Measurement of the cosmic ray flux with the ANITA experiment

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(before Universidade de Santiago de Compostela)

Based on joint work with the ANITA collaboration
and J. Álvarez-Muñiz, W.R. Carvalho Jr., H. Schoorlemmer and E. Zas
H. Schoorlemmer et al., Astropart. Phys. ***77:****32-43, 2016*

Subatech, CNRS, École des Mines de Nantes, Université de Nantes

Take-home message

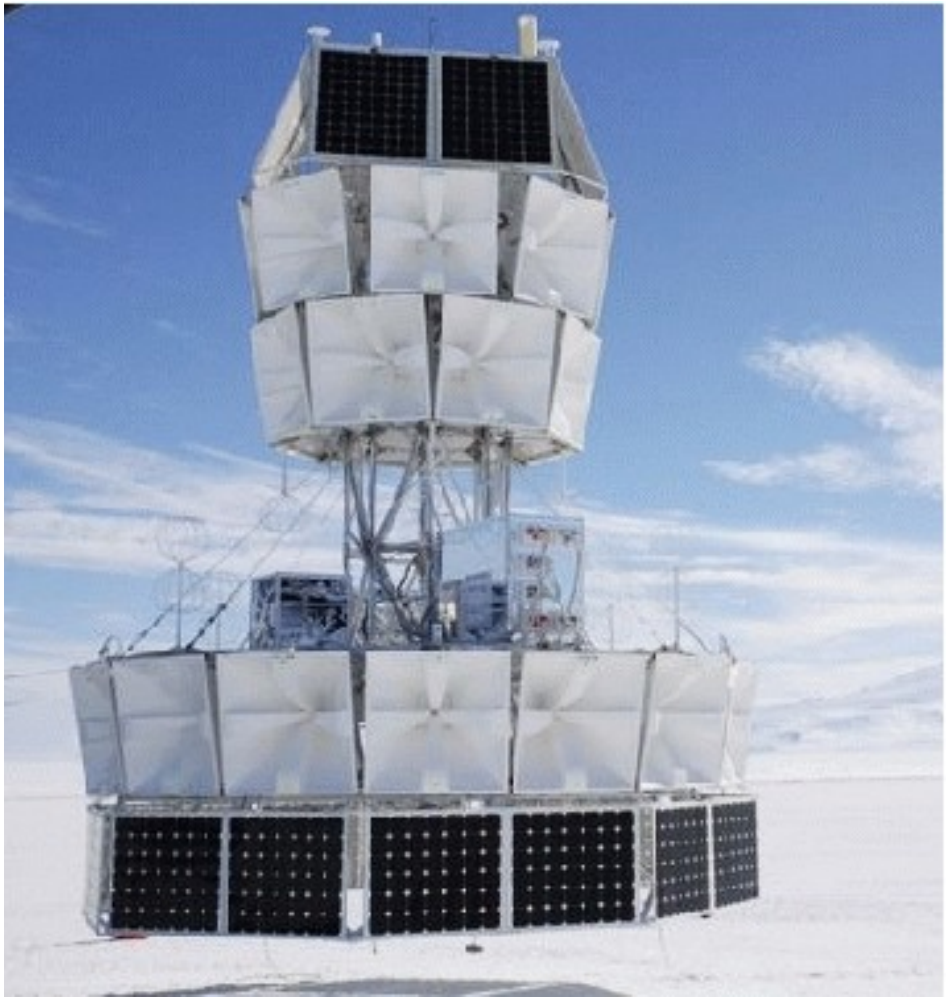
- ANITA is a balloon flying over Antactica equipped with antennas designed to detect neutrino events.
- ANITA I detected 16 Ultra High Energy Cosmic Ray events, 14 of them reflected on the ice.
- We have used the ZHAireS-Reflex MC to analyse the data.
- First radio-only measurement of cosmic ray flux achieved.
- 32 antennas in only a balloon have sufficed for this task.

Energy and flux measurements of ultra-high energy cosmic rays observed during the first ANITA flight
H. Schoorlemmer et al., Astropart. Phys. **77**:32-43, 2016

Experiment

The ANITA experiment

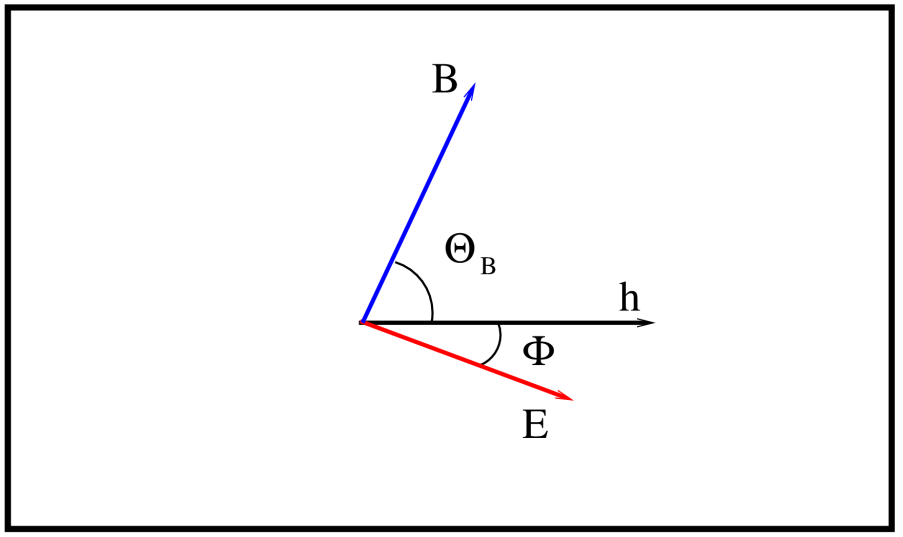
- ANtarctic Impulse Transient Antenna (ANITA)
- Balloon with antennas flying over Antarctica (~ 36 km of altitude)
- Band: 200 MHz – 1200 MHz
- Designed to detect neutrino events
- Why a balloon?
  - To cover ~ 1 Mkm^2
  - Reduce anthropogenic noise
- There have been three flights (ANITA I, II and III). ANITA IV is scheduled for December.

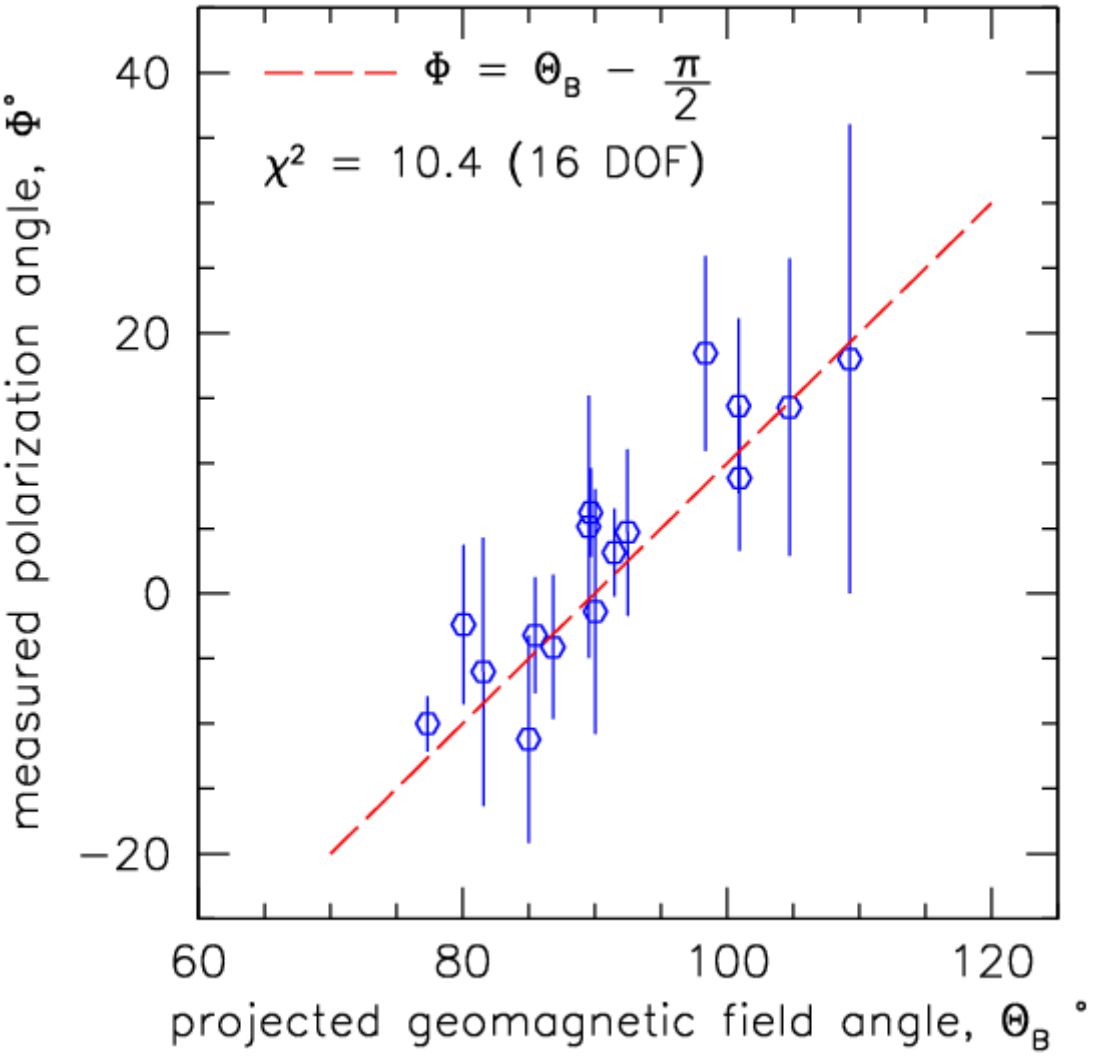


S. Hoover et al. PRL **105** (151101), 2010

Data: UHECR events

- UHECR electric field: created by geomagnetic effect
- Polarised in the **v** x **B** direction

