Prospects in UHE Neutrino Astronomy

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Penn State
XXIX International Conference on Neutrinos
June 30

- ➤Why Ultra-high-energy (UHE, > PeV) Neutrinos?
- ➤Experimental landscape,
  particular focus on radio instruments
- ➤New results from ANITA-4

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  particular focus on radio instruments
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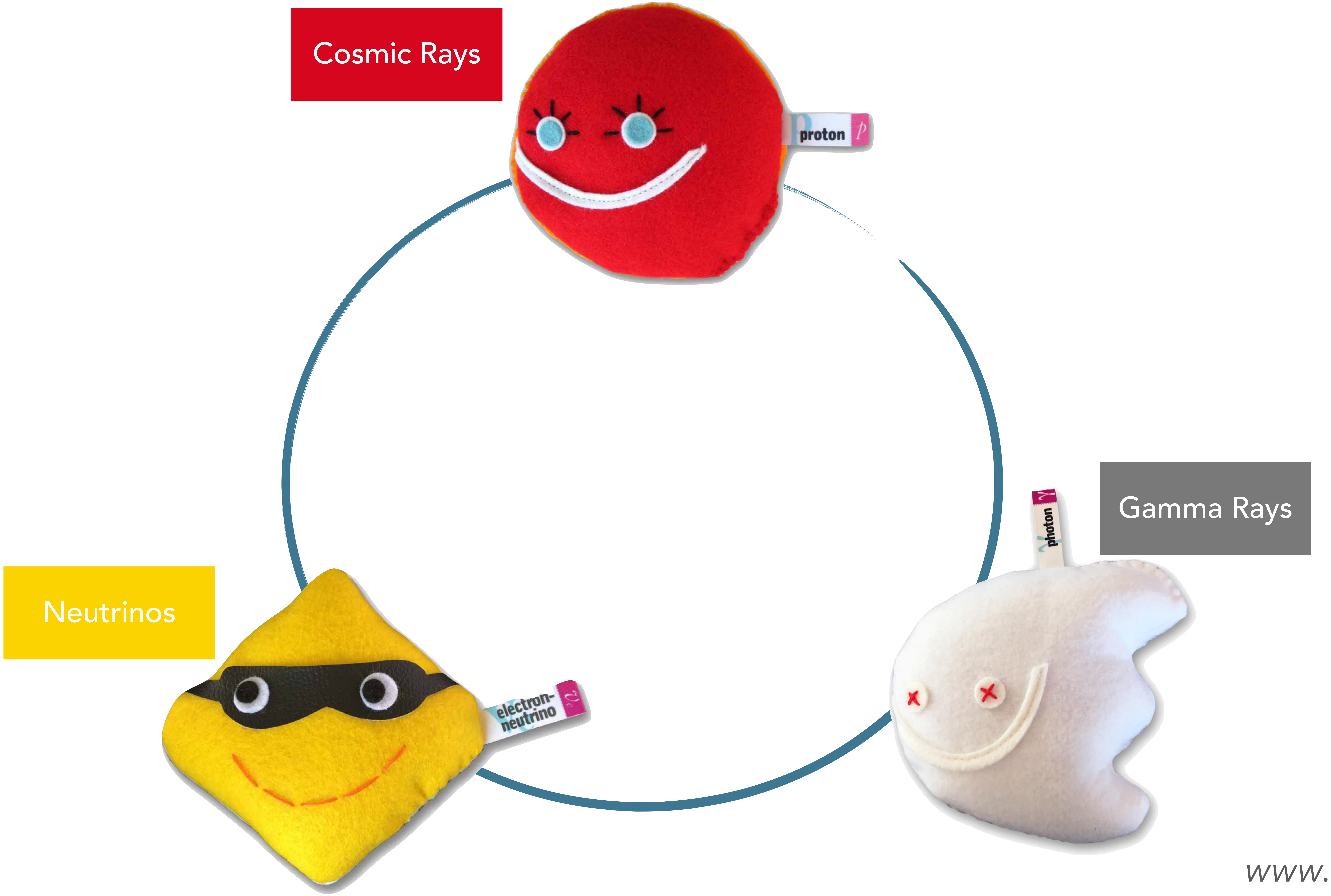
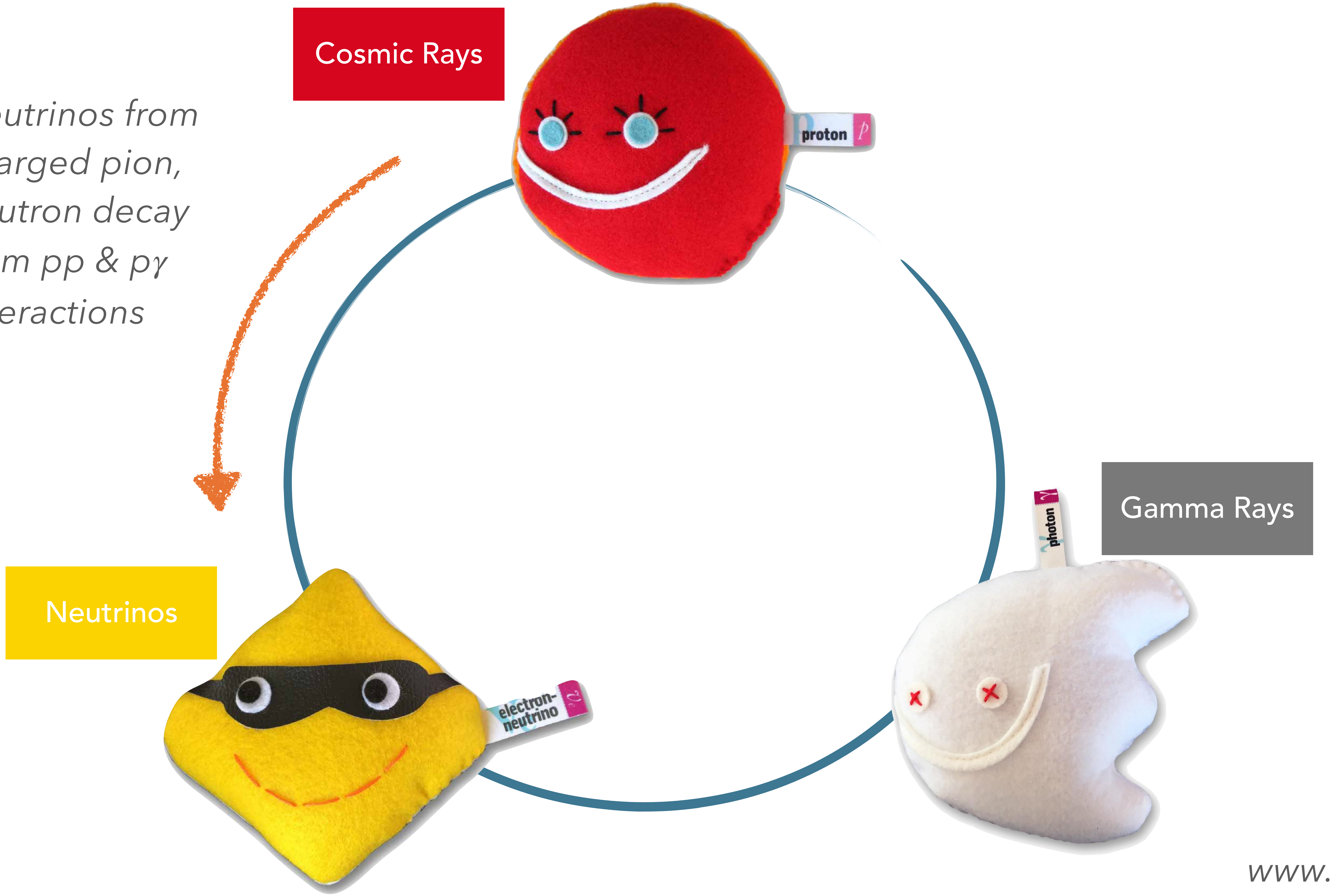
Messenger Particles



MESSENGER PARTICLES

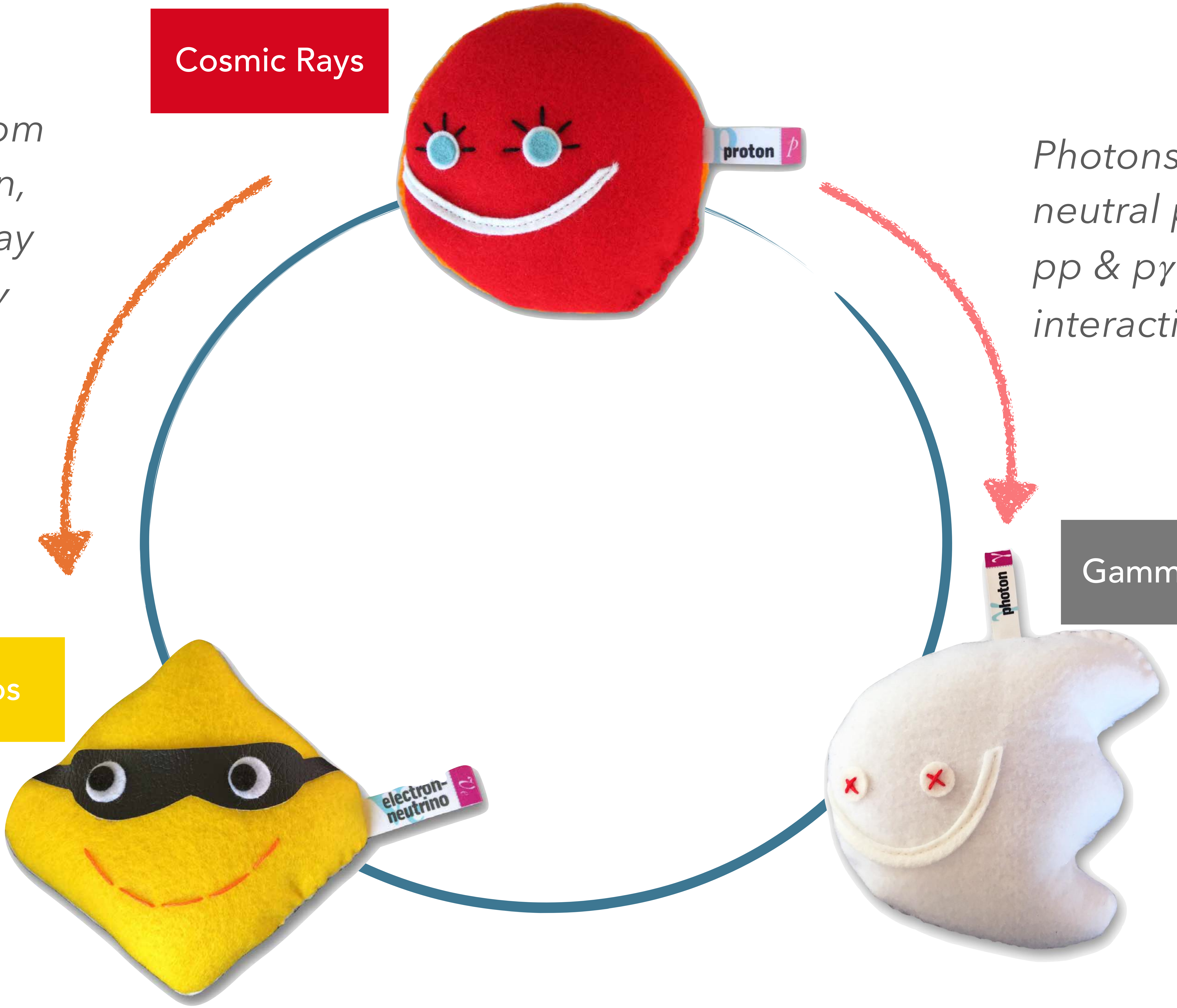
Neutrinos from charged pion, neutron decay from pp & pγ interactions



www.particlezoo.net

Messenger Particles

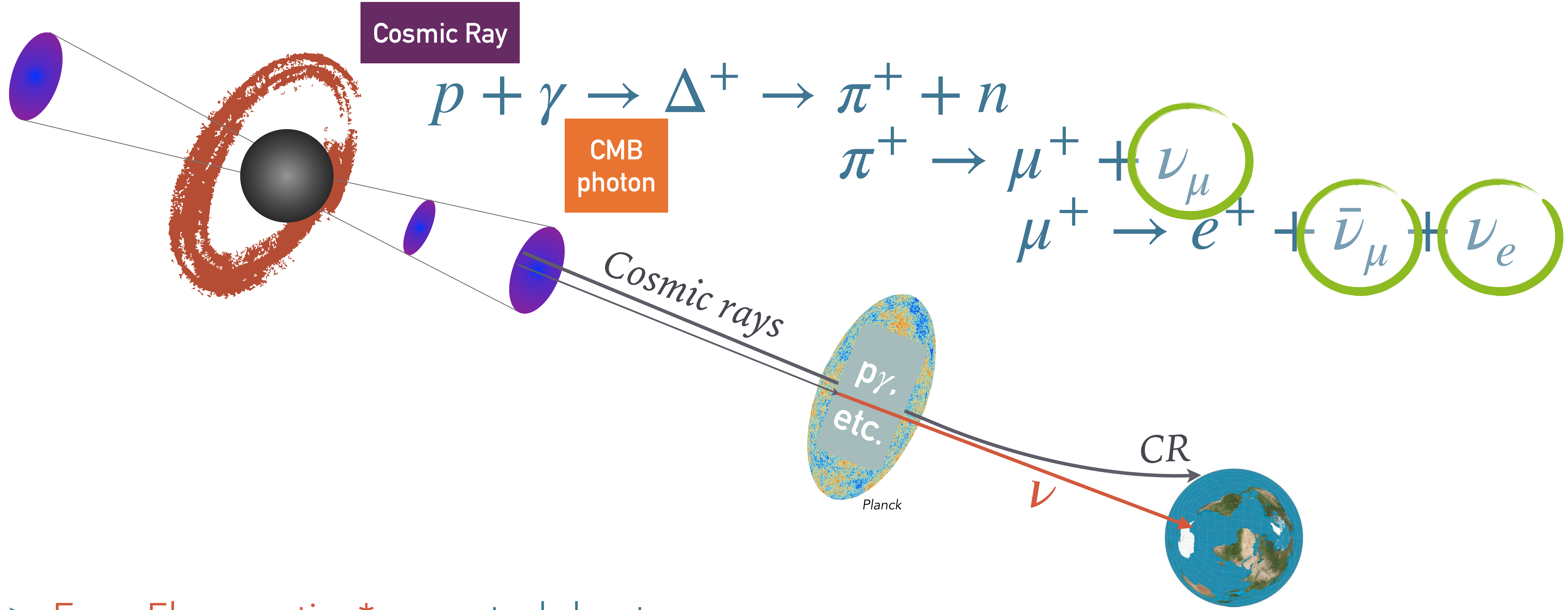
Neutrinos from charged pion, neutron decay from pp & pγ interactions



Photons from neutral pion, from pp & pγ interactions

Multi-Messenger Astrophysics

Cosmogenic Neutrinos Point to the Highest Energy Accelerators

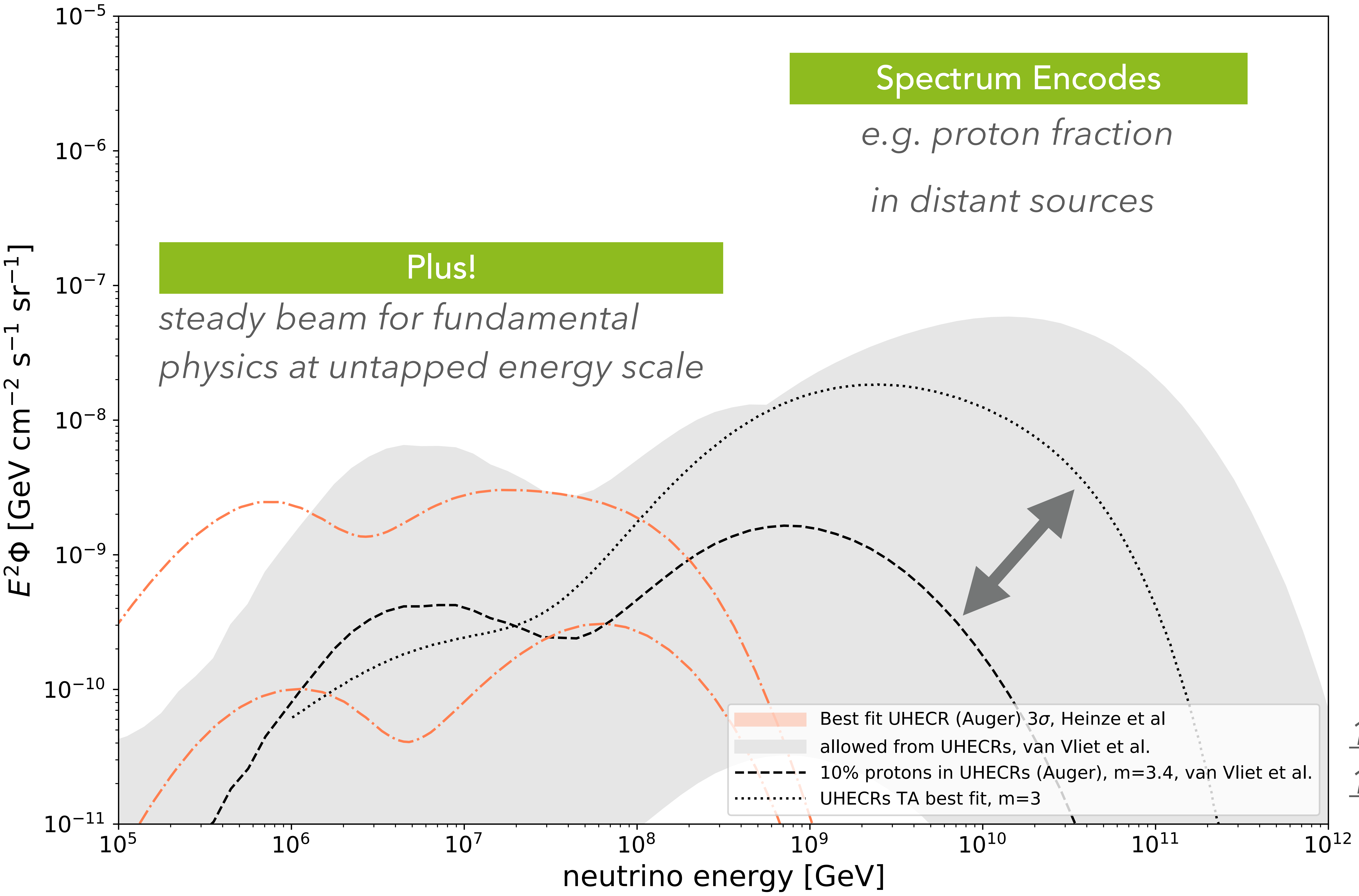


- Even Flavor ratios* expected due to flavor oscillations over Gpc length scales

**Deviations from standard flavor ratios expected from Beyond-Standard-Model scenarios*

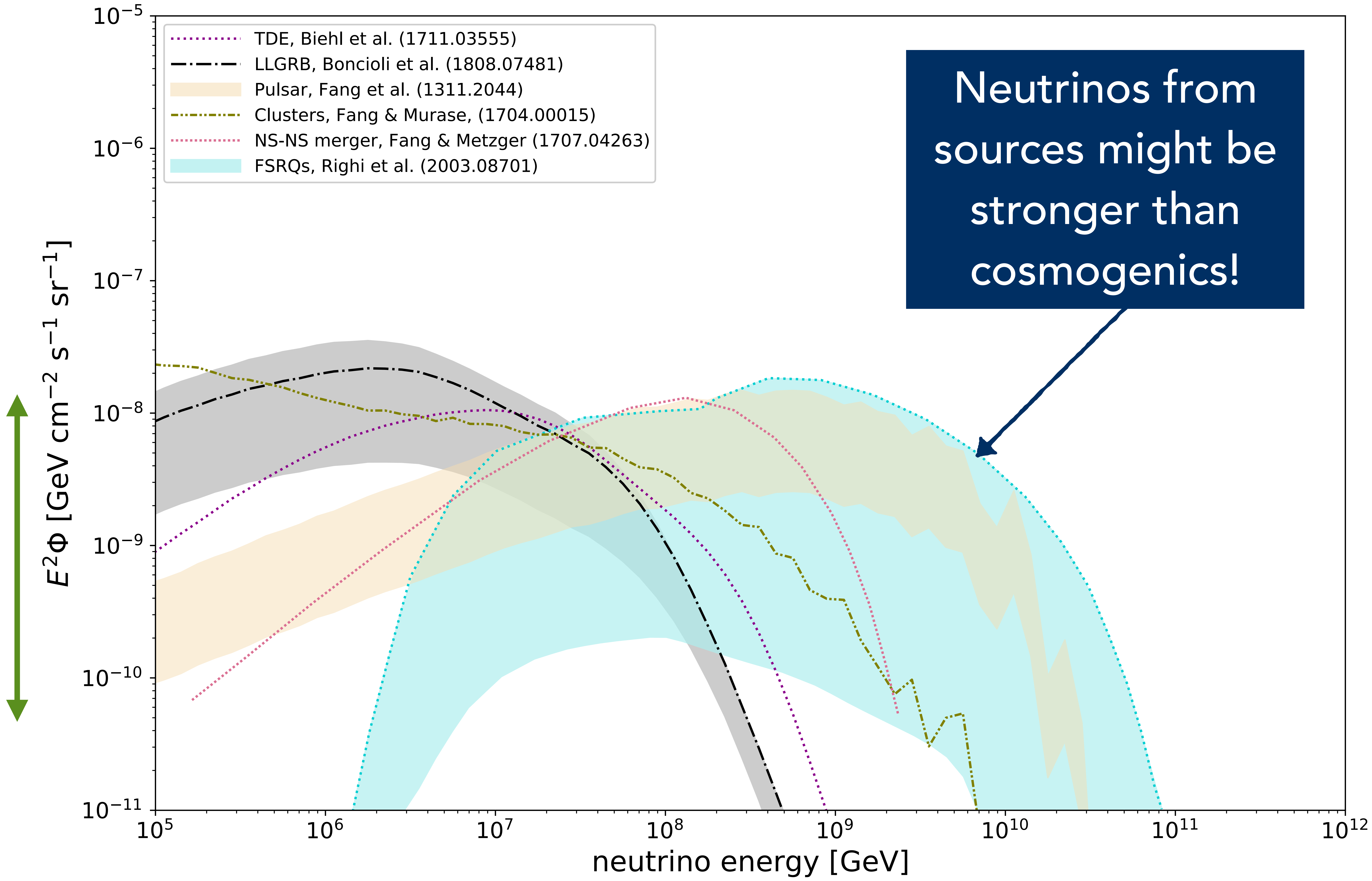
DIFFUSE UHE NEUTRINOS - COSMOGENIC NEUTRINOS

Best fits based on cosmic ray data predict this range of fluxes

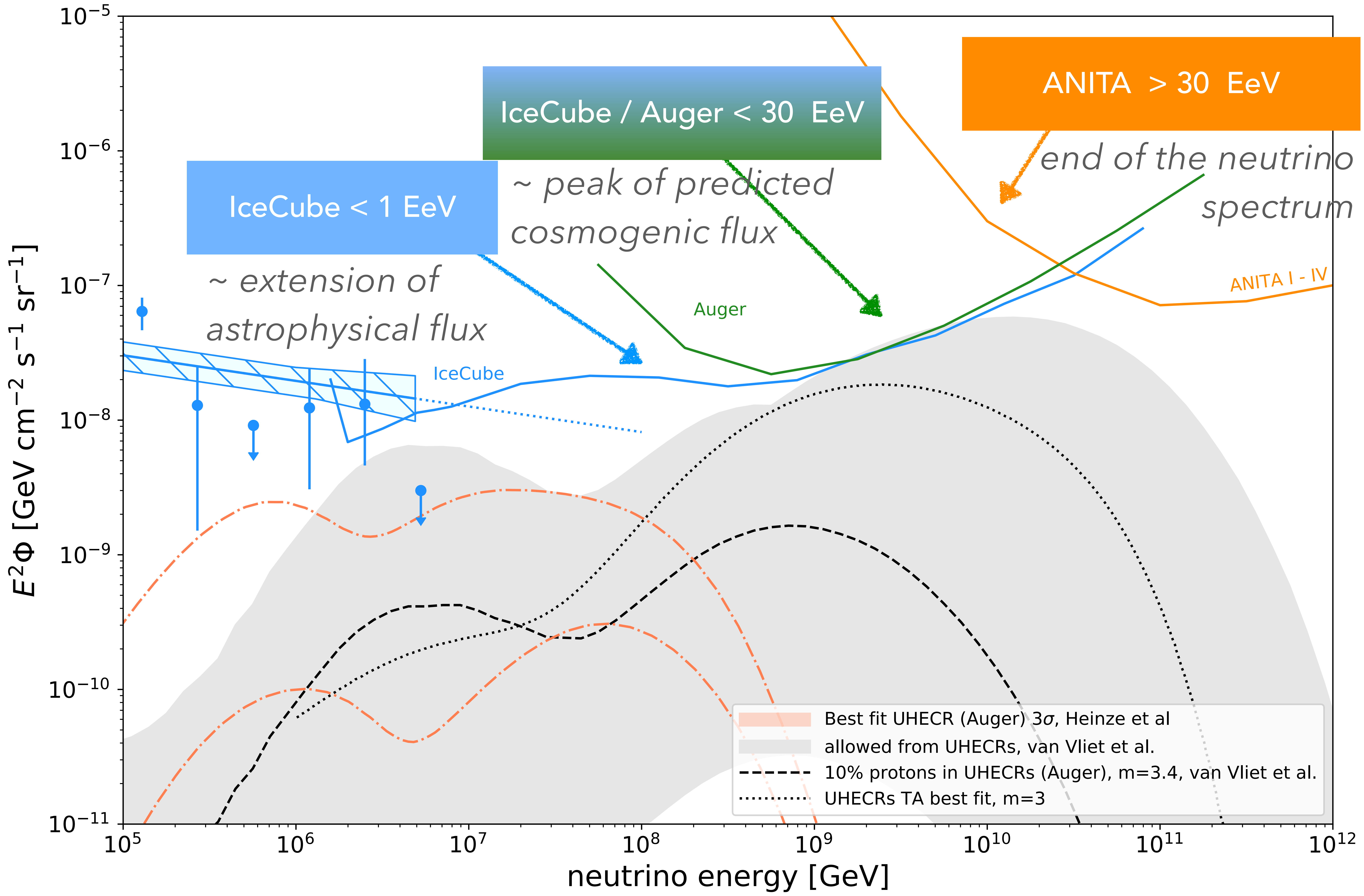


1901.03338
1901.01899

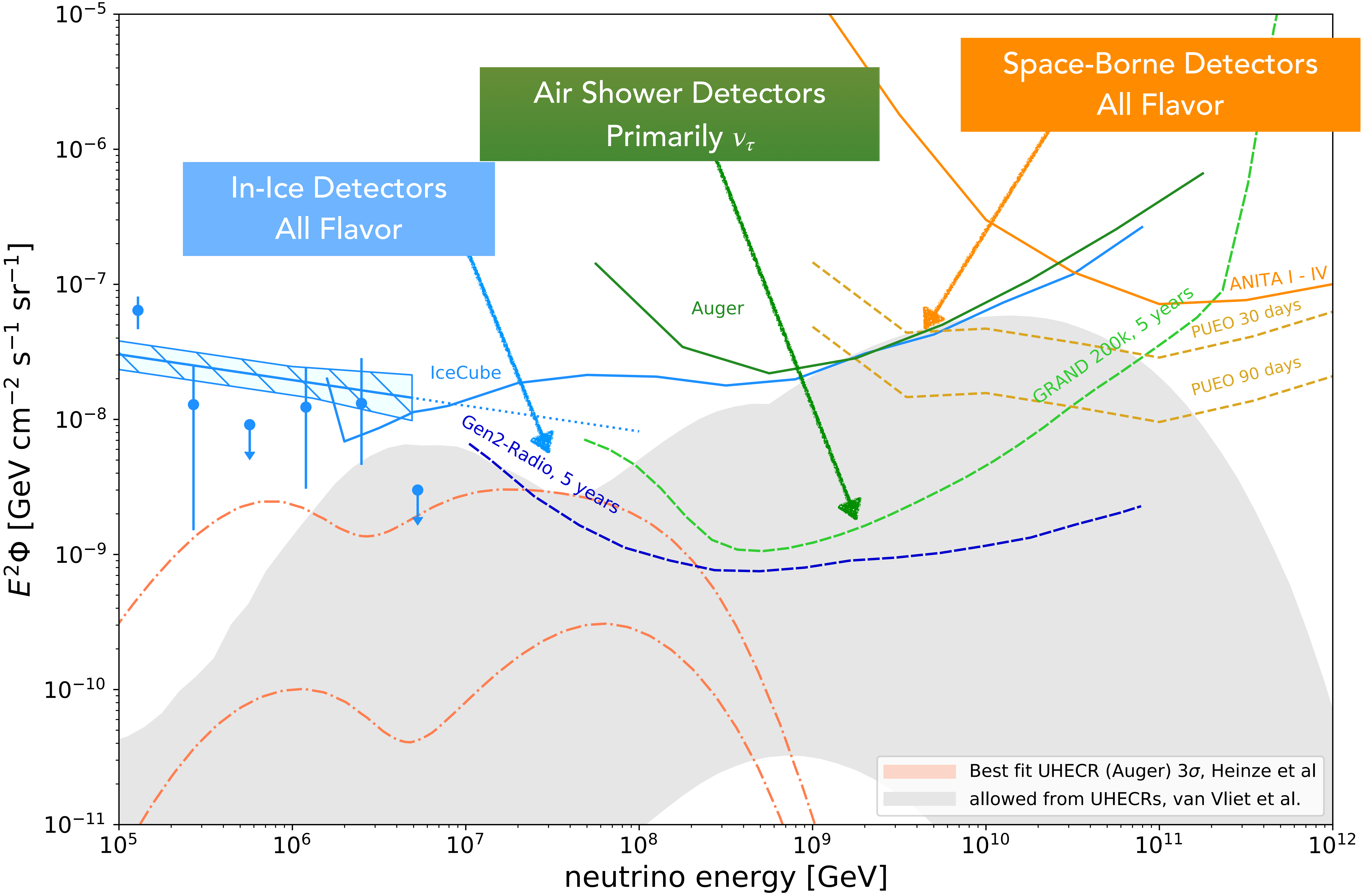
UHE Neutrinos - Astrophysical Neutrinos



DIFFUSE UHE NEUTRINOS - EXPERIMENTAL CONSTRAINTS



Diffuse UHE Neutrinos - Next Generation Radio Detectors

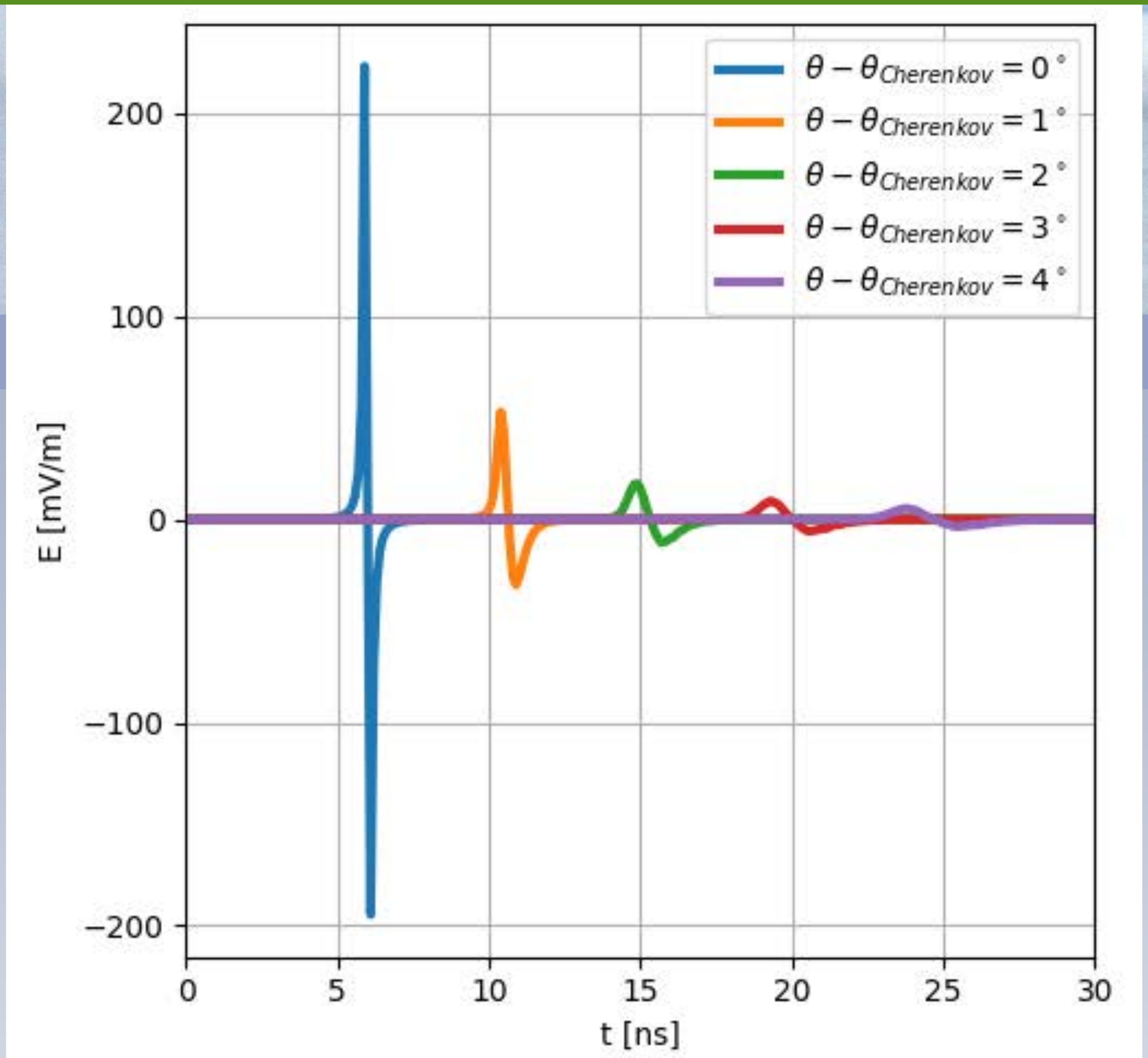


- Why Ultra-high-energy (UHE, >PeV) Neutrinos?
- Experimental landscape,
  particular focus on radio instruments - ice, air, space
- New results from ANITA-4

