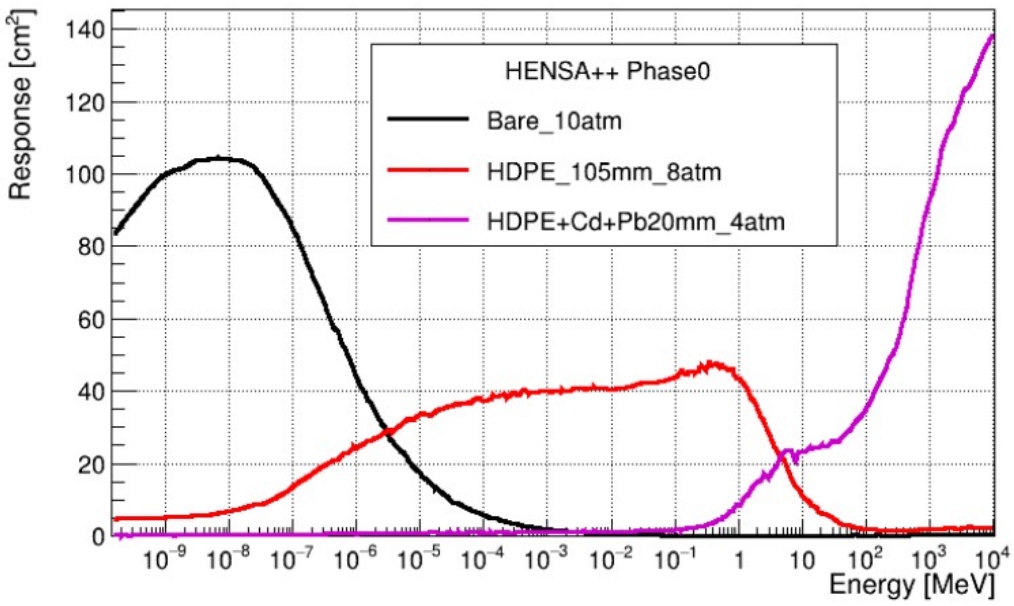
Online data from HENSA++ @ OAJ



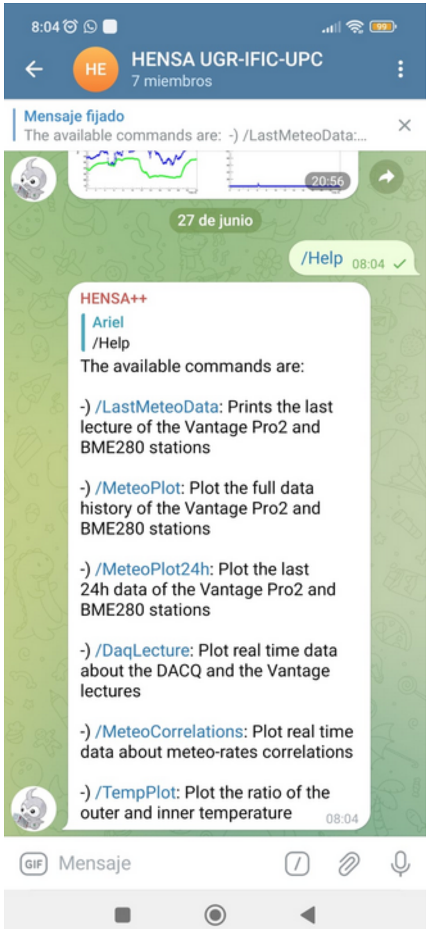


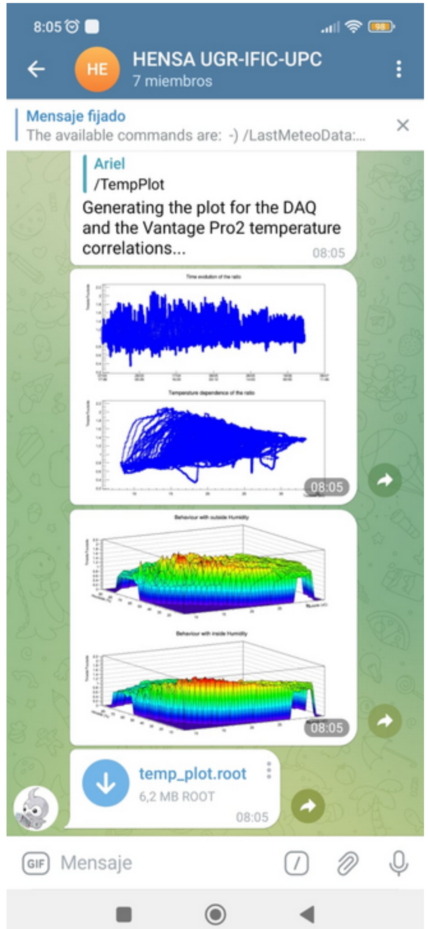


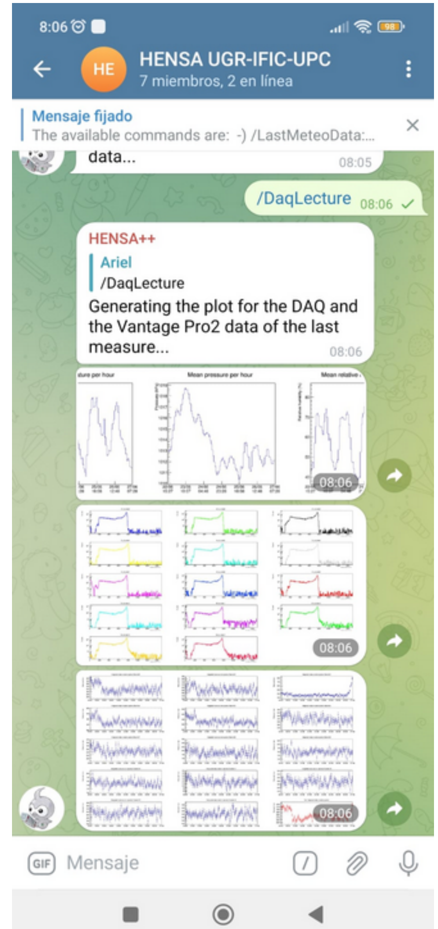


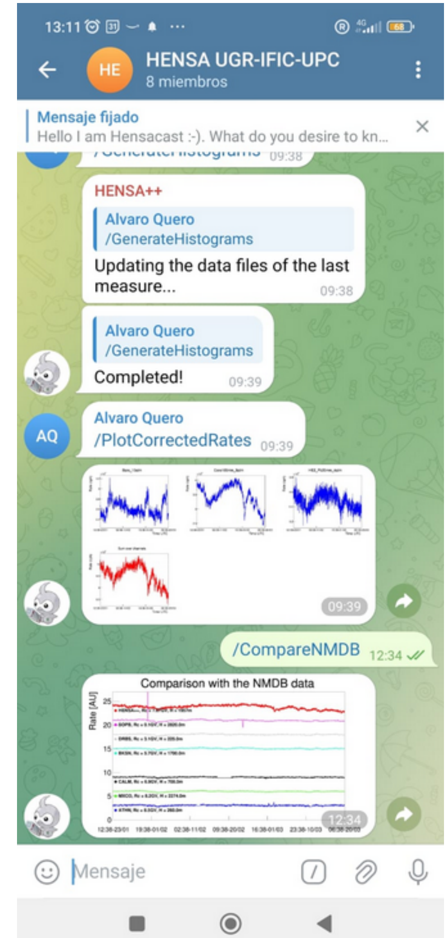


HENSA++ Telegram bot





