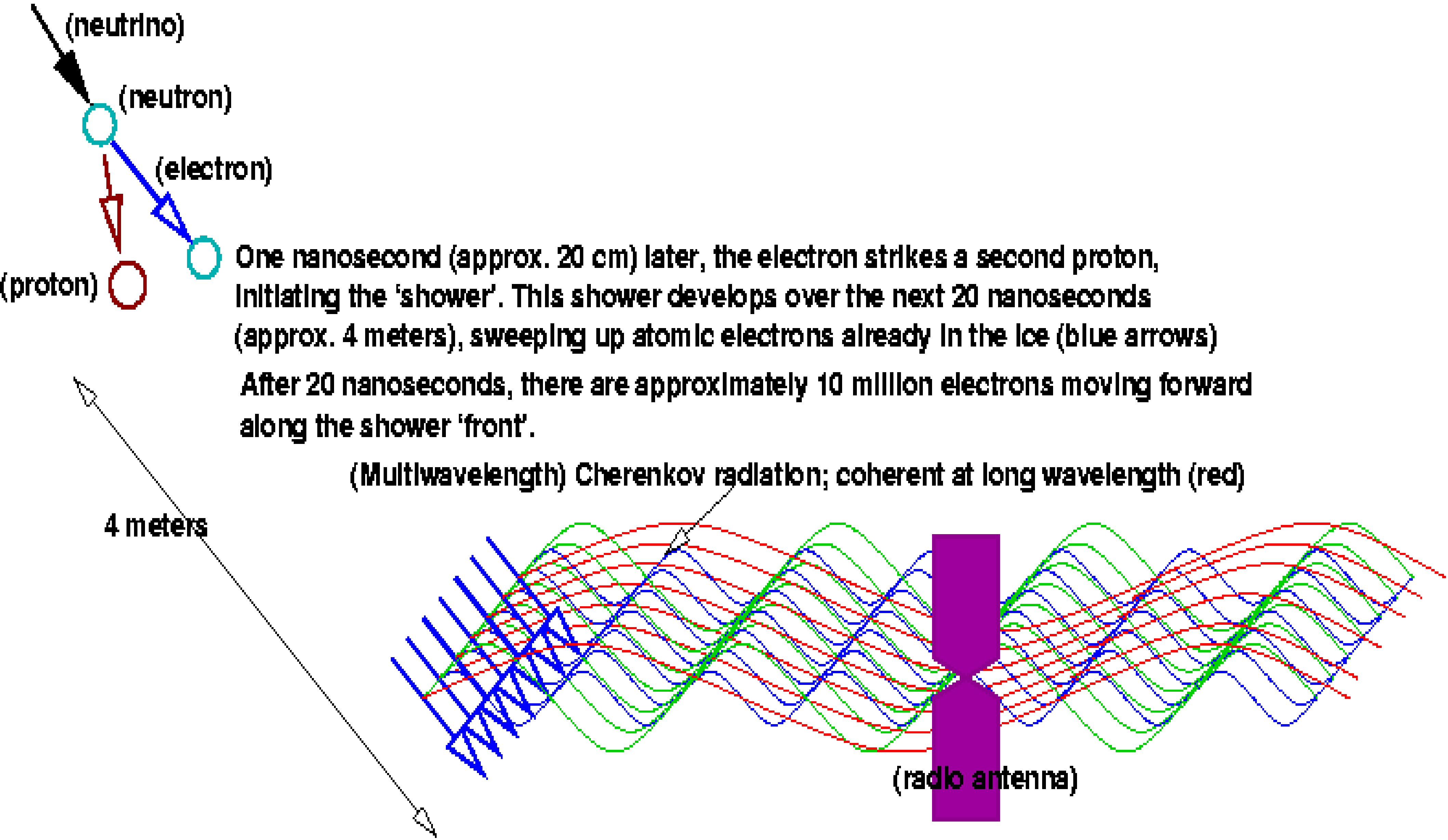
Radiofrequency detection of UHECR *(both protons & neutrinos)* in Antarctica

- detection of RF photons as a CR-observation tool: L_{atten}(ice,f=300 MHz)~1.8 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~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=>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: neutrino + neutron -> proton + electron



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

2$R_{moliere}$ (0.2 m, ice)

5 m

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

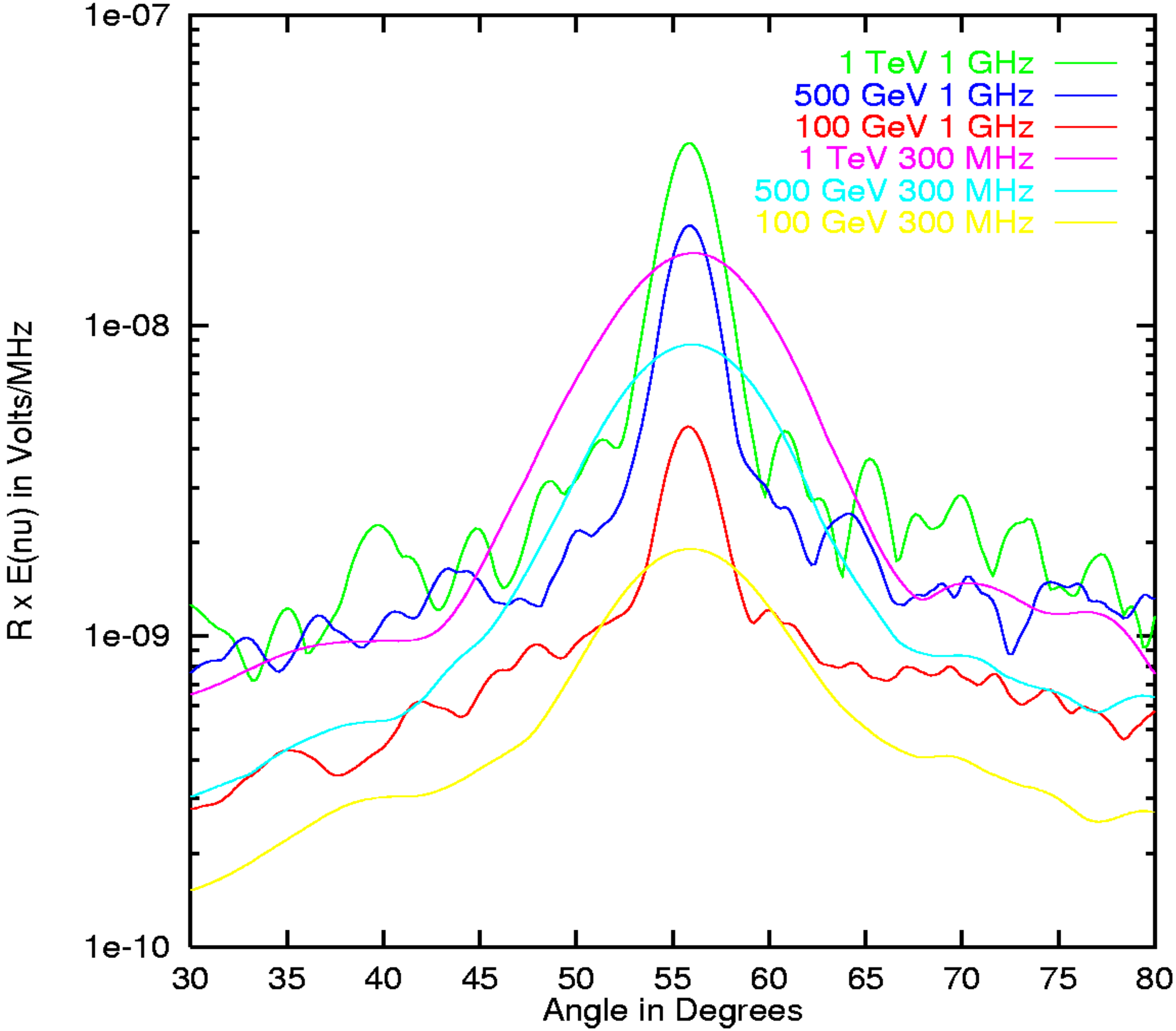
Signal Strength details depend on

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

$\theta_c = 56^o$ +/- 3^o

Frequency/angle correlation: Cone width~FT of transverse charge; **width 'fattens' as inverse of frequency**

Signal height~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)

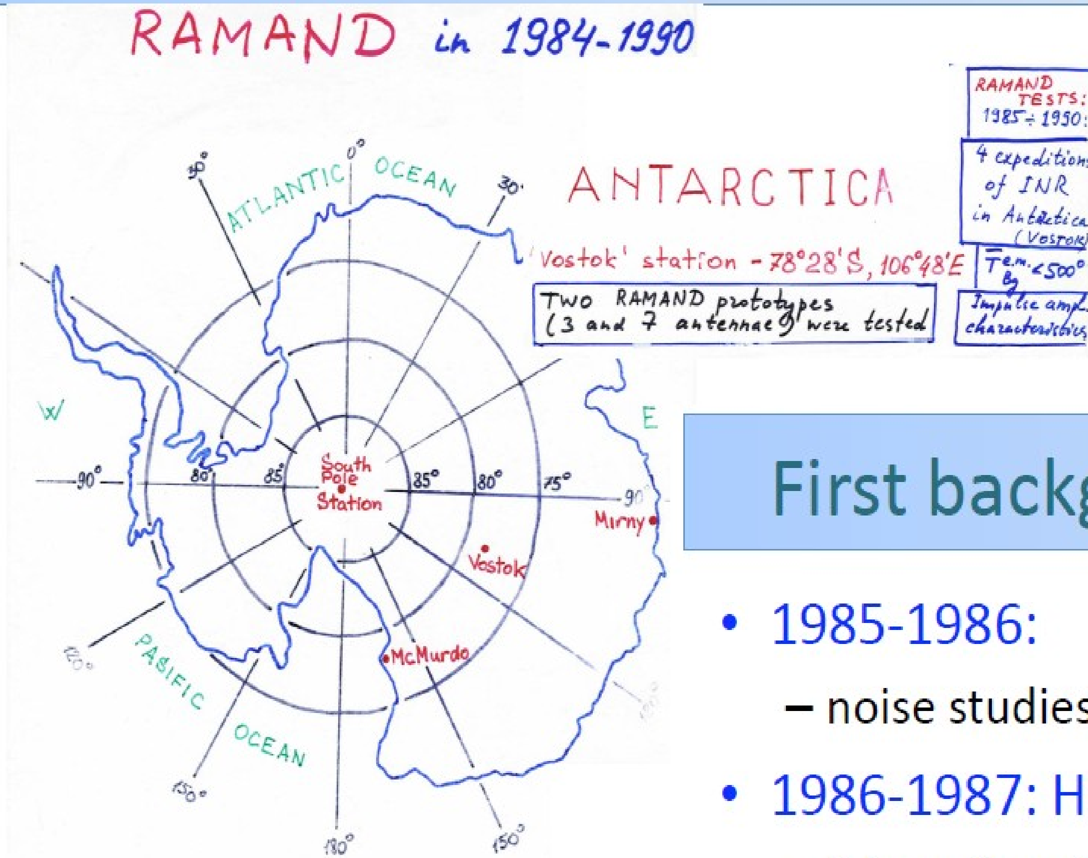
-Comparison of the two in-ice experiments

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^{o} 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.
  - …………………………………………………………

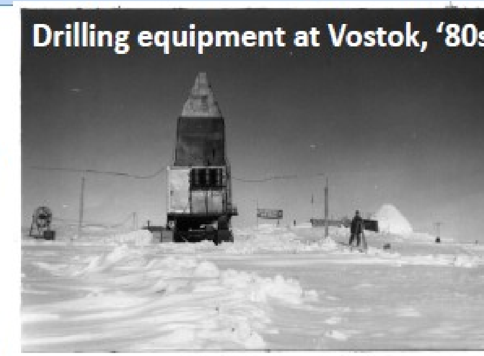
Stations in Antarctica



Kravchenko et al, ARENA 2010 Proceedings

First background studies and Hydra

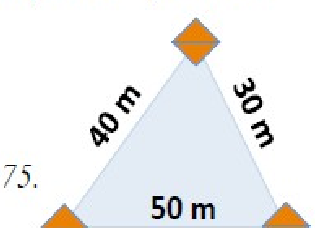
- 1985-1986:
  - noise studies w/ single module
- 1986-1987: Hydra
  - 3 broadband receiver channels
  - Pinger locations reconstructed
  - Man-made backgrounds investigated (sources coincide with station objects)
  - Upper limit on flux of impulse pulses from ice obtained



