Observing cosmic rays using radio signals

Harm Schoorlemmer

Radboud Universiteit

What is a radio signal?

Time dependent

$$\vec{E}(t) = \begin{pmatrix} E_x(t) \\ E_y(t) \\ E_z(t) \end{pmatrix}$$

Frequency dependent

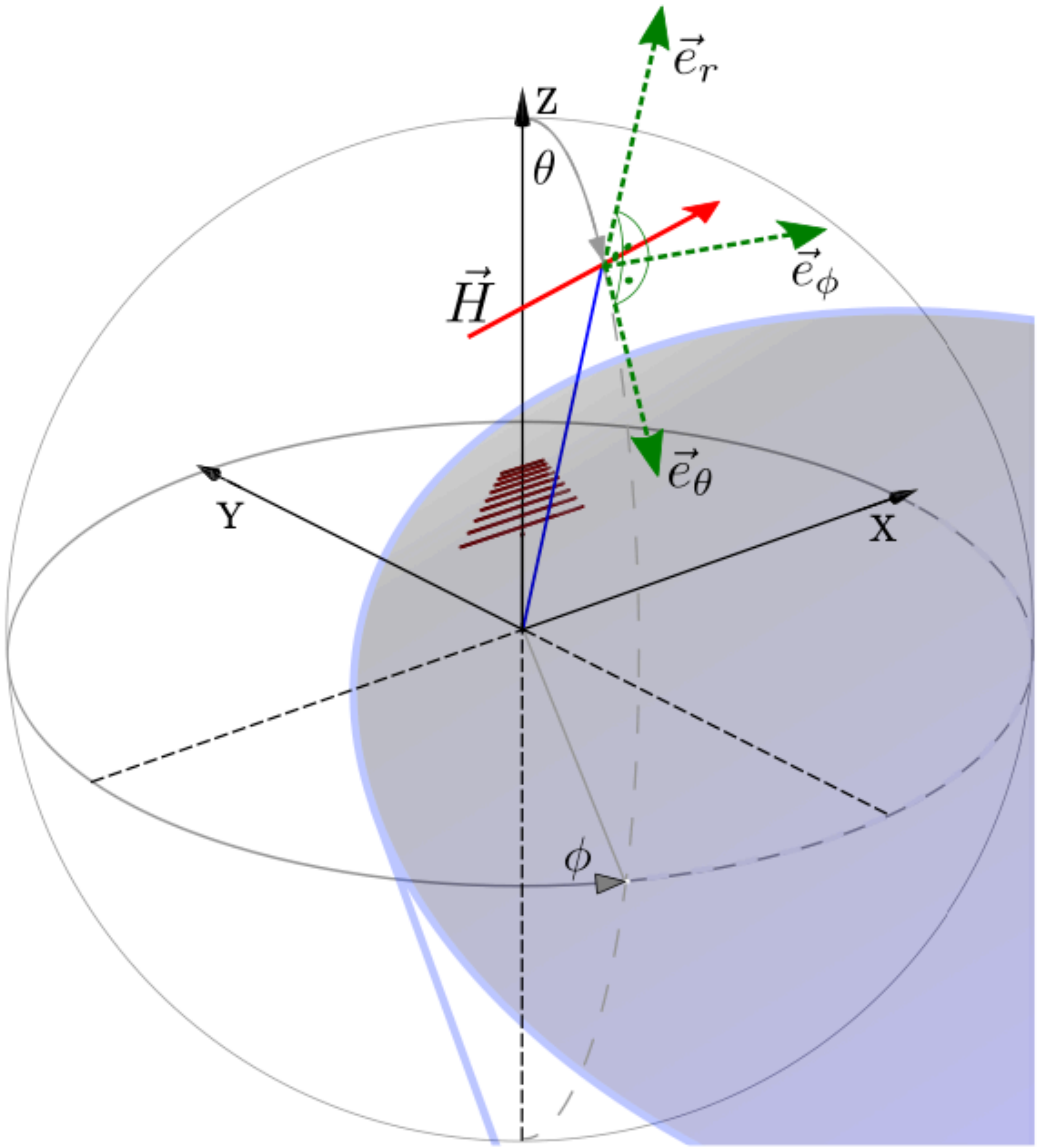
$$\vec{E}(\omega) = \begin{pmatrix} E_x(\omega) \\ E_y(\omega) \\ E_z(\omega) \end{pmatrix}$$

Polarisation: the orientation of the electric-field vector

Polarity: the sign of the polarisation

How do you measure a radio signal?

An antenna



Converts an electric field
into a voltage

$$V(t) = \vec{H}(t) * \vec{E}(t)$$

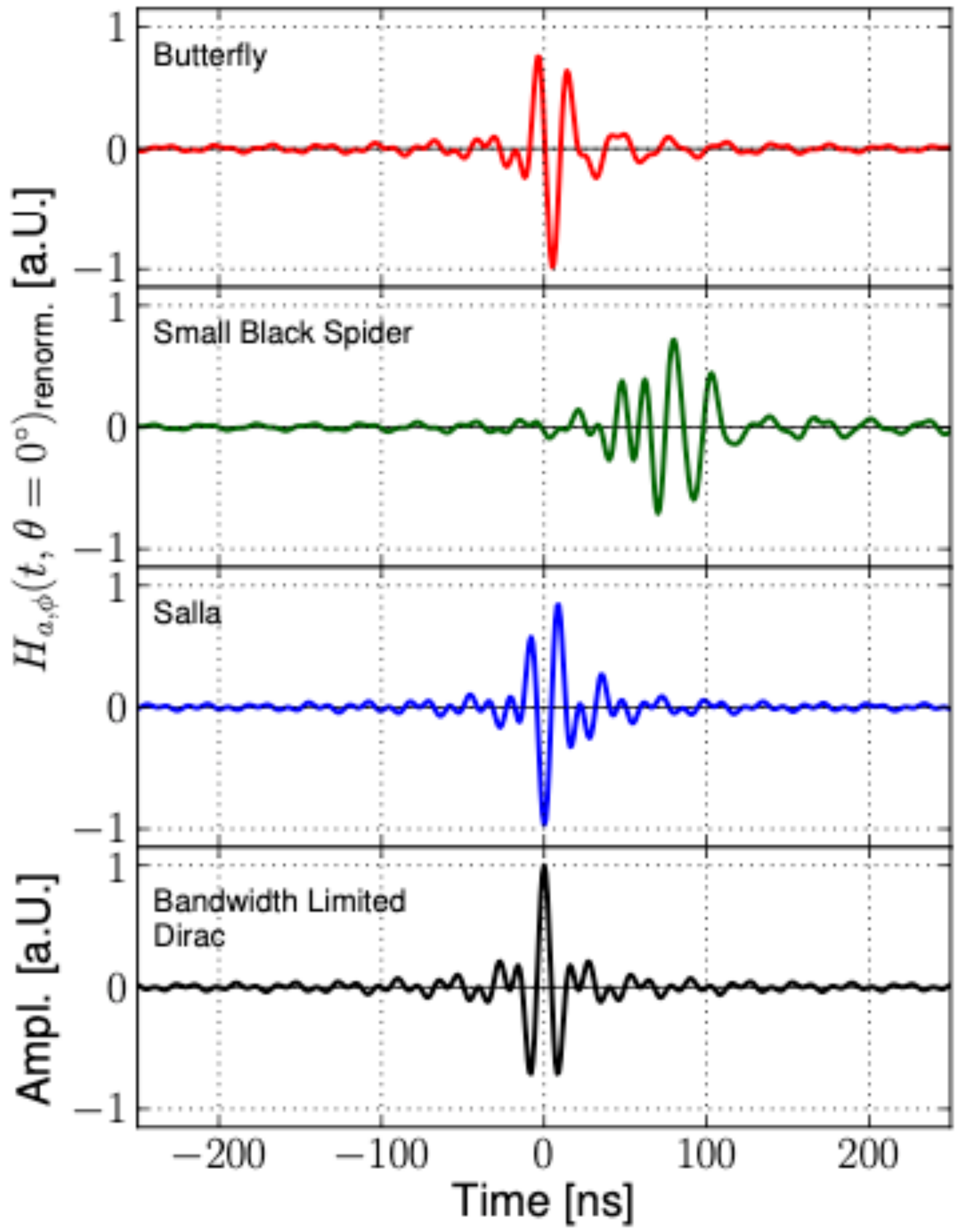
(V) (m) (V/m)

Normally you do this
in the frequency domain

$$\mathcal{V}(\omega) = \vec{\mathcal{H}}(\omega) \cdot \vec{\mathcal{E}}(\omega)$$

Antennas for the Detection of Radio Emission Pulses from Cosmic-Ray induced Air Showers at the Pierre Auger Observatory JINST 7 (2012) P10011

An antenna

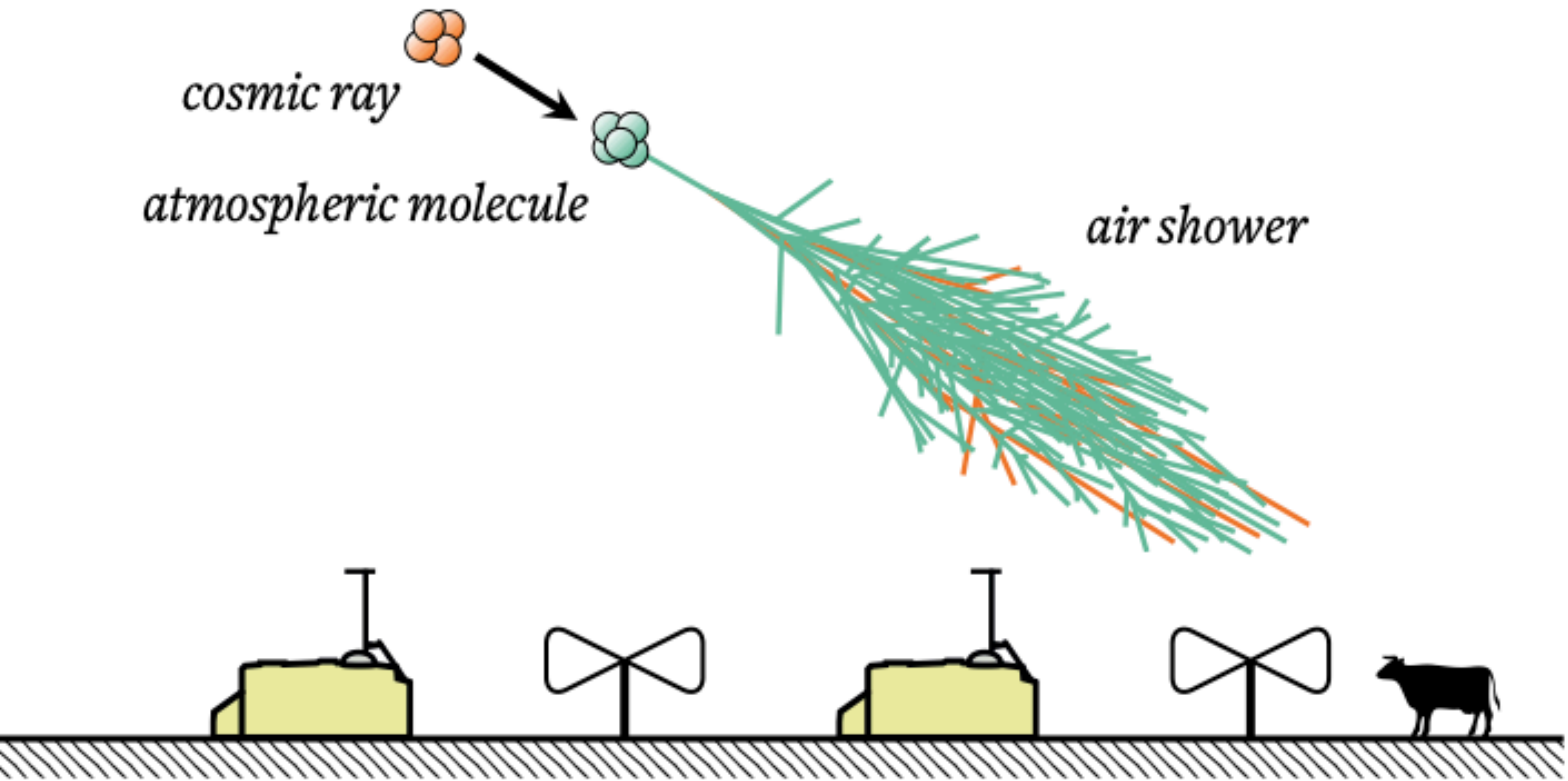


Antennas for the Detection of Radio Emission Pulses from Cosmic-Ray induced Air Showers at the Pierre Auger Observatory JINST 7 (2012) P10011

The effective antenna height is a complex function in the frequency domain

$$\mathcal{V}(\omega) = \vec{\mathcal{H}}(\omega) \cdot \vec{\mathcal{E}}(\omega)$$

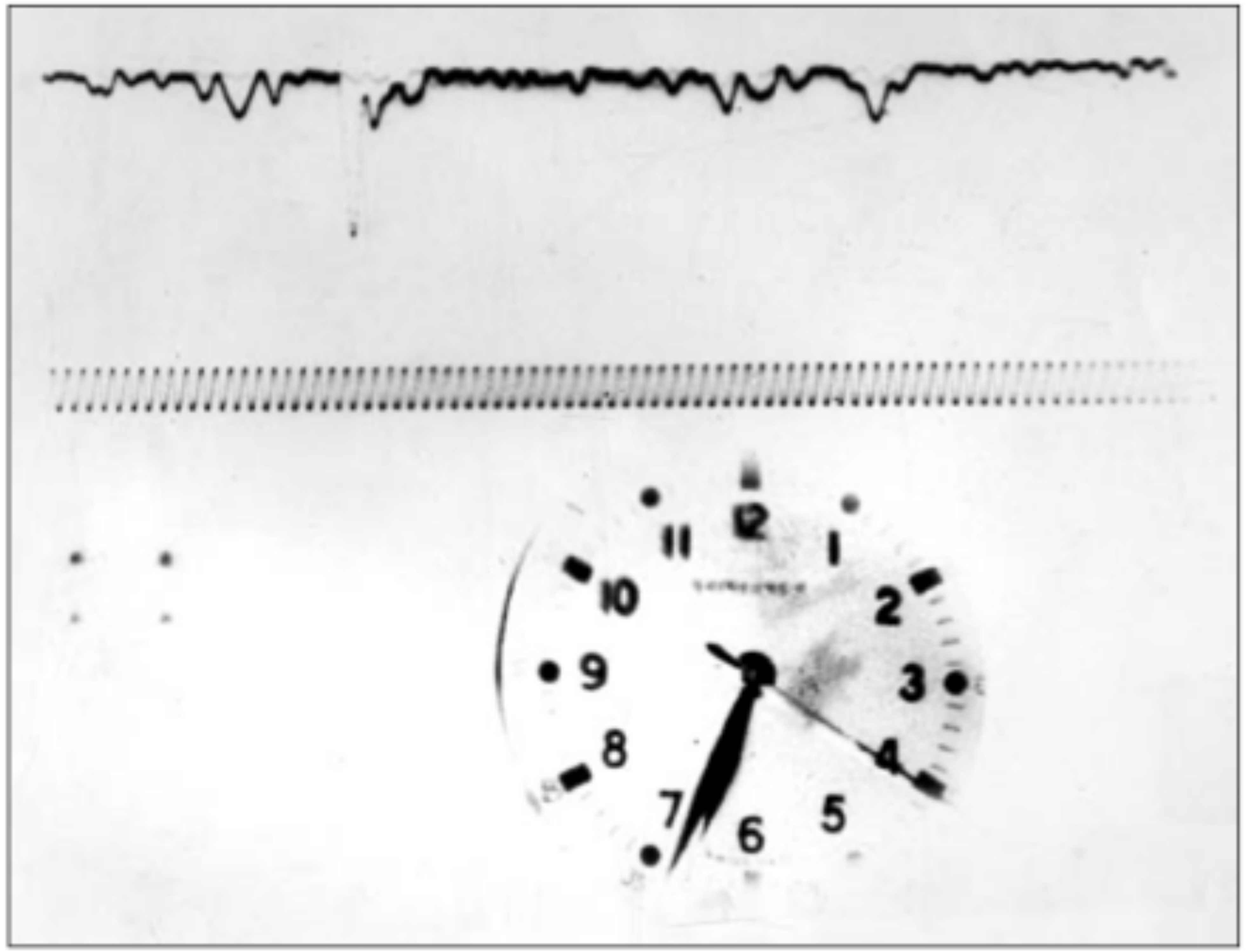
It both contains the gain and the group delay



S. Jansen (PhD thesis)

1964 - Porter, Weekes & Jelly

3 A radio event at 44 MHz as recorded during the first experiment in 1965. The sine wave was used as a timing check. The hodoscope – an array of light-emitting diodes – at bottom left showed which detectors were triggered. The clock and timing waveform were not used in later experiments.



2 Layout of the equipment looking west, from a montage by R A Porter (1967). The dark area shows the position of the large array. The north–south corner reflector can be seen to the west of the array, in front of the Mk2 radio telescope. The white boxes contained the Geiger counters.

A history of radio detection of cosmic-rays - R. Spencer & C. Rapley (Jodrell Bank)

Geomagnetic Emission

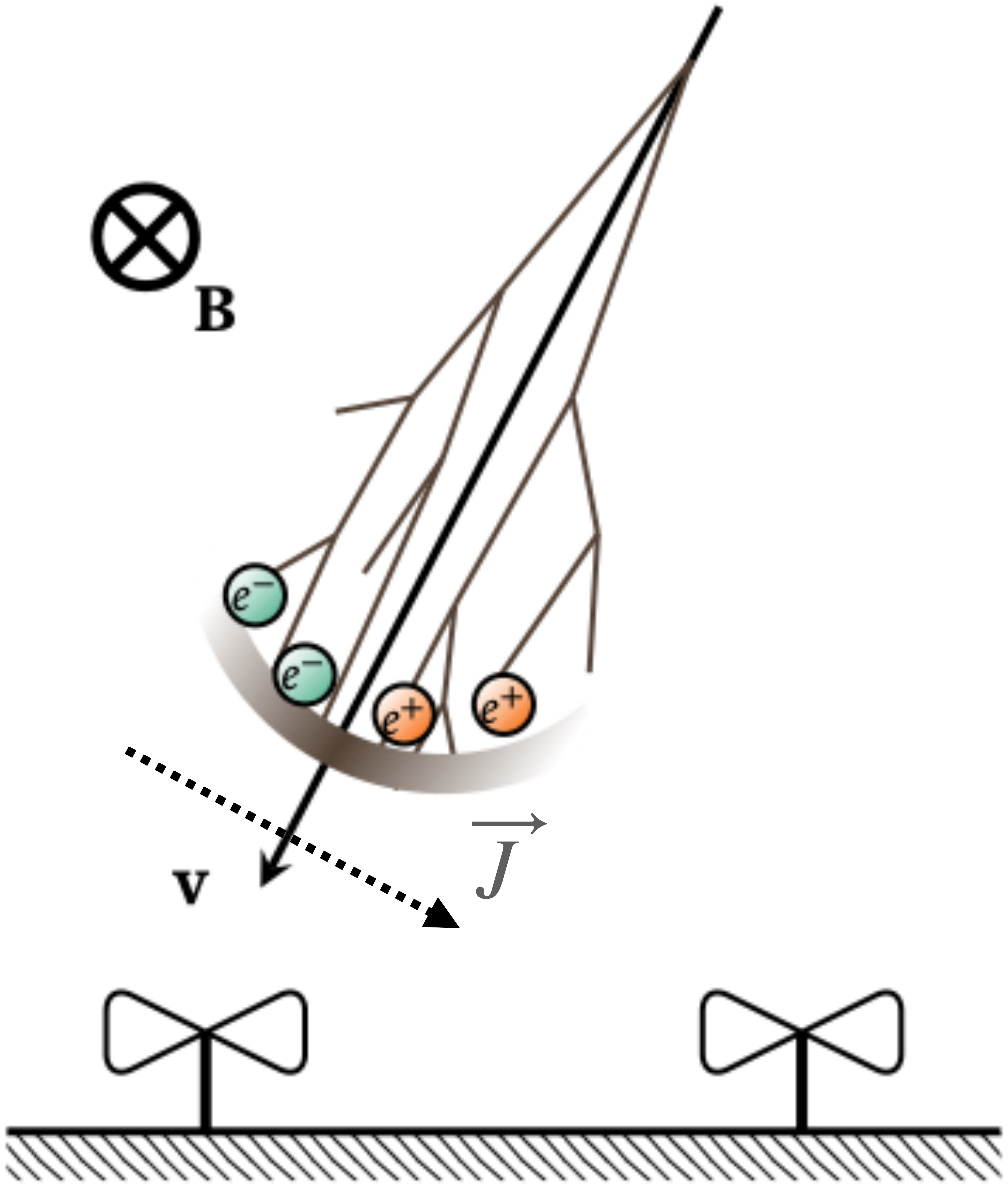
You can think of an air shower as charge & current densities functions

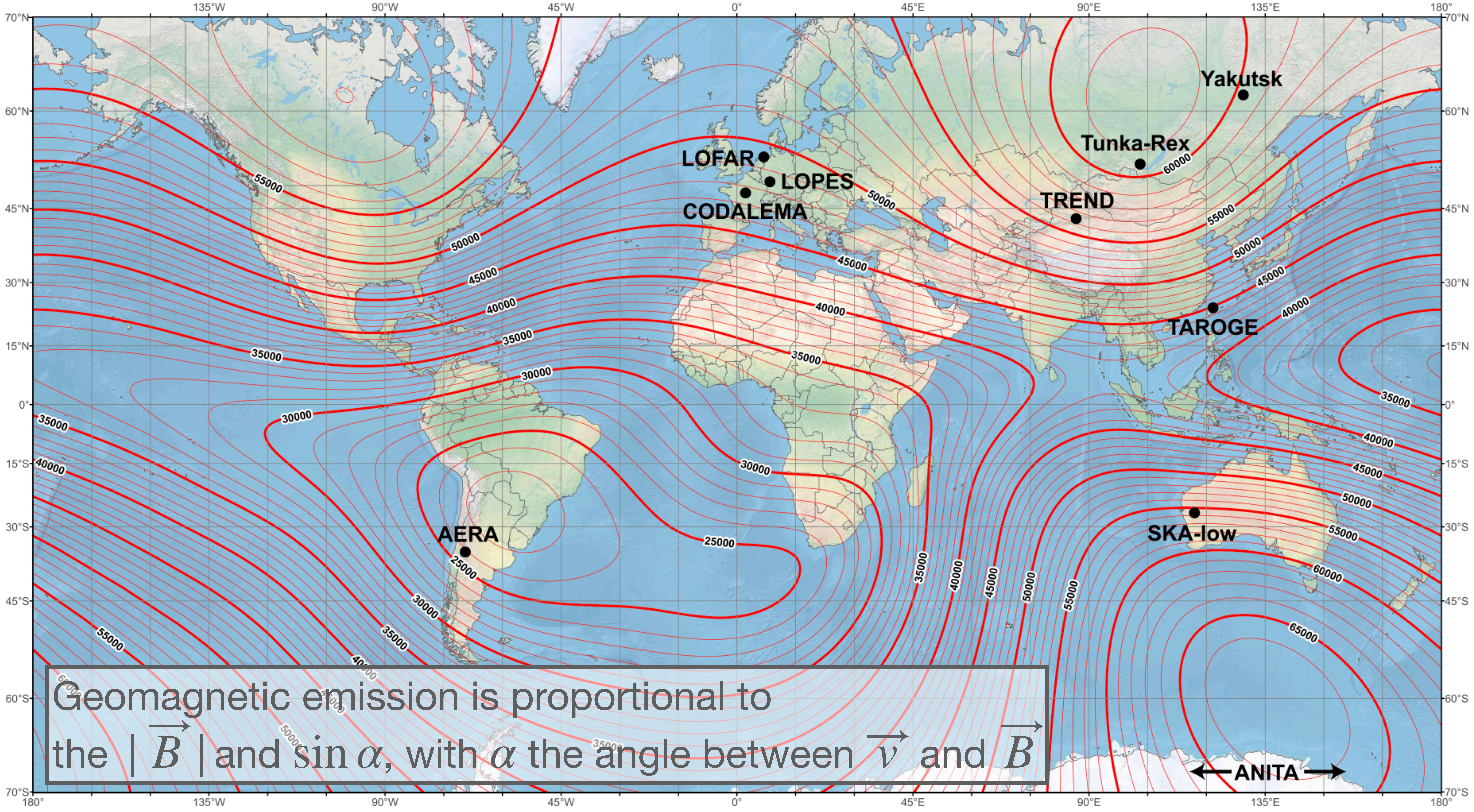
$$J^\mu = (\rho, \underline{\vec{J}})$$

While propagating through the geomagnetic field, a current is setup under the Lorentz force acting on the charge particles

$$\vec{F} = q(\vec{E} + \underline{\vec{v} \times \vec{B}})$$

The time variation of this current cause linear polarised emission in the $-\vec{v} \times \vec{B}$ direction





Geomagnetic emission is proportional to the $|\overrightarrow{B}|$ and $\sin\alpha$, with α the angle between $\overrightarrow{v}$ and $\overrightarrow{B}$

Underlying map (Mercator projection):
Main Geomagnetic Field Total Intensity with contour intervals of 1000 nT developed by NOAA/NGDC & CIRES Map reviewed by NGA and BGS

Overlayed: **Location of radio experiments for cosmic-ray air showers** added on underlying map by Frank G. Schröder

