Escuela José Antonio Balseiro 2016
Nuevas Tendencias en Investigación en Física Médica

(Ultra) fast particle detection and high energy simulations applications

A (personal) compilation made by
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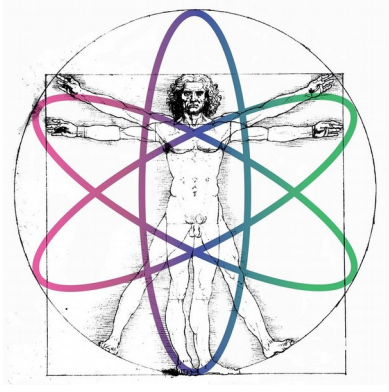
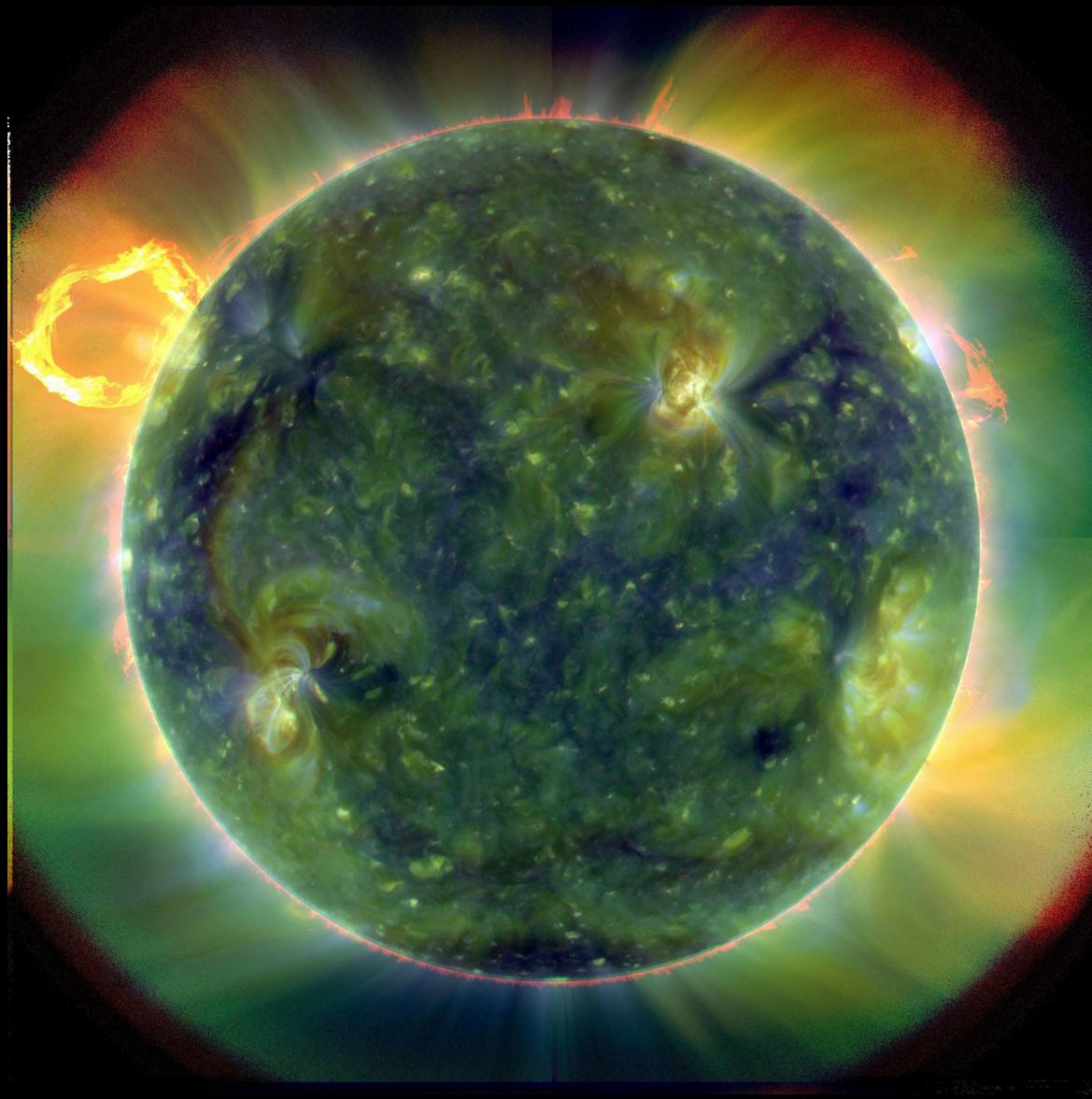
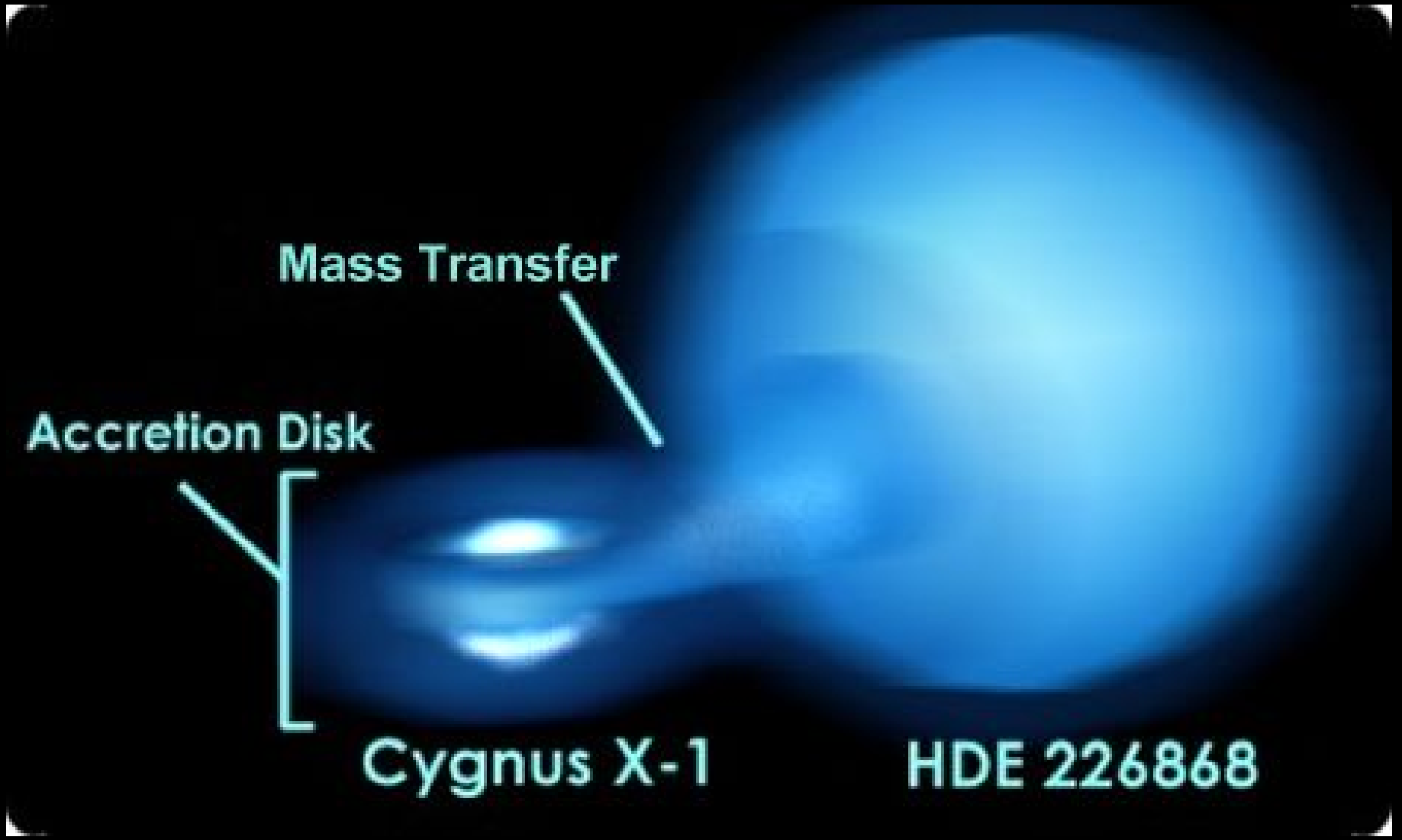
Centro Atómico Bariloche






Mass Transfer
Accretion Disk
Cygnus X-1
HDE 226868

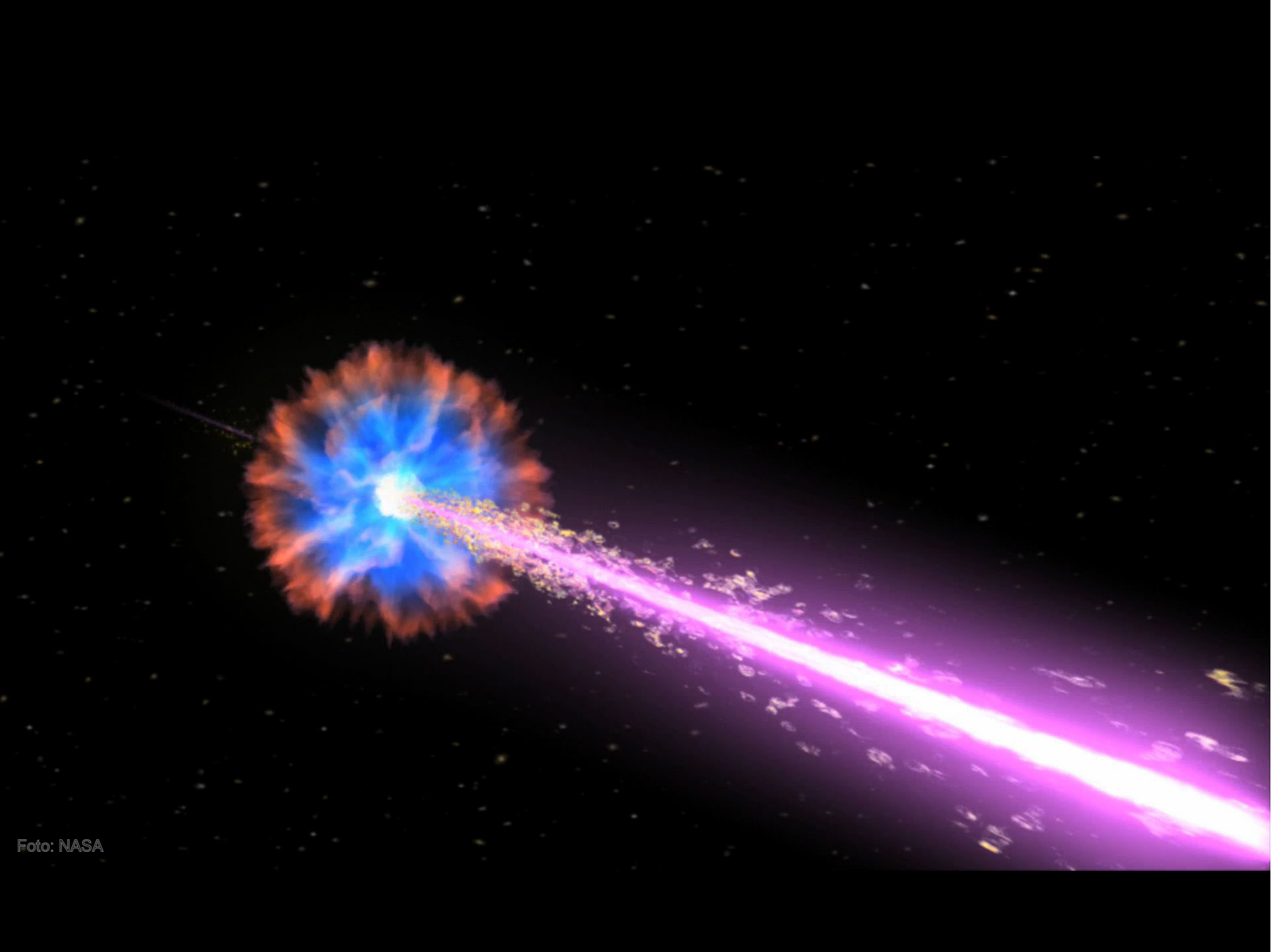
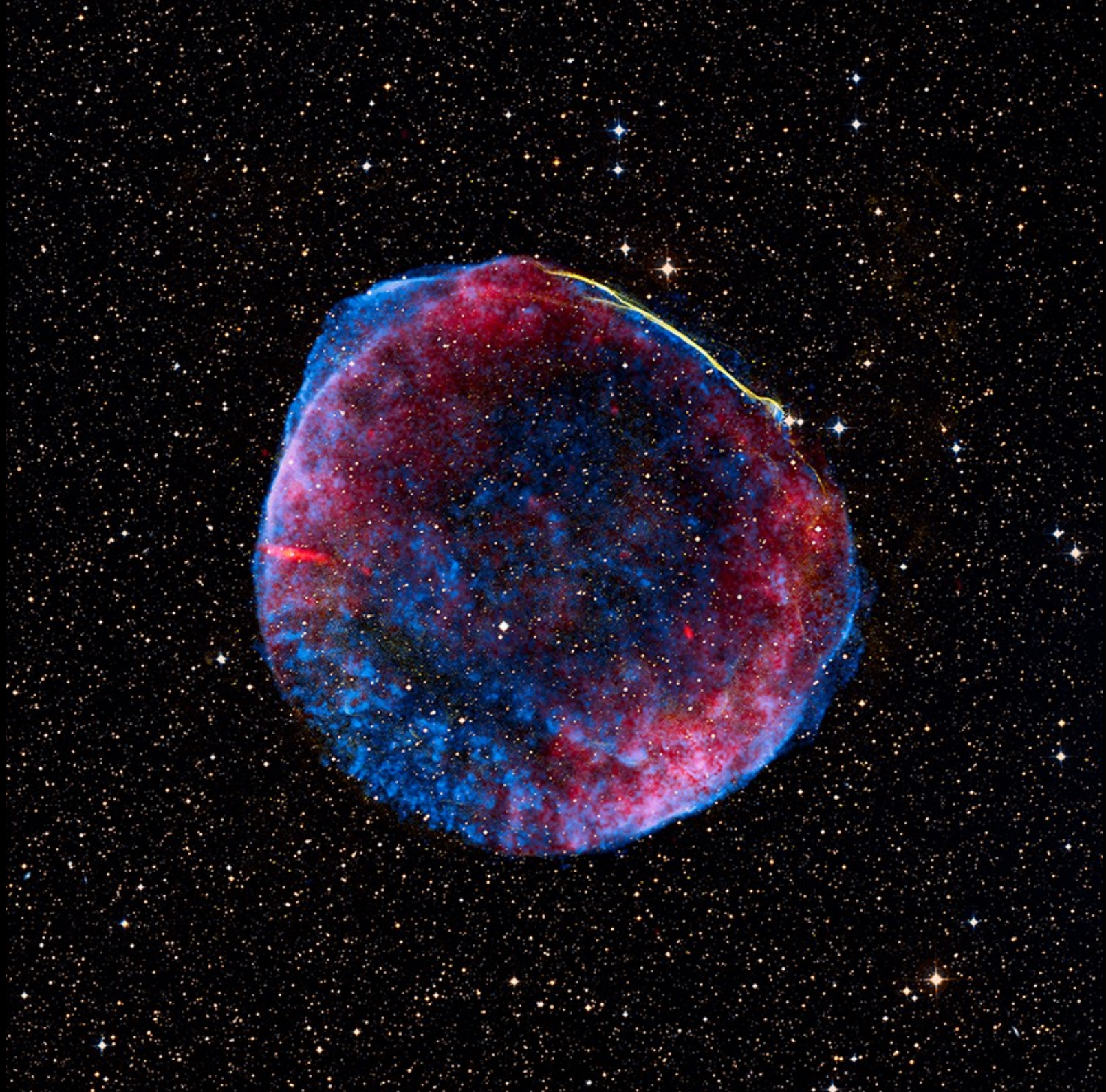


Foto: NASA




Astroparticles are “witnesses” of the most extreme phenomena of the Universe
Foto: NASA

Scopes

Relativistic Astrophysics

Stellar (Solar) Physics

Particle transport

Extreme Data Analysis

Atmospheric Physics

Nuclear & Particle Physics

Radiation Interaction

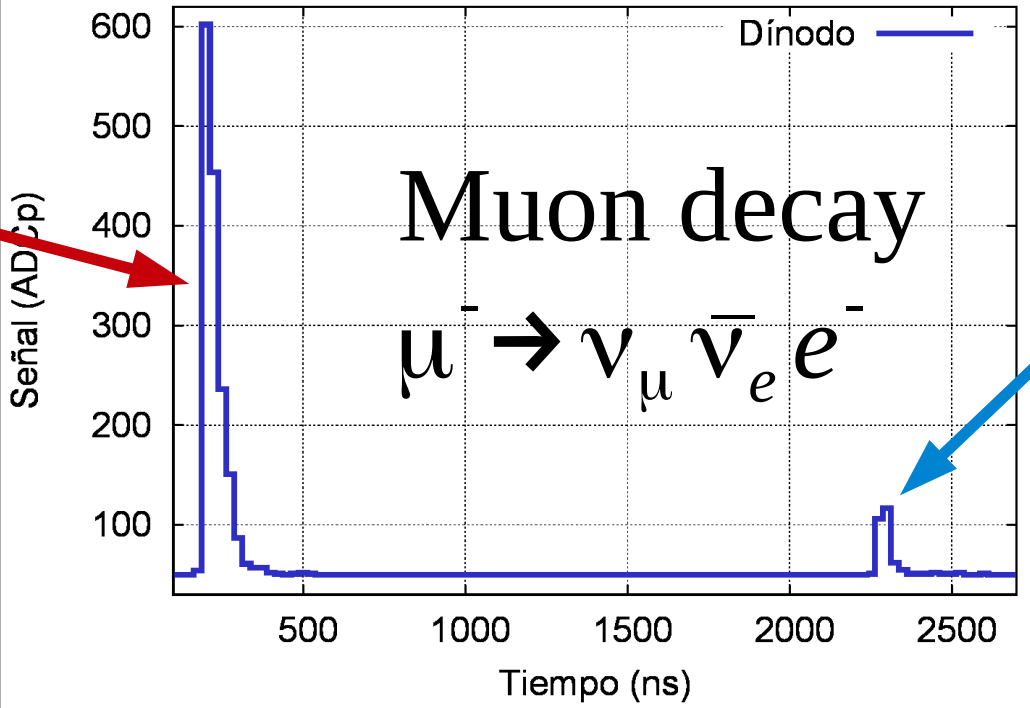
Scopes

- It begins at a Supernova remanent

Scopes

- It begins at a Supernova remanent
- And it ends with complex analysis of complex data

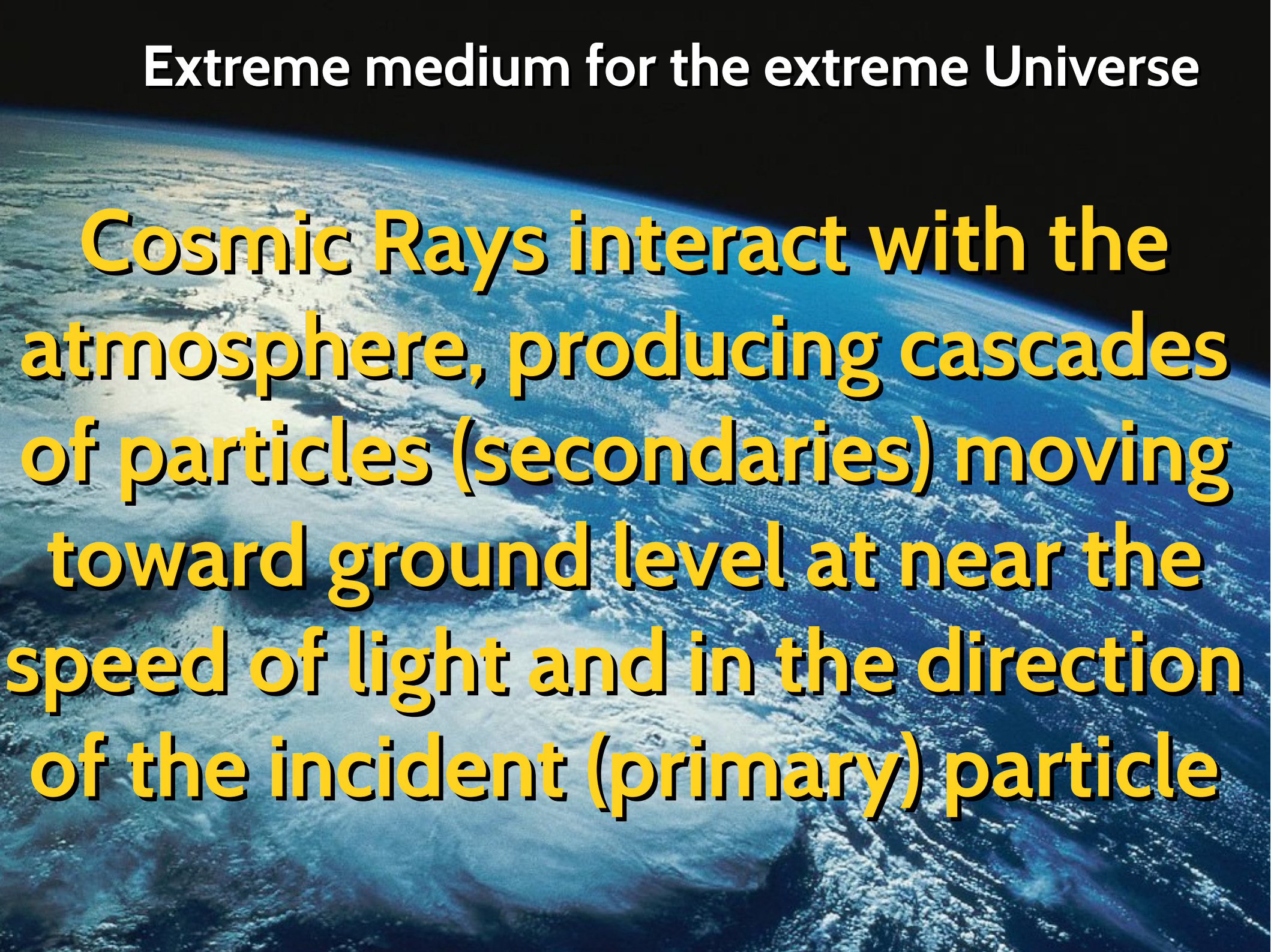
```
50  50  50
61  49  54
139  49  602
91  51  454
59  50  236
60  50  151
53  50  87
53  50  61
50  50  57
51  51  57
50  50  52
51  49  51
51  50  50
50  49  51
51  50  52
50  50  51
# t 4 30008562
# c 663486982
```



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

$\Delta p = 1$

```
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
```



Cosmic Rays interact with the atmosphere, producing cascades of particles (secondaries) moving toward ground level at near the speed of light and in the direction of the incident (primary) particle

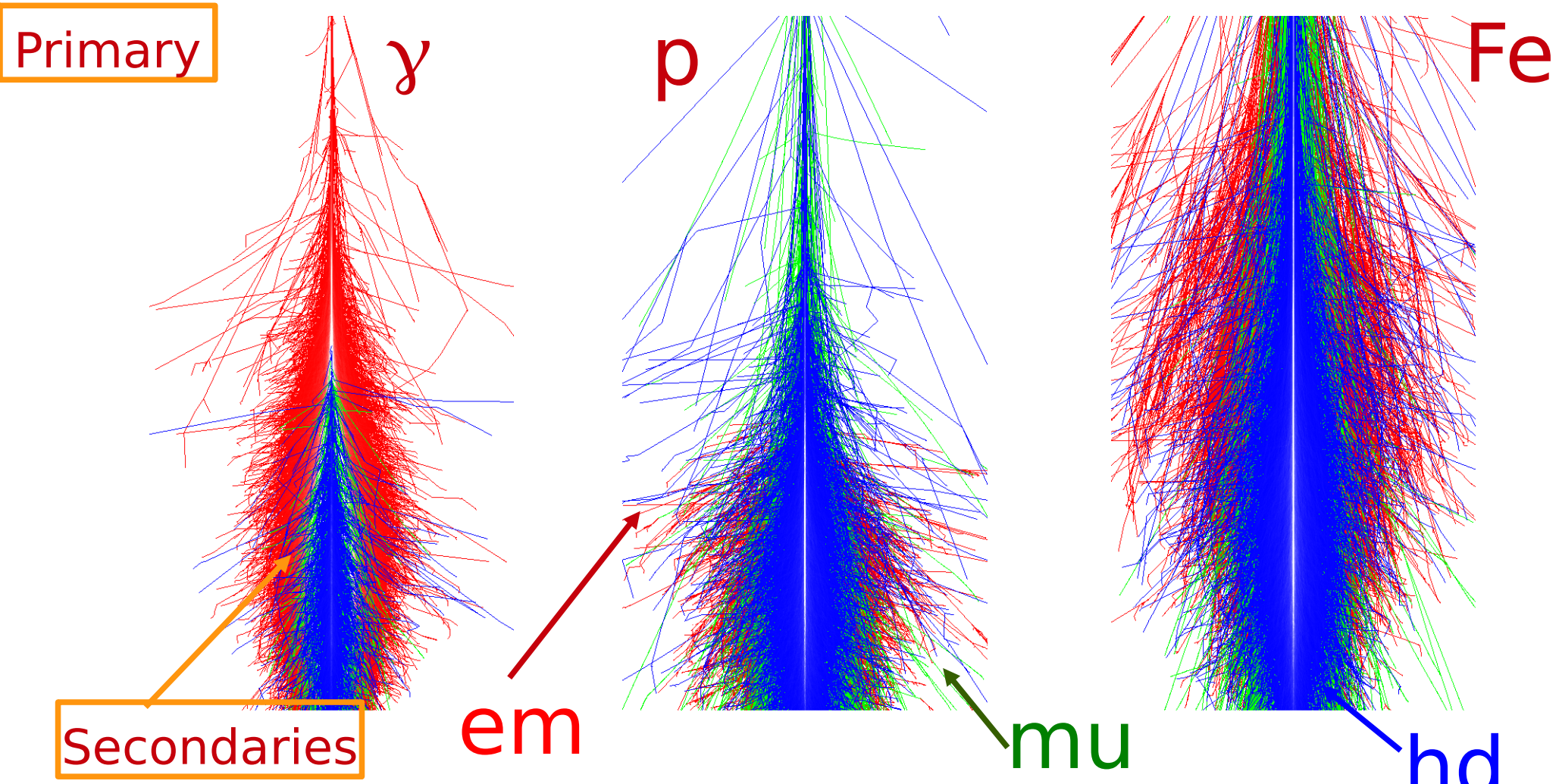
Particle interaction

EAS: Extensive Air Showers

E=5x10^{14} eV

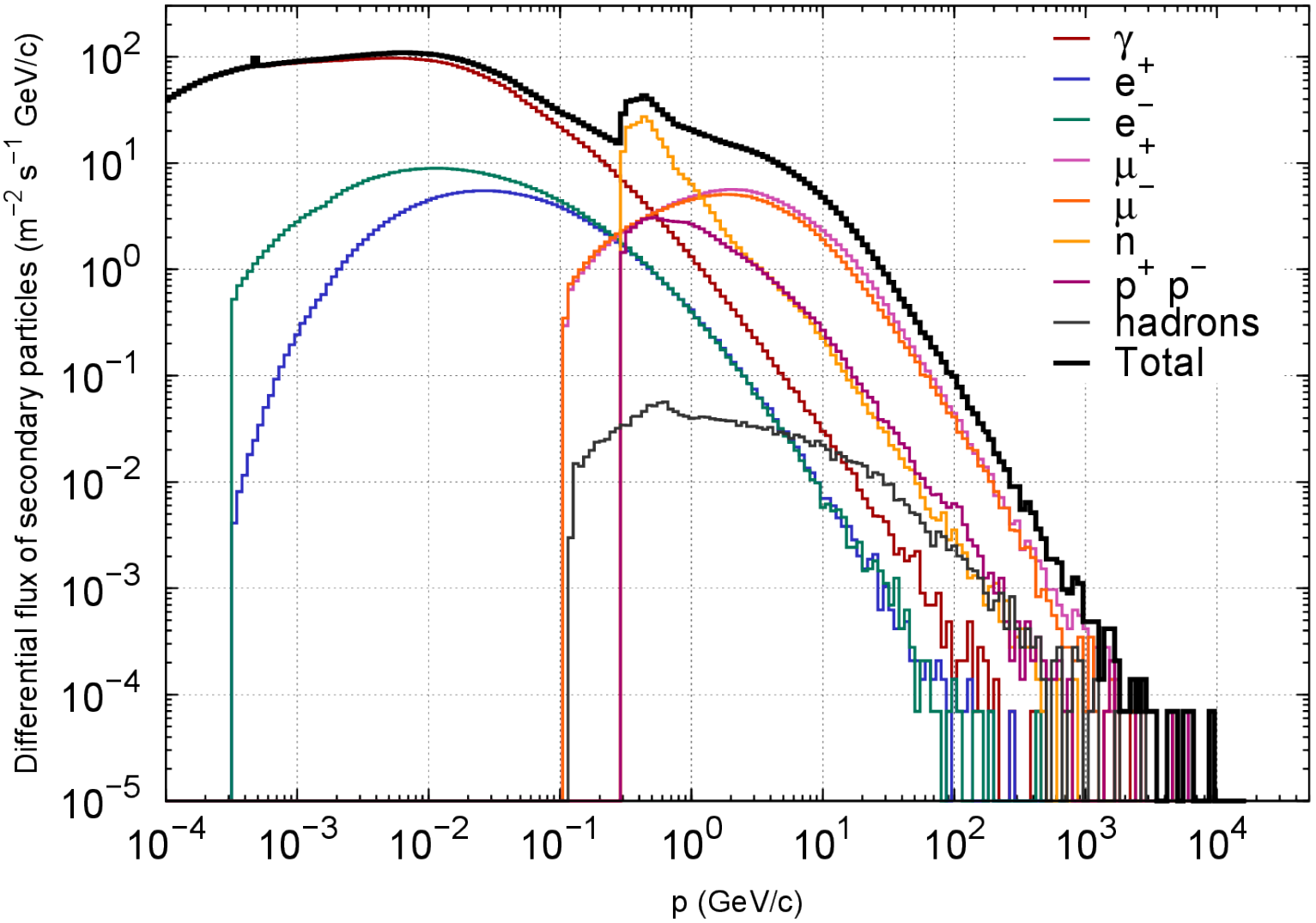
$$p^{+} + Y_{A}^{Z} \rightarrow \gamma + e^{\pm} + \mu^{\pm} + \pi^{\pm,0} + K^{\pm,0} + p^{+} + n + \ldots$$

