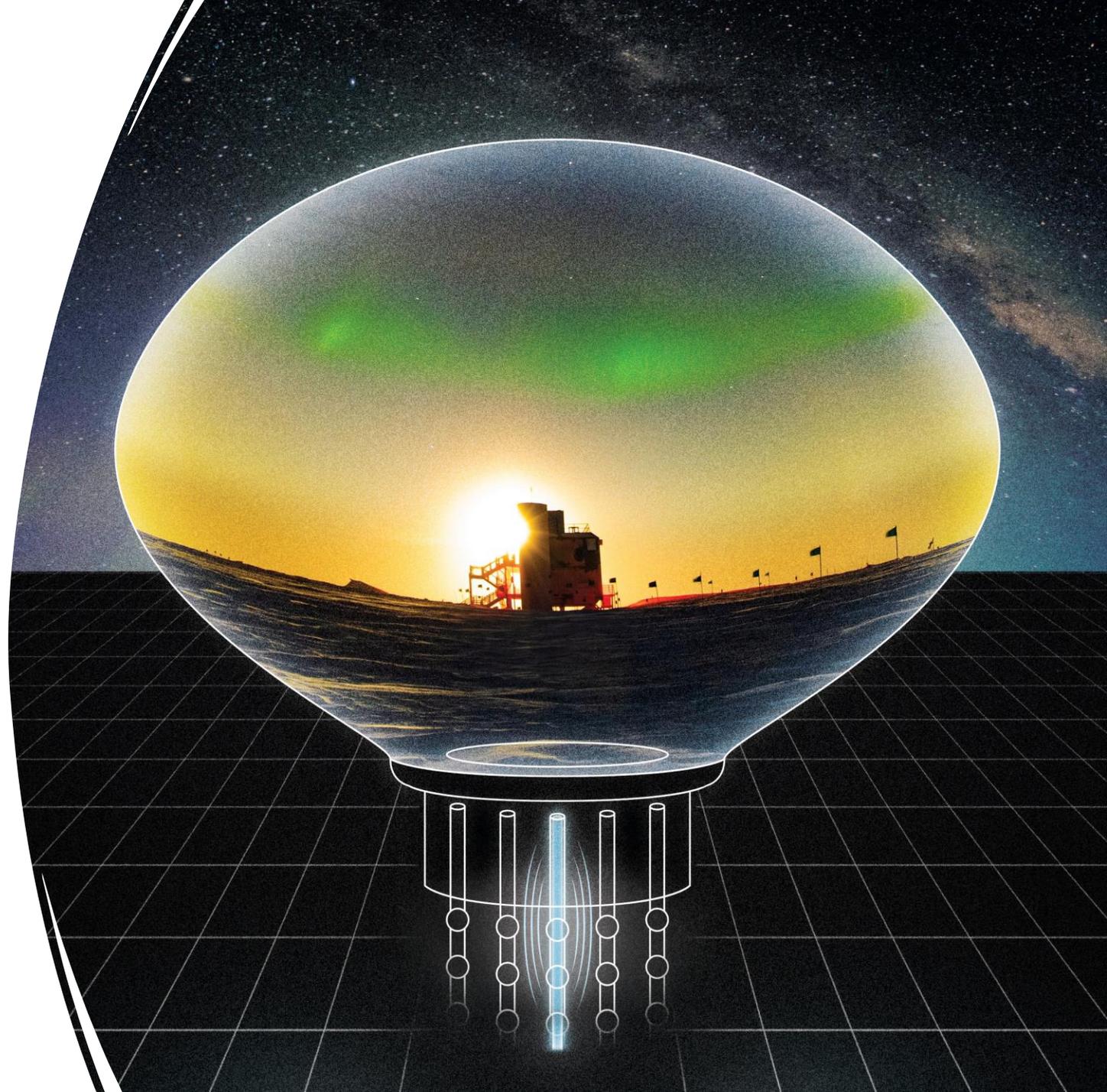




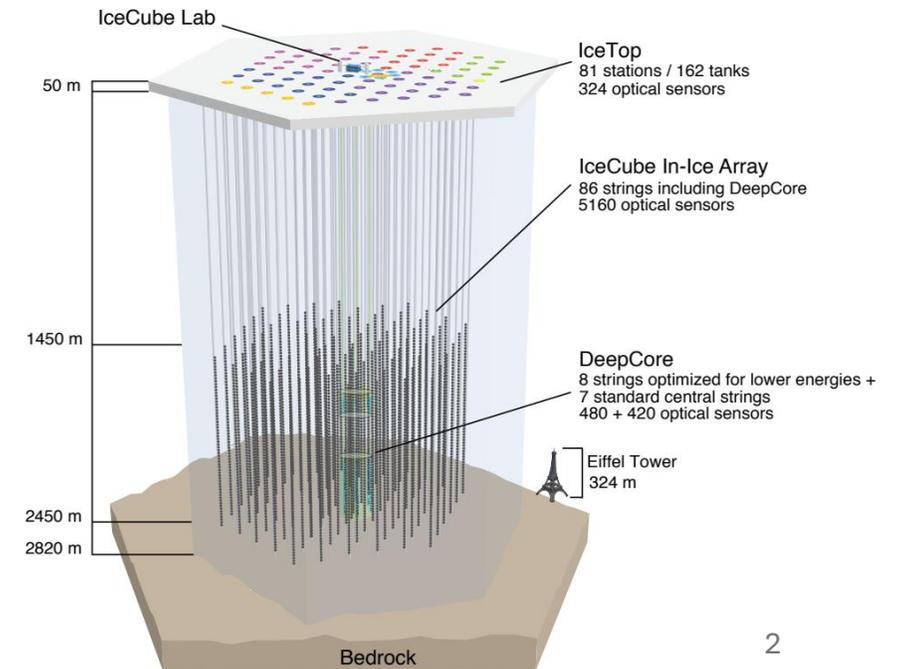
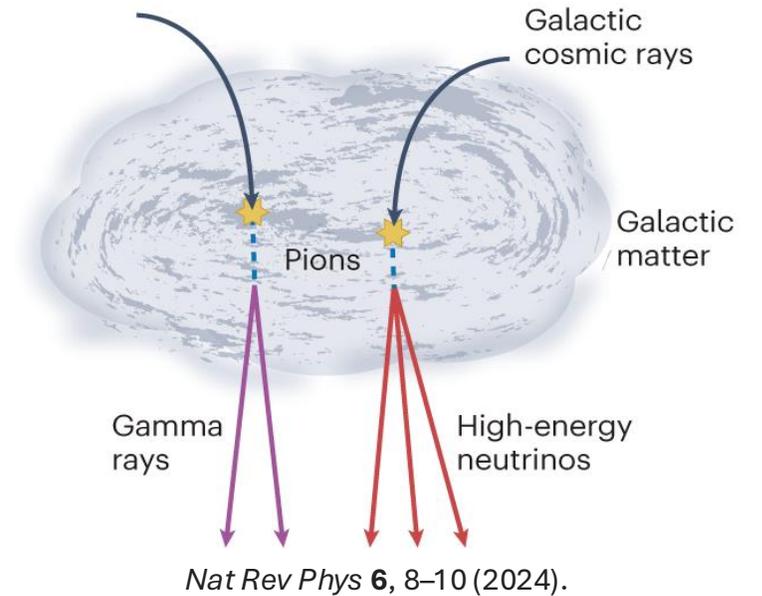
# Measuring the Galactic Plane Neutrino Flux with IceCube

