

# Radio emission from ultra-high energy cosmic-ray showers after reflecting on Earth

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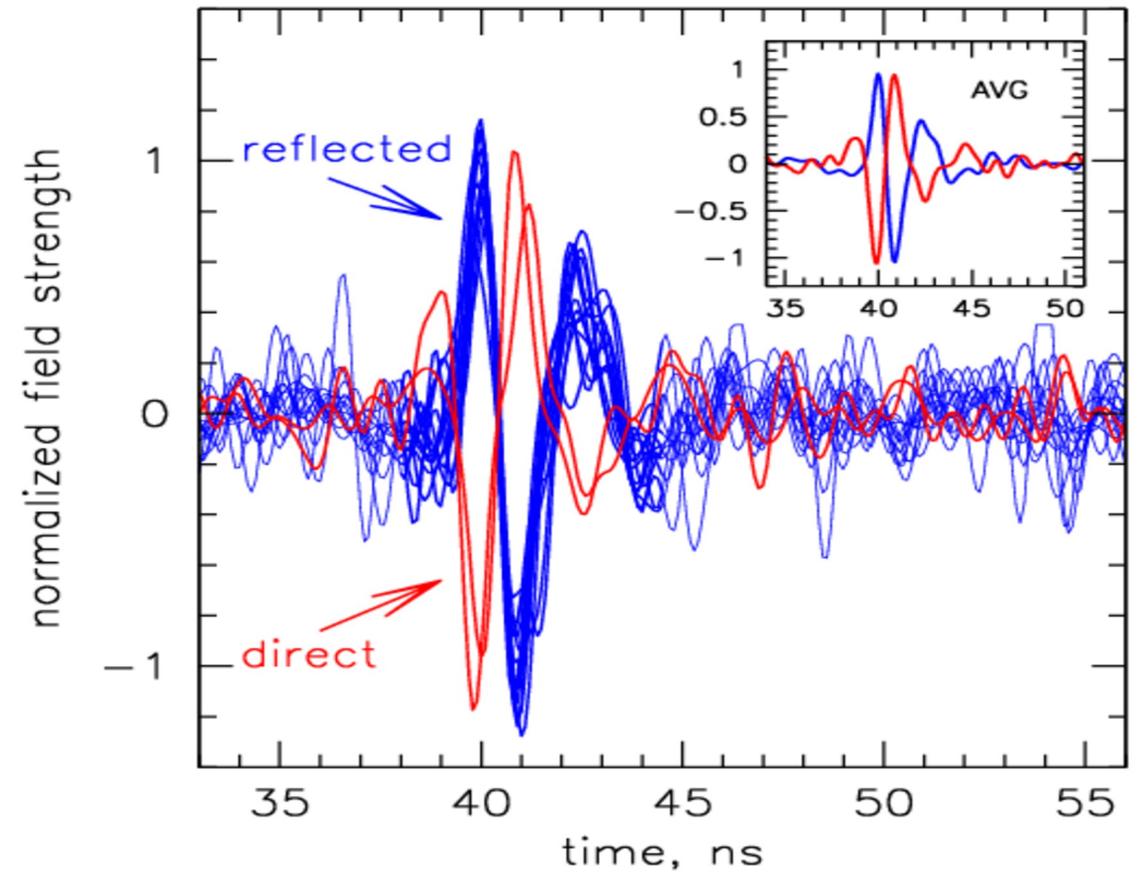
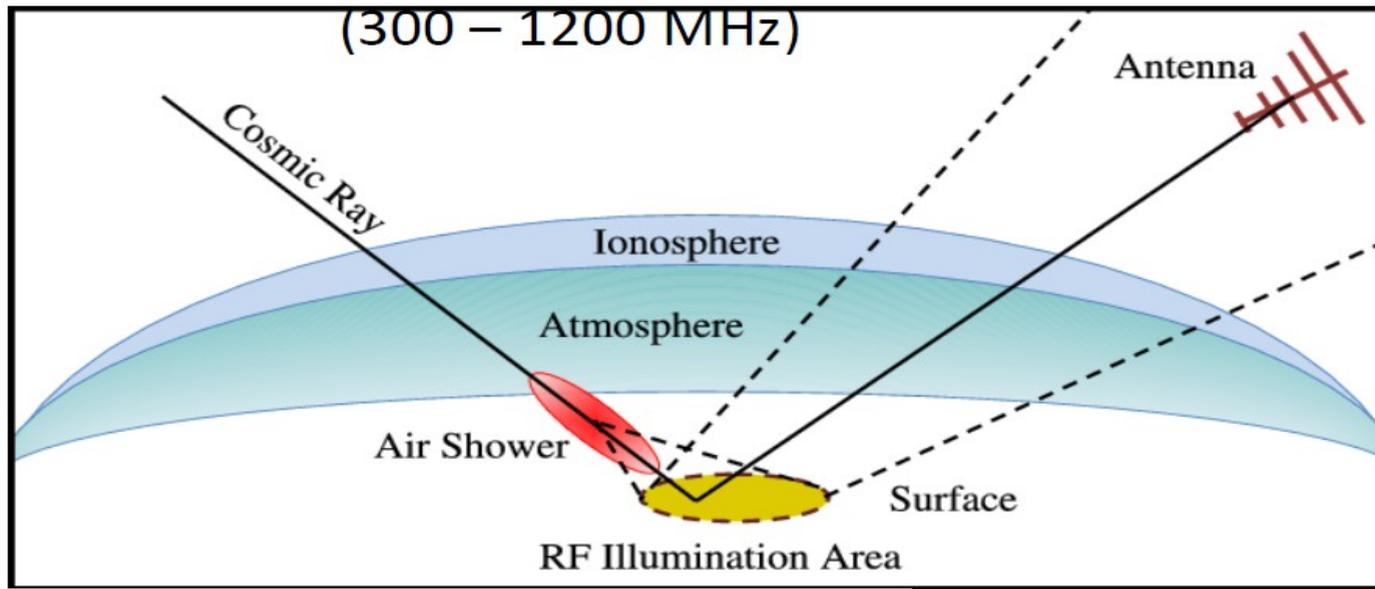
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# Take-home message

- ZHAireS is a Monte Carlo code.
  - Aires for the particle physics MC.
  - ZHS algorithm for the radio emission (electric field).
- Its new implementation allows to treat reflection of the radio emission for the first time.
  - Reflection on a flat surface.
  - Useful for high altitude detection experiments.

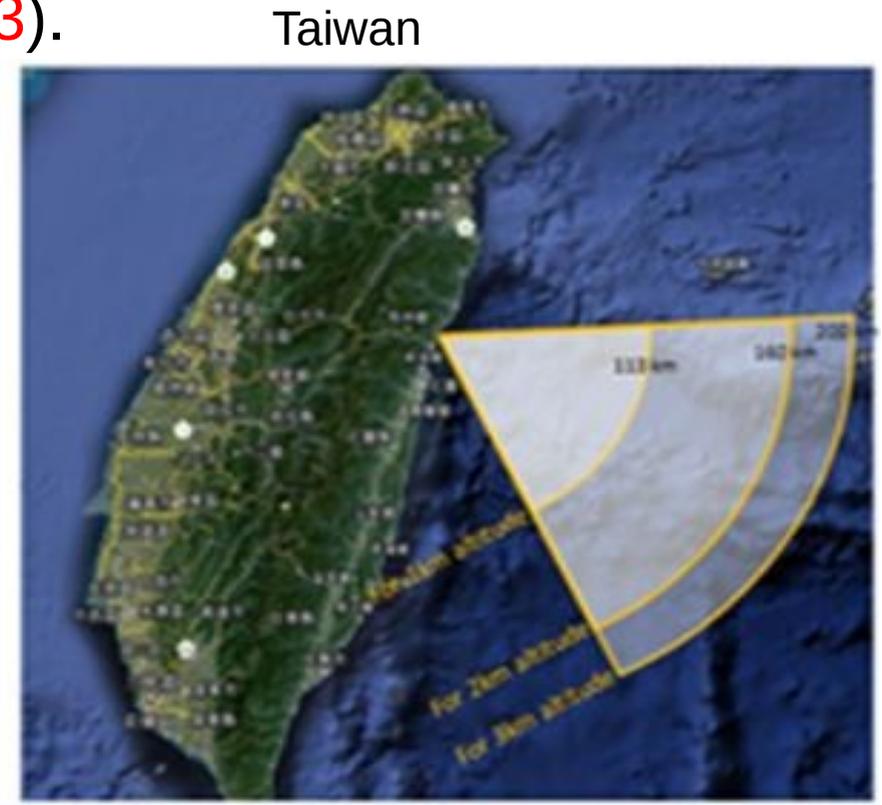
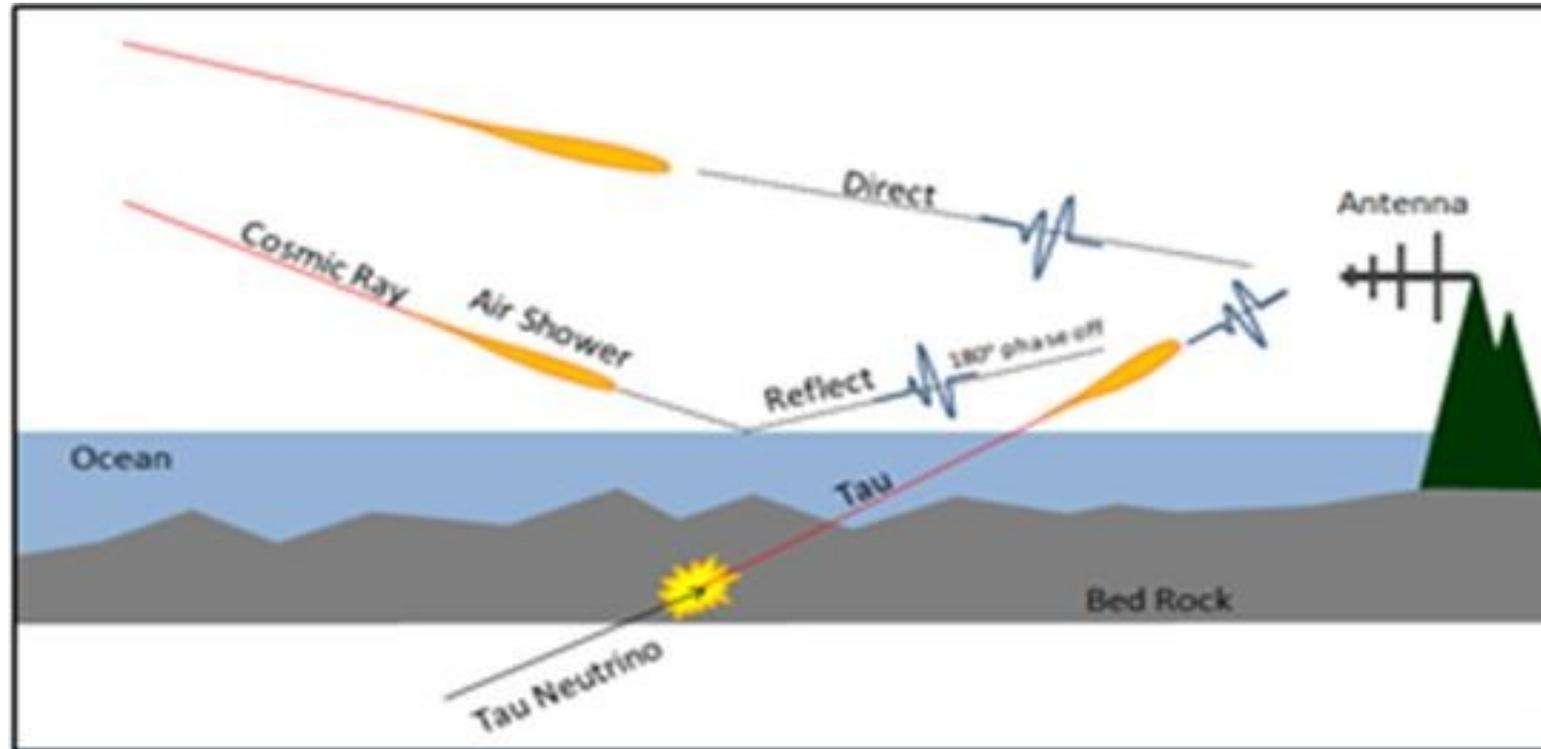
# Motivation: experimental results

- **ANITA** detected **16** UHECR events.
- **14** of those were reflected on the Antarctica ice.



