

Instrumentación aplicada a la sociedad

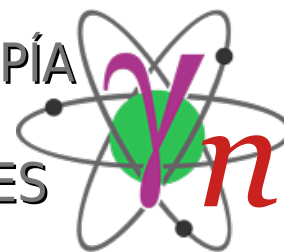
Parte II: Tecnologías de detección de neutrones

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CSIC – Universidad de Valencia
Spain
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Grupo de ESPECTROSCOPIA

GAMMA Y DE NEUTRONES





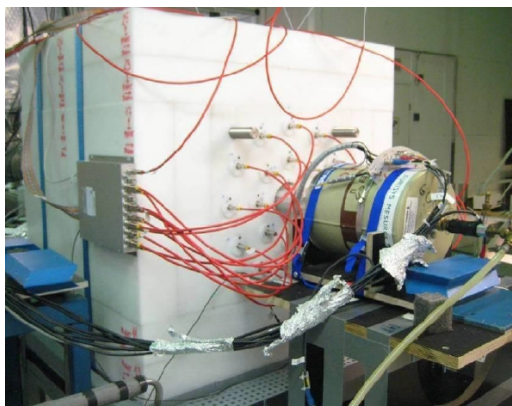
Collaboration IFIC-UPC in neutron detection techniques

IFIC+UPC & neutron detection: 4pi neutron long counters

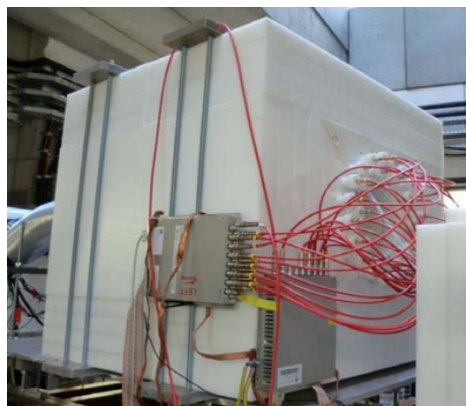
- **More than 12 years collaboration** (5 coordinated projects AEI):
Development and exploitation of moderated neutron counters for nuclear data in astrophysics and technology.

Huge
efficiency
5330 b @ n^{th}

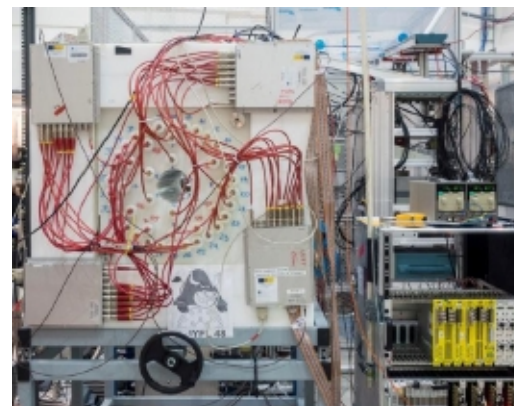
$n + {}^3\text{He} \rightarrow p + {}^3\text{H} + 764\text{keV}$



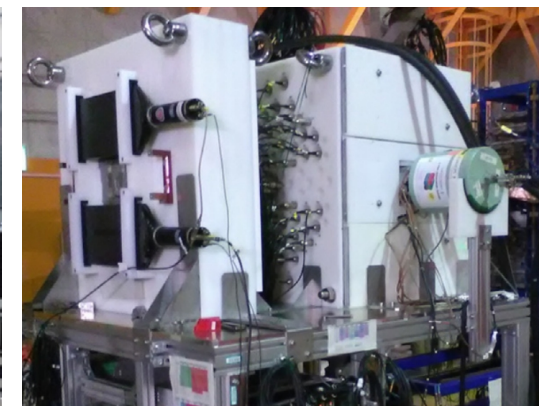
BELEN-20 (2009, EU)



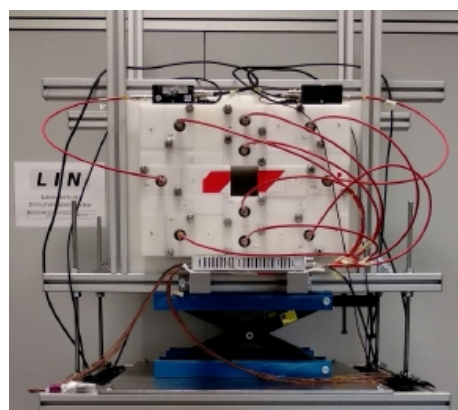
BELEN-30 (2011, EU)



BELEN-48 (2014, EU)



BRIKEN-140H (2016, JP)



miniBELEN (2021): prototype of modular detector for (α, n) reactions and applications



Single HDPE moderator
Module: $10 \times 7 \times 70\text{ cm}^3$

UPC+IFIC ${}^3\text{He}$ -tubes stock for 2022

Detector	Gas	Group	Units	Pressure (atm)	Total length (cm)	Tube length (cm)	Diameter (inch)	Gas length (cm)	Active length (cm)
LDN 252266	${}^3\text{He}$, CO_2	IFIC	10	10	67.59	63.72	1	63.3	60
LND 252231	He_3 , Ar, CO_2	UPC	1	10.1	63.1	53.2	1	53.2	50
LND 252285	${}^3\text{He}$, CO_2	UPC	39	8	67.59	63.72	1	63.3	60
LND 252303	${}^3\text{He}$, CO_2	UPC	1	4	67.59	63.72	1	63.3	60
LND 252248	${}^3\text{He}$, CO_2	UPC	1	20	67.59	63.72	1	63.3	60
LND 252241	He_3 , CO_2	UPC	1	20	38.65	33.97	1	33.97	30.48
LND 252251	${}^3\text{He}$, CO_2	IFIC	1	20	15.35	20.7	1	15.43	13.1
LND 252250	${}^3\text{He}$, CO_2	IFIC	2	10	12.75	7.06	1	7.46	5.13
VT-70060	${}^3\text{He}$, CO_2	UPC	1	8	11	8	0.5	6.4	5
VT-70061	${}^3\text{He}$, CO_2	UPC	2	8	11	8	5/8	6.4	5
Long tubes			52						
Small tubes			7						



${}^3\text{He}$ price: 20-25 €/cm/atm ${}^3\text{He}$!
UPC+IFIC: 59 ${}^3\text{He}$ -tubes, ~ 600 k€
Foreseen 10-15 additional tubes (60 cm) by 2024



What is HENSA?

The High Efficiency Neutron Spectrometry Array (HENSA) is a state-of-the-art detection system for neutron background spectrometry in low radioactivity facilities, such as underground laboratories, and for the measurement of secondary neutrons produced by cosmic-rays.

Currently, the research with HENSA is focused on the study of the neutron background affecting different experiments at the Laboratorio Subterráneo de Canfranc (LSC, Spain) and the characterization of the ambient neutron background by cosmic-rays during solar cycle 25. Early versions of HENSA have been already used for neutron background measurements at the LSC and the shallow-underground laboratory Felsenkeller in Dresden, Germany.

The HENSA detector has been developed as a joint effort by researchers from different international institutions: Instituto de Física Corpuscular (IFIC/CSIC-UV, Spain), Technical University of Catalonia (INTE-UPC, Spain), Universidad Complutense de Madrid (UCM, Spain), Helmholtz-Zentrum Dresden-Rossendorf (HZDR, Germany), TRIUMF (Canada).

Why background neutrons?

High energy neutrons are produced as secondary particles from interactions of cosmic-rays with atoms in the atmosphere. **Cosmic-ray neutrons** are the main component of the ambient neutron background at **ground level** and **high altitudes**. The total flux and the spectral distribution of cosmic-ray neutrons depend mainly on: the solar activity, the geomagnetic position and the altitude. Cosmic-ray neutrons are interesting for a wide range of areas, such as space weather, single event upset (SEU) in microelectronics, cosmic-rays physics and environmental radiation dosimetry.

Neutrons are a challenging source of radiation background affecting experiments dealing with rare event searches. In **underground facilities**, despite cosmic-ray neutron background is largely suppressed, radiogenic neutrons are still produced in the surrounding materials of the facility (rocks and walls) by means of (alpha,n) reactions and spontaneous fission. These neutrons have a large penetrability in matter and they are able to induce background signals in the detectors used for nuclear astrophysics, neutrino and dark matter experiments.

www.hensaproject.org

H E N S A

High Efficiency Neutron Spectrometry Array

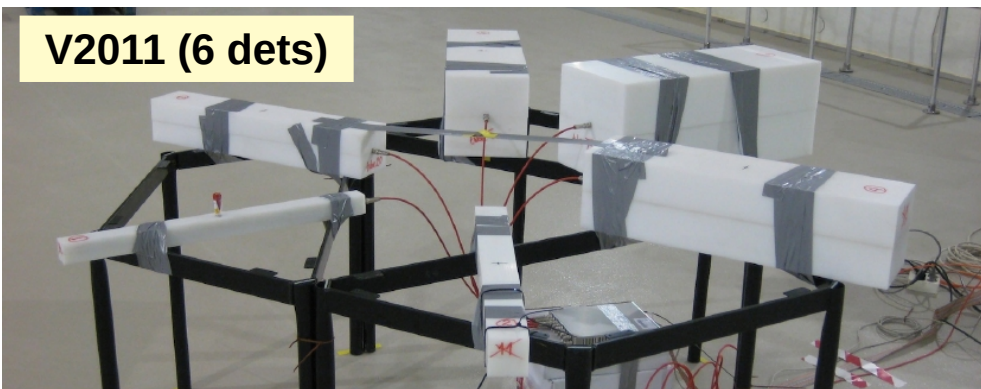
- A unique instrument for high efficiency neutron spectrometry
- Developed and exploited by IFIC-UPC in collaboration with different institutions (UCM, UGR, CIEMAT, HZDR)
- Research & Applications:
 - **Astroparticle physics**
 - **Space weather**
 - **Environmental dosimetry**

Más detalles:
“Práctica Detección de neutrones”
próxima semana!

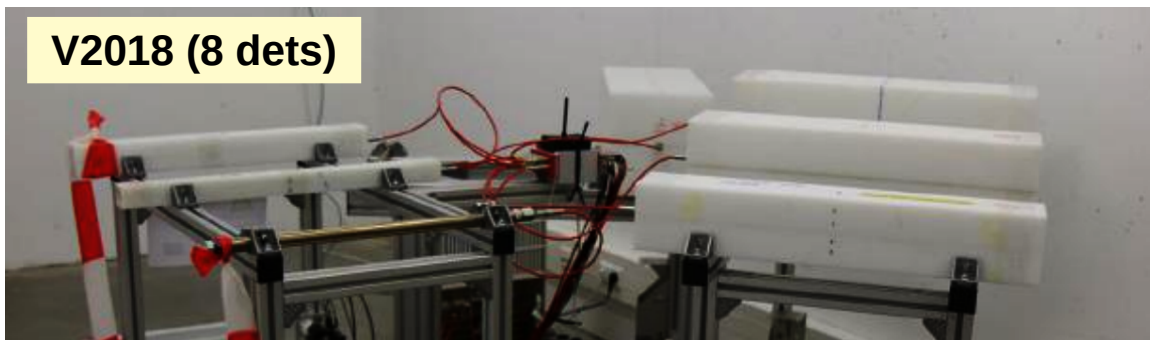
Evolution of the HENSA spectrometer

- 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...

