Radboud Universiteit

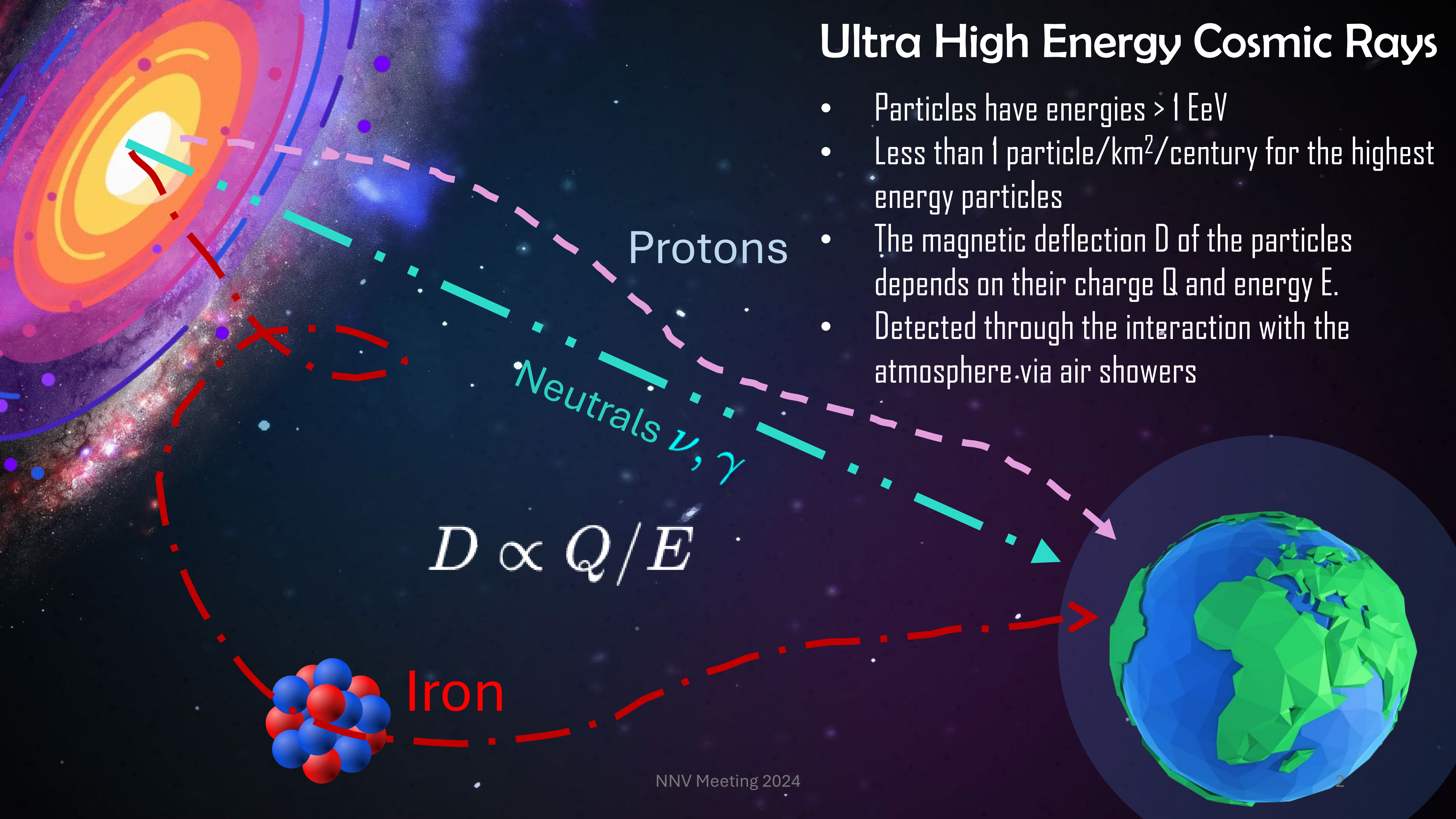
PIERRE AUGER OBSERVATORY

Radio interferometry for AugerPrime RD

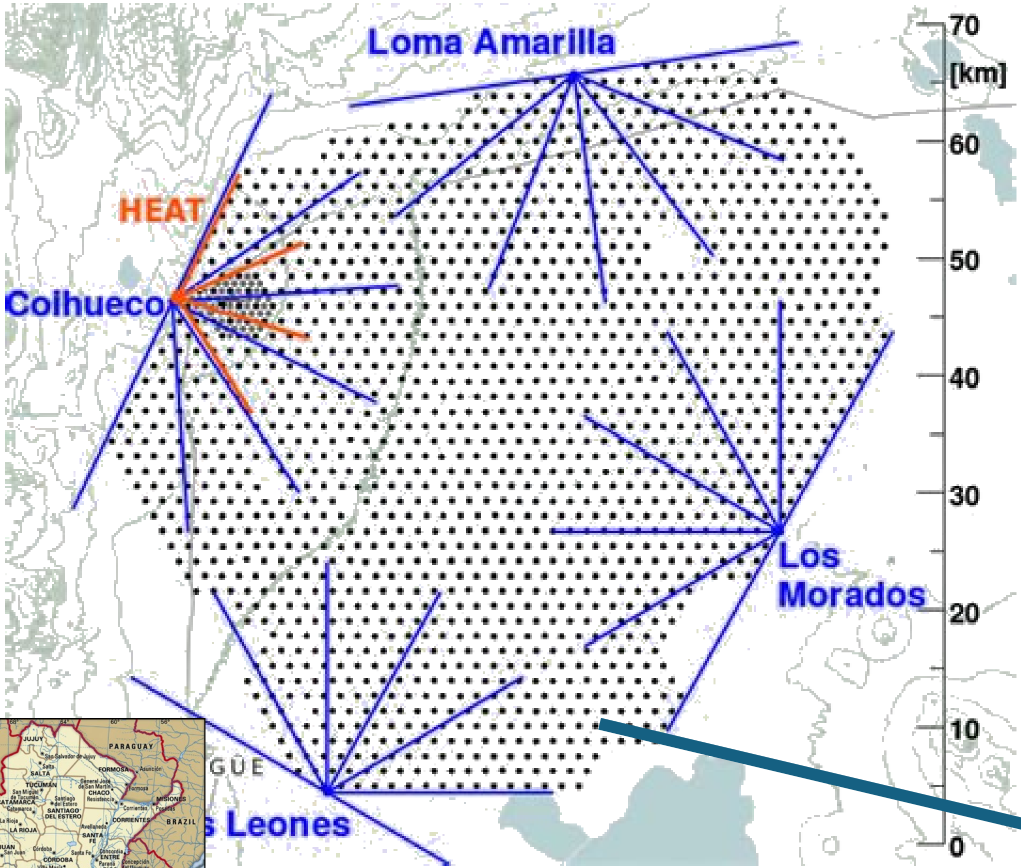
By
Anthony Bwembya
Supervisors:
Harm Schoorlemmer
Charles Timmermans

Ultra High Energy Cosmic Rays

- Particles have energies > 1 EeV
- Less than 1 particle/km^2/century for the highest energy particles
- The magnetic deflection D of the particles depends on their charge Q and energy E.
- Detected through the interaction with the atmosphere via air showers



The Pierre Auger Observatory



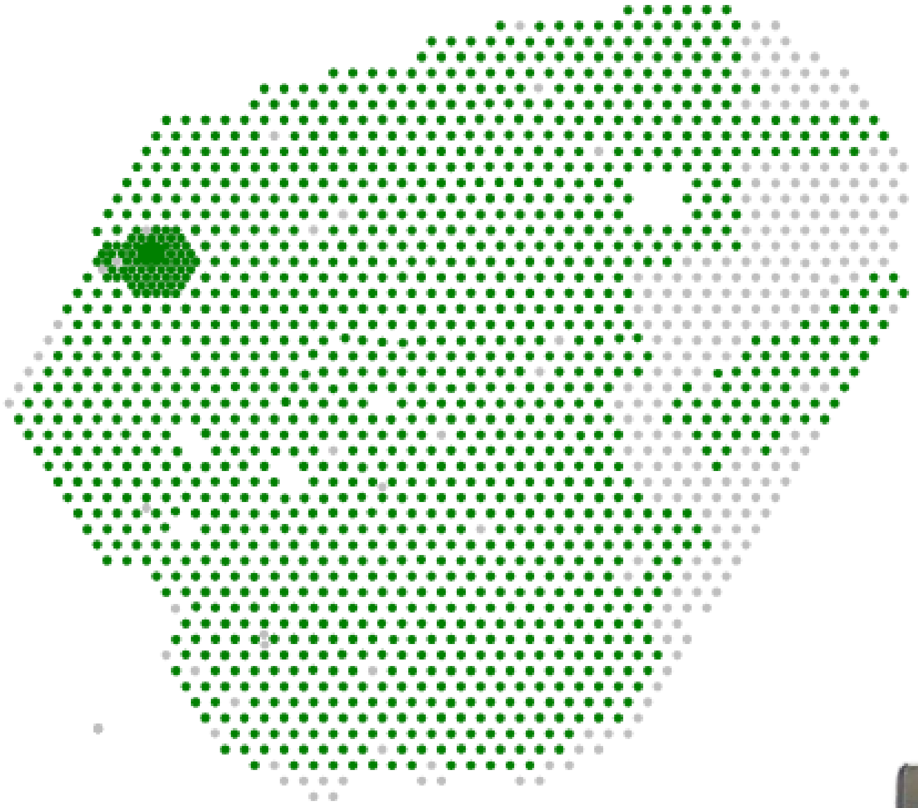
https://east-usa.com/world/images/Argentina.jpg

- located in the Argentinian pampas and has been collecting for 20 years.
- The observatory covers 3000 km^2 in area and comprises of 1660 water Cherenkov tanks.
- Twenty four fluorescence detectors overlooking the array from four locations.
- Currently undergoing an upgrade to **AugerPrime**

