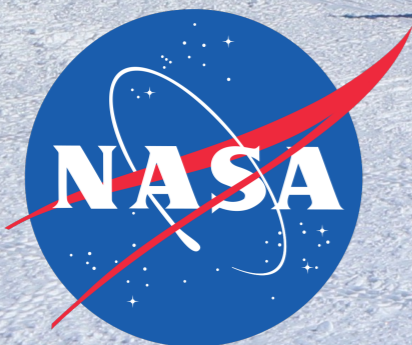


# Hunting UHE neutrinos with ANITA

**Linda Cremonesi**

University of Birmingham Seminar  
June 12th 2019



LEVERHULME  
TRUST



# Outline

- Motivations
- ANITA
- Neutrino(s) in a haystack  
Phys. Rev. D 98, 022001 (2018) & Phys. Rev. D 99, 122001 (2019)
- Unusual upward-going cosmic-ray-like events  
Phys. Rev. Lett. 121, 161102 (2018)
- Future





# Motivations

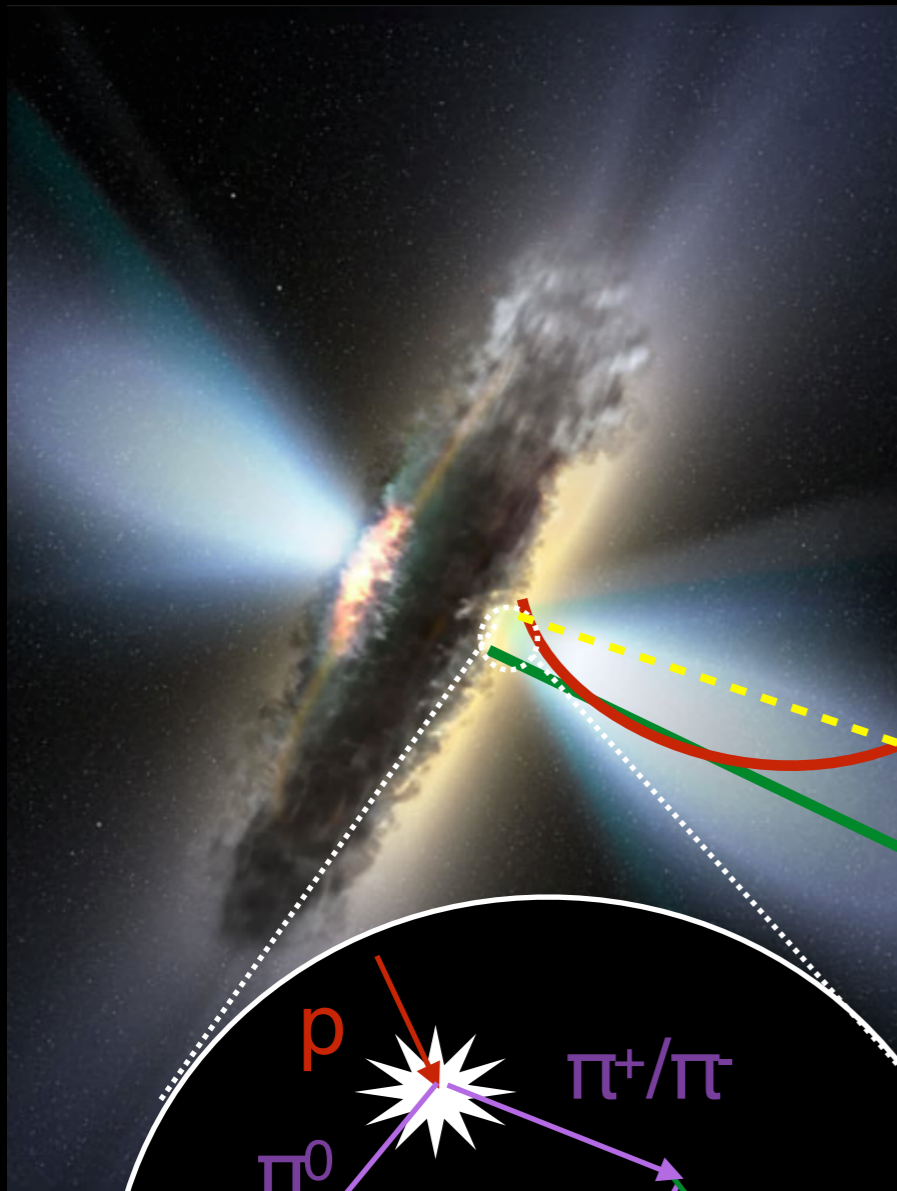
L. Cremonesi

3

“UHE neutrinos and ANITA”



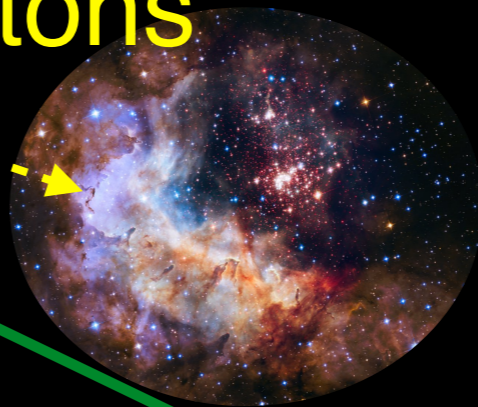
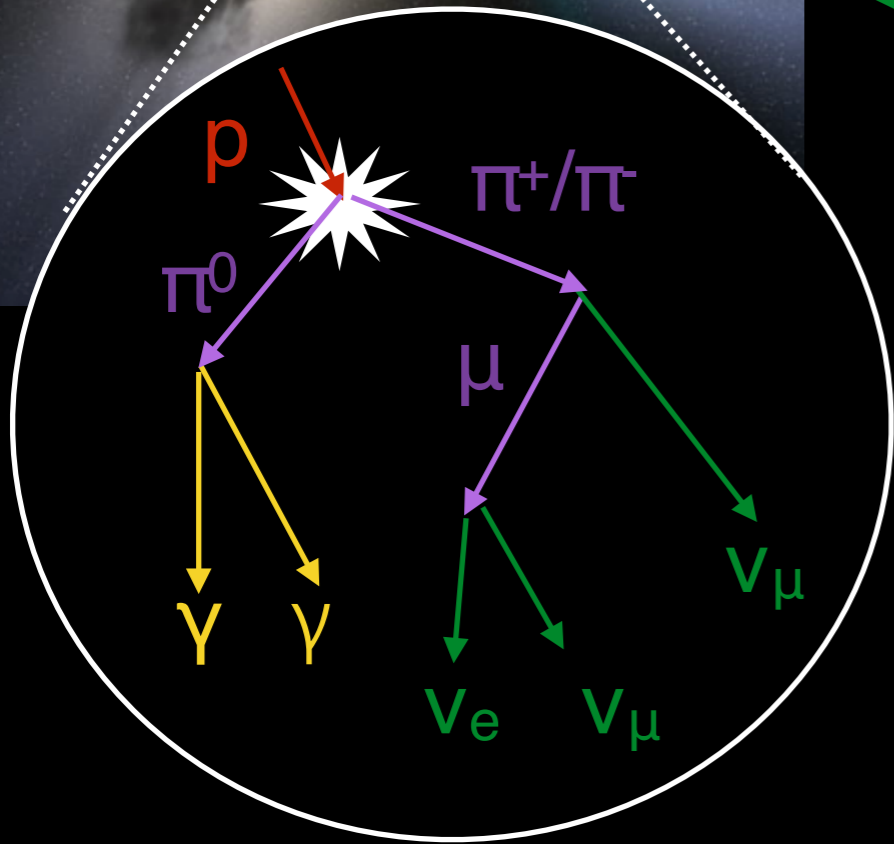
# Why Ultra High Energy neutrinos?



protons

photons

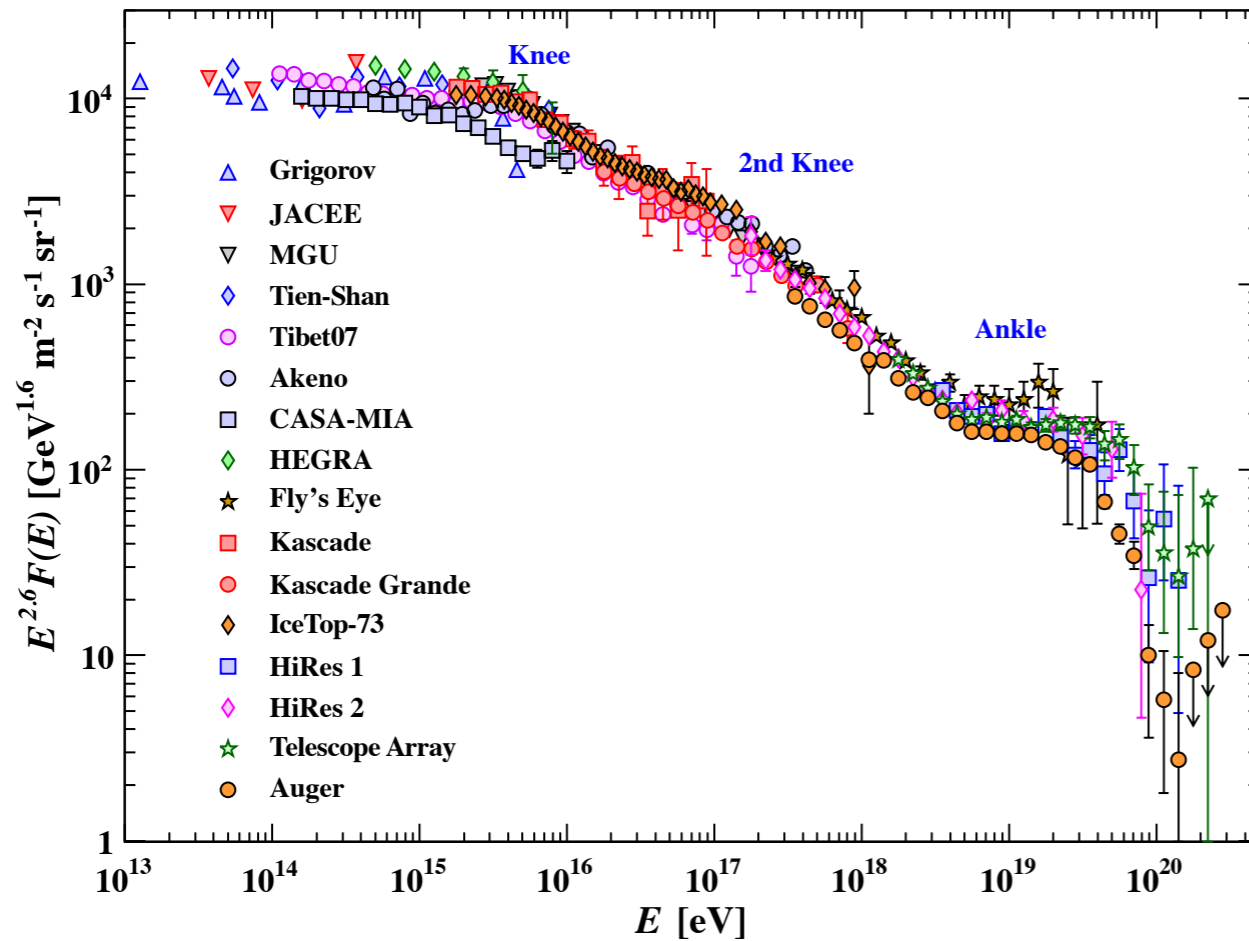
neutrinos



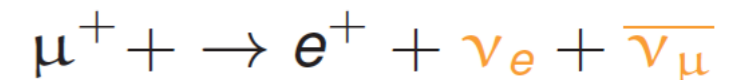
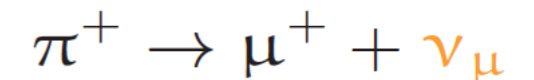
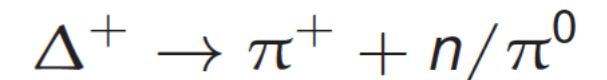
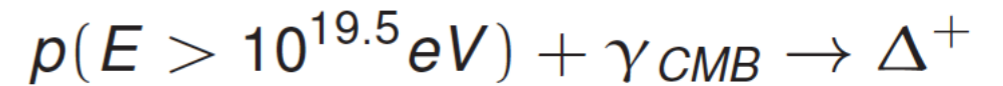


# Cosmogenic neutrinos

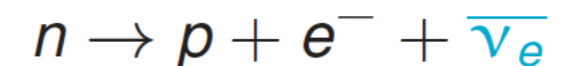
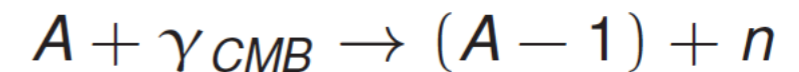
C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016)



$\nu$  from GZK



$\nu$  from photo-disintegration



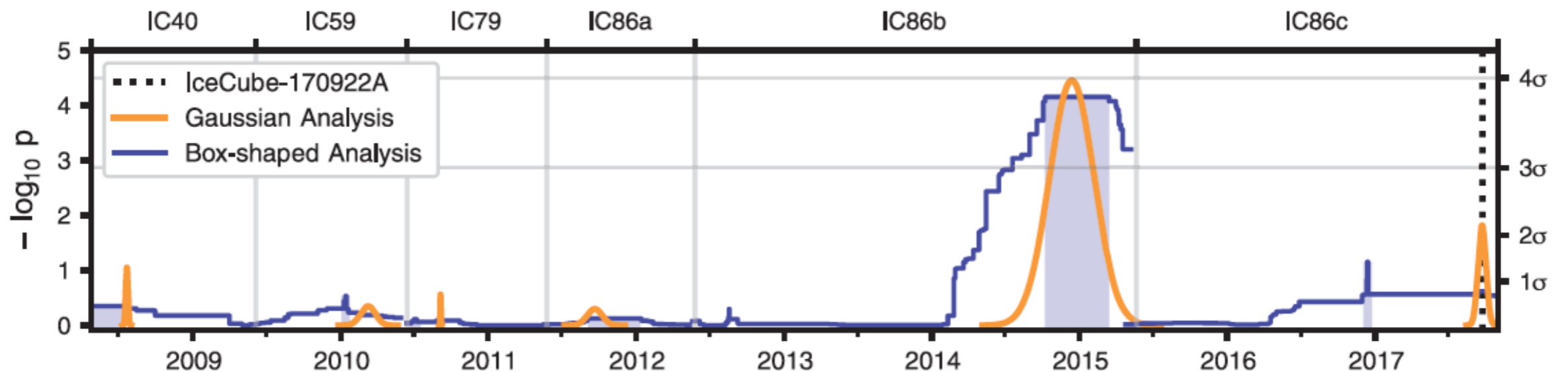
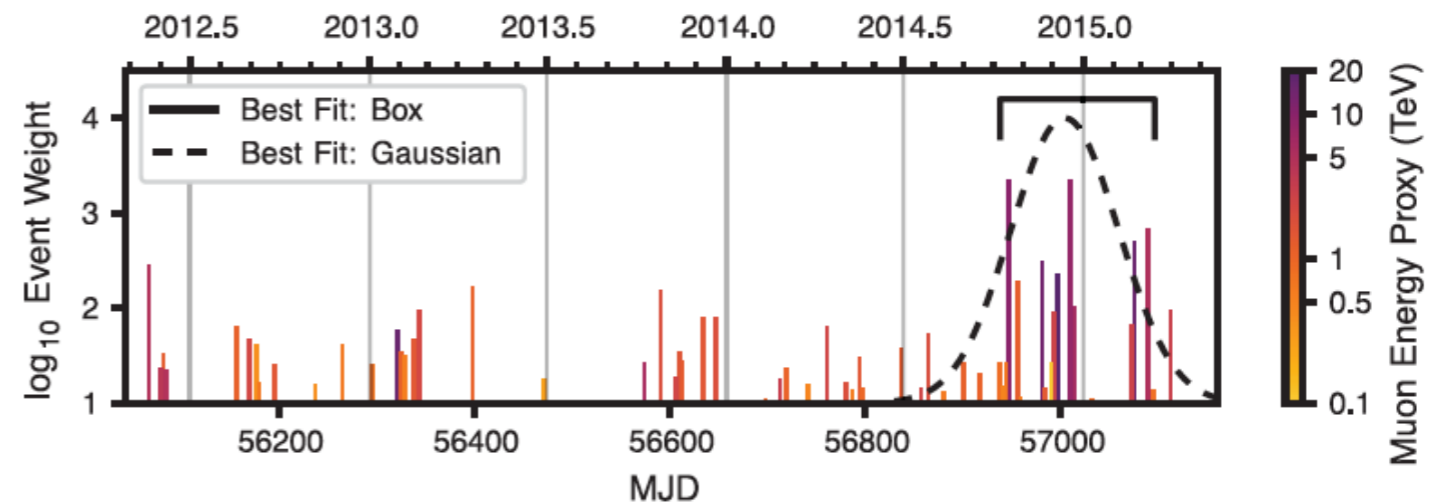
We know cosmic ray energy spectrum over 11 orders of magnitude.

Their sources (especially at the highest energies) are still mostly unknown



# TXS 0506+056

- IceCube identified 13 +/- 5 VHE astrophysical neutrinos from this direction
- Evidence of very high energy neutrino point source: at least some cosmic rays are accelerated up to few PeV in blazars
- Blazars **could** accelerate up to the highest observed cosmic rays, >1E19 eV
- IceCube-Gen2 should see loads



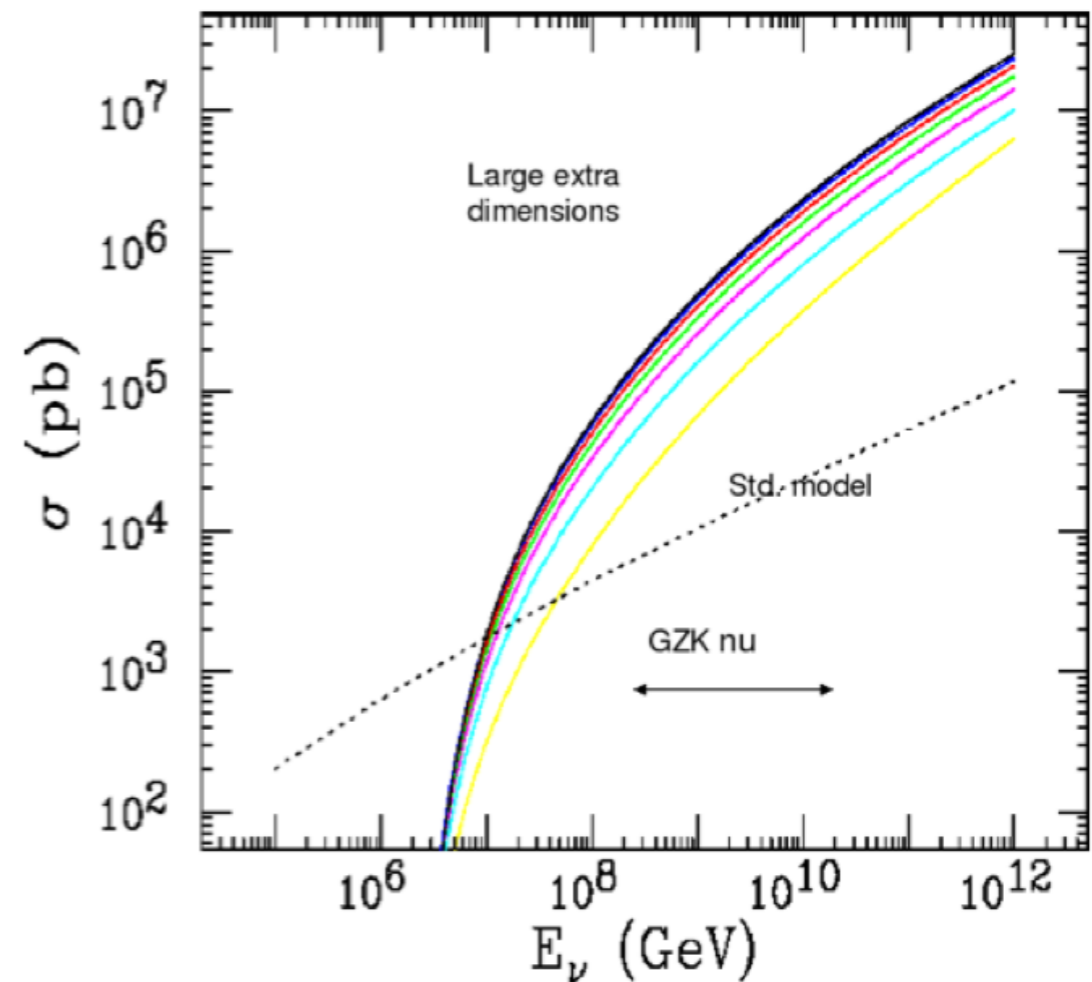
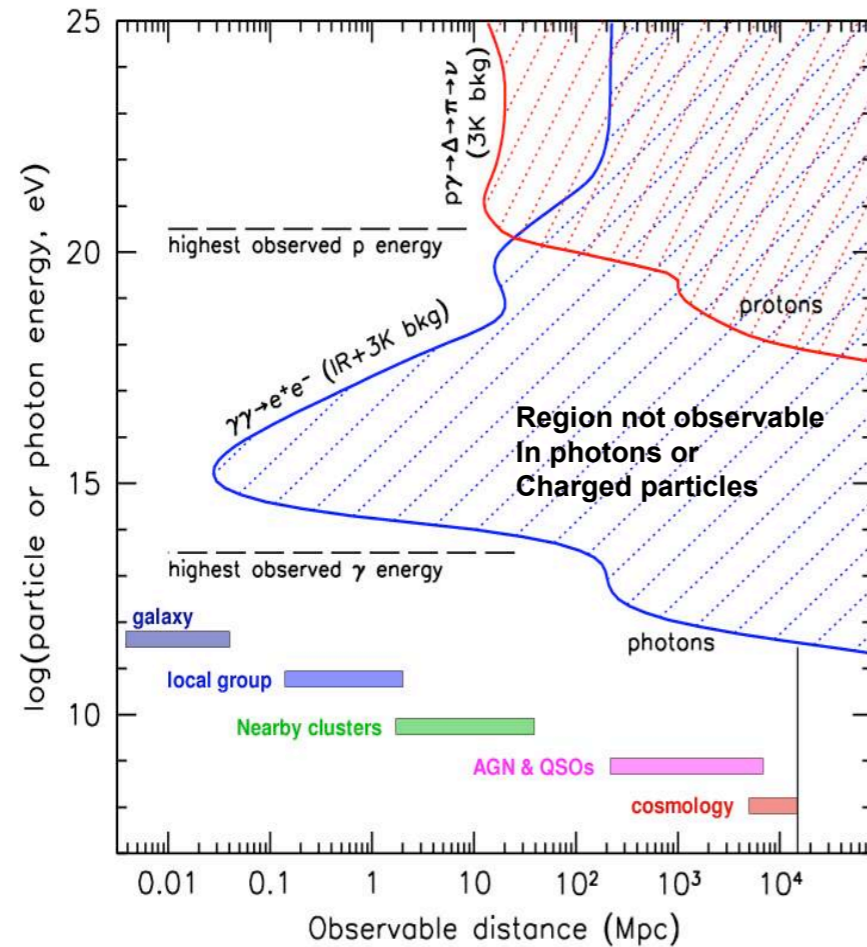


# UHE ( $>E18$ eV) neutrinos

“We can probe distances and energies that other particles can't reach!”



“WOW  
300 TeV centre of mass energy!”

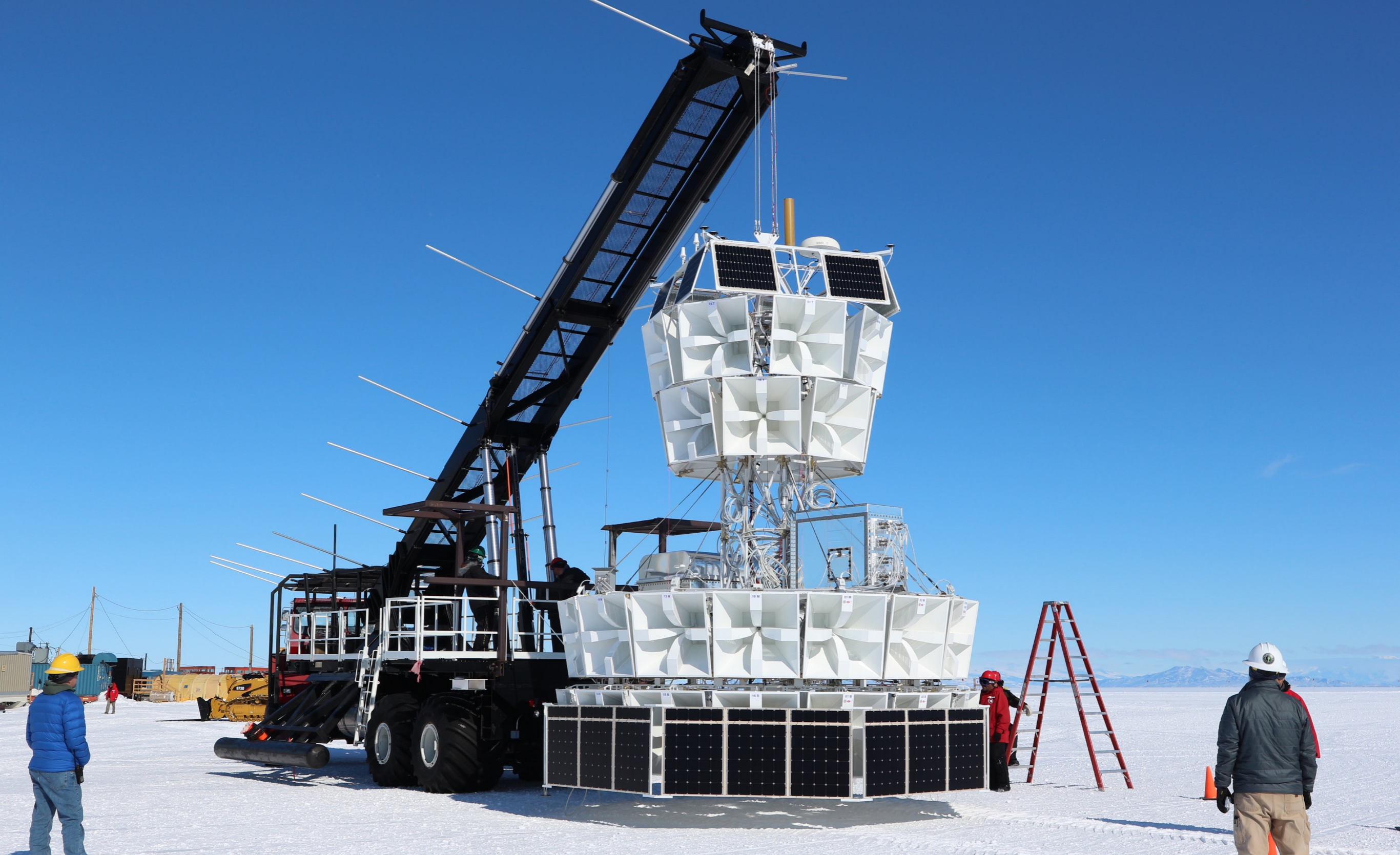




# More motivations

- Implications for neutrino mixing (arXiv:1702.05238)
- Neutrino decay - JCAP 10 (2012) 020
- Ultra high energy neutrino cross-sections (Nature 551 (2017) 596-600, arXiv:1711.11043 )
- Lorentz invariance - Phys. Rev. D 86, 103006
- Sterile neutrinos - arXiv:1802.01611
- Beyond Standard Model particles (staus) - arXiv:1809.09615
- Dark matter - arXiv: 1902.04584

