Hands-on: Cosmic Rays

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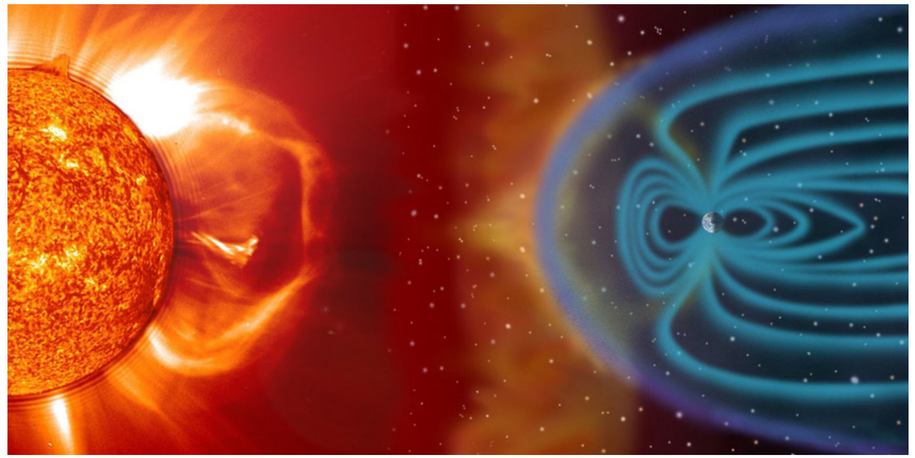
Cosmic Rays

- **Cosmic rays**
  - Charged particles accelerated in the cosmos that continuously bombard Earth
  - Essentially, proton, helium, … , up to iron
  - Above iron abundances decrease dramatically



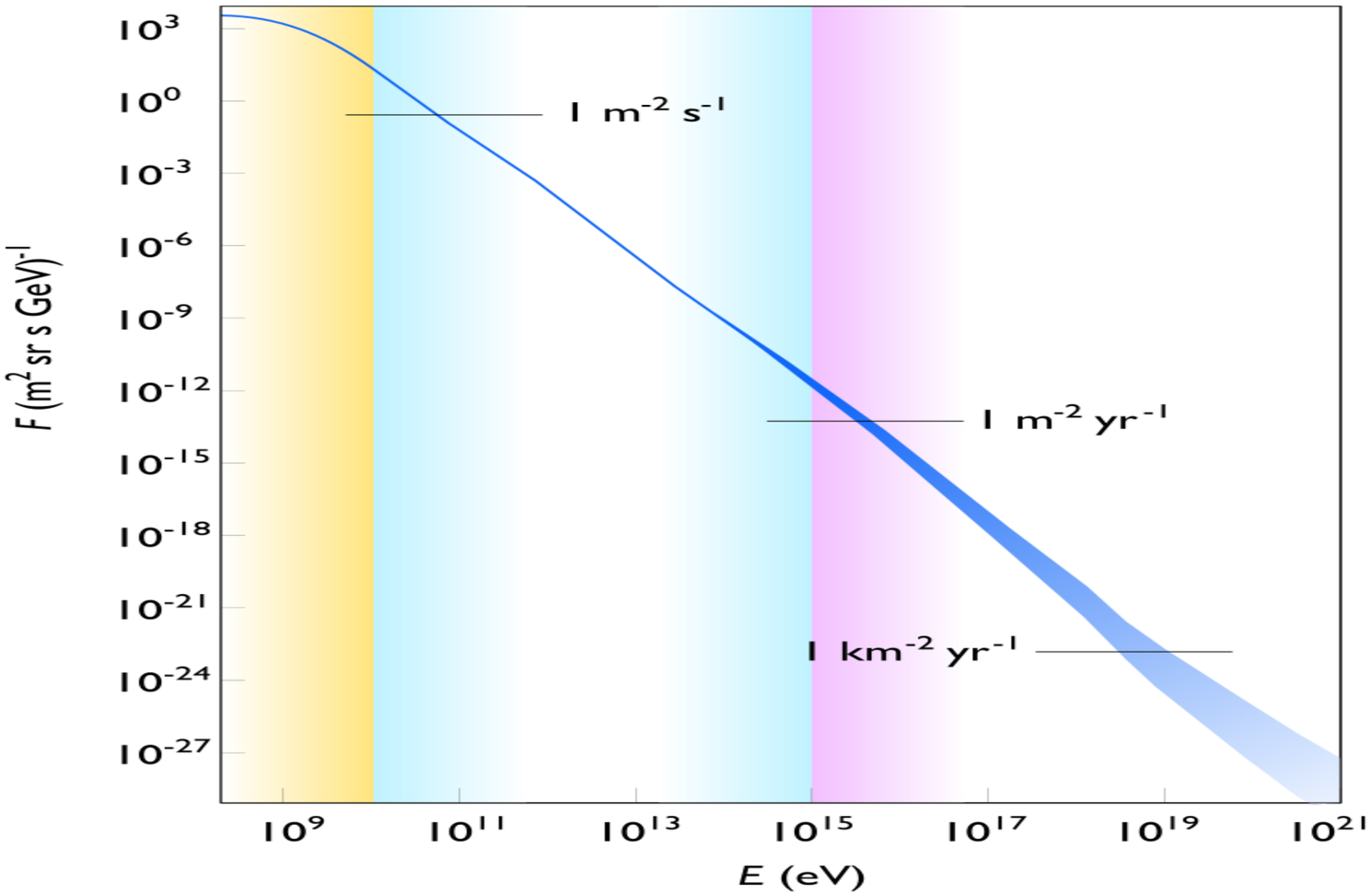
How to observe cosmic rays?

