# Cosmic Ray Detection

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# Outline

- Energy loss by a particle in a medium
- Creation of detectable radiation
- Air Showers
- The Pierre Auger Observatory
- Hands on experimentation

# Basics

- All detection of particles rely on interaction of particles with an active medium, thereby loosing energy and producing a measurable signal

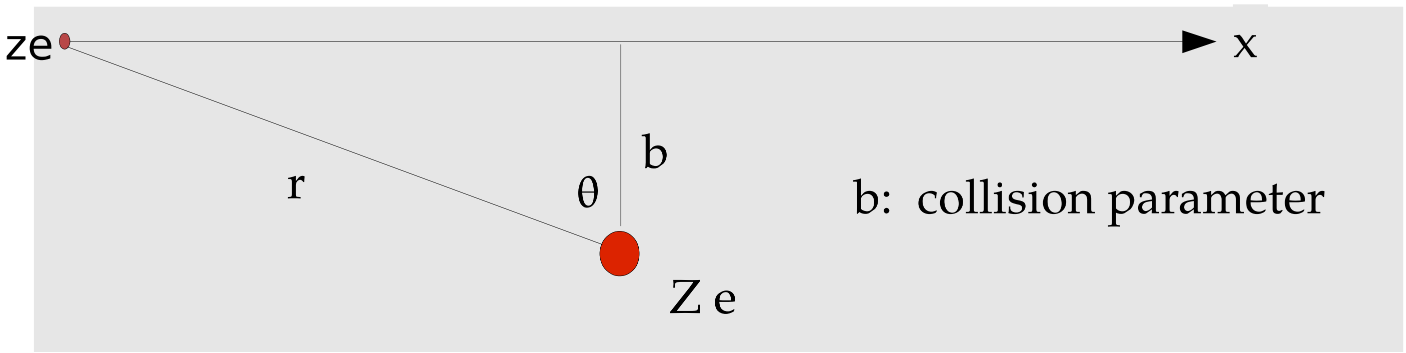
- That measurable signal can be
  - Light
  - Radio waves
  - Sound
  - Heat
  - Bubble density

# Energy loss: Bethe-Bloch

- Ionisation and excitation of the surrounding medium:

    - Air shower detection
    - Signal from water Cherenkov detectors
    - Signal from scintillator detectors
    - Tracking detectors
    - Calorimeters

# Classical Energy-loss formula




Momentum of target particle changes when test particle travels through medium:

$$\Delta\vec{p} = \int_{-\infty}^{+\infty} \vec{F}_{\text{Coulomb}} dt$$

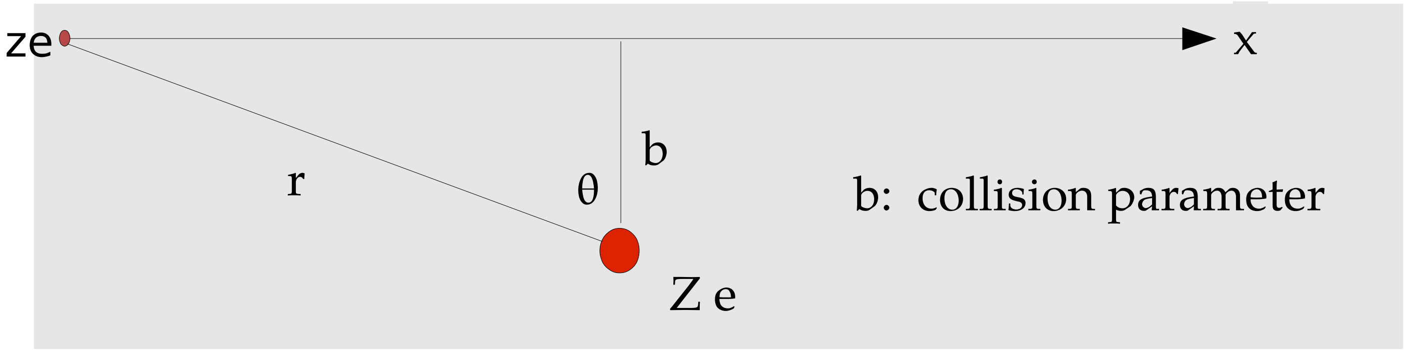
$$\vec{F}_{\text{Coulomb}} = \frac{1}{4\pi\epsilon_0}\frac{zZe^2\vec{r}}{r^2}$$

Integrating from –infinity to +infinity, only transverse force is important:

$$F_T = F_{\text{Coulomb}} \cdot \frac{b}{r(t)} = F_{\text{Coulomb}} \cdot \cos\theta(t)$$

$$F_T = \frac{1}{4\pi\epsilon_0}\frac{zZe^2}{b^2}\cos^3\theta$$

# Classical Energy-loss formula



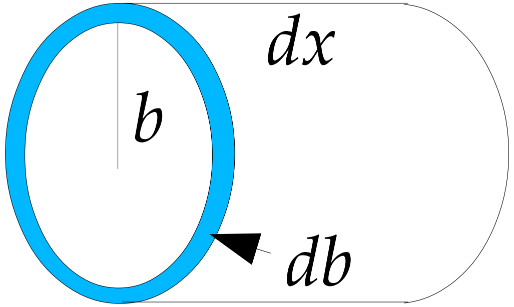

Therefore the energy transfer onto a target with mass $m_t$ is given by

$$\Delta E(b) = \frac{\Delta p(b)^2}{2m_t} = \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{2z^2 Z^2 e^4}{m_t c^2 \beta^2 b^2}$$

Only interactions with electrons are important!

# Classical Energy-loss formula

Let the test particle move through a tube of electrons




Number of electrons: $N_e = 2\pi b \cdot db \cdot dx \cdot n_e$

Electron density: $n_e = N_A \cdot (Z/A) \cdot \rho$

Energy loss due to tube:

$$\begin{aligned} -\mathrm{d}E(b) &= \Delta E(b) n_e \mathrm{d}V \\ &= \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} n_e \frac{\mathrm{d}b}{b} \mathrm{d}x \end{aligned}$$

Integrating over b: $$-\frac{\mathrm{d}E}{\mathrm{d}x} = \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} N_A \cdot (Z/A) \cdot \rho \ln \frac{b_{max}}{b_{min}}$$

# Classical Energy-loss formula

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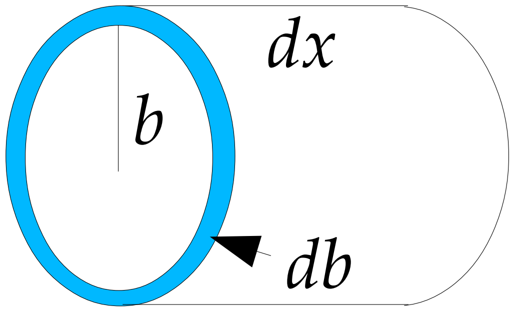



$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} N_A \cdot (Z/A) \cdot \rho \ln \frac{b_{max}}{b_{min}}$$

Maximum energy transfer (central collision): $\Delta E_{max} = 2\gamma^2 m_e \beta^2 c^2$

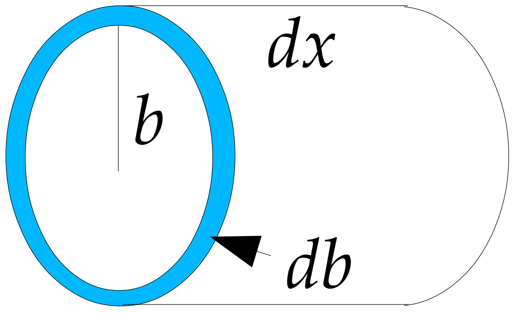
Minimal b: $$b_{min} = \left(\frac{1}{4\pi\epsilon_0}\right) \frac{ze^2}{\gamma m_e c^2 \beta^2}$$

Minimal energy transfer: Mean excitation energy per electron *I*

Maximal b: $$b_{max} = \left(\frac{1}{4\pi\epsilon_0}\right) \frac{ze^2}{c\beta} \sqrt{\frac{2}{m_e I}}$$

# Classical Energy-loss formula

Let the test particle move through a tube of electrons




$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \left(\frac{1}{4\pi\epsilon_0}\right)^2 \frac{4\pi z^2 e^4}{m_e c^2 \beta^2} N_A \cdot (Z/A) \cdot \rho \cdot \frac{1}{2} \ln \frac{2c^2\gamma^2\beta^2 m_e}{I}$$

Electron Density

Average excitation potential

$$W_{\mathrm{max}} = \frac{2m_{\mathrm{e}}c^2\beta^2\gamma^2}{1 + 2\gamma m_{\mathrm{e}}/M + (m_{\mathrm{e}}/M)^2}$$

$$\frac{\delta(\beta\gamma)}{2} \to \ln\left(\frac{\hbar\omega_{\mathrm{plasma}}}{I}\right) + \ln(\beta\gamma) - \frac{1}{2}$$

