The ANITA anomalous events as signatures of a beyond standard model particle

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1809.09615
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Antarctic Impulsive Transient Antenna (ANITA)

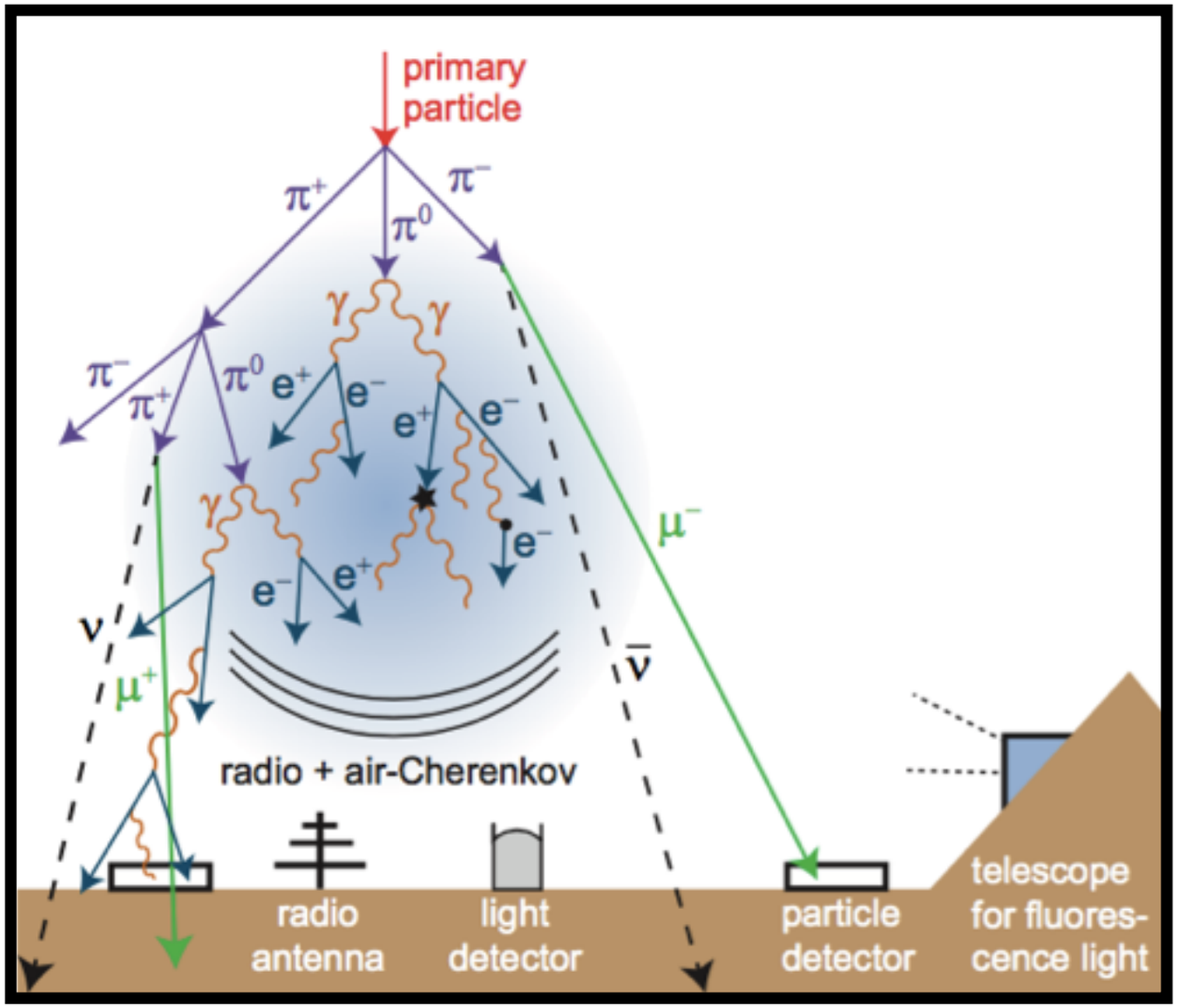
The observable

Nanosecond pulses in the radio

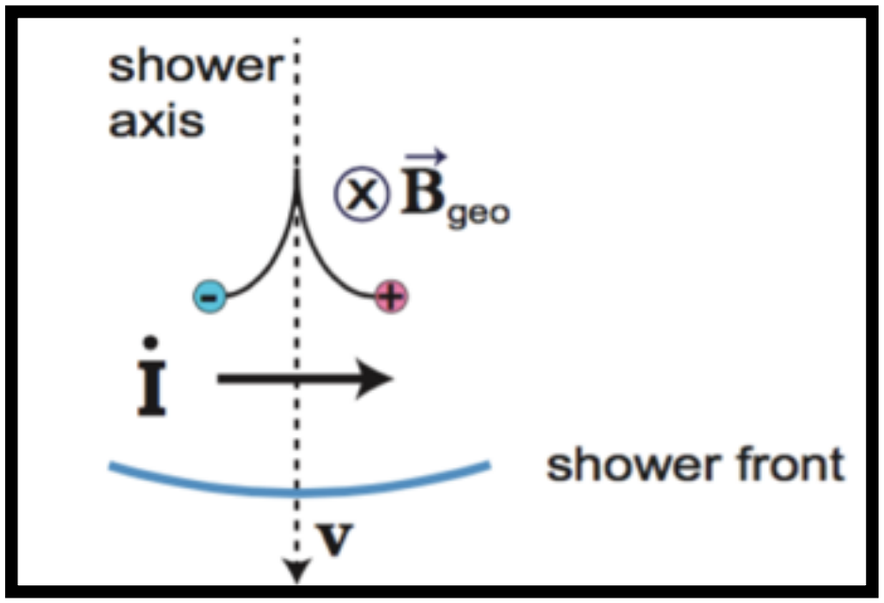
Originating from secondary electron/positrons in a cosmic ray air shower