Water Cherrn

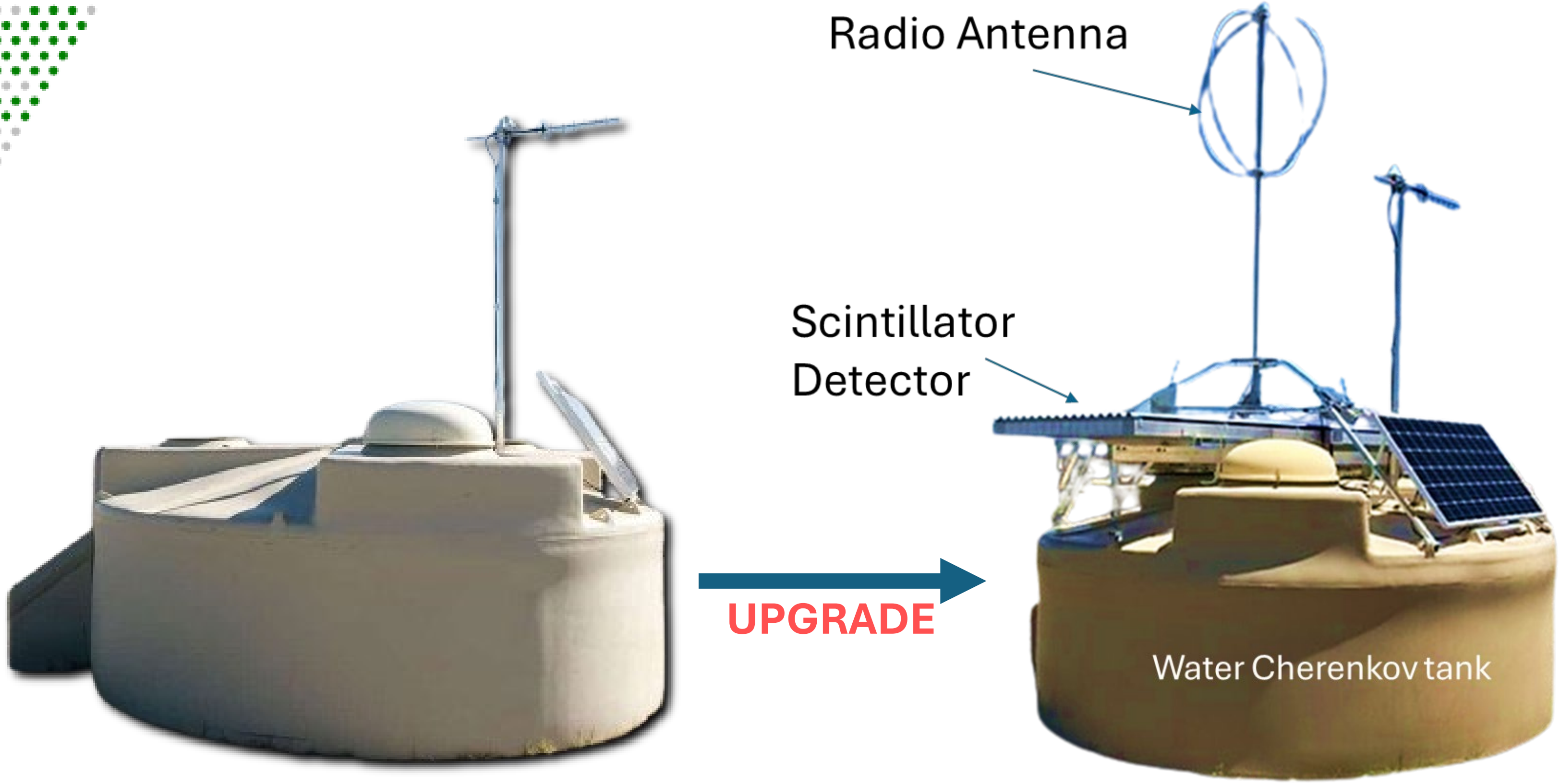
AugerPrime

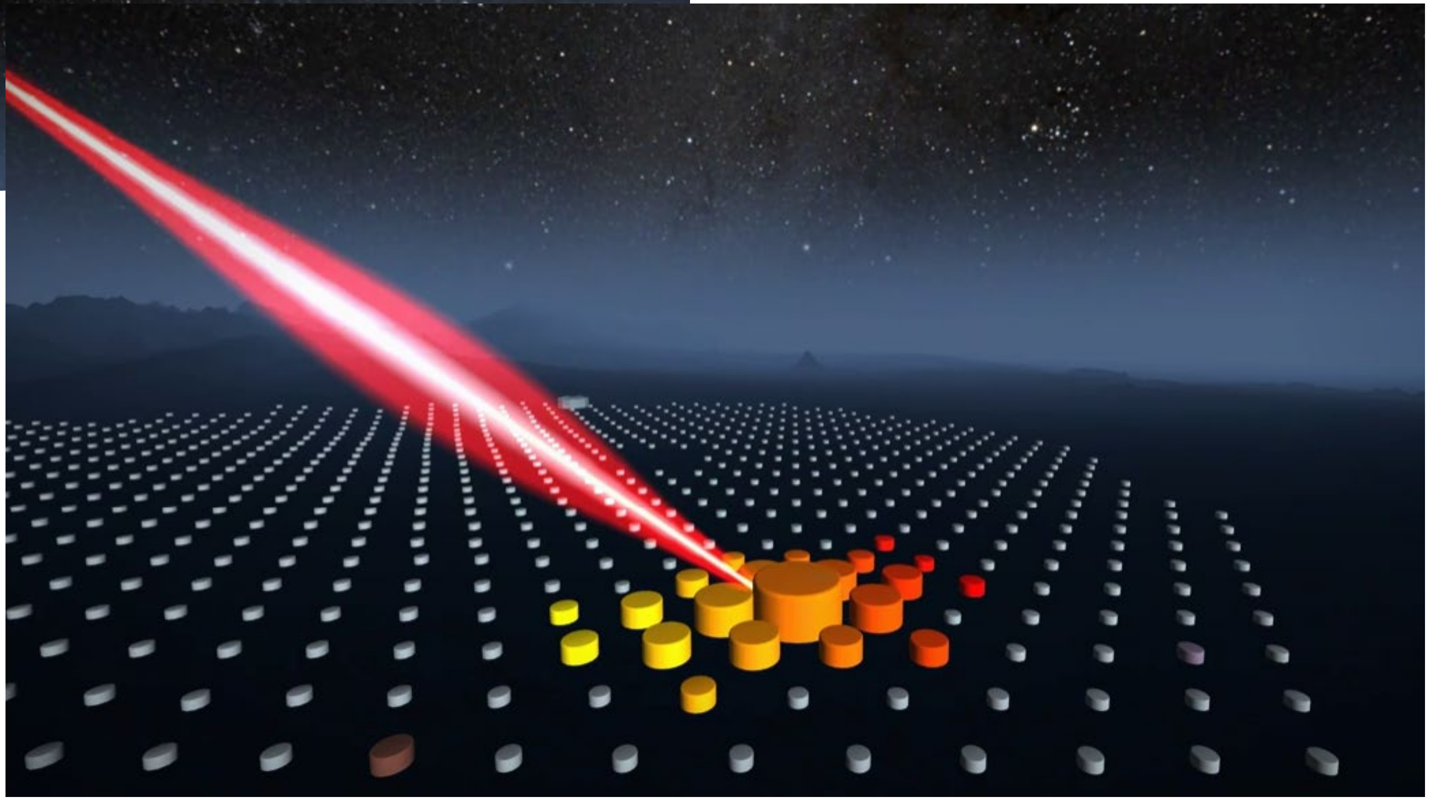
- AugerPrime is set to run for 10 years. New international agreement will be signed this week.
- Extra small PMT, scintillator and radio antenna
- Dutch contribution to upgrade is the radio which will measure very inclined air showers.
- Two polarisations , 30-80 MHz band



1425 Stations Taking Data

11/05/2024

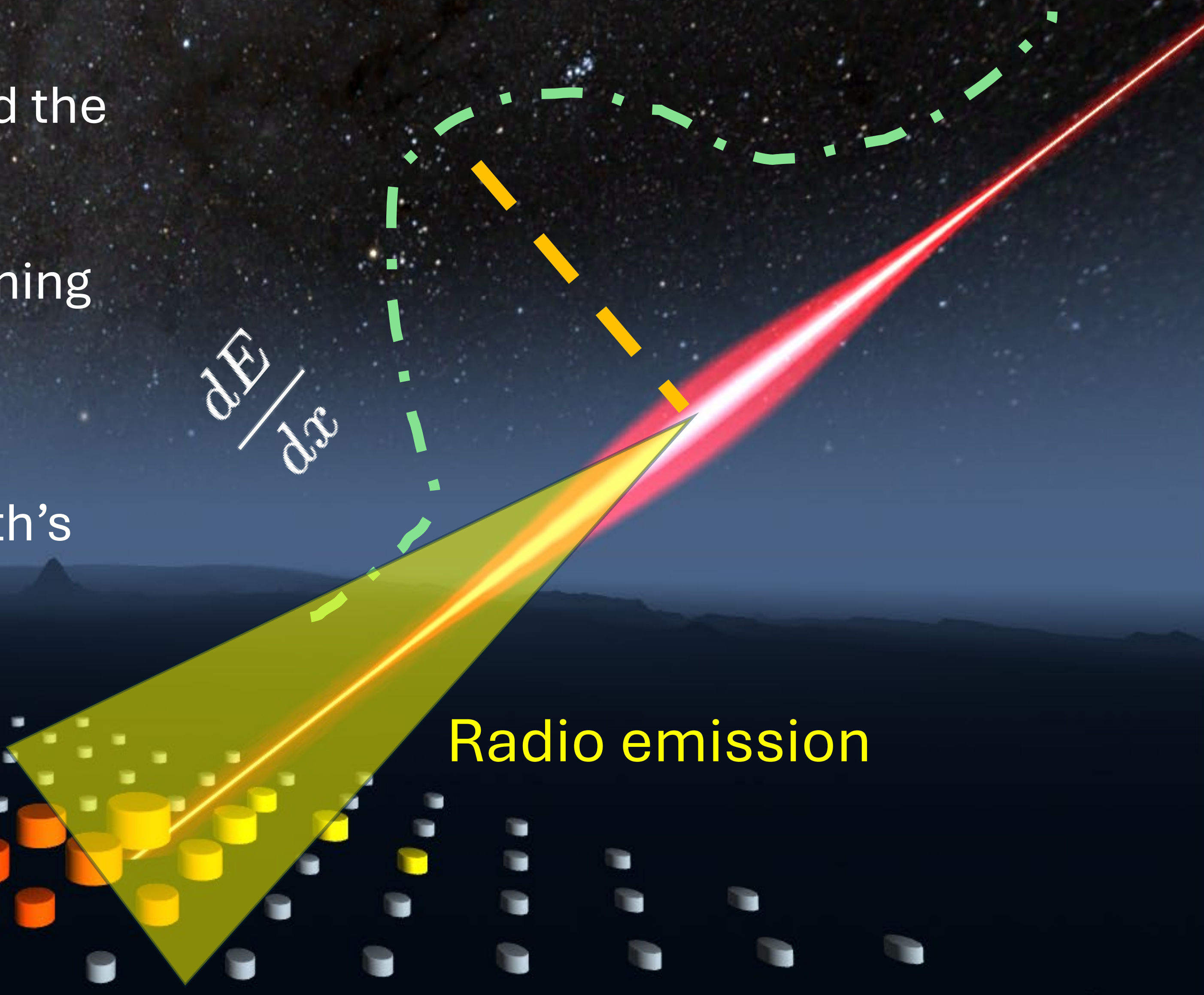




- The primary particle interacts with the atmosphere , creating a cascade of secondary particles.

- This cascade is then measured on the ground to derive the primary particle’s energy, mass and arrival direction .

- The point in particle cascade with the maximum number of particles is called the “Depth of Shower Maximum” or X_{max}
- This depends on the mass of the incoming particle
- A radio signal is generated when the particle cascade interact with the Earth’s magnetic field.

