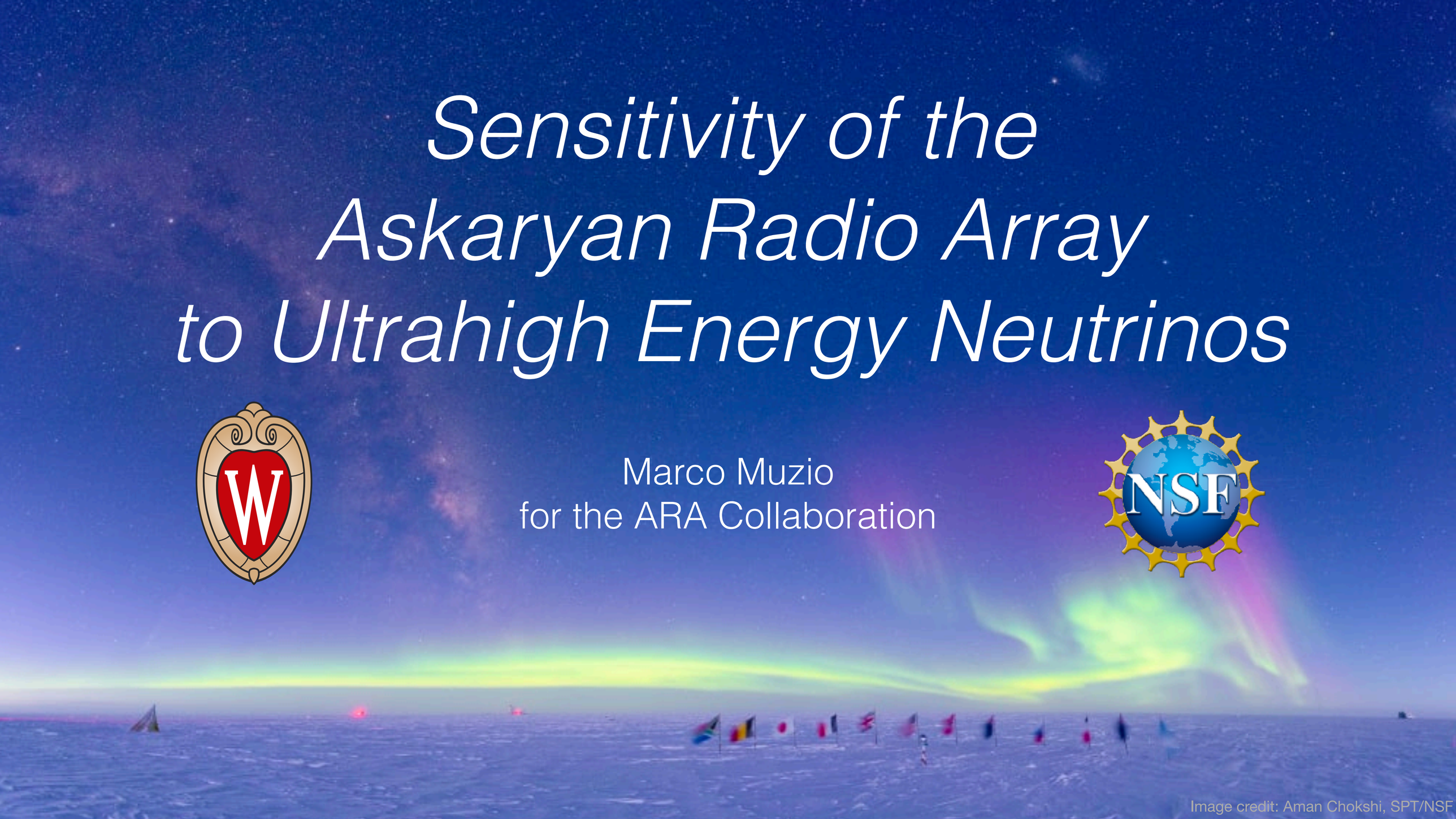
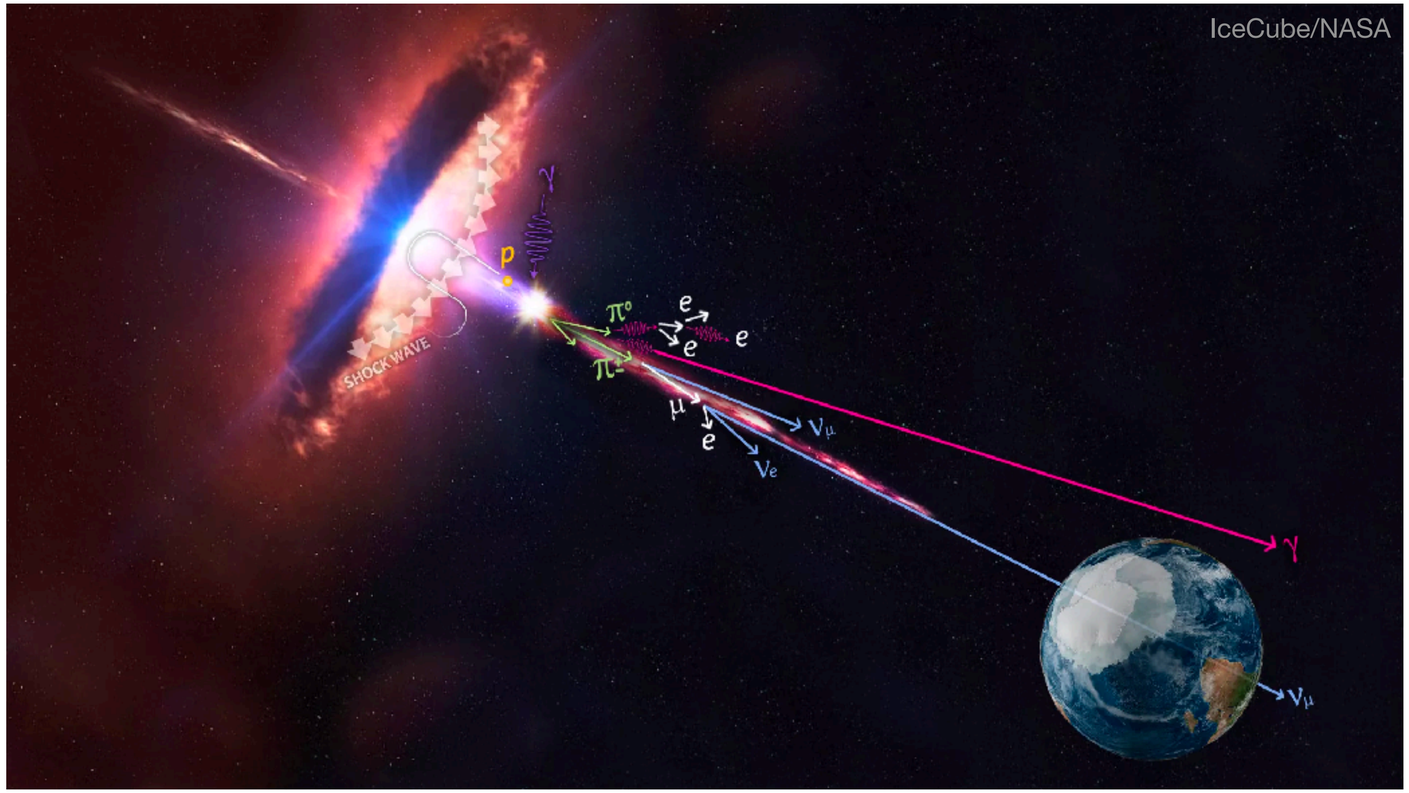
Sensitivity of the Askaryan Radio Array to Ultrahigh Energy Neutrinos

Marco Muzio
for the ARA Collaboration



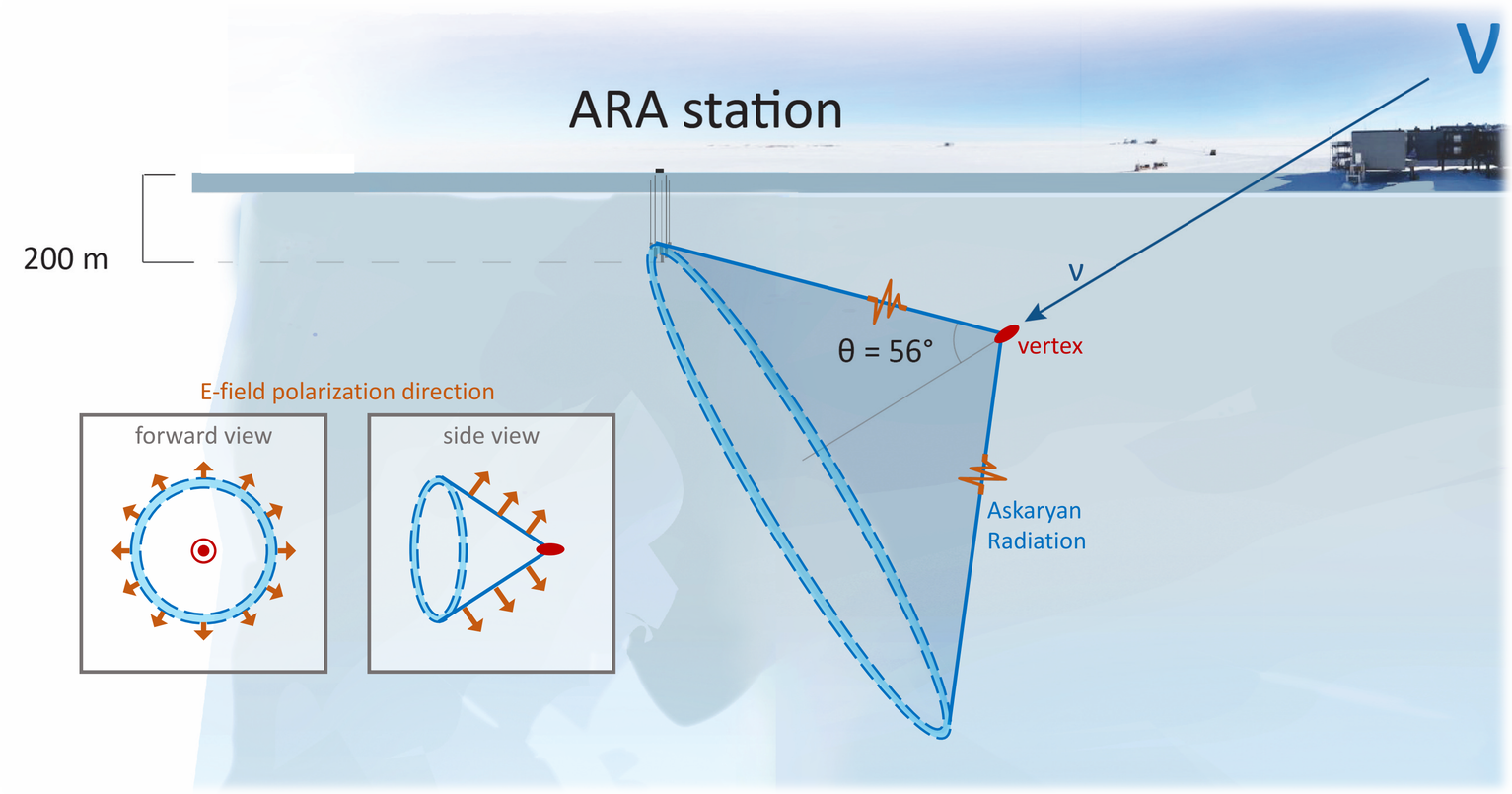
Windows into the UHE Universe

- Sources of UHE CRs remain unknown
- UHECRs themselves only probe the most local sources
  - GZK horizon
  - Extragalactic magnetic horizon
- UHE neutrinos = smoking gun signature of UHECRs
- Probe UHECR sources on cosmological scales
- Point back to sources (no magnetic field deflections)
- Probe particle physics beyond the LHC