In-ice Radio Detection Technique

Askaryan emission: radiation from net negative charge excess in showers

1906.01670

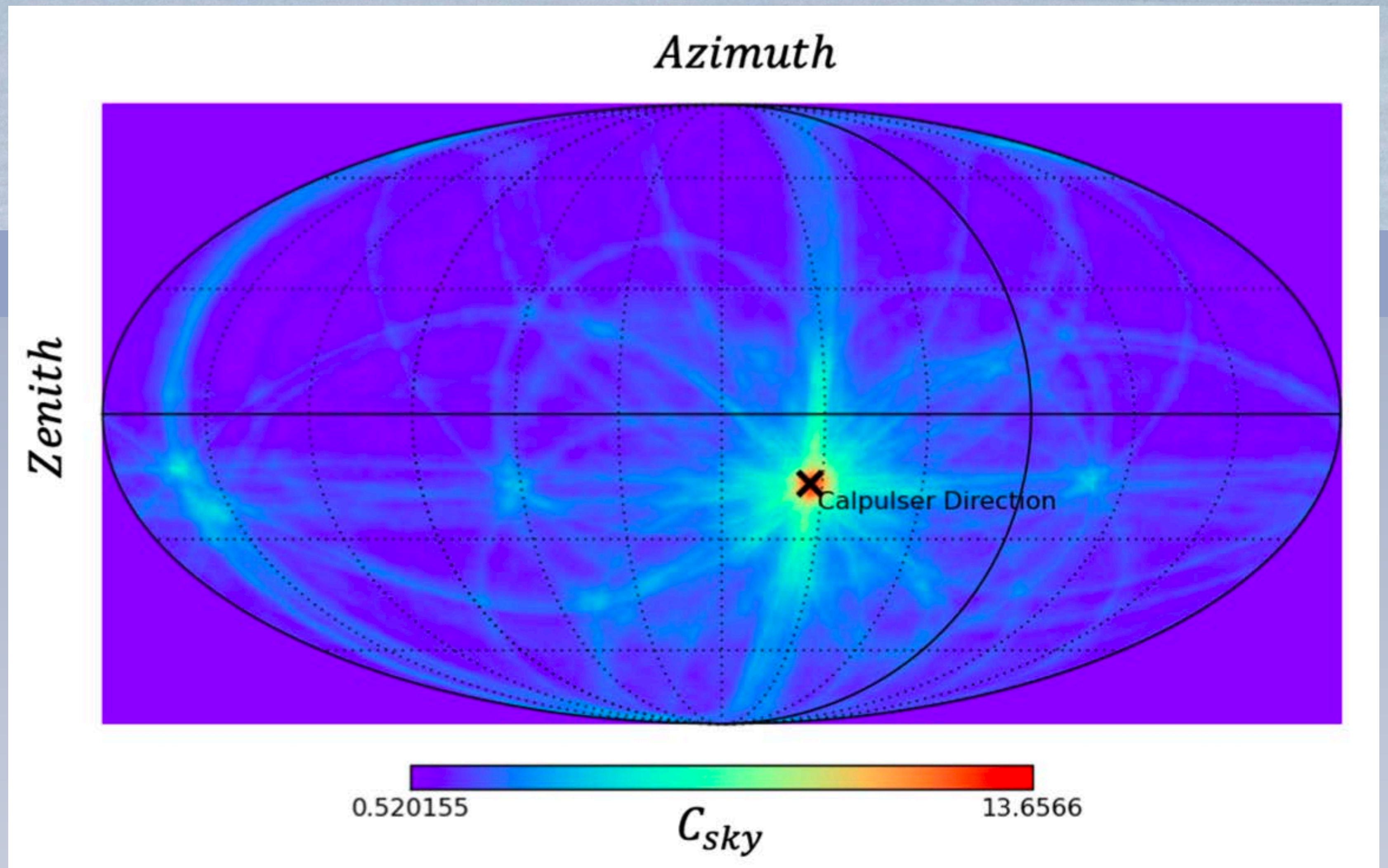



In-ice Radio Detector Depth
Surface
200 m
2000 m
depth
not to scale
Doesn’t need to be this deep because radio propagates long distances
Askaryan Radiation
ν
vertex


In-ice Radio Detector Depth
Surface
200 m
2000 m
depth
not to scale
Askaryan Radiation
ν
vertex

In-ice Radio Detector Design Principles

Multiple antennas at each station reconstruct radio signal via interferometry



1912.00987

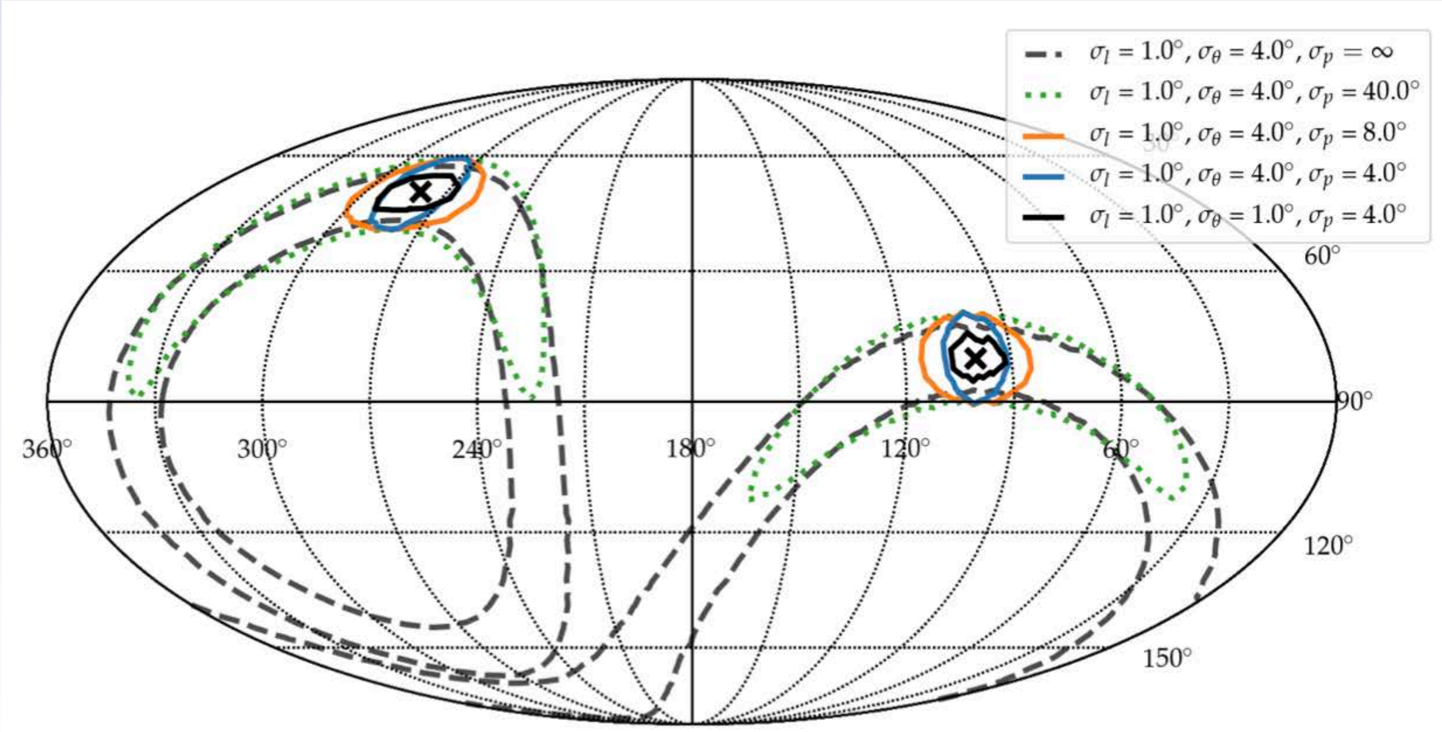
Surface

200 m

Space them by ~ attenuation length so effective volume increases linearly

$L_{atten} \sim 1$ km

Use polarization to reconstruct neutrino direction to ~ degree scale

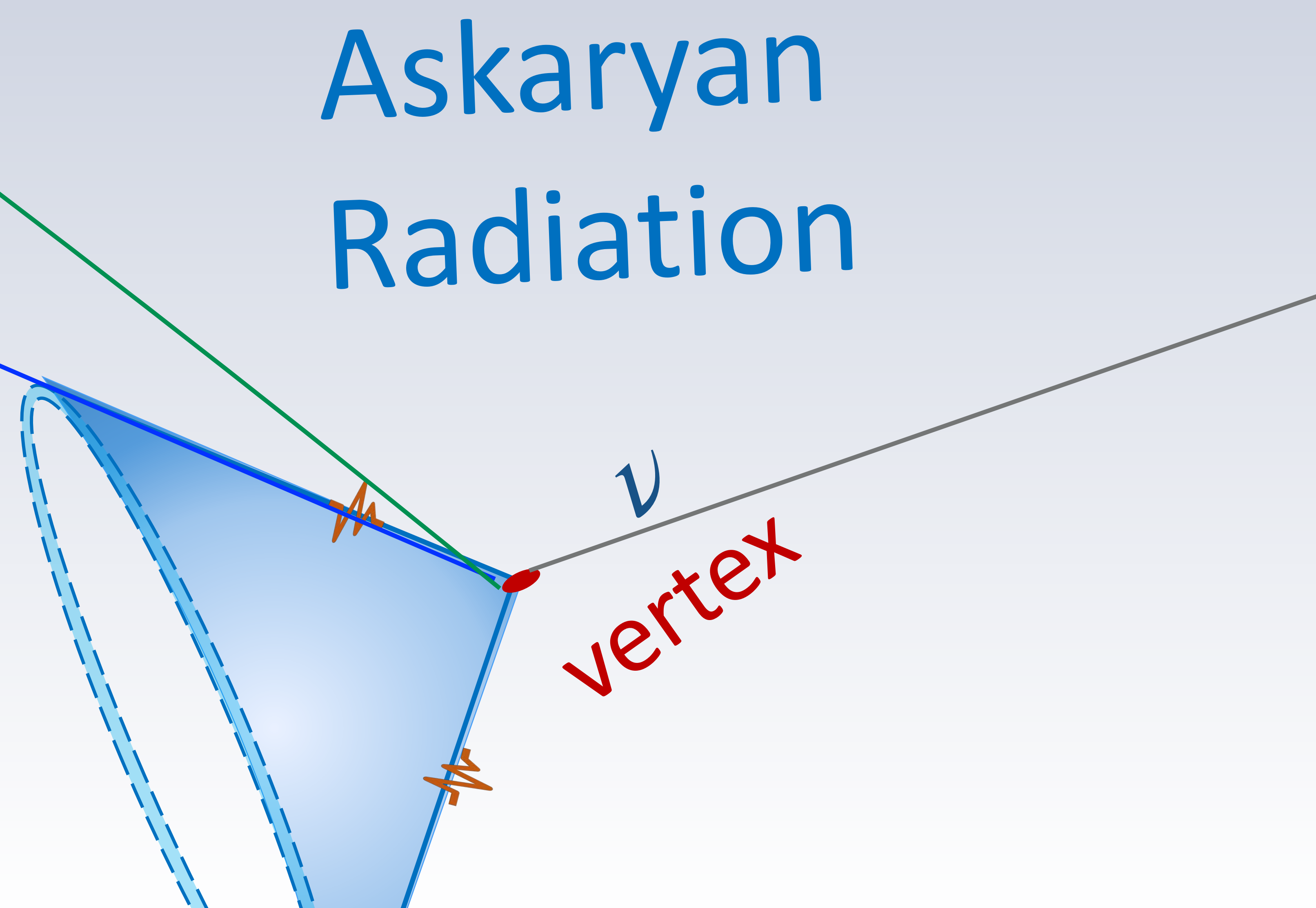


1911.02093

2000 m

depth

not to scale



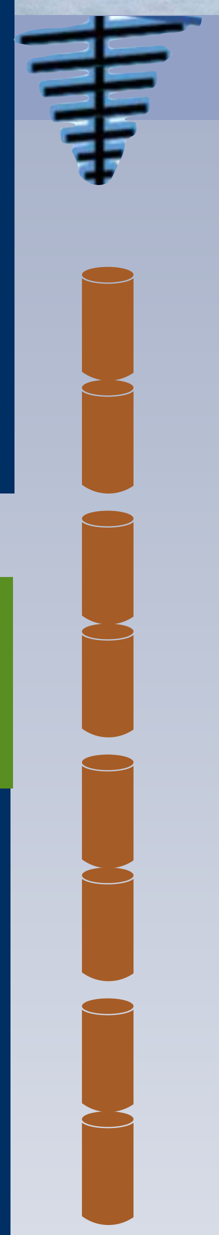
In-ice Radio Detector Designs

Surface Design ARIANNA

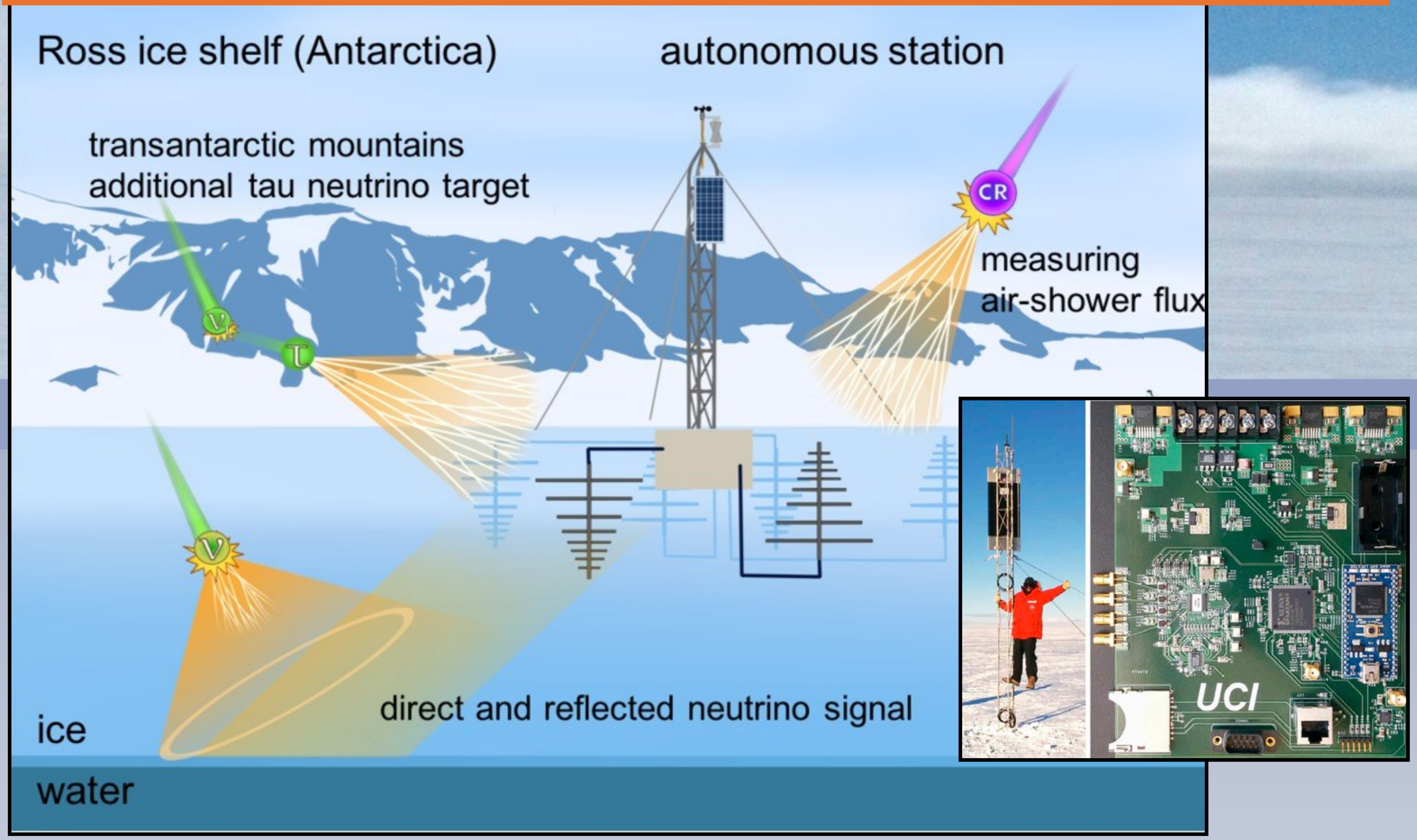
Use larger high gain antennas
Precision reconstruction
No drilling, Fast deployment
Simple cosmic ray veto
Tau neutrinos from nearby mountains

Deep Design ARA

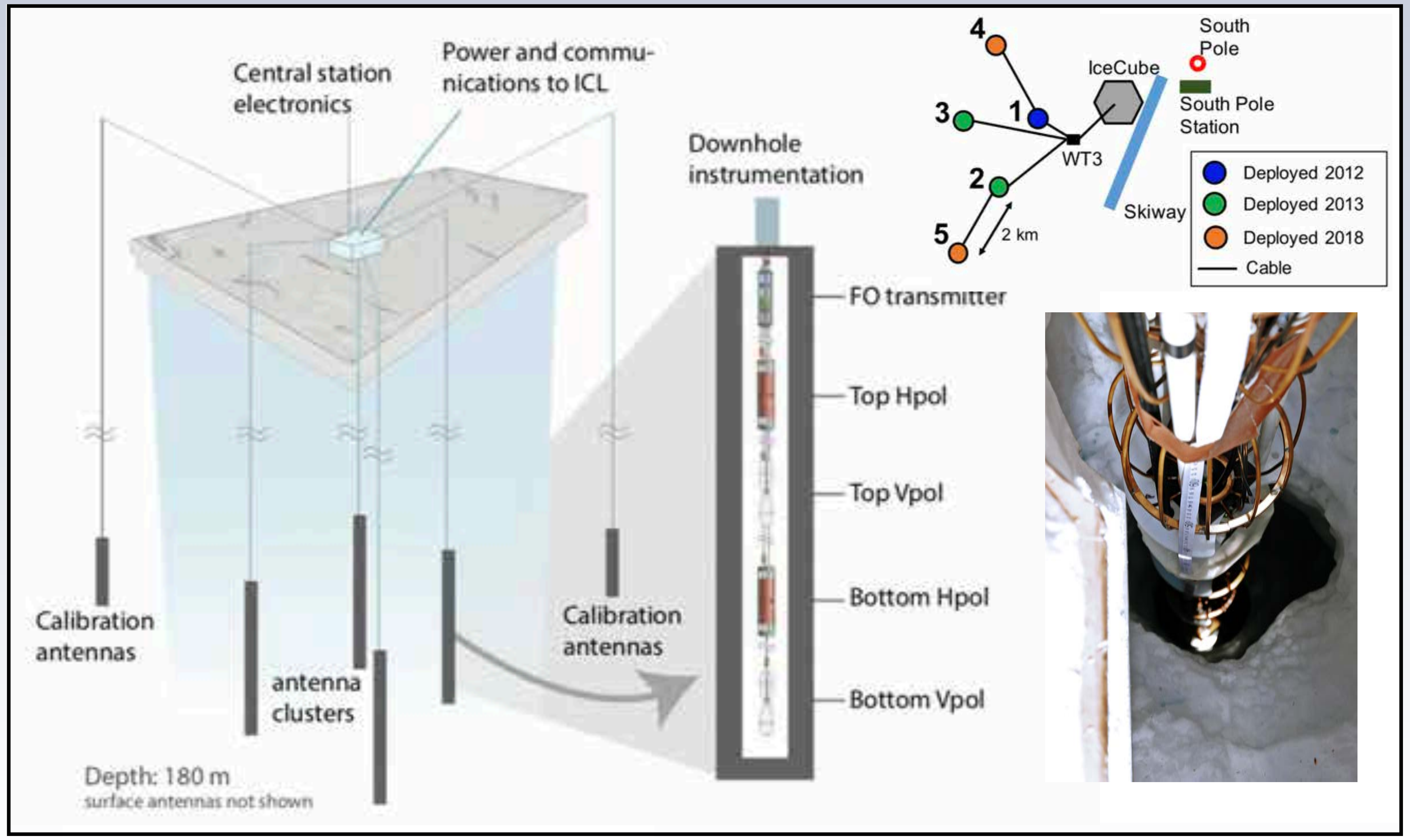
200 m depth accesses large ice volume
Low anthropogenic noise
Phased arrays for low trigger thresholds
Modest drilling requirements ~ 1 day/hole



