Simulating radio signals from cosmic-ray showers reflecting from a surface (ZHAireS-reflex)

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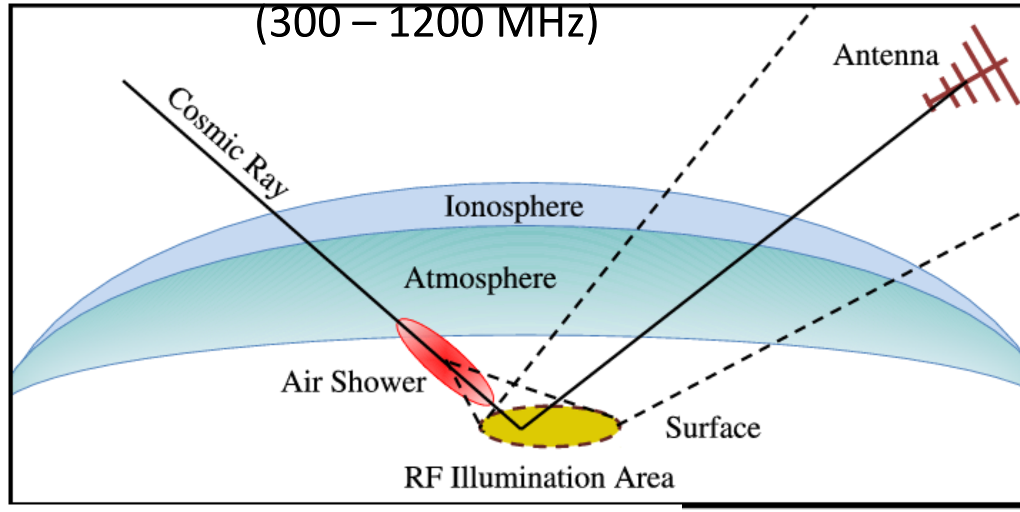
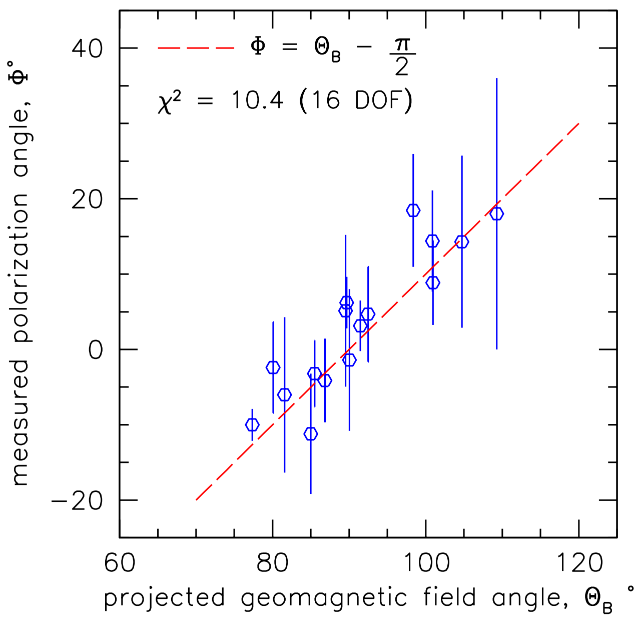
Motivation: UHECR radio detection from high altitudes

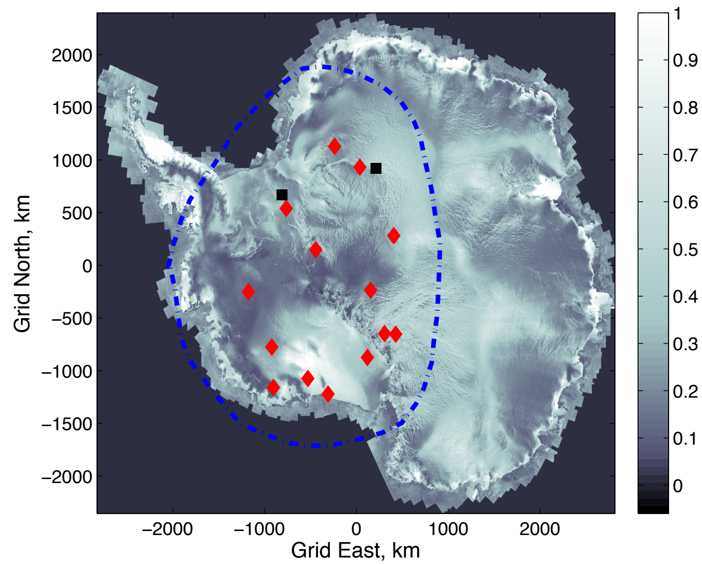
Triggered interest by ANITA

- 16 UHECR Events, 14 reflected
- Compatible with geomagnetic mechanism (correl. with B-field)
- Coherence unexpected at GHz! But simulations give it!

Also: ExaVolt, Sword, ...



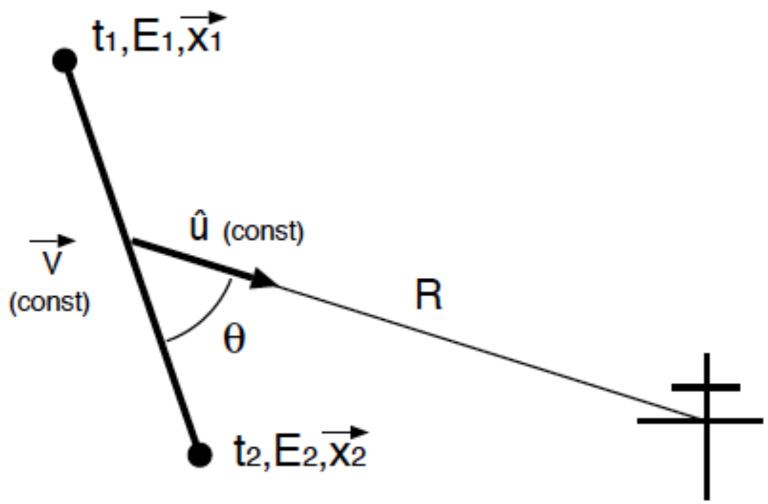




ANITA Collaboration, Phys. Rev. Lett. 105 (2010) 151101

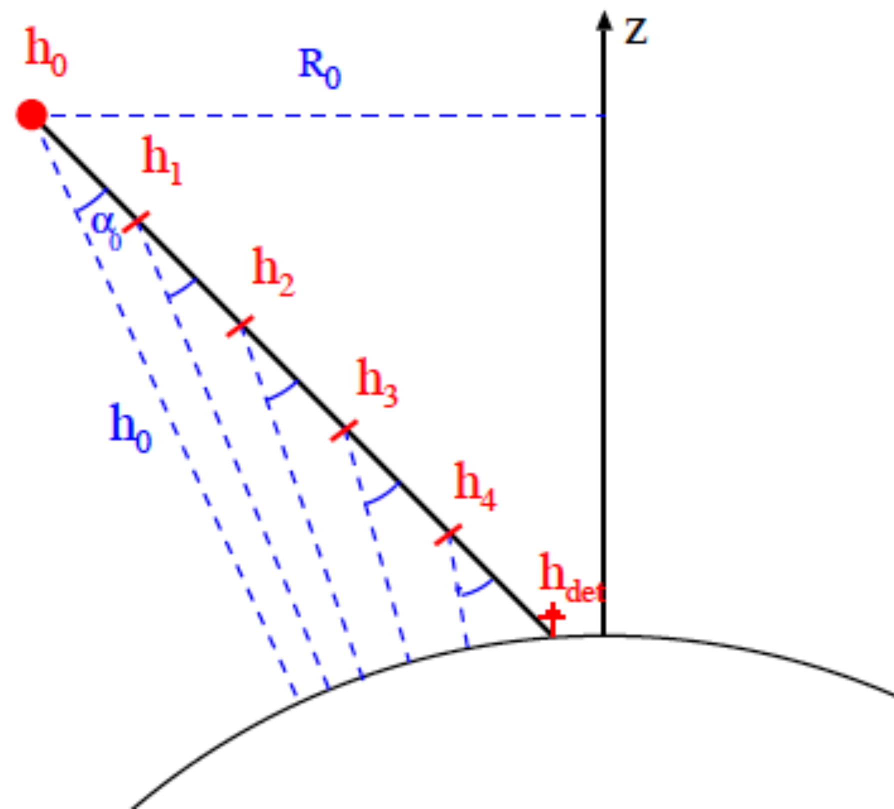
ZHAireS: Marriage of Aires +ZHS formalism (2011)

- **ZHS "**algorithm" 1990 H.R. Allan 1971:
  - Numerical solution of Maxwell's Eqs. (No assumptions on mechanisms)
  - Superposition of contributions from discretized e+ & e- tracks