# Motivation: planned experiments

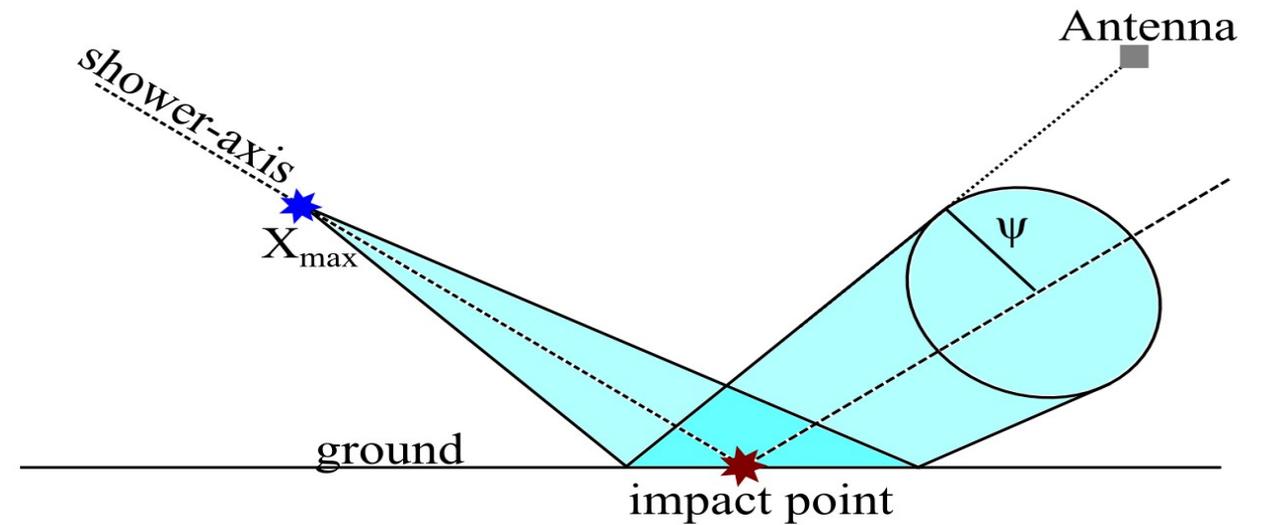
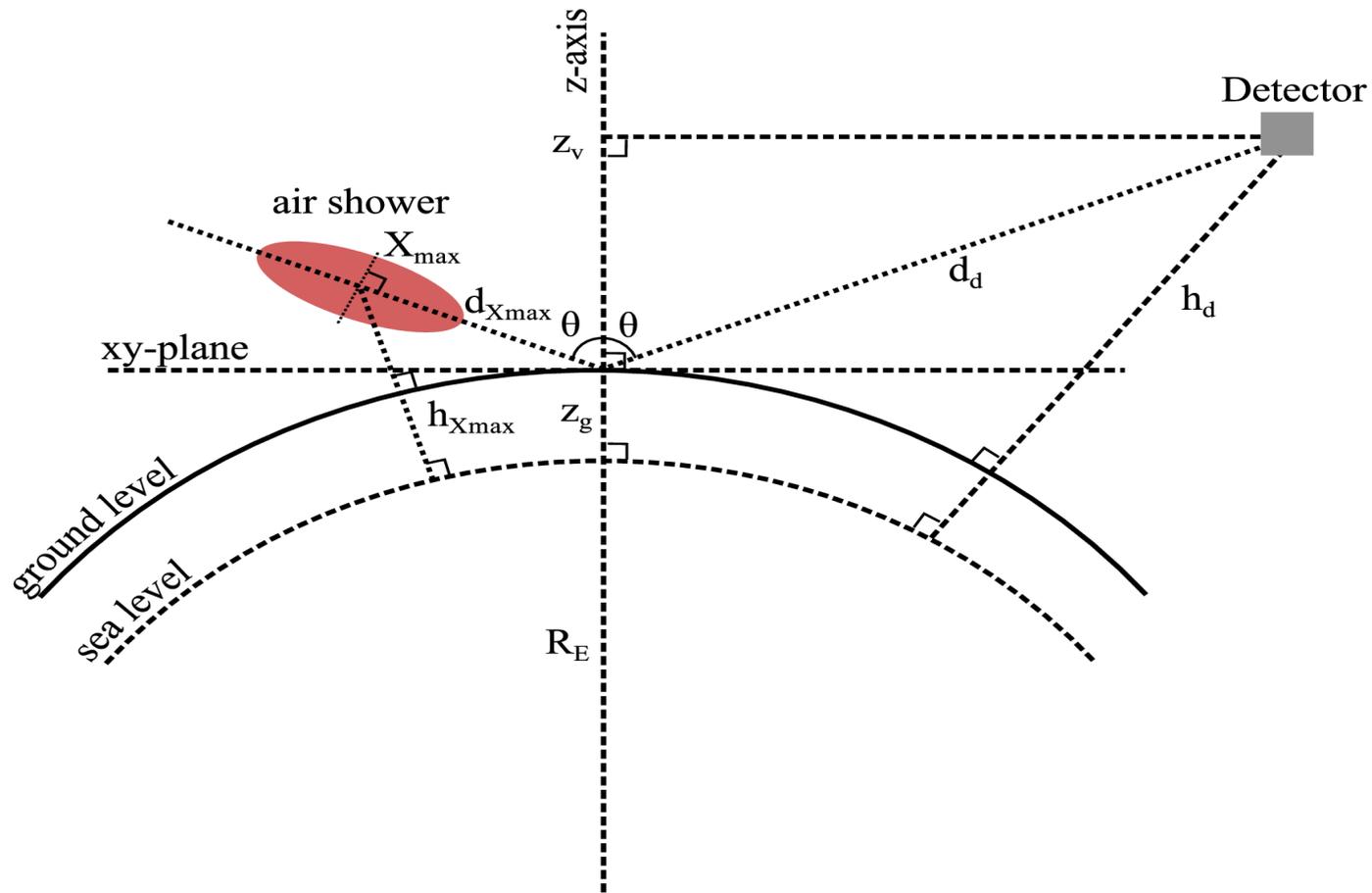
- More **balloon** payloads: ANITA III, ExaVolt (see **A. Romero-Wolf's** talk, **proc. #1151**).
- **Satellites**: SWORD project.
- Observatories on **mountain** tops: TAROGE (proc. **#663**).



See <http://leospa.ntu.edu.tw/experiment-2/experiment-i-ultra-high-energy-neutrinos-and-cosmic-rays/> and proceeding **#663** for this ICRC

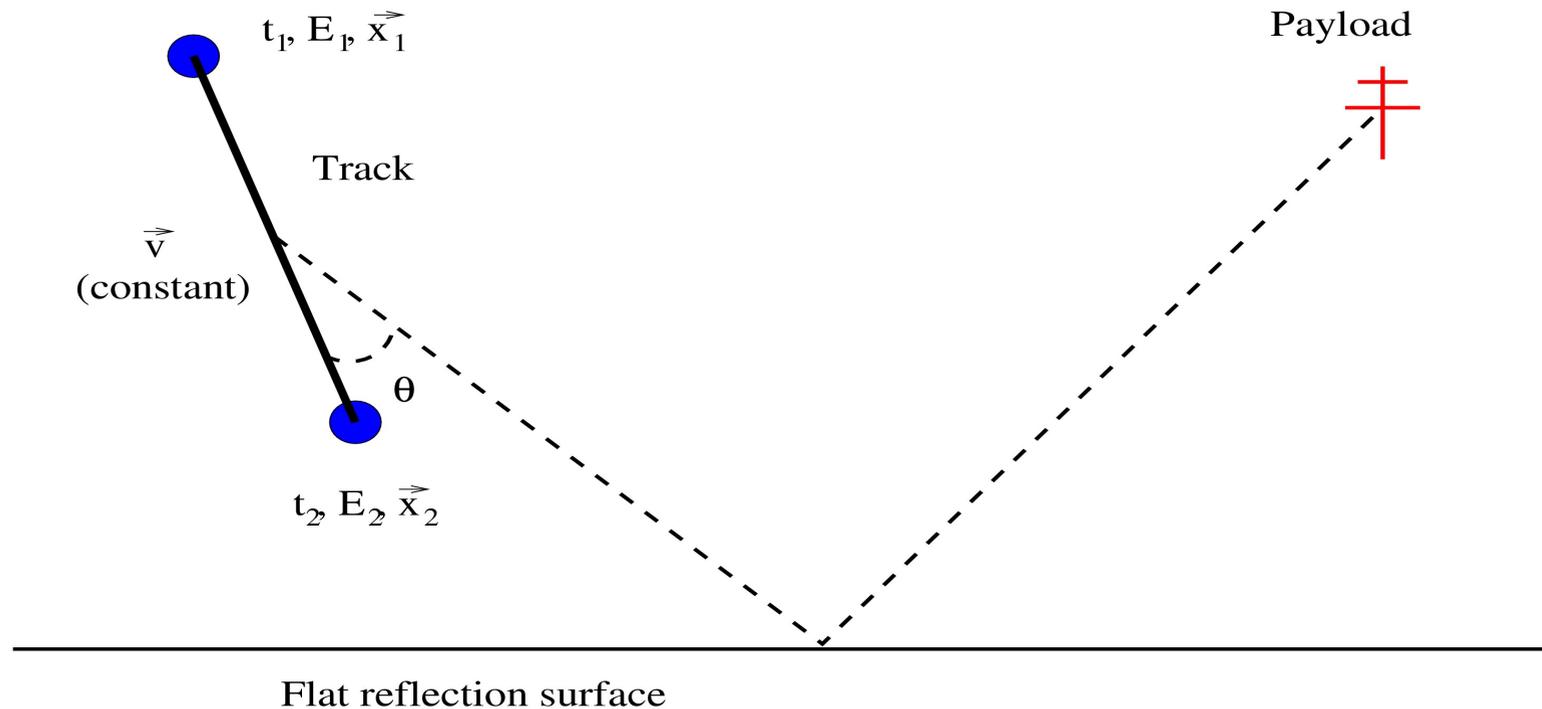
# ZHAireS: Geometry for reflected events

- Reflection: large atmospheric volume
- $\psi$  is the **off-axis angle**



# ZHAireS-Reflex

- ZHAireS MC code:
  - ZHS “algorithm” for the electric field of a particle track
  - Aires MC for air showers
- ZHAireS-Reflex:
  - Electric field reflected on a flat surface
  - Fresnel coefficients at the interface
  - Rectilinear propagation: downwards and upwards.



# Fresnel coefficients

For a medium with **absorption** (complex permittivity) and **conductivity**, we define an **effective permittivity**  $\epsilon_r$ :

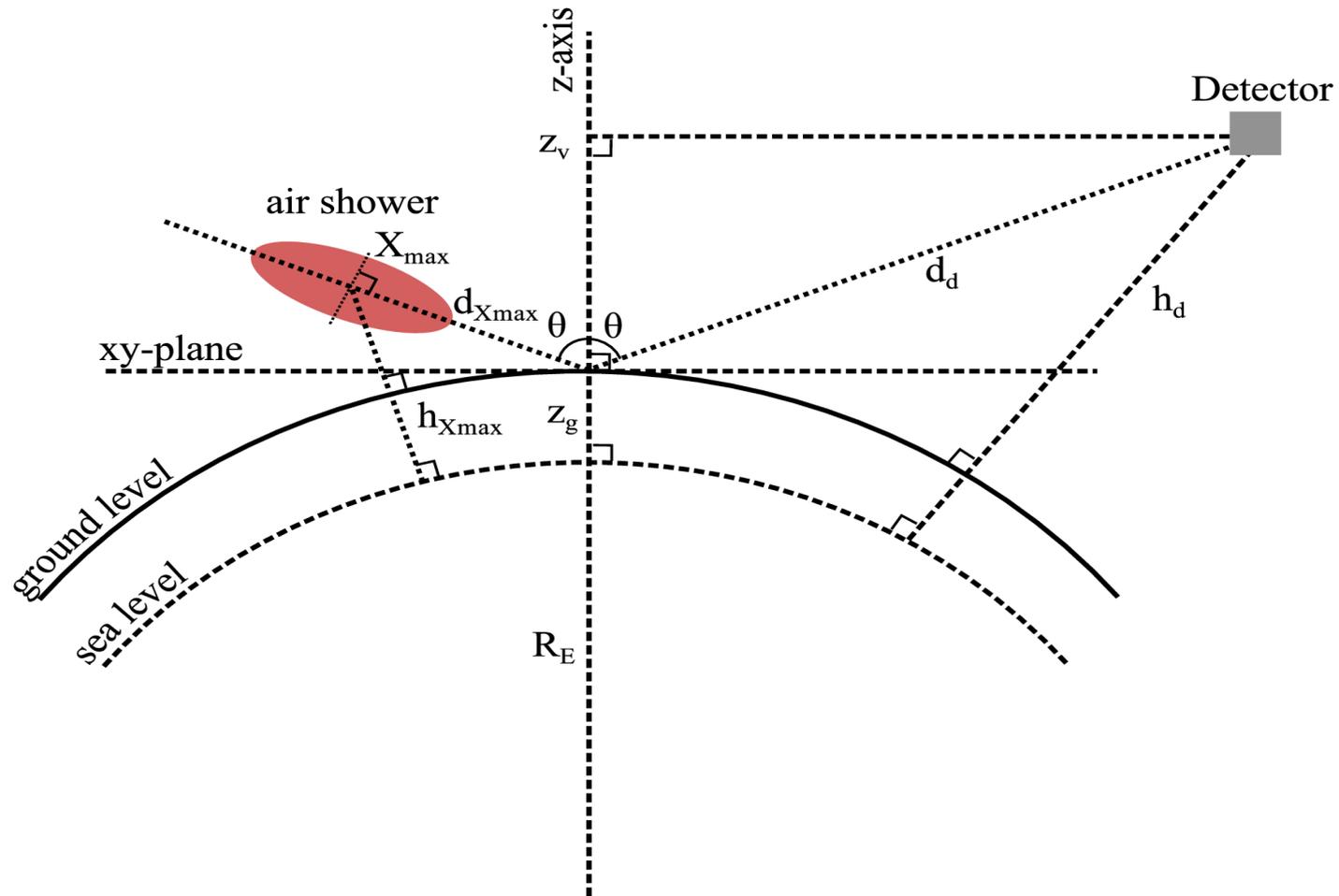
$$\epsilon_r = \frac{\epsilon}{\epsilon_0} + i \frac{\sigma}{\omega \epsilon_0}$$

Fresnel coefficients (medium 1 is lossless):

$$r_{perp} = \frac{n_1 \cos \theta_i - \sqrt{\epsilon_{r2}} \cos \theta_t}{n_1 \cos \theta_i + \sqrt{\epsilon_{r2}} \cos \theta_t} \quad r_{par} = \frac{n_1 \cos \theta_t - \sqrt{\epsilon_{r2}} \cos \theta_i}{n_1 \cos \theta_t + \sqrt{\epsilon_{r2}} \cos \theta_i}$$

