Presentation[†] on the Analysis of a Tau Neutrino Origin for the Near-Horizon Air Shower Events Observed by the Fourth Flight of the Antarctic Impulsive Transient Antenna (ANITA)[‡]

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[‡] R. Prechelt, S. Wissel, A. Romero-Wolf, and 65 others

Outline

→ Introduction

Motivation: The physics

ANITA: The experiment

Anomalous Events: The measurements

The tau hypothesis

Analysis

Conclusion

Ultra High Energy

Weaknesses of the Standard Model

Neutrino mass and oscillation, W mass,

matter-antimatter asymmetry, dark matter, …

$\Rightarrow$ We need to look Beyond the Standard Model

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LHC Energy:

13×10^{12} eV

Ultra High Energy

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LHC Energy:

13×10^{12} eV $\rightarrow$ 13.6×10^{12} eV

Ultra High Energy

Weaknesses of the Standard Model

Neutrino mass and oscillation, W mass, matter-antimatter asymmetry, dark matter, … $\Rightarrow$ We need to look Beyond the Standard Model

LHC Energy:

13×10^{12} eV $\rightarrow$ 13.6×10^{12} eV $\rightarrow$ 14×10^{12} eV

Ultra High Energy

Weaknesses of the Standard Model

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LHC Energy:

13×10^{12} eV $\rightarrow$ 13.6×10^{12} eV $\rightarrow$ 14×10^{12} eV

Could I interest you in

10^{18} eV?

Ultra High Energy

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LHC Energy:

13×10^{12} eV $\rightarrow$ 13.6×10^{12} eV $\rightarrow$ 14×10^{12} eV

Could I interest you in

10^{18} eV? 10^{21} eV?

Ultra High Energy

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LHC Energy:

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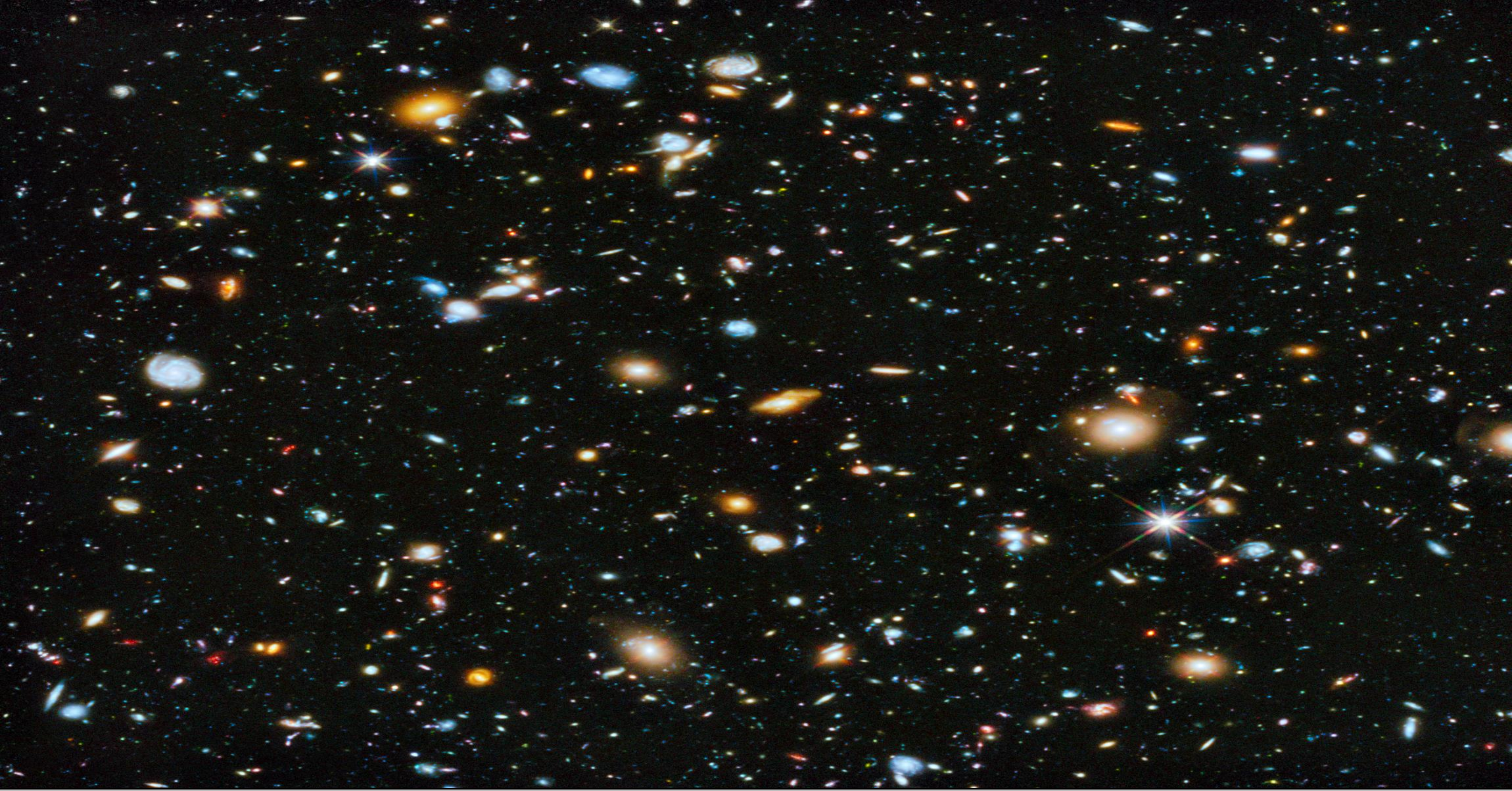
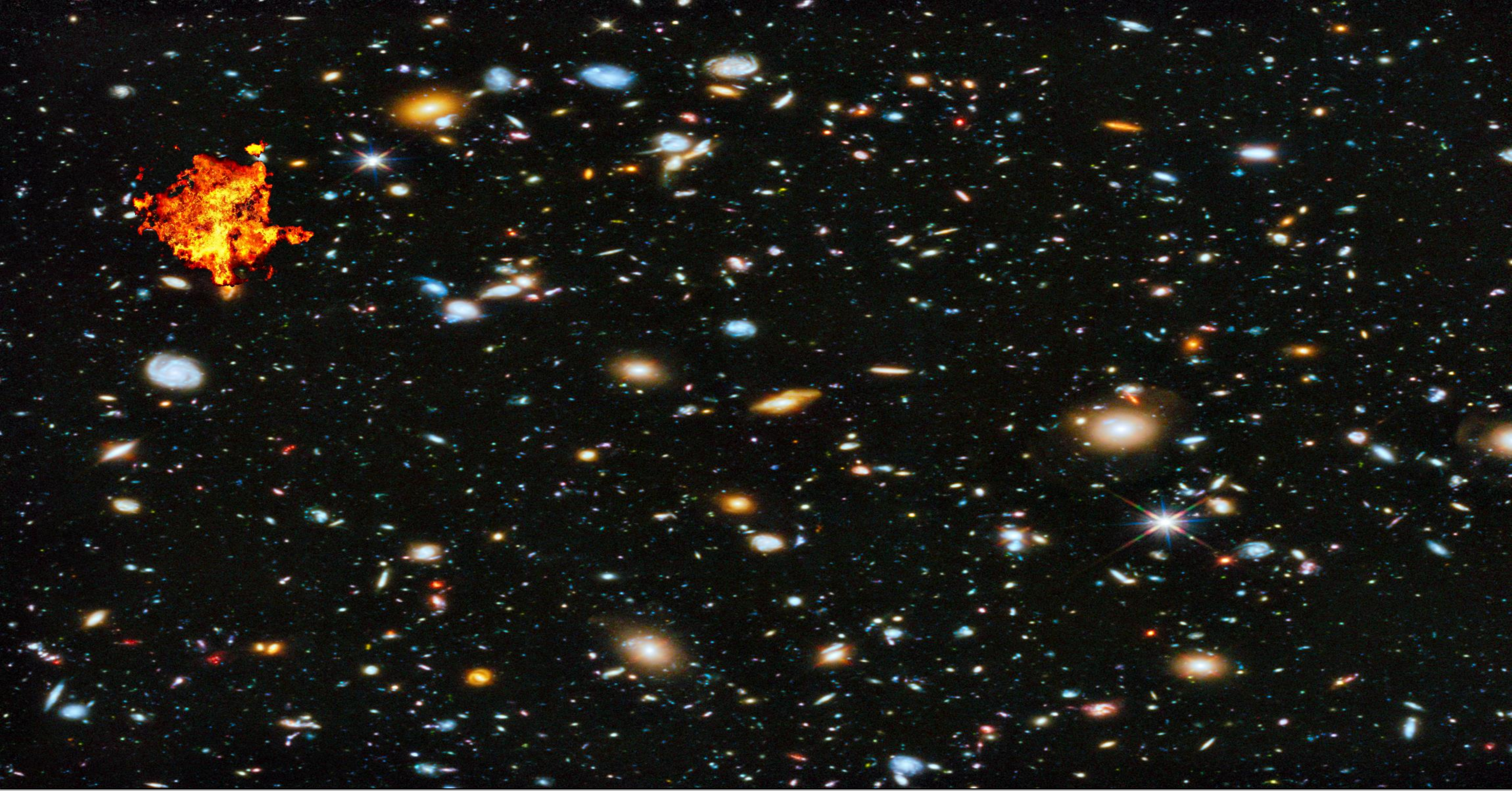
Could I interest you in