You can think of an air shower as charge & current densities functions

$$J^\mu = (\underline{\rho}, \vec{J})$$

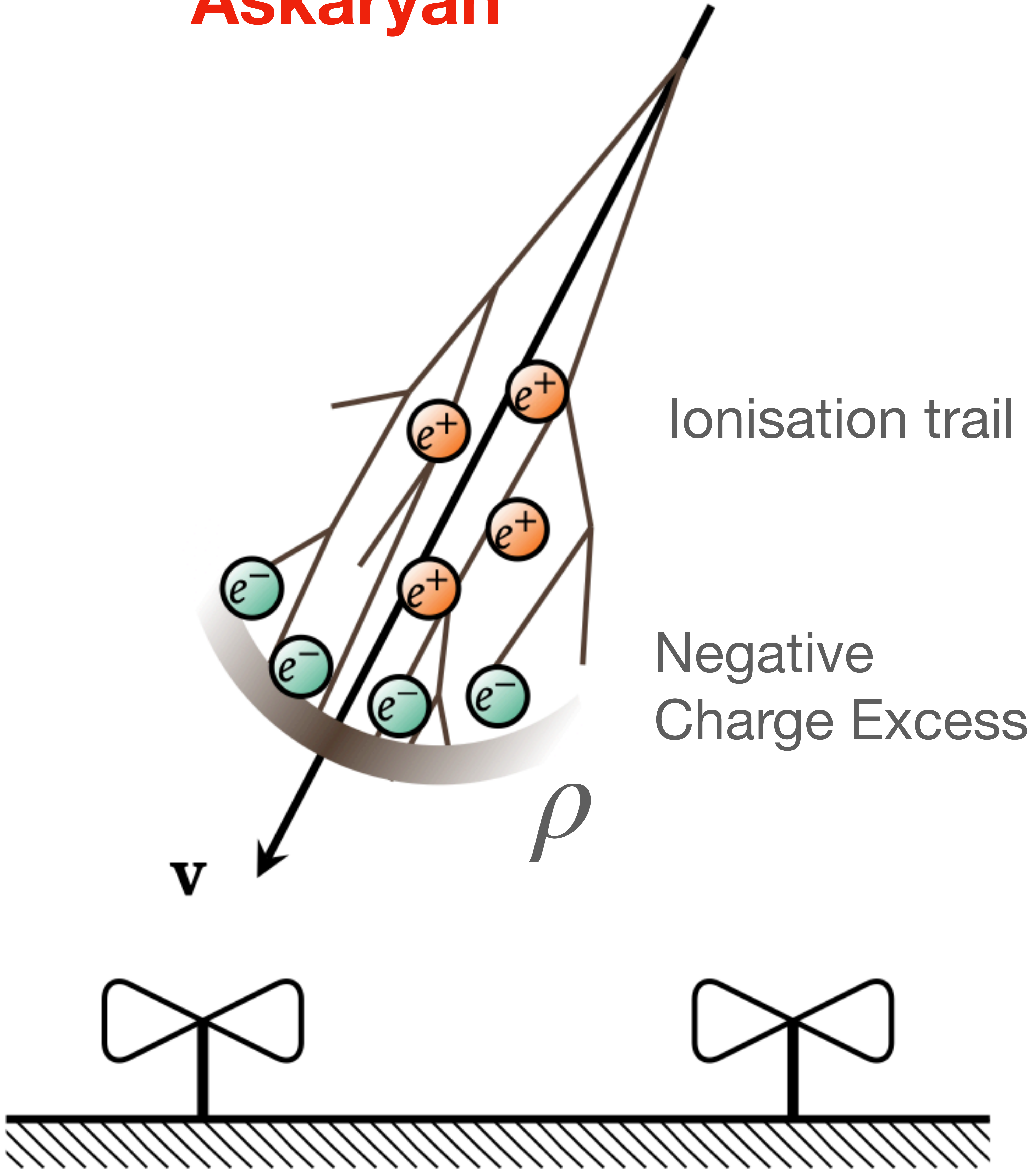
While propagating through the atmosphere, a negative charge density builds up

$$\vec{F} = \underline{q(}\vec{E} + \vec{v} \times \vec{B})$$

The time variation of this charge density causes linear polarised emission in direction of charge excess

Charge Excess Radiation

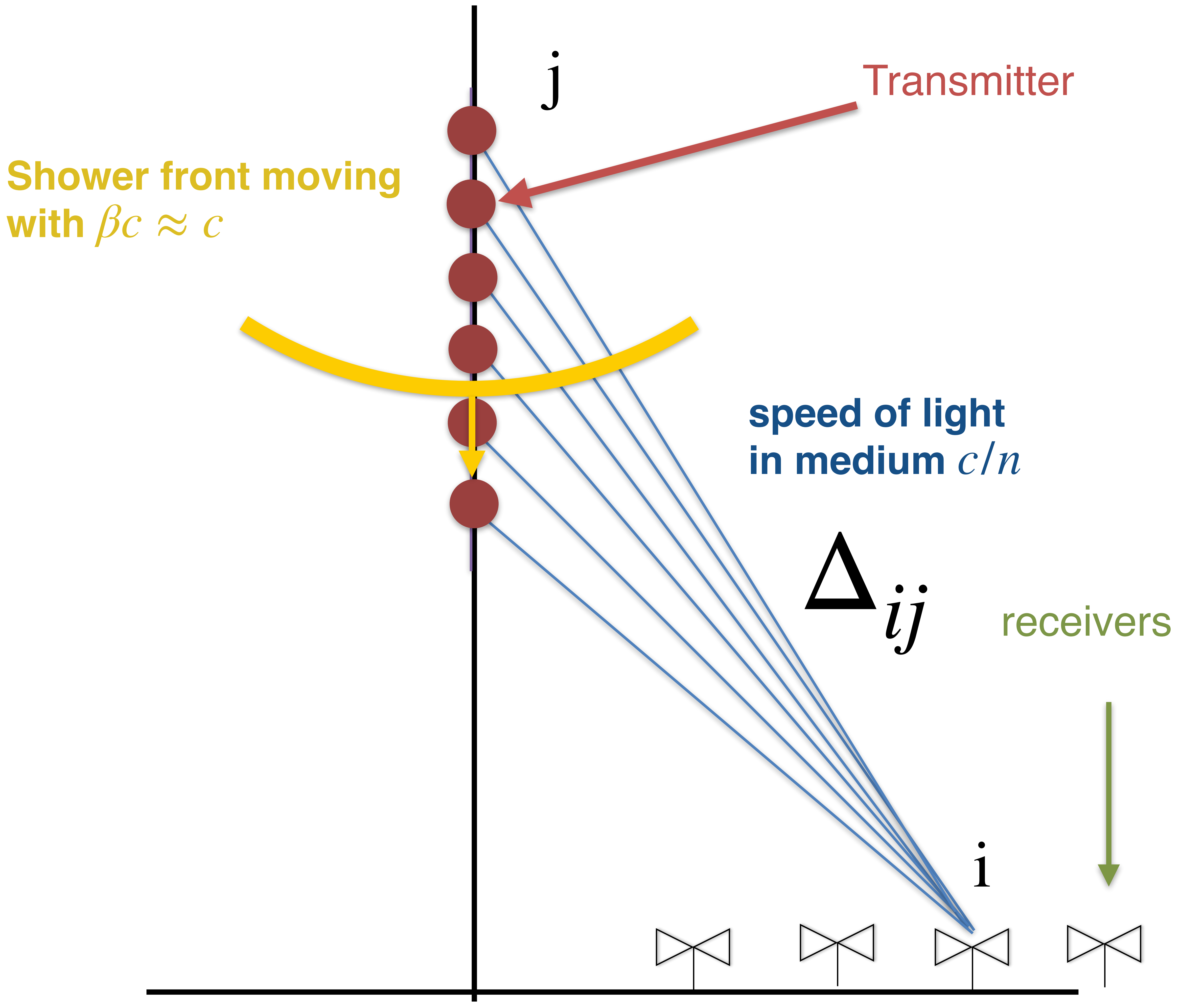
"Askaryan"



You can think of an air shower as a set of particle tracks that all emit individually

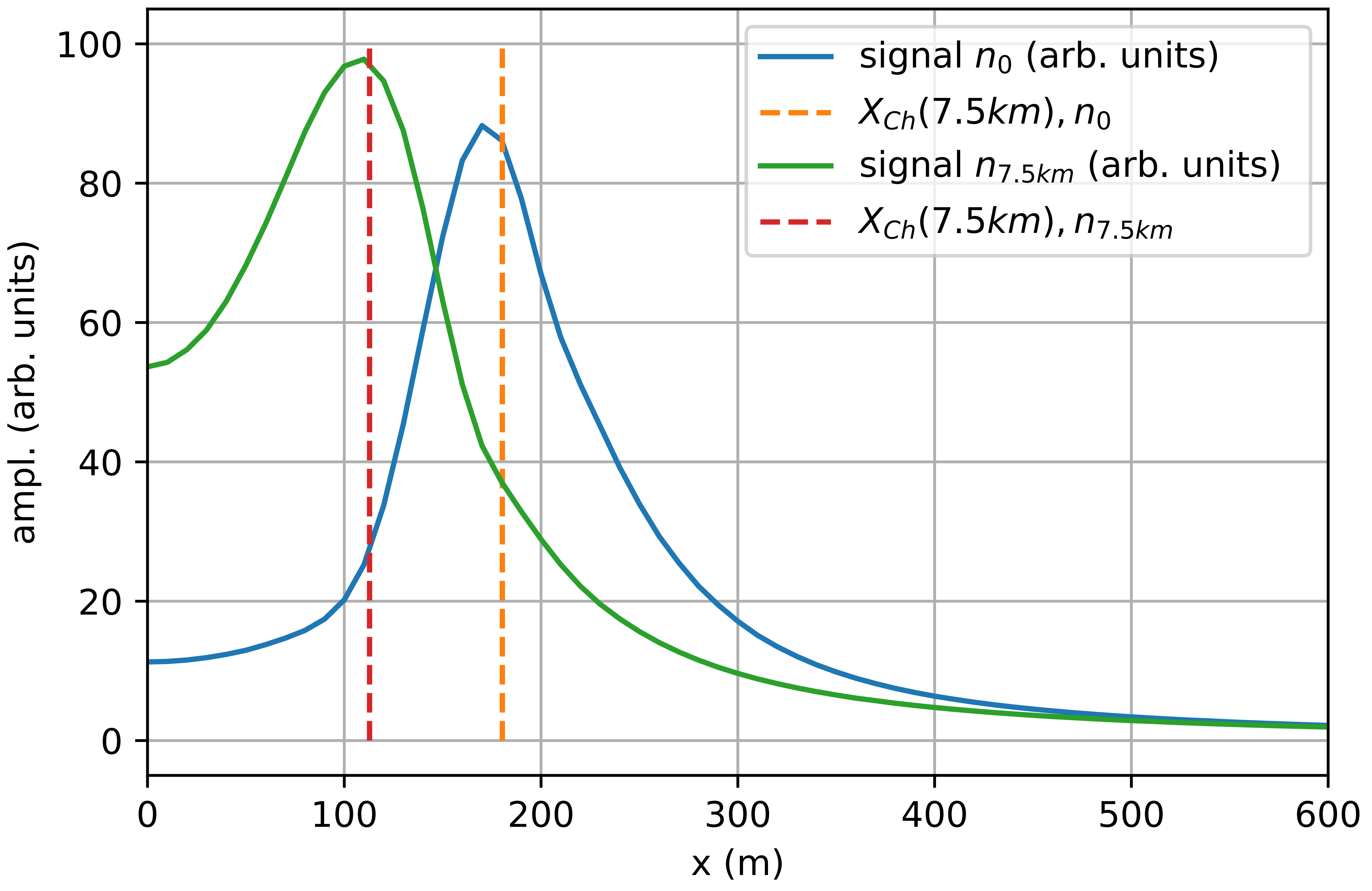
Propagate the emission from transmitters to a receiver and sum all contributions

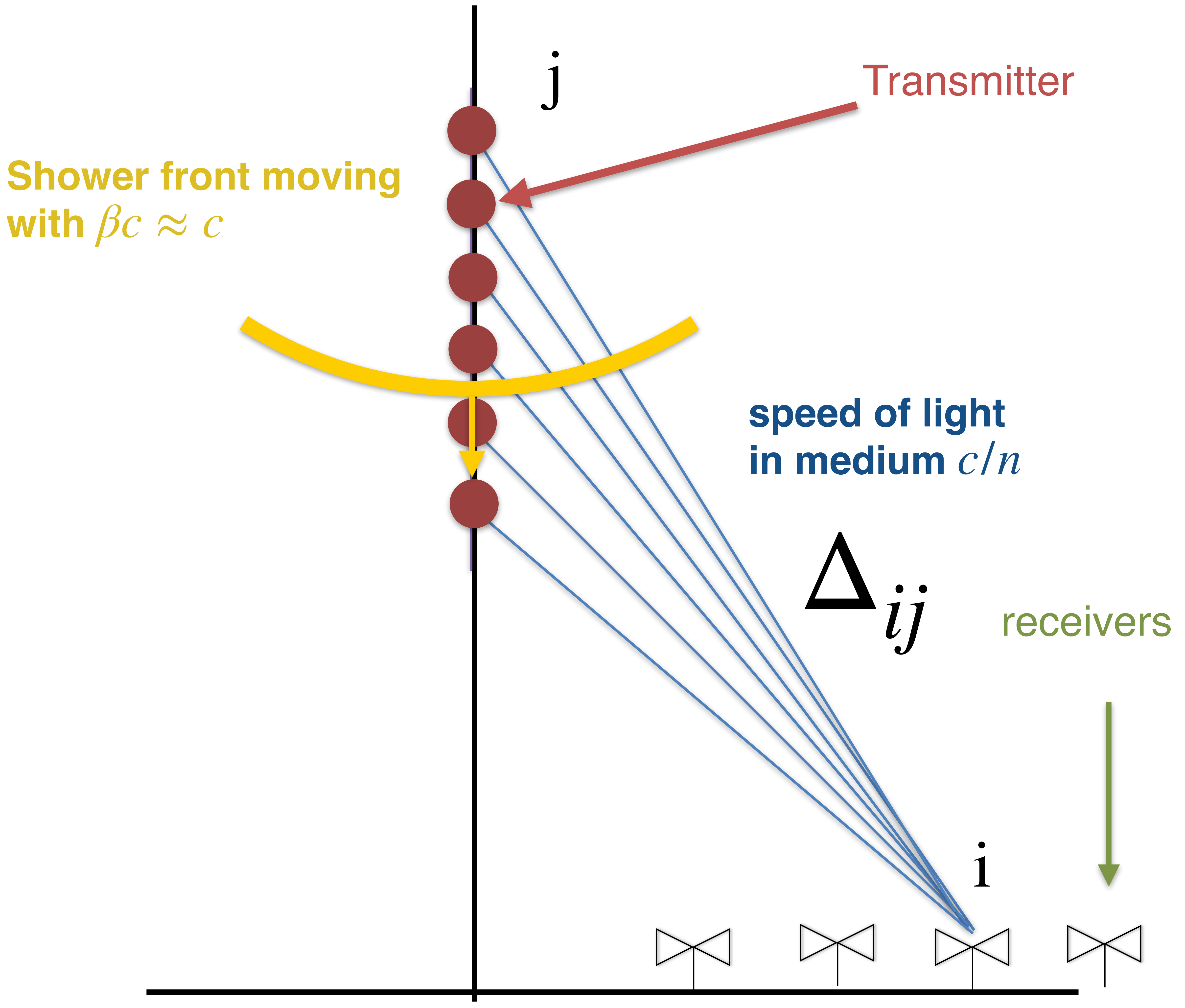
Arrival time differences determine the amount coherence



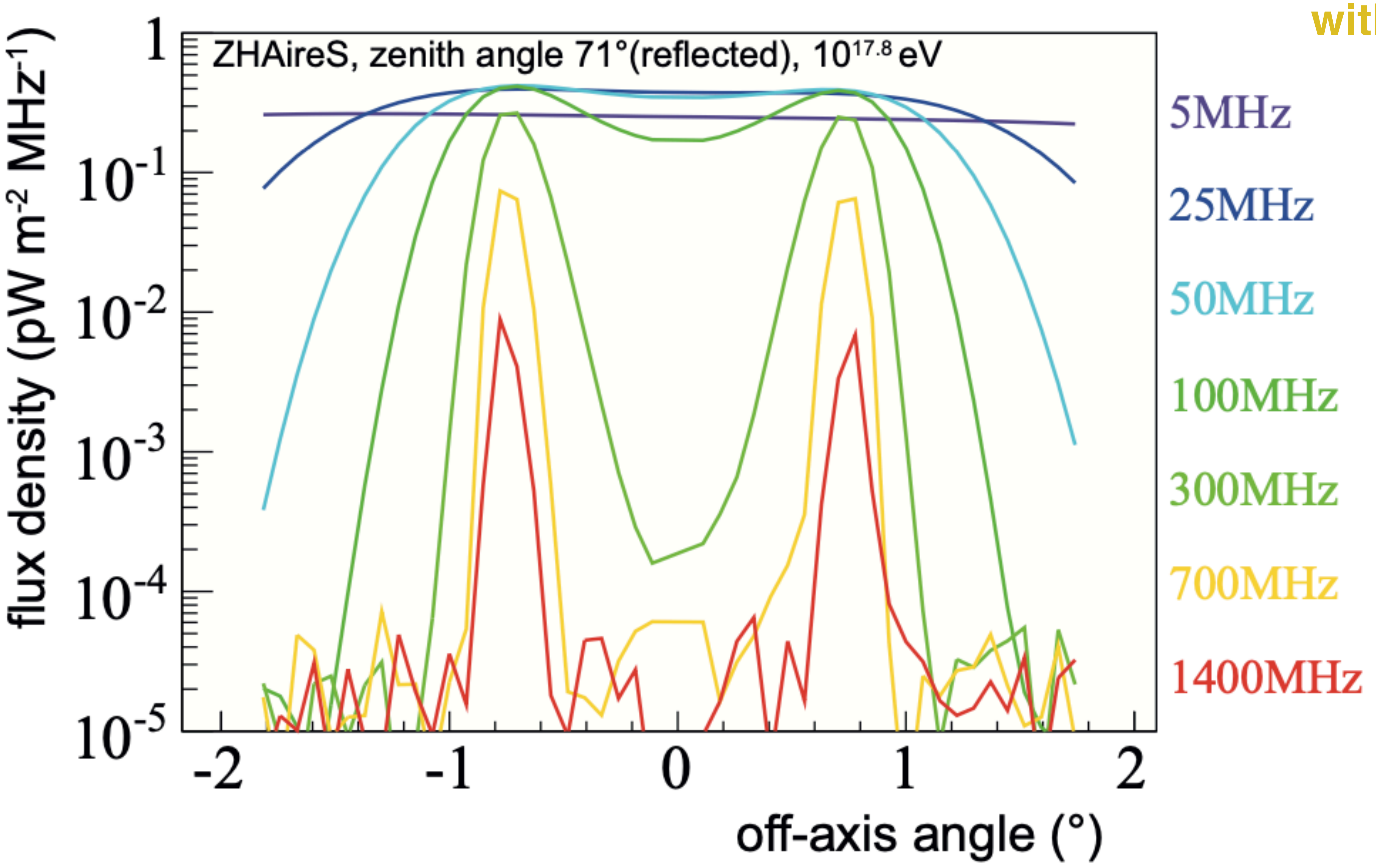
Zas Halzen Stanev (1992 - PRD) / James Huege Falcke Ludwig (2011 PRE)

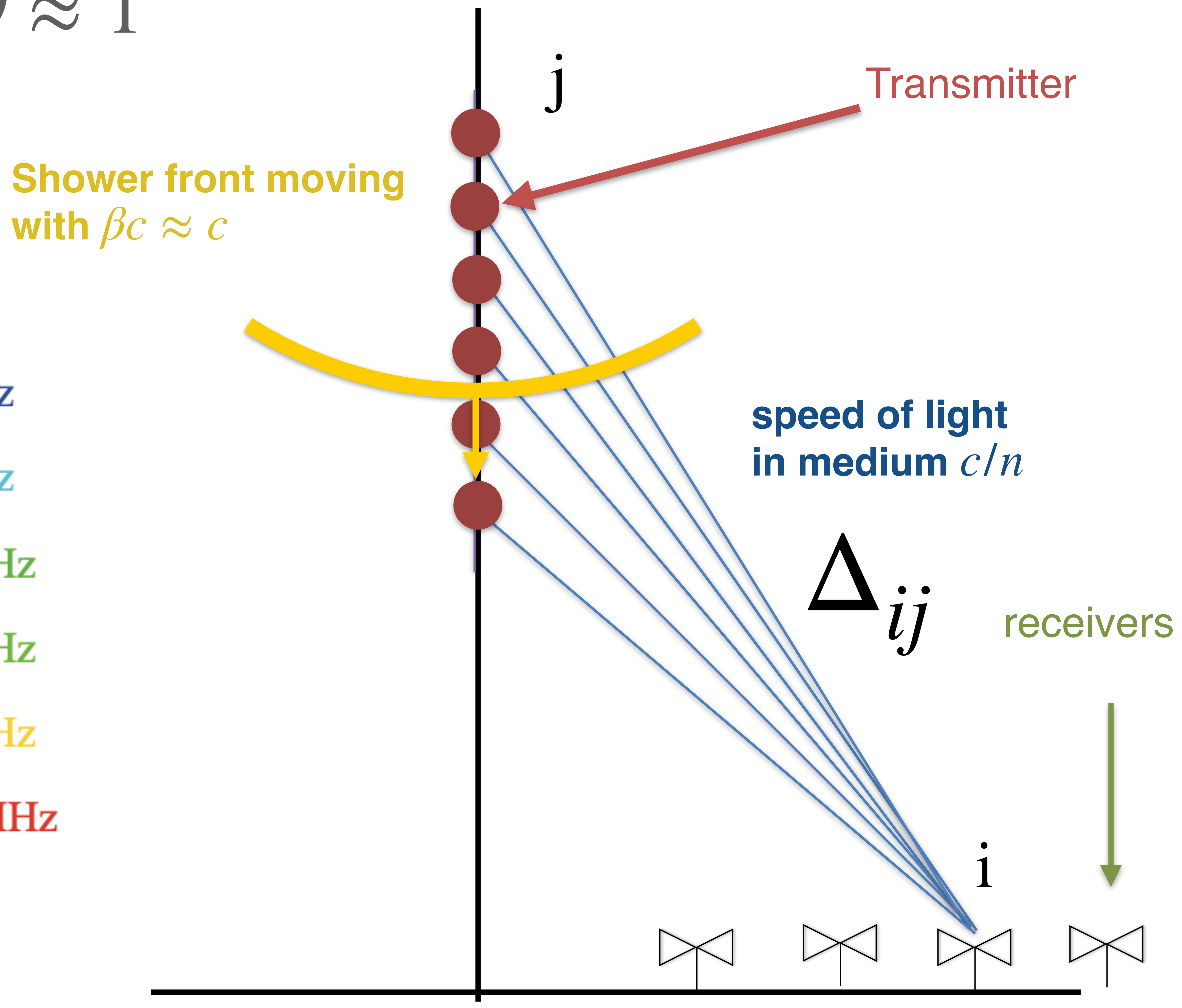
The refractive index n of the atmosphere >1, causes maximum coherence at the "Cherenkov Angle": $\cos\theta = \dfrac{1}{\beta n}$





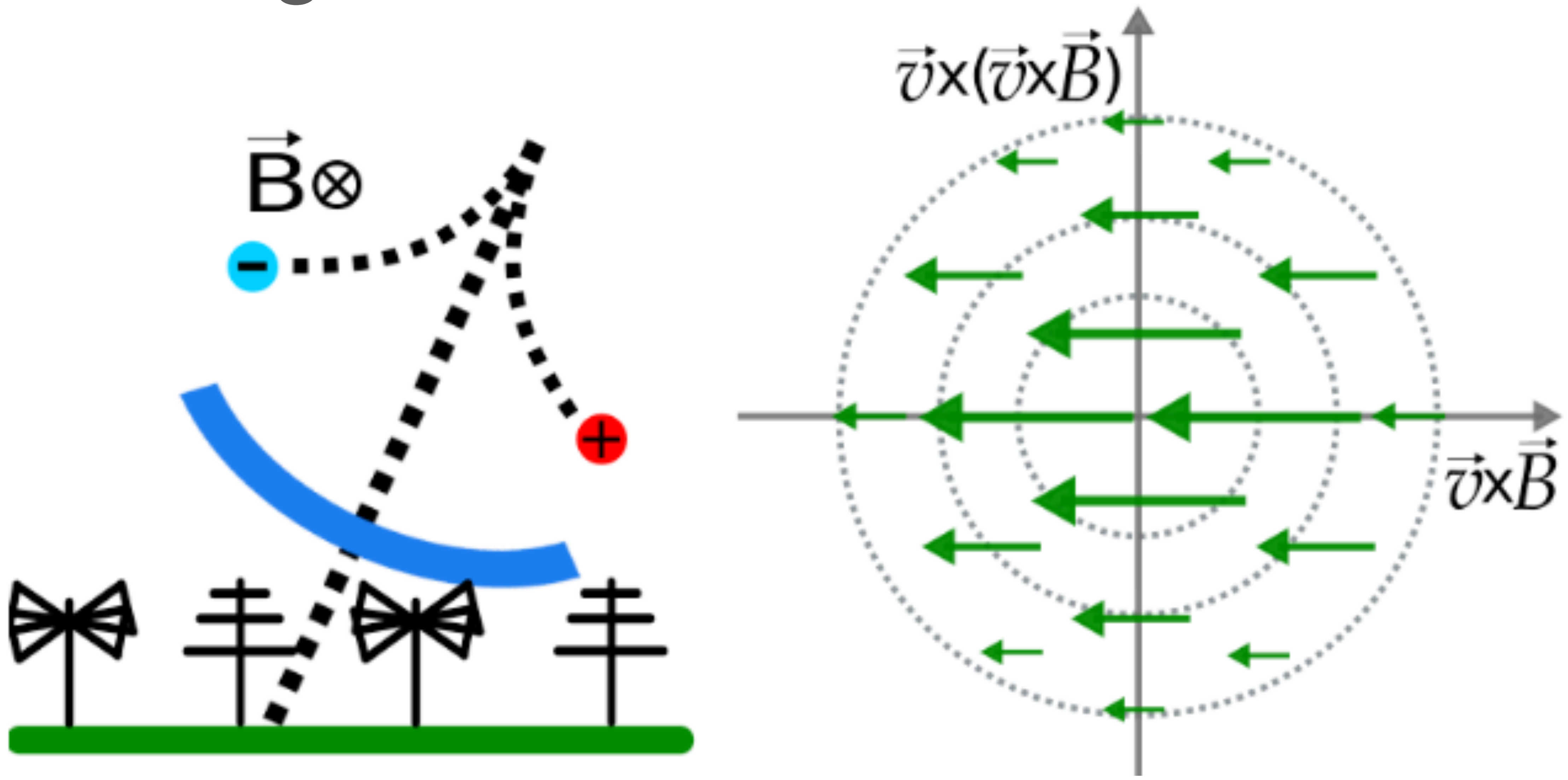
The refractive index n of the atmosphere >1, causes maximum coherence at the "Cherenkov Angle": $\cos\theta = \dfrac{1}{\beta n} \rightarrow \theta \approx 1°$