Matthias Thiesmeyer, Leo Seen, Tianlu Yuan, Lu Lu, Albrecht Karle for the IceCube Collaboration

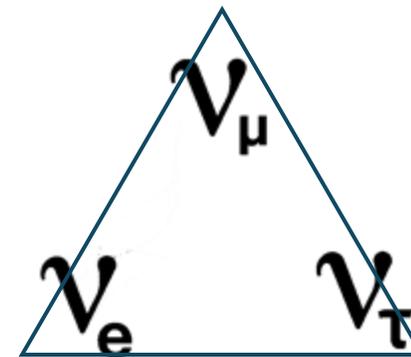


# Neutrinos from the Milky Way

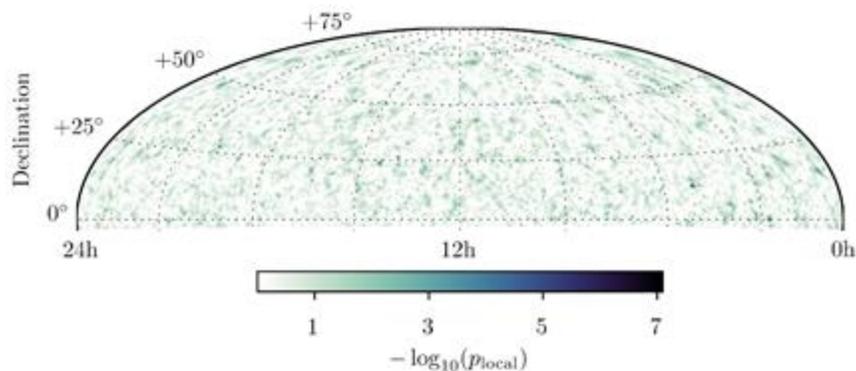
- Interactions of cosmic rays in the interstellar medium can create neutrinos via pion decay
- This leads to a diffuse astrophysical neutrino emission along the galactic plane
- In this analysis four galactic neutrino models are considered (Fermi pi0, Kra5, Kra50, CRINGE)
- The IceCube Neutrino Observatory can detect these neutrinos in different detection channels



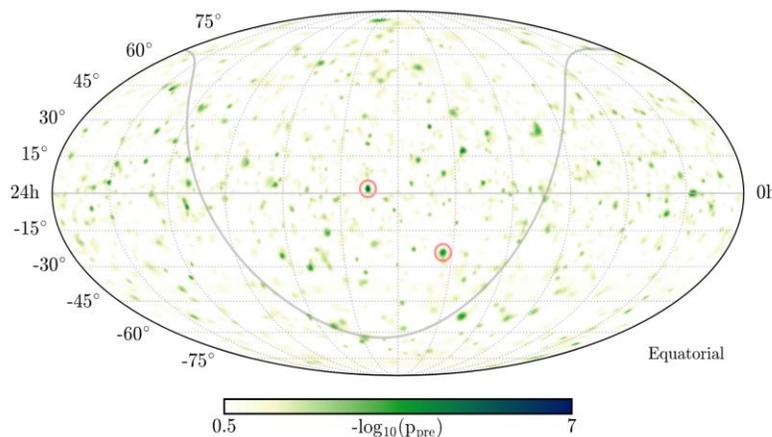
# IceCubE Multi-flavour Astrophysical Neutrino source sample (ICEMAN v1)