Similar to the lossless case

# Simulations for a high altitude detector



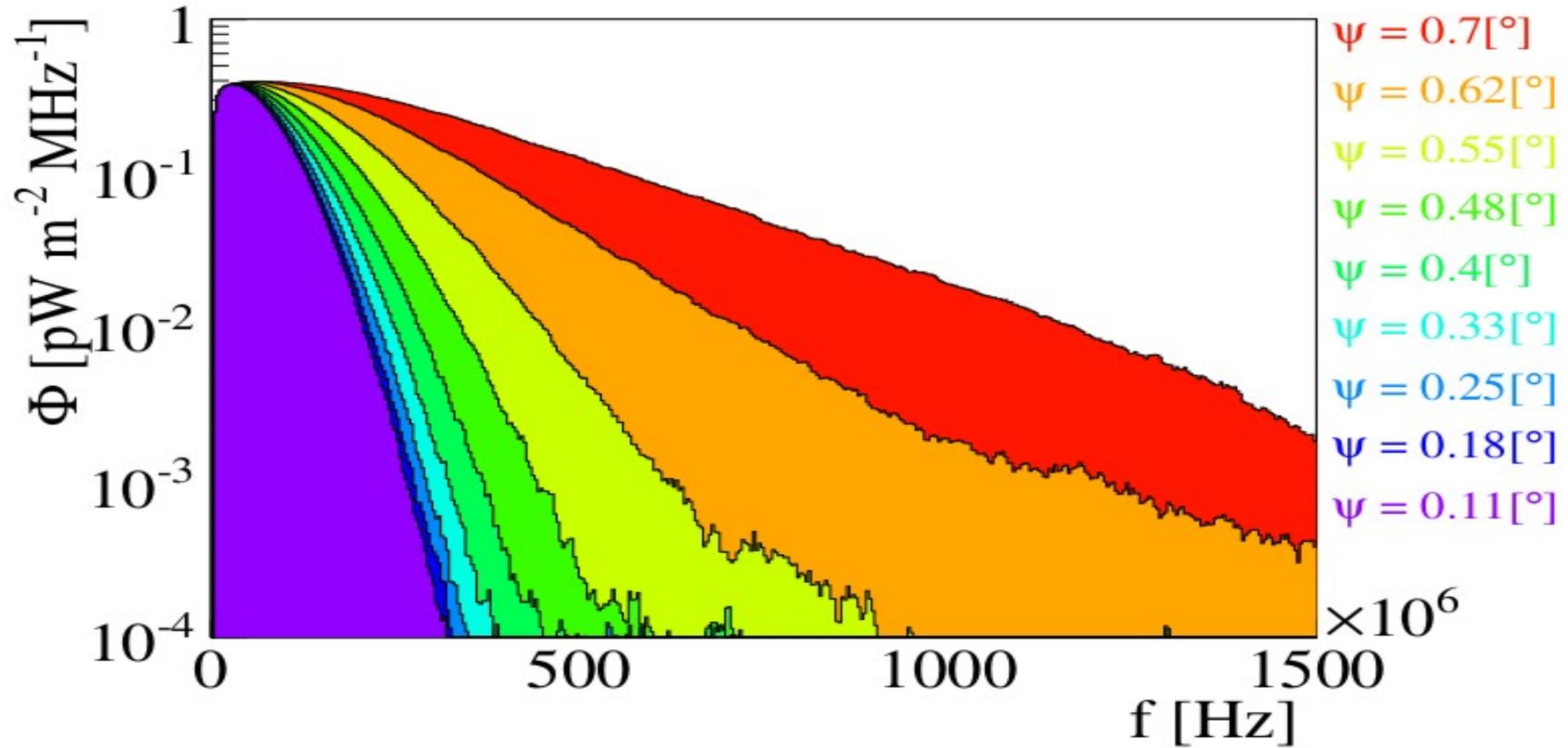
- Antennas at an  
 $h_d = 36$  km
- Ground altitude  
 $z_g = 2$  km
- Firn refractive index: 1.31
- South Pole magnetic field

- We use several primary energies and zenith angles

# Spectrum slope and off-axis angle

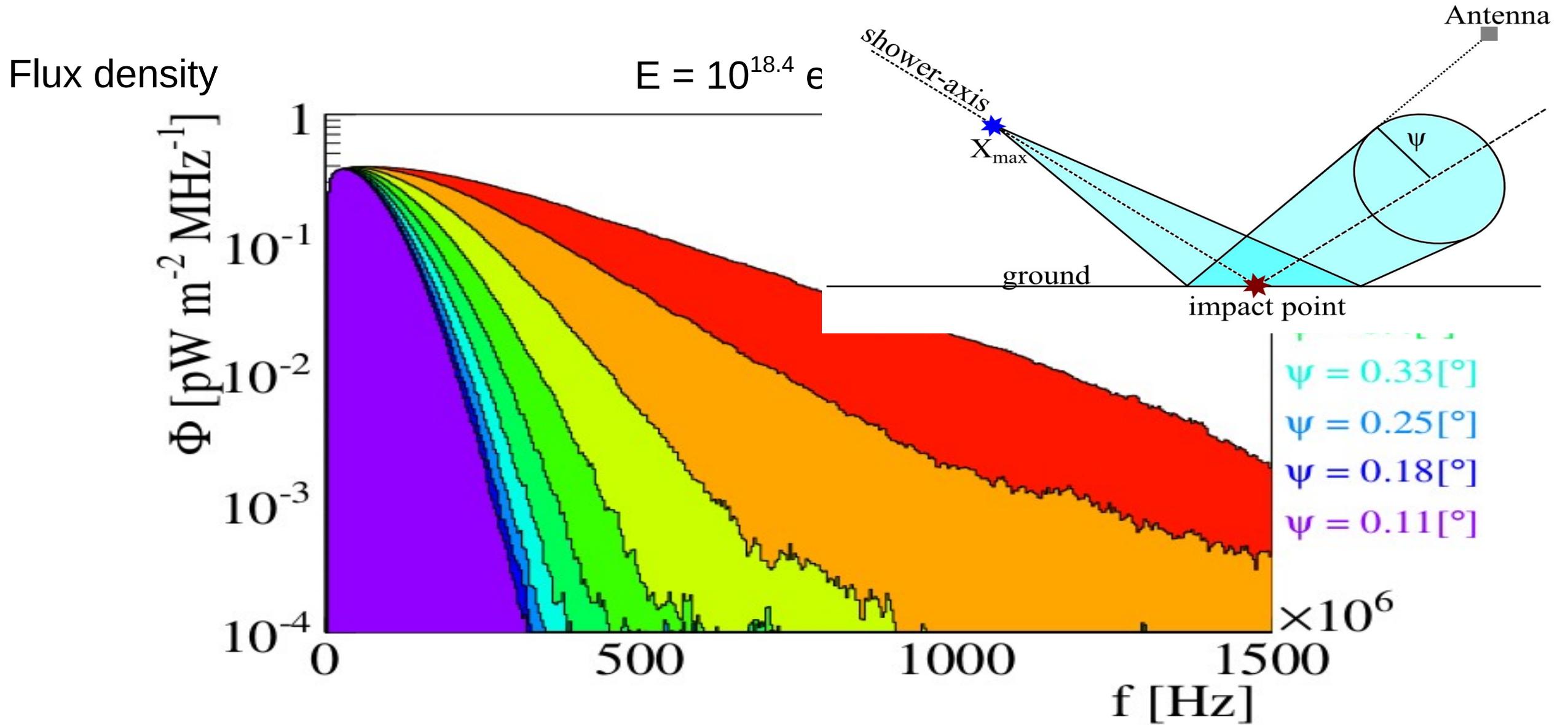
Flux density

$E = 10^{18.4}$  eV,  $\theta = 71^\circ$



Slope depends on the off-axis angle!

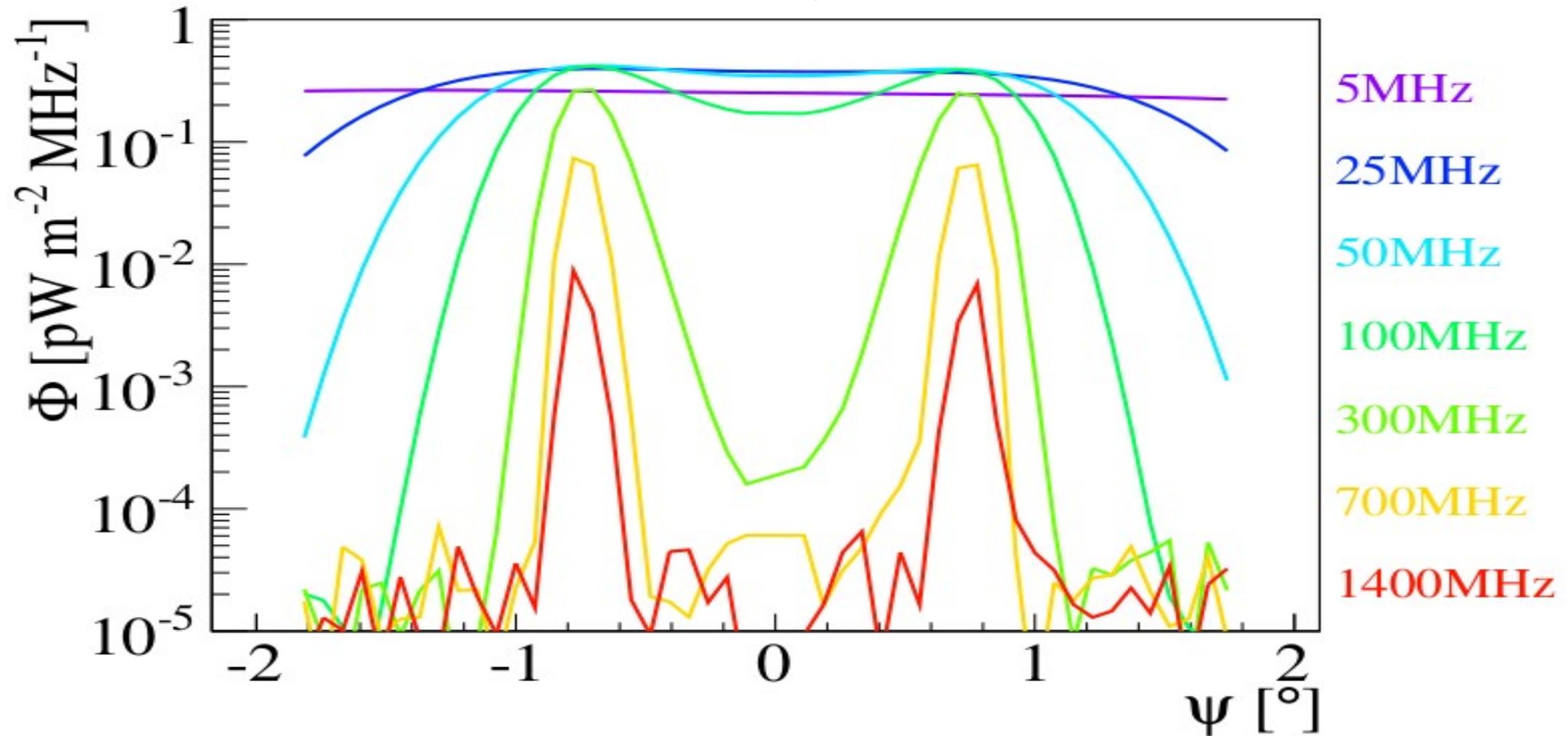
# Spectrum slope and off-axis angle



Slope depends on the off-axis angle!

# Power spectrum as a function of the off-axis

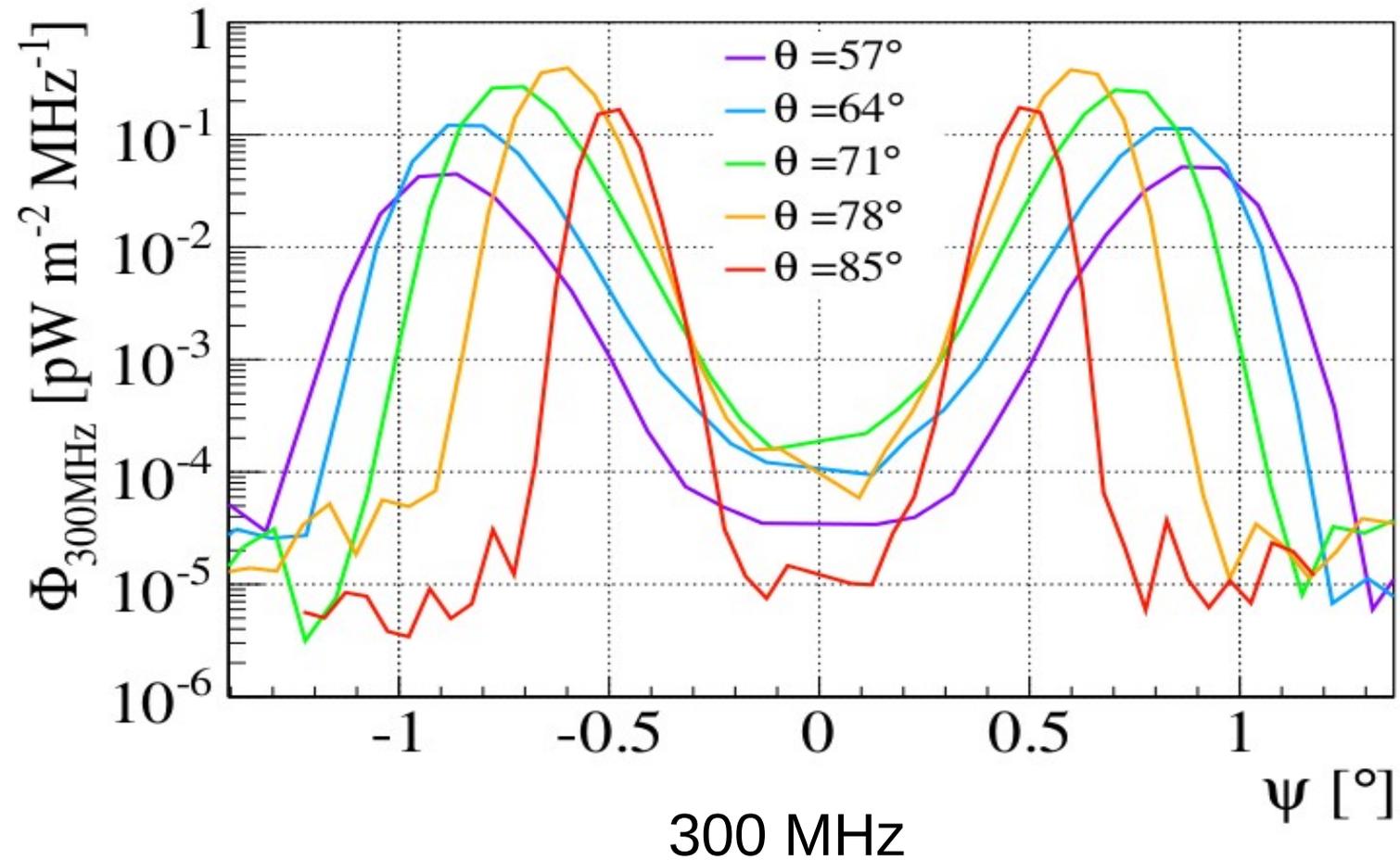
$$E = 10^{18.4} \text{ eV}, \theta = 71^\circ$$



