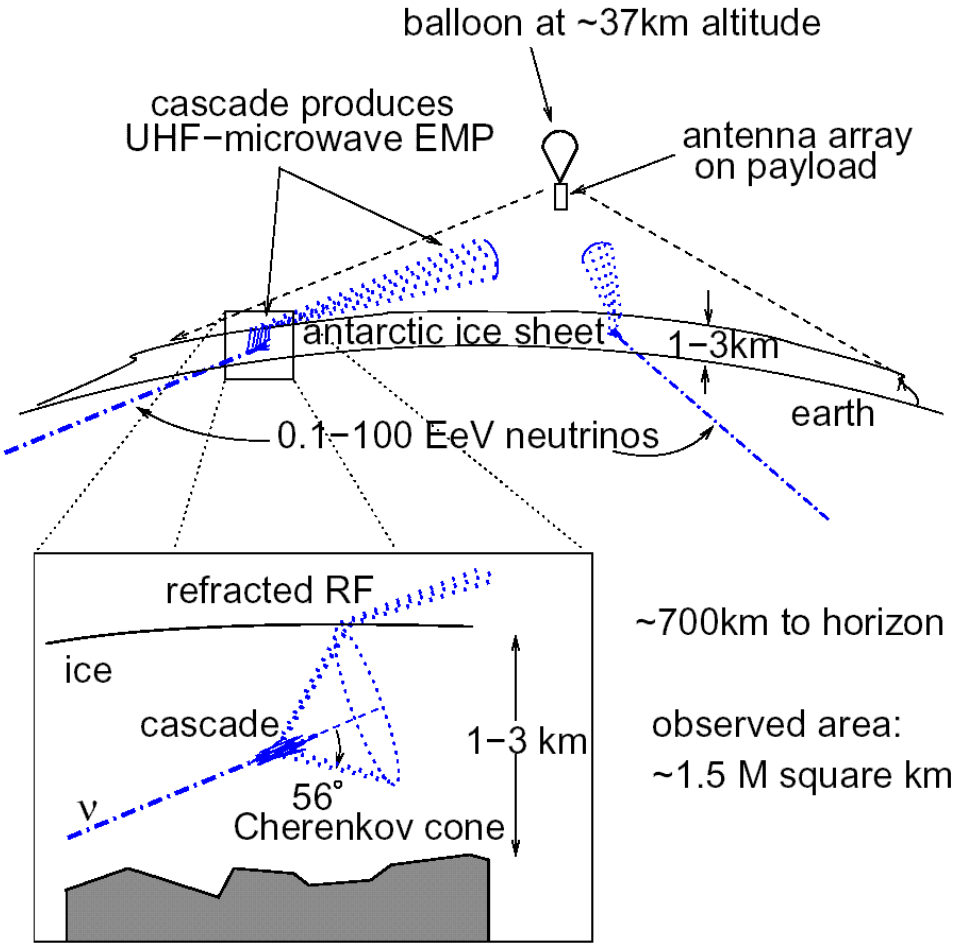
Antarctic Neutrino Detection Experiments Utilizing The Askaryan Effect In-Ice, Which Begin And End With The Letter “A” And Have Either 2 or 3 Syllables (but definitely not more than 3)

- ANITA (balloon)
- ARA (South Pole)

ANITA/ARA 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 $\nu N \rightarrow lN'$+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/ARA concept



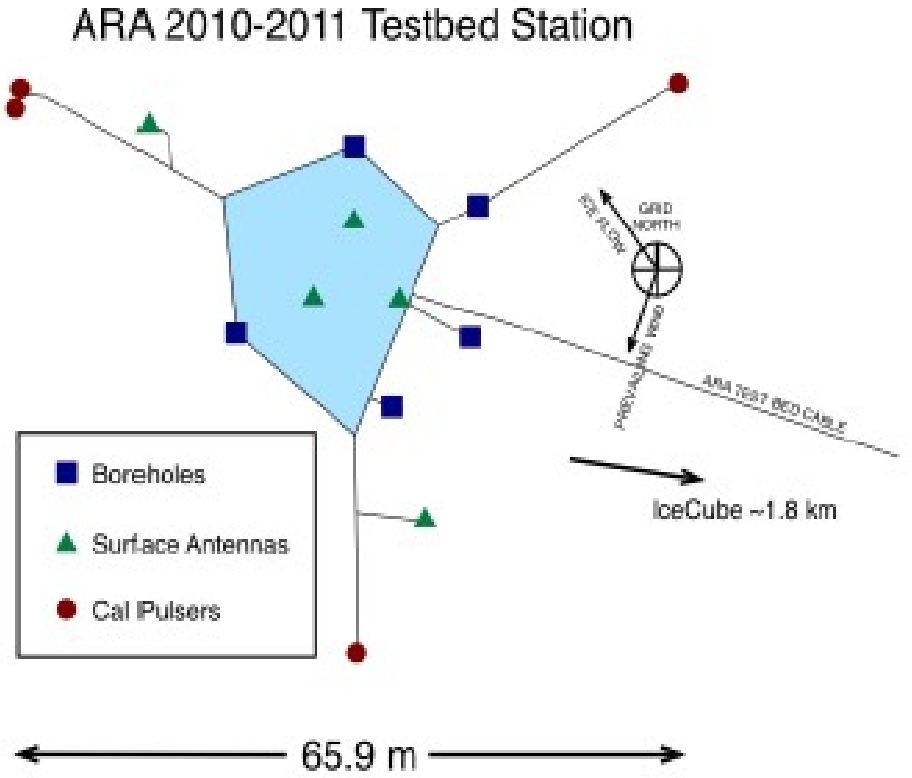


Figure 2: Schematic of the ARA Testbed station.

ANITA/ARA +/-

+ Advantages of the ANITA strategy relative to in-ice:
  - 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
    - Better polarization separation for in-air (or on-surface, a la' ARIANNA)
- 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 ~ 10,000 PeV (10 EeV)
  - 35 day livetime

ANITA 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=final ANITA flight; ~ANITA-3

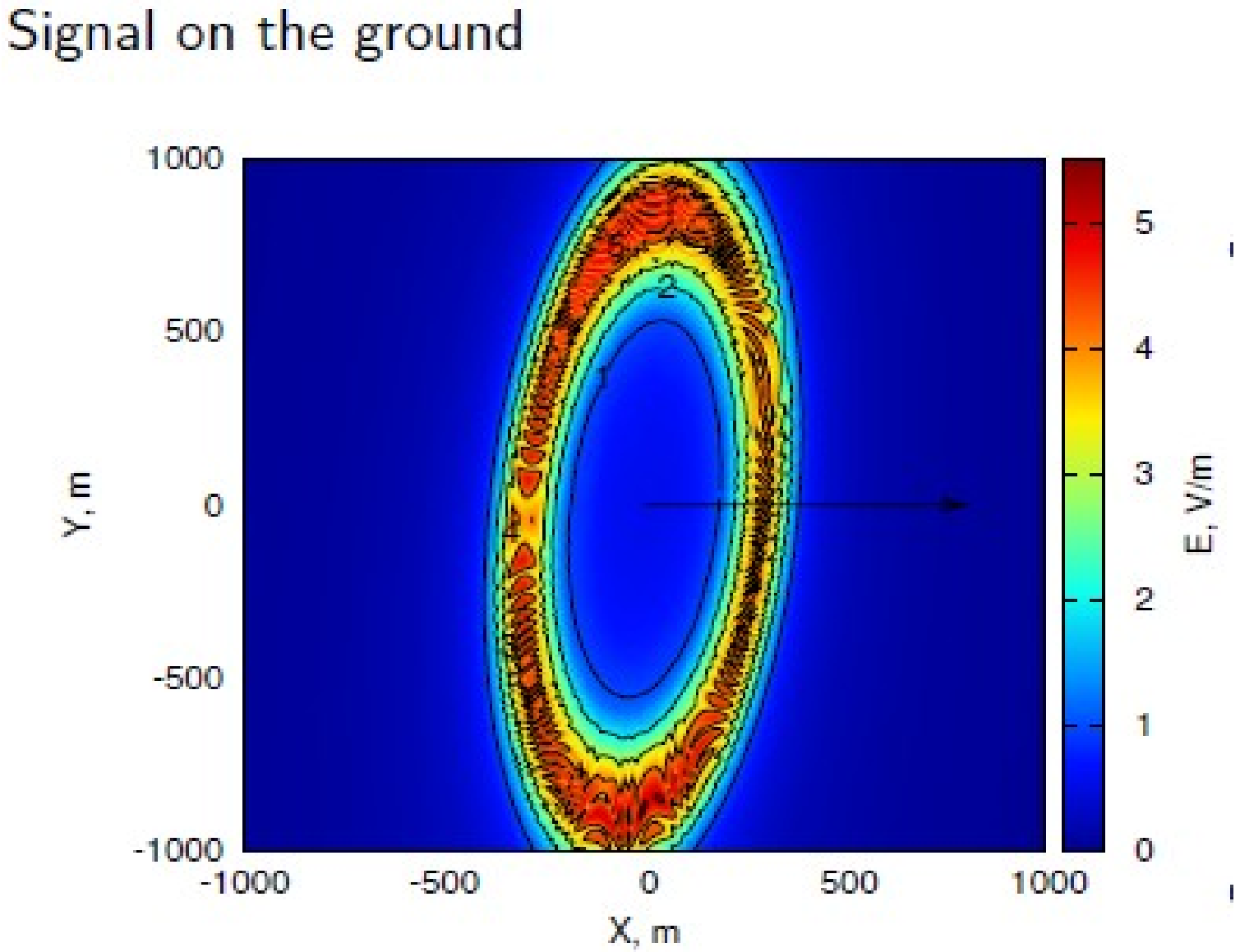
Published Science Results

- Best limits on neutrino flux for $E>10^{19}$ eV +
  - Radioglaciolgy: First direct (i.e., time-domain) measurement of crystalline ice Ih birefringence
  - UL on fluxes of ultra-relativistic monopoles
  - GRB neutrinos
  - Lorentz invariance
  - Surface roughness probed by measuring surface albedo @ λ~1m
  - Unexpectedly, demonstration of ANITA as a charged UHECR detector via radio emissions!
    - 20 Hpol-dominant events via “geomagnetic + Askaryan” radiation
    - Unique to ANITA – triggering at frequencies >200 MHz

Radio Air Shower Energy Measurements

- Two effects:
  - **v** x $\mathbf{B}_{earth}$ (uniform polarization, **E** transverse to $\mathbf{B}_{earth}$)
  - Askaryan in-air: radial **E**
    - (i.e., transverse at all points to Circular Cherenkov ring)

Radio Cherenkov ring (θ_c~1 degree!)

