REPÚBLICA BOLIVARIANA DE VENEZUELA | Ministerio del Poder Popular para CIENCIA Y TECNOLOGÍA

CIDATA

LAGO

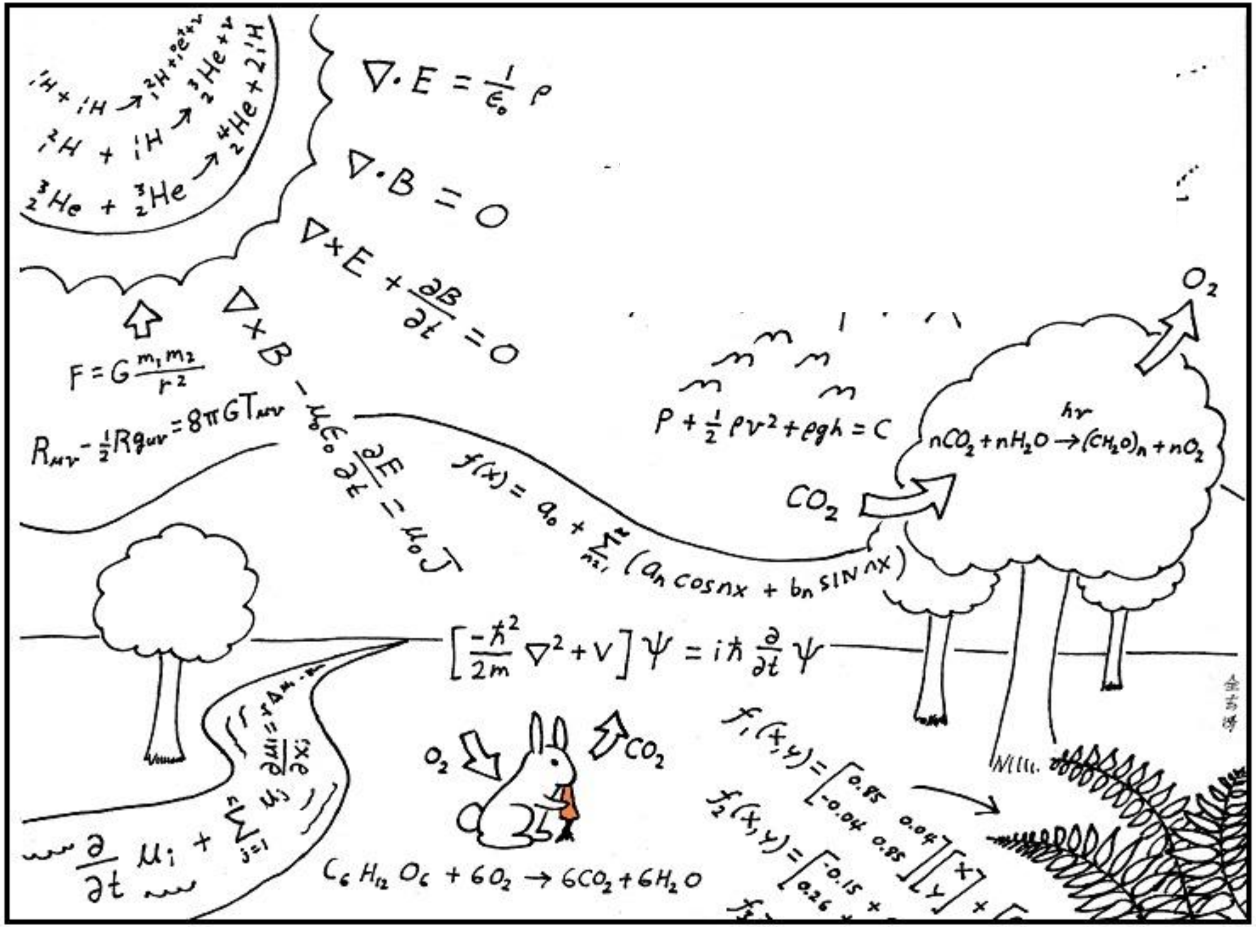
Introducción a los detectores Cherenkov de LAGO

Luis Otiniano
Comisión Nacional de Investigación y Desarrollo Aeroespacial

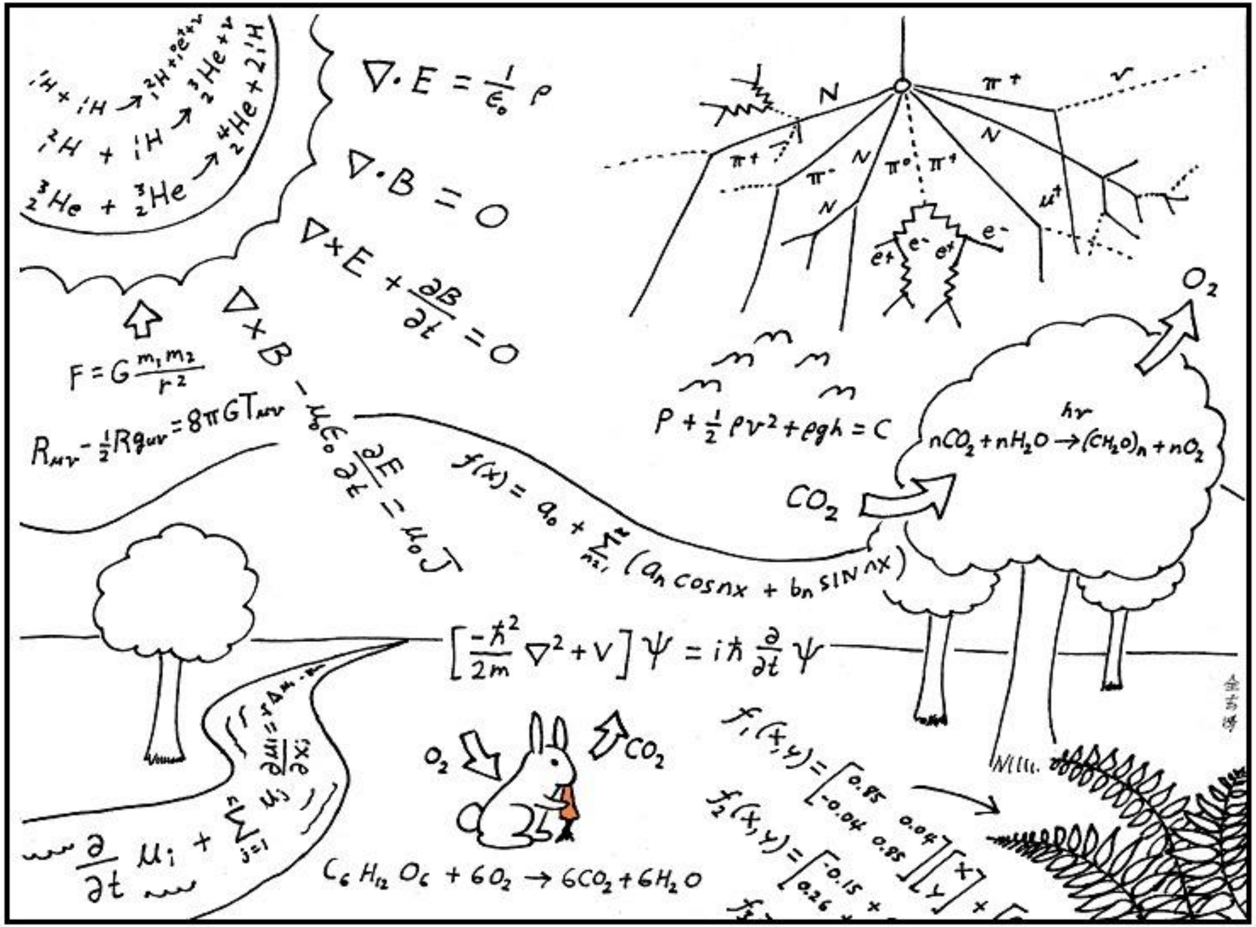
"Encuentro LAGO Venezuela, edición Mérida 2026"

CYTED
PROGRAMA IBEROAMERICANO DE CIENCIA Y TECNOLOGÍA PARA EL DESARROLLO

AGENCIA ESPACIAL DEL PERU
CONIDA



$^1_1H + ^1_1H \to ^2_1H + ^0_{+1}e + \nu$
$^2_1H + ^1_1H \to ^3_2He + \gamma$
$^3_2He + ^3_2He \to ^4_2He + 2^1_1H$
$\nabla \cdot E = \frac{1}{\epsilon_0}\rho$
$\nabla \cdot B = 0$
$\nabla \times E + \frac{\partial B}{\partial t} = 0$
$\nabla \times B - \mu_0\epsilon_0\frac{\partial E}{\partial t} = \mu_0 J$
$F = G\frac{m_1 m_2}{r^2}$
$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = 8\pi G T_{\mu\nu}$
$f(x) = a_0 + \sum_{n=1}^{\infty}(a_n \cos nx + b_n \sin nx)$
$P + \frac{1}{2}\rho v^2 + \rho g h = C$
O_2
$nCO_2 + nH_2O \xrightarrow{h\nu} (CH_2O)_n + nO_2$
CO_2
$\left[\frac{-\hbar^2}{2m}\nabla^2 + V\right]\psi = i\hbar\frac{\partial}{\partial t}\psi$
O_2
CO_2
$\frac{\partial}{\partial t}u_i + \sum_{j=1}^{n} u_j \frac{\partial u_i}{\partial x_j} = \nu\Delta u_i$
$C_6H_{12}O_6 + 6O_2 \to 6CO_2 + 6H_2O$
$f_1(x,y) = \begin{bmatrix}0.85 & 0.04\\ -0.04 & 0.85\end{bmatrix}\begin{bmatrix}x\\ y\end{bmatrix} +$
$f_2(x,y) = \begin{bmatrix}-0.15 \\ 0.26\end{bmatrix}$



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N
π^+
π^-
π^0
ν
μ^+
e^-
e^+
$P + \frac{1}{2}\rho v^2 + \rho g h = C$
O_2
$nCO_2 + nH_2O \xrightarrow{h\nu} (CH_2O)_n + nO_2$
CO_2
$\left[\frac{-\hbar^2}{2m}\nabla^2 + V\right]\psi = i\hbar\frac{\partial}{\partial t}\psi$
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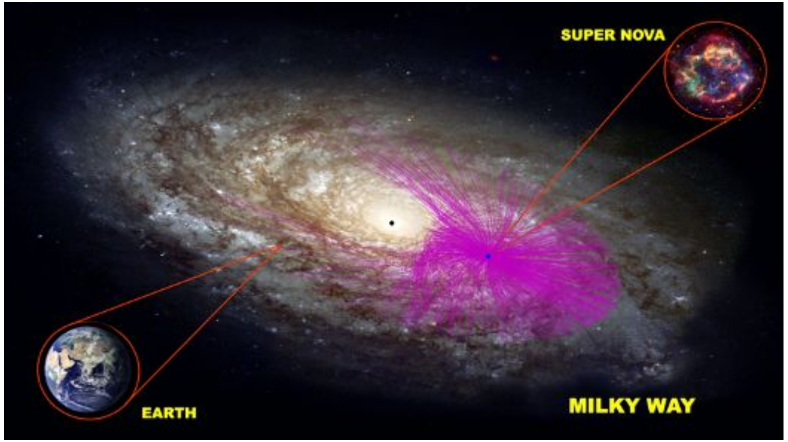
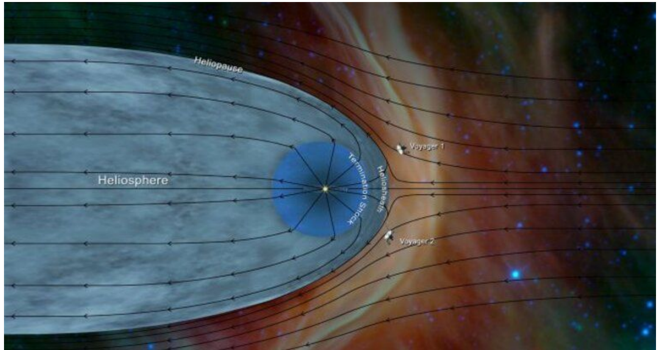
$f_1(x,y) = \begin{bmatrix}0.85 & 0.04\\ -0.04 & 0.85\end{bmatrix}\begin{bmatrix}x\\ y\end{bmatrix} +$
$f_2(x,y) =$