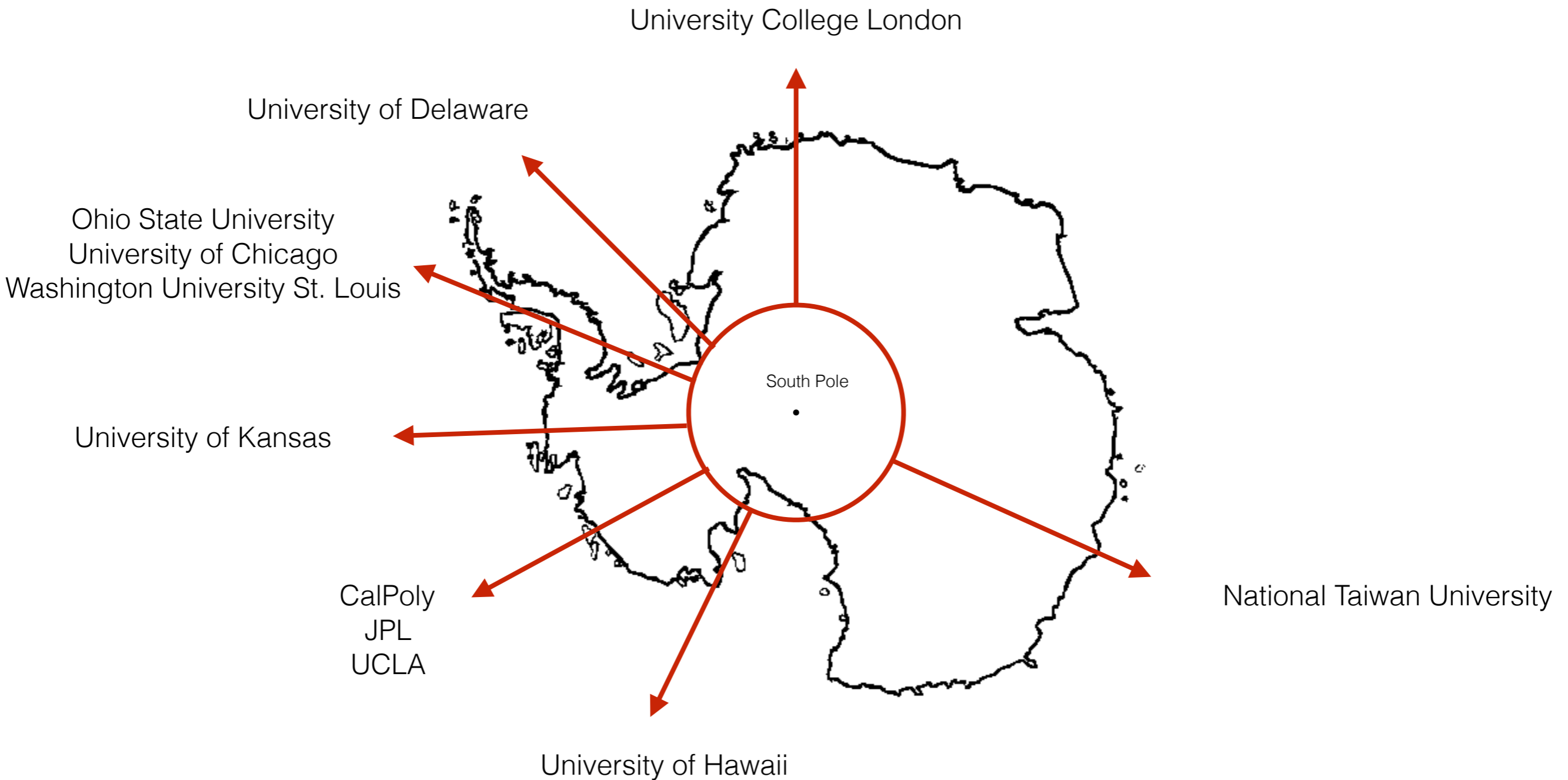




# ANITA



# ANITA collaboration



11 Institutions, ~50 collaborators in a 18 hour time zone

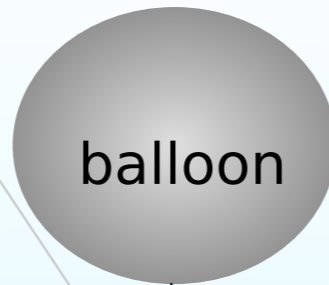


# ANtarctic Impulsive Transient Antenna

Not to scale,  
angles don't  
reflect reality



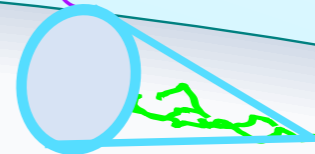
NEUTRINOS = VPOL



balloon



Ice

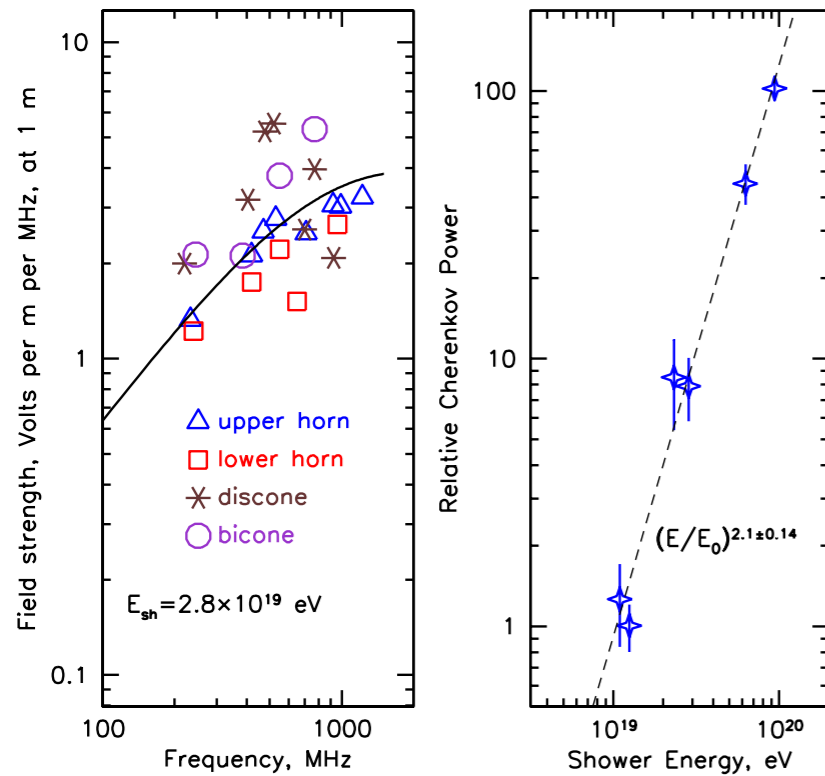


Askaryan  
emission

$\sim$ EeV  
neutrino

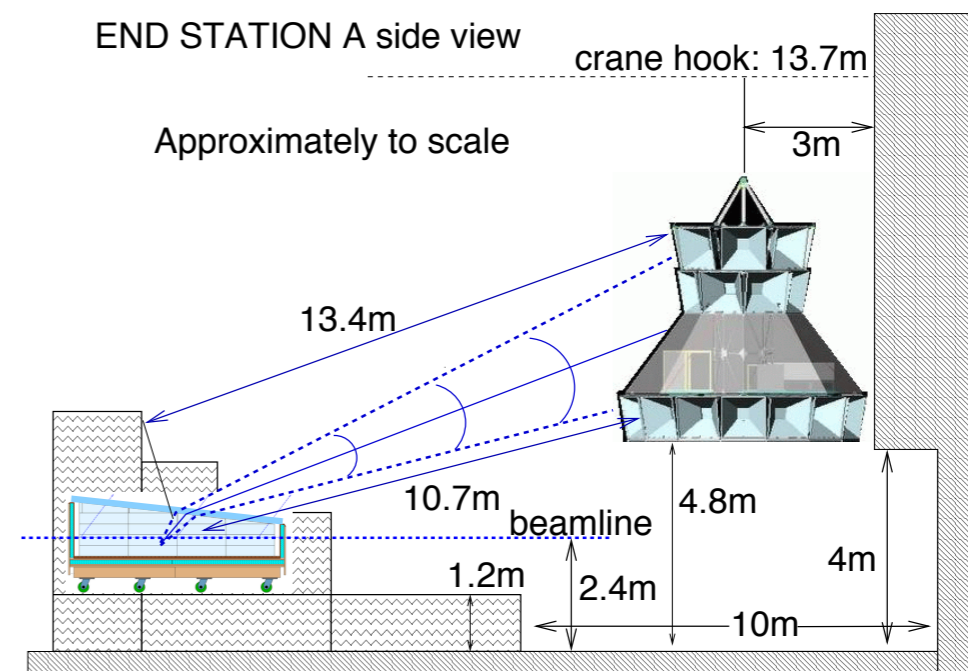
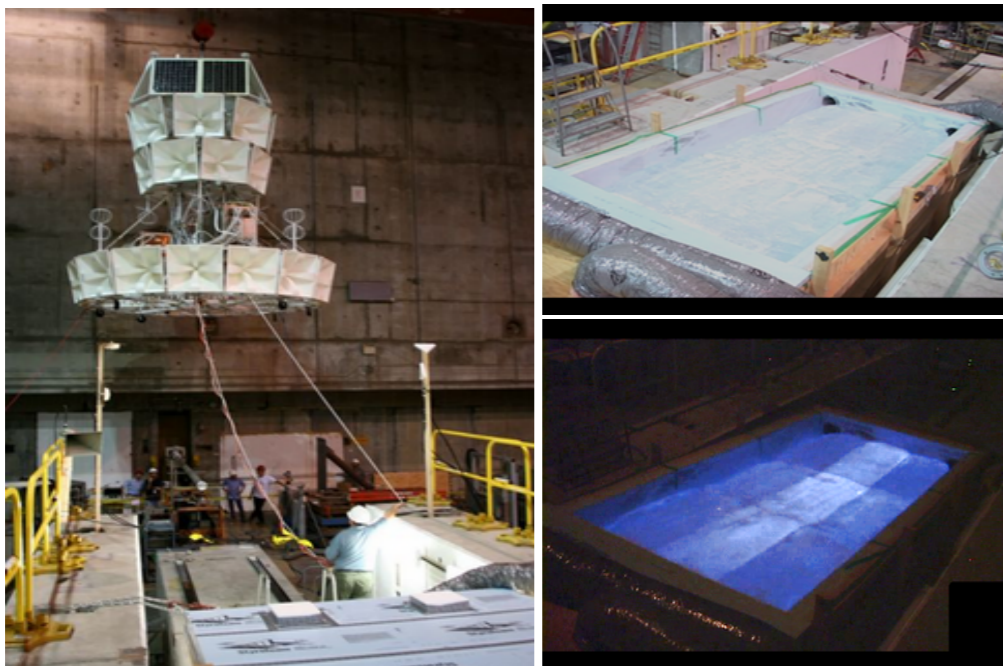


# Askaryan radiation



- Coherent radio emission from EM cascades in a dielectric!
- Measured at SLAC ESA in 2006 by ANITA collaboration
- Fired bunches of  $10^9$  electrons at 28.5 GeV into 7000 kg of ice