ARIANNA : Ross Ice Shelf



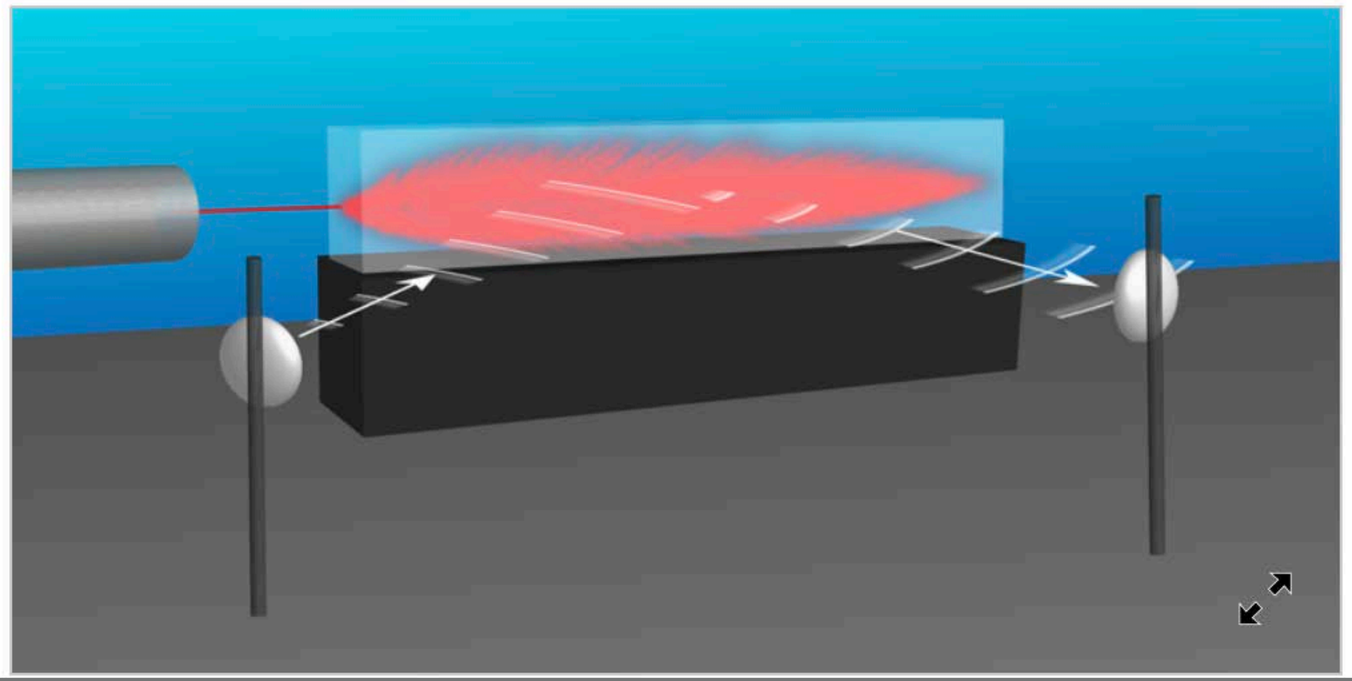
ARA : South Pole

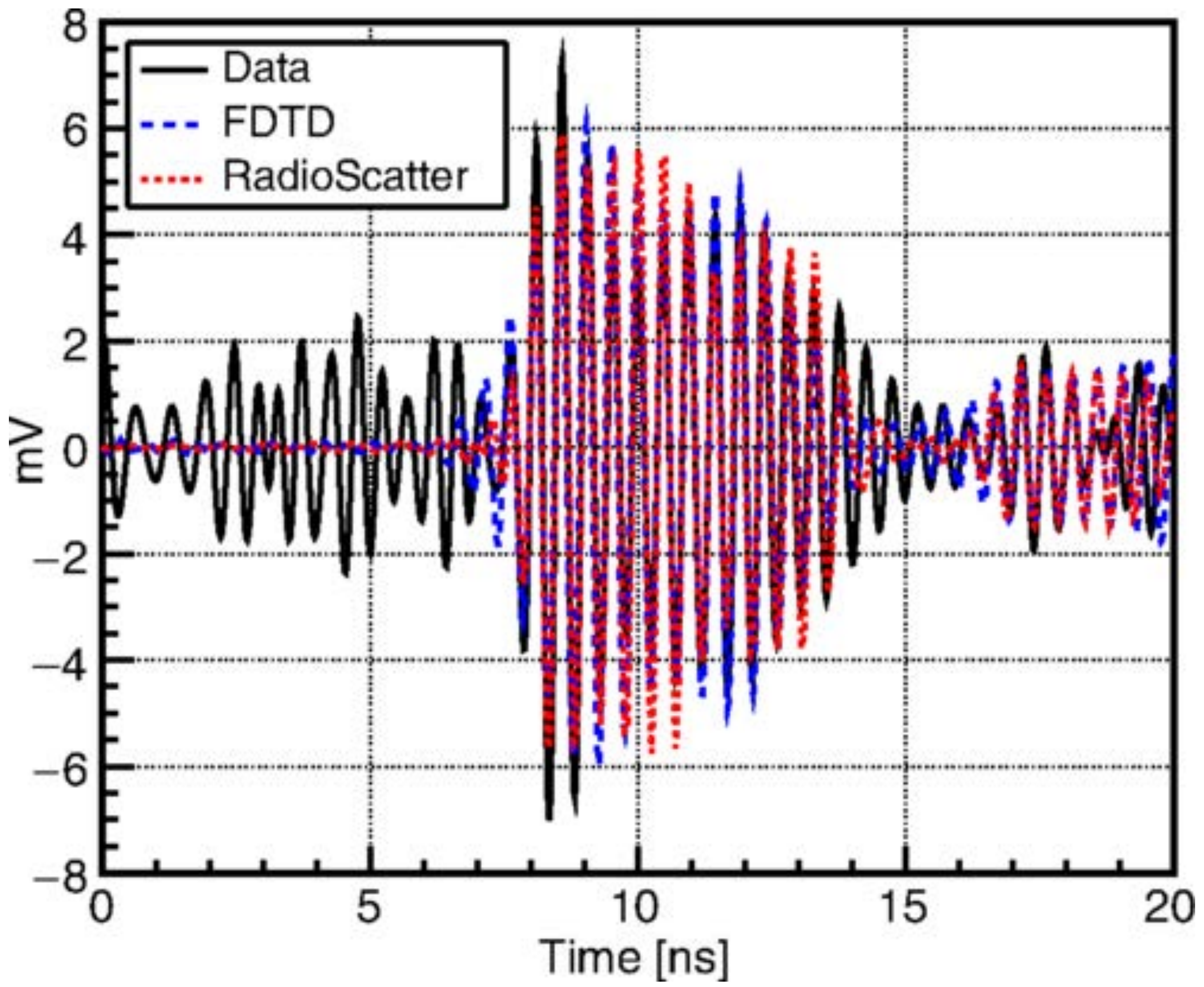


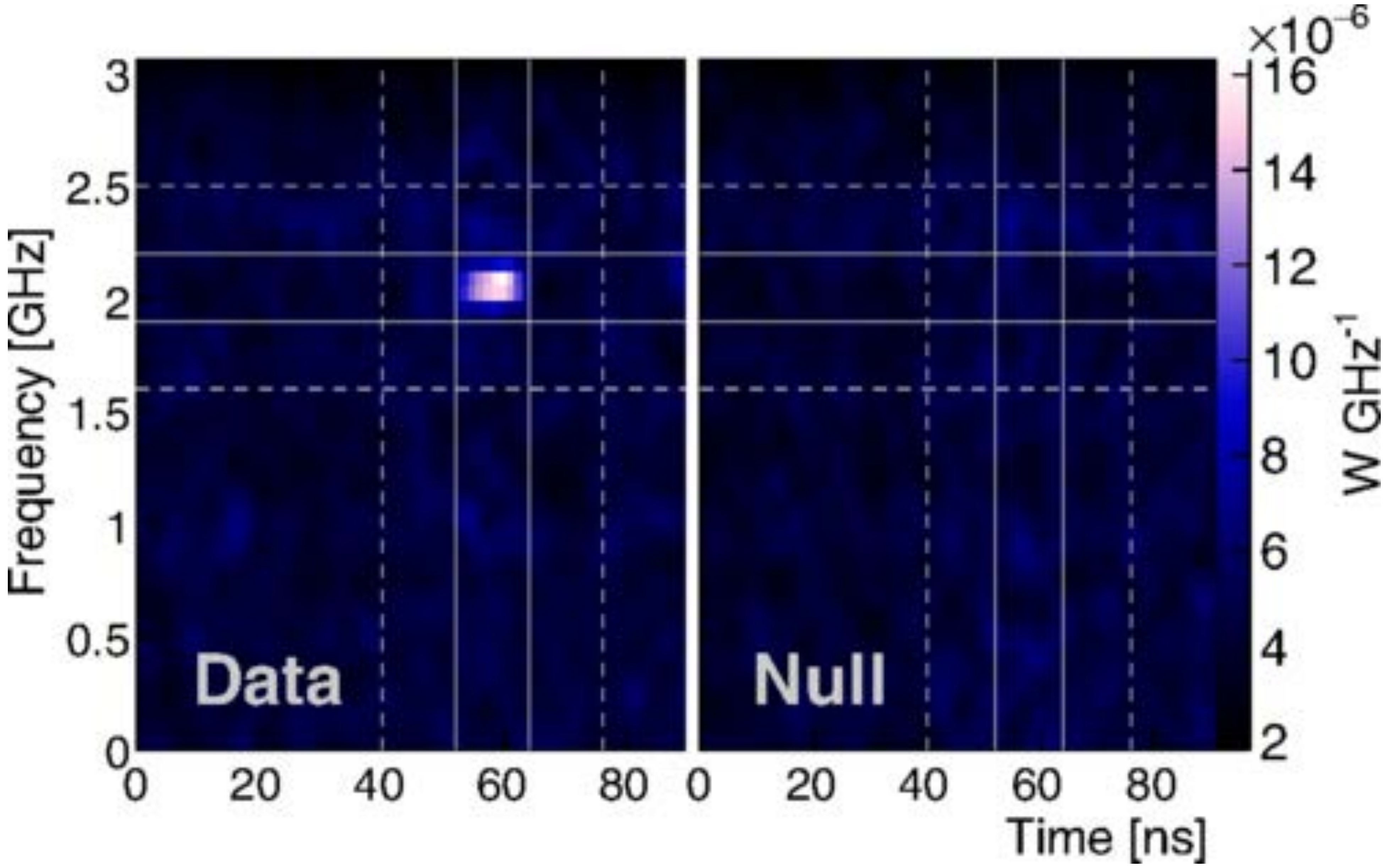
RADAR ECHO TELESCOPE

1910.12830 *See posters #469, 476*

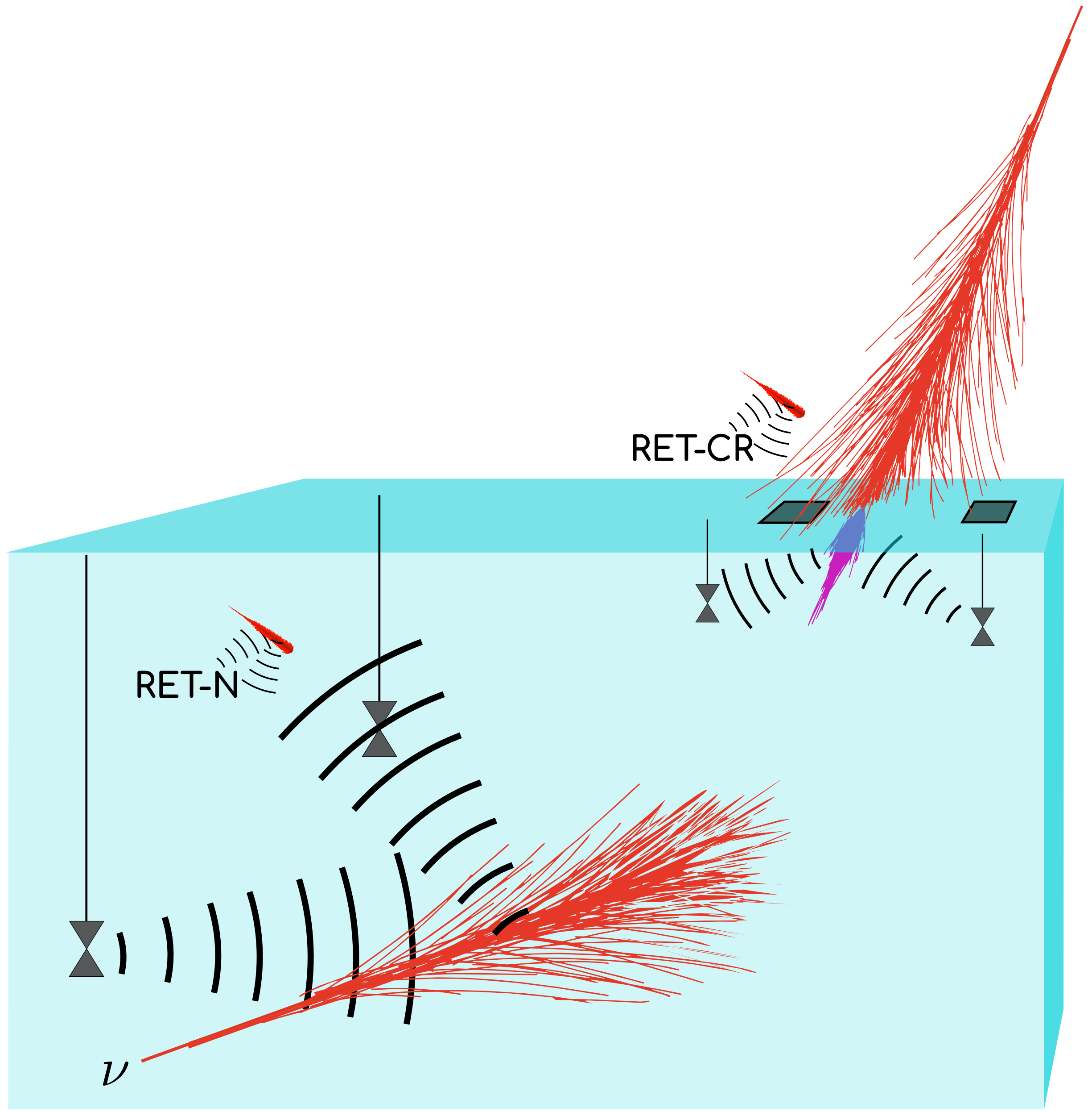
- T576 lab experiments confirm radar bounce off particle showers in dense dielectric HPDE

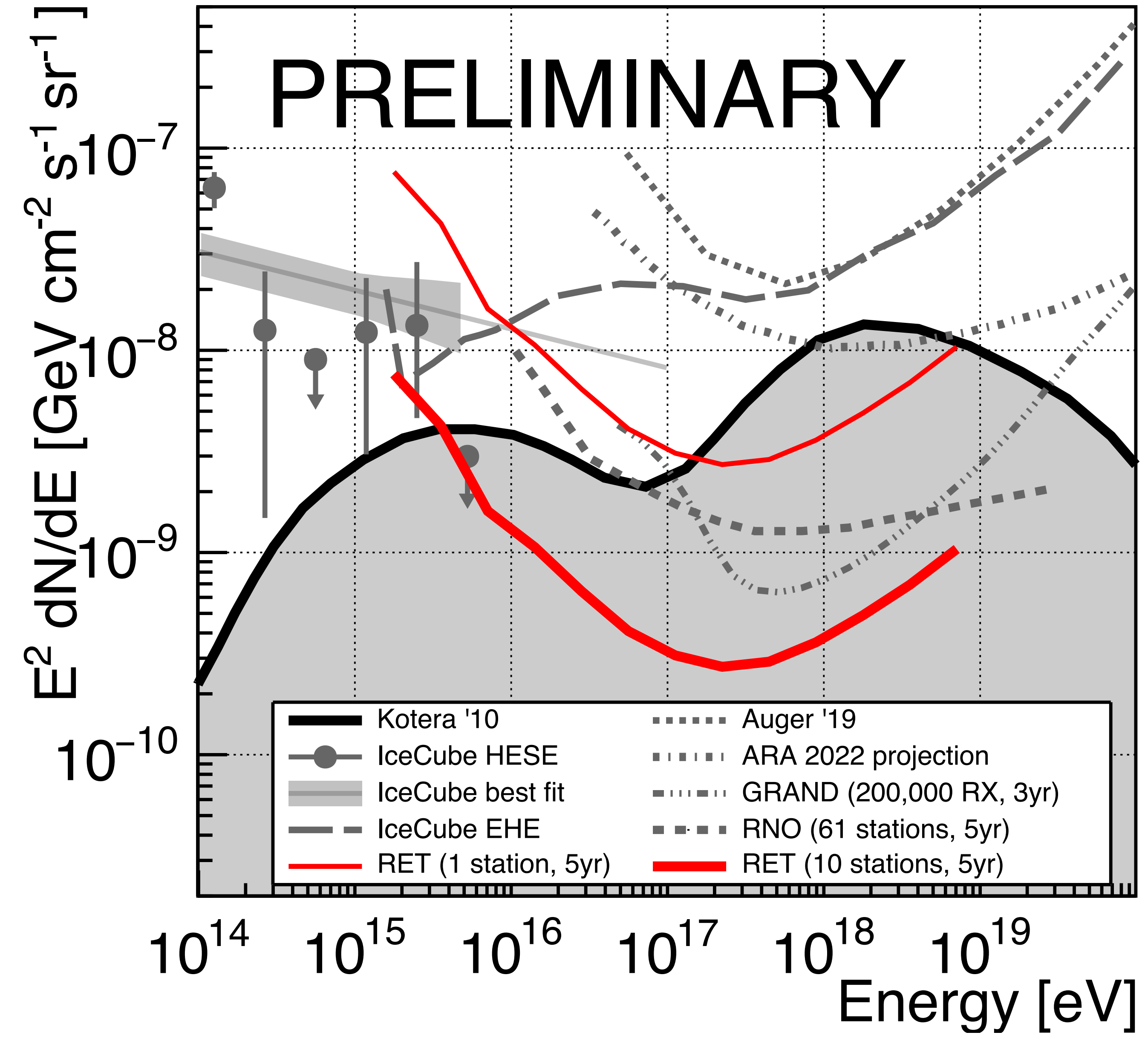


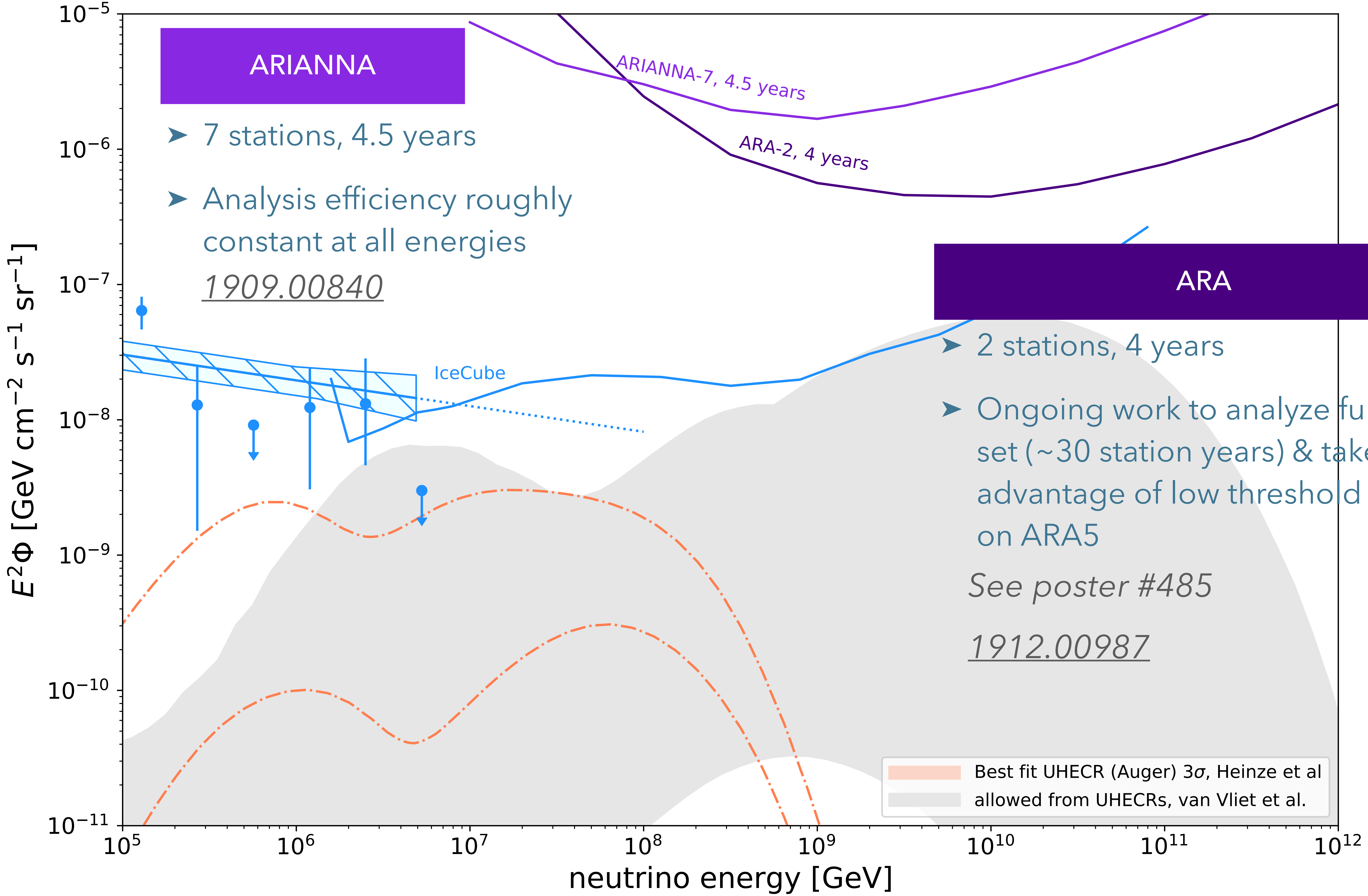




- Proposed prototype to demonstrate with in-ice CR showers at Taylor Dome
- Targeting PeV to EeV energy scale







ARIANNA

- 7 stations, 4.5 years
- Analysis efficiency roughly constant at all energies

1909.00840

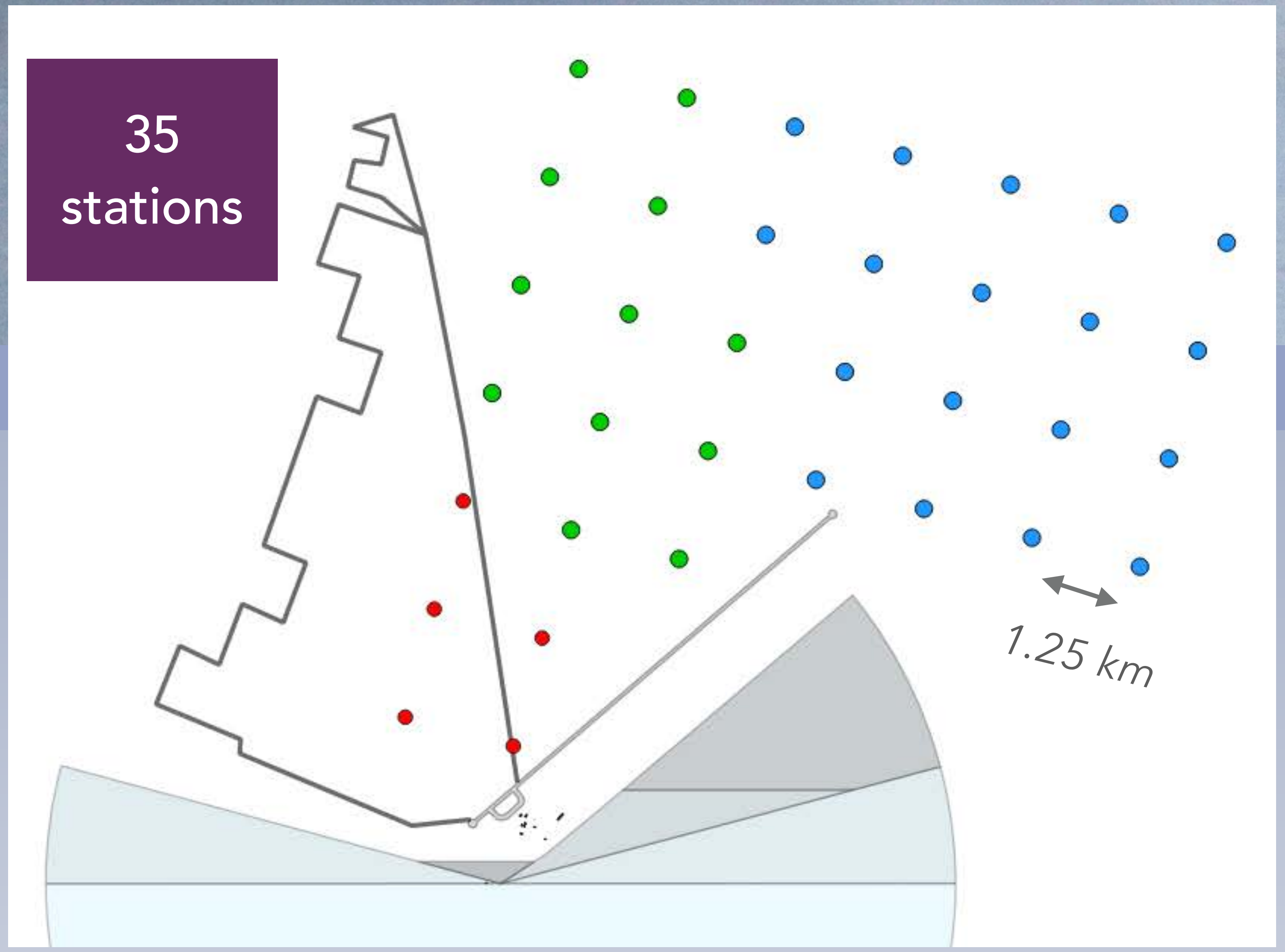
ARA

- 2 stations, 4 years
- Ongoing work to analyze full data set (~30 station years) & take advantage of low threshold events on ARA5

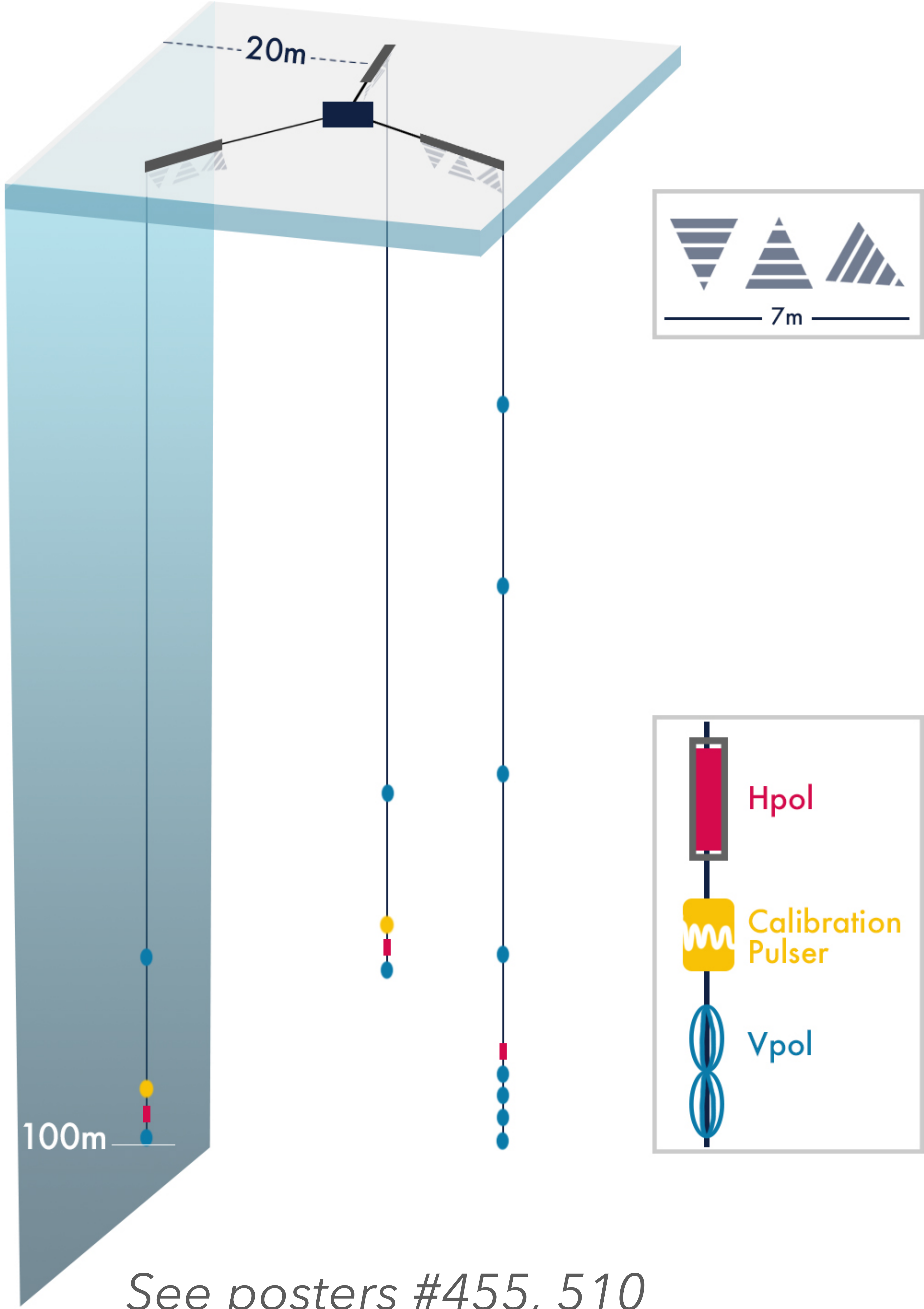
See poster #485

1912.00987

RNO-G : Greenland

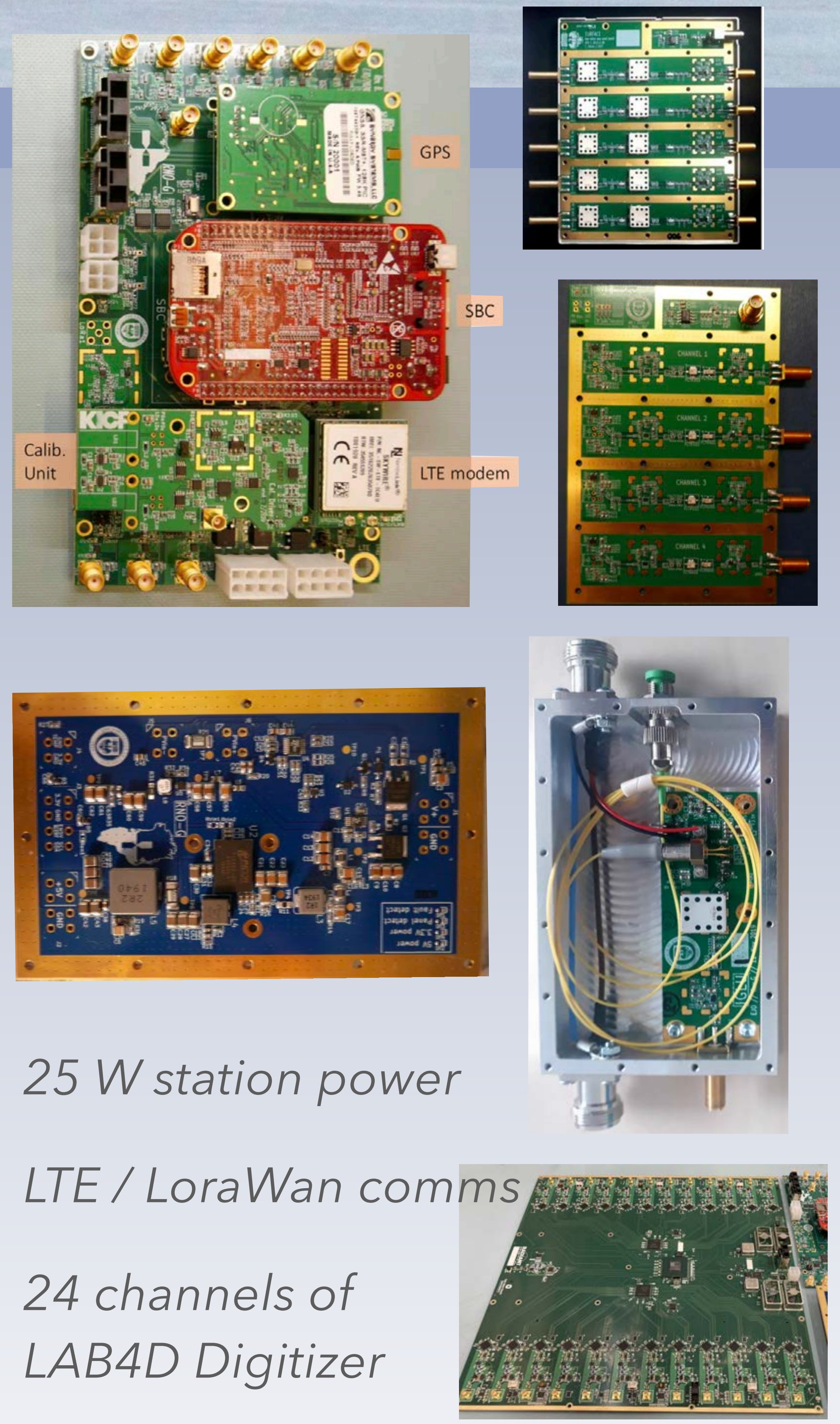


- **Scalable to few 100 km²**
  Autonomous, low power, low cost, efficient & low threshold
- Hybrid Design builds on ARA & ARIANNA:
  - **Surface:**
    CRs, vetos, reconstruction
  - **Deep Phased Trigger:**
    Effective Volume