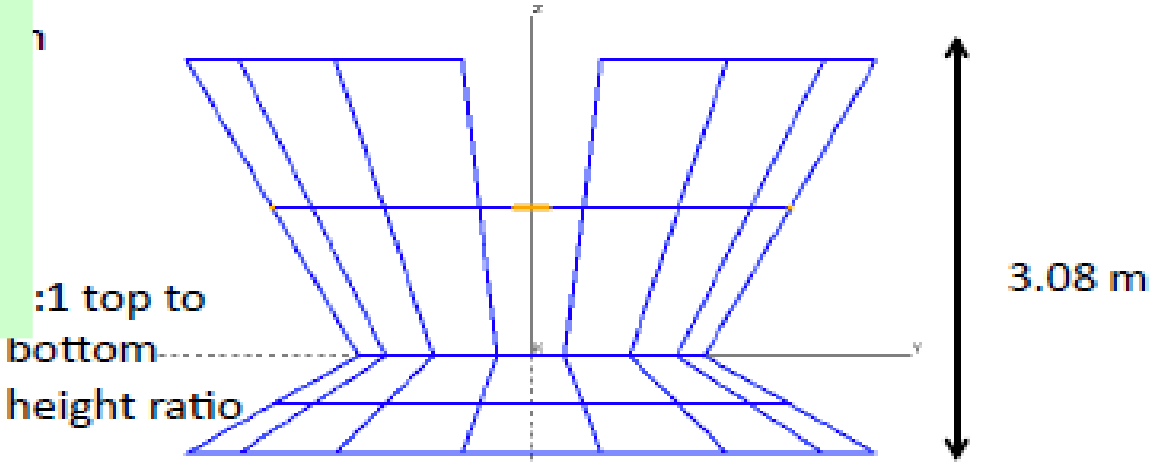


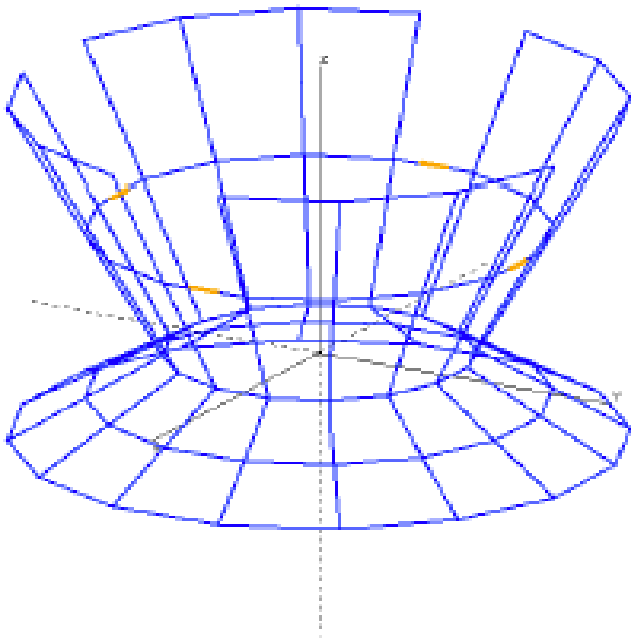
ANITA-2 → ANITA-3

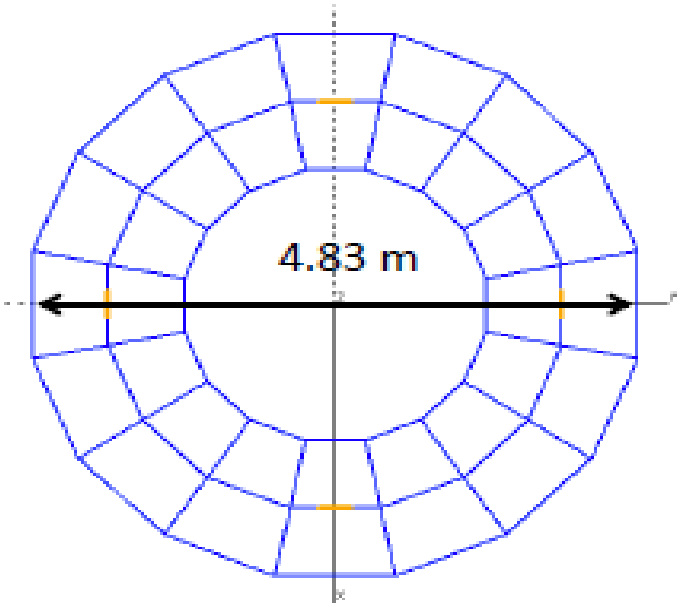
- Improve sensitivity to RF from UHECR EAS
  - Restore Hpol triggers that were dropped in ANITA2 before we realized ANITA was a UHECR detector!
  - Real time, event-by-event interferometry using 3-bit waveforms lowers trigger threshold to ~2.5 SNR
    - Demonstrated performance @ 300 Hz
  - Add cylindrical Hpol Rx with sensitivity down to 80 MHz to bridge low → high frequency understanding of radio emissions from air showers
    - UNIQUE feature of ANITA-continuous coverage over "coherent" → "partially coherent" radio-frequency regime

Hpol low-frequency antenna hangs under gondola

3 m x 5 m!
f>60 MHz







ANITA-3 UHECR

- Expect to see ~10 UHECR per day via radio emissions
  - Threshold ~1 EeV
  - mean observed energy ~30 EeV
  - Modest improvement w/ ANITA-4
- Excellent UHE aperture!
  - **May observe GZK cutoff!**

Improving UHECR energy estimate

AUGER/TA: redundant energy measurements!!

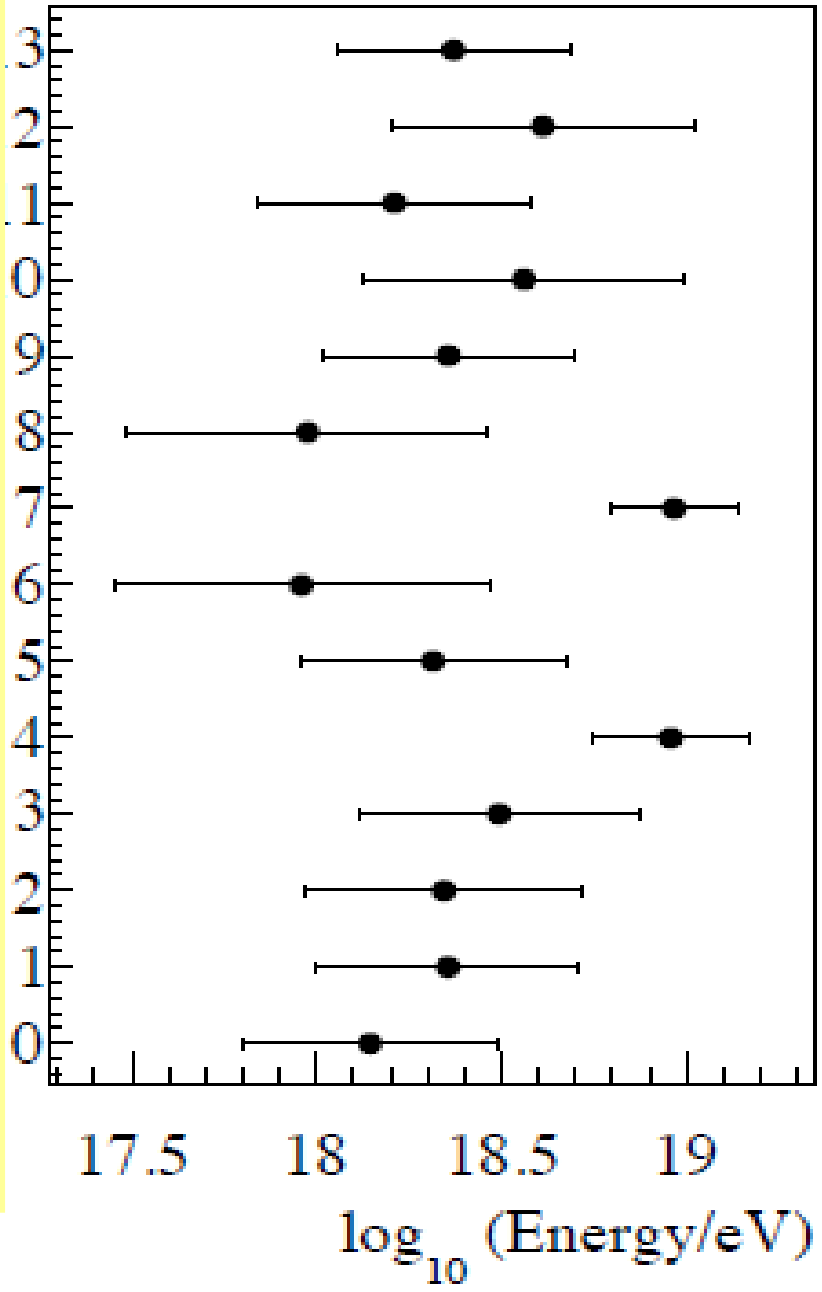
- ANITA – only handle via radio; strategy for reducing energy sys error:
  - lowering sensitivity into “well-modeled” f<200 MHz regime with dedicated Hpol cylinder antenna
  - Dedicated testbeam (T-510) just completed to quantify geomagnetic/Askaryan signals
  - More precise measurements of surface reflectivity/roughness over ANITA passband

