Hunting UHE neutrinos with ANITA

Linda Cremonesi

Laboratoire Leprince-Ringuet Seminar
October 26th 2020

LEVERHULME TRUST

Aside

UK Research and Innovation

Dr Linda Cremonesi

Queen Mary University of London

Future Leaders Fellow

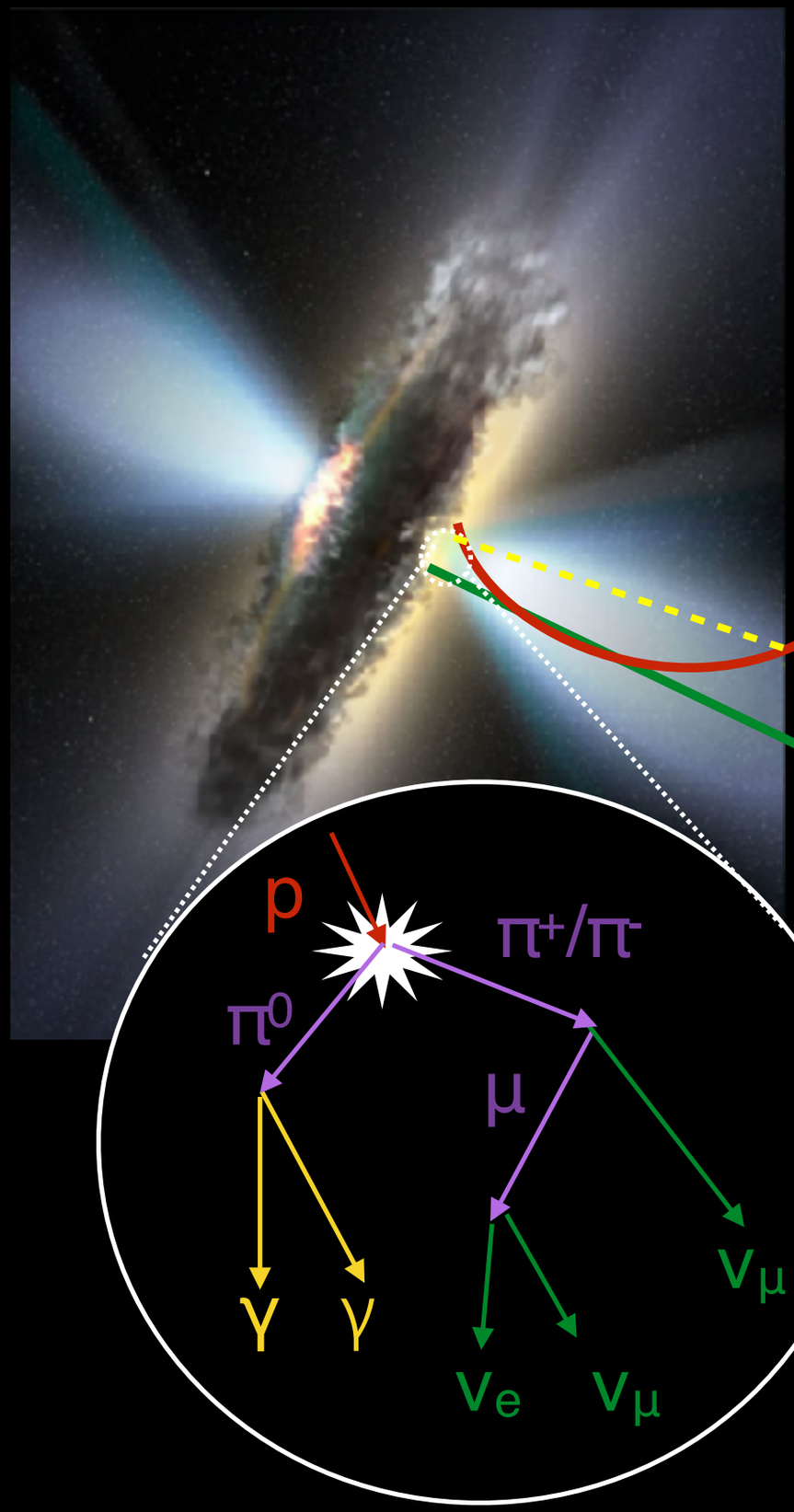
#UKRIFLF

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) and arXiv:2008.05690 [astro-ph.HE]
- Future

Motivations

Why Ultra High Energy neutrinos?



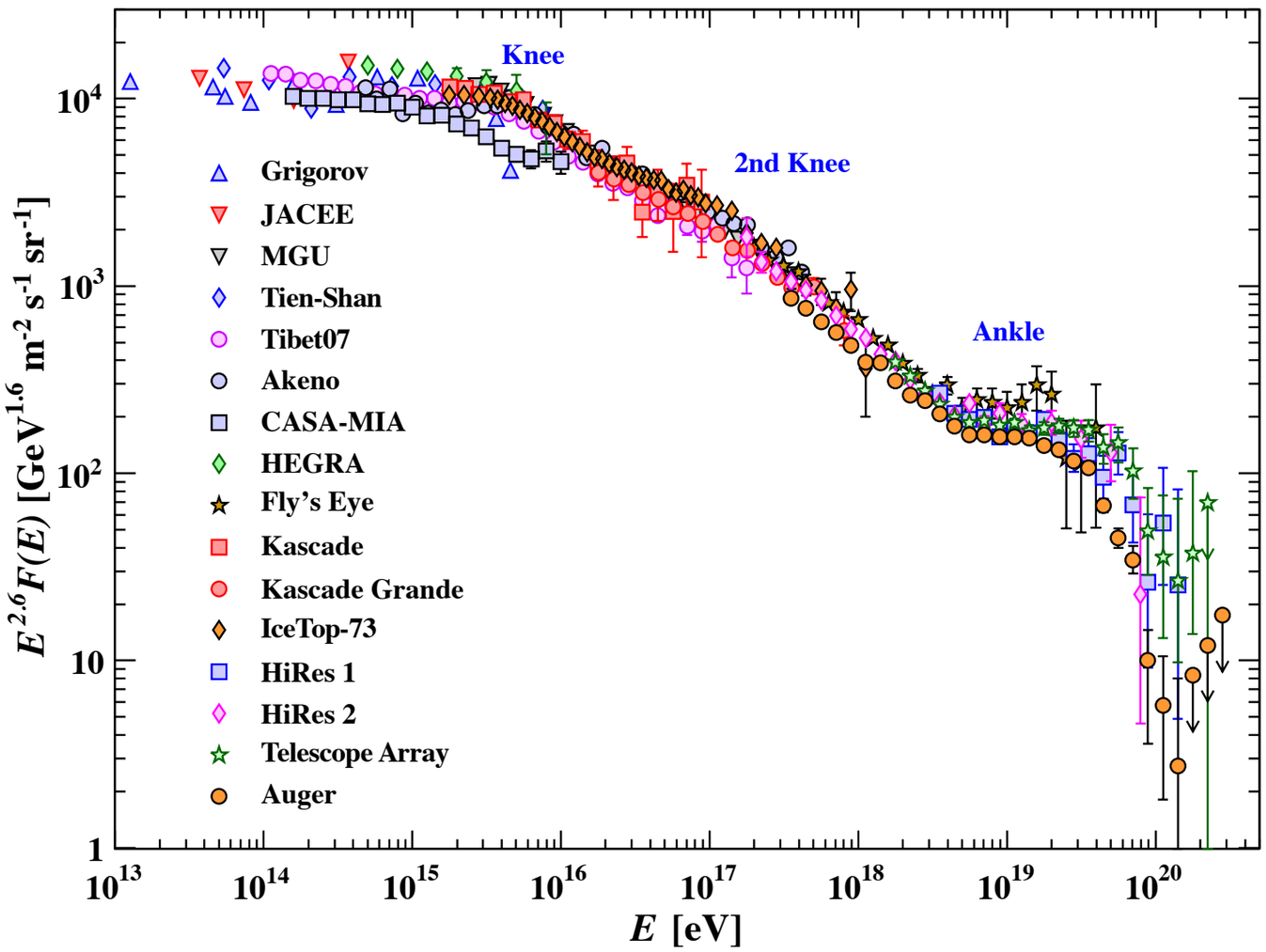
protons

photons

neutrinos

Cosmogenic neutrinos

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



ν from GZK

$$p(E > 10^{19.5} eV) + \gamma_{CMB} \rightarrow \Delta^+$$

$$\Delta^+ \rightarrow \pi^+ + n/\pi^0$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ + \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$$

ν from photo-disintagration

$$A + \gamma_{CMB} \rightarrow (A-1) + n$$

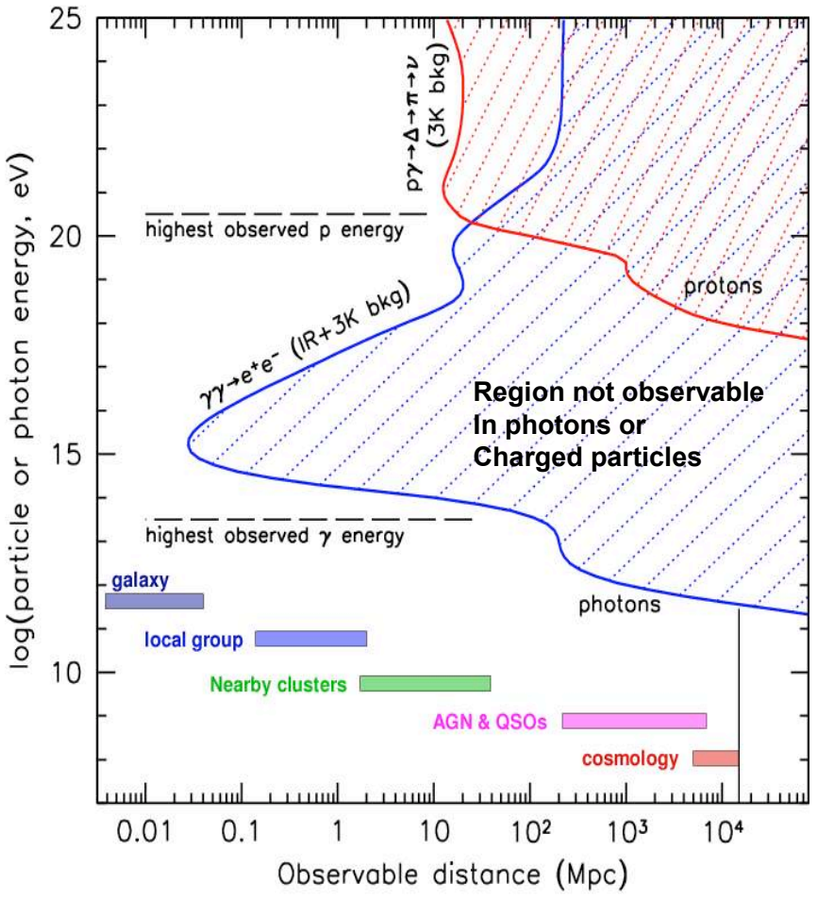
$$n \rightarrow p + e^- + \overline{\nu_e}$$

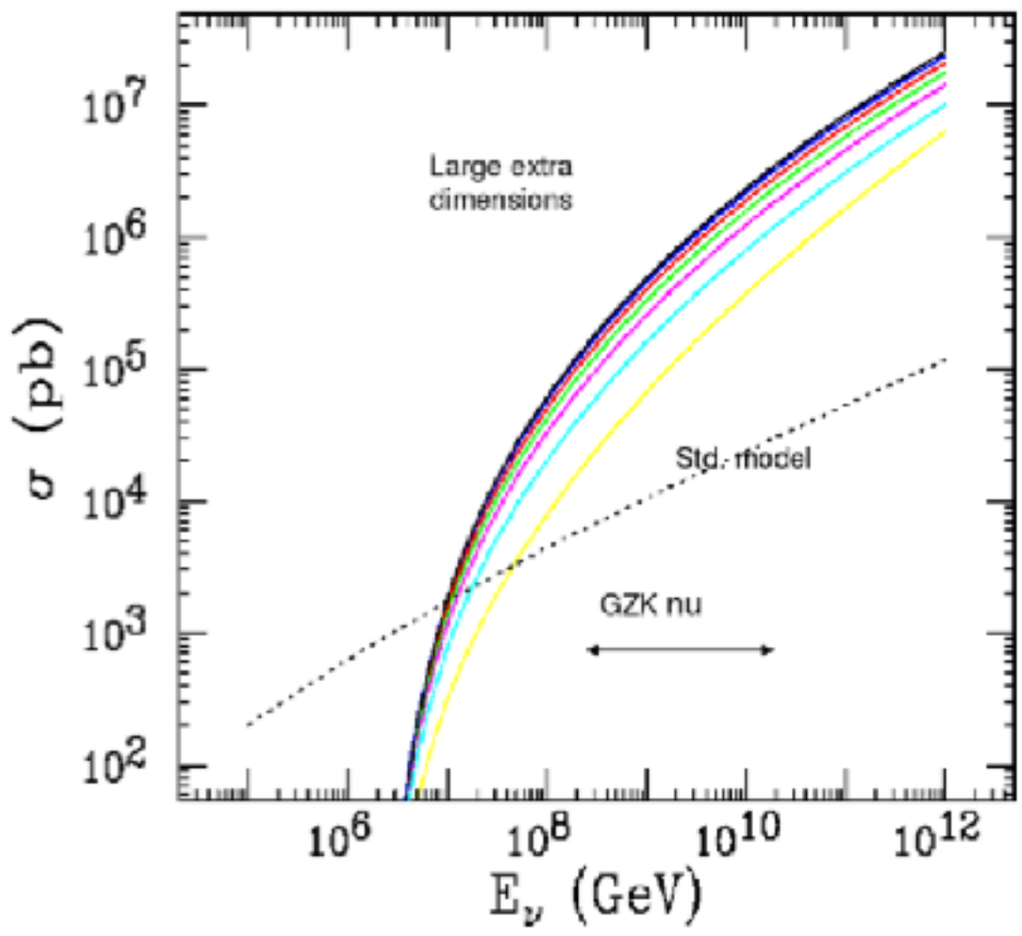
We know cosmic ray energy spectrum over 11 orders of magnitude.
Their sources (especially at the highest energies) are still mostly unknown

UHE (>E18 eV) neutrinos

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

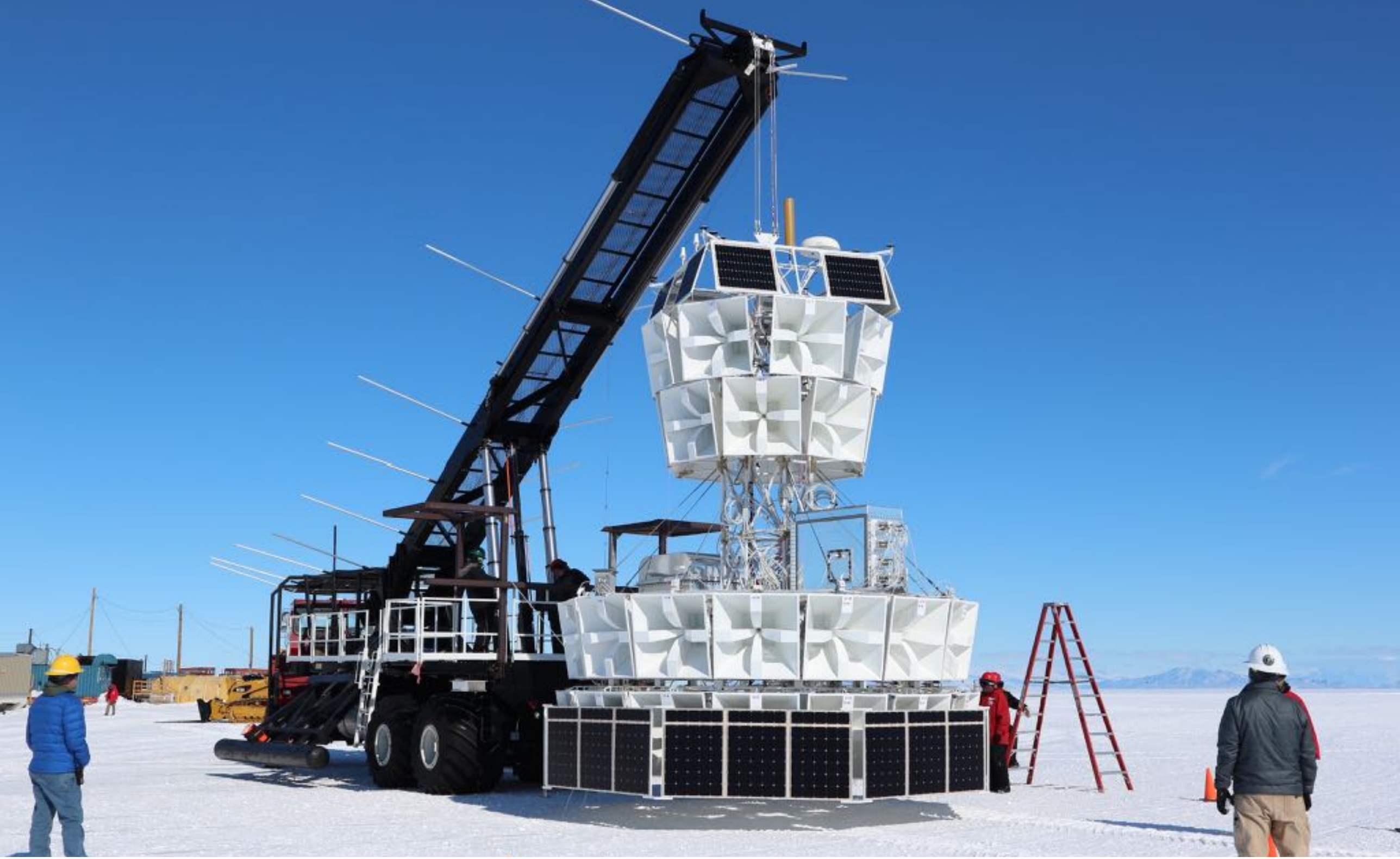
"WOW
300 TeV centre of mass energy!"





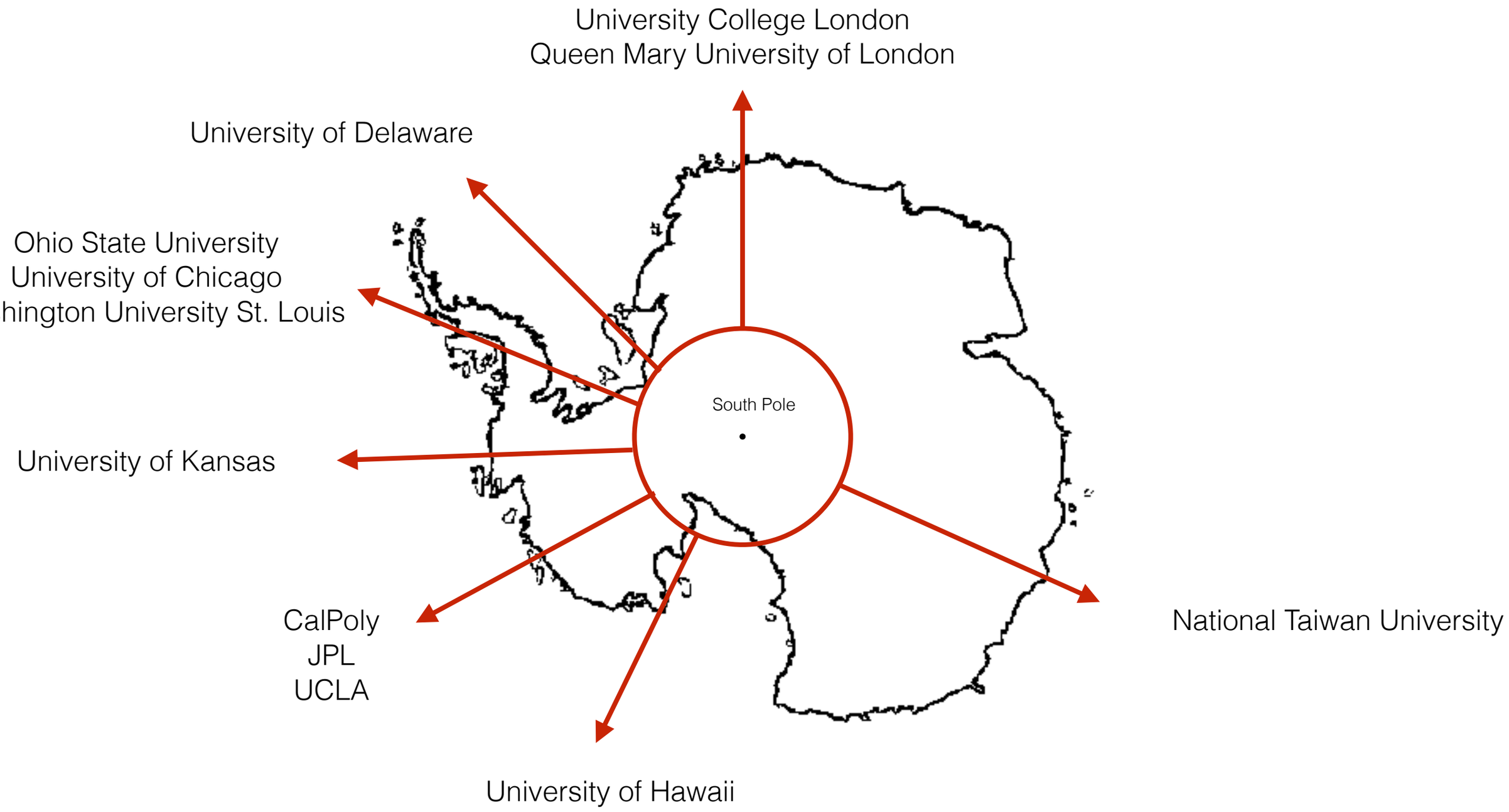
More motivations

- 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



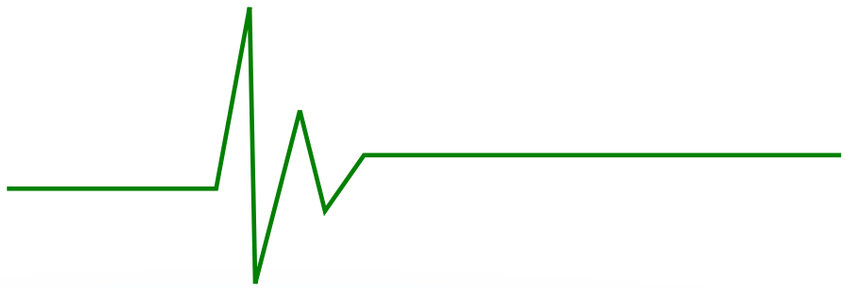
ANITA

ANITA collaboration



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

ANtarctic **I**mpulsive **T**ransient **A**ntenna



Not to scale, angles don't reflect reality

NEUTRINOS = VPOL

balloon

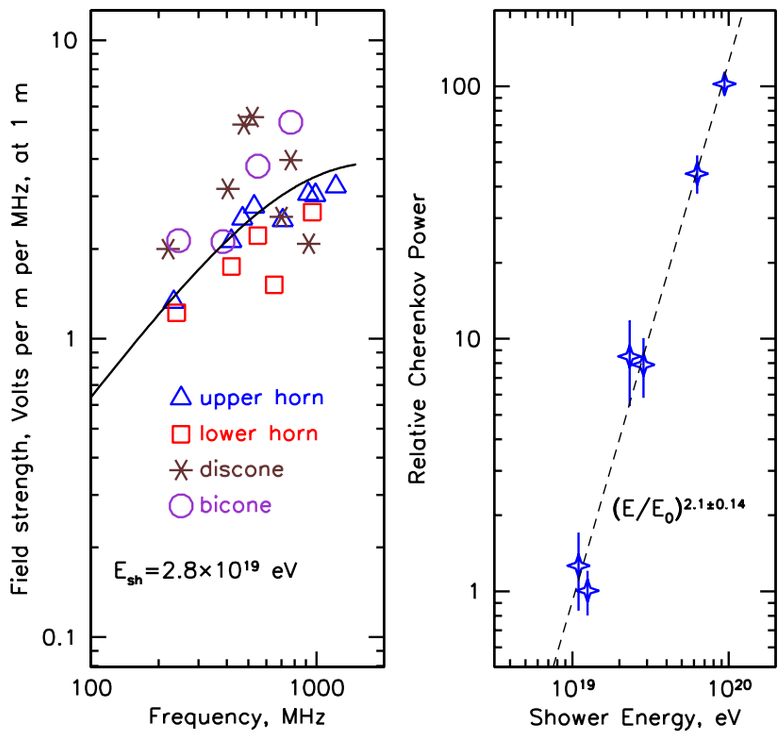
40km altitude

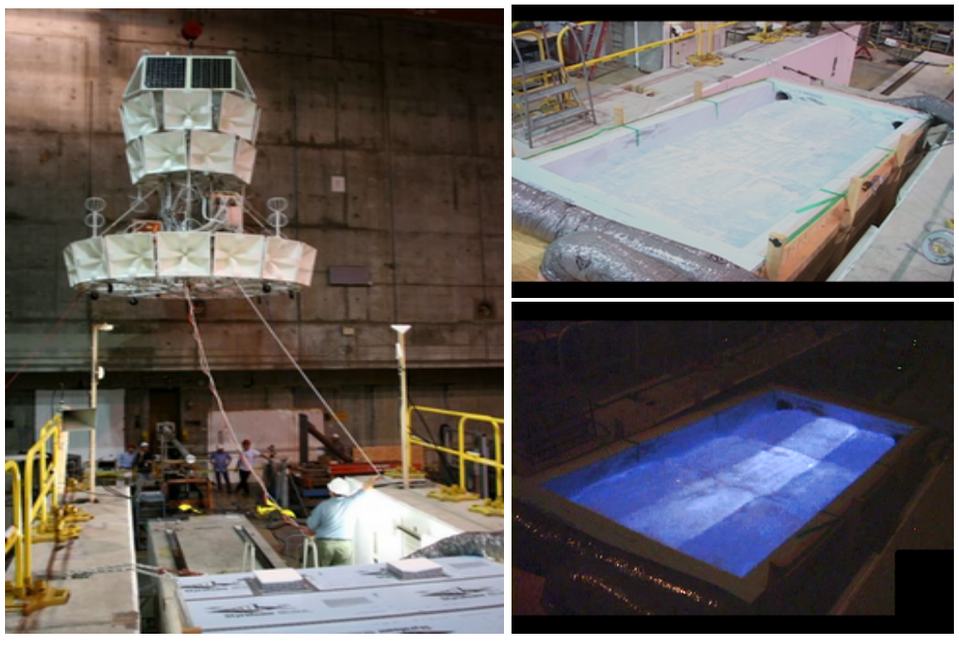
Ice

Askaryan emission

~EeV neutrino

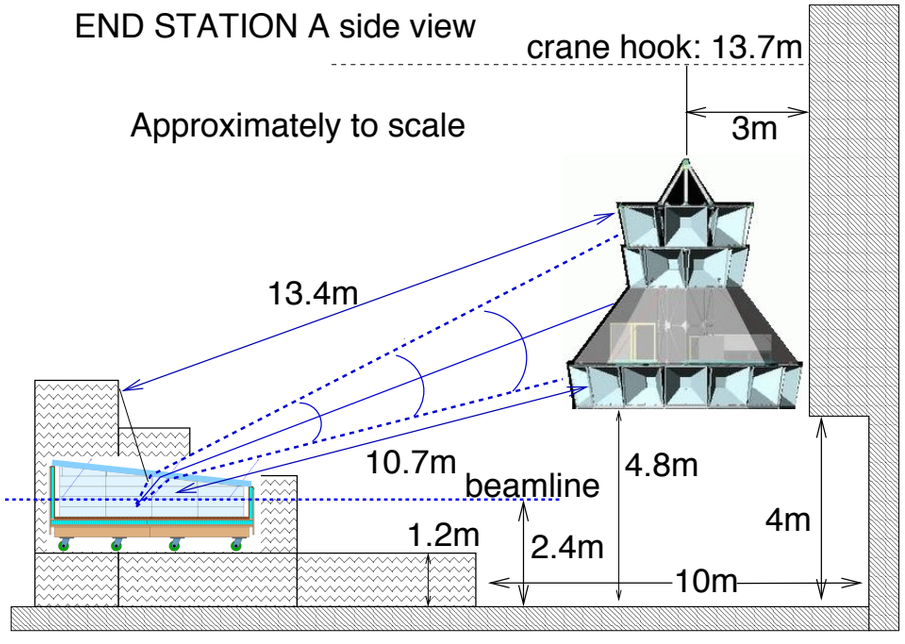
Askaryan radiation



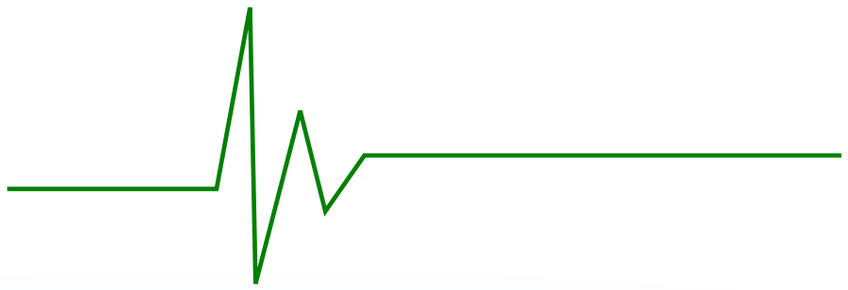


- Coherent radio emission from EM cascades in a dielectric!
- Measured at SLAC ESA in 2006 by ANITA collaboration
- Fired bunches of 10^9 electrons at 28.5 GeV into 7000 kg of ice