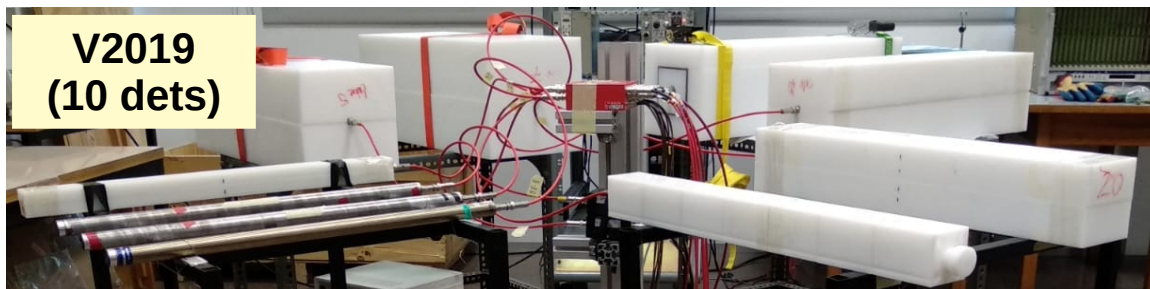
V2011 (6 dets)



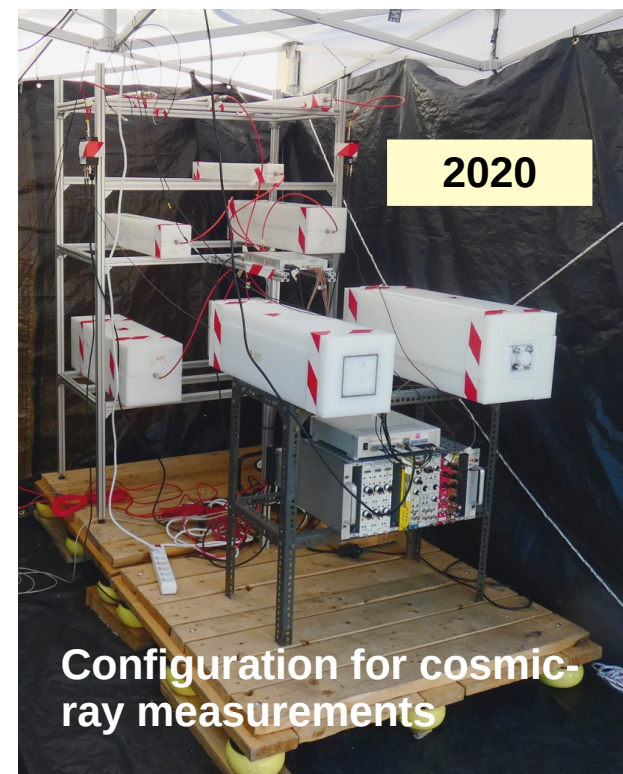
V2018 (8 dets)



V2019 (10 dets)



2020



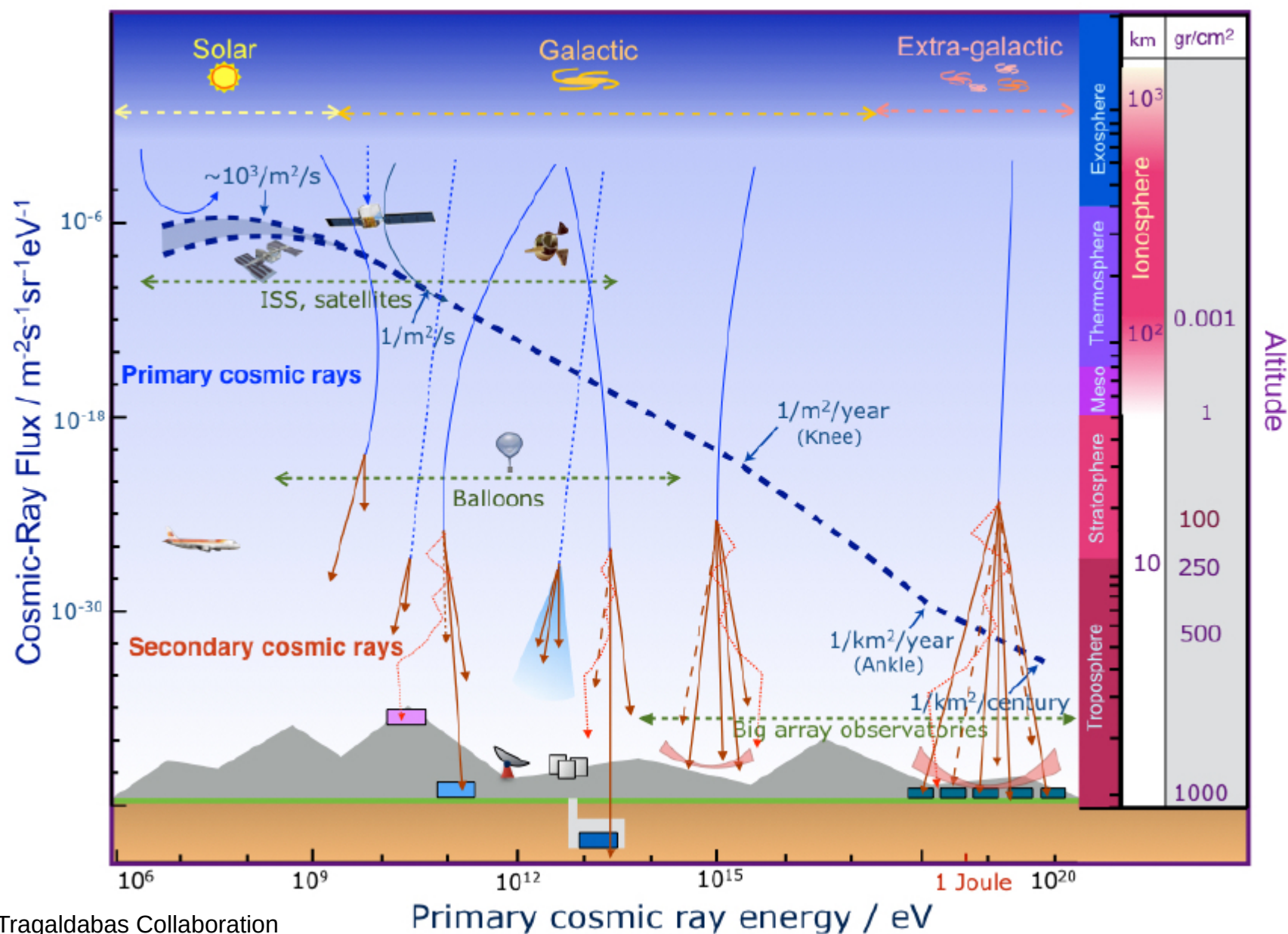
Configuration for cosmic-ray measurements

2020



Van based setup

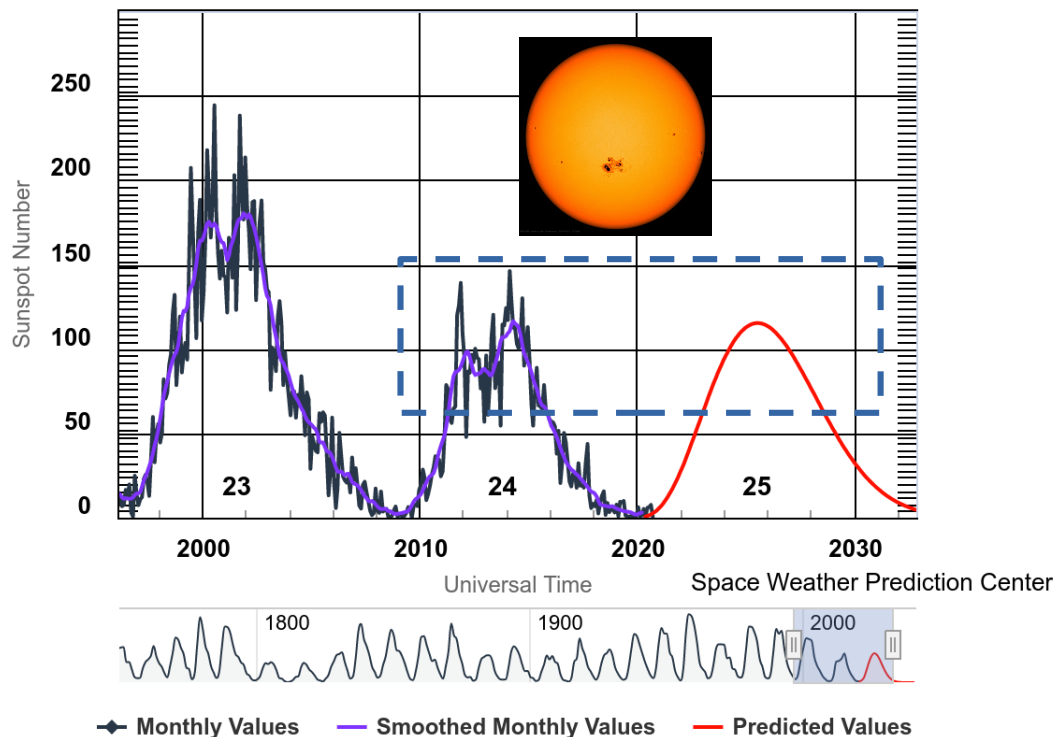
Secondary neutrons produced by cosmic rays