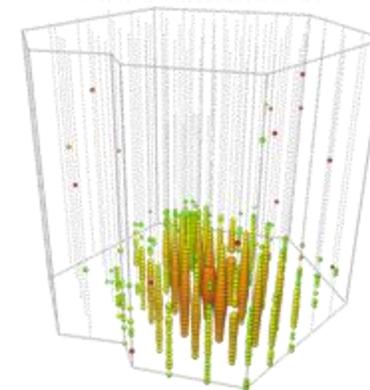
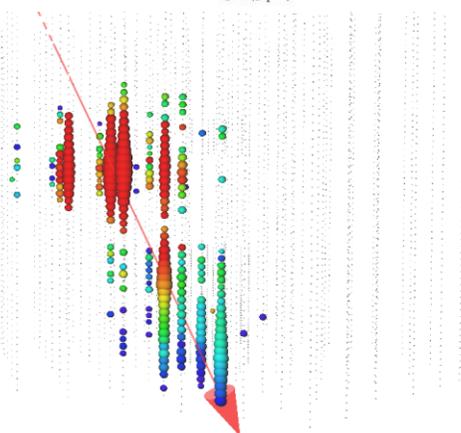
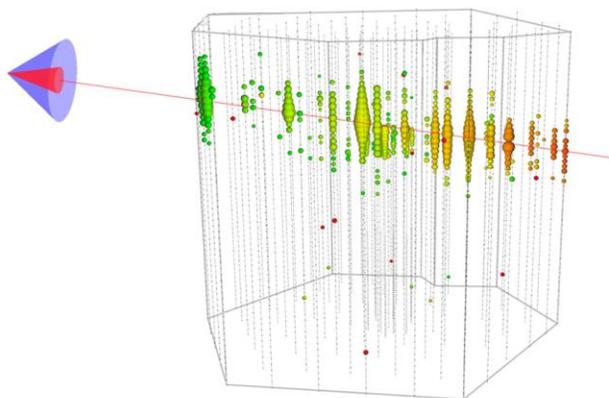
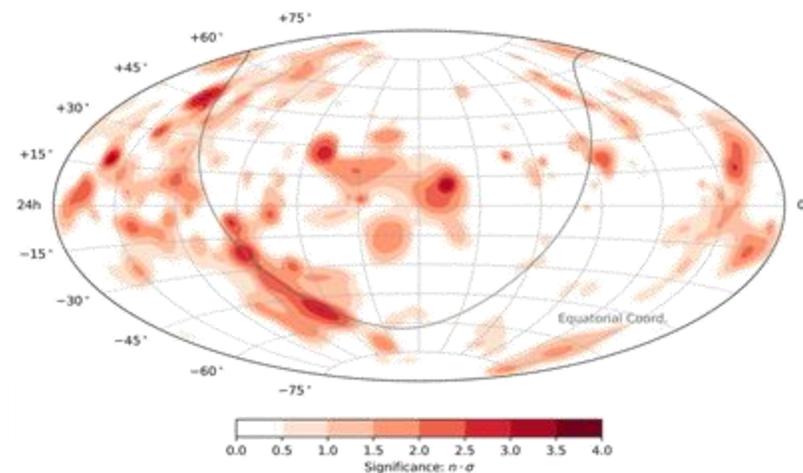
Northern Tracks (NT) - through-going tracks



ESTES - starting tracks

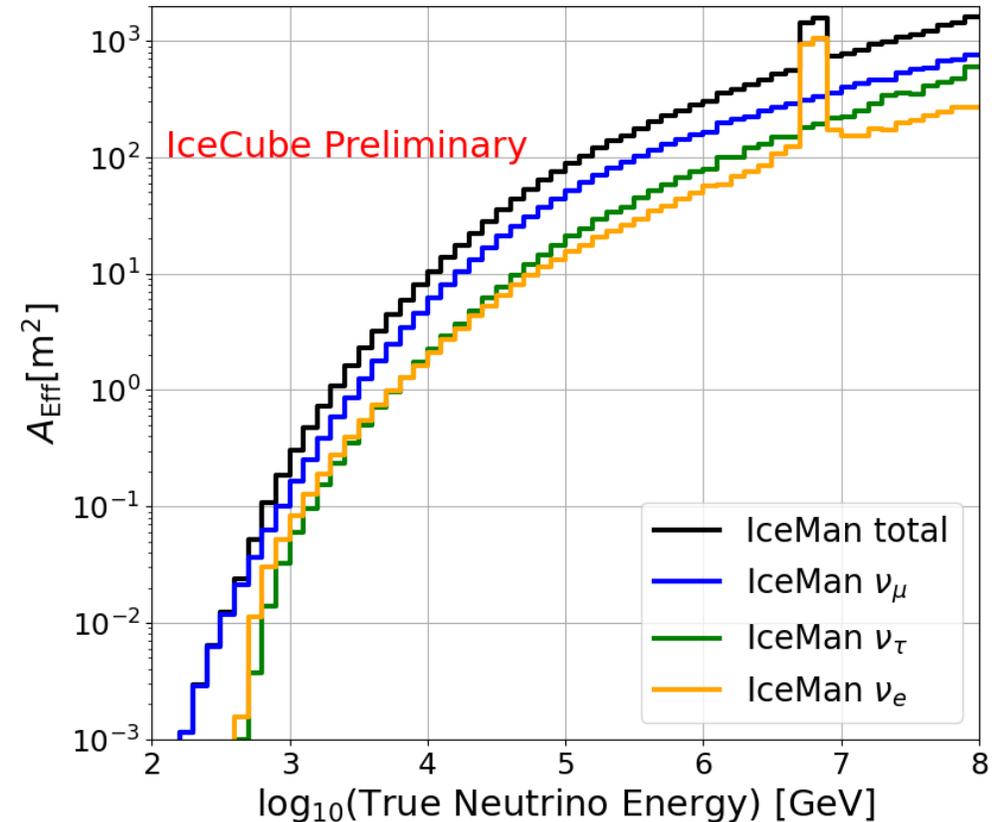


DNN Cascades (DNNC)



# IceMan: a combined dataset

- By combining all three datasets a significantly improved sensitivity is achieved
- The combined set contains over 12 years of livetime
- DNN Cascades and Northern Tracks heavily improve effective area
- ESTES and Northern Tracks improve the angular resolution
- DNN Cascades and ESTES improve astrophysical purity



