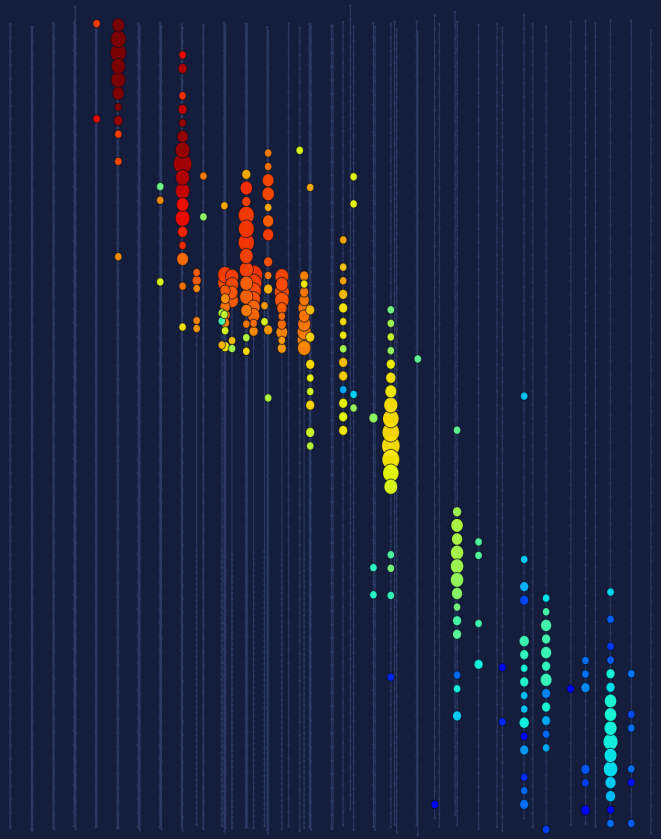
Search for Dark Matter Annihilation in the Sun and Solar Atmospheric Neutrinos with IceCube



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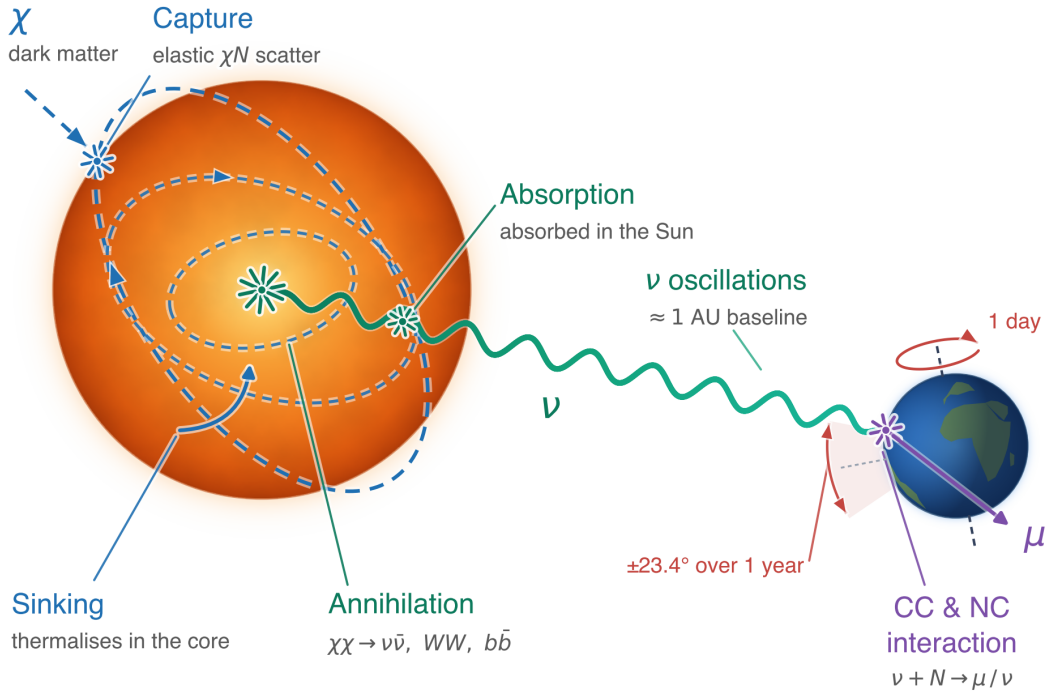
for the IceCube Collaboration