Phys.Rev.Lett.99:171101,2007

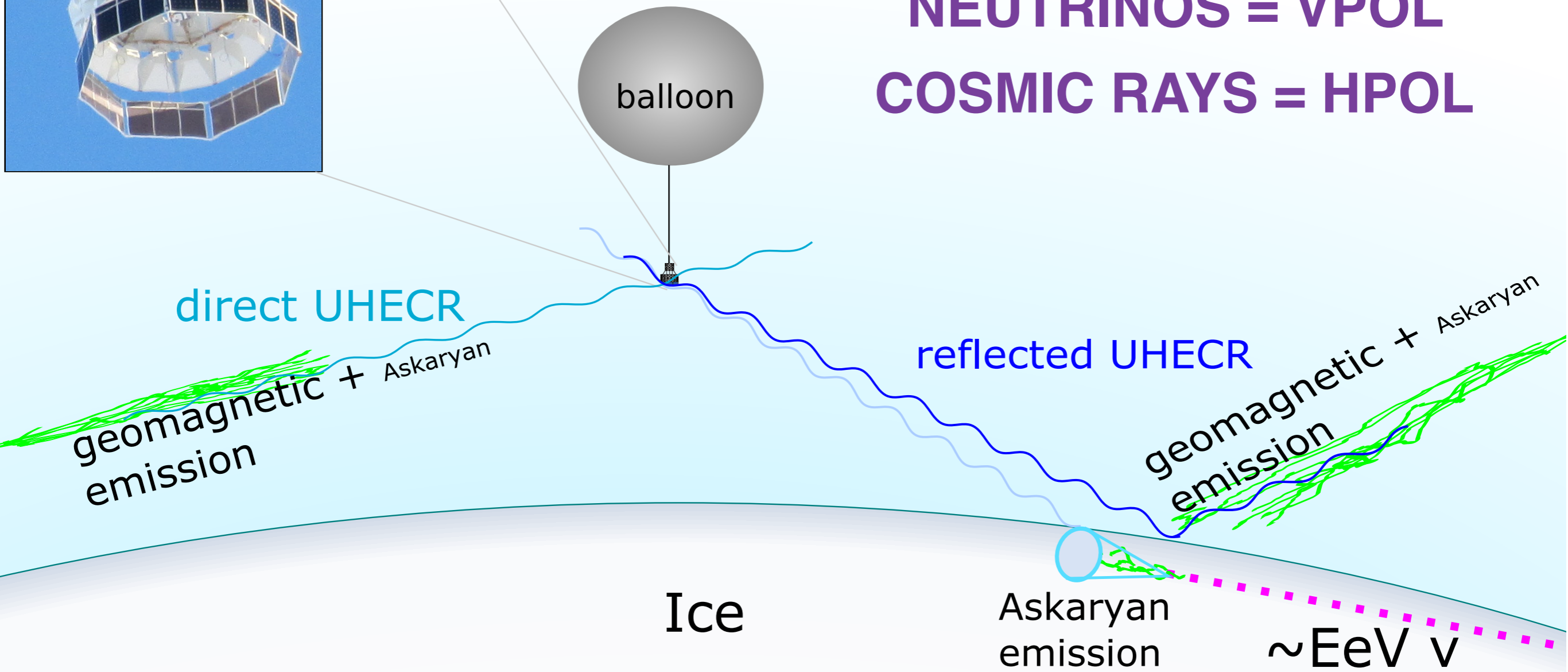


# ANtarctic Impulsive Transient Antenna

Not to scale,  
angles don't  
reflect reality



**NEUTRINOS = VPOL**  
**COSMIC RAYS = HPOL**





# ANITA instrument

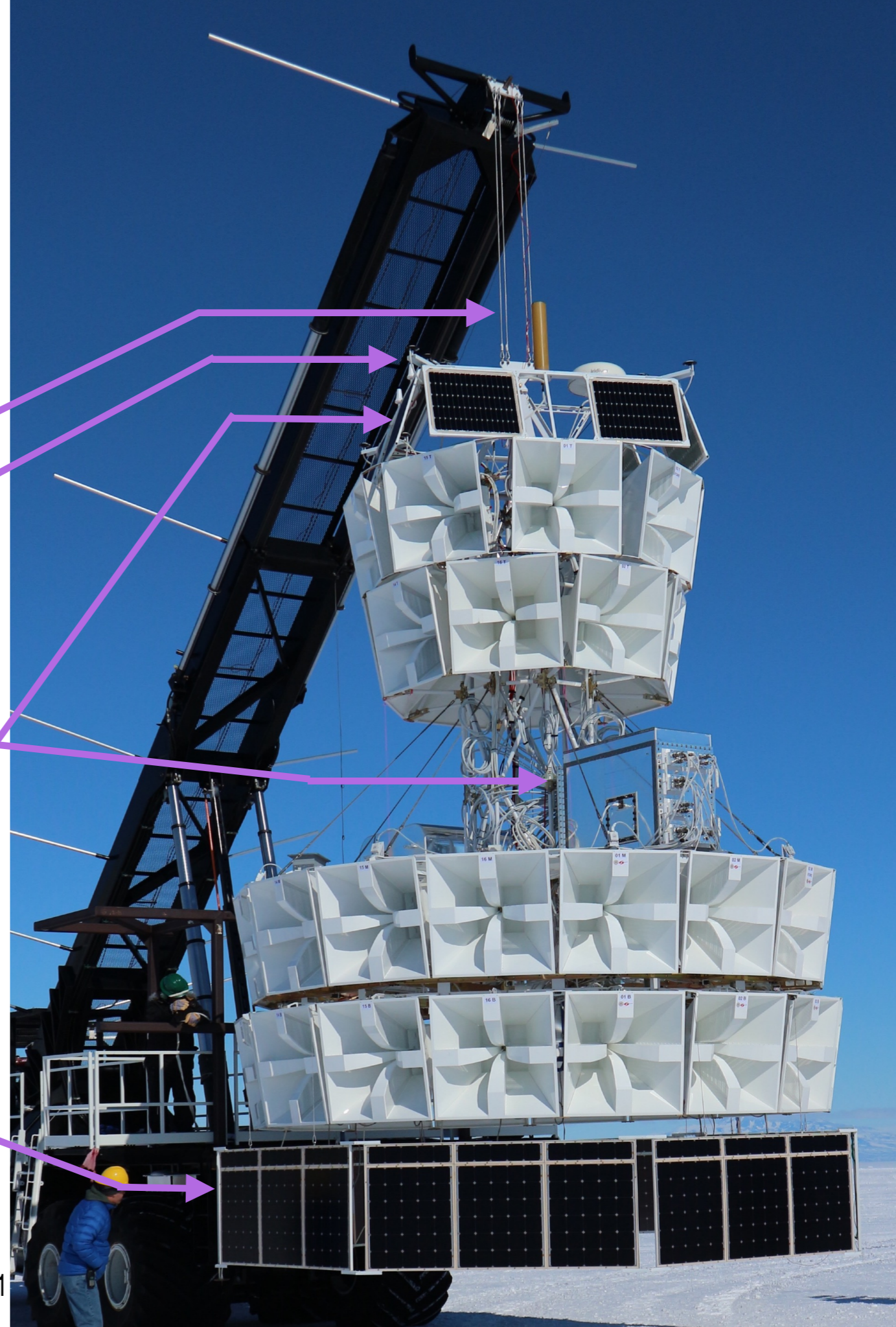
TDRSS & Iridium antennas

GPS antennas

Instrument box

48 quad-ridged  
horn antennas

Solar panels





# ANITA instrument

TDRSS & Iridium antennas

GPS antennas

Instrument box

48 quad-ridged  
horn antennas

Solar panels

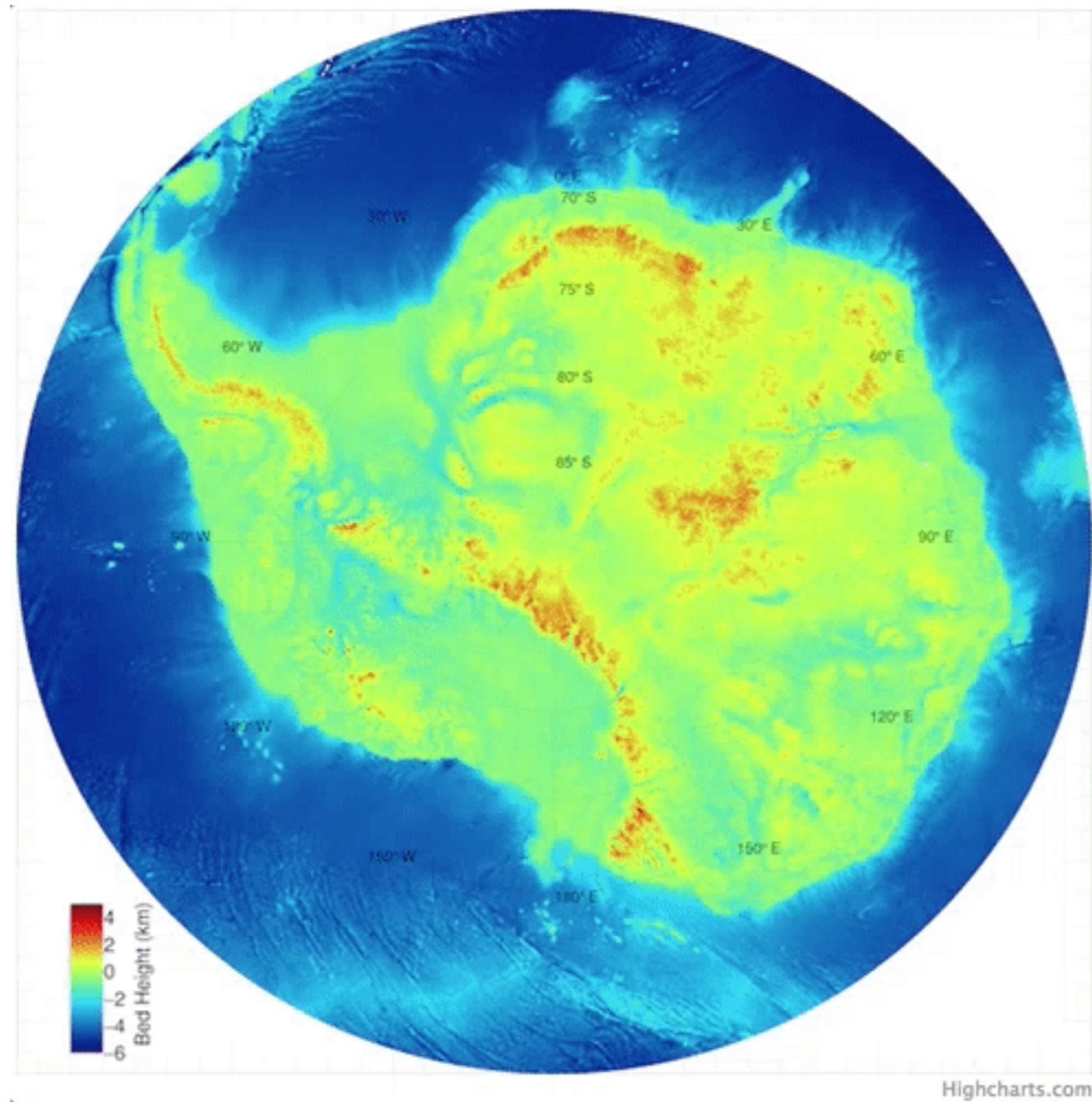




# ANITA-4 taking off

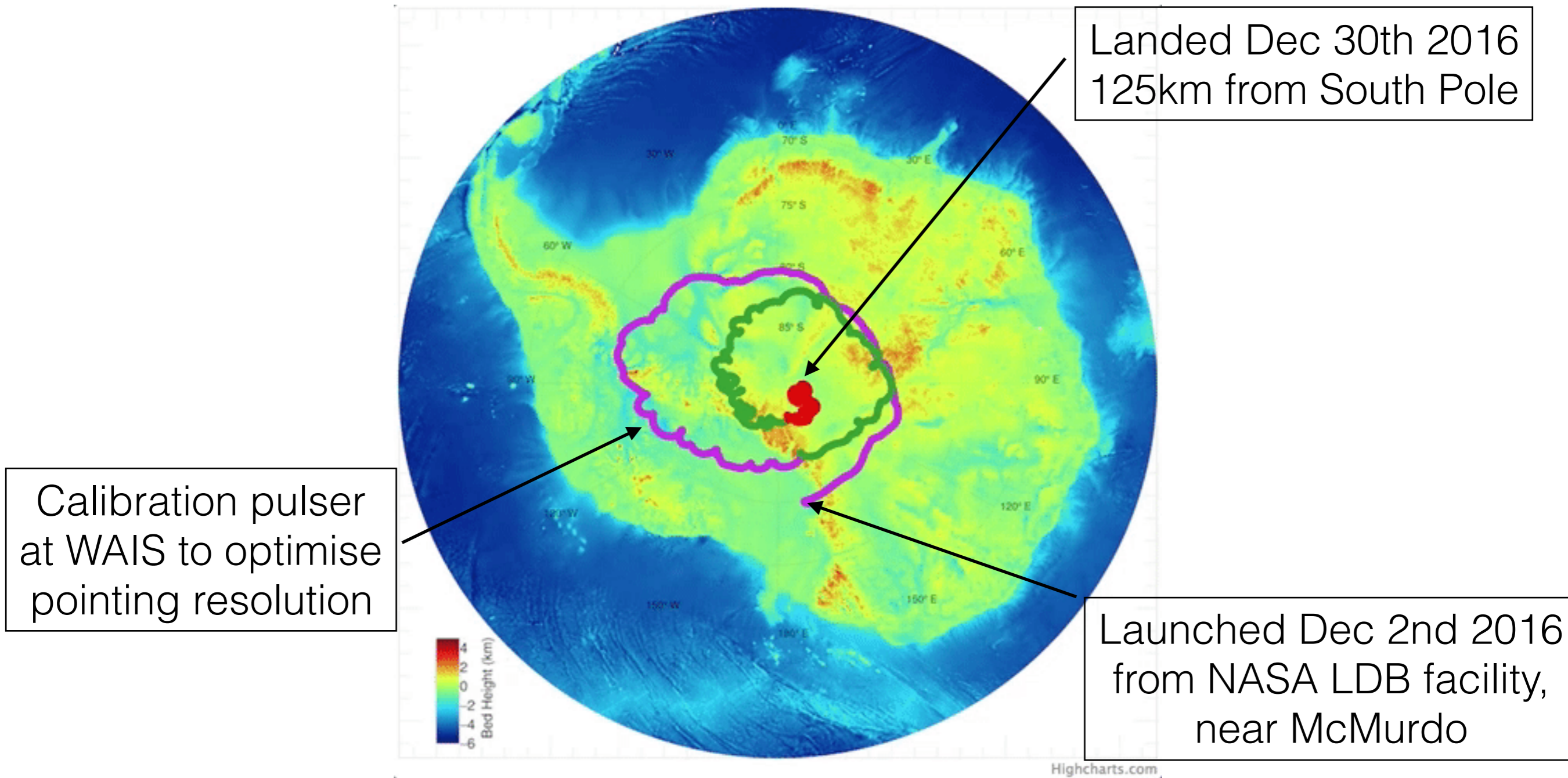


# ANITA-4 flight path





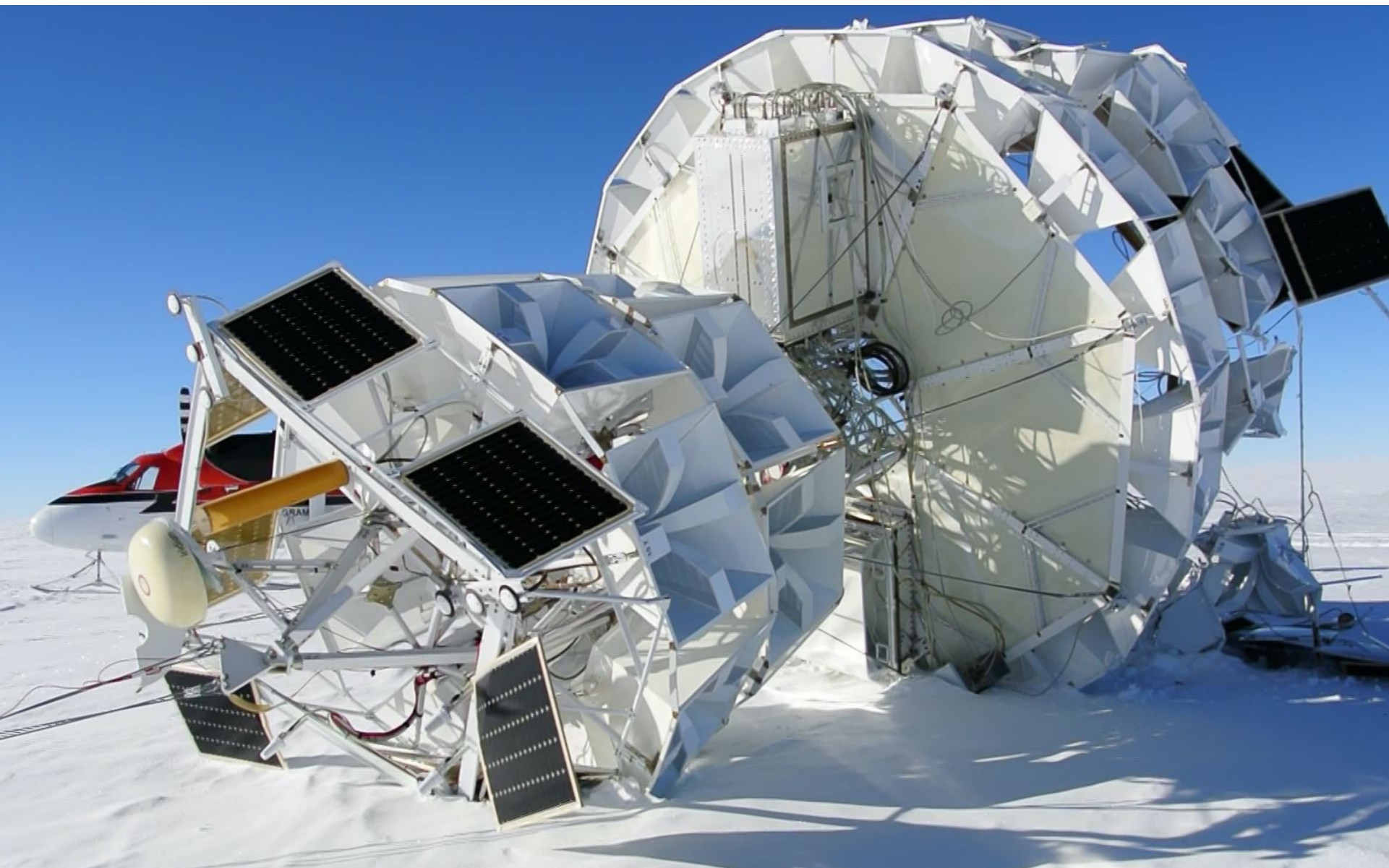
# ANITA-4 flight path





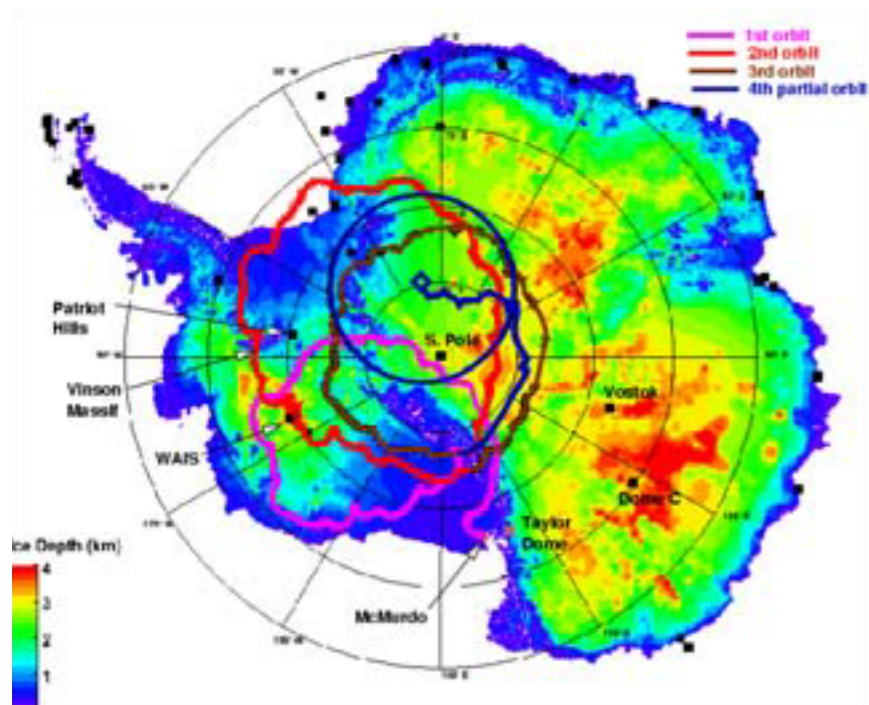
# ANITA-4 Recovery

- Partial recovery done on Jan 10th 2017
- Full recovery done in December 2017



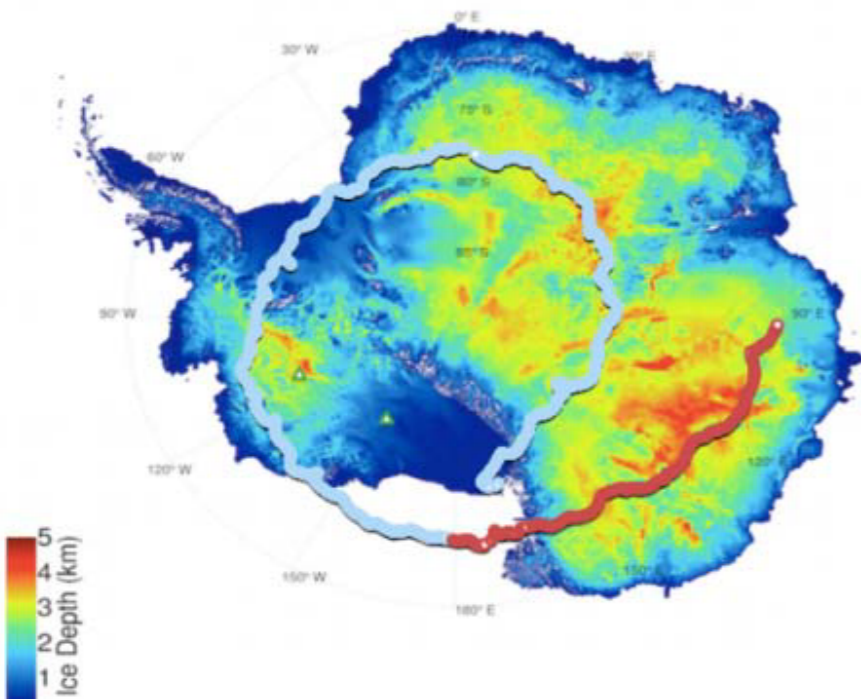
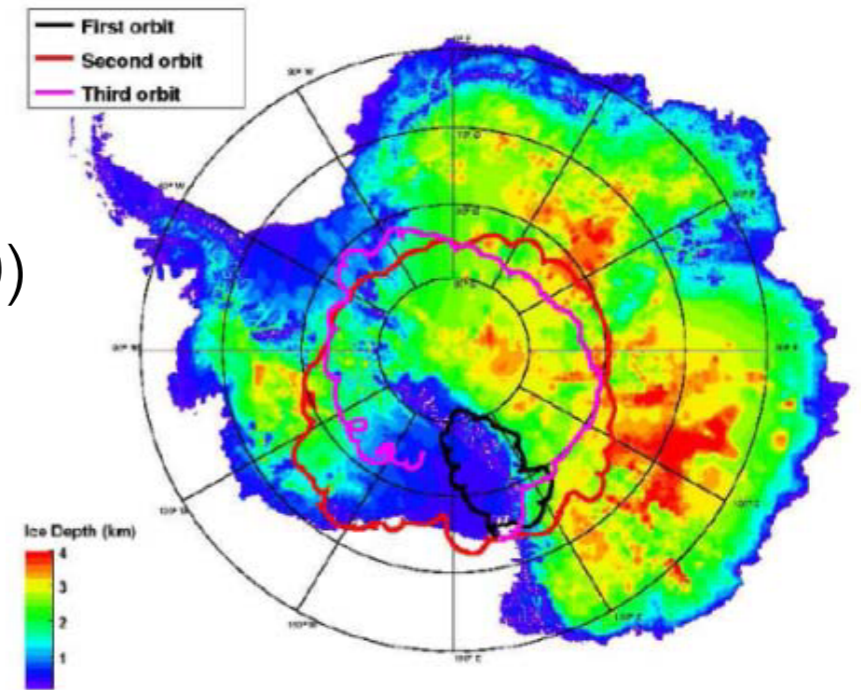


# ANITA Flights



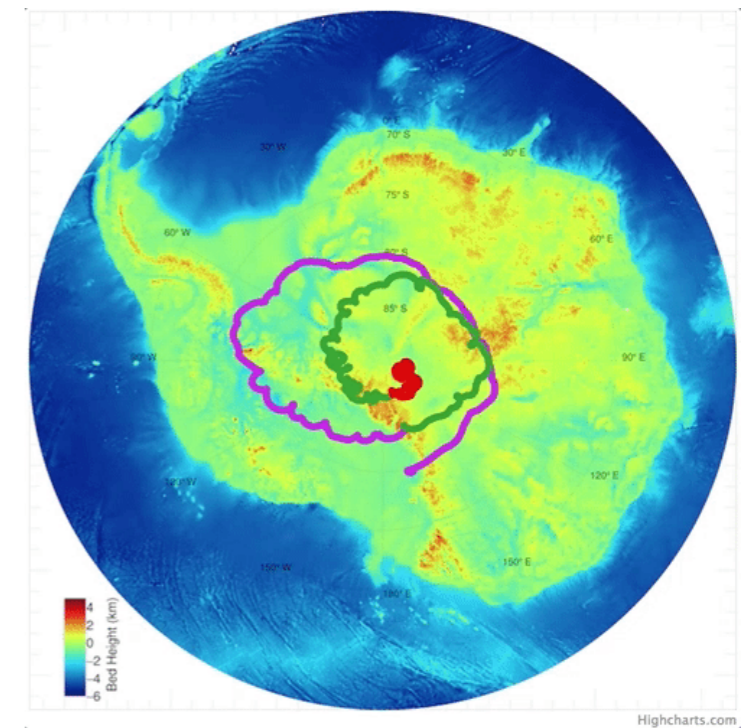
ANITA-1  
(2006-2007)  
35 days

ANITA-2  
(2008-2009)  
30 days



ANITA-3  
(2014-2015)  
22 days

ANITA-4  
(2016)  
30 days





# How ANITA sees the world

V	SURF	Waveform
H	Payload	FFT
V&H	Interferometry	Hilbert
		Average FFT

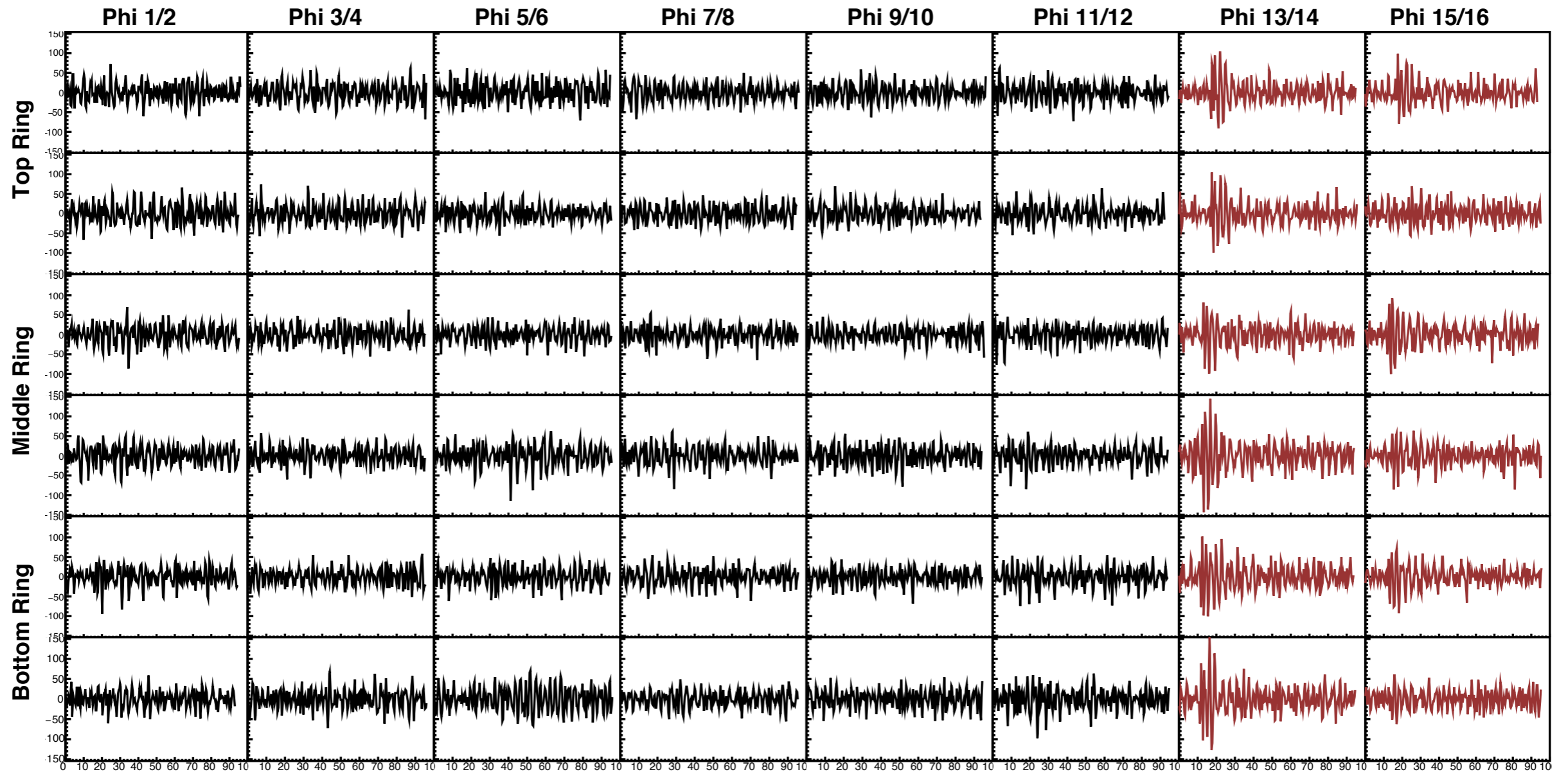
Run: 345  
Event: 58851430

Time: 2015-01-01 13:39:43  
Trigger: 1.214096 ms  
Priority: 3 -- Queue: 3

Trig Num: 930 -- Trig Type: RF  
TURF: 939

TURF This Hold: 0x9  
TURF Active Holds: 0x9  
Labrador CCCCCCCCCC  
Phi Mask: 0

Reset Avg	Play	Next
Go to Event	Rev	Prev.
Event#	Stop	First
		Last





# How ANITA sees the world

V	SURF	Waveform
H	Payload	FFT
V&H	Interferometry	Hilbert
		Average FFT

Run: 345  
Event: 58851430

Time: 2015-01-01 13:39:43  
Trigger: 1.214096 ms  
Priority: 3 -- Queue: 3

Trig Num: 930 -- Trig Type: RF  
TURF: 939

TURF This Hold: 0x9  
TURF Active Holds: 0x9  
Labrador CCCCCCCCCC  
Phi Mask: 0

Reset Avg	Play	Next
Go to Event	Rev	Prev.
Event#	Stop	First
		Last

Phi 1/0

Phi 2/4

Phi 5/6

Phi 7/8

Phi 9/10

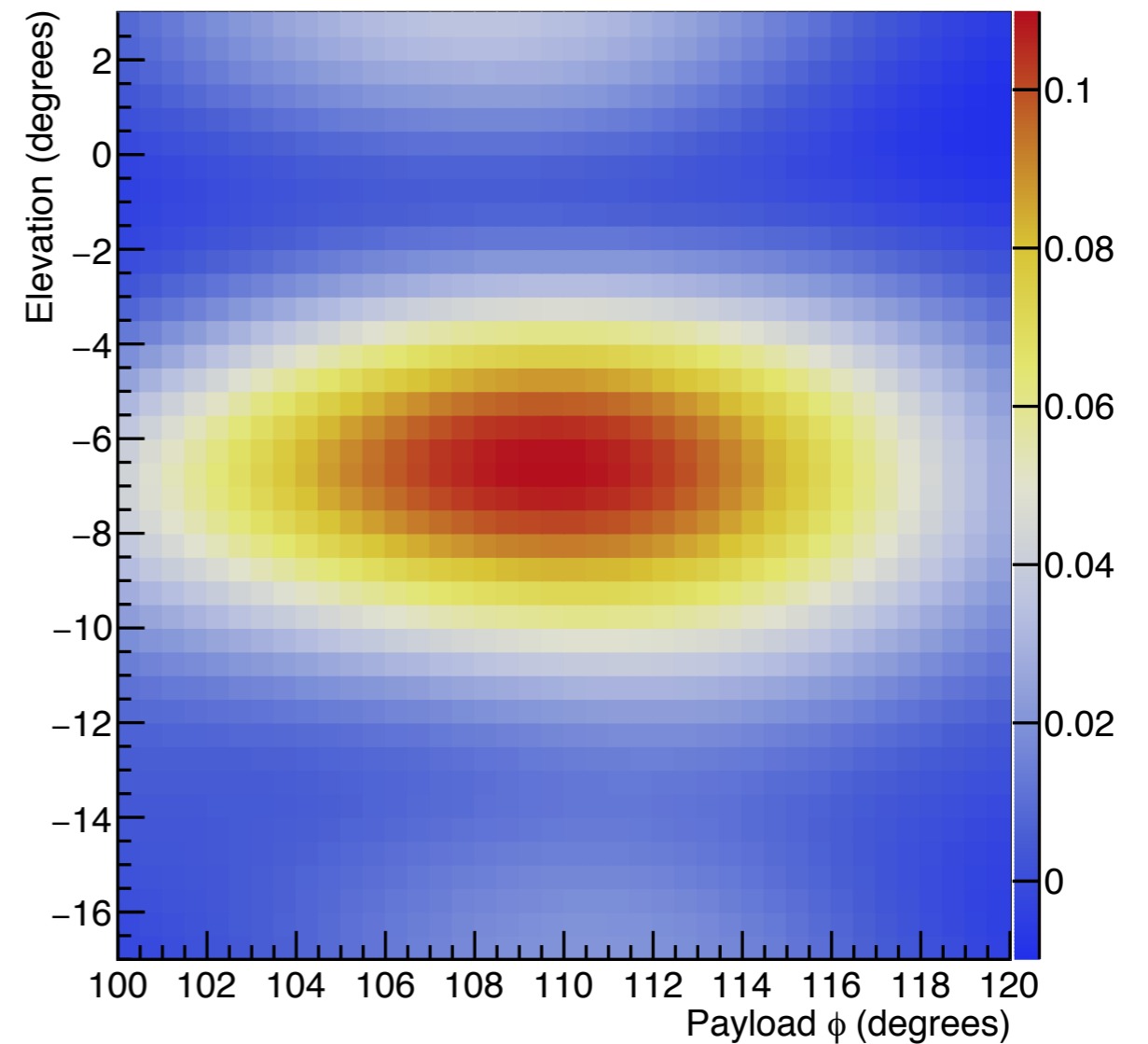
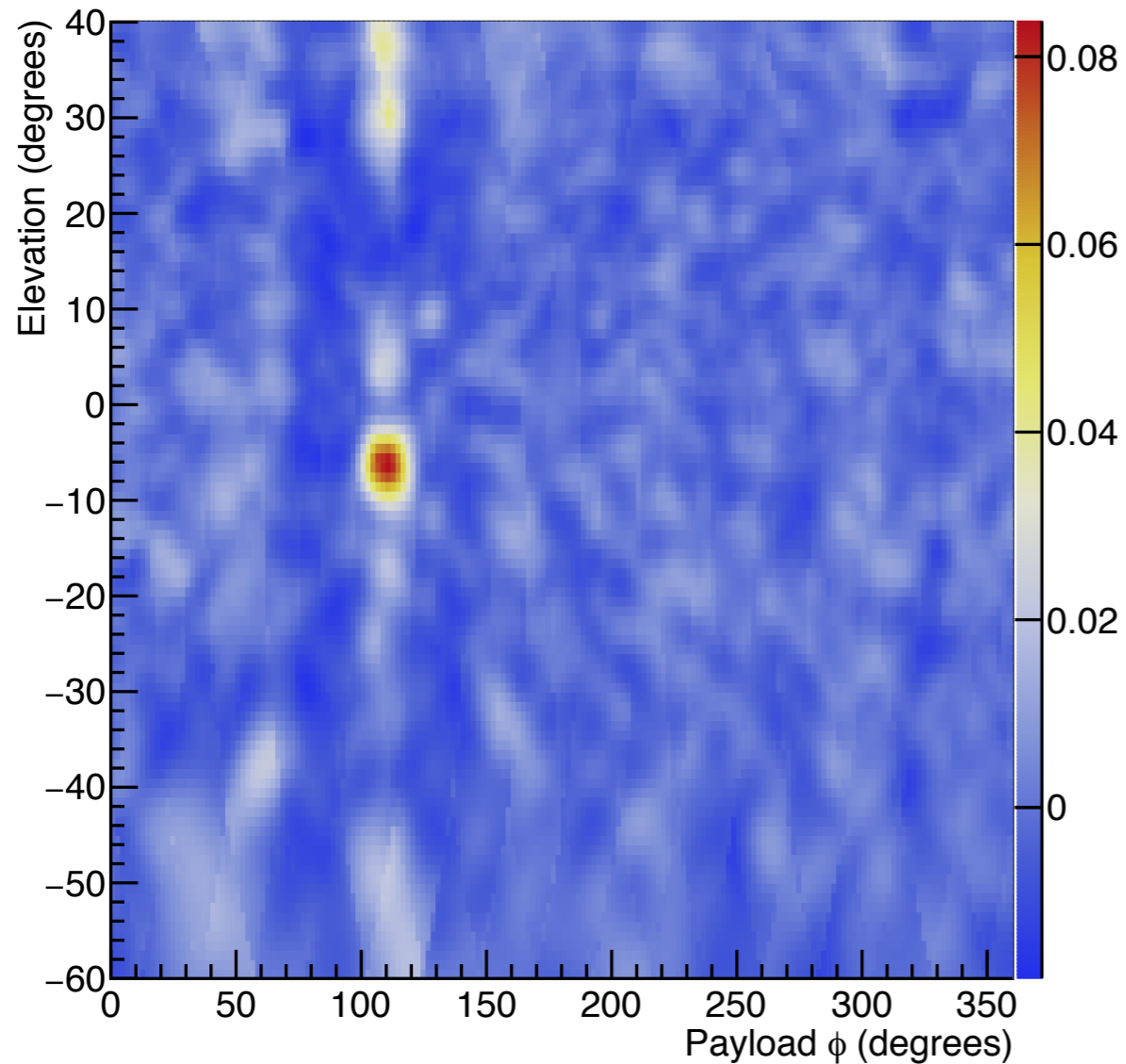
Phi 11/12

Phi 13/14

Phi 15/16

Interferometric Map

Zoomed Map







# Needle(s) in a haystack

L. Cremonesi

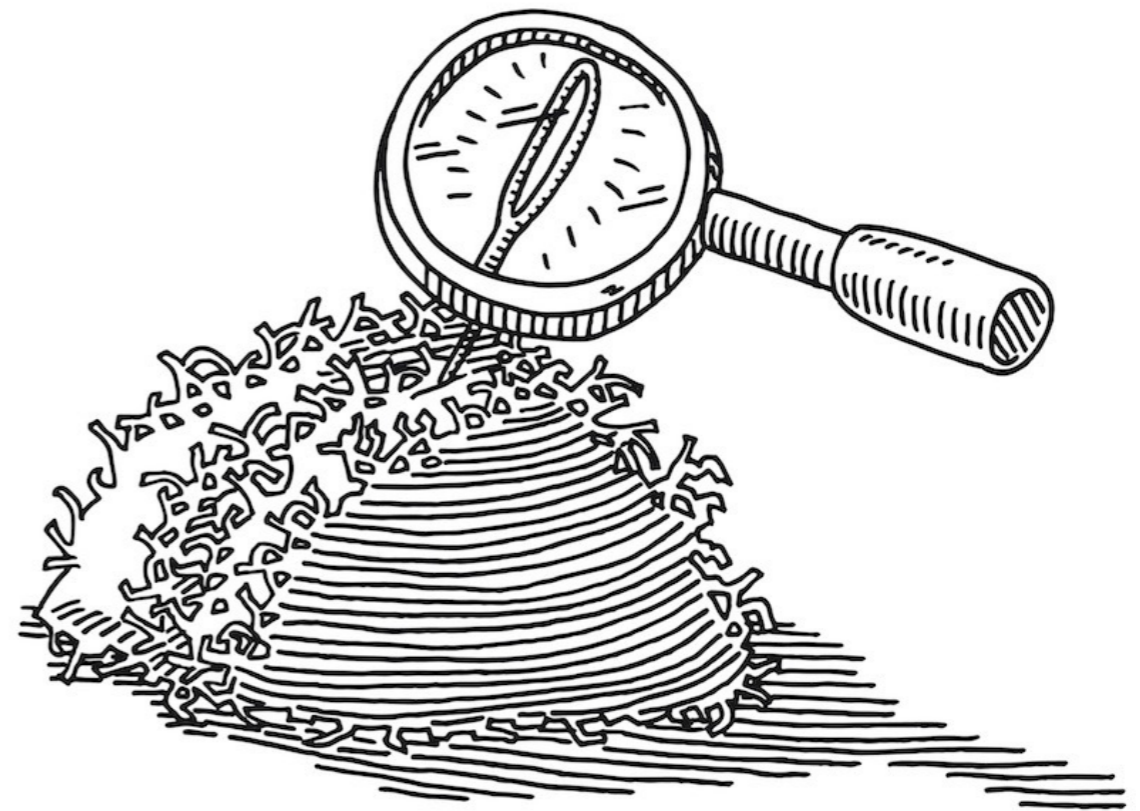
23

“UHE neutrinos and ANITA”



# The challenge

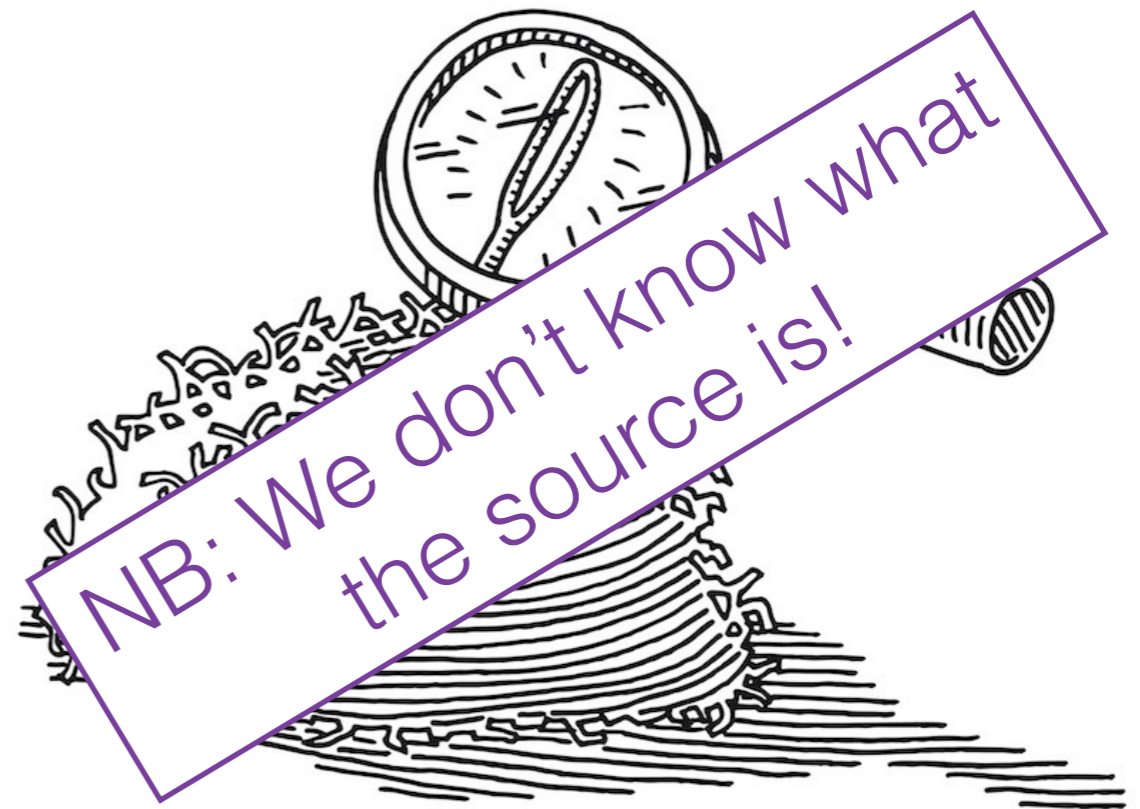
- ~100 million events
- (maybe) a few neutrinos
- Tens of cosmic rays