Phys.Rev.Lett.99:171101,2007



ANtarctic **I**mpulsive **T**ransient **A**ntenna



Not to scale, angles don't reflect reality

NEUTRINOS = VPOL

COSMIC RAYS = HPOL

balloon

direct UHECR

geomagnetic + Askaryan emission

reflected UHECR

geomagnetic + Askaryan emission

Ice

Askaryan emission

~EeV ν

ANITA instrument

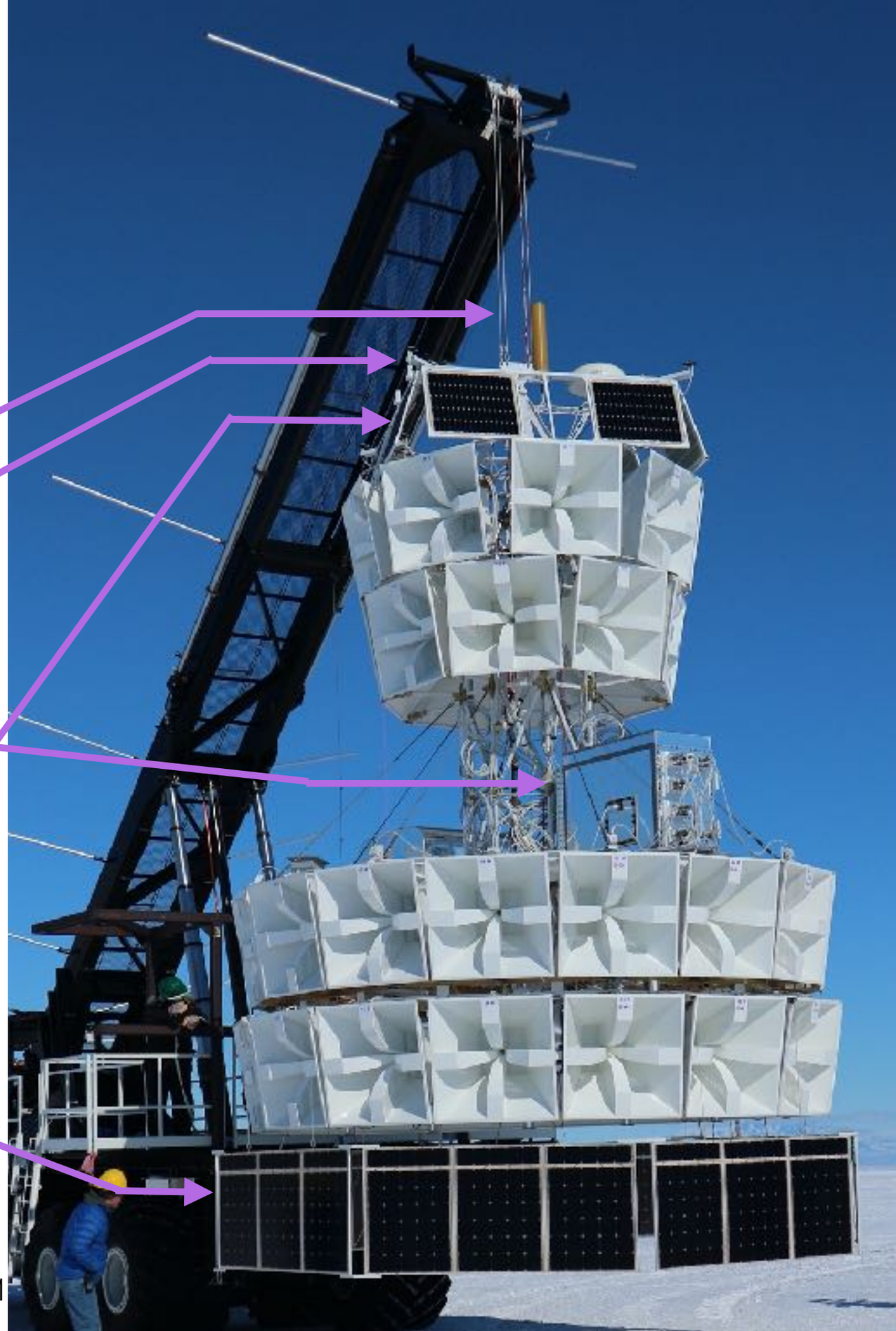
TDRSS & Iridium antennas

GPS antennas

Instrument box

48 quad-ridged horn antennas

Solar panels



ANITA instrument

TDRSS & Iridium antennas

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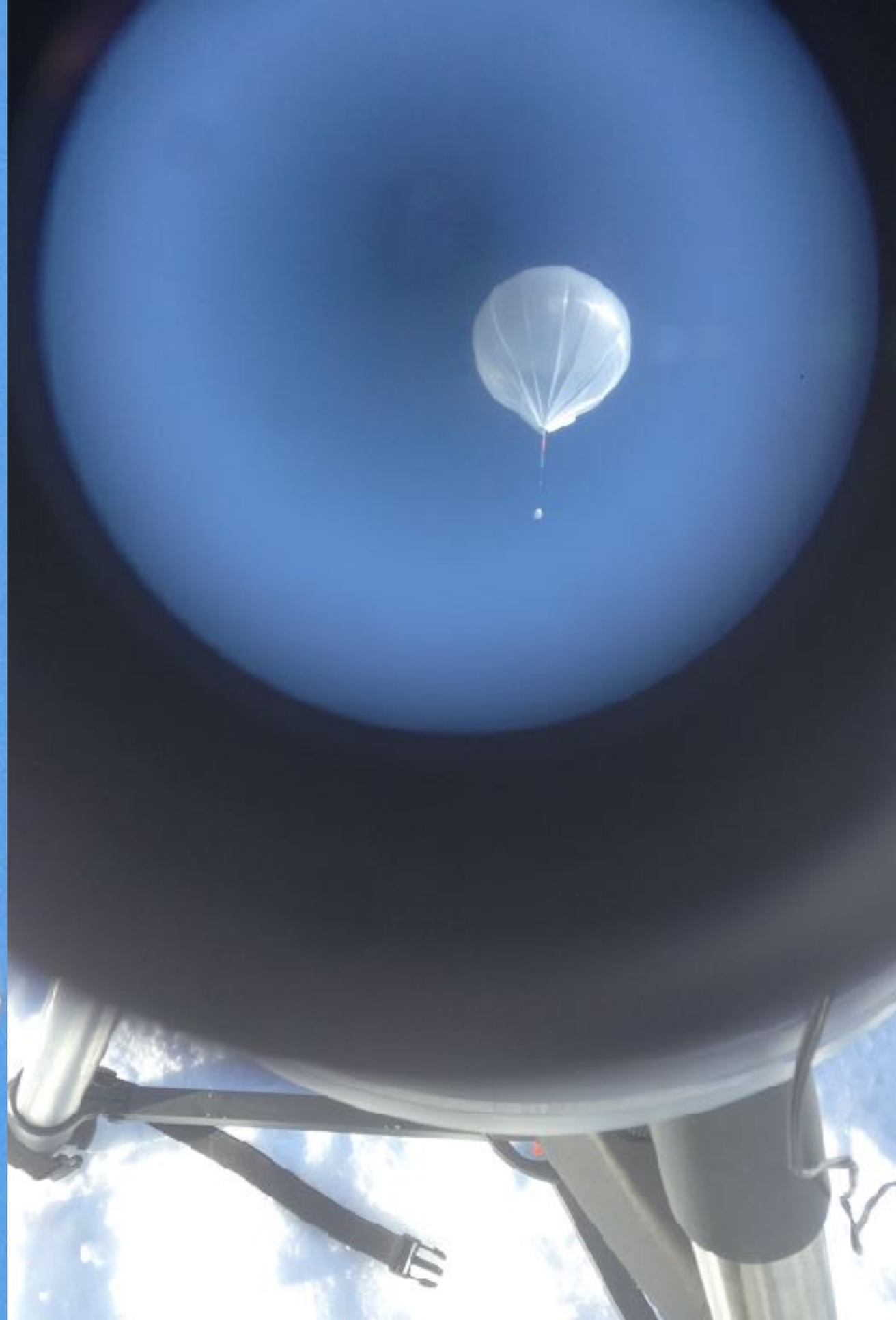
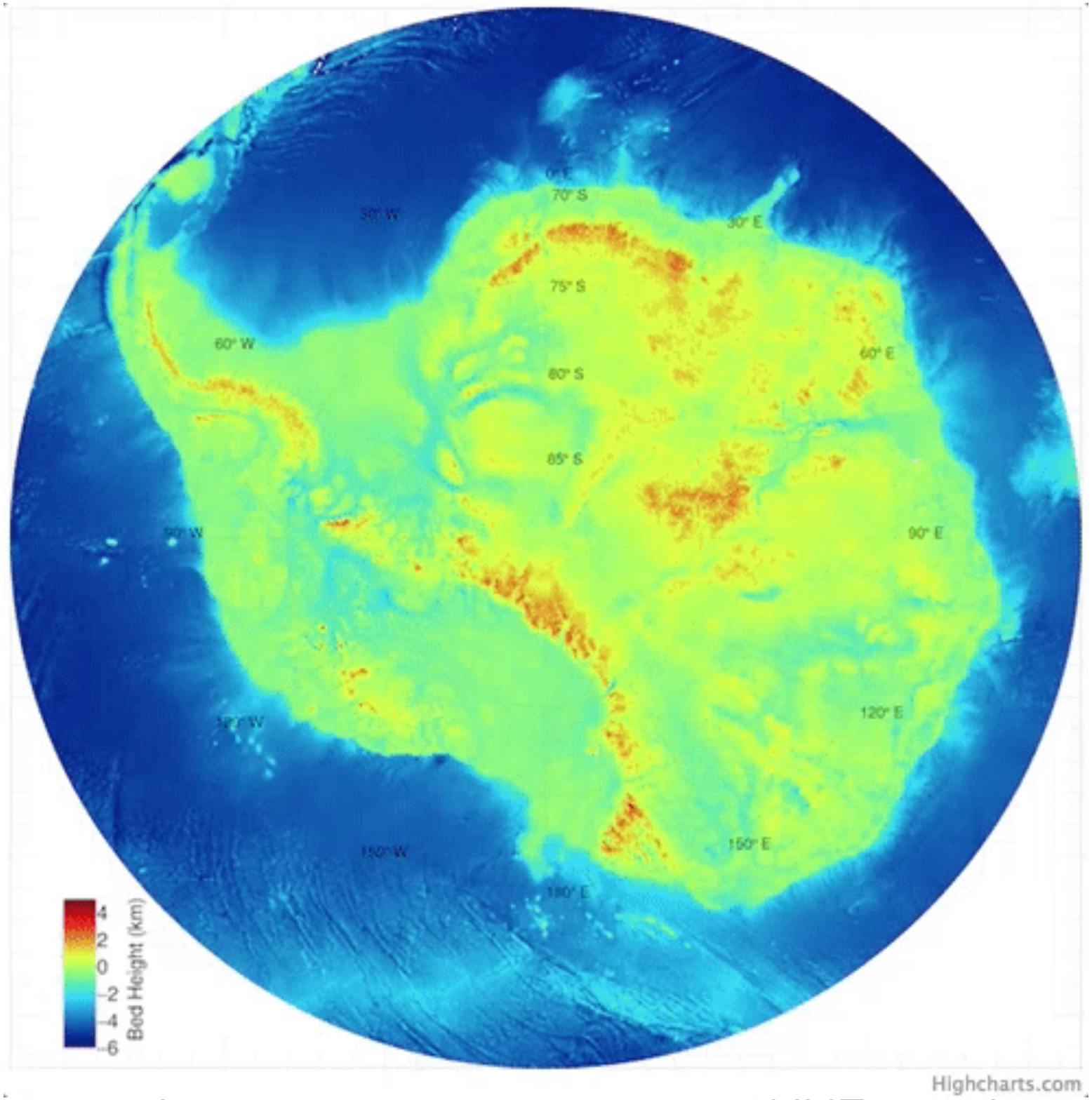
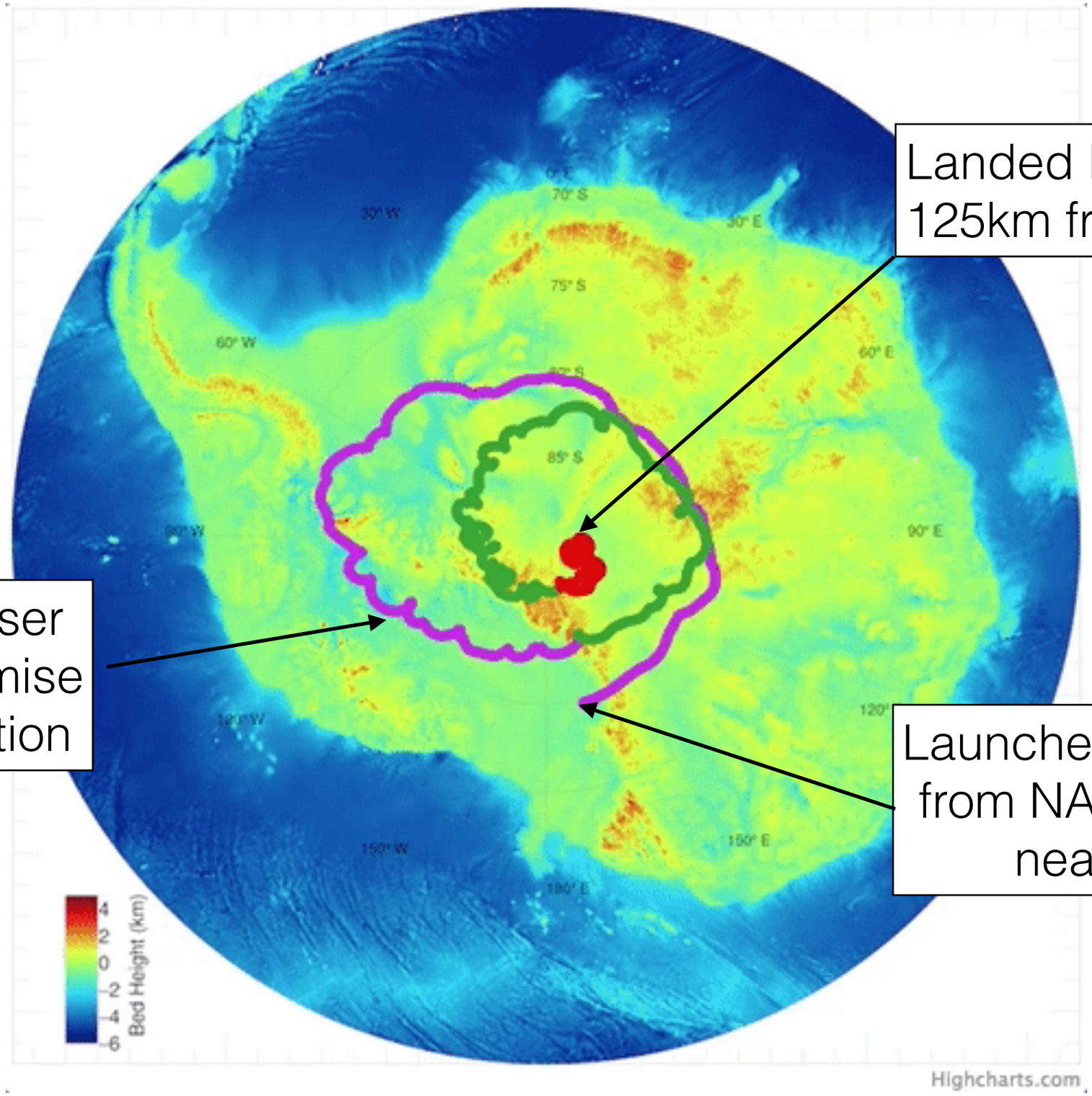