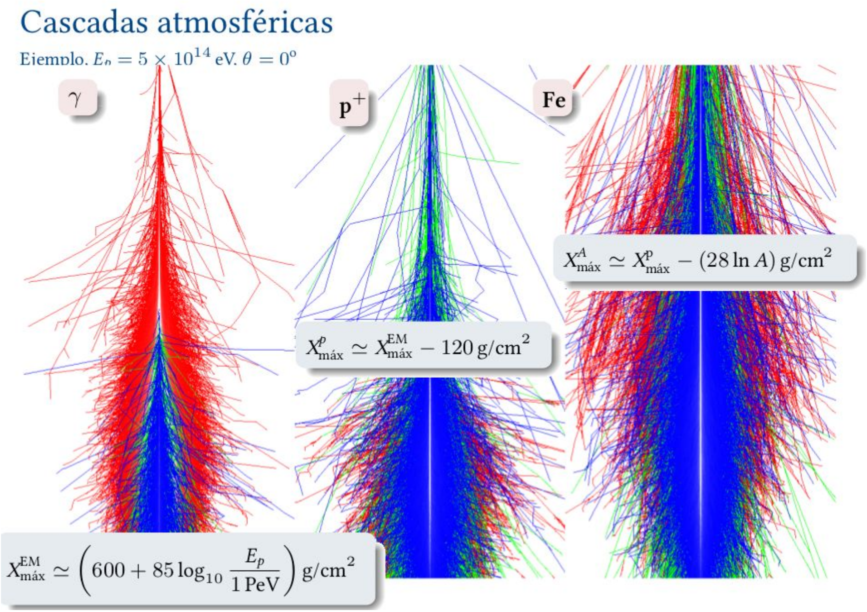
El Escenario

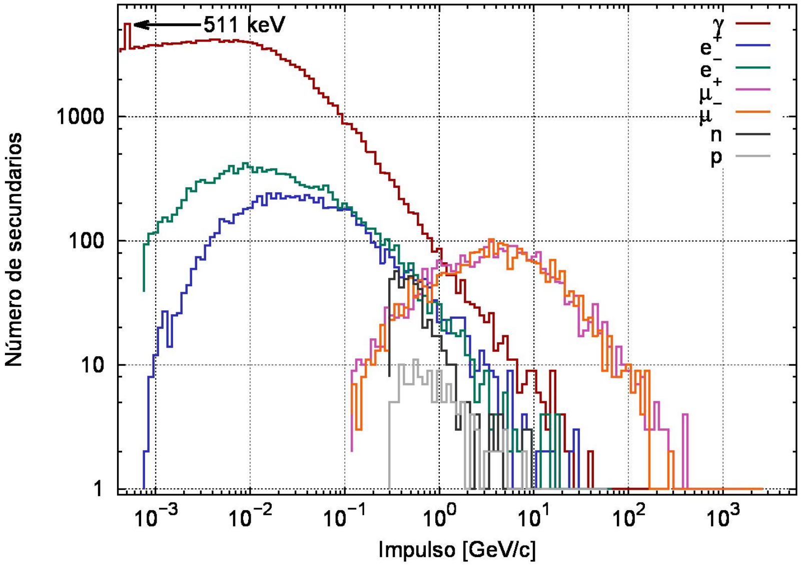


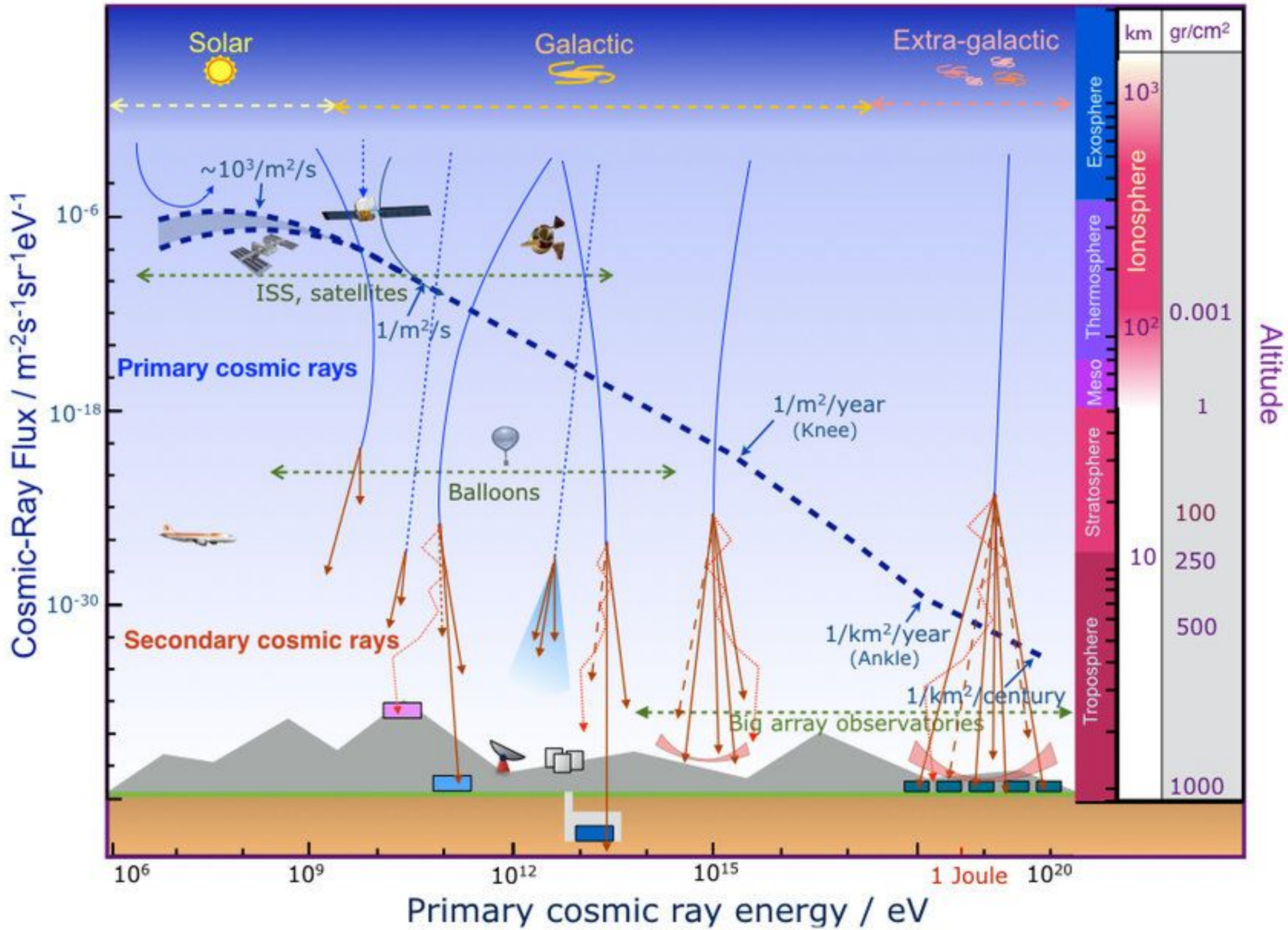


Un viaje que puede durar entre millones y miles de años.

El Escenario

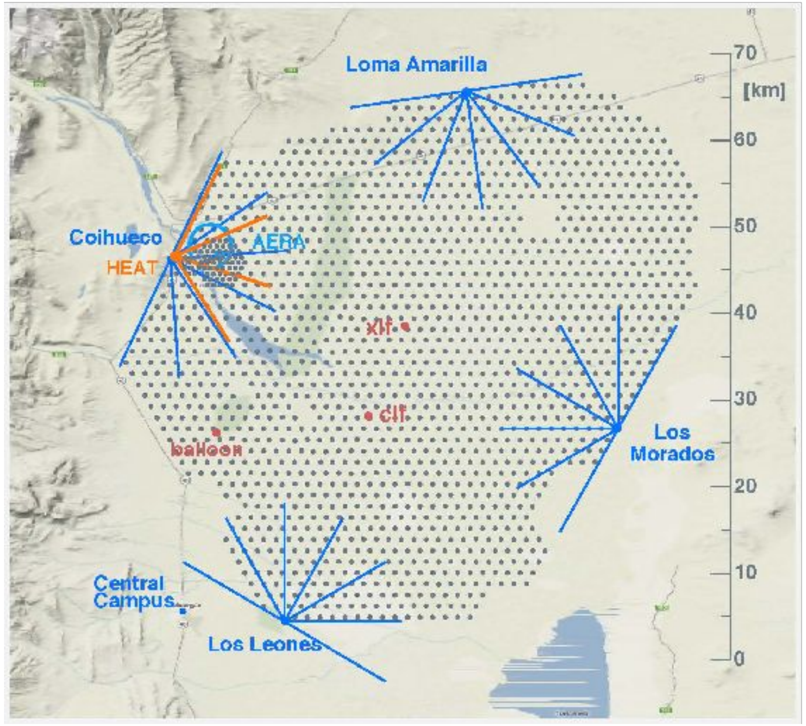


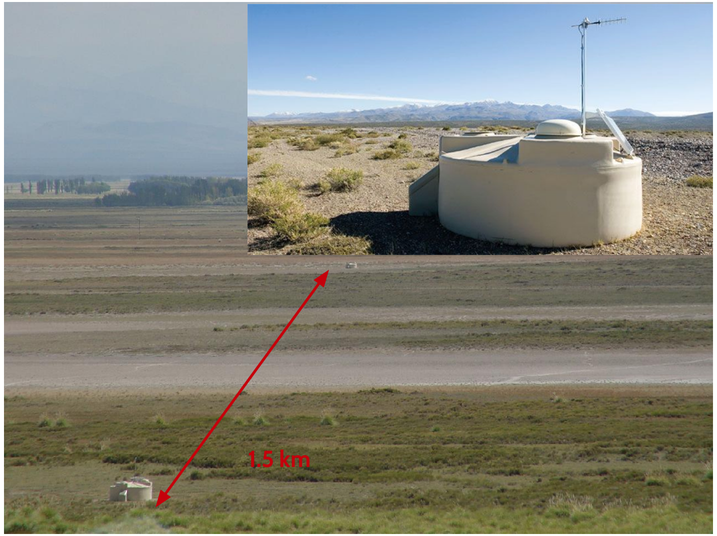


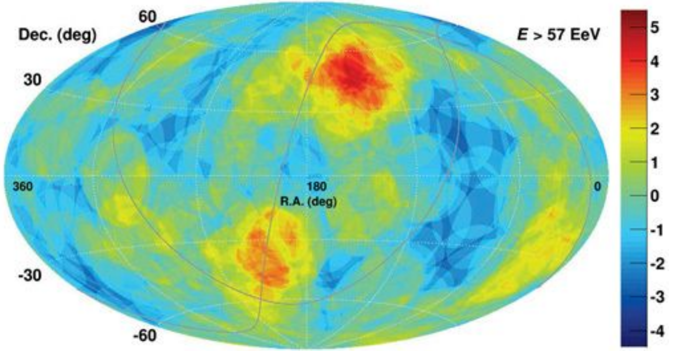


Solar
Galactic
Extra-galactic
~10³/m²/s
ISS, satellites
1/m²/s
Primary cosmic rays
1/m²/year
(Knee)
Balloons
Secondary cosmic rays
1/km²/year
(Ankle)
1/km²/century
Big array observatories
Cosmic-Ray Flux / m⁻²s⁻¹sr⁻¹eV⁻¹
10⁻⁶
10⁻¹⁸
10⁻³⁰
10⁶
10⁹
10¹²
10¹⁵
1 Joule
10²⁰
Primary cosmic ray energy / eV
Exosphere
Thermosphere
Meso
Stratosphere
Troposphere
Ionosphere
km
gr/cm²
10³
10²
10
0.001
1
100
250
500
1000
Altitude

El Observatorio Pierre Auger



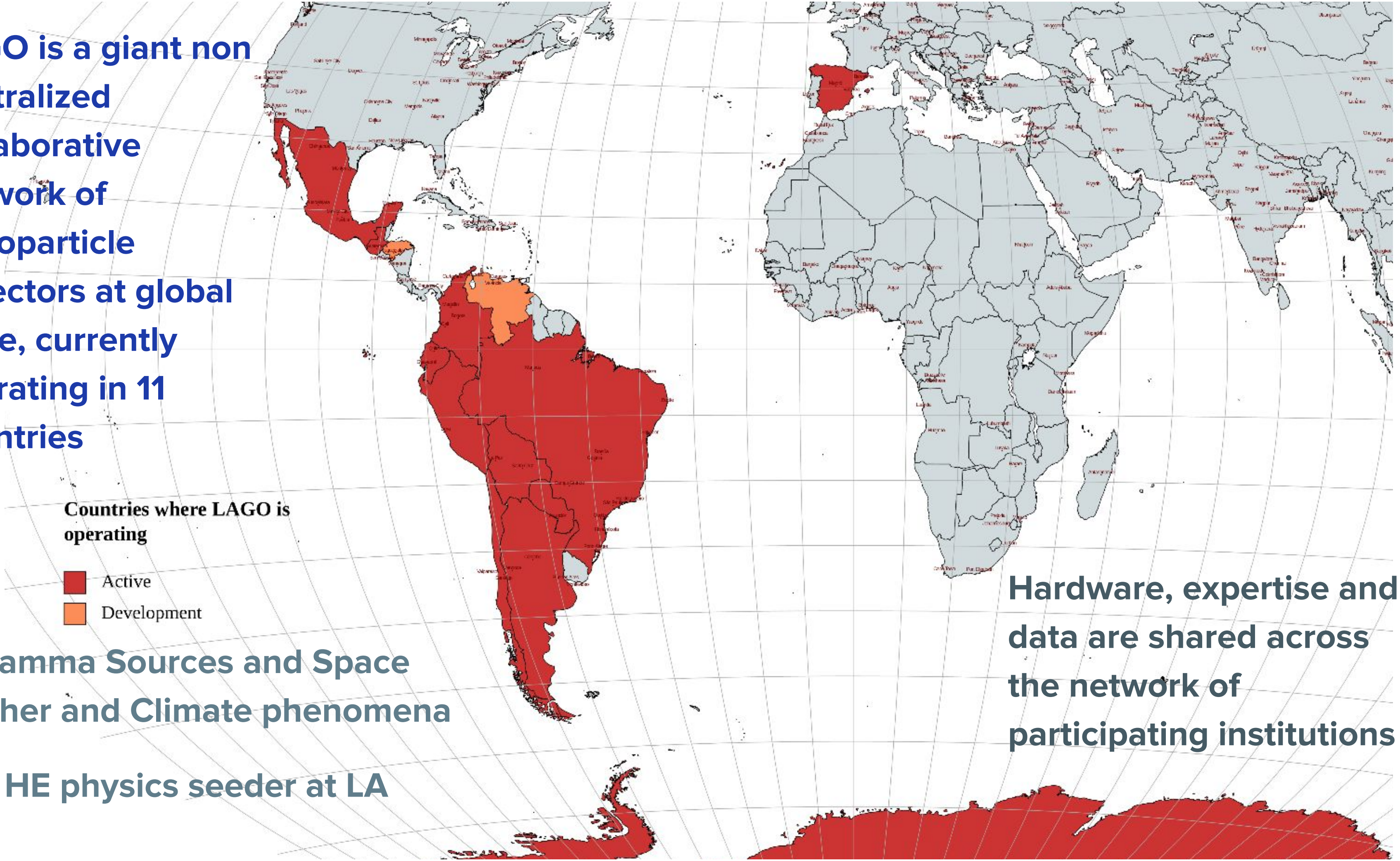




~ (50x60) km = 3000 km^2 instrumented area
1660 Water Cherenkov detectors (16600 m^2 detection area)
27 Fluorescence telescopes surounding the array

LAGO: Observatorio Gigante Latinoamericano

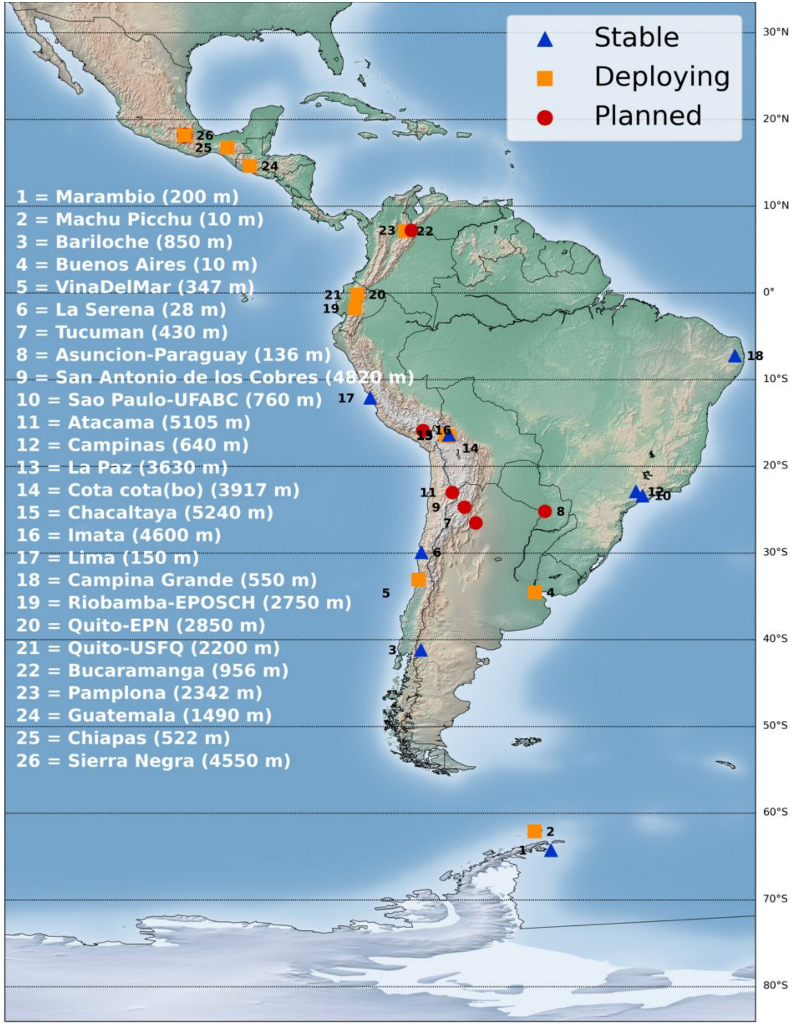
LAGO is a giant non centralized collaborative network of astroparticle detectors at global scale, currently operating in 11 countries