# The challenge

- ~100 million events
- (maybe) a few neutrinos
- Tens of cosmic rays



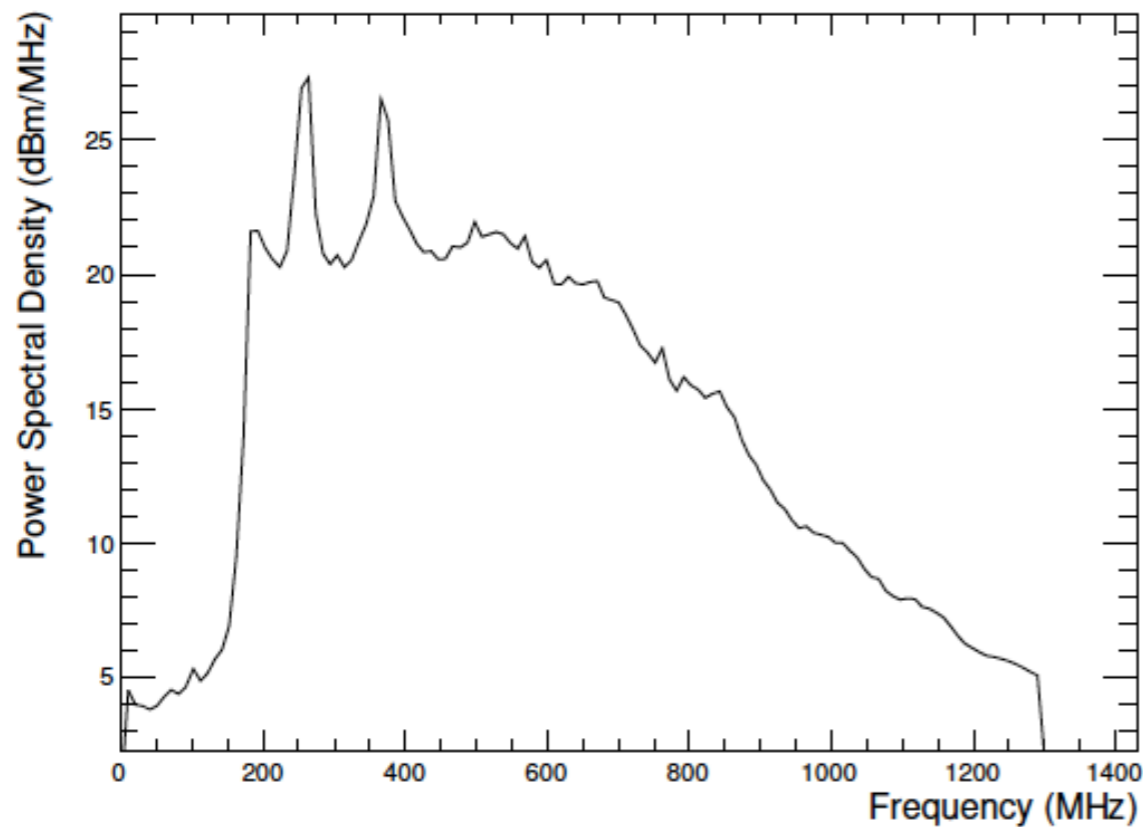


# Backgrounds

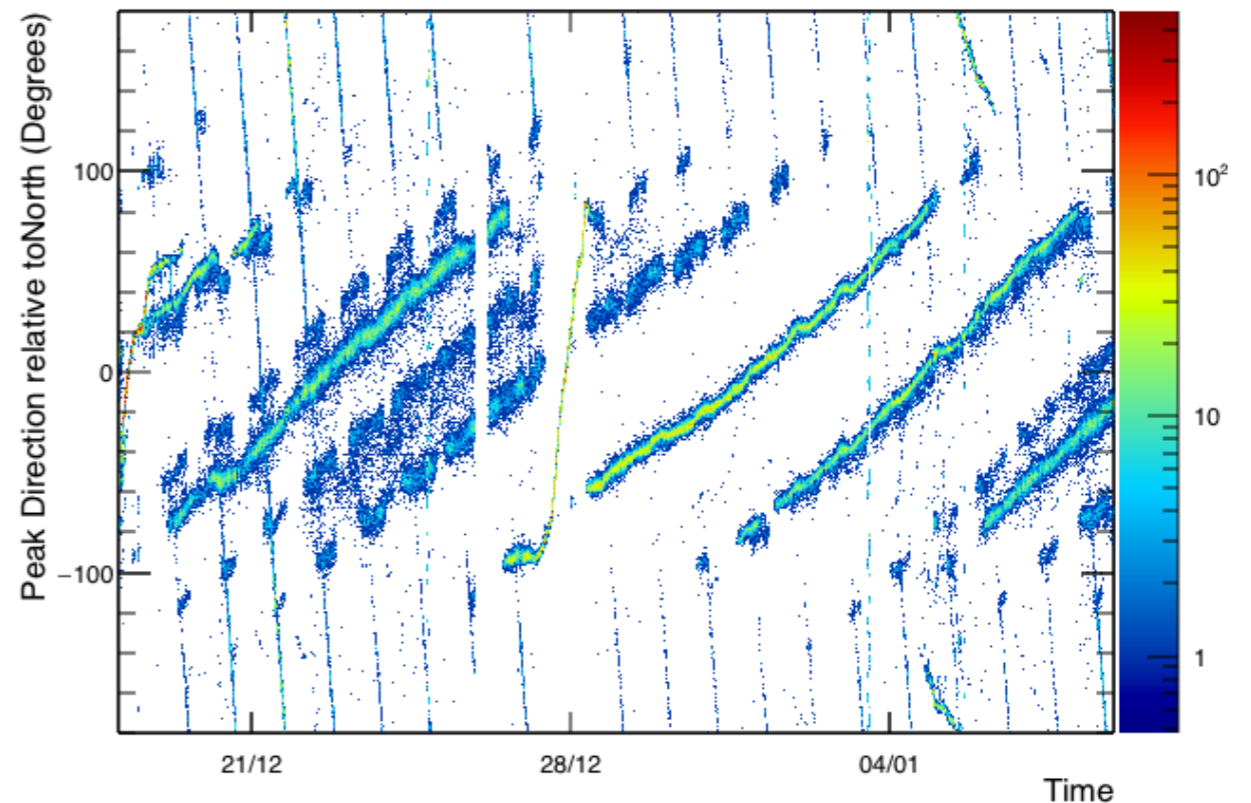
- Continuous waves
- Payload blasts
- Thermal noise
- Anthropogenic impulsive events

# Continuous Waves

- Satellites and human bases using communications in the bands:
  - 260 MHz
  - 380 MHz
- How to get rid of this?
  - ANITA-3: software
  - ANITA-4: hardware



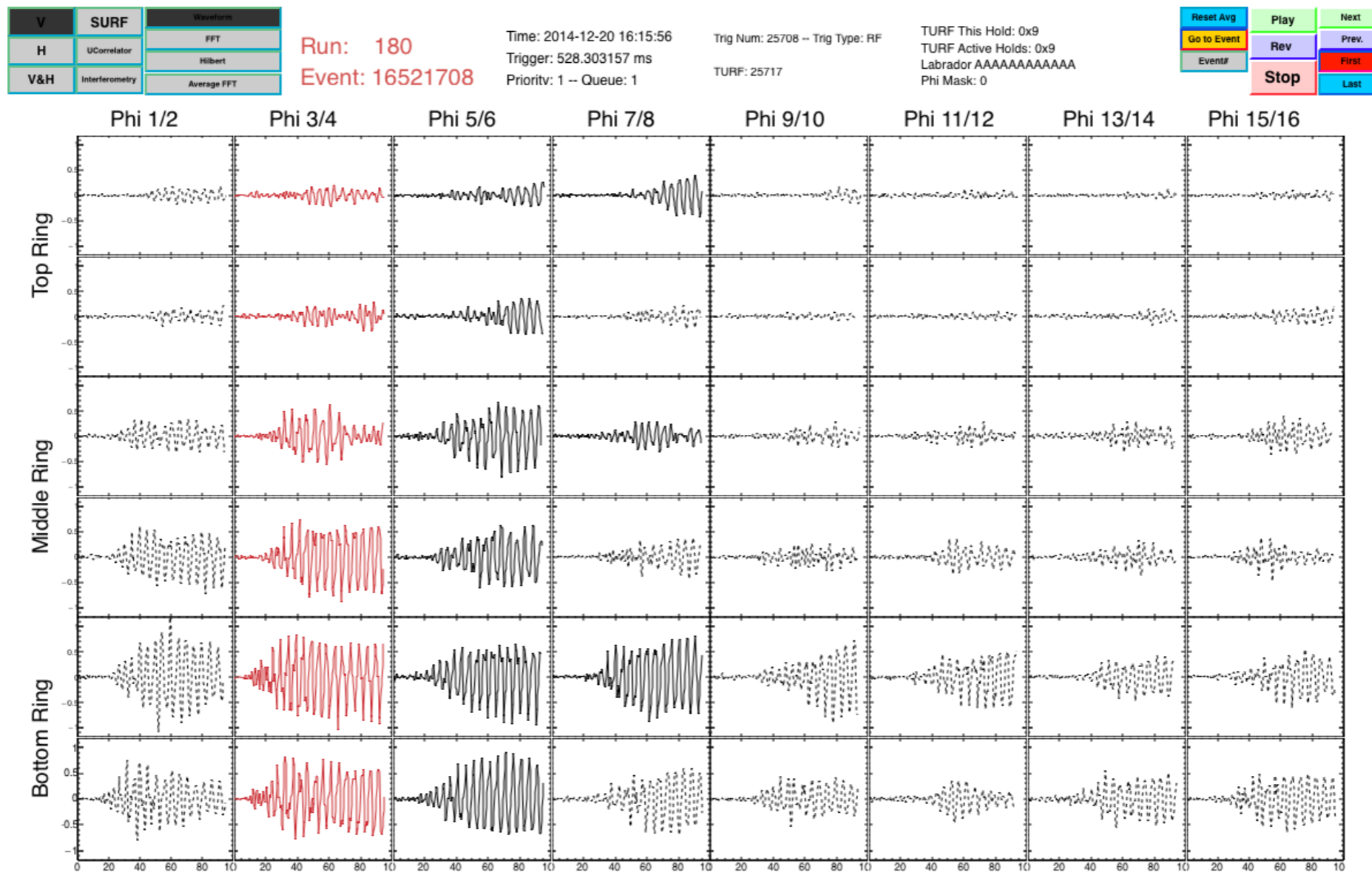
Min Bias Peak Direction





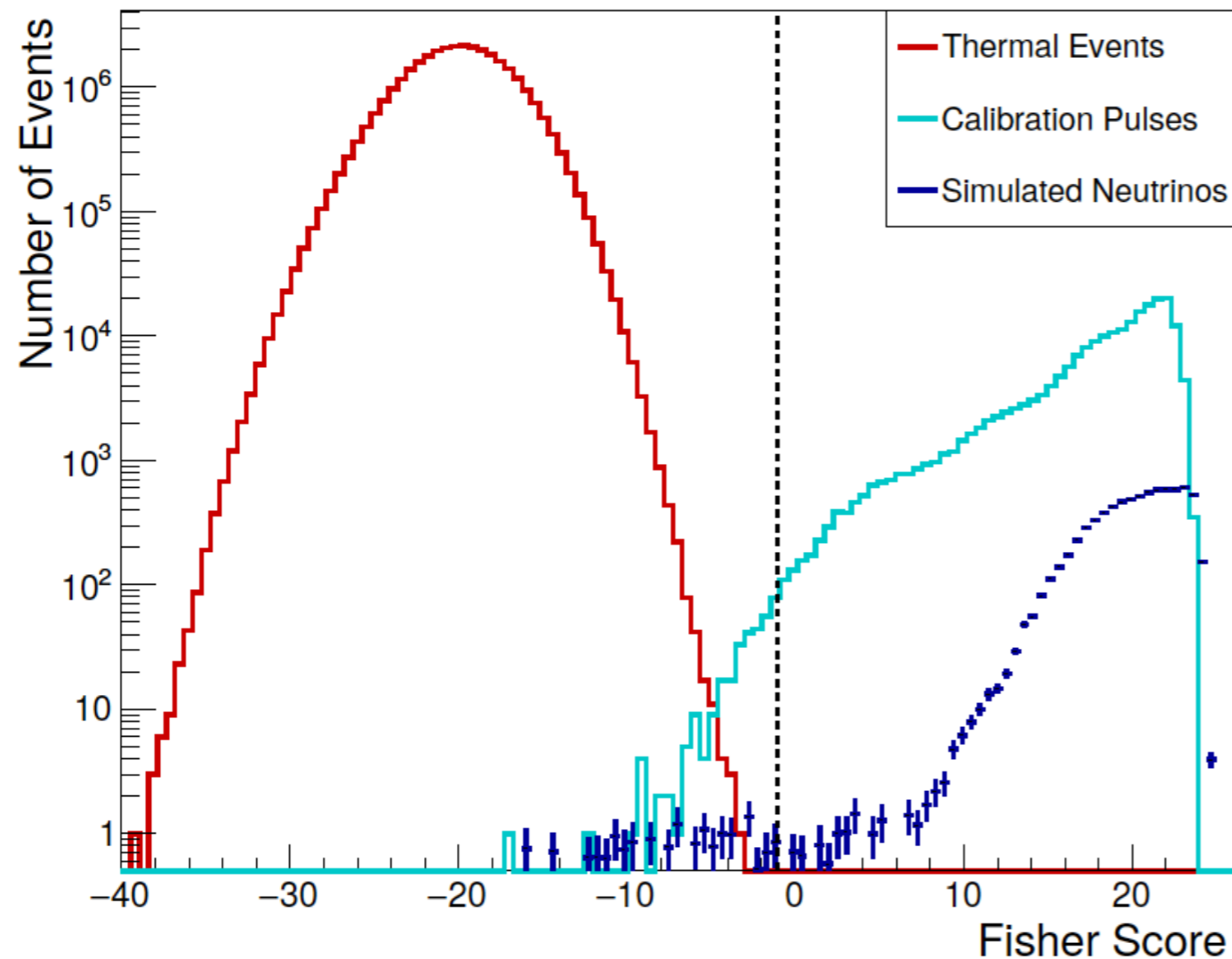
# Payload blasts

- Impulsive radio frequency emissions generated by electronics on board
- Exact origin is unknown
- Removed by simple cuts



# Thermal noise

- Vast majority of ANITA events are thermal noise
- Use Fisher discriminant based on impulsivity variables

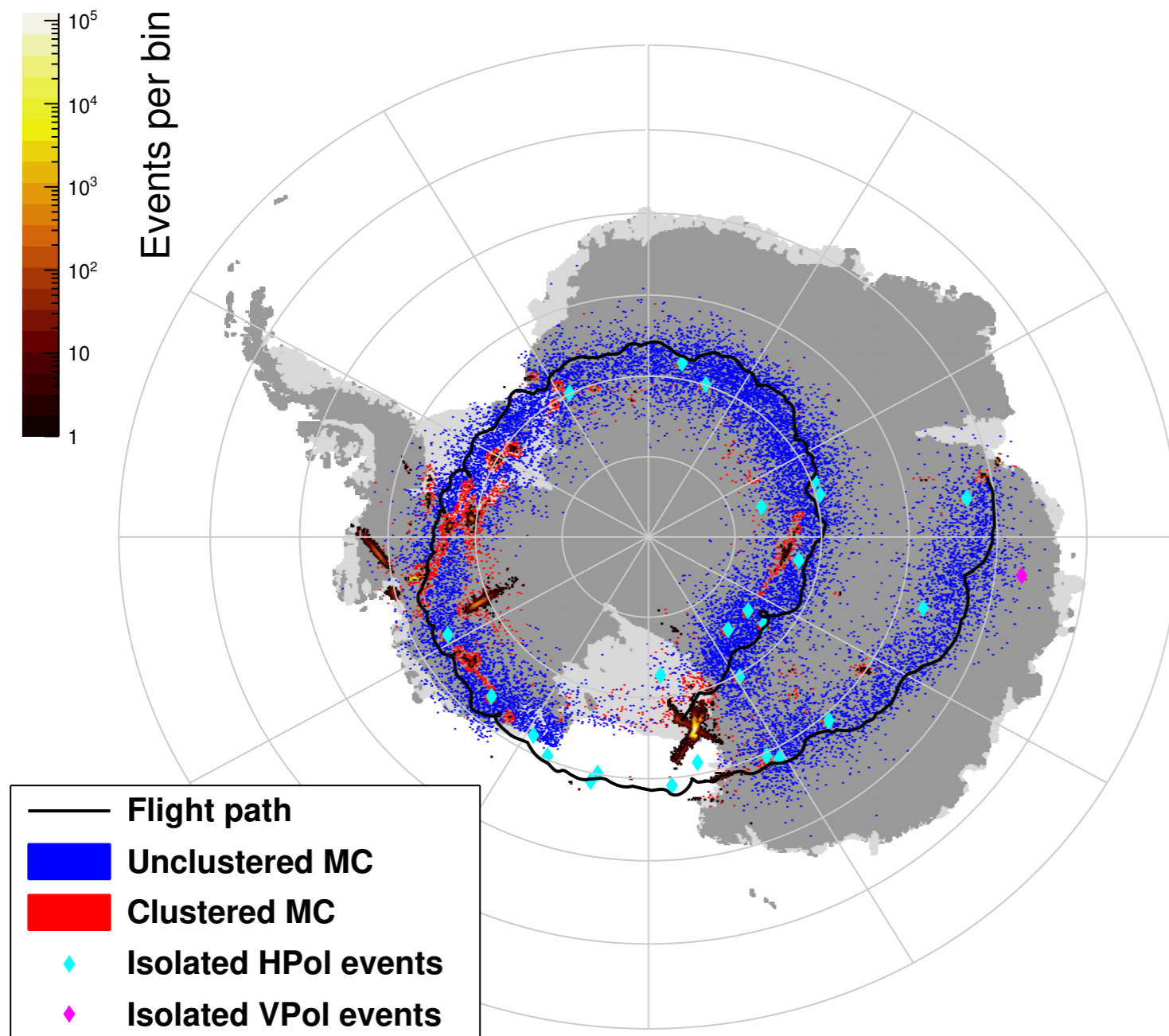


- Background sideband: above horizon triggers
- Simulation: cosmogenic neutrinos following the Kotera mix max model ([arxiv:1903.11043](https://arxiv.org/abs/1903.11043))



# Clustering

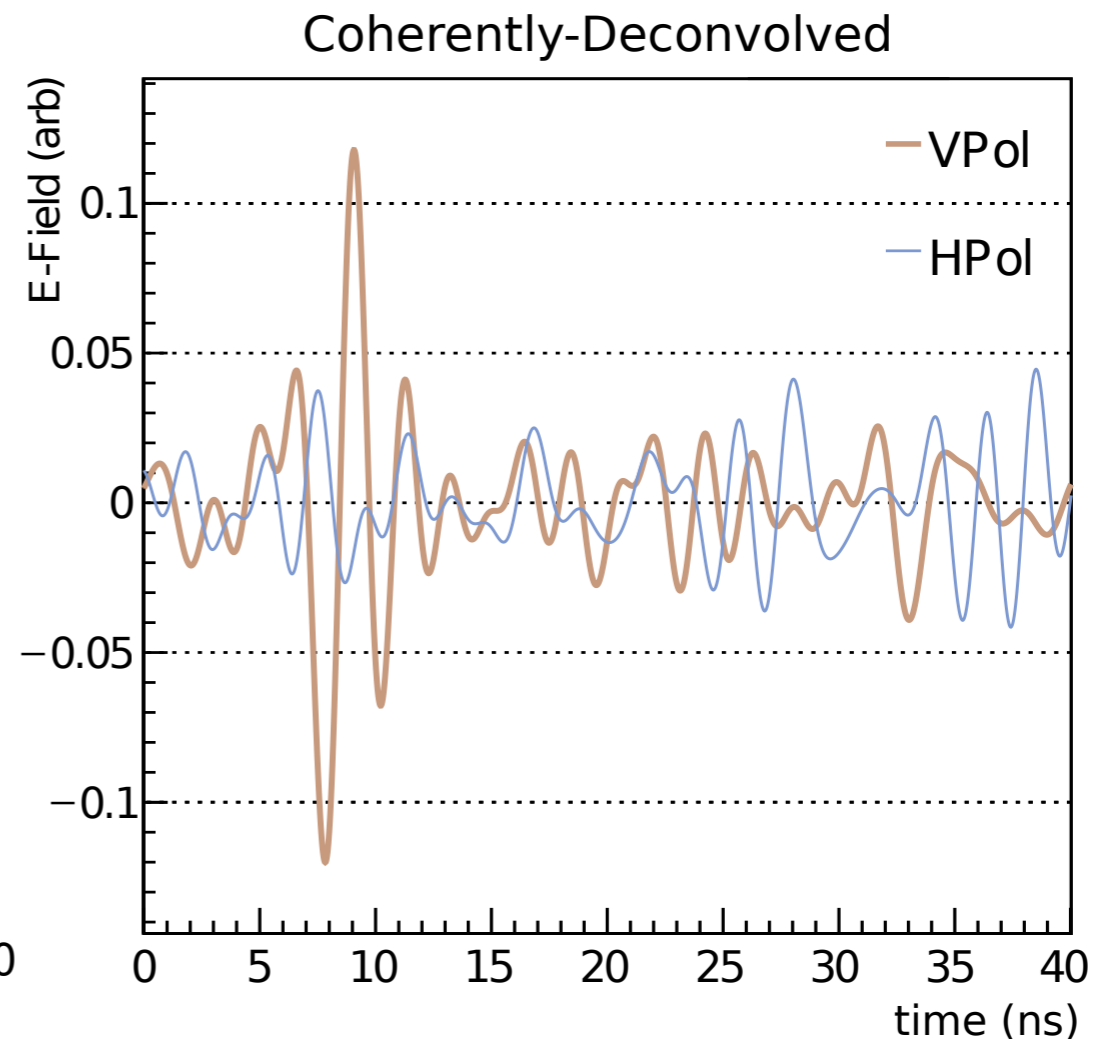
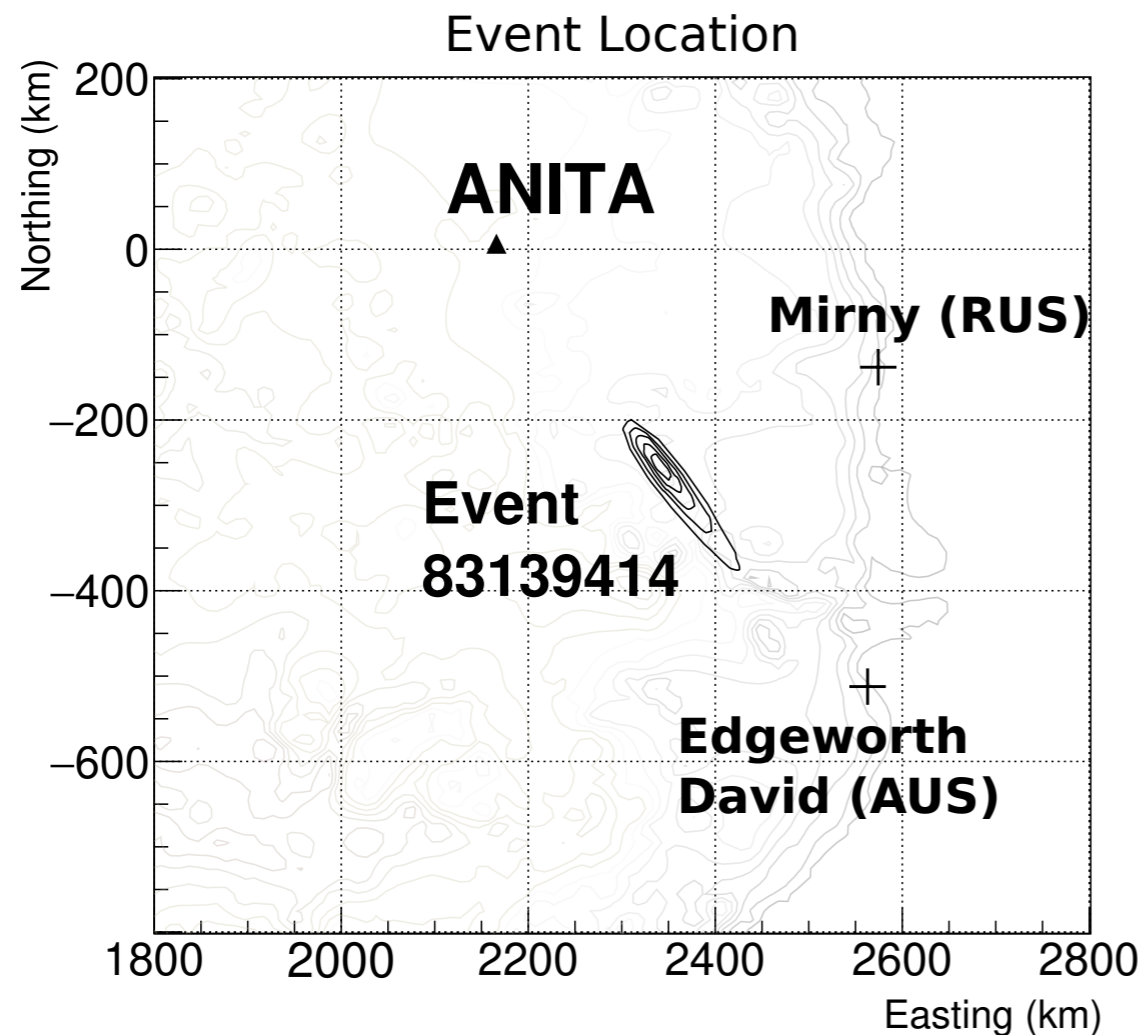
- From previous cuts,  $\sim 500\text{k}$  events



- Look for isolated singlets and doublets
- Remove anything that clusters with human bases
- Remove anything which forms a cluster of 3 or more