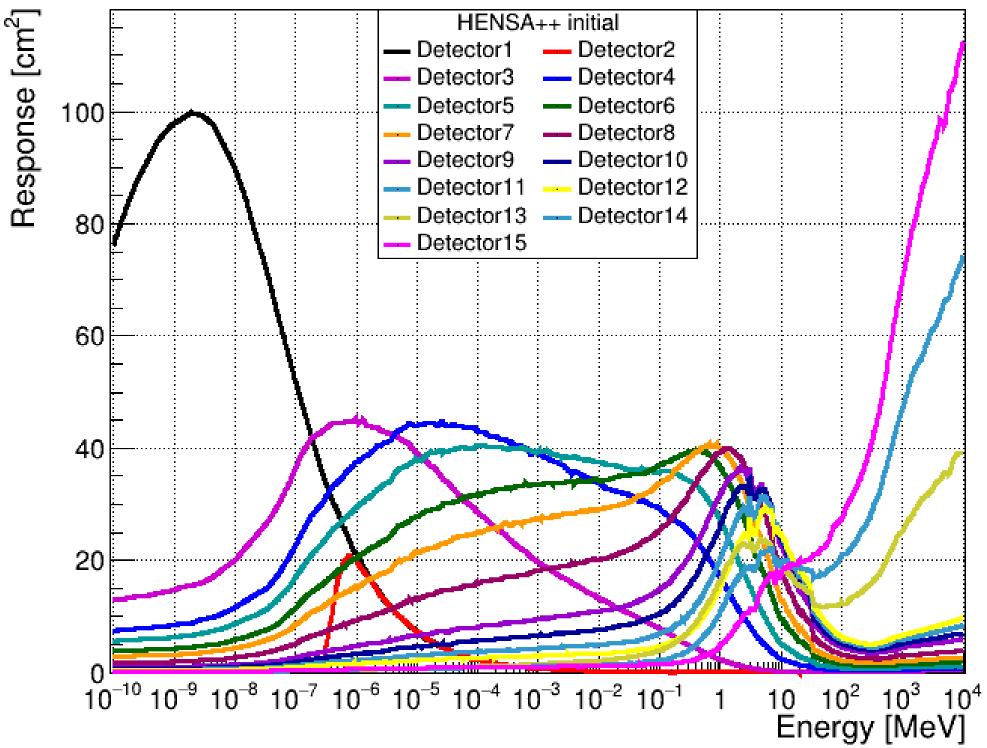




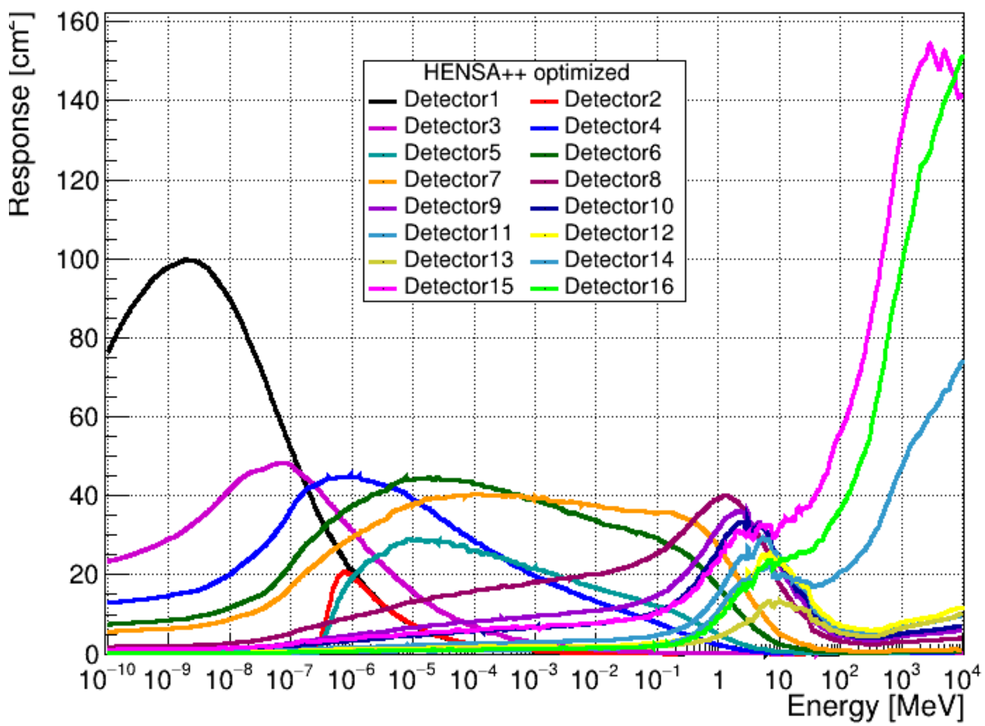
HENSA++ bot: remote "shift" available everywhere with just a mobile phone!

Optimization of responses for HENSA++

HENSA++ proposal design



HENSA++ Optimized version



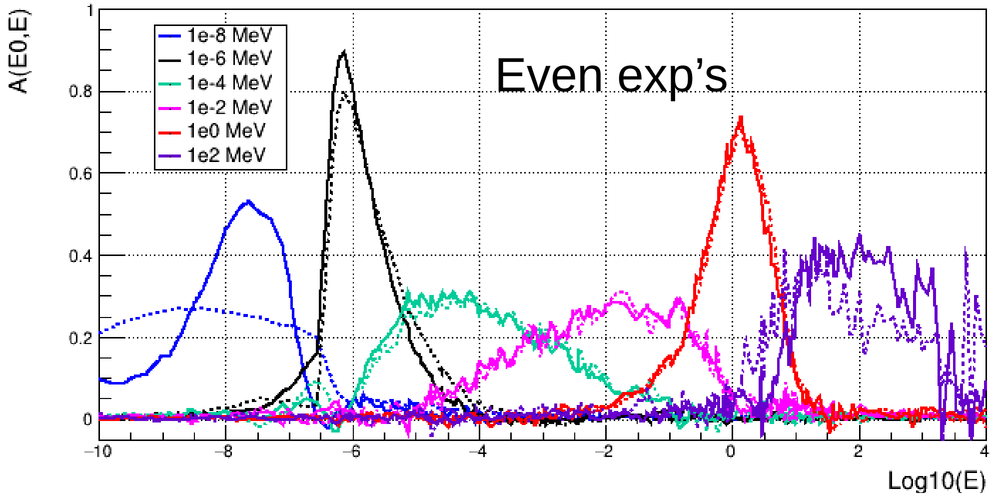
+ Intensive MC calculations have been performed.
+ Explored hundreds of possible detector configurations.
+ Optimization based on improving the resolving power of the array & tradeoff with technical viability (construction & weight).

MC simulations by the Geant4 application ***ParticleCounter***.