Ballon experiments

Satellite experiments

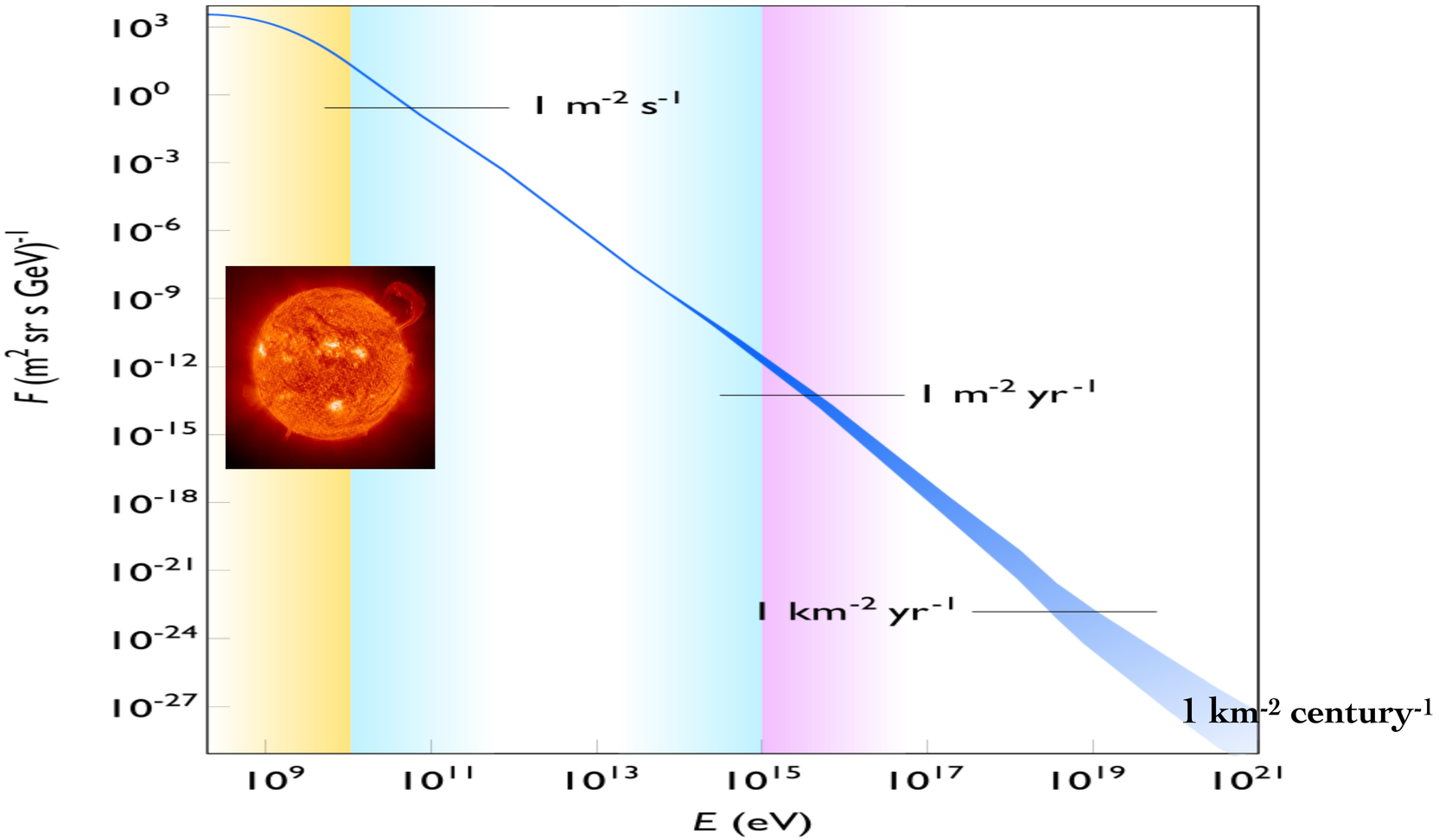
Cosmic ray energy spectrum

Flux - particles per second per area

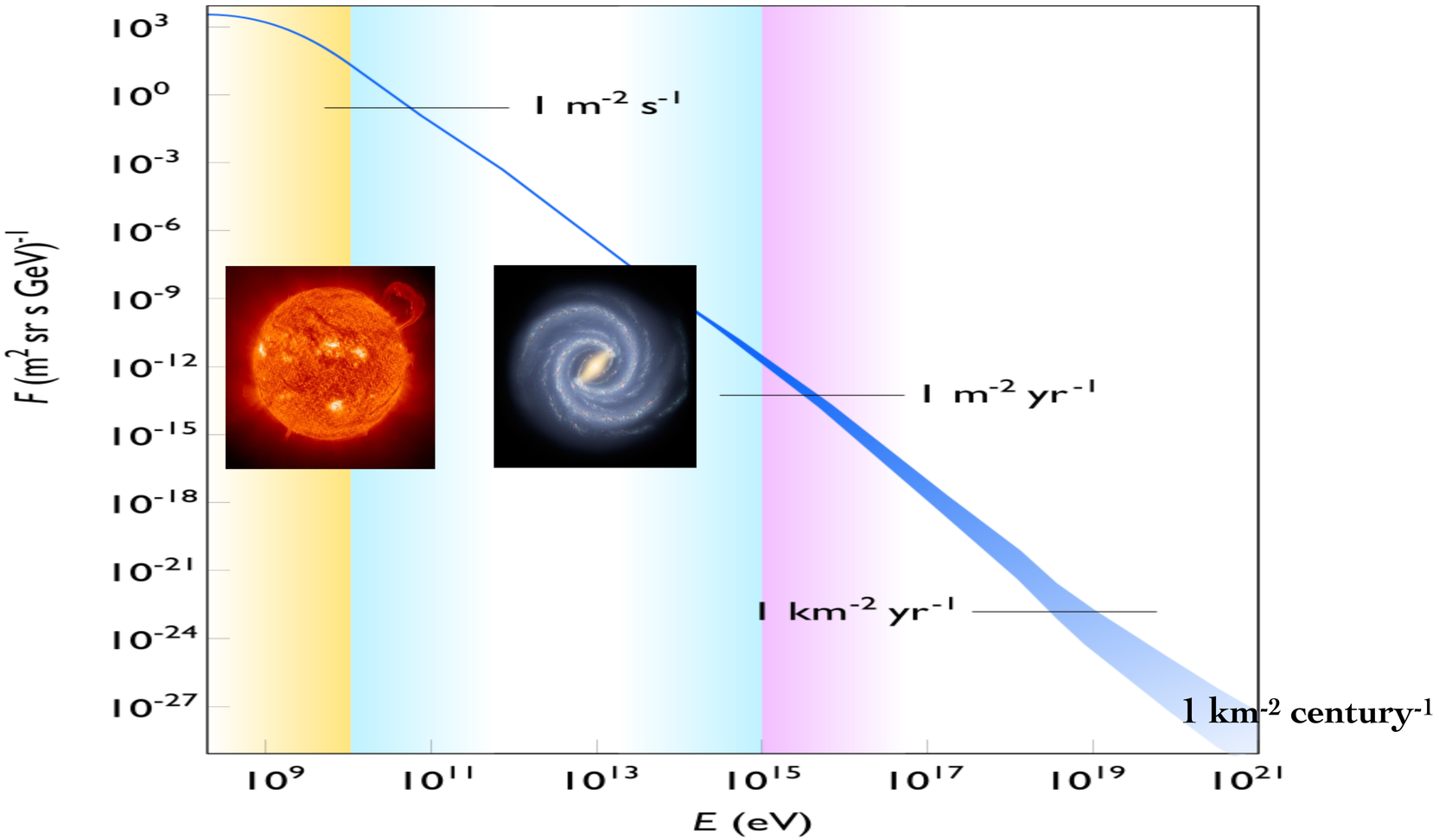


Energy - given in electron Volts

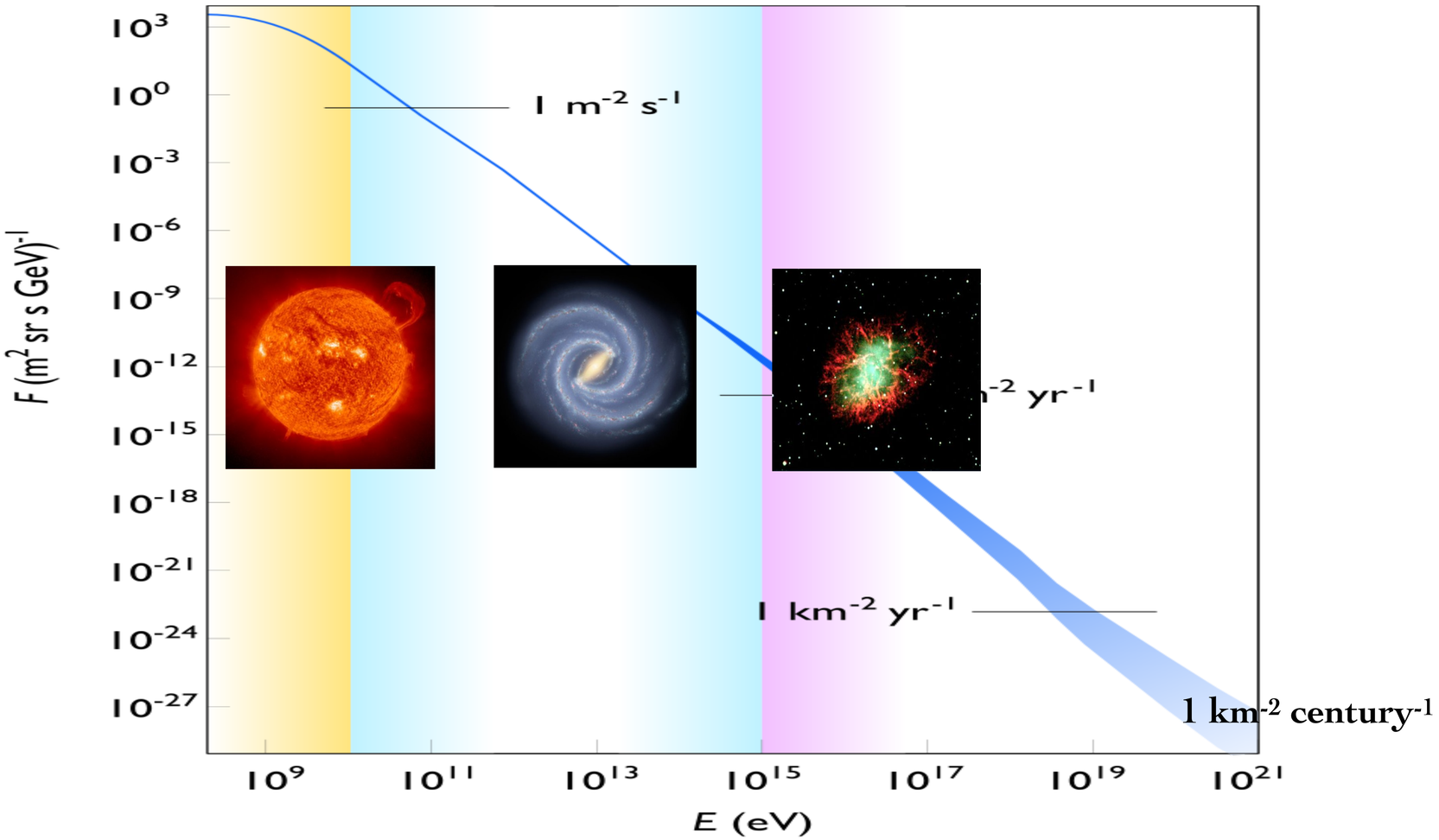
Cosmic ray energy spectrum



