Anita: Radio Detection of Ultra High Energy Cosmic Rays and Neutrinos

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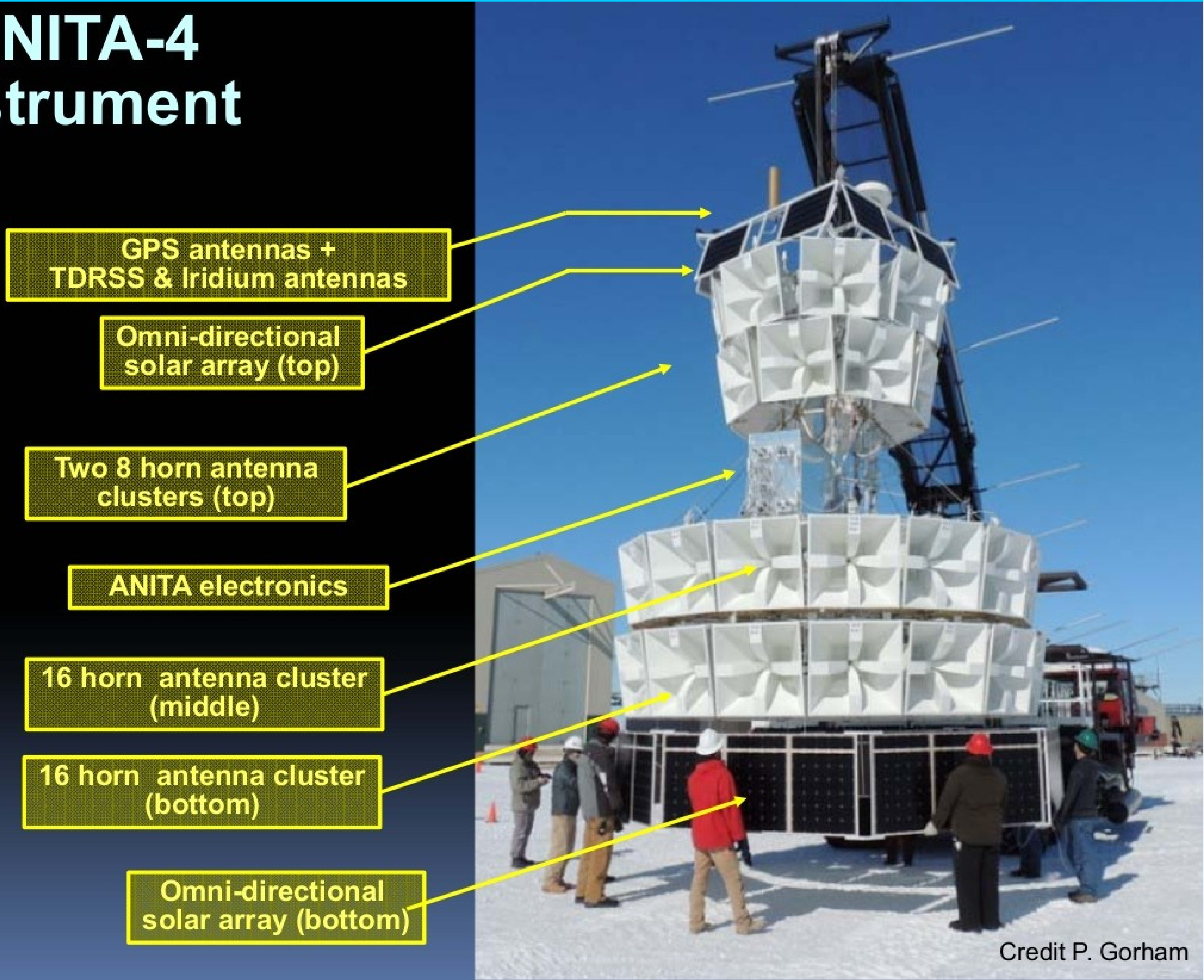
ANITA: ANtarctica Impulsive Transient Antenna

- **Balloon based detector at altitude of 37 Km**
- Detects cosmic rays and neutrinos through observation of radio pulses
- **Cosmic rays: Geo-synchrotron radiation produced in Extensive Air Showers**
- **Neutrinos: Ultra high energy neutrinos produce Cherekov radiation in ice (Askaryan Effect)**

ANITA-4 Instrument



Credit P. Gorham

ANITA Launch

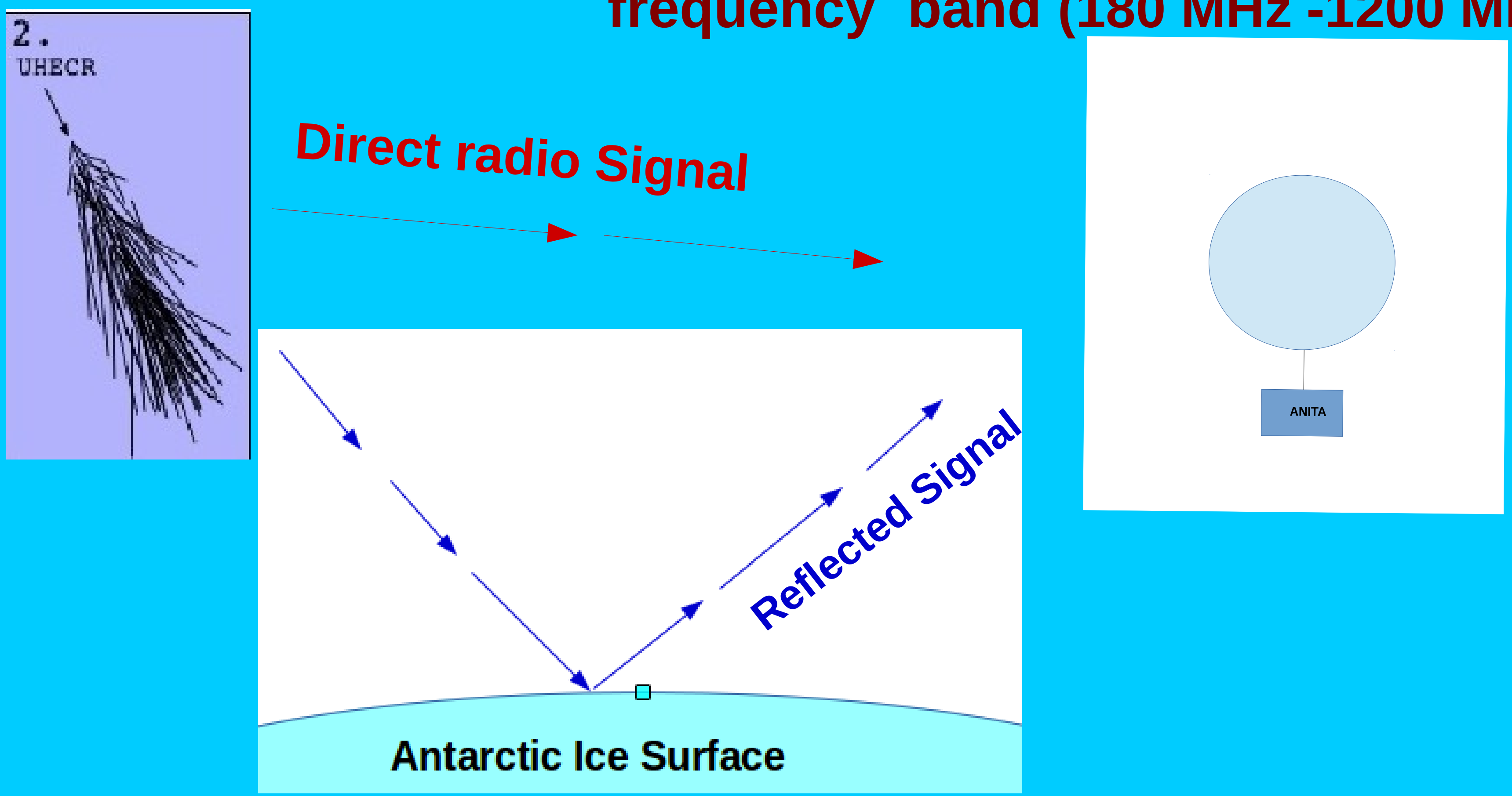
HiCal (High Altitude Calibration) Launch

radio frequency transmitter

Used for Calibration

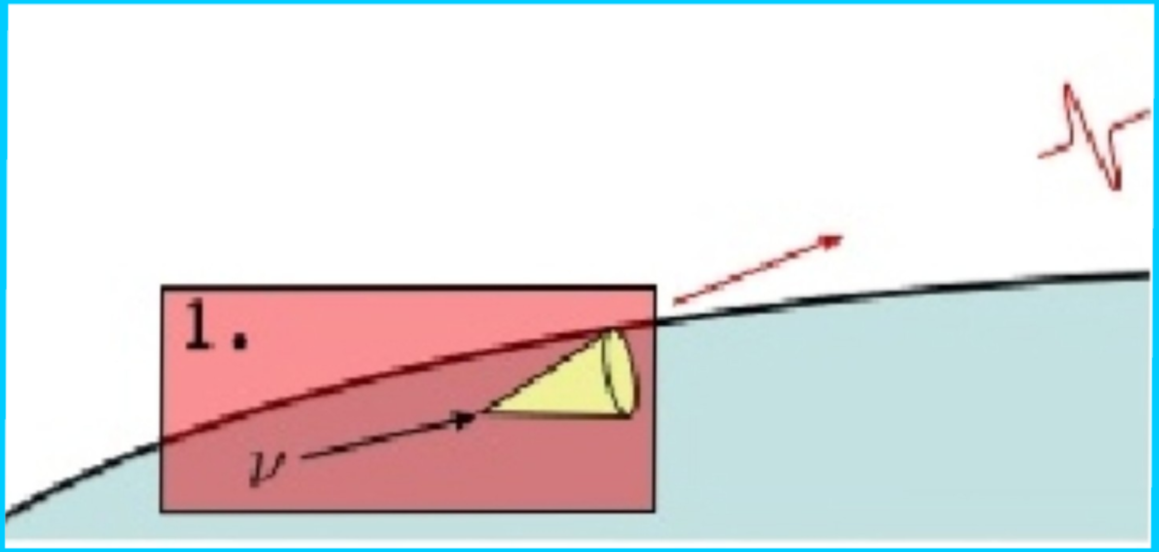
UHE Cosmic Ray Induced Radio Signal

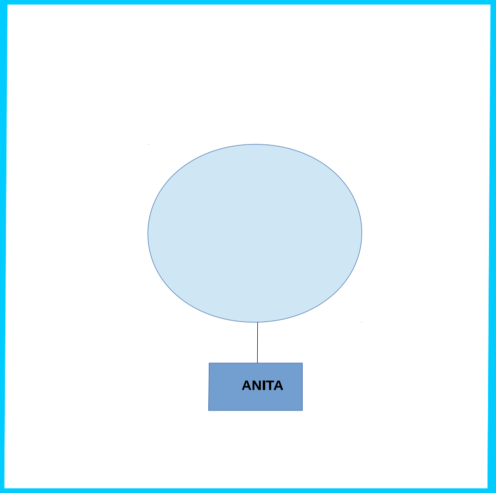
- **Extensive Air Shower (EAS) with Geomagnetic radiation**
- **Coherent emission in ANITA's frequency band (180 MHz -1200 MHz)**



Neutrino detection through Askaryan effect

Neutrino interacts inside ice and produces Cherenkov radiation at radio frequencies.



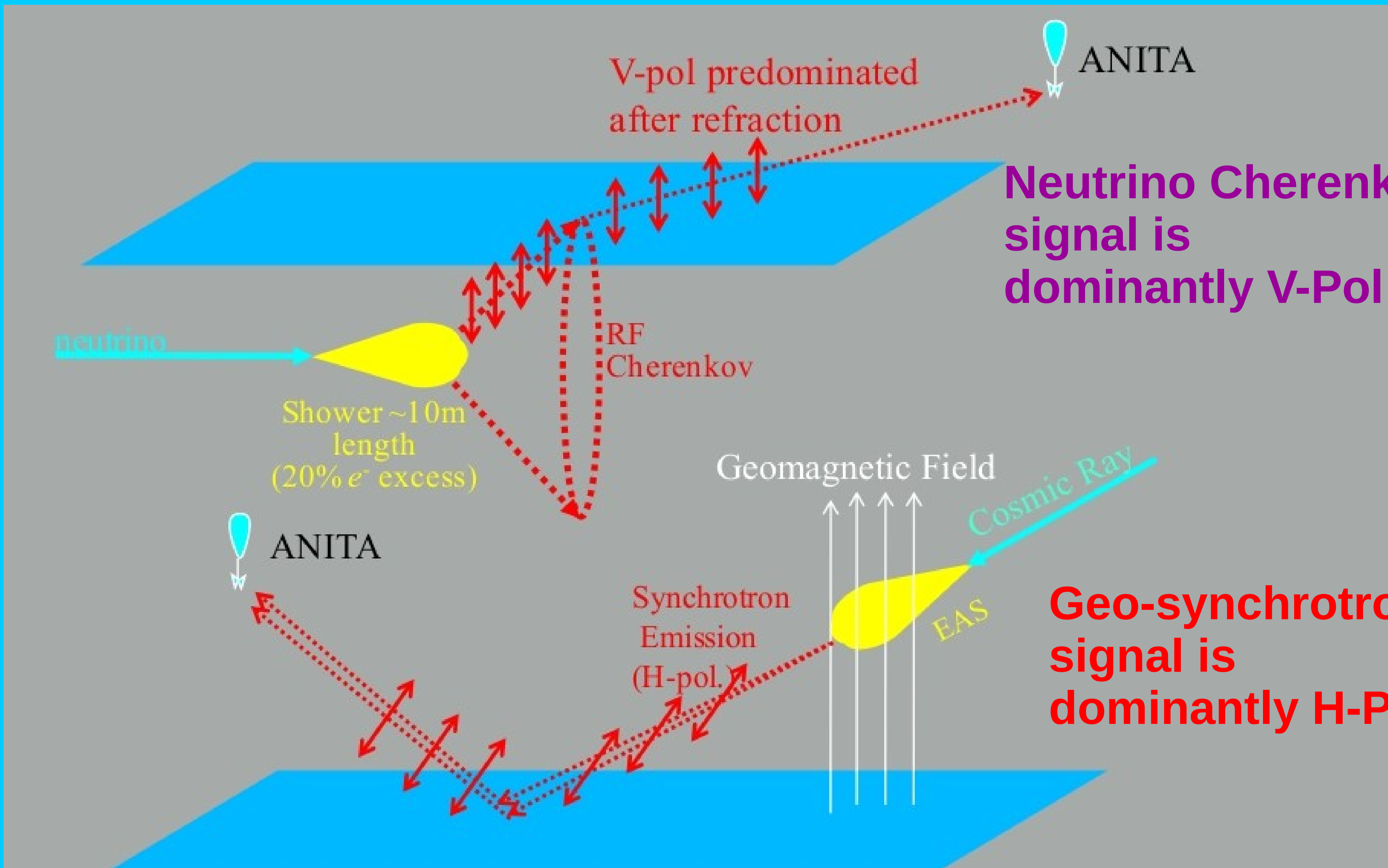


Refracted radio pulse is observed by detector

Radio Signal is strongly polarized

Cosmic Rays: Geo-synchroton Radiation has H-Pol (perp to plane of incidence) due to vertical magnetic field in Antarctica