Accelerated in earth's magnetic field, and interacting with air molecules

The observable



Schroder, 1607.08781



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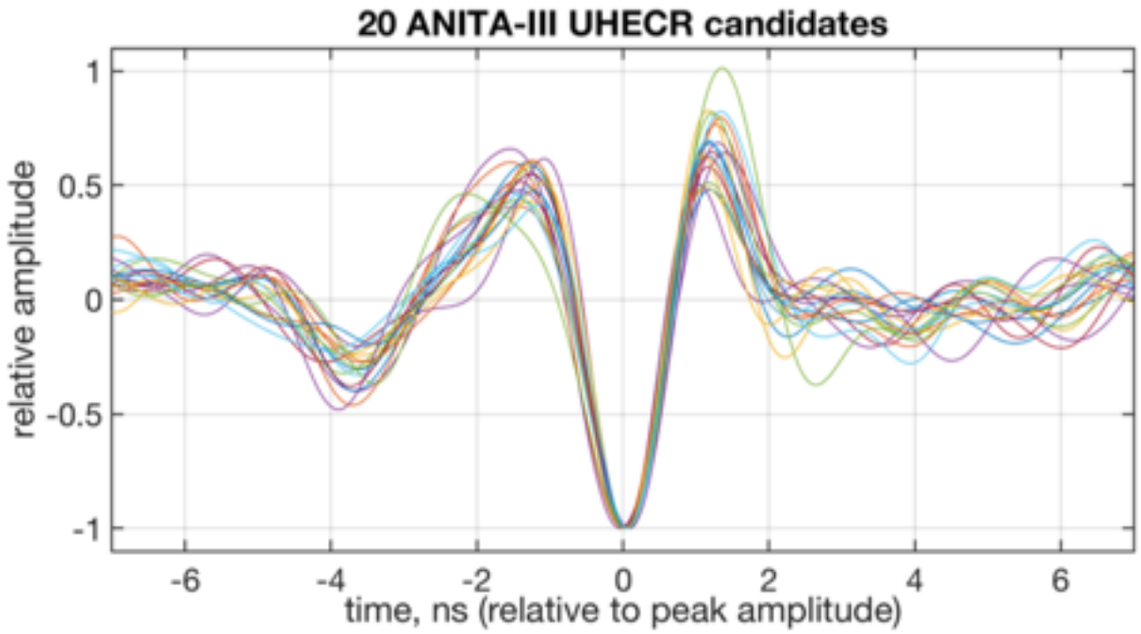

Gorham et al, 1803.05088

What ANITA might see

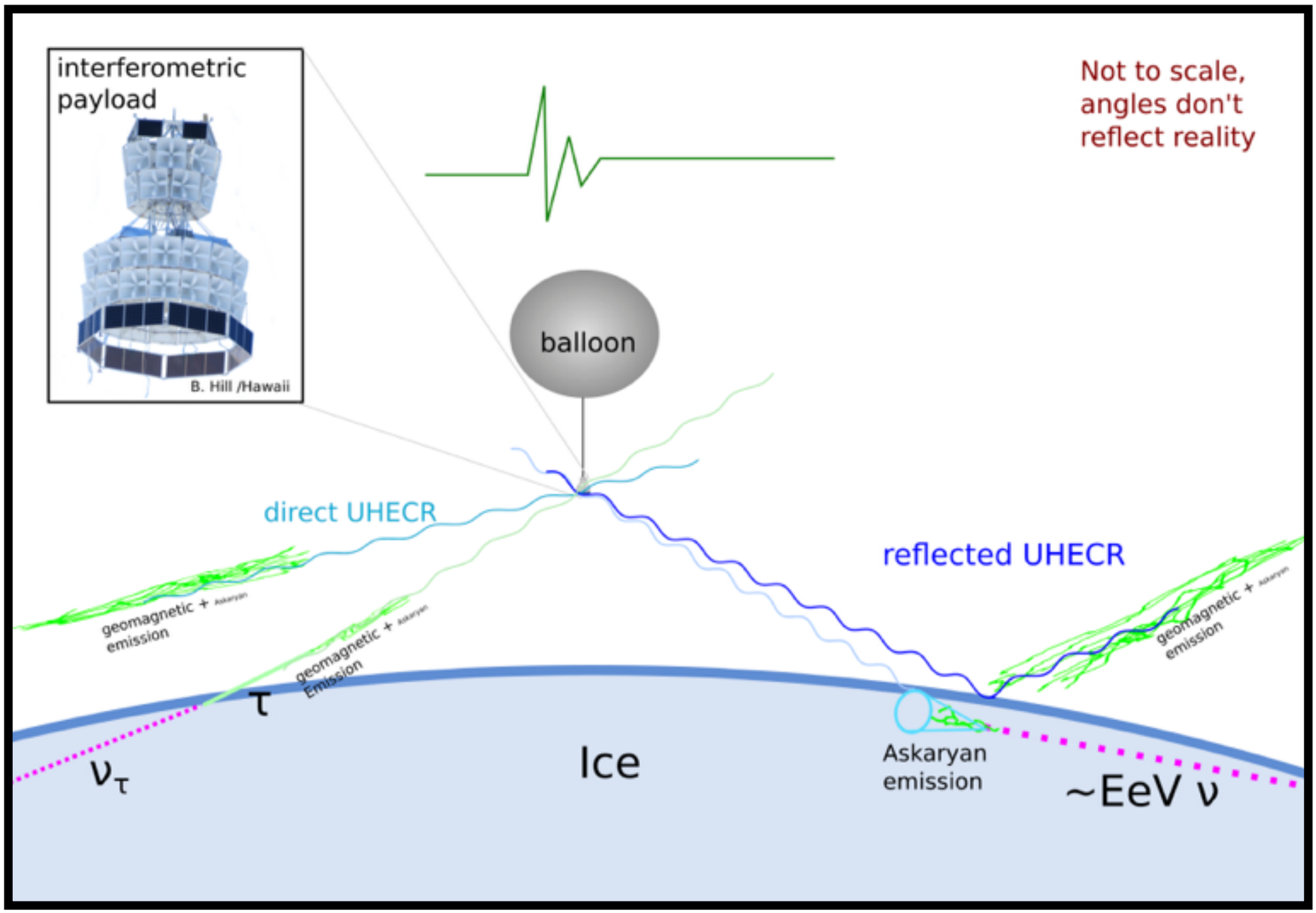

Figure Credit: Cosmin Deaconu

ANITA cosmic ray events

ANITA-I (2006):