10^{18} eV? 10^{21} eV? *More?*





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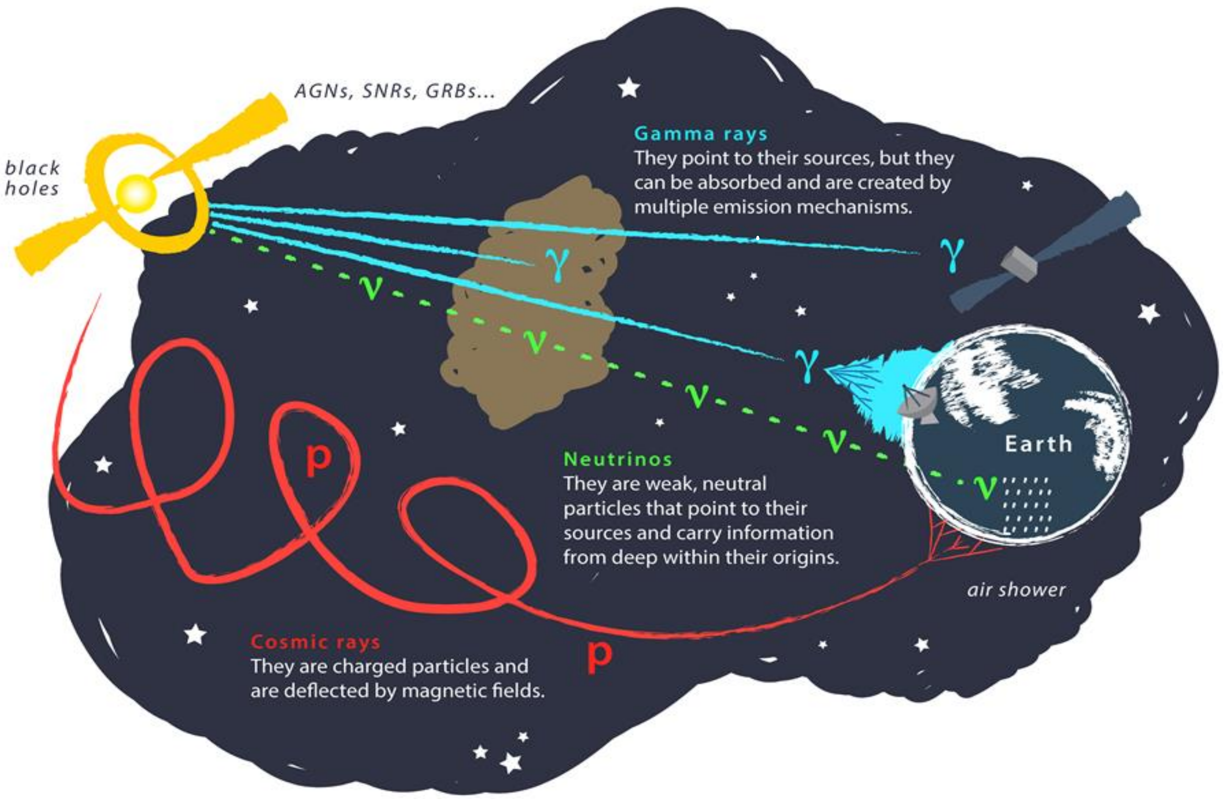
The Appeal of Cosmic Neutrinos

Almost everything decays

Photons can hit things

Same for protons,
which can also deflect

But not neutrinos!