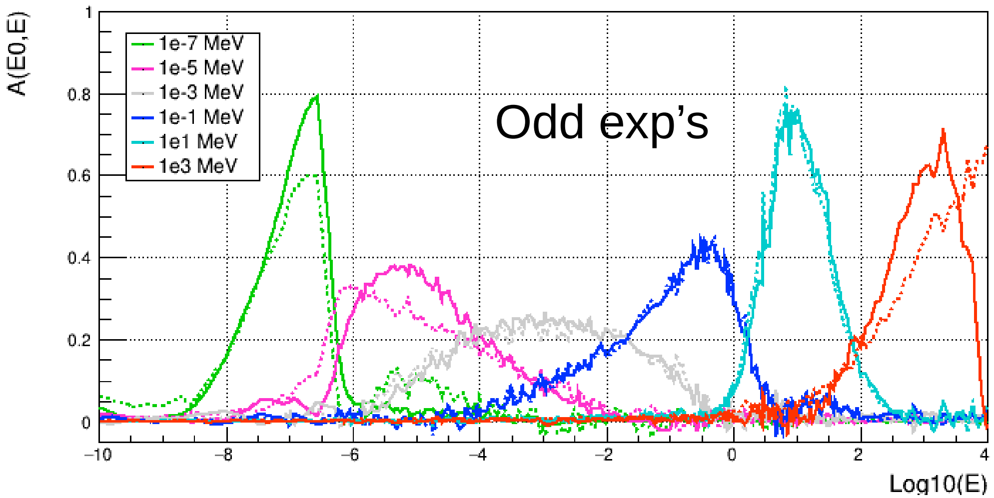
A. Quero, PhD thesis, UGR (Granada)

Final solution: resolving power

A. Quero, PhD thesis, UGR (Granada)

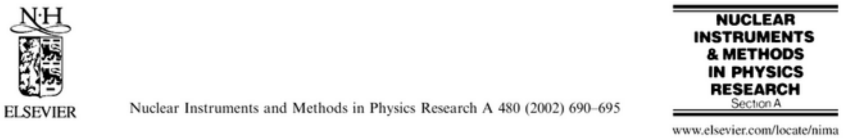


Dotted: Initial | Continuous: Optimized



Comparison of the resolving power moments

LogE	Mean(vInit)	Mean(vOpt)	SD(vOpt)/SD(vInit)-1
-8	-7.72	-7.69	-44.20%
-7	-6.76	-6.86	-51.11%
-6	-5.76	-5.89	-20.37%
-5	-4.93	-4.86	-24.11%
-4	-3.93	-3.98	-4.65%
-3	-3.00	-2.98	-8.27%
-2	-2.07	-2.08	-2.13%
-1	-1.12	-1.09	2.56%
0	-0.08	-0.09	-1.71%
1	0.91	0.94	-2.15%
2	1.43	1.72	-38.90%
3	2.71	2.73	-39.72%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Nuclear Instruments and Methods in Physics Research A 480 (2002) 690–695

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Resolving power of a multisphere neutron spectrometer

Marcel Reginatto*

$$< \phi >_{E_0} = \int A(E_0, E)\phi(E)dE$$

Final version will use 60 cm counters at 4, 8 and a small one (30 cm) at 20 atm.

Acceptance criteria for solutions

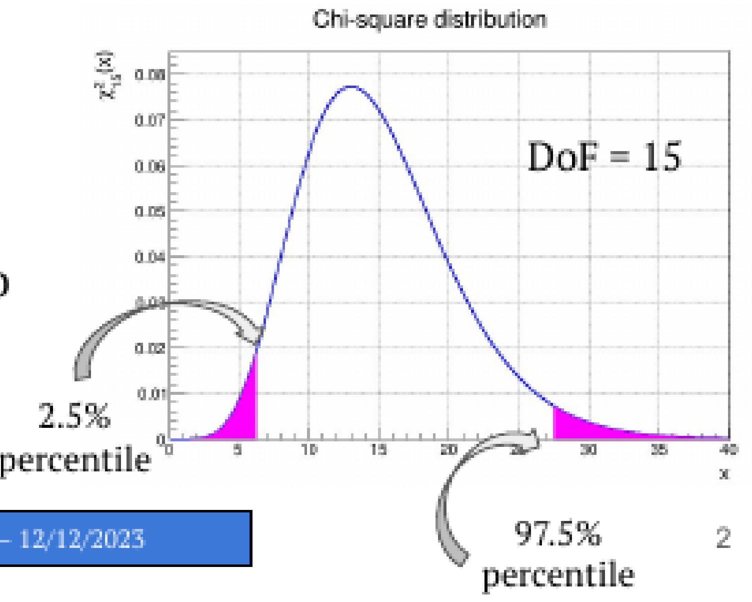
➢ Null hypothesis:

$$H_0 : \{C_i^{unfold}\}_{i=1}^{n} \sim \{C_i^{true}\}_{i=1}^{n}$$

➢ Set a Confidence Interval for the chi-square statistic (Ex: 95%)

