Particle detectors used in cosmic rays research

Anderson Fauth

State University of Campinas – UNICAMP, Brazil

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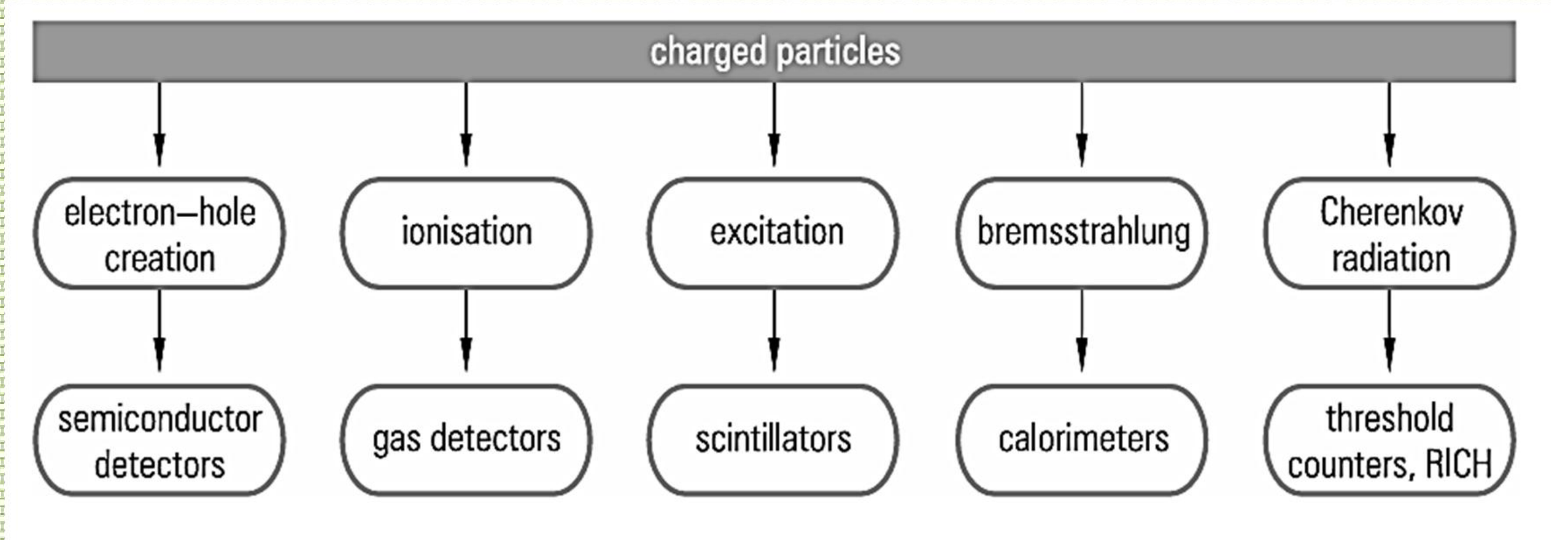
Esc Física Unìversidad Industrial de Santander, Bucaramanga, Colombia

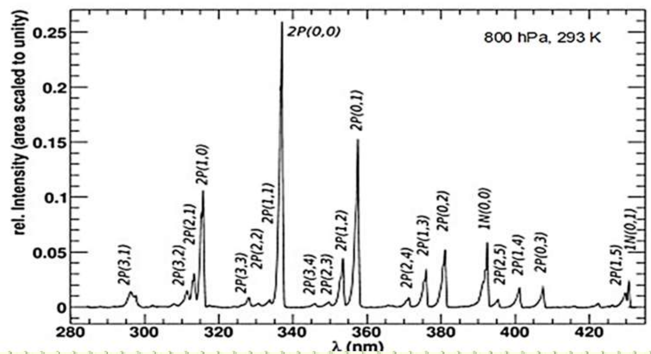
Summary

- A brief history of cosmic rays
- Cosmic rays
- Particle detectors
- Water-Cherenkov Detector

Charged particle interaction → detector type



- excitation of nitrogen in air because of energy deposit from EAS
- spontaneous de-excitation → fluorescence light
- atmosphere dependence because of quenching



The scintillation of gases is used in fluorescence telescopes for energies ≥10^{18} eV

Thermoacoustic – gravitational antenna

Explore - CERN

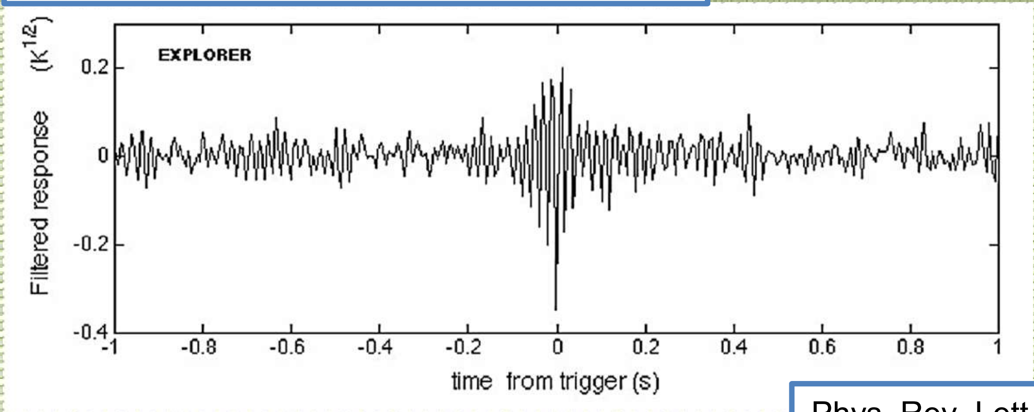
Nautilus National Laboratory, Frascati

Cosmic rays veto

Plastic scintillators

streamer cameras

event triggered by a cosmic ray shower



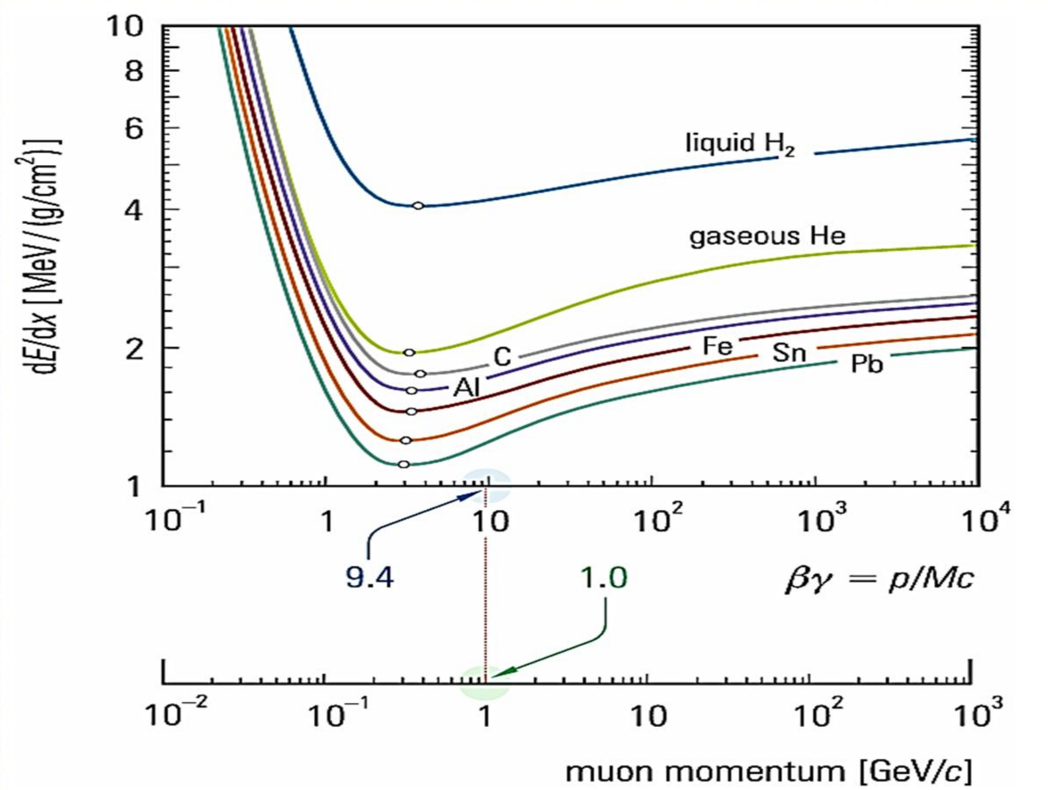
- Explorer, first cosmic ray event detected by a gravitational antenna (stage in 2003)
- Nautilus, veto with Ar/Isobutane mixture for streamer cameras in my doctoral thesis

Phys. Rev. Lett. 91 (2003) 111101

dE/dx by ionization and excitation

- The mechanism that dominates charged-particle interactions is the energy loss by ionization and excitation.
- This energy-loss process is described by the Bethe–Bloch formula:

$$-\frac{\mathrm{d}E}{\mathrm{d}x}\bigg|_{\mathrm{Ion.}} = K \cdot z^2 \frac{Z}{A} \cdot \frac{1}{\beta^2} \left\{ \frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta}{2} \right\}$$

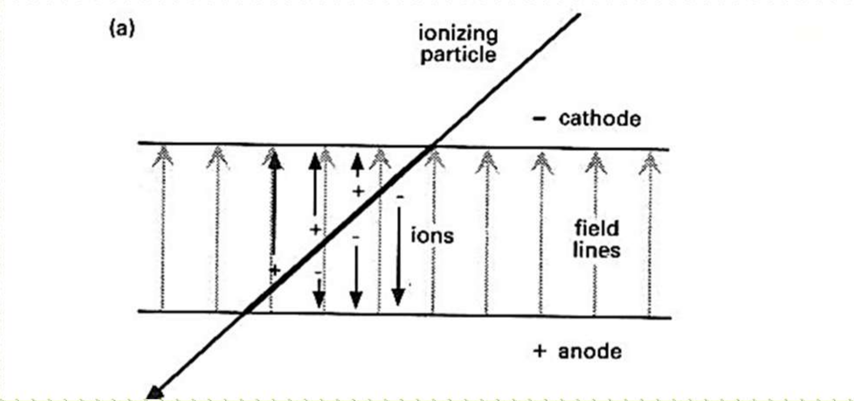


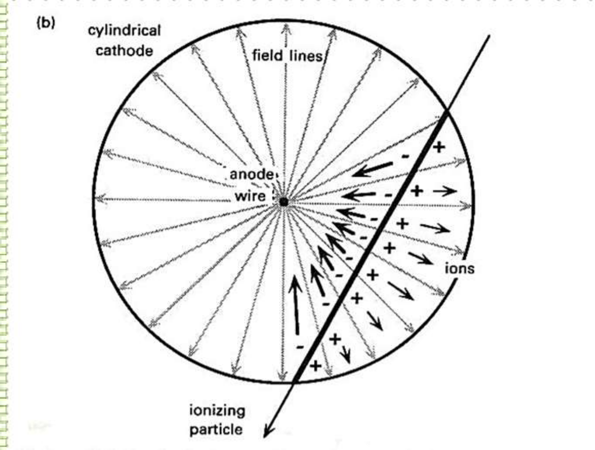
where

- K – $4\pi N_A r_e^2 m_e c^2 = 0.307\,\mathrm{MeV/(g/cm^2)}$;
- N_A – Avogadro number;
- r_e – classical electron radius ($= 2.82\,\mathrm{fm}$);
- $m_e c^2$ – electron rest energy ($= 511\,\mathrm{keV}$);
- z – projectile charge;
- Z, A – target charge and target mass;
- β – projectile velocity ($= v/c$);
- γ – $1/\sqrt{1-\beta^2}$;
- $T_{\max}$ – $\dfrac{2 m_e p^2}{m_0^2 + m_e^2 + 2 m_e E/c^2}$, maximum energy transfer to an electron, m_0—mass of the incident particle, p, E—momentum and total energy of the projectile;
- I – average ionization energy of the target;
- δ – density correction.

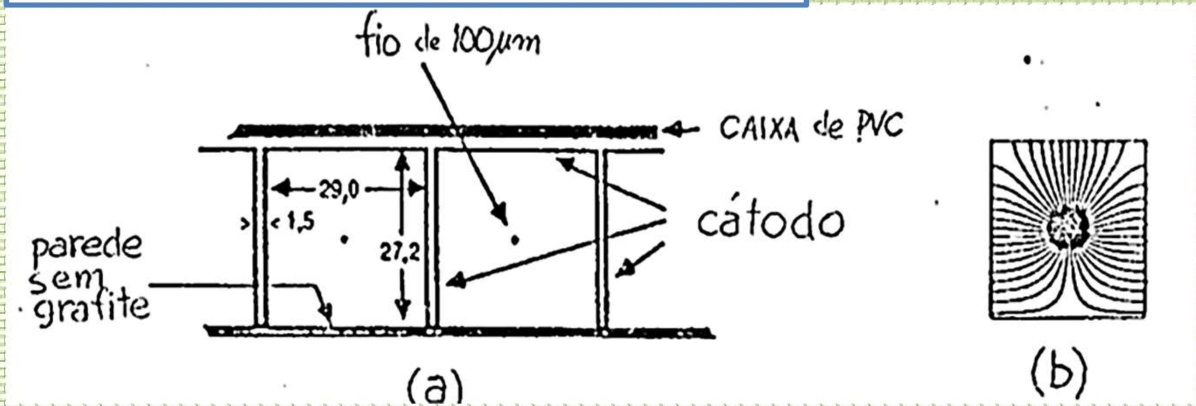
Ionisation and electric field in a gas detector

Resistive Plate Counter (RPC)

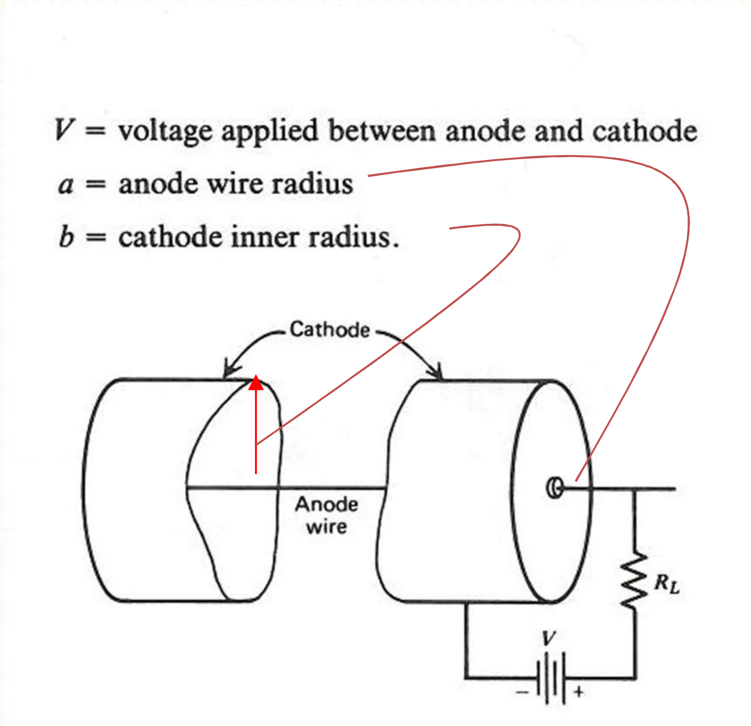


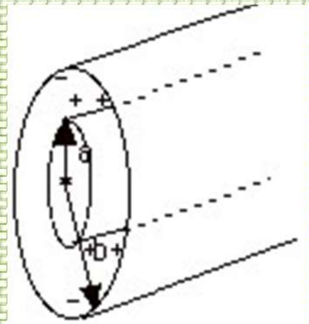


Limited streamer cameras (Iarocci tubes)



