

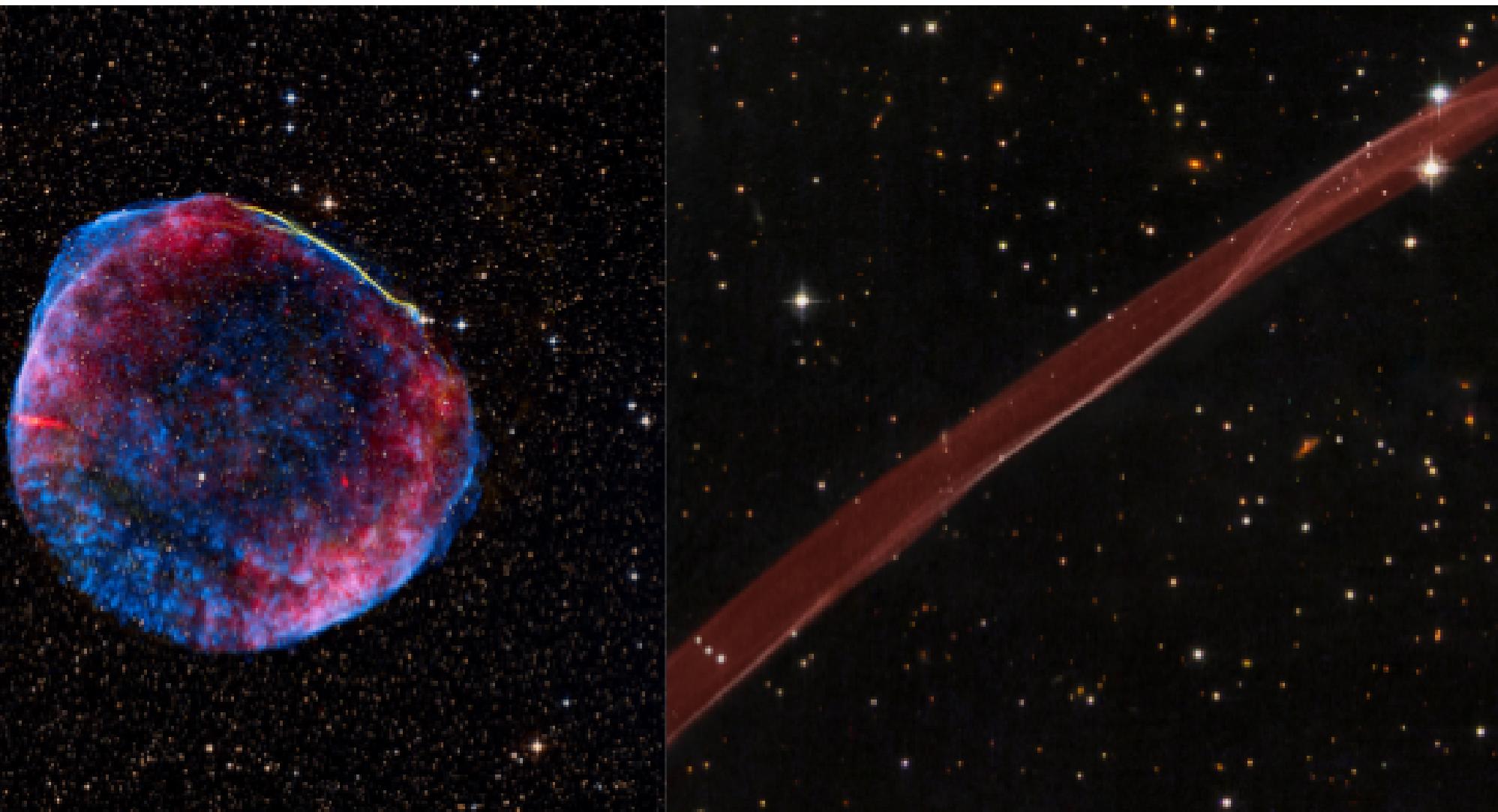
DDAp - ITeDA+KIT

Física de Astropartículas - 2017

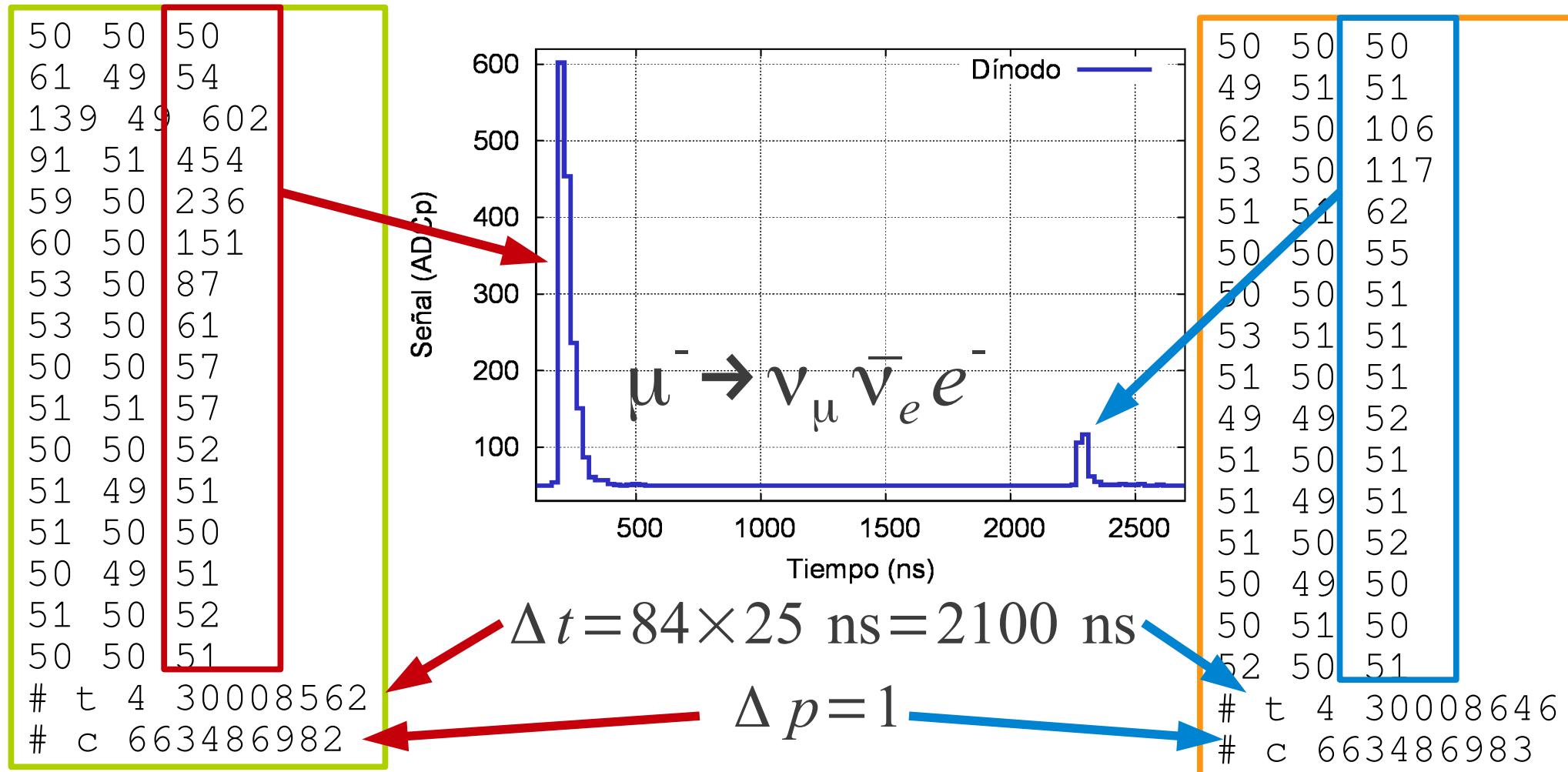
- **Unidad** 04 –Algunas aplicaciones
- **Clase** UO4
- **Cont** Aplicaciones
- **Cátedra** Asorey
- **Web** <https://github.com/asoreyh/astroparticulas>

Alcances

- Comienza en un remanente de supernova

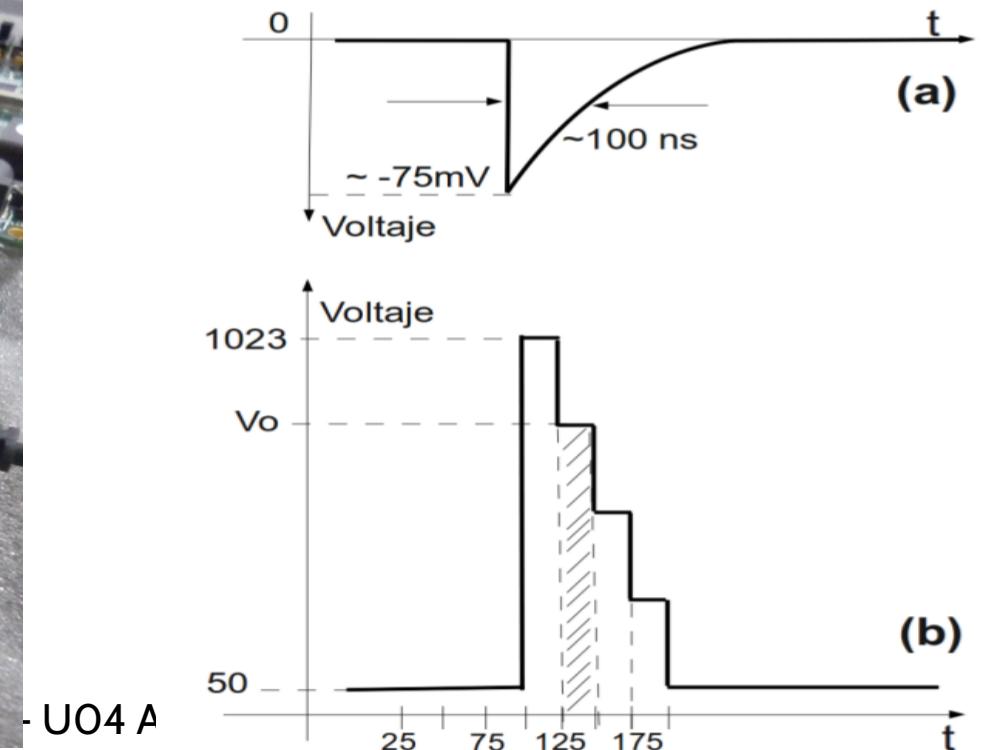
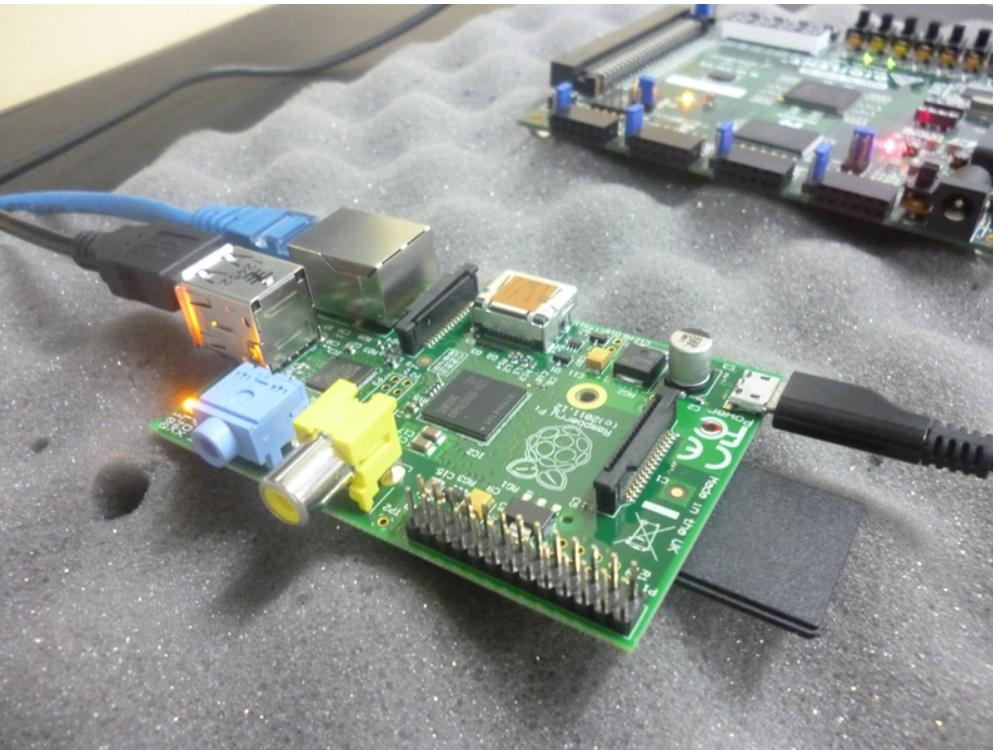


- Comienza en un remanente de supernova
- finaliza en el análisis de un archivo de datos



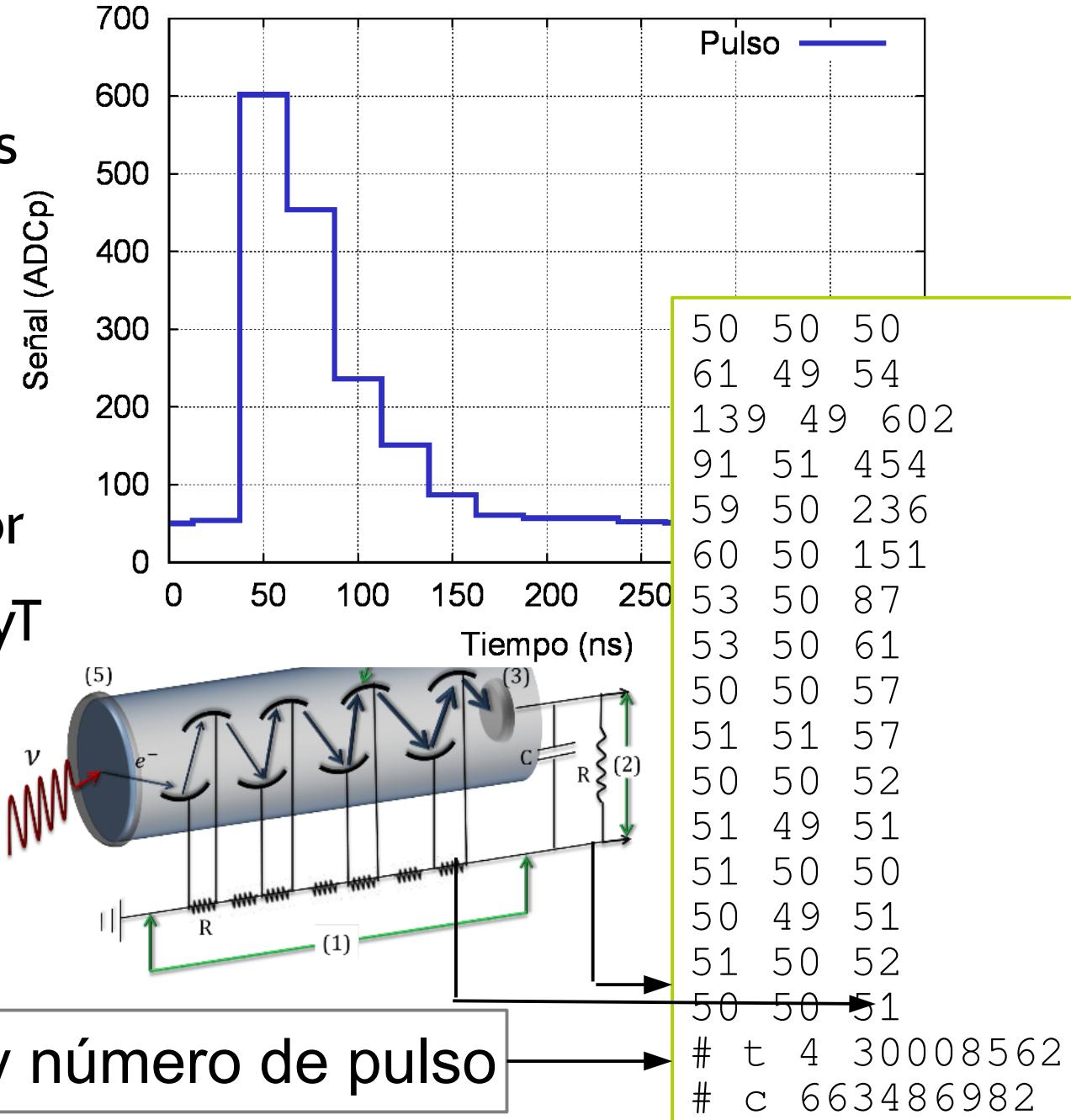
Adquisición de datos

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



Estructura típica de un pulso

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



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	

$$A_3 = 141 \text{ ACD}_q$$
$$P_3 = 67 \text{ ADC}_p$$
$$(A/P)_3 = 2.1$$
$$\Delta t_{83} = 2100 \text{ ns}$$

$$A_3 = 1316 \text{ ACD}_q$$

$$P_3 = 552 \text{ ADC}_p$$

$$(A/P)_3 = 2.4$$

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

$$V_j(t)$$

- Pico

$$P_j = \max[V_j(t) - 50]$$

- Área ← Energía depositada

$$A_j = \left(\int_0^{400 \text{ ns}} [V_j(t) - 50] dt \right) > 0$$

- Área sobre Pico:

$$(A/P)_j = A_j / P_j$$

- Δt (independiente de j)

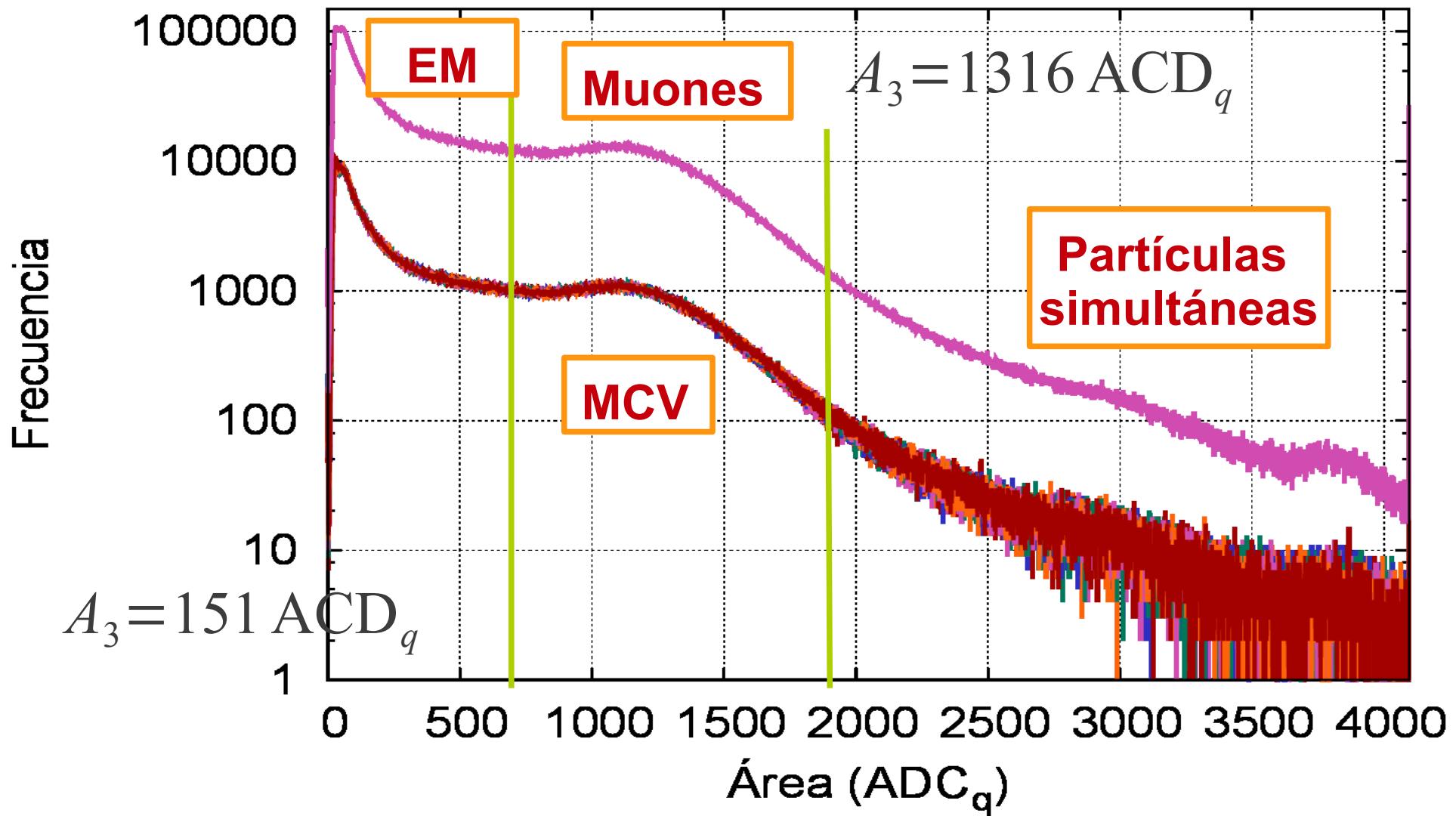
$$\Delta t_i = (\text{tag}_i - \text{tag}_{i-1}) \times 25 \text{ ns}$$



¿Cómo sería el histograma de A_j ?

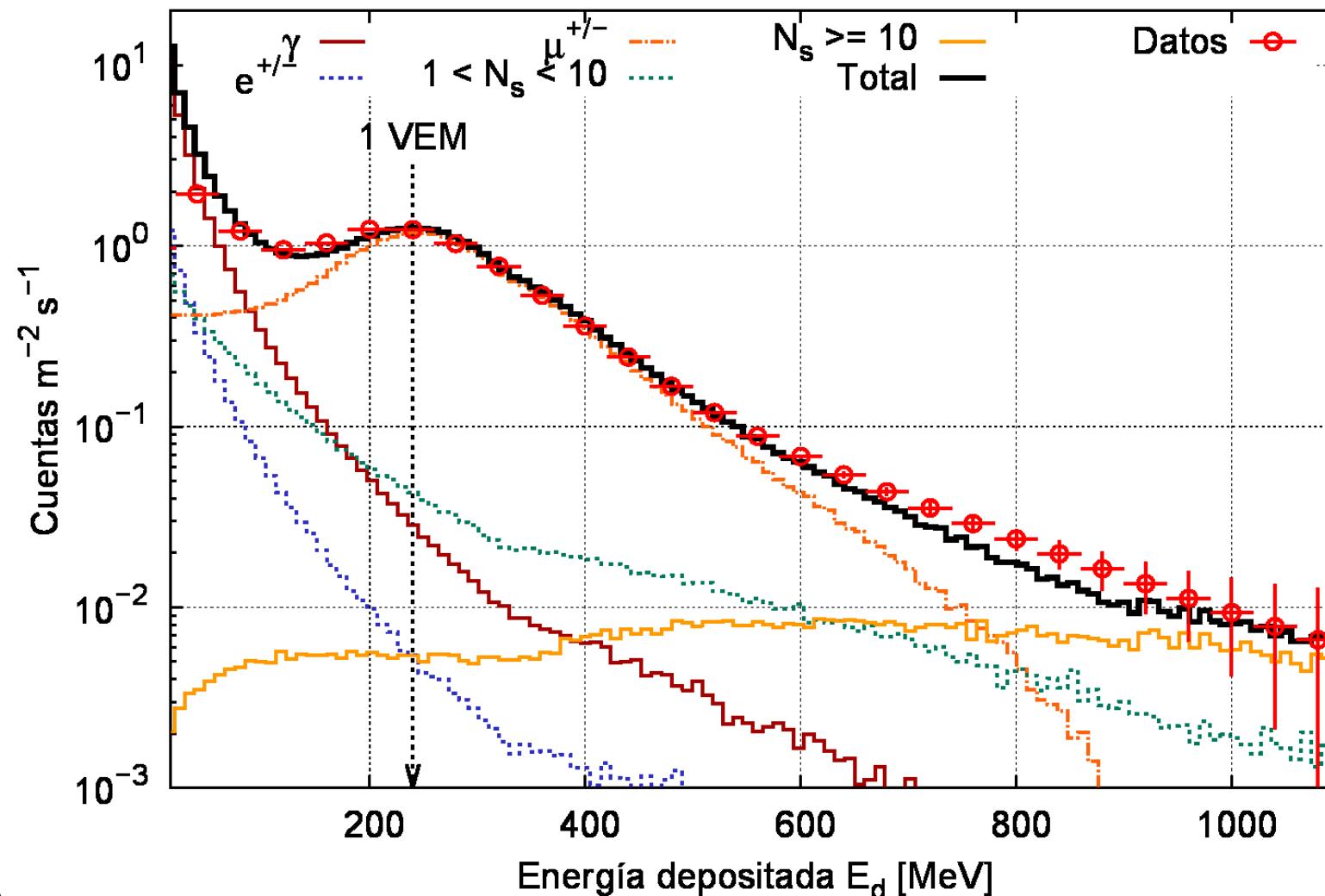
Histograma de áreas

- Área A de cada pulso → histograma de áreas



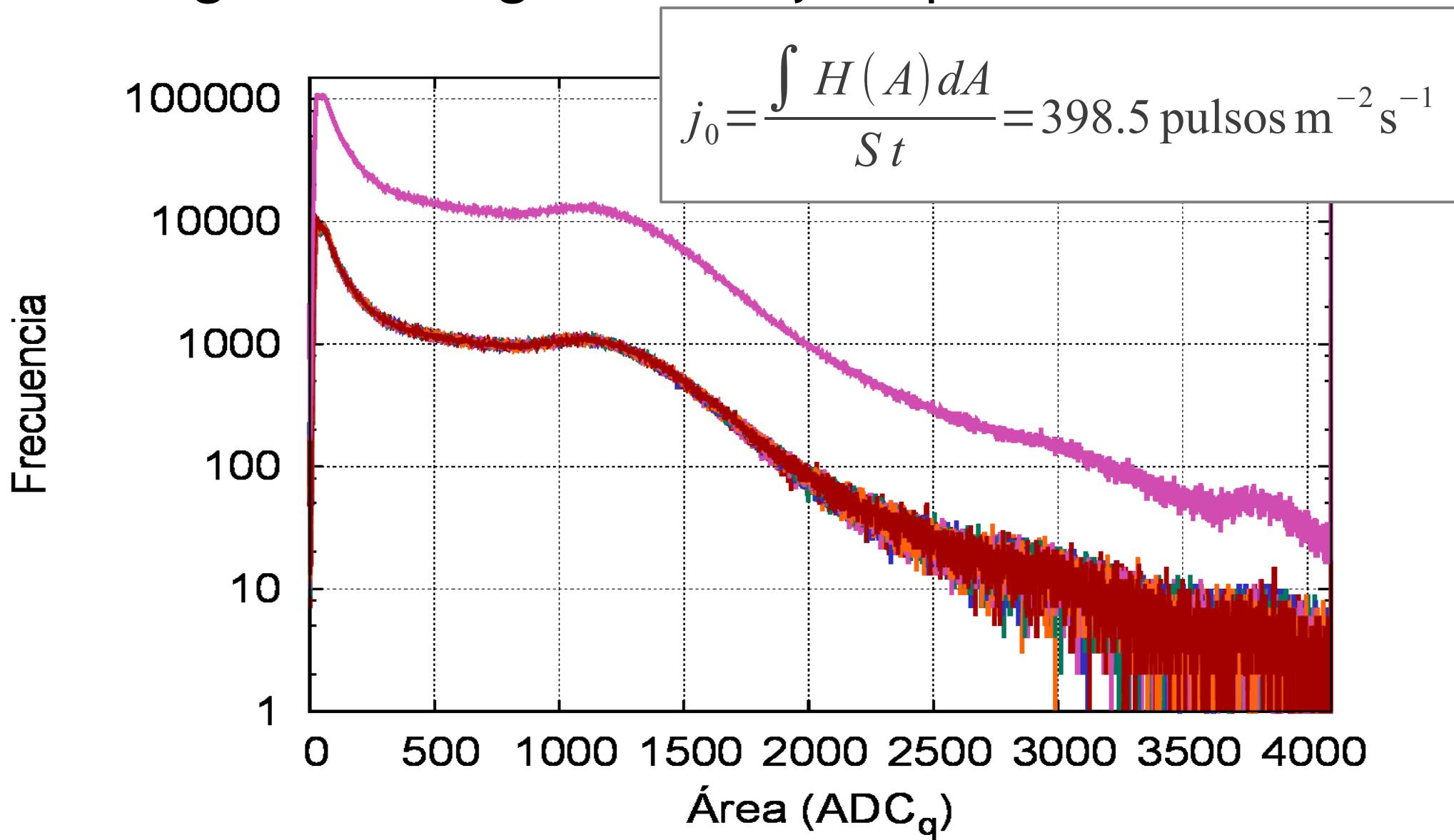
Histograma simulado

Flujo de primarios → (CORSIKA + Sitio) → Flujo de Secundarios
Flujo de secundarios → (G4+Detector) → Señales en el detector



Histograma de áreas

- Integral del histograma → Flujo de partículas



Distribución temporal de señales

- Poisson: sucesos independientes que ocurren a una tasa constante ← Flujo total de secundarios

$$P(x, t) = \frac{(\lambda t)^x e^{-\lambda t}}{x!}$$

- Distribución para el tiempo entre dos pulsos (Δt)
 - No tener pulsos en tiempo Δt , recibir el 1^{er} pulso en $\Delta t + dt$

$$P(\Delta t) \propto e^{-\lambda \Delta t}$$

Distribución Exponencial

- Propiedad: “falta de memoria” (memorylessness)

$$P(t > (l+m) | t > l) = P(t > m)$$

Vida Media del Muón



- Introducir conceptos básicos en
 - Física de Partículas (inc. física nuclear y física relativista)
 - Física de detectores de radiación
 - Técnicas de análisis de datos complejos e inferencia estadística
- Experiencia de Laboratorio destinada a estudiantes de pre y posgrado
- Complejidad y profundidad adaptables al curso, desde ~10 hasta ~60 horas de clase

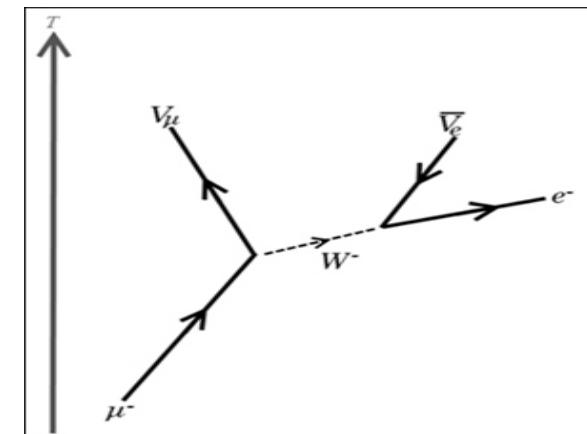
Decaimiento del muón

- Proceso electrodébil
- La vida del muón está “protegida” por la elevada masa de los mediadores W

$$\tau = \frac{1}{\Gamma} = \left(\frac{m_W}{m_\mu g_w} \right)^4 \frac{12\hbar(8\pi)^3}{m_\mu c^2}$$

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

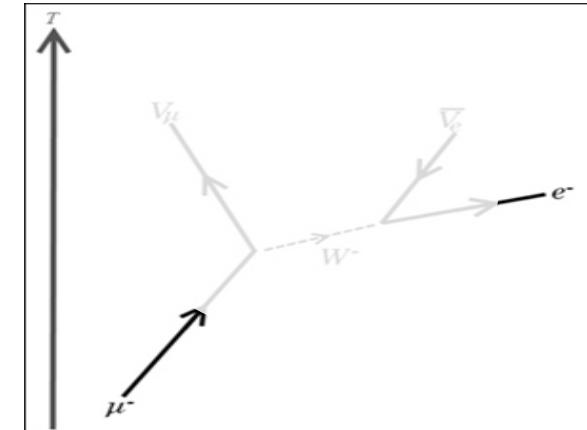
$$g_w = \frac{m_W}{\tau^{1/4} m_\mu} \left(\frac{12\hbar(8\pi)^3}{m_\mu c^2} \right)^{1/4}$$



Decaimiento del muón

- Probabilidad baja de observar el decaimiento de un muón de alta energía

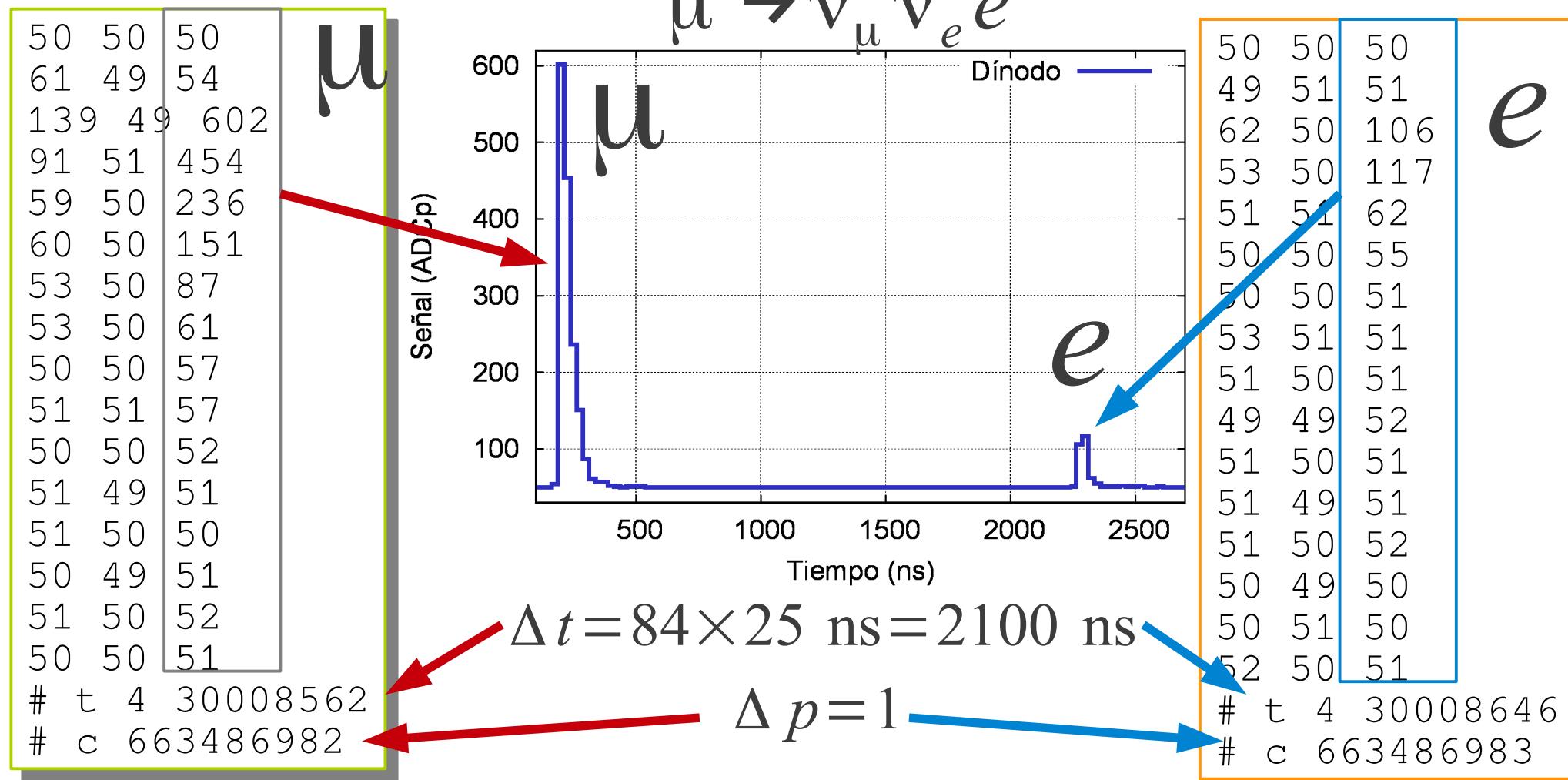
- Sin embargo, si $E_\mu < \sim 500$ MeV
→ Se detiene en el interior del detector



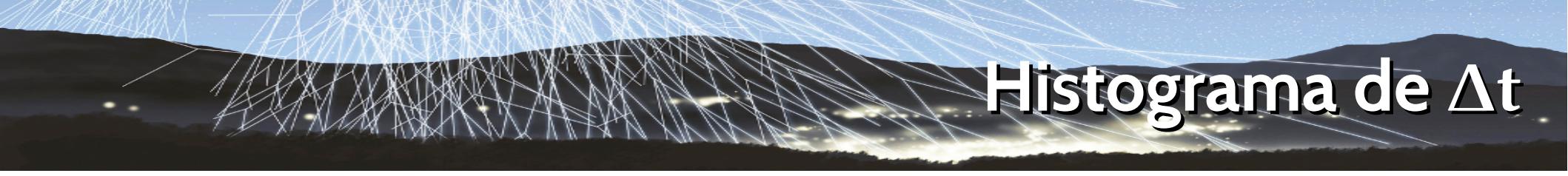
- Pulso del muón → (Decaimiento) → Pulso del electrón
- Existencia de neutrinos vía *missing energy channel*.

Un decaimiento en los datos

- Dos pulsos consecutivos: ingreso del muón, aparición del electrón



Histograma de Δt



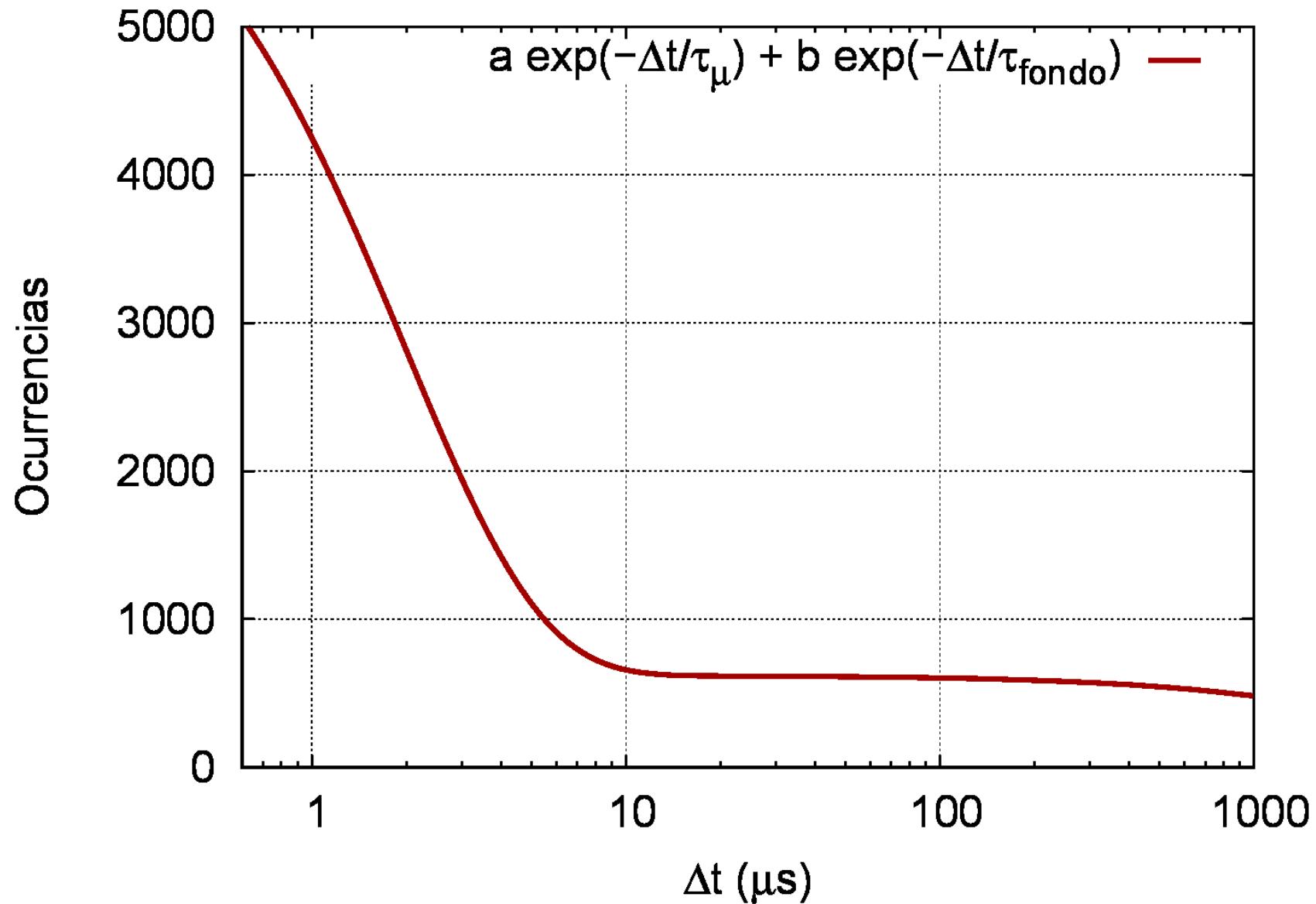
- Calculamos el Δt entre pulsos sucesivos
- La distribución de Δt es un muestreo de las distribuciones de los procesos en el interior:
 - Flujo de secundarios

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

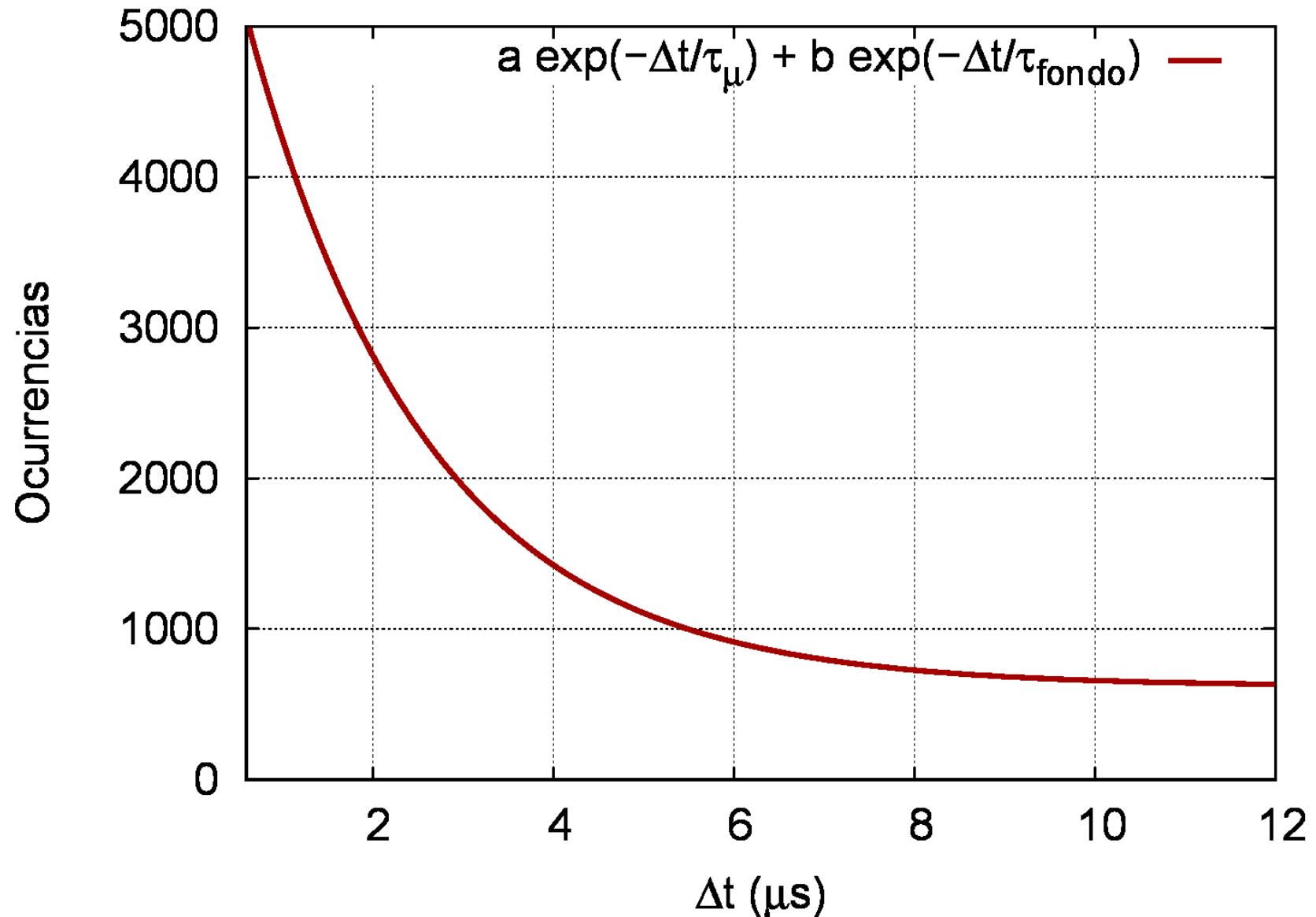
- Decaimento de los muones en el interior del detector
- Tiempos característicos muy diferentes

