Scary Question: Where Do We Go Next?

A Few (Pumpkin) Pie-In-The-Sky Ideas to (maybe) Laugh About

Austin Cummings

TAMBO-Trinity-BEACON/HERON Workshop, Harvard
10/31/2025

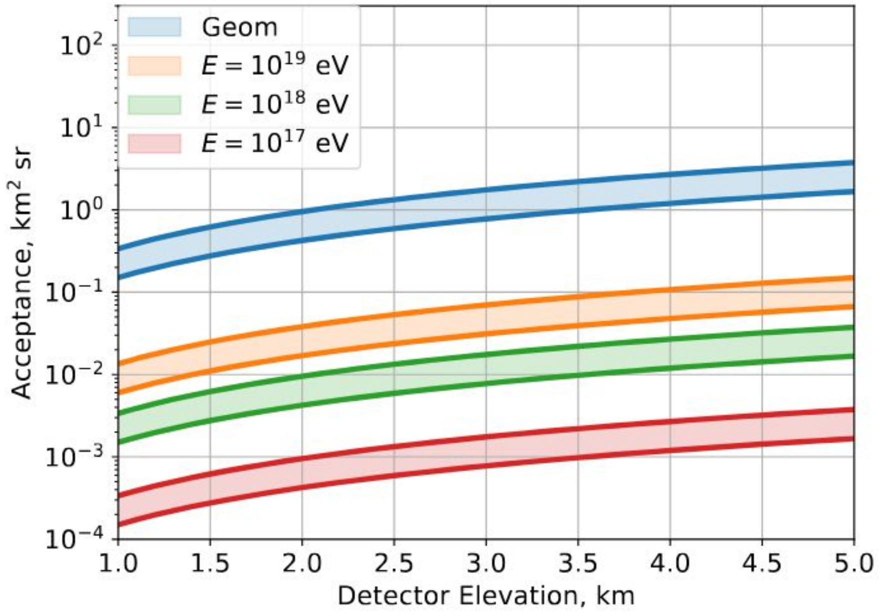
Why Are We Here?

Things common to mountain-top strategies

- Looking for products from a τ-lepton decay in air, typically within a few degrees of the shower axis
  - ν_τ is uniquely astrophysical

- Sensitive to a narrow strip of either Earth or mountains
  - Typically perform better for transients than diffuse

- The higher you go, the more area you see, but typically the higher your energy threshold.
  - Assumptions: maximum P_{exit}, γ = 2.5, same FOV, same $\Delta\theta$ off shower axis $\rightarrow$ event # scaling with energy:
    - 1PeV: 1 event $\rightarrow$ 1 detector
    - 10PeV: 0.92 event $\rightarrow$ 1.1 detector
    - 100PeV: 0.66 event $\rightarrow$ 1.5 detector
    - 1EeV: 0.2 event $\rightarrow$ 5 detector
    - 10EeV: 0.03 event $\rightarrow$ 33 detector



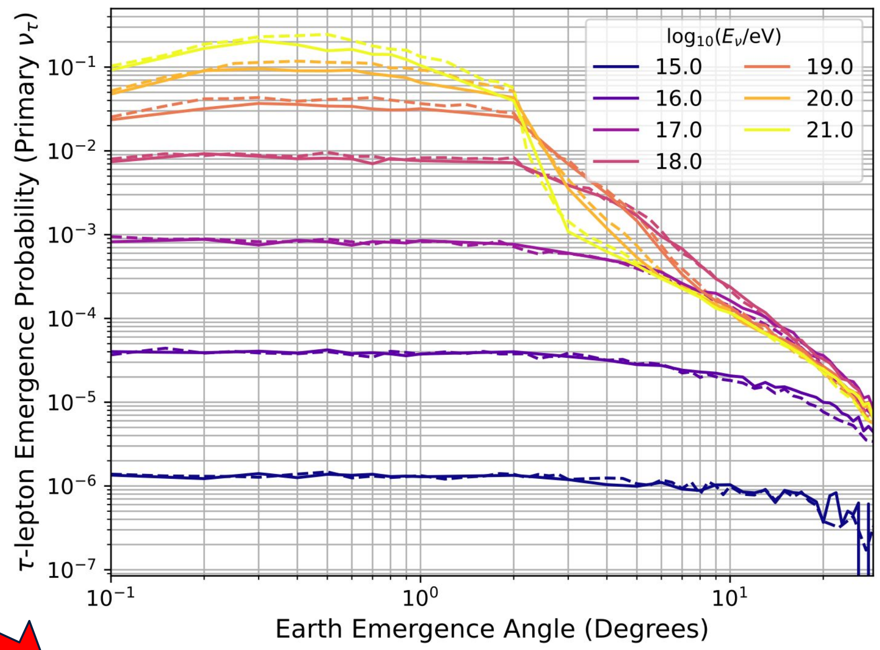
τ-leptons kinda suck

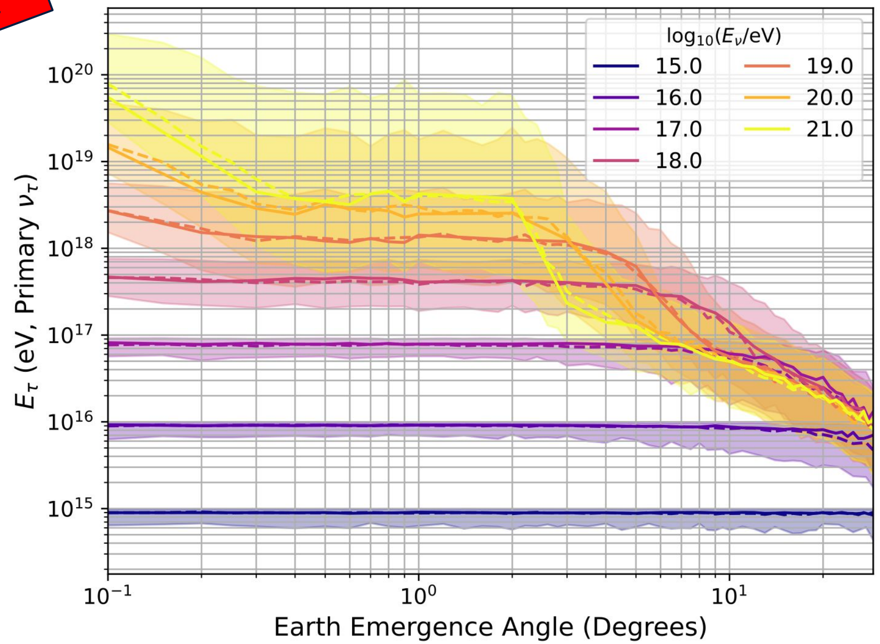
Weaknesses of the ν_τ channel

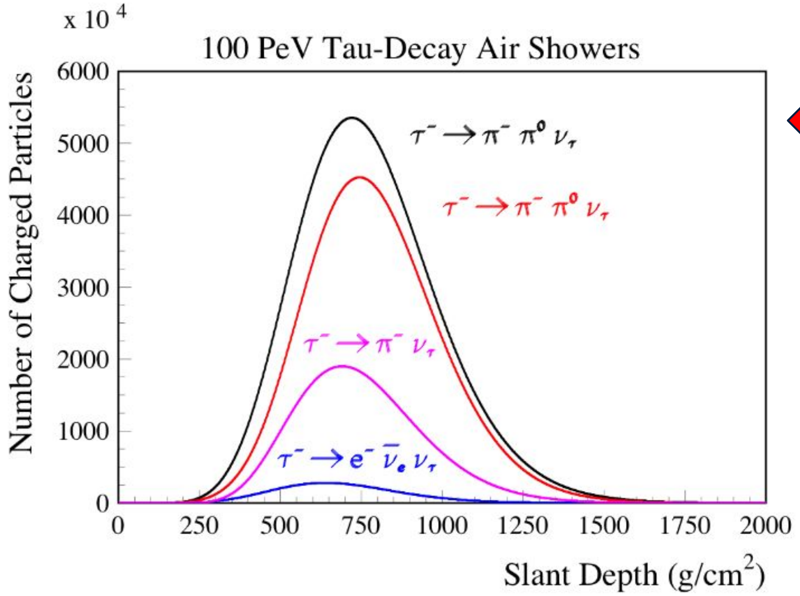
1. You restrict yourself to ⅓ of possible neutrinos!

2. You require propagation through the Earth
   a. Fighting with Earth emergence probability
   b. Large energy losses inside the Earth at high E

3. Extra uncertainties due to τ-lepton decay processes

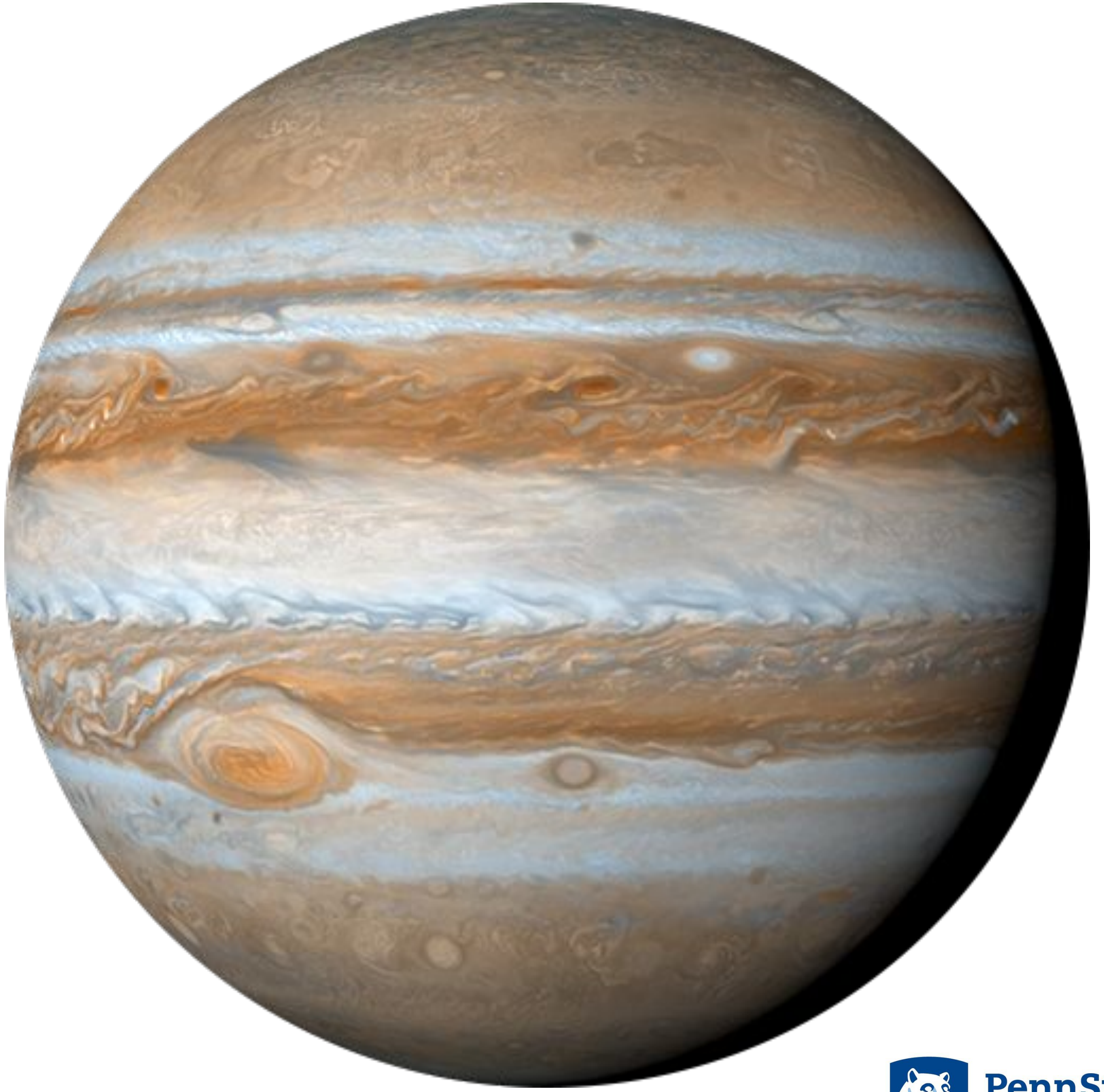






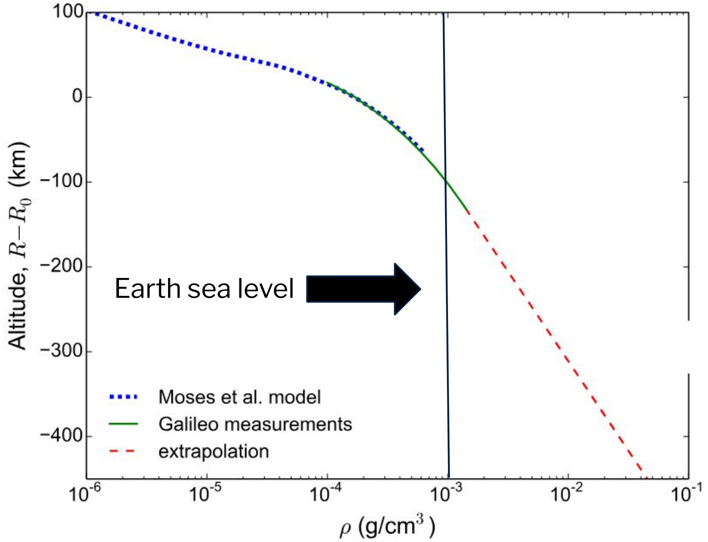
But Austin, what if we *really* like the τ channel?

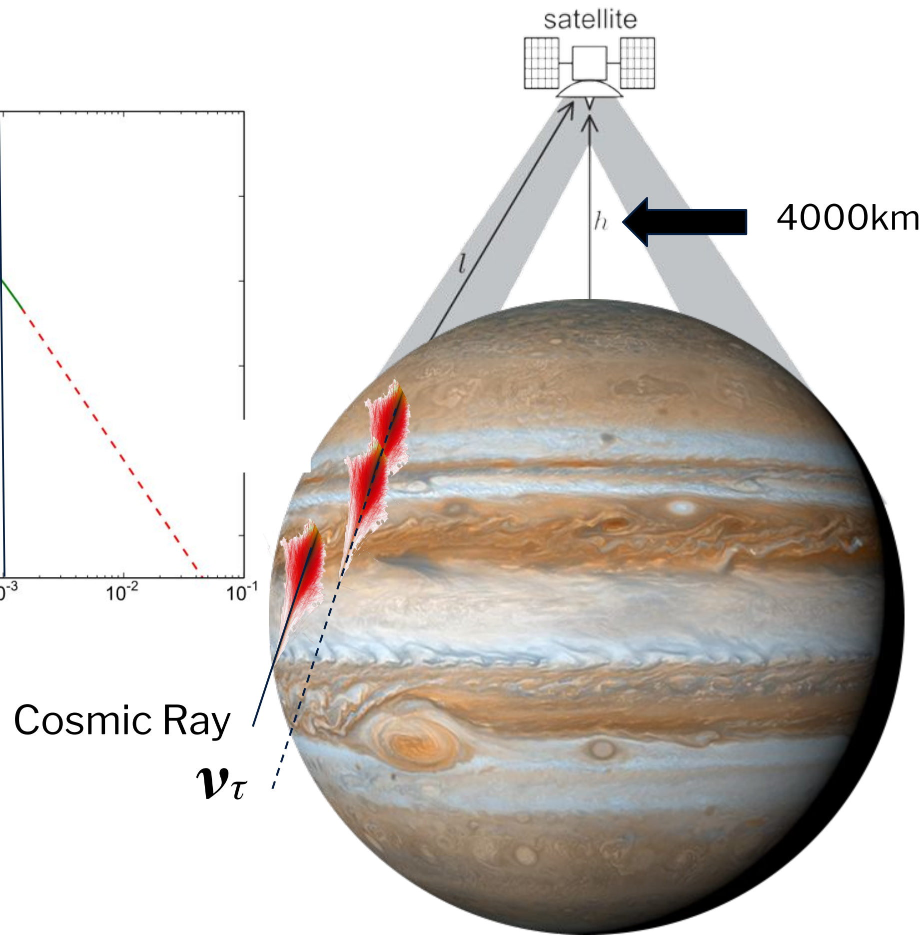
PennState



Jupiter Orbiter

- Huge observation area (10X Earth)
  - Further away: 24000km to horizon, compared to 700km for balloons
- Strong magnetic field (20X Earth)
  - $E_{geo/jov} \propto \mathbf{v} \times \mathbf{B}$
- Variable atmospheric density (H_2)
  - CR screening regions
  - Transparent to radio (no emergence probability problems)
- Low backgrounds:
  - Cosmic rays are screened
  - Jovian emission <100MHz
- … *Sensitive to all flavors*