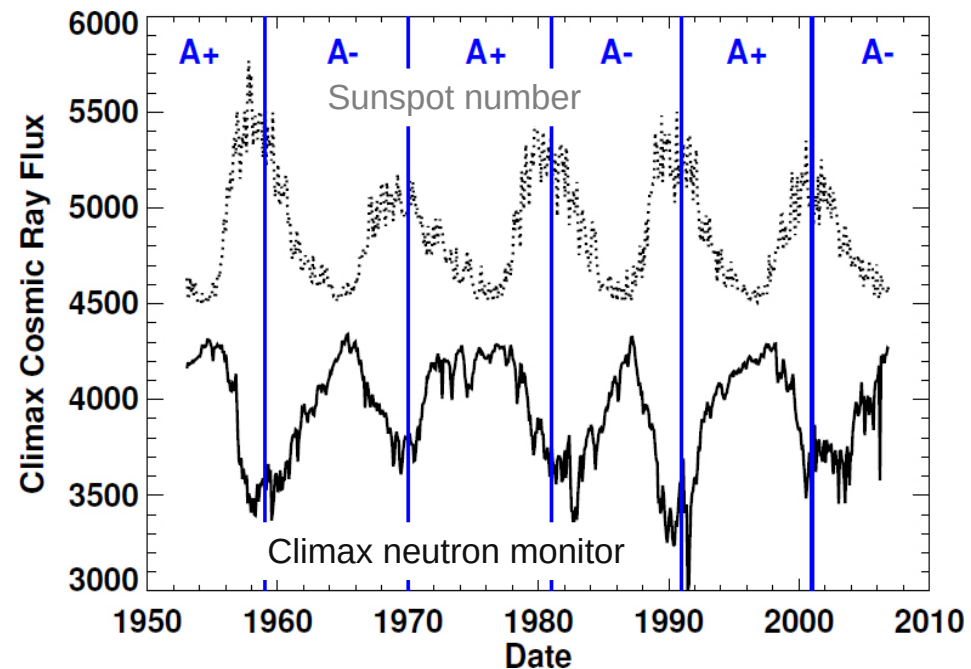
Credits Tragaldabas Collaboration

Cosmic-ray neutrons: space weather

ISES Solar Cycle Sunspot Number Progression



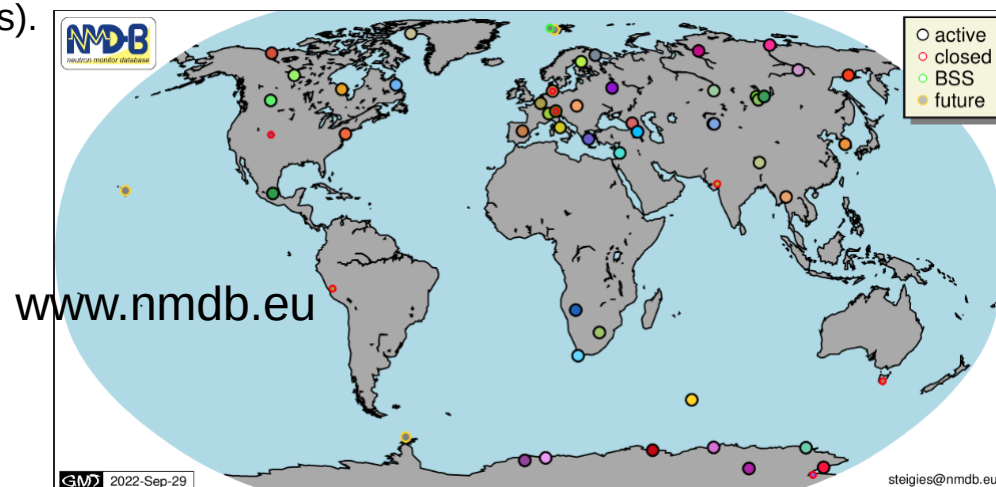
NOAA/NASA forecast for Solar Cycle 25. Maximum solar activity expected for July, 2025 (+/- 8 months). Solar minimum between Cycles 24 and 25 was observed around Dec. 2019 (+/- 6 months).

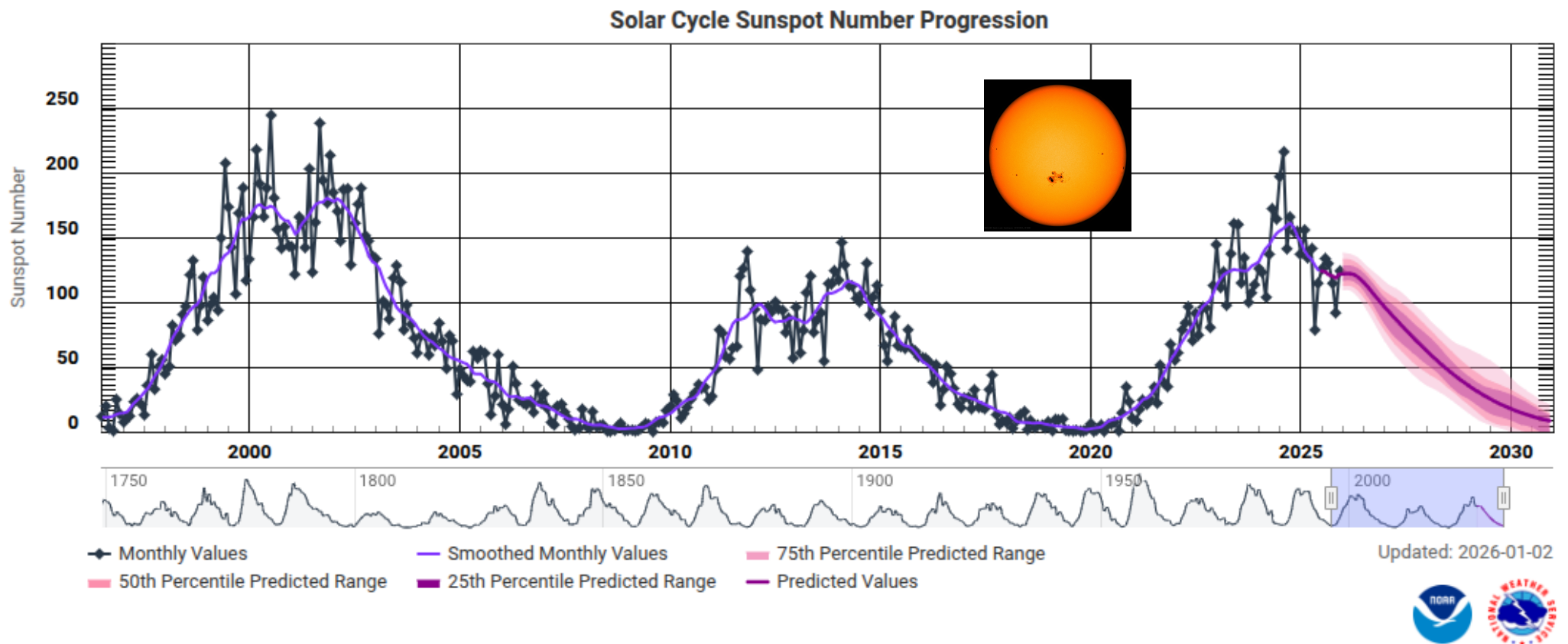


Neutron background anti-correlation with solar cycle. Cosmic Ray flux from the Climax Neutron Monitor and rescaled Sunspot Number.



Monitor de neutrones de Castilla-La Mancha (CaLMa)

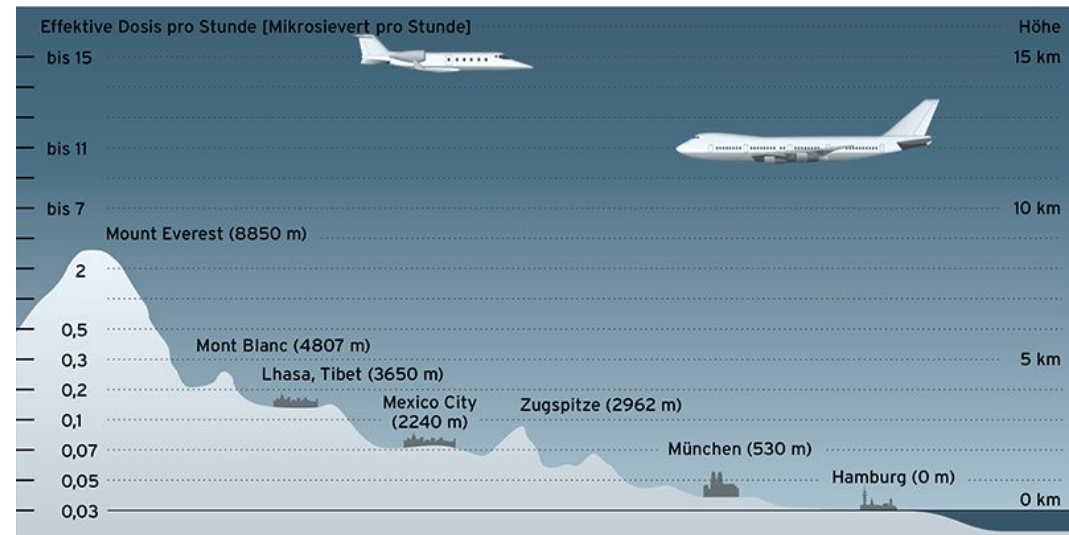
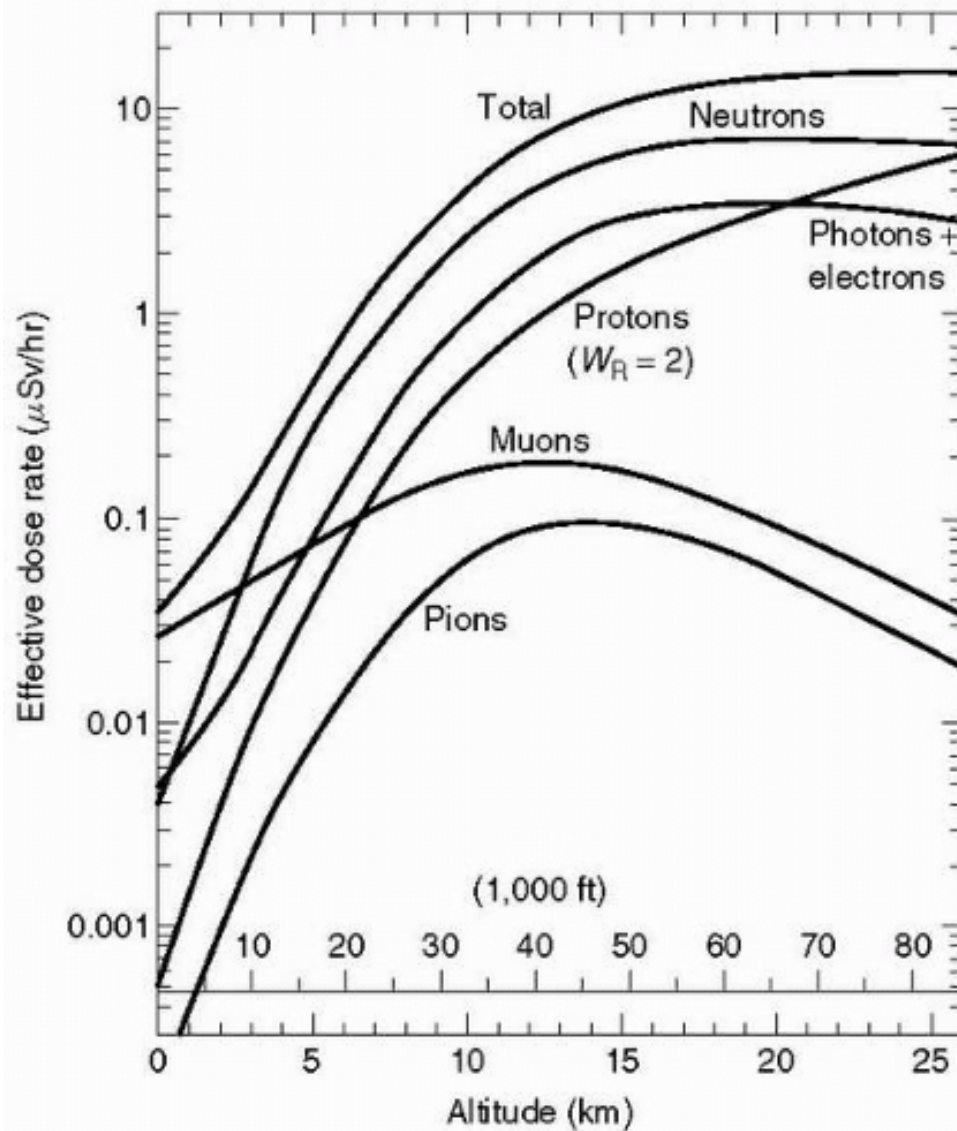
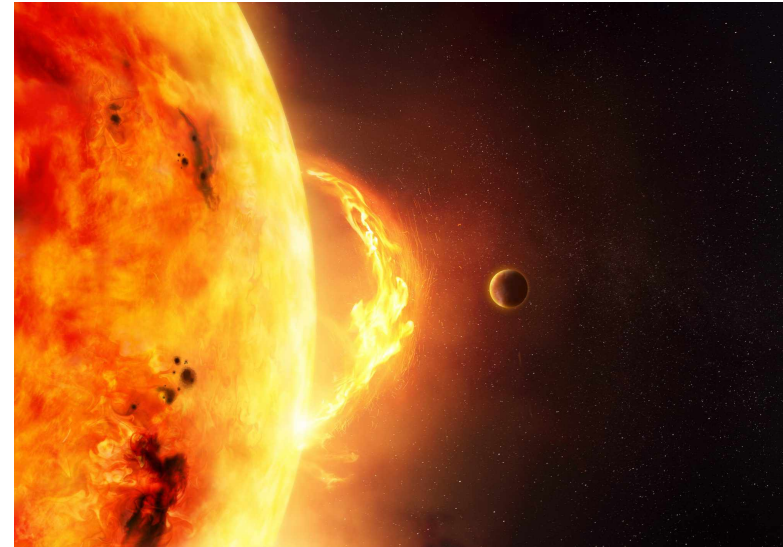