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

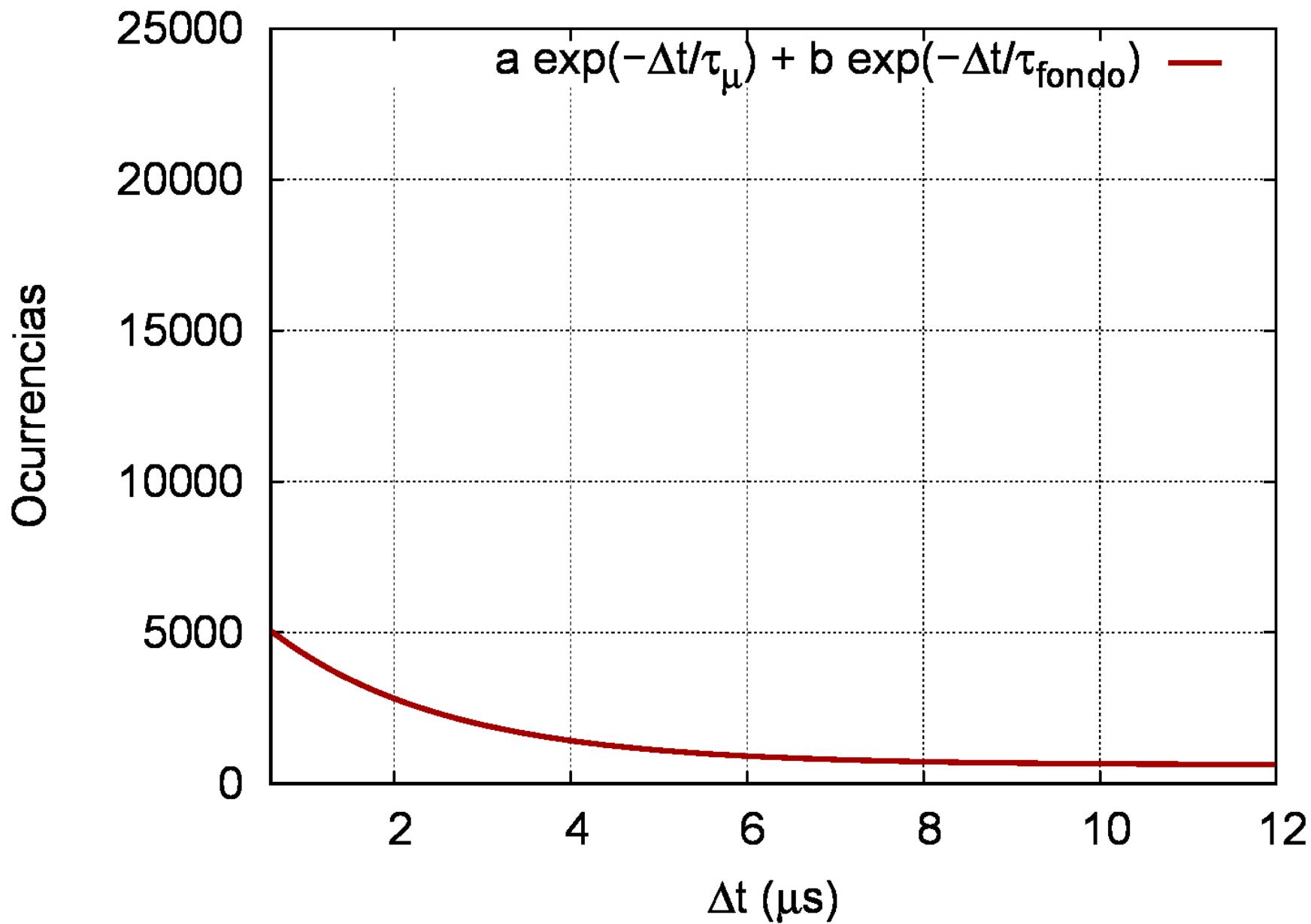
Suma de exponenciales



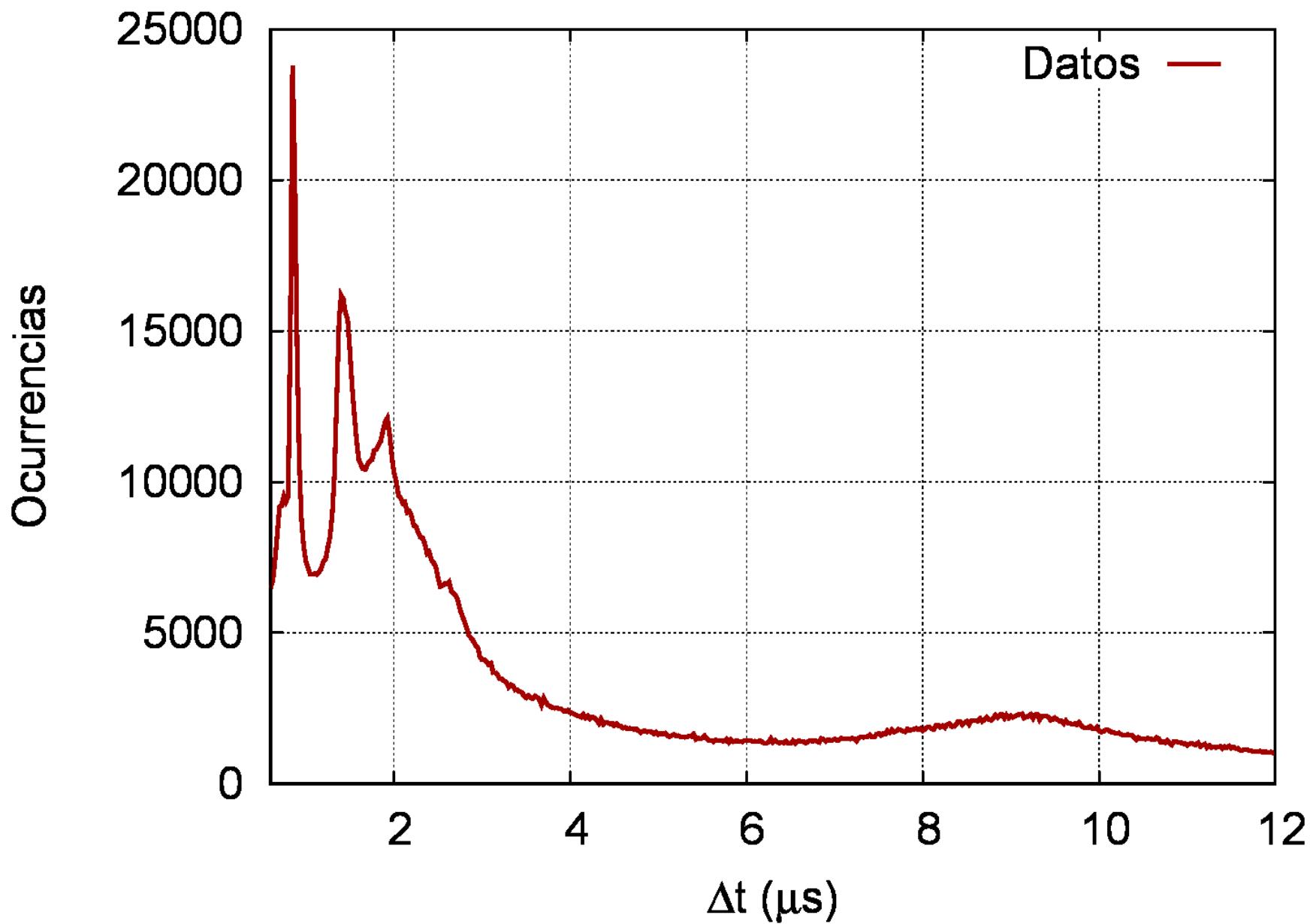
Nos concentramos en $\Delta t \sim \tau_\mu$



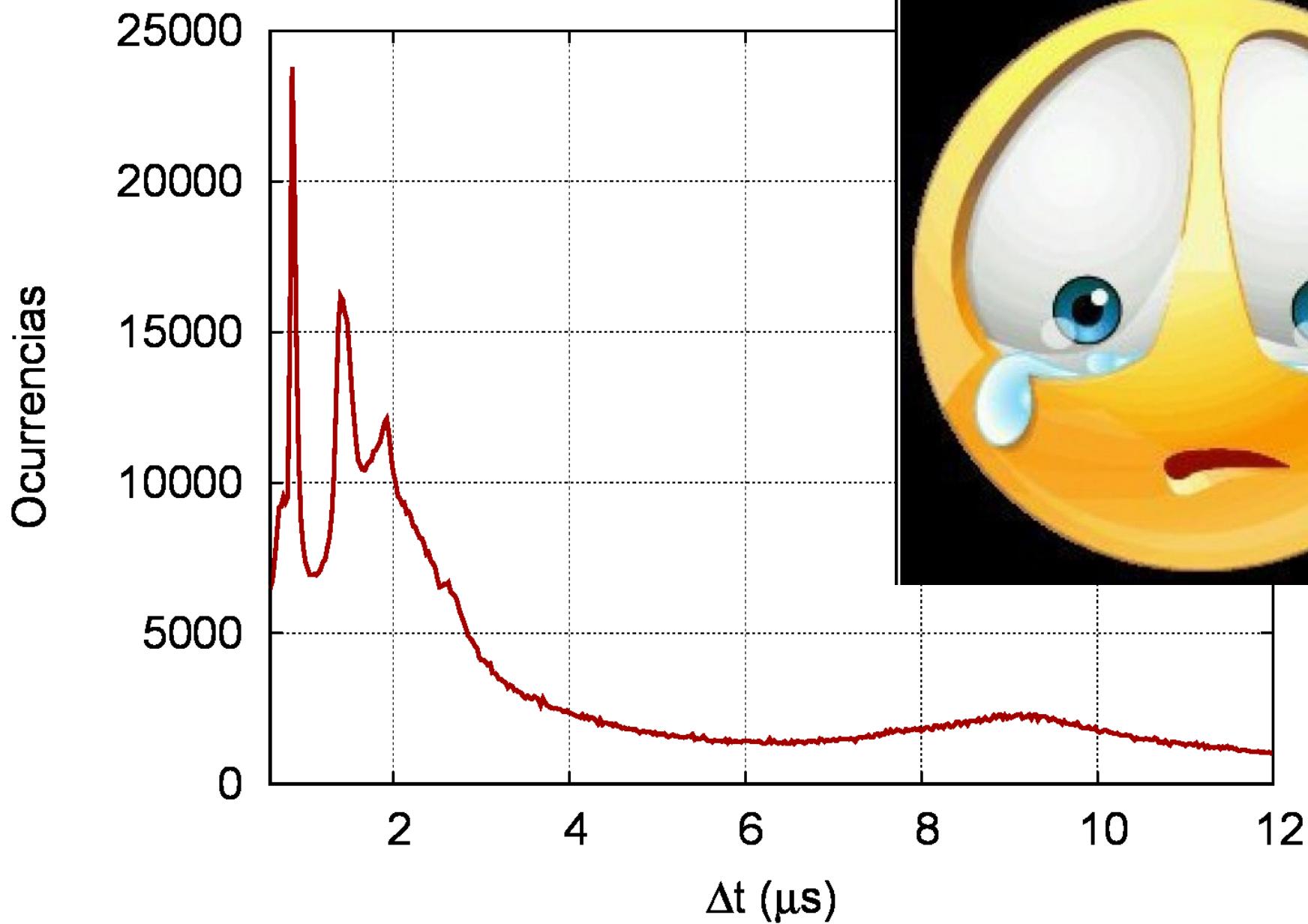
Teórica vs Experimental



Teórica vs Experimental



Teórica vs Experimental

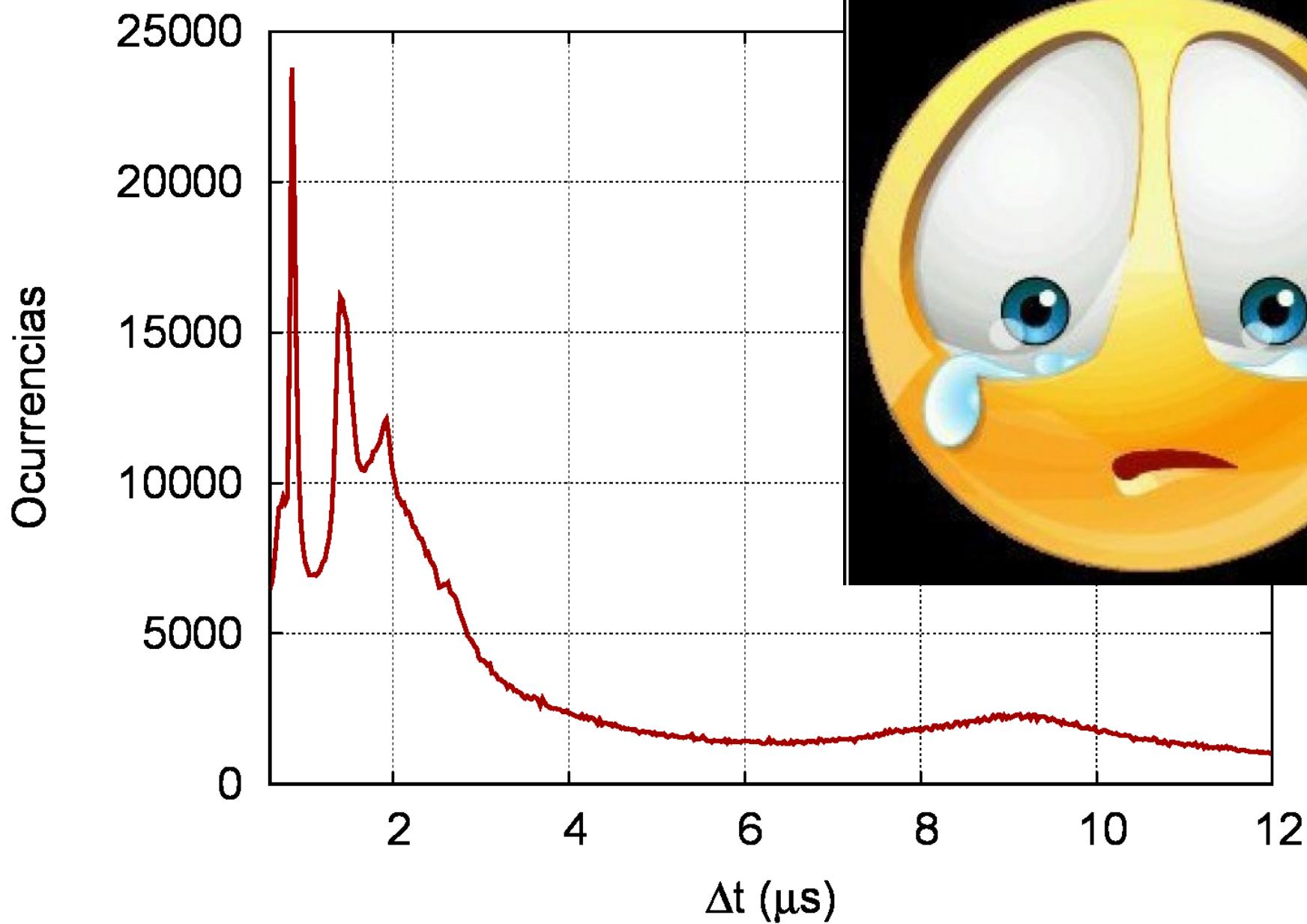




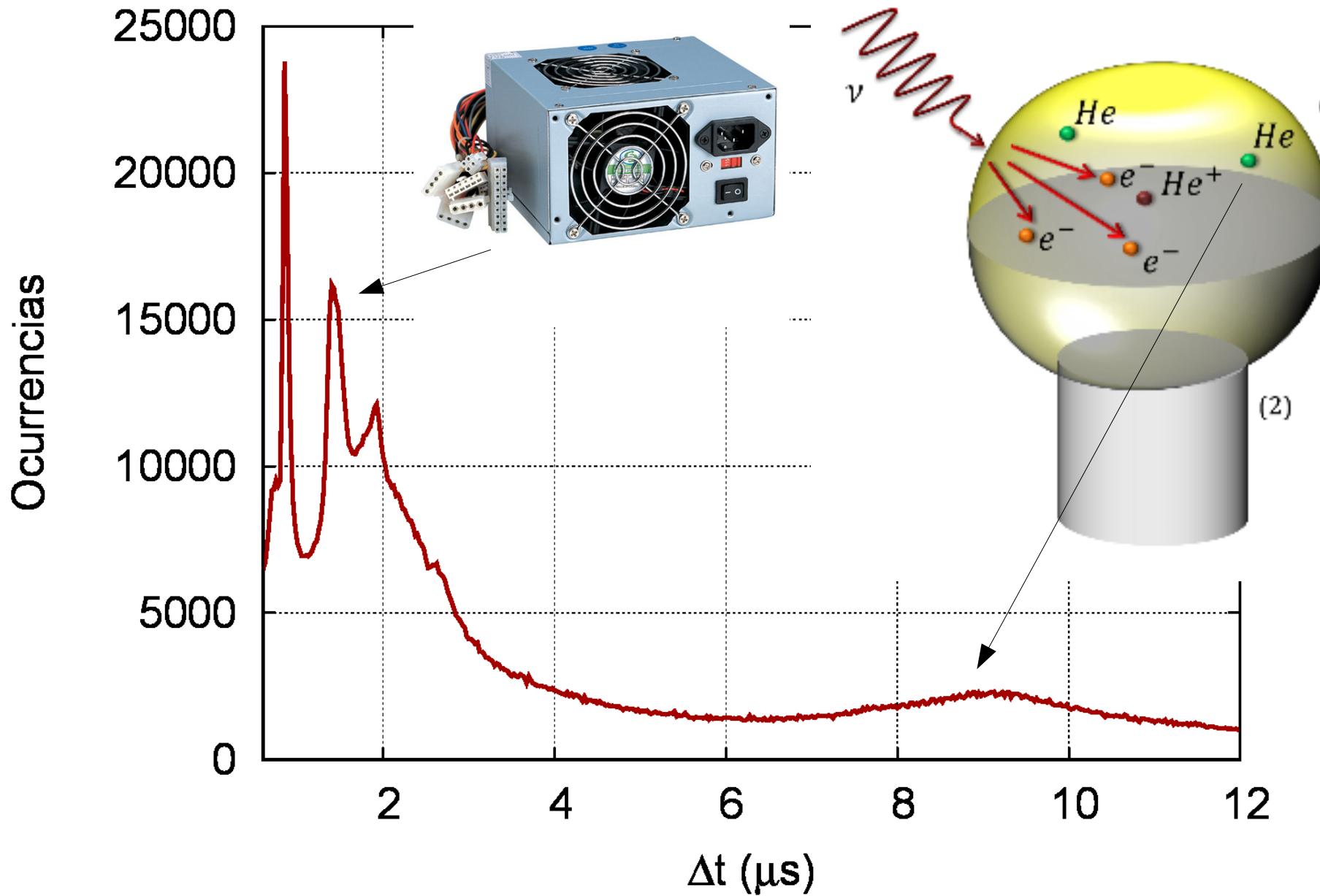
¿Qué significan esos picos?

- Un pico en el histograma de tiempos significa que hay sucesos que ocurren a un “rate” constante
 - Pensemos en un reloj: tengo un pulso cada segundo
- Aquí tenemos una distribución en torno a un valor
 - ¿Relojes? ← Fuentes comutadas
 - ¿Propagación? ← “Afterpulses”:
 - Un photoelectrón ioniza al Helio
 - El ión He^+ migra hacia el photocátodo
 - El ión produce un nuevo photoelectrón
 - El photoelectrón es un pulso nuevo
 - !!!El tiempo entre pulsos depende de la geometría del PMT!!!

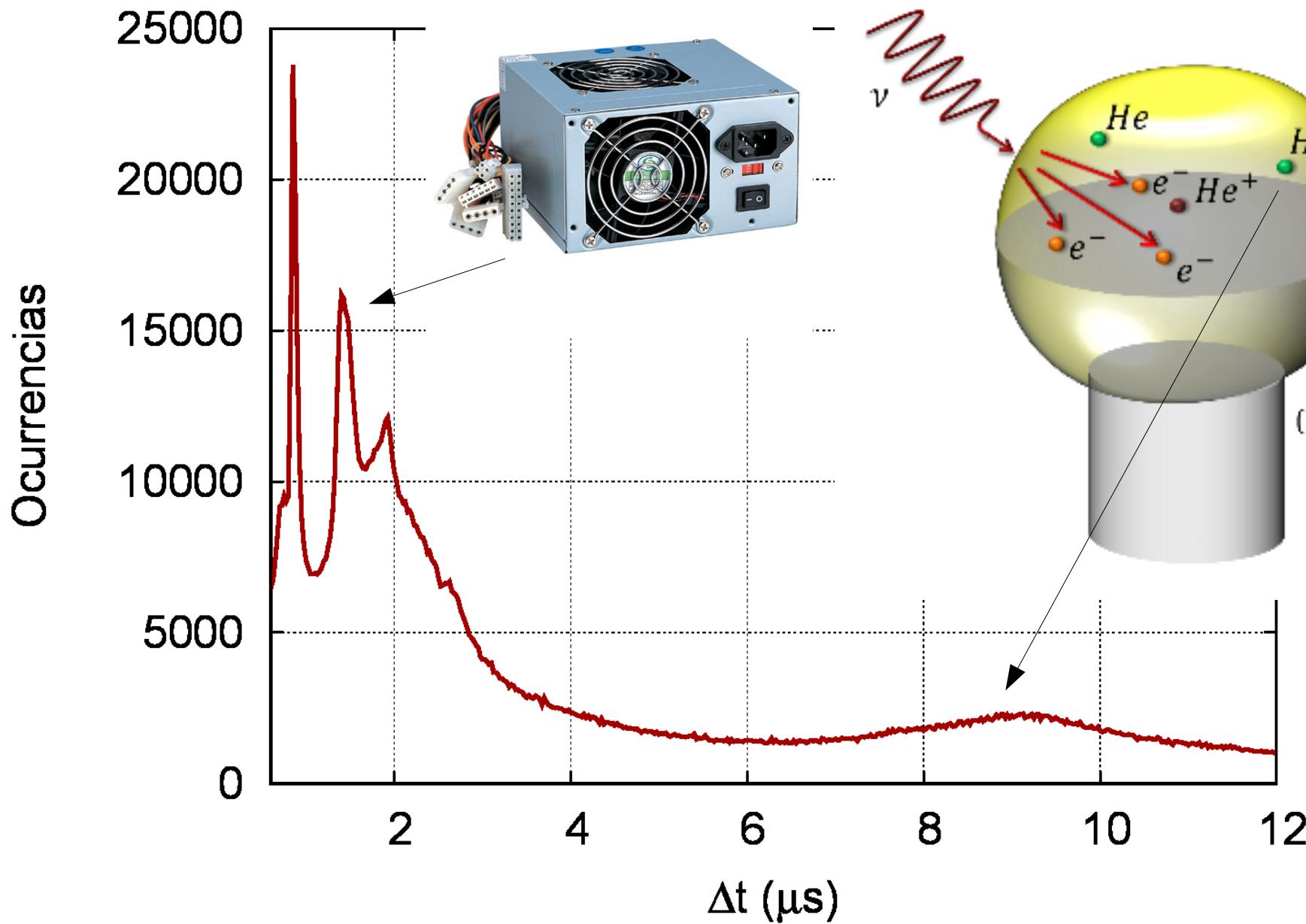
El experimento contraataca



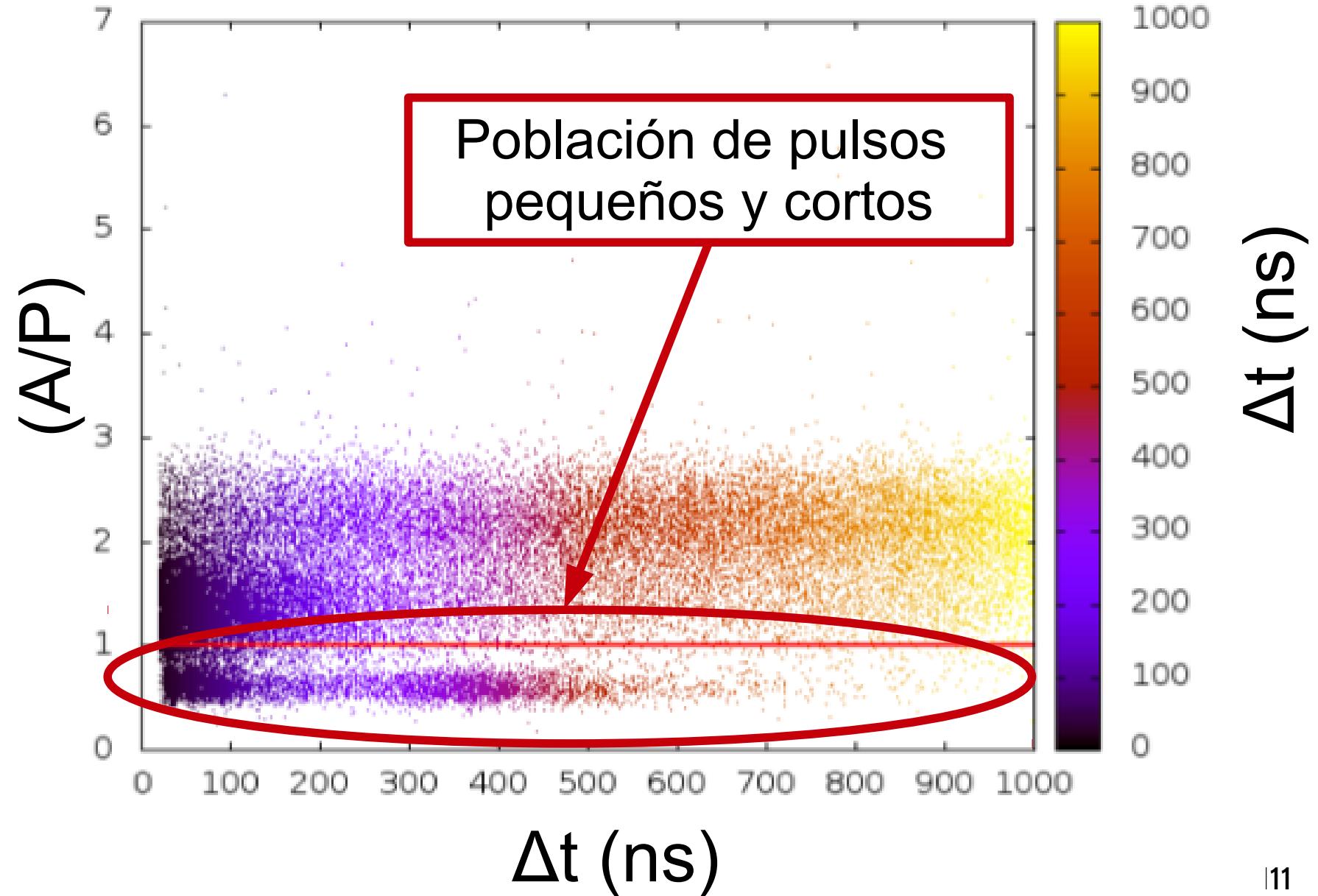
El experimento contraataca



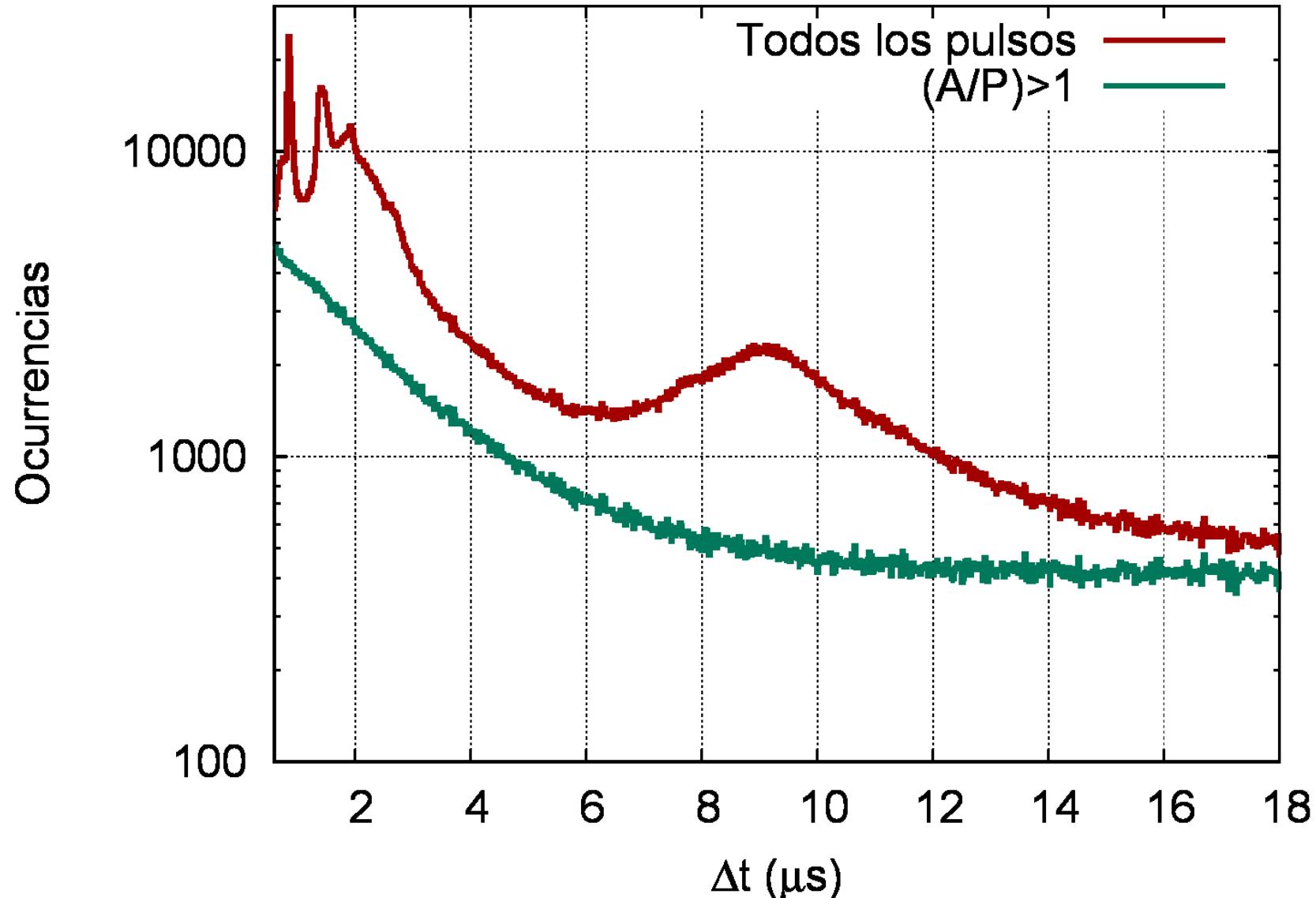
El experimento contraataca



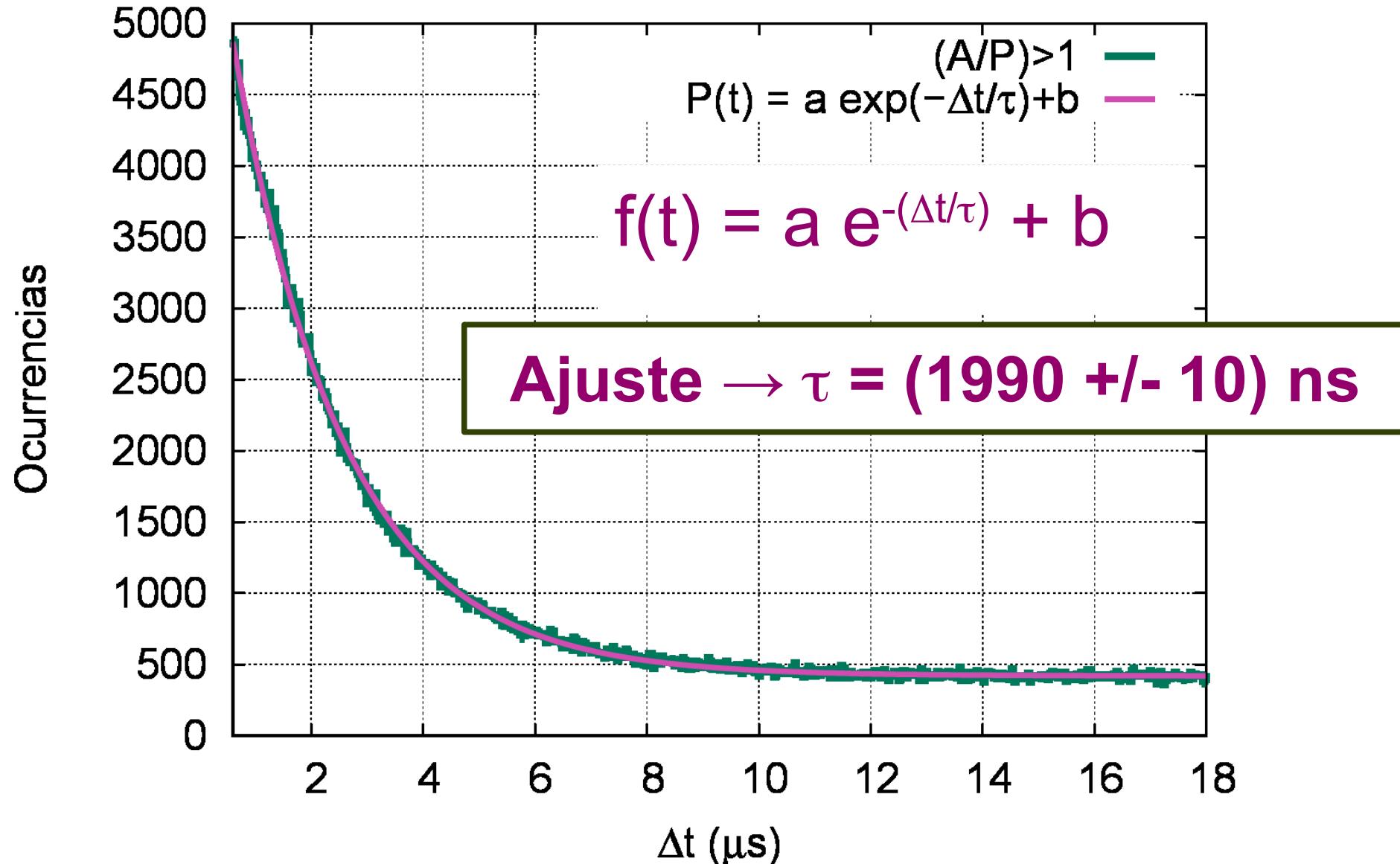
Área/pico vs dt



Solución: Quitar picos si $A/P < 1$, o imponer una segunda condición de trigger



Diferencia de tiempo entre pulsos



Muón en el agua

- Muón en agua

- $\mu^+ \rightarrow$ Libre

Tiempo Decaimiento muon negativo
Ajuste $\rightarrow \tau_{\mu^-} = (1.86 \pm 0.02) \mu s$

- $\mu^- \rightarrow$ Prob. de captura nuclear (similar a la c.e.):

- $\propto Z^4$ del medio

- Alta absorción en ^{35}Cl y ^{36}Cl (lejía, lavandina, NaClO)

- Procesos que compiten para el μ^- :

- Decaimiento
 - Captura

Sólo decaen los que no son absorbidos

$$\tau_{\mu^-} < \tau_0$$

- $\lambda_{\text{obs}} = (N^+ \lambda^+ + N^- \lambda^-) / (N^+ + N^-)$

- Se puede medir la relación N^+/N^-

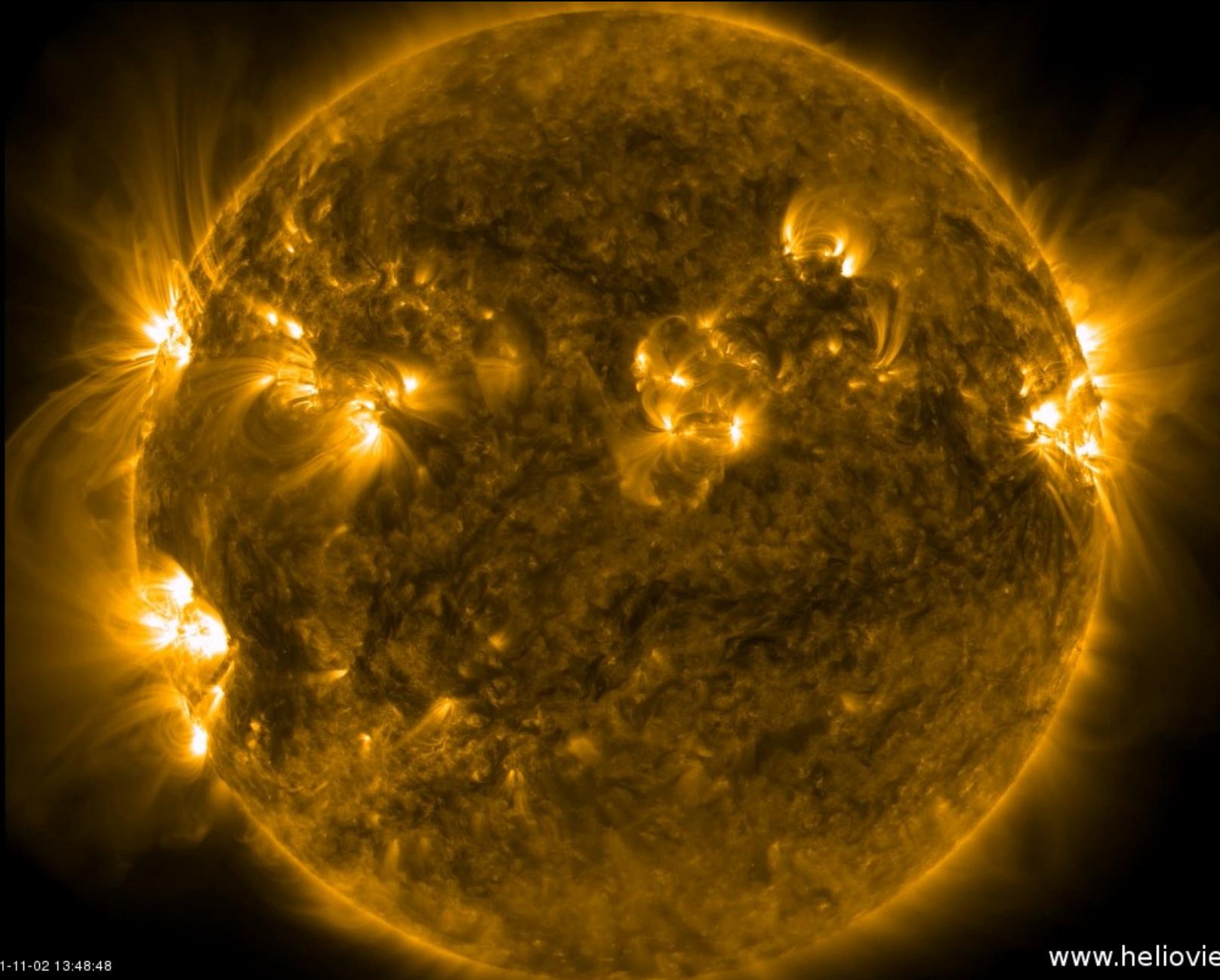
Vida Media del muón en su Universidad

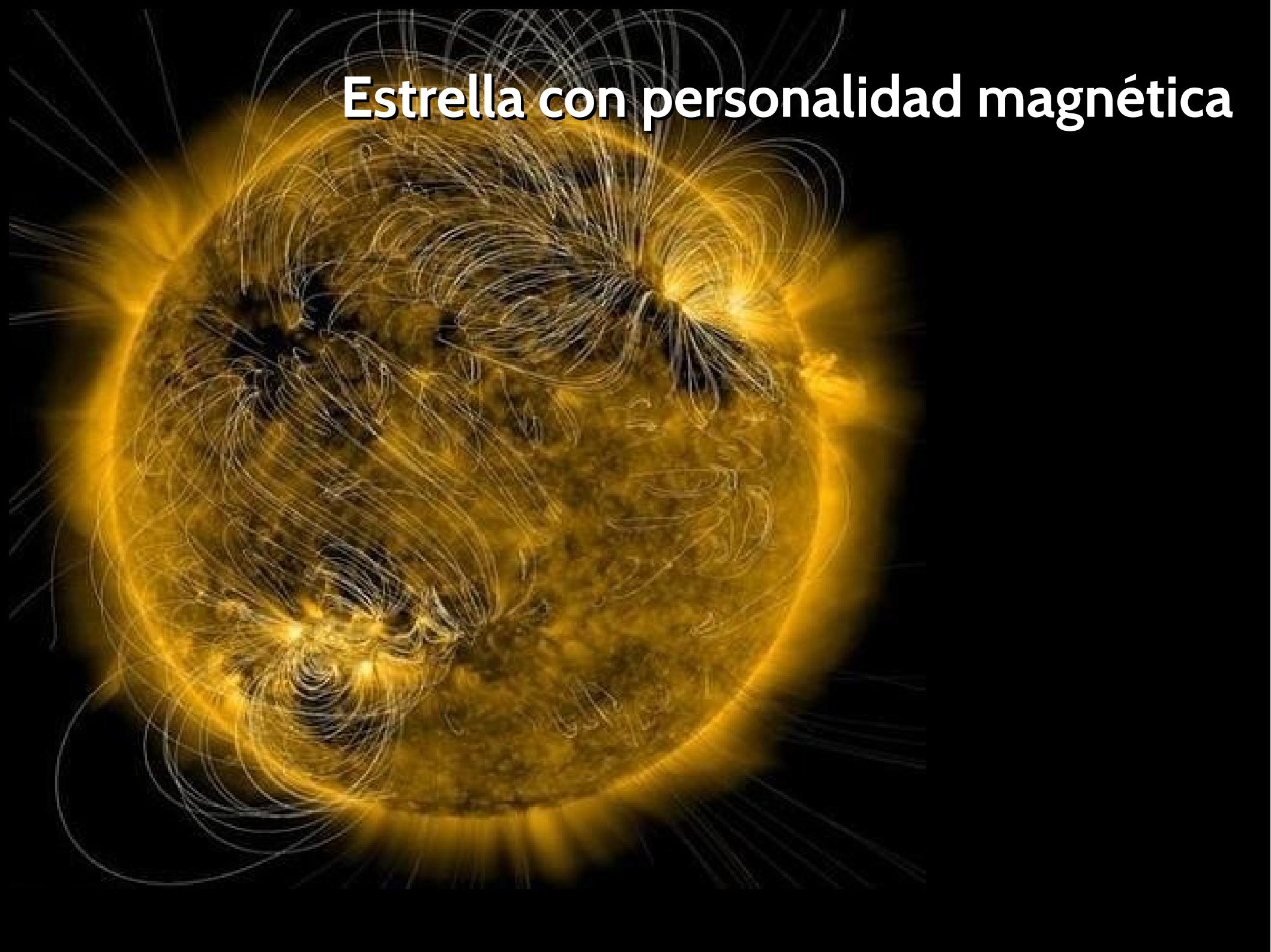
- Vida media en agua (transparencia) y efecto de impurezas
- Relación N^+/N^- como función de la altura
- Mediciones relativistas
- Espectro de Michel del electrón resultante
 - Medición indirecta de la existencia del neutrino (energía faltante)
- Constante de acoplamiento electrodébil ($\tau_\mu \propto g_F$)
- Caracterización de los “afterpulses” de los PMT
- Distribución de señales en el fondo y su variación → Solar
- Medir otras partículas con fuentes (Fuente de neutrones Am-Be)
- Técnicas de análisis de datos complejos