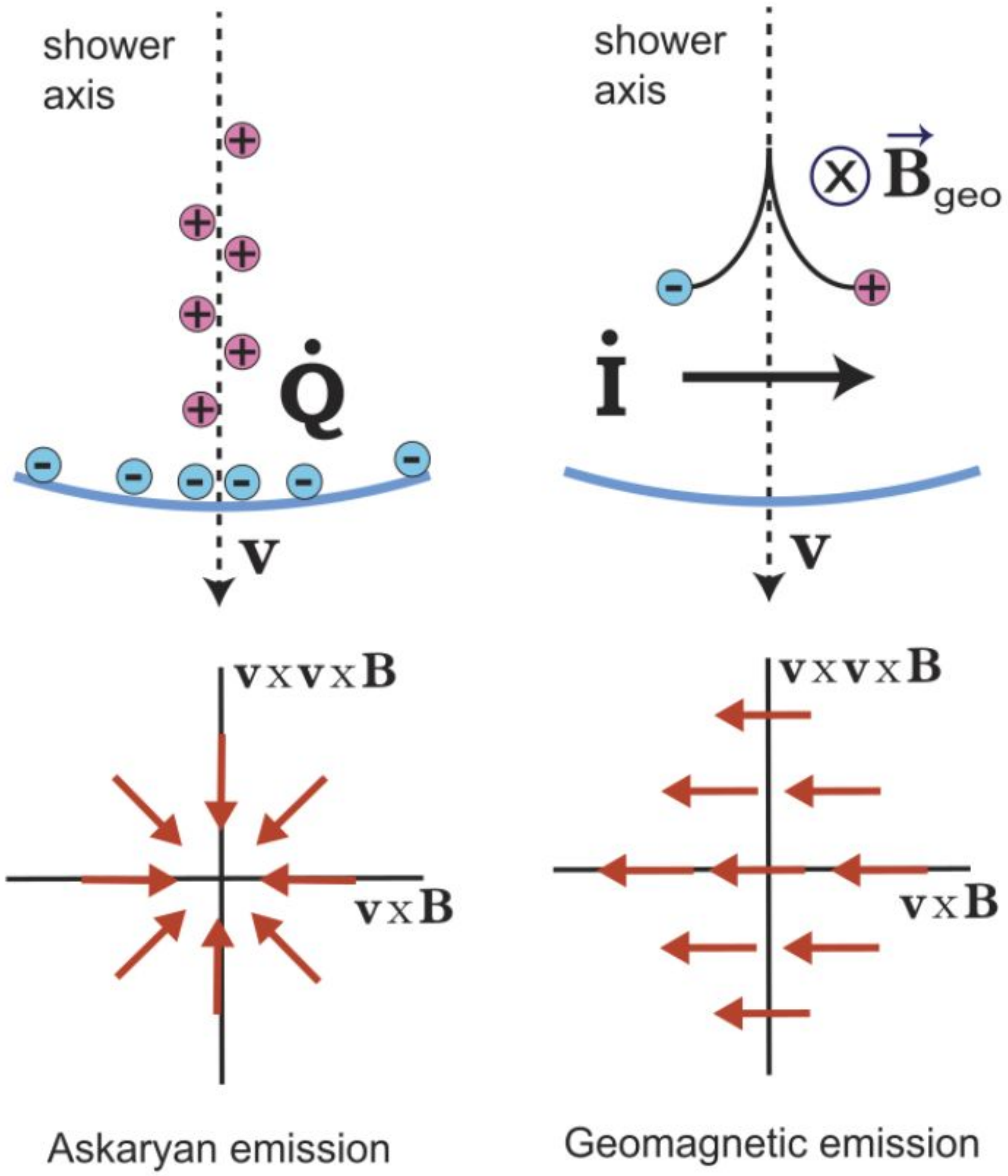
2 conflicting simulation studies:

- J. D. Bray and A. Nelles 2016 ApJ 825 129
- P. B. Rimmer et al 2014 ApJL 787 L25

Let's talk about Askaryan emission

Askaryan Emission

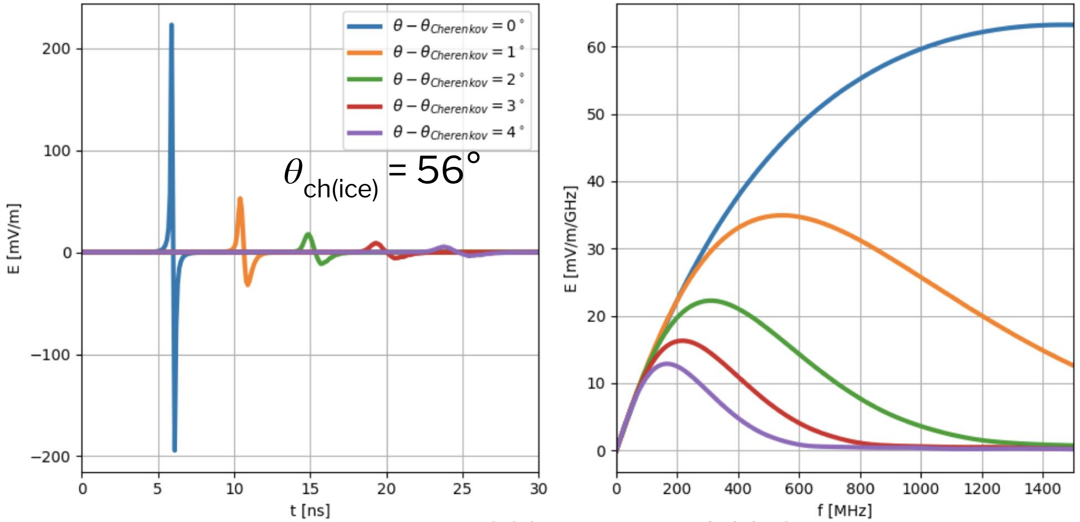
- Positron annihilation → 20% negative charge excess



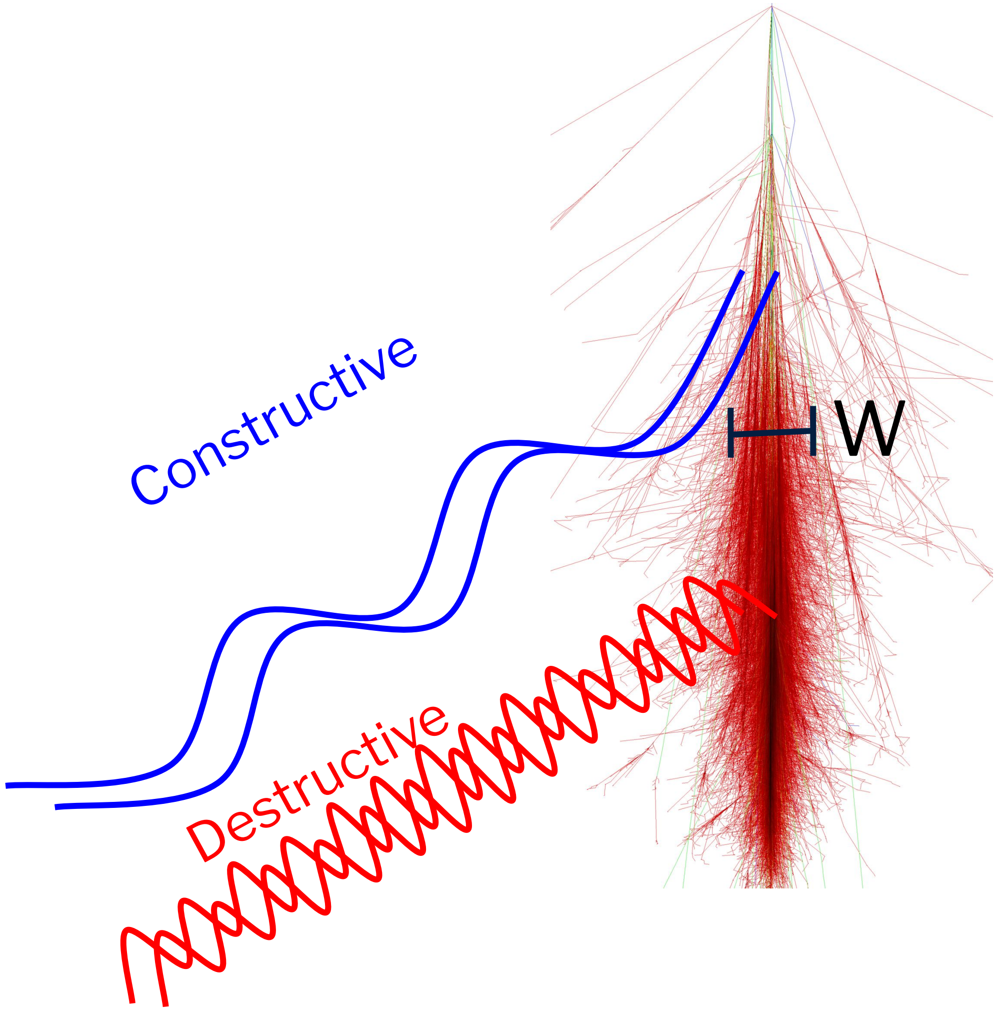
Askaryan Emission

- Positron annihilation → 20% negative charge excess

- Broadband emission from wavelengths comparable to shower width (dominant in dense media)
  - O(10cm) in water → Max freq: O(GHz)
  - O(100m) in air → O(MHz)



Askaryan 1969, NuRadioMC 2019

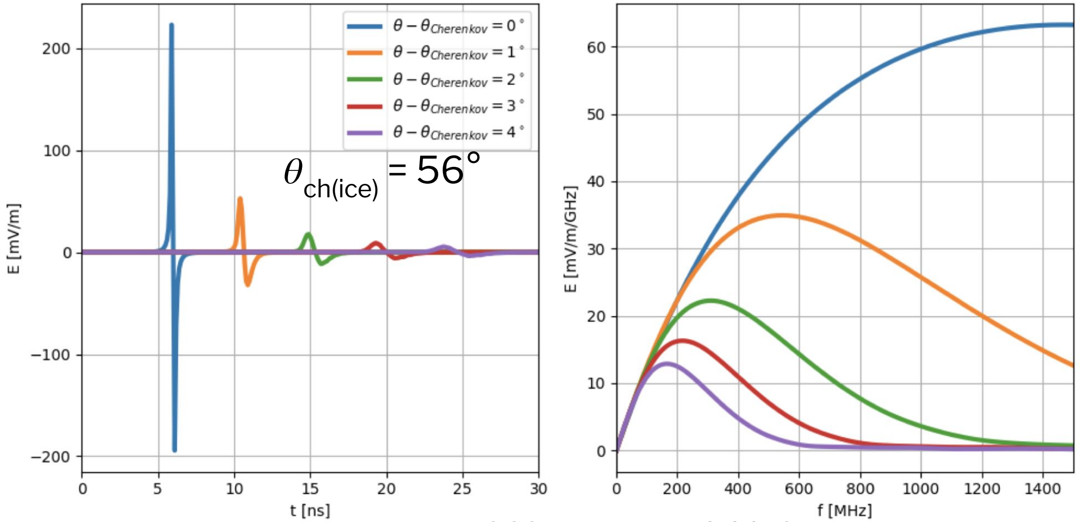


Askaryan Emission

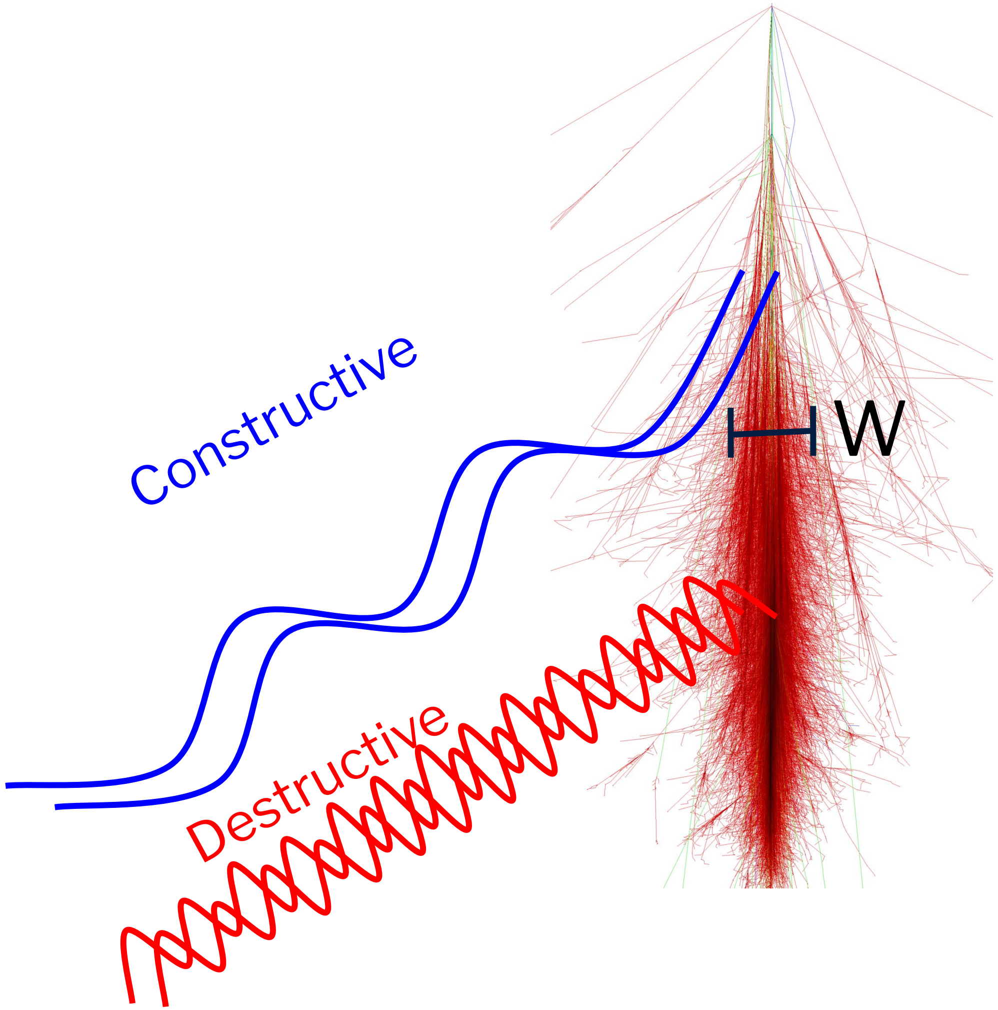
- Positron annihilation → 20% negative charge excess

- Broadband emission from wavelengths comparable to shower width (dominant in dense media)
    - O(10cm) in water → Max freq: O(GHz)
    - O(100m) in air → O(MHz)

- Attenuation length of 1GHz radio in various media:
    - Water: O(1cm/1m, sea/fresh)
    - Rock salt: O(10-100m)
    - Ice: O(1km)

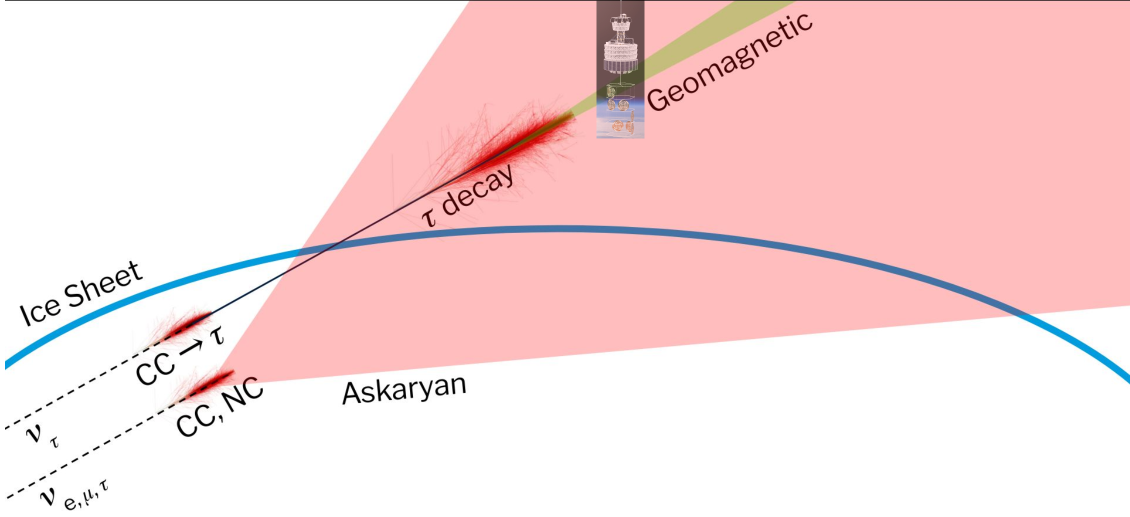


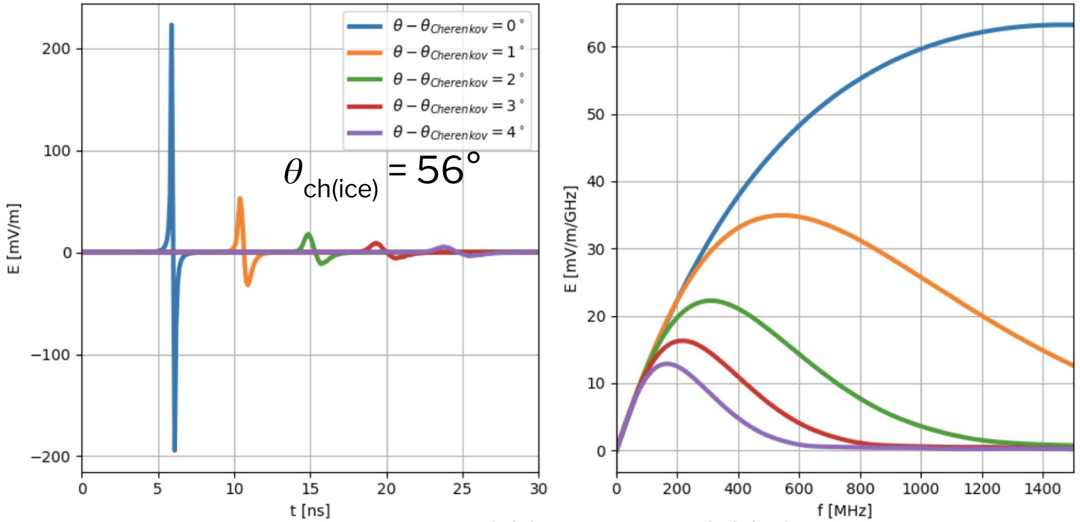
Askaryan 1969, NuRadioMC 2019



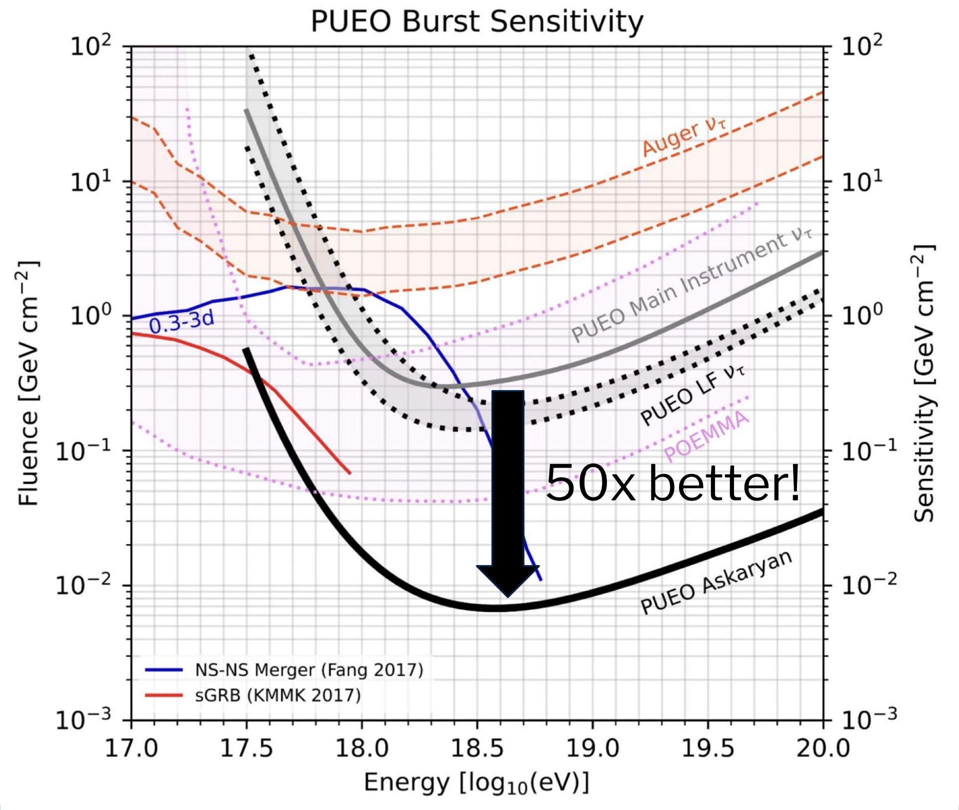
Askaryan Emission

- Positron annihilation → 20% negative charge excess
- Broadband emission from wavelengths comparable to shower width (dominant in dense media)
  - O(10cm) in water → Max freq: O(GHz)
  - O(100m) in air → O(MHz)
- Attenuation length of 1GHz radio in various media:
  - Water: O(1cm/1m, sea/fresh)
  - Rock salt: O(10-100m)
  - Ice: O(1km)