HE Gamma Sources and Space Weather and Climate phenomena

AP & HE physics seeder at LA

Hardware, expertise and data are shared across the network of participating institutions



LAGO is an extended astroparticle observatory at continental scale: from México to Antarctica

- **Scientific goals**
  - **Astroparticle physics to study the extreme universe**
  - **Transient and long term space weather phenomena trough Solar modulation of Cosmic Rays**
  - **Measurement of background radiation at ground level**
- **Academic goals**
  - **Train Latin American students in High Energy and Astroparticle physics**
  - **Build a Latin American network of Astroparticle and Cosmic Rays researchers**

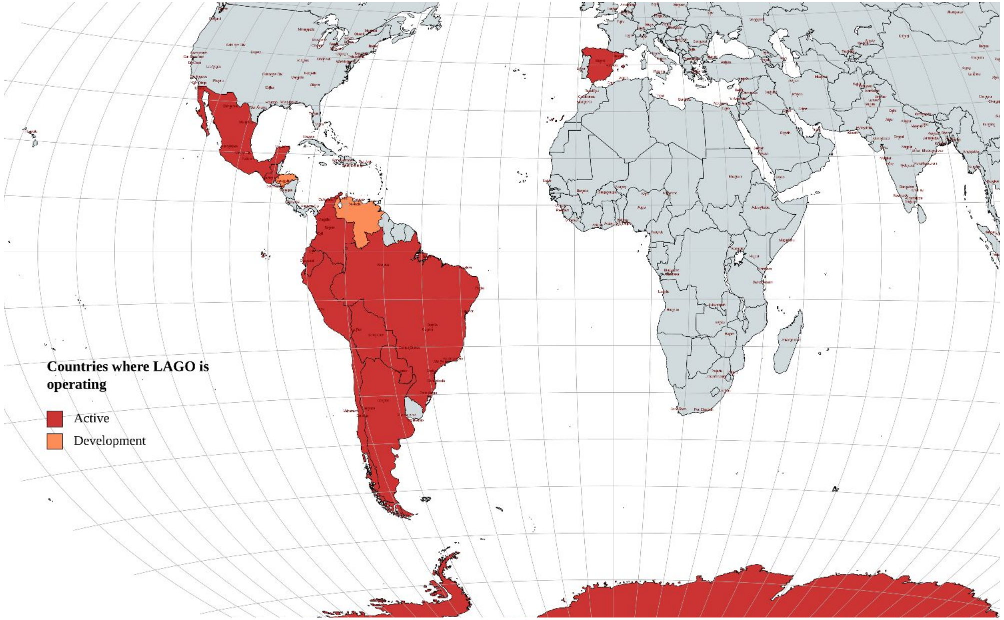
LAGO Virtual

Own designed hierarchical data analysis and virtualized docker-based tools

Measured: 2 TB/year-detector. 4 quality levels: L1: raw data, L2: preliminary, L3: Data Quality, L4: High Quality

Simulated: Up to 1 PB (estimated), EOSC-Synergy thematic service lead by CIEMAT: S0: raw data, S1: simulated and modulated particles at ground, S2: simulated signals at detector level.

Data is transferred to the central repository and is mirrored to several sites (+ each site has its own local data)



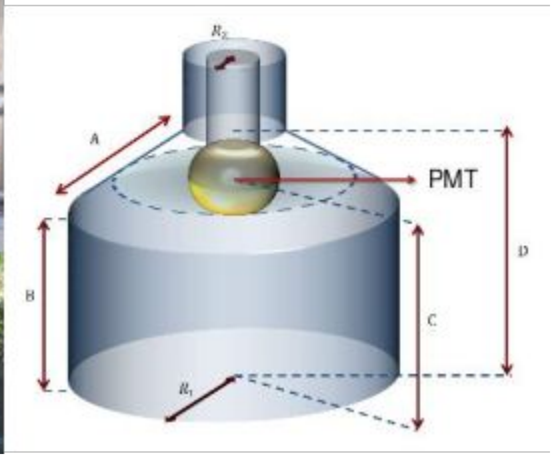
H. Asorey, Red Clara symposium, 2021

El Detector Cherenkov de Agua de LAGO

El detector de LAGO

Autonomous, reliable, simple, cheap and smart (based on SBC and COTS)

WCD with a single PMT (usually provided by LAGO in most of the participating countries)



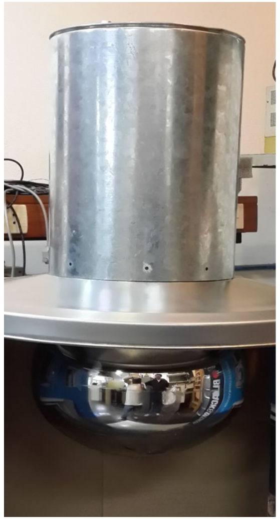
New own designed electronic based on SteamLab RedPitaya

H. Arnaldi et al, IEEE2020

SaaS (Sensors as a Service) Concept

H. Asorey et al, PoS(ICRC2015)

Diversidad de detectores de LAGO

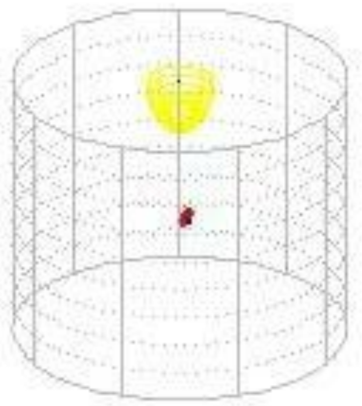


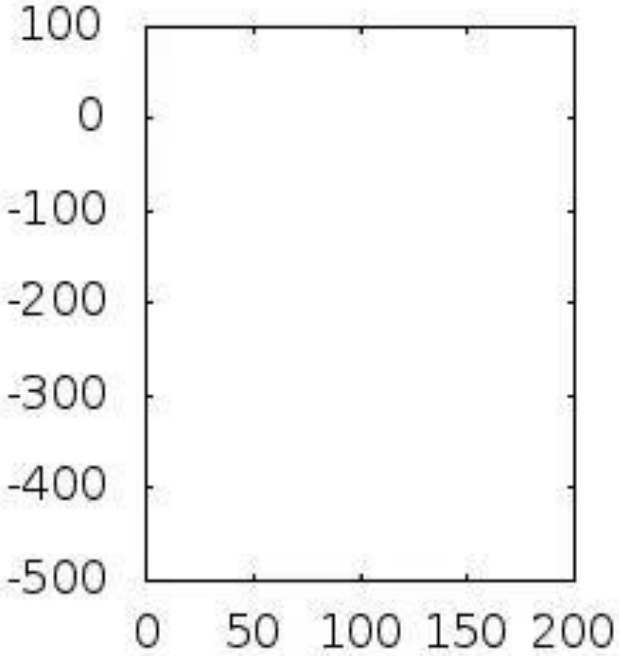
Clima Espacial en LAGO

LAGO studies Earth-Sun connection by measuring the time-evolving secondary signals from ground level. Atmospheric and geomagnetic conditions are continuously monitored

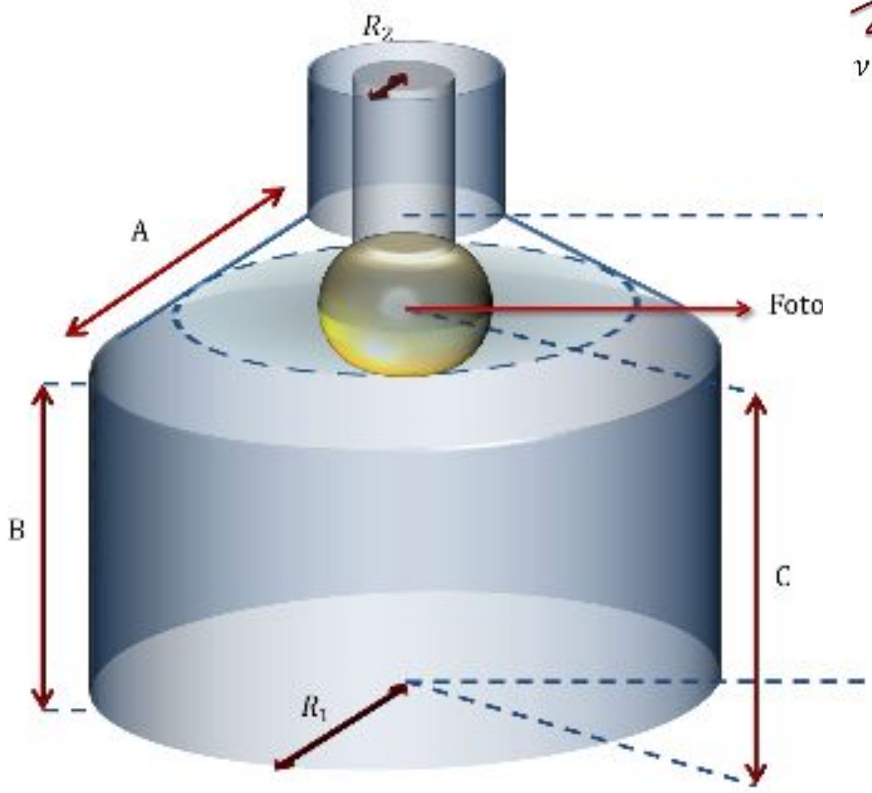
Antarctic dedicated SW sites

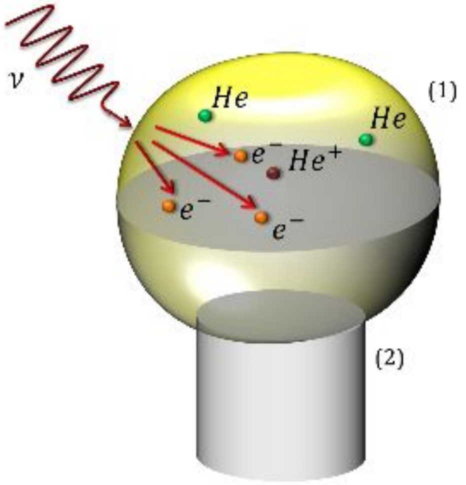
Una simulación de Detector Cherenkov de Agua

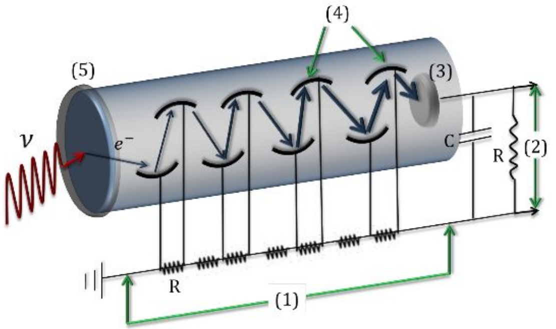




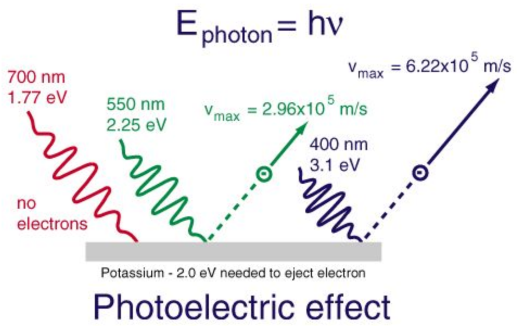
El detector Cherenkov de Agua

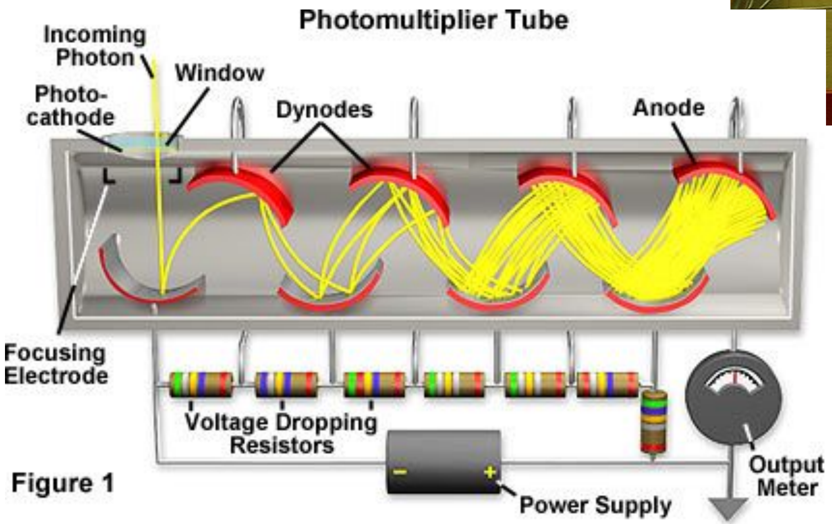






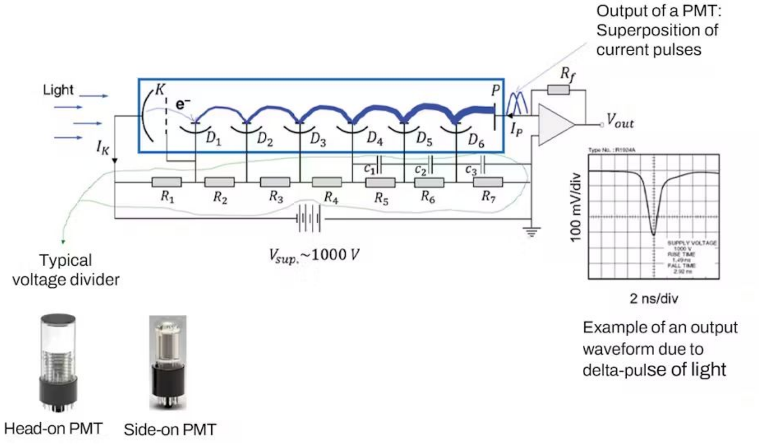
El tubo fotomultiplicador (PMT):

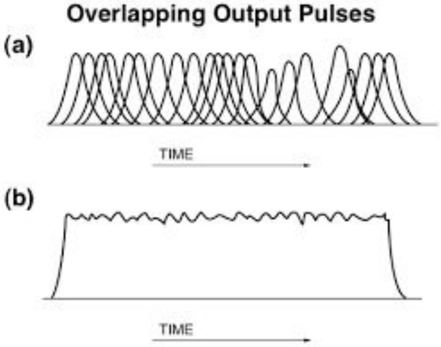


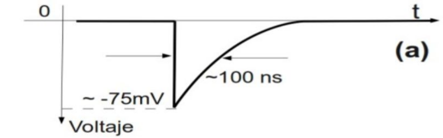


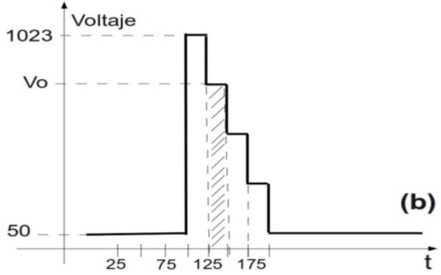
- Transductor: Fotón a una señal de corriente.
- Tubo al vacío.
- Material del fotocátodo: Bialkali.
- Acelera electrones a través de un efecto casada
- Típica corriente de salida del orden de uA