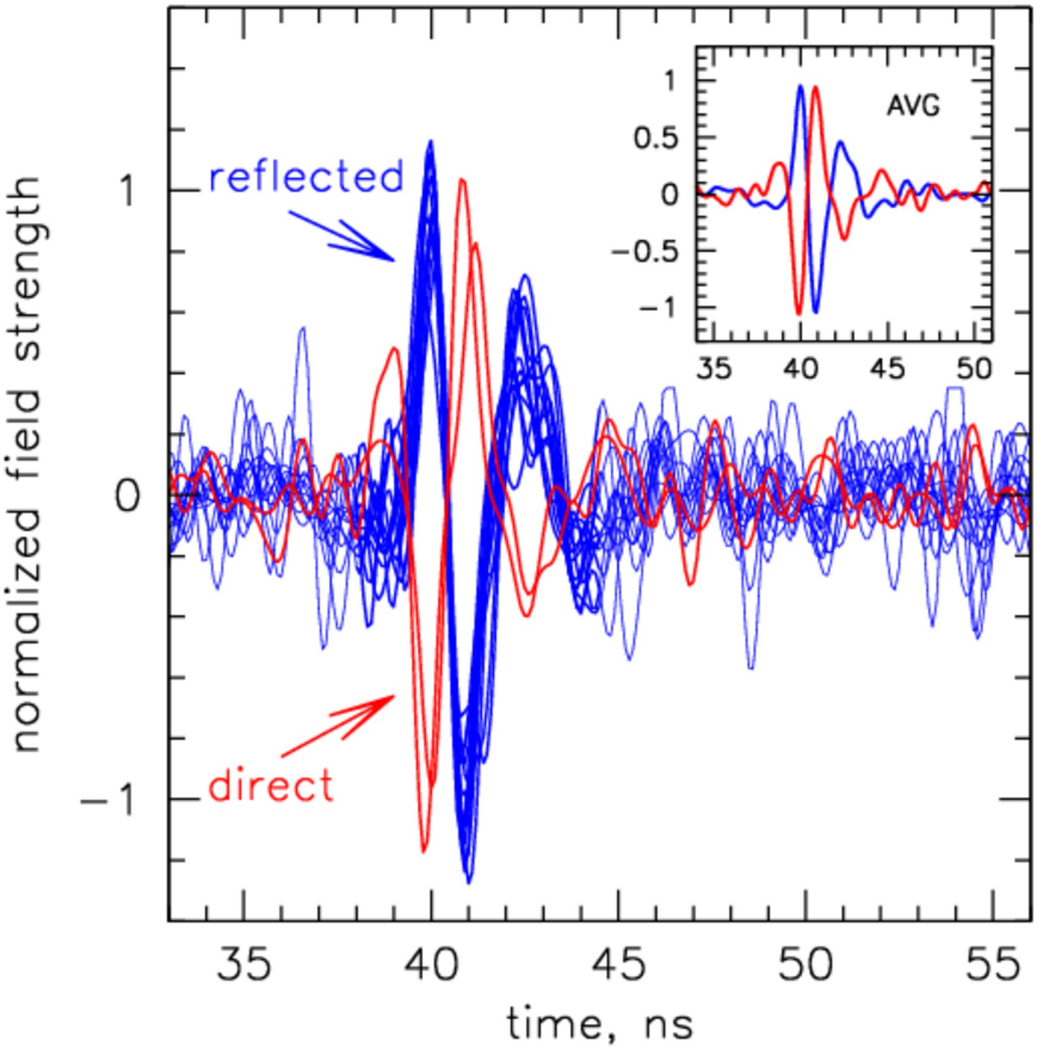




S. Hoover et al. PRL 105(151101), 2010

Data: Reflected UHECR events

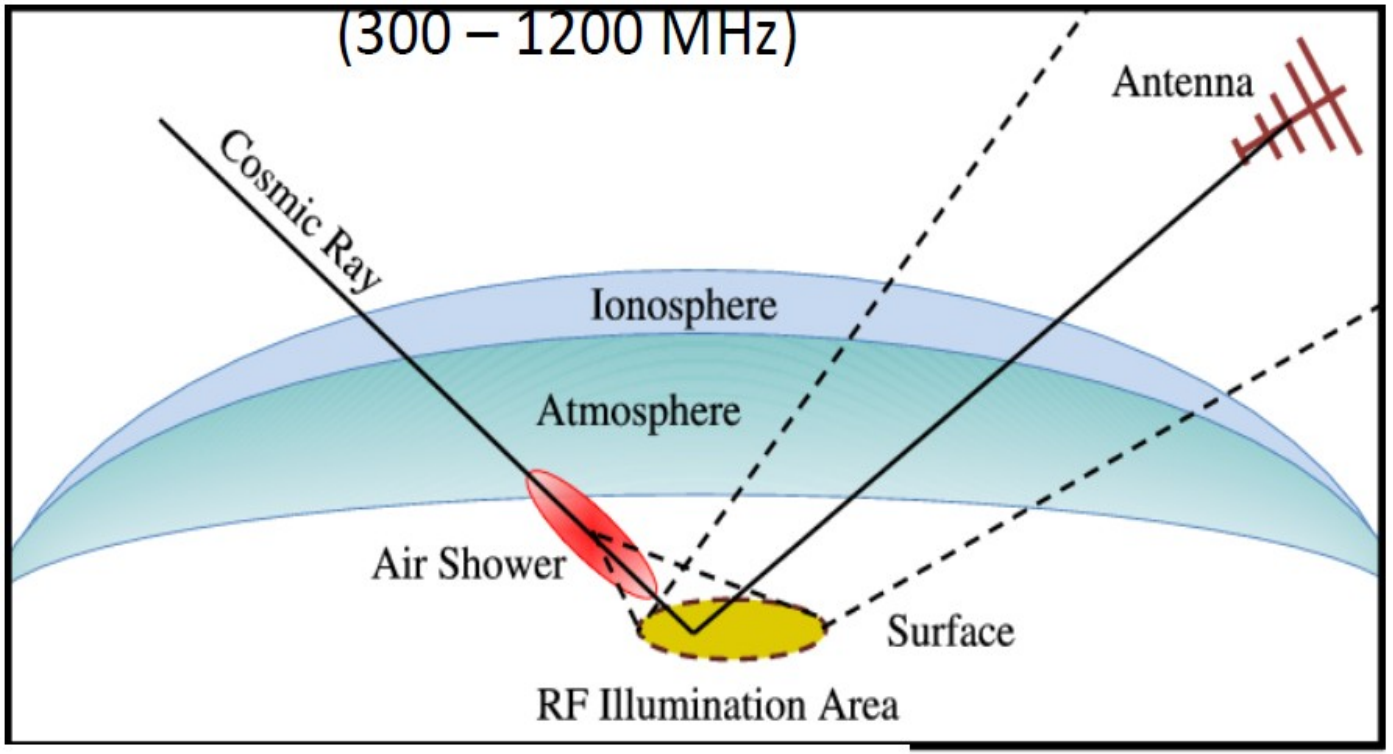
- UHECR electric field: created by geomagnetic effect
- Polarised in the **v** x **B** direction
- Some events arrived from the ground, some from above the horizon
- The first ones had an opposite polarisation than the second ones
- They are reflected events!



S. Hoover et al. PRL 105(151101), 2010

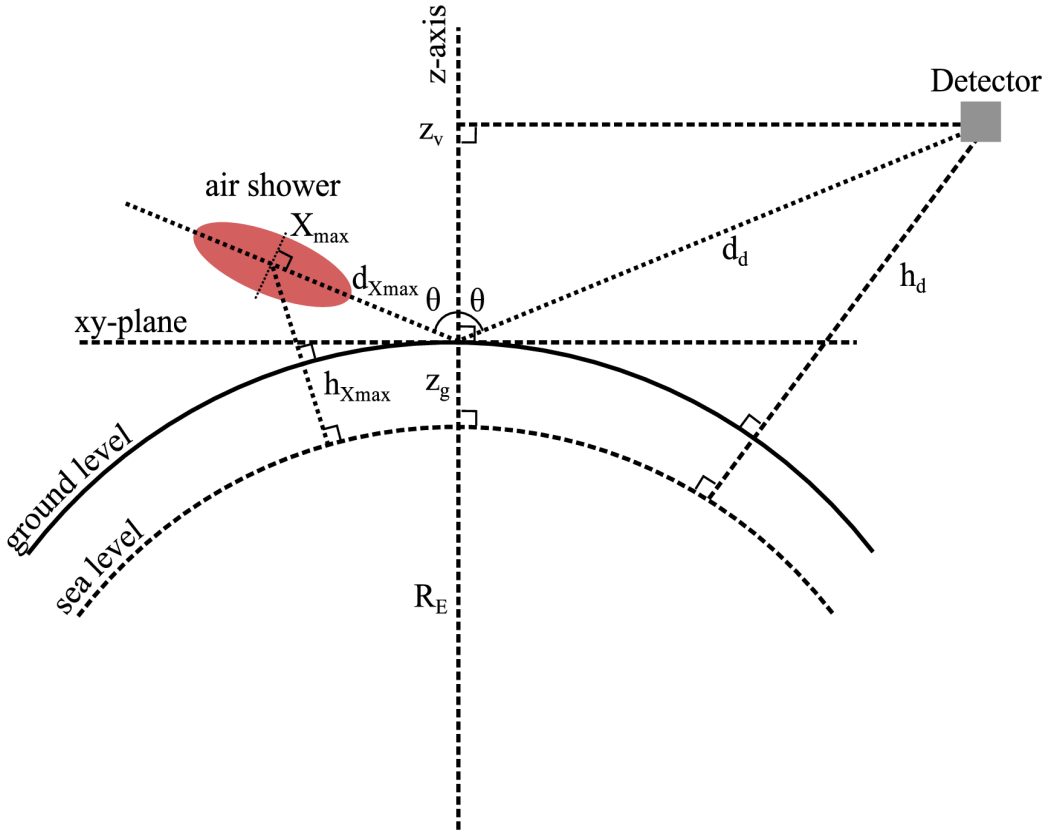
Reflected UHECR events: explanation

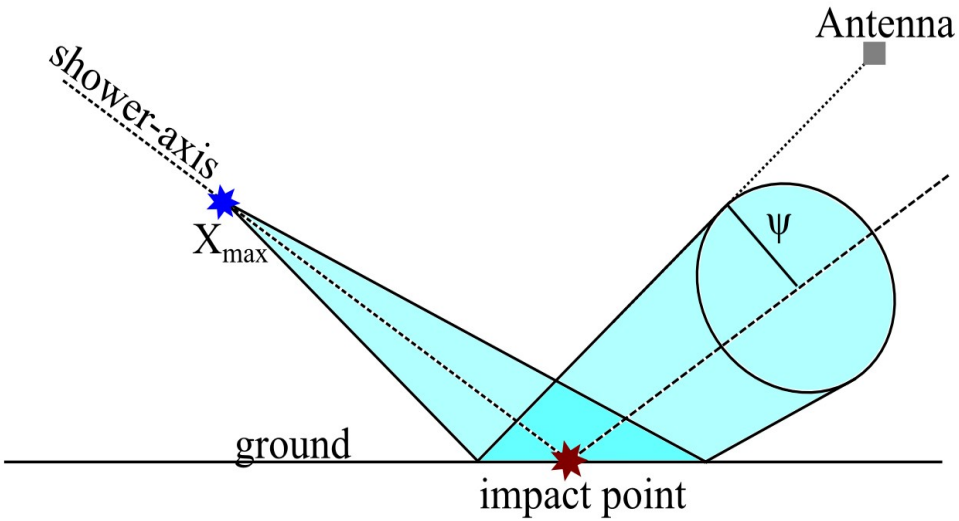
- Cosmic ray creates an air shower
- Air shower creates electric field on the ground (Cherenkov ring)
- Electric field reflected on the ice, detected at antenna



Geometry for reflected events

- ψ is the off-axis angle

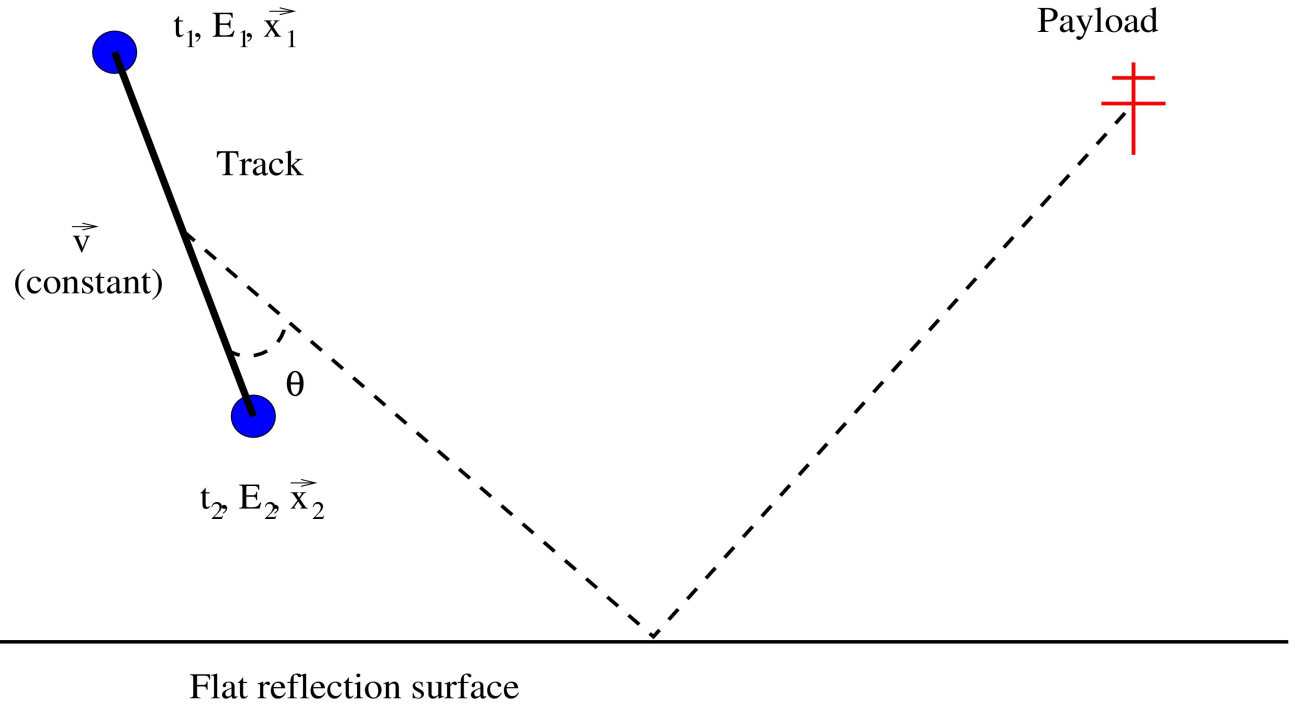




Simulations

ZHAireS

- ZHAireS MC code:
  - ZHS “algorithm” for the electric field of a particle track
  - Aires MC for air showers
- For reflected events, it is important:
  - Model the atmosphere properly (sphericity)
  - Correctly take into account arrival times
  - Treat the reflection on the ground

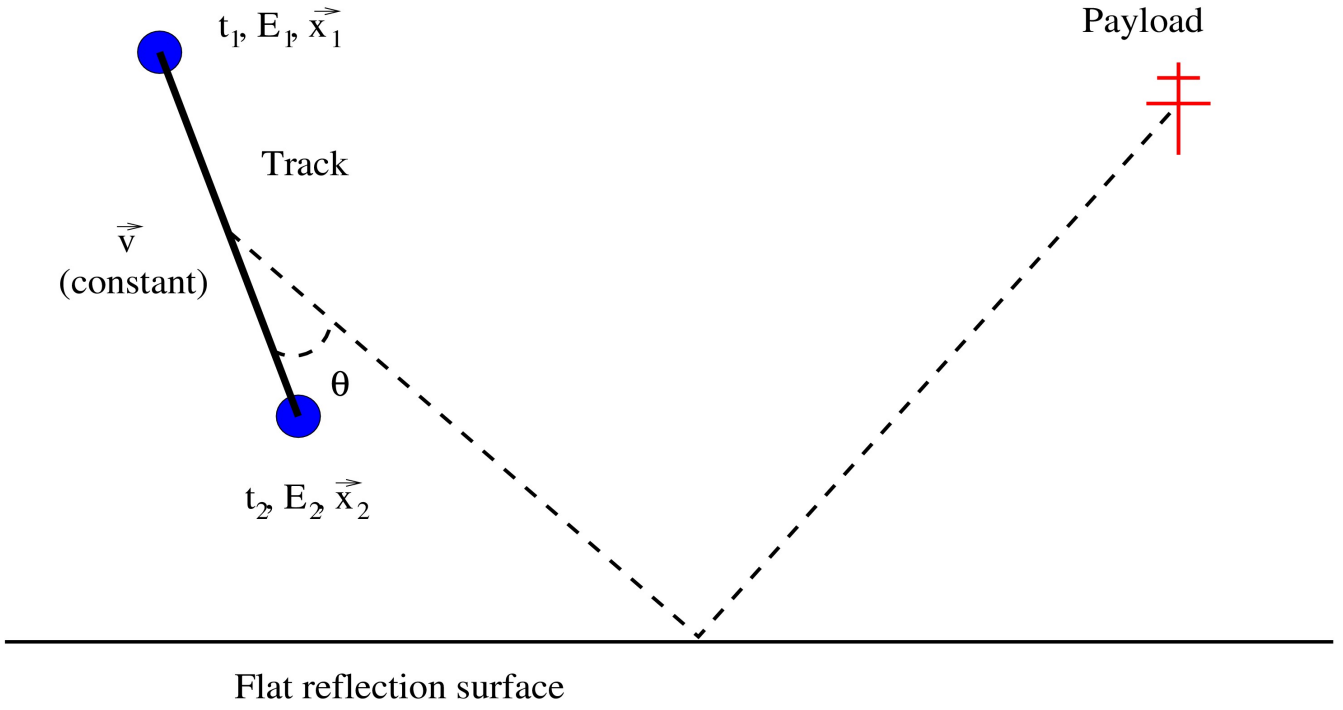


ZHAireS-Reflex

- New version of the ZHAireS code: ZHAireS-Reflex

- Main assumptions:
  - Electric field reflected on a flat surface
  - Fresnel coefficients at the interface
  - Rectilinear propagation: downwards and upwards.