Electric field → drift and amplification

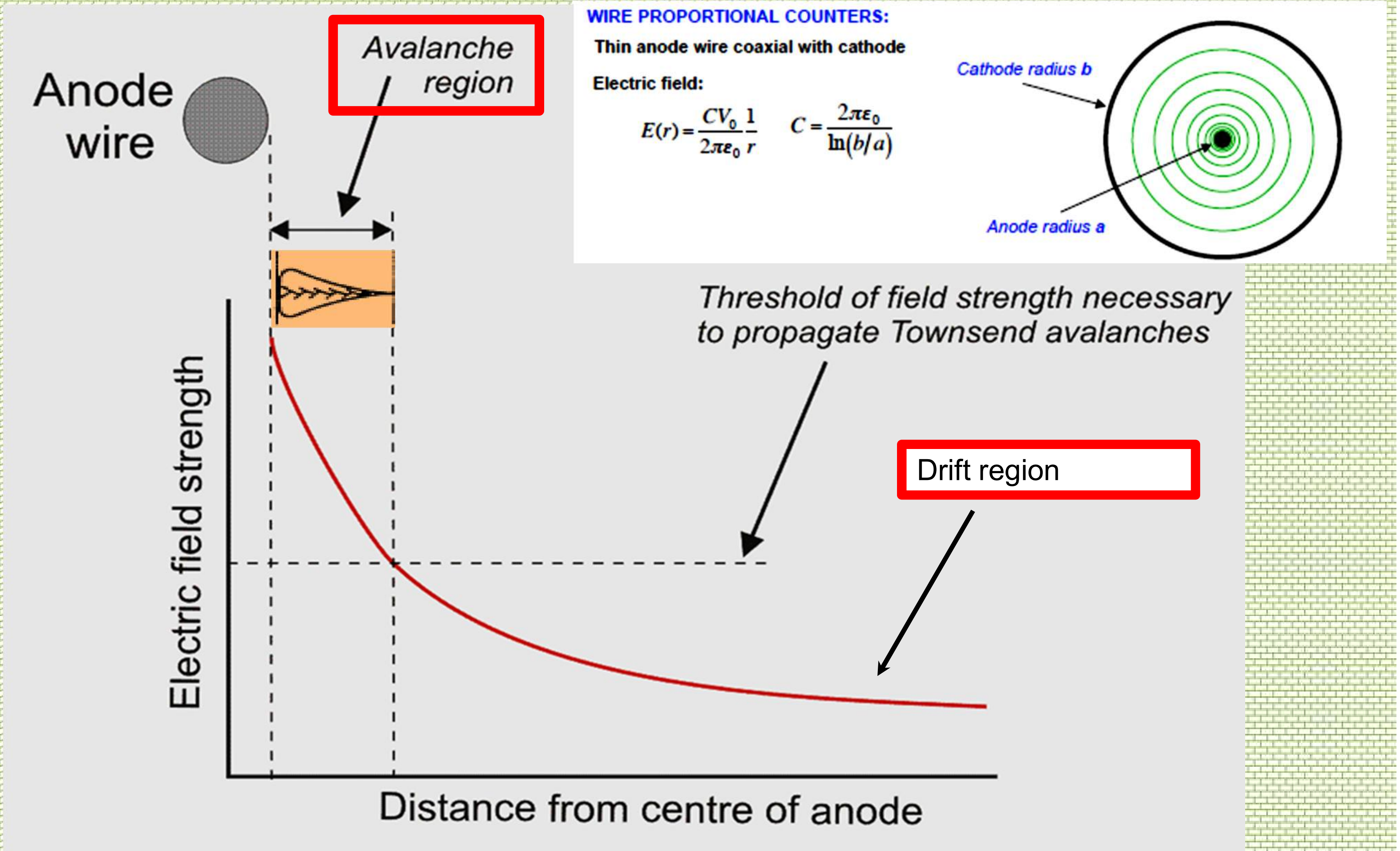




$$\mathscr{E}(r) = \frac{V}{r \ln(b/a)}$$

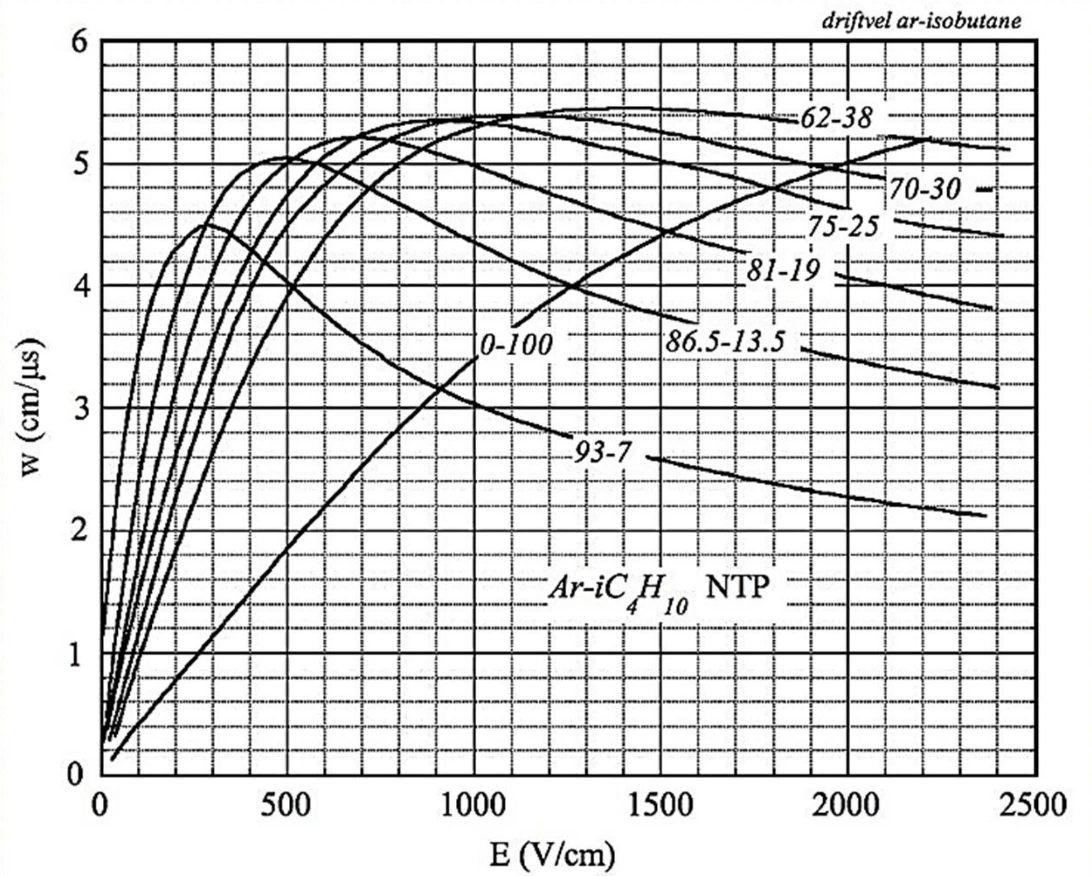
V = 2000Volts
a = 80μm
b = 1cm
E(a)=**5,18 x10⁴** V/cm

Regions: drifting and amplification



Cylindrical geometry easily achieves $E_{threshold}$ ~10^4 V/cm

Electron drift velocity



, Figure 6-9: Electron drift velocity for argon-isobutane mixtures.

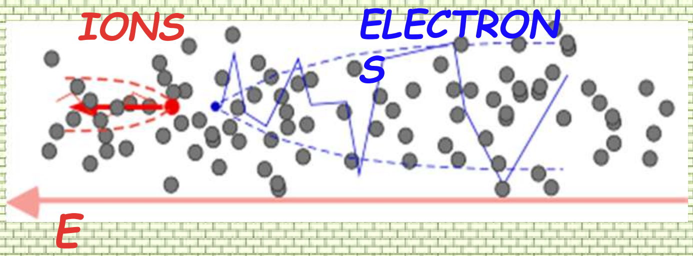
- Depende da mistura gassosa
- Inicialmente aumenta com o campo elérico, mas depois satura
- Para altos ganhos, como streamer limitado esta na região de saturação

A velocidade de arrasto dos íons influencia o tempo morto do detector

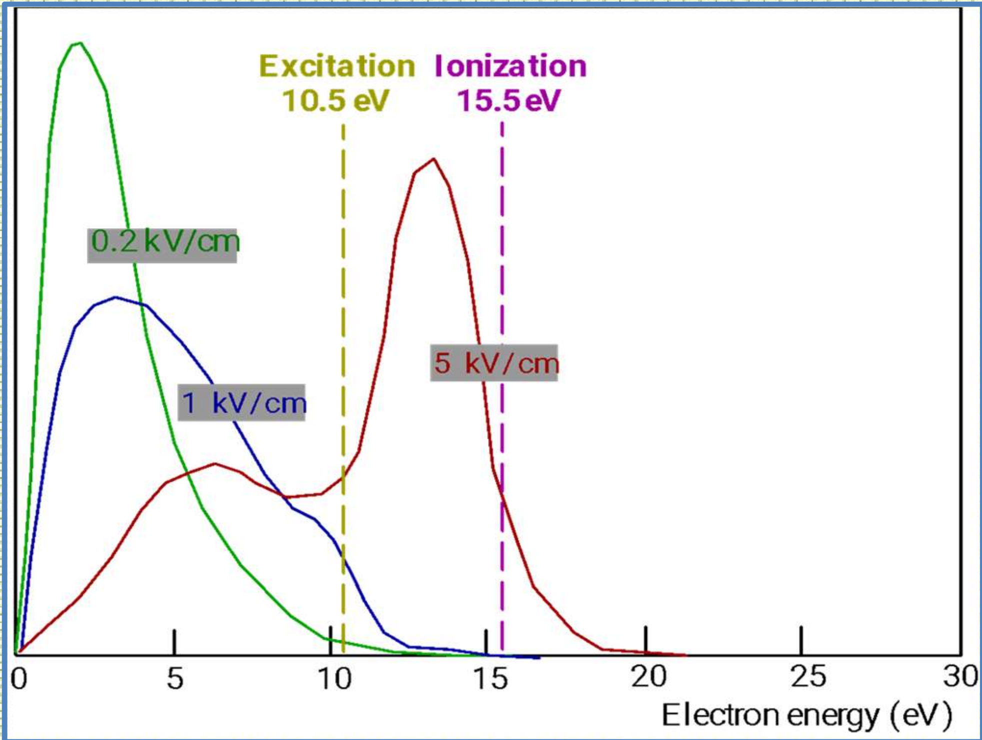
Increasing the field towards charge multiplication

Increasing the field above few kV/cm **electrons accelerate** towards the anode.
If the energy of the electron increases above the first ionization potential of the gas, an additional electron-ion pair is created.

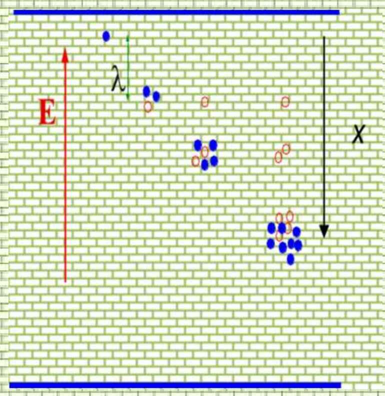
*ELECTRIC FIELD **E > 0**: **CHARGE TRANSPORT AND DIFFUSION***
Movement of the charge along the field direction + multiple collisions with gas molecules

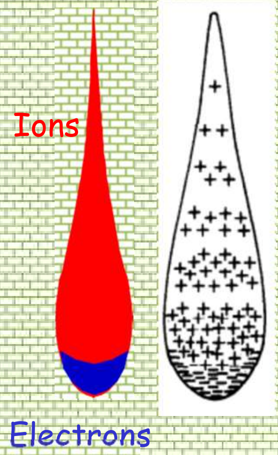


Electrons energy distribution at increasing fields:



Electron arriving at the anode wire: Amplification → avalanche





$$dn = n\,\alpha\,dx$$

$$n(x) = n_0 e^{\alpha x}$$

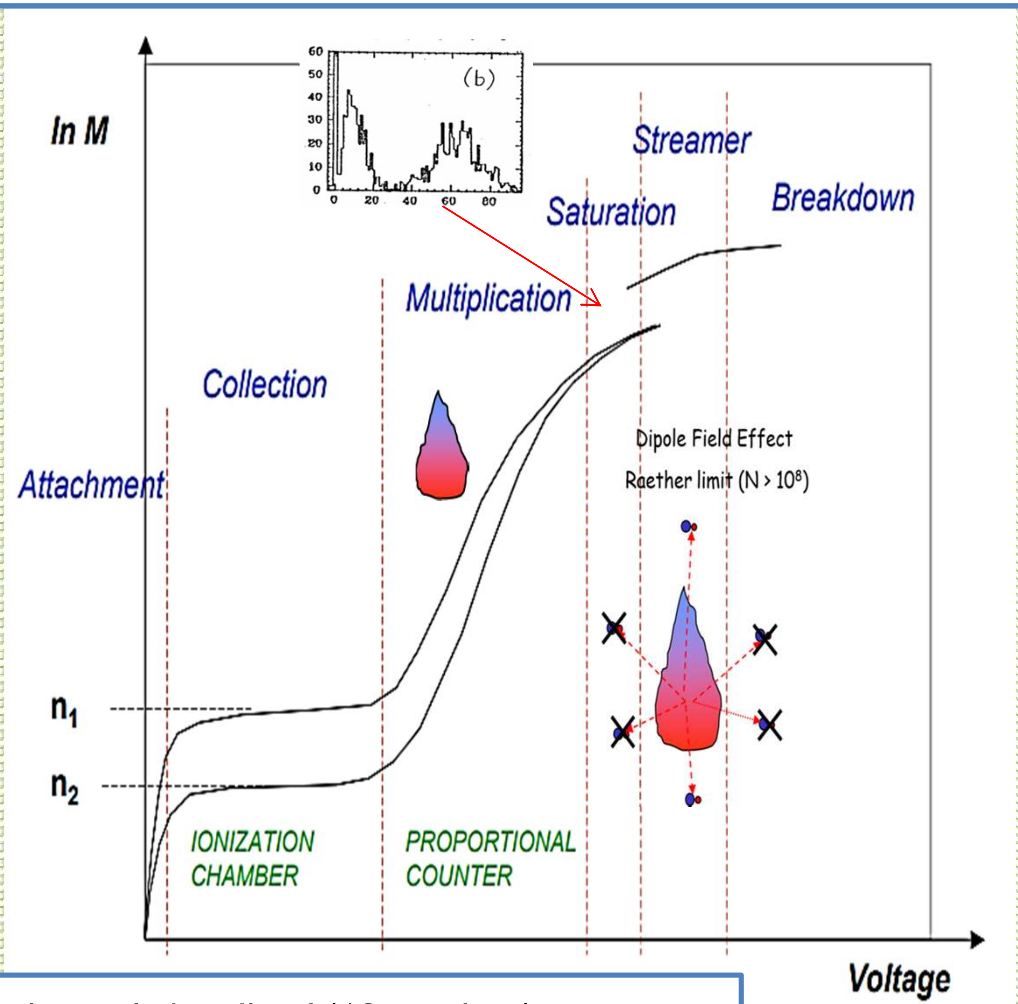
Multiplication factor or Gain

$$M(x) = \frac{n}{n_0} = e^{\alpha x}$$

More generally:

$$M = \int_{x_1}^{x_2} \alpha(x)\,dx$$

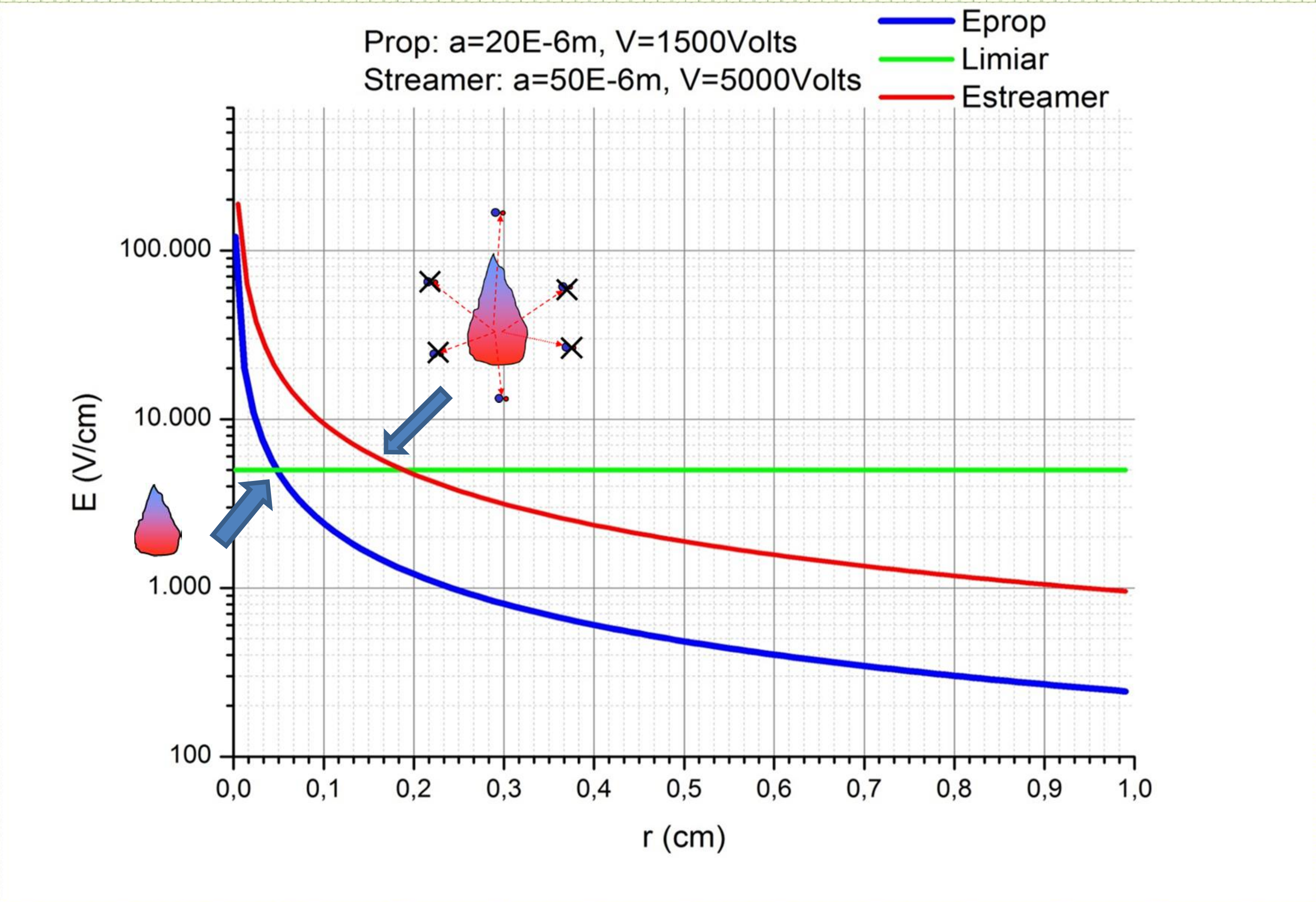
In addition to high voltage, the gas mixture (argon + quenching) and the diameter of the anode wire define the operating mode.