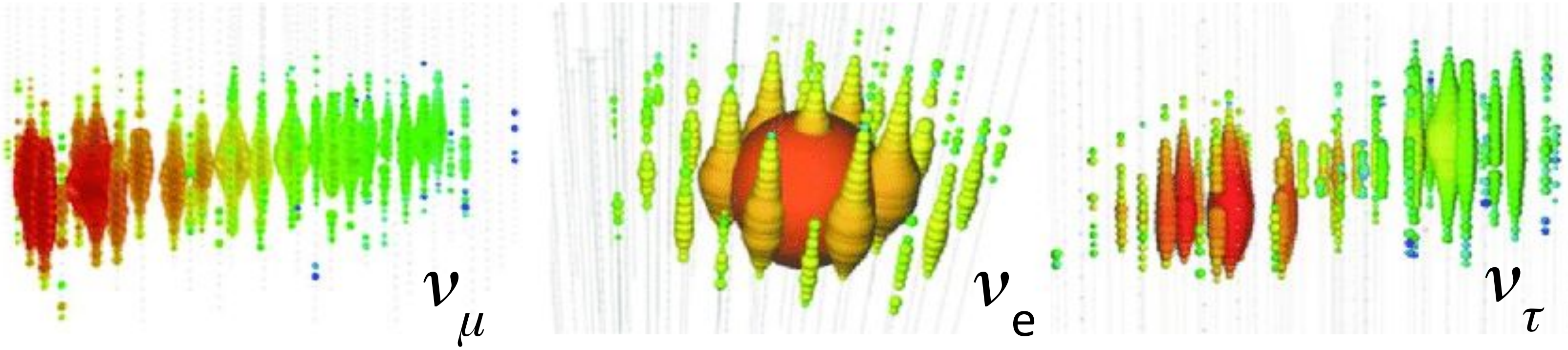


Askaryan 1969, NuRadioMC 2019

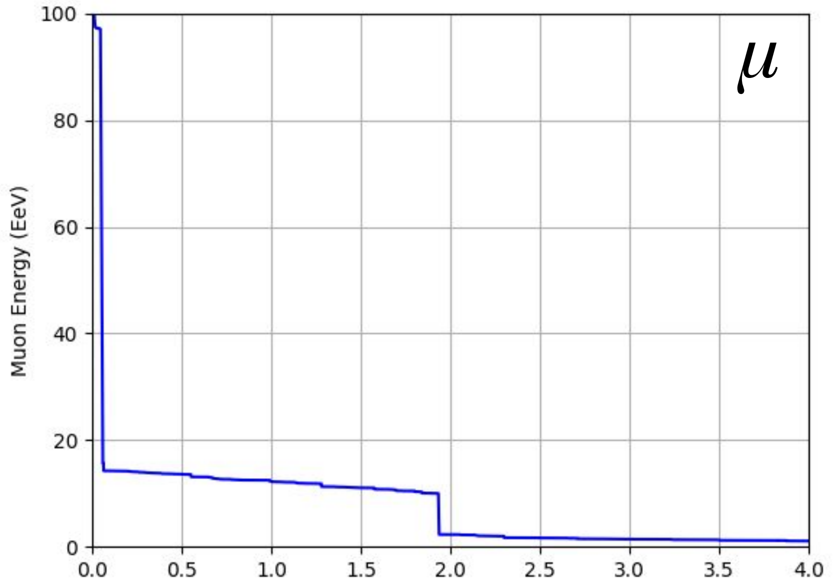


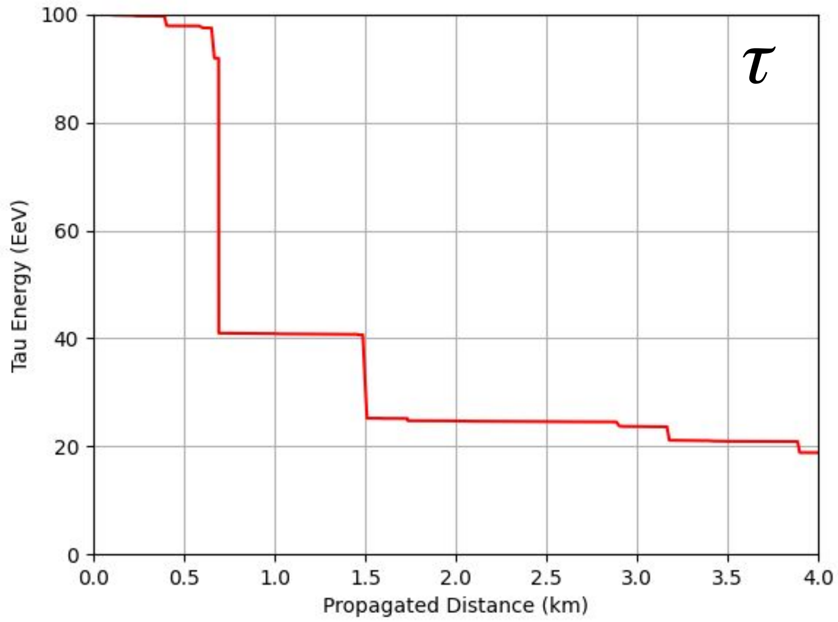
Flavor Measurements in Radio

<u>Example IceCube Event Topologies:</u>



100EeV Primary





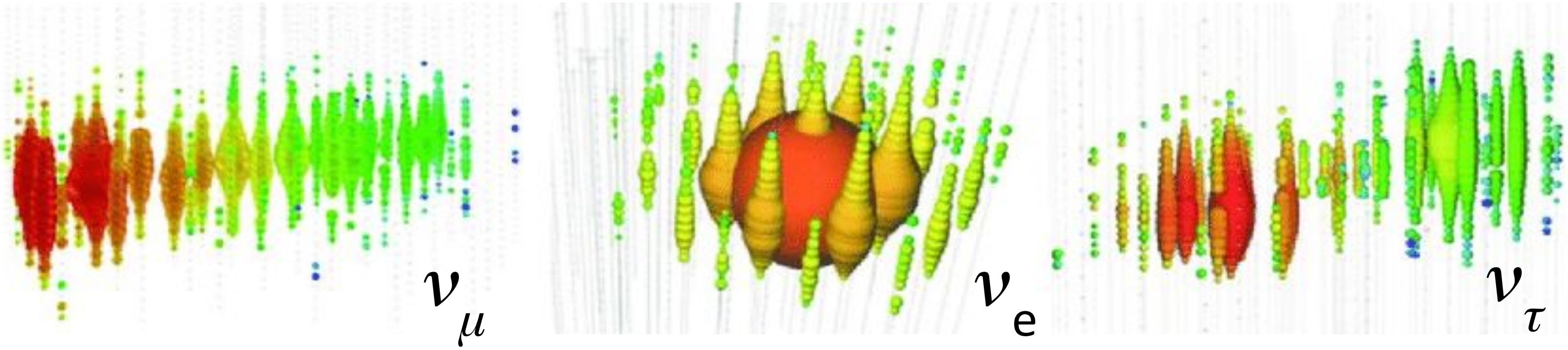
- Coherent Askaryan emission results from the charge excess in particle cascades in dense media (ice)
  - In-ice attenuation length *O*(km) vs *O*(m) for optical

- Radio energy threshold *O*(EeV):
  - Charged lepton stochastic losses (Bremsstrahlung, e± pair production, photonuclear interactions) dominate
    - Interaction length *O*(km) in ice
  - τ-leptons less likely to decay

- No “track” topology: expect single pulse and multi-pulse

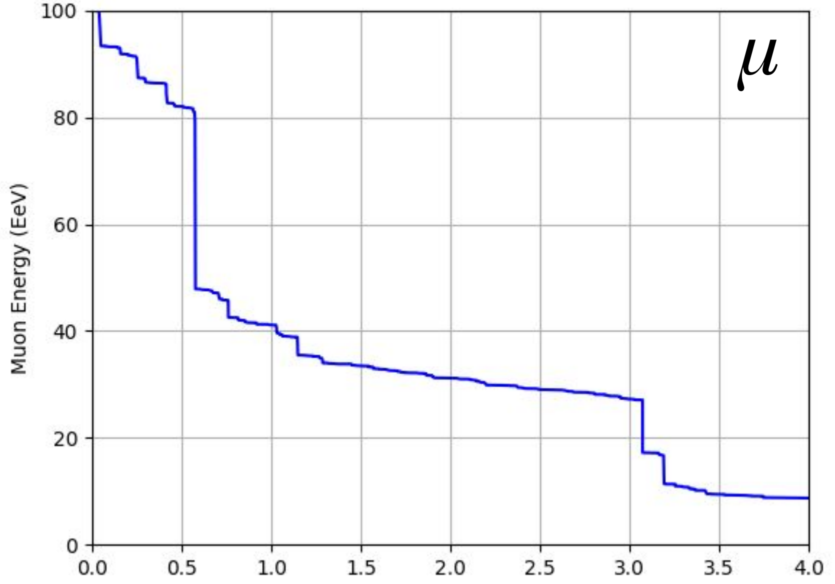
Flavor Measurements in Radio

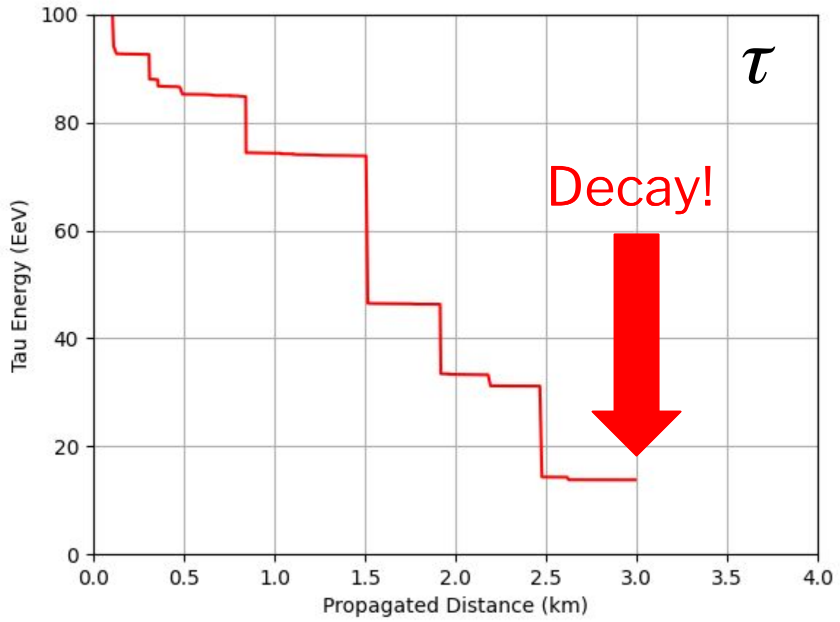
<u>Example IceCube Event Topologies:</u>



- Coherent Askaryan emission results from the charge excess in particle cascades in dense media (ice)
  - In-ice attenuation length *O*(km) vs *O*(m) for optical
- Radio energy threshold *O*(EeV):
  - Charged lepton stochastic losses (Bremsstrahlung, e± pair production, photonuclear interactions) dominate
    - Interaction length *O*(km) in ice
  - τ-leptons less likely to decay
- No "track" topology: expect single pulse and multi-pulse

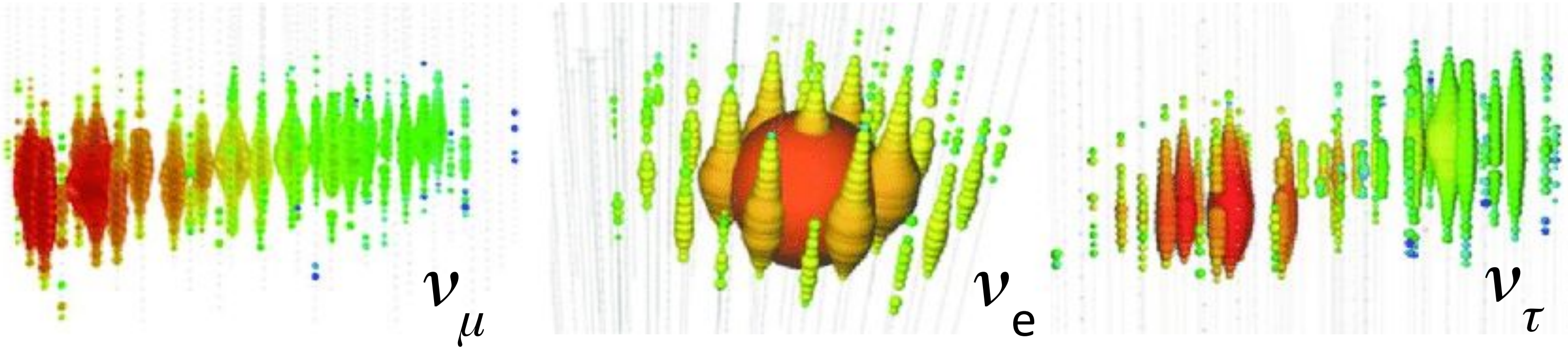
100EeV Primary





Flavor Measurements in Radio

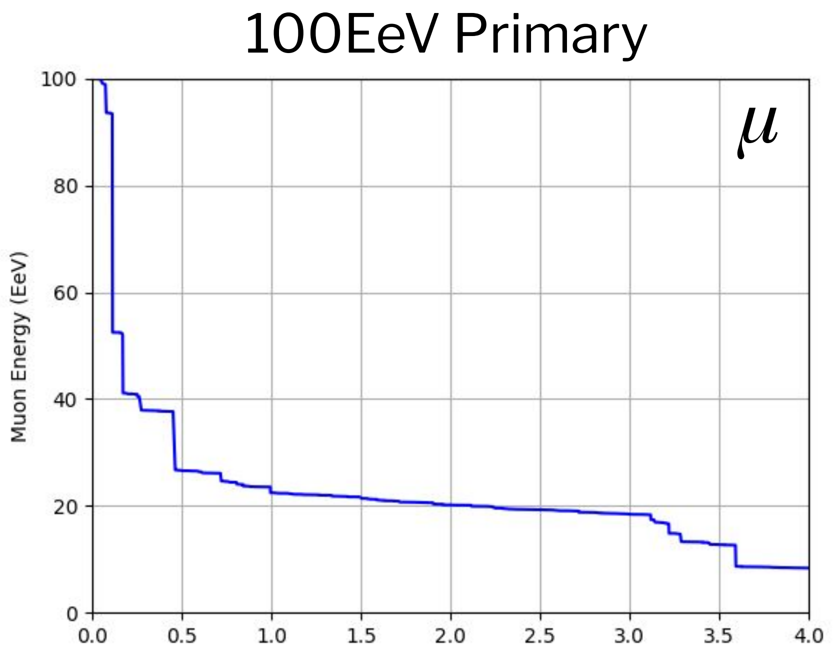
<u>Example IceCube Event Topologies:</u>