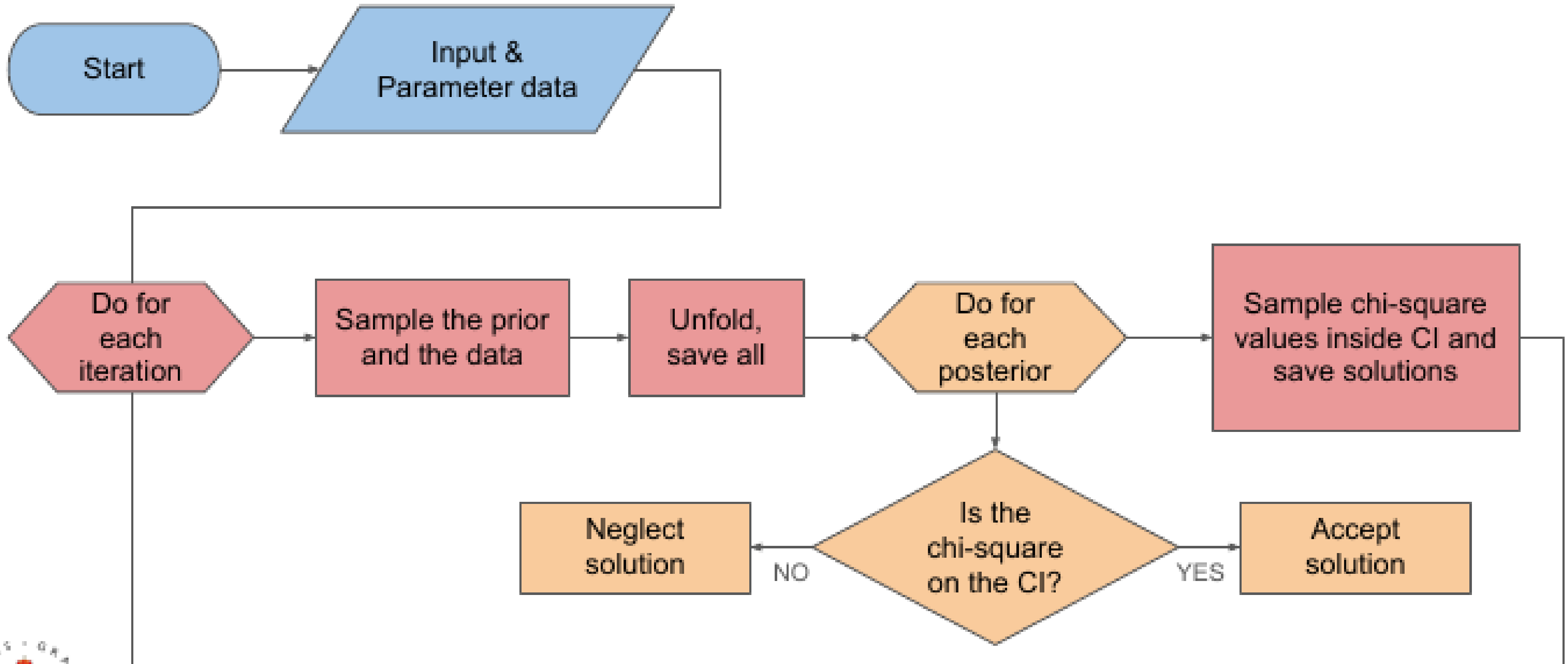
$$\chi^2 = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{C_i^{input} - C_i^{output}}{\sigma_i^{input}}\right)^2$$

➢ If the chi-square value of the unfolding is in the CI, Ho can't be rejected so the solution is accepted



Chi-squared Analysis for POU – A Quero-Ballesteros — 12/12/2023 2

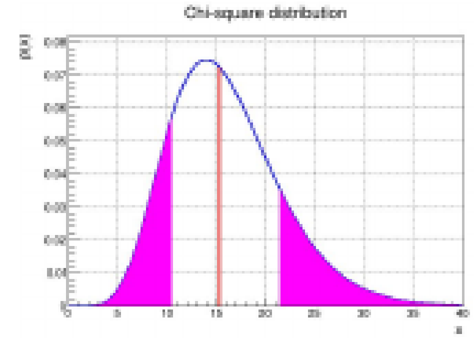
Methodology of POU



Treatment of the solutions

- For each energy bin, we'll obtain a set of solutions $[\phi_i]_{i=1}^{n}$ that constitute a distribution of fluence.

- We want to give a final spectrum with its uncertainty, so:
  - The central value selected is the median of the distribution
  - The uncertainty is given by a Confidence Interval of 1σ (68%)



