HANDS-ON: Espectroscopia de Neutrones Cósmicos

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Repositorio GitHub

https://github.com/flopezus/cosmic-ray-neutron-spectrum-deconvolution-program.git

Instalación rápida:
https://github.com/flopezus/cosmic-ray-neutron-spectrum-deconvolution-program/blob/main/INSTALACION_RAPIDA.md

Formas de ejecutar el código:

- **Instalación local: Docker + root + Jupyter**
- **GitHub Codespaces: root + Jupyter**

Instalación local

Clonamos el repositorio:

git clone
https://github.com/flopezus/cosmic-ray-neutron-spectrum-deconvolutio
n-program.git
cd cosmic-ray-neutron-spectrum-deconvolution-program

Permisos:

chmod +x start_class.sh stop_class.sh test_class.sh

Instalación local

Construye la imagen y ejecuta las comprobaciones:
./test_class.sh

Iniciar la actividad
./start_class.sh

Abre en el navegador:
http://localhost:8888/lab?token=neutrons

Después abre el notebook:
classroom/notebooks/unfolding_local.ipynb

Codespaces

GitHub Codespaces

https://codespaces.new/flopezus/cosmic-ray-neutron-spectrum-deconvolution-program?quickstart=1

Eventos asignados y carpeta en Dropbox

Eventos

https://docs.google.com/spreadsheets/d/1C6qK4rxyLTveLRa_QtLRlB24OCTgCVDeFW2F9oJR3vE/edit?usp=sharing

Subir data

https://www.dropbox.com/request/btr6q9pwob42ipo5zs6x

¿Cómo el ambiente local modifica la señal que medimos?

Efecto

Variables locales

w: humedad & composición del suelo, humedad del aire, lluvias, nieve acumulada, etc

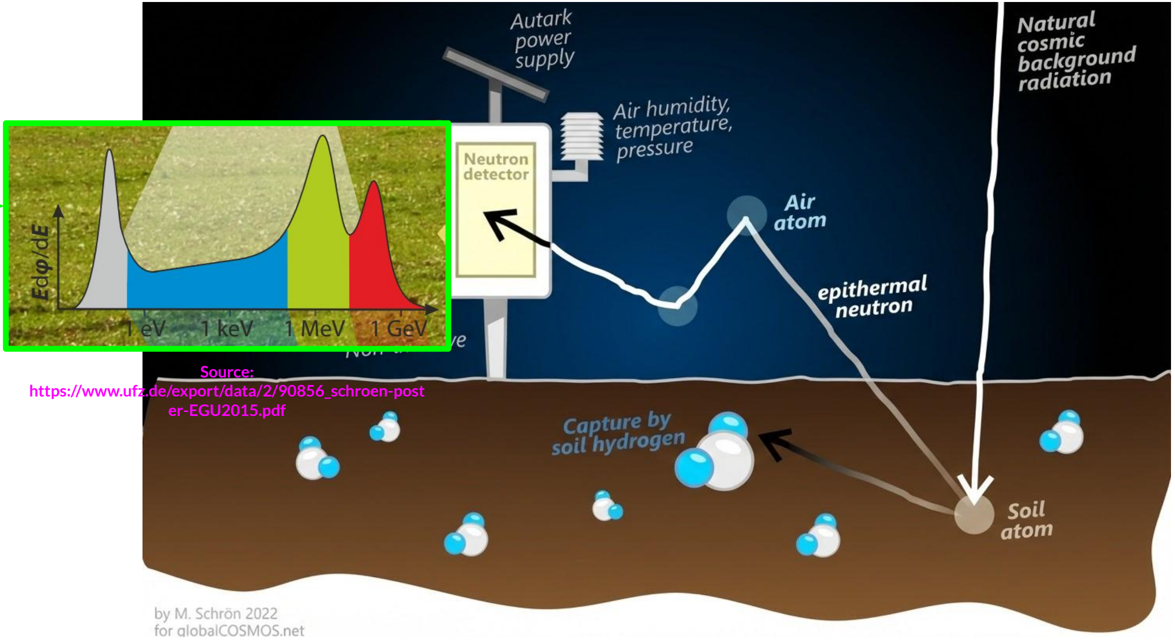
Espectro de neutrones @ nivel del suelo

$$\phi(\mathbf{E}, \mathbf{s}, \mathbf{d}, \mathbf{r_c}, \mathbf{w})$$

Variables globales
s: Actividad solar
d: Profundidad atmosférica
$\mathbf{r_c}$: Rigidez de corte geomagnético

Neutrones < 20 MeV son fuertemente moderados por hidrógeno

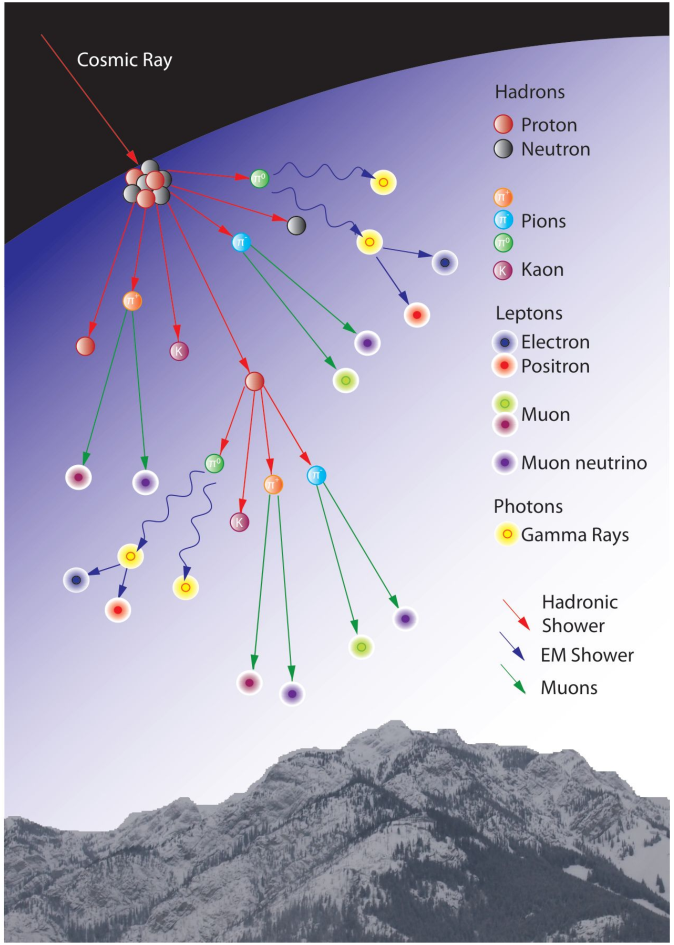
¿Cómo se ve afectado el espectro de neutrones por las variaciones o condiciones ambientales que modifican el contenido de hidrógeno a nivel del suelo?

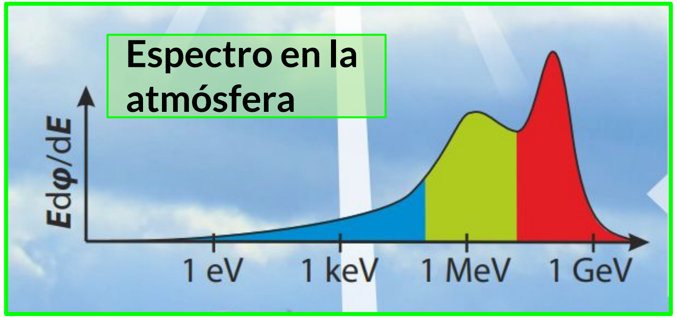


Source: https://www.ufz.de/export/data/2/90856_schroen-poster-EGU2015.pdf

Source: https://www.neptoon.org/en/stable/home/crns-overview/

¿Por qué importa medir bien los neutrones cósmicos en superficie?