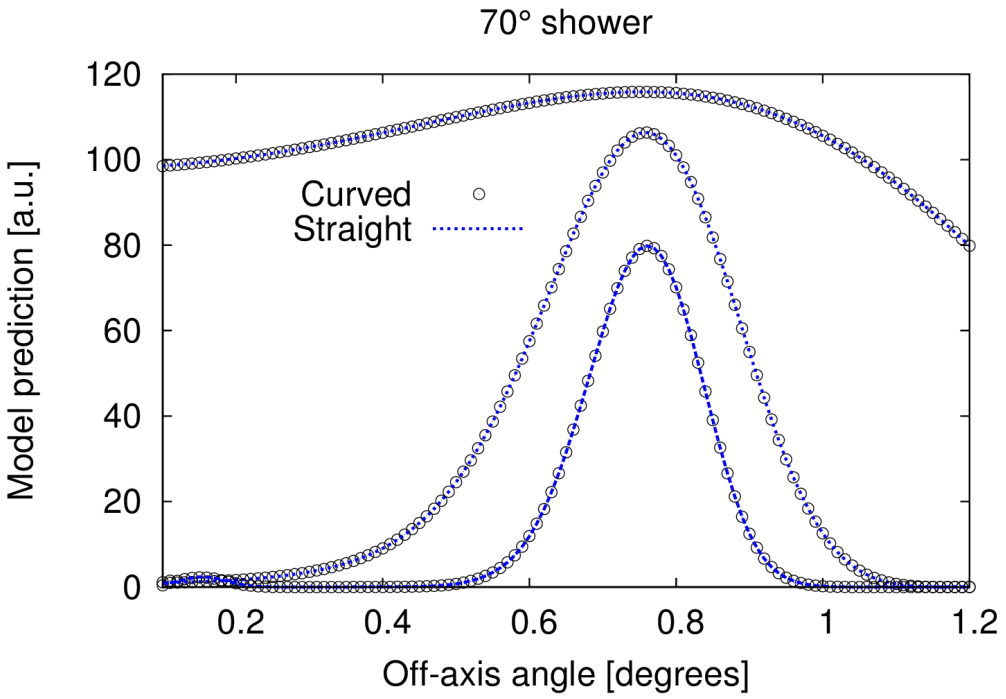
J. Alvarez-Muñiz, W. R. Carvalho Jr., D. García-Fernández, H.Schoorlemmer, E. Zas. Astroparticle Physics **35**:325, 2012

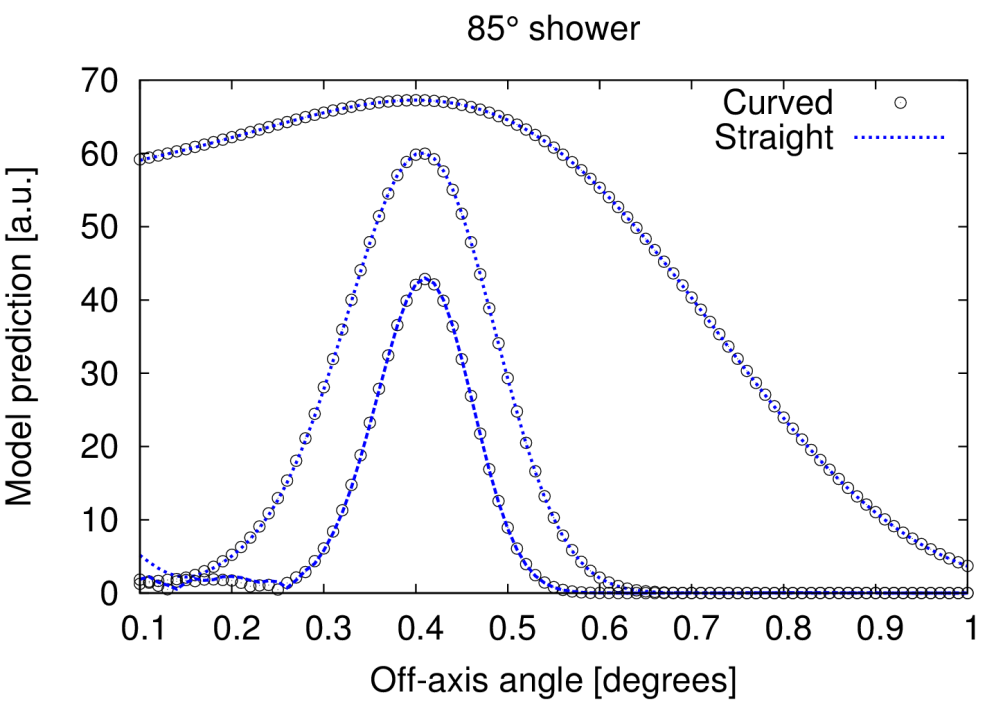


Straight vs curved rays: ray tracing model

- Simple model for checking the straight approximation
- Agreement up to 85º and 900 MHz

$$E \sim \int dt\, N(t) \frac{e^{i\omega t_a}}{r(t)}$$





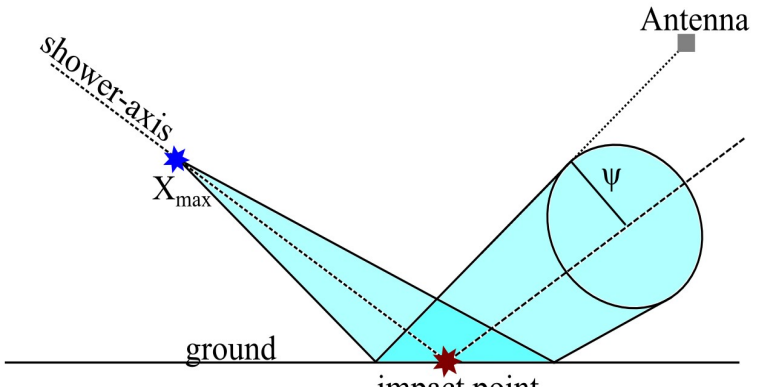
Simulations with ZHAireS-Reflex

- Antennas at a fixed altitude of 36 km
- n = 1,31 for ice
- Ground at 2 km of altitude
- Magnetic field: 55 μT and -70º of inclination
- Zenithal angles: {57º, 64º, 71º, 78º, 85º}
- Energies: {$10^{17.8}$, $10^{18.4}$, 10^{19} , $10^{19.6}$} eV
- Definition of flux (T is a characteristic time):

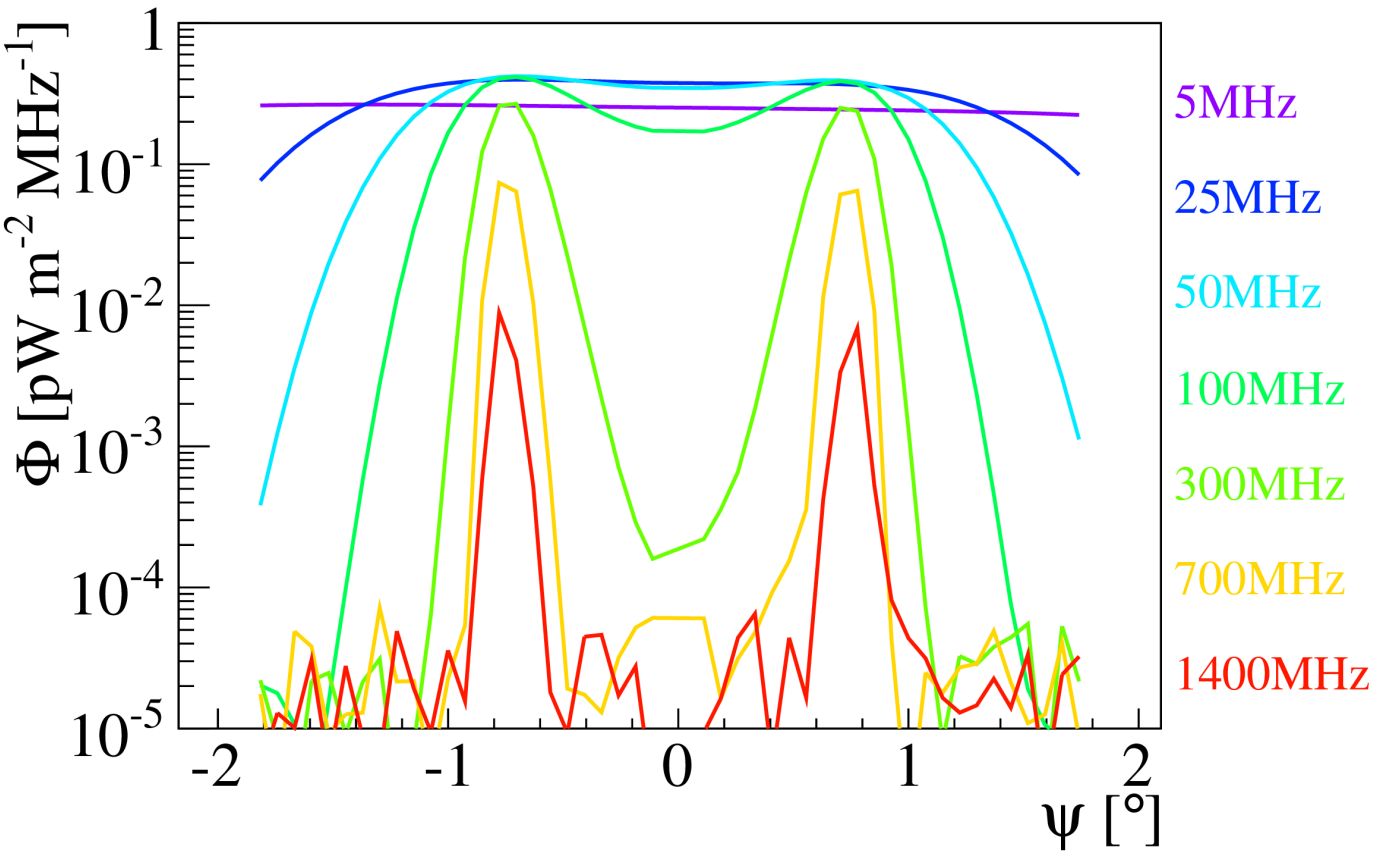
$$\Phi = \frac{c\,\varepsilon_0}{T}\,\boldsymbol{E}(f)^2$$

Results of ZHAireS-Reflex: angular distribution

- Angular region where the field adds coherently even at 1.4 GHz
- Cherenkov cone exists after reflection



71º shower



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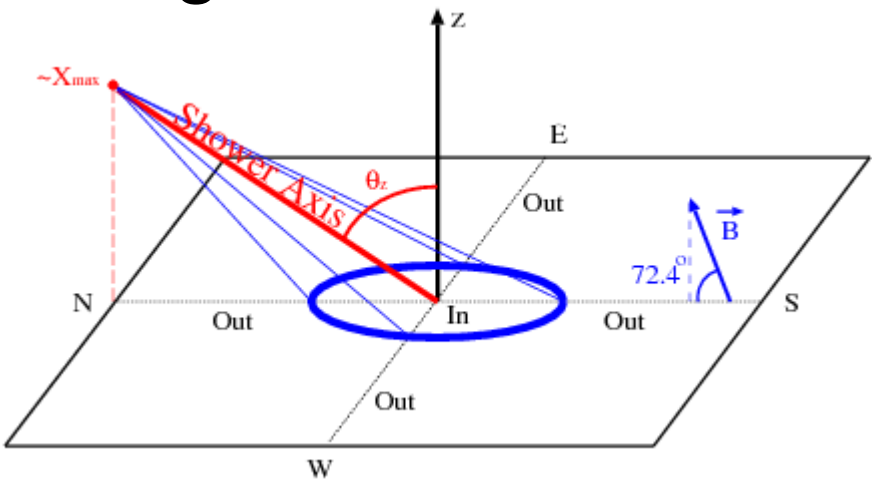