Neutrinos: Cherenkov Radiation produced by ν in ice is dominantly VPOL (parallel to plane of incidence) after refration



Diagrams curtesy of Jiwoo Nam

Neutrino Cherenkov signal is dominantly V-Pol

Geo-synchrotron signal is dominantly H-Pol

ANITA: Types of events

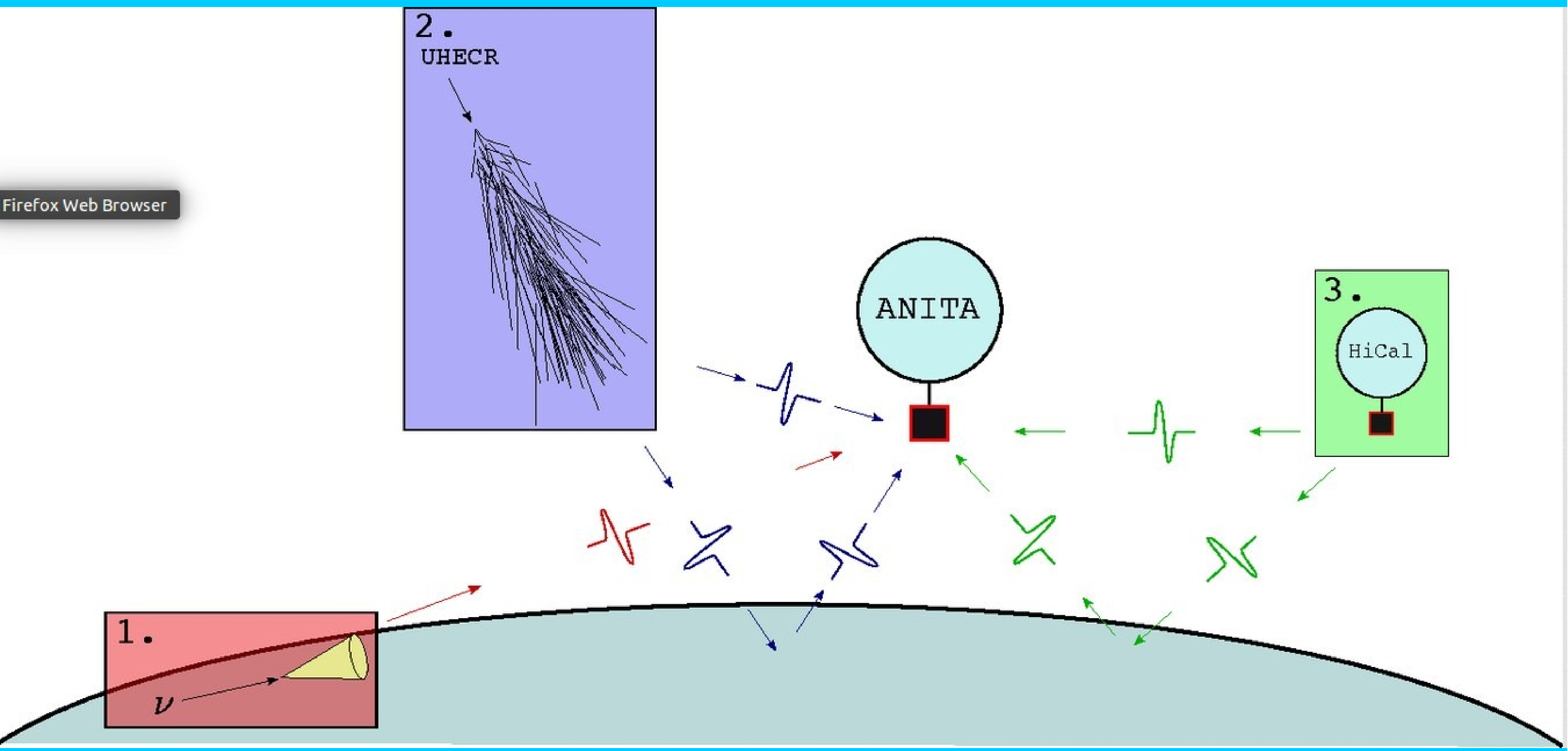
Cosmic Rays: Direct radio pulse (HPOL)

Cosmic Rays: Reflected radio pulse (HPOL)

Neutrino: Askaryan effect, upcoming radio pulse (VPOL)

ν_τ : produces τ lepton in ice which decays to produce an upward radio pulse

HiCal (High Altitude Calibration) radio frequency transmitter



Observations

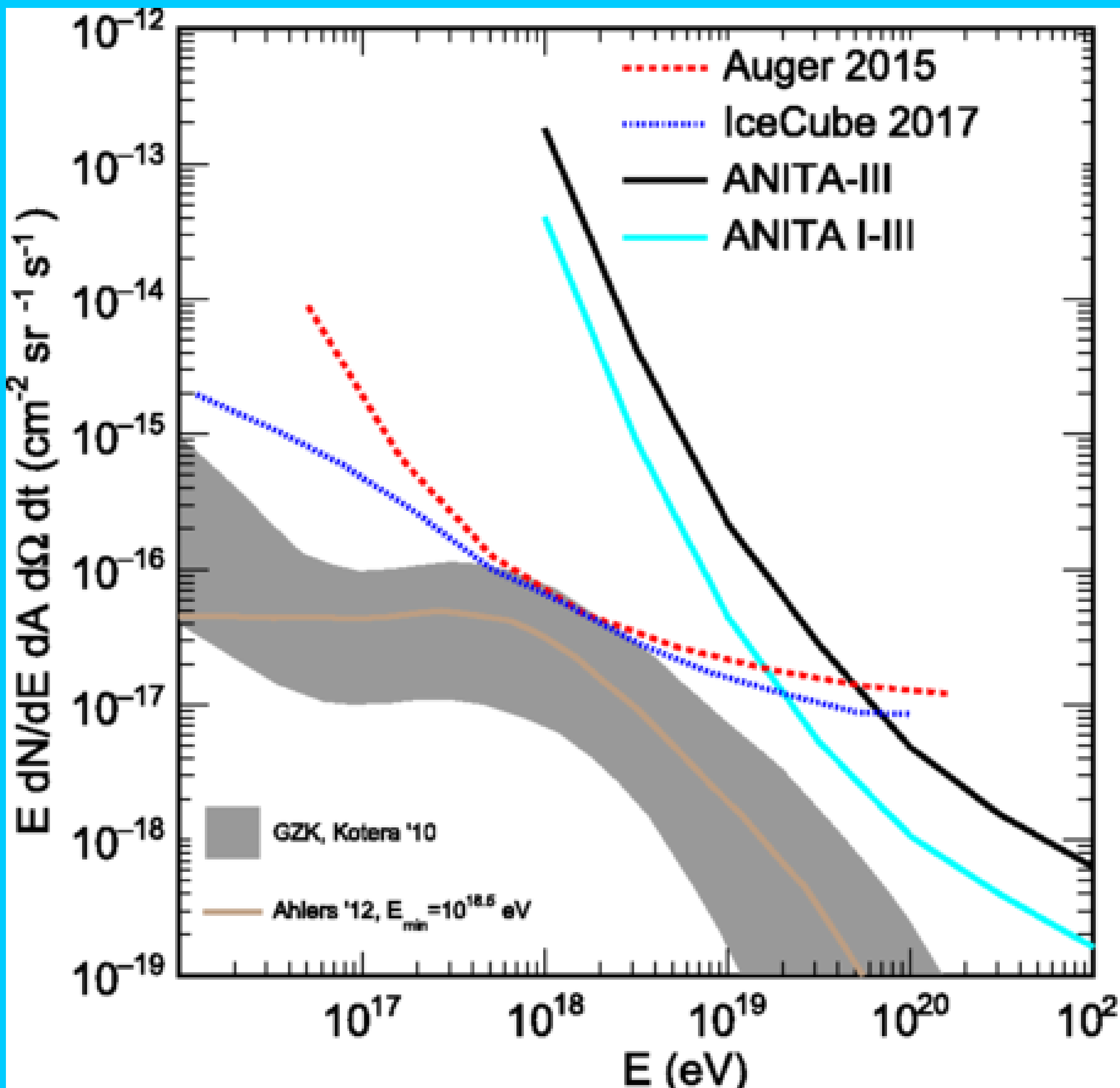
- ANITA - I, II, III, IV have been completed
- **ANITA-I: both H-Pol and V-Pol trigger. Observed 16 cosmic ray events and one upcoming event**
- **ANITA-II: Only V-Pol trigger. Two cosmic ray events and one neutrino event observed**
- **ANITA-III: both H-Pol and V-Pol trigger. Observed 20 cosmic ray events and one upcoming event**

Neutrino Event

- Neutrino event is consistent with Askaryan radio emission with a background of

$$0.7\ (+0.5)(-0.3)$$

ANITA limit on all-flavor-sum diffuse ultra high energy neutrino flux

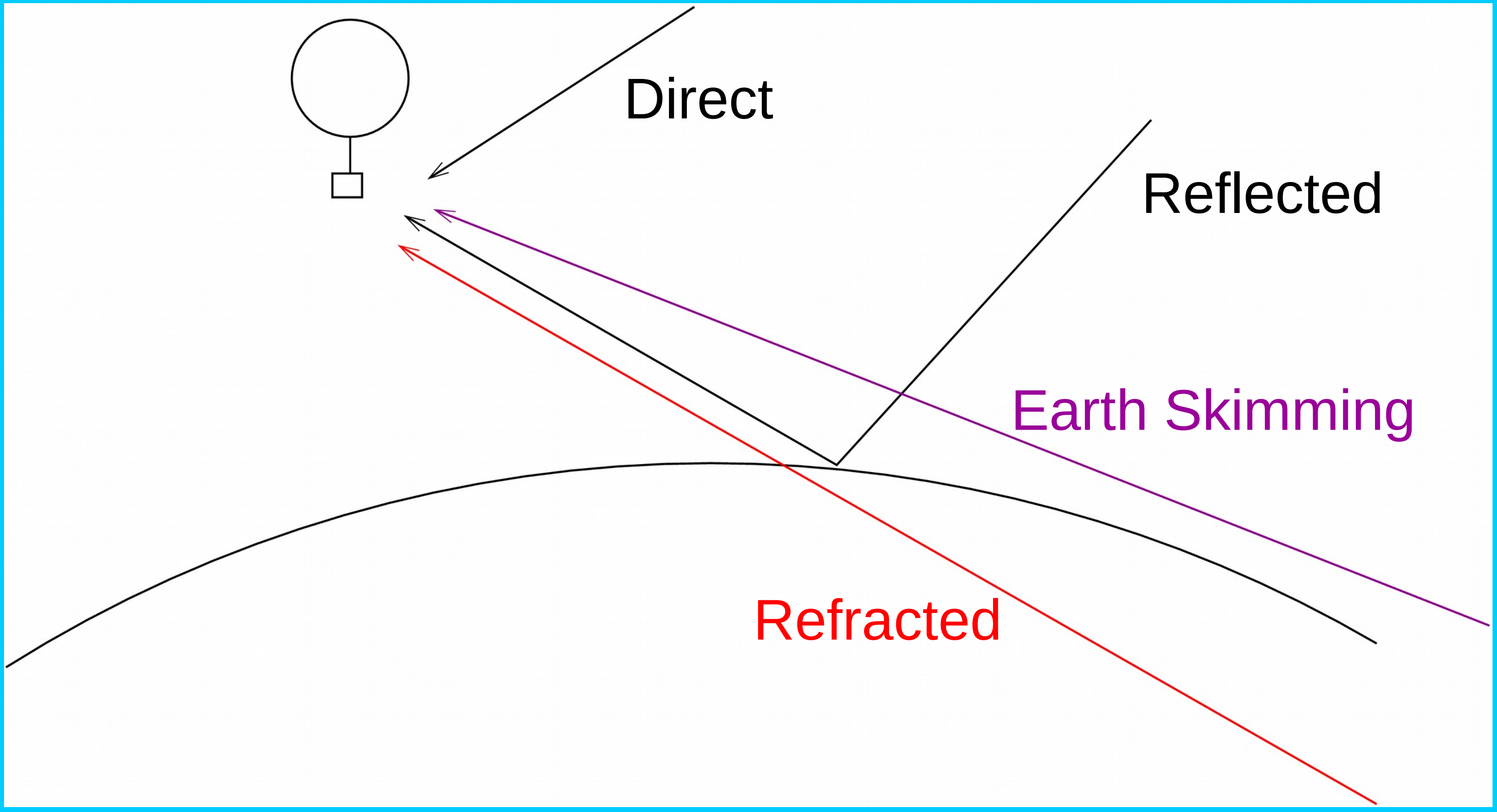


$\log_{10}(E(eV))$	18	18.5	19	19.5	20	20.5	21
$A\ (km^2 \cdot sr)$	0.00038	0.016	0.31	2.5	14	46	109