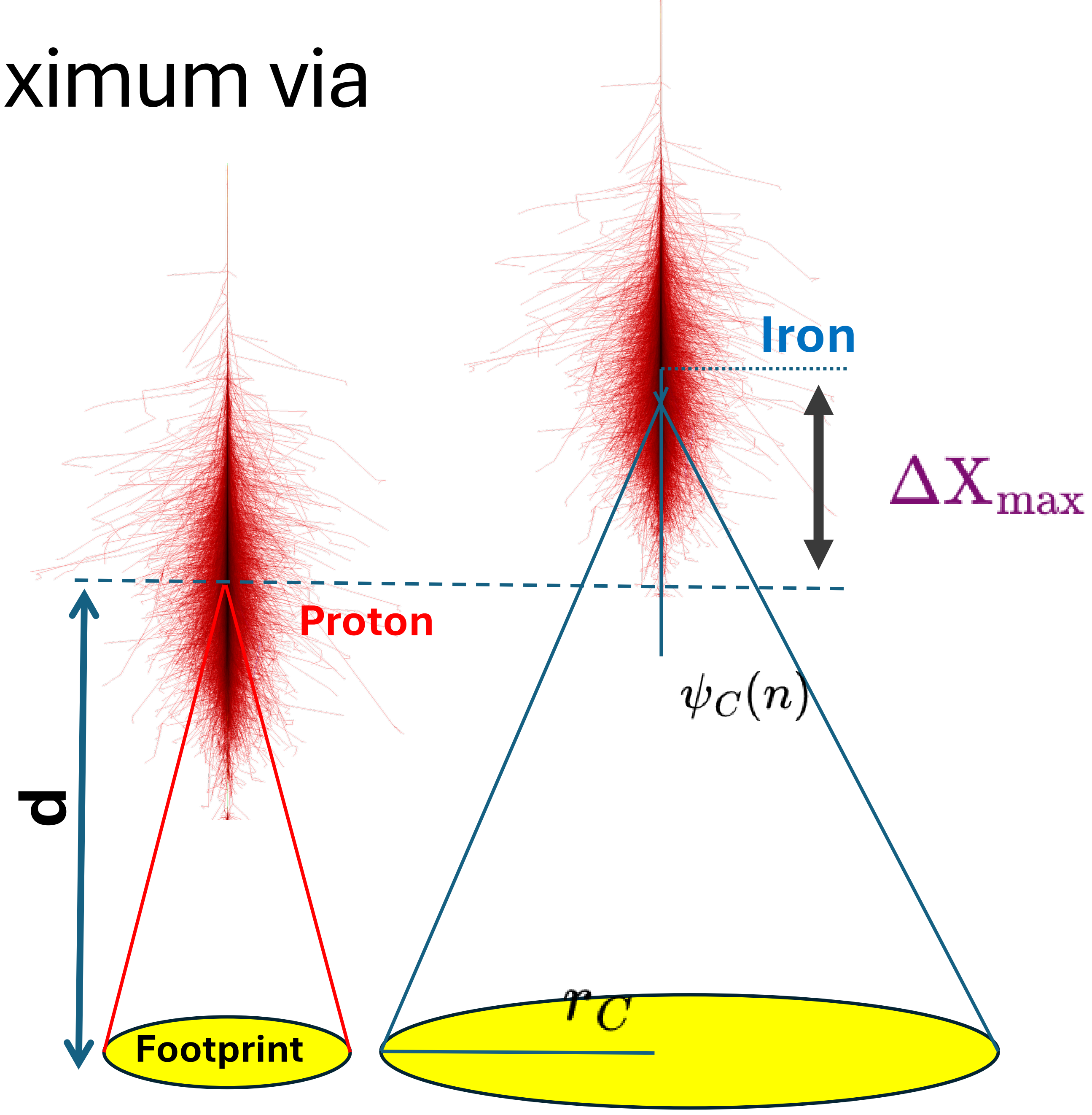


Determining the shower maximum via radio detection

- The determination of the shower maximum is done by measuring the area illuminated on the ground or radio footprint.

- The depth of the shower maximum determines the radius of the footprint.