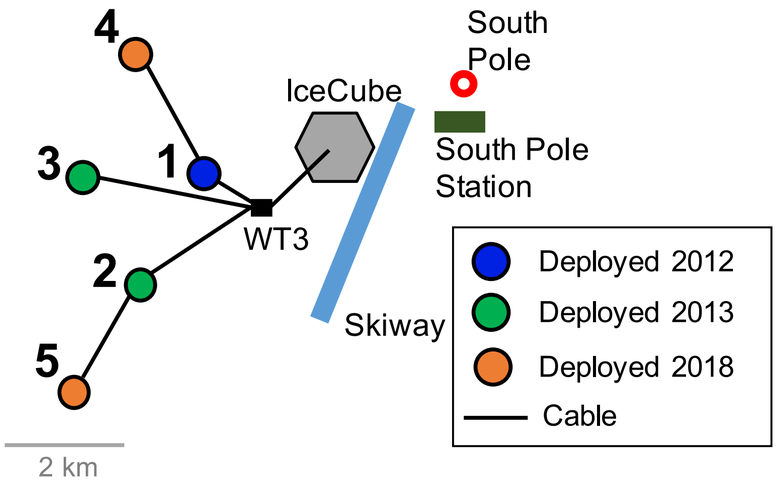
Askaryan Radiation

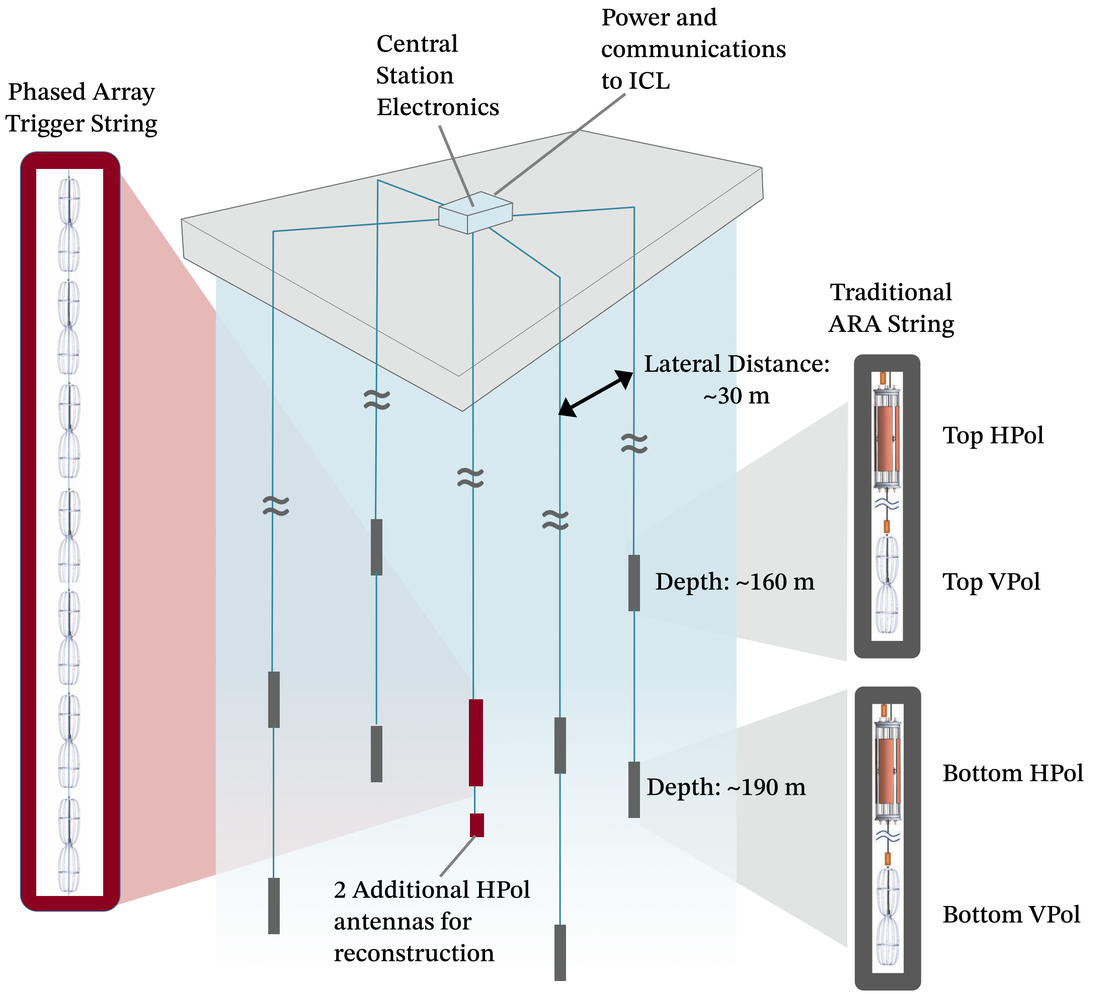
- Neutrino interaction in dense medium initiates particle cascade
- Particle cascade emits pulse of coherent radio emission along Cherenkov cone — Askaryan radiation
- Radio has ~1 km attenuation length in ice
- Radio antenna embedded in ice = efficient monitor of enormous volume



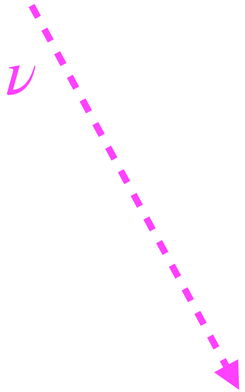
ARA Detector Overview

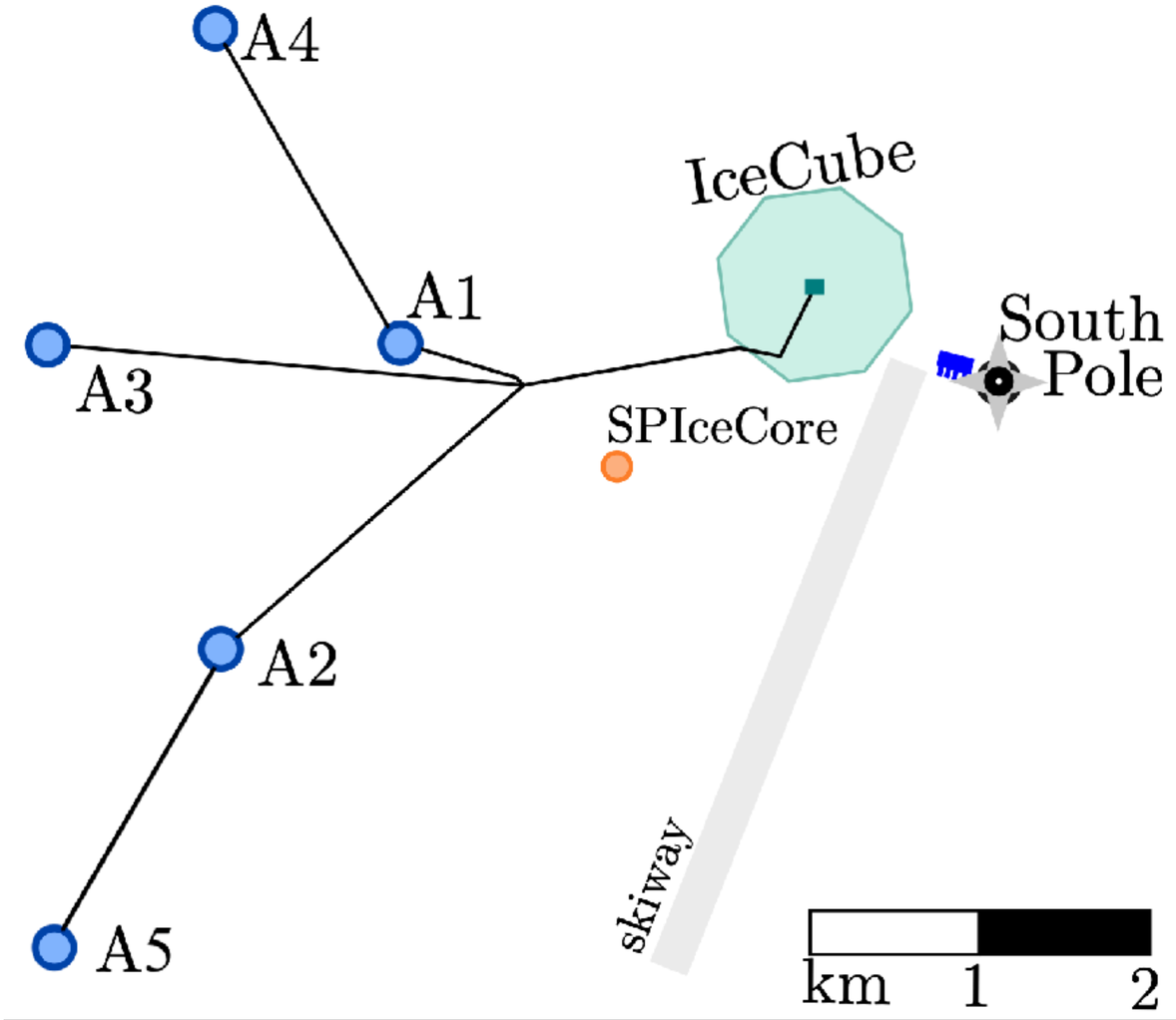
- 5 independent stations on hexagonal grid at South Pole
- Each station has 4 strings embedded in ice
  - Each string has 4 radio antennas (2 VPols & 2 HPols) up to ~200 m deep
  - 3/8 same-polarization coincidence trigger → ~6 Hz trigger (+1 Hz software trigger) rate
- Fifth station (A5) has additional central string: **the Phased Array (PA)**
  - 9 closely packed antennas (7 VPols & 2 HPols) at ~180 m depth
  - **More efficiently triggers** on low signal-to-noise ratio (SNR) signals by adding VPol signals in preset directions (beams)
  - Interferometric trigger → ~11 Hz trigger rate





How Large is ARA?





