

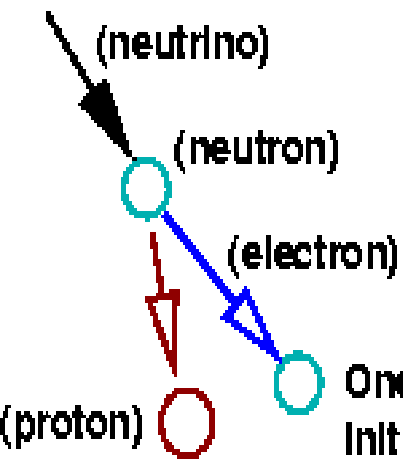
Radiofrequency detection of UHECR (*both protons & neutrinos*) in Antarctica

- detection of RF photons as a CR-observation tool:
 $L_{\text{atten}}(\text{ice}, f=300 \text{ MHz}) \sim 1.8 \text{ km}$
- History & Current Experiments
 - ANITA, ARA, ARIANNA
- Future Plans

Radio Wave EM shower detection (idealize pure EM shower)

- Neutrino-induced (e.g.) EM shower traveling through $n > 1$ medium produces charge excess via
 - Compton scattering (atomic electrons) + Bhabha (e^+ depletion)
 - Charge excess about 0.25 electrons/GeV of primary
- Each charged particle radiates Cherenkov photons with $E \sim hf$;
 - To detect single C-cone, target high-freq. (UV [pmt] vs. Radio, e.g.)
 - But shower gives NET E-field amplitude due to all shower particles
 - Electrons and positron Cherenkov largely cancel
 - Charge excess 'coherent' at wavelengths greater than transverse size (< 1 GHz)
 - For smaller wavelengths, net E-field INCOHERENT sum
 - Finite width of shower $\Rightarrow$ C-cone 'thickness' (few degrees)
- Coherence compensates for hf/photon for $E > 1$ PeV

$t=0$ nanoseconds: Incident electron neutrino (from AGN, e.g.) strikes a neutron (in ice), resulting in the production of a proton plus an electron: $\text{neutrino} + \text{neutron} \rightarrow \text{proton} + \text{electron}$

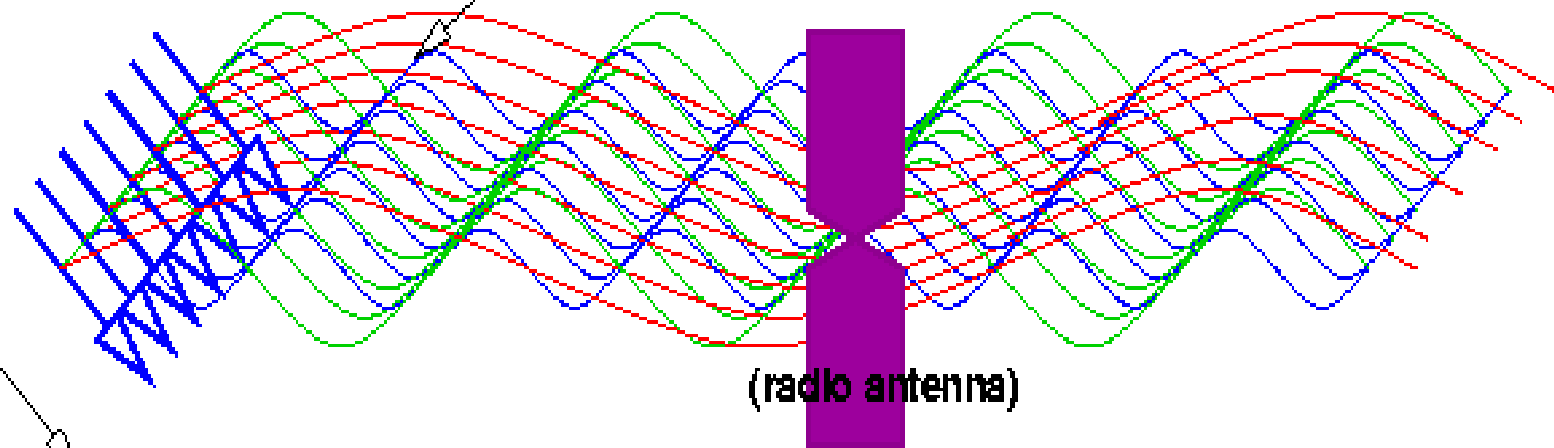


One nanosecond (approx. 20 cm) later, the electron strikes a second proton, initiating the 'shower'. This shower develops over the next 20 nanoseconds (approx. 4 meters), sweeping up atomic electrons already in the ice (blue arrows)

After 20 nanoseconds, there are approximately 10 million electrons moving forward along the shower 'front'.

(Multiwavelength) Cherenkov radiation; coherent at long wavelength (red)

4 meters



These electrons move through the ice at velocities greater than the velocity of light in ice, resulting in a 'sonic boom' of radiation (Cherenkov radiation). It is this Cherenkov radiation which our radiowave sensors (antennas) are designed to detect and measure.

Basic mechanism, in pictures



Askaryan: $Q_s = N_{e^-} - N_{e^+} \sim (E_s/4 \text{ GeV})$

Signal Strength details depend on

- a) length of shower
- b) charge excess
- c) radial profile

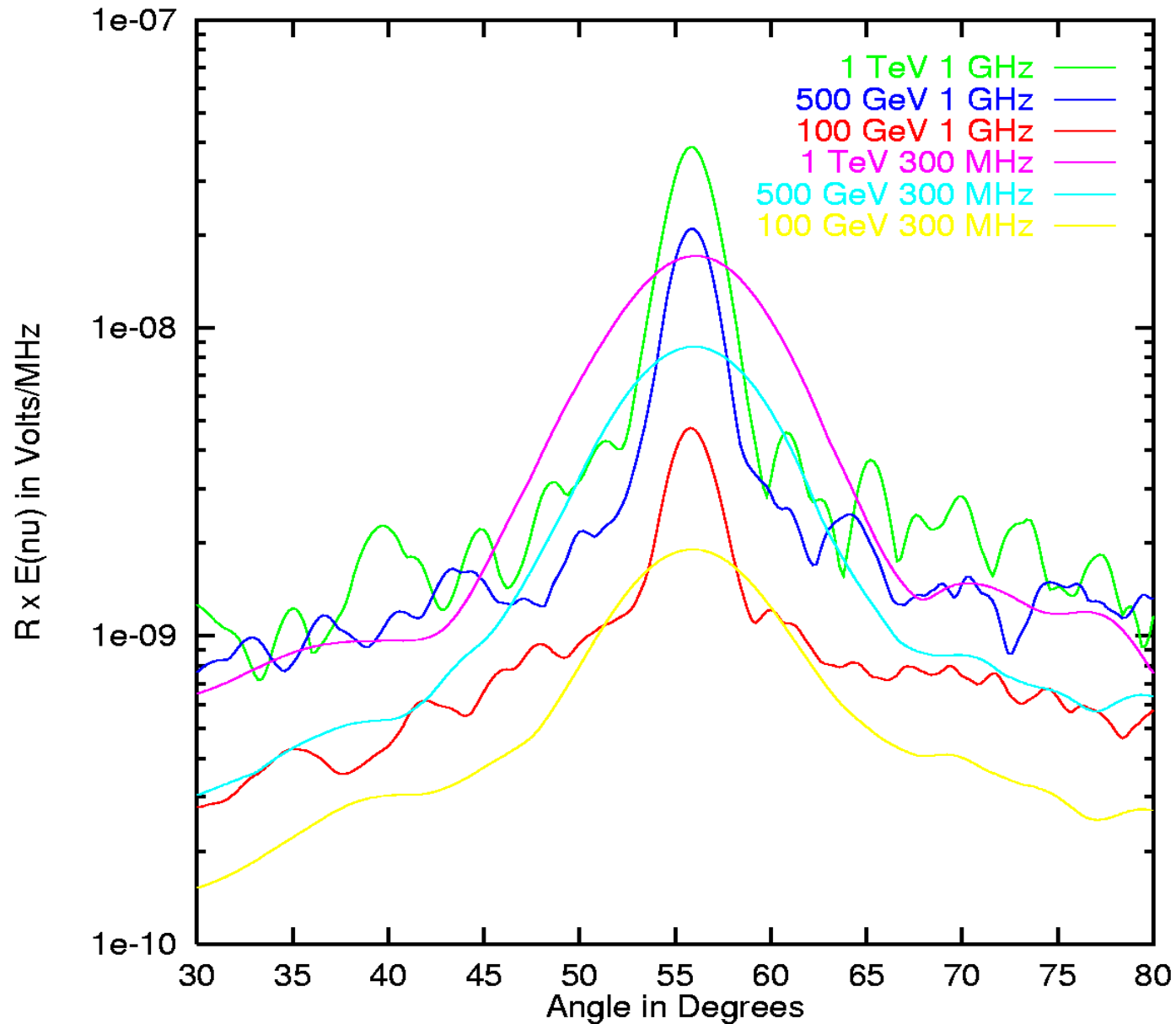


$$\theta_c = 56^\circ \pm 3^\circ$$

Frequency/angle correlation: Cone width $\sim$ FT of transverse charge;

width 'fattens' as inverse of frequency

Signal height $\sim$ total charge x 'tracklength'



Above/In/On-ice Cosmic Ray radio detection

- Some history

 - RAND, RAMAND

- Present efforts:

 - ANITA, ARIANNA, ARA

- Also lunar targets (GLUE, Puschino, LORD) and Jupiter/Saturn moon targets (PRIDE)

- Comparison of the two in-ice experiments

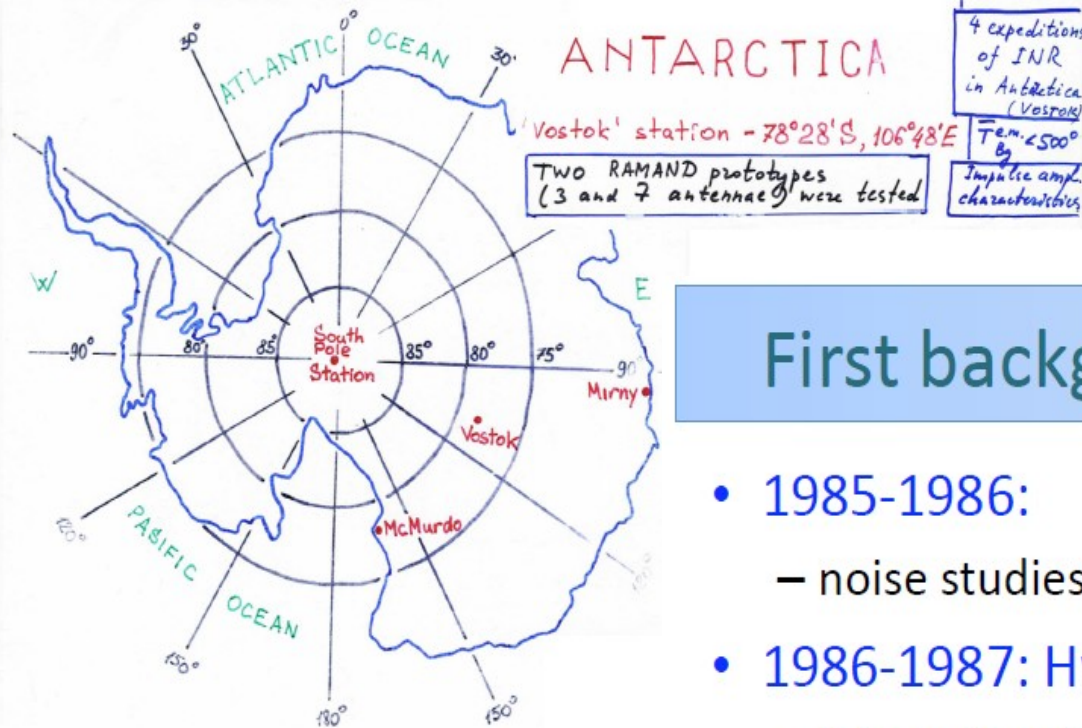
SALSA: in-salt, but RF attenuation length prohibitive

In the beginning...