ANITA-4 flight path

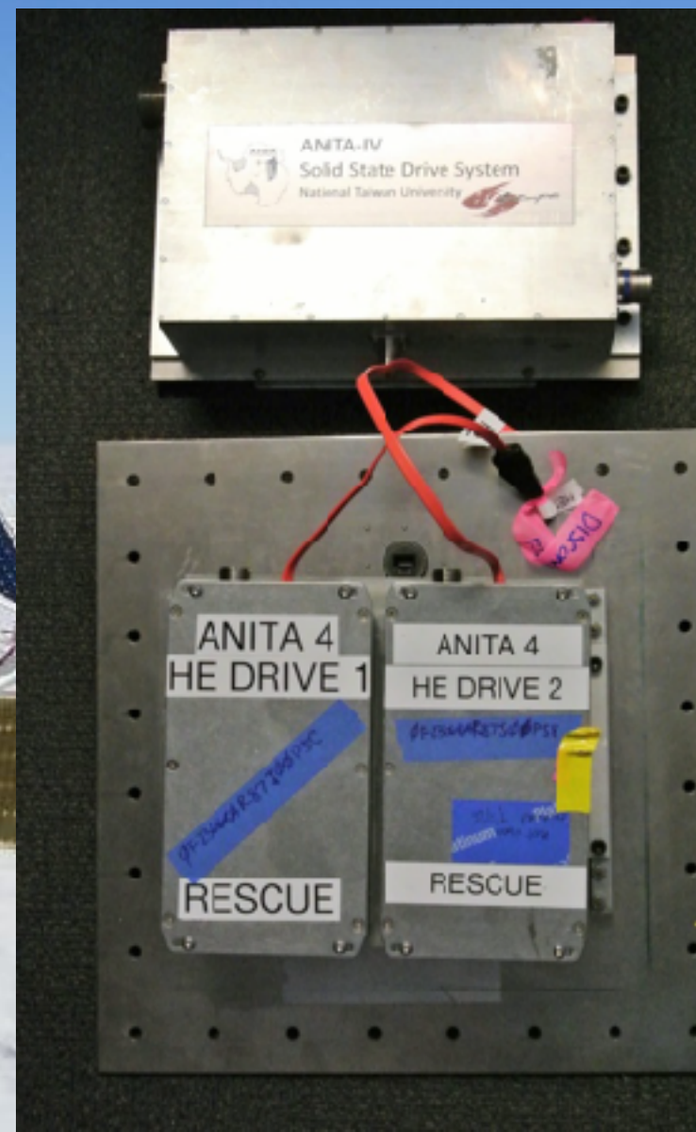


ANITA-4 flight path

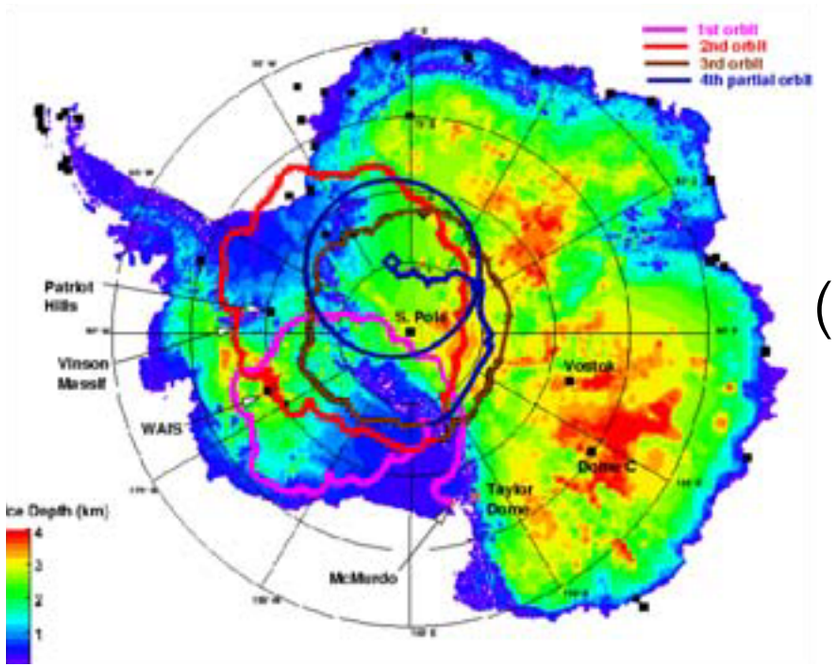


ANITA-4 Recovery

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

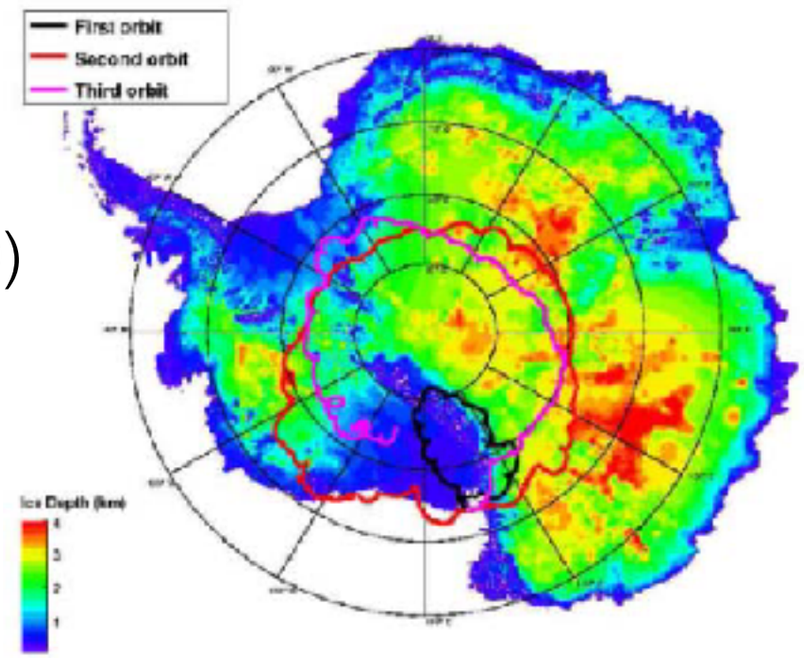


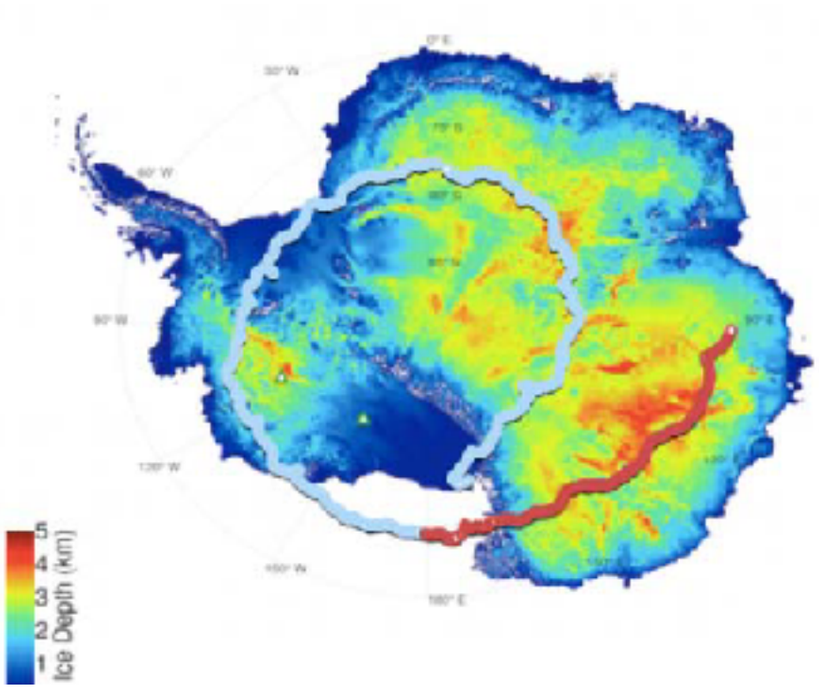
ANITA Flights



ANITA-1
(2006-2007)
35 days

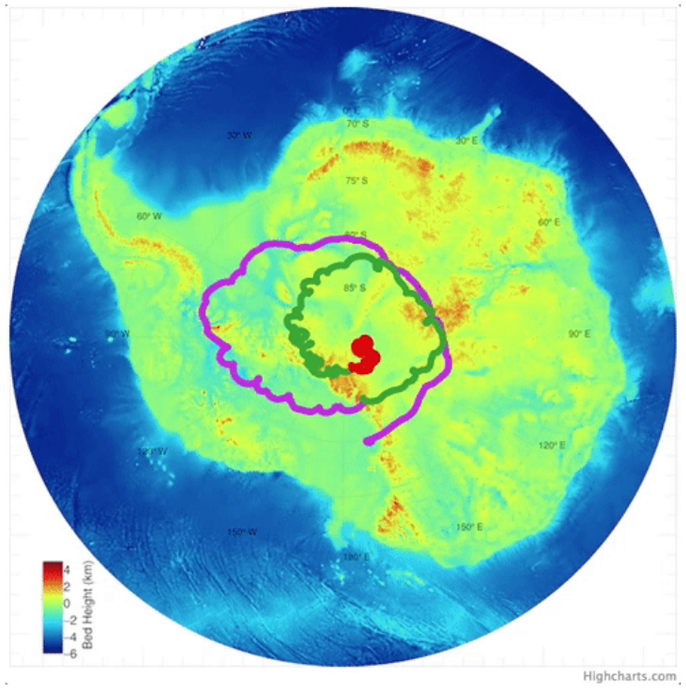
ANITA-2
(2008-2009)
30 days



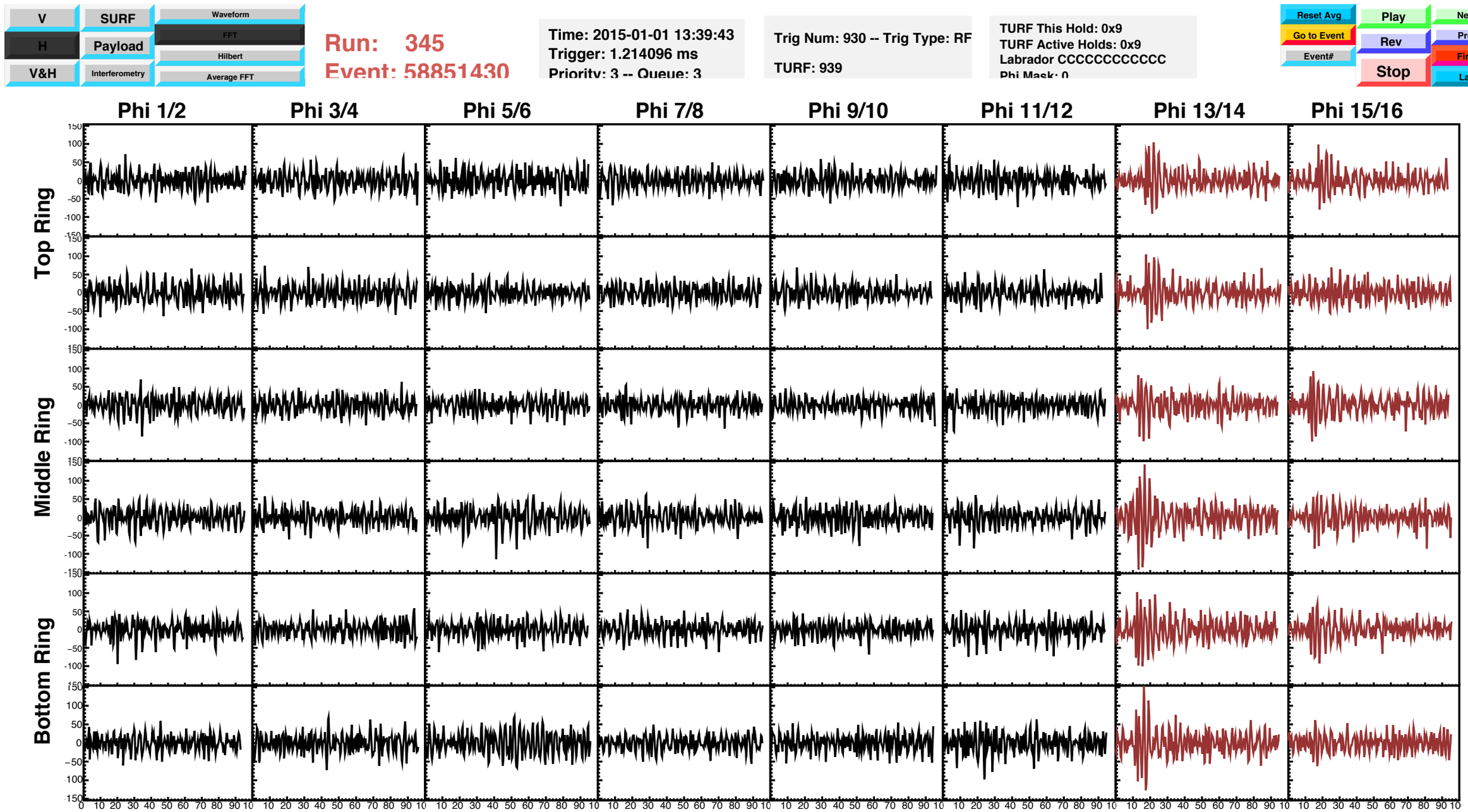


ANITA-3
(2014-2015)
22 days

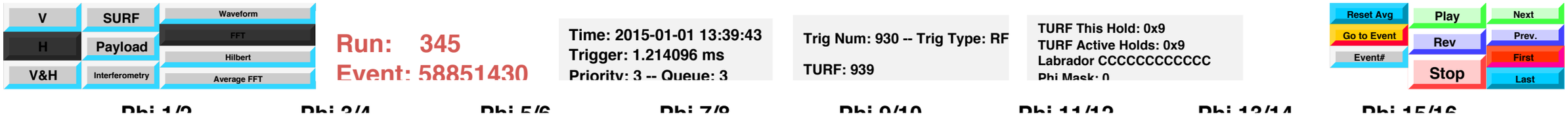
ANITA-4
(2016)
30 days



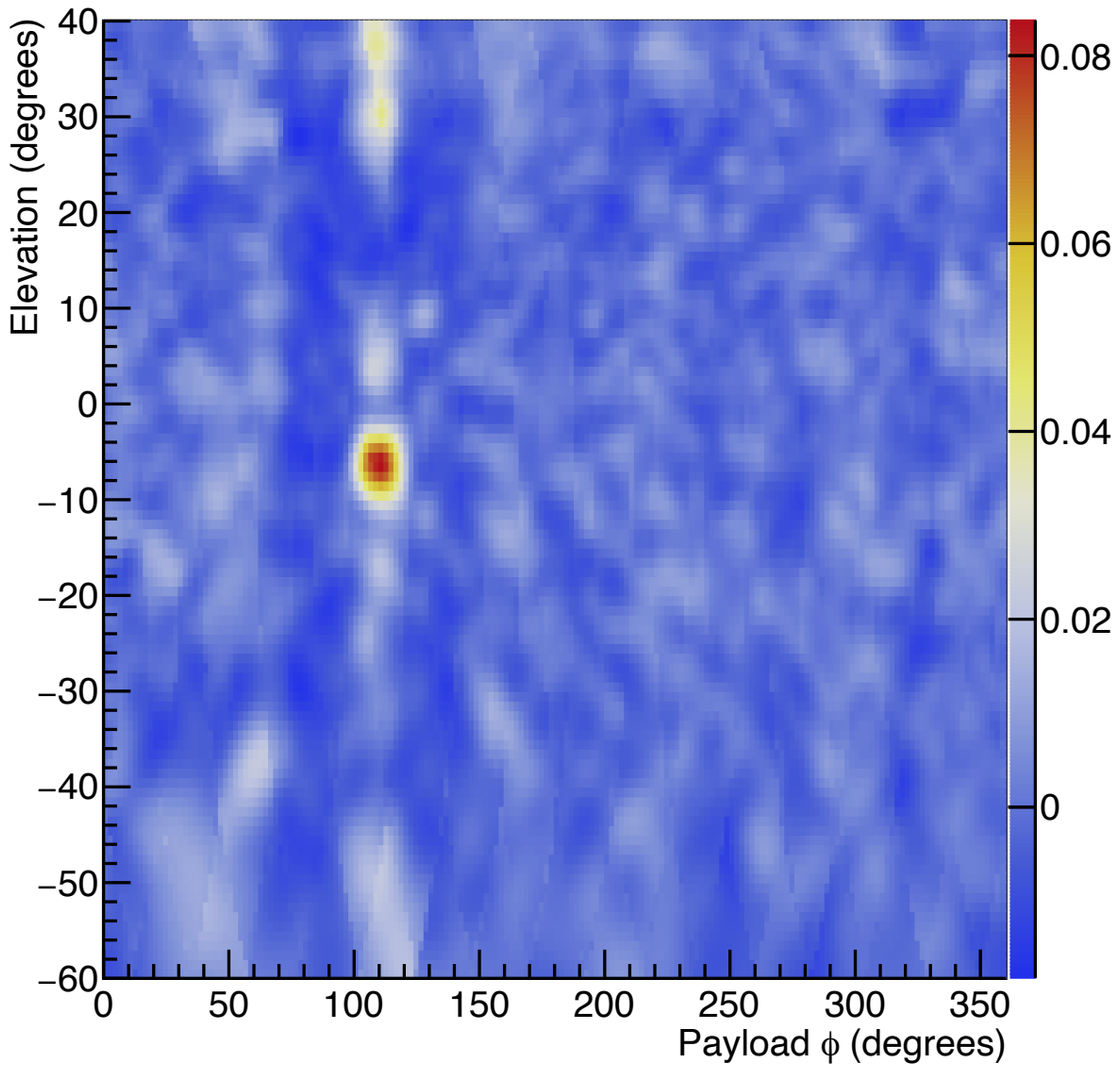
How ANITA sees the world



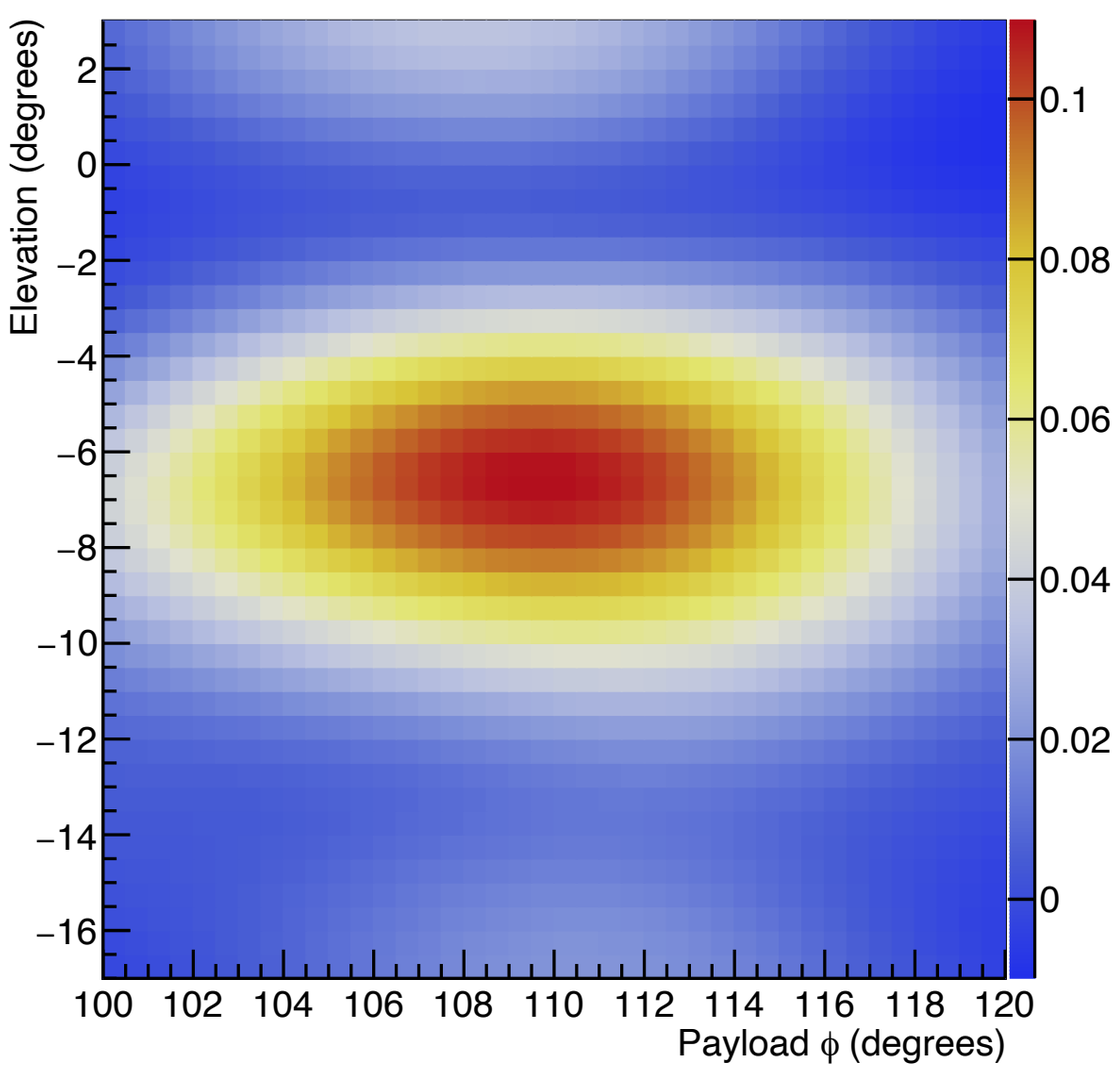
How ANITA sees the world



Interferometric Map



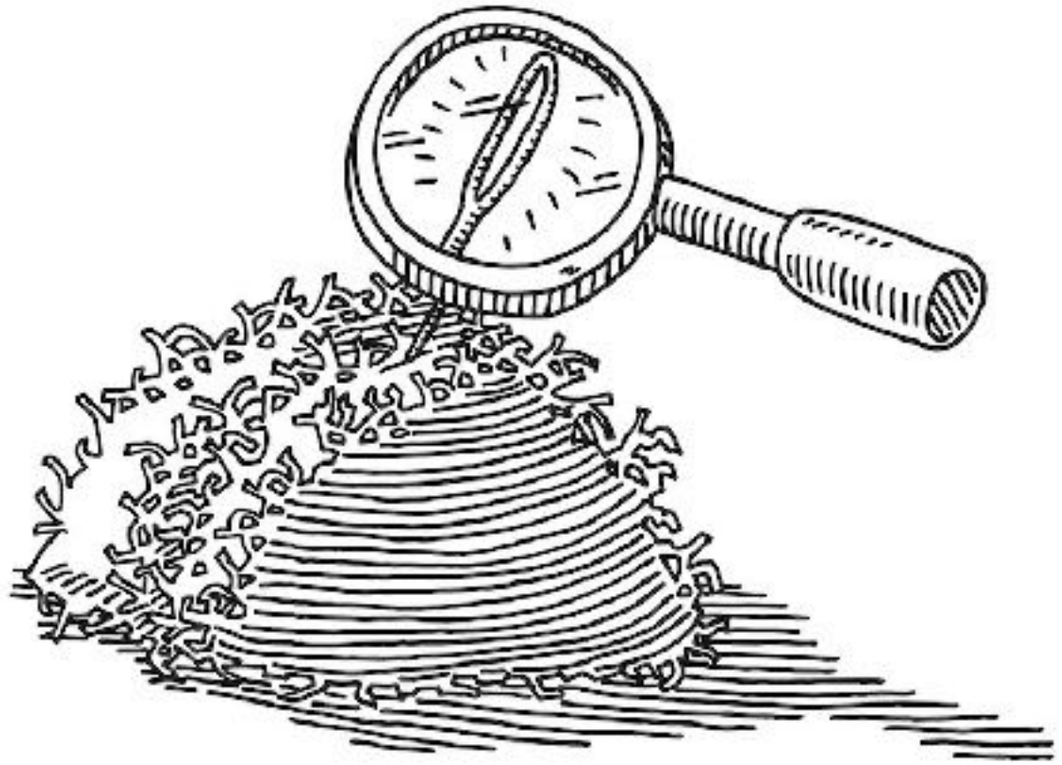
Zoomed Map



Needle(s) in a haystack

The challenge

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

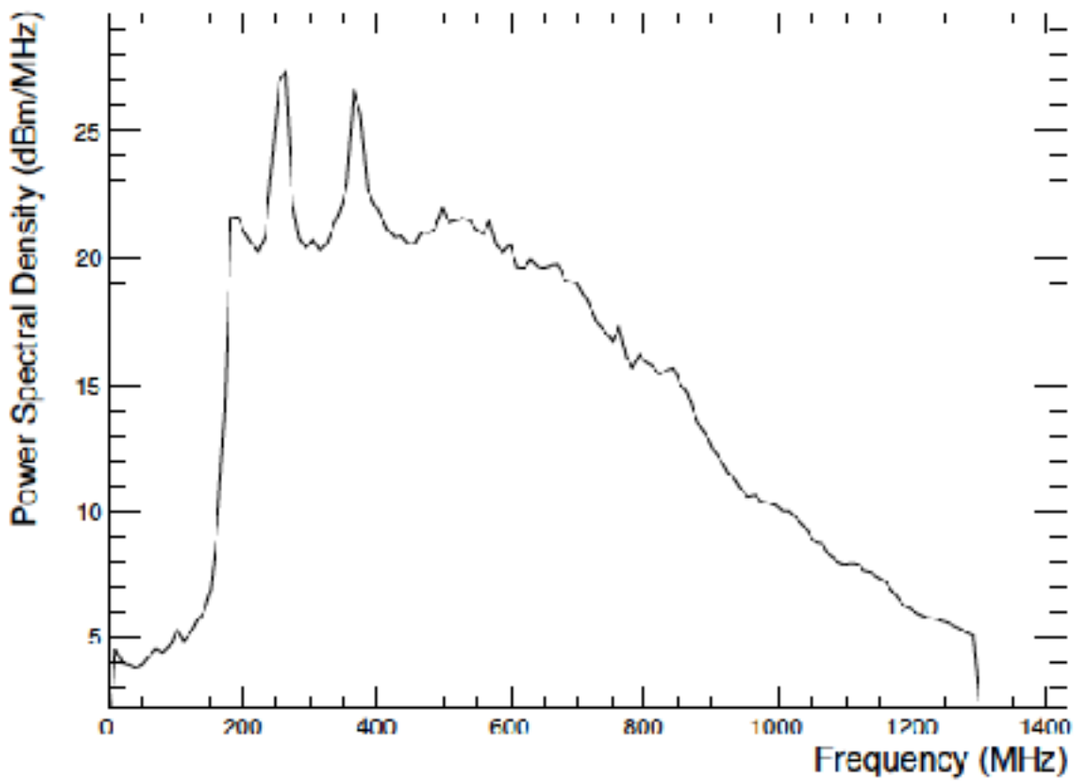


The challenge

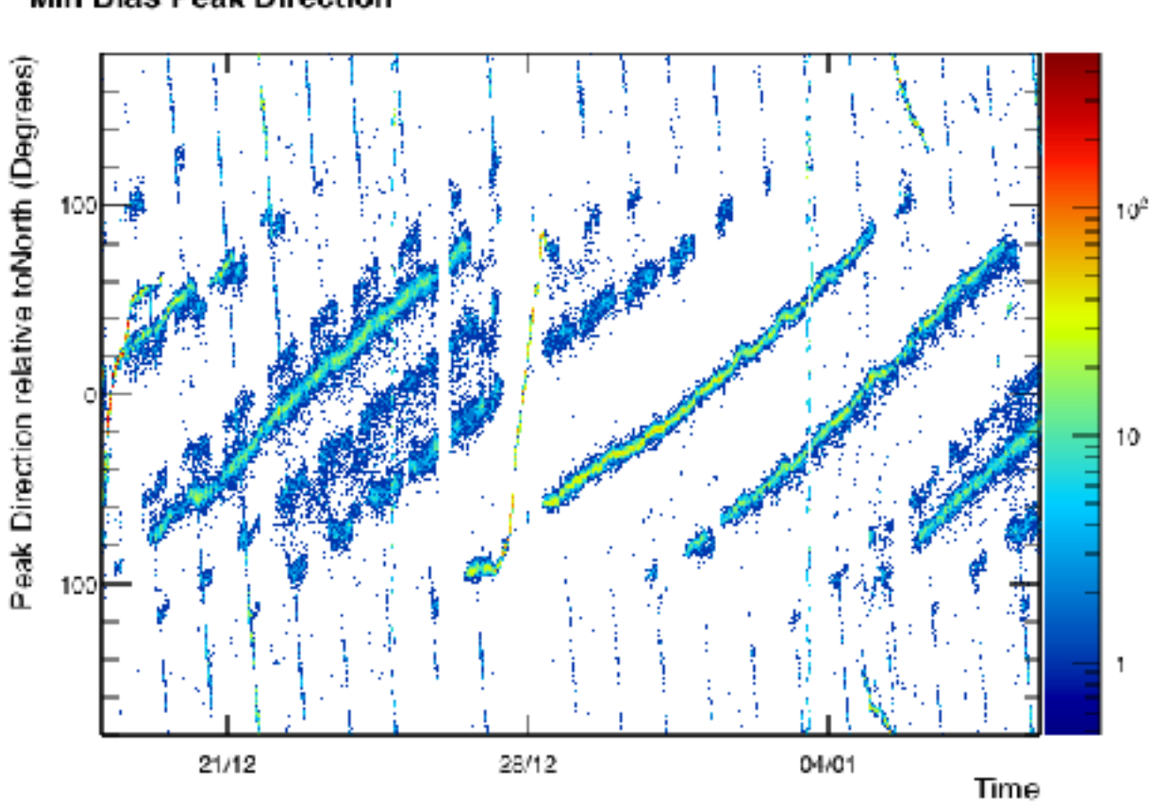
- ~100 million events
- (maybe) a few neutrinos
- Tens of cosmic rays

Continuous Waves

- Satellites and human bases using communications in the bands:
  - 260 MHz
  - 380 MHz

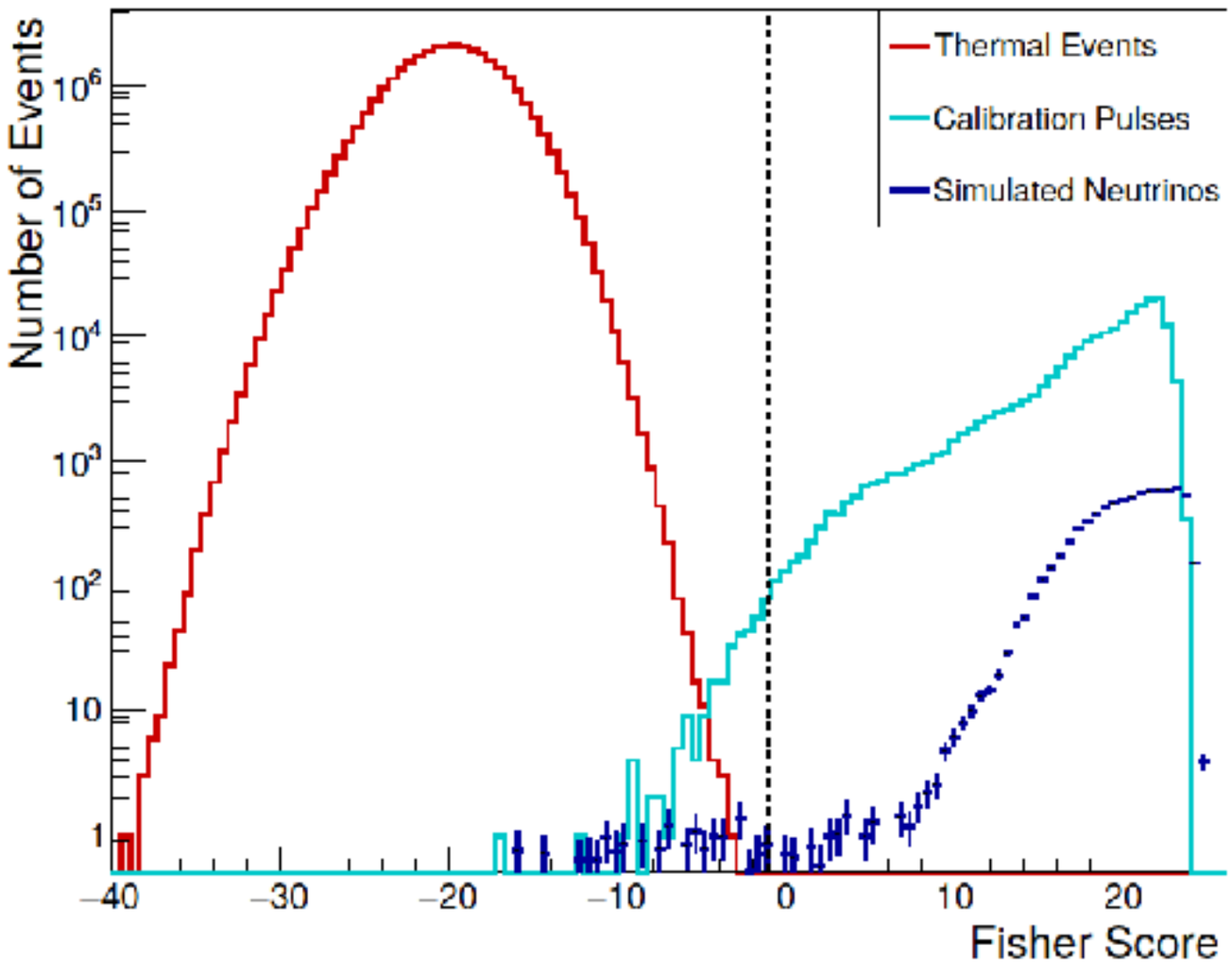


- How to get rid of this?
  - ANITA-3: software
  - ANITA-4: hardware



Thermal noise

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

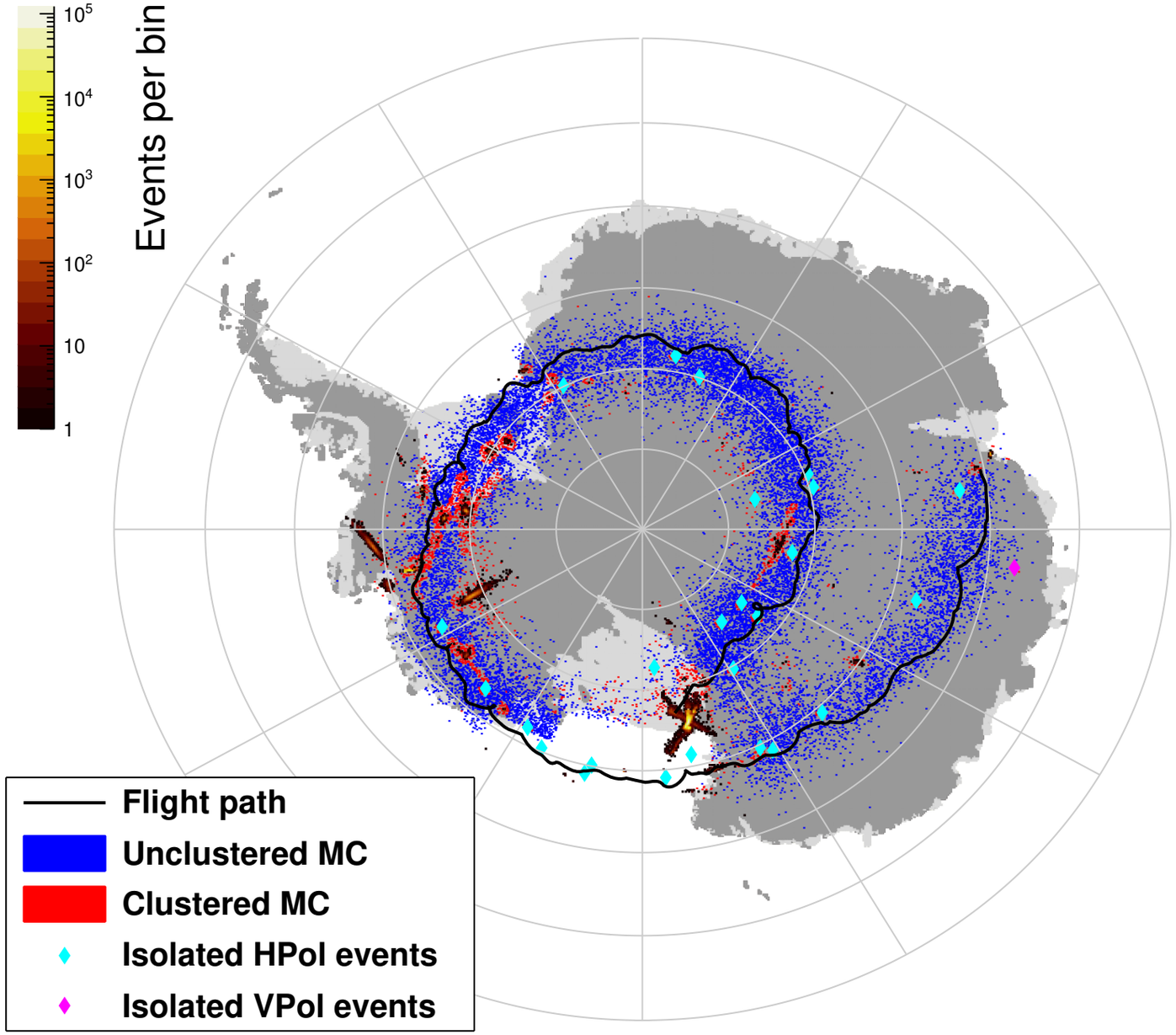


- Background sideband: above horizon triggers
- Simulation: cosmogenic neutrinos following the Kotera mix max model

(JINST 14.08 (2019), P08011)

Clustering

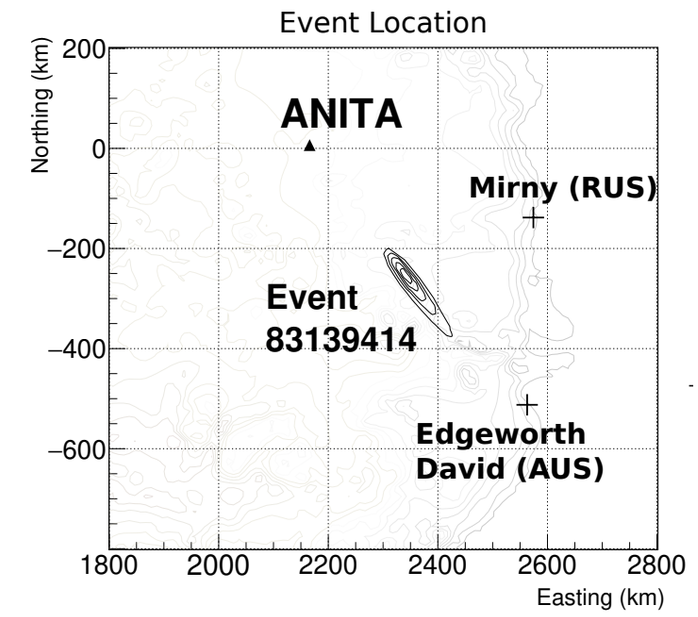
- From previous cuts, ~500k events

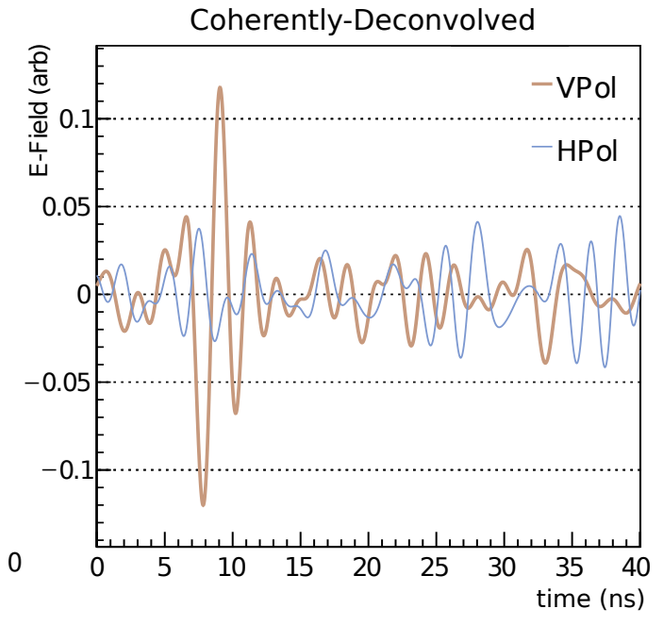


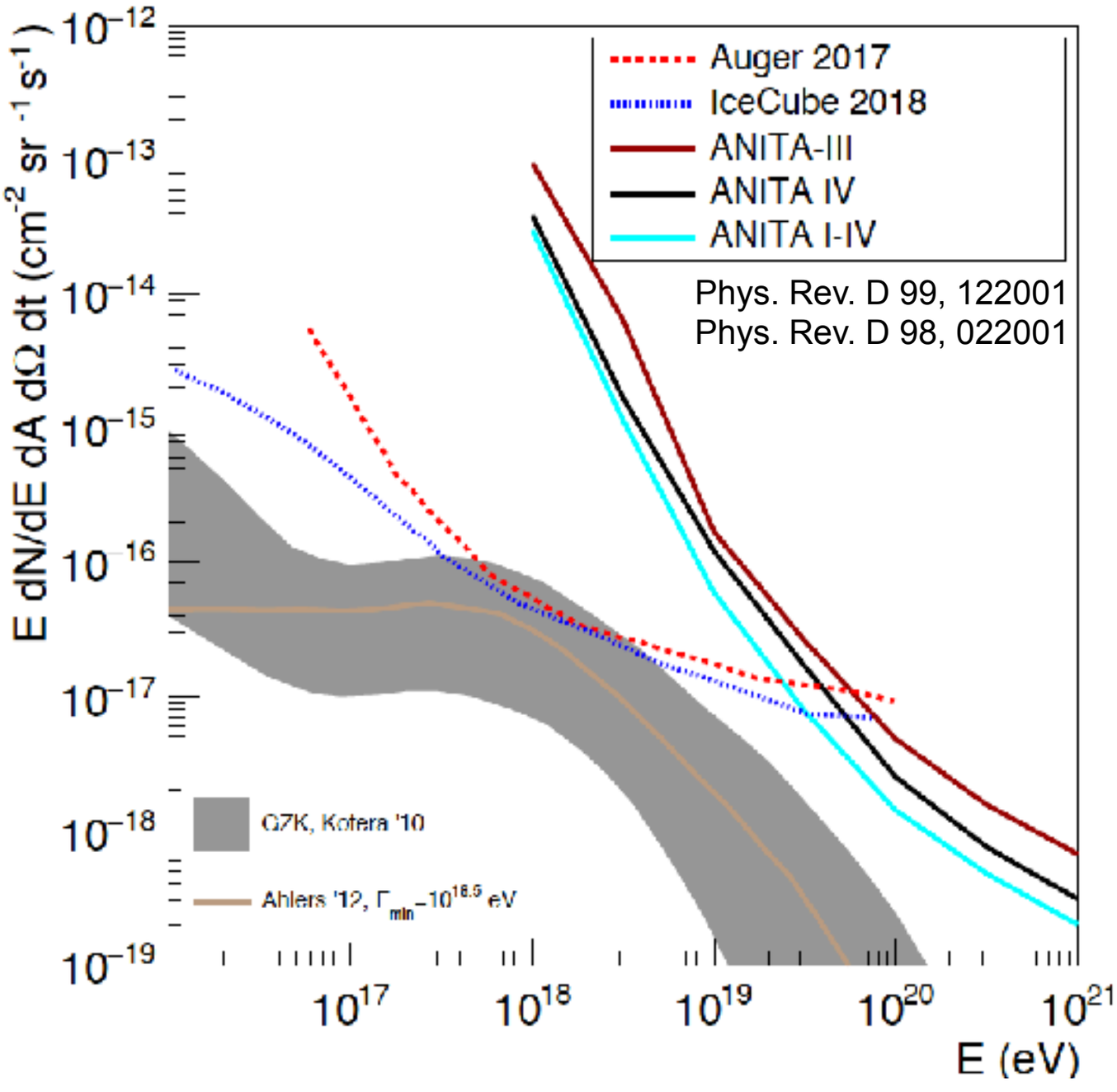
- Look for isolated singlets and doublets
- Remove anything that clusters with human bases
- Remove anything which forms a cluster of 3 or more

ANITA Neutrino Search

- ANITA-3 and ANITA-4 found 2 events consistent with background estimation
- Most stringent limits at the end of the spectrum