- 13 down-going
- 2 upward earth skimming
- 1 up-going

S. Hoover et al, 1005.0035

} Gorham et al, 1603.052185

ANITA-III (2014): Gorham et al, 1803.05088

- 17 down-going
- 2 upward earth skimming
- 1 up-going event,

ANITA-4 (2016): Not yet released

ANITA-5 proposed

The up-going ANITA events

ANITA says $> 3\sigma$ evidence these are genuine Cosmic Ray showers, initiated by particles arriving through the earth

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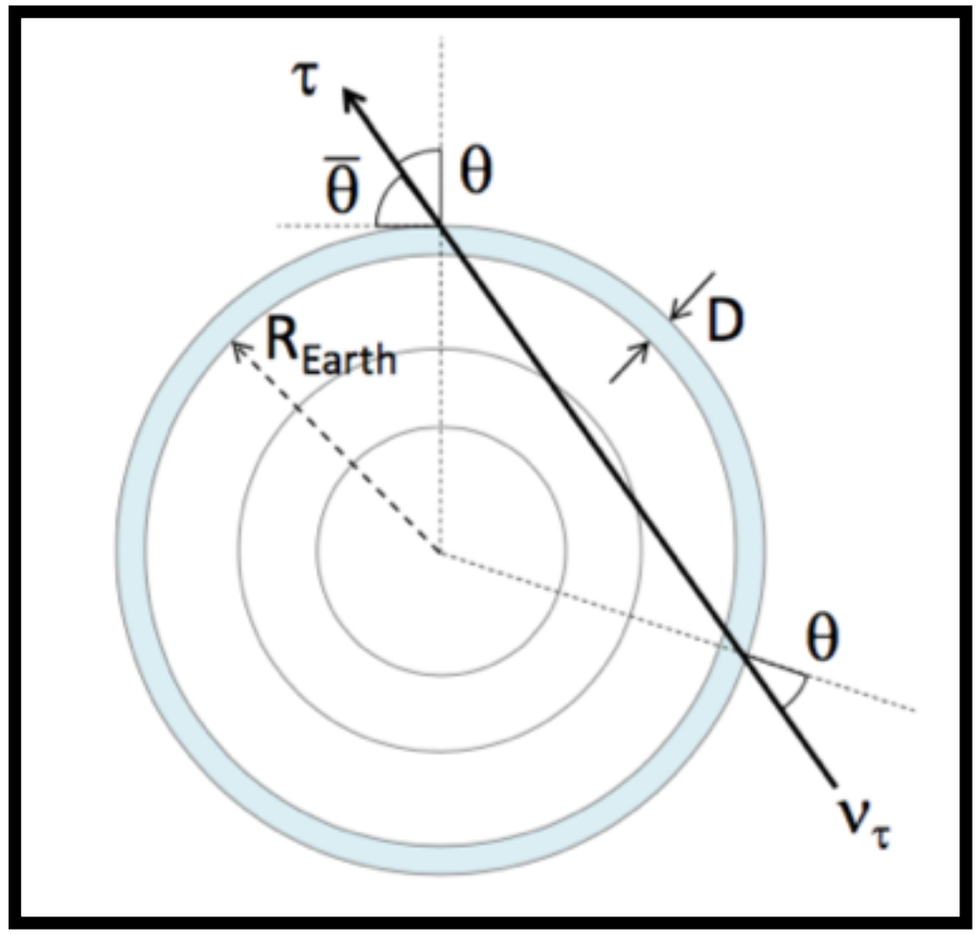
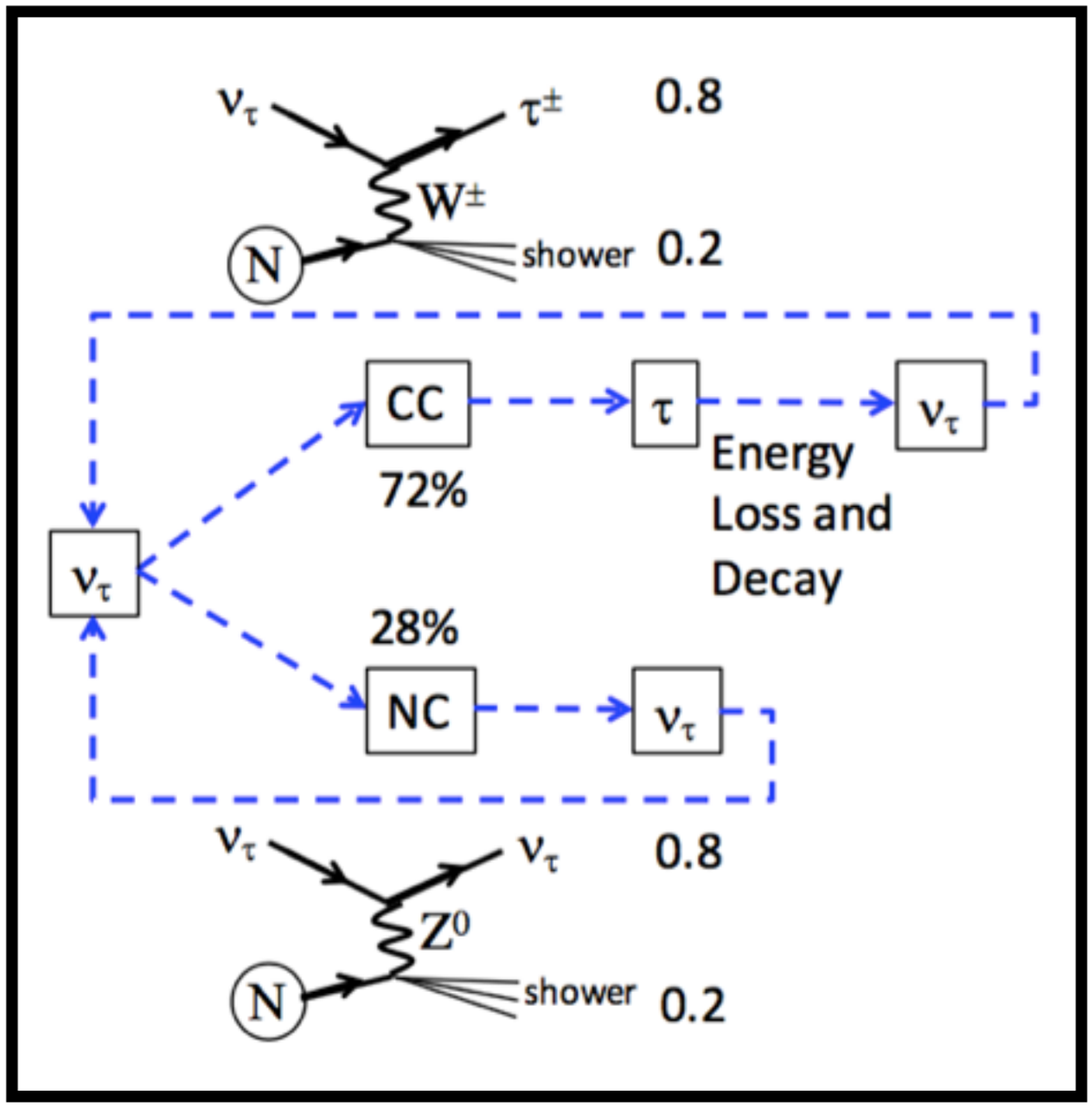
Within the standard model:



Alvarez-Muniz et al, 1707.00334

Modeling the up-going ANITA events



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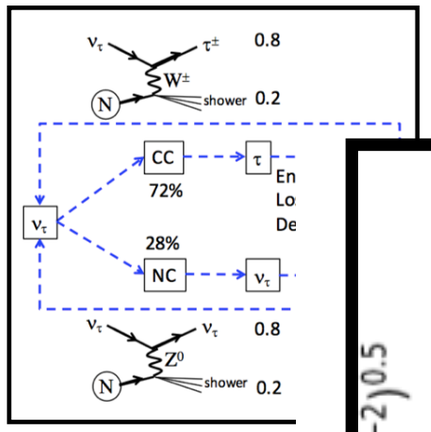
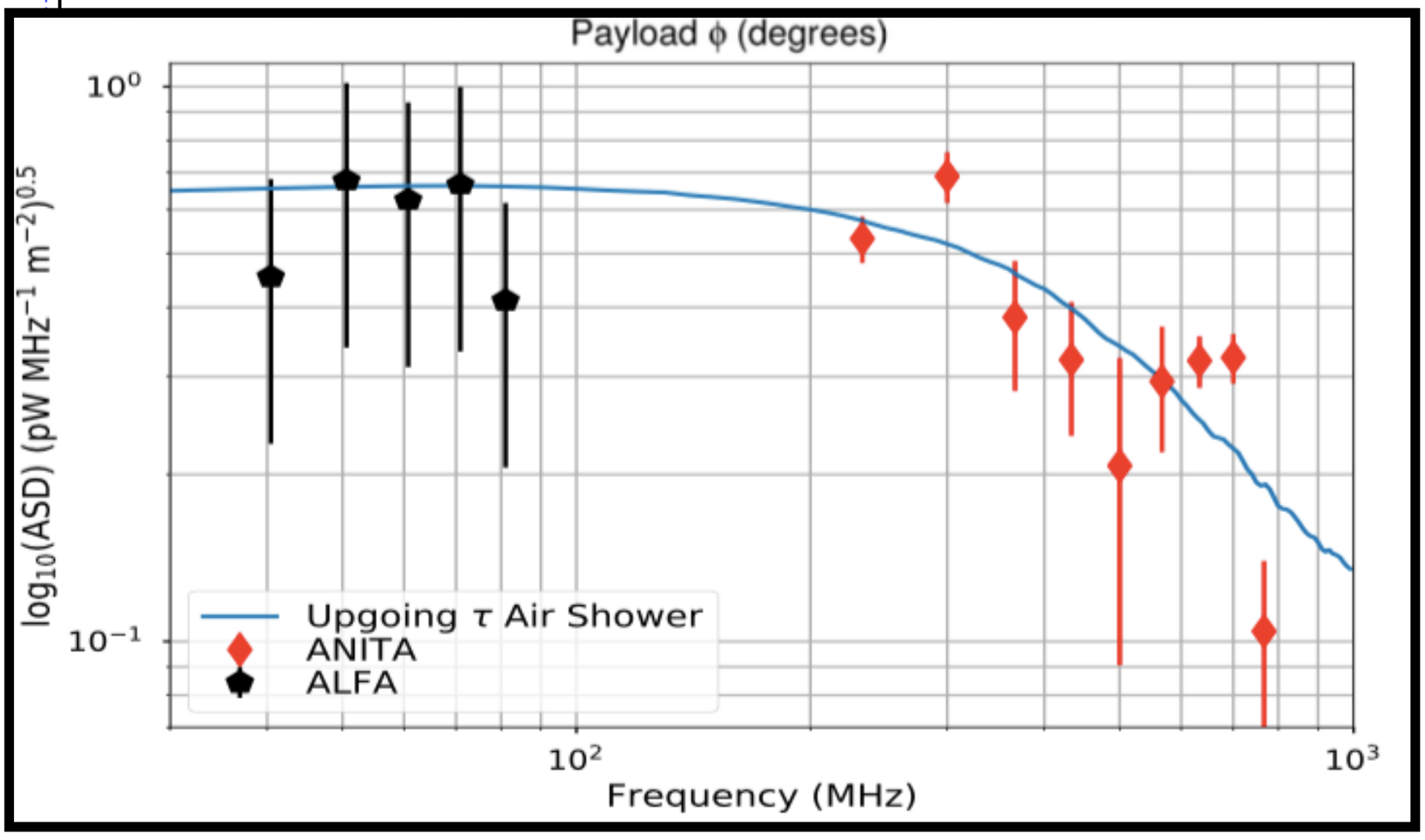




Gorham et al, 1803.05088

Standard model process?

- Straightforward explanation of signal: shower originates from a tau, $E \sim 0.56 \times 10^{18}$ eV

- Extensive (generic) modeling in Alvarez-Muniz et al (1707.00334)

- ANITA collaboration says: "…the interpretation… faces the difficult challenge that…the SM cross-section… will attenuate the flux by 10^{-5}."

Can we see more clearly how likely this is to be a SM process?