- RAMAND:
 - Follows 1983 proposal by Markov and Zheleznykh to instrument surface array at Vostok
 - Aside: Vostok deeper (x1.4) than South Pole
 - Colder than South Pole (surface temp ~5° C colder)
 - Firn layer 90 m
 - vs. 150 m at South Pole
 - Institute of Nuclear Research, Moscow (Zheleznykh and Provorov)
 - Tests at station Vostok by Provorov, 1988-1990
 - \$1M rubles promised to continue research by CCCP on August 18, 1991.
 -

Stations in Antarctica

RAMAND in 1984-1990



Kravchenko et al,
ARENA 2010 Proceedings

First background studies and Hydra

- 1985-1986:
 - noise studies w/ single module
- 1986-1987: Hydra
 - 3 broadband receiver channels
 - Pinger locations reconstructed
 - Man-made backgrounds investigated (sources coincide with station objects)
 - Upper limit on flux of impulse pulses from ice obtained

Drilling equipment at Vostok, '80s

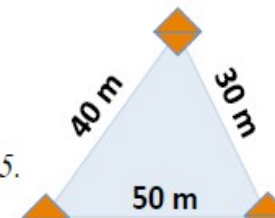


Deployment of radio pinger



Side Note: Hydra
antennas same as
used for Barwick et al
2004 measurement of
 L_{atten} at South Pole

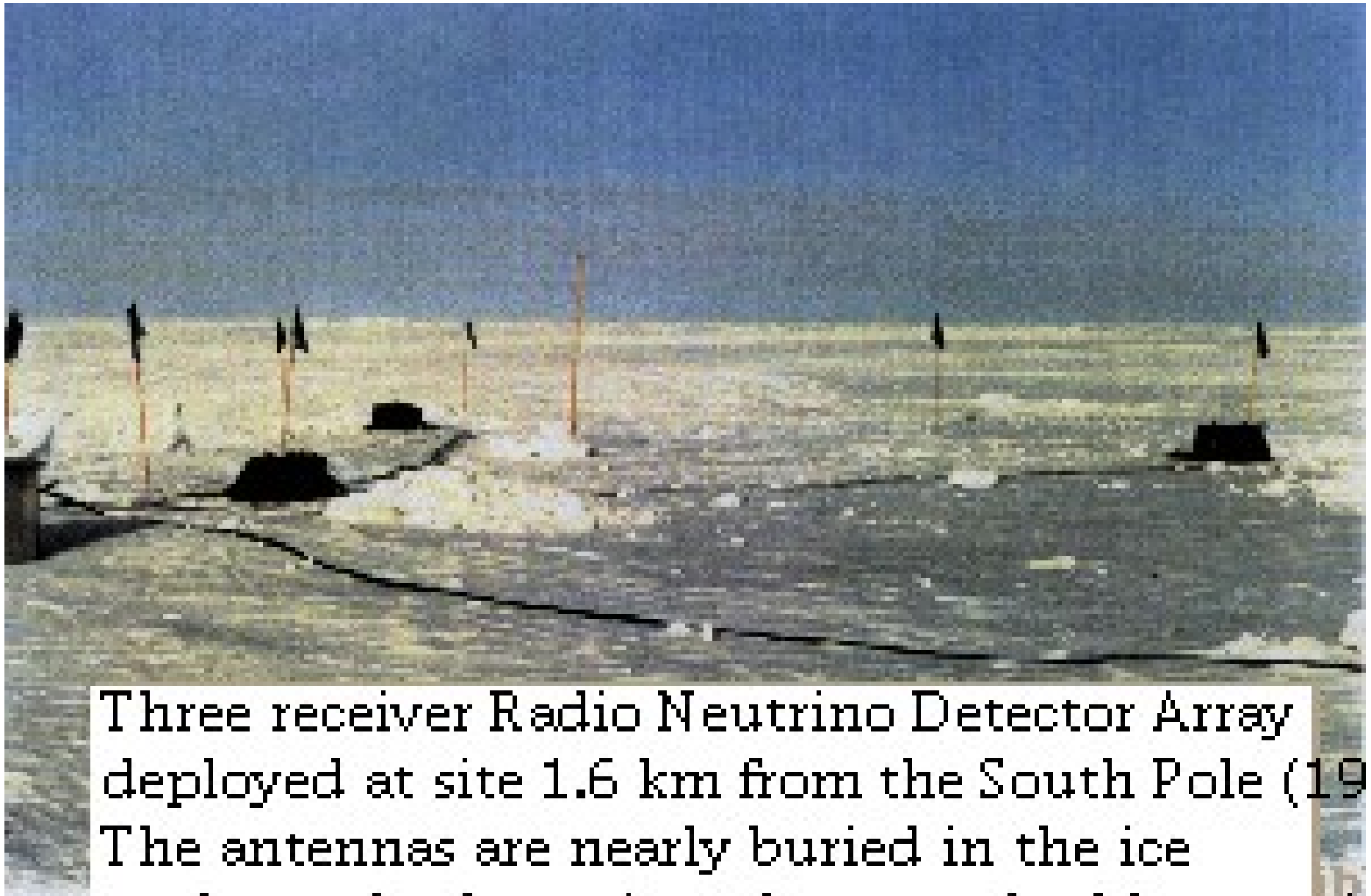
Proc. 20th Inter. Cosmic Ray Conference.
Moscow, "NAUKA", 1987, vol. 6, pp. 472-275.



On the second day (1989-1992)...

- RAND (South Pole):

<http://aether.lbl.gov/www/projects/neutrino/rand/rand.html>



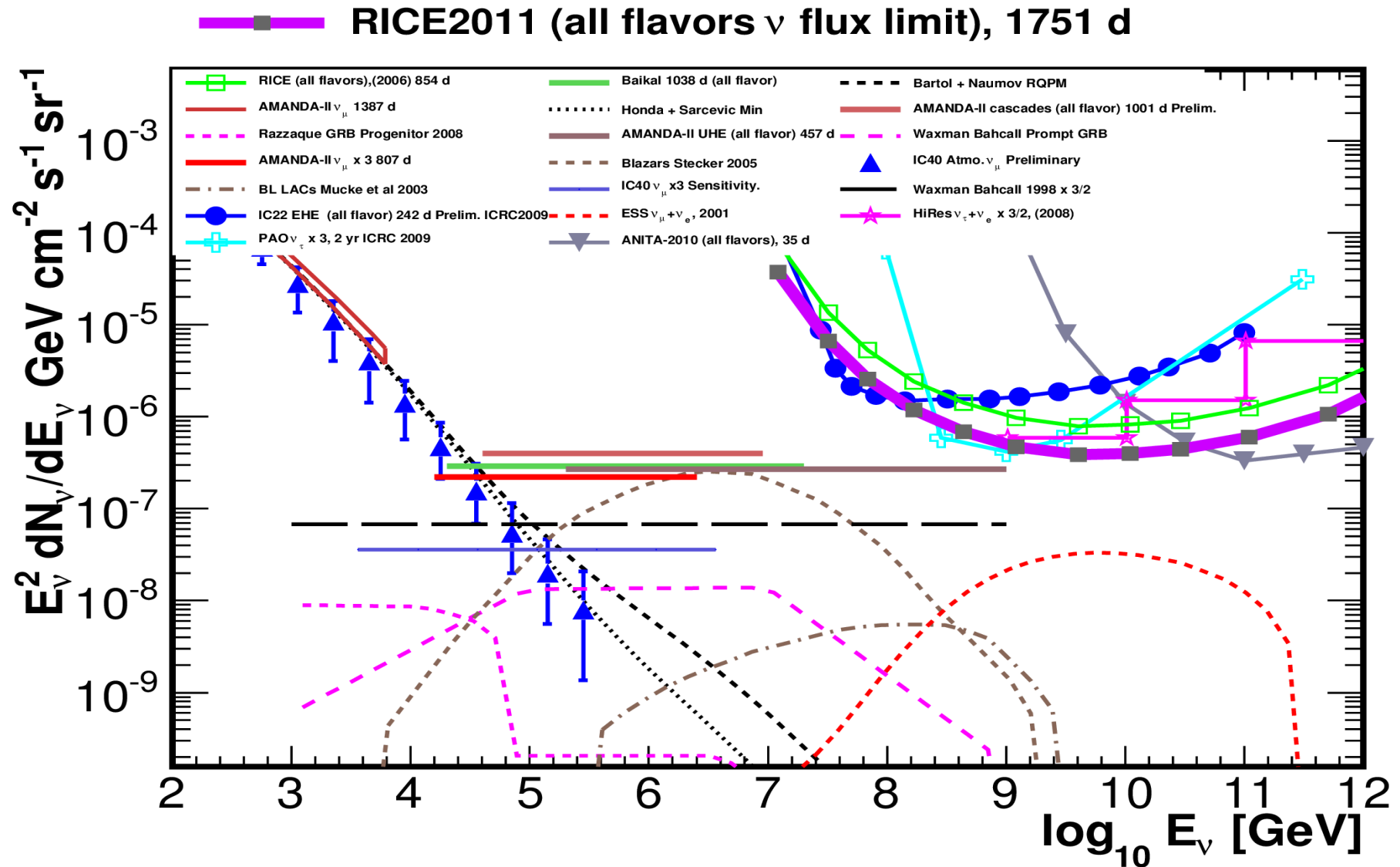
Three receiver Radio Neutrino Detector Array
deployed at site 1.6 km from the South Pole (19
The antennas are nearly buried in the ice

On the second day...

- *“The Smoot Group has performed two preliminary tests of the feasibility of using the Antarctic Ice for radio detection in trips to the South Pole in 1989 and 1991-1992. The December 1991 - January 1992 expedition, under the acronym A.R.C.N.O. (Antarctic Radio Cherenkov Neutrino Observatory), utilized three broad-band receivers singly and in coincidence on the surface. These tests indicated that there was no insurmountable background to the radio detection. However, a surface array is not optimal for radio detector, as the earth is fairly opaque to very ultra-high energies and total internal reflection in the top layer of ice both limit the available observation solid angle.”*

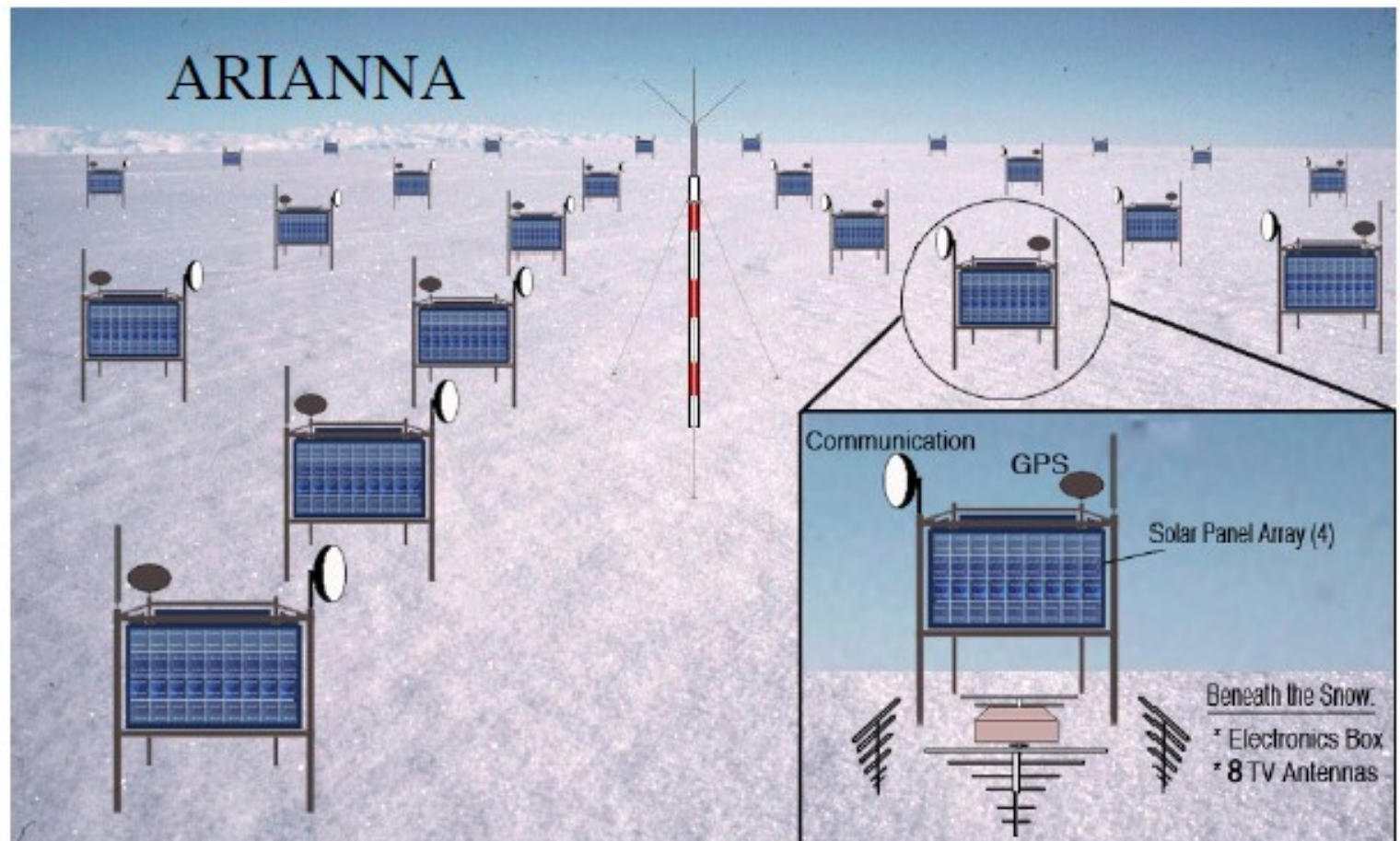
RICE: 20-ch dipole array: $(200\text{m})^3$

- 1995- parasitic* operation vis-a-vis AMANDA / IceCube... Limits on neutrino fluxes:



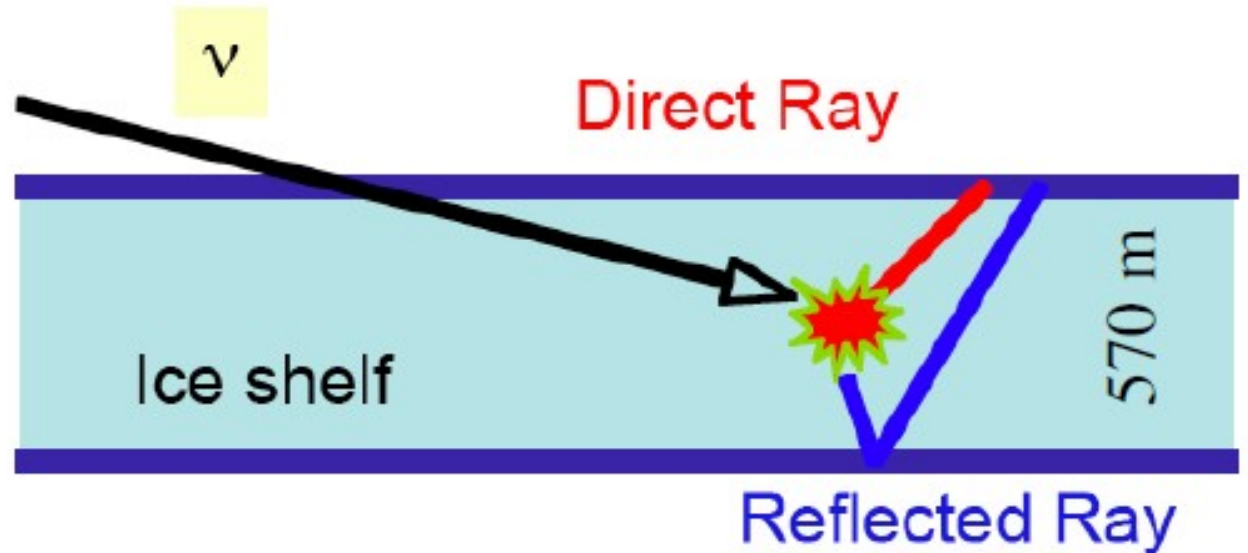
31 x 31 array
[30 km x 30 km]

8 LPDA Rx
110 MHz+
All HPOL!
Air showers?

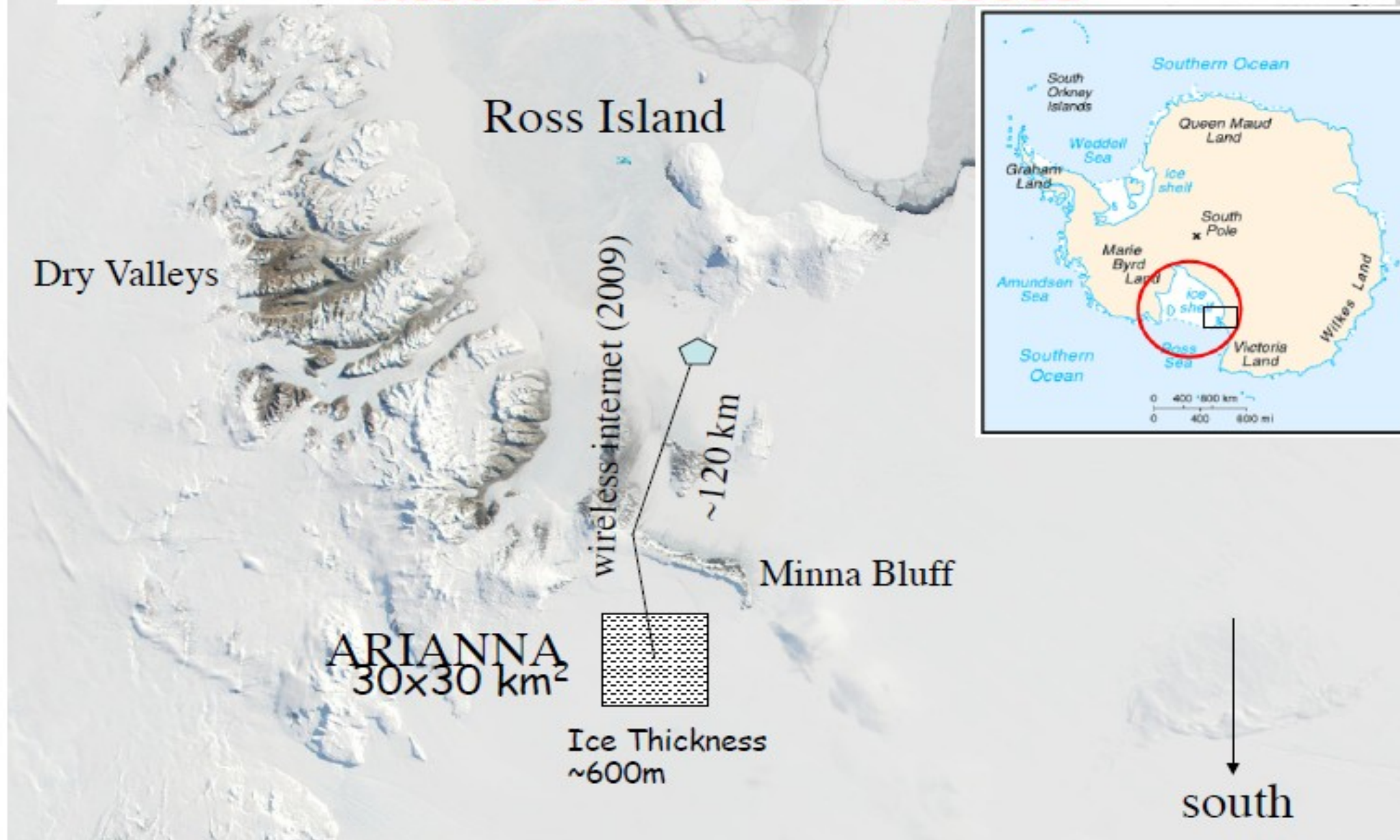


ARIANNA

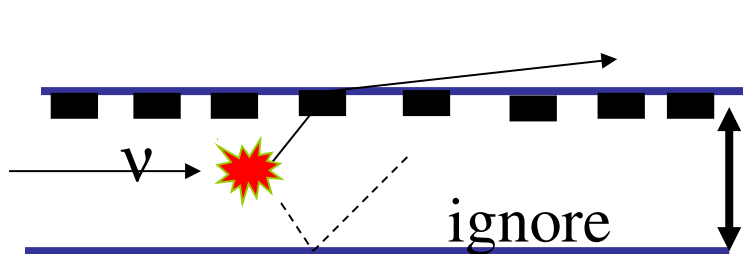
US, S. Korea, England,
New Zealand



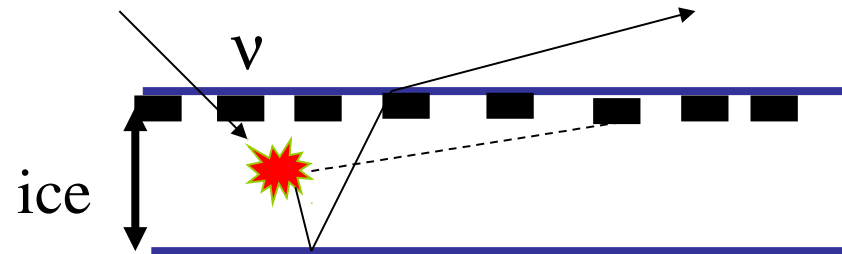
Satellite Image of Victoria Land and Ross Ice Shelf



reflected and direct events



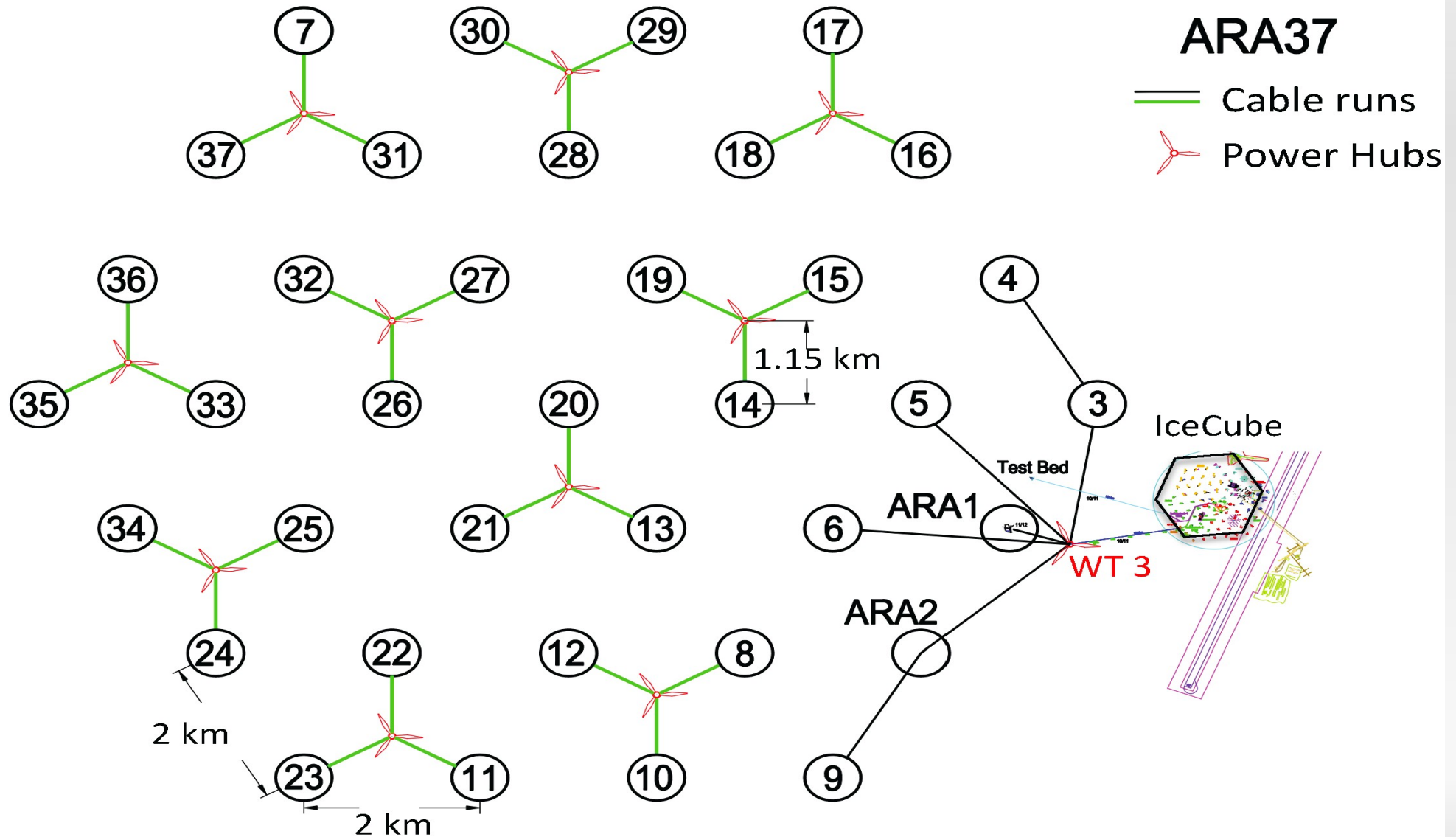
Direct



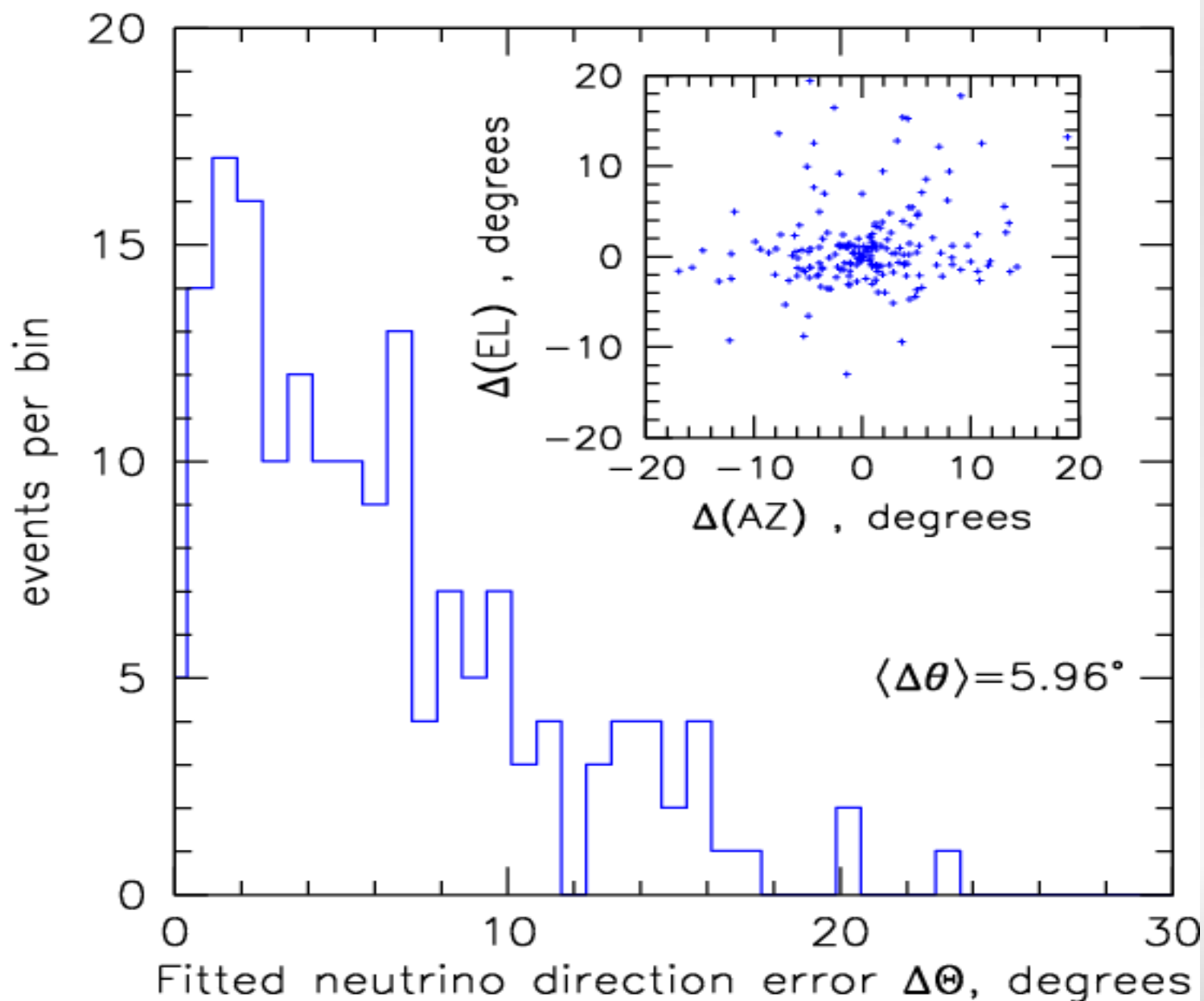
Reflected
(much greater solid angle)

sensitivity to neutrino
cross section !

