Experimental Overview: Natural Sources

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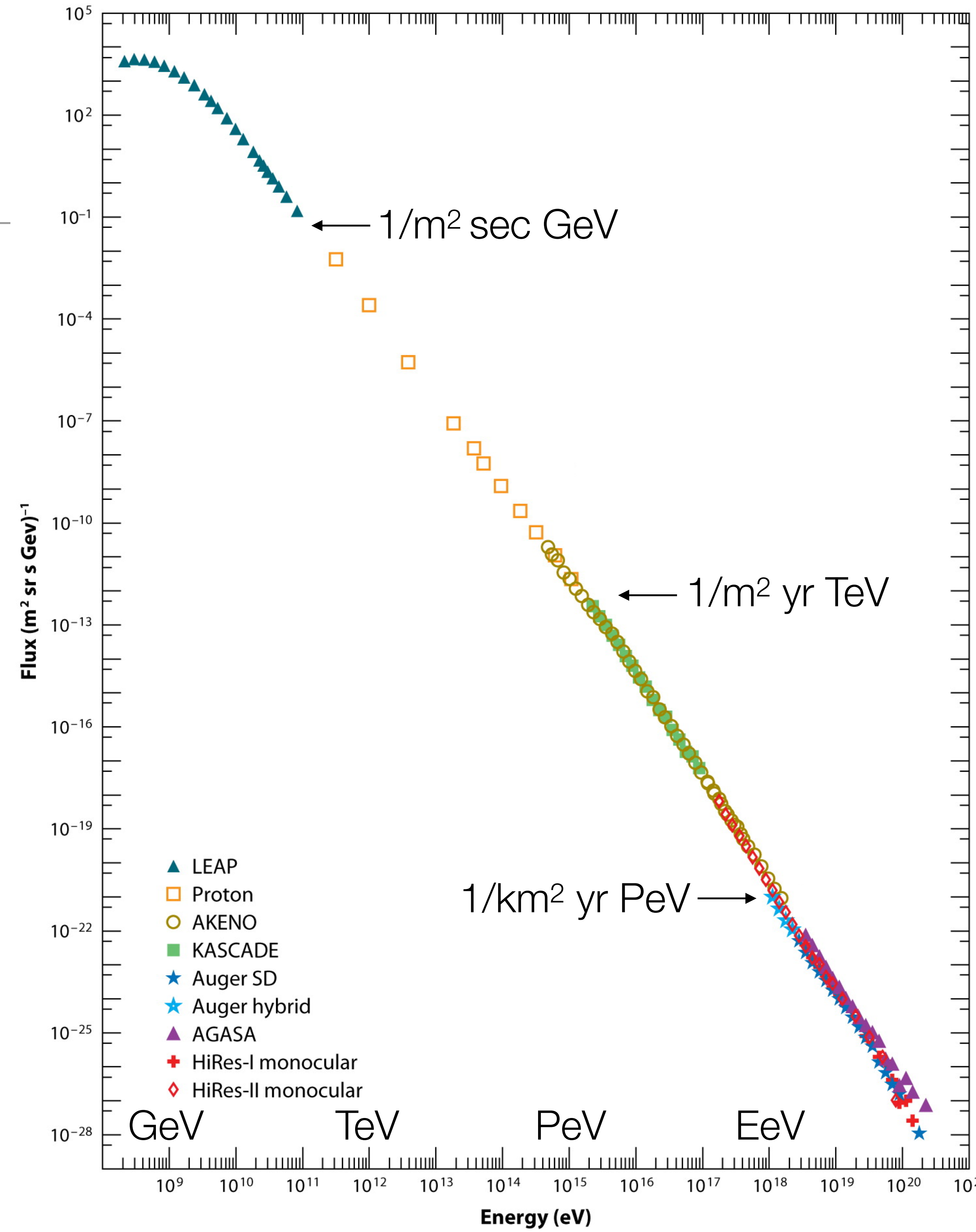
Tau Neutrinos from GeV to EeV 2021
September 28, 2021

Outline

- Production of tau neutrinos in natural sources
- GeV: atmospheric appearance
  - Terrestrial oscillations
  - ν_τ signatures at low energy
- PeV: neutrino telescopes
  - Cosmological oscillations
  - ν_τ signatures at high energy
- EeV: Earth-skimming neutrinos

Natural ν_τ Sources

- Natural sources produce ν_τ the same way we do: start by accelerating hadrons (cosmic rays) into a target
  - Target may be local to the source (astrophysical ν_τ) or here at Earth (atmospheric)
- Natural accelerators provide a *very* broad beam
  - Access to much greater energies (and baselines) than artificial sources
  - Steeply falling cosmic ray spectrum → trade-off between energy and rate



Beatty JJ, Westerhoff S. 2009.
Annu. Rev. Nucl. Part. Sci. 59:319–45

Neutrino Production

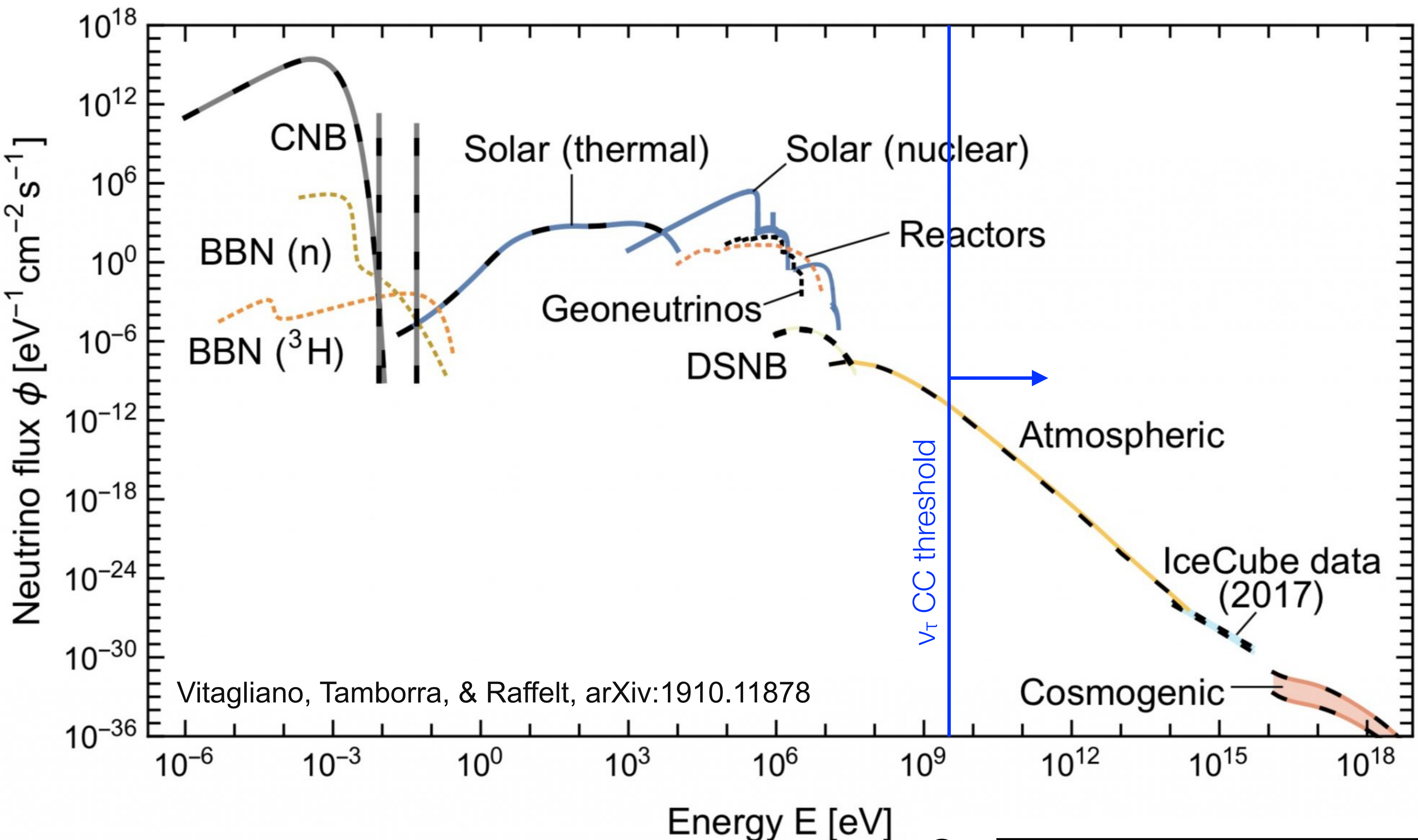
- Wherever and however accelerated, hadrons produce neutrinos via meson decay when they interact with matter or radiation, e.g.:

$$p + p \to \pi^{\pm} + X \qquad\qquad p + \gamma \to \Delta^{+} \to \pi^{+} + n$$