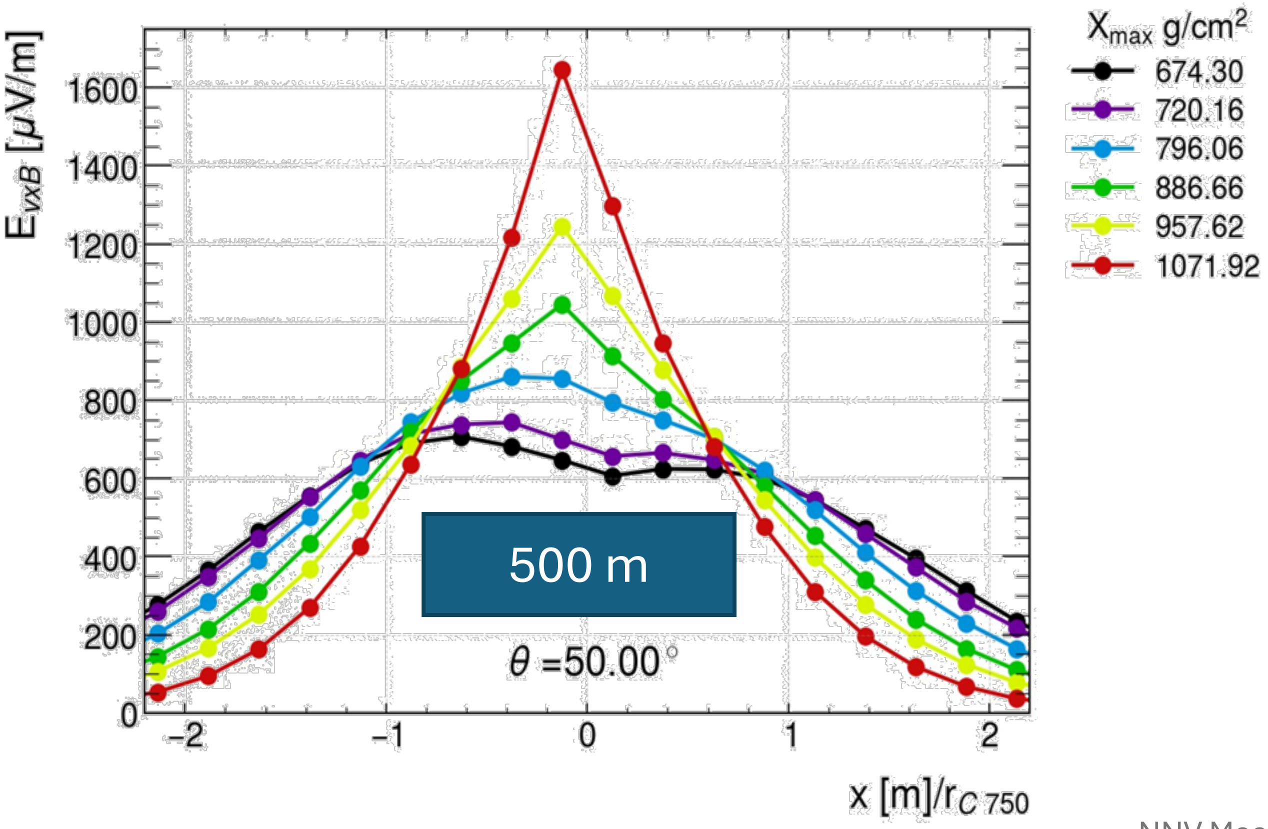
$$r_C = d\tan(\psi_C)$$

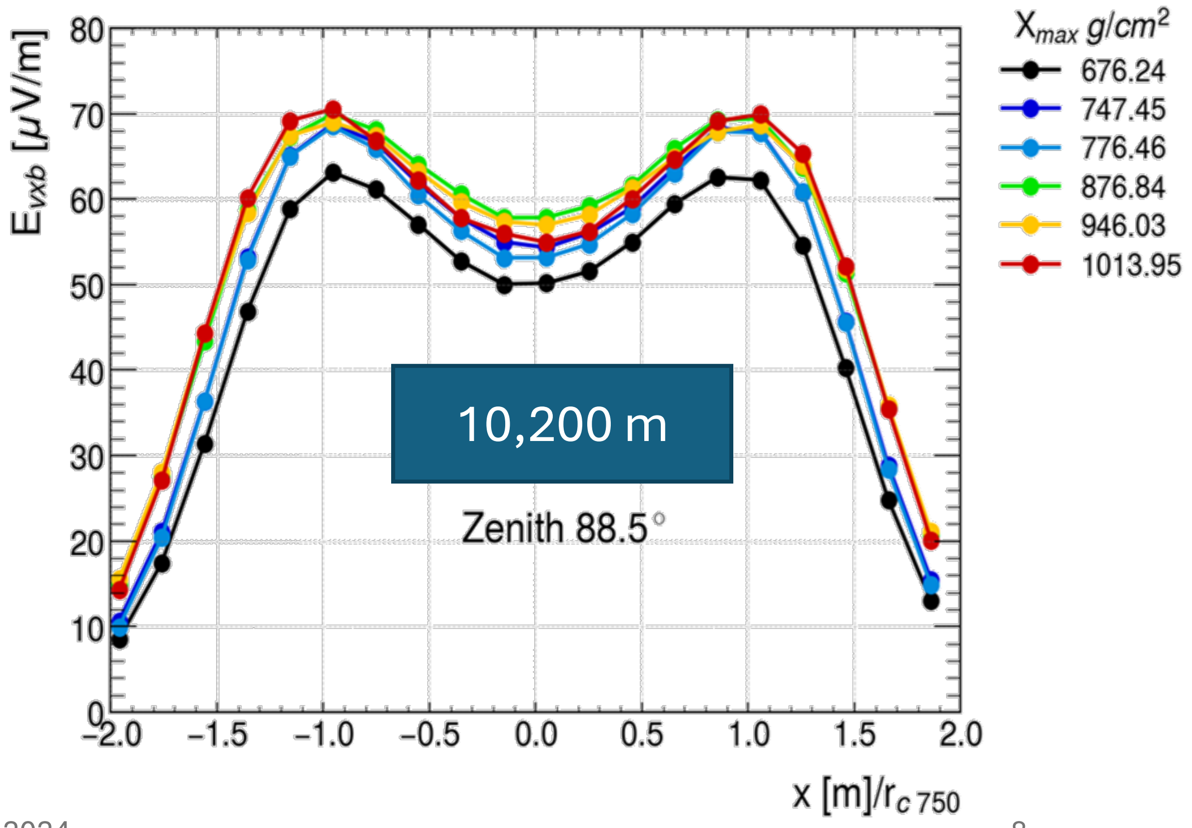


Radio amplitude distribution

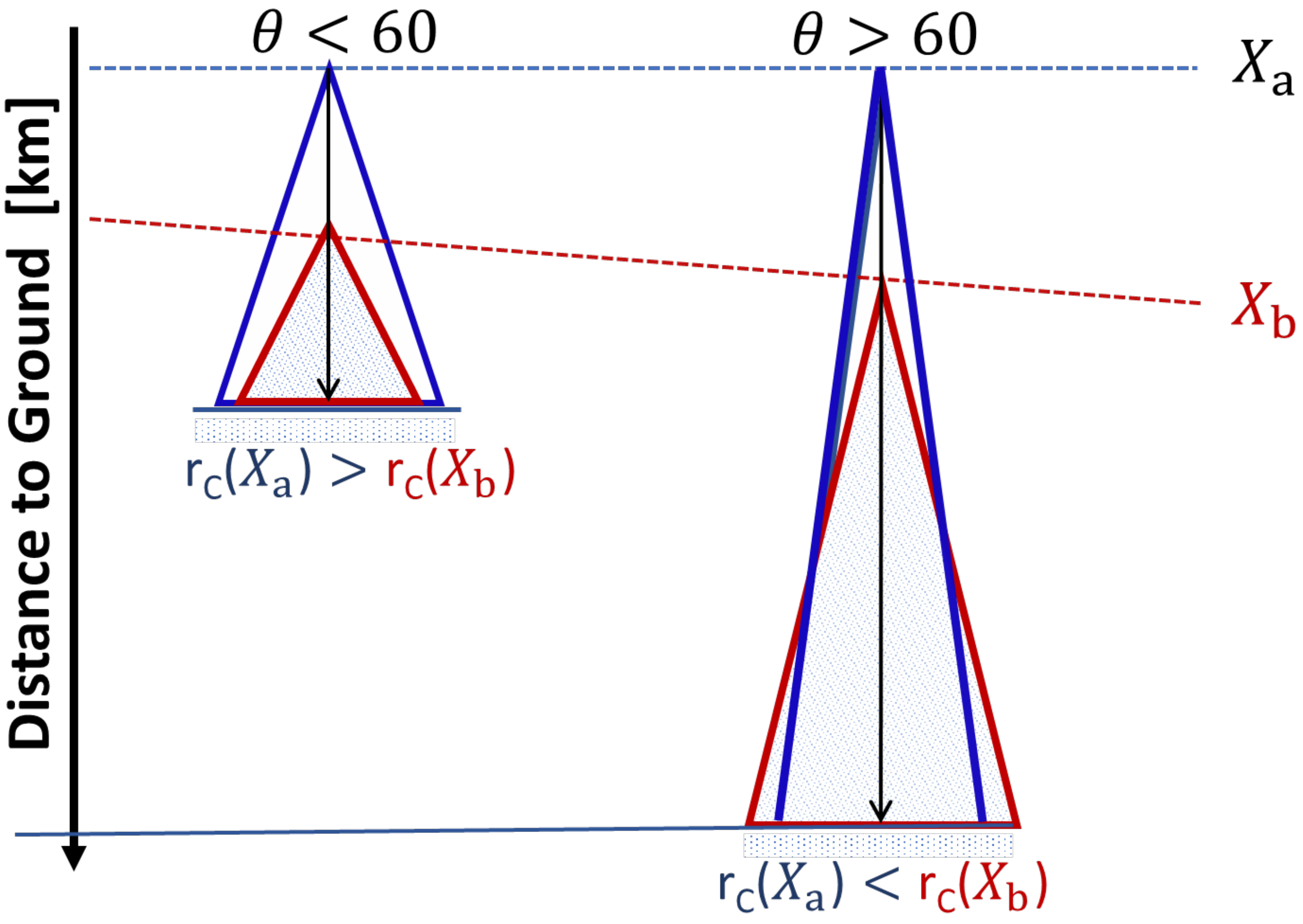
- For small zenith angles < 60 degrees , strong dependance on the shower maximum .
- For showers with zenith angles > 60 degrees, weak/ nontrivial dependance on the shower maximum.

*Simulation:



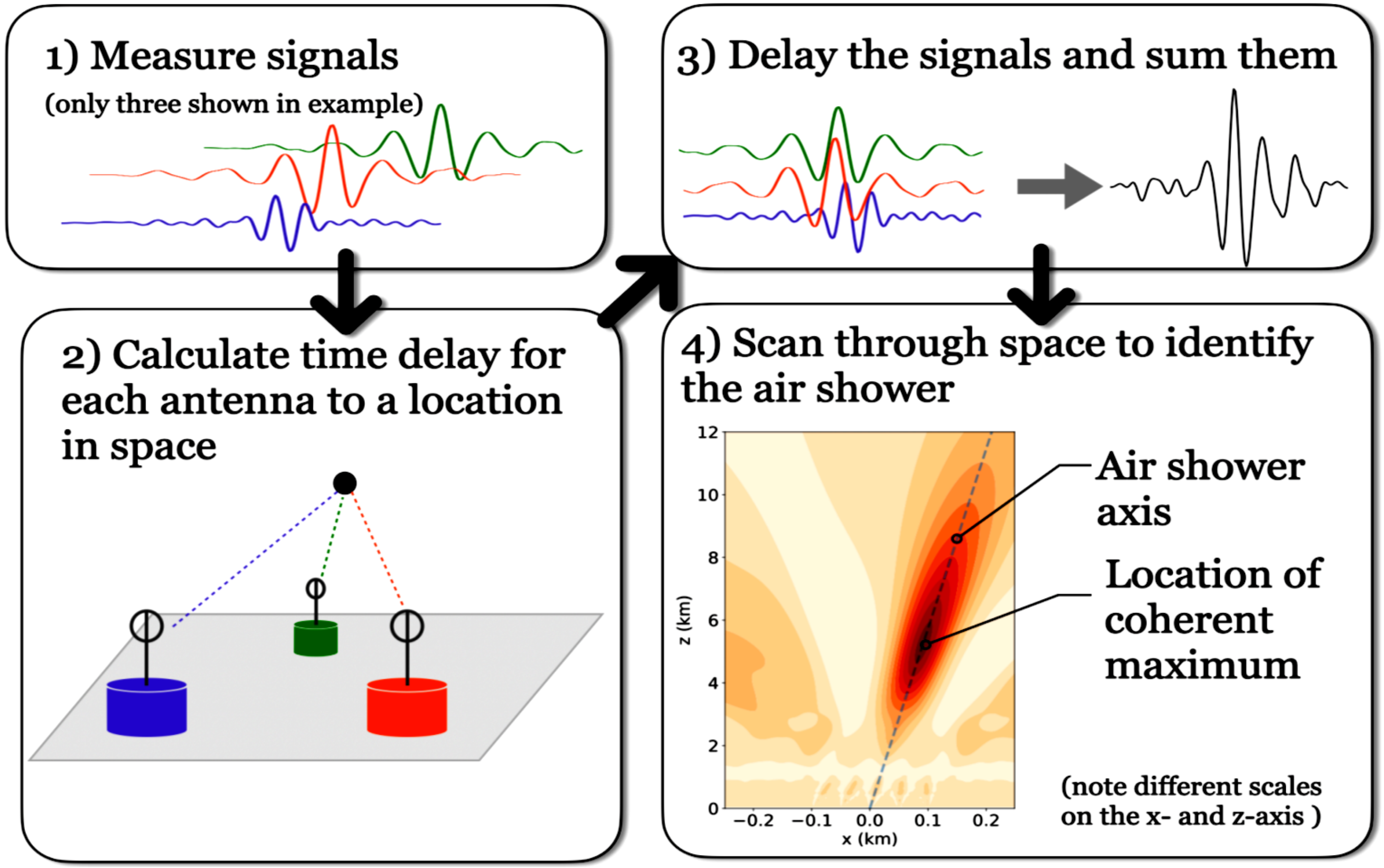


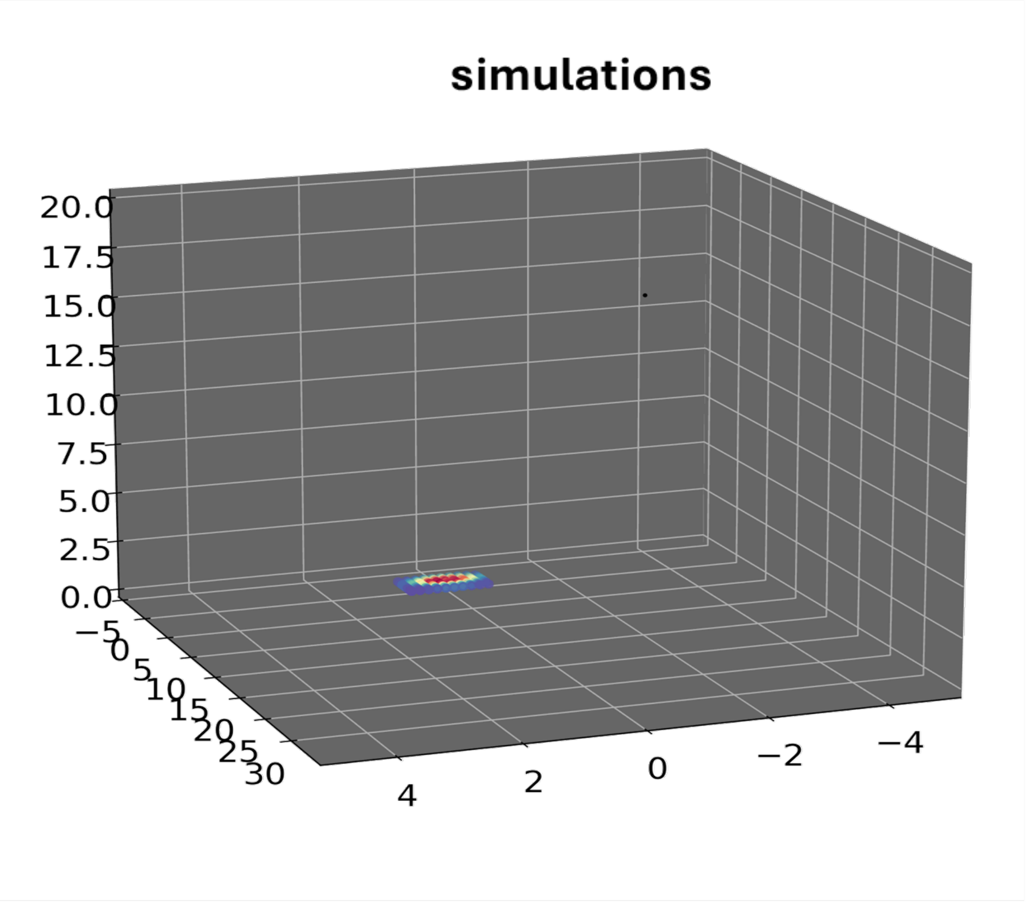
The problem with very inclined showers



- **Shallow showers are at smaller refractive indices and, thus have narrower beams**
- **Deeper showers are at larger refractive indices and, thus have broader beams.**
- **This results in very inclined deep showers projecting larger areas in the ground than shallow ones.**