High-Energy Neutrinos from the Sun

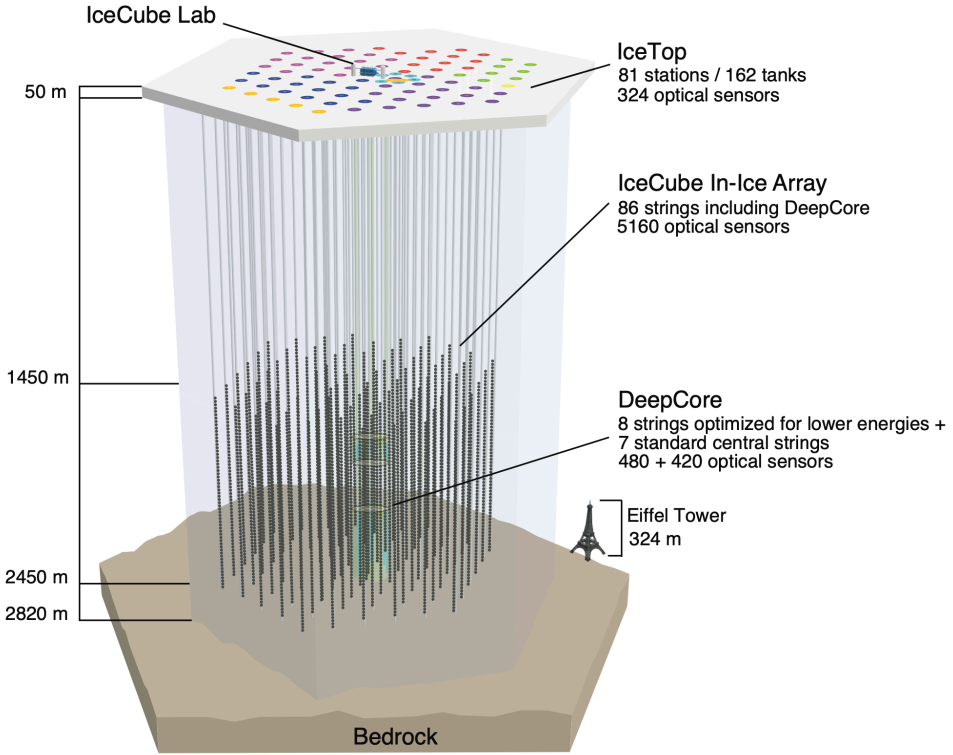
- **Probe dark matter**
  - High-energy ν from WIMP annihilation in the Sun: unique indirect DM signature
  - Spin-dependent DM–proton scattering, complementary to direct detection
- **Solar atmospheric neutrinos**
  - ν from cosmic-ray interactions in the solar atmosphere; not yet observed
  - Complements gamma-ray observations, may explain spectral anomalies [1]