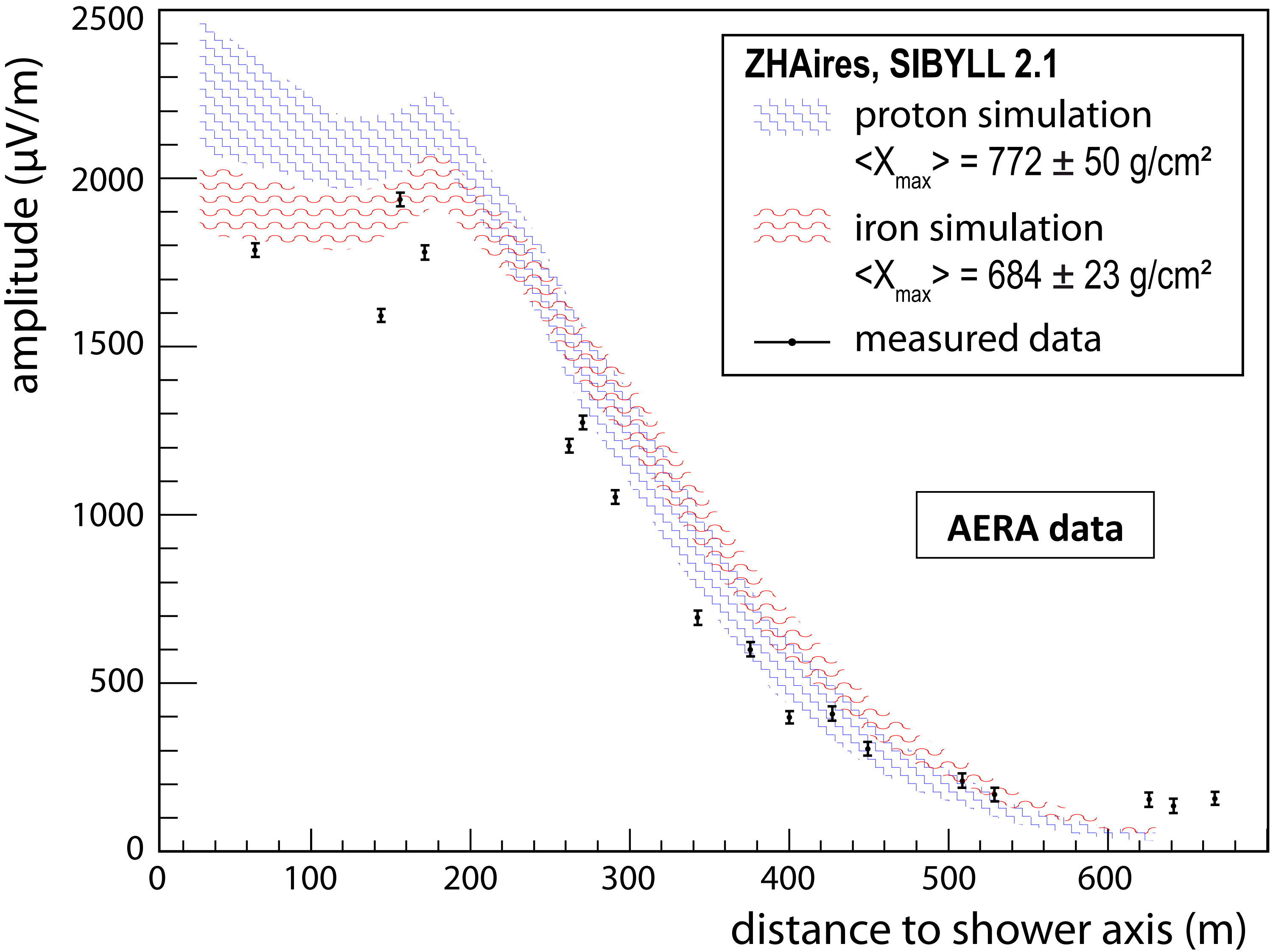


  - ω-domain (1990): terms $e^{i\omega(t+nR/c)}$
    t-domain (2010): travel times->widths
  - Realistic treatment of travel times: variable refractive index n(h) in curved atmosphere (relevant for θ > 80^0)
  - Approximate light rays by straight lines

- **Aires** flexibility:
  - Different primaries (p, Fe, ν,…), energies, directions,…
  - Many hadronic interaction models.
  - Different atmospheres, sites on Earth
  - also works in dense media.



Tested against data



Calculated radiation features:

- Cherenkov cone formed from density at X_{max}
- Cherenkov angle is very small
- Large time compression ➔ sharp buildup of vector potential
- Lateral distribution does not spoil coherence because of small Cherenkov angle
- Coherent signal even at frequencies above 1 GHz
- Qualitative behavior can be partly understood as 1D current moving with the shower front:

$$E \sim \int dt N(t) \frac{e^{i\omega\left(t+\frac{n}{c}r(t)\right)}}{r(t)}$$

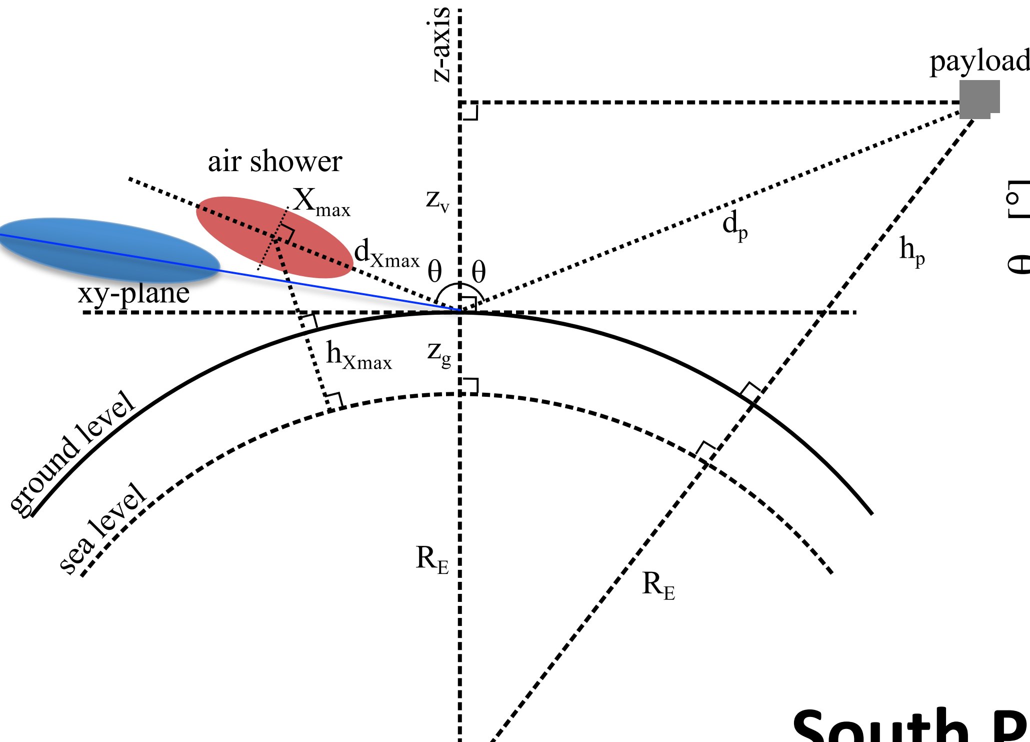
New features to "ZHAireS-reflex"

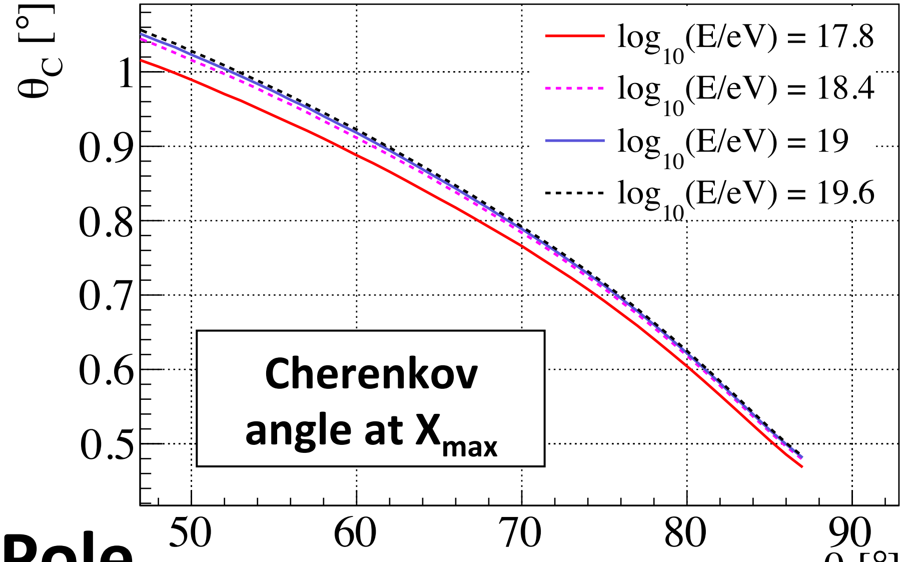
- Modified version of ZHAireS to:
  - calculate radio emission at high altitude after reflection
  - include effect of Fresnel coefficients

- Assumptions:
  - straight "light-ray" propagation (next slides)
  - reflection on flat surface (radio pool is < 30 km radius at θ < 86 deg.)
  - no roughness of reflection surface (see J. Stockham talk at this meeting).

- For each shower particle track:
  - Reflection point on ground leading to payload calculated
  - Contribution → realistic time delays: track to ground & ground to detector
  - Fresnel field reflection coefficients accounted for each contribution