Primary

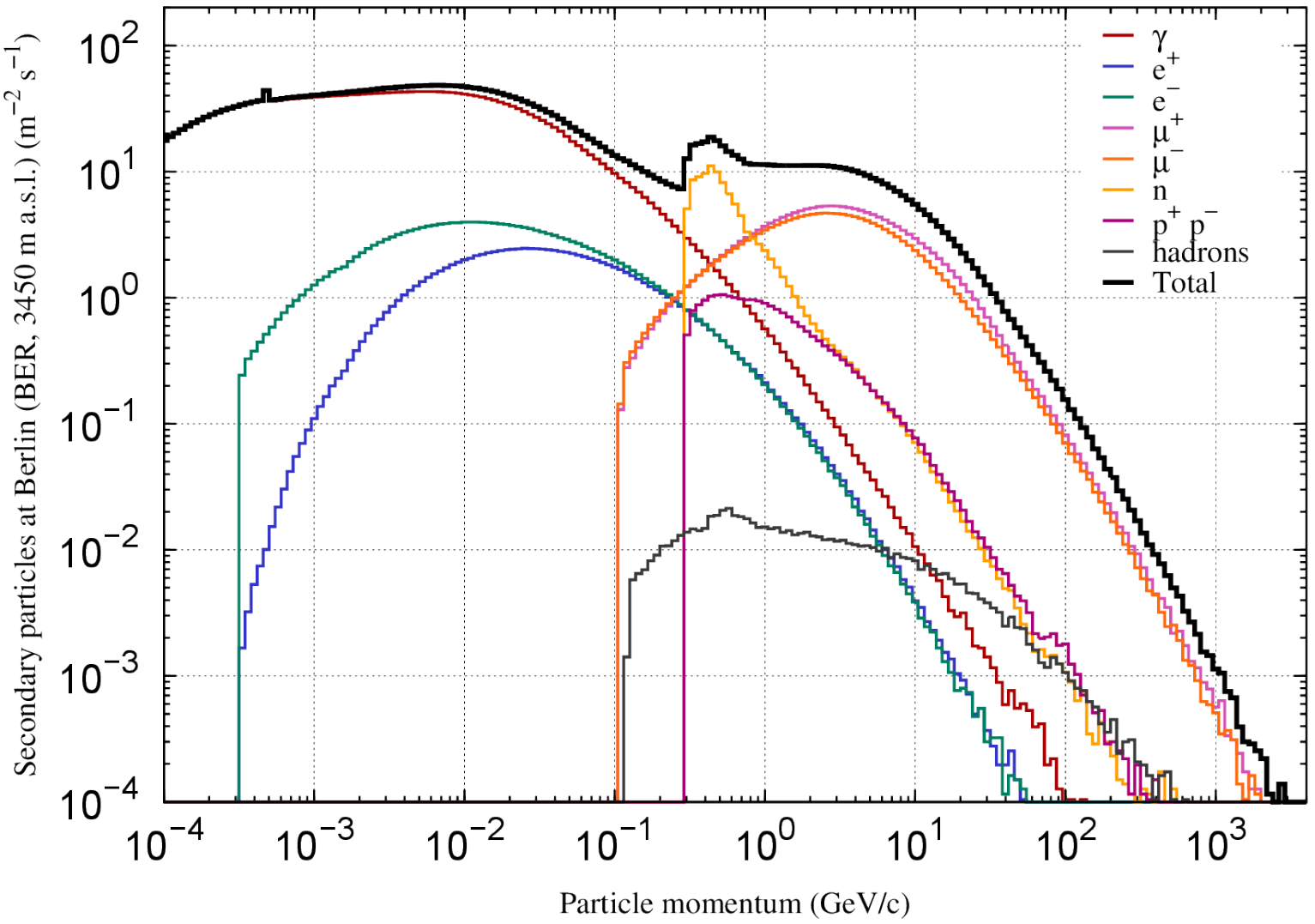


Composition dependent development

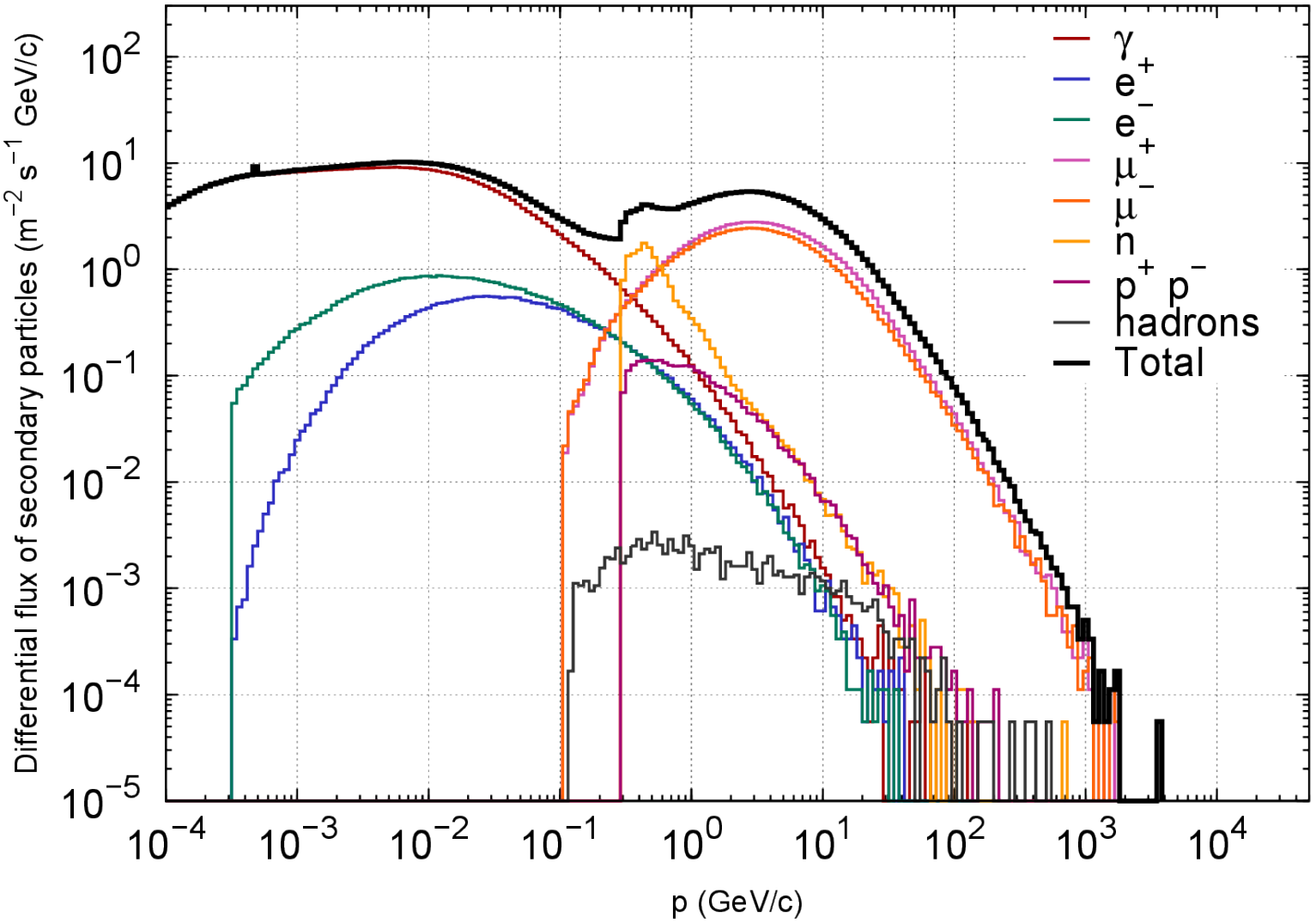
Chacaltaya, Bolivia, 5300 msnm

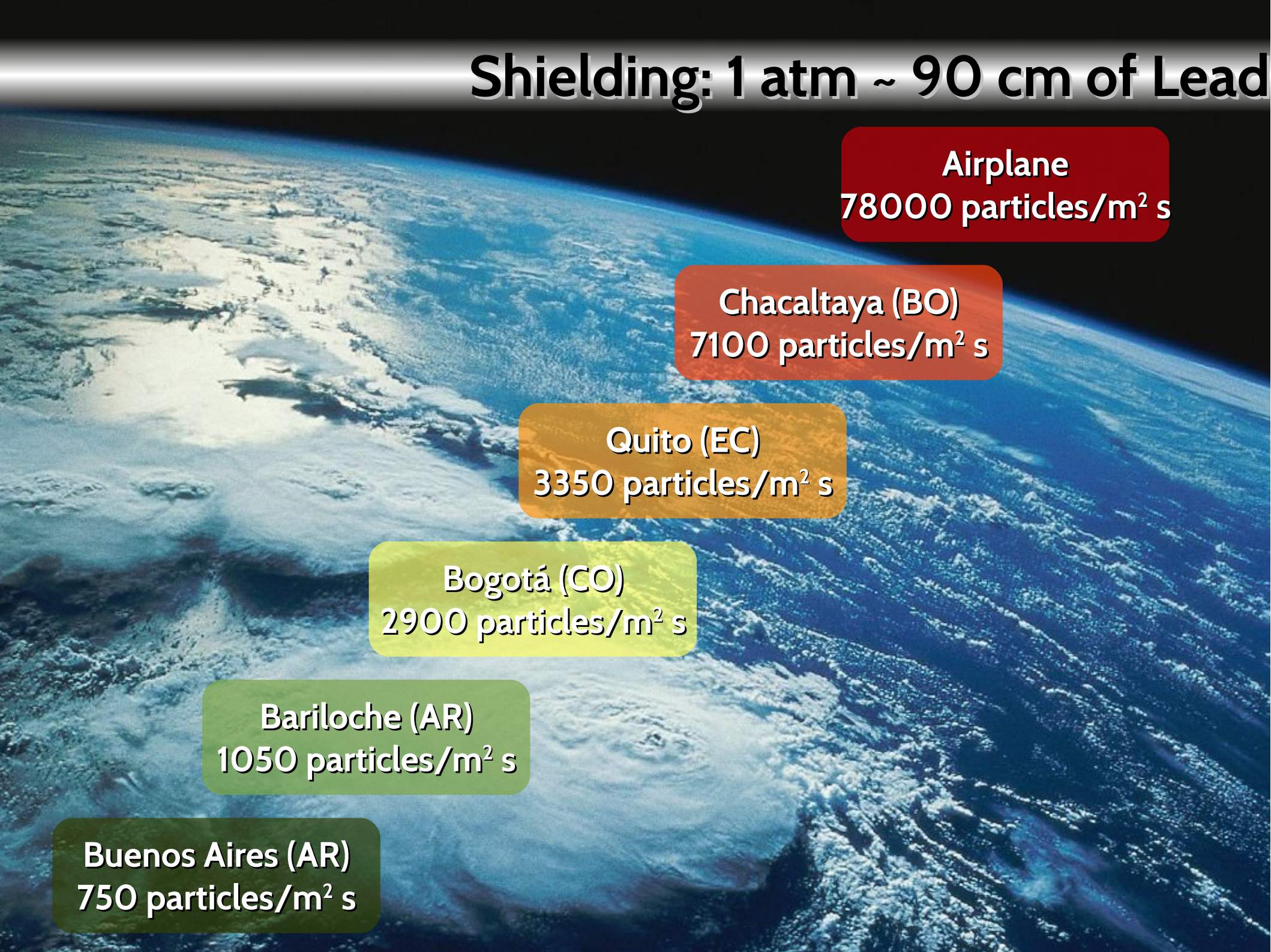


Berlín, Colombia, 3450 msnm



Bariloche, Argentina, 850 msnm




Shielding: 1 atm ~ 90 cm of Lead
Airplane
78000 particles/m² s
Chacaltaya (BO)
7100 particles/m² s
Quito (EC)
3350 particles/m² s
Bogotá (CO)
2900 particles/m² s
Bariloche (AR)
1050 particles/m² s
Buenos Aires (AR)
750 particles/m² s

Extreme simulations for extreme calculations

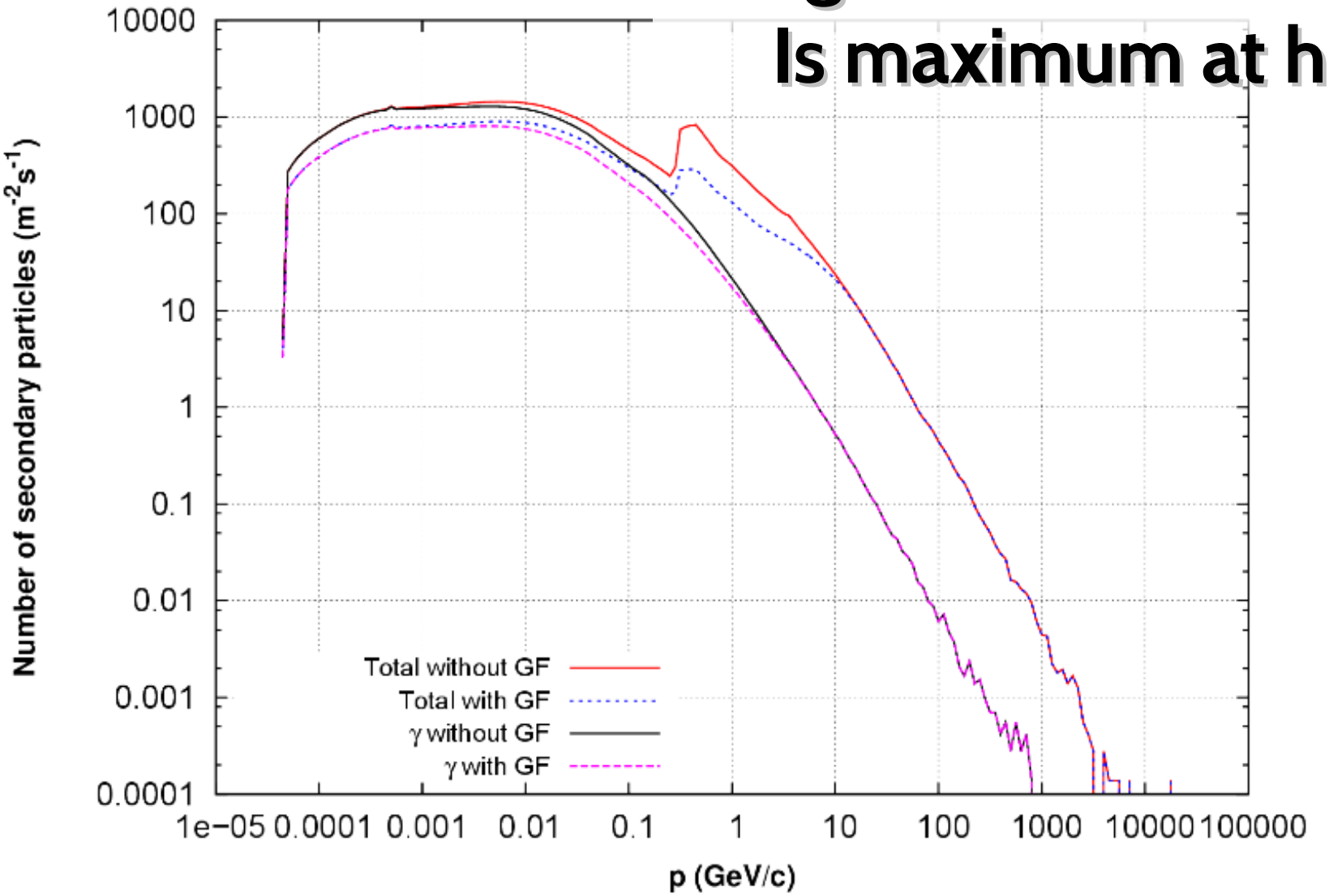
2 Background Radiation on Board

To calculate the expected flux of secondary particles in any place along the plane trajectory, we use a method based on the simulation of the complete flux of primaries within a given range of energy [9], that includes the effect of the rigidity cut-off at different locations in the Earth, that we summarize here:

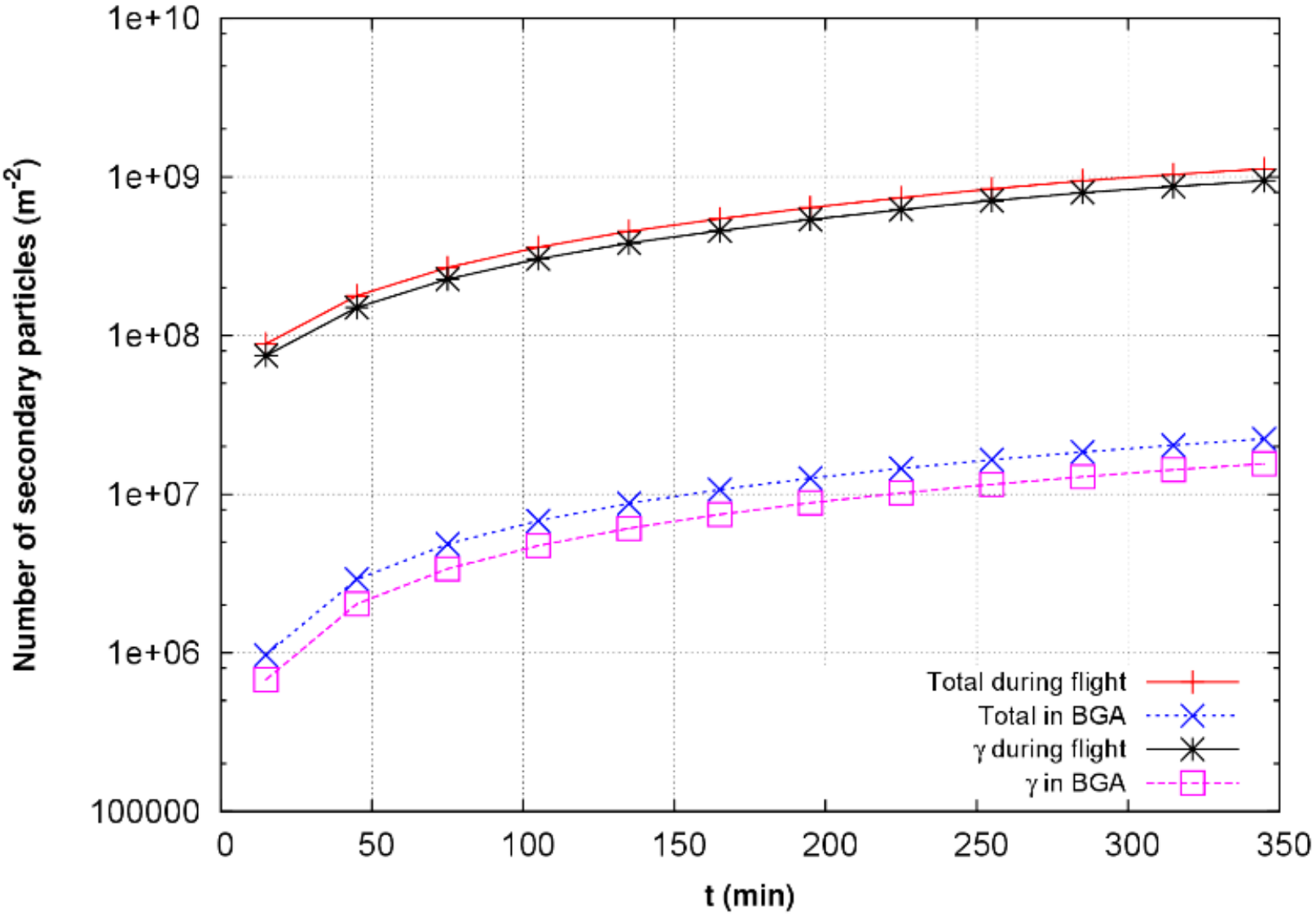
1. Simulation of showers at different altitudes using *CORSIKA*. Features of injected primaries at the top of the atmosphere:
   - Primary nuclei injected: $1 \leq Z_p \leq 26$, $1 \leq A_p \leq 56$
   - Very low initial rigidity cut-off rigidity: $R_c = 4GV$
   - Energy and arrival direction: $(R_c \times Z_p) \leq (E_p/GeV) \leq 10^6$, $0° \leq \theta_p \leq 90°$, $0° \leq \phi_p \leq 360°$
   - Simulation time: $t = 7200s$ (primary particles flux is constant and isotropic)
2. Selection and discretization of routes.
3. Computation of rigidity cut-offs for each point in the trajectory using *Magnetocosmics*.