Arrival to Earth: Air Showers

Interact with atmospheric particle

↓

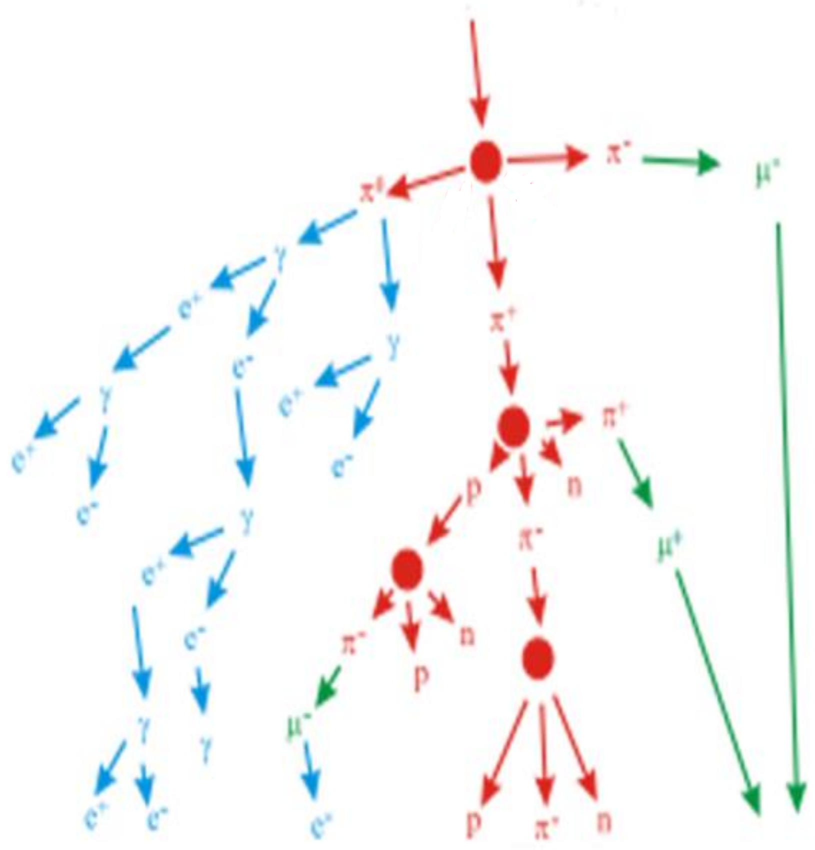
2: Produce more particles

↓

Decay or interact again

↓

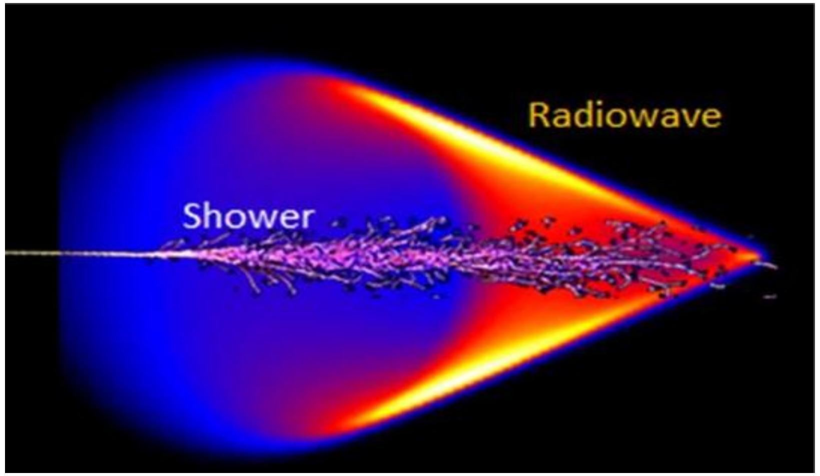
GOTO: 2

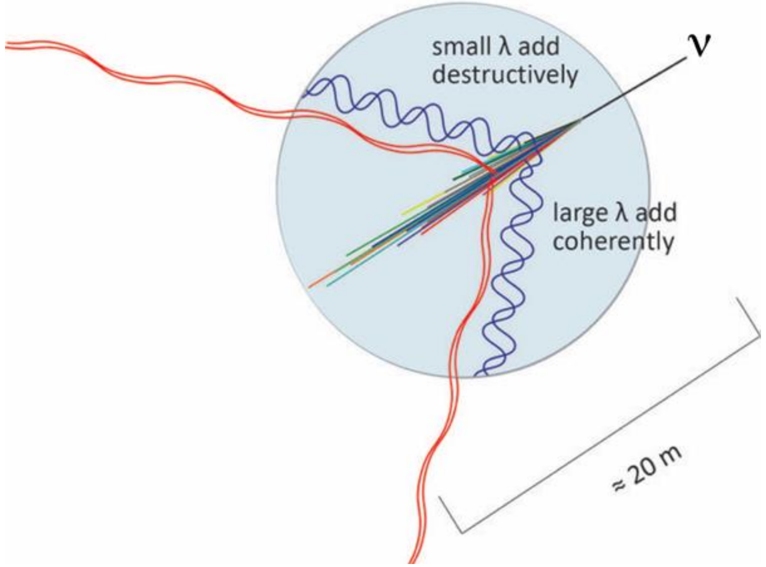


Measurable 1: Cherenkov and Askaryan

Charged particles exceed phase velocity of light

Short wavelengths cancel leaving long wavelengths



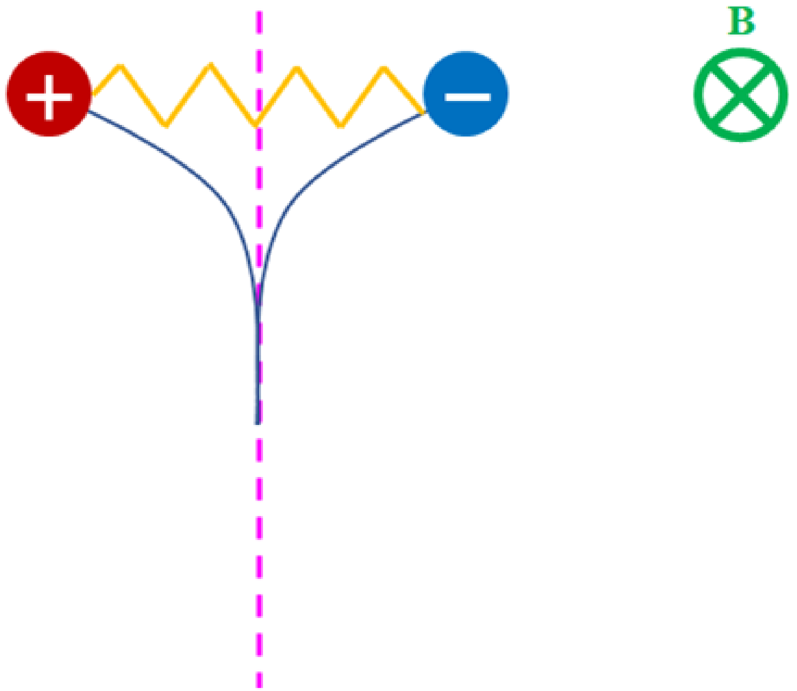


Measurable 2: Geomagnetic

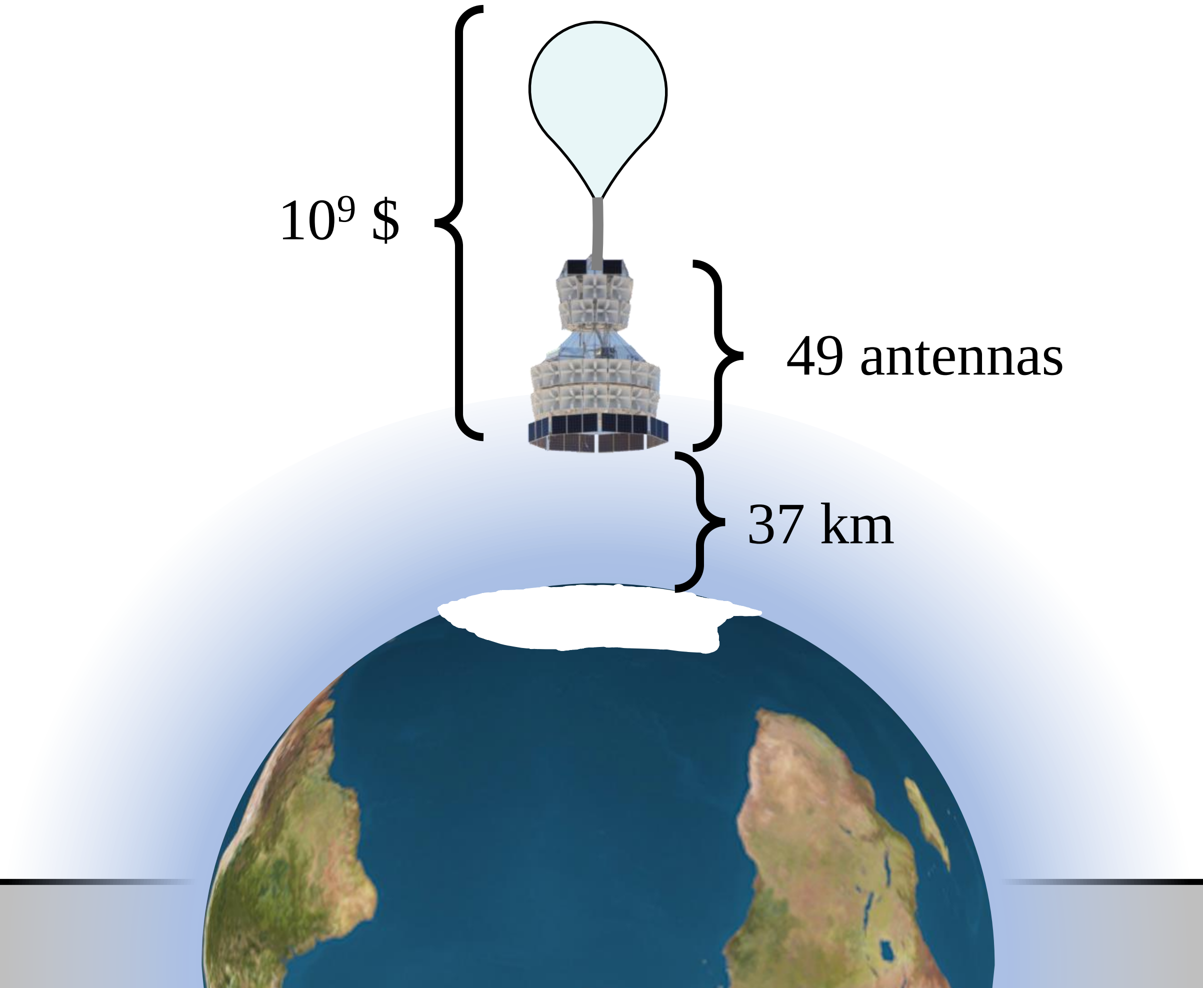
Positively negatively charged particles are deflected by Earth's magnetic field according to

$$\begin{cases} +q(\vec{v} \times \vec{B}) \\ \\ -q(\vec{v} \times \vec{B}) \end{cases} .$$

The separating charges create a changing current, which produces radiation.