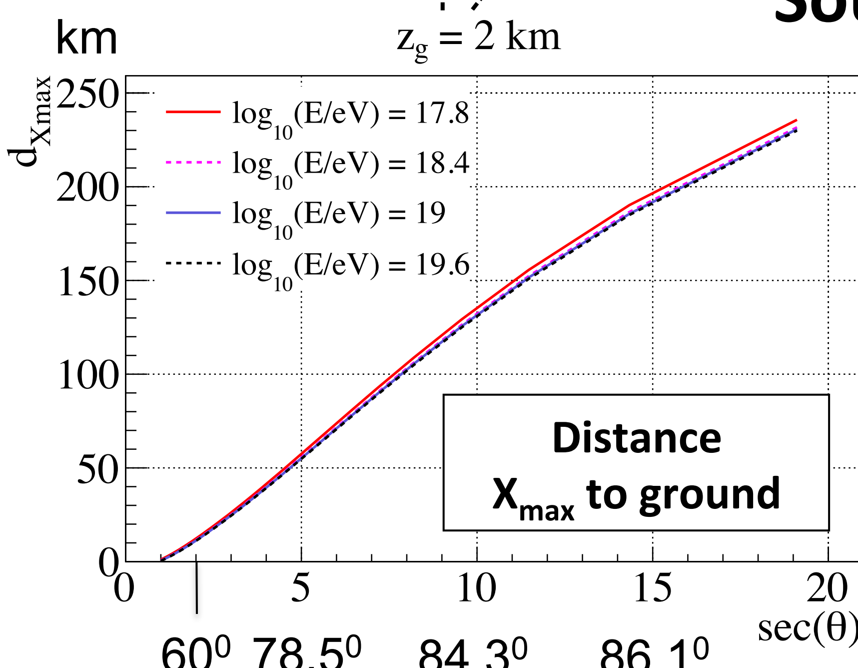
Extreme geometry



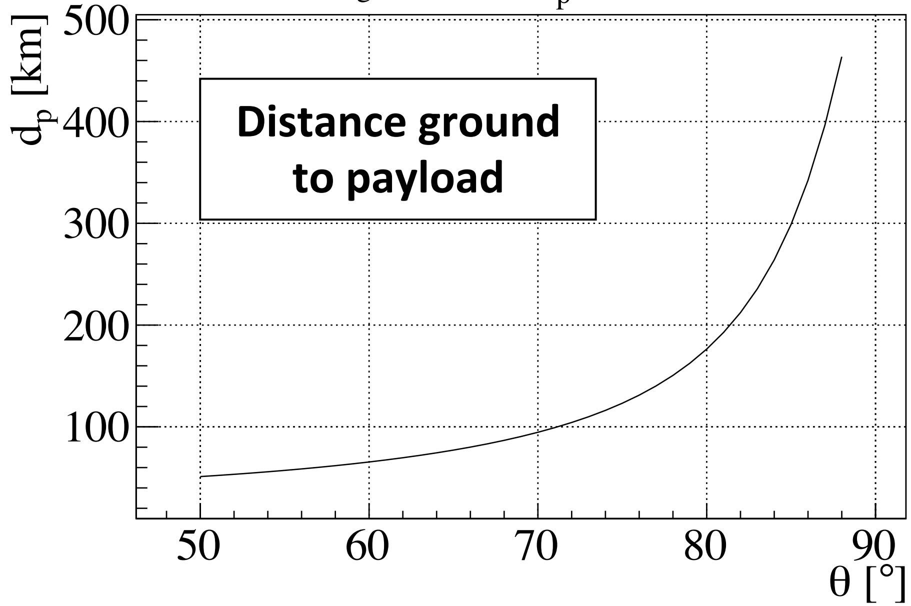


South Pole

$z_g = 2$ km



$z_g = 2$ km, $h_p = 35$ km

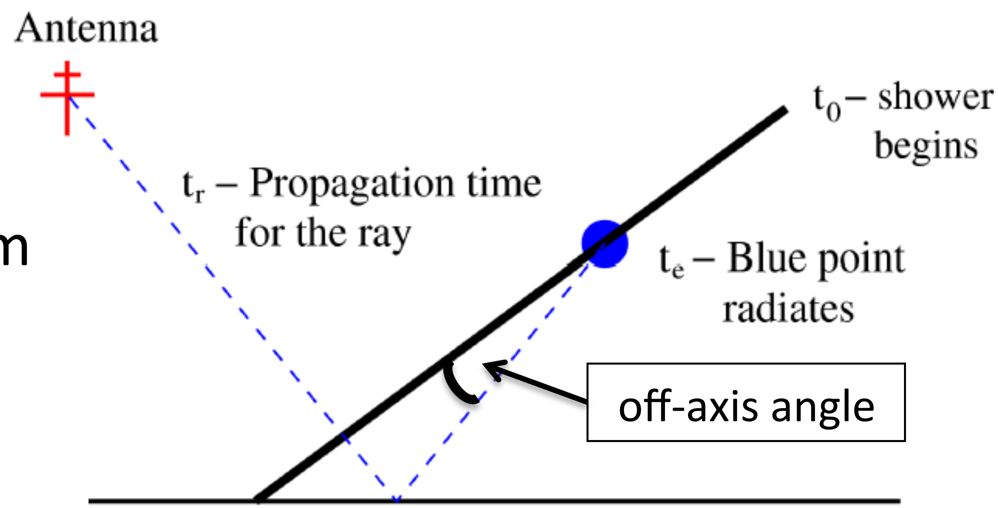


Straight versus curved "rays"

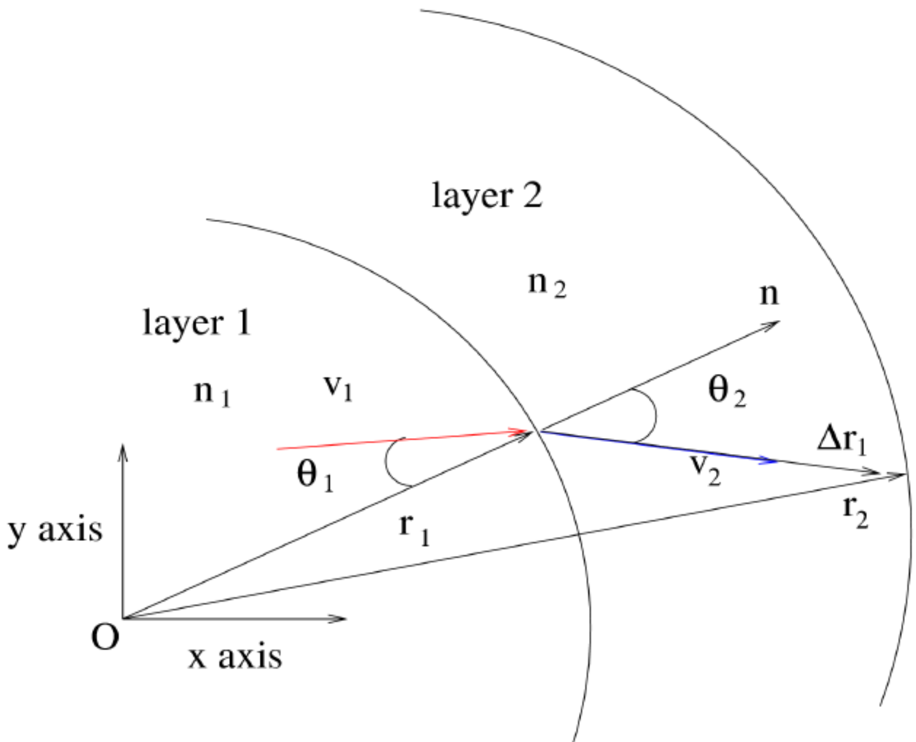
Use qualitative model in 1D:

$$E \sim \int dt N(t) \frac{e^{i\omega(t_e+t_r)}}{r(t)}$$

$$t_a = t_e + t_r$$



and simple ray-tracing algorithm

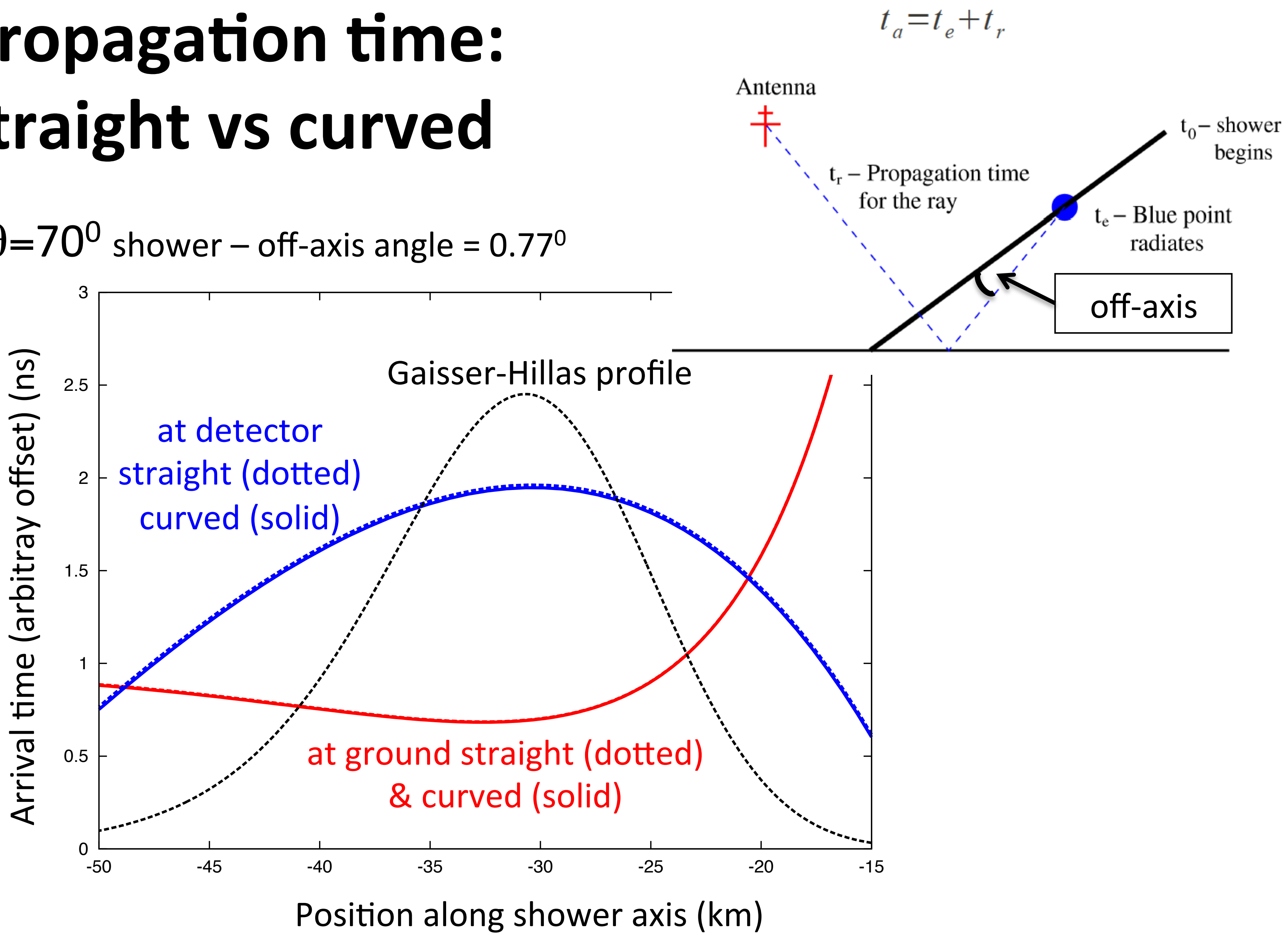


Compare calculations using t_r with

- straight propagation
- curved propagation

propagation time: straight vs curved

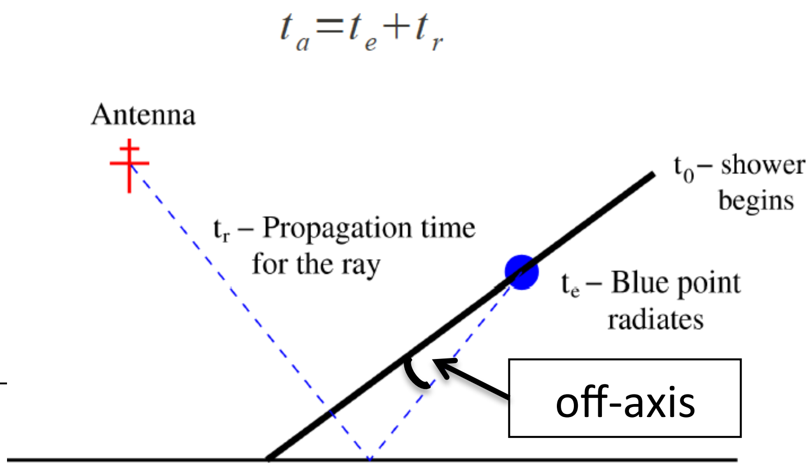
$\theta=70^0$ shower – off-axis angle = 0.77^0