What is actually happening now...

<https://www.swpc.noaa.gov/products/solar-cycle-progression>

Cosmic-ray neutrons: dosimetry



Secondary neutrons by cosmic-rays

Vertical Geomagnetic Cutoff Rigidity 2008

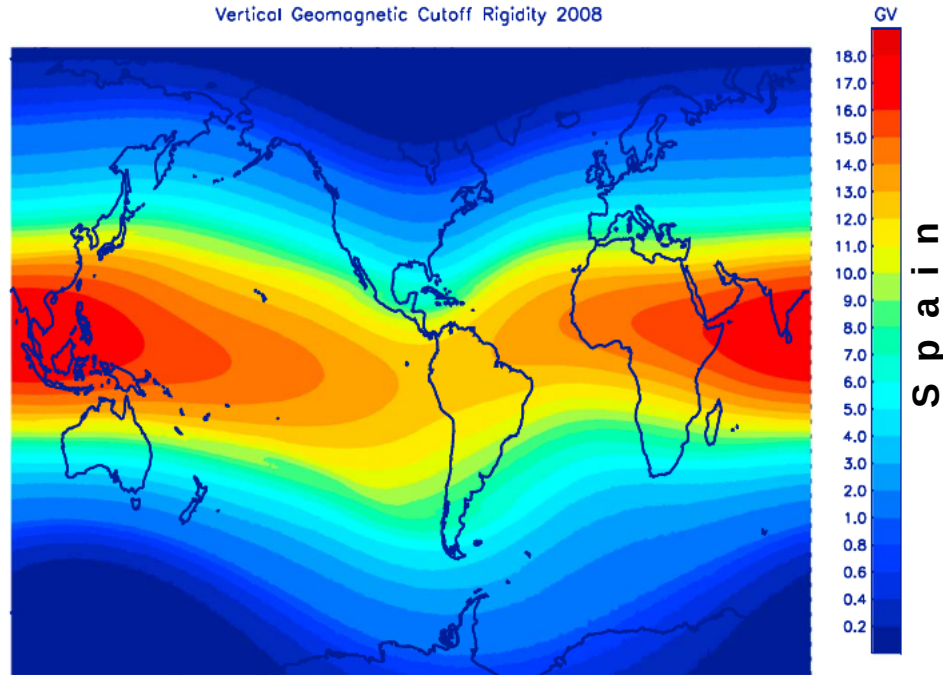


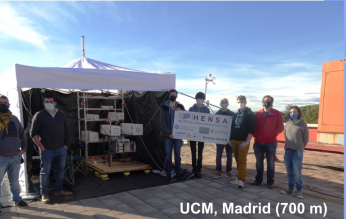
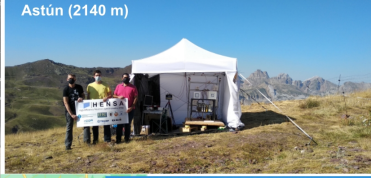
Figure 3. Global grid of vertical geomagnetic cutoff rigidities (GV) calculated from charged particle trajectory simulations in the IGRF field for 2008.

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 (R_c) values from 5 GV to 9 GV. In Ceuta and Melilla, R_c -values are 9.15 GV and 9.6 GV, respectively. In Canary Islands R_c is ~ 11.7 GV.
 - Thus, the whole spanish territory covers a relatively ample range of R_c -values compared to other larger countries (for instance USA with $1.5 \text{ GV} < R_c < 4.7 \text{ GV}$).

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)



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

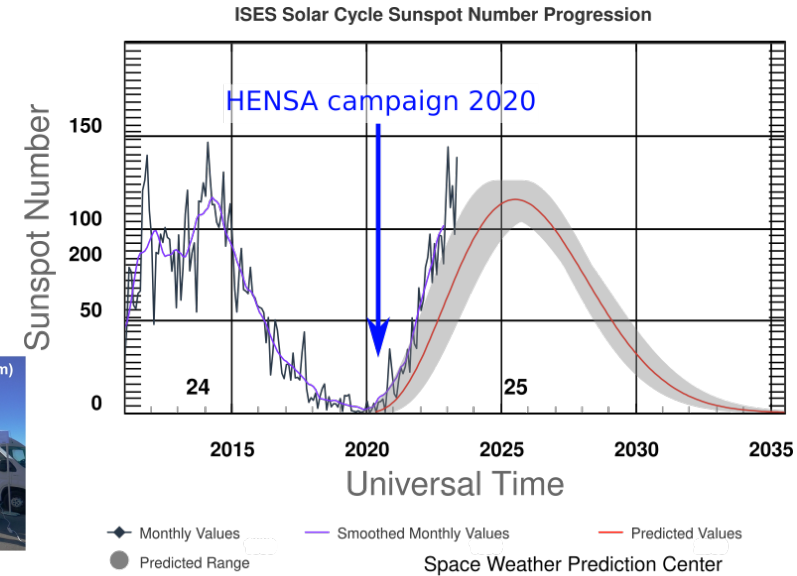
Cosmic ray induced neutron background

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

HENSEA
High Efficiency Neutron Spectrometry Array

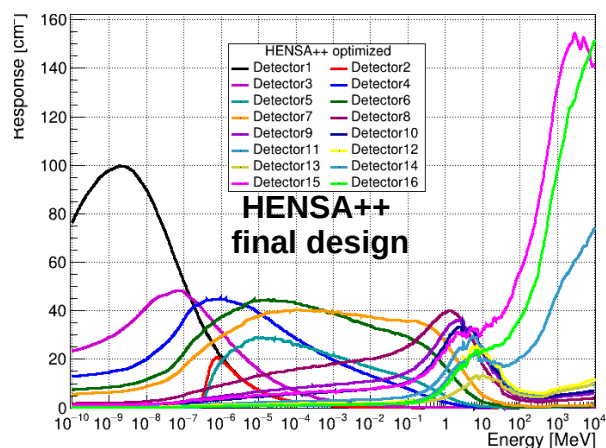
www.hensaproject.org

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



Paper to be released this year!

- **High efficiency spectrometer for space weather applications:**
 - 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 2023-2024** (detector array, electronics and auxiliary systems).
 - **Final deployment in 2024** at the Observatorio Astrofísico de Javalambre (A. Quero, PhD Thesis). Full data available sin July 2025.