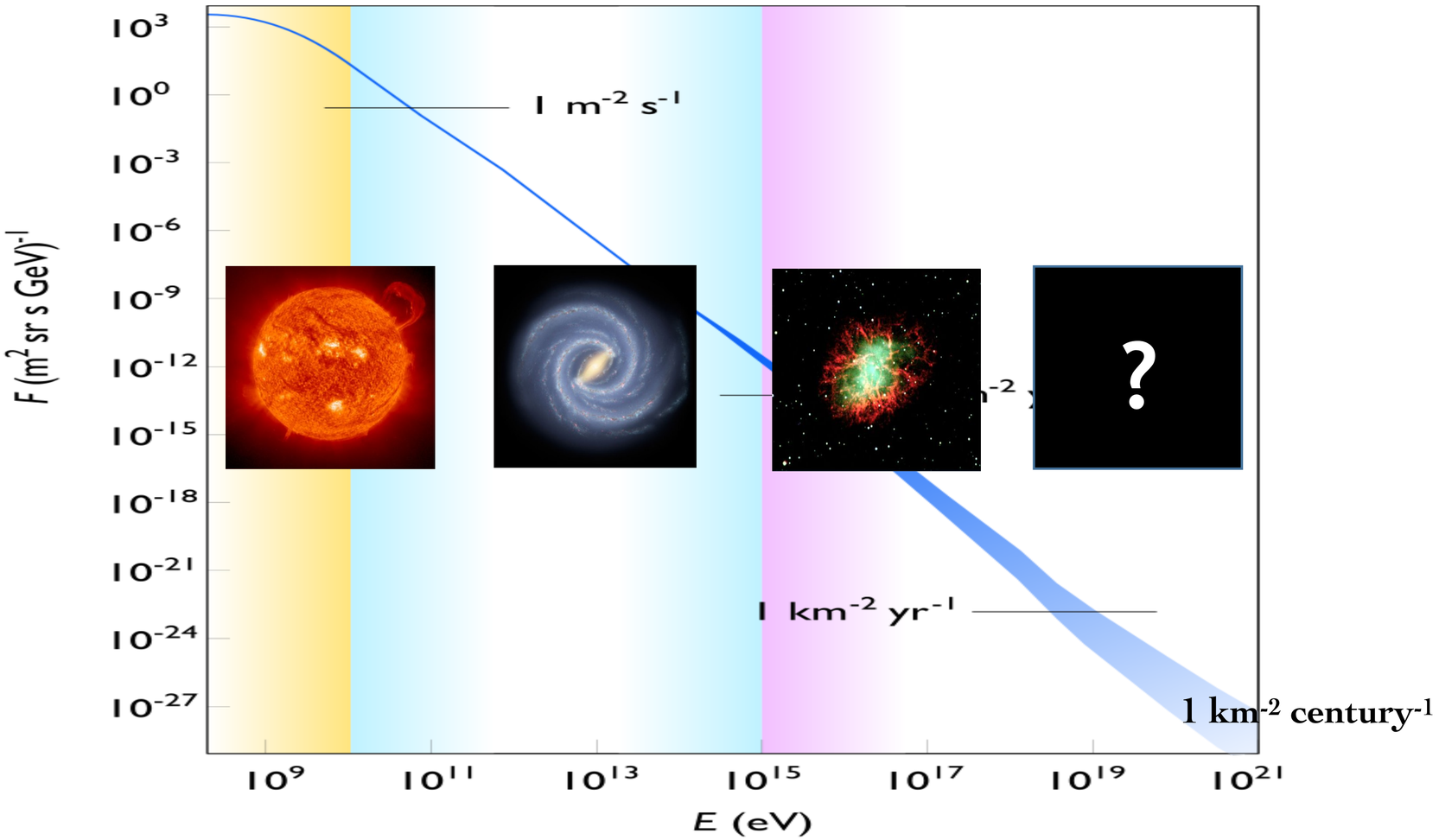
Cosmic ray energy spectrum



Cosmic ray energy spectrum



Cosmic ray energy spectrum



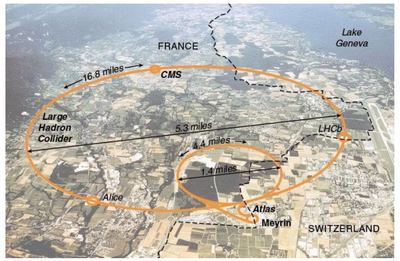
Ultra high energy cosmic rays

- Extremely rare: 1 particle / km^2 / century
- : Highest energy cosmic ray ever observed: $3x10^{20}$ eV