The ARA Experiment at the South Pole

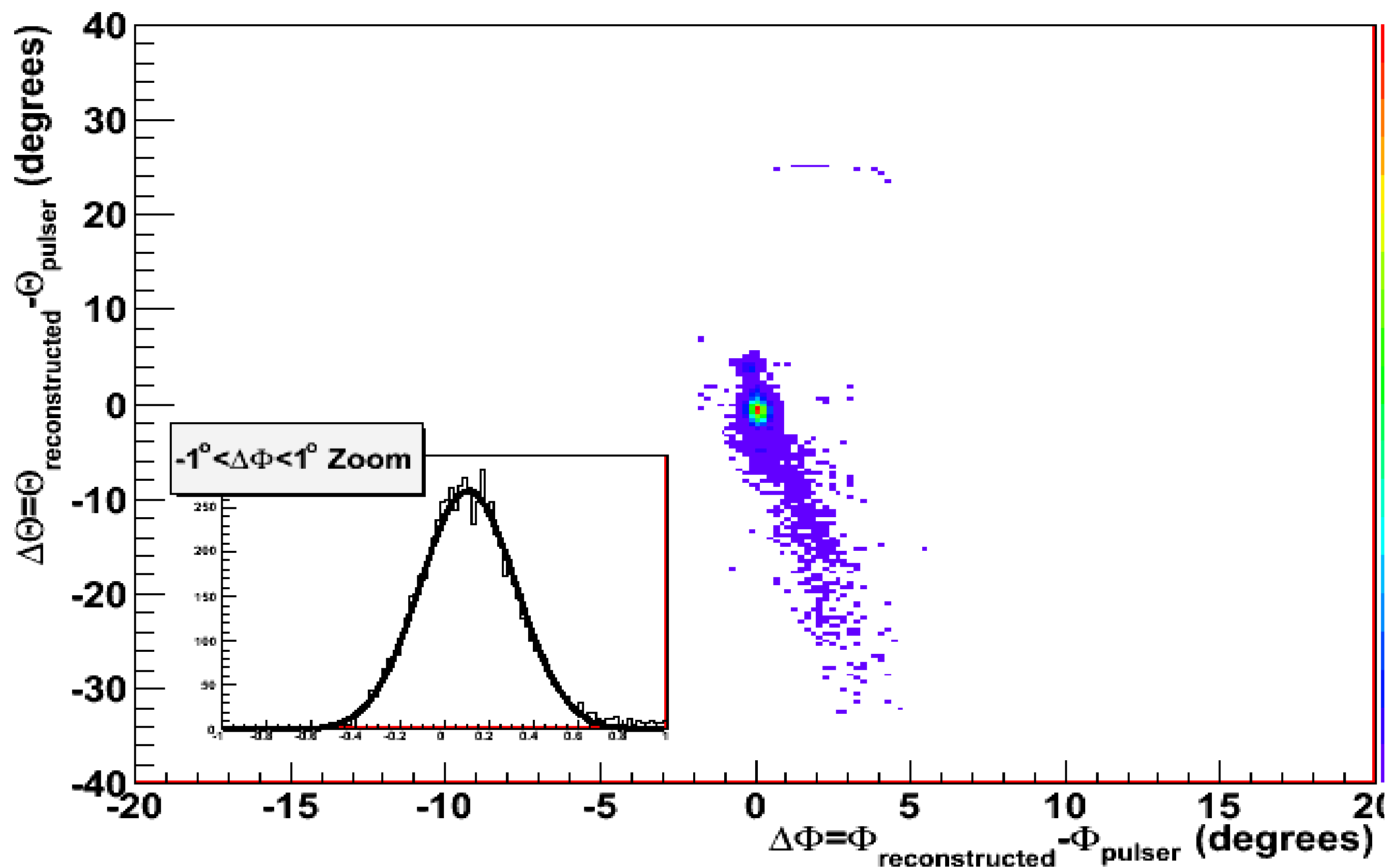


Expected ARA-37 reconstruction Performance: Neutrino Astronomy



ARA angular resolution: $0.2^\circ/0.6^\circ$ in ϕ/θ

Jan 29 Event Reconstruction

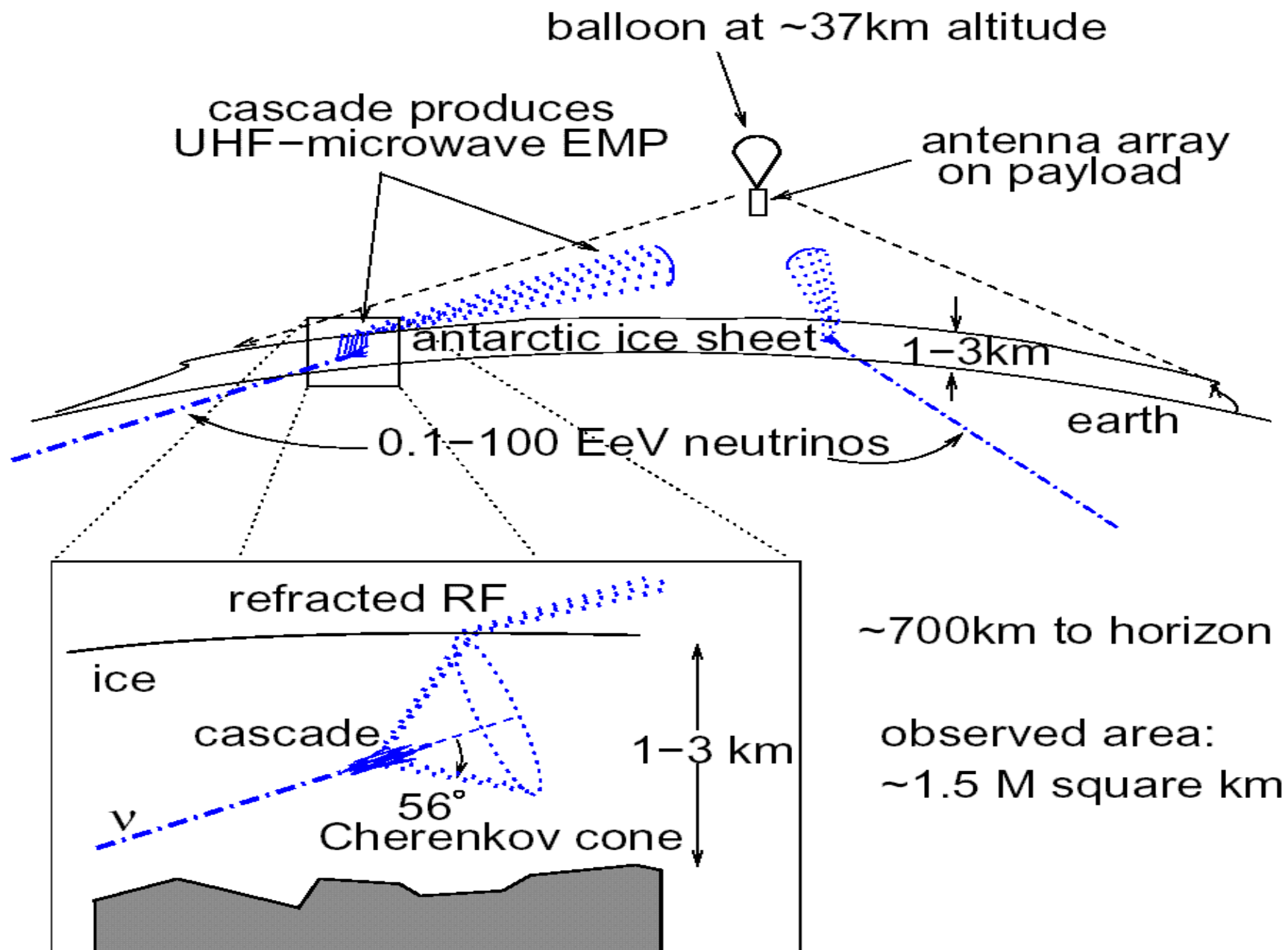


	ARA	ARIANNA
locale	South Pole	MinnaBluff
Trigger Rate	5 Hz	0.1 Hz
Trigger threshold:	$4 \times 4\sigma_{\text{KT}}$ over 256 ns	$4 \times 4\sigma_{\text{KT}}$ over 60 ns
Power Draw	100 W/20 Rx + 2 Tx	10 W/8 Rx + 1 Tx
Frequency band	4 x 25-300 MHz + 16 x 110-900 MHz	8 x 110-900 MHz
Hpol/Vpol	Yes/yes	Yes/no
Attenuation length	1500 m	500 m
$\delta\theta$ resolution	0.5°	2.5°
Air shower response	Yes, via RASTARA	Not yet studies (AFAIK)
Firn ray tracing	Small (for 200 m deployment)	Yes
Tx calibration	1 Hz	Once/run
Uncertainties (Z)	Hpol:VPol response in situ	Antenna response near-surface; ray-tracing to Rx
<u>Future funding</u>	<u>\$7M OPP proposal (not yet)</u>	<u>\$1 M MRI (funded)</u>
neutrinos	50/yr/37 stations (20 Rx/station)	80/yr/961 stations (7 Rx/station)

The ANITA Experiment: Balloon-borne detection



ANITA concept



ANITA science

- Primary mission: “GZK neutrinos” caused by photo-production of UHECR on CMB: $\gamma N \rightarrow \Delta \rightarrow \pi X \rightarrow \nu X$
 - 2013 Observation by IceCube of first UHE non-atmospheric neutrinos ($\sim$ PeV)!
 - Sub-GZK, but perhaps there is a high-energy tail that extends into ANITA sensitive energy range?
- Detection scheme: Coherent RF emitted by shower from $\nu N \rightarrow l N' + \text{shower}$ in-ice collisions.
- Cylindrical shower has dimensions ~ 10 meters in length; ~ 20 cm in diameter; Cherenkov radiation coherent down to $\lambda \sim 20$ cm
 - Strategy pioneered by RICE experiment (1996-2012)
 - Signal verified in two SLAC testbeam experiments

ANITA +/-

+ Advantages of the ANITA strategy:

- Huge, RF-transparent target volume
- Triggering near thermal floor in RF quiet environment
- In-air receivers allow pre-flight calibration
 - Sub-degree resolution in both θ and ϕ

• Disadvantages:

- **Poor depth perception (i.e., cannot tell if an event originated on the surface or sub-surface)**
 - But have several handles on neutrino events, nonetheless!
- Typical distance-to-interaction point is ~ 100 km
 - Neutrino must be energetic enough to produce detectable pulse!
 - Threshold $\sim 10,000$ PeV (10 EeV)
- 35 day livetime

Flight History

- 2004: ANITA-Lite flies 2-chs. Piggyback on TIGER
 - Full verification of DAQ, backgrounds!
- 12/06–1/07: ANITA-1 = First full mission
- 12/08-1/09: ANITA-2 = ANITA-1 + lots of 10-30% improvements to give overall doubling sensitivity!
- 12/14: ANITA-3 = ANITA-2 + significant changes to DAQ, triggering, hardware – targets UHECR detection & extends low- frequency reach
- 12/16: ANITA-4 (proposed)=final ANITA flight; ~ANITA-3