Drilling equipment at Vostok, '80s

Deployment of radio pinger

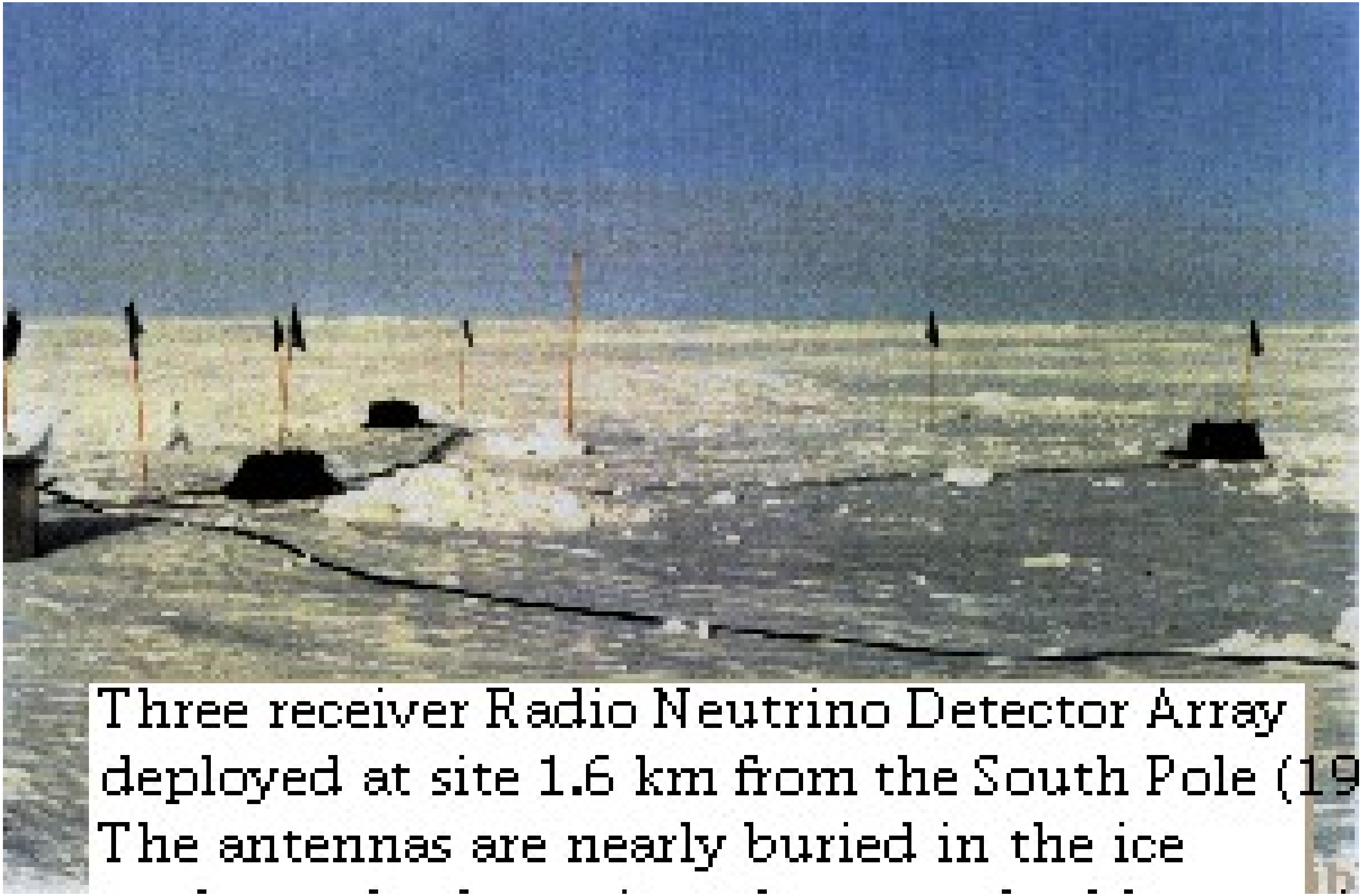
Proc. 20th Inter. Cosmic Ray Conference. Moscow, "NAUKA", 1987, vol. 6, pp. 472-275.



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

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

- RAND (South Pole):
  http://aether.lbl.gov/www/projects/neutrino/rand/rand.html

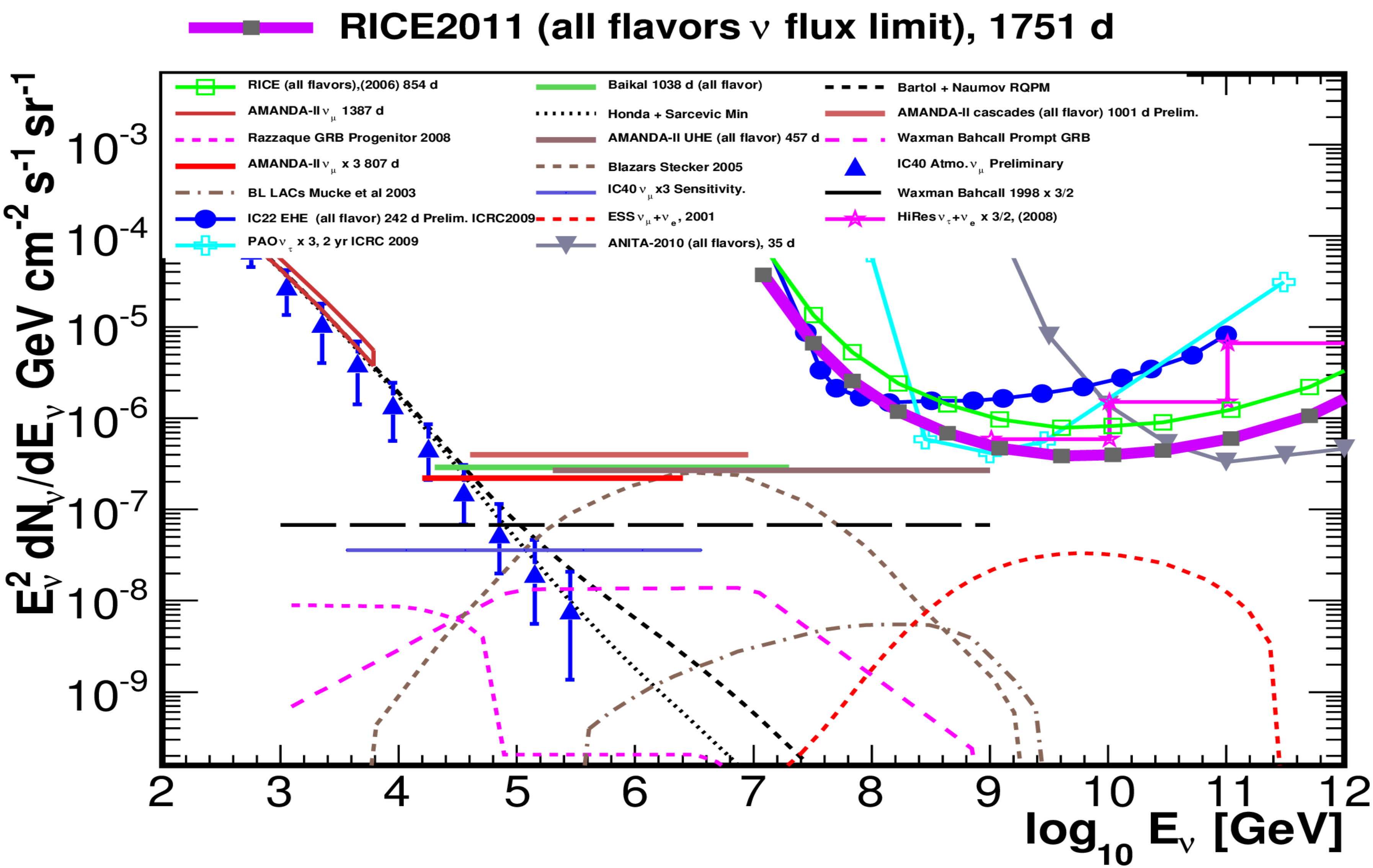


On the second day...

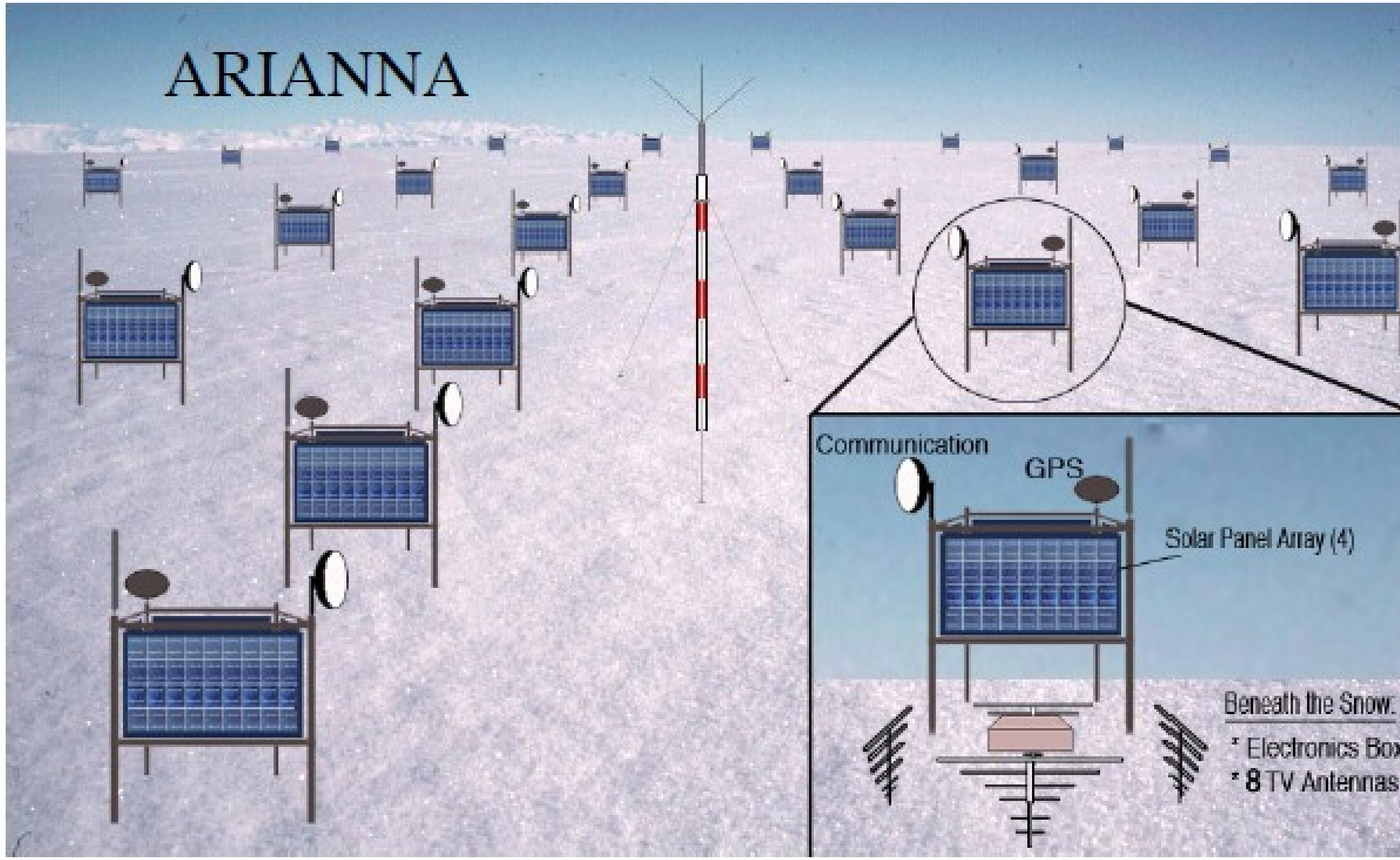
- *"The Smoot Group has performed two preliminary tests of the feasibility of using the Antarctic Ice for radio detection in trips to the South Pole in 1989 and 1991-1992. The December 1991 - January 1992 expedition, under the acronym A.R.C.N.O. (Antarctic Radio Cherenkov Neutrino Observatory), utilized three broad-band receivers singly and in coincidence on the surface. These tests indicated that there was no insurmountable background to the radio detection. <u>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.</u>"*