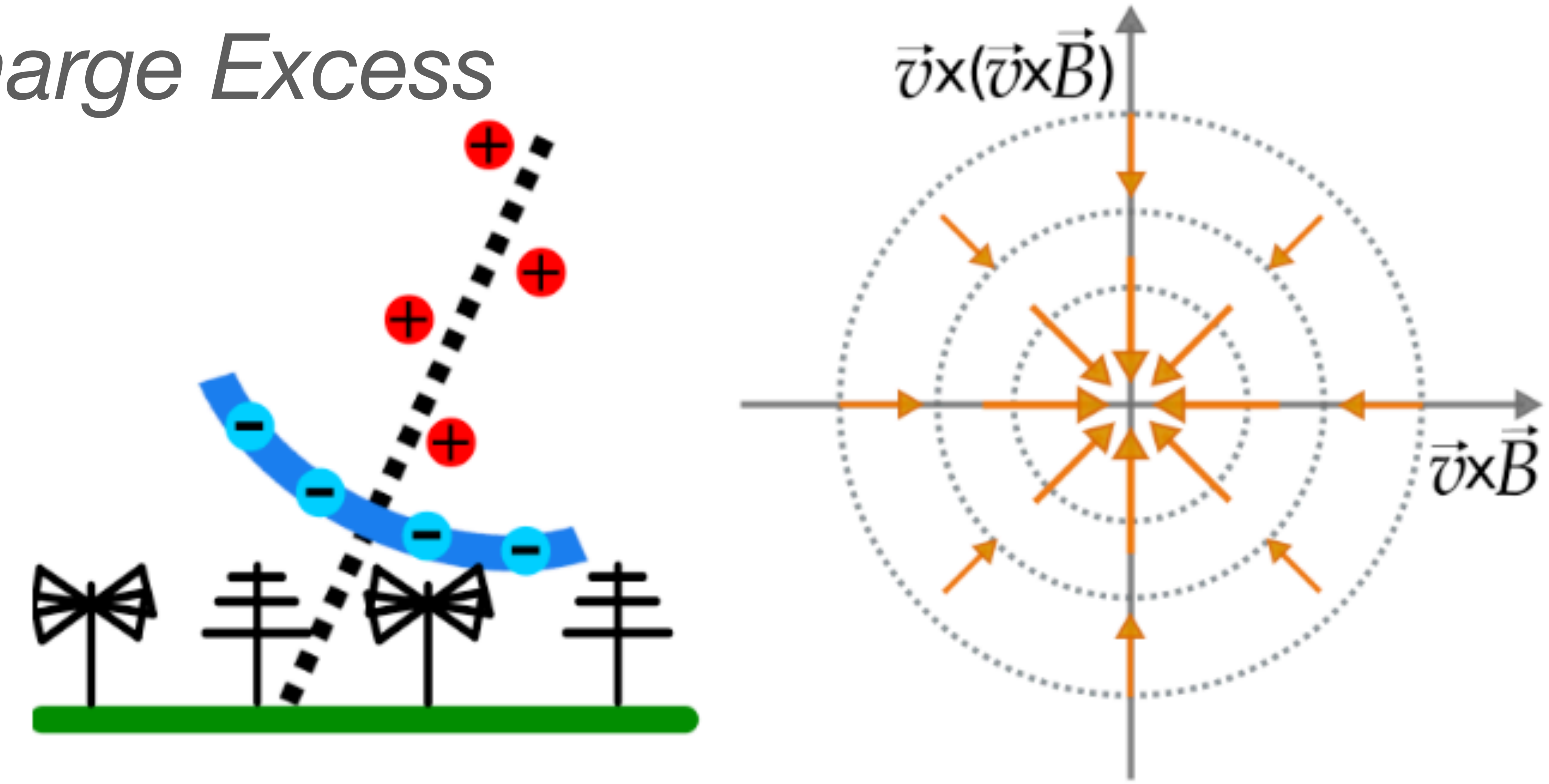


Combining things

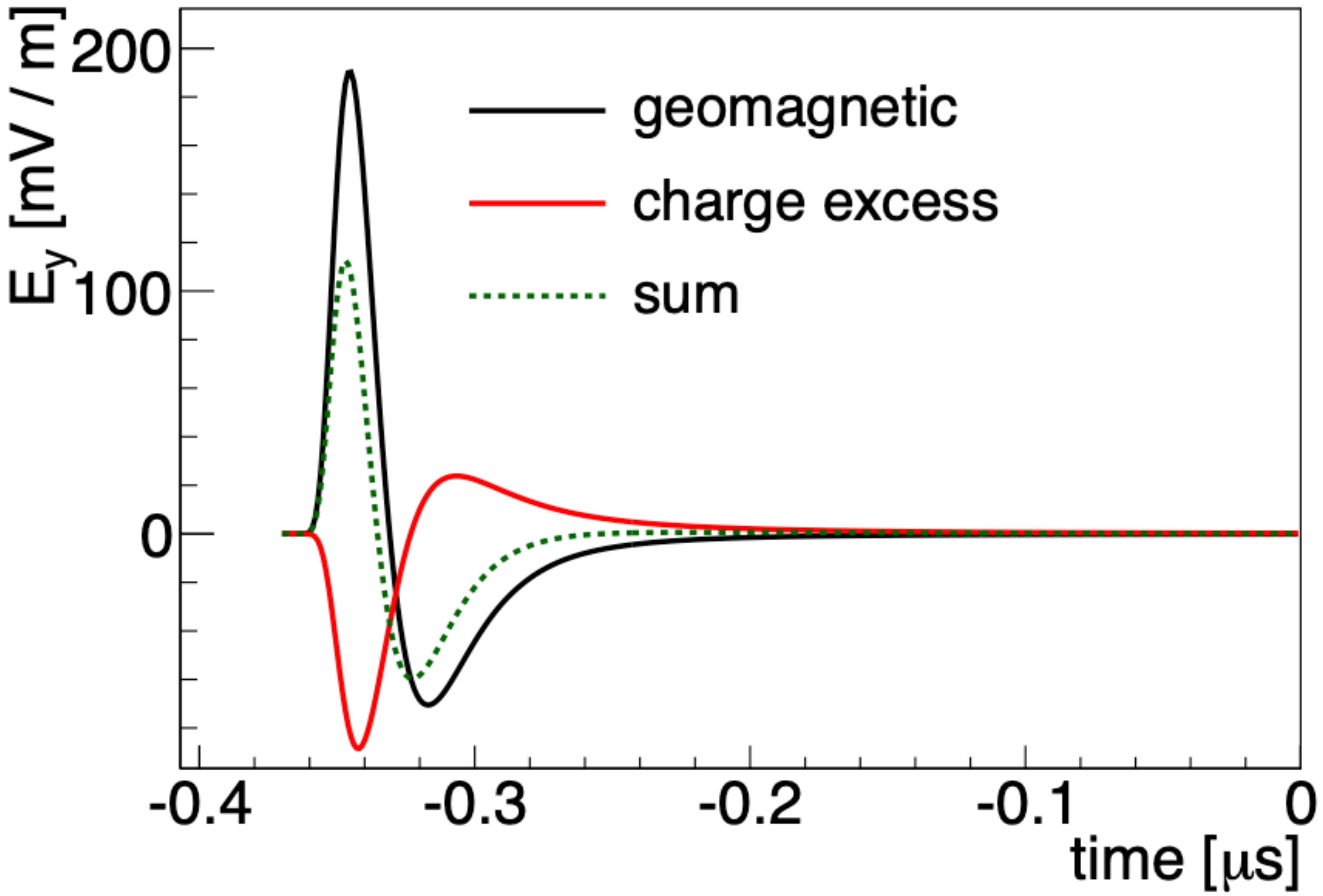
Geomagnetic



Charge Excess

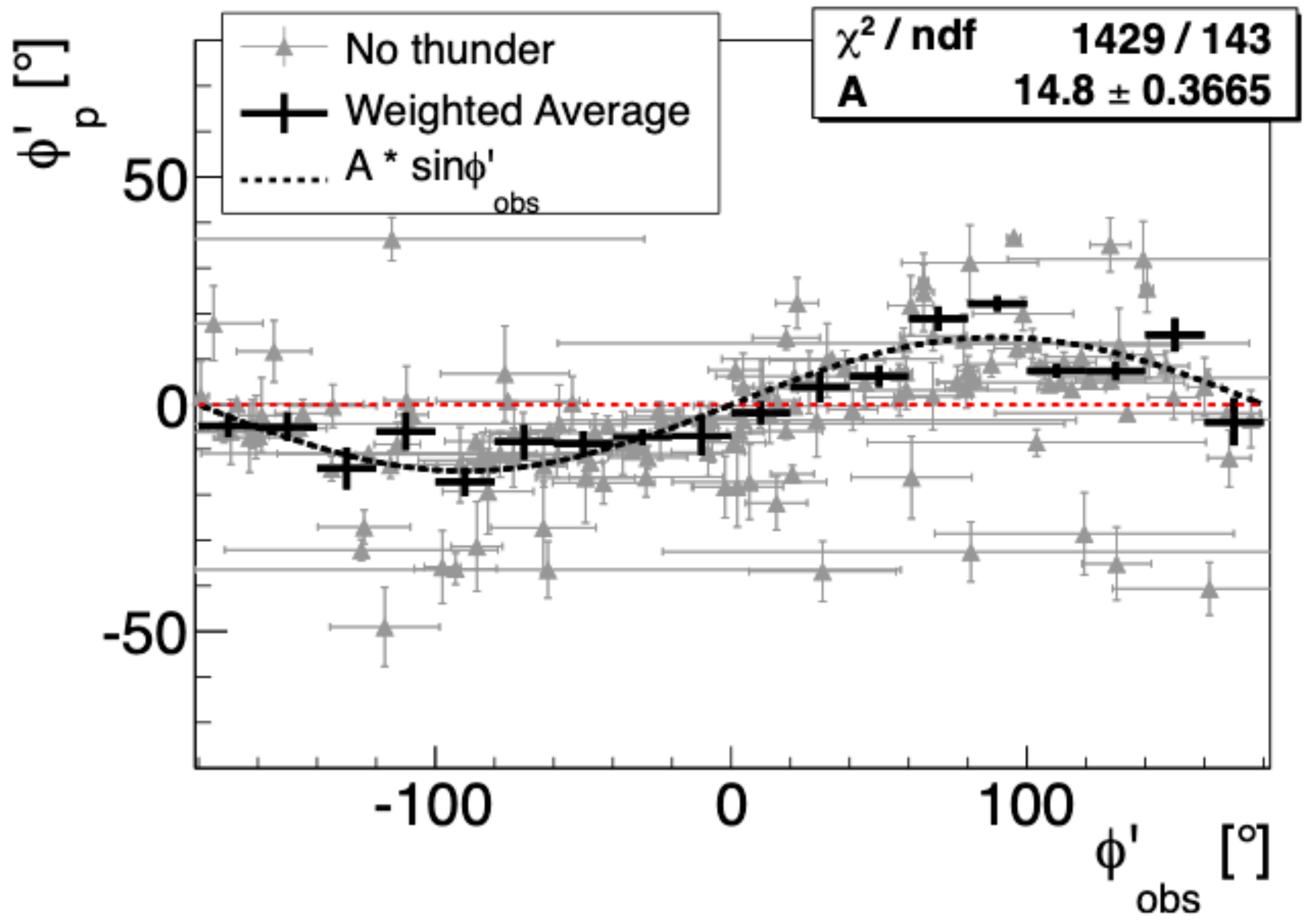


Interference

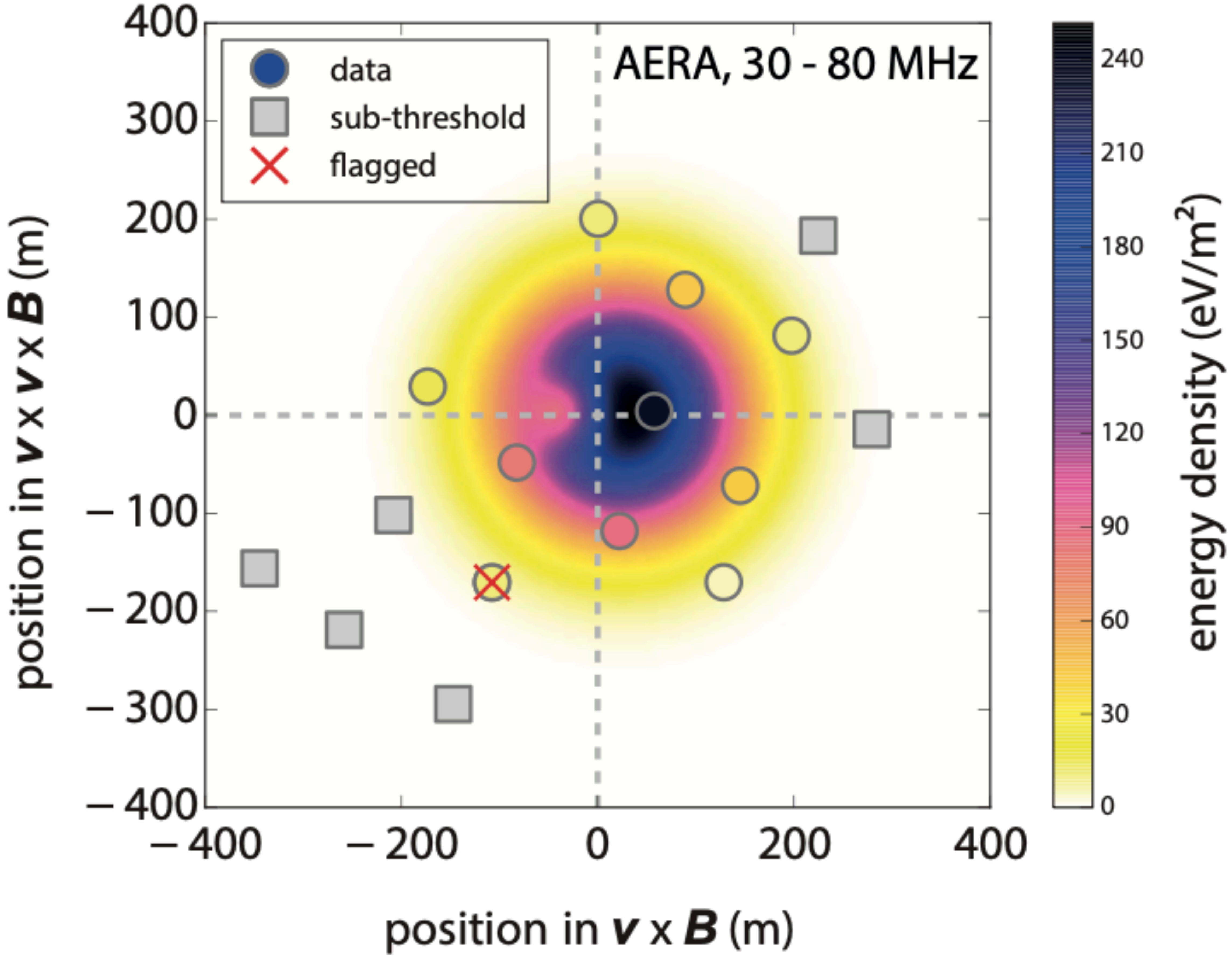


Combining things: interference

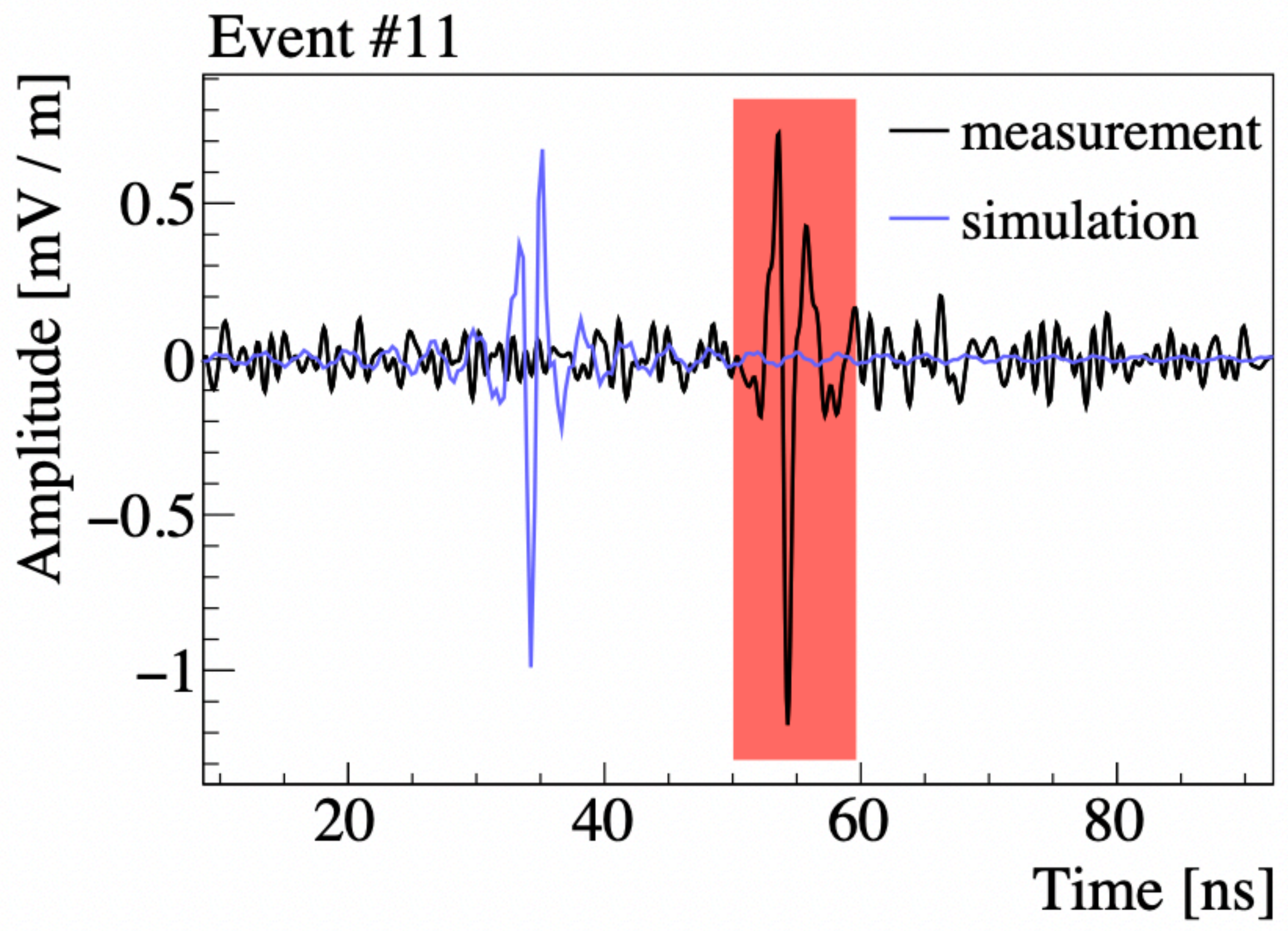
Polarisation angle

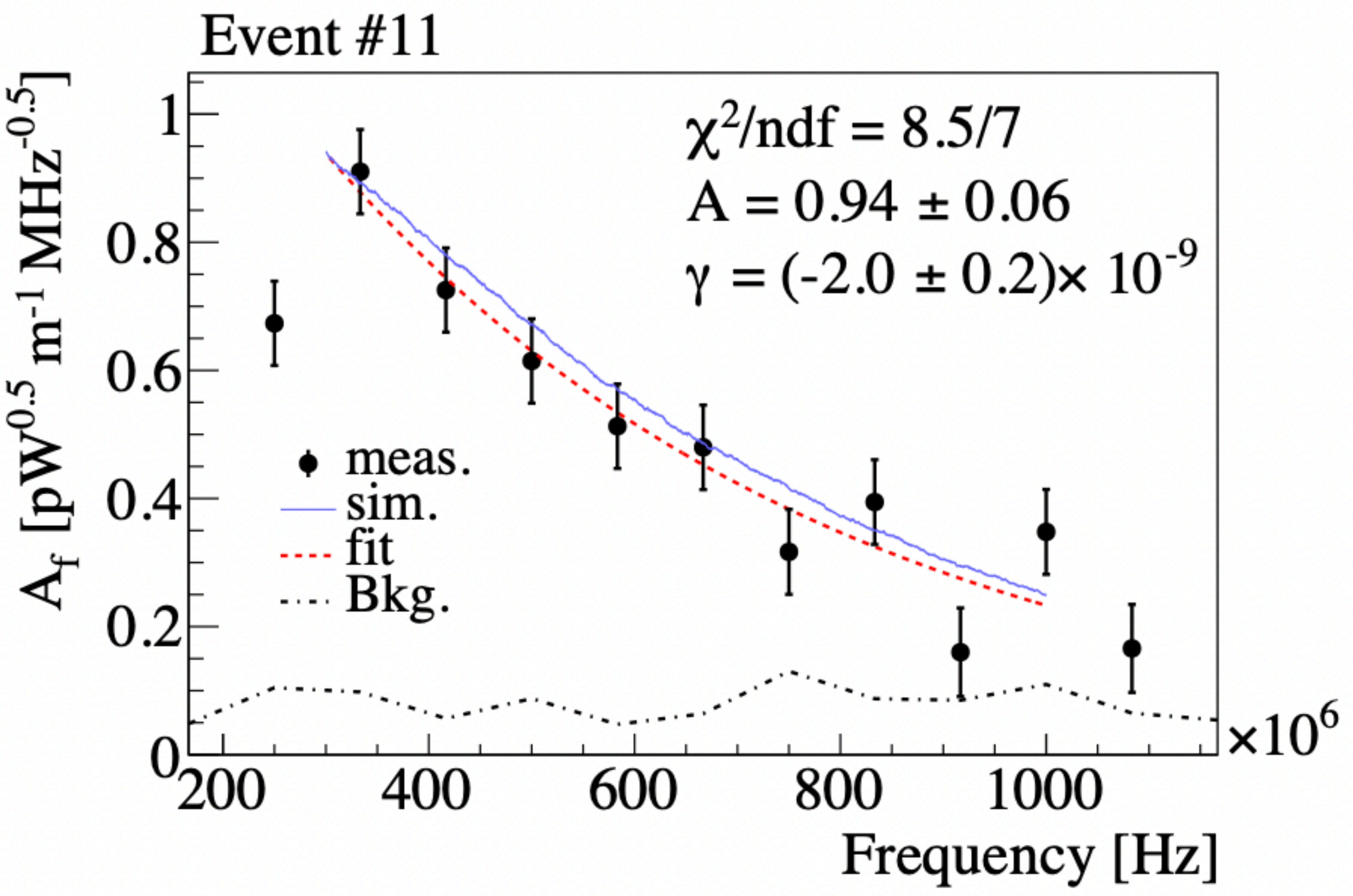


Footprint



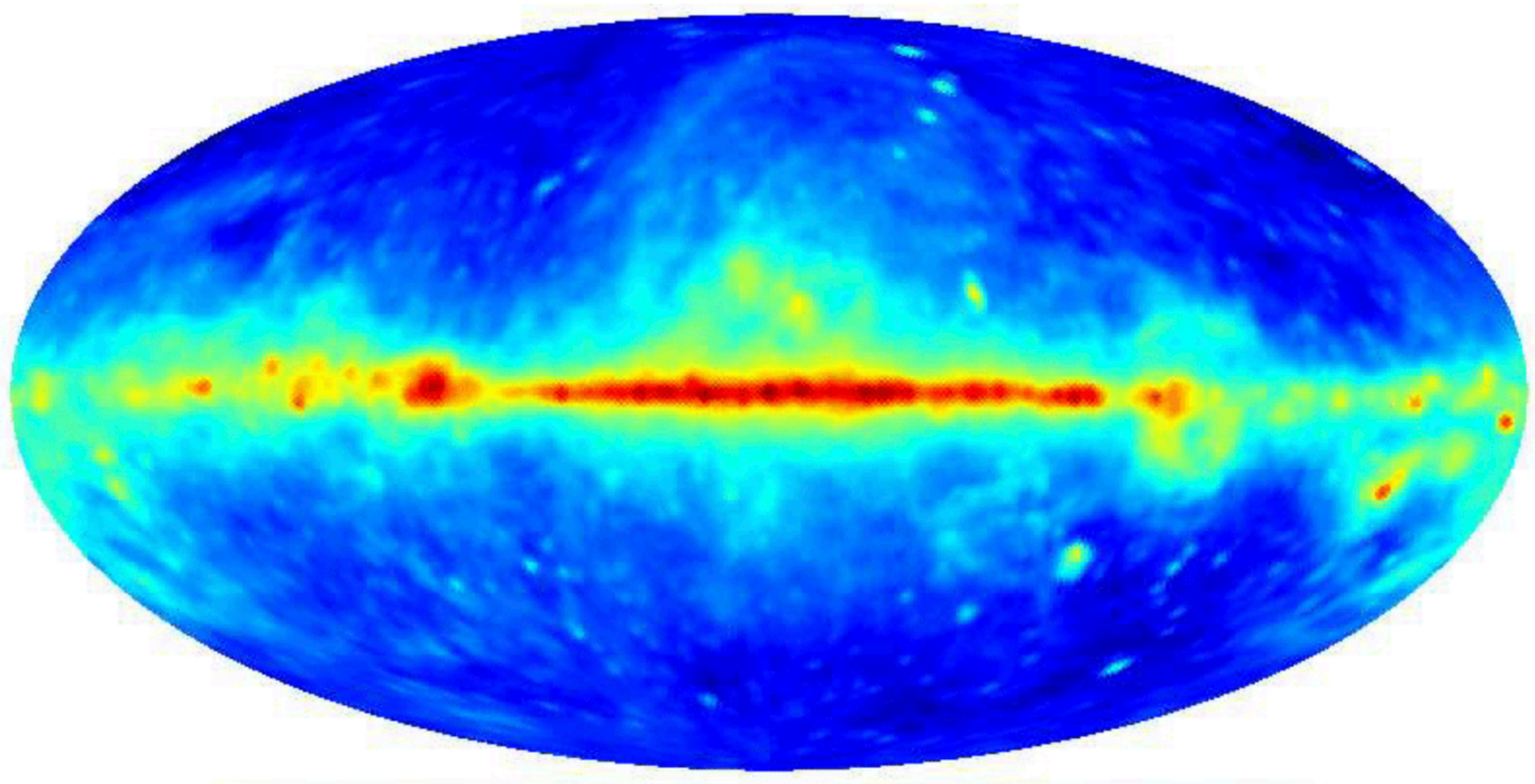
Time and frequency domain



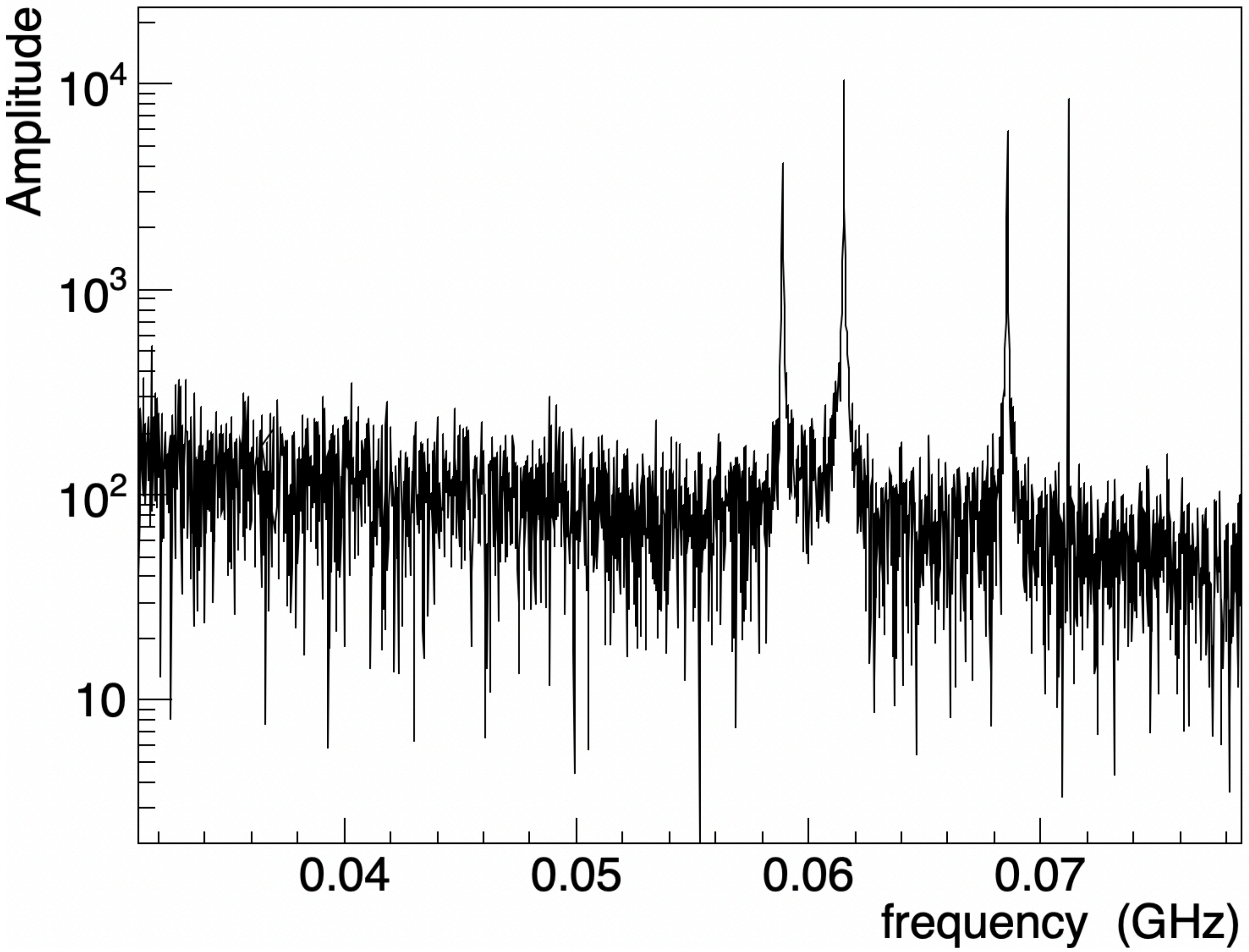


Challenges / Limitations

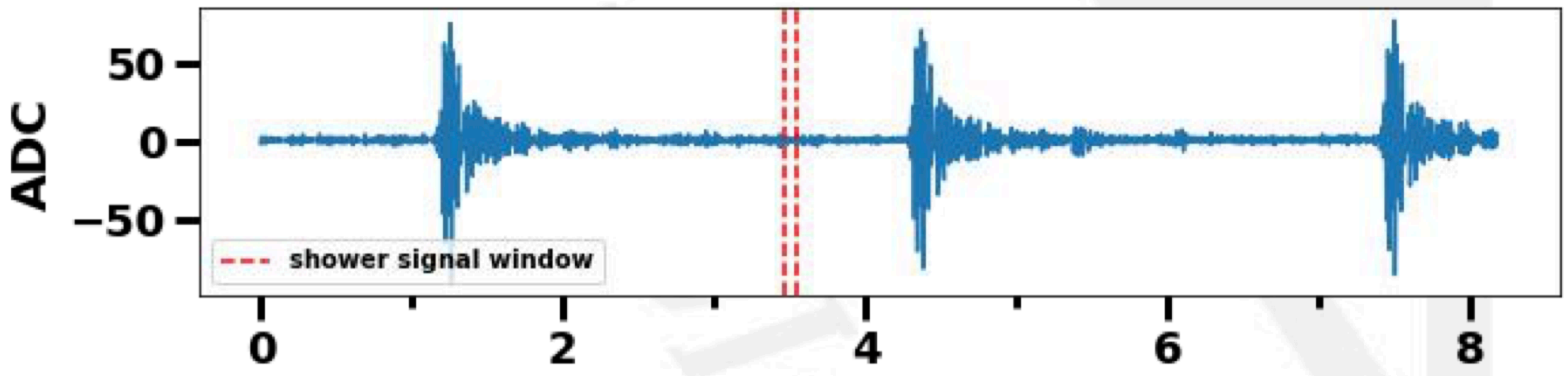
Emission from the Milky way



Man-made narrow-band emission



Man-made pulsed emission



Atmospheric electric fields

Why radio detection?

Neutrino & cosmic ray applications

“Fun”