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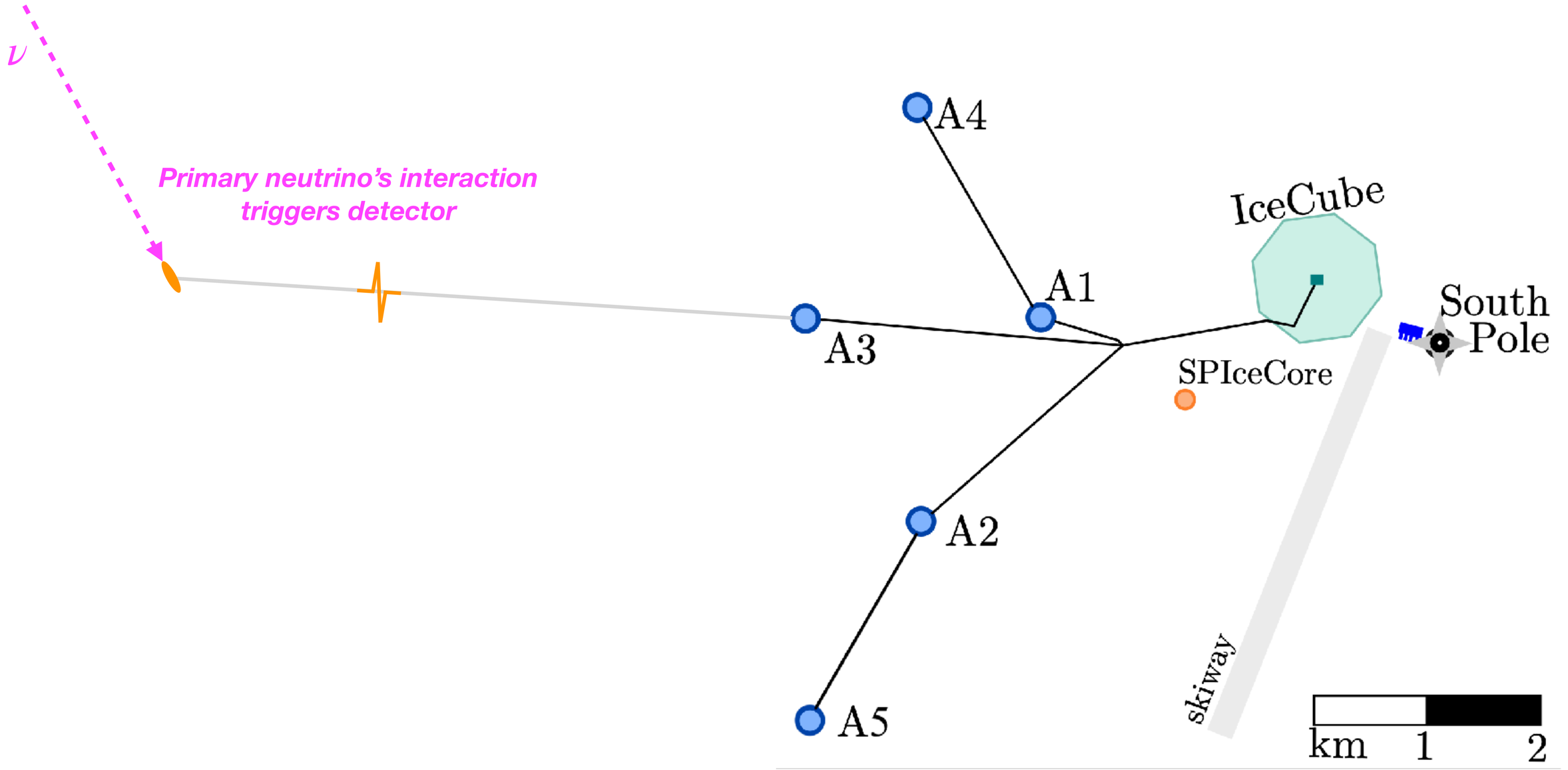

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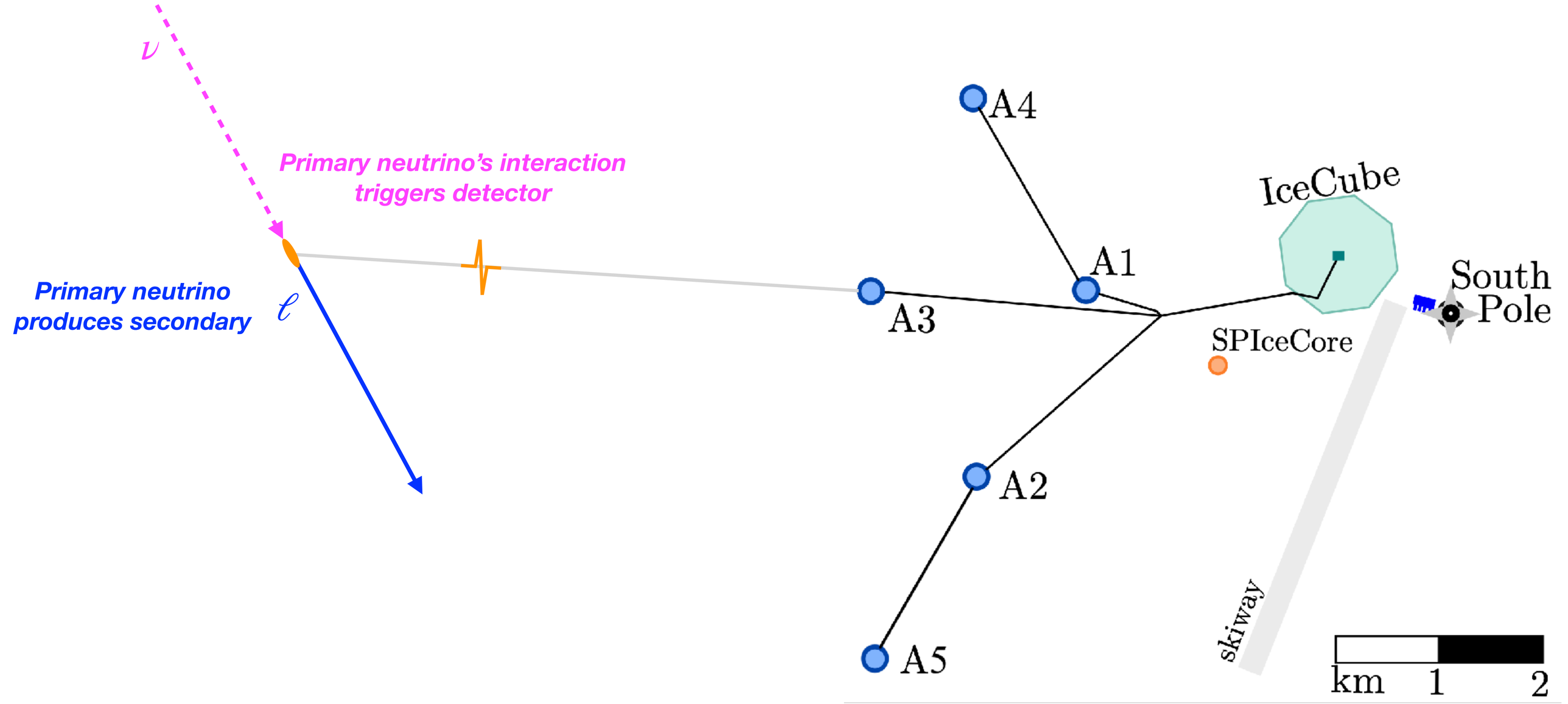

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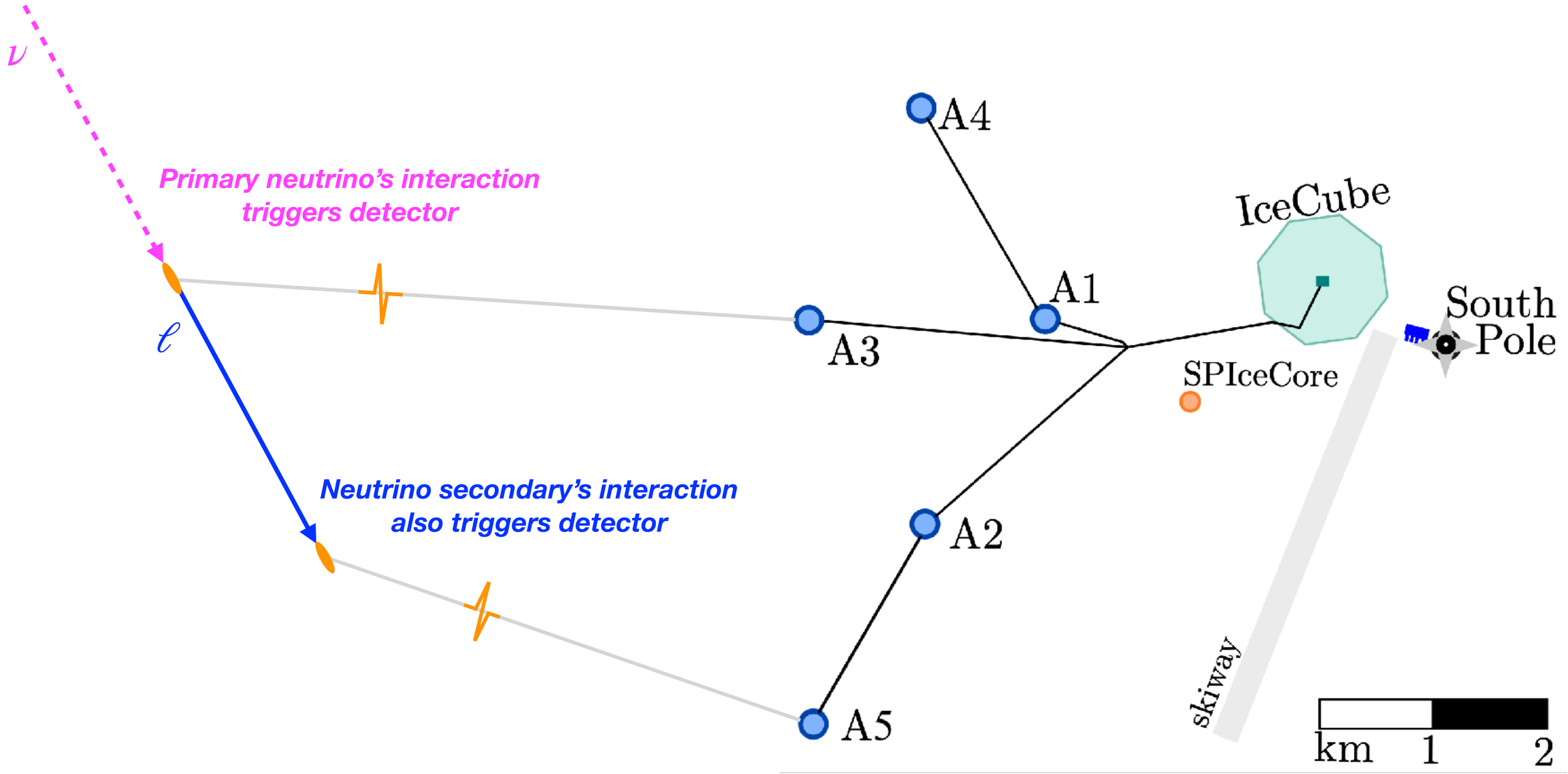

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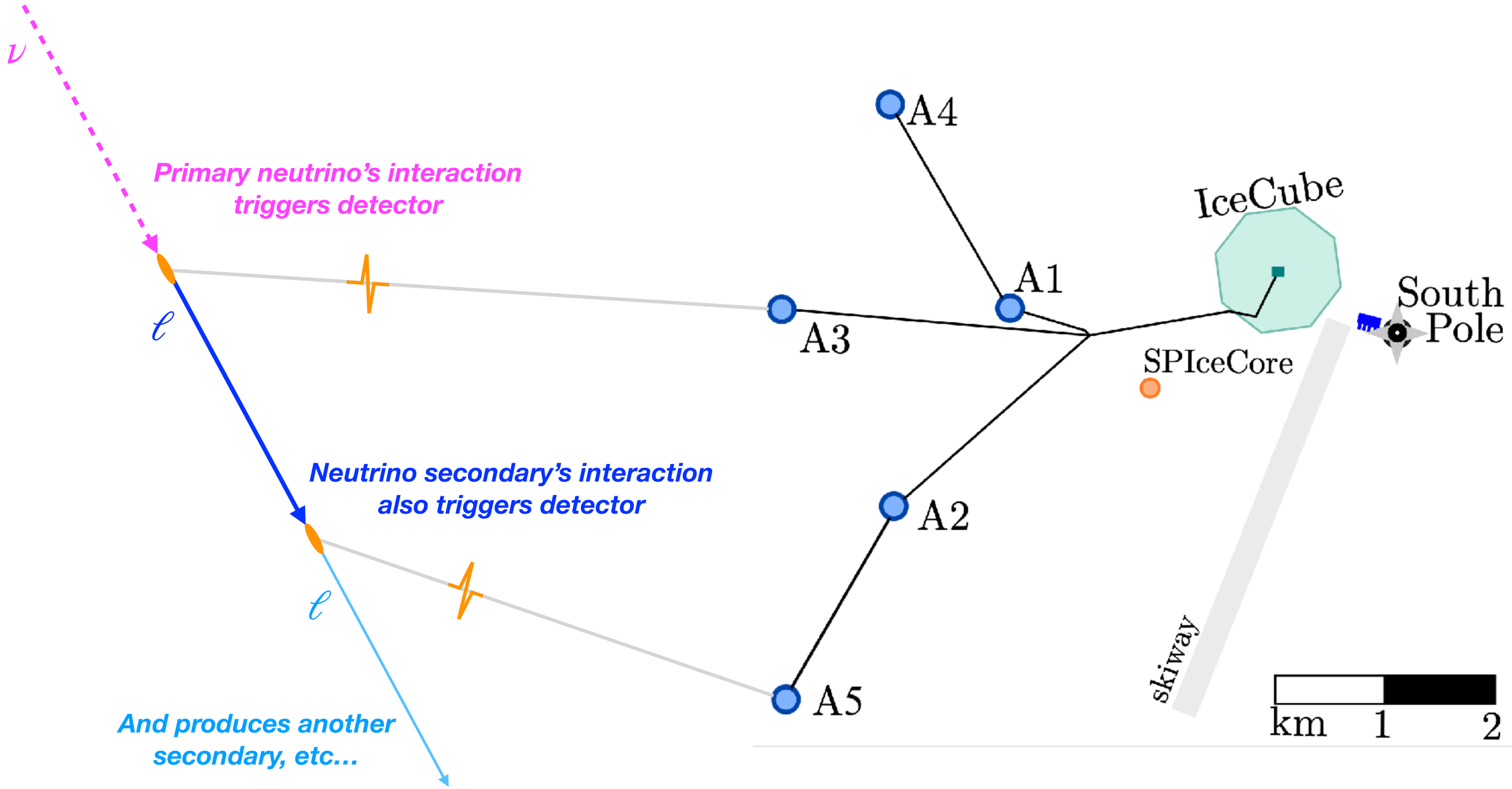