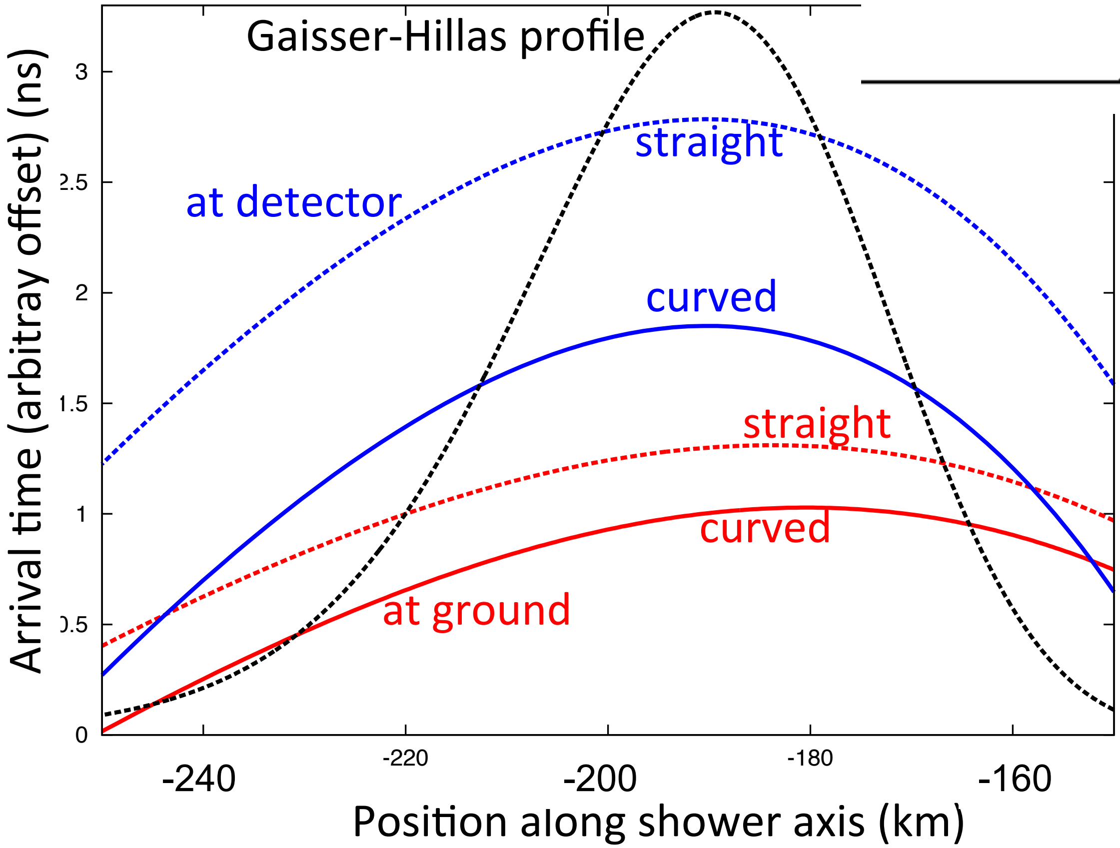


Negligible difference in arrival time between straight & curved propagation up to 70^0

propagation time: straight vs curved

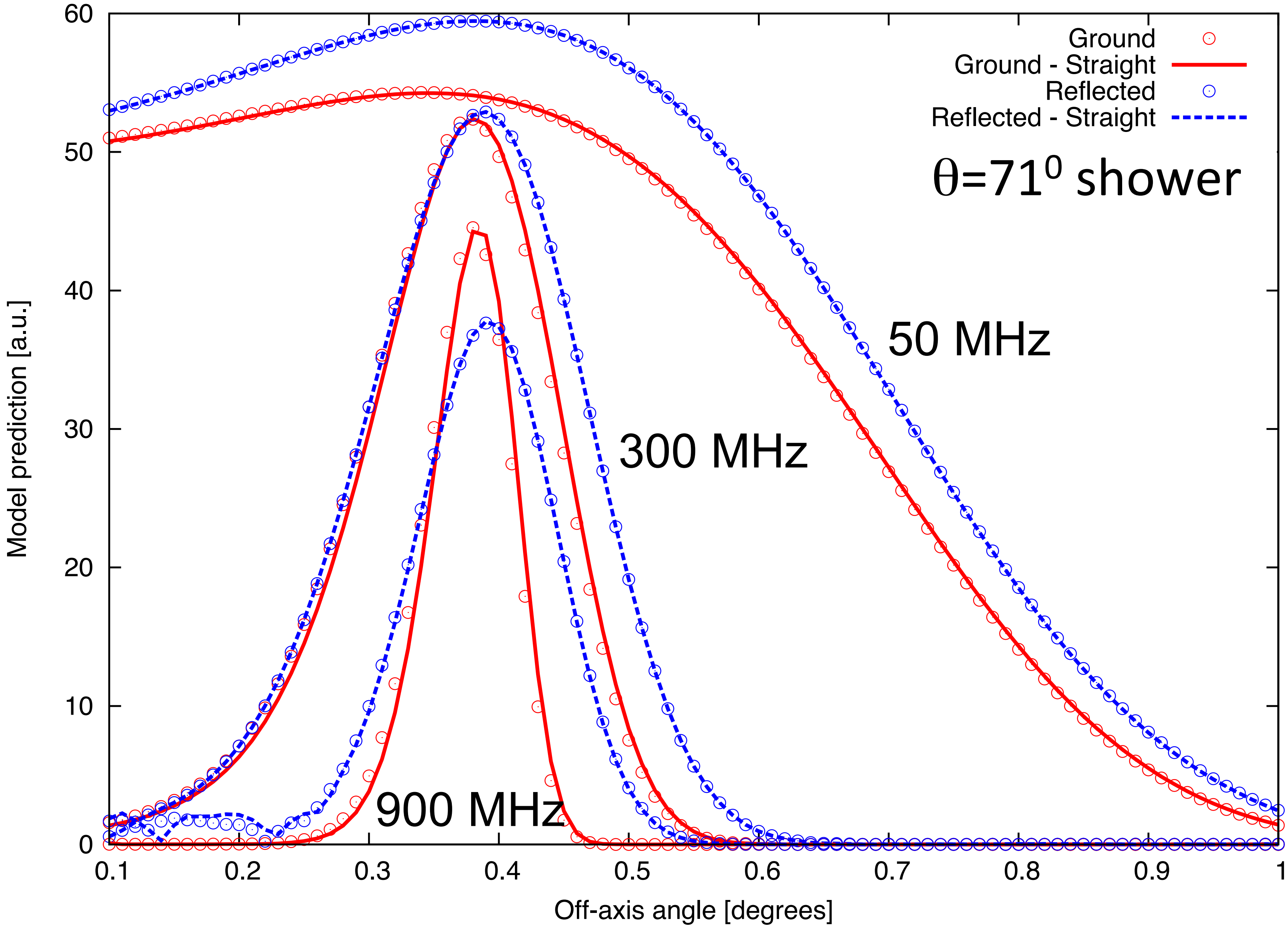
$\theta=85^0$ shower – off-axis angle = 0.4^0





Almost constant time difference between straight & curved: does not affect field

Compare approximation both for ground and detector



Use “ZHAireS-reflex” to

- Compare ground extrapolation to calculation including reflection

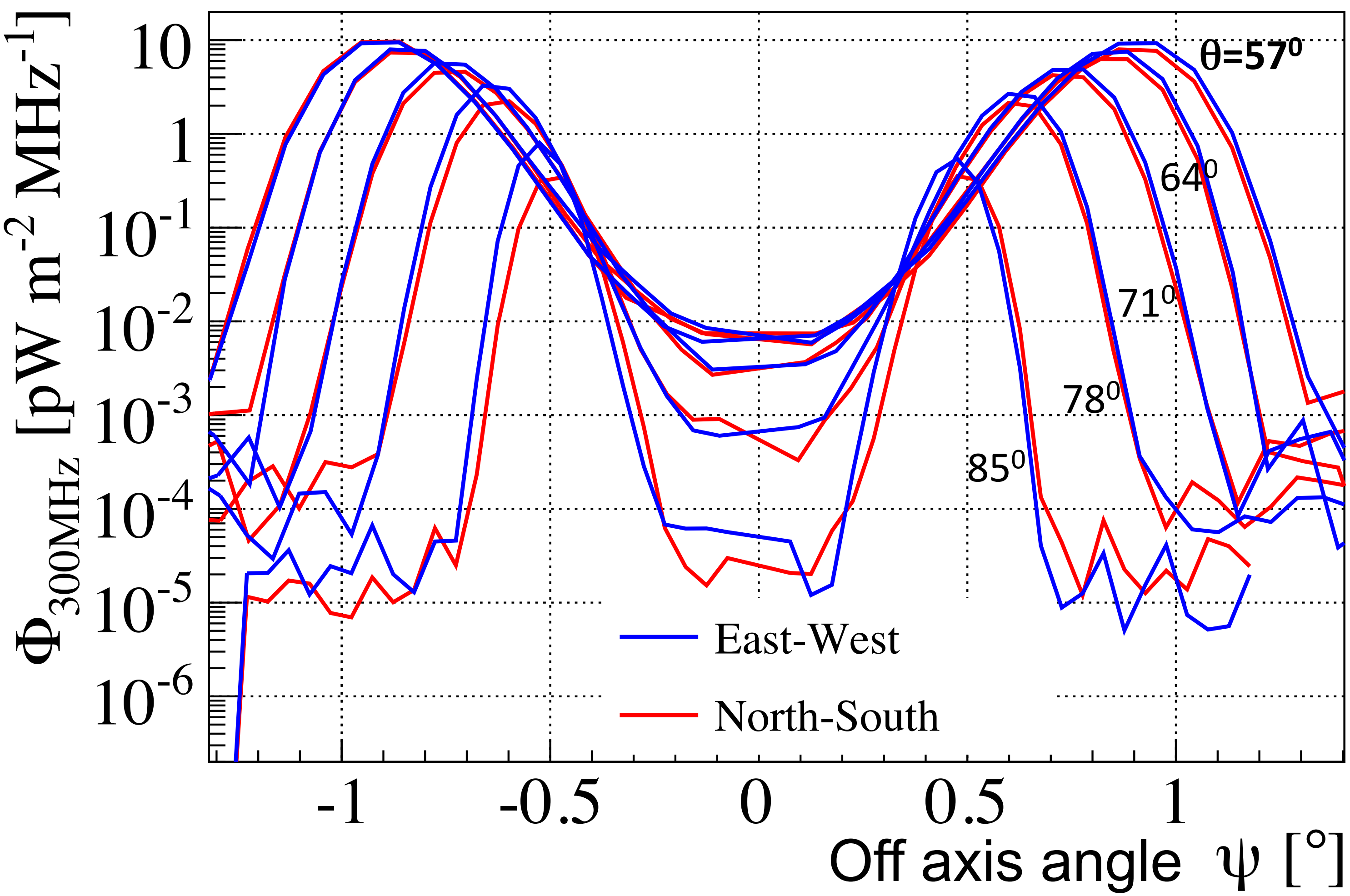
- Compare results with Fresnel coefficients in the calculation to simply applying the coefficients to the result