ANITA



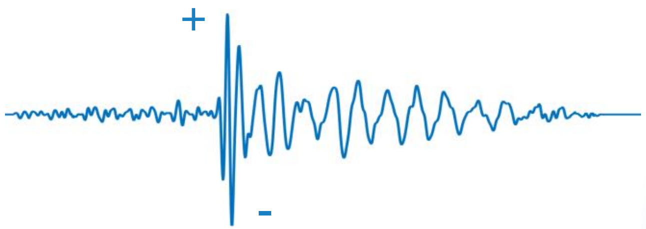
ANITA Events

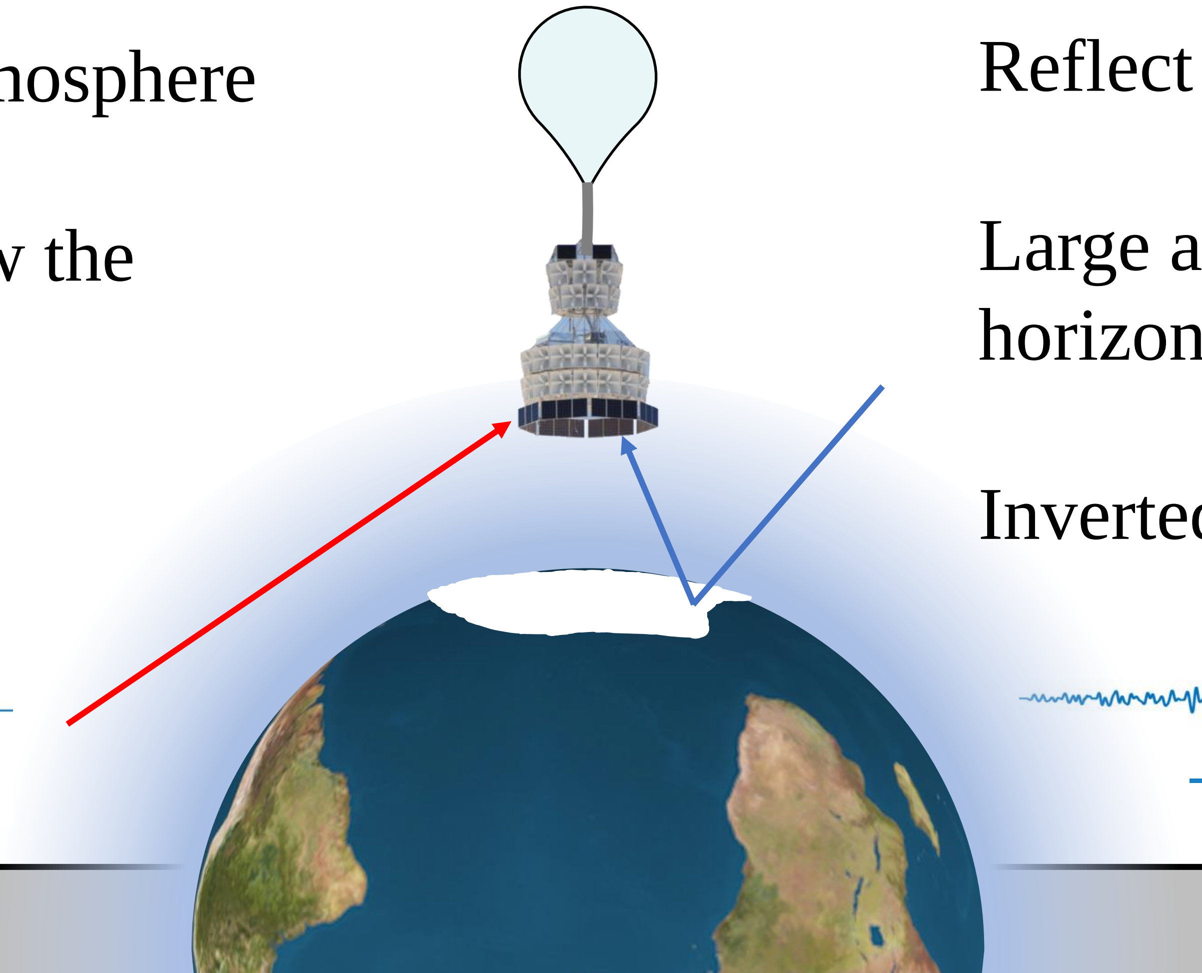
Direct events

Only travel in the atmosphere

Shallow angles below the horizontal

Unaffected polarity



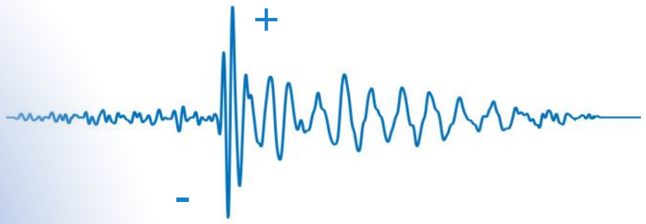


Reflected events

Reflect off the Antarctic ice

Large angles below the horizontal

Inverted polarity

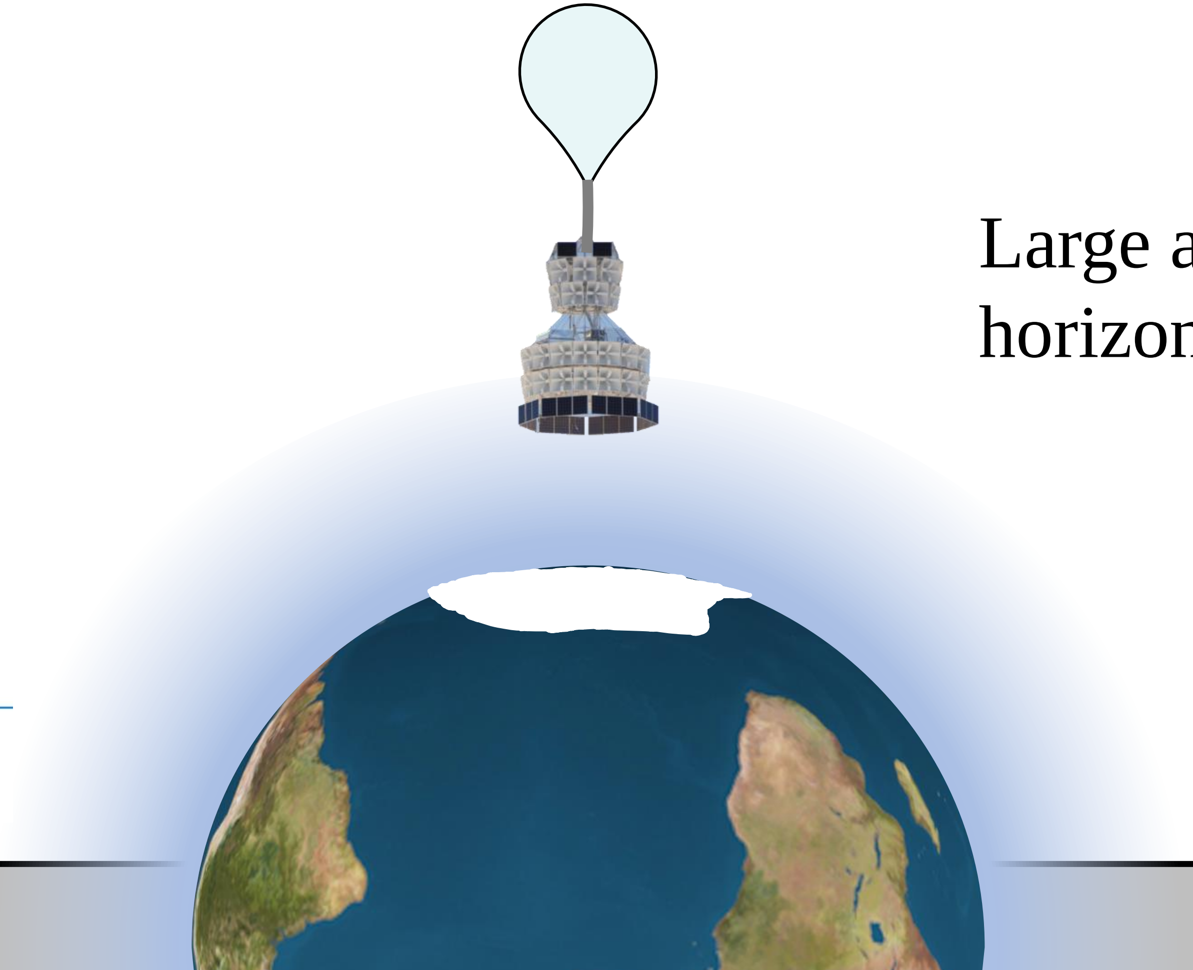


Not even close to scale

Anomalous ANITA Events

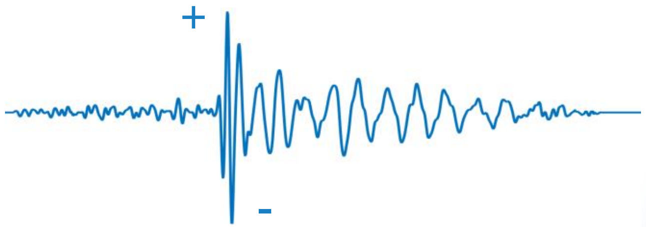
Direct event?

Reflected event?



Large angles below the horizontal

Unaffected polarity



Not even close to scale

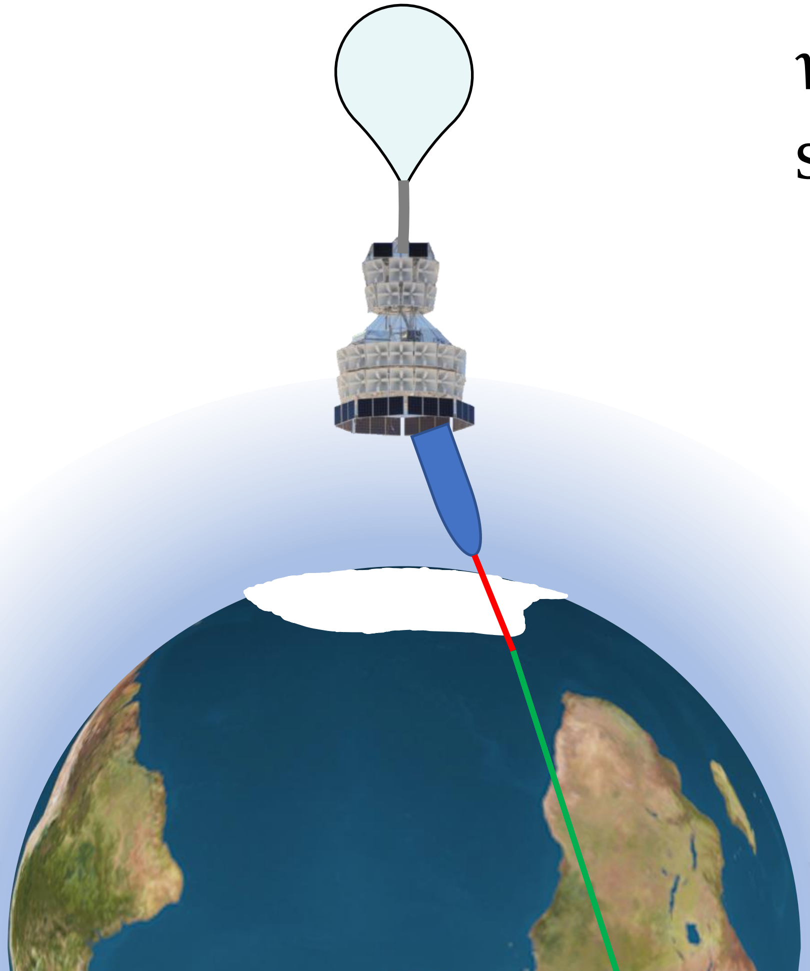
The Tau Neutrino Hypothesis

ν_τ events

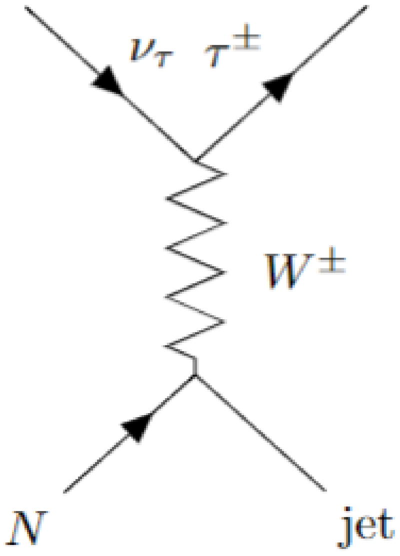
Travel *through* Earth

Large angles below the horizontal

Unaffected polarity



ν_τ enters Earth, τ exits and showers within range



Not even close to scale

Outline

Introduction

→ Analysis

Spectral Analysis

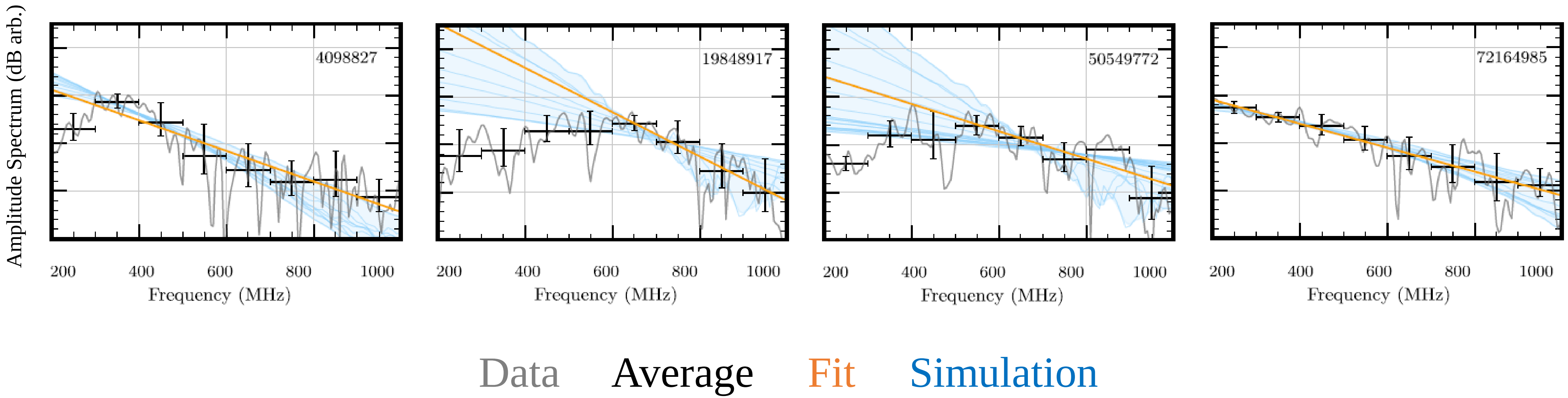
Diffuse Steady Source

Point-like Transient Source

Conclusion

Spectral Analysis

Expected model: $E(f) = Ae^{\gamma(f-300)}, \ \gamma < 0$



Spectral Analysis

Data, fit, and simulations agree very well at high frequency

Power loss at low frequency is likely due to atmospheric effects

Kolmogorov-Smirnov (K-S) test compares fitted model to cosmic ray and τ showers. No disagreement with either