Proyecto: IDIFEDER/2021/002

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

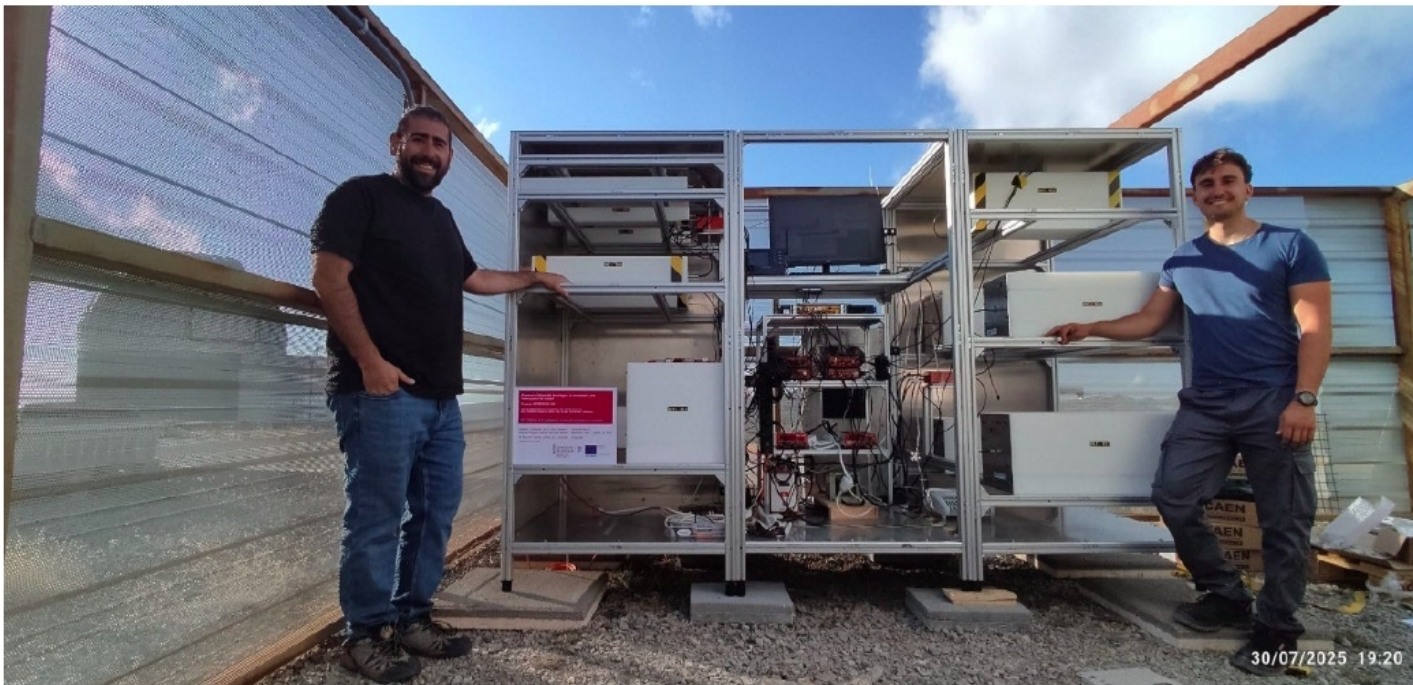
Programa Comunitat Valenciana Fondo
Europeo de Desarrollo regional (FEDER)
2021 - 2027

Subvención: 260.199,21 €

Beneficiario:

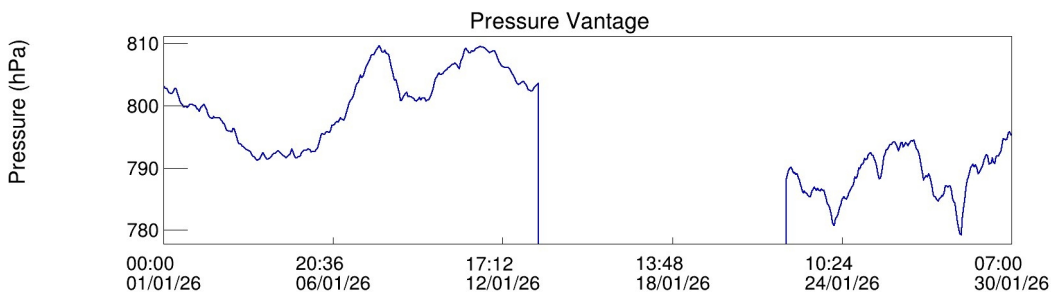
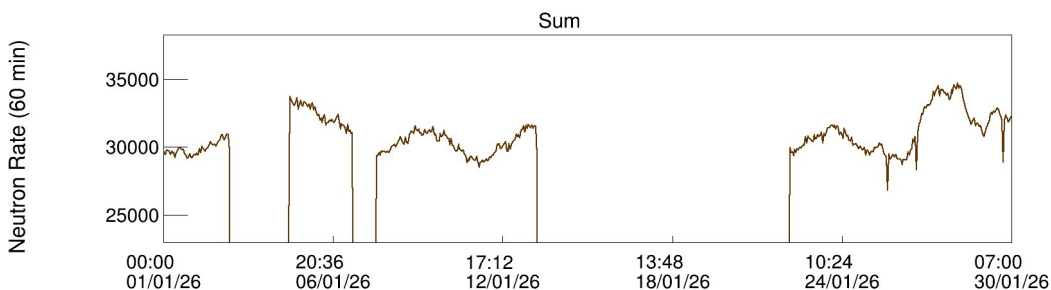
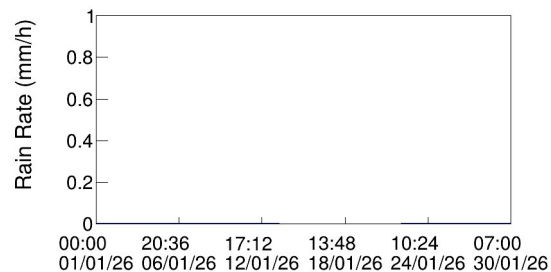
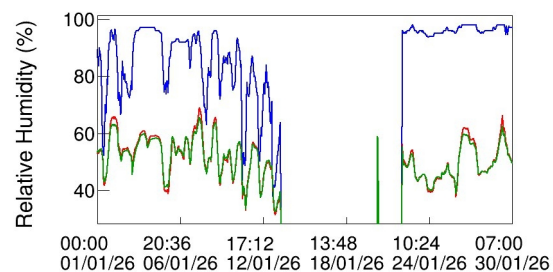
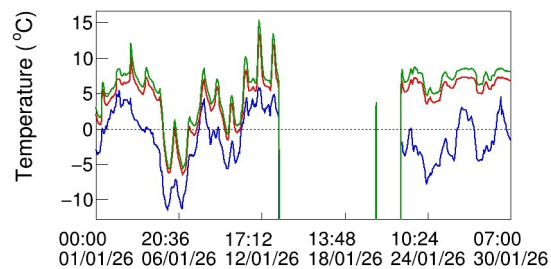
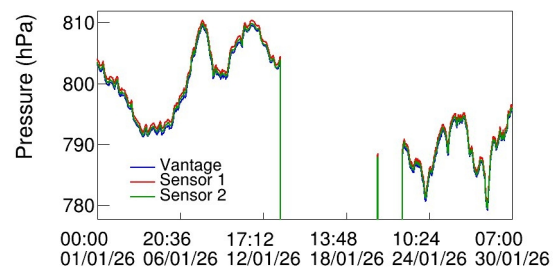
CSIC – Instituto de Física Corpuscular



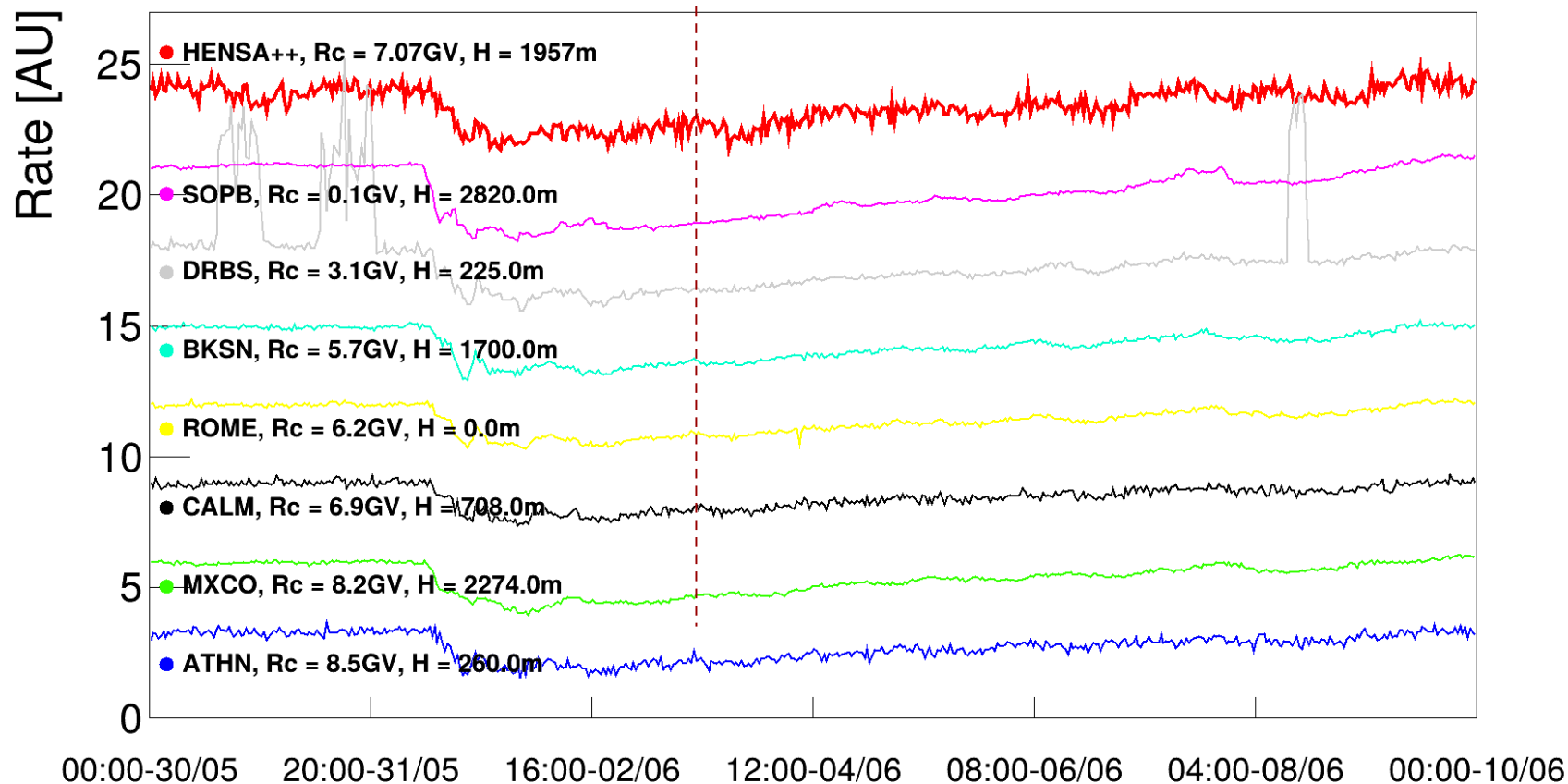


Physics run...