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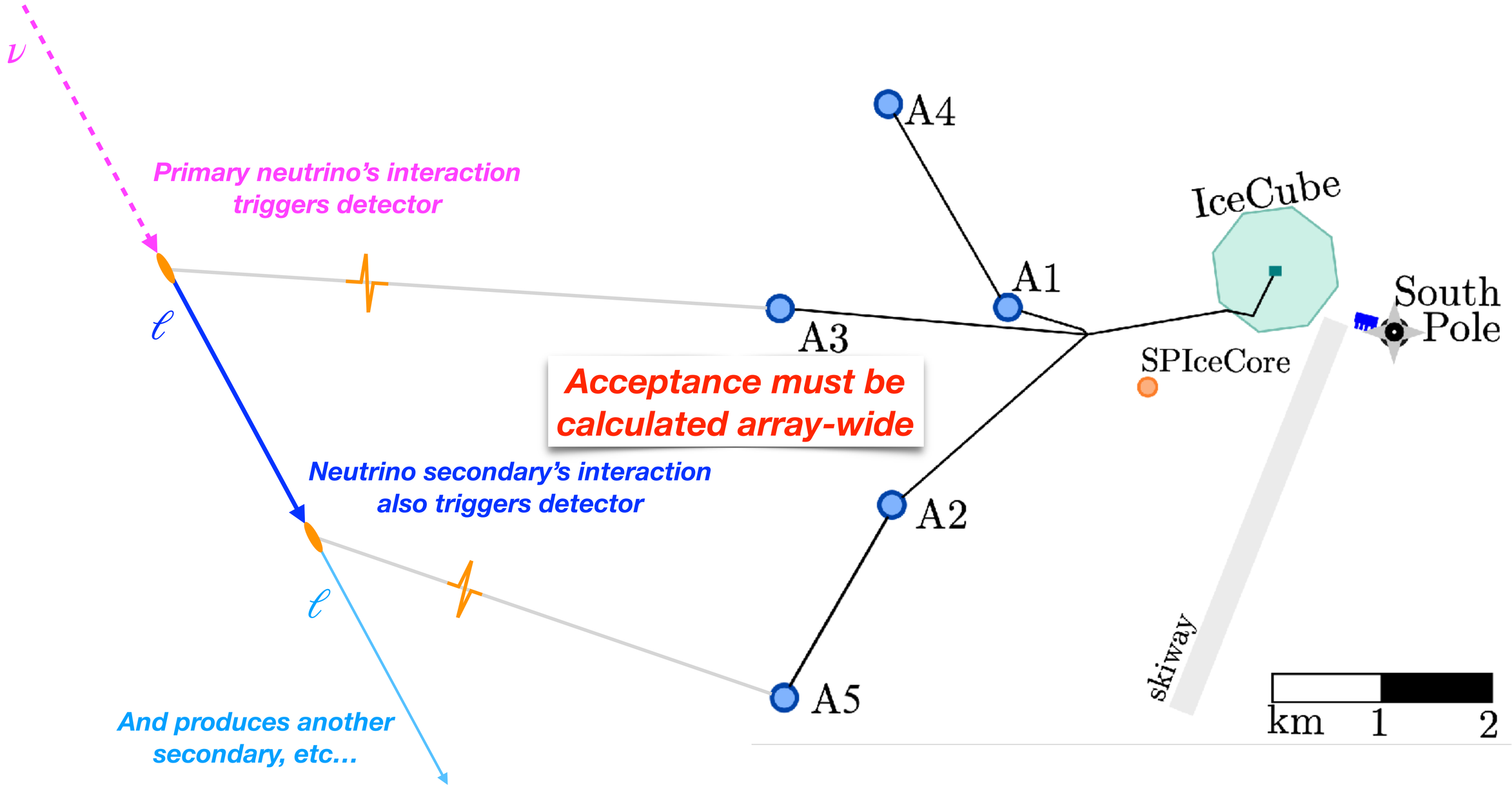

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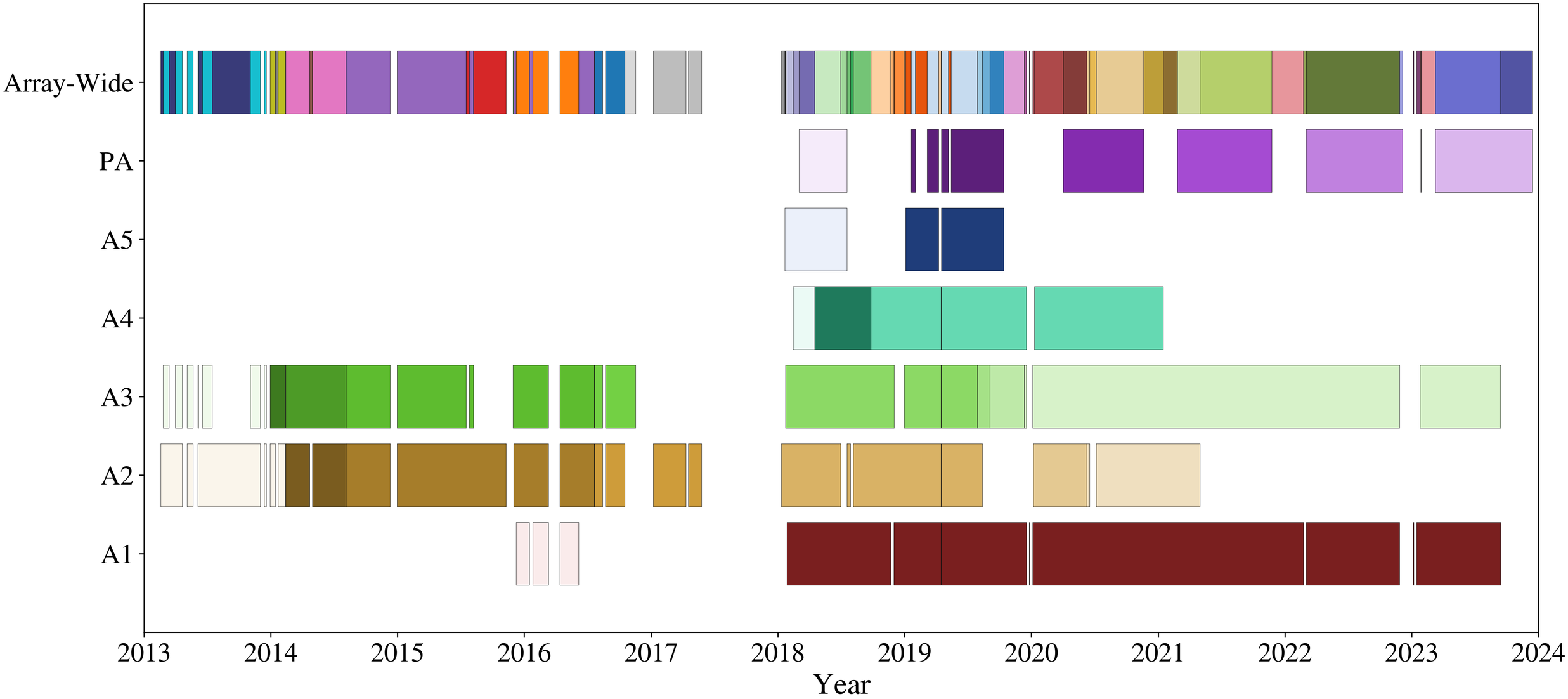

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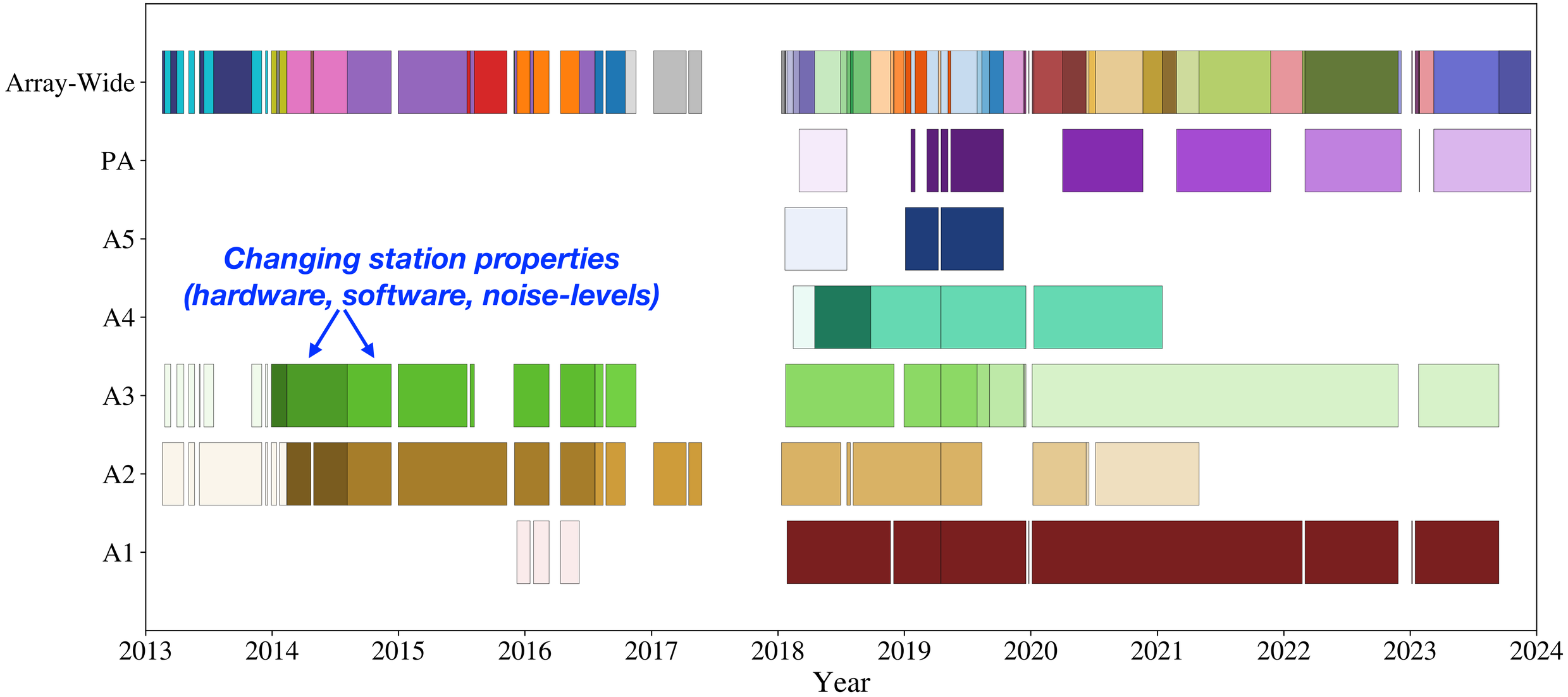

