Neutron spectrometry with HENSA: from underground physics to space weather applications

Ariel Tarifeño-Saldivia

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

Nil Mont-Geli

Institut de Tècniques Energètiques
Universitat Politècnica de Catalunya

nil.mont@upc.edu

HENSA
High Efficiency Neutron Spectrometry Array

OUTLINE

- Neutron spectrometry with Bonner spheres
- The HENSA project
- Neutron background in underground facilities
- Cosmic-ray neutrons
- HENSA++

Neutron spectrometry with Bonner spheres

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

A NEW TYPE OF NEUTRON SPECTROMETER†

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

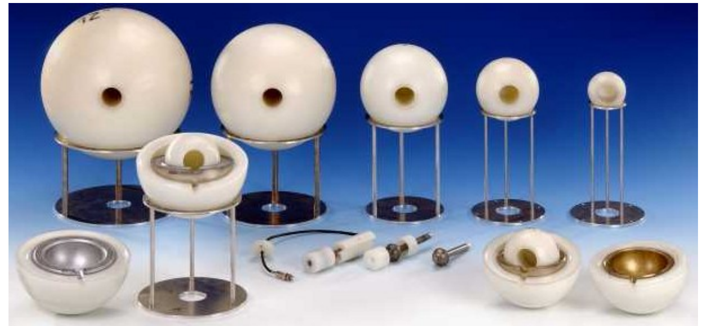
The Rice University, Houston Texas

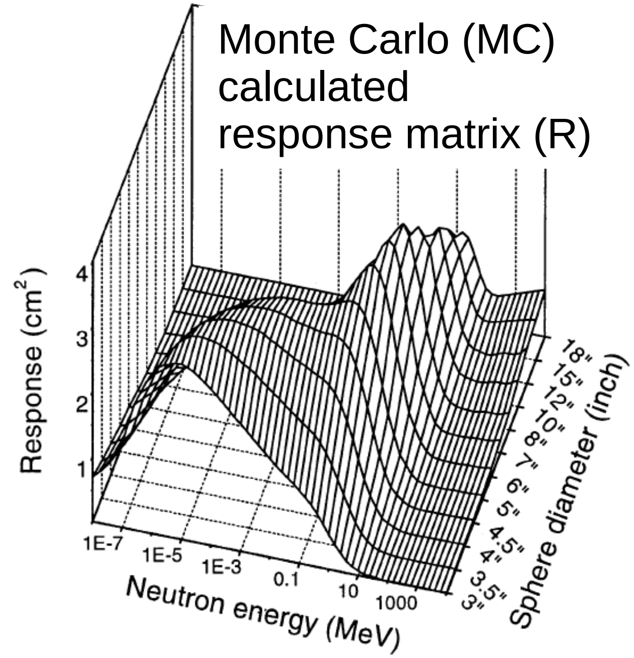
Received 4 July 1960

Neutrons are detected in a small $Li^6I(Eu)$ 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)

- Bonner spheres (BS) spectrometers are among the most known and widespread techniques for neutron spectrometry.
- Moderated proportional neutron counters. Useful from thermal to GeV region.
- Typically 5 up to 14 spheres → ***Ill-posed linear inverse problem*!**

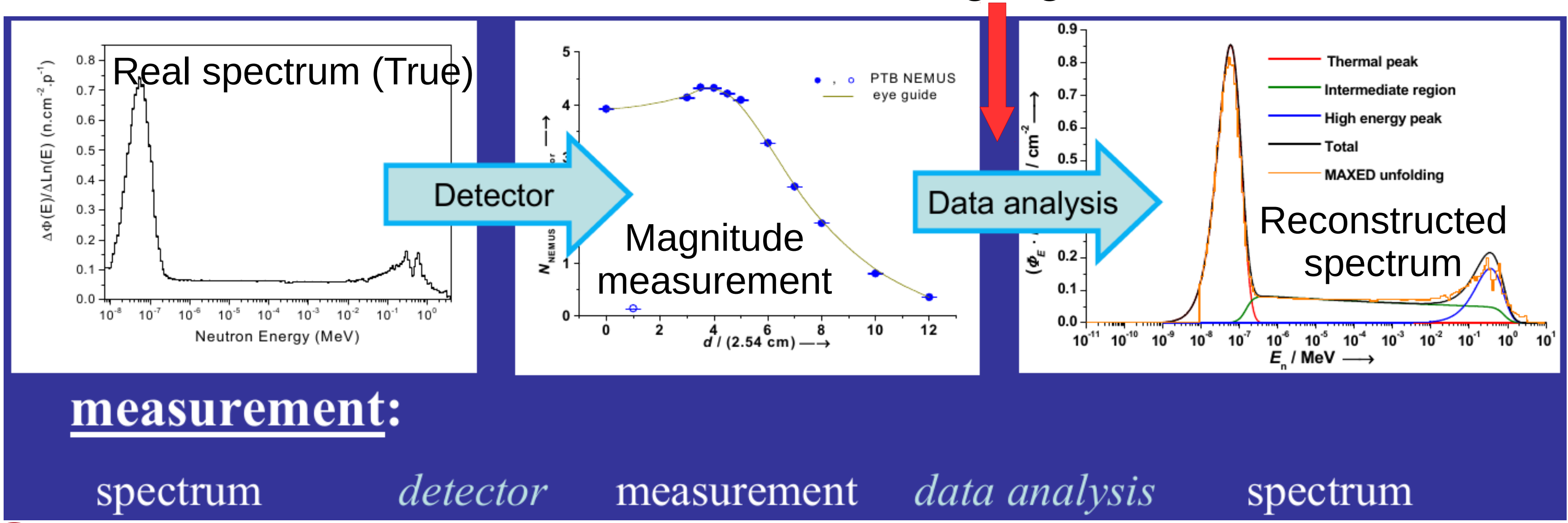




$$M_i = \int R_i(E)\phi(E)\,\mathrm{d}E.$$

$$\rightarrow \quad M_i = \sum_{j=1}^{n} R_{ij}\phi_j$$

Unfolding algorithm



The High Efficiency Neutron Spectrometry Array (HENSA)

- **<u>Original idea by J.L. Tain (IFIC) in 2010</u>**: 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***.

- **Core HENSA collaboration**: IFIC, UPC, UCM, HZDR, TRIUMF.
- **HENSA collaboration at the Canfranc Underground Laboratory**: CIEMAT, ANAIS-112, LSC.
- **HENSA collaboration for space weather**: UGR.

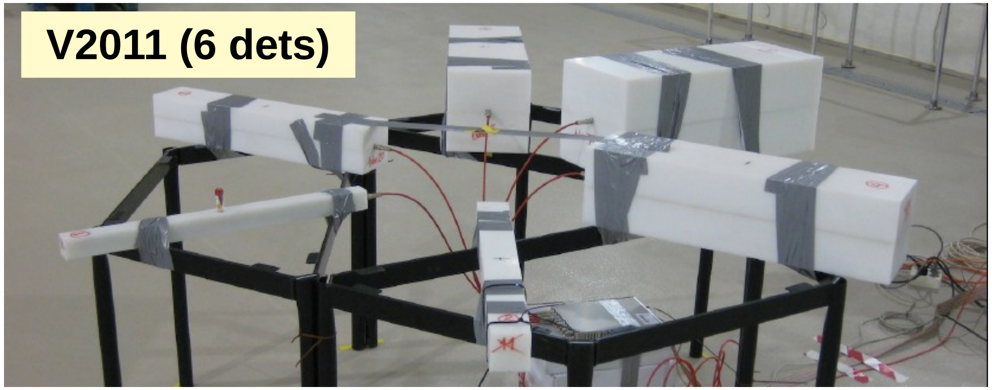
www.hensaproject.org

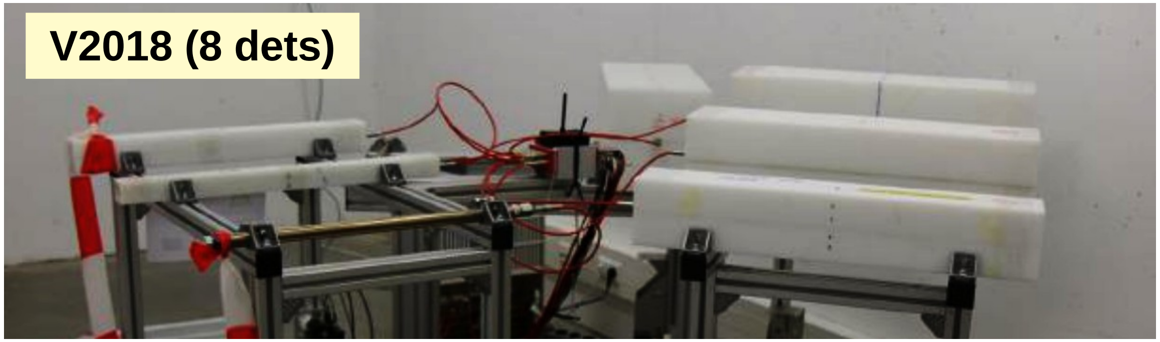
HENSA

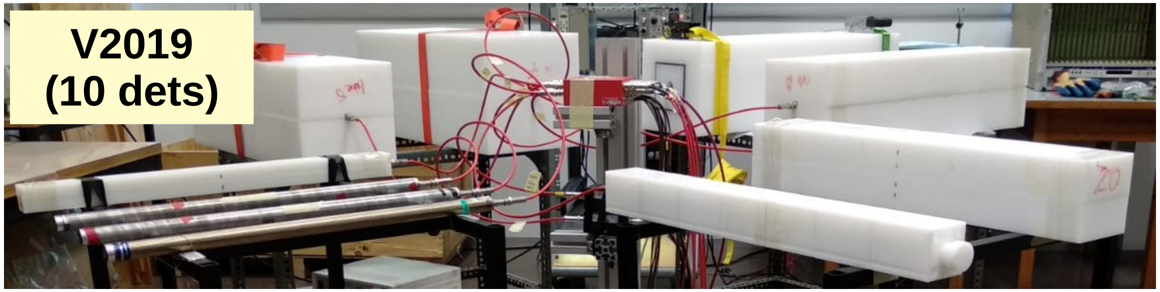
High Efficiency Neutron Spectrometry Array

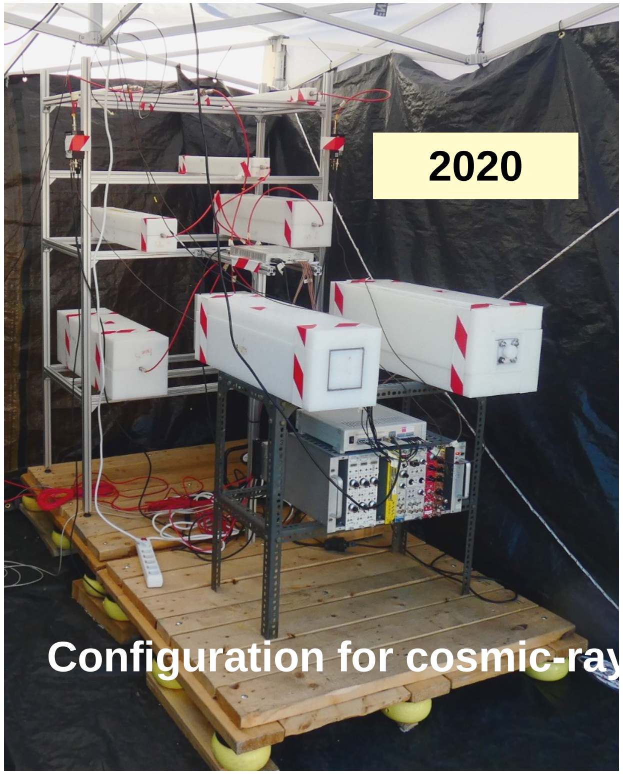
The HENSA project: evolution of the spectrometer

- HENSA is based of the Bonner Spheres Principle. Energy sensitivity from thermal to 10 GeV.
- Potential lines: neutron background in underground facilities, cosmic rays neutrons and space weather, environmental radioactivity...









HENSA setup: version 2019

- The HENSA detector is an array of ten different neutron detectors.
- 3He-filled cylindrical tube model LND-252248 of 2.54 cm of diameter and 60 cm of active length, 10 atm.
- Each He-3 tube is embeded in a matrix of different materials (shieldings, high density poliethylene moderators and lead neutron converters).

Detector name	Material of the coat	Dimensions
Det1	Bare	-
Det2	HDPE	4.5x4.5x70 cm^3
Det3	HDPE	7x7x70 cm^3
Det4	HDPE	12x12x70 cm^3
Det5	HDPE	18x18x70 cm^3
Det6	HDPE	22.5x22.5x70 cm^3
Det7	HDPE	27x27x70 cm^3
Det8	HDPE + Pb	21x21x70 cm^3 + 5mm Pb thickness
Det9	Cd	0.5mm thickness
Det10	HDPE + Pb + Cd	25x25x70 cm^3 + 0.75mm Cd +10mm Pb

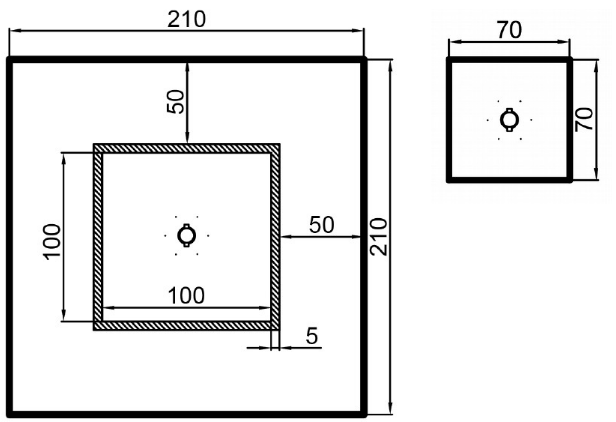
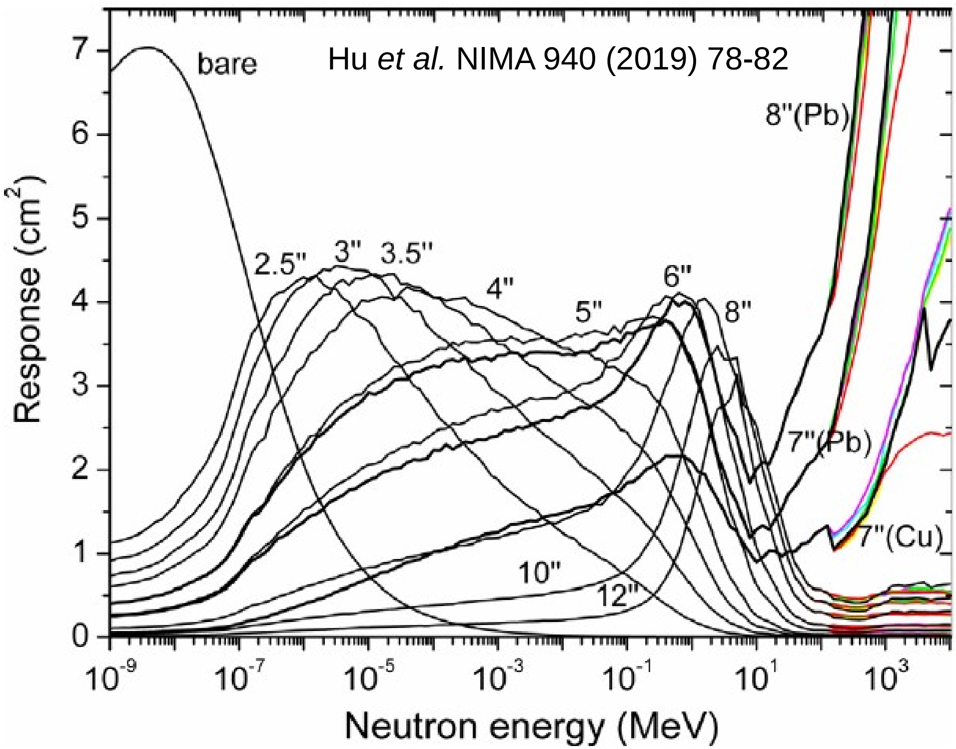