RICE: 20-ch dipole array: (200m)^3

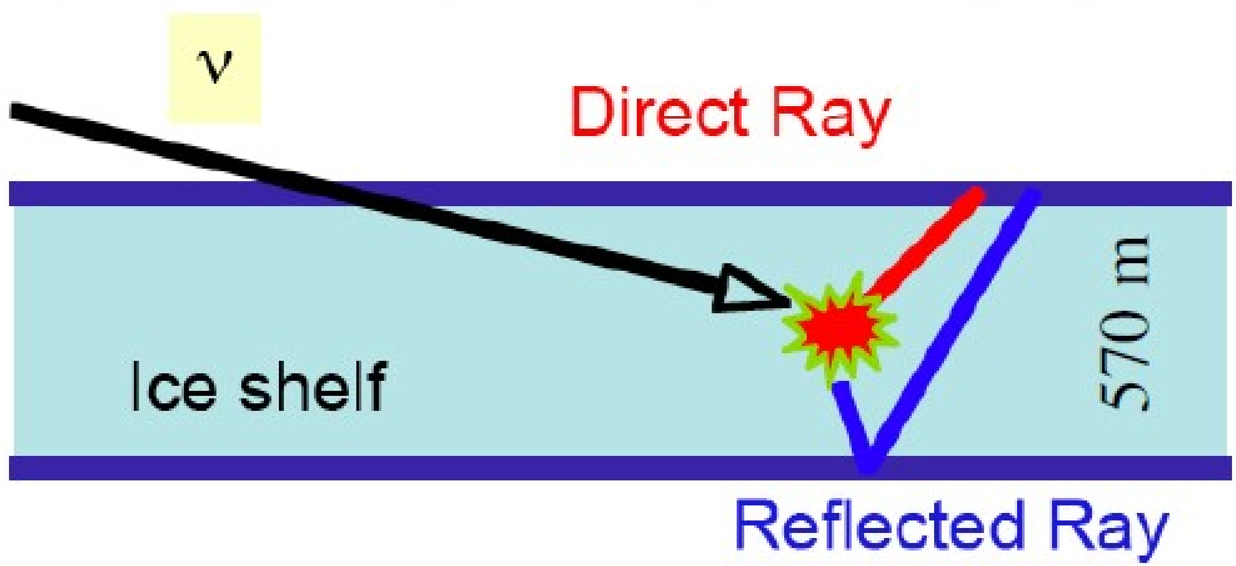
- 1995- parasitic* operation vis-a-vis AMANDA / IceCube... Limits on neutrino fluxes:



31 x 31 array
[30 km x 30 km]



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

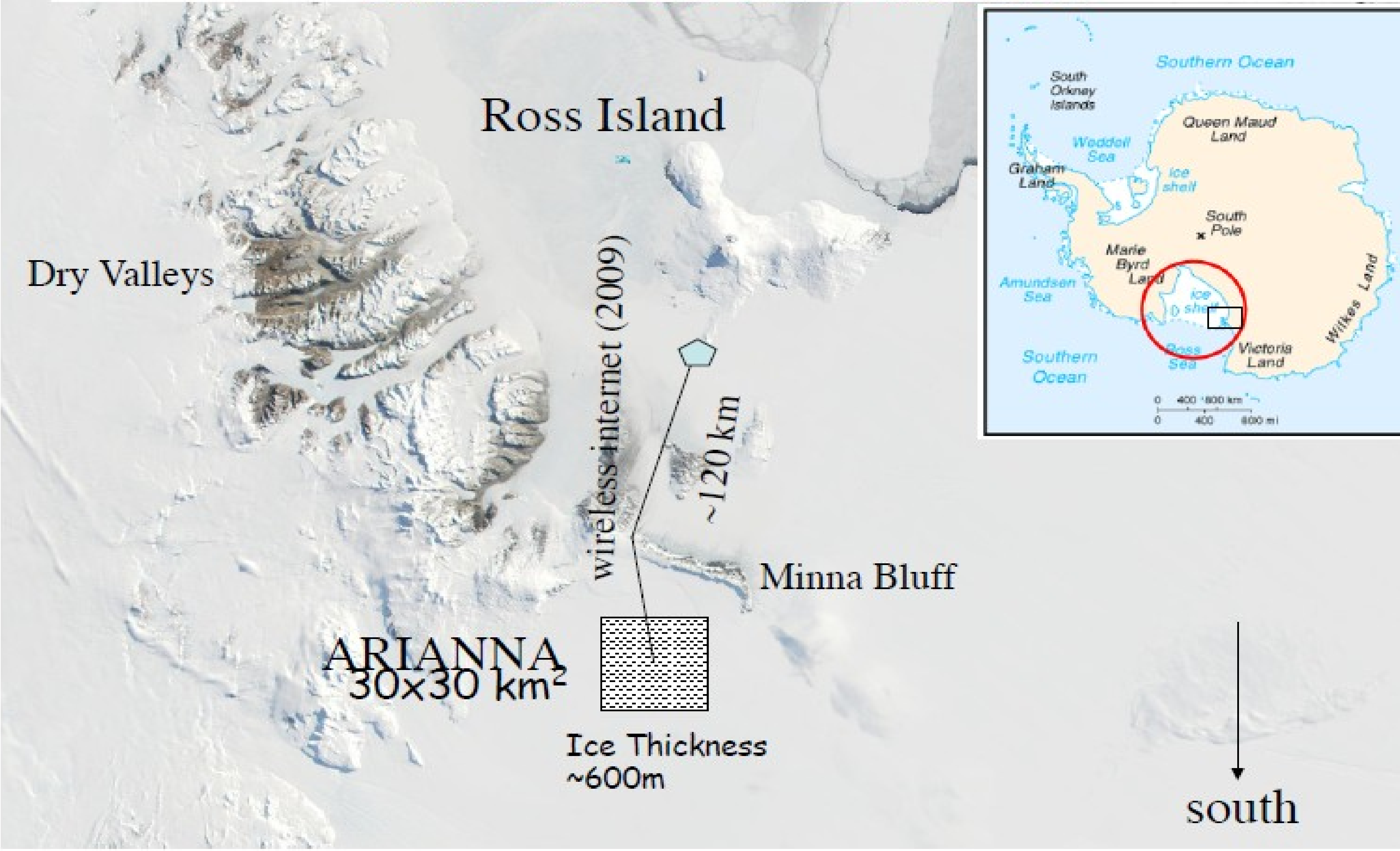


ARIANNA

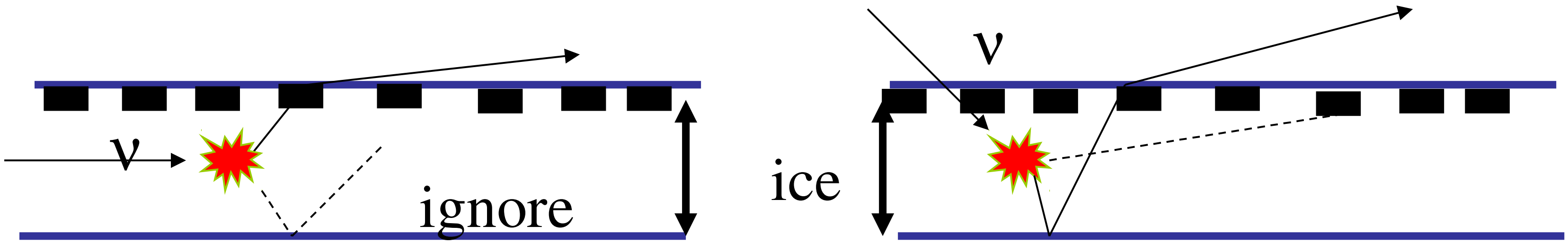
US, S. Korea, England, New Zealand

Barwick, astro-ph/0610631

Satellite Image of Victoria Land and Ross Ice Shelf



reflected and direct events

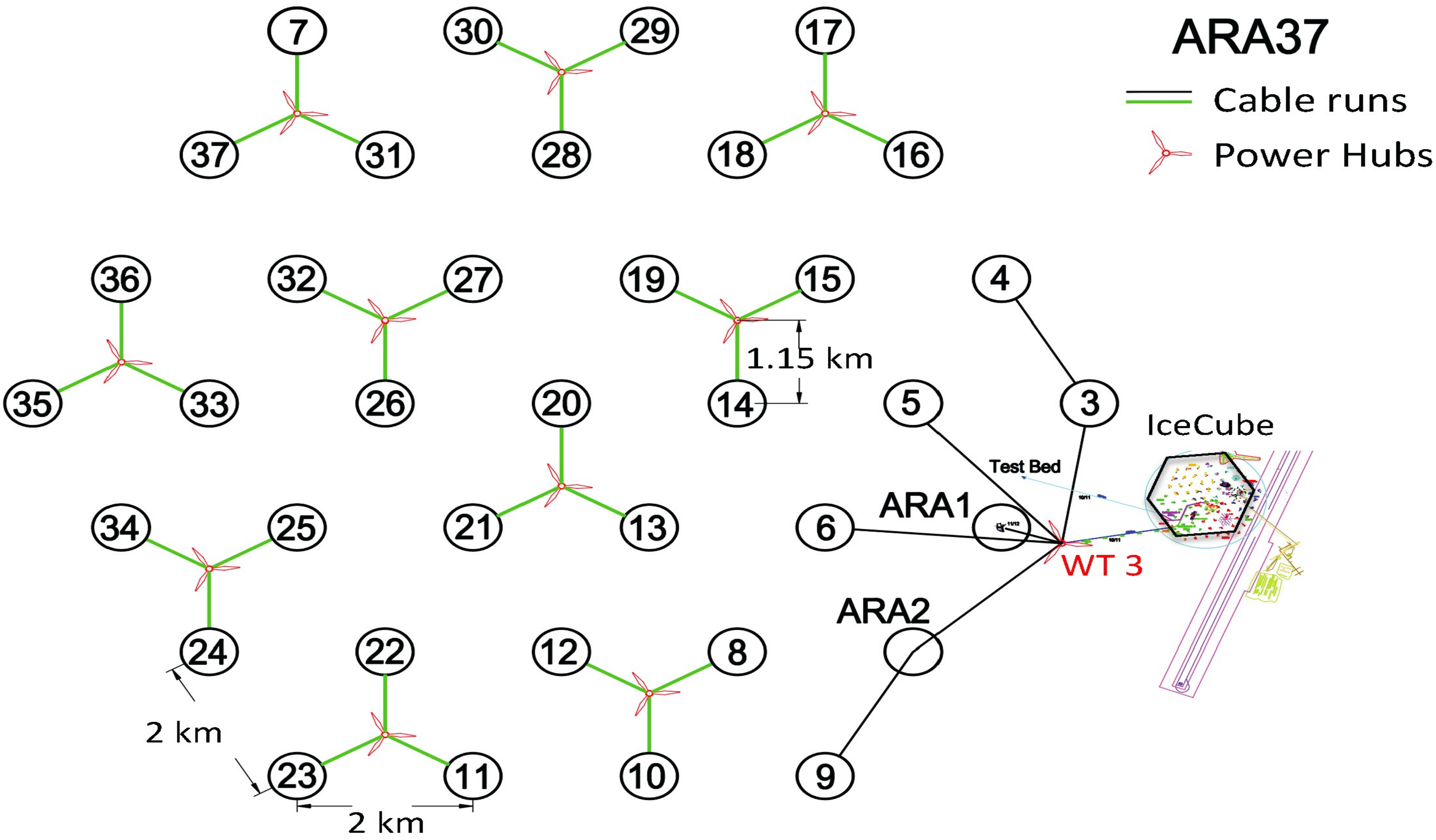


Direct

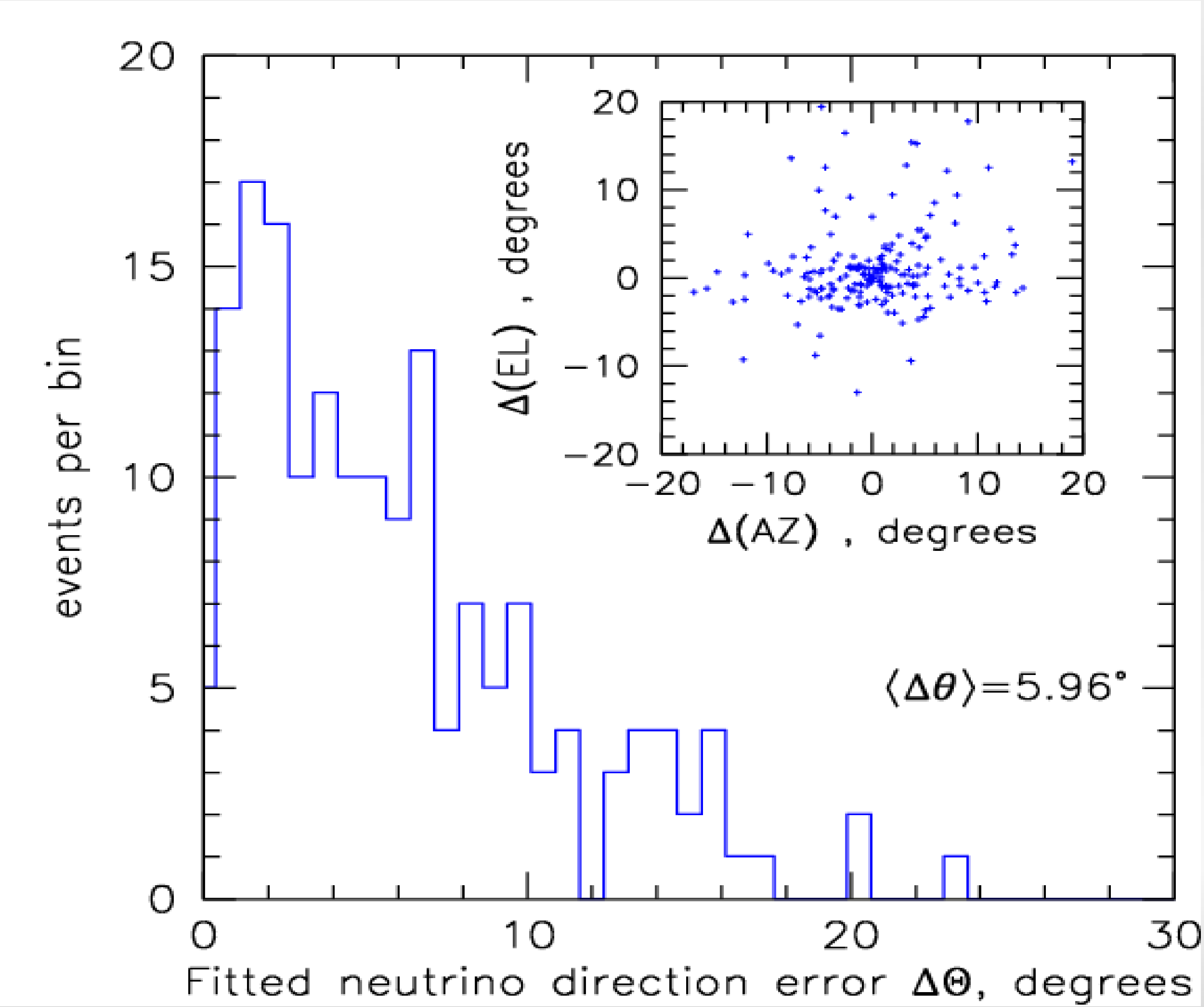
Reflected
(much greater solid angle)

sensitivity to neutrino cross section !