See posters #455, 510

Production Station Electronics

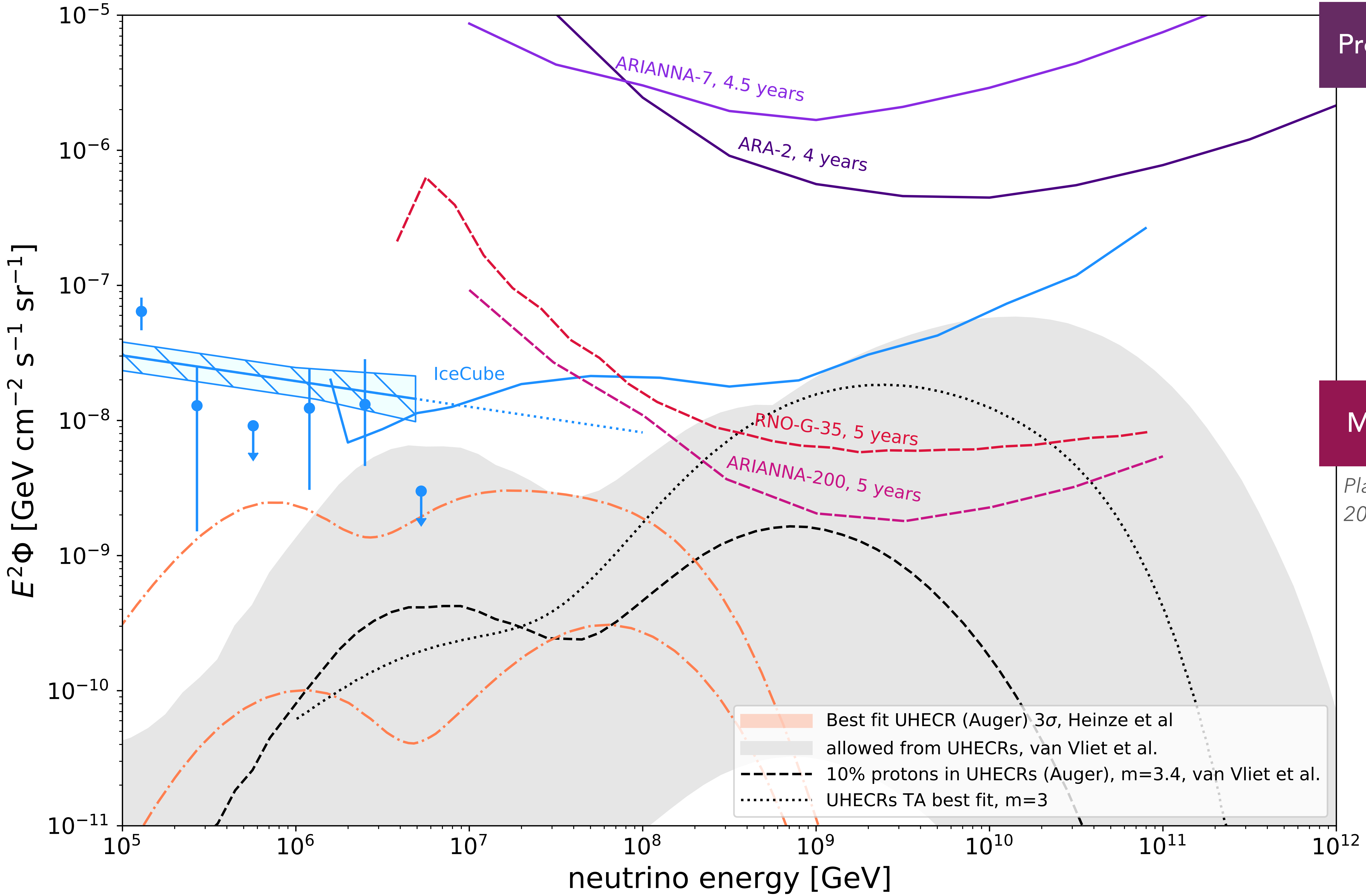


25 W station power

LTE / LoraWan comms

24 channels of LAB4D Digitizer

Low threshold phased trigger ~ SNR of 2



Prototypes

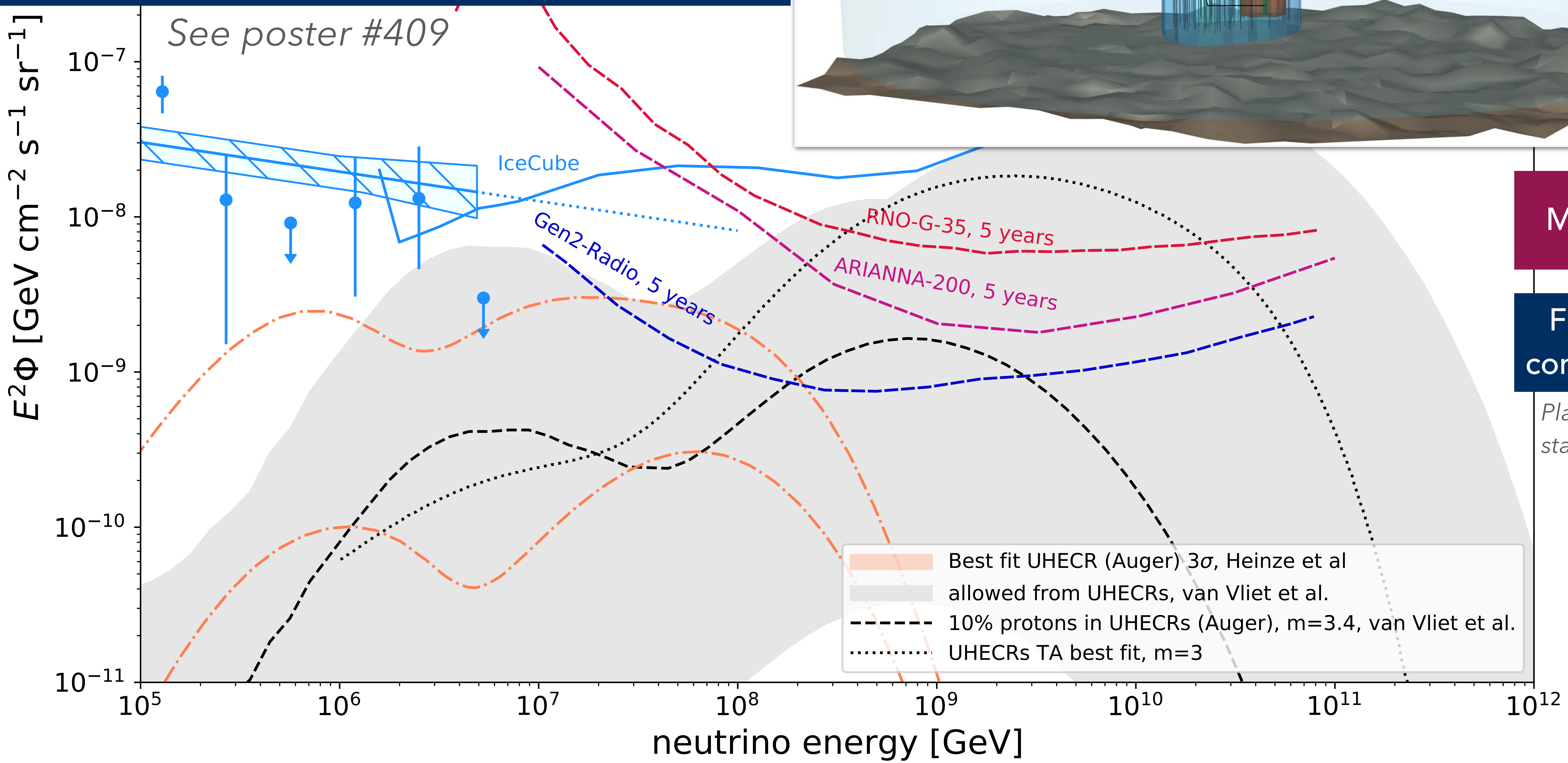
Mid-scale

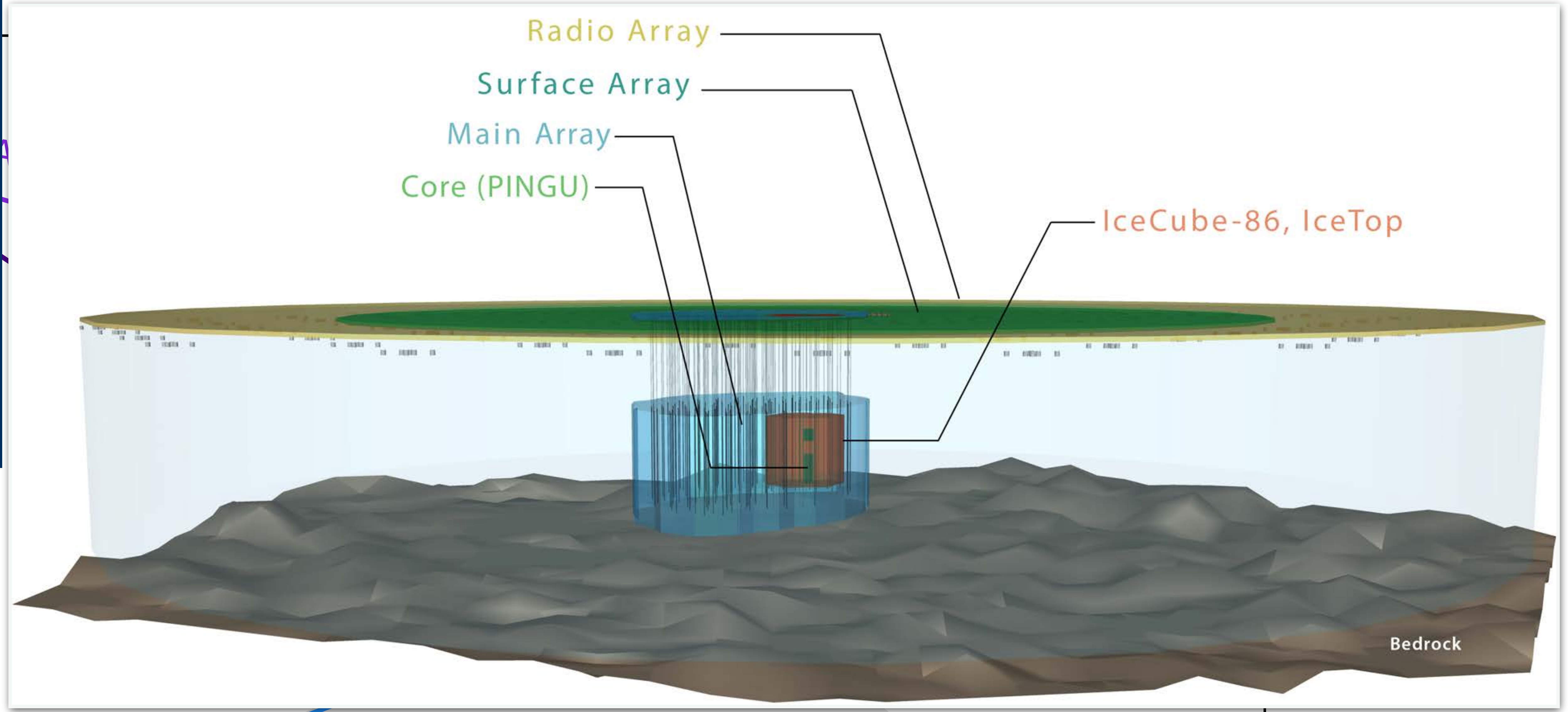
Planned for 2020 to 2028+

IceCube-Gen2-Radio

10x better sensitivity at EeV scale

Building on prototypes & midscale instruments





Mid-scale

Full scale construction

Planned to start 2025

Air Shower Techniques

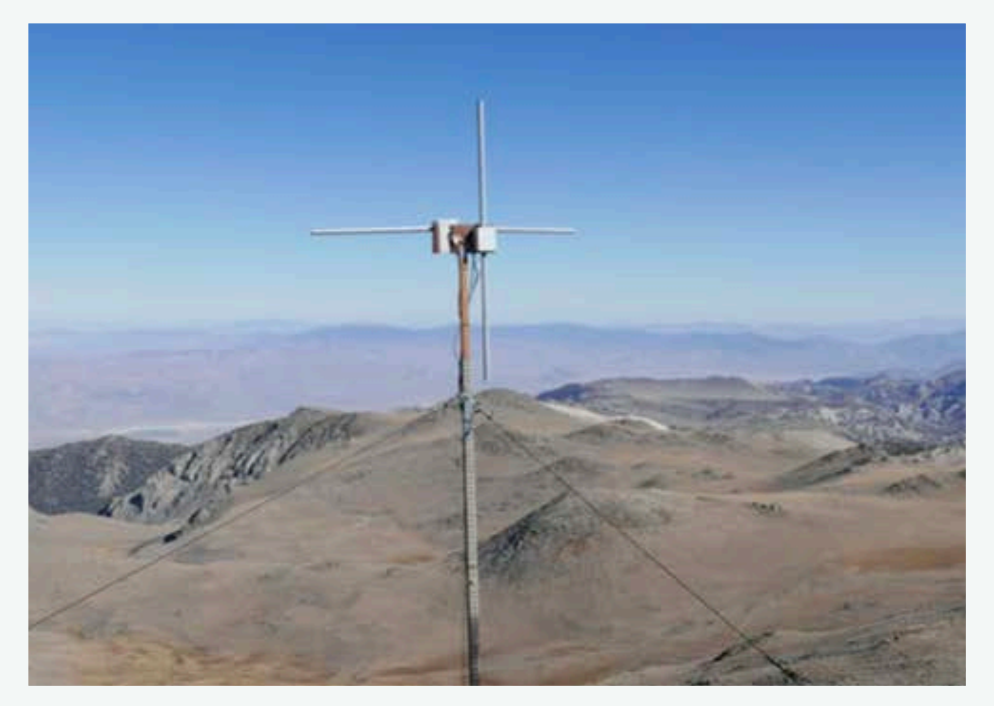
The BEACON Concept

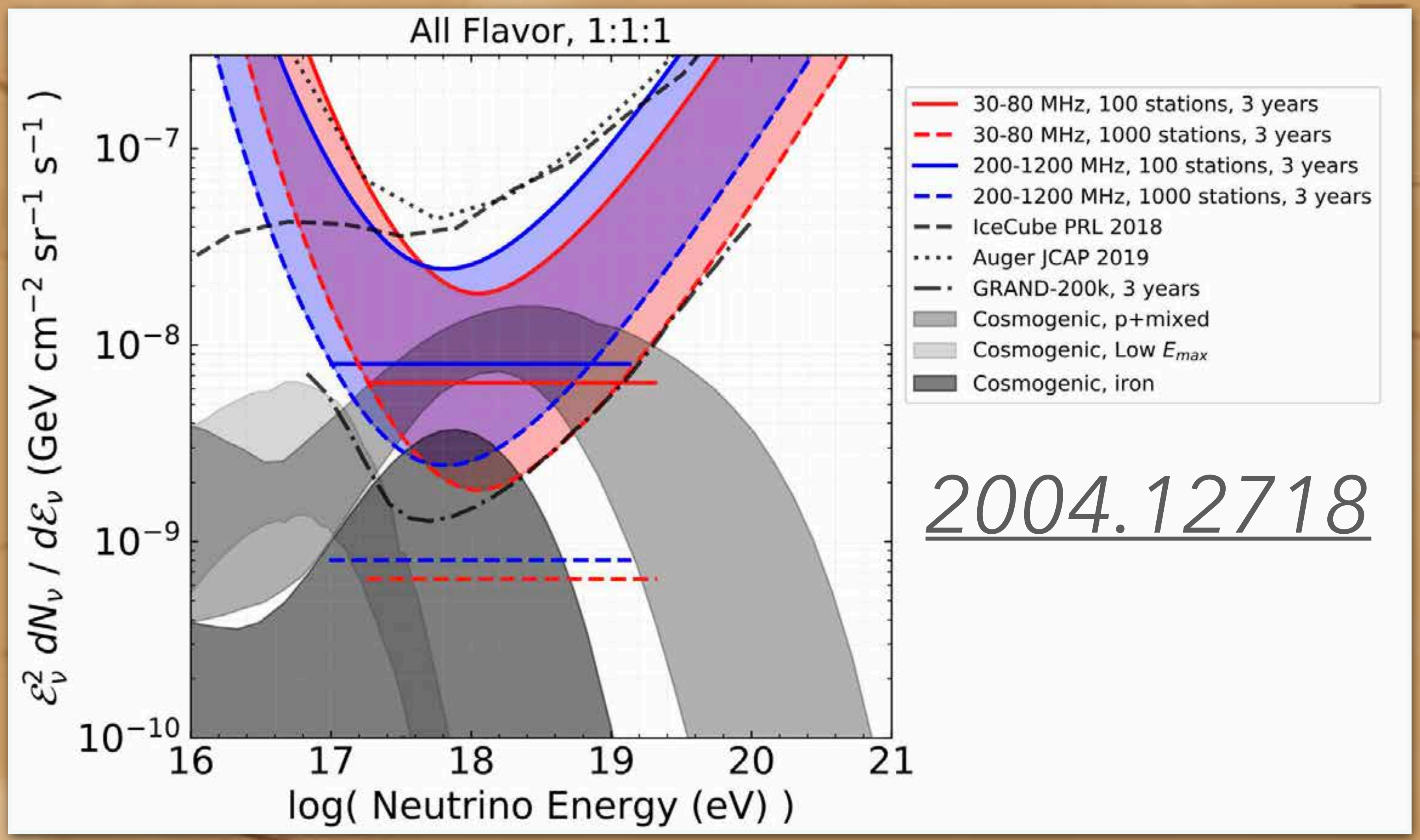
See poster #427

100-1000 stations with ~10 antennas each

Efficient detector due to large area at top of mountain

Targeting $\nu_\tau > 100$ PeV





2004.12718

BEACON Prototype Array:
4 cross-dipole antennas,
30-80 MHz, phased array trigger +
digitizer 500 MSPS, 50 W
Goal: RF-only cosmic ray trigger
Operating since 2018 at
White Mountain Research Station CA

Similar to Taroge (Antarctica), Trinity (imaging Cherenkov)

See also a PeV tau telescope concept TAMBO (Colca Valley)

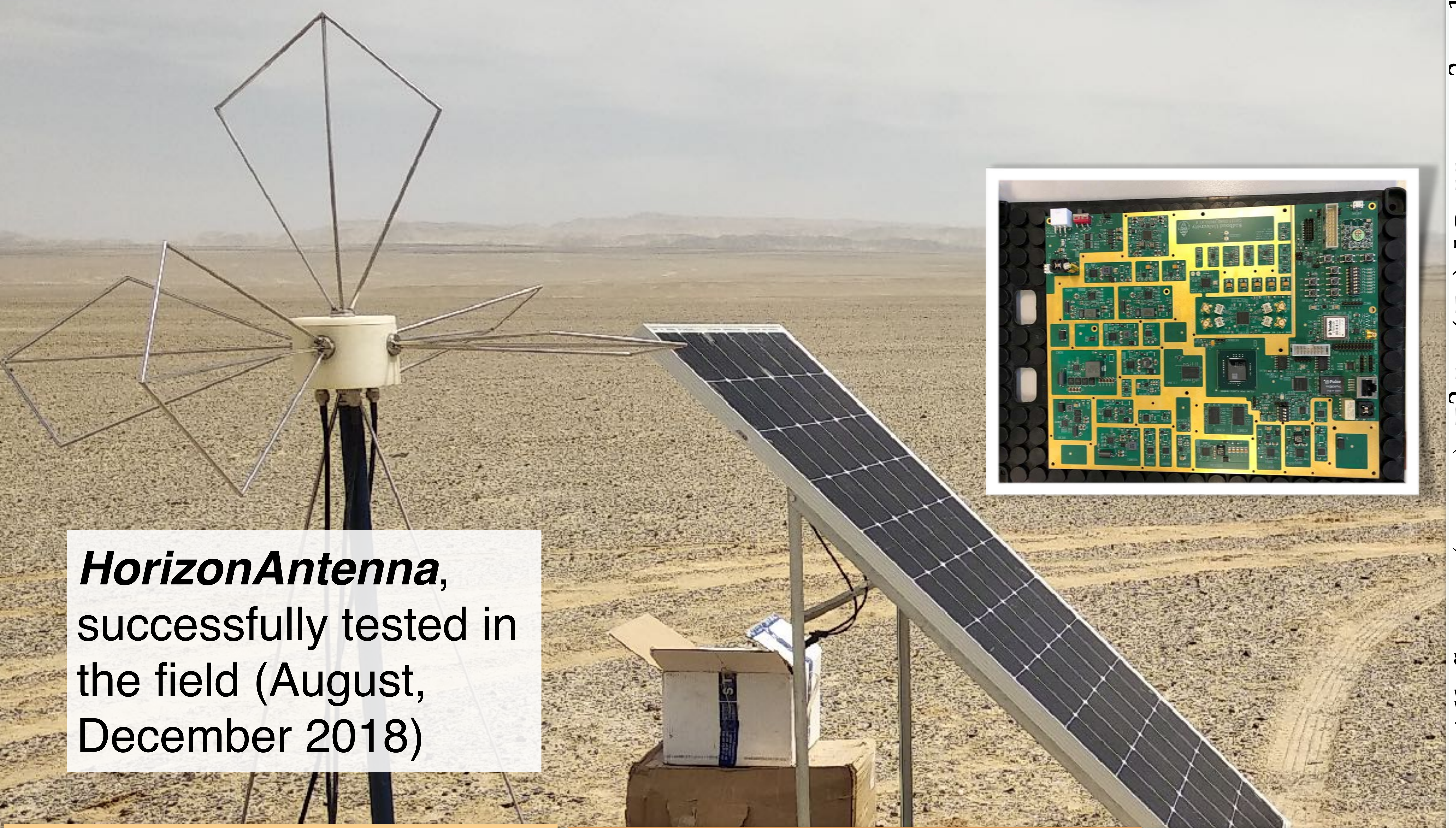
The GRAND Concept

200'000 radio antennas over 200'000 km²

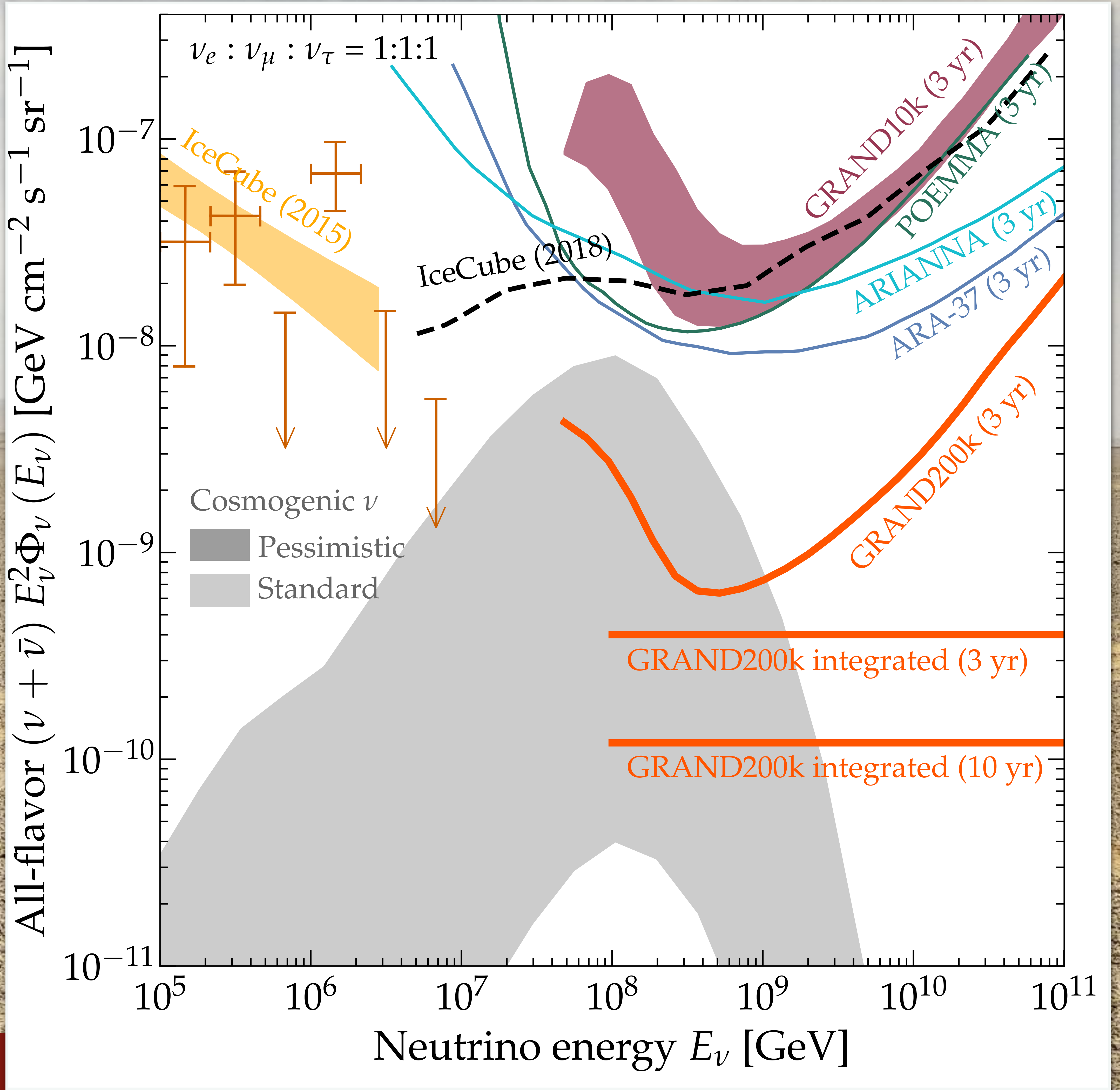
~20 hotspots of 10'000 antennas

over favorable sites in China and worldwide

GRAND's staged approach

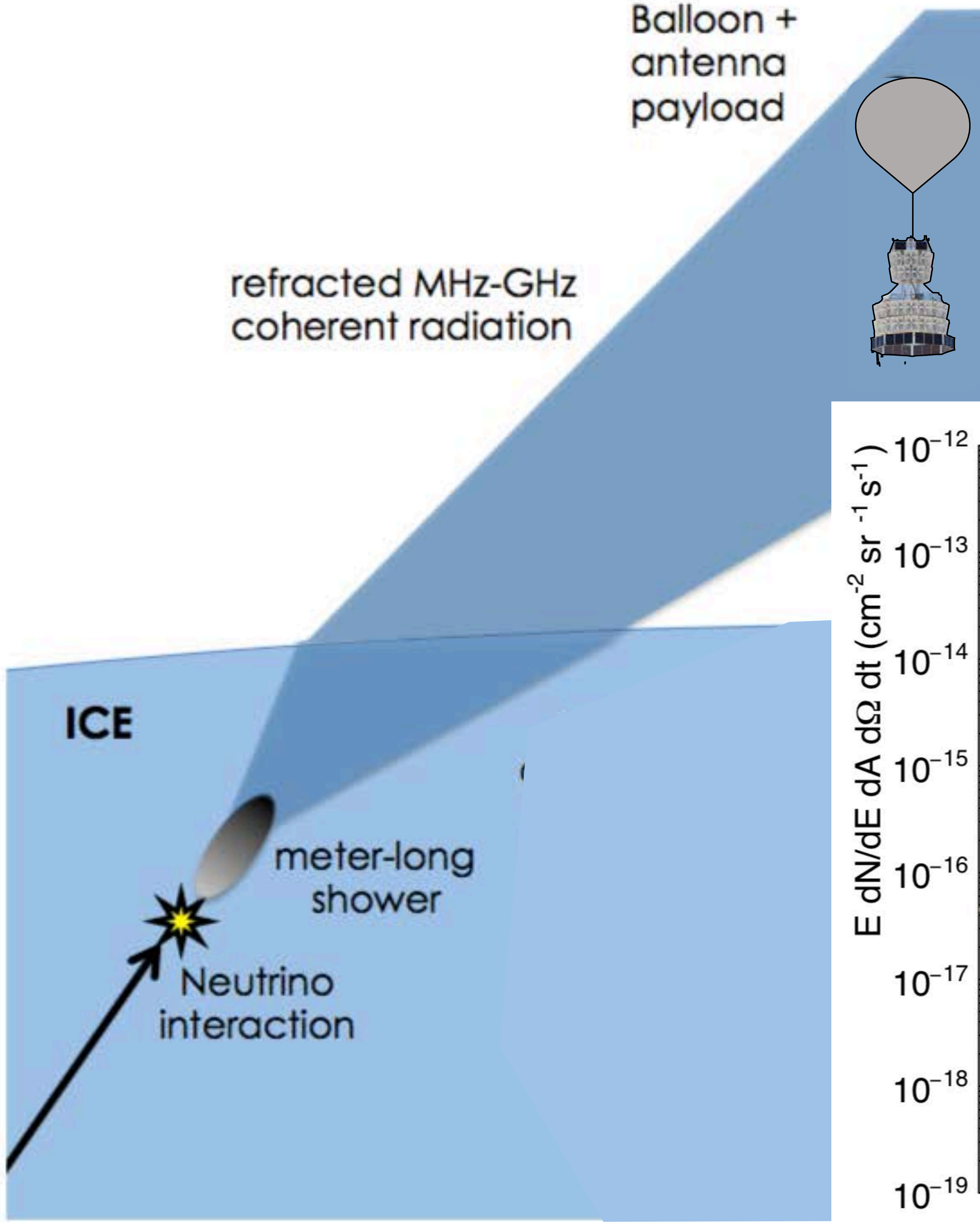


HorizonAntenna, successfully tested in the field (August, December 2018)



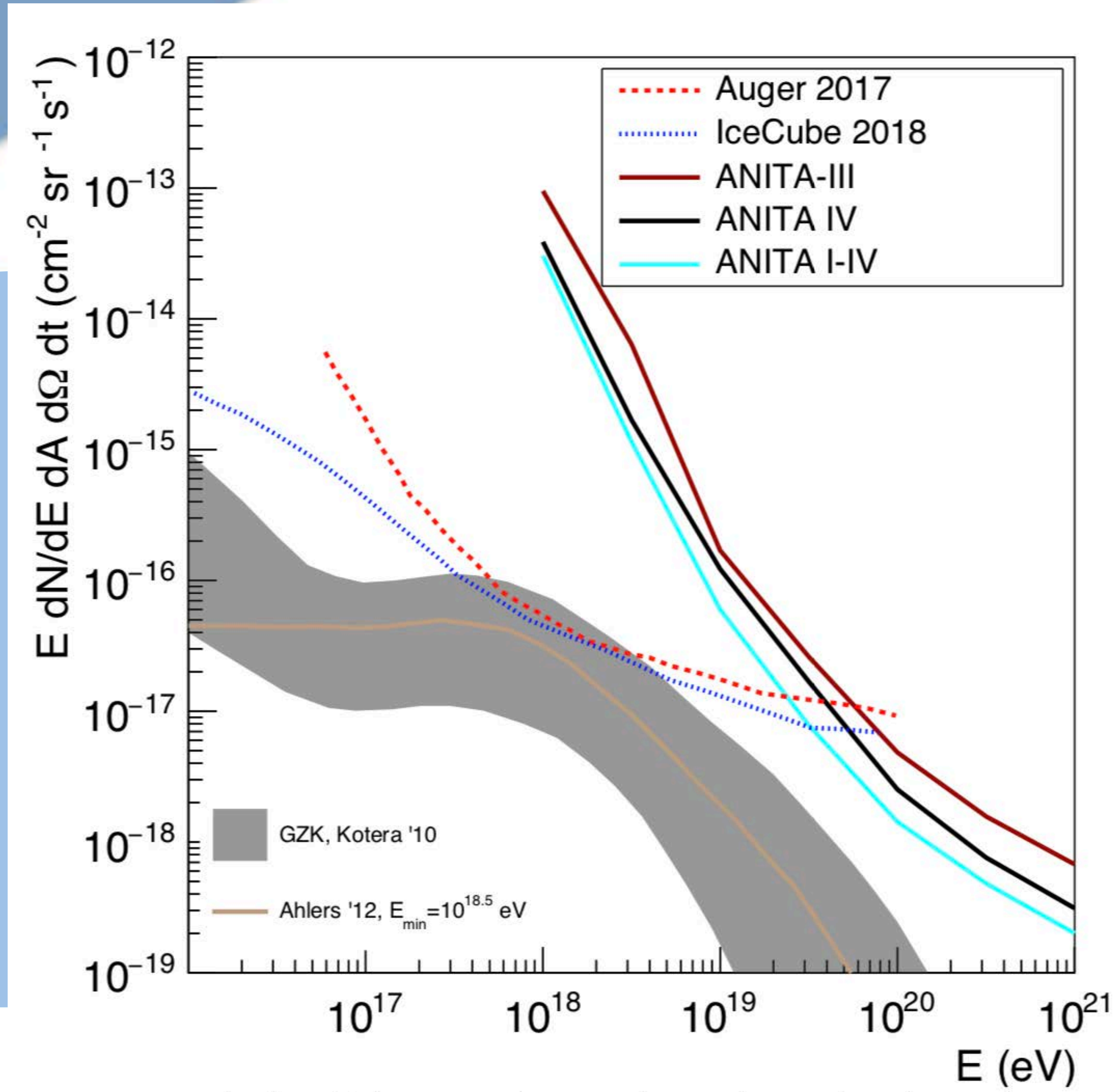
GRANDProto300	GRAND10k	GRAND200k
2021	2025	203X
• 300 antennas over 200 km² • autonomous radio detection of very inclined air-showers • cosmic rays $10^{16.5\text{-}18}$ eV • 1.3 M€ (fully funded, China)	• 10^4 antennas over 10^4 km² • 1st GRAND subarray • discovery of EeV neutrinos for optimistic fluxes • 13 M€ (mostly China)	• 200k antennas over 200k km² • 20 hotspots of 10k antennas on different continents • 1st EeV neutrino detection and/or neutrino astronomy! • 150 M€