Refining A1 UHECR energy-estimates

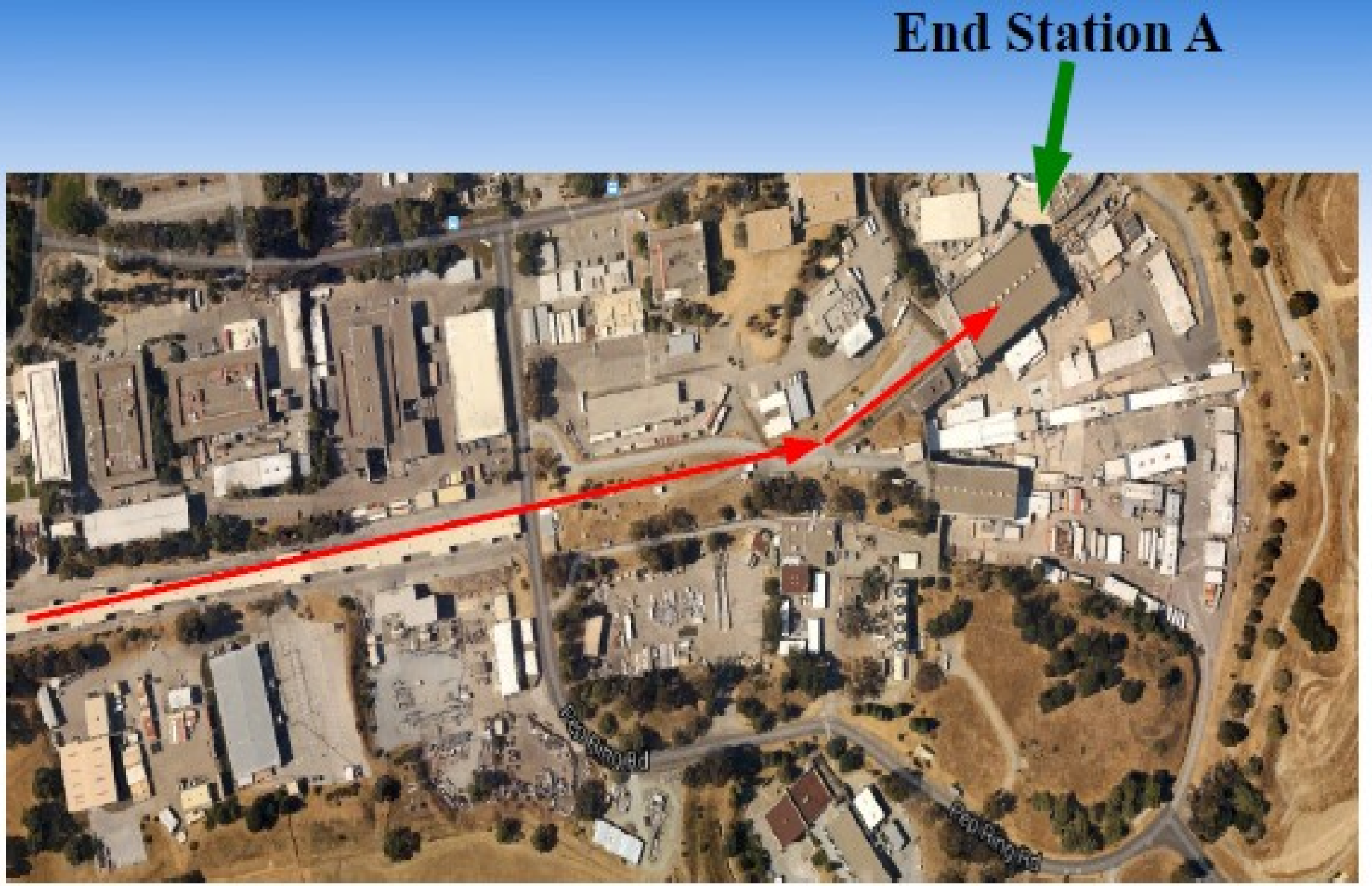
Procedure:

Model CoREAS/ZHSAires prescribes $\Delta\theta_c$ as f(observed) pwer spctrum

Knowing $\Delta\theta_c$, and msrd signal amplitude=>infer UHECR energy

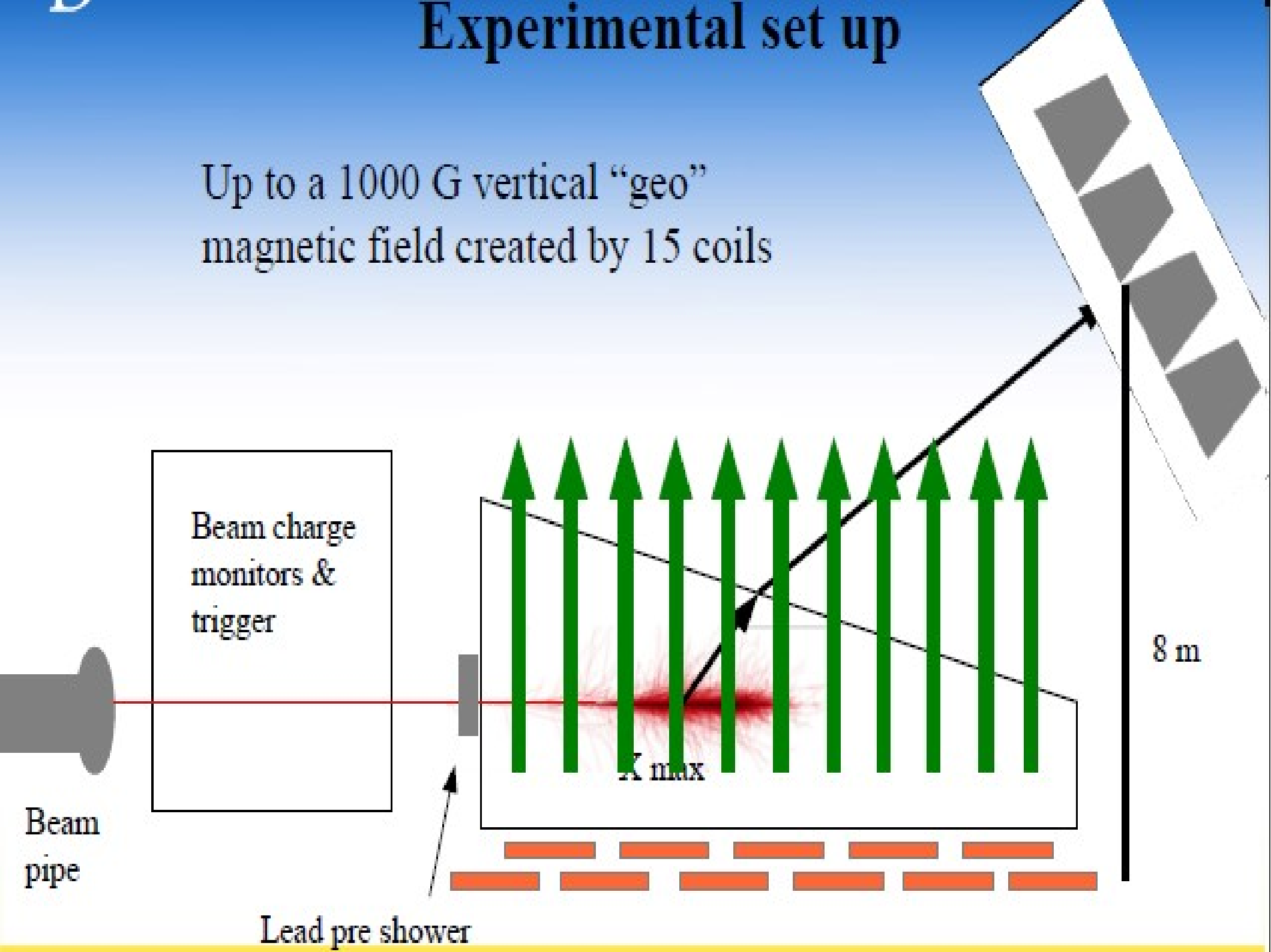


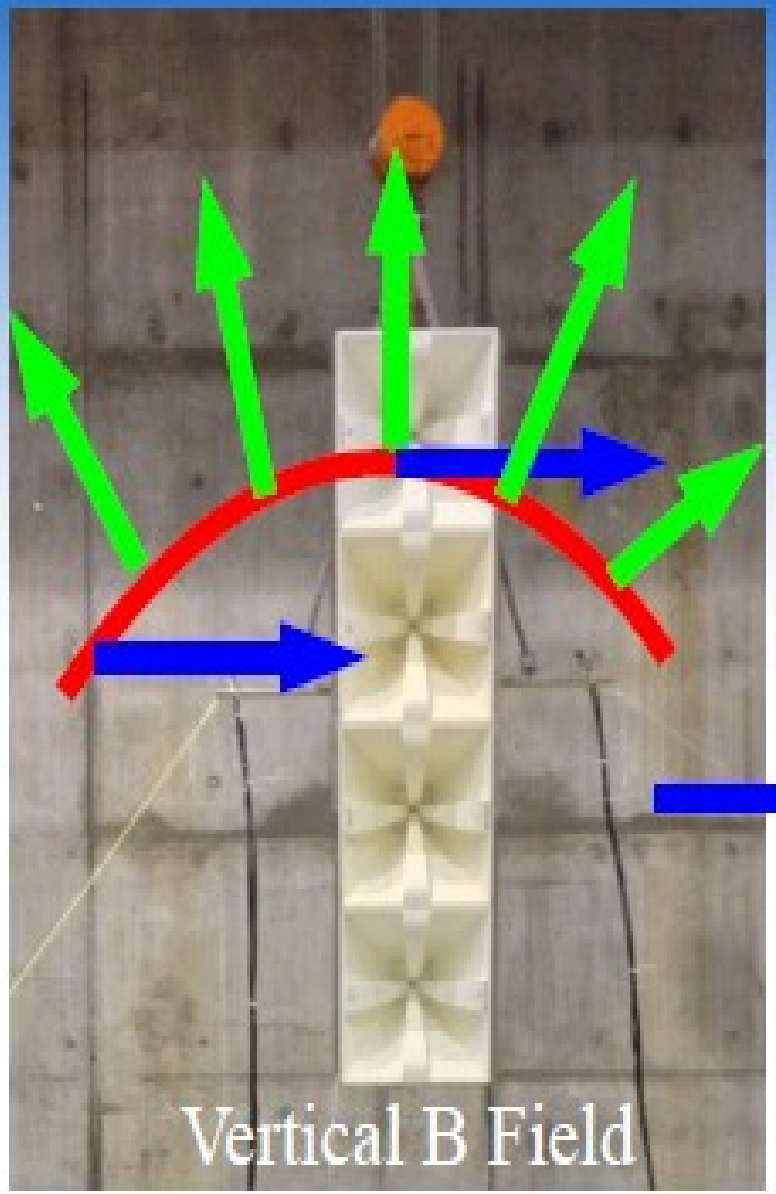
SLAC T-510: Spring, 2014 (data analysis in progress)