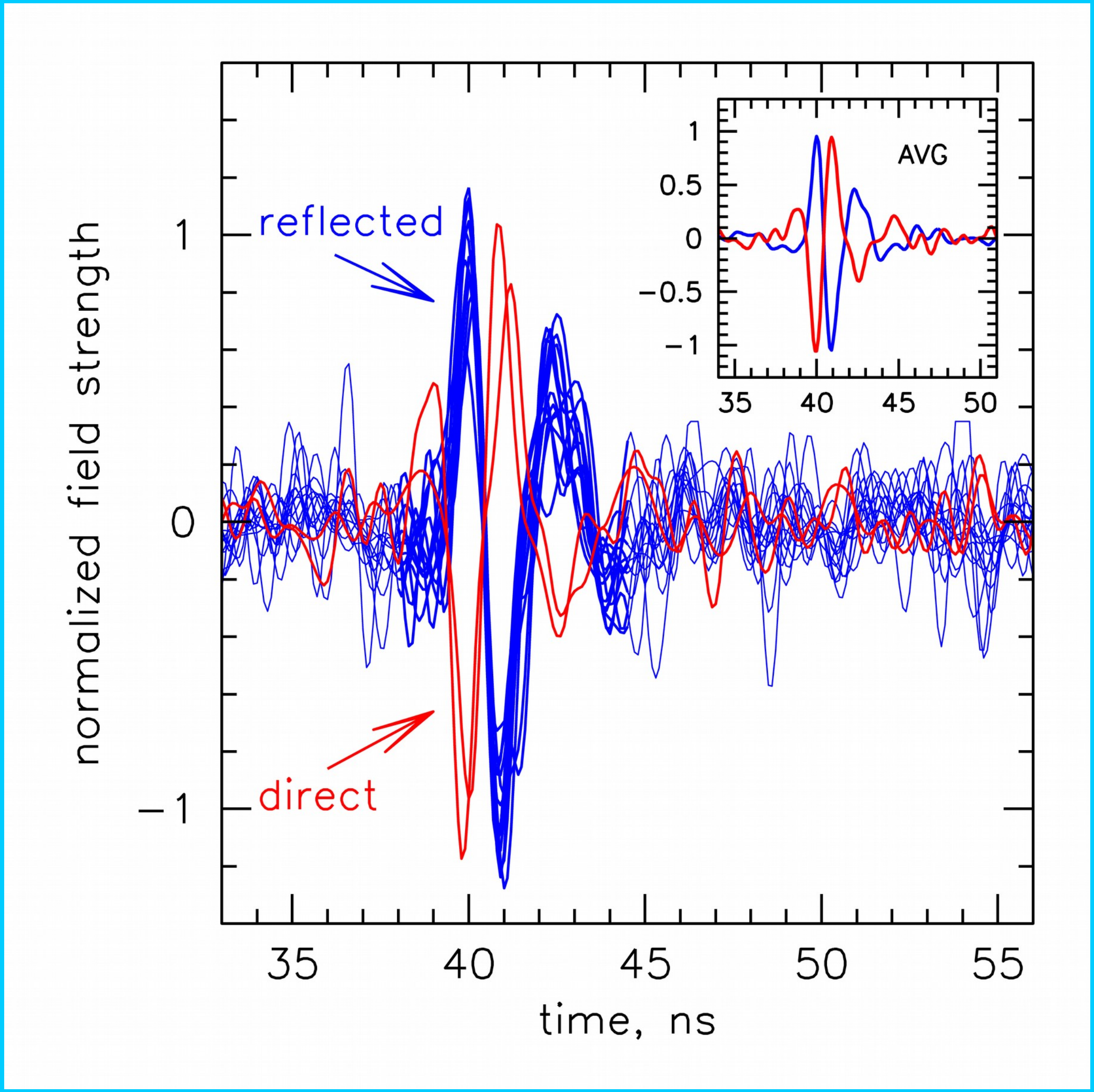
Gorham et al 2018

Mystery Events

- A surprise discovery by ANITA is events which arrive at steep angle (consistent with reflected signal) but do not show the phase inversion

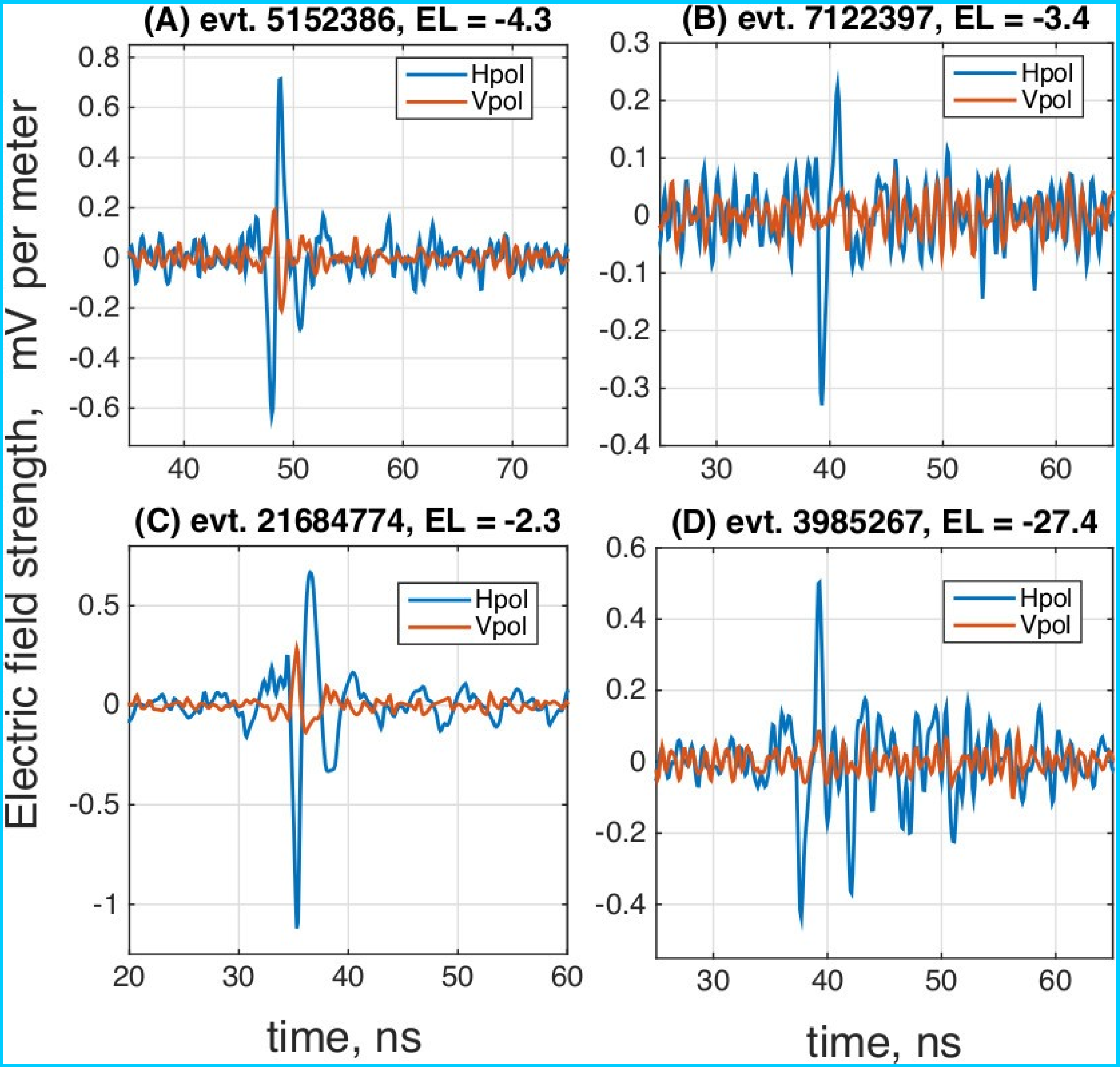


Direct and Reflected Pulses

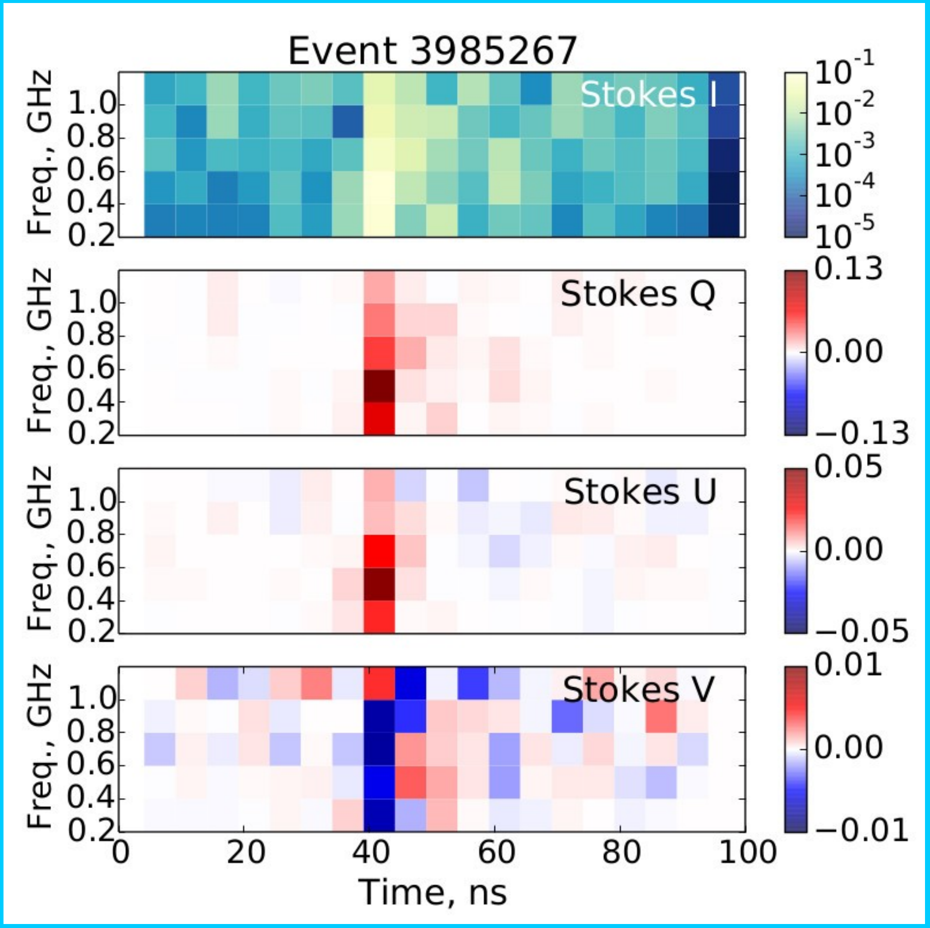


ANITA I

Mystery Event



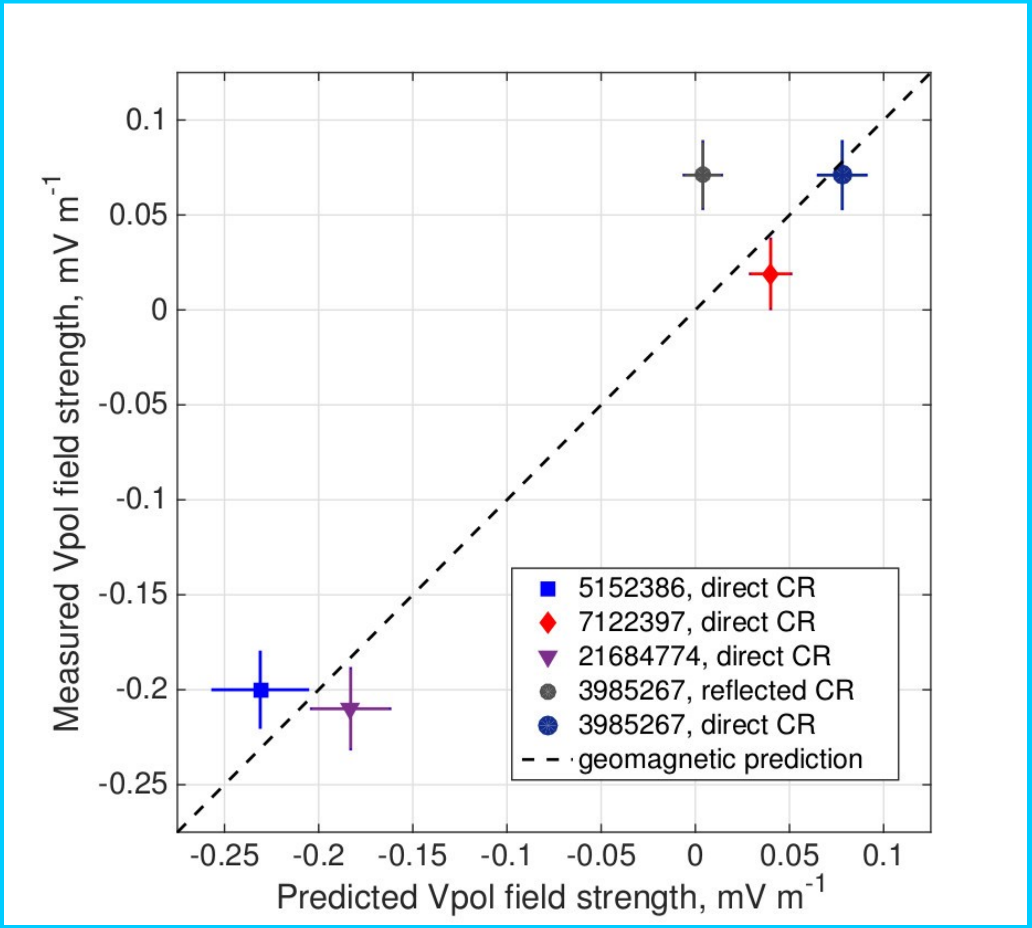
Stokes Parameters (D event)