ANITA
launch;
steps
1 → 6

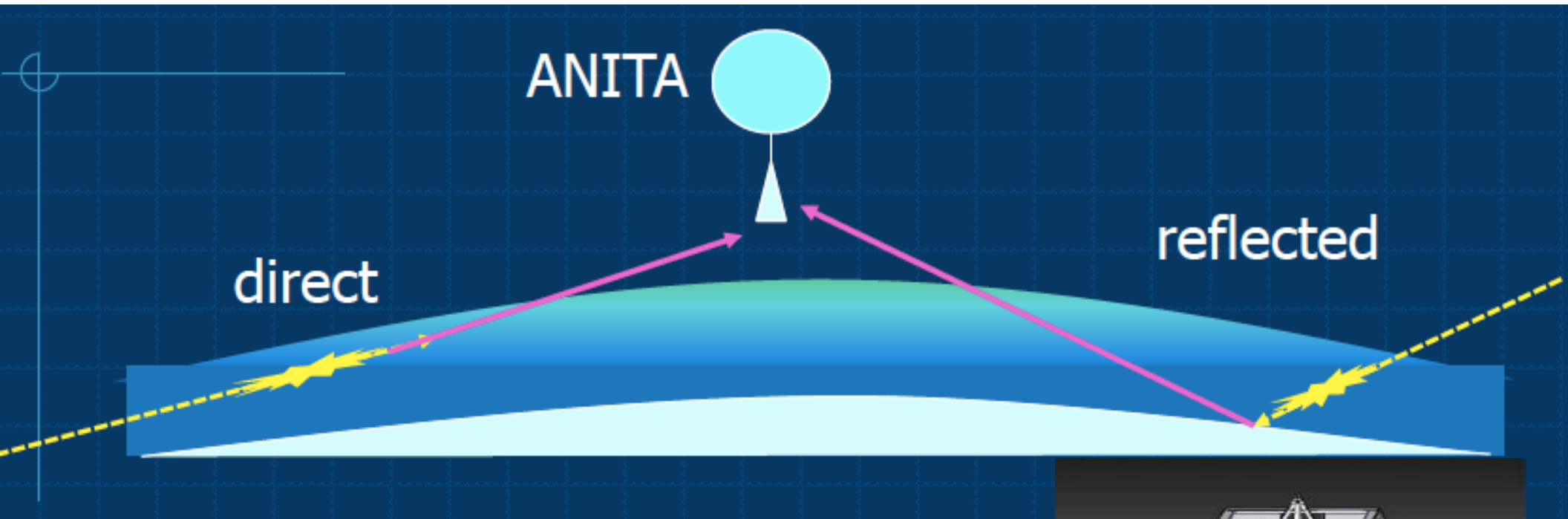




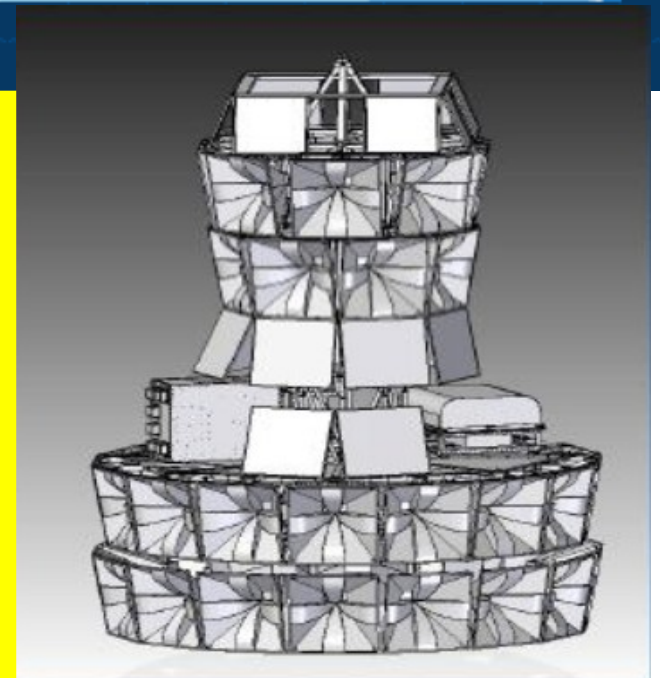


January 9,
2015
ANITA `cut-
down'

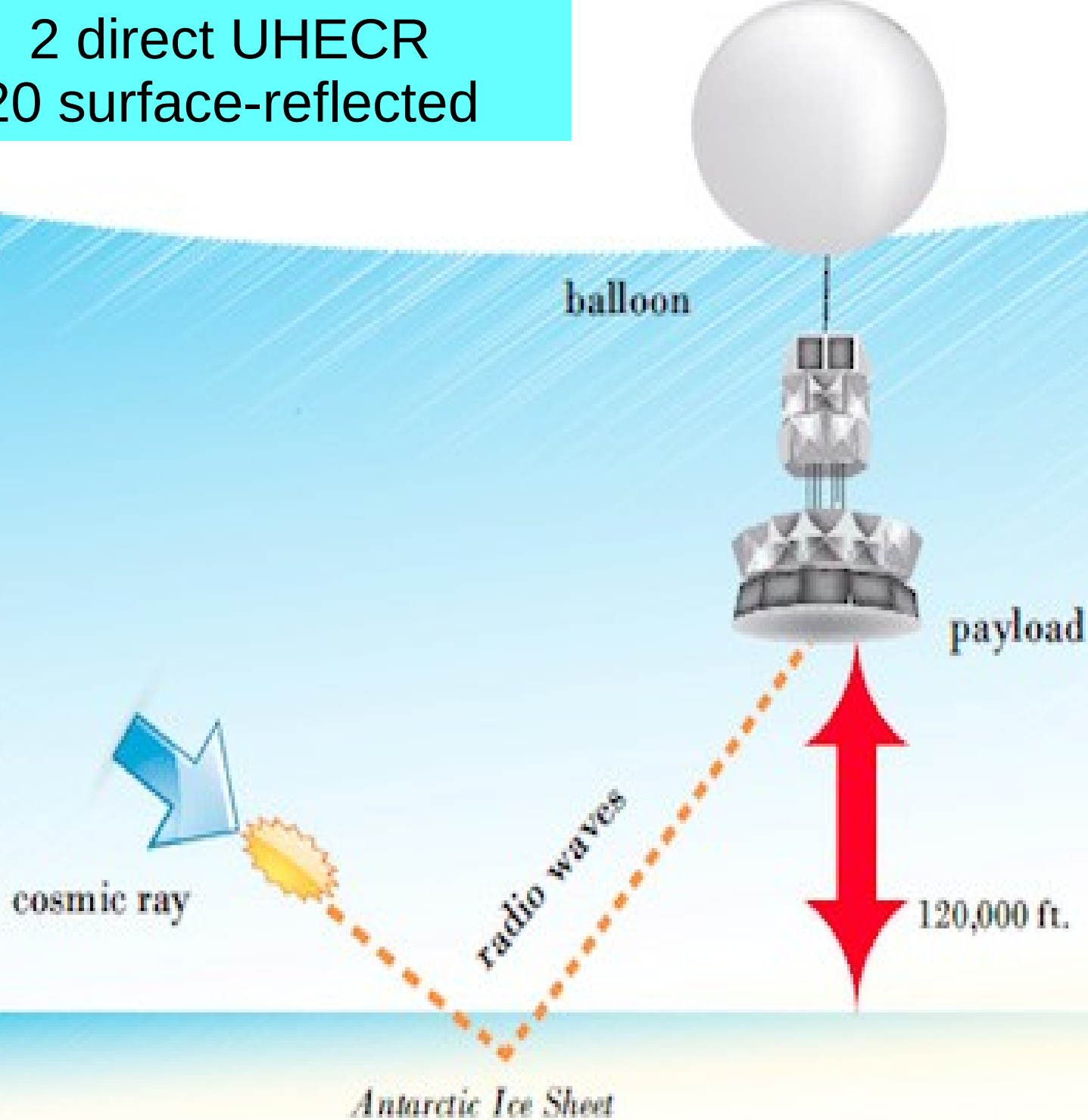
ANITA also detects $\sim 10^{19}$ eV CR



ANITA-III optimized for
UHECR as well as ν flew
over Antarctica in 2014-15



2 direct UHECR
20 surface-reflected



surface roughness from stereoscopic photos



FIG. 1: *Antarctic topography
along Vostok route (I)*



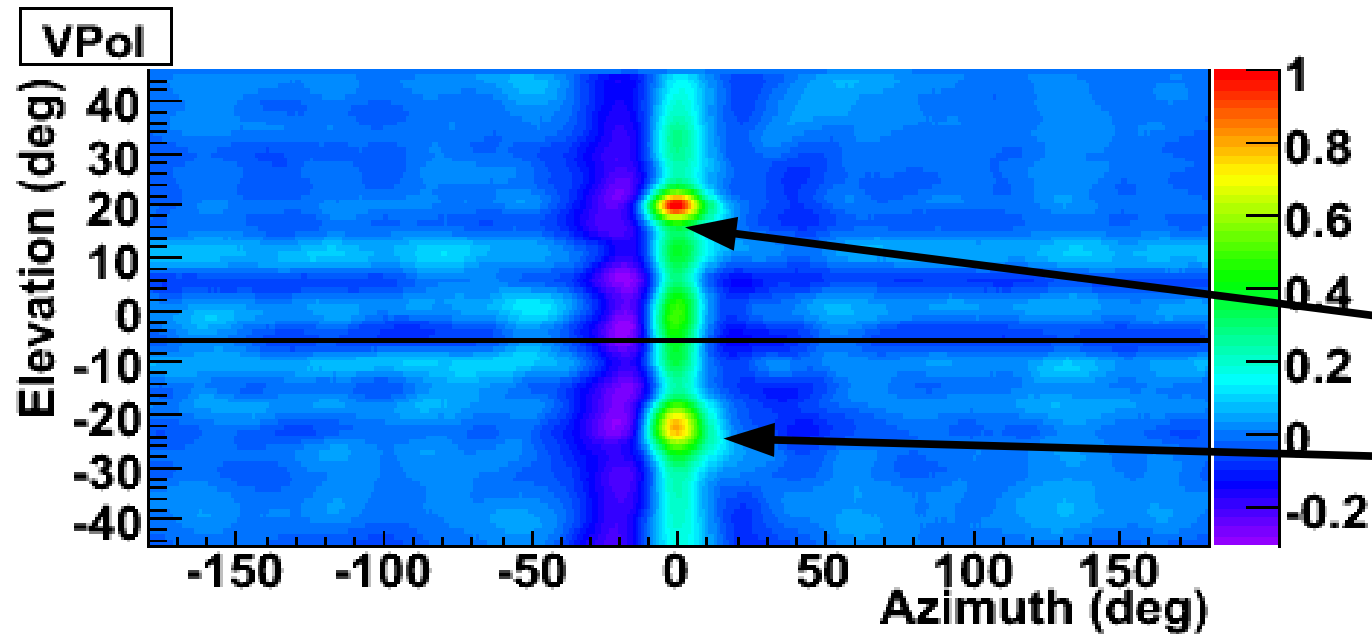
FIG. 2: *Antarctic topography
along Vostok route (II)*



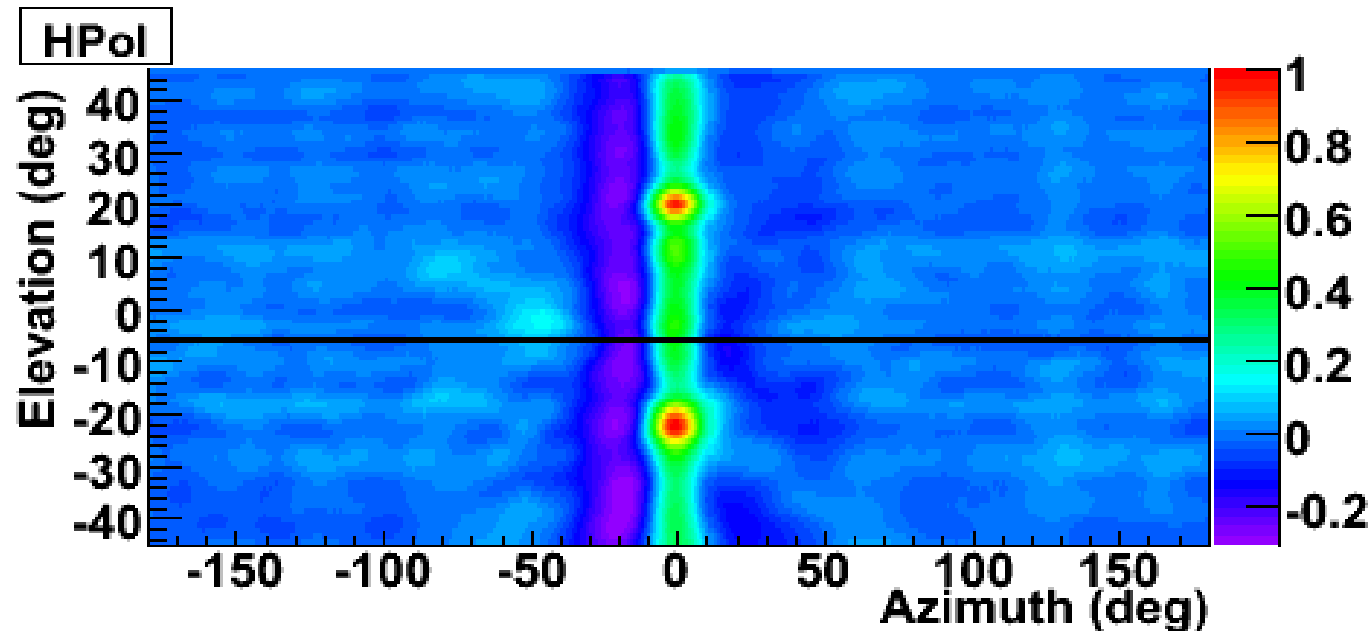
FIG. 3: *Antarctic topography
along Vostok route (III)*