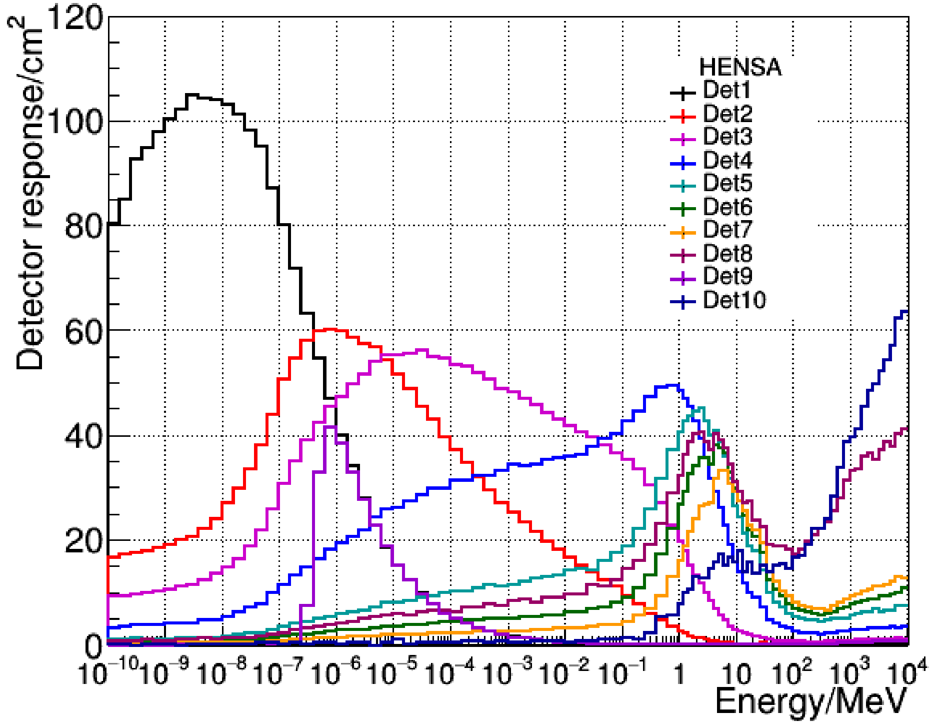
Fig 3.
Left image: section of the D8 detector[6].
Right image: section of the D3 detector[6].

HENSA spectral sensitivity

Standard extended Bonner Spheres



HENSA version 2019



HENSA neutron response is **~5-15 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 fluctuations of the neutron background at ground or air based measurements.

A. Tarifeño-Saldivia
N. Mont-Geli

Neutron background in underground facilities

Origin of the neutron background in underground facilities

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 $5\cdot10^{-5}$ % (^{238}U) of all decays

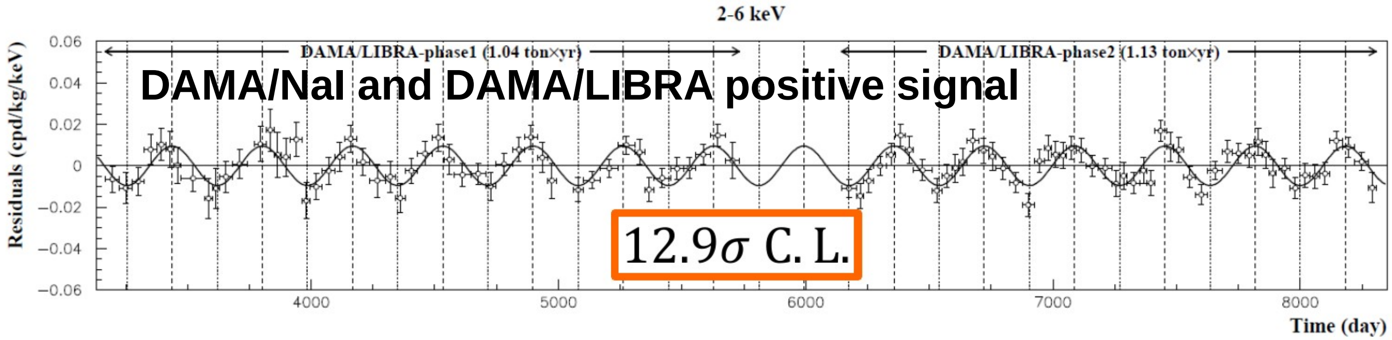
Background neutrons in underground physics

- Underground research: astroparticle physics, nuclear astrophysics experiments, biological and geological studies.
- **Neutron are a limiting factor** in many rare event experiments (e.g. neutrino searches, neutrino-less double-beta decay experiments and dark matter searches).
- In underground nuclear astrophysics, the measurement of several key reactions for the astrophysical s-process requires ultra-low ambient neutron background (CUNA project).
- In Spain, the **Laboratorio Subterráneo de Canfranc** is the reference facility for underground physics (NEXT, ANAIS, ArDM, among others).
- Most of the measurements in underground facilities are based either on thermal neutron counters or scintillators sensitive to fast neutrons. **Fully spectrometric measurements are very scarce!**

Neutron flux at different underground facilities
Compilation from Hu *et al*. NIMA 859 (2017) 37-40.

Underground lab	**Depth (m.w.e)**	**Thermal neutron flux ($cm^{-2}\ s^{-1}$)**	**Fast neutron flux ($cm^{-2}\ s^{-1}$)**
CPL	1000	No data	$(3.00 \pm 0.02 \pm 0.05)\times10^{-5}$
Yang Yang	2000	$(2.42 \pm 0.22)\times10^{-5}$	8×10^{-7}
Soudan	2090	$(0.7 \pm 0.08 \pm 0.08)\times10^{-6}$	No data
Canfranc	2450	$(1.13 \pm 0.02)\times10^{-6}$	$(0.66 \pm 0.01)\times10^{-6}$
Boulby	2800	No data	$(1.72 \pm 0.61 \pm 0.38)\times10^{-6}$
Gran Sasso	3600	$(1.08 \pm 0.02)\times10^{-6}$	$(0.23 \pm 0.07)\times10^{-6}$
Modane	4800	$(1.6 \pm 0.1)\times10^{-6}$	$(4.0 \pm 1.0)\times10^{-6}$
CJPL-I	6720	$(4.00 \pm 0.08)\times10^{-6}$	No data
CJPL-I	6720	$(7.03 \pm 1.81)\times10^{-6}$	$(3.63 \pm 2.77)\times10^{-6}$

An important physical case underground: ANAIS – 112 experiment



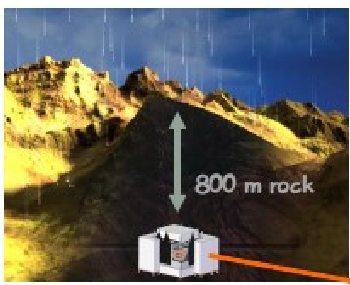
For ANAIS is relevant the measurements of:

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.

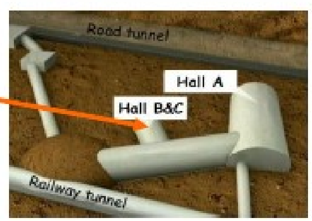
Goal

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)



ANAIS

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

EXPERIMENTAL SET-UP

9 ultrapure NaI(Tl) cylindrical crystals (12.5 kg each) in 3×3 matrix coupled to two Hamamatsu R12669SEL2 PMTs ($QE \sim 40\%$)

Courtesy ANAIS team

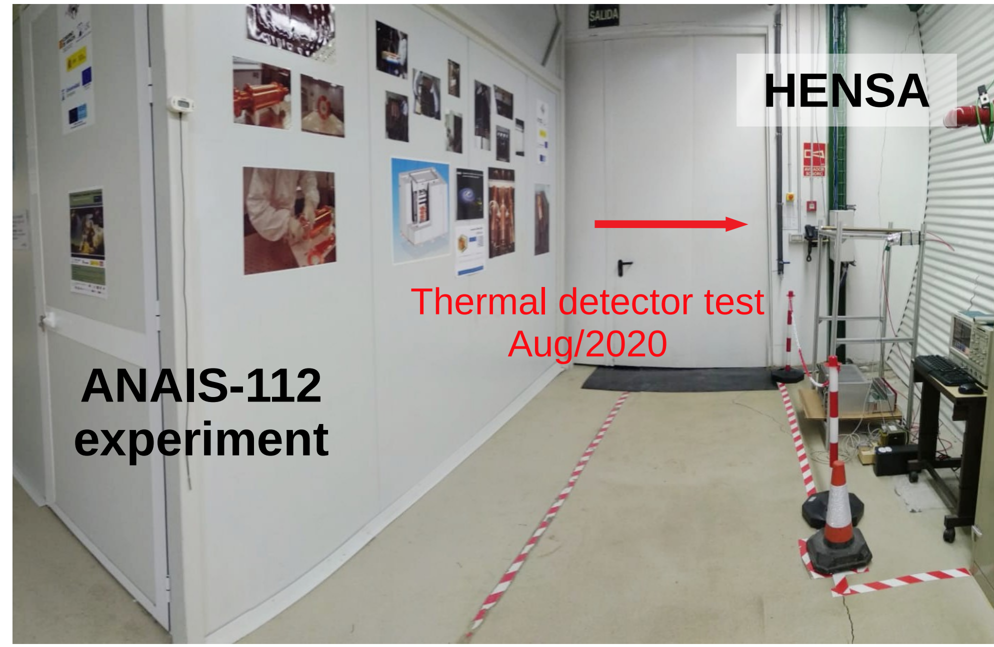
Current activities in underground facilities

Neutron background measurements with HENSA at LSC

Approved expression of interest (EoI-26-2020). Status of quasi-permanent experiment at LSC.

New measurement at **Hall A** @ LSC:
- Data acquisition from **Oct 2019 until March 2021.**
- Data analysis S. Orrigo (IFIC).
(EPJ C 82, 1-11, 2022)

- Continuous monitoring based on reduced HENSA setup (4 dets), **PhD thesis J. Plaza (CIEMAT)**



New measurement at **Hall B** @ LSC:
In collaboration with **ANAIS** experiment (**dark matter search**):
- Measurements started in **March 2021**, Planned until **2024, PhD thesis N. Mont, UPC**
Collaborators:
Marisa Sarsa/María Martínez (ANAIS team, UNIZAR)

Results HENSA hall A @ LSC

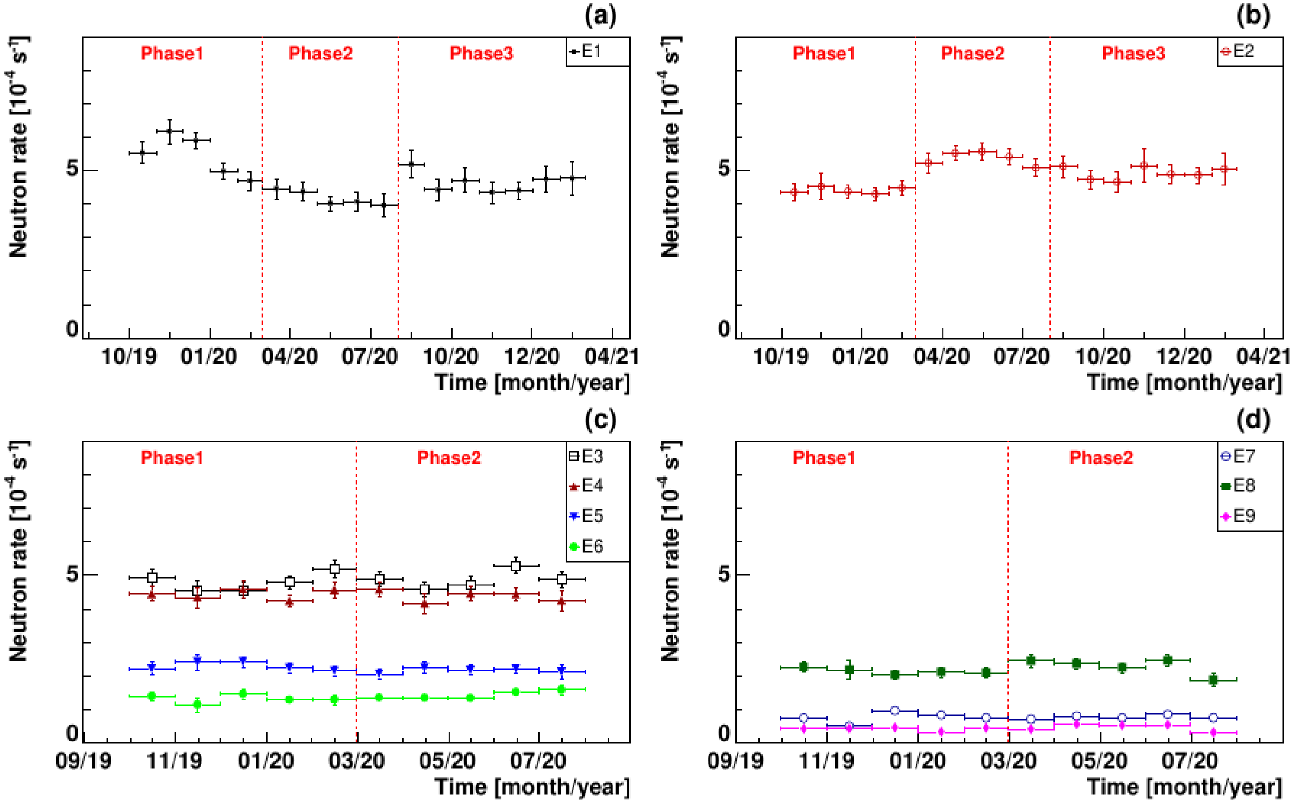
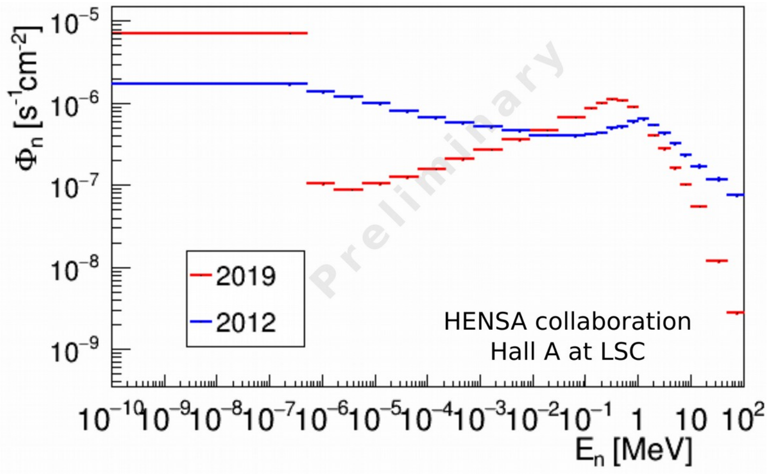


Fig. 4 Long-term evolution of the neutron rate observed during our measurement campaign in the Hall A of LSC in the detectors: (a) E1; (b) E2; (c) E3, E4, E5 and E6; (d) E7, E8 and E9.