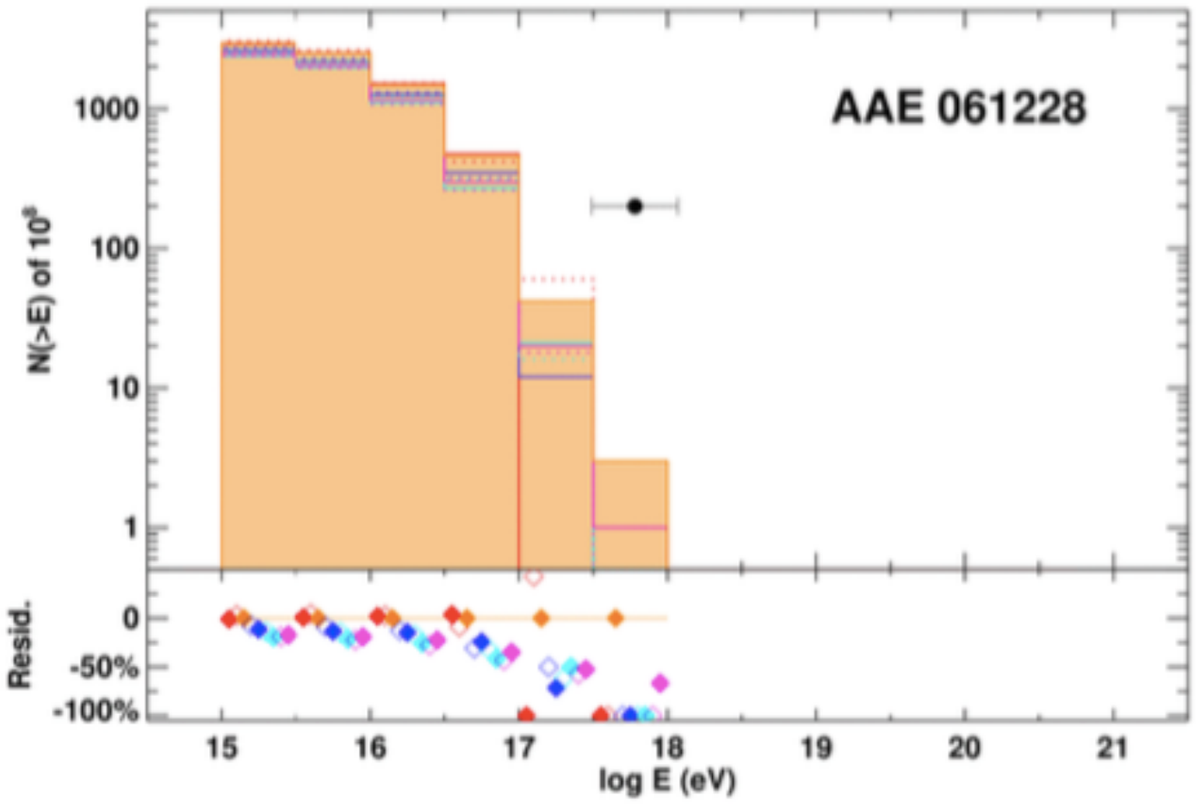
Try to simulate these events directly

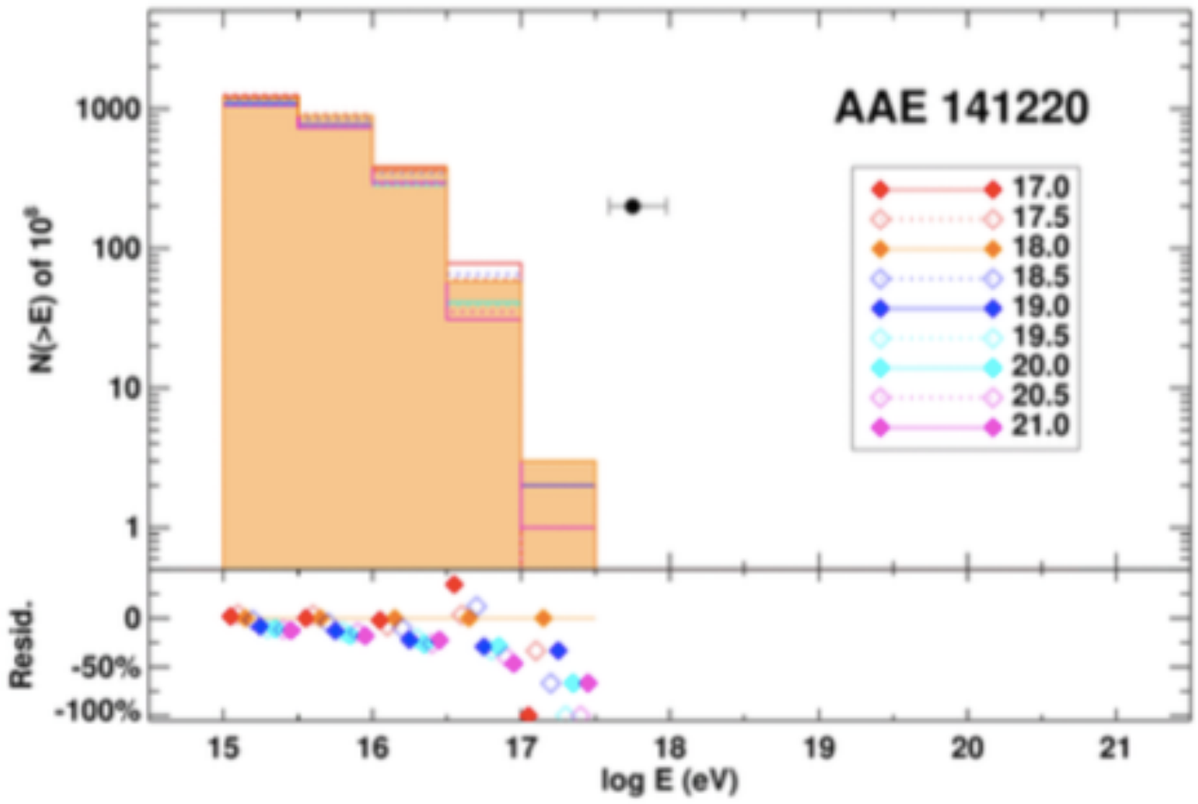
TABLE I. Properties of the ANITA Anomalous Events