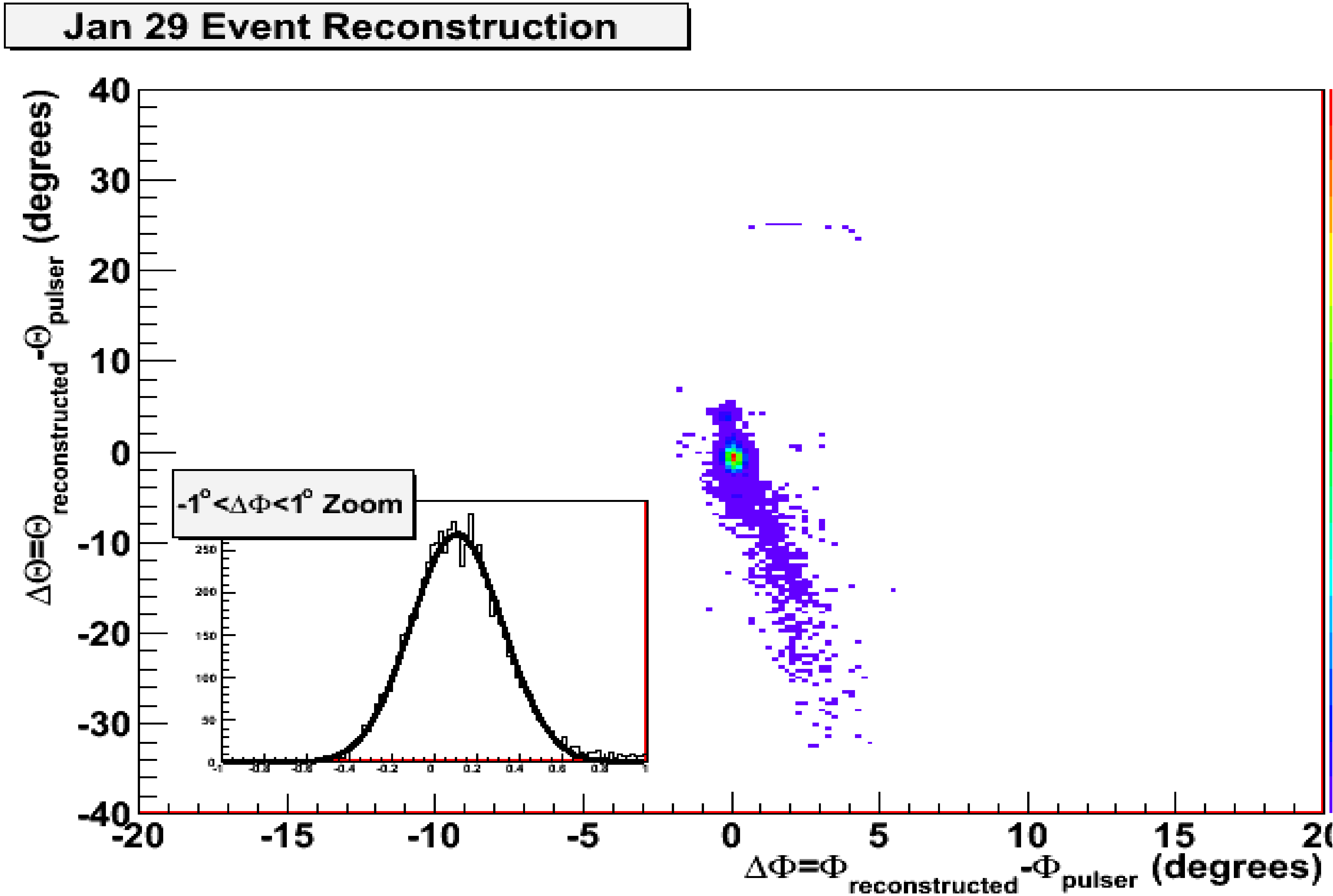
The ARA Experiment at the South Pole



Expected ARA-37 reconstruction Performance: Neutrino Astronomy



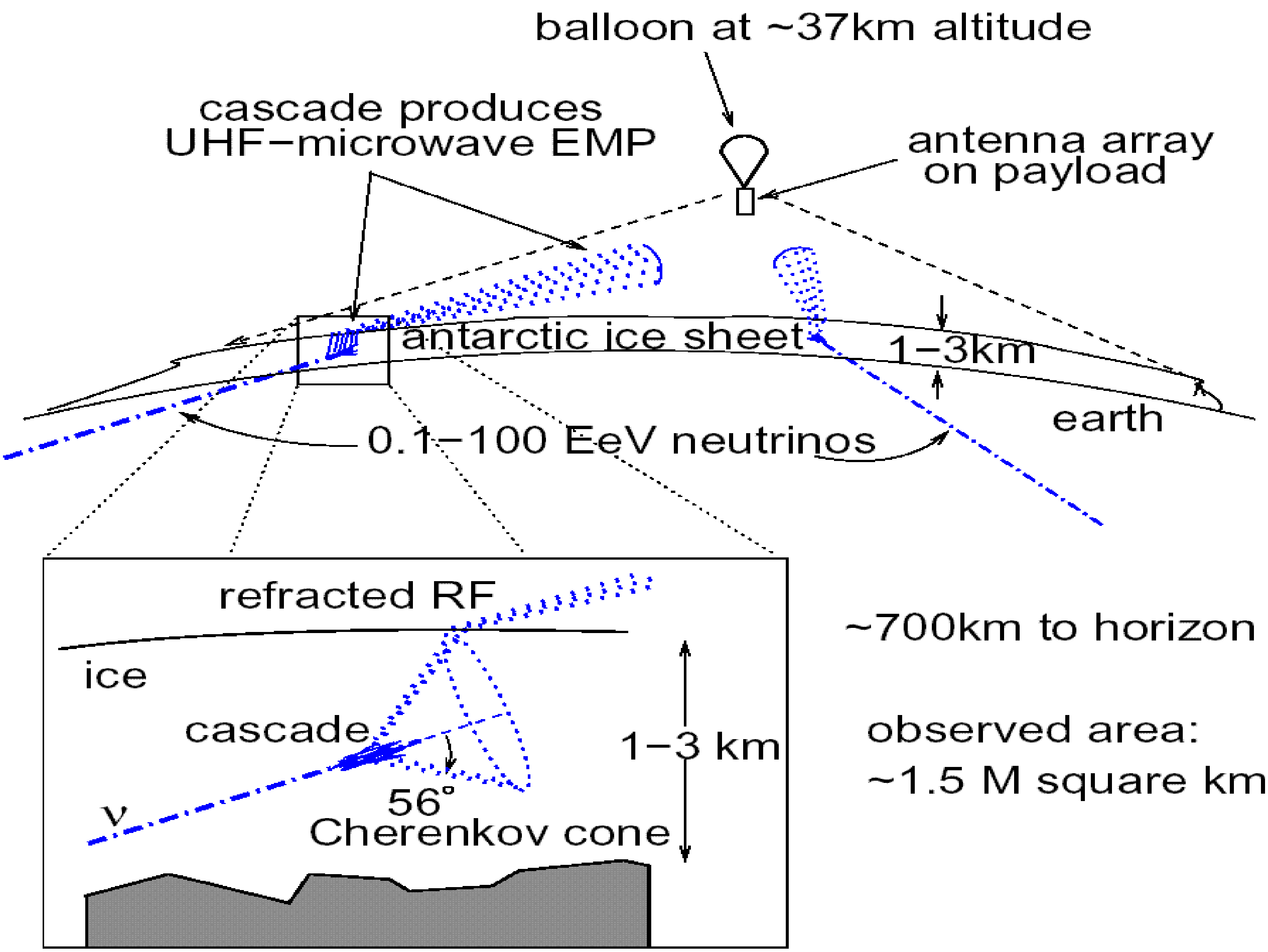
ARA angular resolution: 0.2º/0.6º in ϕ/



	ARA	ARIANNA
locale	South Pole	MinnaBluff
Trigger Rate	5 Hz	0.1 Hz
Trigger threshold:	4 x $4\sigma_{kT}$ over 256 ns	4 x $4\sigma_{kT}$ 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^o	2.5^o
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
Future funding	**$7M OPP proposal (not yet)**	**$1 M MRI (funded)**
neutrinos	50/yr/37 stations (20 Rx/station)	80/yr/961 stations (7 Rx/station)

The ANITA Experiment: Balloon-borne detection

ANITA concept



~700km to horizon

observed area:
~1.5 M square km

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 (~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 $\nu N \rightarrow l N'$+shower in-ice collisions.
- Cylindrical shower has dimensions ~10 meters in length; ~20 cm in diameter; Cherenkov radiation coherent down to lambda~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:
  - ***<u>Poor depth perception (i.e., cannot tell if an event originated on the surface or sub-surface)</u>***
    - 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 ~ 10,000 PeV (10 EeV)
  - 35 day livetime

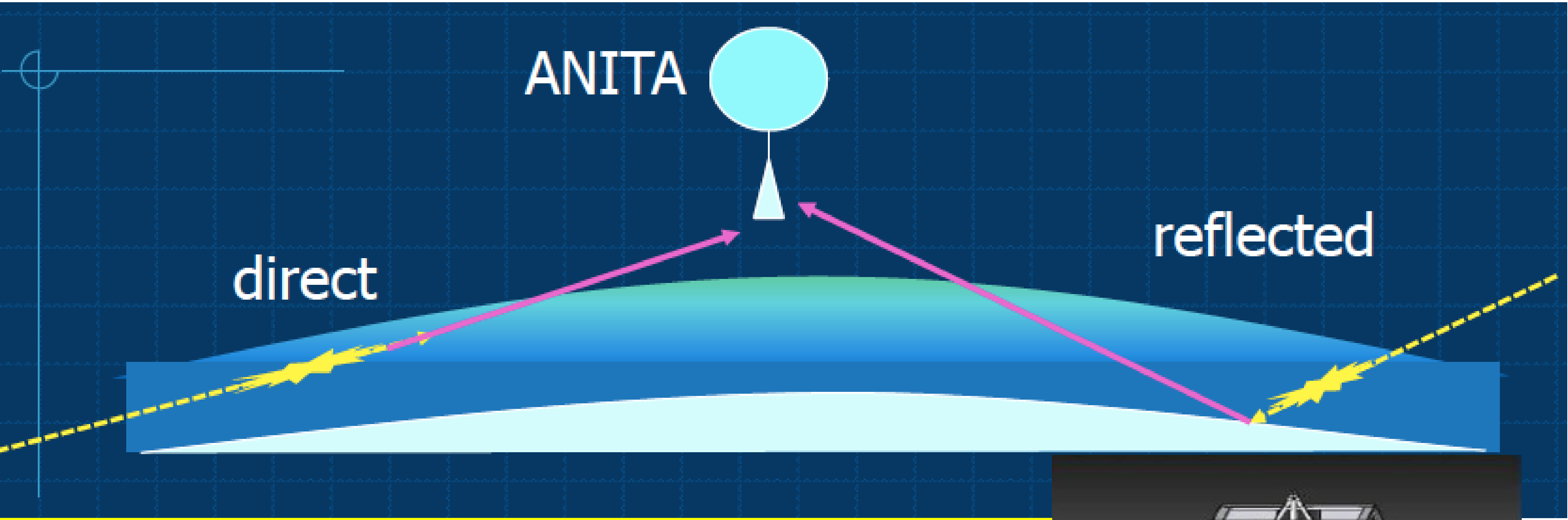
Flight History

- 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

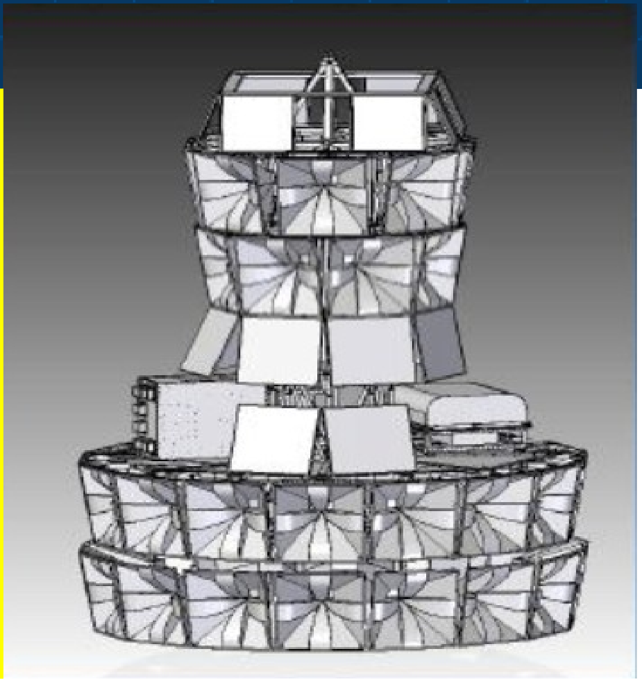
ANITA launch; steps 1 → 6

January 9, 2015
ANITA `cut-down'