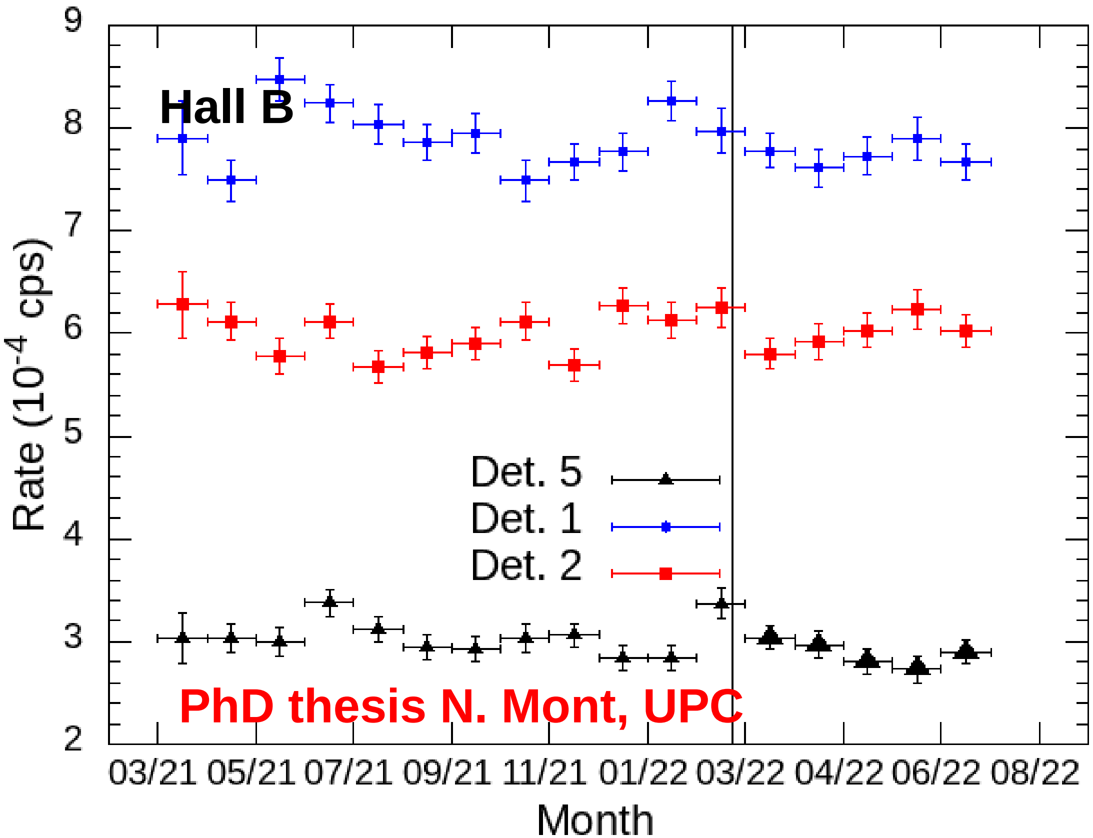
S. Orrigo et *al* 2022, Eur. Phys. J. C **82**, pp 1 – 11.



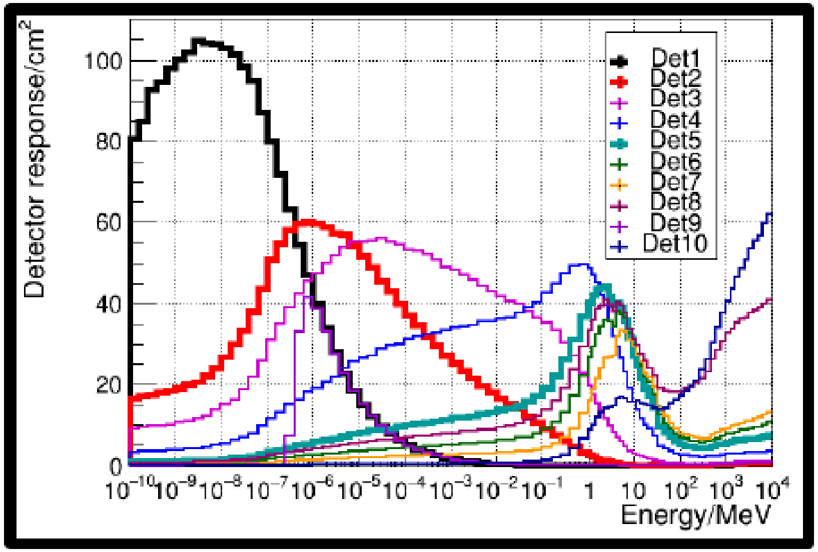
Preliminary result on spectrum reconstruction

Observed 20% larger total flux!

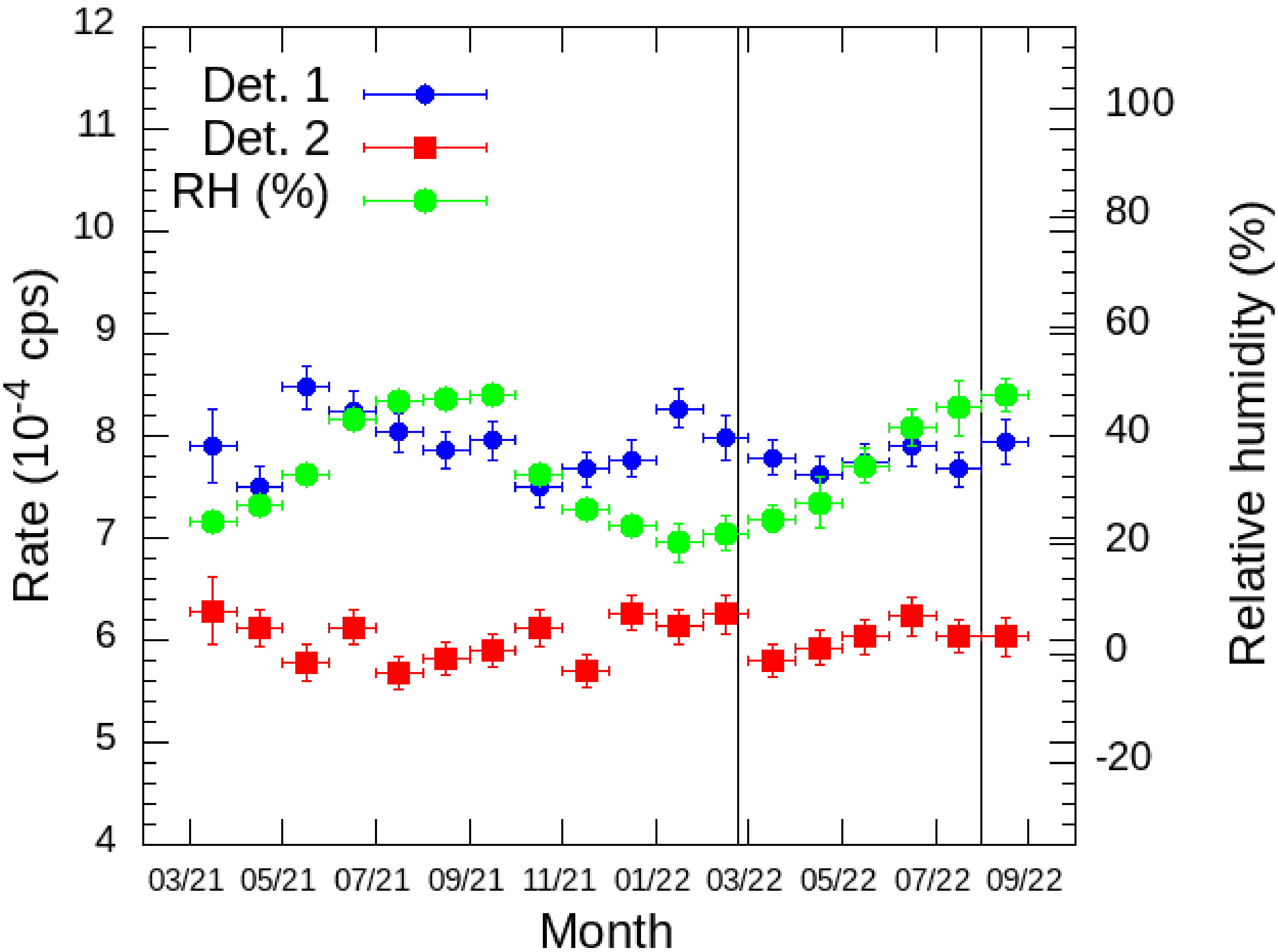
Preliminary results HENSA hall B @ LSC



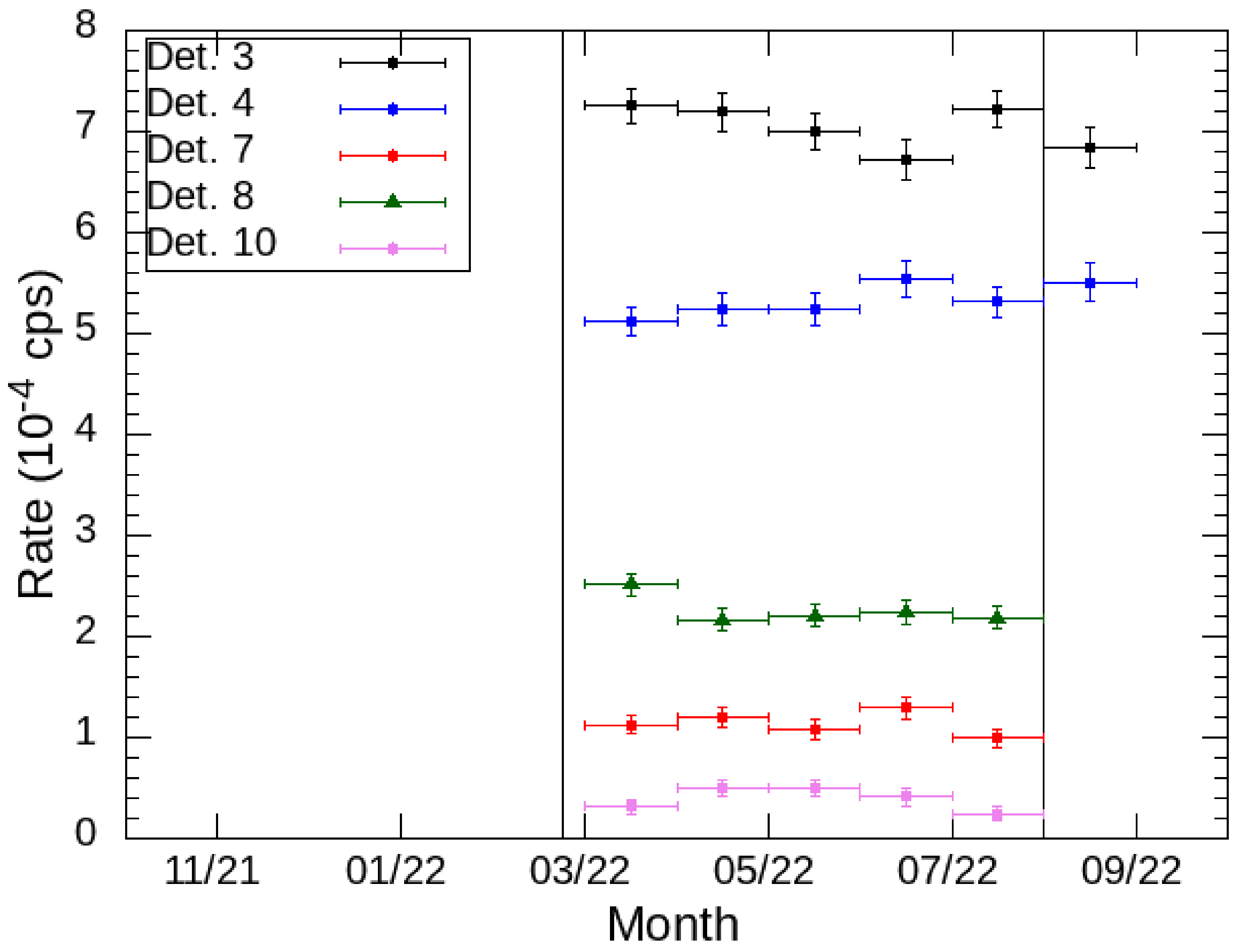
- **Hall B/phase 1**: 3 detectors monitors (thermal, epithermal, fast), March 2021 – Feb 2022.
- **Hall B/phase 2**: full HENSA setup (10 detectors).
- Hall B/phase 3: upgrade on the detector setup, improved resolution (thermal – 20 MeV) based on optimization of the spectral powers (**A. Quero PhD, UGR**).