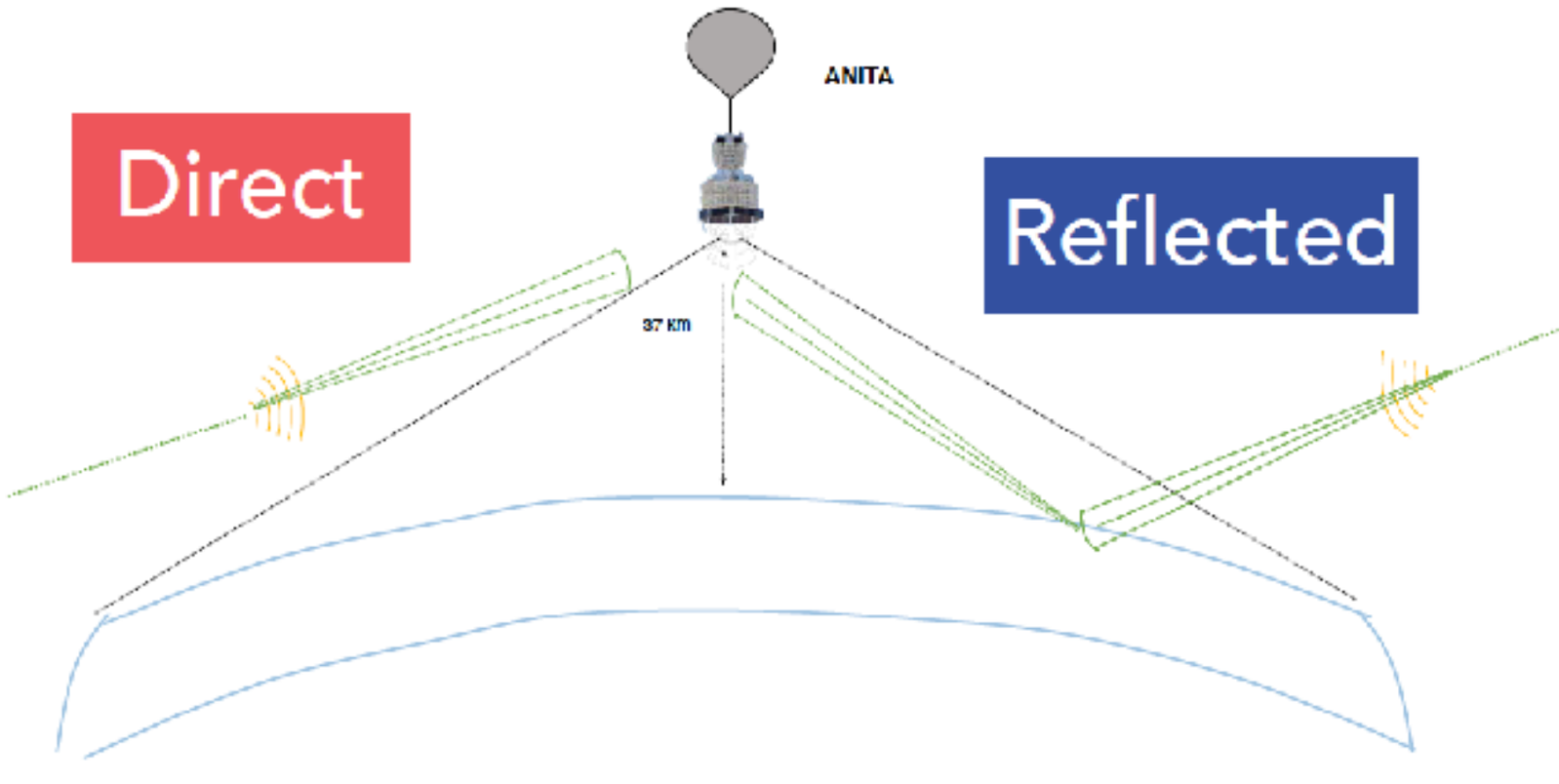
L. Cremonesi

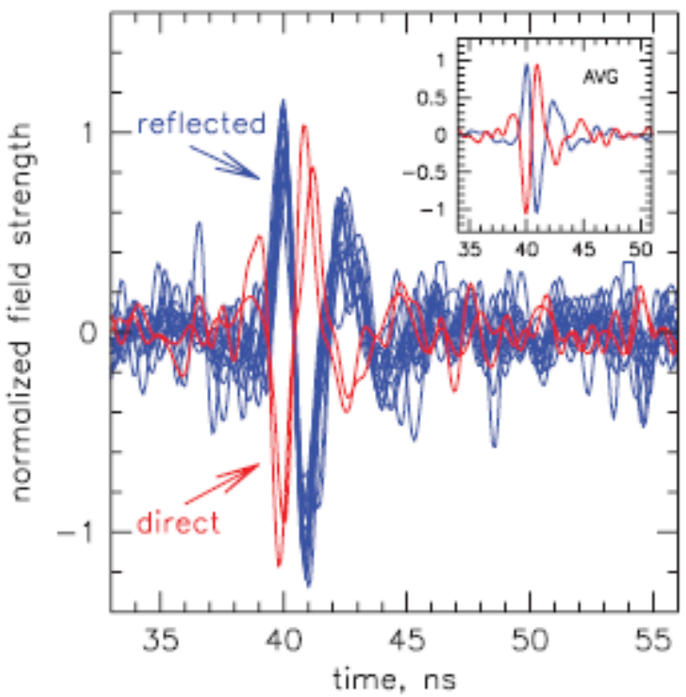
"UHE neutrinos and ANITA"

UHE cosmic rays

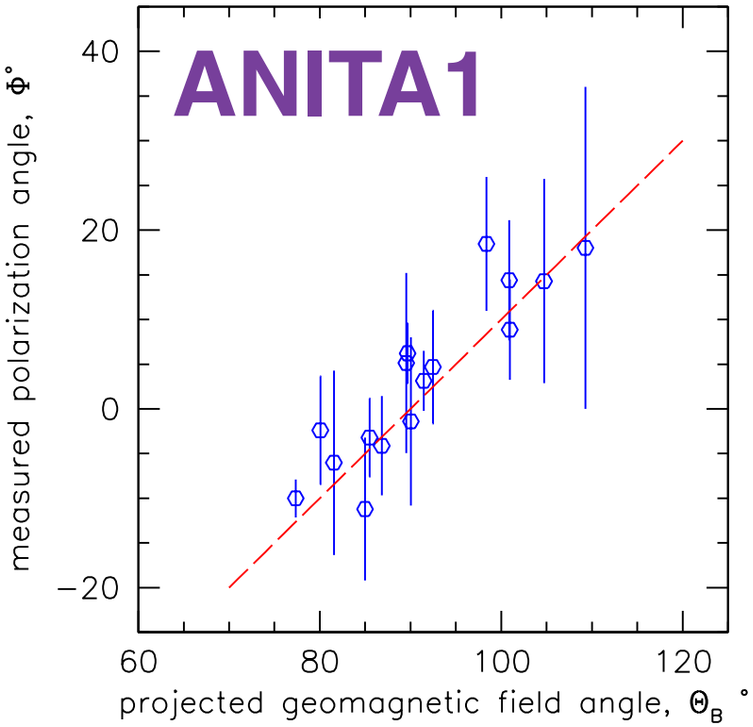
UHECR

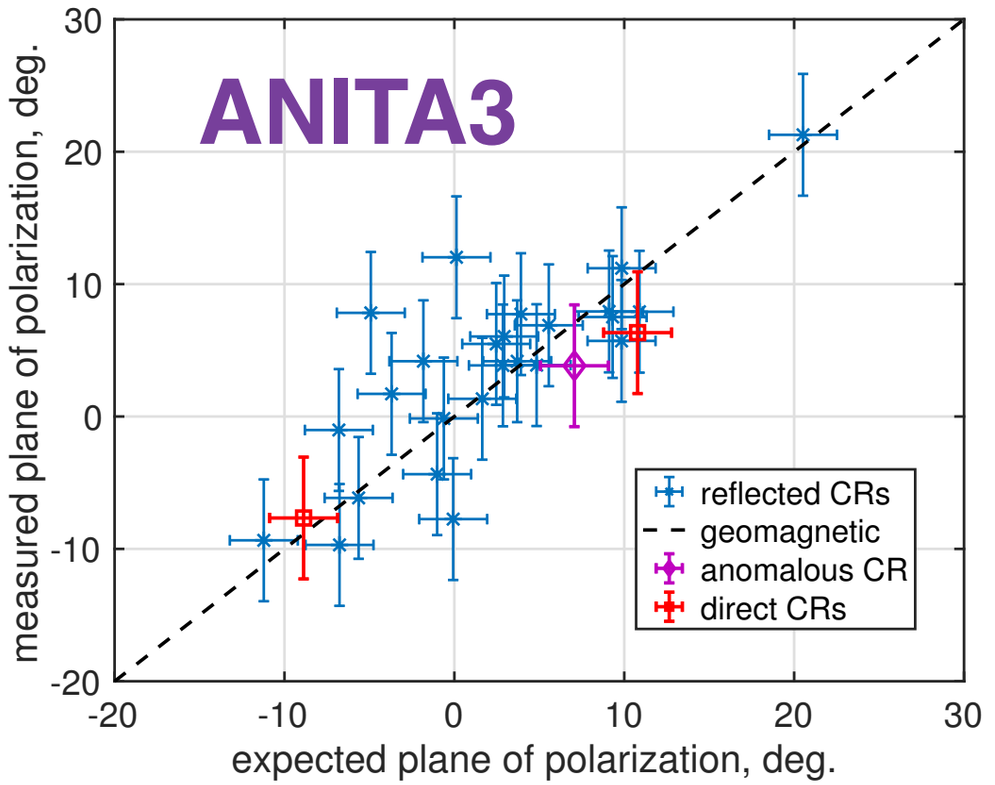
	CR
ANITA-1	16
ANITA-2	2
ANITA-3	28
ANITA-4	29



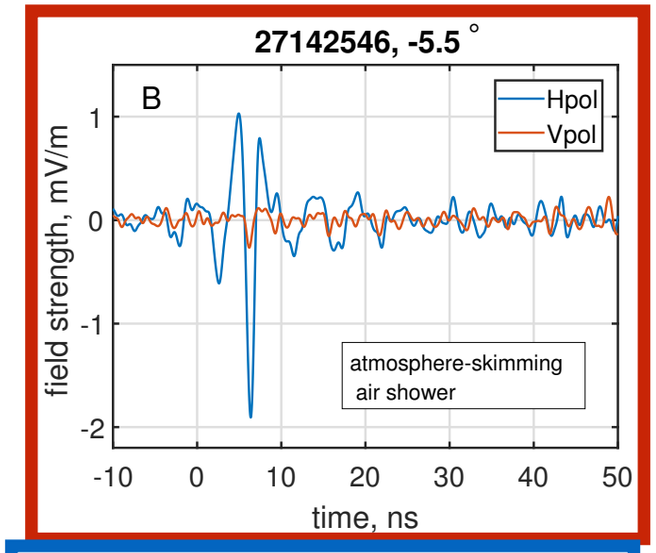


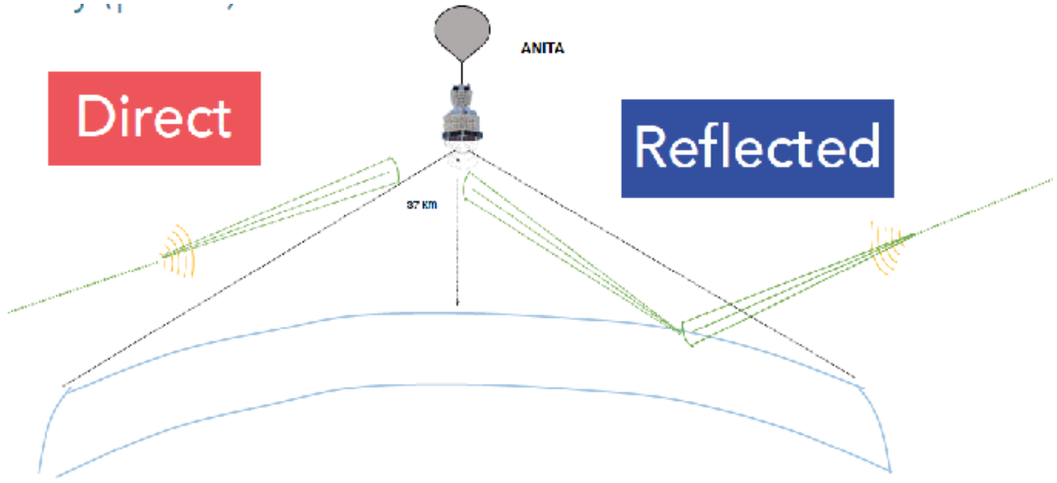
PRL 105, 151101 (2010)

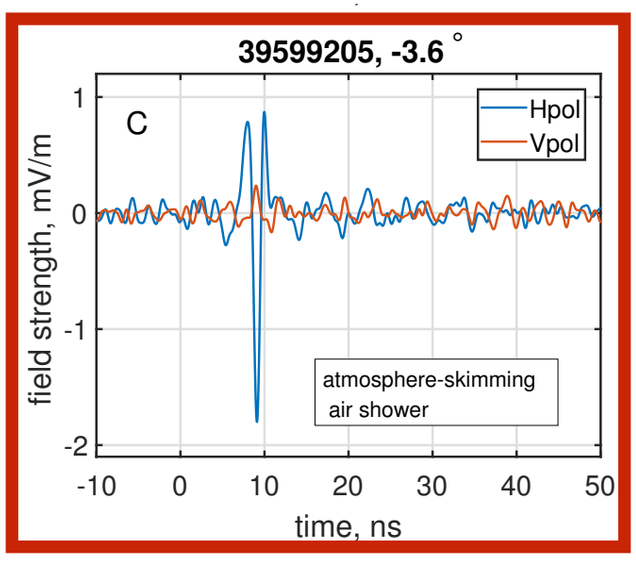


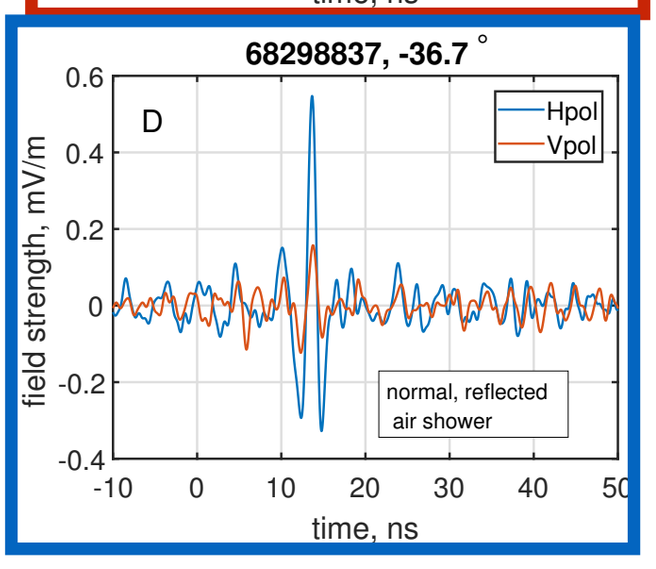


2 mystery events





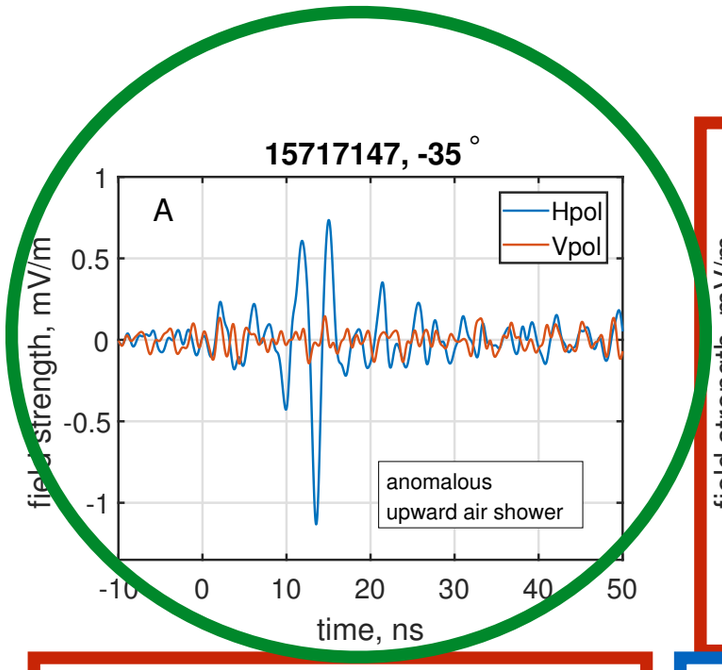


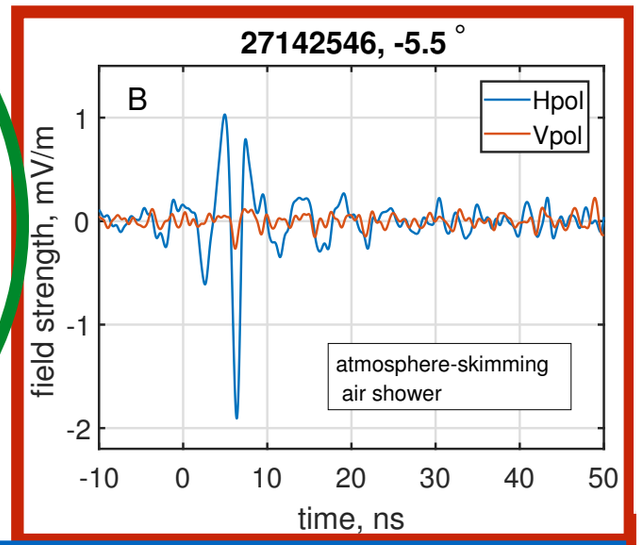


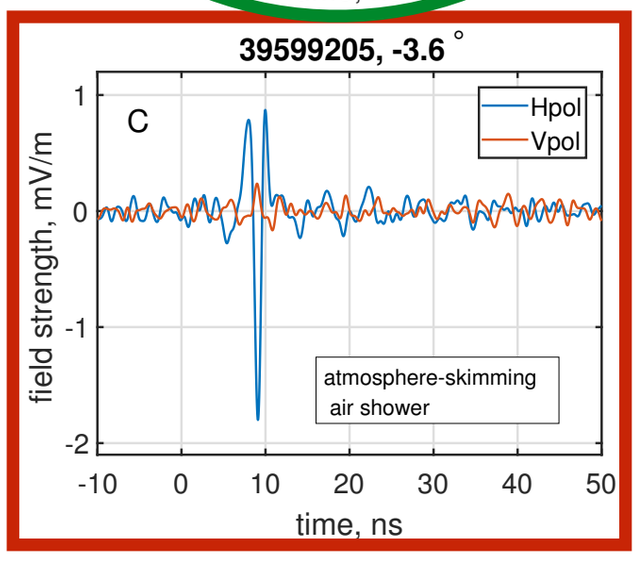
Direct Cosmic Rays

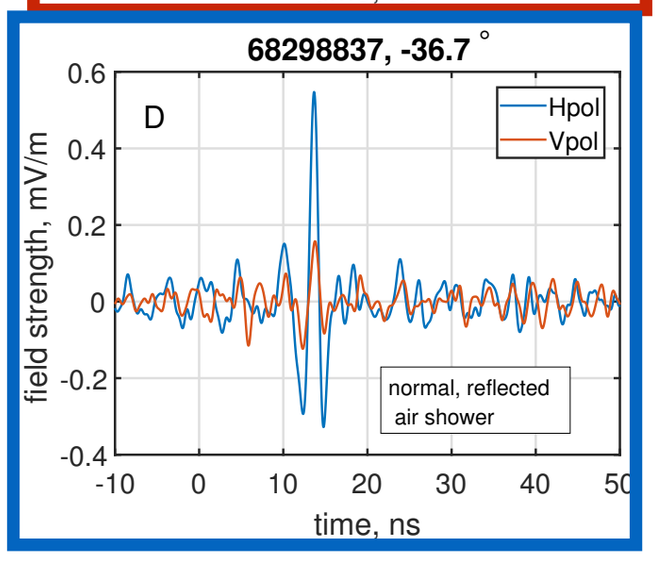
Reflected Cosmic Rays

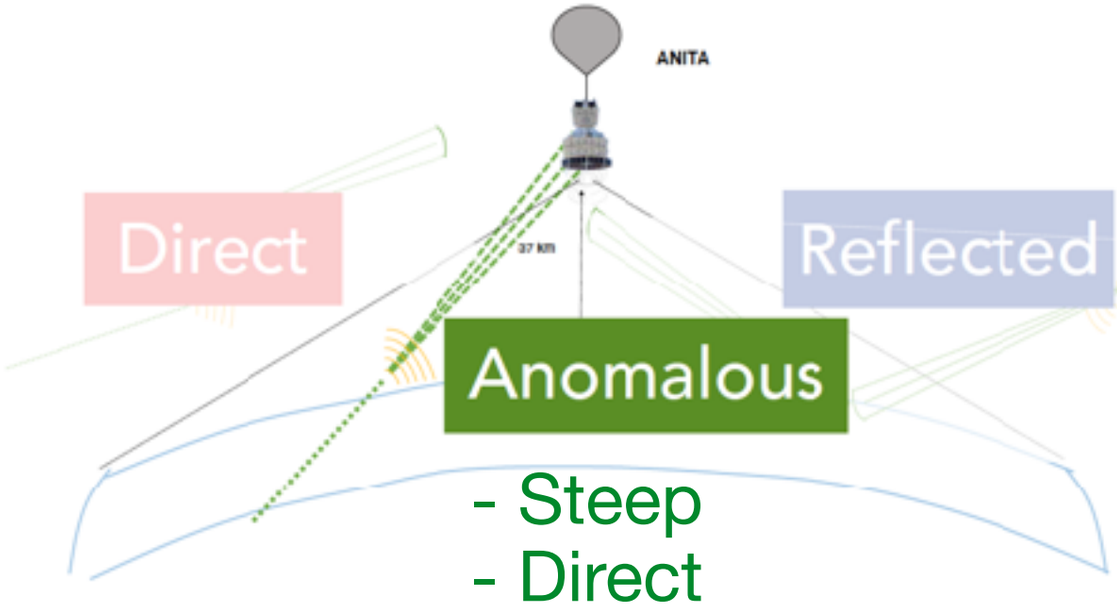
2 mystery events











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}

A lot of interest…

All news is good news?

LIVESCIENCE

NEWS TECH HEALTH PLANET

Live Science > Space

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

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

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.

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An Astonishing Discovery Might Have Just Broken Particle Physics

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By Yasmin Stechbuch

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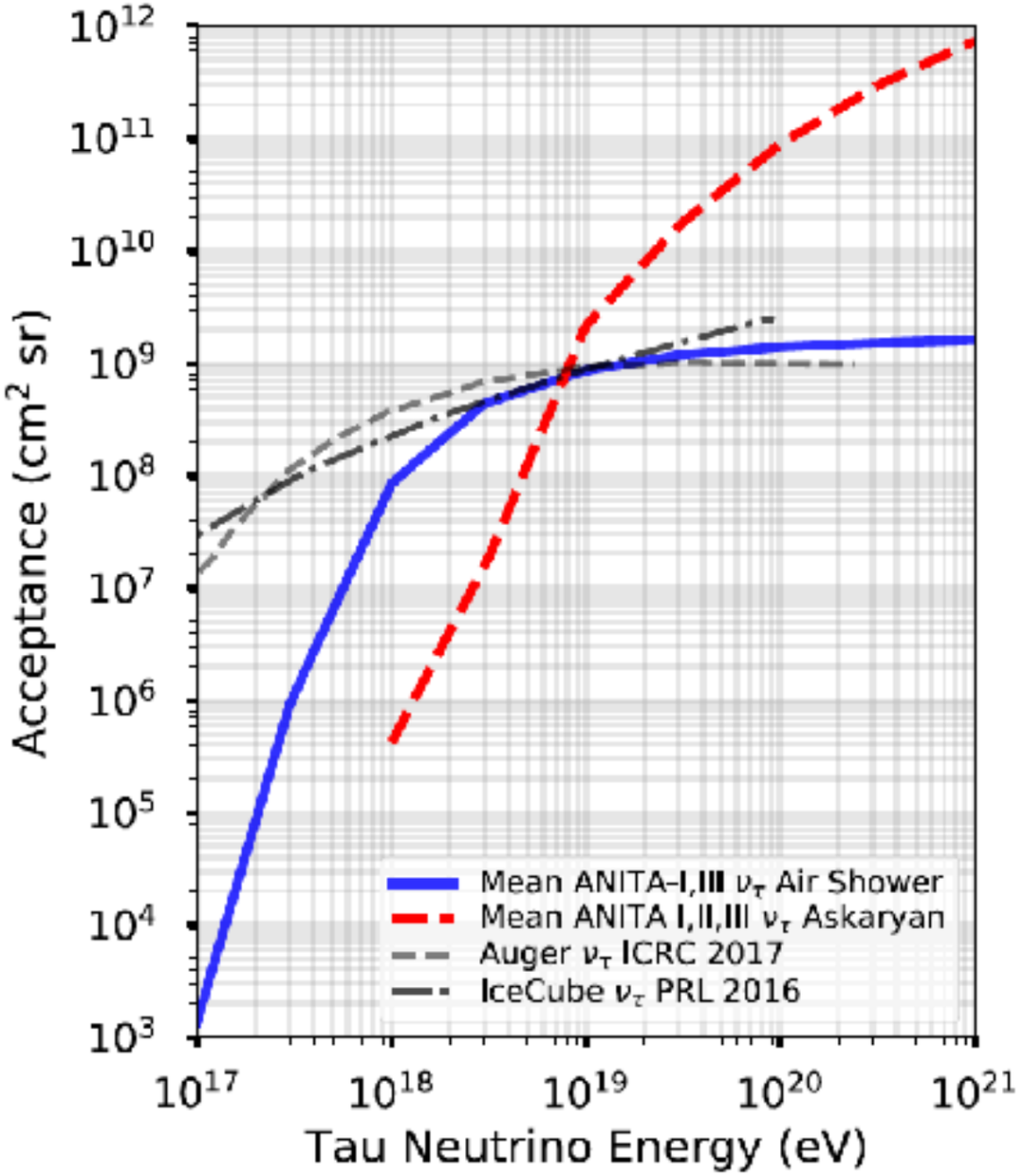
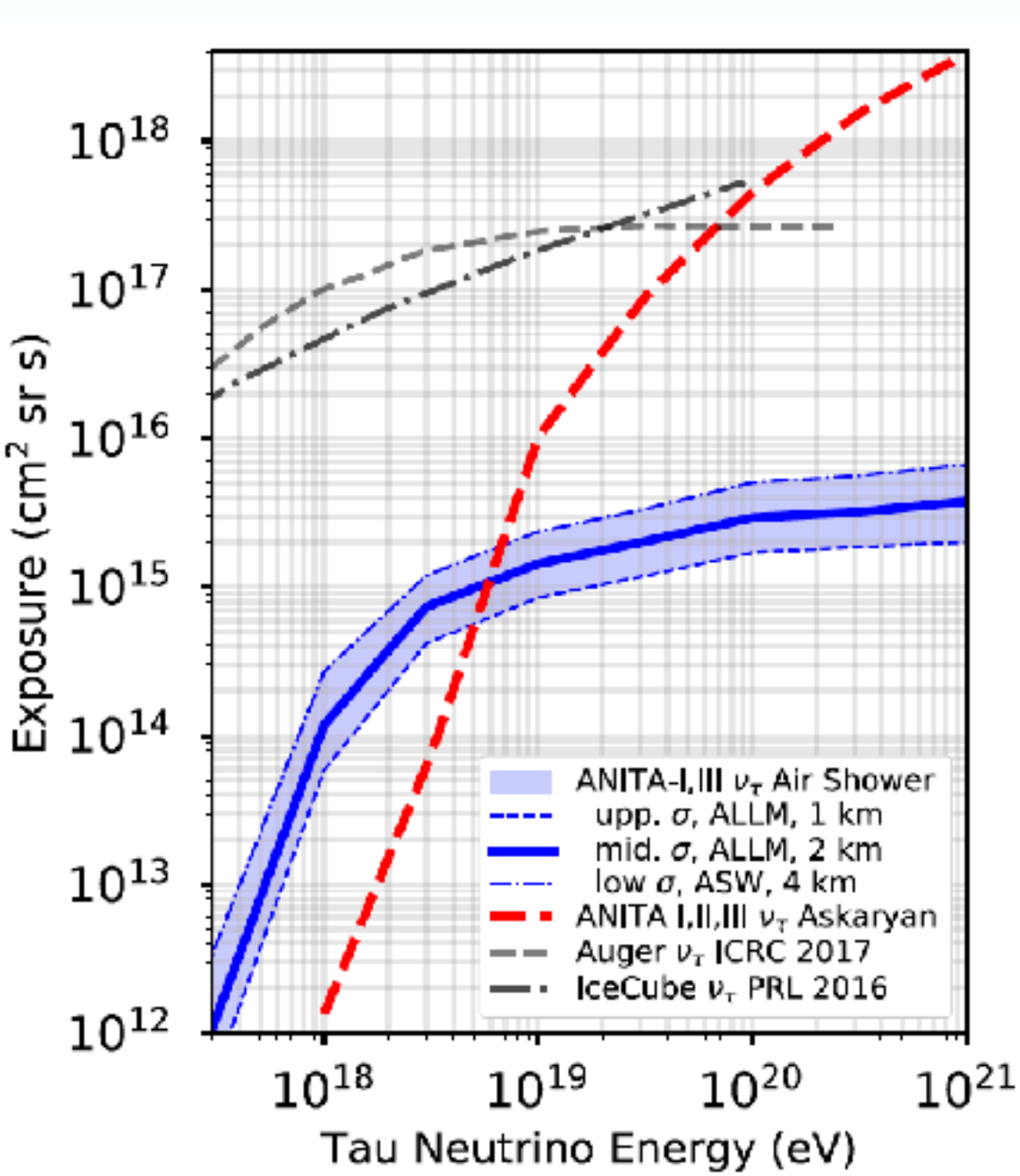
NASA scientists detect parallel universe 'next to ours' where time runs backwards

An experiment in the frozen wastes of Antarctica has revealed evidence of a universe born in the same Big Bang as ours – but with rules of physics that are completely the opposite