NEUTRINOS FROM SPACE : ANITA *See poster #552*



credit: J. Alvarez-Muniz ICRC 2017

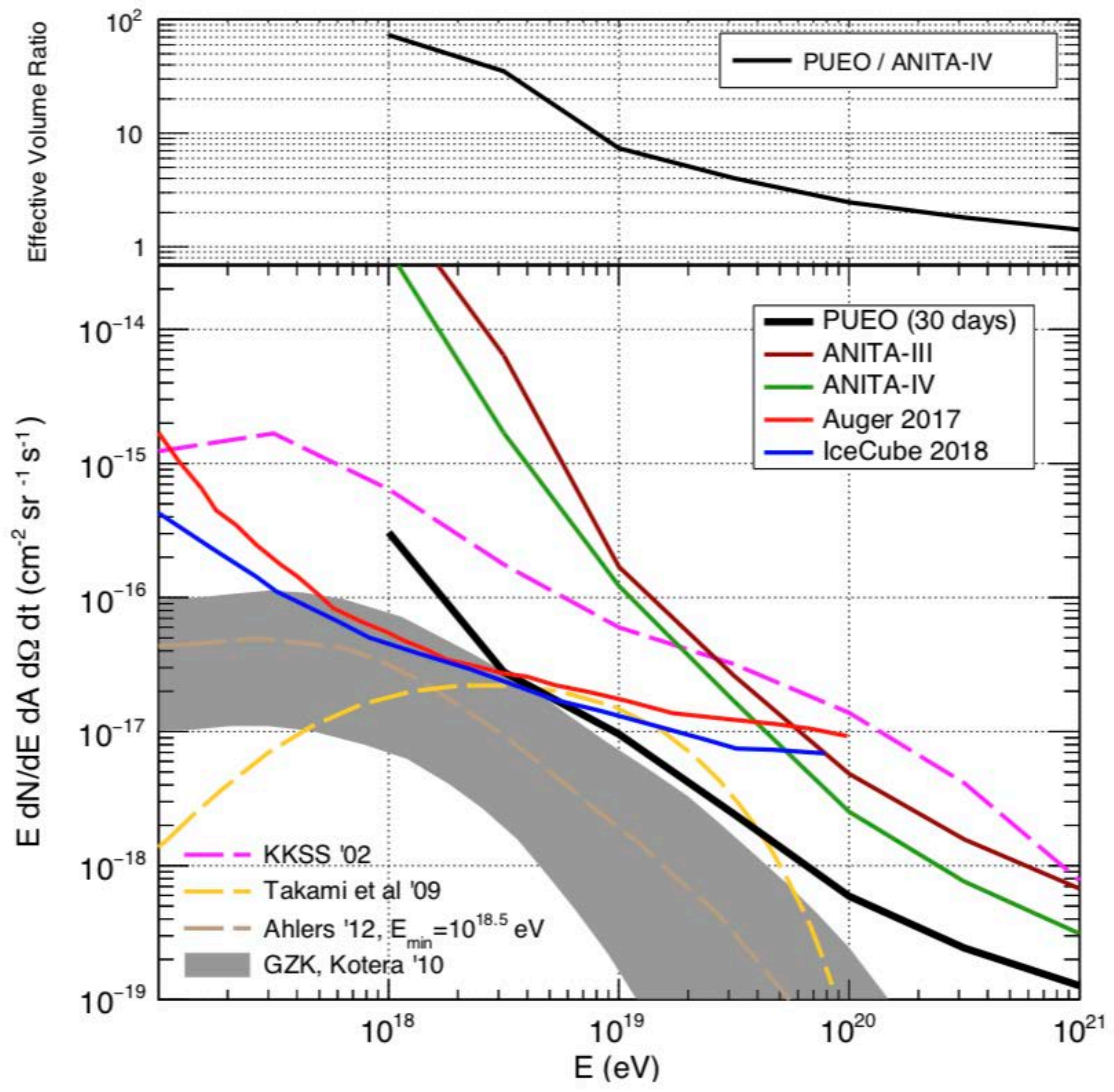
High altitude → large instantaneous detector volume



Best constraints on the end of the neutrino spectrum

NEUTRINOS FROM SPACE : PUEO

See poster #486



Constrain the end of the neutrino spectrum by 4-10x

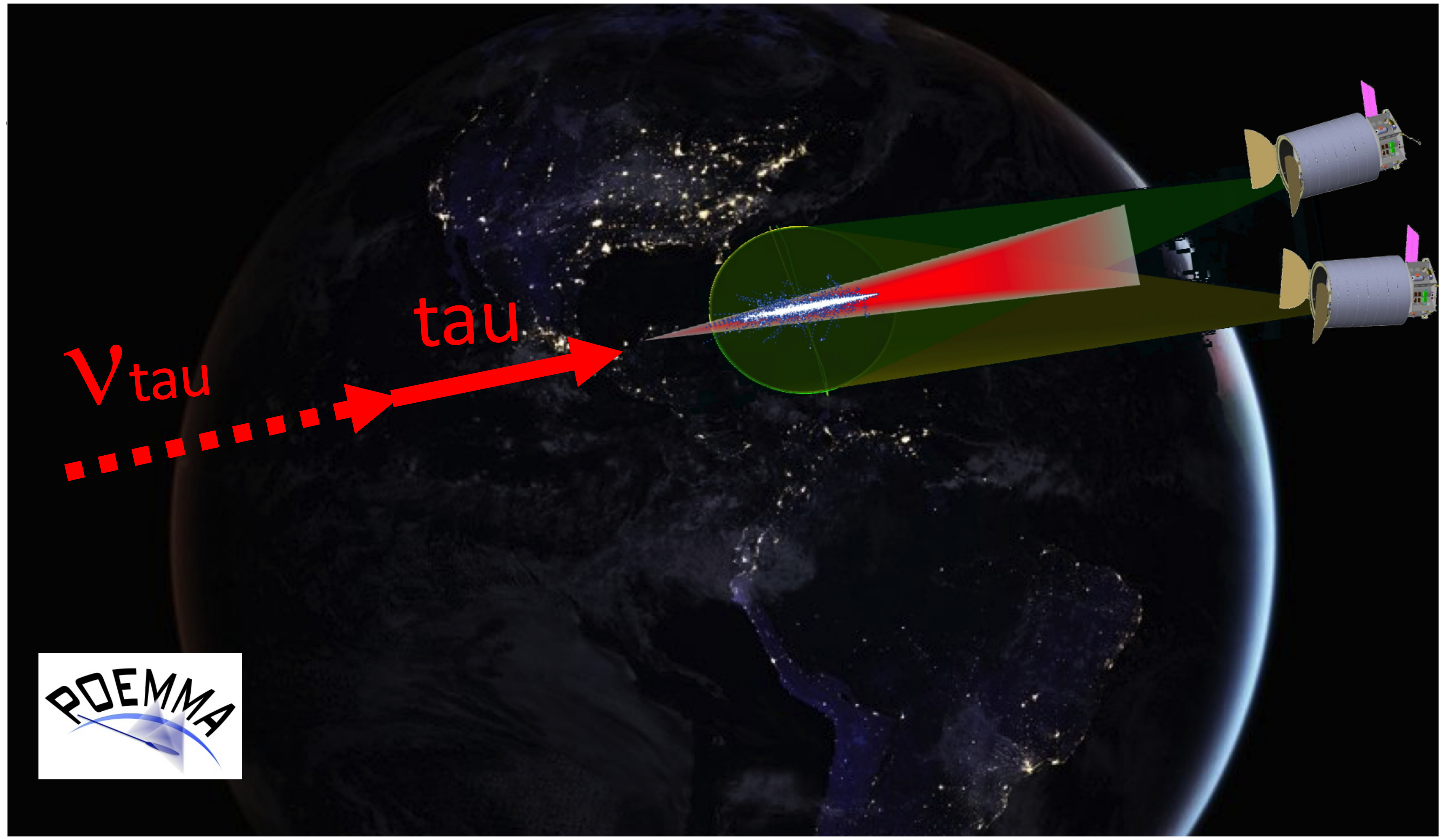
High effective area for transients

Lower threshold by phasing 2x antennas at trigger level

Planning for flight in 2023

NEUTRINOS FROM SPACE : POEMMA

- Upgoing tau neutrinos detected via Optical Cherenkov from stereo satellites
- Tuned for neutrino transients like binary neutron stars, short gamma ray bursts,…



Expected Number of Neutrinos from Binary Neutron Star Mergers

arXiv:1906.07209

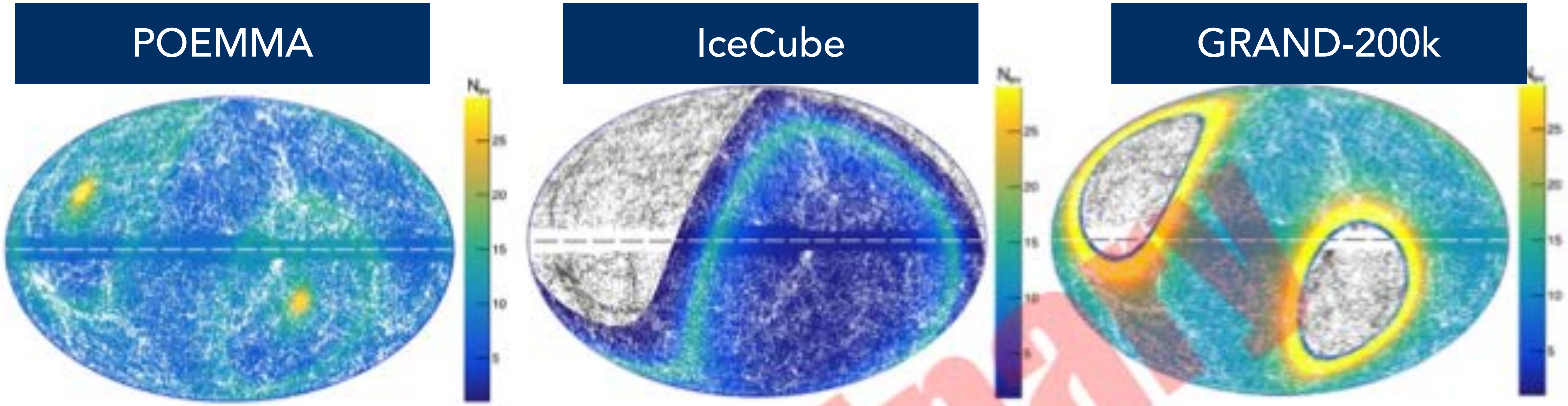


FIG. 7. *Left*: Sky plot of the expected number of neutrino events as a function of galactic coordinates for POEMMA in the long-burst scenario of BNS merger, as in the Fang & Metzger model [21], and placing the source at 5 Mpc. Point sources are galaxies from the 2MRS catalog [74]. *Middle*: Same as at left for IceCube for muon neutrinos. *Right*: Same as at left for GRAND200k. Areas with grey point sources are regions for which the experiment is expected to detect less than one neutrino.

See poster #519

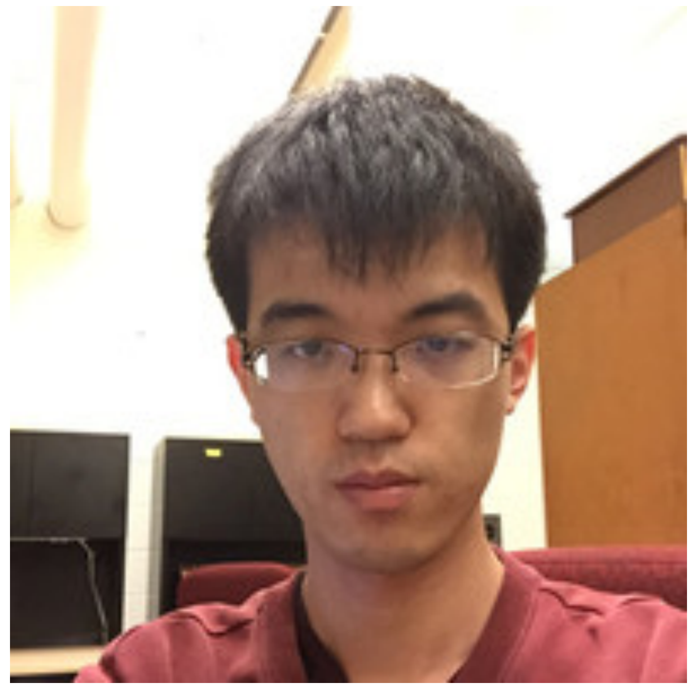
- Why Ultra-high-energy (UHE, >PeV) Neutrinos?

- Experimental landscape,
  particular focus on radio instruments

- New results from ANITA-4

ANITA-IV Cosmic Ray Results

Remy Prechelt, Hawaii
Poster #552



Peng Cao, Delaware

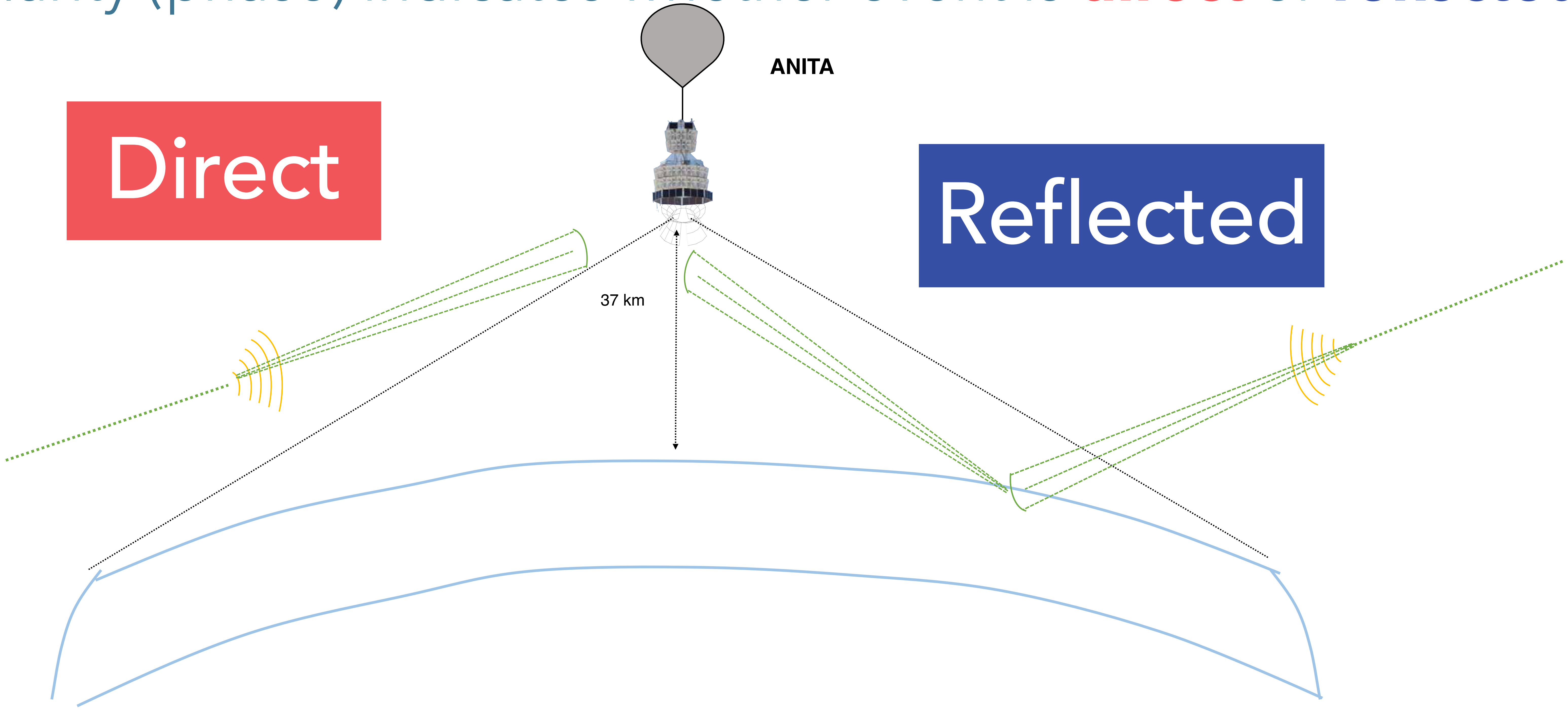
Cosmin Deaconu,
Chicago
Poster #486

Andrew Ludwig,
UCLA, Chicago

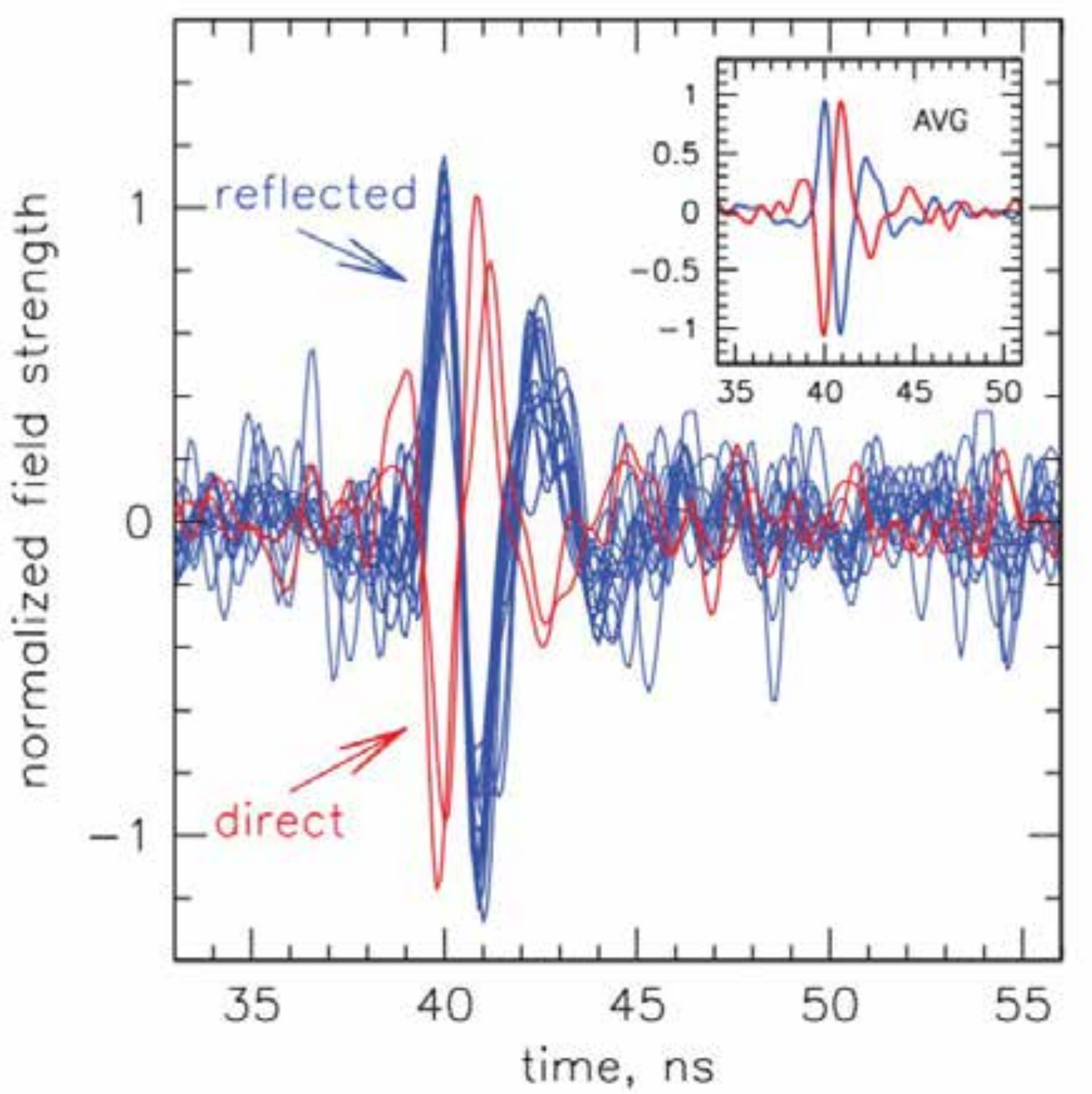
Peter Gorham, Hawaii

ANITA Cosmic Ray and Cosmic Ray-Like Events

- Geomagnetic radio signal from cosmic rays expected to arrive both directly pointed at the payload and reflected off the ice, predominantly Hpol
- Polarity (phase) indicates whether event is **direct** or **reflected**

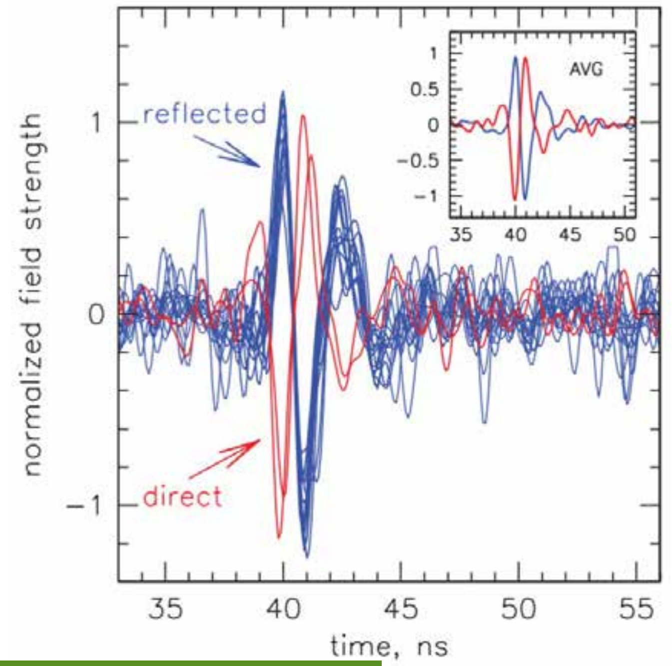


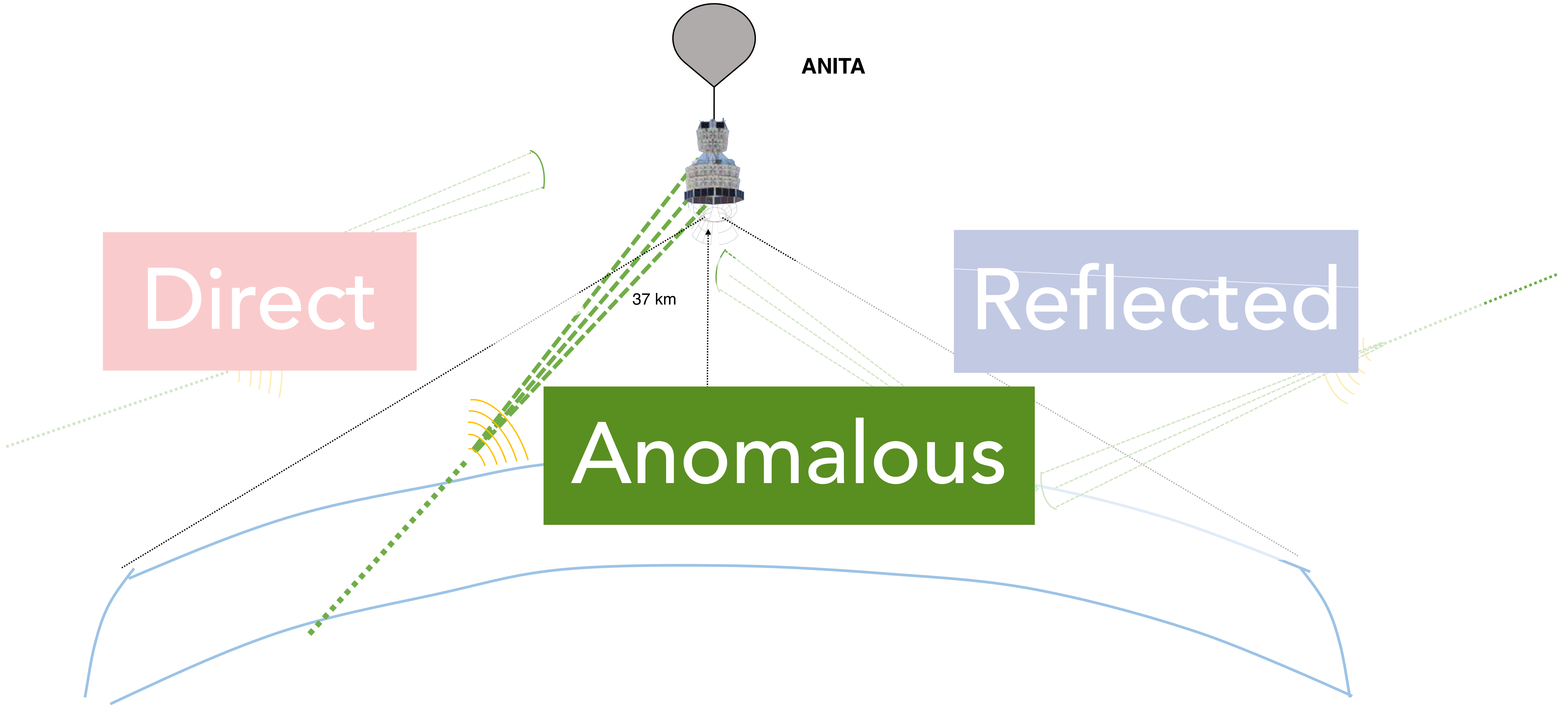
1005.0035



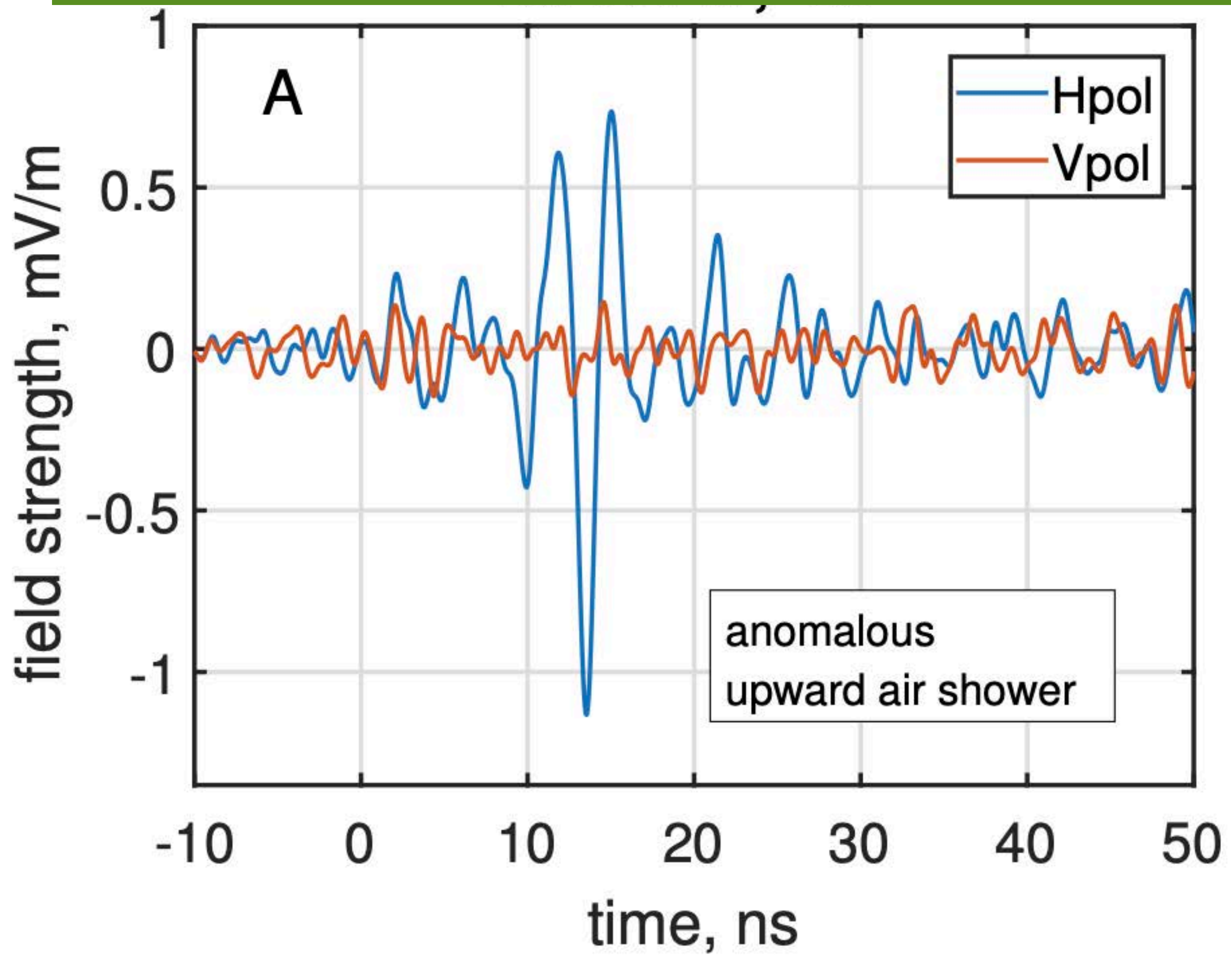
ANITA Cosmic Ray and Cosmic Ray-Like Events

- **ANITA Anomalous Events:** 2 steep, direct CR-like ~0.5 EeV events with polarity <u>inconsistent</u> with their geometry <u>*1803.05088*</u>, <u>*1603.05218*</u>
  (>3σ, A1 θ_H ~ -30°, Effective area A_{eff} $\sim\mathcal{O}(0.01\ \text{m}^2)$ at 0.5 EeV)





ANITA 3 Anomalous Event, -35°



- Tau neutrinos expected at shallower angles near the horizon (A_{eff} $\sim\mathcal{O}(100-1000\ \text{m}^2)$ at 0.5 EeV), but difficult to reconcile steep events with the Standard Model & experimental limits

See poster #476, <u>1811.07261</u>

ANITA-4 CR WAVEFORMS

- Events classified by **1st Dominant Pole***
  - **Reflected:** Down or Down first
  - **Direct:** Up or Up first

*Polarity reconstruction via 4 deconvolution methods using Stokes amplitude to find the peak lobe(s)

ANITA-4 CR WAVEFORMS

- Events classified by **1st Dominant Pole***
  - **Reflected:** Down or Down first
  - **Direct:** Up or Up first

*Polarity reconstruction via 4 deconvolution methods using Stokes amplitude to find the peak lobe(s)