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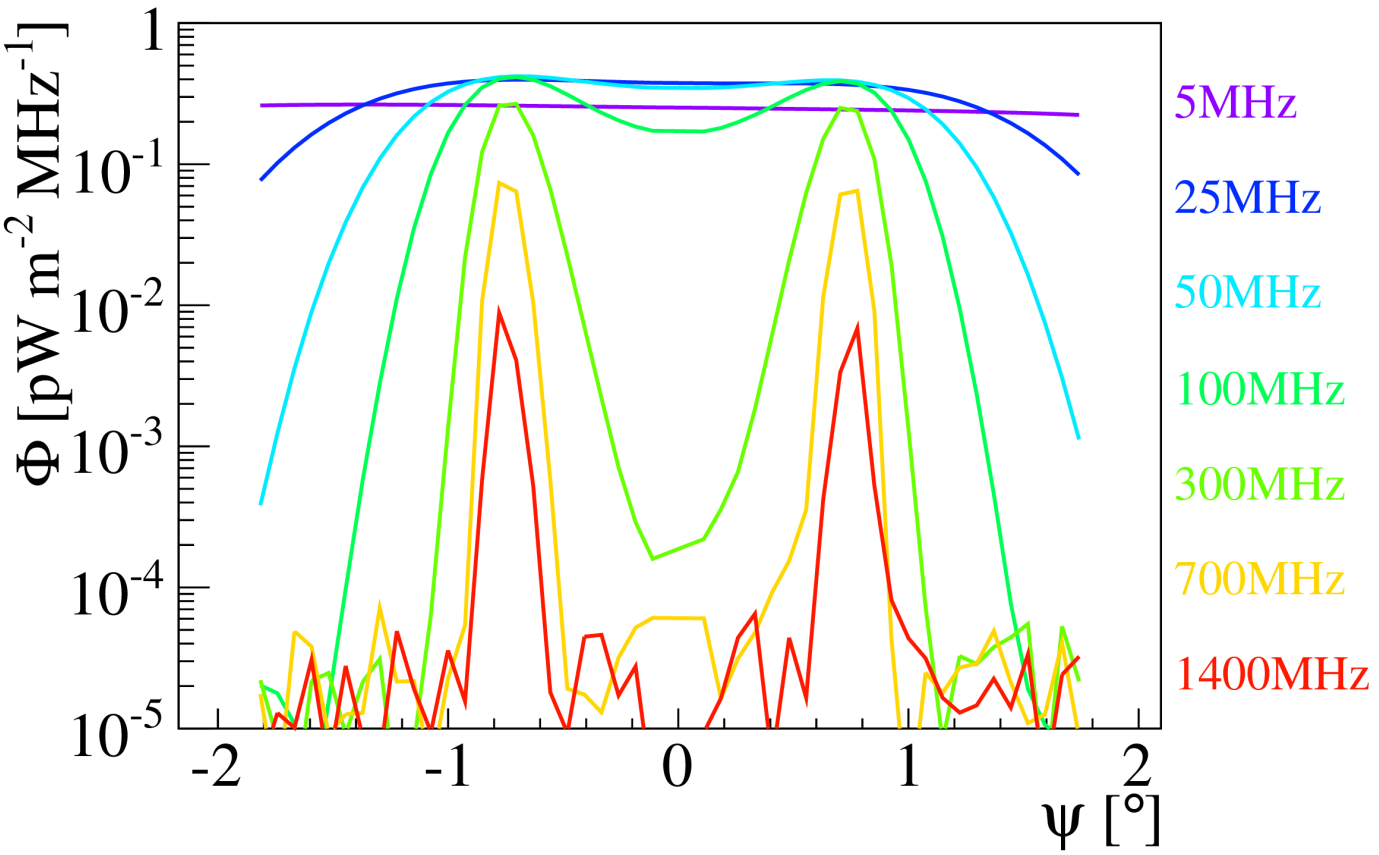
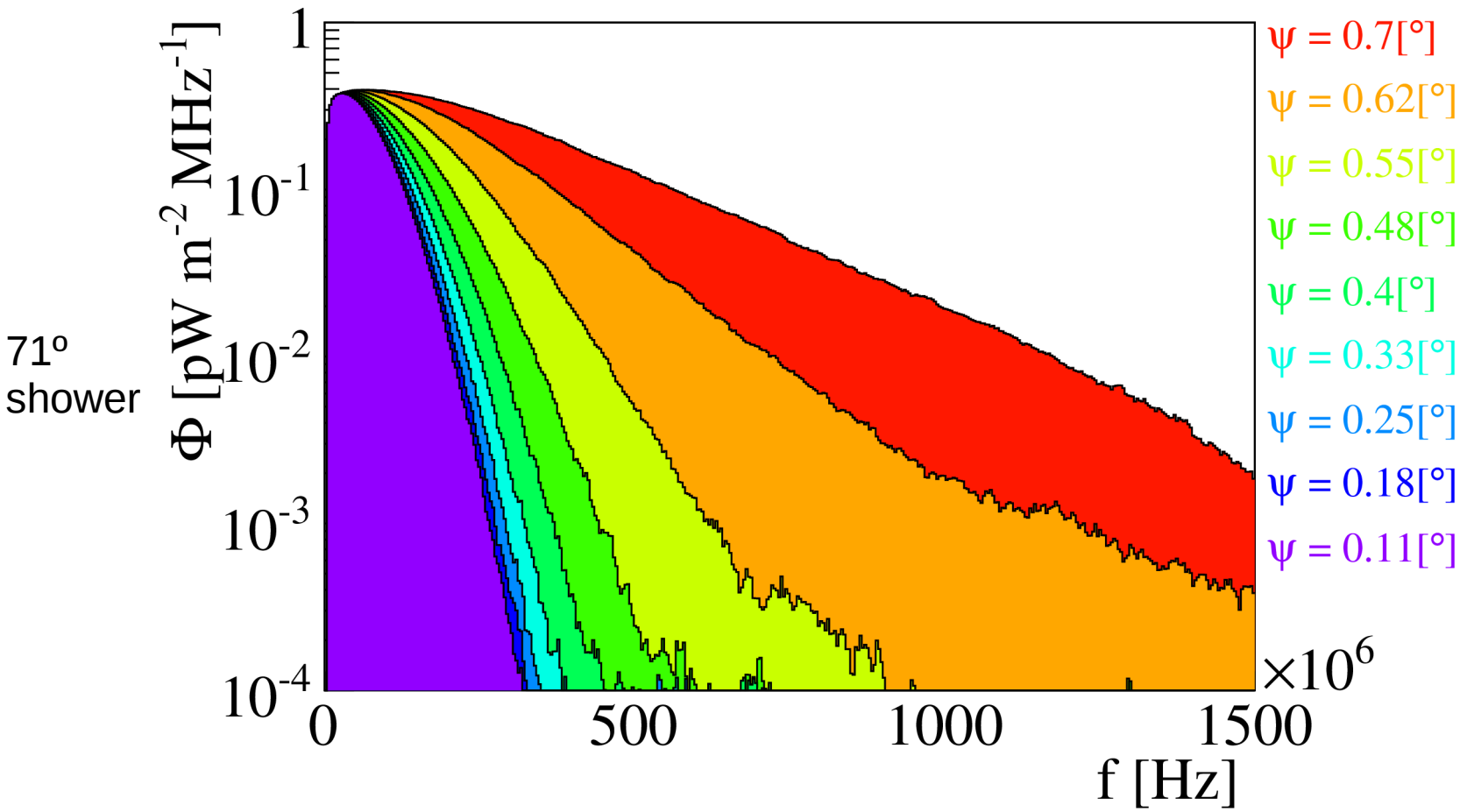


Results of ZHAireS-Reflex: spectrum slope

- Spectrum slope depends on the off-axis angle
- Exponential fall-off
- Measuring the slope, we know the angle relative to the axis



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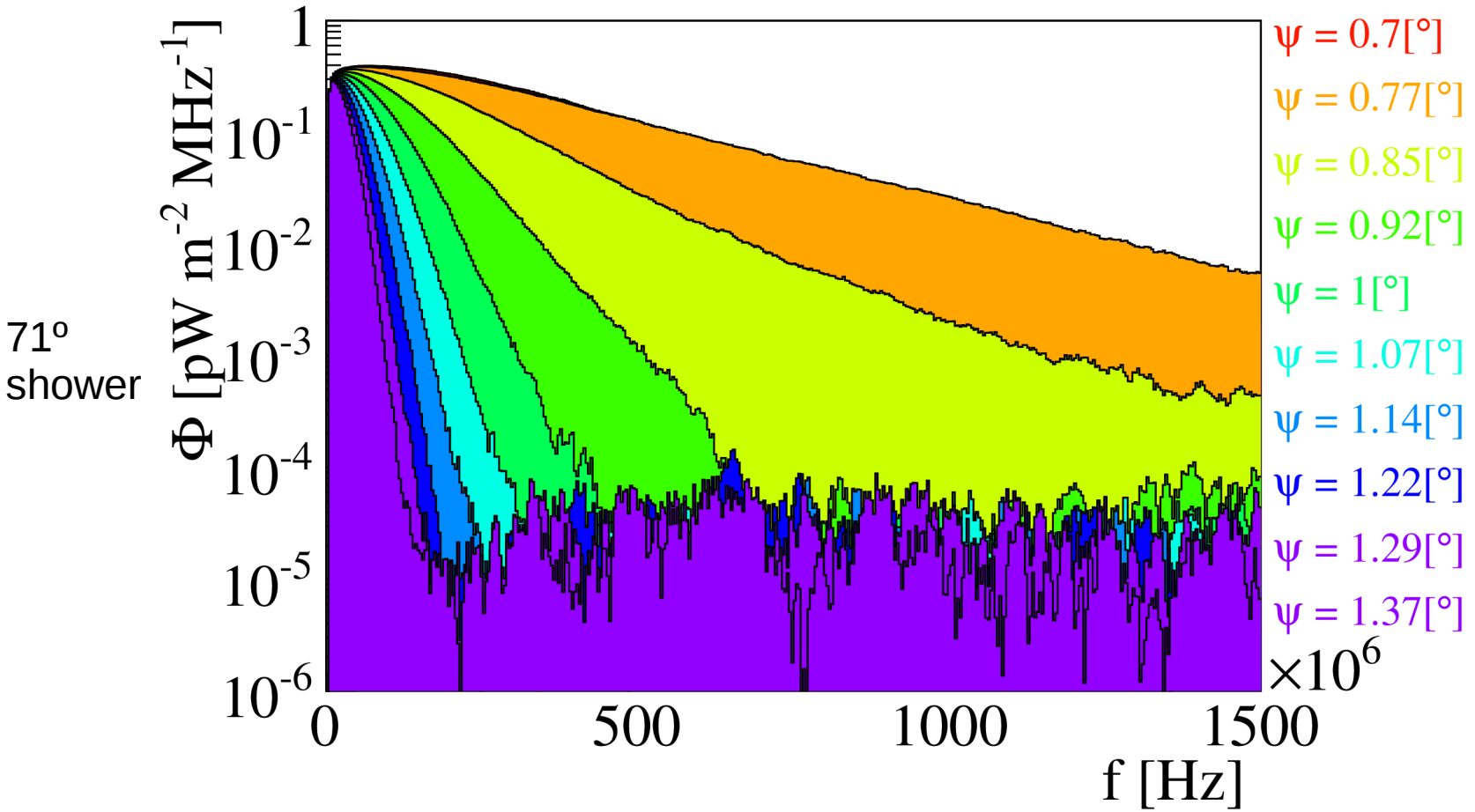
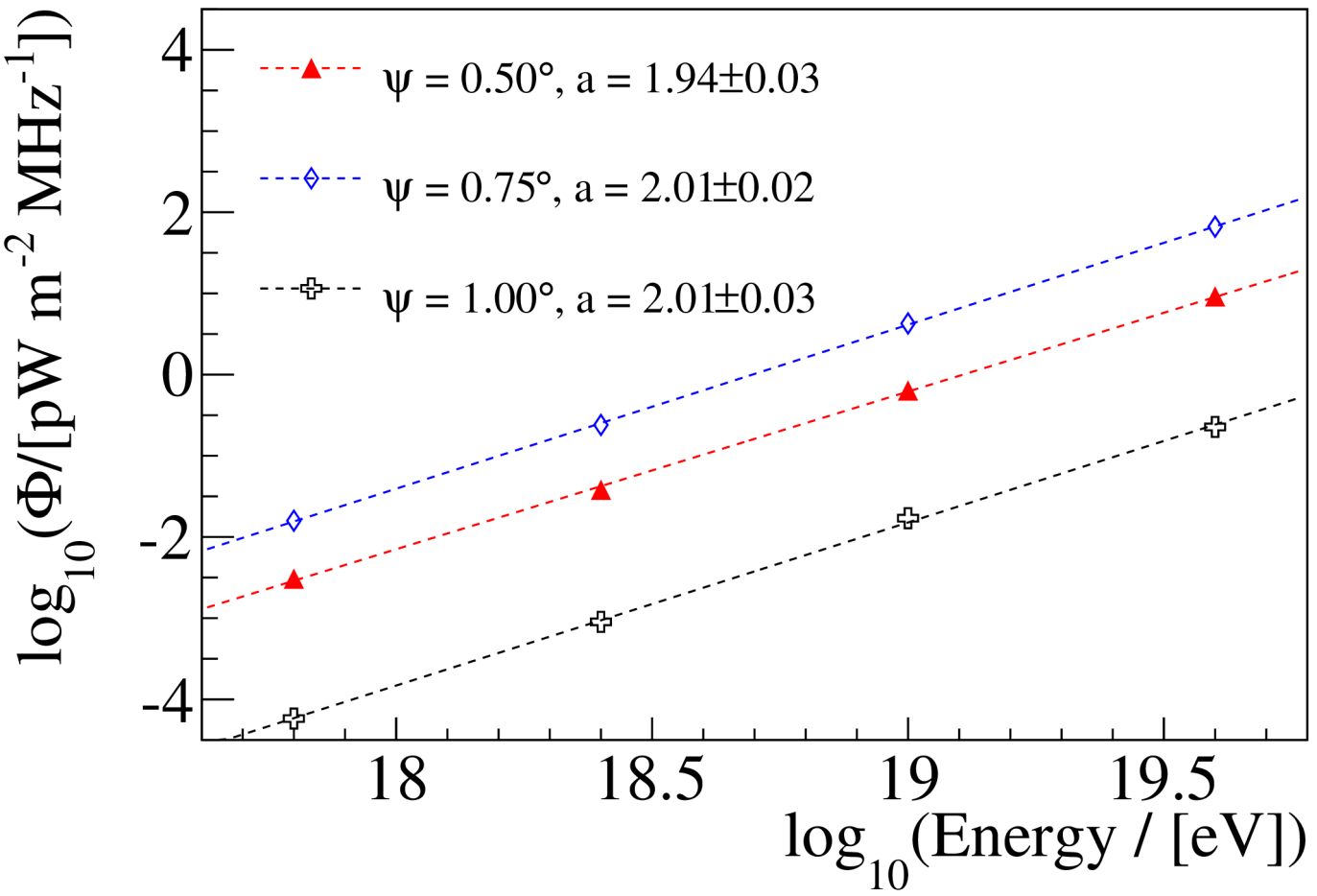


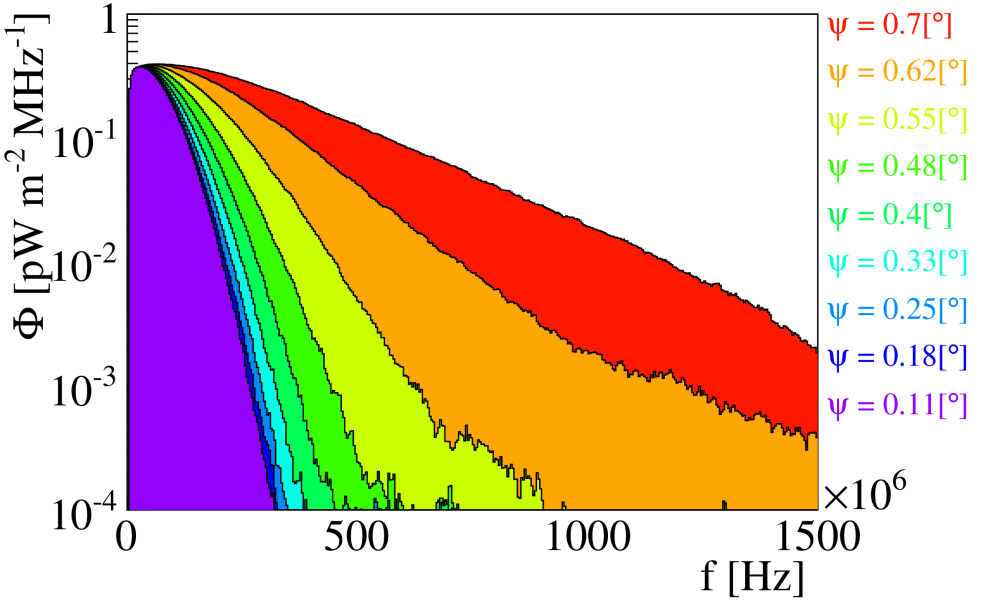
Results of ZHAireS-Reflex: primary energy

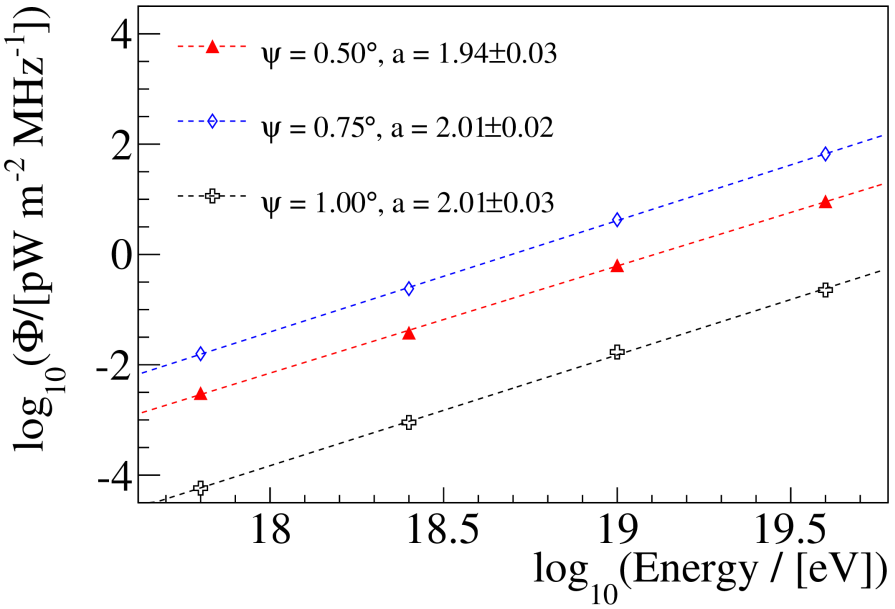
- Electric field flux scales quadratically with primary energy
- Valid for the zenith angles, off-axis angles and frequencies explored.