Dataset	NT	ESTES	DNNC
Event counts	979227	12048	85754

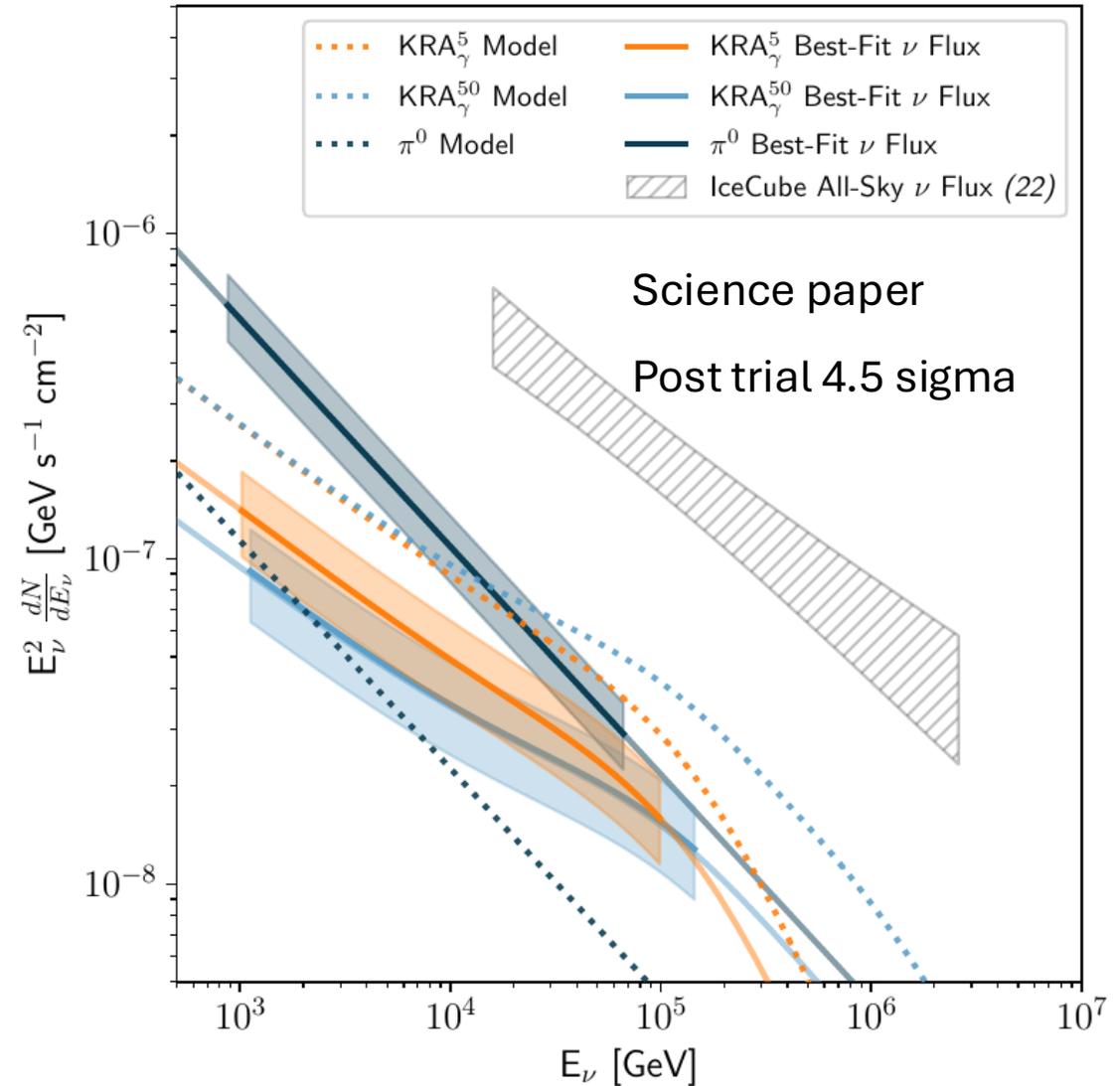
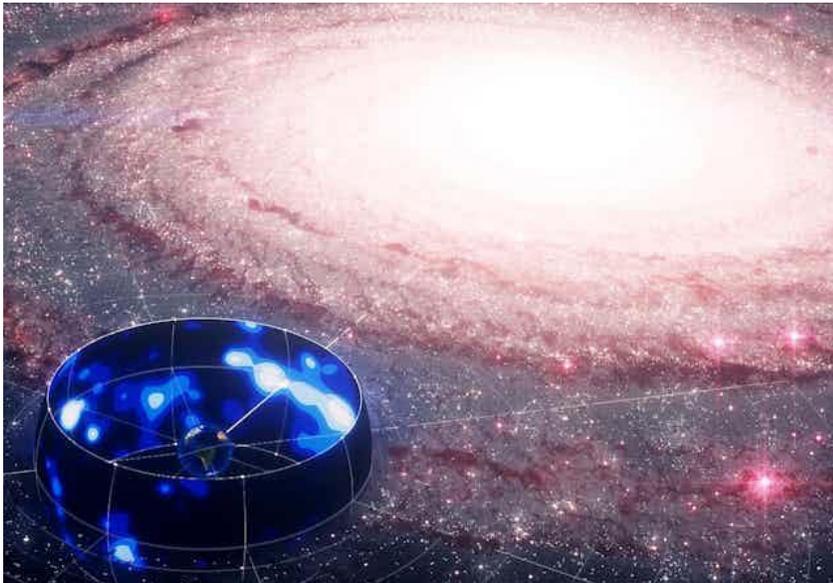
# Based on successes from previous analyses

- DNN Cascades (Published in Science)
- Northern tracks (ICRC Proceeding 2023)
- ESTES (<https://arxiv.org/abs/2501.16440>, publication in progress)

Are tracks and cascades consistent?