La señal del fotomultiplicador









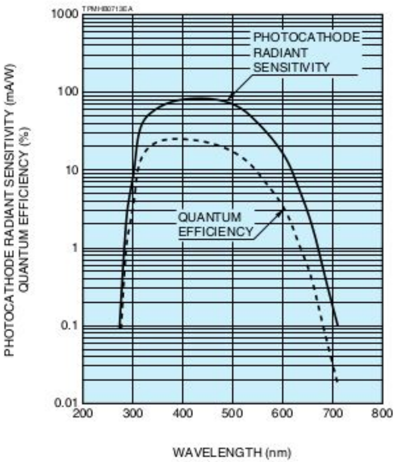
Área bajo la curva

Es proporcional al número de fotones

Hamamatsu R5912

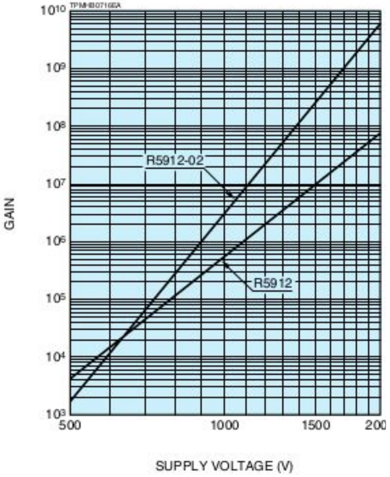
SPECTRAL RESPONSE C

●R5912, R5912-02
●R7081, R7081-20



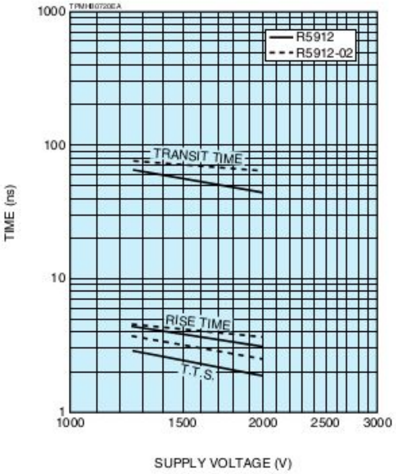
GAIN

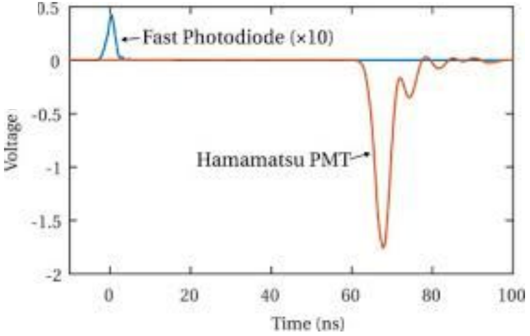
●R5912, R5912-02



TYPICAL TIME RESPONSE

●R5912, R5912-02

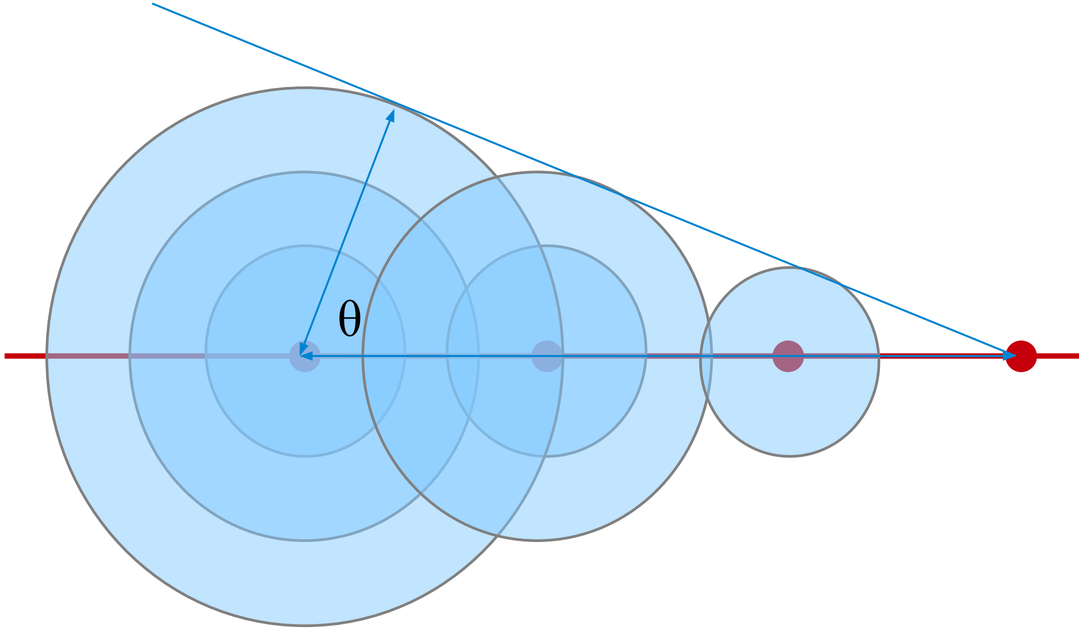


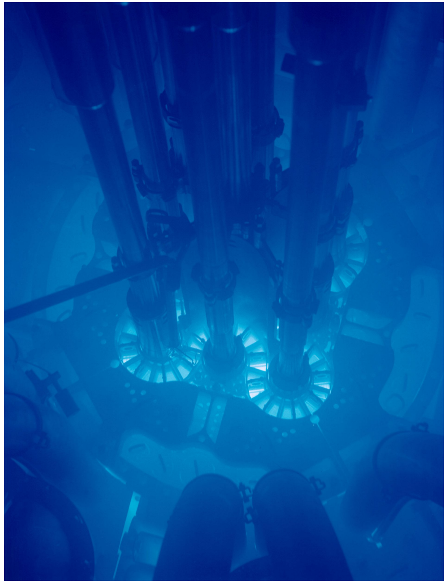


SPECIFICATIONS

Type No.	Diameter (mm) / (inch)	Minimum Effective Area (mm)	Surface Area Min. (cm²)	Surface Area Typ. (cm²)	Dynode Structure	Dynode Number of Stages	Weight (g)
R5912	202 / 8	φ190	330	380	Box & Line	10	approx. 1100
R5912-02	202 / 8	φ190	330	380	Box & Line	14	approx. 1100

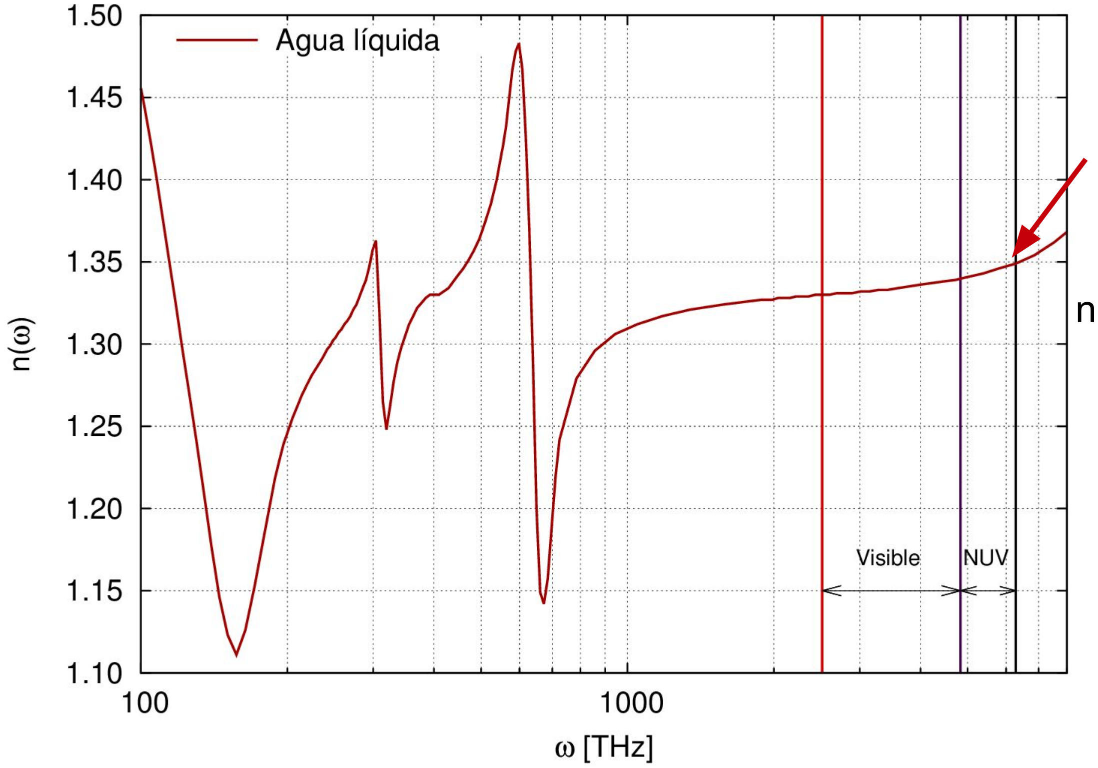
Efecto Cherenkov simplificado





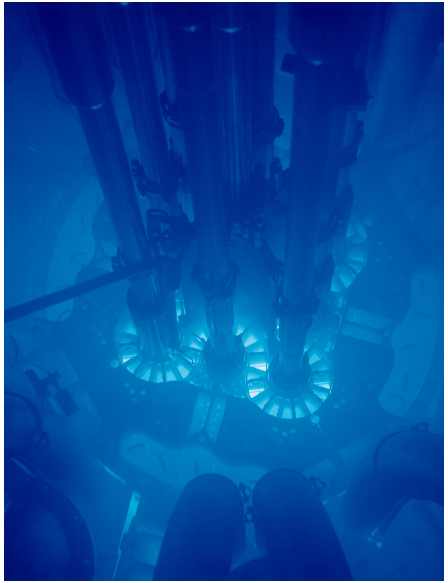
- Medio material con índice de refracción n = cte
- Partícula cargada con velocidad β c > (c/n)