100 % polarized

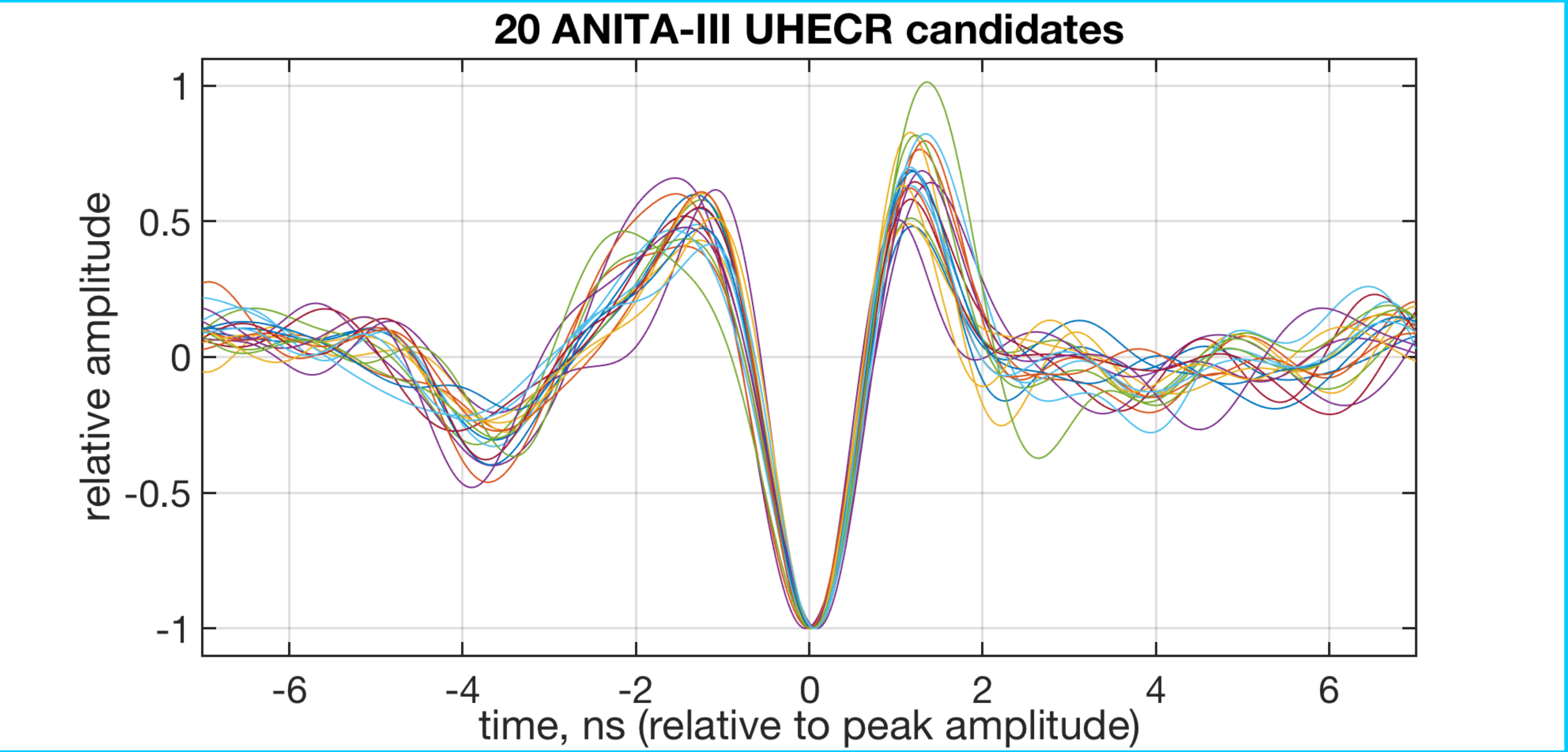
Significant circular polarization

Predicted vs Detected VPOL



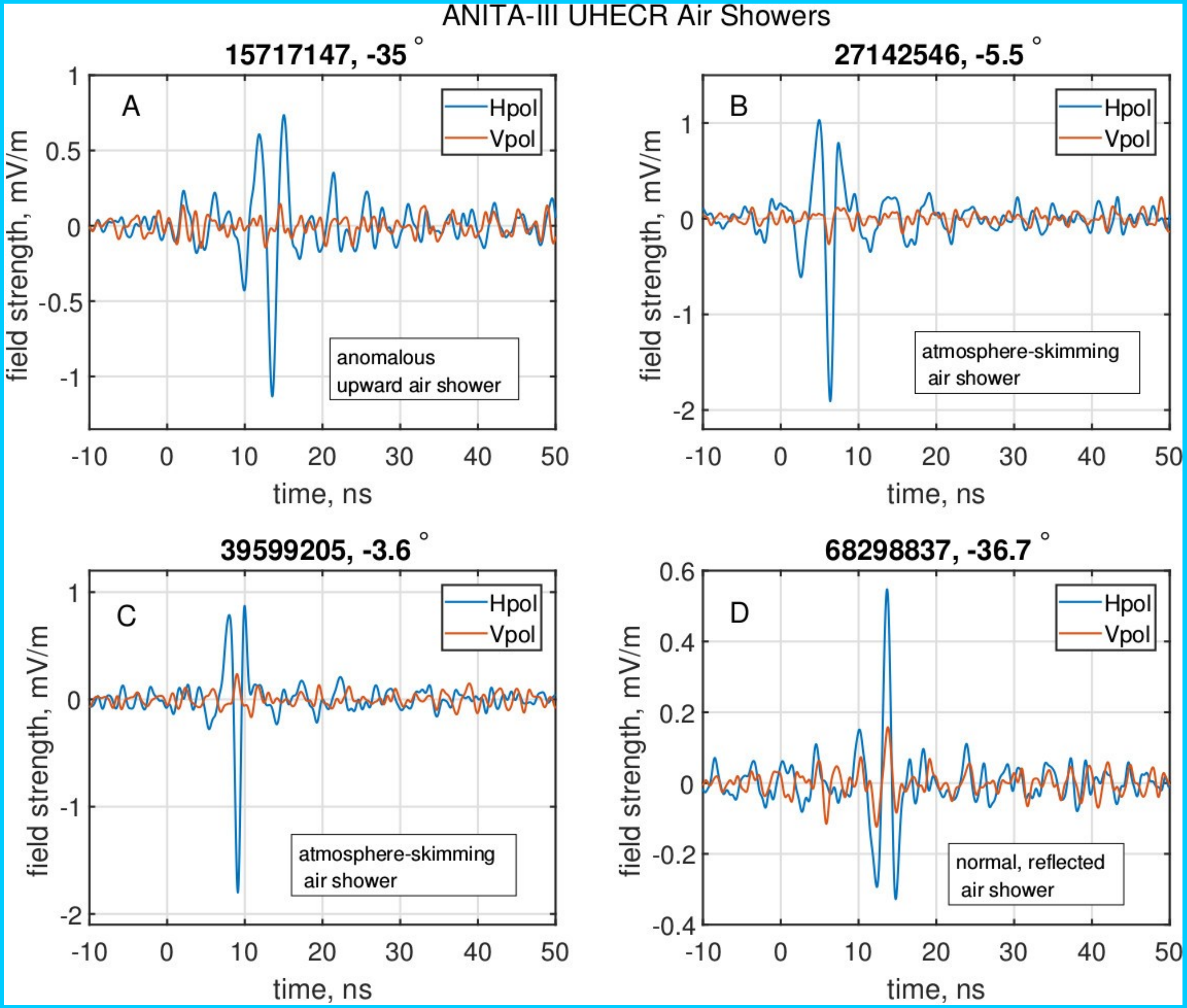
Background = 0.0004 events

ANITA III



20 ANITA-III UHECR candidates
relative amplitude
1
0.5
0
-0.5
-1
-6
-4
-2
0
2
4
6
time, ns (relative to peak amplitude)

Mystery Event: ANITA III



Theoretical Interpretation

- Decay of quasi-stable dark matter particle which may be a right handed neutrino
- Decays into Higgs + Majorana neutrino ν_M
- ν_M produces τ lepton by interaction with ice
- τ lepton initiates air shower observed

Anchordoqui et al 2018

Cherry and Shoemaker 2018 and Huang 2018 suggests sterile neutrino as the explanation of these events

Romero-Wolf et al 2019 rule out τ neutrino as the explanation of these events (requires flux two orders of magnitude larger than the current limit)

Theoretical Framework for Reflected and Refracted Radio Signals

We need the reflected, transmitted wave in the far zone

$$r \gg \lambda$$

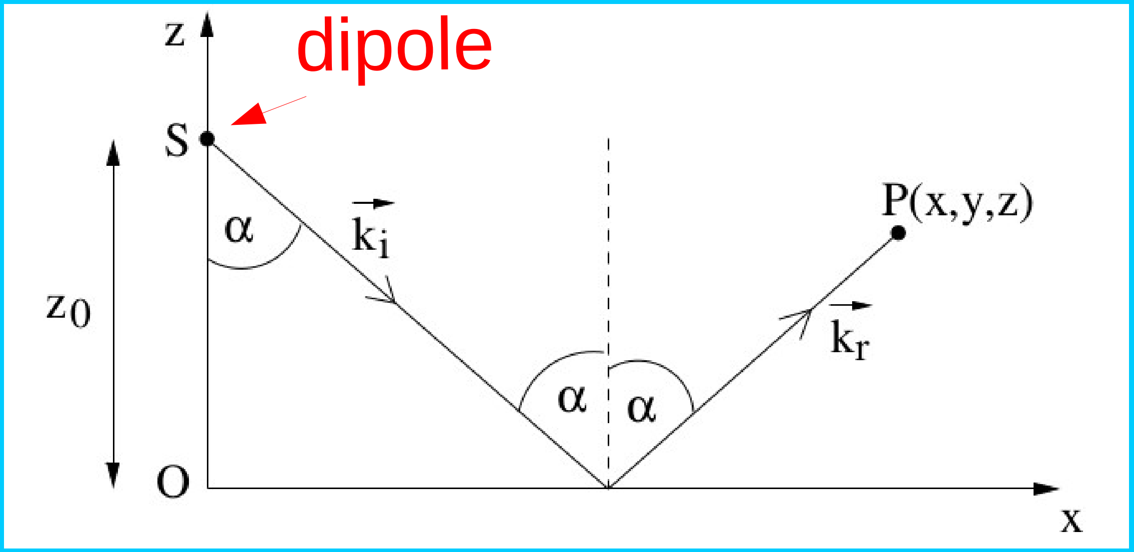
$$r \ll R_{earth}$$

Problems

- **Need to deal with spherical waves. Reflection/refraction with spherical waves is considerably more complicated than with phane waves**
- **Need reflection on spherical surface (Earth)**
- Need to include surface roughness effects

Have developed a reliable formalism to deal with spherical waves and surface curvature using reasonable models for surface roughness

Weyl Formalism for spherical waves



Hertz Potential r >> λ

$$\Pi_y(x,y,z) = \frac{e^{ikR}}{4\pi\epsilon R} + F_1(x,y,z)$$

Primary field

Decompose into plane waves **(α, β)**:

$$\frac{e^{ikR}}{R} = \frac{ik}{2\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}-i\infty} e^{ik[x\sin\alpha\cos\beta+y\sin\alpha\sin\beta+(z_0-z)\cos\alpha]}\sin\alpha d\alpha d\beta$$

$$\vec{k}_i = k\left(\sin\alpha\cos\beta\,\hat{x}+\sin\alpha\sin\beta\,\hat{y}-\cos\alpha\,\hat{z}\right)$$

Polar angle: π-α
Azimuthal ang: β

Incident Electric and Magnetic Fields

$$\vec{E} = \vec{\nabla}(\vec{\nabla} \cdot \vec{\Pi}) + k^2 \vec{\Pi}$$
$$\vec{H} = \frac{k^2}{i\omega\mu}(\vec{\nabla} \times \vec{\Pi})$$