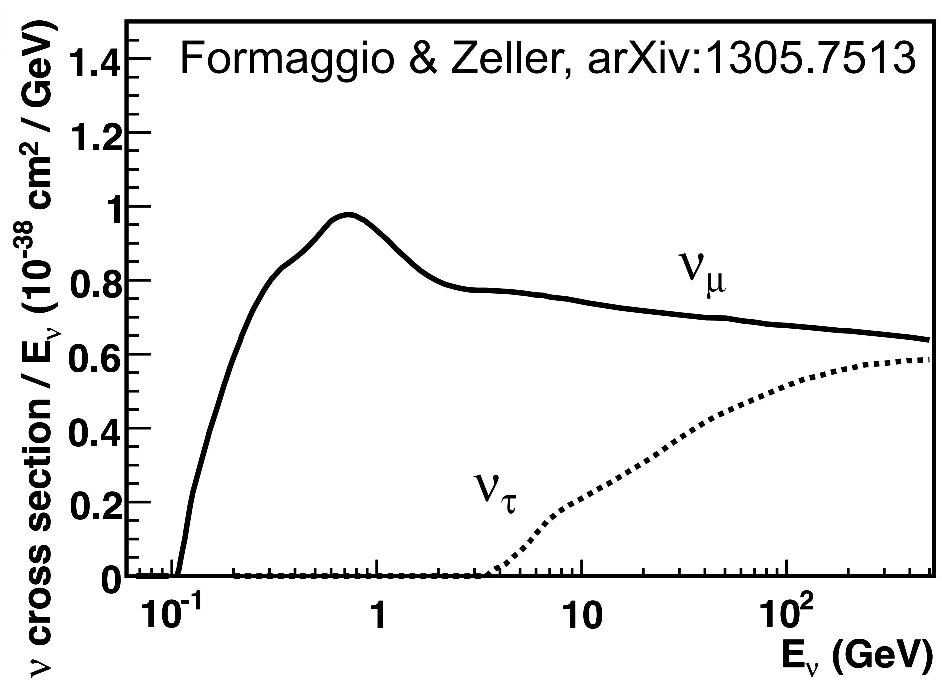
$$\pi^{+} \to \mu^{+} + \nu_{\mu}$$

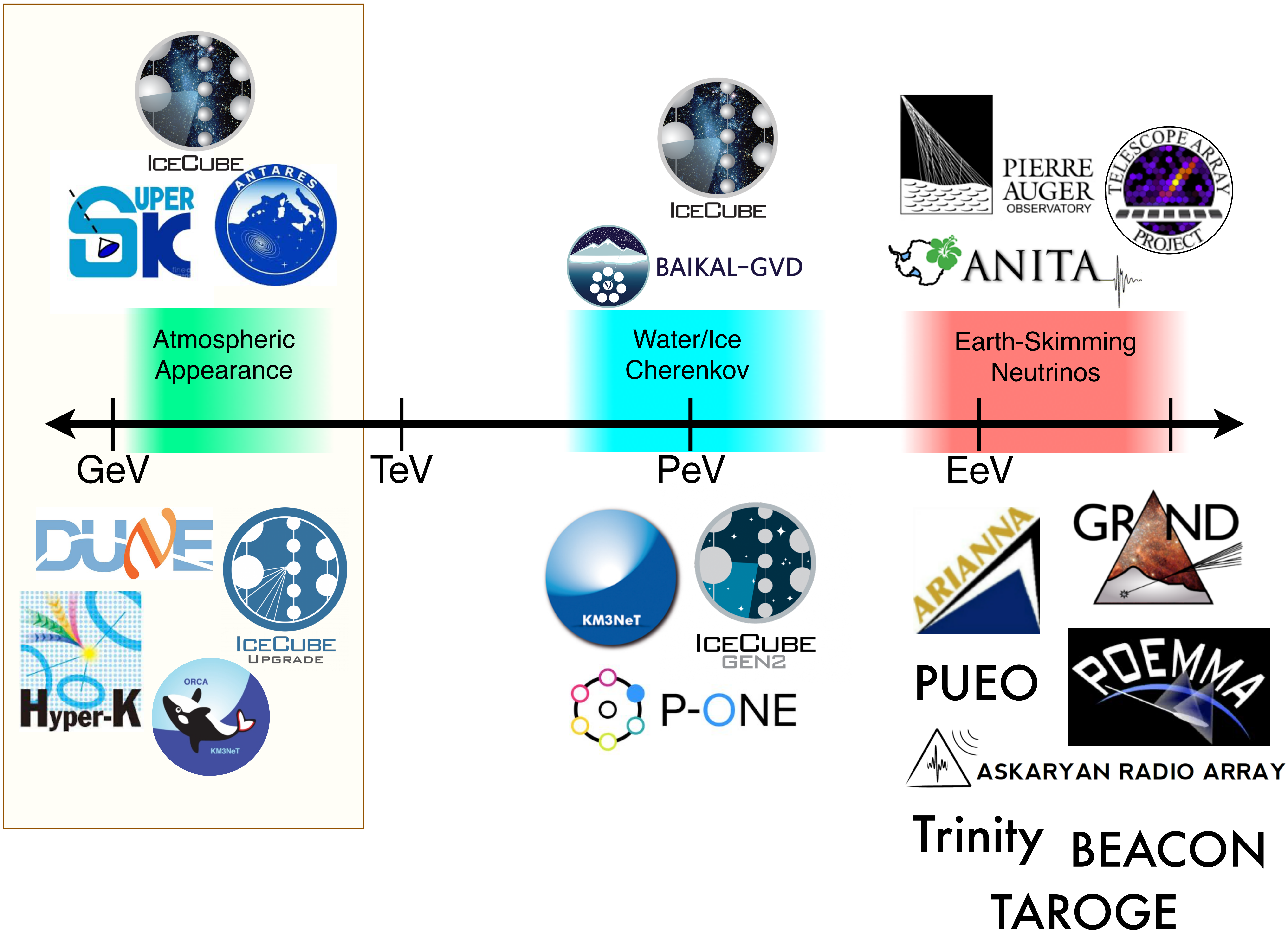
$$\mu^{+} \to e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

- Flavor ratio at production is generically $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, although this can be modified by local conditions
    - ν and $\bar{\nu}$ not distinguished by these detectors; I will use them interchangeably
    - Neutrinos are predominantly from pion and kaon decay (also 1 : 2 : 0), although heavier mesons (e.g. $D^{\pm}$, D^0, D_s, Λ_c) produce a few ν_τ directly
- Very small intrinsic tau neutrino flux; appear due to flavor oscillations



- Neutrino flux falls steeply above MeV scale, $\sigma_{\nu N}$ increases but only ~linearly with E_ν
- Low energy ν_τ CC cross section suppressed by τ lepton mass effects
  - Production threshold 3.5 GeV, but significant kinematic suppression until at least 100 GeV




IceCube
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Atmospheric Appearance
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IceCube Gen2
P-ONE
ARIANNA
GRAND
PUEO
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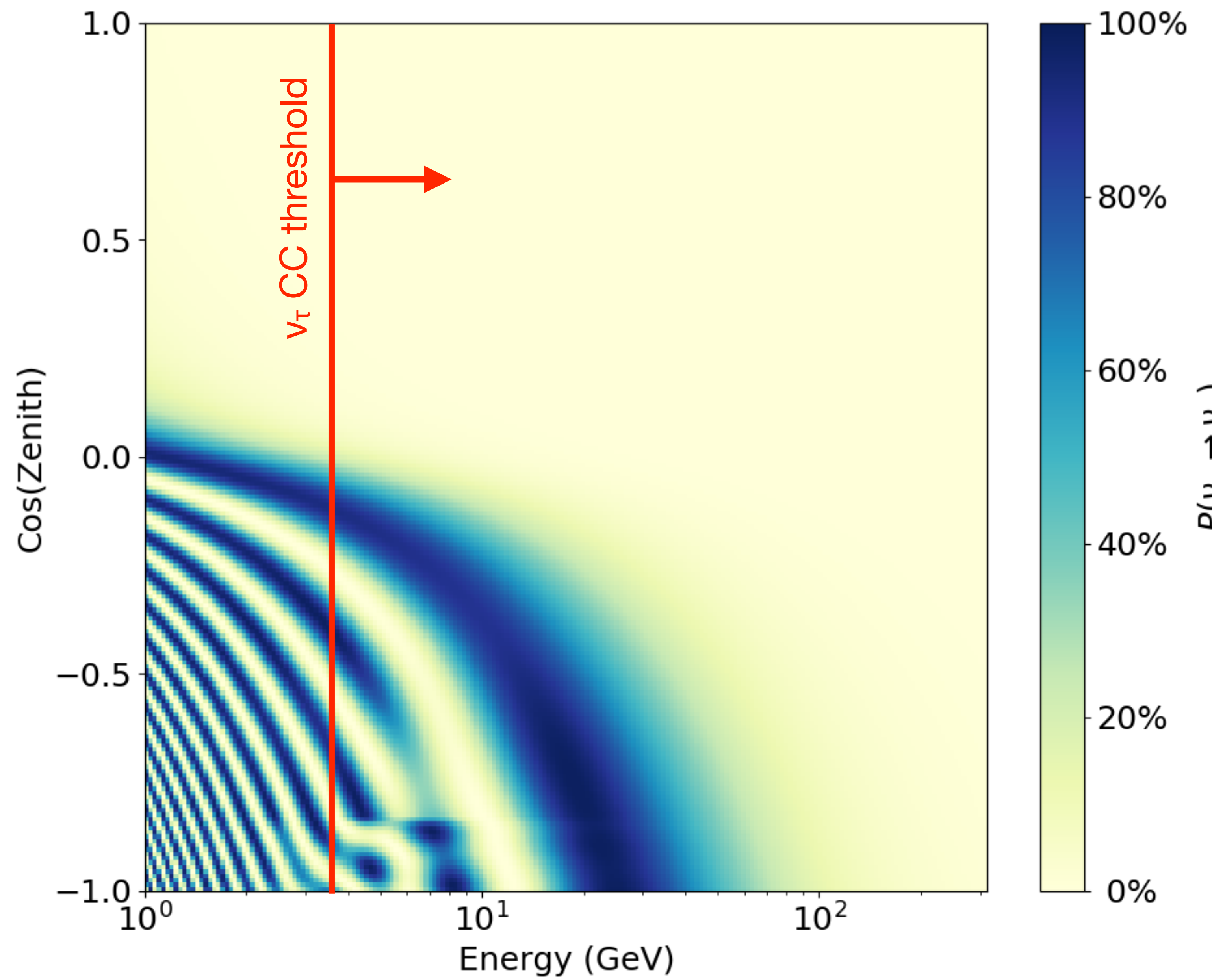
ASKARYAN RADIO ARRAY
Trinity
BEACON
TAROGE

Short Baseline Oscillations

- Atmos. flavor ratio rises with E_ν to $\nu_e : \nu_\mu : \nu_\tau = 1 : 10 : 0$
  - Muons reach ground before decaying, suppressing ν_e flux
- For atmospheric ν_τ, max baseline is only ~13,000 km
  - Essentially two-flavor $\nu_\mu \to \nu_\tau$ oscillations, first maximum at 25 GeV for longest baseline
- Competition between falling spectrum and rising interaction cross section



  - Even at 25 GeV, ν_τ CC cross section is only 40% of ν_μ CC, due to τ mass effect

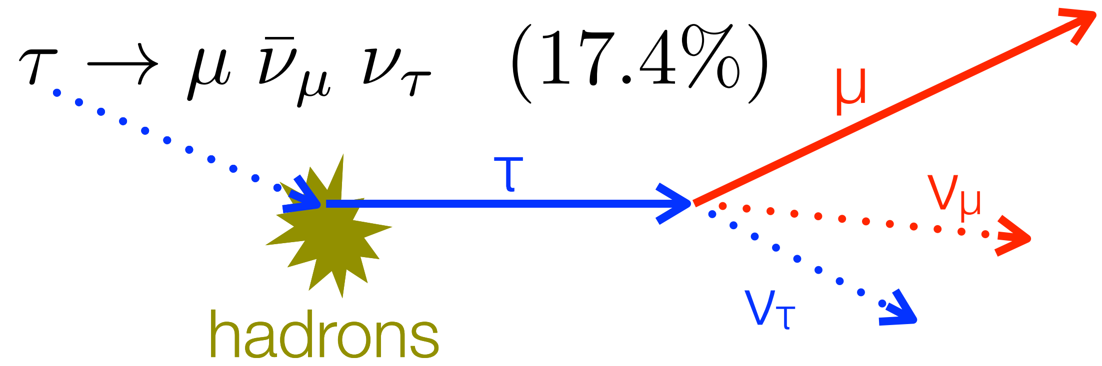
Tau Neutrino Signatures: Low Energy

- Hadronic shower at $\nu_\tau N$ interaction vertex
- τ lepton produces a track similar to a muon, then decays in flight

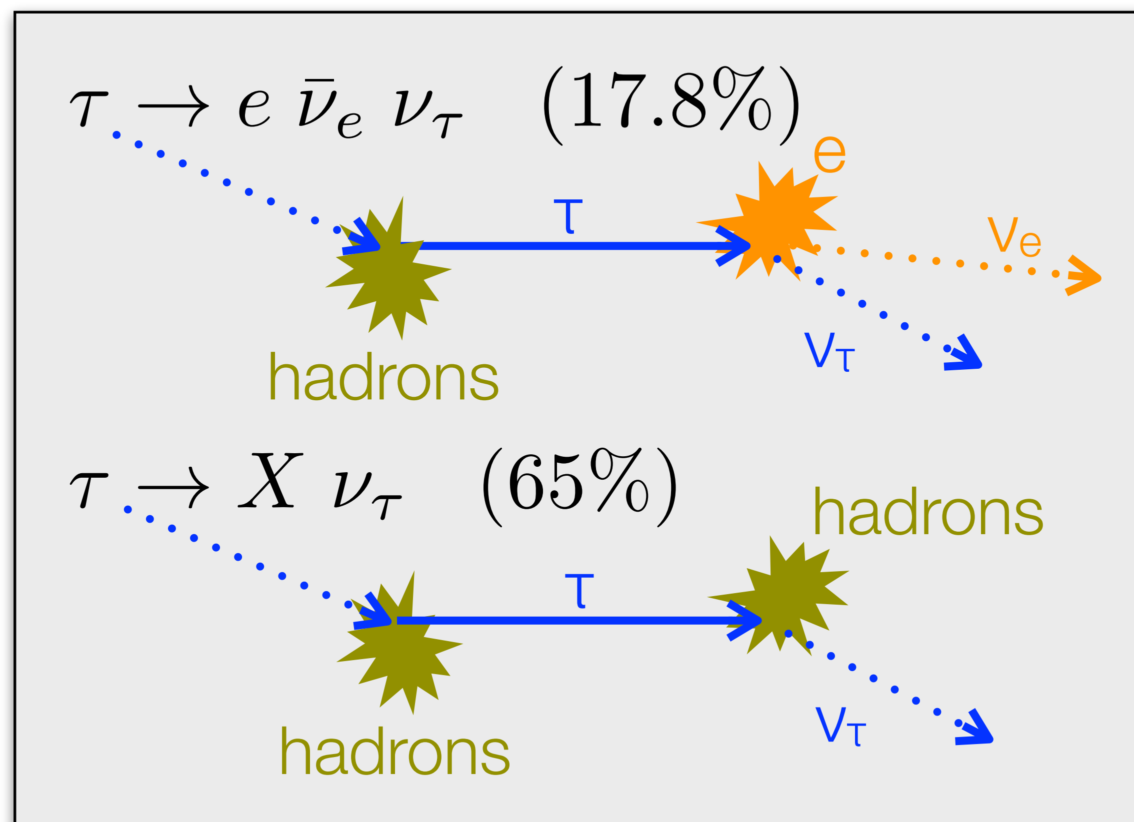
$$\gamma c \tau = \frac{E_\tau}{1.777\ \mathrm{GeV}}\,(87.03\ \mu\mathrm{m})$$

$$= 49\ \mu\mathrm{m/GeV}$$

- Tau neutrino event topologies are very similar to ν_μ CC, ν_e CC, and NC events
  - Discriminate based on energy, direction