Clima Espacial y RC



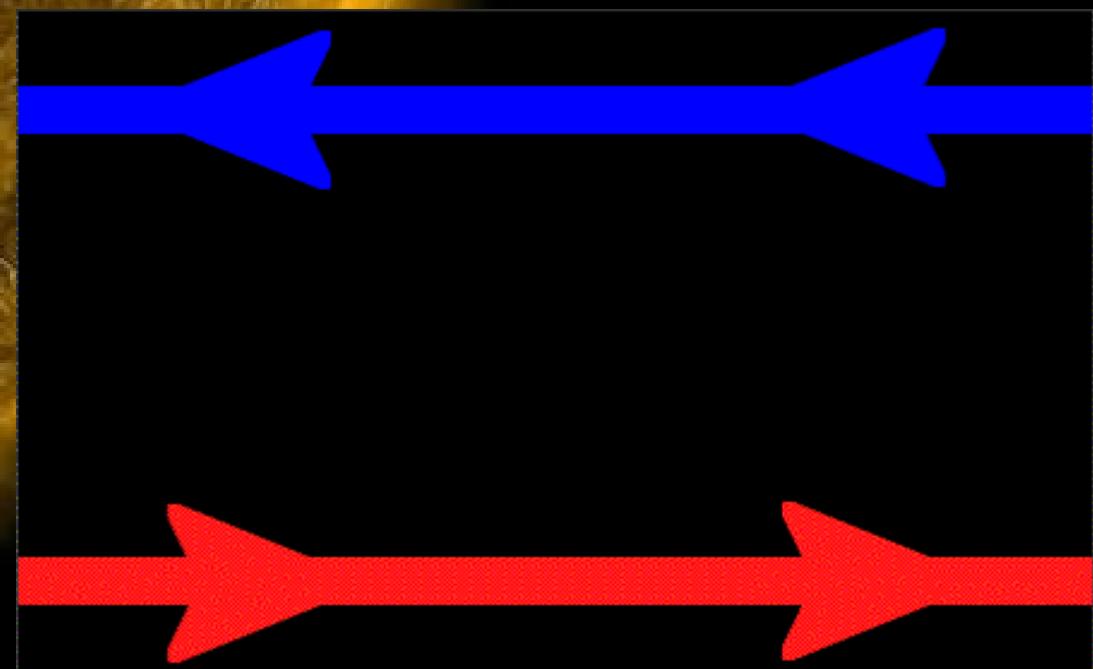
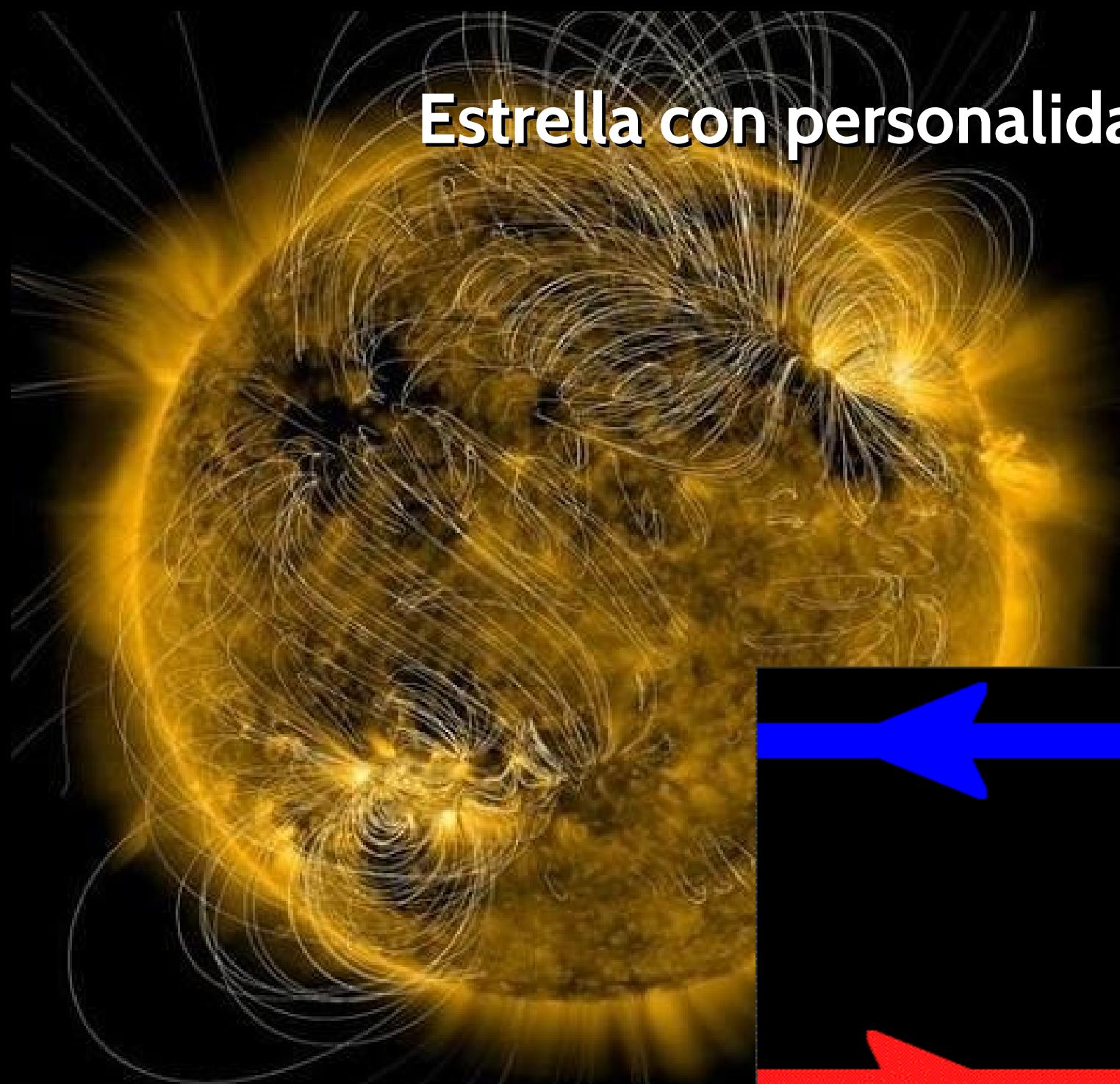
Nuestra Estrella, el Sol



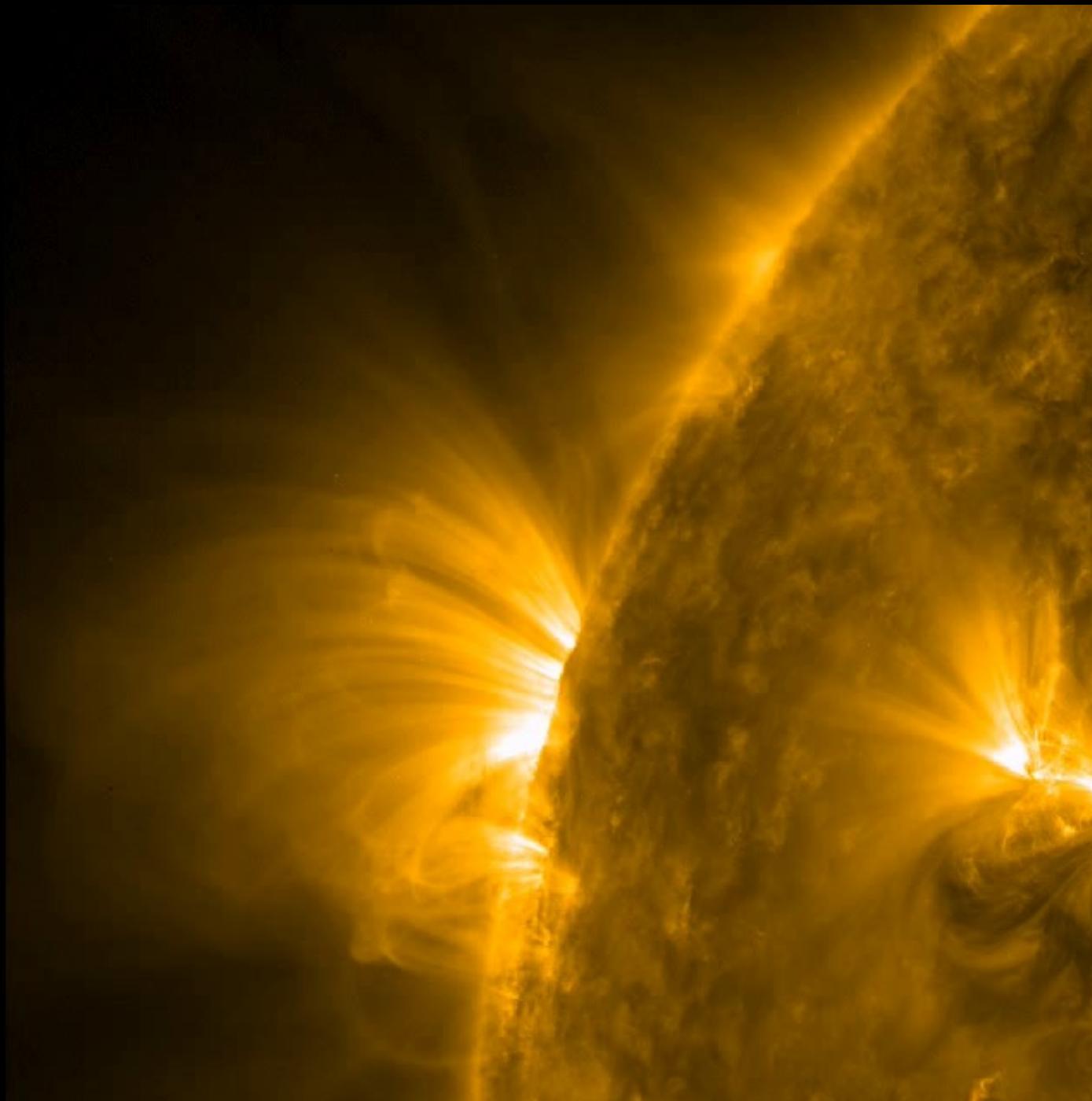
A detailed scientific illustration of a star's surface. The star is depicted in shades of yellow and orange, with a complex network of dark, swirling magnetic field lines visible across its surface. Intense, bright yellow and white regions, representing solar flares or active zones, are scattered throughout the star's visible disk. The background is a deep black, suggesting the void of space.

Estrella con personalidad magnética

Estrella con personalidad magnética



Eyecciones de masa coronal (CME)

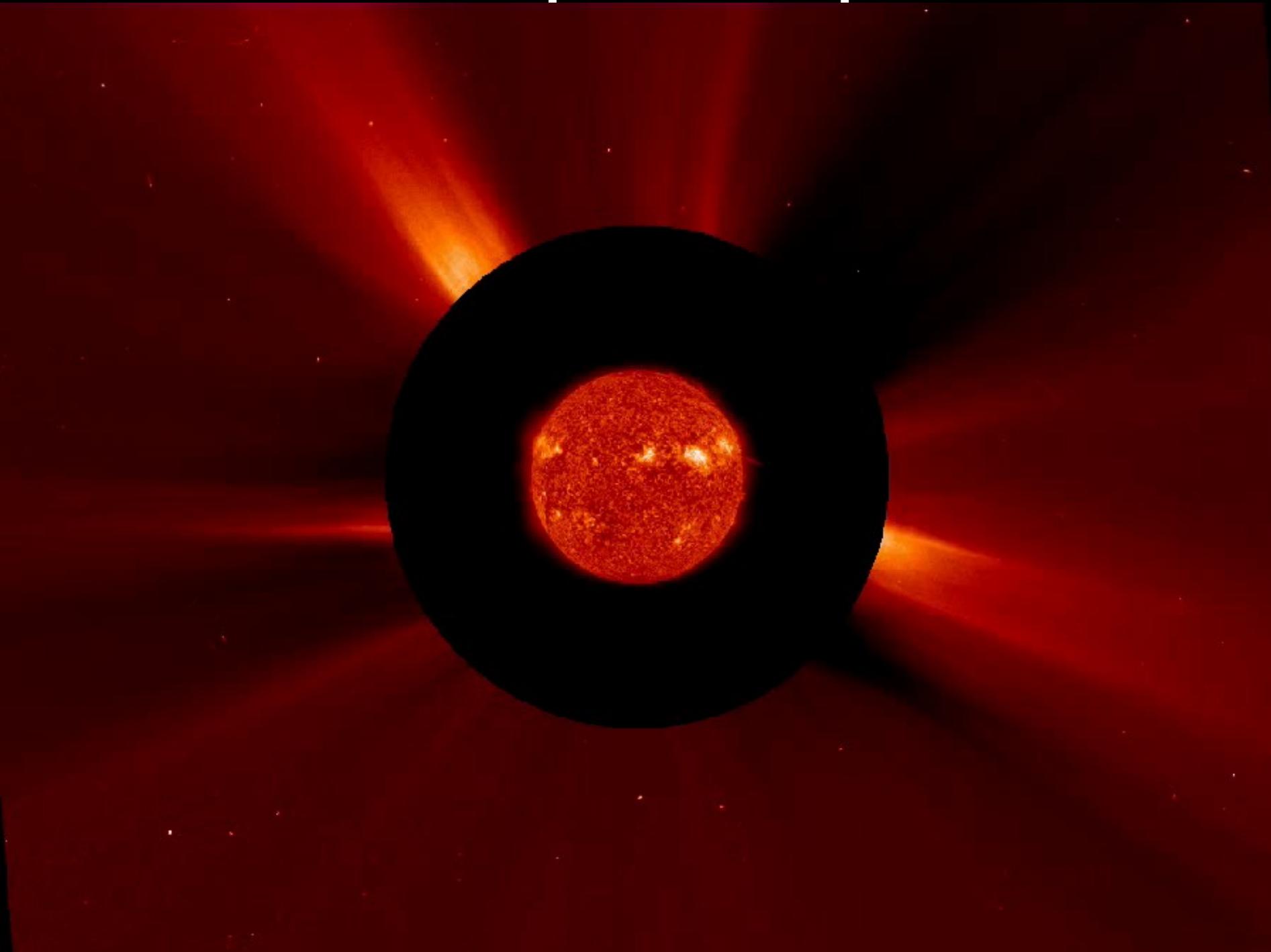


Eyecciones de masa coronal (CME)

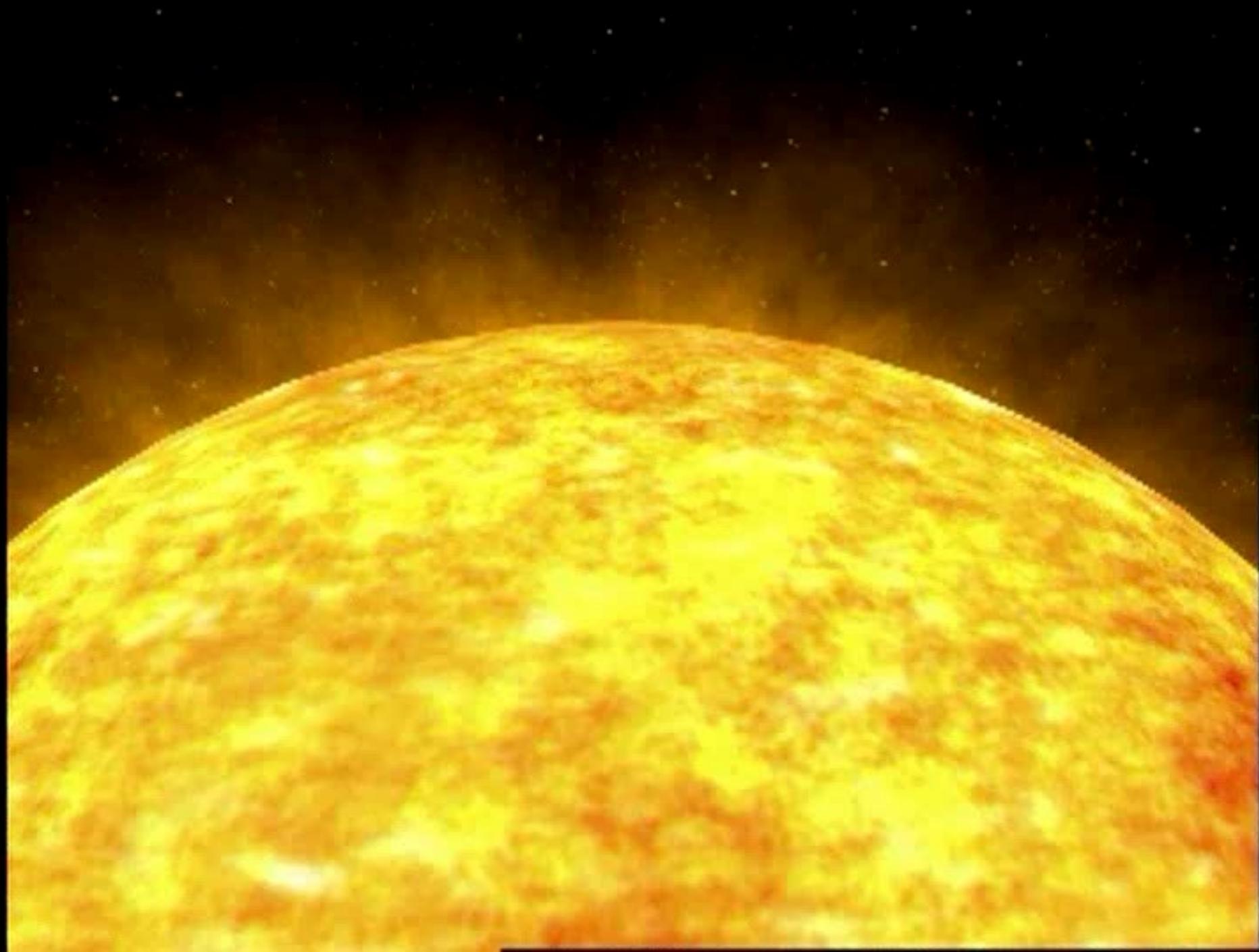


SDO/AIA 304 2011-09-07 22:57:09 UT

en el espacio interplanetario (iCME)



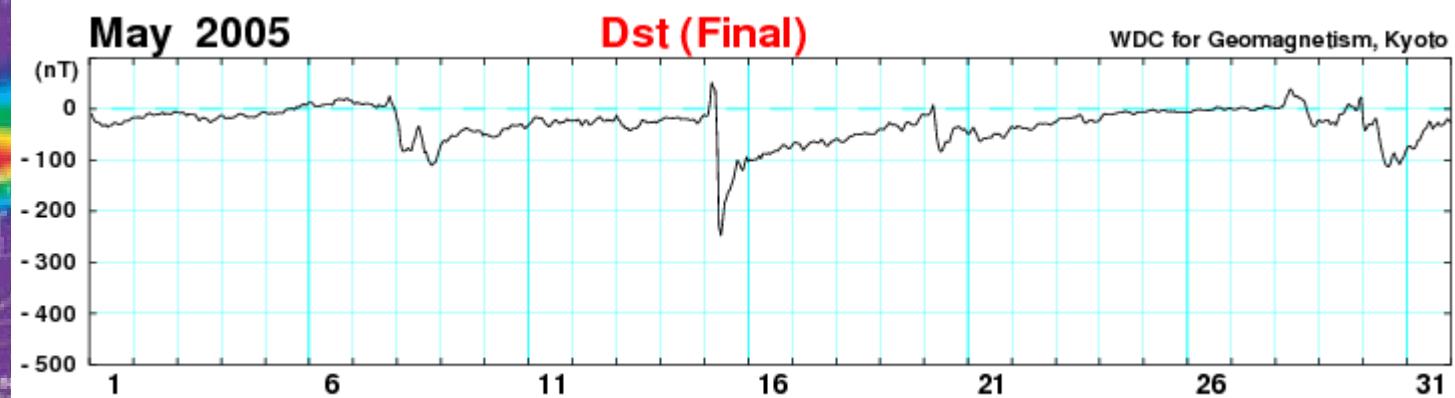
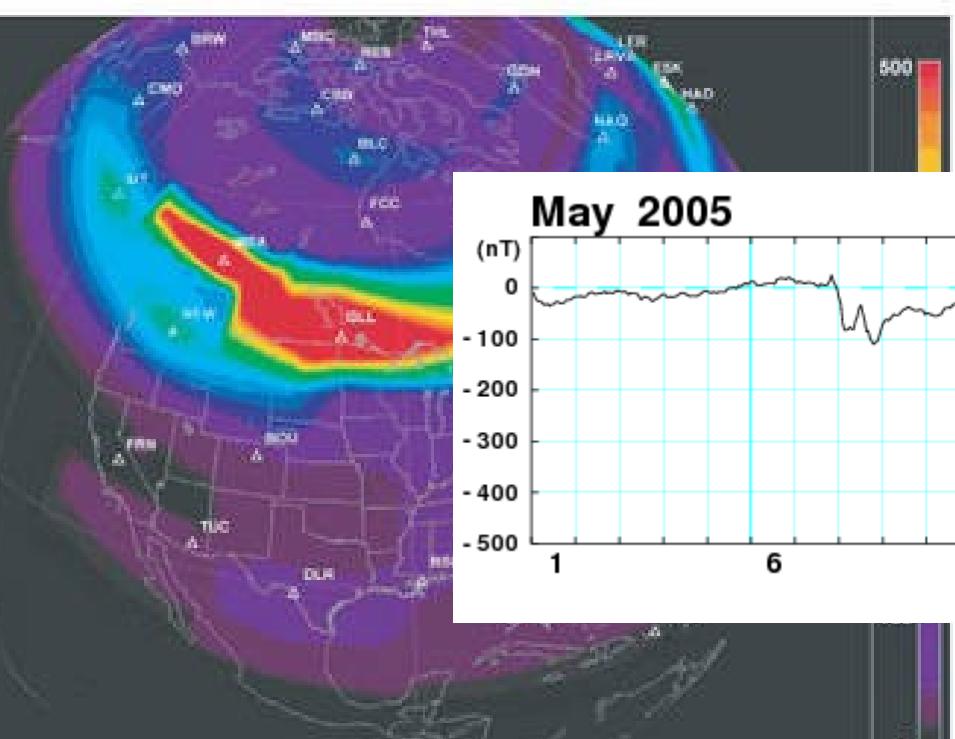
y al llegar a la Tierra



Clima Espacial



Clima Espacial



Geomagnetic field disturbance conditions, dB/dt (nT/min) over North America
7:45 UT on March 13, 1989

Source: Metatech Corporation, Applied Power Solutions



Clima Espacial



Geomagnetic Storm Effects
March 1989

Hydro Quebec Loses Electric Power for 9 Hours

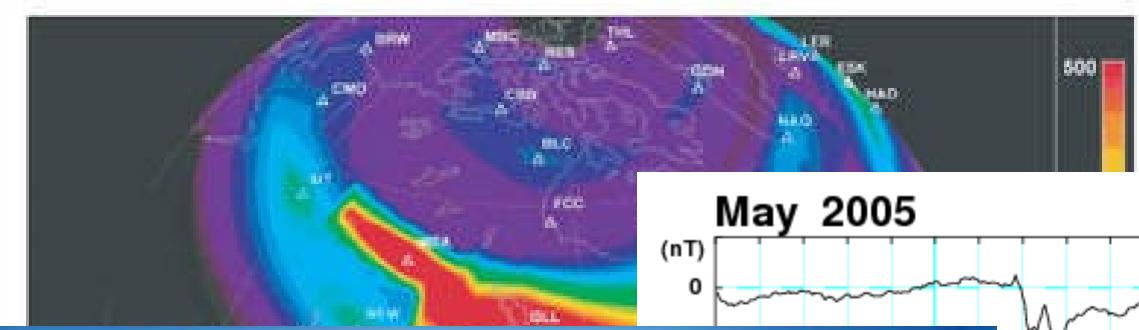
Electric Power Transformer



Transformer Damage



Clima Espacial

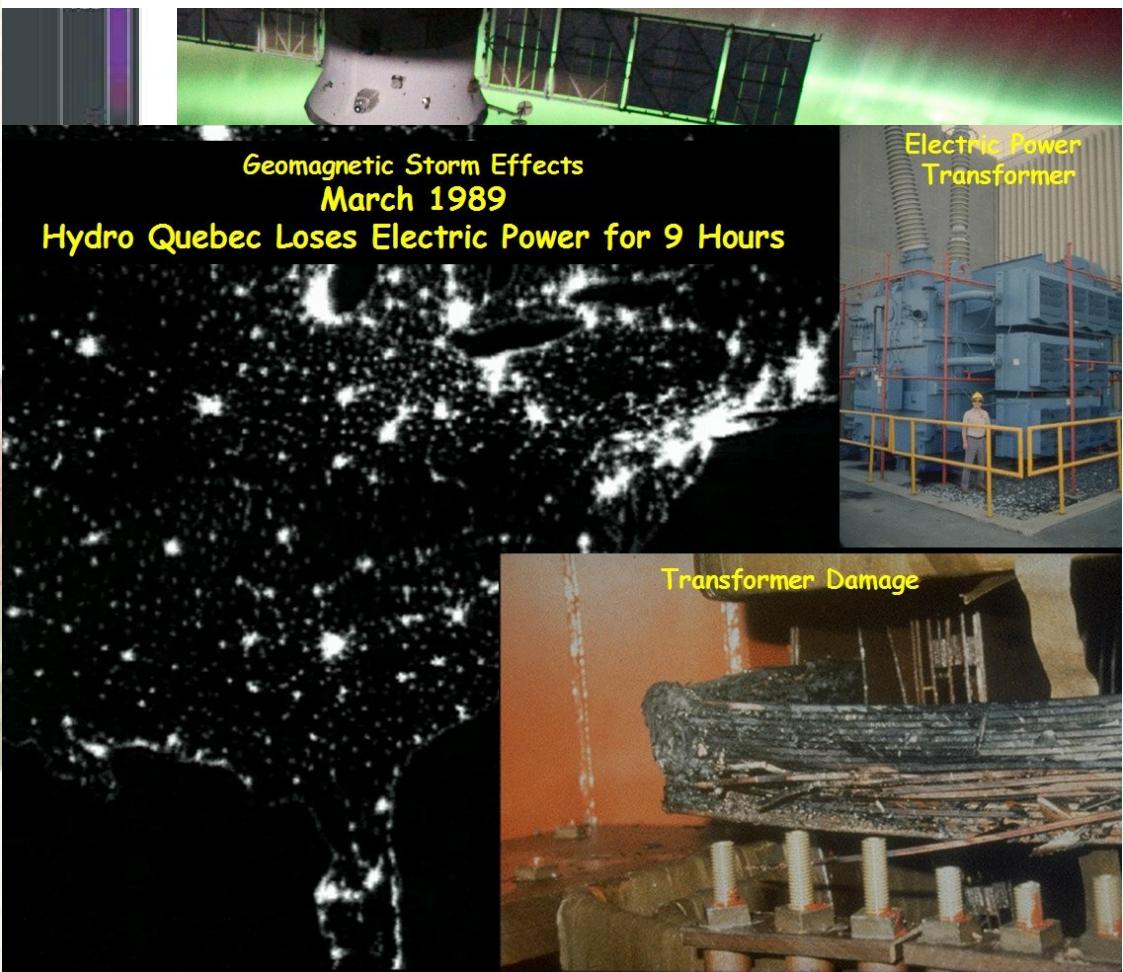


May 2005
(nT)

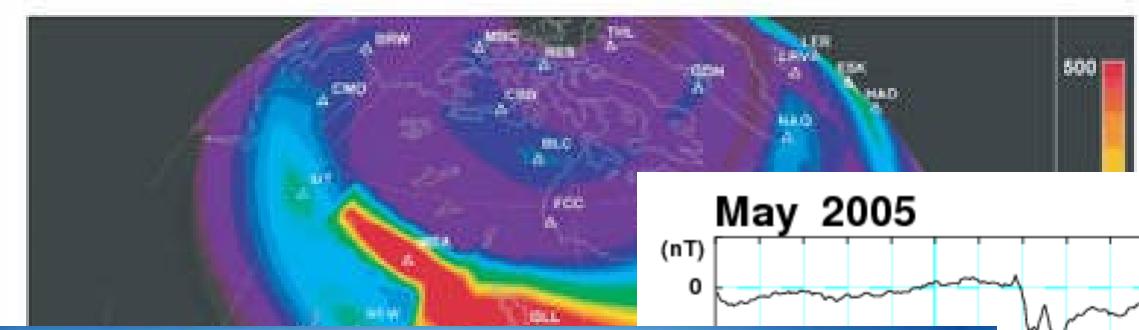


Dst (Final)

WDC for Geomagnetism, Kyoto



Clima Espacial

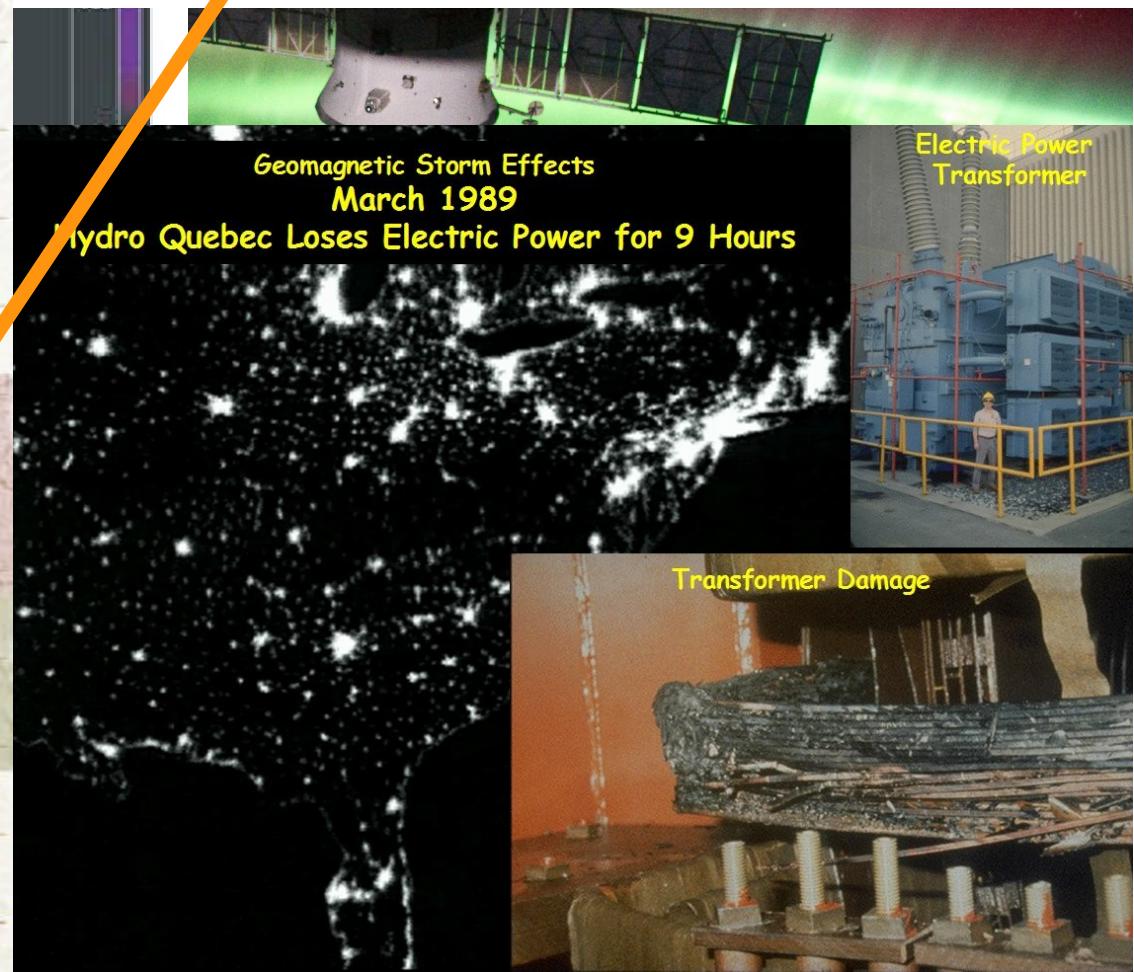


May 2005
(nT)



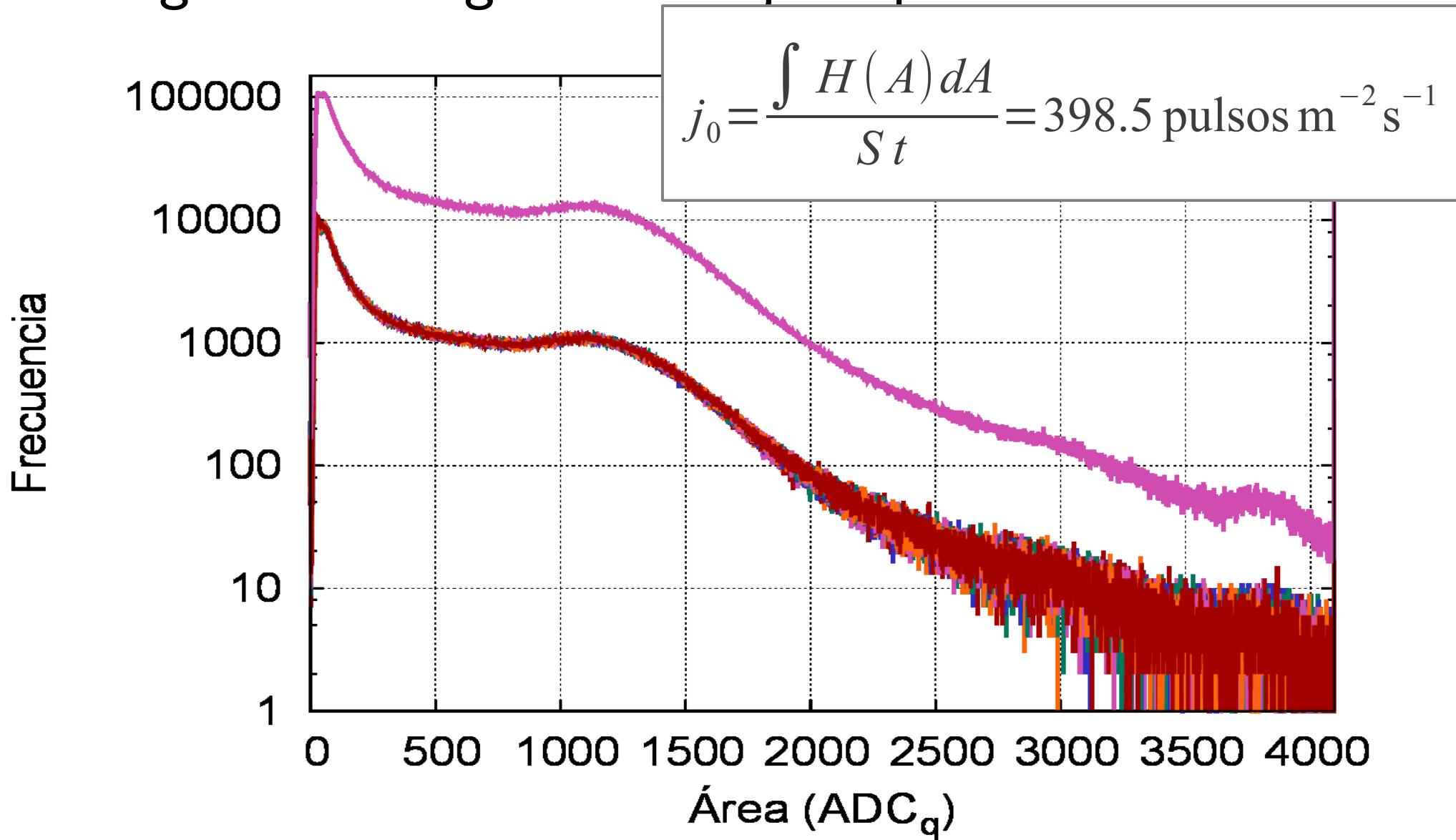
Dst (Final)

WDC for Geomagnetism, Kyoto

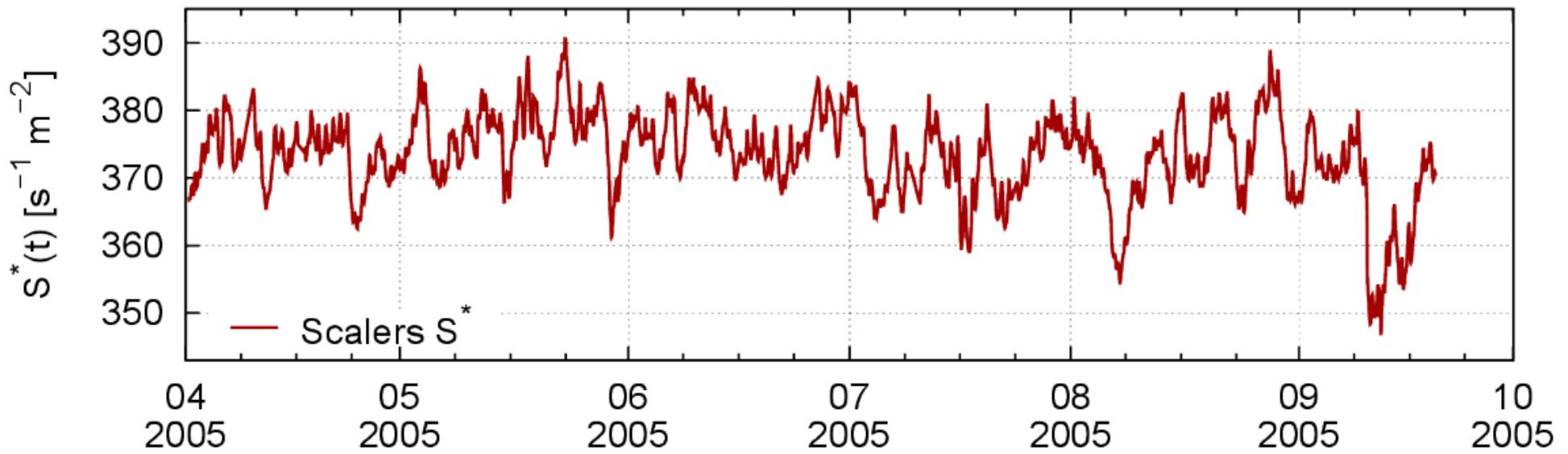


LAGO Space Weather: How to...