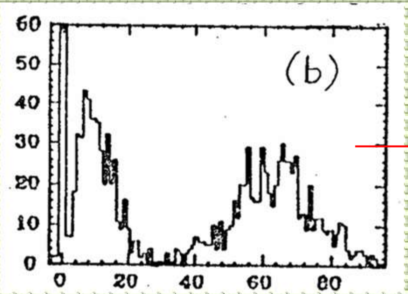
Streamer Limited discharge is localised (12 m tubes)

Proportional, Geiger-Mueller or Streamer?

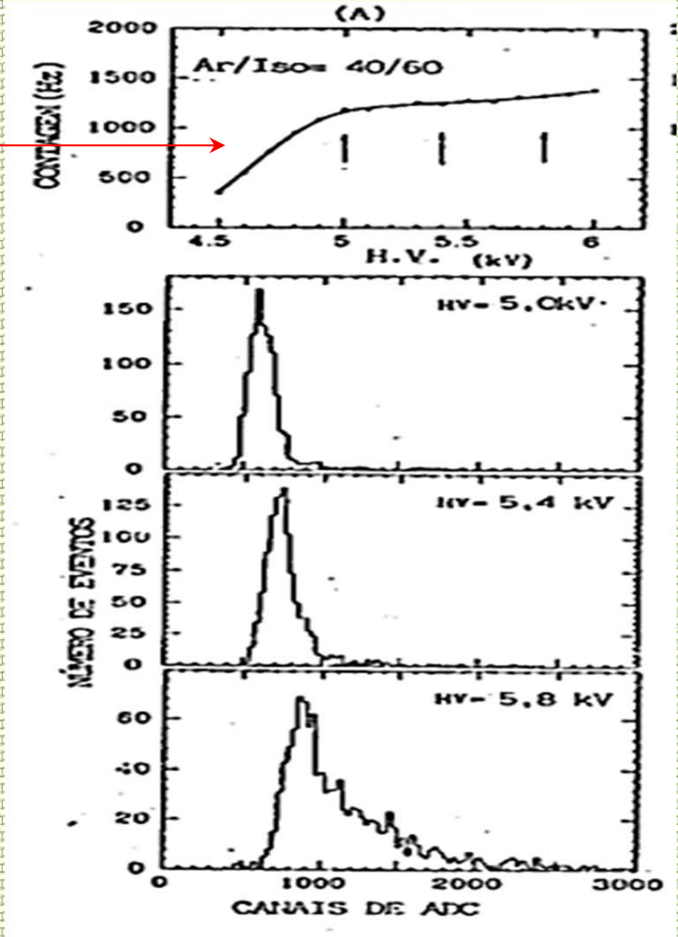
wire diameter, HV, quenching gas

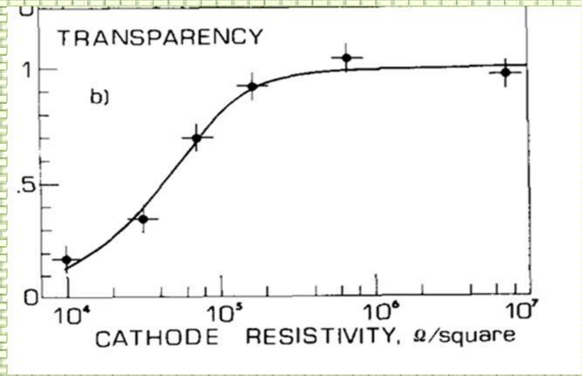


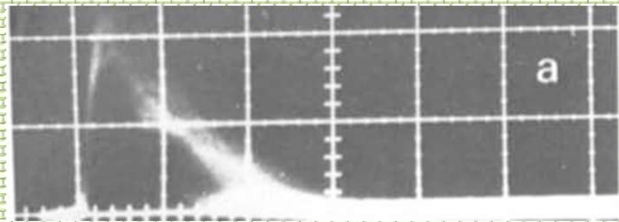
Limited streamer tubes

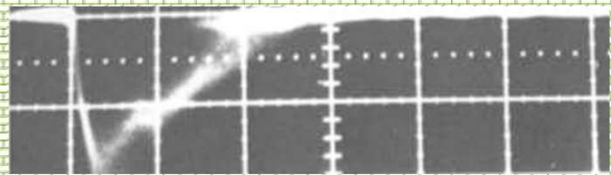


- Pulse → ionising particle
- Large counting platform,
- localised discharge,
- cathode transparency.





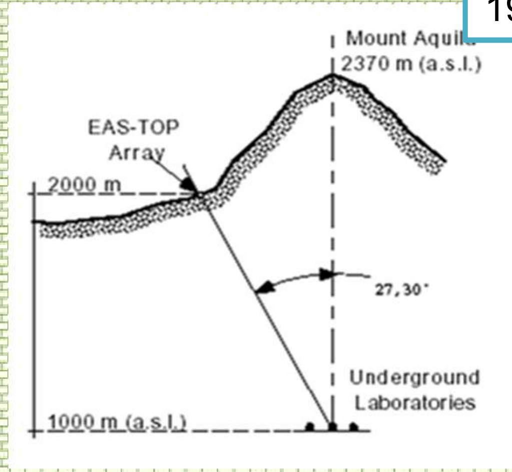




Muon Detector and Hadron Calorimeter

Eas-Top

1989-2002



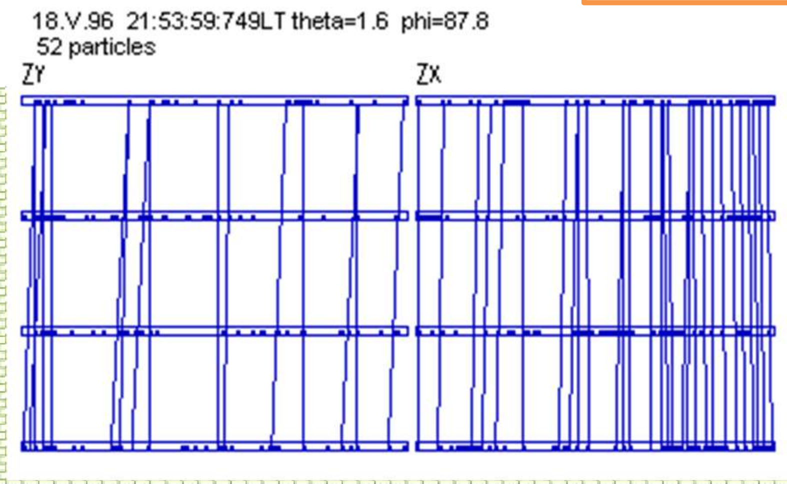
Streamer cameras
e
Proportional chambers

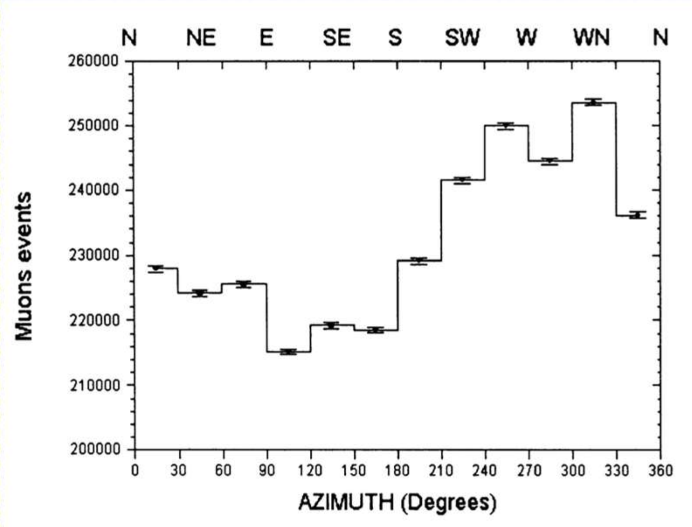
- 12 x 12 x 3 metres
- nine plans
- 2 cam.*streamer*, 1 prop, 13cm Fe
- *streamer*: muon tracking, x (100-micron wires), HV=4650V, 6480 channels
- proportional: 50 micron wire, 40x38cm pads^2, HV=2900 V, 7560 ADC channels (0.03pC/ch)

Eascamp – Detector Central

UNICAMP
512 tubes 3x3 cm² 4.30 m streamer
3 million reconstructed muons

1996-2001

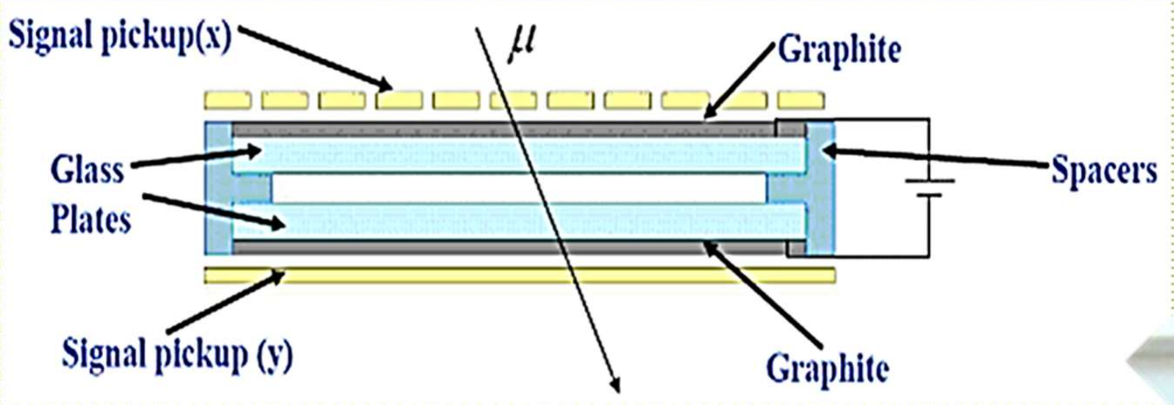




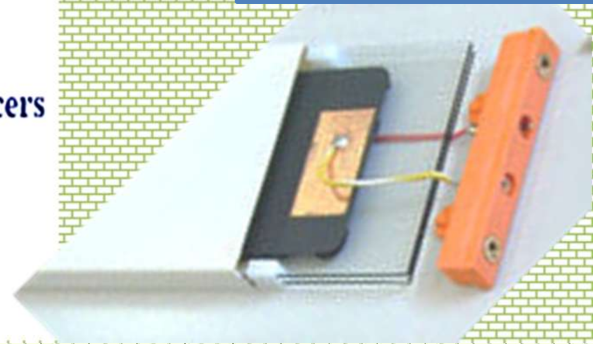
West-East asymmetry of muons: (8.91±0.04)%

Resistive Plate Counter - RPC

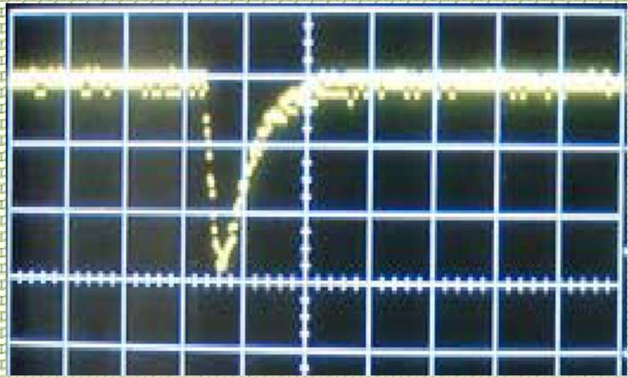
Streamer mode, resistive cathode + time resolution ns



UNICAMP - 1999

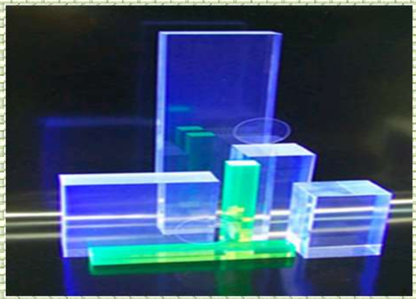


- RPC = trajectography + time measurement
- Resistive electrodes (glass, $\rho \approx 10^{12}$ Ω.cm)
- **Cathode transparent** (graphite coated on glass)
- gap **1mm** (4.4kV)
- Operating in **streamer mode**
- Argon:Isobutane:R134A=68:30:2
- temporal resolution = 4ns @ 4200V, 1nA, *g*ap=1mm
- counting efficiency = 85%

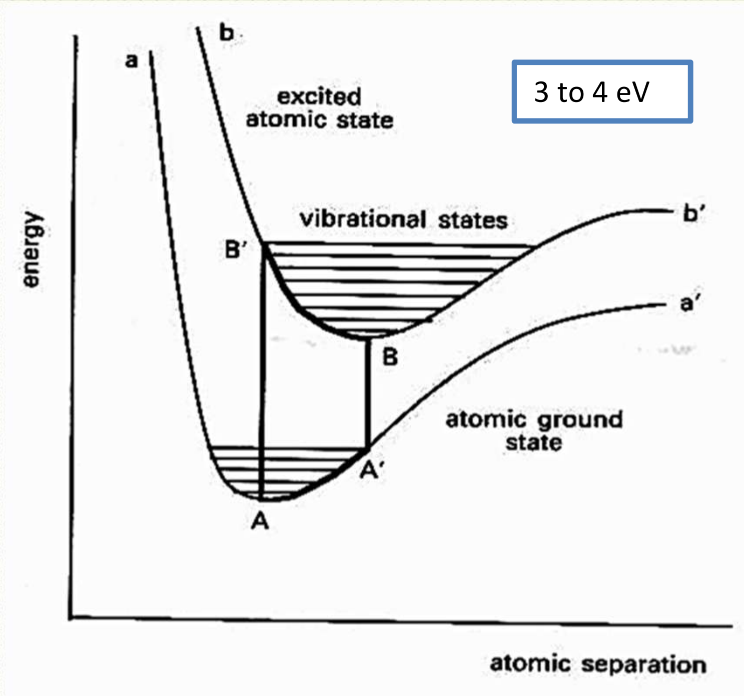


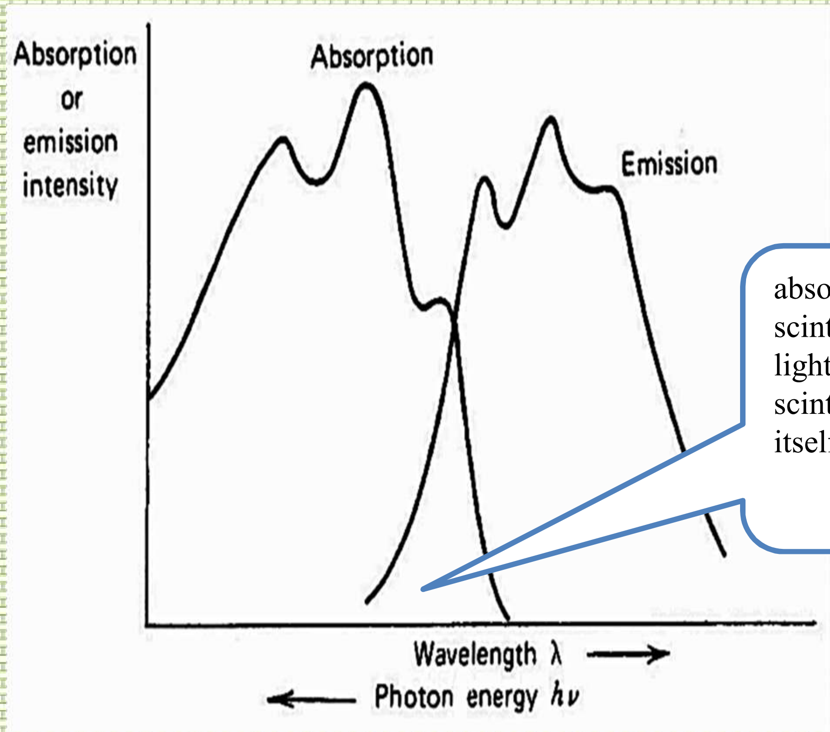
Scale: 50mV:100ns
Gap 1 mm, hv = 4.4 kV

Plastic scintillator



Scintillation of the organic molecule
carbon-based compounds



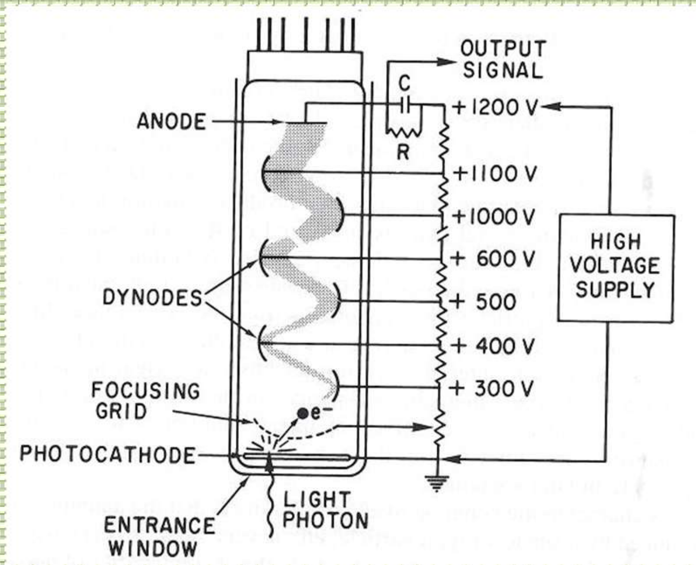


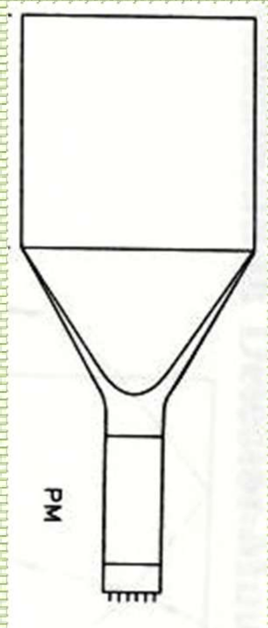
absorption of scintillation light by the scintillator itself

