

TANGO: Deep Learning Based Reconstruction of Sub-TeV Astrophysical Neutrinos in IceCube DeepCore

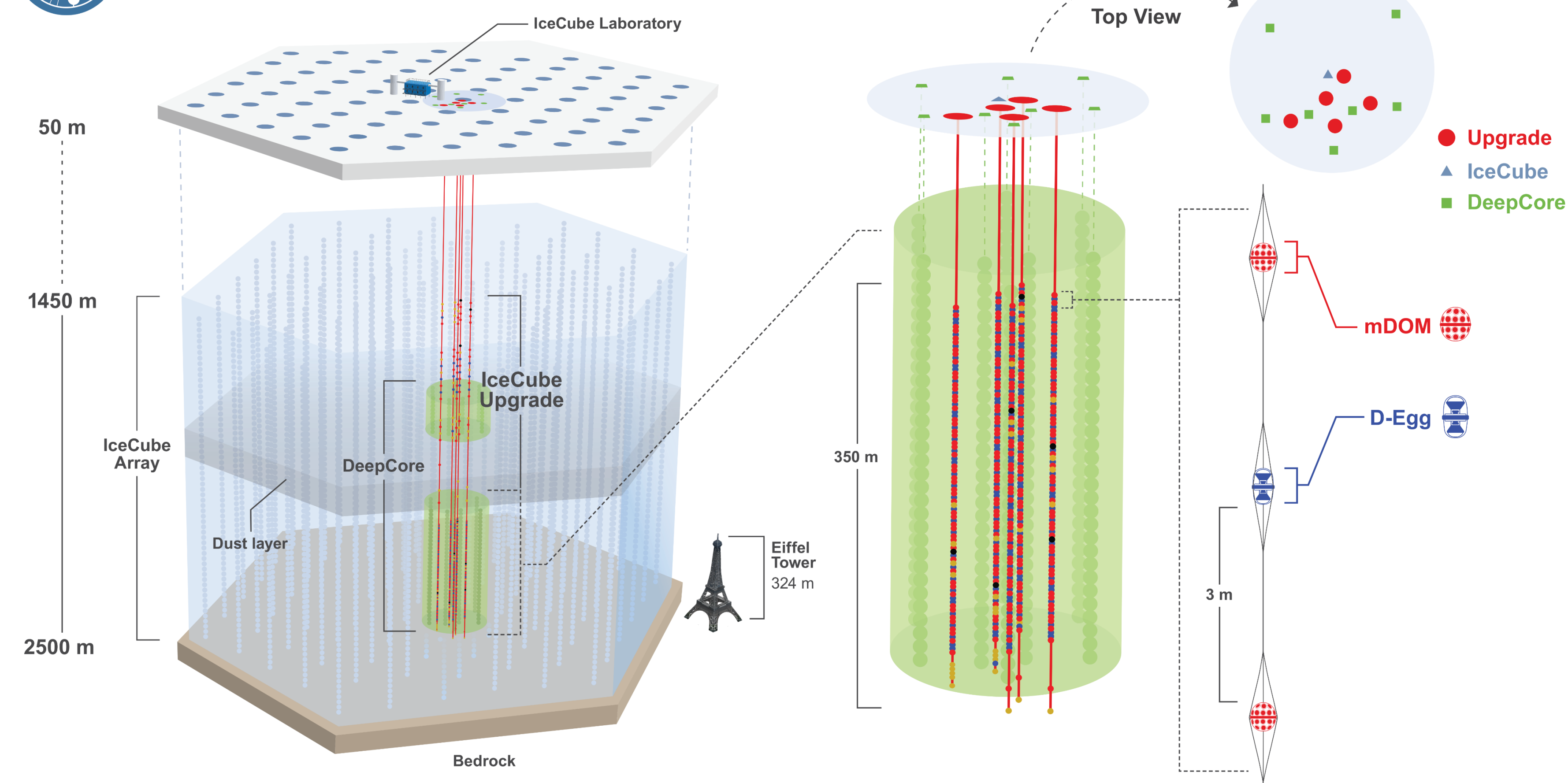


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Abstract The IceCube Neutrino Observatory's DeepCore sub-array lowers the detection threshold to the GeV scale, enabling sub-TeV studies of potential astrophysical neutrino sources such as NGC 1068, previously associated by IceCube with high-energy neutrinos and expected to emit at sub-TeV energies. Reconstruction in this regime is challenged by sparse photon statistics and background noise. Conventional likelihood algorithms require ~15 minutes per event and are often resolution-limited. We present TANGO (Transformer ANGles for GreCO), a deep-learning reconstruction model optimized for the GRECO (GeV Reconstructed Events with Containment for Oscillations) DeepCore dataset, which covers the GeV-to-TeV transition for astrophysical neutrino studies. TANGO combines EdgeConv graph neural networks and Transformer layers to learn local pulse features and global detector-scale dependencies. Using a weighted multi-task loss, it jointly reconstructs neutrino direction and interaction vertex, leveraging correlations between spatial and directional