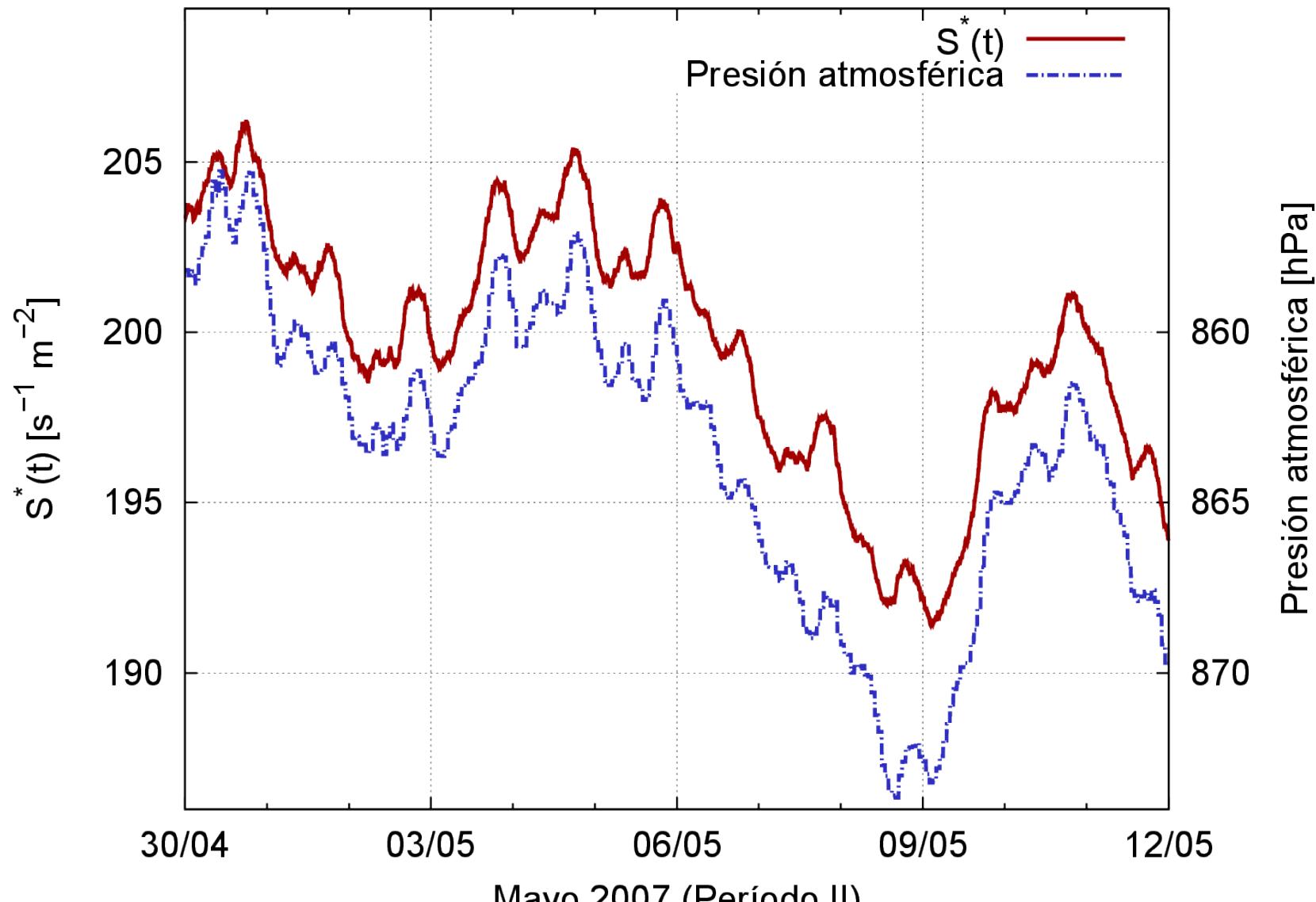
- Integral del histograma → Flujo de partículas



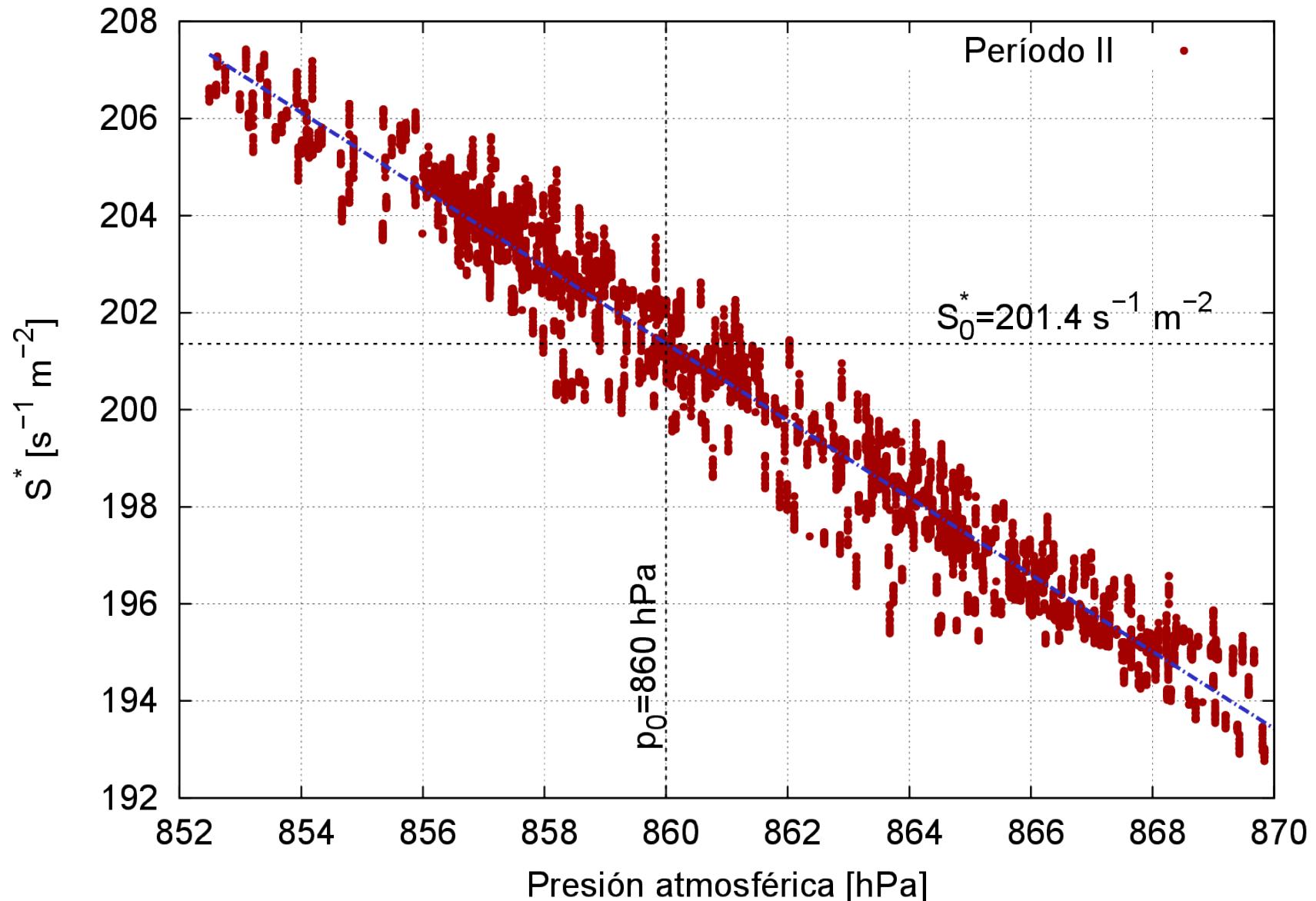
Flujo de secundarios en el detector



Flujo vs (-)presión (anticorrelación)

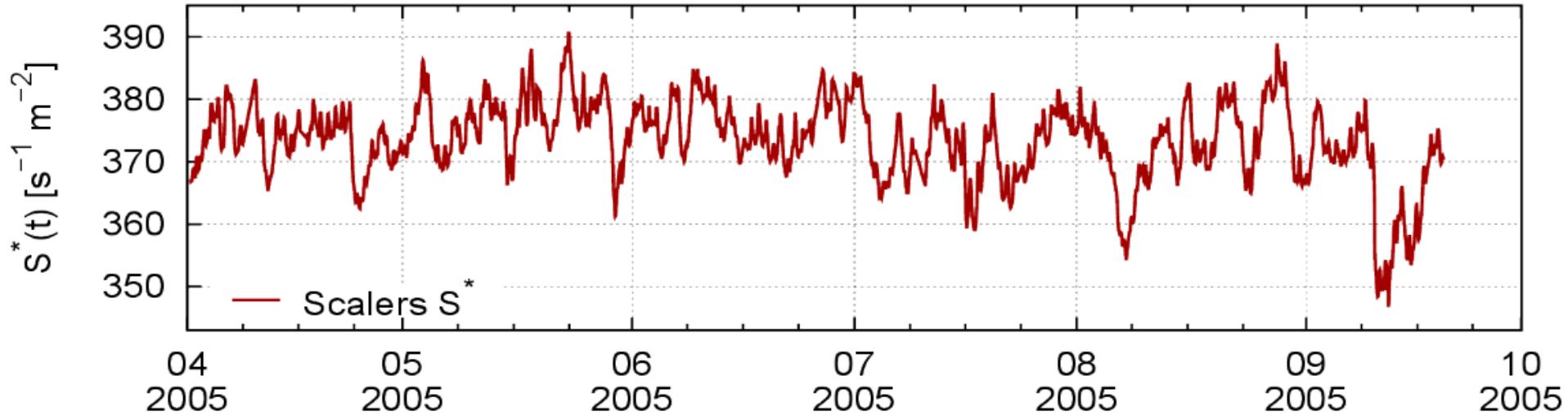


Anticorrelación Flujo vs Patm

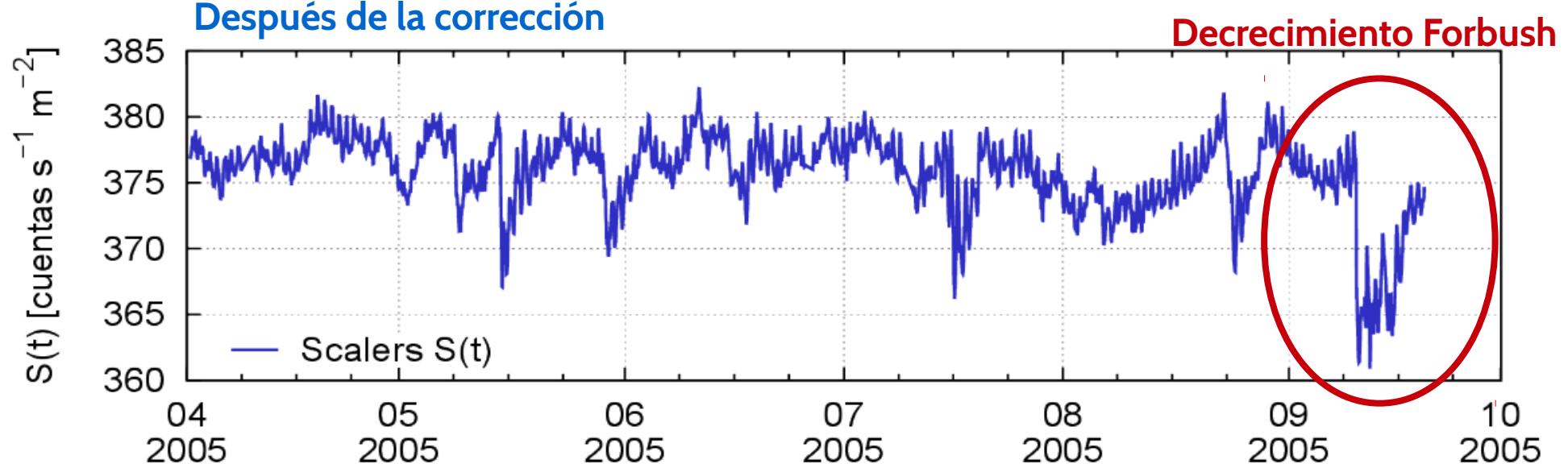


Flujo de secundarios en el detector

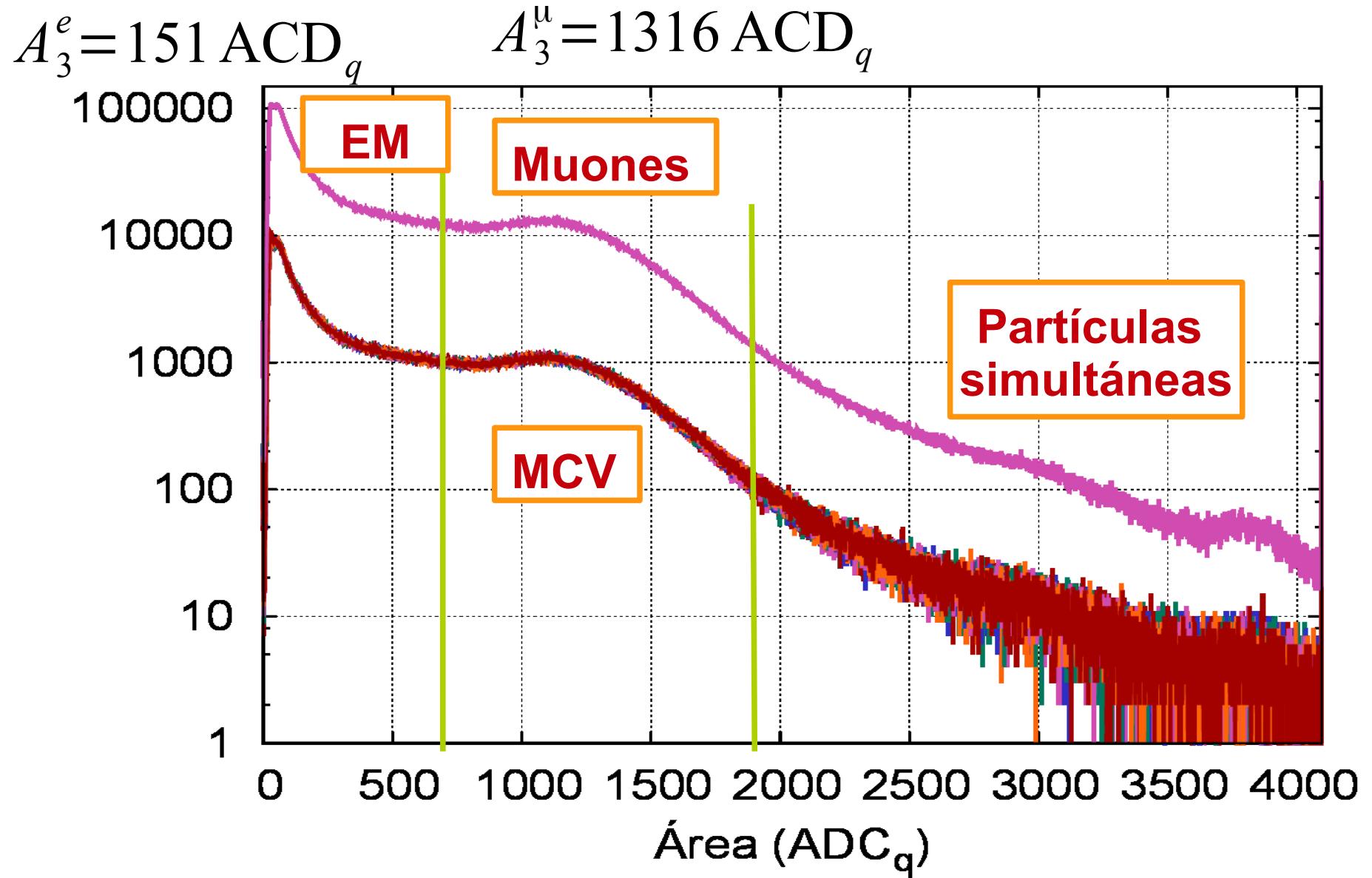
Antes de corregir por efectos atmosféricos



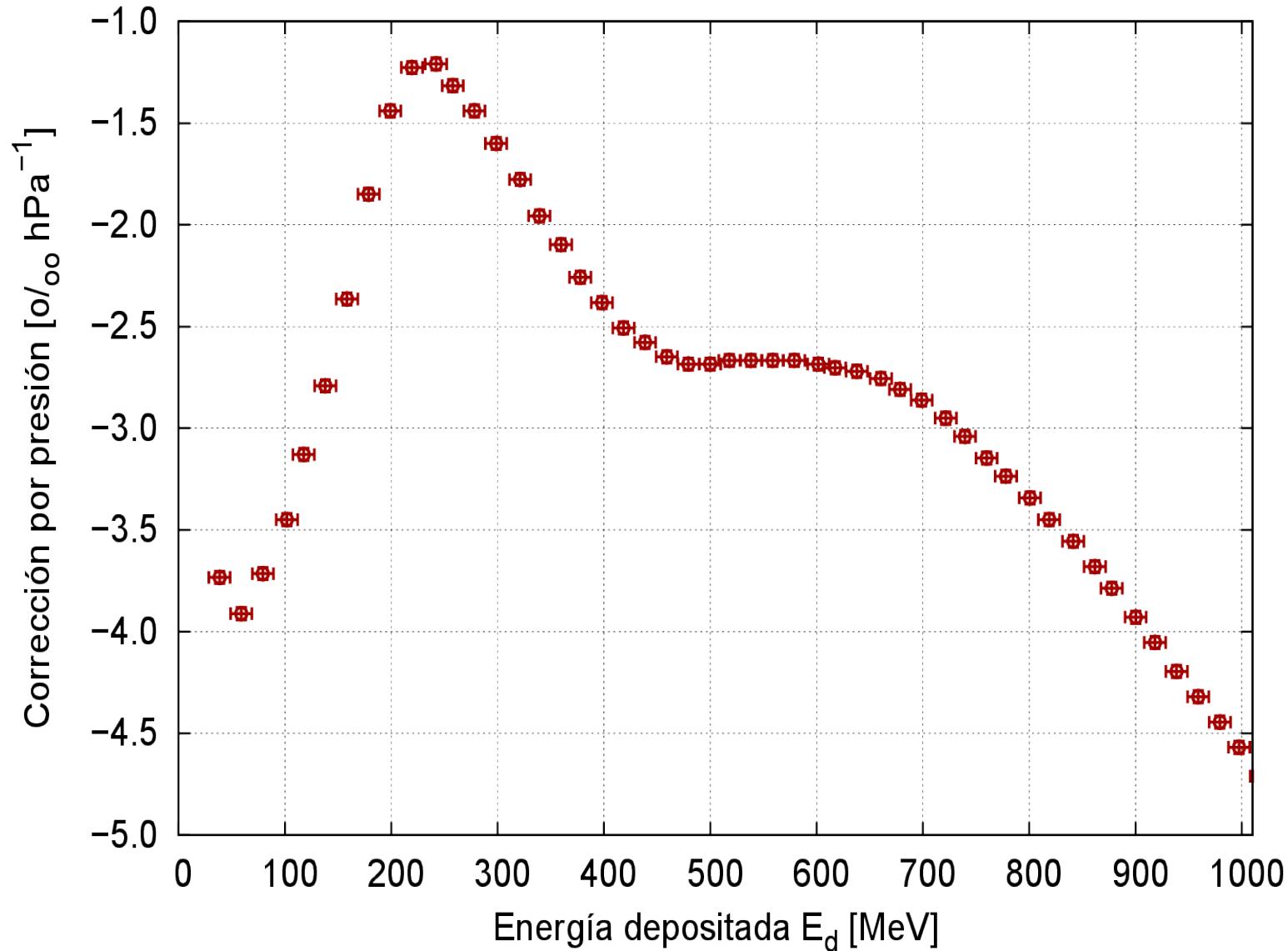
Después de la corrección



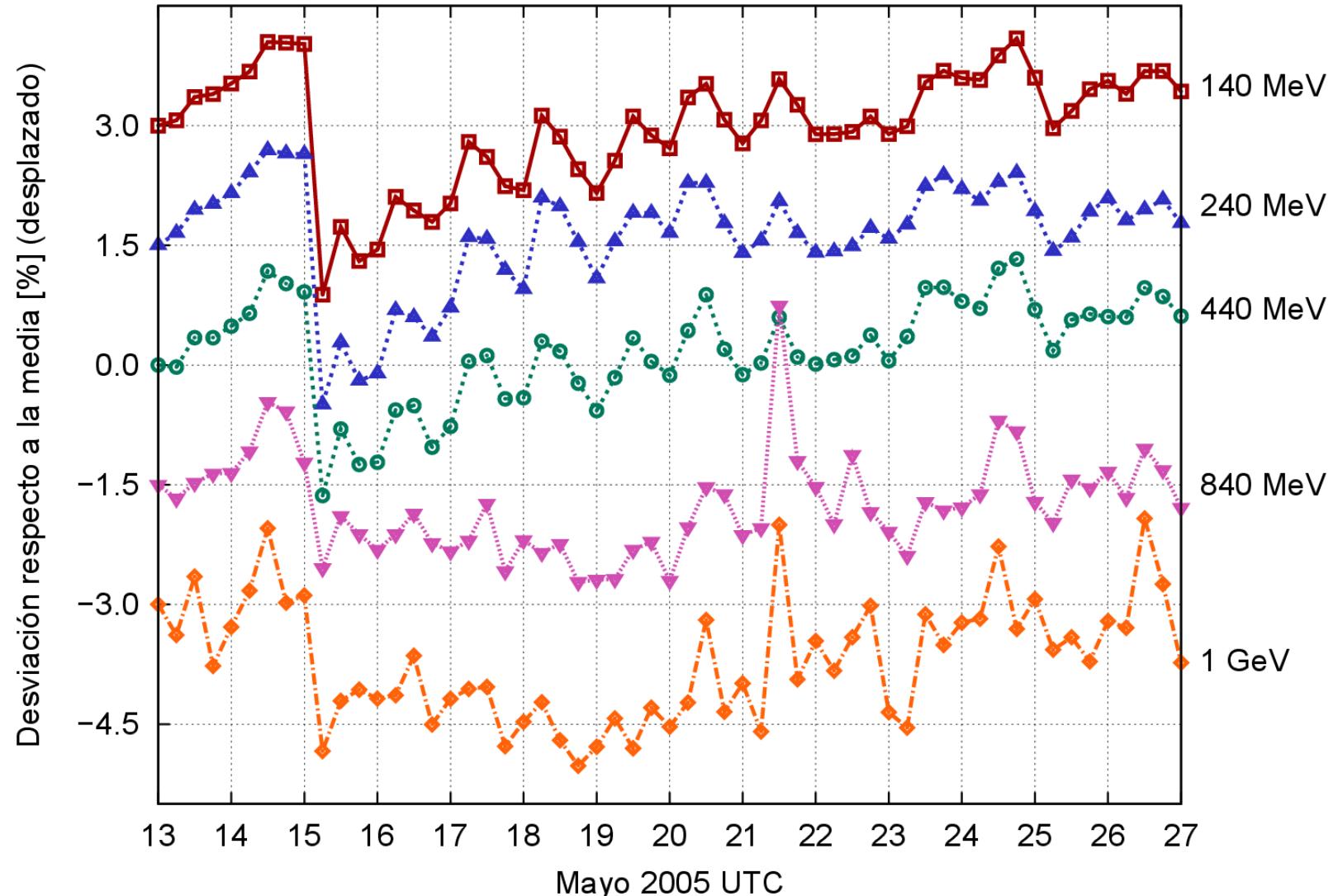
Flujo (Integral) por bandas



Corrección de presión por bandas



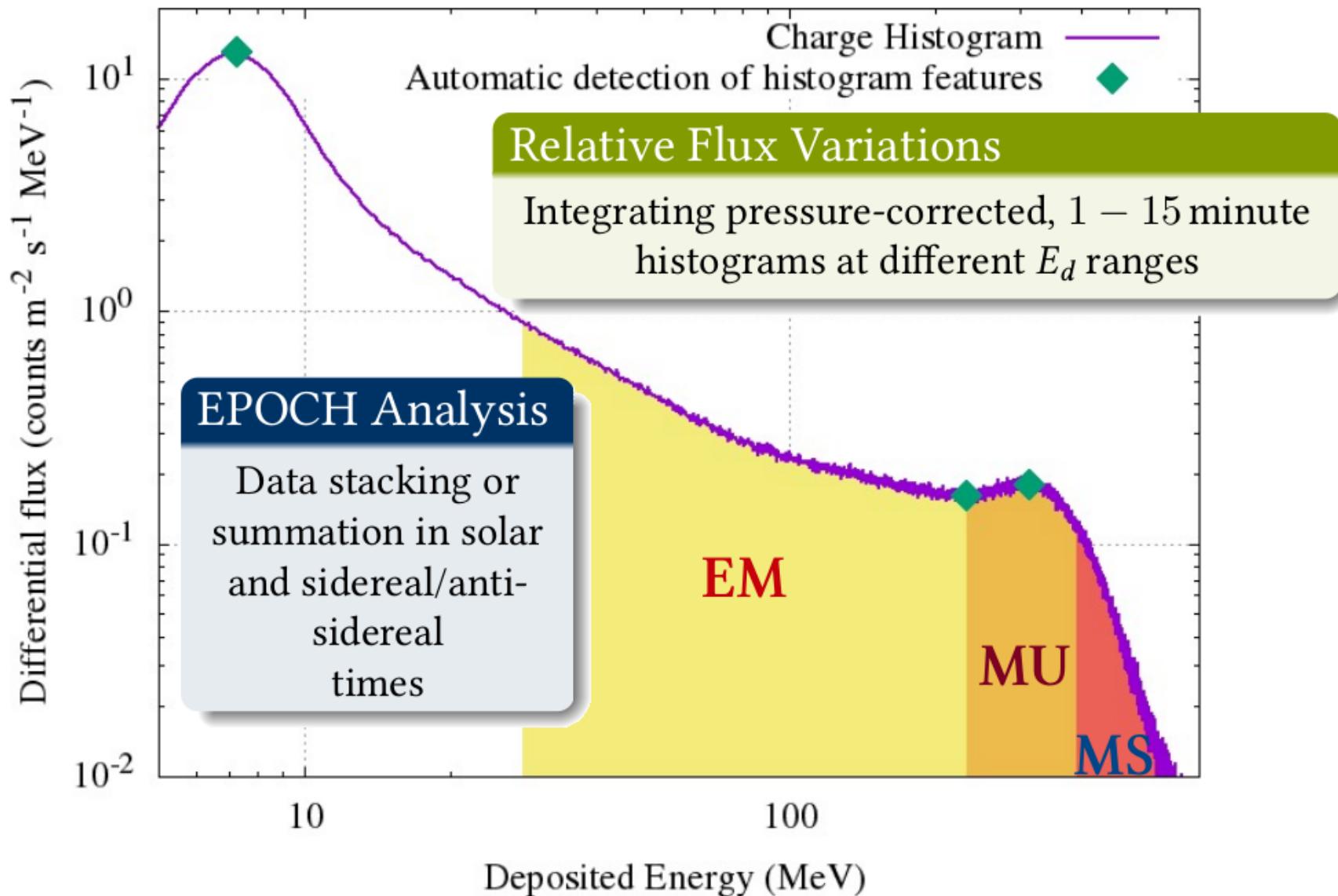
“Tomografía” del Forbush



Análisis MSAT (*multispectral analysis technique*)

Data

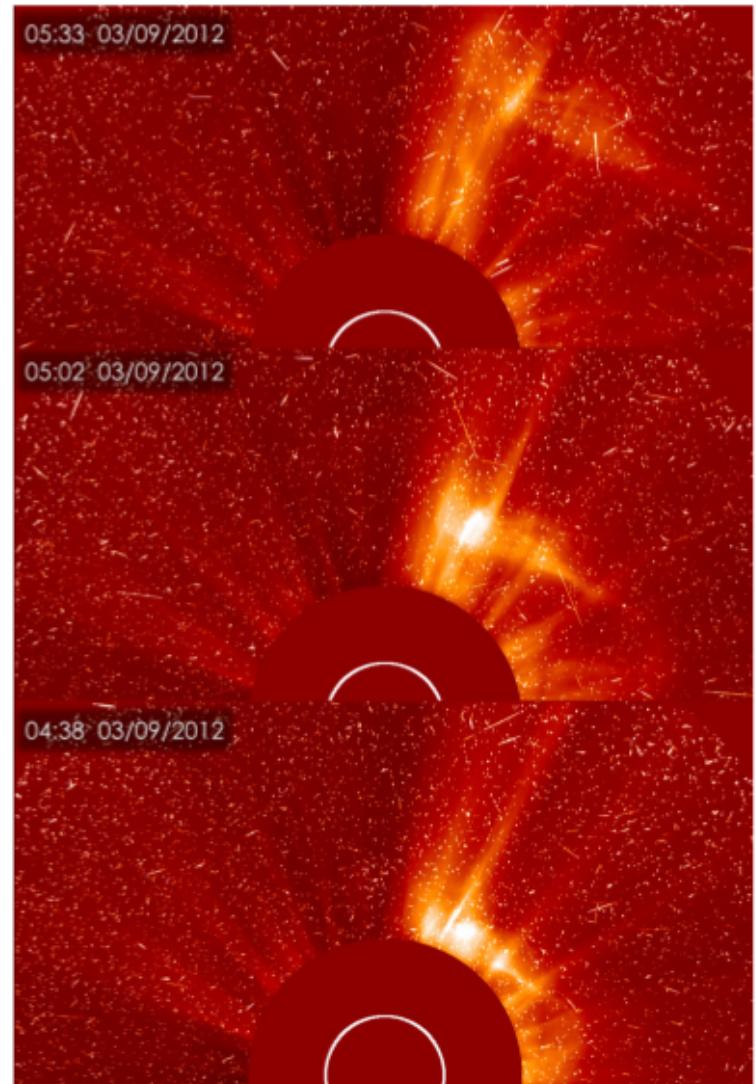
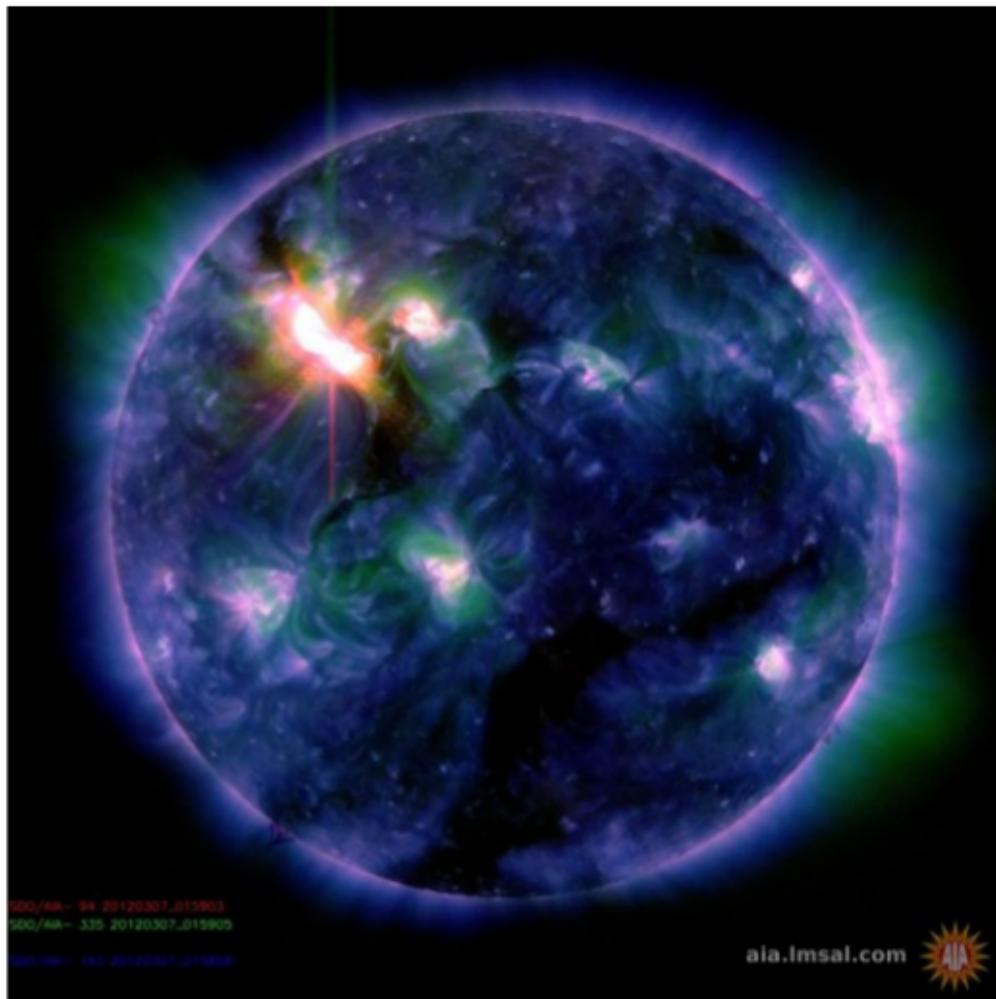
Charge integrated pulse histogram $\xrightarrow[\text{simulations}]{\text{Detector response}}$ deposited energy E_d



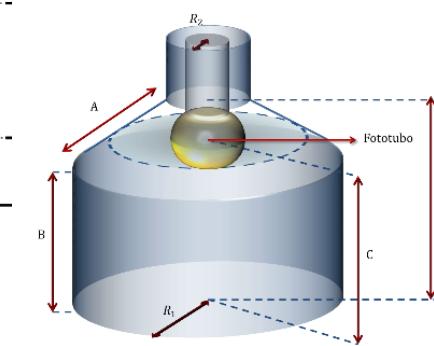
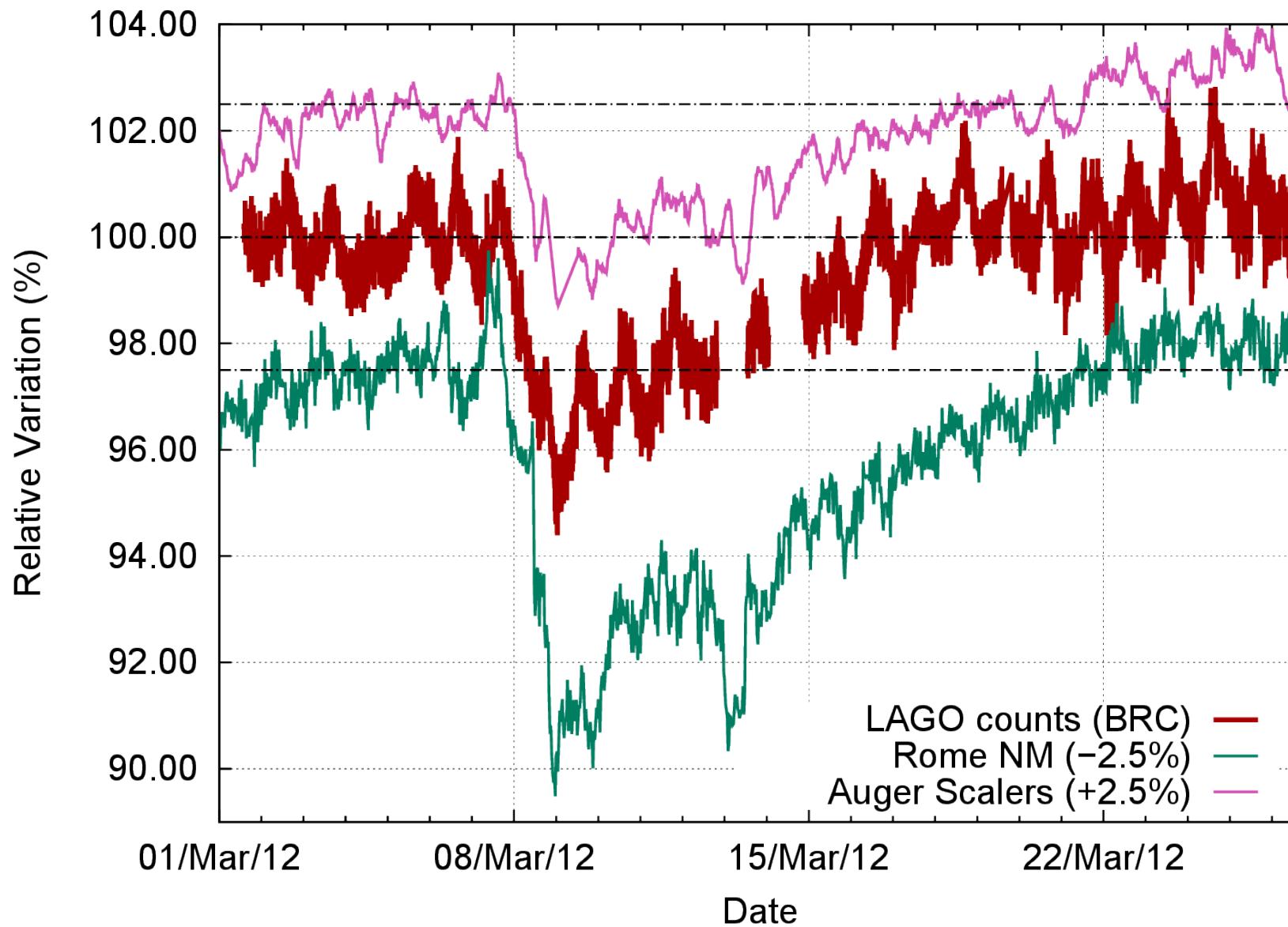
Un caso concreto

March/2012: Solar eruptive event

07/March: X5.4 major solar flare + Halo CME/iCME towards earth + Geomagnetic storm

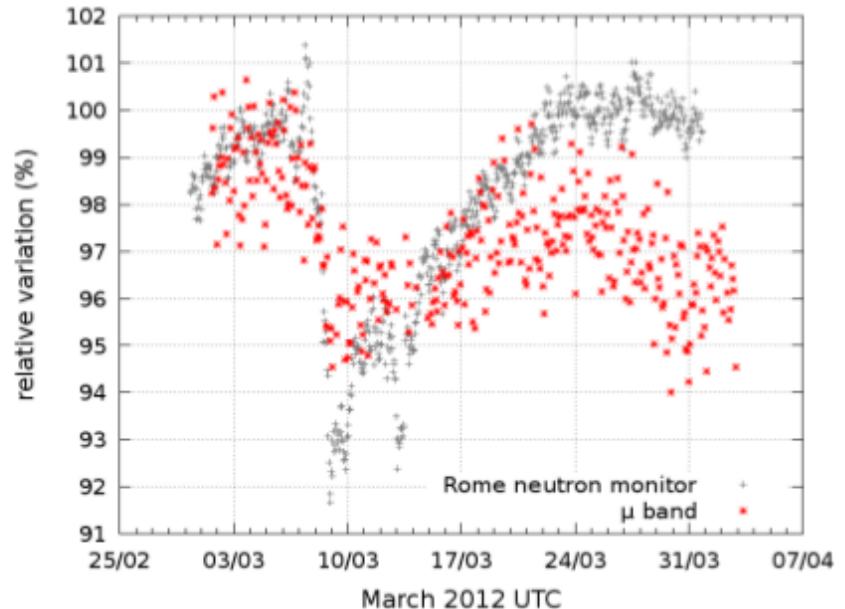
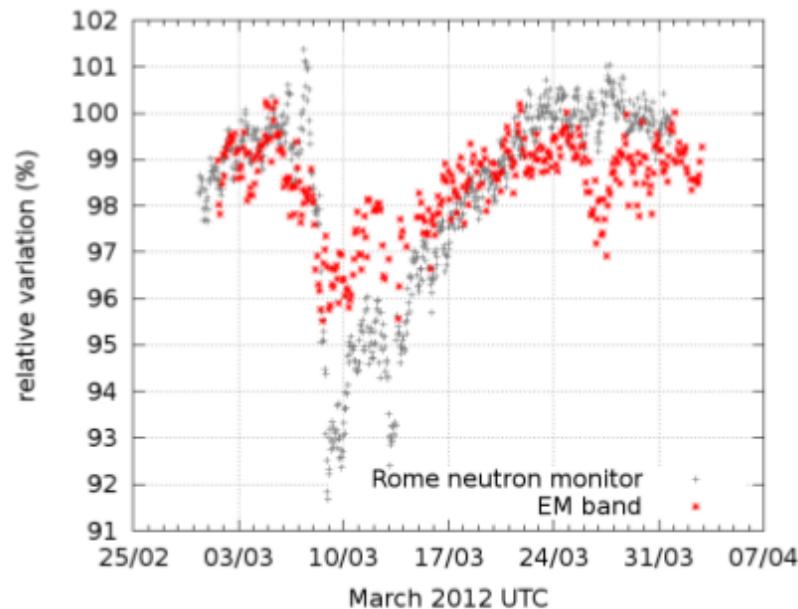


El Programa LAGO Space Weather

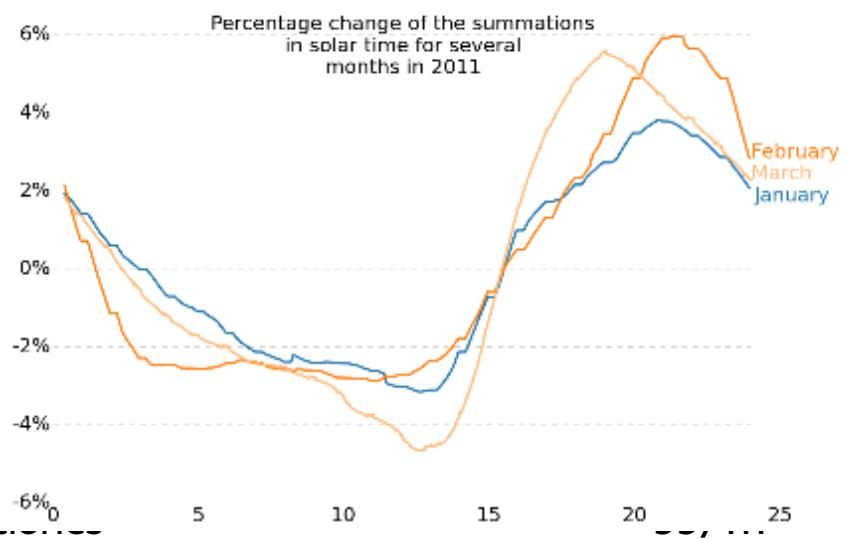
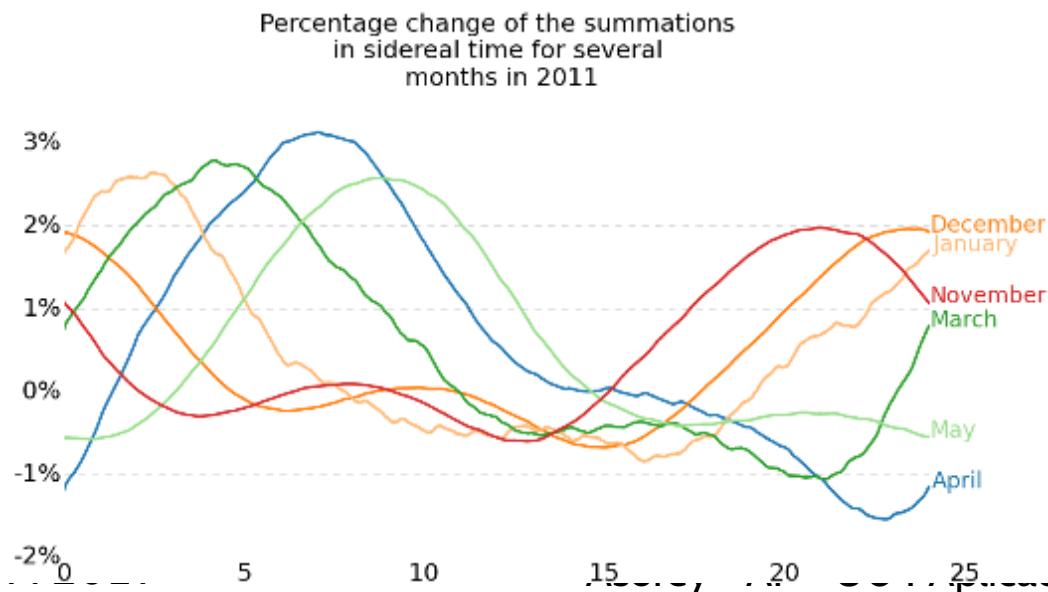


Space Weather Phenomena at single WCD (Underway)

- Multi-spectral analysis of the March/08/2012 Forbush event:



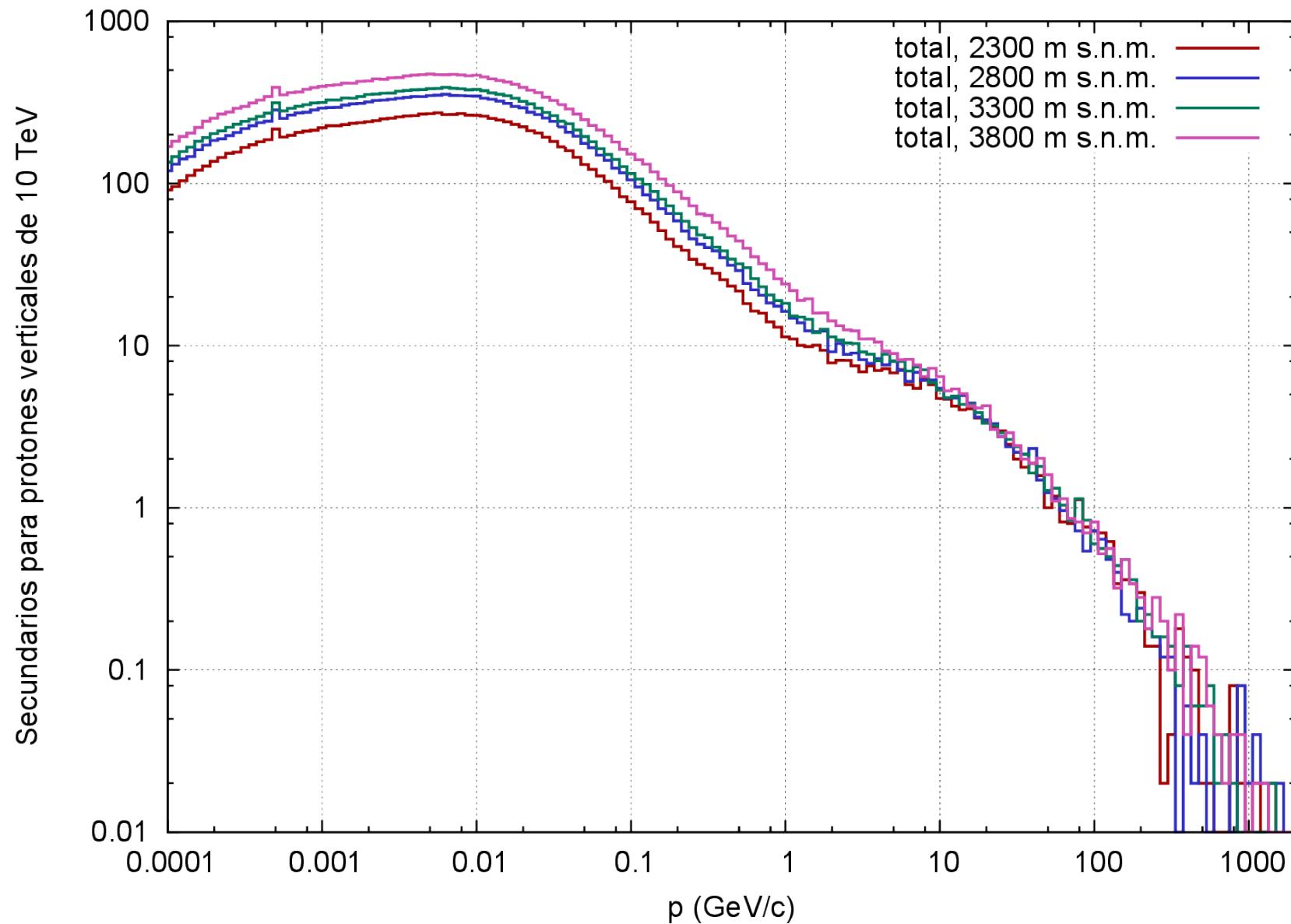
- EPOCH Analysis in Solar and Sidereal times: Solar Daily Modulation