Experimental set up

Up to a 1000 G vertical "geo" magnetic field created by 15 coils





Cherenkov Cone

Askaryan

“Geo” Magnetic

Calibrating surface roughness via stereoscopic photos

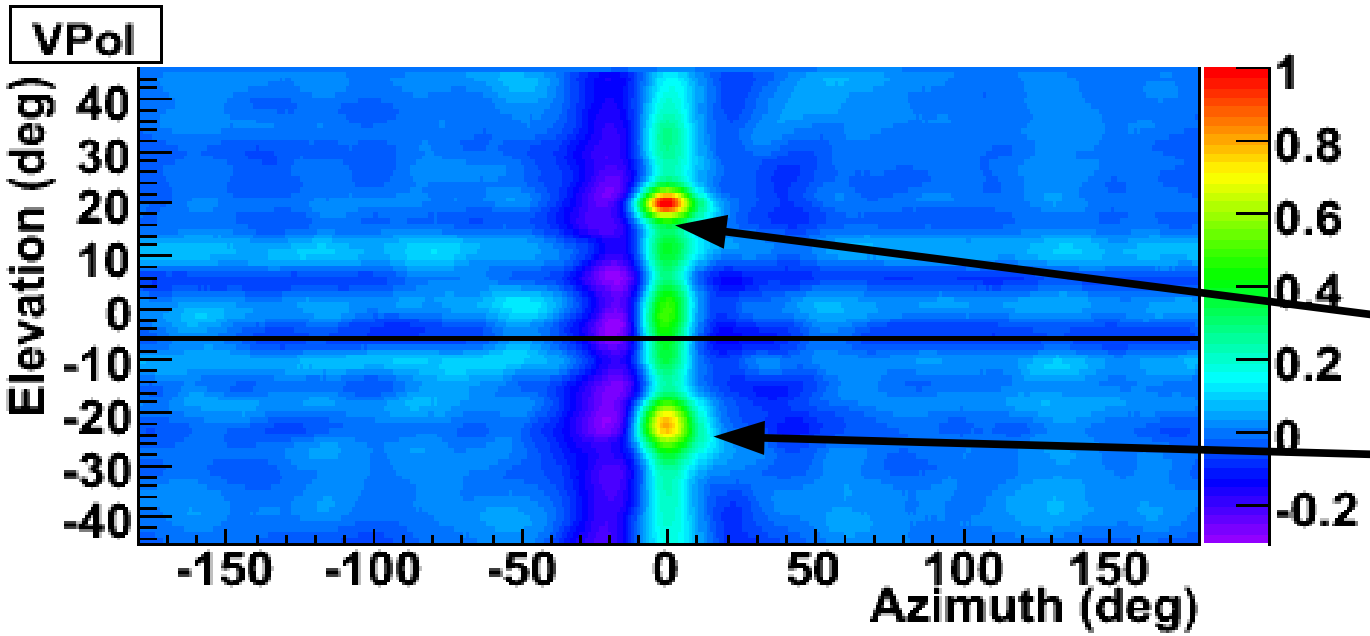
FIG. 1: *Antarctic topography along Vostok route (I)*

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

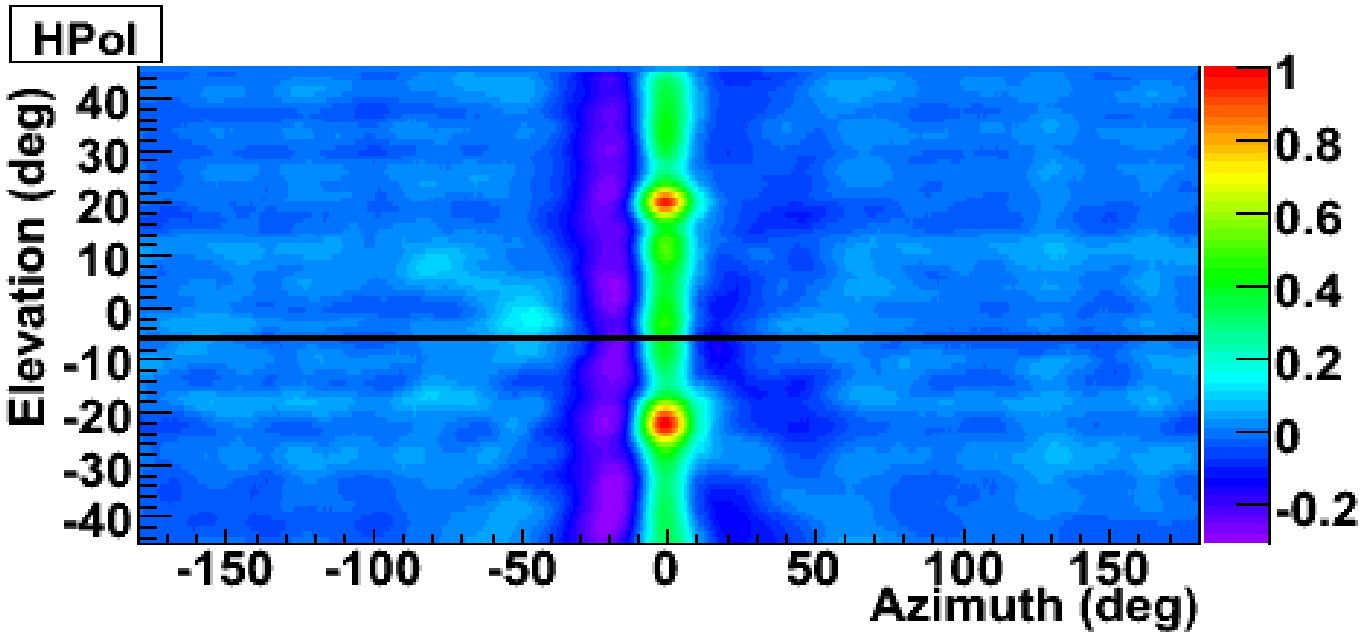
FIG. 3: *Antarctic topography along Vostok route (III)*

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

Calibrating surface roughness via Solar albedo

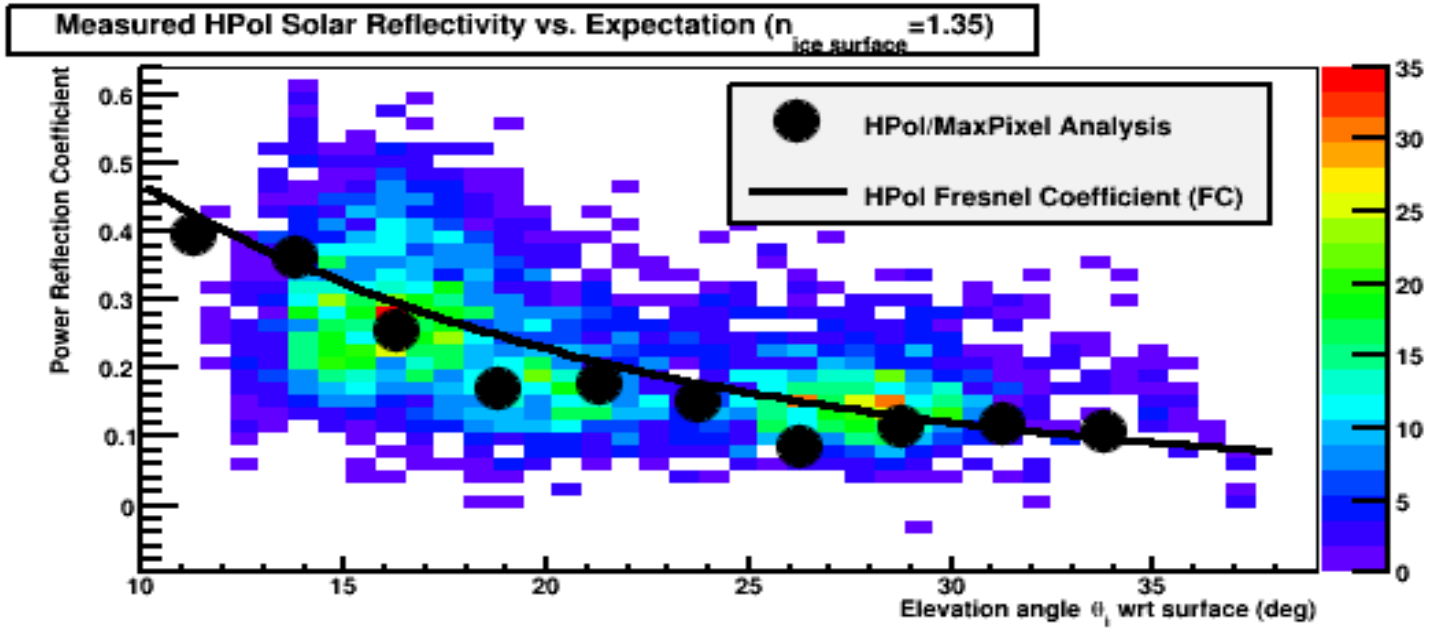


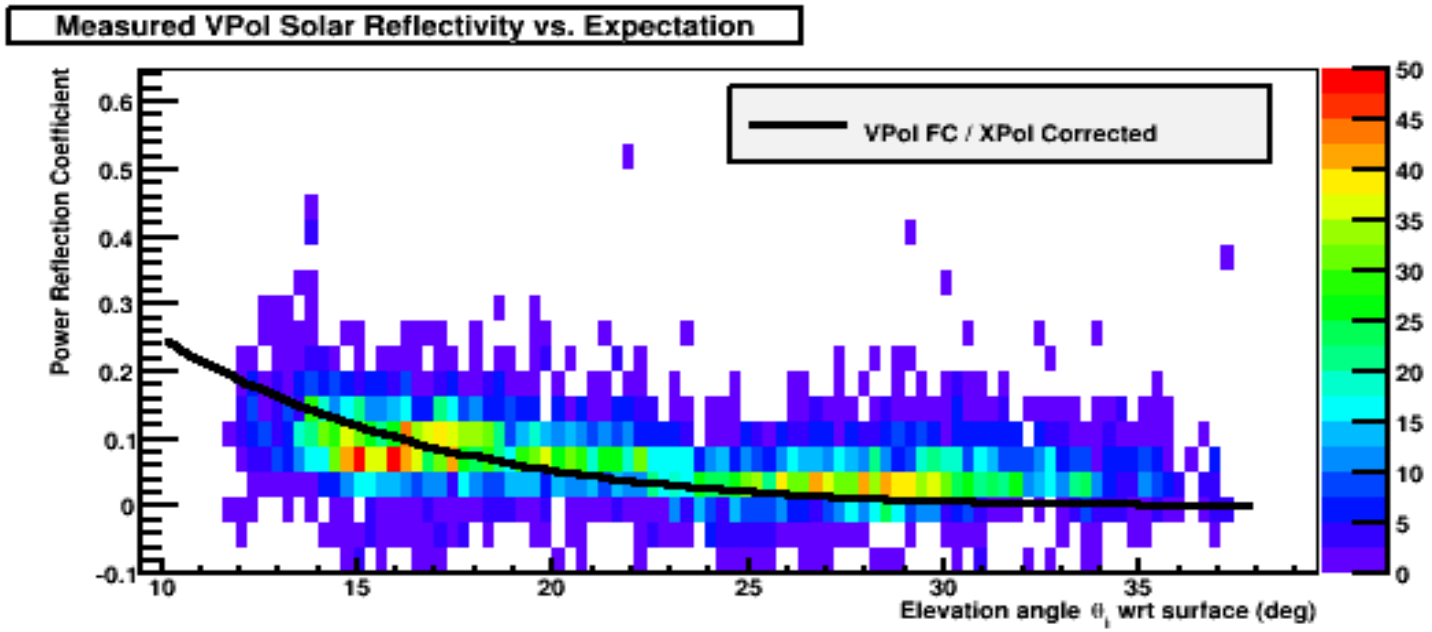
Vpol,
Direct Sun
v. Reflection



Hpol,
Direct Sun
v. Reflection

Agreement with Fresnel Coefficients as f(incidence angle)