“Cheap” - sometimes for “free”

Sensitive to the electromagnetic component in air showers

Why radio detection?

Works 24/7

Dielectric materials are transparent for radio waves

Sensitive to the longitudinal development of the air shower

Emission can be calculated from first principles

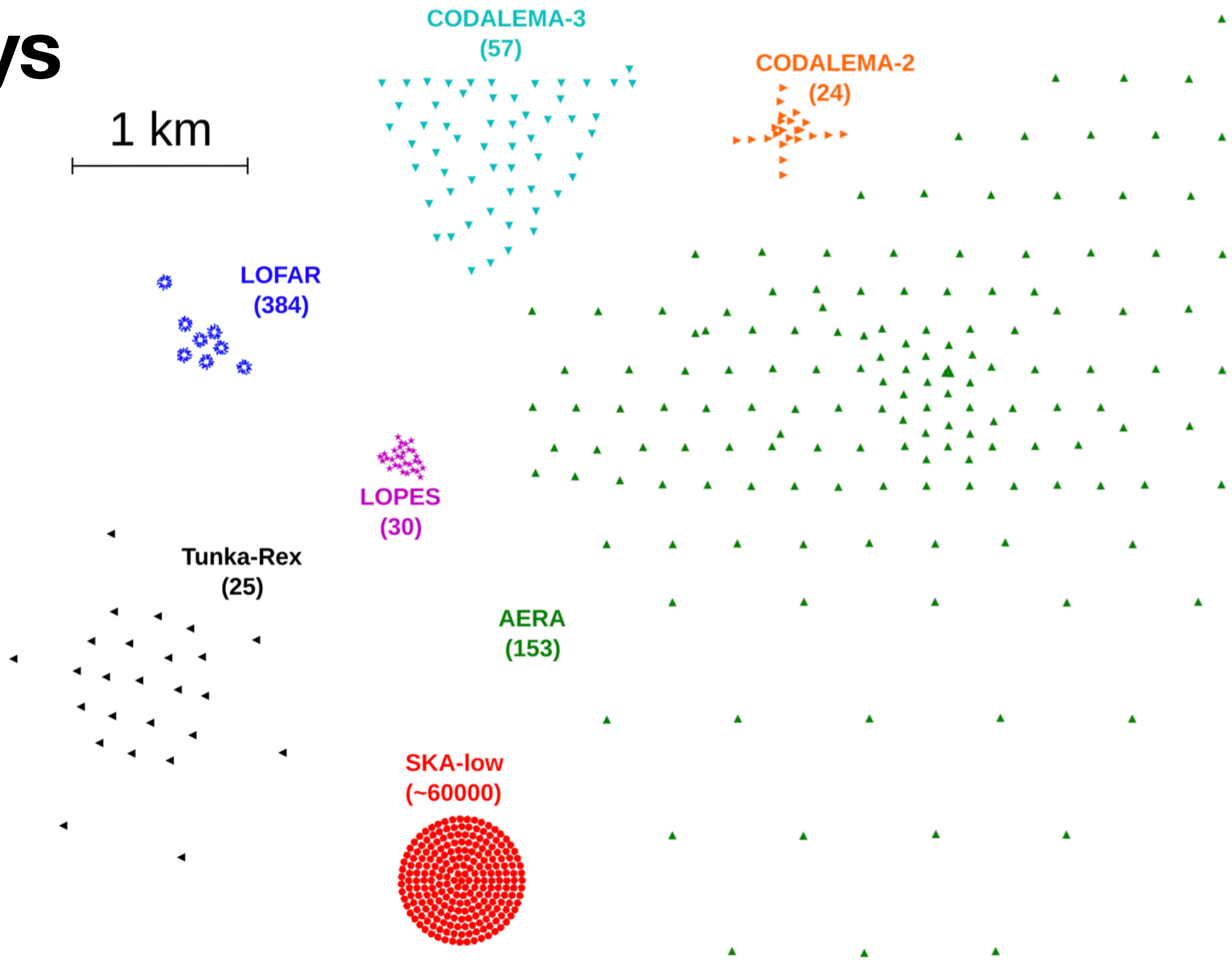
Ground arrays

"Looking up"

In coincidence with other detectors

Or also a radio telescope (LOFAR)

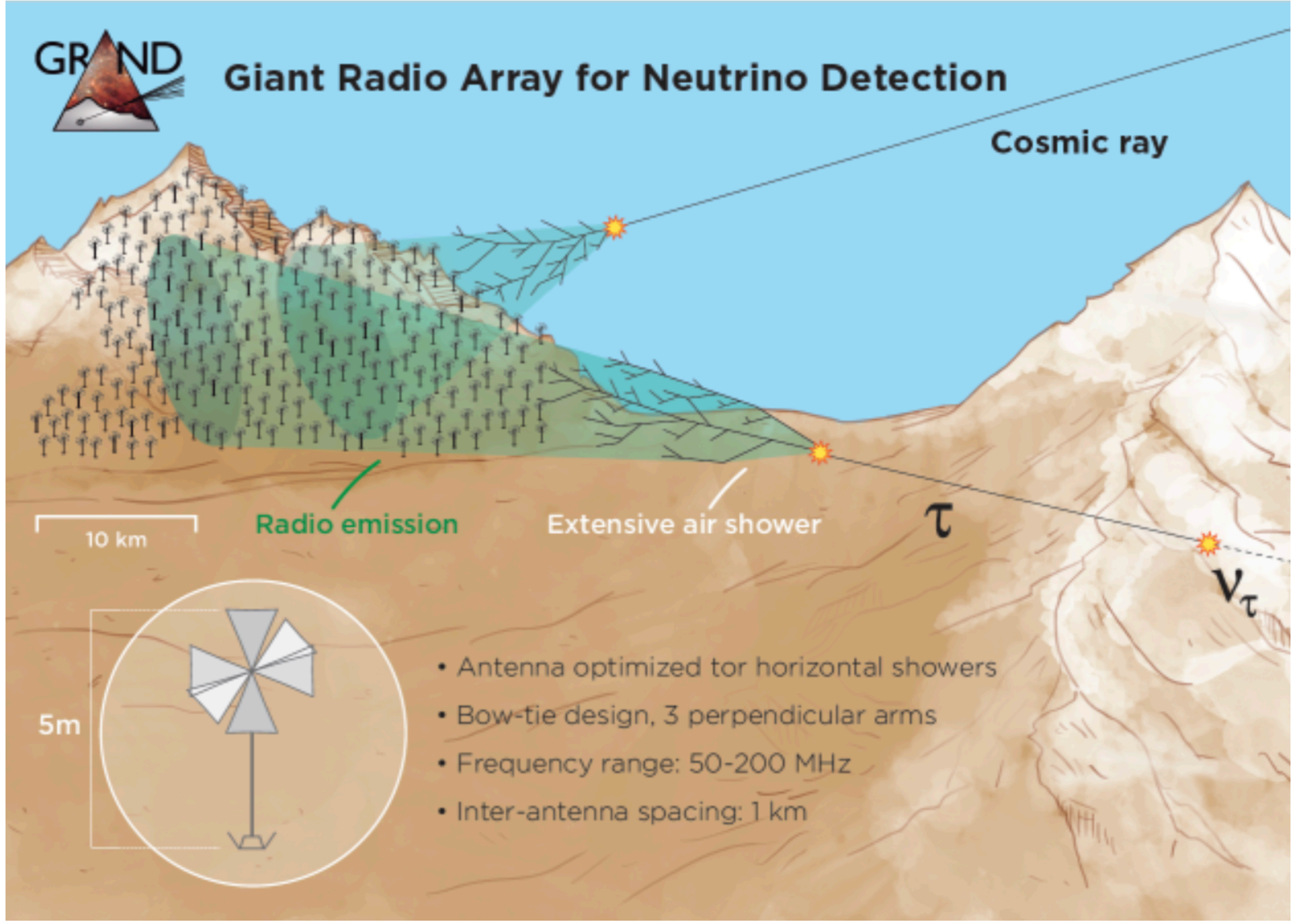
30-80 MHz - Band

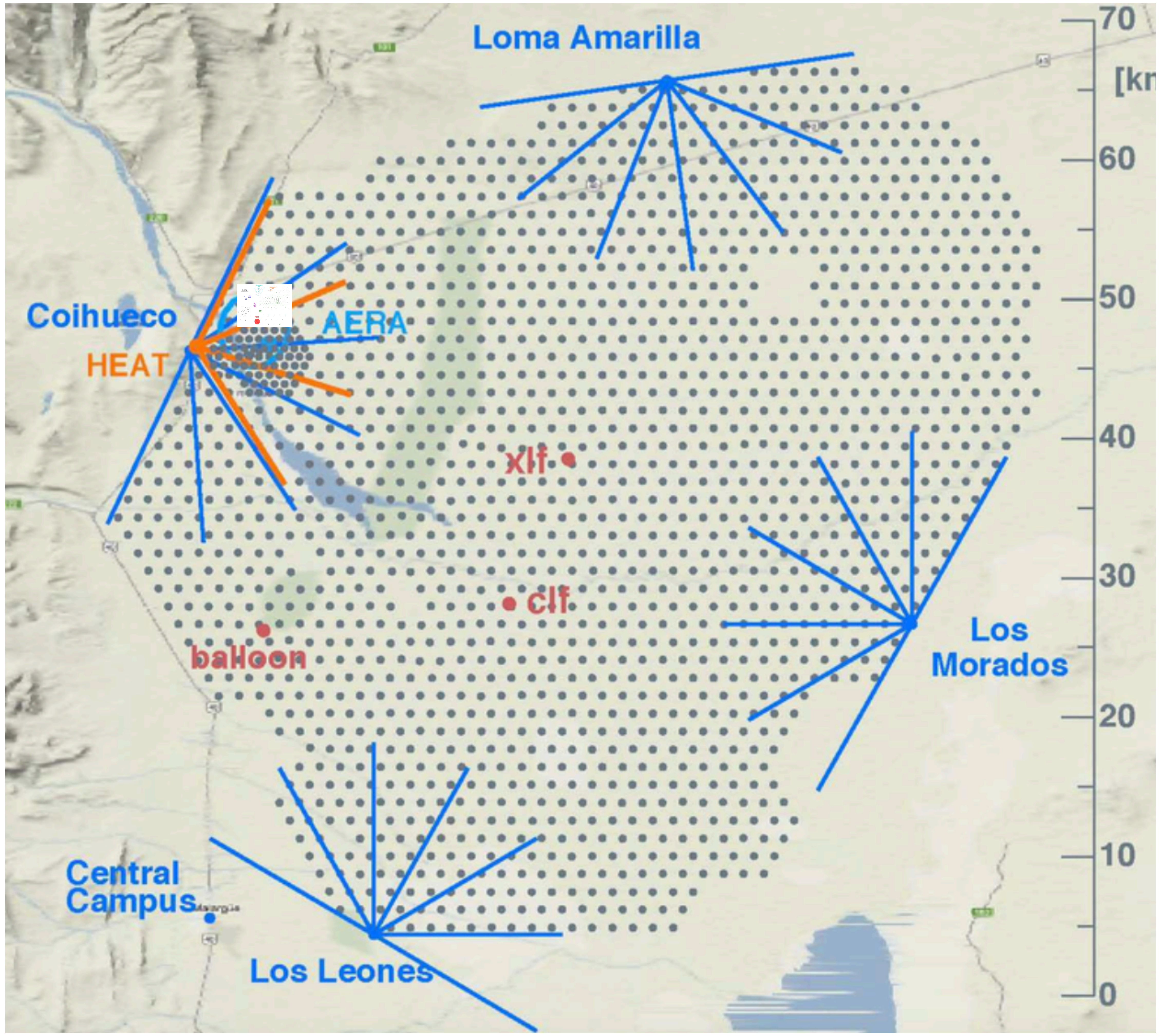


Ground arrays

"Looking to the side"

~km distance between antennas

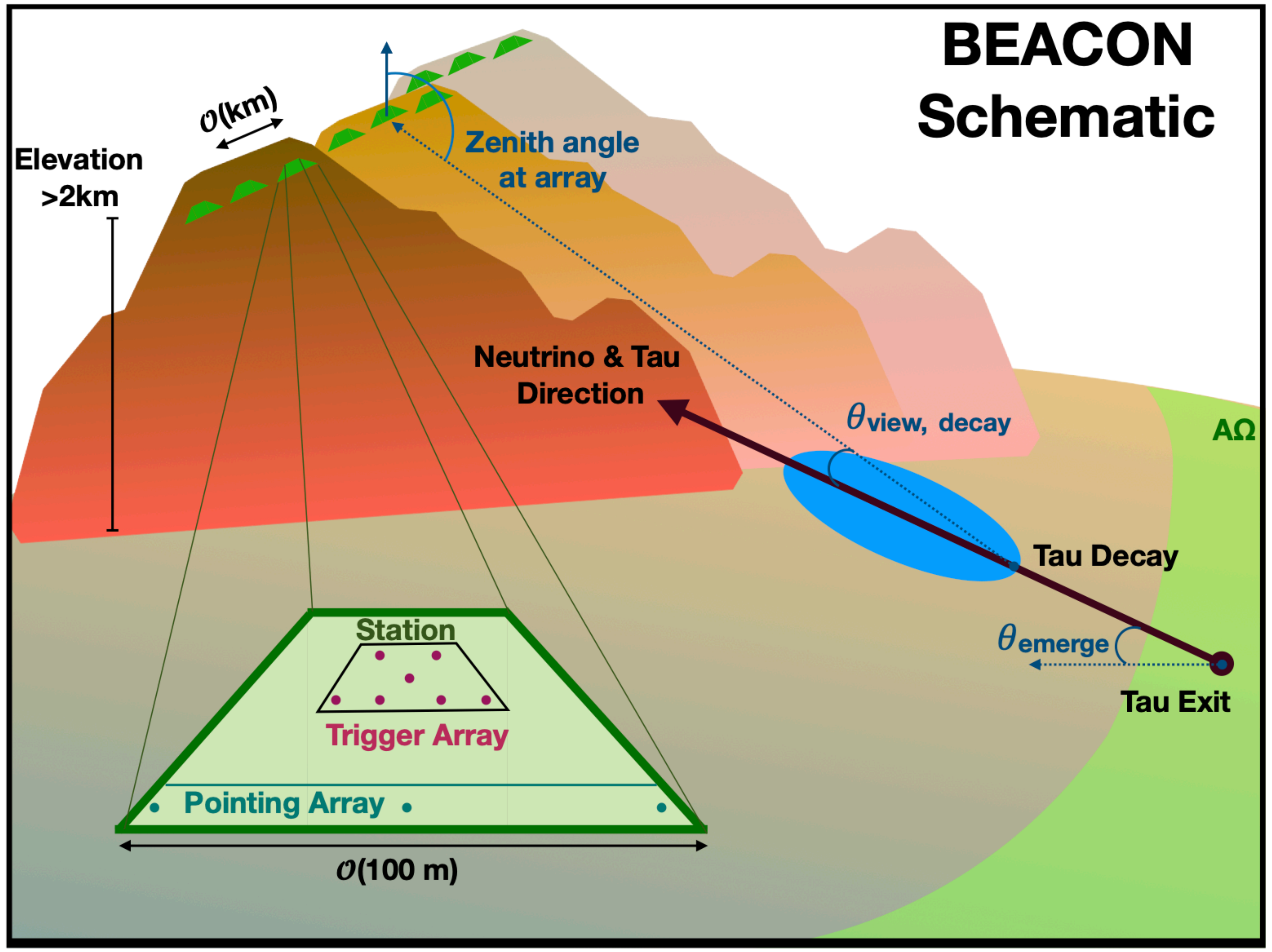


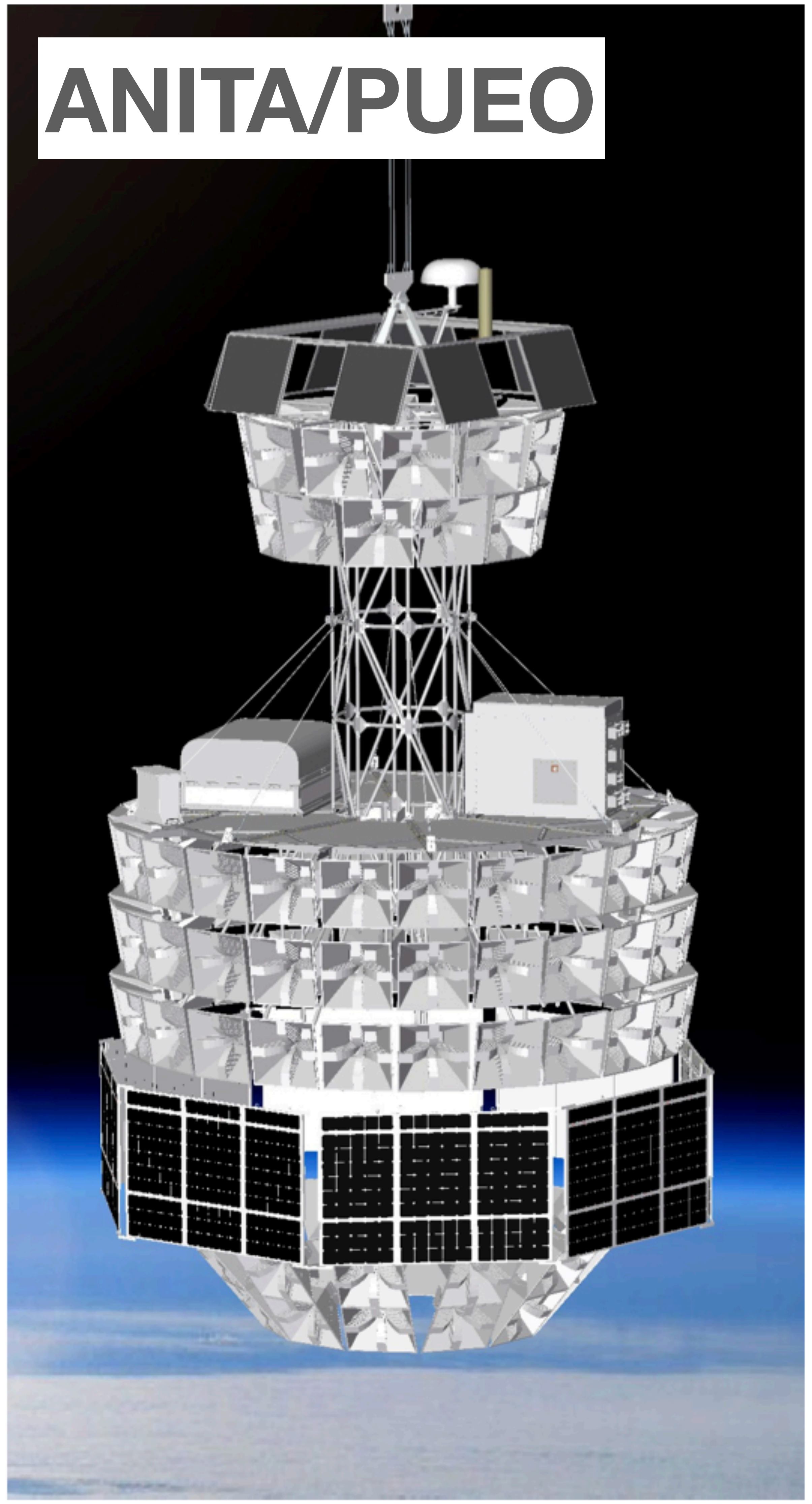


AugerPrime RD

Mountain tops and balloons

"Looking down"