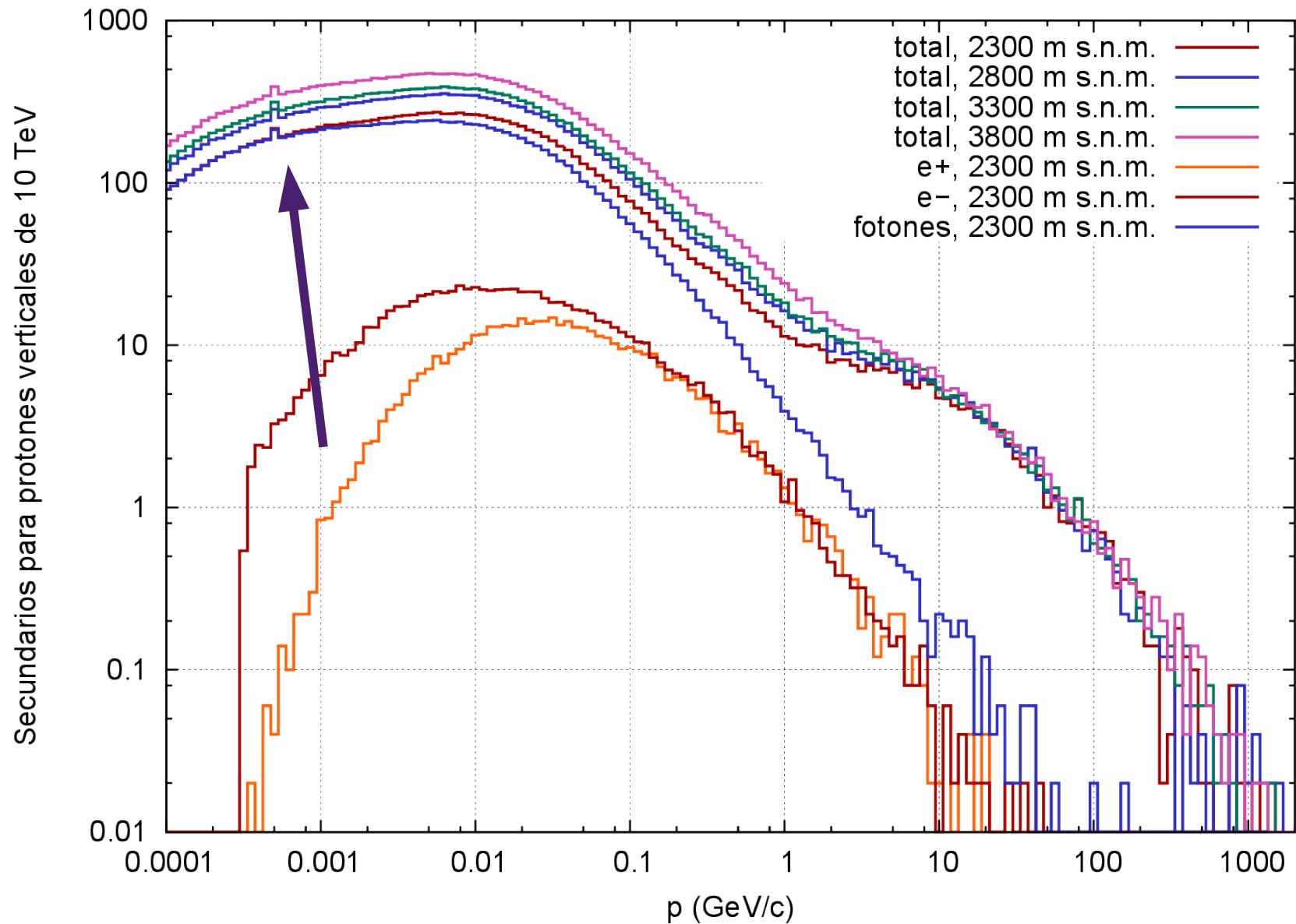
Detailed simulation chain

- Directional rigidity cut-off at each site $R(\varphi, \lambda, \theta, \phi)$
- Primary flux at the top of the atmosphere (CORSIKA simulations for each site (φ, λ, h))
 - ▶ Measured spectra for all nuclei $1 \leq Z_p \leq 26, 1 \leq A_p \leq 56$
 - ▶ $(R(\theta, \phi) \times Z_p) \leq (E_p/\text{GeV}) \leq 10^6, 0^\circ \leq \theta \leq 90^\circ$
 - ▶ Integrated primary flux: $\sim 10^7 - 10^8 \text{ hour}^{-1} \text{ m}^{-2}$ ($\gtrsim 5$ hours at each site)
- Secondary flux at detector level
- Detector response:
 - ▶ Fast and Simple *LAGOFast™* detector simulation
 - ▶ Detailed *GEANT4* model
 - ▶ First attempts on *FLUKA*

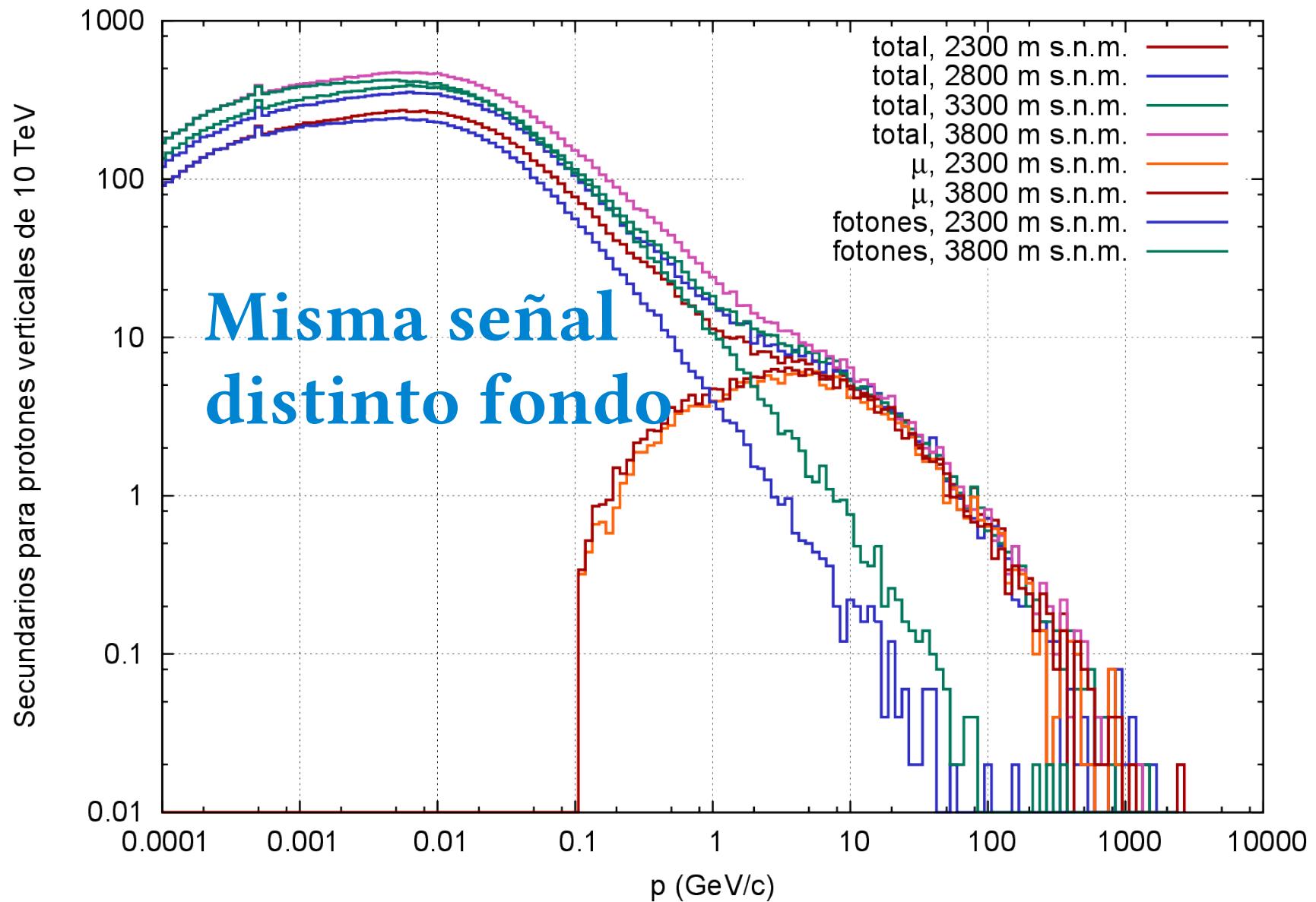
Simulación alturas



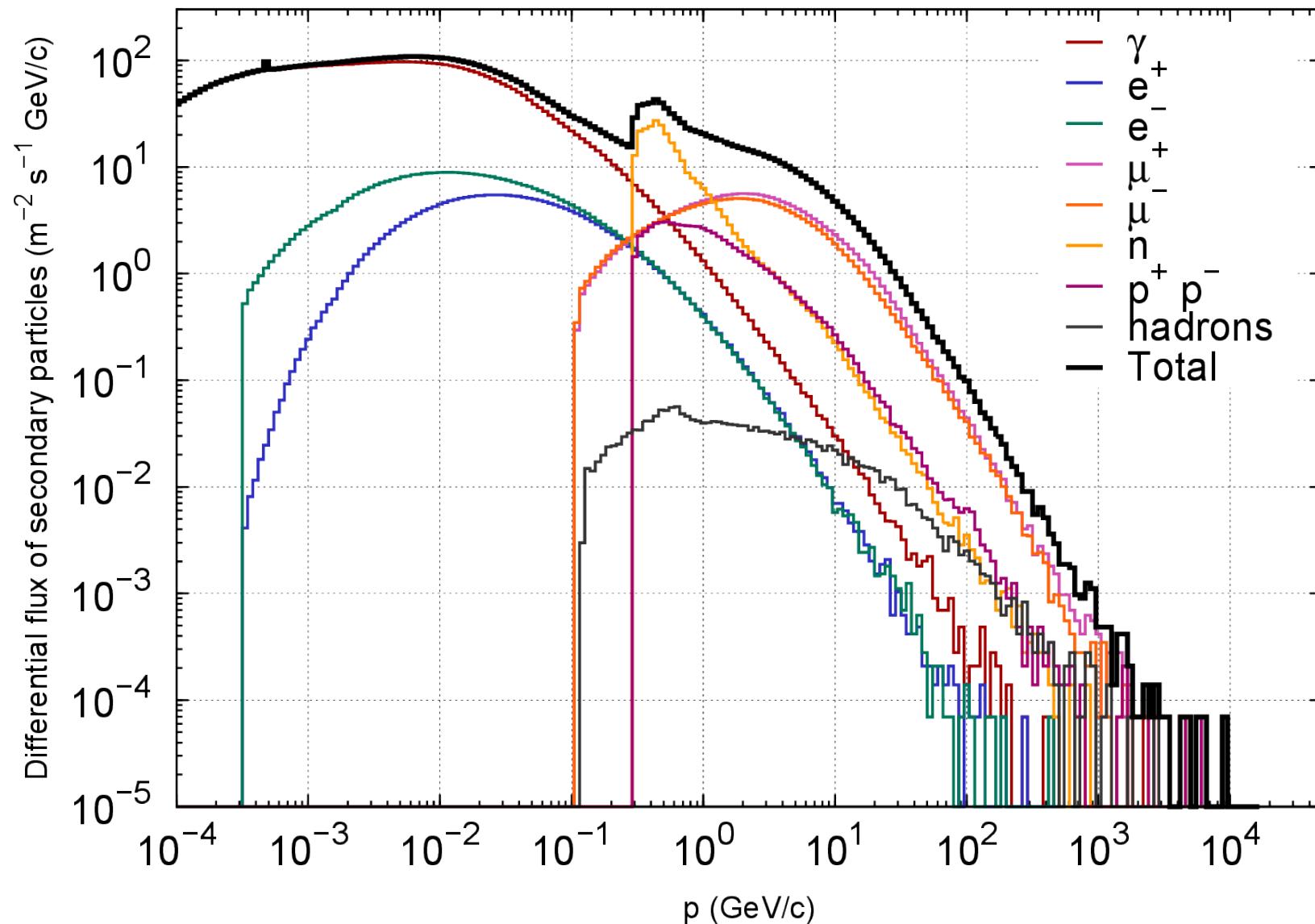
$e^+ e^- \rightarrow \gamma\gamma$



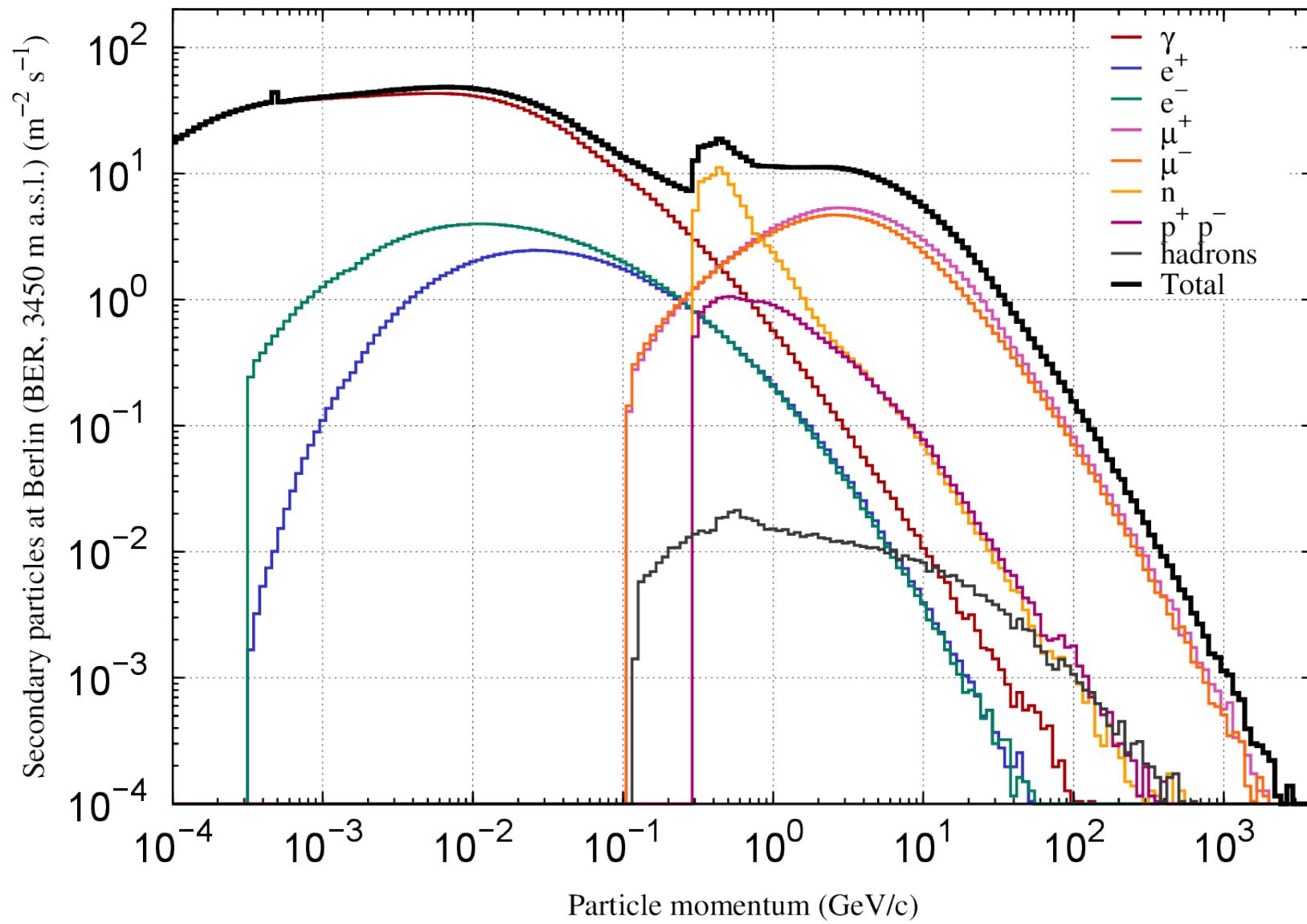
Joroba del muón



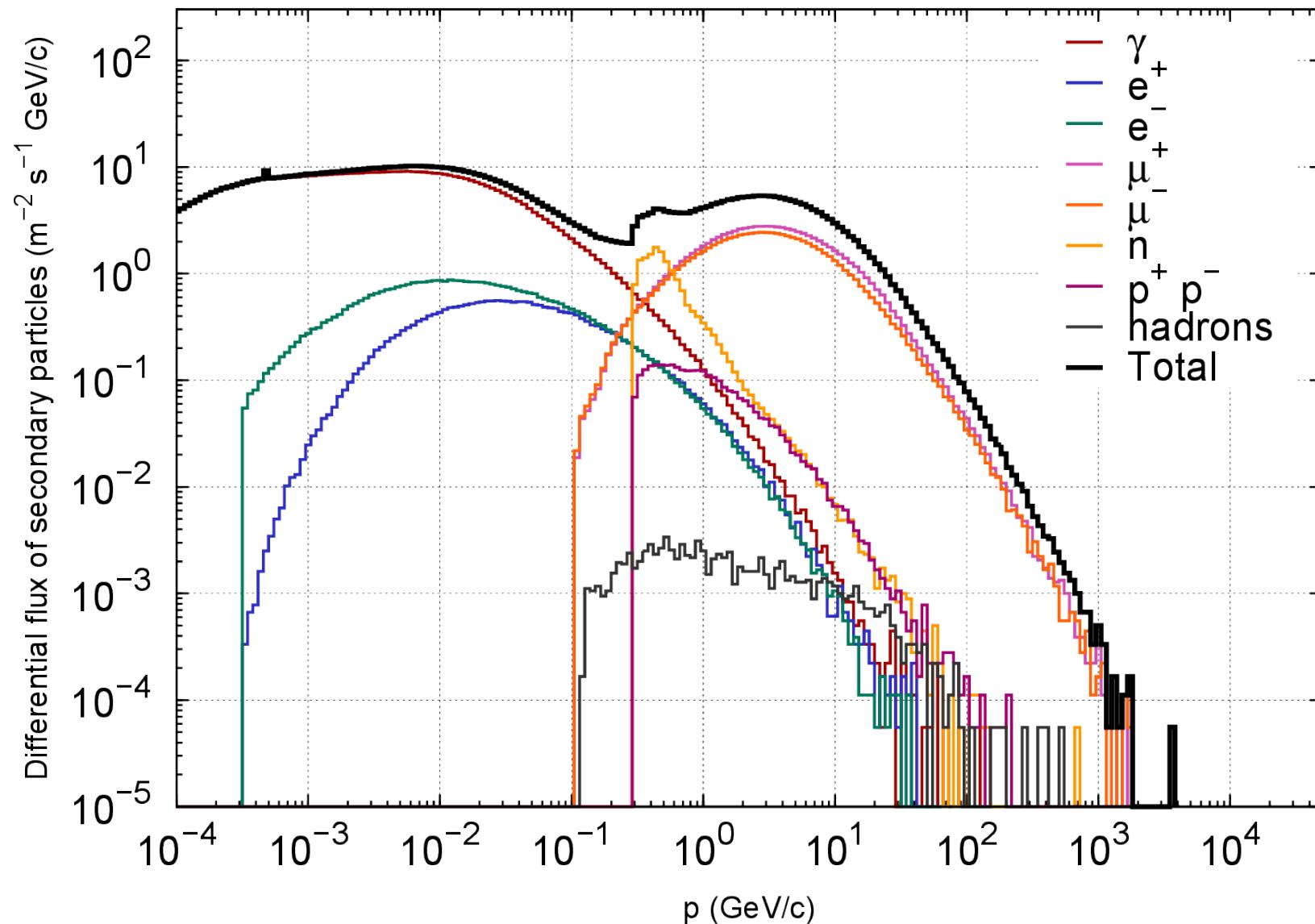
Chacaltaya, Bolivia, 5300 msnm



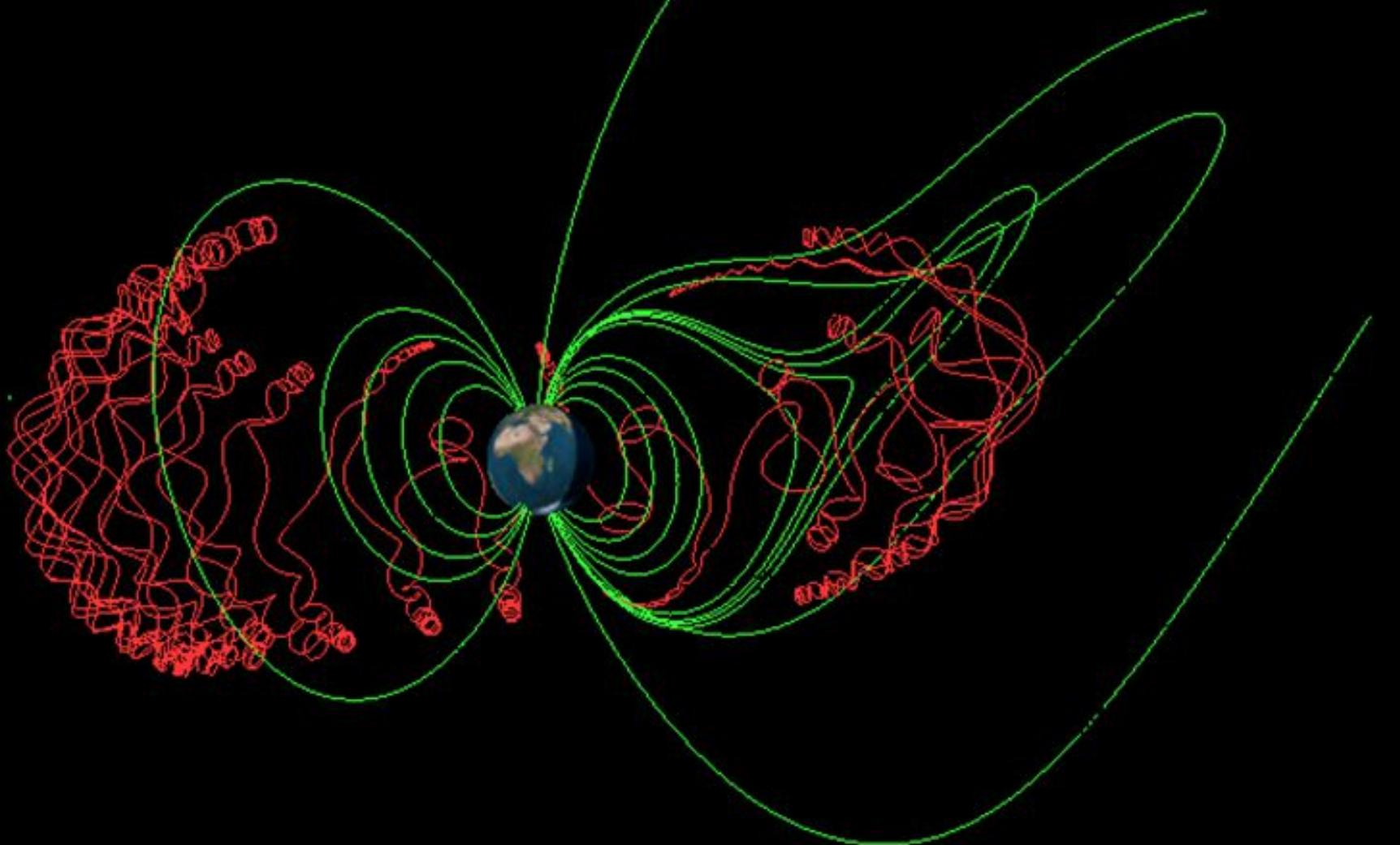
Berlín, Colombia, 3450 msnm



Bariloche, Argentina, 850 msnm



MAGCOS (próximamente en la wiki)



<http://cosray.unibe.ch/~laurent/magnetocosmics/>

Rigidez geomagnética

- A partir de la ecuación de Lorentz

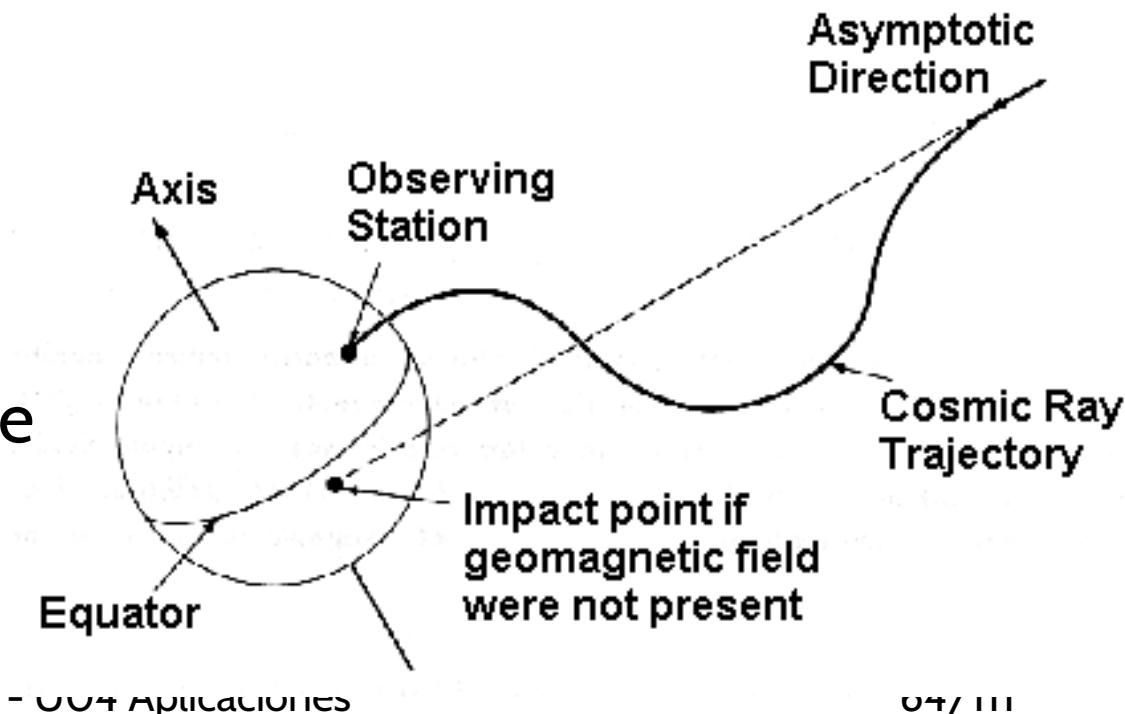
$$\frac{d(m\vec{v})}{dt} = \frac{eZ}{c} (\vec{v} \times \vec{B}) \rightarrow \frac{d\vec{I}_v}{ds} = \frac{eZ}{pc} (\vec{I}_v \times \vec{B}) \equiv \frac{1}{R_m} (\vec{I}_v \times \vec{B})$$

- La rigidez magnética se define entonces como

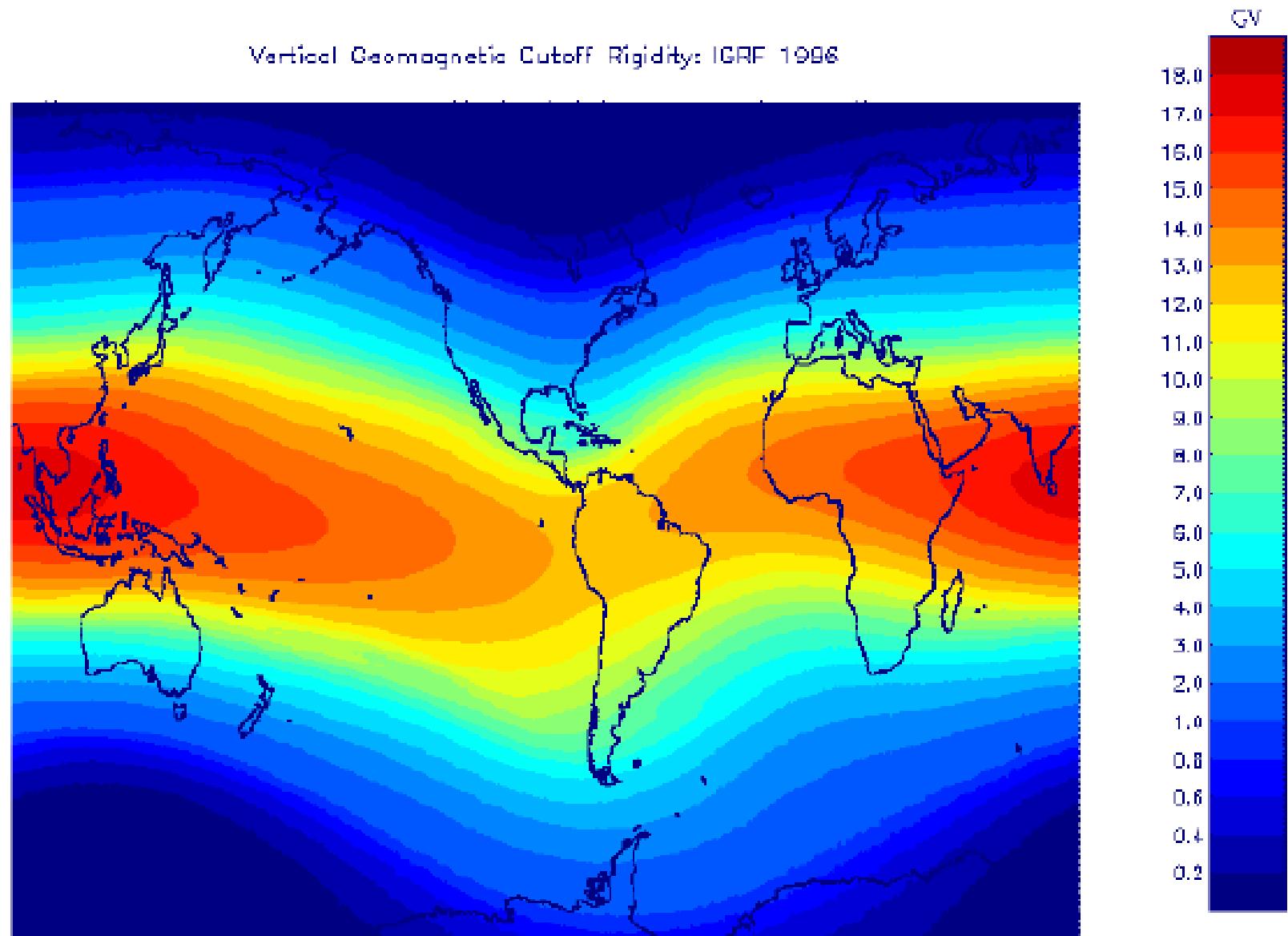
$$R_m = \frac{pc}{Ze}$$

- La rigidez geomagnética es la rigidez inducida por el campo magnético terrestre

$$Rm(\theta, \lambda, h, t) = \frac{pc}{Ze}$$

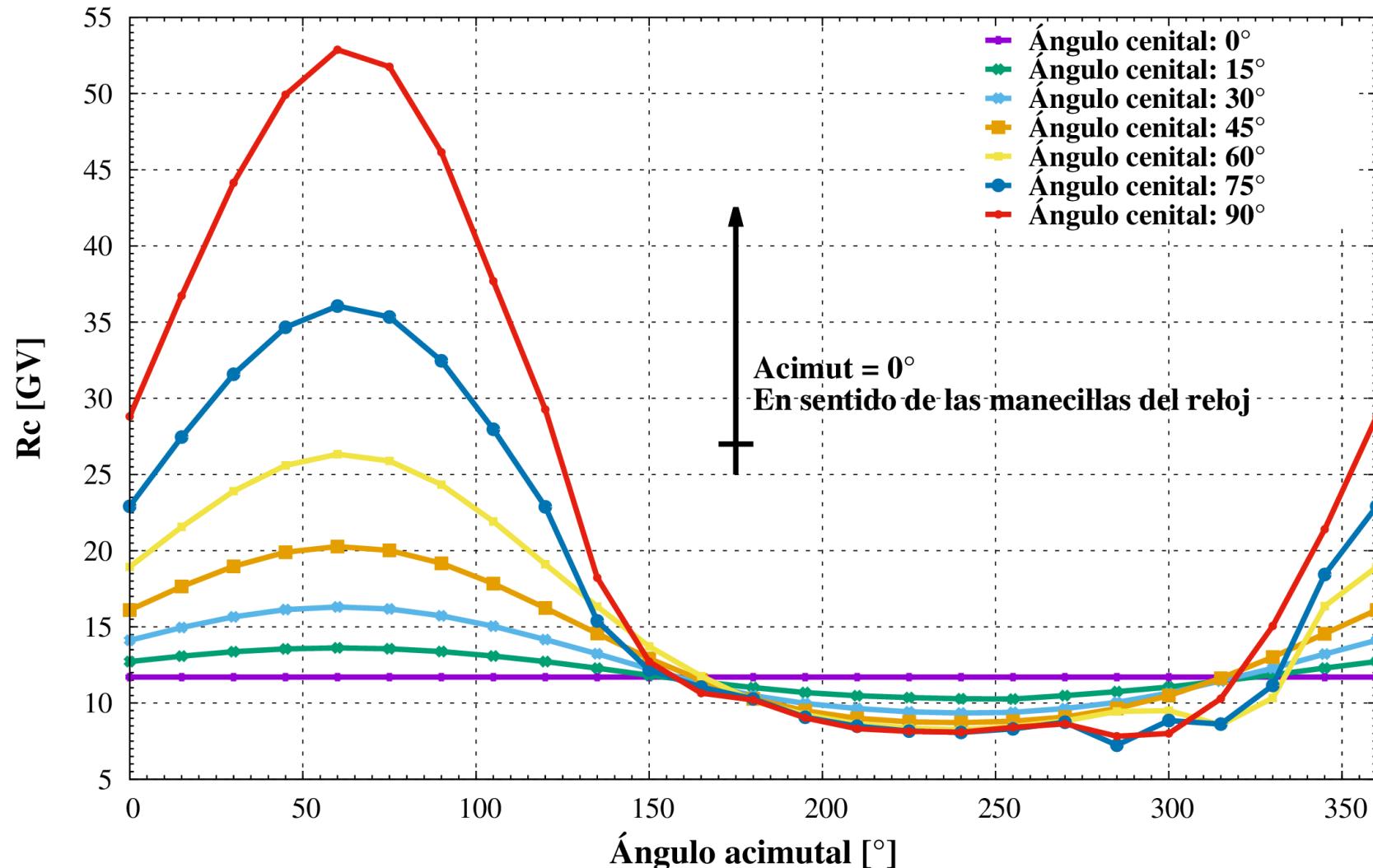


Calculo de la rigidez geomagnetica local



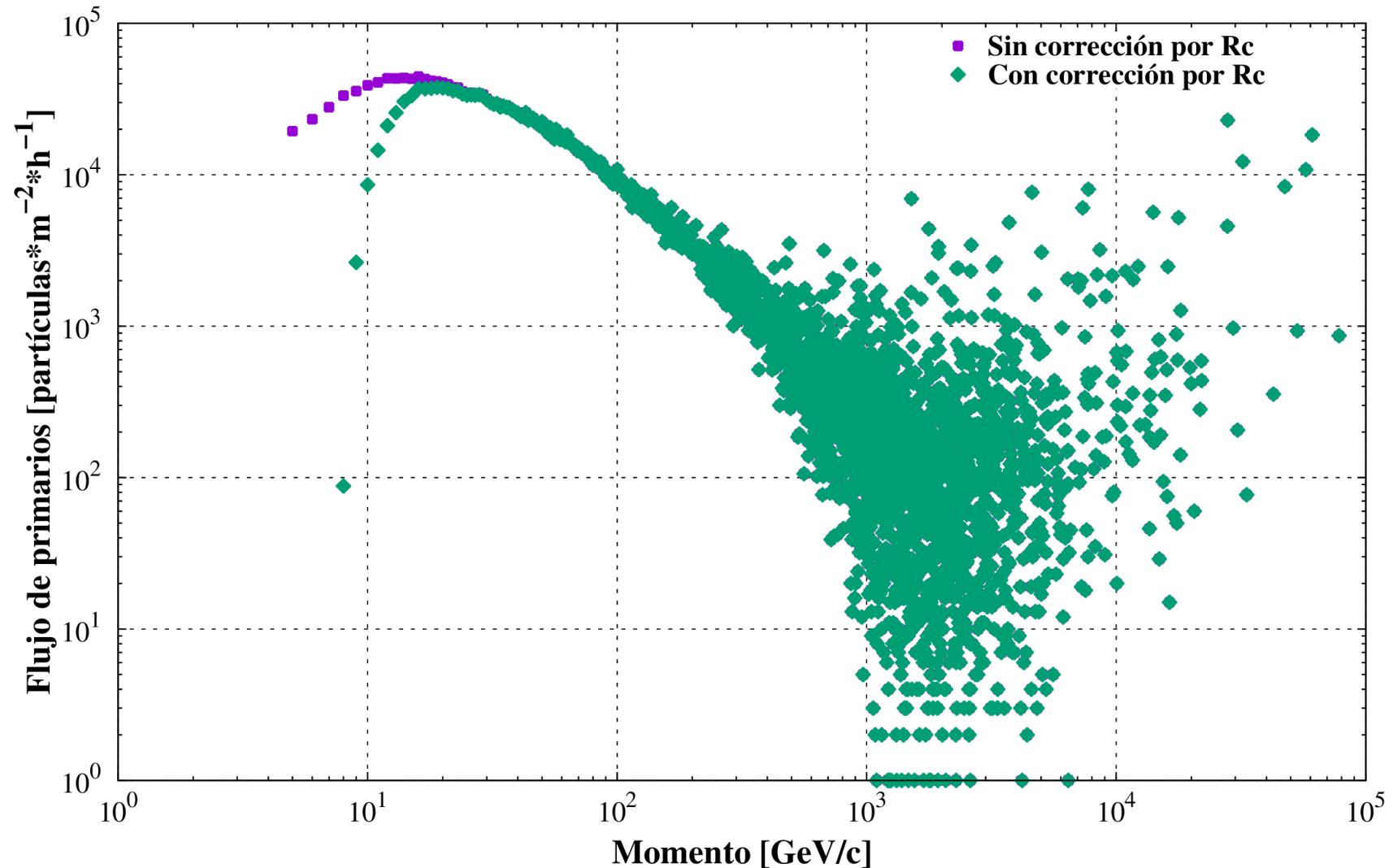
Rigidez direccional en un sitio LAGO

Rigidez de Corte (Rc) a 112.8 km sobre la ciudad de Bucaramanga como Función del ángulo cenital y acimutal



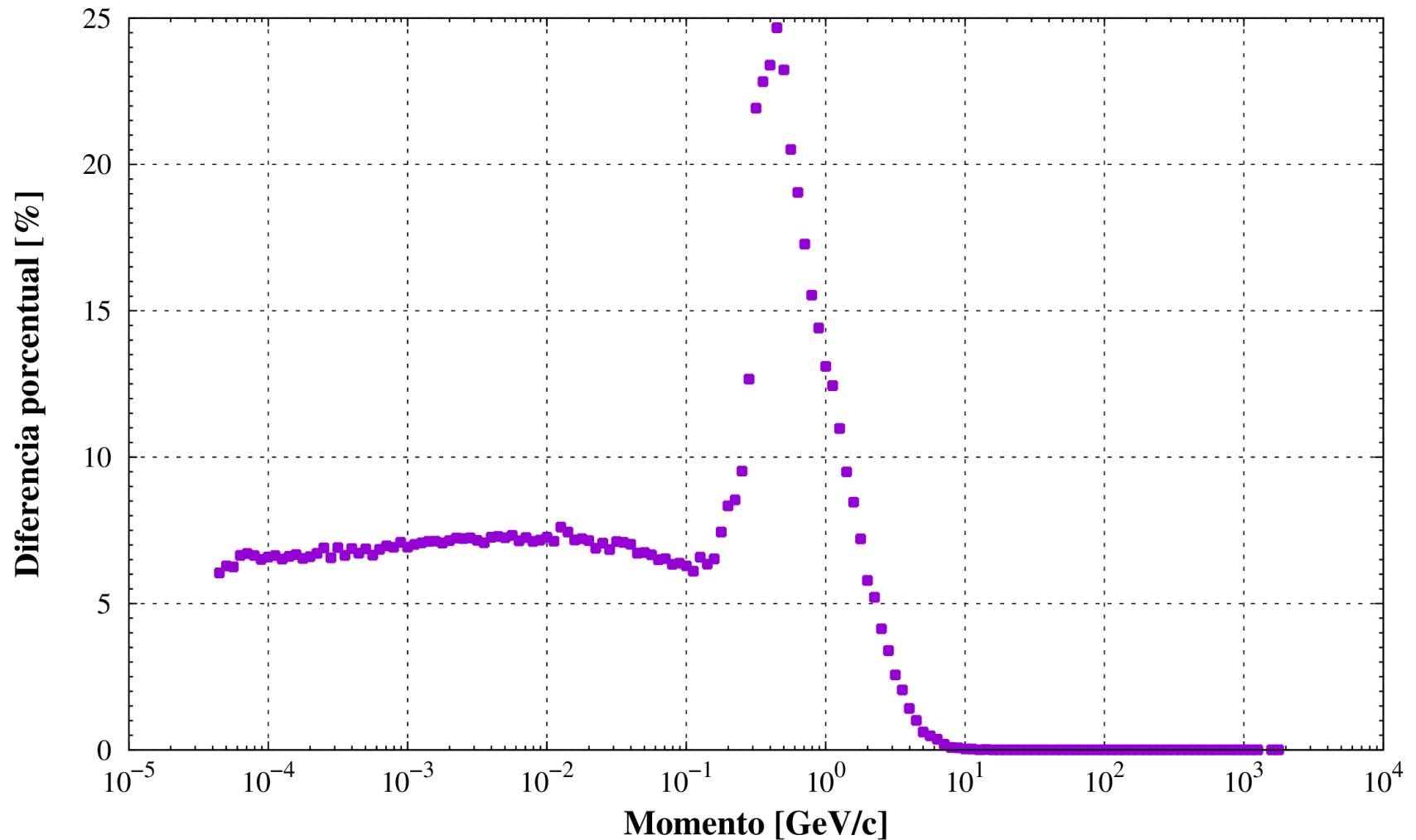
Efecto de la rigidez en la fluencia de primarios

Espectro de rayos cósmicos primarios a 112.8 km s.n.m. sobre Bucaramaga sin corrección por campo geomagnético (morado) y con corrección (verde)

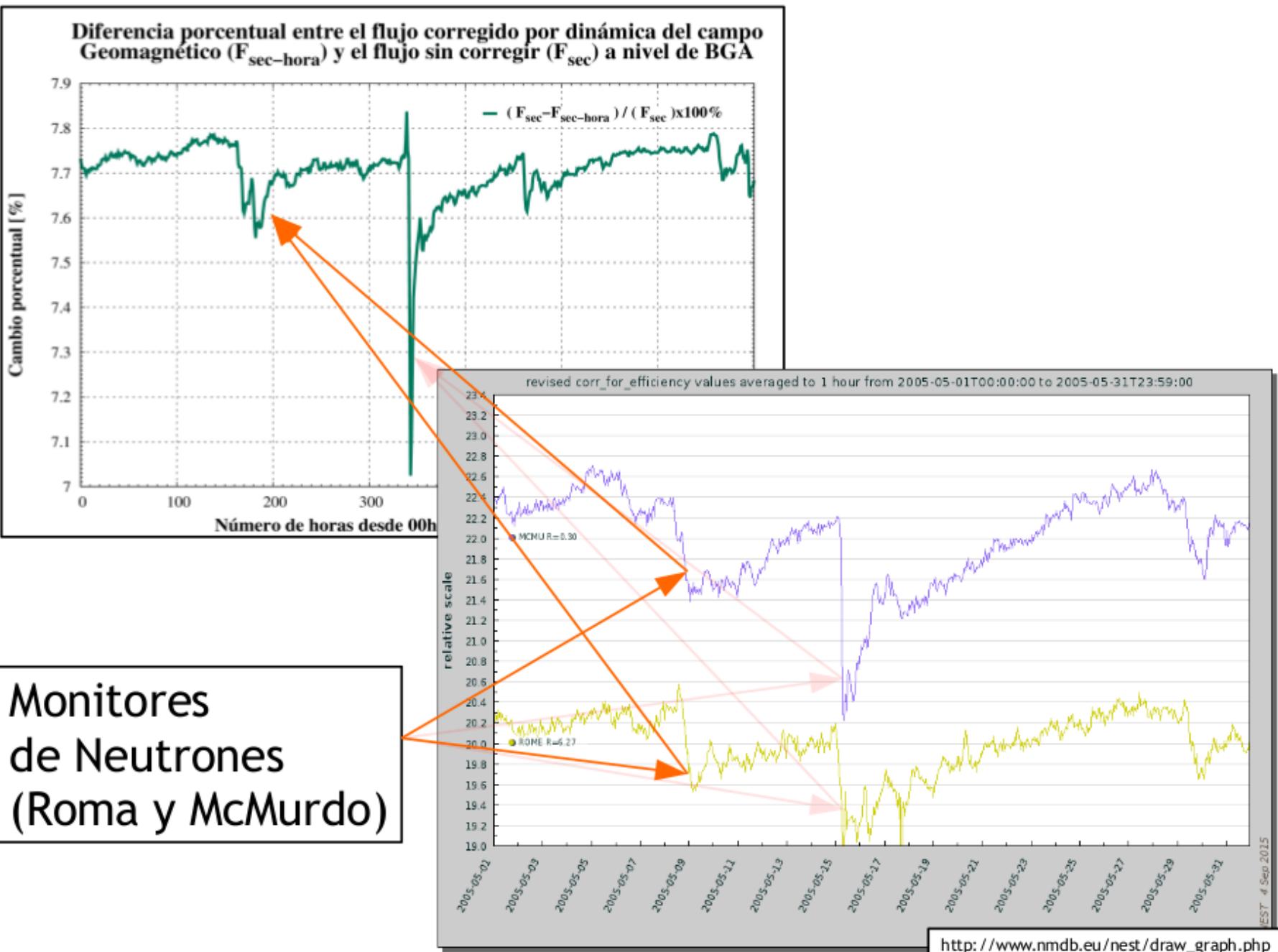


Efecto de la rigidez en la fluencia de secundarios

Diferencia porcentual entre flujo de secundarios producidos por una hora
de flujo e rayos cósmicos sin y con corrección por campo geomagnético
(Bucaramanga, 956 m s.n.m.)