Comparison with the NMDB data

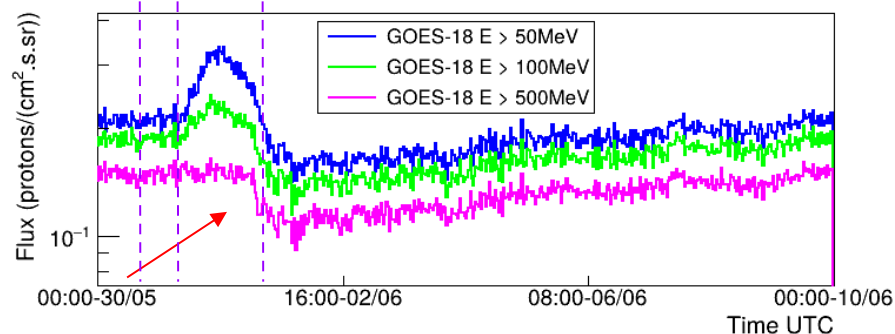
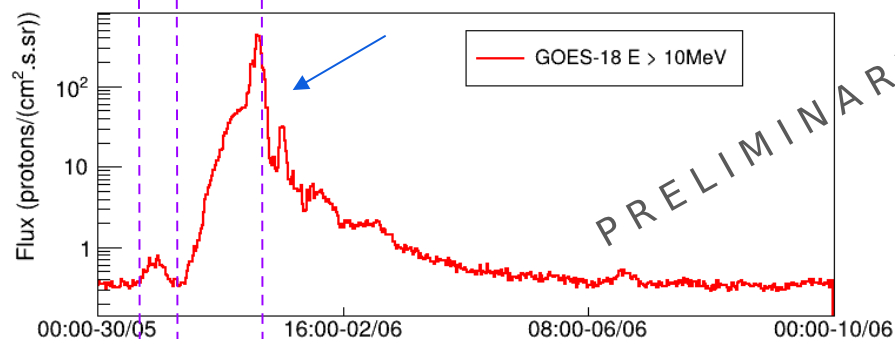
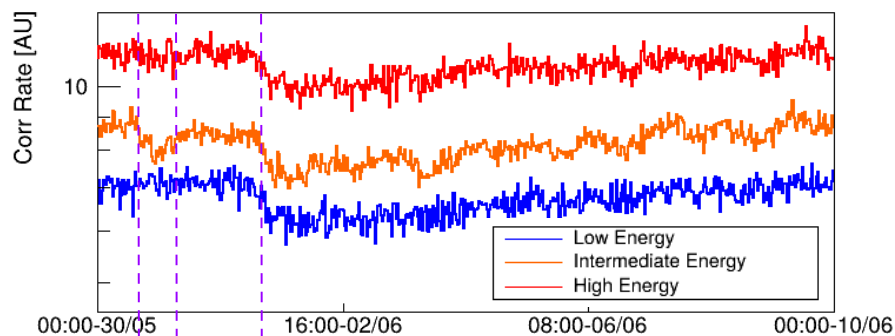


15 mins timescale.

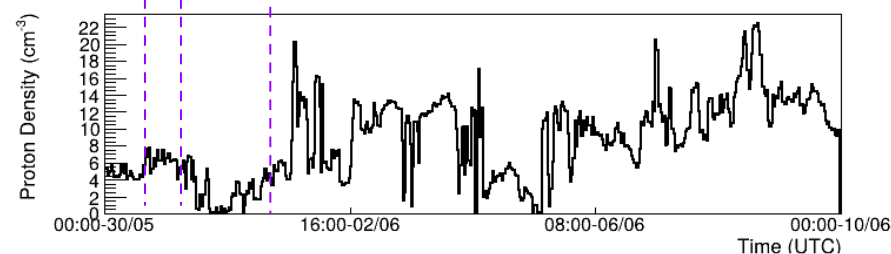
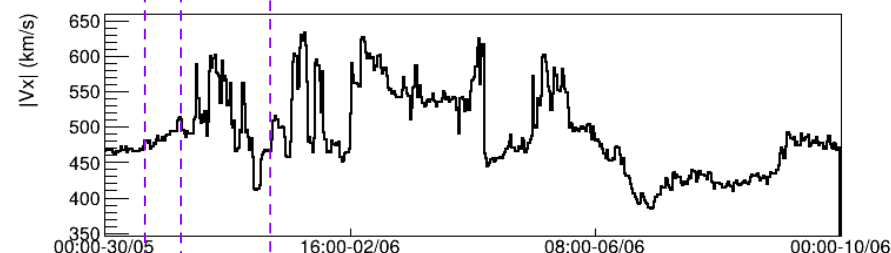
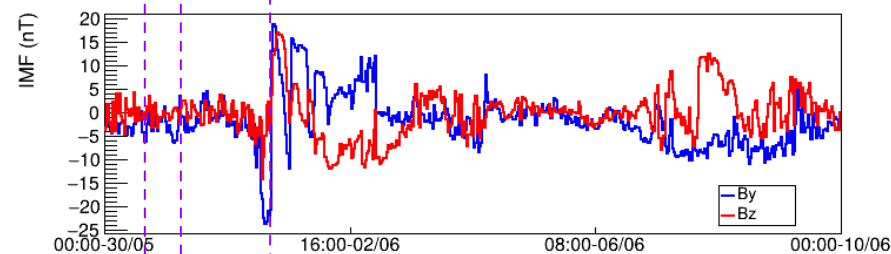
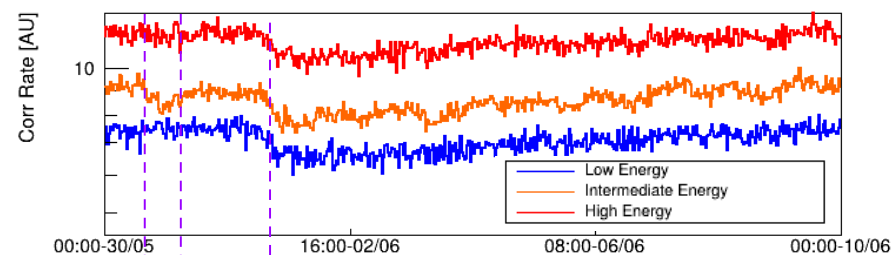
Temporal evolution of the sum of the 3 channels.

Same trend as the NMDB with only 3 detectors!

Some preliminary results



Temporal evolution of the 3 HENSA++ detectors placed at OAJ and the GOES-18 recorded proton flux



Temporal evolution of the 3 HENSA++ detectors placed at OAJ and the NOAA recorded magnetic field, proton density and velocity.



- Big science projects
- Particle therapy facilities
- Industrial applications

Neutrons can dominate the total radiation dose received by workers, patients and public.
Proper detection techniques of neutrons are required (energy sensitivity, time structure, real time monitors).

Limitations current commercial solutions:

- Classical technology: radiation sensor (60's), acquisition/read-out (90-2000's)
- **Portability, 9-18kg** per unit.
- **Poor response** for high neutron energies ($> 20\text{MeV}$).
- Not well suited for complex quasi-continuous or **pulsed neutron fields**.

Some challenges/needs:

- + High energy neutron fields in particle therapy facilities (complex time structure).
- + Beam losses in synchrotron or cyclotron facilities (sudden pulsed fields).
- + Pulsed sources for fundamental research and applications (spallation, fusion neutron sources or high intensity lasers, flash therapy)
- + New recommendations for operational quantities (ICRU95, 2020).

Market price 10 – 15 k€ per unit.



Berthold GmbH.

Ludlum Inc.



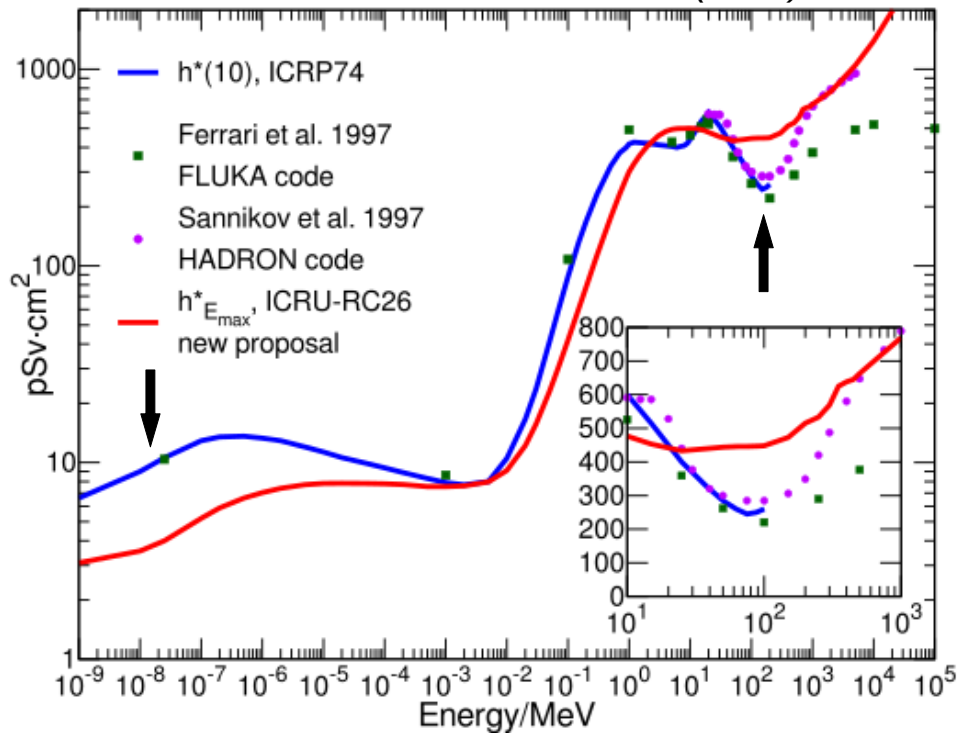
Thermo Fisher

Studs vik



Ambient neutron dosimetry

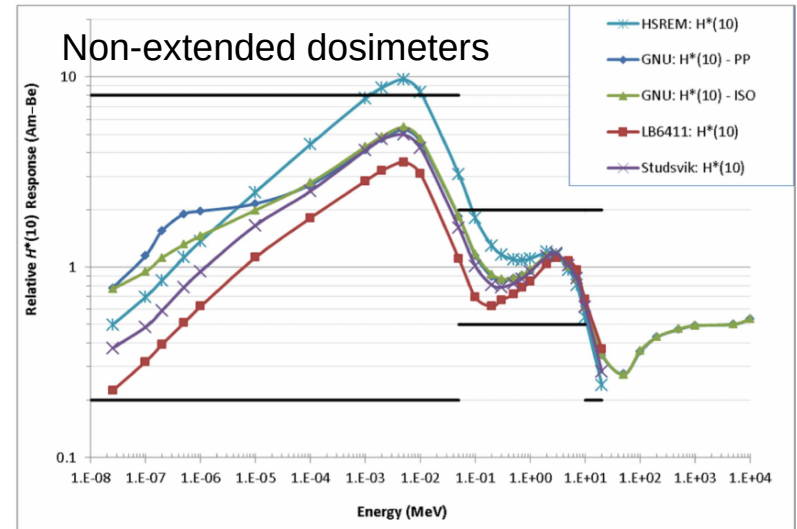
N.E. Hertel et al. *Journal of the ICRU* 20:1 (2020) 7-130.



- + Important **impact for RP in high energy fields** (particle therapy, HE accelerators, air crews).
- + **Some commercial designs may become obsolete** as soon as ICRU95 is incorporated into legal frameworks (5-10 years, ~ 2030).
- + Currently, we are currently on **new dosimeter designs** compatible with ICRU95. Expected prototypes for 2024 (LINDos/LINDosext).