Secondary particles at flight level

Integrated radiation levels
Is maximum at h~14 km

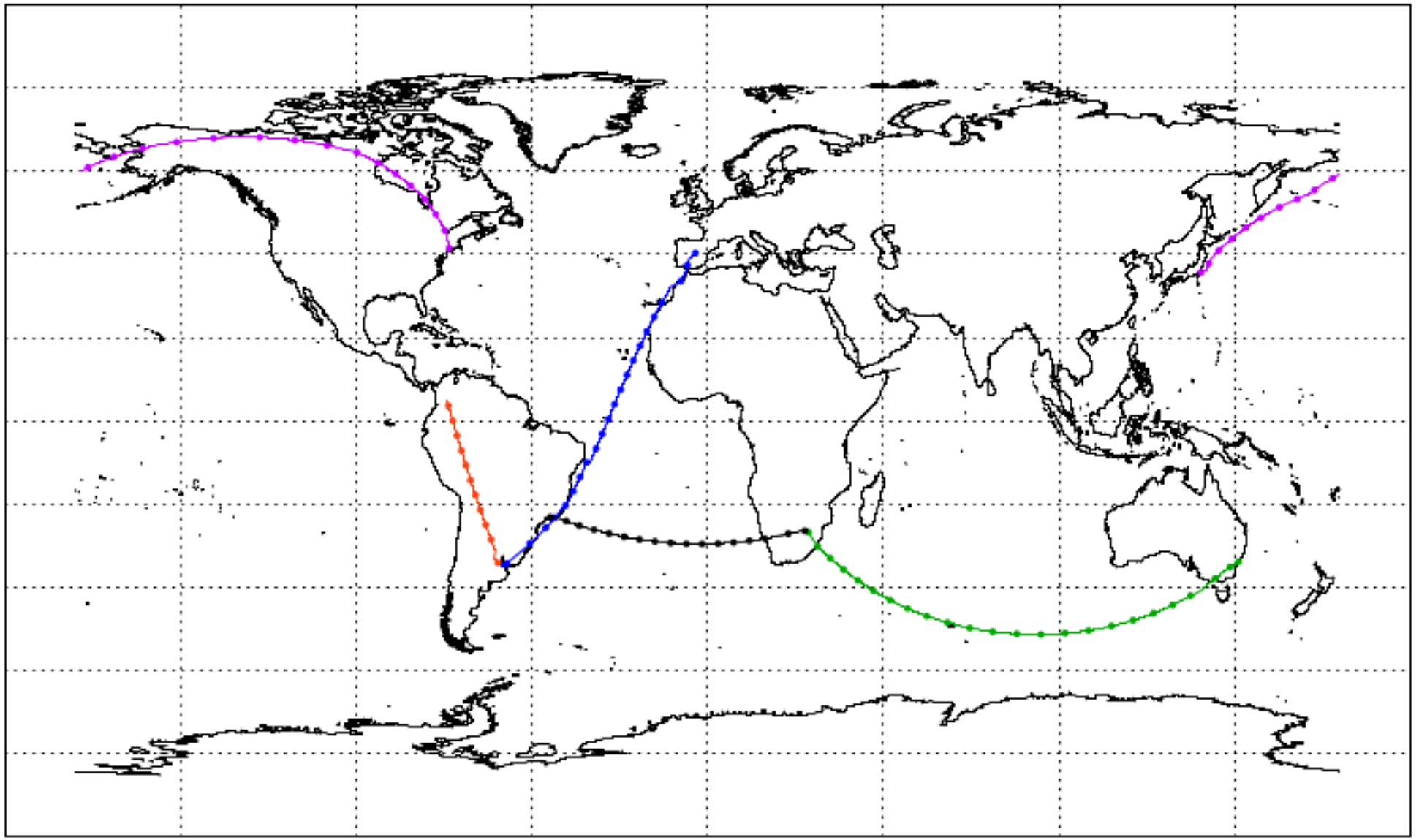


Integrated number of particles

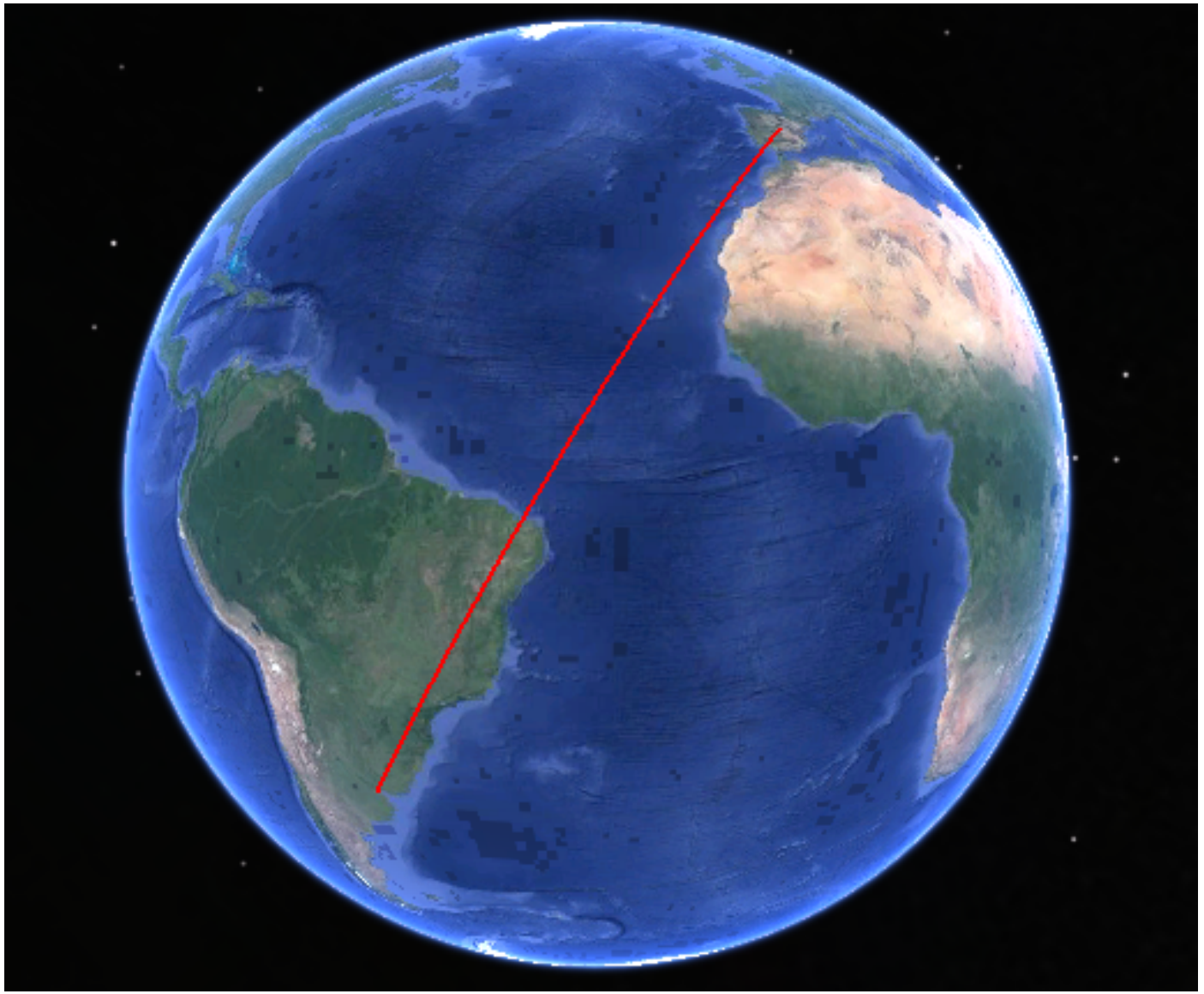


Five commercial routes at h=11km

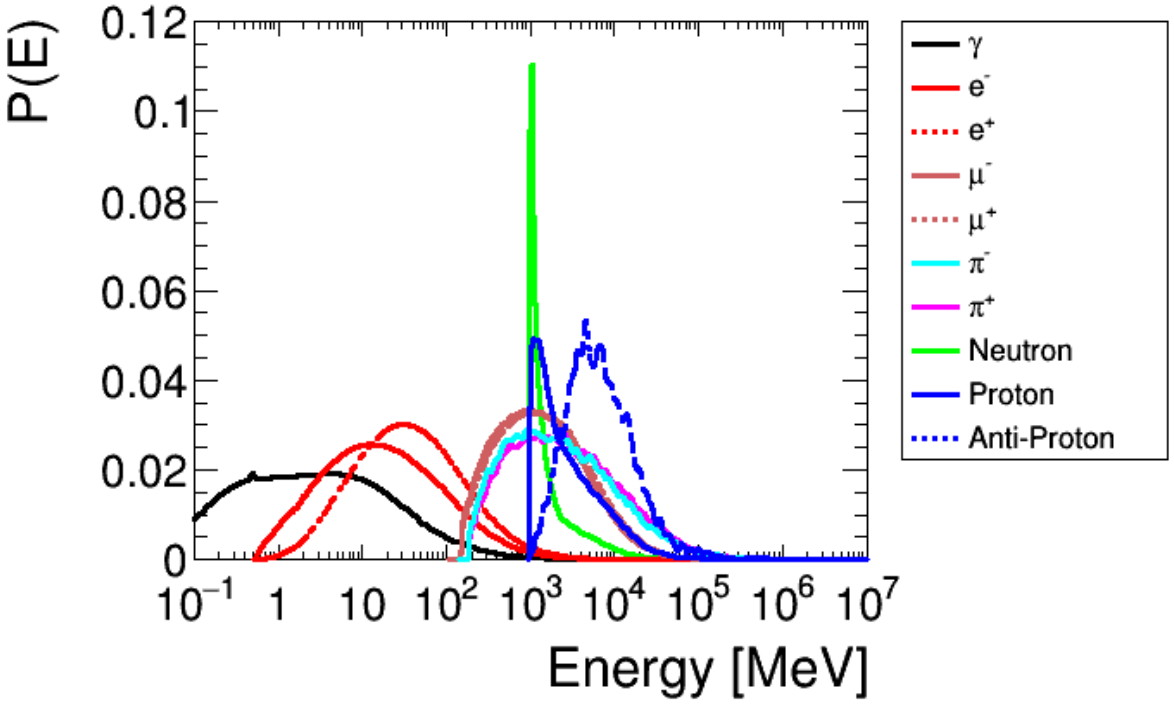
S. Pinilla, H. Asorey, F. Quiñonez, M. Suarez, L. Núñez, 2015, 2016

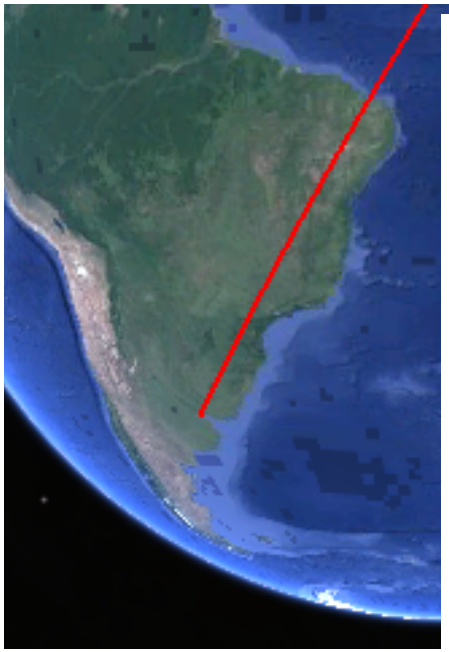


Buenos Aires-Madrid

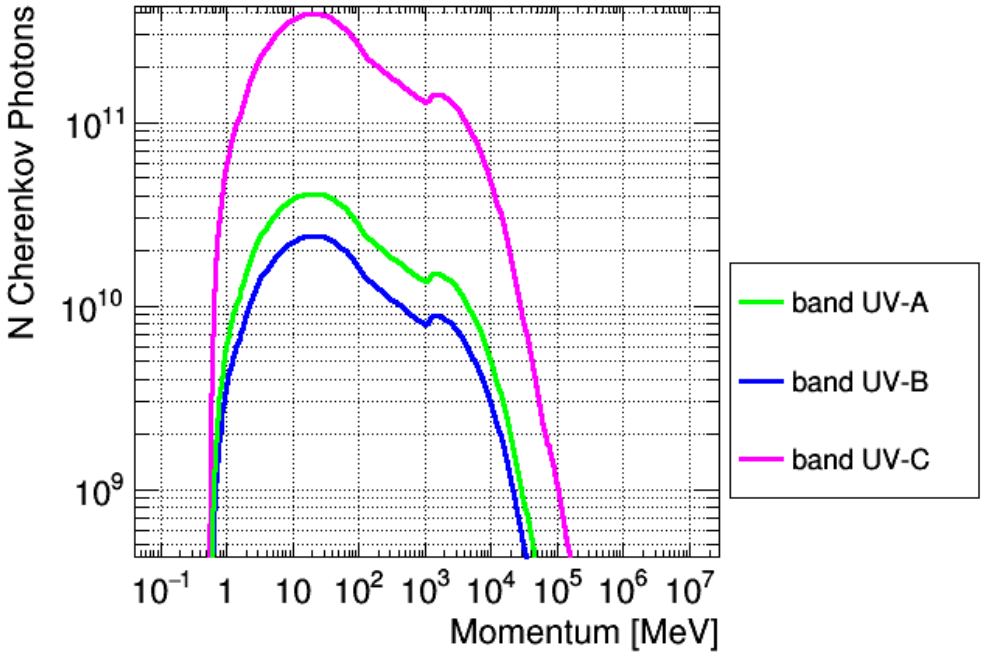


Buenos Aires-Madrid

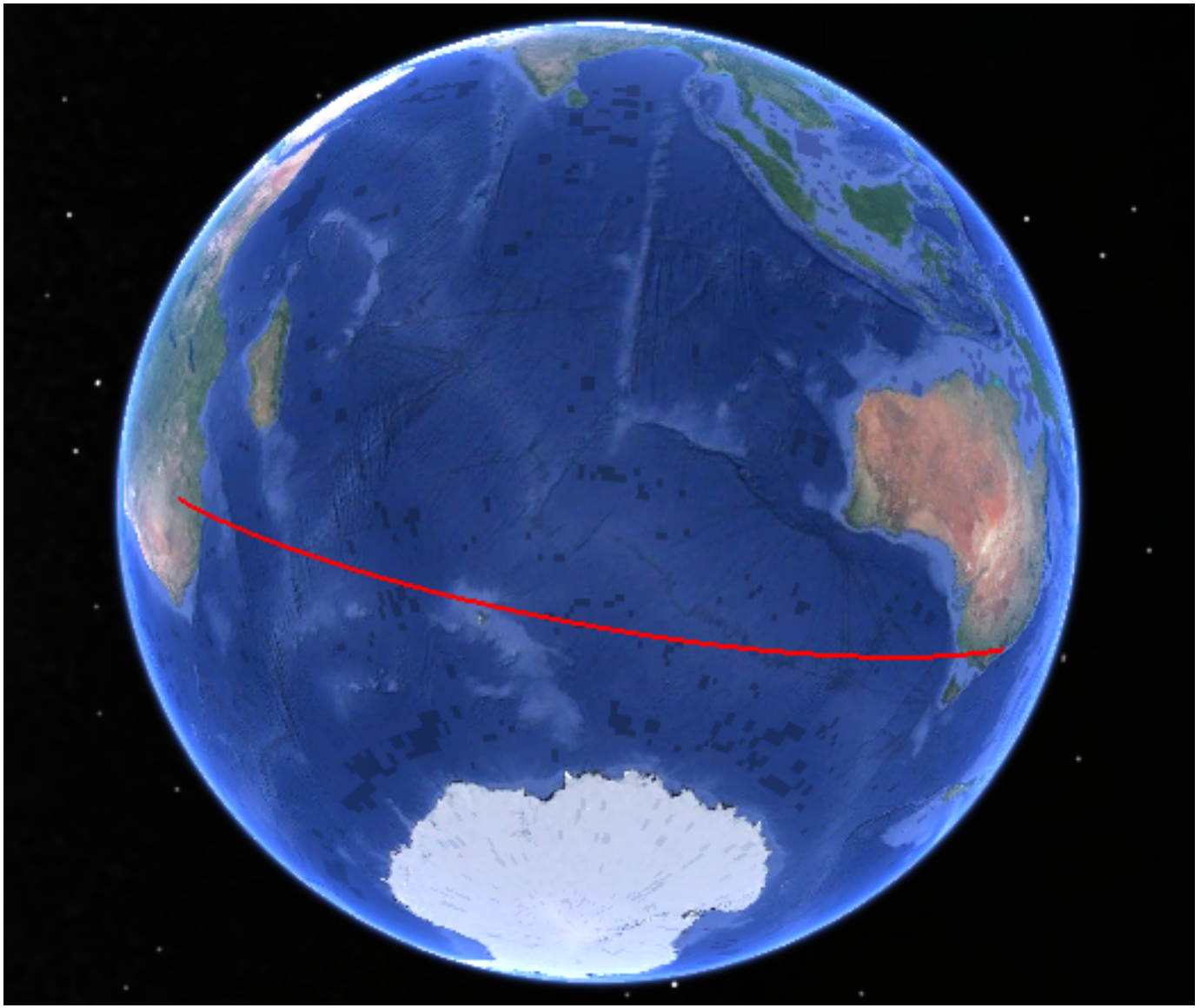


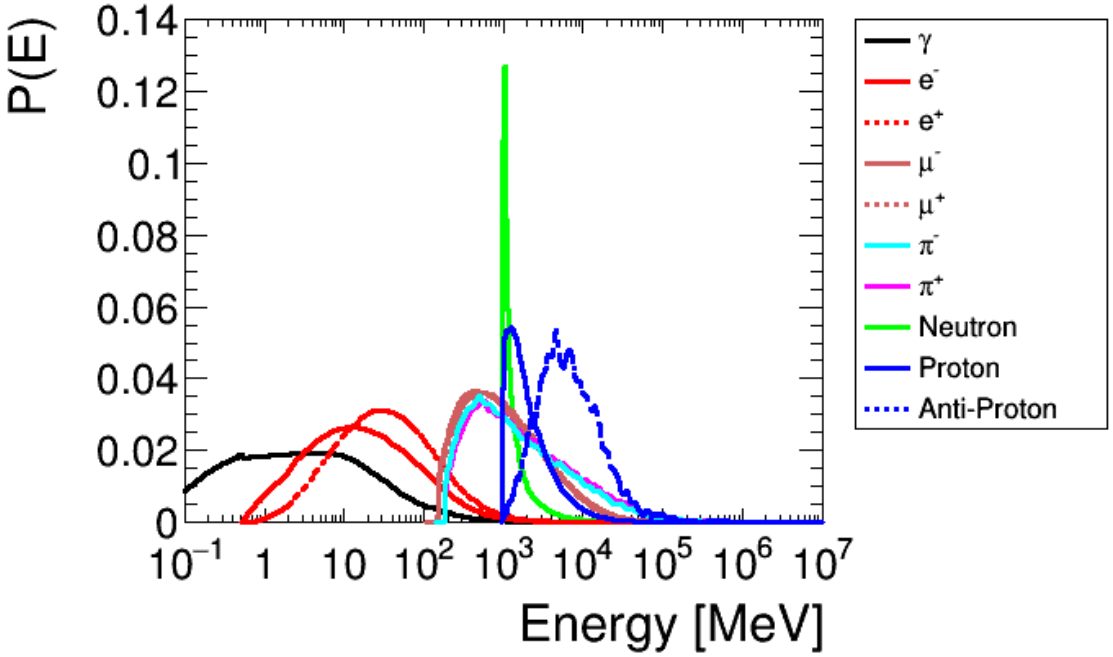


Particle	Number
γ	1735067944
e^-	127663451
e^+	71851951
n	64671348
p	23201761
μ^+	21225806
μ^-	20050559
π^+	267108
π^-	262524
$\bar{p}$	32565
Duration	40560 s
Displacement	10062 km

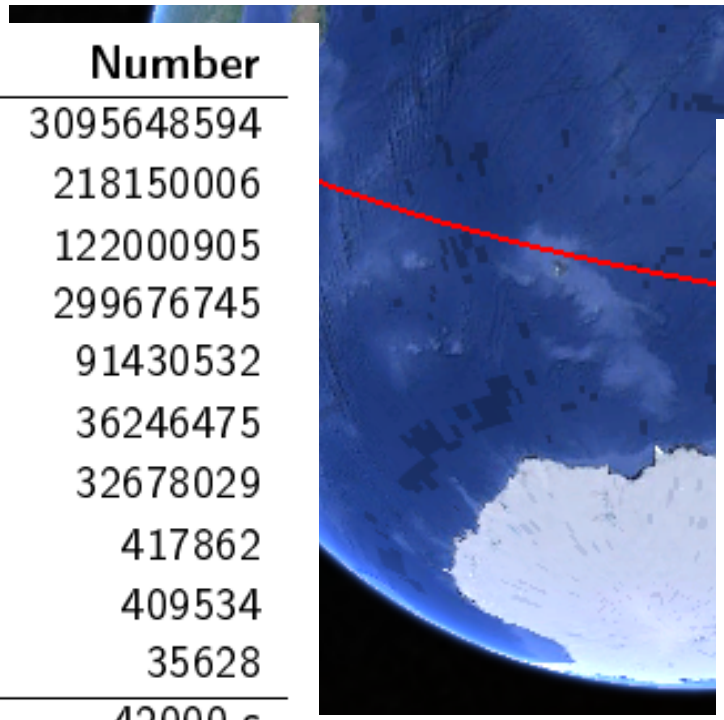


Johanesbourg-Sydney

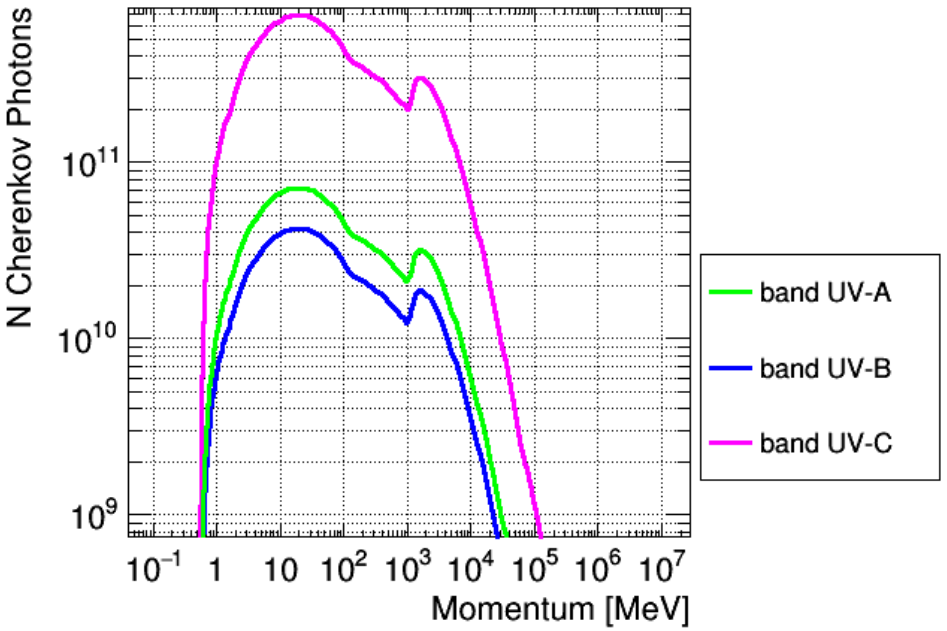




Johanesbourg-Sydney



Particle	Number
γ	3095648594
e^-	218150006
e^+	122000905
n	299676745
p	91430532
μ^+	36246475
μ^-	32678029
π^+	417862
π^-	409534
$\overline{p}$	35628
Duration	42000 s
Displacement	11046 km



Same exposure time at secular GMF conditions

$$d_N = \frac{N_{\text{ruta}} - N_{\text{BGA}}}{N_{\text{BGA}}} \tag{10}$$

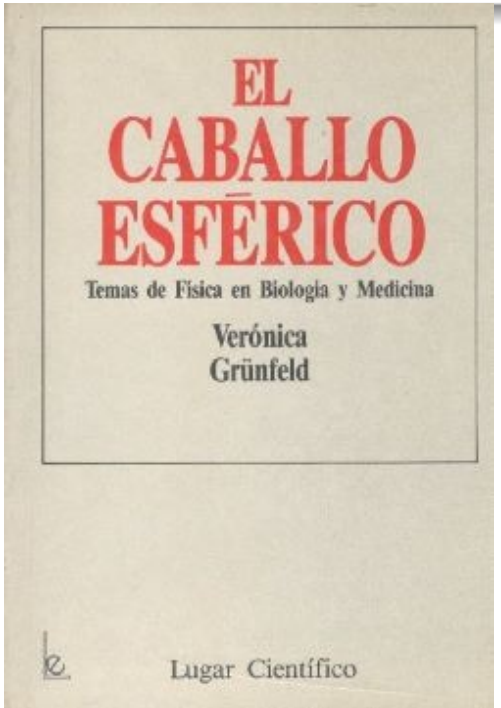
Ruta	γ	e^+	e^-	μ^+	μ^-	n^0	p^+	Otros	Total
BOG-BUE	55.5	56.0	56.2	3.5	3.9	84.6	165.8	122.6	46.1
BUE-MAD	56.6	57.0	57.3	3.6	4.0	90.7	175.9	124.6	47.1
JNB-SYD	93.3	89.3	90.3	6.2	6.5	388.7	638.0	195.6	82.2
NYC-TYO	91.0	87.2	88.1	6.1	6.3	380.6	621.9	190.4	80.2
SAO-JNB	71.3	70.5	70.8	4.9	5.3	162.7	296.6	151.7	60.3

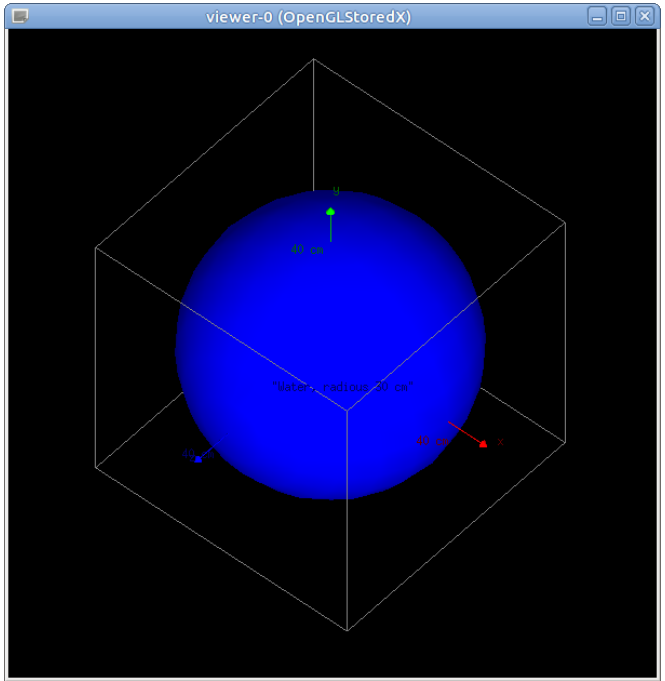
OpenGATE, a GEANT4 implementation for RT

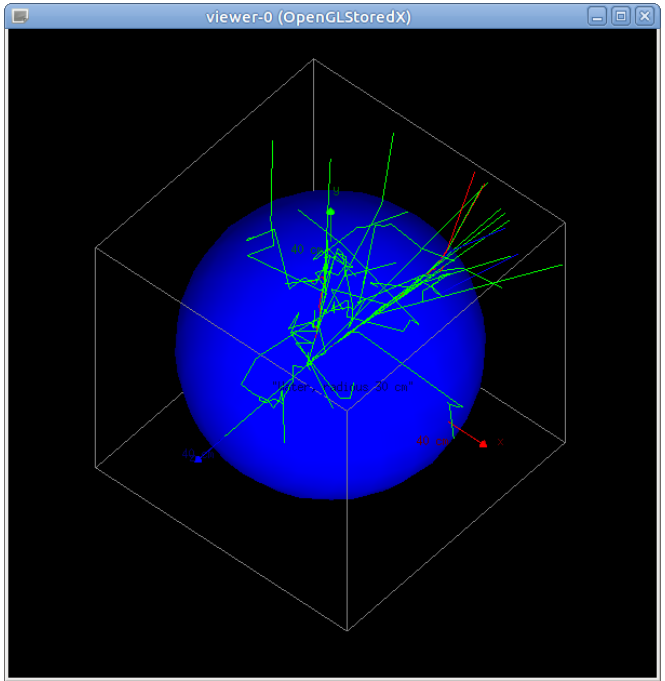
QGSP_BERT_HP GEANT4 Validated Physics List

QGSP_BERT_HP is based on QGSP_BERT list, which is the most recommended list for HEP, it is used in ATLAS. Includes all the standard EM processes. The suffix HP make reference to High Precision on **Neutron interactions**.

- Use Bertini cascade model for hadrons with $E < 10$ GeV.
- Use QGSP (Quark Gluon String Parton) for hadrons with $E \geq 10$ GeV.
- High Precision for Neutrons with $E < 20$ MeV.

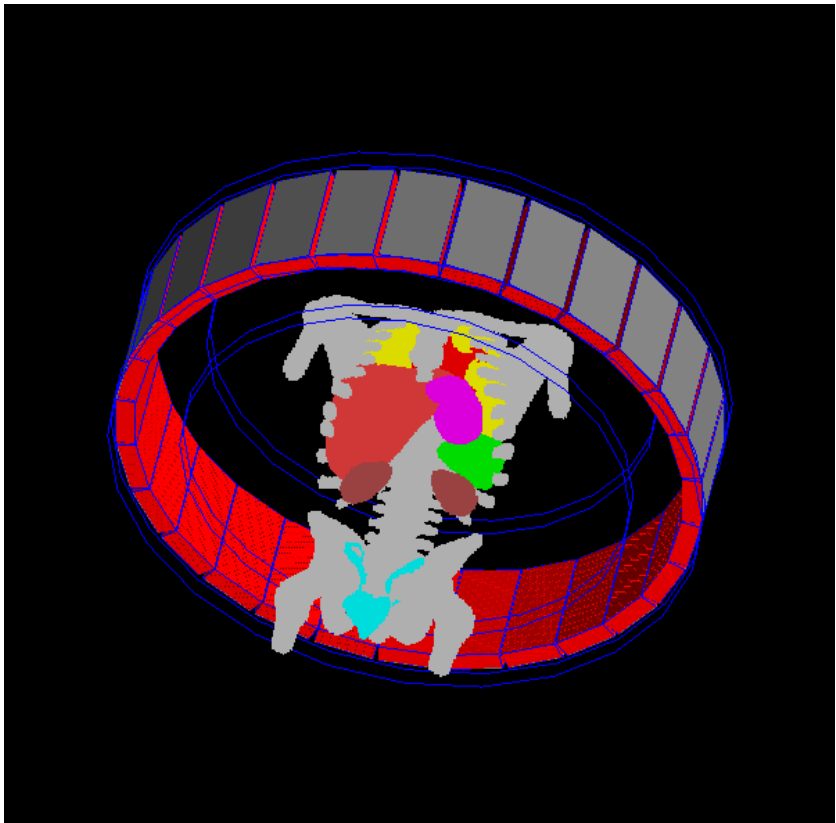




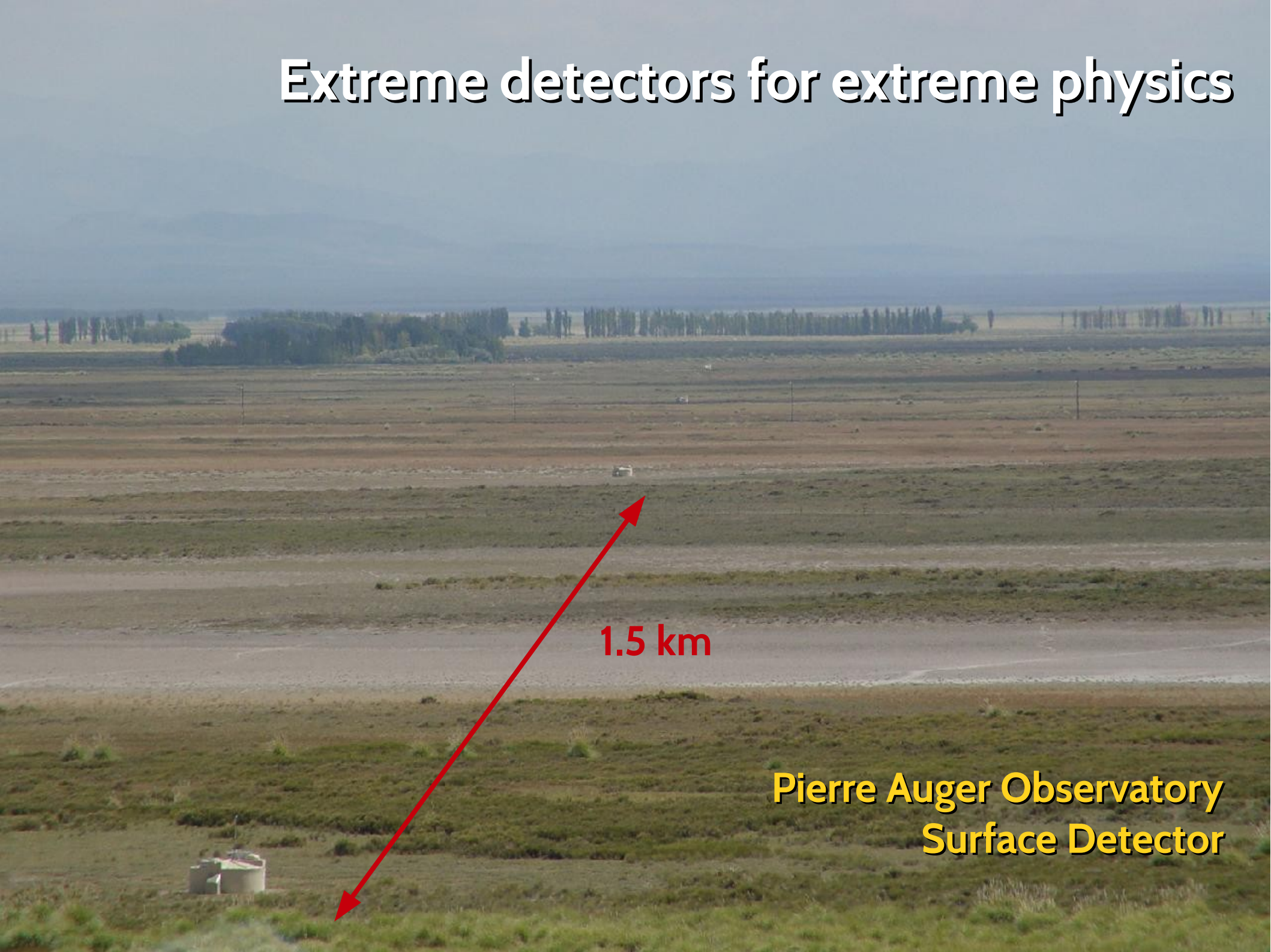


Extreme simulations for extreme calculations

- Work in progress: improve aircraft shielding, improve phantom, detailed studies of resulting Bragg curves, …
- Very preliminary results (last week!) indicates equivalent dose **could reach mSv level under certain space weather conditions**
- Results were validated at ground level using Water Cherenkov detectors. Need to validate at flight level using portable detectors