Incluso para el campo dinámico!



Mientras tanto en algún volcán...



Radiography

- **Problem:**
I want to look “into” my hand
- **Solution #1:**



Radiografías

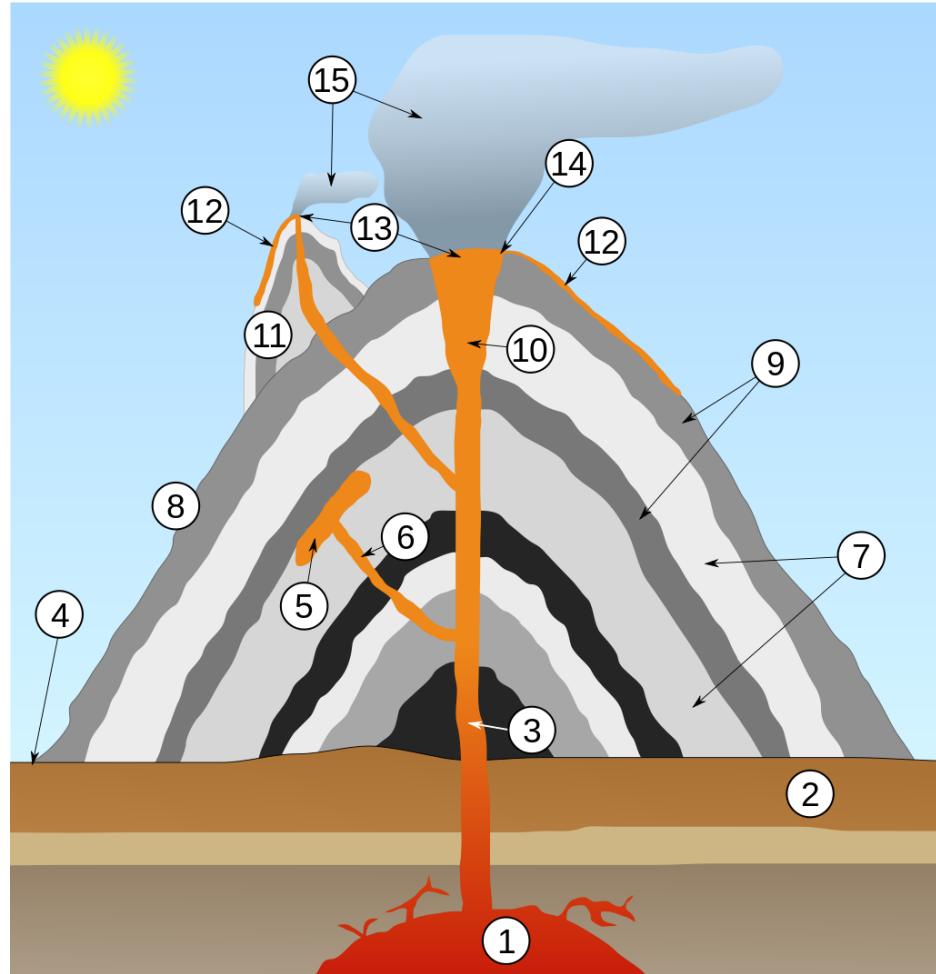
- **Problem:**
I want to look “into” my hand
- **Solution #1:**



- **Solution #2:**
 - Using penetrating radiation
 - RX will be differently absorbed on material type and average
 - Put a RX sensitive detector to density distribution by studying profiles



We want to take a look to volcanoes interior...

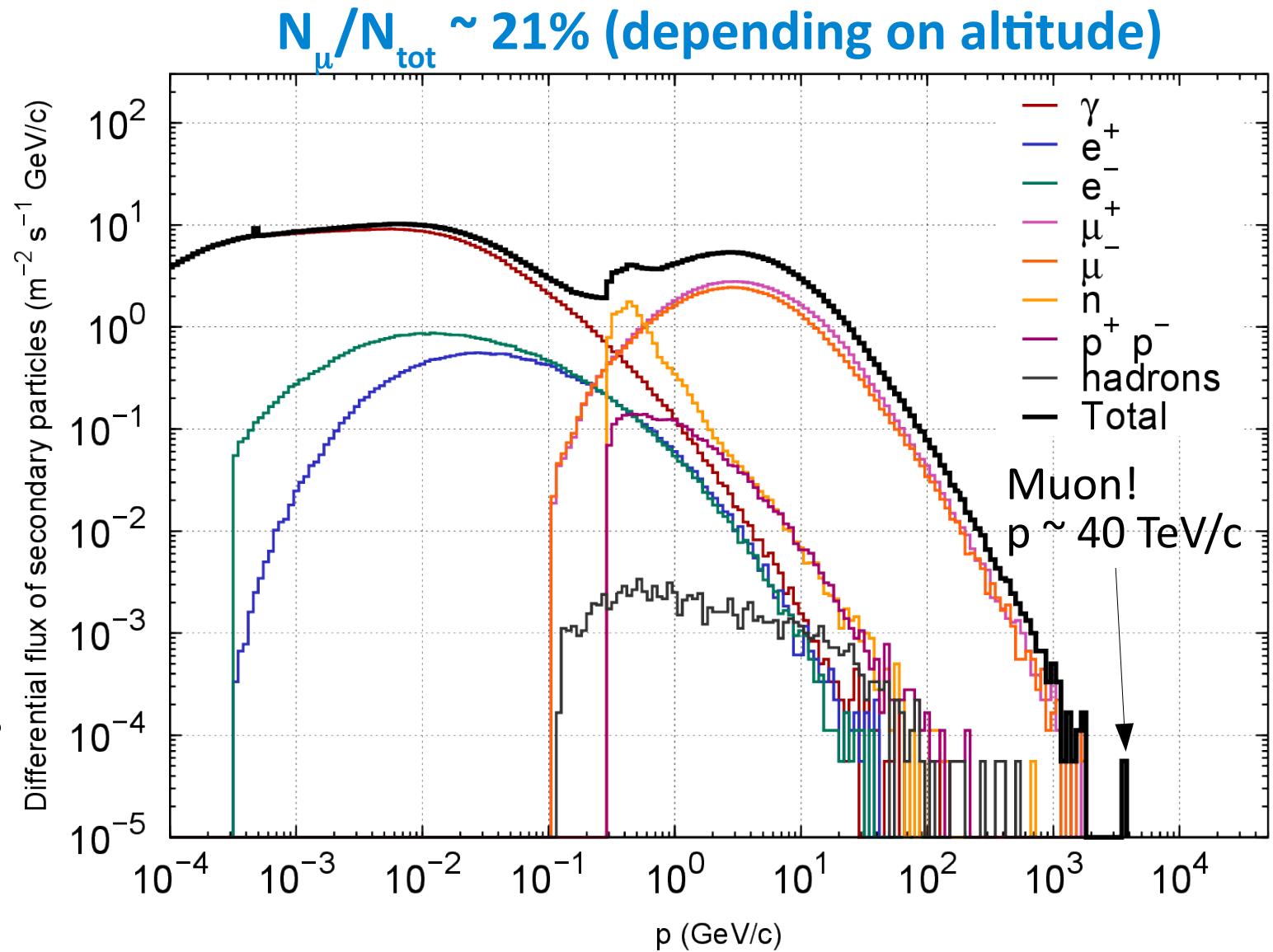


... because we have “personal” motivations...
(2011: Puyehue-Cordón Caulle, 2015: Calbuco)

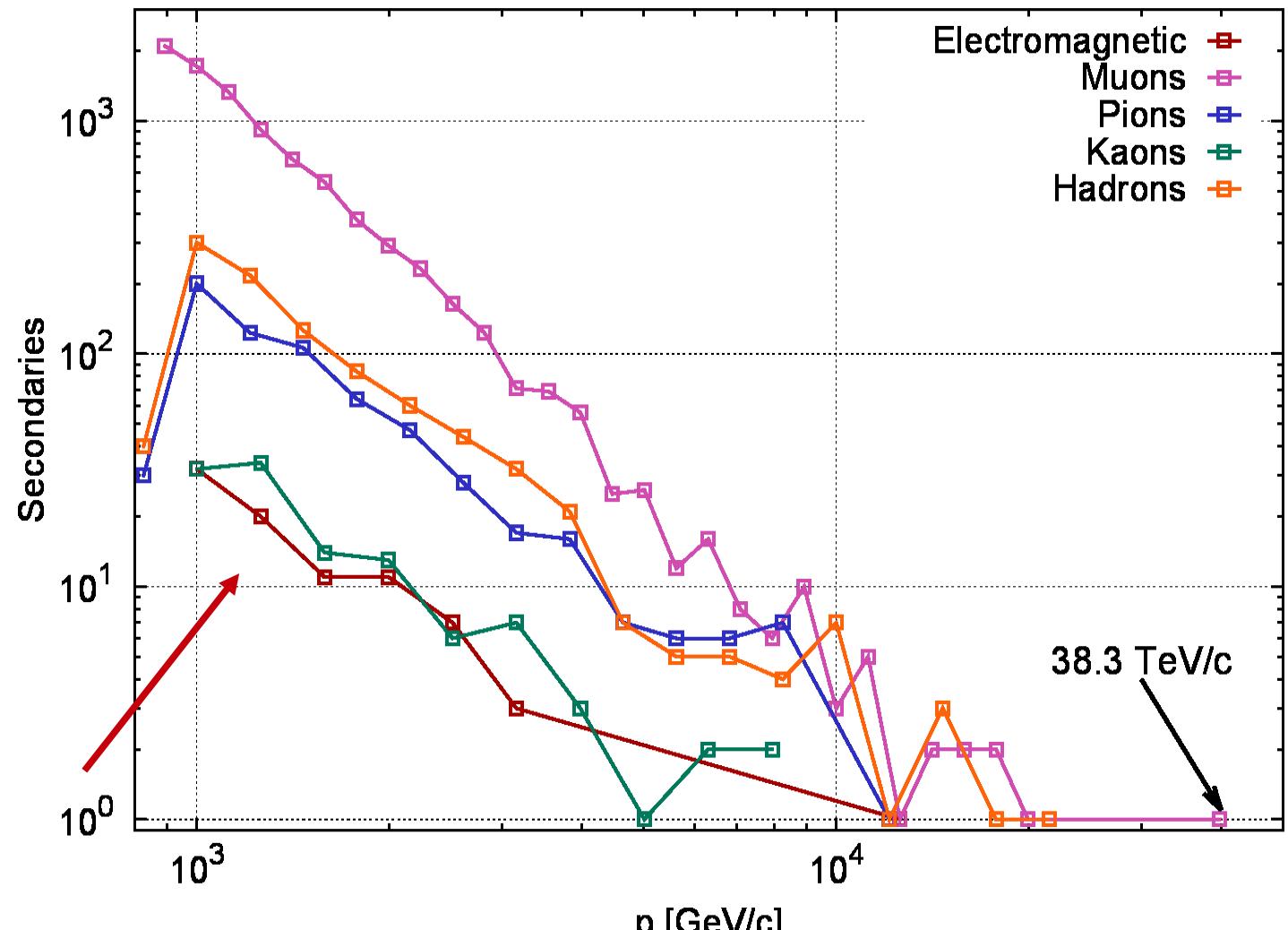
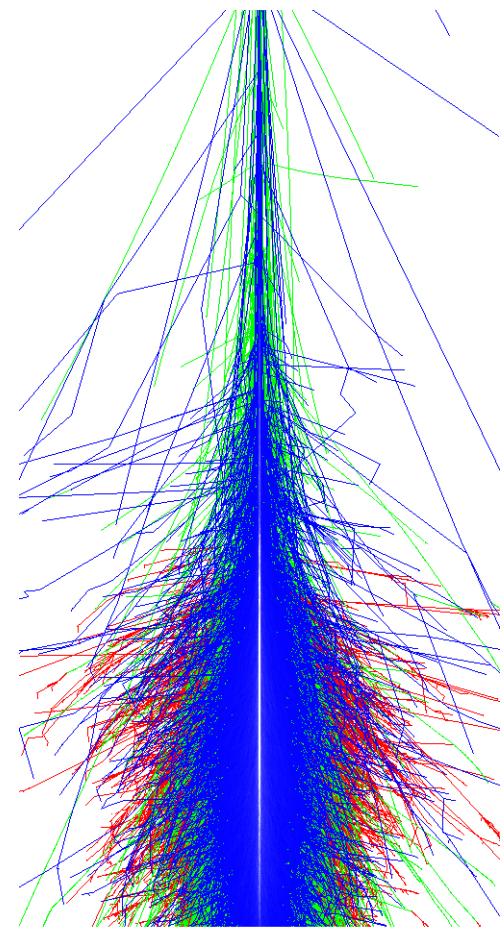


Background secondary flux at Bariloche, Argentina, 850 m a.s.l.

- Complete simulation chain:
- Complete primary flux:
 - ${}^1\text{H}_1 \rightarrow {}^{56}\text{Fe}_{26}$
 - $0^\circ < \theta < 90^\circ$
 - -
 - $180^\circ < \phi < 180^\circ$
 - $Z R_c(\theta, \phi) < E < 10^6 \text{ GeV}$

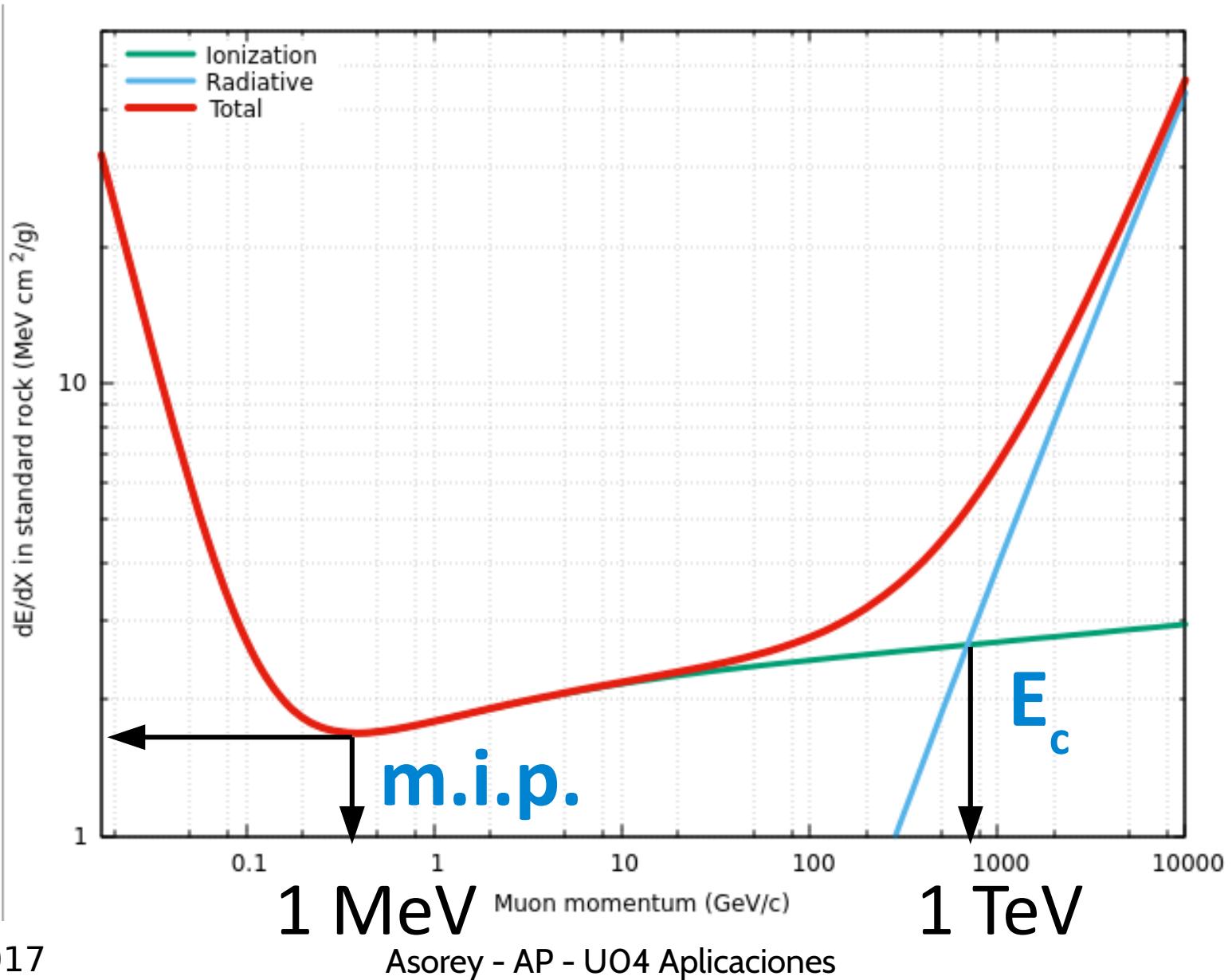


High energy atmospheric muons

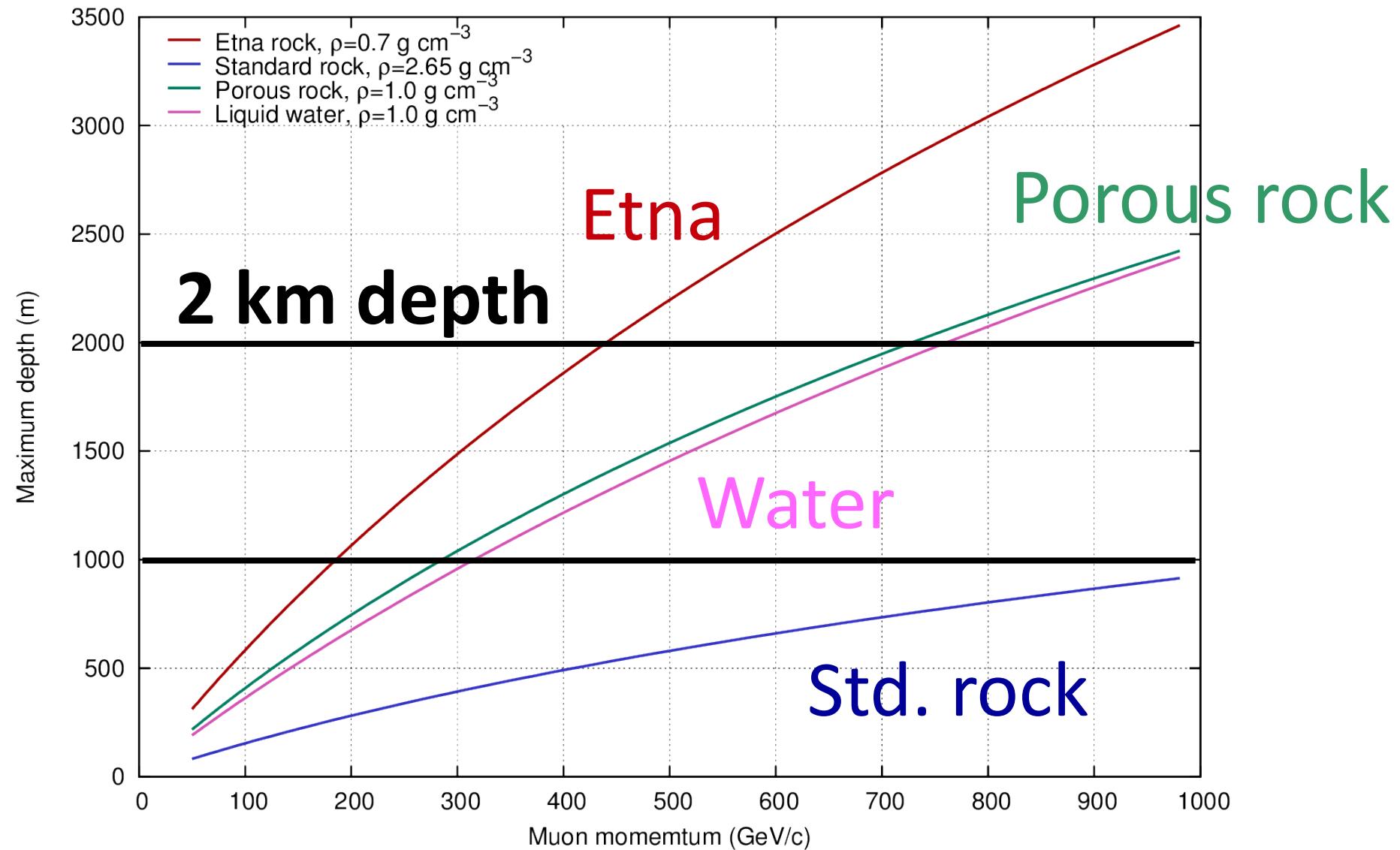


4000 m a.s.l. HE ($E > 800$ GeV) secondaries simulated flux (1 m², 1 month)

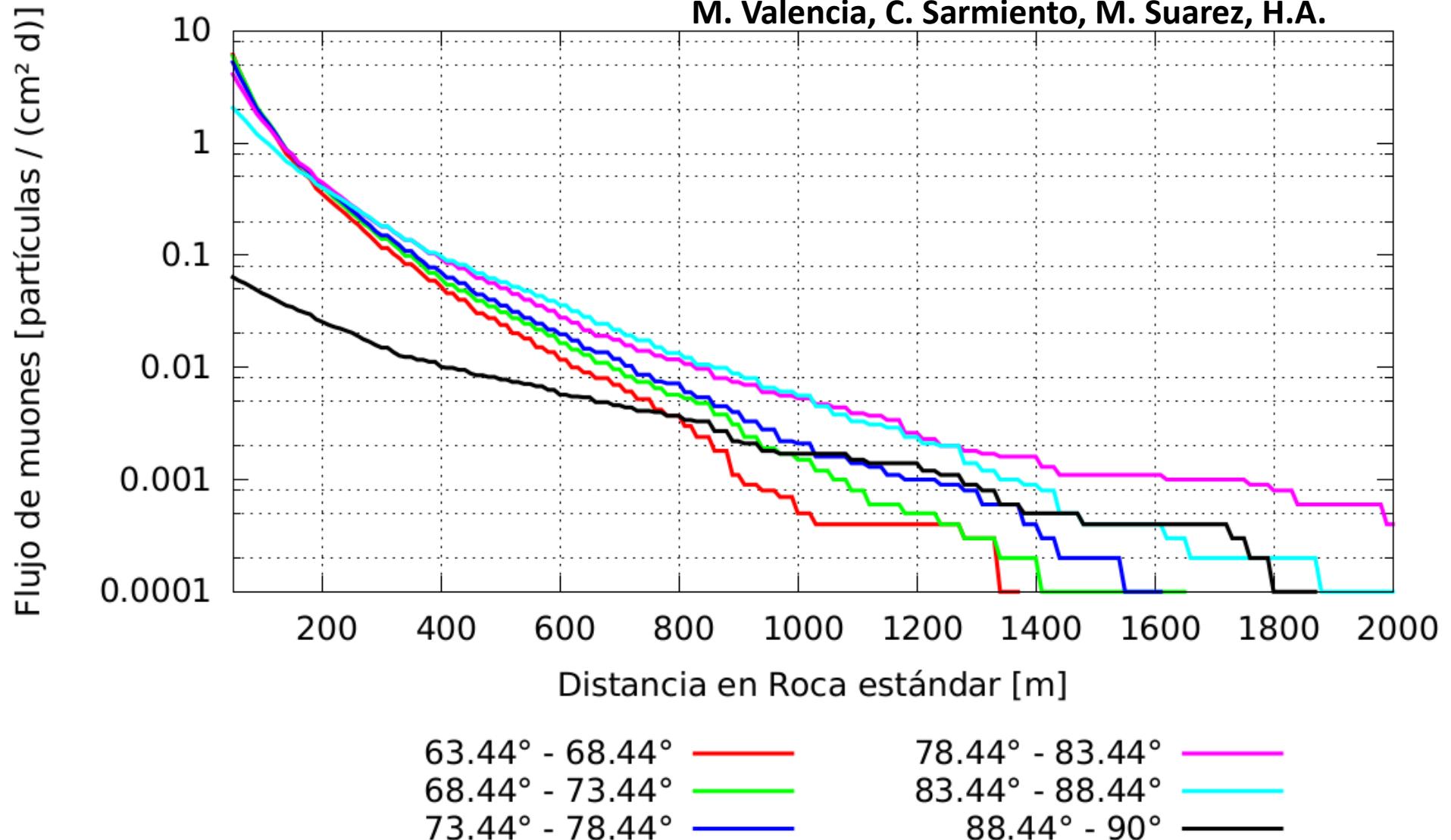
Stopping power for muons in standard rock



Muon range in some standard materials



Directional muon flux + rock interaction (first model, quasi adiabatic integration)



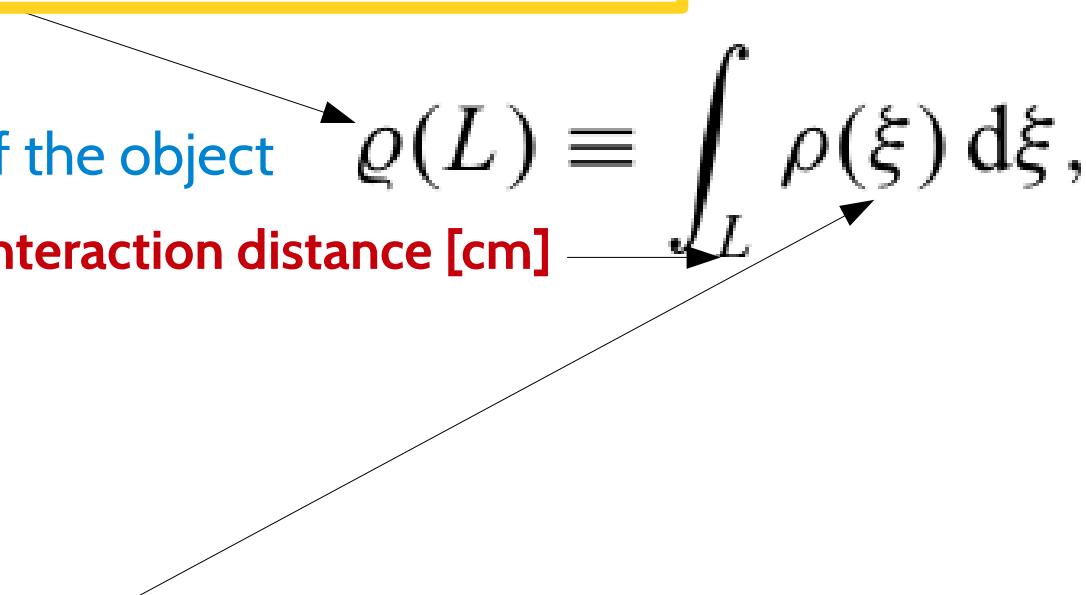


So, up to here...

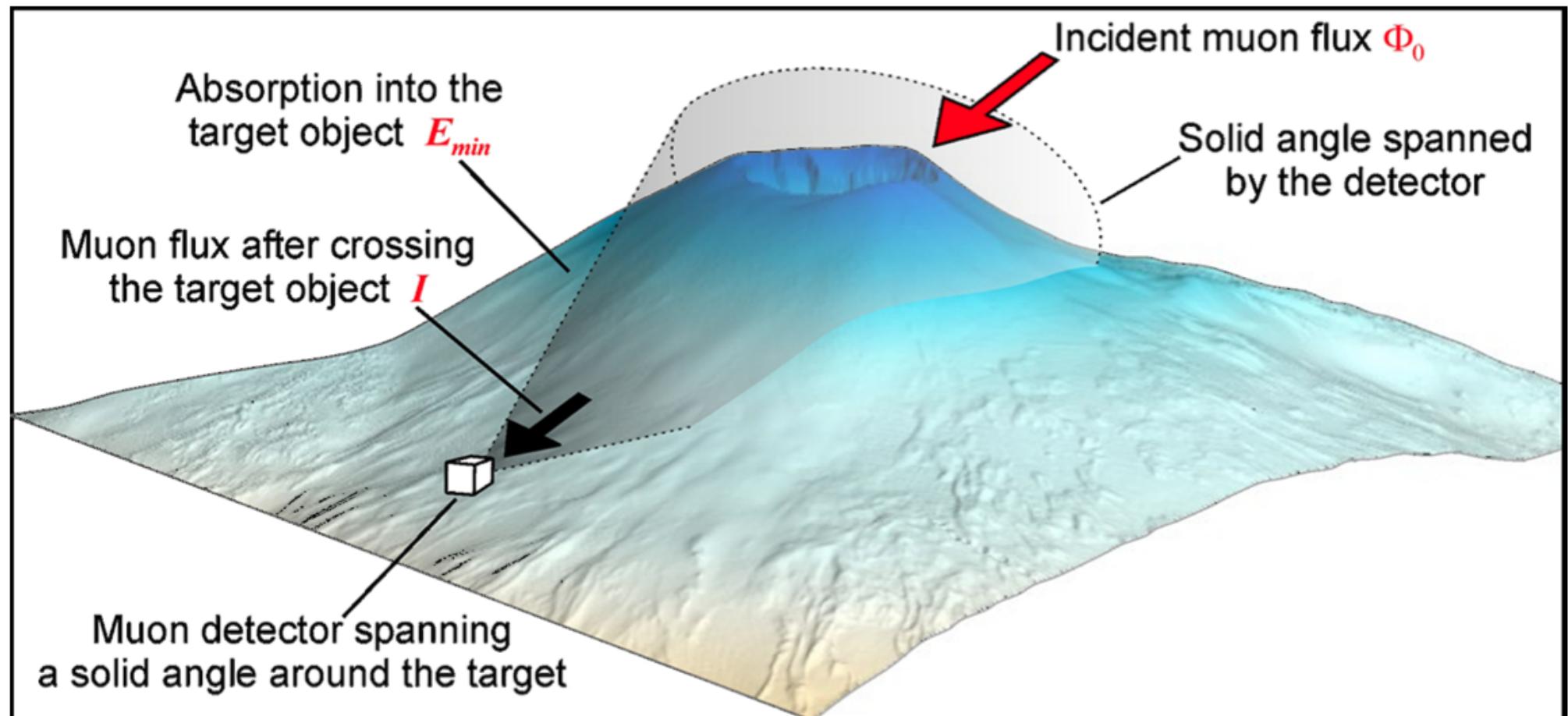
- We found **muons**, a high penetrating particle, originated by the interaction of cosmic rays with the atmosphere
- Muons are available everytime and everywhere (and they are free)
- Muons are able to go across hundreds and even thousands of meters of rock

Muon radiography → “Muongraphy”

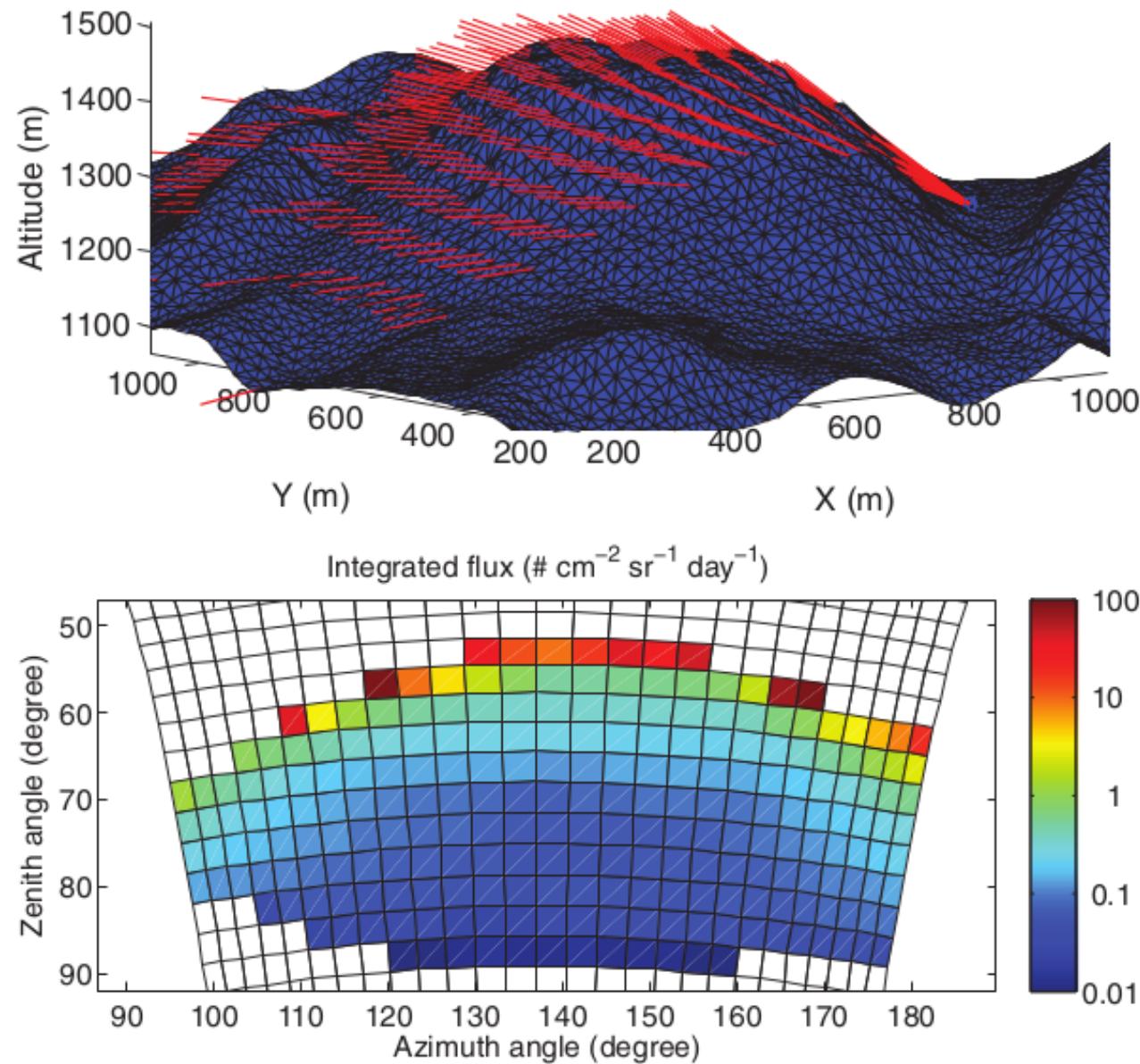
- Suppose you have an object with an unknown density profile, then...
 - ... measure the directional muon flux through this object
 - ... and compare with the muon reference flux
 - → **you get the directional opacity of this object [g/cm²]**
- Additionally...
 - ... obtain the external geometry of the object
 - → **and calculate the directional interaction distance [cm]**
- Finally, from...
 - directional opacity
 - directional interaction distances
 - → **you get the internal density profile along muon propagation direction**

$$\varrho(L) \equiv \int_{-\infty}^L \rho(\xi) d\xi,$$


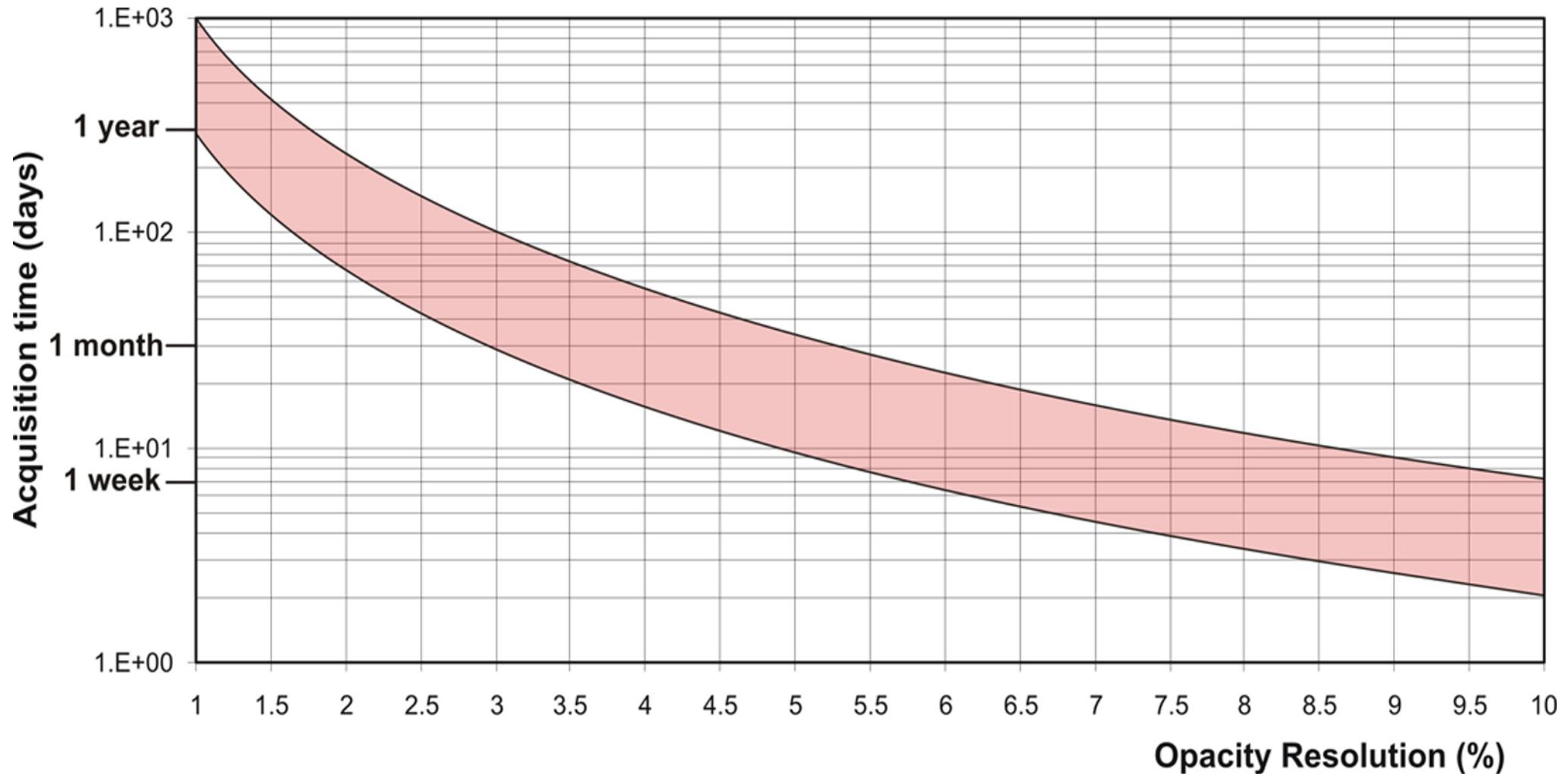
Muon directional flux measurement



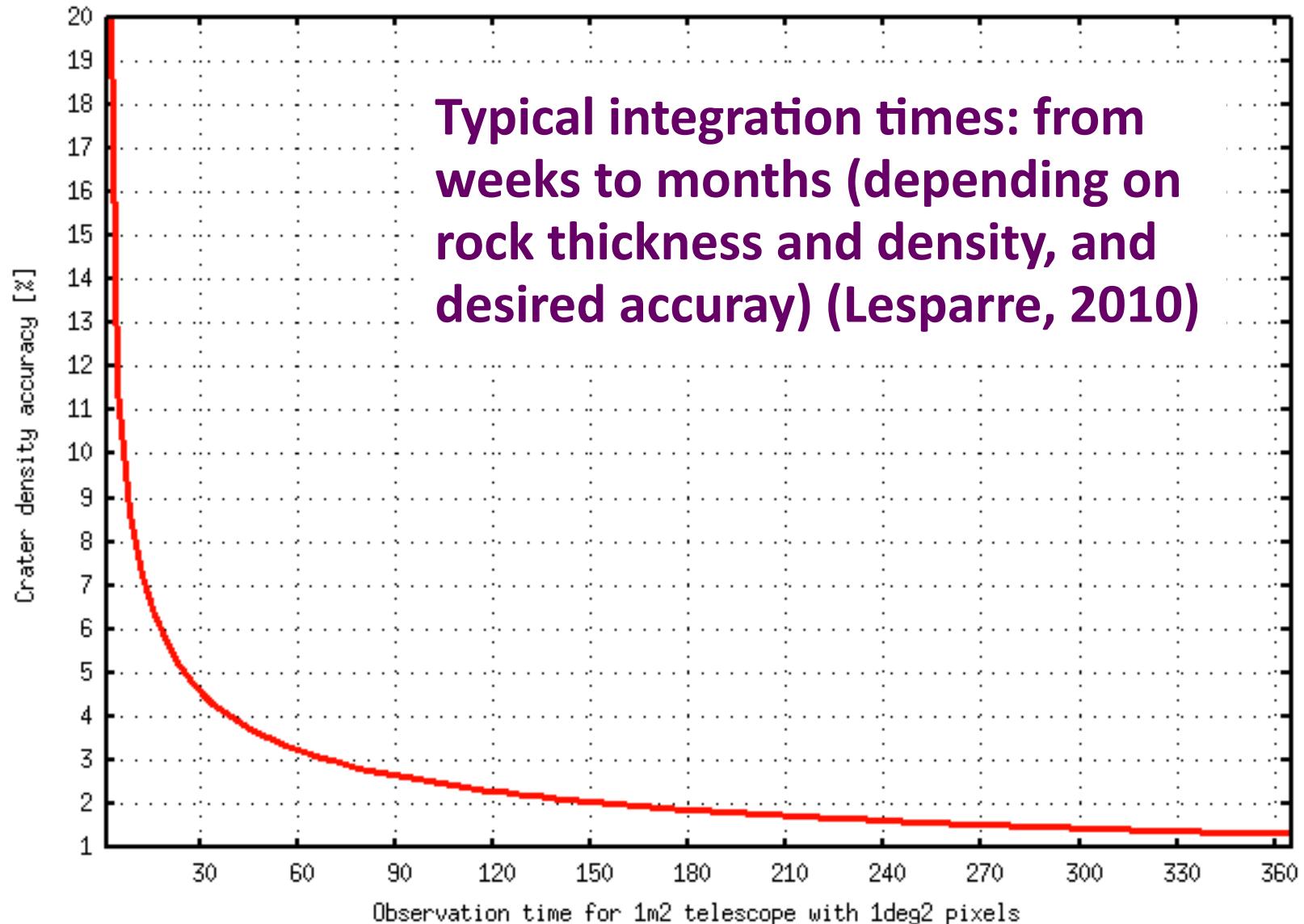
Muon directional flux measurement



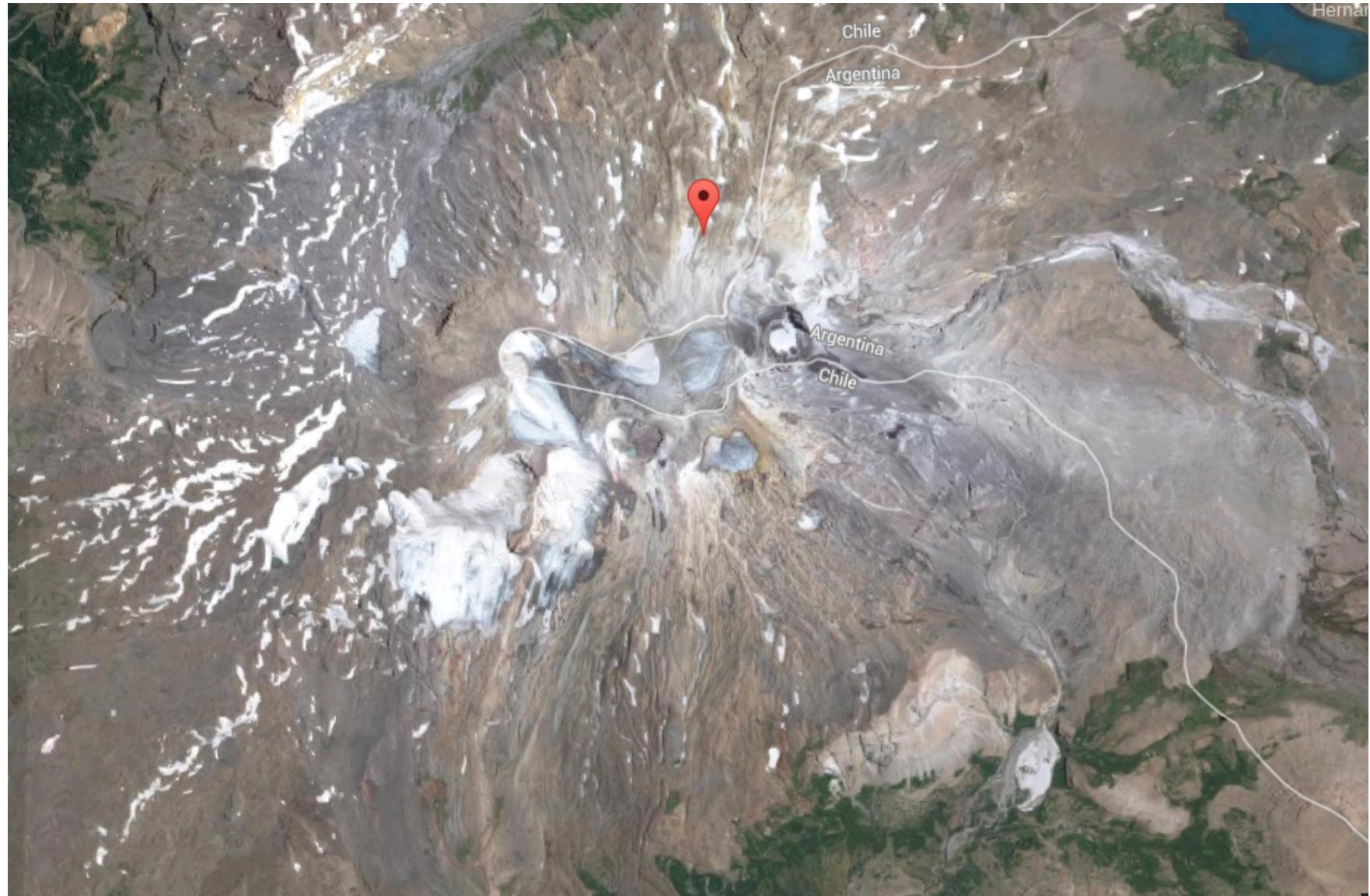
Opacity resolution and observation times