Cherenkov region after reflection  
Diffraction-like pattern

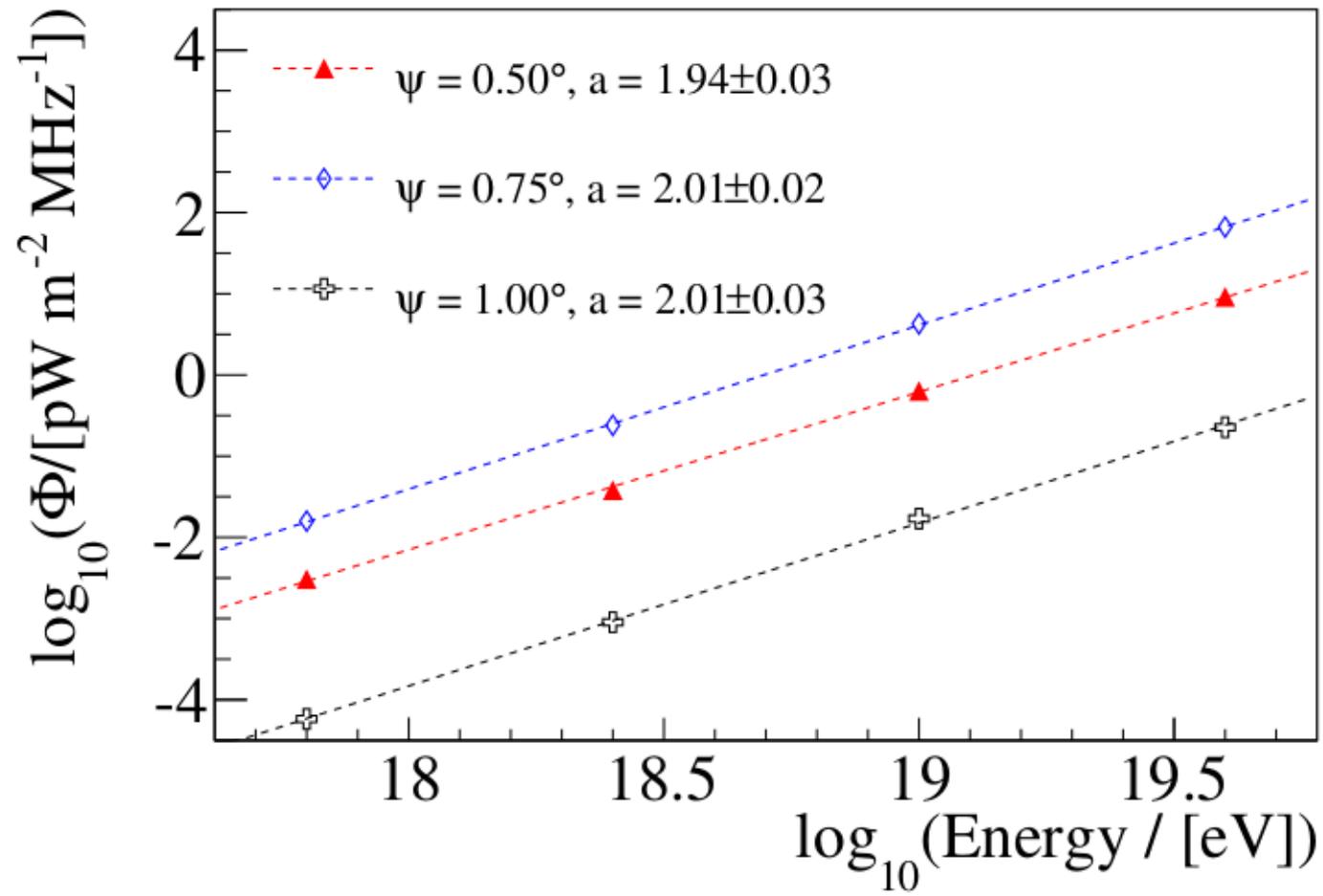
# Zenith angle dependence

- Distance favours low-zenith showers
- However, Fresnel coefficients increase with the zenith angle.
- Maximum around 80°



# Power spectrum vs energy

Quadratic relationship between radio **spectrum power** and primary **particle energy**

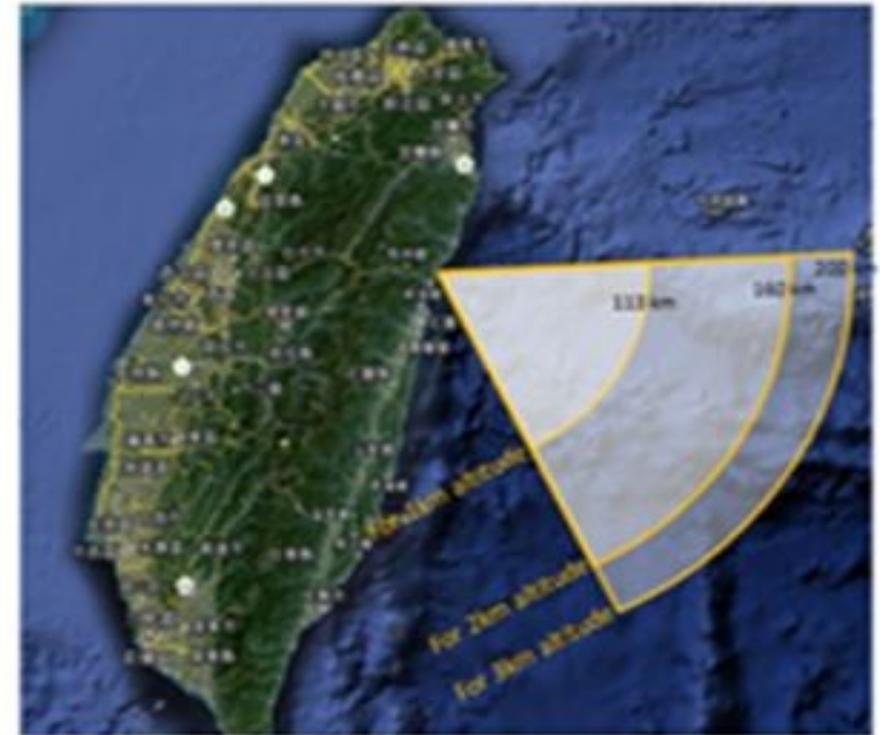
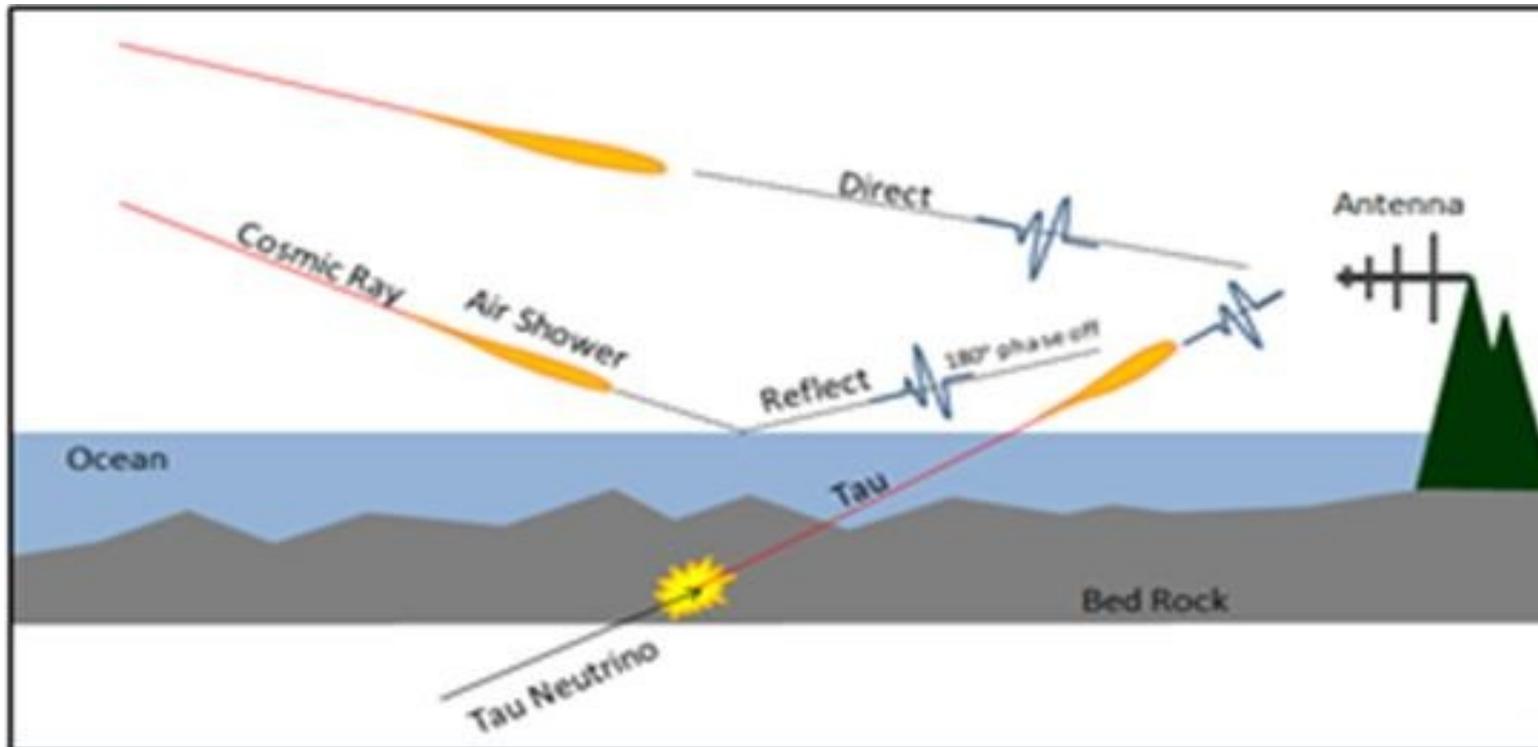


$$\Theta = 71^\circ$$

Basis for **energy** measurement. See [H. Schoorlemmer's](#) talk (proc #272).

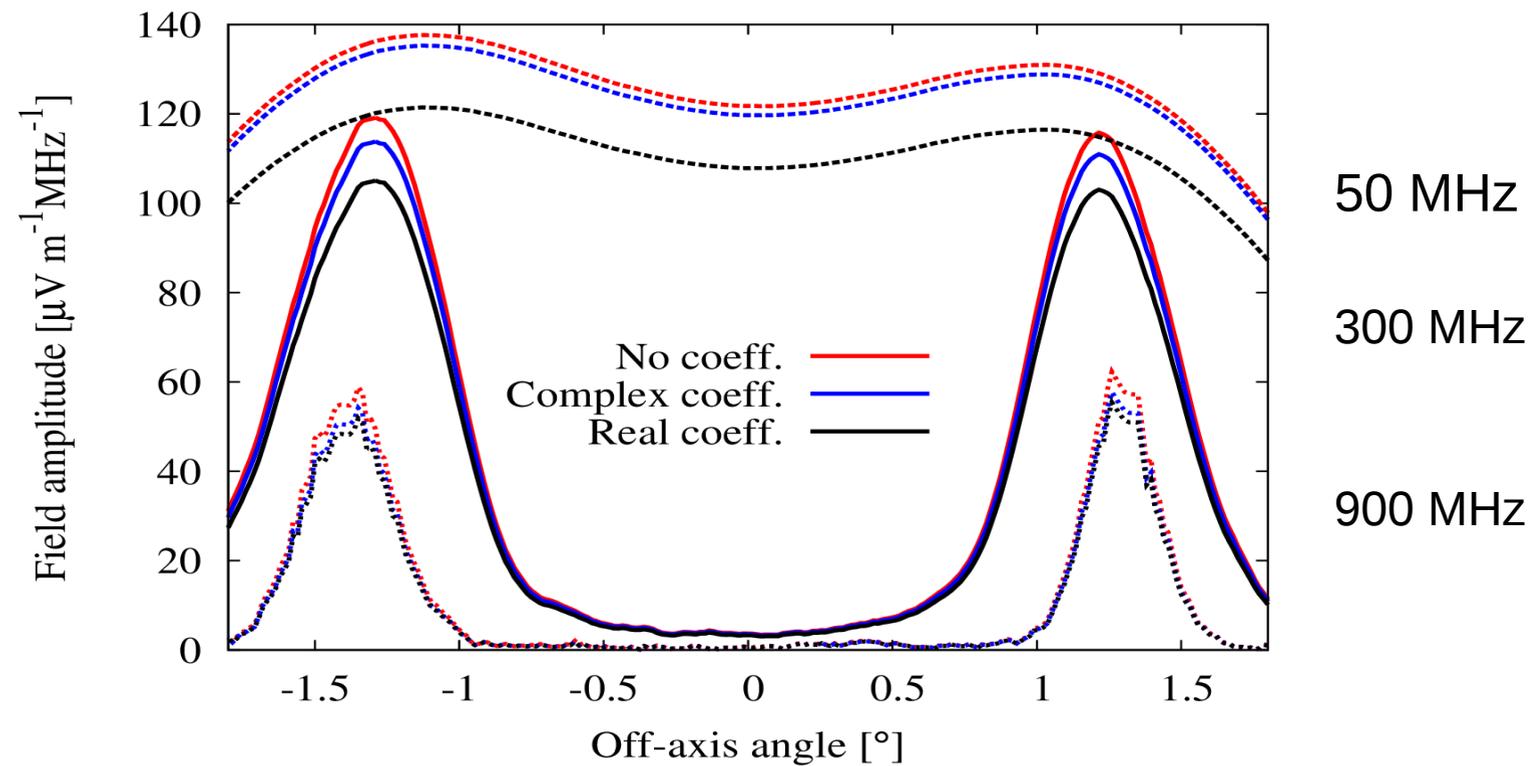
# Observatories on mountain tops: TAROGE