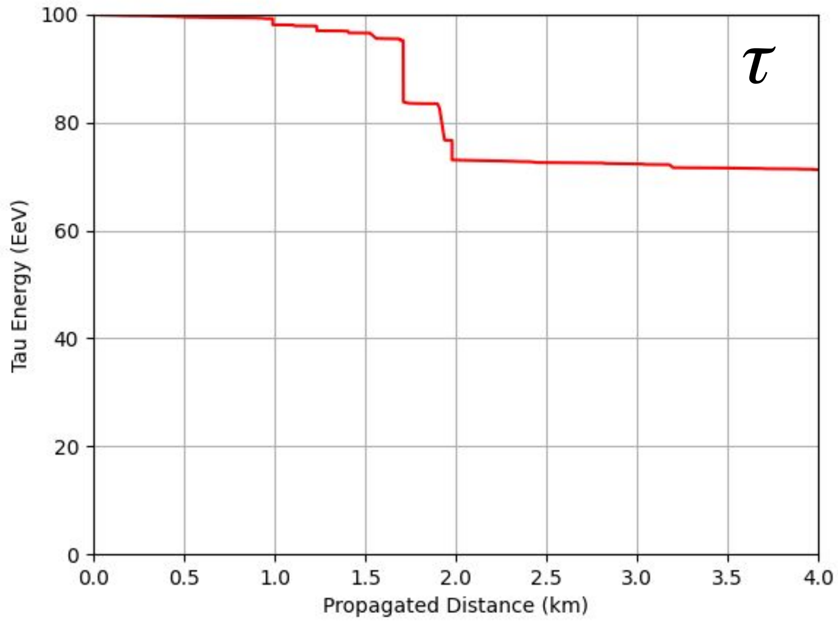


- Coherent Askaryan emission results from the charge excess in particle cascades in dense media (ice)
  - In-ice attenuation length *O*(km) vs *O*(m) for optical

- Radio energy threshold *O*(EeV):
  - Charged lepton stochastic losses (Bremsstrahlung, e± pair production, photonuclear interactions) dominate
    - Interaction length *O*(km) in ice
  - τ-leptons less likely to decay

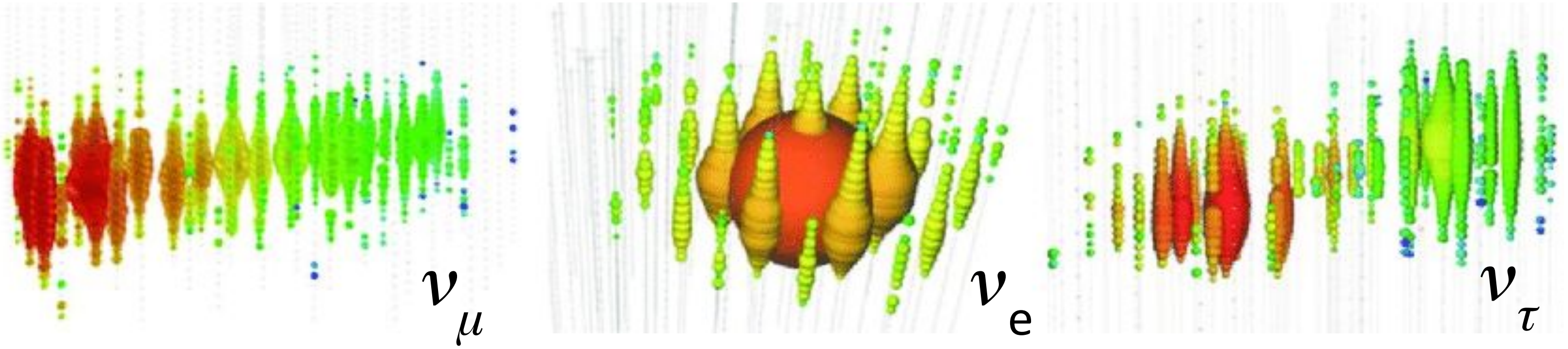
- No “track” topology: expect single pulse and multi-pulse





Flavor Measurements in Radio

Example IceCube Event Topologies:

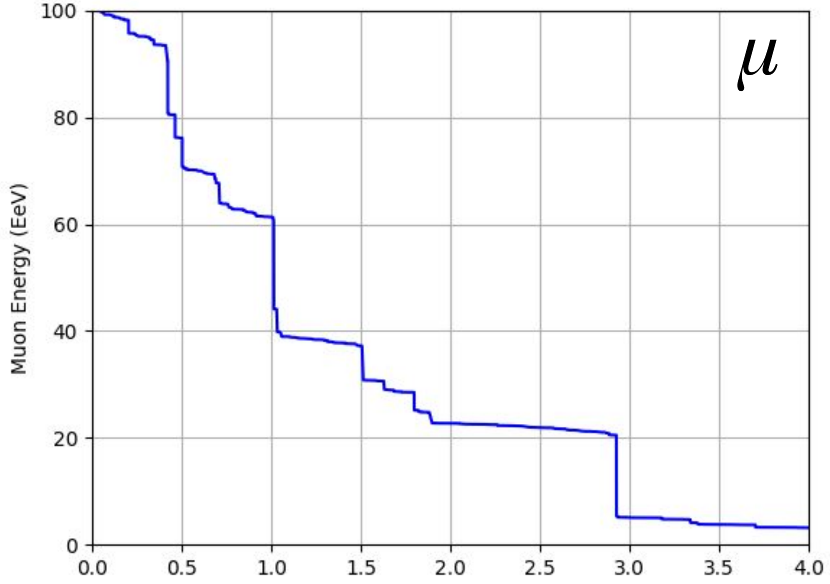


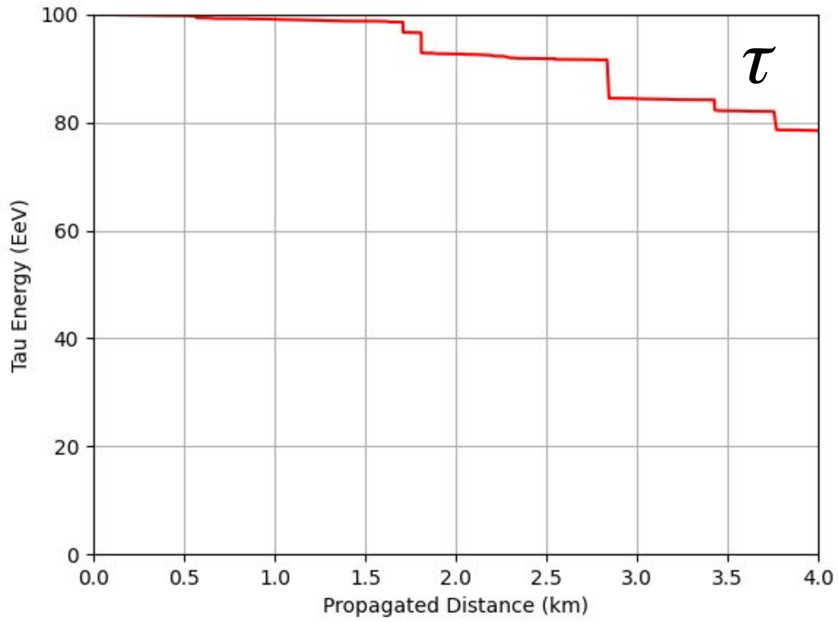
- Coherent Askaryan emission results from the charge excess in particle cascades in dense media (ice)
  - In-ice attenuation length *O*(km) vs *O*(m) for optical

- Radio energy threshold *O*(EeV):
  - Charged lepton stochastic losses (Bremsstrahlung, e± pair production, photonuclear interactions) dominate
    - Interaction length *O*(km) in ice
  - τ-leptons less likely to decay

- No "track" topology: expect single pulse and multi-pulse

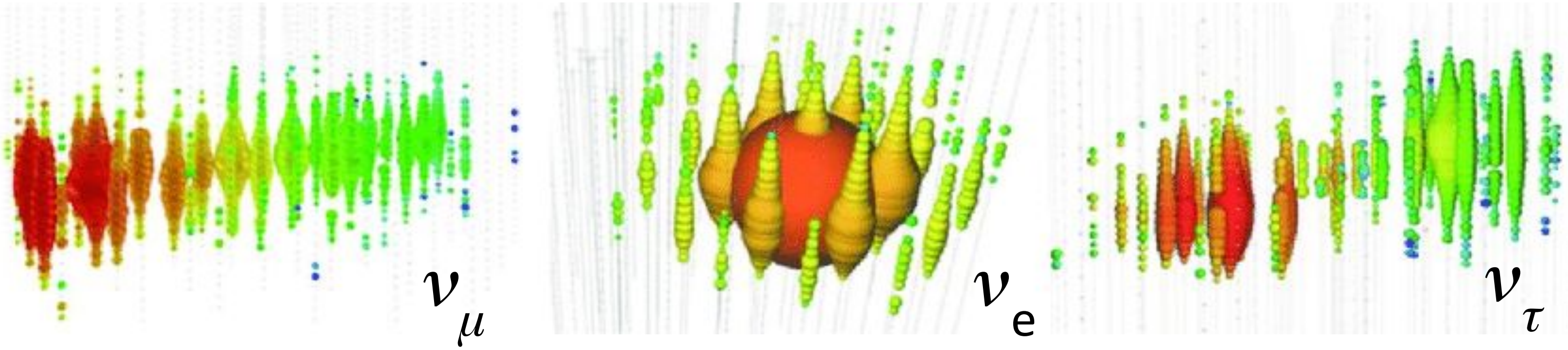
100EeV Primary





Flavor Measurements in Radio

Example IceCube Event Topologies:

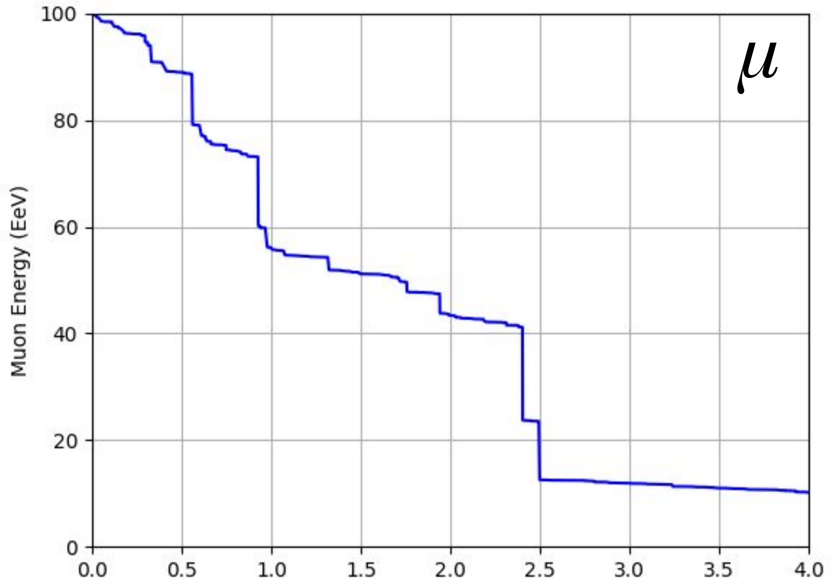


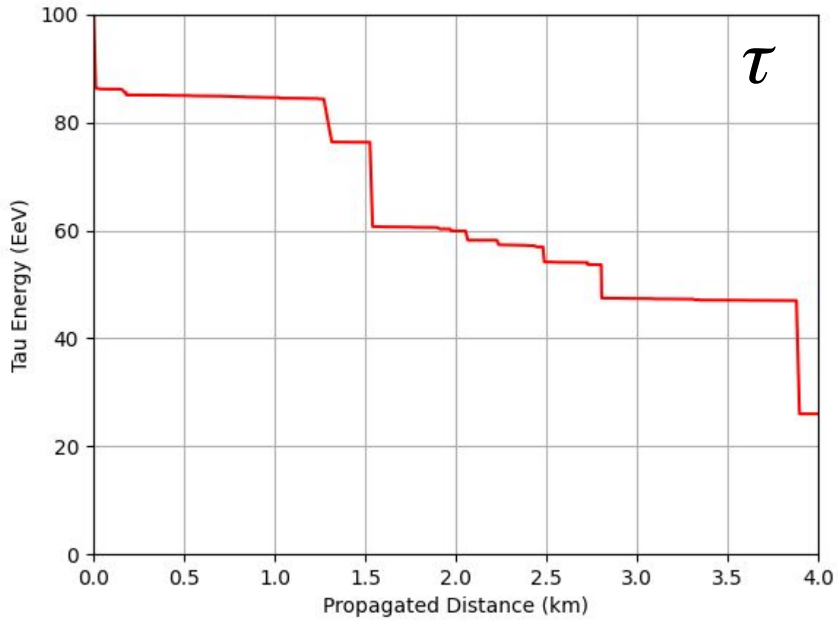
- Coherent Askaryan emission results from the charge excess in particle cascades in dense media (ice)
  - In-ice attenuation length *O*(km) vs *O*(m) for optical

- Radio energy threshold *O*(EeV):
  - Charged lepton stochastic losses (Bremsstrahlung, e± pair production, photonuclear interactions) dominate
    - Interaction length *O*(km) in ice
  - τ-leptons less likely to decay