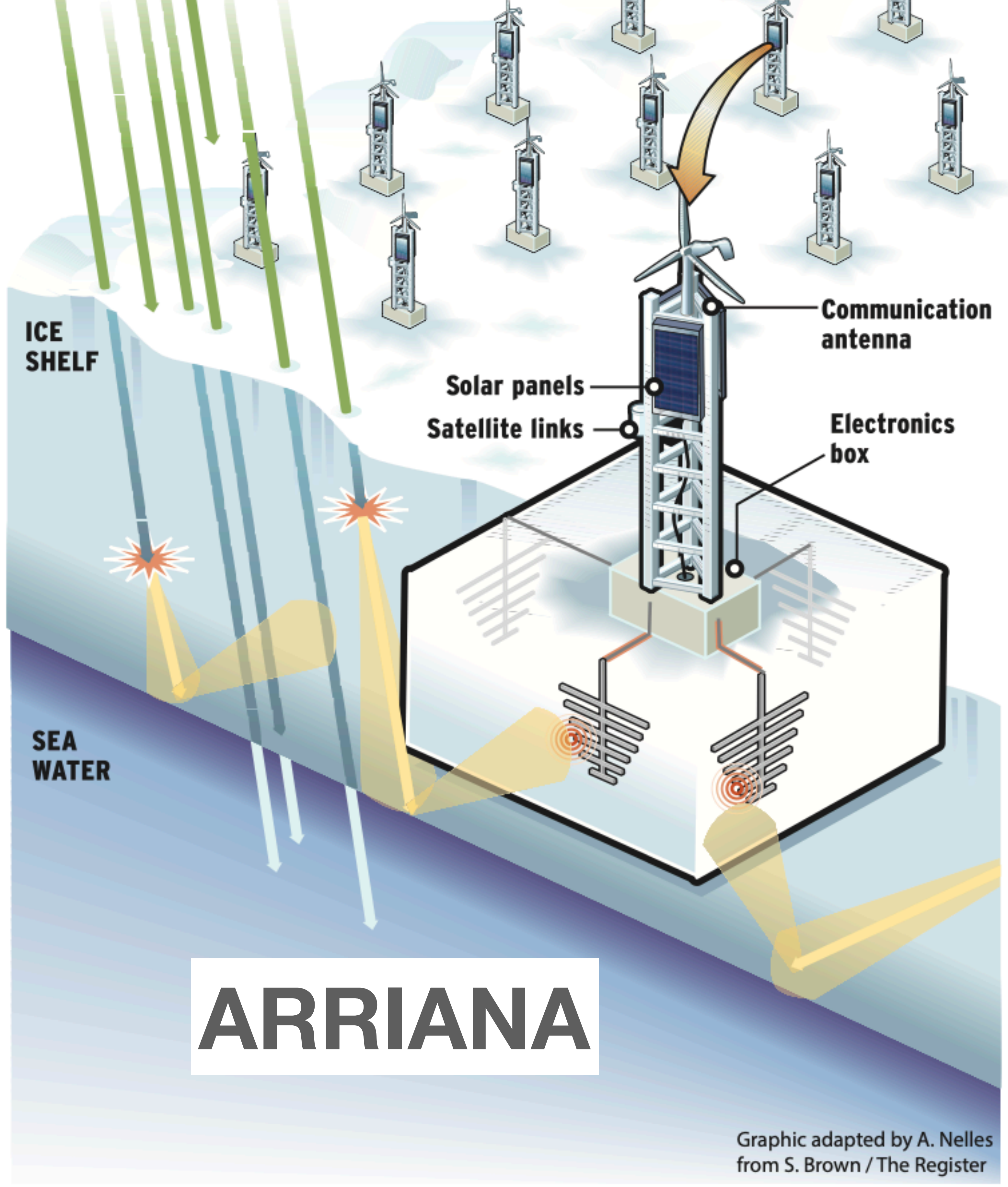
In ice

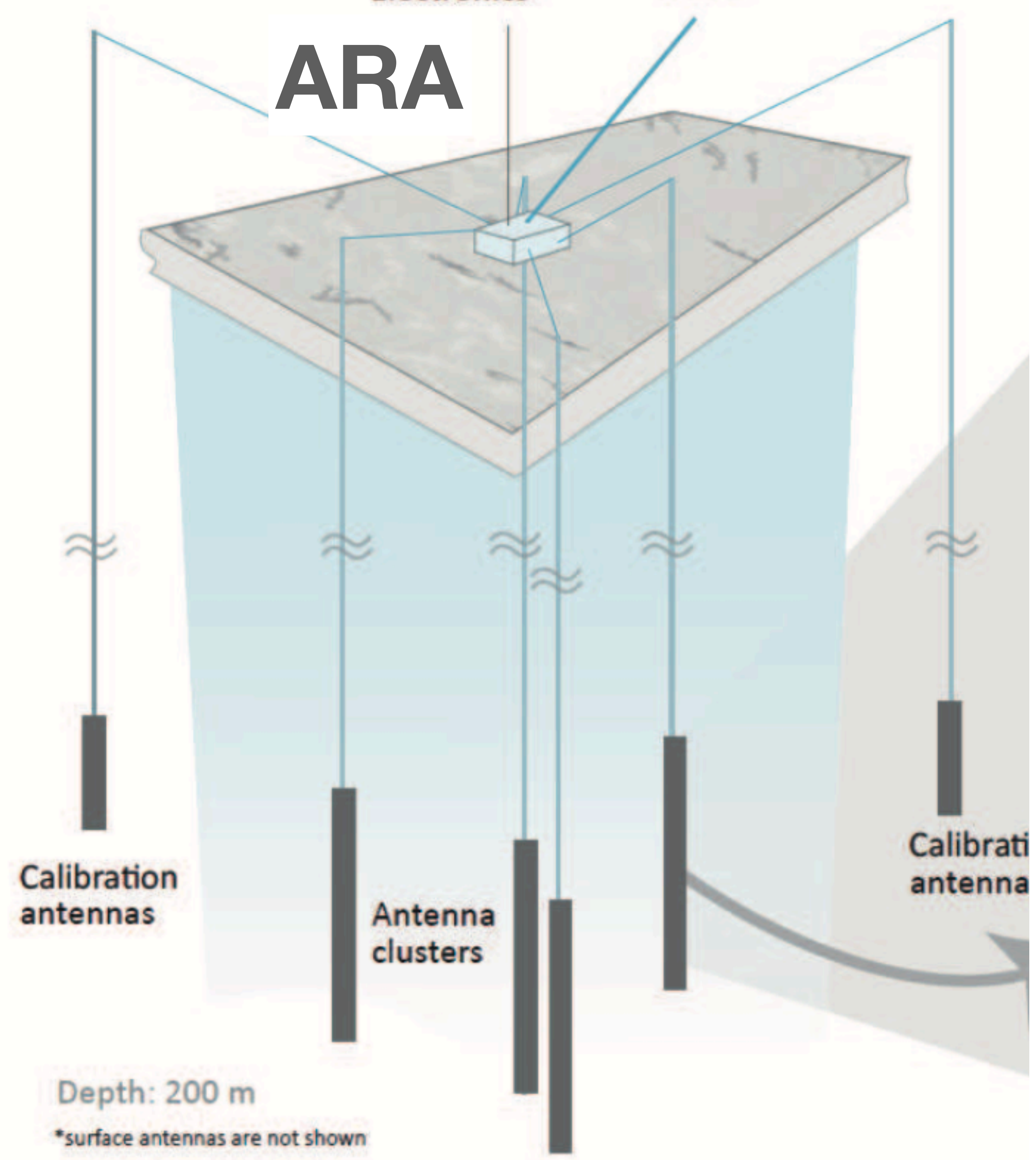
Looking for neutrino induced cascades

Completely dominated by Askaryan radiation

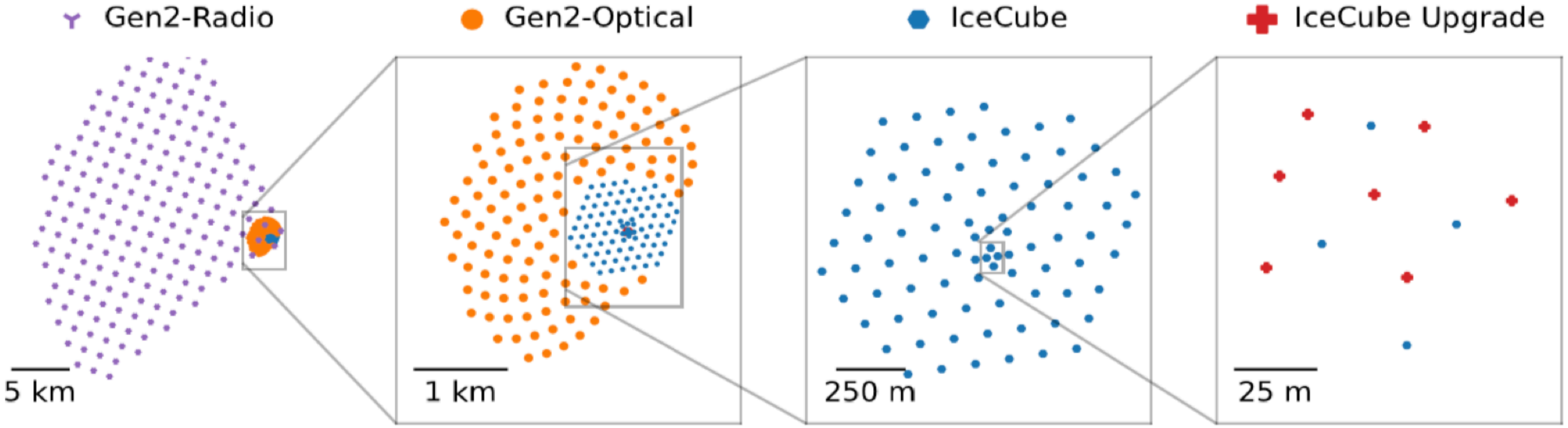
Very pronounced Cherenkov cone

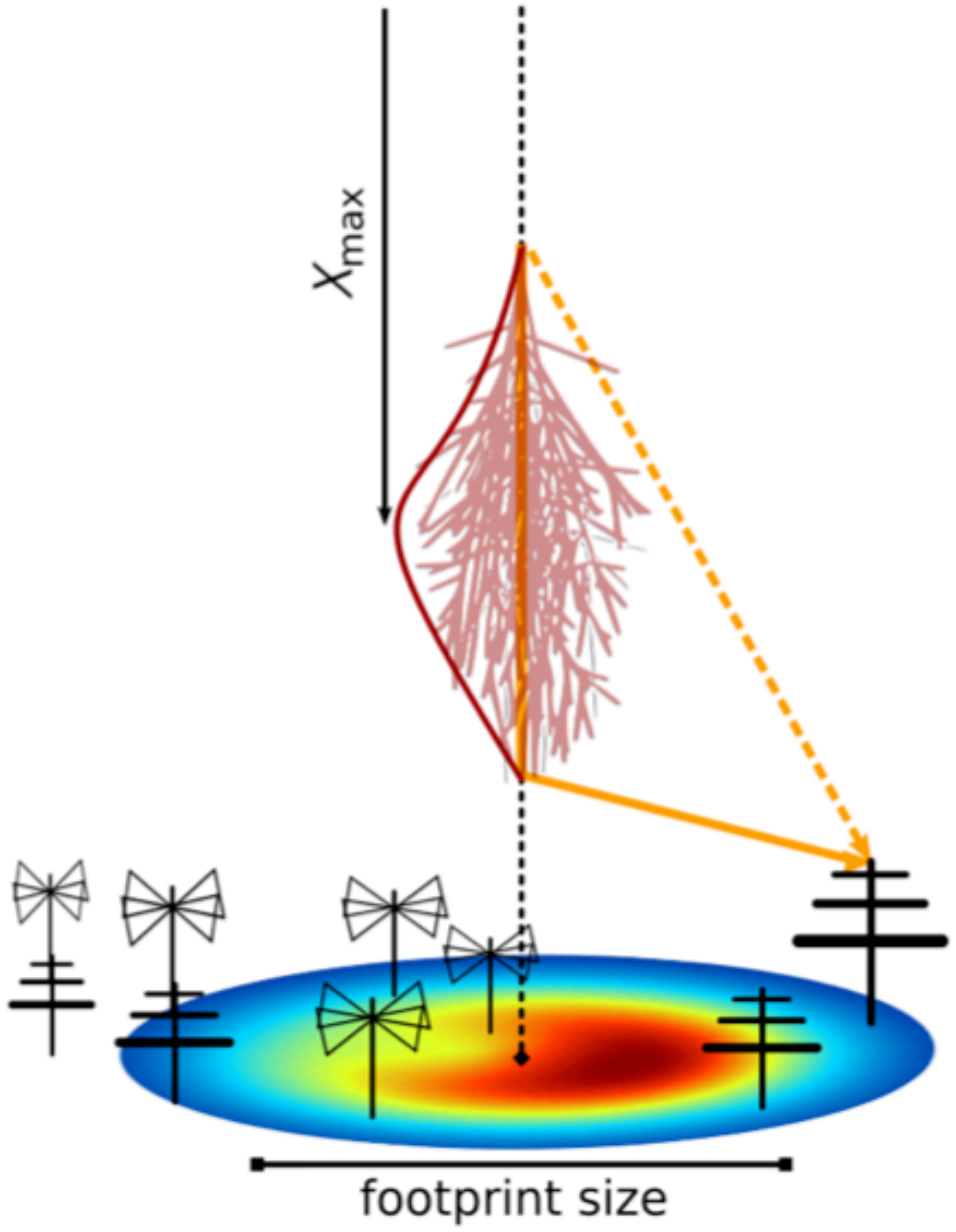
$$\cos\theta = \frac{1}{\beta n} \rightarrow \theta \approx 45^\circ$$





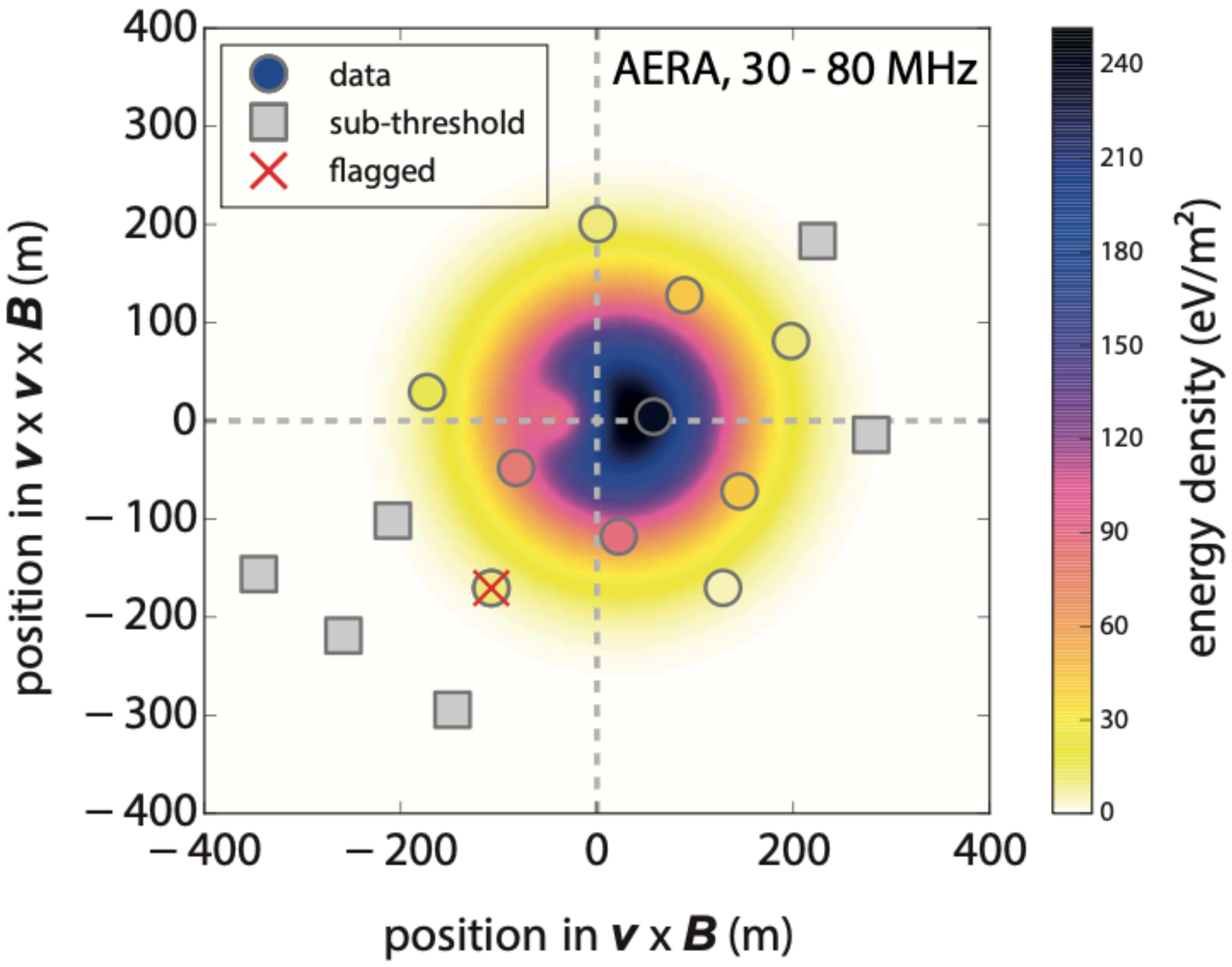
IceCube - Gen2

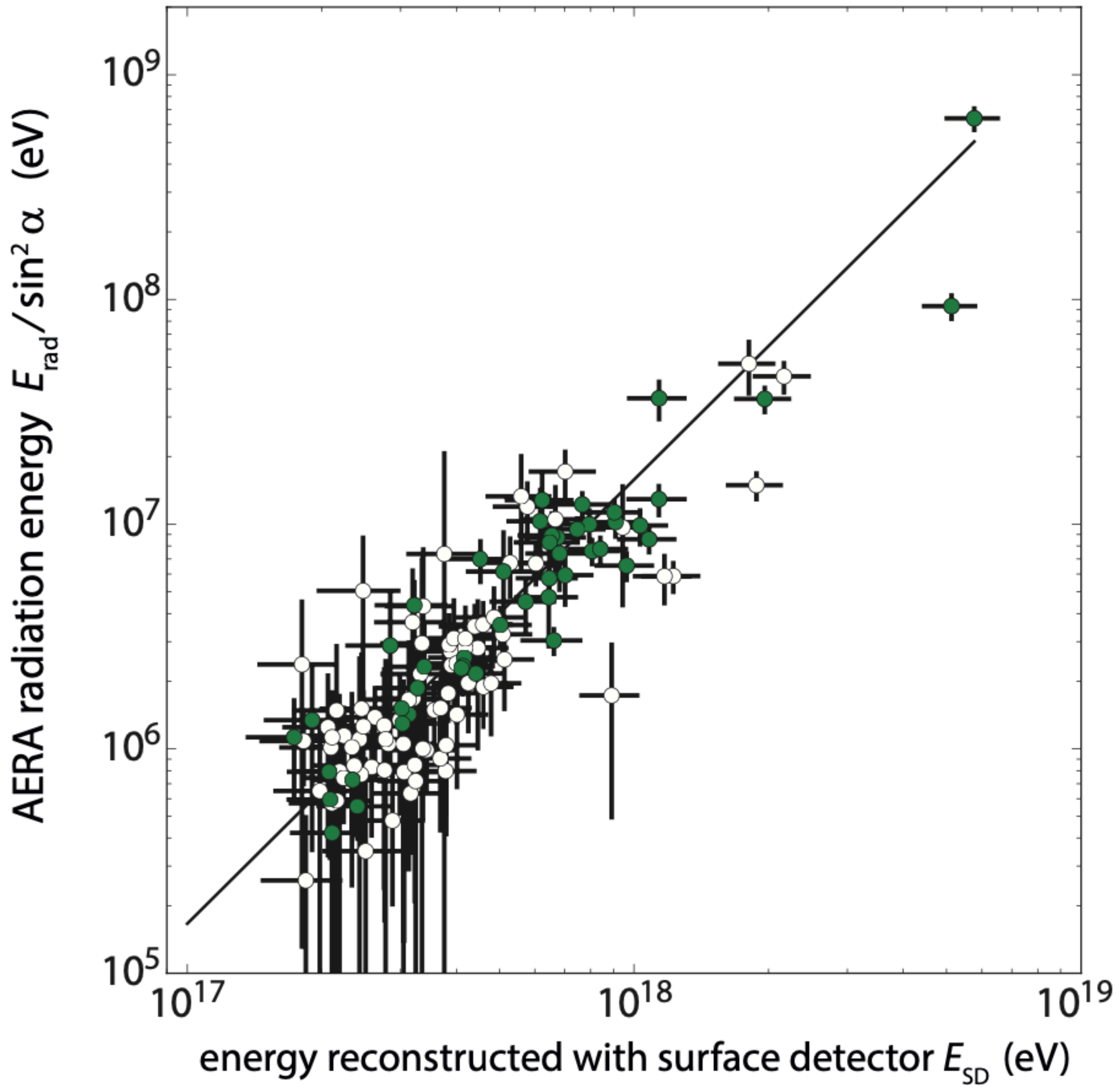



X_{max}
footprint size

Estimating cosmic ray energy (ground arrays)

The electric field strength is proportional to the energy of the primary particle



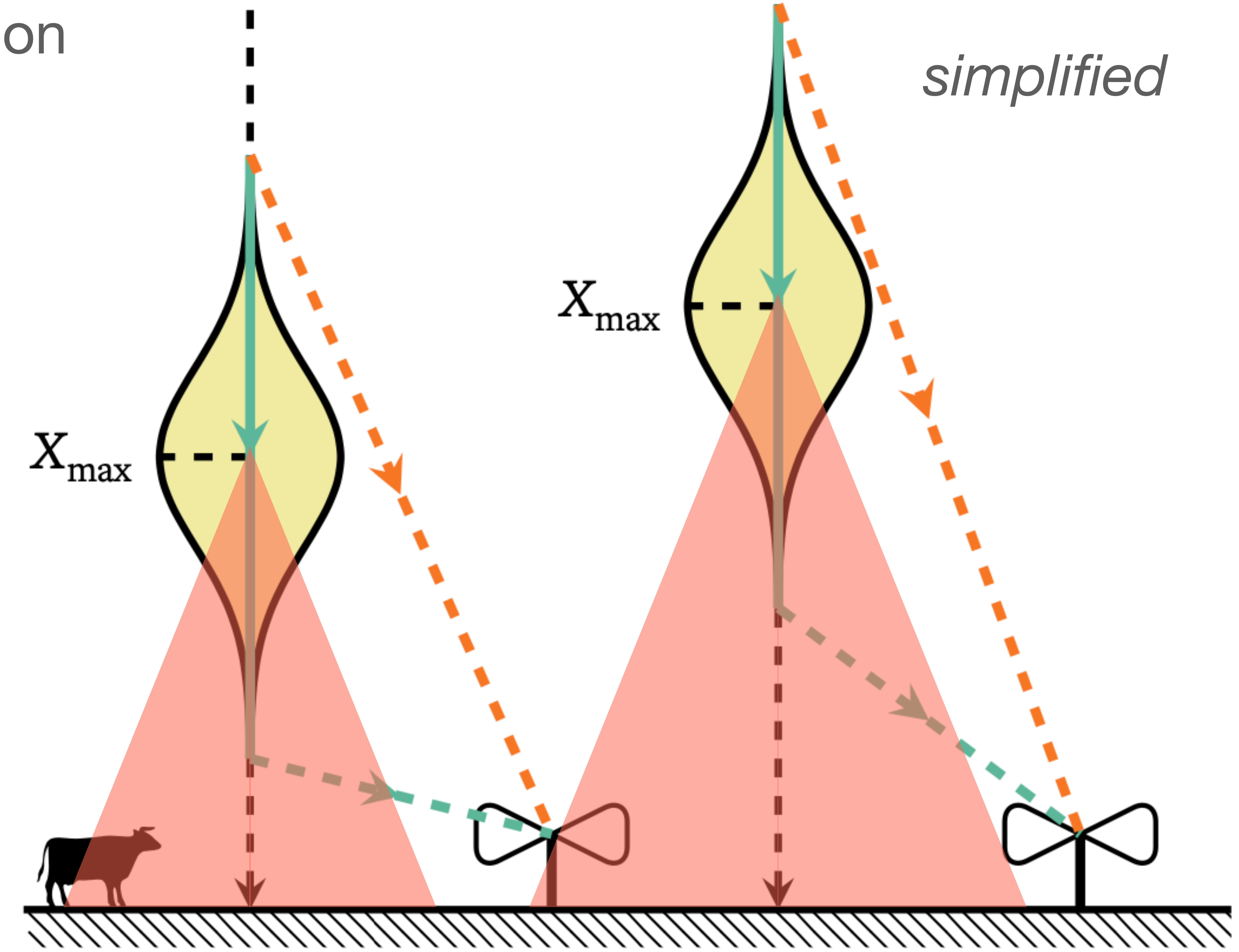


Fit the footprint and use the normalisation

The Pierre Auger Collaboration, PRL 116, 241101 (2016)