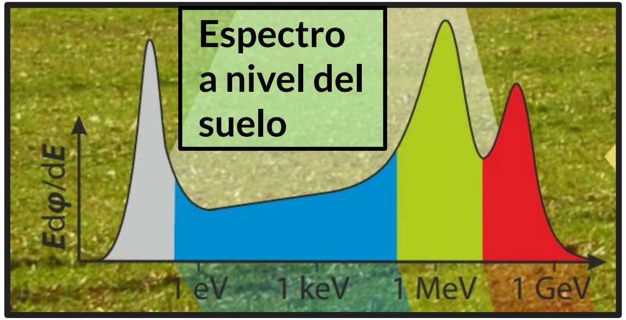




Knockout: ~100 MeV

Evaporación: ~ 1MeV

Interpretar correctamente lo medido: distinguir el efecto del flujo primario (p) de las variables locales



Dispersión elástica

Termalización: ~ 25 meV

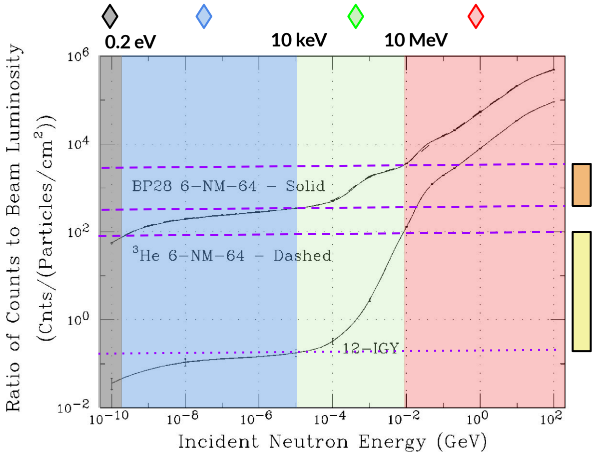
Neutron Monitors (NMs)

Daejeon, South Korea, NM64 (200 m altitude)

Measure high energy neutrons induced by cosmic rays

✱1953: "Pile" type monitor - IGY (1957)
J. A. Simpson

✦1964: Monitor NM-64
H. Carmichael



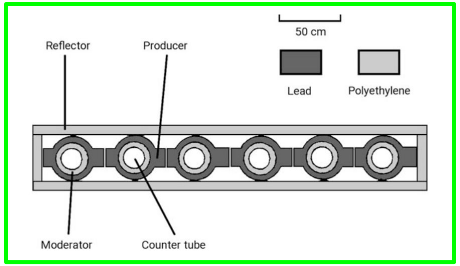
Modified from J, Clem and L. Dorman, *Neutron Monitor Response Functions*, Space Science Reviews, 2000

Gap is reduced

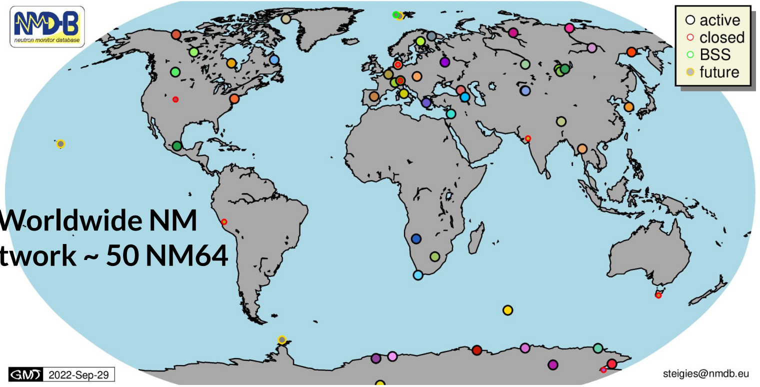
NM-64 ~10^1

IGY ~10^3

Increase ~3 times the efficiency



Neutrons are highly morerated by hydrogen below 20 MeV.



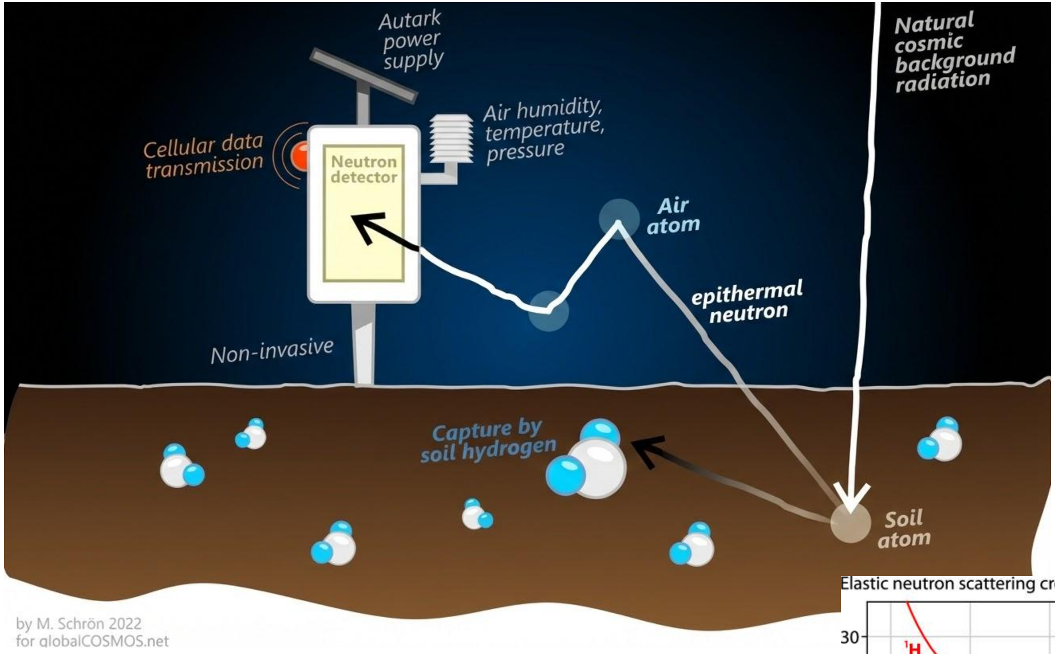
Worldwide NM network ~ 50 NM64

NMDB: Real-time neutron counting rate

✱ J.A Simpson et al., *Cosmic Radiation Intensity-Time Variations and Their Origin. I. Neutron Intensity Variation Method and Meteorological Factors*, Phys. Rev., 1953

✦ C J. Hatton and H. Carmichael, *Experimental investigation of the NM-64 neutron monitor*, Can. J. Phys., 1964

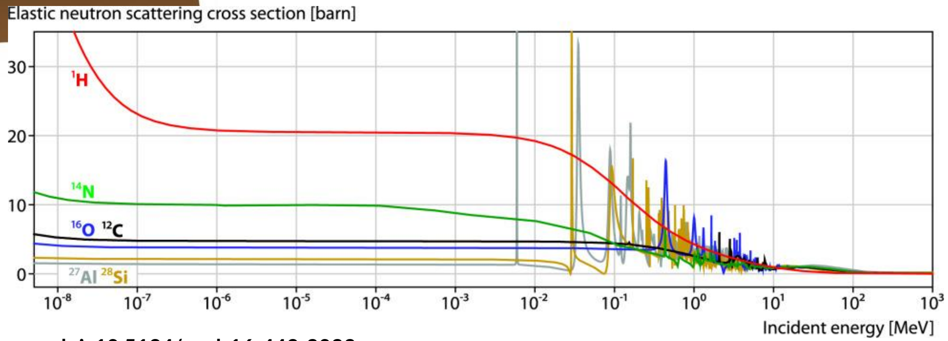
La clave física: el hidrógeno modera neutrones



Source: https://www.neptoon.org/en/stable/home/crns-overview/

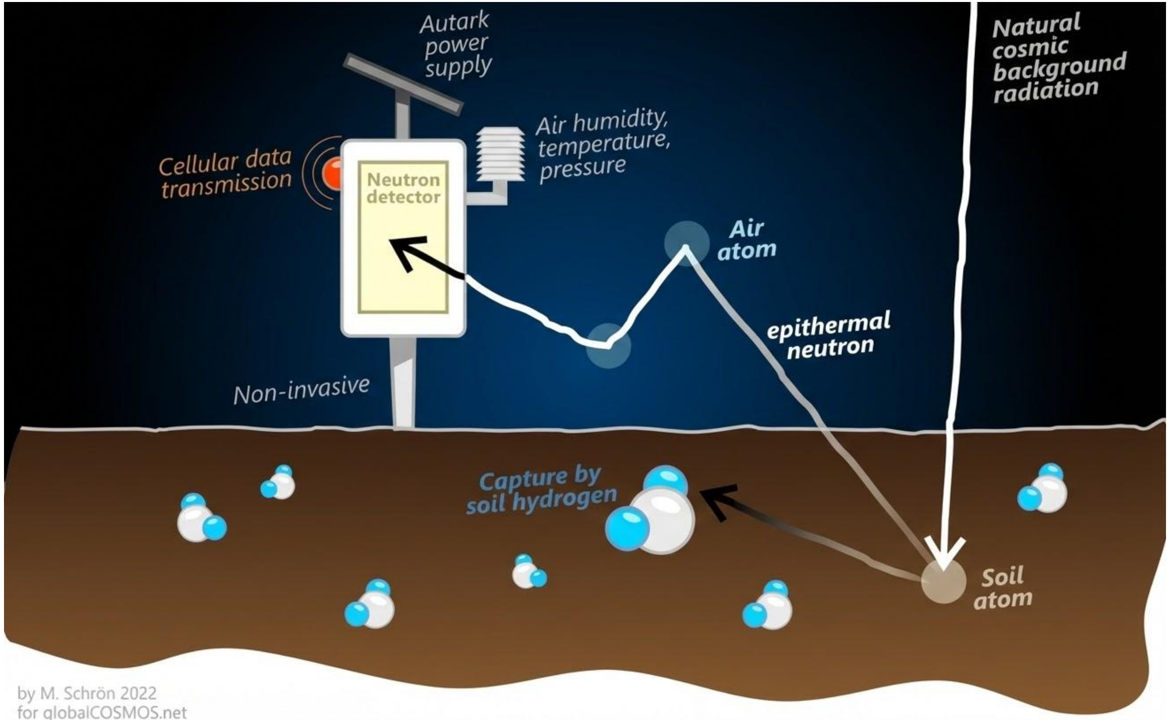
Neutrones < 20 MeV son fuertemente moderados por hidrógeno

Tipo de suelo: absorbedores de neutrones térmicos -> salares (^{6}Li, ^{10}B)



doi: 10.5194/gmd-16-449-2023

Pregunta central



¿Podemos usar la espectroscopía de neutrones secundarios para detectar y seguir cambios ambientales locales en escalas cortas de tiempo?