# ANITA-3: What's left?

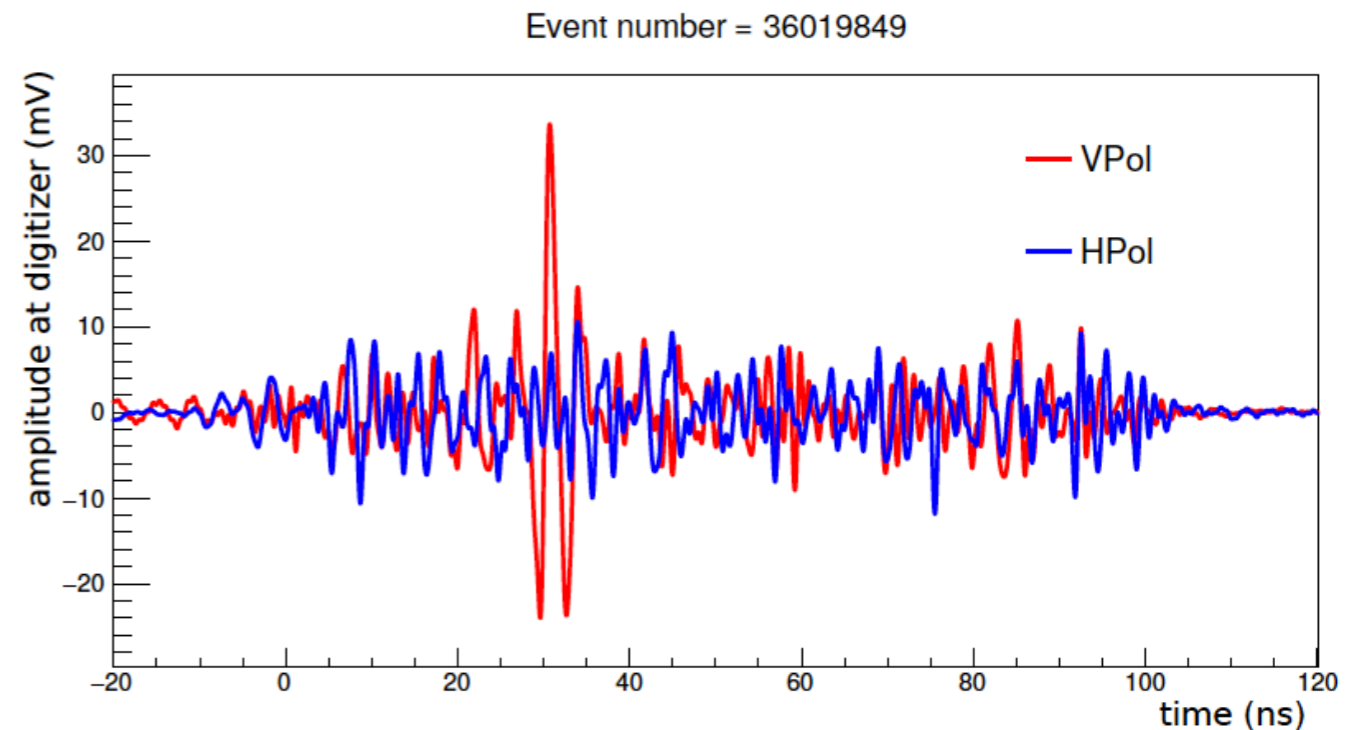
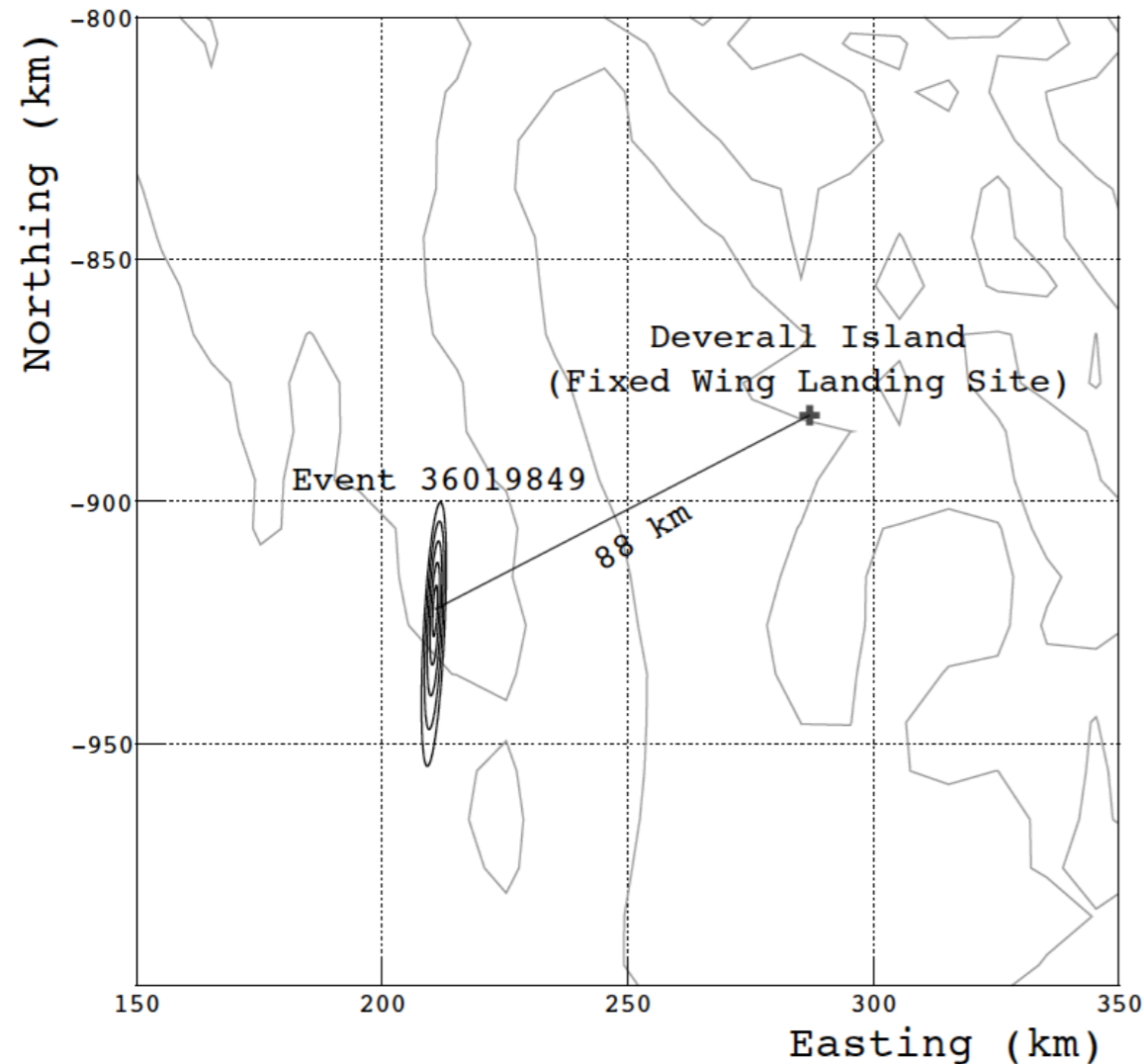
- One V-POL candidate
- Background estimate:  $0.7^{+0.5}_{-0.3}$  per polarisation
- No known human activity within 260km





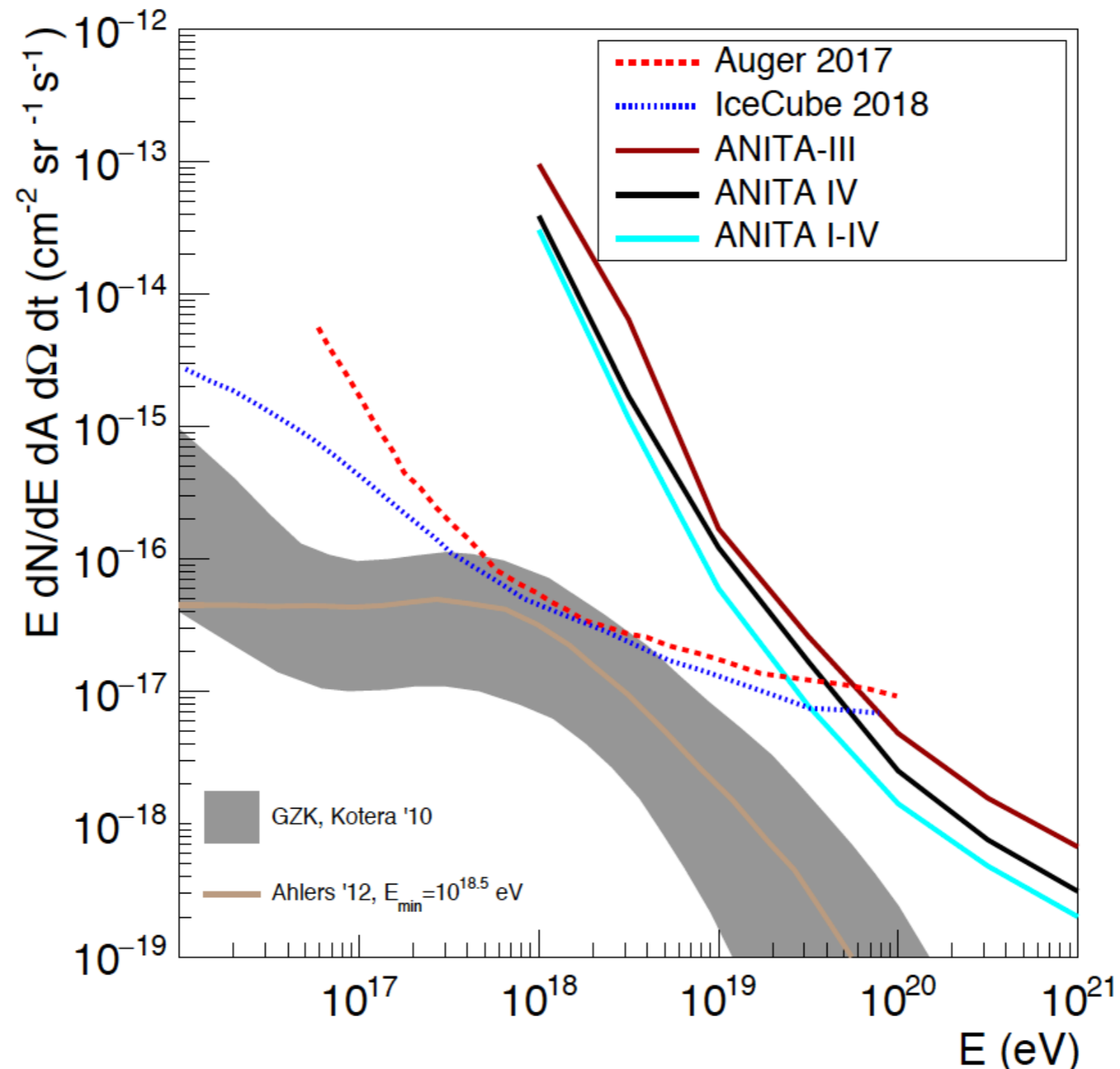
# ANITA-4: What's left?

- One V-POL candidate
- Background estimate:  $0.64^{+0.69}_{-0.45}$  per polarisation
- On Ross Ice Shelf (~300m ice thickness)



# Neutrino limit

Limit on all-flavour-sum diffuse UHE neutrino flux







# UHE cosmic rays

L. Cremonesi

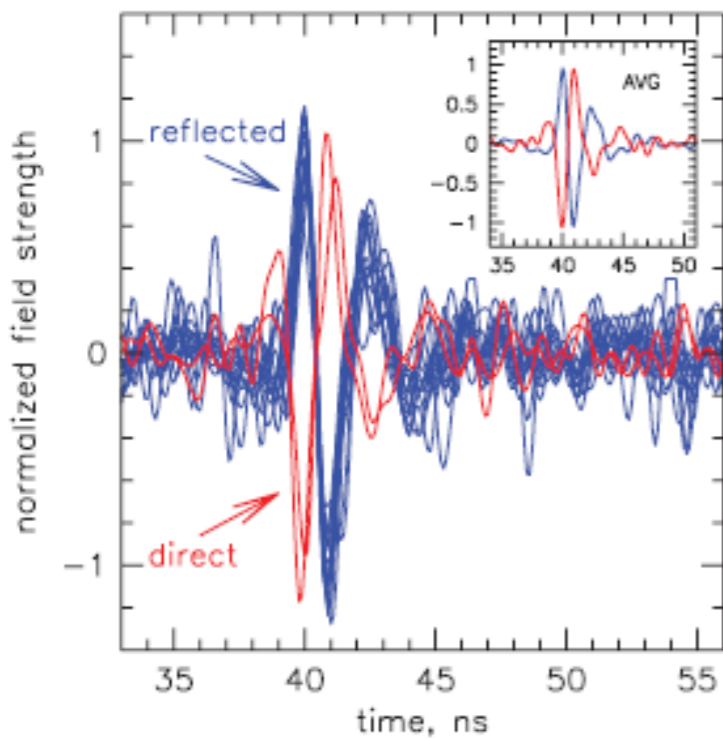
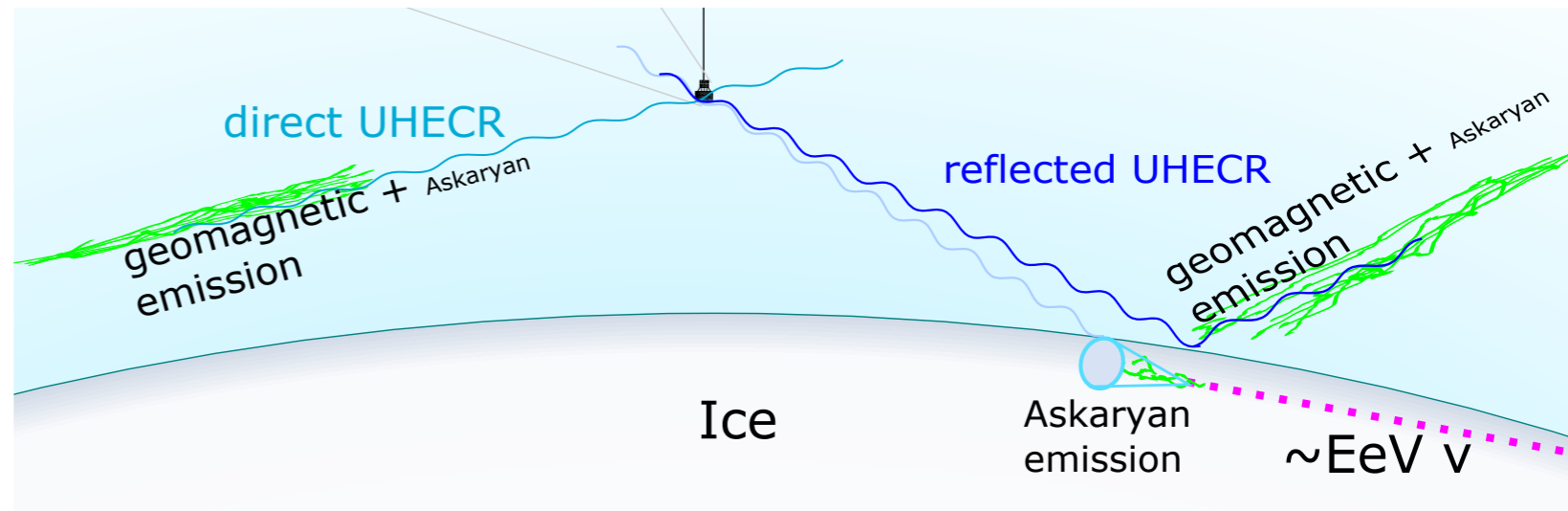
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“UHE neutrinos and ANITA”

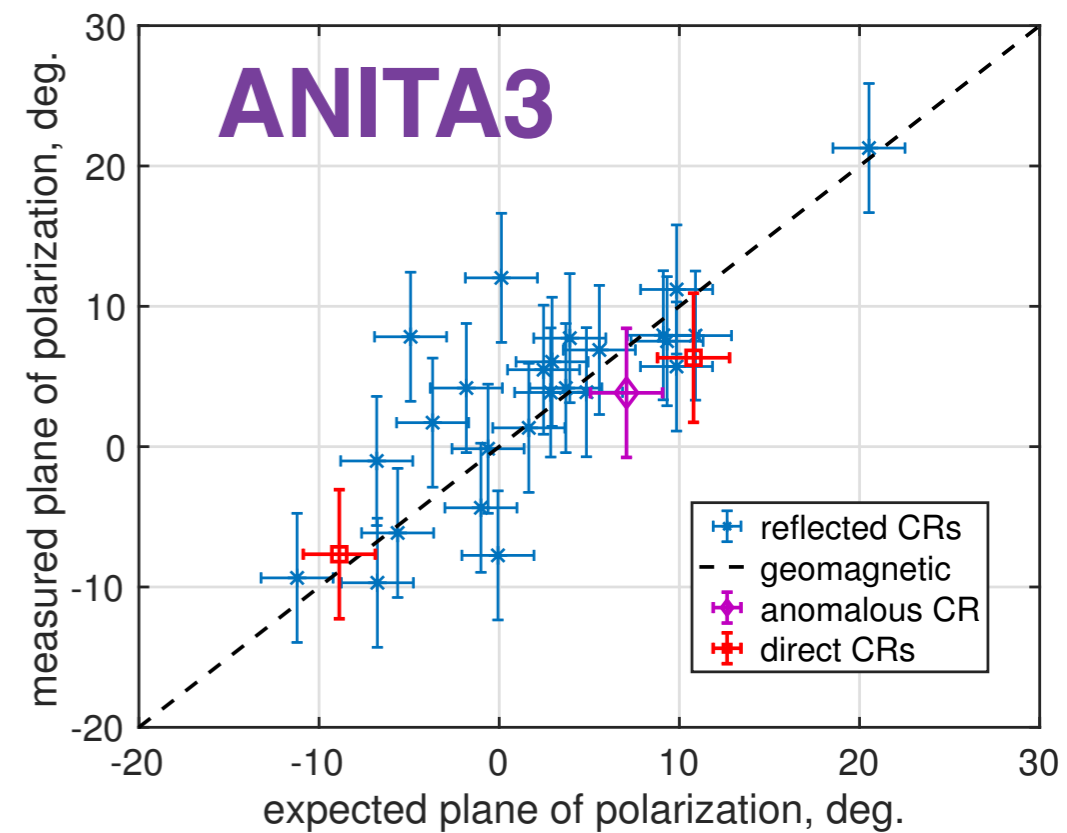
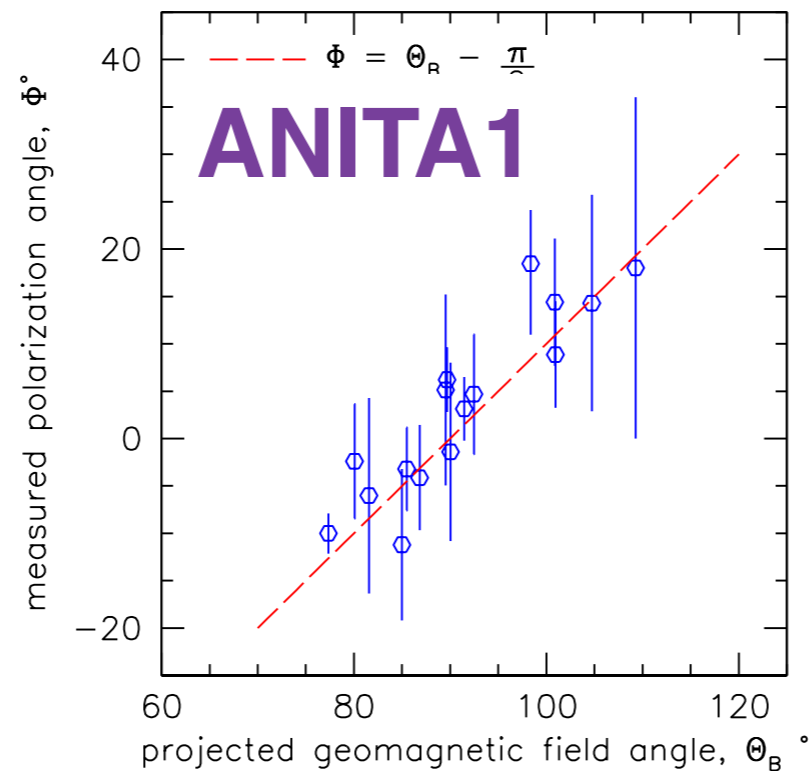


# UHECR

ANITA1: 16 UHECR  
 14 reflected + 2 direct  
 ANITA-2: 2 UHECR  
 H-pol trigger was off  
 ANITA-3: 25 UHECR  
 ANITA-4: analysis in progress



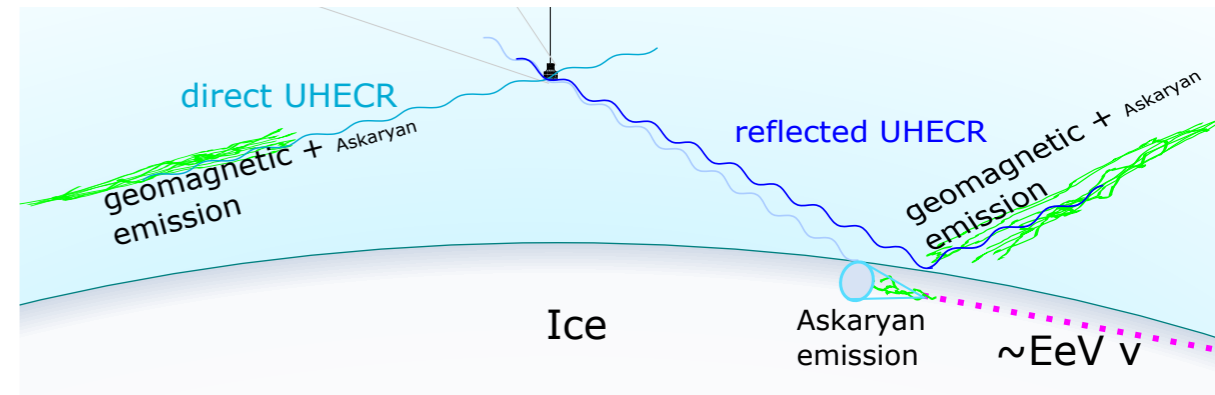
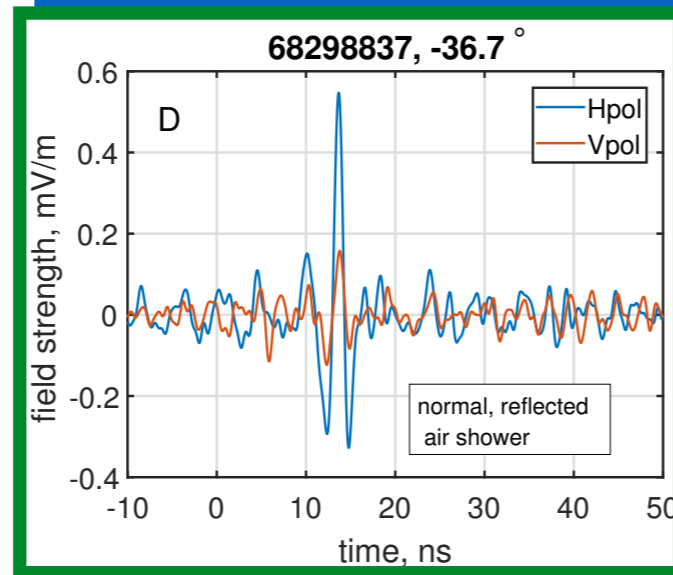
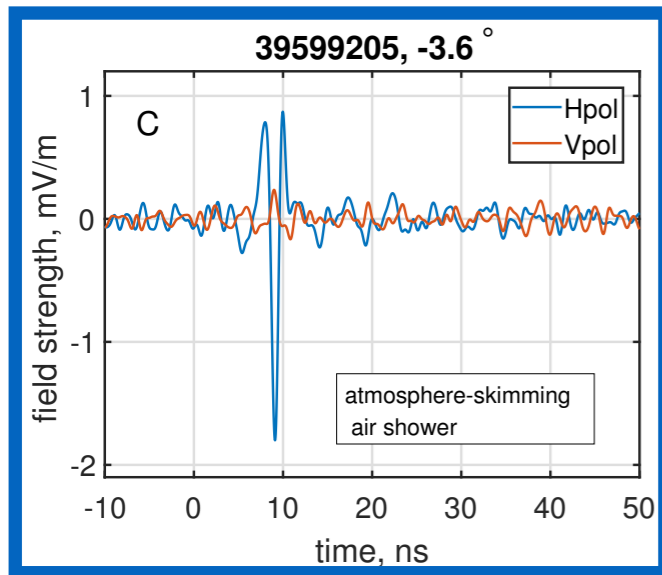
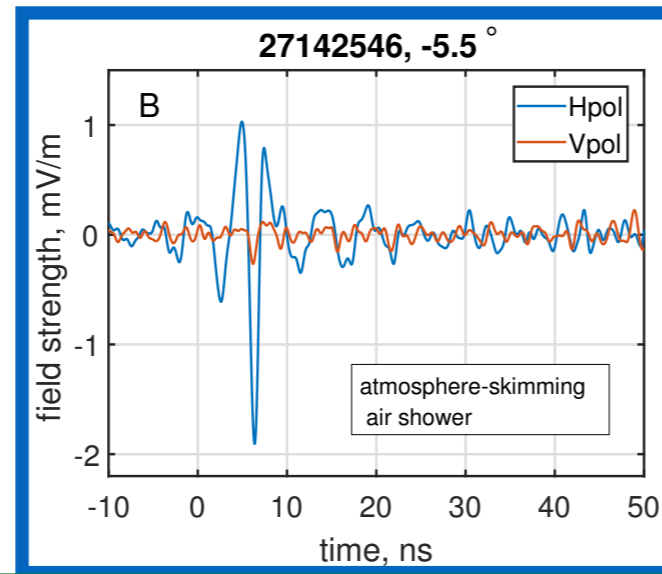
PRL 105, 151101 (2010)



arXiv:1803.05088 [astro-ph.HE]



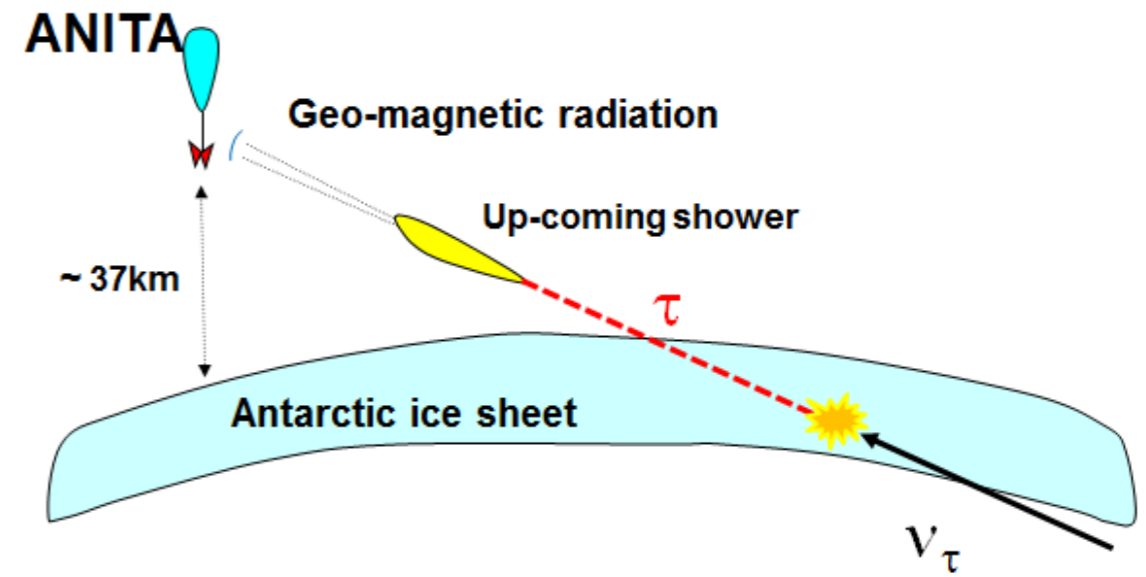
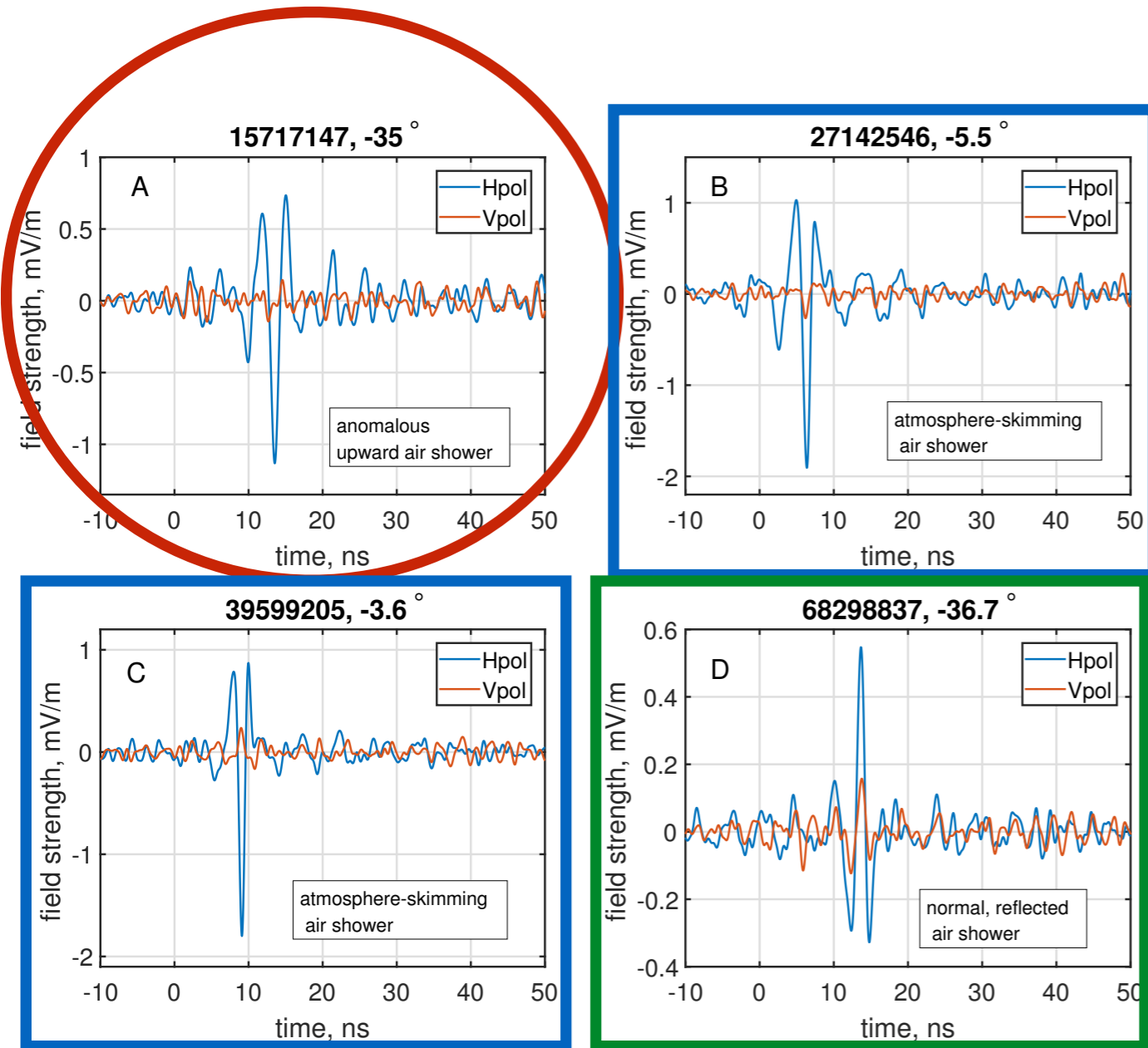
# 2 mystery events



Direct Cosmic Rays

Reflected Cosmic Rays

# 2 mystery events



Direct Cosmic Rays

Reflected Cosmic Rays

NEW PHYSICS ?