Solution : Radio interferometry



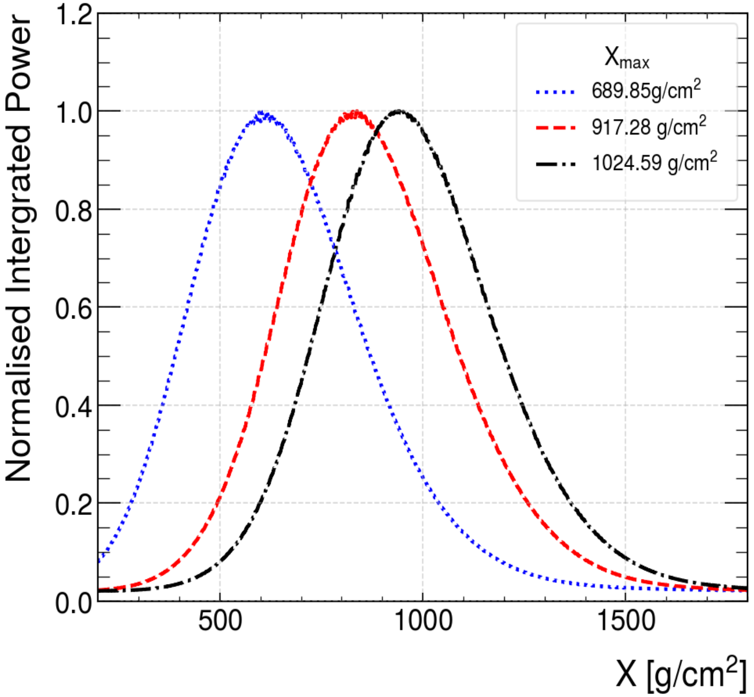


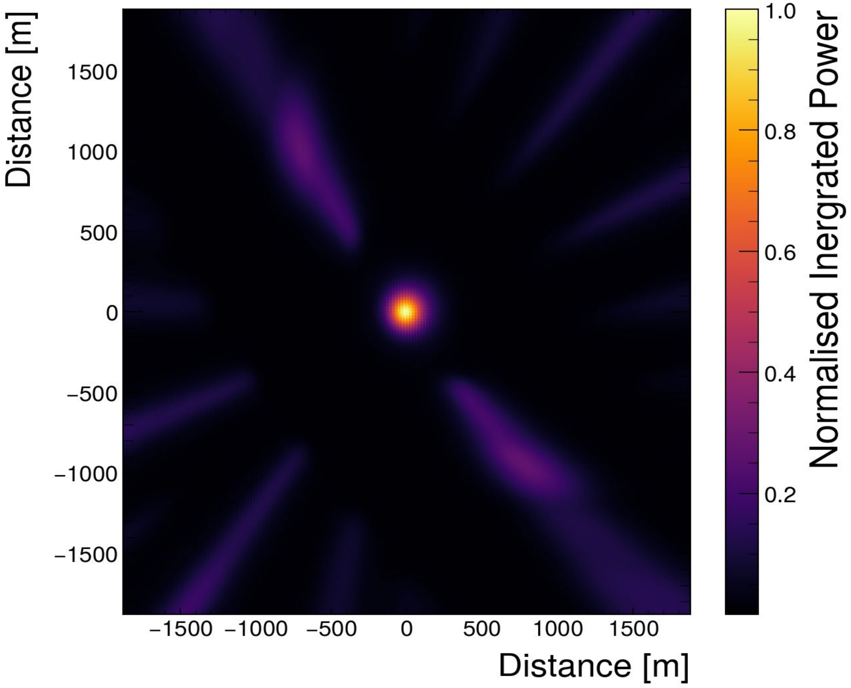
H. Schoorlemmer *et al.*, "Radio Interferometry applied to air showers recorded by the Auger Engineering Radio Array," *ICRC*, Jul. 2023, doi: 10.22323/1.444.0380

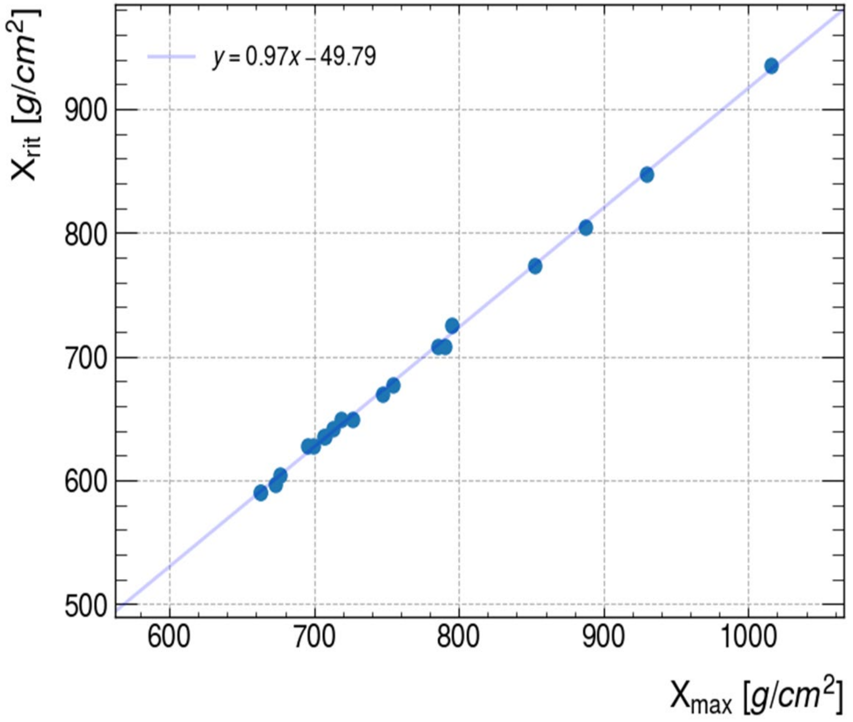
Interferometry for very inclined showers

- Using 1EeV ZHAires proton simulations, with an Auger like atmosphere , altitude and triangular grid at 82 degrees.

*Simulation





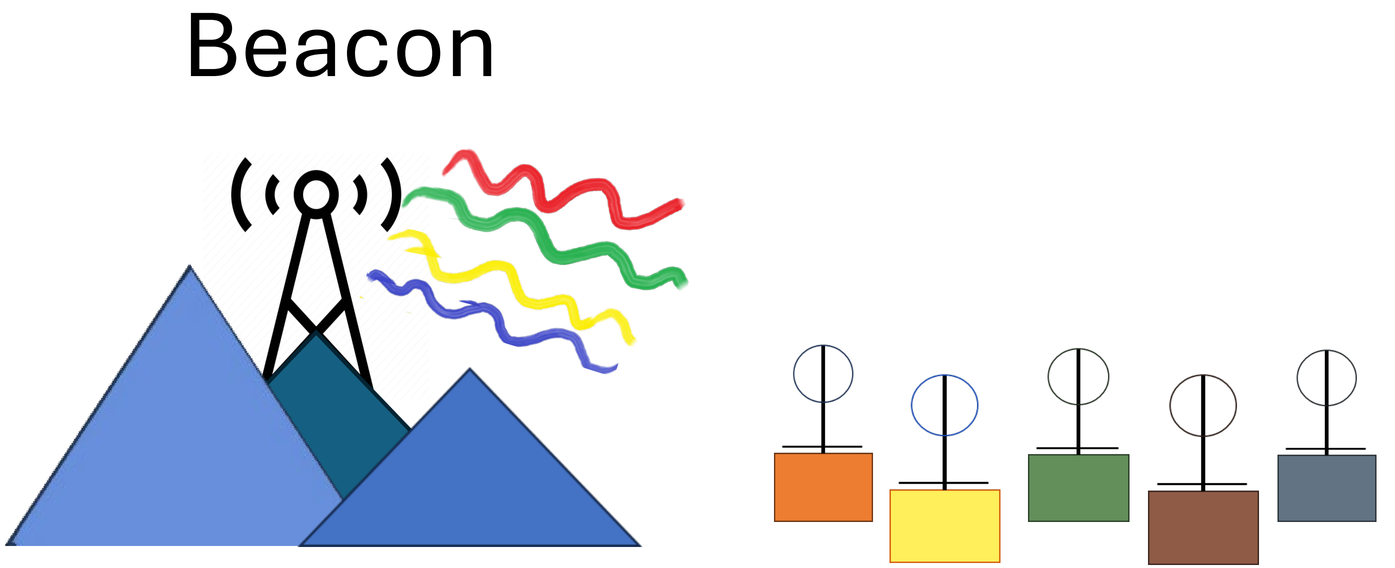


- With interferometry we can determine X_{max} for very inclined air showers with the radio detection technique.

http://aires.fisica.unlp.edu.ar/zhaires/

How to implement interferometry at Augerprime

- This would require:
  - Timing precision **O(ns)**
  - Station localization of the **O(30 cm)**
- A beacon emitting multiple sine waves can reach **O(ns)** demonstrated at Auger on a 10 km scale.
- We will be using the existing beacon as a proof of principle

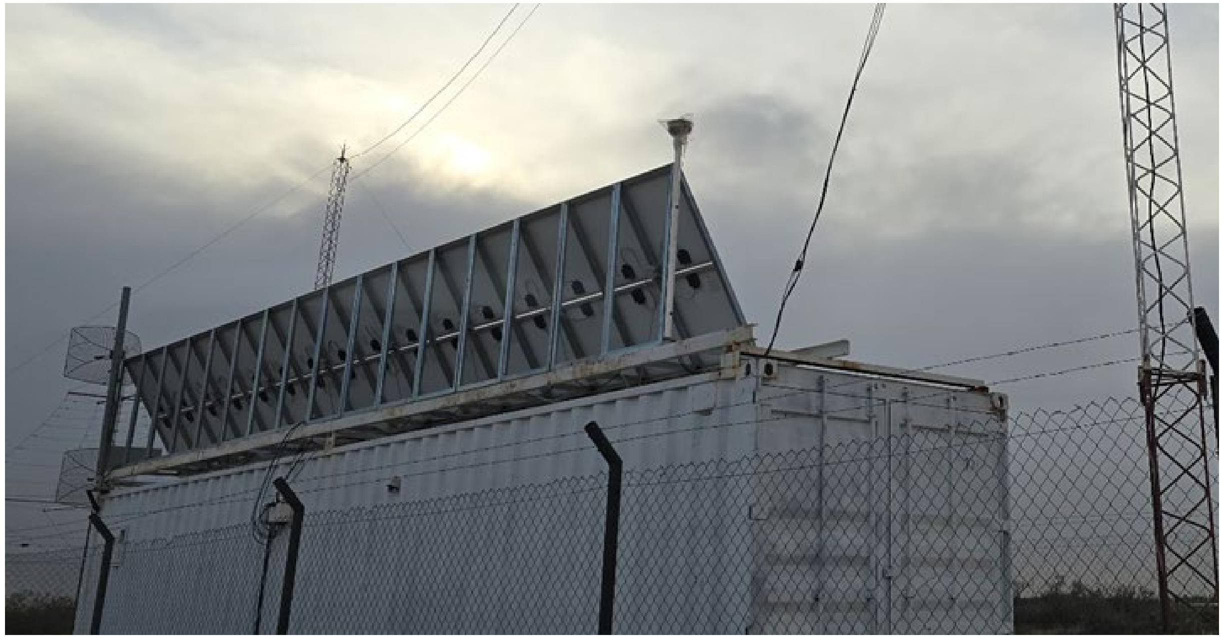


*A. Aab *et al* 2016 *JINST* **11** P01018 :**DOI** 10.1088/1748-0221/11/01/P01018