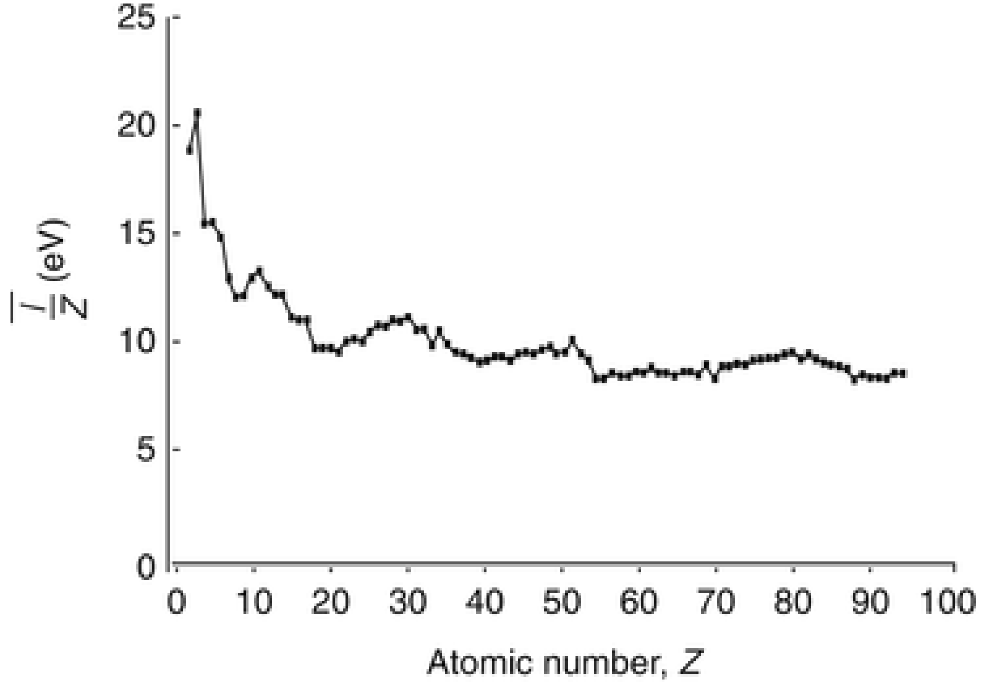
Max E transfer

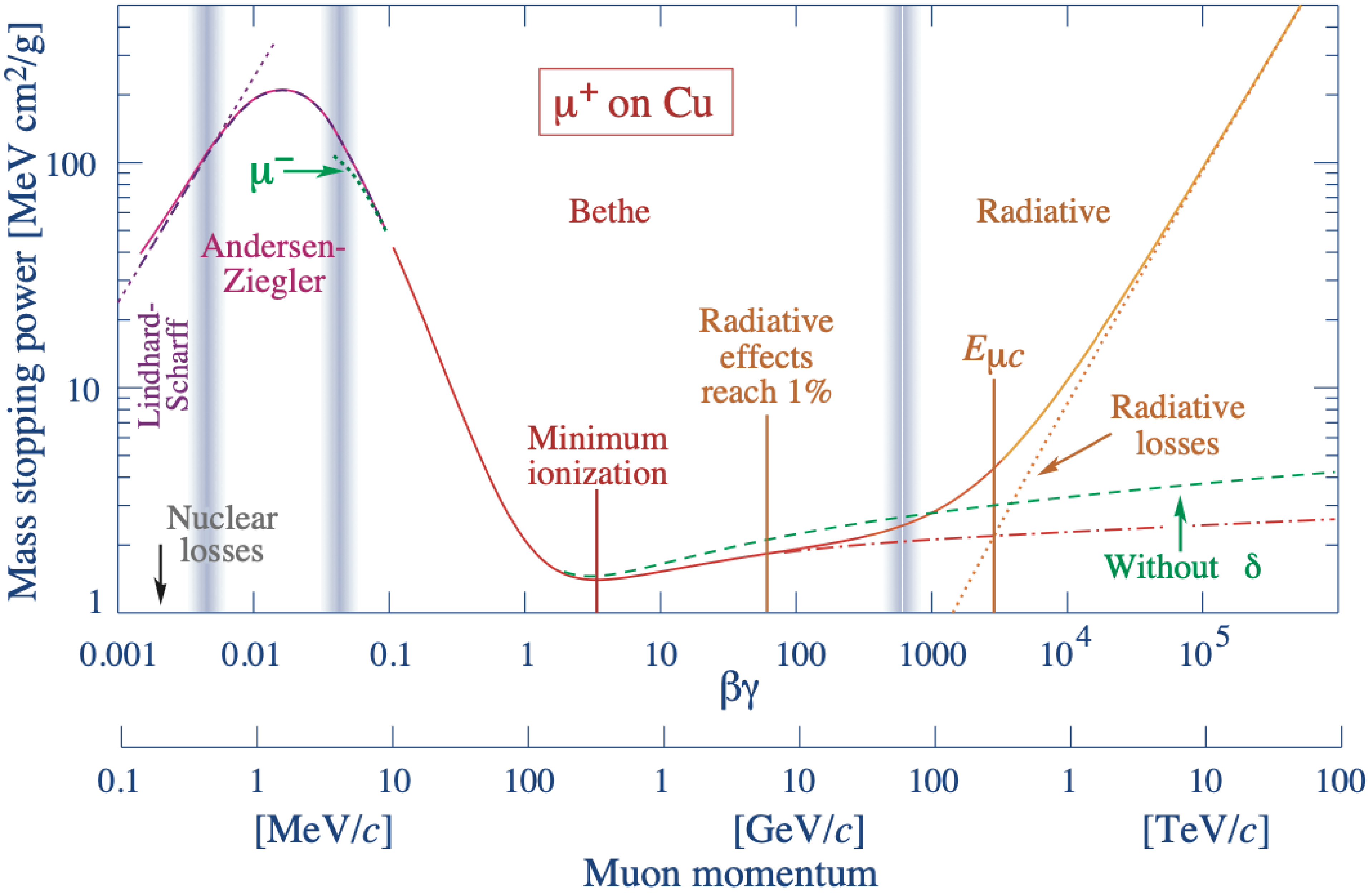
EM field saturation

Bethe-Bloch:

$$\left\langle -\frac{\mathrm{d}E}{\mathrm{d}x} \right\rangle = \rho \;\; K z^2 \, \frac{Z}{A} \, \frac{1}{\beta^2} \left[ \frac{1}{2} \ln\left(\frac{2m_{\mathrm{e}}c^2\beta^2\gamma^2 W_{\mathrm{max}}}{I^2}\right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

| | |
|---|---|
| $m_{\mathrm{e}}$ | mass of the electron, |
| $c$ | speed of light, |
| $K = 4\pi N_{\mathrm{A}} r_{\mathrm{e}}^2 m_{\mathrm{e}} c^2$ | numerical coefficient with value $K = 0.307075$ MeV mol$^{-1}$ cm$^2$ ($N_{\mathrm{A}}$ is Avogadro's number and $r_{\mathrm{e}}$ is the classical radius of the electron), |
| $z$ | charge of the high energy particle traversing the matter, |
| $\beta$, $\gamma$ | velocity as fraction of the light velocity and Lorentz contraction factor of the high energy particle traversing the matter, |
| $\rho$ | the mass density of the matter, |
| $Z$, $A$ | charge and mass number of the atom the matter consists of, |
| $I$ | mean excitation energy for the electrons in the atom, |
| $\delta(\beta\gamma)$ | correction for the polarisation of the matter for very-high-energy particles. |





μ+ on Cu
Mass stopping power [MeV cm²/g]
μ−
Bethe
Radiative
Andersen-
Ziegler
Lindhard-
Scharff
Radiative
effects
reach 1%
Eμc
Radiative
losses
Minimum
ionization
Nuclear
losses
Without δ
βγ
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

# Fluctuations in Energy loss

- Bethe-Bloch describes the average energy loss, not the most probable!
- Landau gave a description of the fluctuations, assuming only the EM-interactions with the electrons in the medium:

$$p((\Delta E)_{\rm mp};\beta\gamma,\Delta x) = \frac{1}{\pi\,\Delta x}\int_{t=0}^{\infty} \mathrm{e}^{-t}\cos\left[t\,\frac{(\Delta E)_{\rm mp}-\beta\gamma}{\Delta x}+\frac{2t}{\pi}\ln\left(\frac{t}{\Delta x}\right)\right]\mathrm{d}t$$

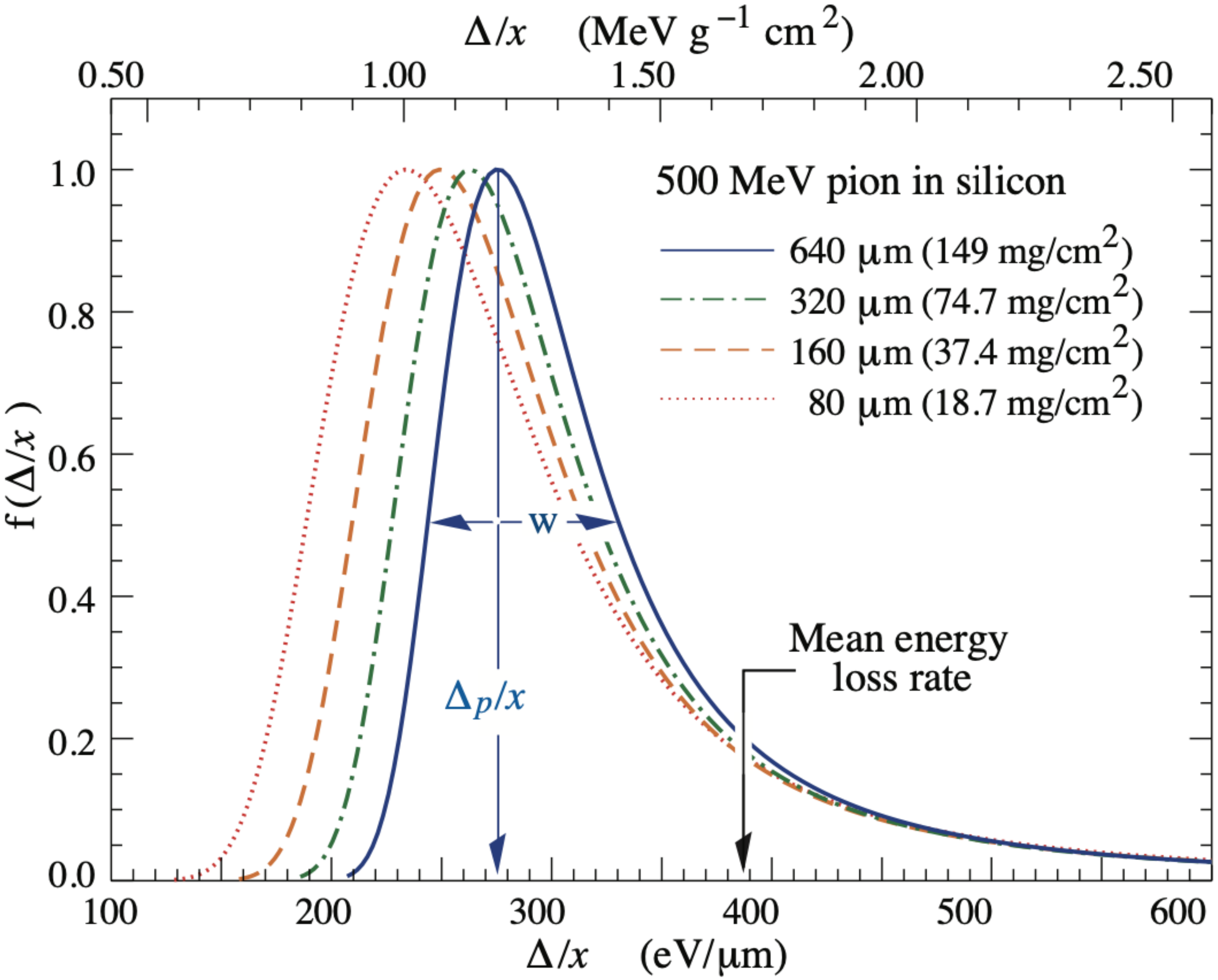
$\Delta$x Thickness of medium
r density of medium

$$(\Delta E)_{\rm mp} = \xi\left[\ln\left(\frac{2m_e c^2\beta^2\gamma^2}{I}\right)+\ln\left(\frac{\xi}{I}\right)+j-\beta^2-\delta(\beta\gamma)\right]$$