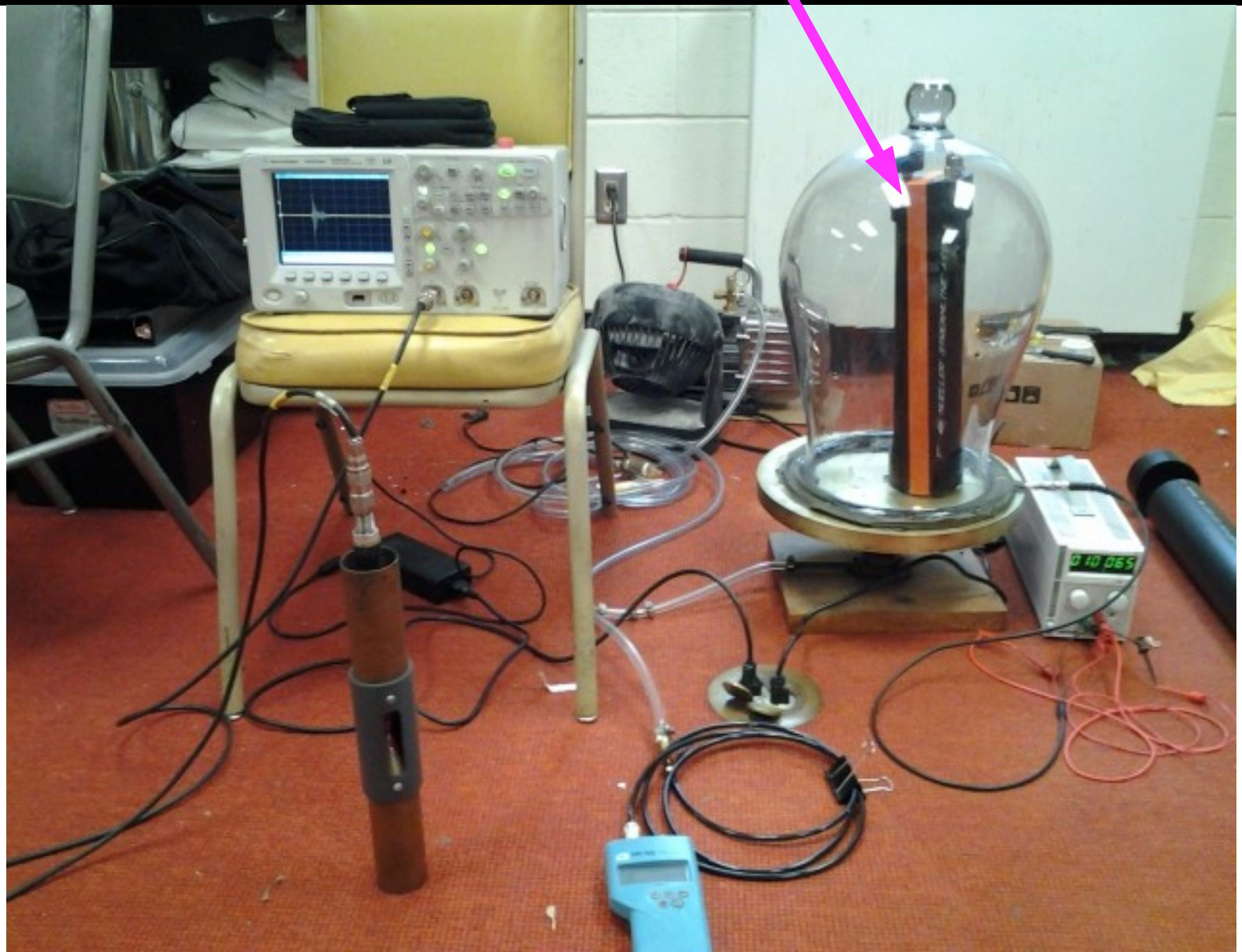


Lines= Fresnel H- (top) & V-Pol (bottom)

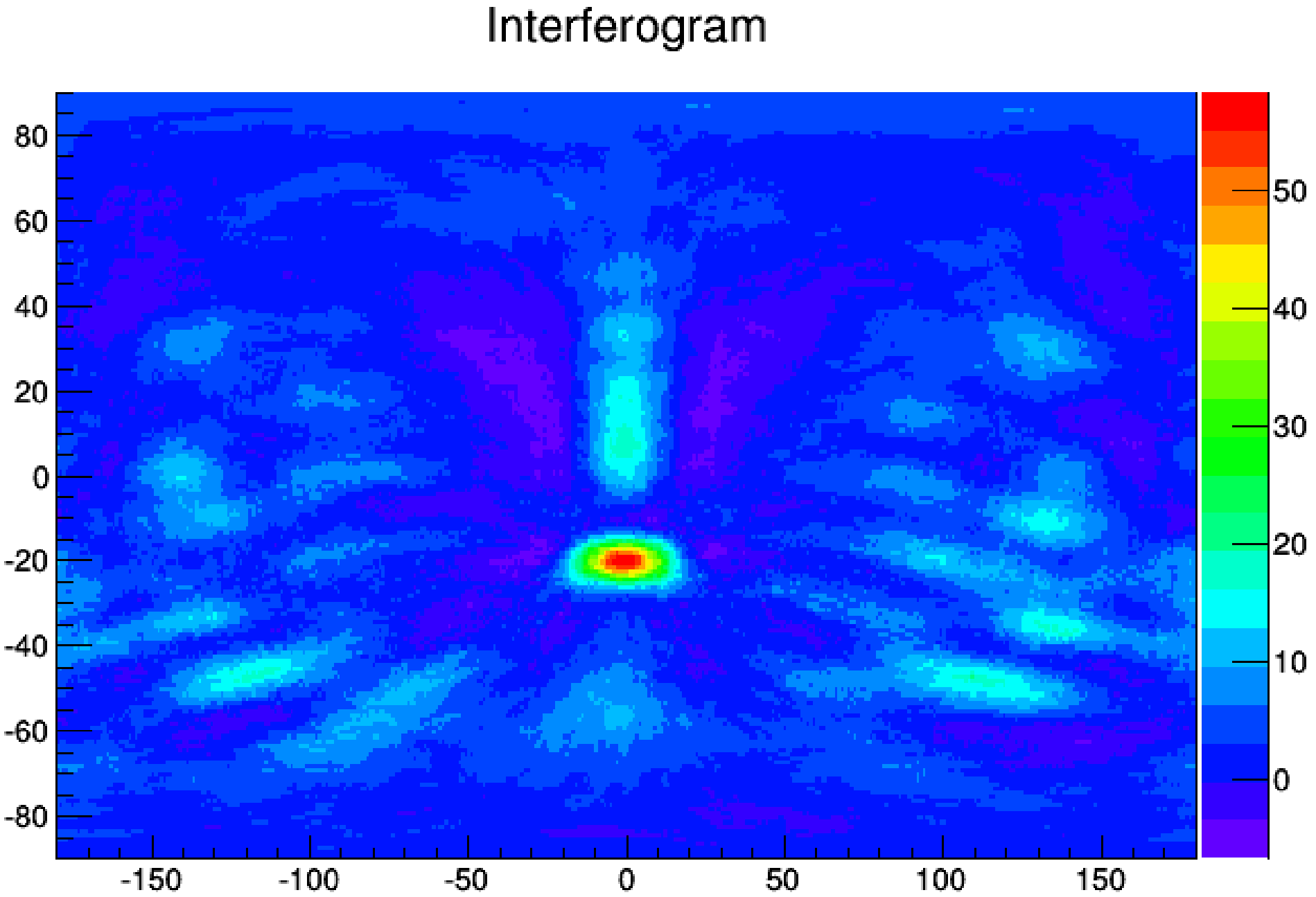
More precise surface reflectivity probe

- 12/14: ANITA HiCal: Pathfinder class balloon, to be launched within hours of main ANITA-3 launch
  - Tx emits both direct + surface-reflected signal
- to fly within 200 km of ANITA for at least one hour
- Hardware:
  - “custom” transmitter that mimics EAS spectrum (ignition coil or piezo sparker [$10 @ Walmart) fed into a RICE-type dipole antenna