- Different reflective surfaces. For TAROGE, **seawater**.
- **Stogryn model** with salinity  $S = 35$  g/kg and  $T = 20$  °C.
- Similar to a medium with  $\epsilon_r \sim 69$  and  $\sigma \sim 5 \Omega^{-1}\text{m}^{-1}$



# Simulation results for TAROGE

- Seawater reflects more than ice:
  - High zenith angles
  - Low frequencies



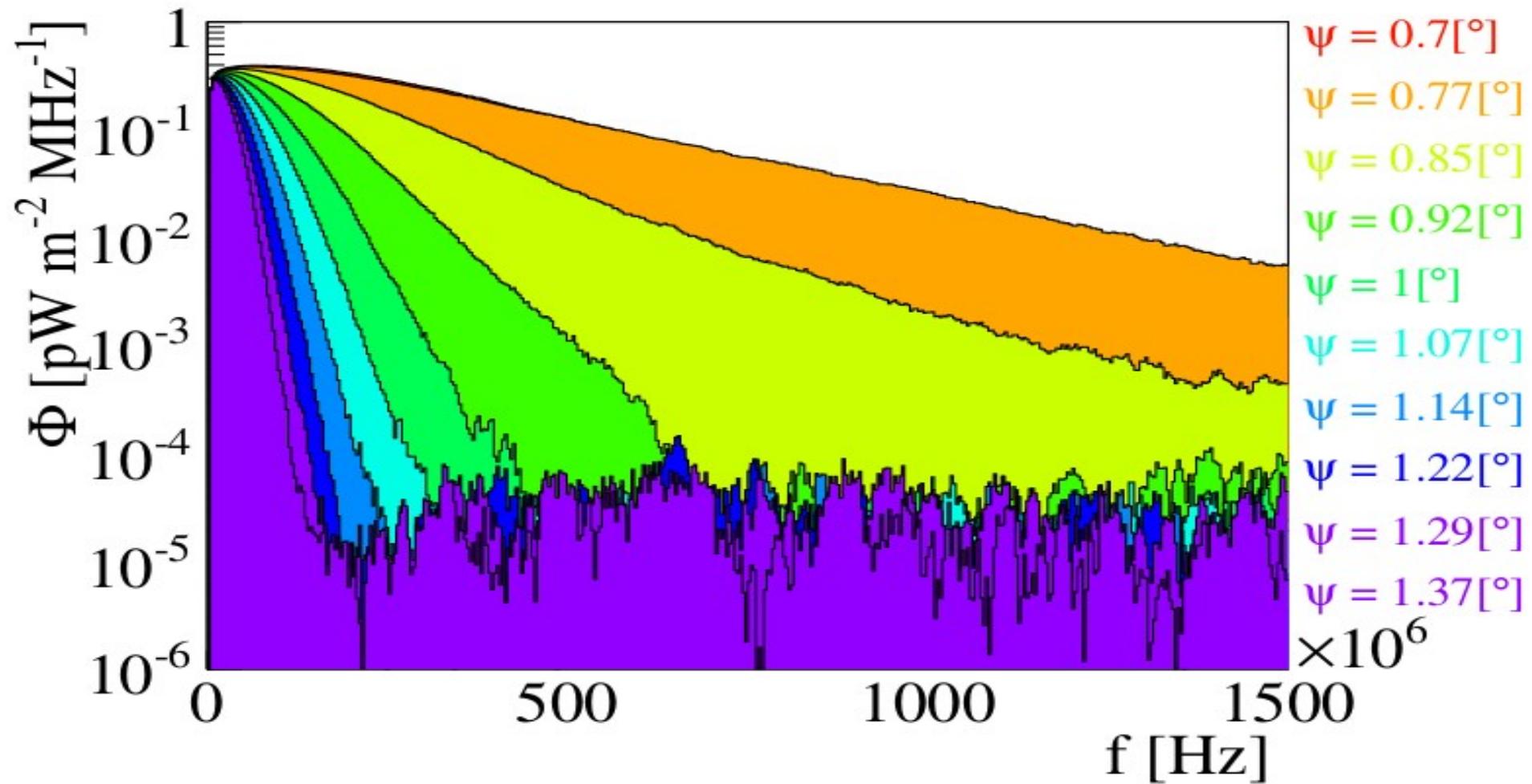
- No roughness taken into account! 1 m wave  $\sim$  750 MHz

# Summary

- ZHAireS has a **new feature** that includes **reflection**
- Applications: **Balloon**-borne antennas, **satellites**, **mountain top** observatories...
- It predicts important properties for experiments:
  - **Off-axis** dependence of the **spectrum**
  - **Scaling** of the radio flux with primary particle **energy**
  - For high-altitude balloons, large zenith angle showers are favoured
- For **mountain top** observatories with seawater as a reflecting surface, reflection is **enhanced** (for a smooth surface)

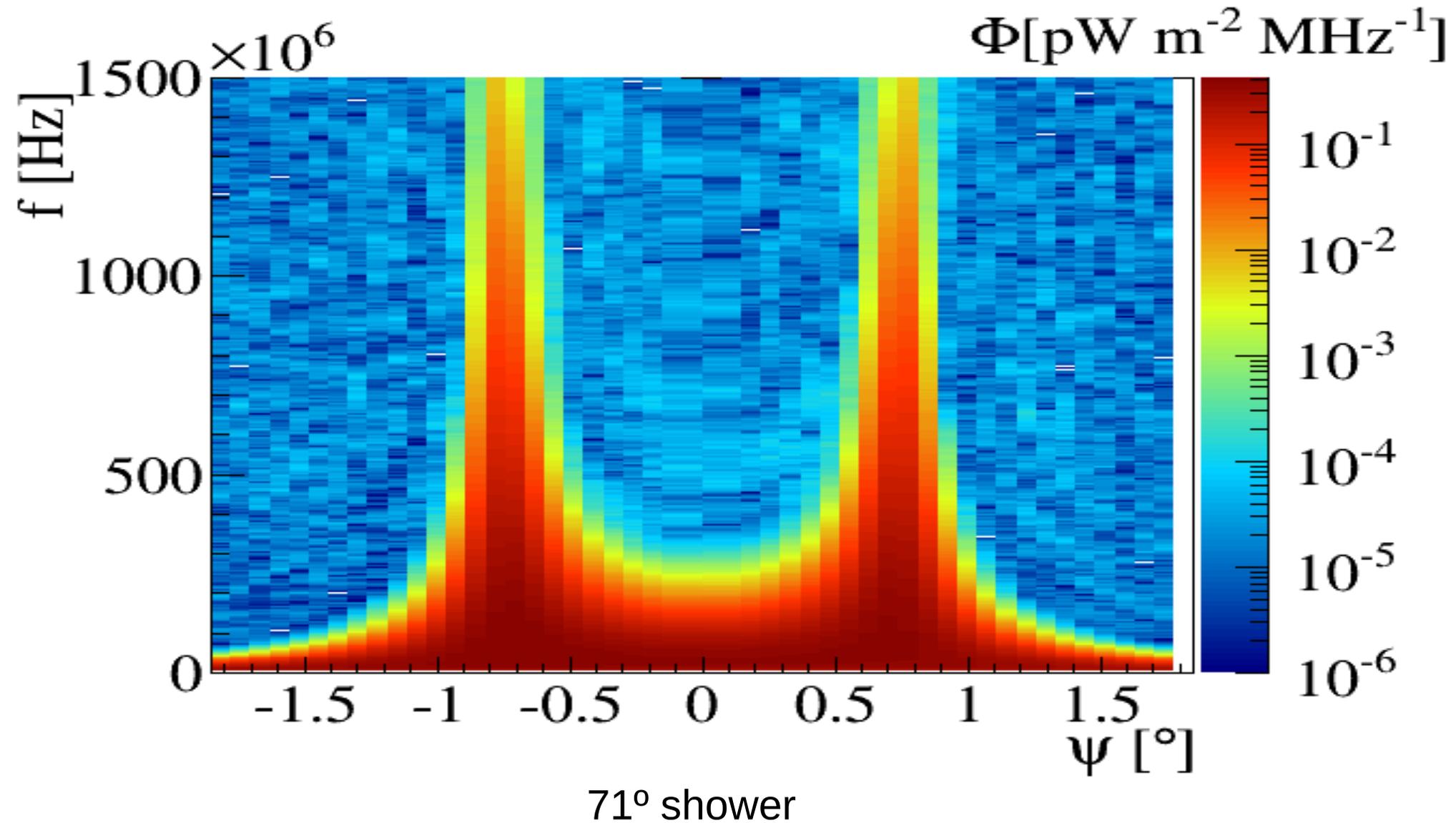
Thank you for listening

# Spectrum outside the Cherenkov cone



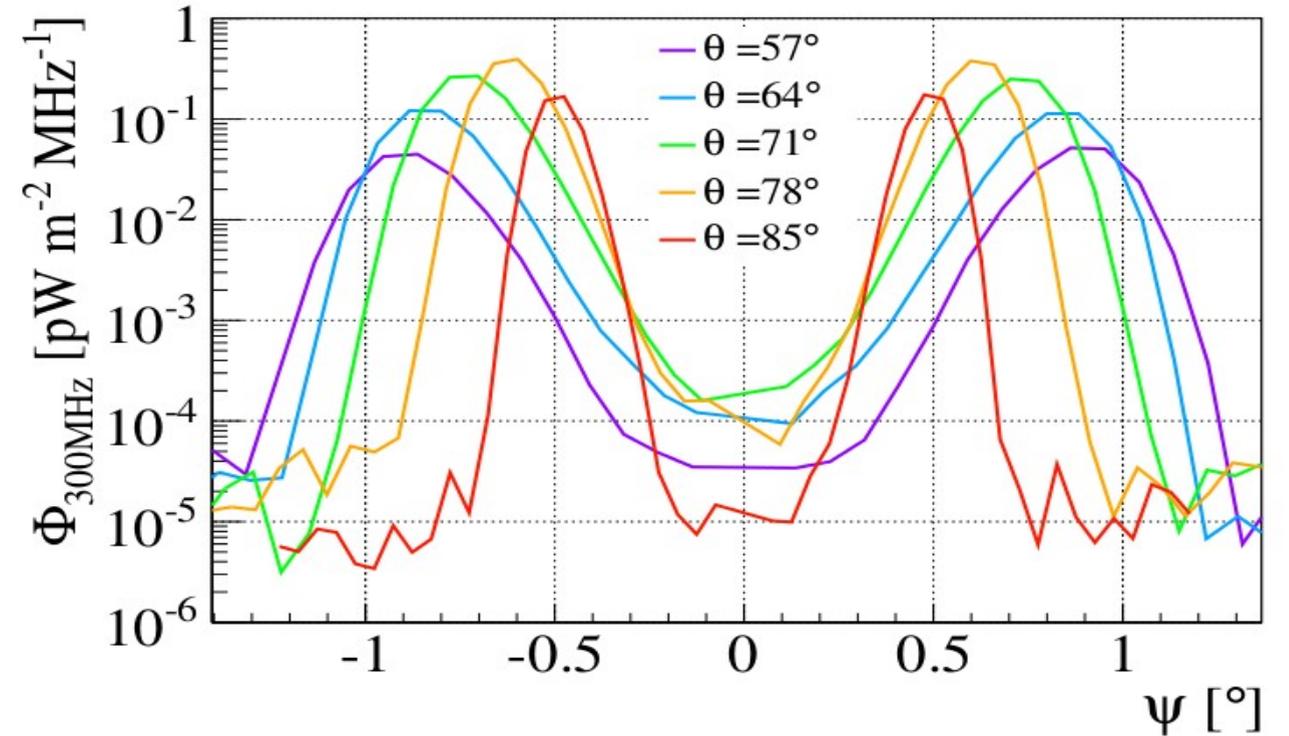
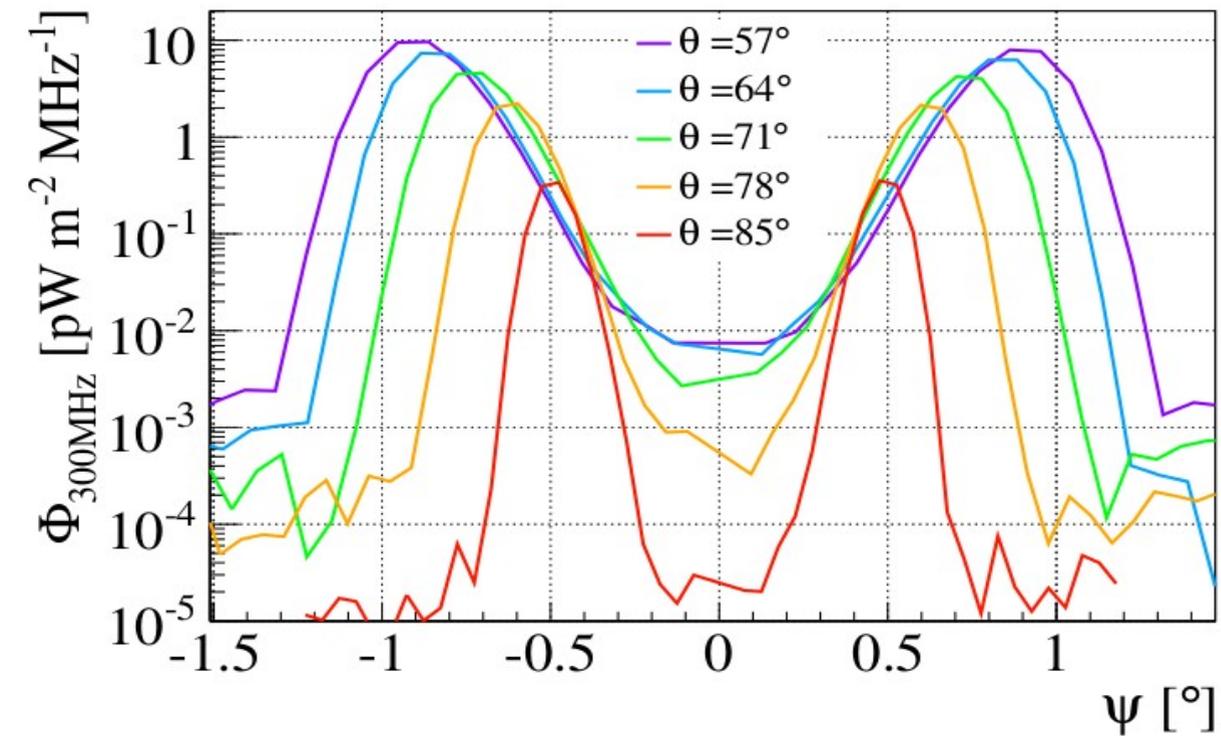
71° shower

