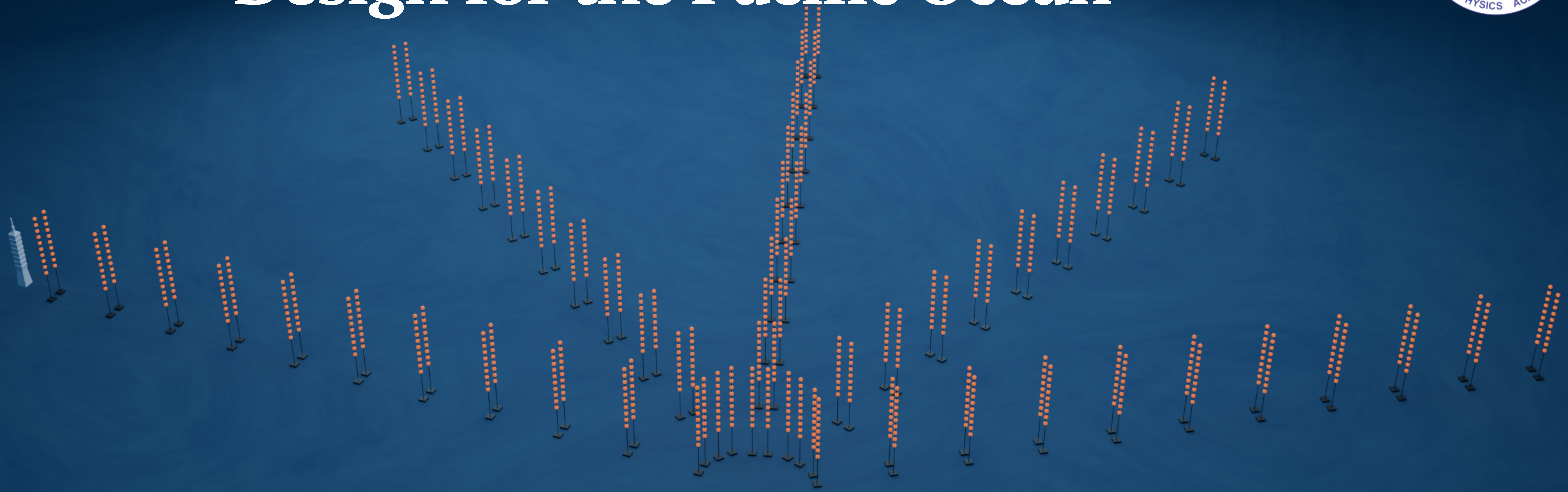
POLARIS: A Sparse Radial Neutrino Telescope Design for the Pacific Ocean



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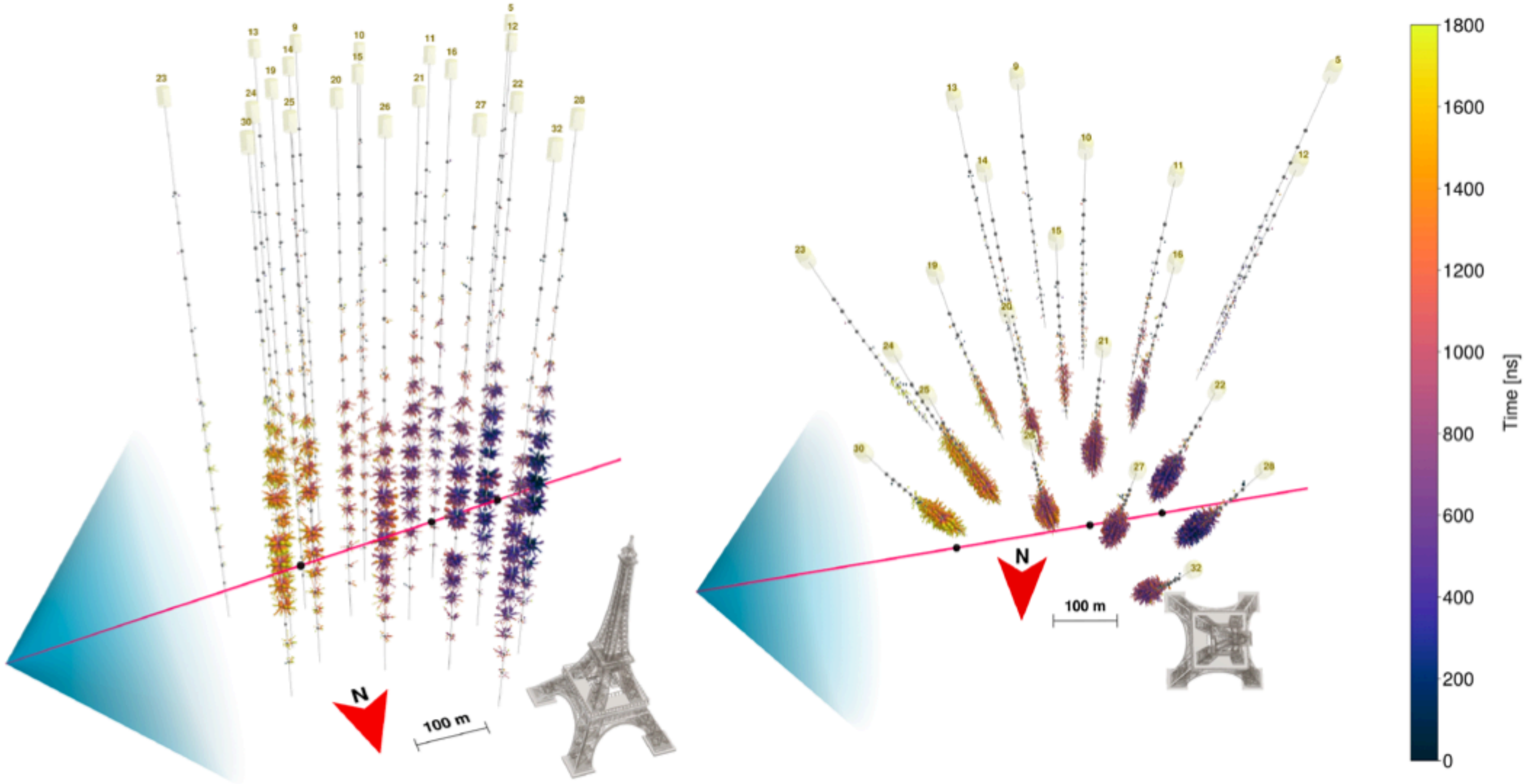
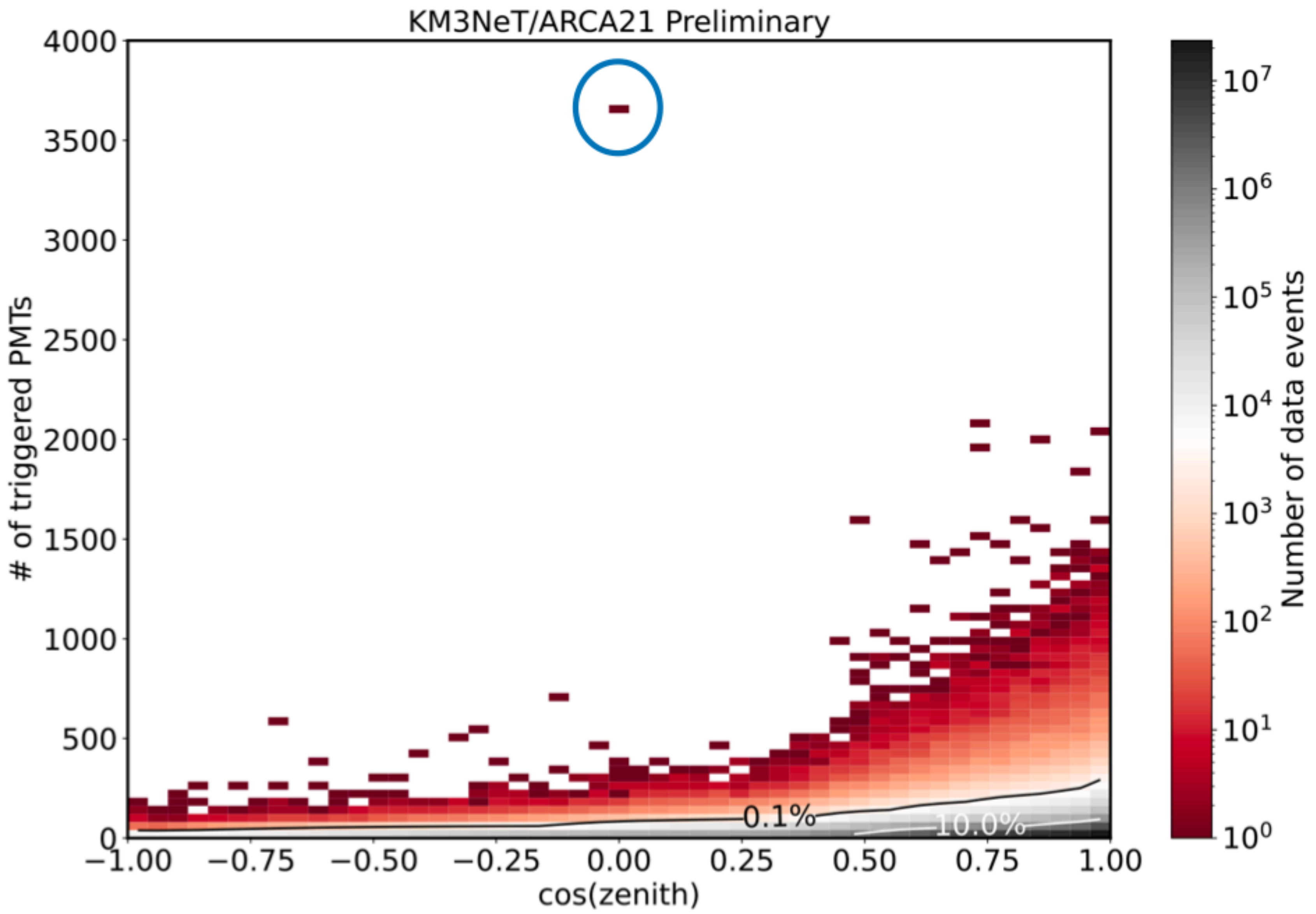
TEVPA

01/09/2026

The highest-energy neutrino measured so far

220^{+550}_{-110} *PeV cosmic neutrino KM3-20230213A measured by KM3NeT (ARCA-21)*





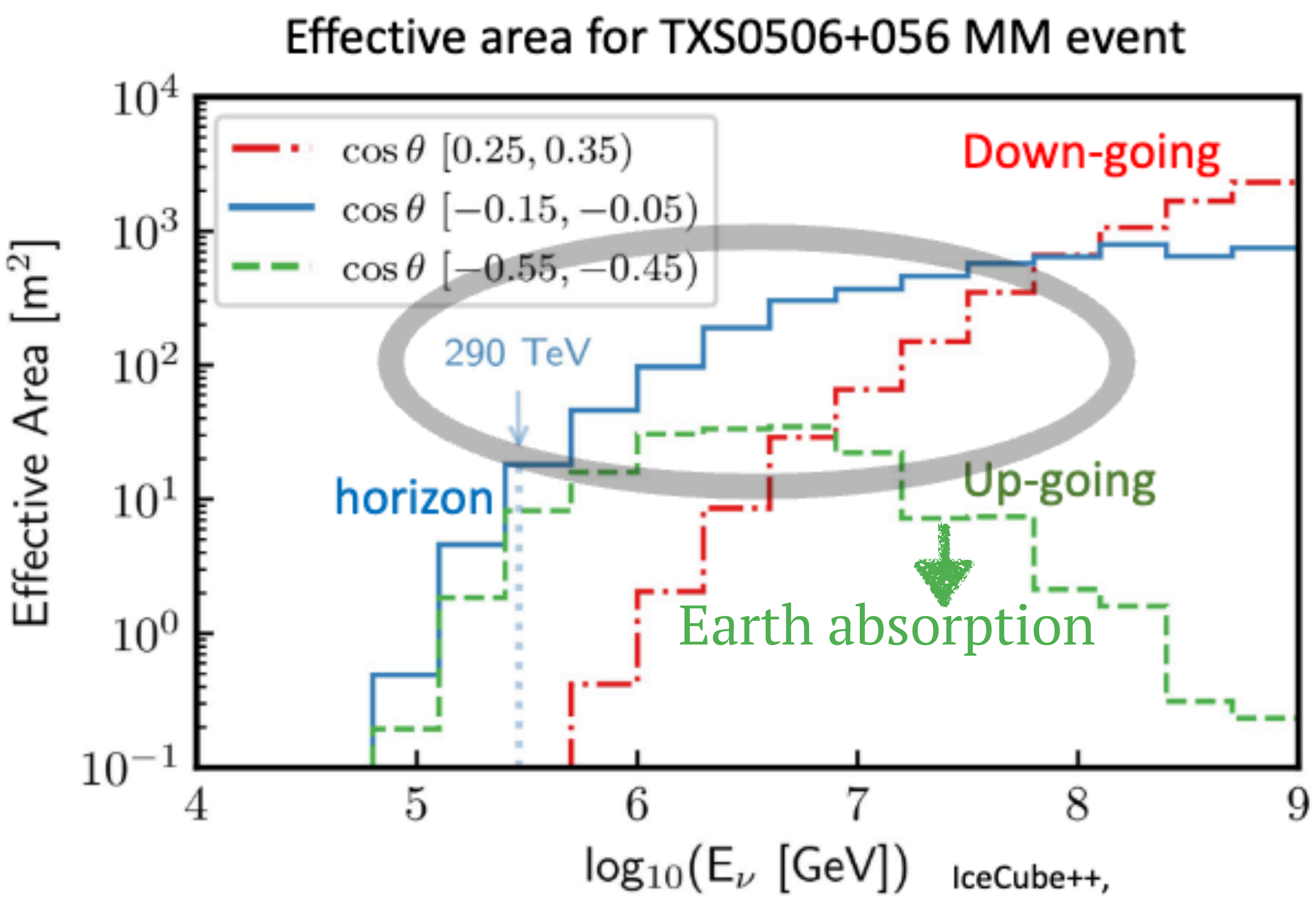
KM3NeT Collab., Nature 638 (2025)