Extreme detectors for extreme physics



Loma Ama
Coihueco
AERA
HEAT
xlf
clf
balloon
Los Morados
Central
40
30
20
10

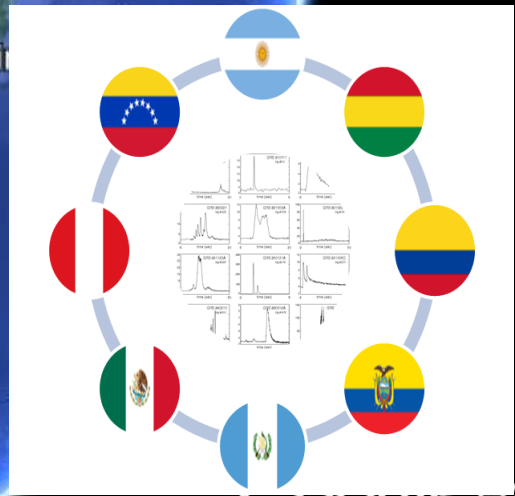
~ (50x60) km = 3000 km² instrumented area

1660 Water Cherenkov detectors (16600 m² detection area)

27 Fluorescence telescopes surounding the array

LAGO: The Latin American Giant Observatory

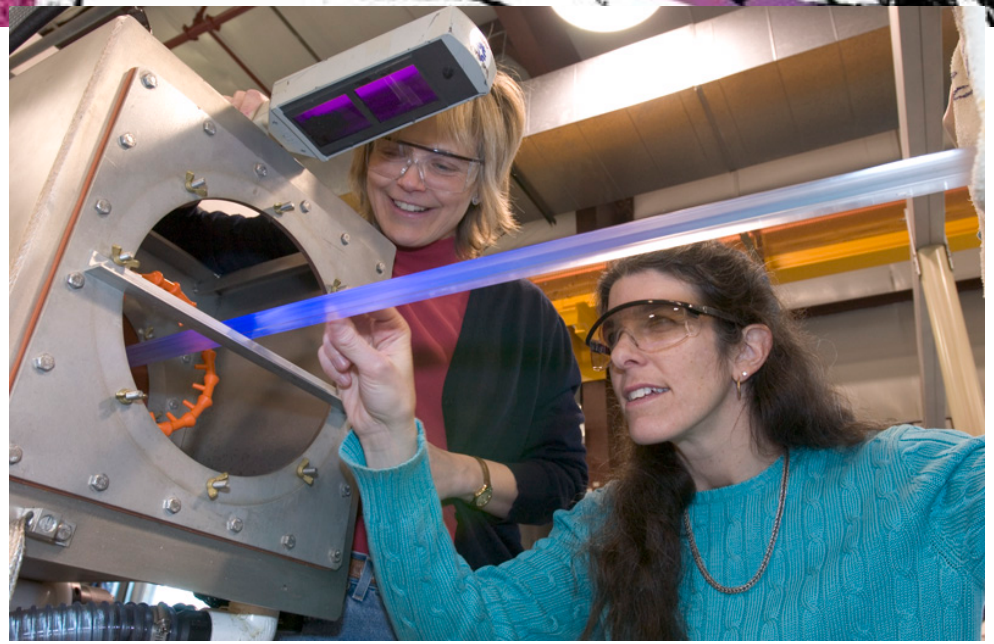
- Nine LA countries + Spain
- LAGO Collaboration: first astroparticle newtork at LA (80 members, 25 institutions)
- A very long baseline array of Water Cherenkov Detectors
- From Mexico to Antarctica

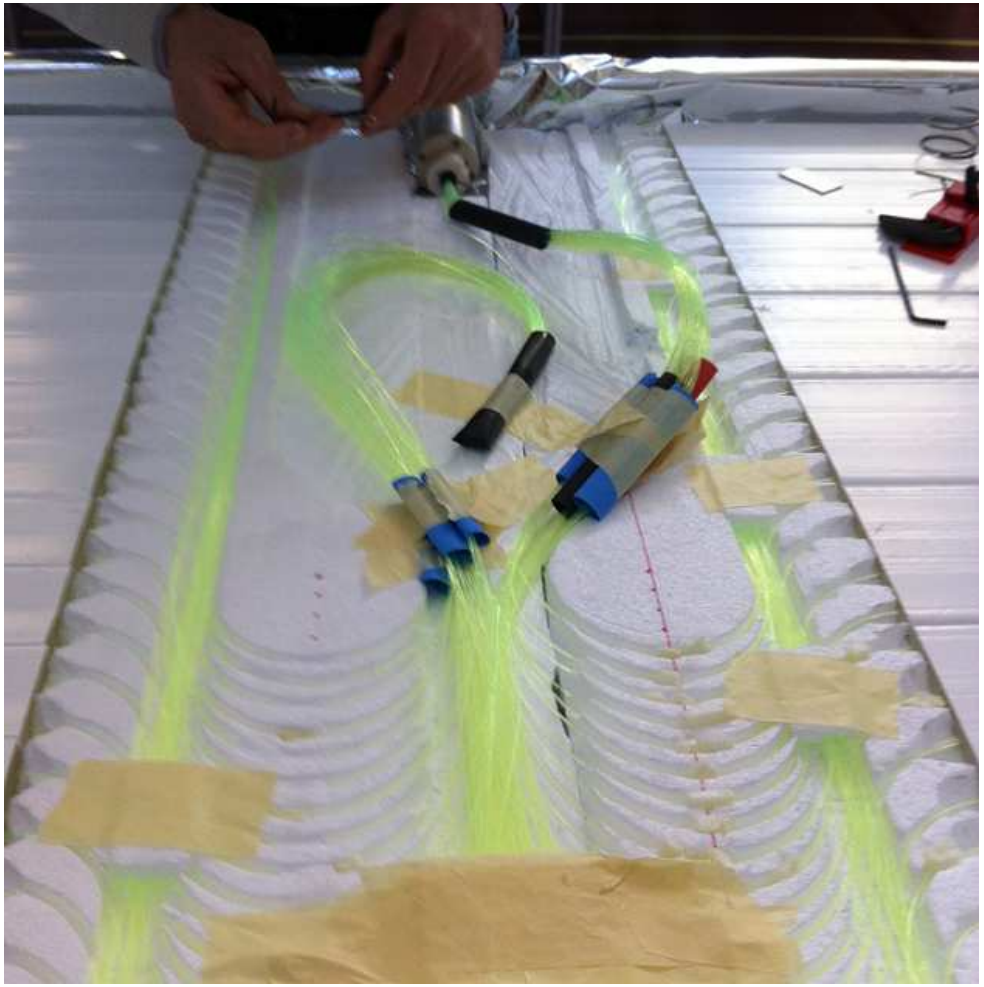


Sierra Negra, México
Pico Espejo, Venezuela
Bucaramanga, Colombia
Berlín, Colombia
Riobamba, Ecuador
Cuzco, Perú
Chacaltaya, Bolivia
La Paz
San Juán, Argenti
Buenos Aires, Argentina
Bariloche, Argentina
Base Marambio, Antártida
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
© 2012 Cnes/Spot Image
Image © 2012 TerraMetrics
Image IBCAO
18°33'14.25" S 79°05'08.58" W elev -4048 m
Eye alt 10069.43

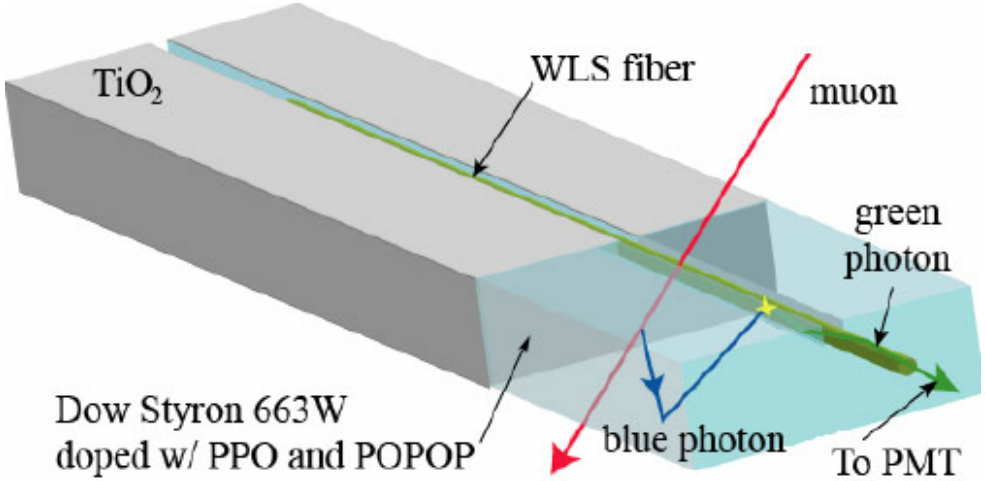
Present status and future perspectives

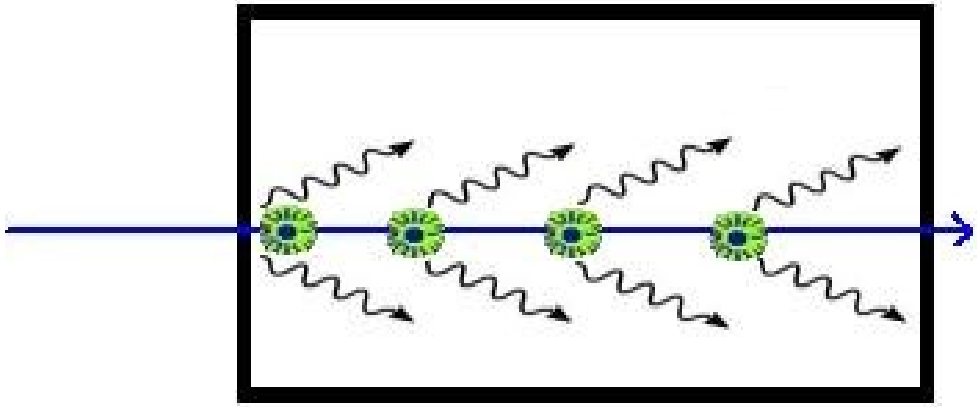
SSD, The Auger Upgrade: plastic scintillators



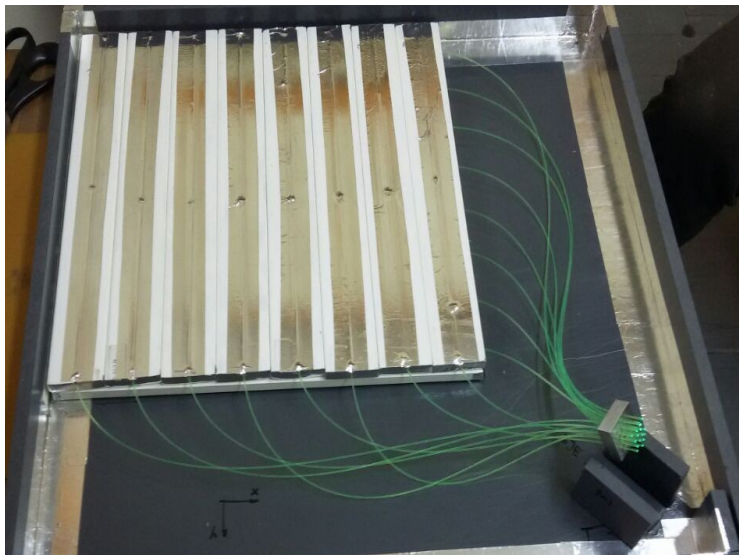


Plastic scintillators

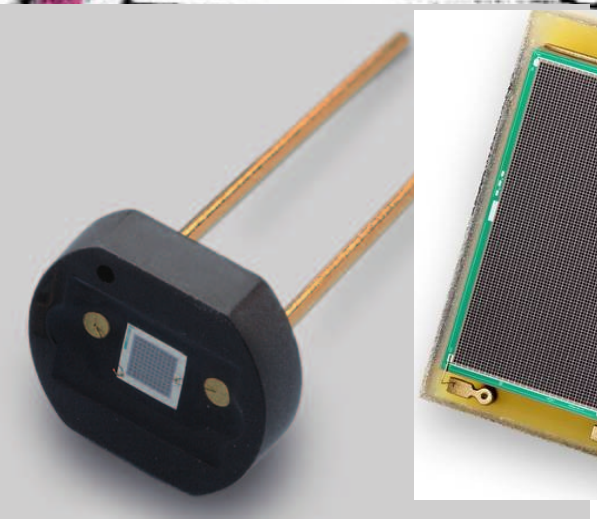


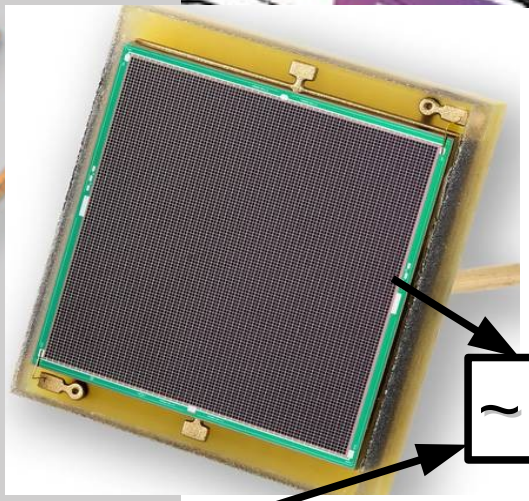


- Polystyrene dopped with PPO (organic scintillator & PoPop (Wavelenght shifter)
- New materials improve usage at high radiation environments



Multi-pixel Silicon PhotoMultiplier (MPPC SiPM)

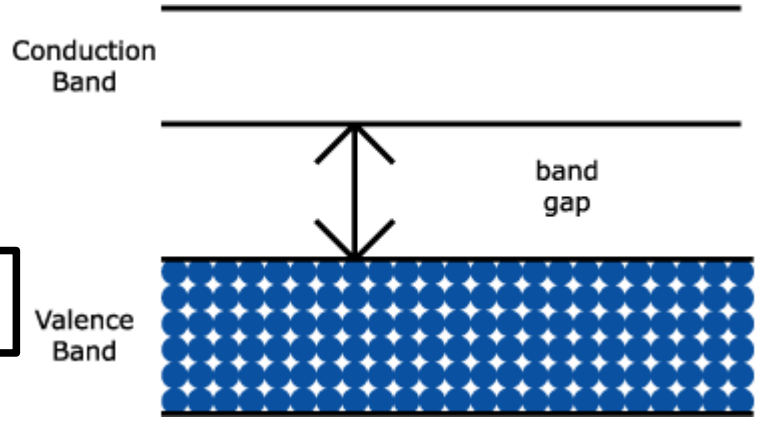




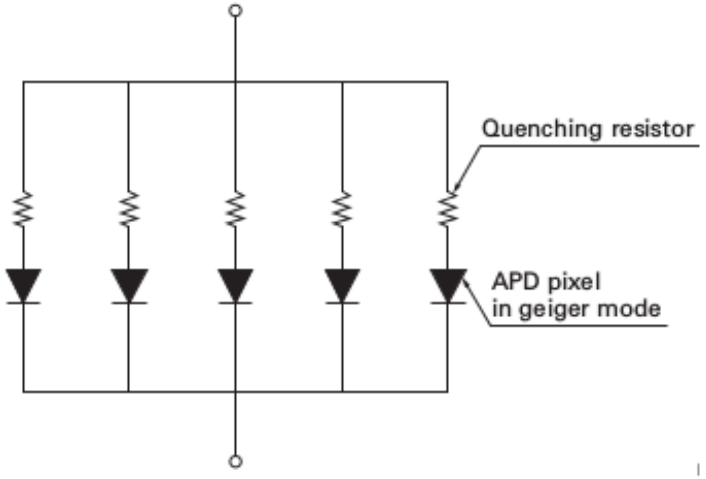
~ 3600

$(50\mu m)$

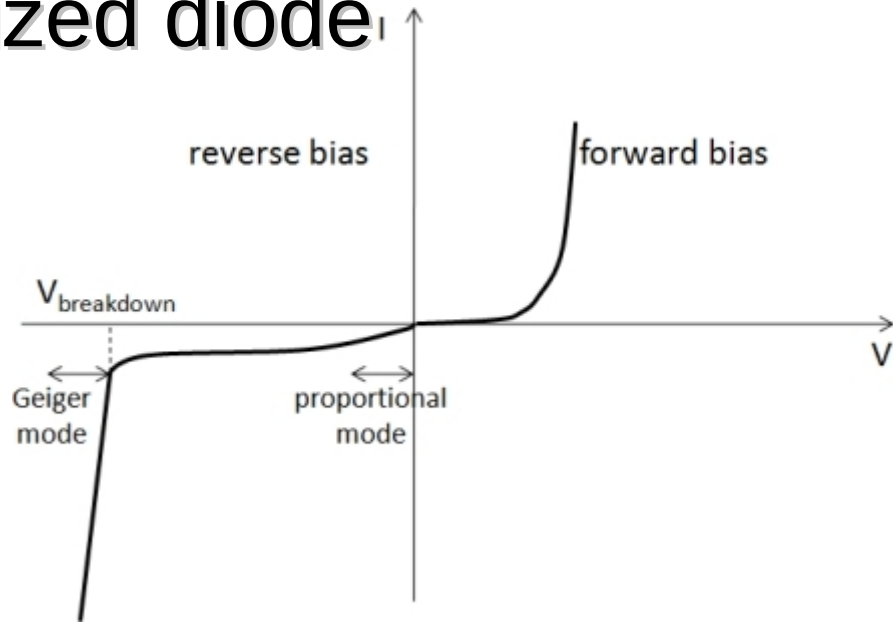
- Semiconductor based



- Multiple pixel

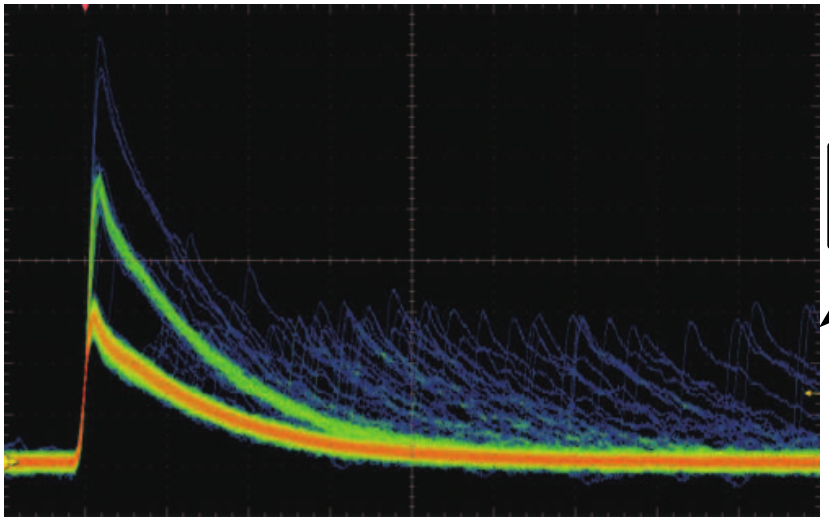


- Works as a reversed polarized diode

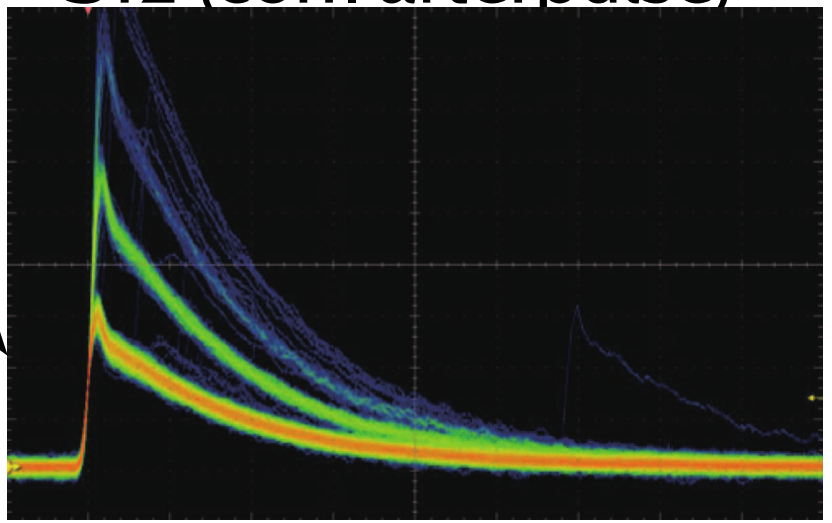


Output

- S11

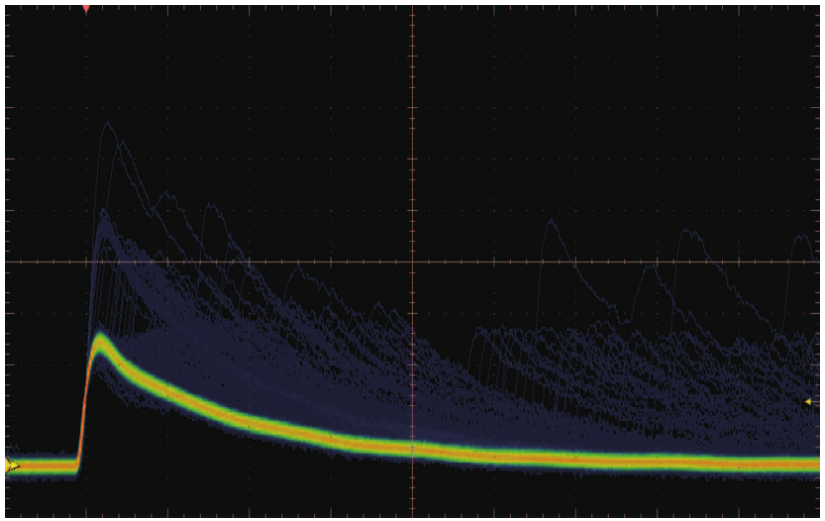


- S12 (corr. afterpulse)



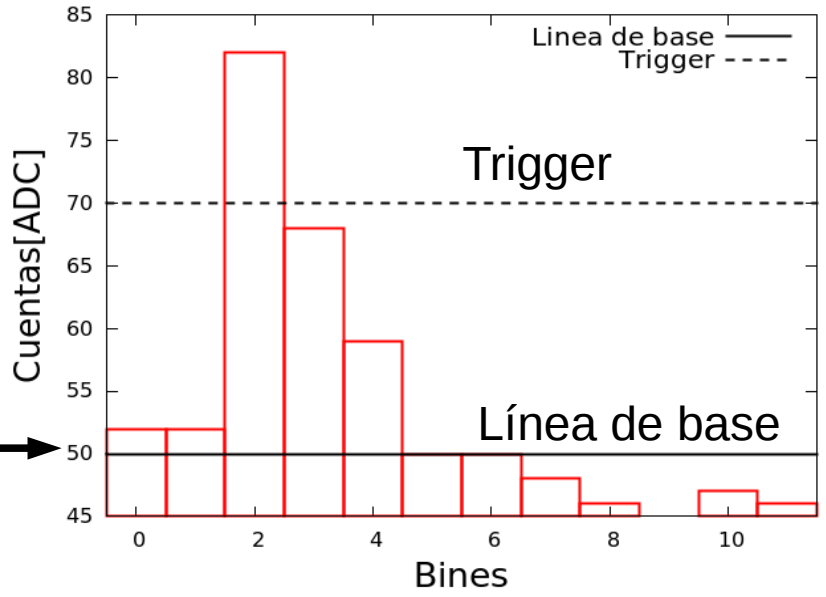
Datasheet

- S13 (corr. crosstalk)