Preliminary results HENSA hall B @ LSC

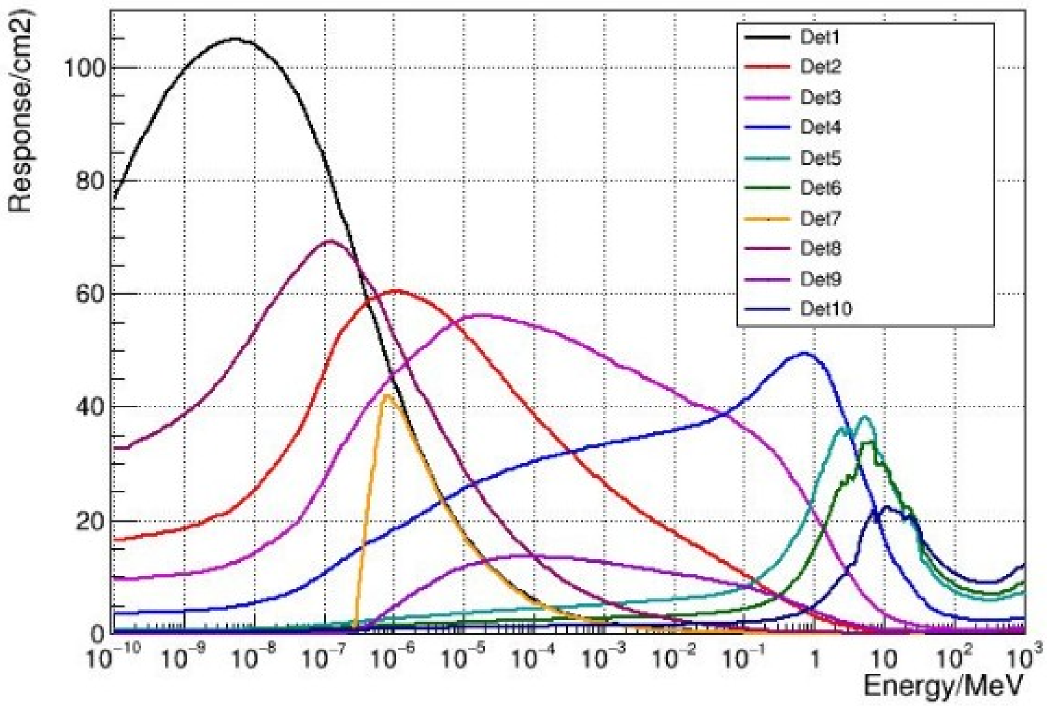


Preliminary results HENSA hall B @ LSC



A. Tarifeño-Saldivia
N. Mont-Geli

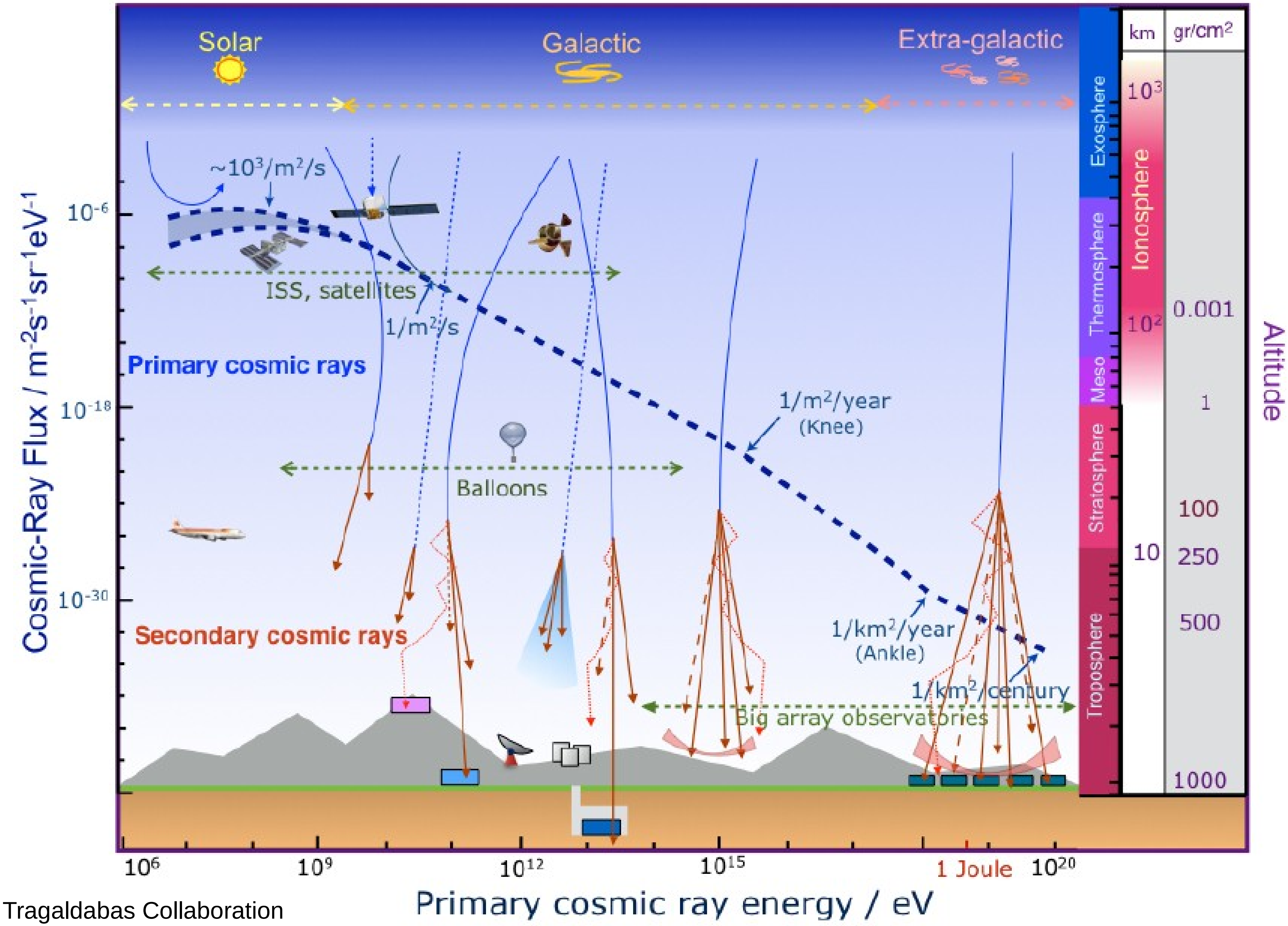
Preliminary results HENSA hall B @ LSC



•**Hall B/phase 3:** since Aug 2022, upgrade on the detector setup, improved resolution (thermal – 20 MeV) based on optimization of the spectral powers (**A. Quero PhD, UGR**).

Cosmic-ray neutrons

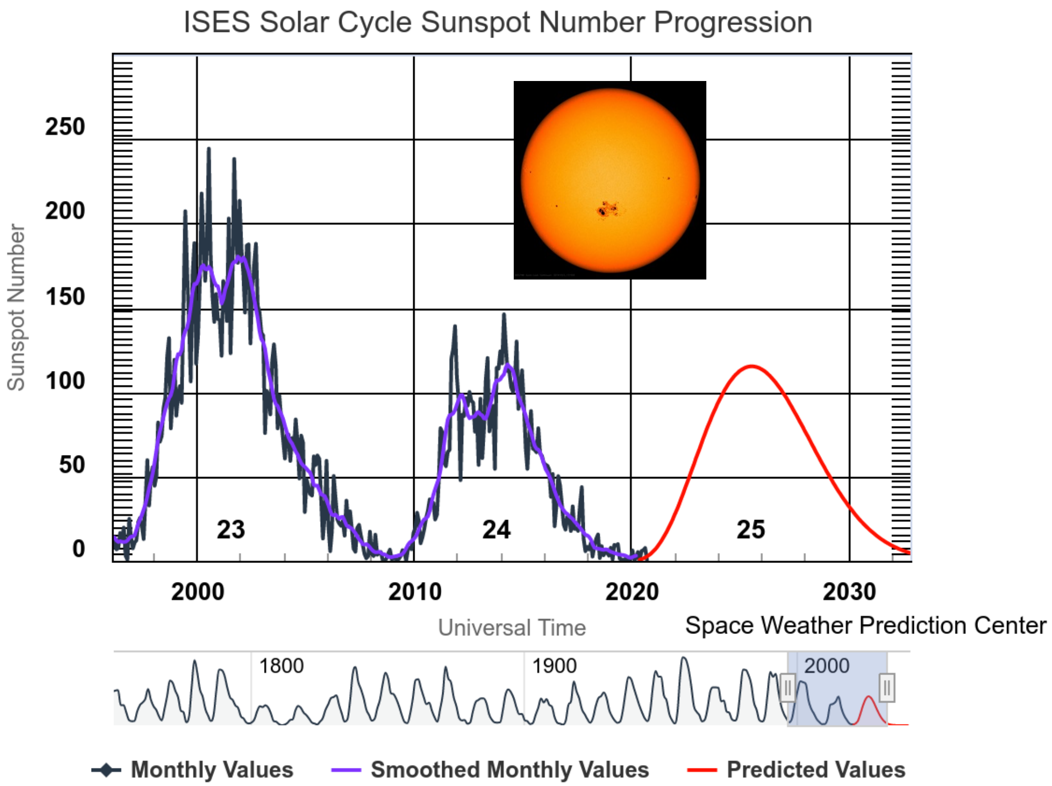
Secondary neutrons produced by cosmic rays



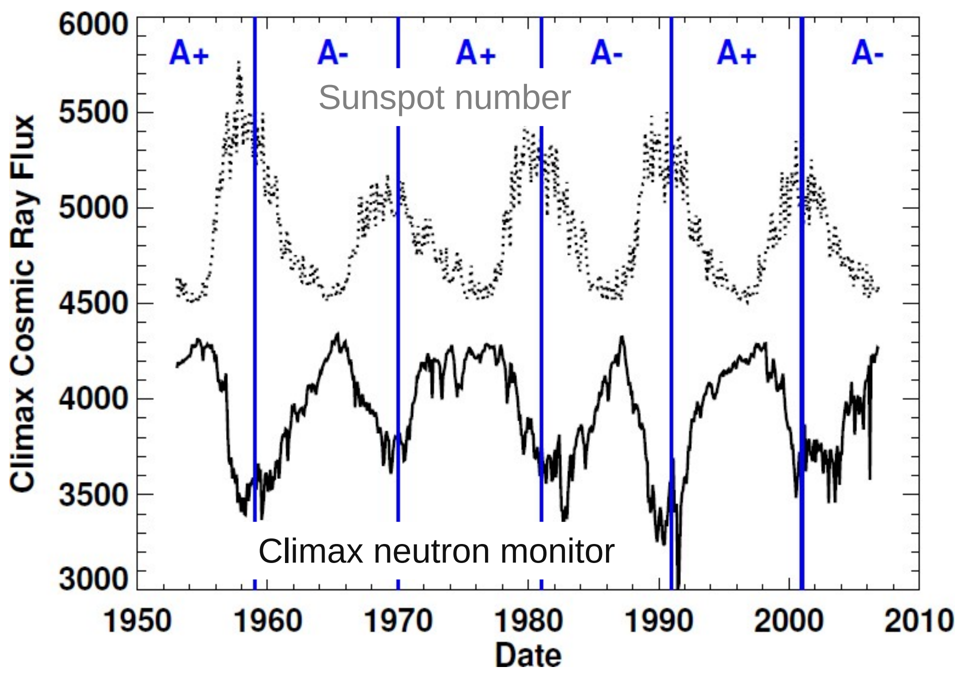
Credits Tragaldabas Collaboration

A. Tarifeño-Saldivia
N. Mont-Geli

Physics of cosmic rays and solar 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.

Reference data from Neutron Monitors (www.nmdb.eu)

Secondary neutrons by cosmic rays

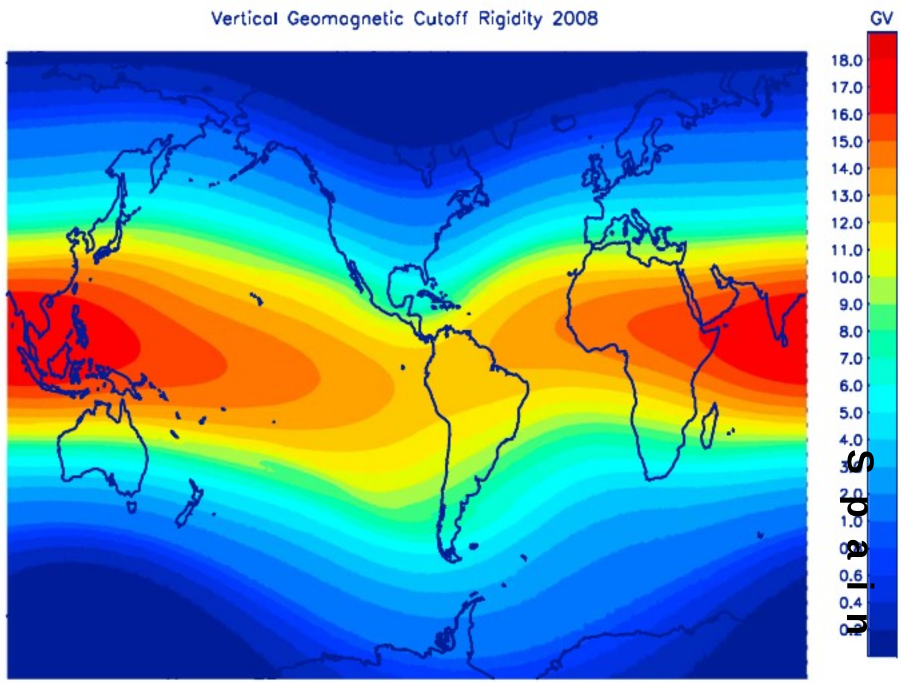


Figure 3. Global grid of vertical geomagnetic cutoff rigidities (GV) calculated from charged particle trajectory simulations in the IGRF field for 2008.

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

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).

•

Most of the calculations models are based on data taken in US ~15 years ago! (Gordon et al. IEEE Trans. Nucl. Sci. 51:6 (2004) 3427-3434)

Mapping cosmic-ray induced neutron background in Spain

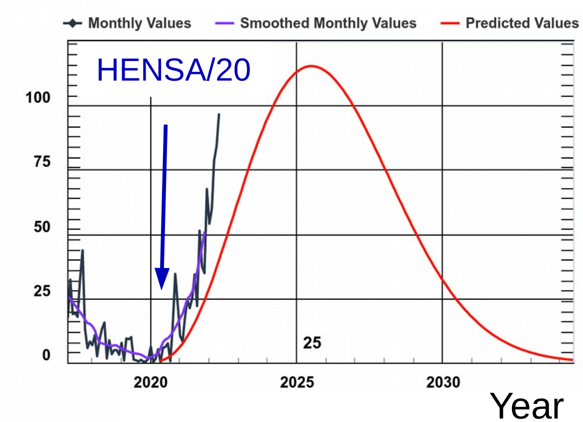
Spain is a good lab for cosmic-ray neutrons in pandemic times

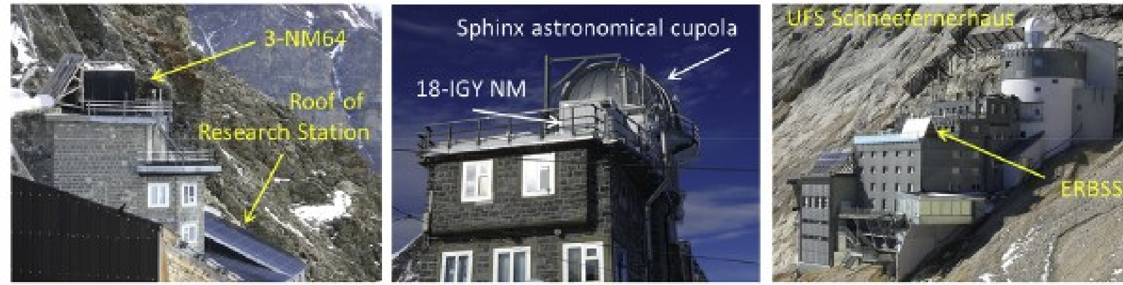
HENSA campaign along the Spanish territory close to the minimum of solar activity (2020, solar cycle #25)

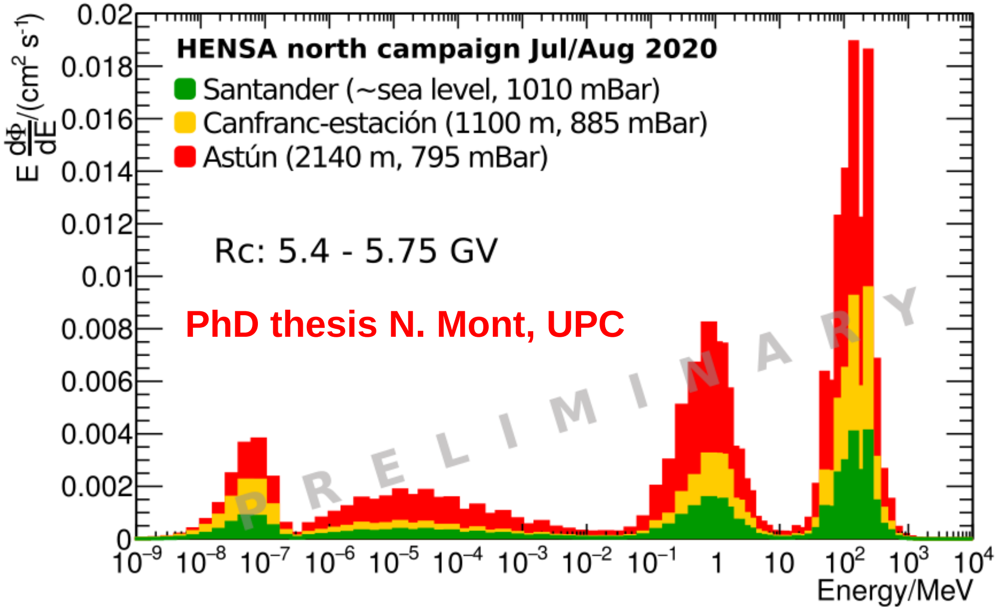
Cosmic ray induced neutron background
- \+ Cosmic ray physics and space weather
- \+ Environmental radiation dosimetry
- \+ Single-event upsets in microelectronics

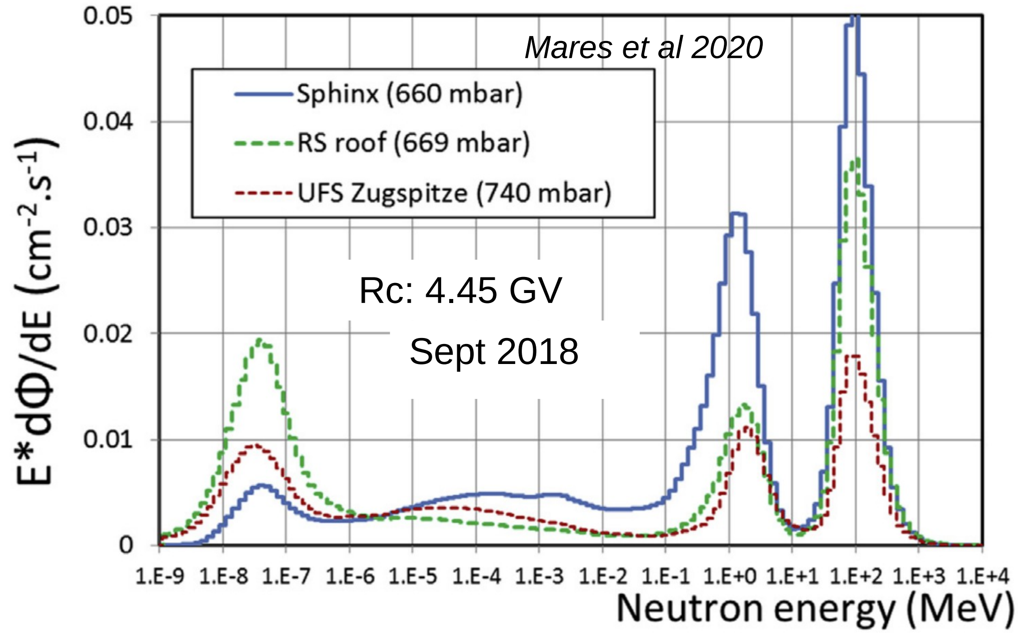
www.hensaproject.org

HENSA
High Efficiency Neutron Spectrometry Array

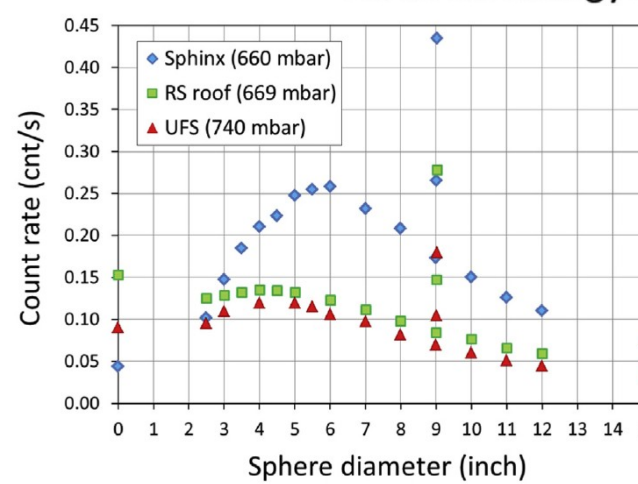








- •Confirmed structure and flux magnitude with HENSA
- •Confirmed effect of higher sensitivity of HENSA with respect to conventional BSS.
- •Over 2000 m altitude, relative uncertainty in count rates at 1h time window is ~2% or less.