Atmospheric muons & neutrinos very unlikely at **horizontal direction** & energy

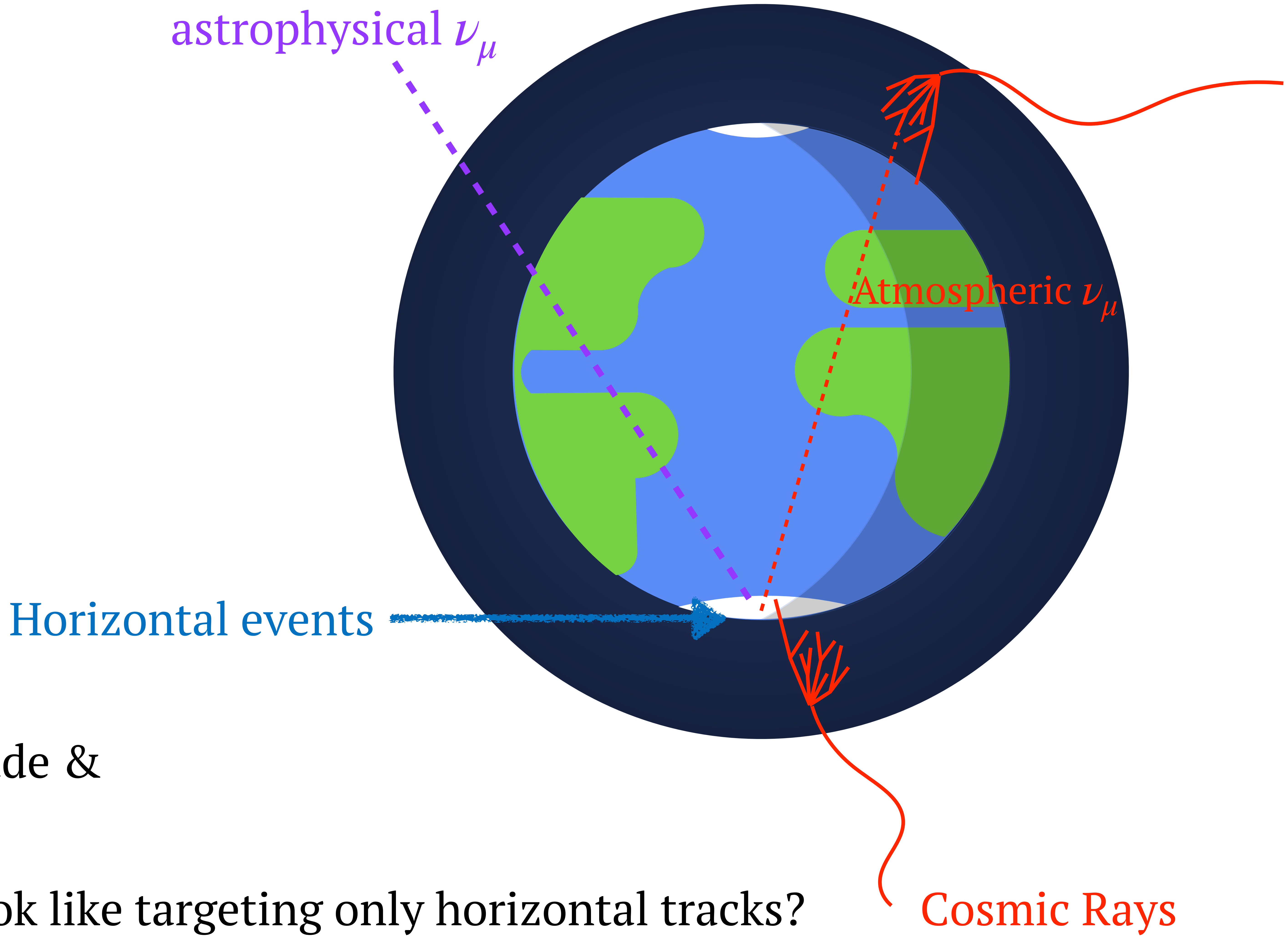
Reconstructed direction: (RA, dec) =(94.3 deg,−7.8 deg)

Horizontal tracks as pathway to PeV events

Example from IceCube



IceCube++, Science/eaat1378, (2018)



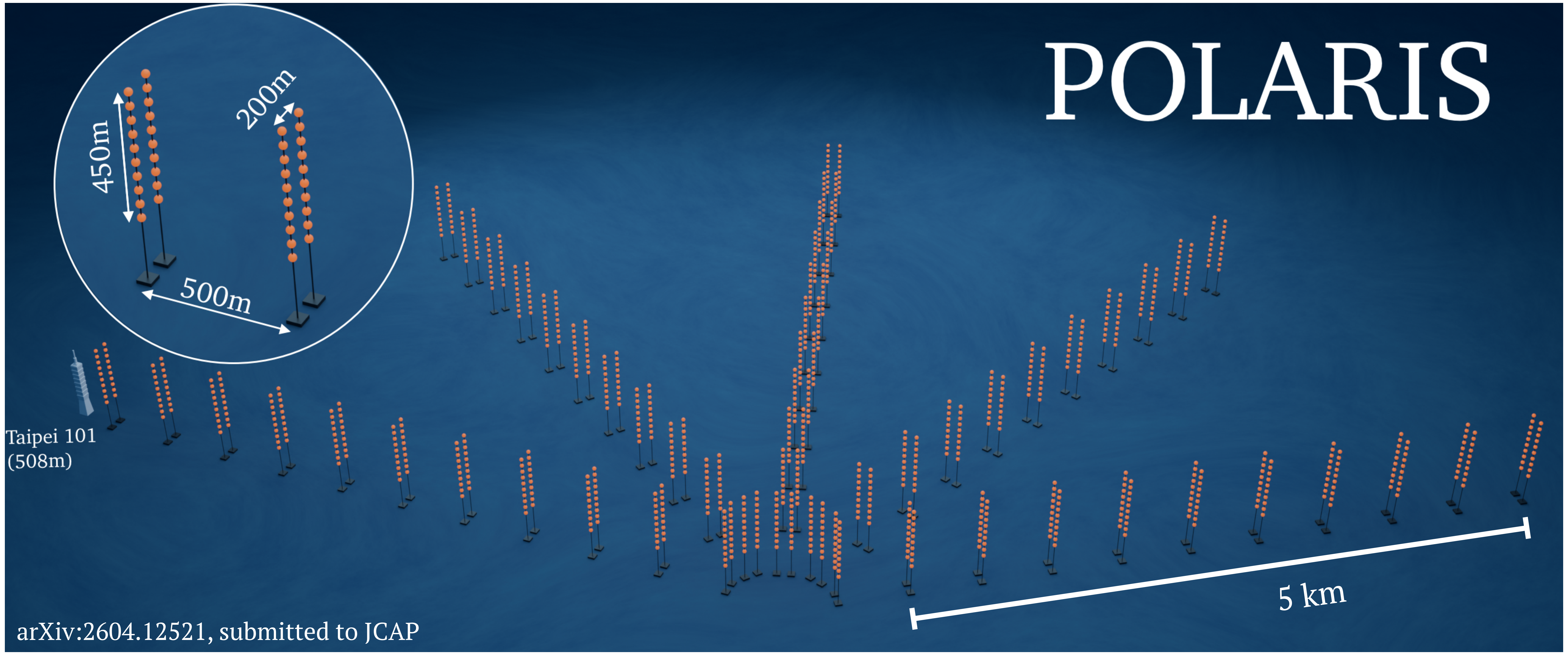
Volume detectors are optimized for both cascade & tracks across sub-GeV to PeV energies

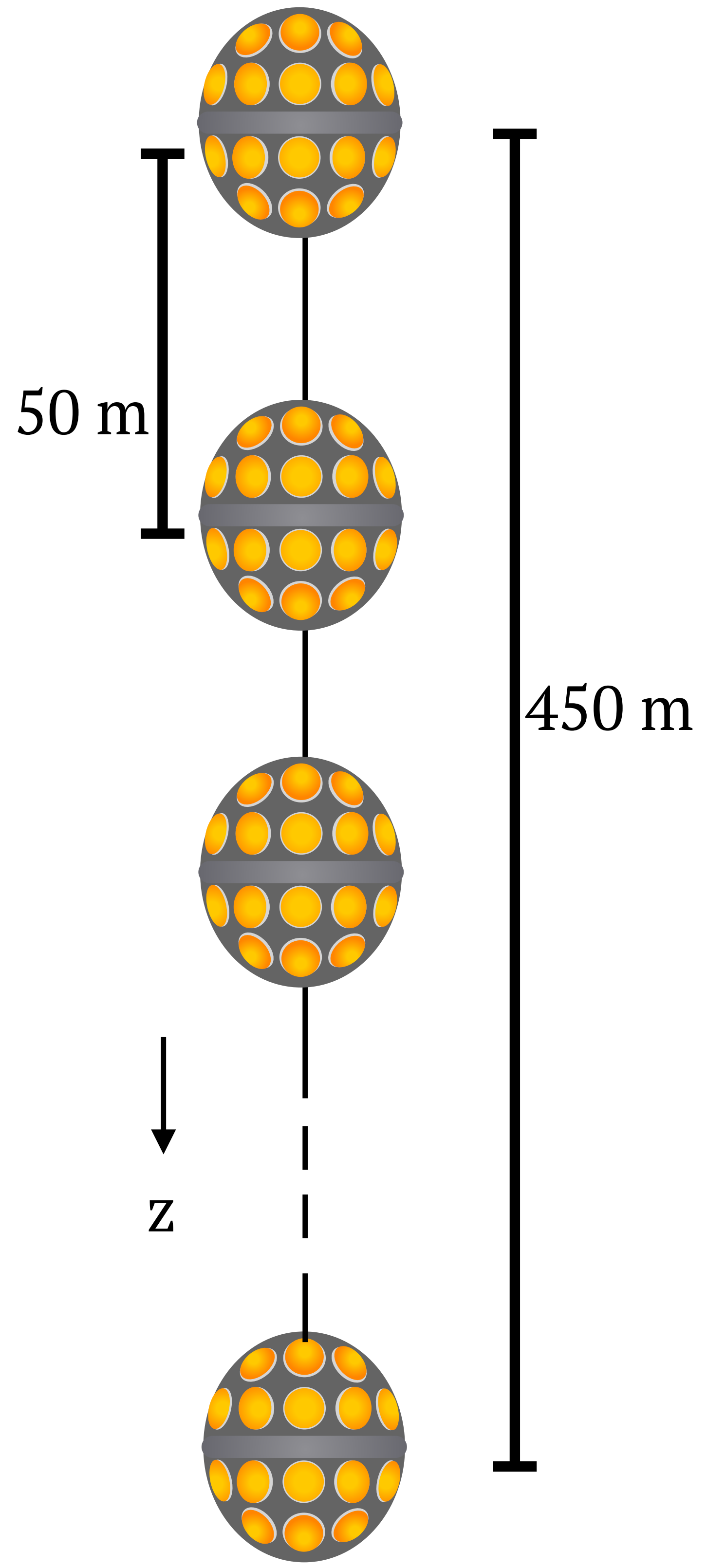
How could a detector geometry look like targeting only horizontal tracks?