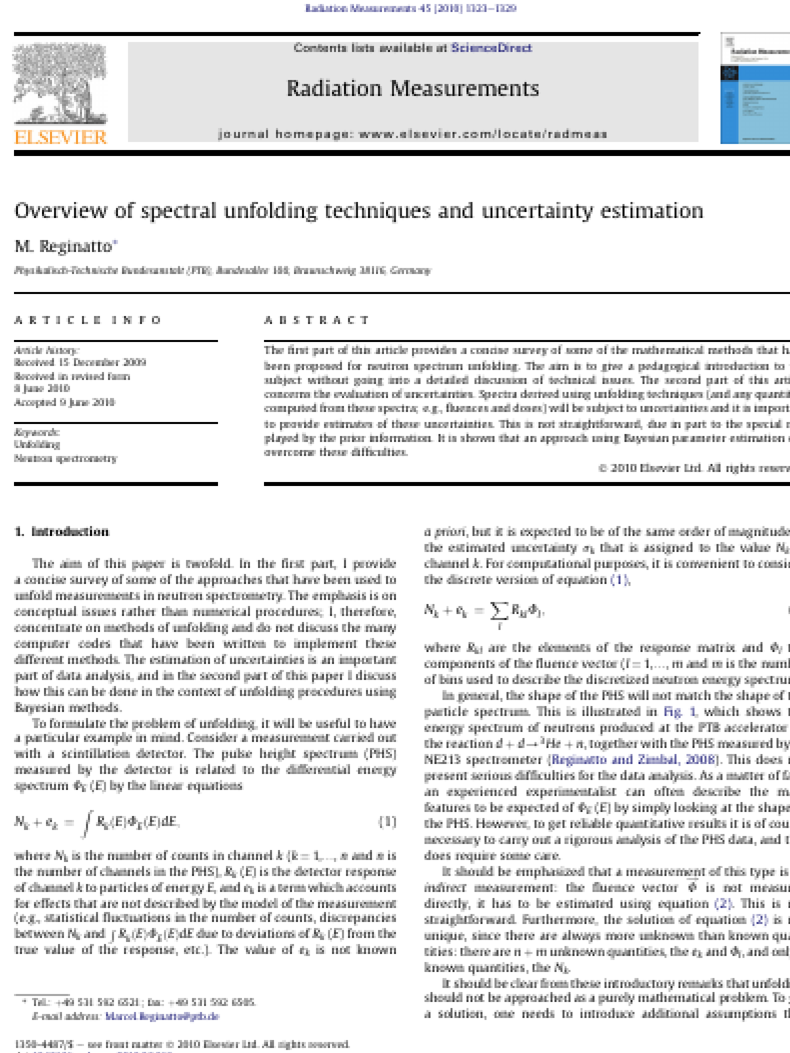
- The same process is employed for the integral values of the fluence and doses in the desired regions.

- With the code, we can calculate: space of solutions, chi-square distribution, covariance matrix, distribution of solutions, chi-square maps for the parameters…

Energy spectrum reconstruction: algorithms

- **Iterative procedures**: usually black-magic recipes!
- **Stochastic methods**: Monte Carlo, genetic algorithms, ...
- **Regularisation**: add constraints to enforce smoothness
- **Least-squares adjustment**
- **Bayesian parameter estimation**: requires an analytical model for fitting
- **Maximum entropy principle:** justifiable from information theory consistent treatment of prior information and uncertainties
- **Machine learning...**

Most of this methods require a-priori information that is retrieved from MC calculations



Radiation Measurements 45 (2010) 1323–1329

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Overview of spectral unfolding techniques and uncertainty estimation

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ABSTRACT

The first part of this article provides a concise survey of some of the mathematical methods that have been proposed for neutron spectrum unfolding. The aim is to give a pedagogical introduction to the subject without going into a detailed discussion of technical issues. The second part of this article concerns the evaluation of uncertainties. Spectra derived using unfolding techniques (and any quantities computed from these spectra, e.g., fluences and doses) will be subject to uncertainties and it is important to provide estimates of these uncertainties. This is not straightforward, due in part to the special role played by the prior information. It is shown that an approach using Bayesian parameter estimation can overcome these difficulties.

1. Introduction

The aim of this paper is twofold. In the first part, I provide a concise survey of some of the approaches that have been used to unfold measurements in neutron spectrometry. The emphasis is on conceptual issues rather than numerical procedures; I, therefore, concentrate on methods of unfolding and do not discuss the many computer codes that have been written to implement these different methods. The estimation of uncertainties is an important part of data analysis, and in the second part of this paper I discuss how this can be done in the context of unfolding procedures using Bayesian methods.

To formulate the problem of unfolding, it will be useful to have a particular example in mind. Consider a measurement carried out with a scintillation detector. The pulse height spectrum (PHS) measured by the detector is related to the differential energy spectrum $\Phi_E(E)$ by the linear equations

$$N_k + \epsilon_k = \int R_k(E)\Phi_E(E)\mathrm{d}E, \quad (1)$$

where N_k is the number of counts in channel k ($k = 1, \ldots, n$ and n is the number of channels in the PHS), $R_k(E)$ is the detector response of channel k to particles of energy E, and ϵ_k is a term which accounts for effects that are not described by the model of the measurement (e.g., statistical fluctuations in the number of counts, discrepancies between N_k and $\int R_k(E)\Phi_E(E)\mathrm{d}E$ due to deviations of $R_k(E)$ from the true value of the response, etc.). The value of ϵ_k is not known a priori, but it is expected to be of the same order of magnitude as the estimated uncertainty σ_k that is assigned to the value N_k of channel k. For computational purposes, it is convenient to consider the discrete version of equation (1),

$$N_k + \epsilon_k = \sum_i R_{ki}\Phi_i, \quad (2)$$

where R_{ki} are the elements of the response matrix and Φ_i the components of the fluence vector ($i = 1, \ldots, m$ and m is the number of bins used to describe the discretized neutron energy spectrum).