τ lepton track is ≲1 mm long, so displaced vertex is not observable with current detectors



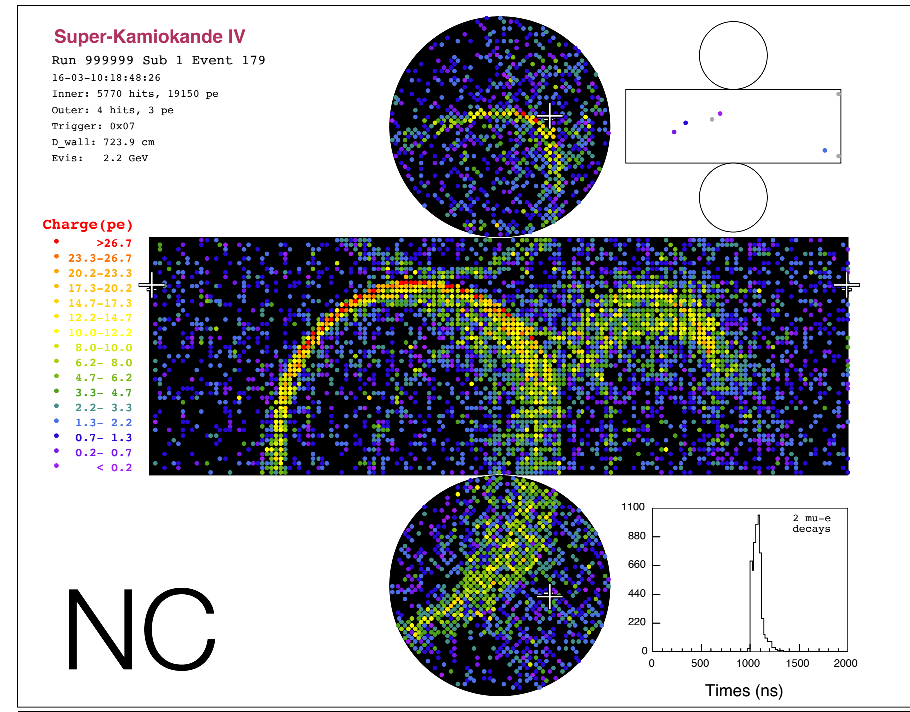
Atmospheric ν_τ Appearance

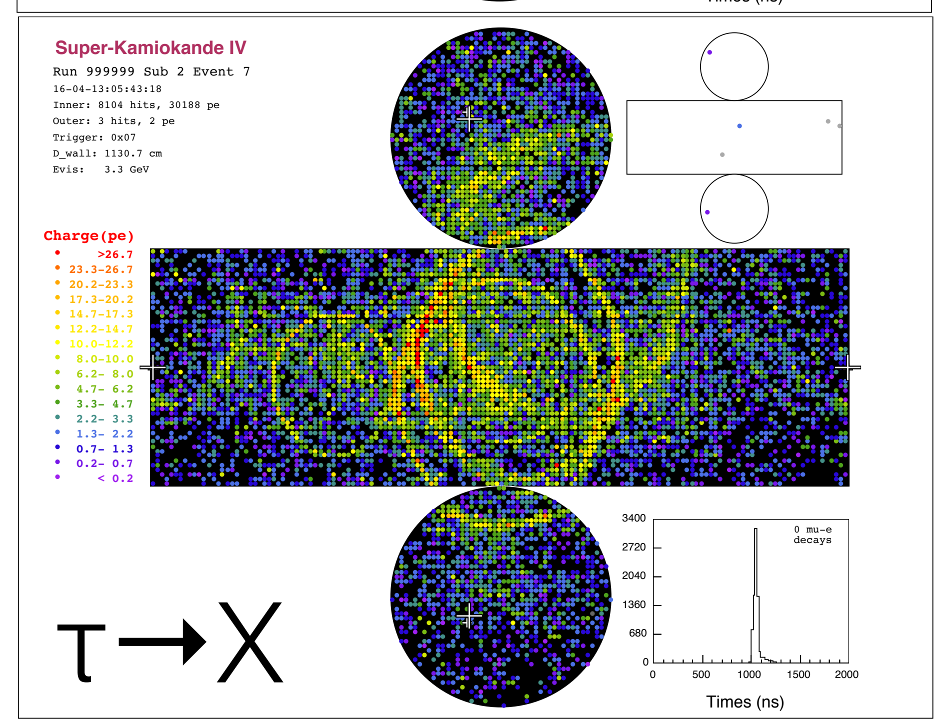
- Best current measurements from Super-K, IceCube DeepCore
- Both follow the same basic strategy:
  - Enhance ν_τ CC signature as much as possible
  - Rely on distinctive angular and/or energy distribution produced by oscillations to measure ν_τ appearance above remaining background
- Super-K is better at event selection; IceCube DeepCore leverages higher statistics to use energy as well as direction in measurement
- DUNE will soon provide much higher resolution of low-energy atmospheric neutrinos…reduce/avoid reliance on energy/angle?

Atmospheric Appearance in Super-Kamiokande

Super-K, arXiv:1711.09436

- Step 1: reject ν_μ and ν_e CC backgrounds, select “multi-ring” events using neural networks
  - $\tau \rightarrow \mu$ events rejected along with ν_μ CC
  - $\tau \rightarrow e$ events rejected along with ν_e CC
  - $\tau \rightarrow X$ decays often produce more particles than NC events
  - ν_τ purity of ~5% in tau-selected sample





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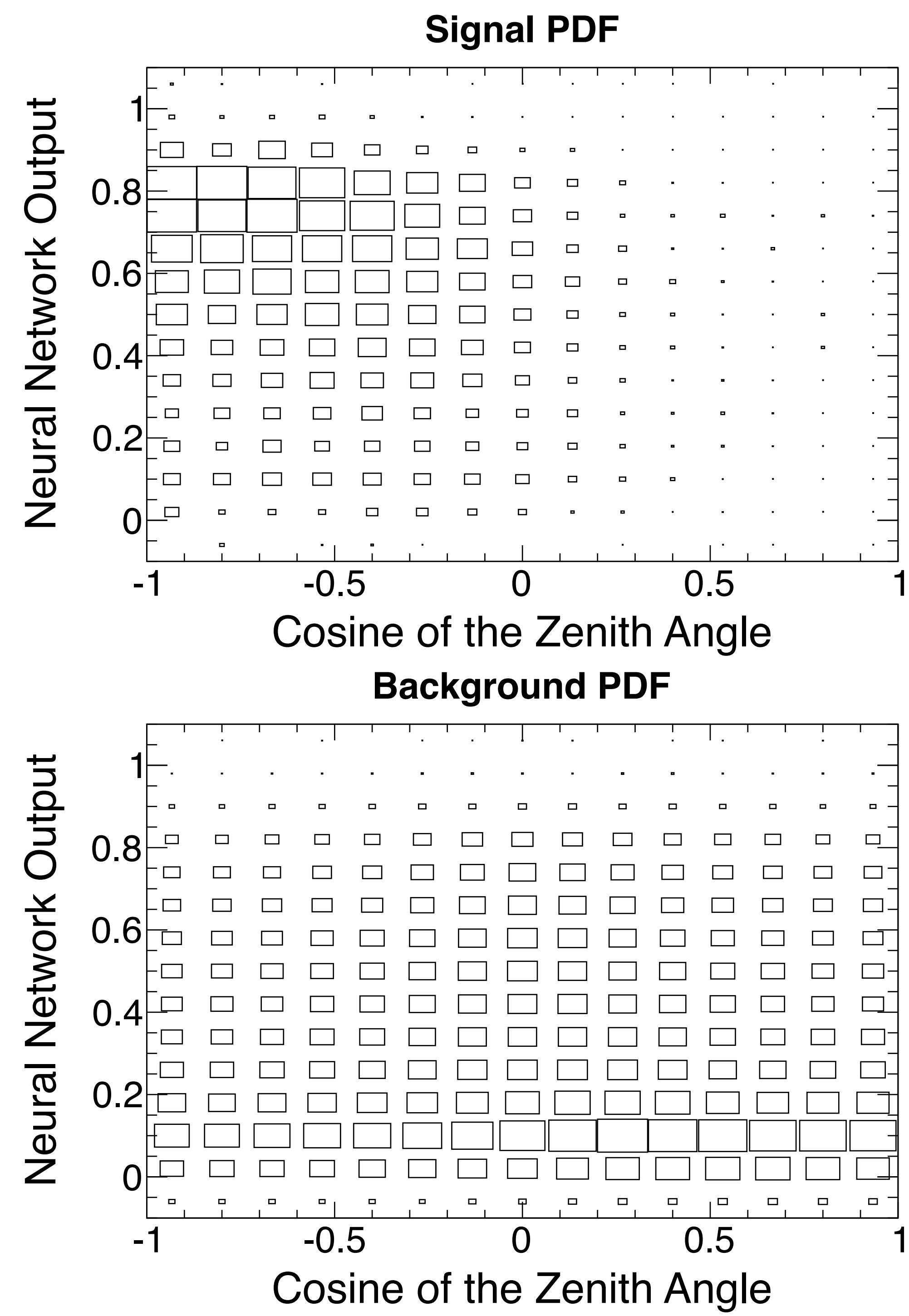
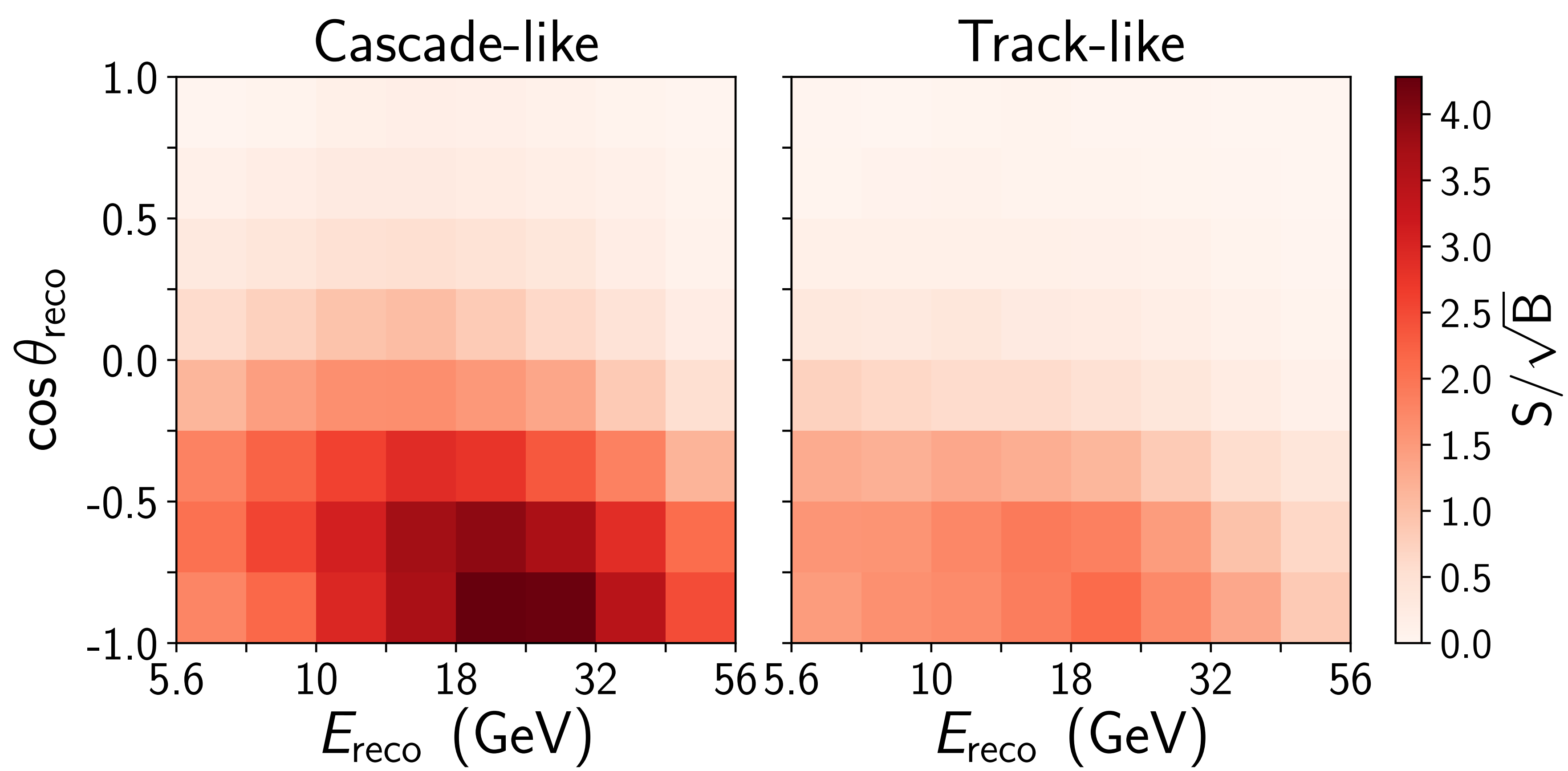
    - ν_τ purity of ~5% in tau-selected sample
- Step 2: Inclusive measurement of ν_τ in 2D space of direction vs. NN score, using known distribution of ν_τ direction due to oscillations