Pacific Ocean Large Area Radial Instrumented Sparse array

Potential site: flat plane with low ocean currents at ~3 km depth

Selected for sensitivity studies





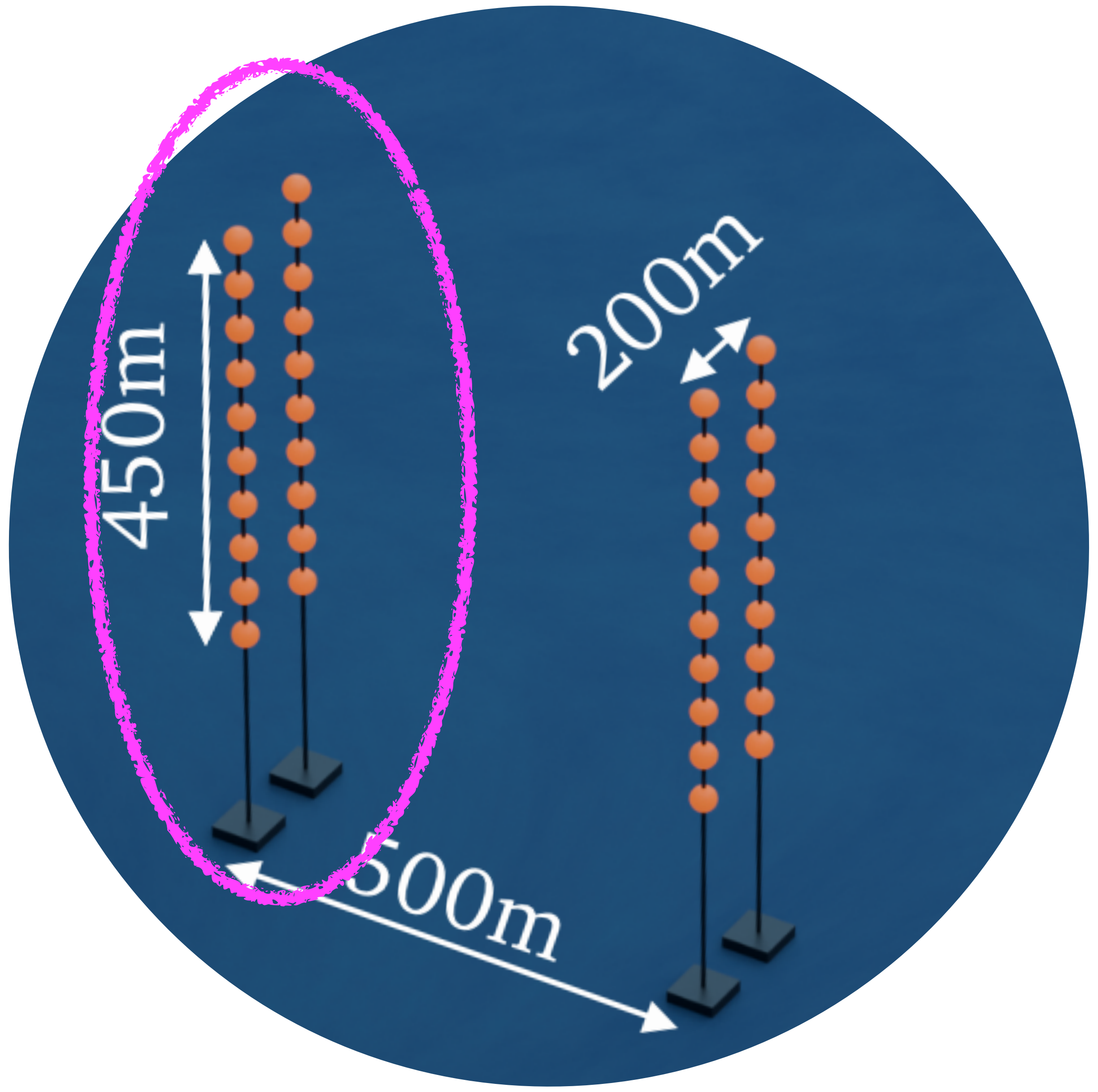
- Neutrino telescope design for detection of astrophysical neutrino sources (10 TeV to 1 EeV)
- Purpose design for **horizontal tracks**
- Large spacing to naturally eliminate cascades & muons —> no further detector design optimization done yet
- Goal: Minimal cost-effective arrangement with ~**1100 optical modules** & comparable sensitivity to other experiments

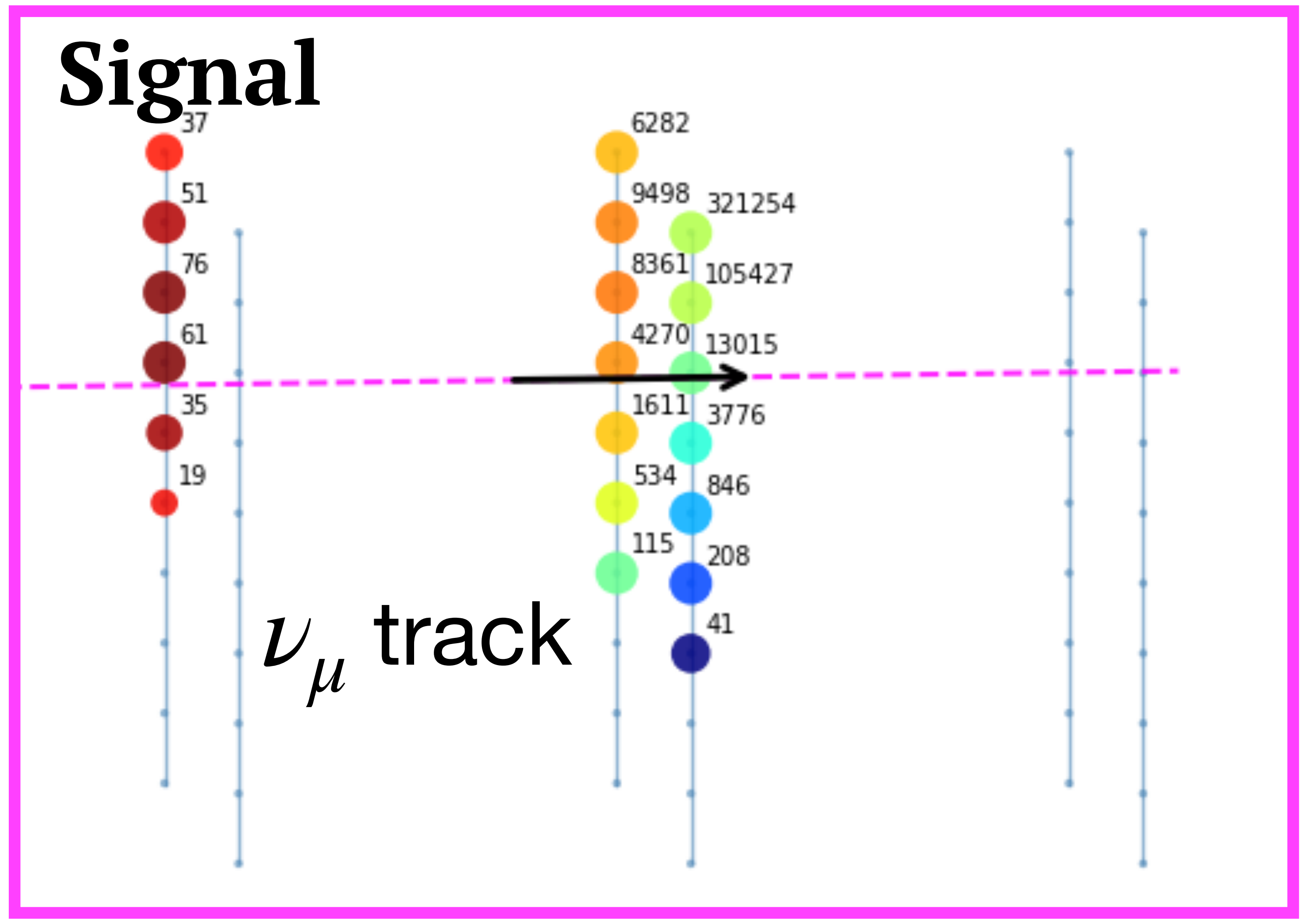
Track Event Selection & Cascade Removal

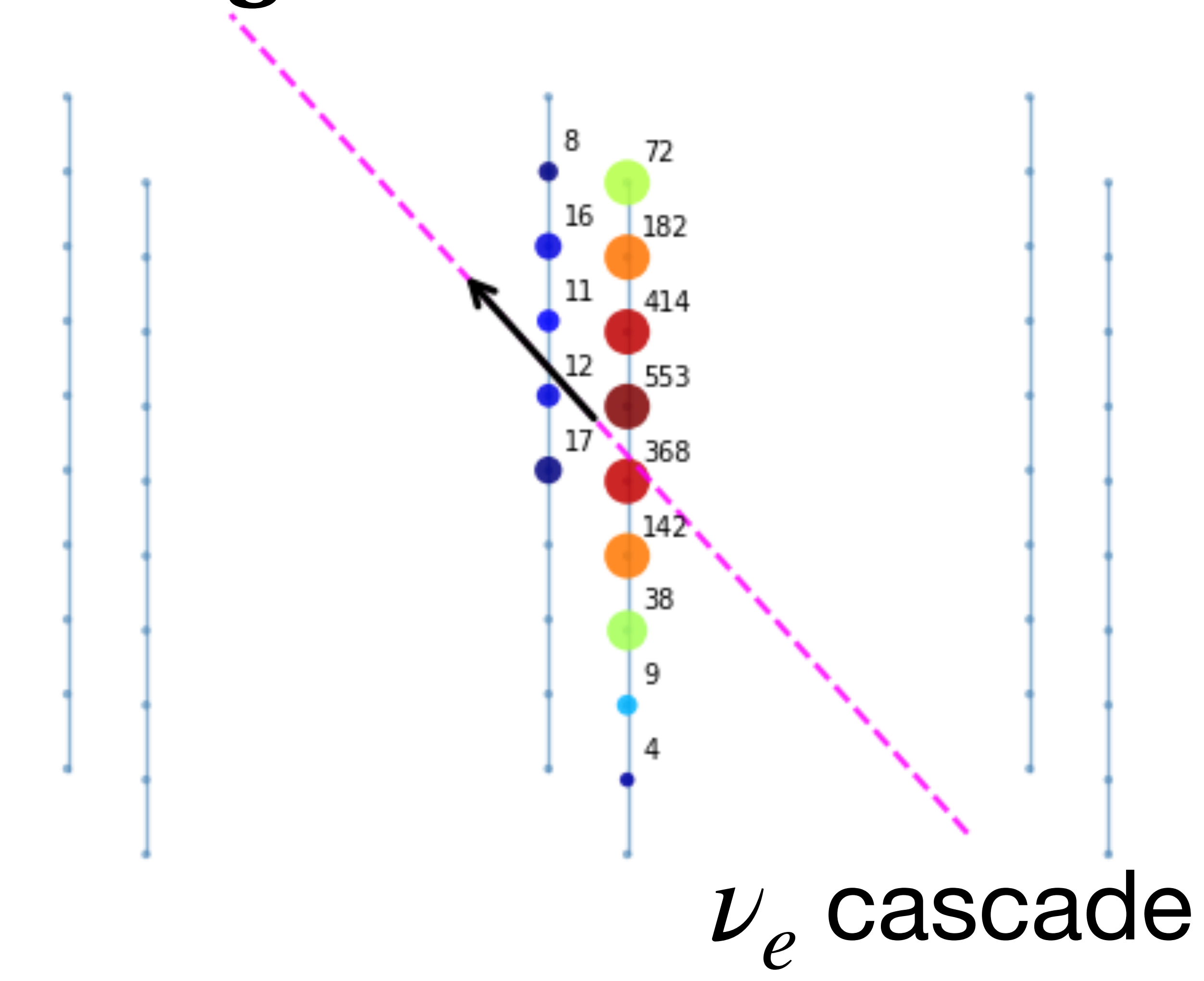
Criterion	Purpose
Hits at a minimum of 2 consecutive gates	Cascade rejection < 1 PeV