Source: https://www.neptoon.org/en/stable/home/crns-overview/

Neutron Spectrum Measurements: BS method, Unfolding

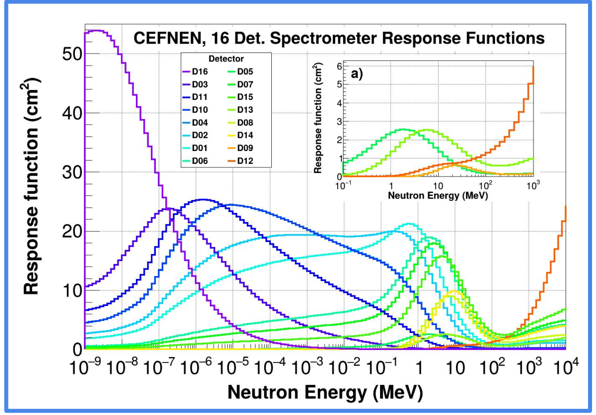
CEFNEN Spectrometer

How can we measure the neutron spectrum?

Sensitivity: meV ➡ GeV

Neutron counting rate

$$\boxed{n_i} = \int_0^\infty \boxed{R_i(E)}\boxed{\phi(E)}dE$$



- -16 moderator-detectors configurations.
- -^{3}He proportional counter, 4 atm, 33 cm long effective, 1” diameter
- -Boxes & cylindrical geometries.
- -Mod mat: HDPE, 5%B-HDPE, Graphite, Cd and Pb.
- -Sensitivity: meV to GeV.

DAQ

- -16 charge-sensitive preamps
- -SIS3316-125 STRUCK Digitizer
- -DAQ Software: GASIFIC (J.A IFIC-UV)

?

Inverse Problem

Effects (CR) → Cause (Neutron flux)

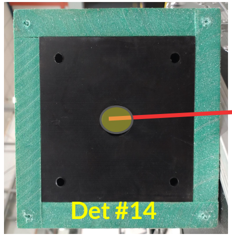
ML Expectation-Maximization (MLEM) unfolding algorithm

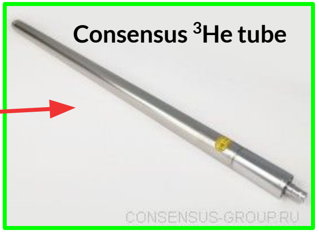
Input

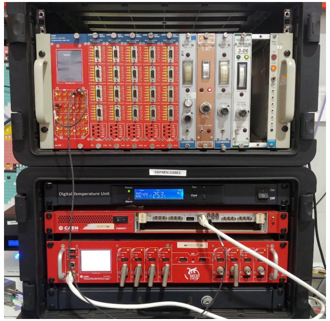
Initial Seed

$$\phi_j^{(s+1)} = \frac{1}{\sum_{i=1}^{N} R_{ij}} \sum_{i=1}^{N} \frac{R_{ij}\phi_j^{(s)} n_i}{\sum_{k=1}^{M} R_{ik}\phi_k^{(s)}\Delta E_k}$$