Property	**AAE 061228**	**AAE 141220**
Flight & Event	ANITA-I #3985267	ANITA-III #15717147
Date & Time (UTC)	2006-12-28 00:33:20	2014-12-20 08:33:22.5
Equatorial coordinates (J2000)	R.A. $282.^{\circ}14064$, Dec. $+20.^{\circ}33043$	R.A. $50.^{\circ}78203$, Dec. $+38.^{\circ}65498$
Energy $\varepsilon_{\rm cr}$	$0.6 \pm 0.4\,$EeV	$0.56^{+0.30}_{-0.20}\,$EeV
Zenith angle z'/z	$117.^{\circ}4$ / $116.^{\circ}8 \pm 0.^{\circ}3$	$125.^{\circ}0$ / $124.^{\circ}5 \pm 0.^{\circ}3$
Earth chord length ℓ	$5740 \pm 60\,$km	$7210 \pm 55\,$km
Mean interaction length for $\varepsilon_\nu = 1\,$EeV	290 km	265 km
$p_{\rm SM}(\varepsilon_\tau > 0.1\,{\rm EeV})$ for $\varepsilon_\nu = 1\,$EeV	4.4×10^{-7}	3.2×10^{-8}
$p_{\rm SM}(z > z_{\rm obs})$ for $\varepsilon_\nu = 1\,$EeV, $\varepsilon_\tau > 0.1\,$EeV	6.7×10^{-5}	3.8×10^{-6}
$n_\tau(1$–$10\,{\rm PeV}) : n_\tau(10$–$100\,{\rm PeV}) : n_\tau(> 0.1\,{\rm EeV})$	34 : 35 : 1	270 : 120 : 1

NuTauSim tool
https://github.com/harmscho/NuTauSim
(Alvarez-Muniz et al, 1707.00334)

Simulation results





Inject 10^8 ν_τ at each half-decade of energy, along each trajectory, look at emergent tau energy

note: most likely $1\ \mathrm{EeV}\ \nu_\tau \rightarrow > 0.1\ \mathrm{EeV}\ \tau$

Fox et al; 1809.09615

Simulation results

Most likely source for emergent high energy tau: $1\ \mathrm{EeV}\ \nu_\tau$

So, inject **1 EeV** neutrinos to find probability of emergent $\tau,\ E_\tau \geq 0.1\,\mathrm{EeV}$

Probability of success:

$(4.4 \pm 0.5) \times 10^{-7}$	AAE 061228
$(3.2 \pm 0.6) \times 10^{-8}$	AAE 141220

Fox et al; 1809.09615

Simulation results

Probability of success:

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Estimating ANITA exposure as $2.7\ \mathrm{km}^2\,\mathrm{sr}\,\mathrm{yr}$,

The ANITA events require an incoming 1EeV neutrino flux of $1.2 \times 10^7\ \mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}$

Auger/IceCube limit: $6\ \mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}$

Fox et al; 1809.09615

How unlikely is the SM scenario?

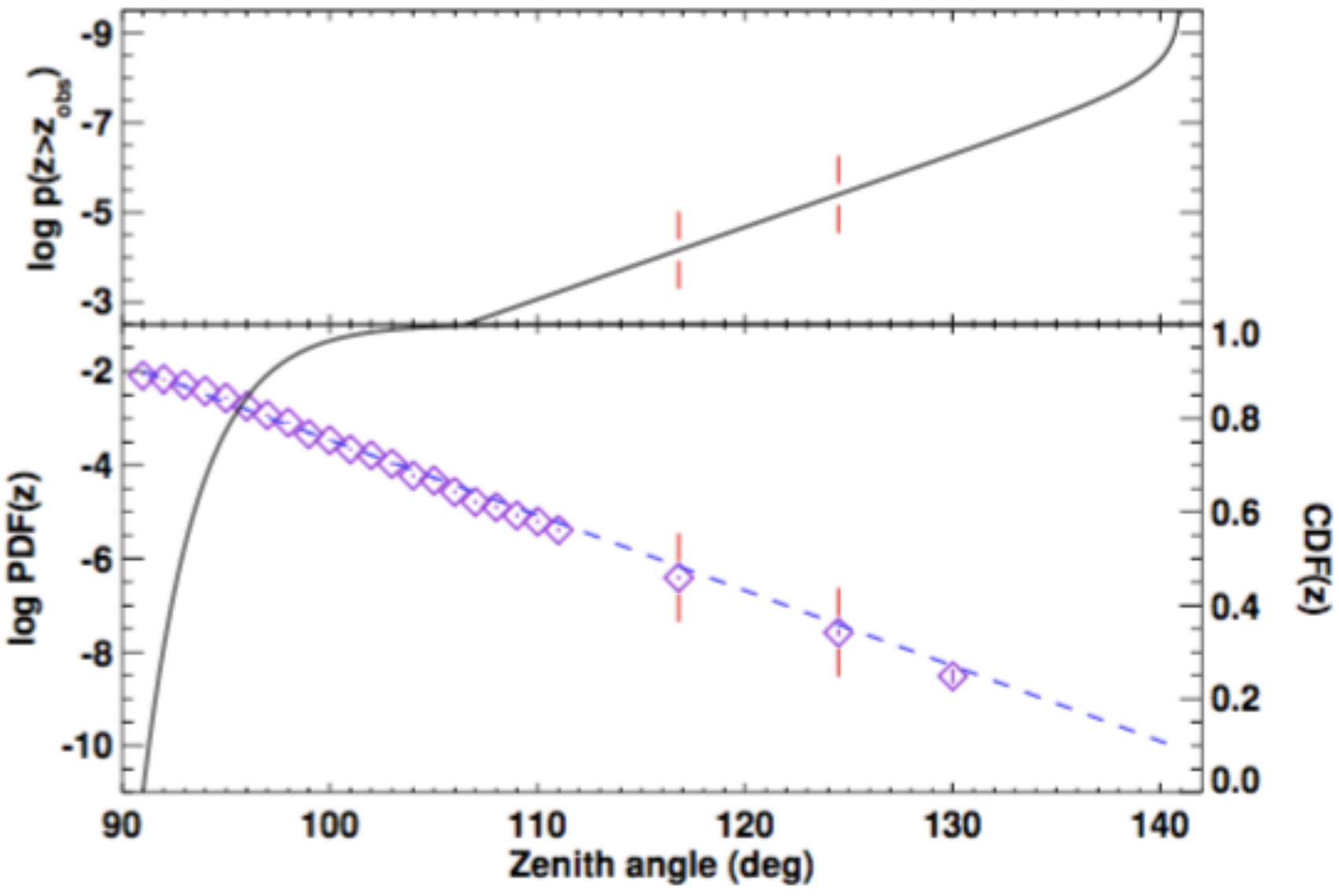
Assume an isotropic flux in agreement with the published limit to find expected number of events