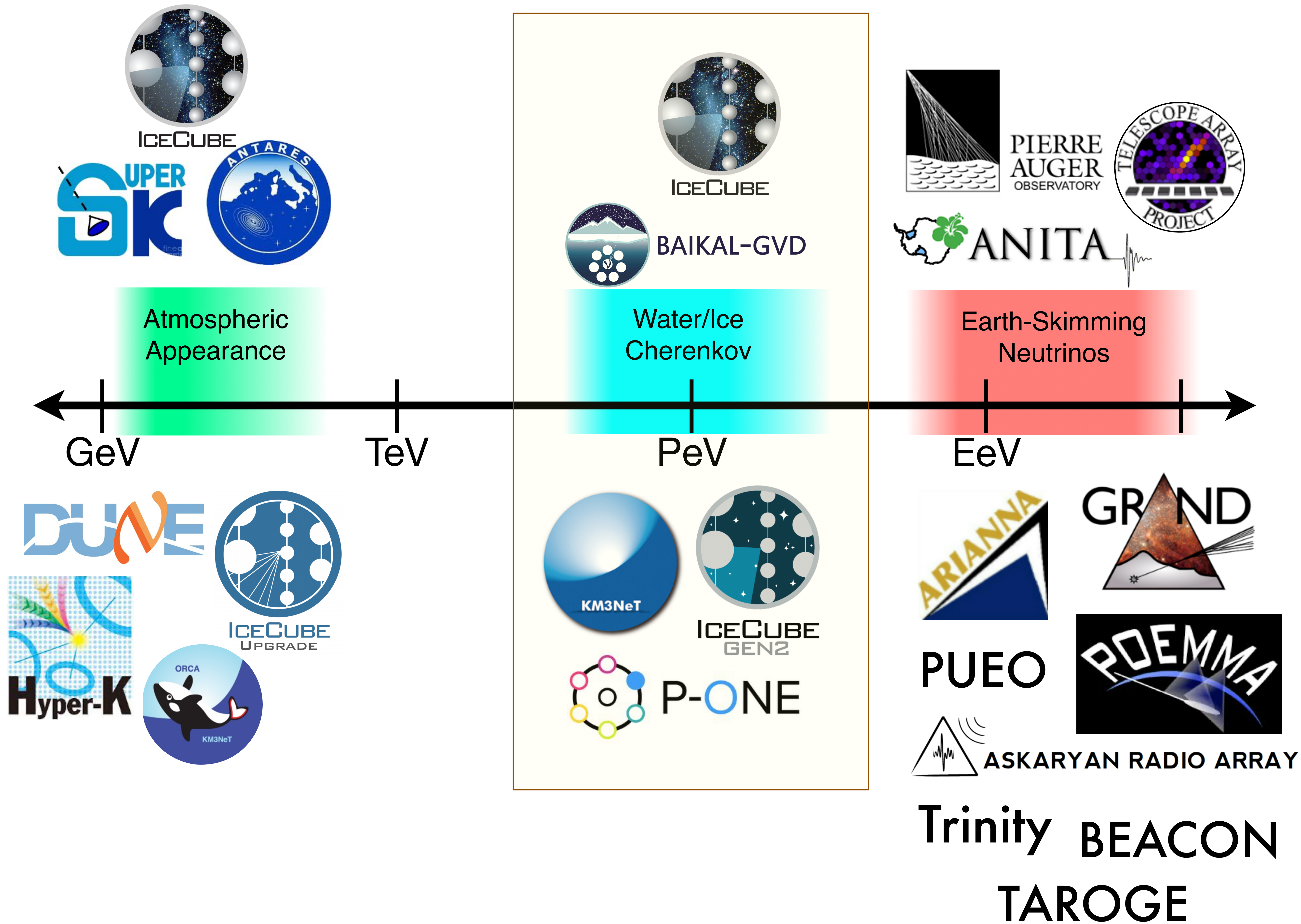
Atmospheric Appearance in IceCube DeepCore

IceCube, arXiv:1901.05366

- Step 1: separate ν_μ CC events, everything else is "cascade-like"
  - NC and ν_e events form a smooth background without oscillation features
  - $\tau \rightarrow \mu$ events are combined with ν_μ CC
  - ν_τ purity of ~3% in cascade sample



- Step 2: Inclusive measurement of ν_τ appearance in 3D space of direction vs. energy vs. particle type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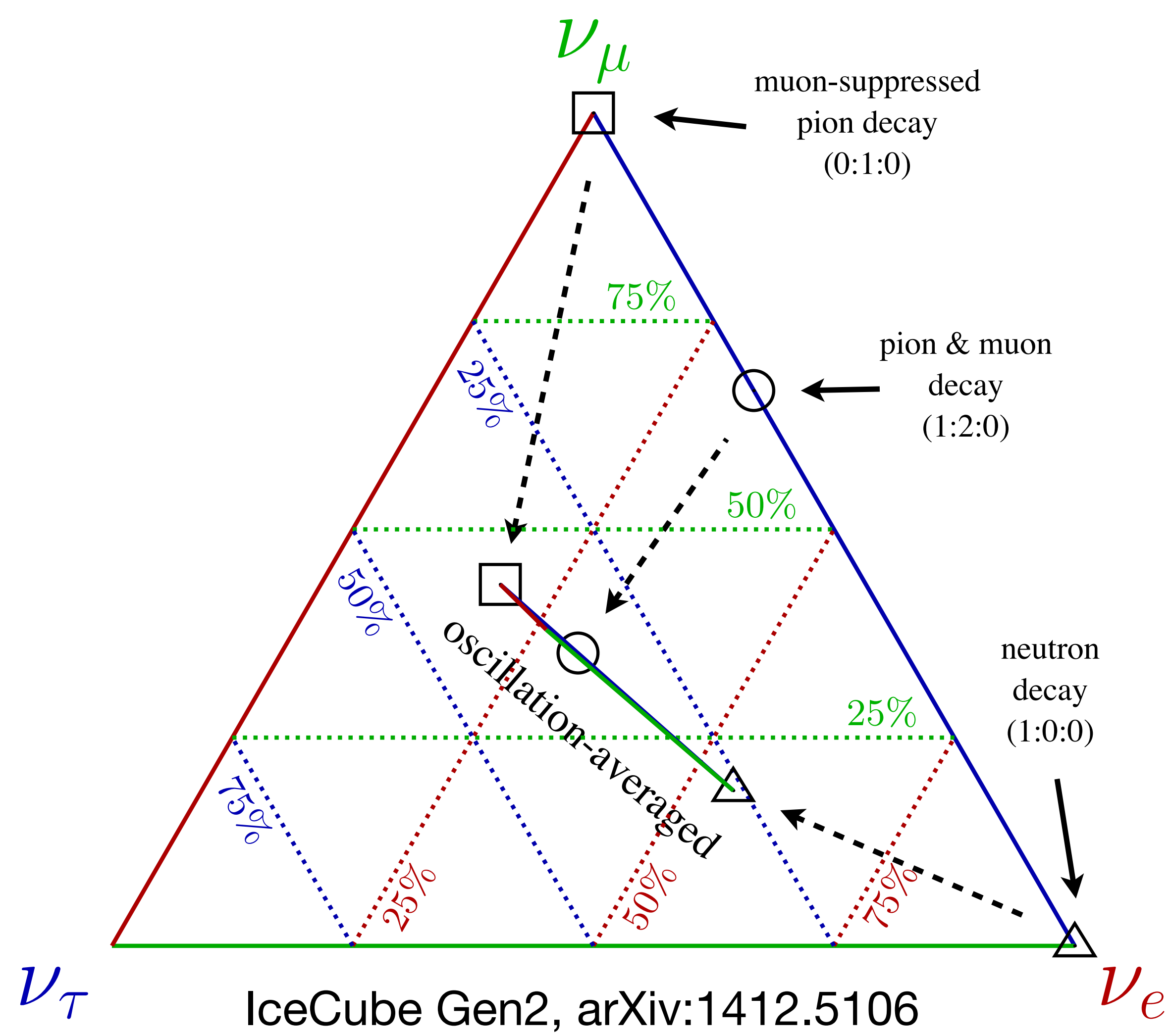
Long Baseline Oscillations

- Over astrophysical baselines, neutrino flavors are fully mixed
  - Even at 10^{20} eV, a 10 kpc baseline (roughly the distance from Earth to Galactic center) corresponds to 45 phase rotations of solar mixing
- Regardless of initial composition, neutrinos at Earth are restricted to a small range of flavor ratios
  - By chance, the 1:2:0 initial flavor ratio of π/K decay leads to almost exact 1:1:1 equality at Earth