Gate

2 vertical strings separated by 200 m in the transverse direction







Simulation done with Prometheus

https://github.com/Harvard-Neutrino/prometheus

Most cascades (E < PeV) do not deposit energy at distances > 500m

Additional cuts on hit distribution & track length to remove PeV cascades

~22% signal efficiency

Astrophysical Potential

Calculate required flux to obtain 5σ detection significance

1. Create **search window** —> defined by angular resolution + 50% containment band

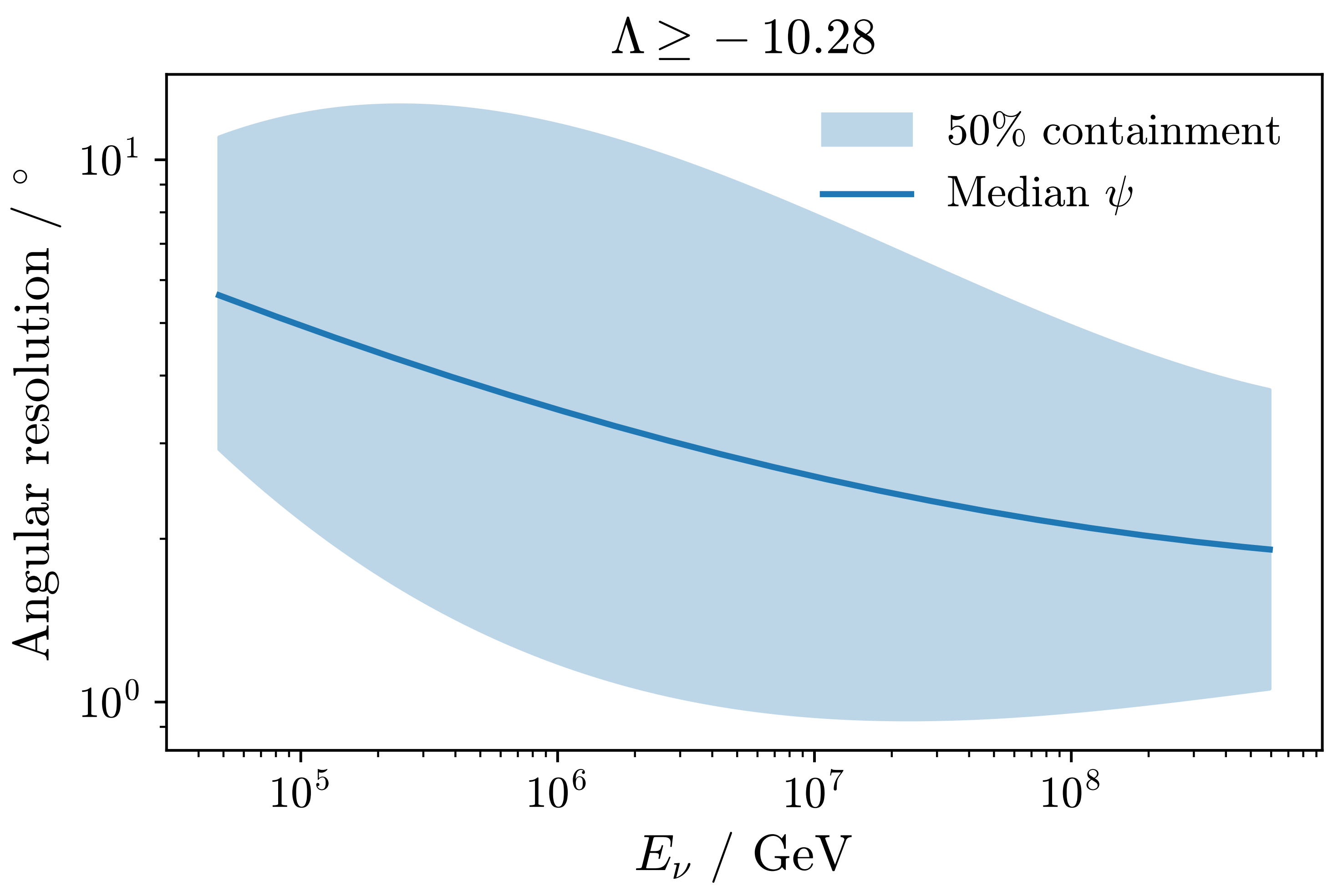
2. # **Signal events** s

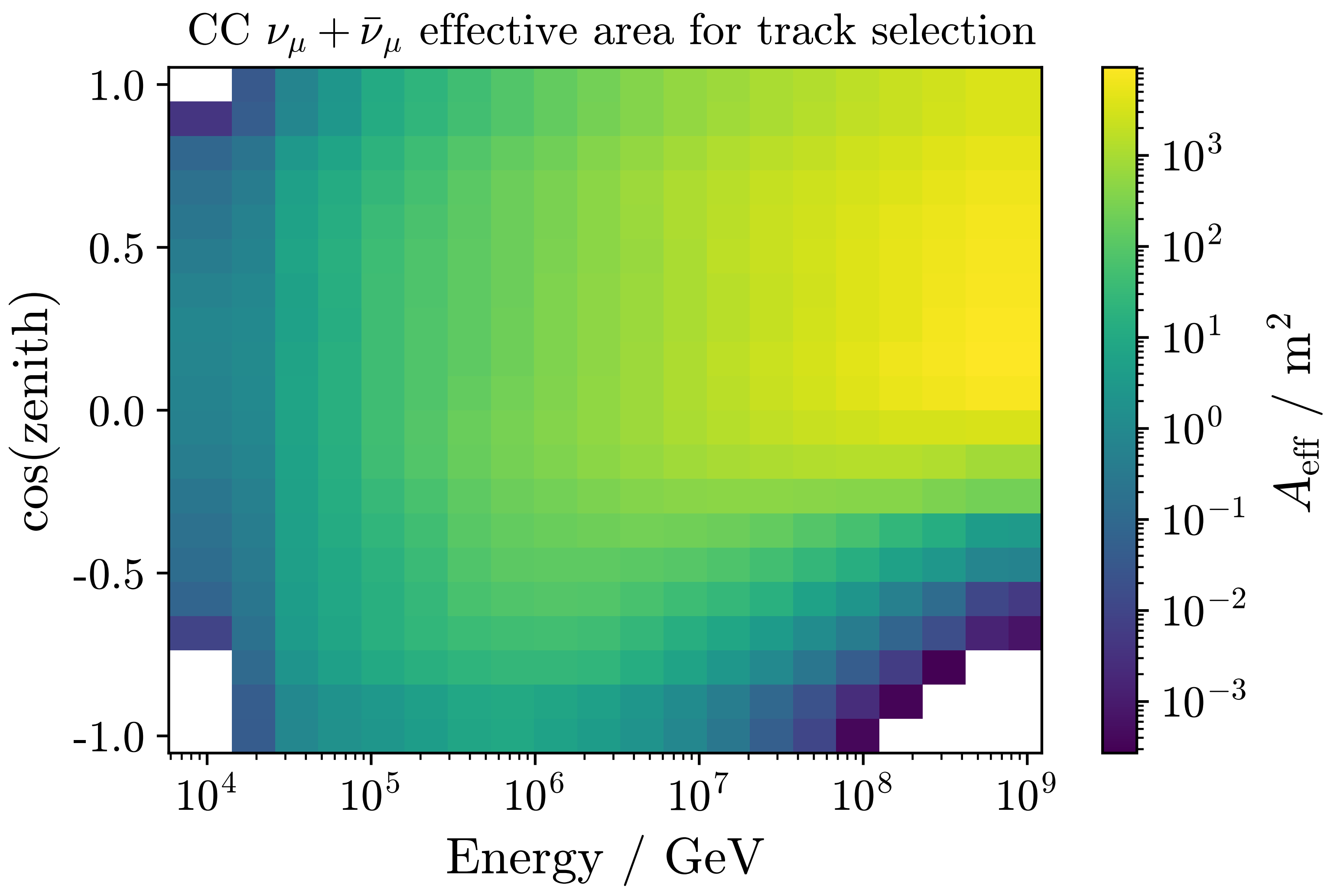
3. # **Background events** b
    - Atmospheric ν_μ: *Daemonflux*
    - Diffuse astrophysical ν_μ: *measured by IceCube*

4. **Poisson LLH fit** to obtain **flux normalization** for 5σ signal over background detection

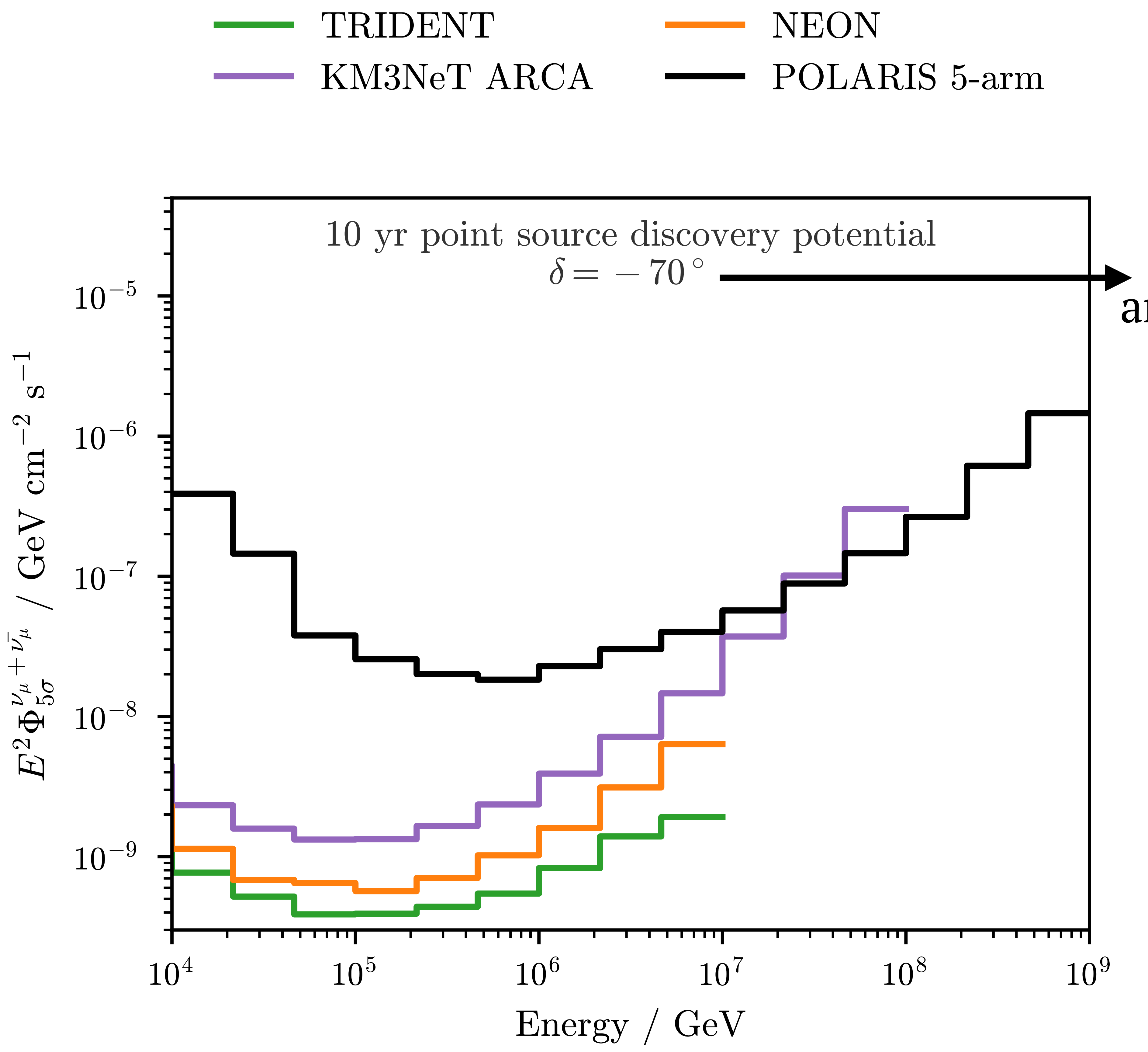
$$\mathrm{TS} = C_0 - C_1 = 2\sum_i \left[(s_i + b_i) - \nu_i \ln(s_i + b_i)\right] - 2\sum_i \left[b_i - \nu_i \ln b_i\right]$$
$$= 25 = 5\sigma$$