Diffuse neutrinos: problem 1

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

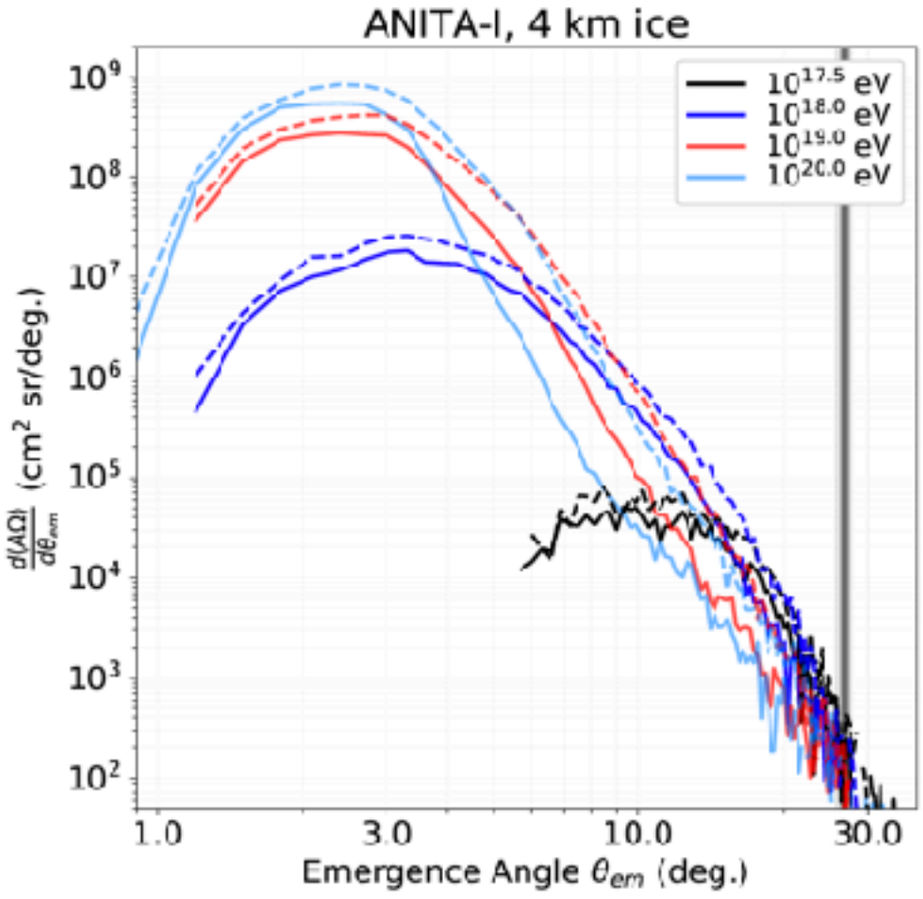


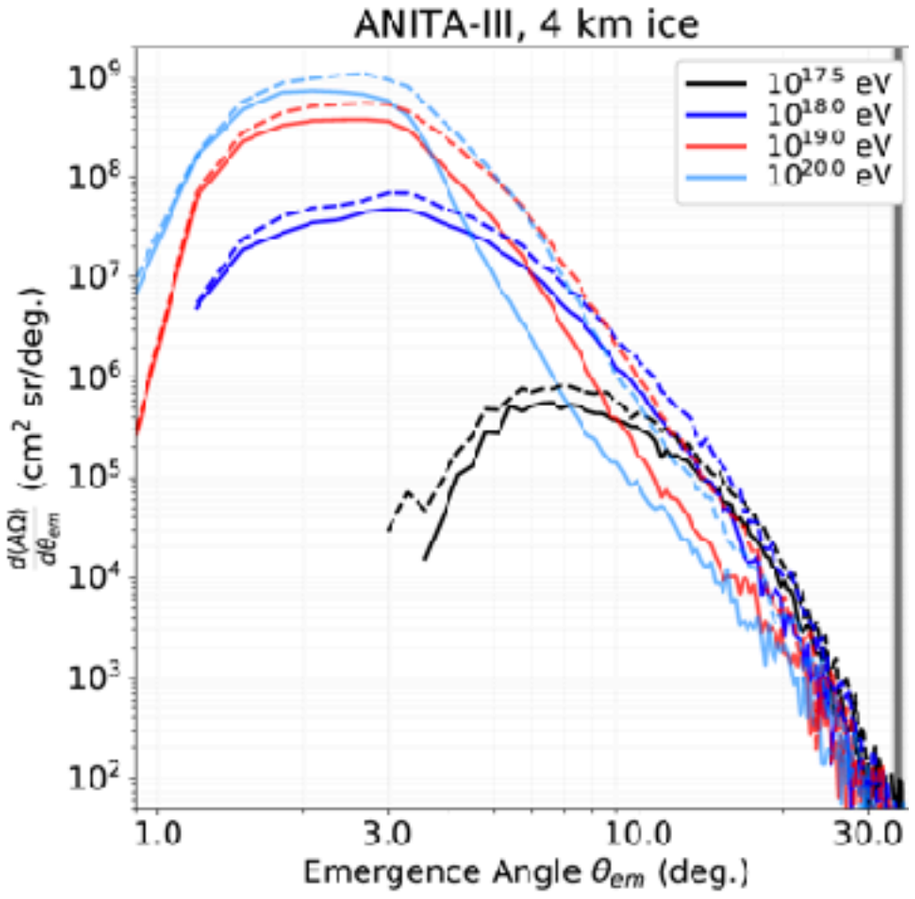


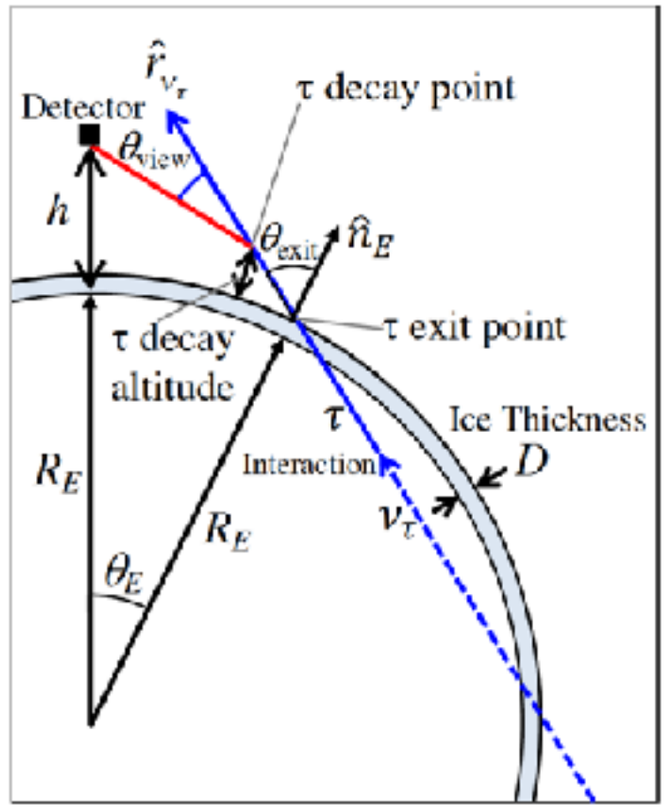
arXiv: 1811.07261

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?



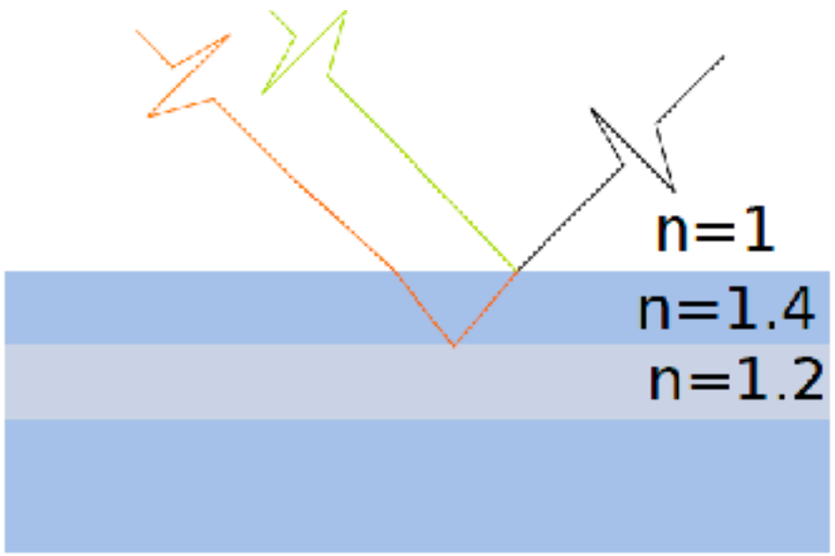




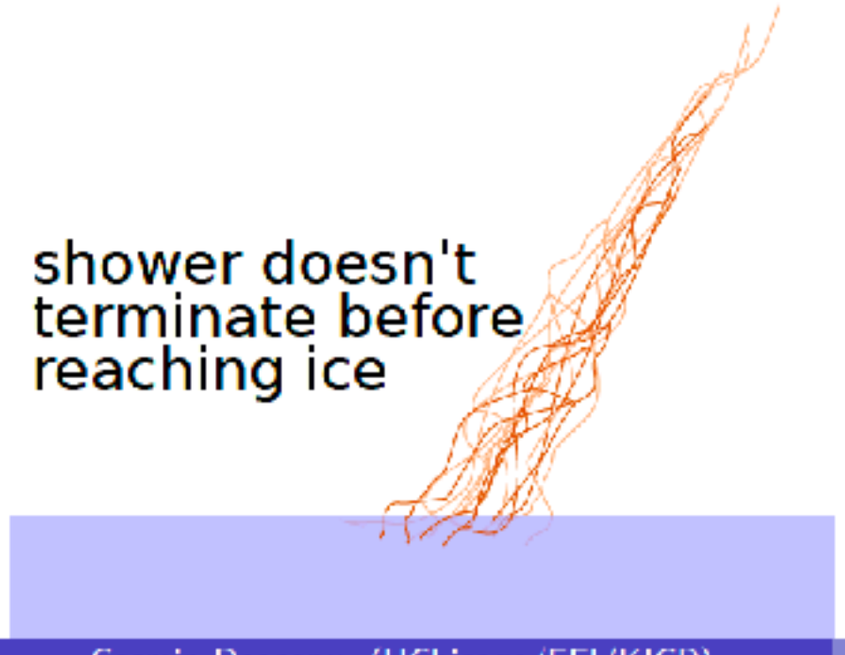
arXiv: 1811.07261

Some Mundane-ish explanations

Slide by C. Deaconu



- Funny ice reflections (Shoemaker et al, arxiv:1905.02846)
  - Possible, but ice would need to have special structure over a large area (Fresnel zone convolved with beam pattern on ground)
  - Would likely need unexpected ice properties, since dielectric constrast from "normal" underice layers would have a very hard time explaining the observations.
  - Lack of non-inversion from HiCal trailing calibration payload suggests that any such reflection can't be common (paper forthcoming)
- Funny EAS emission
  - Maybe there is a class of atypical EAS that look different
  - In particular, some air showers may not terminate before hitting the ice (de Vries and Prohira, arxiv:1903.08750), which could potentially modify shape of the signal.
  - More detailed simulations needed to see if viable.



L. Cremonesi "UHE neutrinos and ANITA"

More fun explanations!

Slide by C. Deaconu

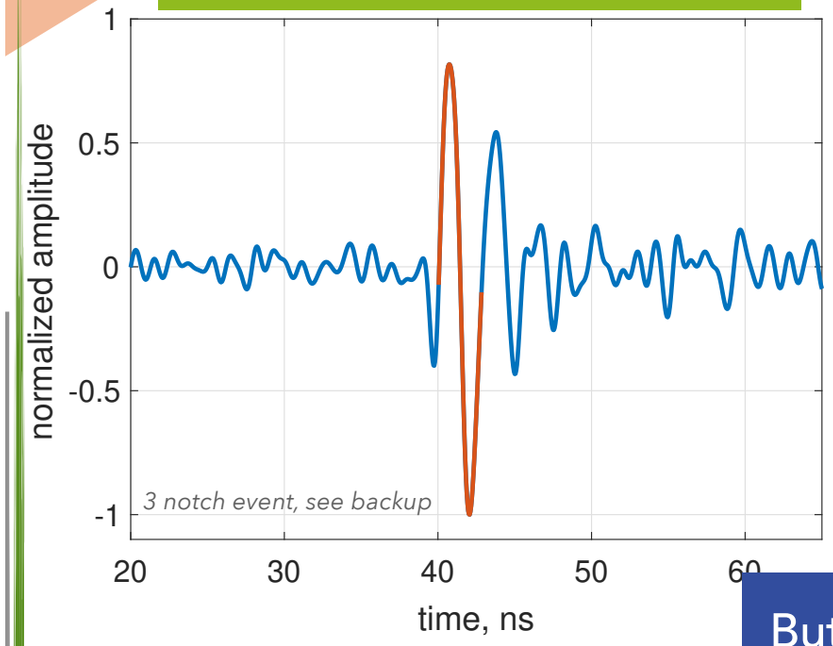
- Many exotic particle or exotic neutrino explanations that eventually produce a τ-induced EAS (See Anchordoqui et al. arxiv:1907.06308 for a summary)
  - +Compatible with observed effect
  - -Non-trivial to evade IceCube or Auger bounds
- Maybe it's actually Askaryan emission, not from an EAS (e.g. Hooper et al., arxiv:1904.12865)
  - +Not in tension with other experiments
  - +Observed polarization and polarity possible if Askaryan shower from some deeply penetrating particle (not a ν).
  - -But the observed polarization and polarity would be a coincidence
- Some other radio emission mechanism entirely (e.g. axions in ionosphere, Esteban et al. arXiv:1905.10372).
  - +Not in tension with other experiments
  - +Testable by looking for other evidence of same mechanism in existing data
  - -Unclear if could produce observed signal without more work.

What has ANITA-4 seen?

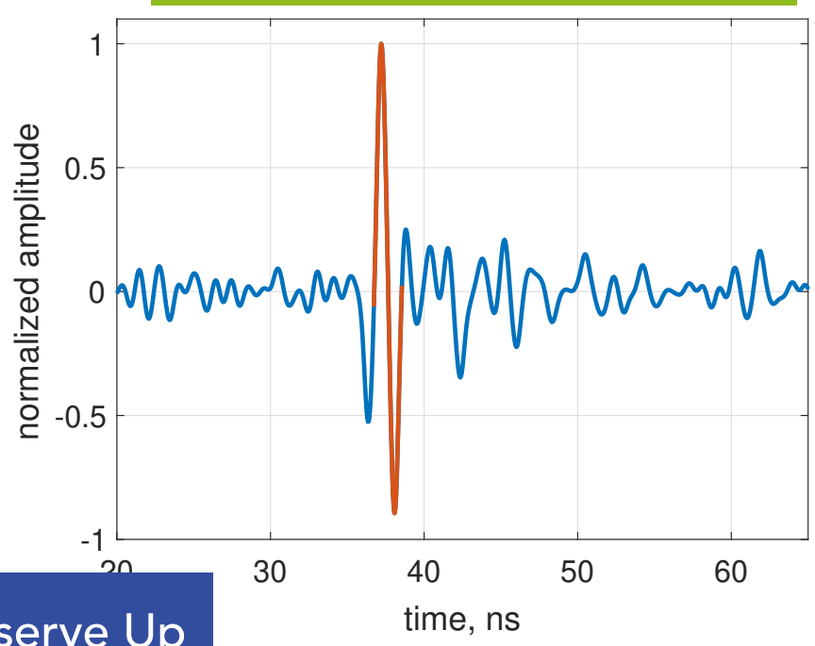
Preliminary

4 Direct Events, Near & Above Horizon

4098827, θ_H = -0.25±0.21°

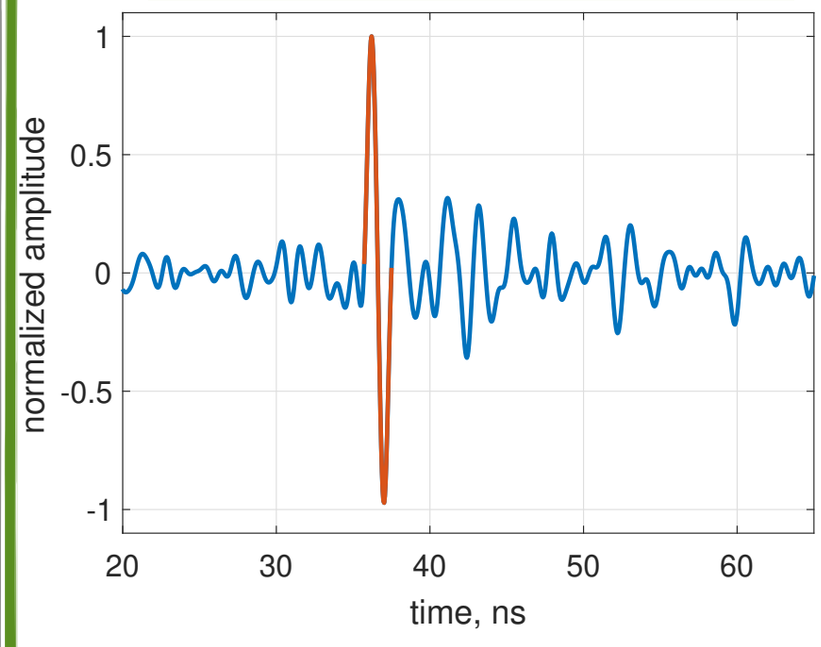


19848917, θ_H=-0.65±0.20°

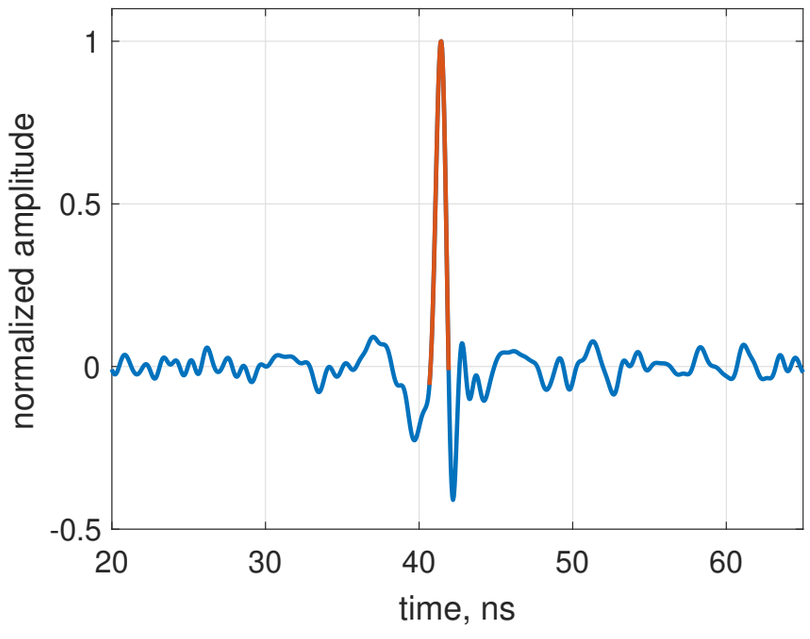


But observe Up

50549772, θ_H = -0.81±0.20°



72164985, θ_H = -0.19±0.10°



37

S. Wissel (Neutrino 2020, talk and video)

ANITA-4 results

- **29 on background of $0.37^{+0.27}_{-0.17}$** events result from blinded search for Hpol, impulsive, isolated events. Remained blind to polarity.

Preliminary

Results from targeted CR search		
	Steep	**Near Horizon**
Angle wrt horizon	> 1°	< 1°
Total Events	23	6
Consistent with Geometry		
Reflected (Down)	21	0
Direct (Up)	0	2
Inconsistent with Geometry		
Direct (Up)	0	4
Indeterminate Polarity		
	2	0
Total	**29**	

ANITA-4 results

- **29 on background of $0.37^{+0.27}_{-0.17}$** events result from blinded search for Hpol, impulsive, isolated events. Remained blind to polarity.

- **4 near horizon events** with **inconsistent polarity** with significance 3.2σ

  - All very near the horizon.

  - Still evaluating tau neutrino hypothesis could be viable.

  - Mundane explanations are harder to invoke, but near-horizon radio propagation is complex and hard to model.

- **No new steep events** with **inconsistent polarity** like in ANITA-1 & ANITA-3

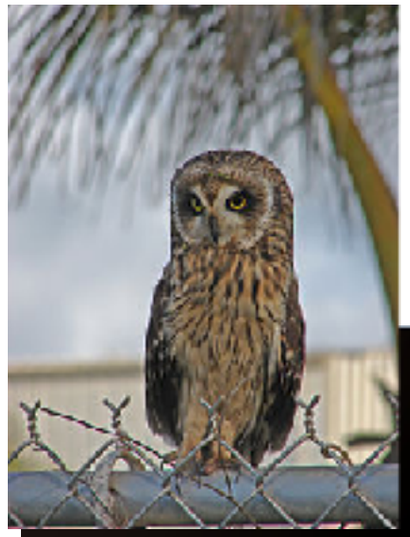
Preliminary

Results from targeted CR search		
	Steep	**Near Horizon**
Angle wrt horizon	> 1°	< 1°
Total Events	23	6
Consistent with Geometry		
Reflected (Down)	21	0
Direct (Up)	0	2
Inconsistent with Geometry		
Direct (Up)	**0**	**4**
Indeterminate Polarity		
	2	0
Total	**29**	

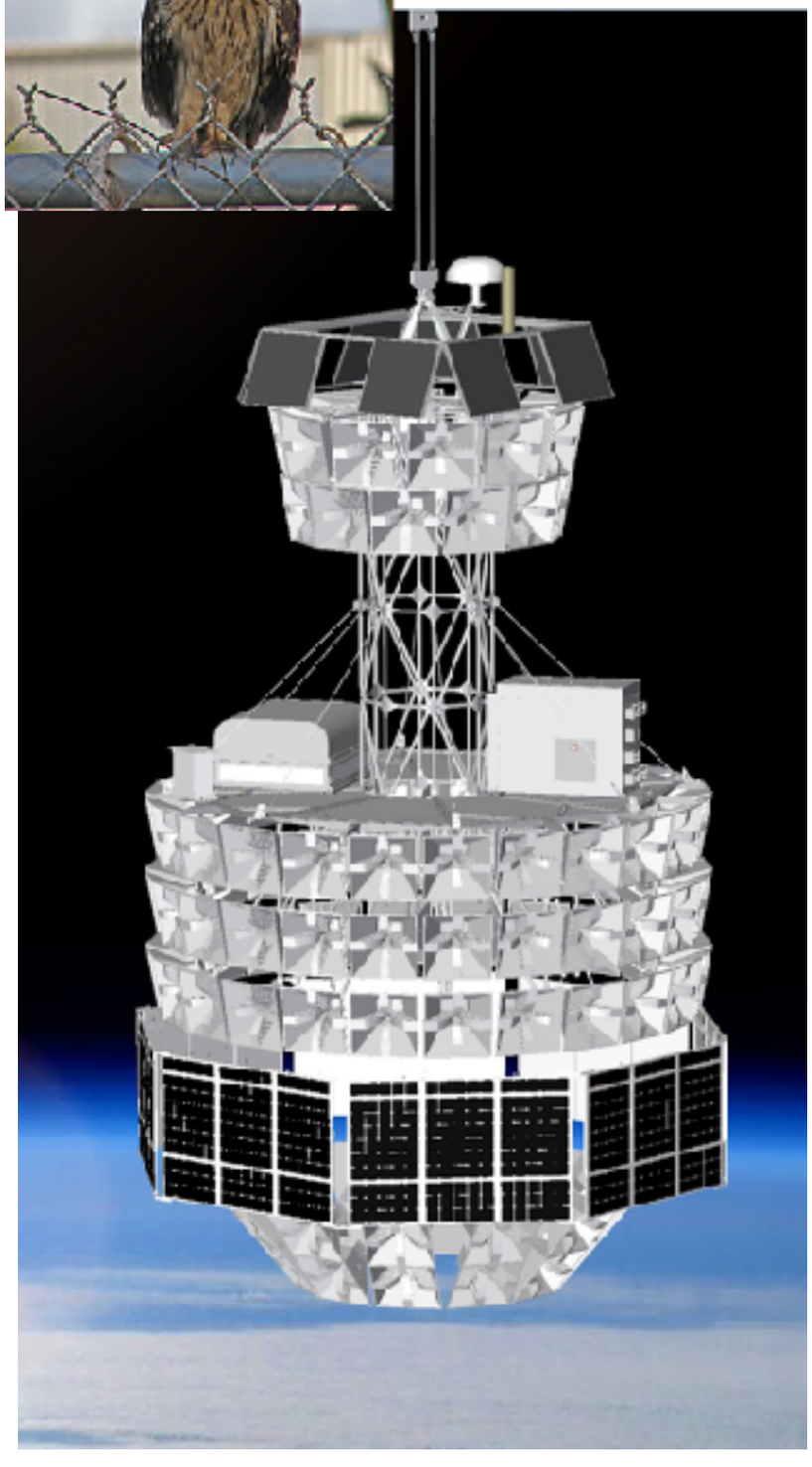
Future

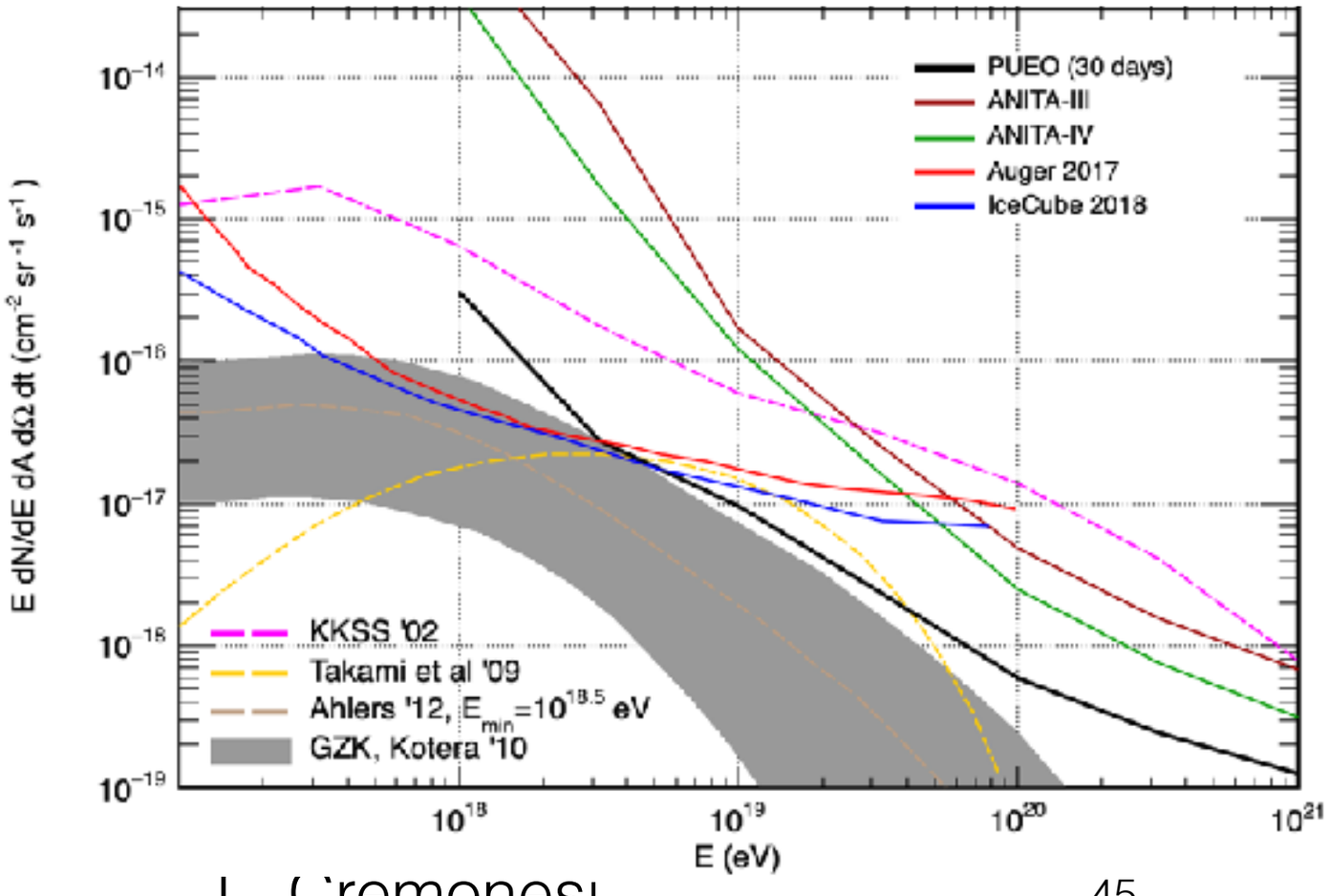
PUEO

- Payload for Ultrahigh Energy Observations
- Up to 10x more sensitive than ANITA-IV for Askaryan channel (2.5x lower threshold than ANITA-IV)
  - More antennas (120 vs. 48) , but higher-frequency (300 MHz vs. 200 MHz cutoff)
- 24 antennas in inclined array for steep “mystery events”
- Could fly as soon as 2024.