Índice de refracción agua

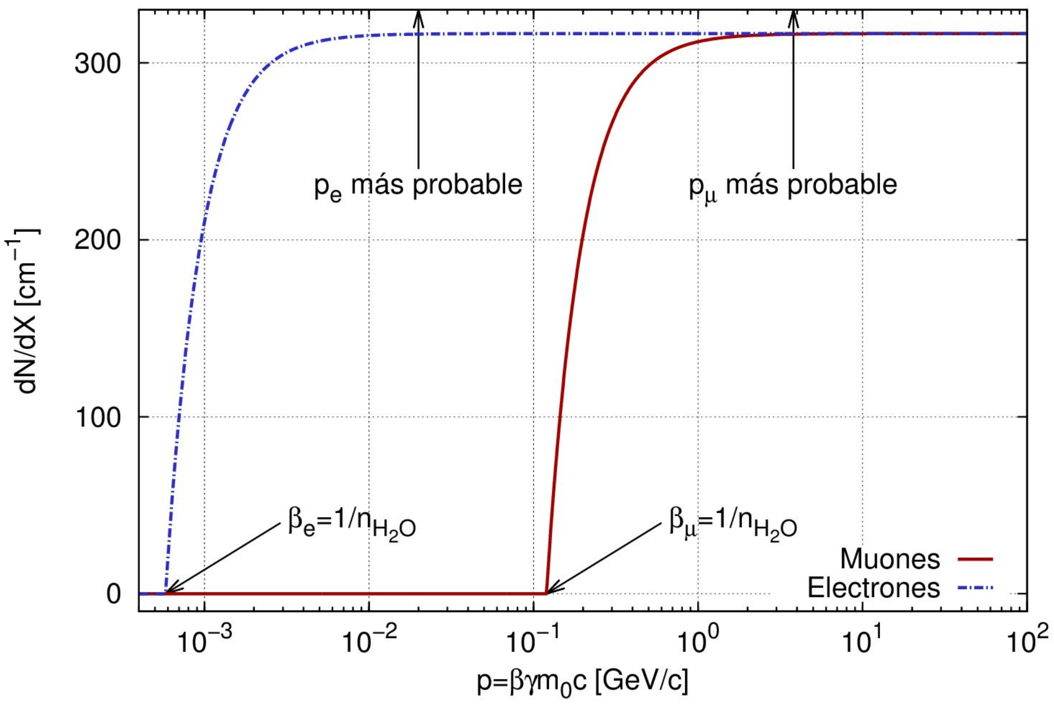


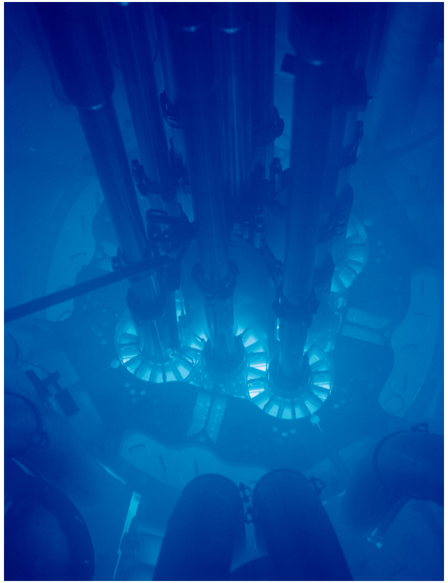
Emisión Cherenkov en Agua

n=1.333

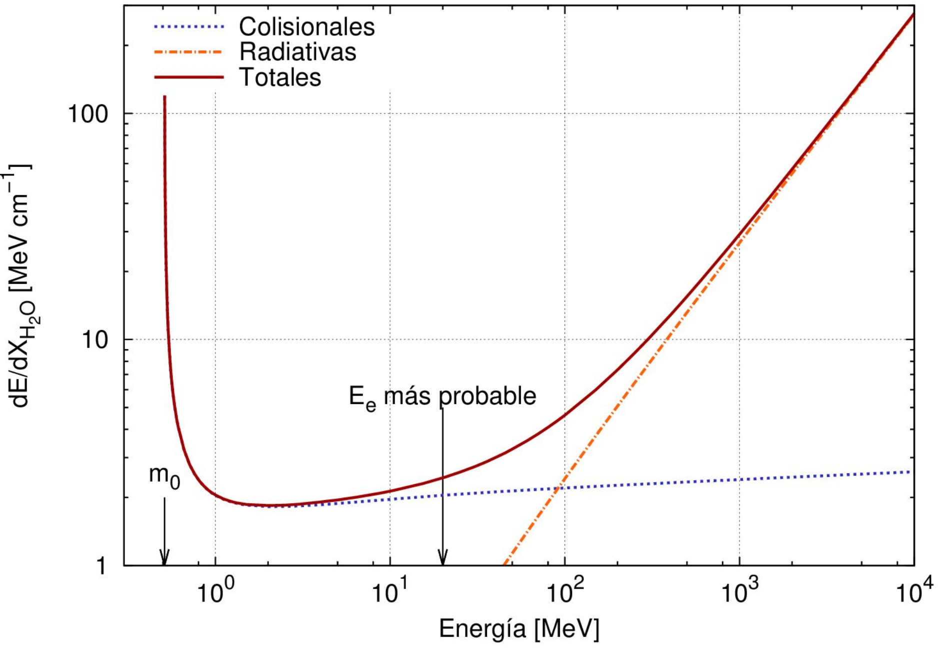


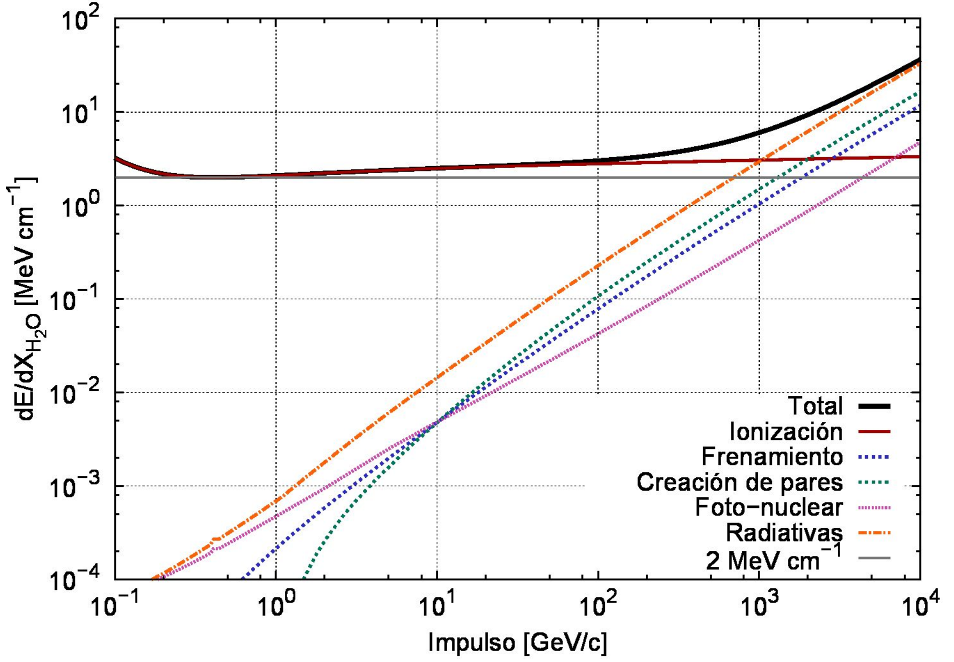
Producción Cherenkov en agua



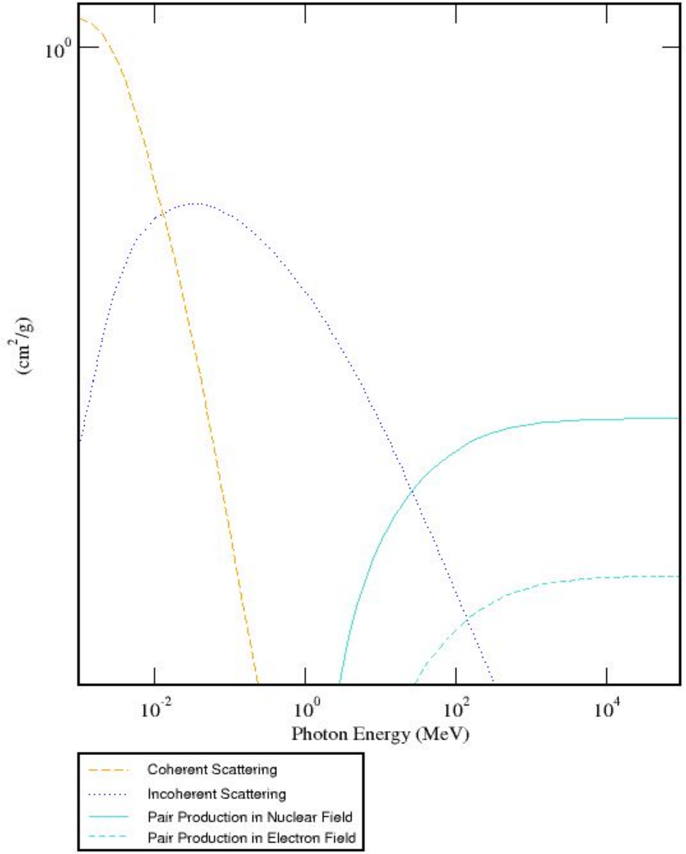


dE/dX electrones vs muones en agua





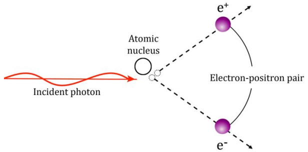
¿Qué pasa con los fotones?



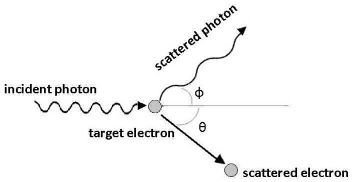
Partículas sin carga → No hay Cherenkov

Pero hay dos efectos adicionales:

1) Producción de pares: un fotón puede producir un par que produzca señal

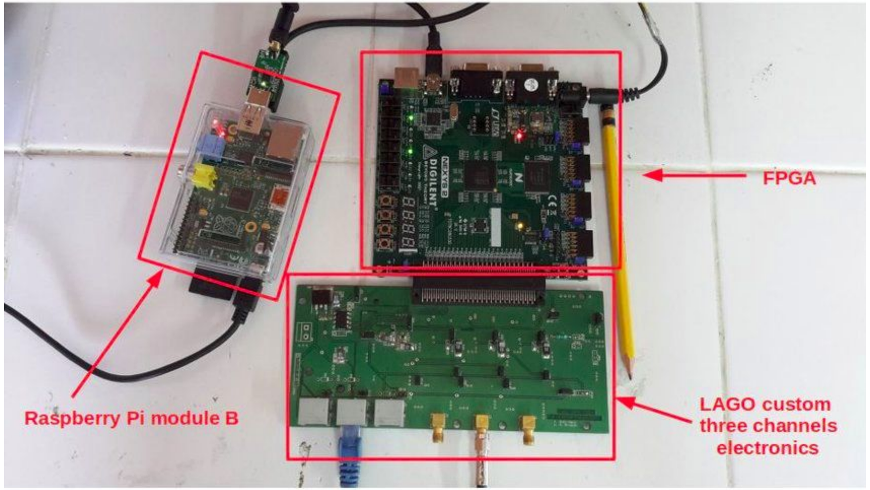


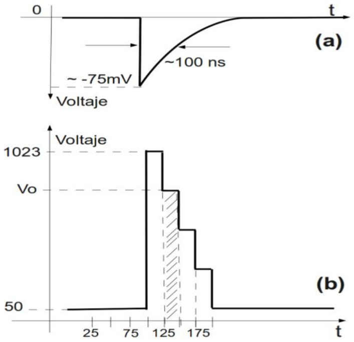
2) Compton: por scattering compton un electrón puede ser promovido



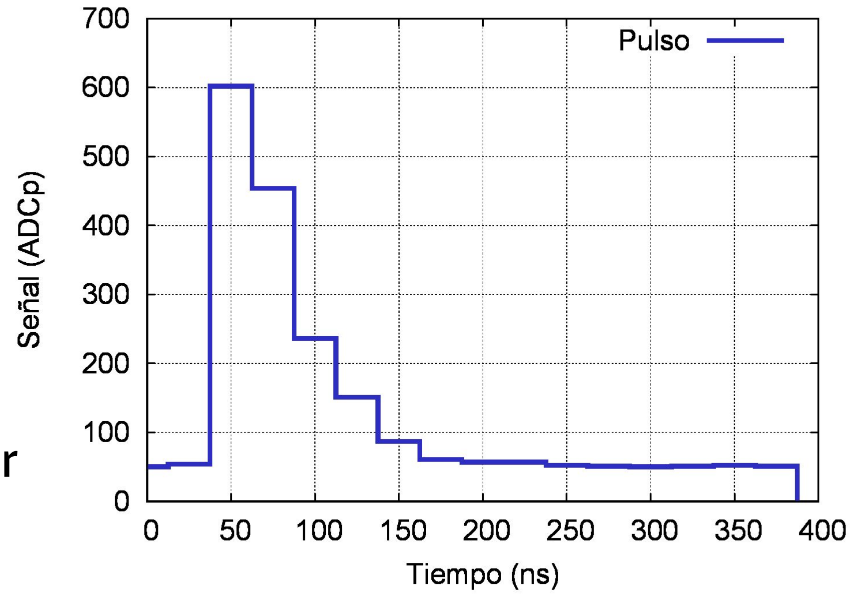
Adquisición de datos

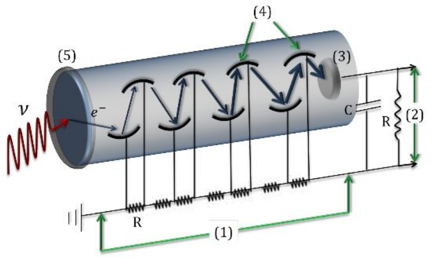
- Señales analógicas (pulsos) en el PMT
- Amplificación de la señal
- Hasta tres canales independientes
- Digitalización FADC 10 bits a 40 MHz (25 ns)





- Datos:
  - Tres (Dos) canales de señales digitalizadas
- Metadatos
  - Id del Detector
  - Telemetría del detector
  - Datos atmosféricos, PyT
  - Datos monitoreo GPS
  - ....
- Una hora por archivo





50 50 50
61 49 54
139 49 602
91 51 454
59 50 236
60 50 151
53 50 87
53 50 61
50 50 57
51 51 57
50 50 52
51 49 51
51 50 50
50 49 51
51 50 52
50 50 51
t 4 30008562
c 663486982

Tag temporal y número de pulso

Definiciones

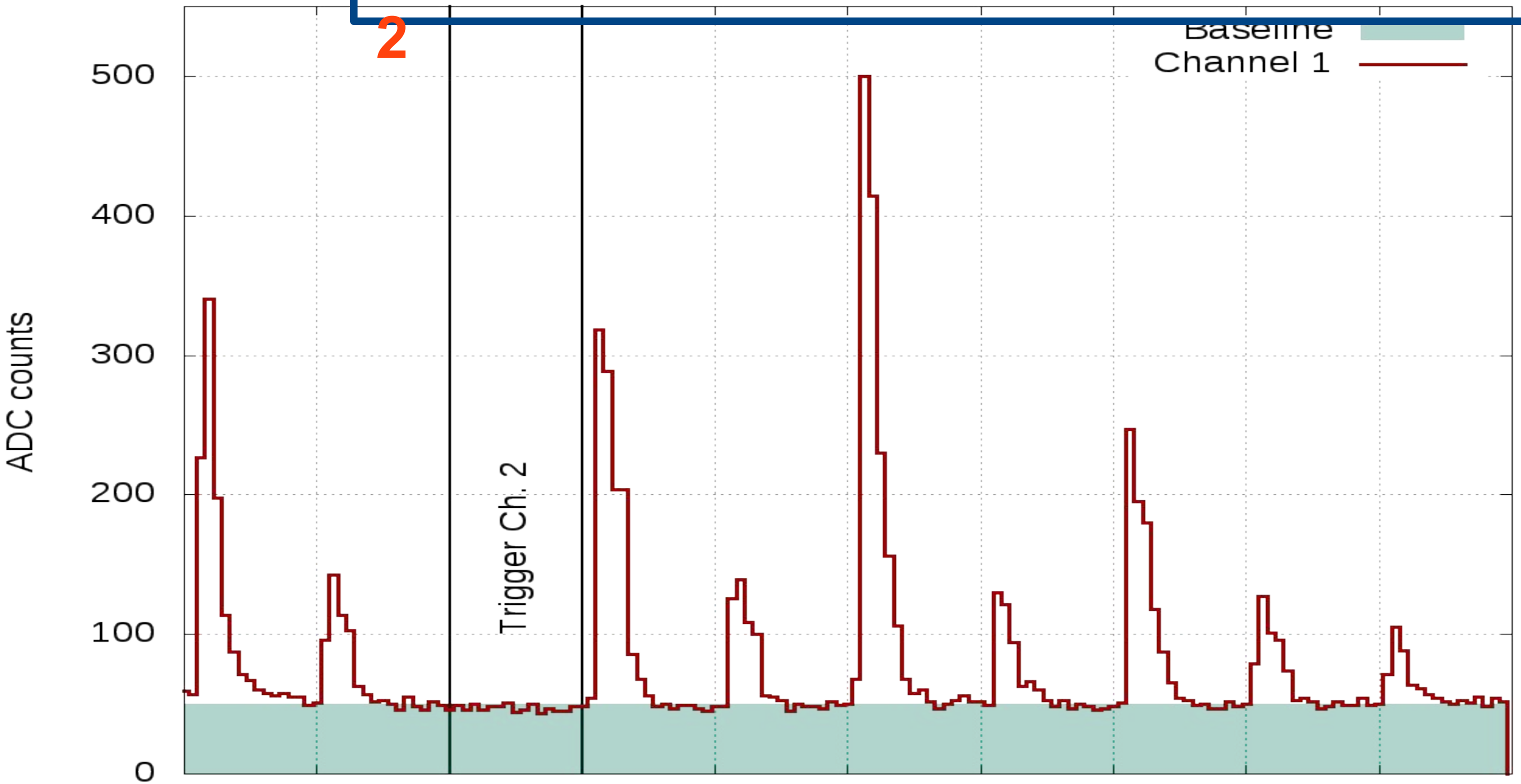
50 50 50
61 49 54
139 49 602
91 51 454
59 50 236
60 50 151
53 50 87
53 50 61
50 50 57
51 51 57
50 50 52
51 49 51
51 50 50
50 49 51
51 50 52
50 50 51
t 4 30008562
c 663486982

50 50 50
49 51 51
62 50 106
53 50 117
51 51 62
50 50 55
50 50 51
53 51 51
51 50 51
49 49 52
51 50 51
51 49 51
51 50 52
50 49 50
50 51 50
52 50 51
t 4 30008646
c 663486983

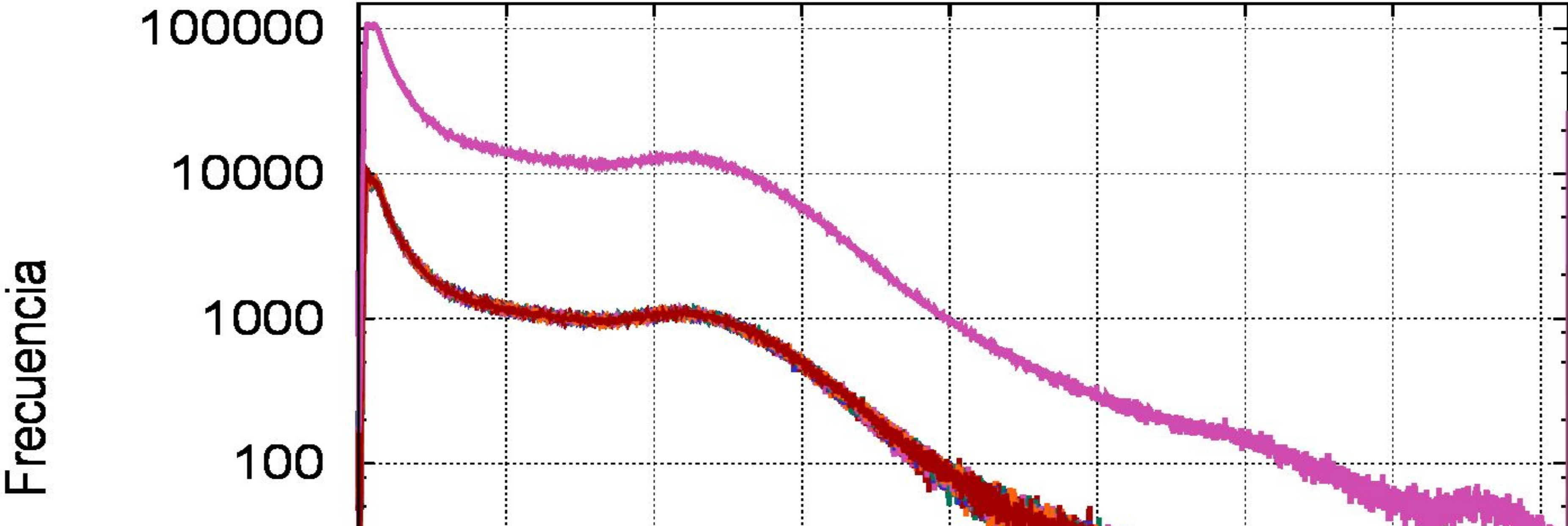
- Pulso canal j
- Pico
- Área ← Energía depositada
- Área sobre Pico:
- Δt (independiente de j)