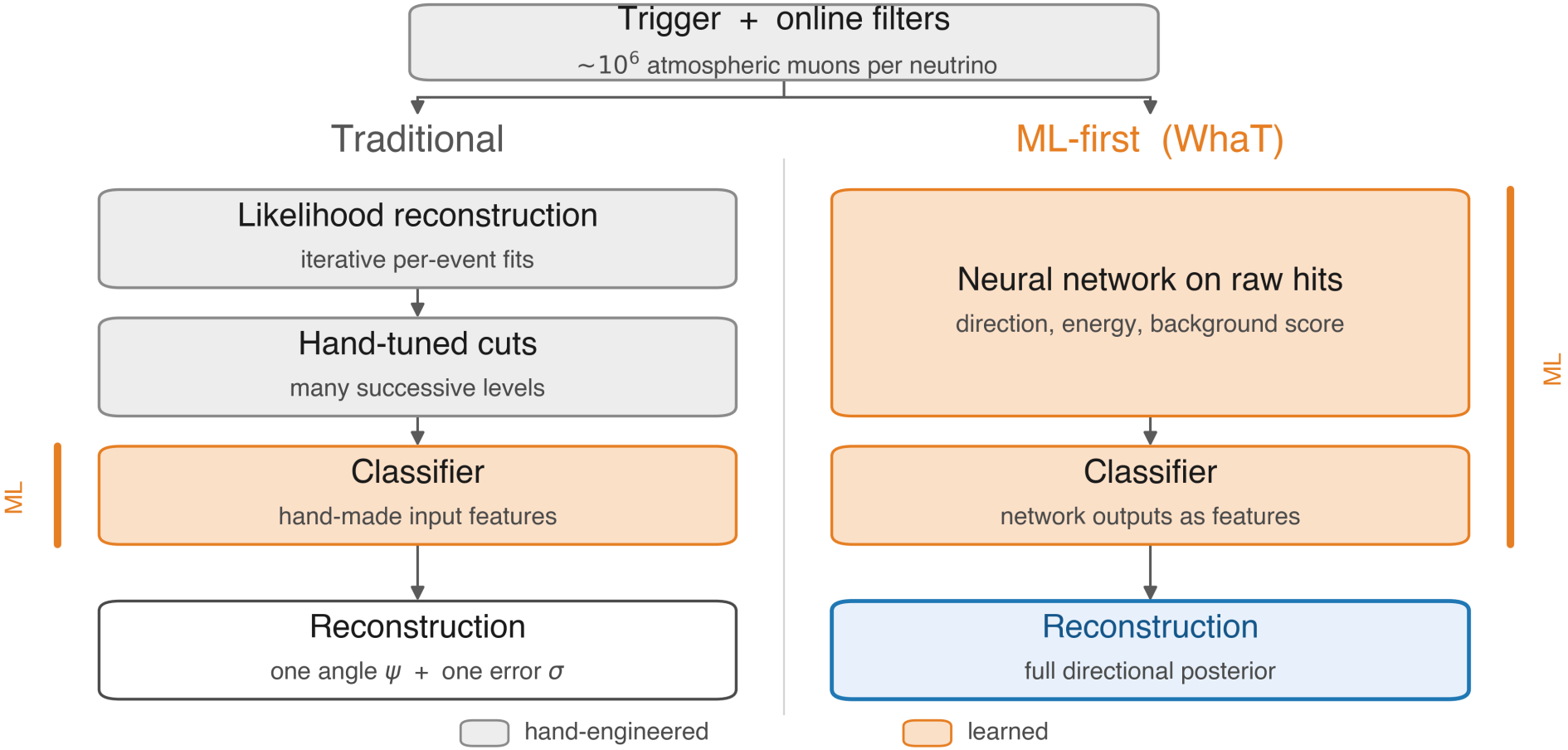
[1] Phys. Rev. Lett. **131**, 051201

IceCube Neutrino Observatory

- **IceCube:** the largest operating neutrino telescope, 1 km³ of Antarctic ice at the South Pole
- 5,160 optical sensors (DOMs) on 86 strings
- Well suited to high-energy solar neutrinos in the ~TeV regime
- We are building a **new event selection** (WHALE-Tracks, or **WhaT**) for this search using **modern machine learning (ML)**