Chord length: 5500-7000 km (20-30,000km water equivalent)  
 1600km SM interaction length @ 1 EeV

Background estimate  $< 10^{-2}$



# All news is good news?

LIVESCIENCE

NEWS TECH HEALTH PLANET EARTH

Live Science > Space

## Bizarre Particles Keep Flying Out of Antarctica's Ice, and They Might Shatter Modern Physics

By Rafi Letzter, Staff Writer | September 26, 2018 08:16pm ET

f 0

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Moveable Hacking Environment Space Gaming Health Tech Science

Twitter Facebook VICE

COSMIC MYSTERIES | By Daniel Oberhaus | Sep 28 2018, 6:40pm

## Mysterious Cosmic Rays Shooting from the Ground in Antarctica Could Break Physics

NASA went searching for micro black holes in Antarctica. Instead, it detected cosmic rays shooting from the ground and some physicists think it could be evidence of a supersymmetric particle.

L. Cremonesi

IFL SCIENCE!



PHYSICS

Scientists Confirm The Electron Is Truly Round, And It's A Big Deal.

PHYSICS

Dandelion Seeds Reveal A New Form Of Aerodynamics

PHYSICS

These Are Stephen Hawking's Last Messages To Humanity

PHYSICS

Stephen Hawking's Final Paper Tackles A Crucial Black Hole Mystery

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DAILY NEWS 28 September 2018

## Weird signals in Antarctica could be hints of a new realm of physics

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OCTOBER 22, 2018

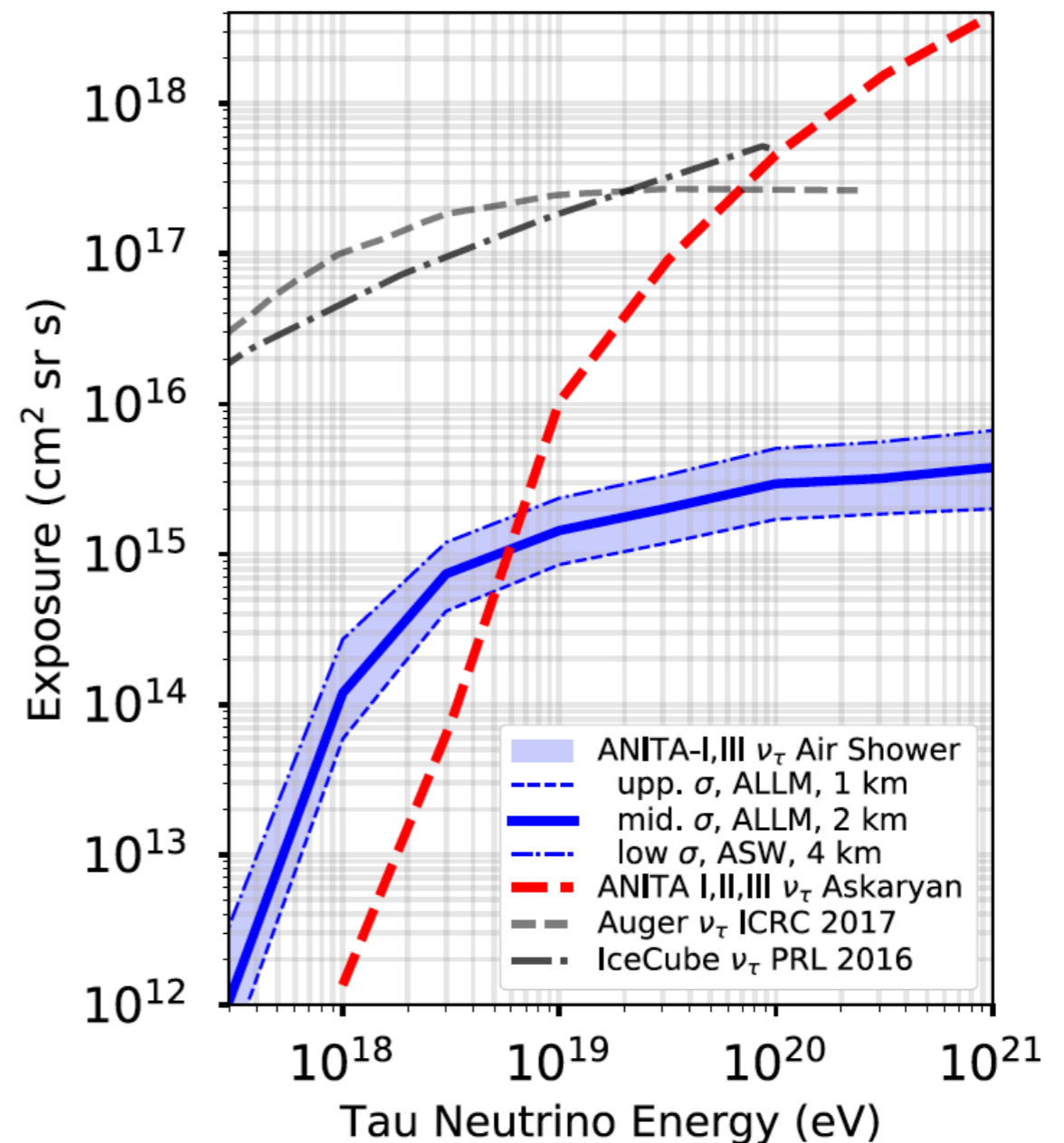
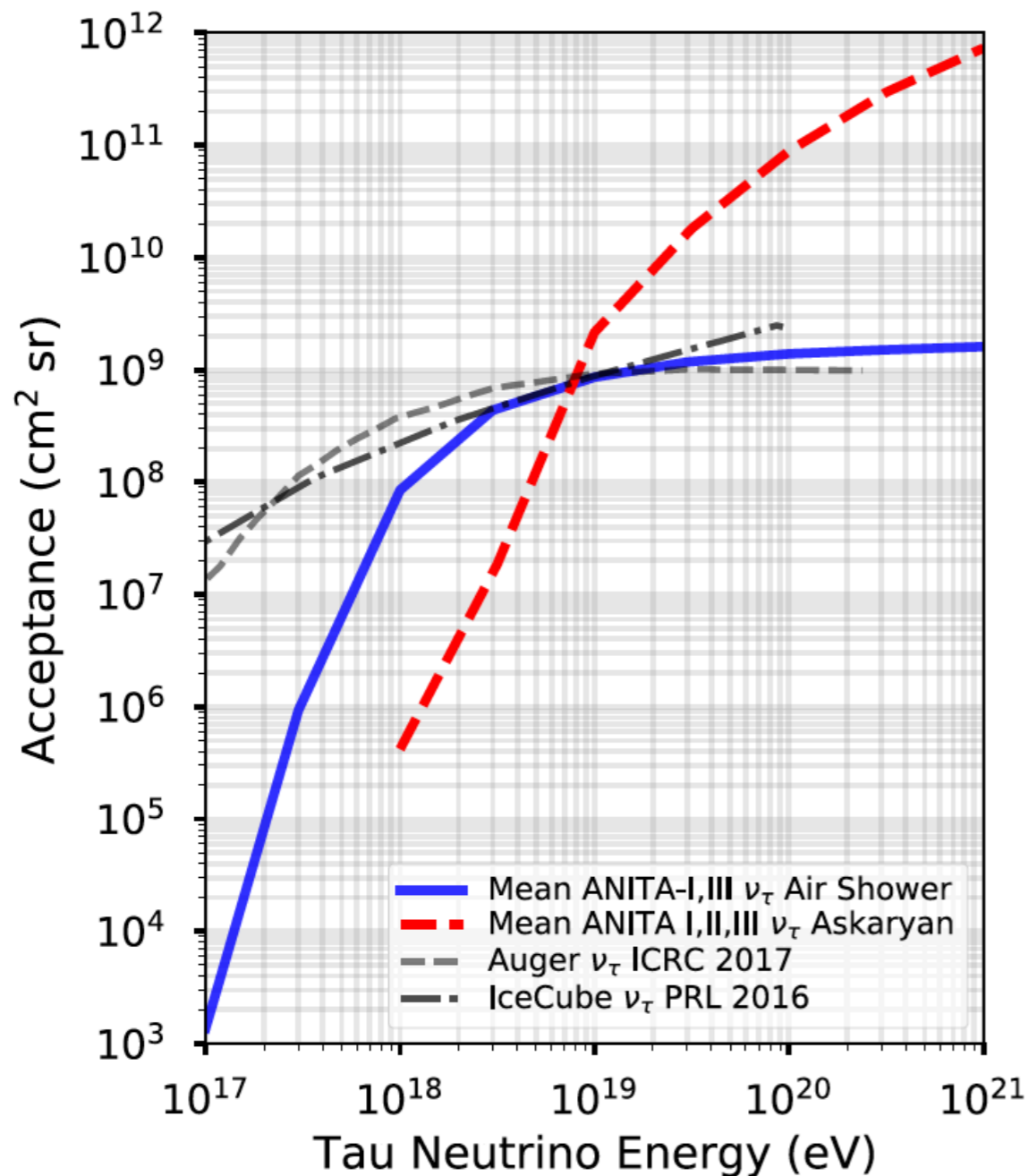
NEWS PARTICLE PHYSICS

## Hints of weird particles from space may defy physicists' standard model

“UHE neutrinos and ANITA”

# Diffuse neutrinos: problem 1

- If these are tau neutrinos why hasn't IceCube seen them?

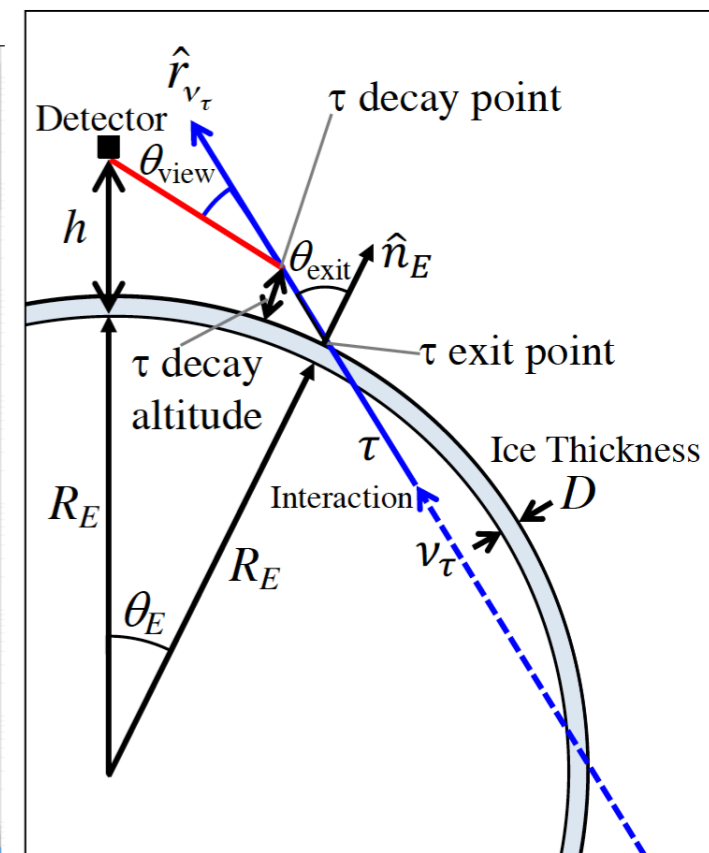
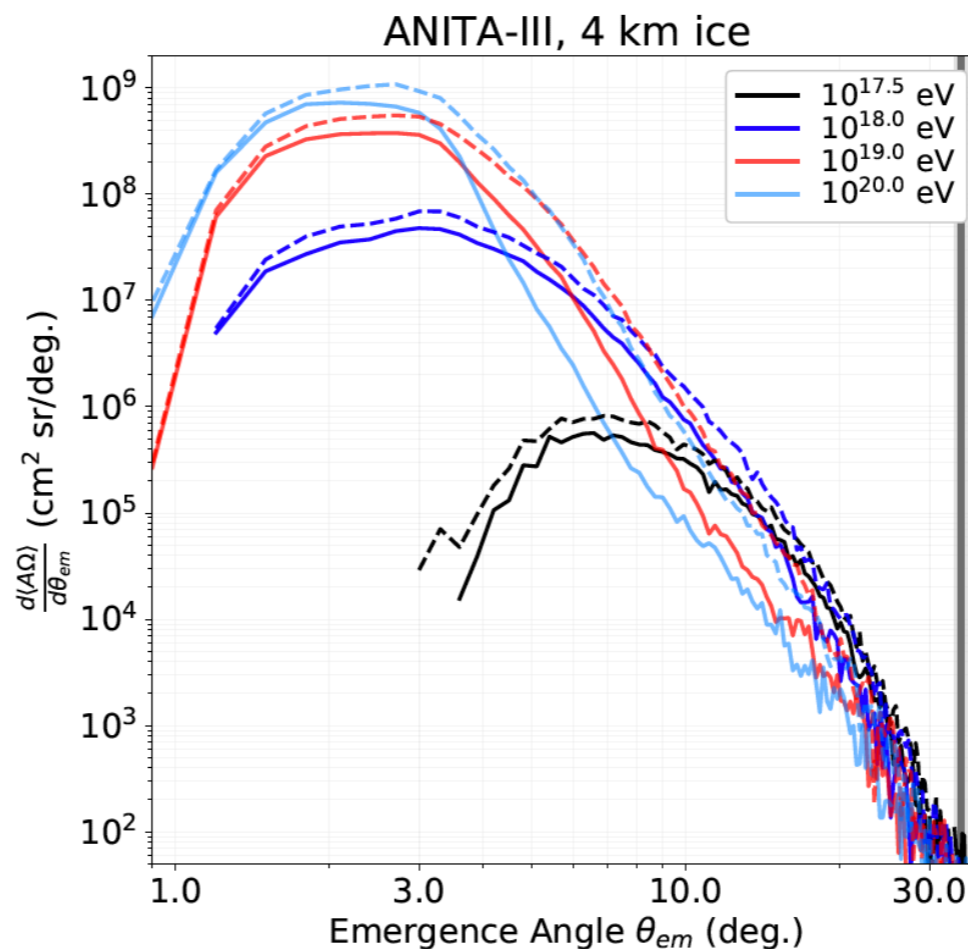
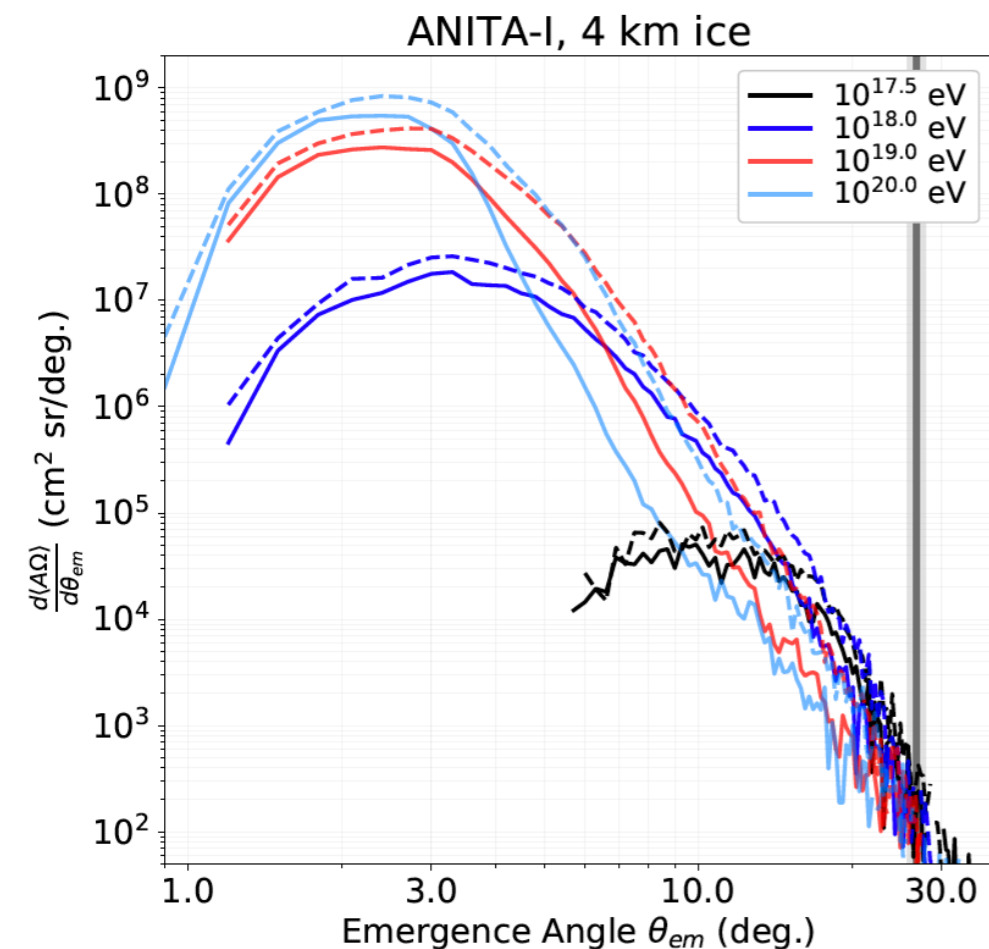


arXiv: 1811.07261



# Diffuse neutrinos: problem 2

- Both ANITA-1 and ANITA-3 events were relatively close to the balloon
- There is much more acceptance close to the horizon
- Where are those tau candidate events?



arXiv: 1811.07261

# Some other interpretations..

- Sterile neutrinos explanation ( $\sigma_{\nu_s} \sim \theta^2 \sigma_\nu$ ), would need powerful transient source to avoid IceCube's constraints  
arXiv:1802.01611
- Decay of massive dark matter candidate ( $>E18$  eV) into two right handed neutrinos  
arXiv: 1902.04584
- Intermediary BSM particle produced in UHECR interactions with low cross-section and and low EM energy losses (stau)  
arXiv:1809.09615
- Powerful transient source search with 1.5 degree error:
  - No concurrent GRBs
  - SN2014dz, type Ia SN at  $z=0.017$ , 5 hours after initial discovery (a posteriori chance association  $2.7\sigma$ )





# Future

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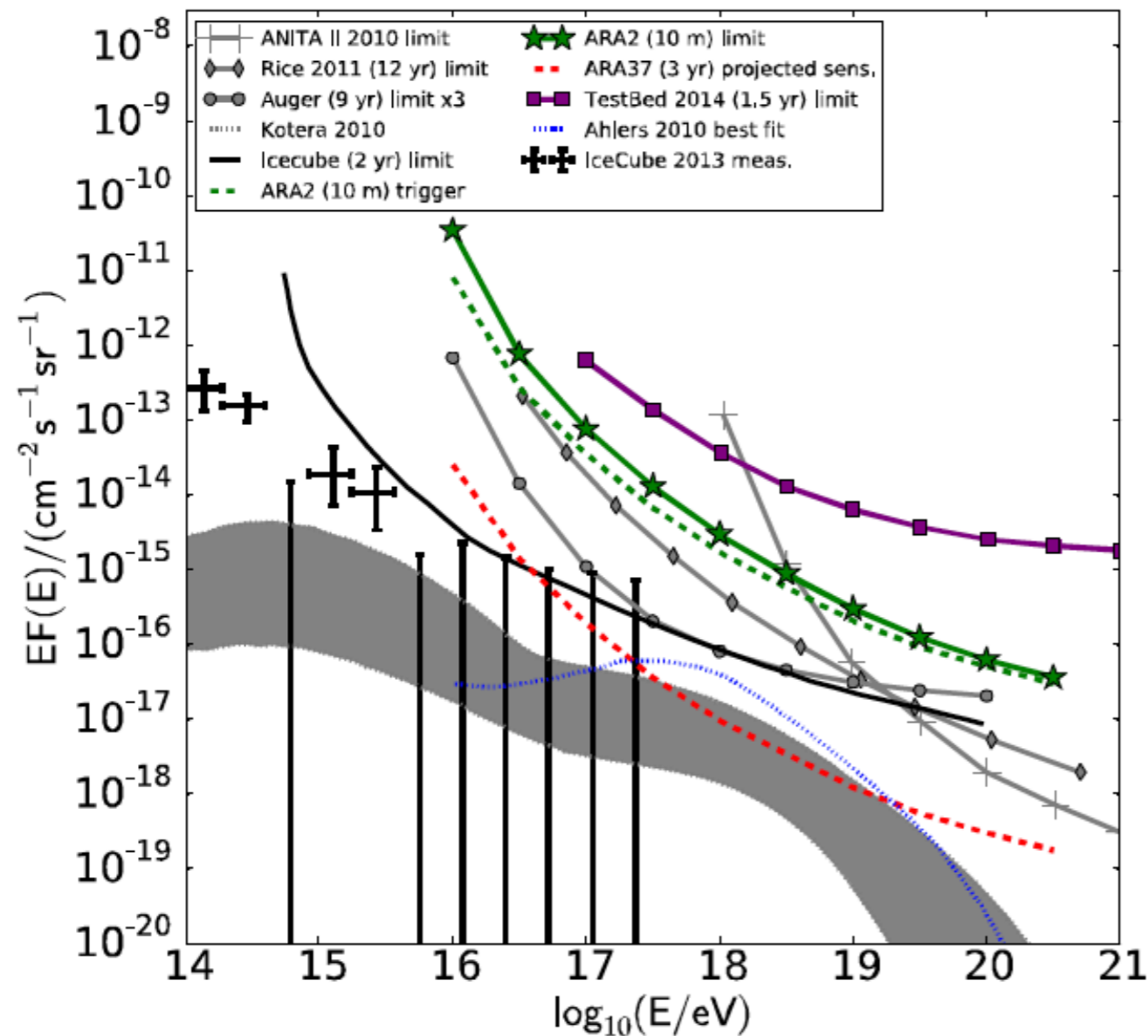
“UHE neutrinos and ANITA”



# ARA

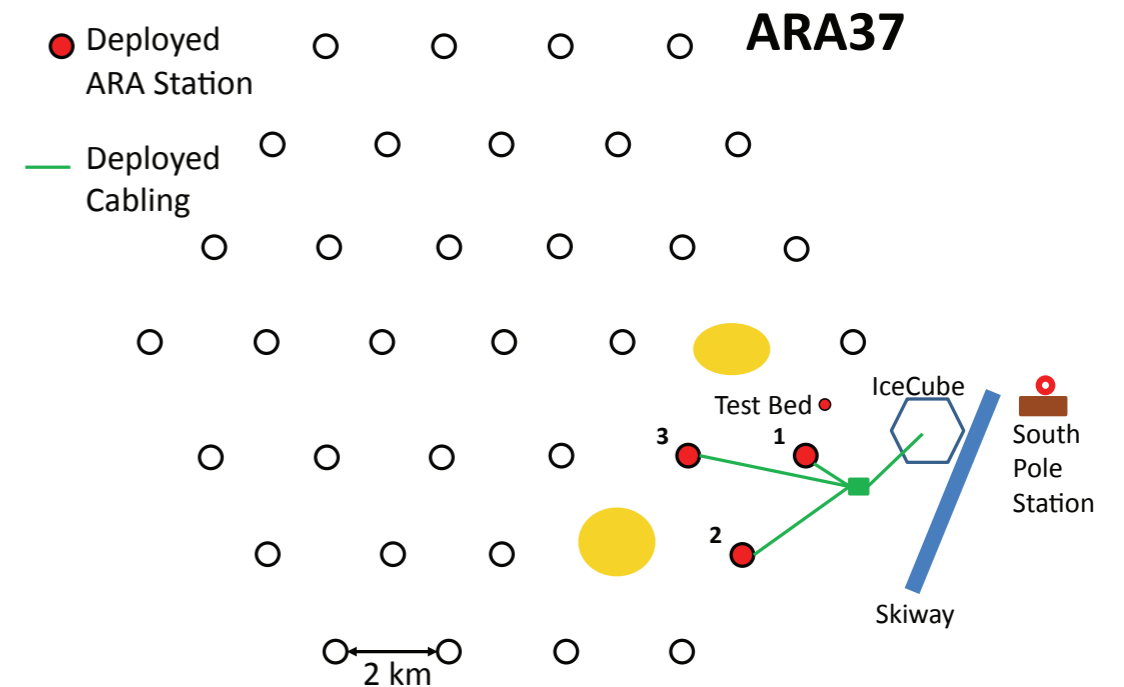
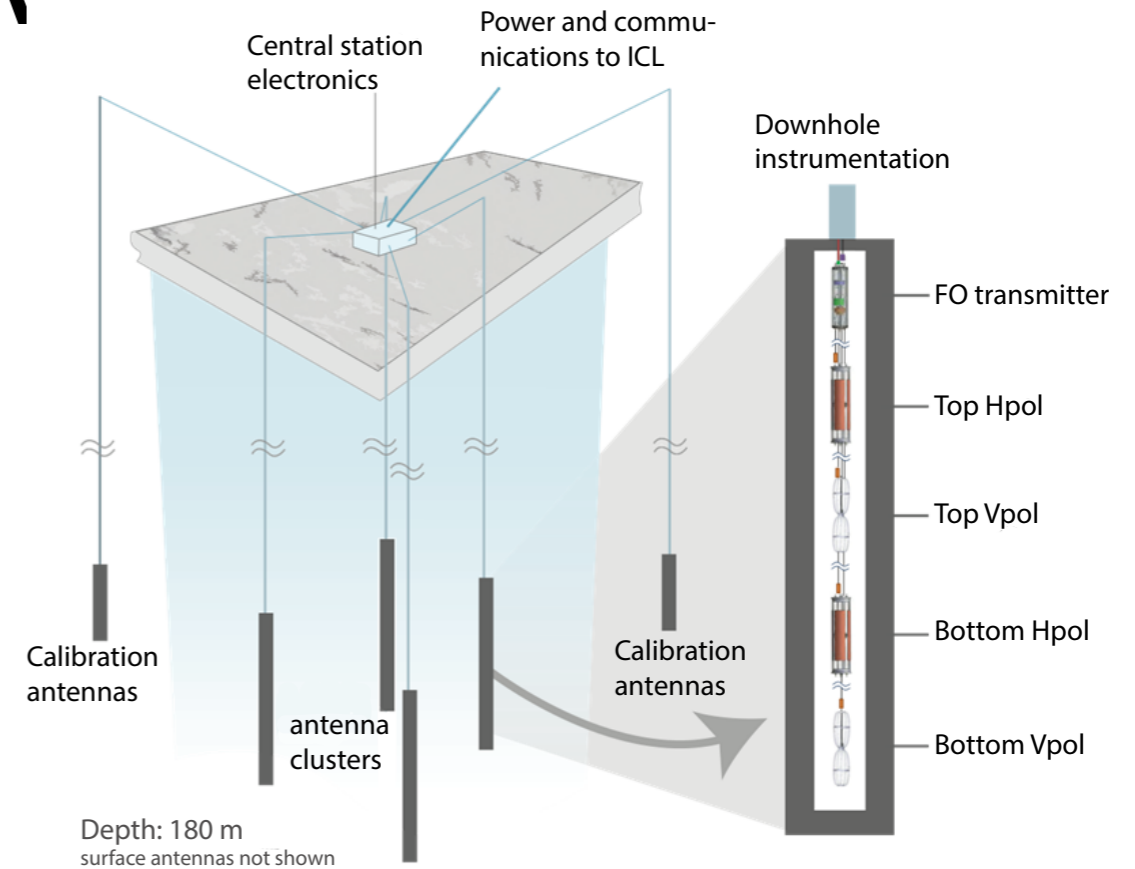
## Askaryan Radio Array: 5 deployed station and 1 phased array