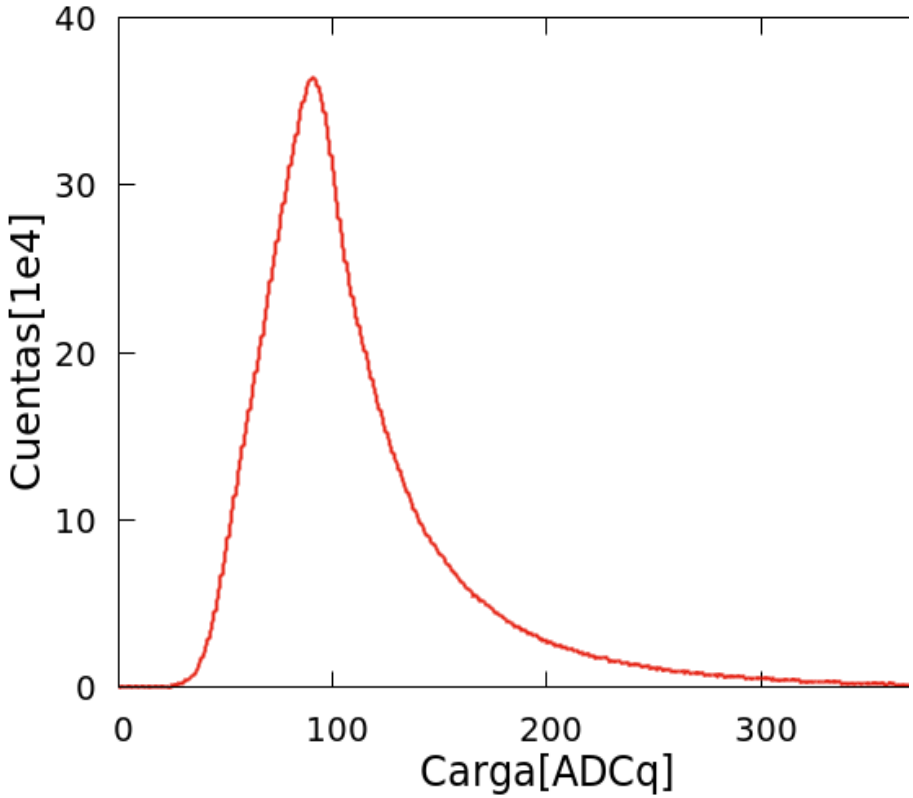


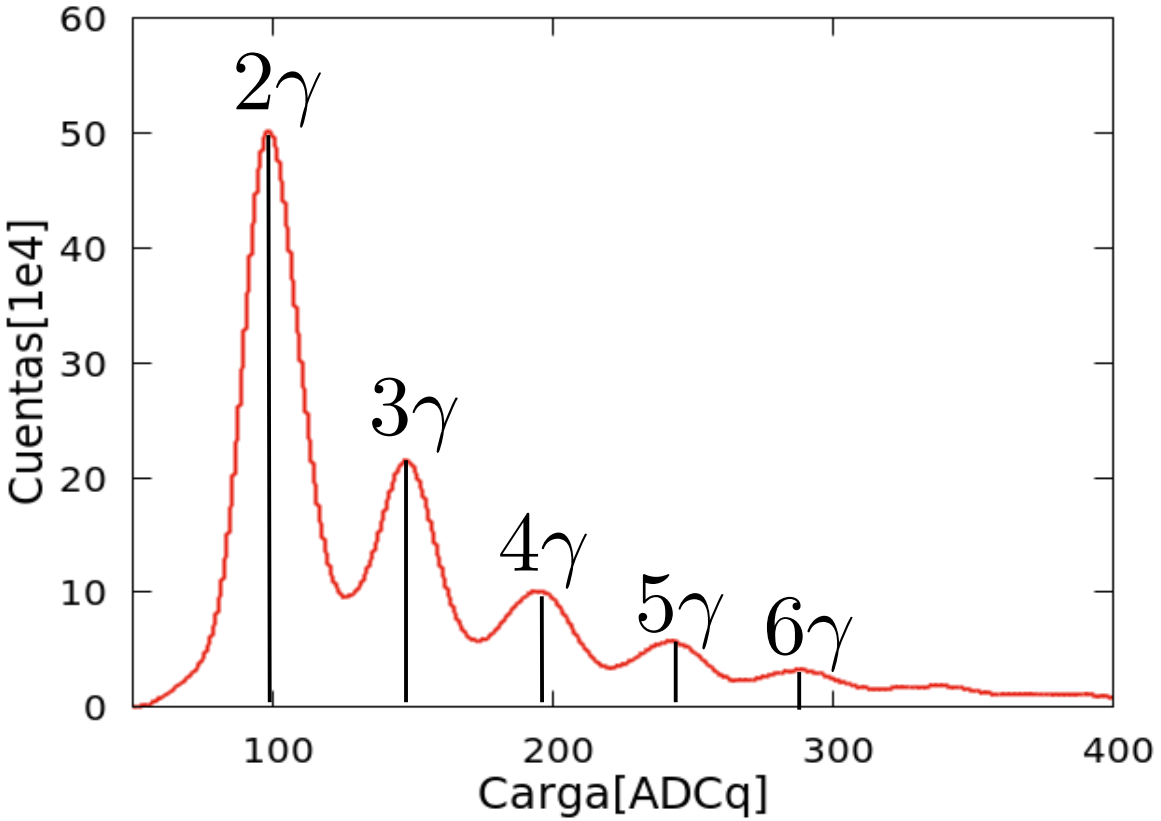
- Discretized

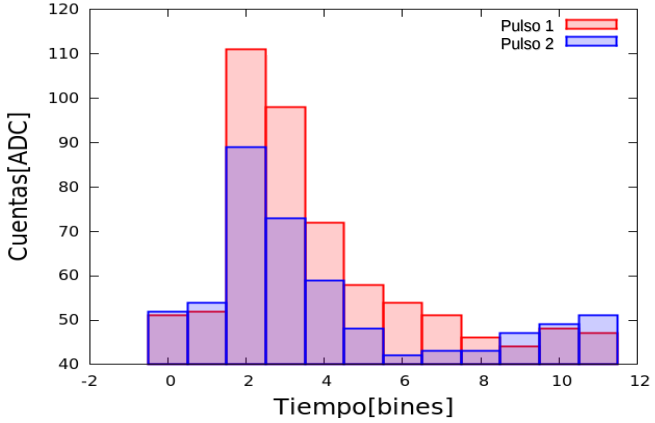
Data



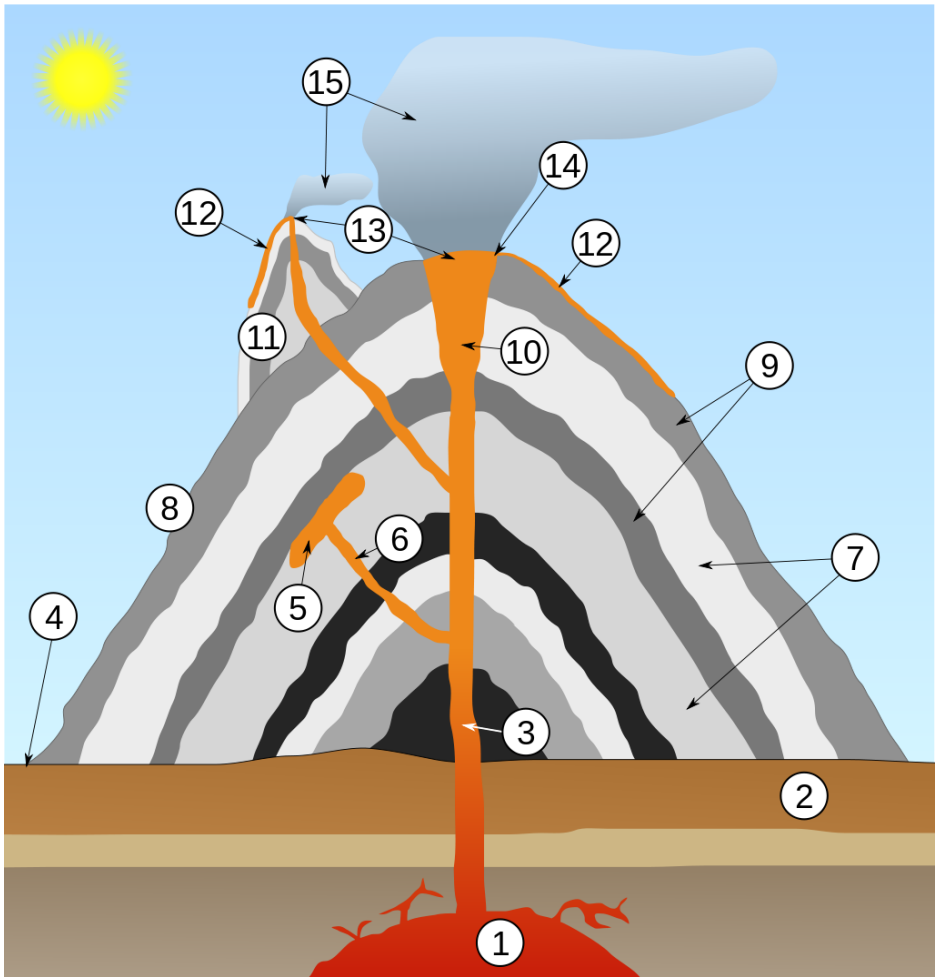
Pulse charge histogram: single photon counts



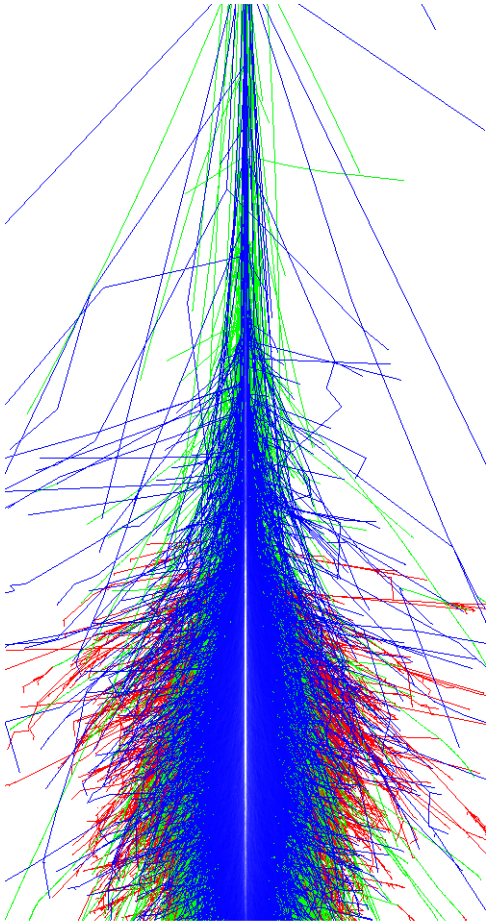


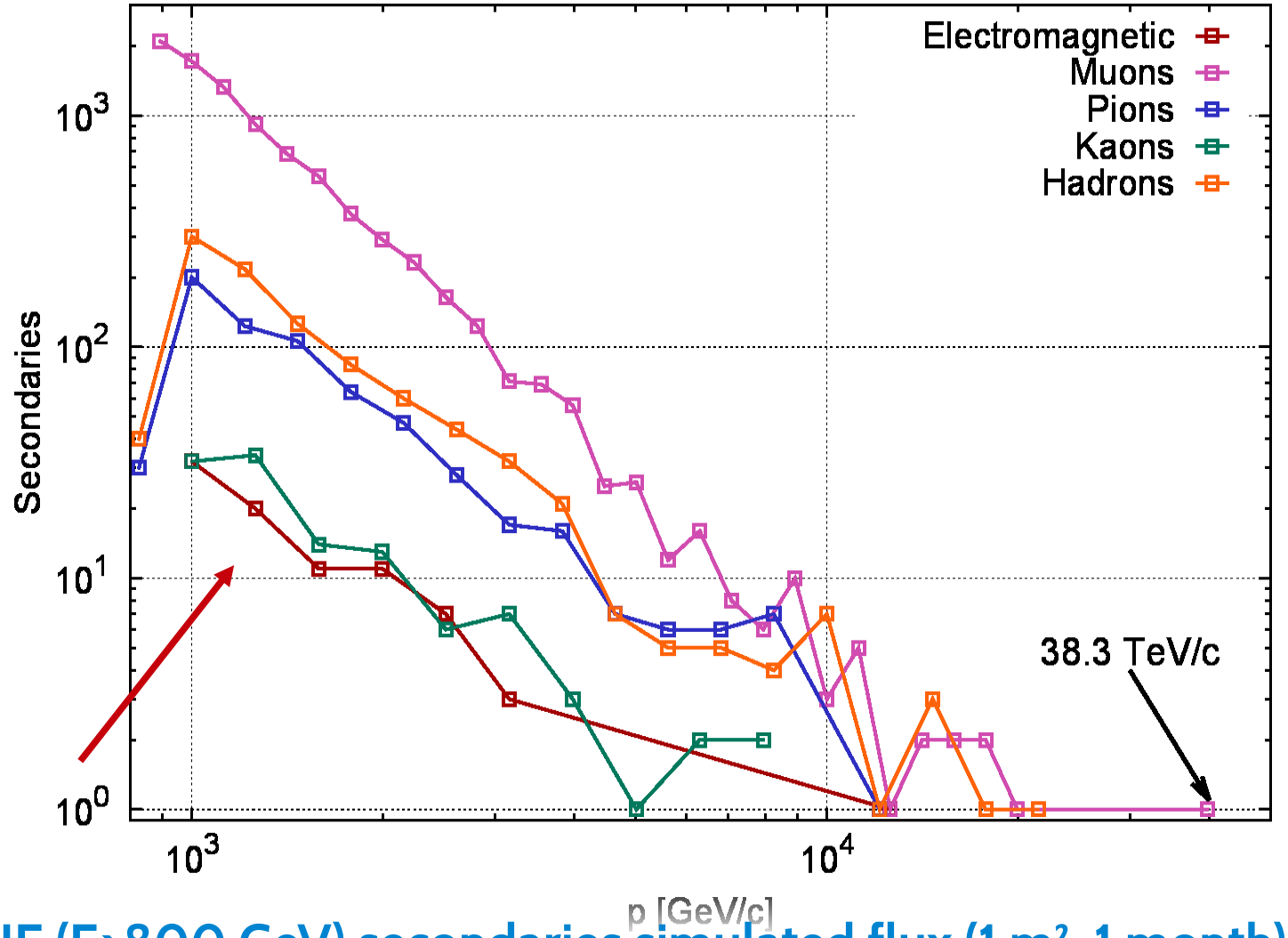


We want to take a look to volcanoes interior...



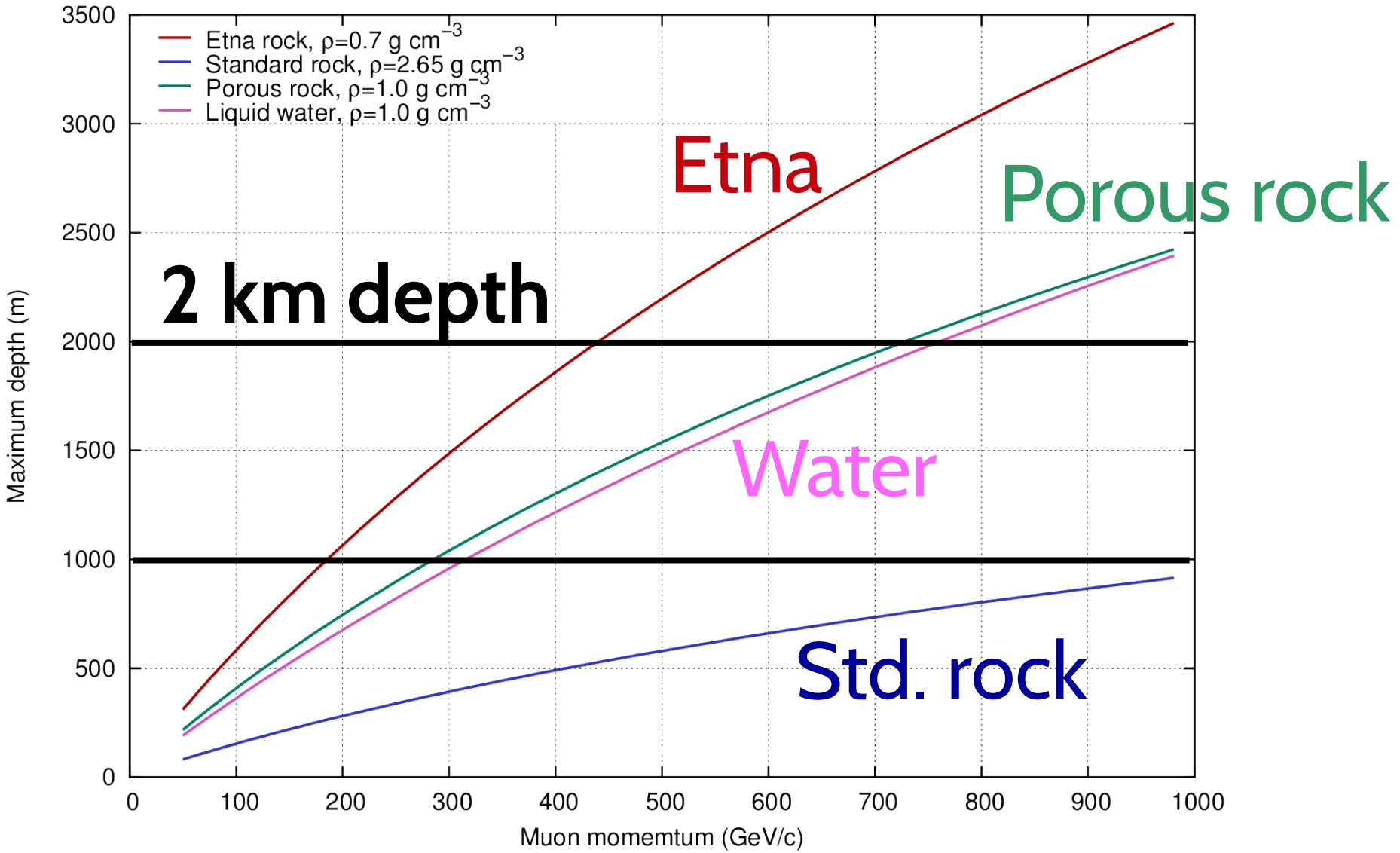
High energy atmospheric muons





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

Muon range in some standard materials



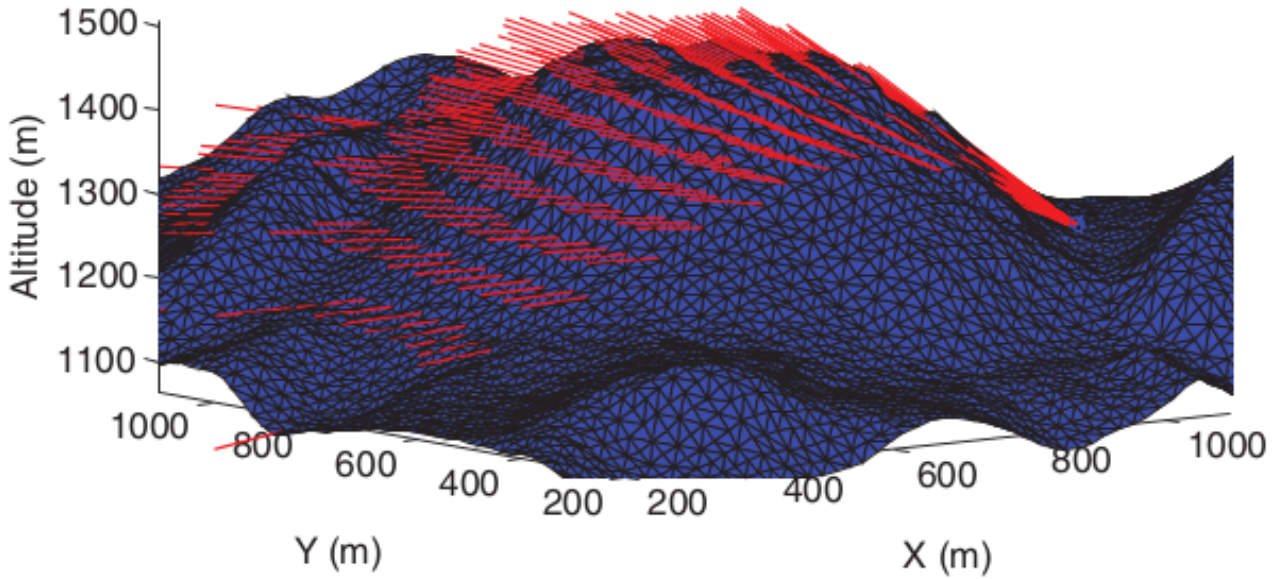
Muon radiography → "Muongraphy"

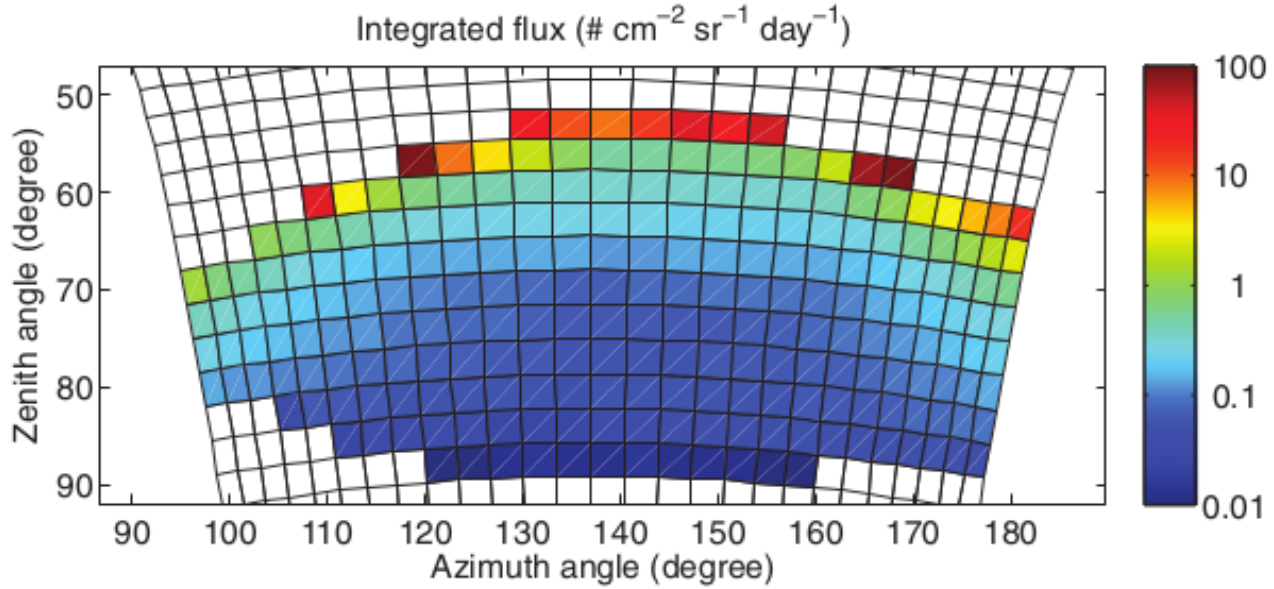
- Suppose you have an object with an unknown density profile, then...
  - ... measure the directional muon flux through this object
  - ... and compare with the muon reference flux
    - **→ you get the directional opacity of this object [g/cm²]**
- Additionally...
  - ... obtain the external geometry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

$$\varrho(L) \equiv \int_L \rho(\xi)\, \mathrm{d}\xi$$

- Finally, from...
  - directional opacity
  - directional interaction distances
    - **→ you get the internal density profile along muon propagation direction**

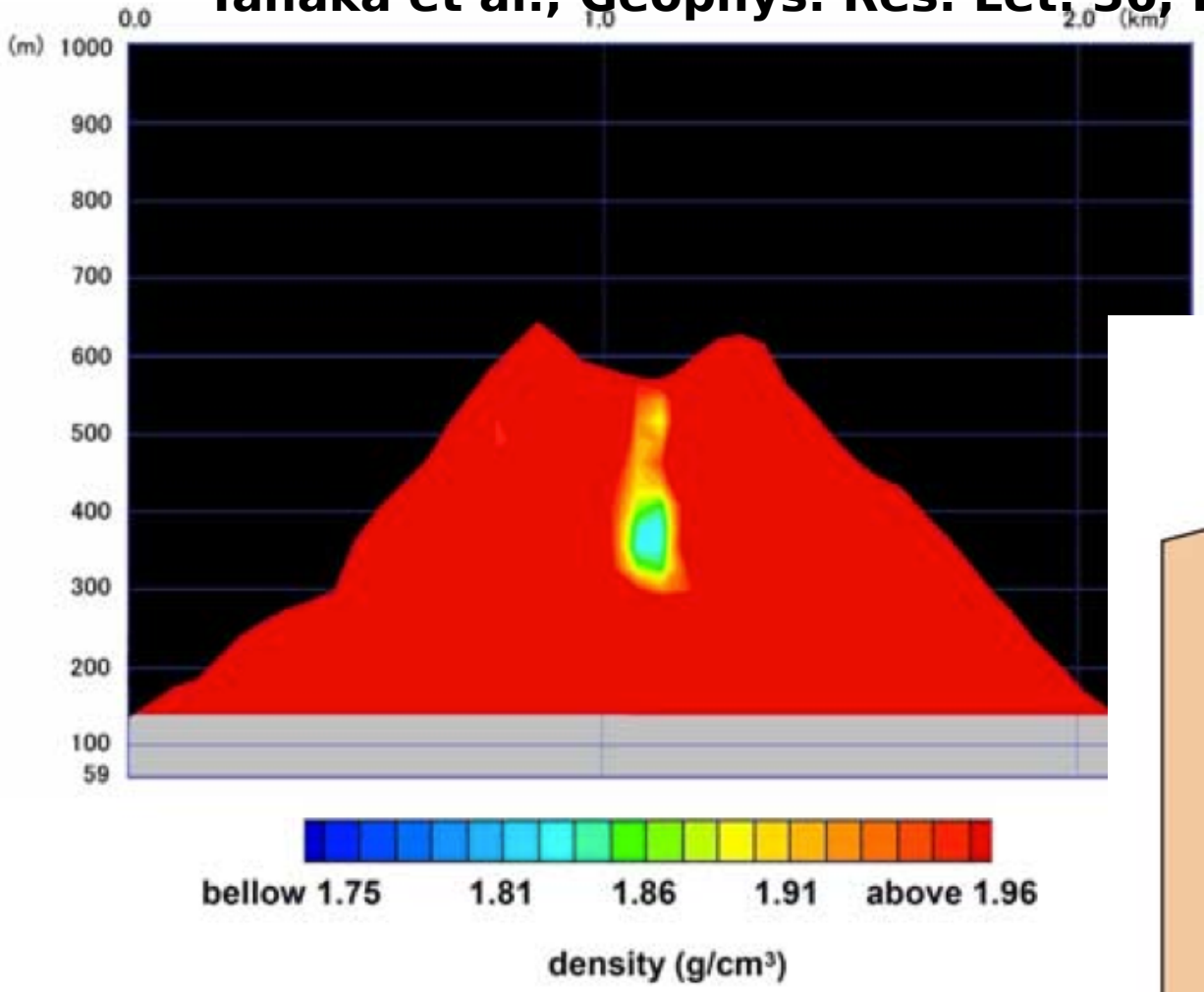
Muon directional flux measurement

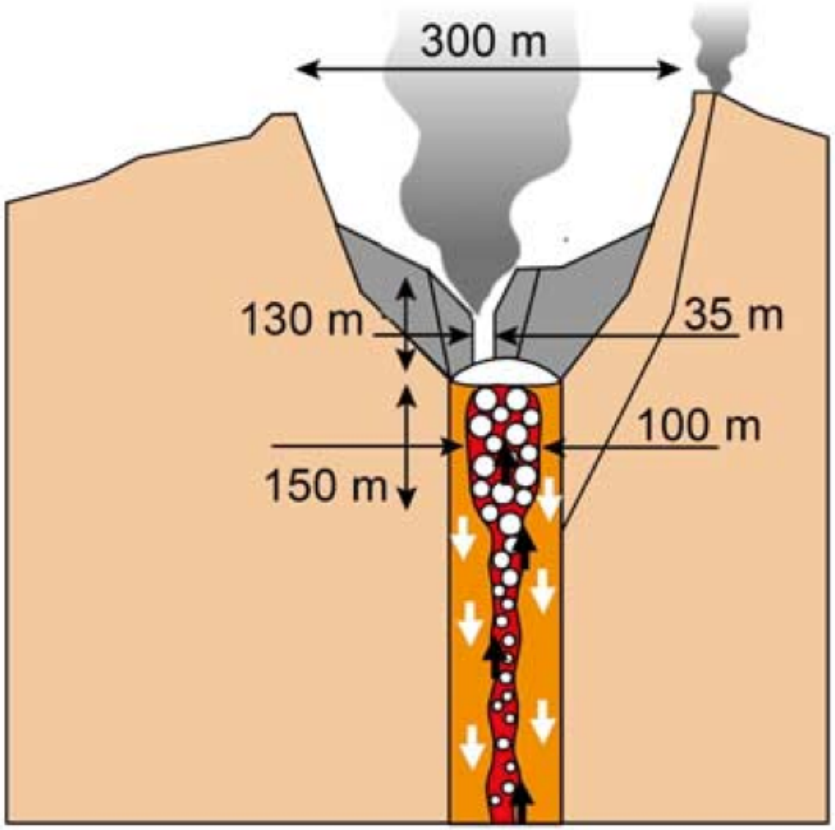




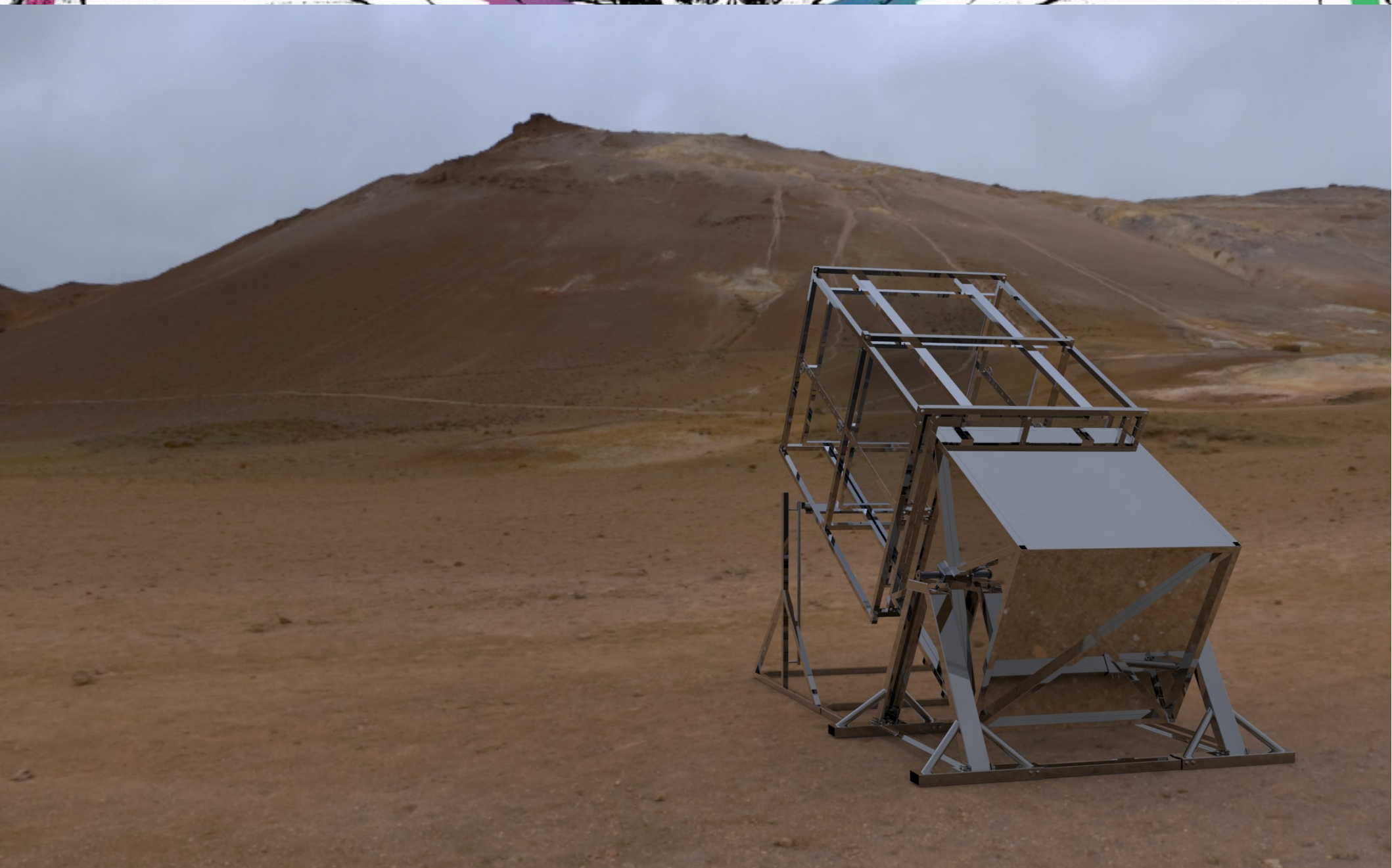
Volcanoes Muongraphy: Mt. Iwodake (Japan)