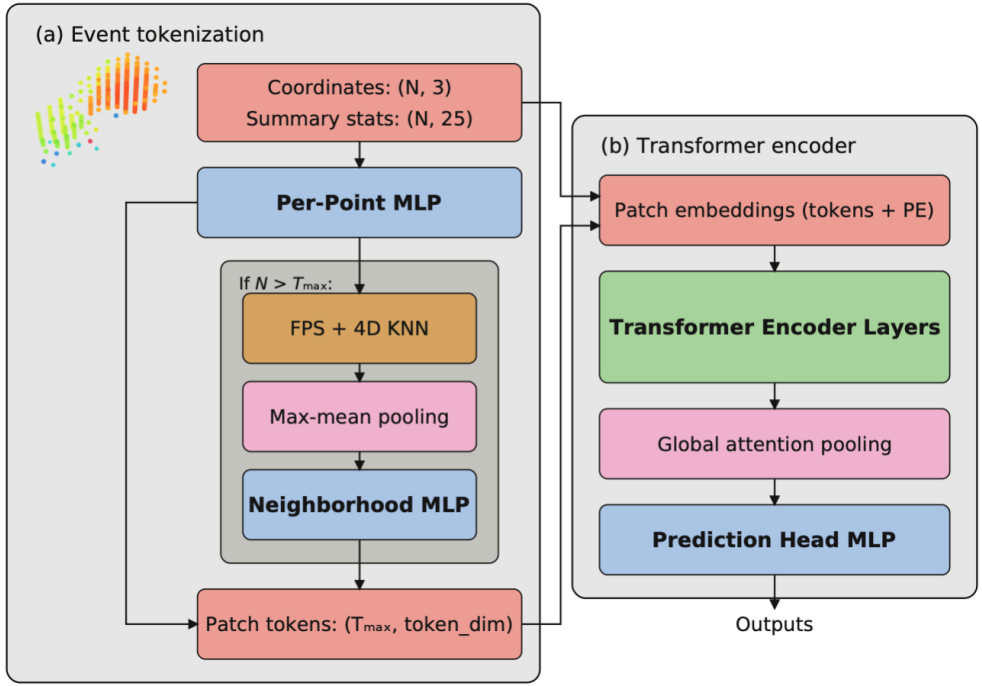
Event Selection



Backbone: Neptune Reconstruction

- **Neptune:** point-transformer event-level reconstruction
  - Input: spatial coords + summary stats per hit DOM
  - Efficient on GPU, CPU-deployable
  - Models: **direction, energy, morphology, neutrino-vs-bkg score**

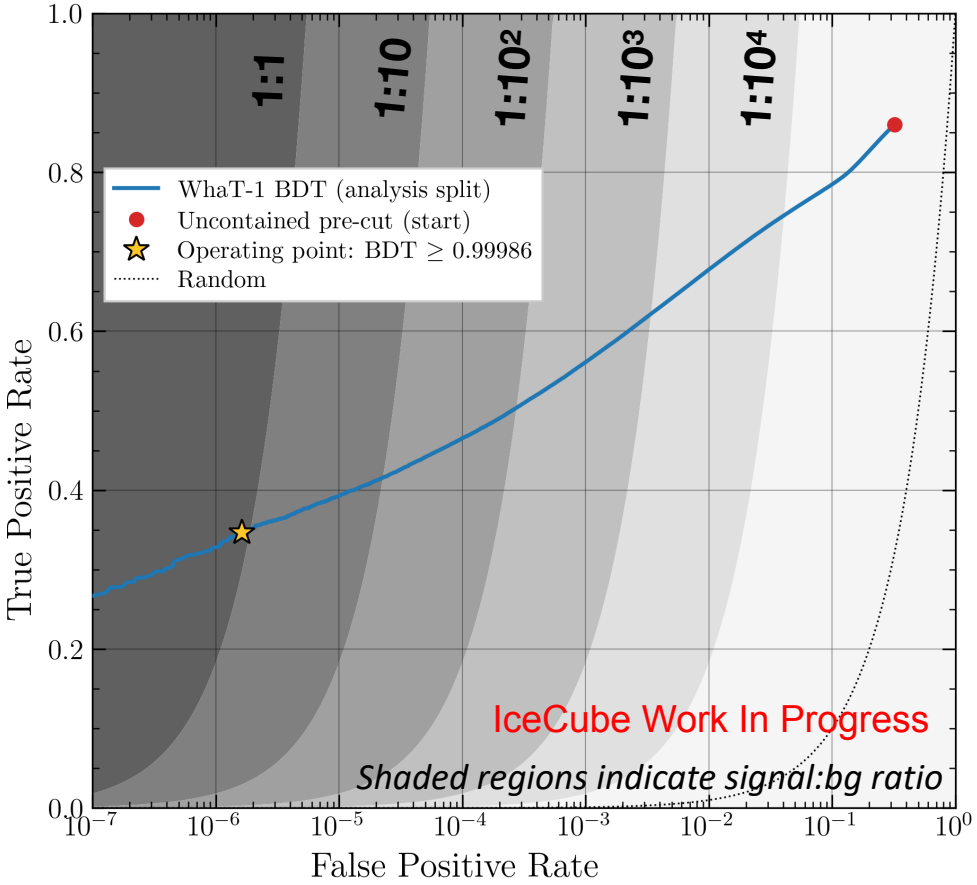
- **Neptune directional model:**
  - Predicts **9 parameters**; the full posterior shape, not just (mean, concentration)
  - **General Angular Gaussian (GAG):** anisotropic generalization of von Mises–Fisher on the sphere