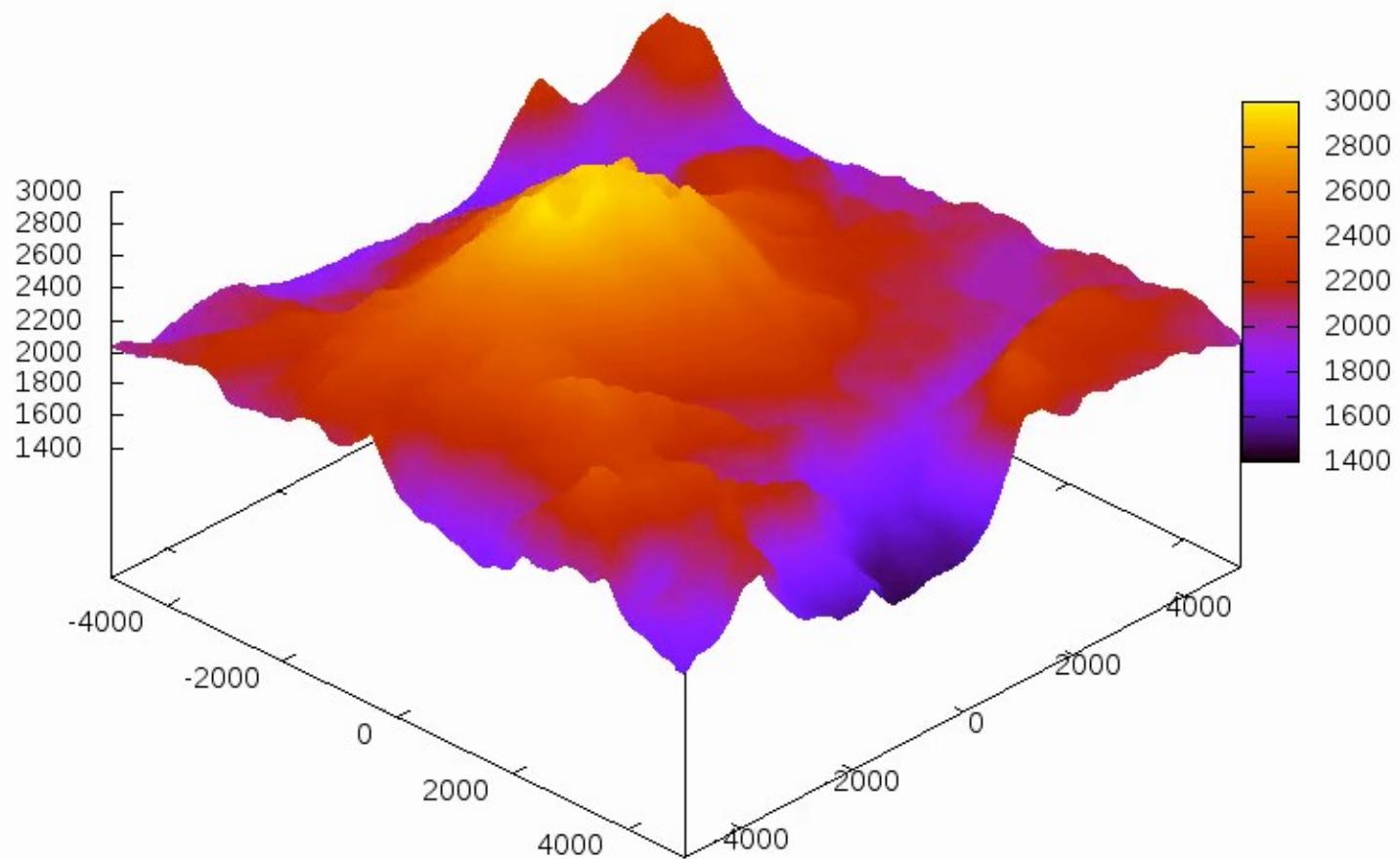
Density resolution and observation times



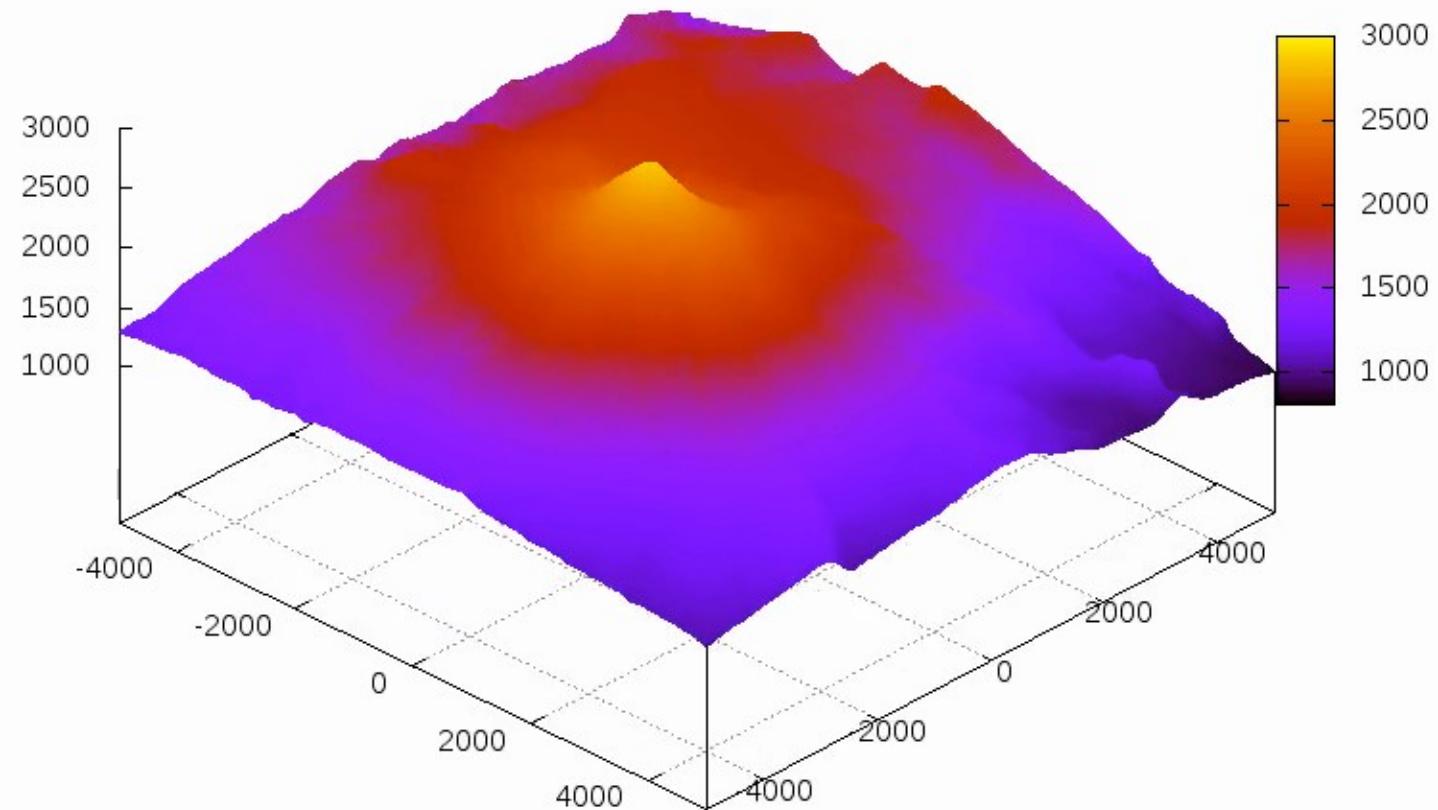
Copahue (Argentina - Chile)



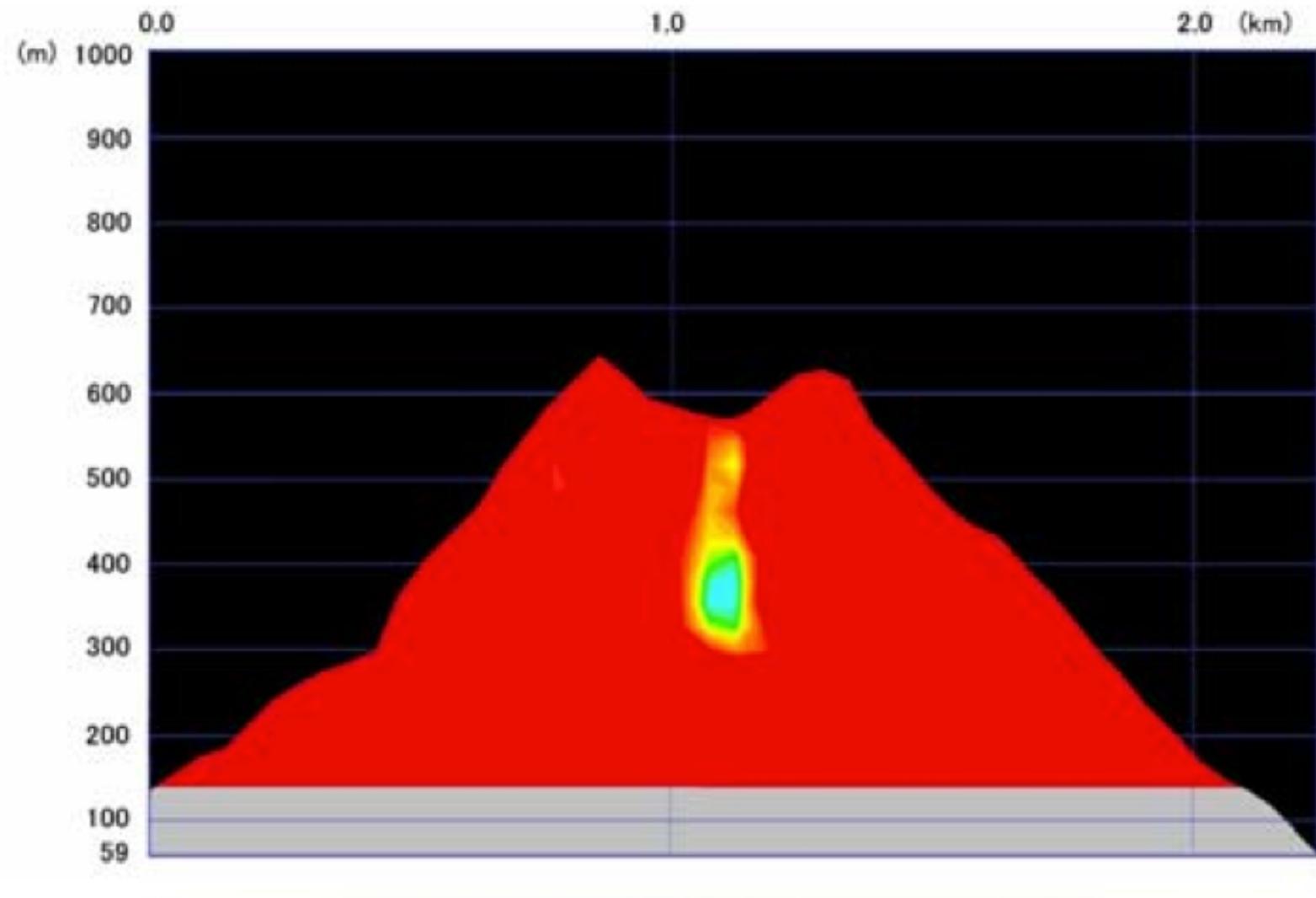
Copahue, 3D elevation model (from SRTM4)



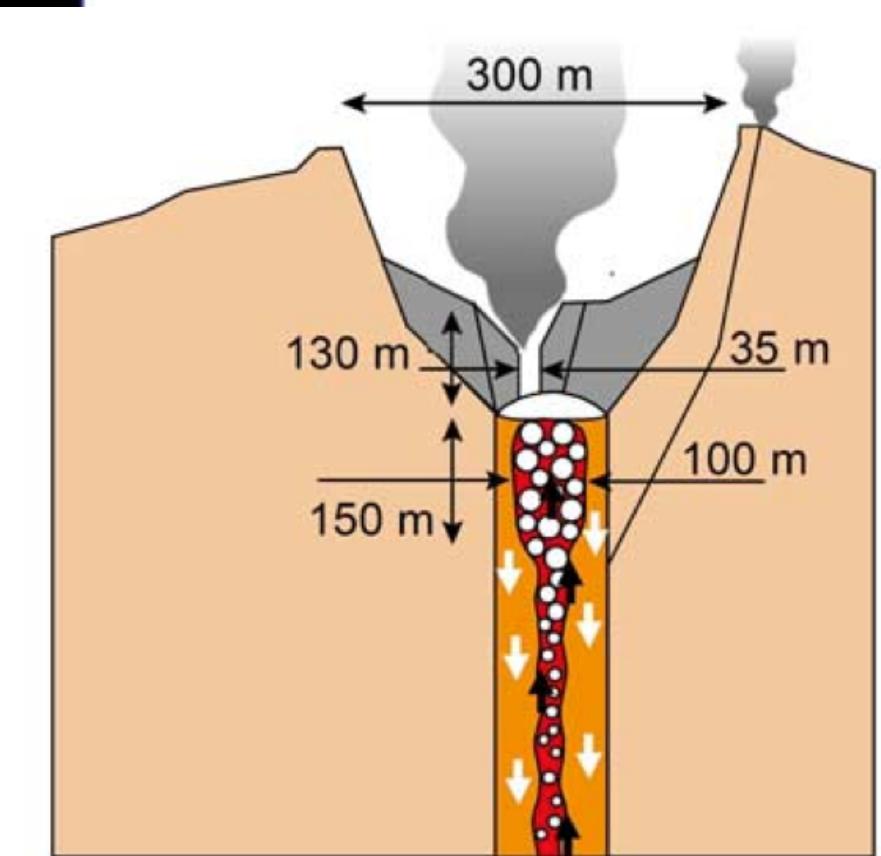
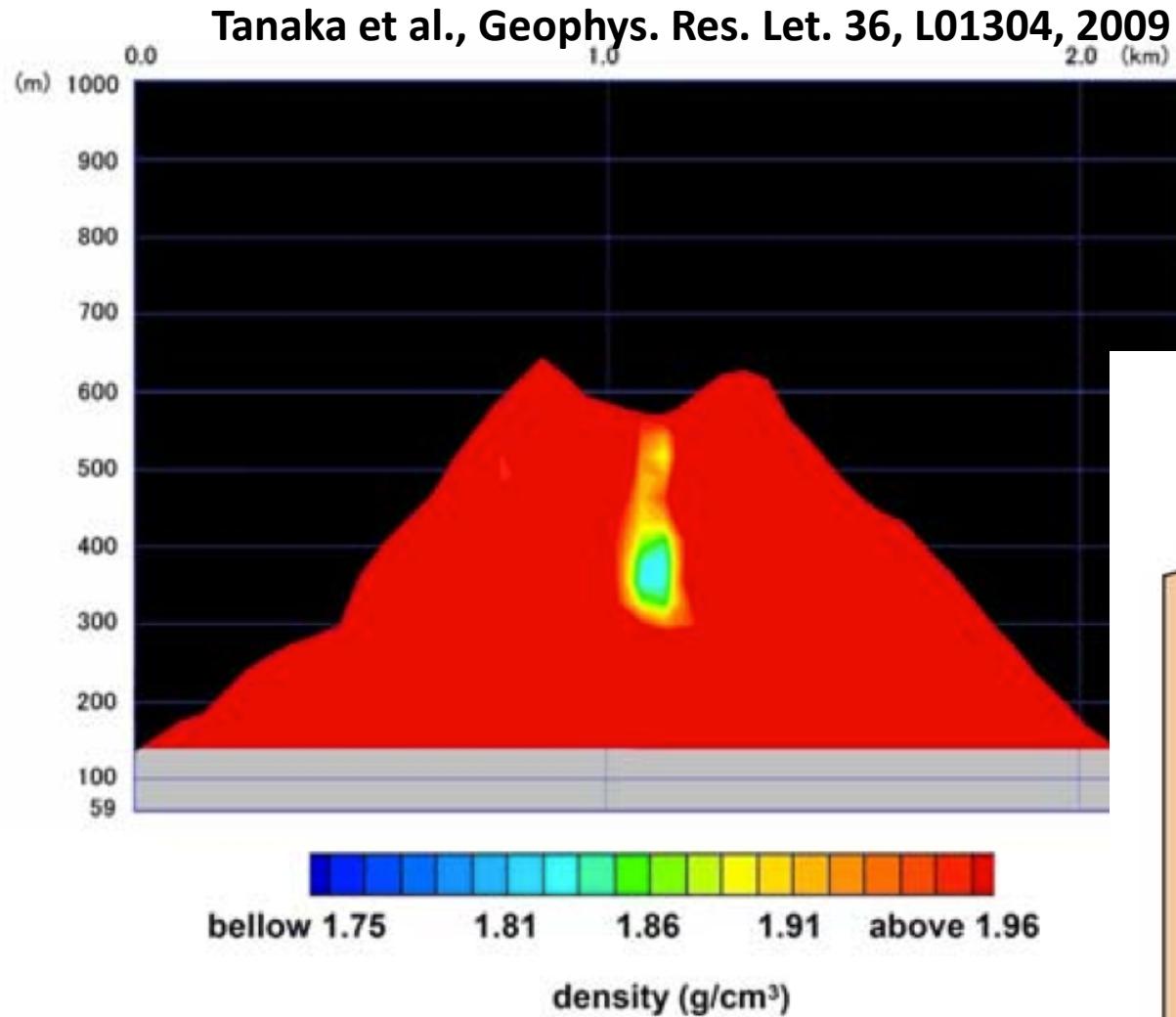
Villarrica, 3D elevation model (from SRTM4)



Volcanoes Muongraphy: Mt. Iwodake (Japan)



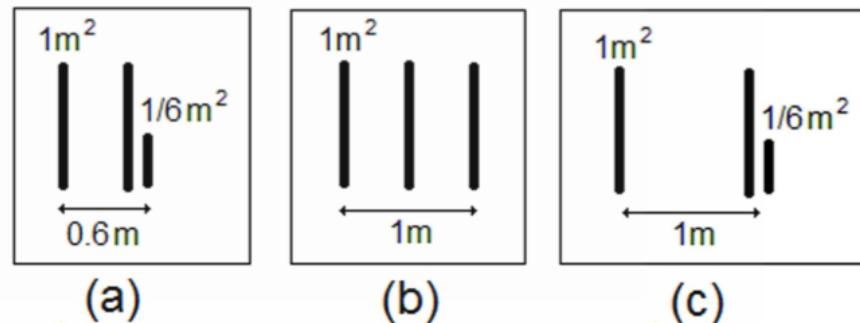
Volcanoes Muongraphy: Mt. Iwodake (Japan)



ToMuVol → Puy de Dôme

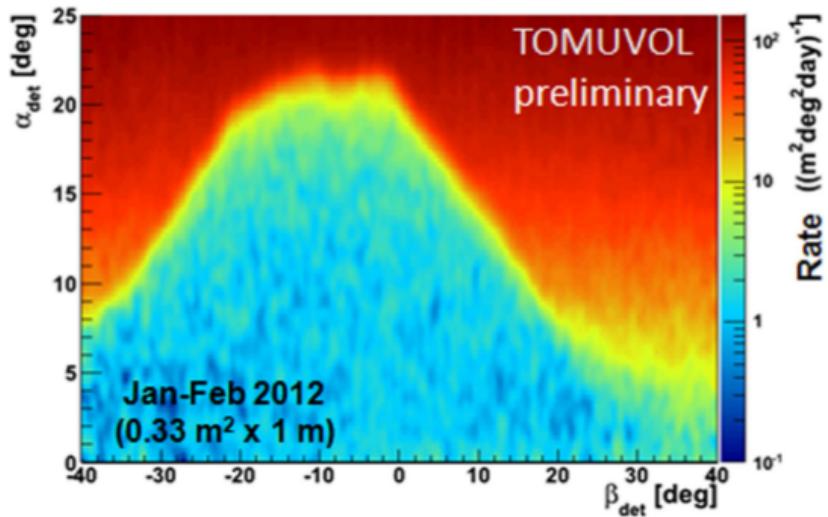
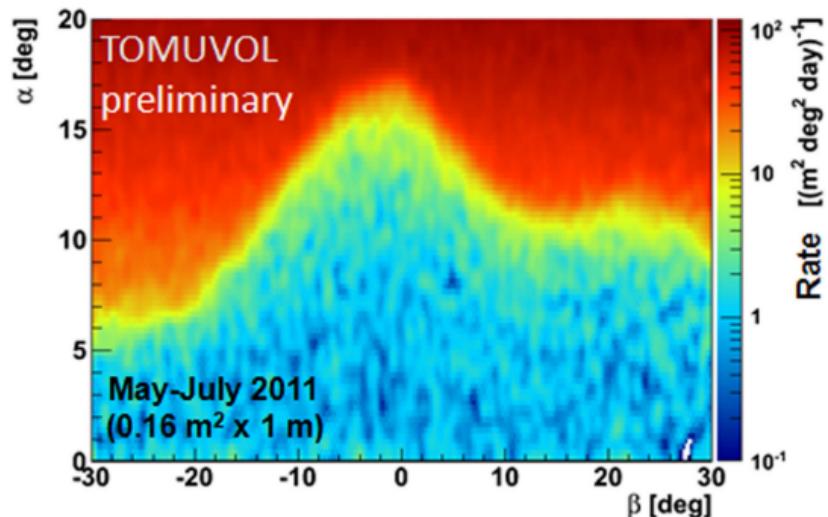
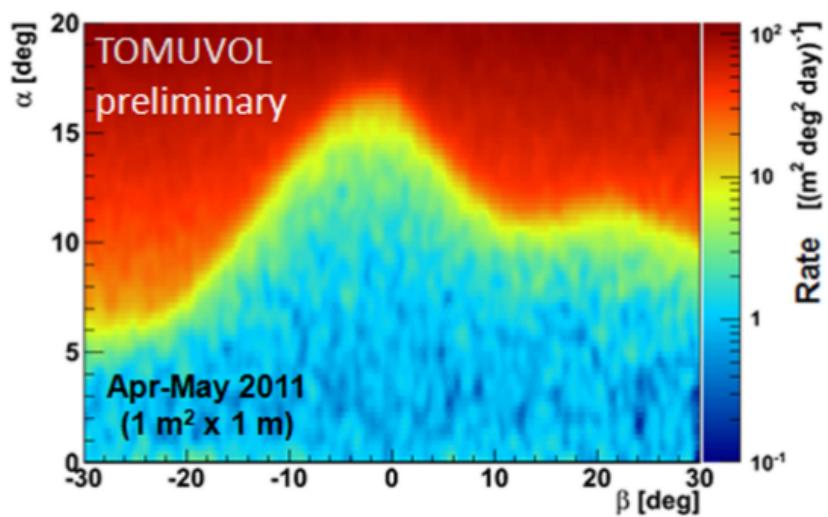
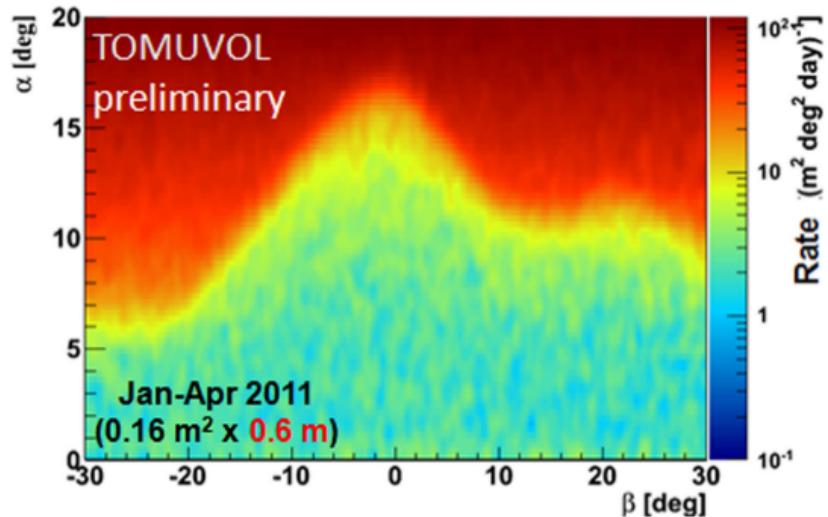


- Inactive volcano
- Artificial concrete cavern
→ 60m thickness
- Essay of several configurations

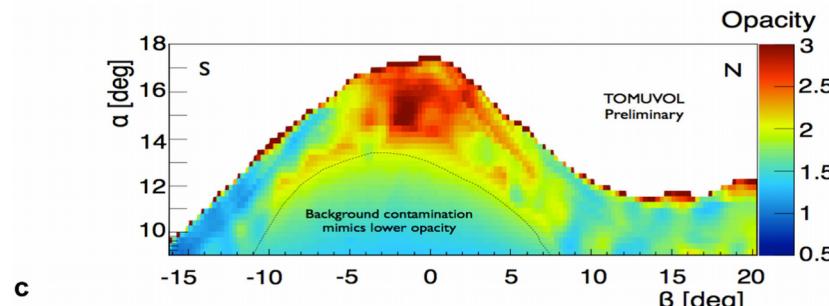
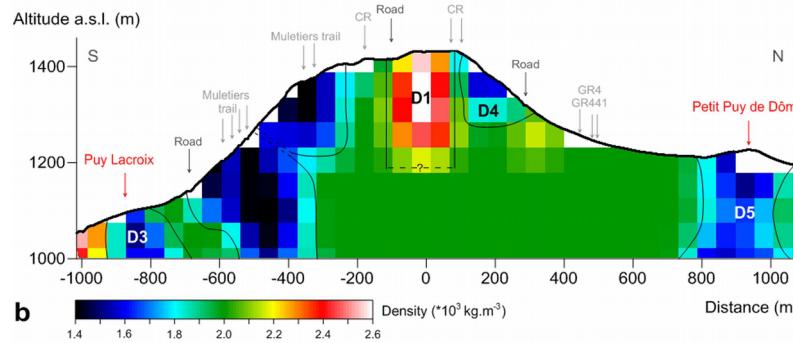
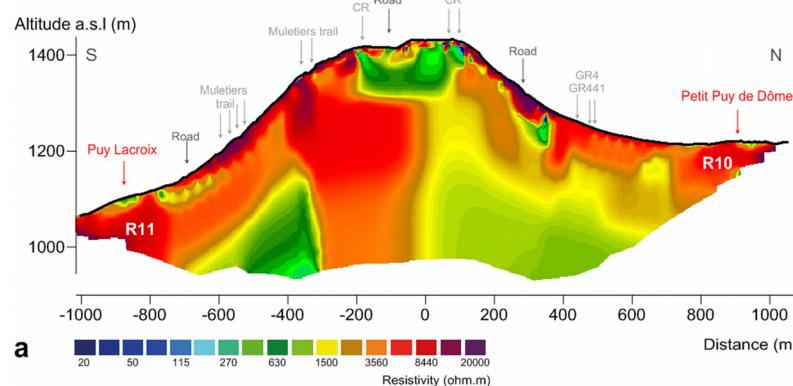


C. Cârloganu et al., Geosci. Instrum. Method. Data Syst., 2, 55–60, 2013

ToMuVol → gaseous Resistive Plate Chamber

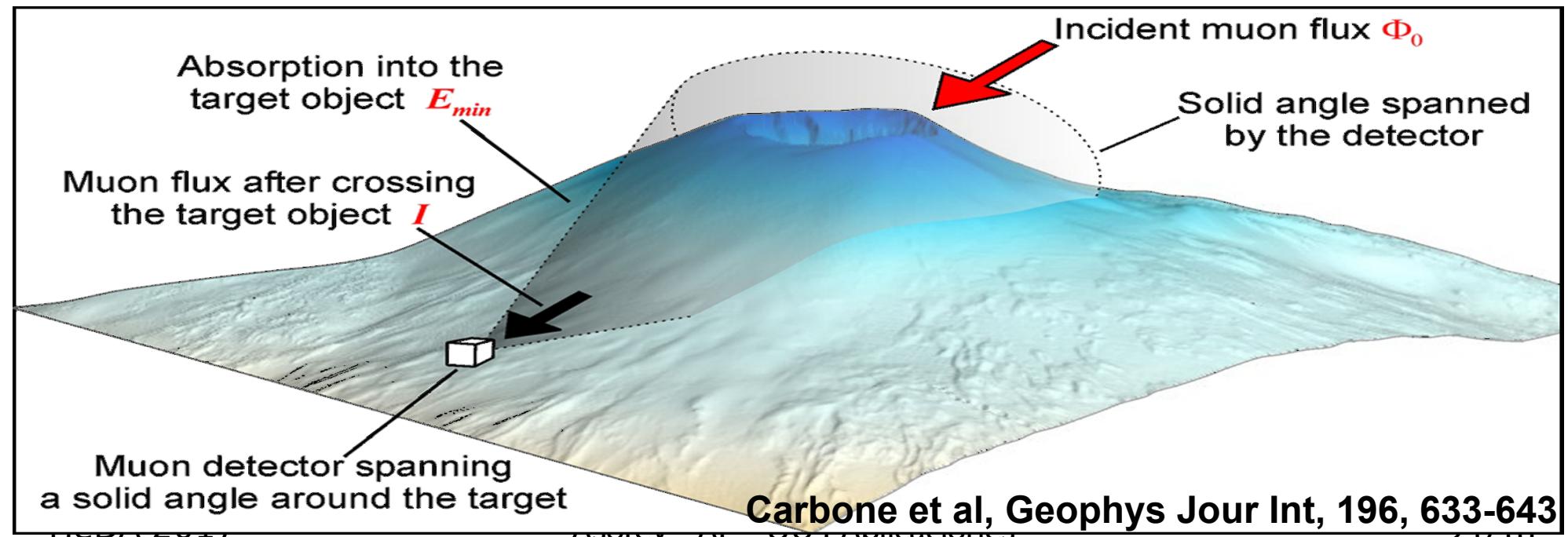
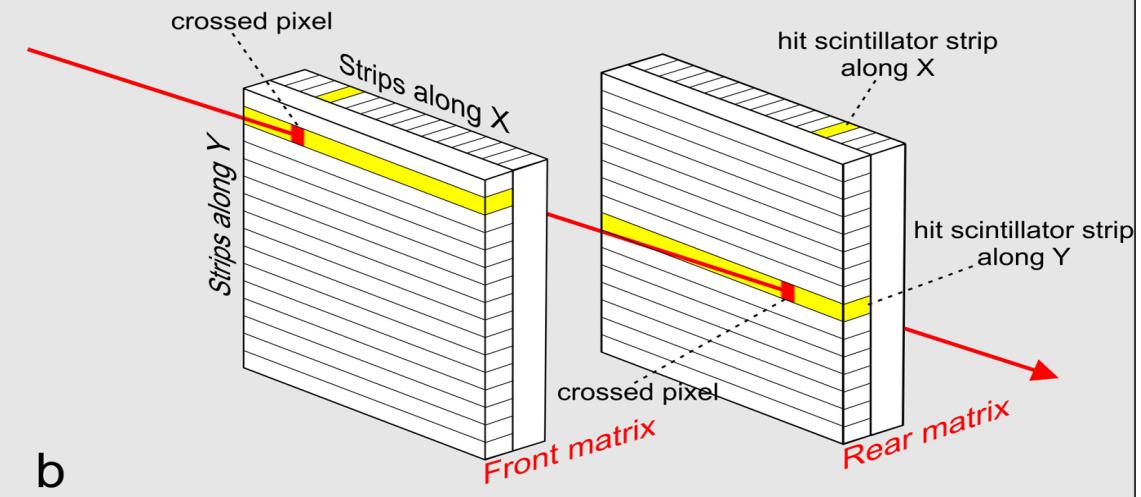
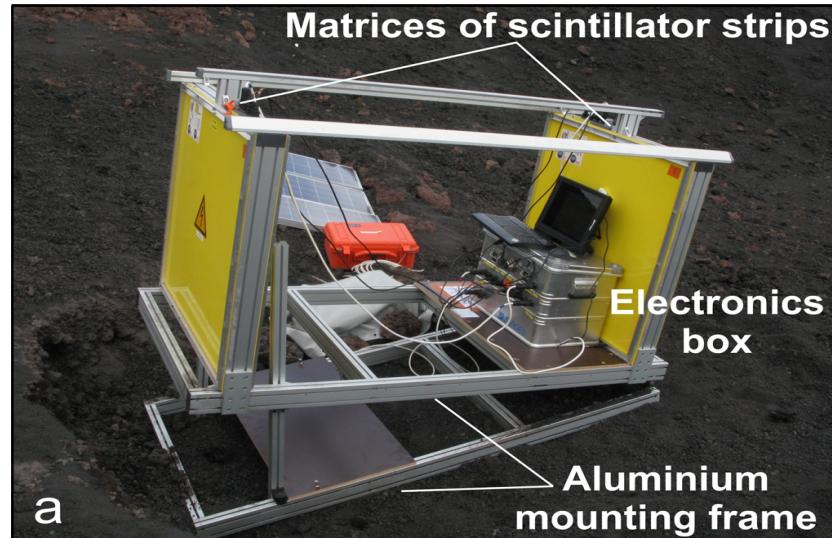