$$\xi = \rho\,\frac{K}{2}\frac{Z}{A}\frac{z^2}{\beta^2}\Delta x$$

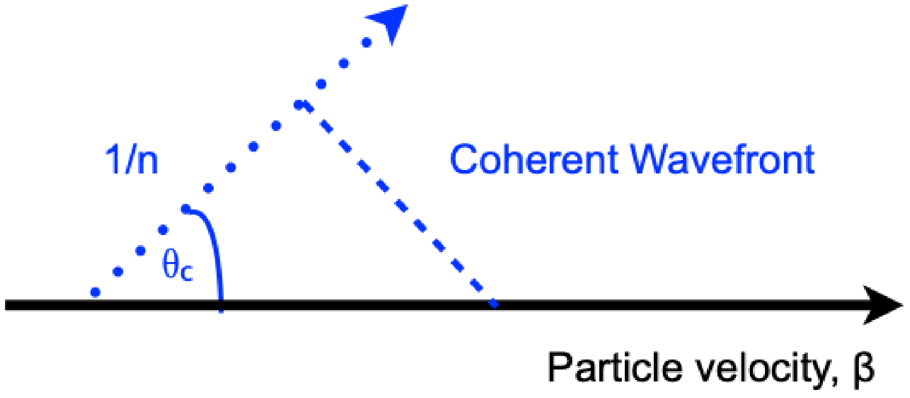
$$j = 0.200$$

# Landau Fluctuations



# Cherenkov Radiation

$$\cos\theta_c = \frac{1}{\beta n}$$




Discovered in 1934 by Cherenkov and Vavilov

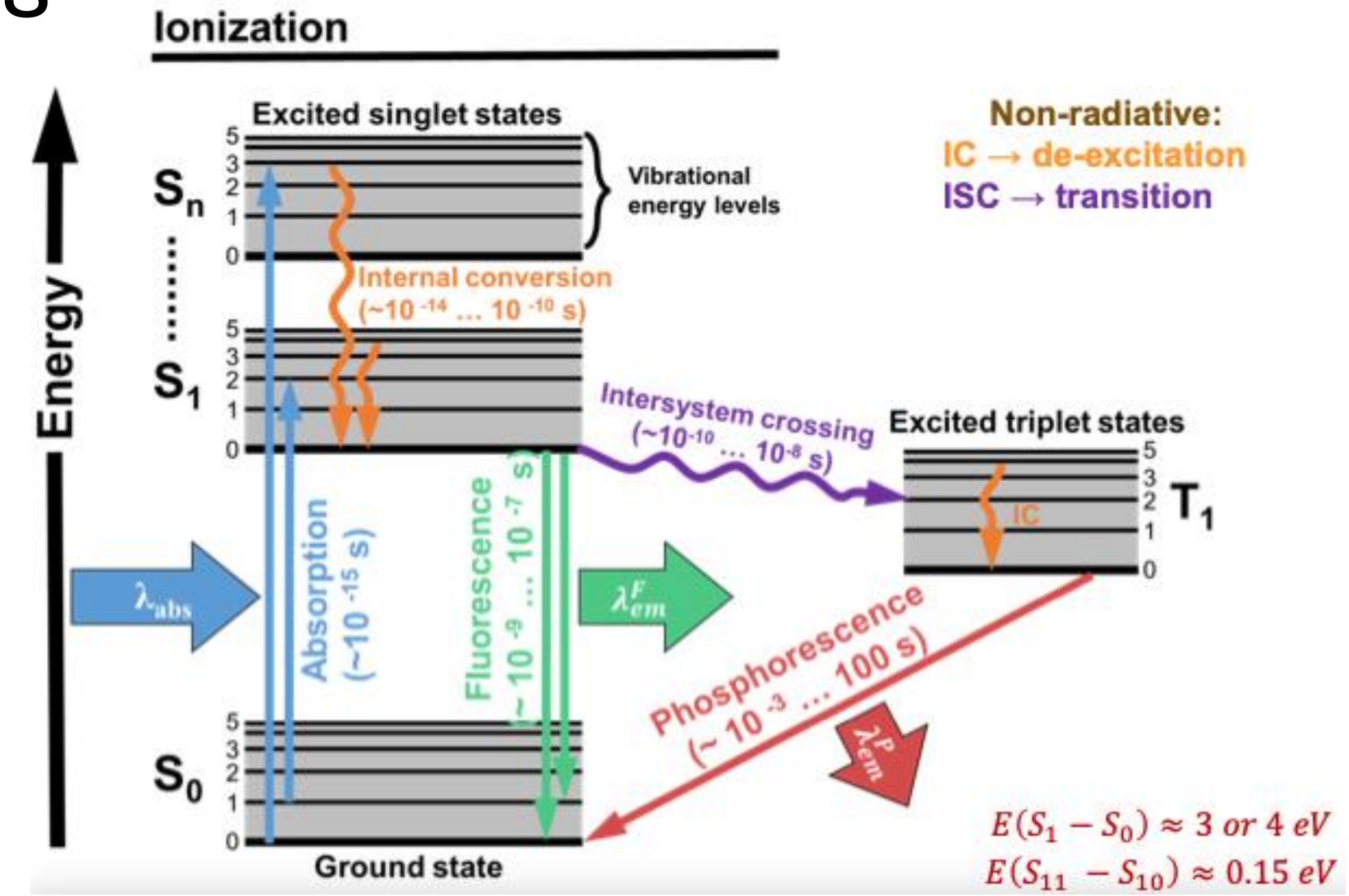
Described in 1937 by Frank and Tamm

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) \qquad N_{\text{p.e.}} = L\frac{\alpha^2 z^2}{r_e\, m_e c^2}\int \epsilon(E)\,\sin^2\theta_c(E)dE$$

- Charged particles cause radiation if their velocity is greater than the local phase velocity of light
- This radiation is coherent at a particular angle relative to the direction of the particle
- In water energy loss is about $10^4$ less than that of ionization!

# Organic scintillators

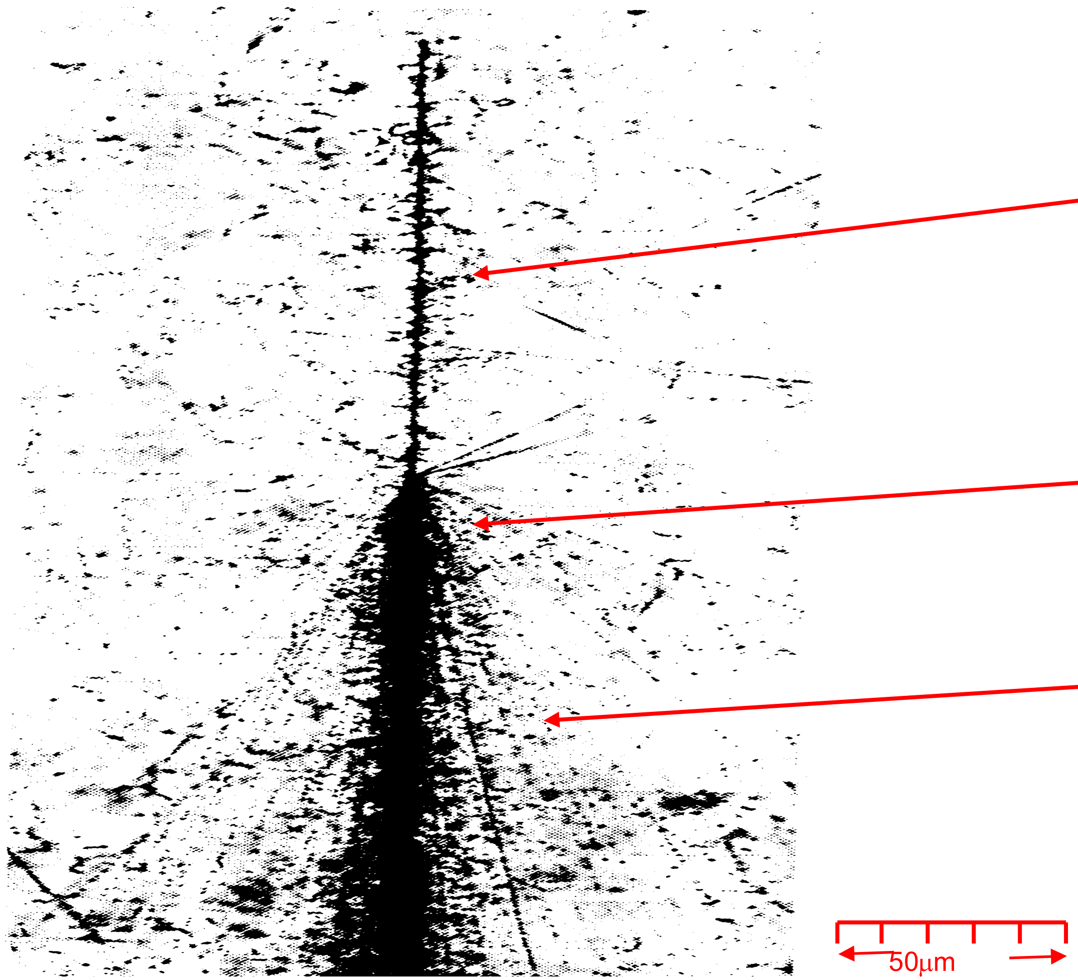
- Low-Z materials
- Fast response time
- Best for electrons and muons



# Schematic of scintillator useage

1. Electromagnetic interaction of radiation with scintillation material
2. Energy transfer to the electronic states of the material (atomic / molecular effect) → excitation and ionization
3. Relaxation of the excited states to the ground state resulting in the emission of photons
4. Collection of photons by photo sensitive device
5. Detection of the signals by associated electronics

# Air Showers




- **A cosmic ray induced shower in an emulsion**

# Energy Transfer

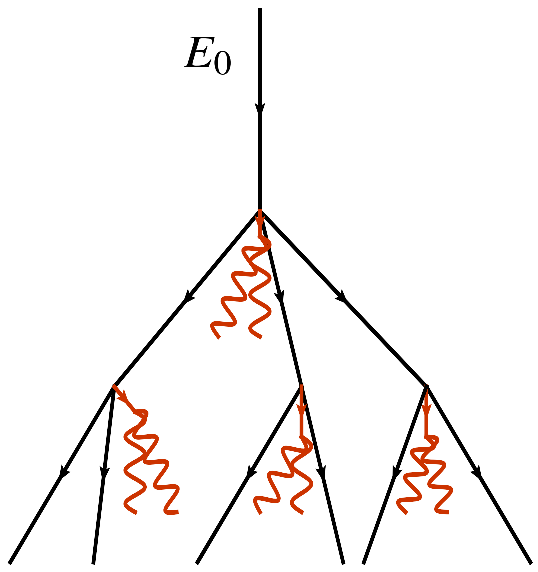
Hadronic energy

$$\frac{2}{3}E_0$$

$$\frac{2}{3}\left(\frac{2}{3}E_0\right)$$

o
o
o

$$E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0$$




*After n generations ...*

$$n = 5, \quad E_{\text{had}} \sim 12\%$$
$$n = 6, \quad E_{\text{had}} \sim 8\%$$