- Study variations with zenith angle

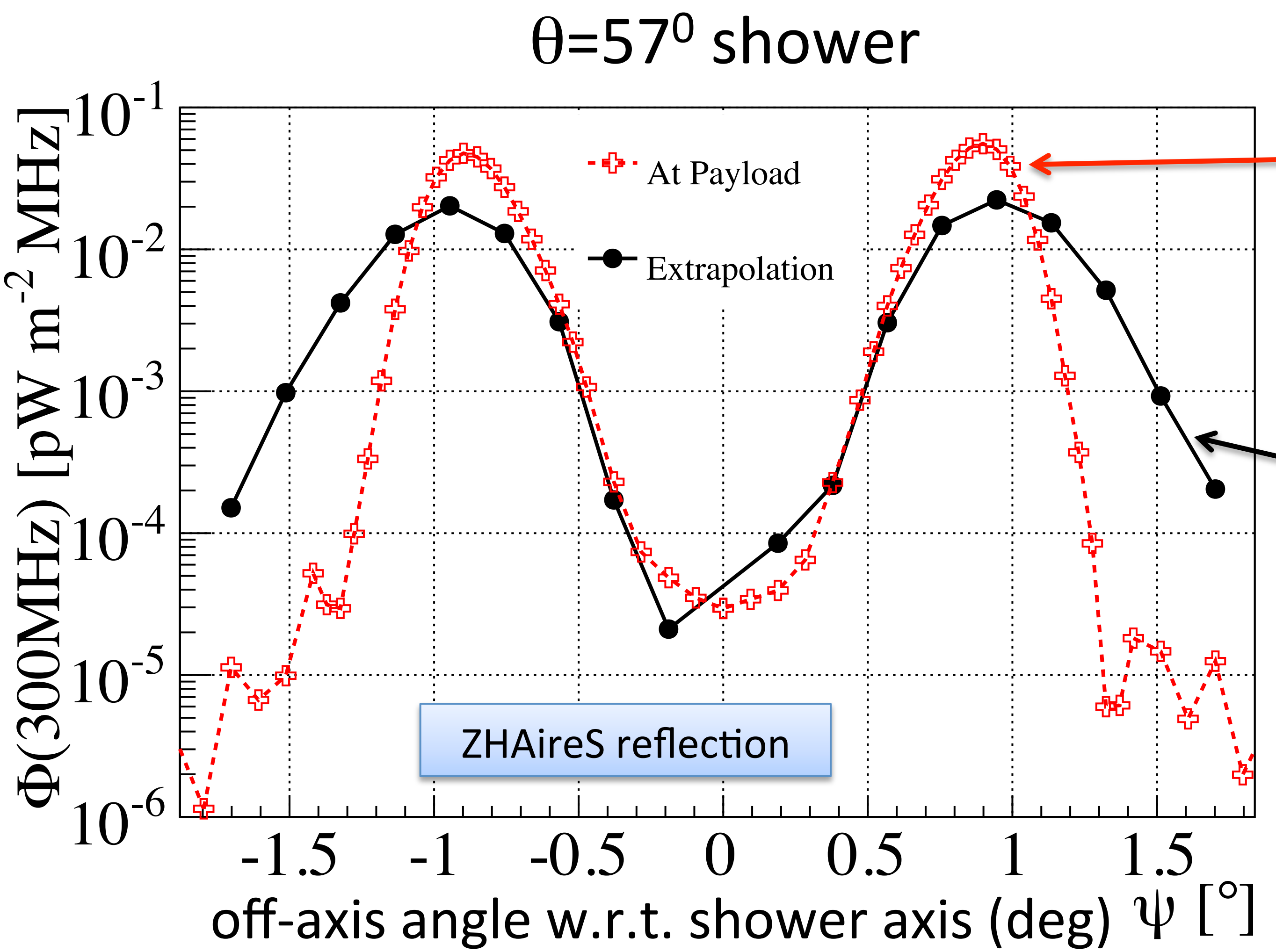
- Test scaling with energy

- Study effects of different off axis angle

Power spectrum: different zeniths



Power spectrum at detector vs ground extrapolation



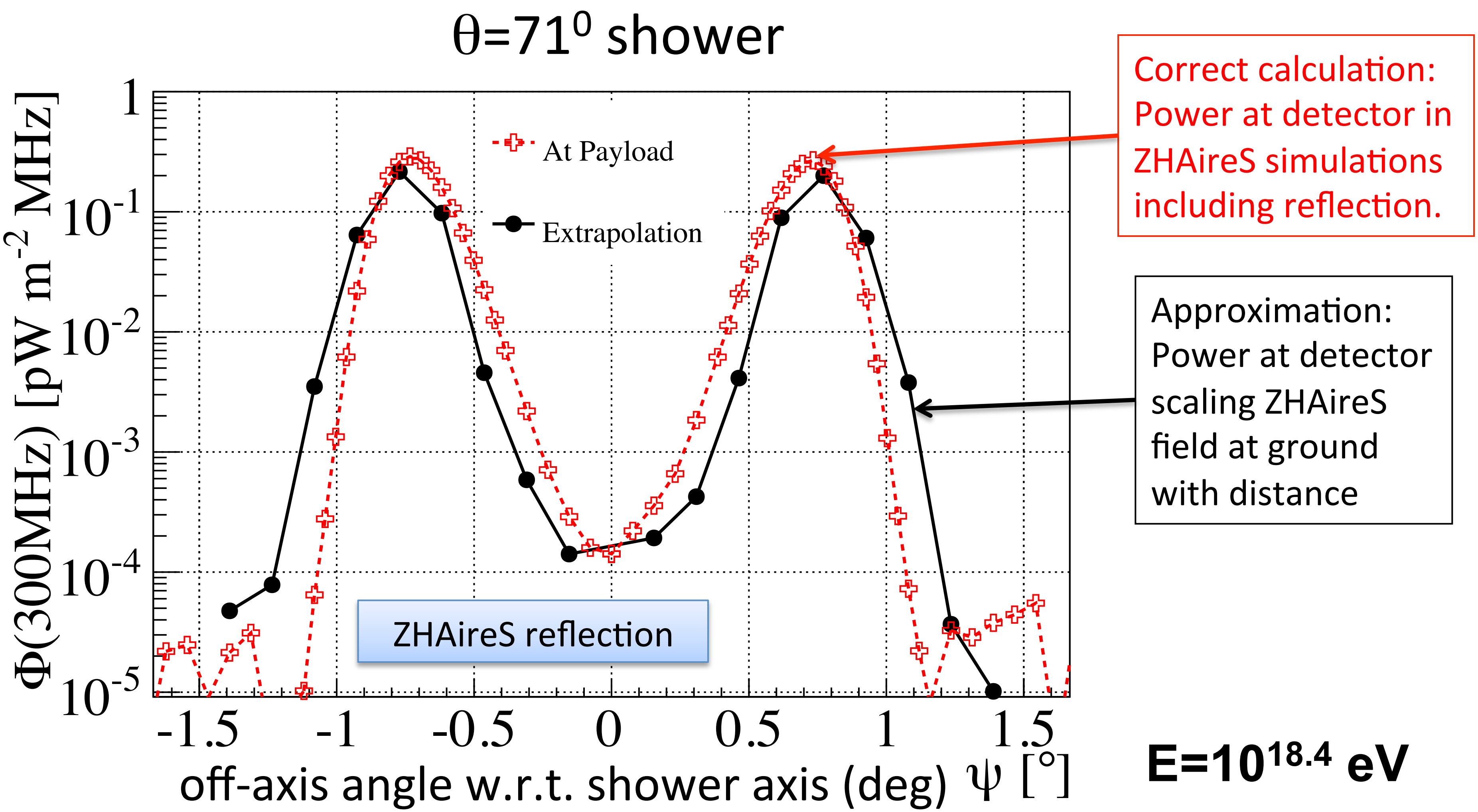
Correct calculation: Power at detector in ZHAireS simulations including reflection.