We are open for scientific collaboration and transference of our technology!

(a) Eakins+ 2018



(b) Recommended limits IEC61005

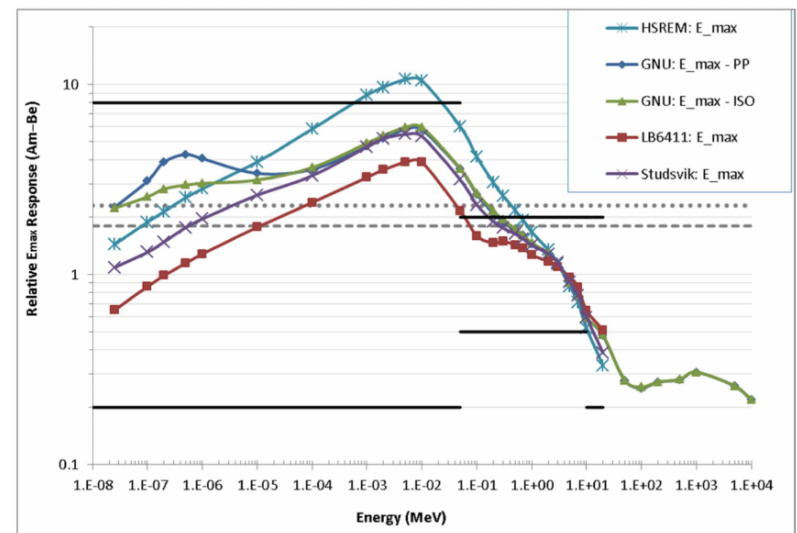
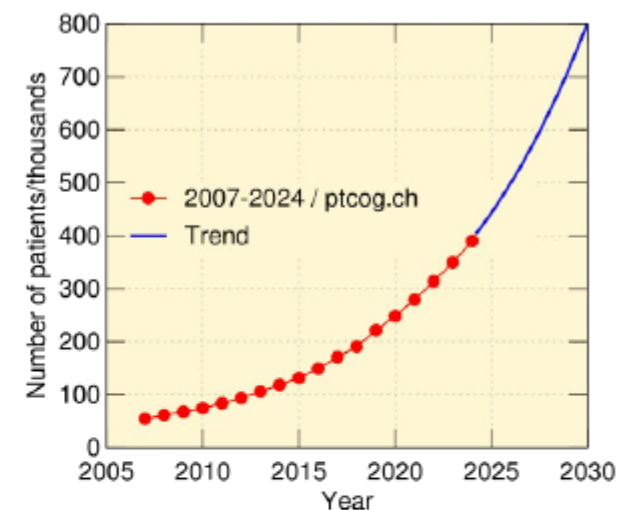


Figure 3. Relative (a) $H^*(10)$ and (b) $E_{\max}$ responses of the LB6411, Studsvik 2202D HSREM and GNU, normalized to their respective responses to $^{241}\text{Am-Be}$. Recommended limits (solid lines), and the effects of recalibrations to the response at 144 keV (dotted line) and 565 keV (dashed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

Cada año:
10 MILLONES de
muertes

274.000 NUEVOS
casos en niños

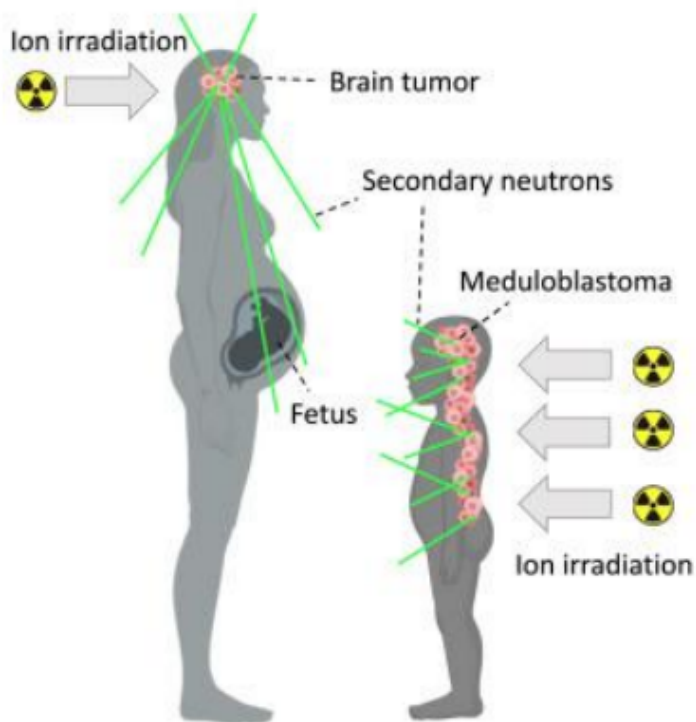


**PROTÓN
TERAPIA**



- ❑ **> 400 mil**
pacientes en
2025
- ❑ **50% niños**

Producción de neutrones secundarios en protonterapia



Riesgo de un nuevo cáncer a largo plazo

- ❑ IMPACTOS:
- Calidad de vida
- Sobrecoste sanidad
(20 - 200 M€/año )
- Productividad

NECESIDADES



Reducir el riesgo de nuevos cánceres



Desarrollo de Herramientas optimización de tratamientos

Opportunities with high societal impact!

LINrem dosimeters: final design



LINrem3:

- + Thermal up to 10 MeV
- + Portability: **3.6 kg**
- + Pulsed field: linear response up to **2000 nSv/bunch**



LINremext3: extended energy range

- + Thermal up to 10 GeV
- + Portability: **10.6 kg**
- + Pulsed field: linear response up to **2000 nSv/bunch**

Areas of application

- + Nuclear power plants
- + Industrial applications with neutrons
- + D-D Fusion and Laser-driven neutron sources
- + Small accelerators/research laboratories
- + Radiotherapy facilities

- + Proton and light ion therapy
- + Ultra-high dose rate (FLASH) therapy
- + D-T Fusion
- + Large and high intensity particle accelerator facilities
- + Aircrew and Space crew dosimetry

- **Demonstrator prototypes for active LINrem/LINremext dosimeters** have been developed and **validated in relevant environments**, including nuclear reactors, fusion and laser-driven neutron sources, and particle therapy facilities.
- **Electronics fully developed at UPC**, including charge-sensitive preamplifiers, high-voltage (HV) and power systems. A **portable digital acquisition system** has been developed at UPC & IFIC. The **first standalone active system is set for release in 2025**.
- **Intellectual property**: Innovative aspects of the detector design are already protected. **Patents granted in the US, EU, and Japan** (US12123991B2, EP4097510, JP2023-518927A).
- **Passive dosimeter** version: Based on TLD 700/600. Technical validation is ongoing, with a **validated final prototype expected by autumn 2025**.
- **New recommendations for operational quantities (ICRU95, 2020)**: A new dosimeter design is under development, with the **first prototype expected by summer 2025**.

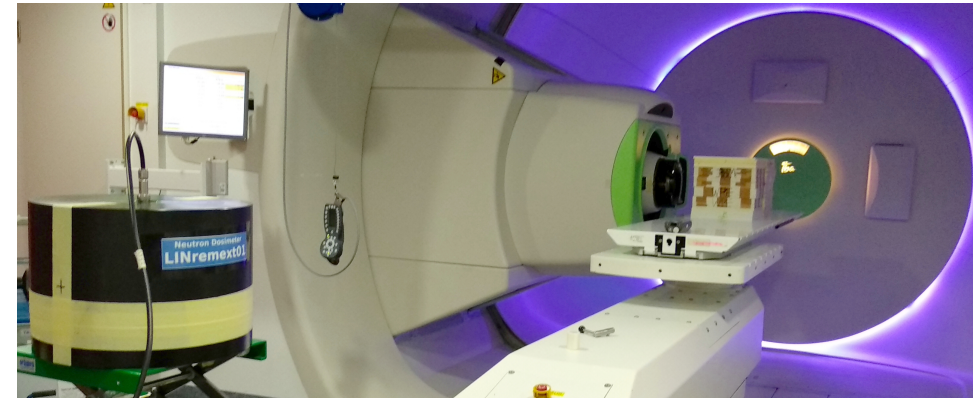
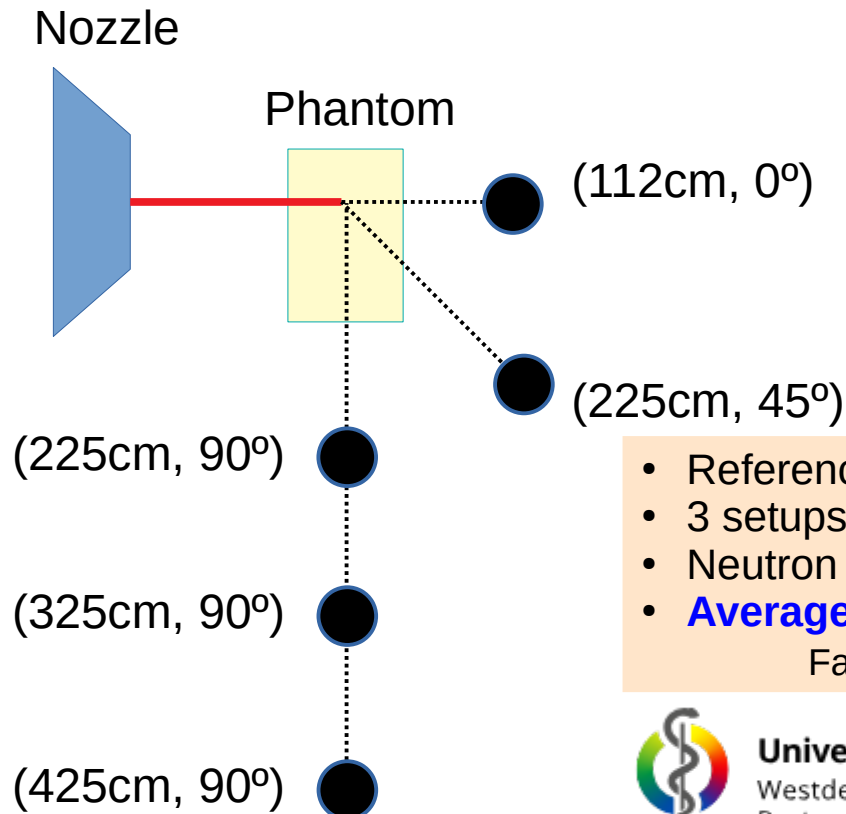
Medical applications with LINrem: out-of-field neutron dosimetry

- Prototype of extended range dosimeter: **LINremext1, 10kg, sensitivity from thermal up to GeVs.**
- LINremext1 designed focusing on the application in proton therapy facilities. Uncertainties in dose determination estimated to be $\sim 10\%$ by detector energy response (systematic).
- Time resolved measurements of the out-of-field secondary neutron dose in PBS proton therapy achieved.