Locating our antennas accurately

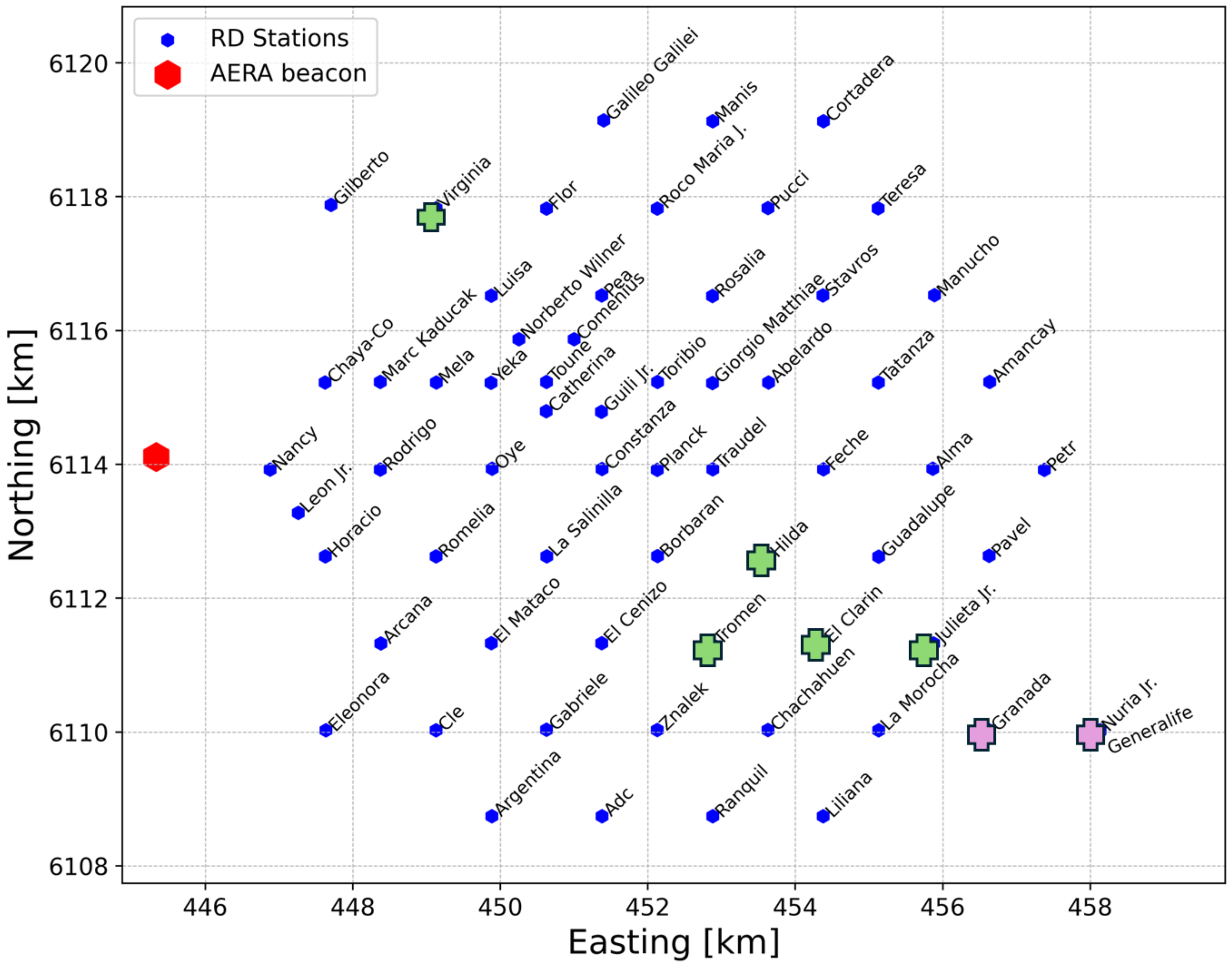
Performed a differential GPS survey campaigns on the RD:

- Ordinary GPS is accurate to about 5 meters.
- Differential GPS can achieve accuracy on the order of a few centimeters.



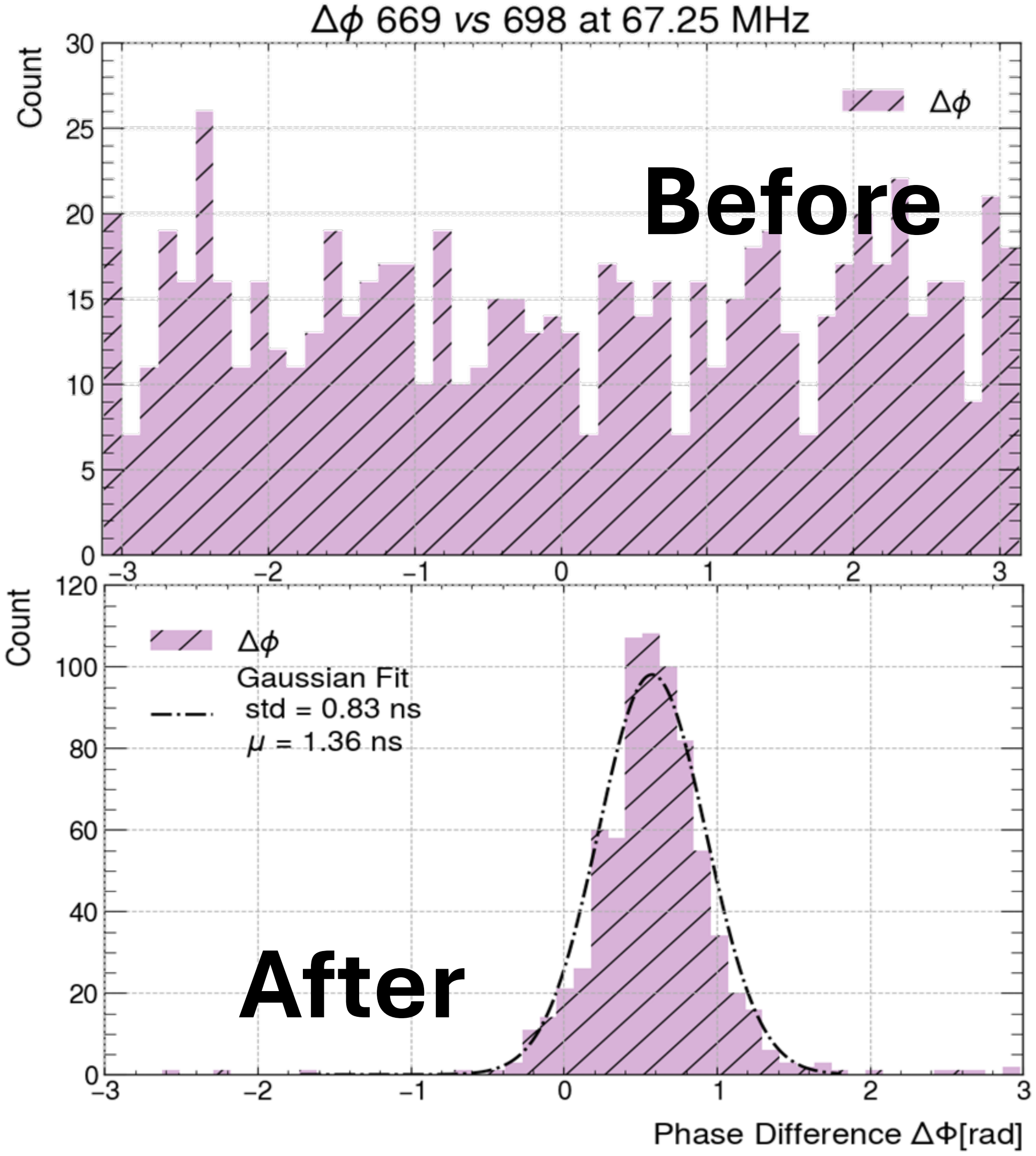
Survey Result

- In total 64 stations were surveyed using DGPS, covering an area of ~35km^2.
- All surveyed stations had enough signal from the beacon to reach **O(ns).**



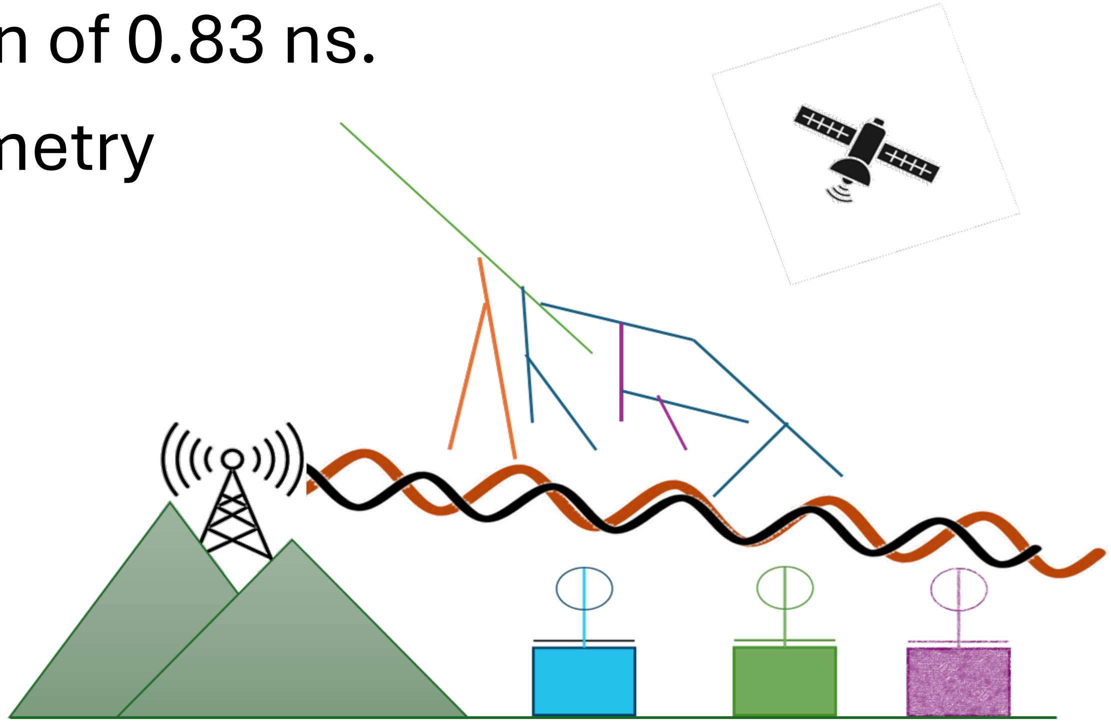
Timing precision of synchronisation

- We use a TV signal, dominant in the EW channel of our antennas, as an independent test to assess the precision of our timing correction.
- **The distribution of phase difference on the TV line gives a standard deviation of 0.83 ns**
- There might be some broadening in the phase difference distribution due to the TV signal being amplitude-modulated.