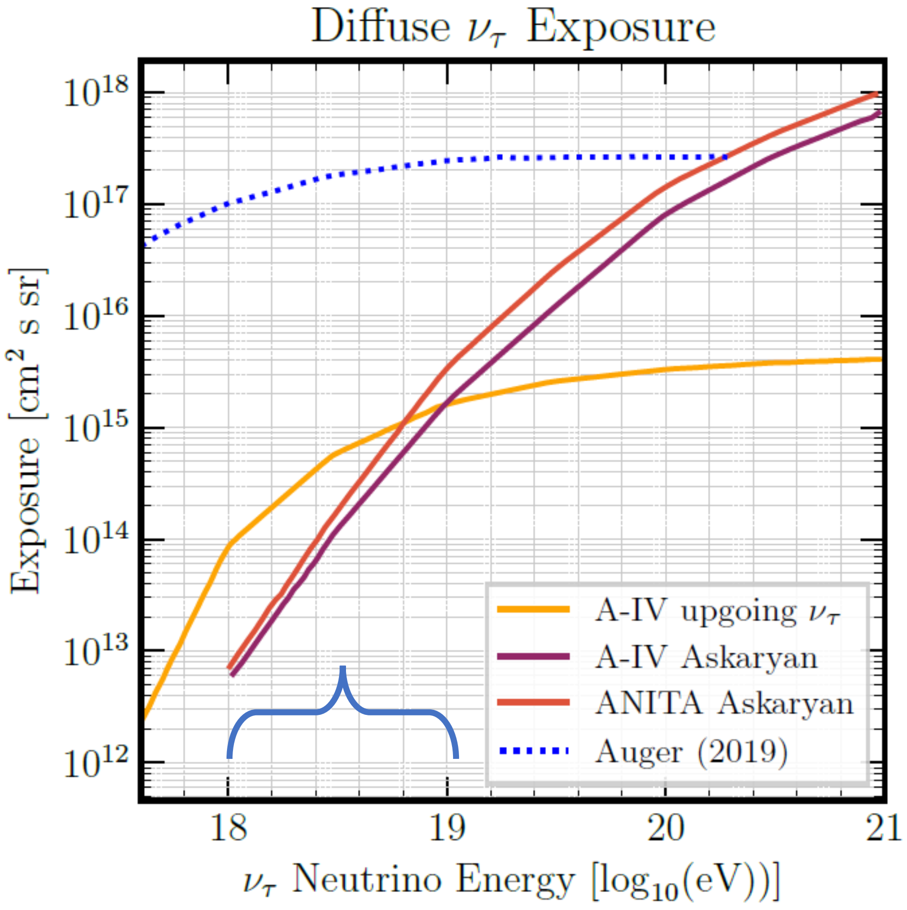
Test	p-value
Near horizon against regular UHECRs	0.48
Near horizon against simulated τ EAS (ZHaireS)	0.45

Diffuse Steady Source

Comparison of the sensitivities of ANITA-IV (28 days) and Auger (~ 3700 days) to ν_τ

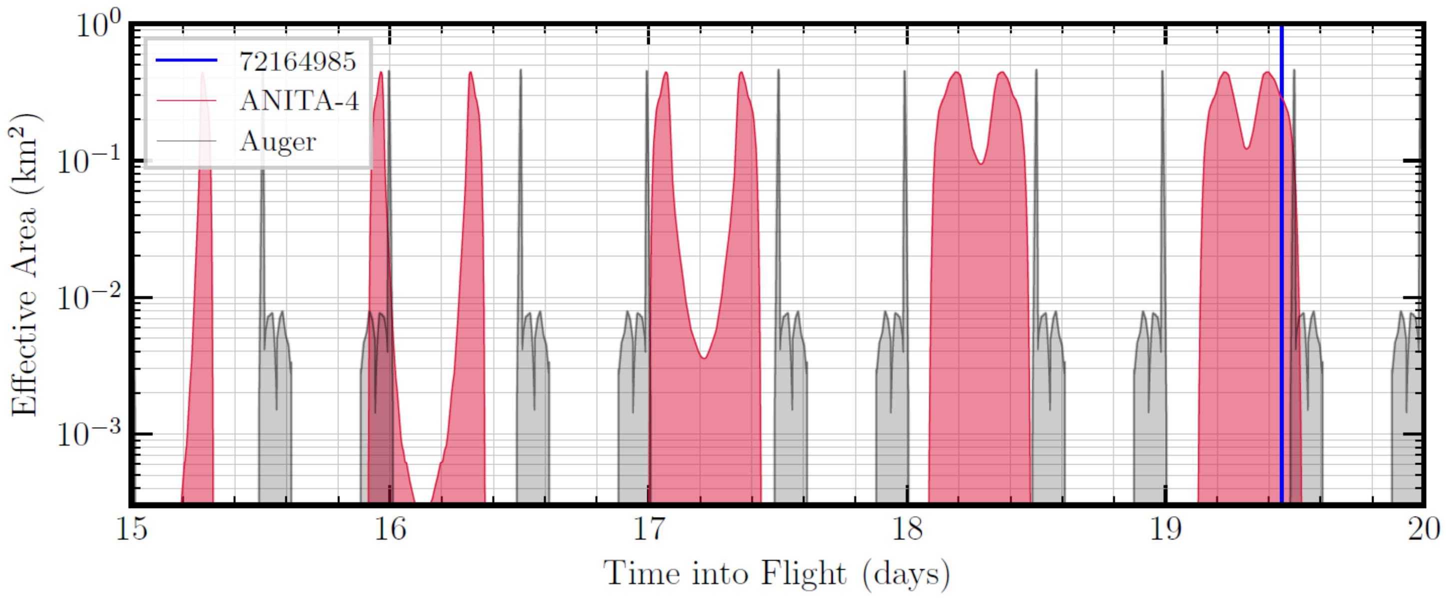
All anomalous events are in the range where Auger is more sensitive (10^{18}-10^{19} eV)

The discrepancy rules out diffuse source



Point-like Transient Source

Depends on ANITA’s location, ANITA’s orientation, time of day, time of year, source’s location, source’s duration, …