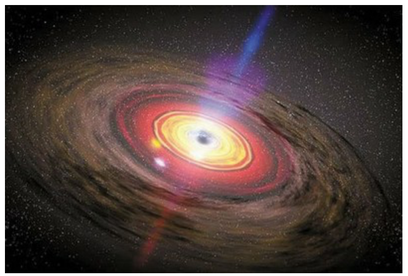
1.5 eV

10 000.0 eV

6 500 000 000 000.0 eV

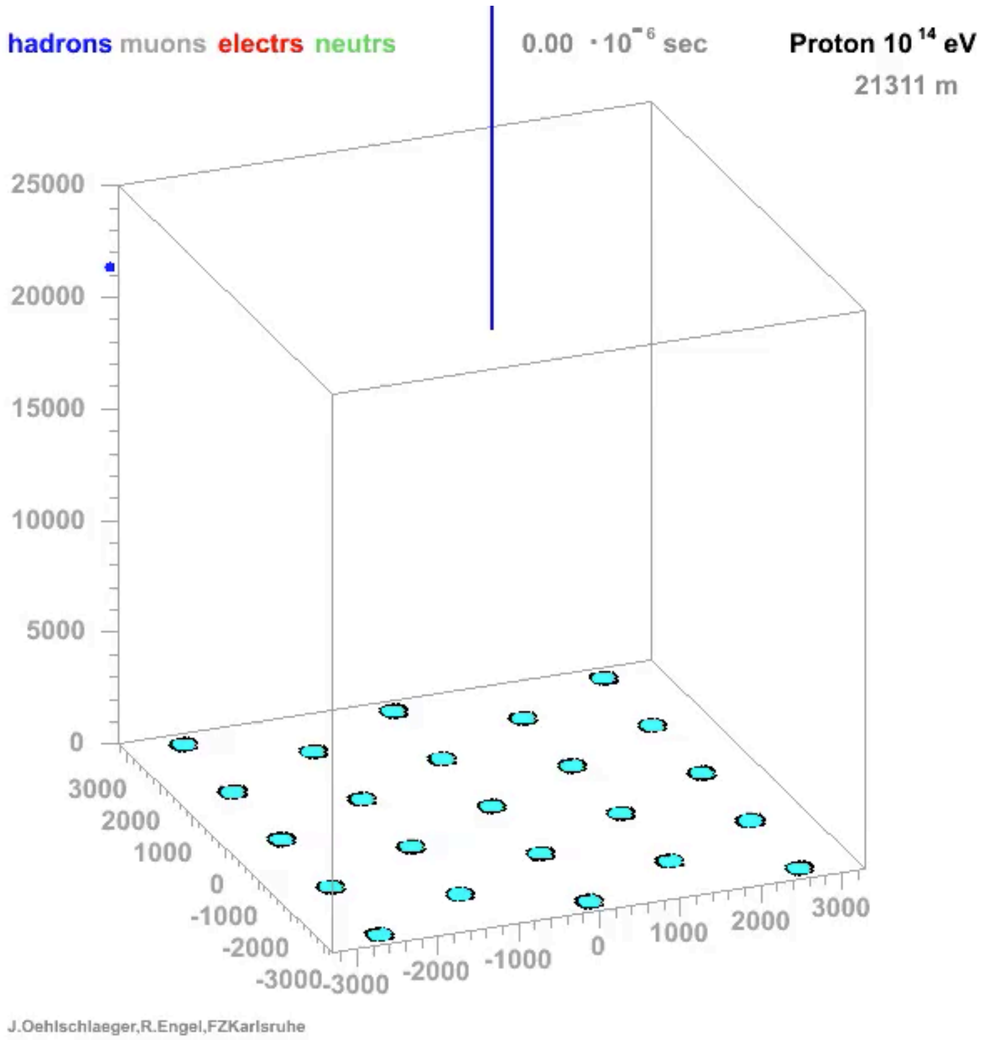


3 000 000 000 000 000 000 000.0 eV



Extensive Air Showers

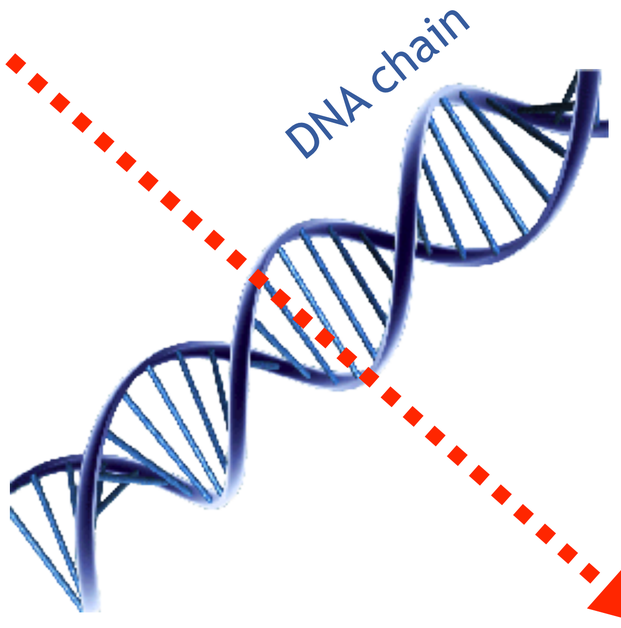
- If the energy of the cosmic ray that enters the atmosphere is sufficiently high it produces a **cascade of particles**
- When **muons** are produced they can reach the Earth surface due to:
  - Low interaction cross-section
  - Special relativity time dilation



Muon sparks chamber @ LIP

The big question

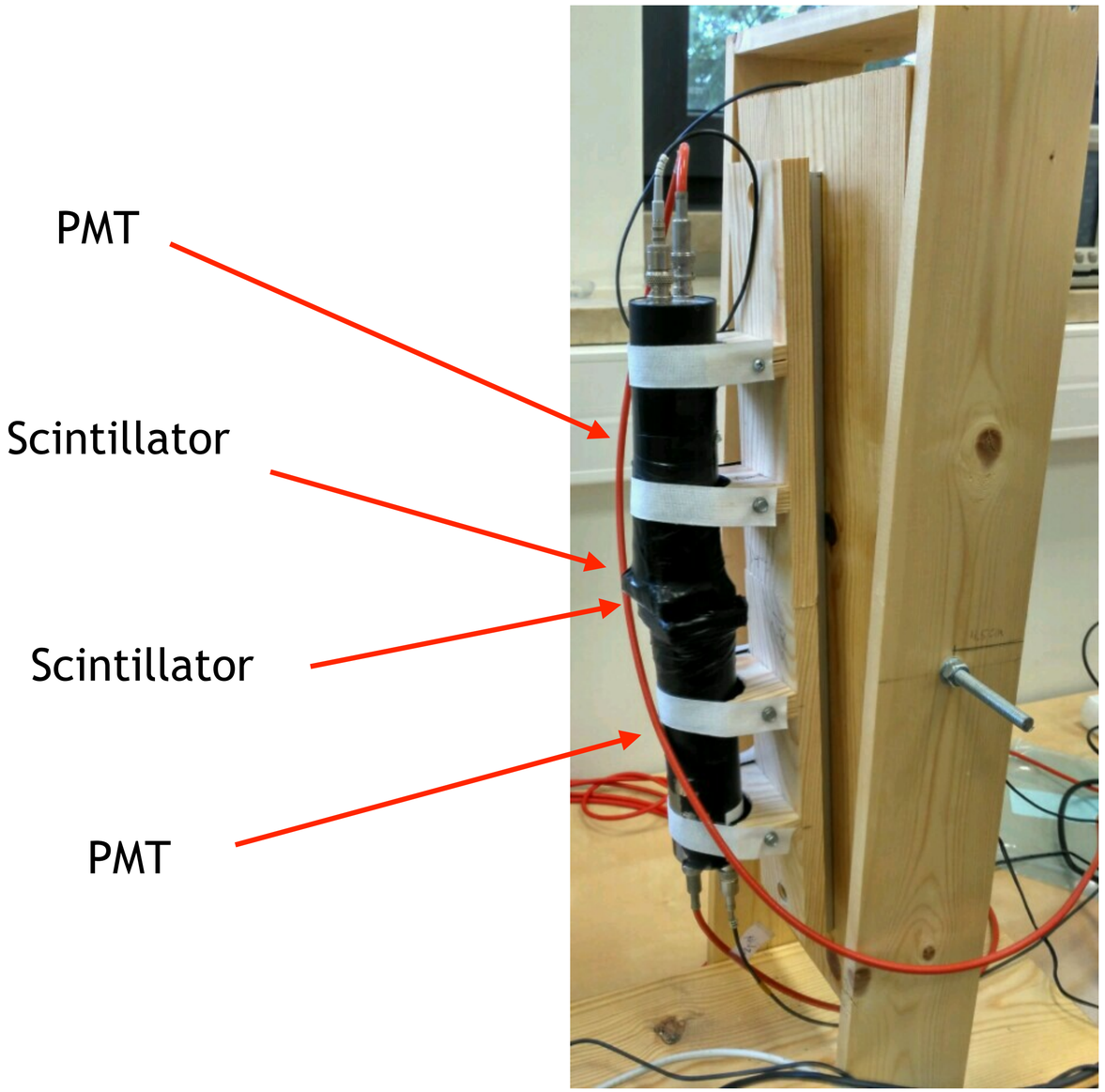
How many muons (radiation) cross my hand per unit of time?



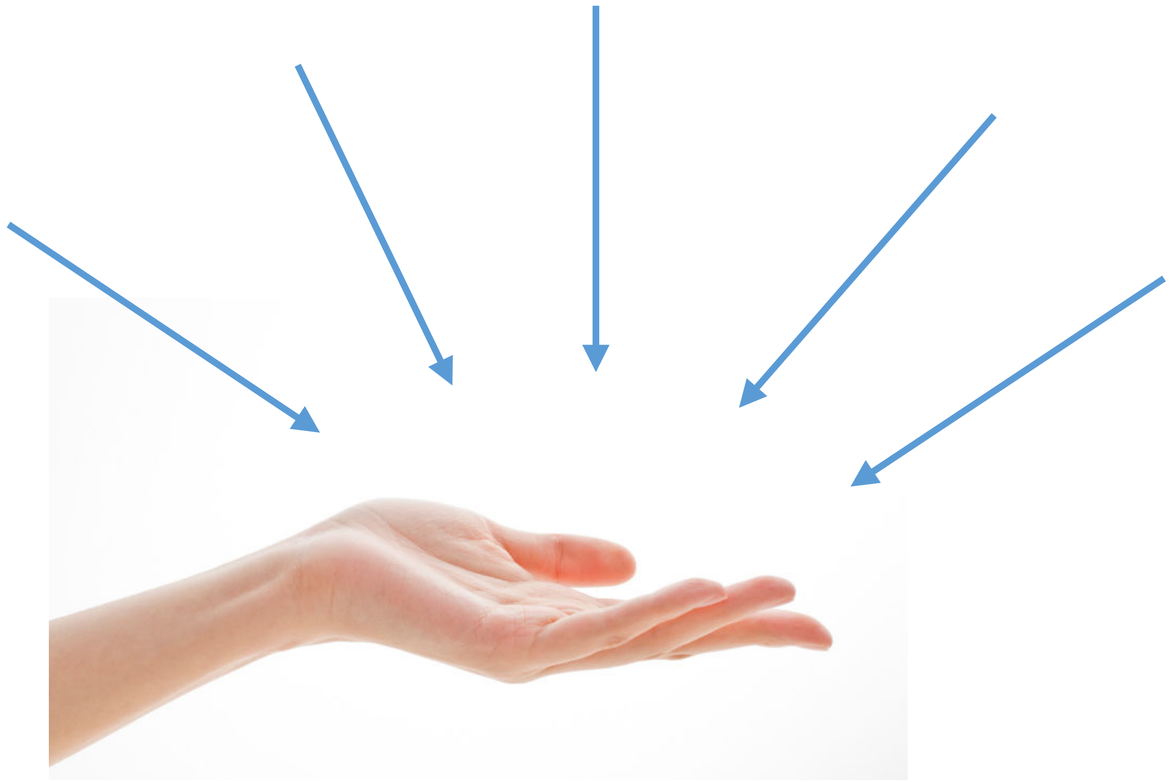
Muon
Ionising radiation!!