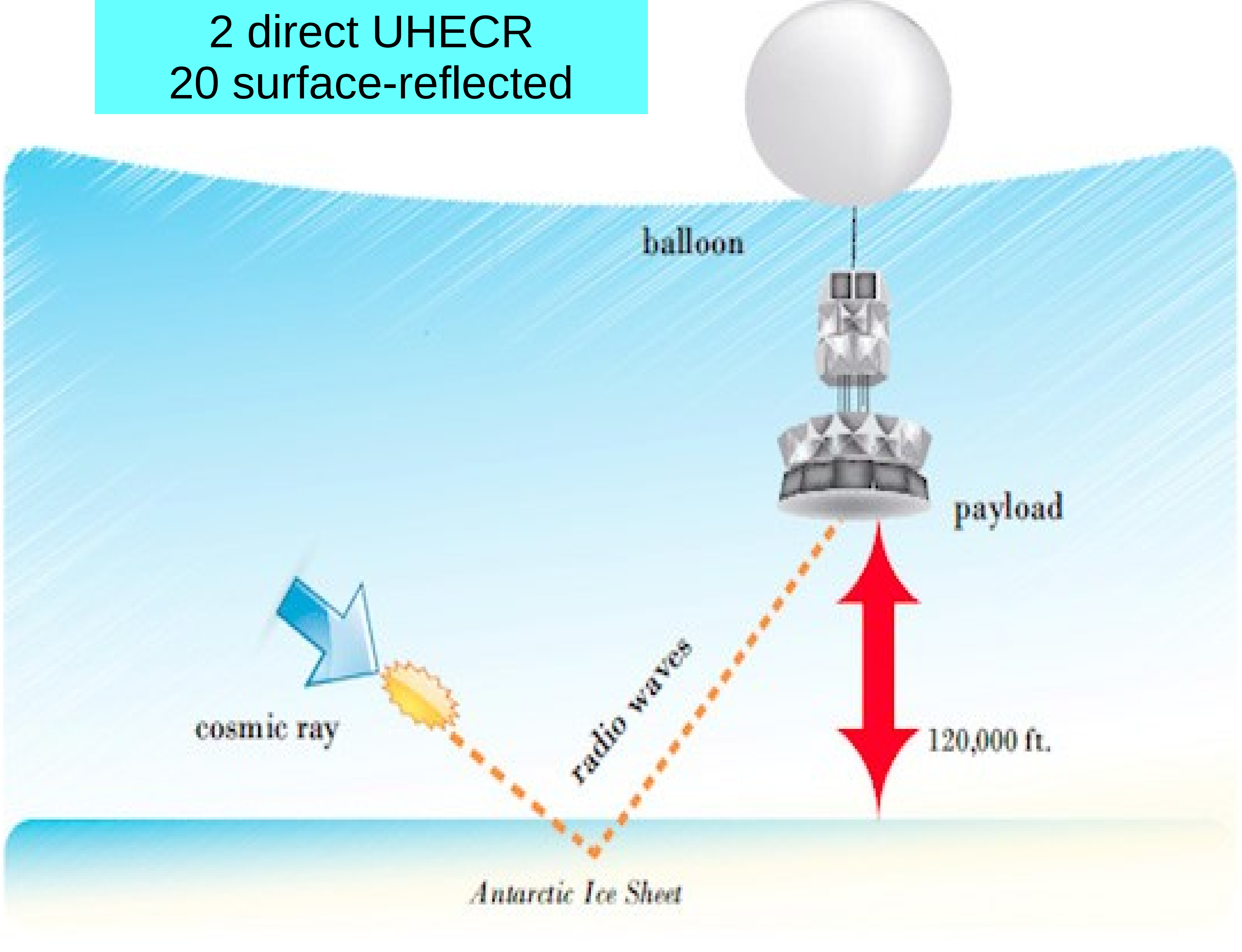
ANITA also detects ~10^{19} eV CR



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

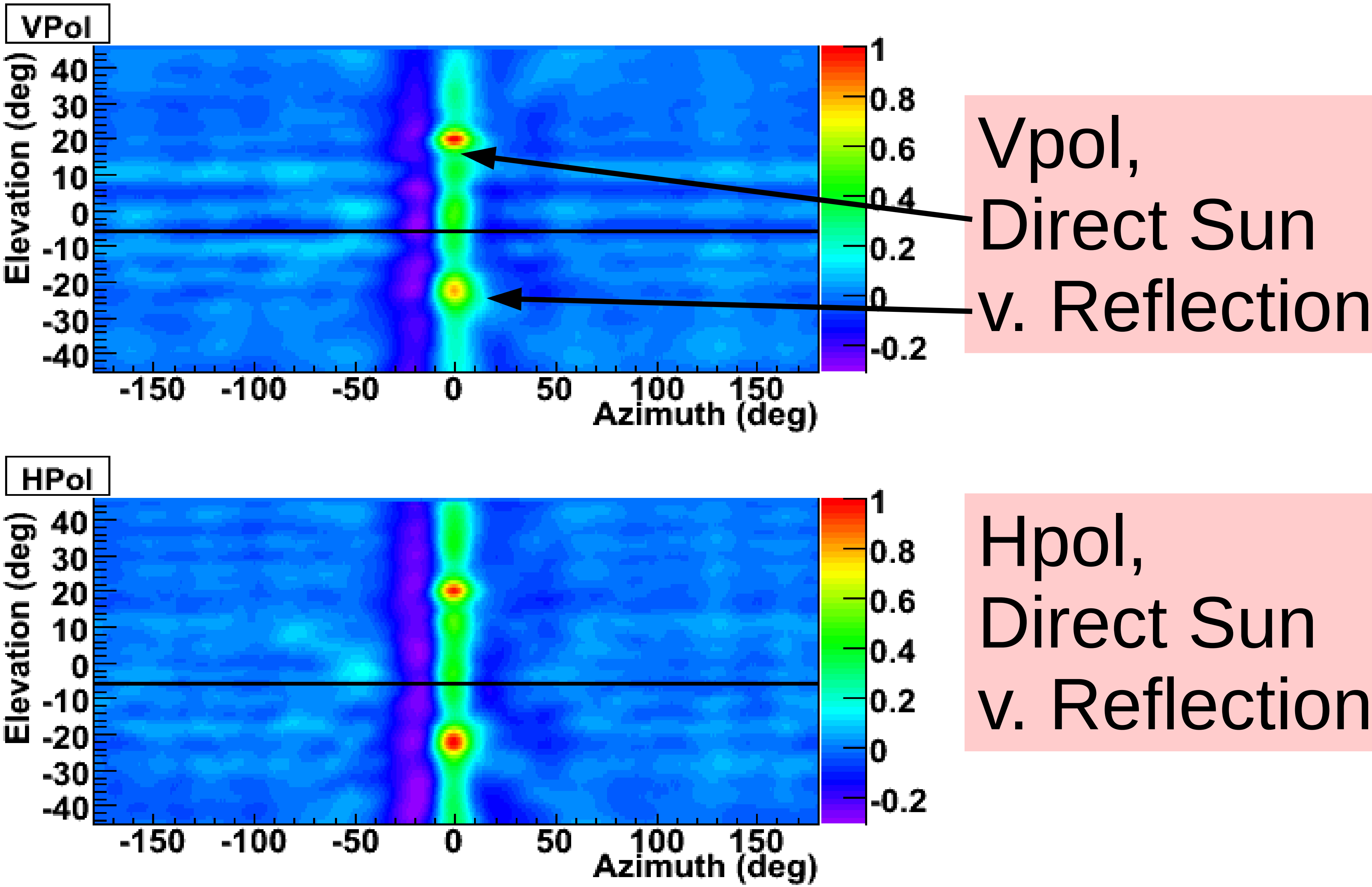
FIG. 1: *Antarctic topography along Vostok route (I)*

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

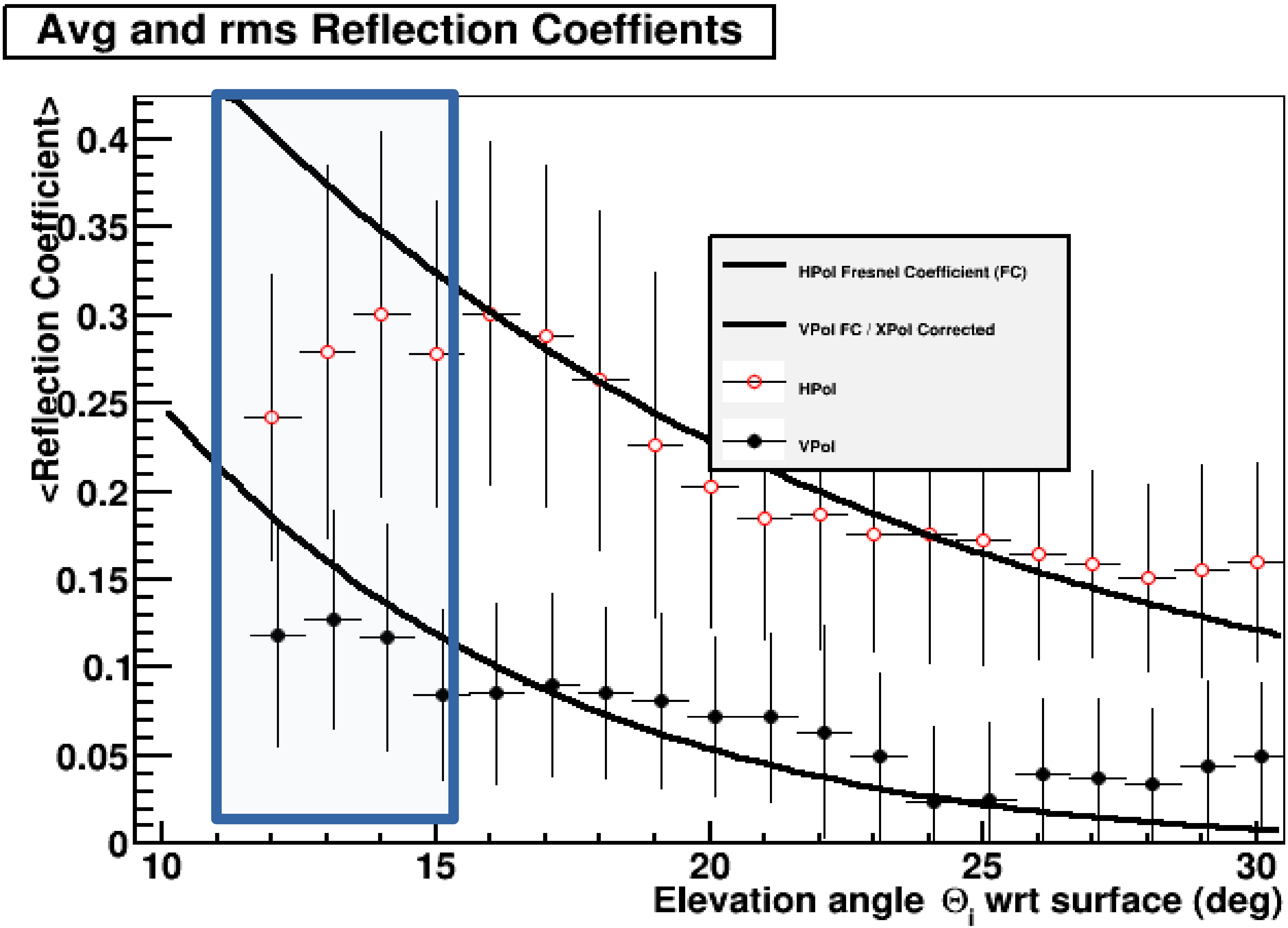
FIG. 3: *Antarctic topography along Vostok route (III)*