Poisson probability to observe two events, when 2.4×10^{-6} expected

$$p_{\text{diffuse}} = 2.9 \times 10^{-12}$$
$$\sim 7\sigma$$

Fox et al; 1809.09615

Or, consider zenith angle distribution



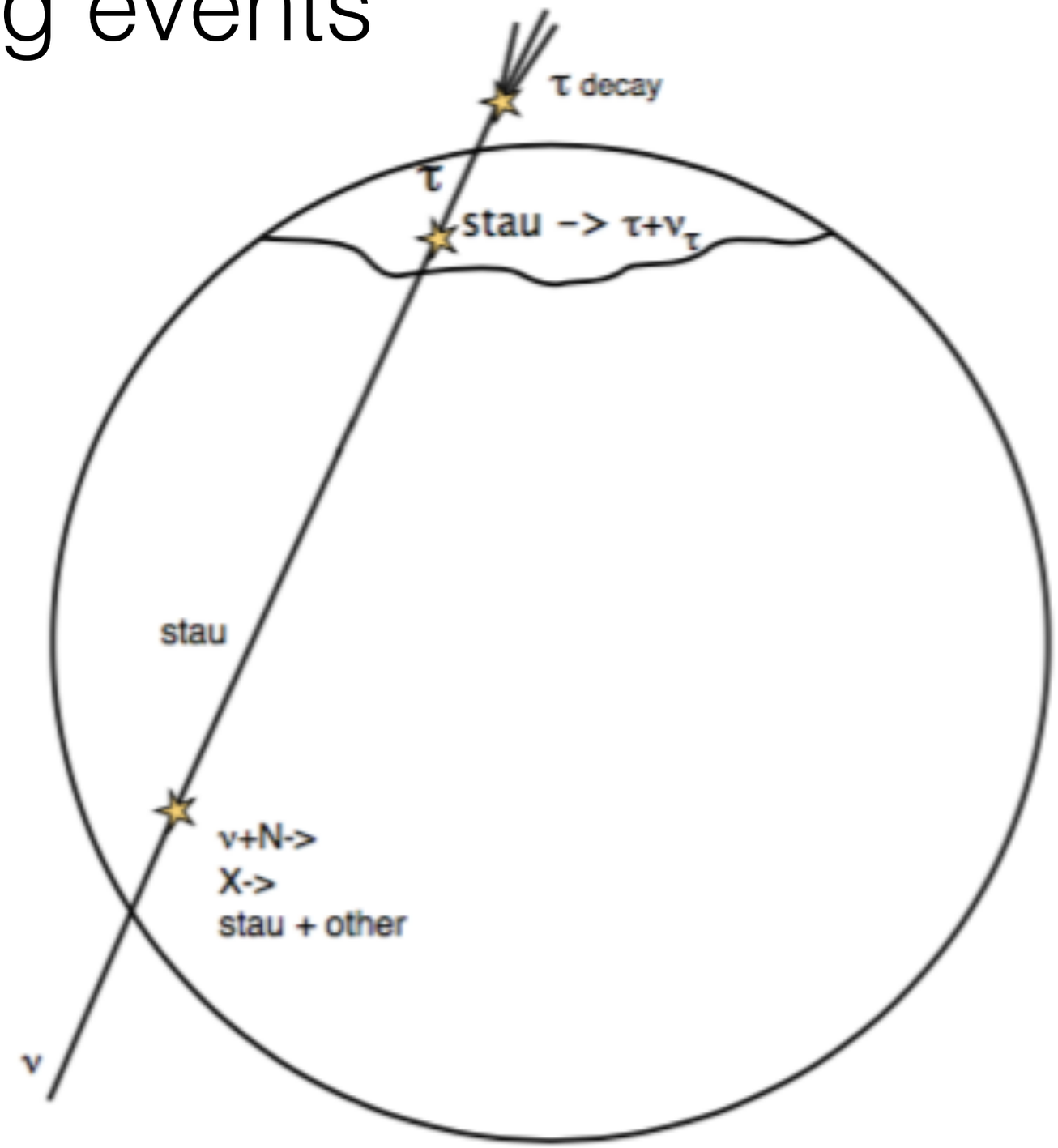
1 EeV neutrinos; probability of emergent $\tau,\ E_\tau \geq 0.1\,\mathrm{EeV}$ is approx. exponential; joint p-value for events

$$5.9 \times 10^{-9}$$

$$\sim 5.8\sigma$$

An old idea for producing such up-going events

SUSY:
- stau NLSP
- gravitino LSP



Albuquerque, Burdman, Chacko, hep-ph/0312197
Ahlers, Kersten, Ringwald hep-ph/0604188
Ando, Beacom, Profumo, Rainwater 0711.2908
Connolly, Allison, Banerjee, 1807.08892 **(figure credit)**

SUSY model parameters

ANITA events provide assumed stau energy,
immediately give stau lifetime -> stau mass

$$0.5\,\mathrm{TeV} \lesssim m_{\tilde{\tau}_R} \lesssim 1.0\,\mathrm{TeV}$$

Intriguingly…..