IceCube Gen2, arXiv:1412.5106

Long Baseline Oscillations

Song, Li, Argüelles, Bustamante & Vincent, arXiv:2012.12893

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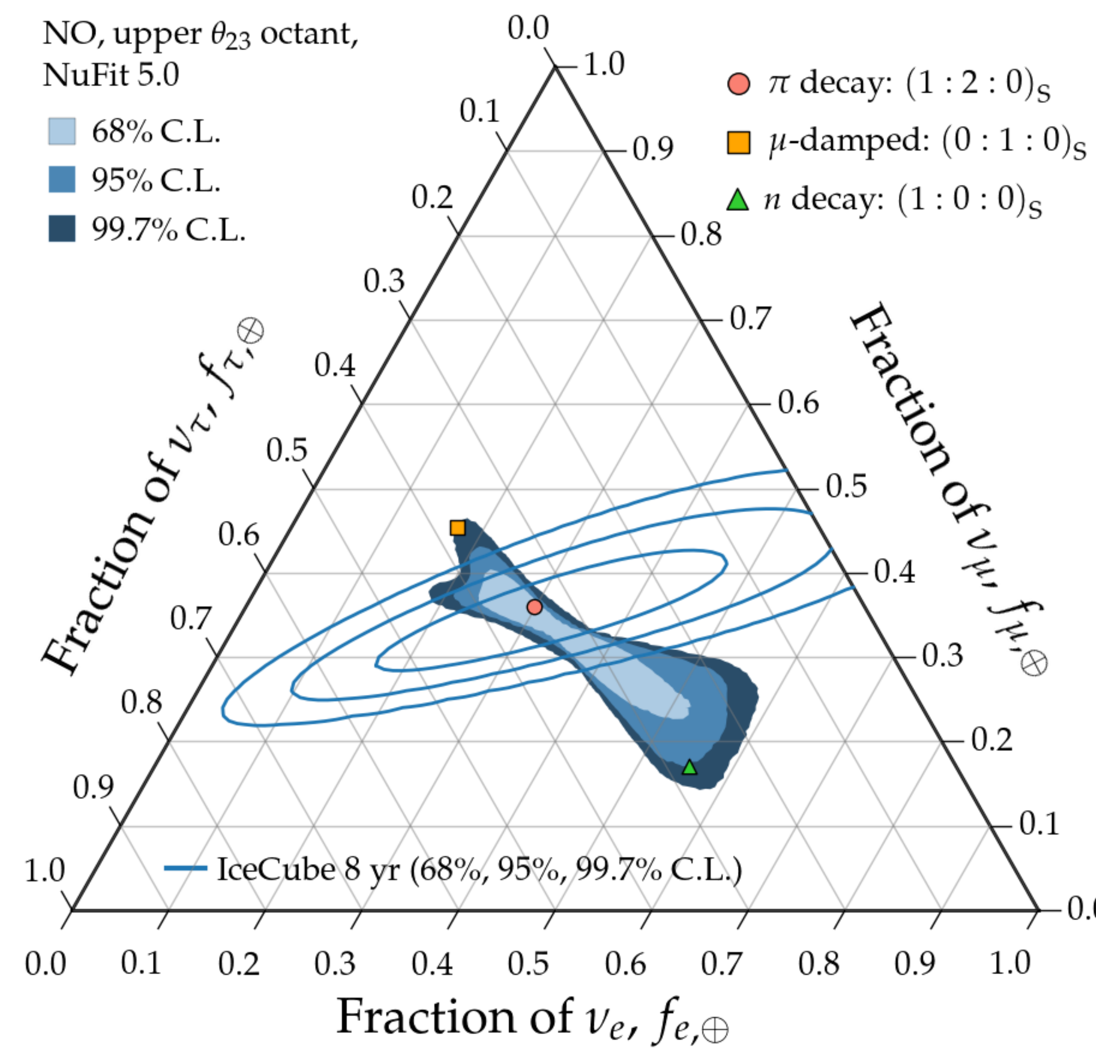

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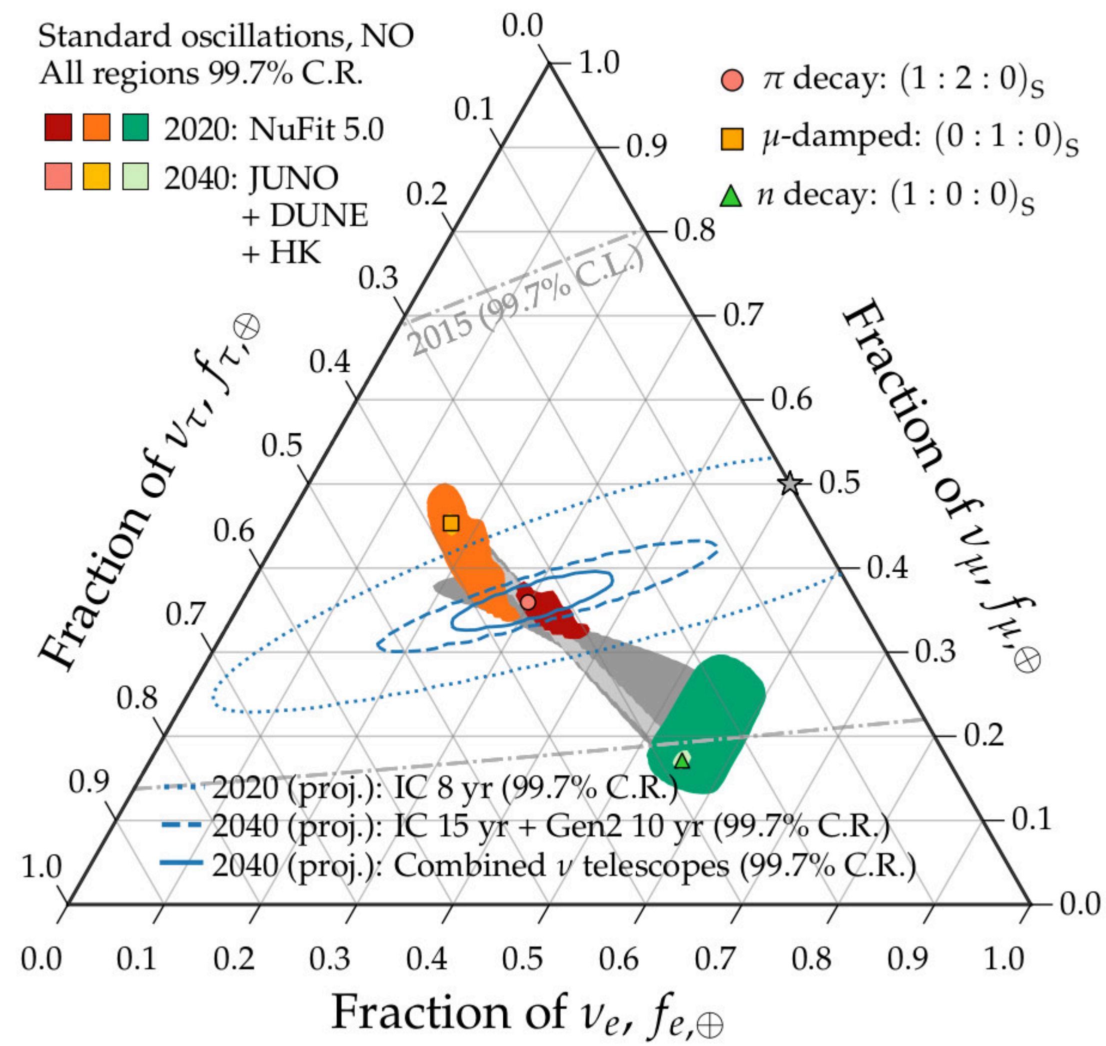
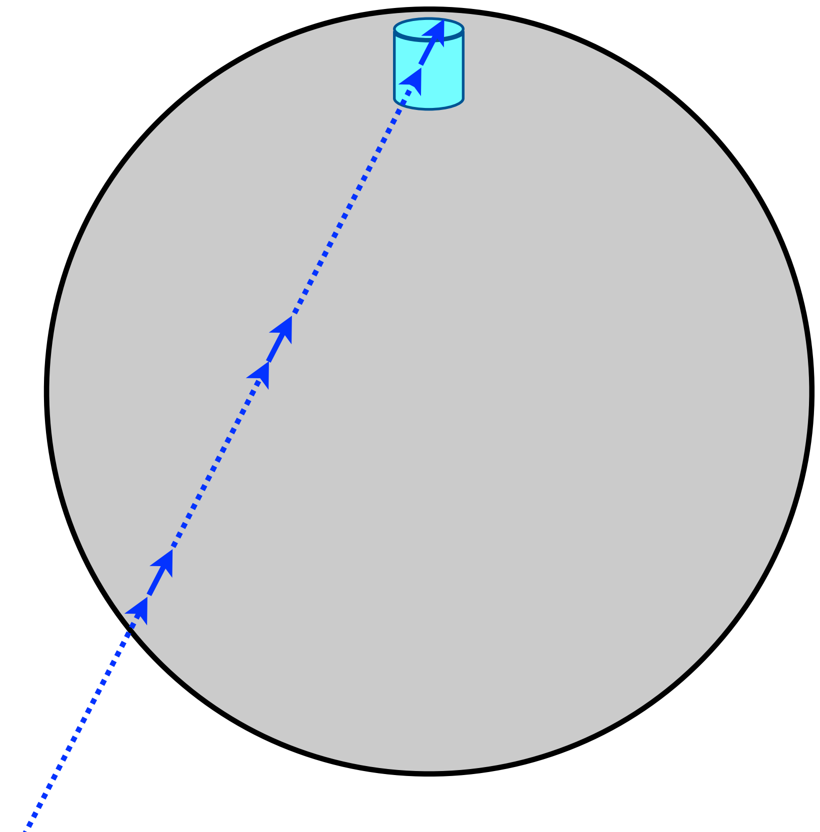
- ν_τ are both probes of astrophysical environment, and nearly BG-free



Earth Absorption and Tau Regeneration

Halzen & Saltzberg, arXiv:hep-ph/9804354

- Neutrino interaction cross section rises approximately linearly with energy
  - Interaction length equals the Earth's column density at ~100 TeV: the Earth becomes opaque to neutrinos
  - Muons and electrons produced in CC interactions deposit energy rapidly in dense matter: neutrinos are absorbed
- Taus decay before losing much energy, even in dense matter, producing a new ν_τ: tau neutrino regeneration