(A. G. Vieregge, et al., JCAP 1602 (2016) no.02, 005)



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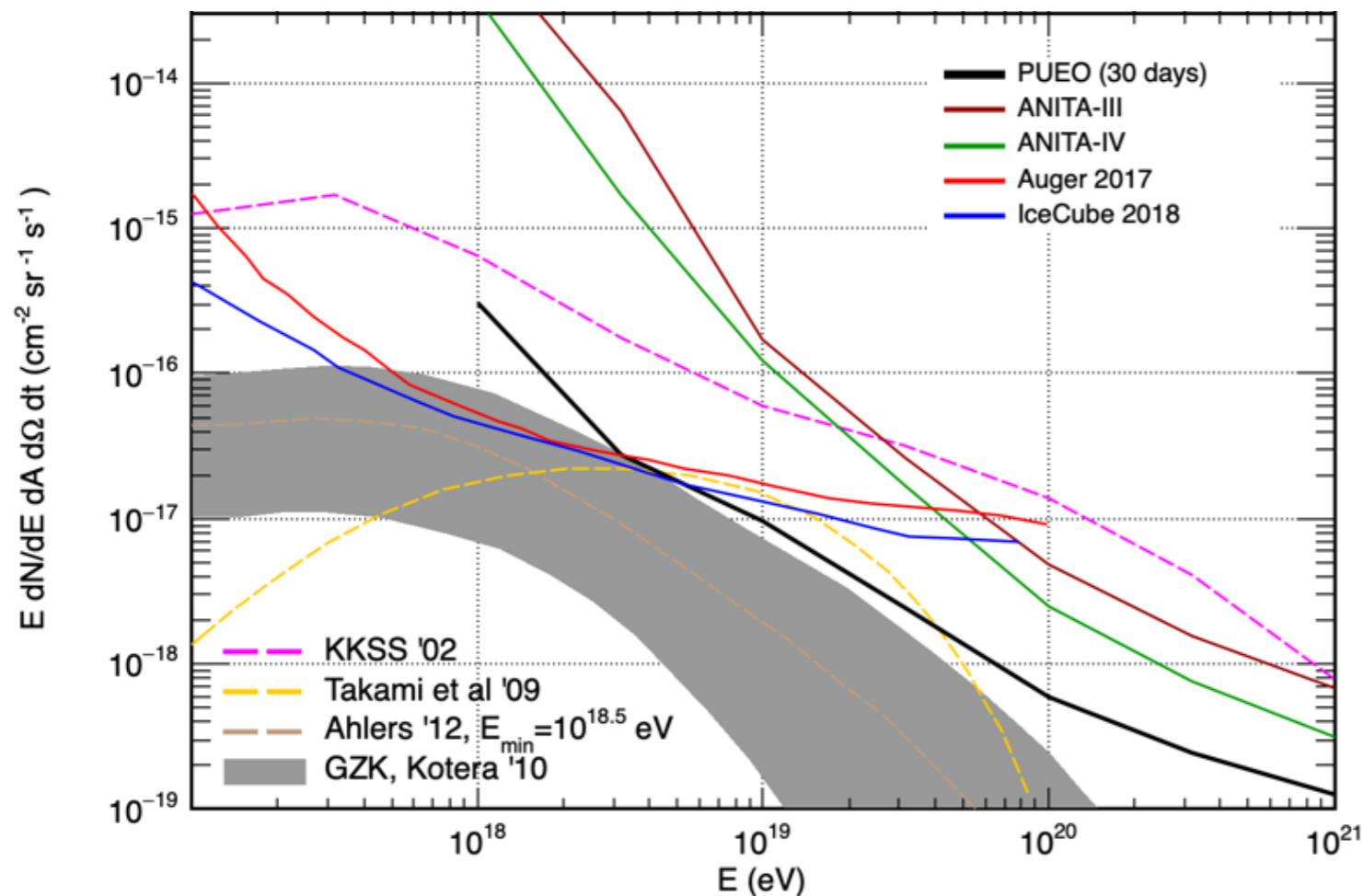


“UHE neutrinos and ANITA”



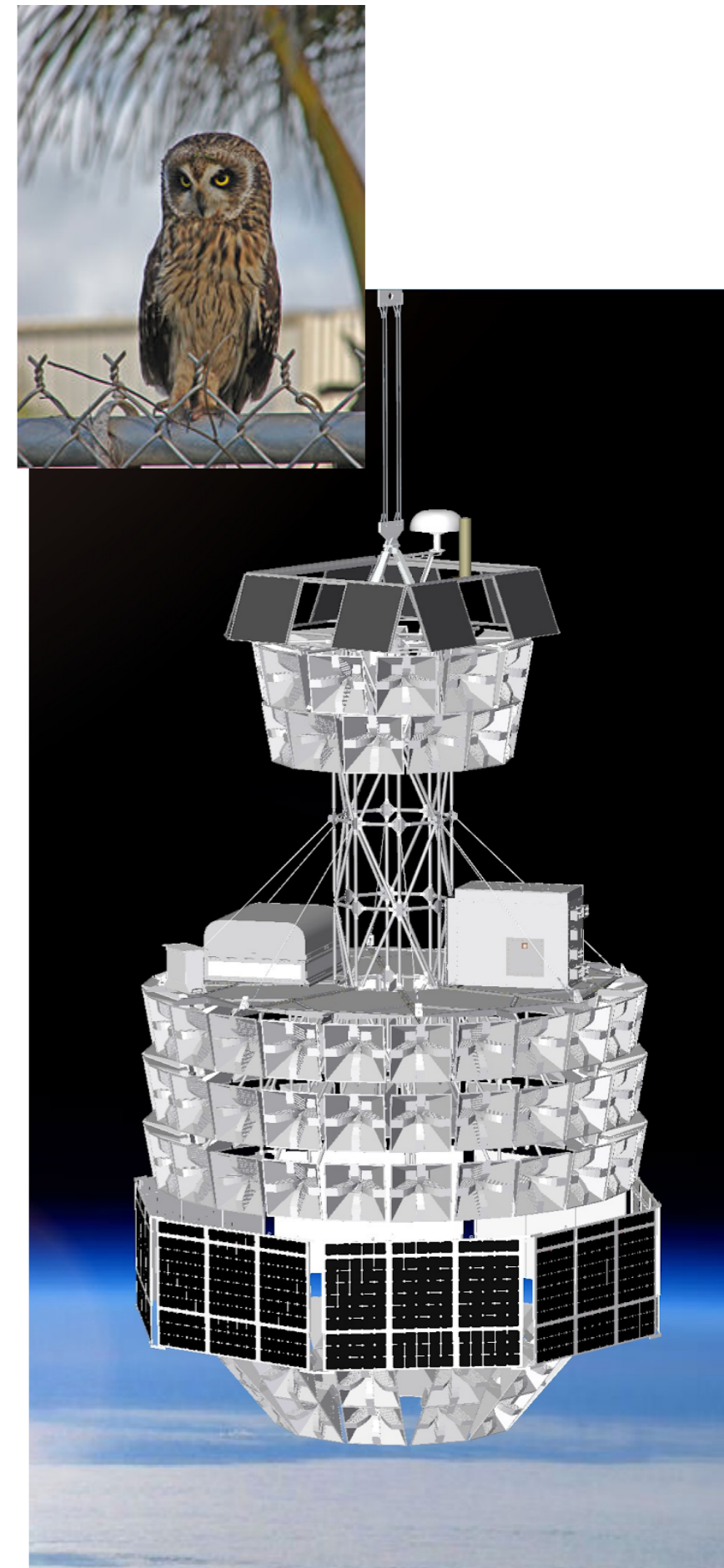
# PUEO

- Payload for Ultrahigh Energy Observations
- 2.5x lower threshold than ANITA-IV
  - More antennas (120 vs. 48) , but higher-frequency (300 MHz vs. 200 MHz cutoff)
  - 16-antennas phased together at a time using a low-bit streaming digitiser as trigger
- 24 antennas in inclined array for steep “mystery events”



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“UHE neutrinos and ANITA”

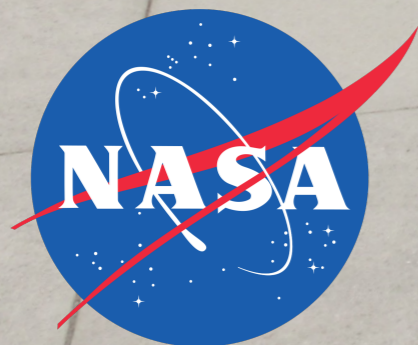
# Summary and future

- The ANITA experiment has a rich physics program:
  - ANITA-3 and ANITA-4 diffuse neutrino analyses: Phys. Rev. D 98, 022001 (2018) & Phys. Rev. D 99, 122001 (2019)
  - ANITA-3 cosmic ray-like analysis: Phys. Rev. Lett. 121, 161102 (2018)
  - Things I didn't cover: iceman simulation (arXiv: 1903.11043), ANITA-3 HiCal (Journal of Astronomical Instrumentation 6.02 (2017): 1740002), GRB searches (ApJ 736 (2011) 50), Lorentz violation (PhysRevD.86.103006), and other analyses
- ANITA-4 cosmic ray like analysis coming out soon!
- UHE neutrino sources (likely correlated with sources of cosmic rays) remain unidentified - exciting times for neutrino astronomy!





THANK YOU



LEVERHULME  
TRUST \_\_\_\_\_





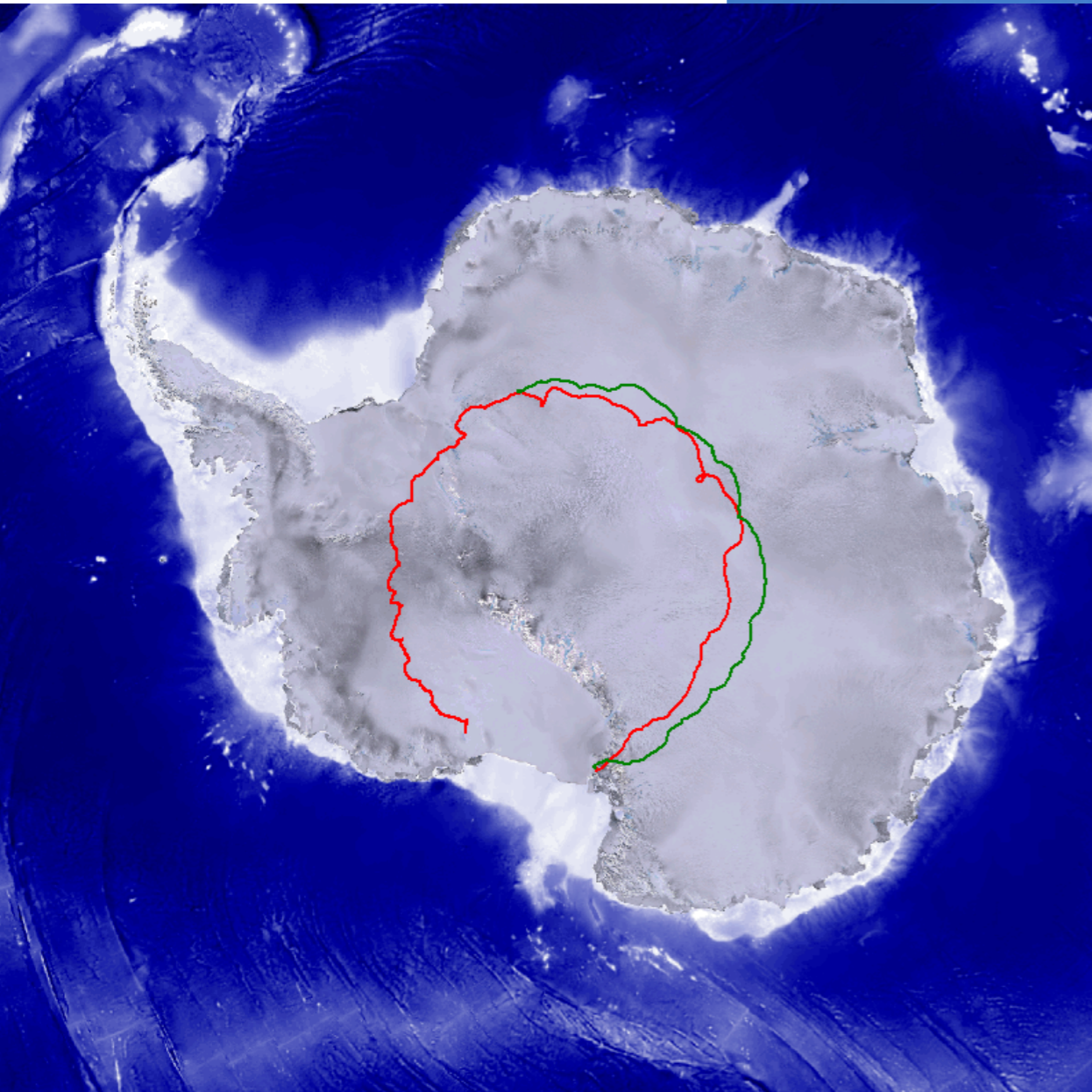
# Back up



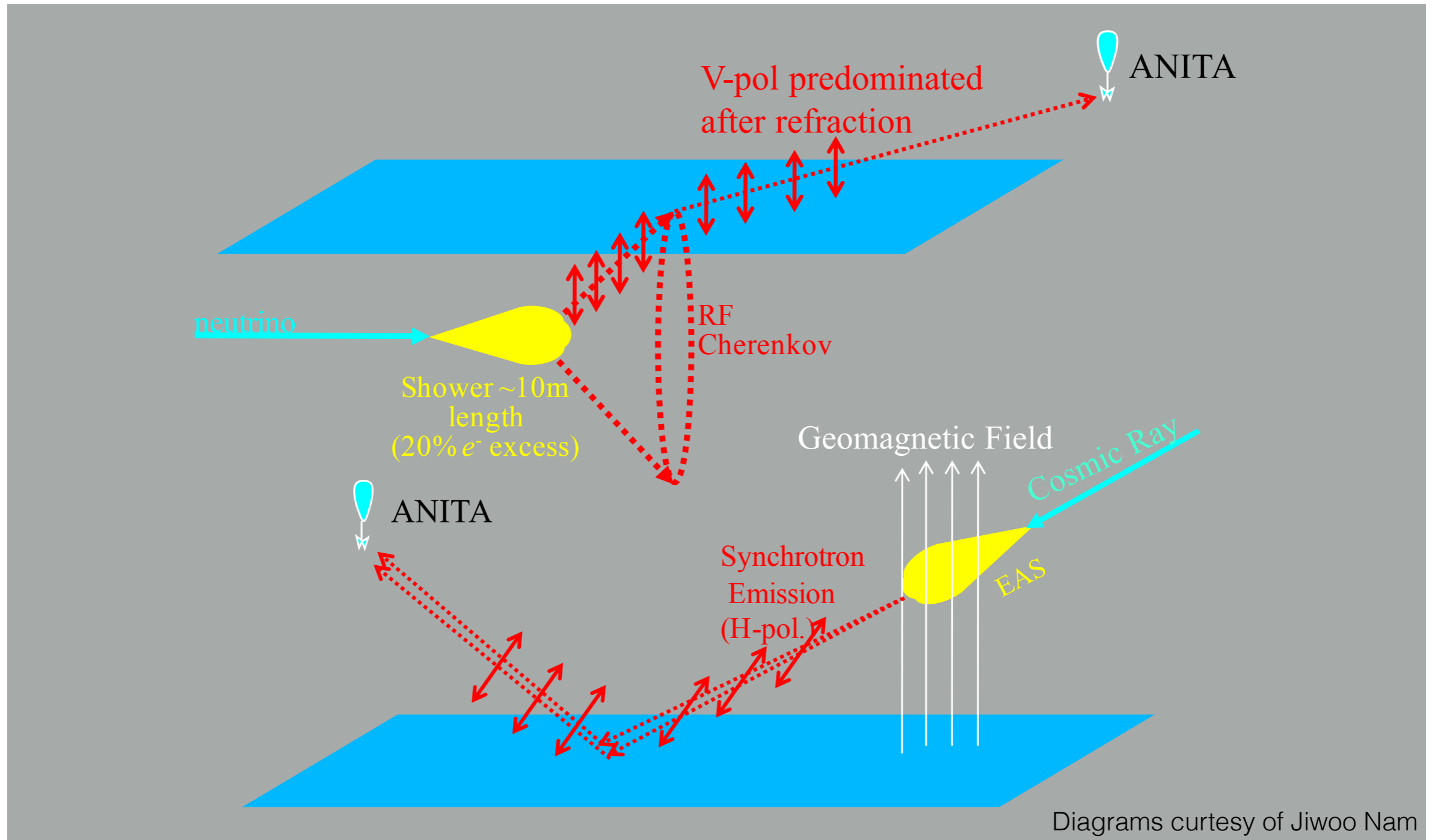
# HiCal

Two calibration payloads (HiCals) launched on ANITA's second pass:

- Periodic calibration pulse
- Use direct and reflected pulse to characterise ice surface and roughness
- HiCal 1 (ANITA-3) results: [arXiv:1703.00415](https://arxiv.org/abs/1703.00415) [astro-ph.IM]



# Neutrinos and Cosmic Rays





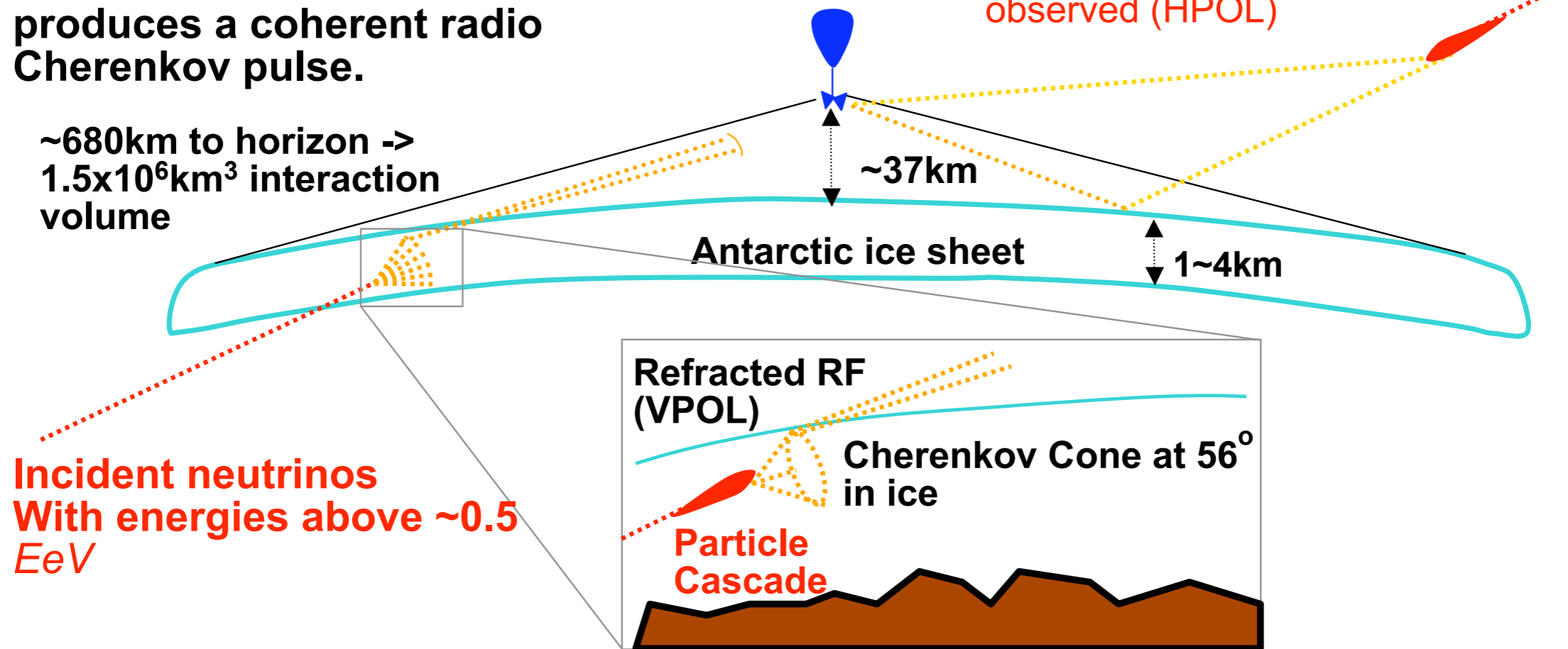
# ANITA

## ANtarctic Impulsive Transient Antenna

A neutrino induced cascade produces a coherent radio Cherenkov pulse.

~680km to horizon ->  
 $1.5 \times 10^6 \text{ km}^3$  interaction volume

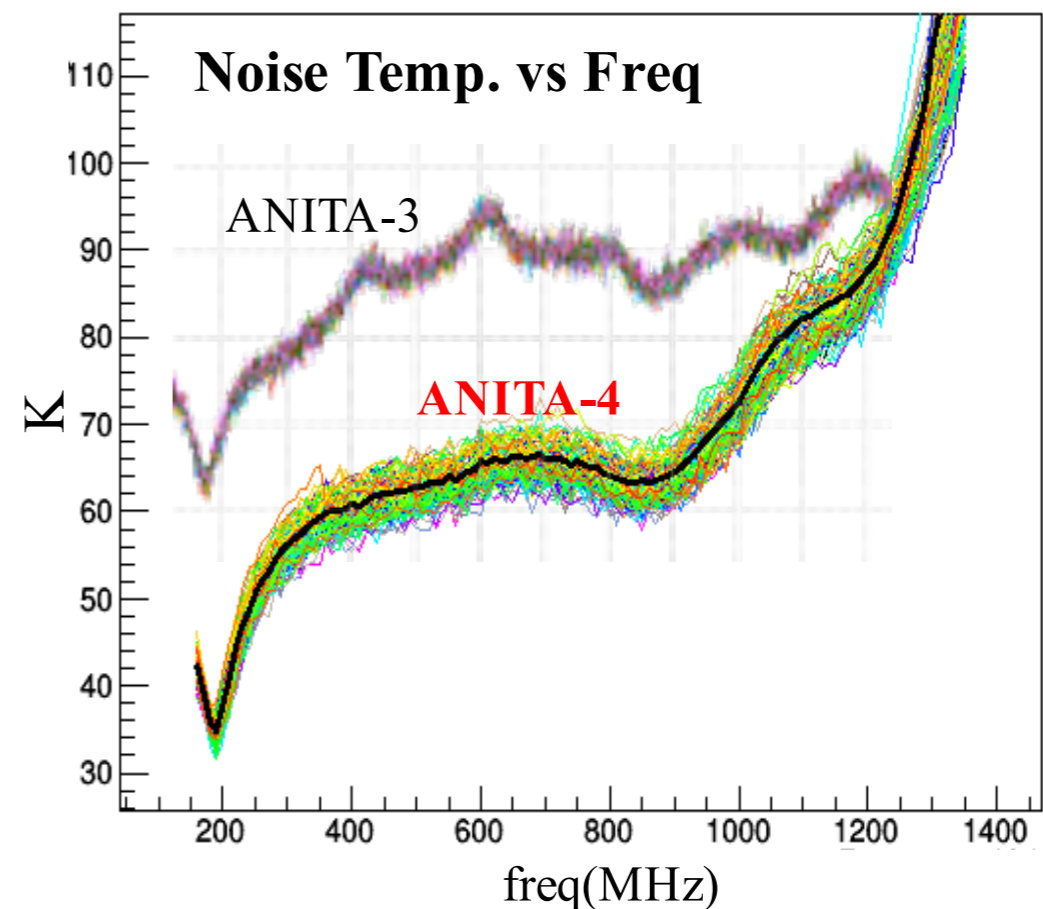
Cosmic ray geo-synchrotron also observed (HPOL)



Incident neutrinos  
With energies above ~0.5  
 $E_{\text{eV}}$

# ANITA-4 improvements

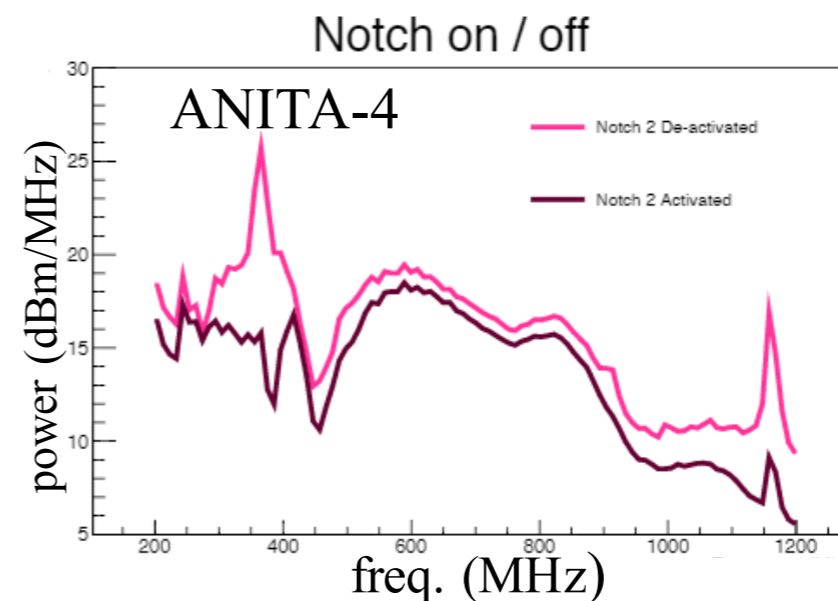
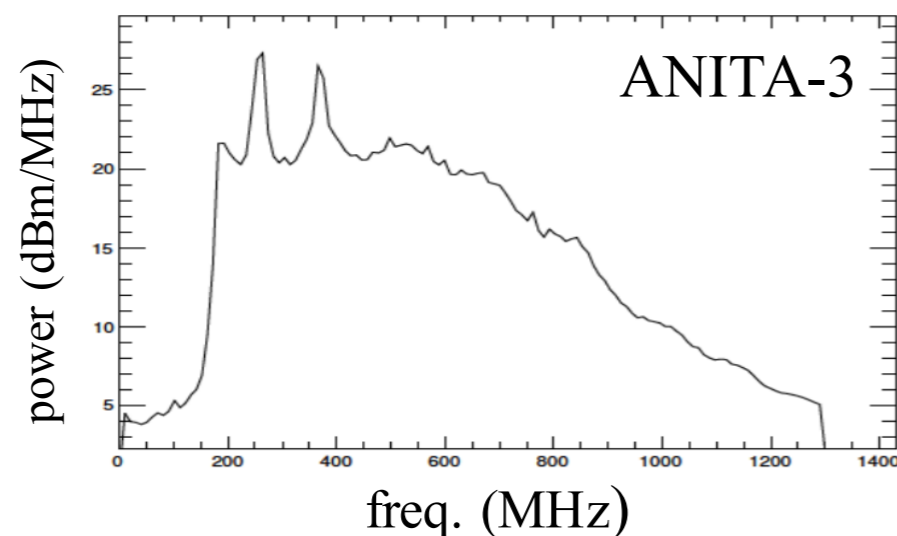
- Using Low Noise Amplifiers for all channels
  - Improvement in noise figure (30-40K)
  - 20% improvement in energy threshold