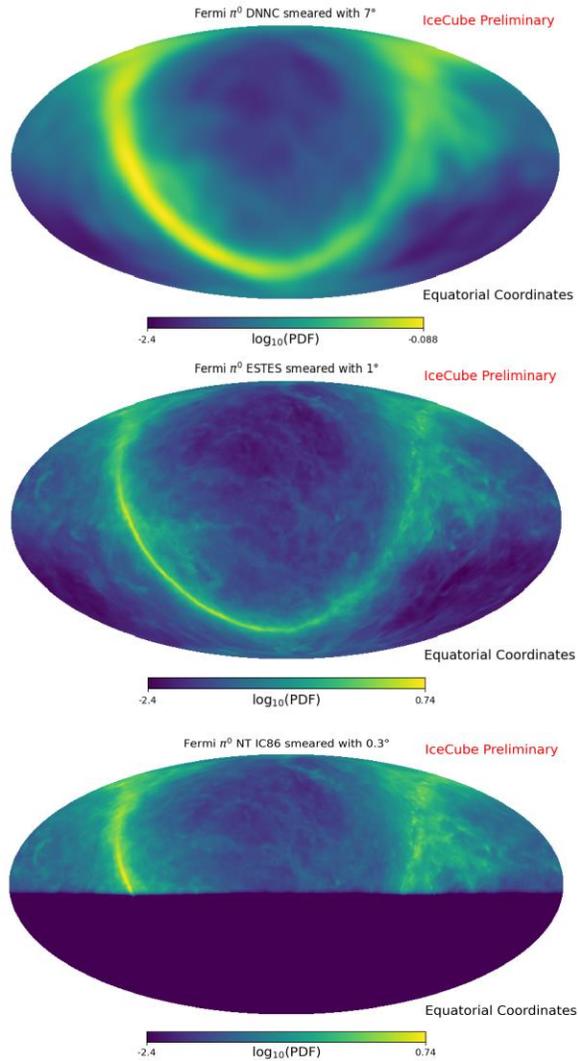
What's the combined p-value?

Why fluxes agree at 100 TeV but in tension at ~TeV?

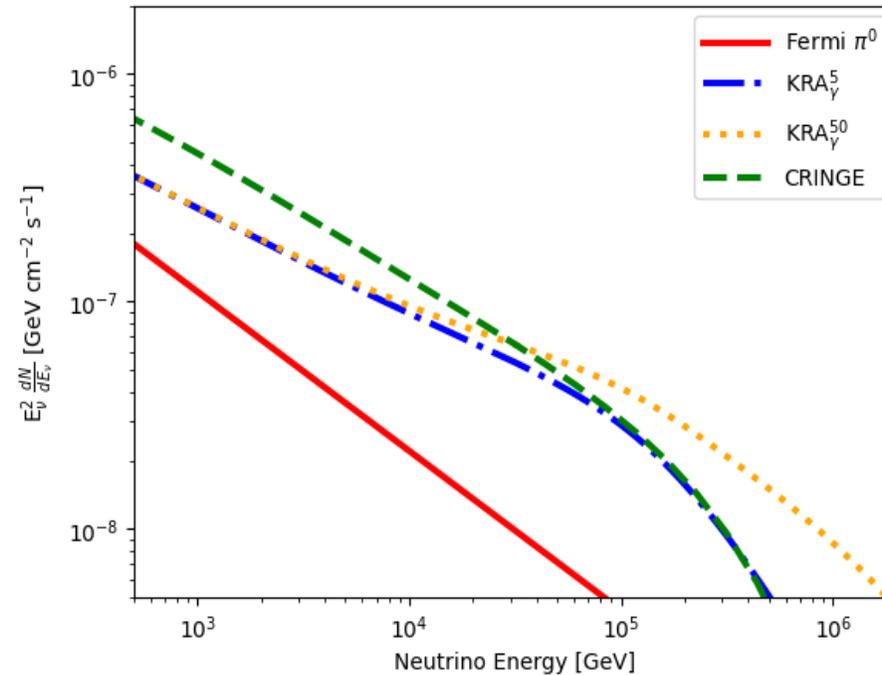


# Method: 3D template fitting via scrambled data

## Spatial



## Energy



## Likelihood

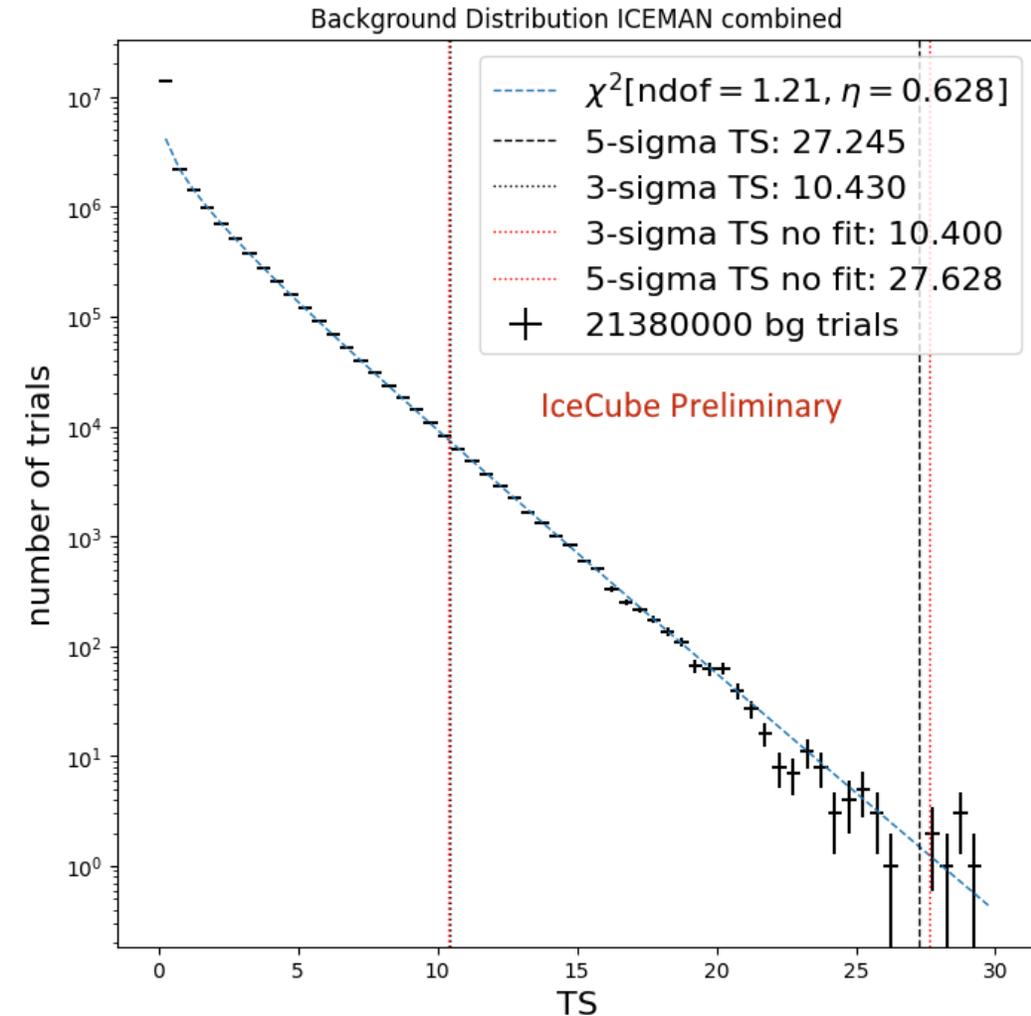
$$\mathcal{L}(n_s) = \prod_j^M \prod_{i=1}^N \frac{n_s a^j}{N^j} S^j(\delta_i^j, \alpha_i^j, E_i^j, \sigma_i^j) + \bar{D}_i^j(\sin(\delta_i^j), E_i^j) - \frac{n_s a^j}{N^j} \bar{S}_i^j(\sin(\delta_i^j), E_i^j, \sigma_i^j)$$