Longitudinal Shower Information

Information is captured twice in the data

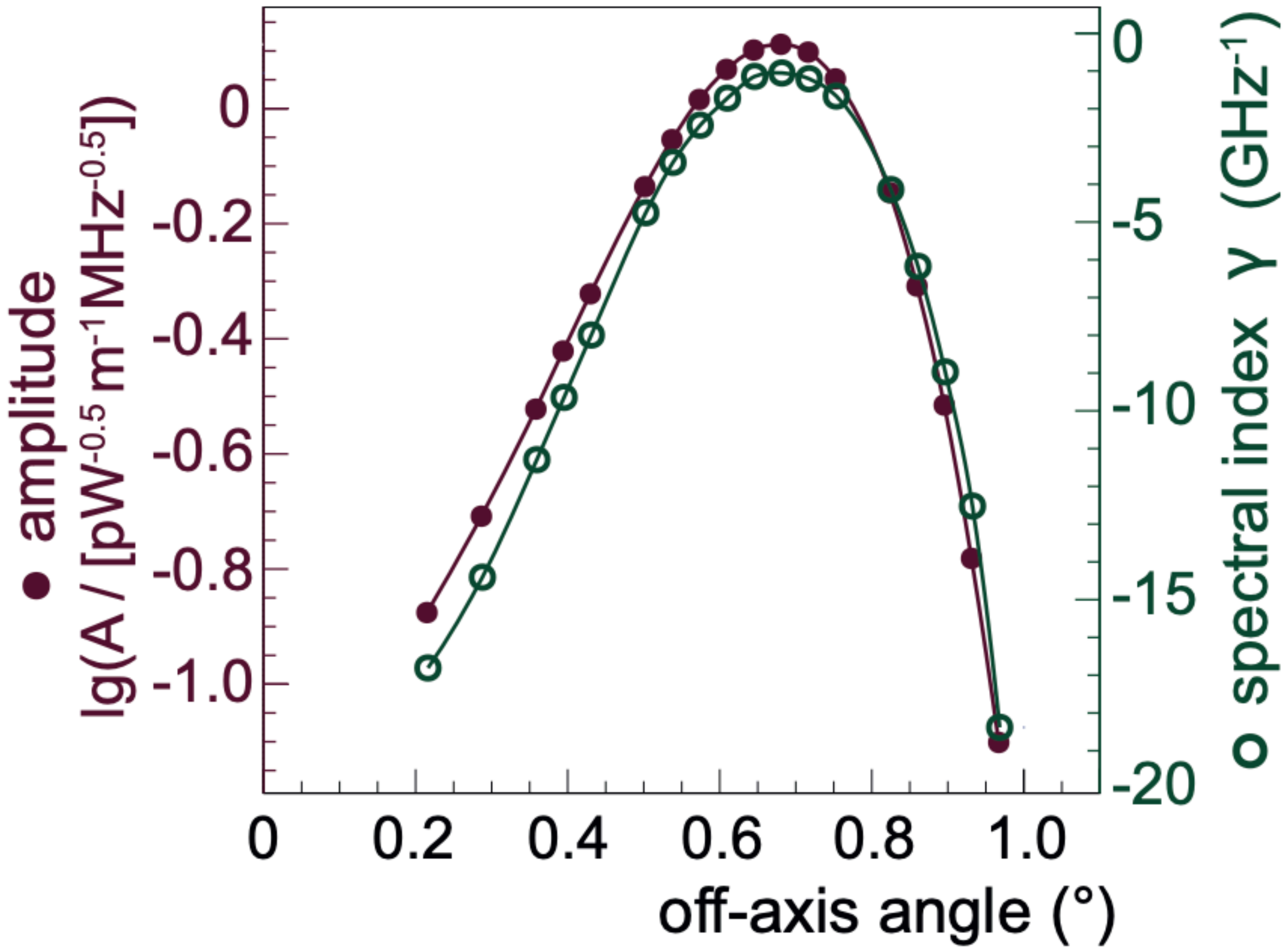


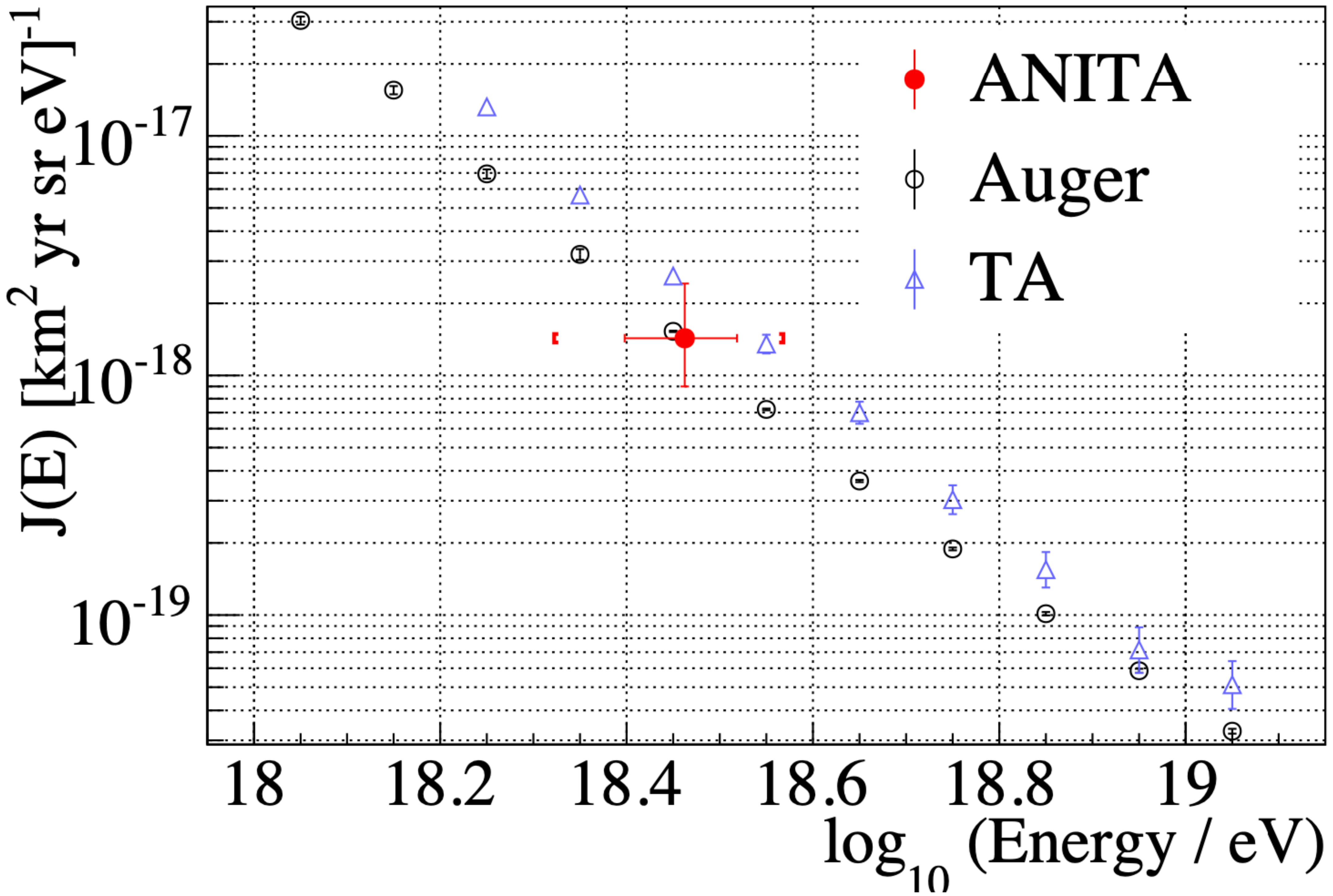
Lower amplitude
Longer pulse
(Steeper frequency spectrum)

Higher amplitude
Shorter pulse
(Flatter frequency spectrum)

Estimating cosmic ray energy (balloon)

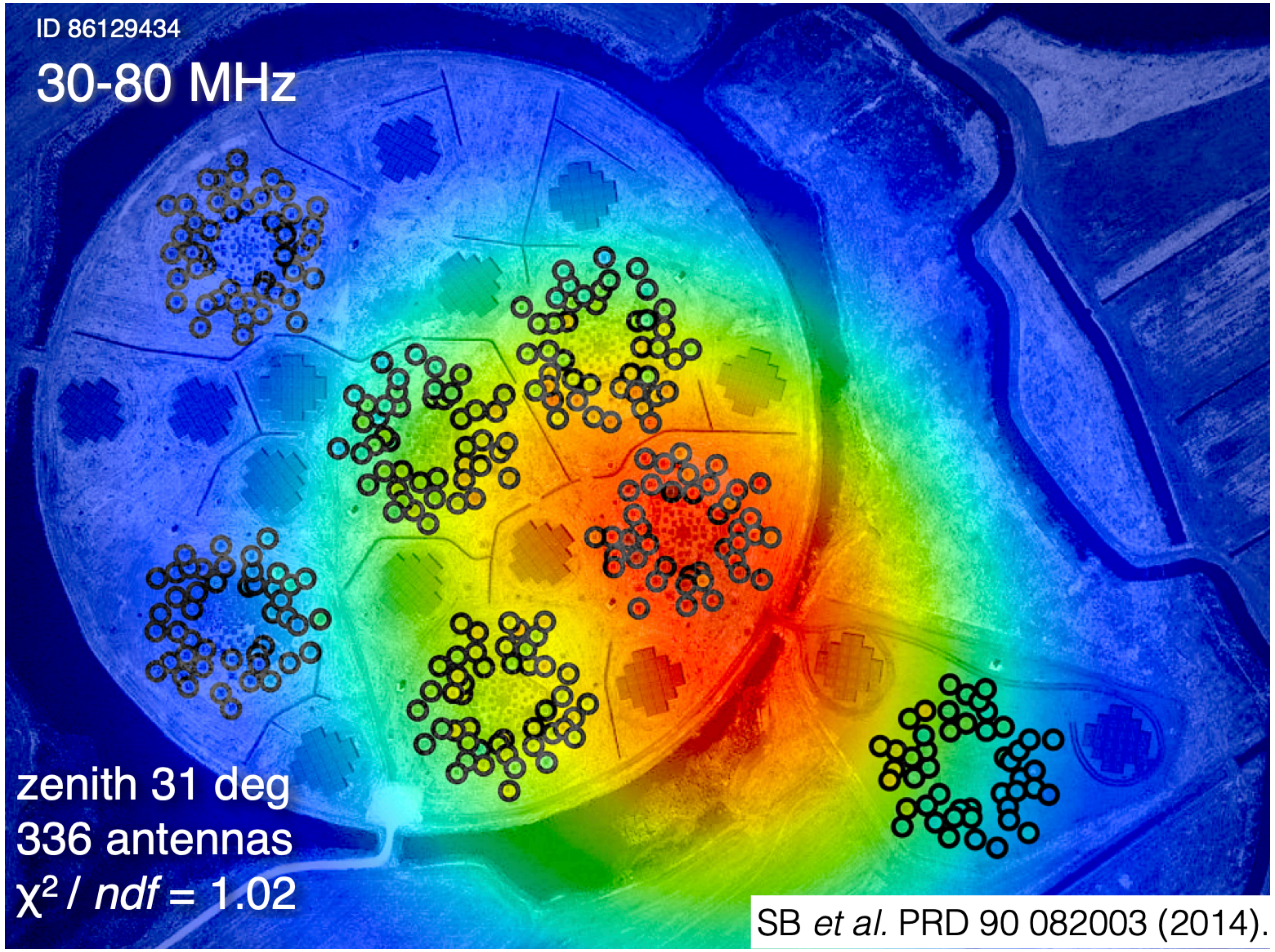
Using the slope of the frequency spectrum to estimate the amplitude on the Cherenkov cone

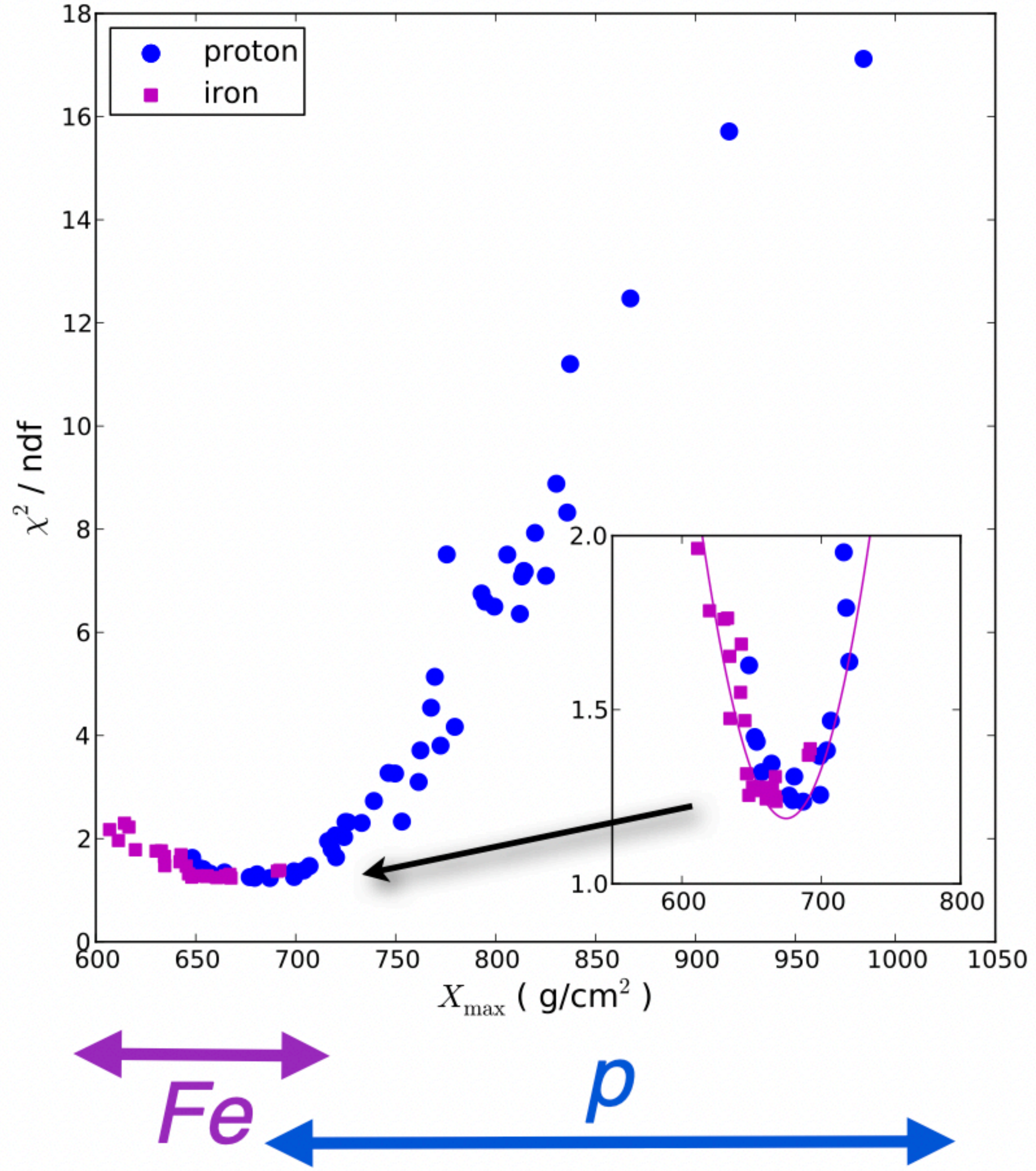




Anita Collaboration, Astroparticle Physics (2016)

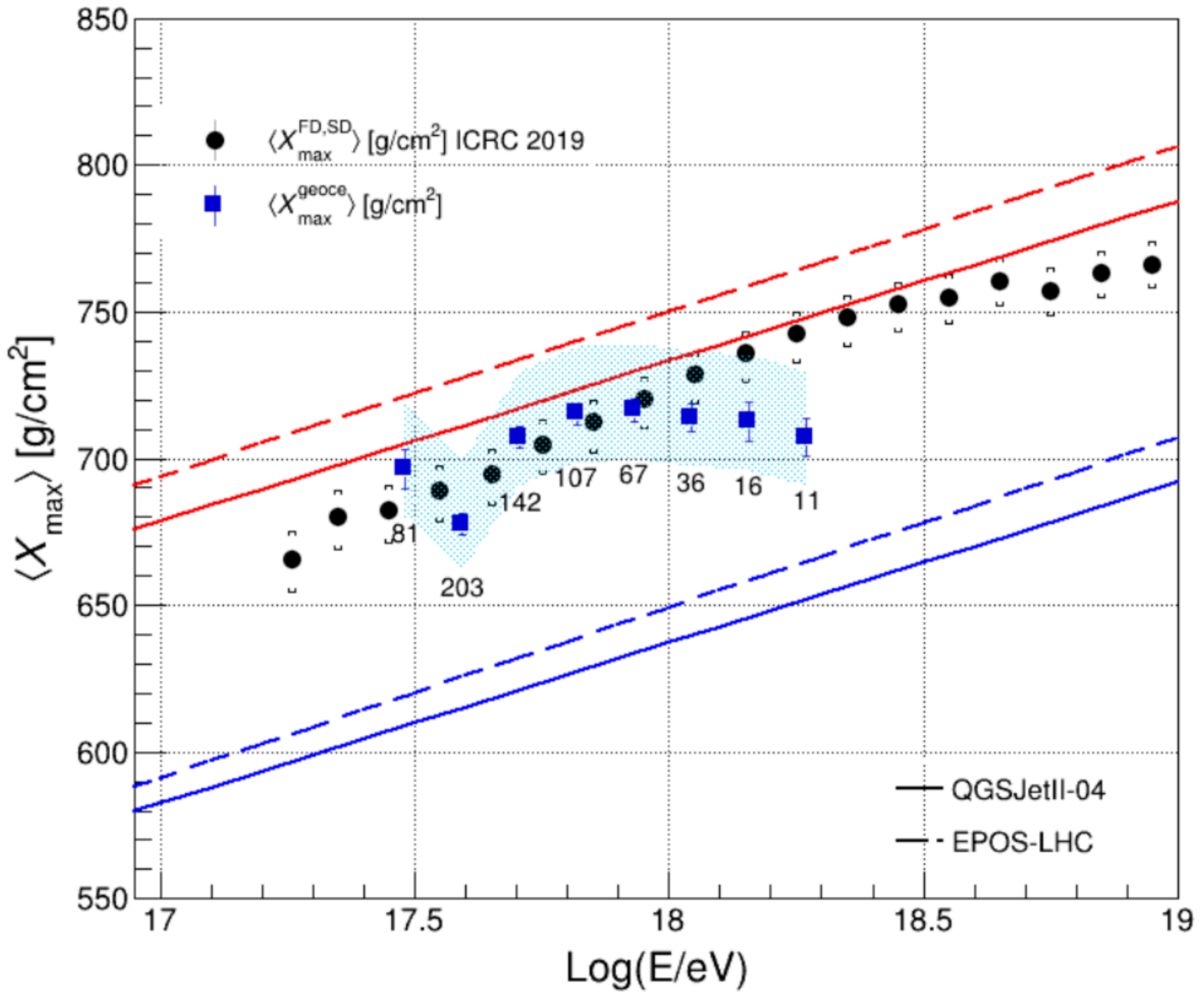
Longitudinal shower development: Composition



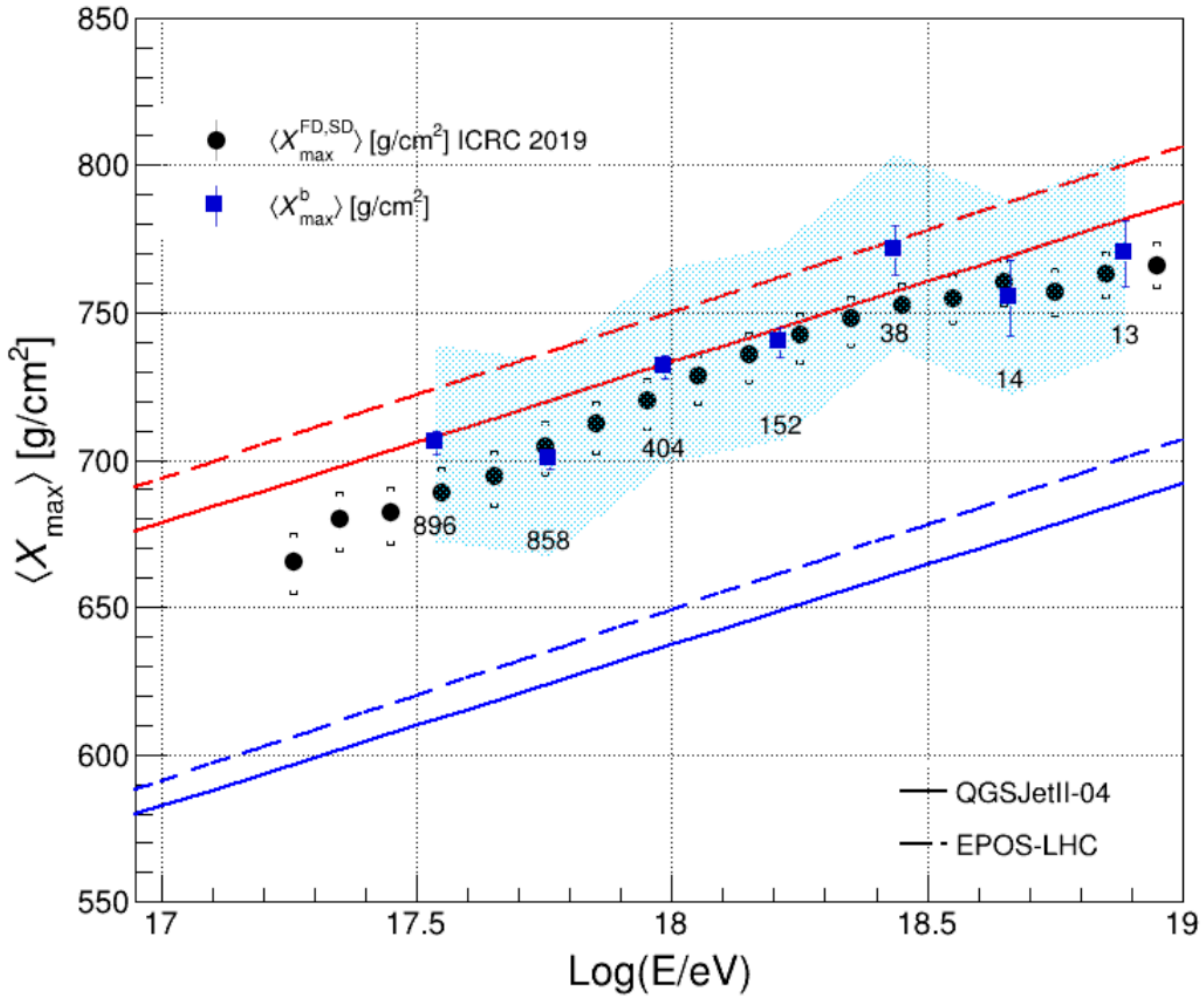


Composition (AERA)