Electromagnetic energy

$$\frac{1}{3}E_0$$

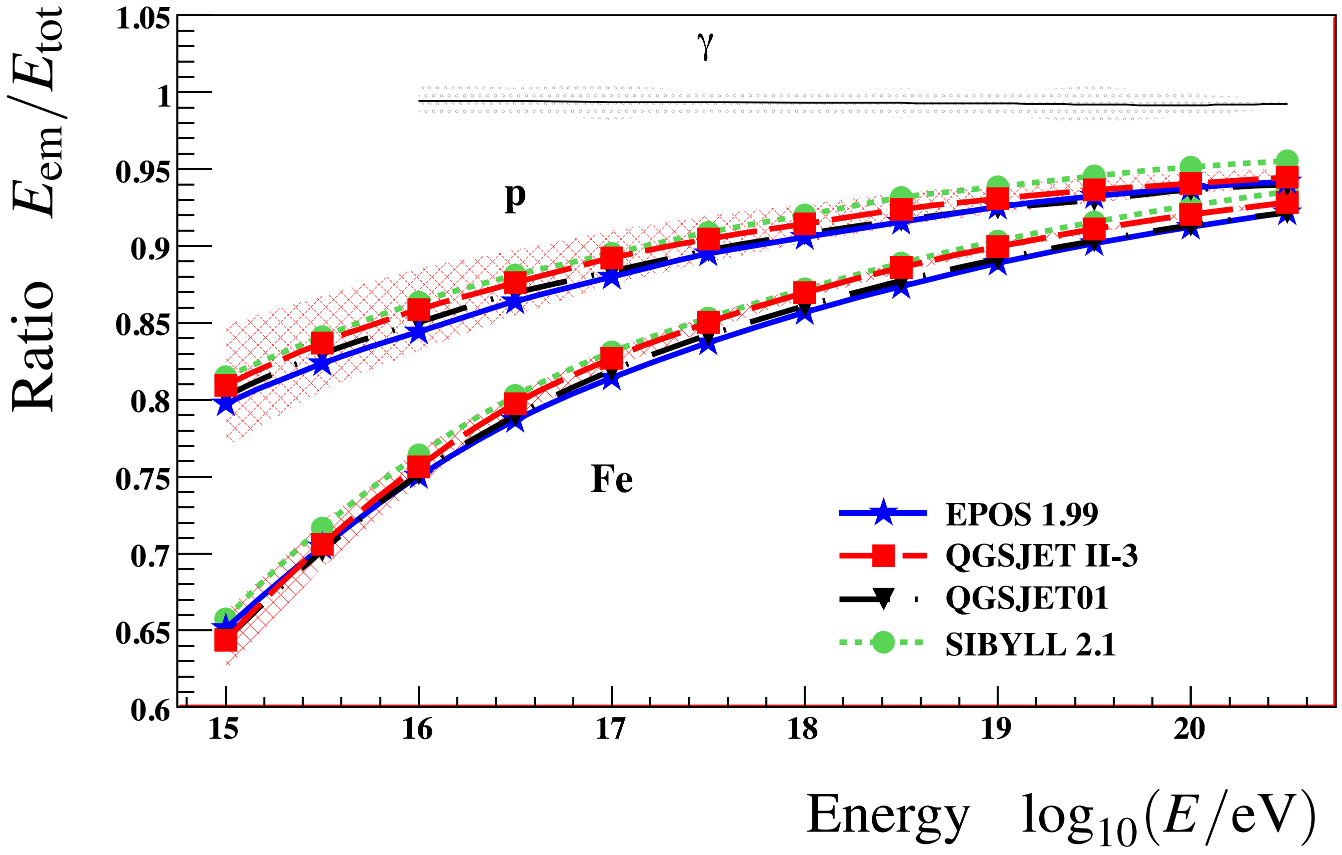
$$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$$