What do we have?

- **Telescope**:
  - 2 *PMTs* each coupled to a *scintillator*
    - Why?
  - The systems detects coincidences
  - The system can be moved as a whole and the PMTs can be moved apart
    - Advantages/disadvantages?

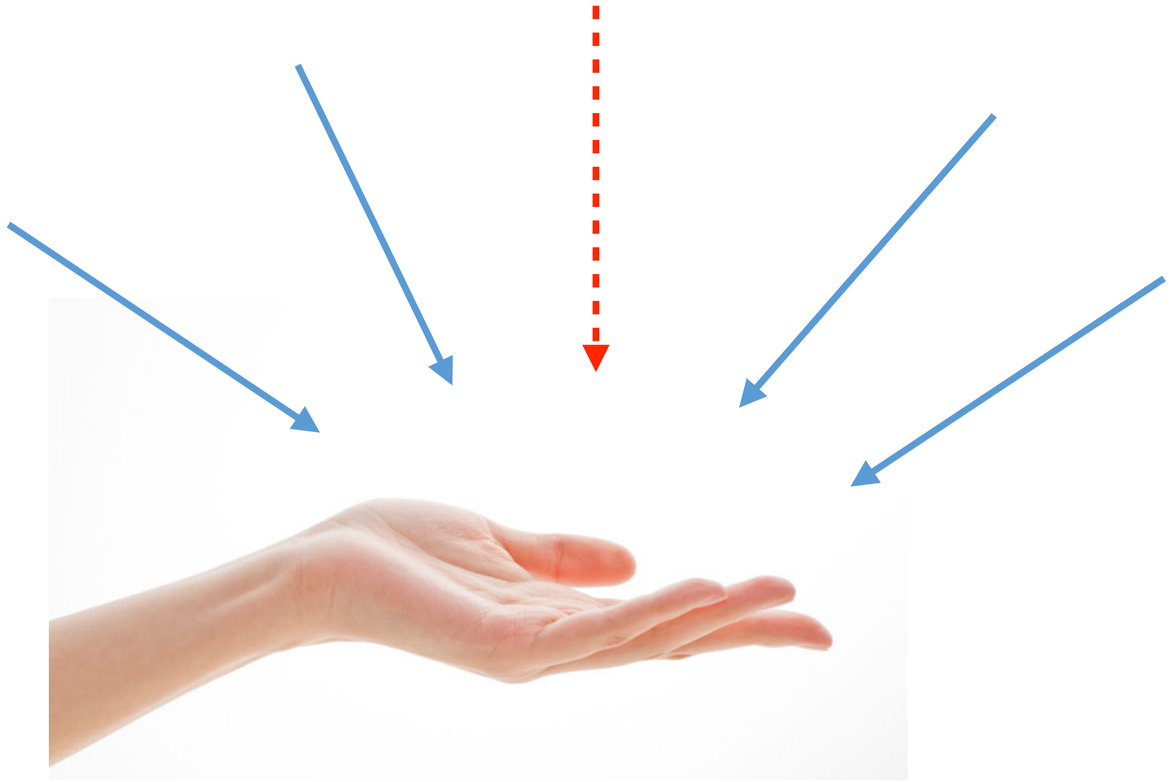


Let’s plan an experiment!



- To know the rate at our hand we need know:
  - Area of the hand
  - Flux for each direction

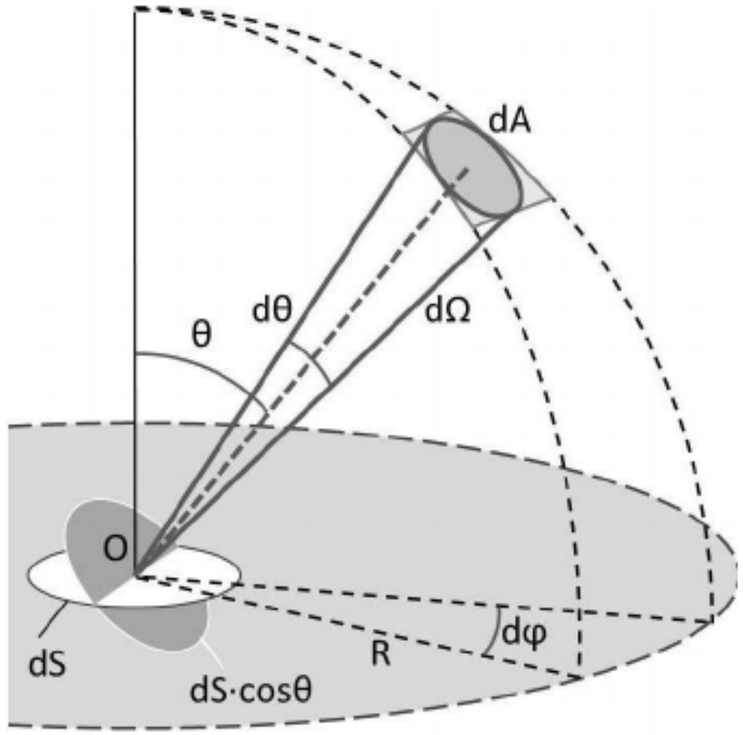
Let’s plan an experiment!



- To know the rate at our hand we need know:
  - Area of the hand
  - Flux for each direction
    - Find the dependence with direction, f(**θ**)
    - Find the vertical flux, I_0

How to compute the rate?

$$\begin{aligned}\text{Rate} &= \int I_0 f(\theta)\cos(\theta) d\Omega dS \\ &= I_0 A_{det} \int f(\theta)\cos(\theta)\sin(\theta) d\theta d\phi \\ &= 2\pi I_0 A_{det} \int_{\theta_{min}}^{\theta_{max}} f(\theta)\cos(\theta)\sin(\theta) d\theta\end{aligned}$$

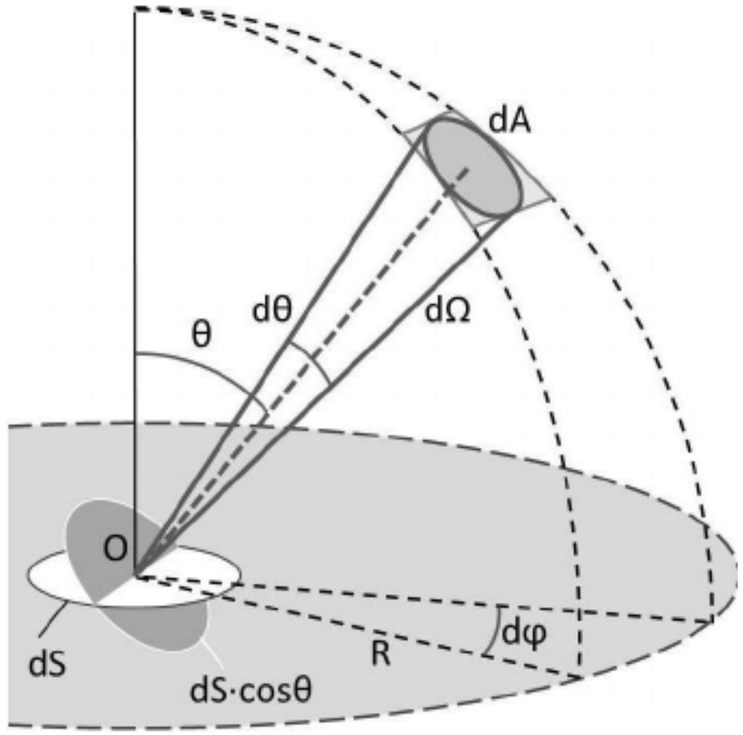


How to compute the rate?

$$\text{Rate} = \int I_0 f(\theta)\cos(\theta) d\Omega dS$$

$$= I_0 A_{det} \int f(\theta)\cos(\theta)\sin(\theta) d\theta d\phi$$

$$= 2\pi I_0 A_{det} \int_{\theta_{min}}^{\theta_{max}} f(\theta)\cos(\theta)\sin(\theta) d\theta$$



Let's start by finding the functional form of f(θ)!!