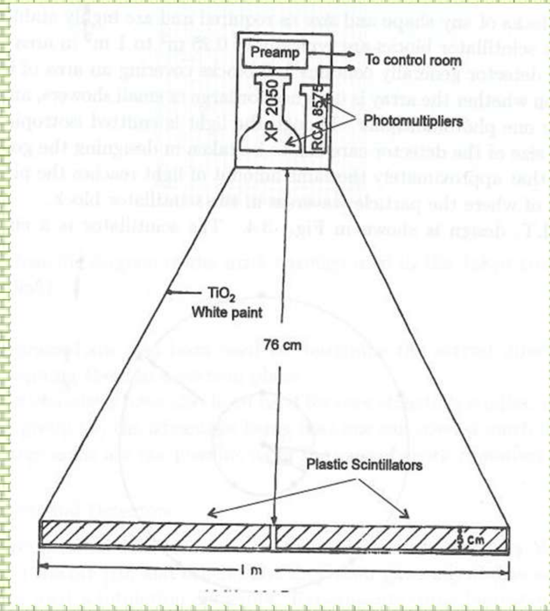
response proportional to the energy deposited and rapid (0.2 ns)

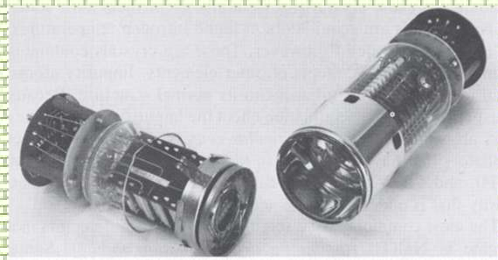
Photomultiplier tubes and light guide

- Converts light into electrons
- and amplifies G ~10^7





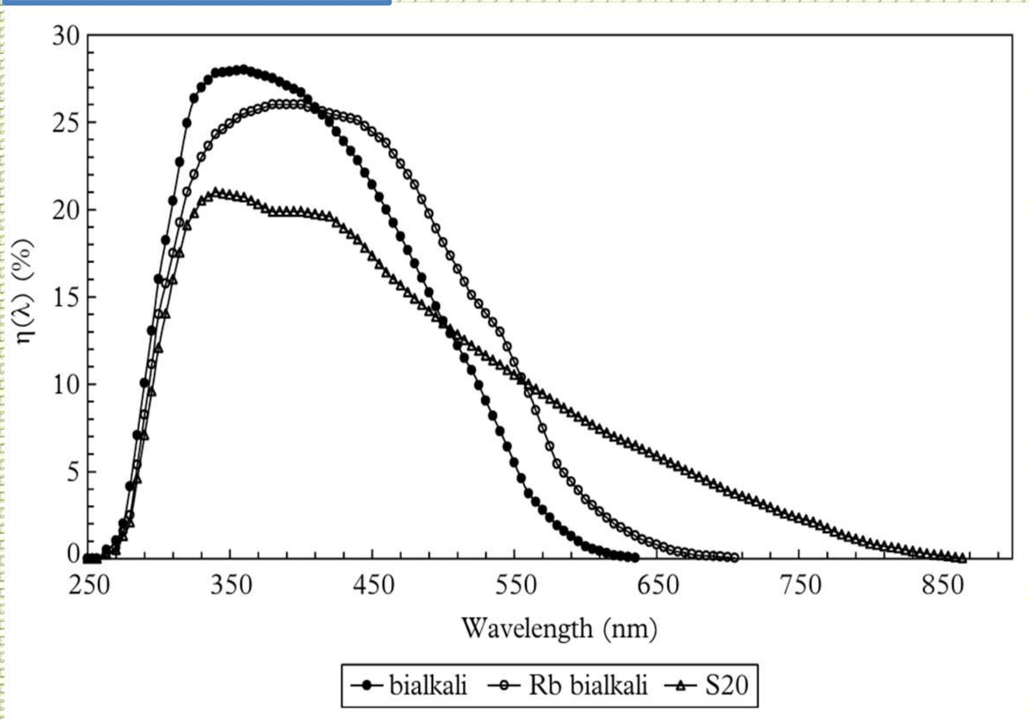




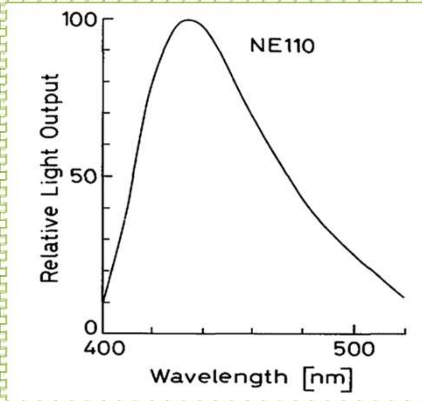
Quantum efficiency of PMT and photon emission by the scintillator

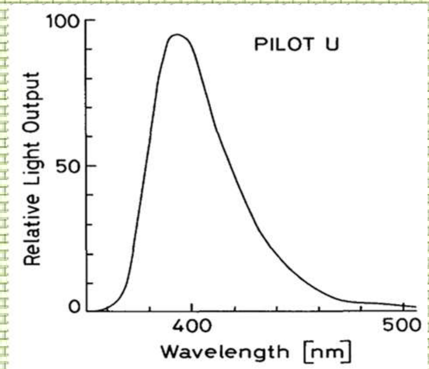
The majority of PMT applications are served by just three photocathode types: bialkali (K2CsSb), rubidium bialkali (Rb2CsSb), and S20 (Na2KSbCs) with spectral responses shown below

Quantum efficiency

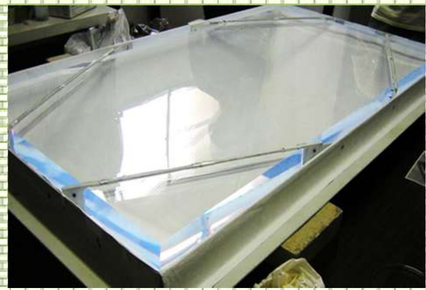


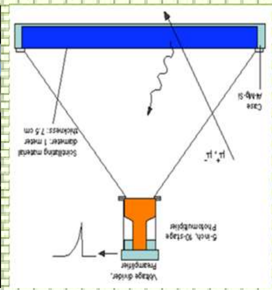
Cintiladores plásticos





Muonca - UNICAMP





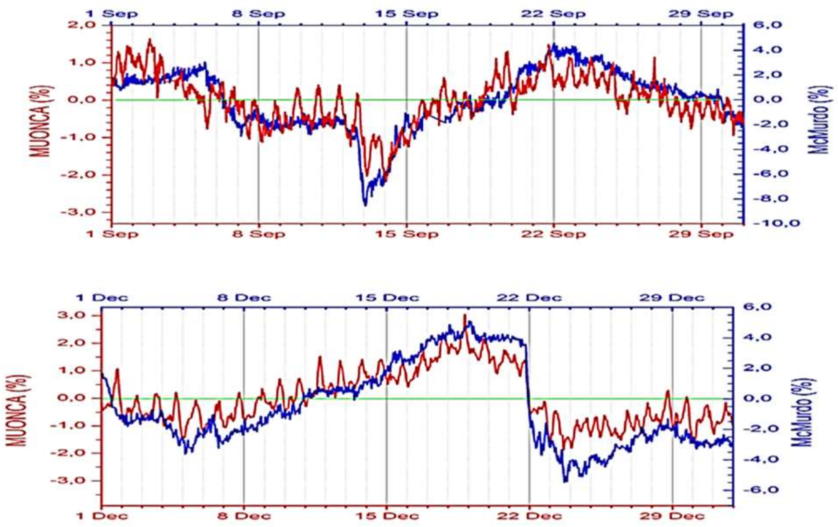
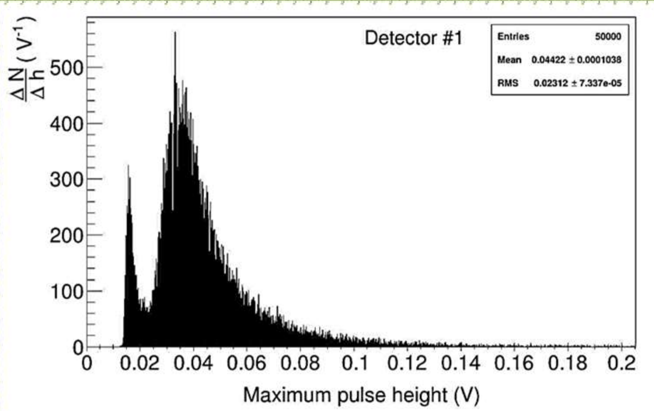


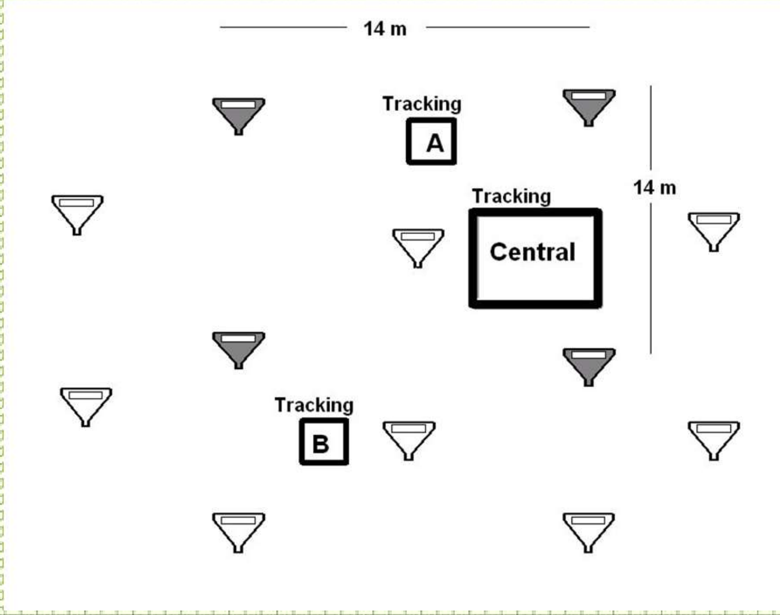
Figure 6: The MUONCA monitor and McMurdo variation percentages, in September (upper) and December 2014 (down).

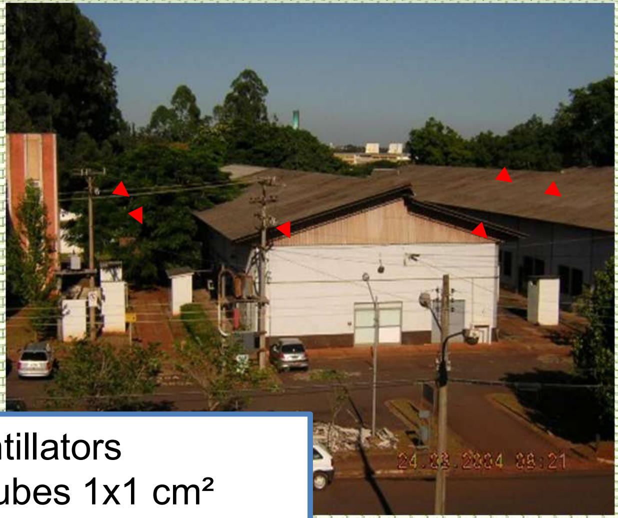


Forbush Decrease detected by Muonca

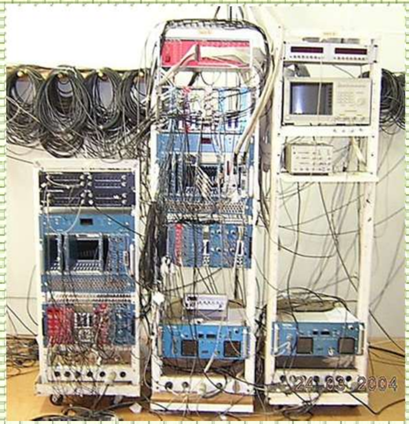
EASCamp - UNICAMP

Unicamp, 1993–2000

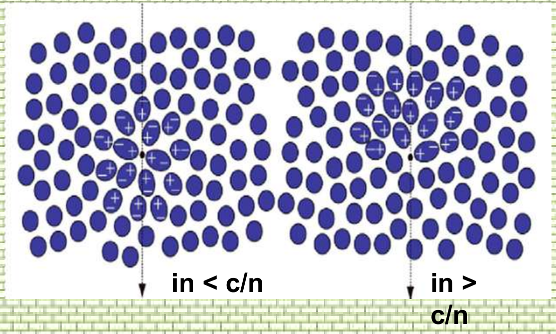


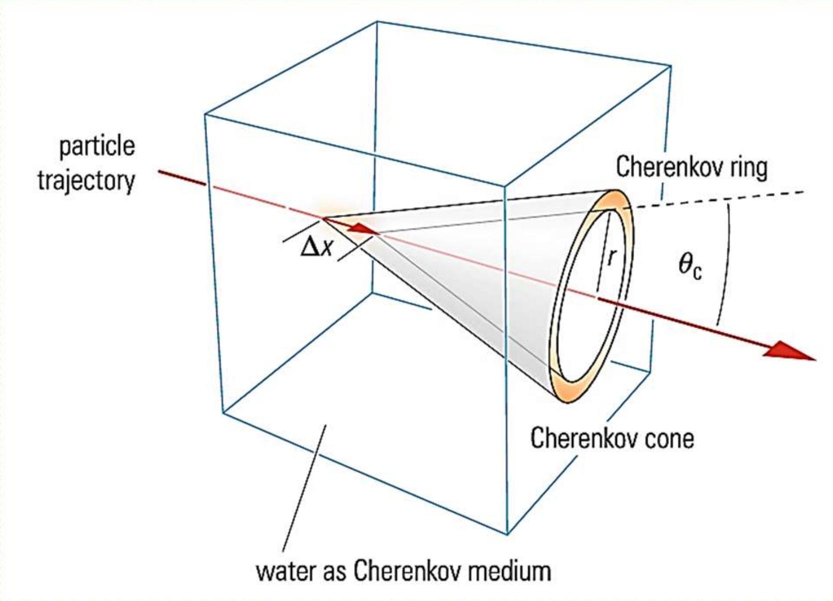


- Plastic scintillators
- Streamer tubes 1x1 cm²
- Streamer tubes 3x3 cm²



Cherenkov radiation





- Radiation emitted by charged particles travelling faster than the speed of light in a transparent dielectric medium.
- The polarisation of the atoms in the medium creates electric dipoles whose temporal variation leads to the emission of radiation.
- Photons generate a cone of light

The energy loss through Cherenkov radiation is small compared to other mechanisms of interaction, it is of the order of 1/1000th of the energy loss by ionization.

Cherenkov radiation

An electrically charged particle travelling through a transparent dielectric medium with refractive index n and velocity **v > c/n** emits Cherenkov radiation.

condition for issuance

$$v > \frac{c}{n} \quad \text{ou} \quad \beta > \frac{1}{n}$$

onde $\beta = v/c$ e n é o índice de refração do meio.