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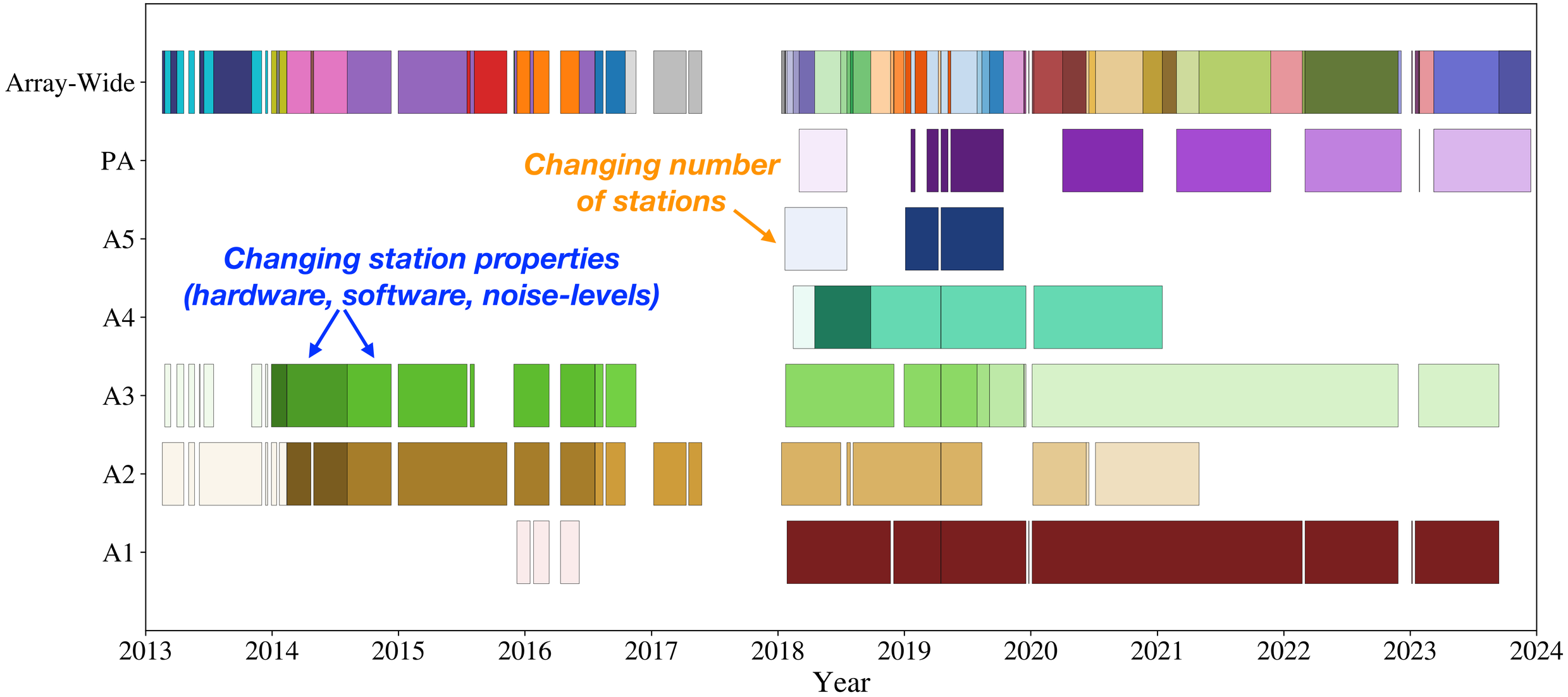

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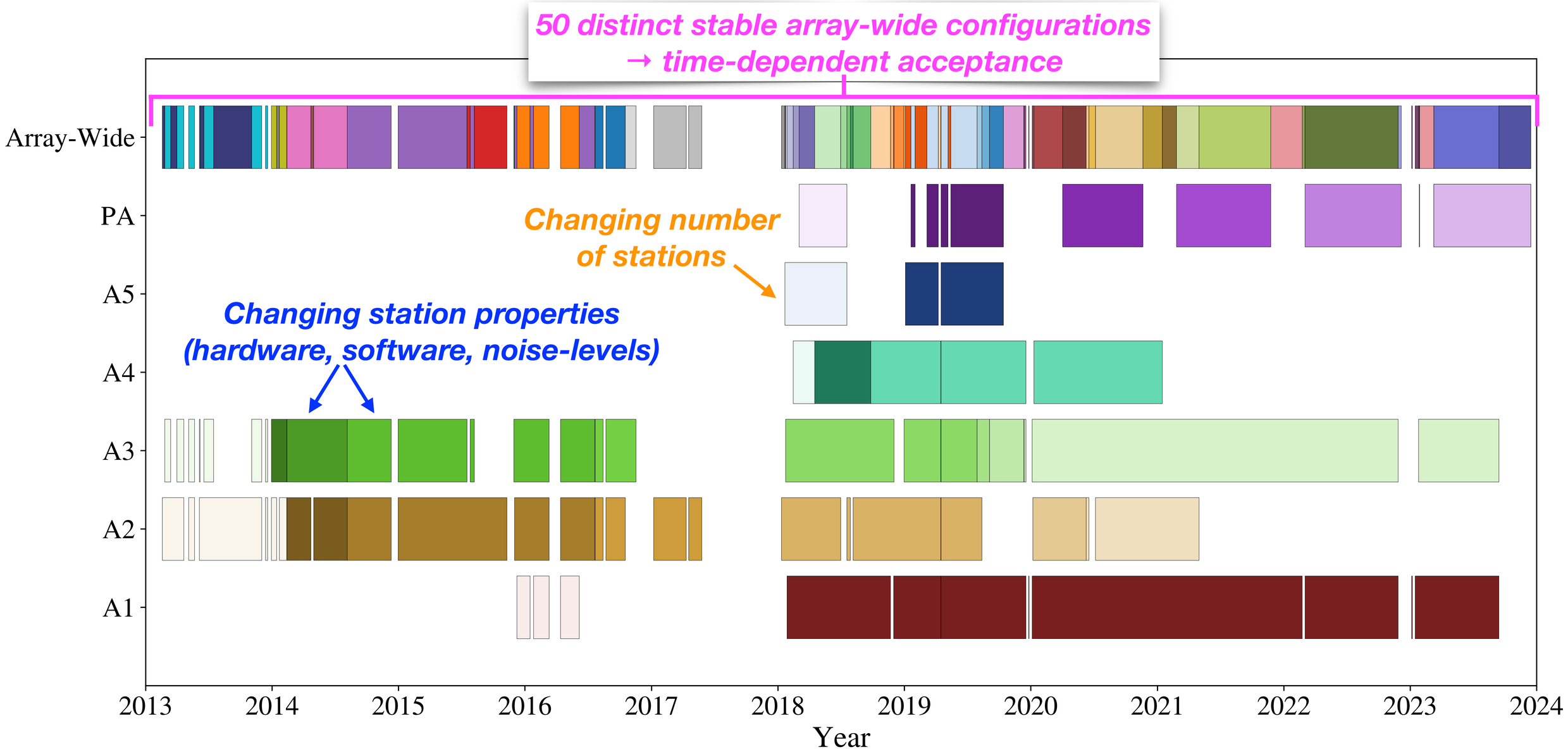


Overview of Simulation Pipeline

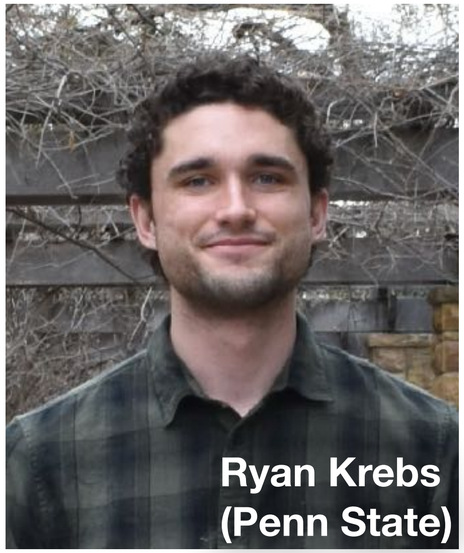
Array-Wide Event Library Generation with NuLeptonSim

→

Single-Station Detector Simulation with AraSim

→

Array-Wide Acceptance Calculation


Ryan Krebs
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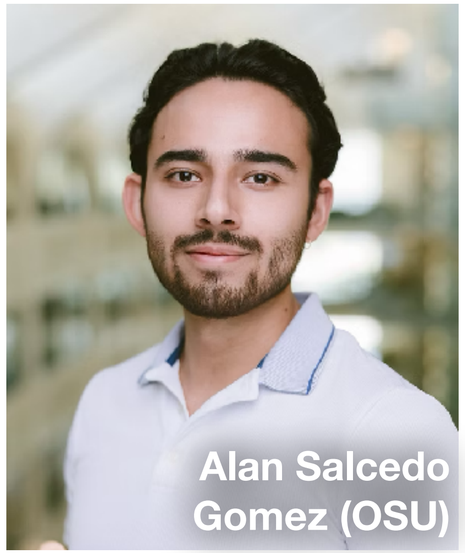
Abby Bishop
(UW Madison)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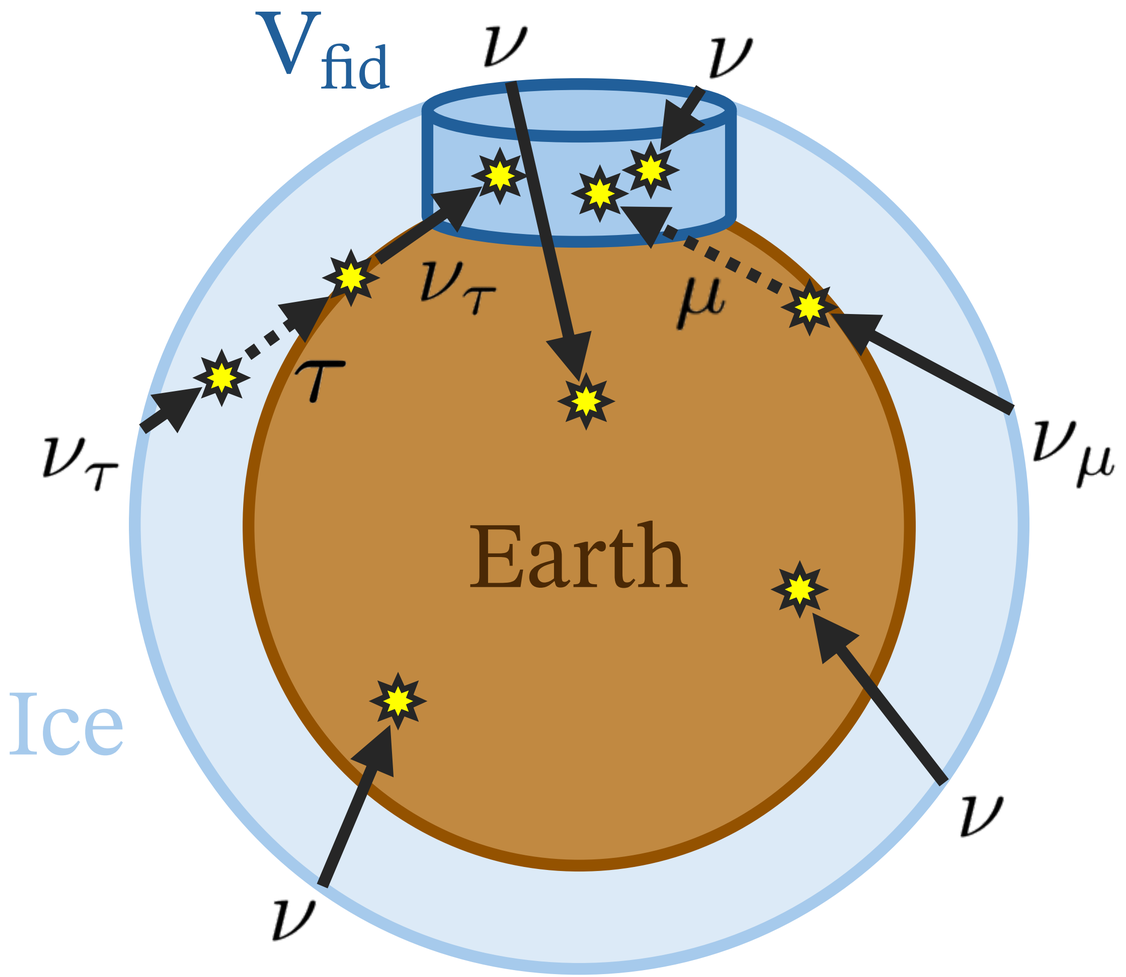
Alden et al. (ARA Collaboration), submitted to PRD, arXiv:2605.04268