HENSA and space weather (HENSA++)

Characterization of cosmic ray neutrons produced during extreme solar weather events during cycle #25 (foreseen for 2022 -2030)

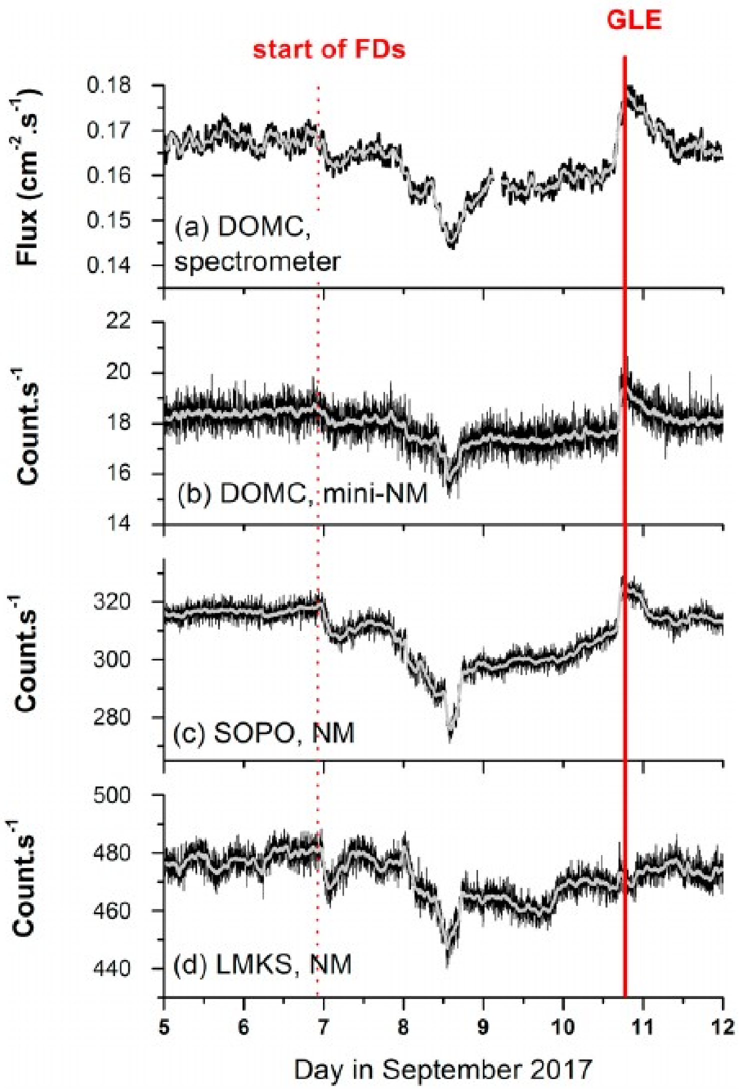
•Ground Level Enhancement (GLE) are produced strong flux of high-energy solar particles.

•Seminal works by *Rühm et al* 2009 (GLE #65) and *Hubert et al* 2019 (GLE #72) with standard Bonner Spheres Spectrometers.

•Required precision data on neutron flux variations on the scale of less than 1h.

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

Require high altitude sites and continuous measurements



HENSA++: new infrastructure for neutron spectrometry

Promover el desarrollo tecnológico, la innovación y una investigación de calidad

Proyecto: IDIFEDER/2021/002

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

OT01: Refuerzo de la investigación, el desarrollo tecnológico y la innovación

Actuación cofinanciada por la Unión Europea a través del Programa Operativo del Fondo Europeo de Desarrollo Regional (FEDER) de la Comunitat Valenciana 2014 – 2020.

Ayuda: 260.199,21 €

Beneficiario: CSIC – Instituto de Física Corpuscular

IFIC INSTITUT DE FÍSICA CORPUSCULAR

GENERALITAT VALENCIANA TOTS A UNA veu
Conselleria d'Innovació, Universitats, Ciència i Societat Digital

Fondo Europeo de Desarrollo Regional
Una manera de hacer Europa
UNIÓN EUROPEA

Dedicated HENSA setup for cosmic neutrons:
- 15 detectors (3He, 60cm, 4 atm)
- dedicated electronics
- mechanics.
- Permanent site to be decided! (Sierra Nevada, Javalambre, La Molina)

PhD thesis
A. Quero, UGR

•**"Small" spectrometer particle accelerator environments:**
- Up to 15 detectors (3He, 5cm, 10 atm) + dedicated electronics + mechanics.
- Focus on neutron background in research and medical facilities, pulsed sources.

HENSA

High Efficiency Neutron Spectrometry Array

HENSA COLLABORATION: INSTITUTIONS & PEOPLE

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

A. Tarifeño-Sadivia, J.L. Tain, S.E.A. Orrigo, B. Rubio, E. Nácher, J. Agramunt, A. Algora, J. Balibrea-Correa, L. Caballero, C. Domingo-Pardo, I. Ladarescu, J. Lerendegui-Marco.

- Institute of Energy Technologies (UPC)

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

- Universidad Complutense de Madrid (UCM)

L.M. Fraile, V. Martínez Nouvillas

- Helmholtz-Zentrum Dresden-Rossendorf (HZDR)

D. Bemmerer, M. Grieger

- TRIUMF

I. Dillmann

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

HENSA collaboration for cosmic-rays & space weather

- Universidad de Granada

A. Lallena, A. Quero

www.hensaproject.org

BACKUP SLIDES

Bonner's Sphere Technique

Bonner spheres spectrometers: advantages and drawbacks*

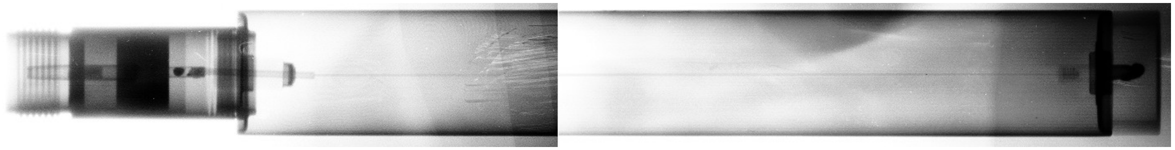
Characteristic	Verdict	Comment
Energy resolution	Poor	Restricted by similarity of response functions available
Energy range	Excellent	The only spectrometer presently available which will cover the energy range from thermal to the GeV region
Sensitivity	Good	High sensitivity by comparison with other neutron spectrometers, and can be varied by changing the thermal sensor
Operation	Simple but lengthy	Making measurements is simple, with no really complex electronics, but it can be time consuming
Angular response	Isotropic	Do not need to know the direction of the neutron field. Ideal for deriving ambient dose equivalent, but provides no angular data for deriving effective dose
Spectrum unfolding	Potential for errors	Complex unfolding code required, and the under-determined problem means that any solution is not unique; significant errors are possible
Photon discrimination	Good	By the choice of an appropriate sensor systems can be made insensitive, even to intense photon fields

* Extracted from D.J. Thomas, A.V. Alevra / NIMA 476 (2002) 12–20

HENSA setup

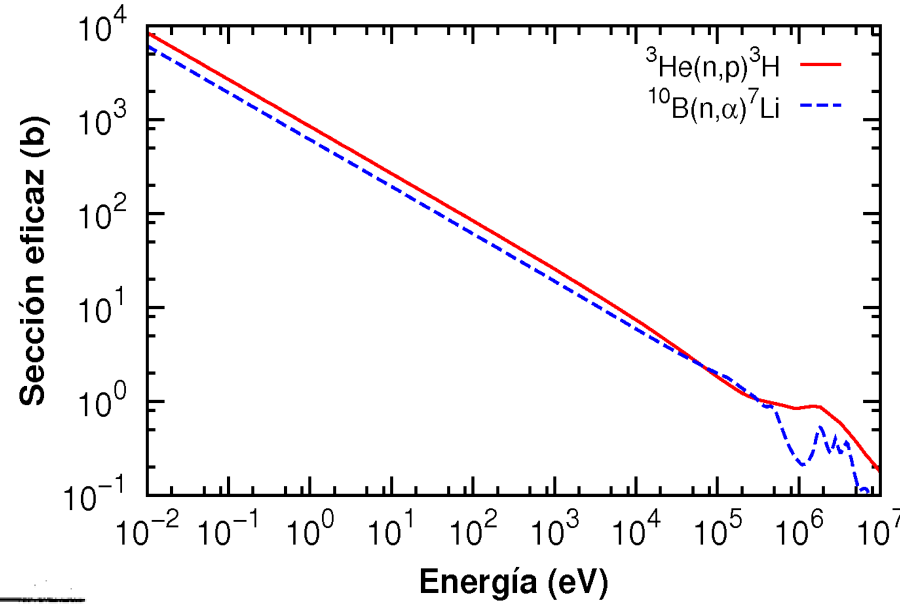
A. Tarifeño-Saldivia
N. Mont-Geli

HENSA setup: “active part”



Detection reaction:

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

	Interaction Probability	
Thermal Detectors	**Thermal Neutron**	**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
	Interaction Probability	
Fast Detectors	**1-MeV Neutron**	**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 low gamma-ray sensitivity makes these detectors very attractive for neutron spectroscopy (Bonner spheres).

Digital acquisition system: GASIFIC70

Control software developed by IFIC (J. Agramunt et al)

SIS3316 Characteristics:

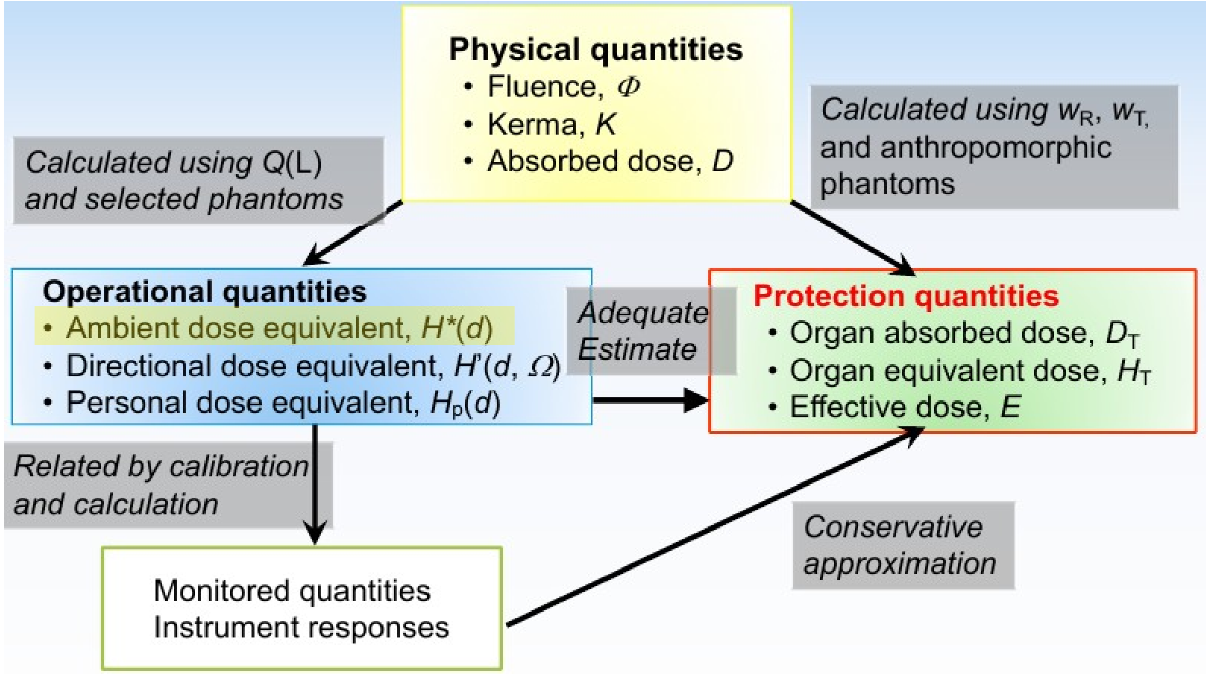
- •16CH, 250MHz sampling digitizer 125MHz Band width
- •64MSamples memory/channel (in two swap pages)
- •Readout simultaneous to acquisition
- •14-bit resolution (12 effective bits)

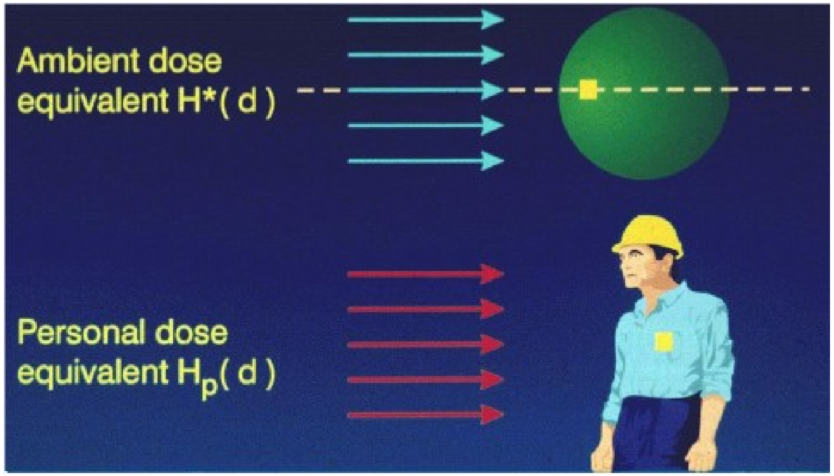
Portable digital acquisition system:

- Based on the digitizer Struck SIS3316.
- Controlled by GASIFIC70 via ethernet conection.
- Online and offline acquisition modes.
- Internal timestamp, ideal for data sorting and correlation analysis.
- For use with neutron counters, silicon detectors, HPGe, scintillators, etc.

Ambient dosimetry

Neutron dosimetry (right now!)