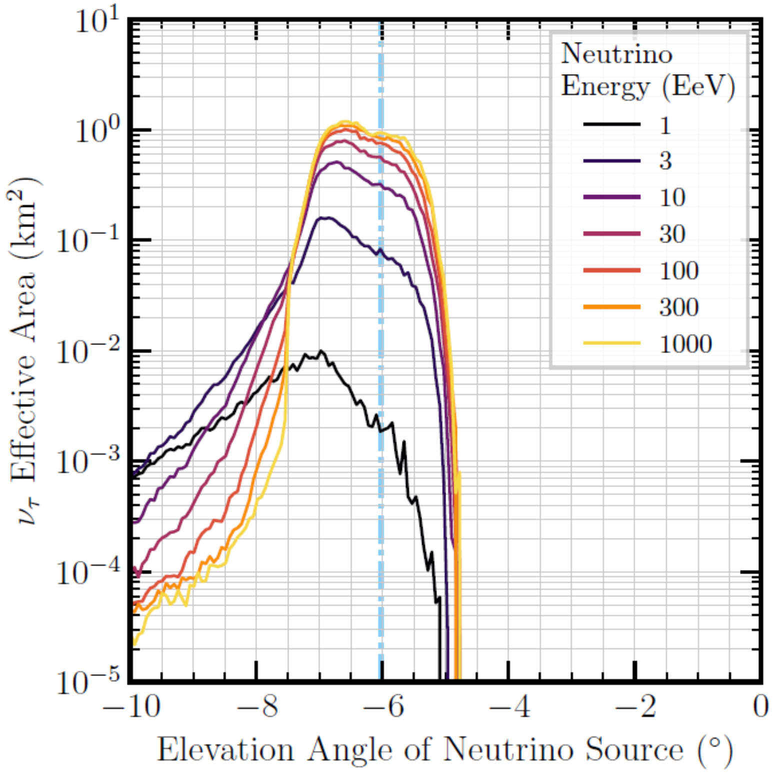
Point-like Transient Source

Energy curves matching the anomalous events were fed as simulation parameters

K-S test compares anomalous events to simulations

No disagreements

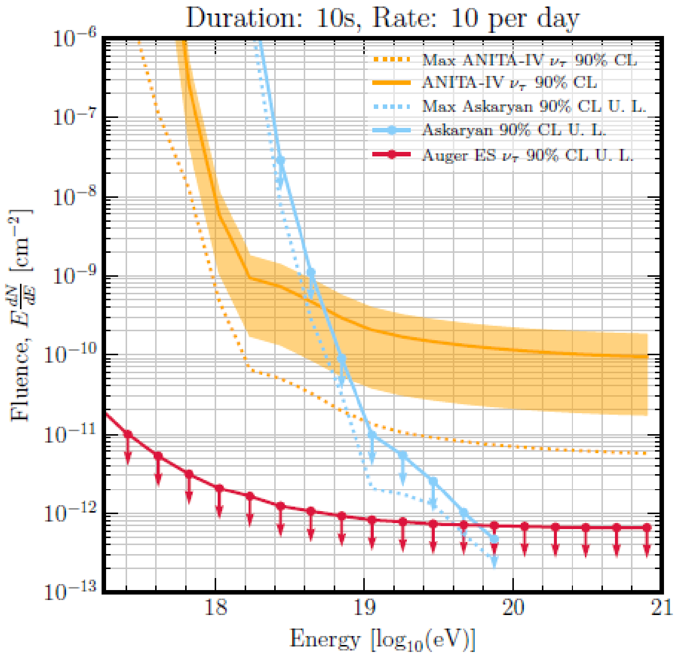
Event	KS p-value
4098872	0.95
19848917	0.60
50594772	0.72
72164985	0.85
All Events	0.19



Point-like Transient Source

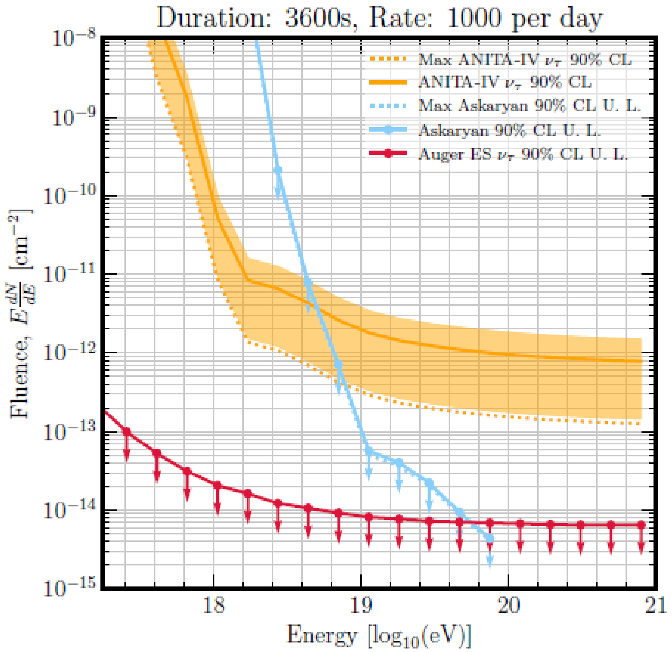
If ANITA-IV detected 3-4 ν_τ events, how many should Auger have?

Both experiments were simulated for short- and long-duration sources



Again, strong tension with the limit set by Auger

Very unlikely that ANITA detected a few and Auger detected none



Outline

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Analysis

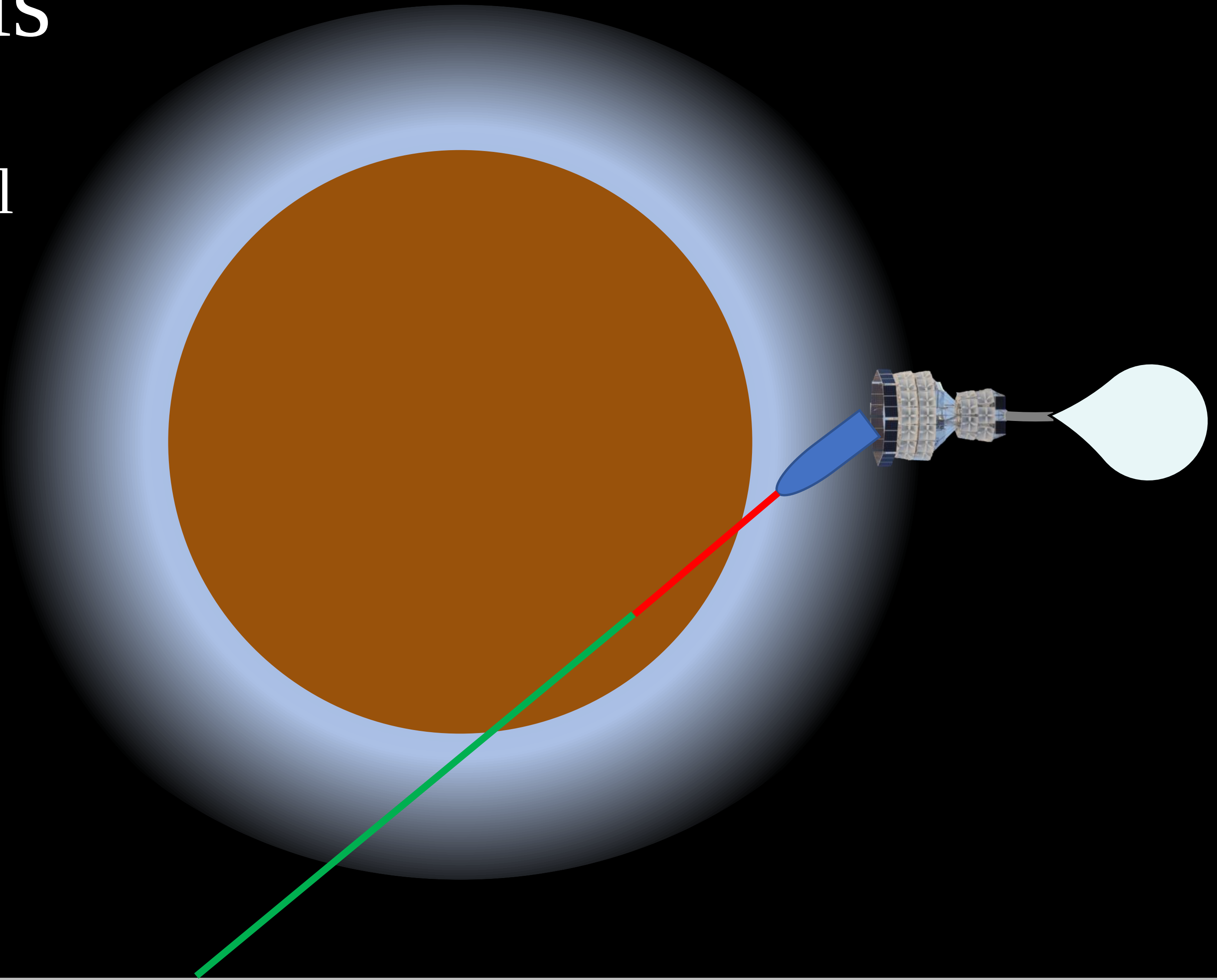
→ Conclusion

The Hypothesis

Energetic astrophysical sources produce ultra high energy ν_τ

ν_τ decays to τ decays to shower

ANITA detects geometry-polarity mismatch

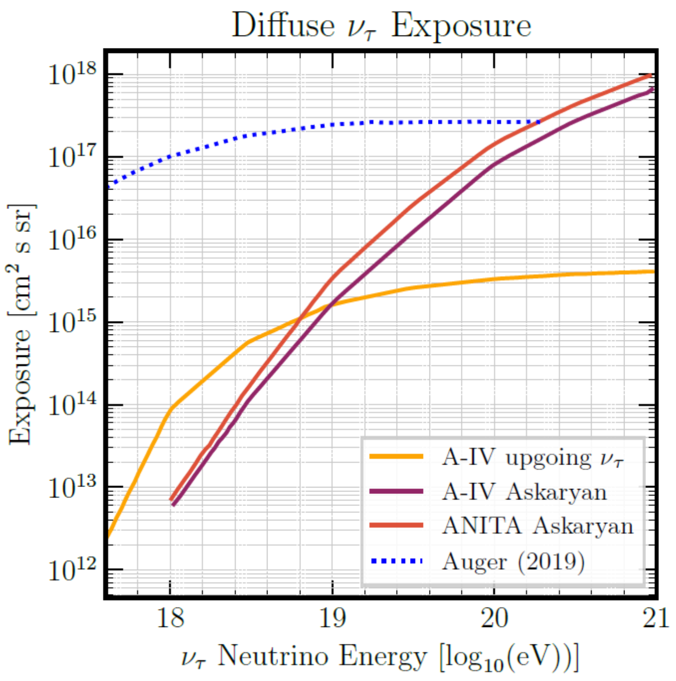


Does it work with diffuse and steady ν_τ flux?