PoS ICRC2025 (2025) 1218

WhaT-1 BDT

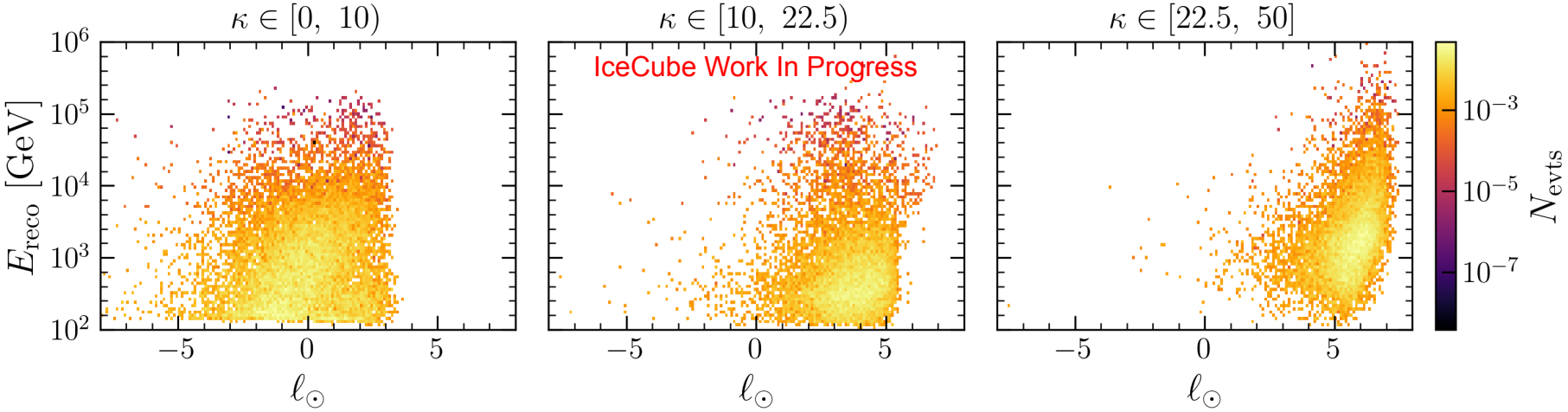
- **WhaT Level 1 (WhaT-1) BDT:** gradient-boosted classifier built on top of Neptune to reject atmospheric muons
  - Features: Neptune outputs + common reconstructed quantities
- **Pre-cut first:** cut away events that Neptune classified as *uncontained*
  - Resolves data-MC disagreement
- **Operating point: BDT ≥ 0.99986**, slightly into the neutrino-dominated regime



Analysis Method

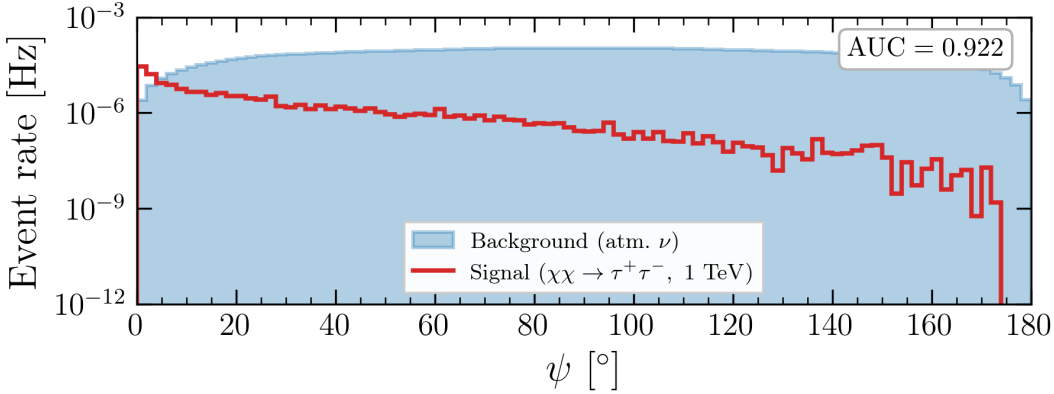
[2] IceCube Collab., arXiv:2507.08457 (2025)