Approximation: Power at detector scaling ZHAireS field at ground with distance

$E=10^{18.4}$ eV

300 MHz

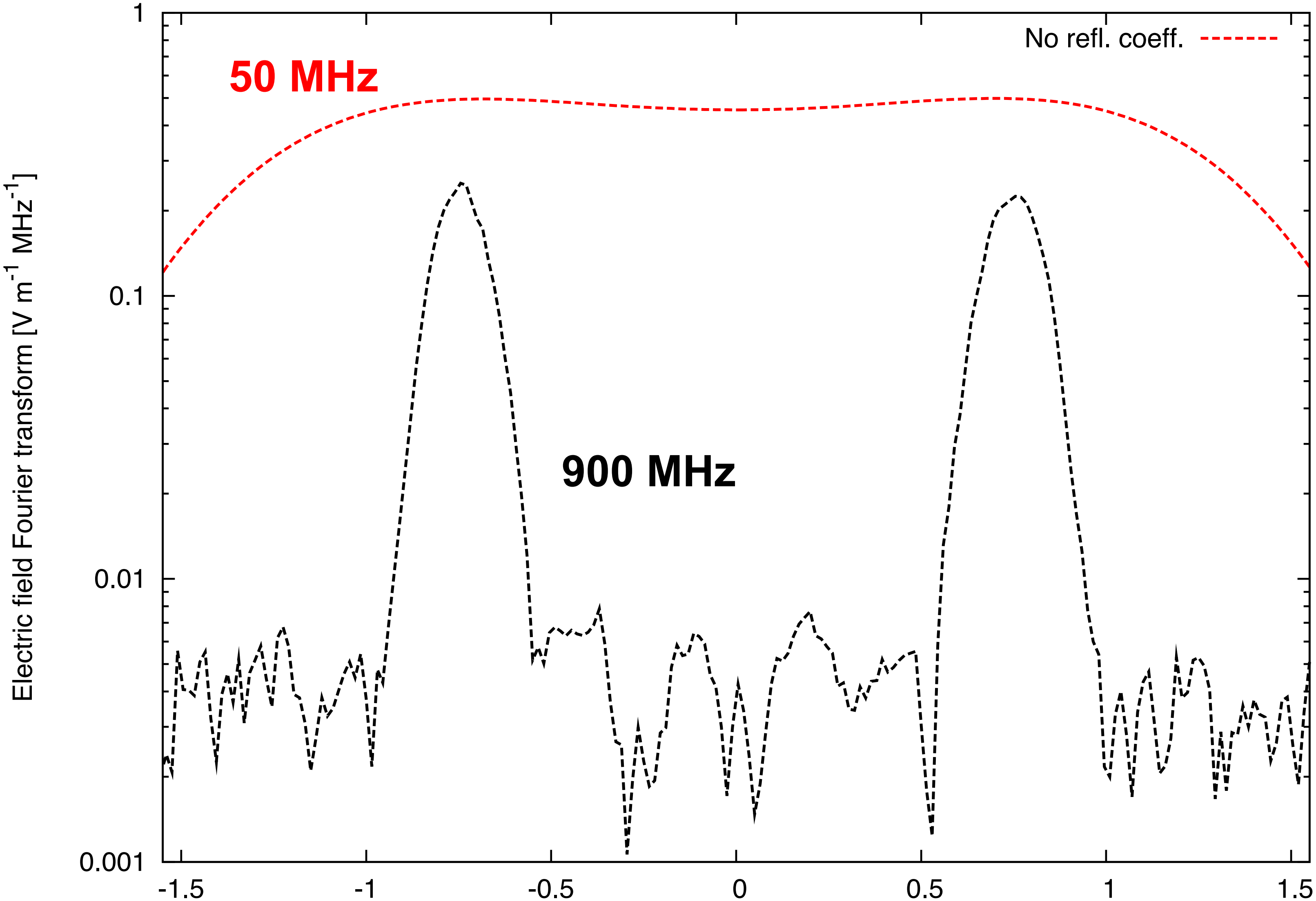
Power spectrum at detector vs ground extrapolation



$E=10^{18.4}$ eV

300 MHz

Fresnel coefficients: ignored

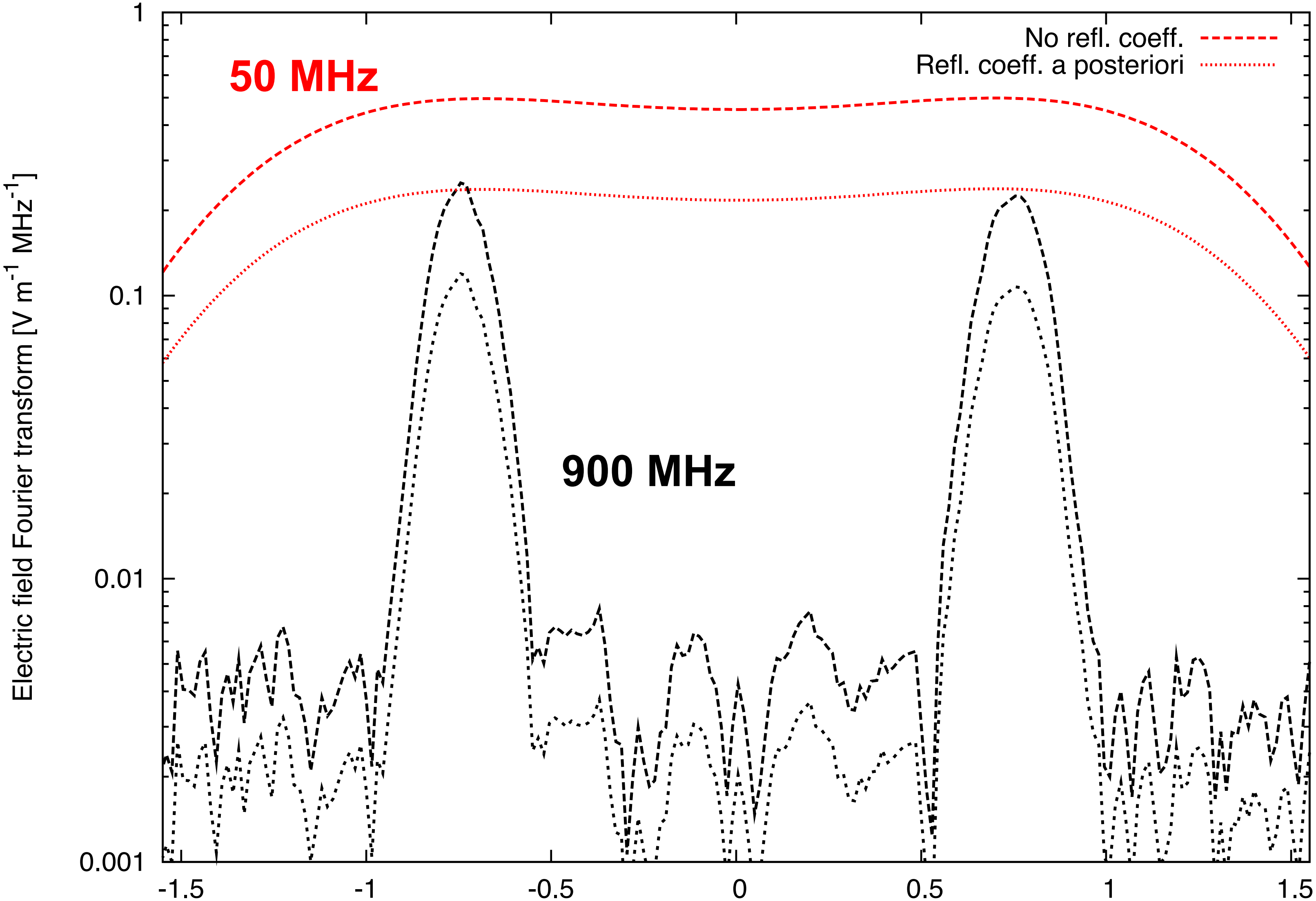


off-axis angle (deg)

$E=10^{19}$ eV

$\theta=70^0$ shower

Fresnel coefficients: a posteriori

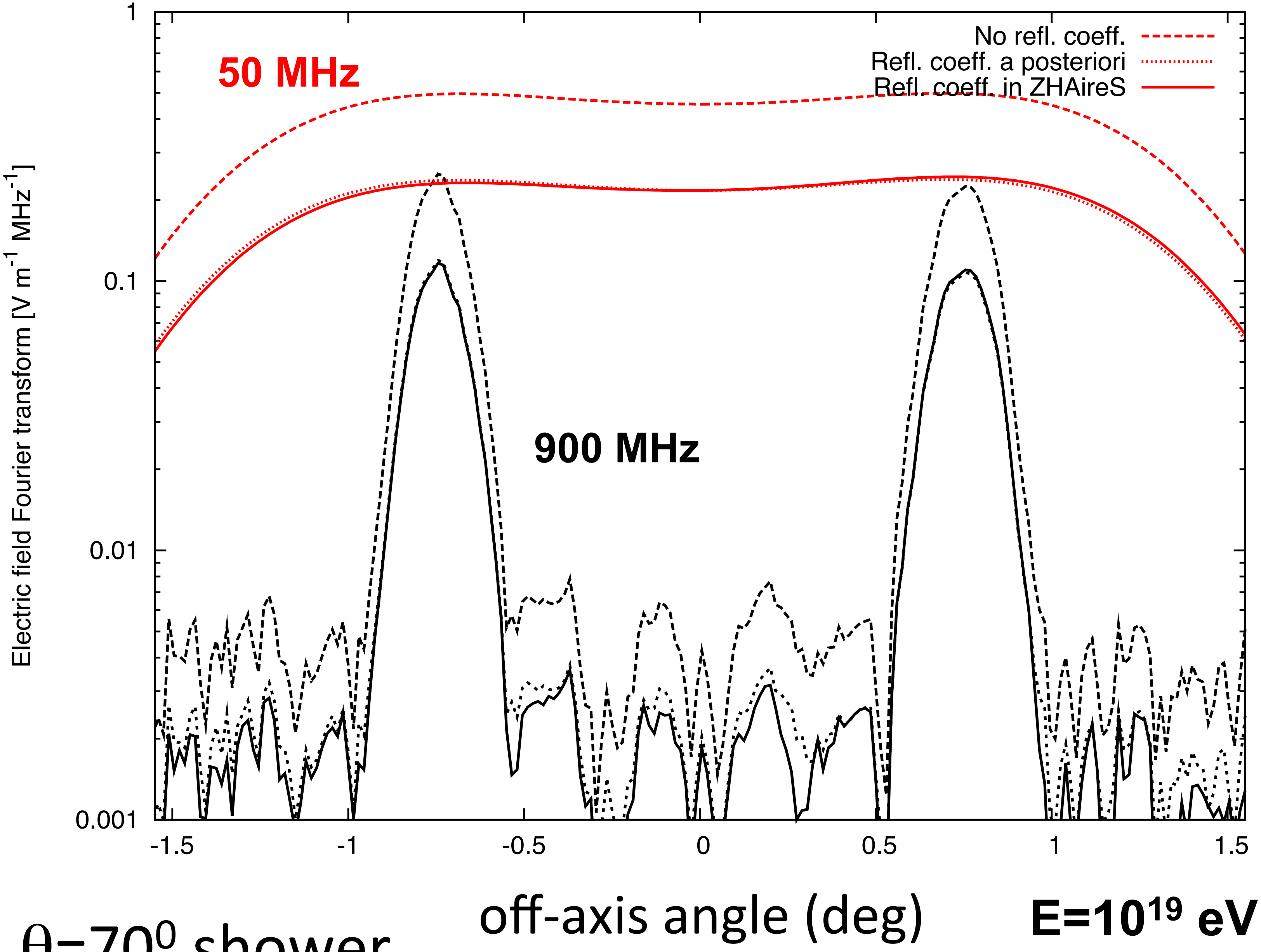


off-axis angle (deg)