Results of ZHAireS-Reflex: energy measurement

- Spectrum slope depends on the off-axis angle
- Electric field flux scales quadratically with primary energy (for the zenith angles, off-axis angles and frequencies relevant)



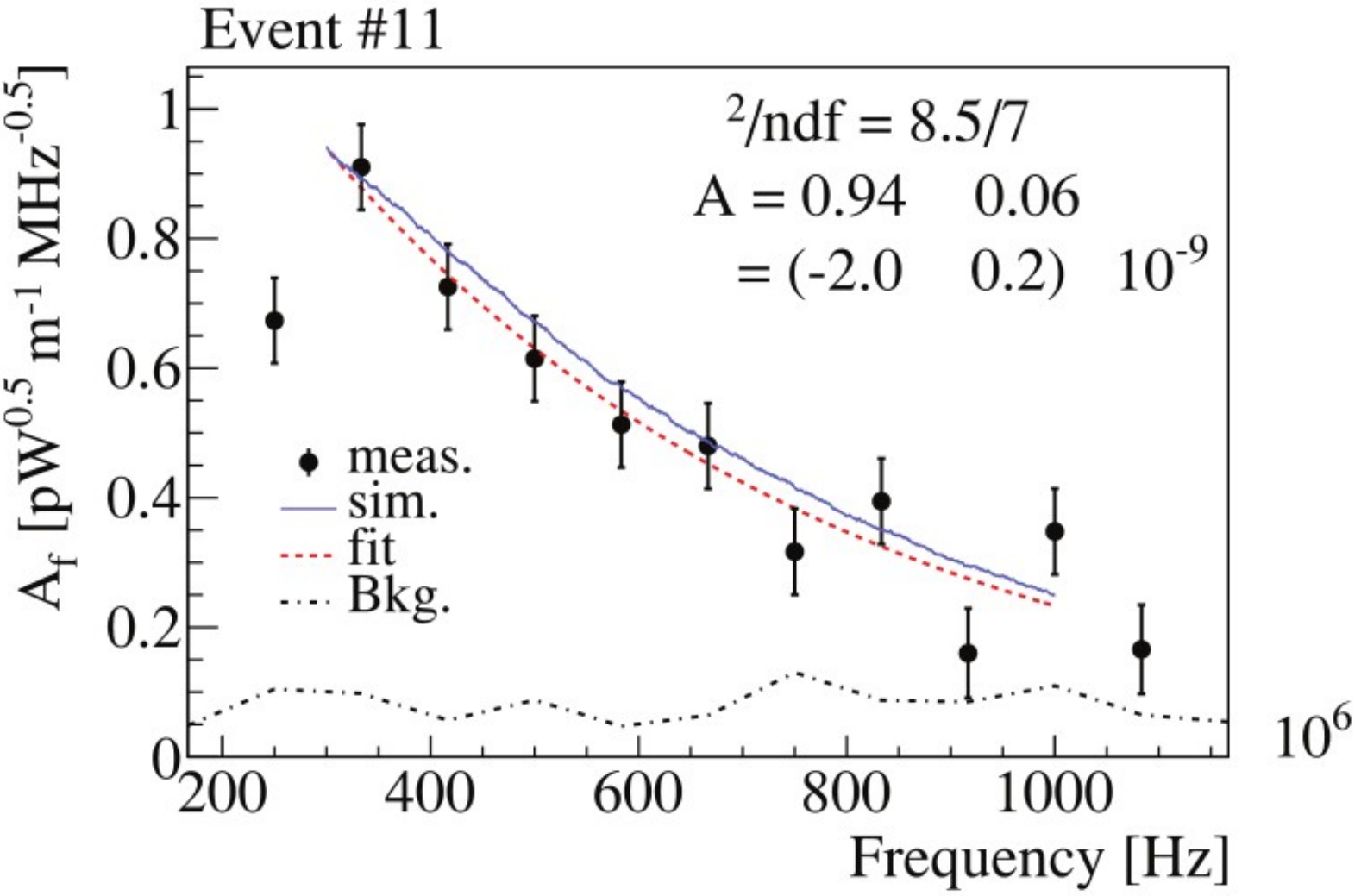


Method for energy measurement:
- Spectrum slope gives the off-axis
- Electric field at the Cherenkov angle can be obtained
- Flux at the Cherenkov angle gives the primary particle energy

Analysis

ANITA spectrum: analysis

- Exponential fall-off, as in the simulations



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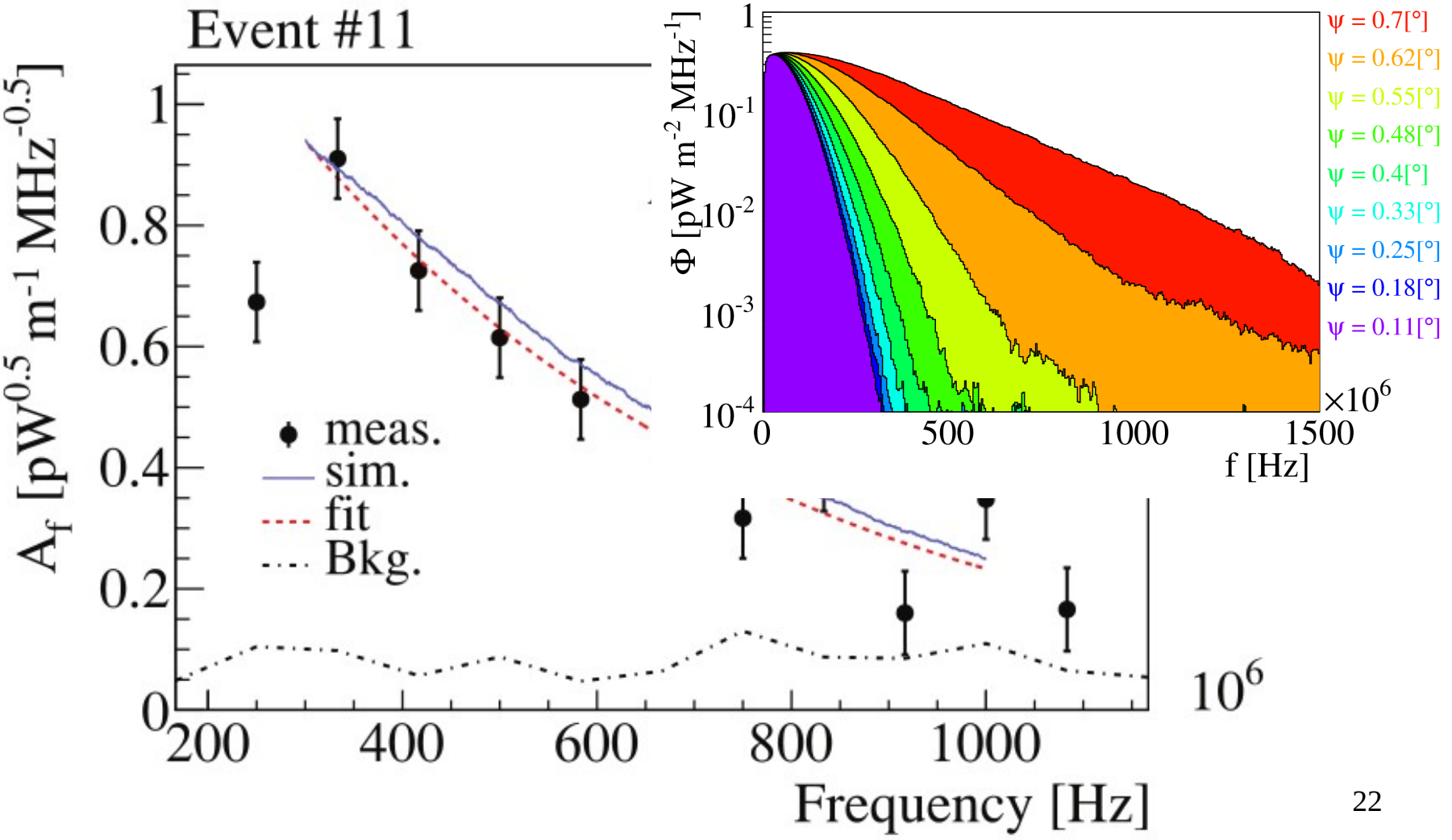
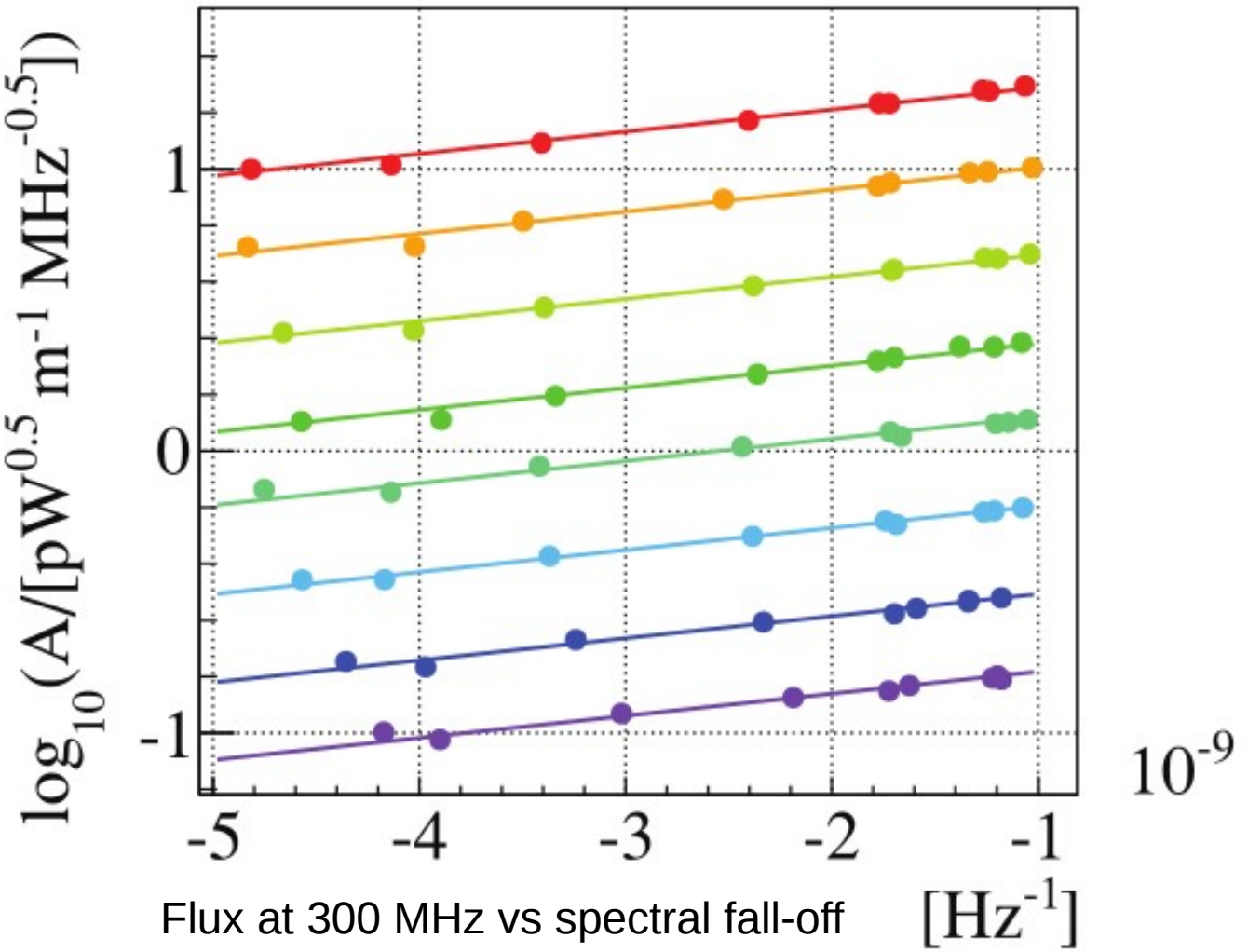