$$\text{TS} = 2 \ln \left[ \frac{\mathcal{L}(\hat{n}_s)}{\mathcal{L}(n_s = 0)} \right]$$

$M$ : subsamples

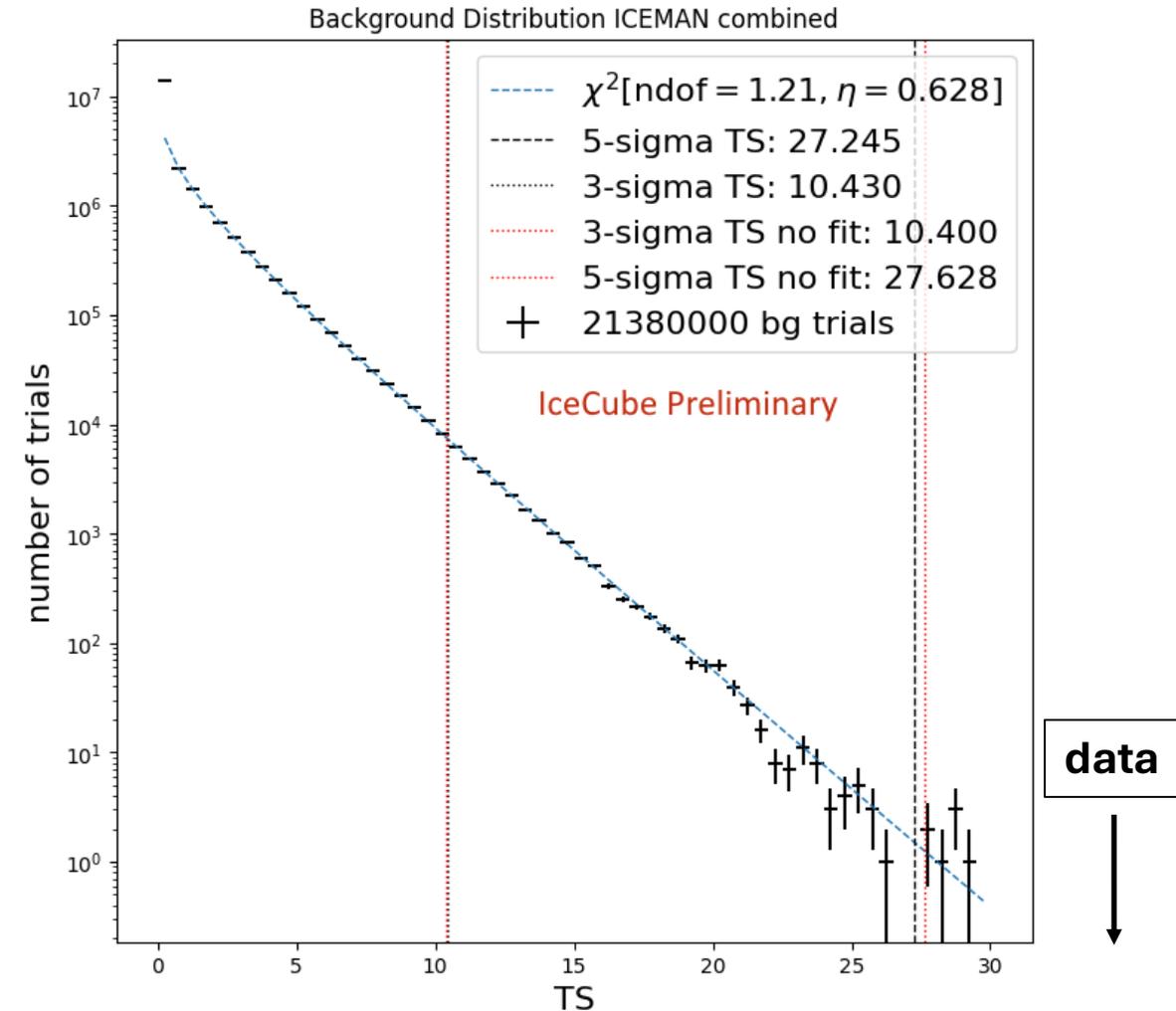
$N$ : #events per subsample

# Combined Background Distribution



- Tested 4 templates
  - Fermi pi0
  - KRA gamma 5
  - KRA gamma 50
  - CRINGE with unresolved sources
- TS distribution based on ~21.3 million trials
- Comparing of the highest TS to this distribution allows for trials correction
- Method accounts for template correlation