E=10^{19} eV

$\theta=70^0$ shower

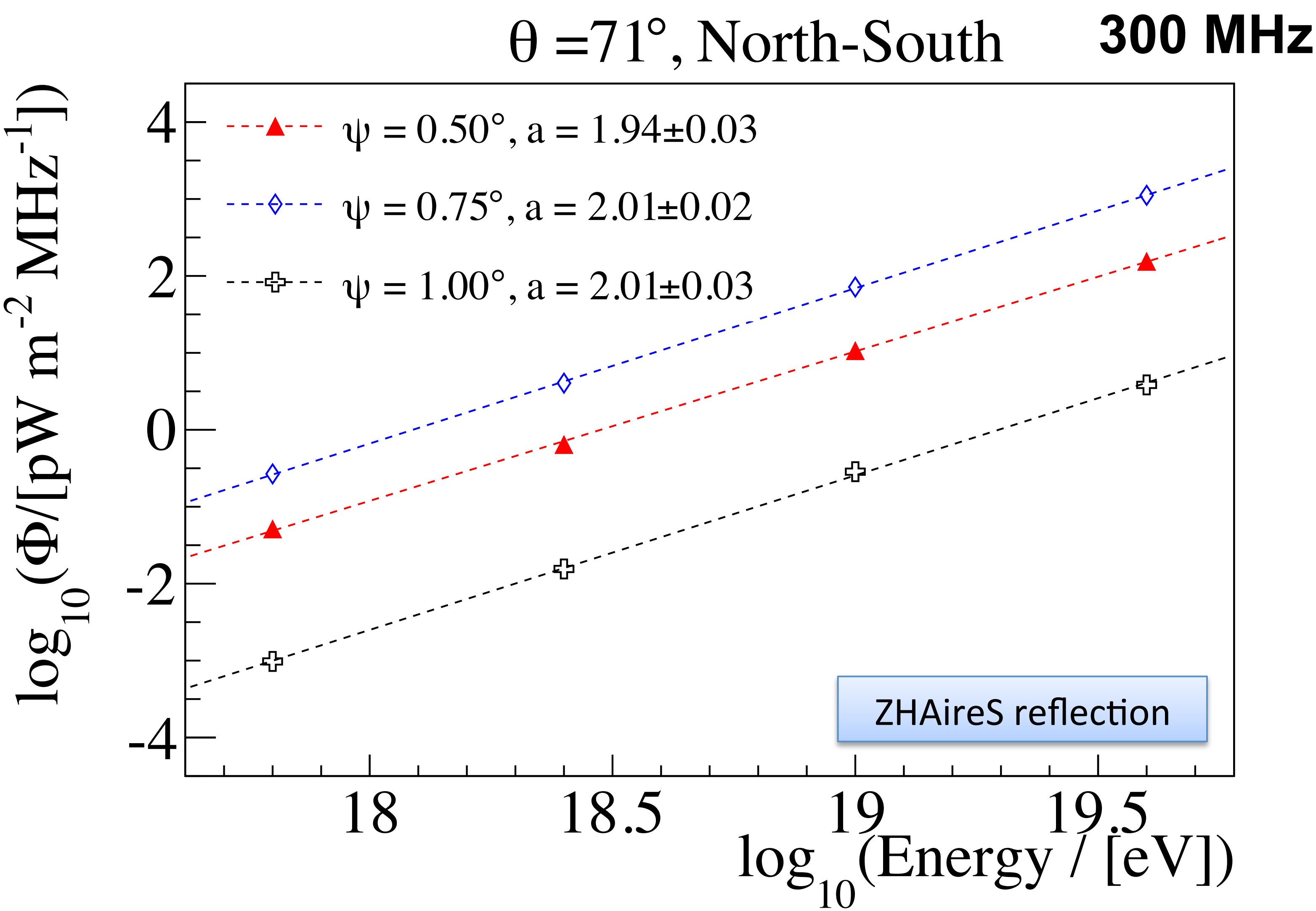
Fresnel coefficients: in ZHAireS



E=10^{19} eV

$\theta=70^0$ shower

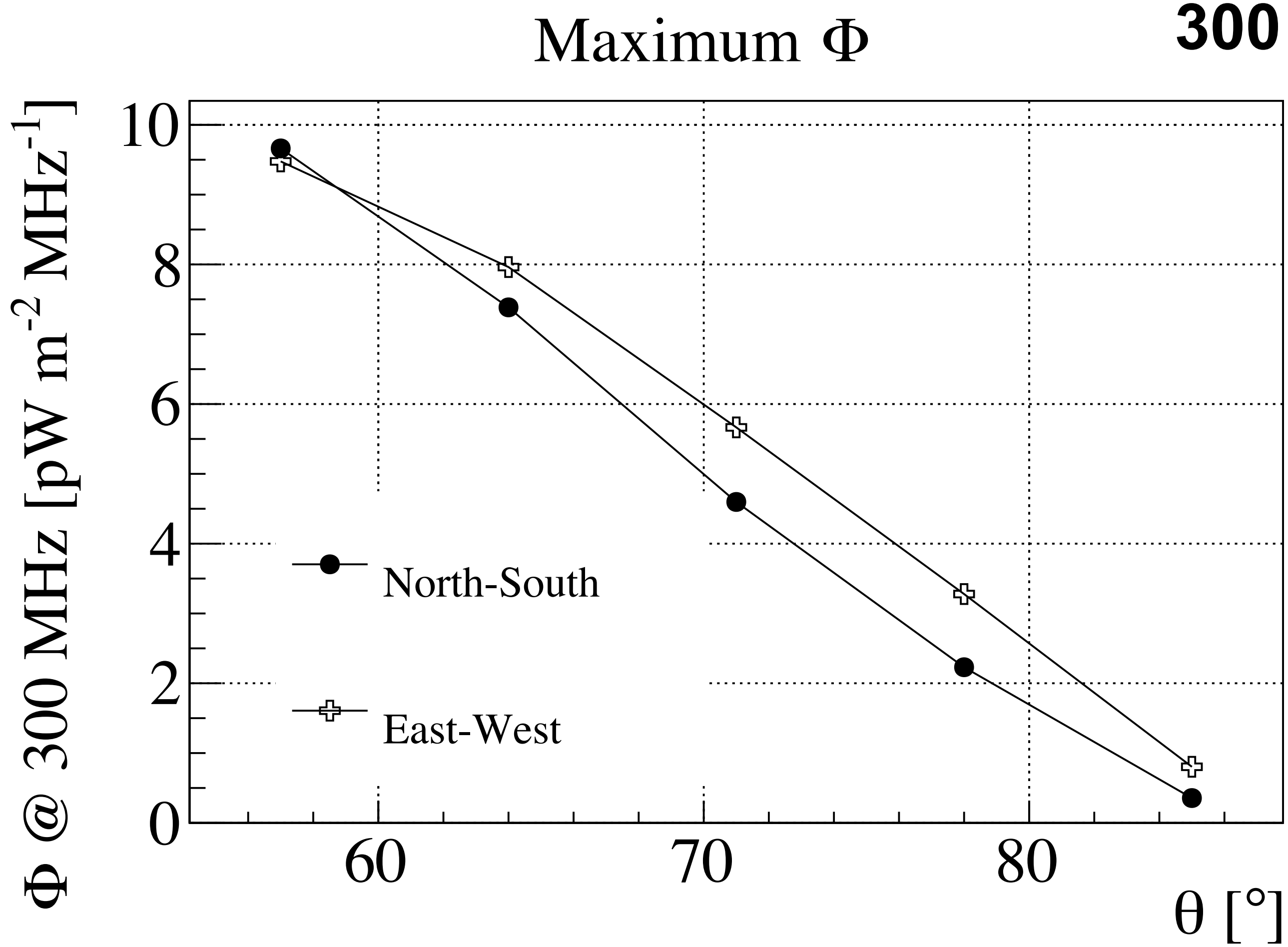
Energy Scaling



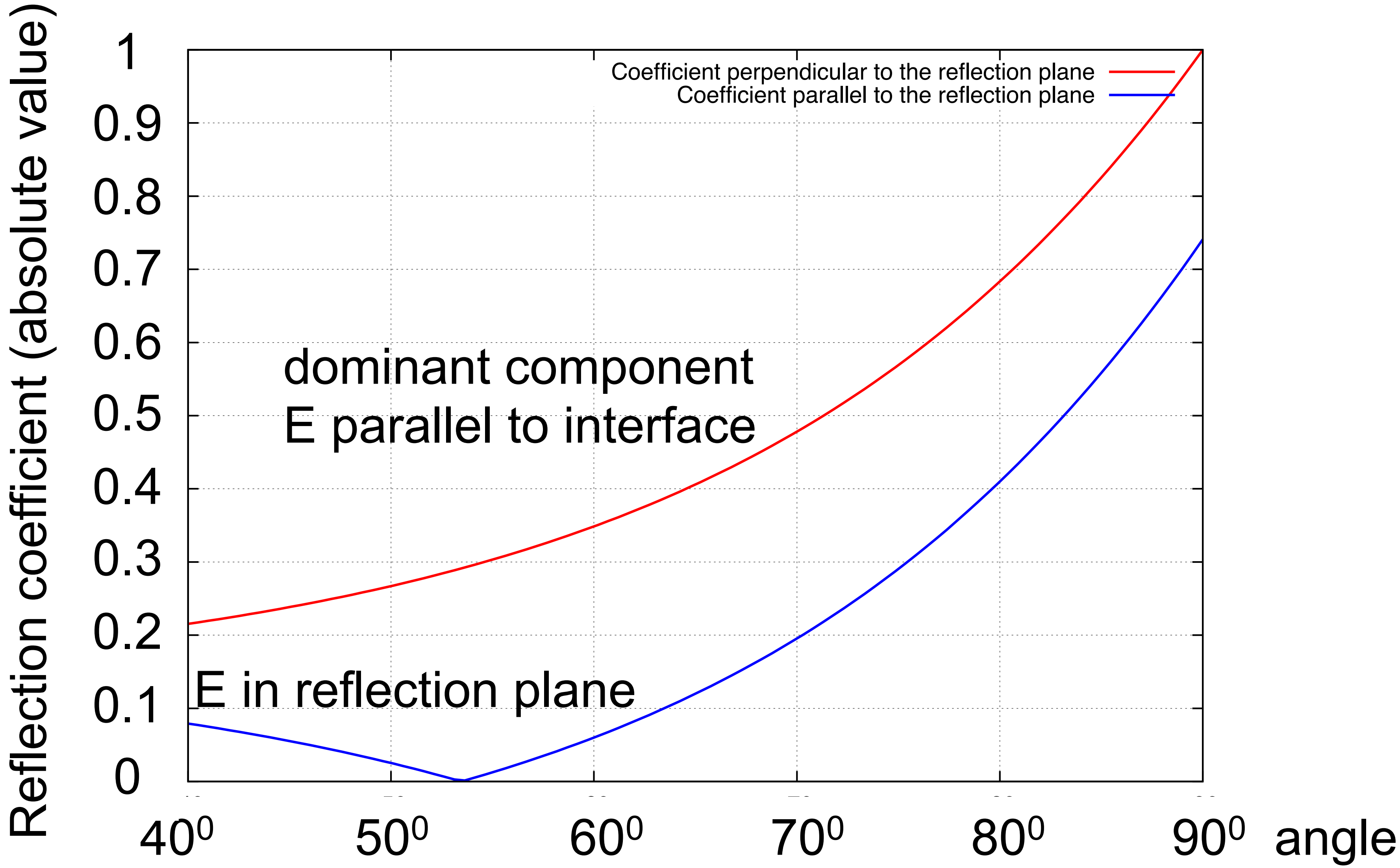
Measuring flux density & off-axis angle (spectral slope) => energy determination