Fit for the fall-off

- Each color is a different zenithal angle

$$\log|\boldsymbol{E}_c| = \log|\boldsymbol{E}| + b(\gamma - \gamma_c)$$

b, γ_c, from simulations

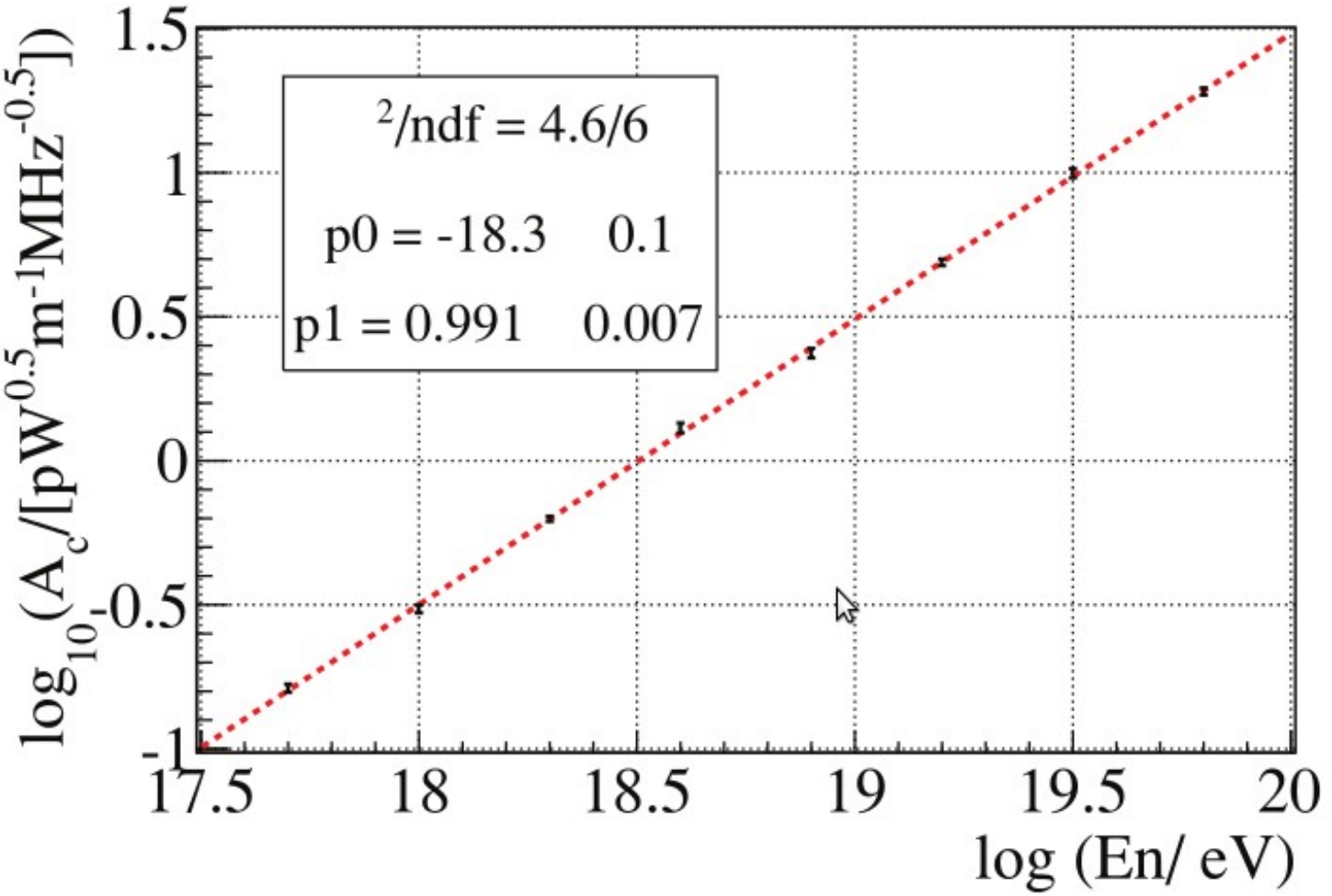


Flux at 300 MHz vs spectral fall-off

Fit for the energy

- Flux at Cherenkov angle gives primary energy

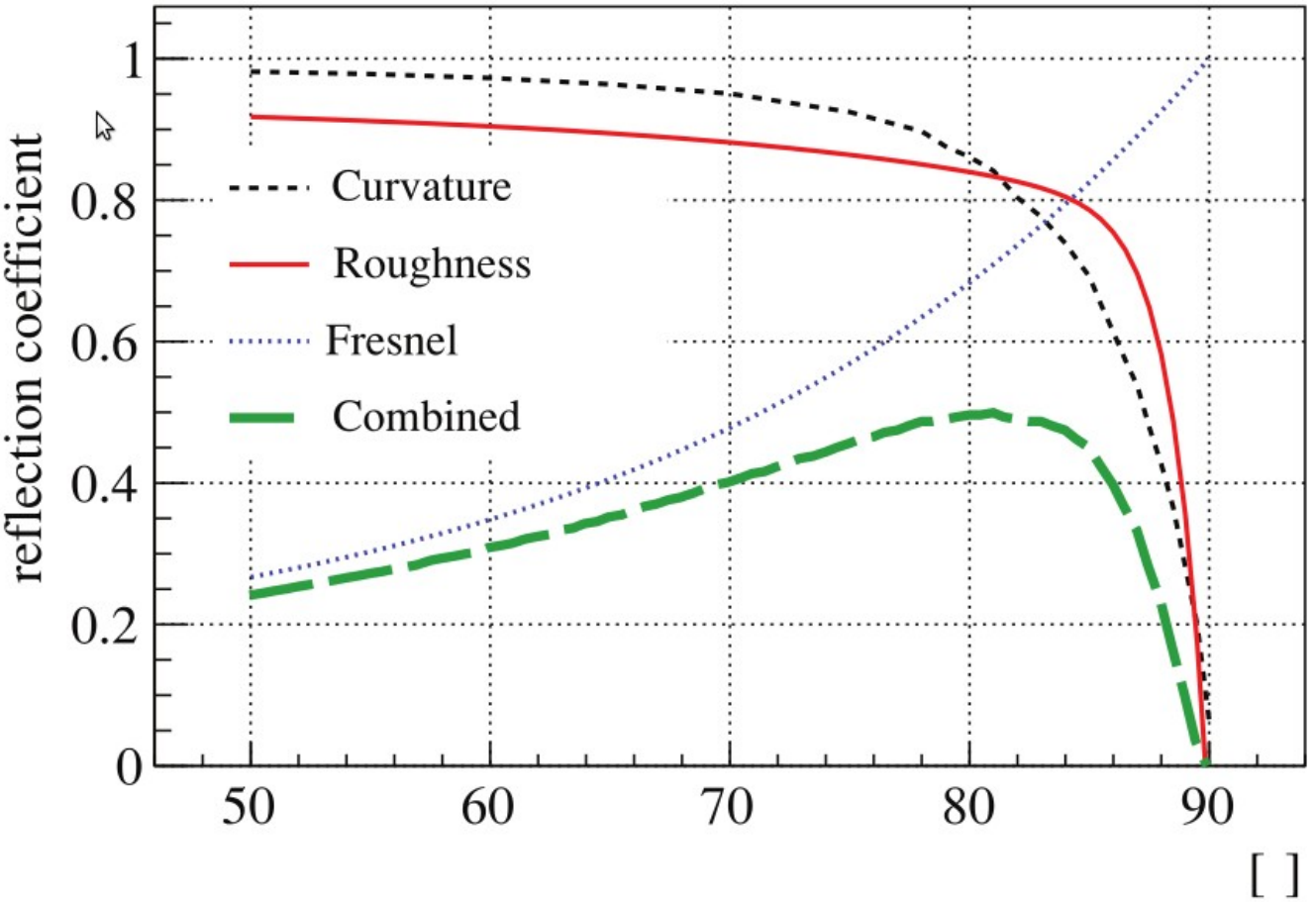
$$\log E_{primary} = \frac{1}{p_1}\left(\log\left|\left(\boldsymbol{E_c}\right)\right| - p_0\right)$$



Reflection effects

- Curvature of the Earth defocuses the wave
- Surface roughness destroys coherence (high frequencies)

600 MHz



Sources of uncertainty

- Ambiguity in the direction of the air shower (off-axis known)
- Uncertainty on Xmax
- Variation in atmospheric refractive index
- Variation in snow (firn) refractive index
- Calibration of the instruments
- Simulation package (ZHAireS vs CoREAS)
- Fit parameters
- Experimental measurements (d'oh!)

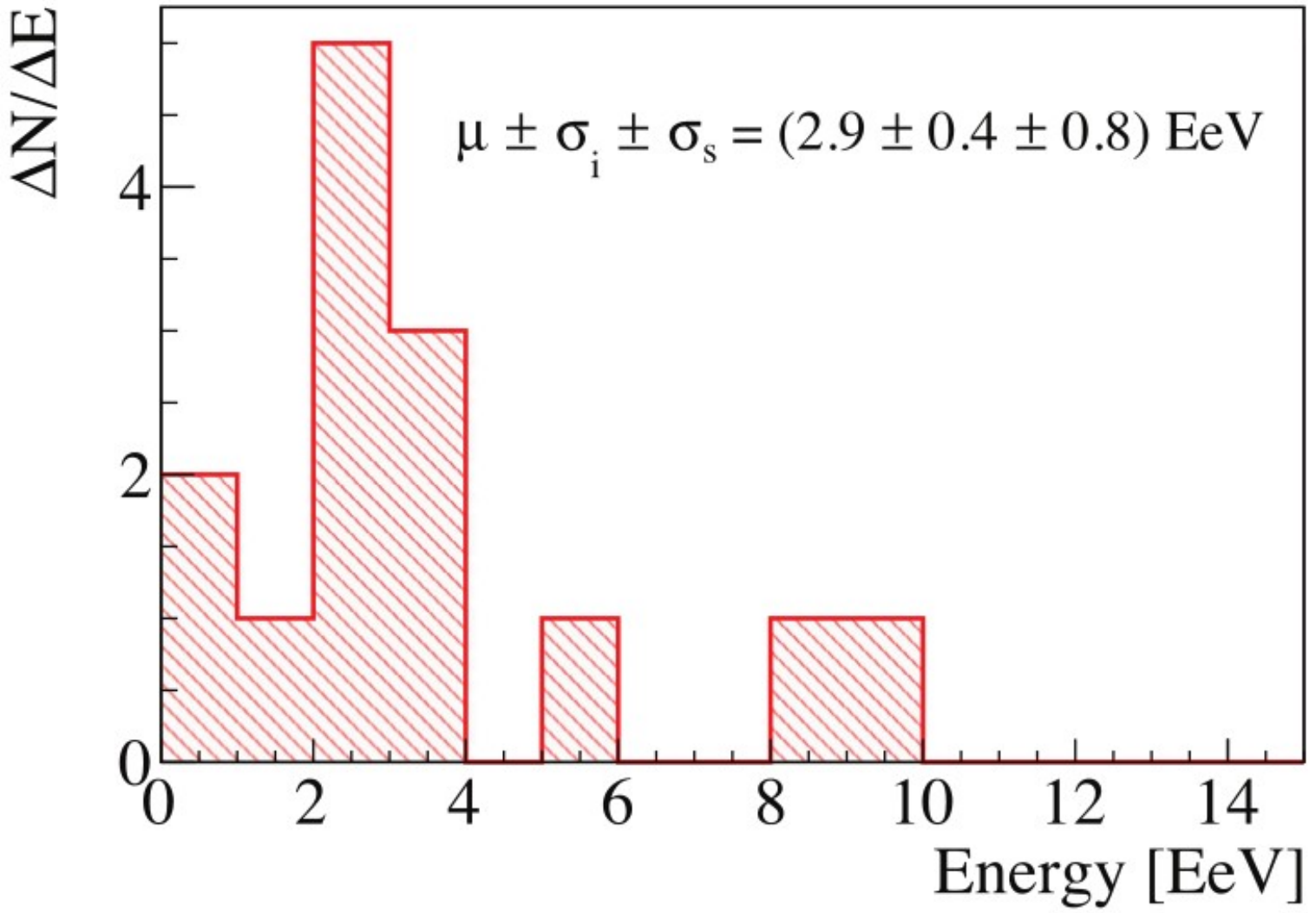
- All taken into account!

Events data

Event numbers	θ (°)	A ($pW^{0.5}\,m^{-1}\,MHz^{-0.5}$)	γ (Hz^{-1})
1	84.6	0.25 ± 0.03	$-1.6 \pm 0.5 \times 10^{-9}$
2	80.4	0.72 ± 0.04	$-2.2 \pm 0.2 \times 10^{-9}$
3	65.5	0.75 ± 0.08	$-2.3 \pm 0.5 \times 10^{-9}$
4	65.6	0.71 ± 0.06	$-2.5 \pm 0.4 \times 10^{-9}$
5	64.0	2.90 ± 0.13	$-3.1 \pm 0.2 \times 10^{-9}$
6	68.7	0.73 ± 0.04	$-1.7 \pm 0.2 \times 10^{-9}$
7	74.9	0.31 ± 0.04	$-2.0 \pm 0.6 \times 10^{-9}$
8	57.0	0.66 ± 0.13	$-3.2 \pm 1.5 \times 10^{-9}$
9	74.5	0.34 ± 0.05	$-2.3 \pm 0.6 \times 10^{-9}$
10	78.8	0.61 ± 0.05	$-3.2 \pm 0.4 \times 10^{-9}$
11	70.5	0.94 ± 0.06	$-2.0 \pm 0.2 \times 10^{-9}$
12	79.1	0.39 ± 0.05	$-2.4 \pm 0.6 \times 10^{-9}$
13	81.9	0.72 ± 0.06	$-4.0 \pm 0.6 \times 10^{-9}$
14	78.6	0.57 ± 0.04	$-2.2 \pm 0.3 \times 10^{-9}$

Mean energy

- Uncertainties: individual events and energy scale.