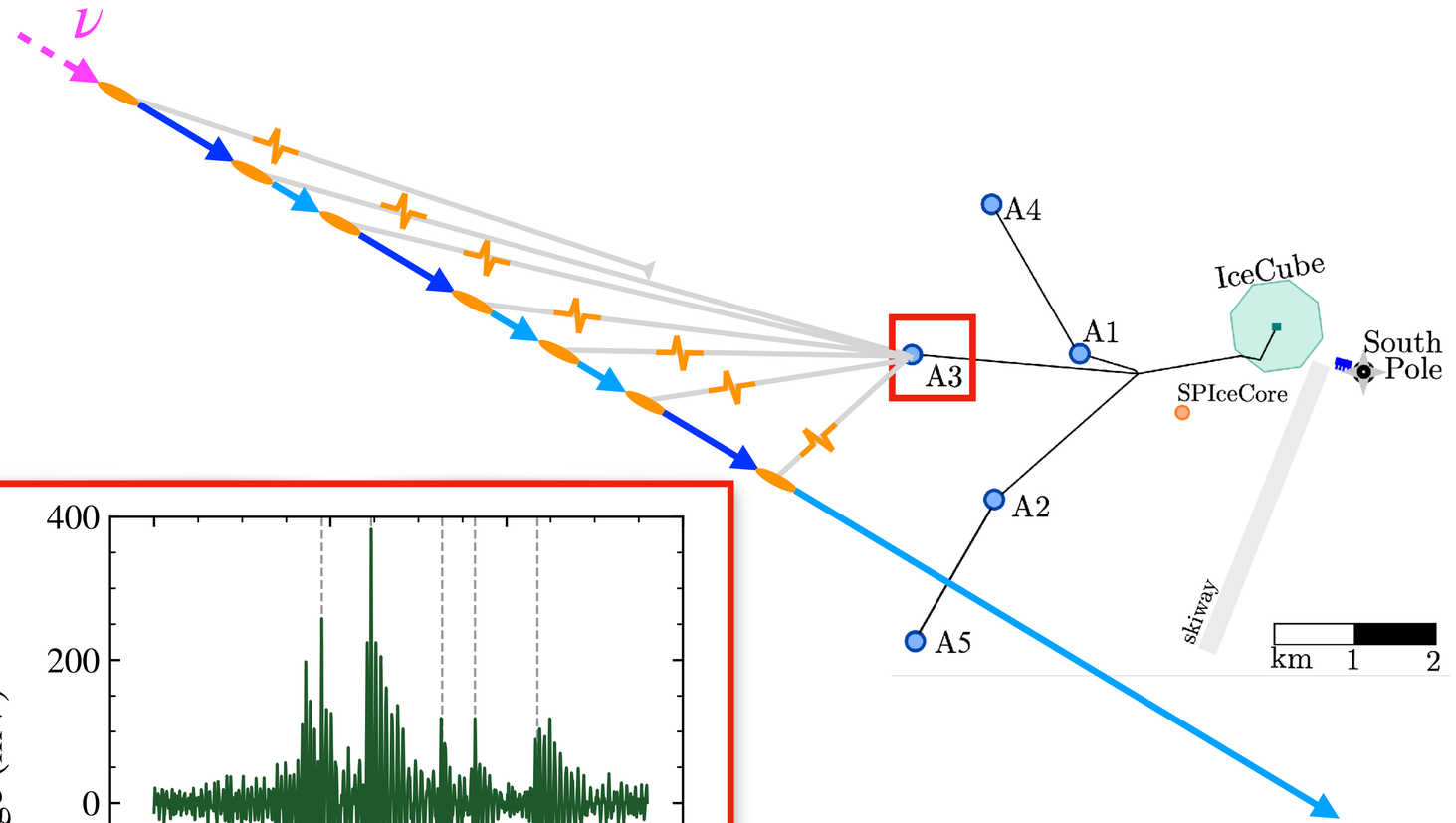
Array-Wide Event Library Generation

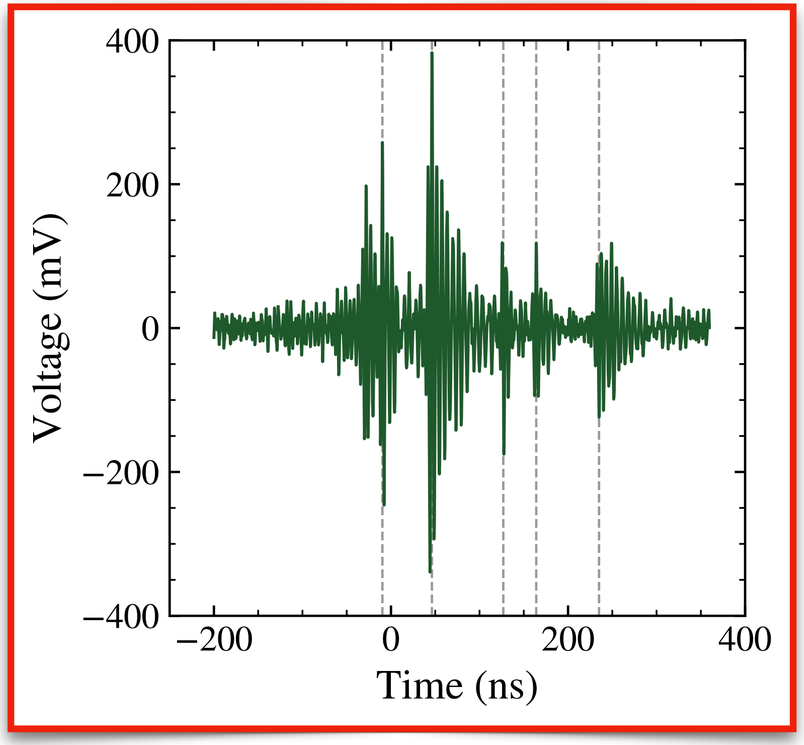
- NuLeptonSim is used to generate array-wide event library
- Forward propagate primary neutrinos & secondaries towards uniformly sampled points in fiducial volume
  - 15 km radius, 3 km high cylinder centered on A2
  - Directions uniformly sampled in 4π
- Save all interaction vertices in fiducial volume
  - All vertices carry a tracking ID denoting their primary neutrino



Single-Station Detector Simulation

- Each station-config is simulated independently with AraSim
- All interaction with same primary neutrino ID are simulated together
  - Signals combined into a single trace with proper relative timing
  - Trigger simulation is carried out iteratively & accounting for deadtime
- Major improvements made to AraSim
  - More faithful gain & noise models
  - Direct measurements of antenna gain





Array-Wide Acceptance Calculation

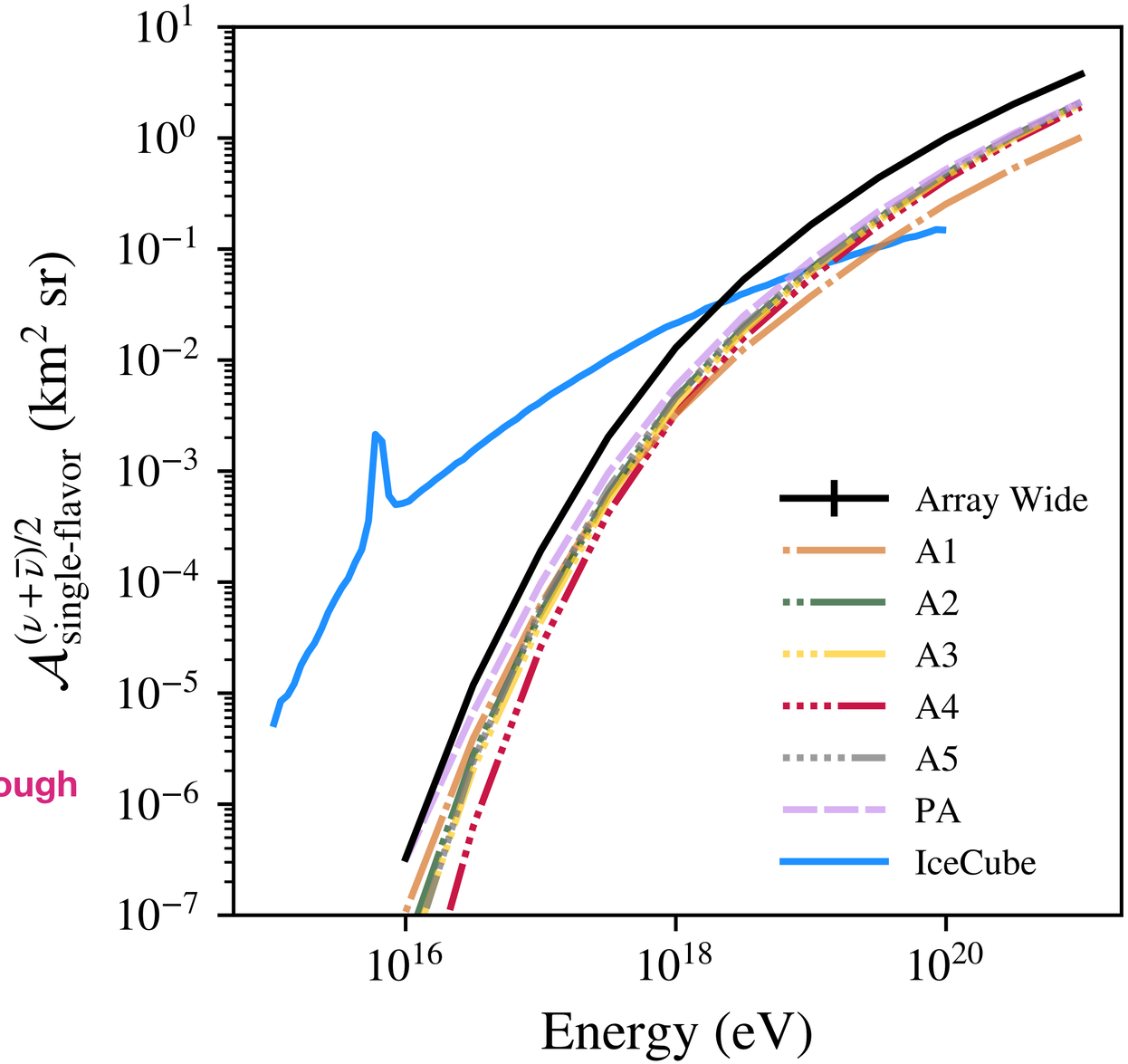
- Station-level simulations are aggregated to calculate array-wide acceptance
- Triggers which share the same primary neutrino ID are counted once