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

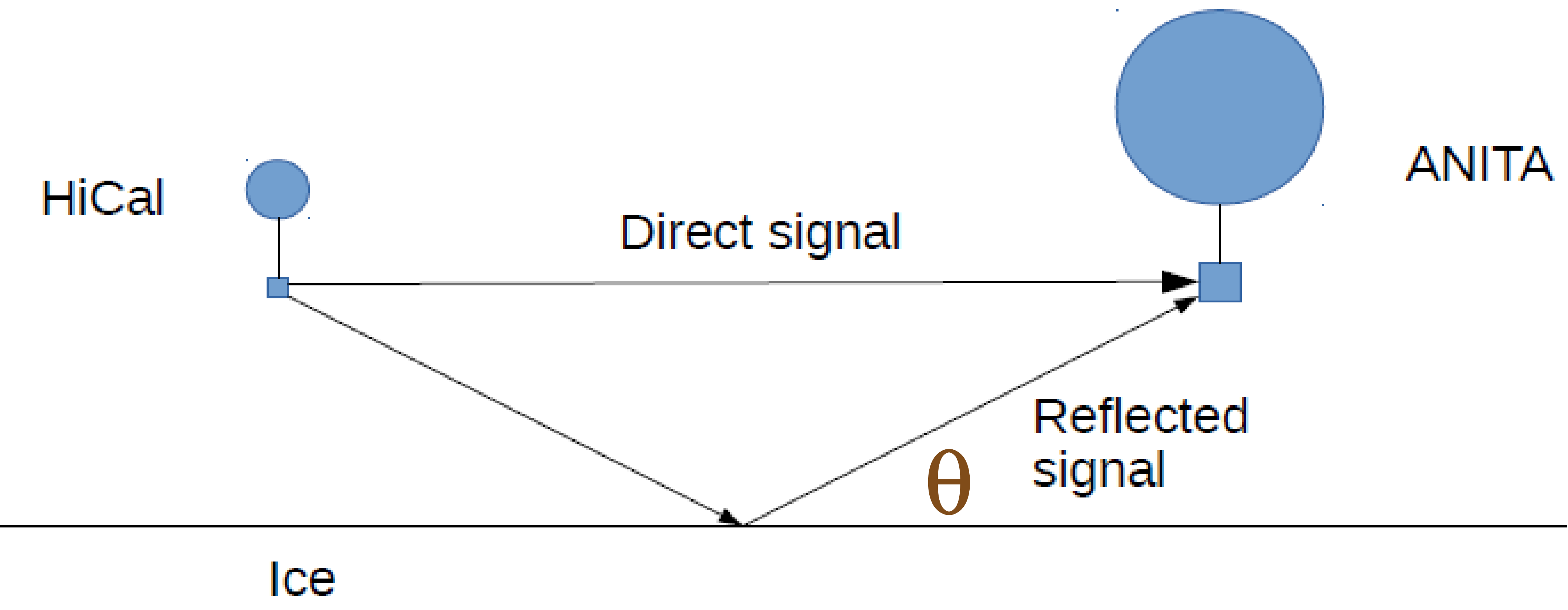
Calibrating surface roughness via Solar albedo



Agreement with Fresnel Coefficients as f(incidence angle)