4 additional events
near the horizon, but *below* it

Expect the same polarity as the reflected events: **Down**

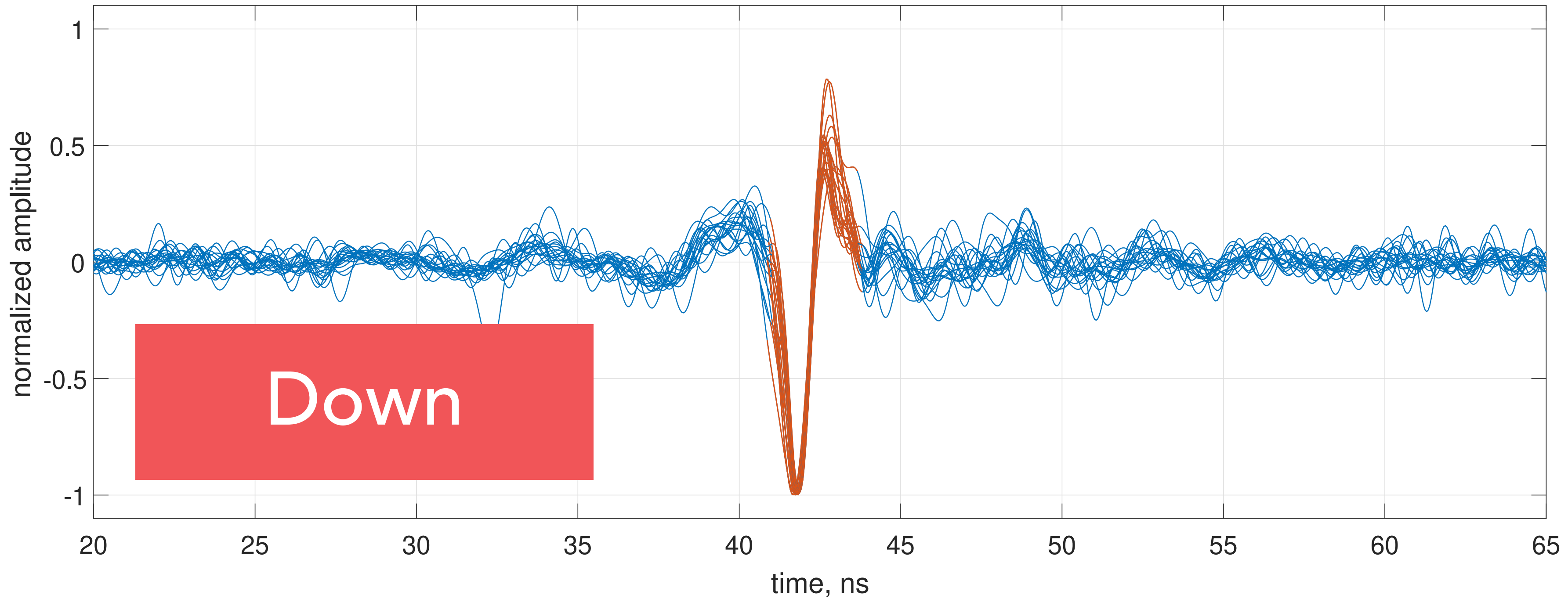
ANITA-4 CR Waveforms

Preliminary

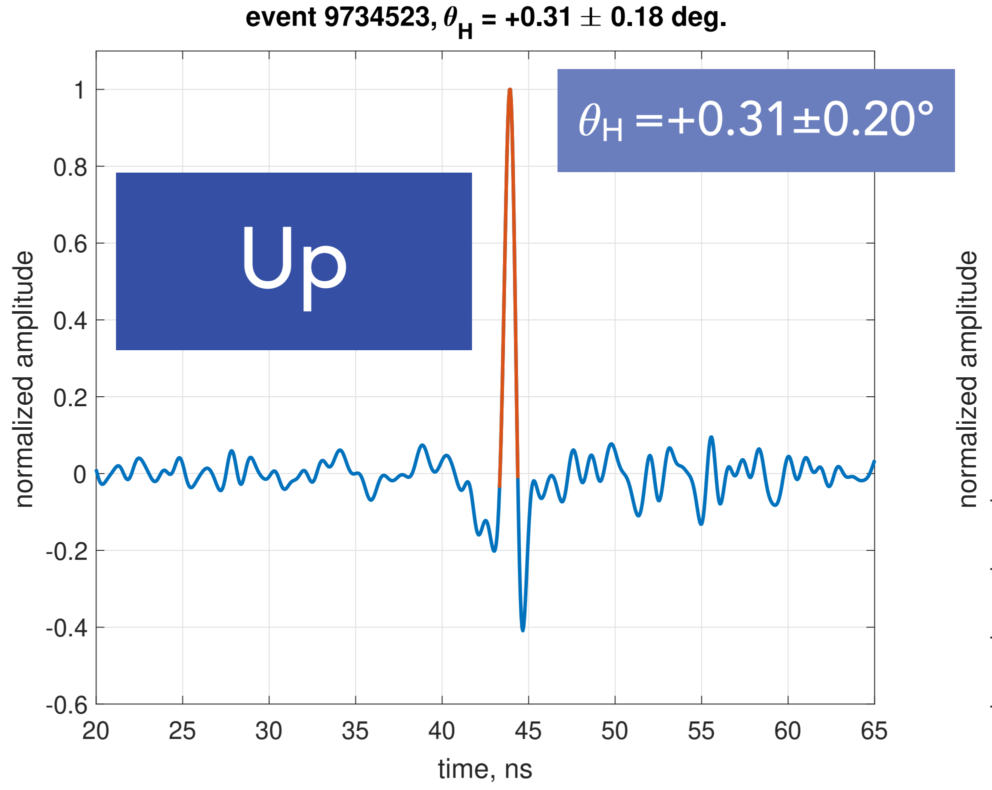
- Events classified by **1st Dominant Pole***
  - **Reflected:** Down or Down first
  - **Direct:** Up or Up first

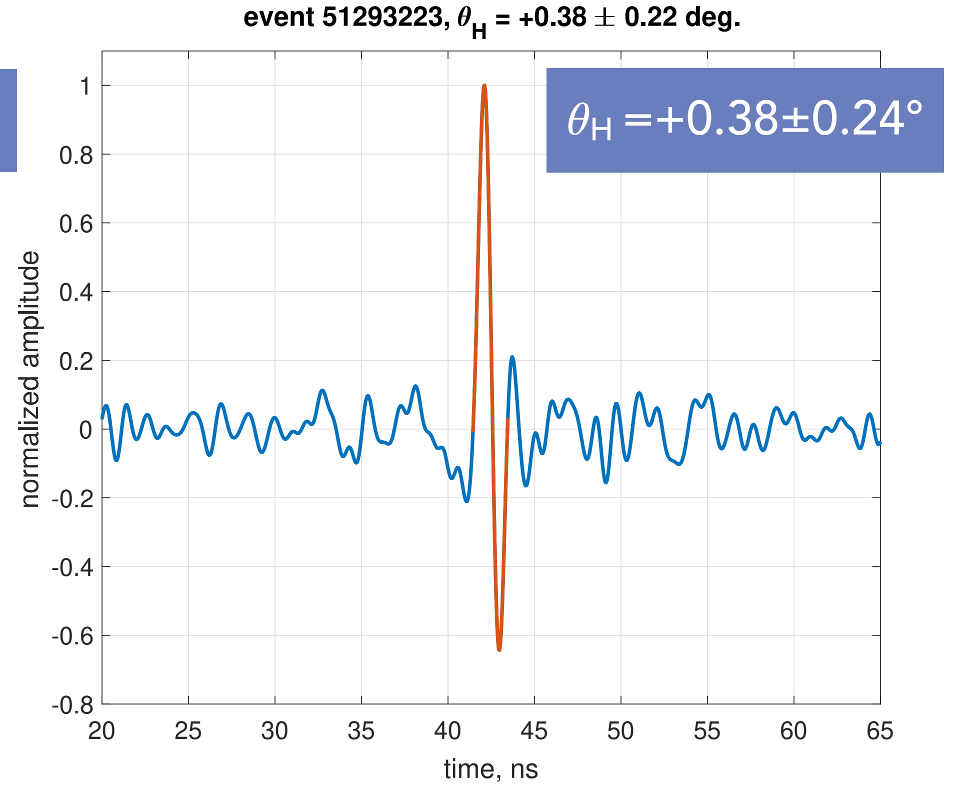
*Polarity reconstruction via 4 deconvolution methods using Stokes amplitude to find the peak lobe(s)

21 Reflected Events, Below Horizon



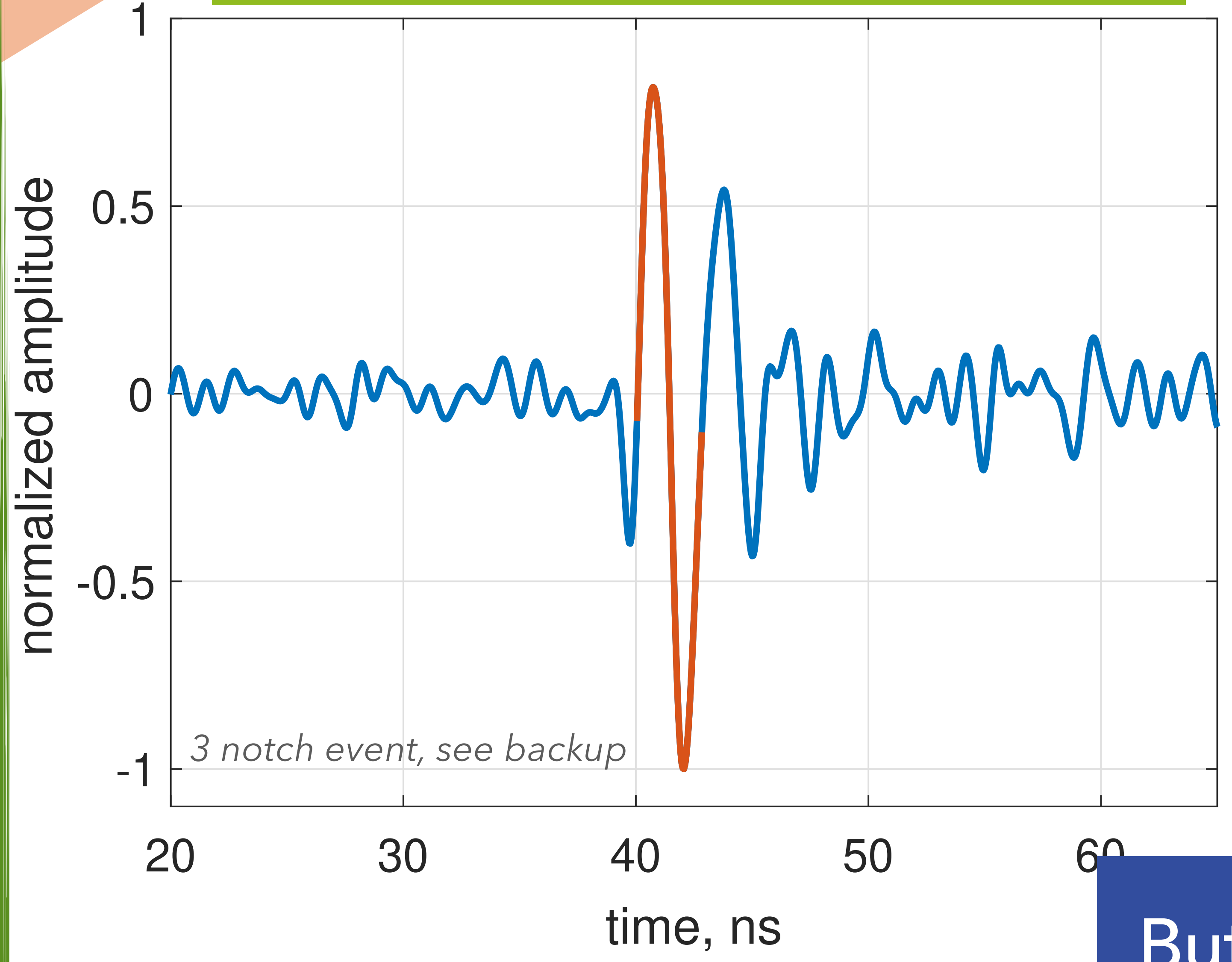
2 Direct Events, Near & Above Horizon



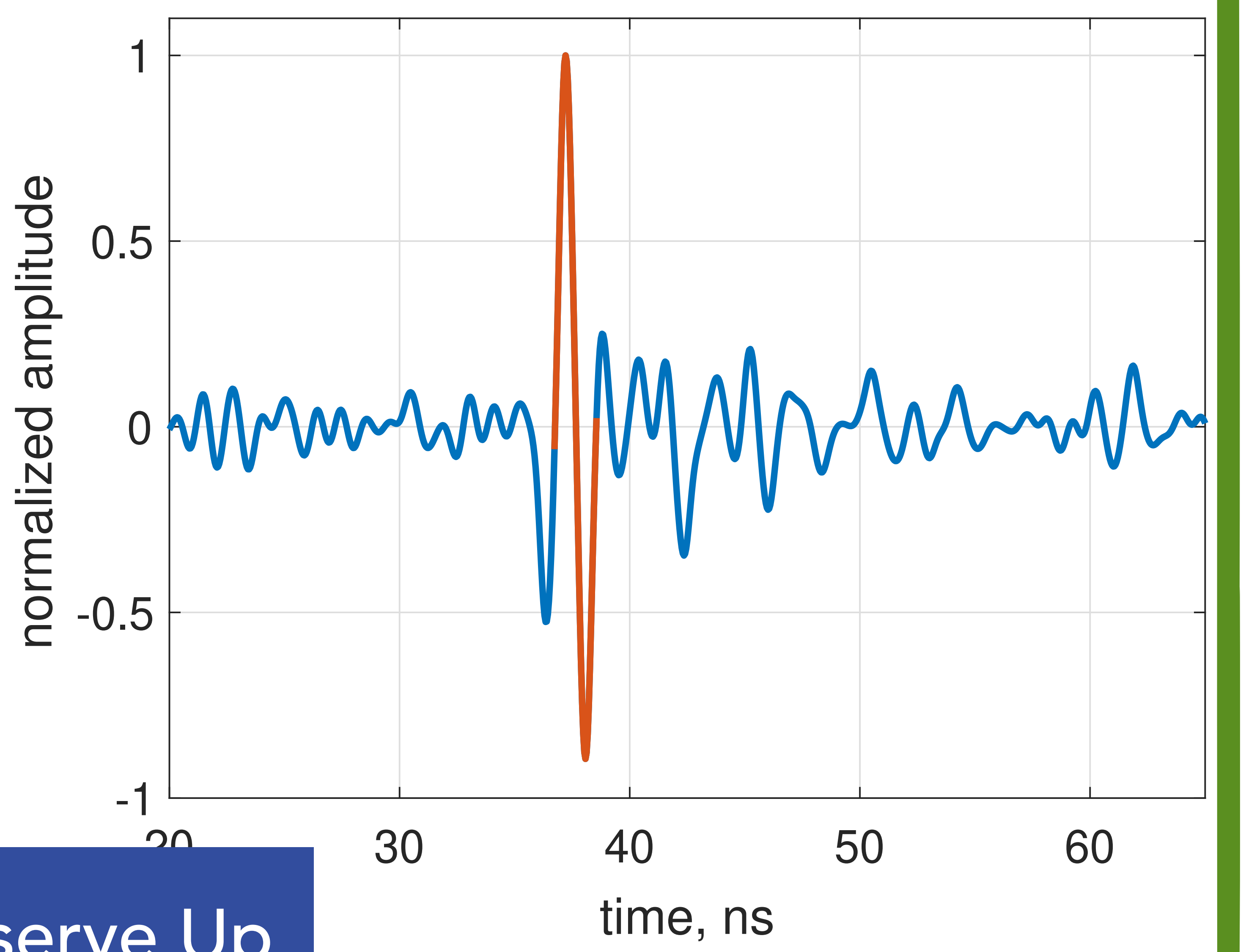


4 Direct Events, Near & Above Horizon

4098827, θ_H = -0.25±0.21°

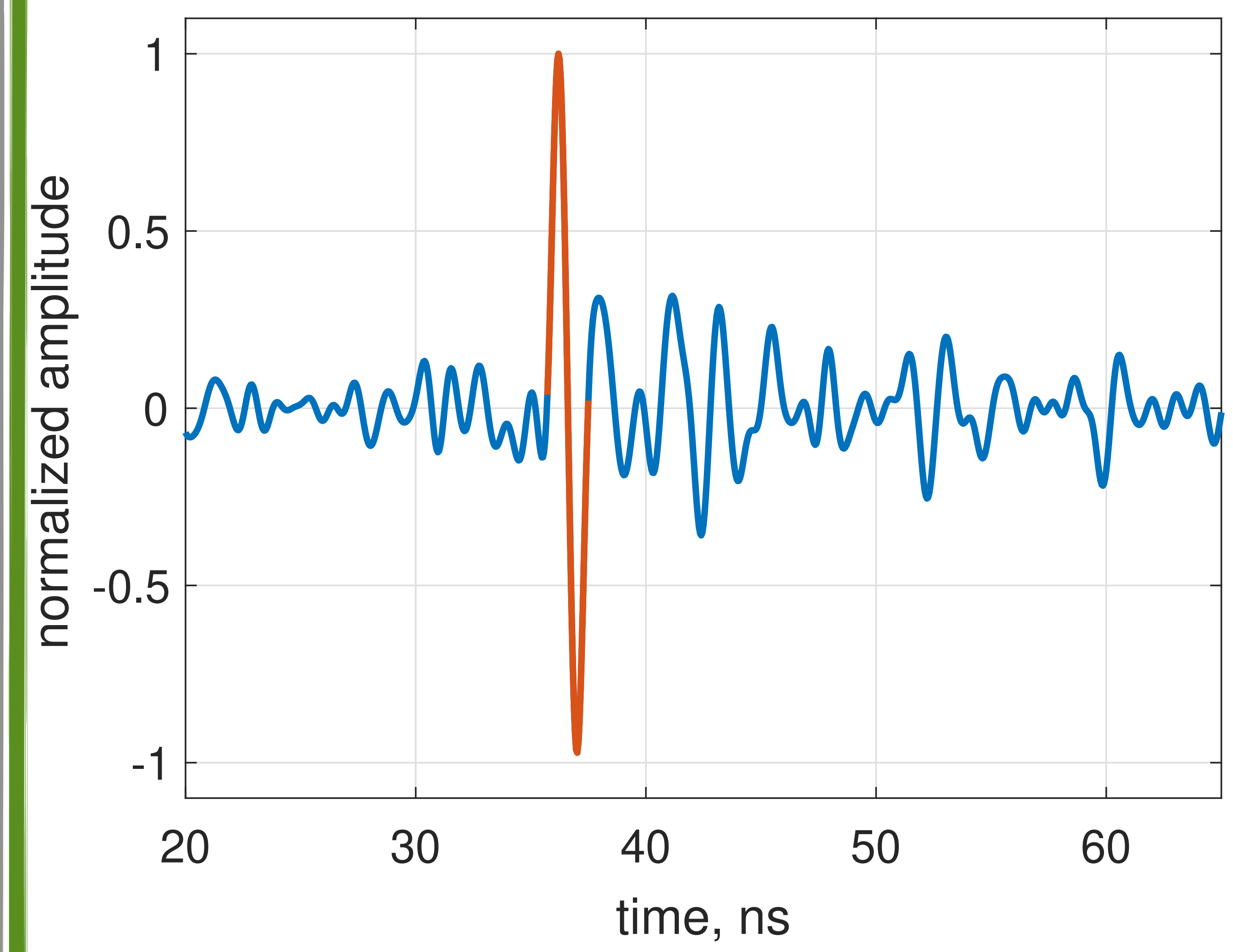


19848917, θ_H=-0.65±0.20°

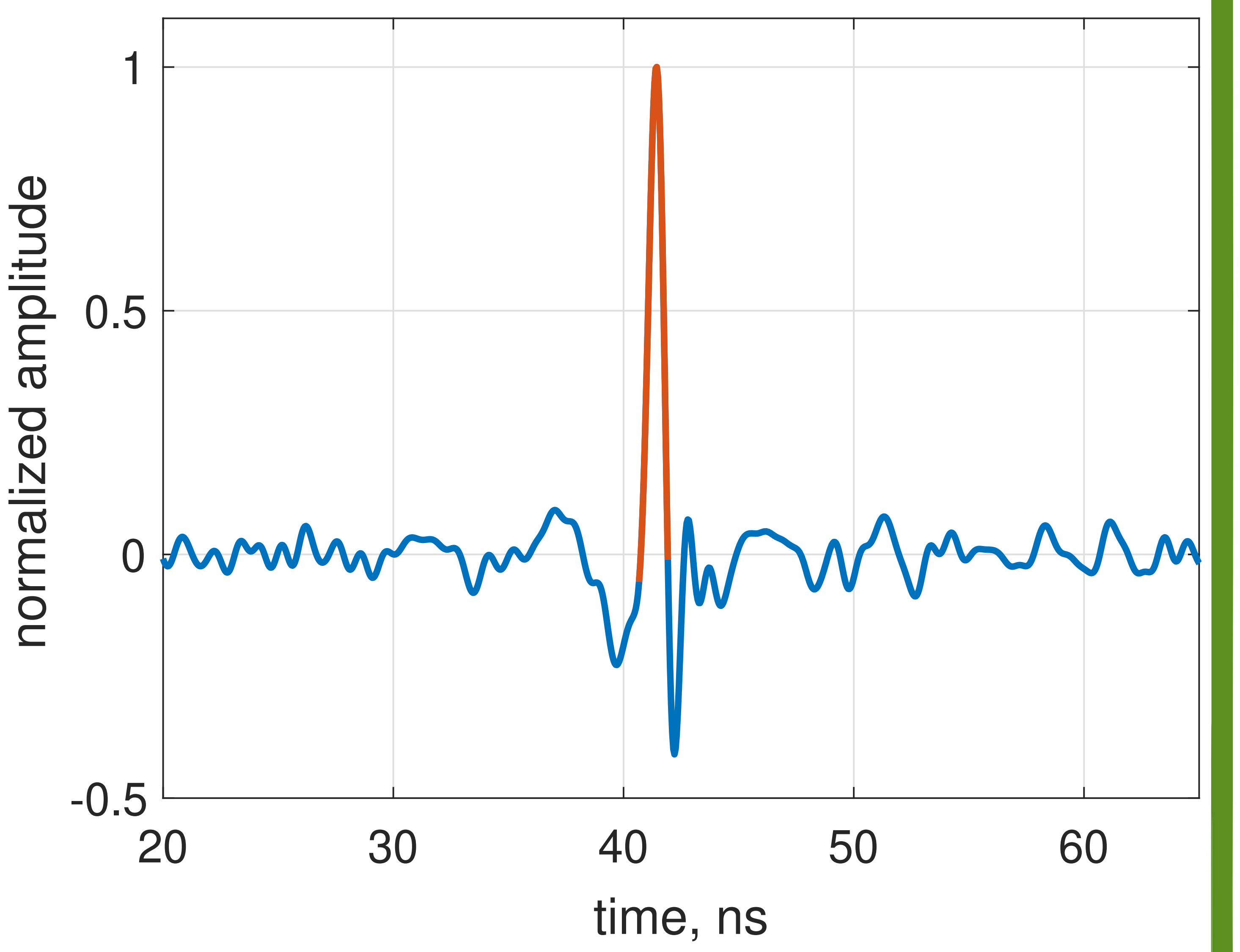


But observe Up

50549772, θ_H = -0.81±0.20°



72164985, θ_H = -0.19±0.10°



ANITA-4 Air Shower 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*

Results from targeted CR search		
	Steep	**Near Horizon**
Angle wrt horizon	> 1°	< 1°
Total Events	23	6
Total	**29**	

Preliminary

**Polarity reblinded to account for errors in system impulse response used to reconstruct polarity.*

Polarity reconstruction in A4 is more complicated than than in earlier flights due to the time-dependent system response imposed by programmable notch filters in the signal chain.

ANITA-4 Air Shower 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 / 27 near horizon events** with inconsistent polarity with significance **~3σ** Preliminary
- Systematics in significance estimate include :
  - anthropogenic background per polarity ($0.19^{+0.14}_{-0.09}$ events)
  - polarity mis-reconstruction (10^{-2} for 1 event; 10^{-4} others)
  - pointing error ($\delta\theta$ = 0.1°, bias ±0.1°)
  - radio propagation effects (refraction, ice surface, ray defocusing)
- **No new steep events** with inconsistent polarity like in ANITA-1 & ANITA-3

Results from targeted CR search (Preliminary)

Angle wrt horizon	Steep > 1°	Near Horizon < 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**	

See posters #552 (ANITA-4) and #486 (PUEO)

Summary and Outlook

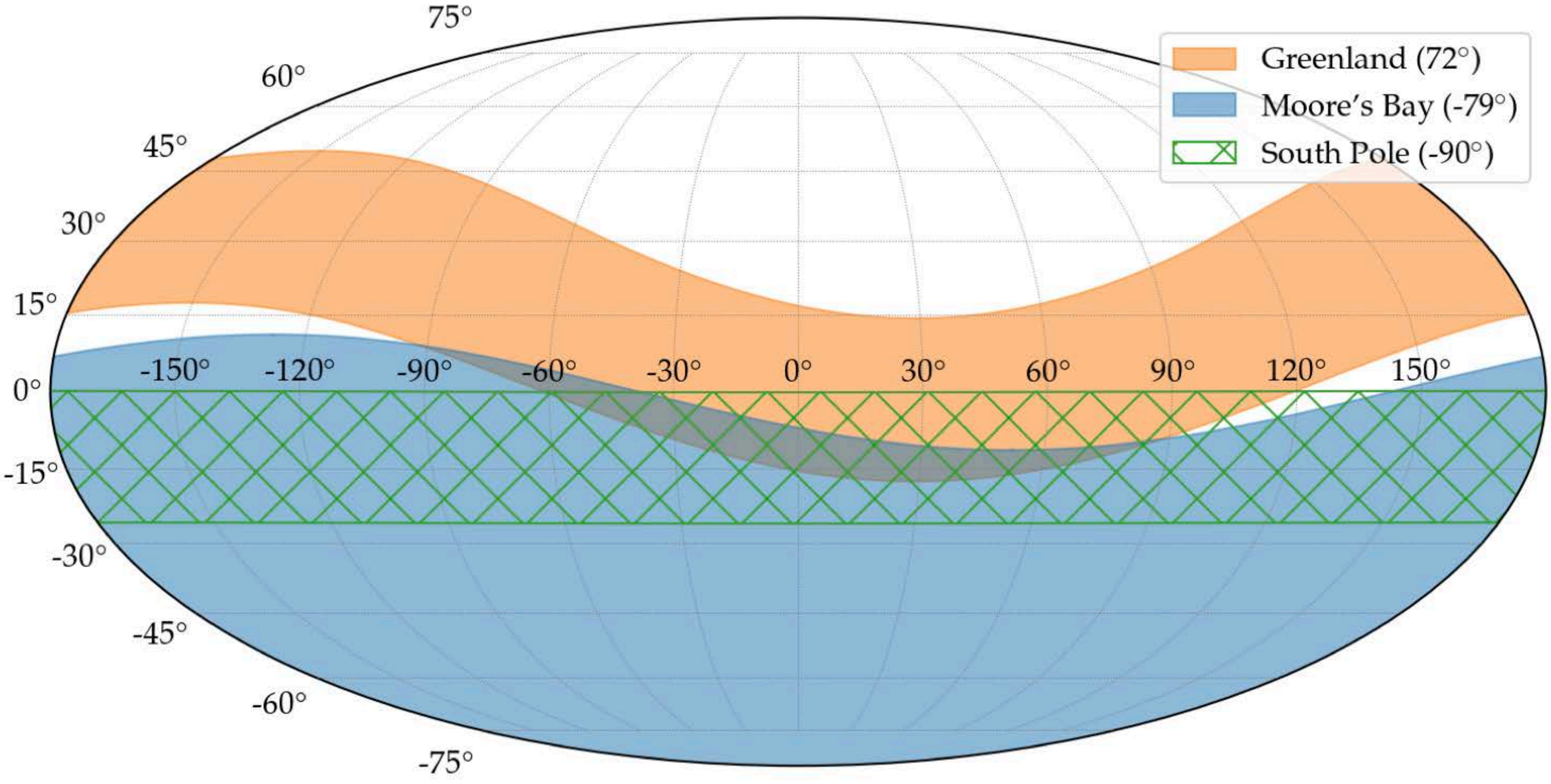
- **Exciting Things on the Horizon:**
  - While still consistent with backgrounds, ANITA-4 may be observing a new class of events near the horizon Preliminary
  - No new steep anomalous events in ANITA-4 dataset
  - Followup with PUEO and other experiments will be important

Summary and Outlook

- **Exciting Things on the Horizon:**
  - While still consistent with backgrounds, ANITA-4 may be observing a new class of events near the horizon (Preliminary)
  - No new steep anomalous events in ANITA-4 dataset
  - Followup with PUEO and other experiments will be important
- **Radio experiments are maturing**
  - Experiments preparing for mid-scale sensitivities at least an order of magnitude lower than current state-of-the art
  - Several promising proposed experimental designs
  - Next gen detectors hold promise to discover UHE neutrinos within 10 years & begin neutrino astronomy in new energy regime