$$\Phi_j^{(s=0)}$$

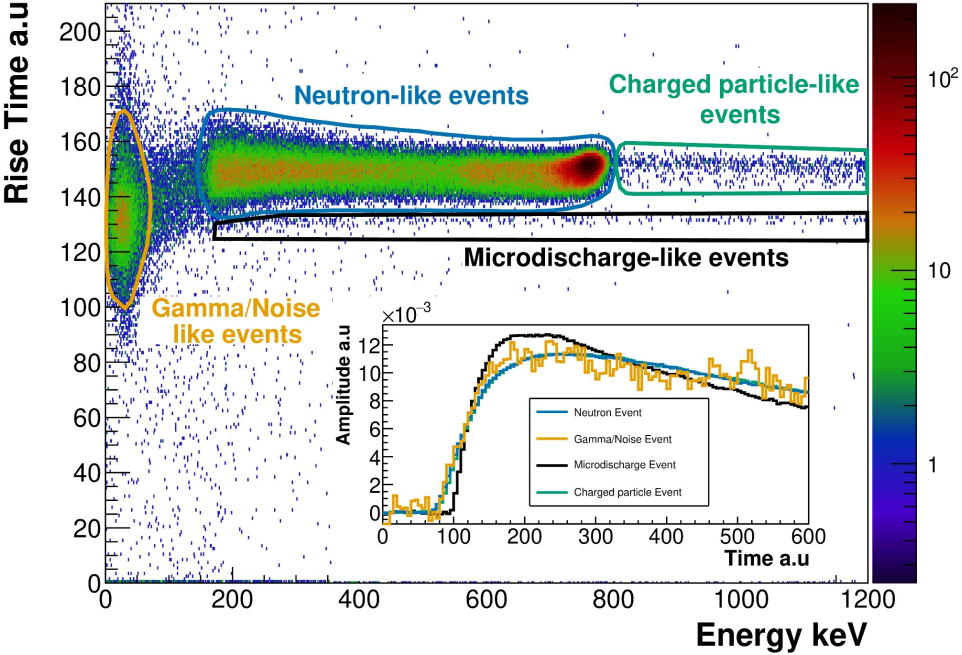


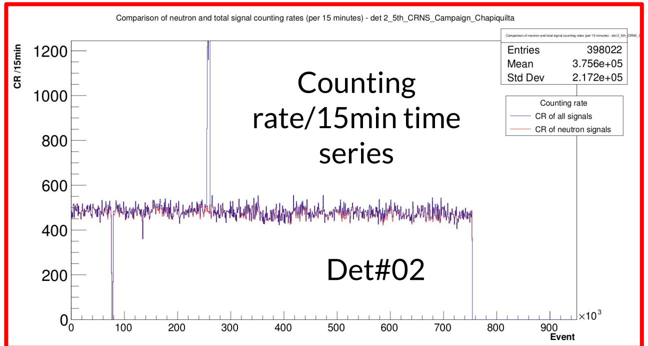


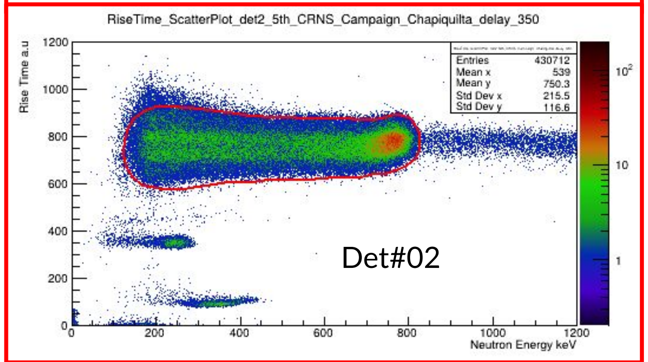


Data Analysis - Preprocessing

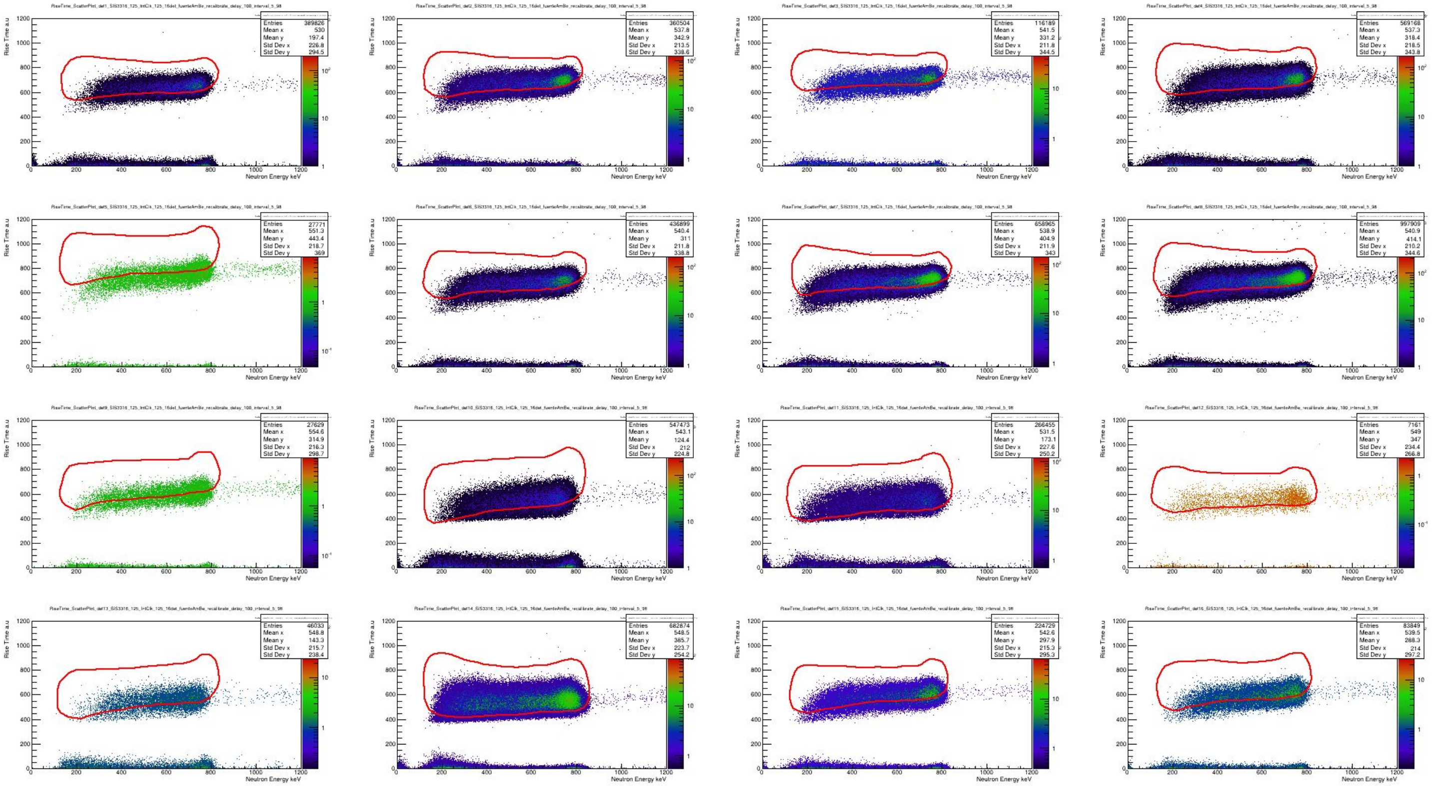
Digital Constant Fraction Discriminator (CFD) → **Filter out noise/others from neutron signals**







Variaciones del valor de delay - CFD



Neutron Spectra Unfolding

We have: Counting rates & response functions

Neutron Counting Rate

$$n_i = \int_0^\infty R_i(E)\phi(E)dE$$

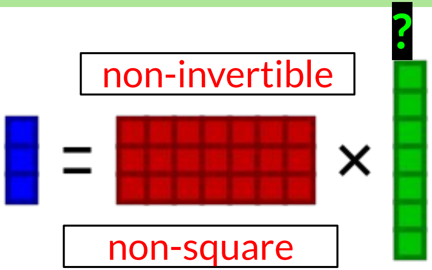
discretize

$$n_i = \sum_{j=1}^{M} R_{ij}\Phi_j$$

$$\begin{pmatrix} n_1 \\ \vdots \\ n_{16} \end{pmatrix}_{16\times1} = \begin{pmatrix} R_1(E_1) & \cdots & R_1(E_{150}) \\ \cdots & \cdots & \cdots \\ R_{16}(E_1) & \cdots & R_{16}(E_{150}) \end{pmatrix}_{16\times150} \times \begin{pmatrix} \Phi(E_1) \\ \vdots \\ \Phi(E_{150}) \end{pmatrix}_{150\times1}$$

- **Ideally, we want a solution that fits the data while remaining physically plausible.**

An underdetermined system: more unknowns than equations



Inverse Problem → Effects (CR) → Cause (Neutron flux)

Unfolding Algorithms

Table 1
Representative environmental BSS campaigns and analysis choices used to position this work.

Site	Coordinates	Altitude (m)	Detectors	Energy range (MeV)	Integration	Unfolding/uncertainty
Zugspitze [17]	47.4°N, 10.9°E	2963	14	10^{-9}–10^{3}	144 h[a]	SAND-II; no reported.
ER-2 aircraft [18,19]	19–56°N, 76–127°W	0–20.3 km	12–14	10^{-9}–10^{5}	8 min–168 h	MAXED; no reported.
PTB-NEMUS [20,21]	26–86°N, 147.8°W–127.0°E	75 m–12 km	16	10^{-9}–10^{4}	30 min–24 h	MAXED/GRAVEL; code-based.
USA [22]	29.7–44.3°N, 71.3–106.3°W	14–3450	14	10^{-9}–10^{4}	1–168 h[b]	MAXED; estimated from detector responses.
Koldewey & UFS [23–25]	78.9°N, 11.9°E/ 47.4°N, 11°E	0/2650	16	10^{-9}–10^{4}	6 h	MSANDB; iteration stability.
France-HERMEIS [26]	42.9–43.9°N, 5.5°–0.1°E	518–2885	12	10^{-8}–10^{4}	30 min–24 h	GRAVEL; from fluence distributions.
Taiwan-BCS [27,28]	24.9°N, 121.3°E	224	16 cyl.	10^{-9}–10^{4}	24 h	MAXED; no reported
Beijing [29]	40.0°N, 116.3°E	64	13	10^{-9}–10^{4}	24 h	MAXED/GRAVEL; estimation
Testa Grigia [30]	45.9°N, 7.7°E	3480	8	10^{-9}–10^{4}	1–15 h	FRUIT; FRUIT-SGM propagation.
Jungfraujoch & UFS [31]	46.5°N, 8.0°E/ 47.4°N, 11°E	2650–3572	16–18	10^{-9}–10^{4}	1 h	MSANDB; from fluence distribution.
Spain-HENSA [32]	40–42°N, 0–0.5°W	0–2300	16 boxes	10^{-9}–10^{4}	30 min–24 h	MLEM/MAXED, GRAVEL/POU; MC-based.
LCO-CEFNEN (this work)	**29.0°S, 70.7°W**	**2320**	**11 boxes/5 cyl.**	10^{-9}–10^{4}	**15 min–1 h**	**MLEM + Bootstrap; parametric bootstrapping.**

[a] Detector times were selected to keep counting uncertainty below 2.5%.
[b] Until most detectors accumulated >10,000 neutron events.

Maximum Likelihood Expectation Maximization (MLEM)

Iterative algorithm for finding maximum likelihood solutions in problems that contain incomplete observations

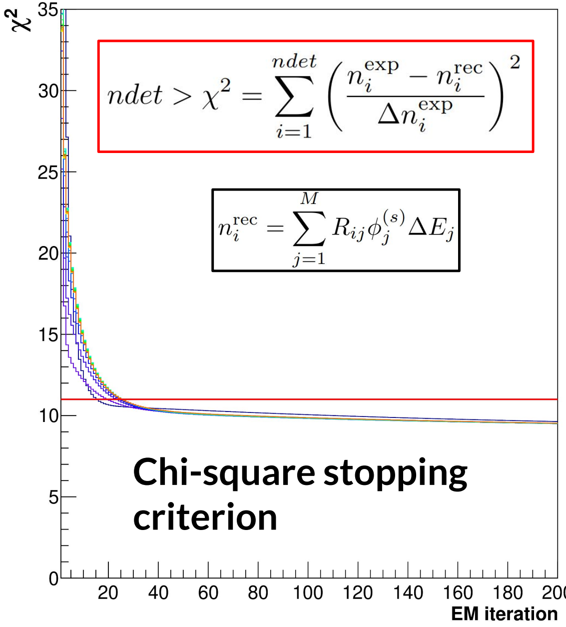
$$\phi_j^{(s+1)} = \frac{\phi_j^{(s)}}{\sum_{i=1}^{N} R_{ij}} \sum_{i=1}^{N} \frac{R_{ij} n_i}{\sum_{k=1}^{M} R_{ik} \phi_k^{(s)} \Delta E_k}$$