information. Trained and evaluated on simulated GRECO events, TANGO reduces inference time to ~10 ms per event and improves angular resolution by factors of 1.2–2.5 relative to likelihood methods. Vertex position reconstruction improves more strongly: vertical depth resolution by 1.7–2.5 and radial resolution by 5–10. TANGO also provides robust angular-uncertainty estimates, correcting systematic biases in traditional reconstruction, thereby enhancing IceCube sensitivity to sub-TeV sources and providing a validated framework for the IceCube Upgrade.



Figure 1



The IceCube Neutrino Observatory at South Pole

- **DeepCore**: a subarray of IceCube, tailored for GeV – TeV neutrino detection
- **Upgrade**: 5 new strings, recently deployed, lower energy threshold & better measurements
- **GRECO^[1] dataset**: use DeepCore low energy events for astrophysical purpose

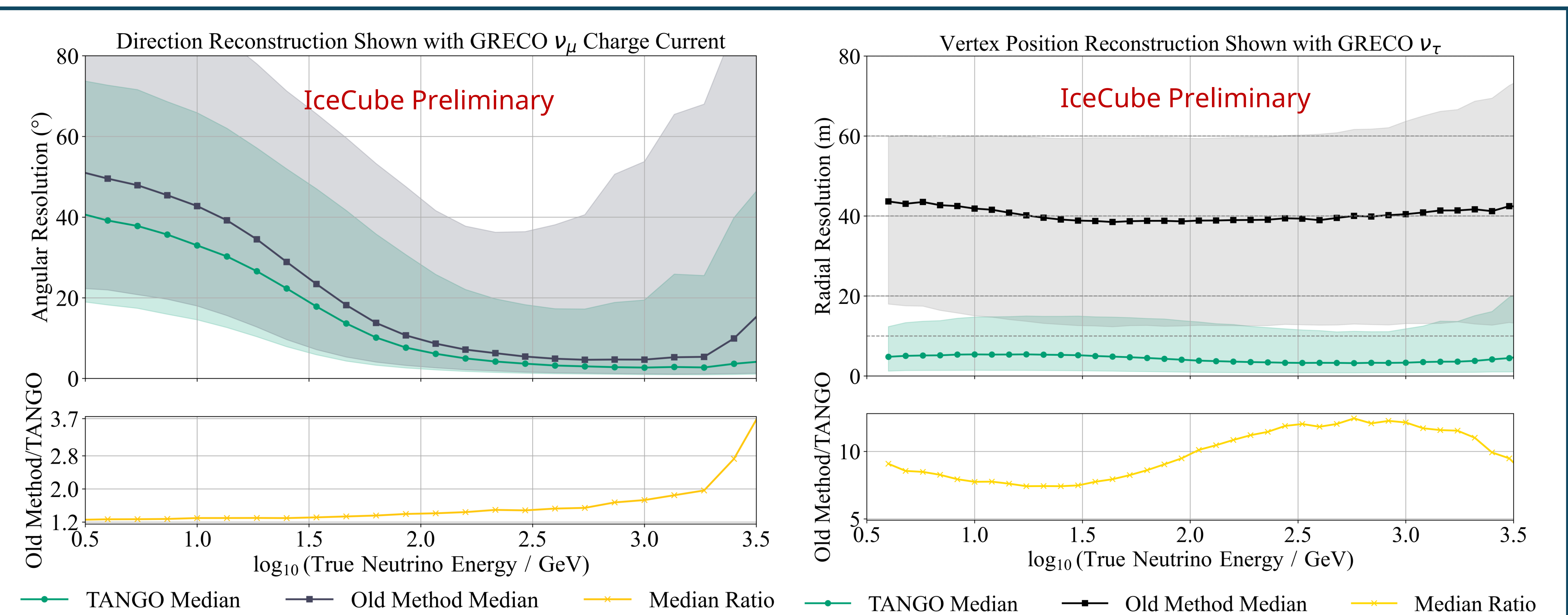


Figure 2

Model architecture of TANGO
TANGO was modified from 1st place solution of “Neutrinos in Deep Ice” Kaggle competition^[2]. Trained on a joint task combining directional and positional loss, TANGO predicts neutrino direction and interaction vertex position simultaneously with unprecedented accuracy and efficiency on GRECO events.