Inputs: angular resolution + effective area



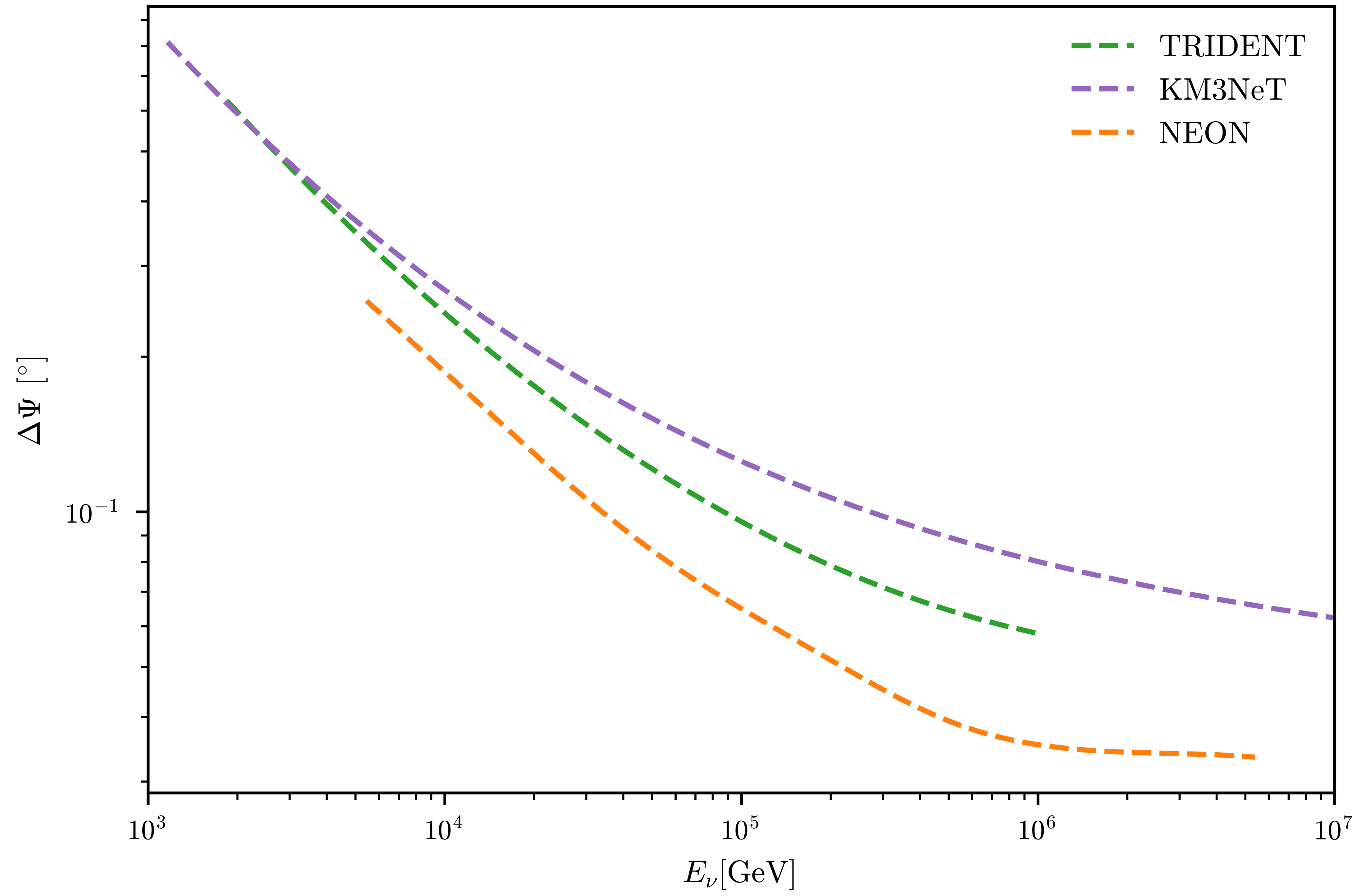


Point Source Sensitivity



Mostly horizontal/upgoing arrival directions for POLARIS

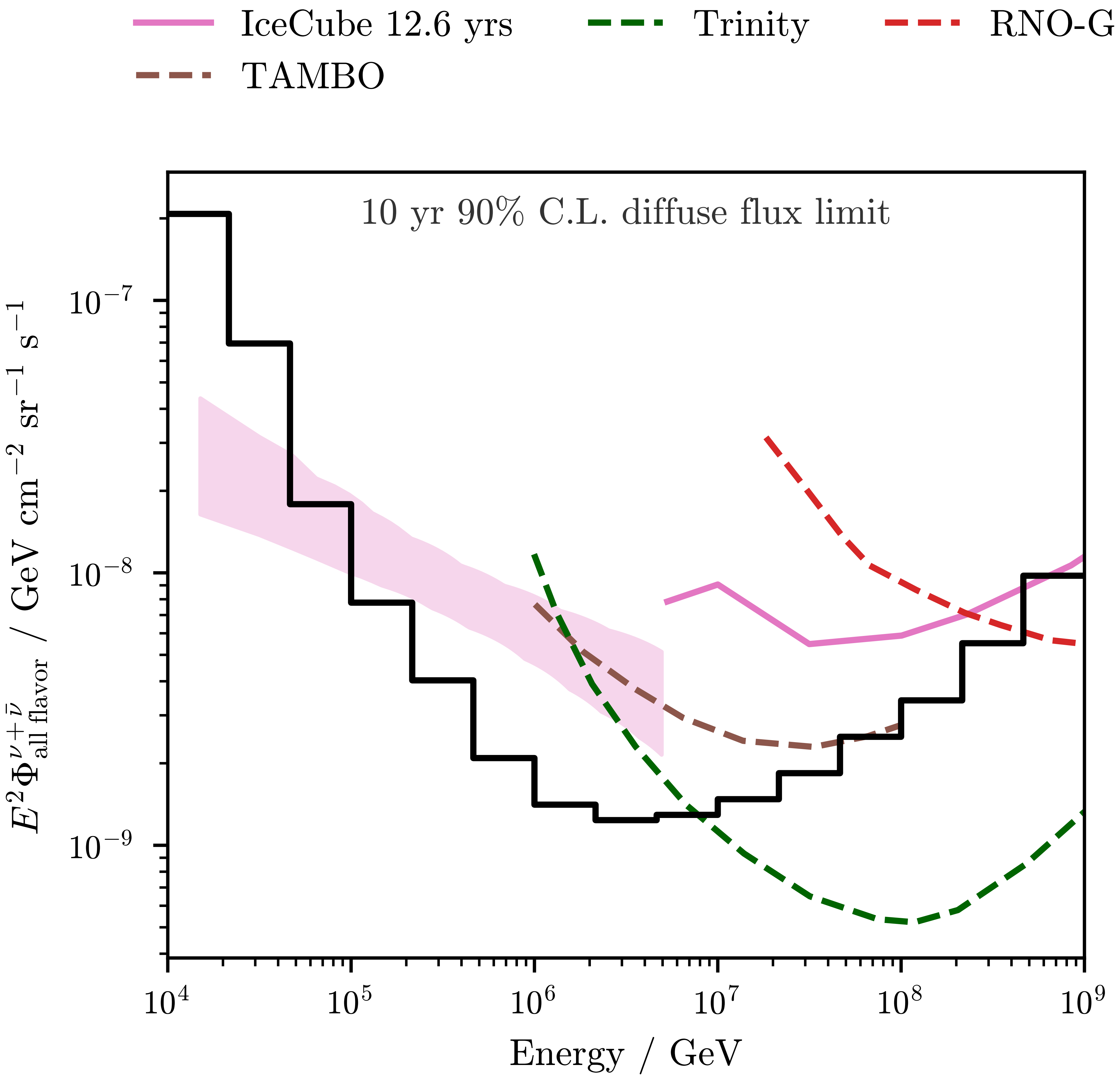
Results of other experiments calculated with published effective area & angular resolution (+ 0.5° margin)



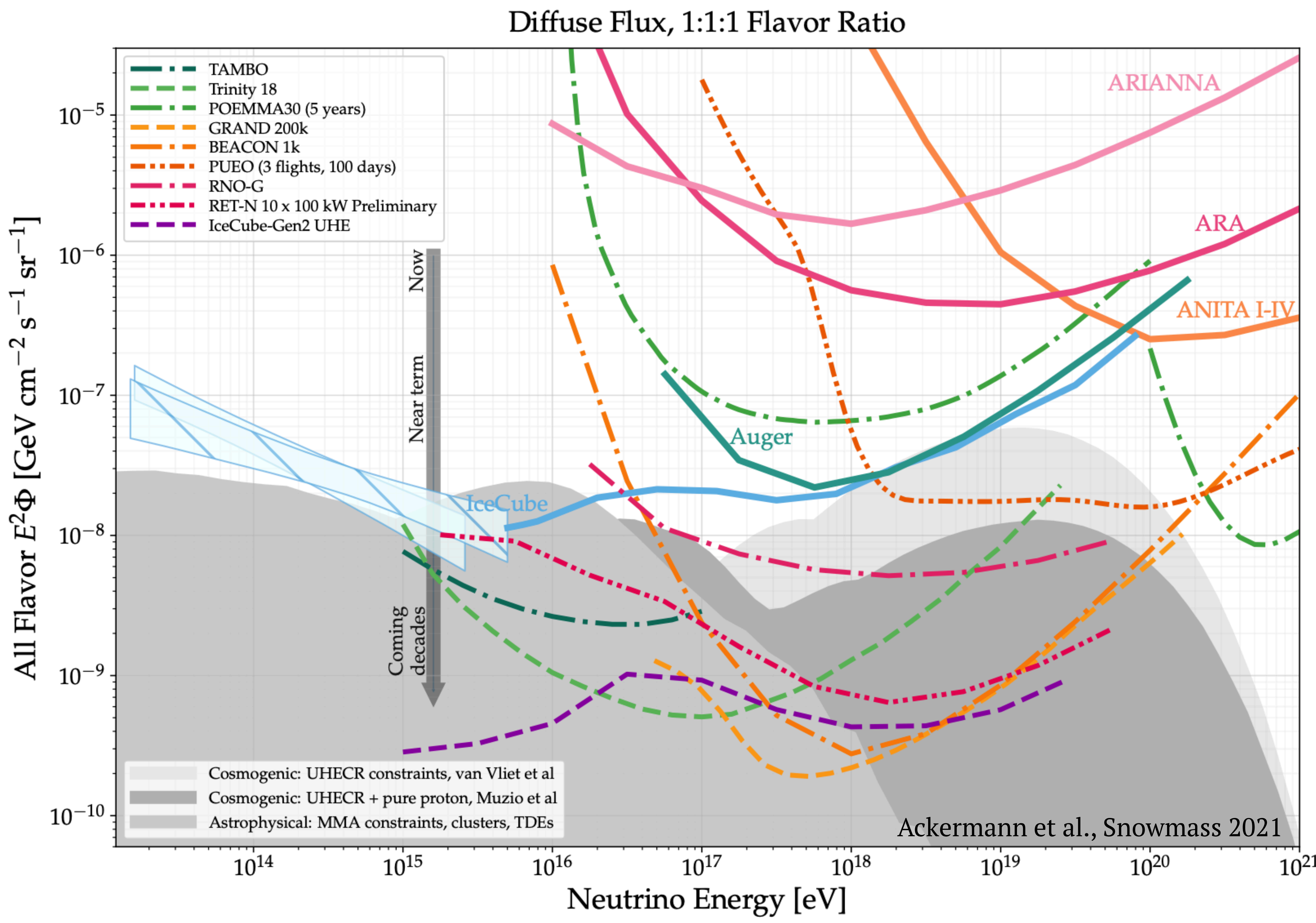
POLARIS exceeds ARCA at multi-PeV energies at ~1/4 optical modules, larger next-generation out-of-reach due to angular resolution compromise

Diffuse flux limit

Follows same calculation as point-source sensitivity



Next-generation detector landscape

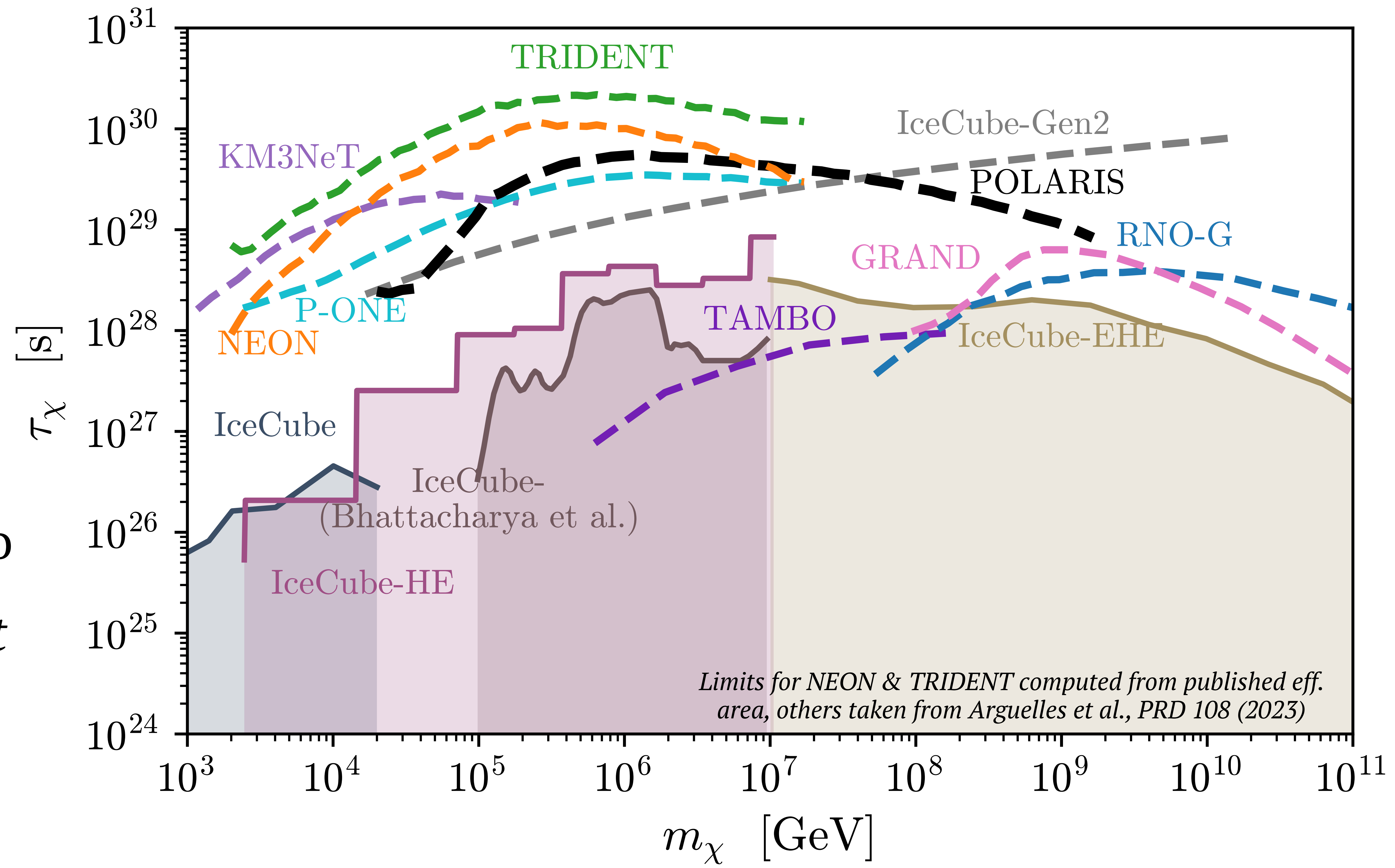


Competitive limit in the PeV range compared to ν_τ & radio neutrino detectors driven by effective area