- No "track" topology: expect single pulse and multi-pulse

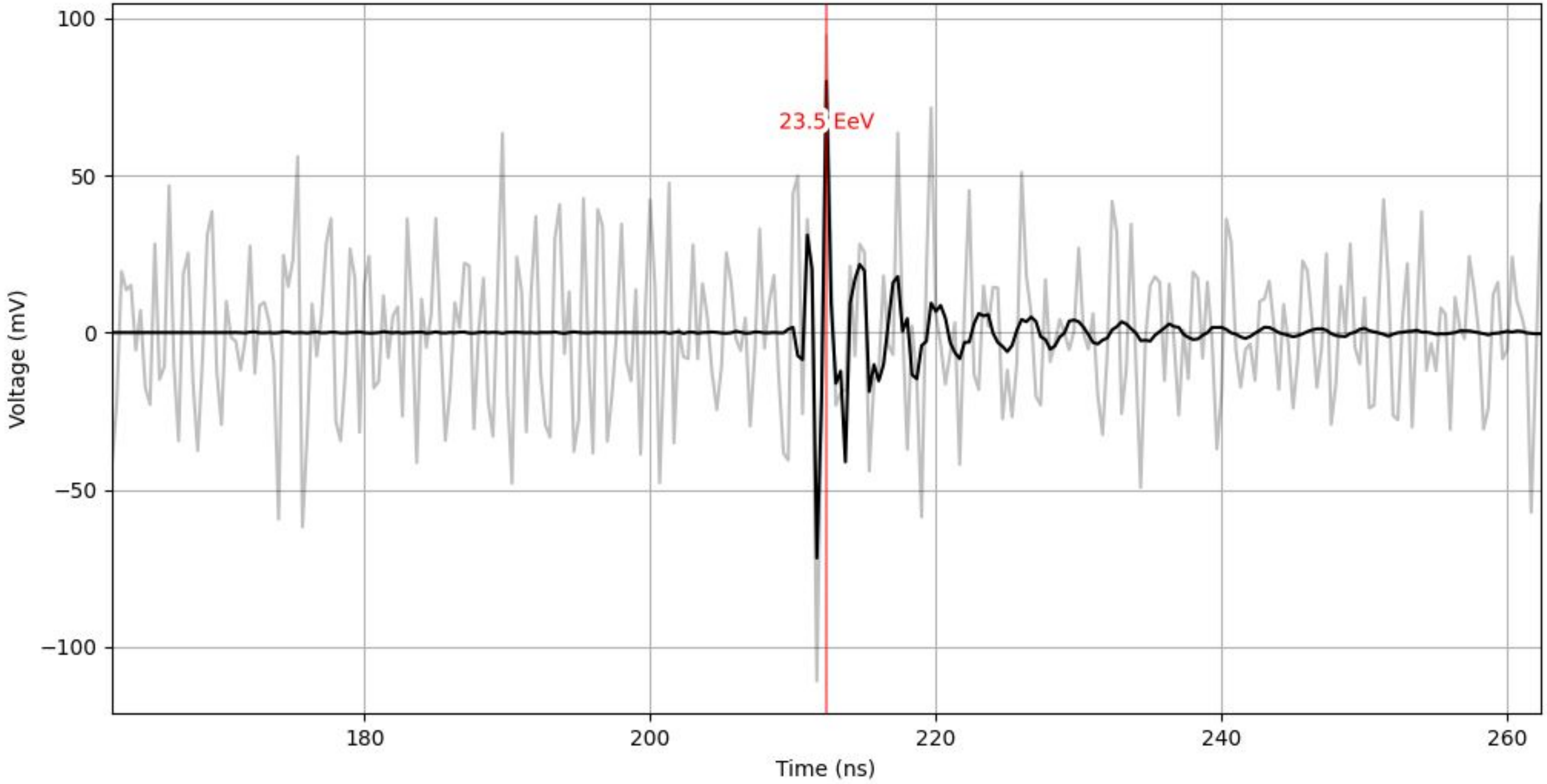
100EeV Primary



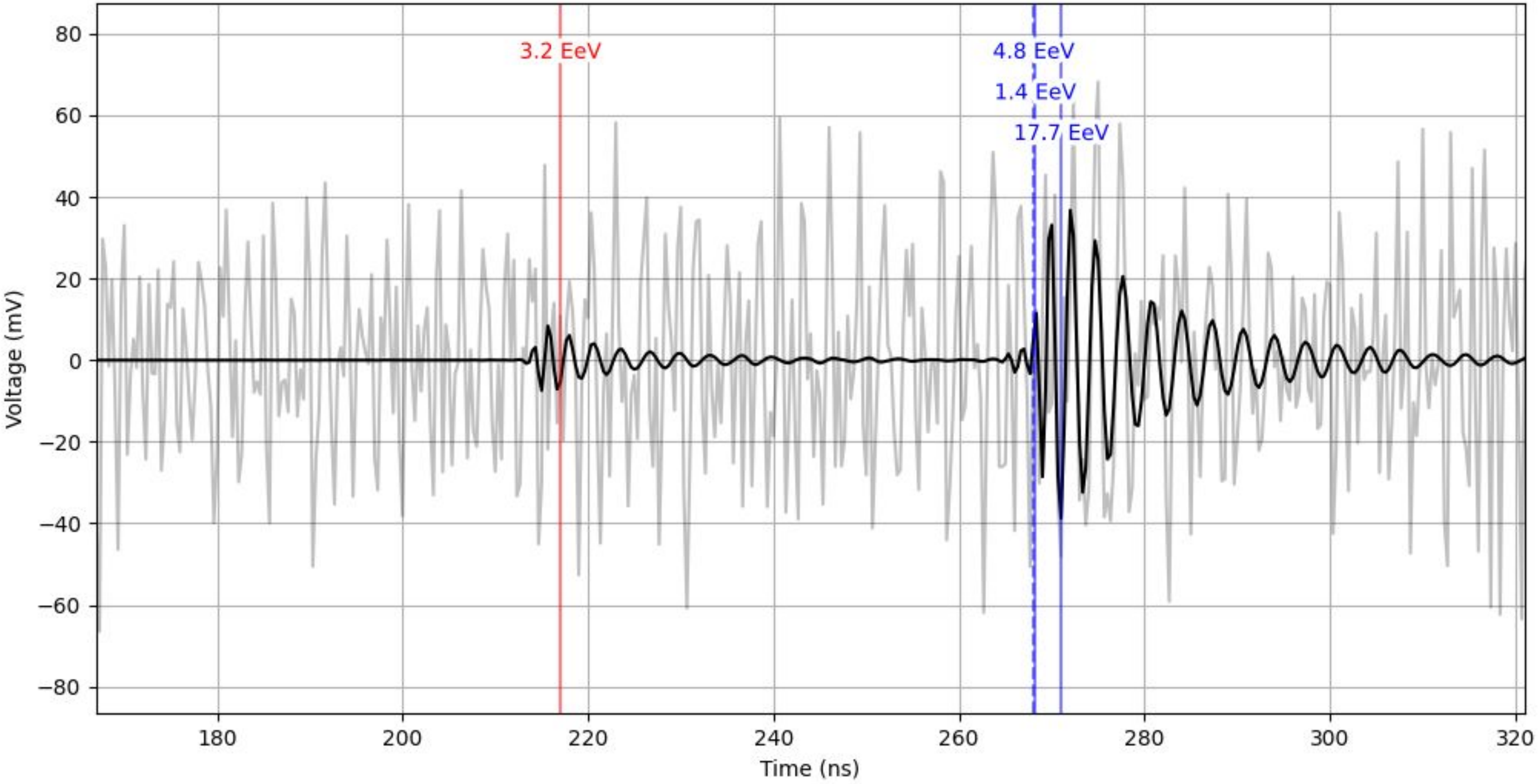


Example ν_μ Waveforms

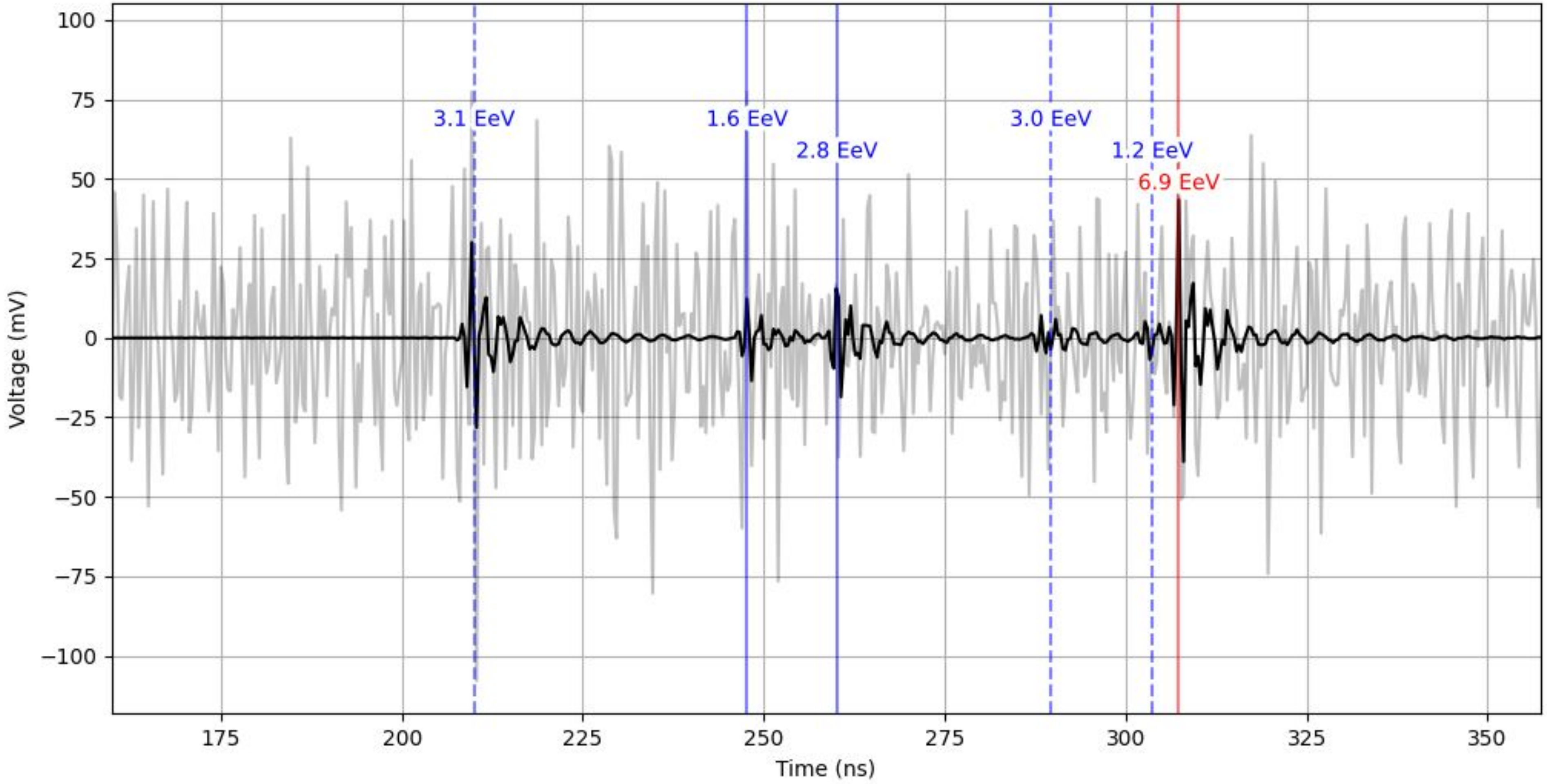
Example ν_μ Interactions (E_ν = 30EeV)



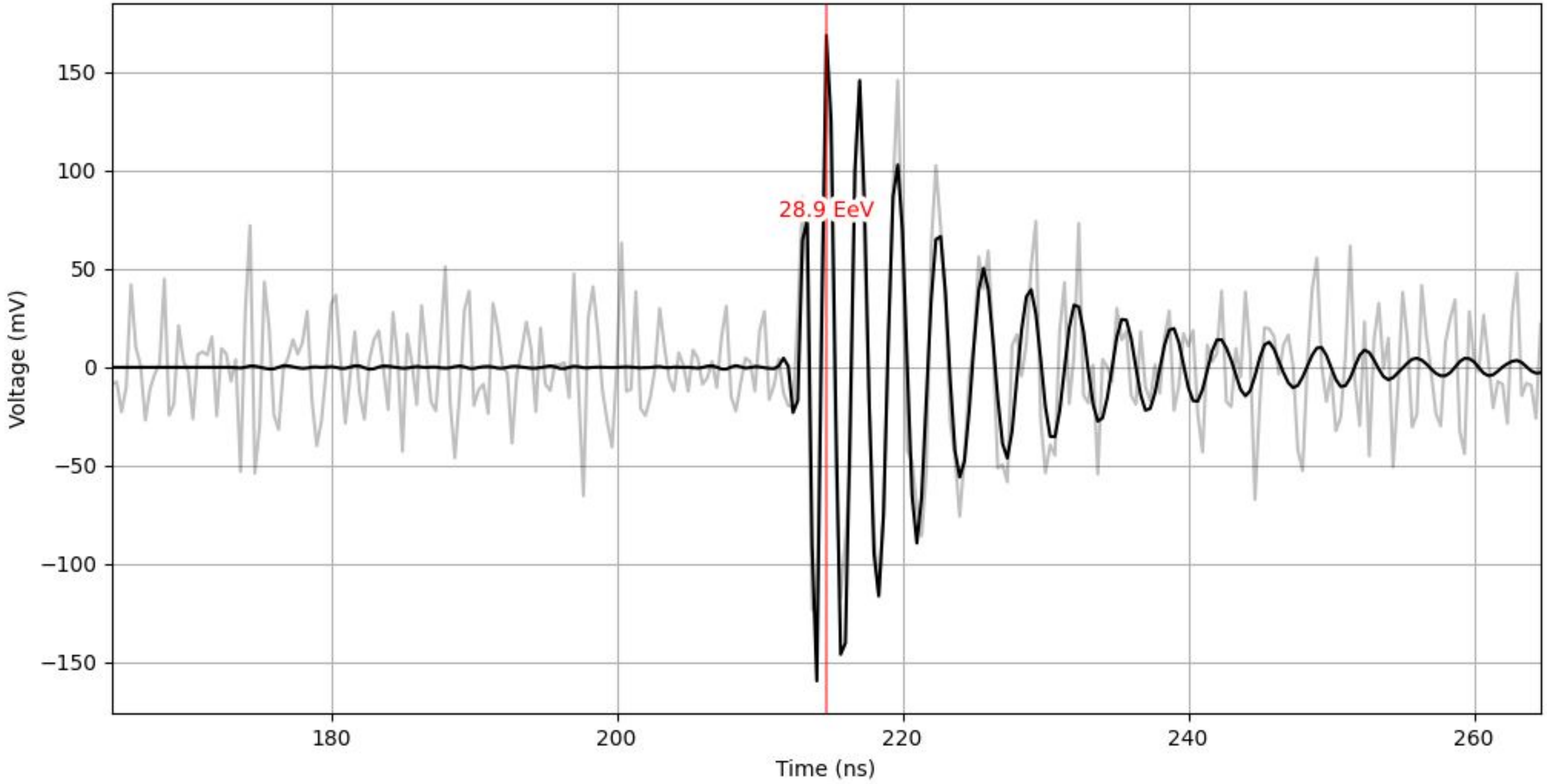
Example ν_μ Interactions (E_ν = 30EeV)



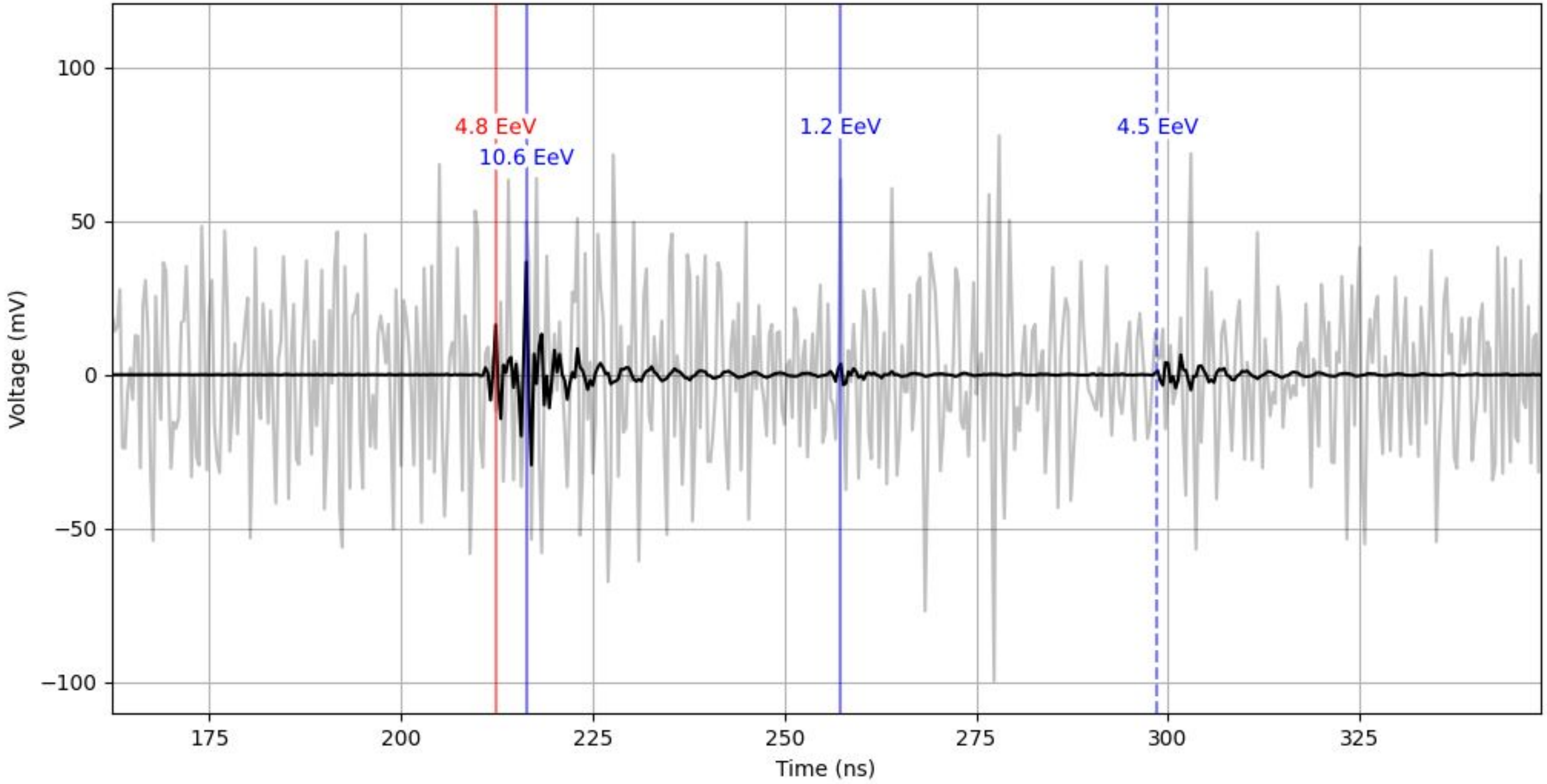
Example ν_μ Interactions (E_ν = 30EeV)



Example ν_μ Interactions (E_ν = 30EeV)

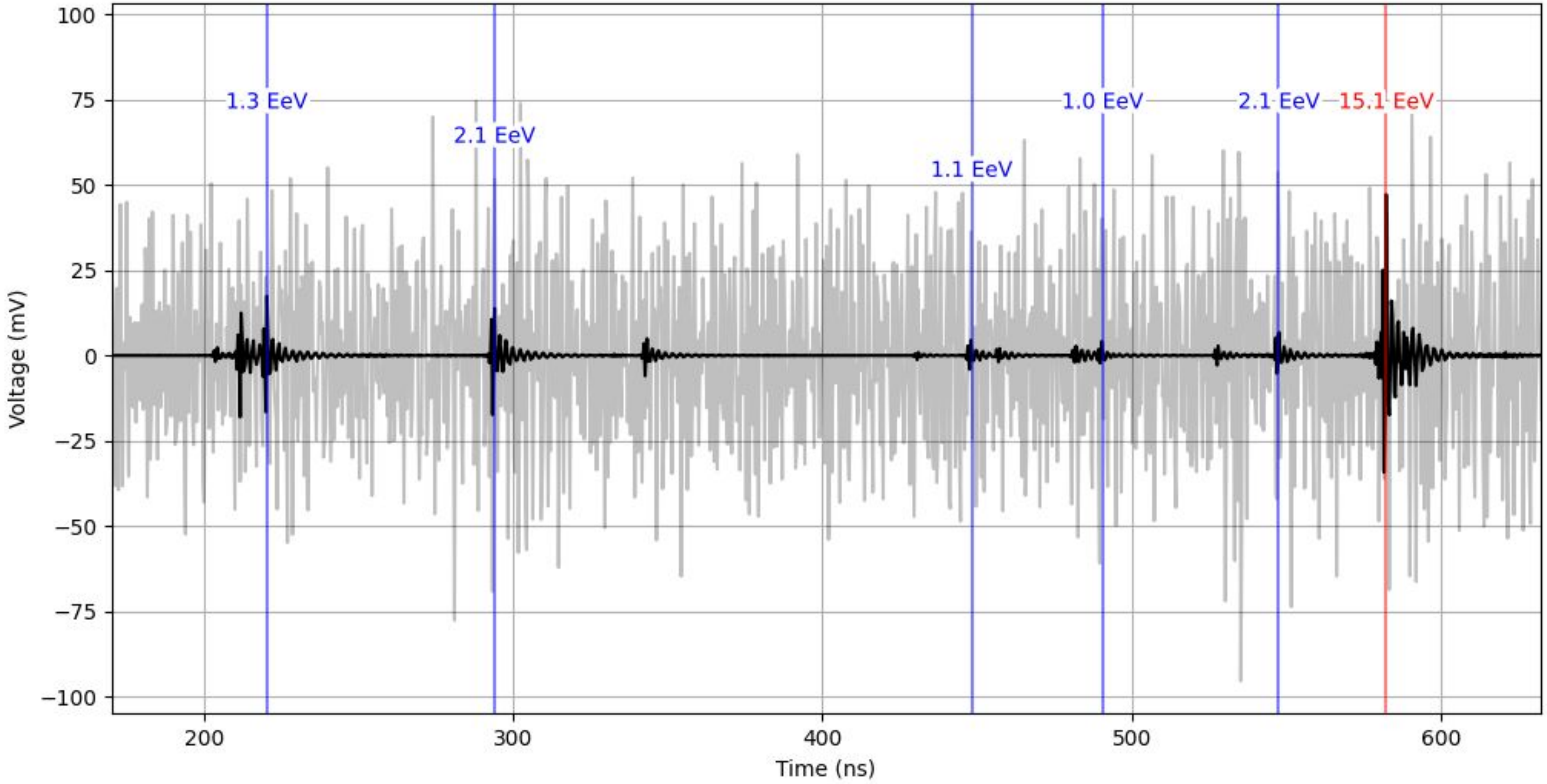


Example ν_μ Interactions (E_ν = 30EeV)