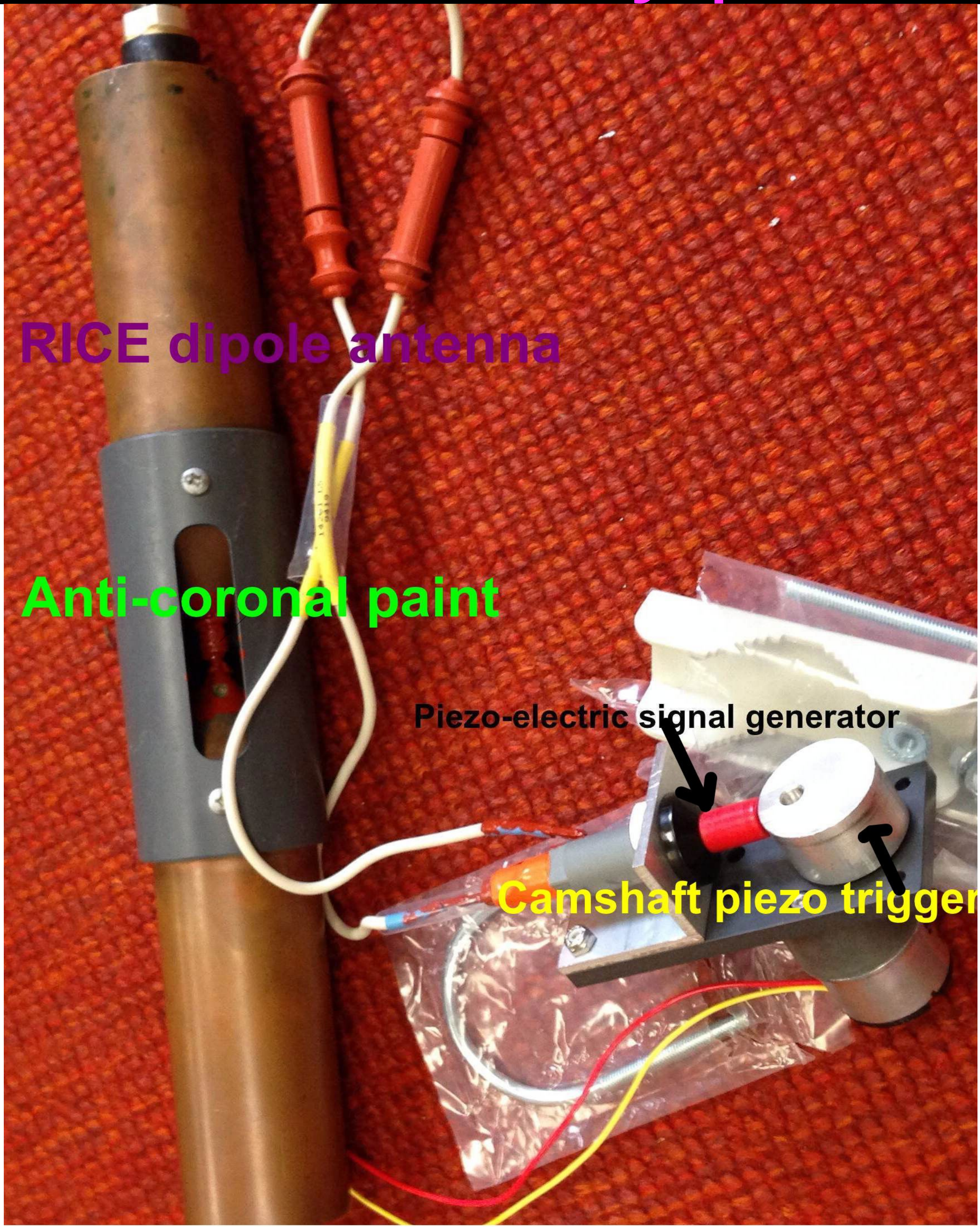


HiCal-trailer balloon to measure roughness

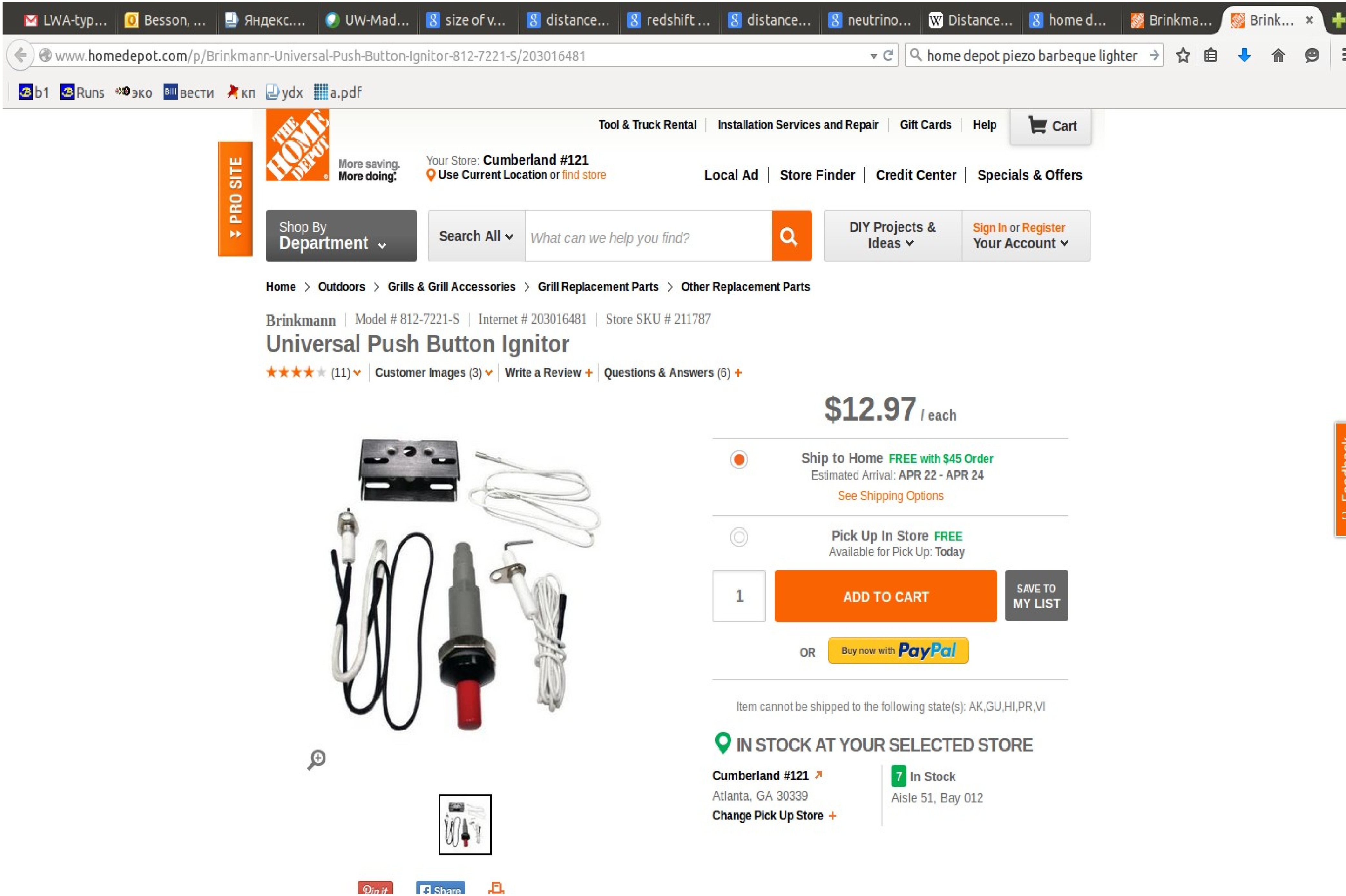


More precise surface reflectivity probe

- 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

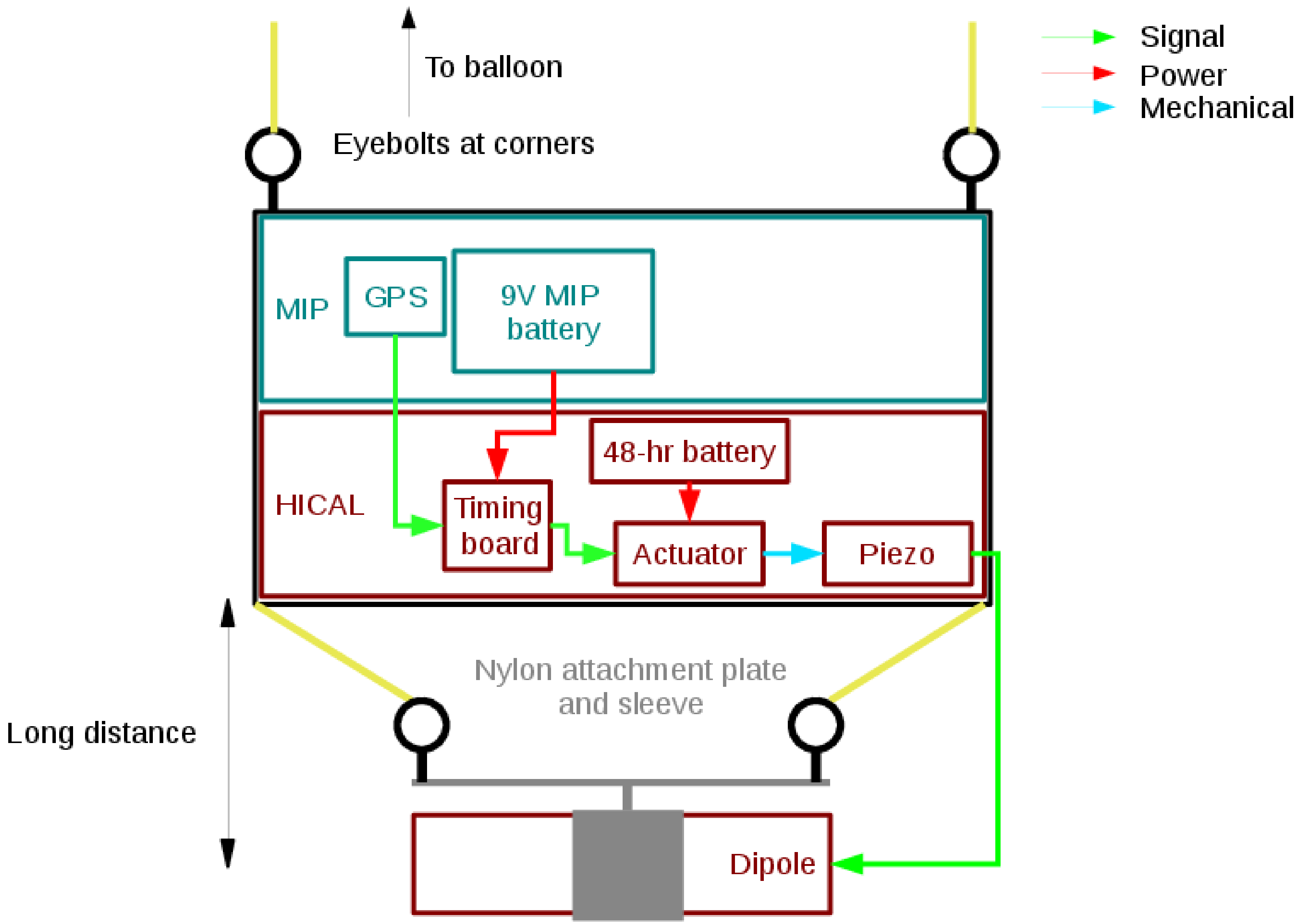


RF transmitter



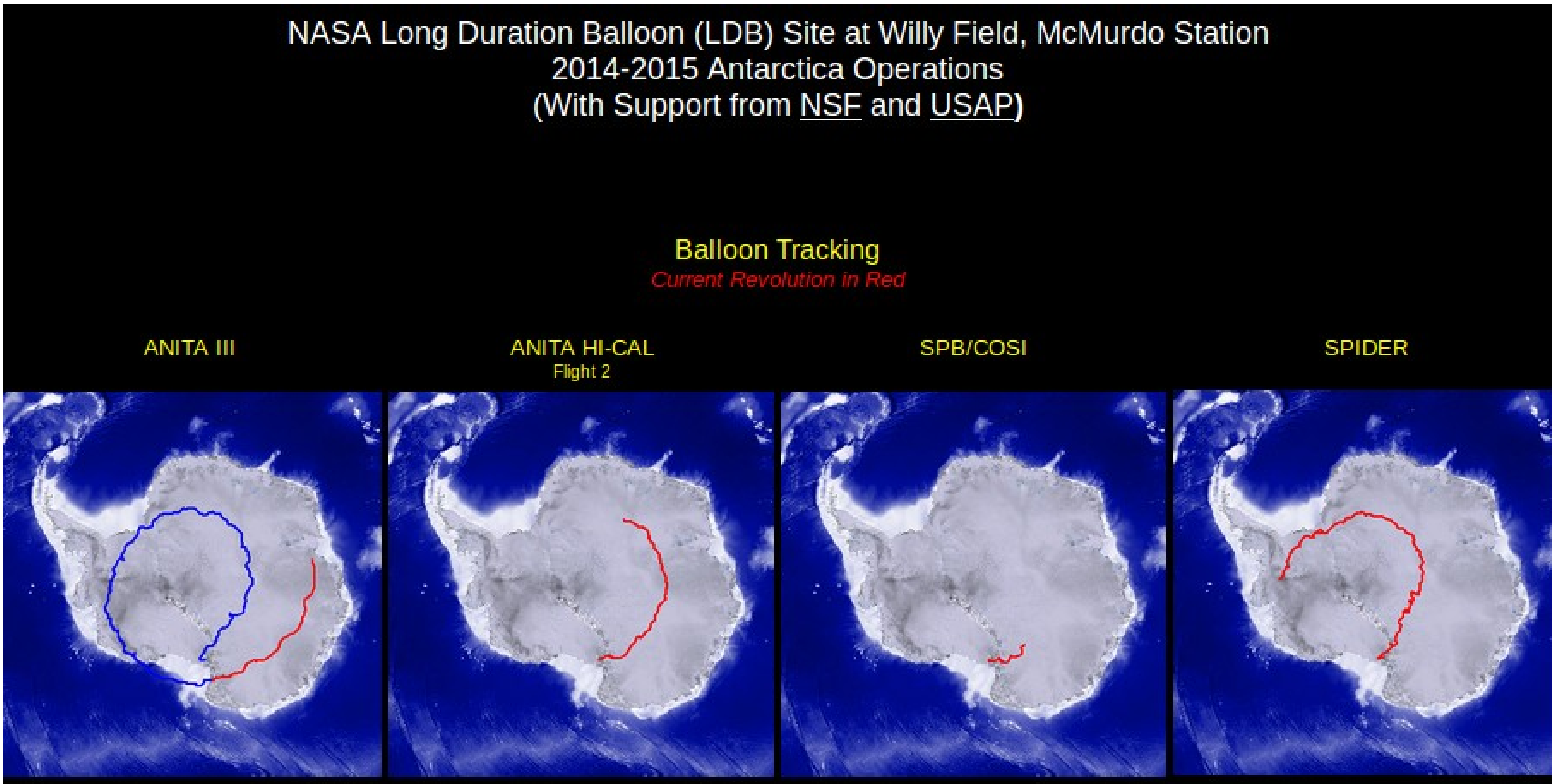
HiCal sparker at 5 mB

HiCal schematic

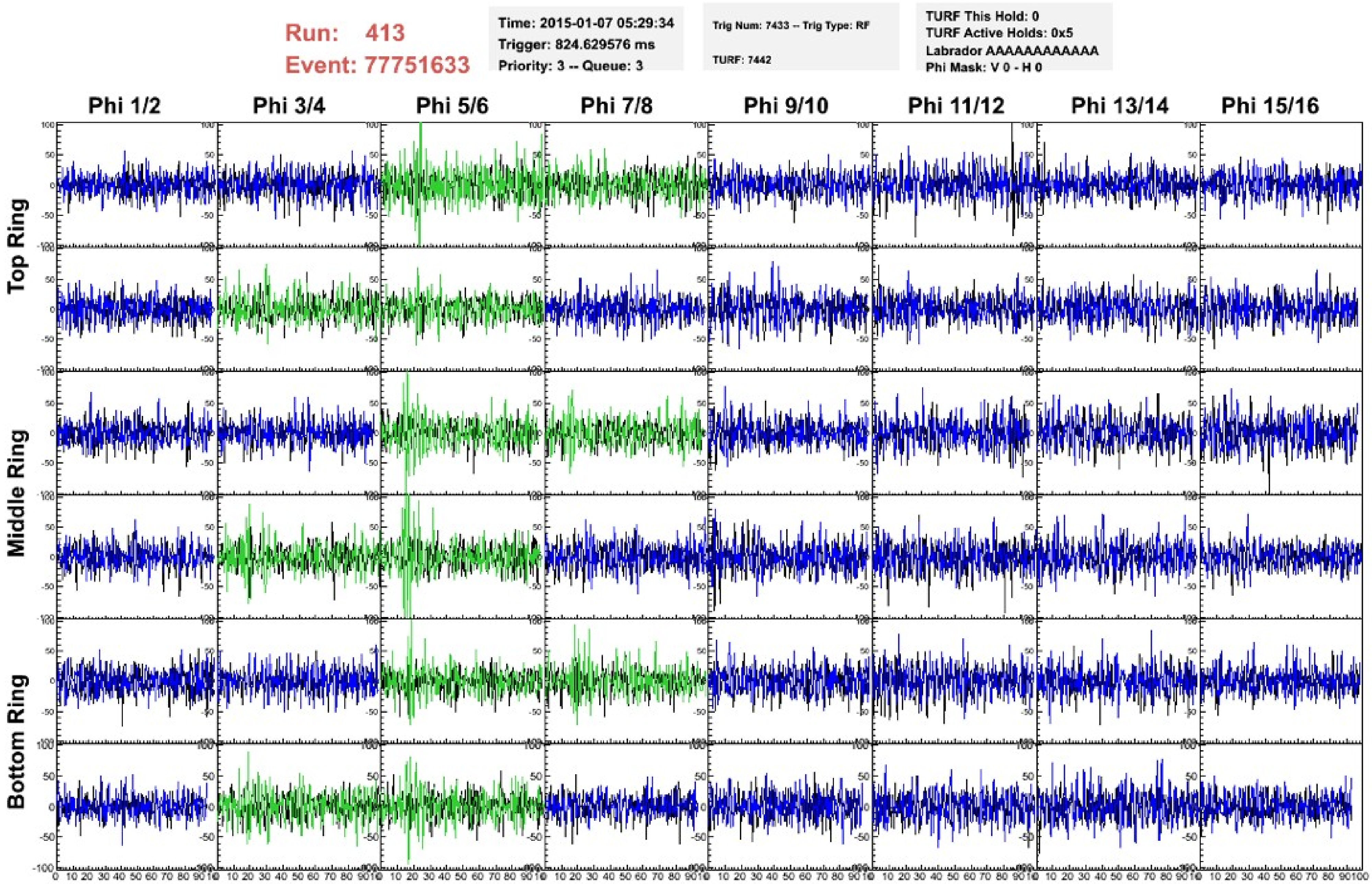


HiCal Launch (Jan. 5, 2015)