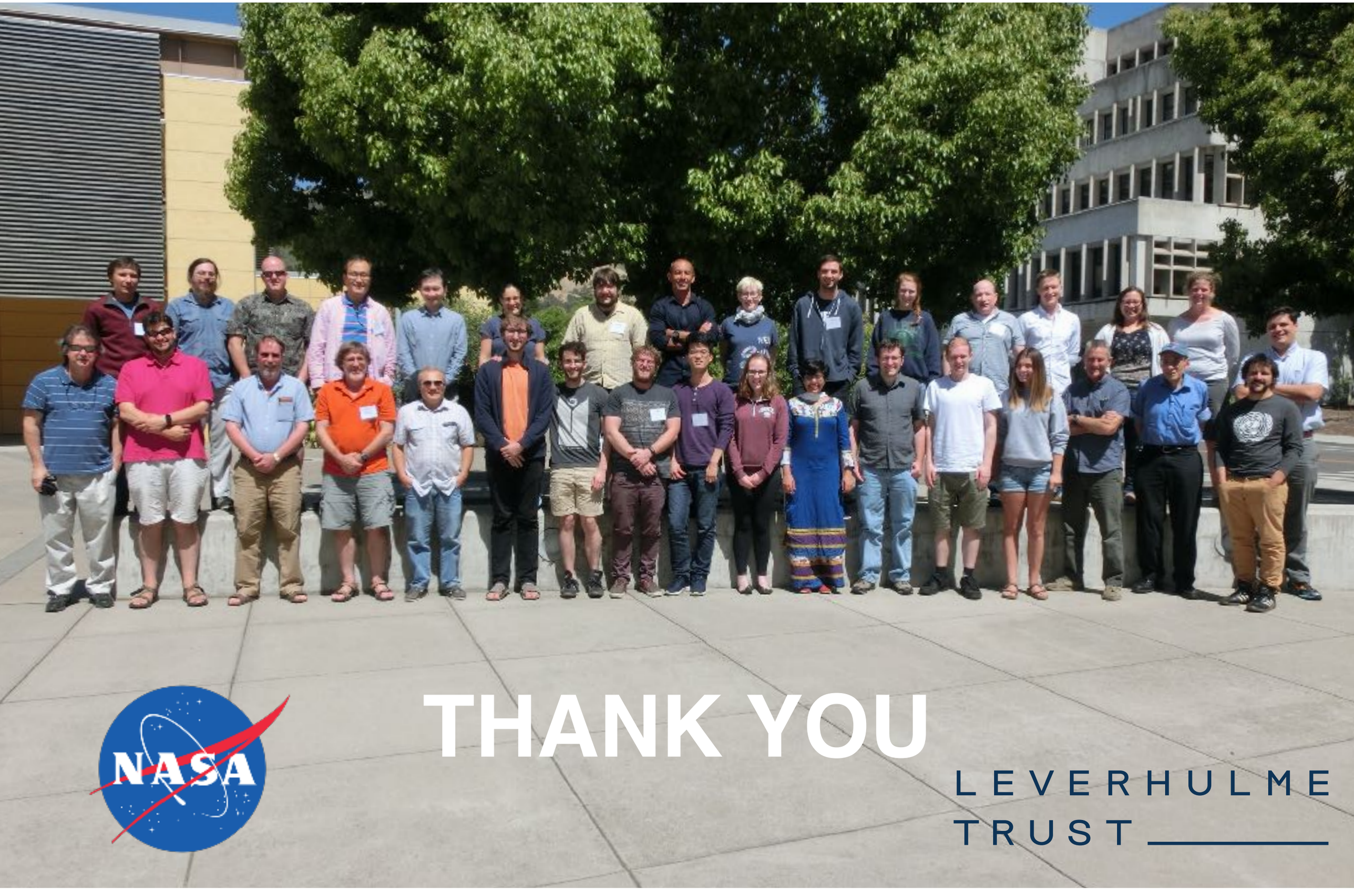
arXiv:2010.02892 [astro-ph.IM]





Summary and future

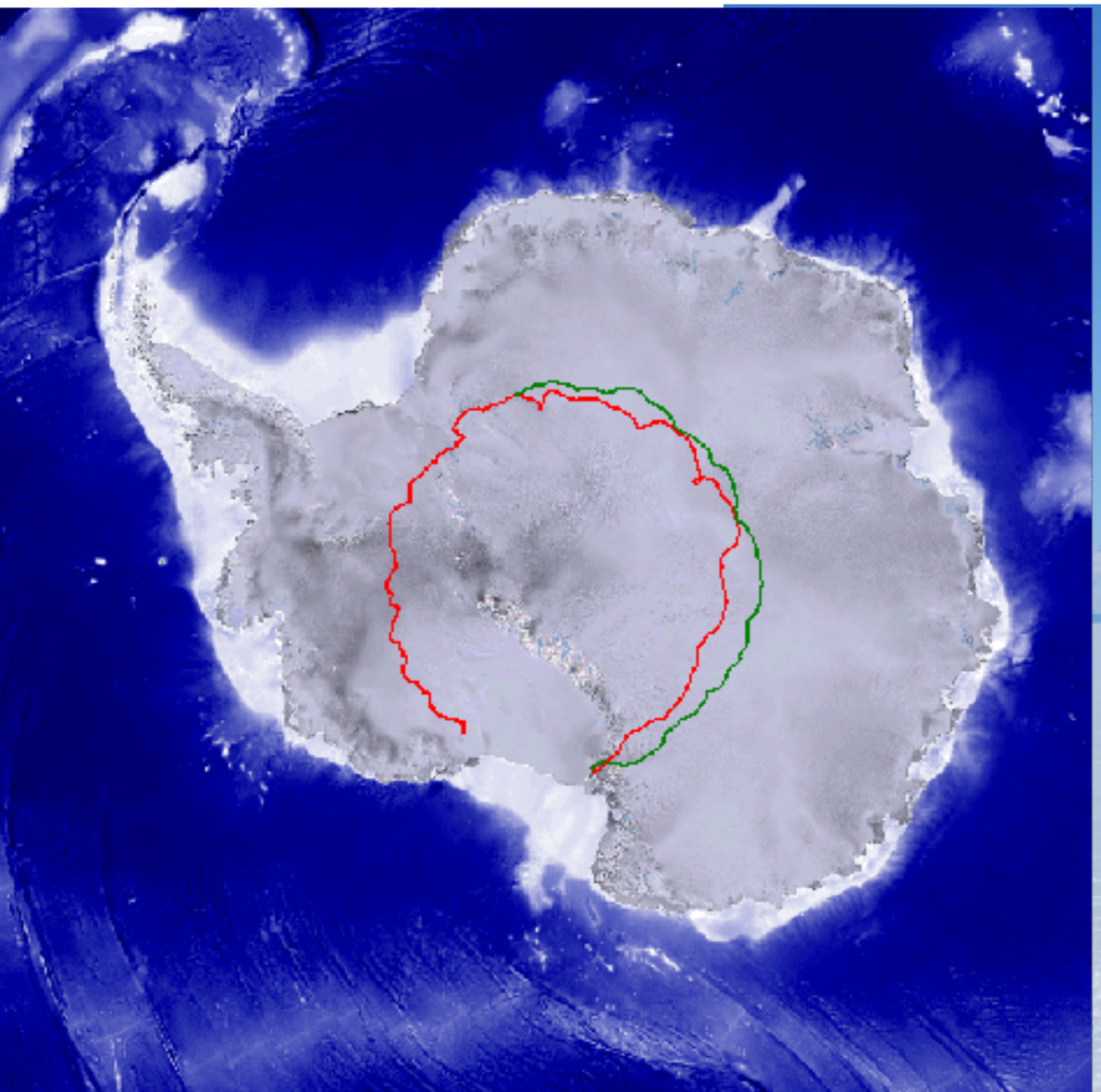
- The ANITA experiment has a rich physics program:
  - ANITA-3 and ANITA-4 diffuse neutrino analyses: Phys. Rev. D 98, 022001 (2018) & Phys. Rev. D 99,122001 (2019)
  - ANITA-3 and ANITA-4 cosmic ray-like analysis: Phys. Rev. Lett. 121, 161102 (2018) & arXiv:2008.05690 [astro-ph.HE]
  - Things I didn't cover: icemc simulation (JINST 14.08 (2019) P08011), ANITA-3 HiCal (Journal of Astronomical Instrumentation 6.02 (2017): 1740002), Source searches (arXiv:2010.02869 [astro-ph.HE] and ApJ 736 (2011) 50) , Lorentz violation (PhysRevD.86.103006), and other analyses
- ANITA-4 source coincidence analyses also coming out soon!


THANK YOU
NASA
LEVERHULME
TRUST

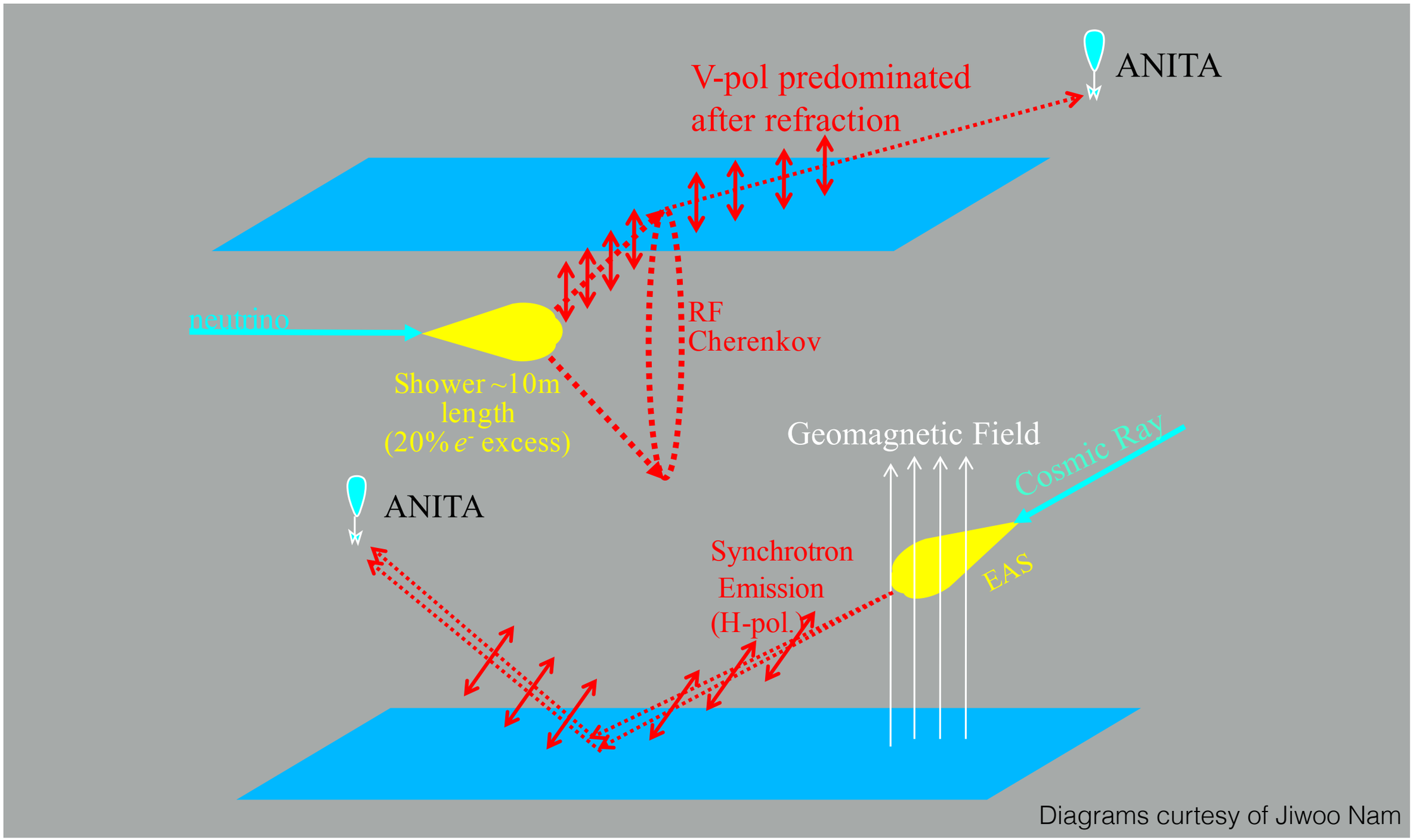
Back up

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 [astro-ph.IM]



Neutrinos and Cosmic Rays

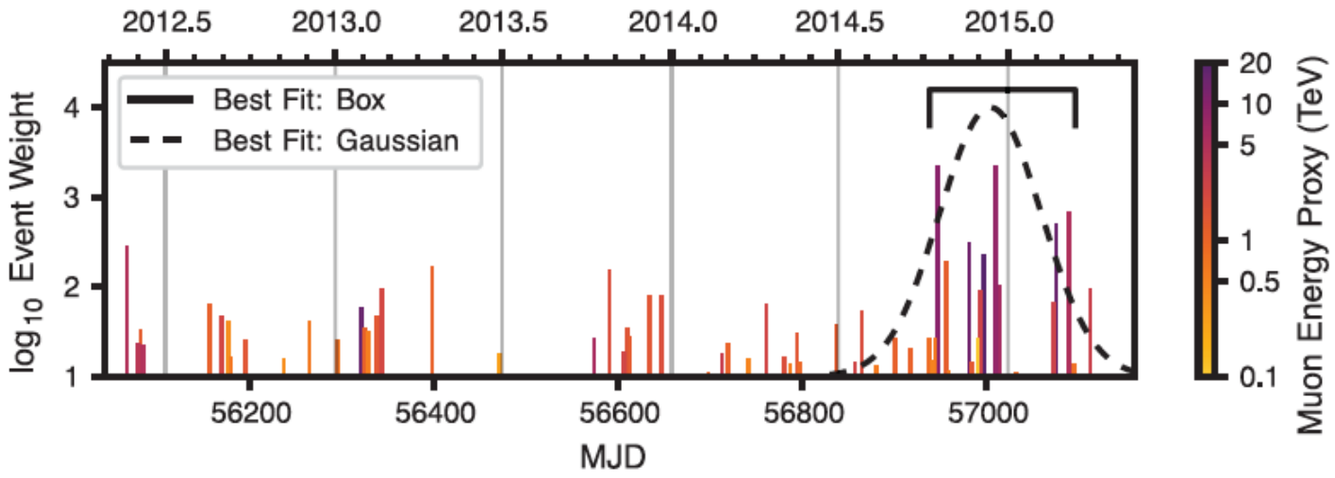


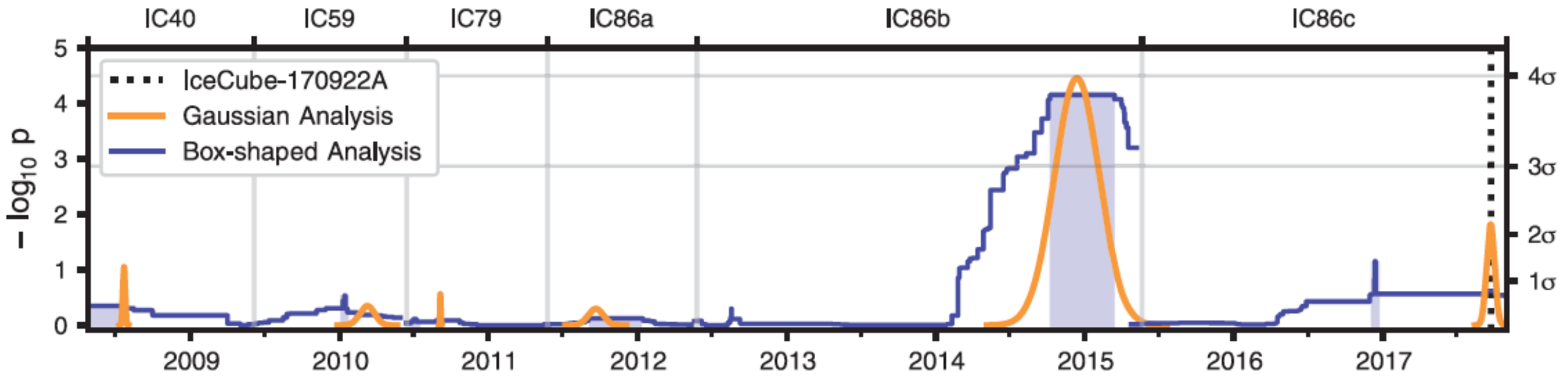
Diagrams curtesy of Jiwoo Nam

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

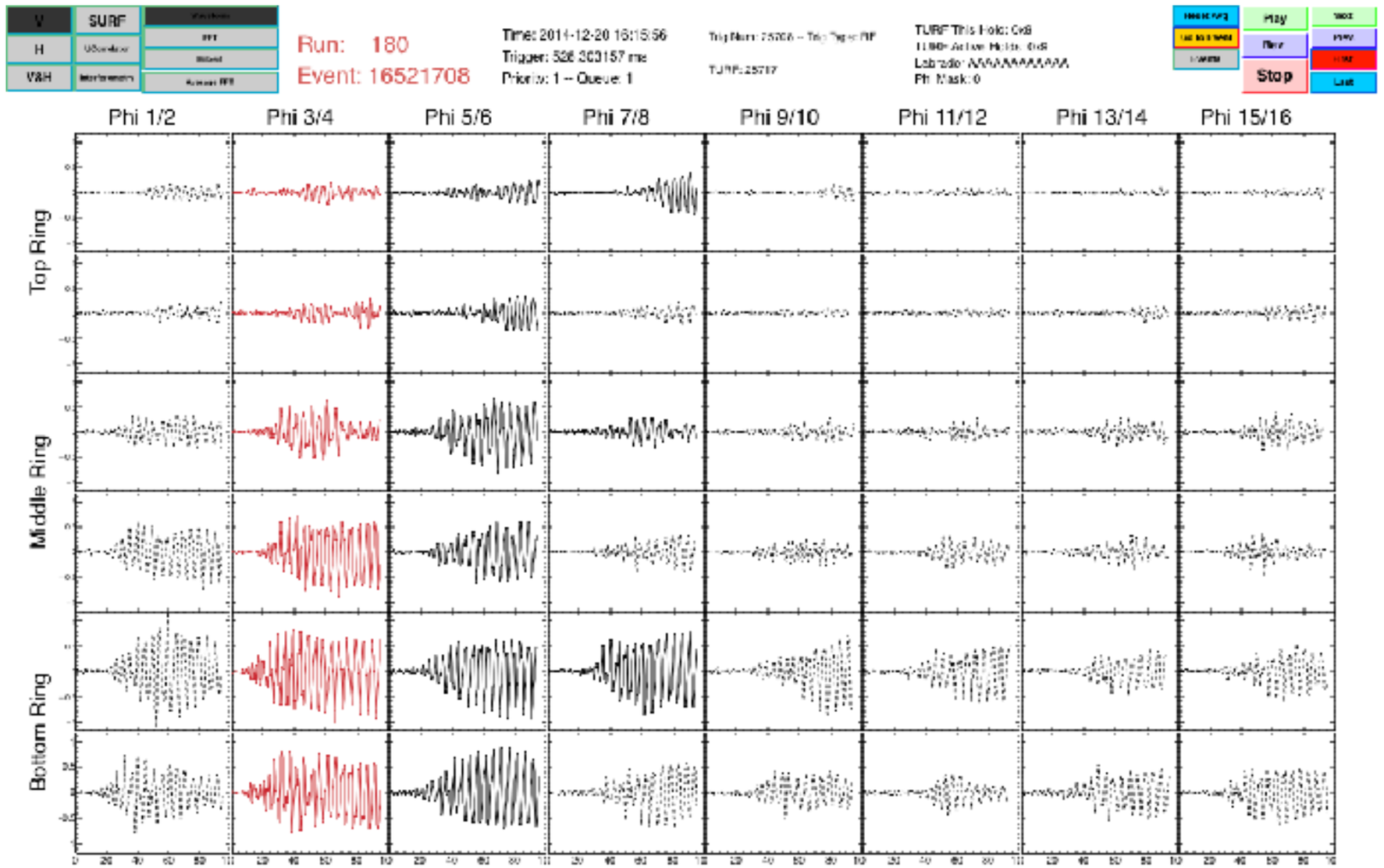
- Blazars **could** accelerate up to the highest observed cosmic rays, >1E19 eV
- IceCube-Gen2 should see loads





Payload blasts

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

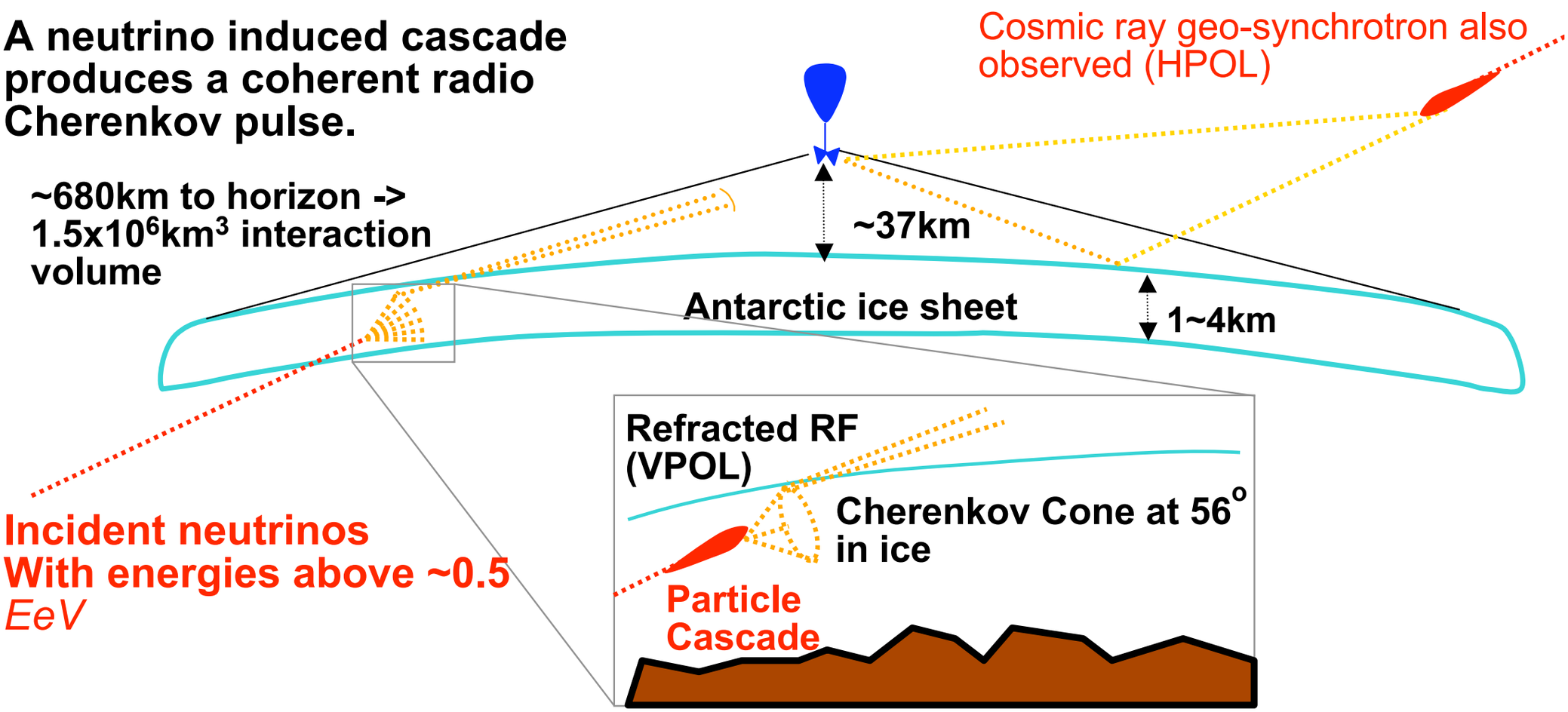


ANITA

ANtarctic **I**mpulsive **T**ransient **A**ntenna

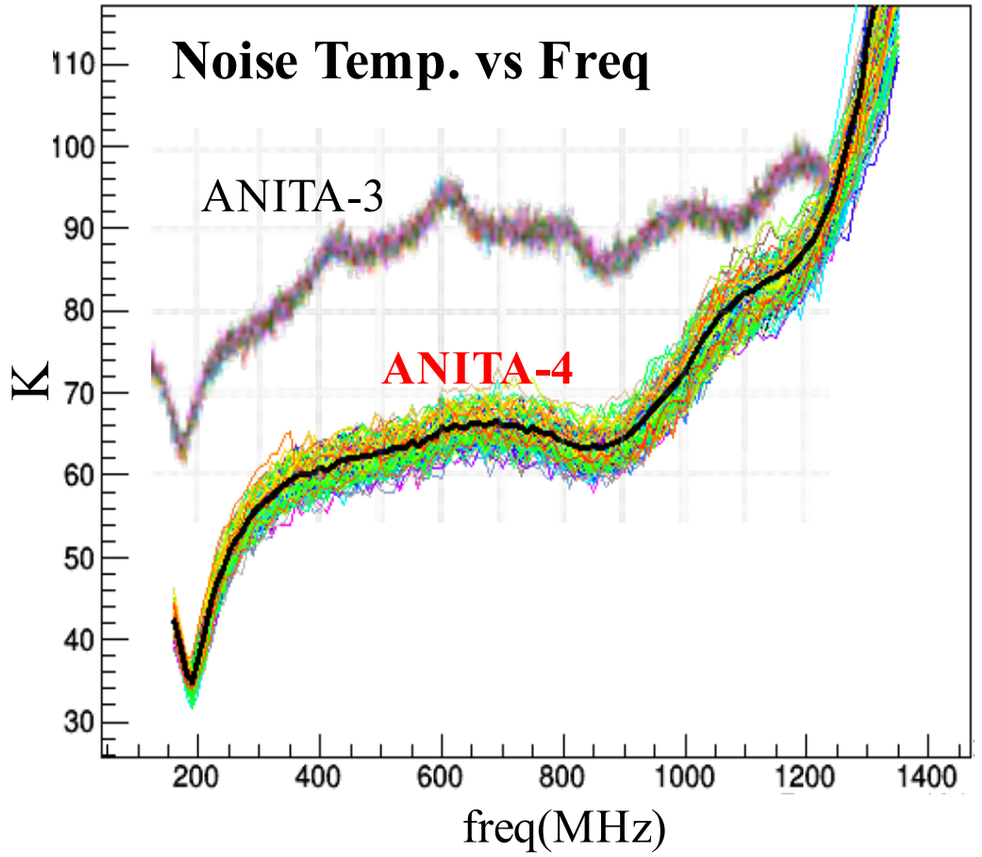
A neutrino induced cascade produces a coherent radio Cherenkov pulse.

~680km to horizon -> 1.5x10^{6}km^3 interaction volume



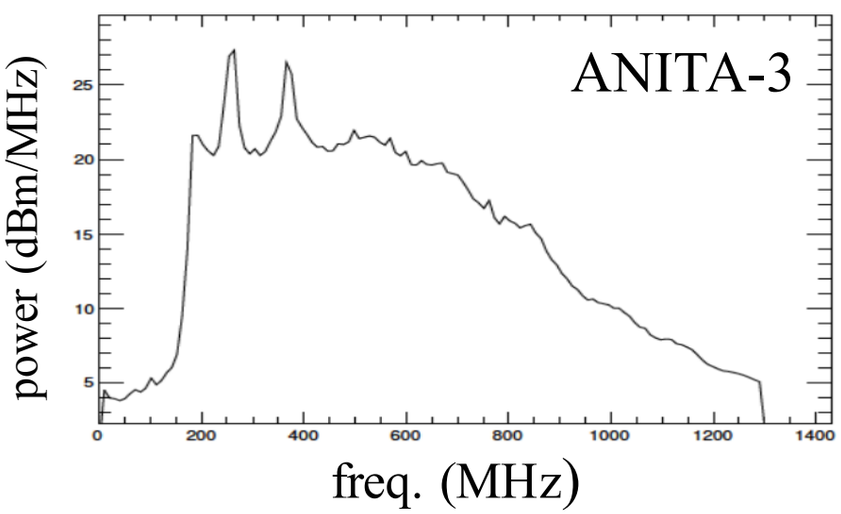
ANITA-4 improvements

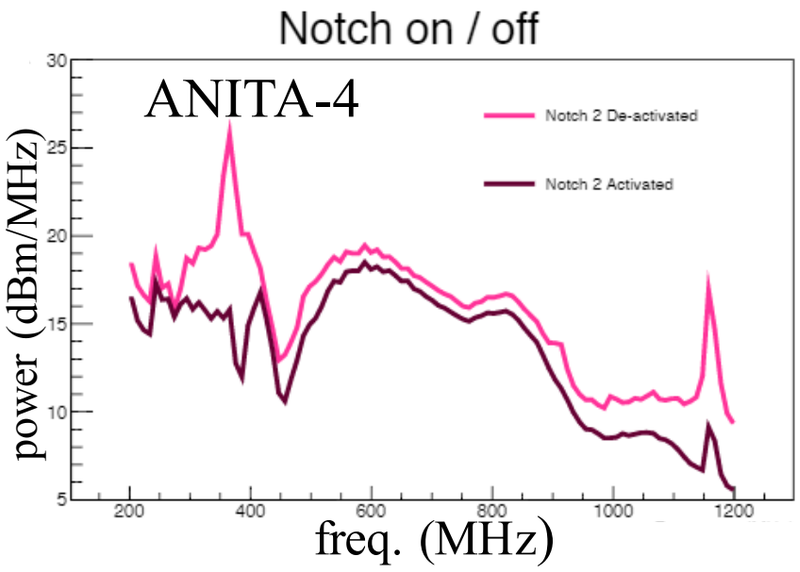
- Using Low Noise Amplifiers for all channels
  - Improvement in noise figure (30-40K)
  - 20% improvement in energy threshold