HiCal sparker at 5 mB

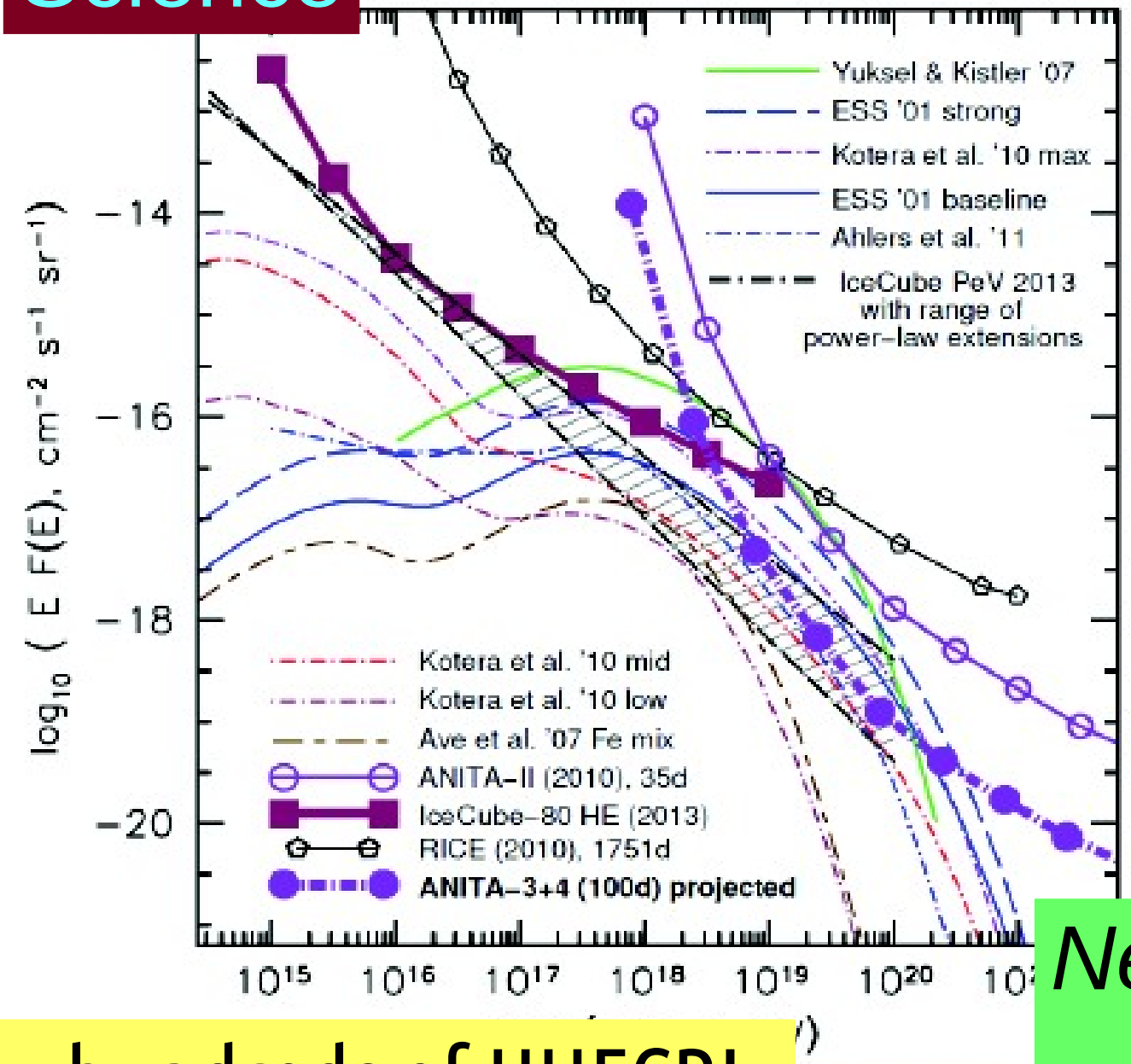


Simulated HiCal signal at r=200 km



A3+ A4 Science

Neutrino sensitivity

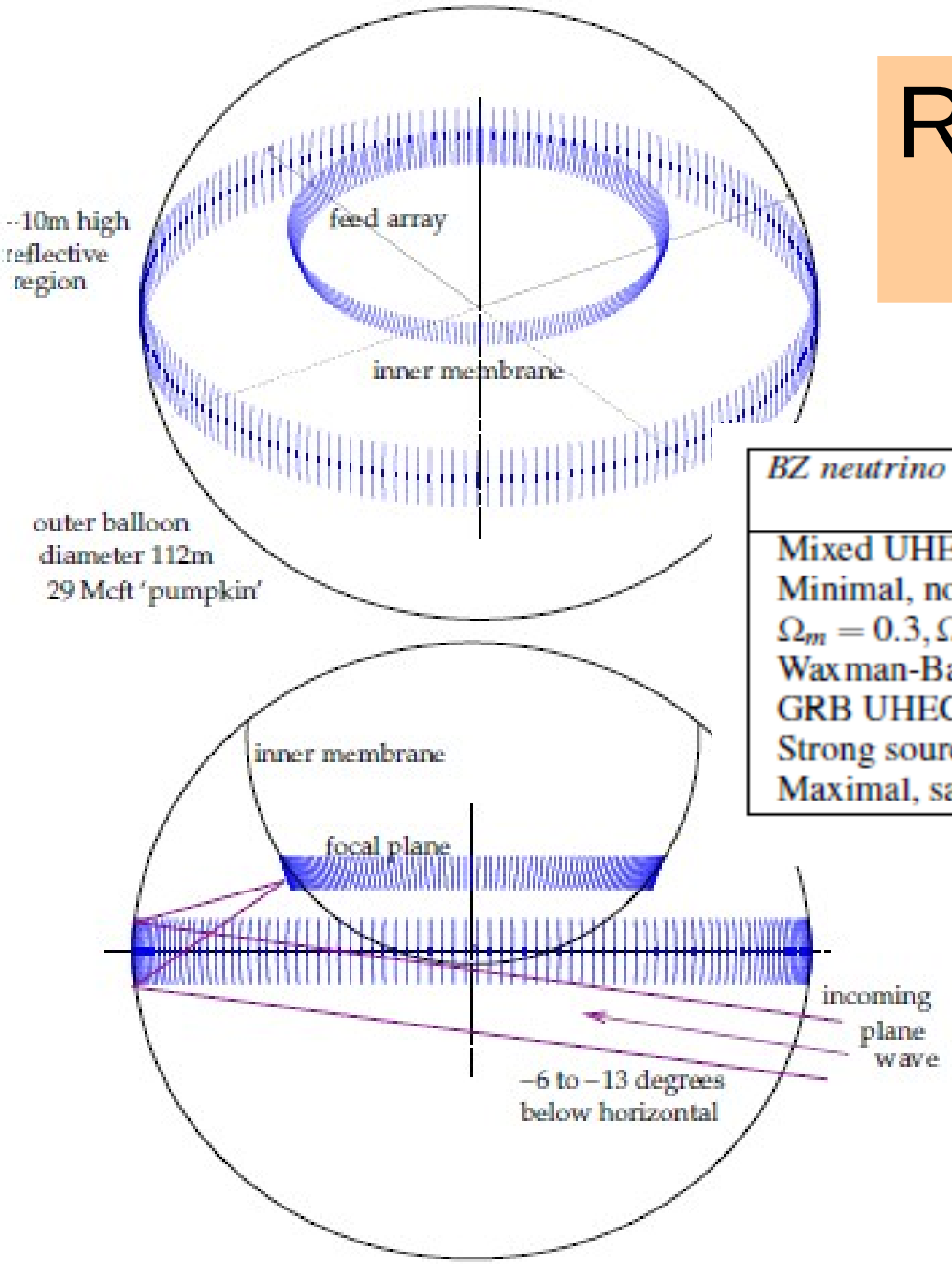


- ANITA-3+4: assume 50+50 days(x3 over ANITA-2)
- Factor of ~30% in trigger threshold, 20% in antenna area, better reconstruction & EMI control
- Net gain x3-5 in event rate
- Total improvement: ~1 order of magnitude

Next big thing is...

+ hundreds of UHECR!