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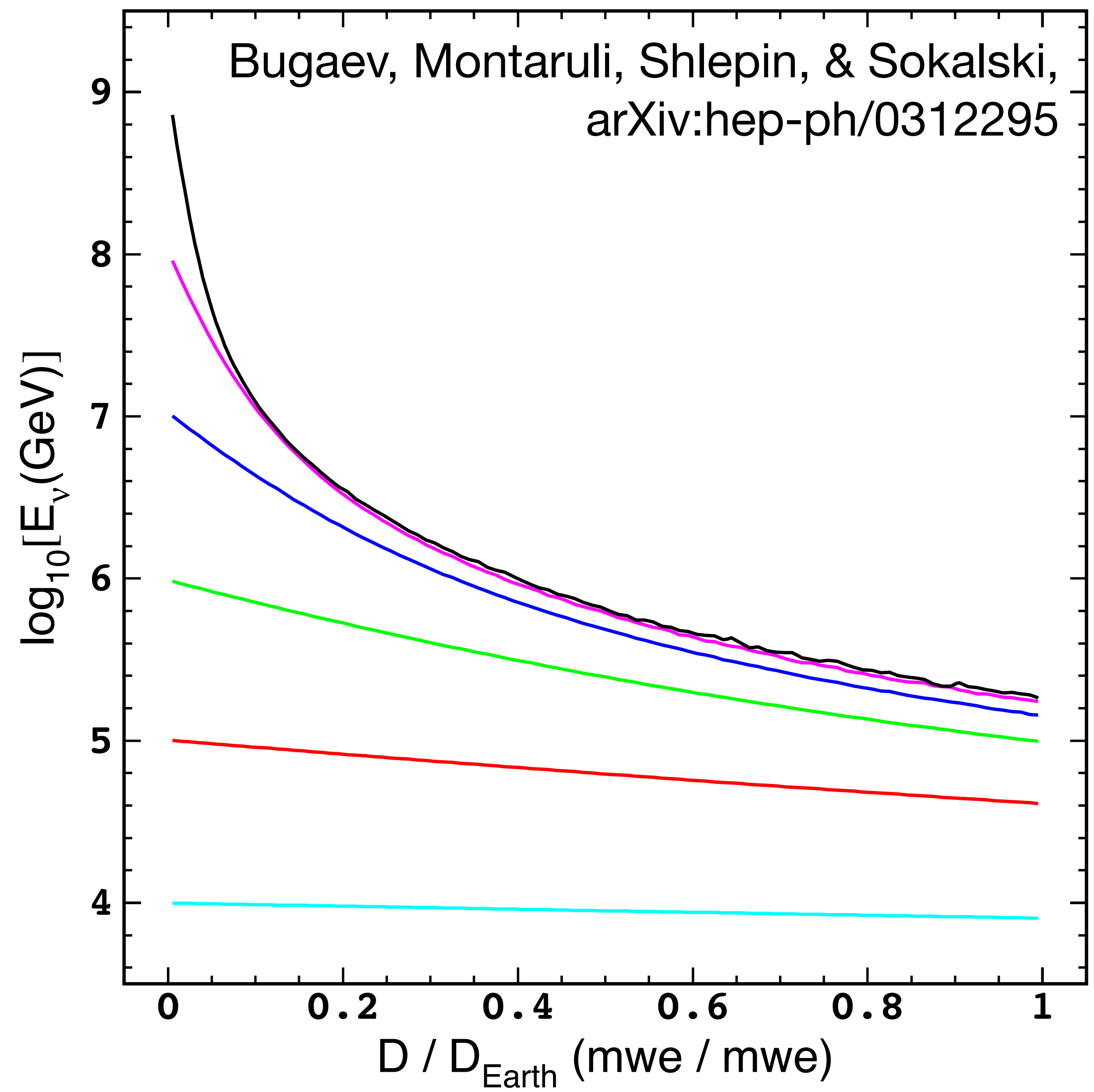
  - Earth-crossing neutrinos are detected at a few hundred TeV, regardless of original E_ν
  - Neutrinos observable at higher energy only near horizon



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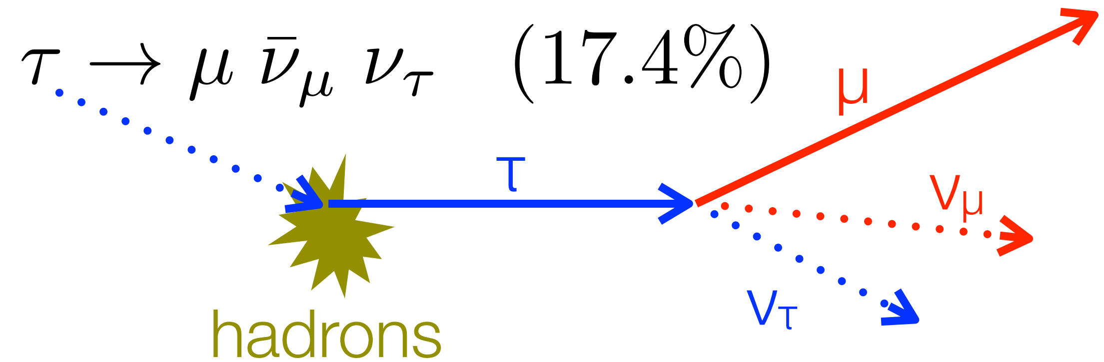
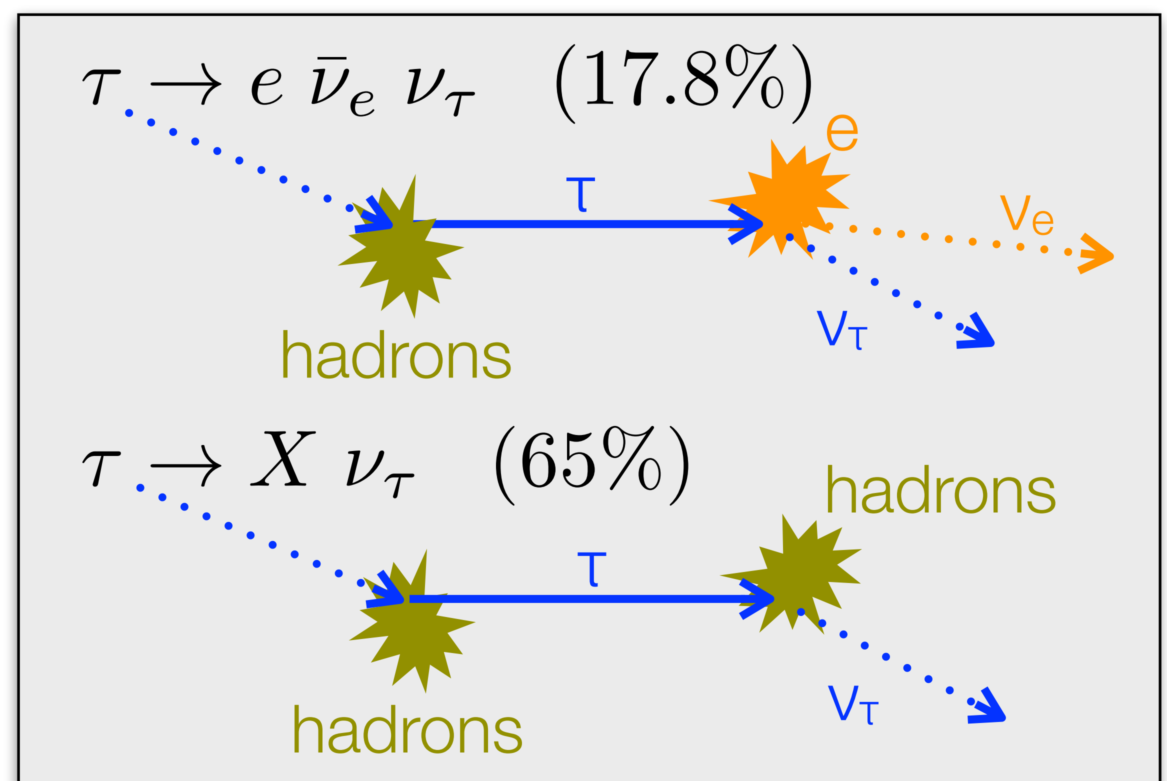
$$= 49\ \mathrm{m/PeV}$$

  - τ track is dimmer than a muon of equal energy – but not dim
  - Hadronic and electromagnetic showers not distinguished

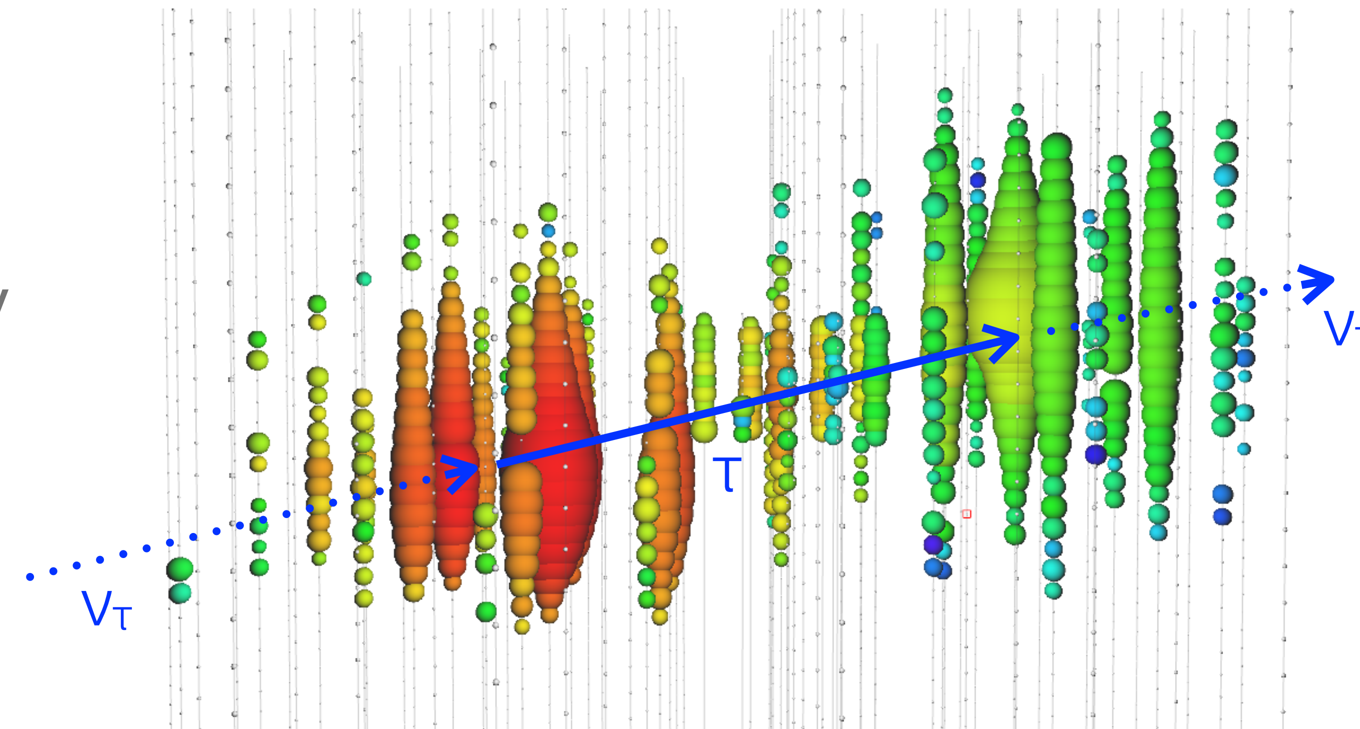


kink becomes undetectable at high E.
track brightening theoretically observable, but requires considerable luck

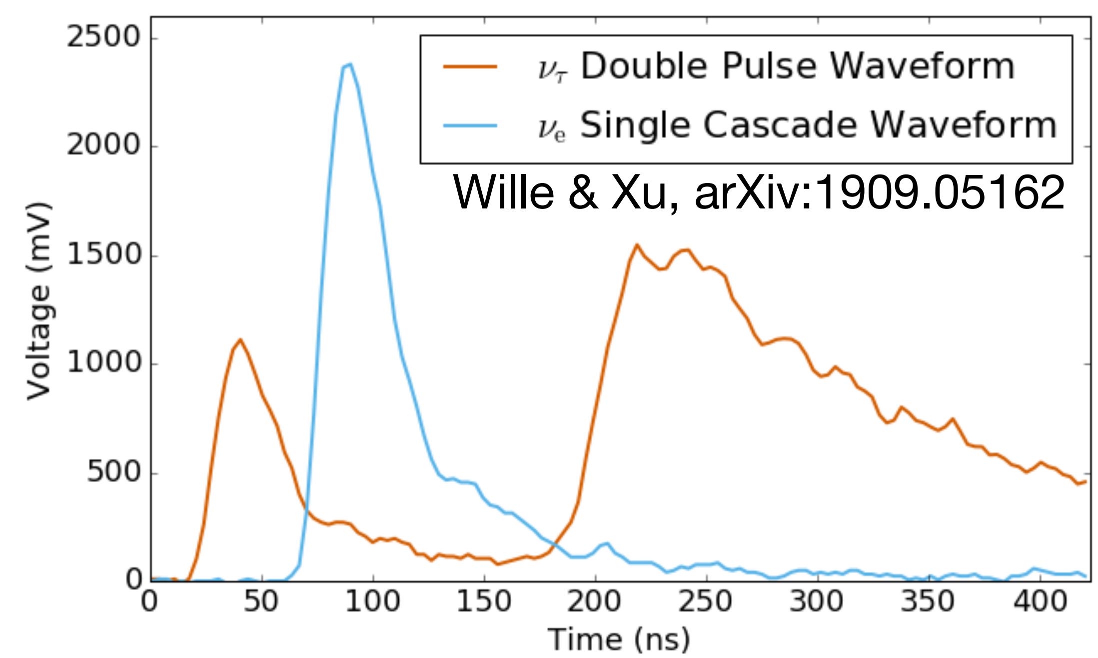


ν_τ in Very Large Volume Neutrino Telescopes

Learned & Pakvasa, arXiv:hep-ph/9405296,
Beacom, Bell, Hooper, Pakvasa, & Weiler, arXiv:hep-ph/0307025