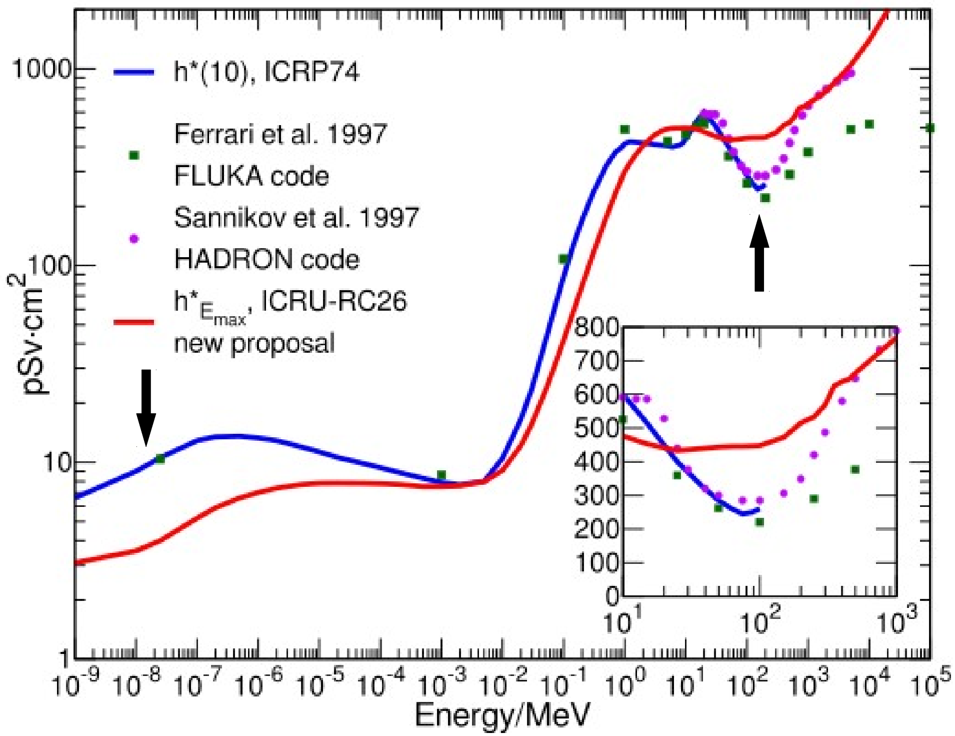




- For area monitoring, the operational quantity to link the external radiation to the effective dose is the ambient
- Ambient dose equivalent at a point in a radiation field is the dose equivalent that would be produced by the co
- The recommended value of *d* for effective dose is *d*=10mm.
- Originally computed with the Q-L relationship of ICRP 26; now with ICRP Publication 60 revised Q-L (ICRU R

Recommendations are evolving!

New recommendations and impact



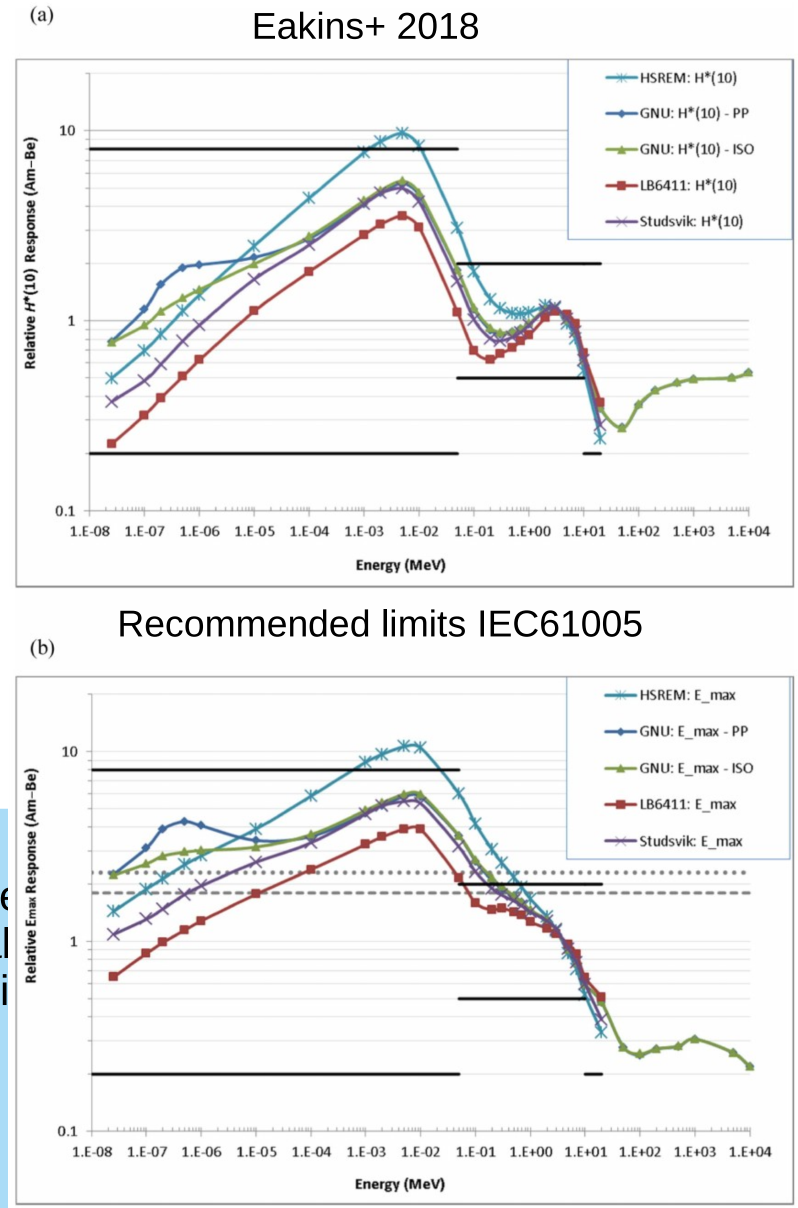


Figure 3. Relative (a) $H^*(10)$ and (b) E_{max} responses of the LB6411, Studsvik 2202D HSREM and GNU, normalized to their respective responses to ^{241}Am-Be Recommended limits (*solid lines*), and the effects of recalibrations to the response at 144 keV (*dotted line*) and 565 keV (*dashed line*), are also indicated.

NEEDS ⟶ **Opportunities for R&D+i**

- Industry and workers: cost reduction and optimization of proce
- Patients: risk control of secondary cancers in modern medical
- New facilities: radiation protection challenges associated to bi

Solar weather events?

Neutron background in underground facilities

Neutron flux modulation in underground facilities

ISSN 1063-7796, Physics of Particles and Nuclei, 2017, Vol. 48, No. 1, pp. 34–37. © Pleiades Publishing, Ltd., 2017.

The Study of the Thermal Neutron Flux in the Deep Underground Laboratory DULB-4900

V. V. Alekseenko[a], Yu. M. Gavrilyuk[a], A. M. Gangapshev[a, *], A. M. Gezhaev
D. D. Dzhappuev[a], V. V. Kazalov[a], A. U. Kudzhaev[a], V. V. Kuzminov[a], S. I. Panas
S. S. Ratkevich[b], D. A. Tekueva[a], and S. P. Yakimenko[a]
[a]Institute for Nuclear Research, RAS, Moscow, Russia
[b]Kharkiv National University, Kharkiv, Ukraine
*e-mail: gangapsh@list.ru

Abstract—We report on the study of thermal neutron flux using monitors based on mixture of Zn
LiF enriched with a lithium-6 isotope at the deep underground laboratory DULB-4900 at the Ba
trino Observatory. An annual modulation of thermal neutron flux in DULB-4900 is observed. Ex
evidences were obtained of correlation between the long-term thermal neutron flux variations and
lute humidity of the air in laboratory. The amplitude of the modulation exceed 5% of total neutro

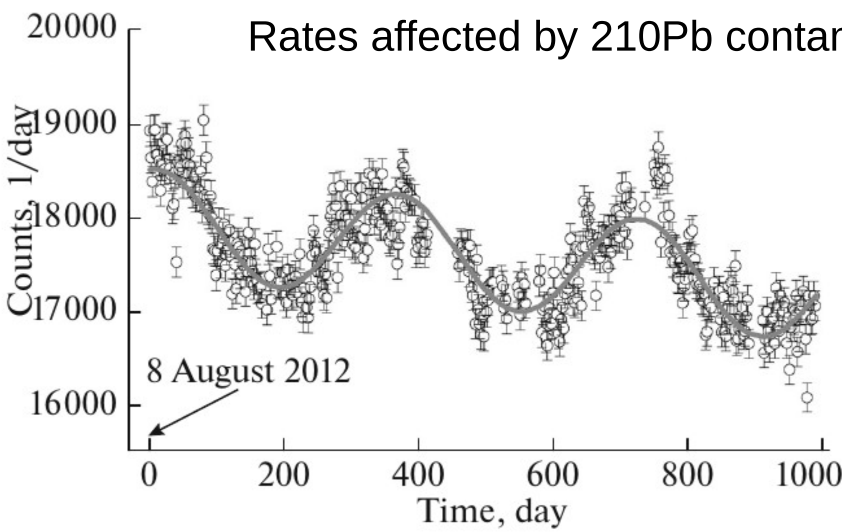
DOI: 10.1134/S1063779616060022

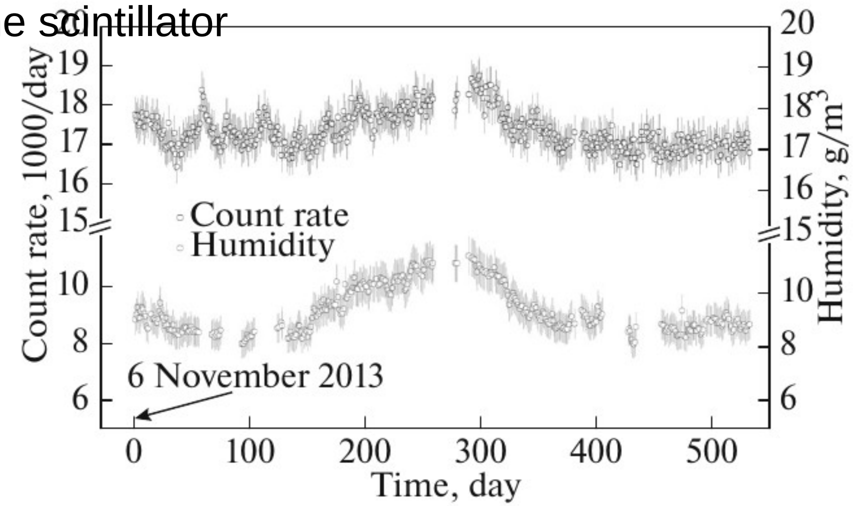
Large volume detectors (6LiF + ZnS(Ag))

Themal flux:
~ 10^{-9} – 10^{-6} MeV

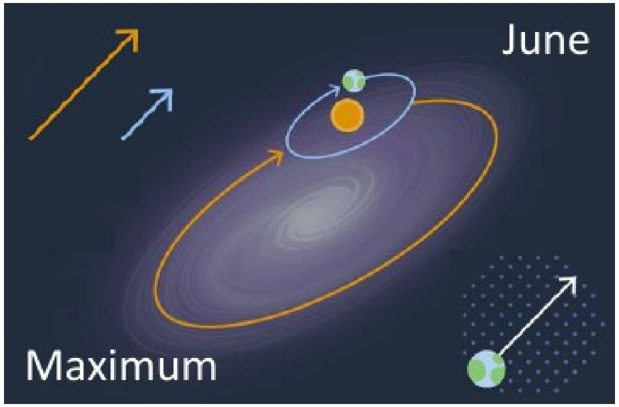
No fully spectrometric studies yet!

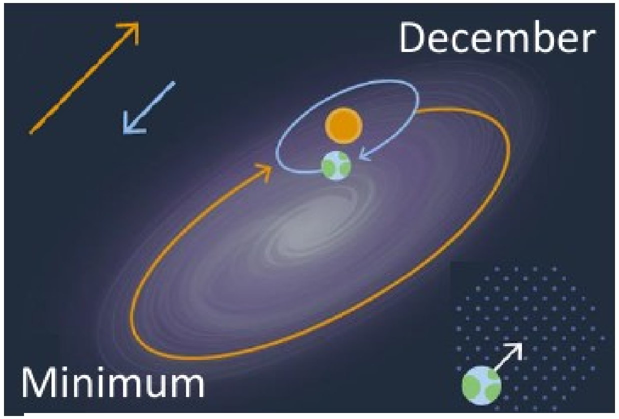
Rates affected by 210Pb contaminant in the scintillator



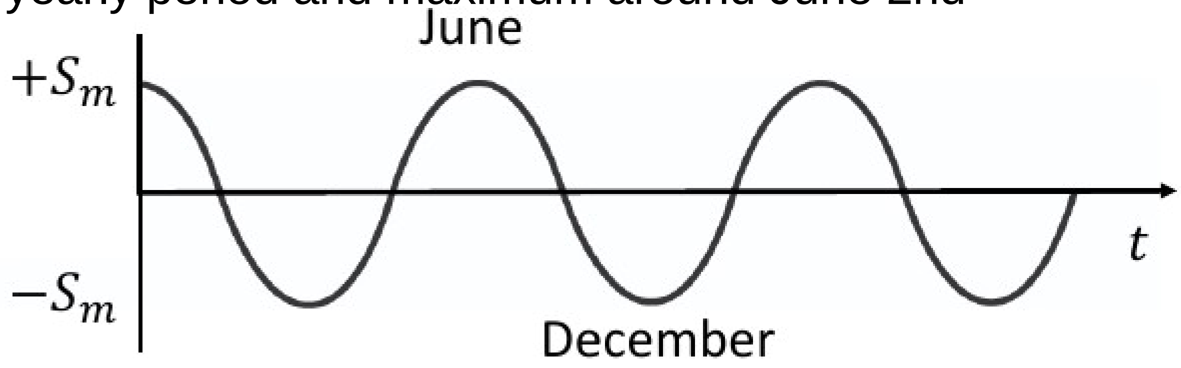


An important physical case: dark matter annual modulation

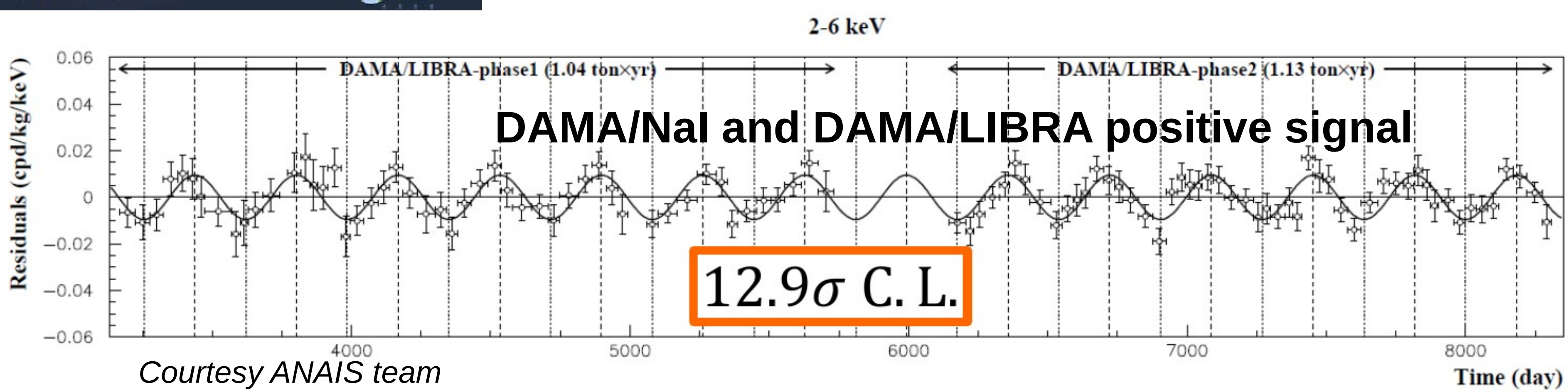




Detection rate would have a cosine behaviour with a yearly period and maximum around June 2nd



$$R(t) = S_0 + S_m \cdot \cos\left(2\pi \frac{t - t_0}{T}\right)$$



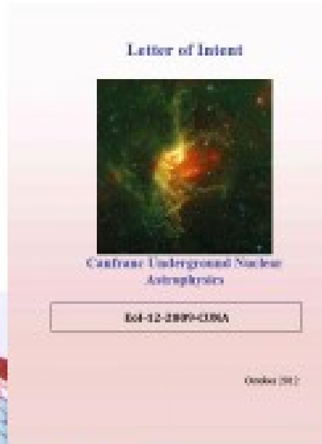
DAMA/NaI and DAMA/LIBRA positive signal

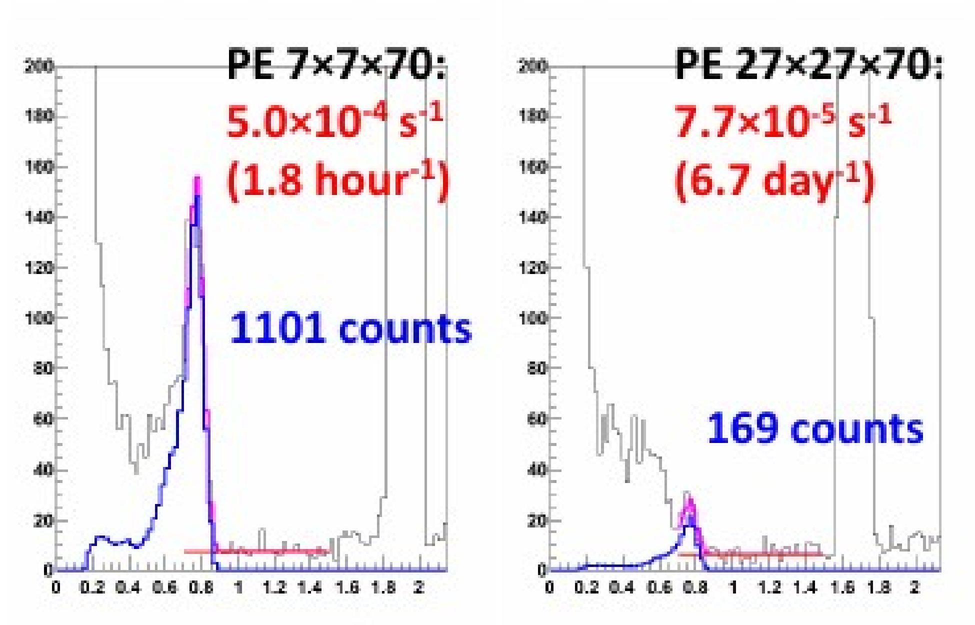
12.9σ C. L.