o
o
o

$$E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$

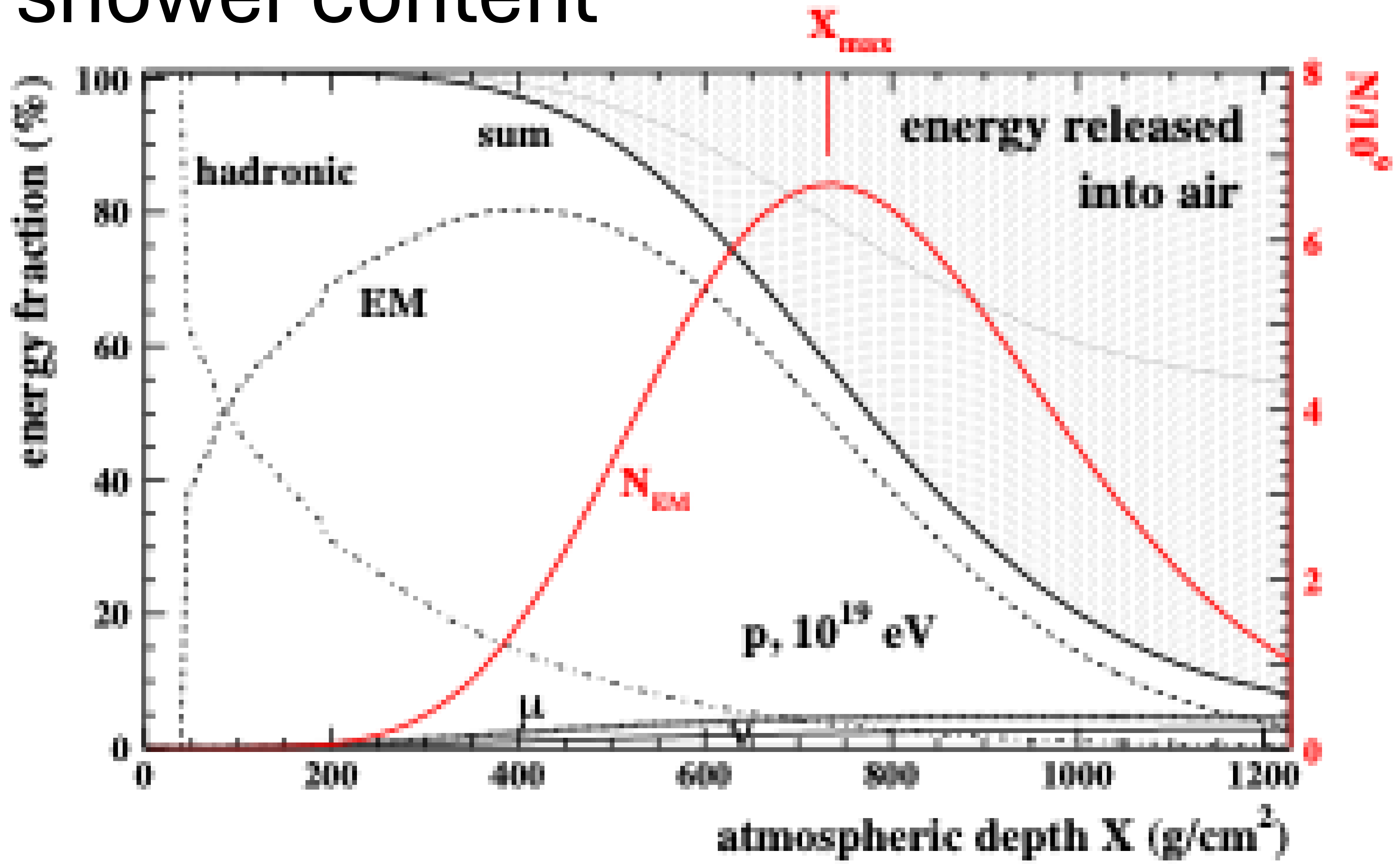
# Energy Transfer

*(RE, Pierog, Heck, ARNPS 2011)*

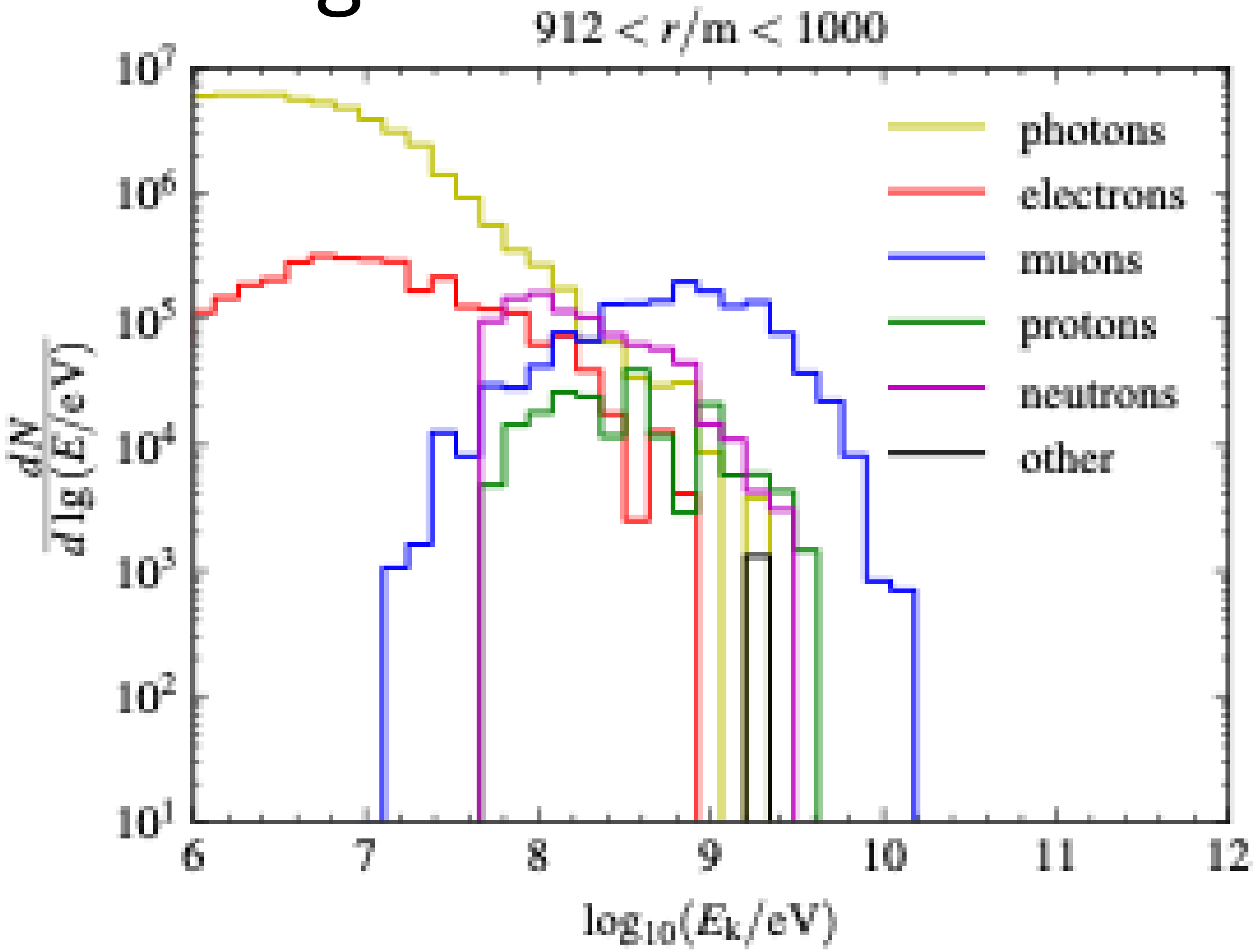



**At low energy muons carry away a significant fraction of the energy**

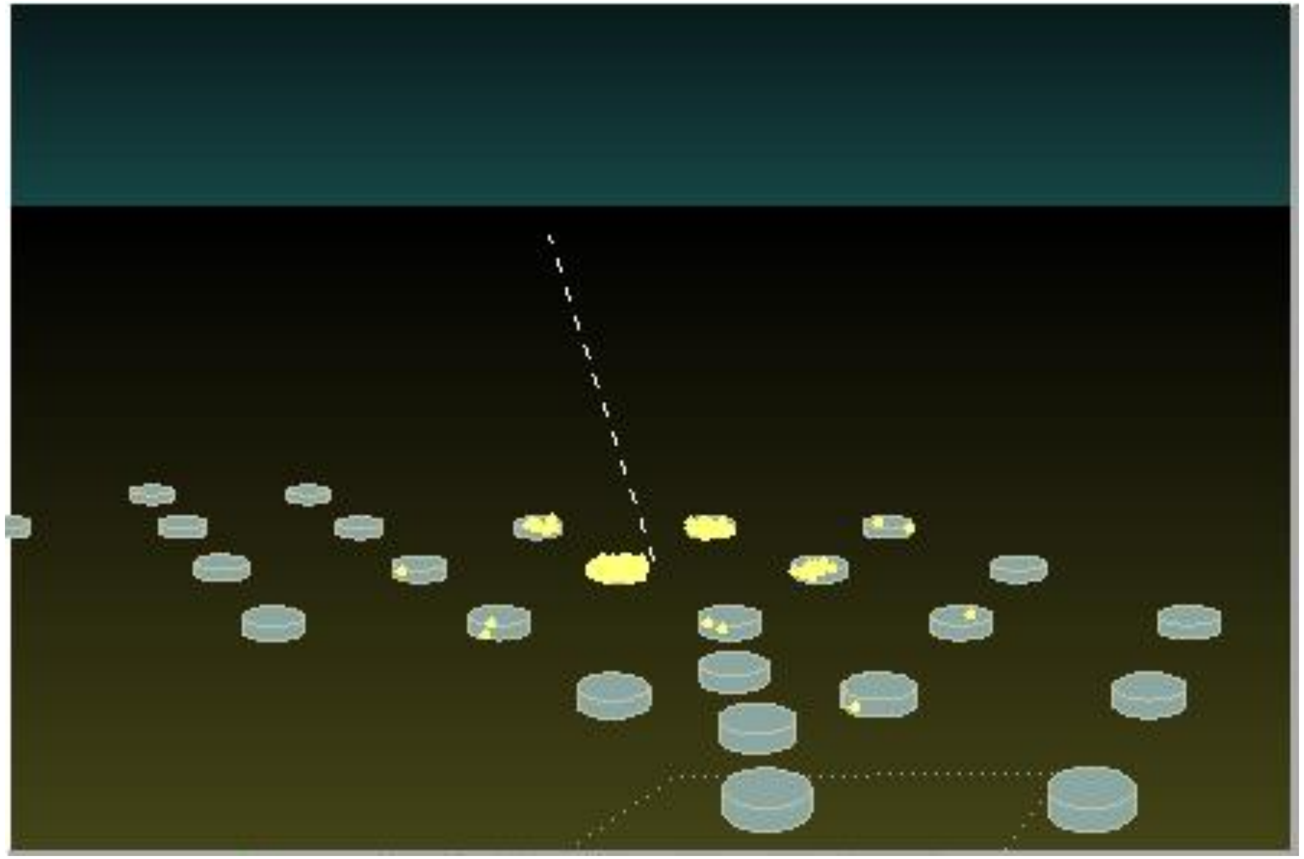
# Air shower content



# Particle Energies



# Rough description of An Air shower



**An electromagnetic current of changing size moving through the atmosphere at the speed of light**

# Creation of a radio signal

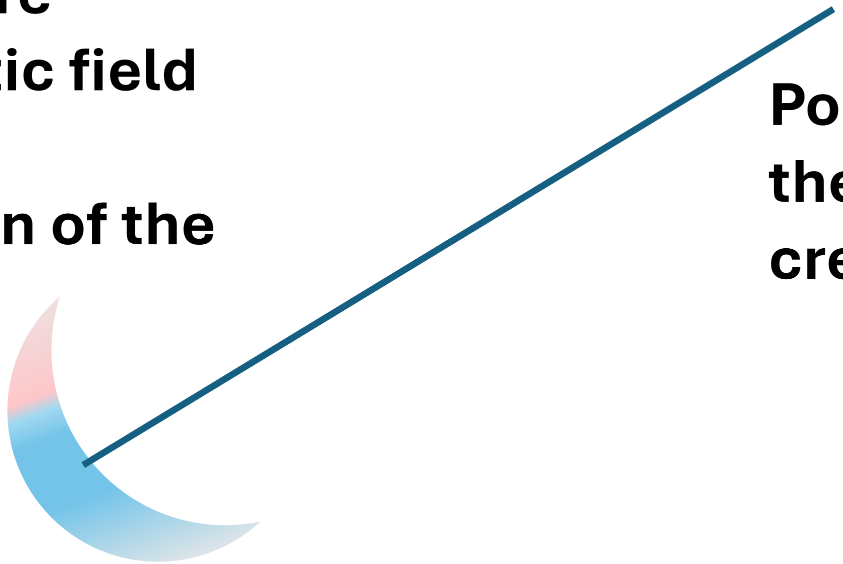
**Macroscopic: Compare the air shower to a wire in which a changing current is induced that is moving perpendicular to its length with the speed of light**

**Microscopic: Trajectories of individual electrons and positrons are influenced by magnetic fields causing synchrotron radiation**

# Macroscopic picture of the Radio Signal

**Electrons and positrons are deflected in Earth magnetic field**

**Net current in the direction of the Lorentz Force**



**Positive Ions travel slower than the air shower particles, but are created at the speed of the shower**

**Simulation Codes:**
**EVA**
**MGMR3D**
**(Krijn de Vries, Olaf Scholten)**

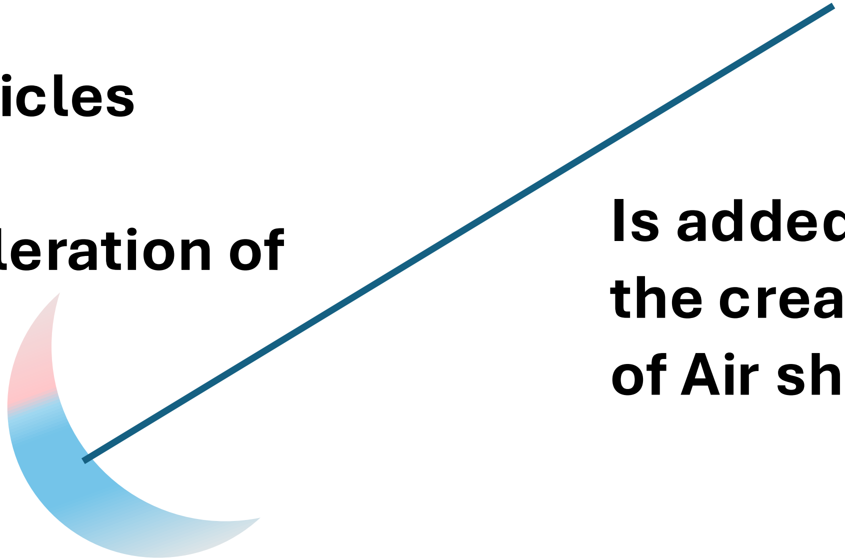
**Shower front has a net-negative charge due to:**

**Compton Scattering**
**Knock out electrons**
**Positron annihilation**

# MIcroscopic picture of the Radio Signal

**Follow individual particles**

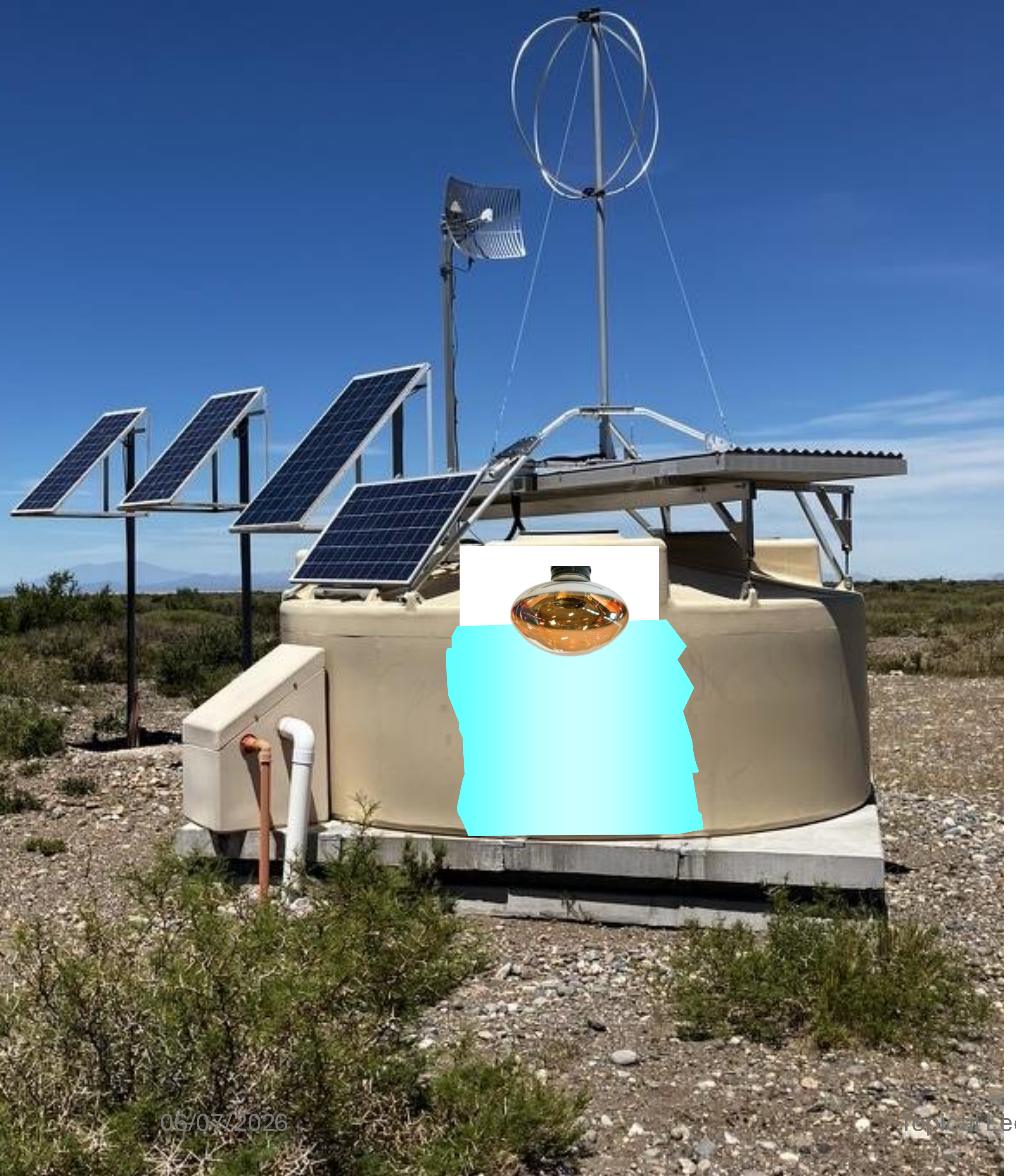
**Emission due to acceleration of charged particles**