All sky-averaged probability to generate vertex in fiducial volume

$$\mathcal{A}(E) = \frac{4\pi V_{\mathrm{fid}} \langle p_{\mathrm{acc}} \rangle (E)}{N} \sum_{i}^{N_{\mathrm{trig}}} \frac{1}{L_i}$$

Number of distinct primary neutrinos in event library

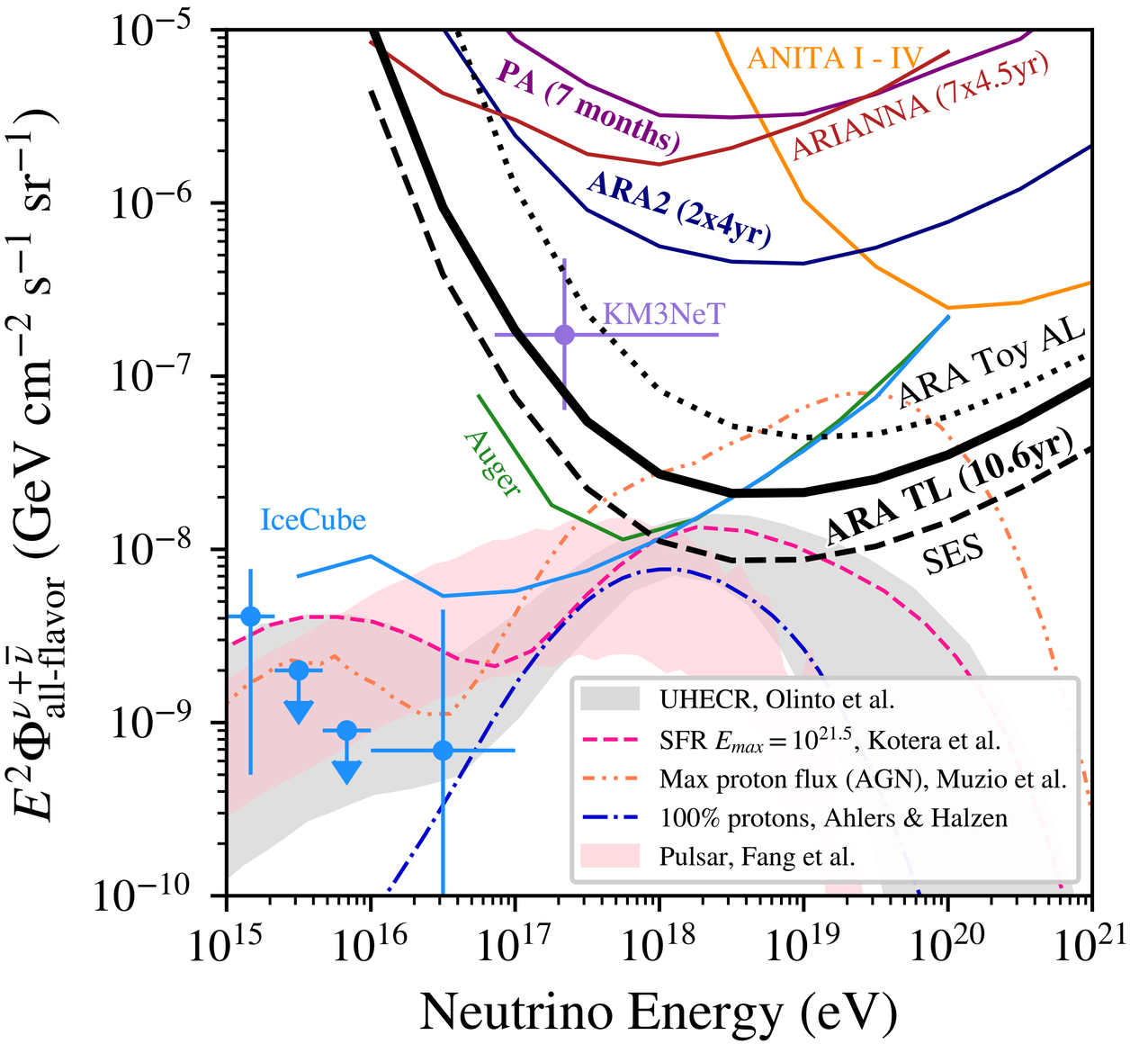
Length of chord through fiducial volume



Sensitivity Projection

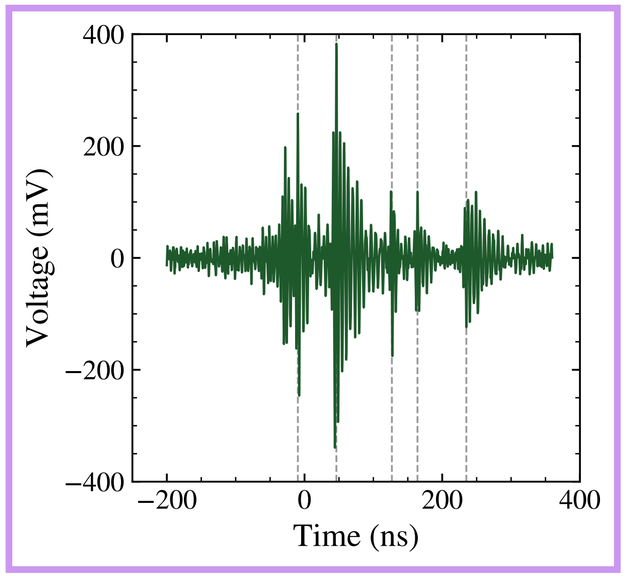
- Total exposure calculated summing acceptance over all array-wide configurations from 2013-2023
- Trigger-level sensitivity probes several UHE neutrino flux models and KM3NeT flux
- Toy event selection demonstrates potential effect of signal efficiency
  - SNR ≥ 5
  - Elevation angle from below total internal reflection angle minus 5°

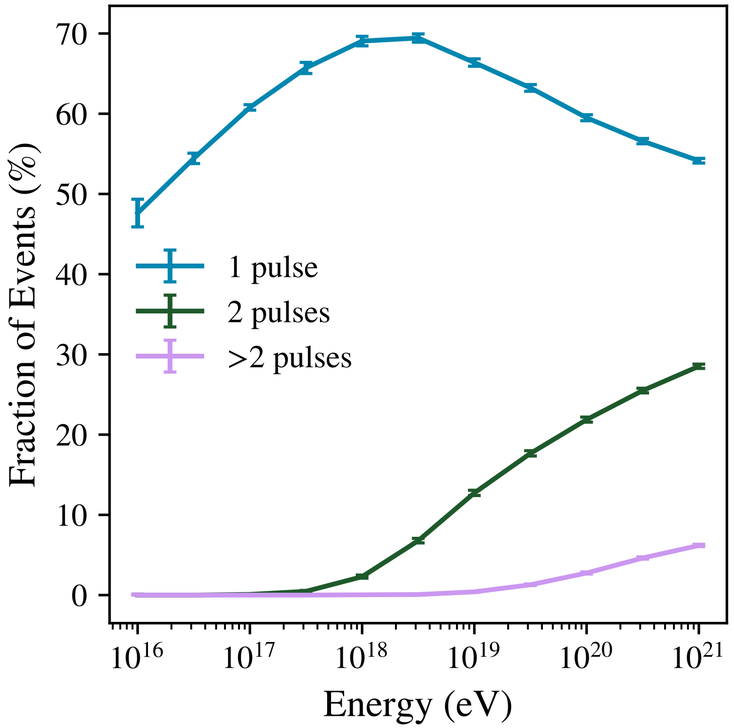
Flux Model	Trigger	Analysis	Multi-station
Muzio	13.01	6.28	1.82
Kotera	2.27	0.95	0.20
100% Protons	0.96	0.36	0.06
Fang Pulsars	1.46	0.48	0.06
KM3NeT	13.71	4.24	0.36