Linear kinetic energy

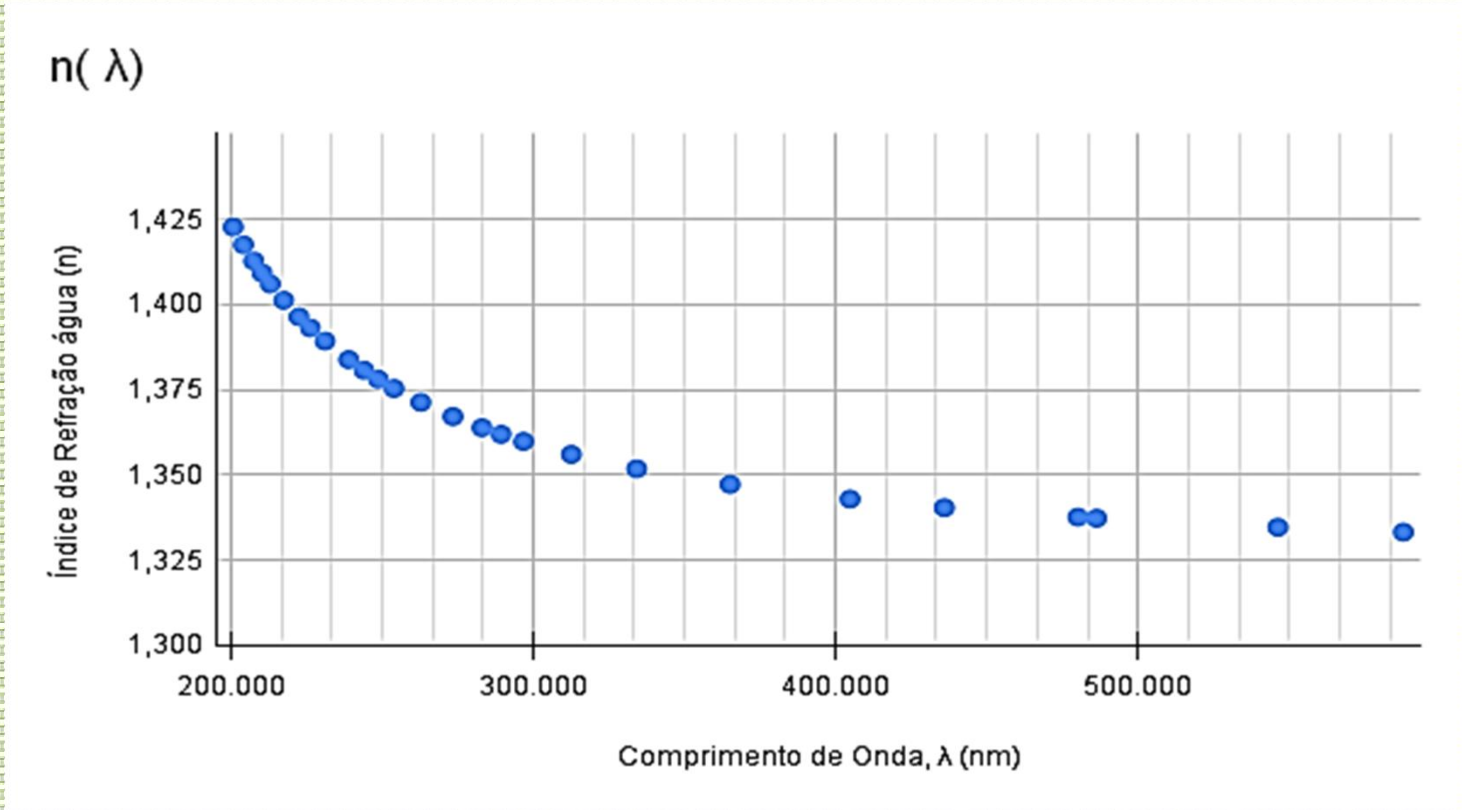
$$K_{\text{th}} = E_{\text{th}} - m_0c^2 = \frac{m_0c^2}{\sqrt{1-\beta_{\text{th}}^2}} - m_0c^2$$

$$\beta_{\text{th}} = 1/n$$

Refractive index of water n=1.33

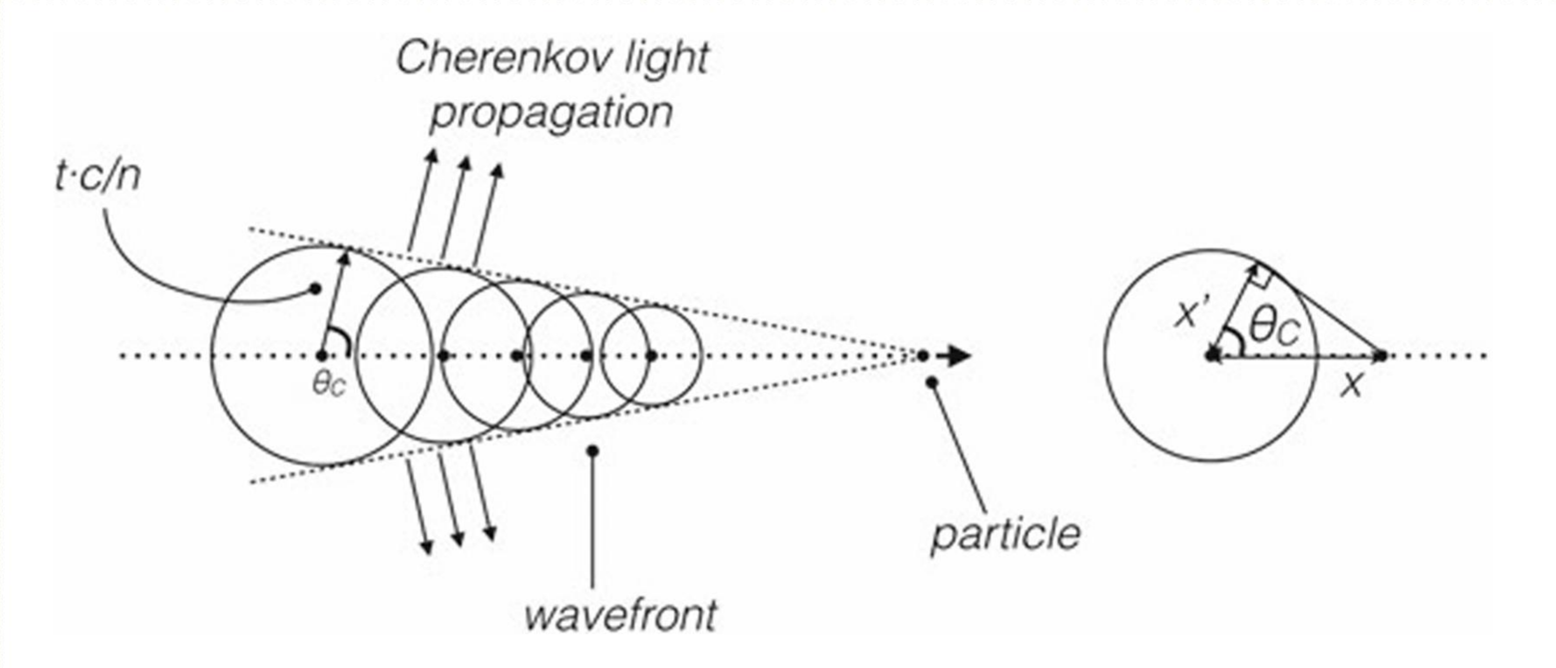
Particular	Massa (MeV)	Energia mínima Cherenkov em água
Elétron / Póstron	0,511	≈ 0,26 MeV
Múon	105,66	≈ 55 MeV
Próton	938,27	≈ 0,49 GeV

n_{water} (λ)



n(λ)
1,425
1,400
1,375
1,350
1,325
1,300
Índice de Refração água (n)
200.000
300.000
400.000
500.000
Comprimento de Onda, λ (nm)

Cherenkov angle



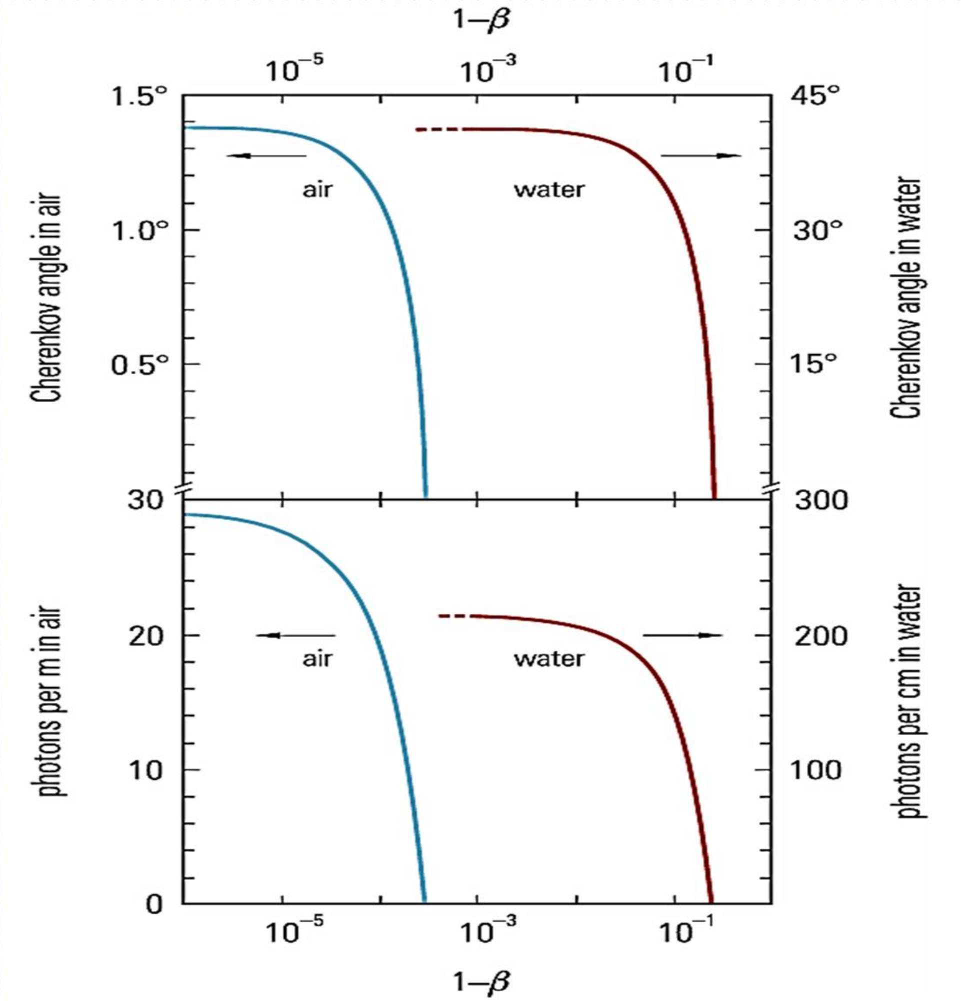
$$\cos\theta_C = \frac{x'}{x} = \frac{ct}{n}\frac{1}{vt} = \frac{1}{\beta n(\nu)}$$

$$\theta_C = \arccos\frac{1}{n\beta}$$

$dN_{photons}/dx$

number of photons produced per centimeter

λ1 = 400nm up to λ2 = 700nm



$$\frac{dN}{dx} = 2\pi\alpha z^2 \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2} \sin^2\theta_C$$
$$\approx 490\, z^2 \sin^2\theta_C\, \mathrm{cm}^{-1}\,.$$

z is the particle's charge

For relativistic particles (β ≈ 1), the Cherenkov angle is 42° in water

In water, around 220 photons per centimeter are produced by a singly charged relativistic particle.

Water-Cherenkov Detectors on the Earth's surface

Objectives for the WCD

- Measure the **flow of charged and relativistic secondary cosmic rays** on the Earth's surface with a WCD, which is predominantly a particle counter.
- **Research activities**
    - flow transients associated with Forbush events
    - flow of muons, electrons and neutrons
    - ratio of positive and negative muon flux decaying
    - measurement of the vertical intensity of muons
    - Compton–Getting effect
    - particle detection techniques using WCD
    - neutron detection with WCD
    - Monte Carlo simulation
        - ARTI-CORSICA
        - Witch-Giant 4
        - South Atlantic Magnetic Anomaly
    - others

- Didactic experimental activities
    - instrumentation for high-energy physics
    - fast, modern electronics (ADC, FPGA, TDC, counters)
    - DAq with scanners
        - code optimisation in C/C++, Julia
        - dead time detector+code
    - detector acceptance and detector efficiency
    - modern physics: muon lifetime
    - barometric correction of secondary cosmic ray flux
    - others

Features of WCD

- Tank size (height 1.5 m, width approx. 70 cm to fit through laboratory doors)
- Installation location (preferably inside the laboratory)
- Lock material (preferably stainless steel)
- Mandatory inner lining (preferably Tyvek)
- Water quality (preferably deionised, resistivity 18 MΩ.cm)

- PMT installation (5" to 9" depending on tank size and water quality + Tyvek)
- Moisture in front-end electronics (voltage divider and HV module)

Arduino for measuring

Humidity and temperature in front-end electronics
barometric pressure, Bosh BMP280 sensor

Data recording

- **Red Pitaya** 2ch ADC 2ch DAC STEMlab 125-14
- GPS or NTP (UTC time)
- What to register?

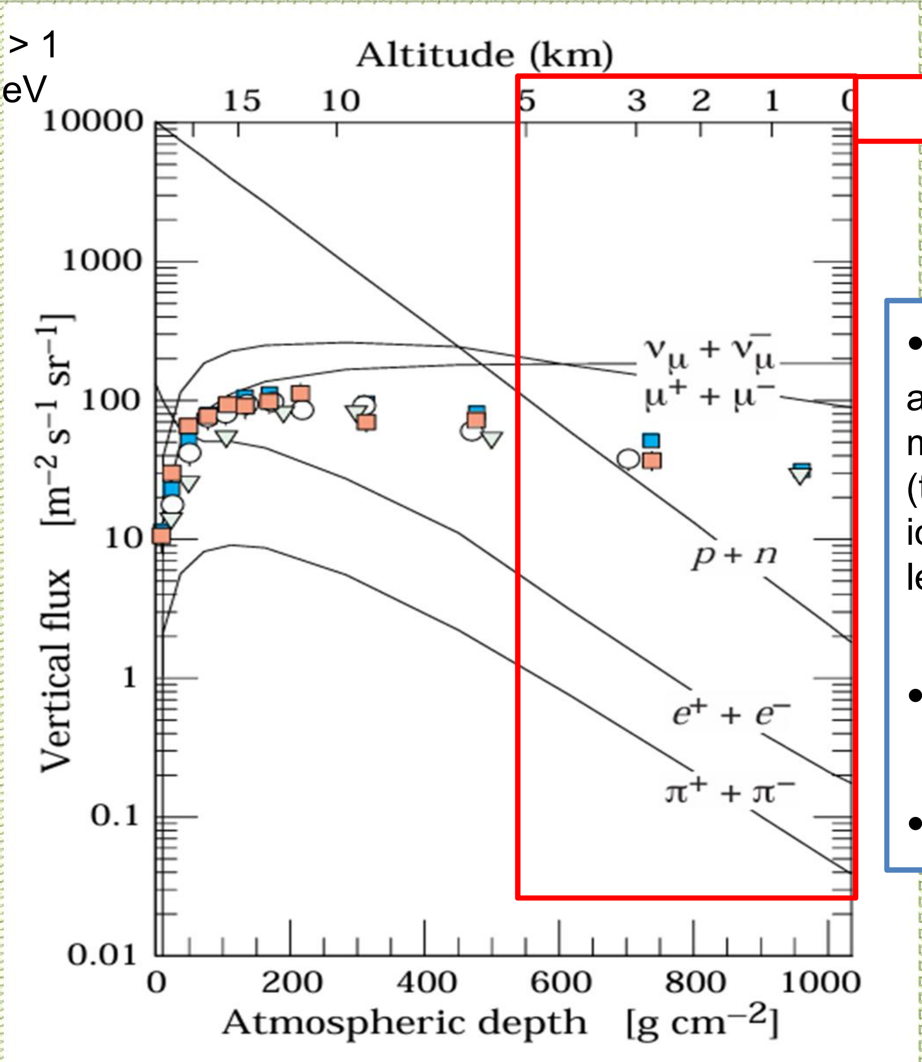
count every N seconds (N depends on the size and altitude, latitude of the WCD)
barometric pressure
hourly register spectrum with approximately 10,000 events

Slow control: humidity, temperature, electrical network

Clean electrical network for the WCD DAq (good grounding and, if possible, independent)

Secondary cosmic rays in the WCD

E > 1 GeV



Single detector at Earth's surface

LAGO's **Single** Water Cherenkov Detectors

- Múons

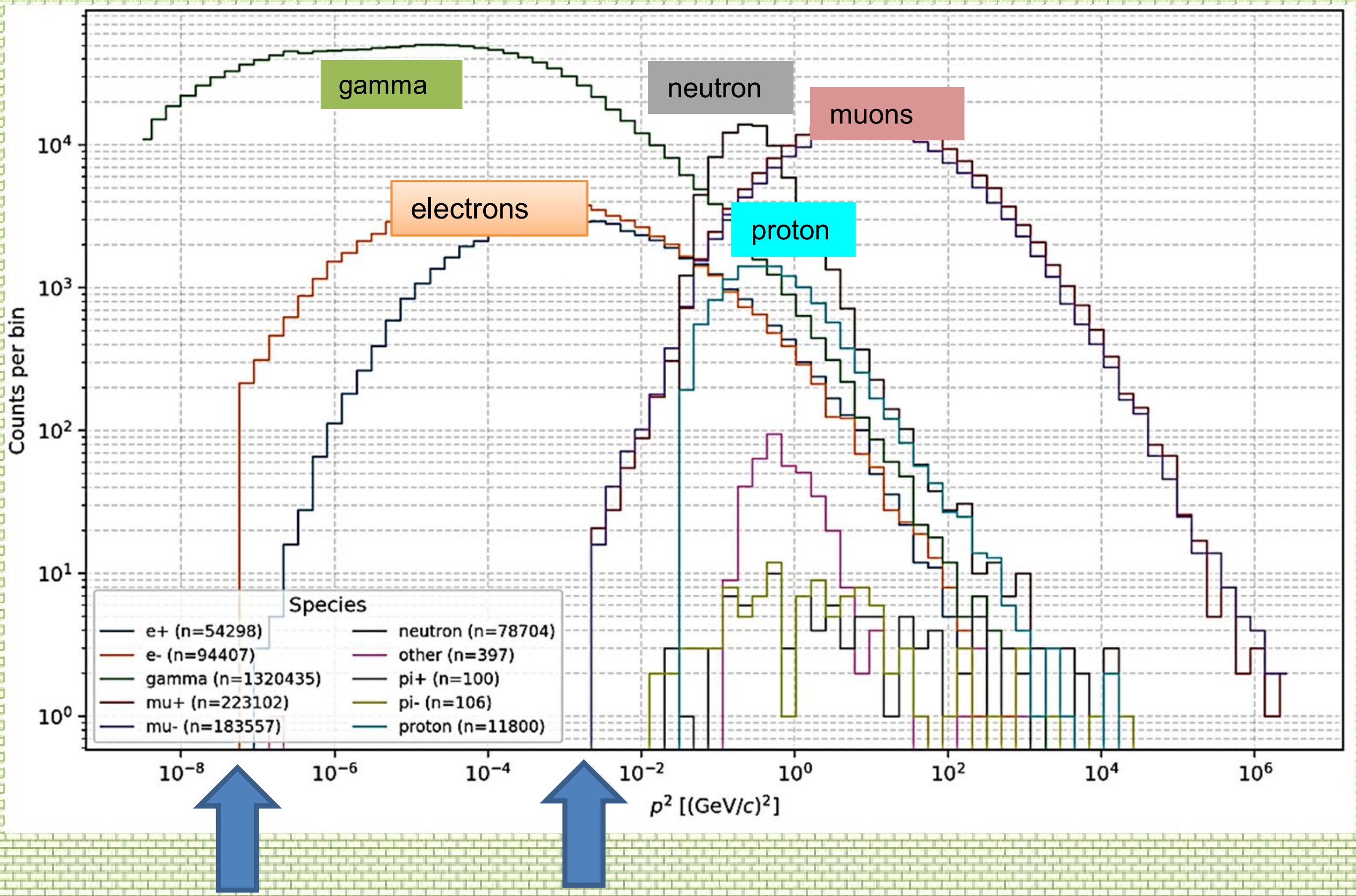
are the most numerous charged particles. Most muons are produced high in the atmosphere (typically 15 km) and lose about 2 GeV to ionization before reaching the ground at sea level.