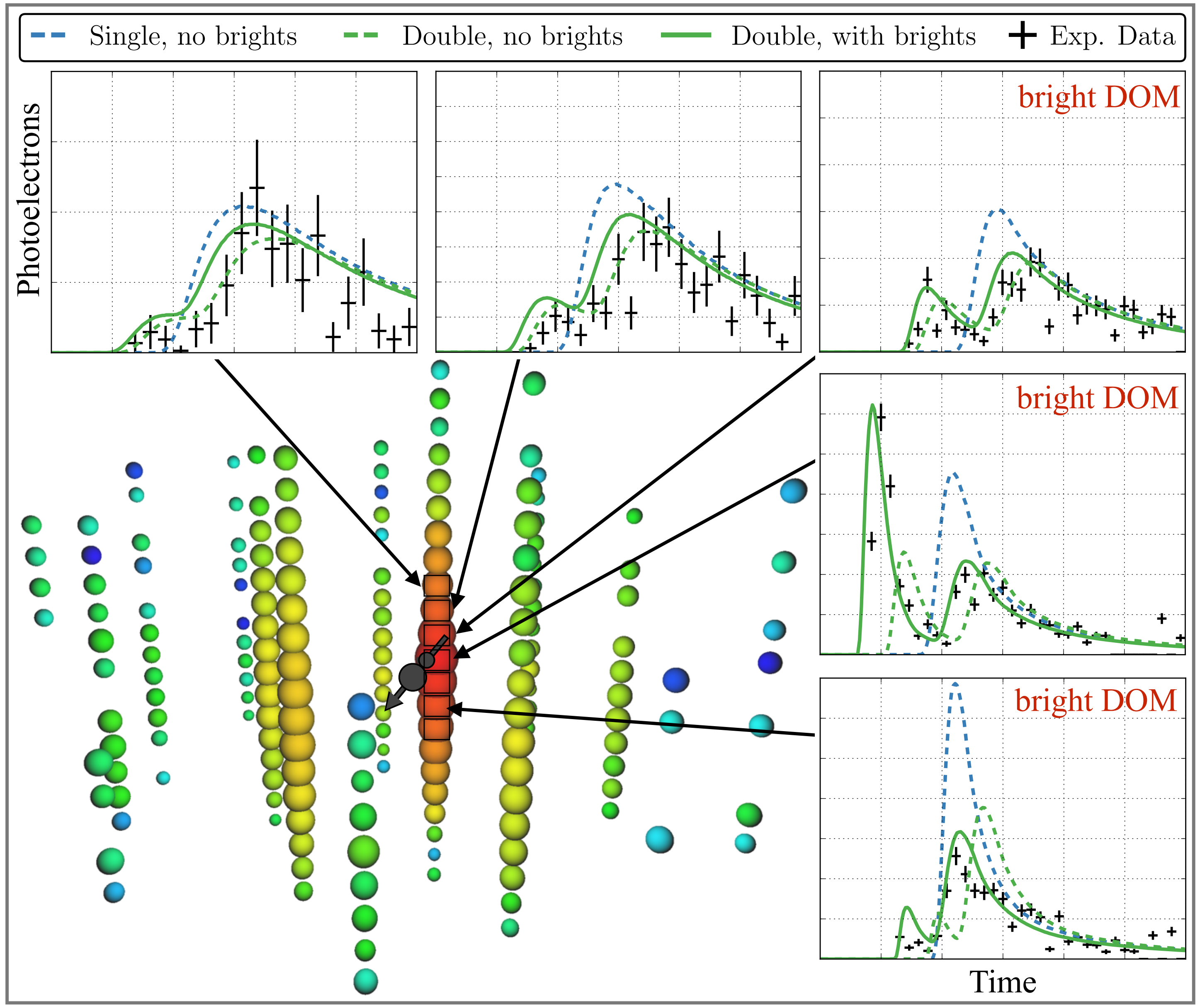
- Classic signature in neutrino telescopes is a "double bang"
  - In reality, the bangs aren't cleanly separated below several PeV
  - Most tau events will be a "double pulse" – the two bangs are separated in time but not in space



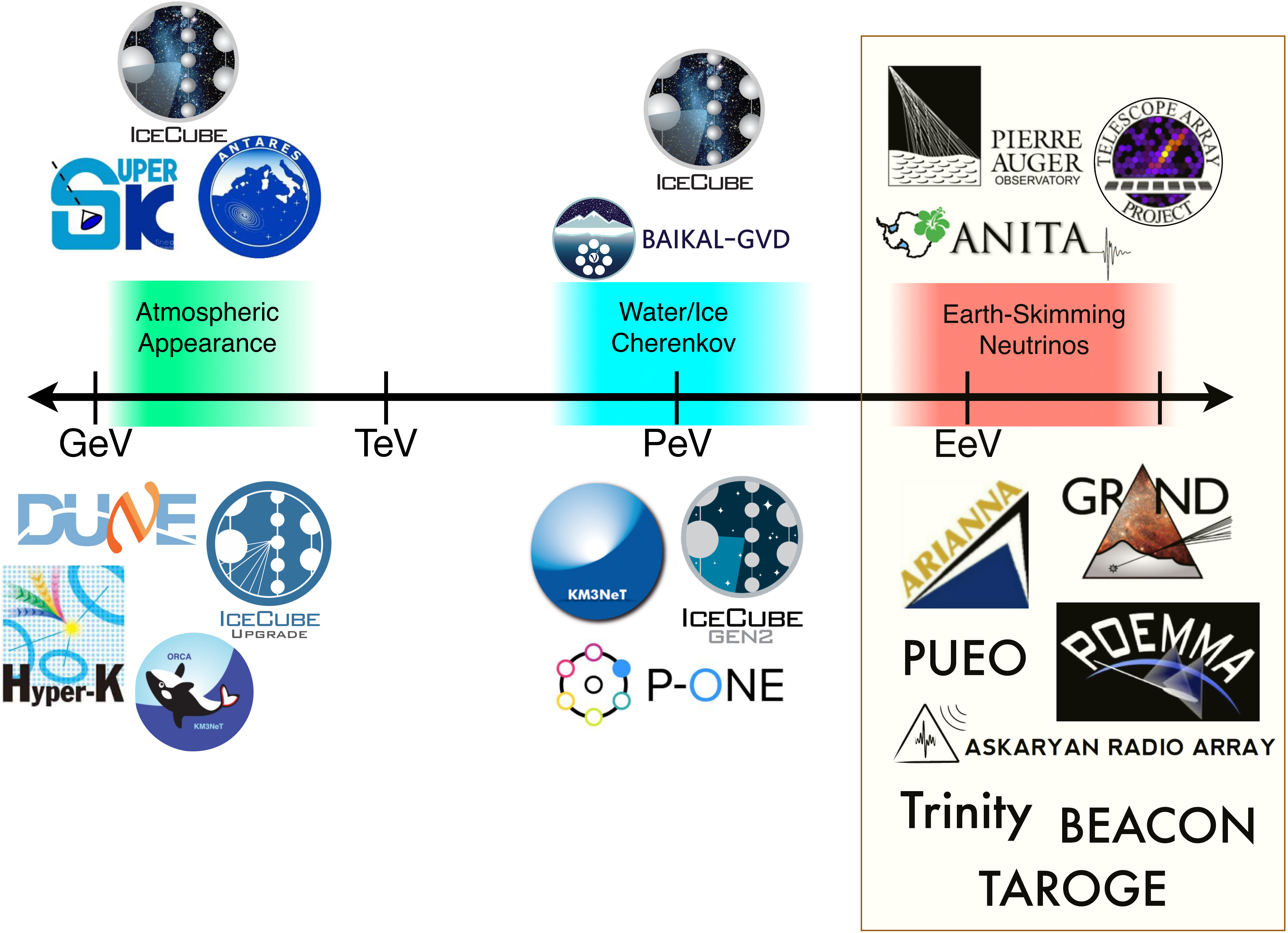
- At higher energy, the τ track becomes longer than the detector
  - Tau leptons can be ID'd by decay-in-flight of very energetic tracks ("lollipops") – but rates very low

First Detection of Astrophysical ν_τ

IceCube, arXiv:2011.03561



- More and larger neutrino telescopes required for more events (KM3NeT, Baikal-GVD, IceCube Gen2, P-ONE)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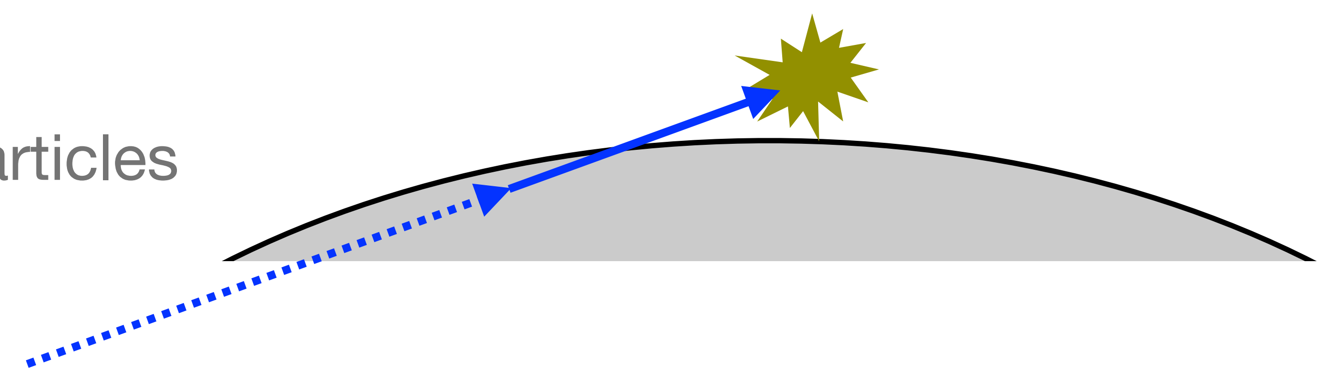
TAROGE