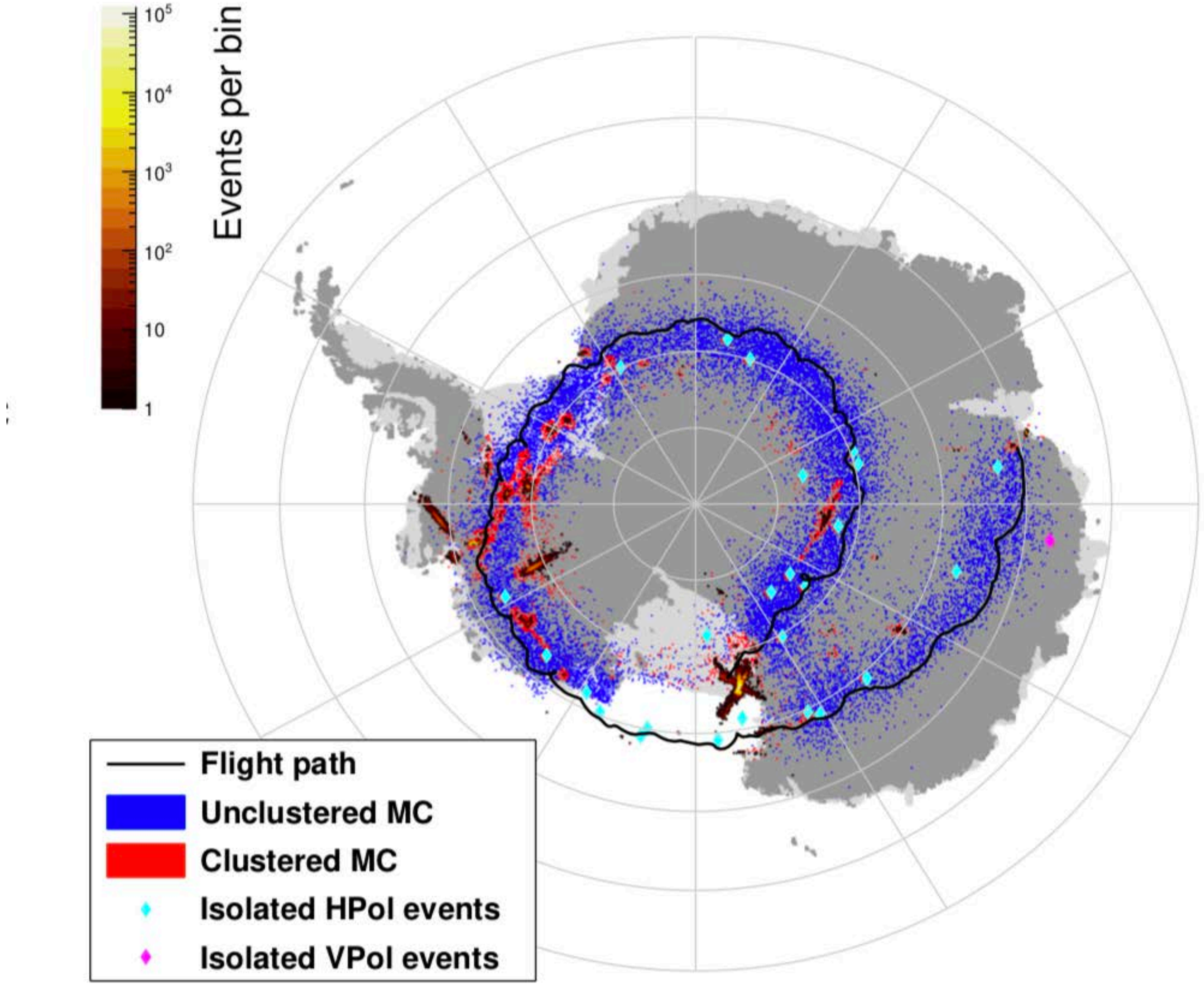
Backup Slides

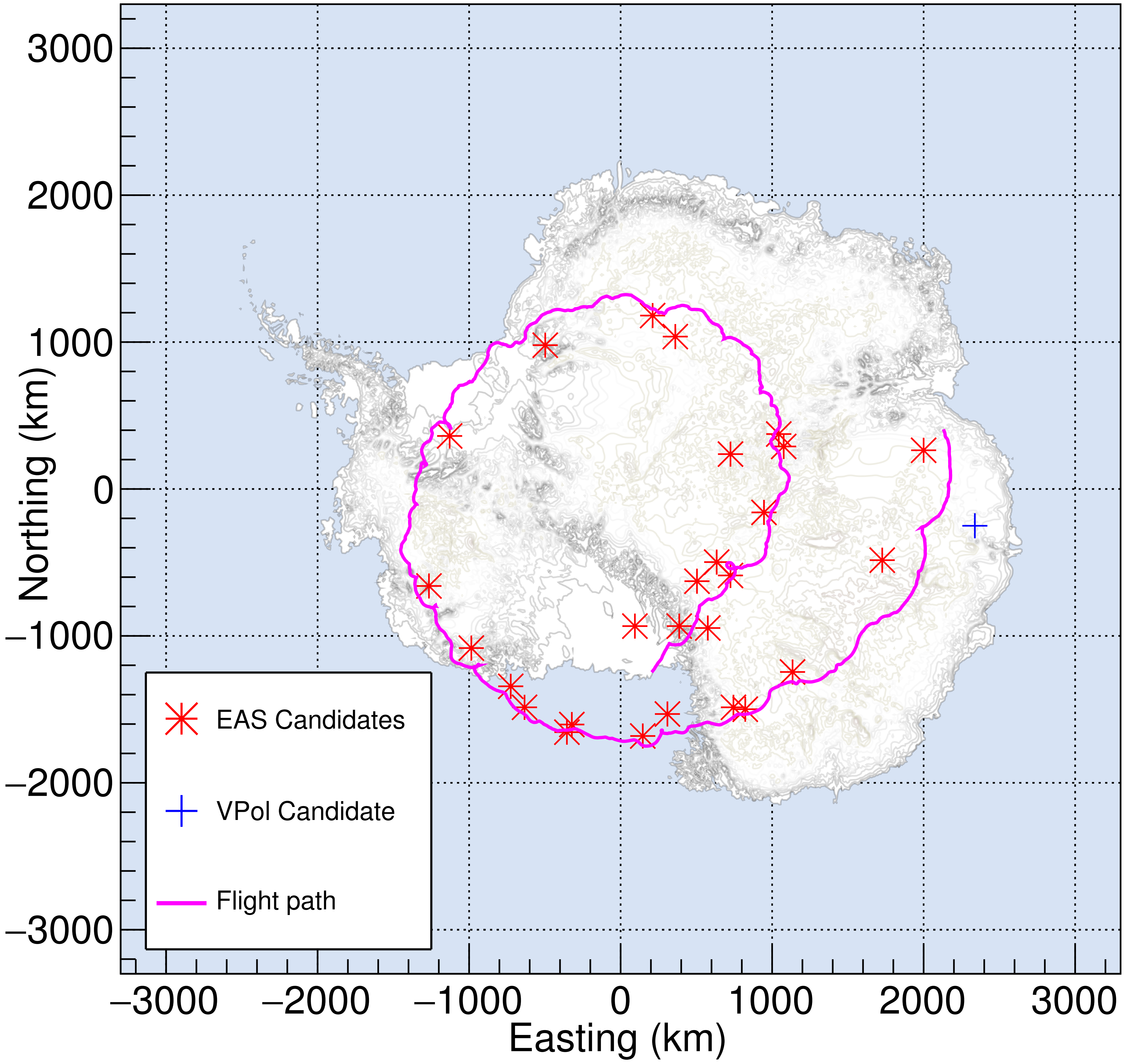
In-ice Detectors Sky Coverage



ANITA Blinded Neutrino Search

- Clustering identifies isolated singlet events candidates
- **Neutrinos:** vertical polarization
- **Cosmic rays:** horizontal polarization

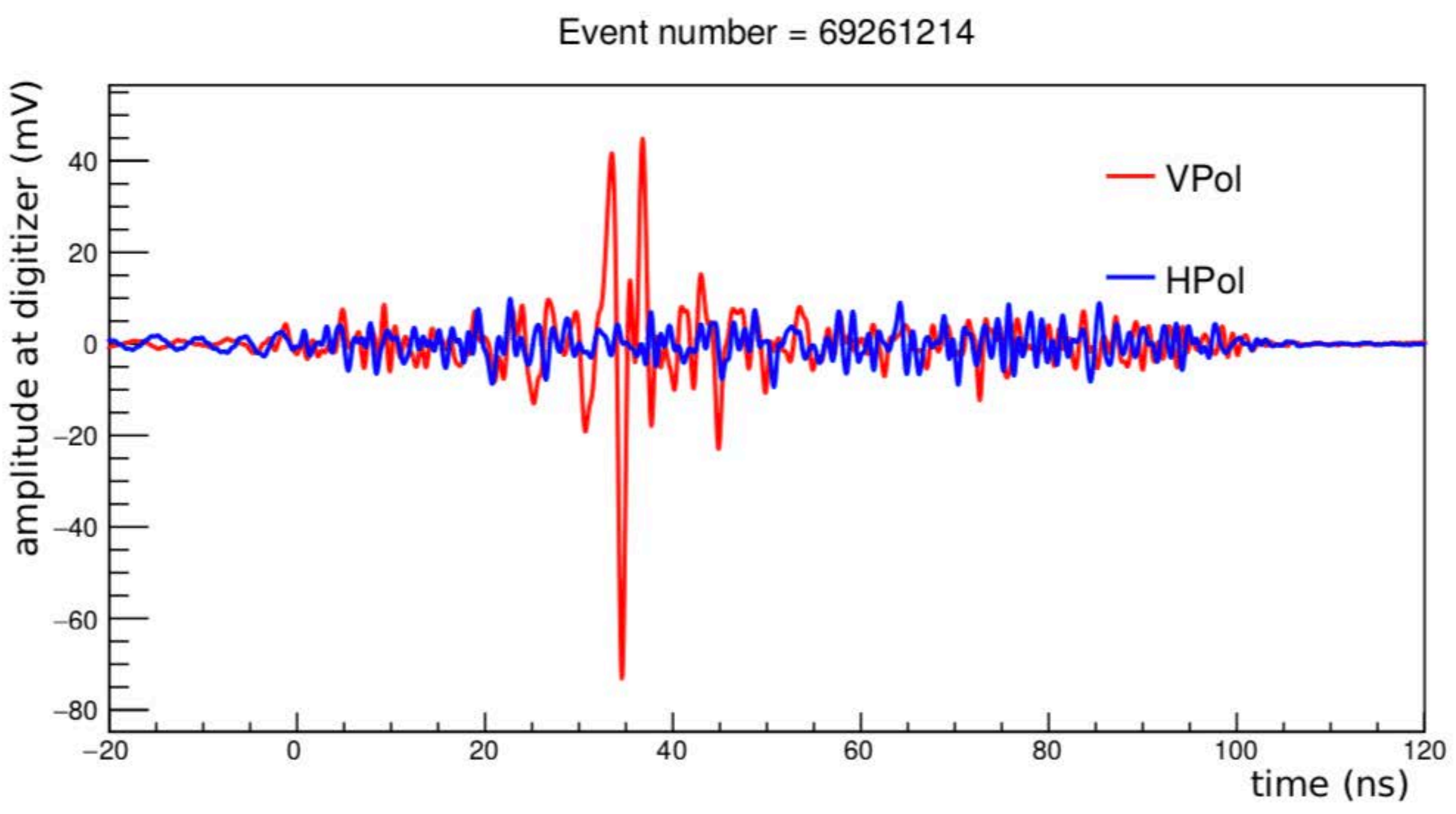


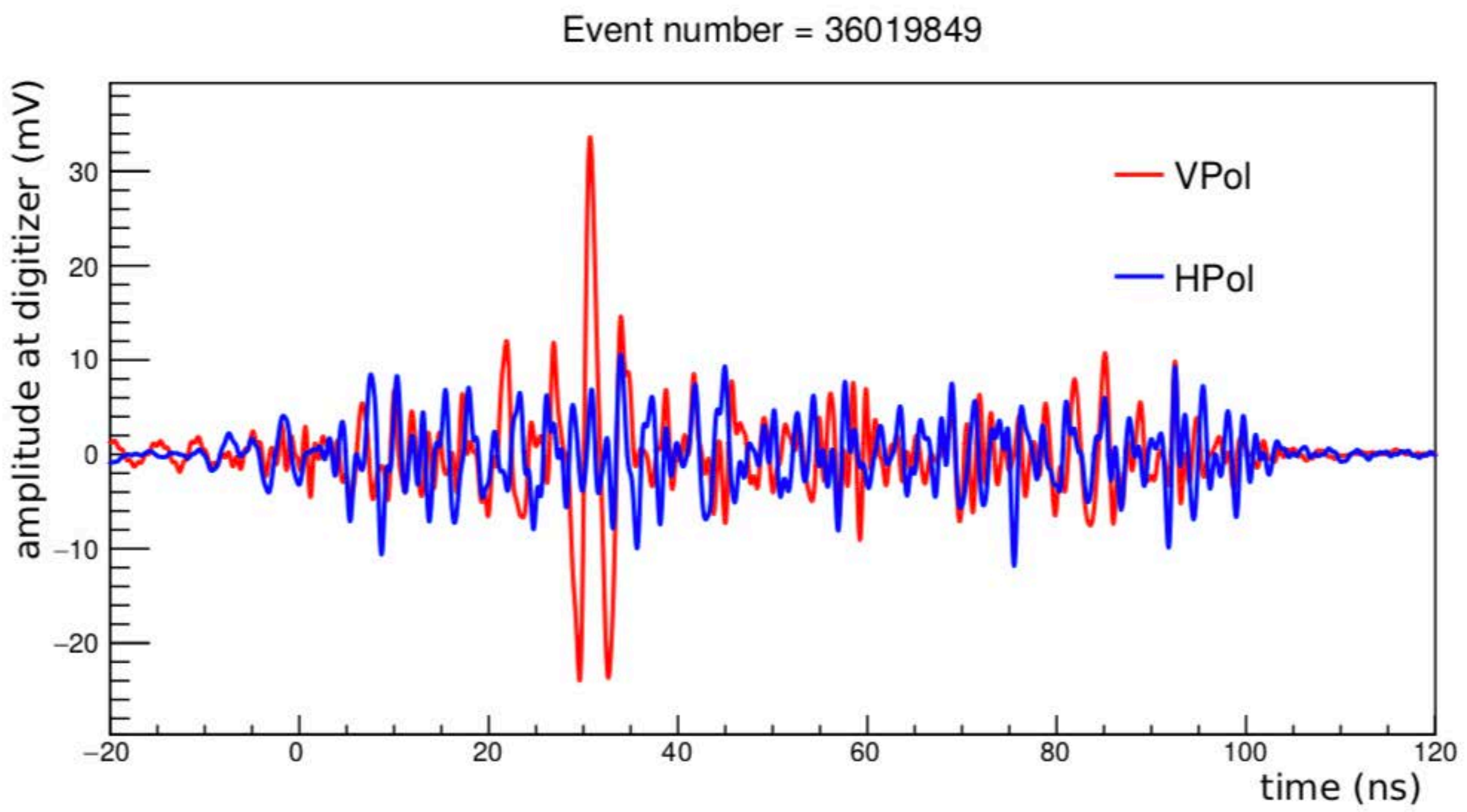


ANITA-3 Search
ANITA PRD 98 022001 2018

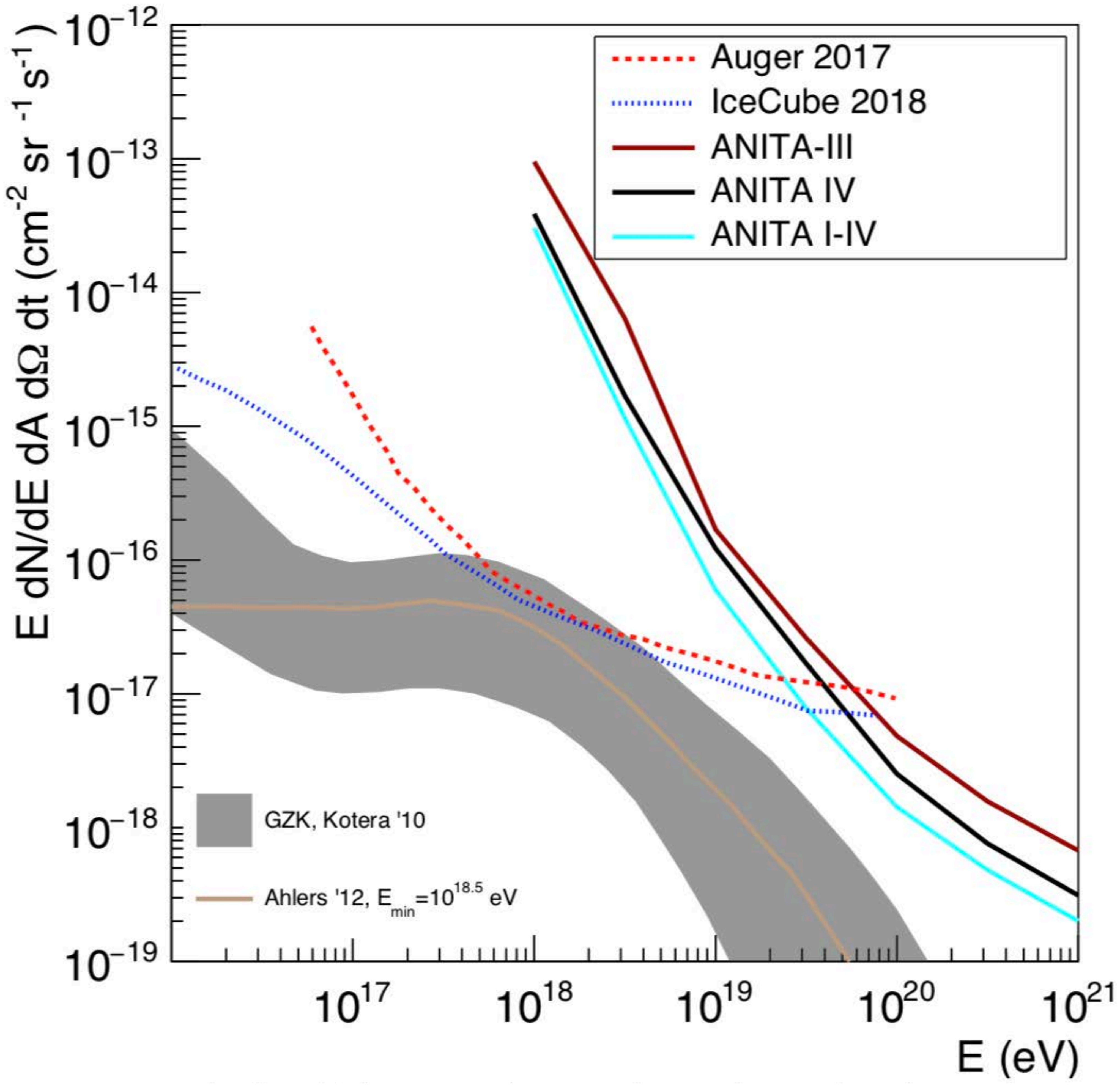
ANITA-4 Neutrino Search Results

- Two analyses each find 1 candidate event on backgrounds of 0.34 and 0.64





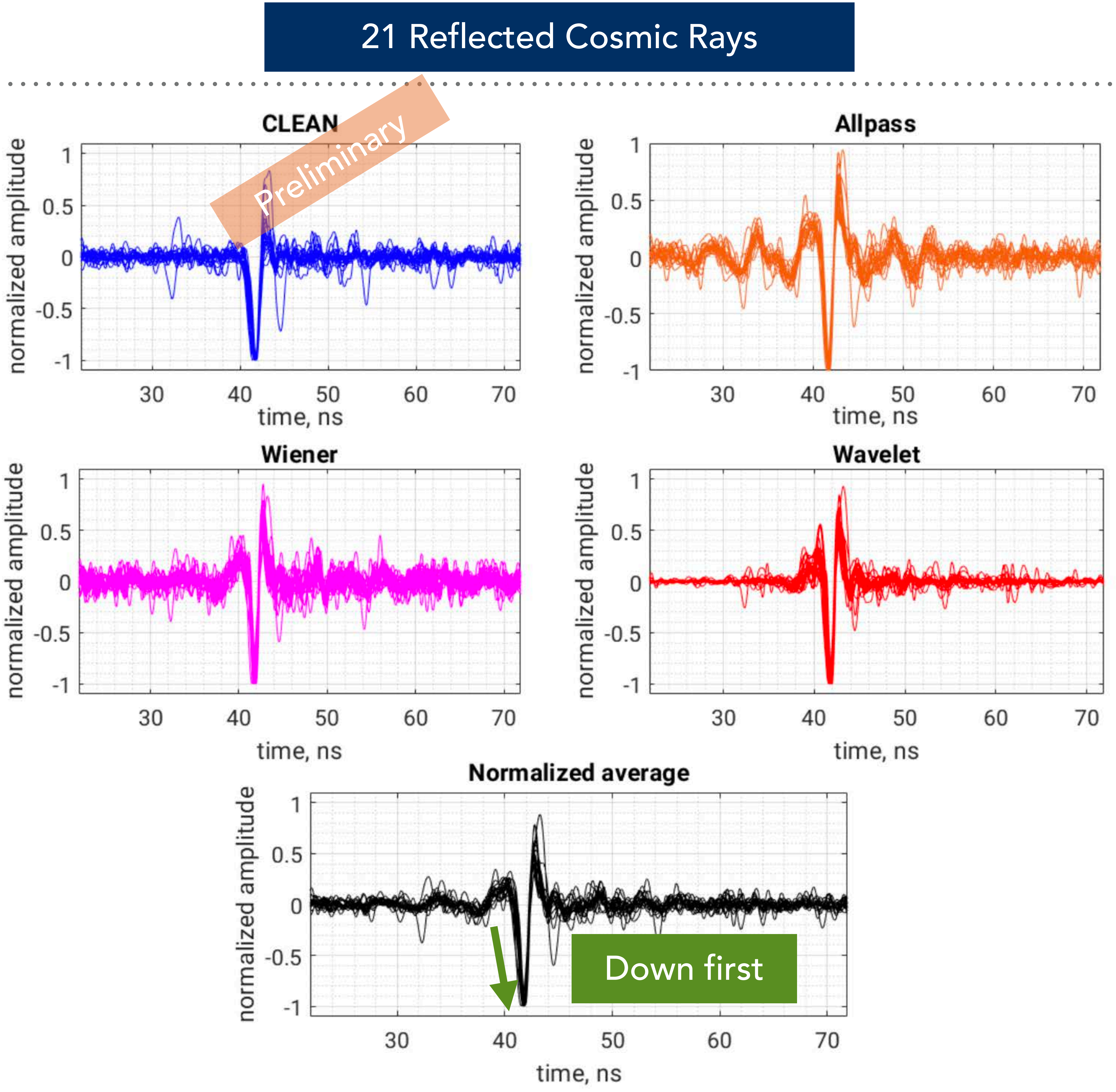
- Set strongest upper limit on isotropic flux above $10^{19.5}$ eV



ANITA arXiv:1902.04005

POLARITY RECONSTRUCTION

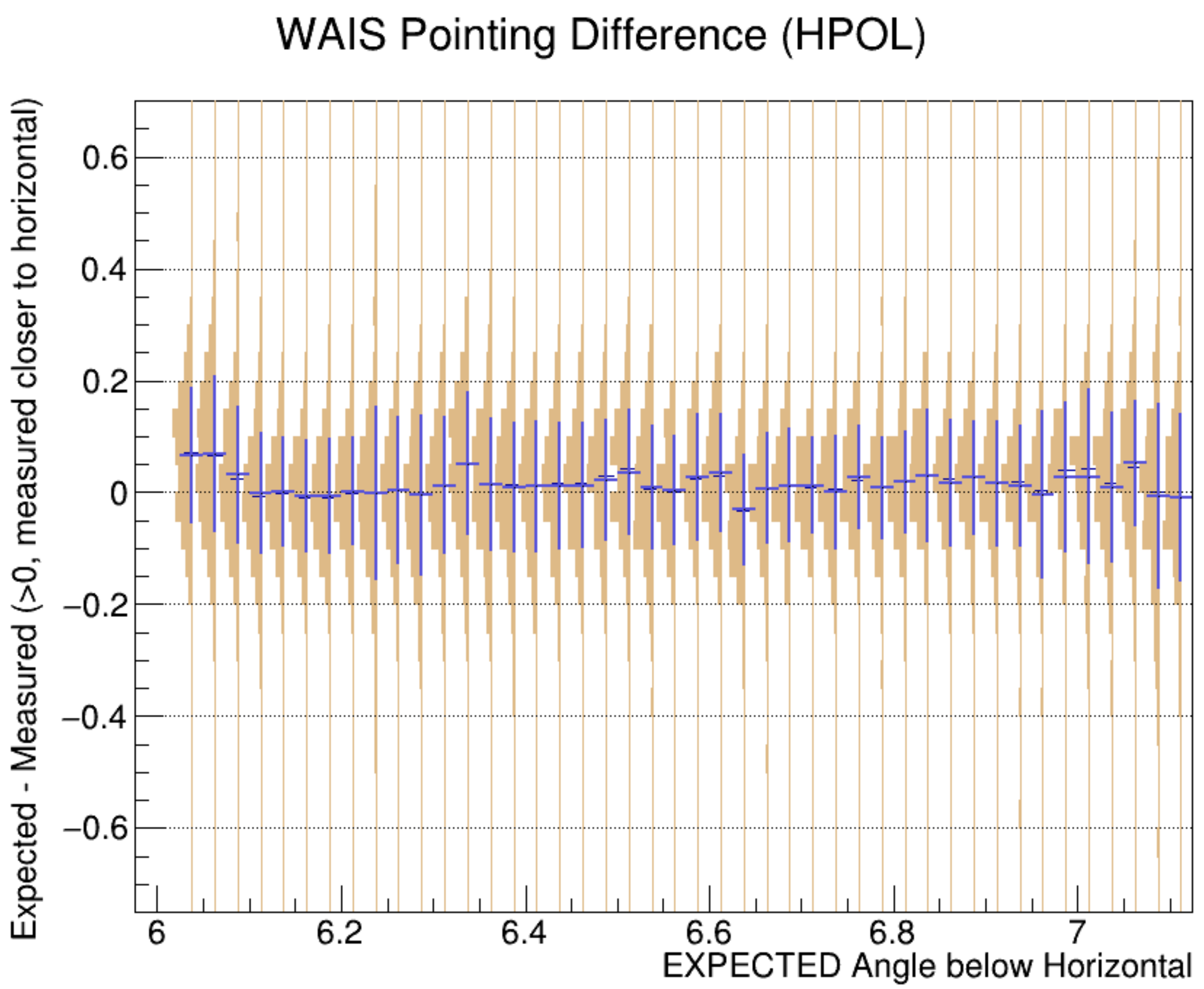
- Polarity reconstructed by deconvolving the response of the ANITA instrument, which disperses and attenuates the signal
- Average of four deconvolution methods → Polarity measure
- Polarity predominately determinedly the sign of the leading pole, but in practice depends on waveform shape
- In Monte Carlo with different noise realizations, polarity CL at the 1e-4 level, except 19848917 (2e-2)

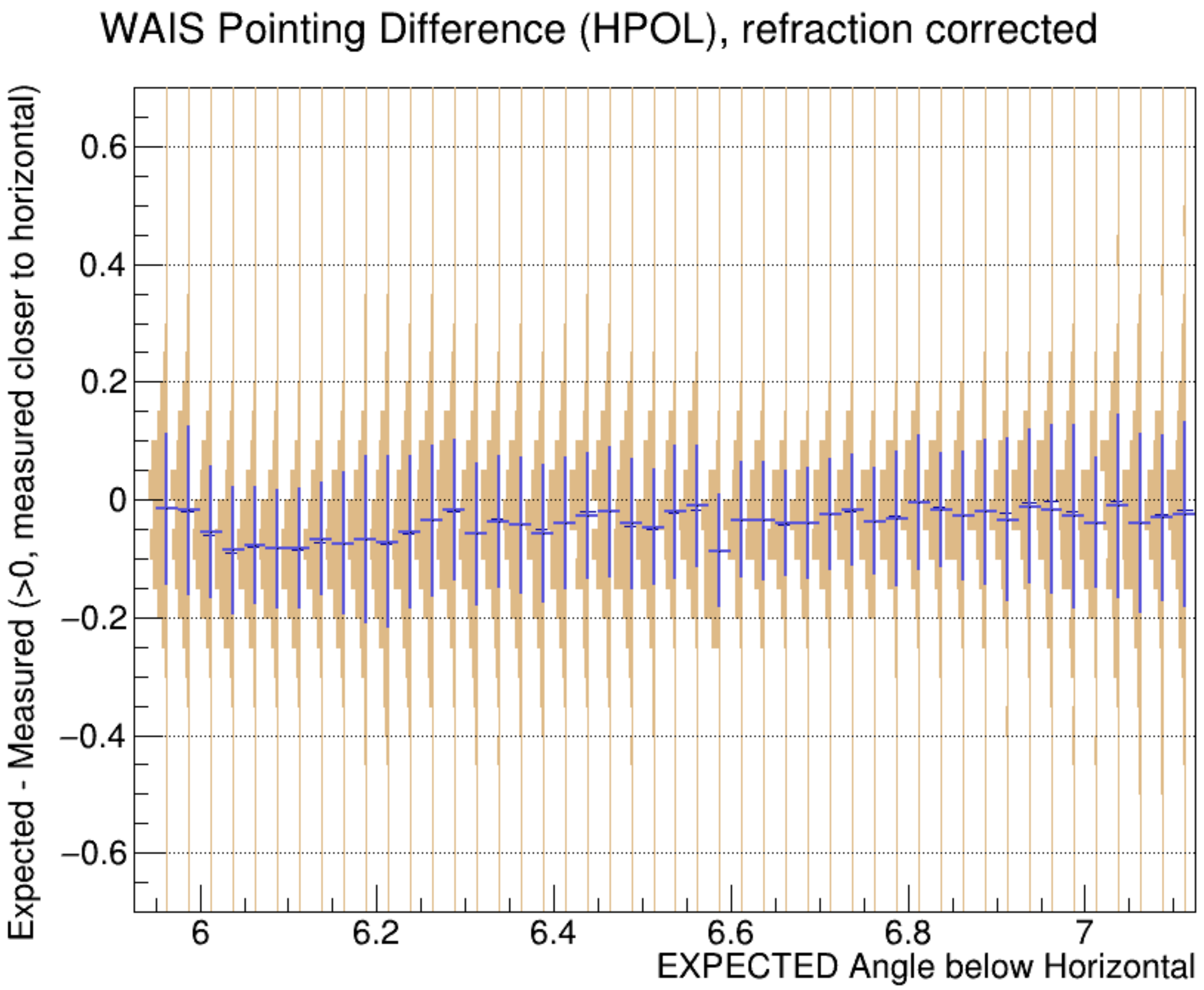


POINTING RESOLUTION, RECONSTRUCTION & SYSTEMATICS AT THE HORIZON

- Calibration pulsers in remote location (WAIS Divide) reconstruct known location within $\delta\theta = 0.1°$
- Difference between the apparent horizon and the apparent reconstructed position requires refraction correction (+0.1°) and reconstruction of the apparent horizon (+0.1°)
- Systematic bias near the horizon observed with WAIS pulsers, HiCal pulser (on separate payload) ,and RFI from the South Pole suggest possible bias ±0.1°. Studies ongoing.
- Horizon buffer in significance tests included due to occultation of reflected rays near the horizon, validated with GPS measurements