**1/14 Data taken by AARI, St. Petersburg –
reconstruction of point-clouds in progress**

Calibrating surface roughness via Solar albedo



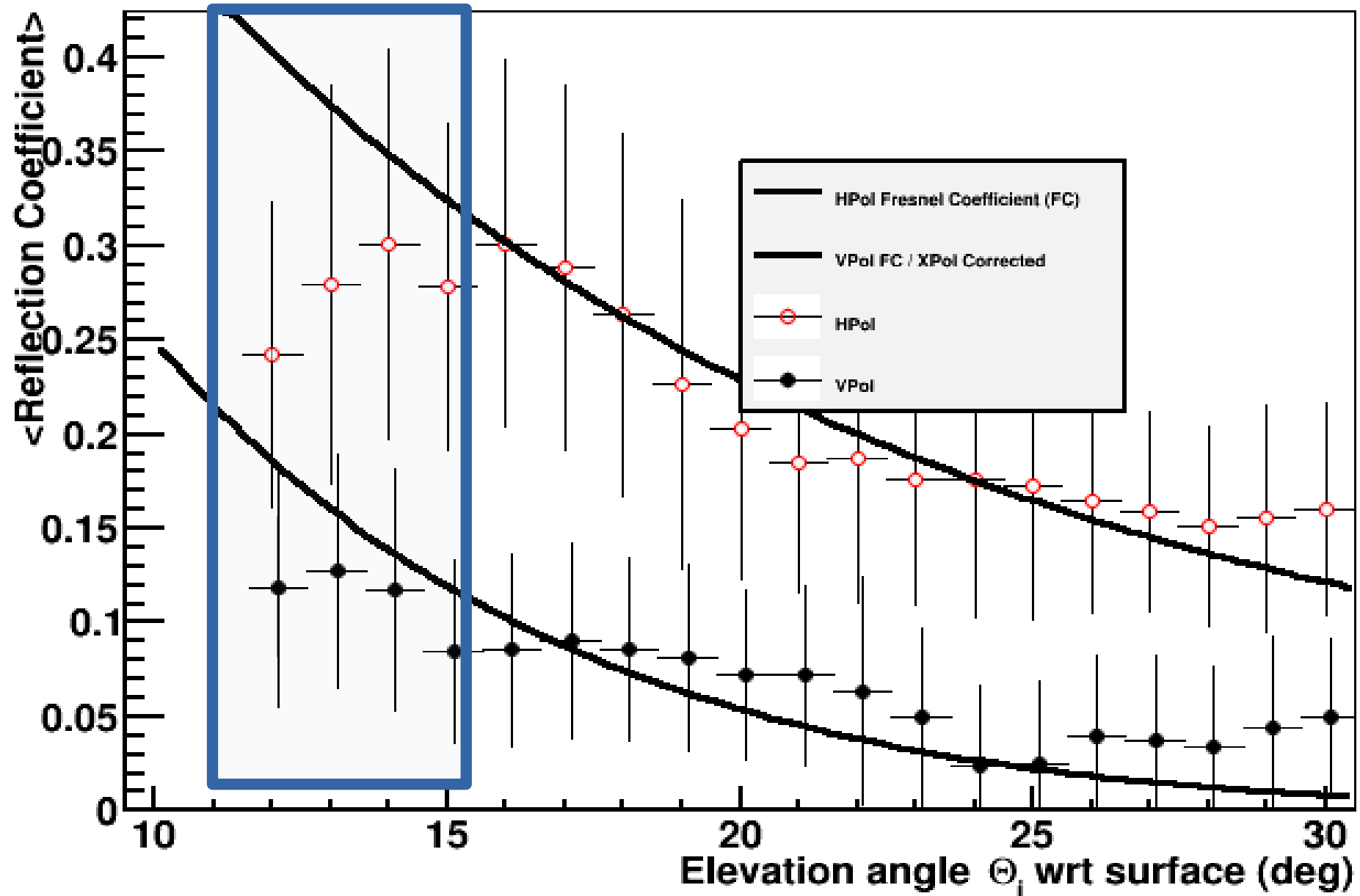
Vpol,
Direct Sun
v. Reflection



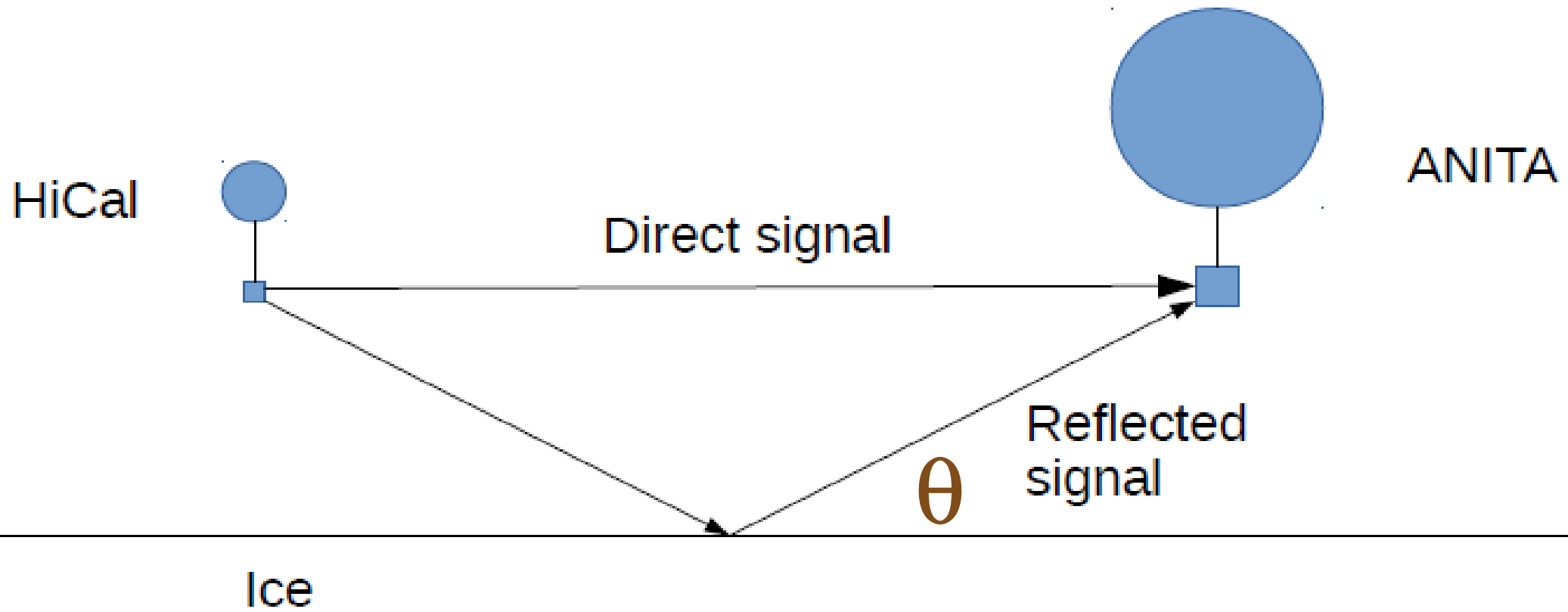
Hpol,
Direct Sun
v. Reflection

Agreement with Fresnel Coefficients as f(incidence angle)

Avg and rms Reflection Coefficients

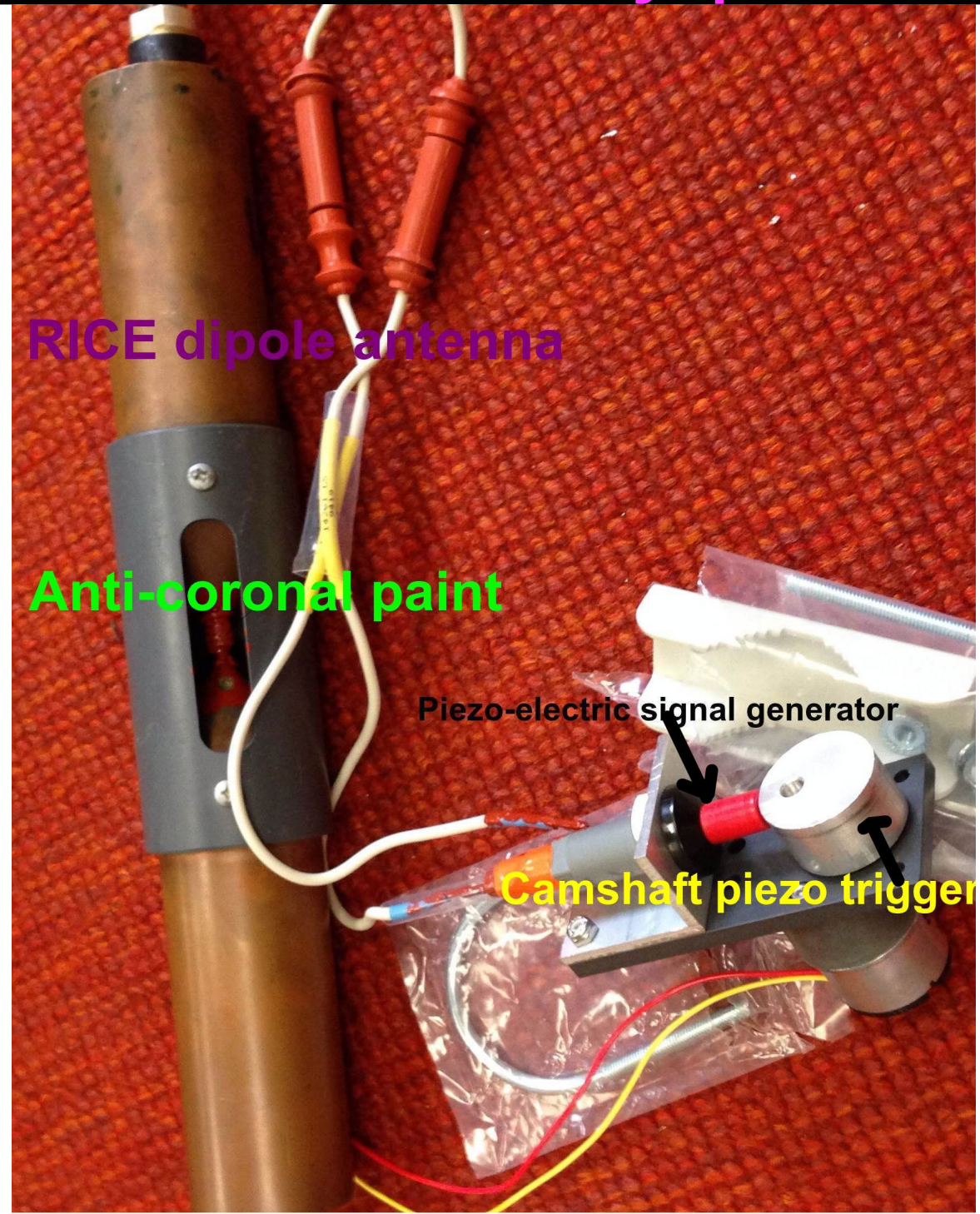


HiCal-trailer balloon to measure roughness



More precise surface reflectivity probe

- 12/14: ANITA HiCal: Pathfinder class balloon, launched after main ANITA-3 launch
 - Tx emits both direct + surface-reflected signal
- Hardware:
 - “custom” transmitter that mimics EAS spectrum (ignition coil or piezo sparker [\$10 from WalMart]) fed into a RICE-type dipole antenna



RF transmitter

LWA-ty...Besson, ...Яндекс...UW-Mad...size of v...distance...redshift...distance...neutrino...Distance...home d...Brinkma...Brink...x

www.homedepot.com/p/Brinkmann-Universal-Push-Button-Ignitor-812-7221-S/203016481home depot piezo barbeque lighter

b1RunsЭКОВестиКПydxa.pdf

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Brinkmann | Model # 812-7221-S | Internet # 203016481 | Store SKU # 211787