# 2D plot for the electric field lateral distribution



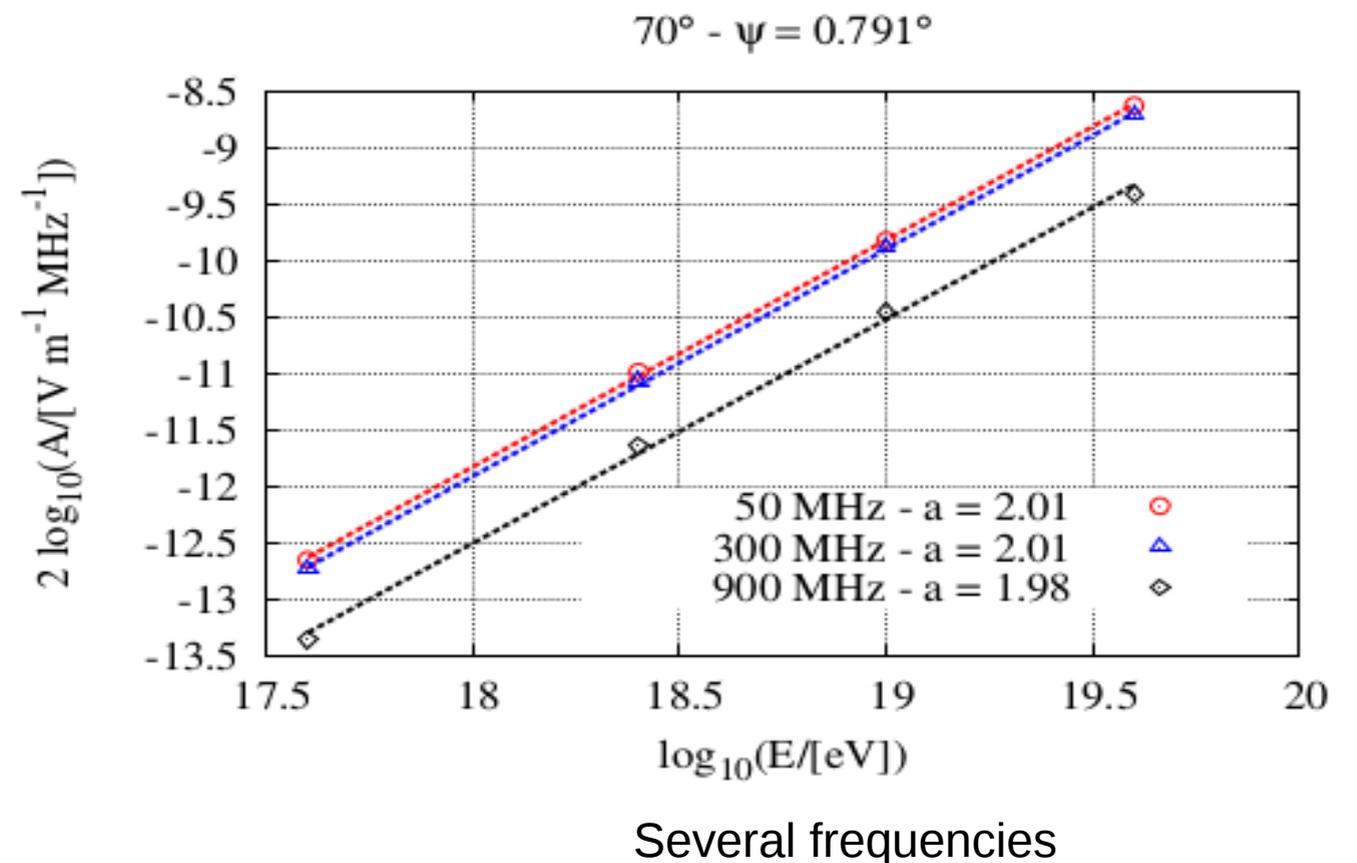
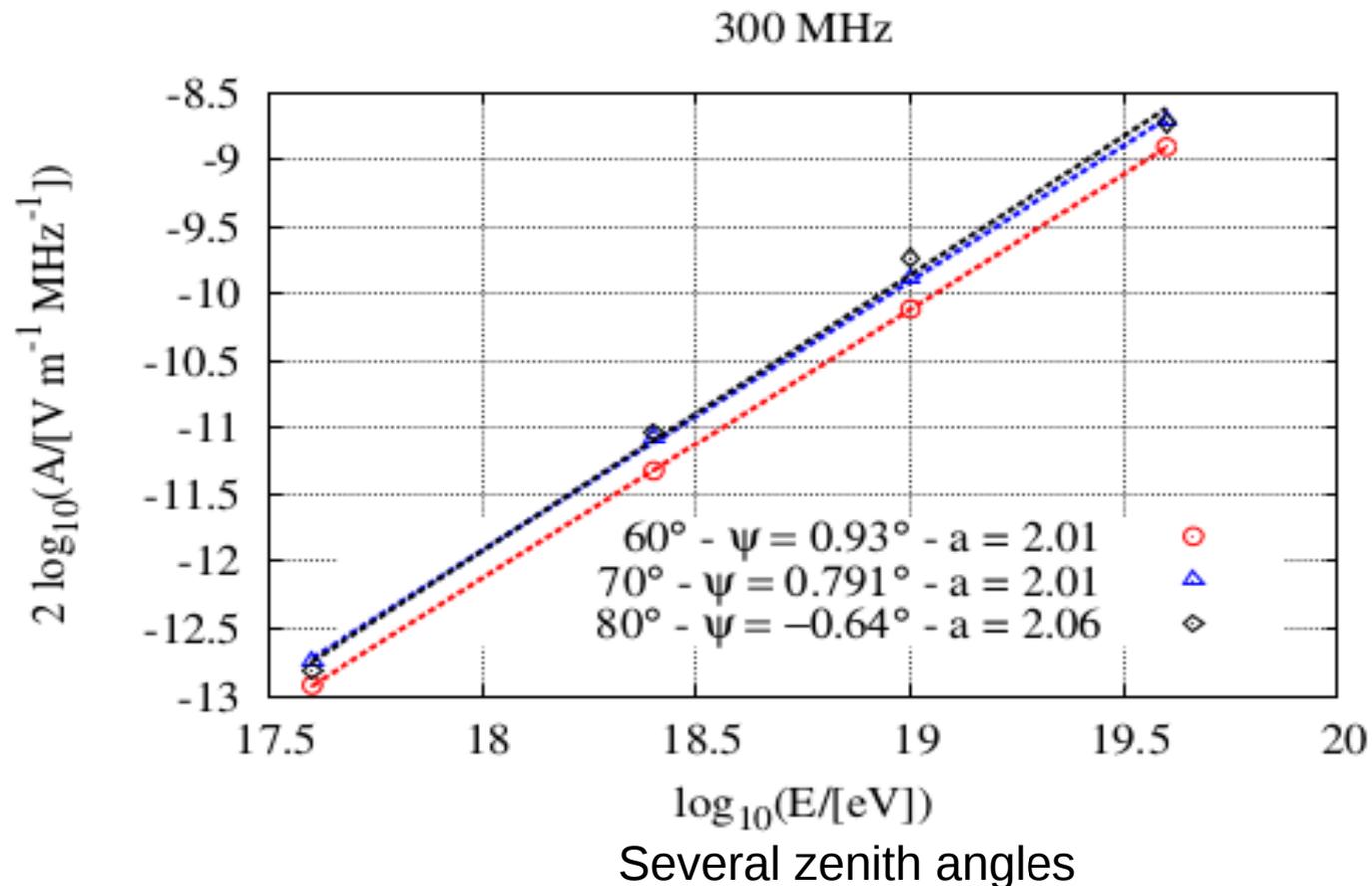
# Zenith angle with vs without coefficients

- Distance favours low-zenith showers
- However, Fresnel coefficients increase with the zenith angle.
- Maximum around  $80^\circ$

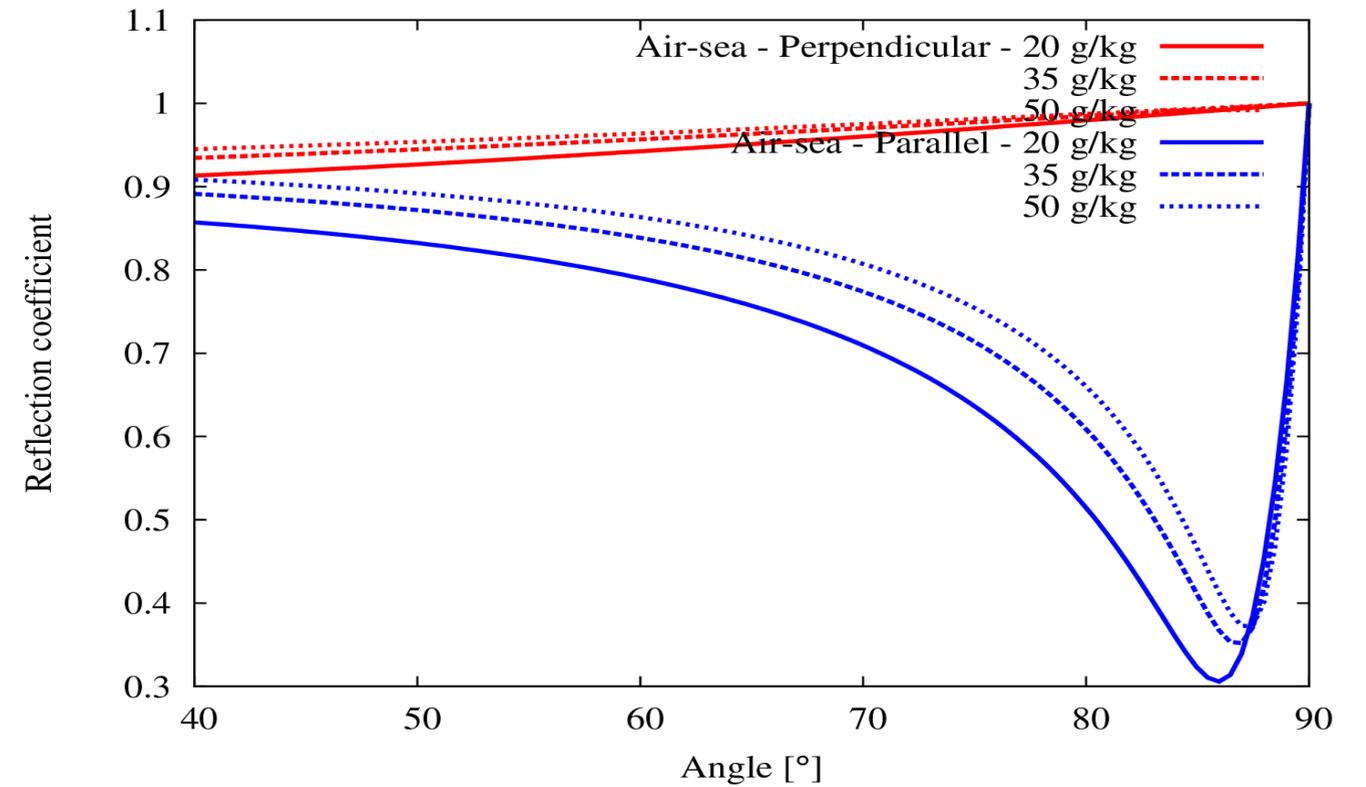
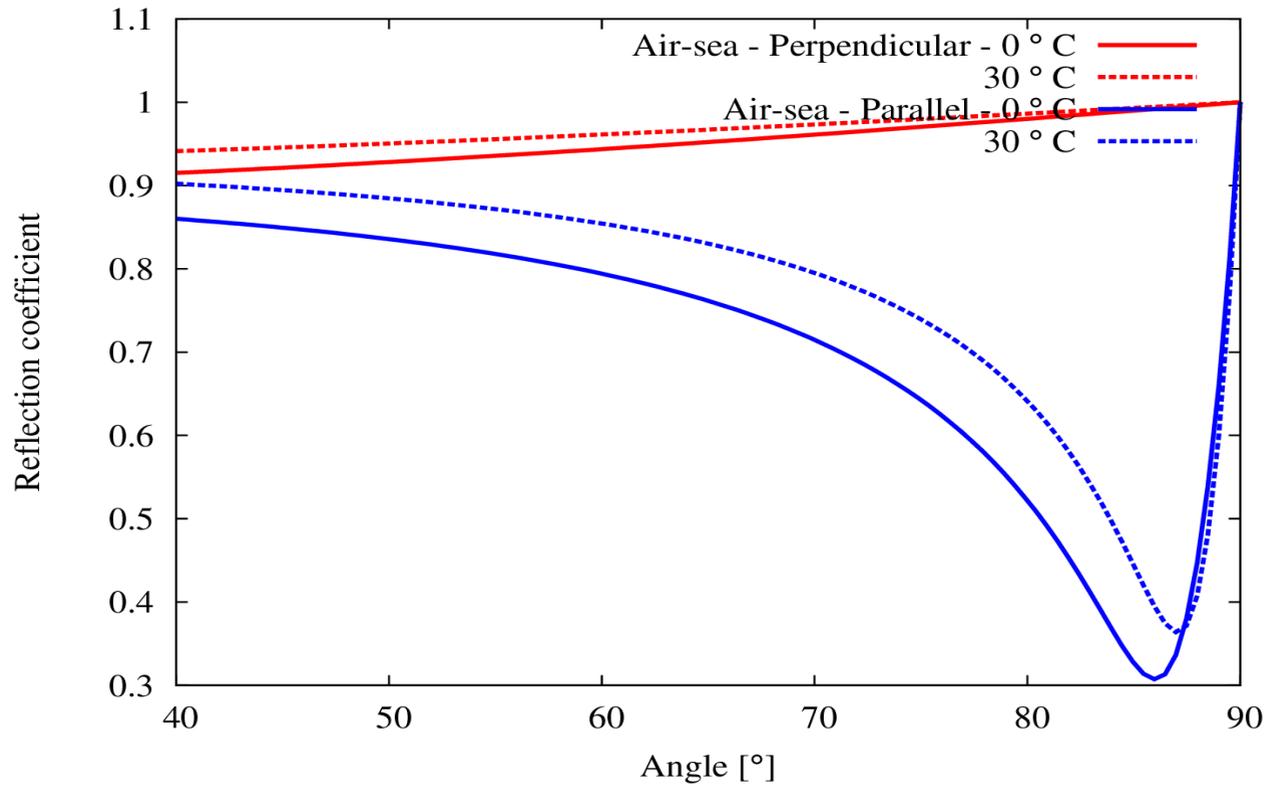