In general, the shape of the PHS will not match the shape of the particle spectrum. This is illustrated in Fig. 1, which shows the energy spectrum of neutrons produced at the PTB accelerator by the reaction $d + d \rightarrow {}^3He + n$, together with the PHS measured by an NE213 spectrometer (Reginatto and Zimbal, 2008). This does not present serious difficulties for the data analysis. As a matter of fact, an experienced experimentalist can often describe the main features to be expected of $\Phi_E(E)$ by simply looking at the shape of the PHS. However, to get reliable quantitative results it is of course necessary to carry out a rigorous analysis of the PHS data, and this does require some care.

It should be emphasized that a measurement of this type is an indirect measurement: the fluence vector $\vec{\Phi}$ is not measured directly, it has to be estimated using equation (2). This is not straightforward. Furthermore, the solution of equation (2) is not unique, since there are always more unknown than known quantities: there are $n + m$ unknown quantities, the ϵ_k and Φ_i, and only n known quantities, the N_k.

It should be clear from these introductory remarks that unfolding should not be approached as a purely mathematical problem. To get a solution, one needs to introduce additional assumptions that

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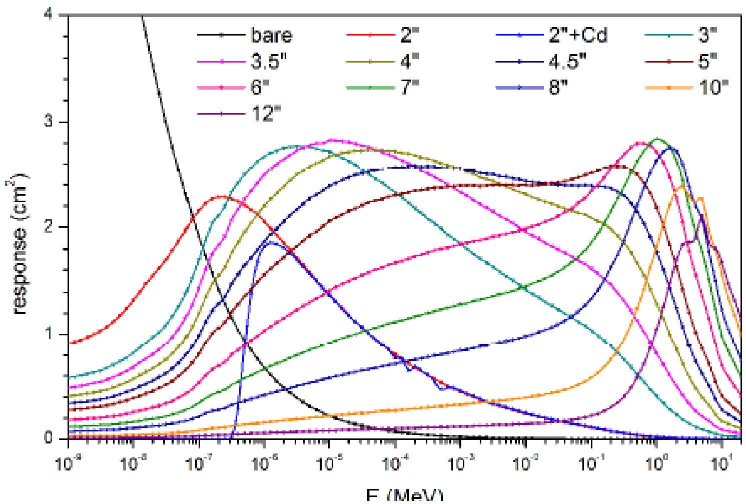
M. Reginatto, Rad. Meas. 45 (2010) 1323-1329

Energy spectrum reconstruction: trained users



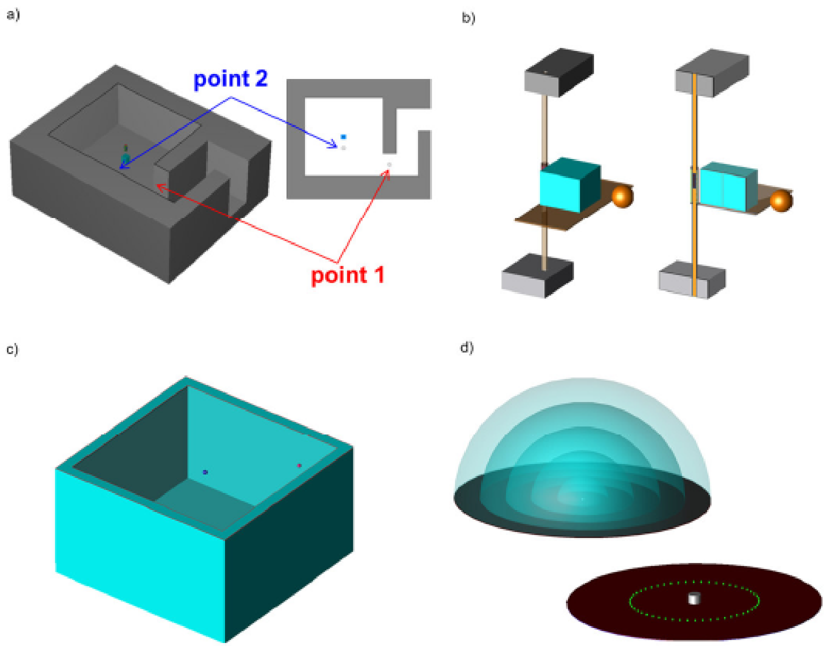


Fig. 2: Irradiation scenarios: a) medical LINAC (2 measurement points); b) workplace; c) calibration facility; d) skyshine

Results of the EURADOS international comparison exercise on neutron spectra unfolding in Bonner spheres spectrometry

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Rad. Meas. 153 (2022) 106755

Table 1 Summary of participants unfolded codes, solved scenarios and pre-information method.