Comparison with other techniques

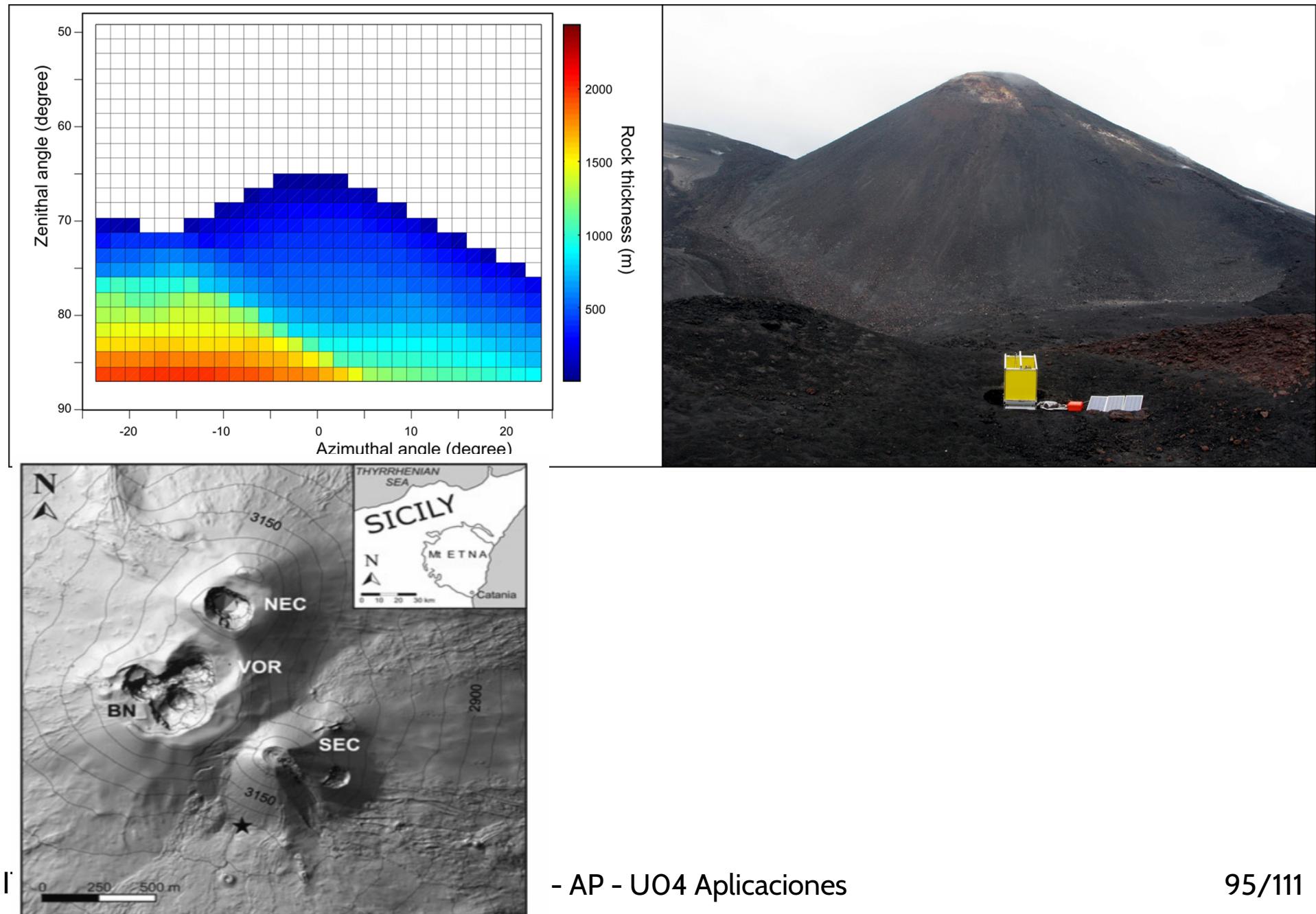


- ERT (Electrical Resistivity Tomography)
- Gravimetry
- Muongraphy

MuRay: Mt. Etna



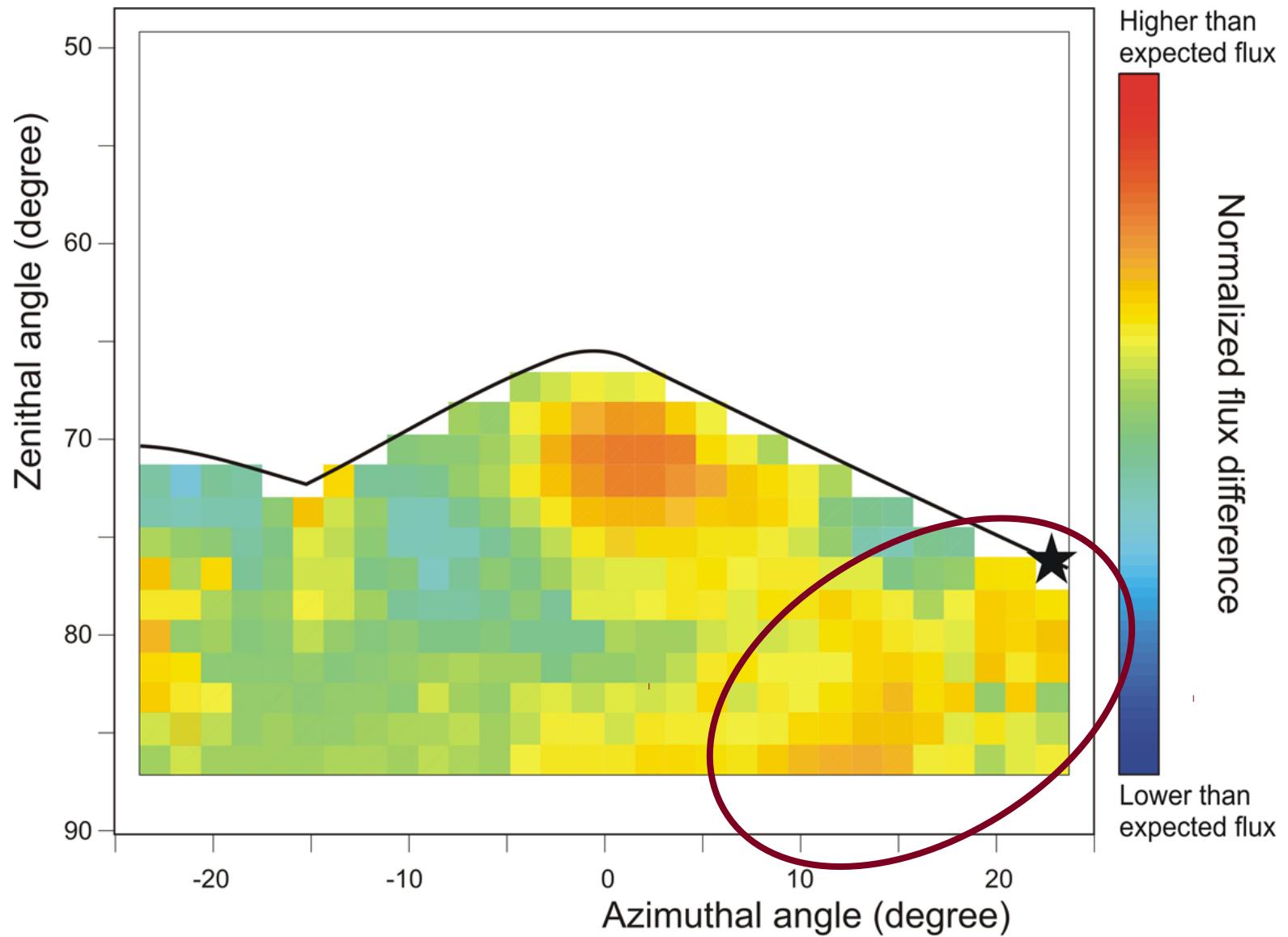
Rock thickness and camera position



Mt. Etna 2008 secondary eruption

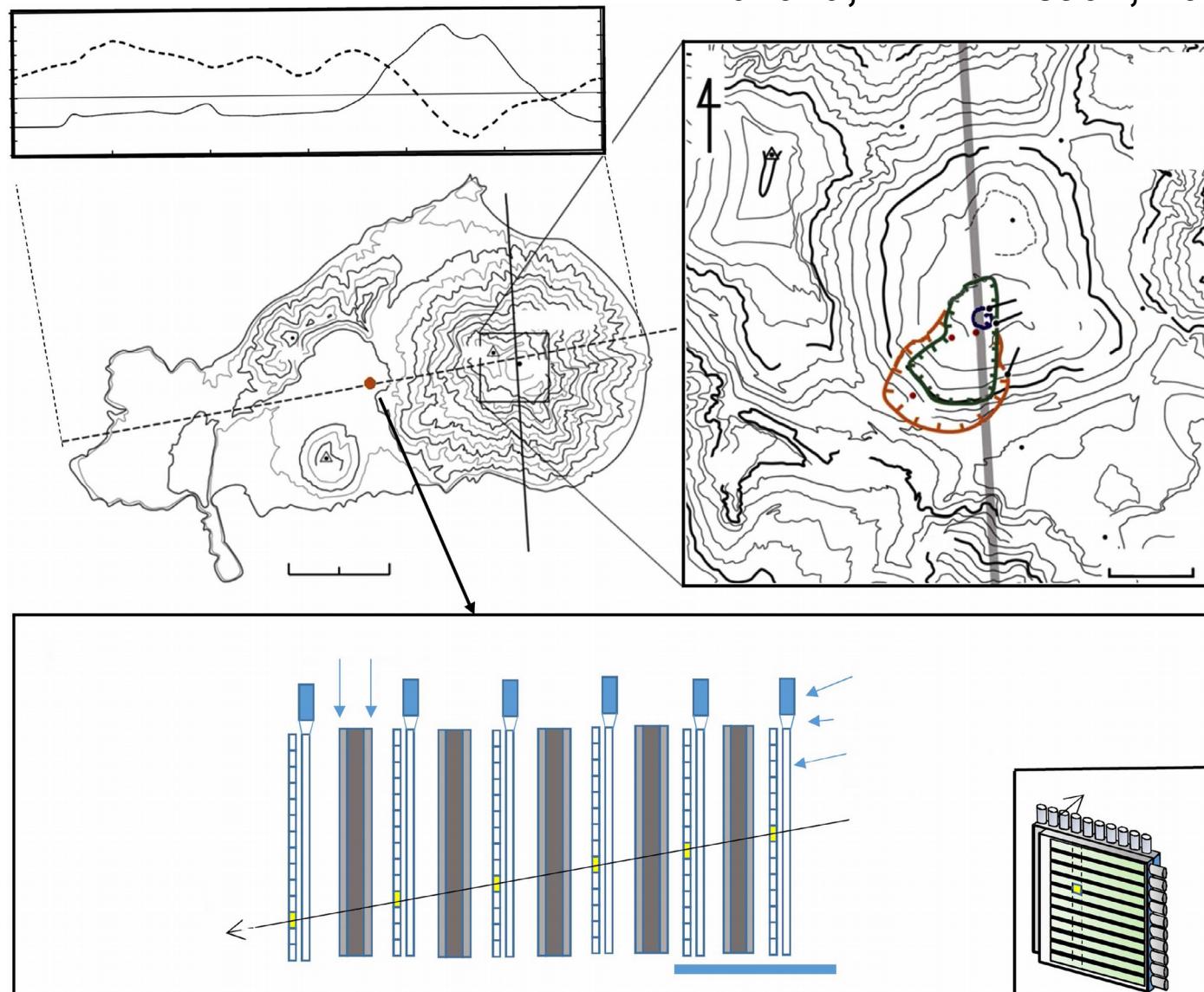


Density Profiles observed in 2010

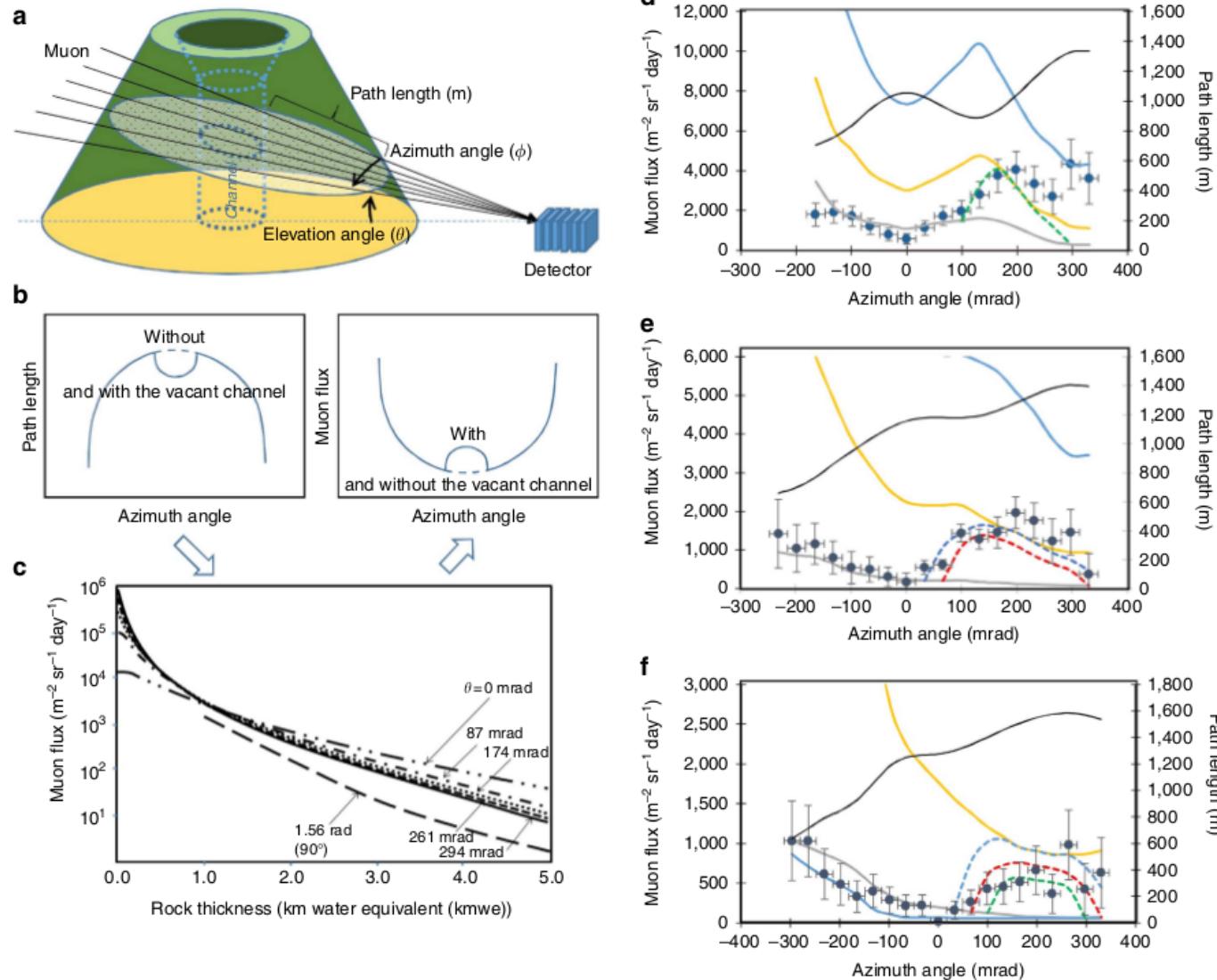


Mt. Satsuma-Iwojima

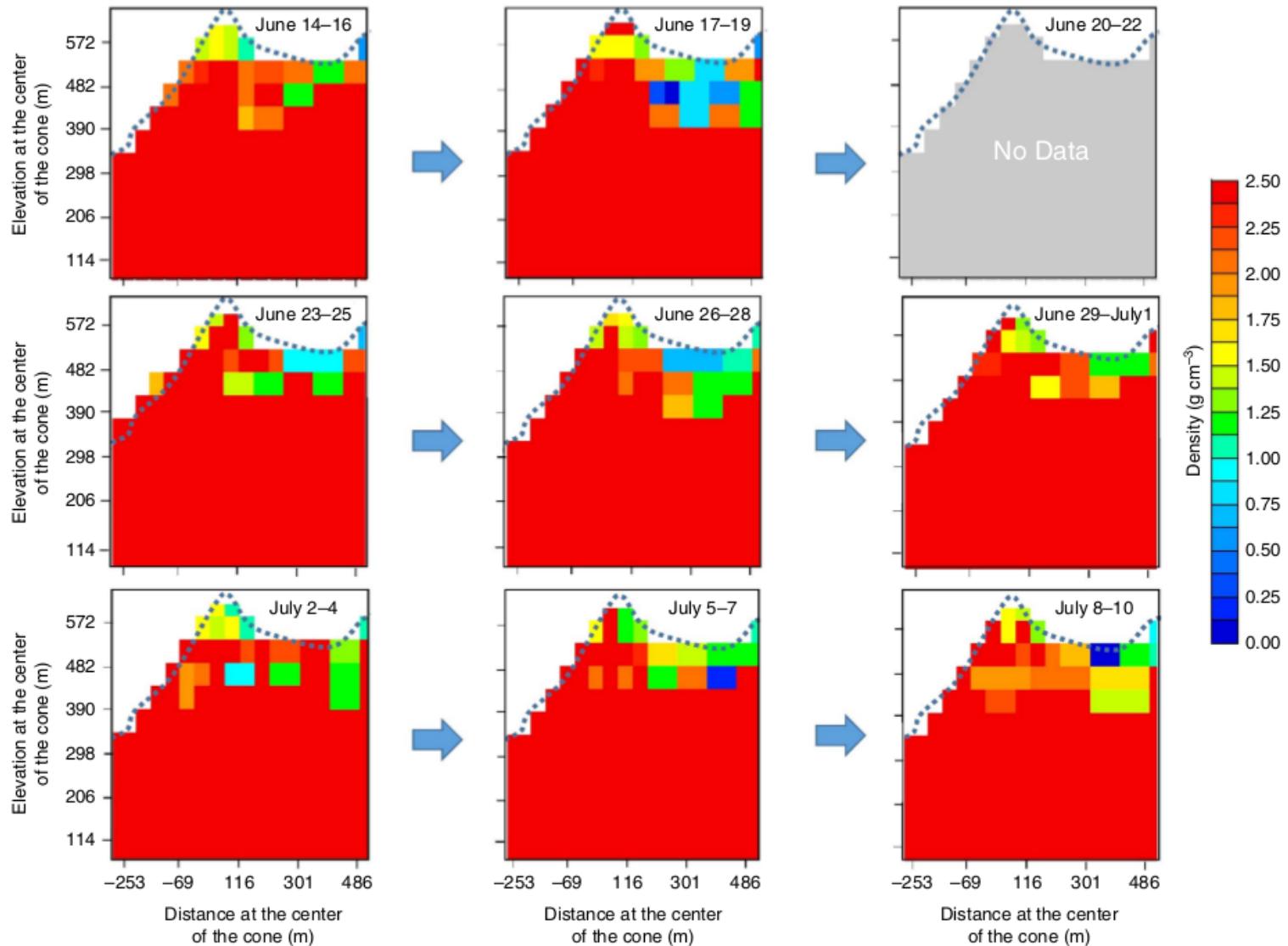
Tanaka, H. K. M. et al., Nat. Commun. 5:3381 (2014)



Real time measurements



Time Lapse of the lava motion at summit



Time Lapse of the lava motion at summit





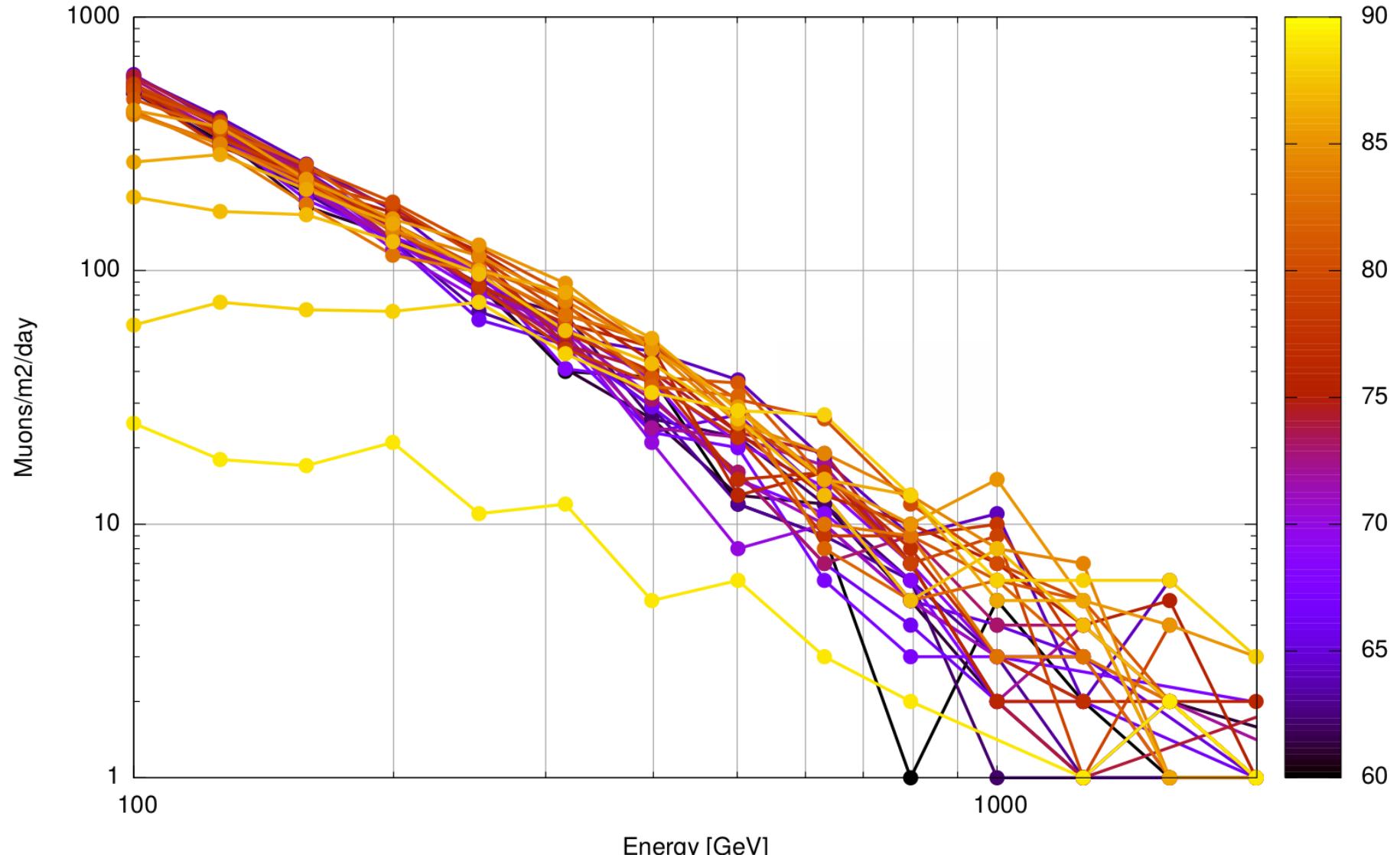
Our project: MuBar/MuTe

- Muon telescope for directional flux measurements
- Innovative camera design
- Participating institutions (for now!):
 - Argentina: CAB/IB
 - Colombia: UIS, UdeTol, SGC/Ingeominas, UdeNar
- Interested
 - CONIDA (Peru) , USFQ (Ecuador)

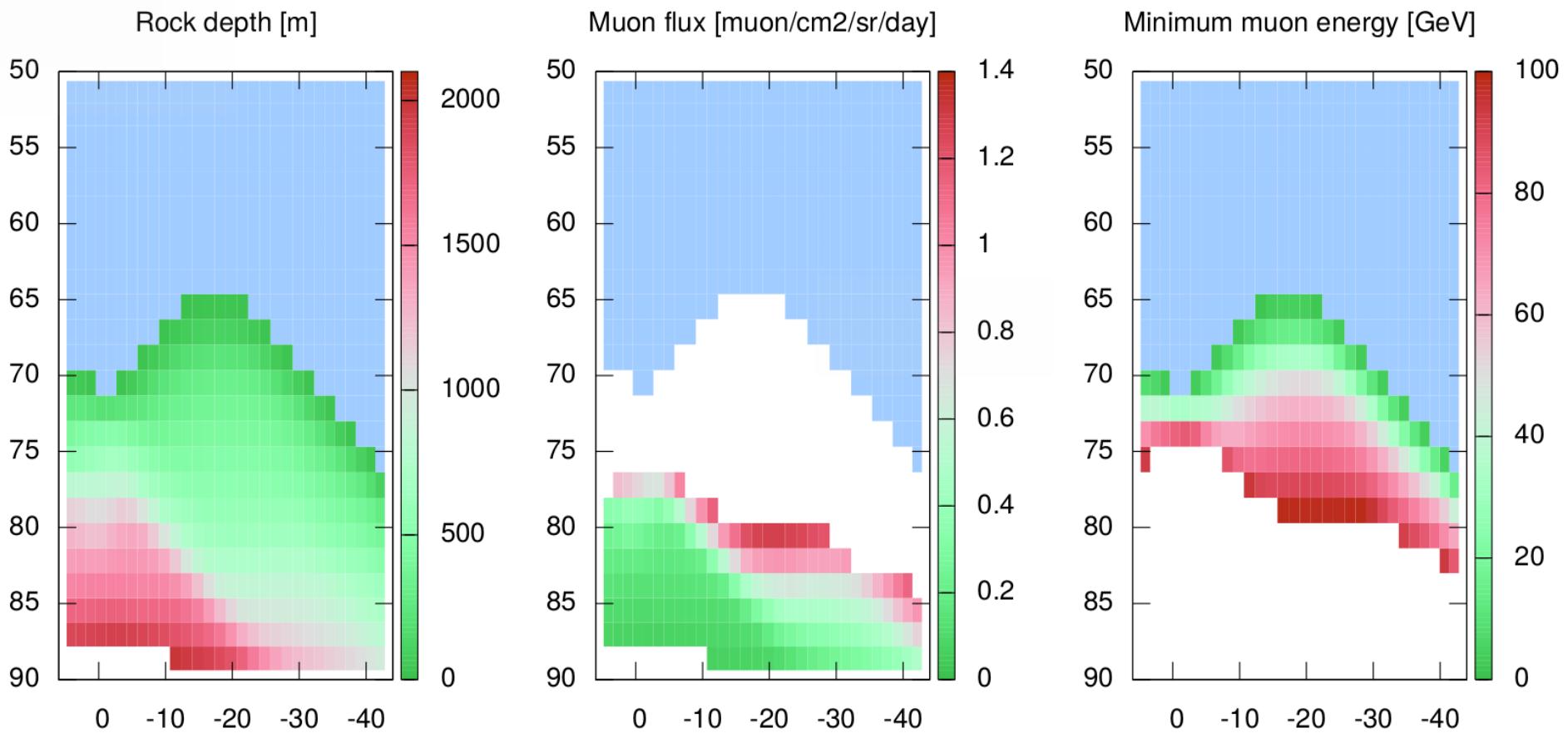
MuTe/MuBar: Muon Telescope for muongraphy



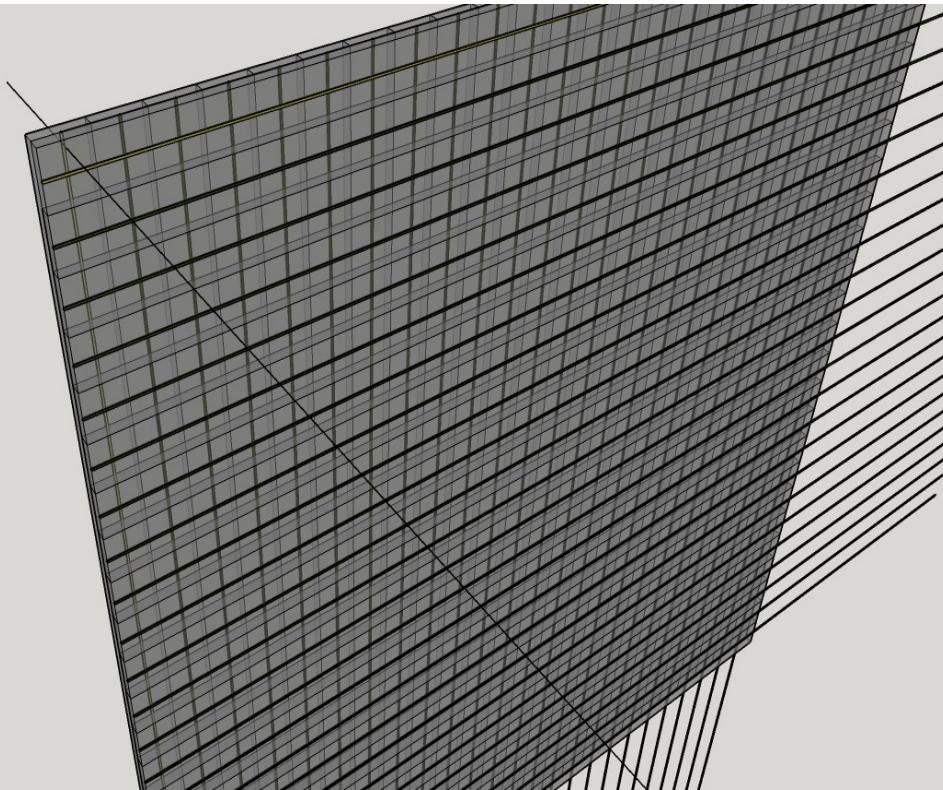
First attempts: Mt Etna (sims and data analysis)



First attempts: ITeDA (SIMS and data analysis) (muon energy up to 100 GeV)



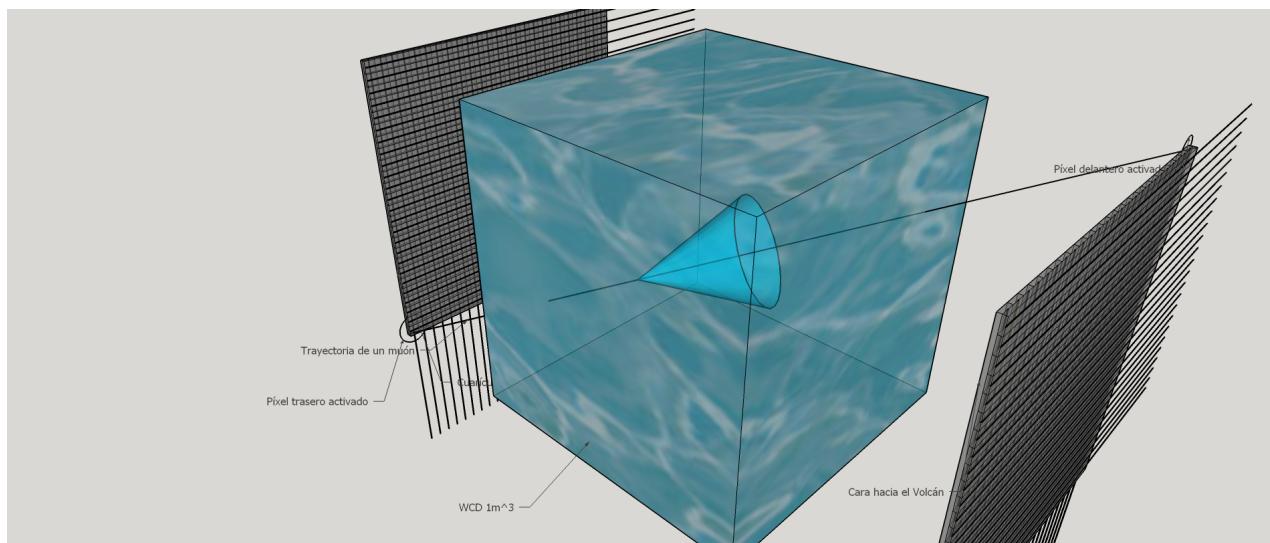
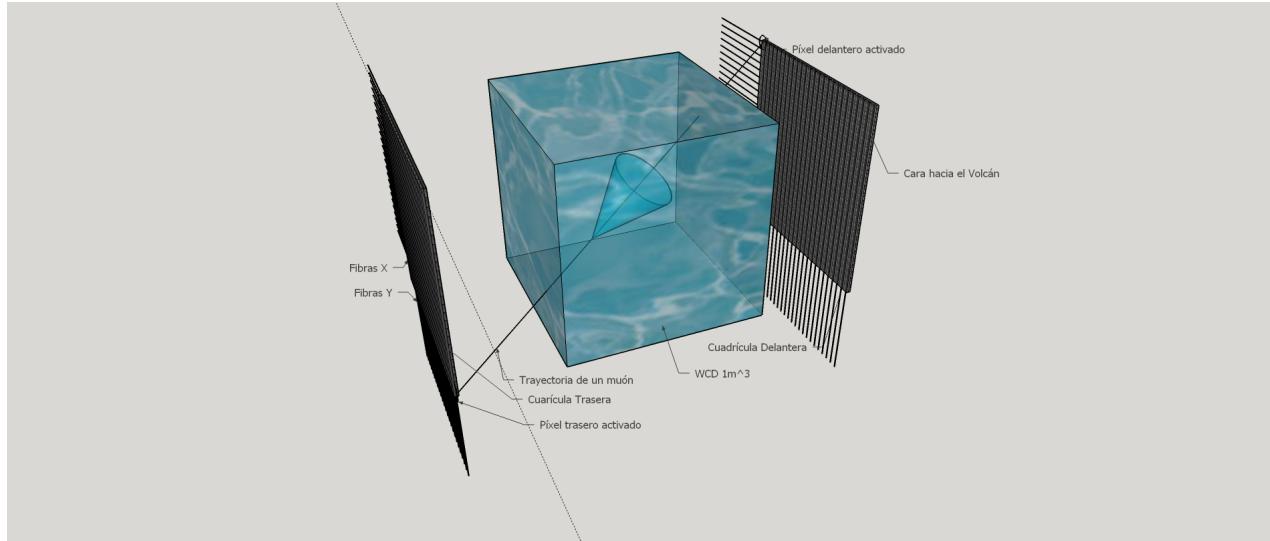
Preliminary: our Muon Camera (under design)



- 30 (4x1)cm plastic scintillator strips
→ 900 pixels (XY plane)
- Two XY planes separated by 2 m
- One water Cherenkov detector in between to obtain a high energy electromagnetic veto

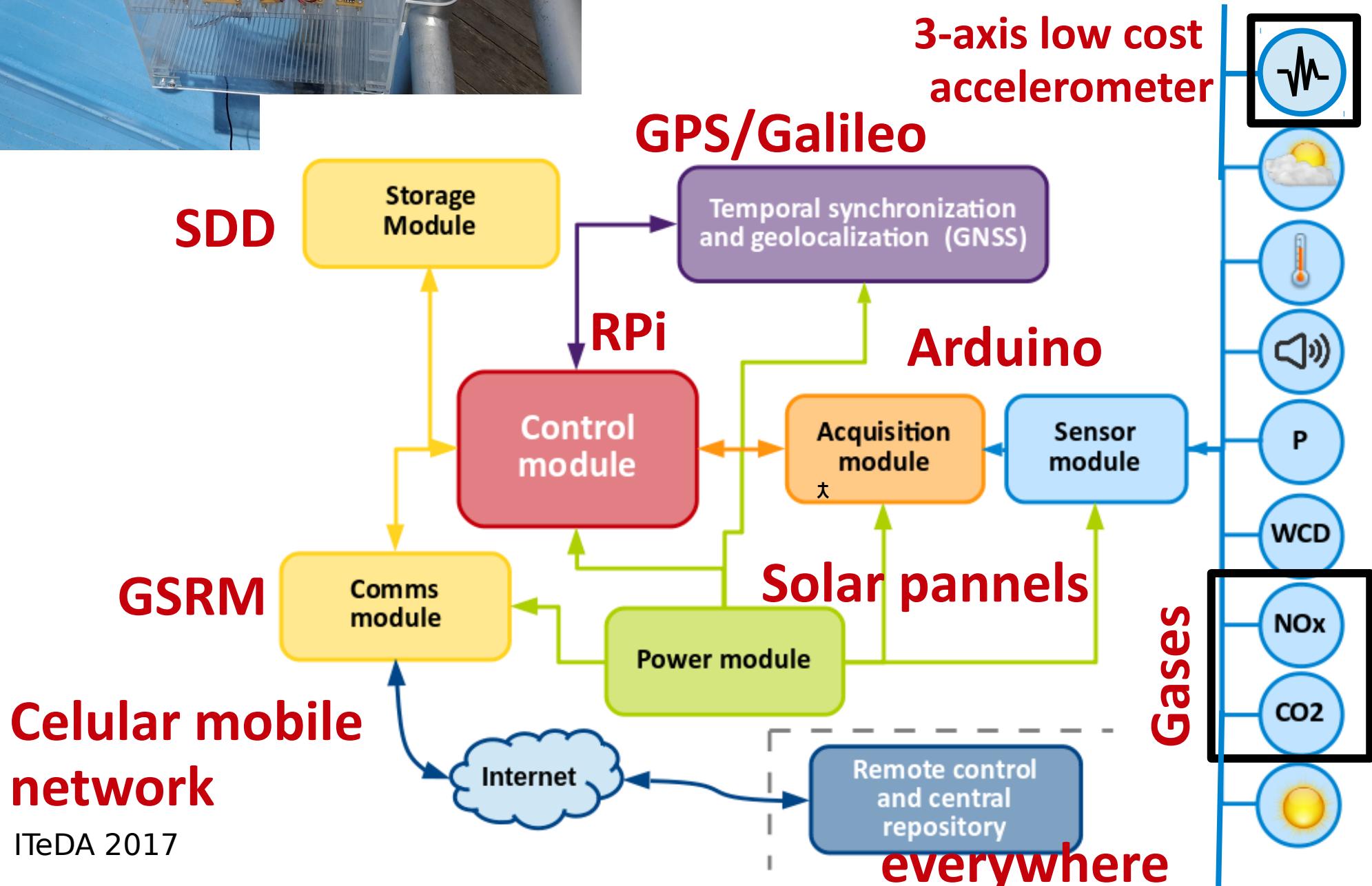
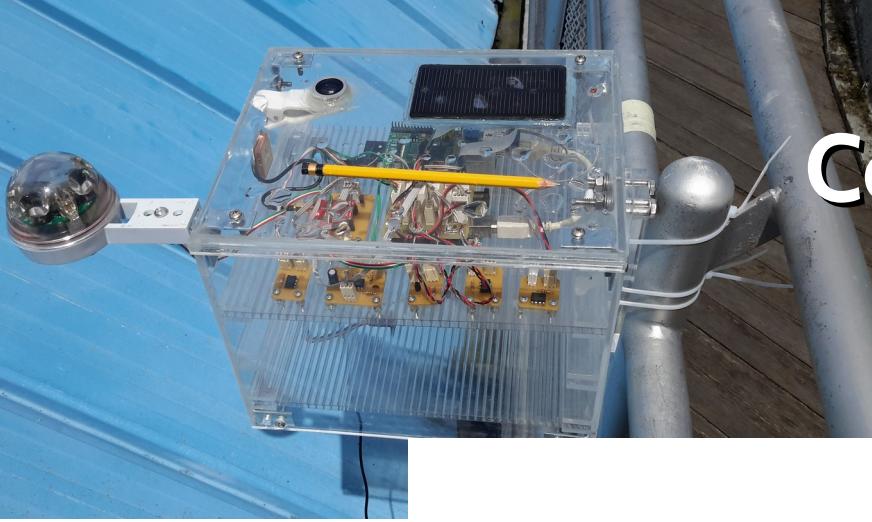
- Two planes of “Minos” like polyestyrene plastic scintillator
 - (PoP+PoPoP) organic scintillator mixture
- Clad and wavelength shifter optical fiber at strip centre
- 120 SiPM (Hamamatsu MPPC)
- Raspberry-Arduino based atmospheric monitoring system
- CITIROC based electronic
- Programmable and configurable on board self trigger using FPGA
- Low power automatic and autonomous system

MuTe (Muon Telescope)

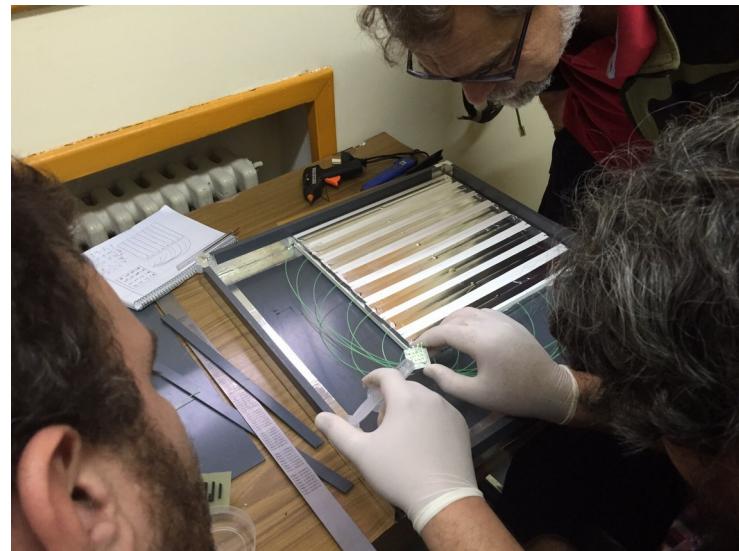
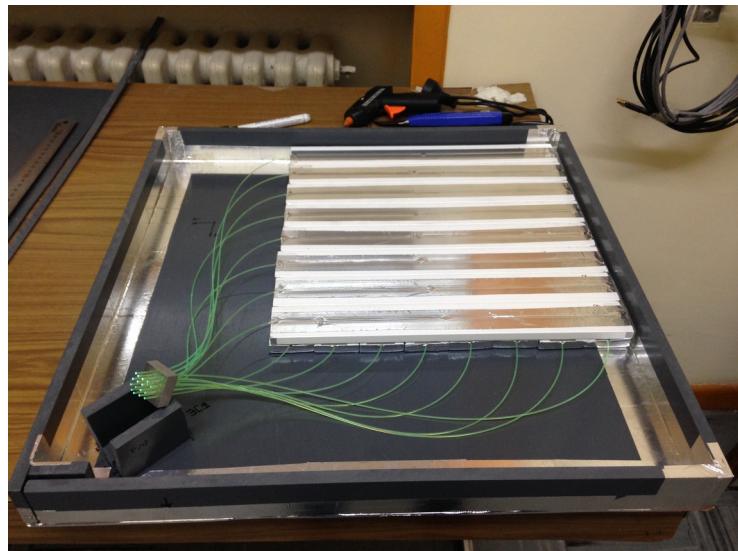
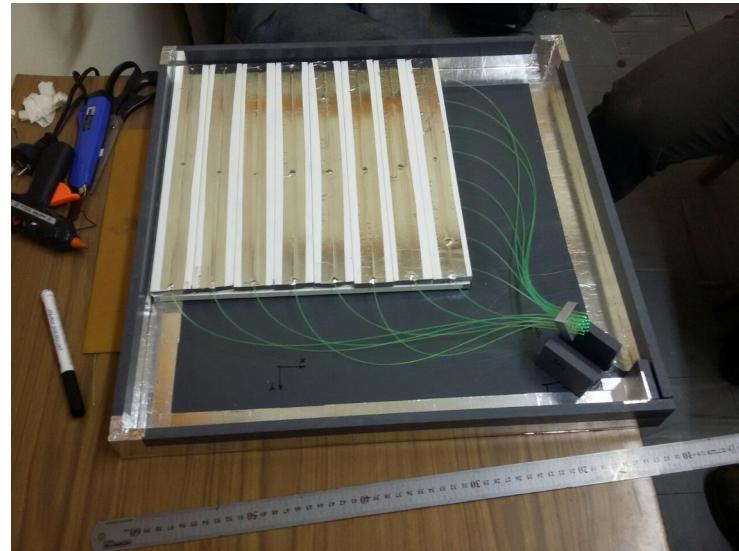
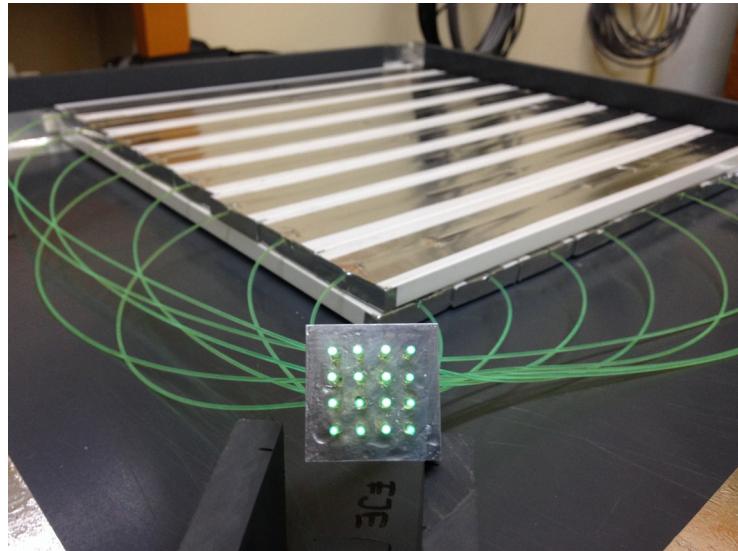


- Innovative:
 - Use a WCD as an active absorbant
 - 1.2m water → ~ 5 X_{EM}
- Local measurement of atmospheric muon flux
- SiPM instead of multi-anode pixel
 - No crosstalk
 - Lower budget
 - Lower power consuption
 - Simple global design

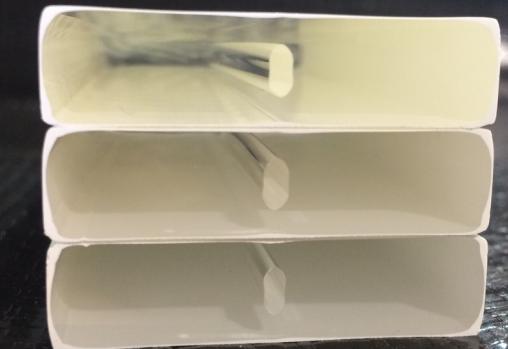
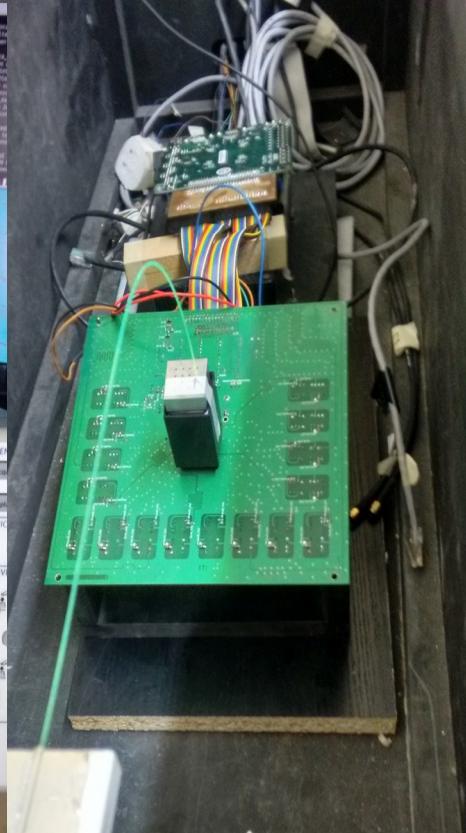
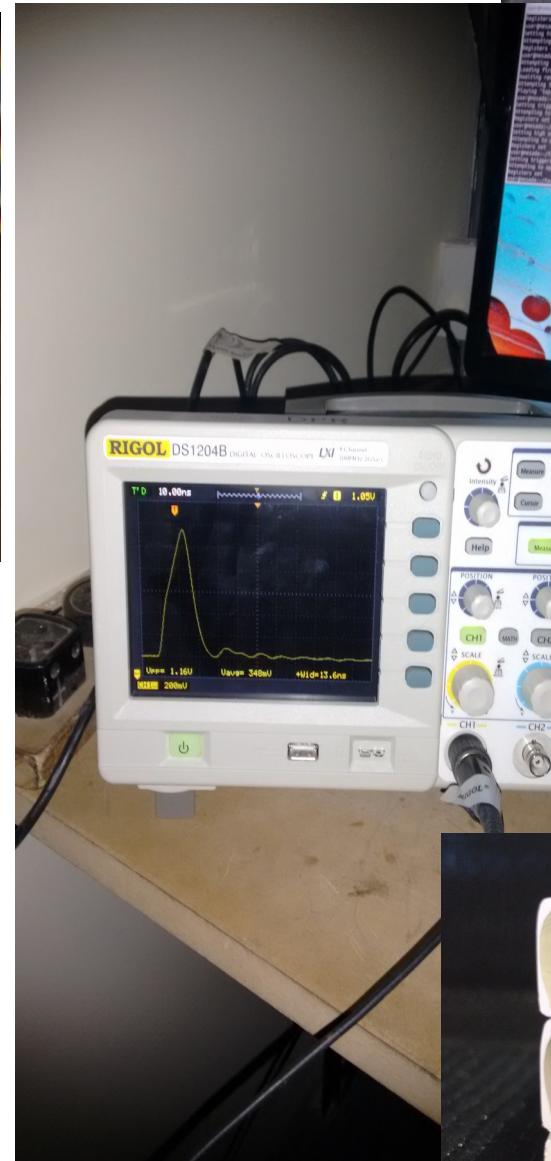
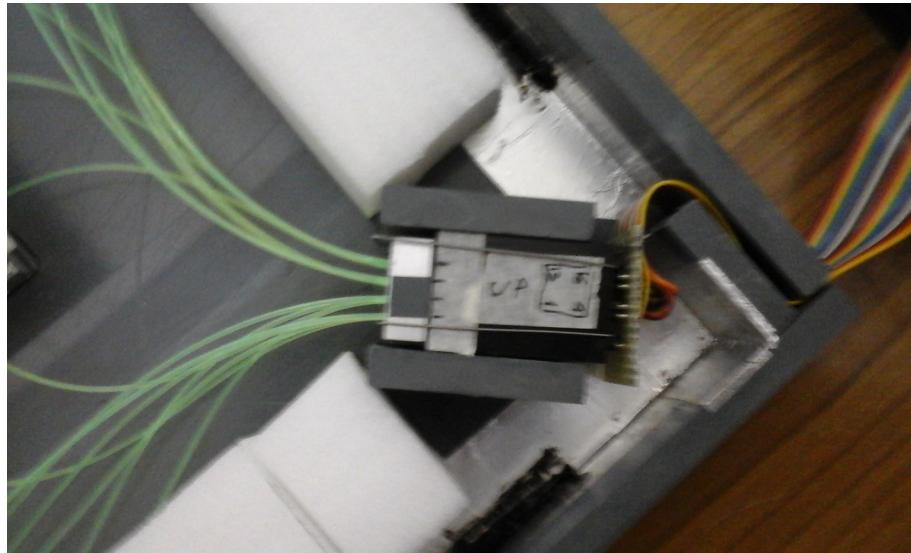
Autonomous Station for Control and Data Aquisition Sensors



MuBar prototype



First tests



Possible target at Copahue?