The measurement

Inclination	Time Interval	Number of events	Rate (Hz)	Error in Rate
0°				
30°				
60°				
90°				

- Time to fill this table
  - First two columns : *measure using the telescope*
  - Last two columns : *compute using measured data*

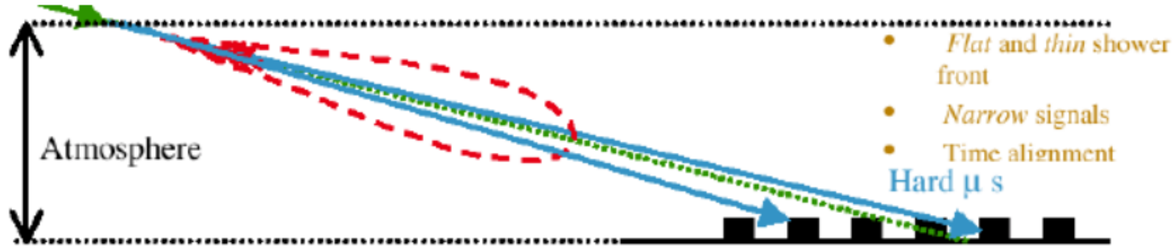
Formulas

$$\text{Rate} = \frac{\text{Counts}}{\text{Time interval}} = \frac{N}{\Delta t}$$

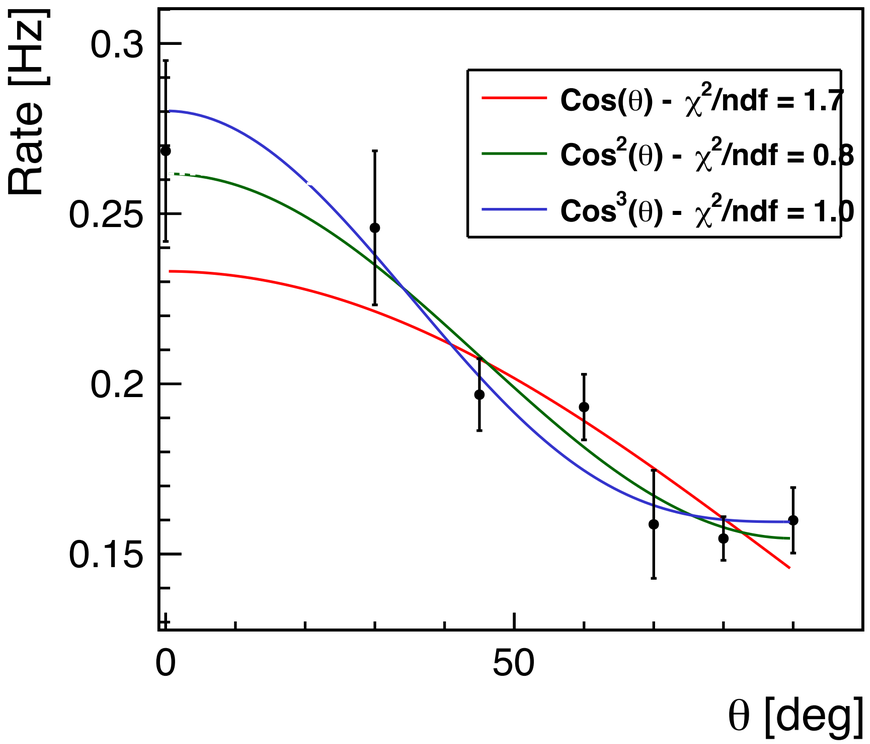
$$(\varepsilon_r)^2 = \left(\frac{dr}{dN}\right)^2 (\varepsilon_N)^2 = \left(\frac{1}{\Delta t}\right)^2 (\sqrt{N})^2$$

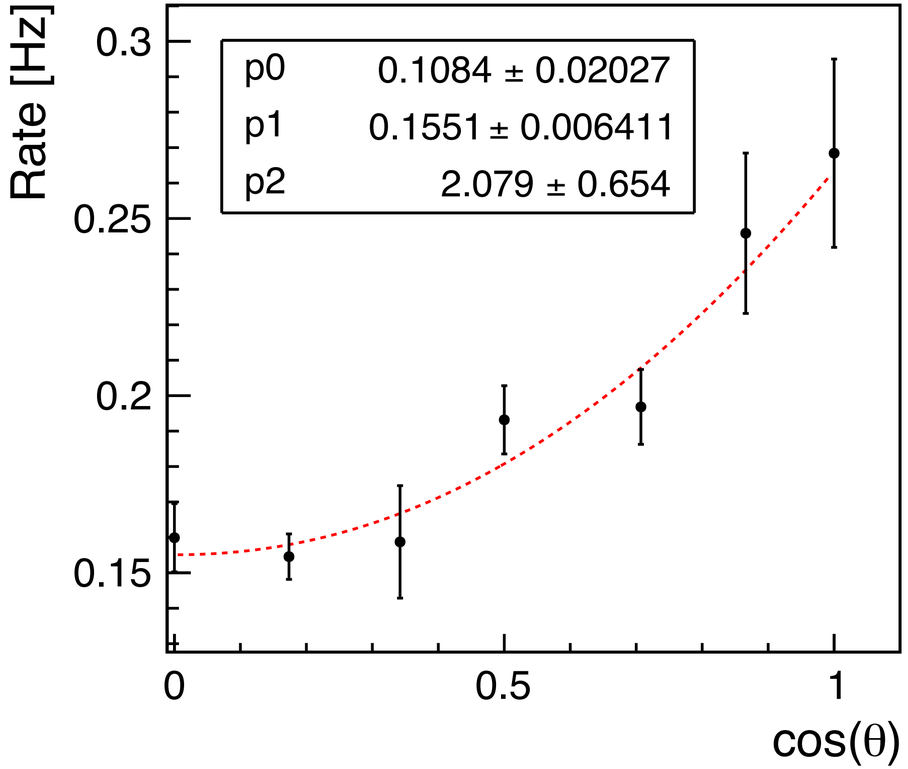
Dependence with zenith angle

- Obtain the functional form of f(θ)
  - Lets try:
    - $f(\theta) = a\cos^{\gamma}(\theta) + b \quad \text{with } \gamma \in [0, 4]$
    - Use this function to fit Rate vs. Zenith angle



Cheating…


Rate [Hz]
0.3
0.25
0.2
0.15
0
50
θ [deg]
Cos(θ) - χ²/ndf = 1.7
Cos²(θ) - χ²/ndf = 0.8
Cos³(θ) - χ²/ndf = 1.0


Rate [Hz]
0.3
0.25
0.2
0.15
0
0.5
1
cos(θ)
p0 0.1084 ± 0.02027
p1 0.1551 ± 0.006411
p2 2.079 ± 0.654