Tanaka et al., Geophys. Res. Let, 36, L01304, 2009

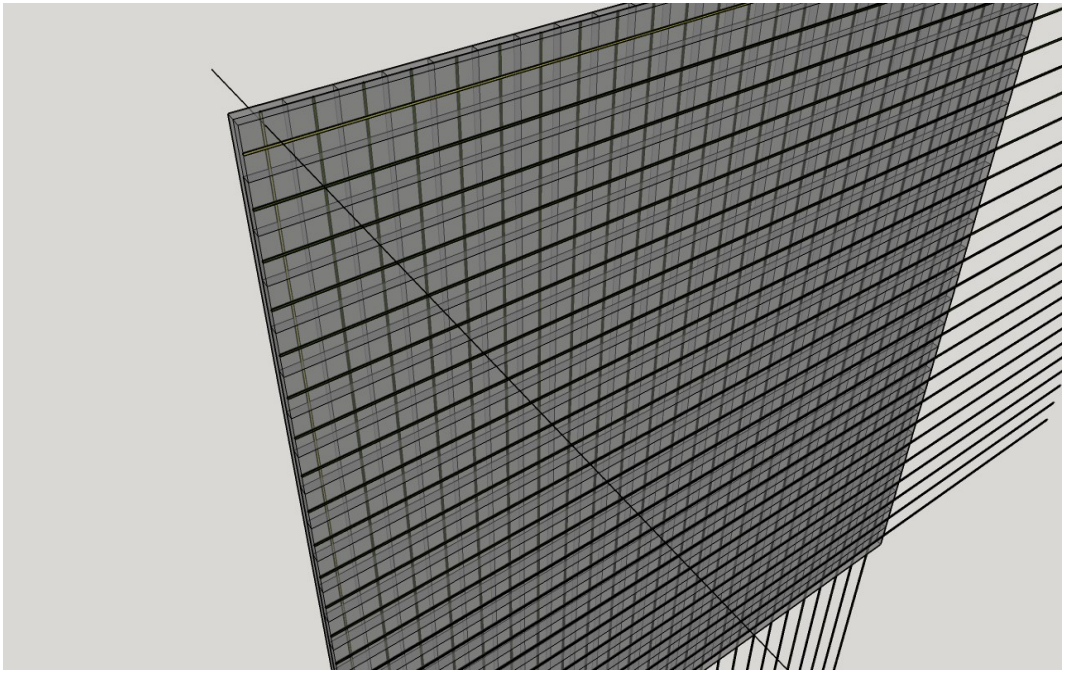




MuTe/MuBar: Muon Telescope for muongraphy



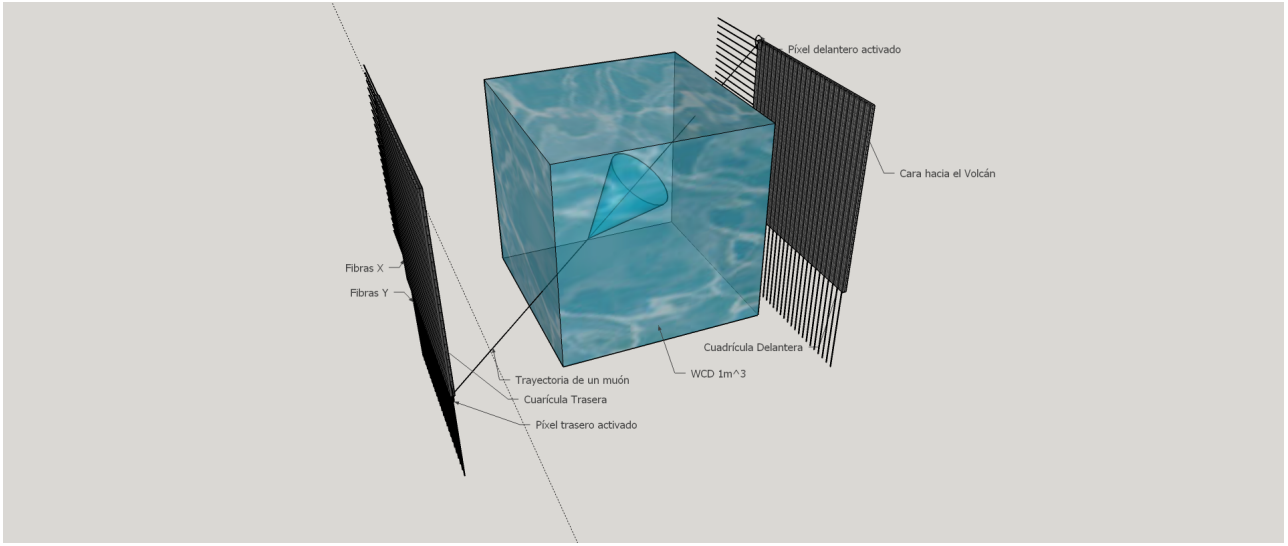
Muon Camera

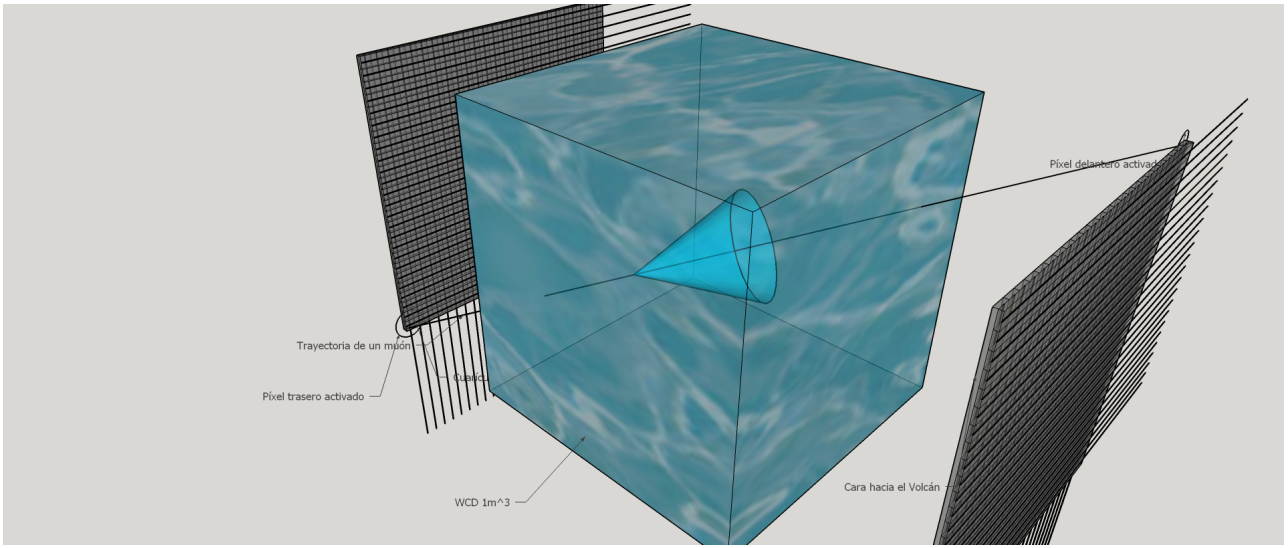


- 30 (4x1)cm plastic scintillator strips
  → 900 pixels (XY plane)
- Two XY planes separated by 2 m
- One water Cherenkov detector in between to obtain a high energy electromagnetic veto

- Two planes of "Minos" like polyestyrene plastic scintillator
  - (PoP+PoPoP) organic scintillator mixture
- Cladded 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

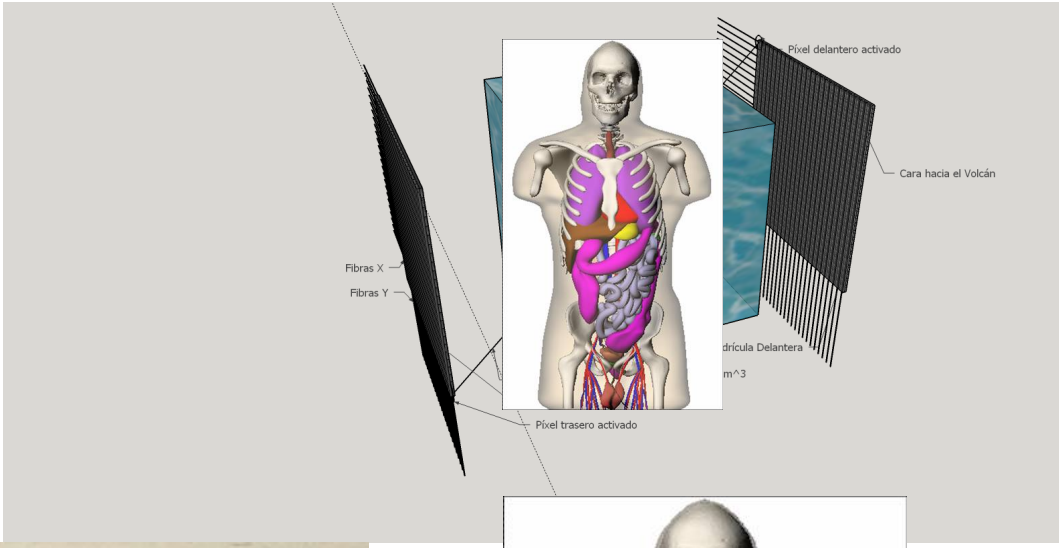
MuTe (Muon Telescope)

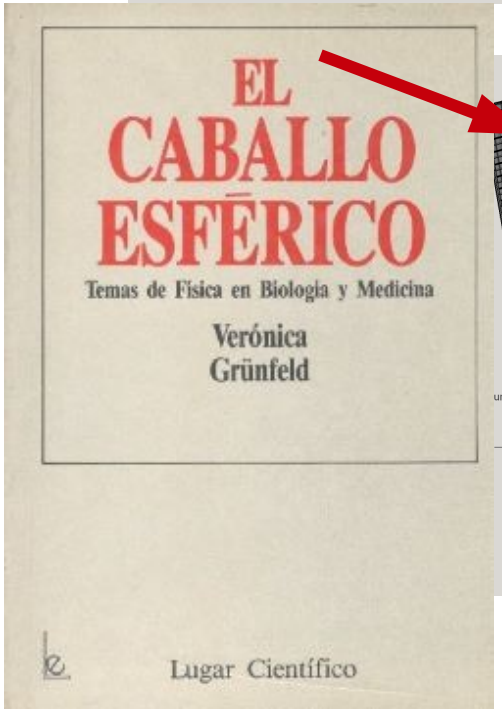


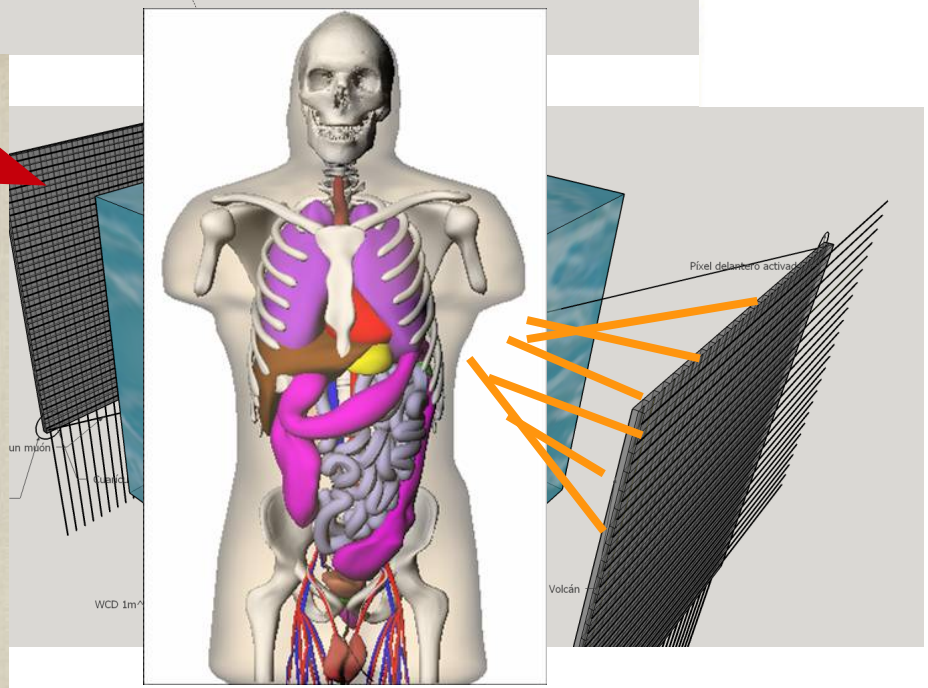


- Innovative:
  - Use a WCD as an active absorbant
  - 1.2m water → ~ 5 X_{EM}
- Local measurement of atmospheric muon flux
- SiPM instead of multi-anode pixel
  - No crostalk
  - Lower budget
  - Lower power consuption
  - Simple global design

Now replace “water” by “warm salt water”... and use, eg, amorphous Silicon flat panels







Ionizing radiation detection using commercial CMOS COTS

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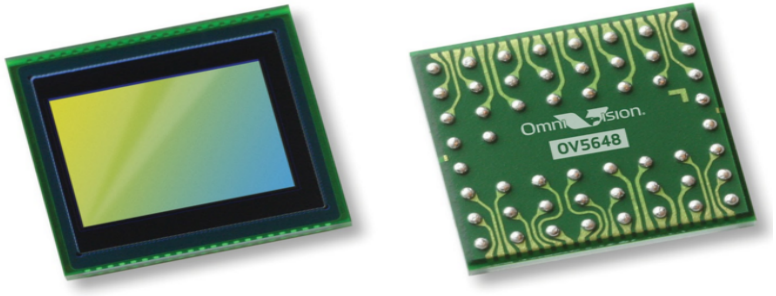
[3] Departamento de Física de Neutrones, CAB, CNEA, CONICET
*previamente

24/Oct/2016

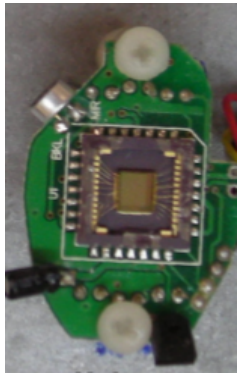
CMOS?

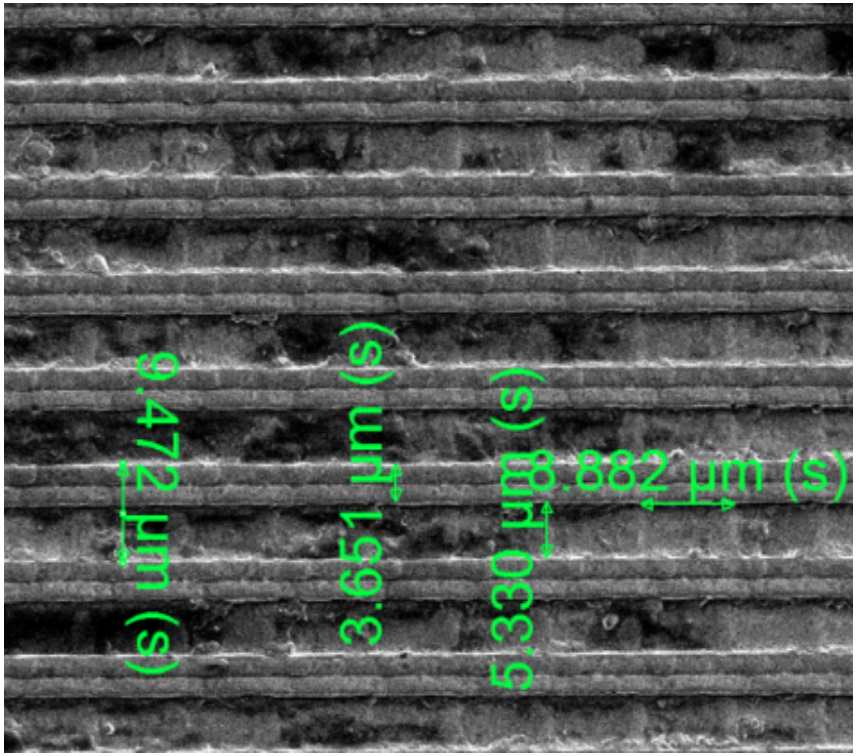


- Improved sensitivity, consumtion, speed and cost, when compared with CCD
- System on chip: amplifier, signal conversion and prosesing in a single chip
- Camera universality → don't blame us of Instagram cat pictures

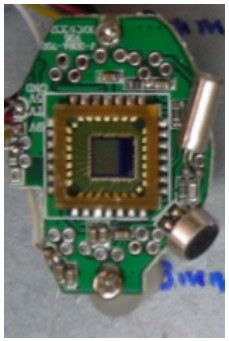
Typical commercial imaging sensors
CMOS COTS

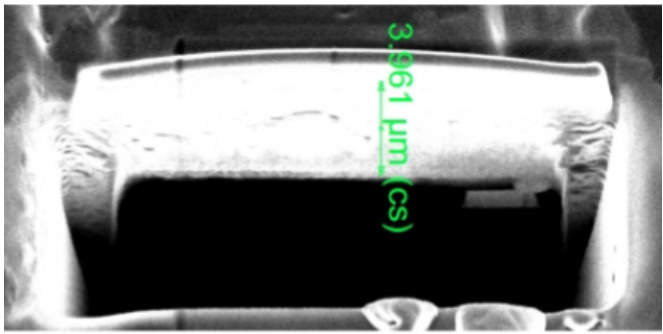
Sensor ByN:
OmniVision OV5116N
0.25'' 320x240 pixels
11µm pitch

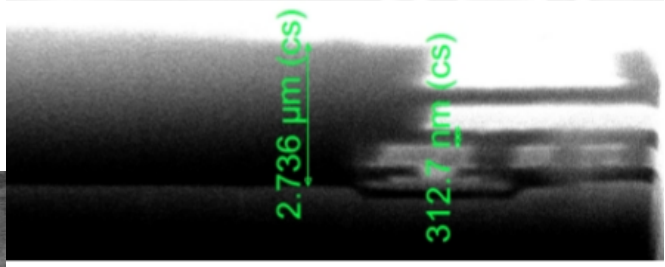


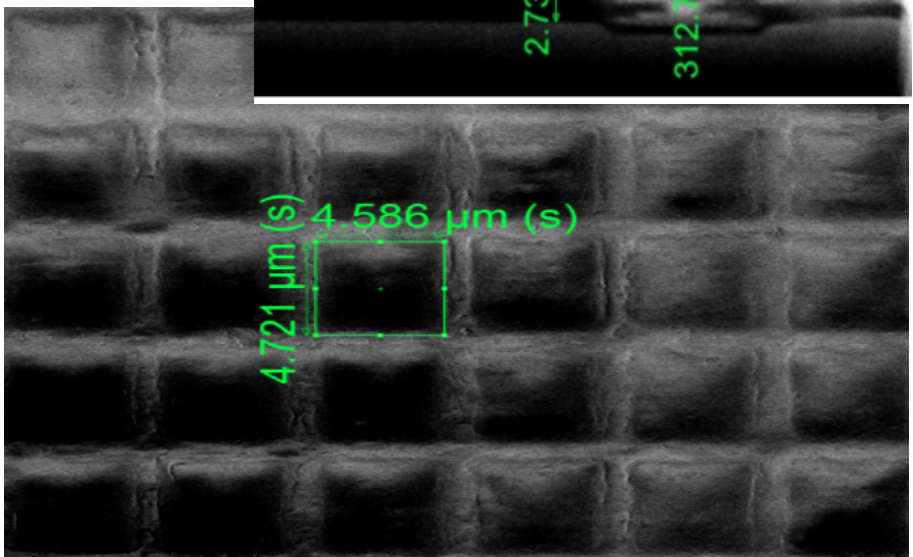


Sensor Color:
APTINA MT9V011
0.25'' 640 x 480 pixels,
5.6µm pitch



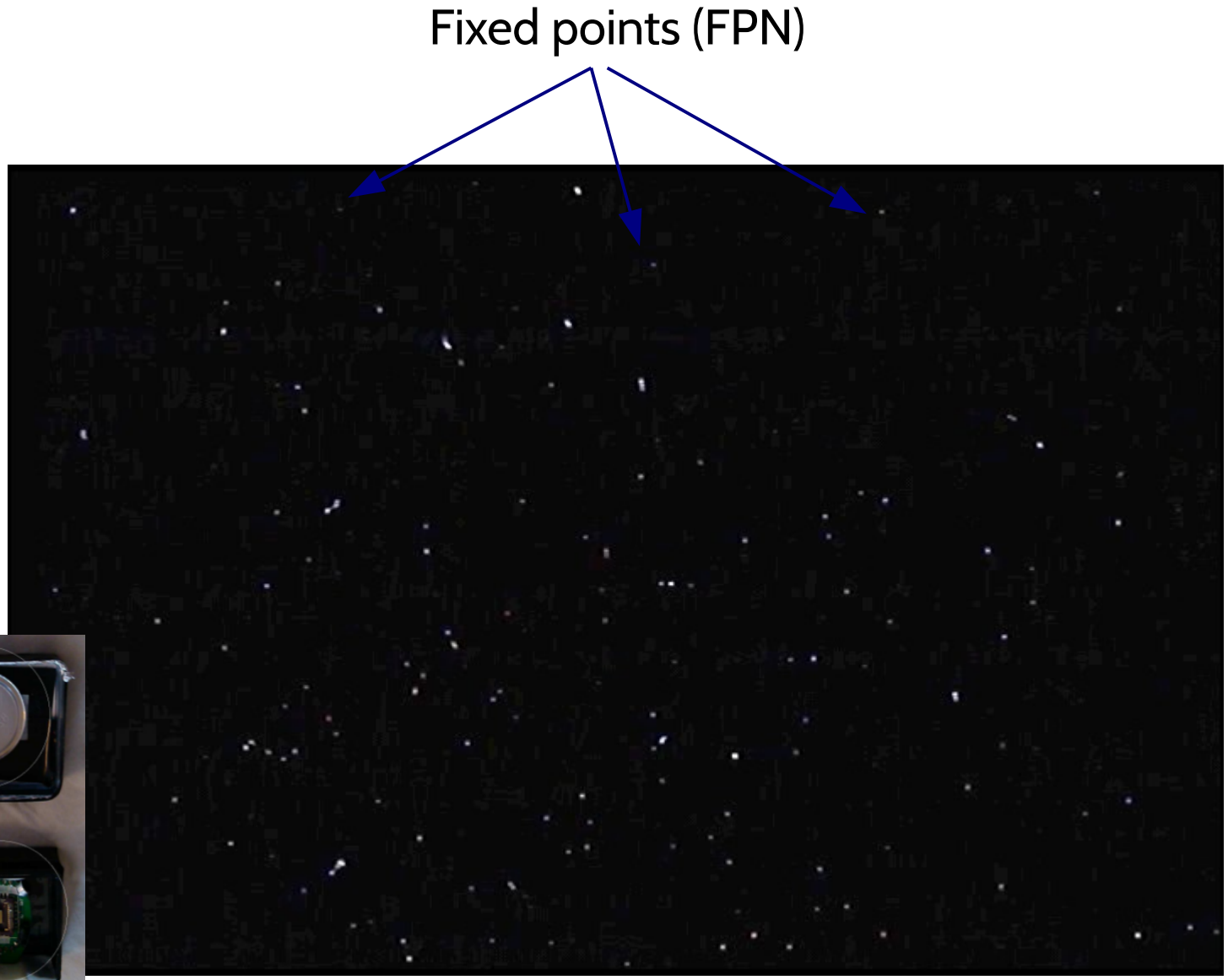






Ionizing particle detection

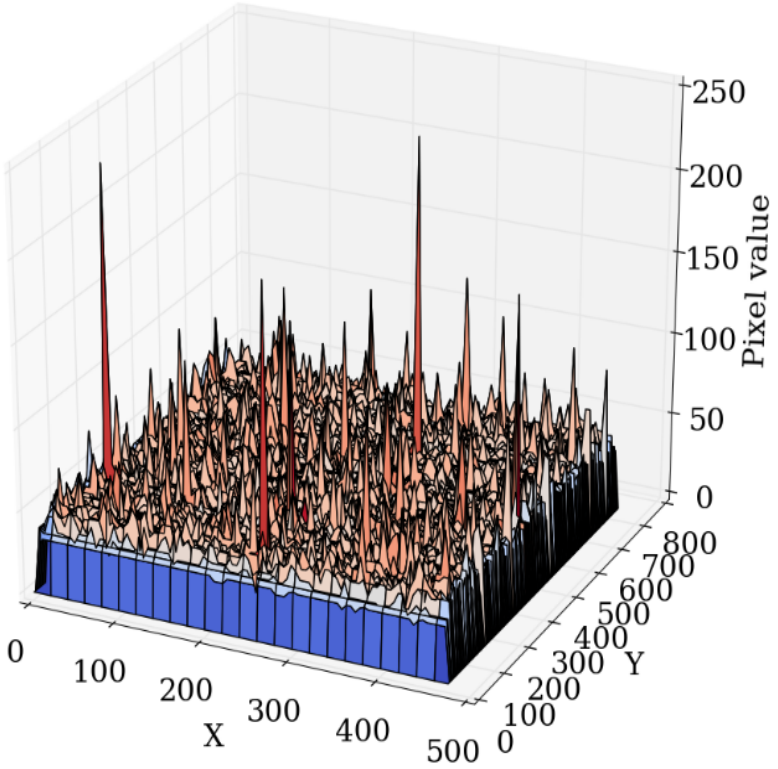
We can see
1- Events
2- Fixed points
3- Non zero Background (average dark current)



Fixed Pattern Noise

Defective pixels and thermal noise introduce a non-zero background (fixed pattern noise, FPN)

Auto-regresive filter: fast and low computational cost. Can be easily implemented on FPGA systems