Preliminary





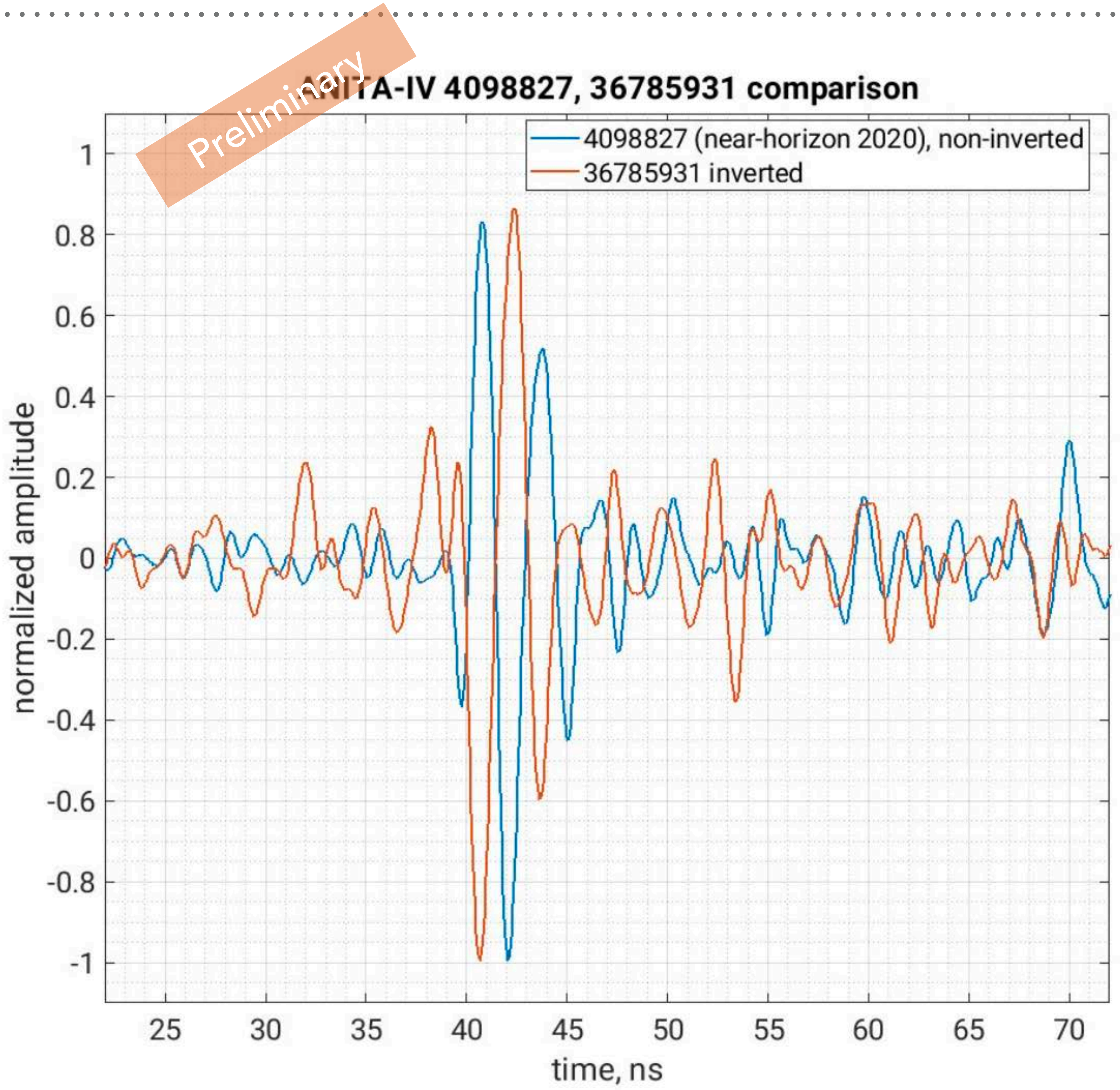
SIGNIFICANCE TESTS

Background assumed	Horizon buffer	Pointing bias	P-value	Normal statistics σ
Anthropogenic non-inverted + above-horizon pointing errors + polarity flips, producing 4 or more non-inverted below-horizon events out of 27	0.0	0.0	3.9e-4	3.36
	0.1	0.0	1.1e-4	3.69
	0.0	-0.1	3.7e-3	2.68
	0.1	-0.1	3.9e-4	3.36
	0.0	+0.1	1.2e-4	3.67
	0.1	+0.1	7.5e-5	3.8

Preliminary

Three Notch Events

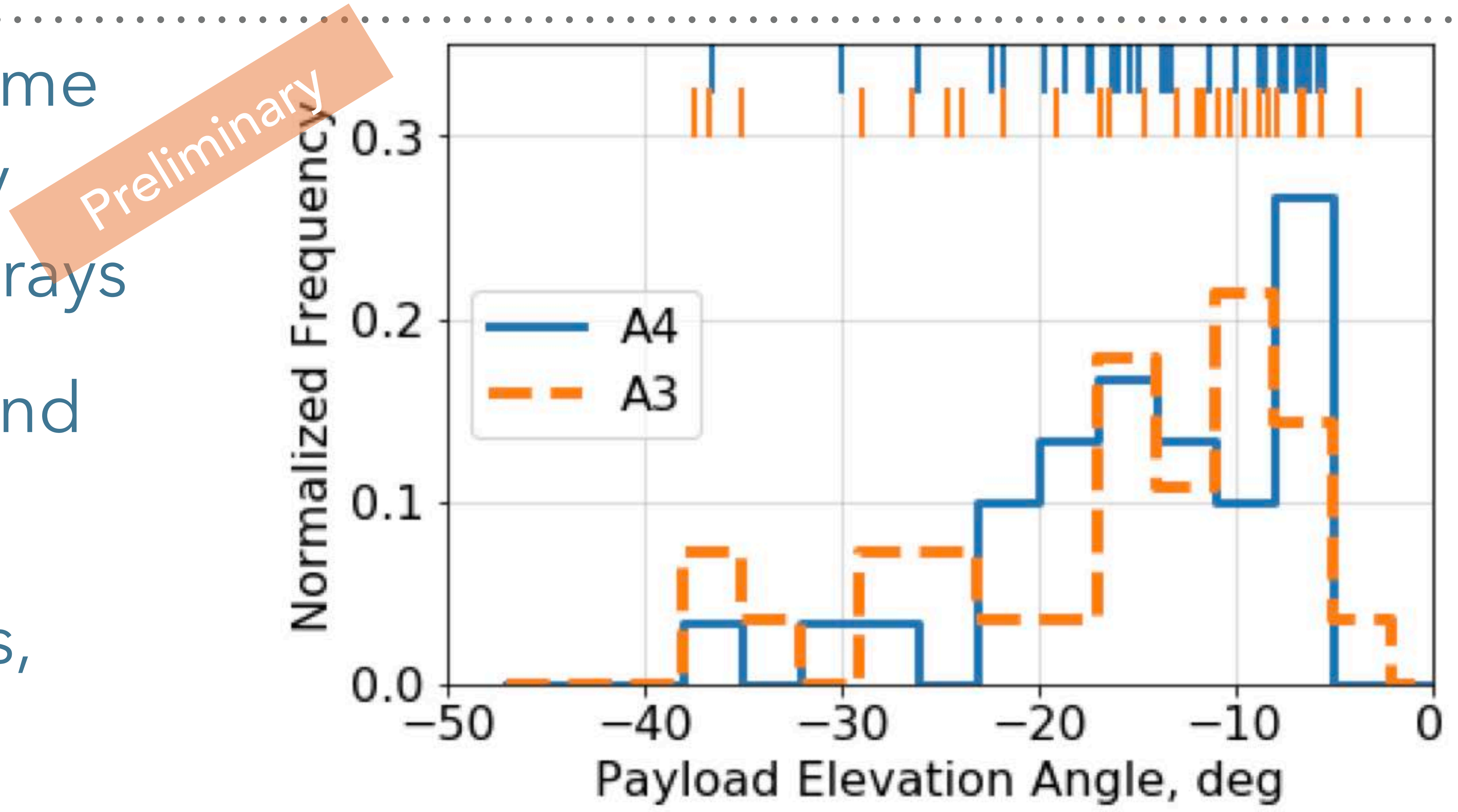
- Two three-notch events observed with opposite polarity
  - **4098827:** anomalous near horizon
  - **36785931:** normal, steep cosmic ray
- Deconvolution complicated by programmable notch filters, each combination of filters requires different system impulse response

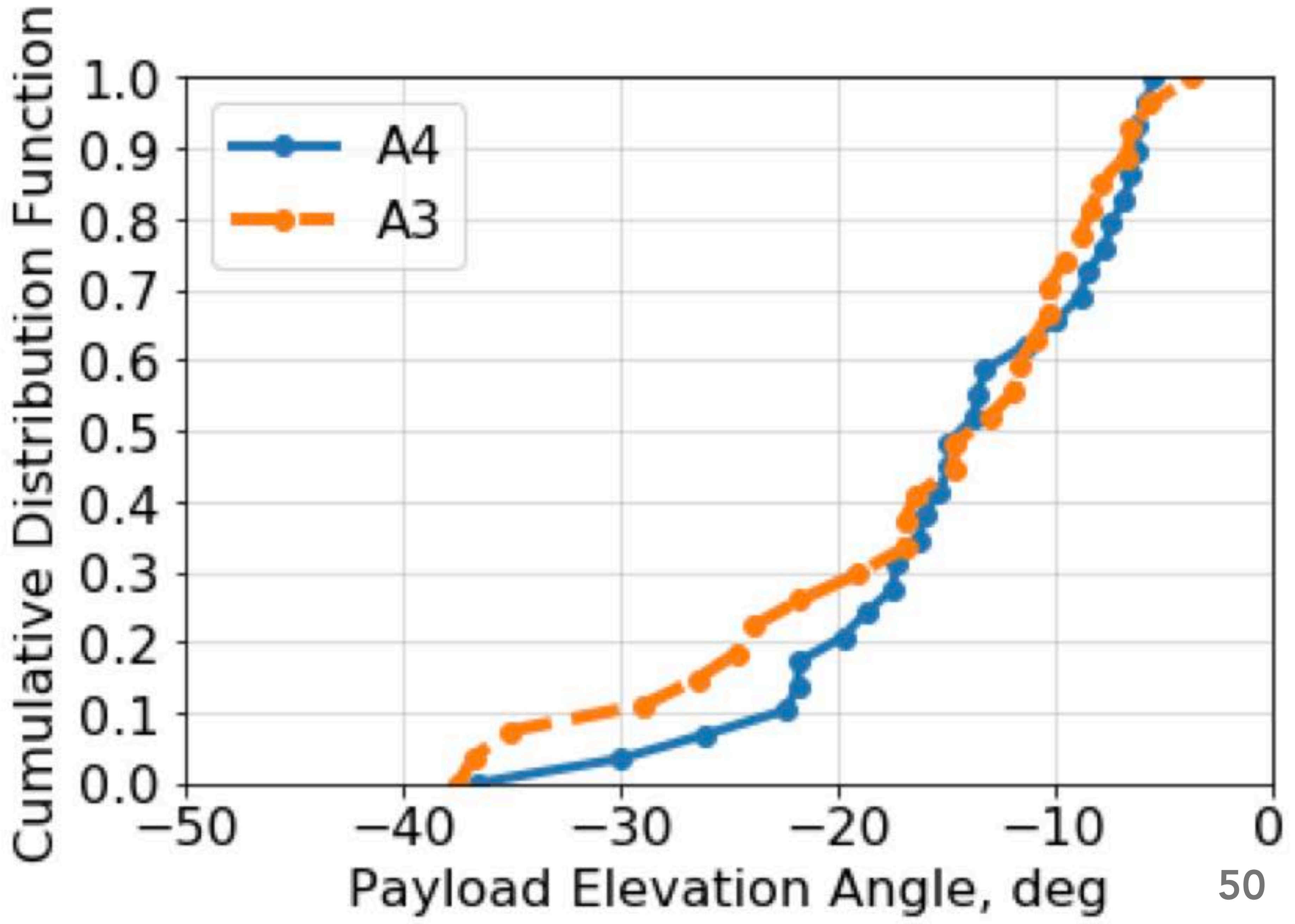


ANITA-3 and ANITA-4 CR Event Statistics

- A4 had a 20% lower threshold and 50% higher livetime compared with A3, but notch filters at low frequency reduced sensitivity to the steep spectrum of cosmic rays
- A4 trigger and notches biased for flatter spectrum and weaker CR events, closer to the Cherenkov angle
- Results in comparable numbers of cosmic ray events, but more near horizon events

	Total CR Events	Near Horizon Events
ANITA-3	28	3
ANITA-4	29	6

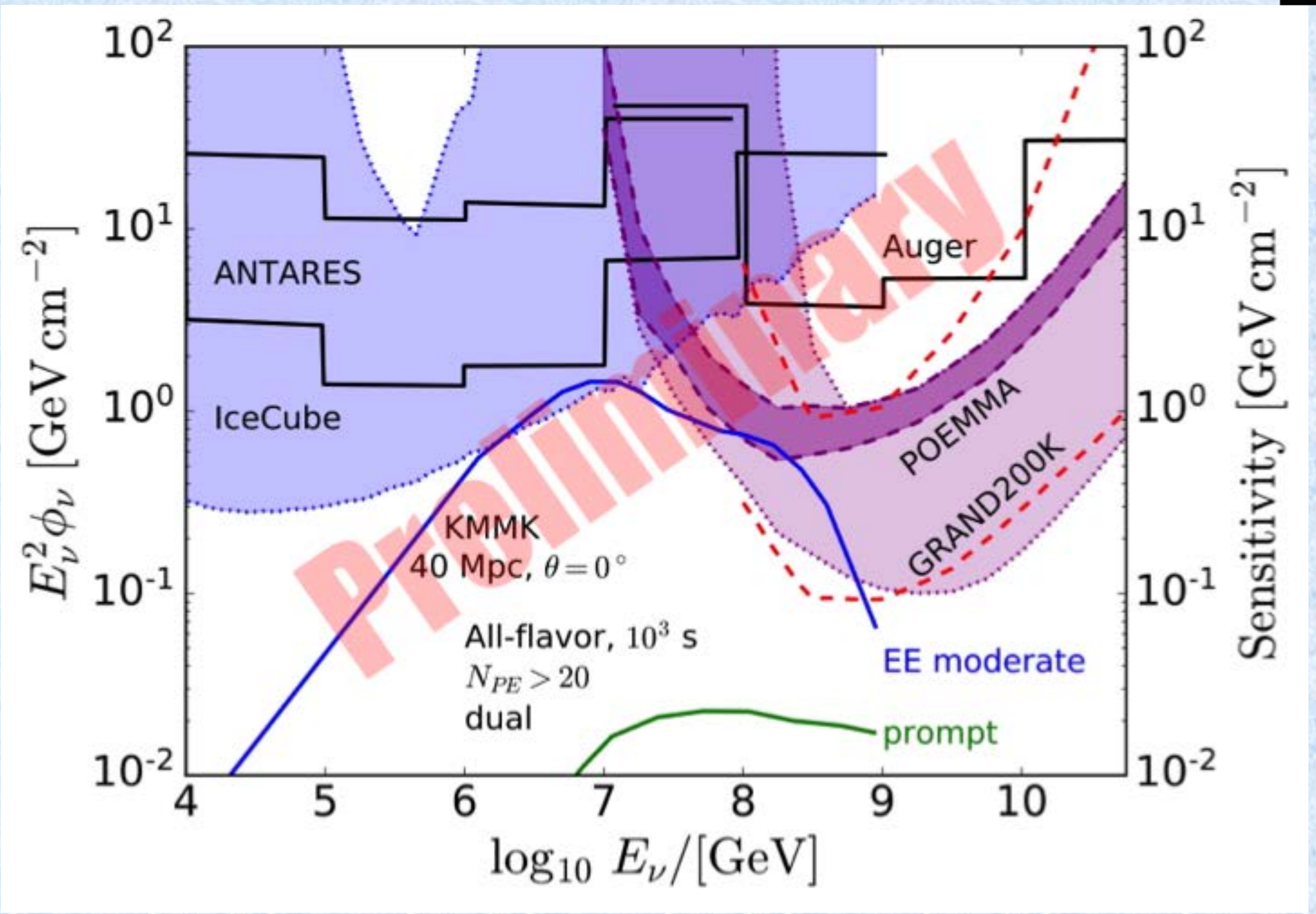


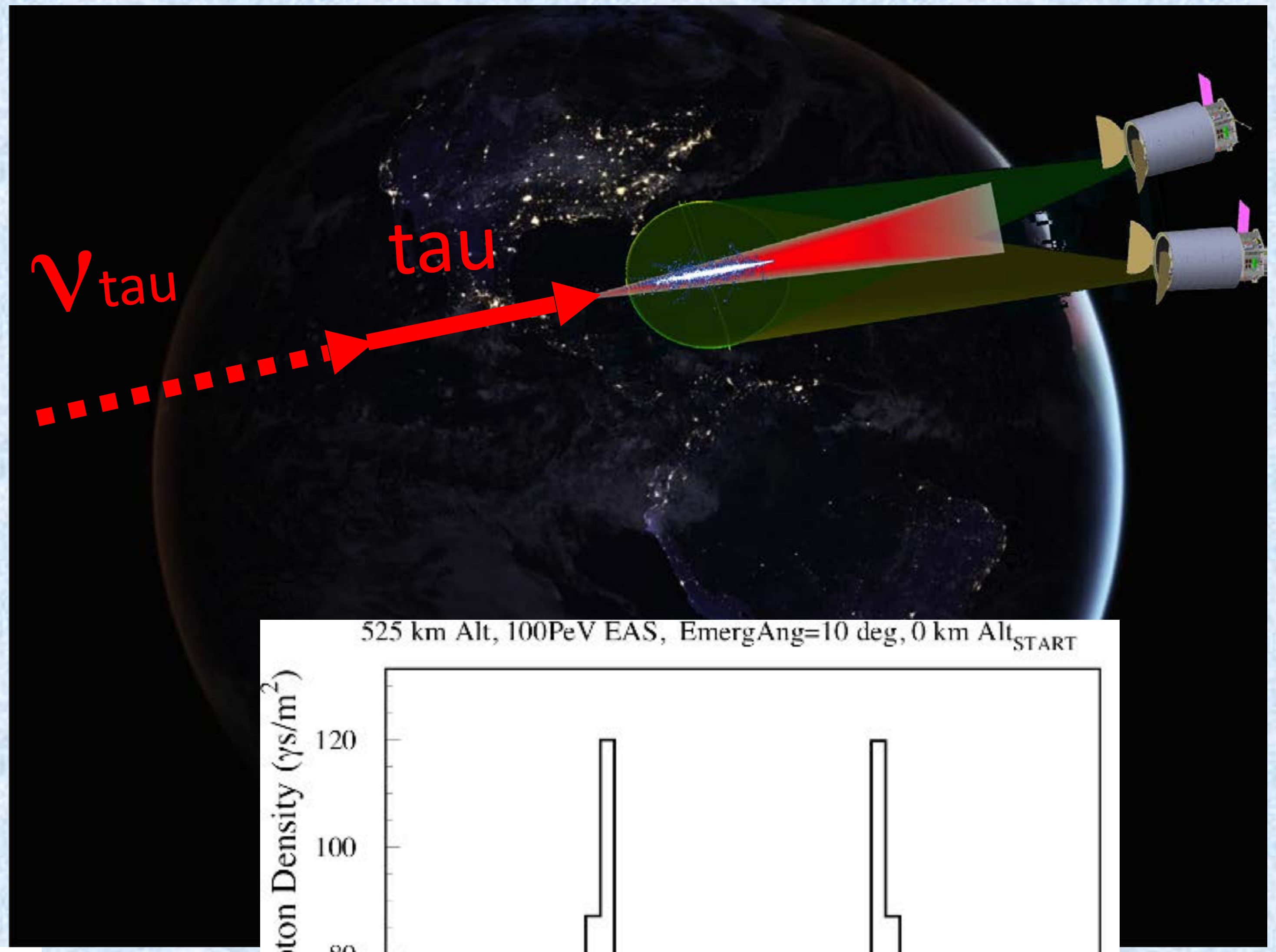


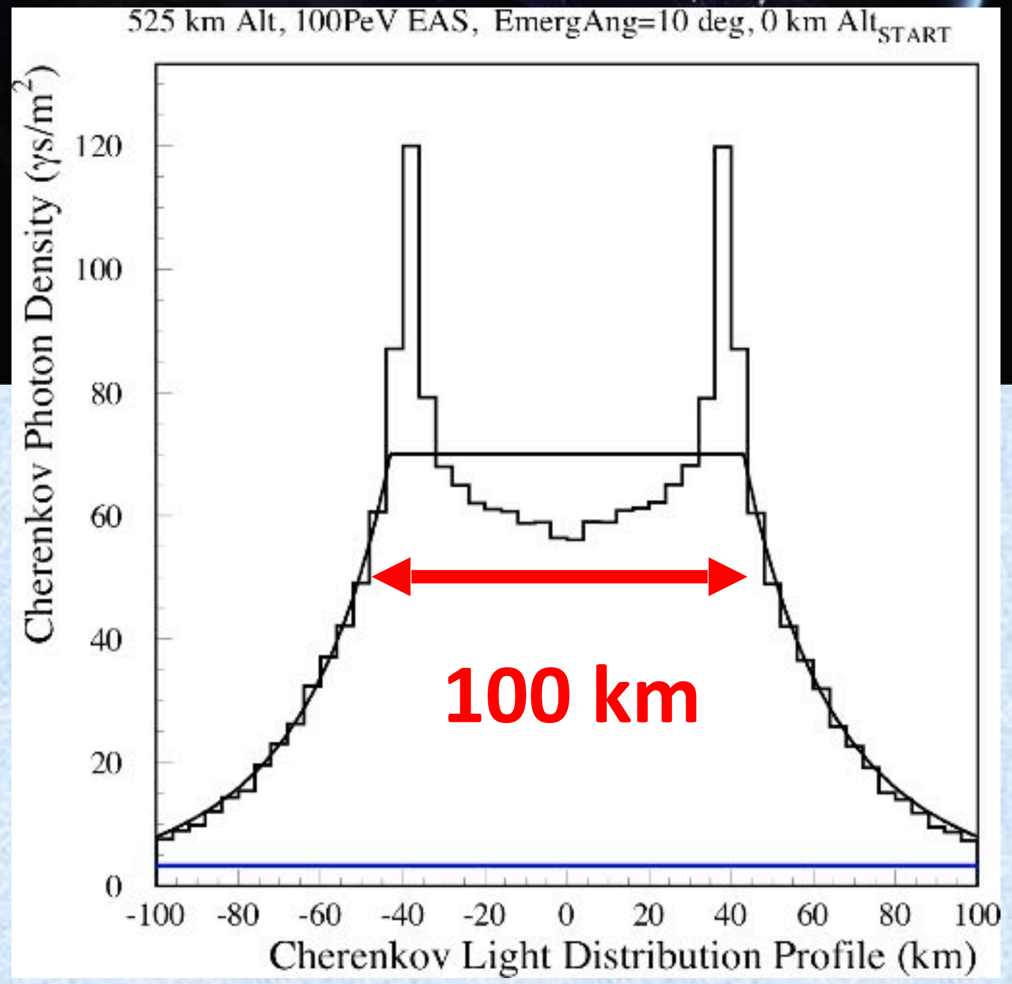
POEMMA: Transient Cosmic Neutrino Sensitivity: SEE *arXiv:1906.07209*

Short Bursts:

- 500 s to slew to source after alert
- 1000 s burst duration
- Source celestial location optimal
- Two independent Cher measurements
  - 300 km Satellite Separation
- 20 PE threshold:
  - Background rate < 10^{-3}/year





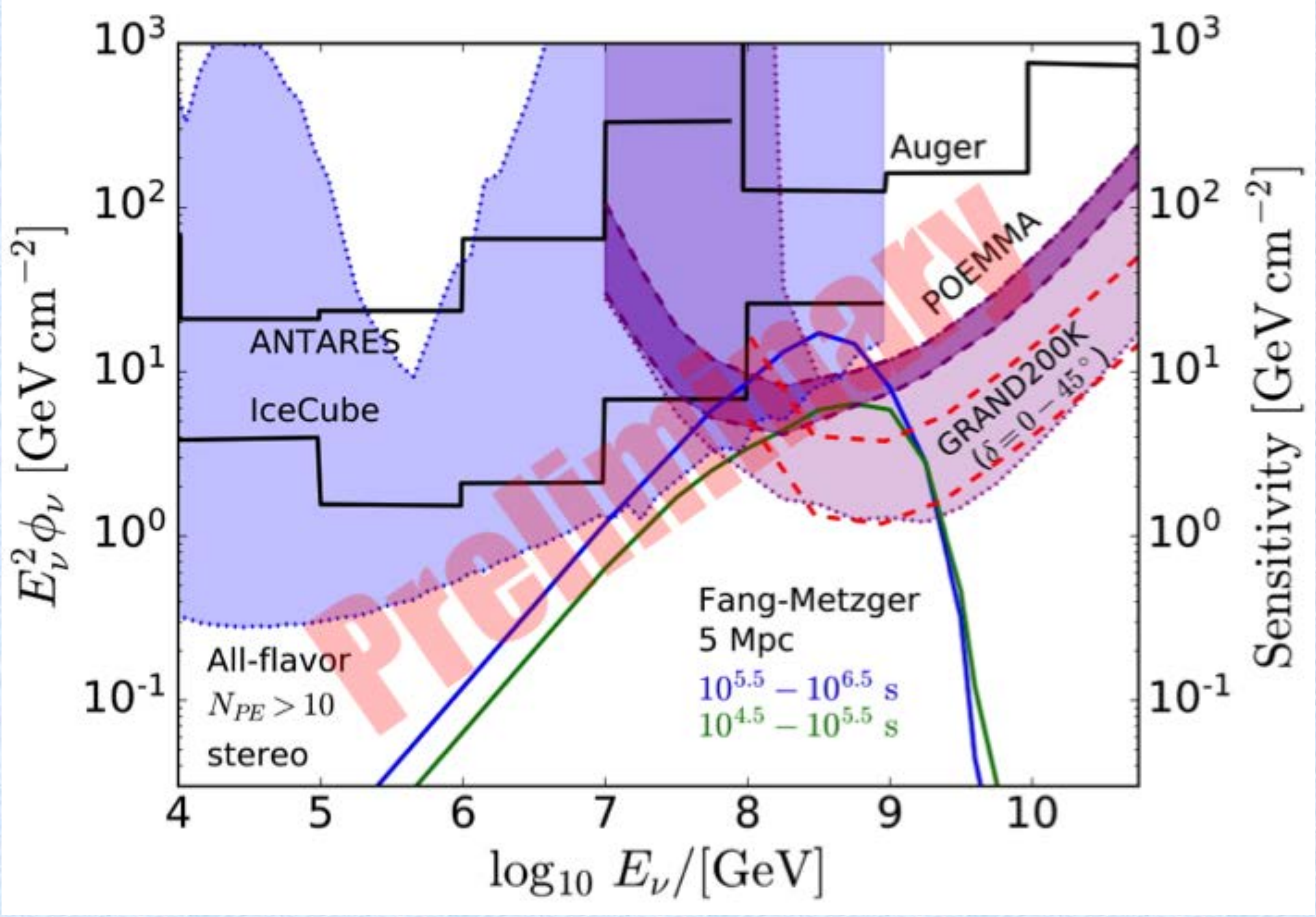


Optical Cherenkov 'spot' at 525 km altitude from τ-lepton upward EAS

IceCube, ANTARES, Auger Limits for NS-NS merger GW170817

Long Bursts:

- 1 day to set SatSep to 50 km
- Burst duration ≳ 10^5 s (models in plot)
- Average Sun and moon effects
- Simultaneous Cher measurements
  - 50 km Satellite Separation
- 10 PE threshold (time coincidence):
  - Background rate < 10^{-3}/year



POEMMA: ToO sky sensitivity vs Ground Experiments: SEE *arXiv:1906.07209*

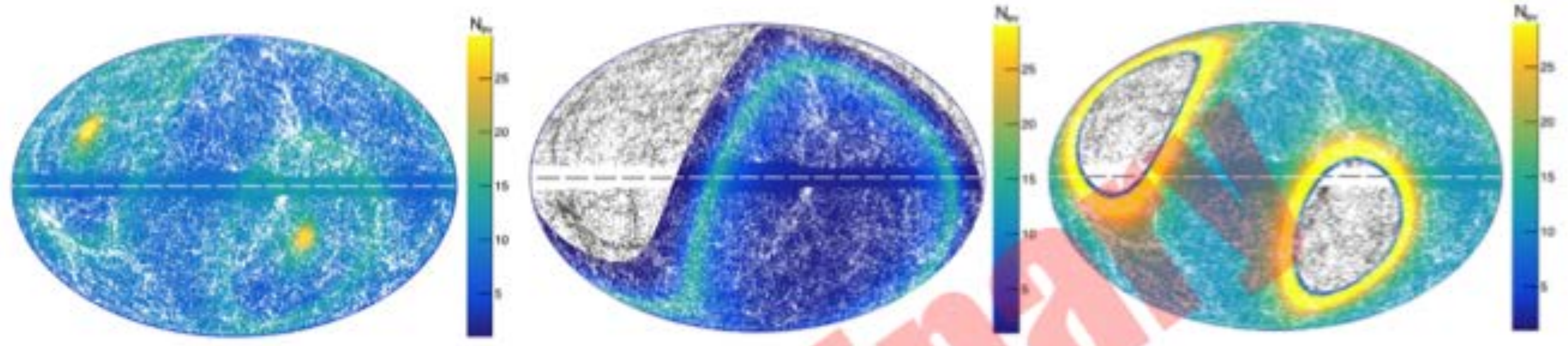


FIG. 7. *Left*: Sky plot of the expected number of neutrino events as a function of galactic coordinates for POEMMA in the long-burst scenario of BNS merger, as in the Fang & Metzger model [21], and placing the source at 5 Mpc. Point sources are galaxies from the 2MRS catalog [74]. *Middle*: Same as at left for IceCube for muon neutrinos. *Right*: Same as at left for GRAND200k. Areas with grey point sources are regions for which the experiment is expected to detect less than one neutrino.

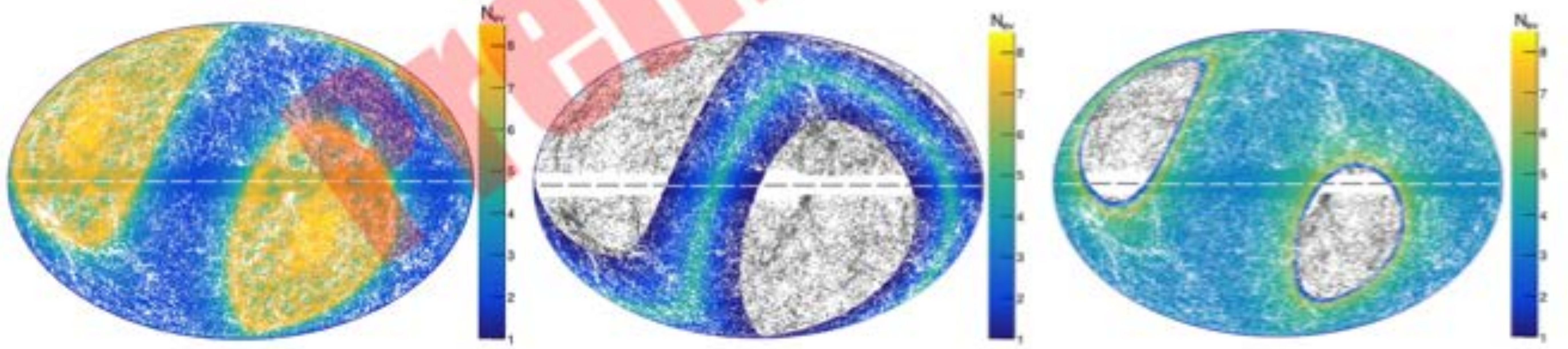


FIG. 8. *Left*: Sky plot of the expected number of neutrino events as a function of galactic coordinates for POEMMA in the "best-case" short-burst scenario of an sGRB with moderate EE, as in the KMMK model [16], and placing the source at 40 Mpc. Point sources are galaxies from the 2MRS catalog [74]. *Middle*: Same as at left for IceCube for muon neutrinos. *Right*: Same as at left for GRAND200k. Areas with grey point sources are regions for which the experiment is expected to detect less than one neutrino.