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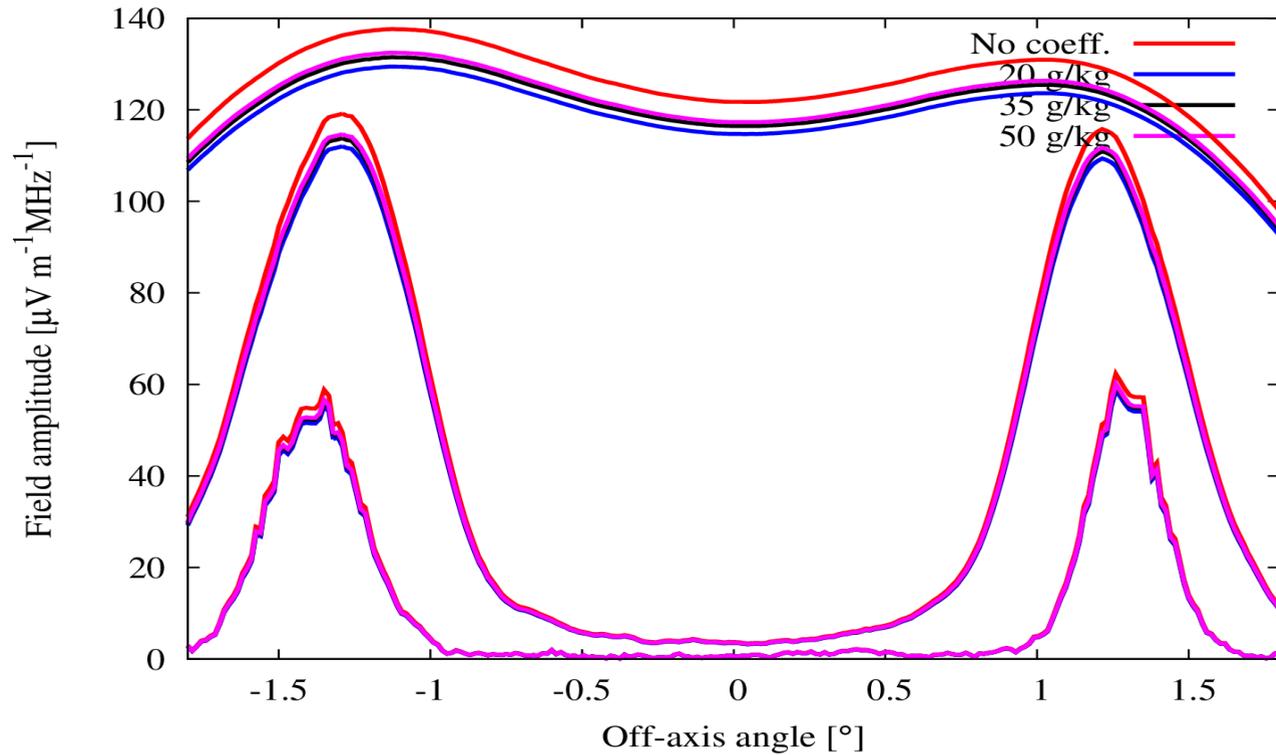
- Quadratic relationship is **maintained** for several shower angles, off-axis angles and frequencies.
- **Critical** for energy measurements with radio. See Harm Schoorlemmer's talk.



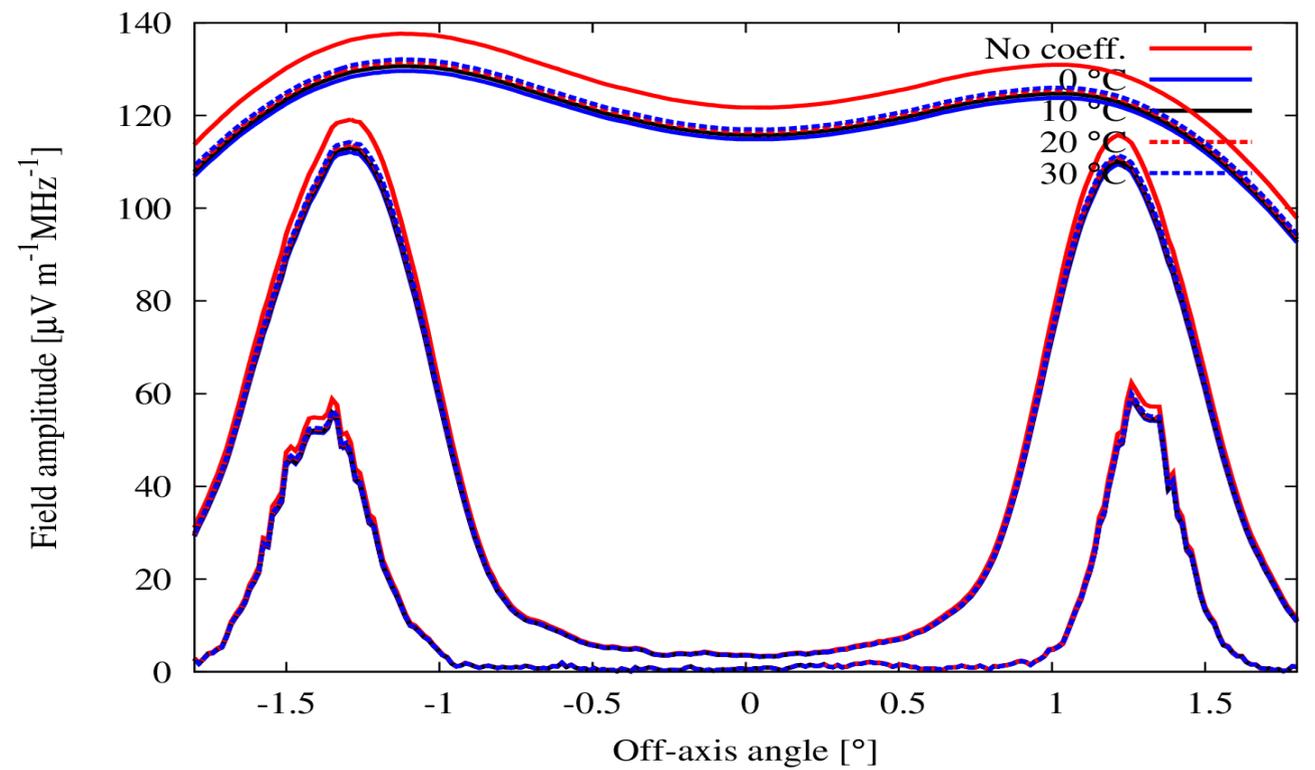
# Fresnel coefficients: salinity and temperature