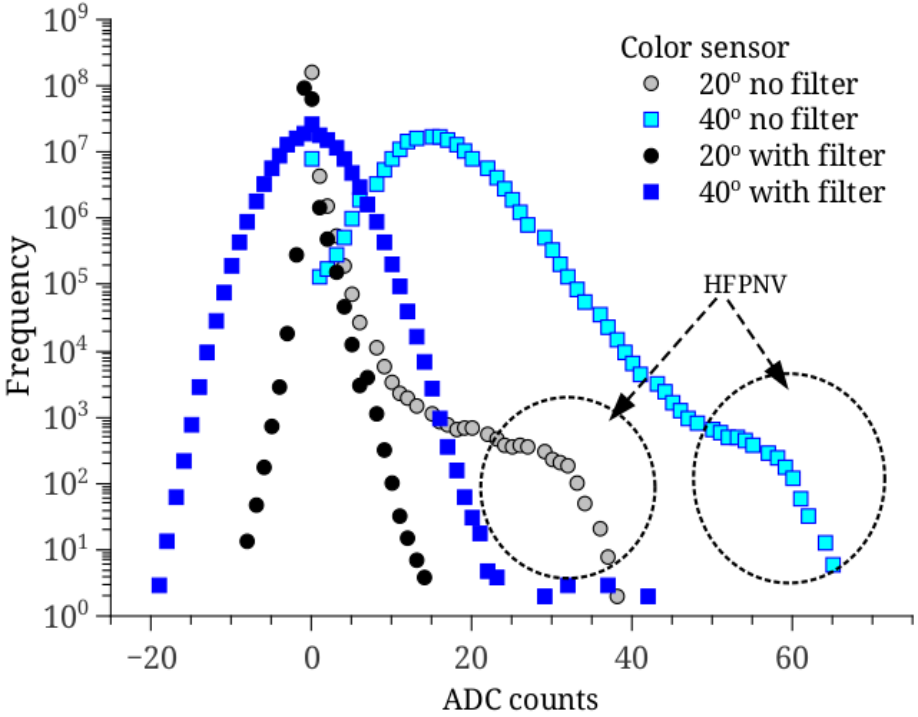
$$I_{FPN}(n) = I_{FPN}(n-1) \cdot (1-a) + I_{READ}(n) \cdot a$$

$$I_{CLEAN}(n) = I_{READ}(n) - I_{FPN}(n)$$

Fixed Pattern Noise

Extremely reduced false-positives pixels

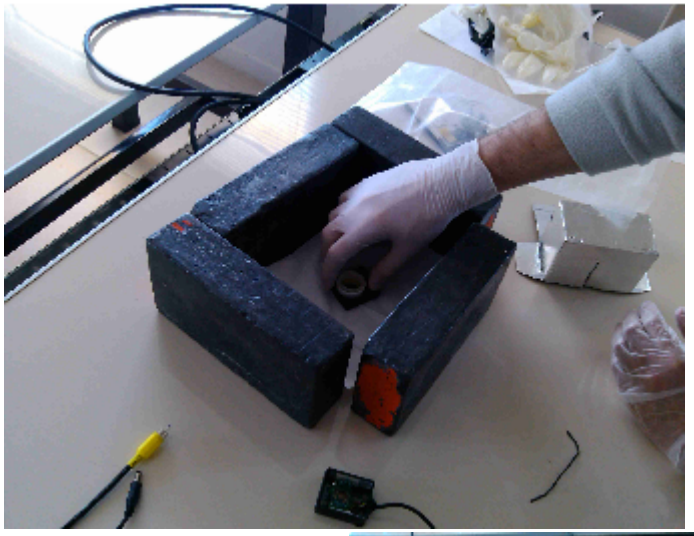
Pixels with signals above a low threshold can be considered as a real (physics) event

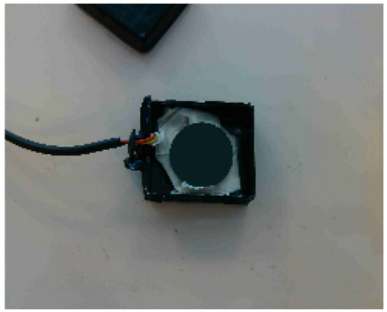


Particle response

Different particle sources irradiation:

- β, γ ^{137}Cs
- X-ray ^{55}Fe
- β ^{152}Eu
- γ ^{60}Co, ^{133}Ba
- α, γ ^{241}Am and ^{235}U

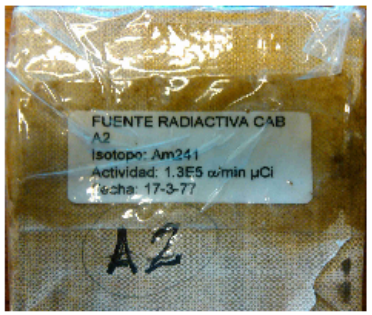




^{235}U

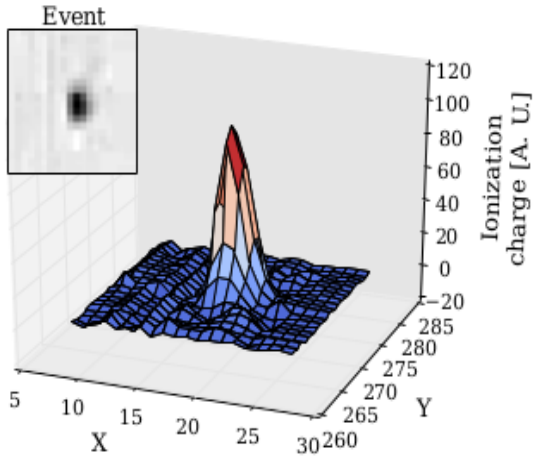
^{137}Cs

^{60}Co

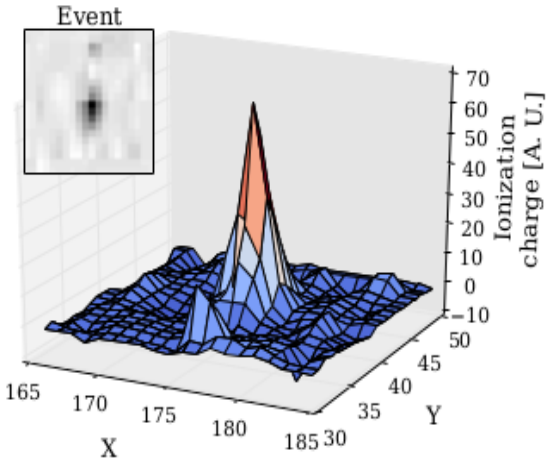


^{241}Am (con blindaje)

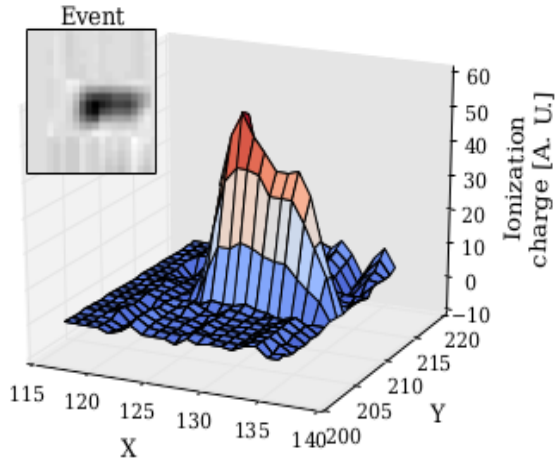
Particle response



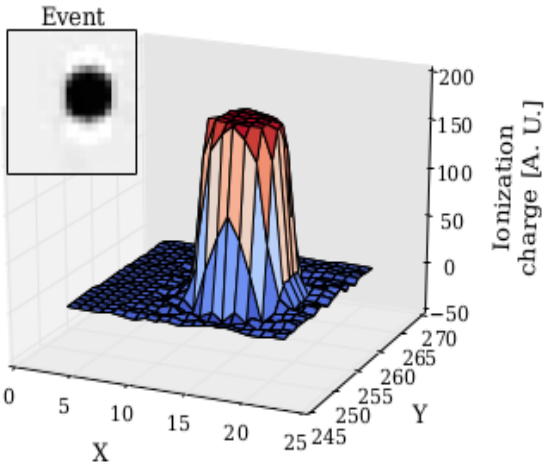
(a) β ^{137}Cs



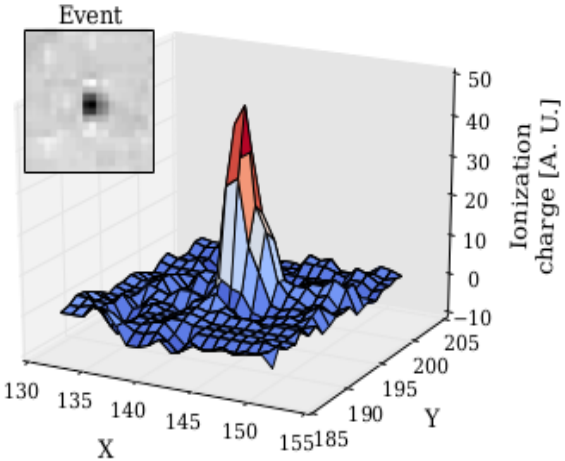
(b) γ ^{137}Cs



(c) γ ^{137}Cs



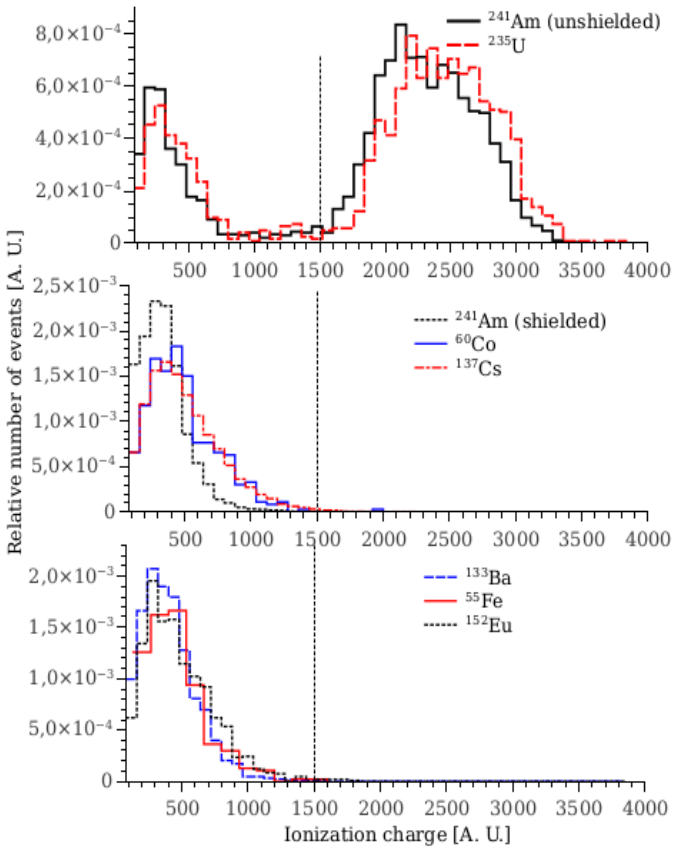
(d) α ^{241}Am



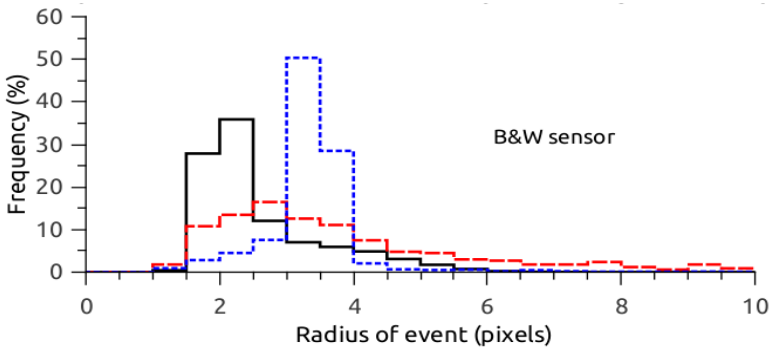
(e) X ^{55}Fe

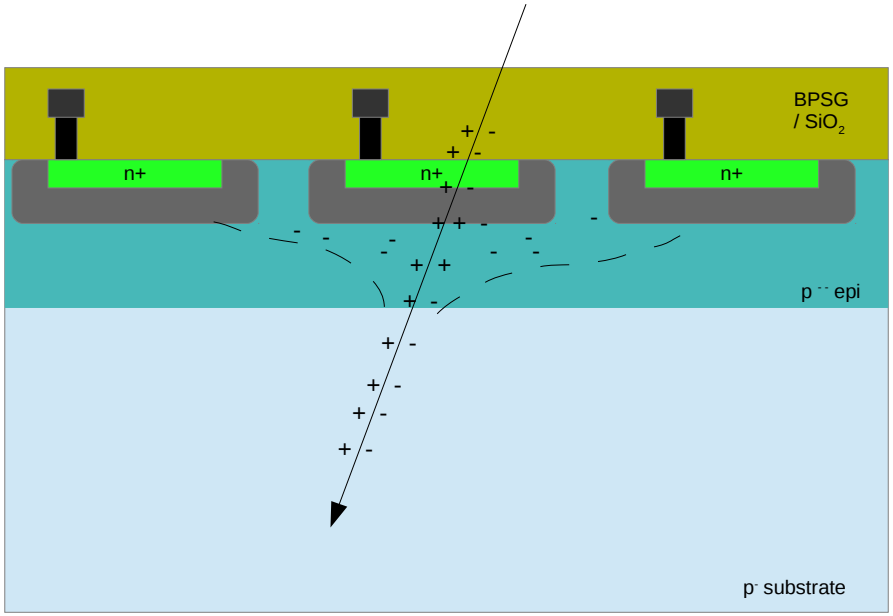
Pixel clusterization

Radius (px)

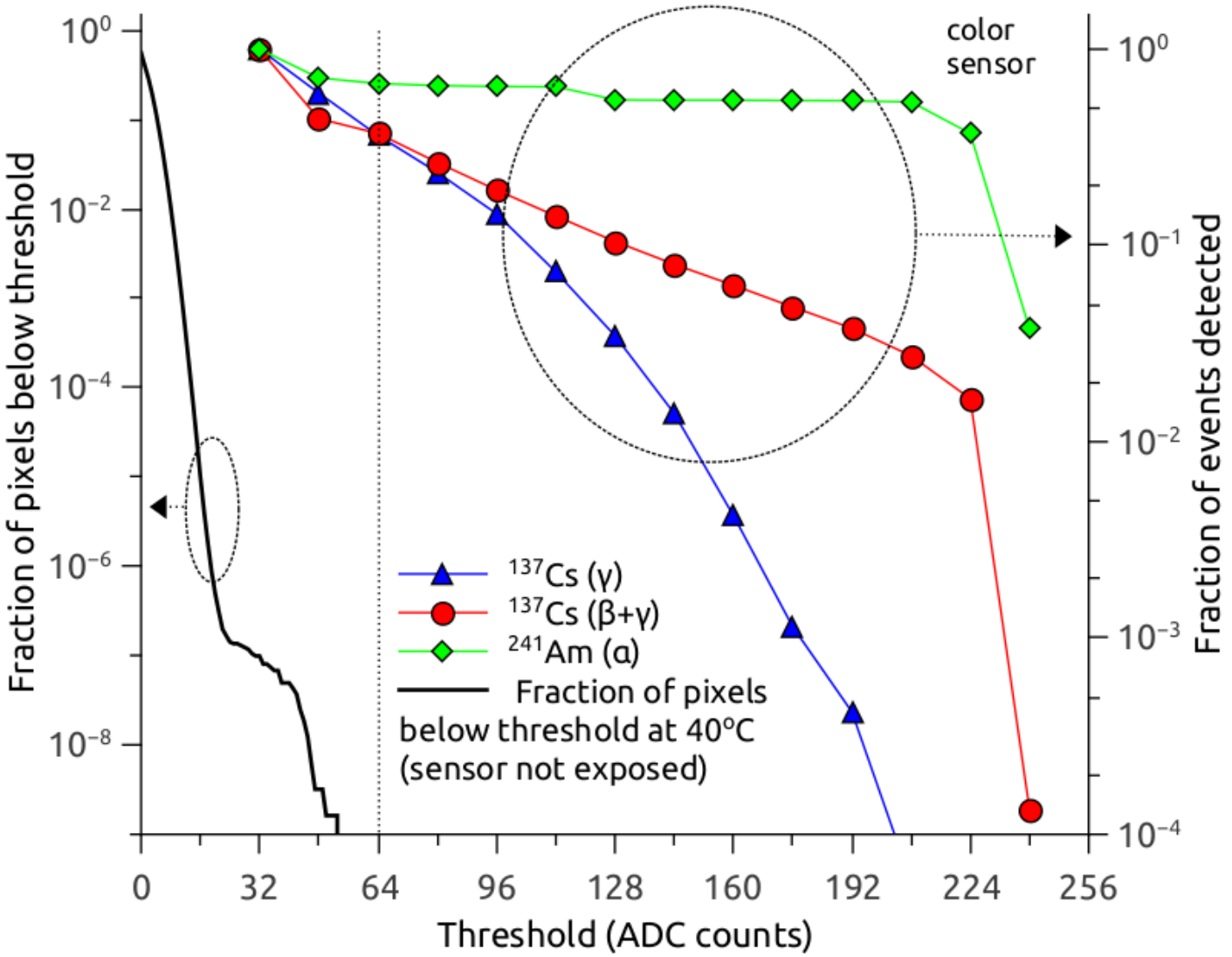


Deposited charge



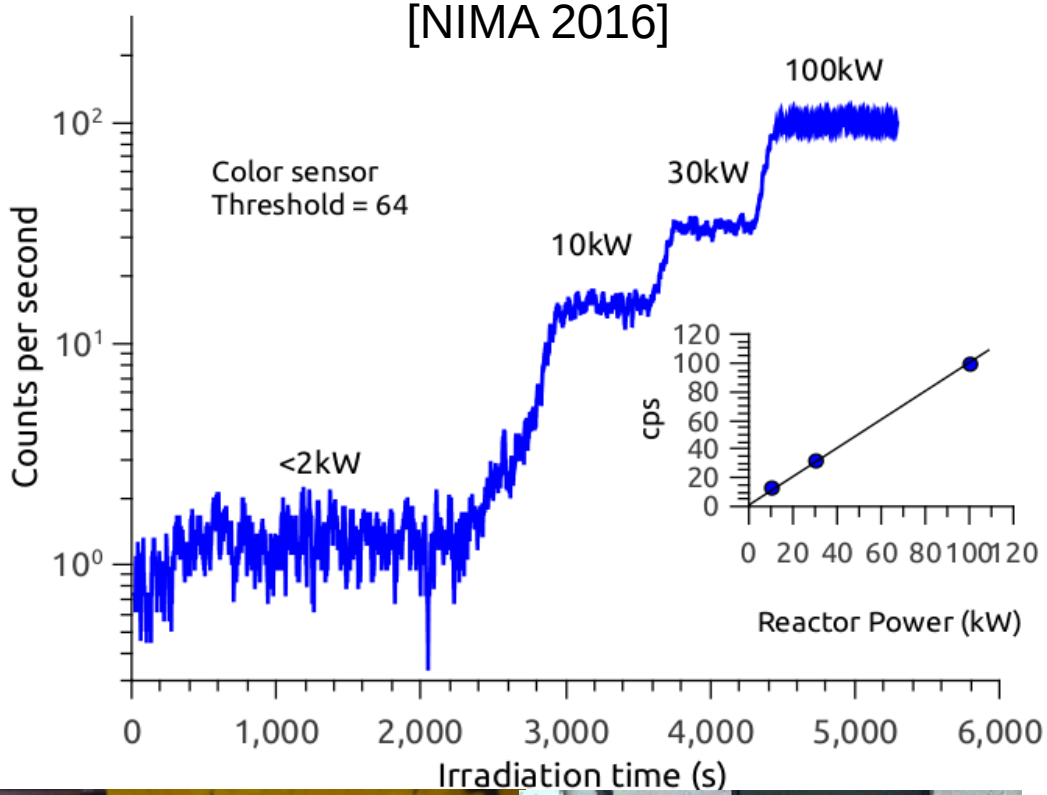


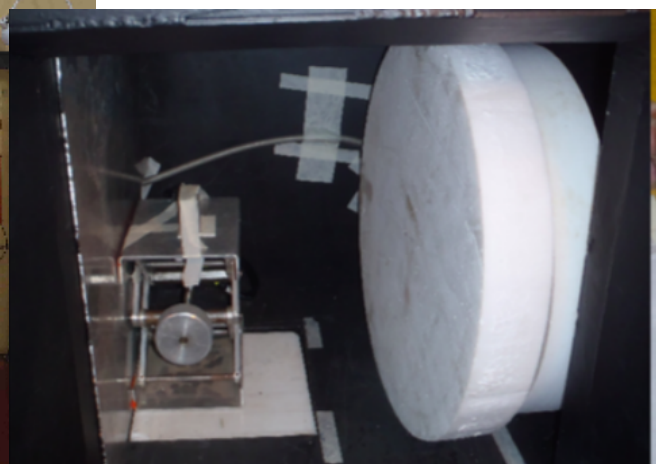
Detections threshold optimization
Robustness vs sensitivity Tradeoff

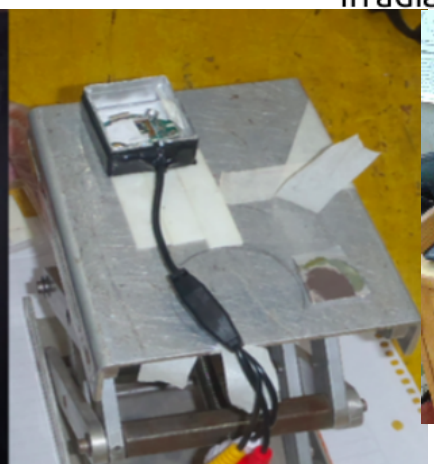


RA6 experiment tests

[NIMA 2016]



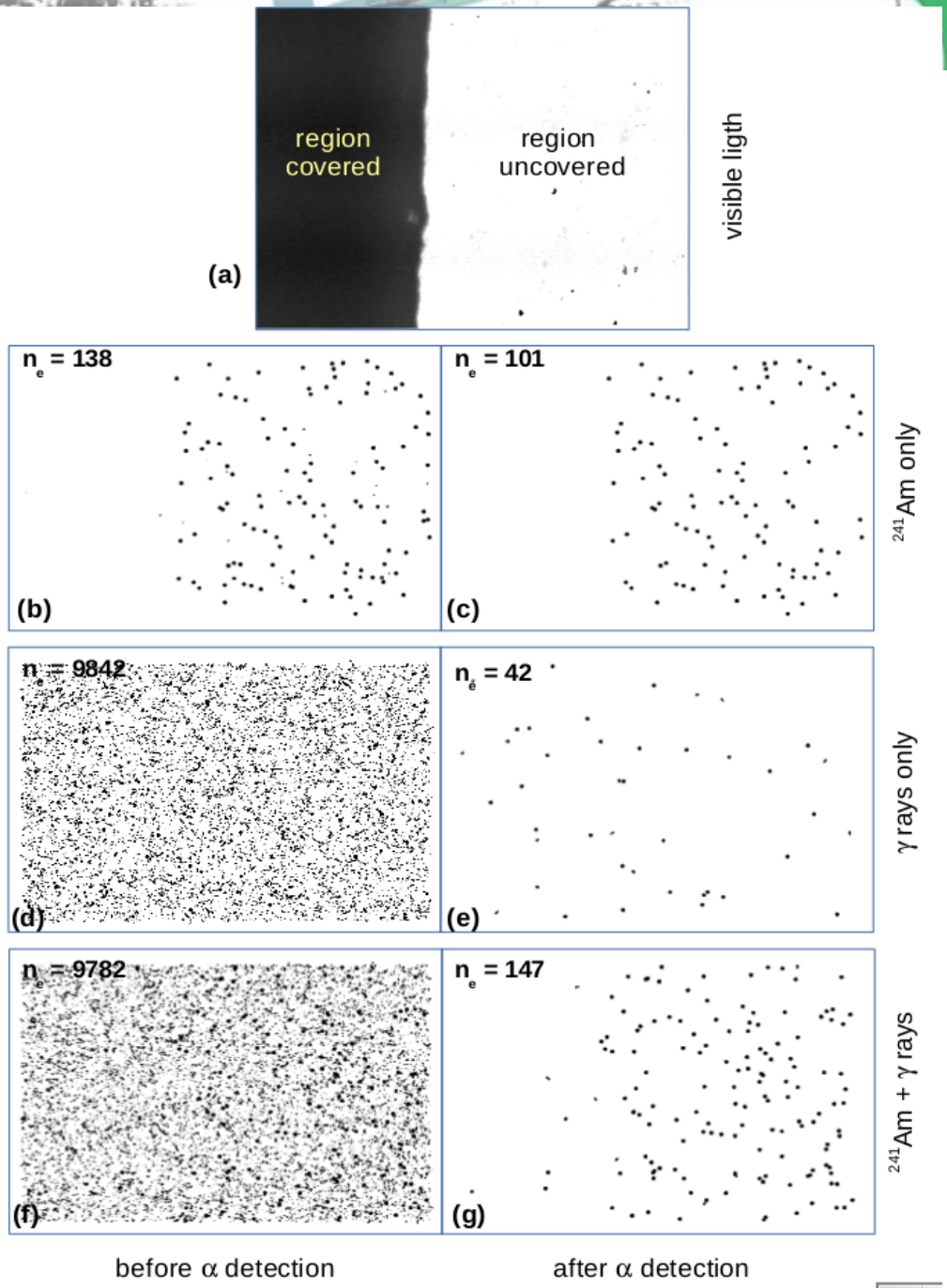




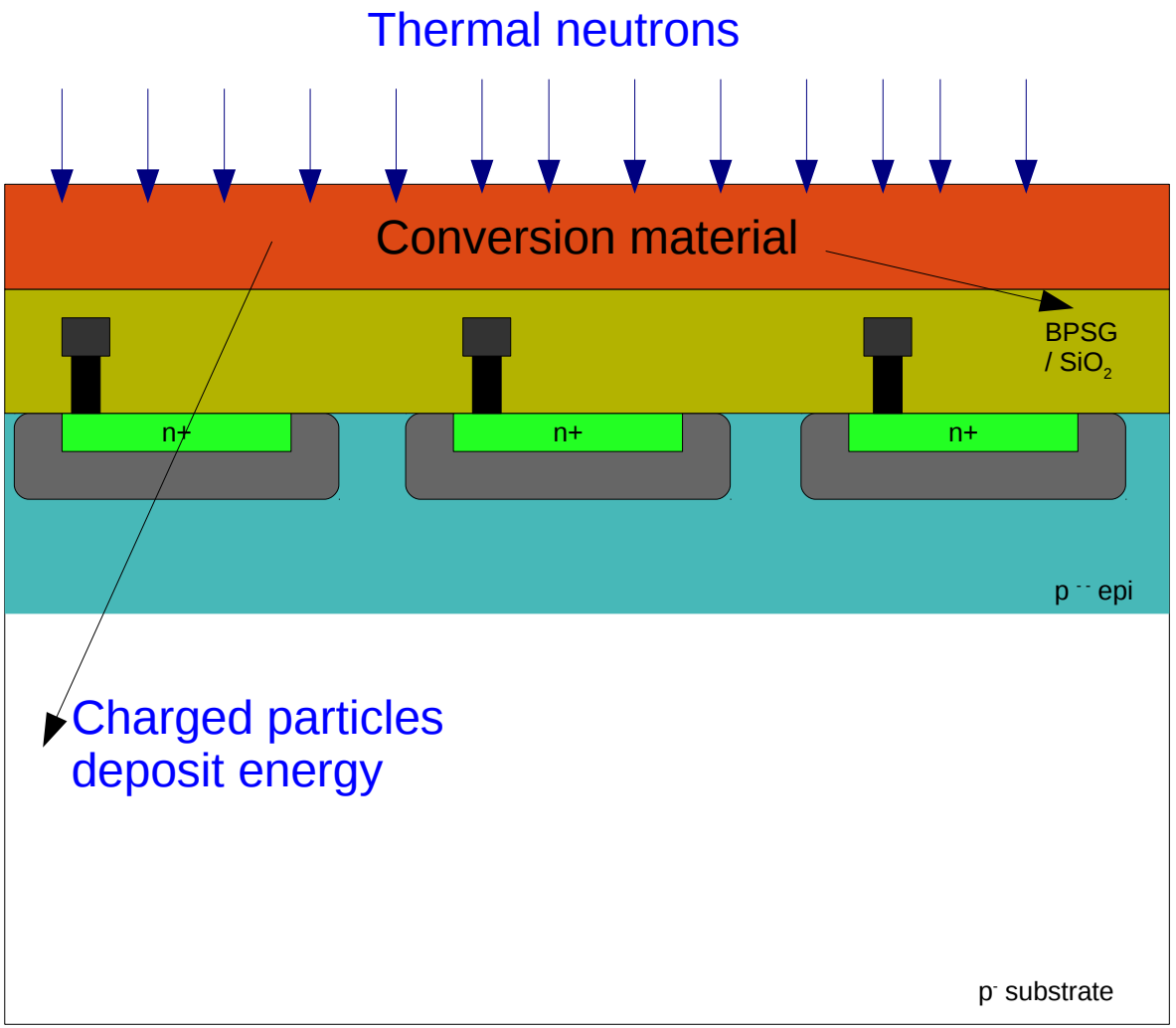
Particle identification

q>3000adc counts
radii > 2.5
max>125

0.4% false-positive (gammas instead of alpha)