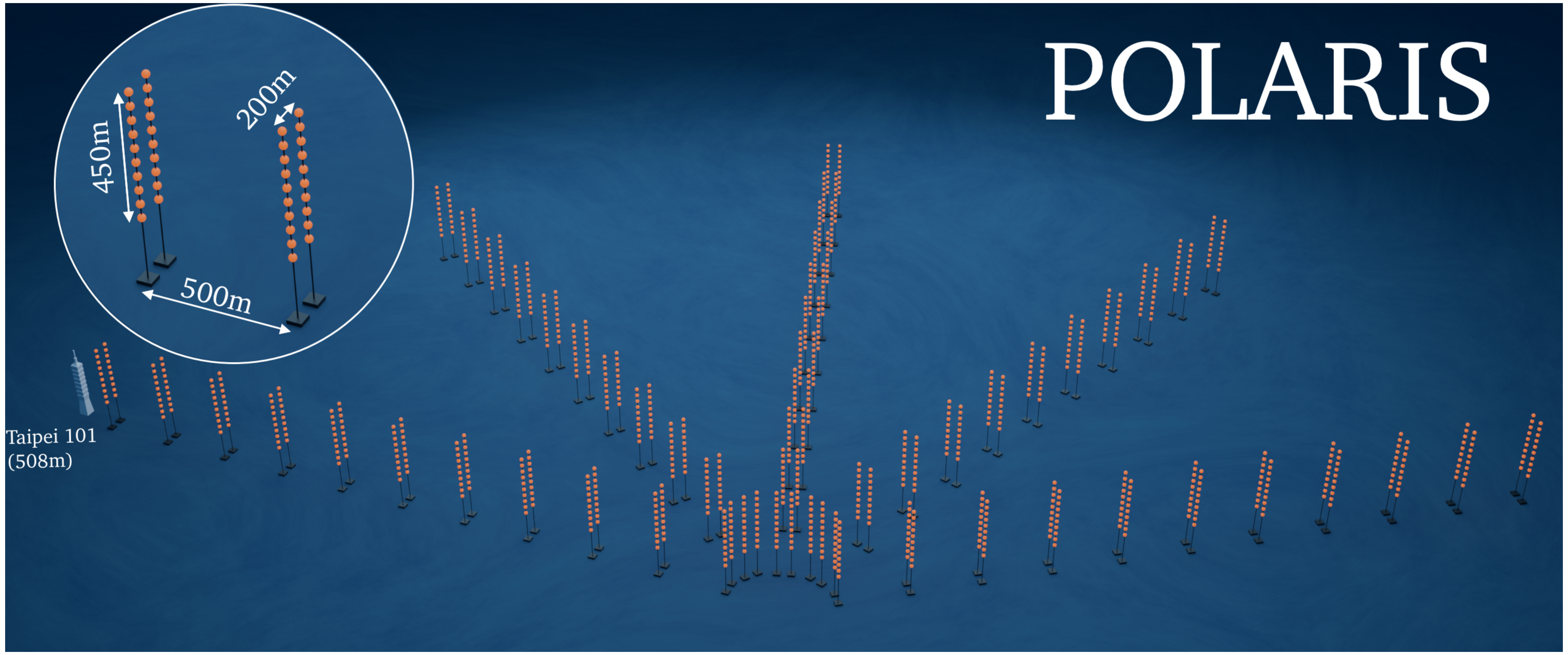
Dark Matter Decay Limit

- Heavy dark matter in the Galactic halo decays to neutrinos at $E_\nu = m_\chi/2$
- Reuse 90% CL upper limit on diffuse flux to derive lower limit on dark matter lifetime τ_χ (5 years)
- D-factor: DM density integrated along line of sight, summed over the full sky —> decay searches sensitive to outer halo
- Galactic DM profile following *Arguelles et al, PRD 108 (2023)*: NFW with γ=1.2 (steeper than standard cuspy profile)

5-year limit

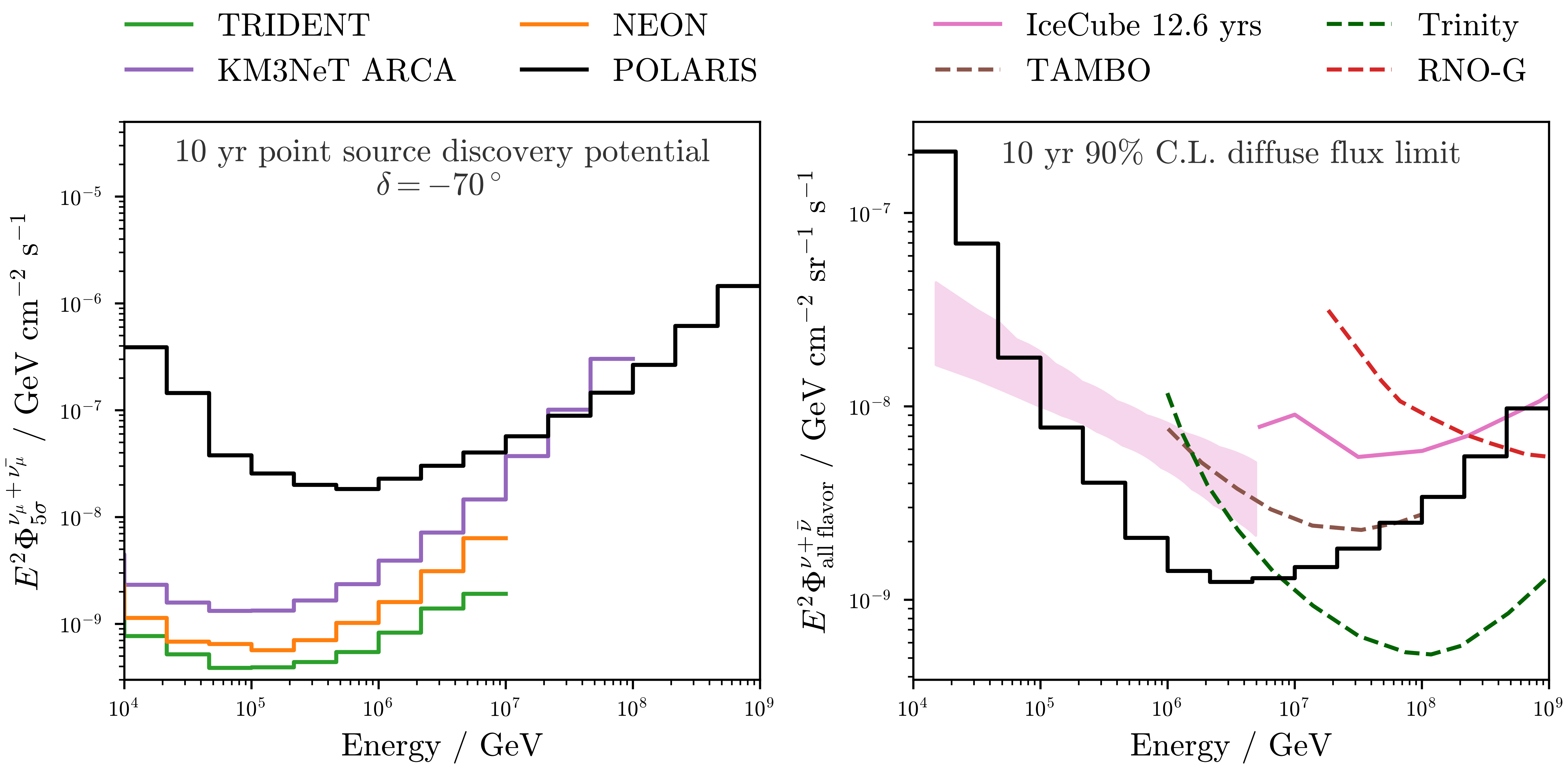


POLARIS exceeds KM3NeT above $m_\chi \geq 10^5$ GeV, IceCube-Gen2 up to 44 PeV, NEON above 10^7 GeV



arXiv

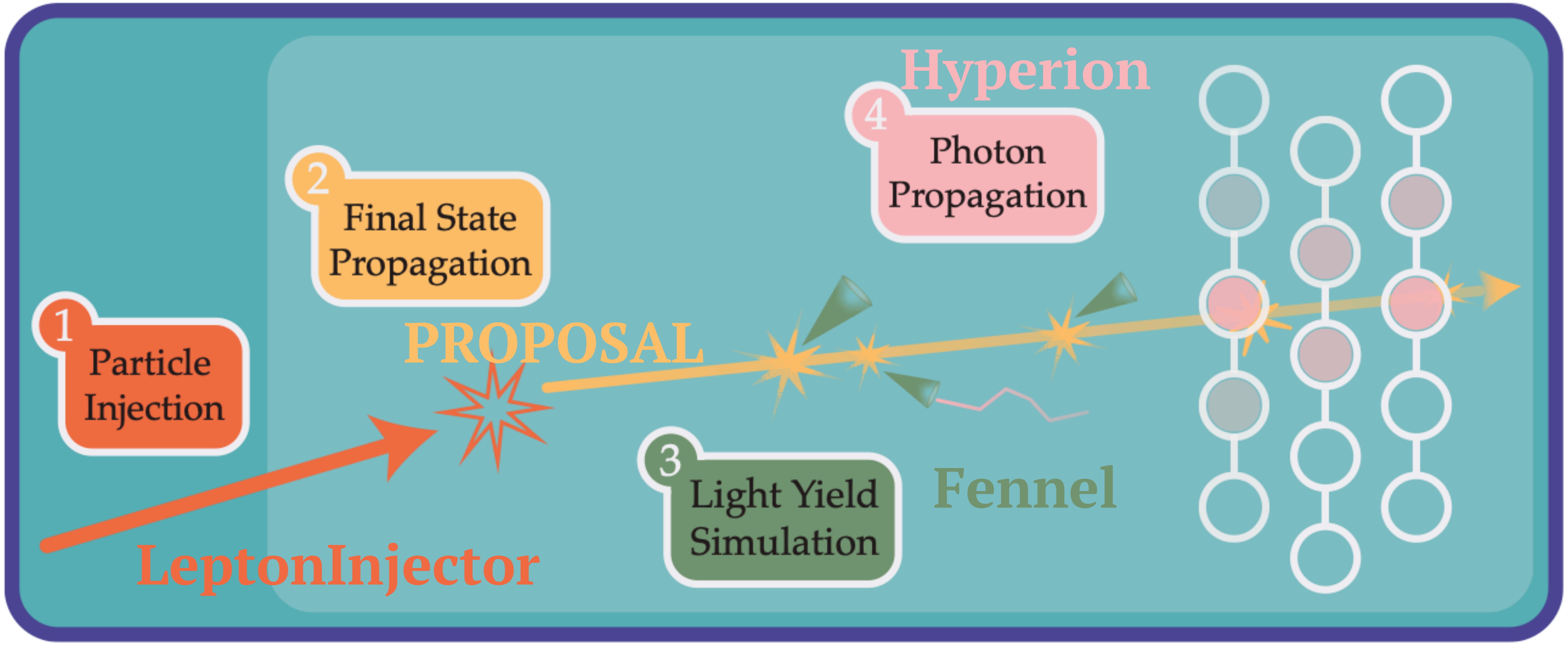
- Novel **sparse neutrino detector** design for **horizontal tracks** —> one candidate geometry, not yet optimized
- Geometry naturally removes cascade events
- Point-source sensitivity exceeds KM3NeT-ARCA at multi-PeV energies
- Diffuse flux & dark matter lifetime limits are **competitive with next-generation experiments** driven by large effective area



Backup

Simulation Chain: Prometheus

All flavor event simulation of any detector geometry in water/ice



Lazar et al., Comput.Phys.Commun. 304 (2024)

https://github.com/Harvard-Neutrino/prometheus

Simulation Settings

Event Injection

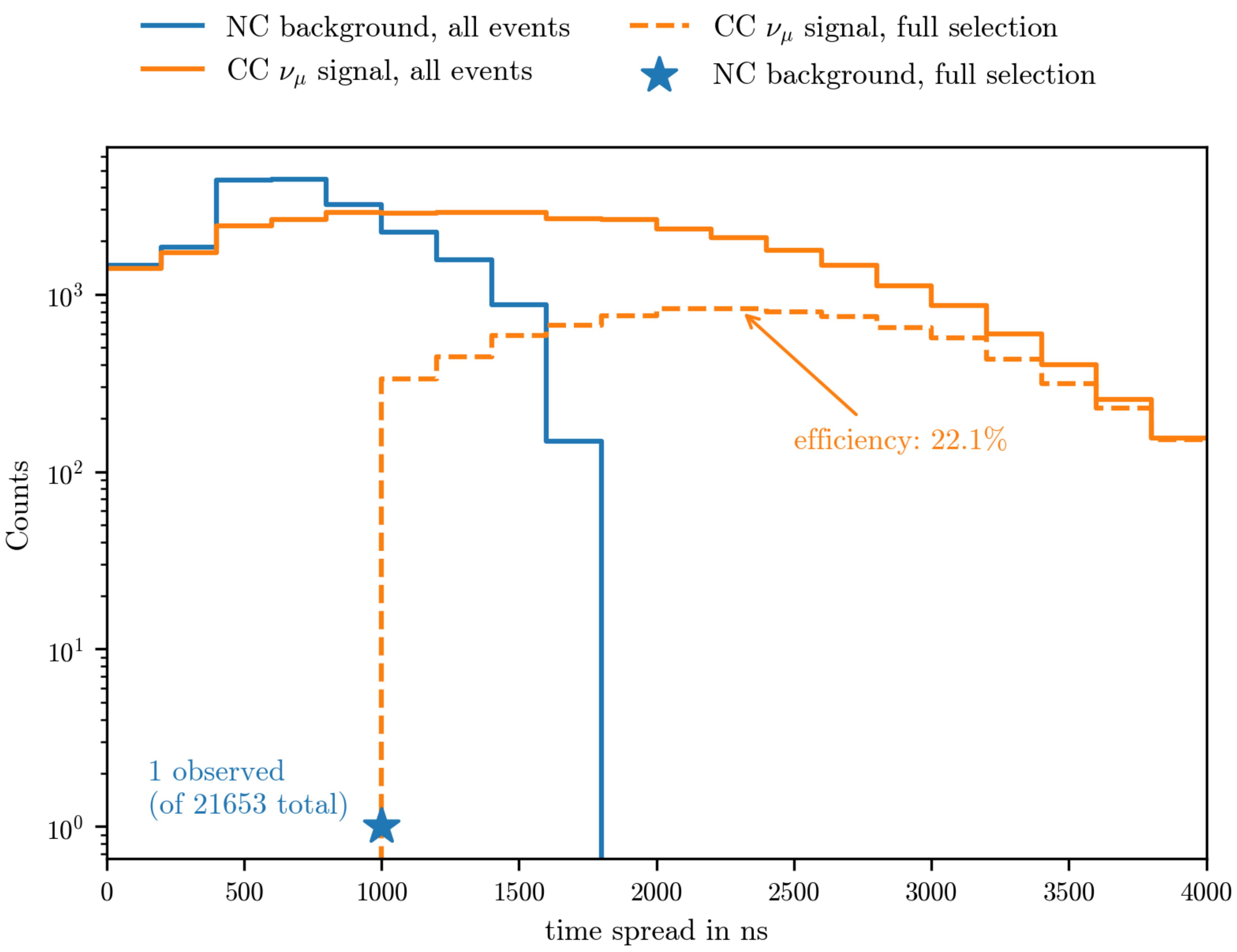
- Direction: uniform
- Energy: 10 TeV — 1 EeV
- Single detector arm