For each plane wave **(α, β)**

$$\vec{E}_{inc} = \frac{ik^3}{8\epsilon\pi^2}\tilde{\Pi}\left[-\sin^2\alpha\cos\beta\sin\beta\hat{x} + (1-\sin^2\alpha\sin^2\beta)\hat{y} + (\sin\alpha\sin\beta\cos\alpha)\hat{z}\right]$$
$$\vec{H}_{inc} = \frac{ik^2\omega}{8\pi^2}\tilde{\Pi}\left[\cos\alpha\hat{x} + (\cos\beta\sin\alpha)\hat{z}\right] .$$

$$\tilde{\Pi} = e^{ikz_0\cos(\alpha)} e^{ik(x\sin\alpha\cos\beta + y\sin\alpha\sin\beta - z\cos\alpha)}$$

Each plane wave is split into components perpendicular (s) and parallel (p) to the plane of incidence and treated independently

$$\vec{E}_q = \vec{E}_q^s + \vec{E}_q^p$$

$$\vec{H}_q = \vec{H}_q^s + \vec{H}_q^p$$

Reflection, Transmission

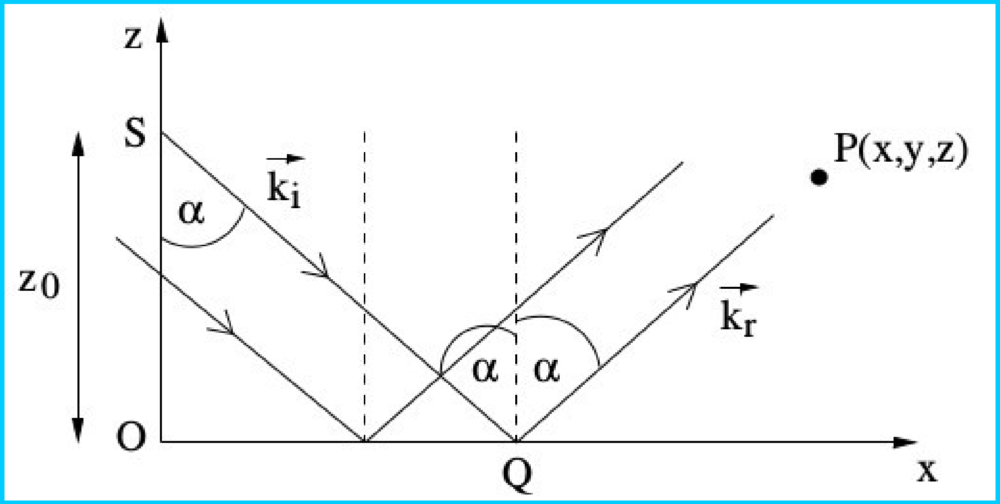
Fresnel formalism: Compute reflected, transmitted electric and magnetic fields for each component by imposing boundary conditions at the interface

add contributions from all plane waves

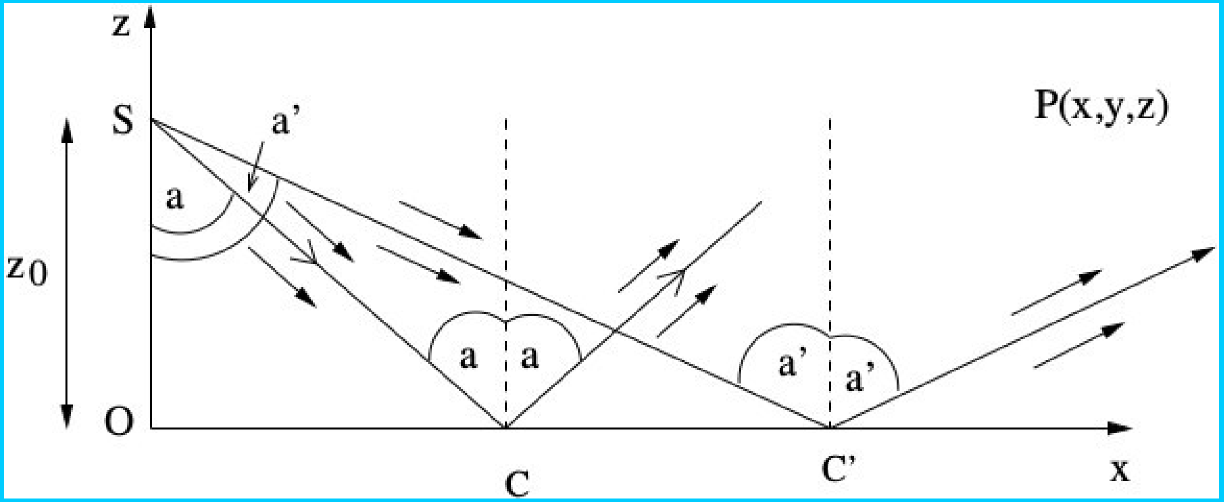
Finally compute H-Pol (or V-Pol)

H-Pol: y-comp of reflected and transmitted Electric field in y=0 plane

Reflection from Smooth Flat Surface



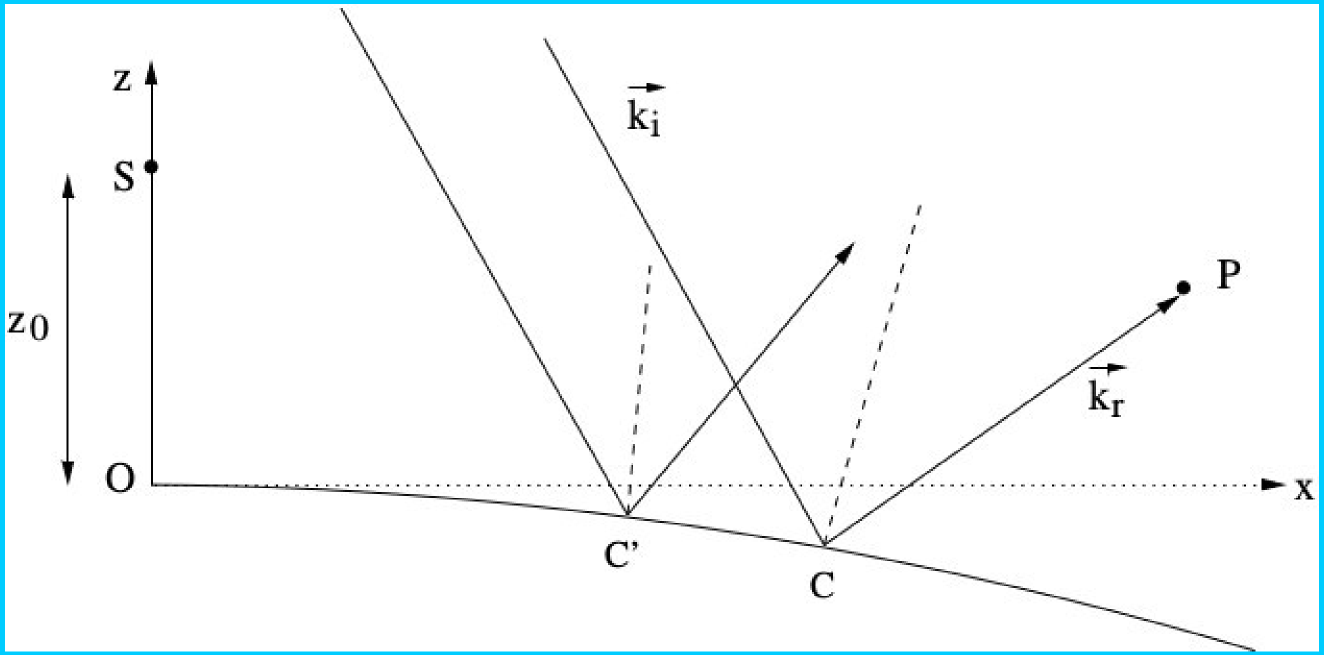
Reflected wave for each incident plane wave is a plane wave



Need to add contributions from all plane waves

The final result for spherical wave matches with Fresnel reflection

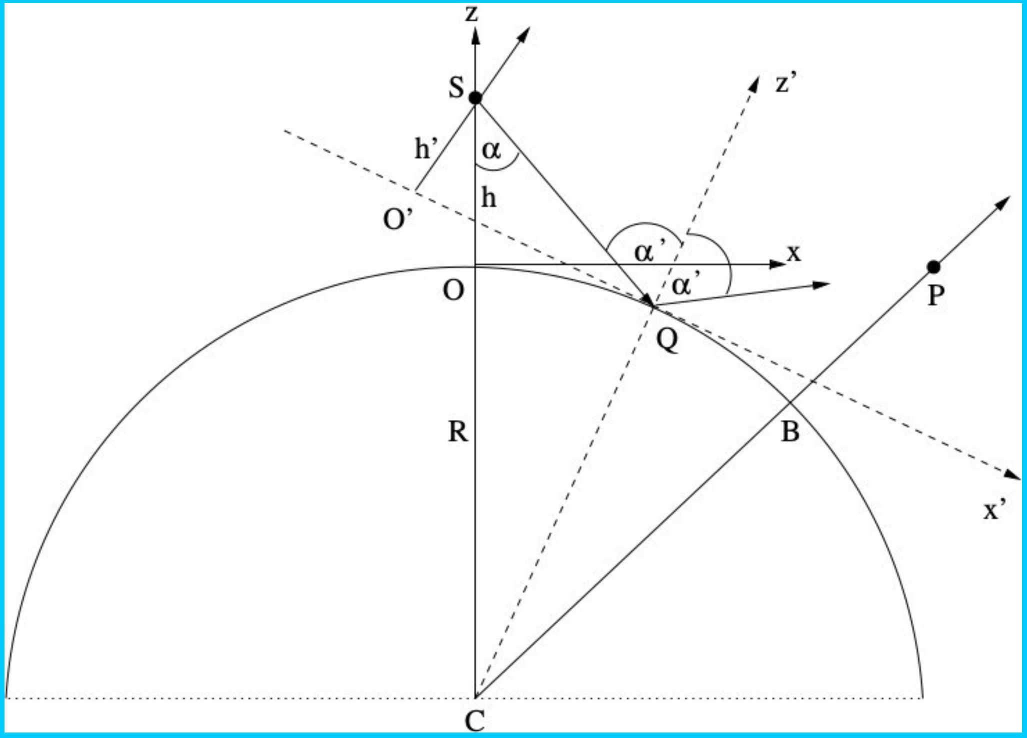
Reflection from Smooth Spherical Surface (Earth)



Reflected wave for each incident plane wave is not a plane wave

Reflection from Smooth Spherical Surface (Earth)

- **We may approximate the reflected wave for each incident plane wave to be a plane wave**
- **For each plane wave we identify a tangent plane on surface at Q which acts as a plane reflecting surface**



Q is the point where wave vector from S meets the surface

Antarctic Surface Roughnes Model

Gorham's roughness model

$$F(k,\rho,\theta) = \exp[-2k^2\sigma_h(\rho_\perp)^2\cos^2\theta_z]$$

$$\sigma_h(L) = \sigma_h(L_0)\left(\frac{L}{L_0}\right)^H$$

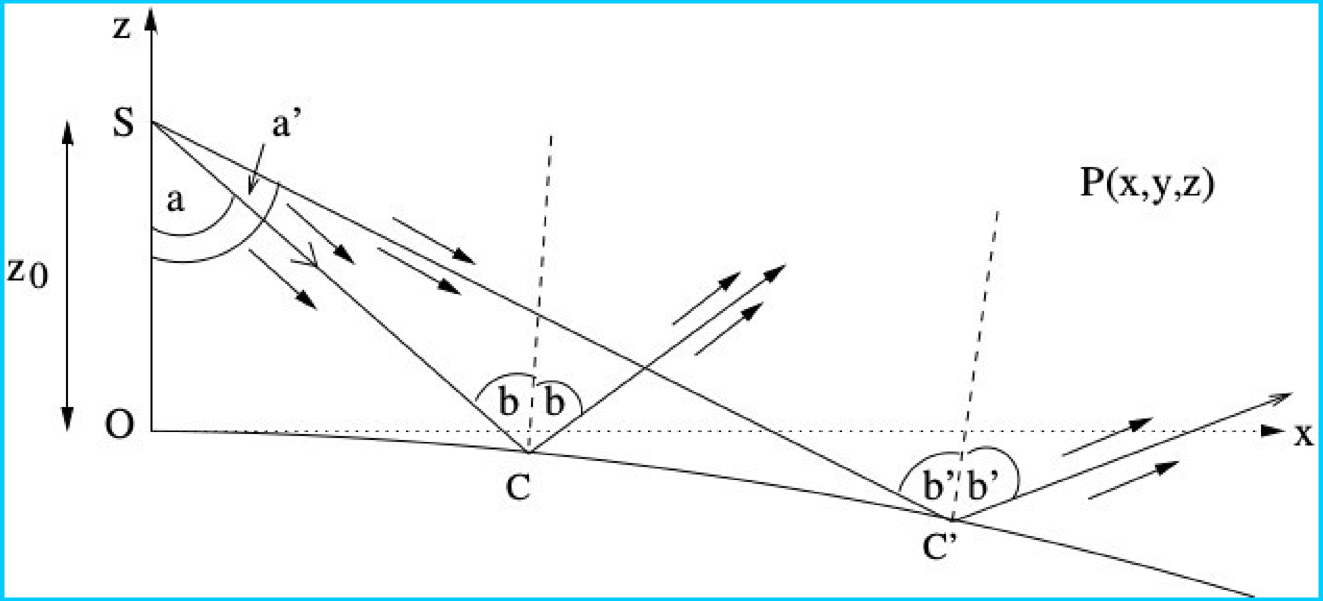
$\rho_\perp^2 = x^2 + y^2$ Perp distance from specular point