Variation with zenith angle no Fresnel coeffiecients

300 MHz

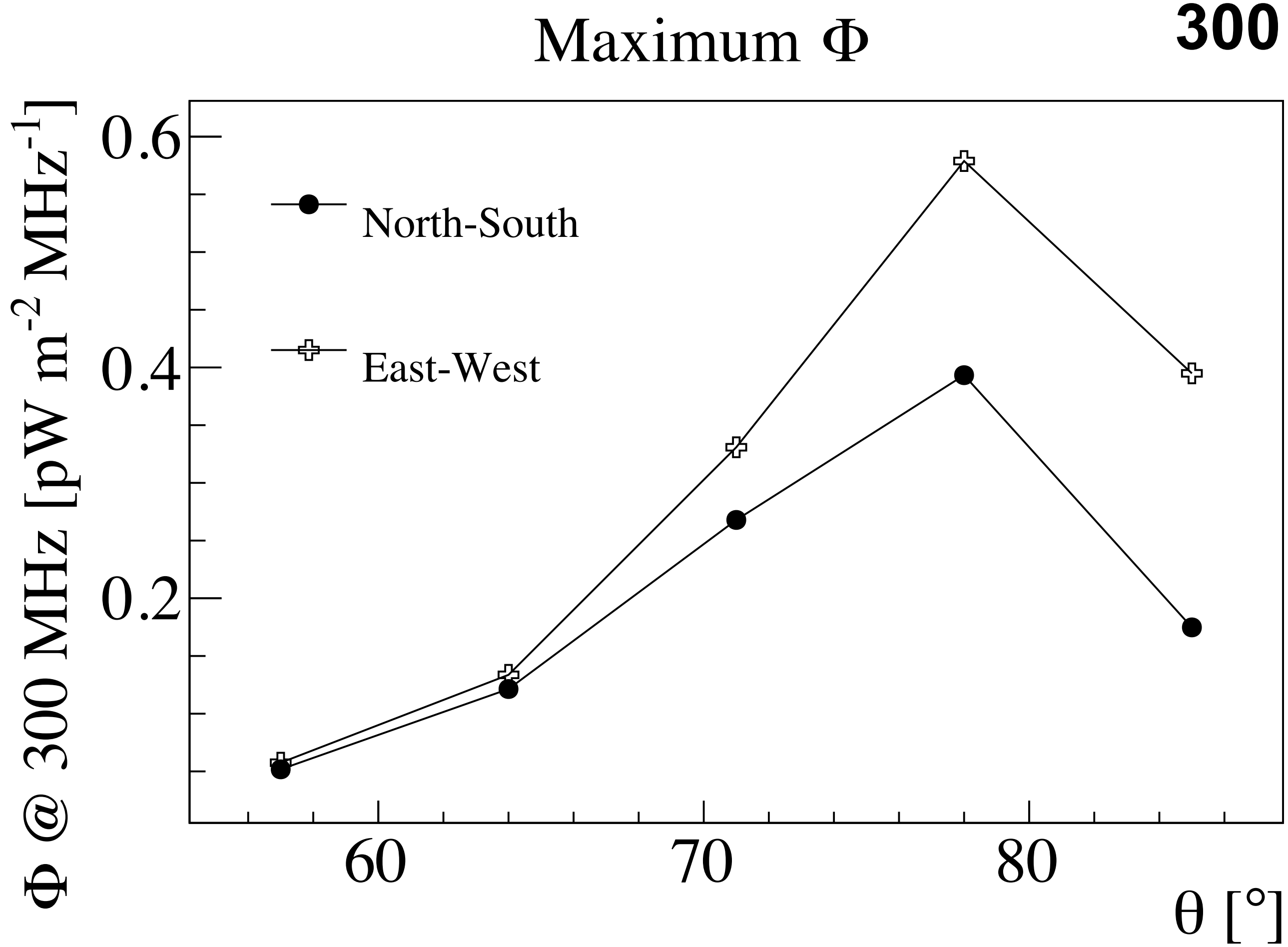


Fresnel coeffiecients for radiowaves and ice

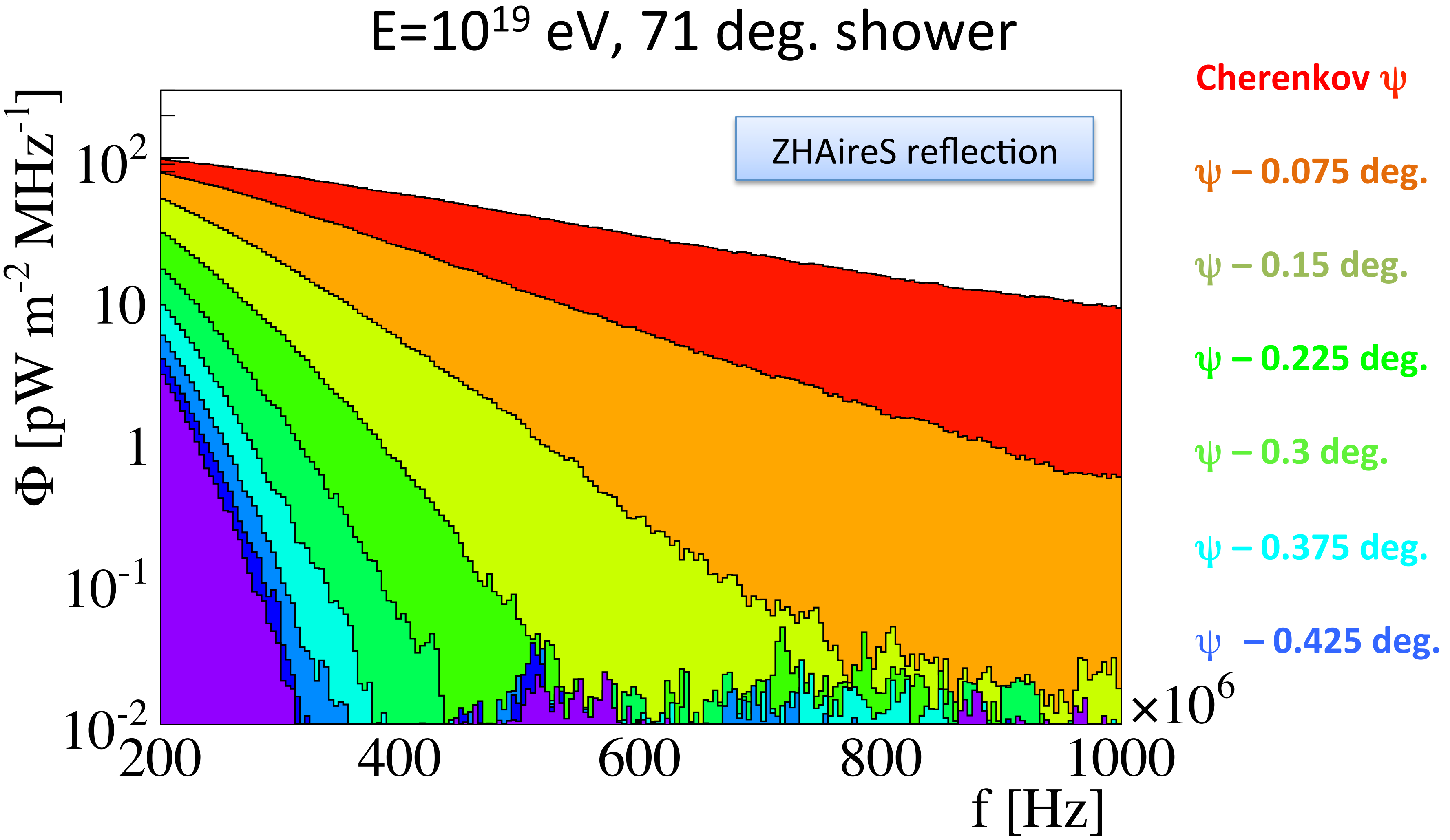


Variation with zenith angle with Fresnel coeffiecients

300 MHz



Frequency spectrum at detector



Spectrum flattens as observer moves towards Cherenkov angle

Conclusions

- Compare ground extrapolation to calculation including reflection
  Conclusion: Large distance effects are very important

- Compare results with Fresnel coefficients in the calculation to simply applying the coefficients to the result
  Conclusion: Reflection coefficient can be applied a posteriori

- Study variations with zenith angle
  Conclusion: Fresnel coefficients enhance large zenith angle

- Test scaling with energy
  Conclusion: Scaling is remarkable for a given geometry

- Study effects of different off axis angle
  Conclusion: Spectral differences allow off axis determination