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





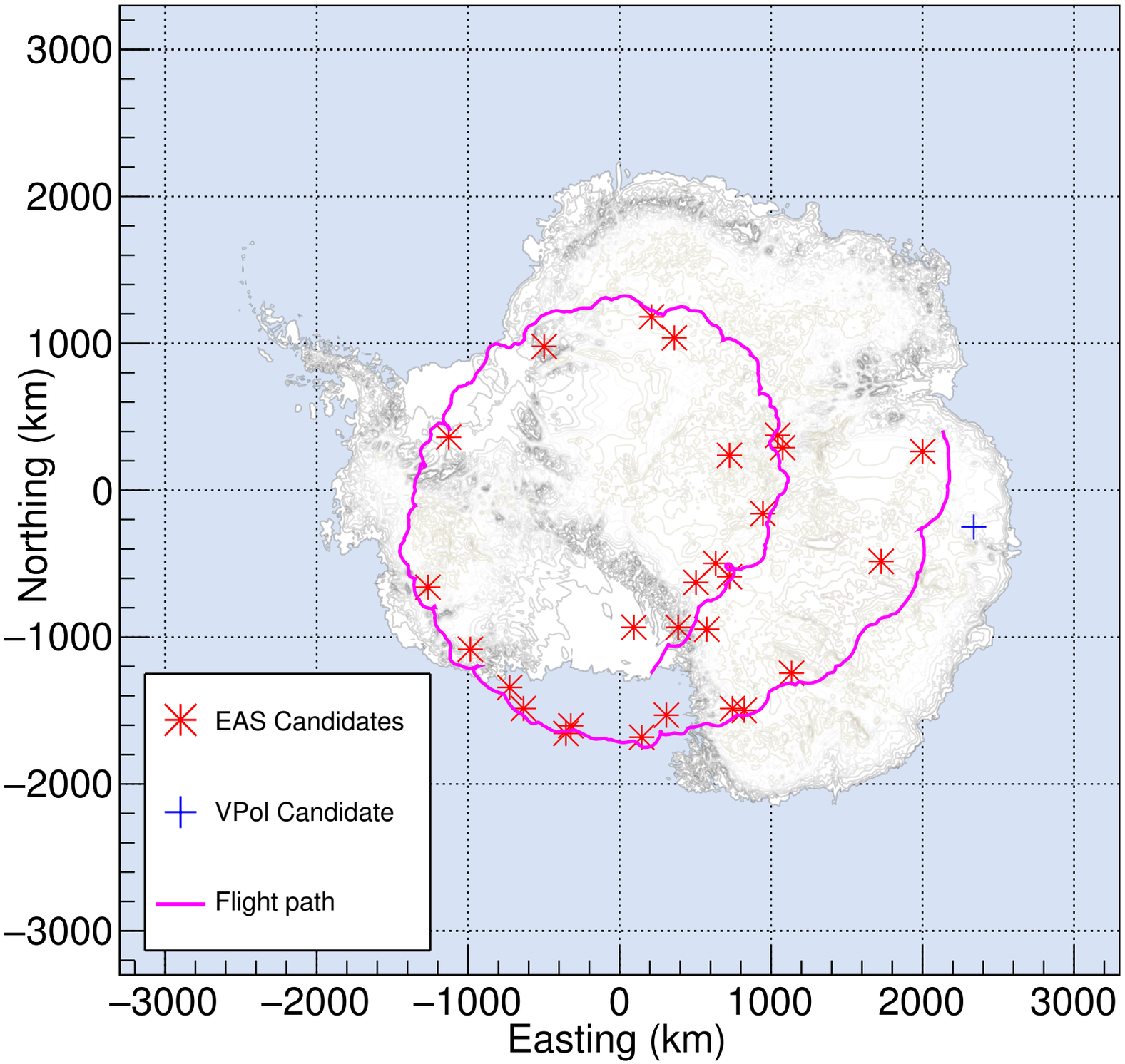
ANITA-4 improvements

- 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

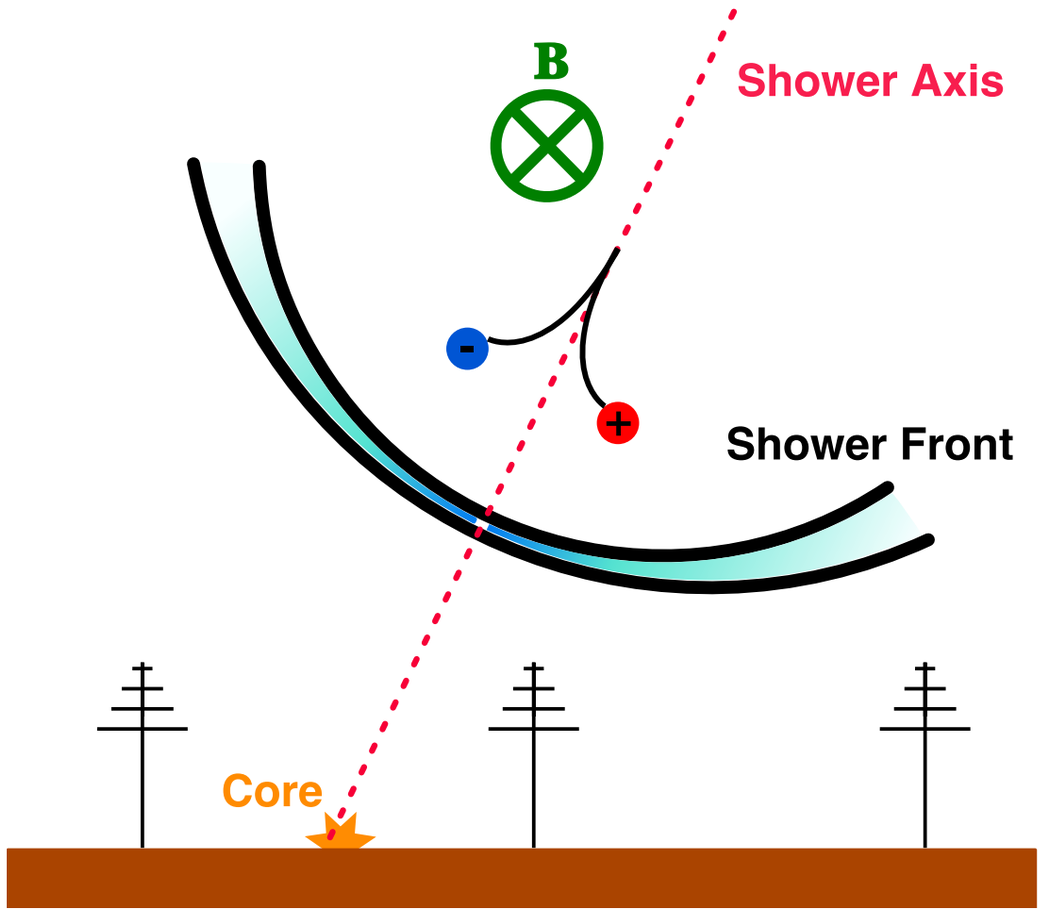
ANITA-3 efficiencies

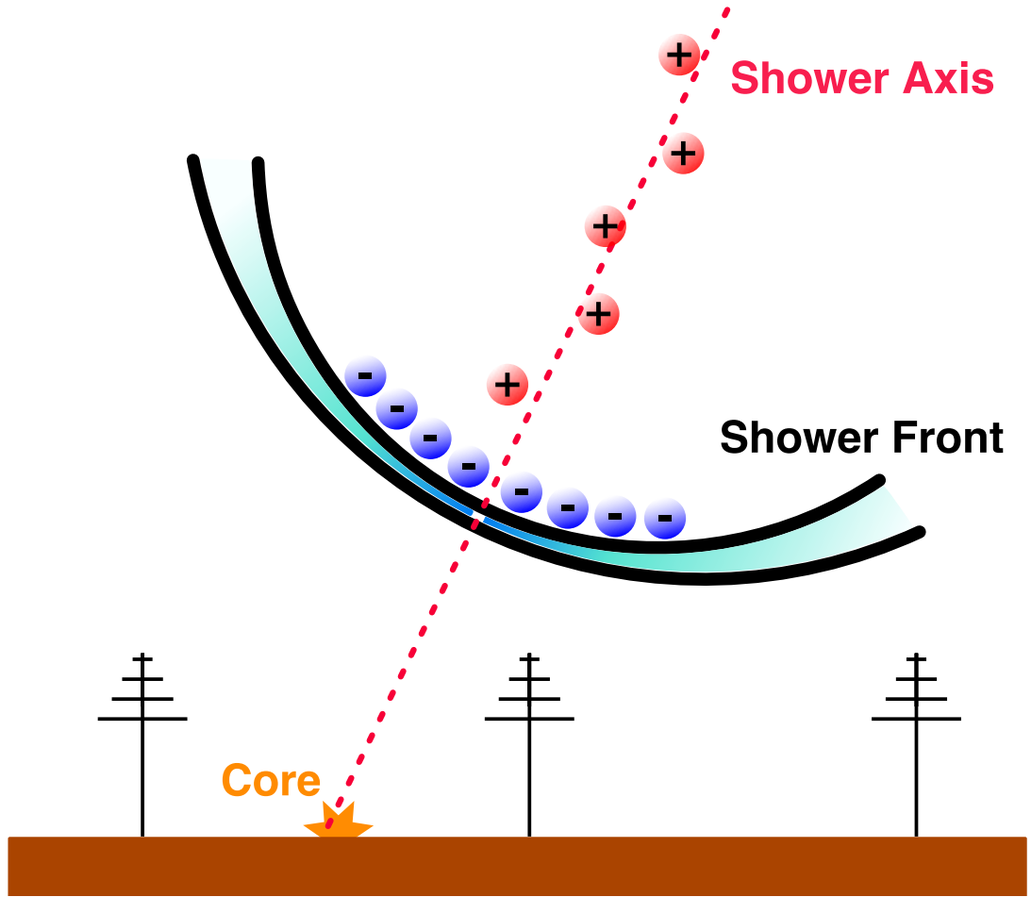
Cut	HPOL data	VPOL data	MC efficiency
None	36,700,502	38,274,132	1
Data quality	18,811,772	20,565,939	0.96
Blast	15,655,493	16,474,185	0.95
Thermal	311,795	169,824	0.88
Clustering	25	1	0.72

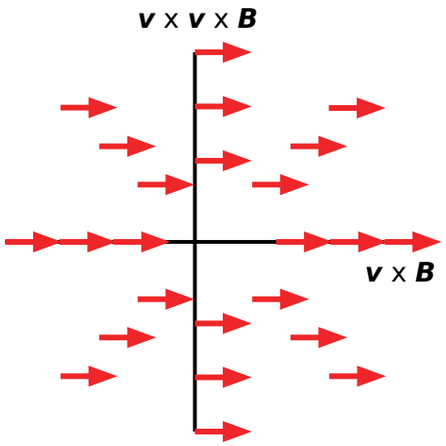
Better map


3000
2000
1000
0
−1000
−2000
−3000
Northing (km)
−3000
−2000
−1000
0
1000
2000
3000
Easting (km)
EAS Candidates
VPol Candidate
Flight path

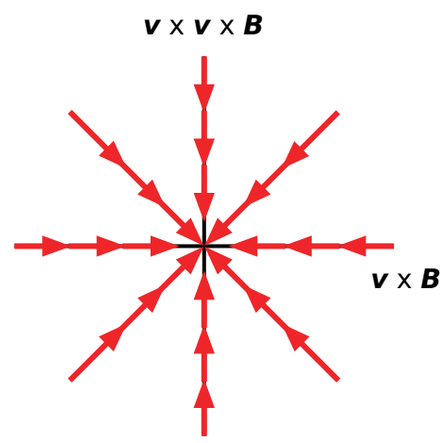
Air showers are complicated…



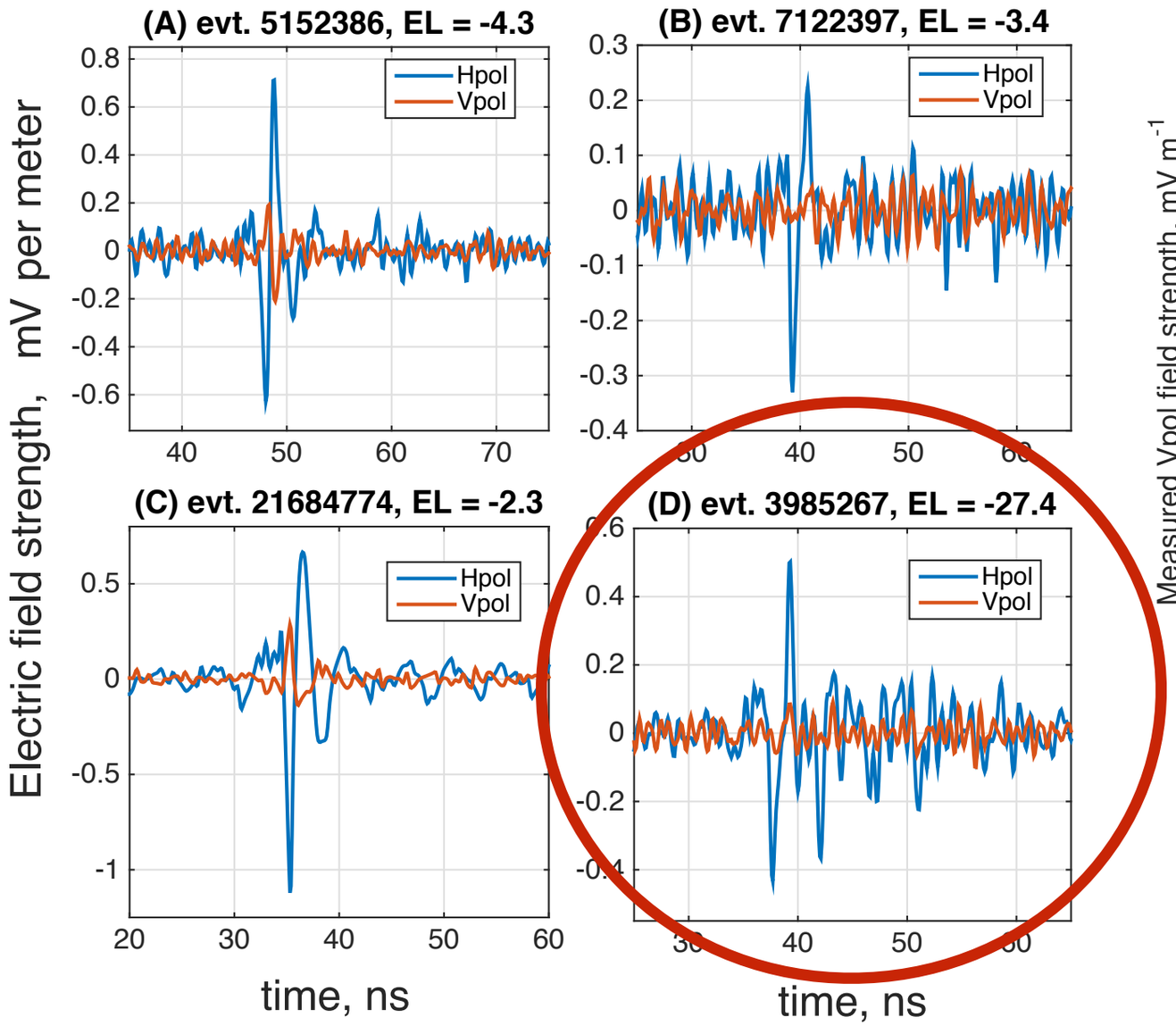


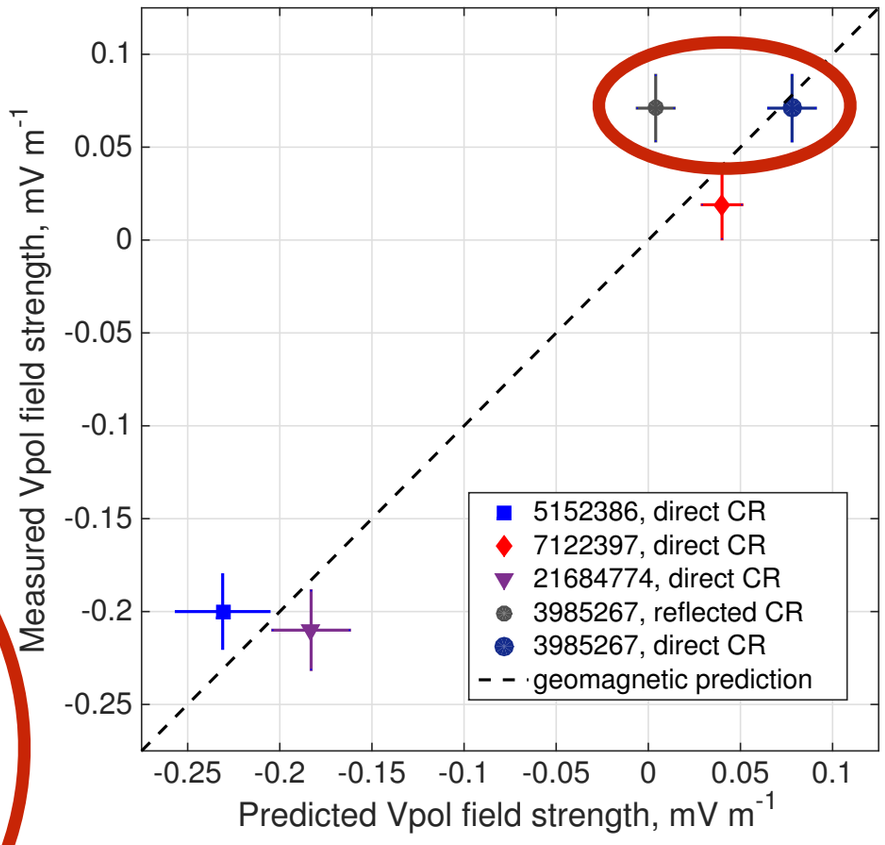


–Geomagnetic component from positron-electron separation
–Askaryan component
–Cherenkov effects from the varying refractive index of air, compresses pulse giving high frequency component



ANITA-1 mystery event



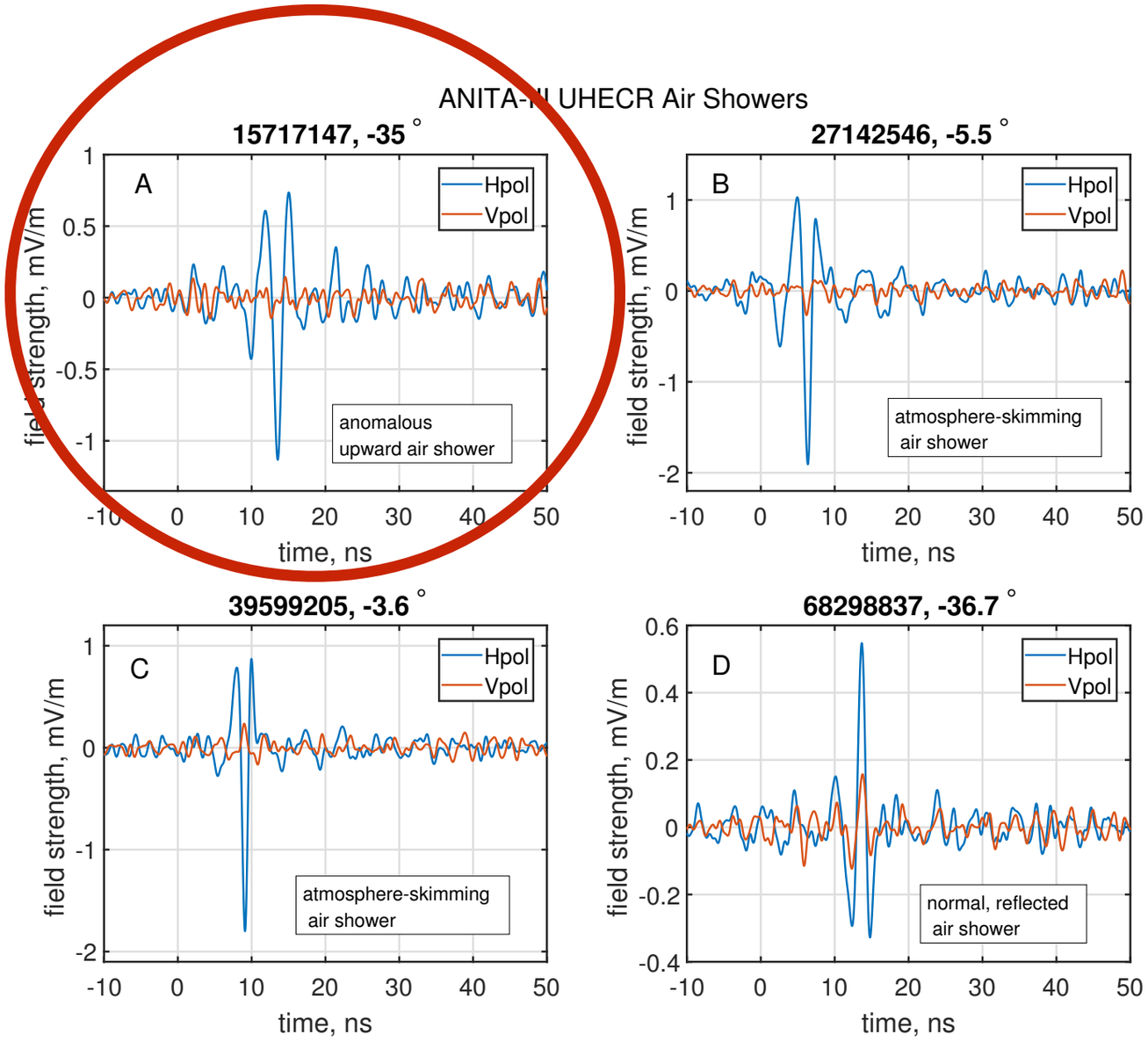


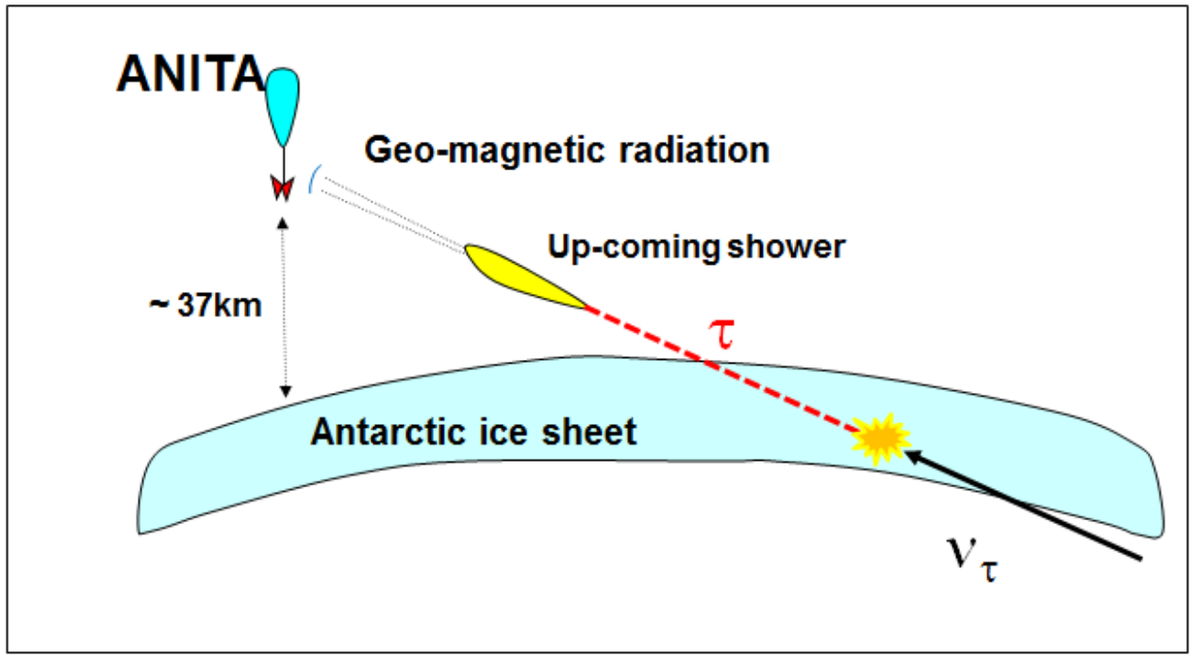
A strong H-pol non-inverted signal seen!

- Expected background events: 4×10^{-4}
- 27.4 deg below horizon, E = 0.6 ± 0.4 EeV

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

And ANITA-3 mystery event





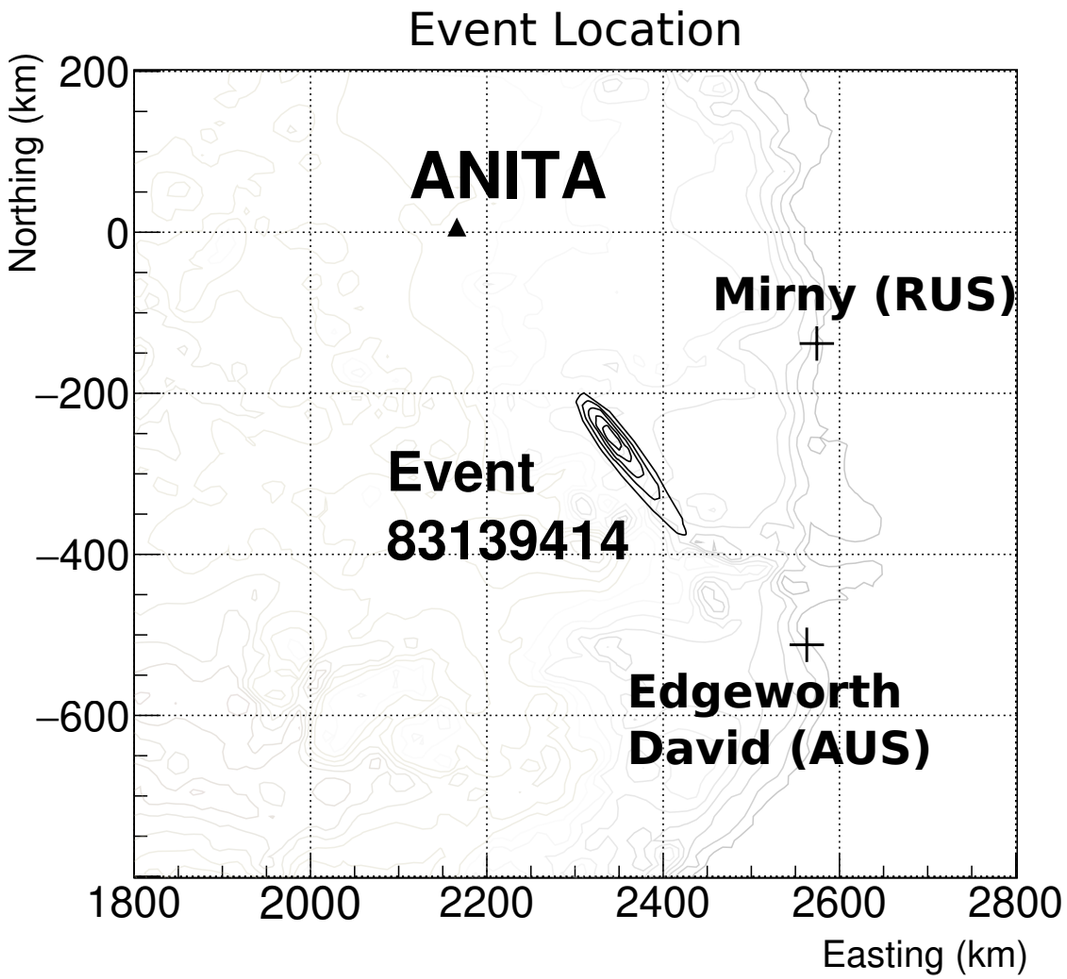
event, flight	3985267, ANITA-I	15717147, ANITA-III
date, time	2006-12-28,00:33:20UTC	2014-12-20,08:33:22.5UTC
Lat., Lon.[1]	-82.6559, 17.2842	-81.39856, 129.01626
Altitude	2.56 km	2.75 km
Ice depth	3.53 km	3.22 km
El., Az.	$-27.4 \pm 0.3°, 159.62 \pm 0.7°$	$-35.0 \pm 0.3°, 61.41 \pm 0.7°$
RA, Dec[2]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

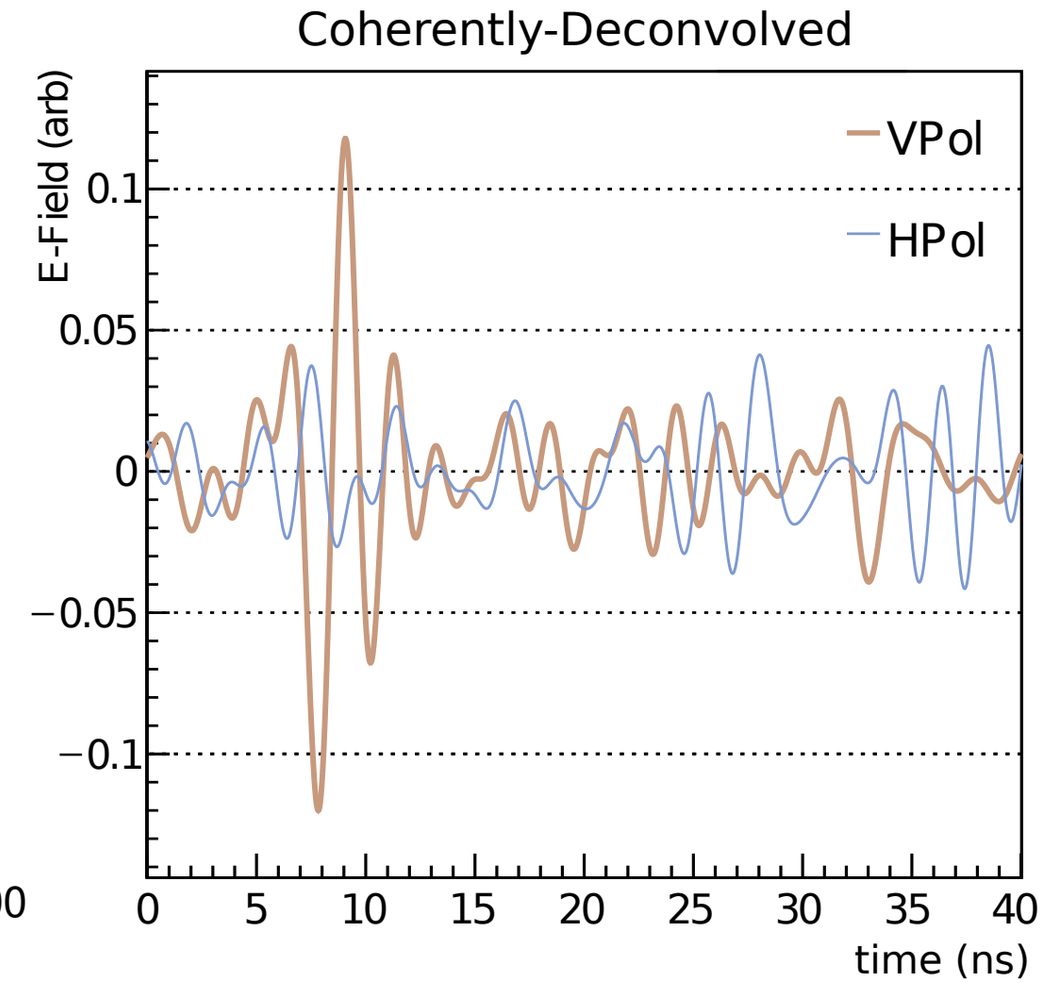
Chord length: 5500-7000 km (20-30,000km water equivalent)
1600km SM interaction length @ 1 EeV

Background estimate < 10^{-2}

ANITA-3: What's left?