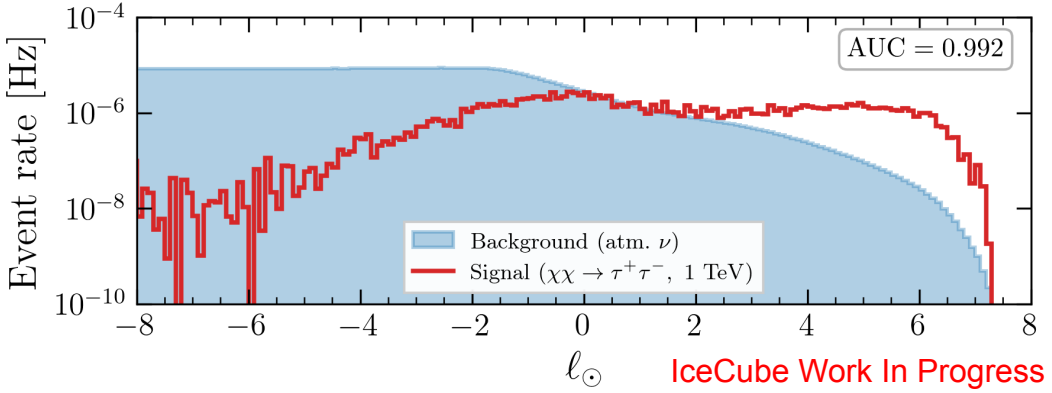
- We adopt the same analysis framework as the previous analysis [2], with some adjustments
- **Original approach:** 2D binned Poisson likelihood (E_{reco}, ψ), where ψ is the opening angle between Sun and reconstructed direction
- **ℓ⊙** = log Neptune GAG posterior at the Sun's direction; replaces ψ
- **New approach:** 3D binned fit in **(ℓ⊙, E_{reco}, κ)**
  - κ = GAG concentration parameter (↑ κ = ↓ angular uncertainty), jointly predicted with direction by Neptune



$\ell_\odot$ vs ψ: Discriminator Comparison

- **ψ**: opening angle to the Sun (previous analysis)
- **$\ell_\odot$**: log GAG posterior at the Sun's direction
- Signal benchmark: χχ → ττ, 1 TeV WIMP
- AUC is the standard binary classification metric:
  - Using ψ as the discriminating variable, **AUC = 0.922**
  - Using $\ell_\odot$ as the discriminating variable, **AUC = 0.992**



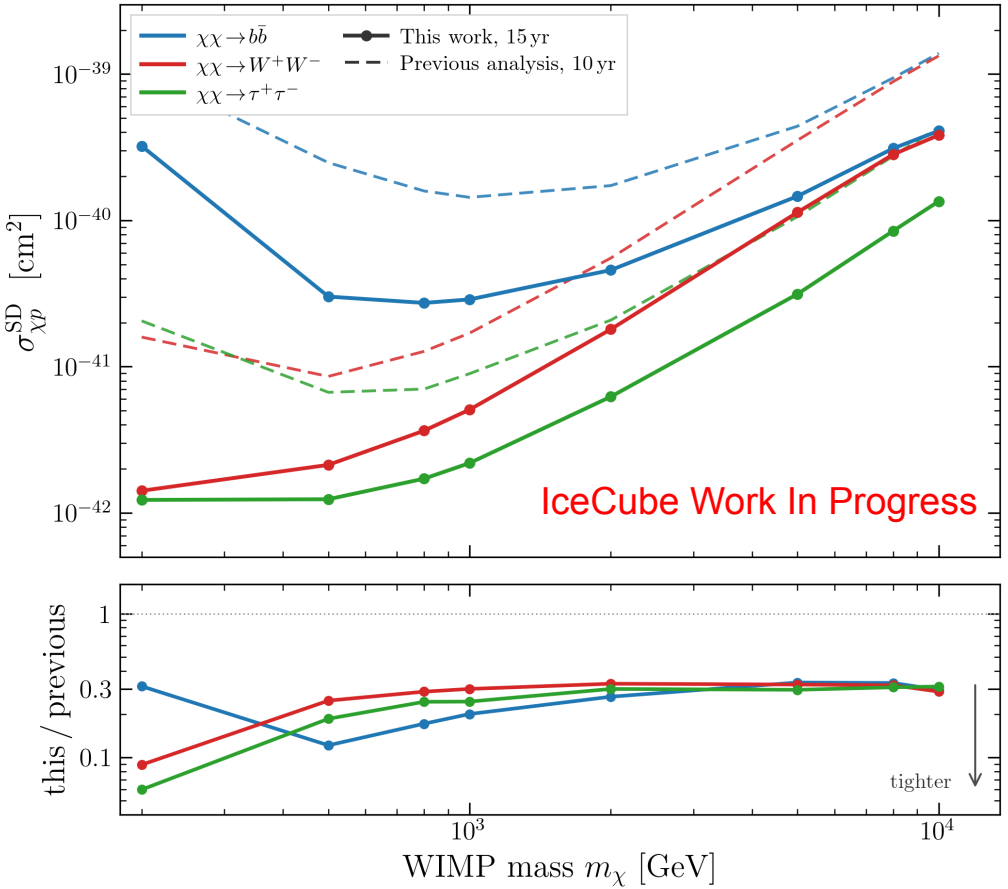


IceCube Work In Progress

DM Sensitivity

- **15-yr SD WIMP–proton sensitivity** vs DM mass (200–10000 GeV)
  - 3 annihilation channels: $\chi\chi \rightarrow b\bar{b}$, WW, $\tau\tau$
- **Median expected sensitivity** from this analysis compared to the sensitivities from the previous analysis
- Best improvement is > order of magnitude