Earth-Skimming Neutrinos

A. Letessier-Selvon, arXiv:astro-ph/0009444

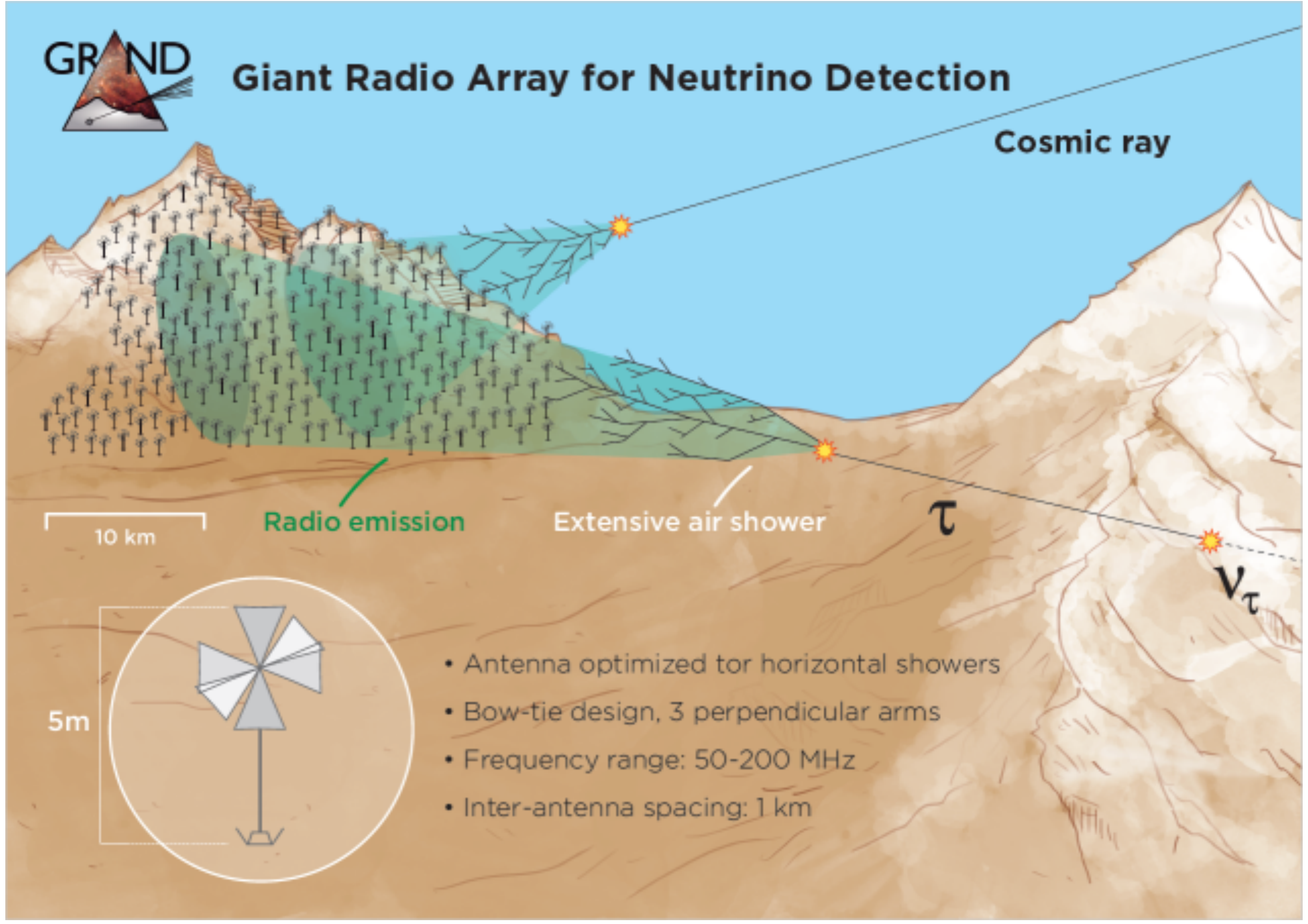
- At EeV scales, $\sigma_{\nu N}$ is large enough for neutrinos to interact in relatively short lengths of matter (or even in the atmosphere)
    - The τ lepton may carry enough energy to emerge before decaying in flight
- Similar to ultrahigh energy cosmic rays (UHECR), the air shower from the τ decay may be observed via:
    - Nitrogen fluorescence or charged particles
    - Cherenkov emission
    - Radio emission



- Geometry is the challenge: the signature of ν_τ is an *up-going* air shower
    - (Other neutrino flavors can be detected in searches for young, highly inclined showers, but ν_τ can't be identified)

Earth-Skimming Neutrinos: Ground-Based

- First searches conducted by Auger, TA using particles + fluorescence, but no neutrinos detected so far
- Follow-up proposals for dedicated experiments at mountainous sites, now at prototype stage
    - Charged particles in air showers coherently emit radio waves as well as Cherenkov light
    - Both types of emission are beamed, detectable at many 10's of km
    - Radio detectors (GRAND, BEACON, TAROGE, ARIANNA-HCR) have higher duty cycle than Cherenkov detectors (TRINITY), but need to reject background from reflected CR showers (reversed phase)

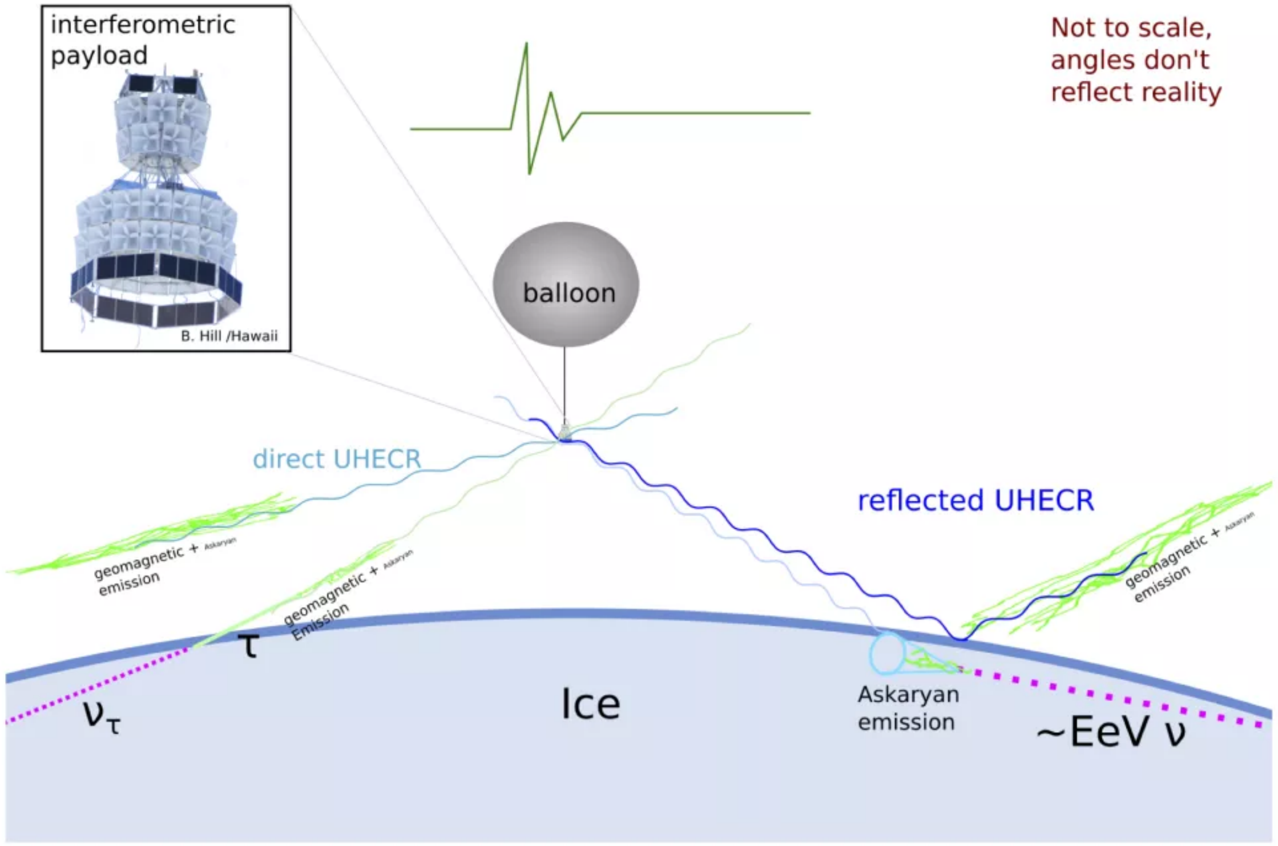


- Tau neutrinos also detectable by Antarctic radio neutrino detectors (ARA, ARIANNA)

Earth-Skimming Neutrinos: ANITA Anomaly

ANITA arXiv:1603.05218, 1803.05088

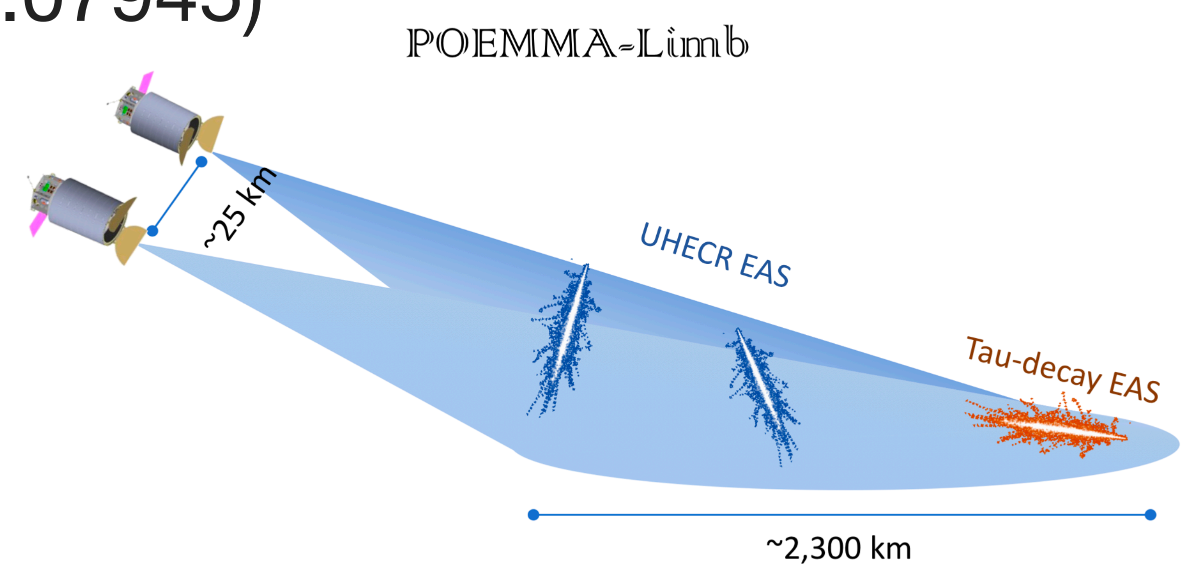
- ANITA: balloon-borne radio detector circling Antarctica
  - Ice is RF-transparent, ANITA sensitive to showers within or emerging from the ice cap
- Two anomalous events, inconsistent with reflected cosmic ray showers



- *But* steeply up-going (27°, 36° below horizon), not Earth-skimming!
  - Chord lengths through Earth of as many as 18 SM neutrino interaction lengths
  - Both events ~6 x 10^{17} eV, orders of magnitude too high for regenerated ν_τ
  - Currently no generally-accepted explanation for these events

Earth-Skimming Neutrinos: Balloons and Space

- Two proposed missions for UHE ν_τ detection
- PUEO: balloon-borne (arXiv:2010.02892)
  - Successor to ANITA, with improved antennae and phased-array trigger for reduced energy threshold
  - Sensitive to Earth-skimming ν_τ, follow up on ANITA anomaly
- POEMMA: space-borne (arXiv:2012.07945)
  - Two spacecraft sensitive to both fluorescence and Cherenkov emission
  - Detect both UHECR and Earth-skimming ν_τ in limb observation mode



Summary

- Natural sources of neutrinos offer access energies and baselines far beyond those achievable with accelerators
- Flavor oscillations lead to significant fluxes of tau neutrinos at several energy scales
  - Atmospheric ν_τ from a few GeV to the 100 GeV scale
  - Astrophysical ν_τ, identifiable above a few 100 TeV, but at much lower rates
  - Measurements of ν_τ rates enable searches for new physics, as well as probing extreme astrophysical environments
- A range of techniques for detection at different energy scales
  - Improved detectors offer increased prospects for detection of both atmospheric and astrophysical ν_τ