# Combined Background Distribution



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  - Fermi pi0
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# DNN Cascades as the driving sample

- Fermi  $\pi^0$  is the most significant model with **5.7 sigma post trial**,  $p \sim 5.9e-9$
- DNN Cascades is the data set with by far the biggest contribution with over 5 sigma locally
- The lower contribution of the track sets is due to field of view, astrophysical purity and effective area

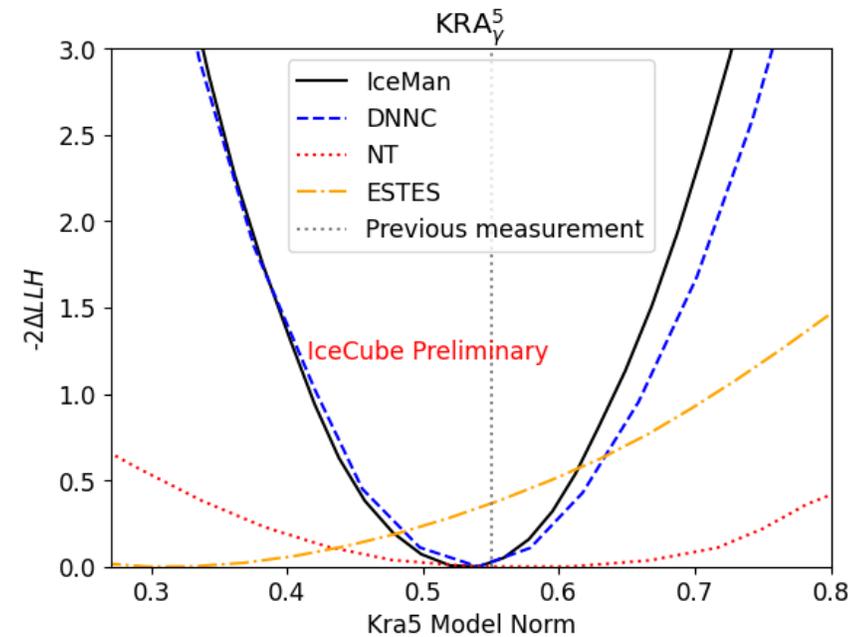
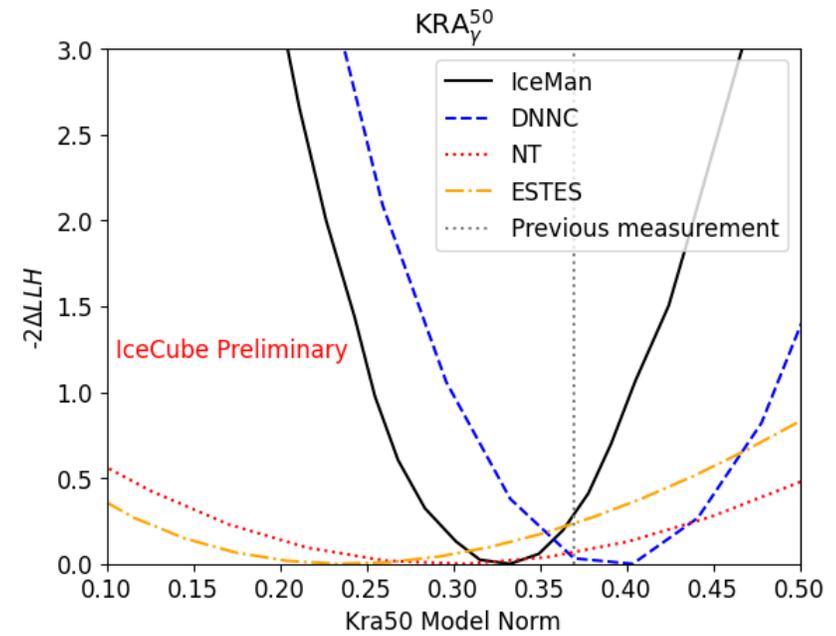
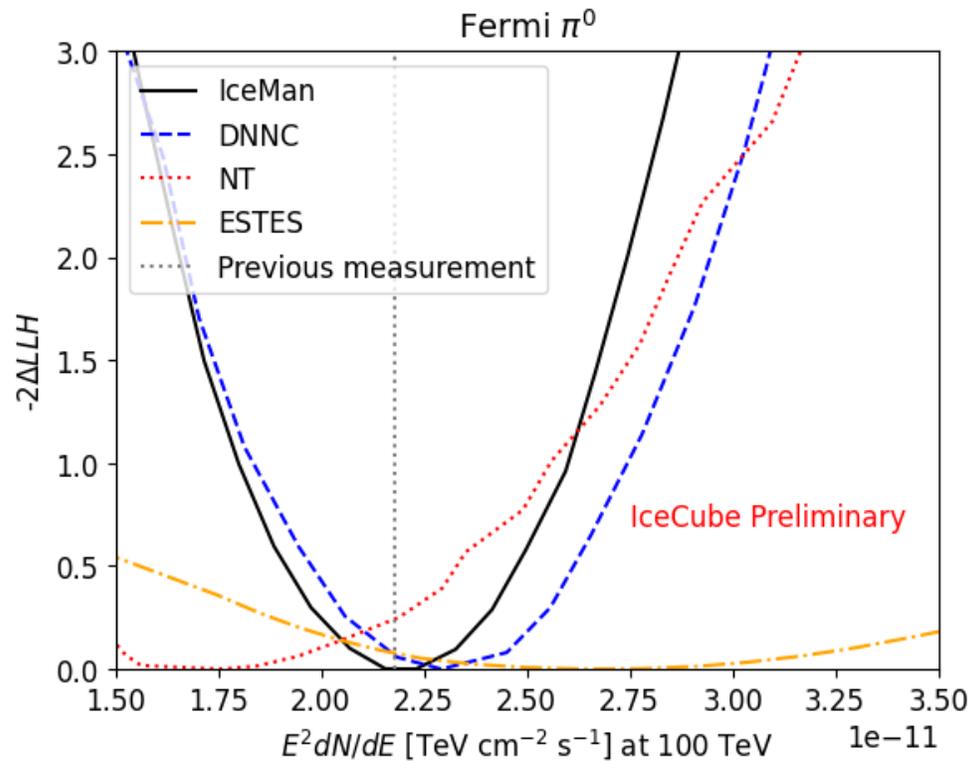
Channel	Fermi $\pi^0$	CRINGE	KRA $_{\gamma}^5$	KRA $_{\gamma}^{50}$
All flavours (IceMan)	5.97 $\sigma$	5.64 $\sigma$	5.34 $\sigma$	5.10 $\sigma$
Showers / cascades (DNNC)	5.29 $\sigma$	4.89 $\sigma$	5.05 $\sigma$	4.97 $\sigma$
Through-going muon tracks (NT)	2.22 $\sigma$	2.20 $\sigma$	1.60 $\sigma$	1.13 $\sigma$
Starting muon tracks (ESTES)	1.61 $\sigma$	1.77 $\sigma$	1.23 $\sigma$	1.23 $\sigma$