participant	unfolding method	LINAC	workplace	calibration room	skyshine	pre-information
a	B-UNCLE	x	x	x	x	not clearly indicated
b	FRUIT	x	x	x	x	choice of parametric model
c	FRUIT	x	x	x	x	choice of parametric model
d	FRUIT	x	x	x	x	missing information
e	GRUPINT, ANGELO, ZOTT99	x	x	x	x	MCNP6
f	UMG 3.3	x		x		MCNP6
g	UMG 3.3	x				default spectrum from literature
h	UMG 3.3	x	x	x	x	MCNPX 2.5
i	UMG 3.3		x	x	x	MCNP6
j	UMG package: MXD_FC33		x	x		MCNP6
k	MAXED	x	x	x	x	problem dependent
l	GRAVEL	x	x	x	x	problem dependent
m	MXD_FC33 and IQU_FC33	x	x	x	x	problem dependent
n	MAXED	x	x	x	x	MCNP5
o	MAXED / UMG			x		MCNP5
p	MAXED 2000			x		not clearly indicated
q	MSITER / MIEKE		x	x		MCNP5
r	WinBUGS	x	x	x	x	choice of parametric model
s	basic Tykhonov method	x	x	x	x	none
t	self-made	x	x	x	x	none
u	self-made			x		none

Energy spectrum reconstruction: trained users

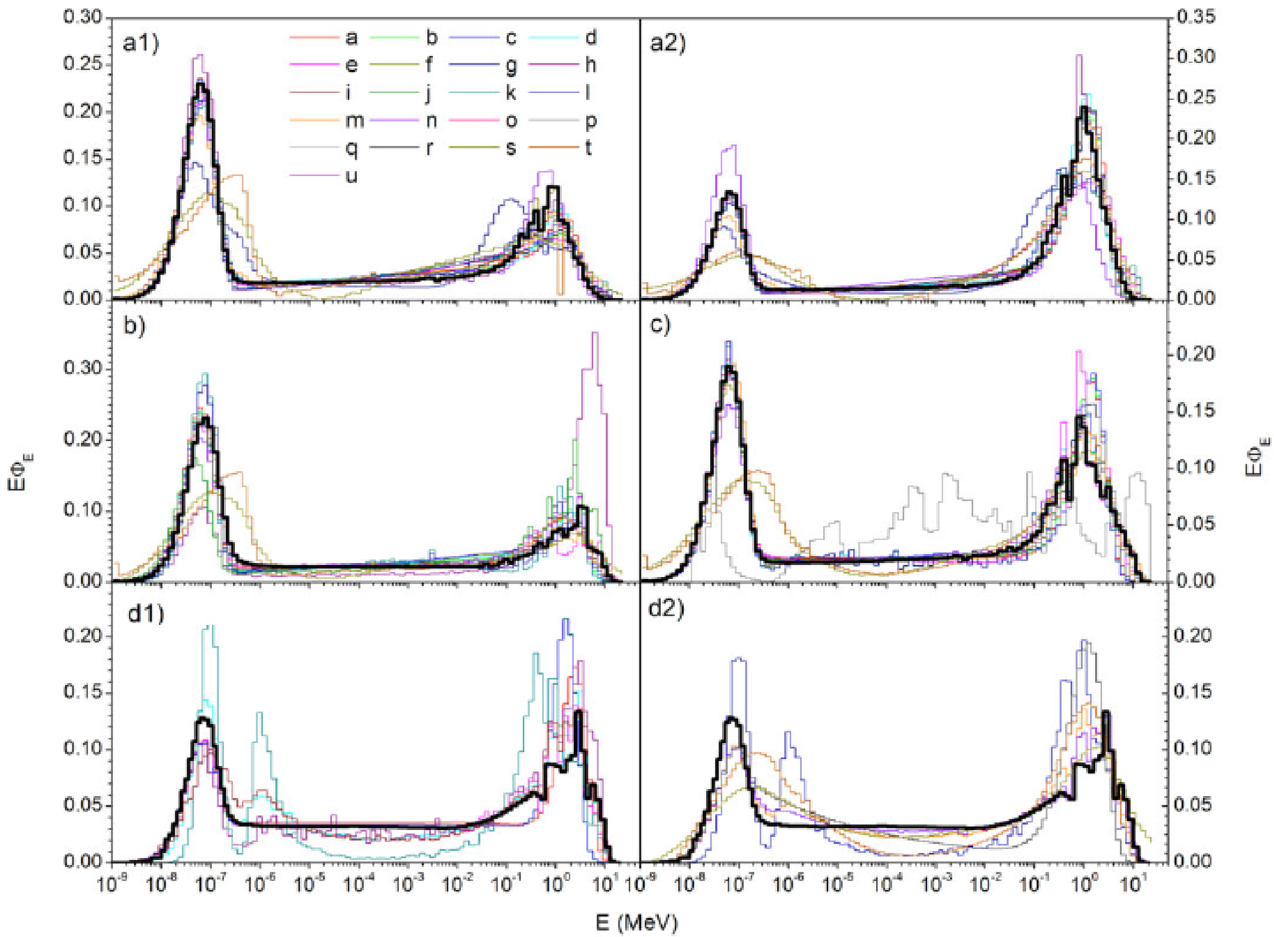

Fig. 3: Participants unfolded spectra (in colour) compared with the reference spectra for: a1) LINAC scenario, point 1 (at the entrance of the maze); a2) LINAC, point 2 (1 m from the isocentre); b) workplace; c) calibration facility; d) skyshine.