Estructura del archivo de pulsos

name_(no)gps_YYYY_MM_DD_HHhMM.dat.bz2

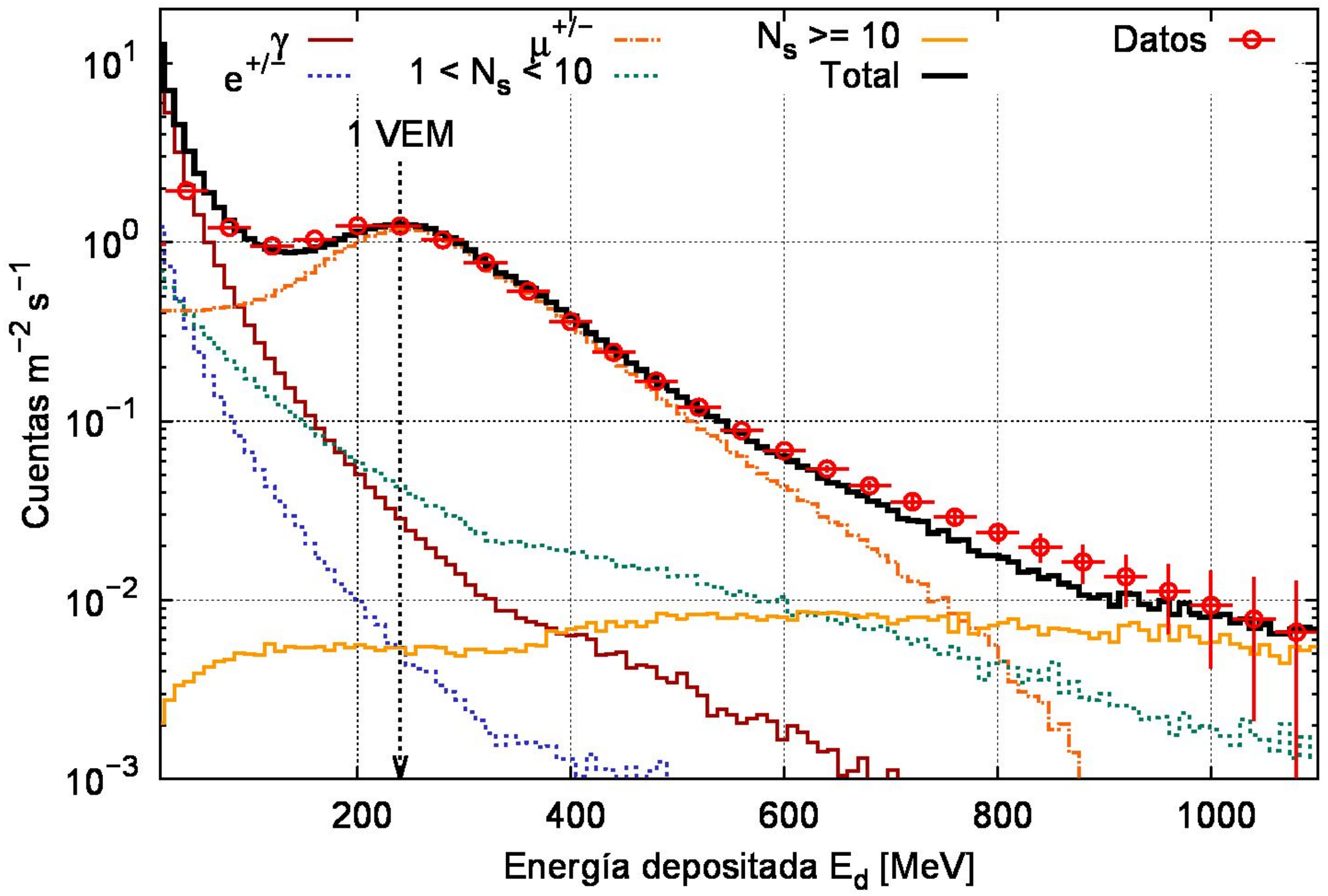


- Área A de cada pulso → histograma de áreas

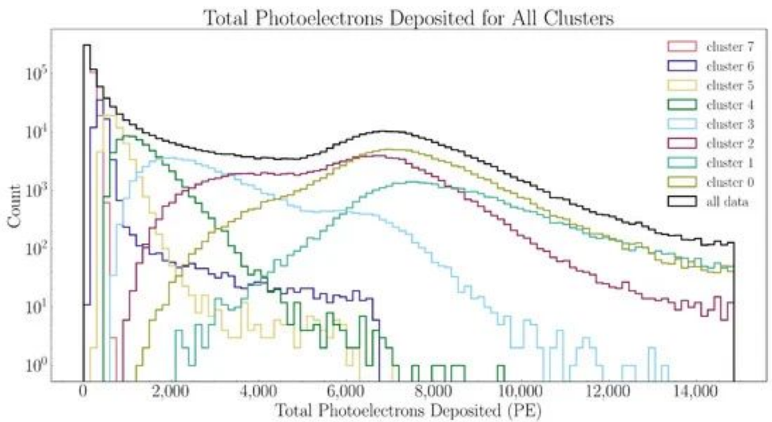


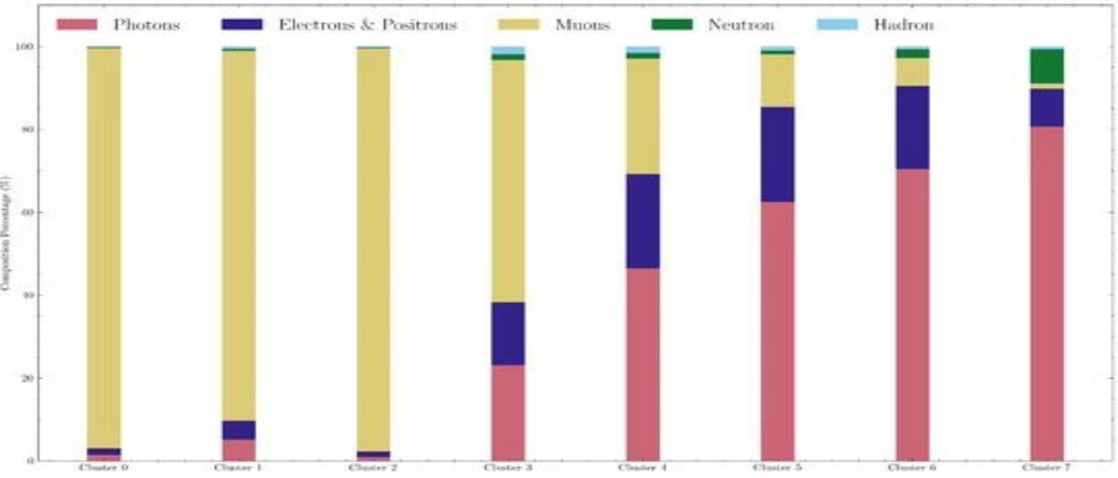
Flujo de primarios → (CORSIKA + Sitio) → Flujo de Secundarios

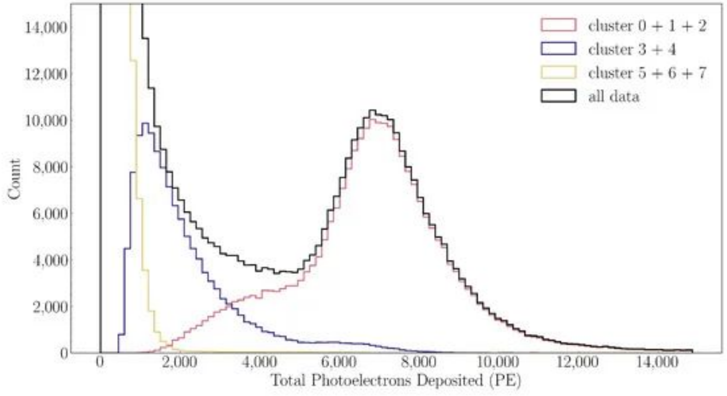
Flujo de secundarios → (G4+Detector) → Señales en el detector



Enhanced Particle Classification in Water Cherenkov Detectors Using Machine Learning: Modeling and Validation with Monte Carlo Simulation Datasets

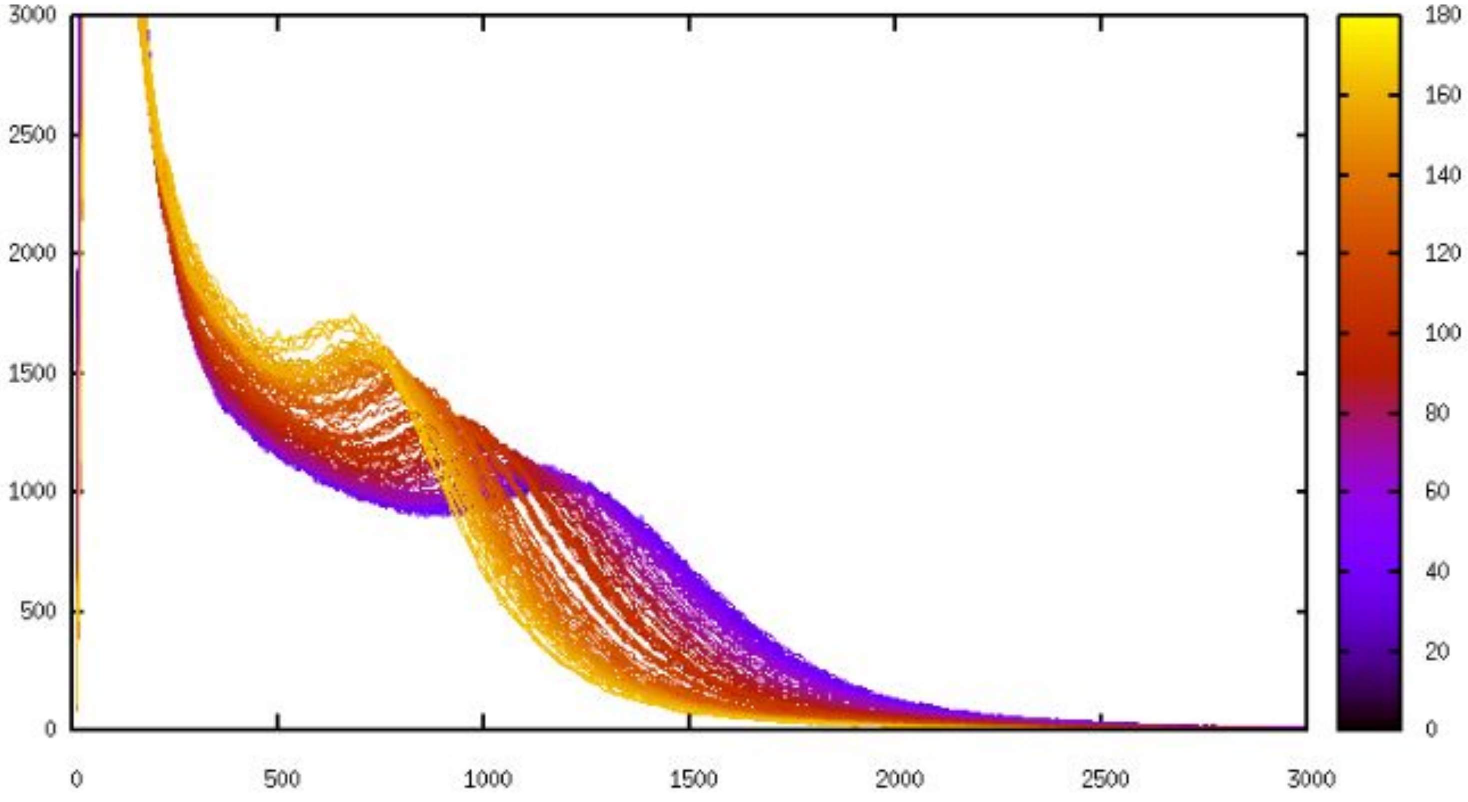




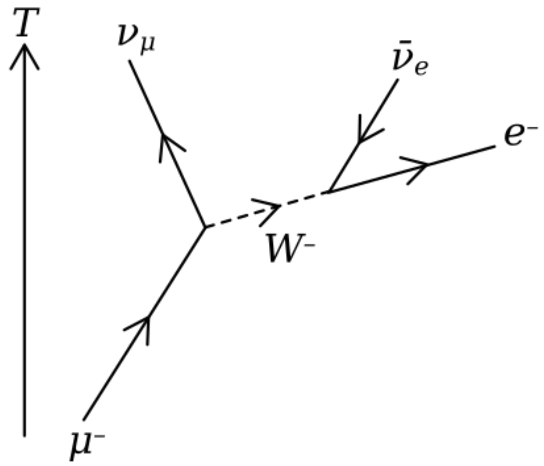


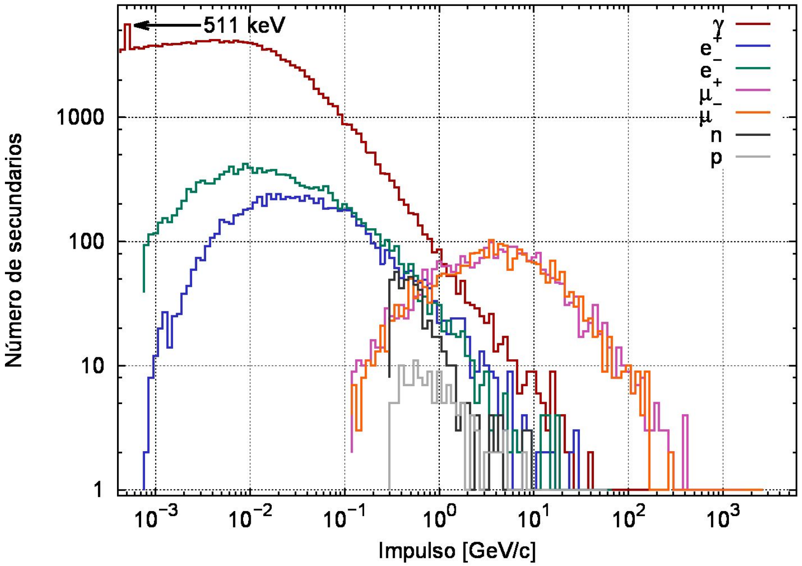
El detector real de LAGO

Impacto de la calidad del agua



Decaimiento del Muón





$$\tau_\mu = (2197.03 \pm 0.04)\,\text{ns}$$

Histograma de Diferencias Temporales

- Calculamos el Δt entre pulsos sucesivos
- La distribución de Δt es un muestreo de las distribucion de los procesos en el interior:
  - Flujo de secundarios