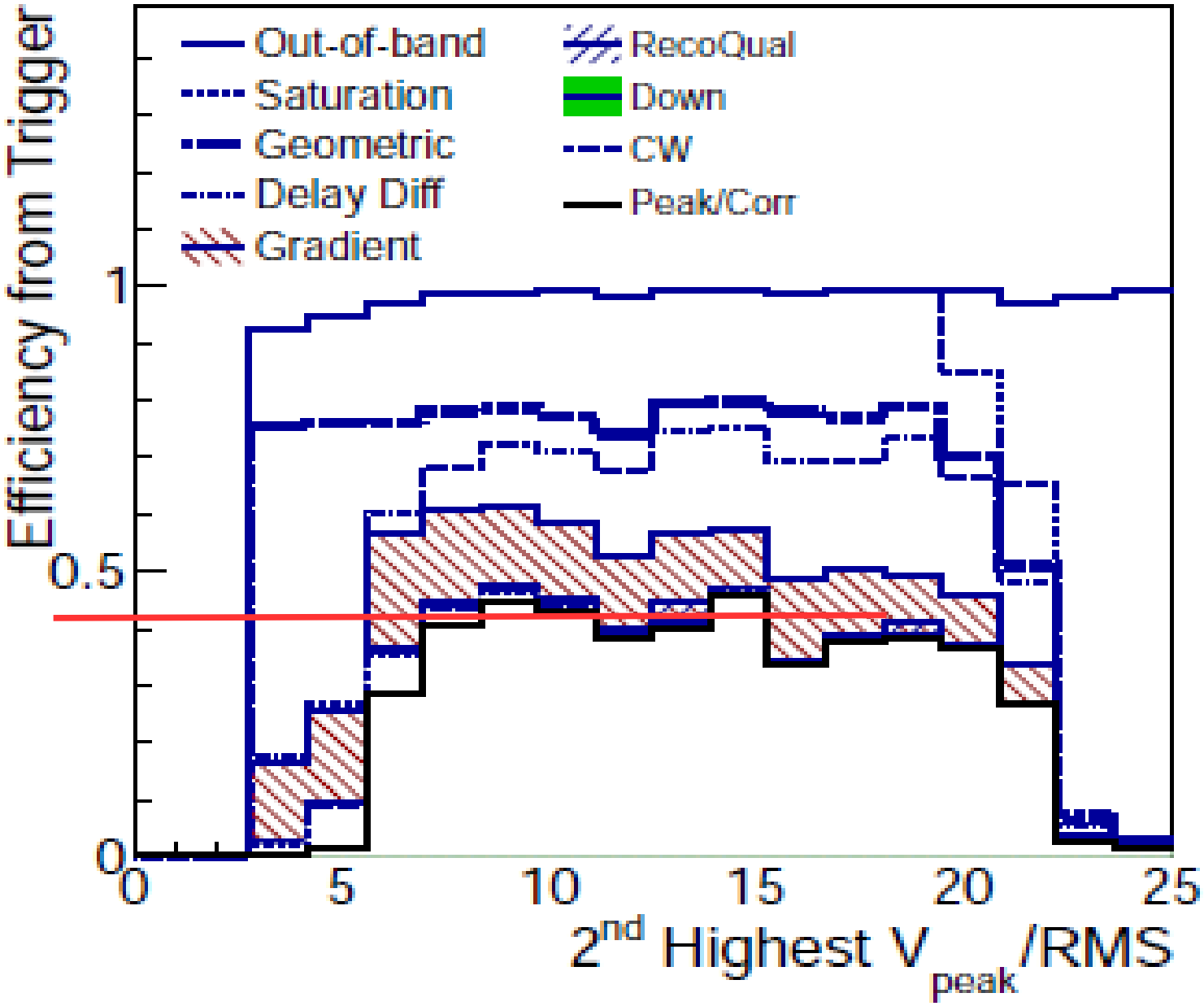
EVA: The balloon is the antenna



Reflectors guide RF to Inner feed array

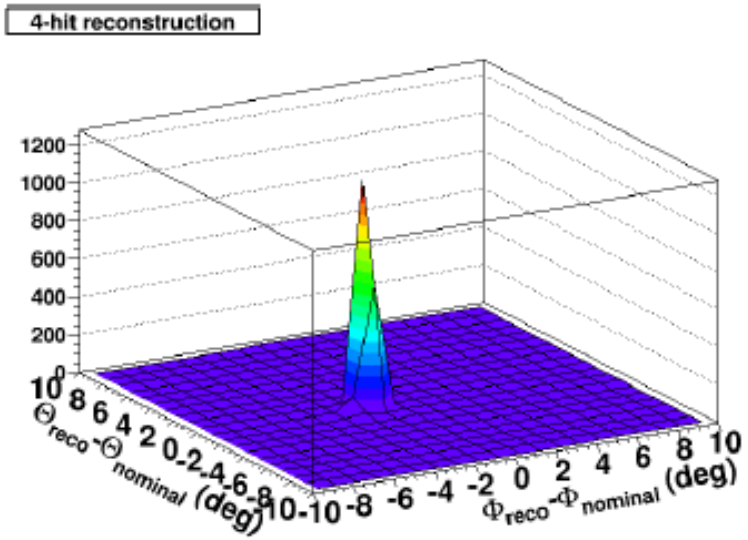
BZ neutrino models	*Events, ANITA-II, 28d*	*Events, EVA, 50d*	*ratio, EVA/ANITA*
Mixed UHECR composition [30]	0.05	5.0	100
Minimal, no evolution [3, 32, 33]	0.3-0.9	9.2-38	~ 40
$\Omega_m = 0.3, \Omega_\Lambda = 0.7$, Standard model [3]	0.7	29	41
Waxman-Bahcall E^{-2} flux (minimal) [34]	0.49	6.5	13
GRB 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

2014 ARA neutrino detection efficiency (3 analyses)

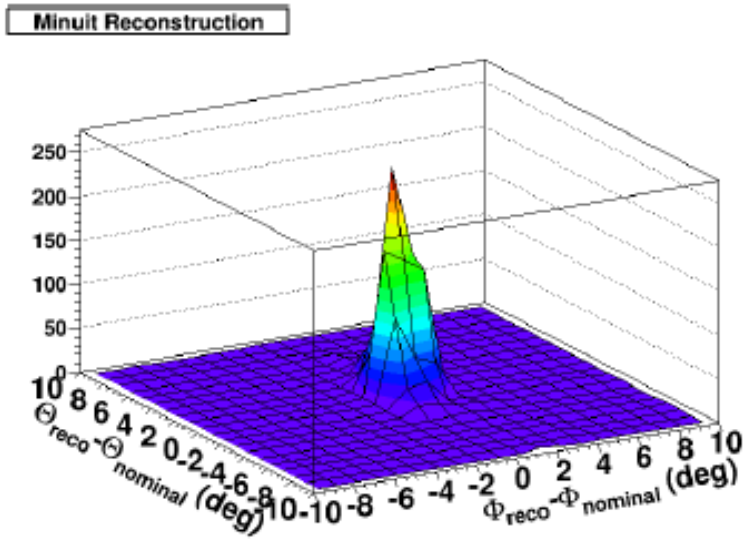


Plateau efficiency~40%; at high SNR, lose efficiency by, e.g., requiring that electronics are not saturated

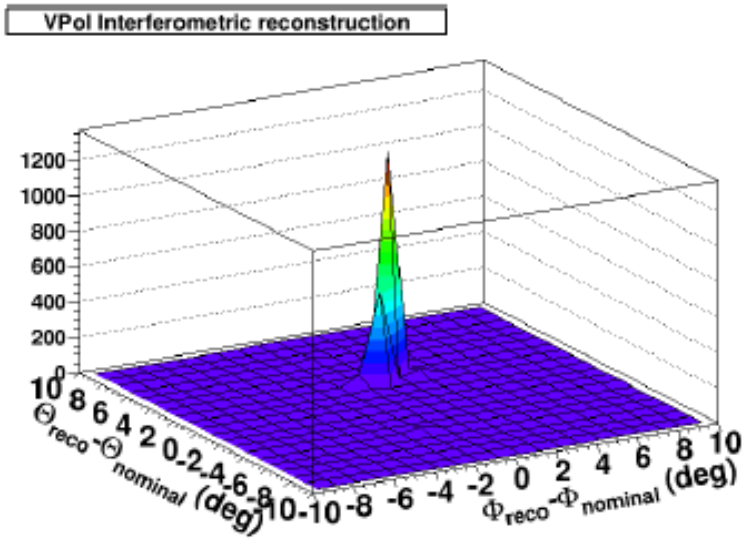
ARA source reconstruction – 3 complementary techniques – resolution ~0.5º to neutrino interaction point

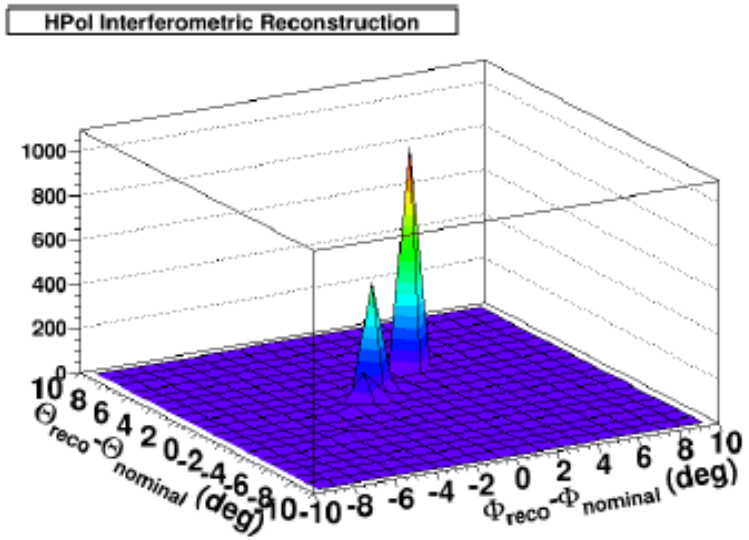


(a)

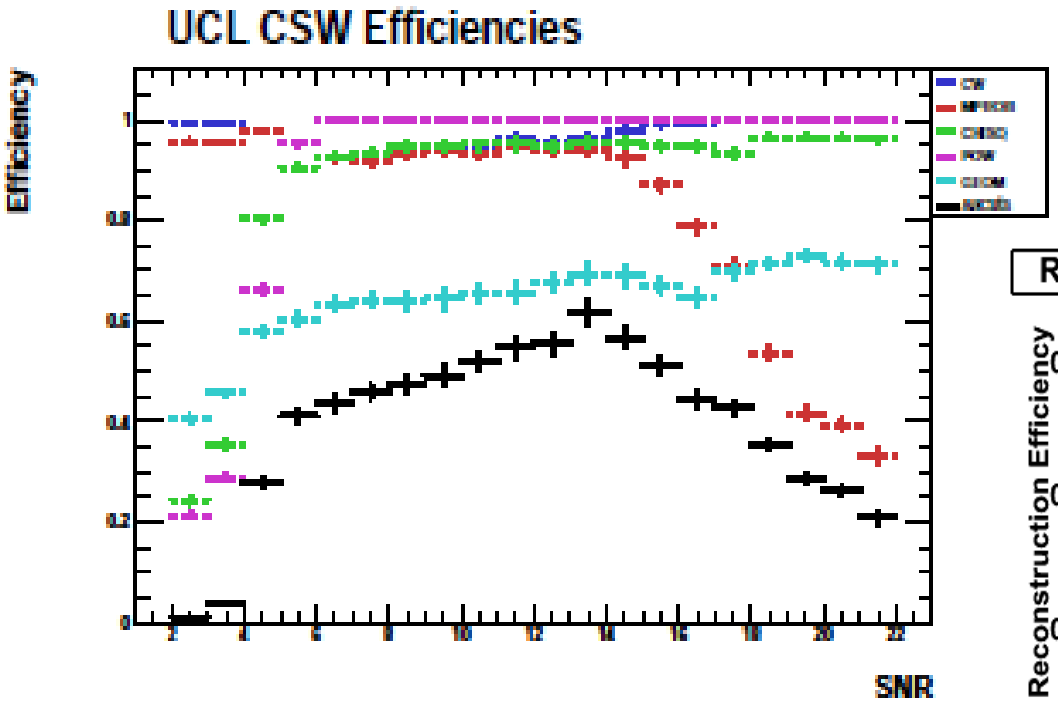


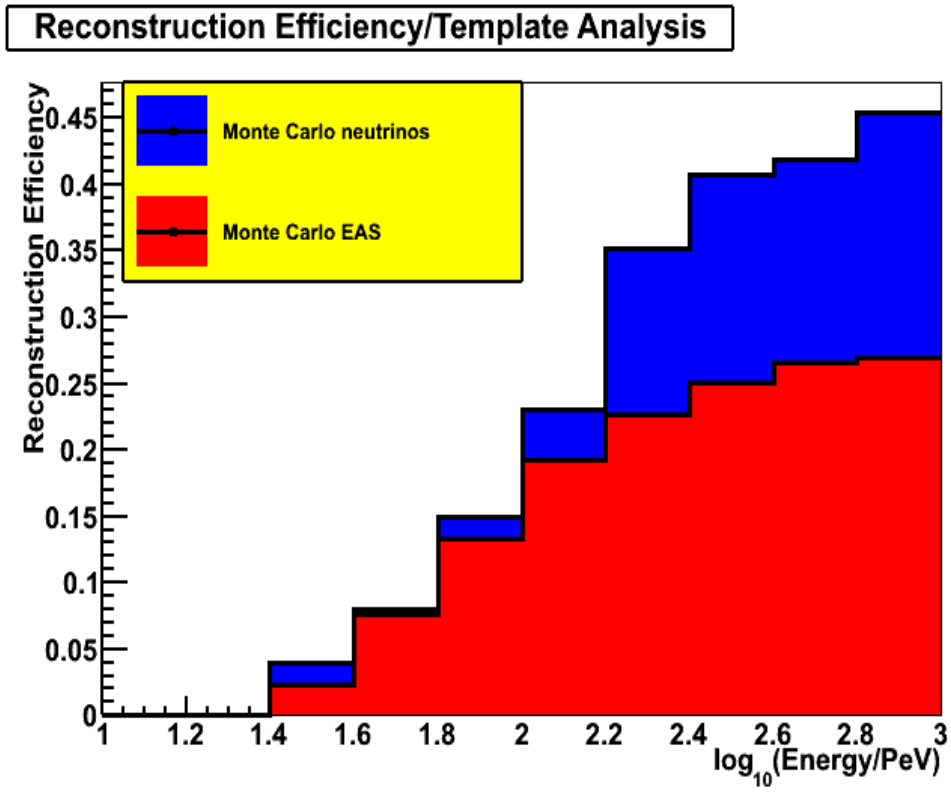
(b)