Universal Push Button Ignitor

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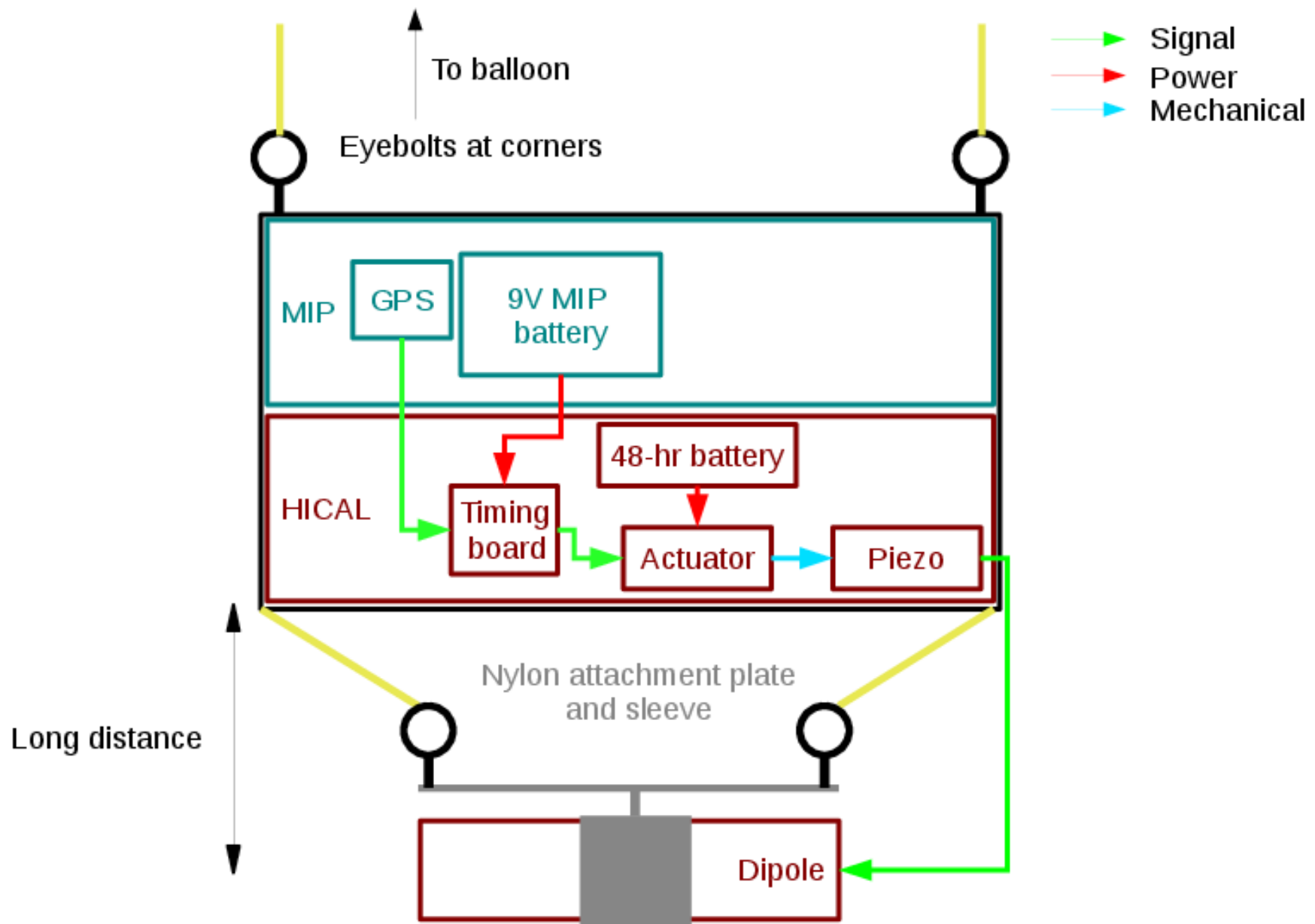
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Feedback

HiCal sparker at 5 mB



HiCal schematic



HiCal Launch (Jan. 5, 2015)



Flight Paths, Dec. 2014-Jan. 2015

NASA Long Duration Balloon (LDB) Site at Willy Field, McMurdo Station
2014-2015 Antarctica Operations
(With Support from NSF and USAP)

Balloon Tracking

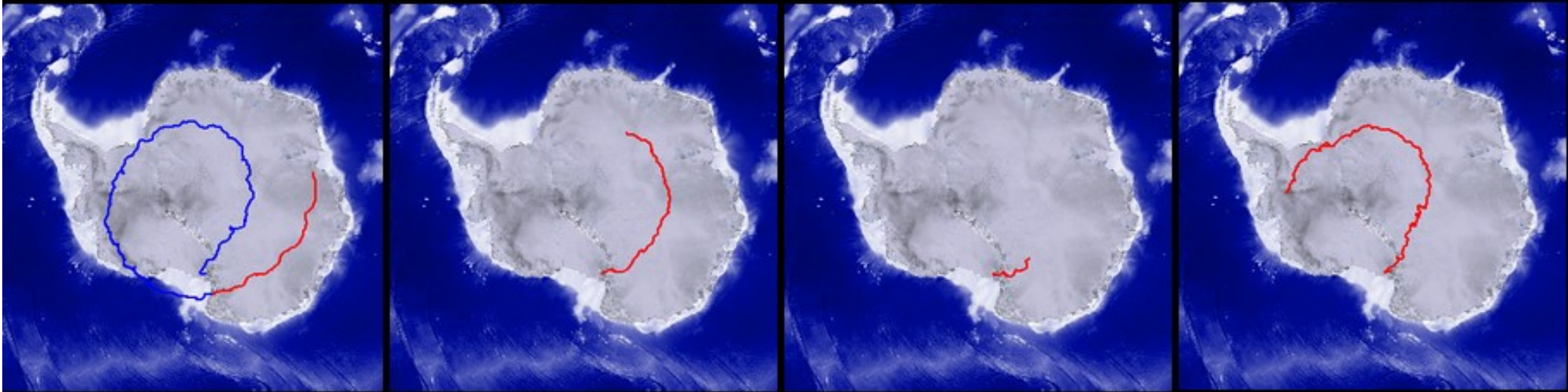
Current Revolution in Red

ANITA III

ANITA HI-CAL
Flight 2

SPB/COSI

SPIDER



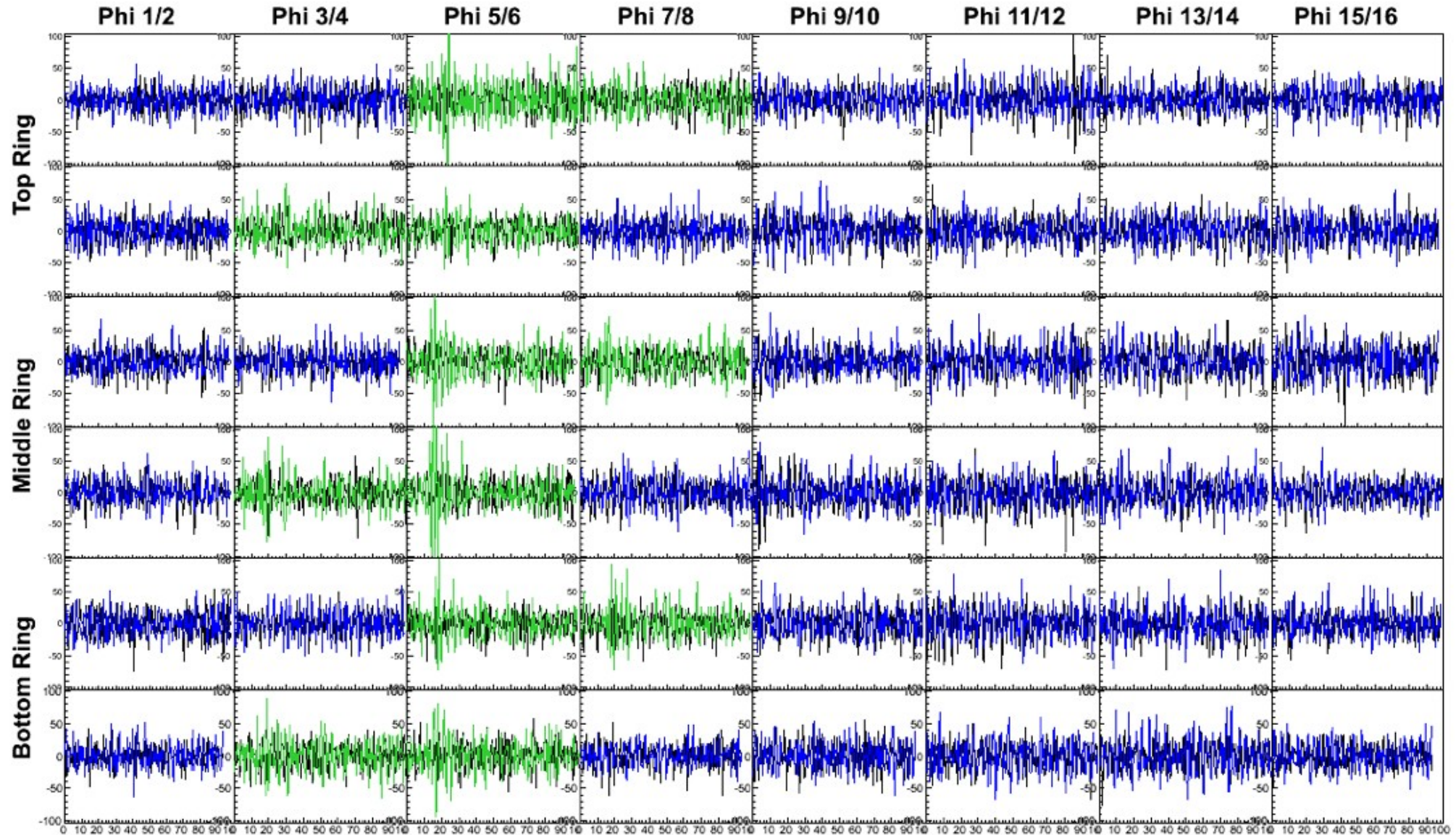
Event 1-HiCal observed from 750 km!

Run: 413
Event: 77751633

Time: 2015-01-07 05:29:34
Trigger: 824.629576 ms
Priority: 3 -- Queue: 3

Trig Num: 7433 -- Trig Type: RF
TURF: 7442

TURF This Hold: 0
TURF Active Holds: 0x5
Labrador AAAAAAAAAAAAAA
Phi Mask: V 0 - H 0



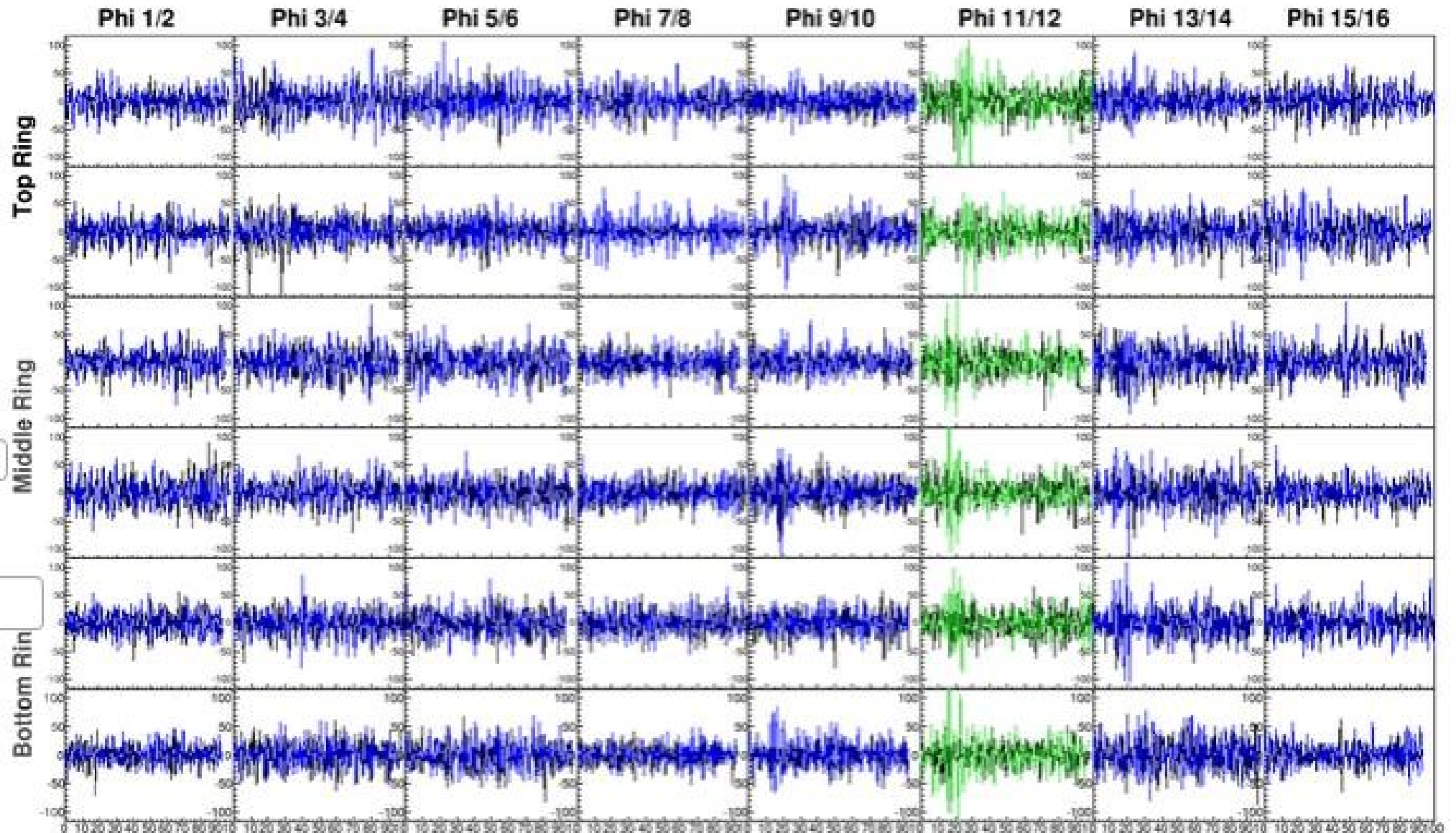
HiCal Event-2 (at float)