# Variation of the electric field with temperature and salinity - $60^\circ$

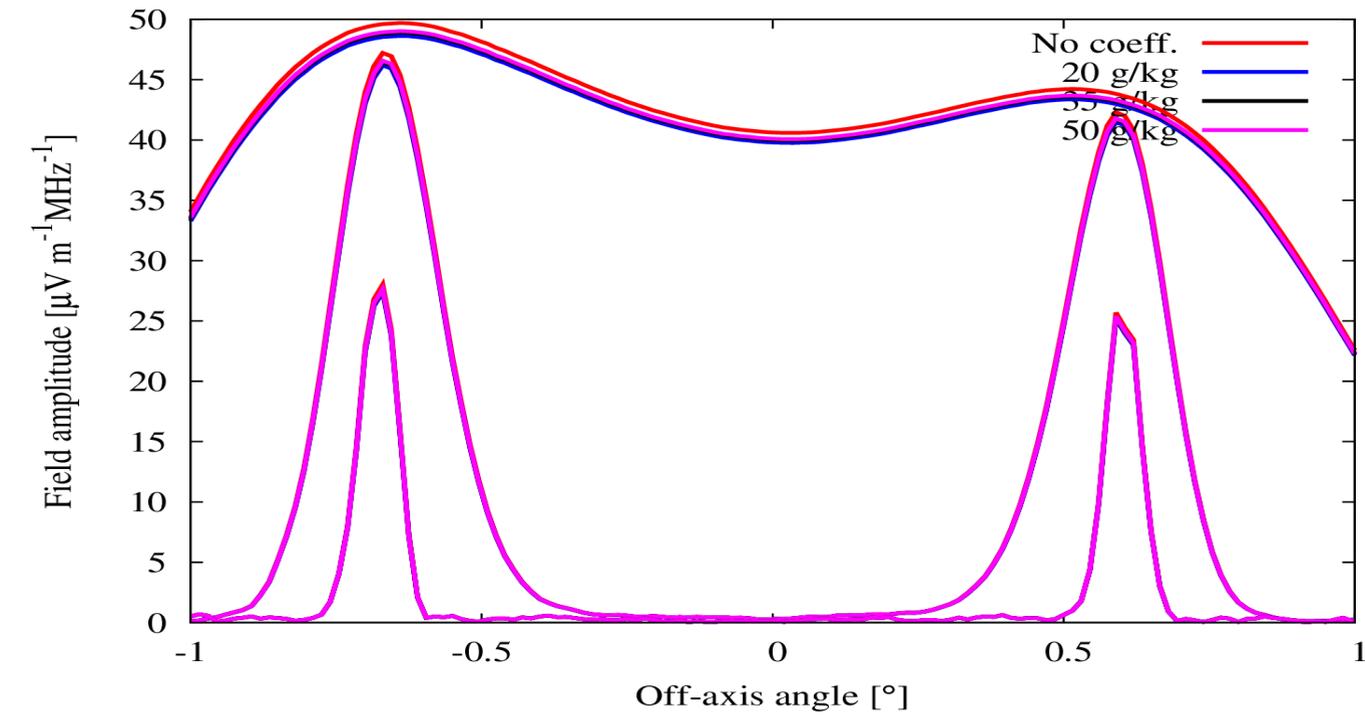


$60^\circ$  – Variation with salinity

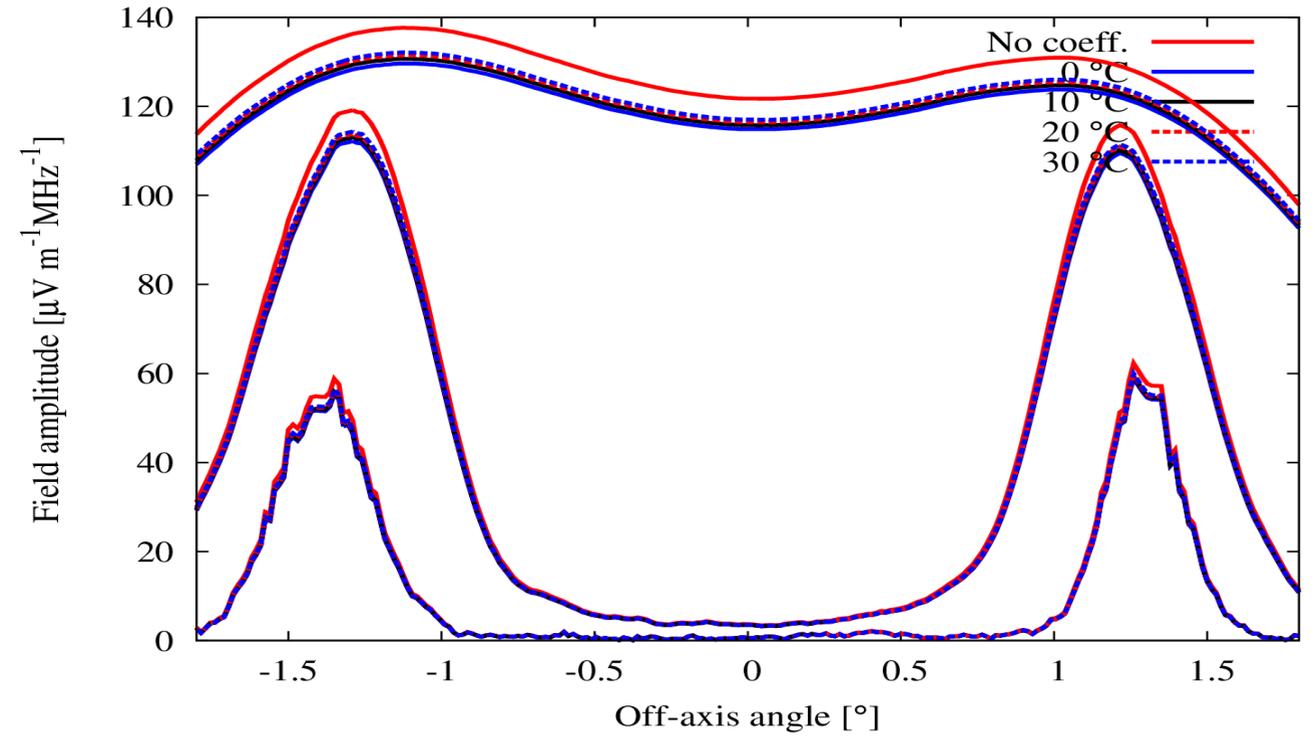


$60^\circ$  – Variation with temperature

# Variation of the electric field with temperature and salinity - $80^\circ$



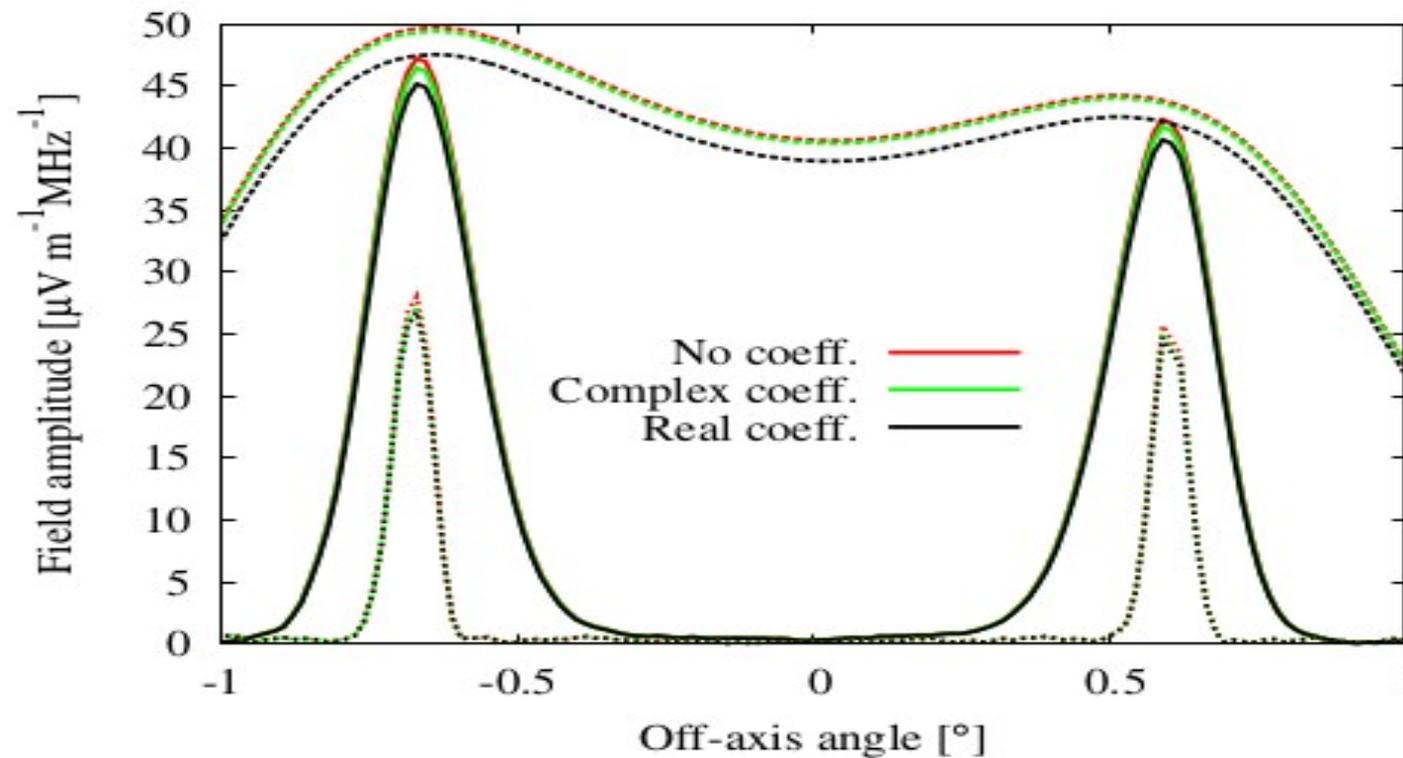
$80^\circ$  – Variation with salinity



$80^\circ$  – Variation with temperature

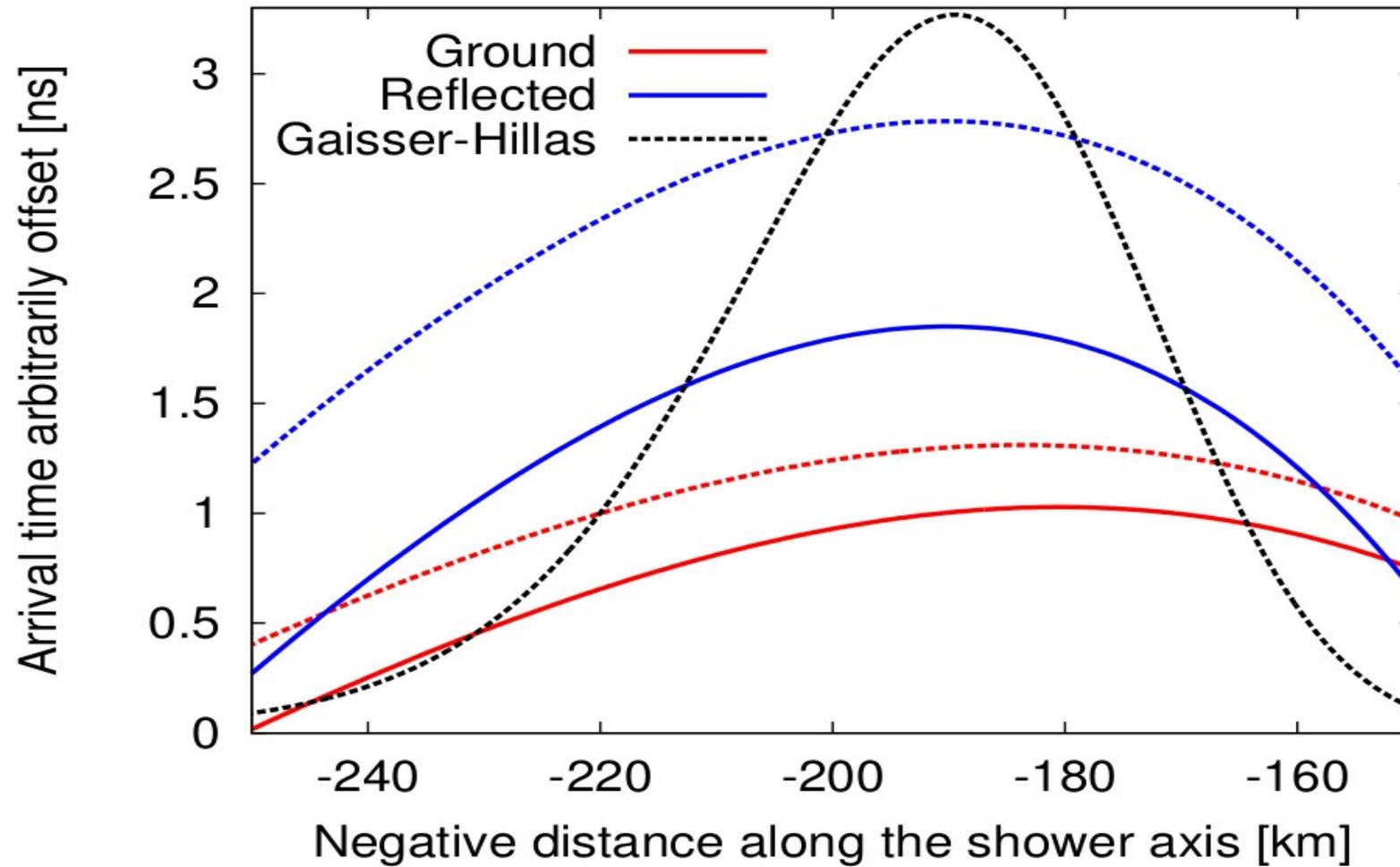
# Simulation results for TAROGE

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  - Low frequencies
- No roughness taken into account! 1 m wave ~ 750 MHz



80° shower

# Straight vs curved rays

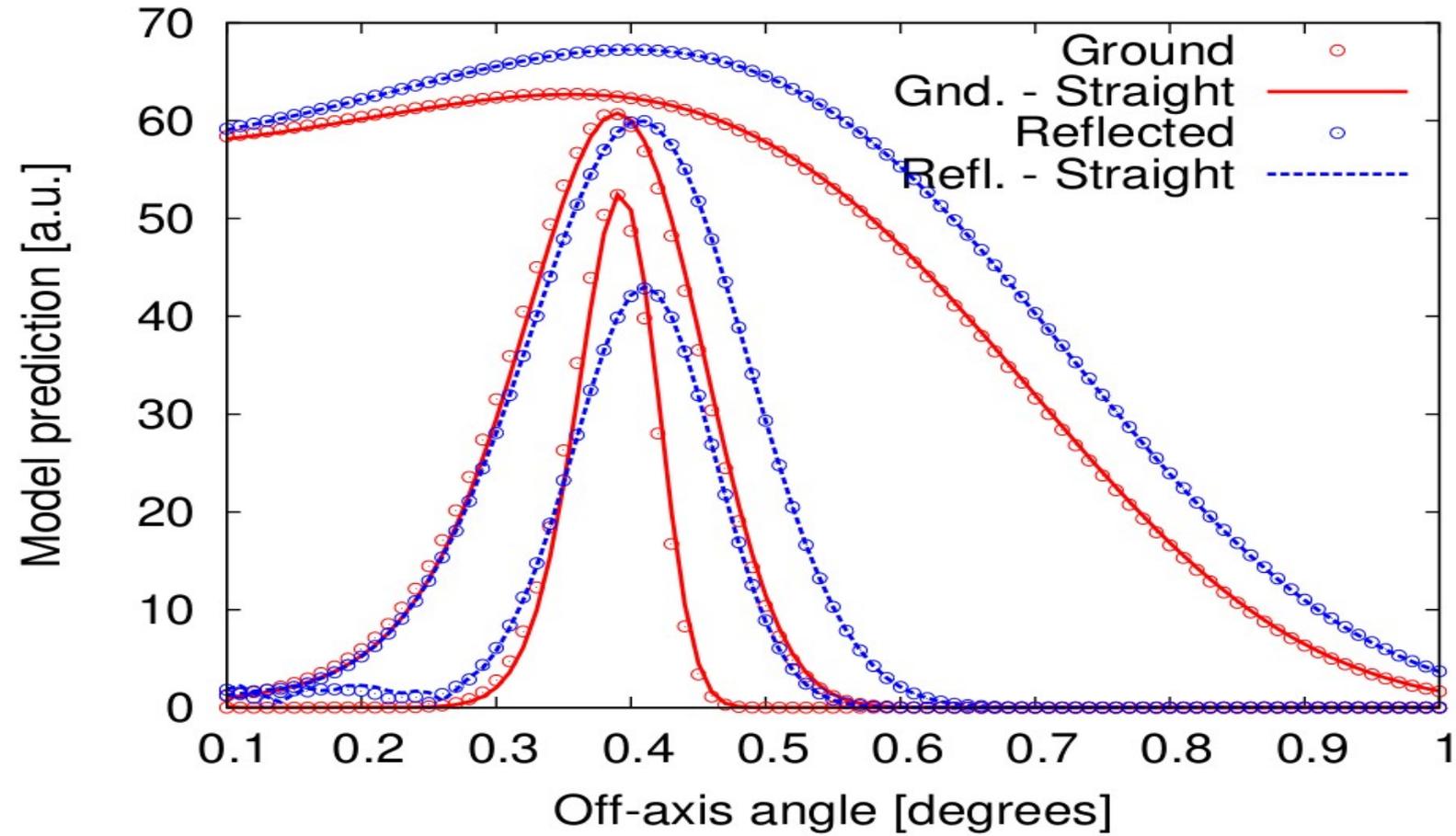


Payload at 50 km of altitude:  
20 ps of offset difference ~  
12.5 GHz maximum

Ground: 200 ps of offset  
difference ~ 1.25 GHz  
maximum

$$\Theta = 85^\circ$$

# Straight vs curved rays



$$\Theta = 85^\circ$$