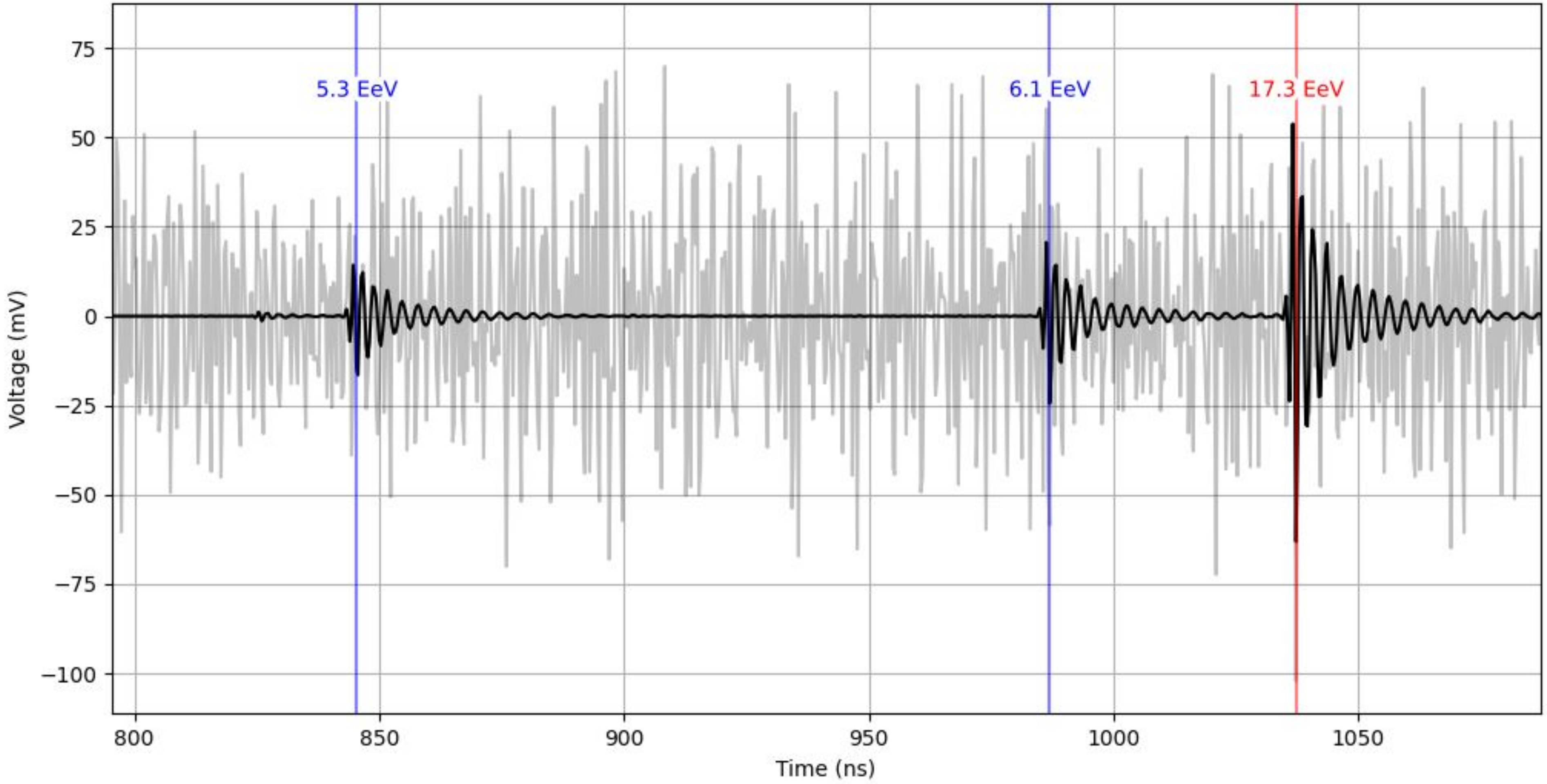


Example ν_τ Waveforms

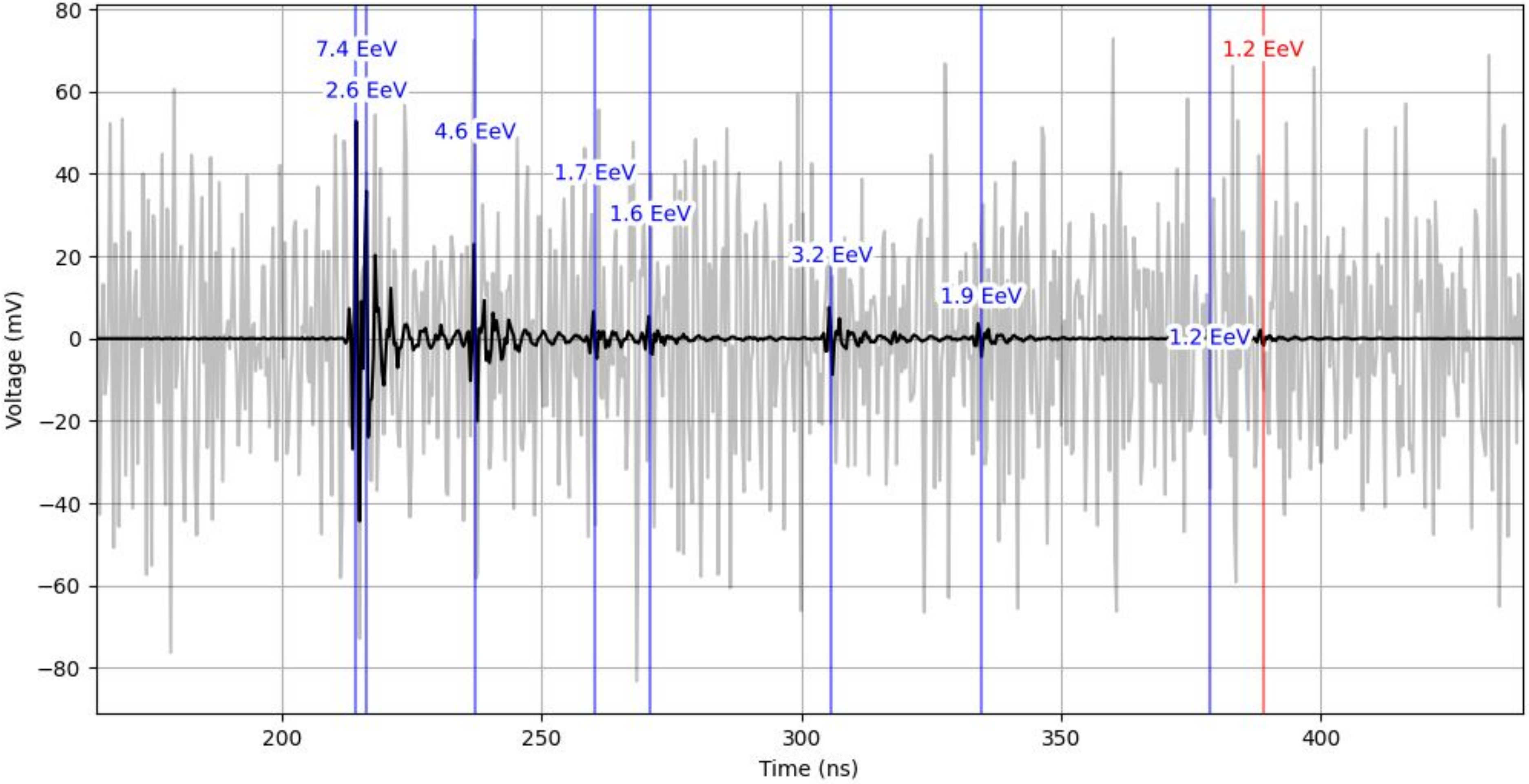
Example ν_τ Interactions (E_ν = 30EeV)



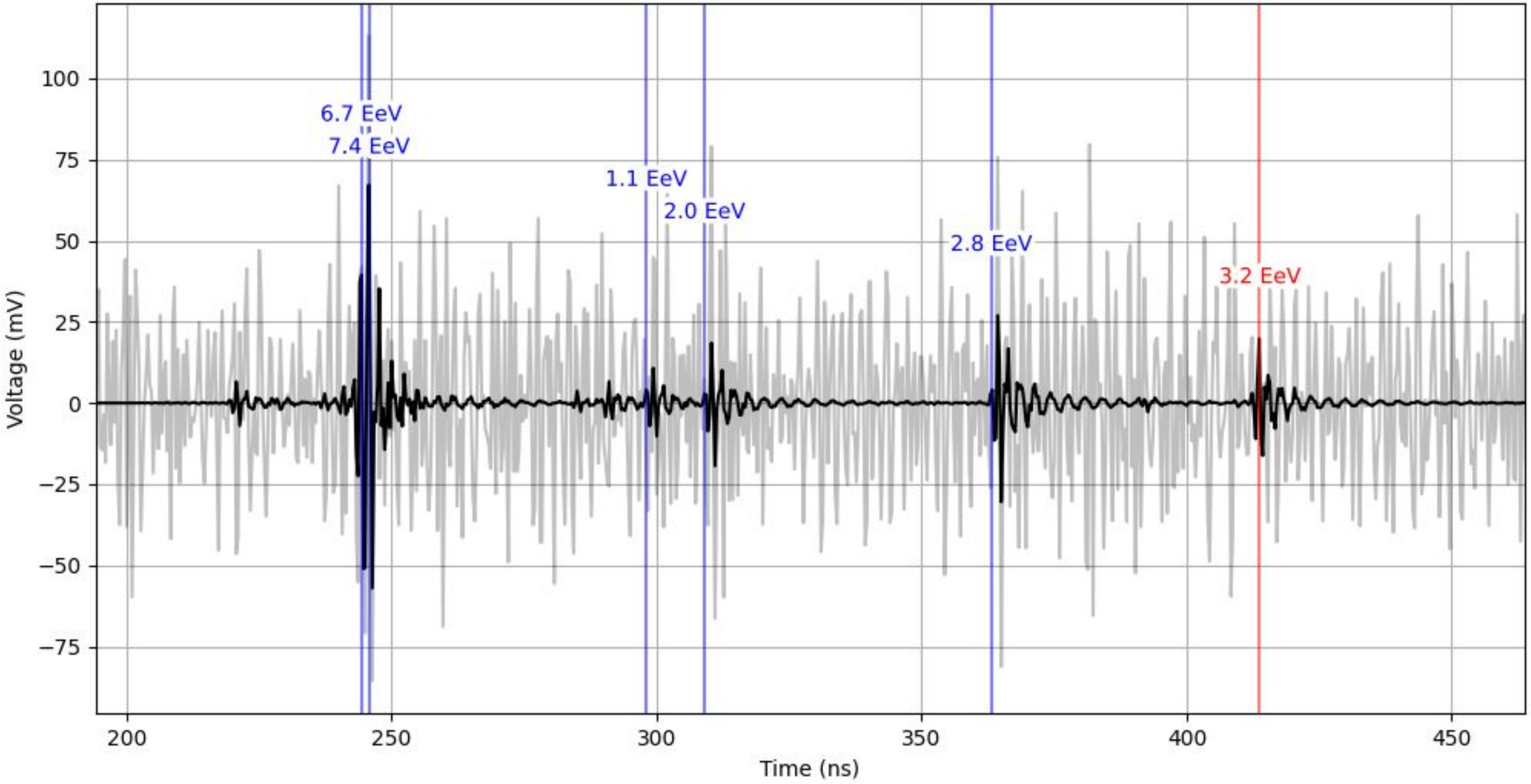
Example ν_τ Interactions (E_ν = 30EeV)



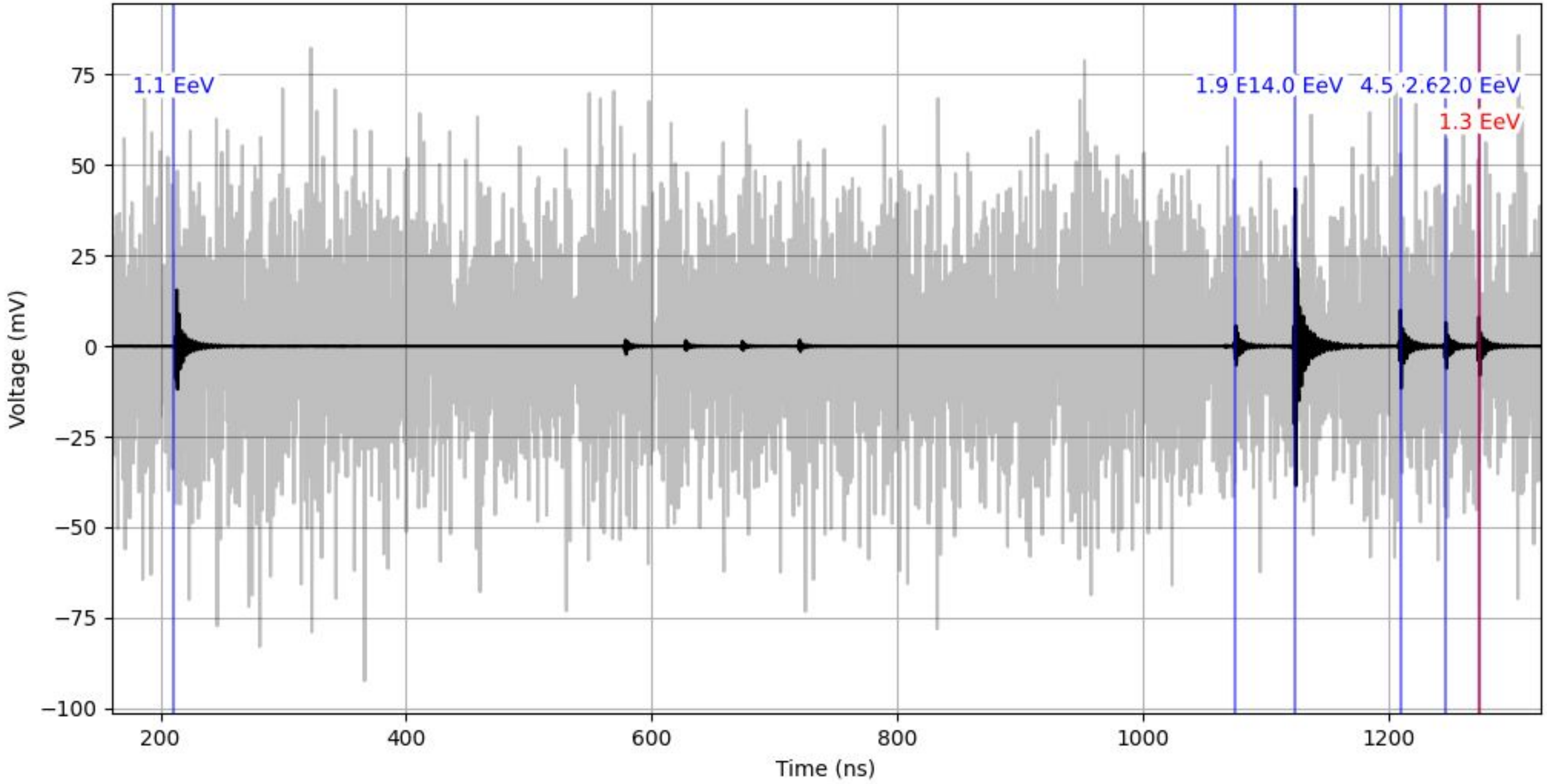
Example ν_τ Interactions (E_ν = 30EeV)



Example ν_τ Interactions (E_ν = 30EeV)



Example ν_τ Interactions (E_ν = 30EeV)



If you liked Jupiter, you’re going to love this

PennState

Ice Moon Orbiter

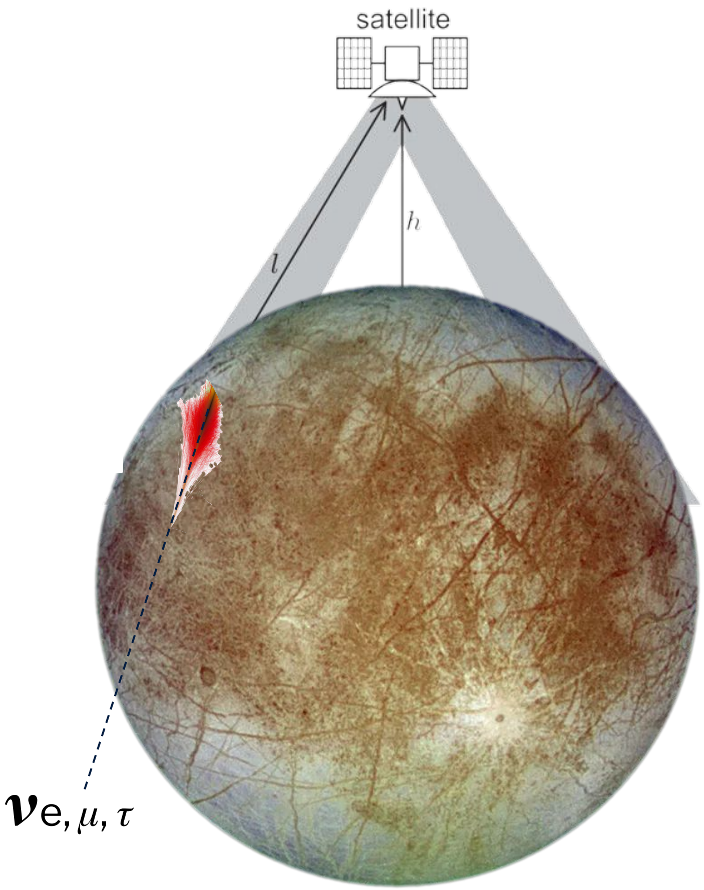
- Many candidate moons to choose from

Candidate Moon	Diameter (km)	Ice Thickness (km)	Atmosphere?	Orbitable?
Enceladus	500	20	No	Yes
Titan	5150	200	Yes	Yes
Europa	3100	20	Yes	Kinda
Triton	2700	>5	No	Yes