Amplitude

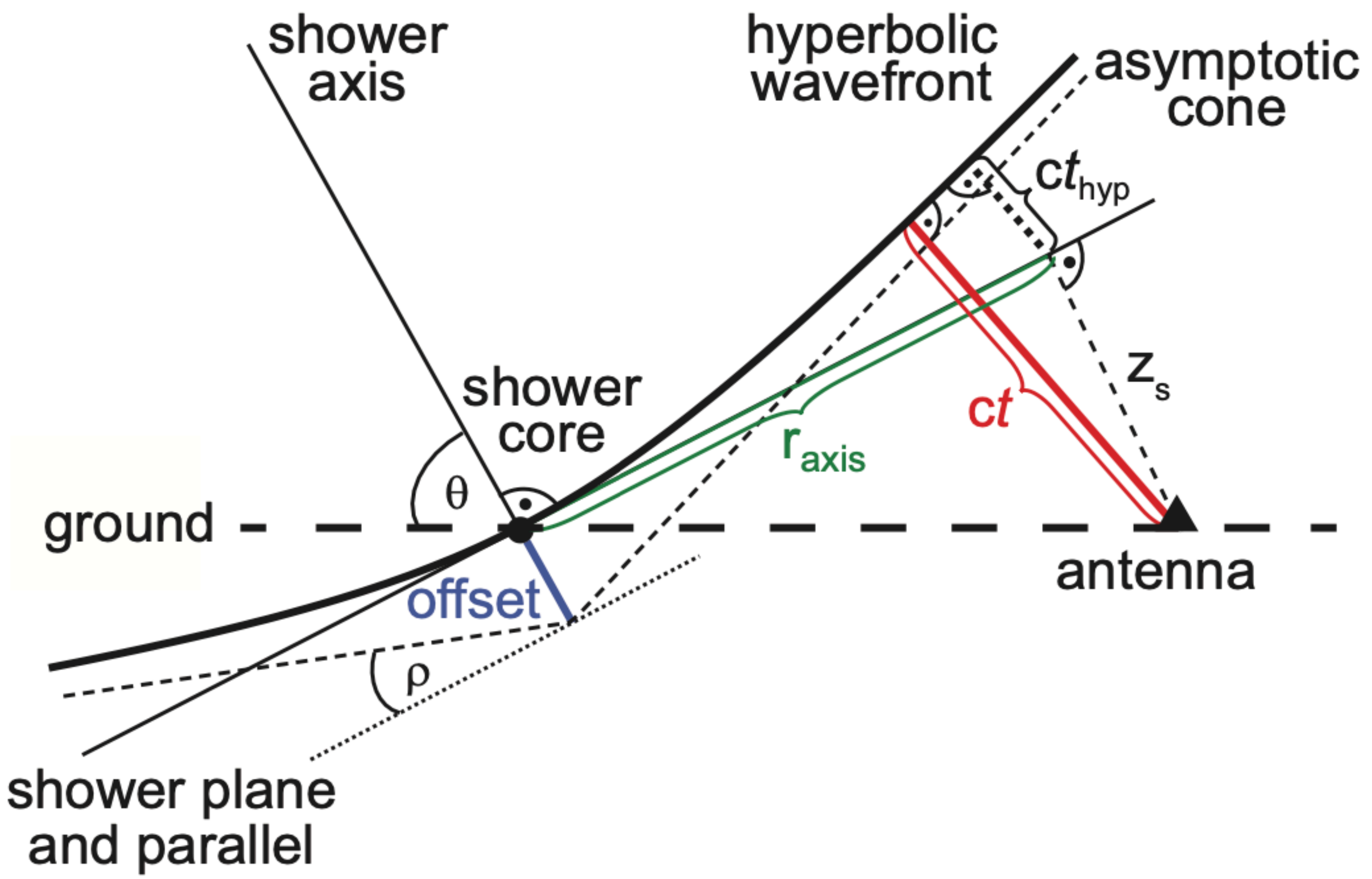


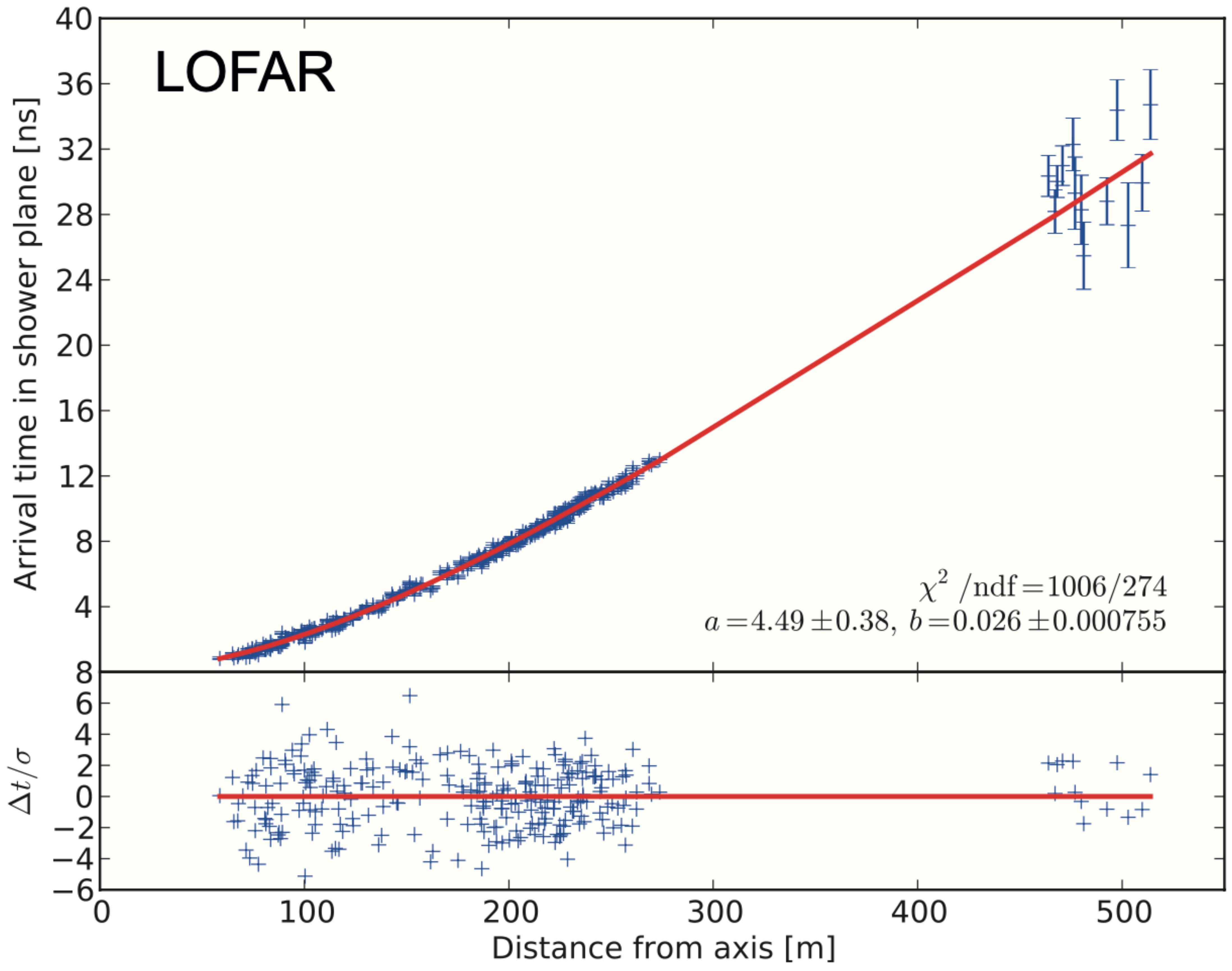
Spectral Index



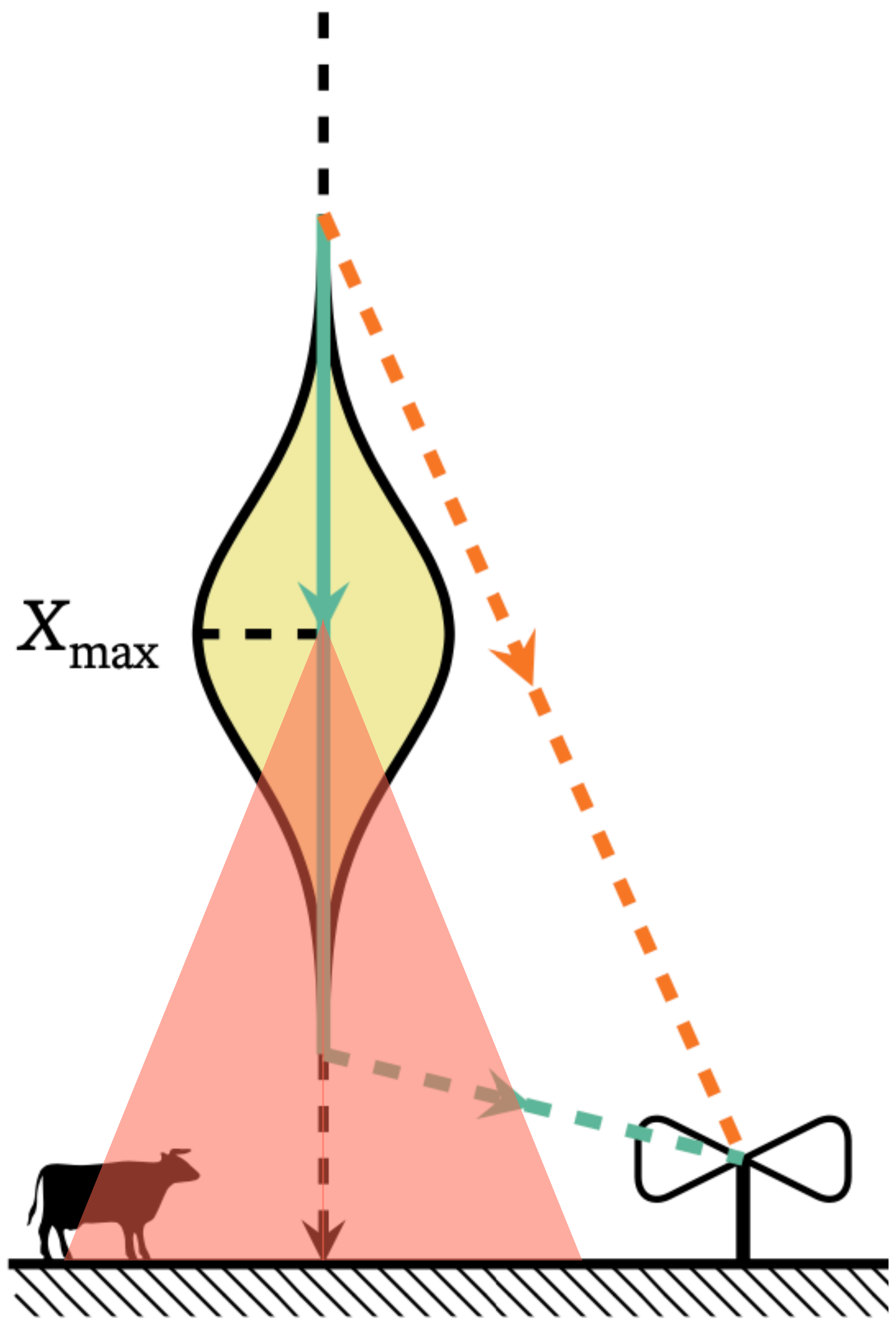
PhD, Fabrizia Canfora

Direction reconstruction





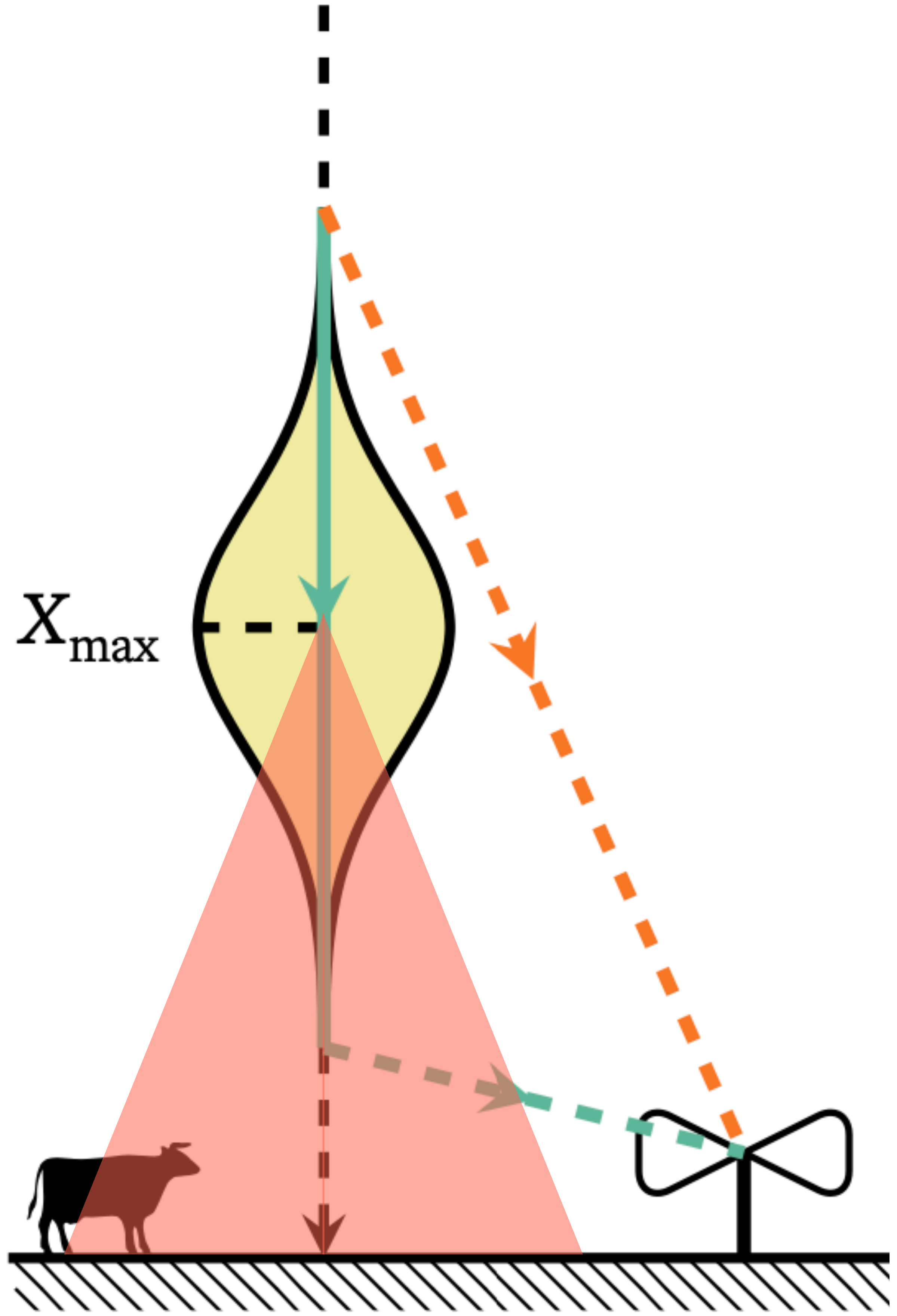
What about higher energy?



Cherenkov Cone: ~100 m

Energy range $10^{17\text{-}18}$ eV

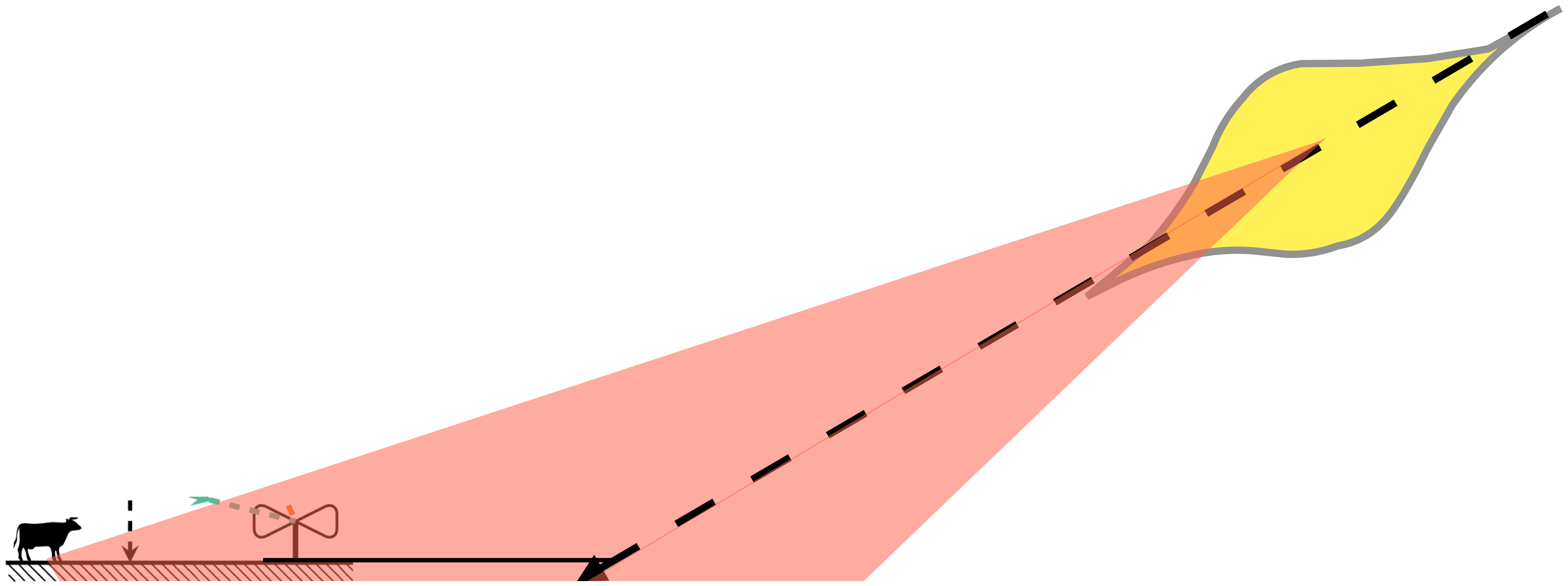
What about higher energy?



Cherenkov Cone: ~100 m

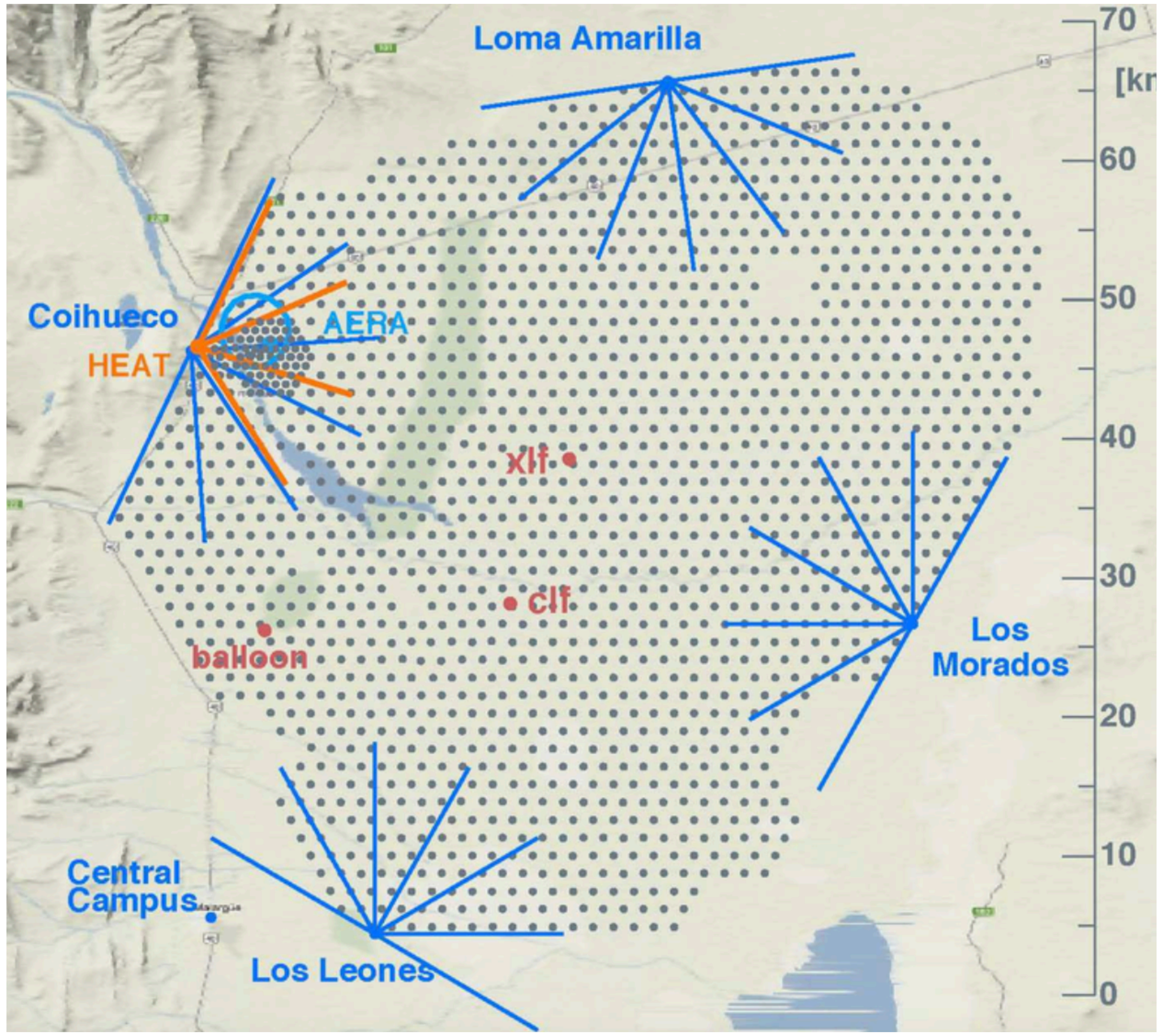
Energy range 10^{17-18} eV

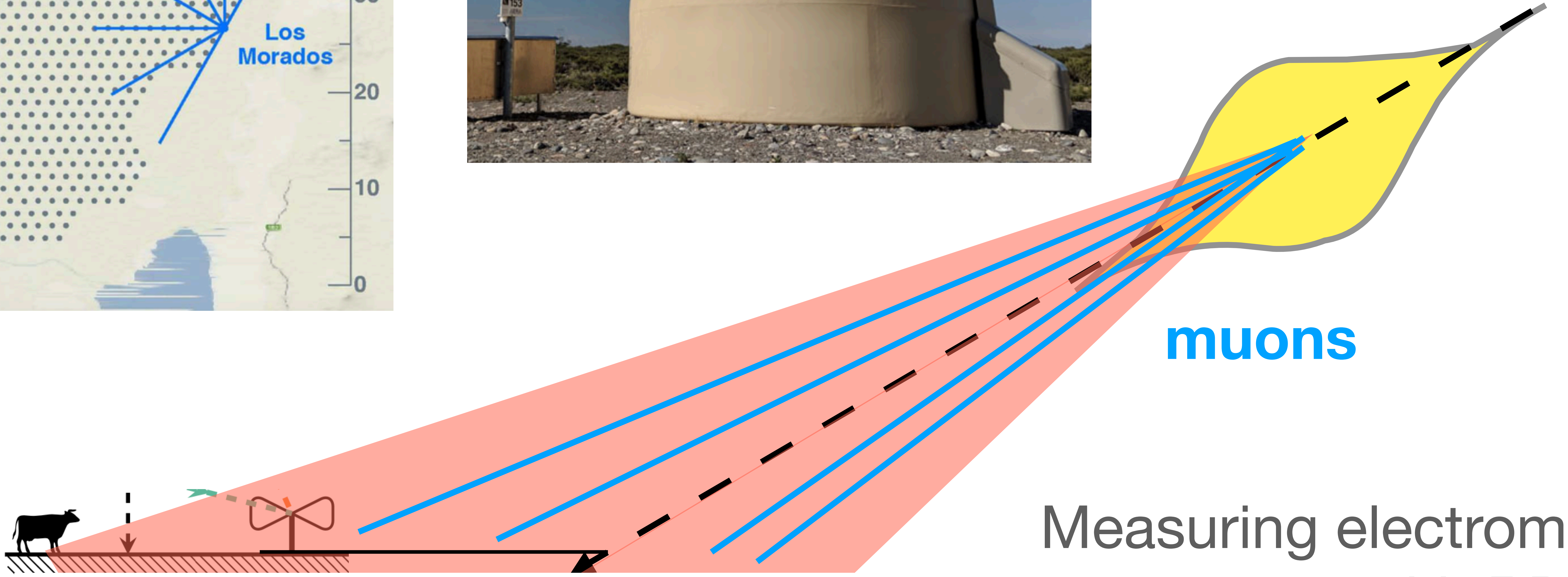
“Look sidewards”



Cherenkov Cone: ~1000 m

Energy range 10^{18-19} eV



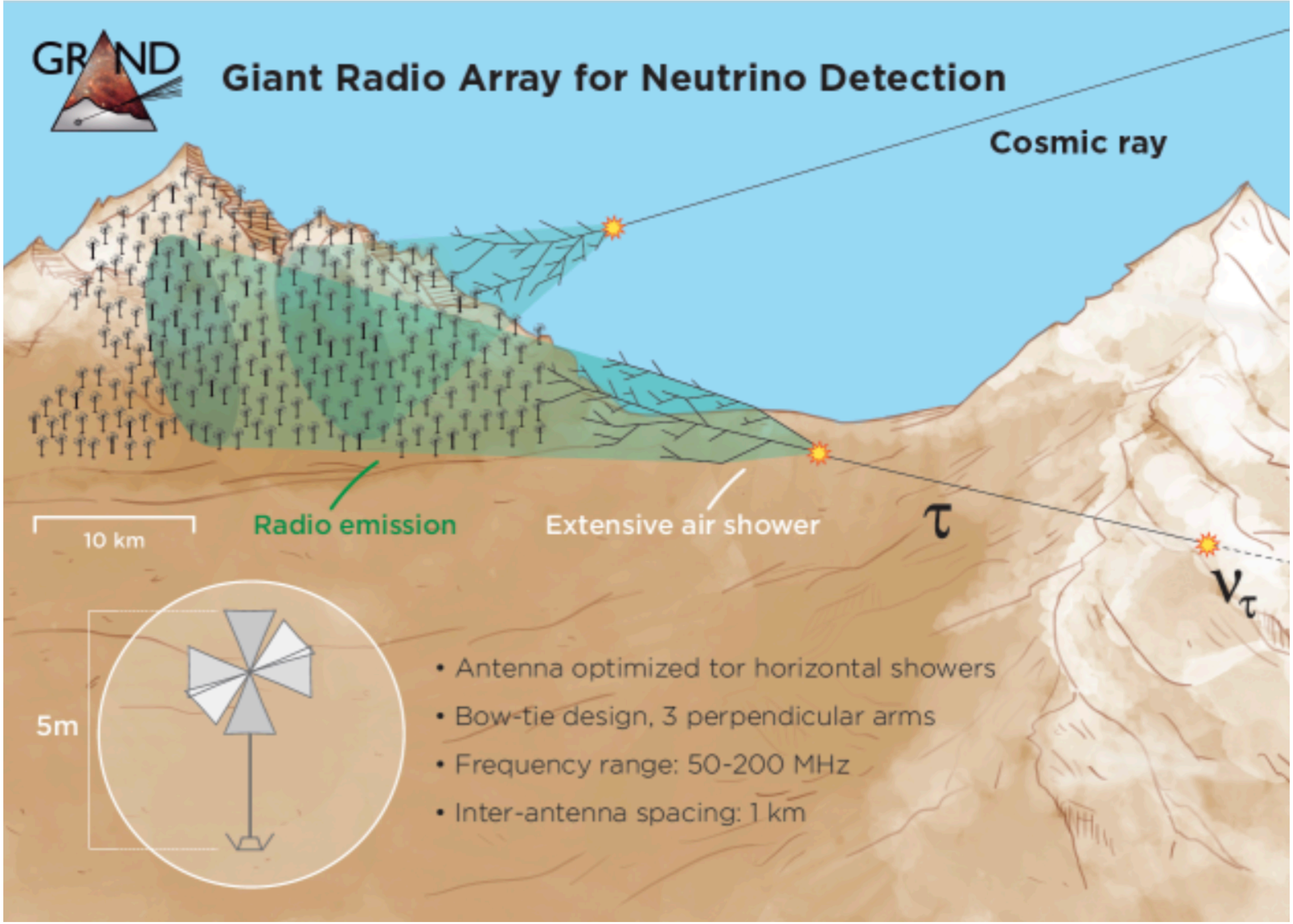


Measuring electromagnetic component with RD

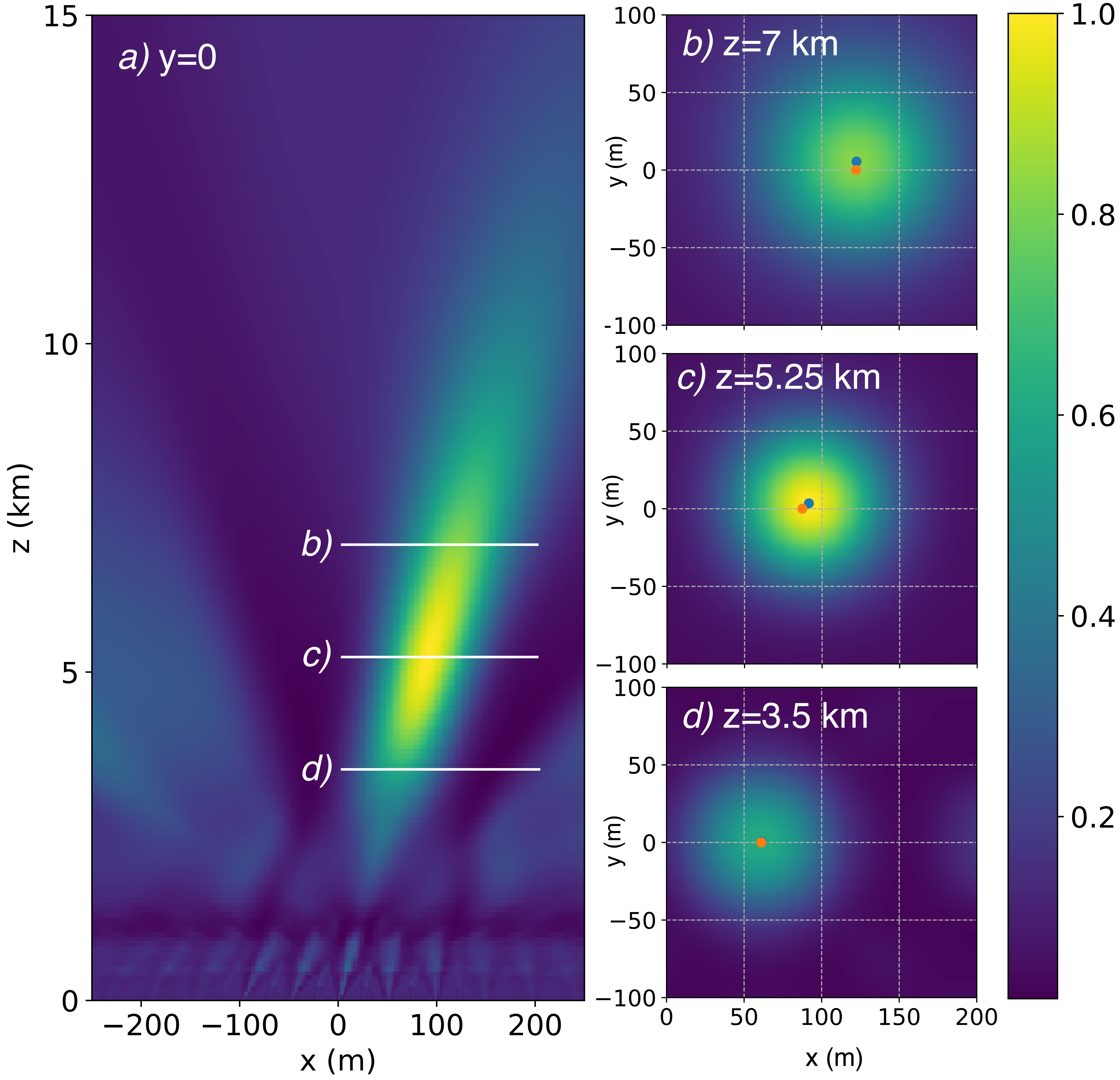
Measuring muons with WCD

Cherenkov Cone: ~1000 m

Energy range $10^{18\text{-}19}$ eV

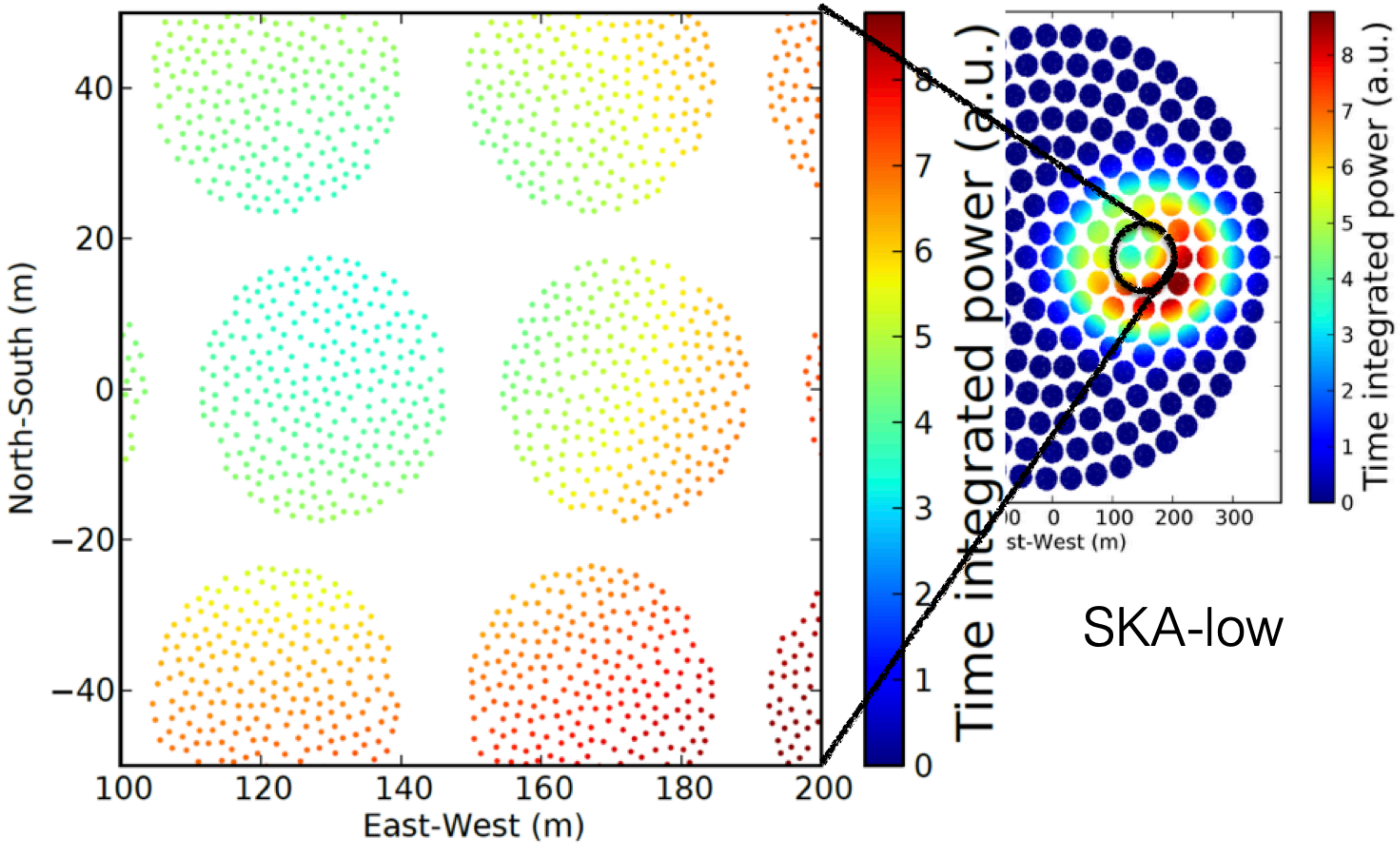

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
Radio emission
Extensive air shower
10 km
τ
ντ
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km

What about lower energy?