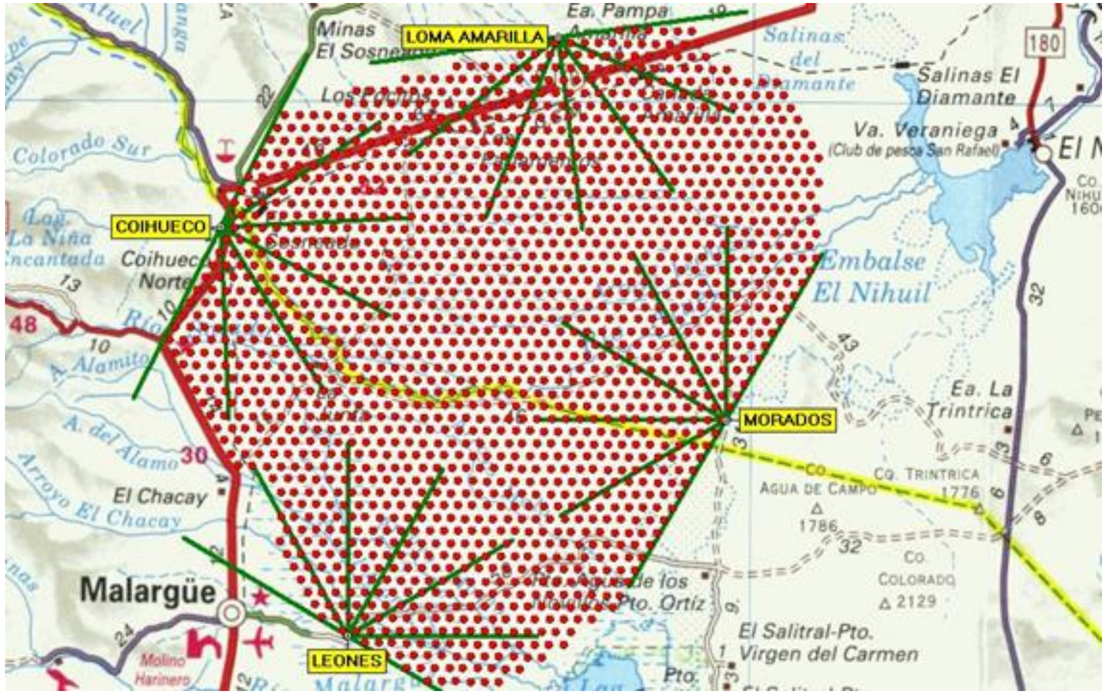
**Is added to a code for simulation of the creation of particle simulation of Air showers code**

**Simulation Codes:**
**COREAS**
**ZHAIRES**
**(Huege,**
**Zas, Halsen, Stanev)**

**Makes no assumption on different emission mechanisms**



# The Pierre Auger Observatory



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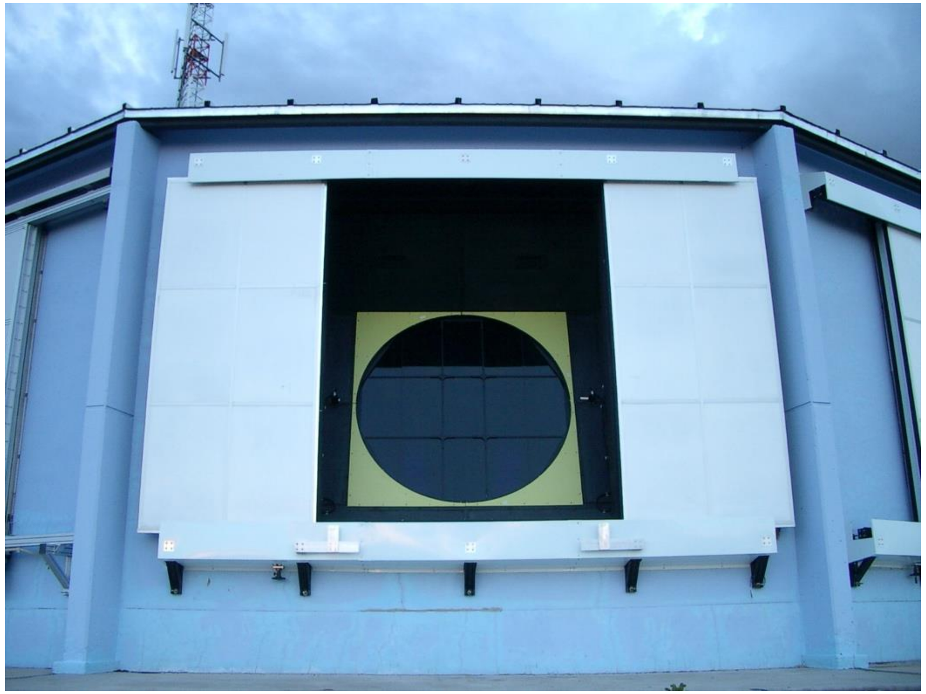