Event: 80016631

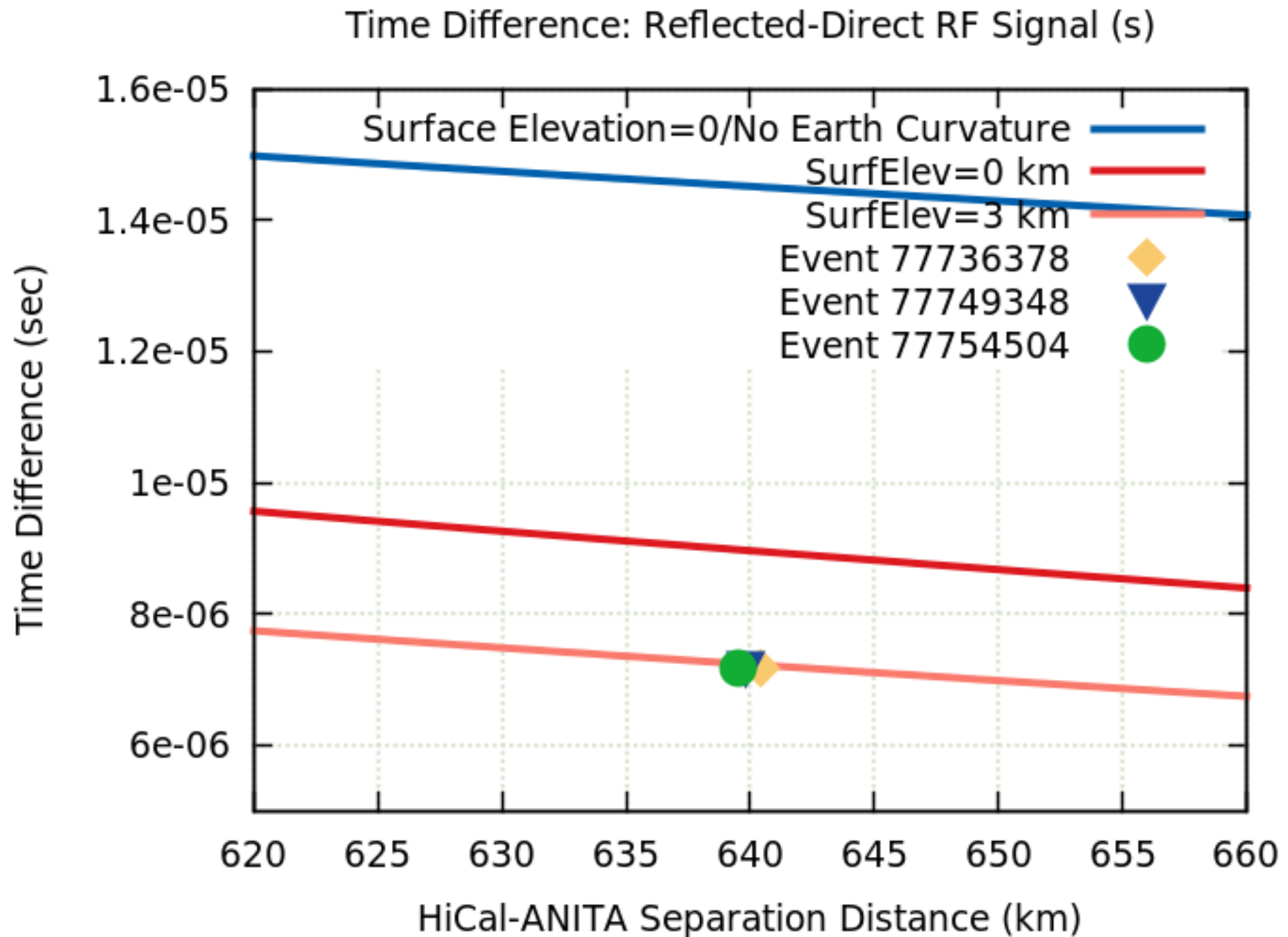
Priority: 3 - Queue: 3

TURP: 214444

Labrador 888888888888
Phi Mask: 0

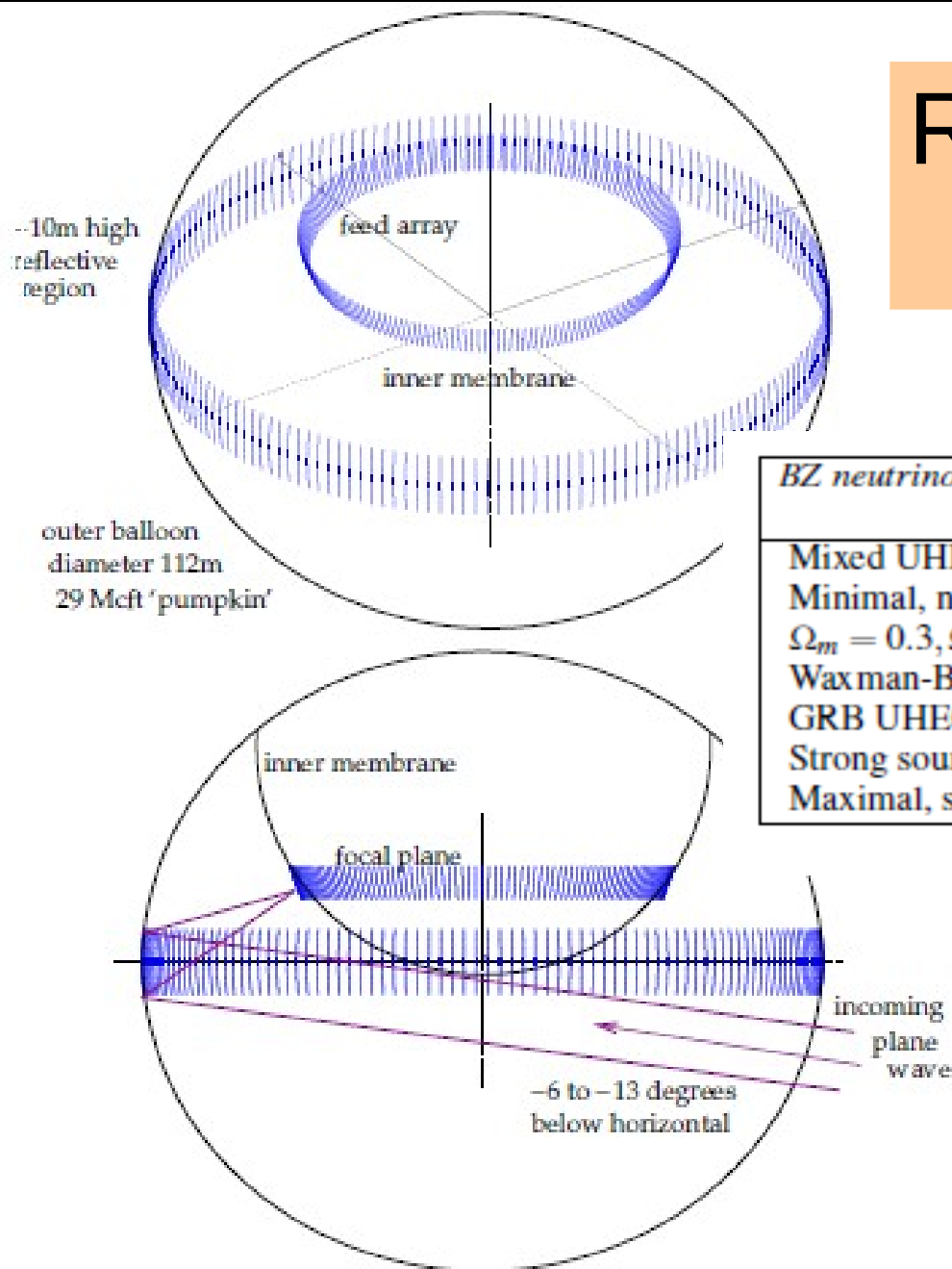


Also, surface reflections observed!



EVA: The balloon is the antenna

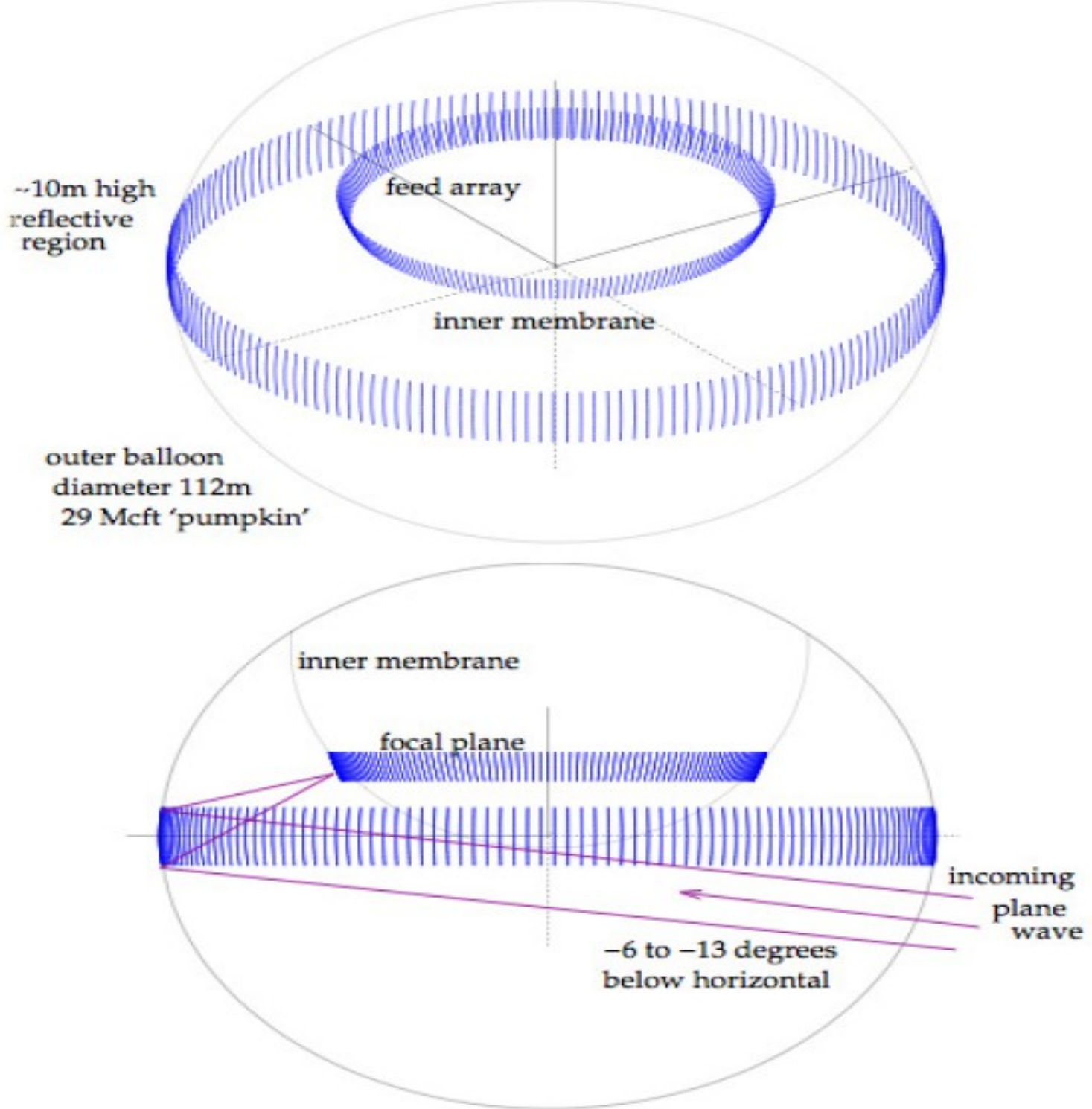
Reflectors guide RF to
Inner feed array



<i>BZ neutrino models</i>	<i>Events, ANITA-II, 28d</i>	<i>Events, EVA, 50d</i>	<i>ratio, EVA/ANITA</i>
Mixed UHECR composition [30]	0.05	5.0	100
Minimal, no evolution [3, 32, 33]	0.3-0.9	9.2-38	~ 40
$\Omega_m = 0.3, \Omega_\Lambda = 0.7$, Standard model [3]	0.7	29	41
Waxman-Bahcall E^{-2} flux (minimal) [34]	0.49	6.5	13
GRB UHECR-sources [46]	1.44	66	46
Strong source z -evolution [3, 31, 33]	2.2-5.3	40-60	11-18
Maximal, saturate all bounds [31, 33]	16-25	180-220	~ 10



EVA –
the
future:
the
medium
is the
message



Summary

- ARA2+ARA3 + ARA4+ARA5 (2016-17)
- ARIANNA now has 7 working stations (summer only)
- ANITA-3 data analysis in progress
- In addition to enhanced neutrino sensitivity, effort to maximize UHECR sensitivity AND reduce systematic errors on UHECR energy estimate
 - Target 25% overall energy error
- ANITA-4 (we hope) flies again in 2 years, then..EVA!