Any histogram that maximizes the log-likelihood of the unfolding problem is called a maximum likelihood estimator $\hat{\phi}_{ML}$ f ϕ

The ML estimate can always be found computationally by using the expectation-maximization (EM) algorithm (Dempster et al. (1977))

To avoid overfitting, we applied **regularization** techniques

Early stopping: stop when the output no longer improves



Maximum Likelihood Expectation Maximization (MLEM)

$$\phi_j^{(s+1)} = \frac{\phi_j^{(s)}}{\sum_{i=1}^{N} R_{ij}} \sum_{i=1}^{N} \frac{R_{ij} n_i}{\sum_{k=1}^{M} R_{ik} \phi_k^{(s)} \Delta E_k}$$

1) Chi-square stopping criterion

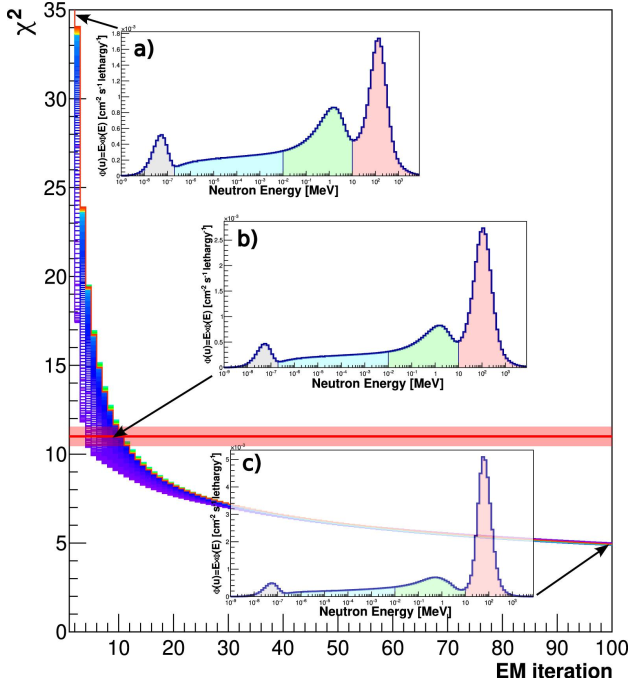
$$ndet > \chi^2 = \sum_{i=1}^{ndet} \left(\frac{n_i^{\exp} - n_i^{\mathrm{rec}}}{\Delta n_i^{\exp}} \right)^2$$

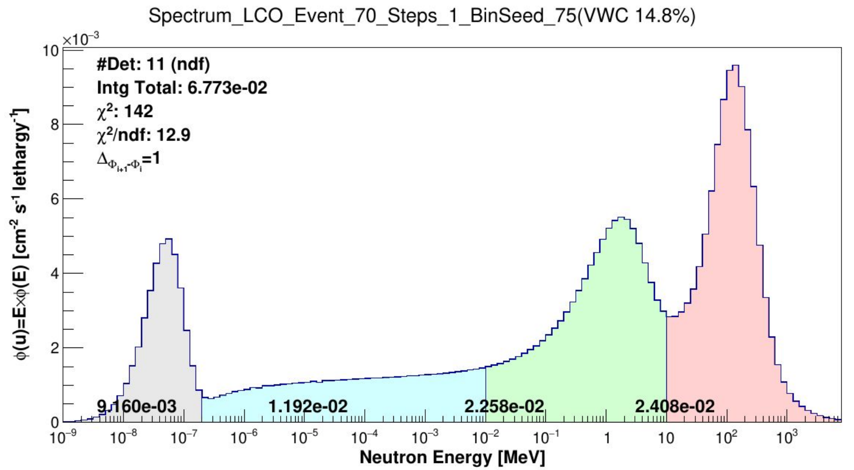
$$n_i^{\mathrm{rec}} = \sum_{j=1}^{M} R_{ij} \phi_j^{(s)} \Delta E_j$$

2) Diff stopping criterion

$$\Delta\Phi = \frac{\sum_{j=1}^{M=129} \left| \Phi_j^{(s+1)} - \Phi_j^{(s)} \right|}{\sum_{j=1}^{M=129} \Phi_j^{(s)}} < 0.02$$

3) #iterations (MLEM) < 20



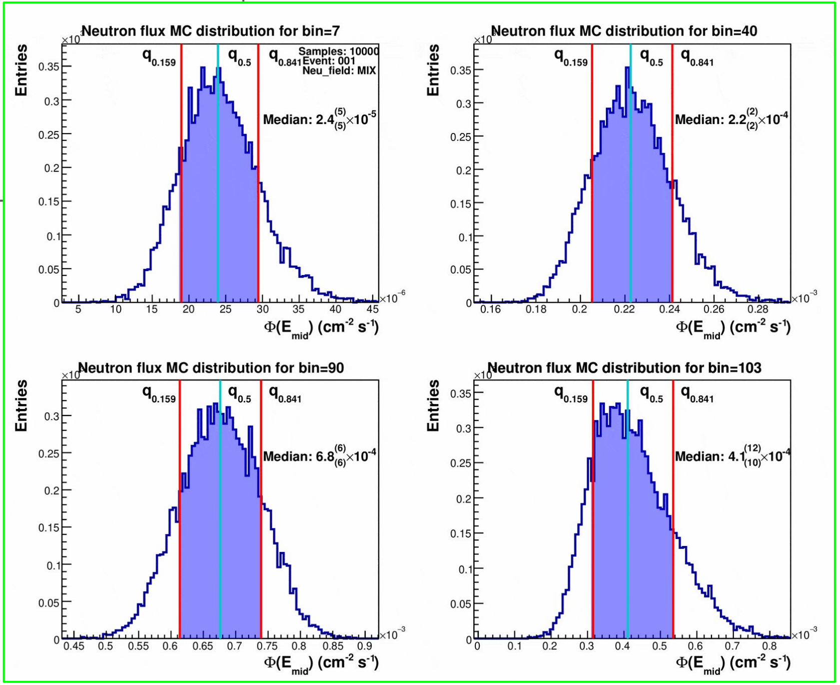


MLEM - Uncertainty Quantification with Bootstrap MC

- a) For each channel i, we obtain a resampled observation n_i^* by randomly sampling from a Gaussian distribution with mean $\mu = n_{i,\text{meas}}$ and standard deviation $\sigma = \sqrt{n_{i,\text{meas}}}$).

$$n_i^* = \mathcal{N}(\mu = n_{i,\text{meas}}, \sigma = \sqrt{n_{i,\text{meas}}})$$

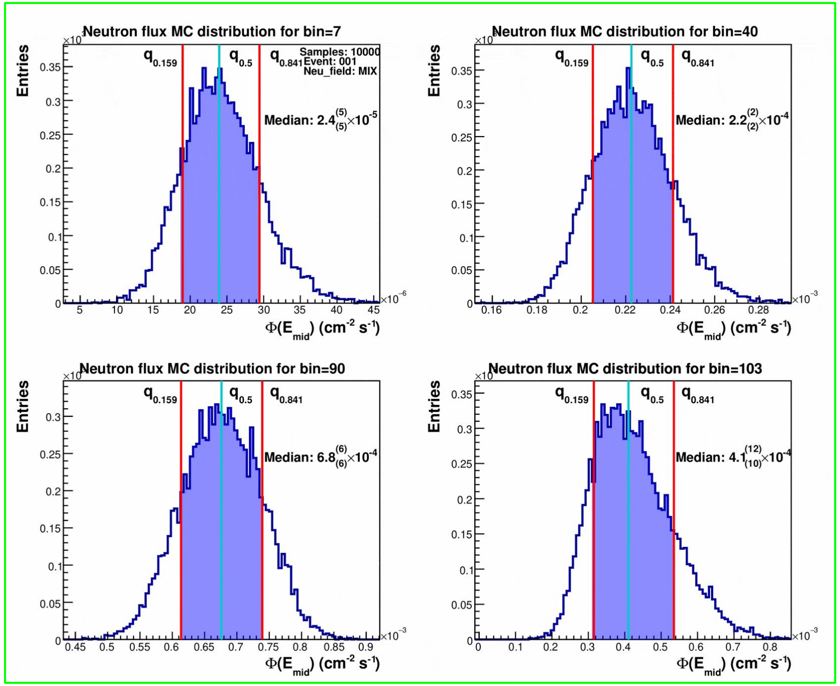
- b) Applied MLEM on $\boldsymbol{n}^* = (n_1^*, \ldots, n_d^*)$ to obtain $\hat{\Phi}^*$
- c) Repeat M times from a)