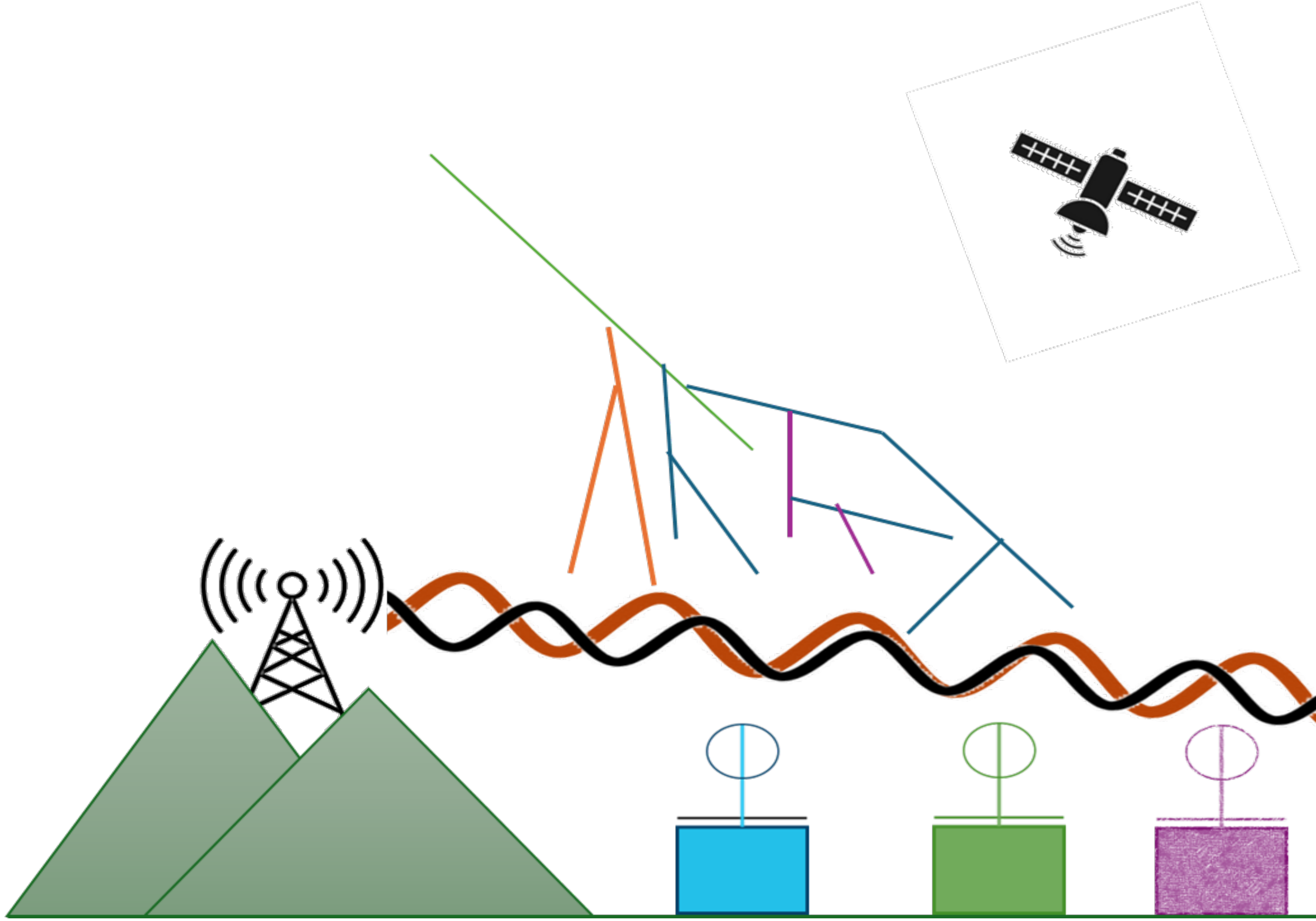


Outlook

- Interferometry can determine in the X_{max} of very inclined showers .
- Currently have surveyed an area of ~ 35 km^2 .
- Aim to increase the range of the beacon and number of surveyed stations soon.
- We can synchronise the RD to a precision of 0.83 ns.
- Selection candidate events for interferometry

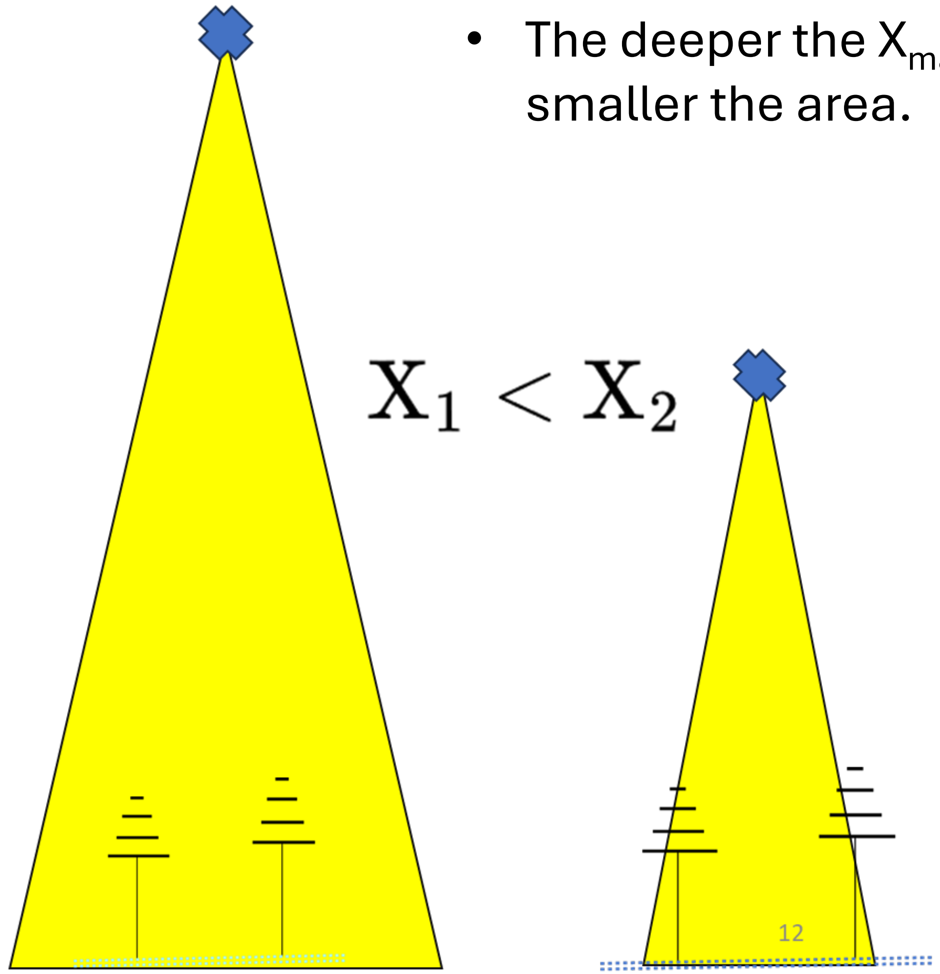


- End



Effects of X_{max} and n on the footprint

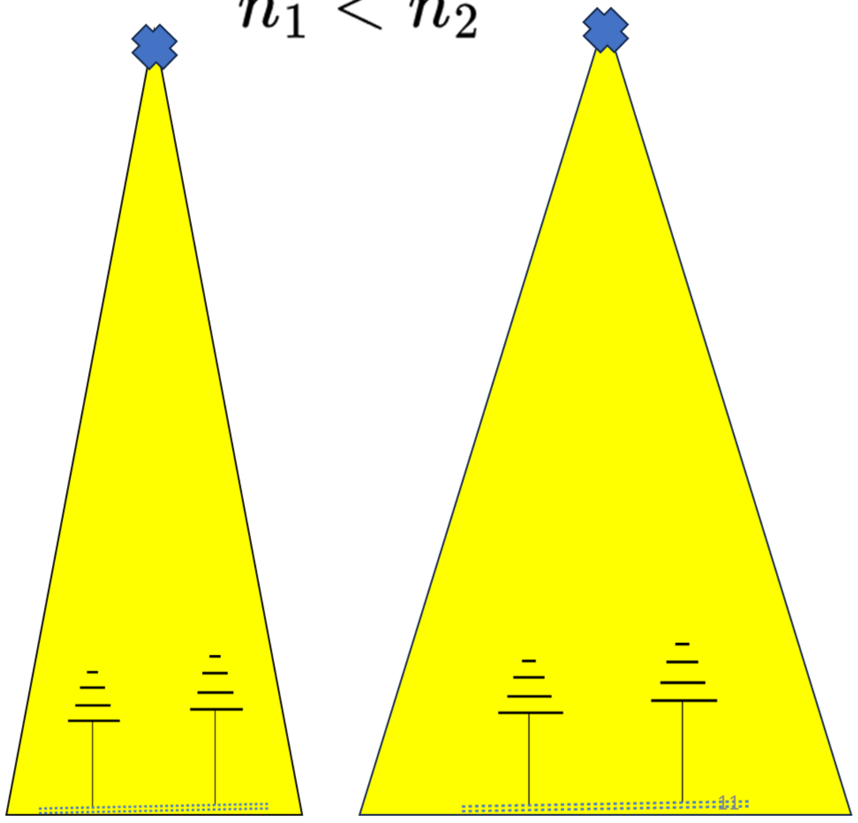
- The deeper the X_{max} the smaller the area.



$$X_1 < X_2$$

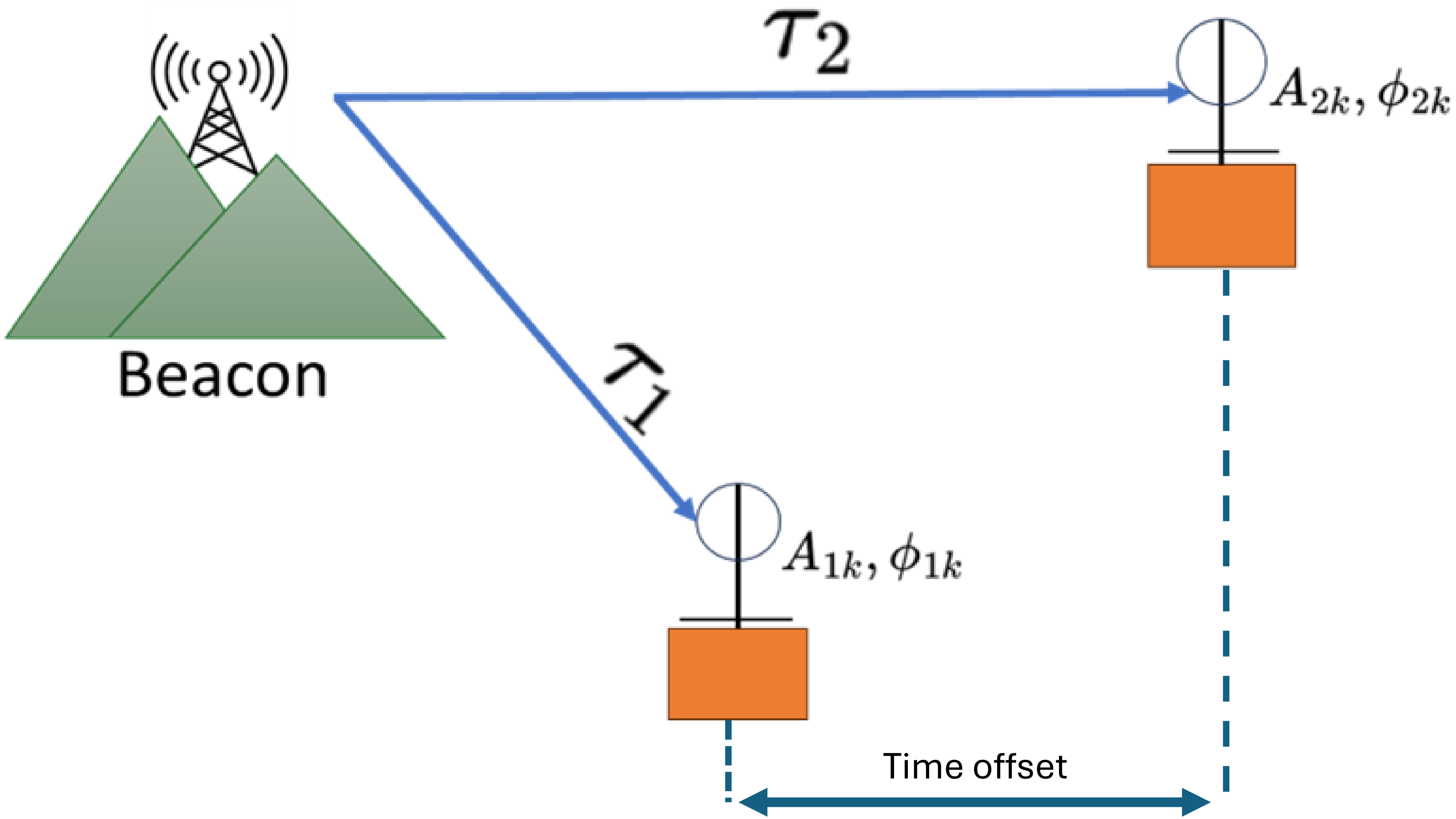
- The greater the n the wider the opening angle.