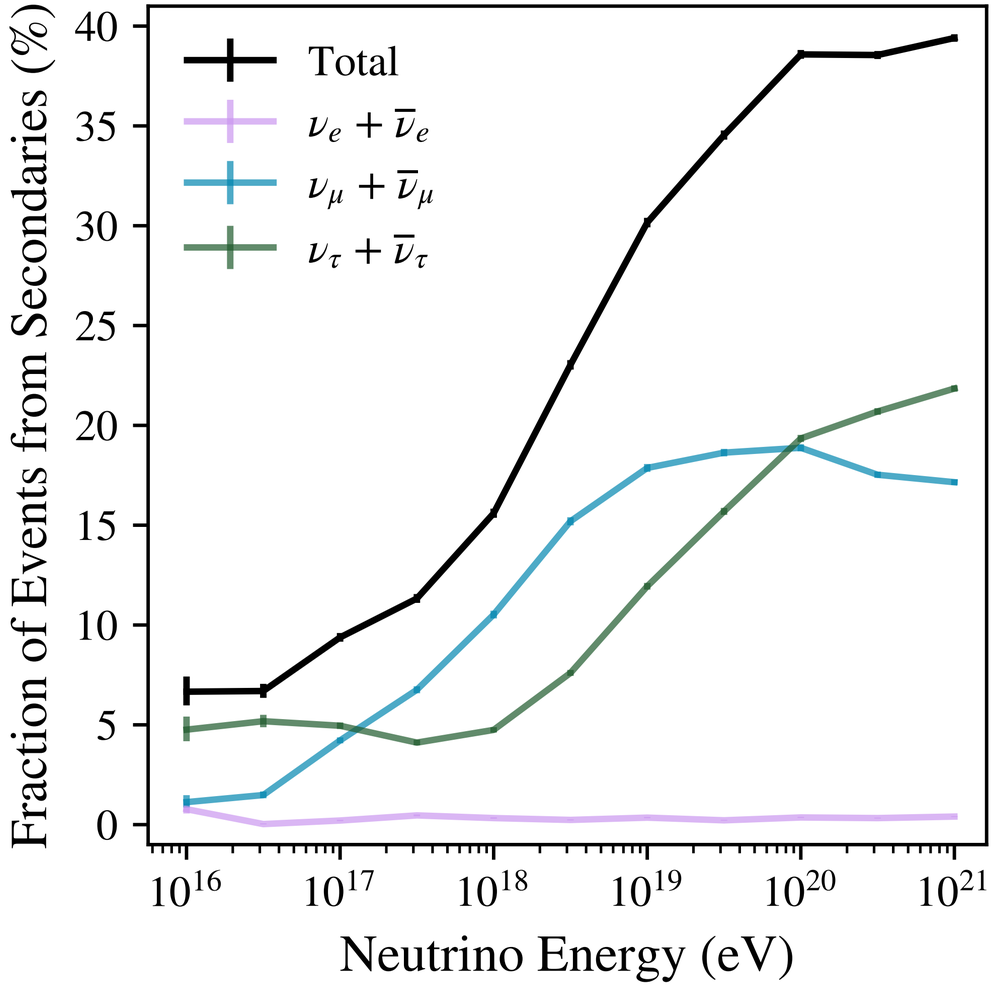


Contribution of Secondaries

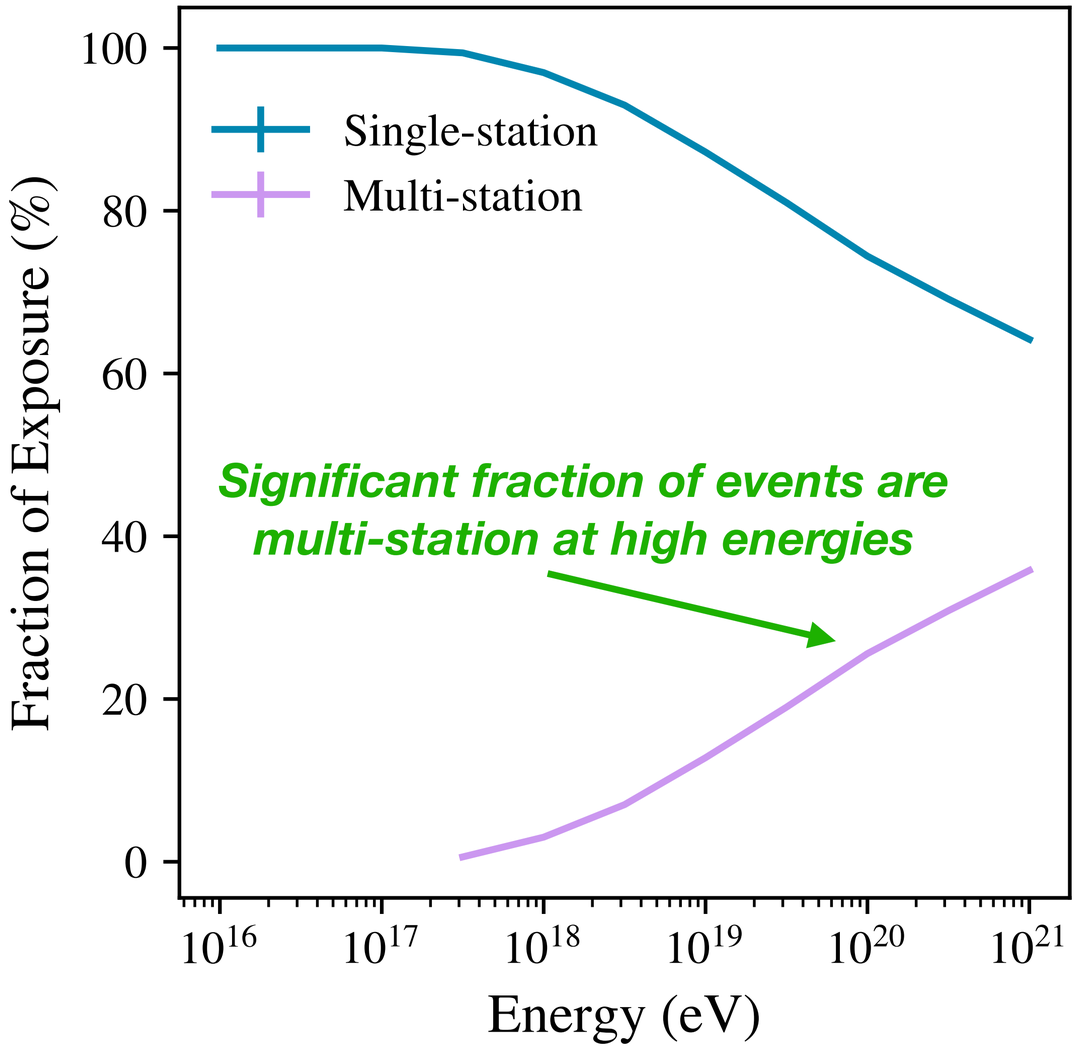
- ~40% triggers from secondaries at highest energies
- Secondaries can lead to non-trivial waveforms
  - ≥ 20% of events have ≥ 2 distinct pulses in trace above ~30 EeV
  - Important to consider in analysis

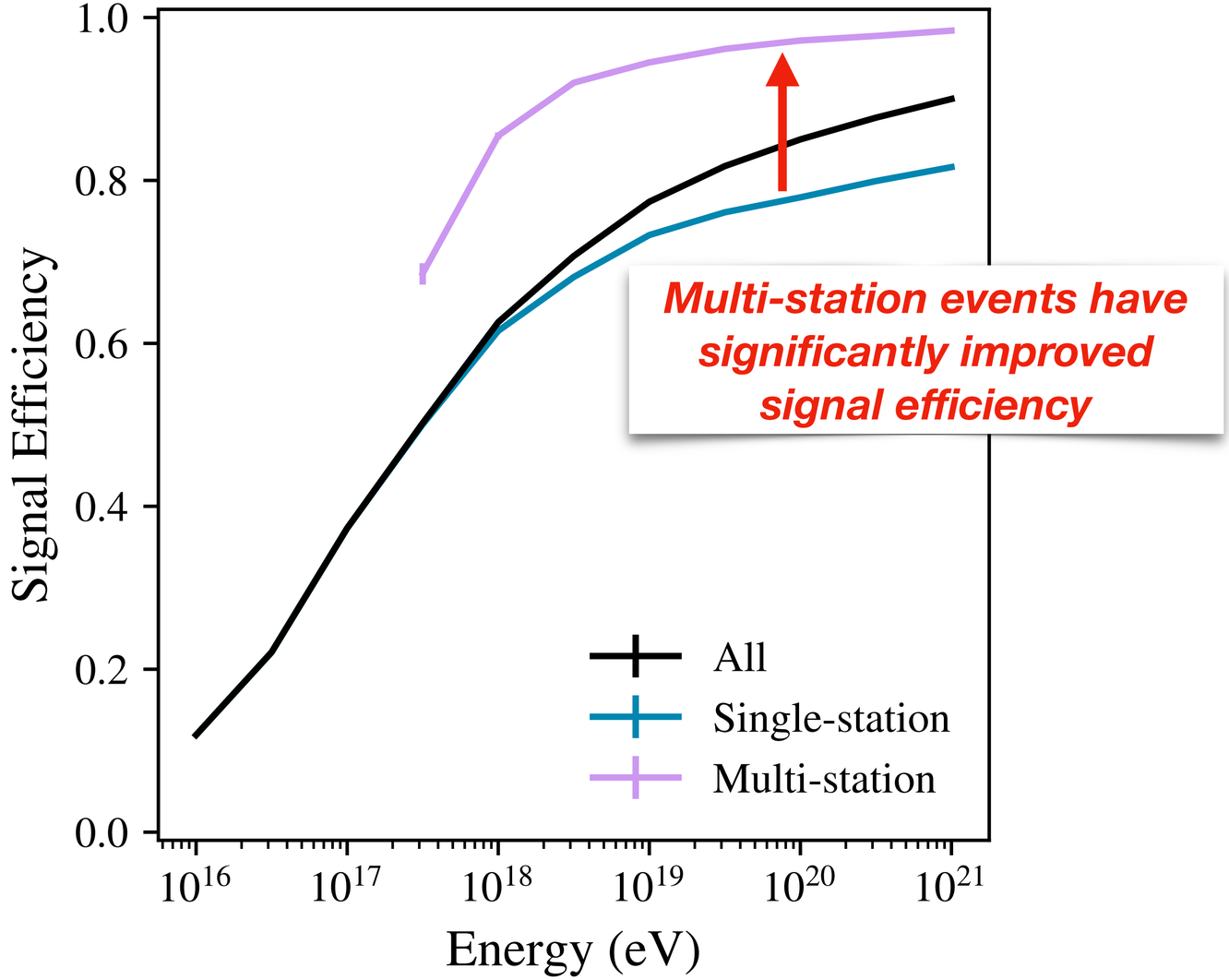






Multi-Station Triggers

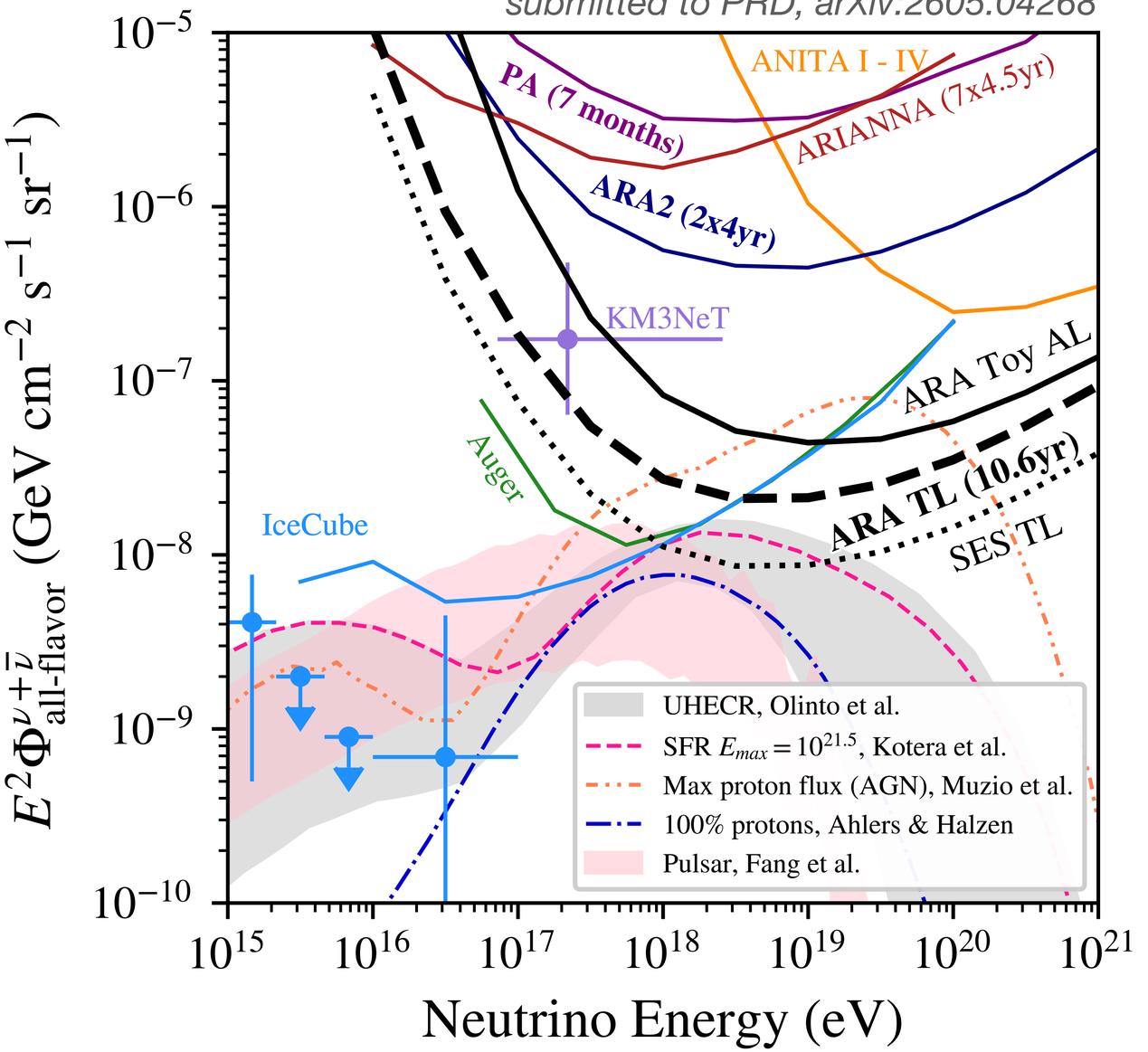




Summary

- Calculated array-wide sensitivity of ARA
  - Accounted for secondaries & time-dependence of array
- ARA probes several UHE neutrino flux models & KM3NeT flux at trigger-level
- Potential to place strongest constraints beyond ~10 EeV
- Large contribution to sensitivity from secondaries
  - Create non-trivial waveforms
- Multi-station triggers are common at high energies
  - Higher analysis efficiency → important to consider in future array designs

Alden et al. (ARA Collaboration), submitted to PRD, arXiv:2605.04268



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