Standard Model says no problem

Test	p-value
Near horizon against regular UHECRs	0.48
Near horizon against simulated τ EAS (ZHaireS)	0.45

Auger says no

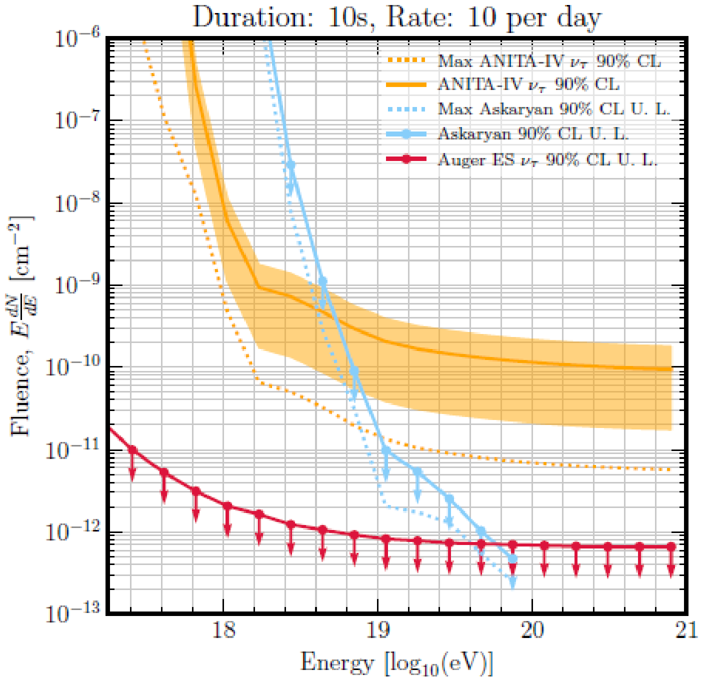


Does it work with point and transient ν_τ flux?

Standard Model says no problem

Event	KS p-value
4098872	0.95
19848917	0.60
50594772	0.72
72164985	0.85
All Events	0.19

Auger says no



Conclusion

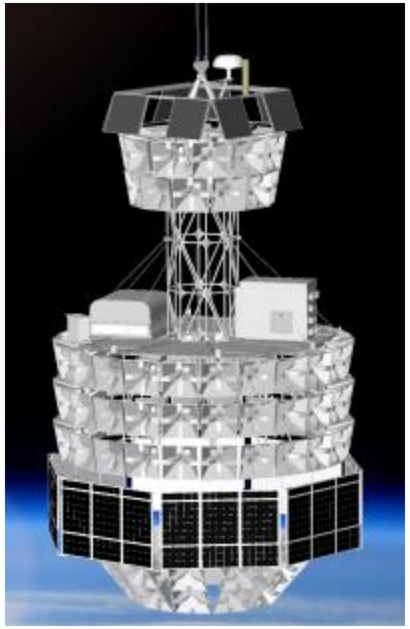
"We find that while these events are not observationally *inconsistent* in UHE ν_τ's, the implied fluence necessary for ANITA-IV to have observed ~3 of these events is in tension with Auger's existing ν_τ limits at all simulated energies…"

What's Next?

Assume a new identity

$\Rightarrow$

(and undergo upgrades)



ANITA

PUEO

Further References

A Comprehensive Approach to Tau-Lepton Production by High-Energy Tau Neutrinos Propagating Through Earth

Alvarez-Muñiz et al.

Unusual Near-horizon Cosmic-ray-like Events Observed by ANITA-IV

Gorham et al.

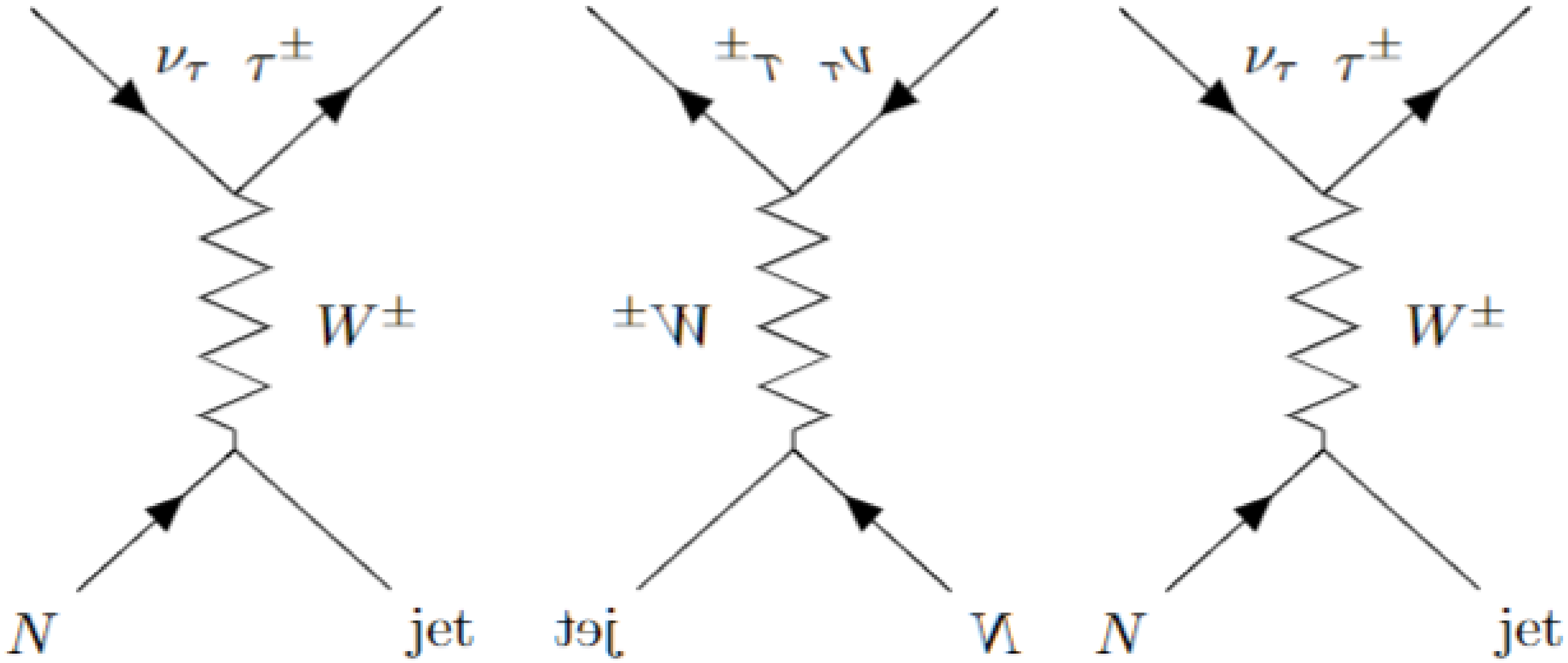
The Payload for Ultrahigh Energy Observations (PUEO): A White Paper

Abarr et al.

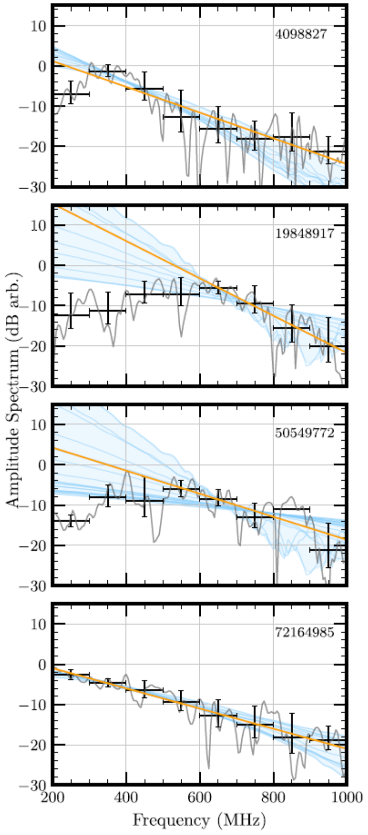
Probability of tau observation = probability of [(tau exiting Earth)(tau decay)(shower)(enough energy)(ANITA trigger)

$$
\begin{aligned}
P_{obs}(t, E_\nu, \hat{r}, \vec{x}_E) = & \int dE_\tau \; P_{exit}\left(E_\tau \mid E_\nu, \theta_{em}\right) \\
& \int ds_{decay} \; P_{decay}\left(s_{decay} \mid E_\tau\right) \\
& \int dE_{EAS} \; P_{EAS}\left(E_{EAS} \mid E_\tau\right) \\
& \int d\mathcal{E} \; P_{\mathcal{E}}\left(\mathcal{E} \mid E_{EAS}, s_{decay}, \hat{r}_\nu, \right) \\
& \qquad P_{trig}\left(\vec{x}_{\mathrm{ANITA}} \mid \mathcal{E}, s_{decay}, \hat{r}_\nu\right)
\end{aligned} \tag{2}
$$

This hypothesis was rejected for ANITA-I and ANITA-III because of the regeneration effect. By crossing symmetry, the interaction where a tau neutrino goes to a tau lepton can happen in reverse: the tau lepton goes to tau neutrino. For every cycle, about 20% of the tau energy is lost to the jet. If the path through Earth is too long, this happens too many times, and the resulting shower doesn’t have enough energy to trigger ANITA. This was the case for ANITA-I and ANITA-III, because the angles for the anomalous events were too steep. For ANITA-IV, the angles are shallow enough for the path length through Earth to be small.



Spectral analysis: Electric field is expected to decay exponentially for >300 MHz. Grey is raw data. Black is average for bins of 100 MHz. Orange is $Ae^{\{-\gamma f\}}$ fitted to black. Blue is simulations with similar parameters. One event agrees well. One event agrees very well. Two events agree only at high frequency. Low-frequency disagreement might be due to atmospheric effects. More later.