Courtesy ANAIS team

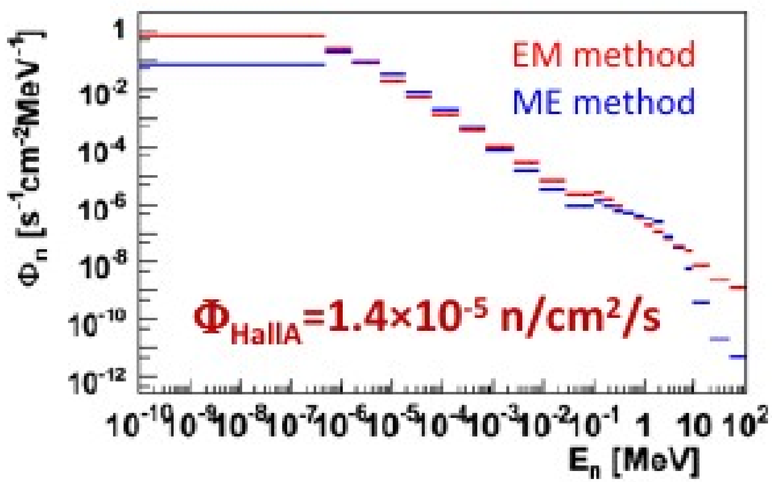
Previous underground activities: HENSA measurements at LSC

The CUNA project @ LSC





First measurement of the neutron background at LSC

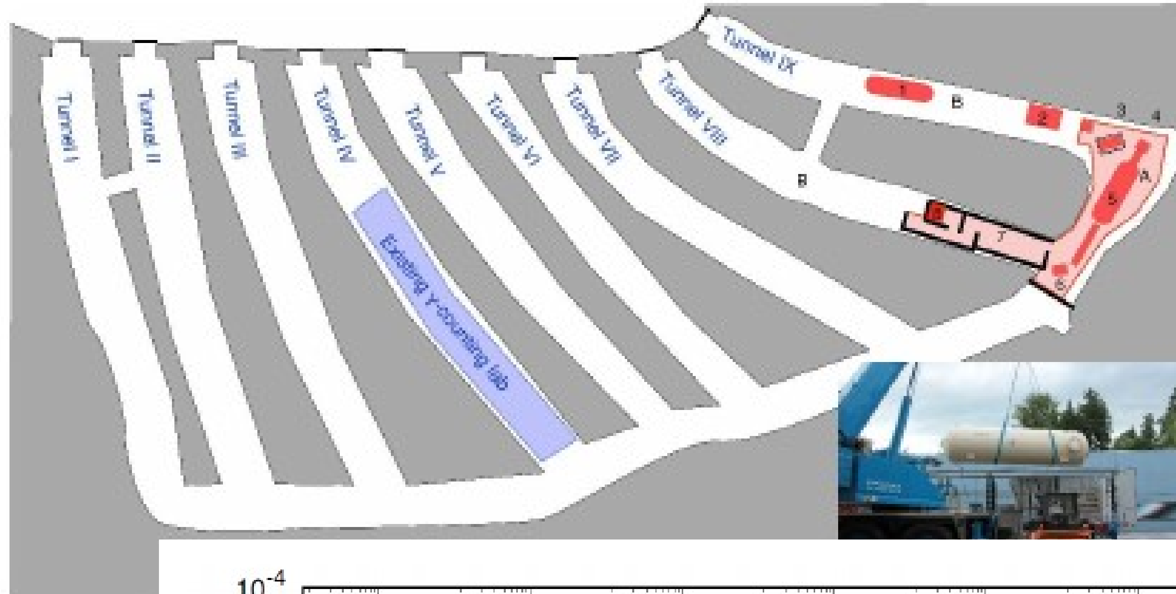


M.D. Jordan et al., Astroparticle Physics **42** (2013) 1 + Corrigendum

Previous underground activities: measurements at Felsenkeller

Two measurement campaigns (2014 & 2018)

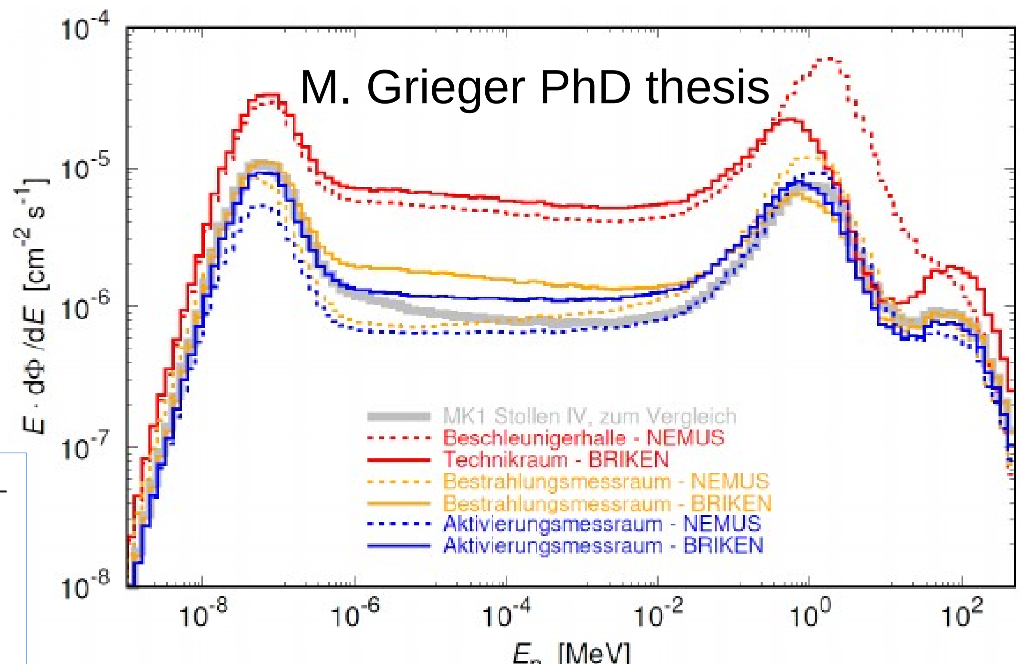
- System of nine tunnels built for Felsenkeller brewery in 1856-59
- 5 MV Pelletron ion accelerator for ^{1}H, ^{4}He, ^{12}C beams
- Combination of µ attenuation by 45 m rock and active µ veto



PHYSICAL REVIEW D **101**, 123027 (2020)

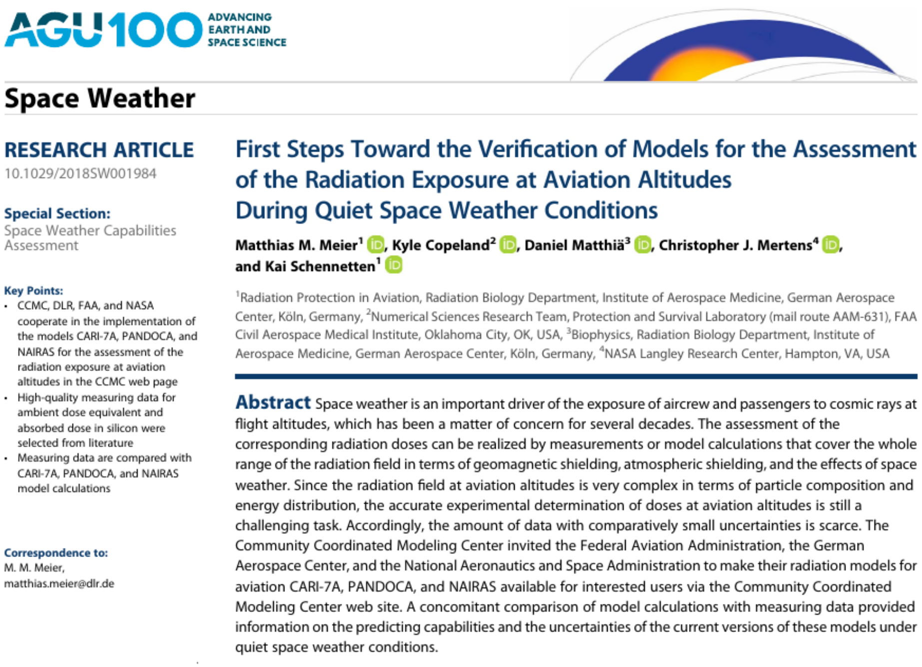
Neutron flux and spectrum in the Dresden Felsenkeller underground facility studied by moderated ^{3}He counters

M. Grieger,[1,2] T. Hensel,[1,2] J. Agramunt,[3] D. Bemmerer,[1,*] D. Degering,[4] I. Dillmann,[5] L. M. Fraile,[6] D. Jordan,[3] U. Köster,[7] M. Marta,[5] S. E. Müller,[1] T. Szücs,[1] J. L. Taín,[3] and K. Zuber[2]



Cosmic ray neutrons with HENSA

Environmental radiation dosimetry



AGU100 ADVANCING EARTH AND SPACE SCIENCE

Space Weather

RESEARCH ARTICLE
10.1029/2018SW001984

Special Section:
Space Weather Capabilities Assessment

First Steps Toward the Verification of Models for the Assessment of the Radiation Exposure at Aviation Altitudes During Quiet Space Weather Conditions

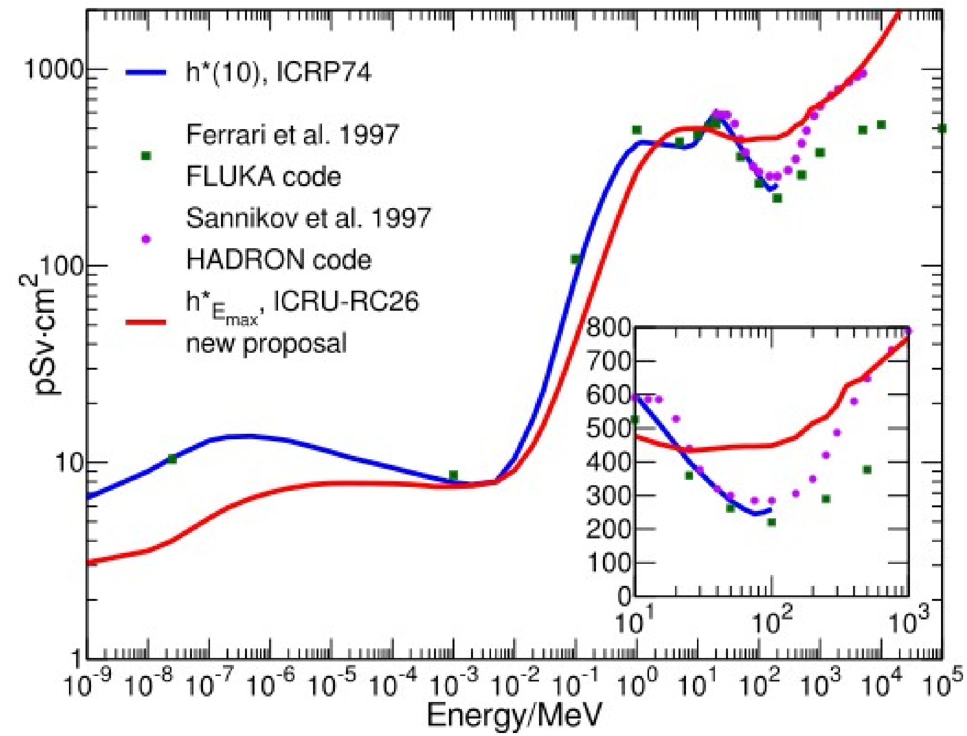
Matthias M. Meier[1], Kyle Copeland[2], Daniel Matthiä[3], Christopher J. Mertens[4], and Kai Schennetten[1]

[1]Radiation Protection in Aviation, Radiation Biology Department, Institute of Aerospace Medicine, German Aerospace Center, Köln, Germany, [2]Numerical Sciences Research Team, Protection and Survival Laboratory (mail route AAM-631), FAA Civil Aerospace Medical Institute, Oklahoma City, OK, USA, [3]Biophysics, Radiation Biology Department, Institute of Aerospace Medicine, German Aerospace Center, Köln, Germany, [4]NASA Langley Research Center, Hampton, VA, USA

Key Points:
- CCMC, DLR, FAA, and NASA cooperate in the implementation of the models CARI-7A, PANDOCA, and NAIRAS for the assessment of the radiation exposure at aviation altitudes in the CCMC web page
- High-quality measuring data for ambient dose equivalent and absorbed dose in silicon were selected from literature
- Measuring data are compared with CARI-7A, PANDOCA, and NAIRAS model calculations

Correspondence to:
M. M. Meier,
matthias.meier@dlr.de

Abstract Space weather is an important driver of the exposure of aircrew and passengers to cosmic rays at flight altitudes, which has been a matter of concern for several decades. The assessment of the corresponding radiation doses can be realized by measurements or model calculations that cover the whole range of the radiation field in terms of geomagnetic shielding, atmospheric shielding, and the effects of space weather. Since the radiation field at aviation altitudes is very complex in terms of particle composition and energy distribution, the accurate experimental determination of doses at aviation altitudes is still a challenging task. Accordingly, the amount of data with comparatively small uncertainties is scarce. The Community Coordinated Modeling Center invited the Federal Aviation Administration, the German Aerospace Center, and the National Aeronautics and Space Administration to make their radiation models for aviation CARI-7A, PANDOCA, and NAIRAS available for interested users via the Community Coordinated Modeling Center web site. A concomitant comparison of model calculations with measuring data provided information on the predicting capabilities and the uncertainties of the current versions of these models under quiet space weather conditions.



Determination of radiation doses radiation at aviation altitudes:

•Precise experimental data is very scarce.

•Measurements during severe space weather radiation events.