Reference

- [1]: R. Abbasi *et al* (IceCube Collaboration) 2023 *ApJ* 953 160
- [2]: Bukhari, H., Chakraborty, D., Eller, P. *et al*. 2024 *Eur. Phys. J. C* 84, 646
- [3]: M. G. Aartsen *et al* (IceCube Collaboration) 2019 *Phys. Rev. D* 99, 032007

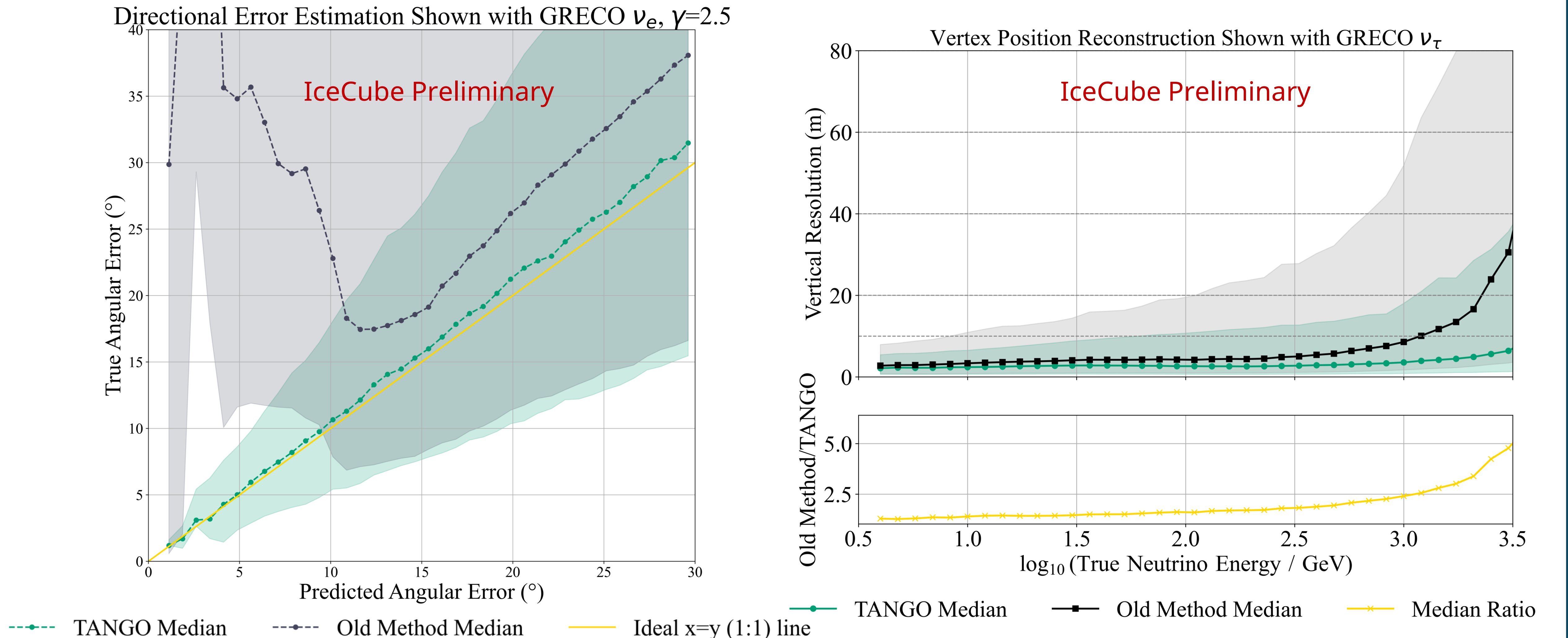


Figure 3

Reconstruction performance: TANGO vs. Old Method^[1,3]. For simplicity not all flavors are shown.

Top Left: neutrino direction reconstruction performance evaluated on GRECO ν_μ charge current (often referred as “track”) MC events. The bottom panel shows an improvement factor of at least 1.2x on angular resolution. **Bottom Left: angular error estimation** on the predicted neutrino direction evaluated on GRECO ν_e MC events. **Top Right: neutrino interaction vertex position** reconstruction evaluated on GRECO ν_τ MC events’ radial coordinate. **Bottom Right: neutrino interaction vertex position** reconstruction evaluated on GRECO ν_τ MC events’ vertical coordinate. Bottom panels show improvement factor. Radial and vertical direction are evaluated separately given the detector’s asymmetric geometry in these direction, which results in the difference in improvements.