  - Current/future multiyear missions to visit these moons:
    - Europe Clipper (launched October 2024)
    - JUICE (launched April 2023)
    - Enceladus Orbiter/Lander (proposed 2040)

- Sensitive to all flavors
  - Flavor identification from multi-pulse events and structure

- Peak sensitivity ~EeV-10EeV
  - Compensates by having huge collection area
  - May be pushed down by beamforming techniques/low backgrounds
  - Potentially longer attenuation lengths in methane/dry ice

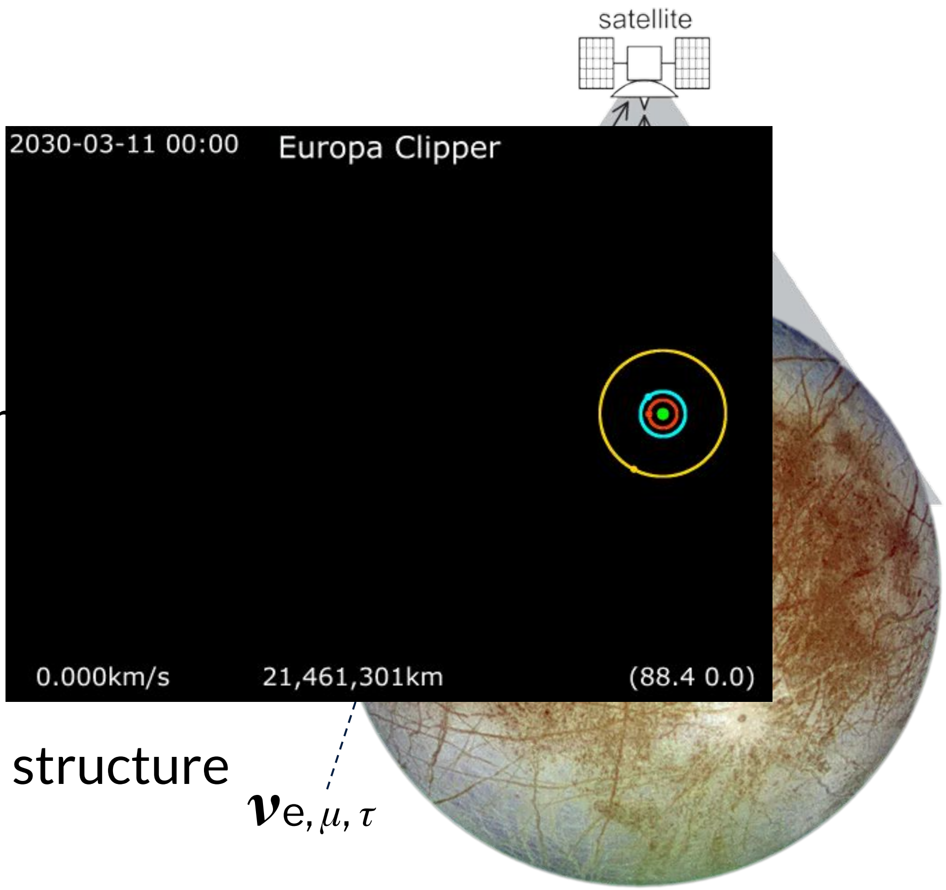


Ice Moon Orbiter

- Many candidate moons to choose from

Candidate Moon	Diameter (km)	Ice Thickness (km)	Atmosphere?	Orbitable?
Enceladus	500	20	No	Yes
Titan	5150	200	Yes	Yes
Europa	3100	20	Yes	Kinda
Triton	2700	>5	No	Yes

  - Current/future multiyear missions to visit these
    - Europe Clipper (launched October 2024)
    - JUICE (launched April 2023)
    - Enceladus Orbiter/Lander (proposed 2040)



- Sensitive to all flavors
  - Flavor identification from multi-pulse events and structure

- Peak sensitivity ~EeV-10EeV
  - Compensates by having huge collection area
  - May be pushed down by beamforming techniques/low backgrounds
  - Potentially longer attenuation lengths in methane/dry ice

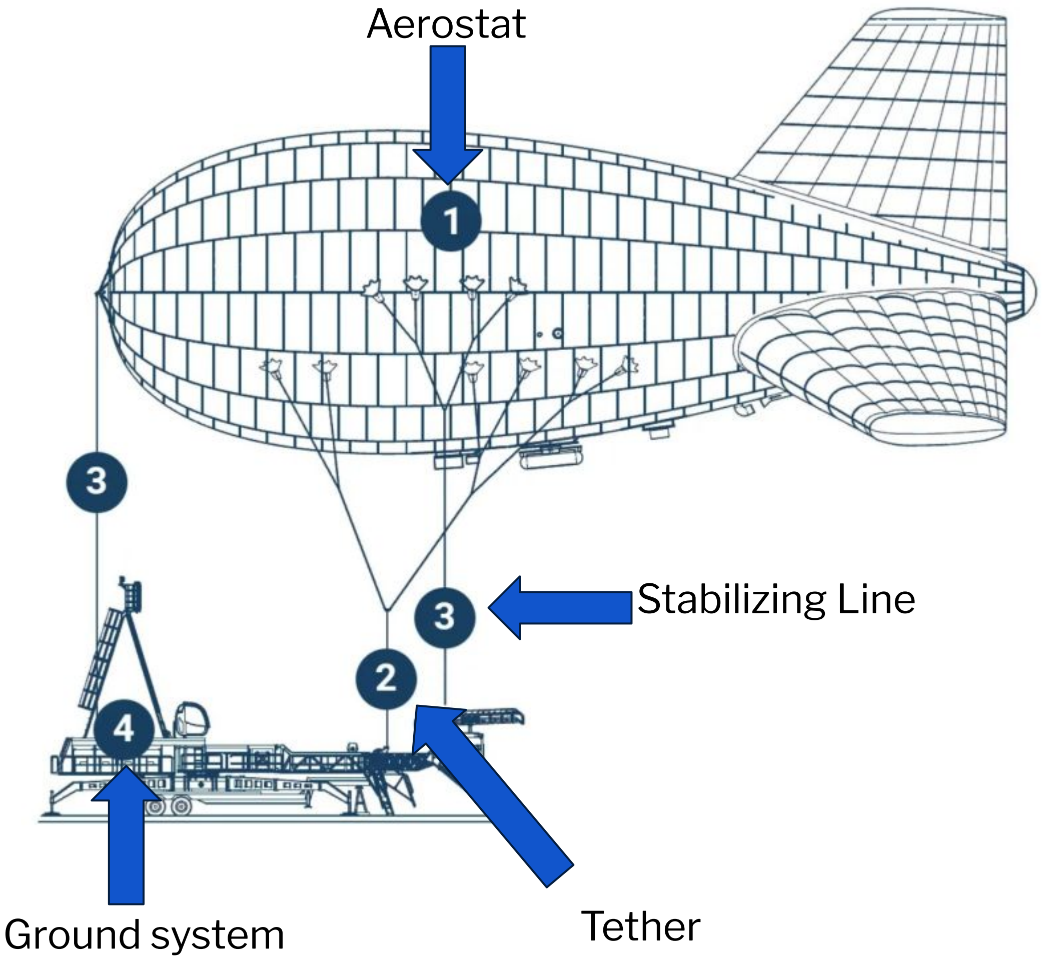
Okay, but what do I think is actually possible?

PennState

Tethered Balloons

- Concept: a more permanent high-altitude Askaryan detector over ice ala PUEO
  - Sweet spot: a lot of target area & >30d of time

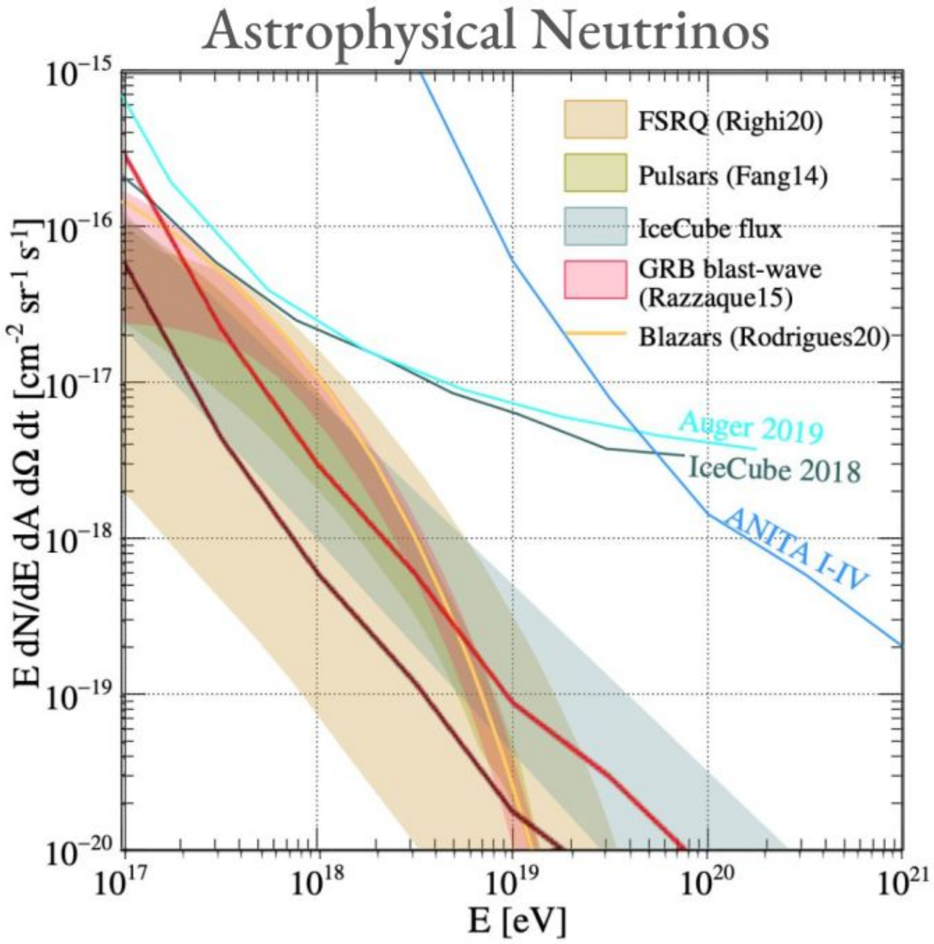
- Mission characteristics:
  - Max float altitude: 10km
  - Weight limit: 300kg (includes power)
  - Expected float time ~weeks, and must be grounded in high winds
  - O($10M/aerostat)
  - Straightforward extension to multiple stations



*Idea and work by R. Scrandis and C. Deaconu

Tethered Balloons

- Concept: a more permanent high-altitude Askaryan detector over ice ala PUEO
    - Sweet spot: a lot of target area & >30d of time
- Mission characteristics:
    - Max float altitude: 10km
    - Weight limit: 300kg (includes power)
    - Expected float time ~weeks, and must be grounded in high winds
    - *O*($10M/aerostat)
    - Straightforward extension to multiple stations
- With 1yr of total flight time, would set the best limits on UHE neutrinos to date



*Idea and work by R. Scrandis and C. Deaconu

But actually, my favorite idea

Mountaintop radio detection!

Mountaintop radio detection!

... just on an Antarctic mountain

PennState

No, seriously!

- Transantarctic mountains span a large portion of the continent

No, seriously!

- Transantarctic mountains span a large portion of the continent

- Requirements:

No, seriously!

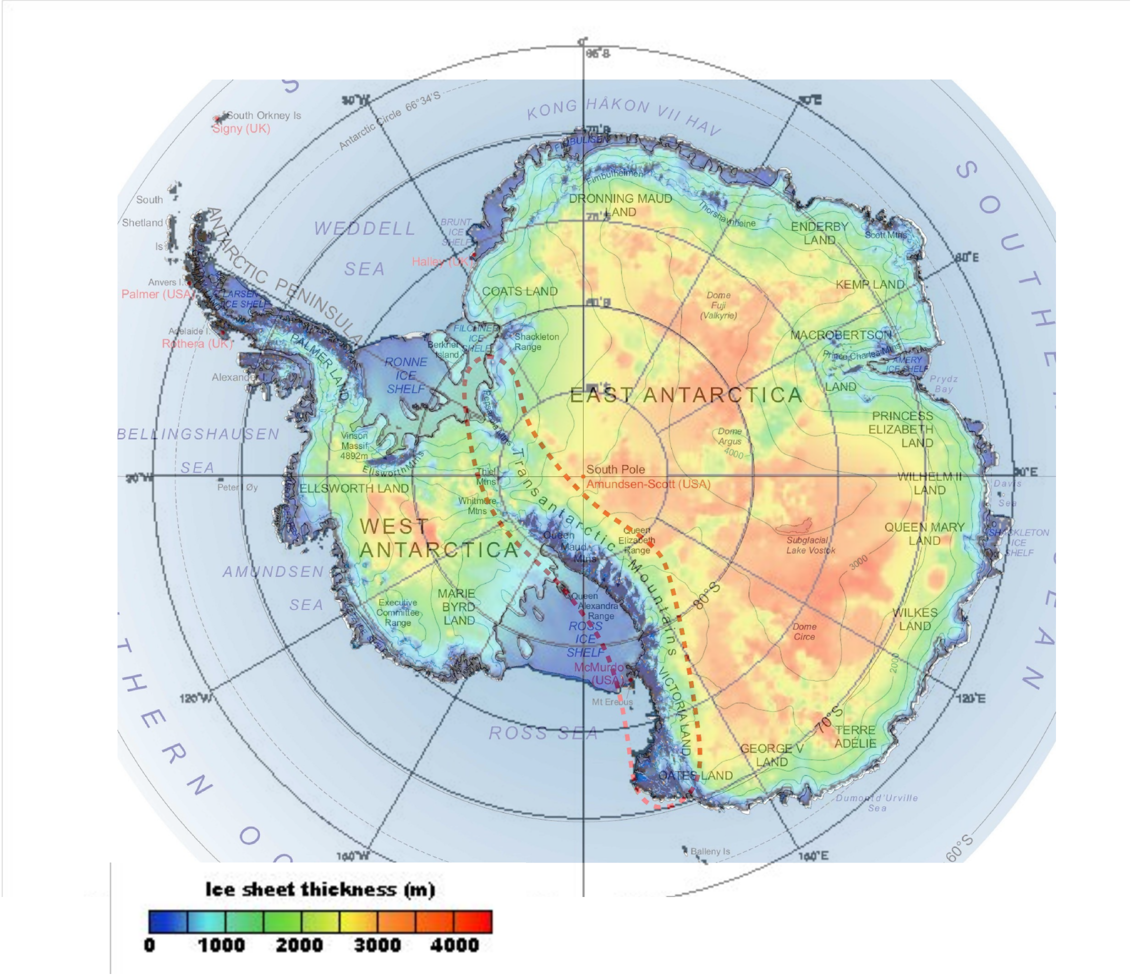
- Transantarctic mountains span a large portion of the continent

- Requirements:
  - Deep ice

No, seriously!

- Transantarctic mountains span a large portion of the continent

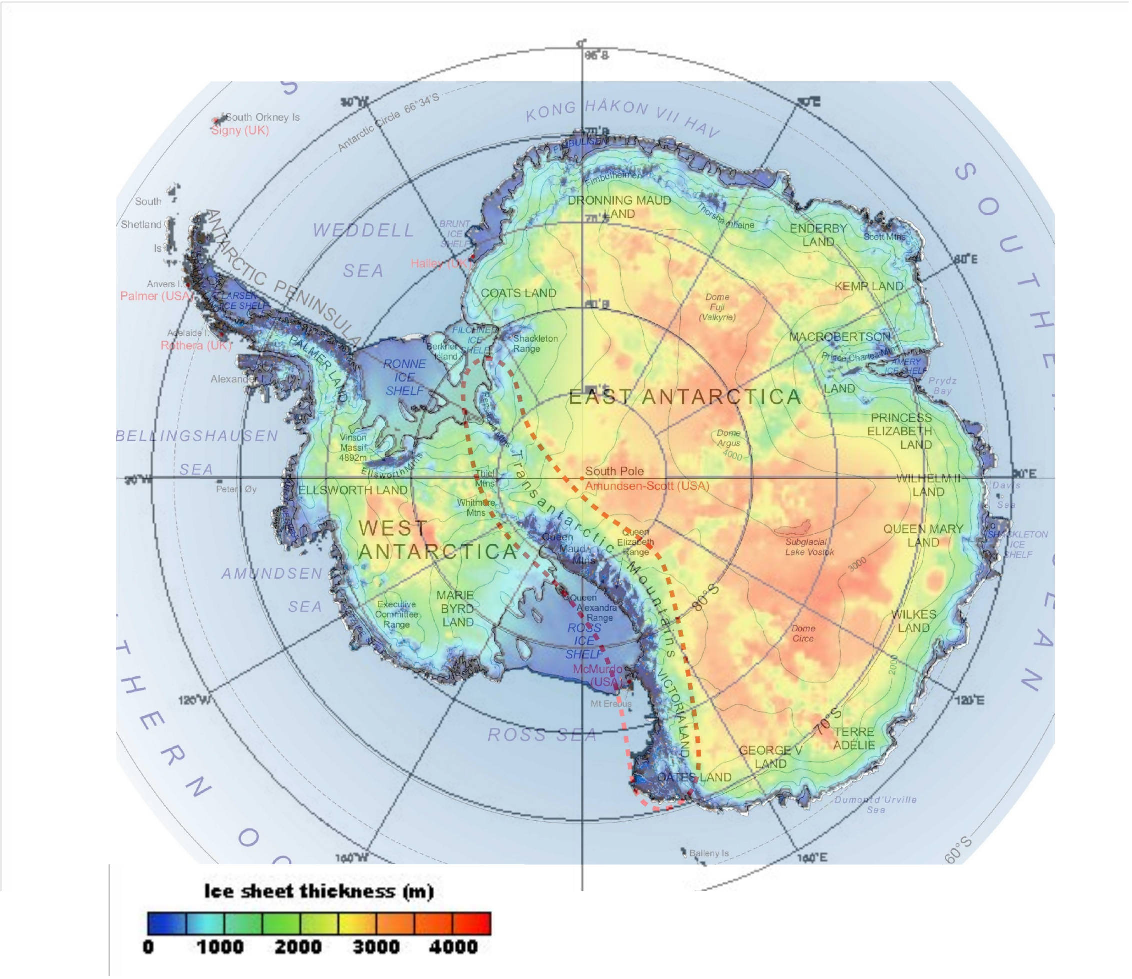
- Requirements:
  - Deep ice
    - Many, many locations with d>2km



No, seriously!