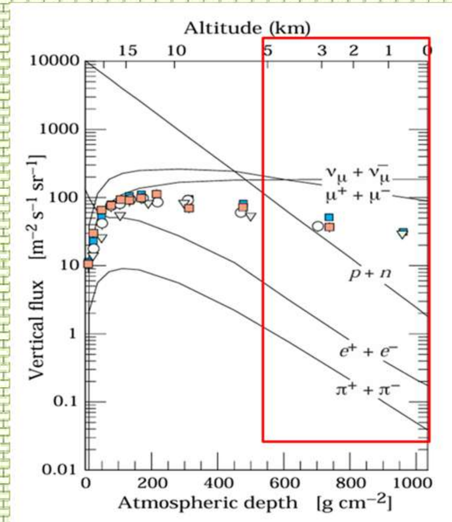
- Protons, neutrons

- Electrons, positrons

Arti - Tanca

Sarmiento-Cano, C., Suárez-Durán, M., Calderón-Ardila, R. et al. The ARTI framework: cosmic rays atmospheric background simulations. Eur. Phys. J. C 82, 1019 (2022). https://doi.org/10.1140/epjc/s10052-022-10883-z

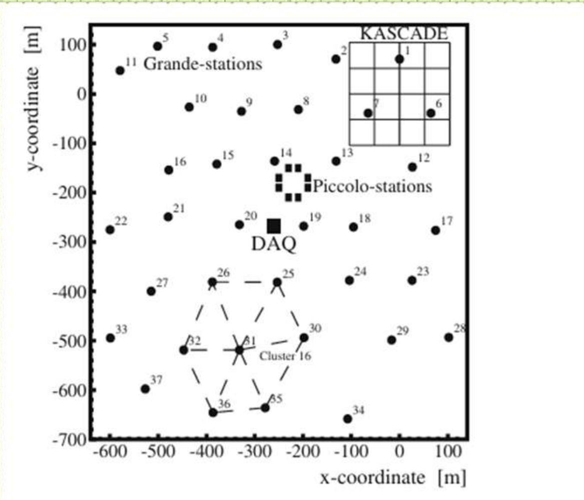




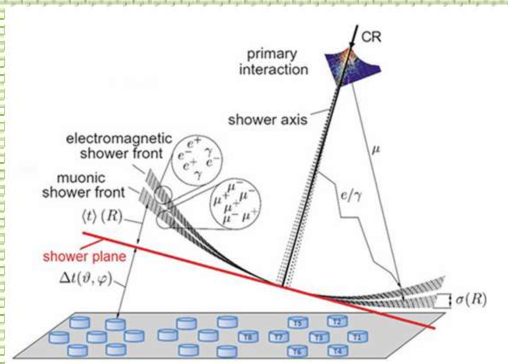
Threshold to generate Cherenkov radiation in water

Triggering experiments on the Earth's surface

Trigger:
temporal coincidence of the pulse of N detectors.
EAS detector



ure 1. The arrangement of the KASCADE-Grande detectors



Trigger:
Temporal coincidence of two overlapping detectors.
Muon detector

Trigger:
All pulses above a discrimination threshold.
Single particle detector

Energia mínima para gerar radiação Cherenkov

A radiação Cherenkov é emitida por uma partícula carregada quando ela se move em um meio dielétrico com uma velocidade (*v*) maior do que a velocidade da luz nesse meio (c/n). A condição para a emissão é:

$$v > \frac{c}{n} \quad \text{ou} \quad \beta > \frac{1}{n}$$

onde $\beta = v/c$ e n é o índice de refração do meio.

$$K_{\text{th}} = E_{\text{th}} - m_0c^2 = \frac{m_0c^2}{\sqrt{1-\beta_{\text{th}}^2}} - m_0c^2$$

Para a água, o índice de refração é tipicamente n ~ 1,33

$$K_{\text{th}} = m_0c^2\left(\frac{1}{\sqrt{1-1/n^2}} - 1\right)$$

$$P_{\text{th}} = \frac{m_0c}{\sqrt{1-\beta_{\text{th}}^2}}\beta_{\text{th}} = m_0c\frac{1}{\sqrt{n^2-1}}$$

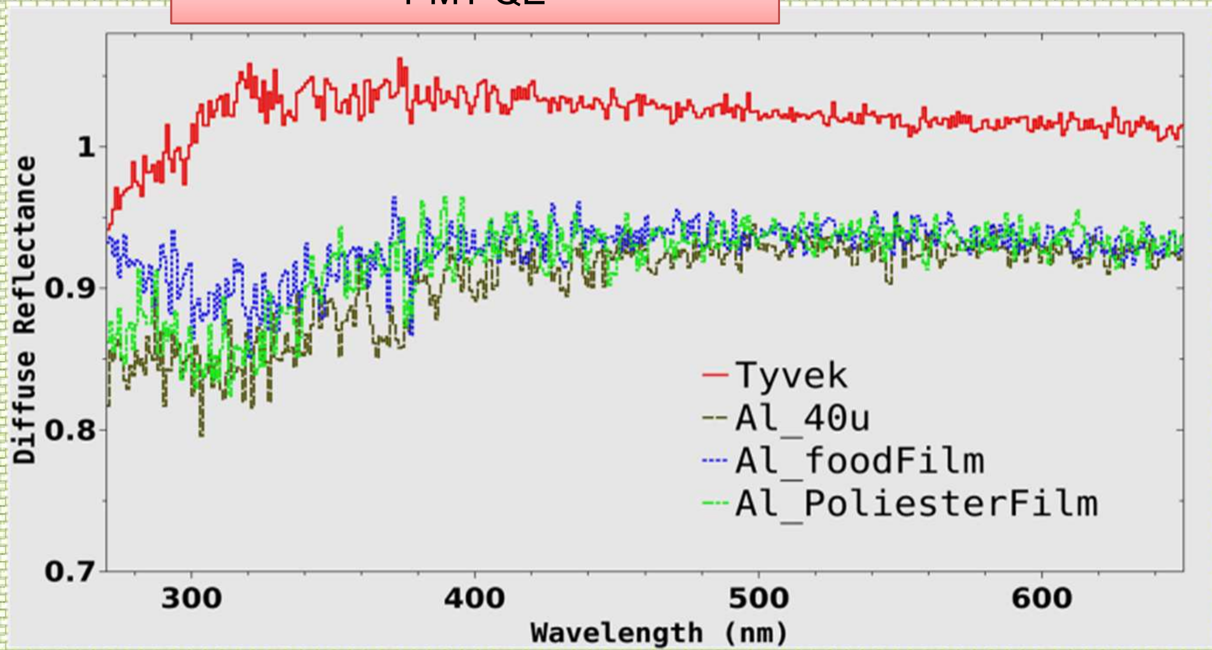
Para radiação Cherenkov em água temos:

Partícula	Energia de Repouso m_0c^2	**K_{th} (MeV)**	P_{th} (GeV/c)
Elétron / Pósitron	0,511 MeV	**0,264**	0,000440
Múon	105,7 MeV	**54,5**	0,0911
Próton	938,3 MeV	**484,8**	0,8088

Internal lining with Tyvek

- Cherenkov photons are produced in the downward direction.
- The PMT is located at the top and needs to receive a sufficient number of Cherenkov photons in order to obtain a charge (or amplitude) spectrum that shows the muon peak.
- It is essential that Tyvek be used so that these photons reach the PMT.

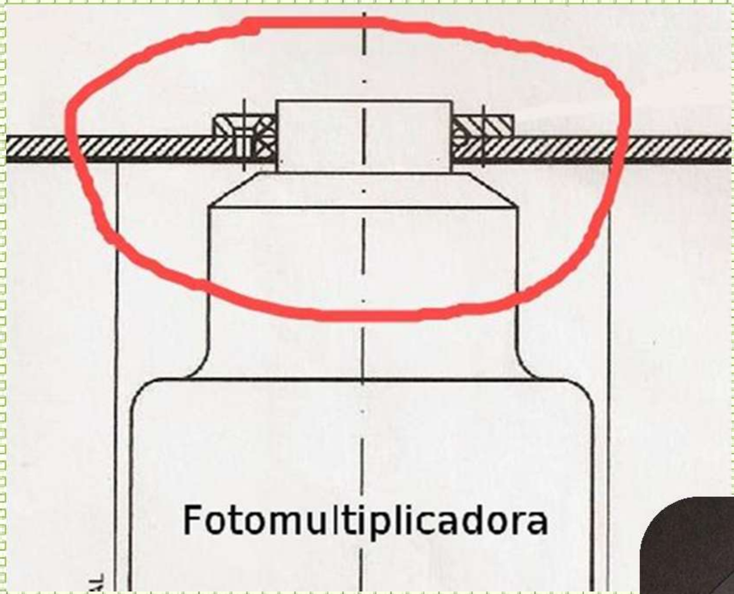
PMT QE

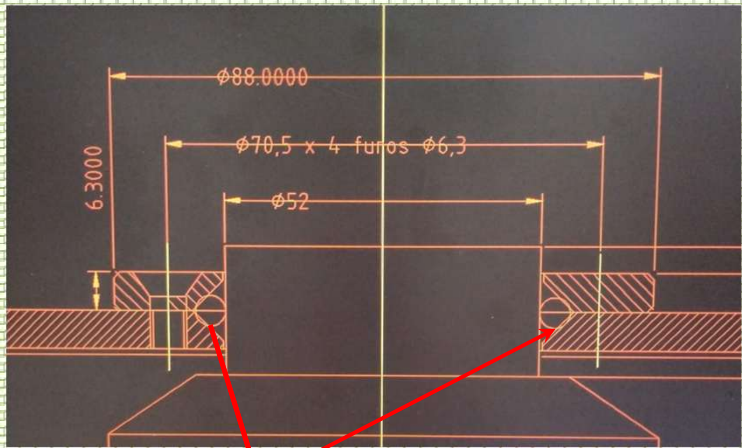


https://doi.org/10.1016/S0920-5632(99)00300-X

PMT-HV-Humidity

- The solution depends on the tank model and installation location.
- Waterproof connectors are expensive, difficult to purchase, and have a limited number of wires.
- If the PMT has a plastic socket, it is possible to have a part that leaves the PMT connectors outside the tank.