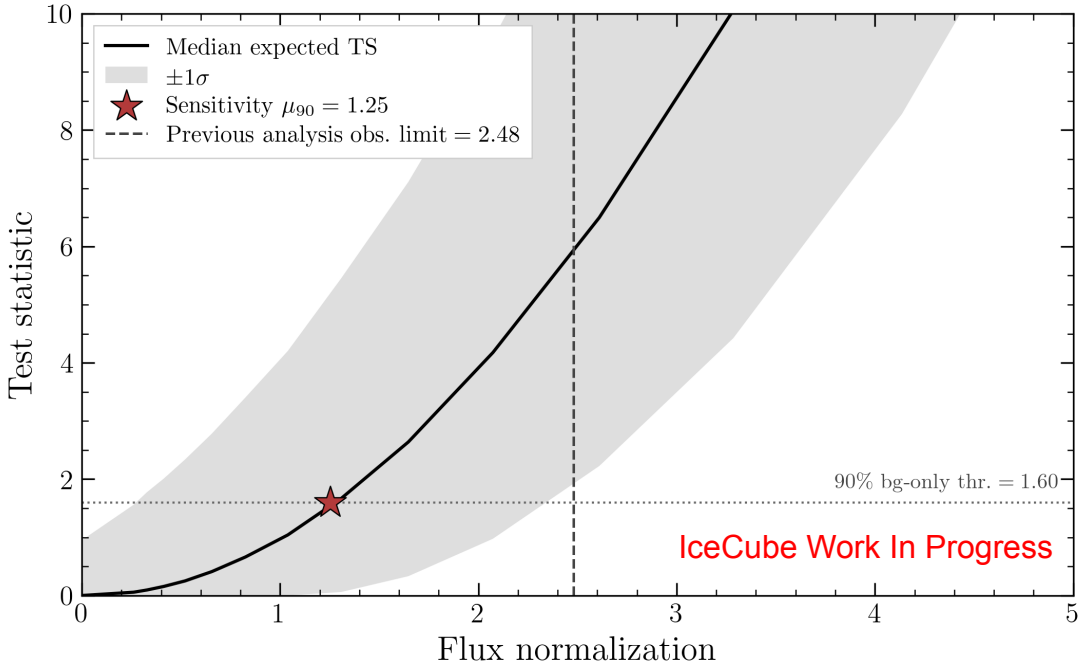
All channels tighter than previous analysis (10 yr)



Solar Atm. ν Sensitivity

Expected 90% CL flux-norm UL: 2.48× (prev. analysis) → **1.25×**

- Signal flux: SIBYLL 2.3 (ppMRS) × H4a/GH-combined primaries
- Solar-atm treated as signal; DM norm fixed to zero, flux norm scanned as signal strength
- Trial scan over flux norm values, 50k pseudo-experiments each



Summary & Outlook

Summary

- We developed a new ML-based selection **WHALE-Tracks** from the ground-up
- Per-event directional likelihood $\ell_{\odot}$ from Neptune's GAG posterior replaces ψ in the 3D binned fit
- Beyond gains from increased livetime, the new event selection and reconstruction substantially improve sensitivity to both DM and solar atmospheric ν signals.

Outlook

- Explore further refinements to the final-level directional reconstruction
- Explore alternatives / improvements to the likelihood method
- Characterize systematics

Thank you!

Backup

Effective Area: WhaT vs Northern Tracks

- **Reference:** IC2025 NorthernTracks (previous analysis's selection)
  - $\nu + \bar{\nu}$, upgoing ($\cos\theta \in [-1, 0]$)
- **WhaT-1 exceeds or matches NorthernTracks**
  - Largest gains at low E: low-mass DM and the solar atm. ν peak
  - Roughly matching at highest energies