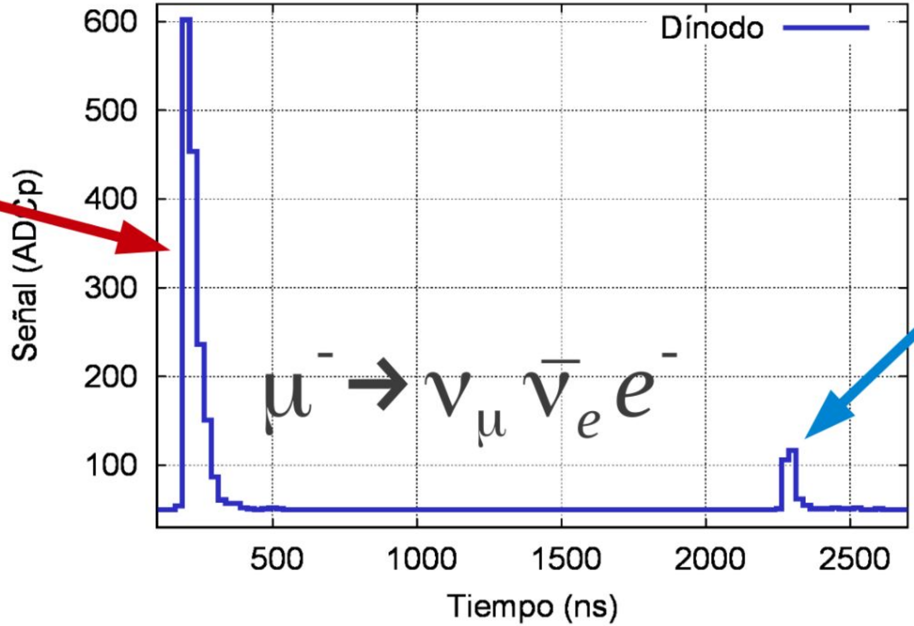
$$\left(\lambda_{\text{fondo}}\right)^{-1} \equiv \tau_{\text{fondo}} \simeq 2.5\,\text{ms} = 2.5 \times 10^{3}\,\mu\,\text{s}$$

  - Decaimento de los muones en el interior del detector

$$\left(\lambda_{\mu}\right)^{-1} \equiv \tau_{\mu} \simeq 2.2\,\mu\,\text{s}$$

- Tiempos característicos muy diferentes

```
50 50 50
61 49 54
139 49 602
91 51 454
59 50 236
60 50 151
53 50 87
53 50 61
50 50 57
51 51 57
50 50 52
51 49 51
51 50 50
50 49 51
51 50 52
50 50 51
# t 4 30008562
# c 663486982
```

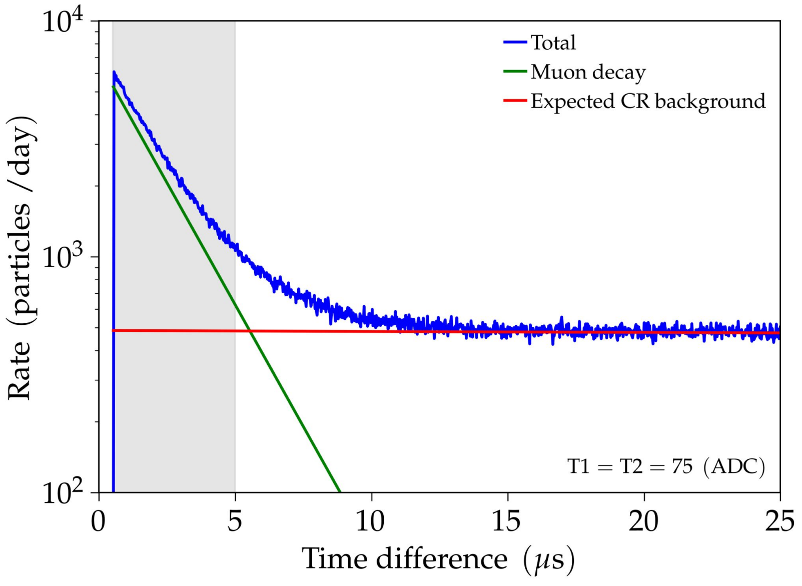


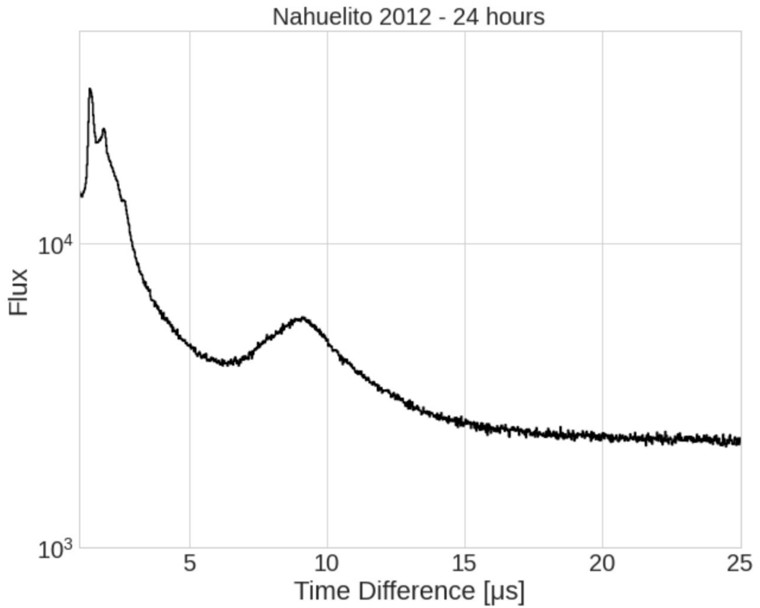
$$\Delta t = 84 \times 25 \text{ ns} = 2100 \text{ ns}$$

$$\Delta p = 1$$

```
50 50 50
49 51 51
62 50 106
53 50 117
51 51 62
50 50 55
50 50 51
53 51 51
51 50 51
49 49 52
51 50 51
51 49 51
51 50 52
50 49 50
50 51 50
52 50 51
# t 4 30008646
# c 663486983
```

Histograma de Diferencias Temporales

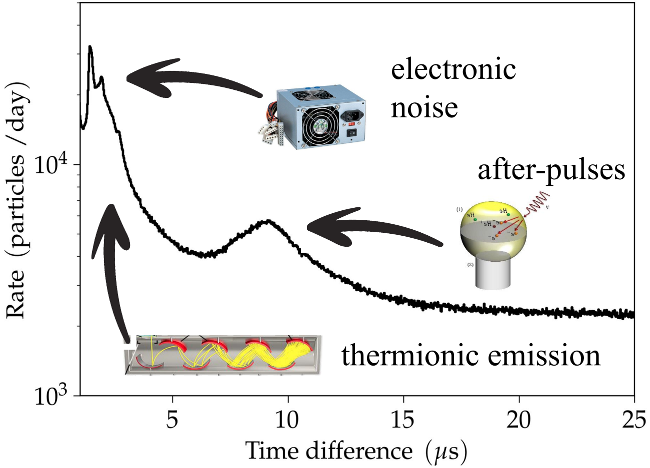




Measurement of the Muon Lifetime and the Michel Spectrum in the LAGO Water Cherenkov Detectors as a tool to improve energy calibration and to enhance the signal-to-noise ratio

L. Otiniano, A. Taboada, H. Asorey, I. Sidelnik, C. Castromonte, A. Campos-Fauth
for the LAGO Collaboration

Time difference between two consecutive pulses histogram

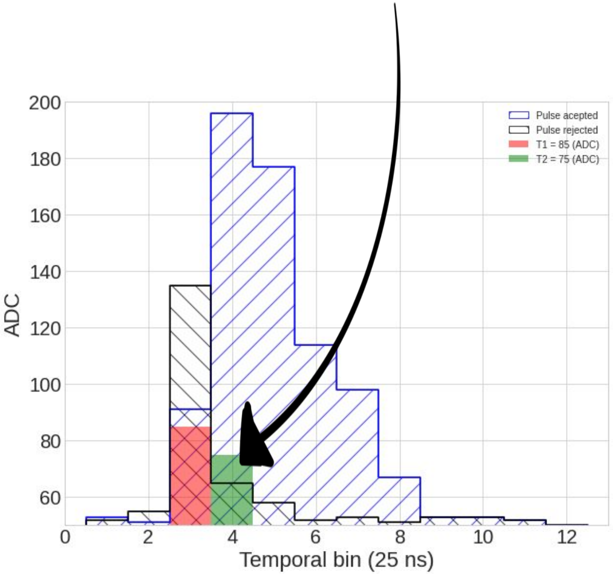


Noises in WCD are clearly visible

Short pulse width ~ ns

Noise Rejecting strategy

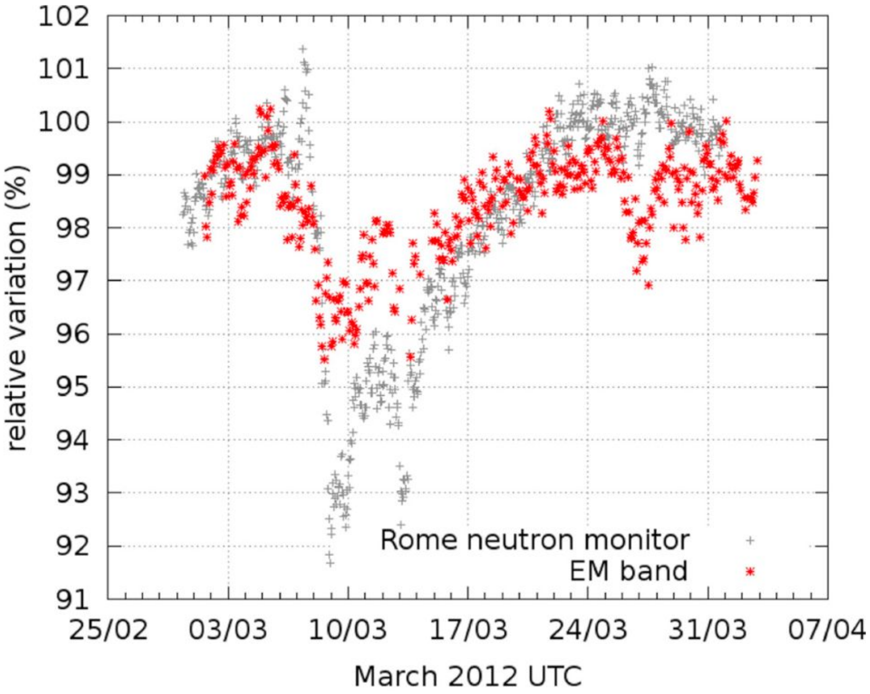
Impose a secondary trigger



eMuon Decay as a Robust Long-Term Calibration Method for Water Cherenkov Detectors

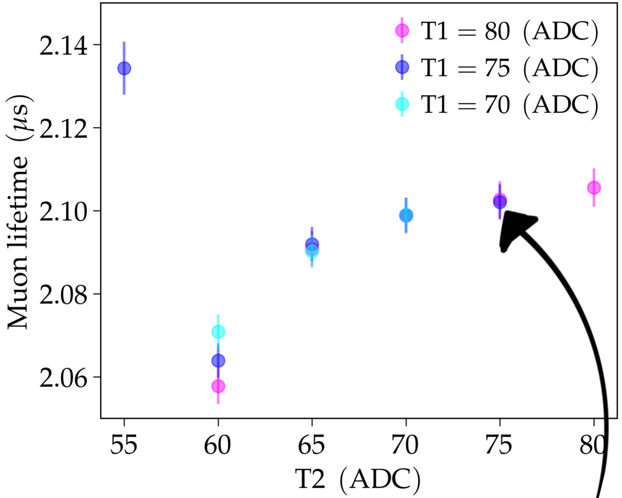
Dos detectores WCD de la red LAGO: uno en Bariloche, Argentina (Nahuelito, izquierda -2012) y el otro en Arequipa, Perú (Characatito, centro -2022). La luz Cherenkov producida en agua purificada por las partículas secundarias de las lluvias atmosféricas extensas (EAS) que ingresan al detector se mide mediante un tubo fotomultiplicador (PMT) de 9 pulgadas centrado en la parte superior del detector (derecha).

¿Porqué estudiar un detector del 2012?



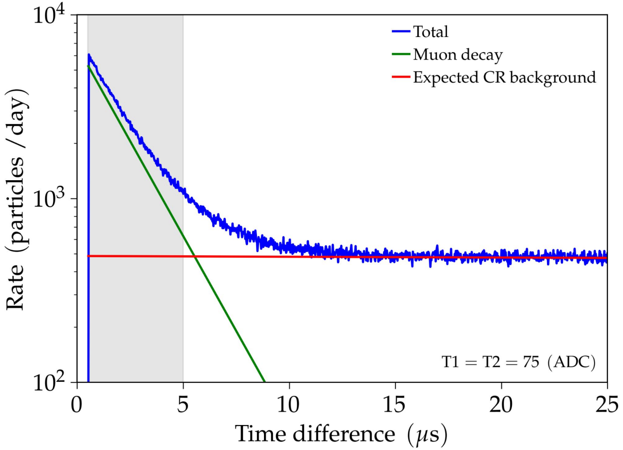
Pico del ciclo de actividad solar

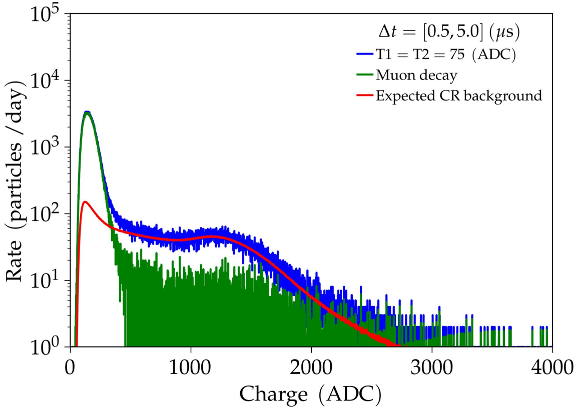
Measurement of the Muon Lifetime and the Michel Spectrum in the LAGO Water Cherenkov Detectors as a tool to improve energy calibration and to enhance the signal-to-noise ratio