Thermal neutron detection

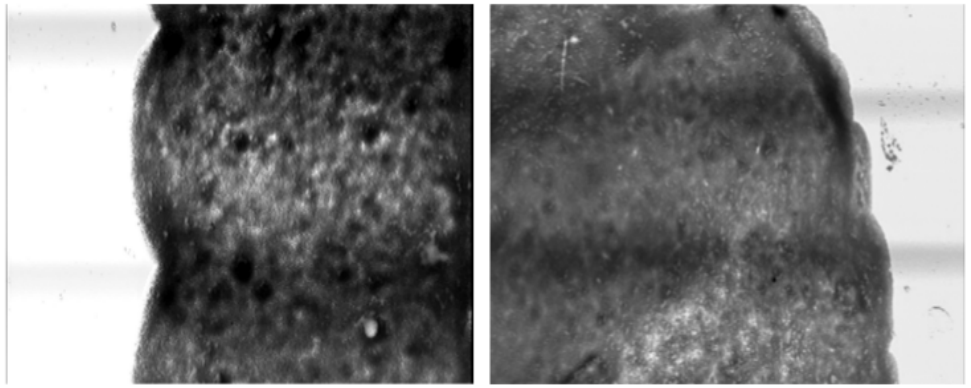


Boron and Gadolinium conversion

BNCT, neutrography, space weather, homeland security safeguard

Gadolinium oxide (Gd_2O_3) response
Signal amplification

Cámara blanco y negro Cámara color



Captura tomada con luz de la zona del sensor cubierta con Gd

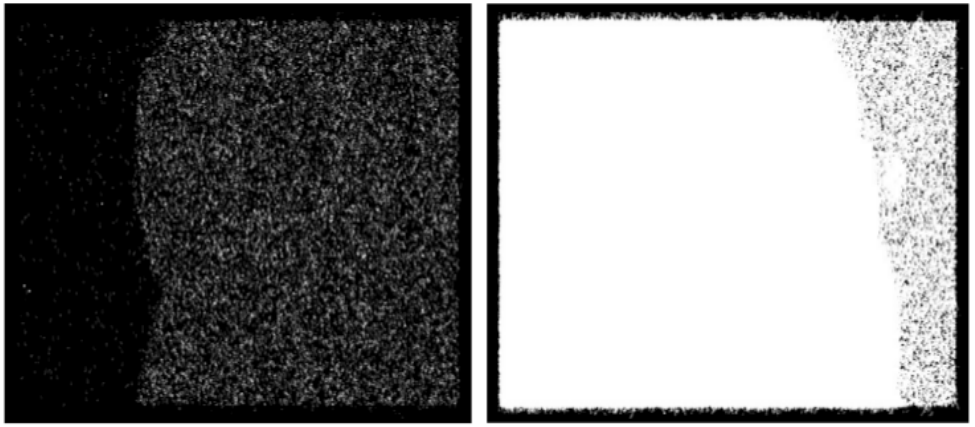
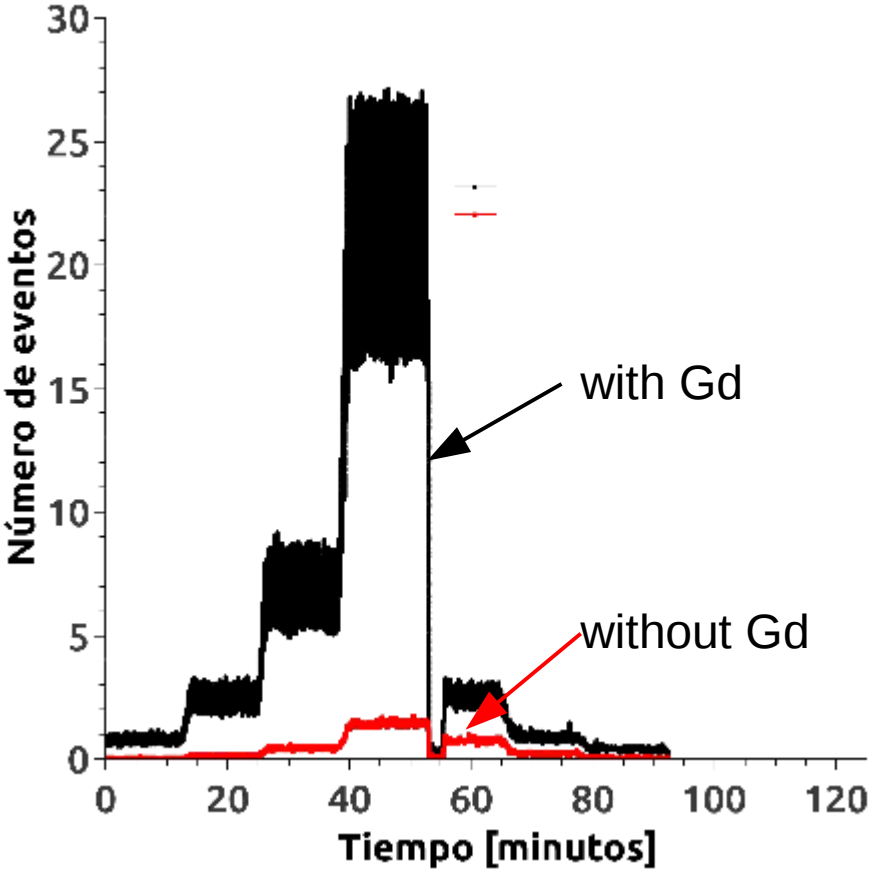


Imagen de todos los eventos capturados en el video

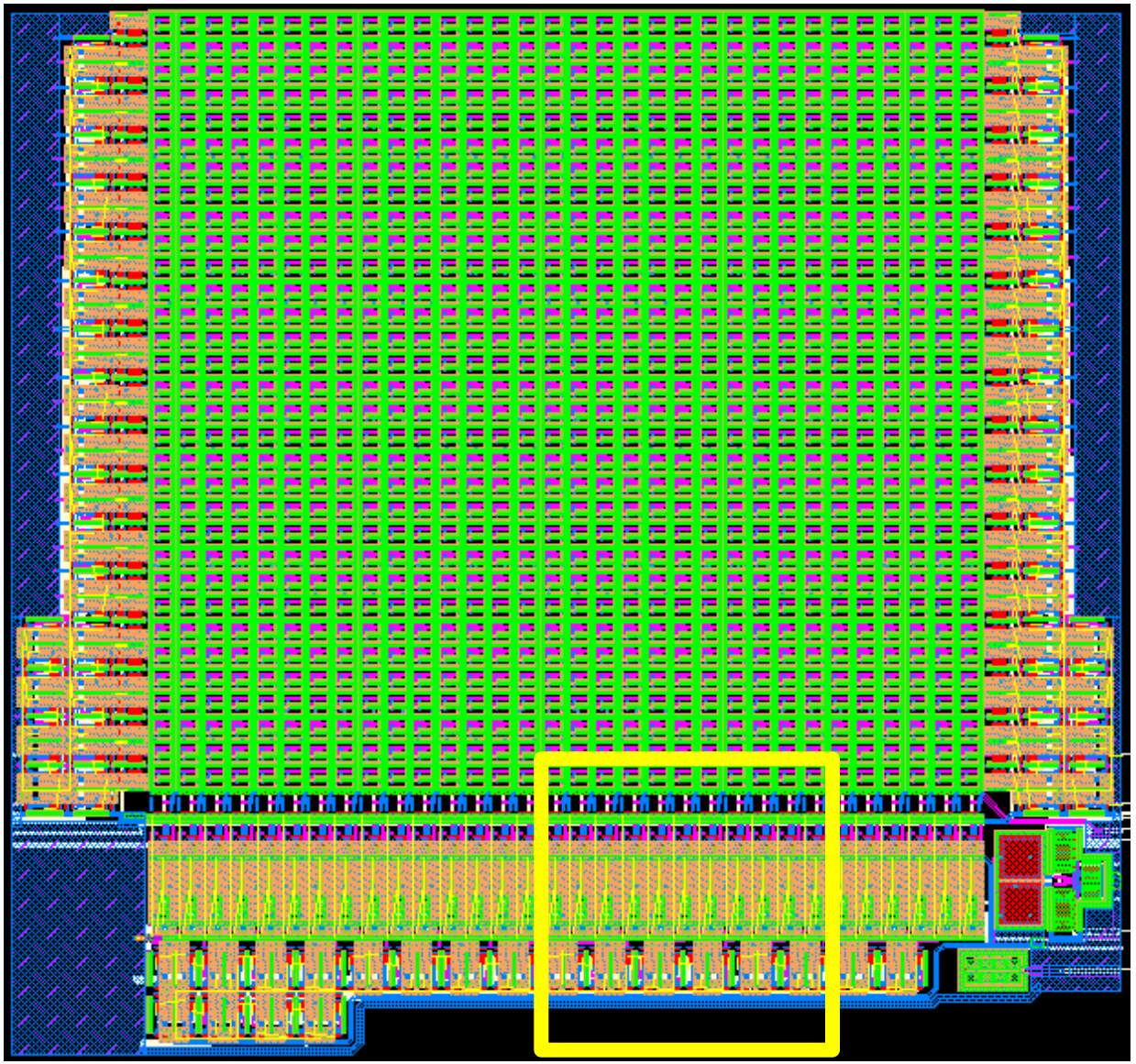


Integrated dose damage: ^{60}Co source (PISI-CNEA)

B&W camera, 2hs exposure at 200Gy/h.

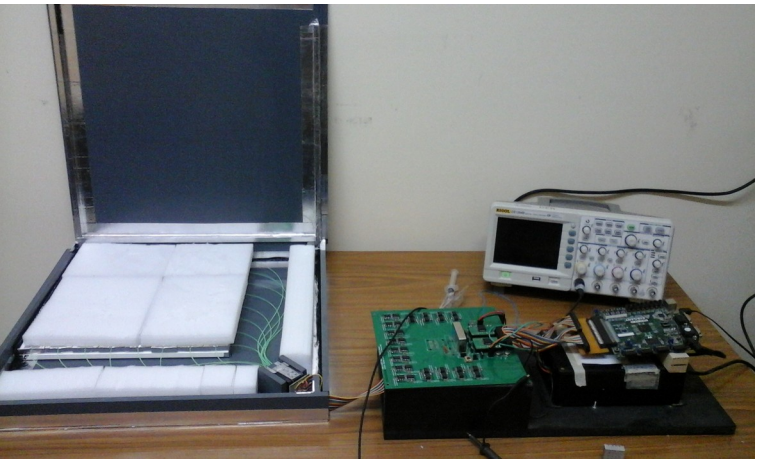
- 180Gy: dark current increase
- 280Gy: Column saturation
- 400Gy: Sync issues

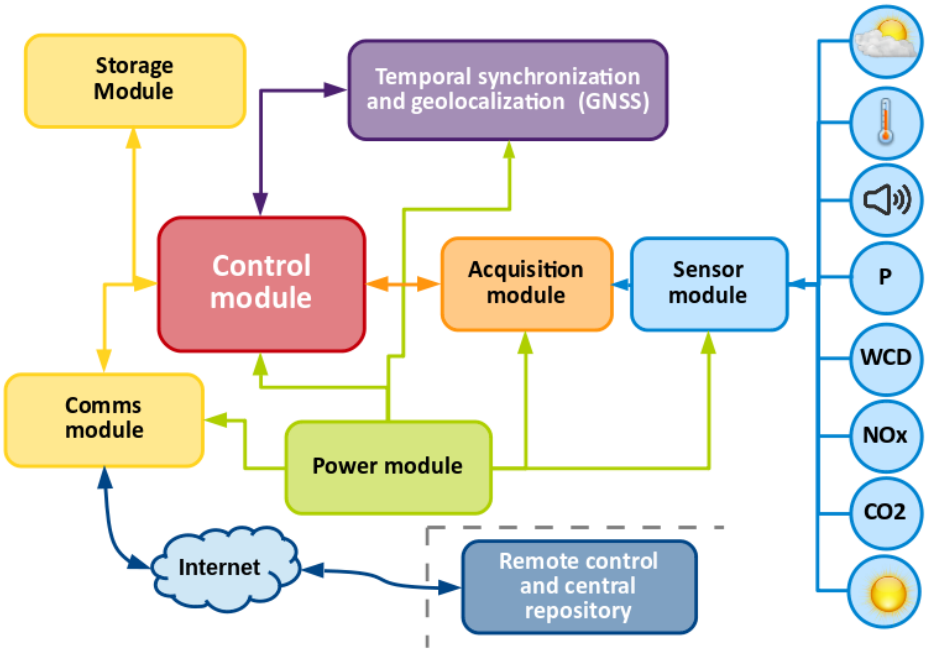
Own CMOS development for high radiation environments



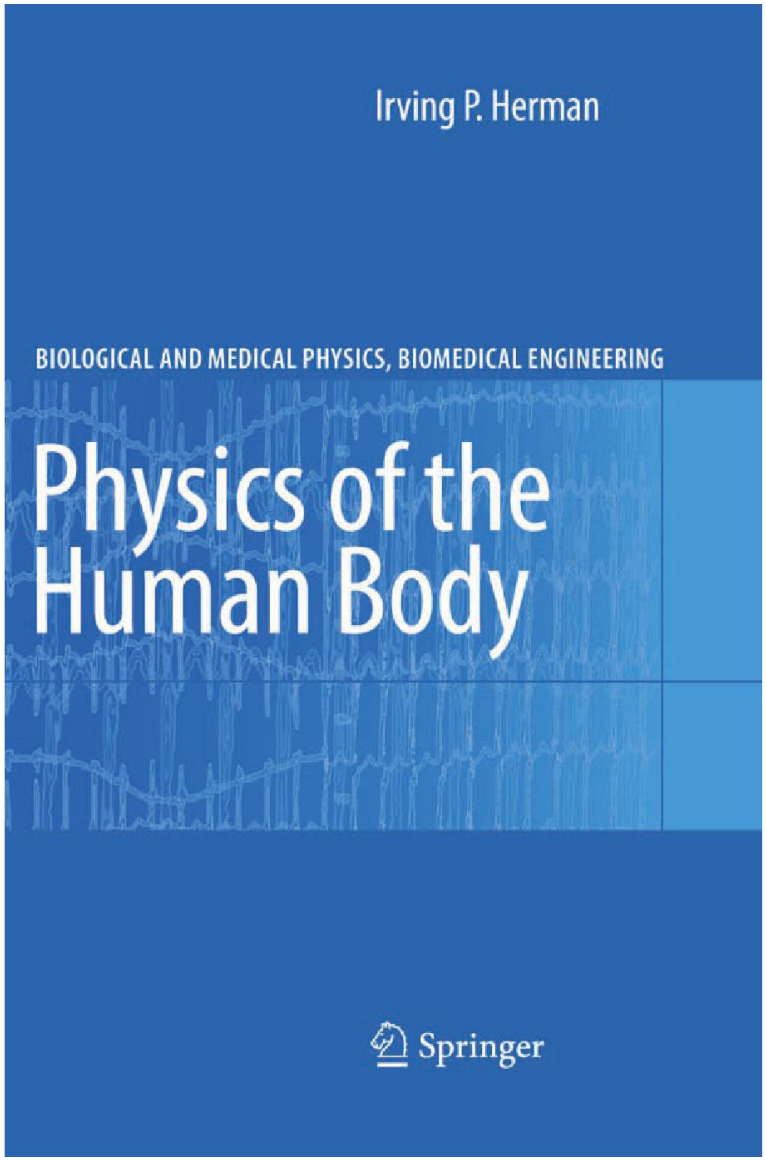
Extreme electronics for extreme detectors

- OMEGA based IN2P3 multi-channel ADC (MAROC, CITIROC)
- FPGA based electronics & "**sensor as a peripheral concept**"
- (Ultra) fast electronic response (> 100 Mhz)
- Commercial on-the-shelves adquisition and control modules: WiFi, Bluetooth, Linux, C++ & Python, low cost, low power consumtion



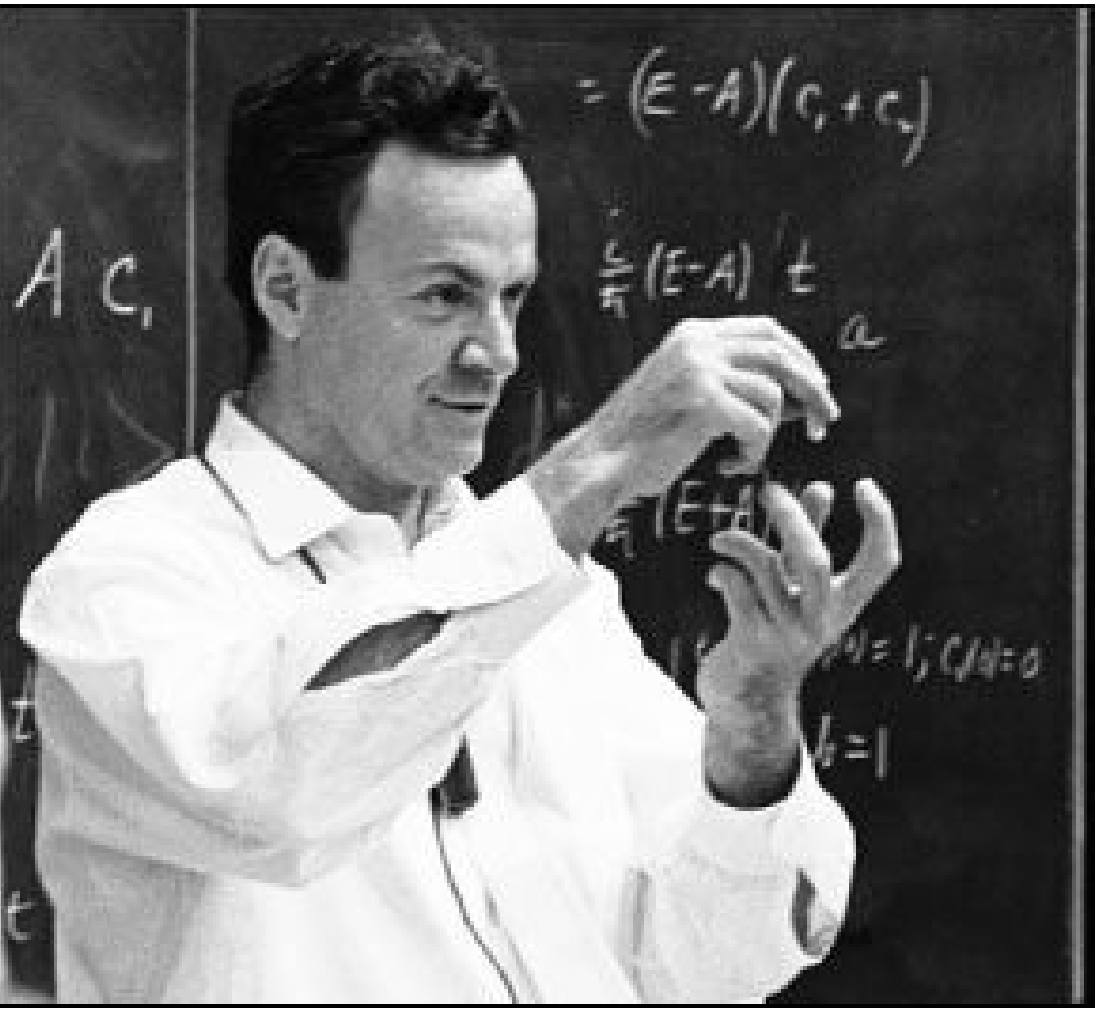


Why translational 1?



- "***Much of the problem we have in comprehending specialists in any field is in understanding their jargon, and not in understanding their ideas***. *This is particularly true for medicine. Much of medical jargon of interest to us is the terminology used in anatomy, and much of that in anatomy relates to directions and positions*"
- La medicina es descriptiva

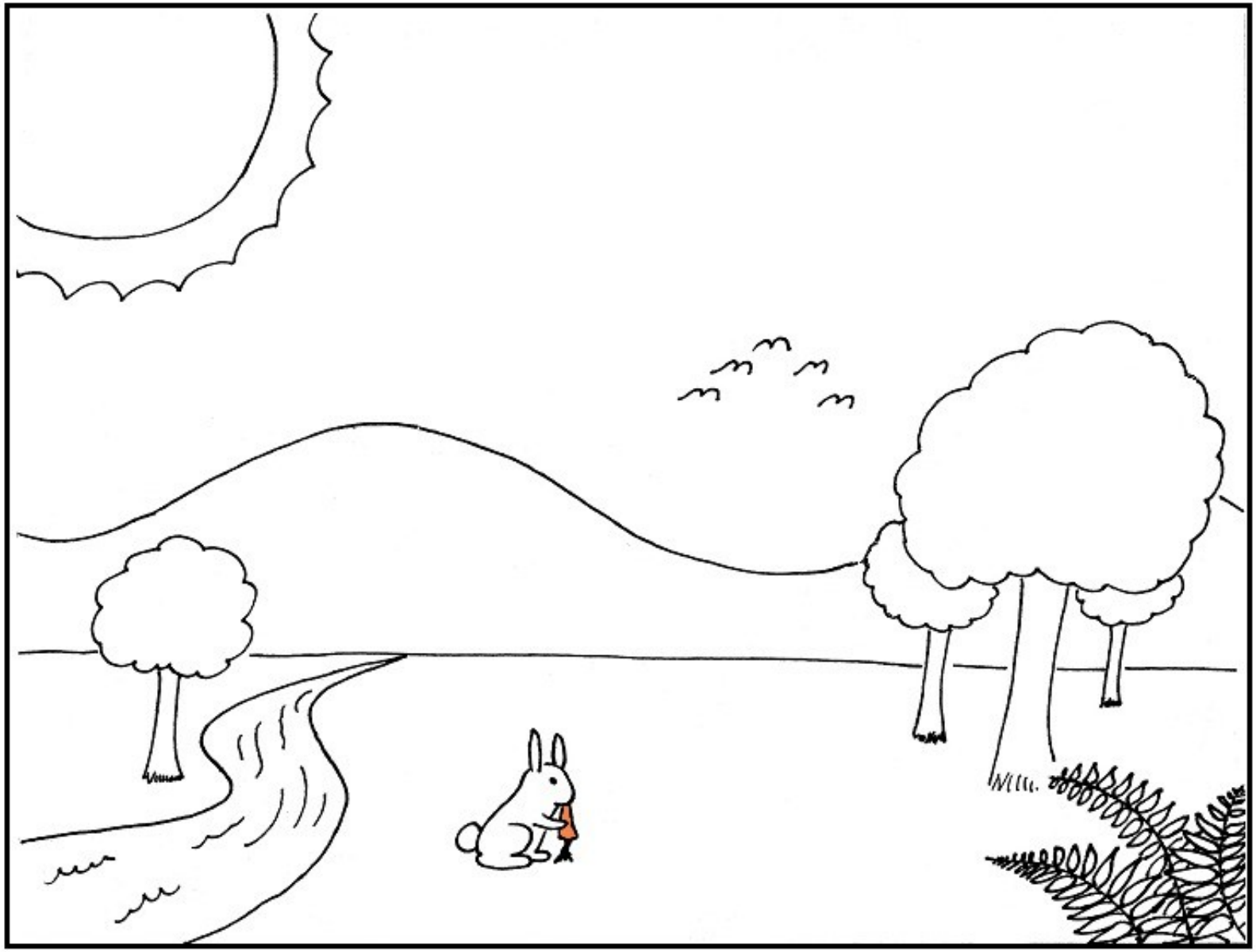
Why translational 2?



*"By a direct translation of the solutions (**of course the same mathematical equations must have the same solutions**) it is possible to solve problems in other fields with the same ease–or with the same difficulty–as in electrostatics"*

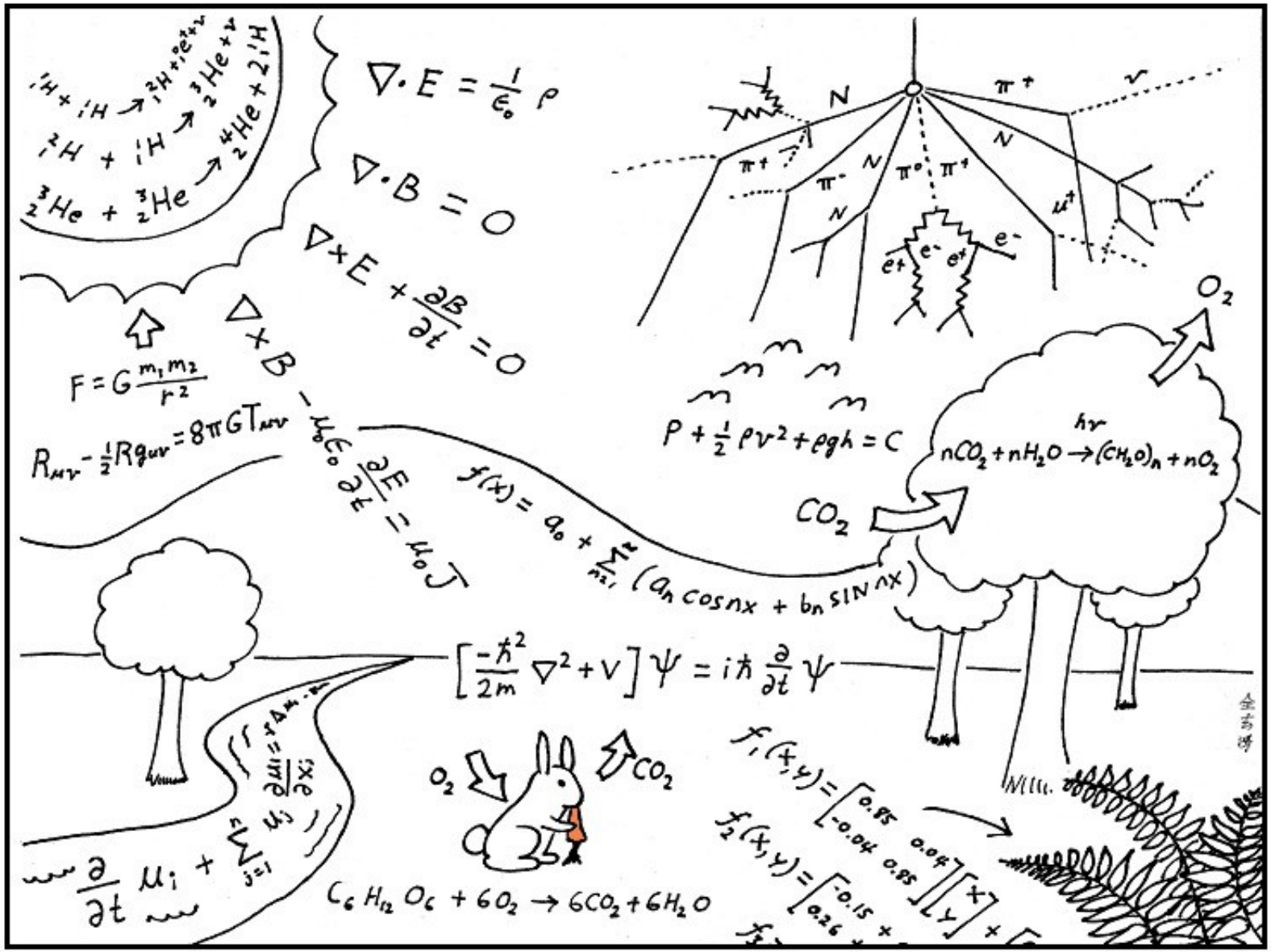
Richard Feymann, Lectures, Vol II p 12-1

Why translational 3?



This is what your University did to your brain

Sue them!



Extreme questions for extreme deseases

Can we (physicists) help people who is really suffering a serious desease?

Yes!

Let's do it together

Thank you very much