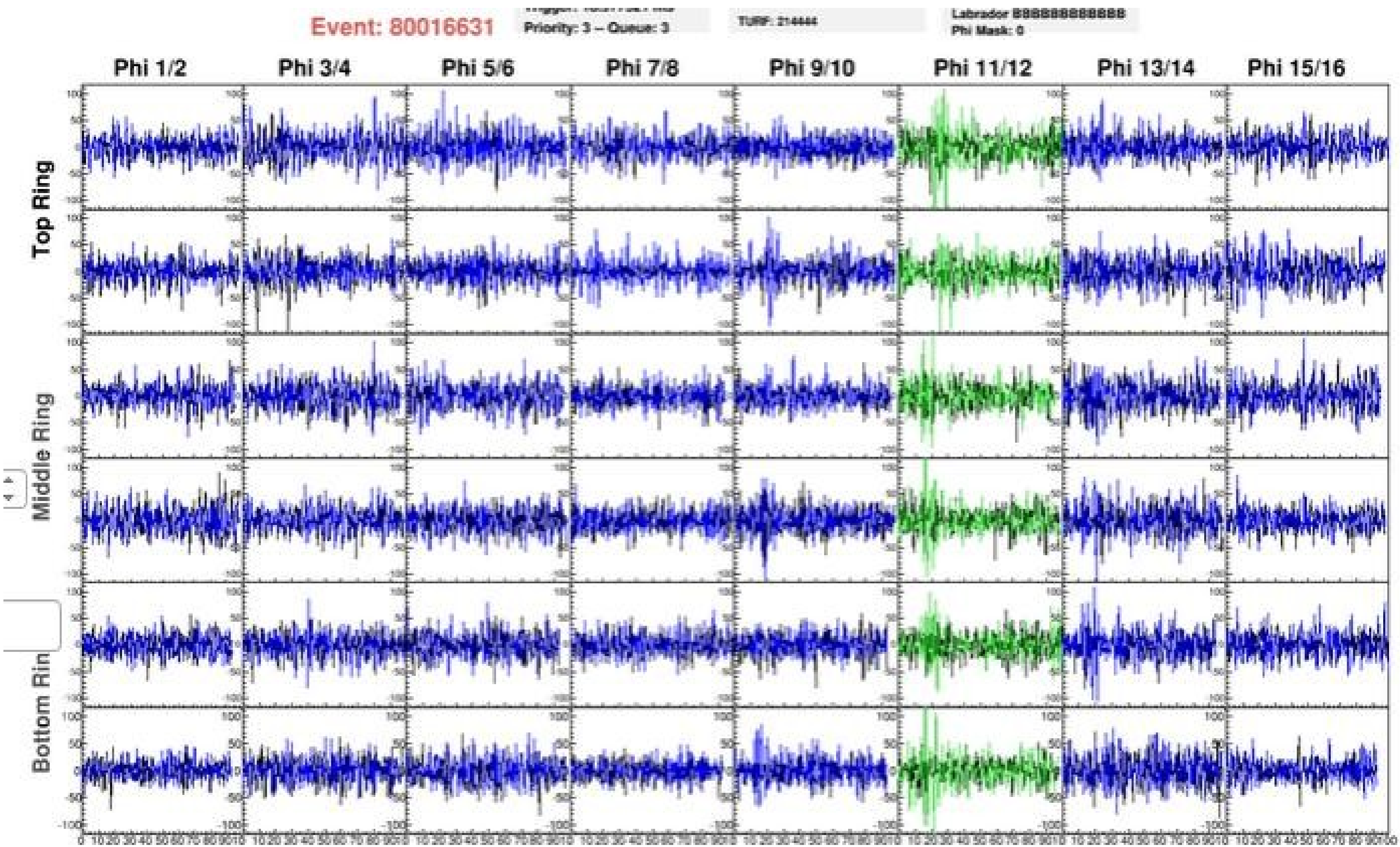
Flight Paths, Dec. 2014-Jan. 2015



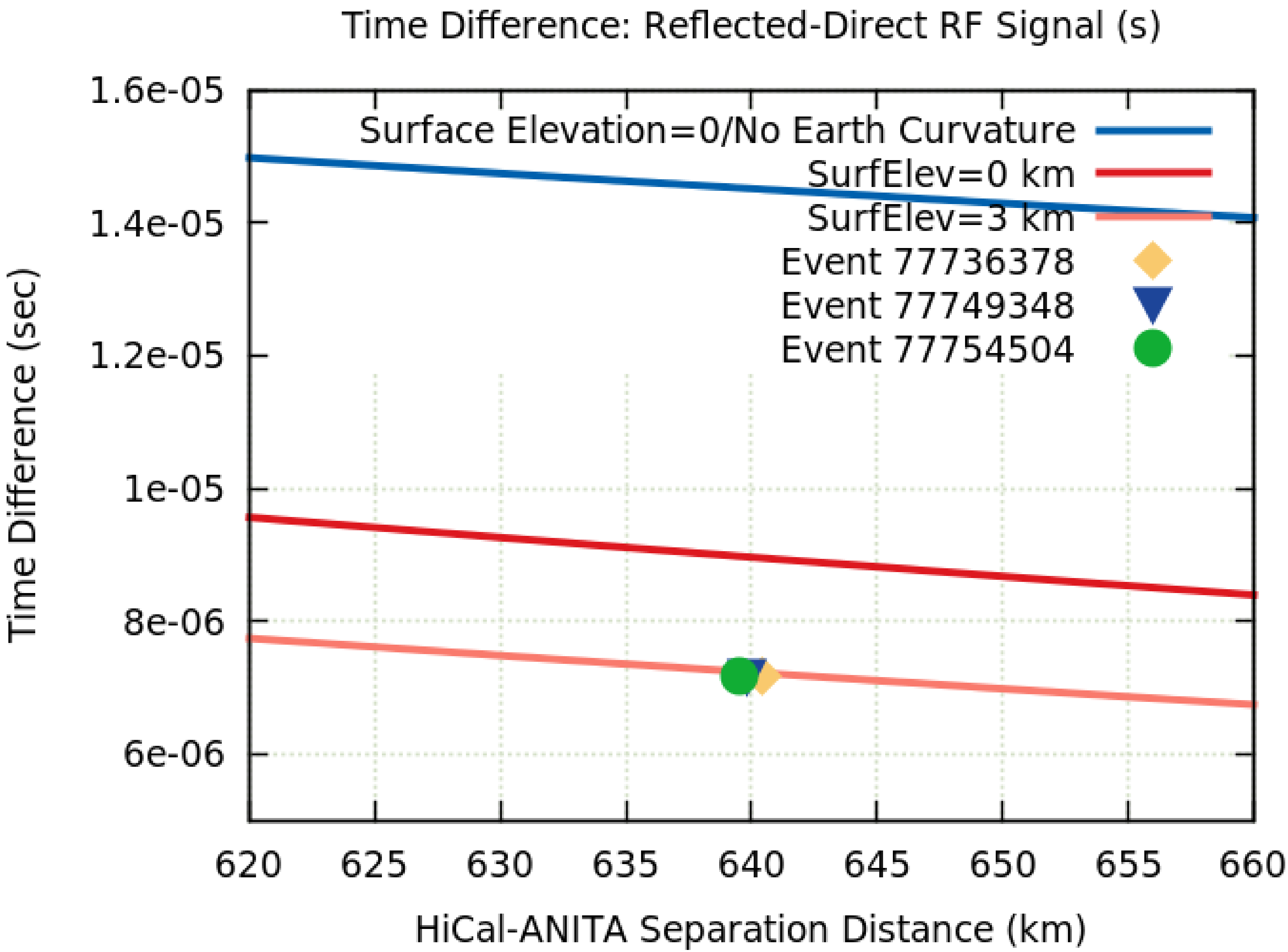
Event 1-HiCal observed from 750 km!



HiCal Event-2 (at float)

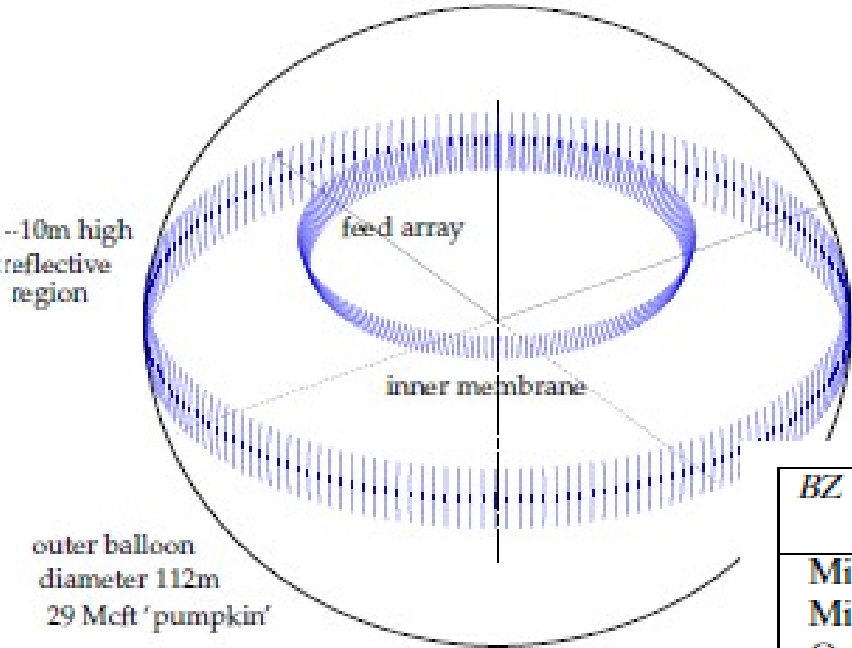


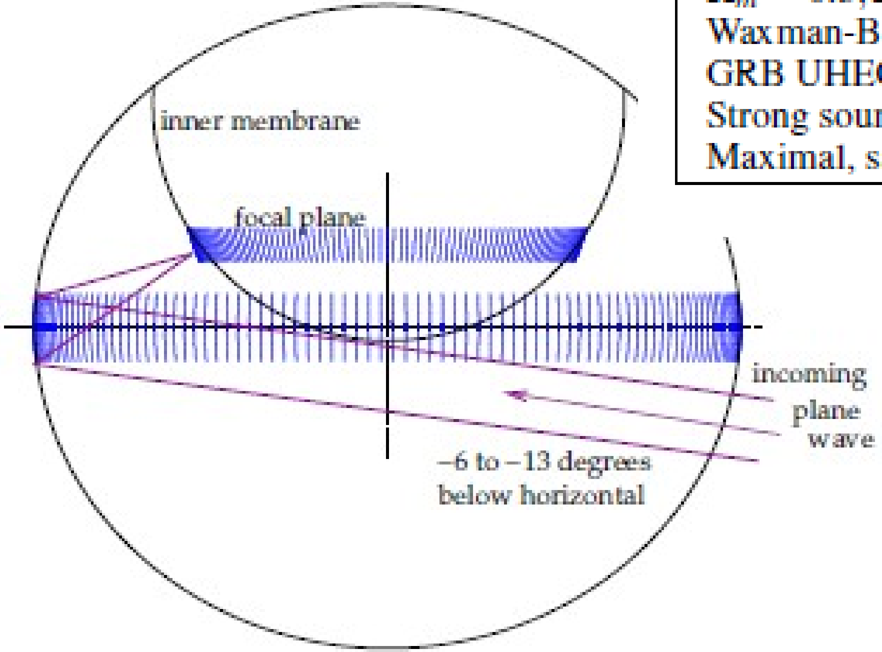
Also, surface reflections observed!



EVA: The balloon is the antenna

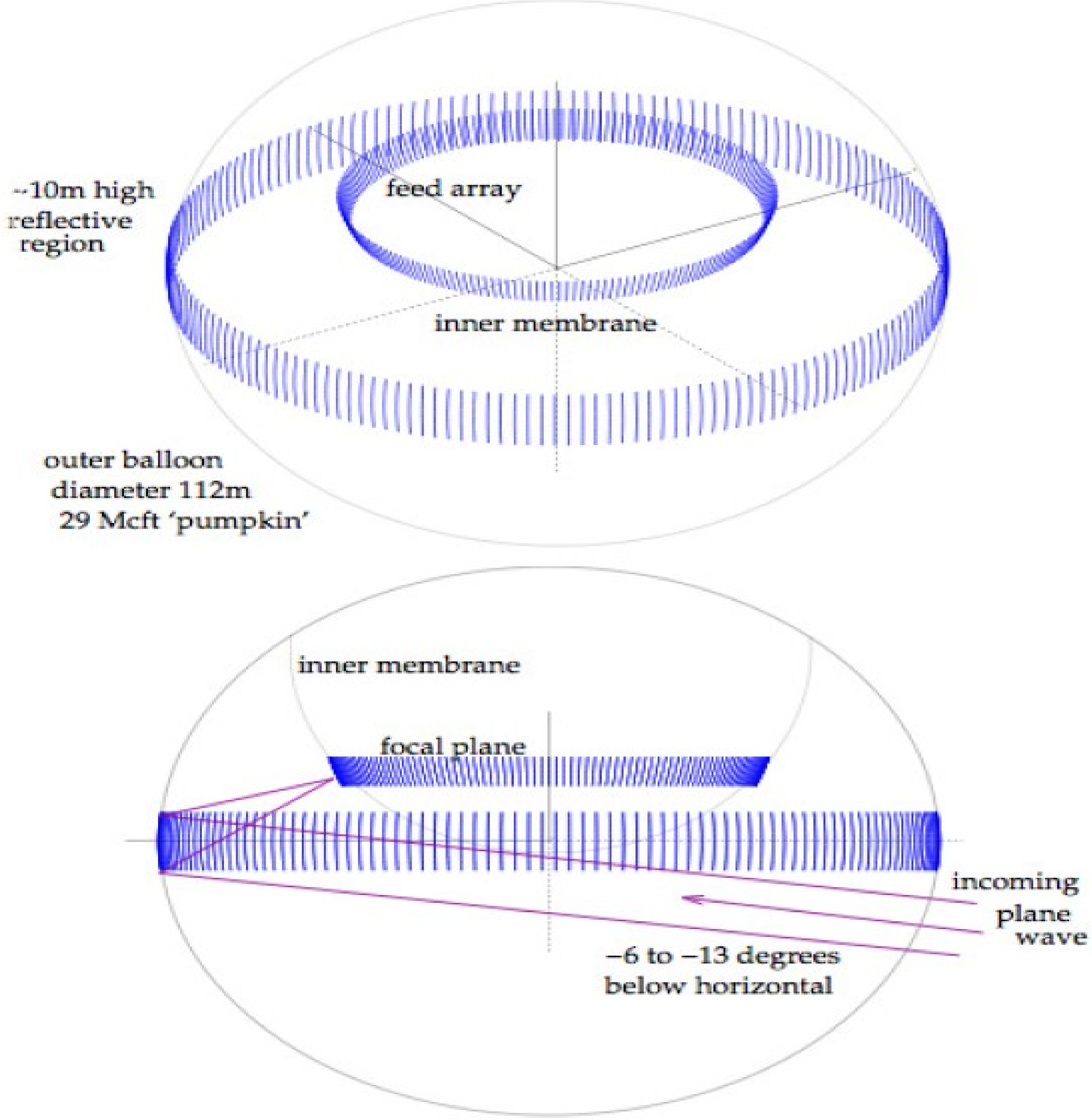
Reflectors guide RF to Inner feed array





BZ neutrino models	*Events, ANITA-II, 28d*	*Events, EVA, 50d*	*ratio, EVA/ANITA*
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!