We look for stable value of muon lifetime measure from time spectrum

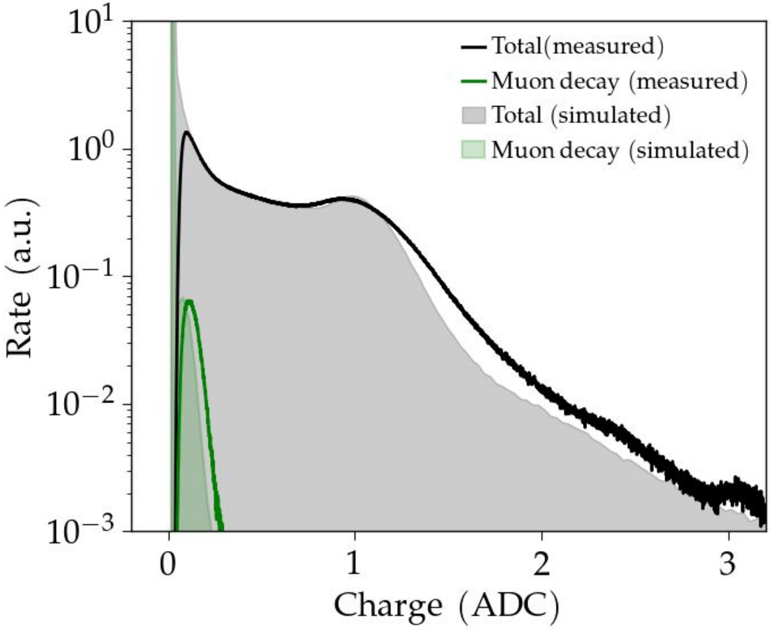
>90% of muon decay events are present in the 0.5-5 μs band of the time between consecutive pulses histogram





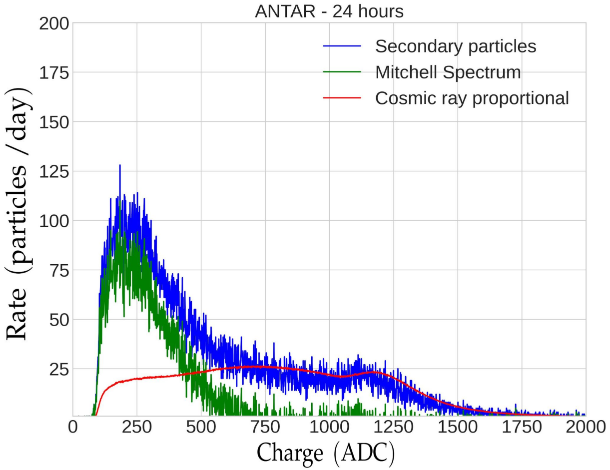
Michel spectrum is obtained from this band after background correction

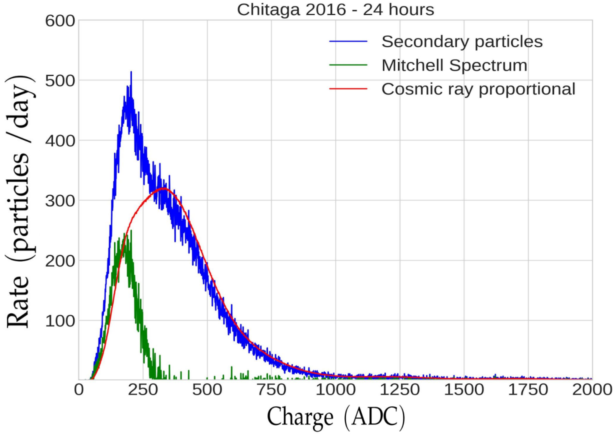
Measurement of the Muon Lifetime and the Michel Spectrum in the LAGO Water Cherenkov Detectors as a tool to improve energy calibration and to enhance the signal-to-noise ratio



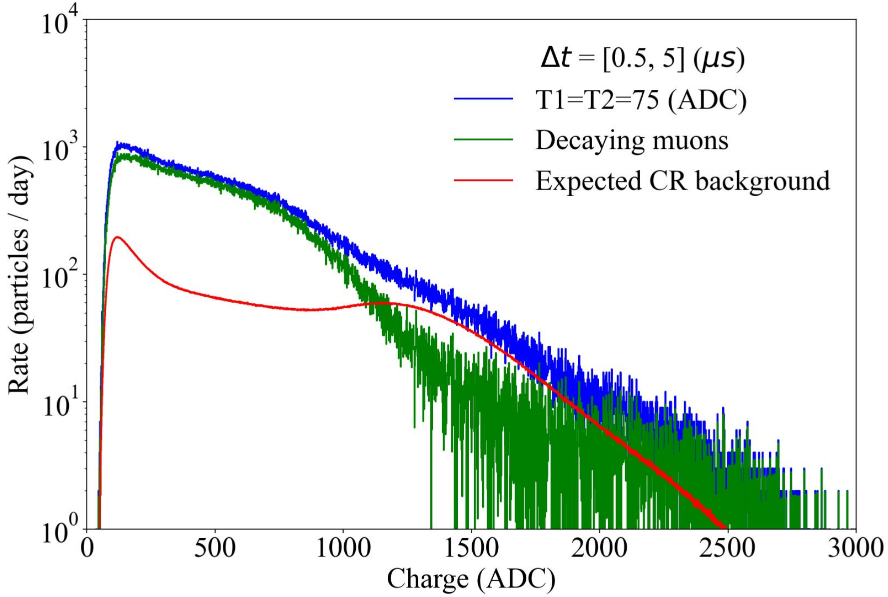
Good agreement with simulations

This process is being used for correcting operative datasets of LAGO WCDs



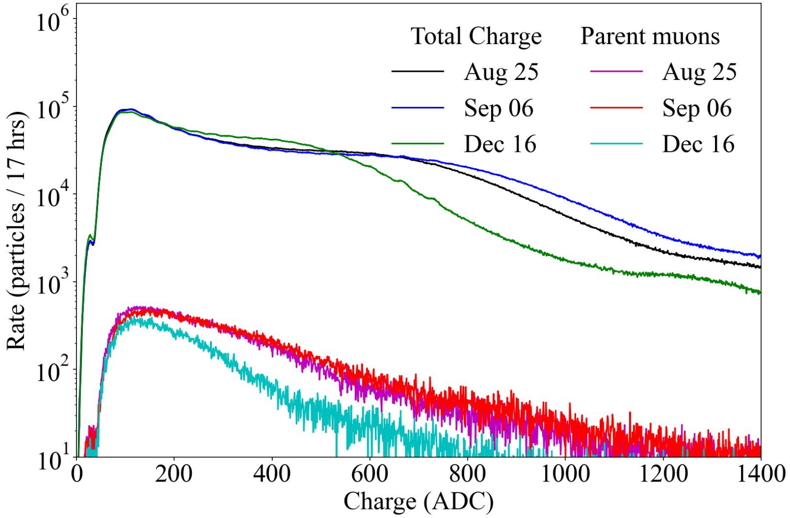


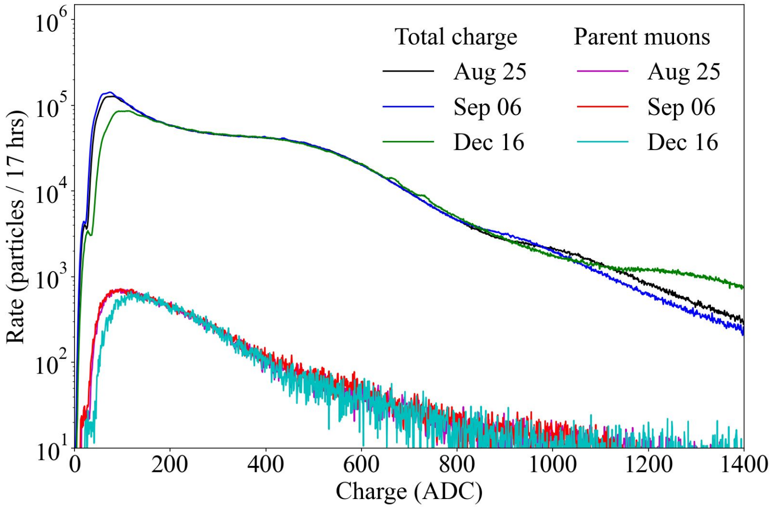
eMuon Decay as a Robust Long-Term Calibration Method for Water Cherenkov Detectors



Se estima el espectro de carga de los muones progenitores seleccionando el primero de dos pulsos consecutivos con una separación temporal de entre 0,5 y 5 μs, y restando el flujo de SP esperado del histograma de carga.

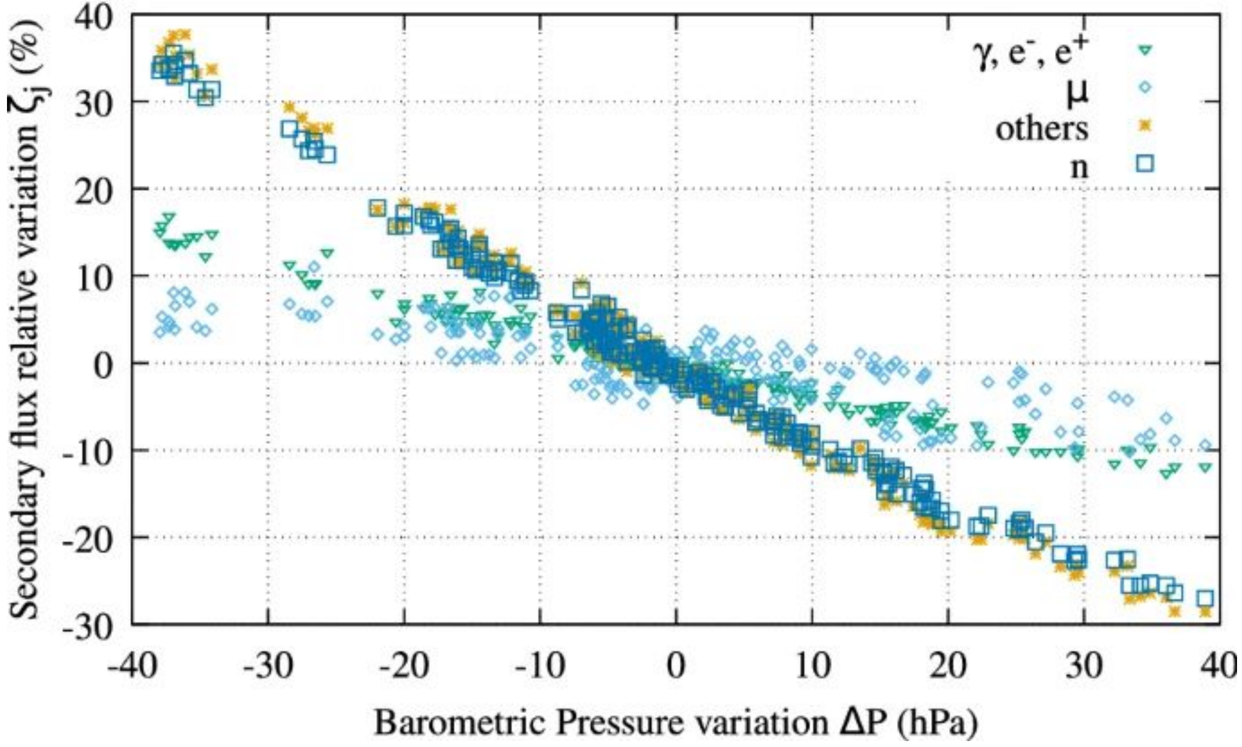
Decaying muon charge spectra as a robust long-term calibration tool for water cherenkov detectors





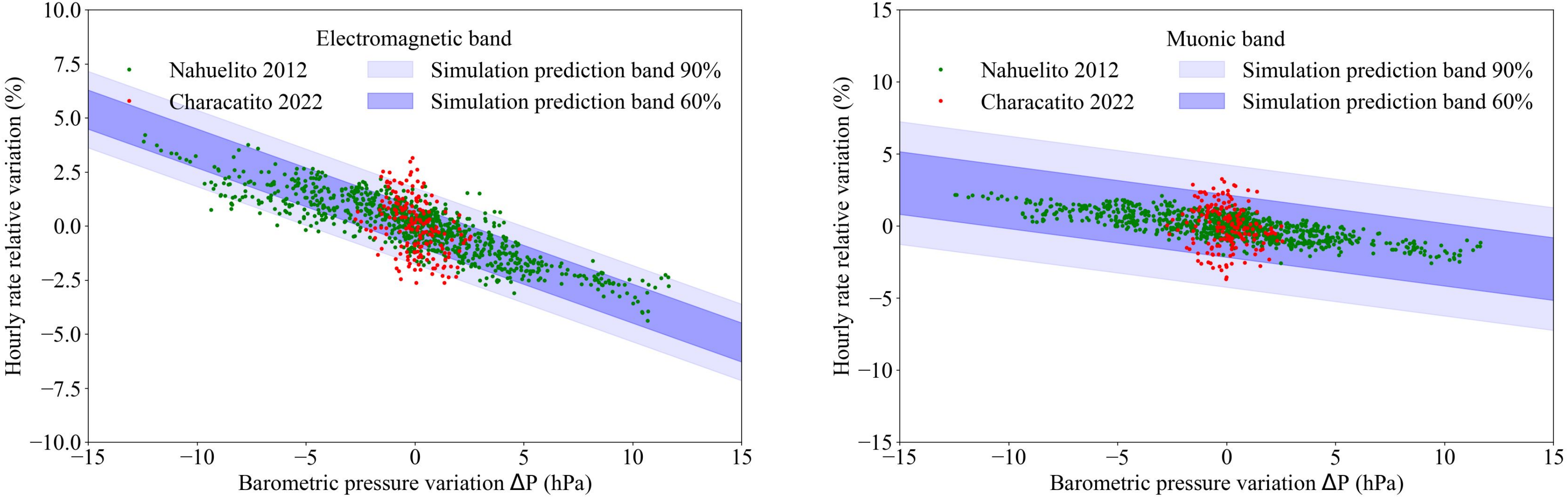
Quispe, D., Sarmiento, C., Otiniano, L., Asorey, H., Castromonte, C., Yanyachi, R., ... & LAGO Collaboration. (2026). ***Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*****, 171415.**

El Escenario



Selin, A. N., Sidelnik, I., Cano, C. S., Asorey, H., & Nuñez, L. (2026). Two stage gamma–neutron source classification in water Cherenkov detectors: Energy threshold screening and machine learning pulse analysis. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *1088*, 171517.

Decaying muon charge spectra as a robust long-term calibration tool for water cherenkov detectors



Conclusiones

- Hemos desarrollado una metodología novedosa para la calibración a largo plazo de los detectores Cherenkov de agua de LAGO, basada en la determinación precisa de los espectros de desintegración de muones.

- Este enfoque se está replicando actualmente en múltiples emplazamientos de LAGO, incluyendo aquellos situados a gran altitud.

- Además, puede integrarse en el sistema de adquisición de datos (DAQ) mediante la monitorización continua de los eventos candidatos a desintegración de muones, lo que permite una calibración robusta y autónoma durante periodos de tiempo prolongados.

- Localmente se debe reproducir este análisis identificando los espectro de de decaimiento del muón y los electrones asociados.

REPÚBLICA BOLIVARIANA DE VENEZUELA | Ministerio del Poder Popular para CIENCIA Y TECNOLOGÍA

CIDATA

LAGO

¡Muchas gracias!

Luis Otiniano
Comisión Nacional de Investigación y Desarrollo Aeroespacial

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PROGRAMA IBEROAMERICANO DE CIENCIA Y TECNOLOGÍA PARA EL DESARROLLO

“Encuentro LAGO Venezuela, edición Mérida 2026”

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