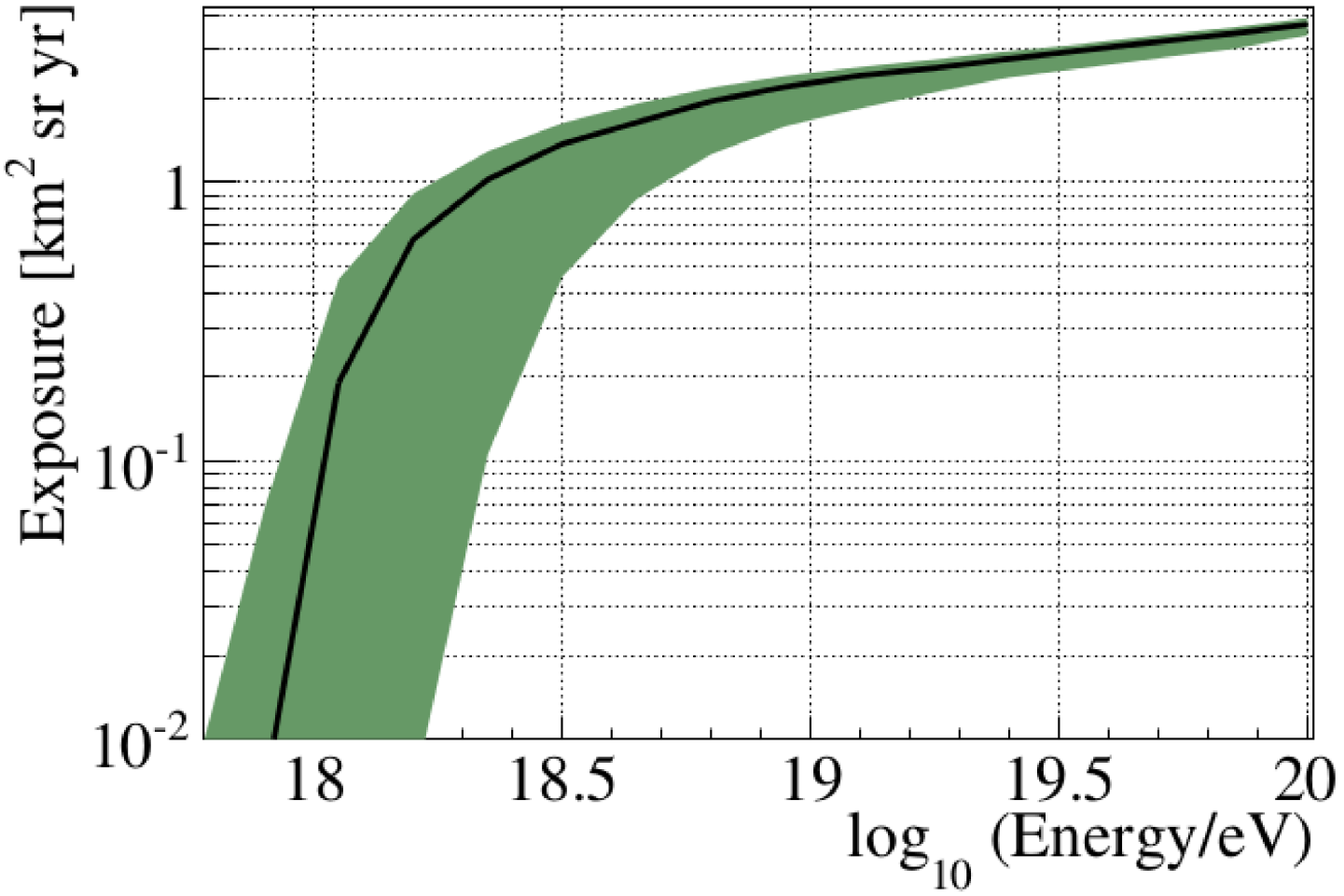


Acceptance or exposure

- If we want to measure a flux, we need the acceptance or

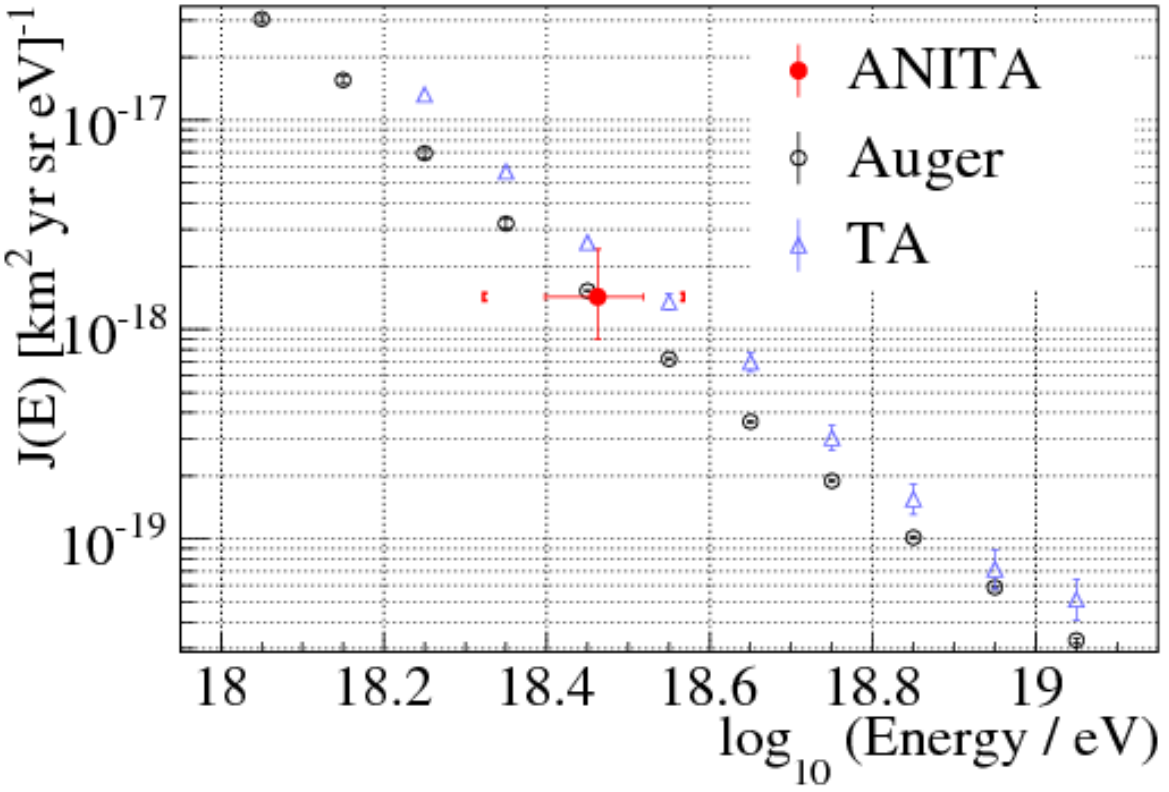
  exposure = number of detected events / incident CR flux

- Simulation of the ANITA flight. Full particle MC, electric field simulation and ANITA instrumentation.



First CR spectrum measurement with radio only

- Made by the ANITA collaboration using ZHAireS-Reflex
- Proof of the capability of radio as a stand-alone technique



H. Schoorlemmer et al., Astropart. Phys. **77:**32-43, 2016

Future of the technique?

- ANITA III has already flown. Designed for exploiting the reflection technique. Analysis underway. ANITA IV scheduled to fly December 2016
- New projects:
  - SWORD, a satellite (arxiv:1302.1263v1)
  - EVA (ExaVolt antenna), a super-pressurised balloon with toroidal reflectors
  - TAROGE, using the sea as reflecting surface (ICRC 2015 #663)

S. Wissel for the ANITA Col, ICRC proc. 2015 #1111

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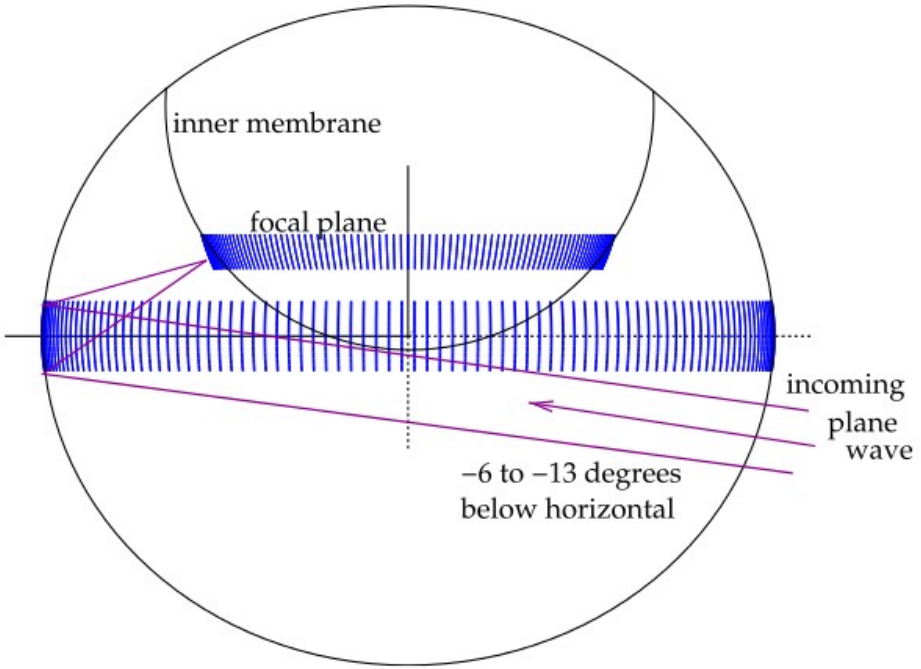


Astropart. Phys **35**:242-256, 2011

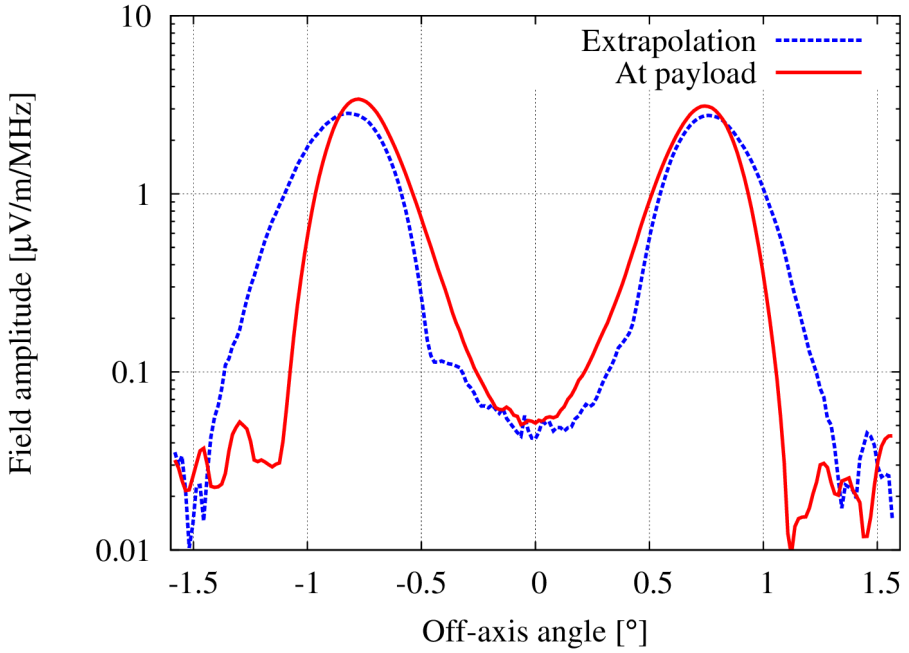
Outlook and conclusions

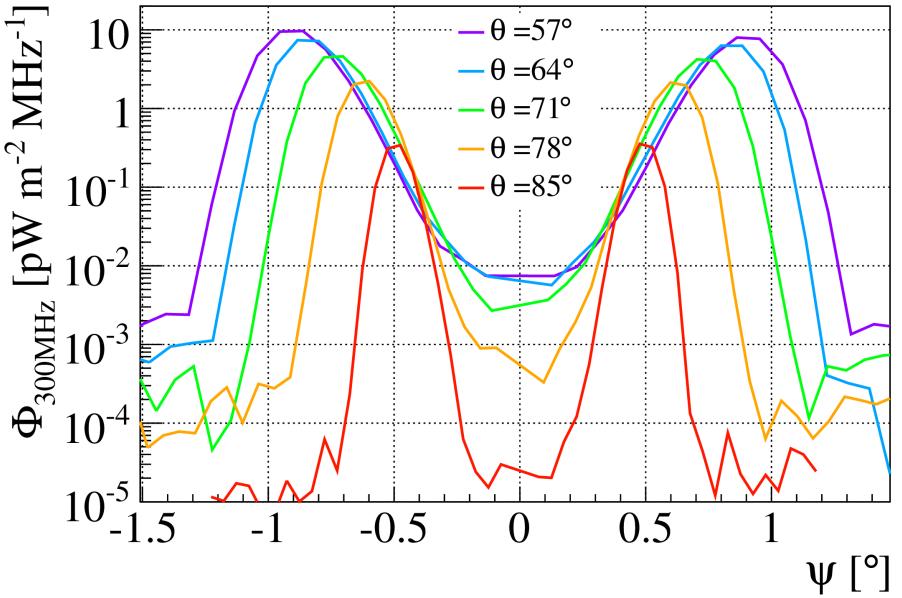
- ANITA I has detected 14 reflected UHECR events. ANITA III analysis underway
- These data have been used to produce the first cosmic ray flux measurement using only the radio technique
- The code ZHAireS-Reflex has been crucial in this process
- New experiments intend to use this technique for future measurements

Thank you!

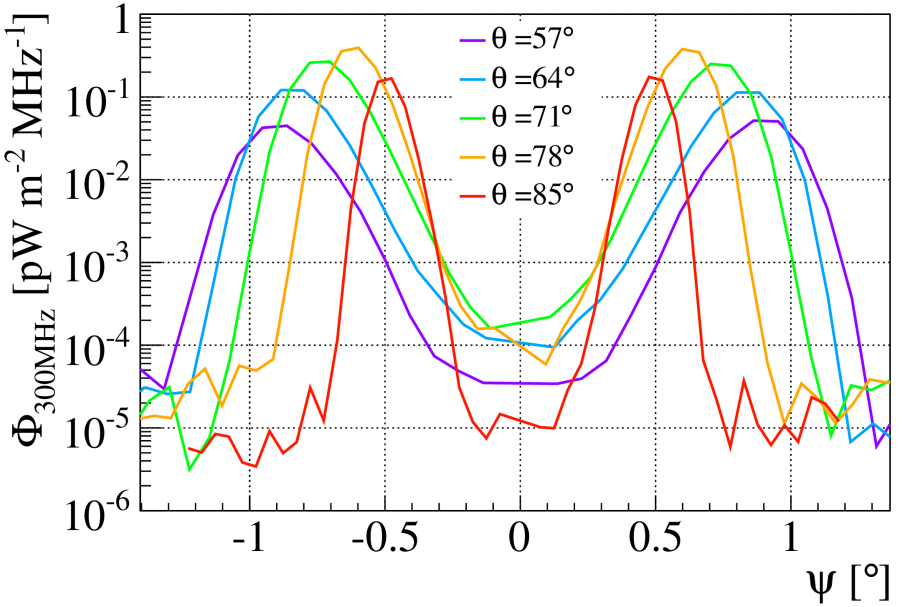
Results of ZHAireS-Reflex

- Field should **not** be calculated on the ground and extrapolated
- Fresnel coefficients favour high-zenith showers





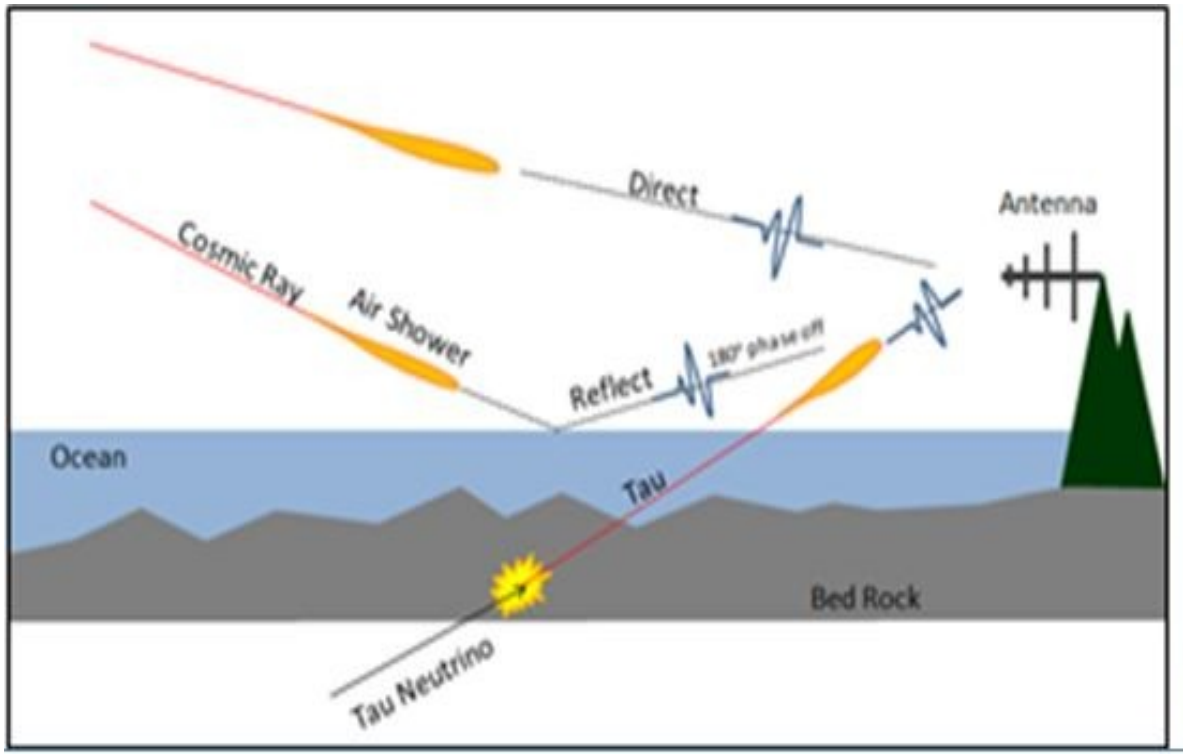
Without Fresnel coeff.