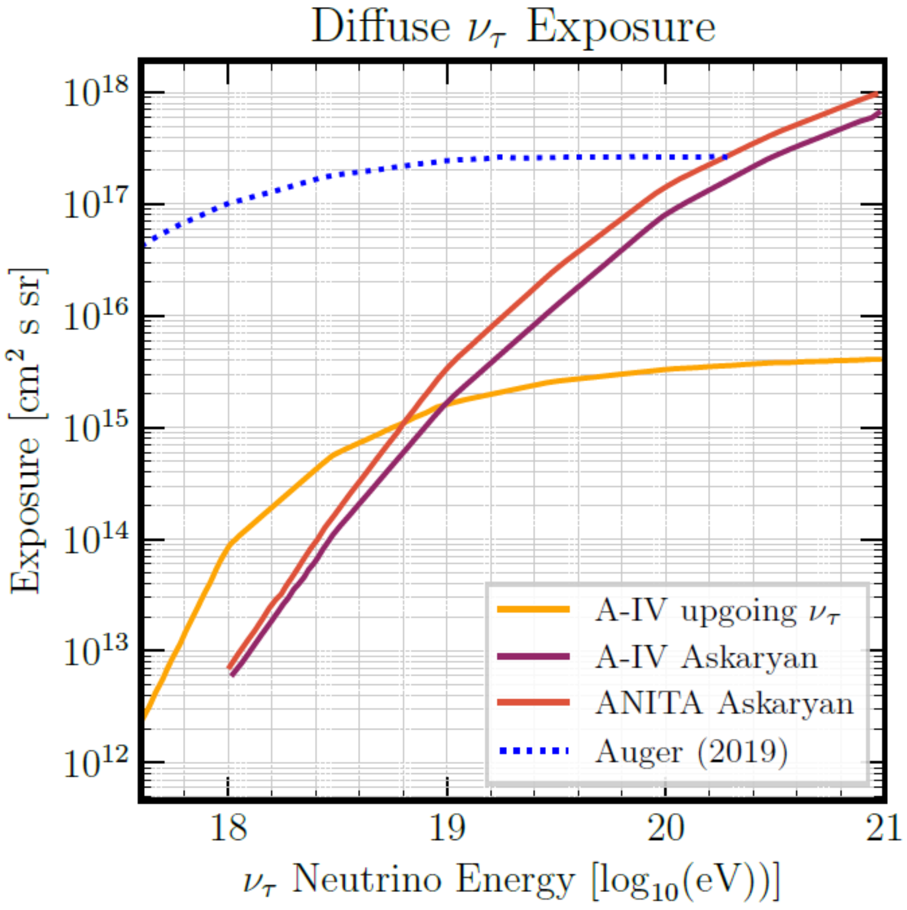
Kolmogorov-Smirnov test is a test of the equality of continuous probability distributions. When done for observed anomalous events against cosmic ray events, large p-values are found, so the hypothesis is not rejected. Same thing for observed anomalous events against simulated tau-induced showers.

Test	p-value
Near horizon against regular UHECRs	0.48
Near horizon against simulated τ EAS (ZHaireS)	0.45

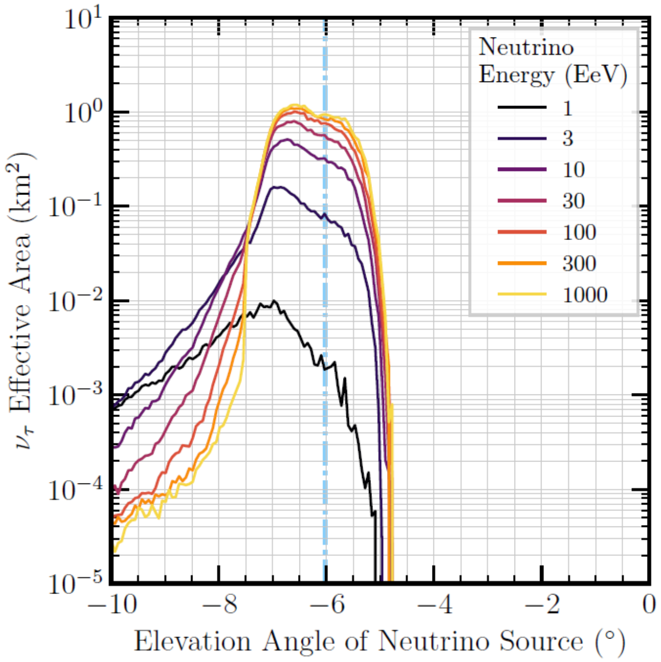
Auger is vastly more sensitive to tau neutrinos from a diffuse source, yet it (maybe) never detected similar events. Makes it unlikely that ANITA did. ANITA's exposure is higher for over ~10^{20} eV. But all four anomalous events have energies lower than that. Different energy estimates are based on reconstructions based on different models. IceCube (not shown in the plot) is also much higher than ANITA.

TABLE II: The most-likely reconstructed neutrino energies, using the MCMC approach described in § IV A 1, for various priors on the neutrino flux.

Event	$E_{\nu,\gamma=-1}$ (EeV)	$E_{\nu,\gamma=-2}$ (EeV)	$E_{\nu,\gamma=-3}$ (EeV)
4098827	$49.8^{+80.3}_{-37.7}$	$12.5^{+29.9}_{-7.4}$	$5.2^{+6.0}_{-2.5}$
19848917	$31.9^{+76.0}_{-24.5}$	$5.2^{+11.0}_{-2.9}$	$2.6^{+3.1}_{-1.1}$
50549772	$45.4^{+83.4}_{-34.4}$	$8.8^{+19.5}_{-4.9}$	$4.3^{+4.8}_{-2.1}$
72164985	$60.3^{+88.9}_{-38.2}$	$15.1^{+27.3}_{-7.6}$	$8.9^{+10.5}_{-4.5}$



Sensitivity to tau neutrinos from a point-like source as a function of elevation angle of the source is plotted. K-S tests are done again for the anomalous events against simulations with the energy curves closest to the energies reconstructed for the anomalous events, assuming $\gamma = -2$. The hypothesis is not rejected for any event.



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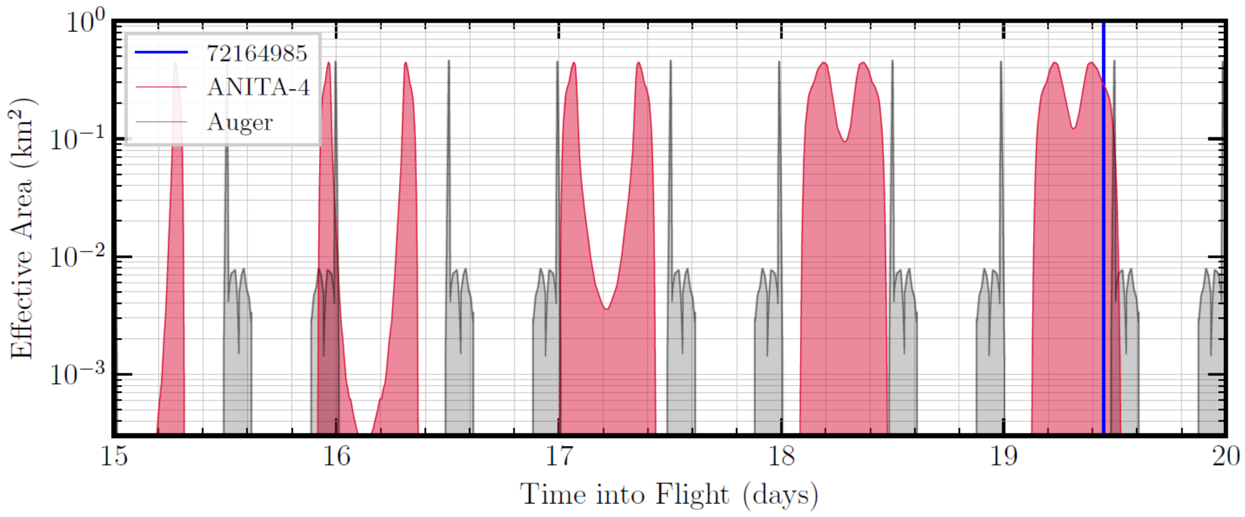
ANITA's field of view to events changes a lot based on its location, orientation, and time of day. Effective area can be plotted as a function of time to account for all that. Auger included for comparison. All four anomalous events were detected at time of peak effective area for ANITA, off those for Auger. This allows ANITA to set different sensitivity limits for point-like sources. However, because sources can move in and out of ANITA's field of view, it is more likely to detect events from short-duration transient sources (<15 minutes) than long-duration ones (>1 day).



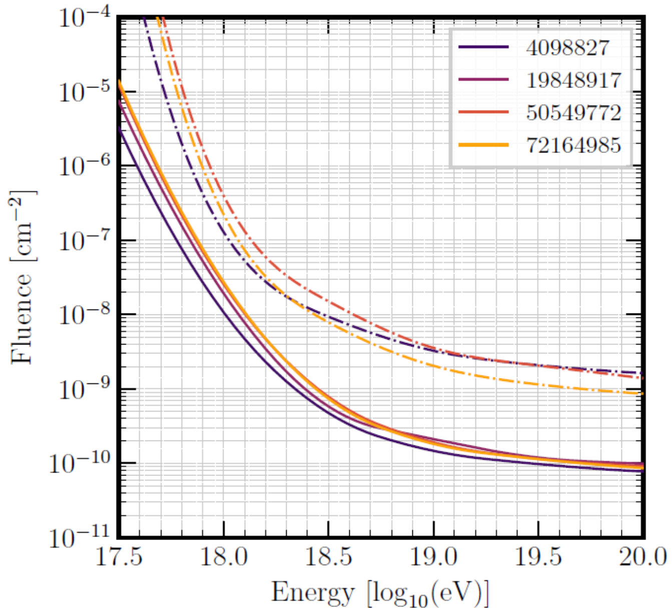


FIG. 18: ANITA's sensitivity to short-duration (< 15 minute) (solid) and long duration (> 1 day) (dashed) transient neutrino sources at the location of each of the four near-horizon events observed in ANITA-IV.

Not exactly sure what this is. Looks cool though.