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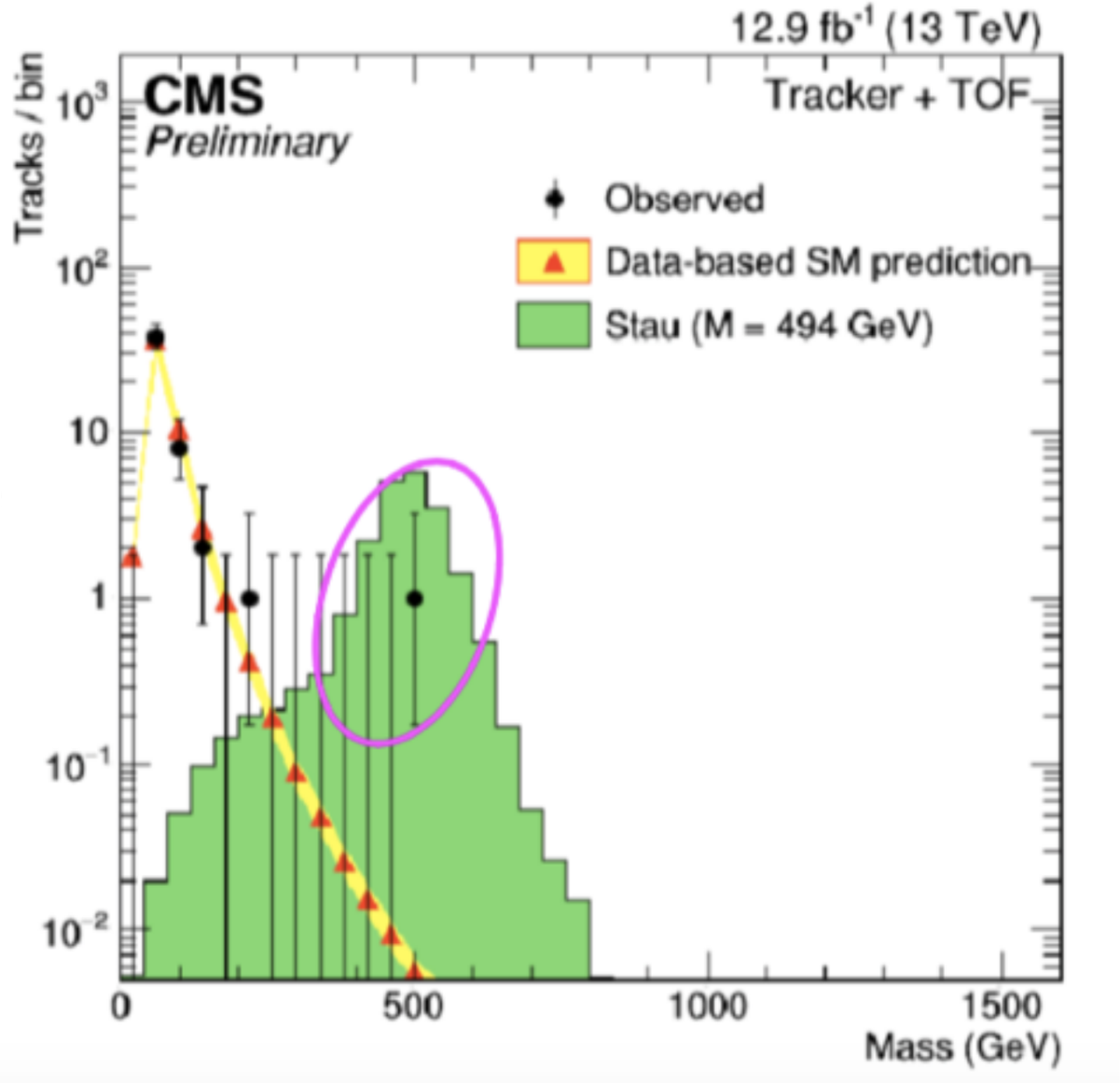

Intriguingly…..

……2016 search for stable charged particles (more data exists)

https://cds.cern.ch/record/2205281

(CMS published results: 1609.08382)

SUSY model parameters

ANITA events provide assumed stau energy, immediately give stau lifetime -> stau mass

$$0.5\,\mathrm{TeV} \lesssim m_{\tilde{\tau}_R} \lesssim 1.0\,\mathrm{TeV}$$

Then,

- SUSY breaking scale: $\sim 10^7\,\mathrm{GeV}$
- gravitino mass: $\sim 25\,\mathrm{keV}$ (cosmologically disfavored)

But, this scenario seems unlikely to predict observed rate (and zenith angle distribution)

eg, Albuquerque, Burdman, Chacko, hep-ph/0312197

General challenges for this type of explanation

incoming neutrinos

$$E_s^f \frac{d\Phi_s^f}{dE_s^f} = \int_0^{X_{\max}} \left(E_\nu \frac{d\Phi_\nu}{dE_\nu} \right) \ldots$$

X = column depth

Ando, Beacom, Profumo, Rainwater
0711.2908

General challenges for this type of explanation

incoming neutrinos

produce the new particle

$$E_s^f \frac{d\Phi_s^f}{dE_s^f} = \int_0^{X_{\max}} \left(E_\nu \frac{d\Phi_\nu}{dE_\nu} \right) \left(\frac{\sigma_{\rm SUSY}(E_\nu)}{\sigma_{\rm SM}(E_\nu)} \right) \left(\frac{E_s^f}{E_s^i} \right)$$

$$\times \left[\quad \right]$$

X = column depth

Ando, Beacom, Profumo, Rainwater
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$$E_s^f \frac{d\Phi_s^f}{dE_s^f} = \int_0^{X_{\max}} \left(E_\nu \frac{d\Phi_\nu}{dE_\nu} \right) \left(\frac{\sigma_{\rm SUSY}(E_\nu)}{\sigma_{\rm SM}(E_\nu)} \right) \left(\frac{E_s^f}{E_s^i} \right) \times \left[\frac{\exp[-(X_{\max} - X)\sigma_{\rm SM}(E_\nu)/m_p}{m_p/\sigma_{\rm SM}(E_\nu)} \right] e^{\beta_s X}$$

propagation: lose neutrinos, staus lose energy

X = column depth

Ando, Beacom, Profumo, Rainwater
0711.2908

What else has been tried?

- Sterile neutrinos (Cherry, Shoemaker, 1802.01611; Huang, 1804.05362)
- Decaying dark matter inside the earth
  - R-parity violating SUSY model, EeV gravitino DM (Dudas et al, 1805.07342) (but rate is too low)
  - minimal extension of SM by 3 RH neutrinos ("CPT universe") (Anchordoqui et al, 1803.11554)
- CR shower is bino-initiated (RPV SUSY) (Collins et al, 1810.08479)

Explaining the zenith angle distribution?

- Anisotropic/transient neutrino fluxes
- Unexpected distribution of new particle matter inside the earth
- ???

An additional challenge/opportunity: What should IceCube see?

- IceCube sees no anomalies
- Exposure is 1-60 times ANITA (depending on scenario)

But, IceCube could have taus masquerading as muons…
(Kistler, Laha, 1605.08781)

…although with energy a bit low for ANITA stau: $0.07\,\mathrm{EeV}$

Conclusions…

More data exists already: ANITA, LHC, IceCube, Auger

Going beyond our old workhorse BSM ideas:

How can we best exploit this data for new, paradigm shifting, constraints on BSM physics?