Θ_z = reflection angle

Reflected fields get multiplied by this factor

$$E_{\mathrm{ref},y} = \frac{1}{2}\frac{ik^3}{8\epsilon\pi^2}\tilde{\Pi}_{S,r}F(k,\rho,\theta)[f_r'^s(1+\cos 2\beta) - f_r'^p\cos\alpha\cos(2\alpha'-\alpha)(1-\cos 2\beta)]$$

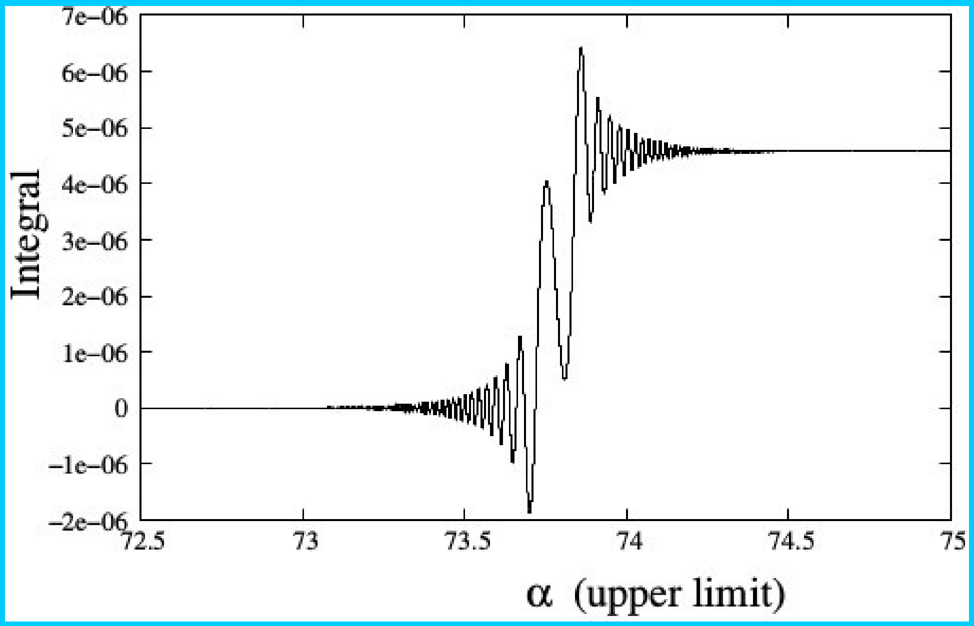
Spherical Surface

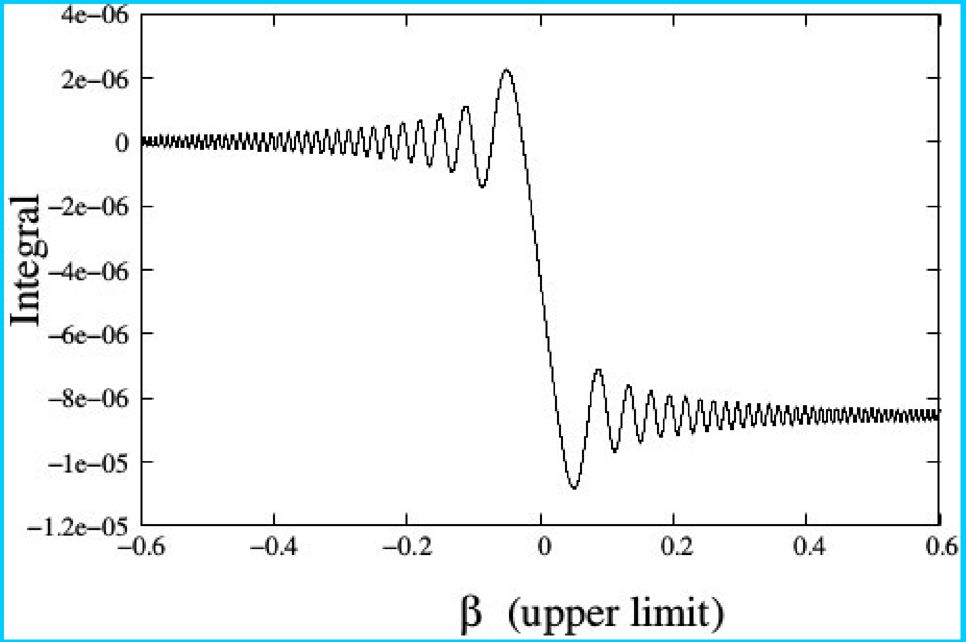


Need to add contributions from all plane waves

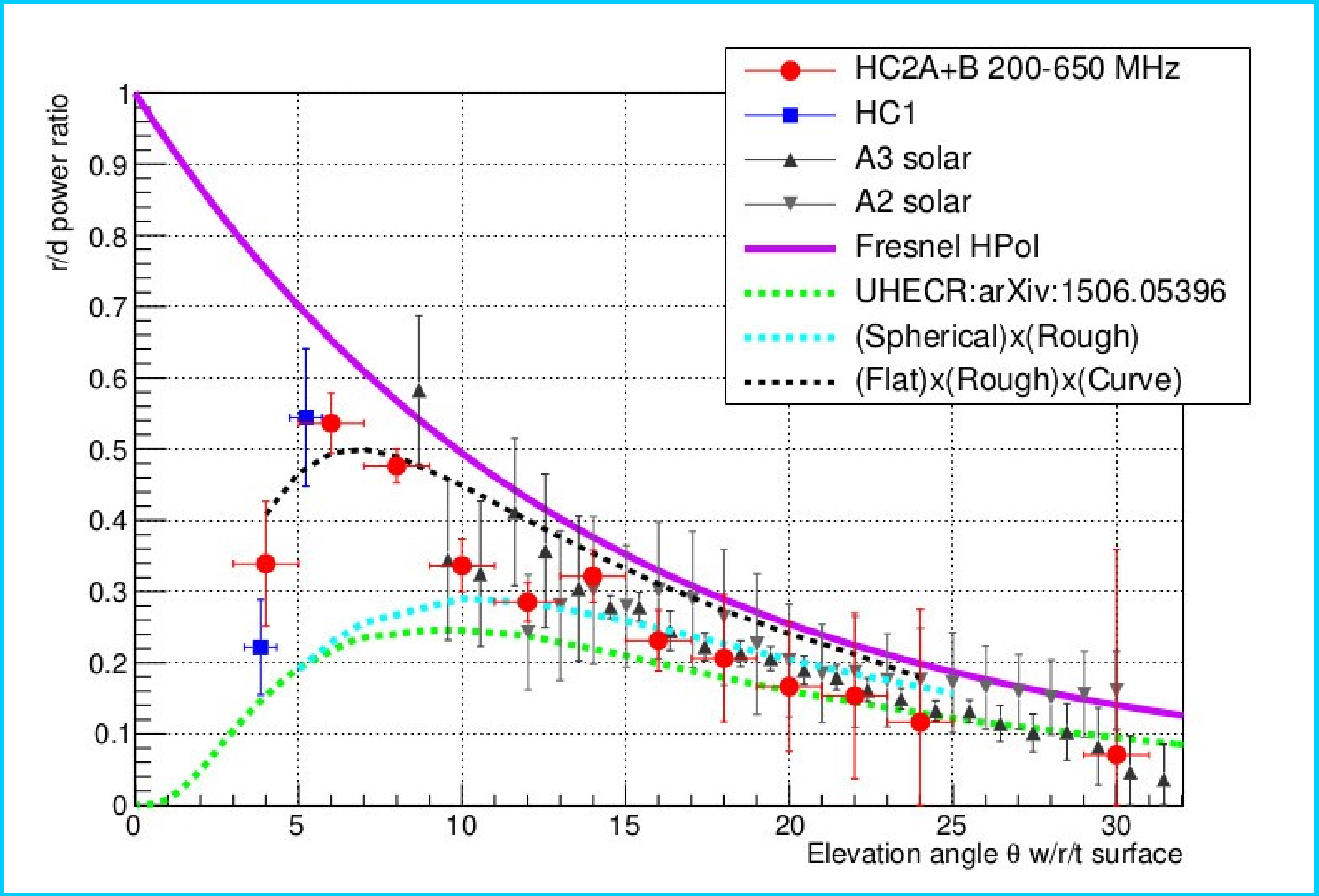
Reflection from Antarctica Surface

- The plane wave approximation works partially since we get dominant contribution from close to specular point





Comparison with HiCal



Agrees with HiCal data for large elevation angles (refl. ang. w.r.t. surface)

Deviates at small angles

A flat space calculation with curvature effects included geometrically works but is not rigourous

Prohira, Novikov, Dasgupta et al. PHYS. REV. D 98, 042004 (2018)

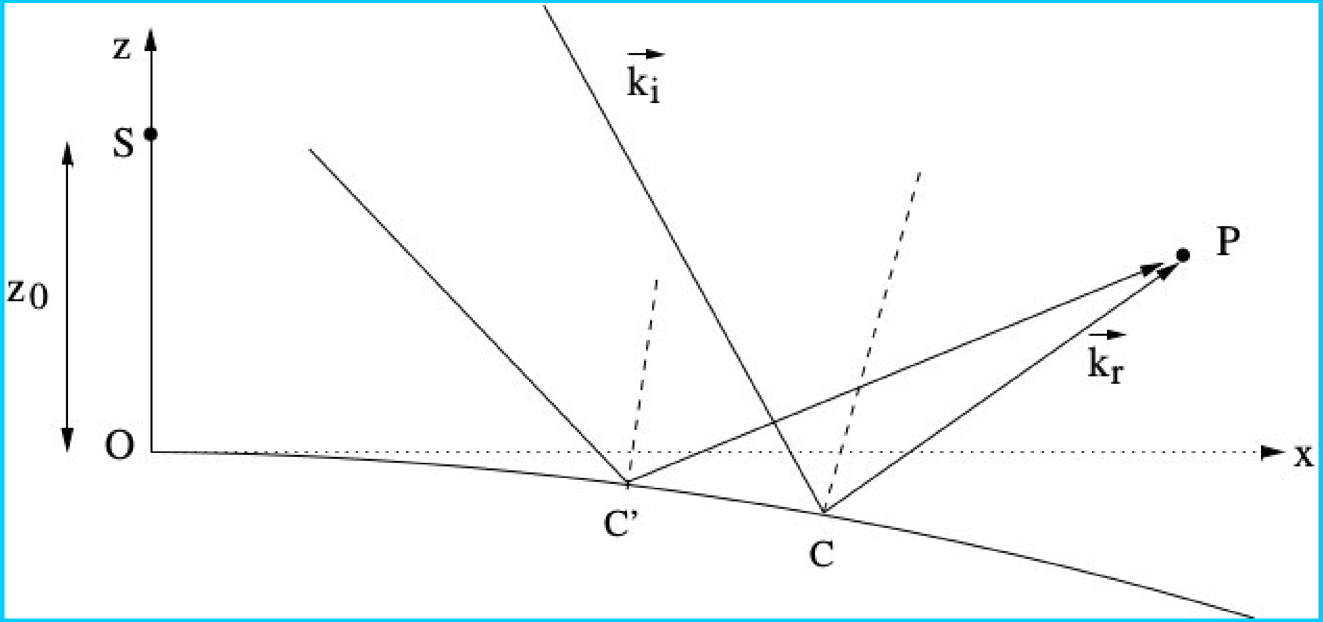
Local Plane Wave Approximation

- We assume that for each incident plane wave, the reflected wave from a spherical surface **can be approximated as a plane wave in a small neighbourhood of any point**
- **We can simply draw a tangent plane at any point on the reflected wave front. This defines the plane wave front at that point**