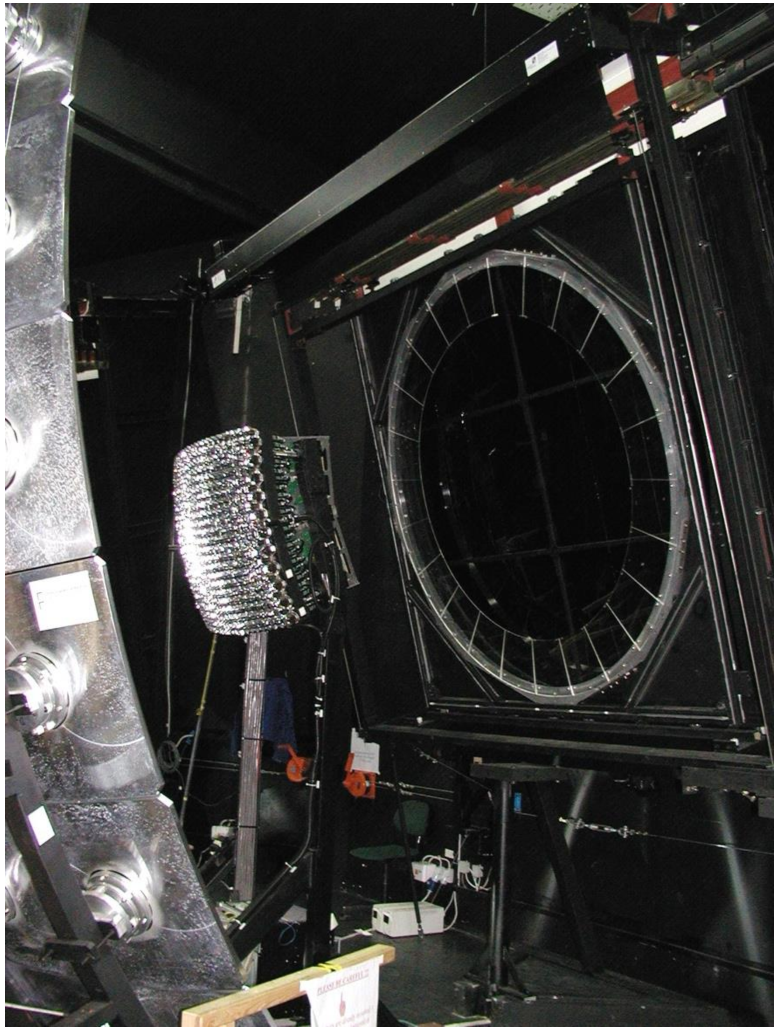

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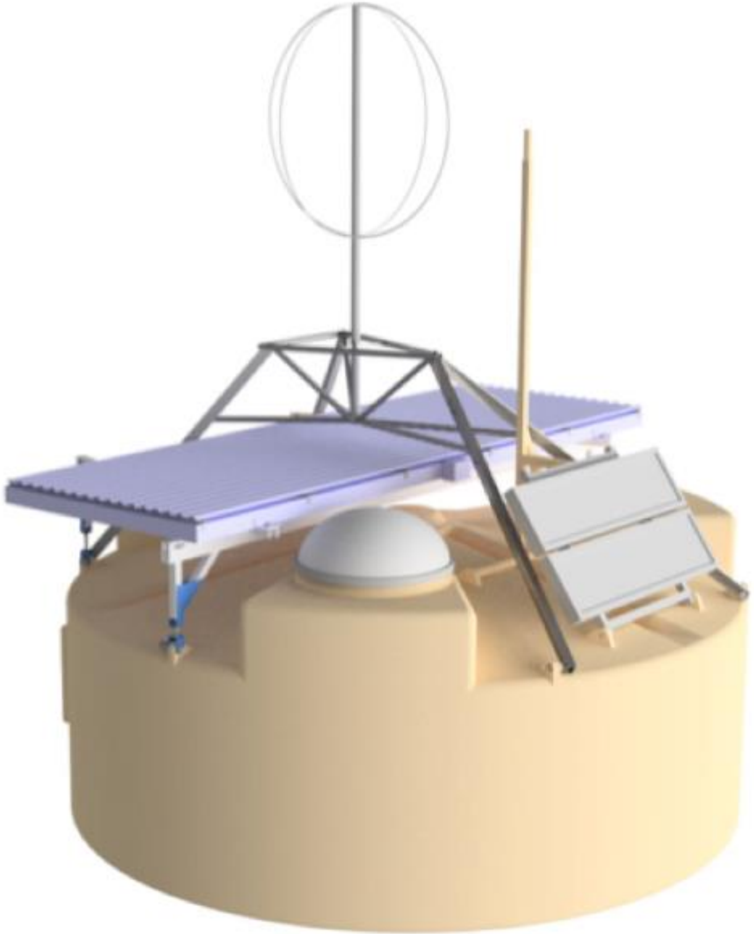
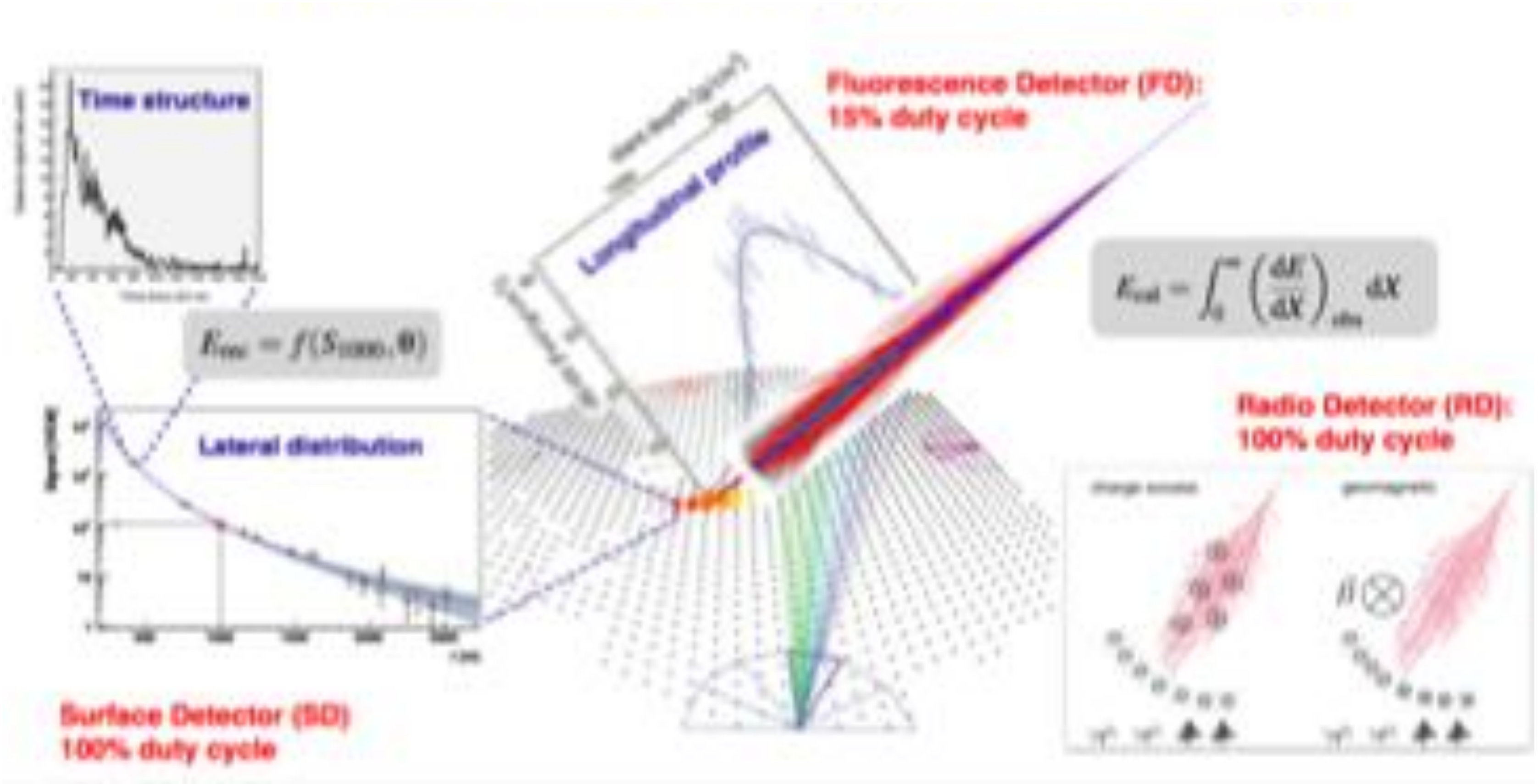
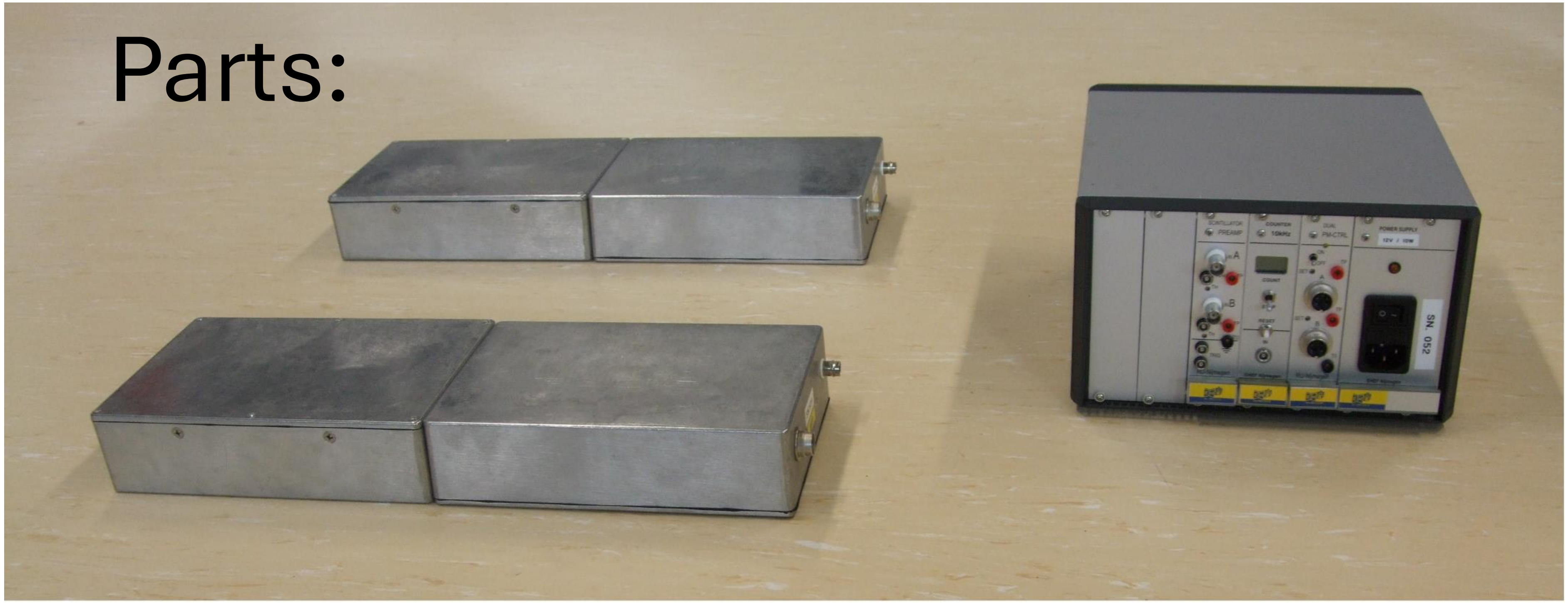




# Hands-on: Determine the (vertical) muon flux

Parts:



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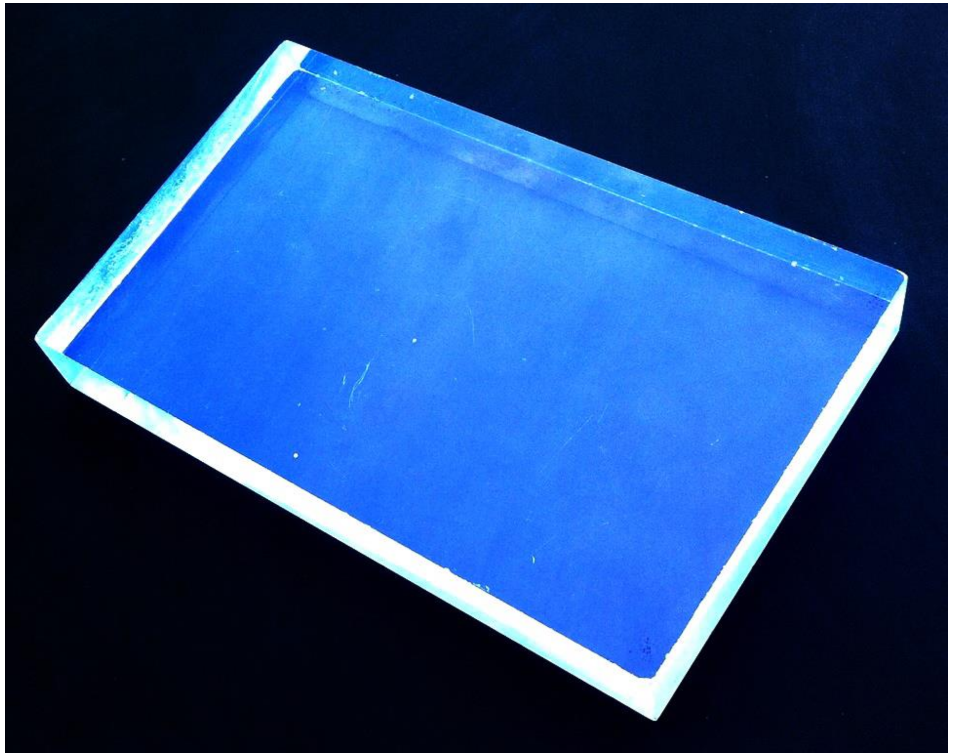