LINrem detectors @ WPE

- Phantom 30x30x60, water equivalent RW3 material.
- R20M10

Angle/deg	D/cm	Eq_Setup
0	112	Farah.Pos1
45	225	Farah.Pos2
90	225	Farah.Pos3
90	325	Farah.Pos5
90	425	Farah.Pos6



- Reference values from Bonner sphere spectrometers (EURADOS).
- 3 setups for comparison.
- Neutron $H^*(10)$ from BS in Pos. 5 and 6 is not provided in the article.
- **Average delivery dose rate ~ 5 Gy/min (clinical).**

Farah et. al. Med. Phys. 42 (5), pp. 2572-2584 (2015)



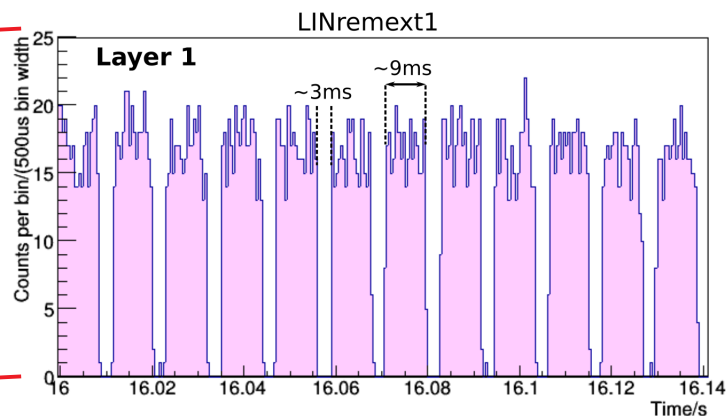
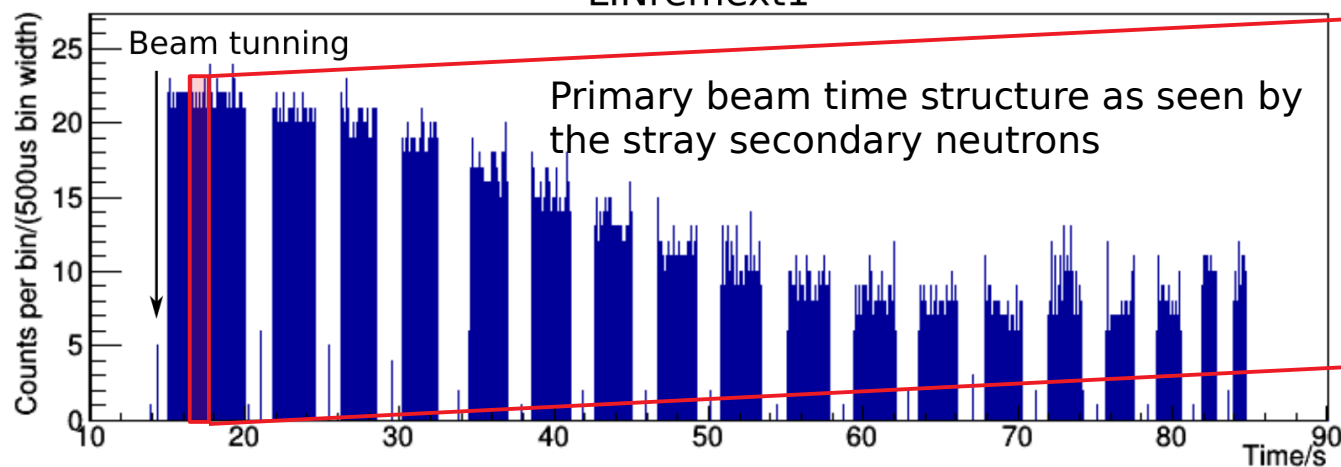
Universitätsmedizin Essen
Westdeutsches
Protonentherapiezentrum (WPE)

In collaboration with C. Bäumer and J. Wulff

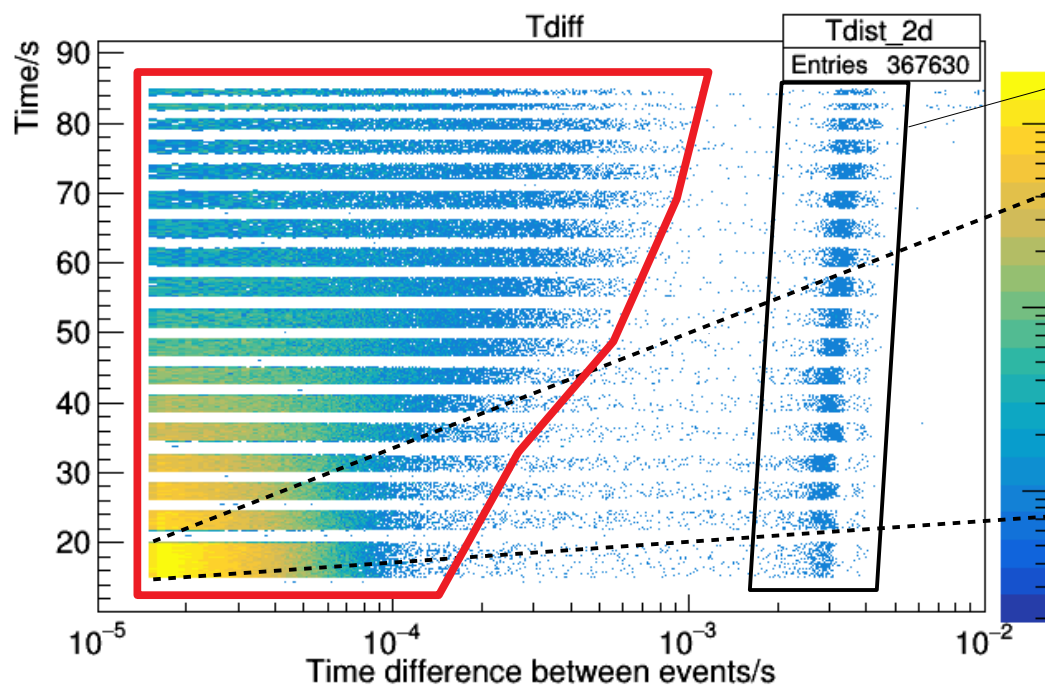
Time-resolved dosimetry in PBS

(R20M10, 112cm, 0°)

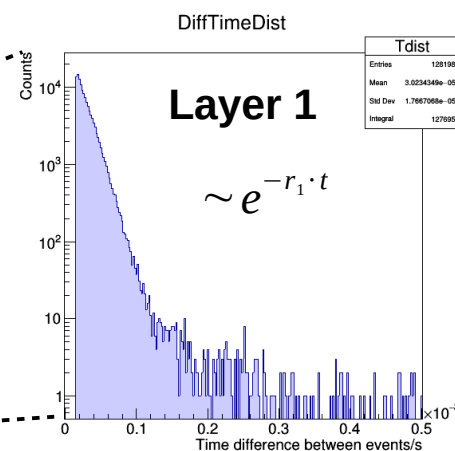
Complex time structure (quasi-continuous neutron field)
LINremext1



Layer: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18



Time difference between spots



Analysis of the waiting time distribution to obtain dose rate for the different layers

- **LINrem prototypes able to be transfer to users (TRL $\geq$ 7):** I+D for integration of electronics, DAQ and front-end into a single/portable module (continuous & pulsed fields).
- **Other potential applications:** Flash therapy, High intensity laser facilities
- **HENSA++ project:** NESTA / Advanced instrumentation on neutron detection for space weather and medical applications

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:

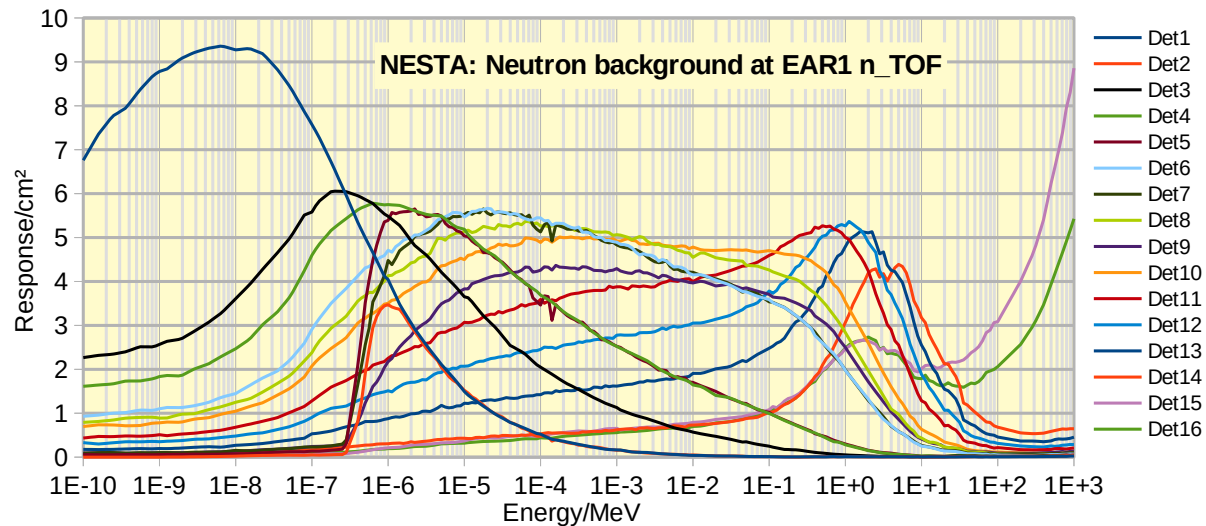
CSIC – Instituto de Física Corpuscular



- **Dedicated spectrometer for medical applications:**
 - 15 detectors (3He, 10 atm, 5 cm AL) able to operate in parallel.
 - Fully based on digital electronics.
 - Focus on out-of-field measurements in PT centers and medical LINACS.
 - Commissioning in 2024.

B. Brusasco, PhD thesis (UPC)

NESTA: NESTED NEUTRON SPECTROMETRY ARRAY



NESTA during test campaign at n_TOF @ CERN

- Nested spectrometer for neutron background measurements on accelerator environments (Bonner's sphere principle).
- Sensitivity from thermal up to 10 GeV.
- Suited for continuous and high intensity pulsed neutron fields (*Rev. Sci. Instrum.* **85**, 013502 (2014)).
- Developed in collaboration by IFIC & UPC groups.



GRACIAS!!!!!!!

Preguntas?

Oportunidades de tesis doctoral en estos proyectos?