$$n_1 < n_2$$



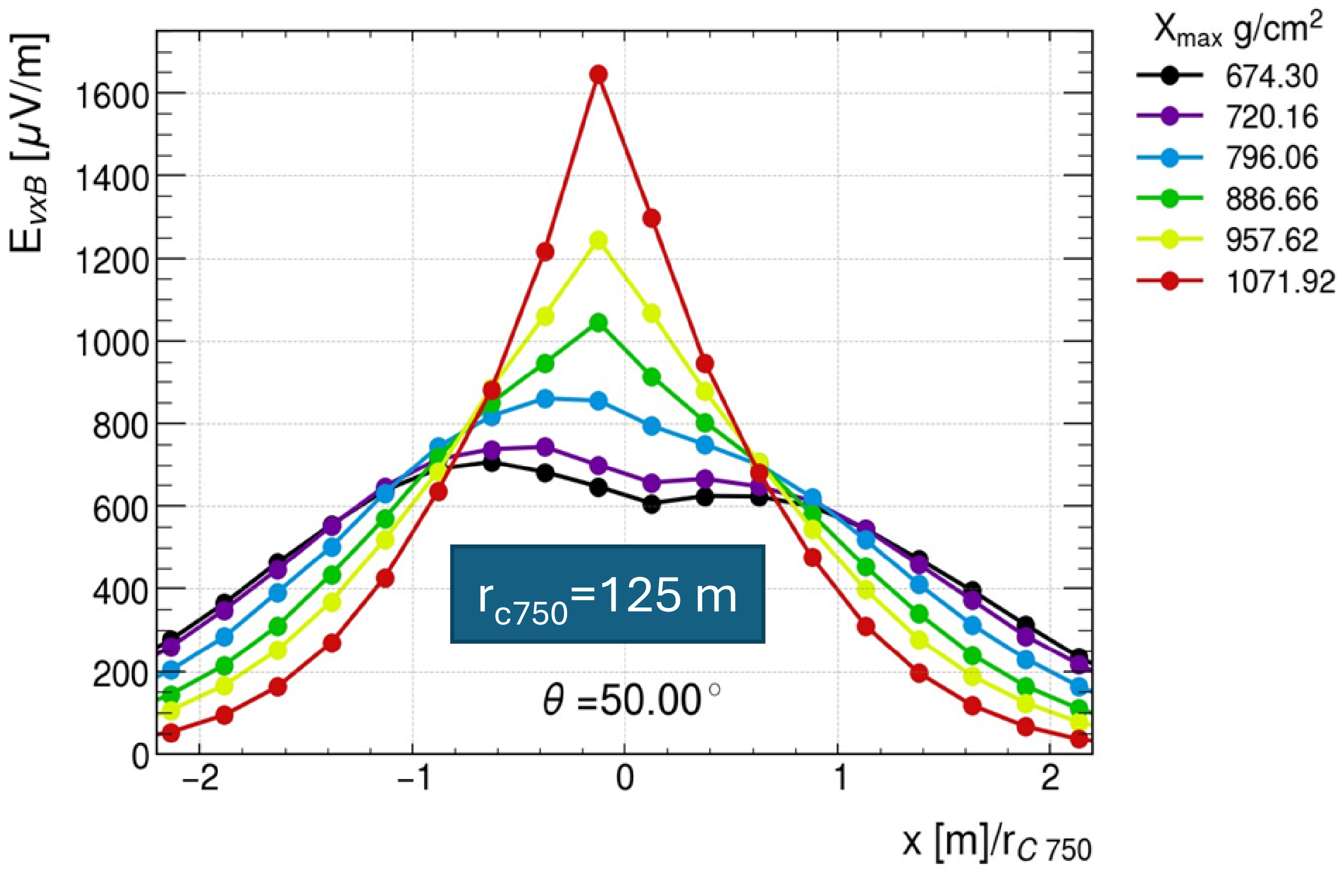
Synchronisation

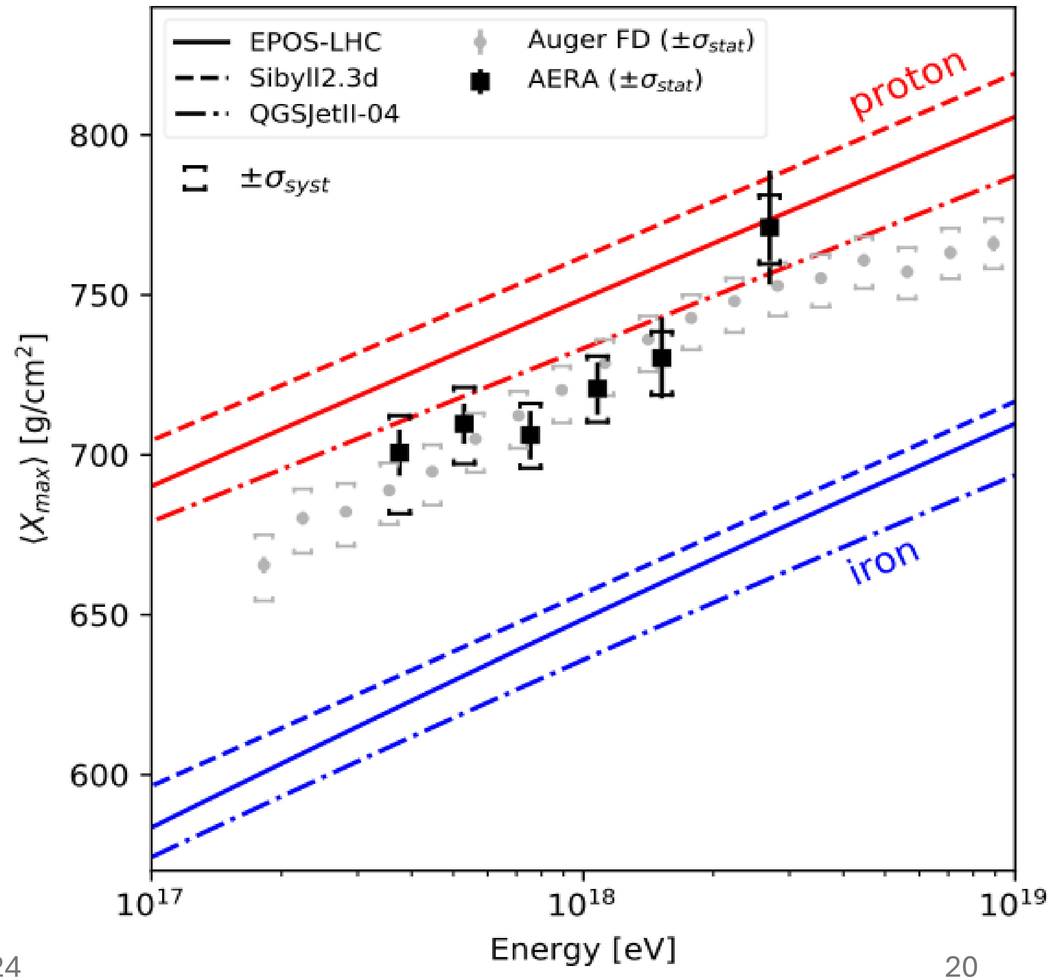
::Extra::



Simulated radio amplitude distribution ::Extra::

Auger Collaboration* , Radio Measurements of the Depth of Air-Shower Maximum at the Pierre Auger Observatory.





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::Extra::

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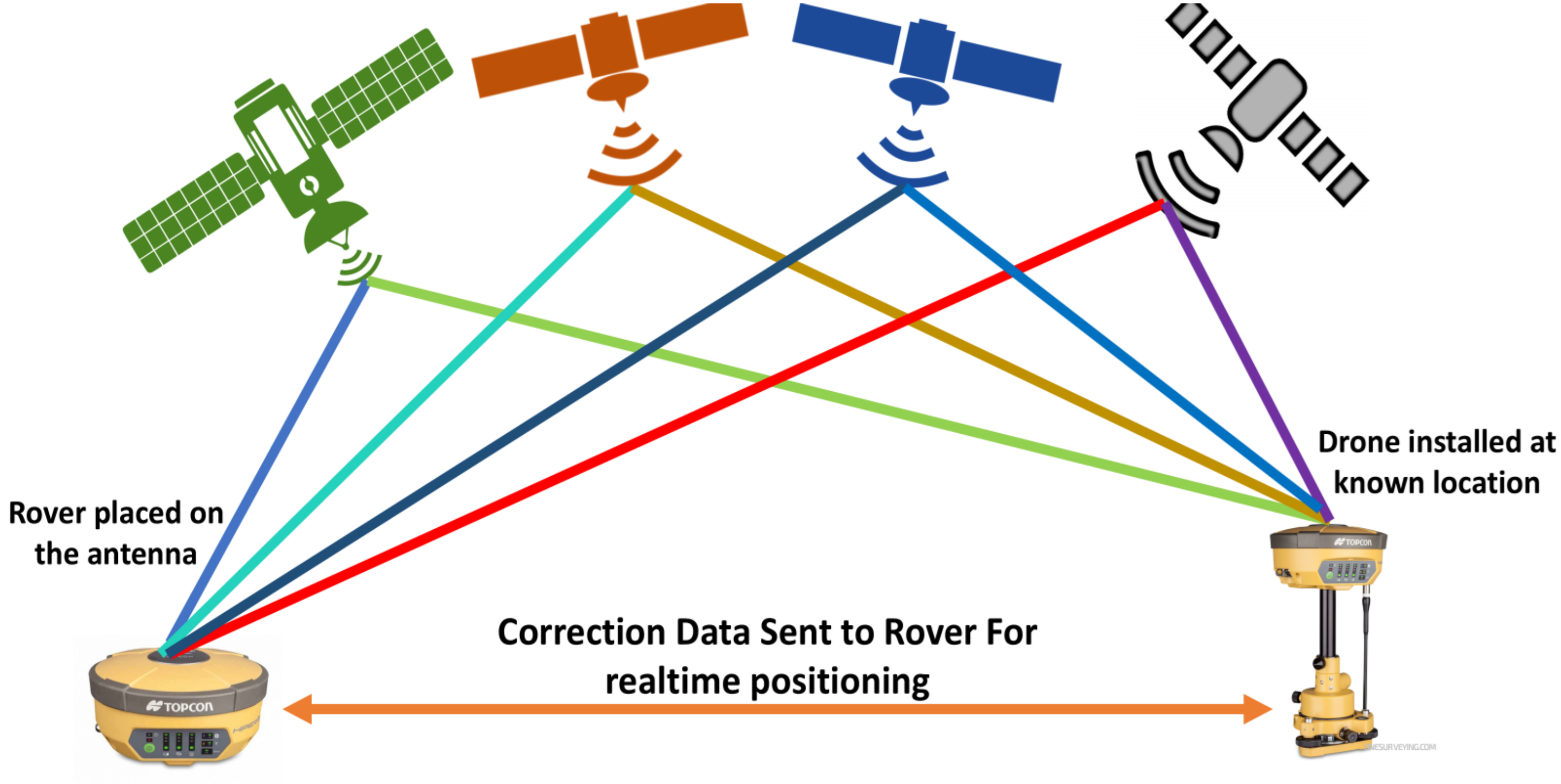

- The primary particle interacts with the atmosphere , creating a cascade of secondary particles.

- This cascade is then measured on the ground to derive the primary particle's energy, mass and arrival direction .

https://opendata.auger.org/display.php