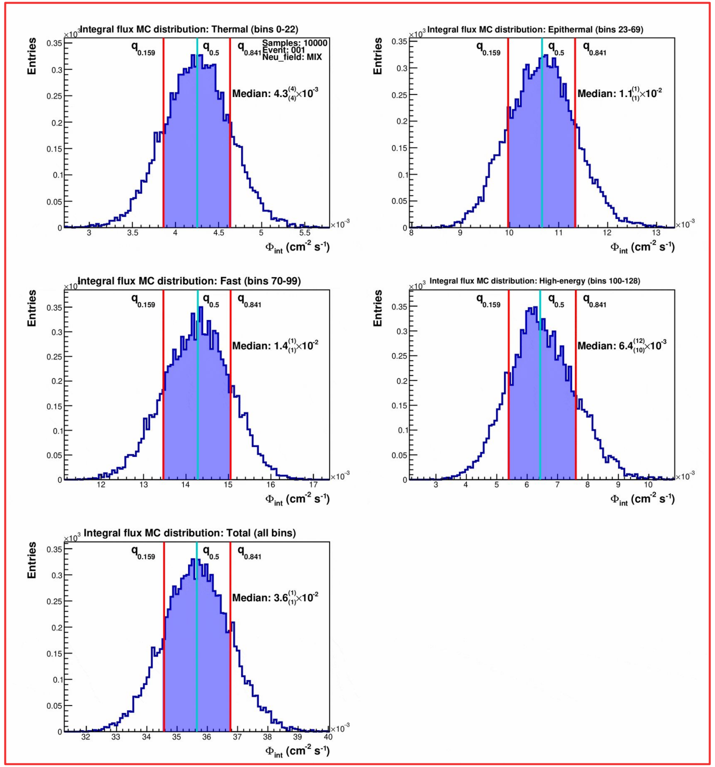
The bootstrap sample $\{\hat{\phi}^{*(1)}(E), ..., \hat{\phi}^{*(M)}(E)\}$ in each j energy group follows the sampling distribution of $\hat{\phi}_{ML}$ the true value of ϕ as the observed value of our estimator in each j energy group.

MLEM - Uncertainty Quantification with Bootstrap MC

By *j*-energy bin per event



By integral flux value per energy region per event



Algoritmo

Algorithm 1 Parametric Bootstrap MLEM Algorithm

Input: Neutron count measurement $\mathbf{n}_{\mathrm{i,exp}}$, EXPACS/PARMA neutron flux seed $\boldsymbol{\Phi}_{\mathrm{Expacs}}(\mathbf{E_j})$, Spectrometer response function matrix $(\mathbf{R})_{\mathrm{i\times j}}$

Output: Estimated neutron flux and its uncertainties $\boldsymbol{\Phi}_{\mathrm{exp}}(\mathbf{E_j})^{+\Delta\boldsymbol{\Phi}(\mathbf{E_j})}_{-\Delta\boldsymbol{\Phi}(\mathbf{E_j})}$.

for *event* **in** total number of events **do**

    (1) Set MC parameters:

    • Total MC iterations $N = 2 \times 10^6$

    • Maximum accepted MC iterations $= 1 \times 10^4$

    (2) Set MLEM stopping criteria parameters:

    • Number of detectors: D

    • $\Delta_{\Phi}^{\max} = 0.02$

    • $\mathrm{MLME}_{it}^{\max} = 21$

    (3) Read the ICRP116 binning (energies, widths) and the EXPACS/PARMA flux seeds for the current location.

    for $k = 1$ **to** N **do**

        (4) Random generators:

        • Randomly select a neutron flux seed vector $\Phi_{\mathrm{seed}}(E_j) \in \{S_{\mathrm{EXPACS/PARMA}}\}$.

        • Randomly select a neutron count value $n_{i,G}$ from a Gaussian distribution $G(n_{i,\mathrm{exp}}, \sqrt{n_{i,\mathrm{exp}}})$.

        while $(\chi^2)^{(s)} > D$ **OR** $\Delta_{\Phi}^{(s)} > \Delta_{\Phi}^{\max}$ **do**

            (5) Perform one iteration of MLEM unfolding.

            if $\mathrm{MLEM}_{it} \geq \mathrm{MLME}_{it}^{\max}$ **then**

                break

            end if

        end while

        (6) Extract key values in last step s: $\mathrm{MLEM}_{it} = s$, $(\chi^2)^{(s)}$, $\Delta_{\Phi}^{(s)}$.

        if $\mathrm{MLEM}_{it} \leq \mathrm{MLME}_{it}^{\max}$ **AND** $(\chi^2)^{(s)} < D$ **AND** $\Delta_{\Phi}^{(s)} < \Delta_{\Phi}^{\max}$ **then**

            (7) Accept the result and save the $\boldsymbol{\Phi}(\mathbf{E_j})$ vector

        else

            Reject the result

        end if

        Keep track of accepted vs. rejected events, update progress

    end for

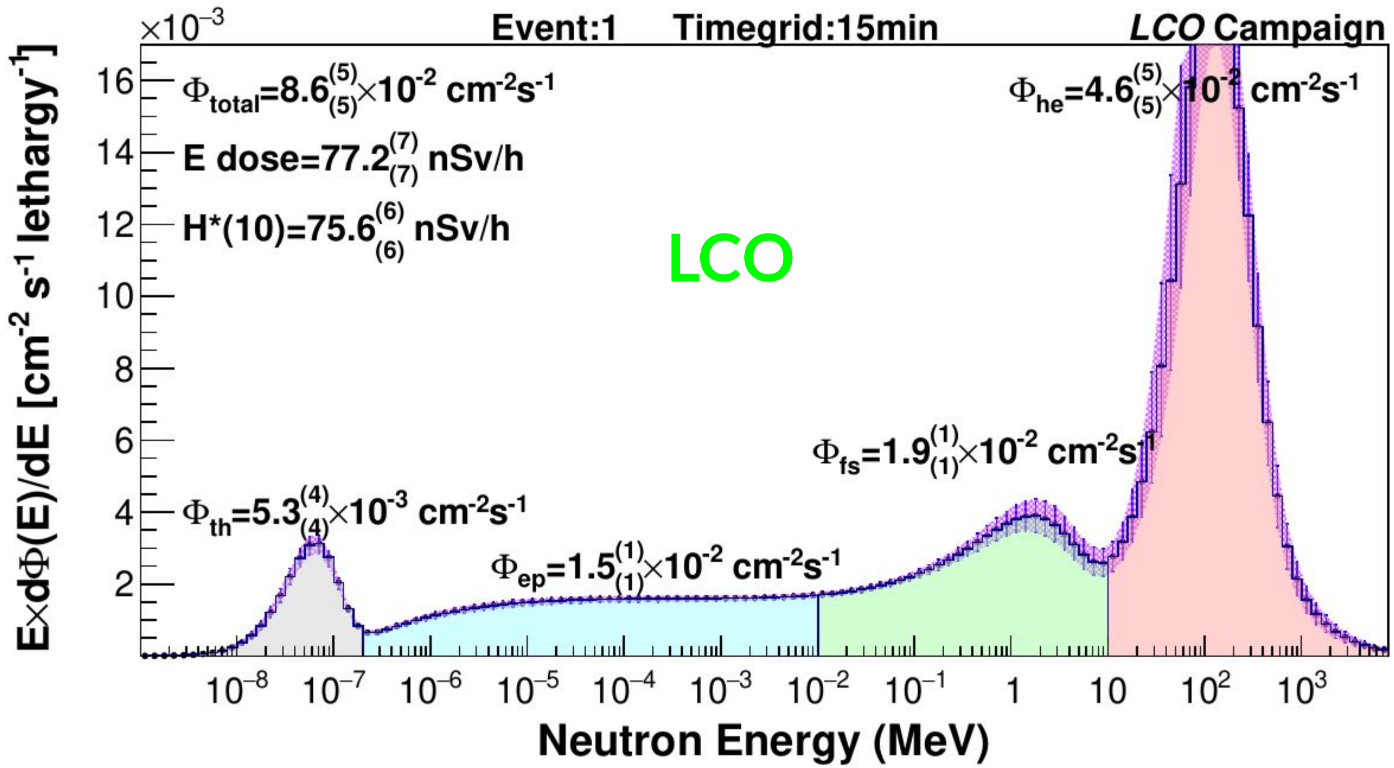
    Store accepted results and print final statistics (accepted vs. rejected), runtime, etc.

end for

(8) From the distribution of $\{\boldsymbol{\Phi}(\mathbf{E_j})\}$ produced by the Bootstrap MLEM process for each event, calculate the median (50th percentile) along with the 15.865th and 84.135th percentiles in order to obtain the flux estimate and its confidence interval. Apply the same procedure to the integral-flux distributions and to the ambient dose equivalent.