Medium

- Optical properties: *South China Sea* ($\lambda_{abs} \approx 27$ m & $\lambda_{scat} \approx 63$ m, closed available measurements)

Track Event Selection & Cascade Removal

Criterion	Purpose
Hits at a minimum of 2 consecutive gates	Cascade rejection < 1 PeV
Spatial & temporal hit distributions: Δt > 1000 ns Lmax >500 m	PeV cascade removal



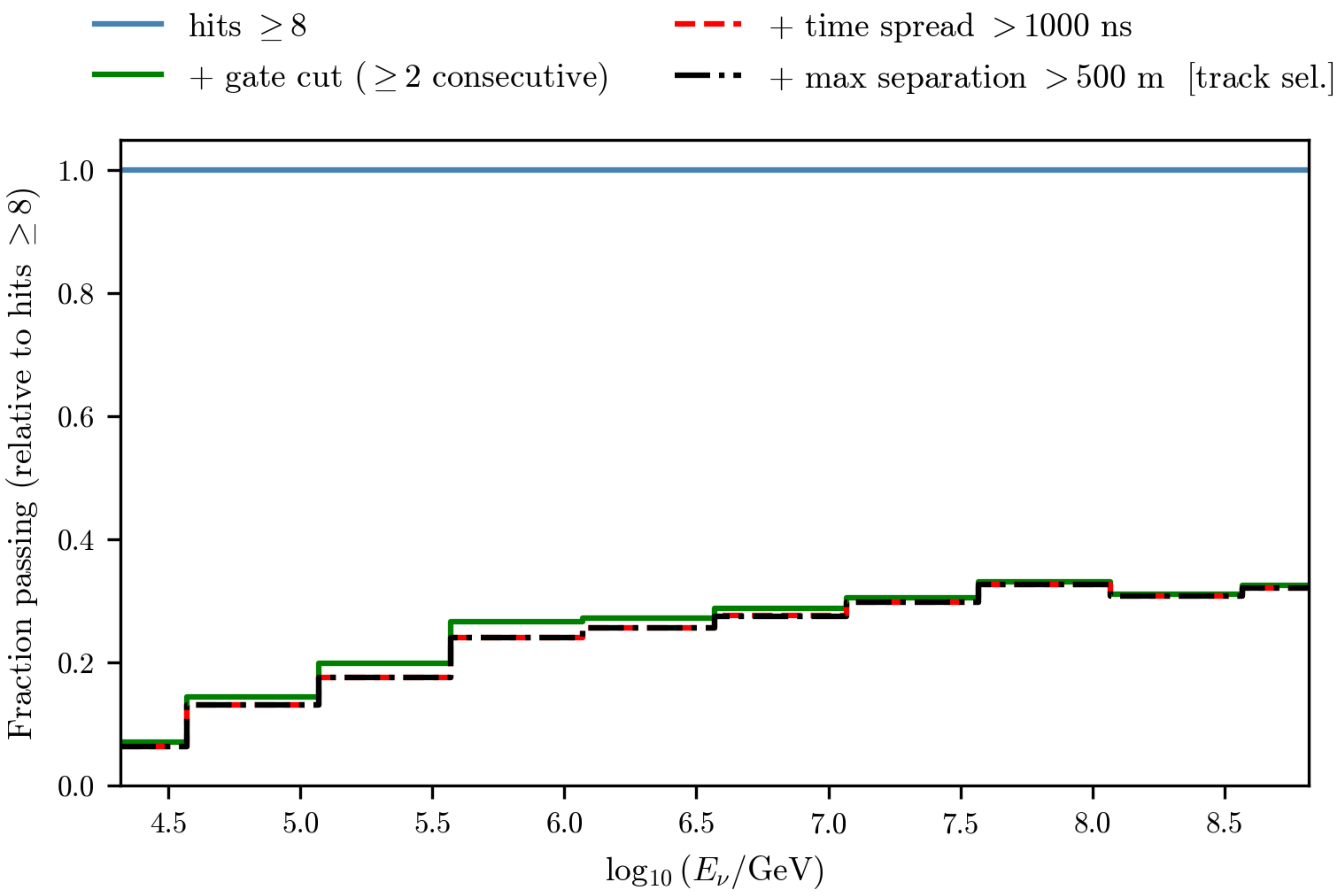
max hit separation length $L_{\max} = \max_{i,j} \left\| \vec{r}_i - \vec{r}_j \right\|$

time spread $\Delta t = t_{\max} - t_{\min}$

Track Event Selection & Cascade Removal

Criterion	Purpose
Hits at a minimum of 2 consecutive gates	Cascade rejection < 1 PeV
Spatial & temporal hit distributions: Δt > 1000 ns Lmax >500 m	PeV cascade removal
⩾2 hits/20 ns/ DOM	K-40 noise suppression

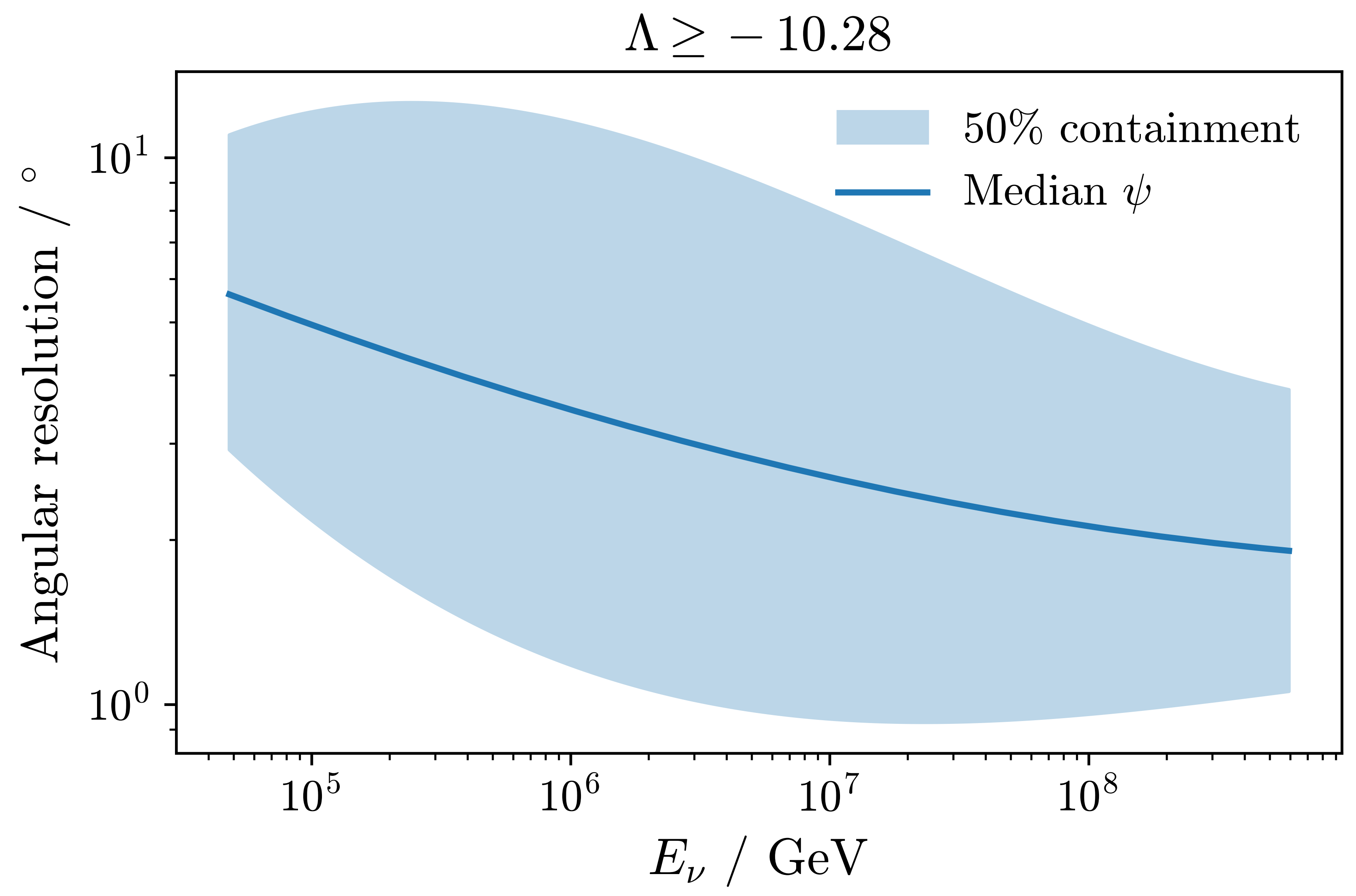
Event selection efficiency for POLARIS

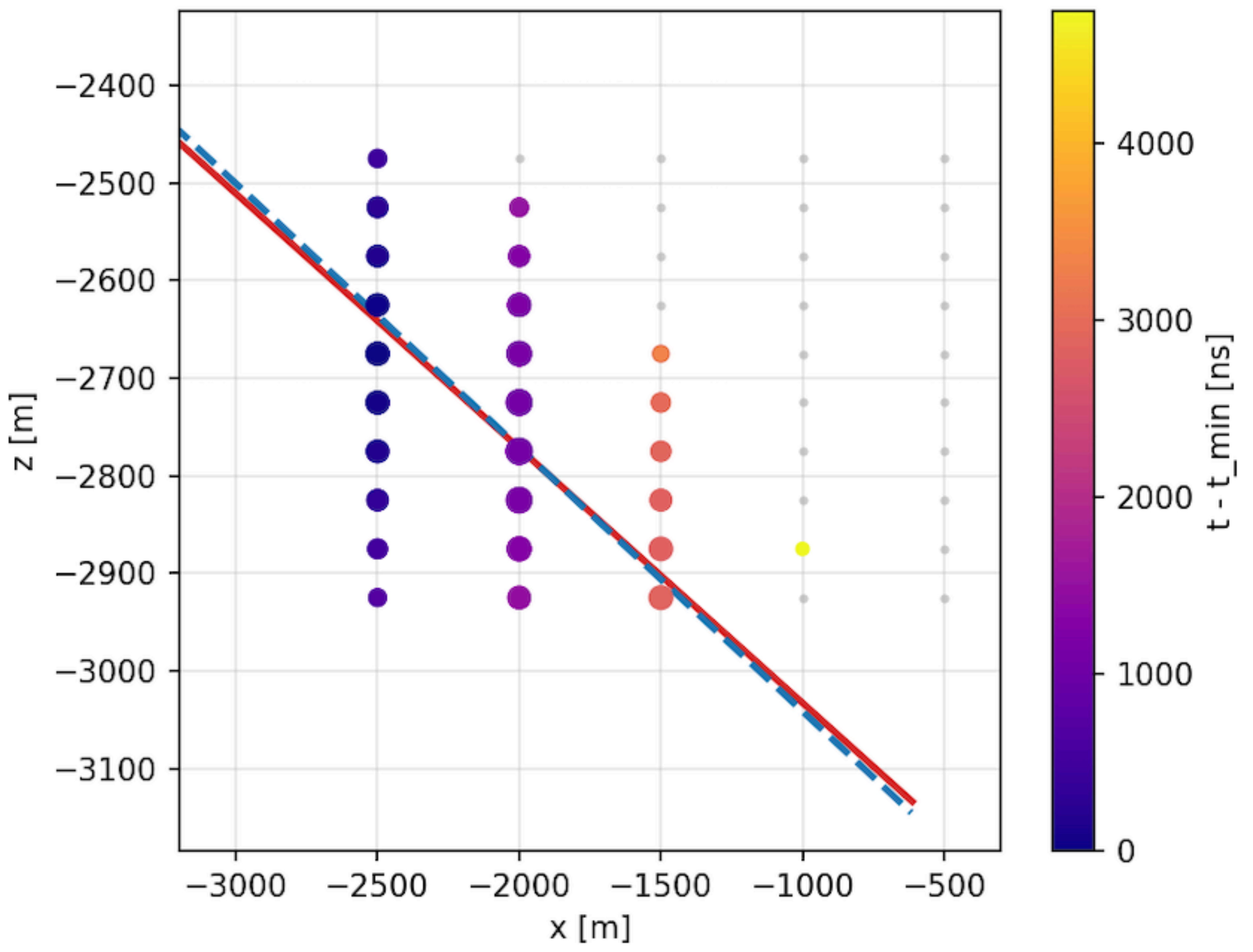


Reconstruction

Likelihood fit based on timing, no PMT-hit information available—> conservative estimate