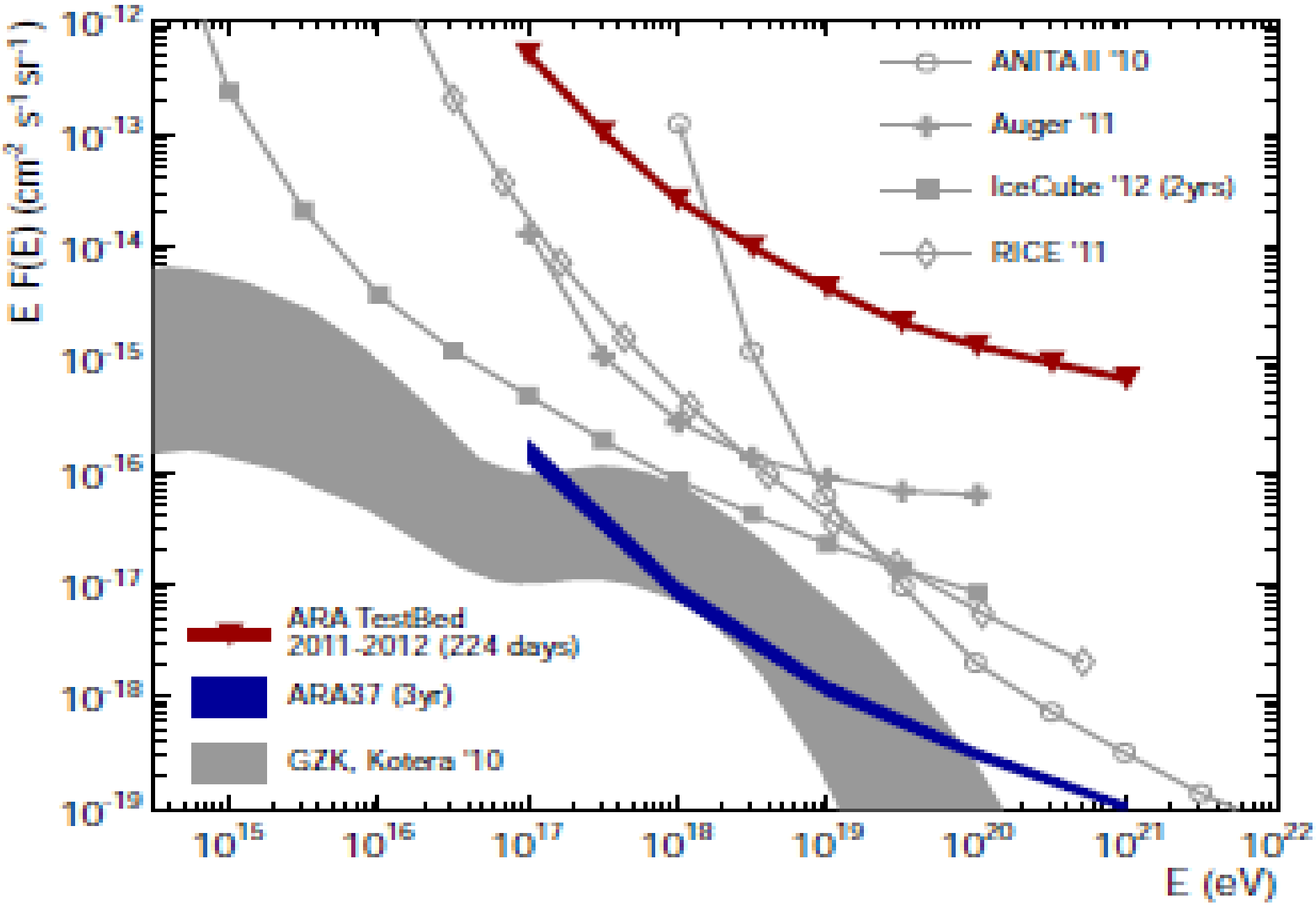


Coherently Summed Waveform and template-based analysis (latter: independent MC simulation!)





ARA result


E F(E) (cm^{-2} s^{-1}sr^{-1})
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
E (eV)
ANITA II '10
Auger '11
IceCube '12 (2yrs)
RICE '11
ARA TestBed
2011-2012 (224 days)
ARA37 (3yr)
GZK, Kotera '10

Summary

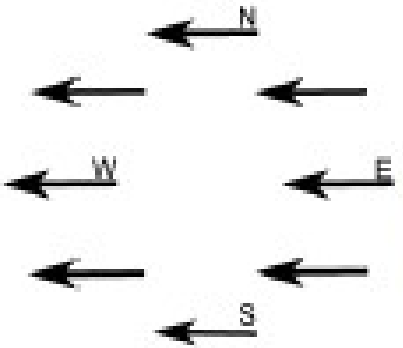
- ANITA-3 will fly in December, with major hardware improvements over ANITA-2; HiCal to follow
- In addition to enhanced neutrino sensitivity, effort to maximize UHECR sensitivity AND reduce systematic errors on UHECR energy estimate
  - Target 25% overall energy error
- ANITA-4 has just been approved for 2016-17 flight.
- ARA currently = testbed + 3 “deep” stations. ARA-2 & ARA-3 neutrino limit en route within the next couple of months.
- But, future uncertain. No funding for two years, and no more deployment until 2015-16 (at the earliest).

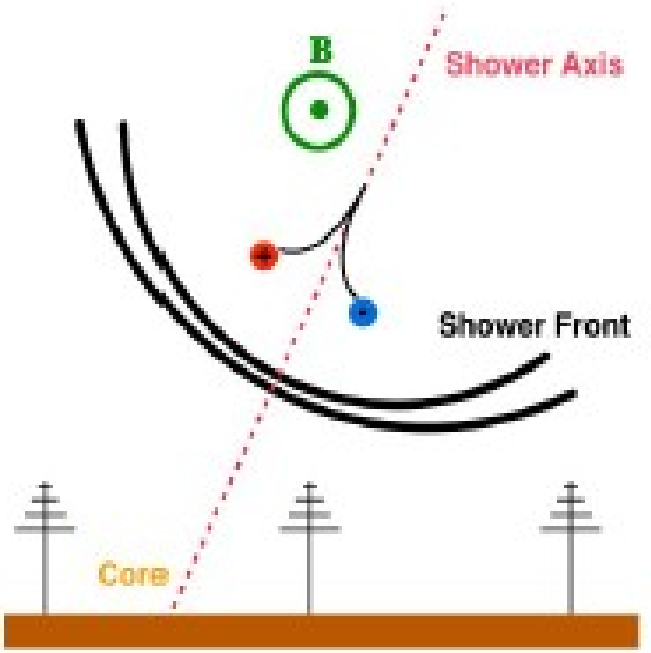
Emission of radio signals from air showers

- Coherent at MHz frequency
- two main emission mechanisms:

1. Geomagnetic emission

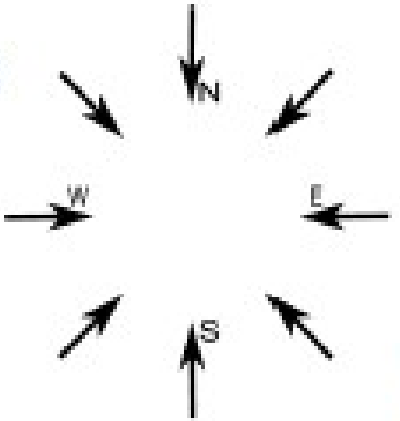
Deflection of e^- and e^+ in Earth´s magnetic field
→ time dependent transverse current,
linearly polarised $\vec{E} \propto \vec{v} \times \vec{B}$

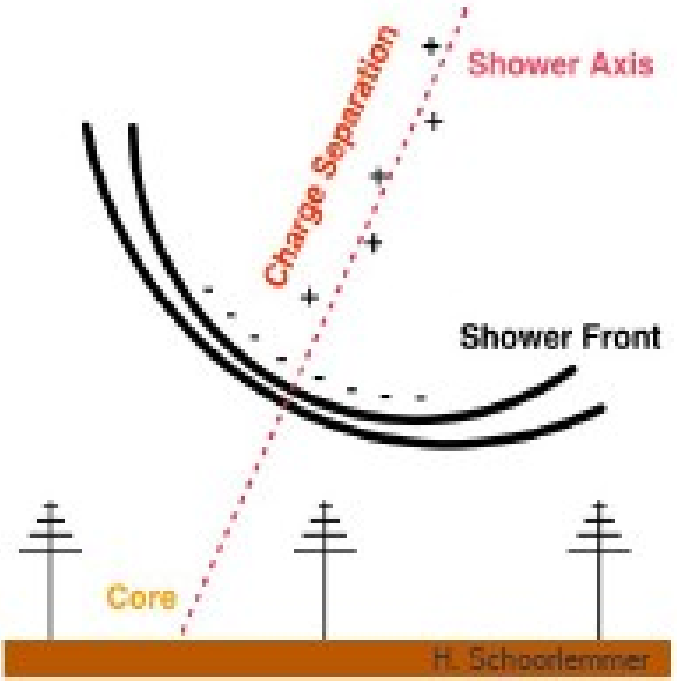




2. Askaryan effect

Time variation of net charge excess
→ linearly polarised,
$\vec{E}$ radial oriented around shower axis





Same mechanism as in-ice,
But larger size=>coherence
@lower frequencies