• $\Phi_{\mathrm{exp}}(E_j) \approx \mathrm{median} = q_{0.5}$, • $-\Delta\Phi(E_j) = \mathrm{median} - q_{0.15865}$, • $+\Delta\Phi(E_j) = q_{0.84135} - \mathrm{median}$

Neutron flux energy distribution @LCO



Chile como laboratorio natural

Exponer al espectrómetro de neutrones a distintos niveles de: humedad/tipos de suelo, humedad del aire, lluvia y eventos de nieve.

CHILE

Lat: -17

Lat: -56

Estación Meteorológica Portatil RAWS-F (Campbell)

Fusión de datos

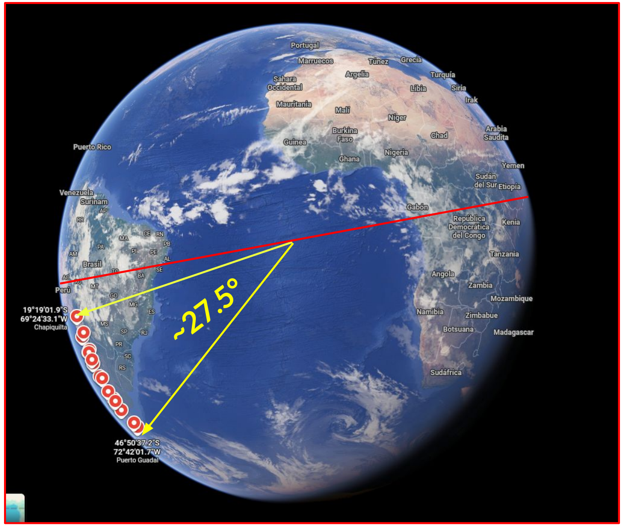
Análisis de correlaciones

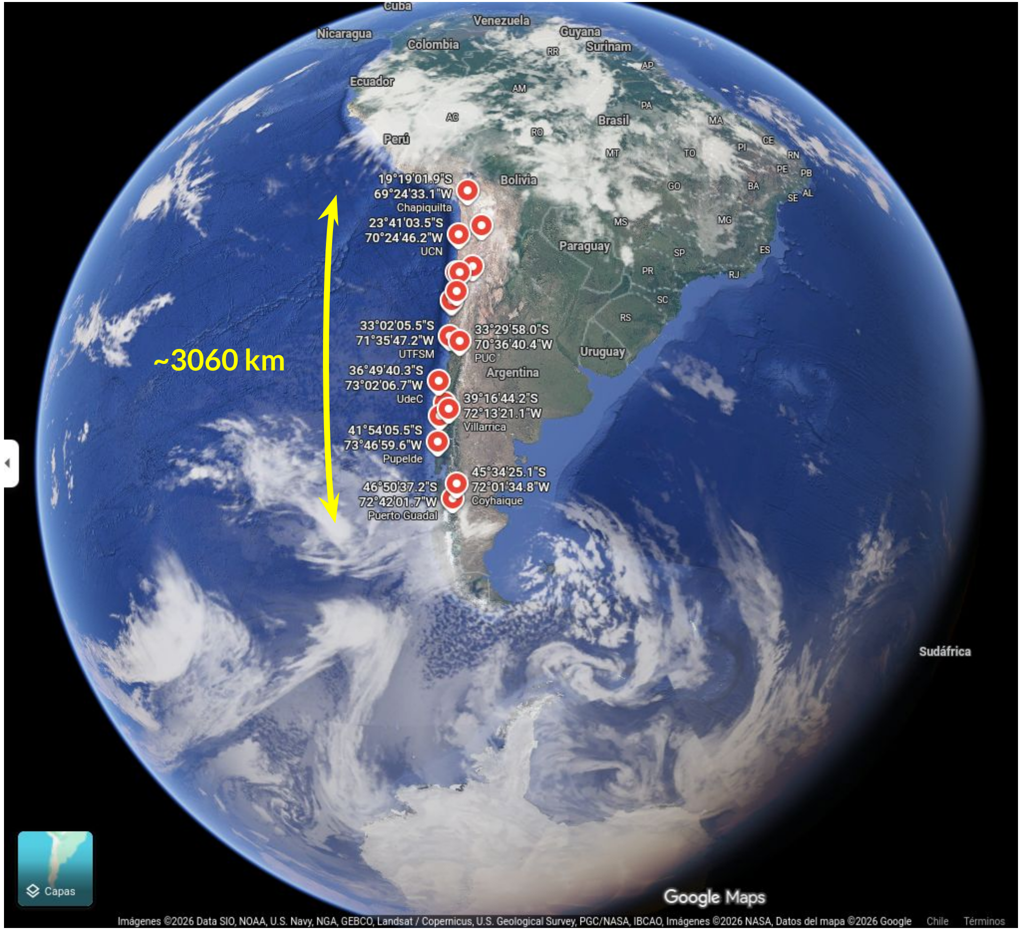
-Humedad del suelo
-Humedad relativa del aire
-Temperatura del aire
-Acumulación de lluvia
-Composición del suelo

Campañas Experimentales

CHILE

-6 Camp. Exp (2022-2025):
-18 locaciones: gran altura, nivel del mar, desiertos, salares, bosques, orilla de lagos, zonas urbanas, quebradas
-Distancia recorrida: > 3,000 km



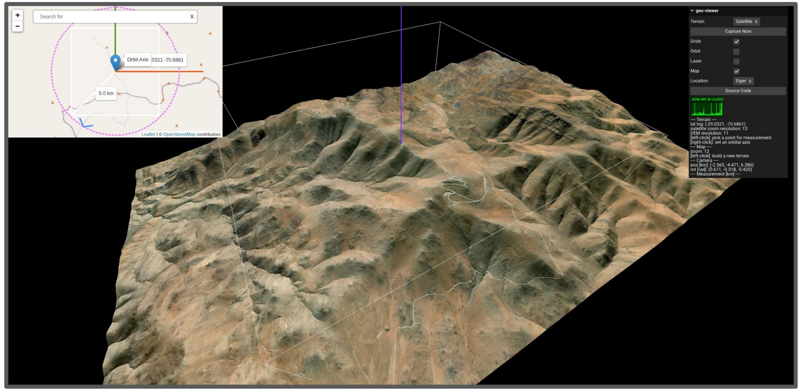


Campañas Experimentales

Caso de estudio: Observatorio Las Campanas

Measurement parameters for the LCO campaign.

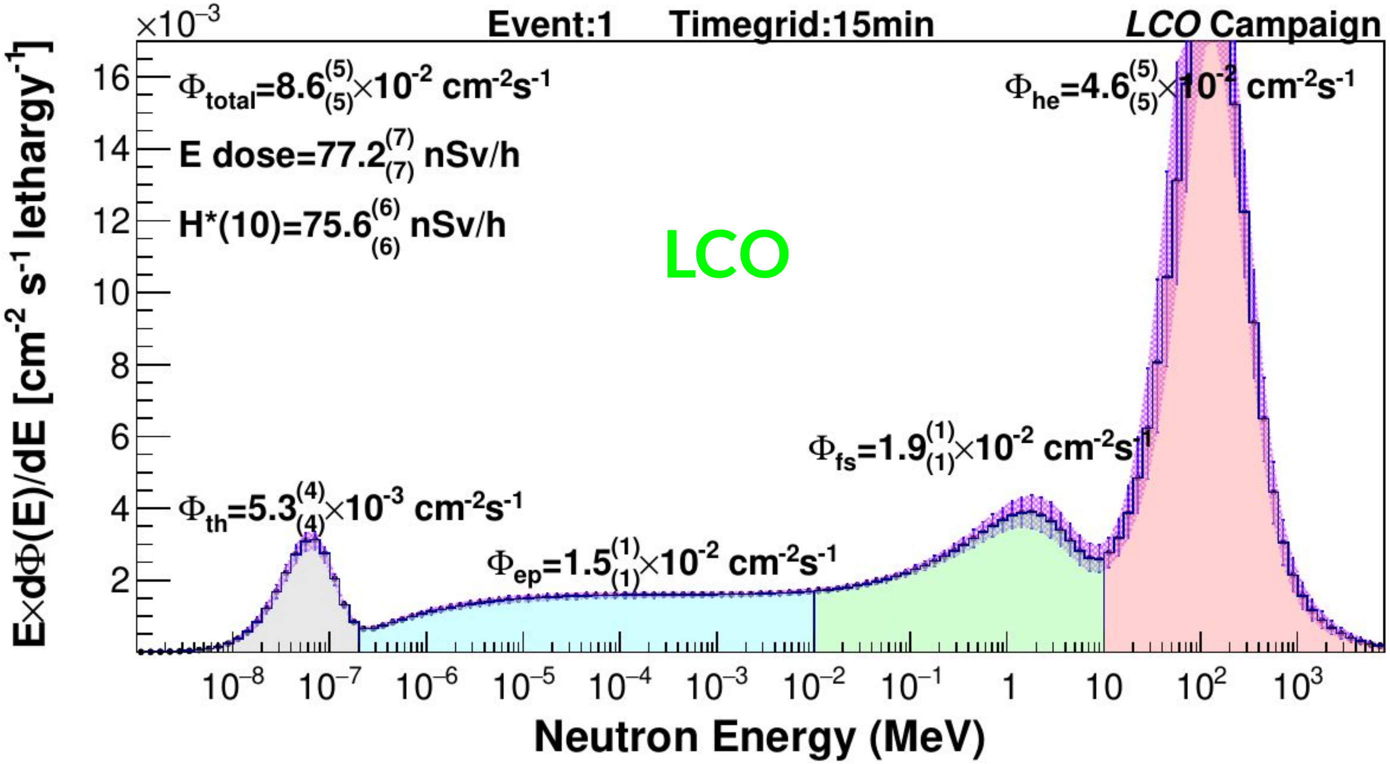
Location	Lat.	Long.	Altitude (m)	Duration (h)	Dates (UTC)
Las Campanas (LCO)	−29.0	−70.7	2319	72.4	2023-07-10 to 13