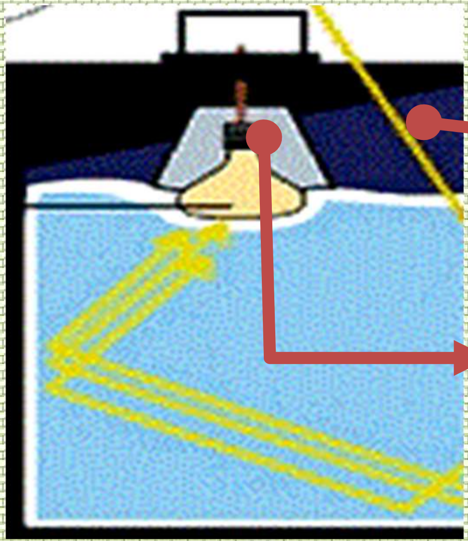


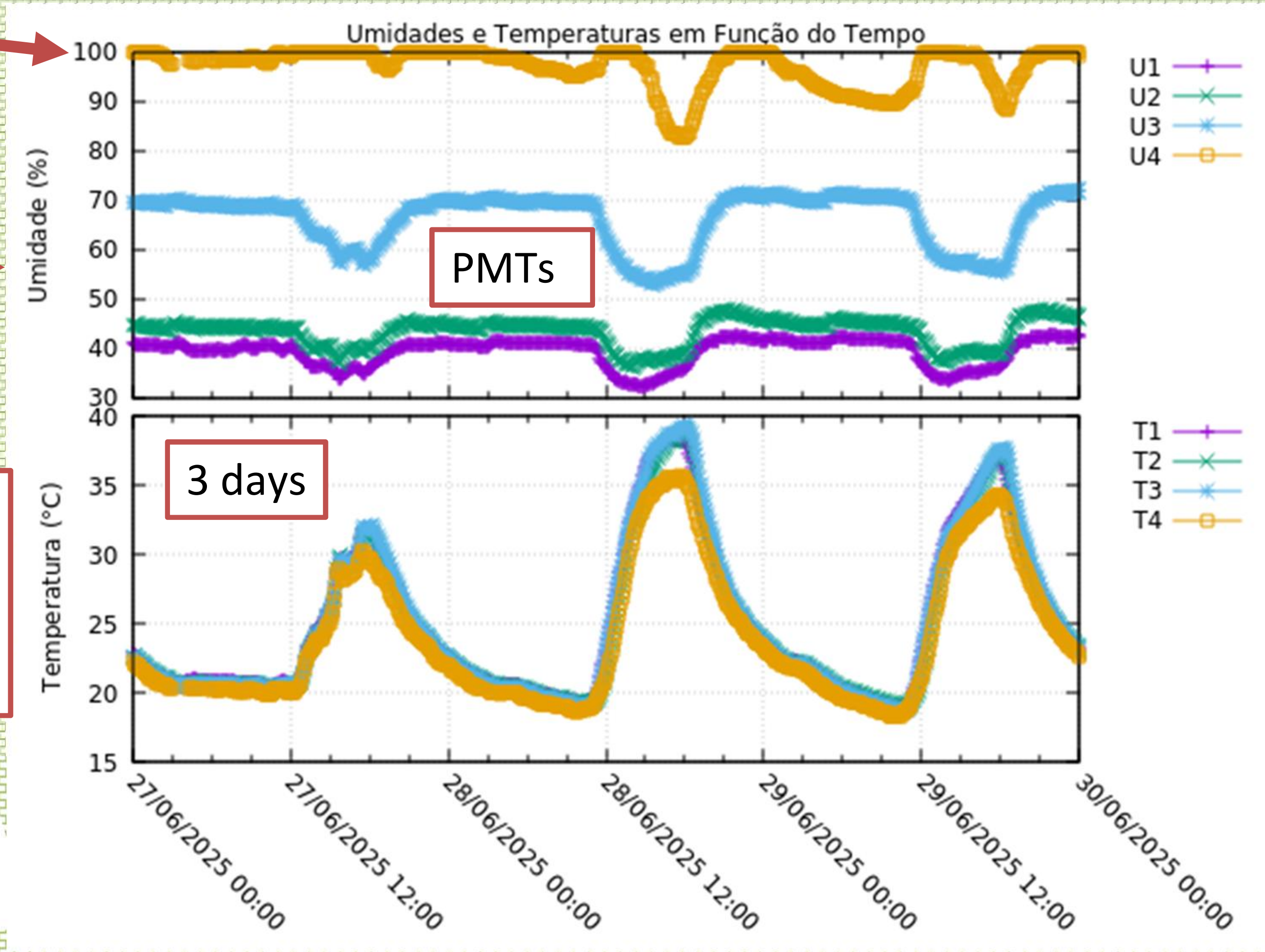


O-ring

Slow control: humidity and temperature

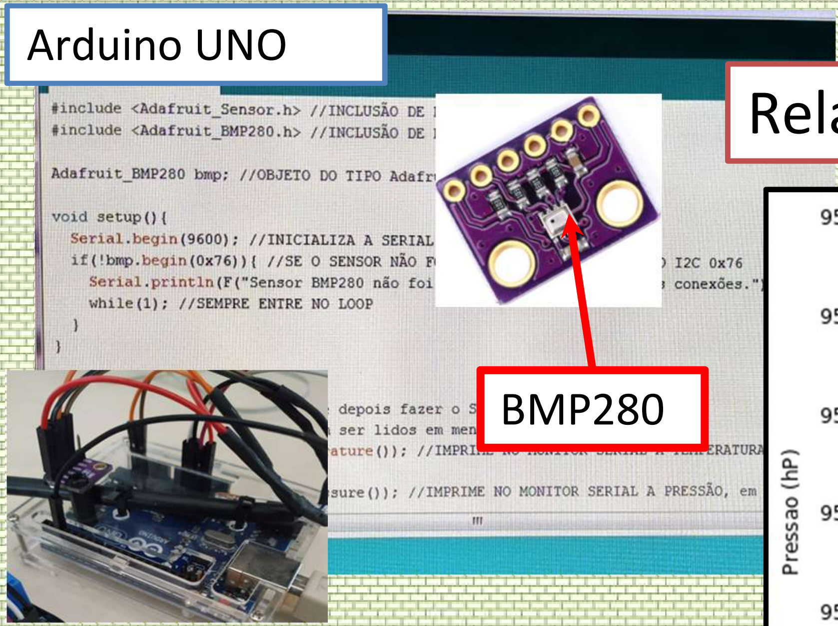
AM2302 DHT22
temperature and humidity



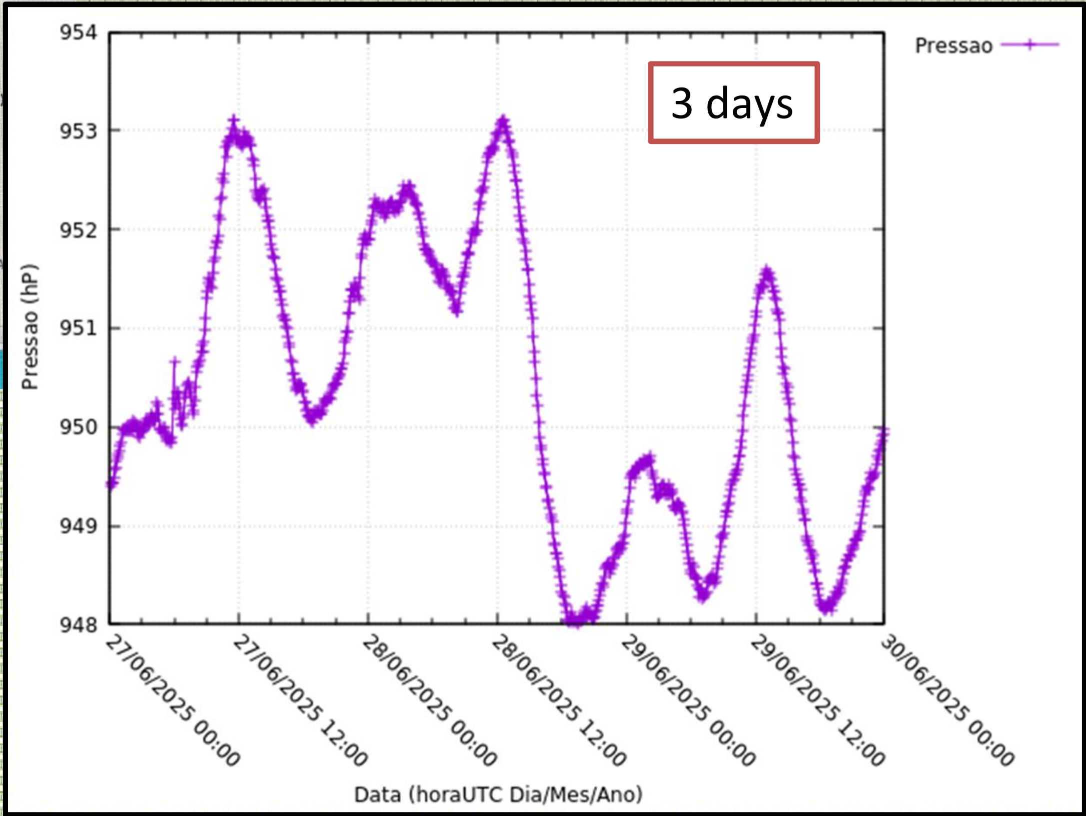


3 humidity sensors inside the cauldron and 1 outsid it, but inside Tanca

Barometric pressure



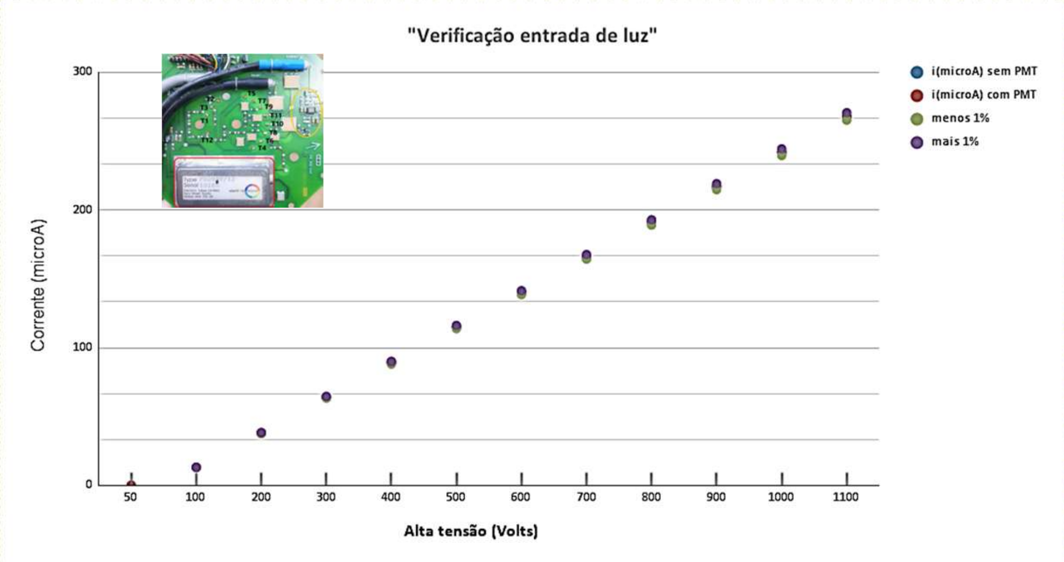
Relative accuracy pressure: ±0.12 hPA



- C/C++ codigo, Ttree ROOT
- ou Python read USB port and write ASCI file

External light input verification

- PMT burns out if it is under high voltage and exposed to many photons, even a hole imperceptible to the naked eye!
- HV sources with current control, which protect the PMT, are very expensive.
- Currently, 4W, 2000V HV modules are used.
- Before use the PMT:
- Disconnect the PMT from the front end (voltage divider) and plot the current (V) curve. If you do not have a HV source that allows this measurement with an accuracy of ~ 10 μA, **carefully** assemble a box to use a multimeter in series.



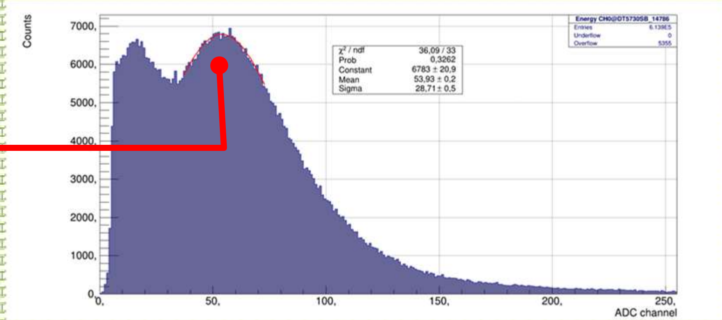
I(hv) curve for:

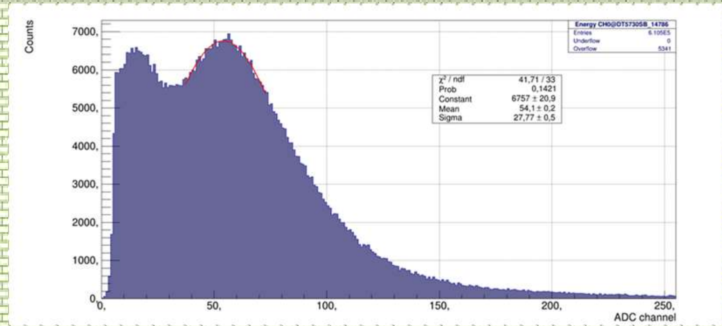
- Divider without PMT
- Divider with PMT

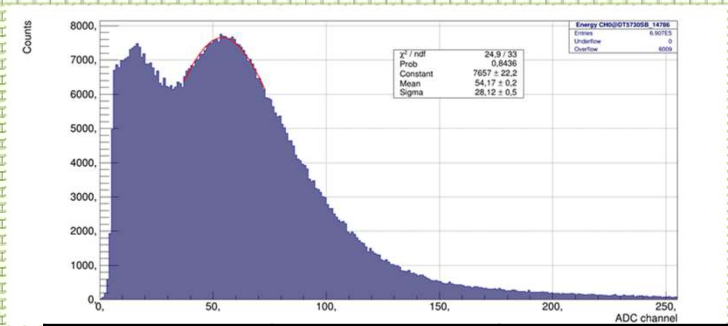
- **The current with PMT should not exceed ~1% of the current value without PMT.**

Muon peak

- If it is only a PMT, it is essential to obtain the muon peak.
- Measure noise (2 to 10 mV/50Ω) with an oscilloscope.
- Discrimination threshold of 15 mV
- Perform several charge spectra until you obtain the muon peak.
- BE CAREFUL not to burn the PMT
- Check beforehand that no light is entering the tank!
- Every month, take a spectrum of the muon peak. It shows if the water and other components of the experiment are good.







PMT1	PMT2	PMT3
998 V	1050 V	1130 V

Daq-electrical network-no break

- Notebook computer (does not interrupt acquisition during short power outages)
- **No break** to protect against transients and maintain acquisition in the eventual short power interruptions.

- Digitizer, preferably Red Pitaya (see Denis' presentation)

What to register?

- Counts every 30 or 60 seconds, timestamp in UTC and Epoch Time

Recording all waveforms requires a lot of hard disk space and backups.
Waveforms are necessary for:

- Measurement of the mean lifetime of the muon
- More detailed study of Forbush events
- Study to identify components of local cosmic radiation
- However, the code may have the option to record waveforms when desired.
- Advance warning (e-mail) of magnetic storms can be obtained from lists on NASA and other websites.

Forbush observed by neutron and muon detector

https://www.nmdb.eu/

- All Forbush events observed with WCD are also observed by neutron monitors.
- The reverse is not true.
- The barometric coefficient of muons is much smaller than that of neutrons. It is possible to observe relatively intense Forbushes in the WCD without barometric correction.

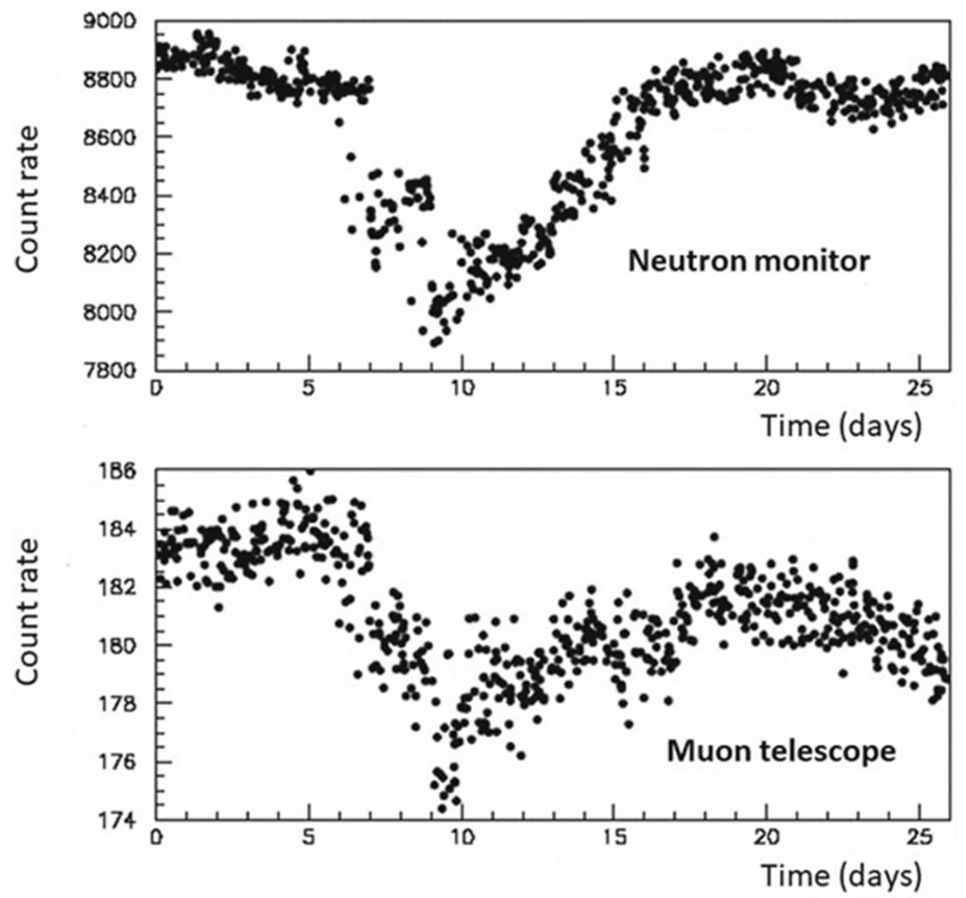
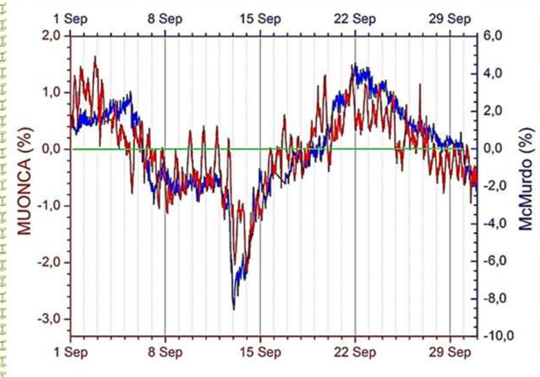
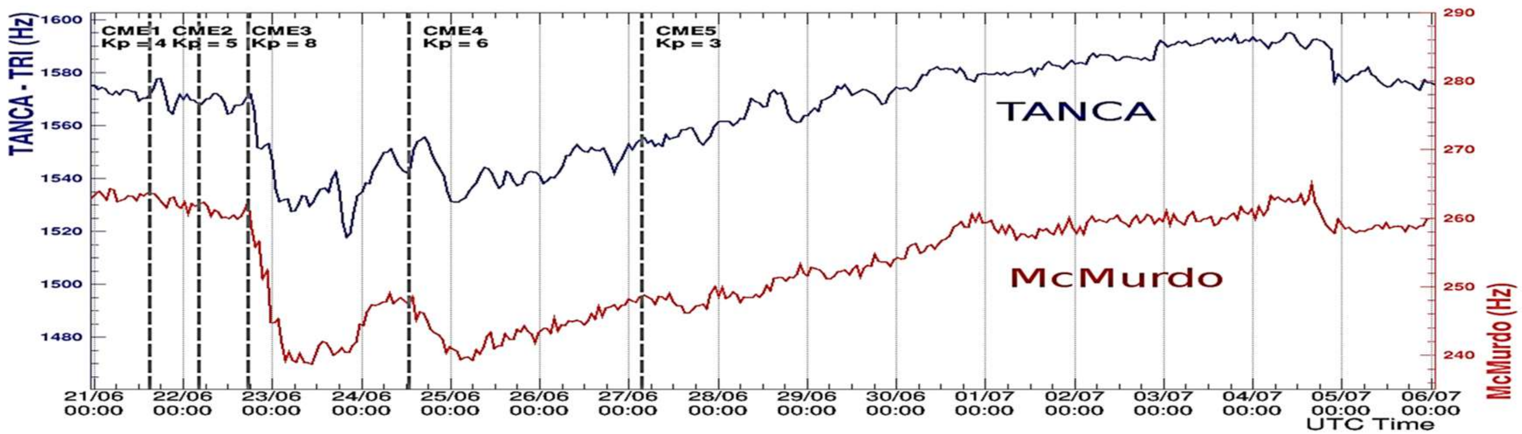


Fig. 12.9 Comparison between the intensity measured by a neutron monitor station located in Moscow and a muon detector operating in Adelaide (Australia), during the month of November 2004 [LaRocca2005]

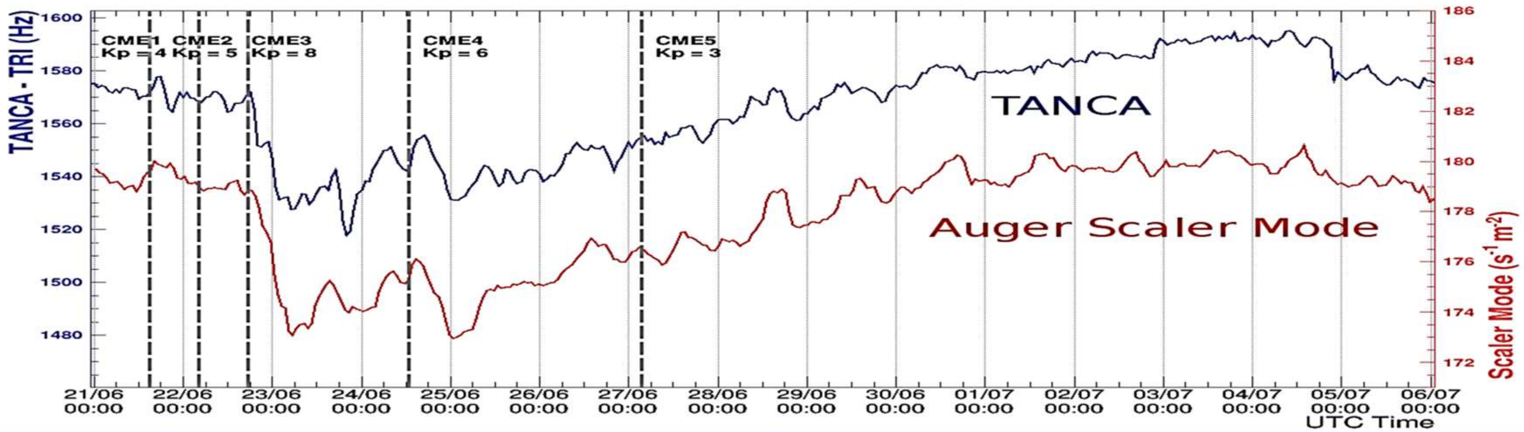


Forbush detection by TANCA, McMurdo and Auger Scaler Mode

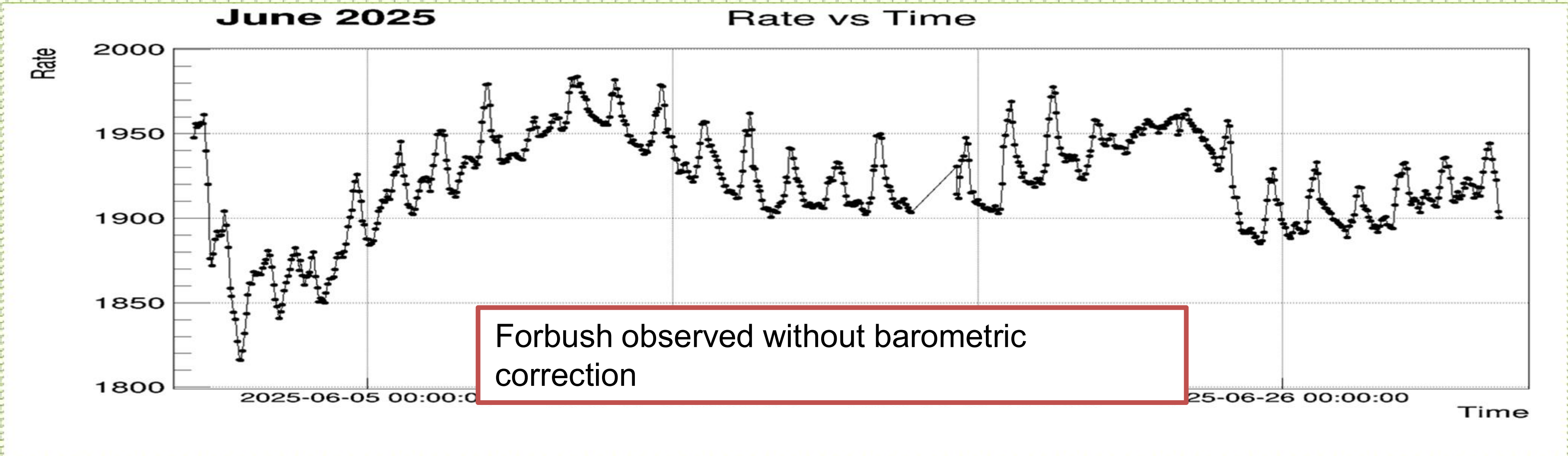
The McMurdo neutron monitor is located at the Southh Pole and has a very low geomagnetic cut-off.