Knowing f(θ) compute I_0

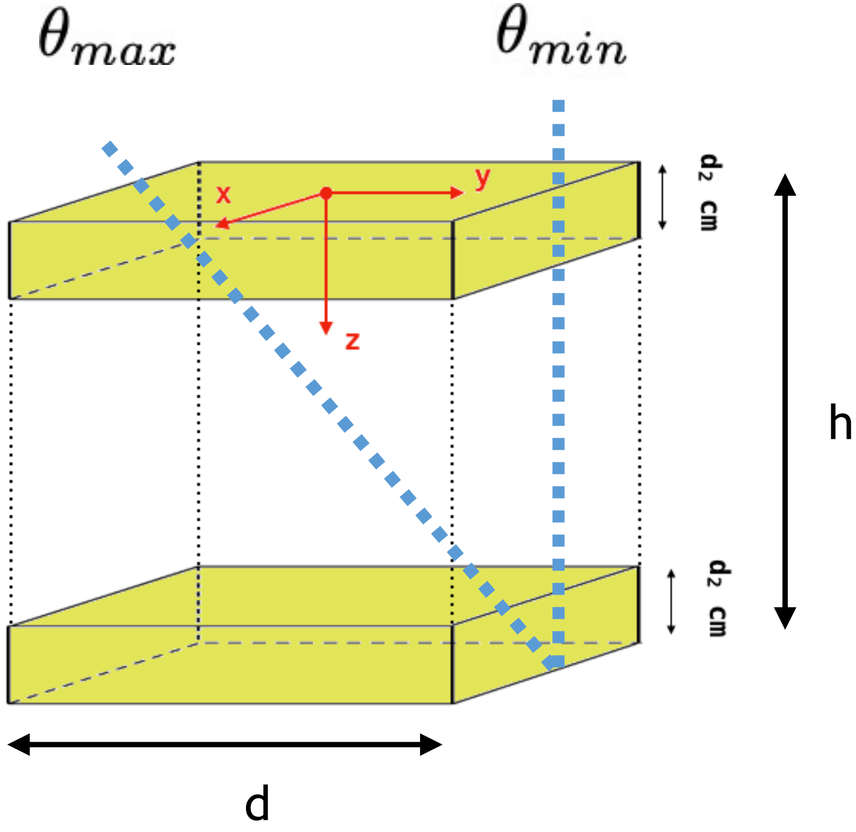
$$\text{Rate} = 2\pi I_0 A_{det} \int_{\theta_{min}}^{\theta_{max}} \cos^2(\theta)\cos(\theta)\sin(\theta)d\theta$$

$$= 2\pi I_0 A_{det} \int_{\theta_{min}}^{\theta_{max}} \cos^3(\theta)\sin(\theta)d\theta$$

$$= 2\pi I_0 A_{det} \left[-\frac{1}{4}\cos^4(\theta)\right]_{\theta_{min}}^{\theta_{max}}$$

$$\theta_{min} = 0°$$

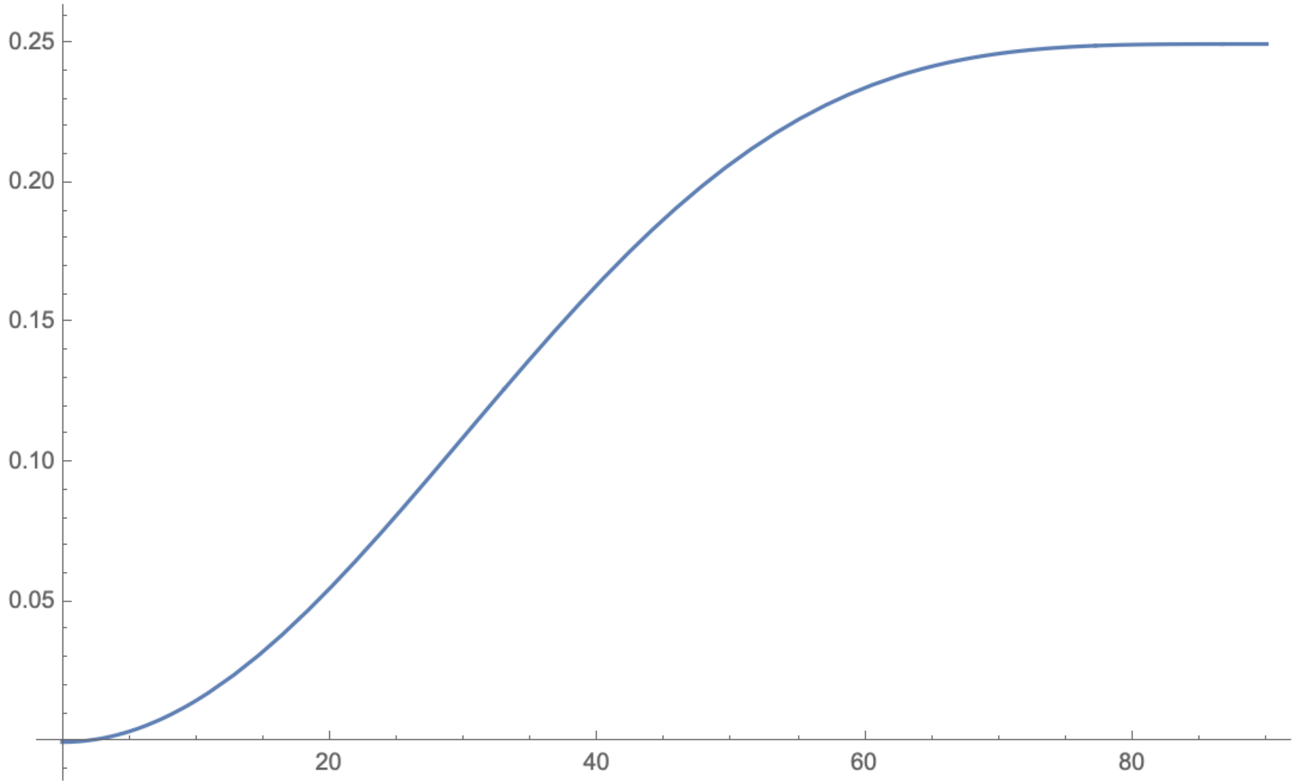
$$\theta_{max} = \arctan\left(\frac{d}{h}\right)$$



Acceptance variation with zenith angle

```
In[28]:= Plot[Evaluate[Integrate[(Cos[x])^3 Sin[x], {x, 0, y Degree}]], {y, 0, 90}]
```