Source: https://github.com/w3reality/three-geo

-Locación a gran altitud
-Suelo seco y rocoso
-Lluvia y caída de nieve

¿Qué le pasa al espectro cuando cambia el ambiente local?



¿Qué le pasa al espectro cuando cambia el ambiente local?

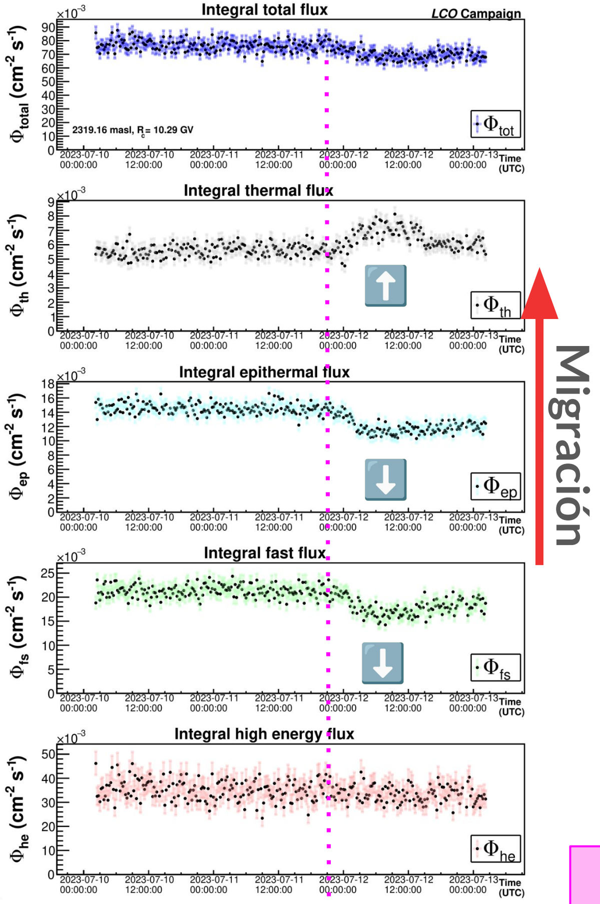
$\boxed{\Phi_{total}}$ Total

$\boxed{\Phi_{th}}$ Thermal

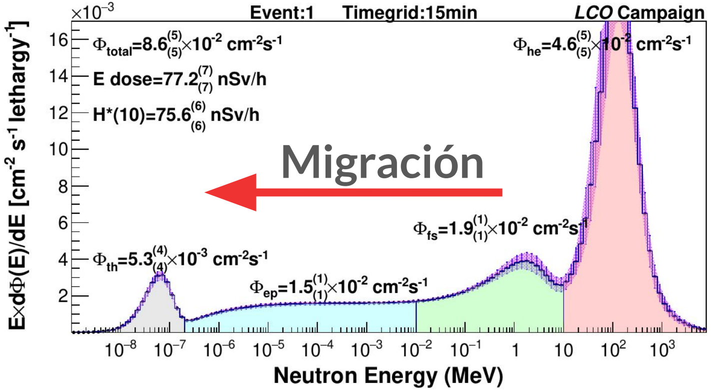
$\boxed{\Phi_{ep}}$ Epithermal

$\boxed{\Phi_{fs}}$ Fast

$\boxed{\Phi_{he}}$ High energy



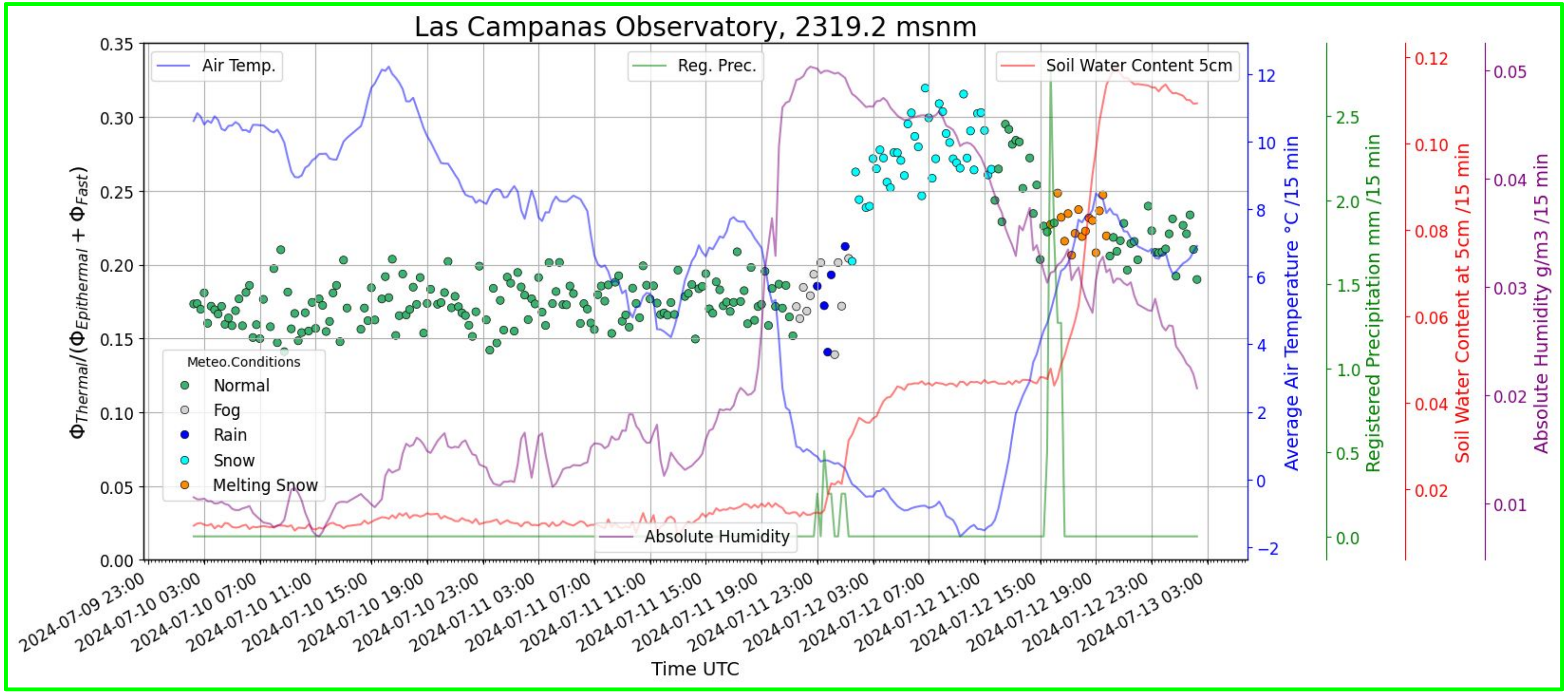
Inicio: Lluvia & nevazón



⬆️ Flujo neutrones térmicos

⬇️ Flujo de neutrones epitermicos y rápidos

Un observable robusto: $\mathcal{R}(t) \equiv \frac{\Phi_{\rm th}}{\Phi_{\rm ep} + \Phi_{\rm fs}}$



Notion

Notion

https://brawny-burst-06f.notion.site/Taller_notion-3ae869bc25a
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