# ANITA-4 improvements

- Using Low Noise Amplifiers for all channels
  - Improvement in noise figure (30-40K)
  - 20% improvement in energy threshold
- Tunable Universal Filter Frontend
  - Reduce Carrier Waves noise coming from Satellites



# ANITA-4 improvements

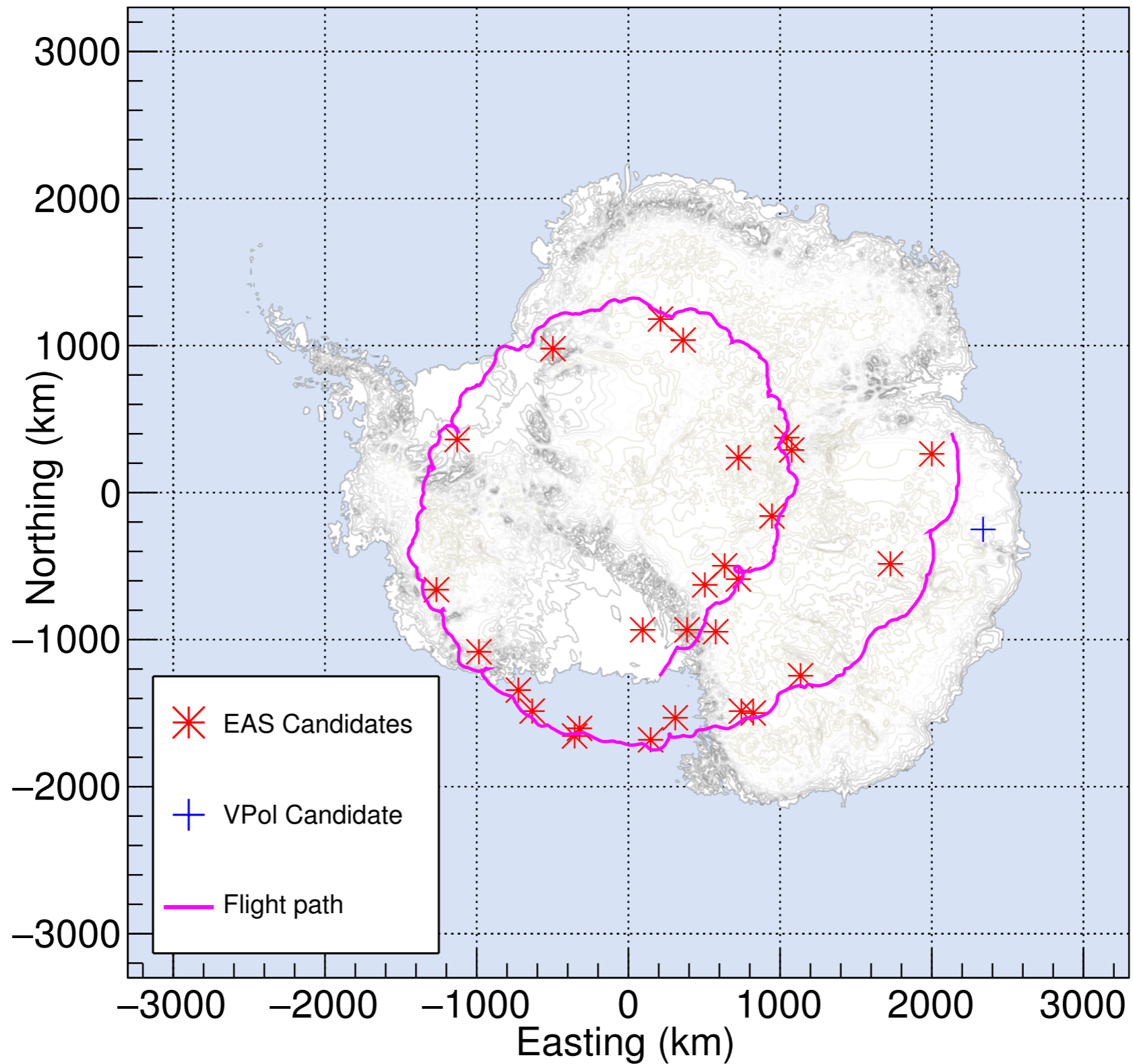
- Using Low Noise Amplifiers for all channels
  - Improvement in noise figure (30-40K)
  - 20% improvement in energy threshold
- Tunable Universal Filter Frontend
  - Reduce Carrier Waves noise coming from Satellites
- Trigger on Left and Right Circular Polarisation coincidences
  - Satellite noise predominantly circularly polarised (either LCP or RCP) → 2.5 improvement in acceptance



# ANITA-3 efficiencies

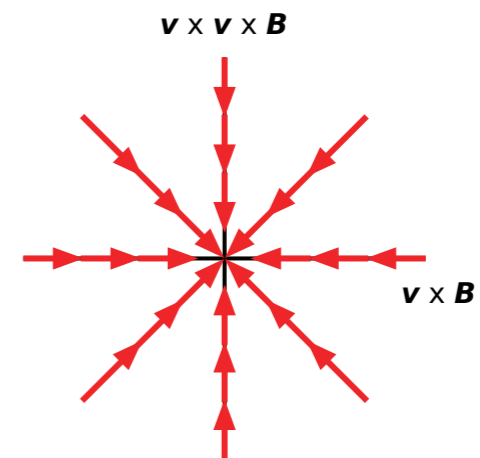
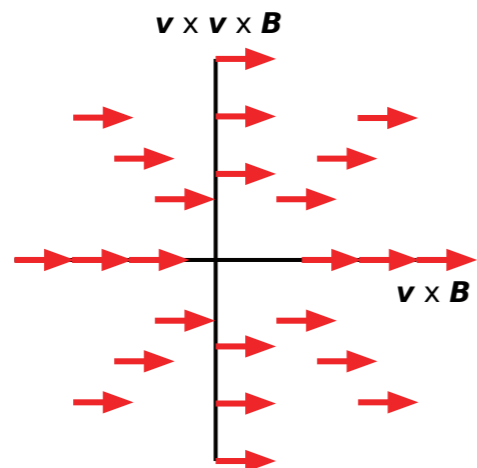
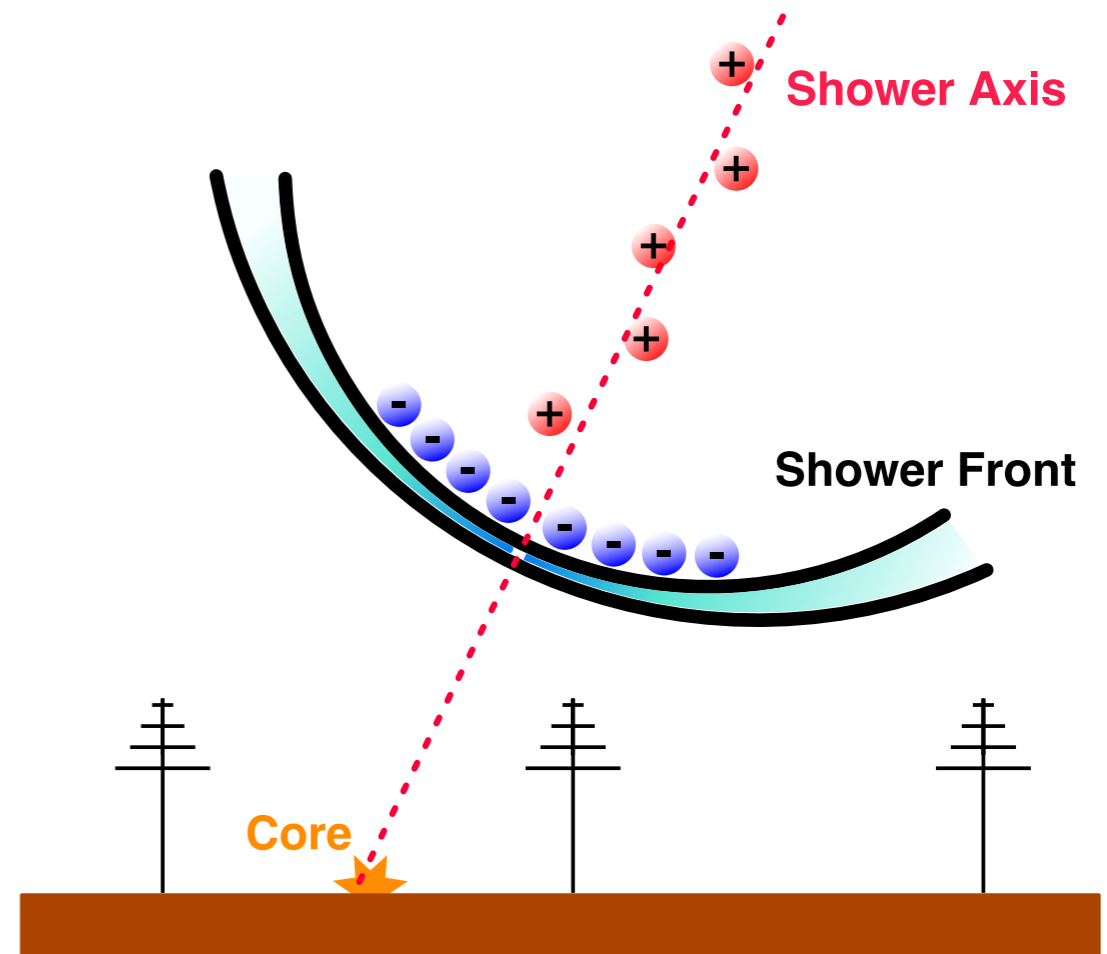
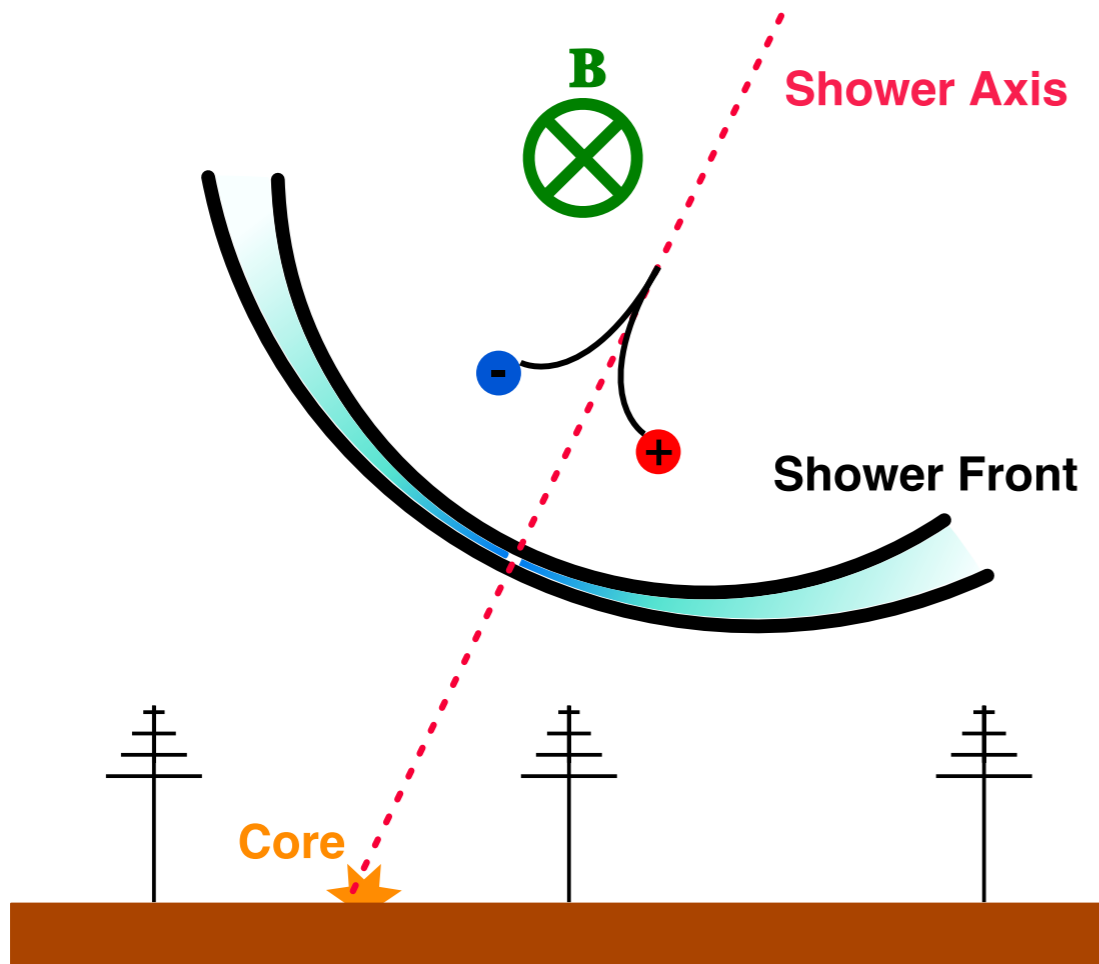
Cut	HPOL data	VPOL data	MC efficiency
None	36,700,502	38,274,132	1
Data quality	18,811,772	20,565,939	0.96
Blast	15,655,493	16,474,185	0.95
Thermal	311,795	169,824	0.88
Clustering	25	1	0.72

# Better map





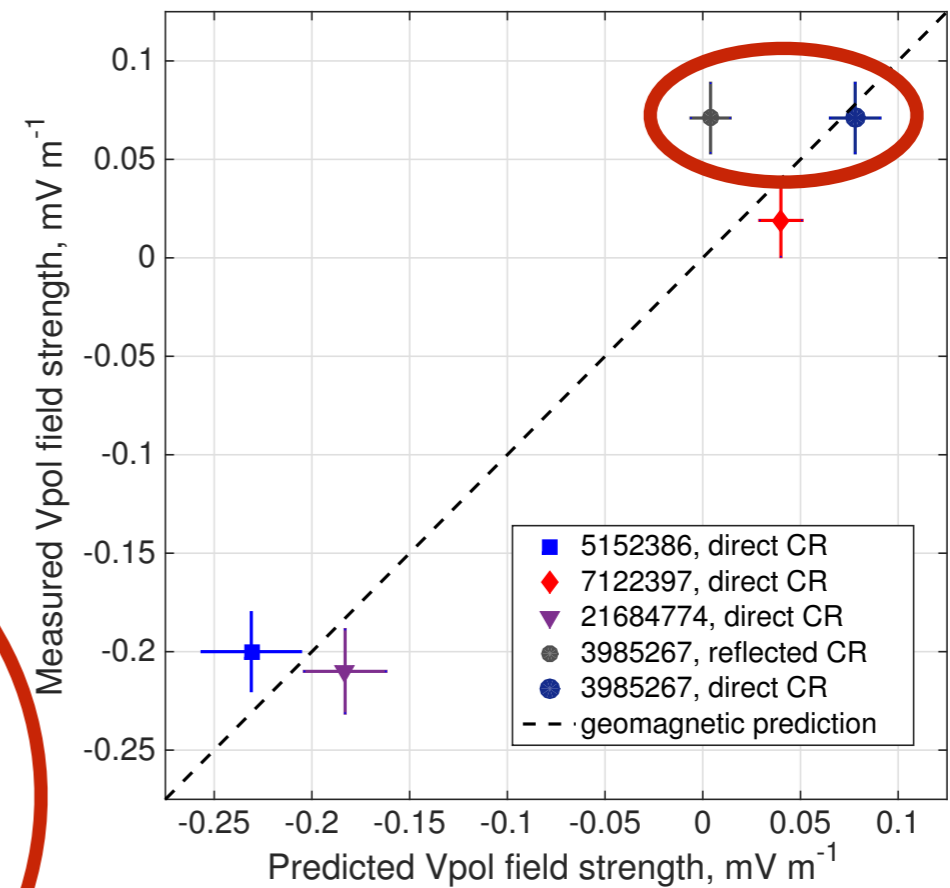
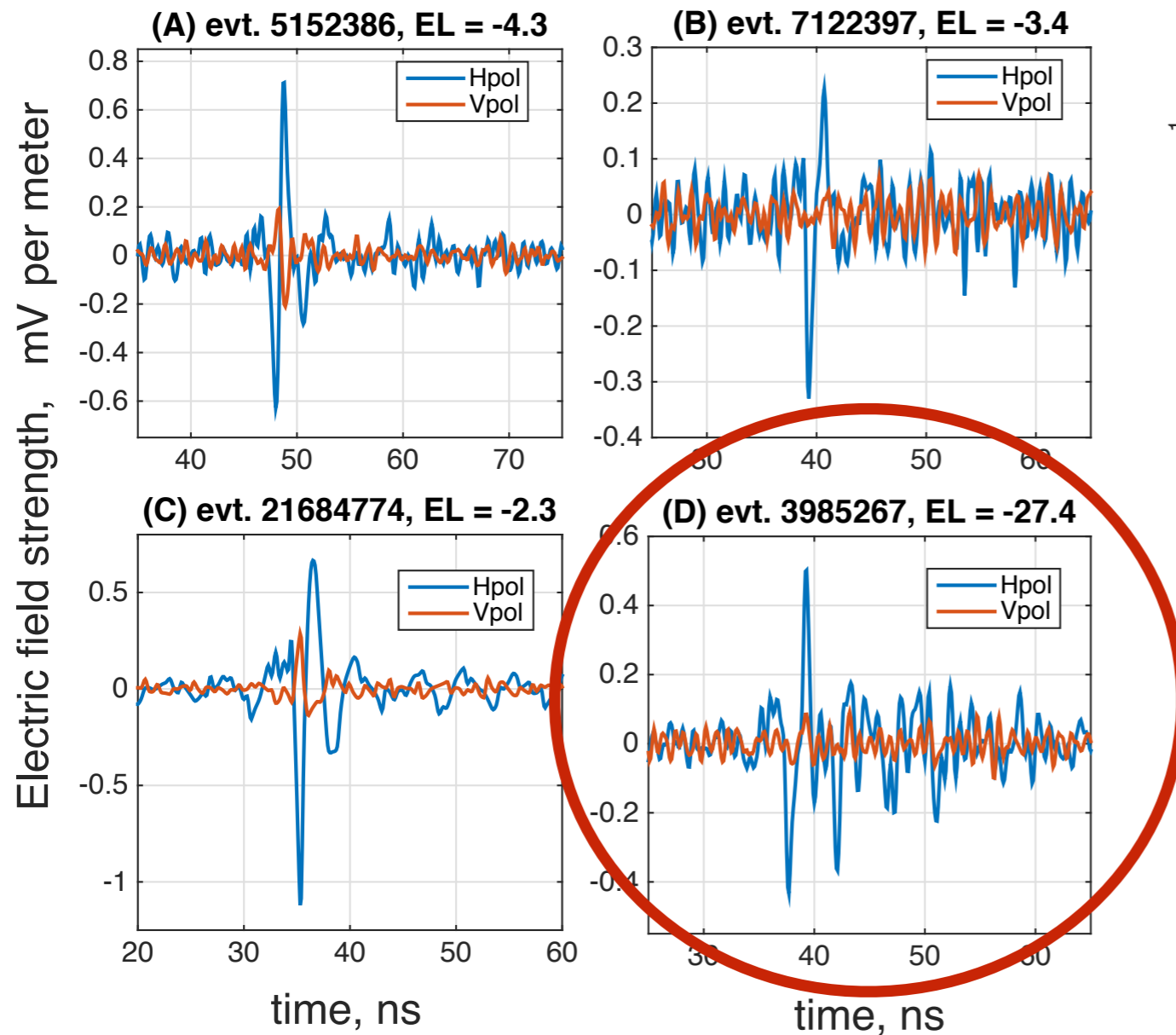
# UHECR



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# ANITA-1 mystery event



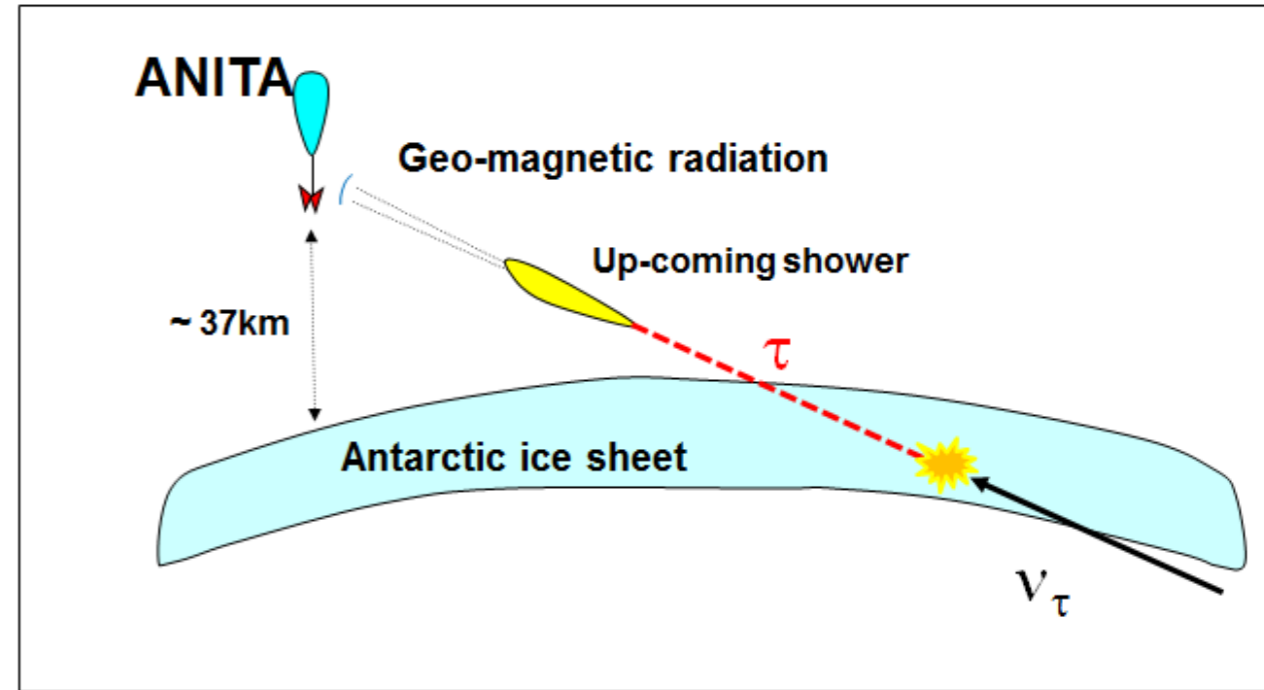
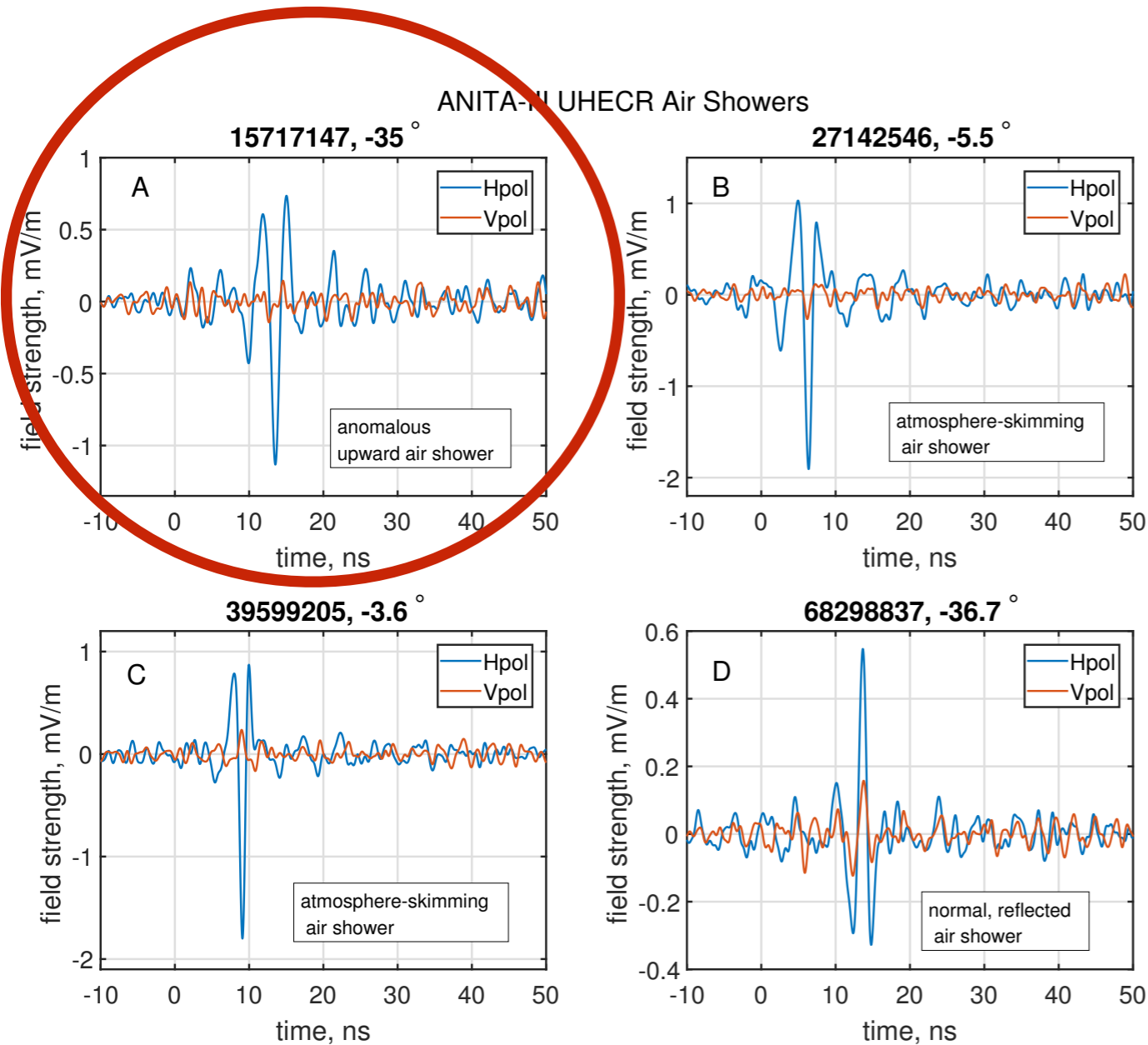
A strong H-pol non-inverted signal seen!

- Expected background events:  $4 \times 10^{-4}$
- 27.4 deg below horizon,  $E = 0.6 \pm 0.4$  EeV

Phys. Rev. Lett. 117, 071101 (2016)



# And ANITA-3 mystery event



event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon. <sup>(1)</sup>	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3^\circ, 159.62 \pm 0.7^\circ$	$-35.0 \pm 0.3^\circ, 61.41 \pm 0.7^\circ$
RA, Dec <sup>(2)</sup>	282.14064, +20.33043	50.78203, +38.65498
$E_{shower}^{(3)}$	$0.6 \pm 0.4$ EeV	$0.56^{+0.3}_{-0.2}$ EeV

Chord length: 5500-7000 km (20-30,000km water equivalent)  
 1600km SM interaction length @ 1 EeV

Background estimate  $< 10^{-2}$