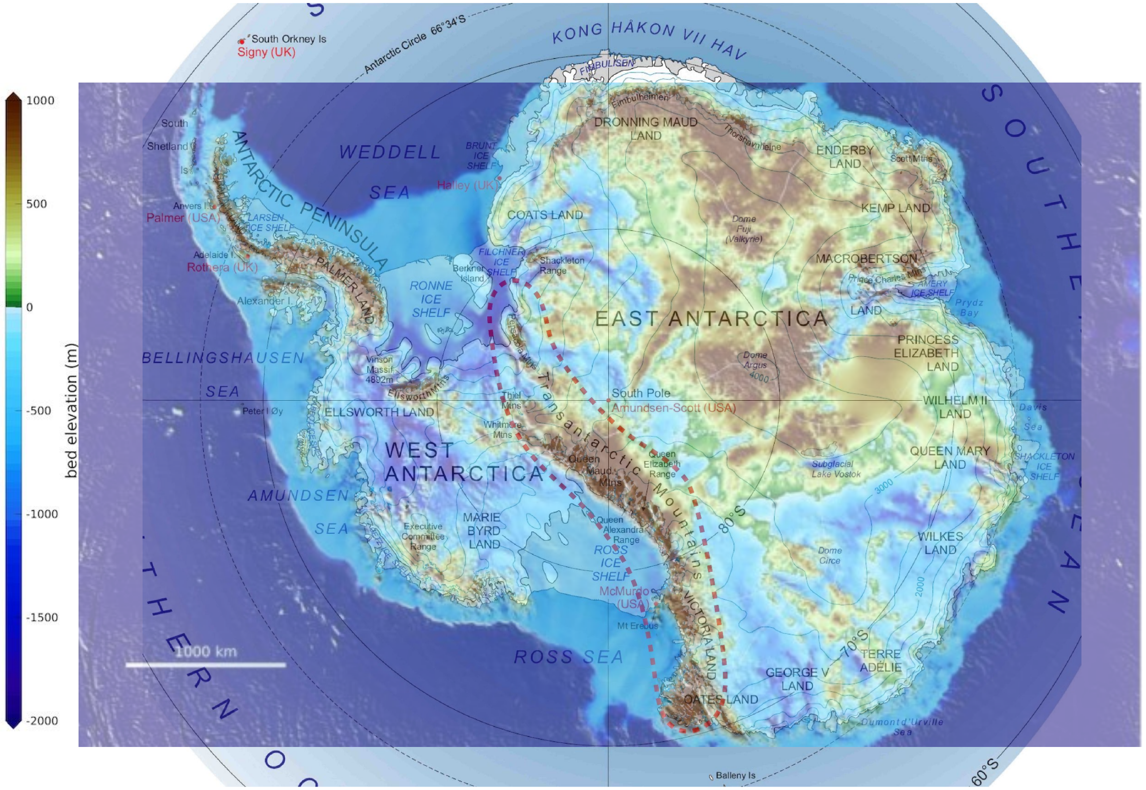
- Transantarctic mountains span a large portion of the continent

- Requirements:
  - Deep ice
    - Many, many locations with d>2km
  - High altitude OVER deep ice



No, seriously!

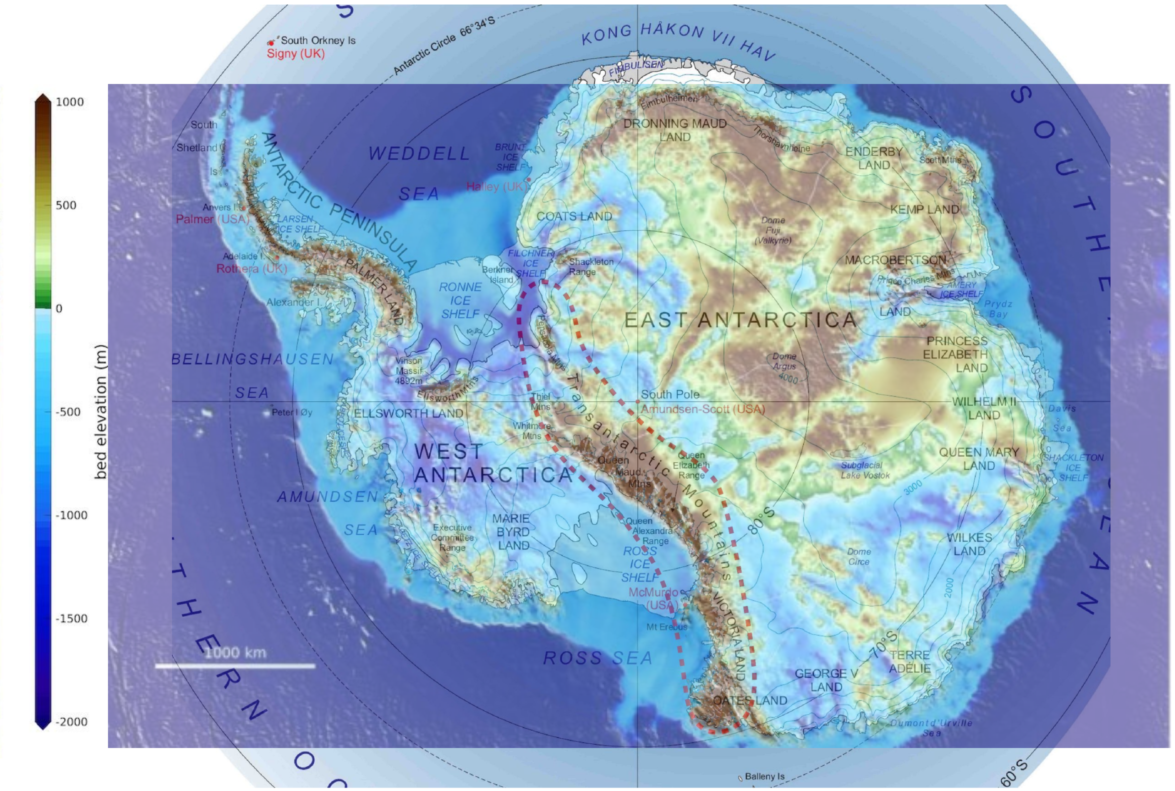
- Transantarctic mountains span a large portion of the continent
- Requirements:
  - Deep ice
    - Many, many locations with d>2km
  - High altitude OVER deep ice



No, seriously!

- Transantarctic mountains span a large portion of the continent

- Requirements:
  - Deep ice
    - Many, many locations with d>2km
  - High altitude OVER deep ice
    - Southern & central have sites with Δh ~ 1.5km
    - West & Peninsula hav sites with Δh ~ 2.5km

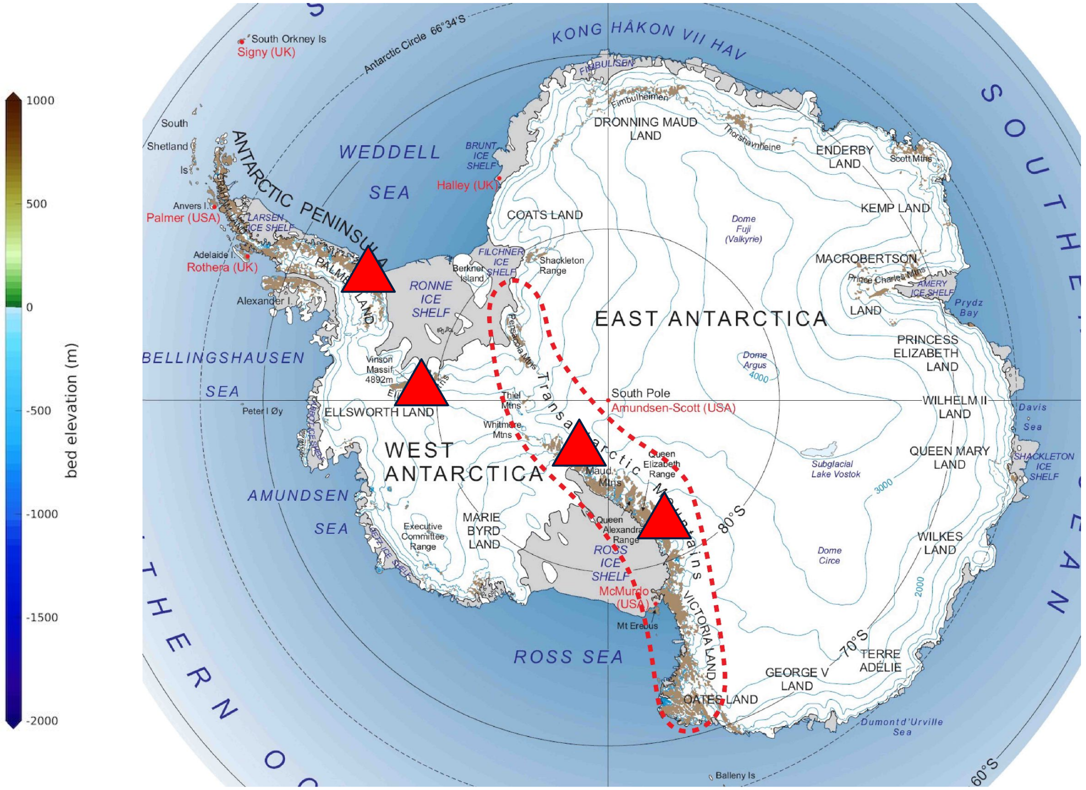


No, seriously!

- Transantarctic mountains span a large portion of the continent

- Requirements:
  - Deep ice
    - Many, many locations with d>2km
  - High altitude OVER deep ice
    - Southern & central have sites with Δh ~ 1.5km
    - West & Peninsula hav sites with Δh ~ 2.5km

- Pros:
  - Askaryan (more events, flavor), long runtime, it’s cool

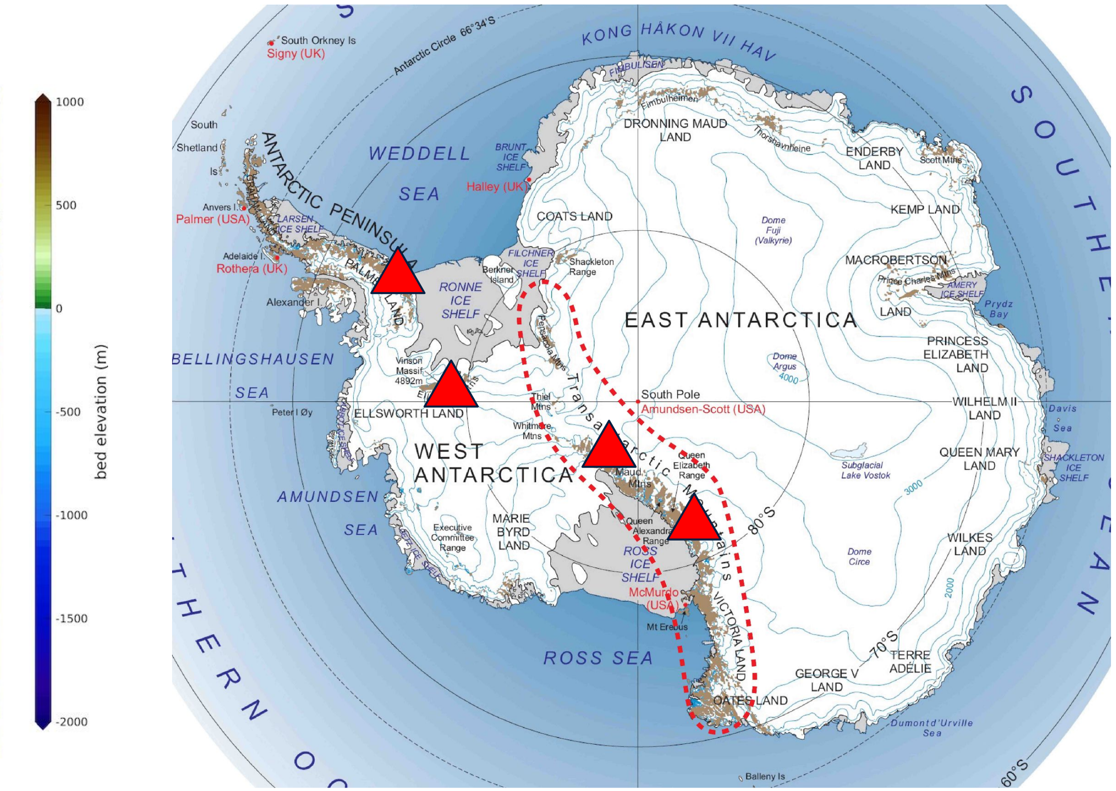


No, seriously!

- Transantarctic mountains span a large portion of the continent

- Requirements:
  - Deep ice
    - Many, many locations with d>2km
  - High altitude OVER deep ice
    - Southern & central have sites with Δh ~ 1.5km
    - West & Peninsula hav sites with Δh ~ 2.5km

- Pros:
  - Askaryan (events, flavor), runtime, heritage, cool



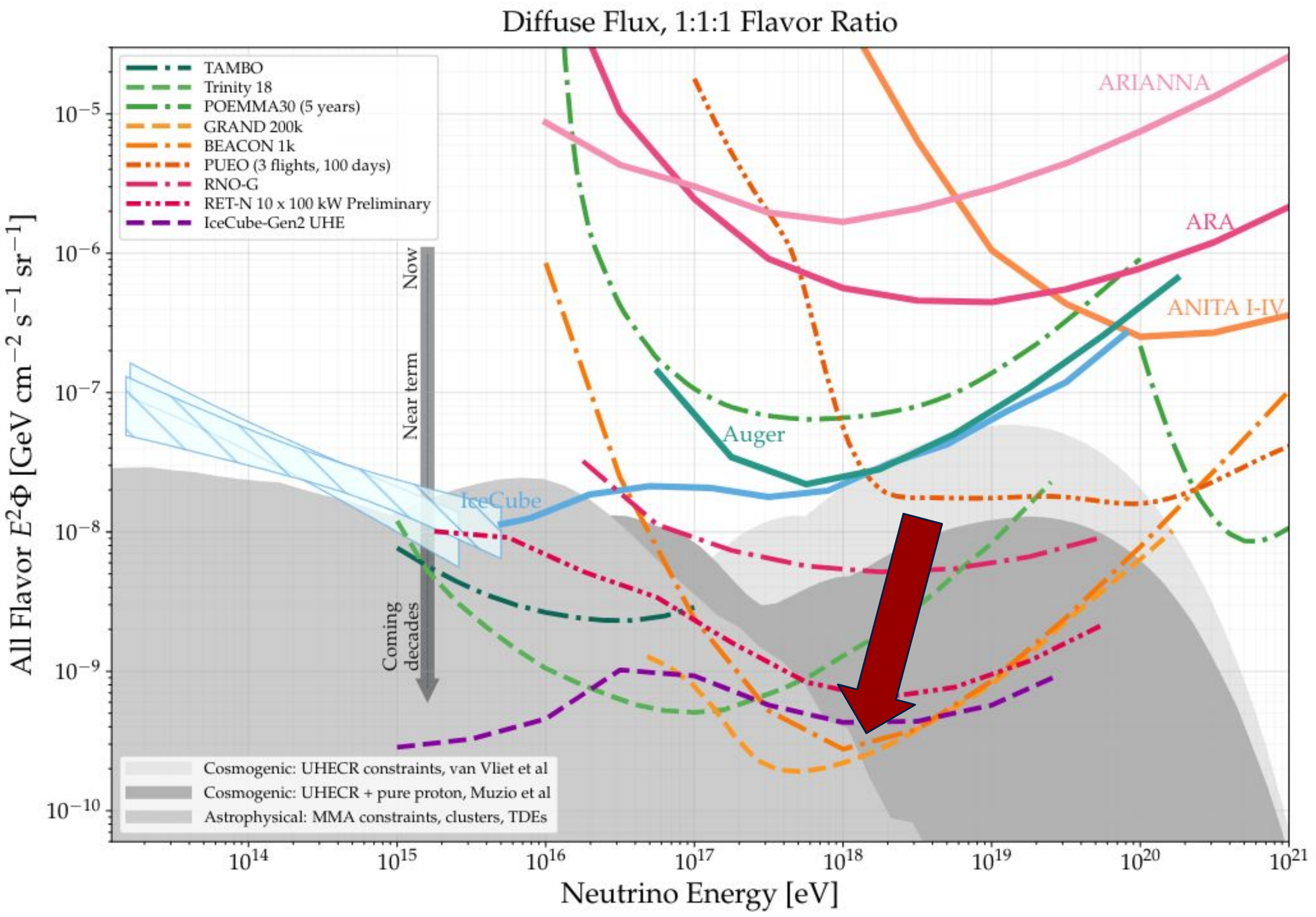
- *Cons:*
  - *Deployment, power, durability*

No, seriously!

- Transantarctic mountains span a large portion of the continent

- Requirements:
  - Deep ice
    - Many, many locations with d>2km
  - High altitude OVER deep ice
    - Southern & central have sites with Δh ~ 1.5km
    - West & Peninsula hav sites with Δh ~ 2.5km

- Pros:
  - Askaryan (events, flavor), runtime, heritage, cool



- *Cons:*
  - *Deployment, power, durability*

Anyone else have any ideas?