•Model verification for the radiation field due to ga... (quiet space weathe...

New recommendations on radiation protectio...

✗ICRU 95 officially released in 2021.

✗Important changes on thermal&high energy regi...

✗**Ambient dosimetry data should be updated!**

Measurements on high-terrestrial altitudes helps to constrain calculation models.

Single-events upsets in microelectronics

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 1, JANUARY 2017 529

Single Event Effects in Si and SiC Power MOSFETs Due to Terrestrial Neutrons

A. Akturk, *Member, IEEE*, R. Wilkins, *Member, IEEE*, J. McGarrity, *Fellow, IEEE*, and B. Gersey

***Abstract*—Experimental investigation of neutron induced single event failures and the associated device cross sections as well as low altitude failure-in-time (FIT) curves in silicon (Si) and silicon carbide (SiC) power MOSFETs at room temperature are reported along with possible explanation of failure mechanisms in SiC devices. Neutrons are found to give rise to significantly fewer failures in SiC power MOSFETs compared to their Si equivalents; however, SiC power MOSFETs do exhibit catastrophic failures when exposed to neutrons that simulate the terrestrial spectrum.**

***Index Terms*—Failure in time, power device reliability, silicon carbide, terrestrial neutrons.**

I. INTRODUCTION

AS SiC power MOSFETs aim to replace Si power MOSFETs and IGBTs in the high voltage range, i.e. >800 V and as high as 15 kV, the terrestrial neutron radiation hardness of these SiC power devices needs to be examined to prevent unexpected system failures. To this end, we investigate single event neutron induced failures in SiC devices from different vendors in three voltage ranges in the off condition. This is achieved using the commercially available parts with rated voltages of 1700 V, 1200 V and 650 V. Additionally, we test silicon power MOSFETs with voltage ratings >1200 V to show the relative ruggedness of SiC components. This paper summarizes our measurements and calculated FIT rates for these devices, along with possible preliminary investigation of failure mechanisms in these devices.

The very high altitude terrestrial neutrons are byproducts of cosmic rays such as high energy protons, alphas and heavy ions interacting with Earth's atmosphere. These interactions result in neutrons, protons, pions, muons, electrons and electromagnetic waves. After these first interactions, further ...

... the newly created neutrons give rise to a high flux of neutrons traveling vast distances in the atmosphere, even reaching low altitudes, as shown by the cosmic shower [1], [2] plot in Figure 1.

The terrestrial neutron flux reaches a peak at roughly 60,000 feet. At 30,000 feet, the integral neutron flux drops to roughly one tenth of its peak value. At sea level, it drops by an additional two orders of magnitude; however, the neutron flux at sea level, which is roughly <25 n/cm^{2}hr for E > 1 MeV, can still cause upsets and failures for electronics and power switches. Furthermore, at sea level, approximately 95% of the cosmic shower constituents are neutrons [2].

The terrestrial neutron induced failures and upsets have been reported by the Si power electronics community and by data centers and supercomputer users [3]–[8]. The problem only exacerbates as the electronics and power switches are used in higher altitudes due to exponentially rising neutron flux levels with increasing altitudes. These higher neutron levels can render a power device that is safe to use at sea level, i.e. expected not to fail within its lifetime, a risky choice for use on a mountaintop due to its rising Failure In Time (FIT) rates.

More specifically, the neutrons have been shown to cause failures in power devices via interactions with lattice atoms, as shown in Figure 2. The neutrons cannot directly ionize charge in the device; however the neutron lattice collisions, depicted in Figure 2b, giving rise to recoil atoms or spallation products are very efficient in creating charge spikes along their trajectories. Some of the resulting knock-ons are shown in Figure 2a along with their energy distribution curve that is a result of the terrestrial neutron flux energy distribution and the neutron-lattice atom interaction.

...

***Abstract*—Experimental investigation of neutron induced single event failures and the associated device cross sections as well as low altitude failure-in-time (FIT) curves in silicon (Si) and silicon carbide (SiC) power MOSFETs at room temperature are reported along with possible explanation of failure mechanisms in SiC devices. Neutrons are found to give rise to significantly fewer failures in SiC power MOSFETs compared to their Si equivalents; however, SiC power MOSFETs do exhibit catastrophic failures when exposed to neutrons that simulate the terrestrial spectrum.**

Digital Object Identifier 10.1109/TNS.2016.2640945

... on-resistance and tolerable oxide field in the off state.

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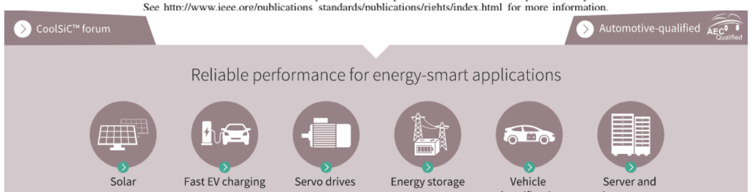

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Cosmic particles can change elections and cause planes to fall through the sky, scientists warn

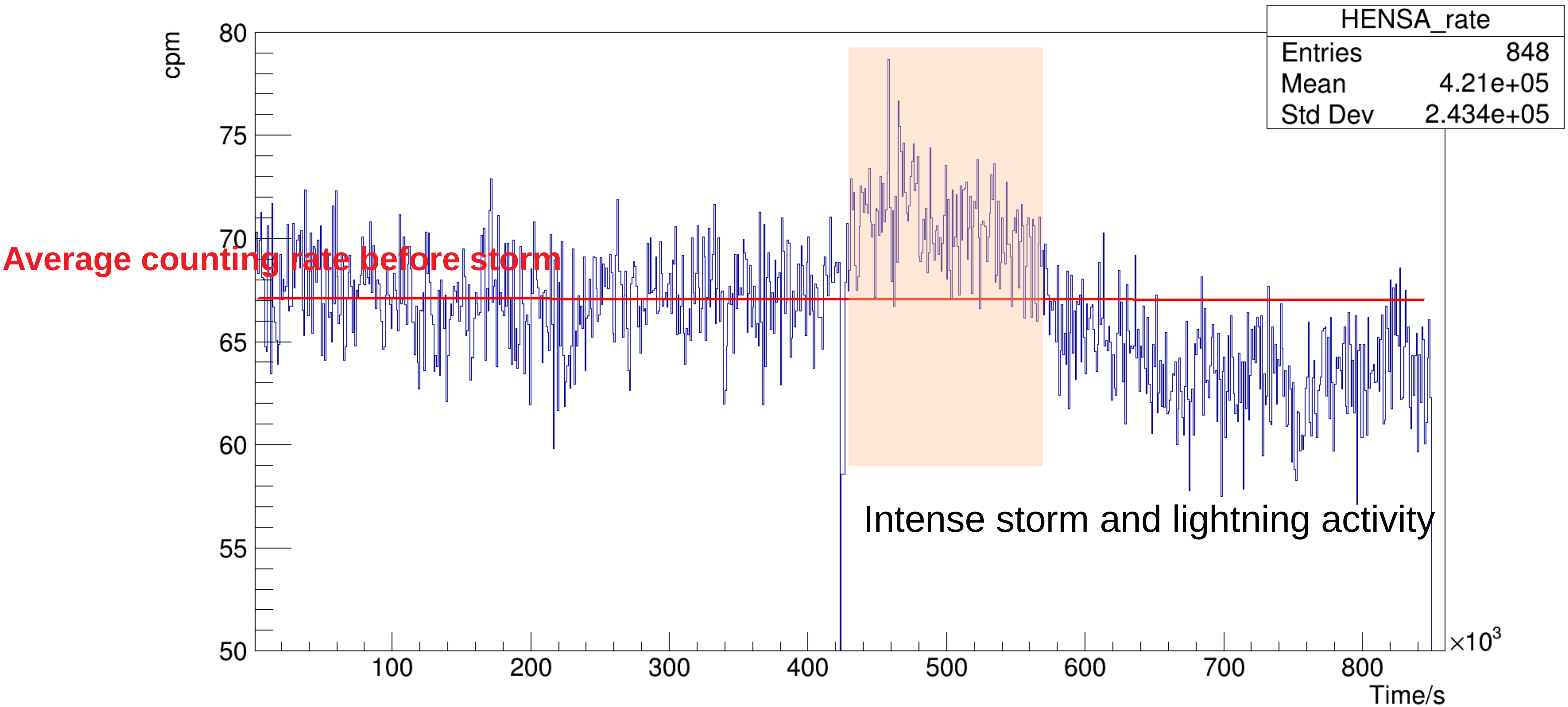
Tiny invisible particles can cause bits of information held by computers to 'flip' with potentially serious ramifications

Ian Johnston Science Correspondent in Boston | @montaukian | Friday 17 February 2017 16:40

https://www.independent.co.uk/news/science/subatomic-particles-cosmic-rays-computers-change-elections-planes-autopilot-a7584616.html

Data on cosmic rays neutrons helps to improved knowledge

HENSA: sensitivity to environmental conditions



- Fluctuations of the counting rates have been observed during and after the intense storm which affected Ba
- This is connected to changes on the barometric pressure due to the DANA.
- **A search of lightning correlated neutrons will be done!**

Options for TFG/TFM!

HENSA++ project: spectrometry of cosmic-ray neutrons and space weather

- Detector redesign (15 dets) with focus on cosmic ray neutrons
- Commissioning
- First campaign (2023 -) with focus on space weather applications

PhD A. Quero (UGR)

Possible sites in Spain (Iberian Peninsula):

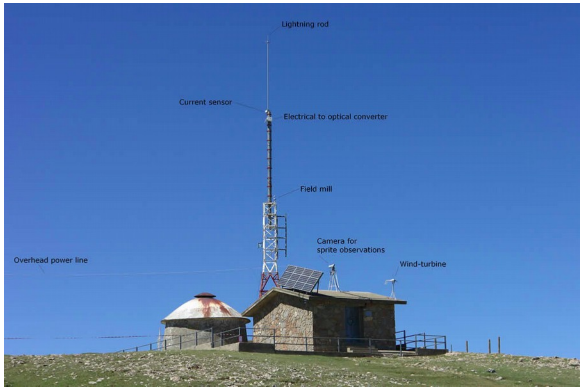
1) Tossa d'Alp @ 2537 m (**UPC Lightning group**)

2) **U. de Granada facilities in Sierra Nevada**
(collaboration with **Antonio Lallena/UGR**)

- Antiguo Observatorio del Mojón del Trigo @ 2605 m.
- Mountain hut nearby Veleta peak > 3000 m.

3) Observatorio astronómico de Sierra Nevada (2850 m), CSIC.

4) Observatorio astronómico de Javalambre (1950 m), CEFCA.



Other applications with HENSA

Neutron production in lightning discharges

- Neutron burst are generated by natural means in atmospheric discharges (lightning).
- Satisfactory explanation about the neutron production mechanism remained elusive since the 80's.
- First evidence of photonuclear mechanism 14N(g,n)13N by **E**
- Laboratory scale experiment demonstrated by **Agafanov et al**
- Photonuclear mechanism predicts (Diniz et al. 2018) a prompt

Laboratory experiments on lightning:

PRL **111,** 115003 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Agafanov et al. 2013

Observation of Neutron Bursts Produced by Laboratory High-Voltage Atmospheric Discharge

A. V. Agafonov,[1] A. V. Bagulya,[1] O. D. Dalkarov,[1,2] M. A. Negodaev,[1] A. V. Oginov,[1,*] A. S. Rusetskiy,[1] V. A. Ryabov,[1] and K. V. Shpakov[1]

[1]*P.N. Lebedev Physical Institute of the Russian Academy of Sciences (FIAN), Leninsky Prospekt, 53, Moscow 119991, Russia*
[2]*Centre for Fundamental Research (MIEM NRU HSE), Myasnizkaya, 20, Moscow 101000, Russia*
(Received 10 April 2013; published 12 September 2013)

Collaboration with **Joan Montaña**, UPC Lightning Researc
Lightning High Voltage Testing Laboratory – LABELEC

Exp & sim. of natural lightning:

LETTER 23 NOVEMBER 2017 | VOL 551 | NATURE | 481
doi:10.1038/nature24630

Enoto et al. 2017

Photonuclear reactions triggered by lightning discharge

Teruaki Enoto[1], Yuuki Wada[2,3], Yoshihiro Furuta[2], Kazuhiro Nakazawa[2,4], Takayuki Yuasa[5], Kazufumi Okuda[2], Kazuo Makishima[6], Mitsuteru Sato[7], Yousuke Sato[8], Toshio Nakano[3], Daigo Umemoto[9] & Harufumi Tsuchiya[10]

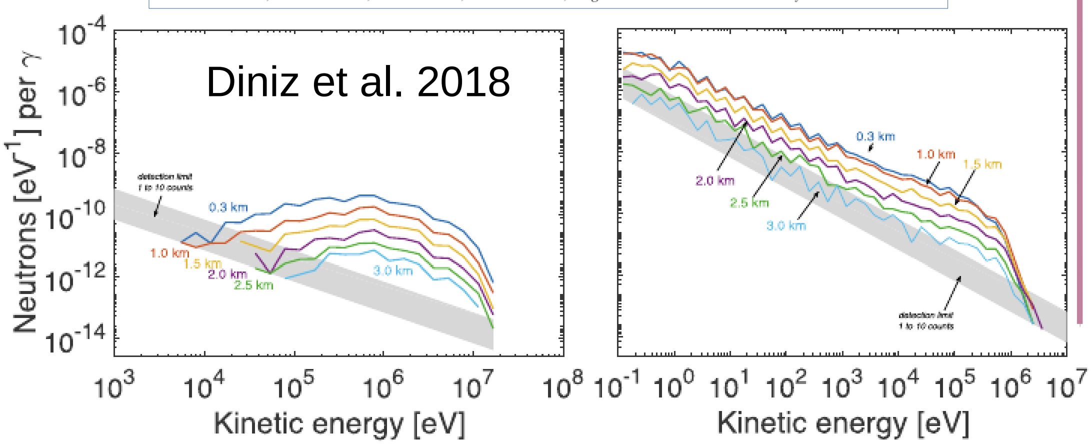
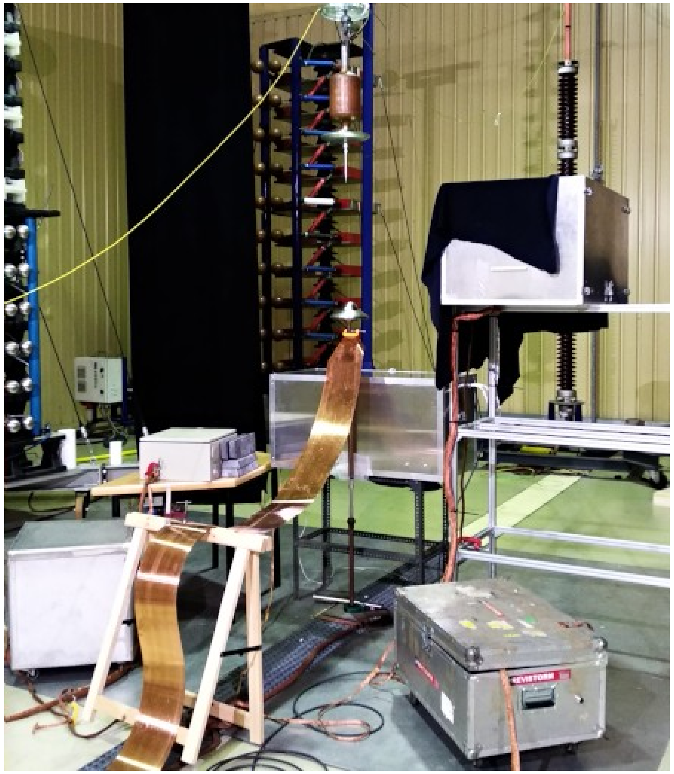


Figure 5. Energy distributions of photons (top row) and neutrons (bottom row) as in Figures 1 and 2, but now differentiated between arriving before 0.1 ms (left column) or after 0.1 ms (right column).



First test in 2