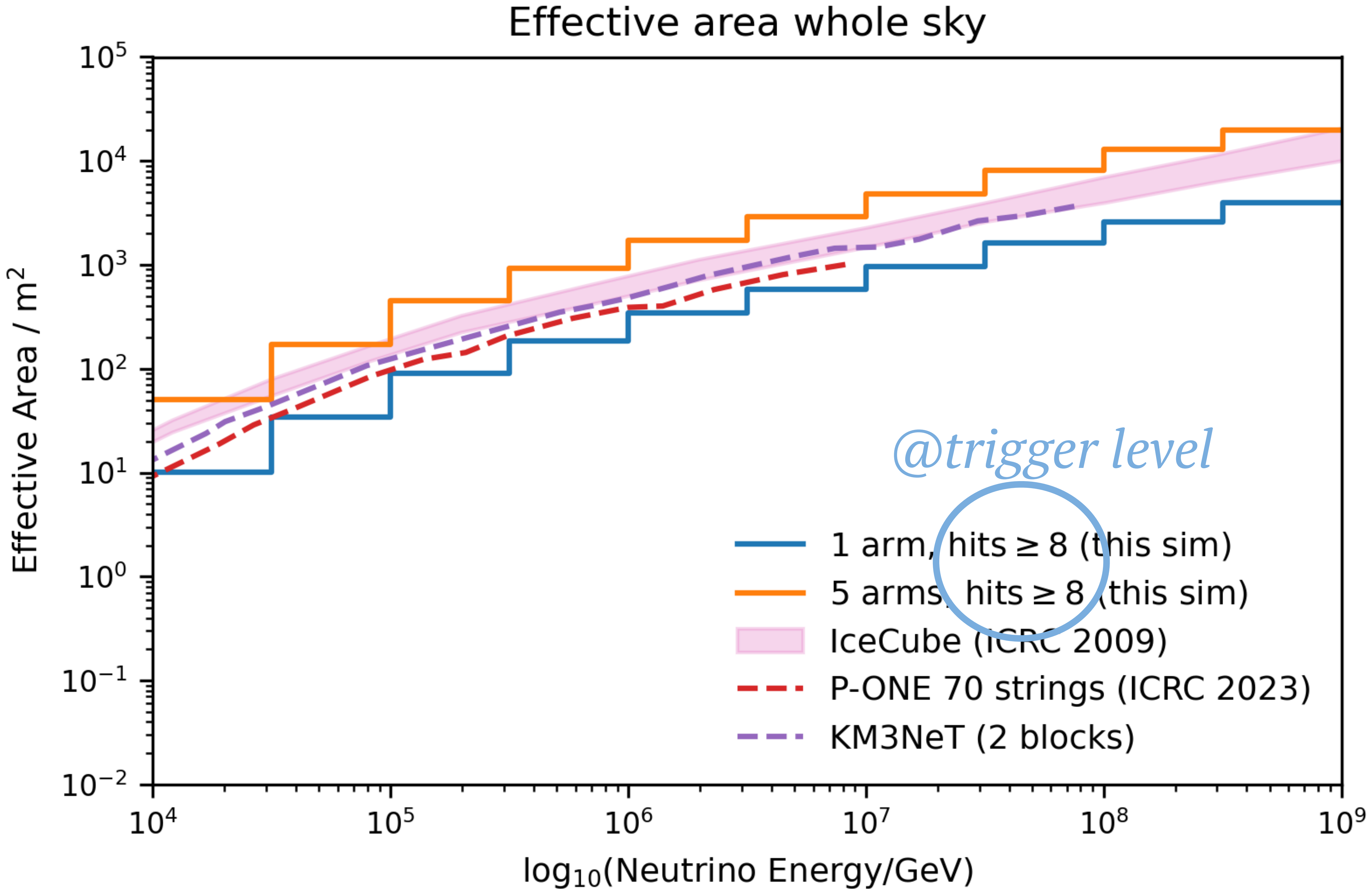
- Linear fit to hit times & position to find initial starting direction
- ANTARES method: 9 rotated/shifted variants of this direction (N_{comp}) each refit to the likelihood
- Quality score combining fit value and agreement:
  $$\Lambda = -\frac{\mathscr{L}_{\text{best}}}{\text{dof}} + \alpha\,(N_{\text{comp}} - 1)$$
- $\Lambda \geq -10.28$ keeps 50% of the events

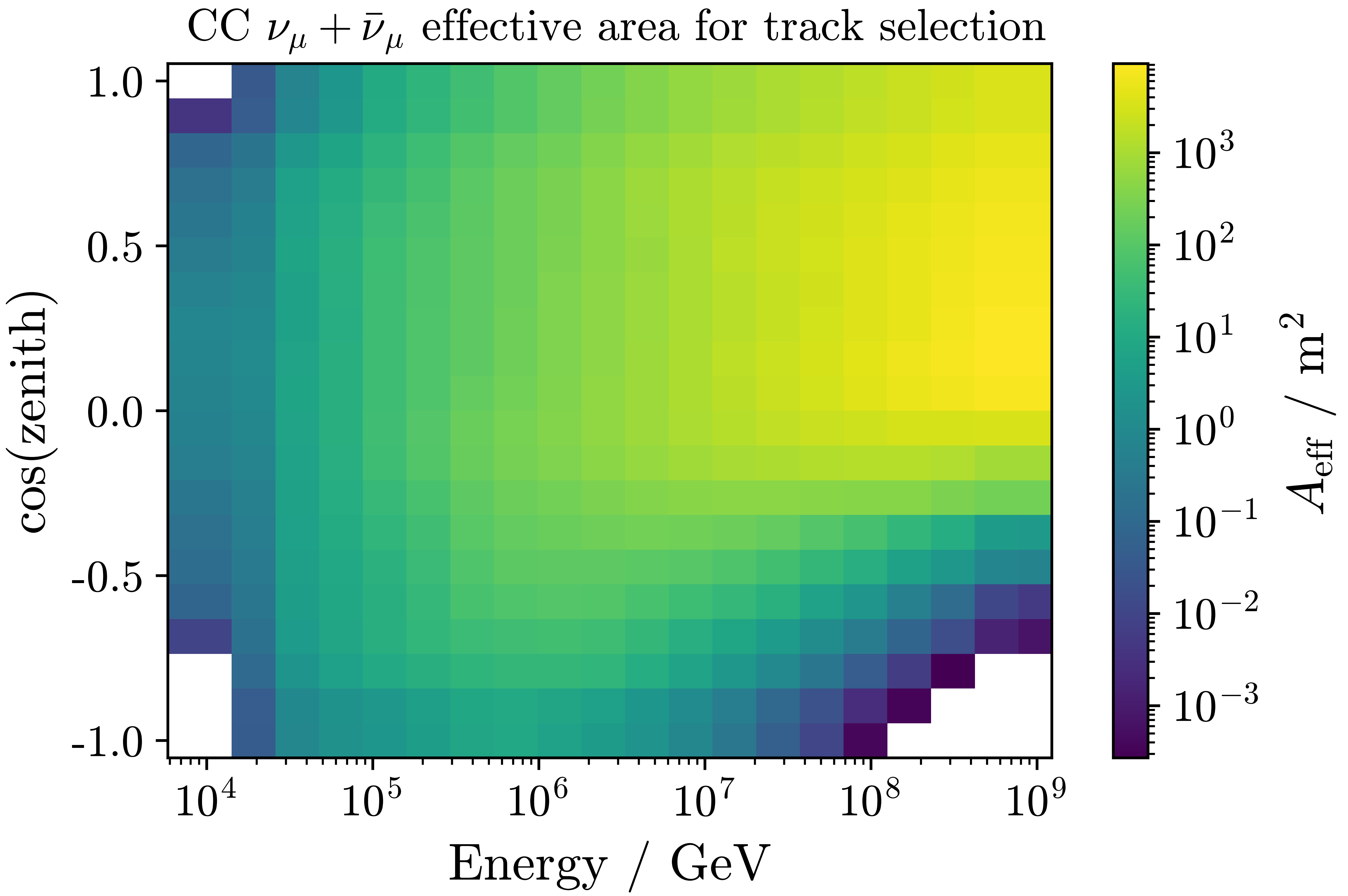




Comparing Detector Performances: effective area

$$N_{\text{detected}} = T \times \iint \frac{d^2\Phi}{dE\,d\Omega}(E,\theta,\phi) \times A_{\text{eff}}(E,\theta,\phi)\,dE\,d\Omega$$





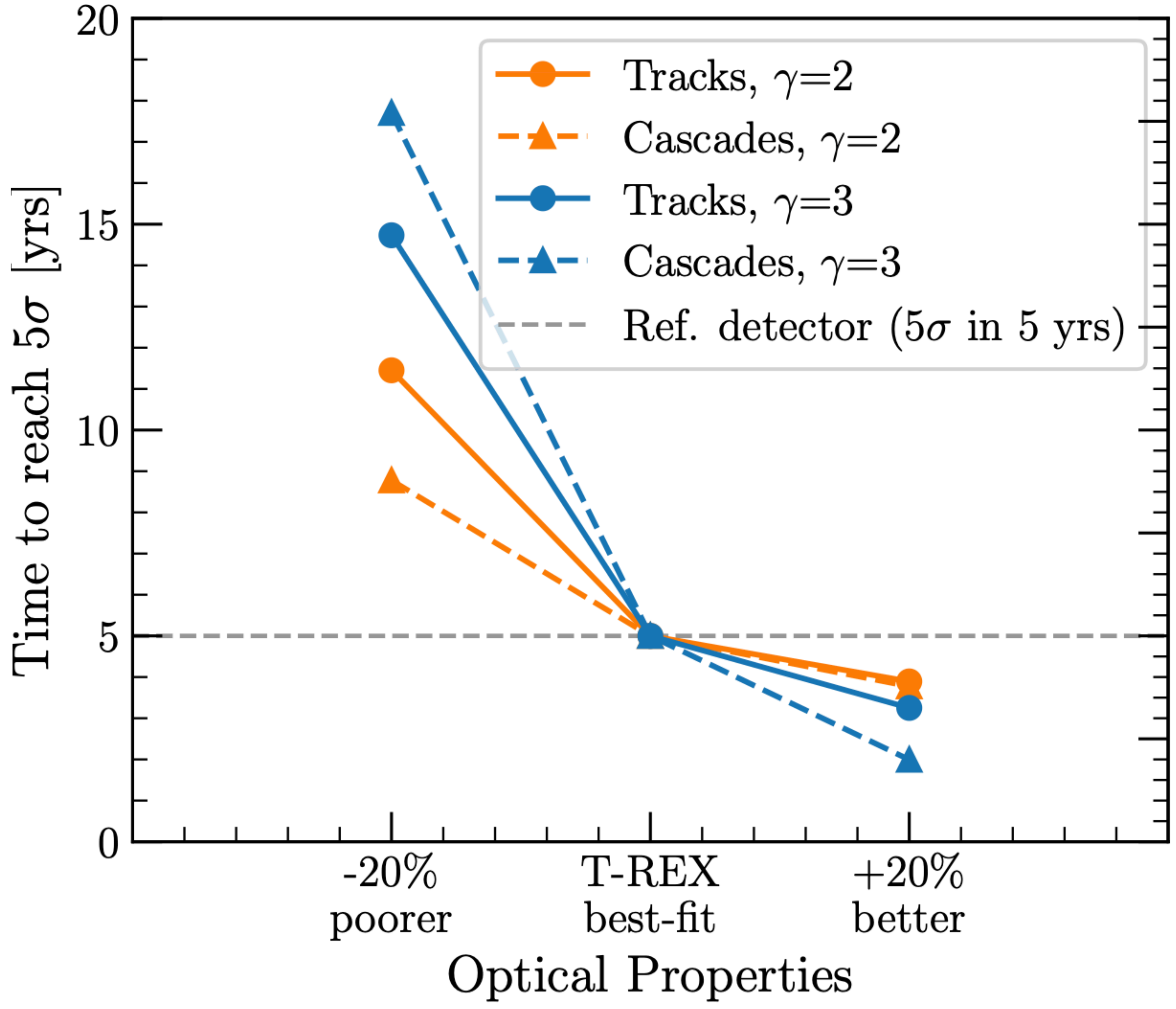
Beware: Impact of Water Properties

- Lesson learnt from TRIDENT: **optical properties** can have a **larger effect** than geometry on source **detection potential**

- Calculation done for power law flux of a source at $\sin\delta = 0$

No over-optimization of detector geometry before site investigation!

Morton-Blake et al. PRD 113 (2026)



Calculation done for power law flux of a source at $\sin\delta = 0$