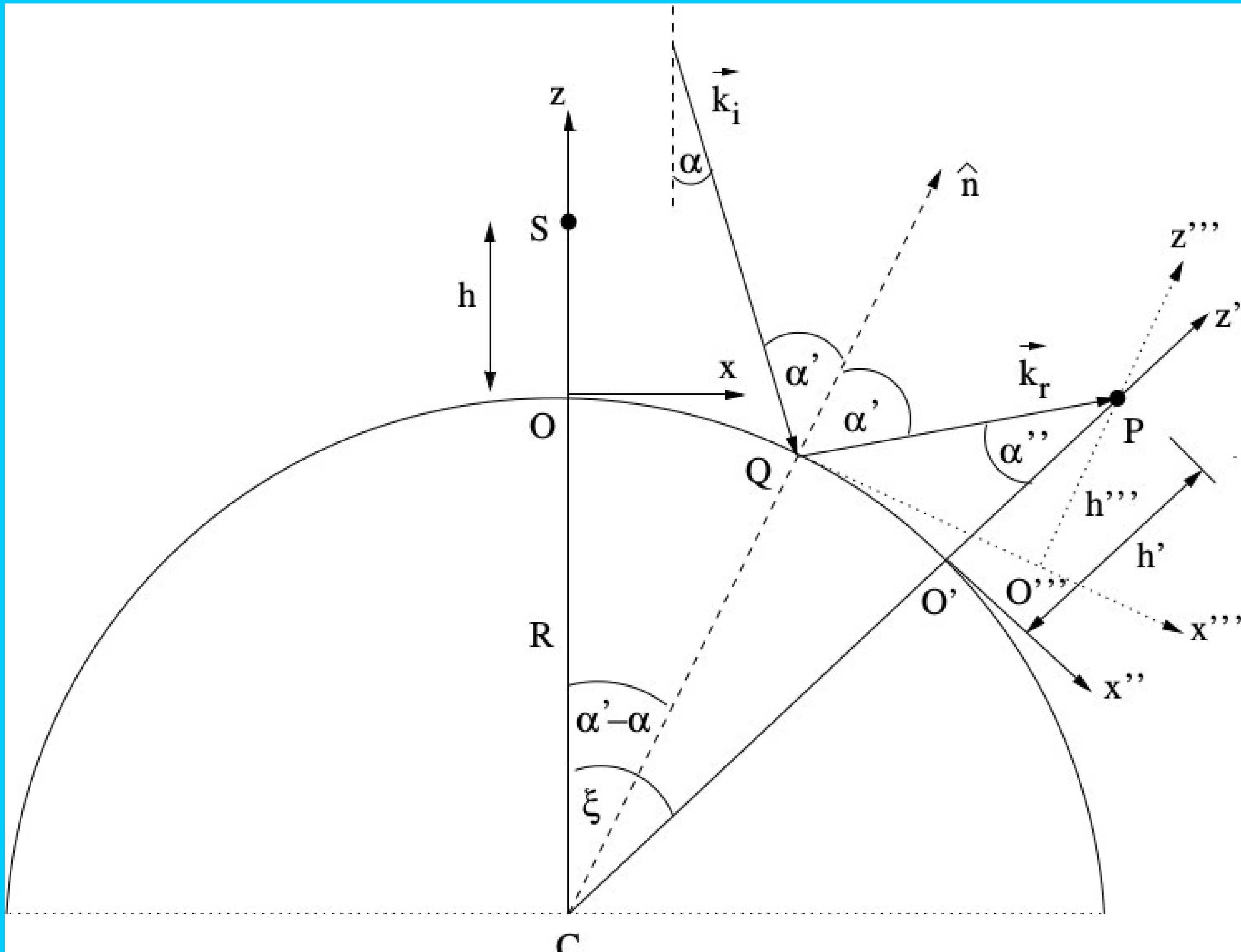
Local Plane Wave Approximation: Implementation

At the observation point P, we consider a particular reflected k vector $\vec{k}_r$

Determine where it meets the surface (C) and identify the incident plane wave vector $\vec{k}_i$

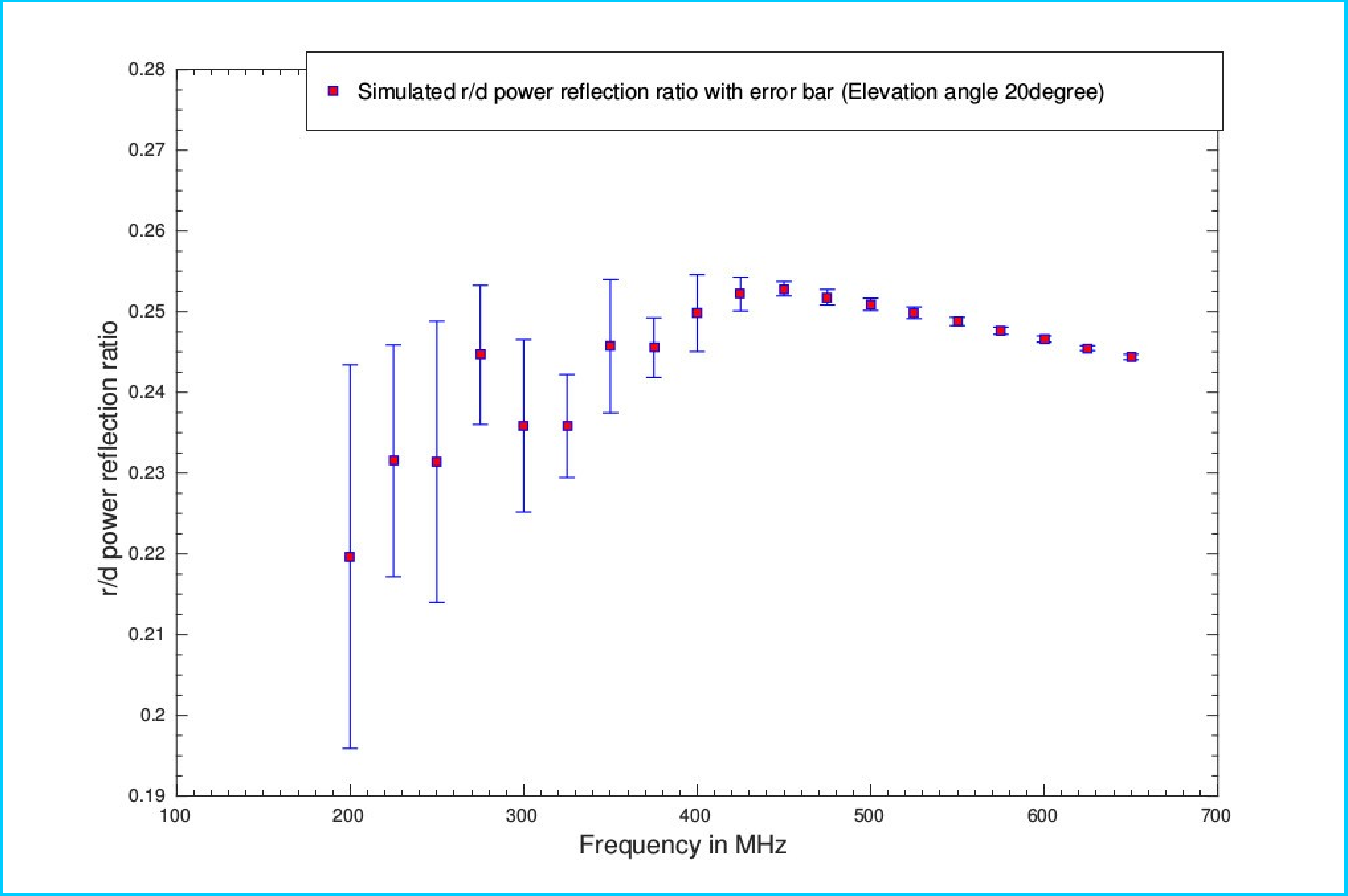


Finally sum over all incident plane waves

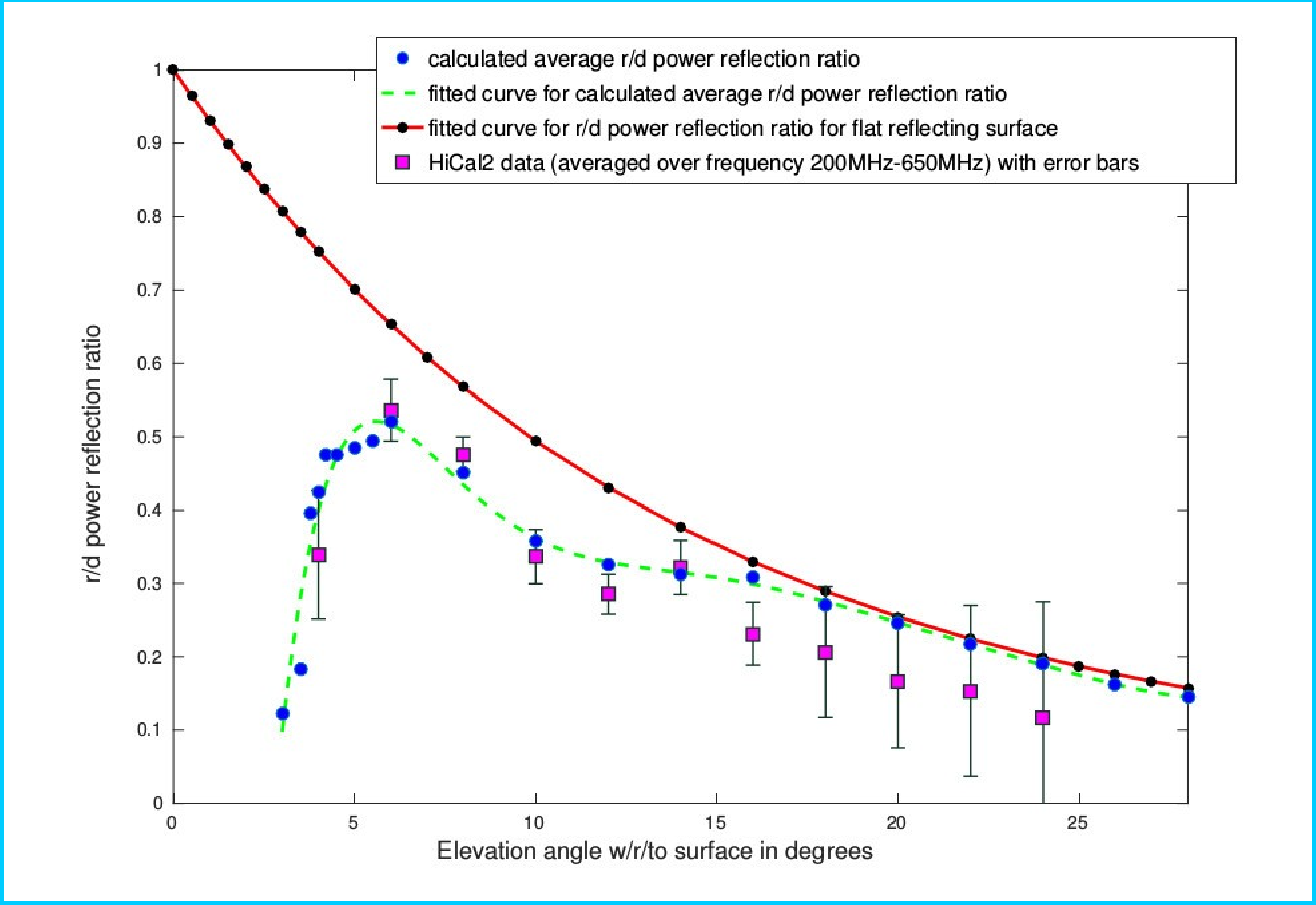


For each α, β the reflected wave vector points towards P

Power Reflection Ratio as function of frequency



Comparison with HiCal



Averaged over 200-650 Mhz

Agrees with data for all angles

Reflection of Pulses

We study reflection of pulses in order to understand the mystery events

Perhaps with some generalized roughness models the polarity can be reversed

Reflection of Pulses

Obtain Fourier components of the incident pulse

$$\widetilde{F}(n)=\sum_{t=0}^{N-1} f(t)\,\mathrm{e}^{i\frac{2\pi n}{N}t}$$

f(p) = pulse in time domain

$$\widetilde{F}(n)=\widetilde{F}_{real}(n)+i\,\widetilde{F}_{imag}(n)$$

Direct Field

$$E_d(t,r)=\frac{1}{N}\sum_{n=0}^{N-1}\left(\widetilde{F}_{real}(n)+i\,\widetilde{F}_{imag}(n)\right)\frac{\mathrm{e}^{-i\frac{2\pi nt}{N}}}{r}$$

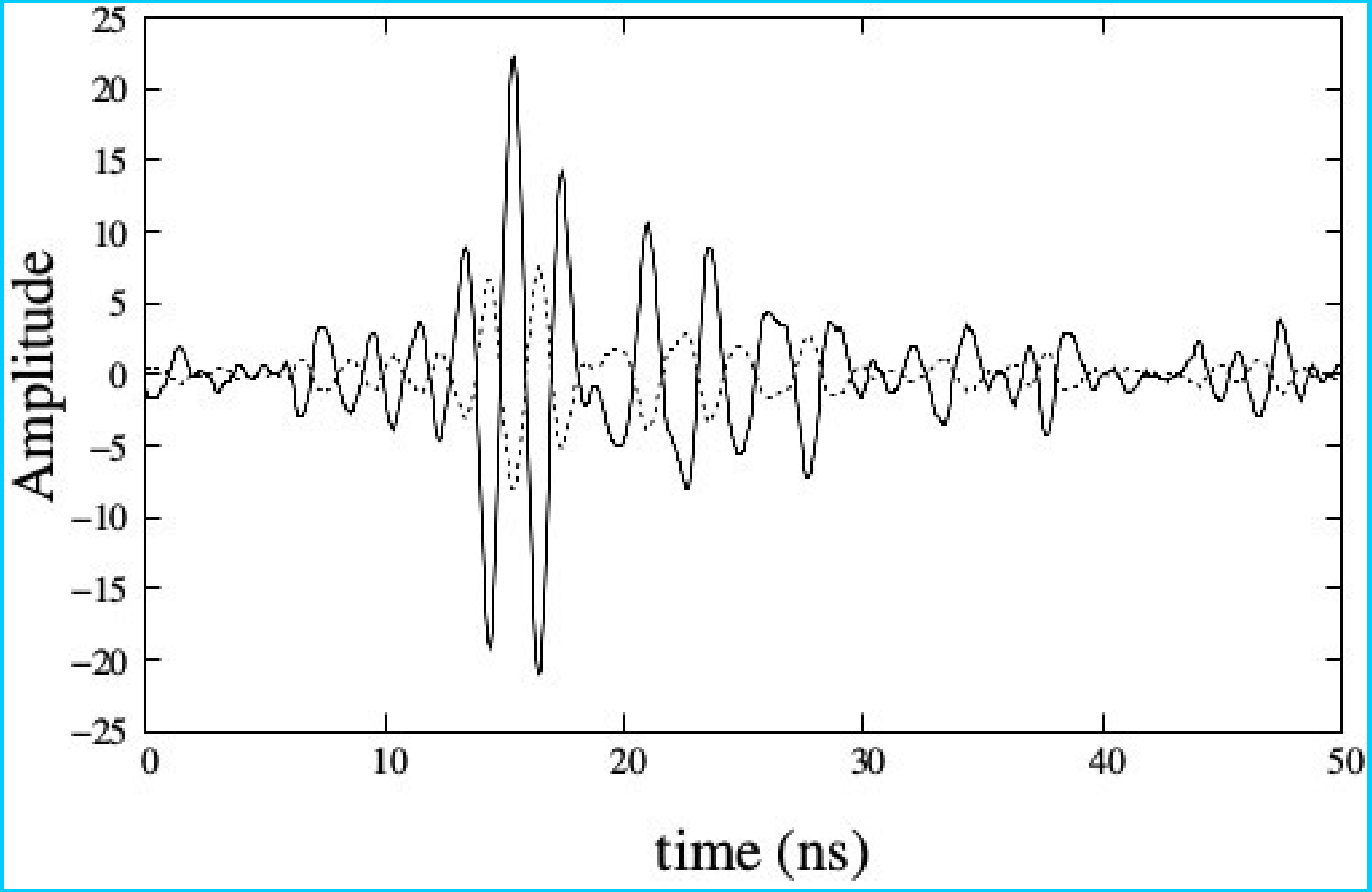
Sum over monochromatic spherical waves or dipole radiators, y=0 plane, E_y component