With Fresnel coeff.

Motivation: planned experiments

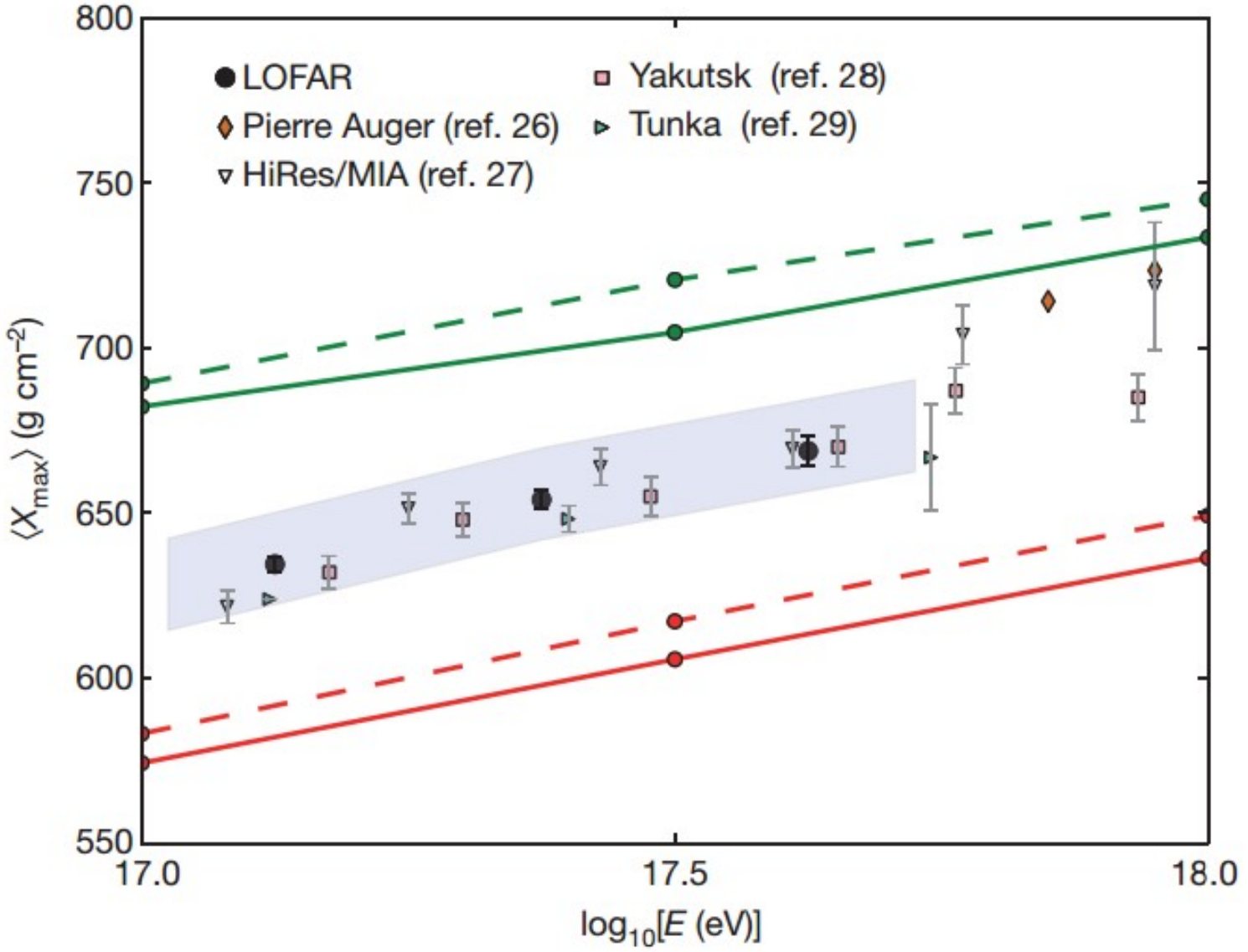
- More balloon payloads: ANITA III, ExaVolt.
- Satellites: SWORD project.
- Observatories on mountain tops: TAROGE.



Taiwan

See http://lecospa.ntu.edu.tw/experiment-2/experiment-i-ultra-high-energy-neutrinos-and-cosmic-rays/ and proceedings for this ICRC

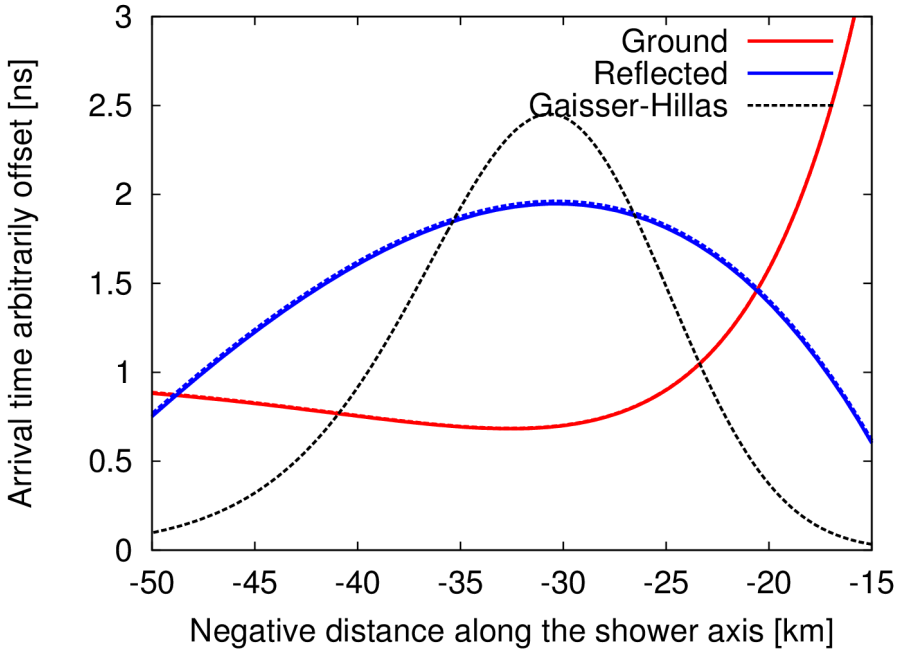
Composition at LOFAR



Straight vs curved rays

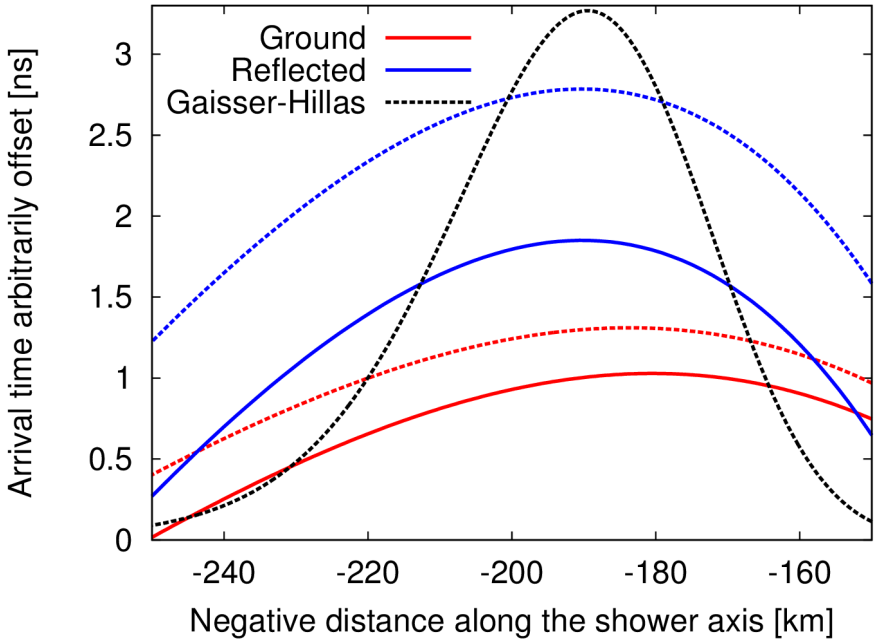
- We check with the ray tracing program the difference in arrival times (straight vs curved rays)
- This gives us an upper frequency for the straight approximation.

70º shower – 33 km of altitude



Ground: ~ 50 ps → ~ 5 GHz

85º shower – 50 km of altitude

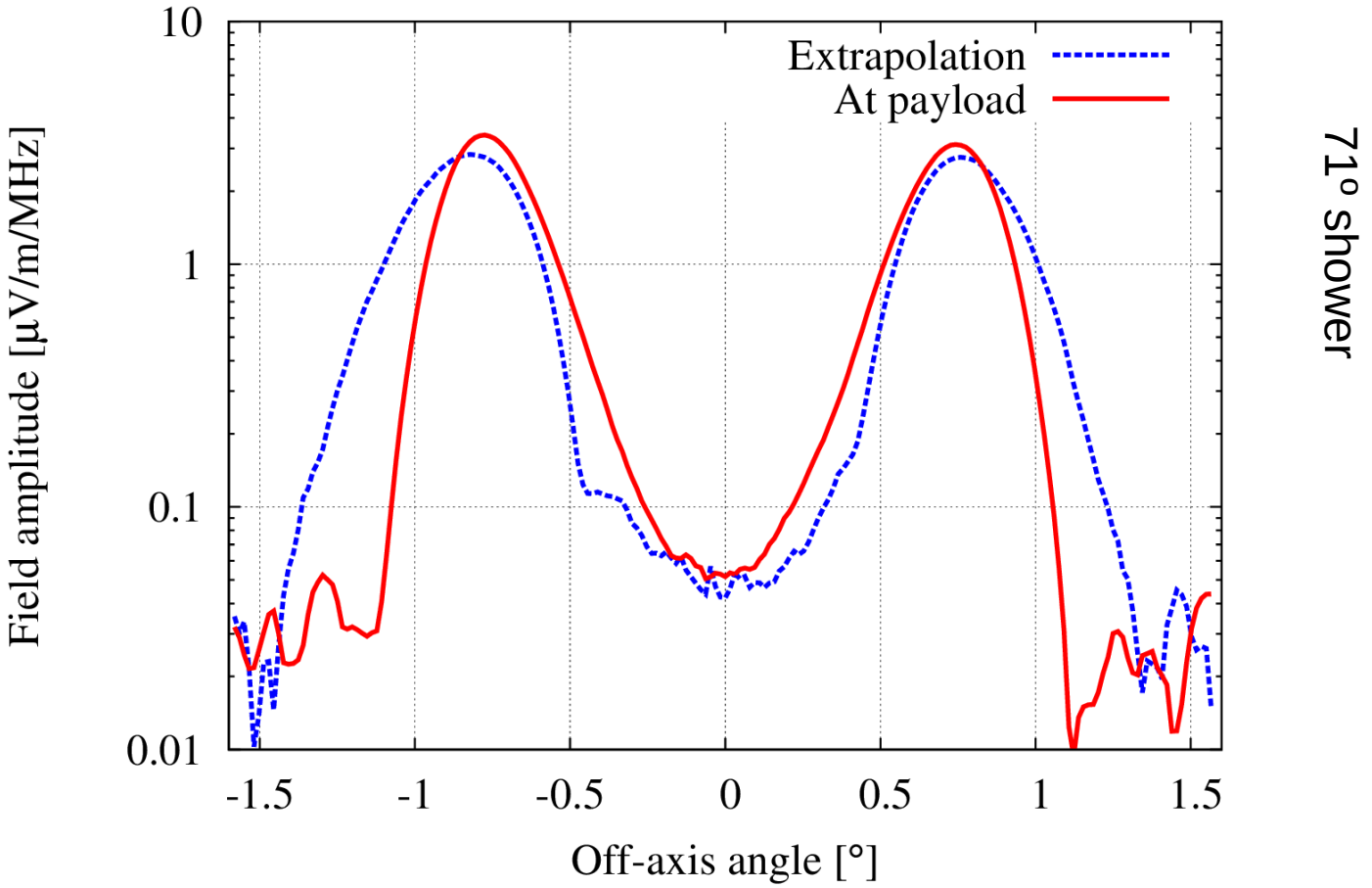


Ground: ~ 200 ps → ~ 1.25 GHz
Reflected: ~ 20 ps → ~ 12.5 GHz

Time offsets are irrelevant

Results of ZHAireS-Reflex: extrapolation

- Extrapolating the field (or mirror approach) with the inverse of the distance is not a good approximation
- Accurate wave propagation is important



Results of ZHAireS-Reflex: Fresnel coeffs

- Fresnel coefficients change significantly the field as a function of the shower zenith angle
- Maximum emission around 80º