Out[28]=

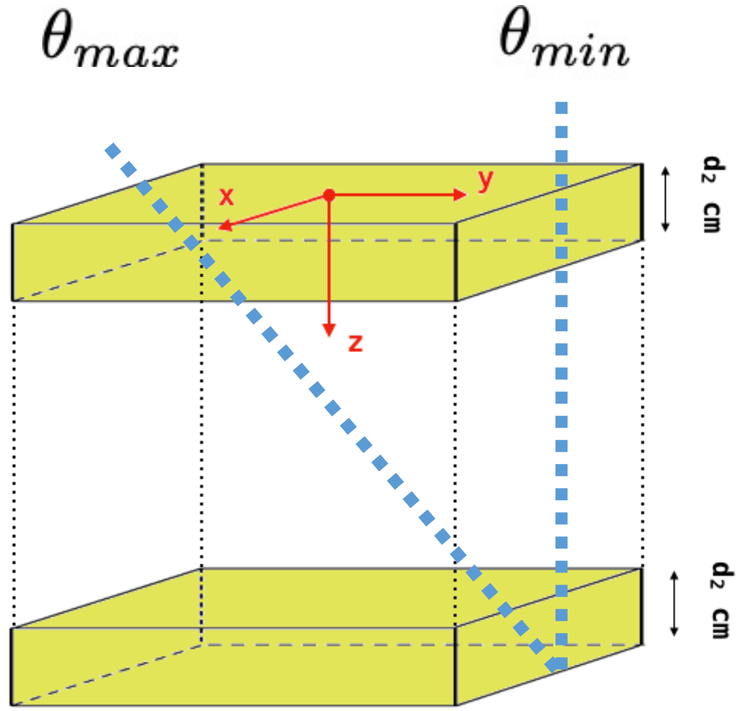


Zenith Angle

Knowing f(θ) compute I_0

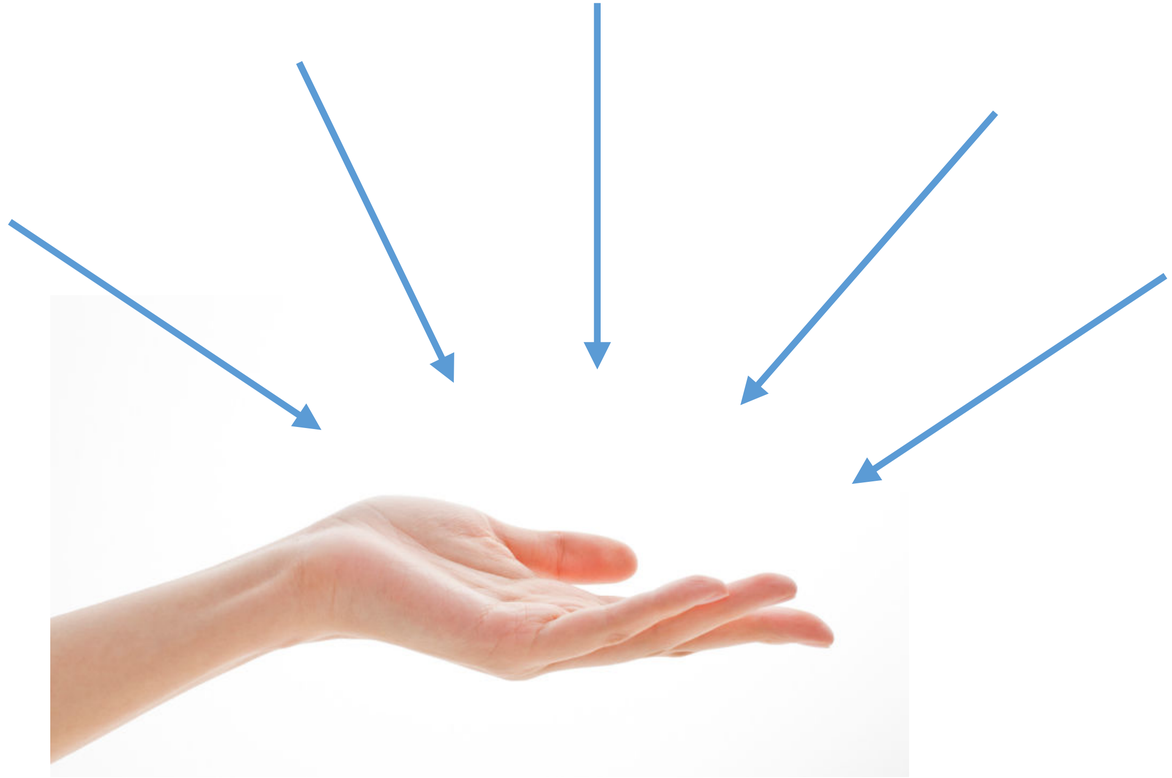
$$\text{Rate} = 2\pi I_0 A_{det} \int_{\theta_{min}}^{\theta_{max}} \cos^2(\theta)\cos(\theta)\sin(\theta)d\theta$$

$$I_0 = \frac{R(\theta = 0°)}{2\pi A_{det}\left[-\frac{1}{4}\cos^4(\theta)\right]_{\theta_{min}}^{\theta_{max}}} \; [\text{cm}^{-2}\,\text{s}^{-1}\,sr^{-1}]$$



- Value taken from literature:
  - $I_0 \approx 70\,\text{m}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$ for $E_\mu > 1\,\text{GeV}$

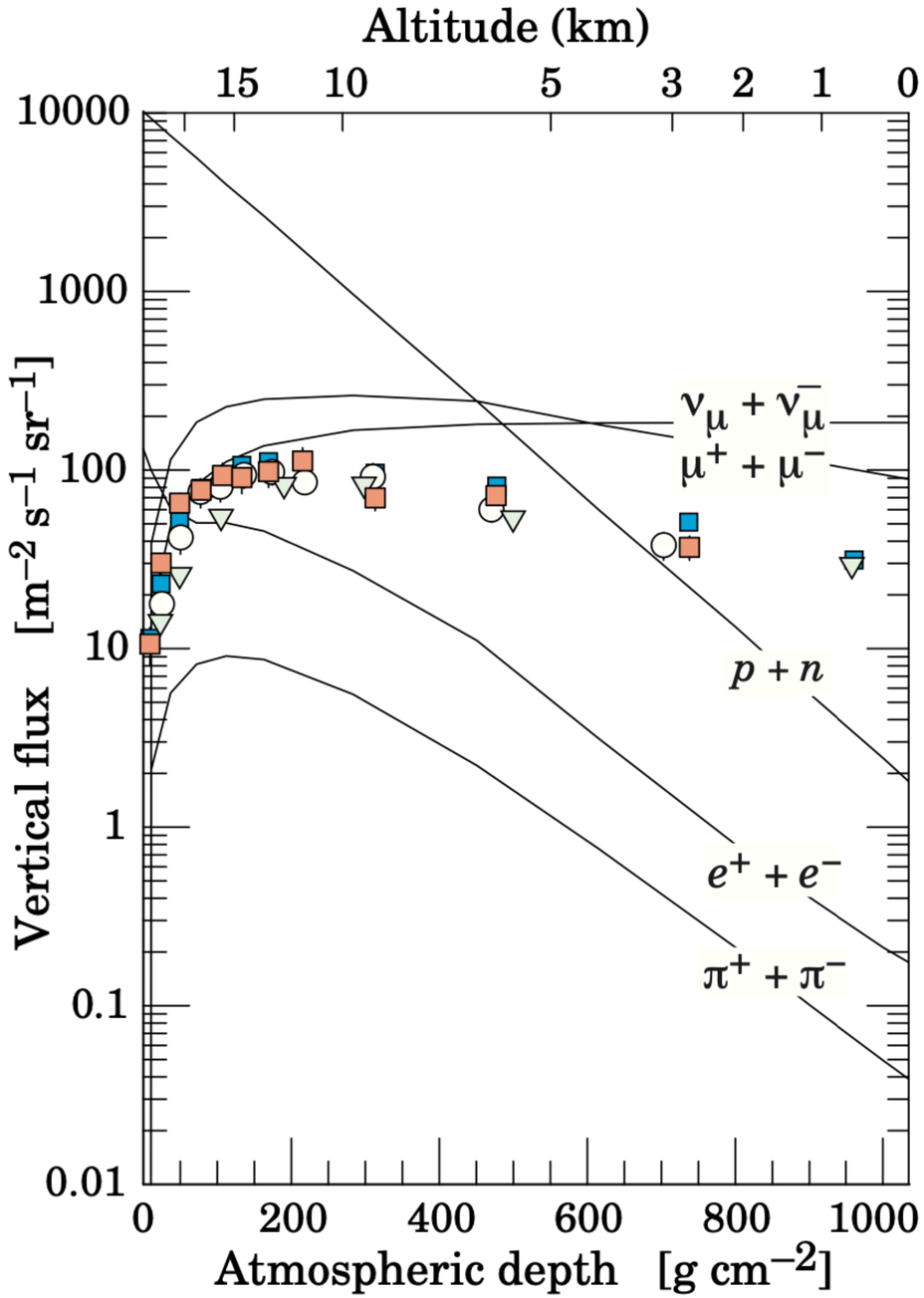
So… How many muons pass by your hand per unit of time?



$$\text{Rate} = 2\pi I_0 A_{det} \left[-\frac{1}{4}\cos^4(\theta) \right]_0^{\frac{\pi}{2}} \quad [\text{muons/s}]$$

Particles flux vs. Altitude

(taken from the PDG)



Acknowledgements

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REPÚBLICA PORTUGUESA

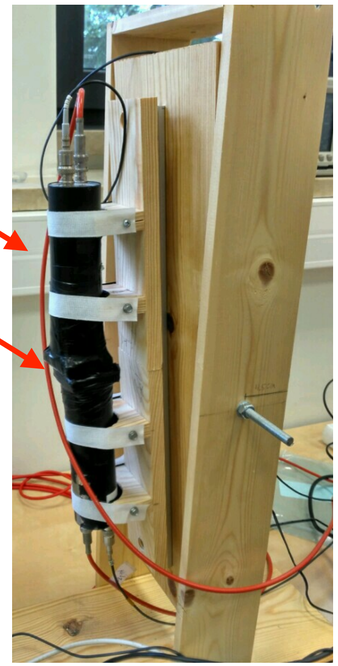
LIP

TÉCNICO LISBOA

Backup slides

Hands-on: Cosmic Rays

- **Cosmic rays**
  - Charged particles accelerated in the cosmos that continuously bombard Earth
- Questions:
  - *Can these harmful particles reach the Earth?*
  - *If yes, what's their rate?*
  - *Does the flux depends on the direction?*



Extensive Air Showers