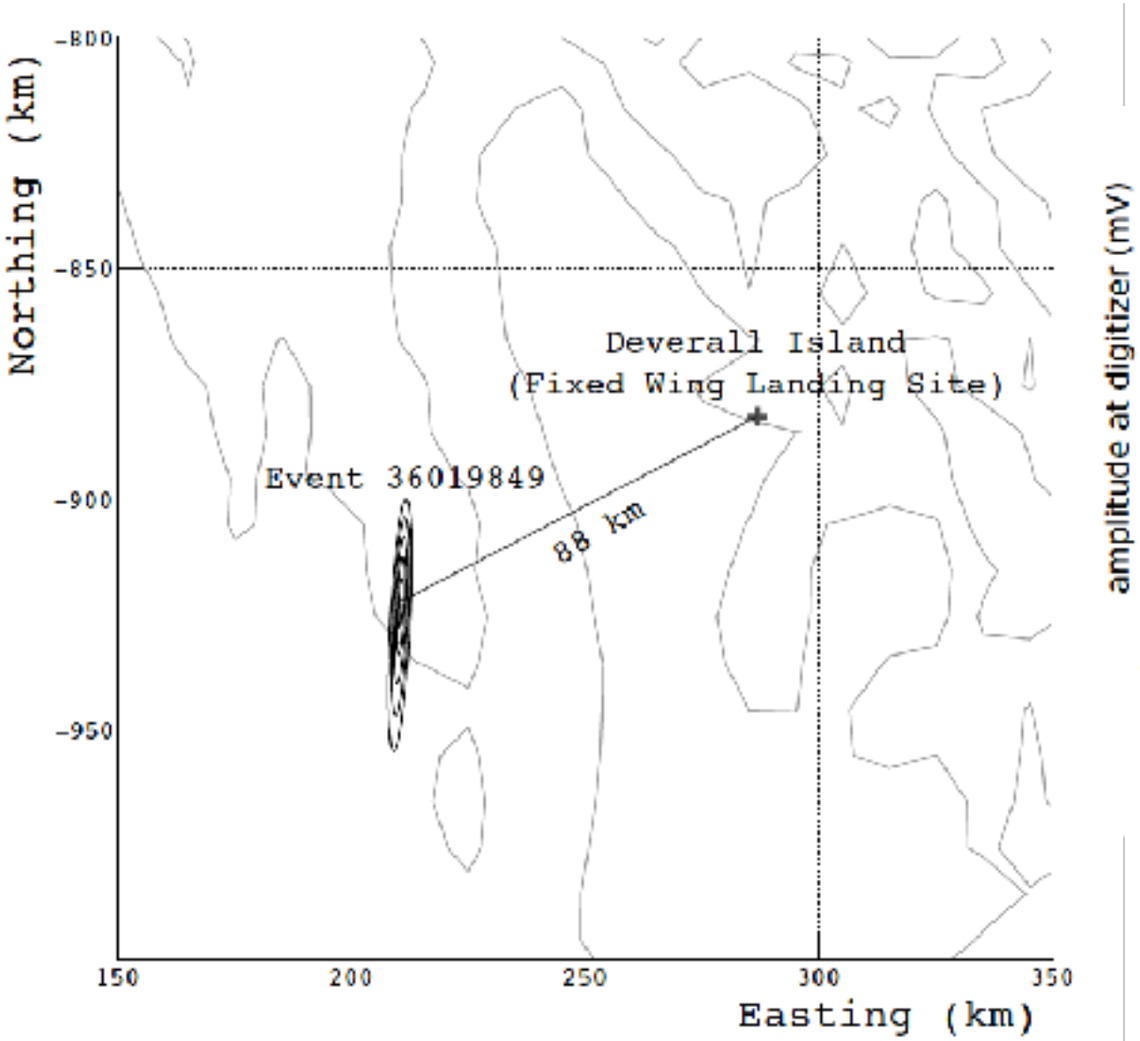
- One V-POL candidate
- Background estimate: $0.7^{+0.5}_{-0.3}$ per polarisation
- No known human activity within 260km

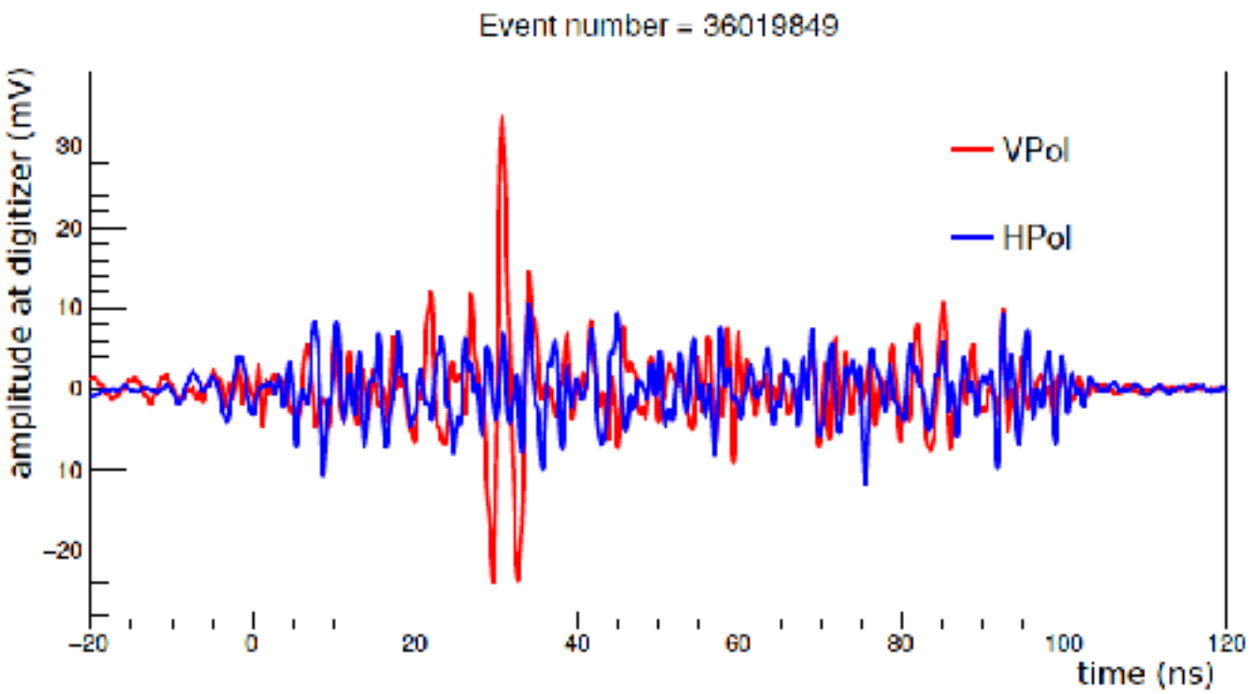




ANITA-4: What's left?

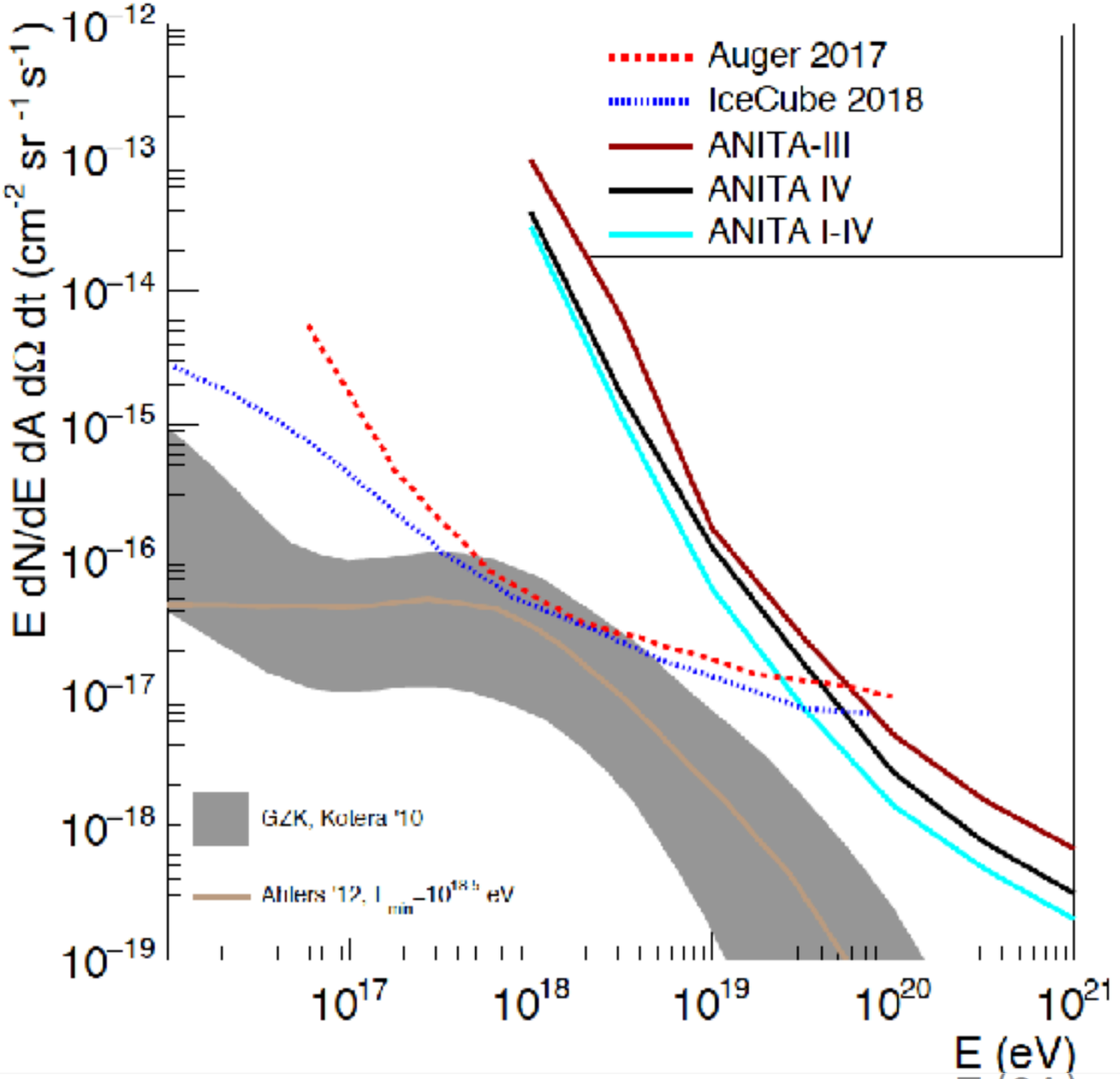
- One V-POL candidate
- Background estimate: $0.64^{+0.69}_{-0.45}$ per polarisation
- On Ross Ice Shelf (~300m ice thickness)





Neutrino limit

Limit on all-flavour-sum diffuse UHE neutrino flux



Some other interpretations..

- Sterile neutrinos explanation ($\sigma_{vs} \sim \theta^2 \sigma_v$), 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

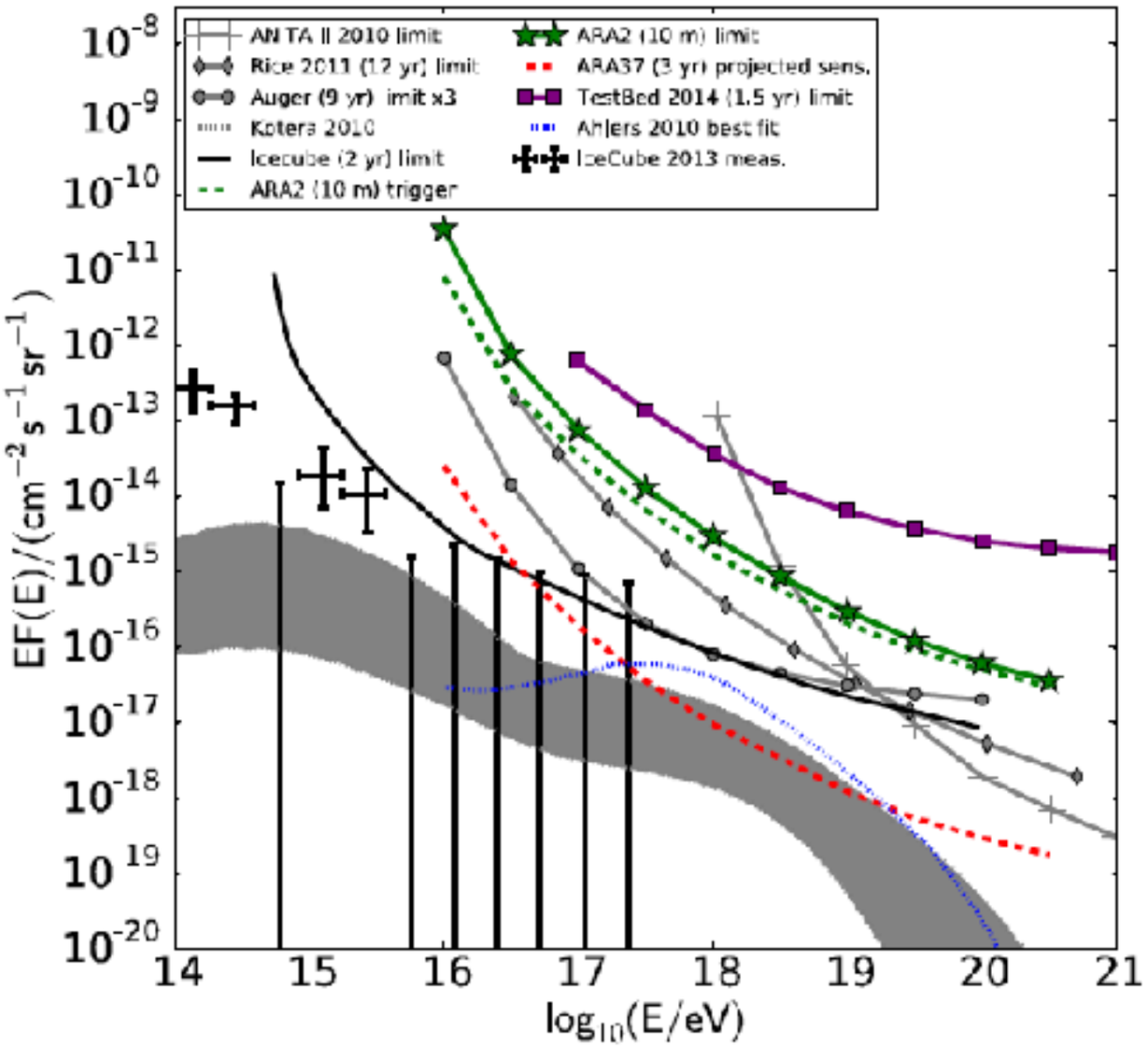
  - SN2014dz, type Ia SN at z=0.017, 5 hours after initial discovery (a posteriori chance association 2.7σ)

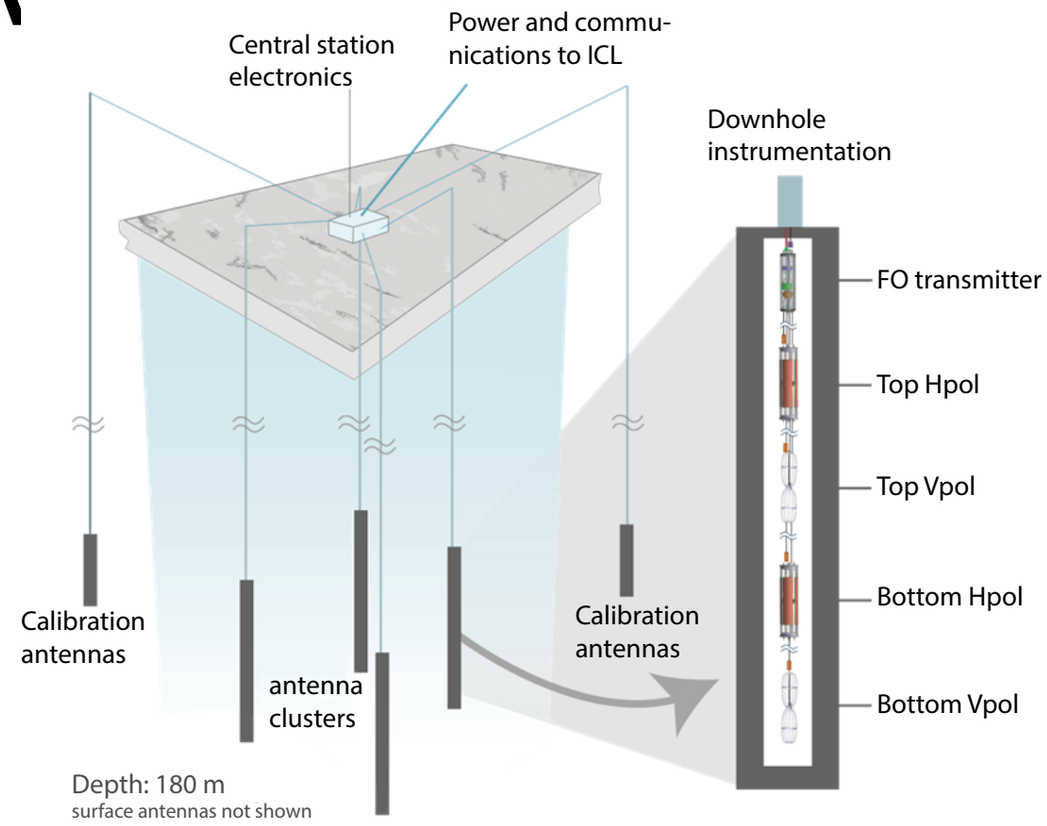
  - IceCube point-source analysis excluded the possibility of them coming from a transient source (arXiv: 2001.01737)

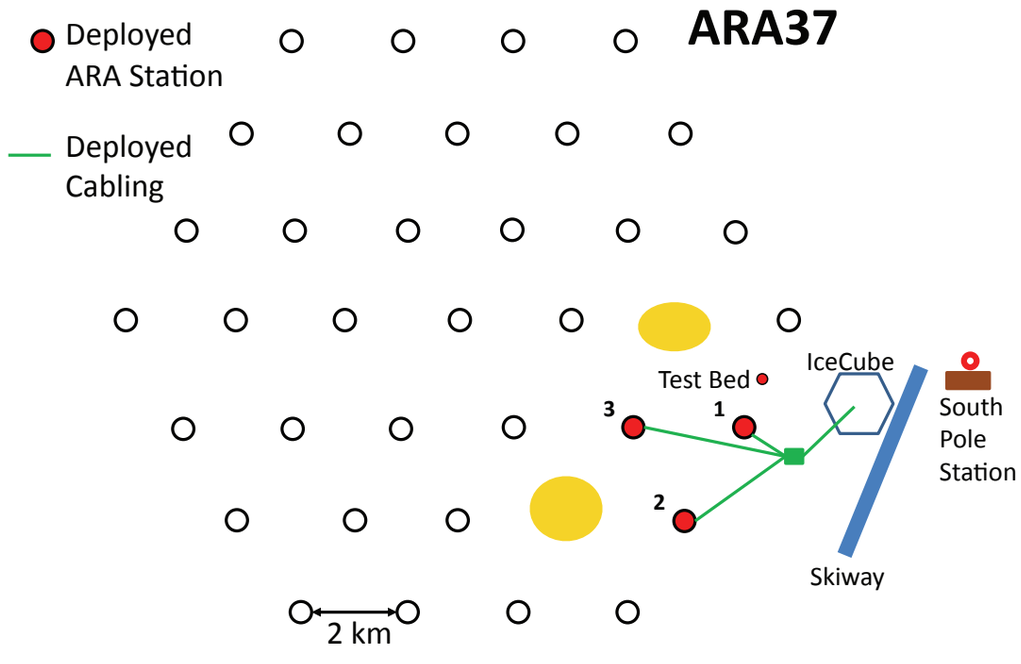
ARA

Askaryan Radio Array: 5 deployed station and 1 phased array

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



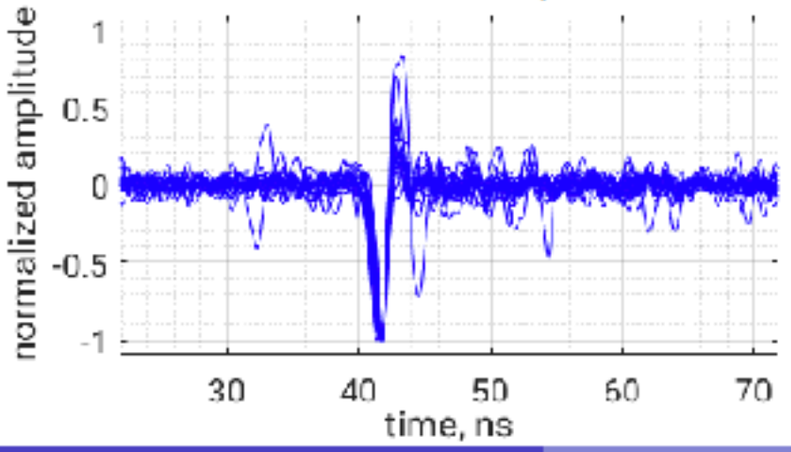




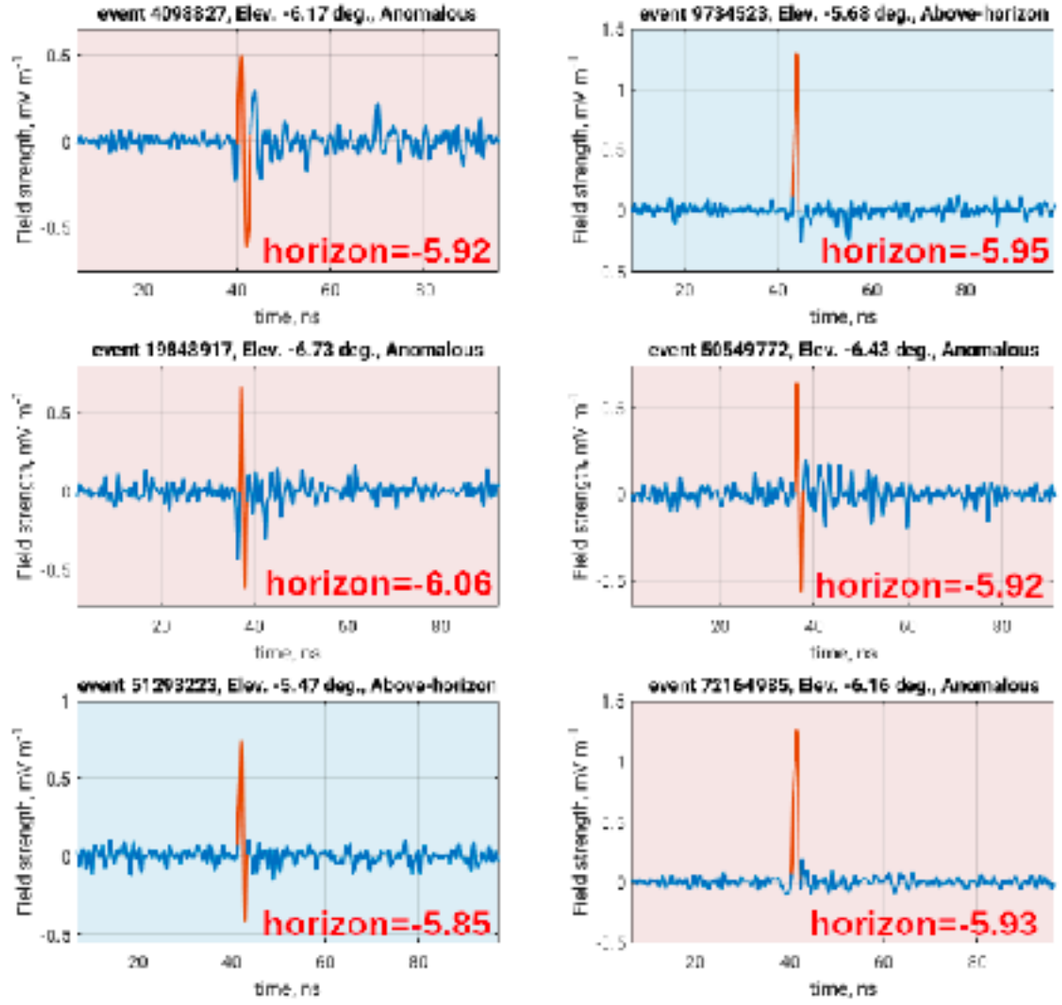
Hot off the presses: upward showers in ANITA-IV?

- Time-dependent filters made polarity determination more complicated in ANITA-IV.
- **4 upward-shower candidates identified**
- But... all very near horizon ($\sim -6^\circ$)
- $\sim 3.2\sigma$ that ensemble not explained by:
  - mispointed above-horizon air shower (including systematics!)
  - anthropogenic background (est. $0.37^{+0.27}_{-0.17}$)
  - misidentified polarity

21 reflected, below-horizon events (CLEAN-deconvolved):



6 unreflected events, 4 (barely) below-horizon (CLEAN-deconvolved):



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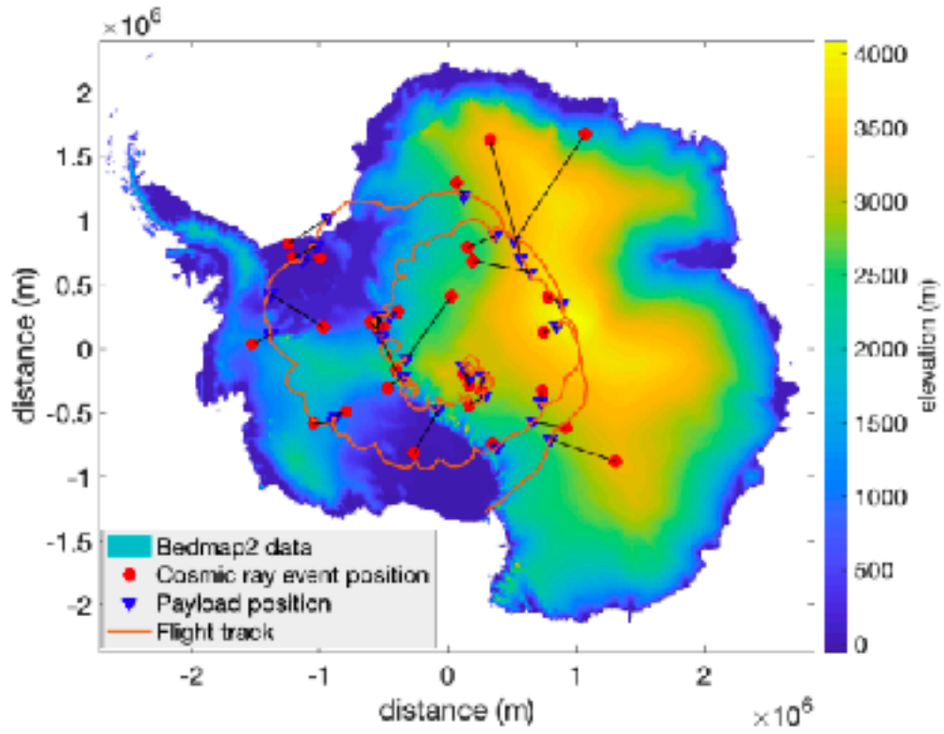
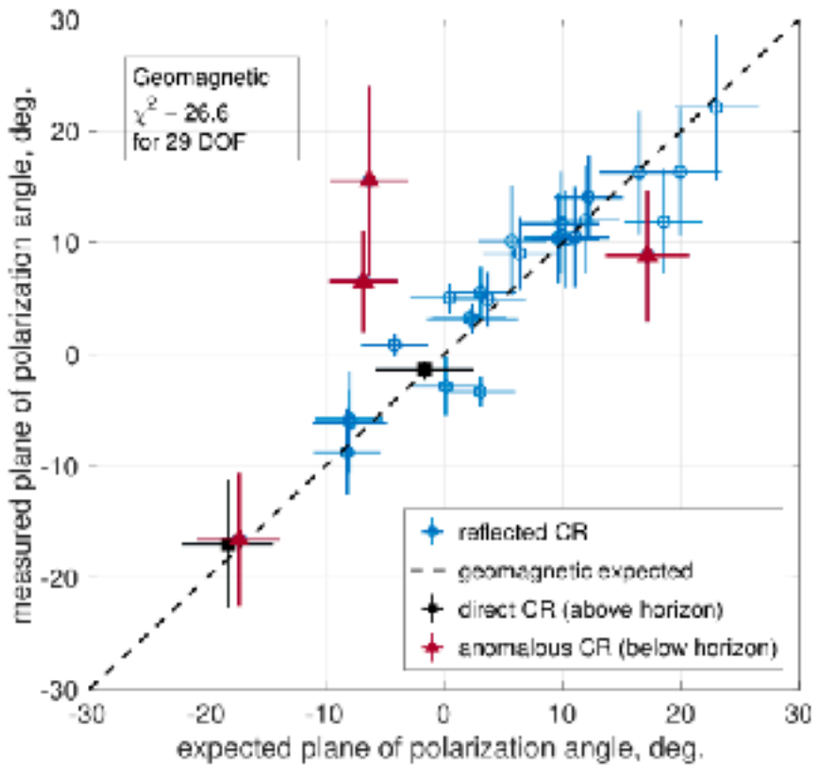
More details on the ANITA-IV events

Check arXiv tonight! (Finally) submitted to PRL.





event #	mm dd hh mm ss UTC 2016	Apparent source location Lat.°,Lon.°, alt., m	elev. angle degrees	horizon angle degrees	azimuth degrees	Payload location Lat.°, Lon.°, alt., km	Type	Energy EeV
4098827	12 03 10 03 27	-75.71, 123.99, 3184	$-6.17 \mid 0.21$	$-5.92 \mid 0.02$	337.70	-80.157, 131.210, 38.86	NI	$1.5 \mid 0.7$
9734523	12 05 12 55 40	-71.862, 32.61, 19000[b]	-5.64 ± 0.20	-5.95 ± 0.02	2.01	-80.9, 31.6, 39.25	AH	...
19848917	12 08 11 44 54	-80.818 , -79.87, 758	-6.71 ± 0.2	-6.06 ± 0.02	194.34	-76.66, -72.86, 38.97	NI	0.9 ± 0.5
50549772	12 16 15 03 19	-83.483, 14.73, 2572	6.73 ± 0.2	5.92 ± 0.02	234.08	-81.95, 47.29, 38.52	NI	0.8 ± 0.3
51293223	12 16 19 08 08	-74.800, 11.43, 18600[b]	-5.38 ± 0.24	-5.85 ± 0.02	306.45	-81.7, 39.2, 37.53	AH	...
72164985	12 22 06 28 14	-86.598, 0.35, 2589	-6.12 ± 0.10	-5.93 ± 0.02	140.03	-86.93, -104.29, 38.58	NI	3.9 ± 2.5

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Interpretation of ANITA-IV events

- These are qualitatively different than previous apparent upward showers (very close to horizon rather than steeply upgoing).
  - The fact that we didn't see any new steep events is not enough to rule those out (in fact there were two events with indeterminate polarity we could not confidently classify one way or another, including one that was steep)
  - No easy way to combine significances across flights.
- Still evaluating if tau neutrino hypothesis could be viable
  - Not obviously unviable like it was for steep events, due to less Earth absorption and ANITA's large instantaneous exposure
- Some proposed mundane explanations are harder to invoke:
  - Much larger ice reflection area, would require greater conspiracy of ice effects
  - Grazing air showers don't hit ice
- But, near-horizon radio propagation is complex and hard to model. Possible that more detailed future modeling will reveal additional systematics in addition to the ones we are already considering.

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