Extreme accuracy @ 10^{16} eV

Combine interferometry with high density arrays



SKA-low

To conclude…

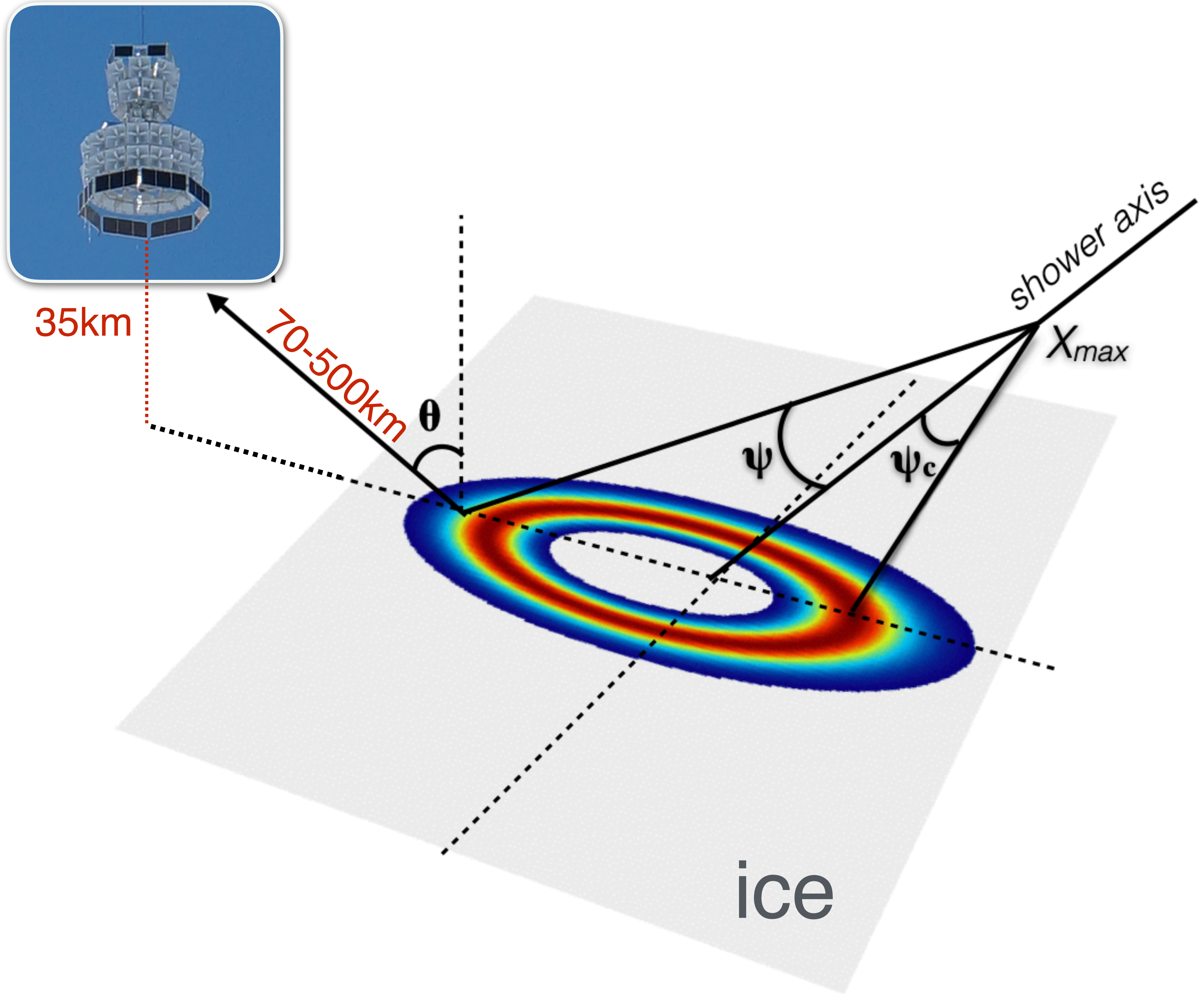
Radio signal from particle cascades well understood

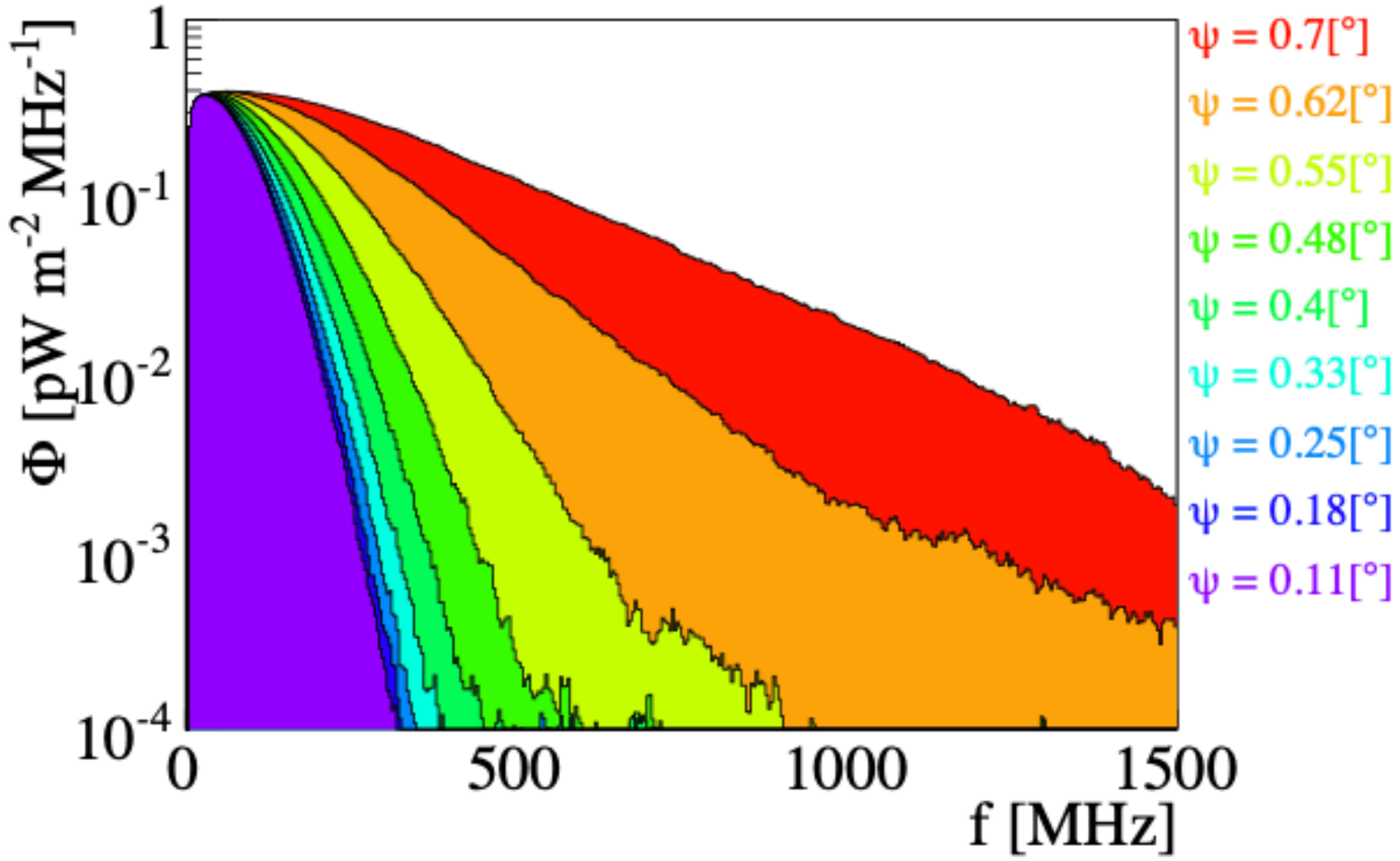
Reconstructions of air shower parameters proven

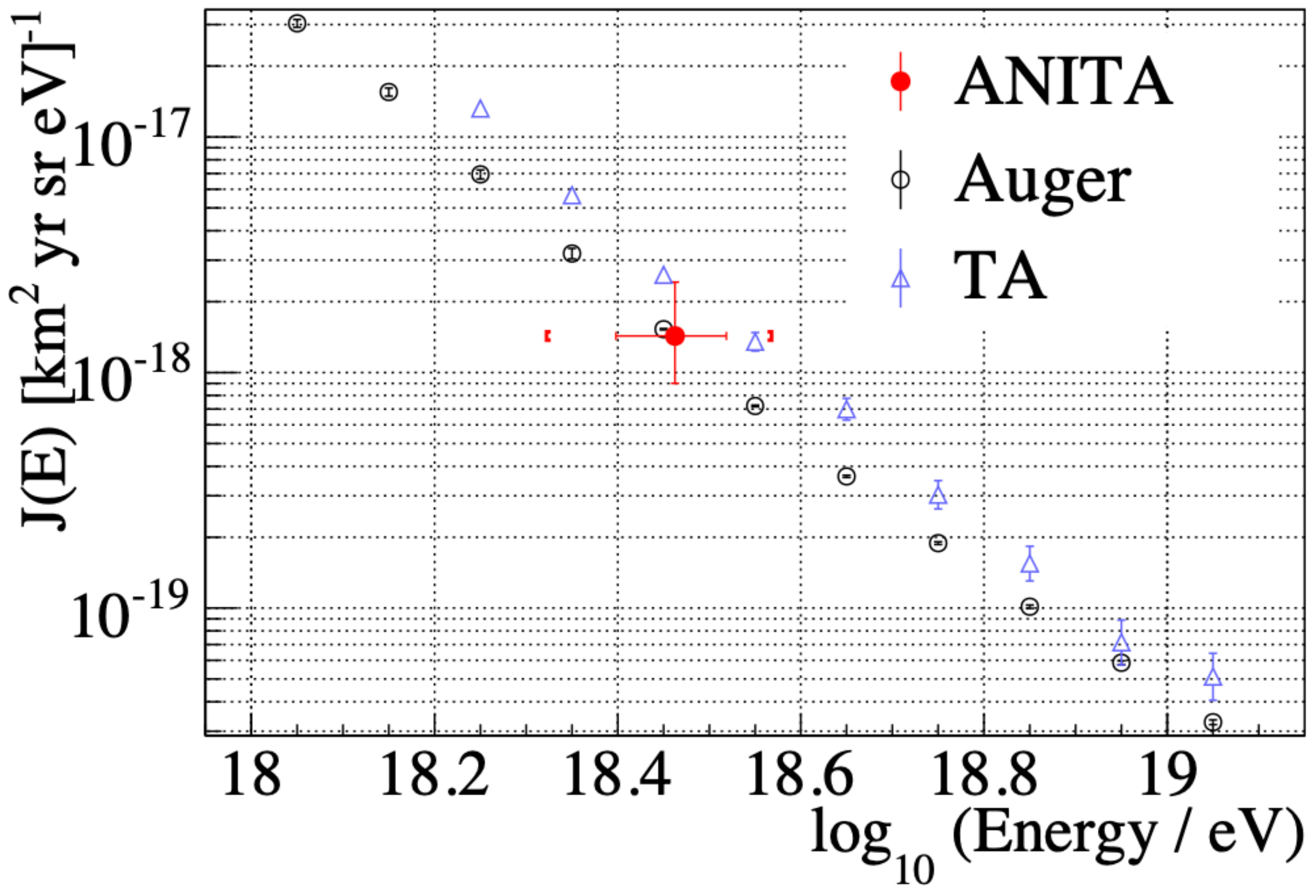
Exciting new applications

Measuring the energy of cosmic particles using the radio emission from air showers (300 - 1000 MHz)

- Radio emission from air showers are reflected off the Antarctic ice.
- Array of wide-band antennas measures the emission at ~35km above sea-level
- **Energy for each event can be estimated by measuring the power spectral density**
- **First cosmic-ray flux estimated from radio measurements**
- Introduction of angular representation to describe radio emission from inclined events







H. Schoorlemmer, K. Belov, Andrés Romero-Wolf, D. García-Fernández, V. Bugaev, S.A. Wissel and *the ANITA collaboration.* "Energy and flux measurements of ultra-high energy cosmic rays observed during the first ANITA flight". Astroparticle Physics, **77**, April 2016 doi:10.1016/j.astropartphys.2016.01.001

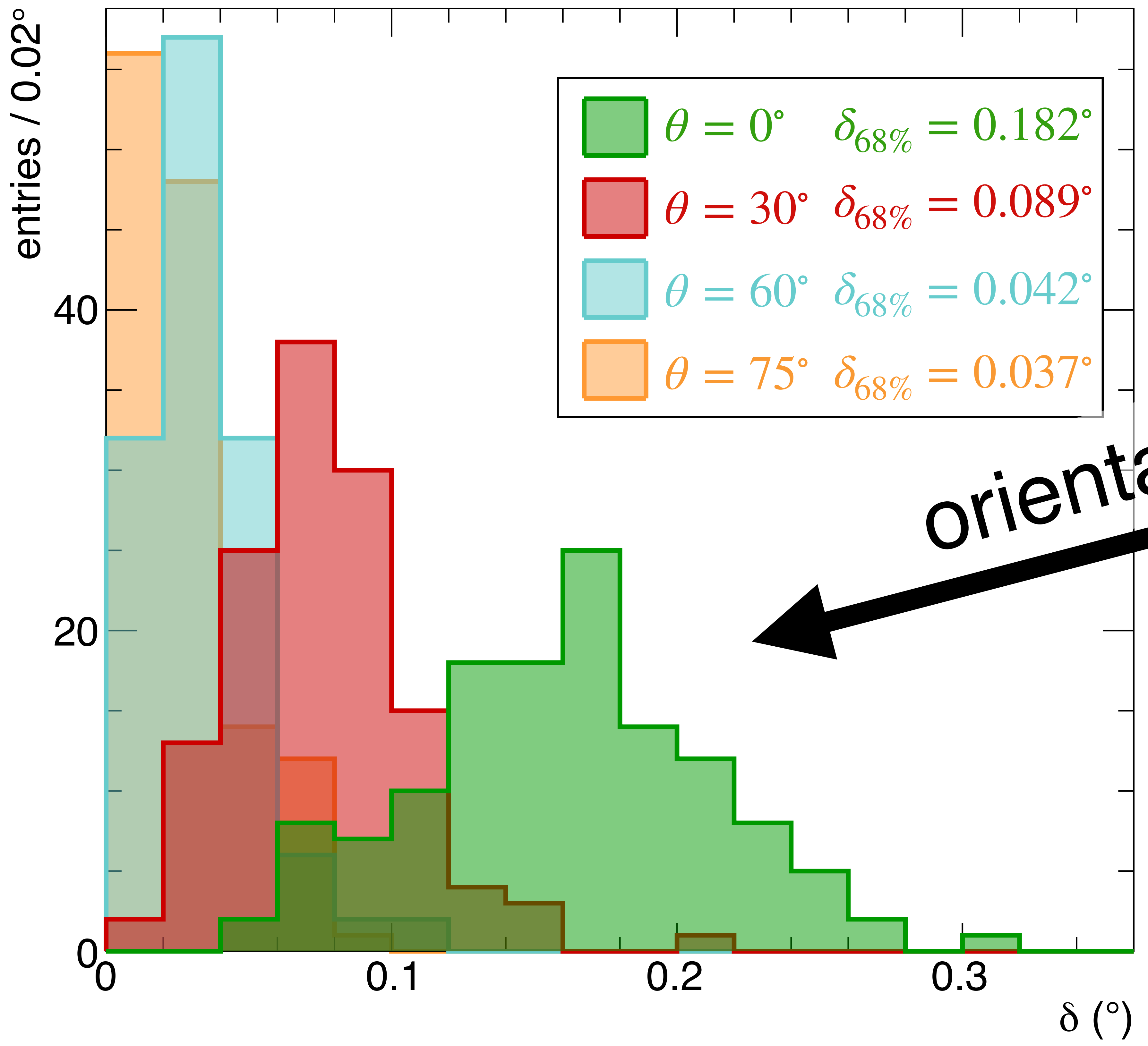
J. Alvarez-Muñiz, W. R . C. Carvalho Jr., D. García-Fernández, H. Schoorlemmer, E. Zas . "Simulations of reflected radio signals from cosmic ray induced air showers". Astroparticle Physics, **66**, June 2015, doi:10.1016/j.astropartphys.2014.12.005

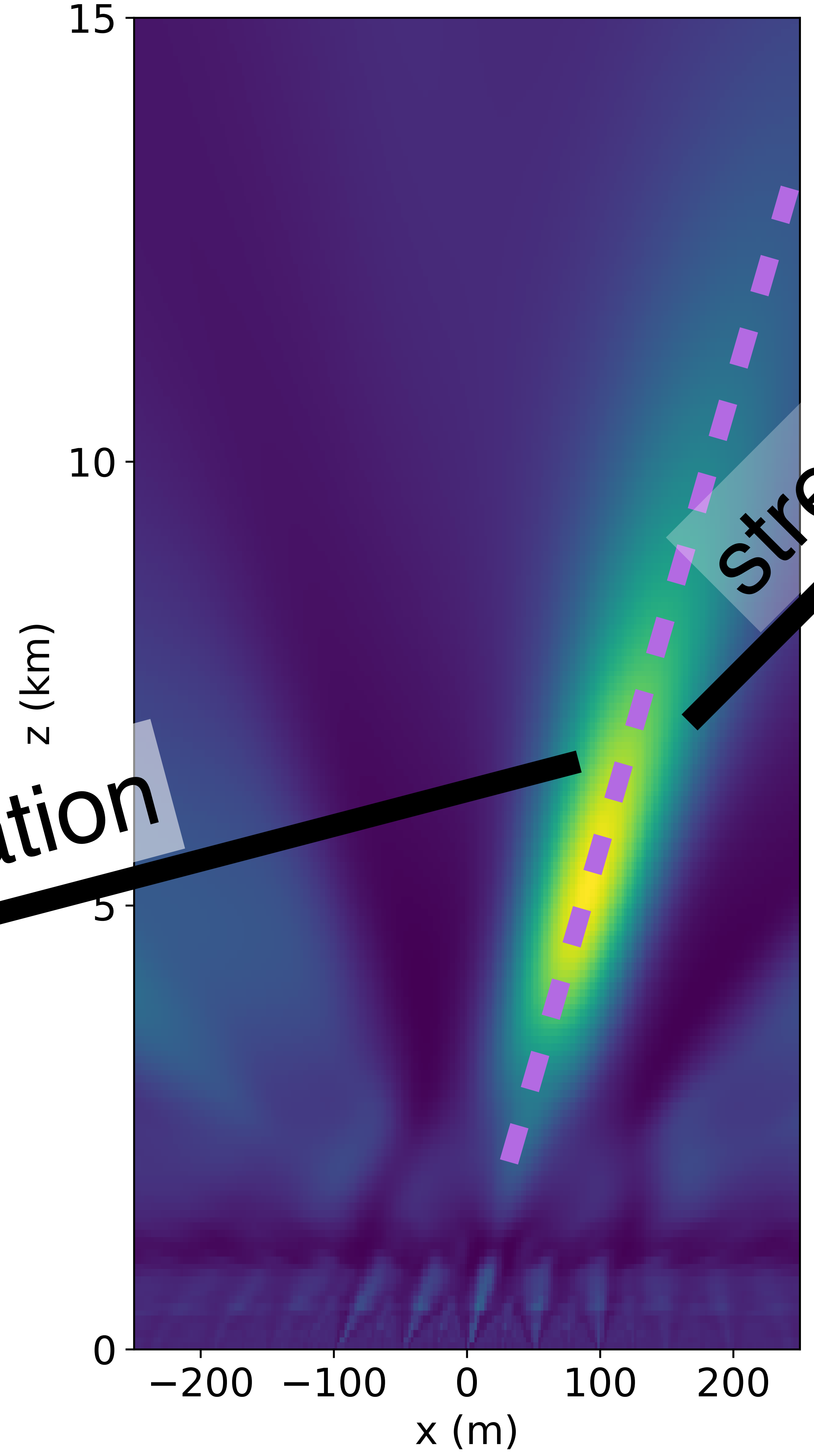
Reconstruction of direction and depth of shower maximum

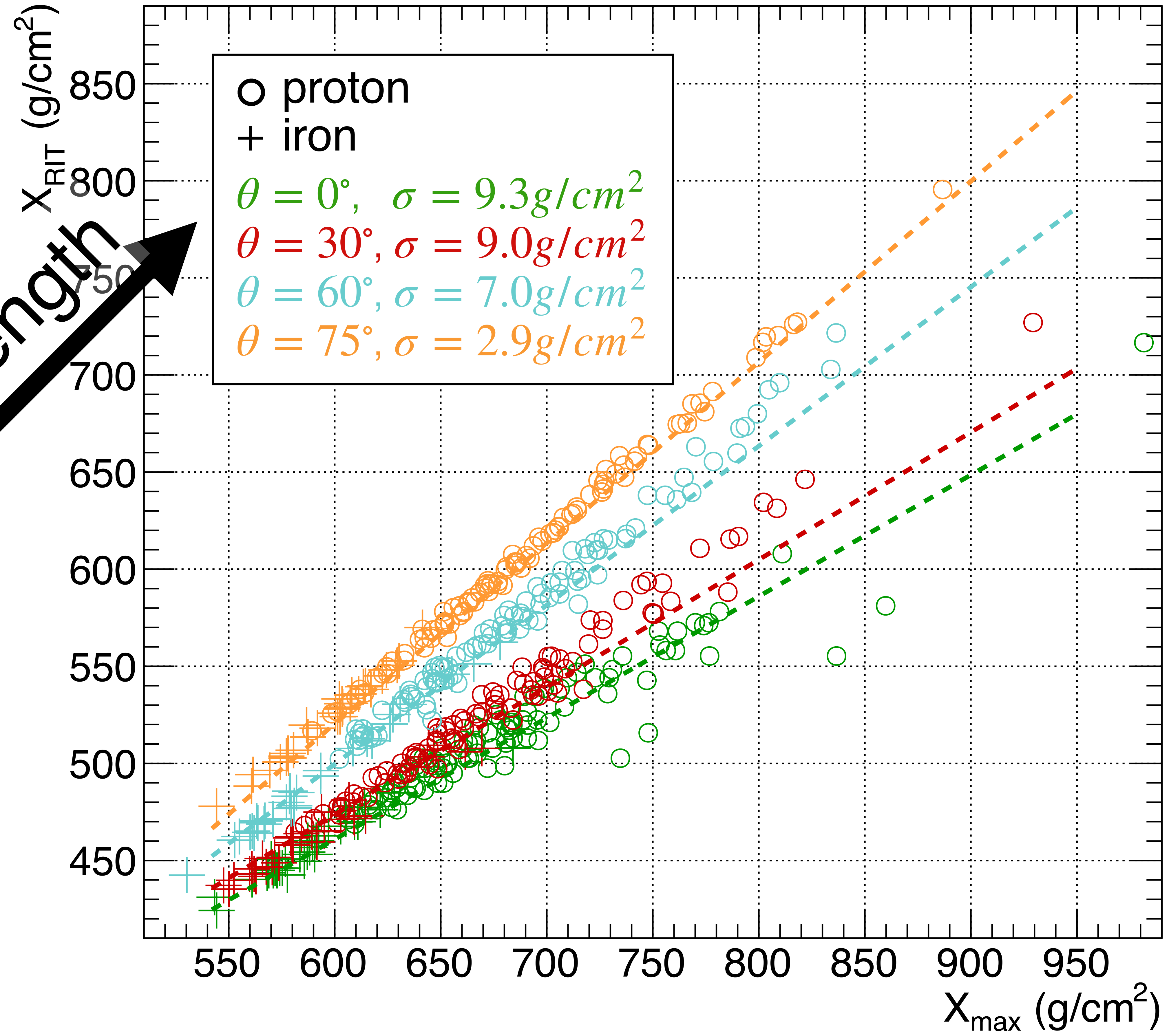
Deflection, absorption and acceleration depends on particle charge: composition is crucial

- Straightforward accurate reconstruction of direction and shower maximum
- Use of "sub-threshold" antennas and full waveforms

Reconstruction of shower axis







Measuring air showers with balloons