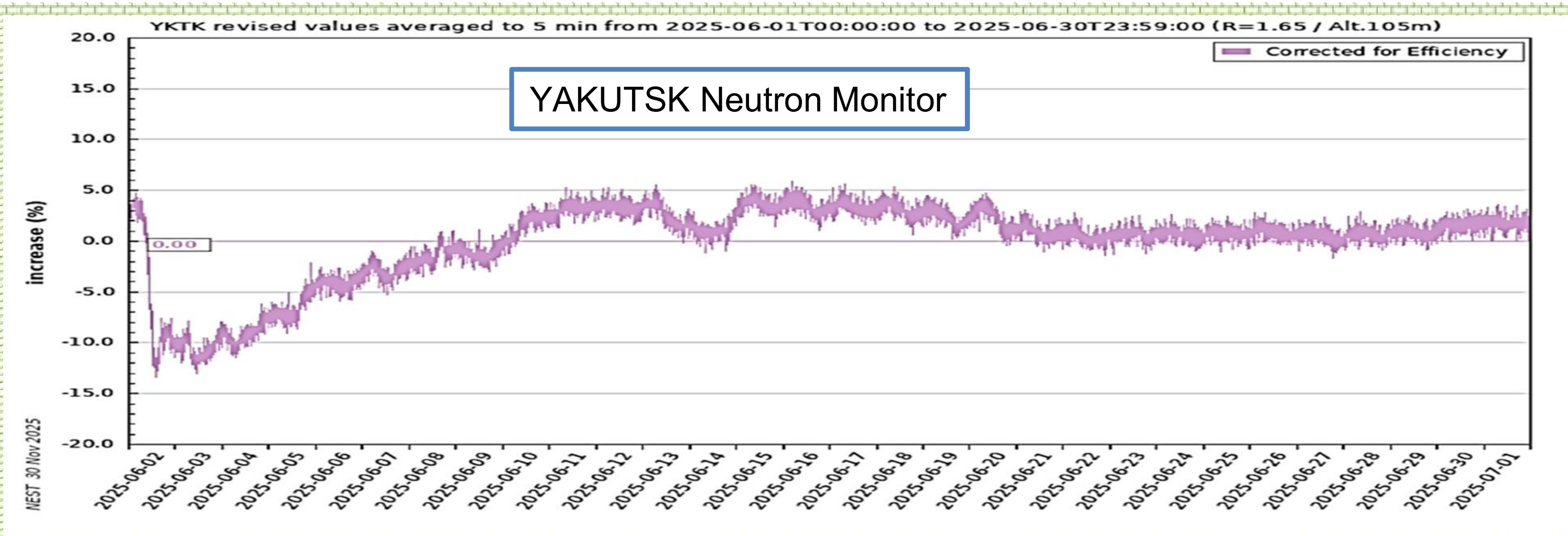


The Auger Scaler Mode (single particle technique) is 15 minutes time averaged data from the Pierre Auger Observatory surface detectors. It is placed at Malargue, Argentina



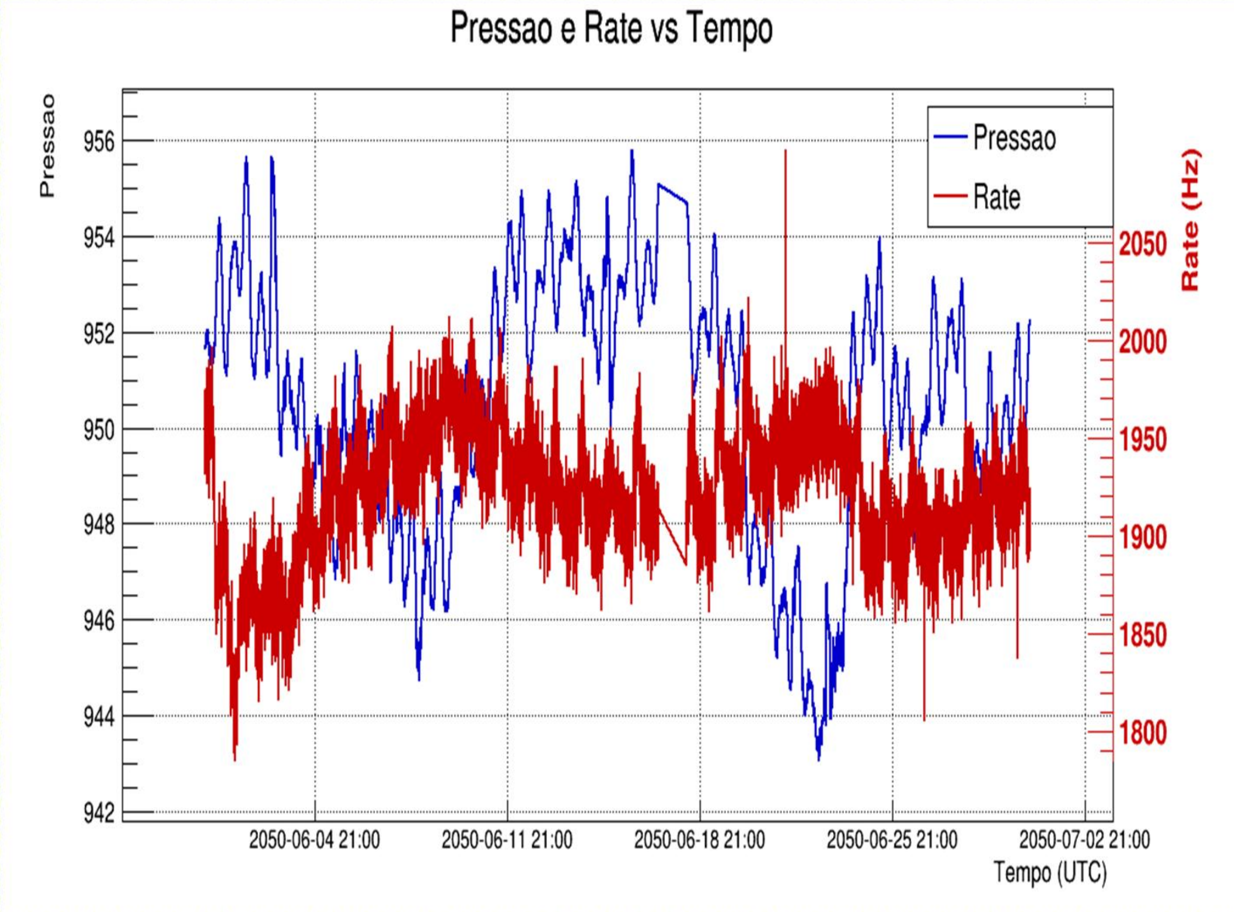
Tanca trigger rate in June 2025





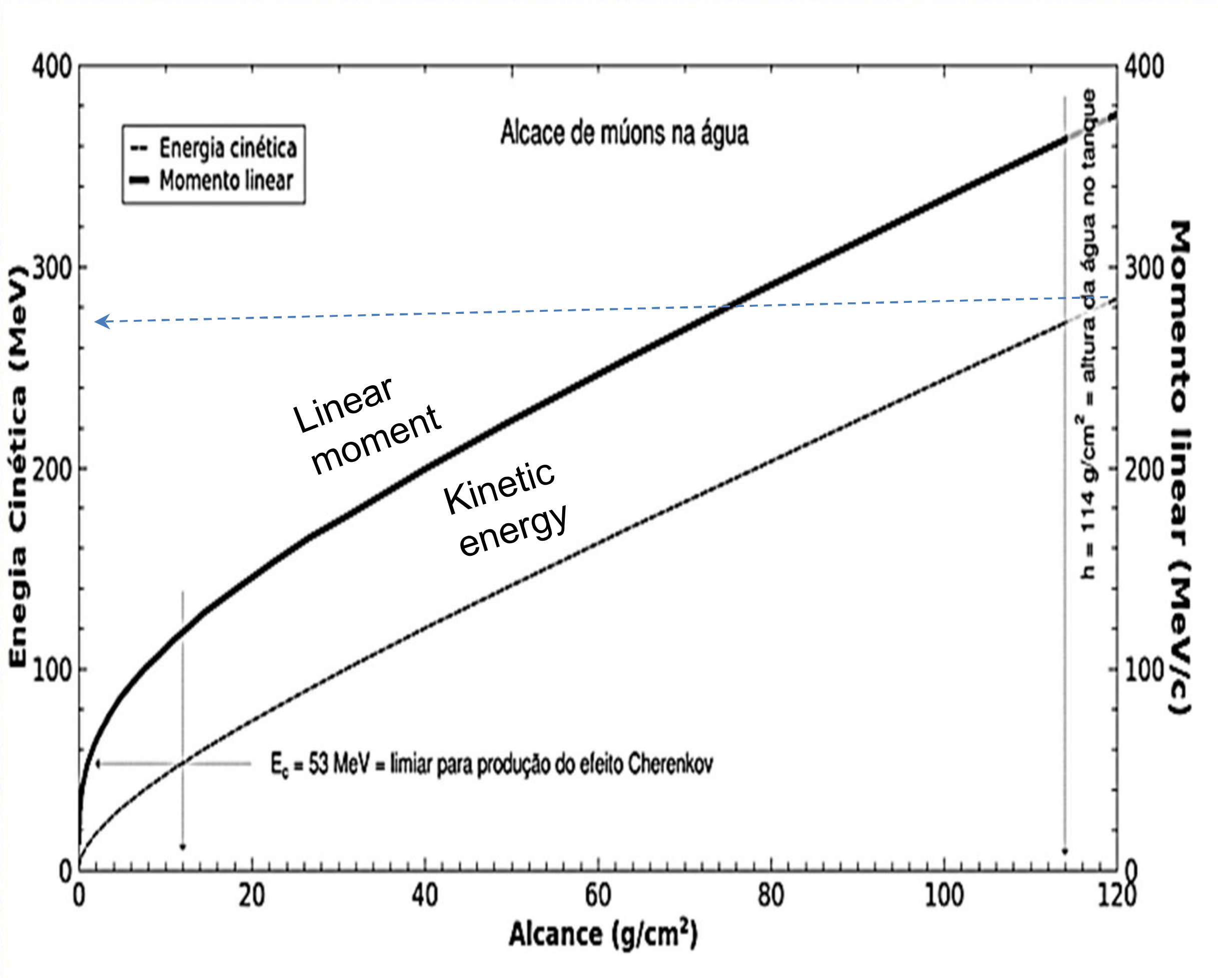
Plot rate and pressure vs time

June 2025



- The pressure data shows the barometric tide.
- The count data also shows the barometric tide.
- The two data points show the anti-correlation between count and pressure.

Muon range in water



- Tank, h=1.14 m water column
- Muons with energy > 260 MeV pass through the tank
- Muons with < 260 MeV stop and decay
- What is the muon decay rate in WCD?

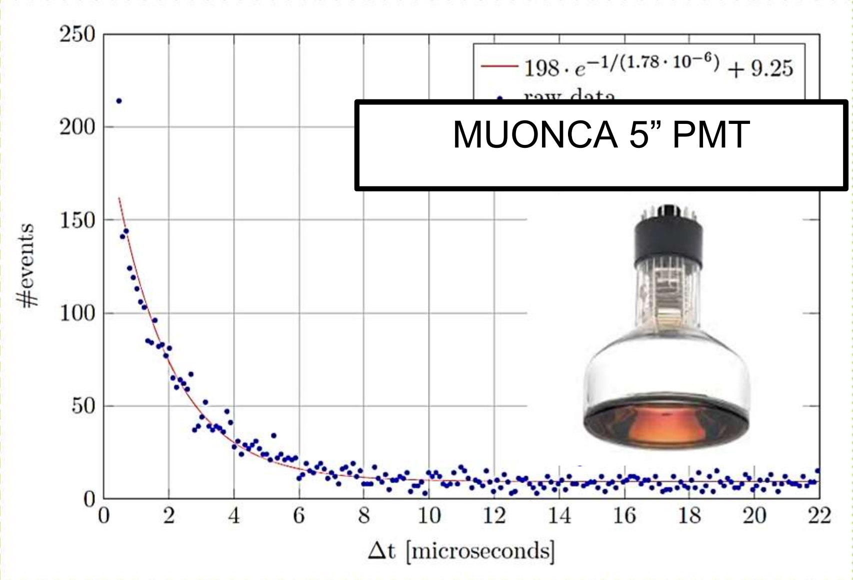
Brazilian Journal of Physics Teaching, vol. 32, no. 4, 4502 (2010)
www.sbfisica.org.br

The muon decay

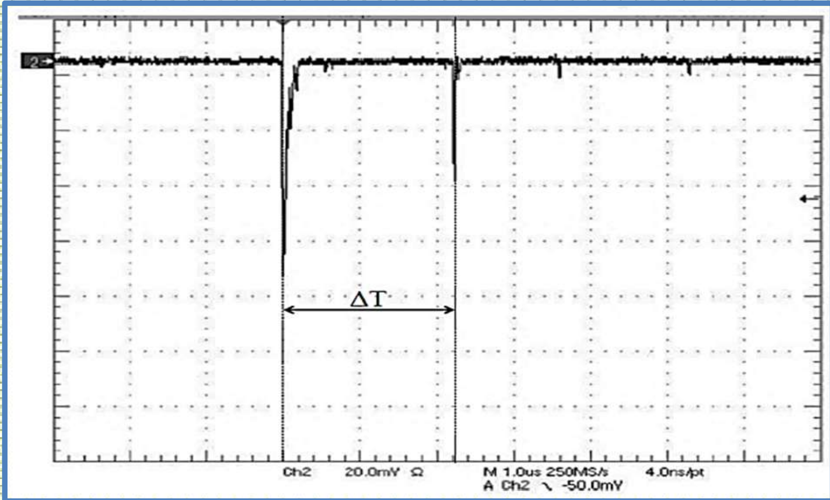
The study of the **muon lifetime** by looking the histogram of the time difference between successive pulses

$$f(t) = A \cdot \exp\left(-\frac{t}{\tau}\right) + C$$

$$f(t) = 198 \cdot \exp\left(-\frac{t}{1.78 \cdot 10^{-6}}\right) + 9.25$$



MUONCA 5” PMT

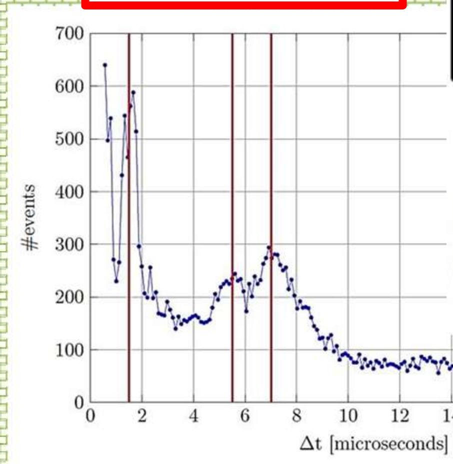


DAq=osciloscopio 60 MHz
USB
Python, C++

Afterpulses

TANCA-LAGO

9” PMT



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