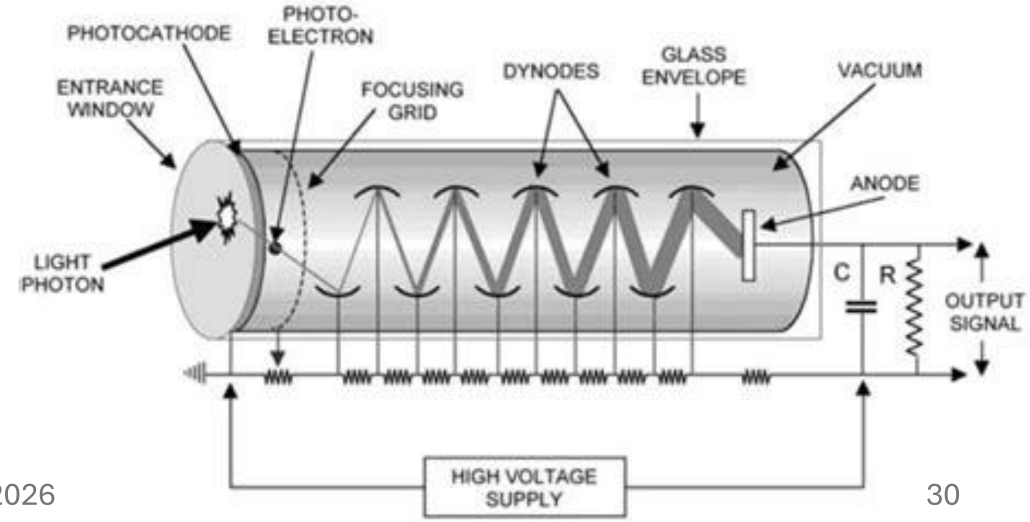

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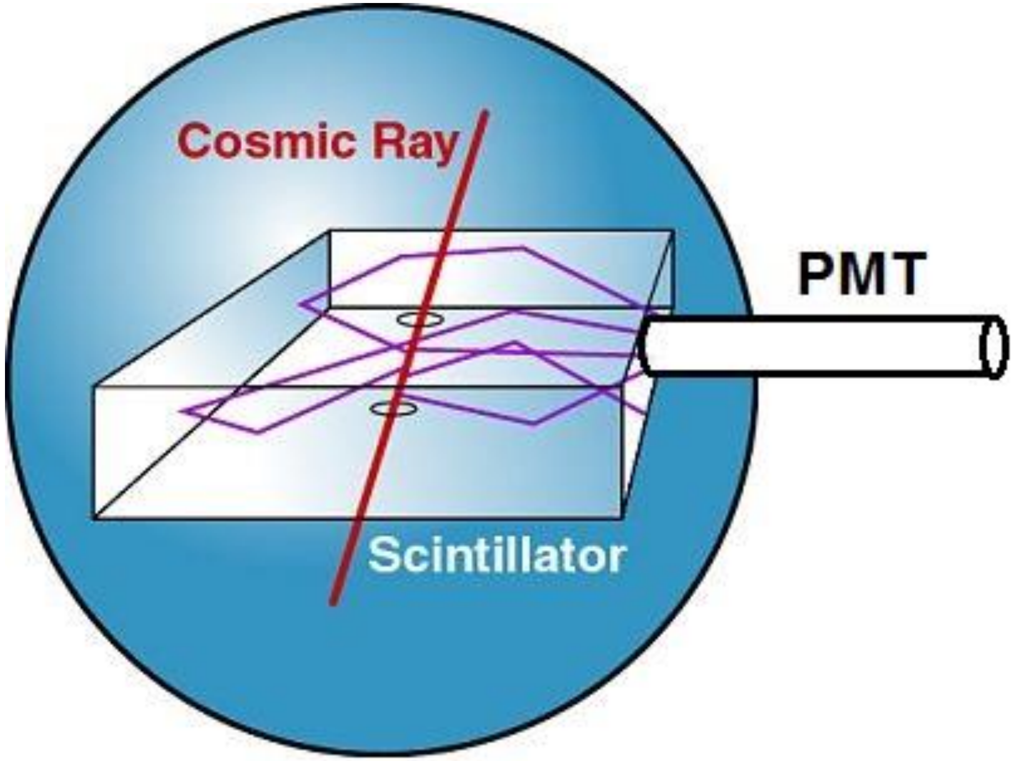
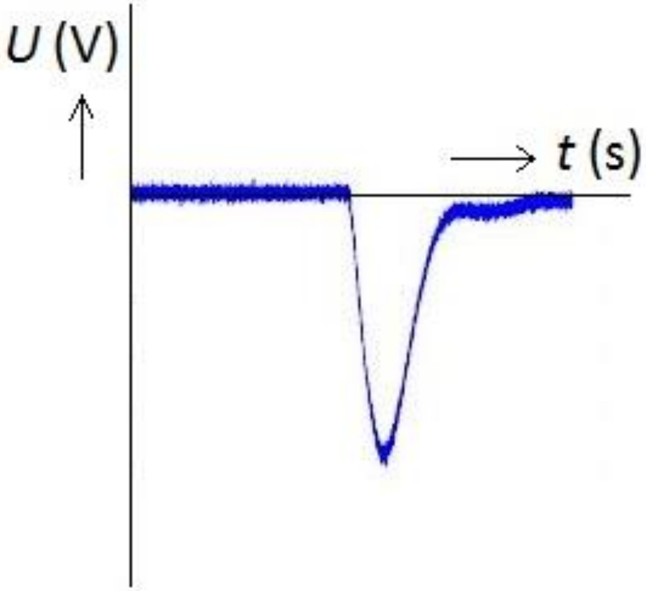



1-2% of energy loss is converted in fotons → $10^5$ fotons/muon

~1% of fotons reach PMT

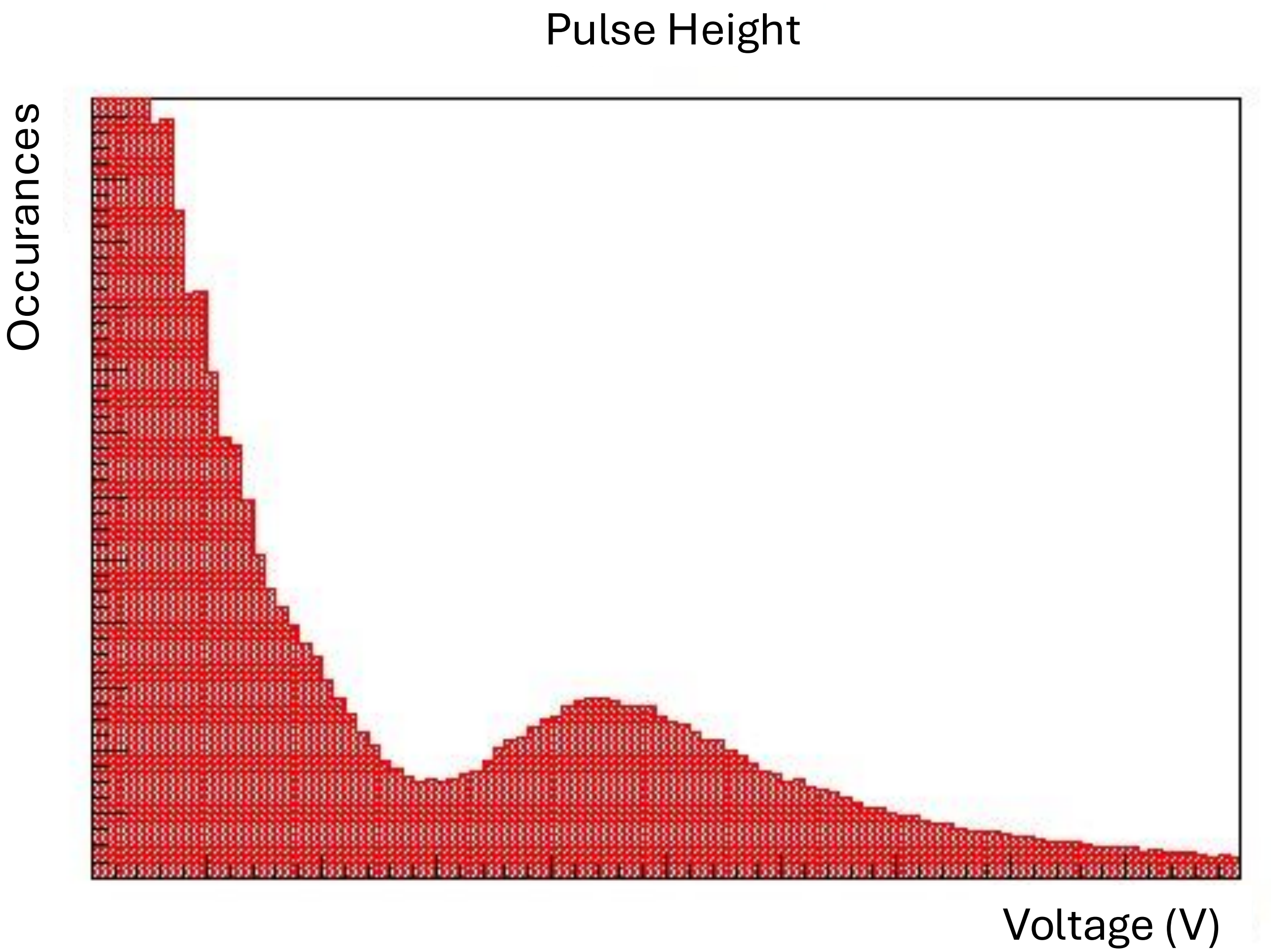
Efficiency PMT ~30%

Amplification PMT ~$10^5$




Pulseheight ~20 mV
Pulsewidth ~ 25 ns

# Hands-on: Determine the (vertical) muon flux



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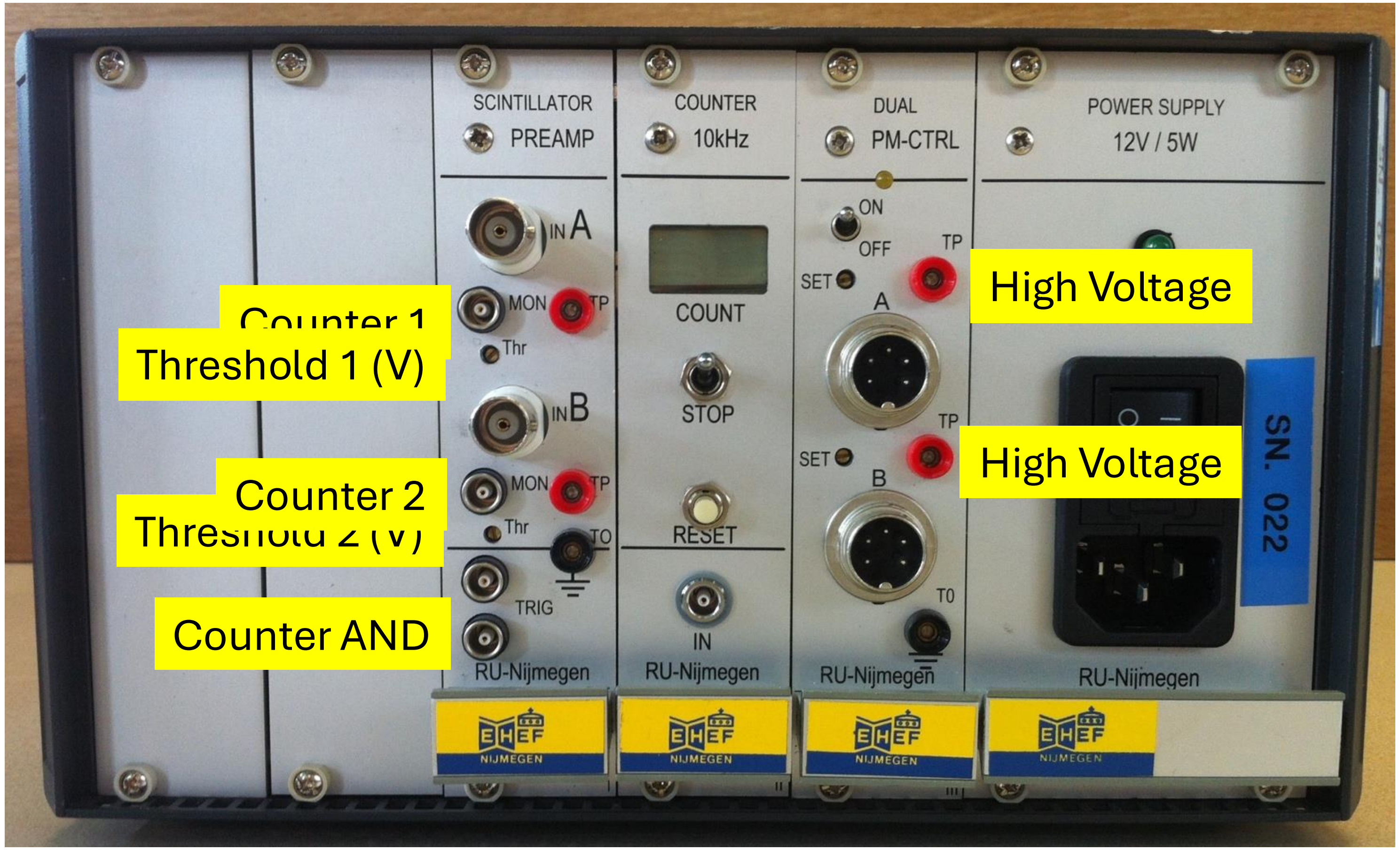

# Hands-on: Determine the (vertical) muon flux

- Determine good HV values and thresholds

- Determine the efficiency of your setup

- Determine the amount of noise in your setup

- Determine the vertical flux, including its uncertainty