Reflected Pulse

$$E_{ref,y}(t,r)=\frac{1}{N}\sum_{n=0}^{N-1}\frac{ik}{2\pi}\chi(\omega,r)\left(\widetilde{F}_{real}(n)+i\widetilde{F}_{imag}(n)\right)\mathrm{e}^{-i\frac{2\pi nt}{N}}$$

χ(ω,r) is an integral over angles α, β corresponding to different plane waves for each monochromatic spherical wave

Reflection of Pulses



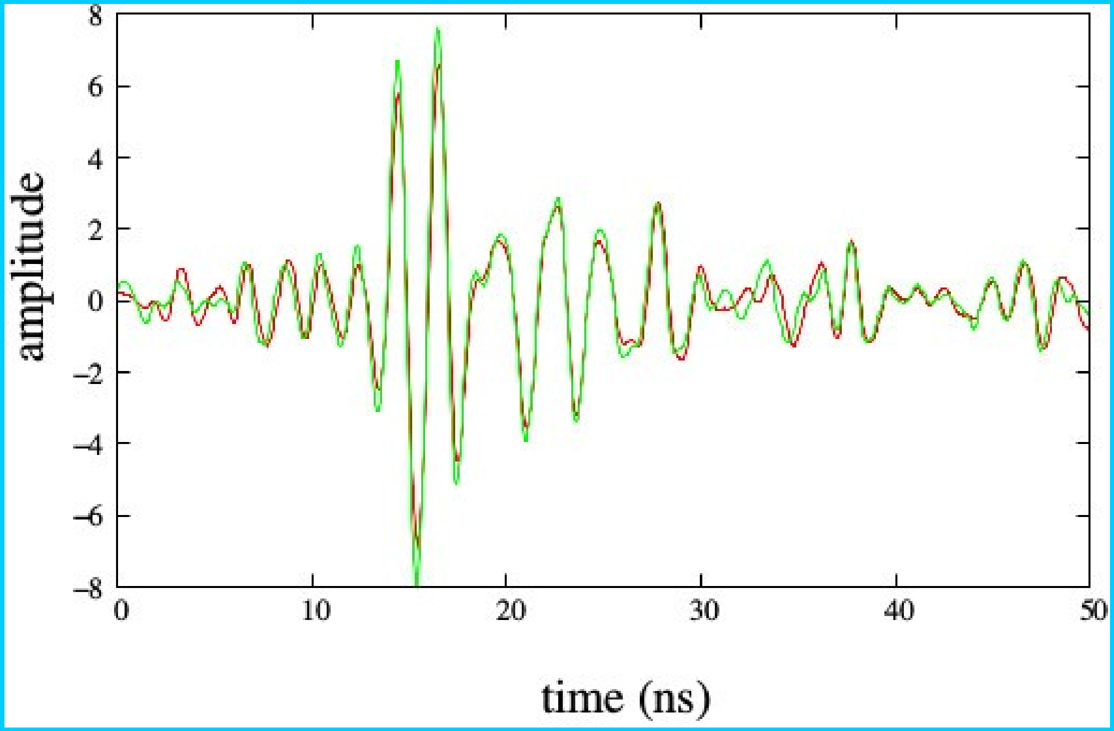
We see the 180 degree phase inversion, as expected

Reflection of Pulses, with asymmetric roughness model

$$F(k,\rho,\theta) = \exp[-2k^2\sigma_h(\rho_\perp)^2 \cos^2\theta_z]$$

$$\sigma_h(L) = \sigma_h(L_0)\left(\frac{L}{L_0}\right)^H$$

$$\rho_\perp^2 = x^2 + (\xi y)^2$$



The phase inversion is still present **but the relative amplitude of peaks and dips change.** **Hence there is some possibility of misidentification**

Green ξ = 1
Red ξ = 0.25

Another Roughness Model

$$F(k,\rho,\theta) = \exp\left(-(k-k_0)^2 \sigma_h^2(\rho_\perp)\cos^2(\theta_z)\right)$$

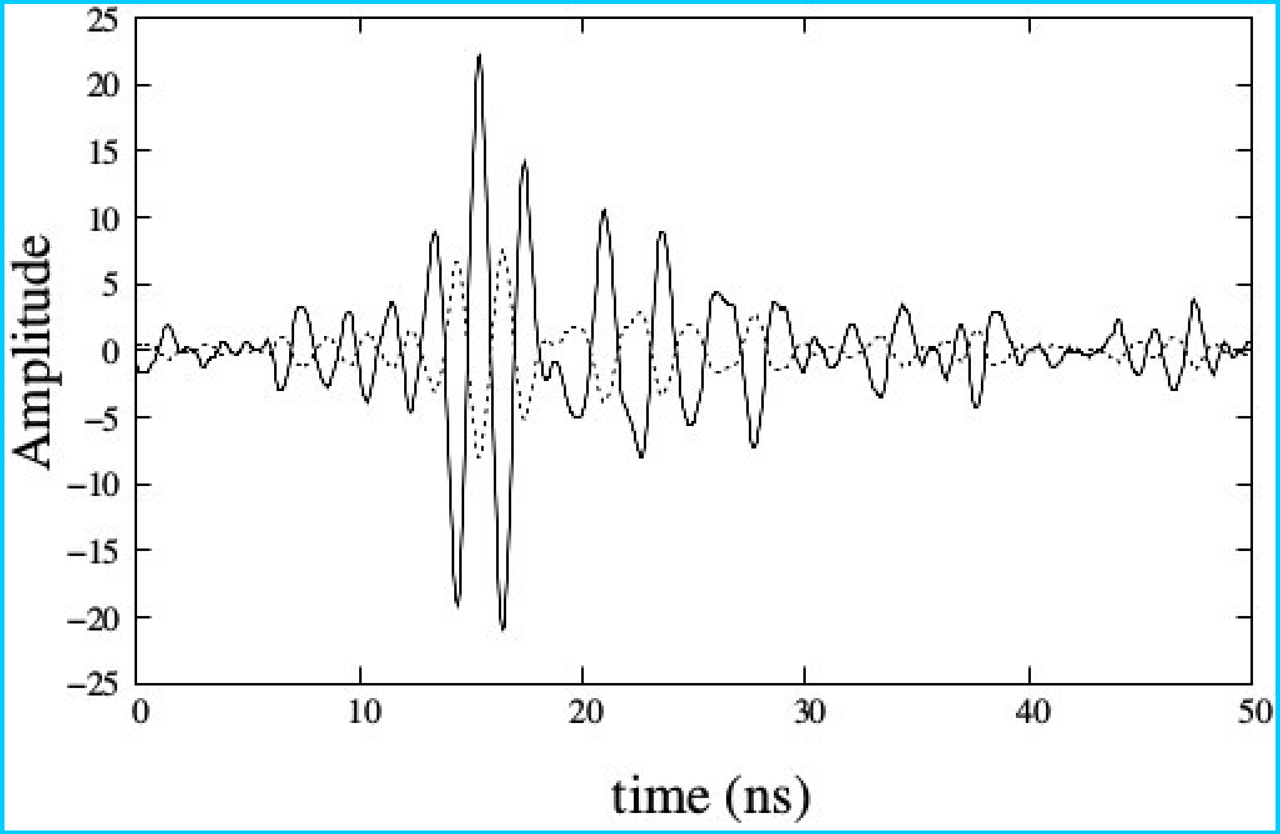
Generalized Roughness Models

We find:

Relative amplitude of peaks and dips can change, leading to misidentification of reflected as direct signal

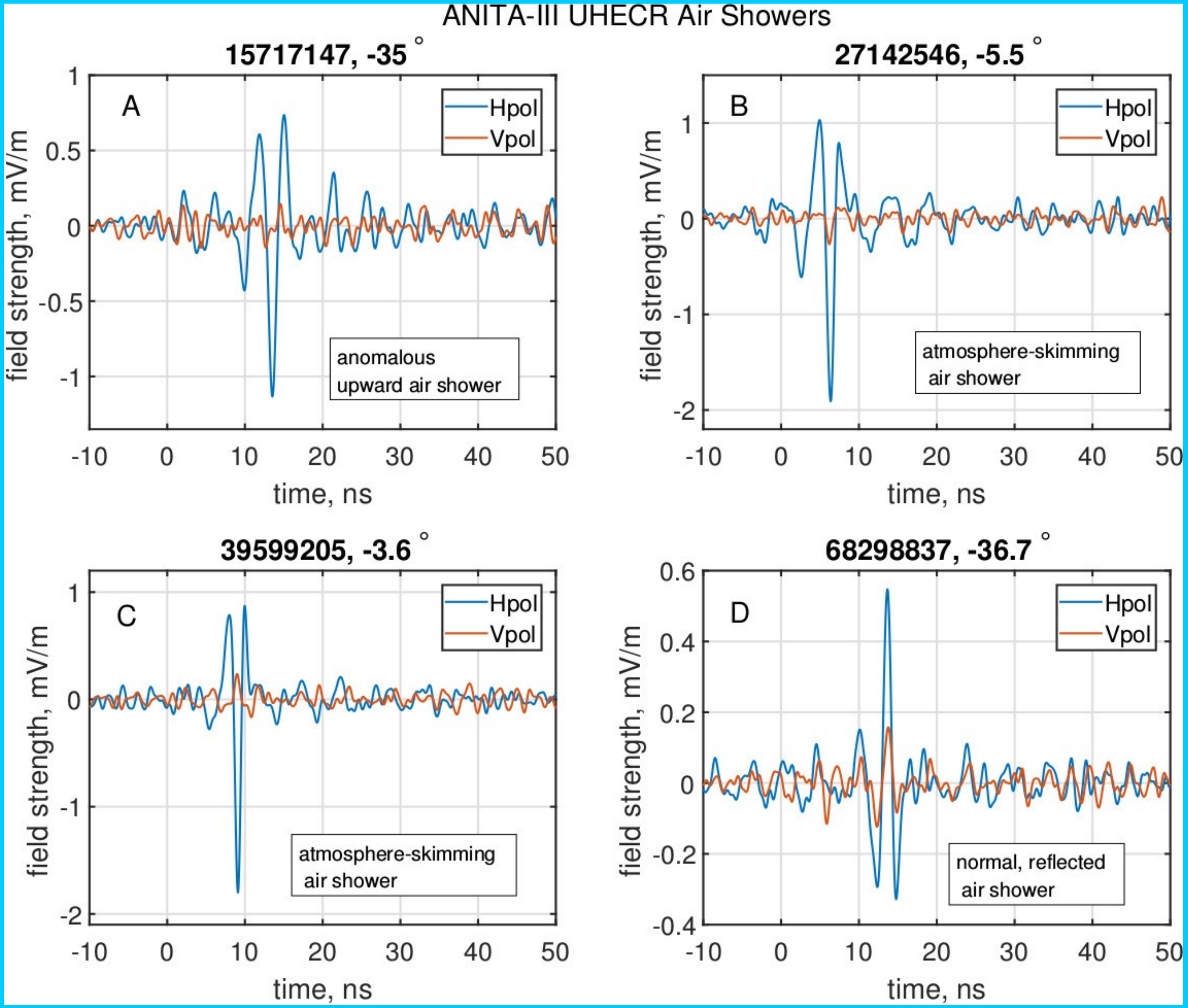
However for the models studied so far the effect is not large and can arise only in cases when the difference between the two is not large

A Sample Pulse with small difference (HiCal)



Misidentification is possible

ANITA III event: Difference is large



Misidentification does not seem possible

Work in progress

Conclusions

ANITA has observed very interesting events which in all likelihood represent Physics beyond the standard model

We have developed a rigourous model in order to handle reflection, refraction of radio pulses

The power reflection coefficient has been found to be in good agreement with HiCal data

The main uncertainty arises from the roughness effects which have to be modelled. But these appear to be relatively small

Conclusions

We see the expected change in polarity between direct and reflected pulses.

This relationship can be misinterpreted in some cases when the difference in amplitude between dominant peak and dip is small

But for the observed ANITA III event this difference is rather large. Hence misidentification does not seem possible