Local significances of the four tested models

For results with the previous version of DNNC see contribution #41 by Riya Shah

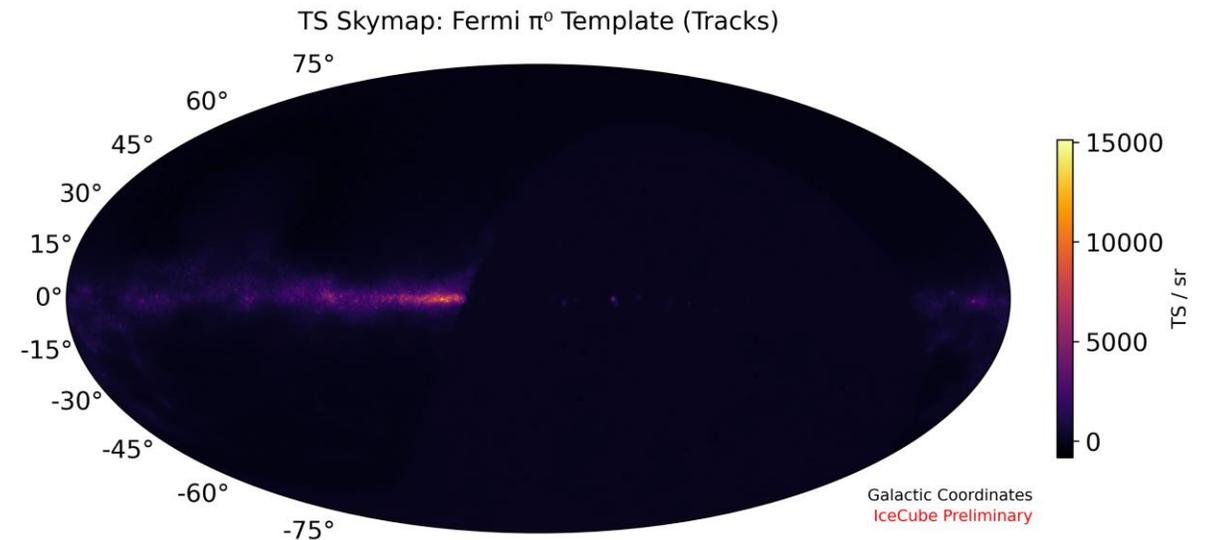
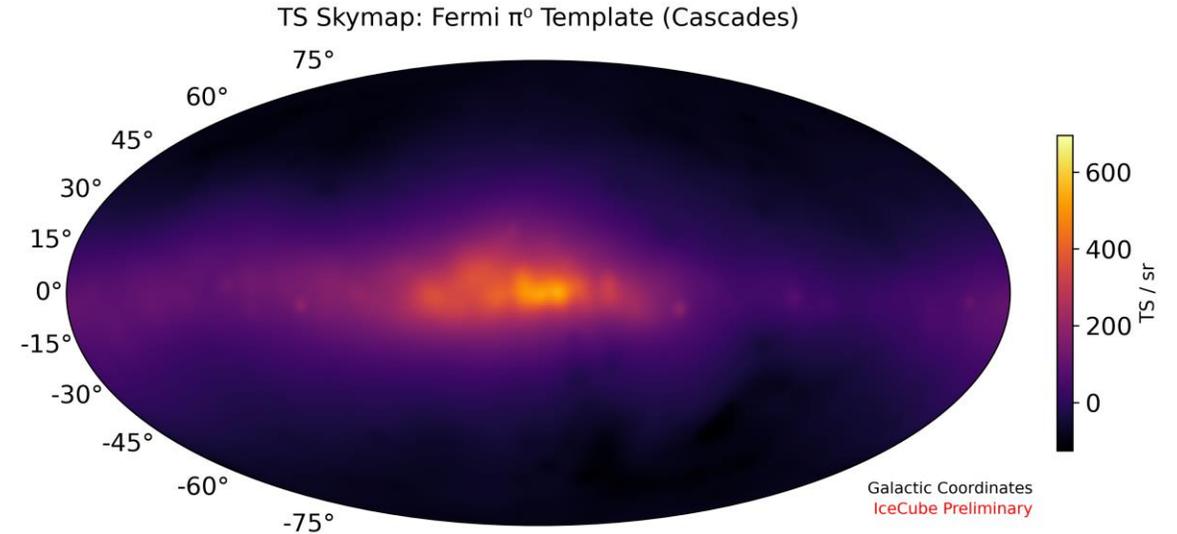
# Best fit flux

- Best fit consistent with previous science paper result
- Tracks and cascades in agreements within uncertainties



# Spatial TS Distribution

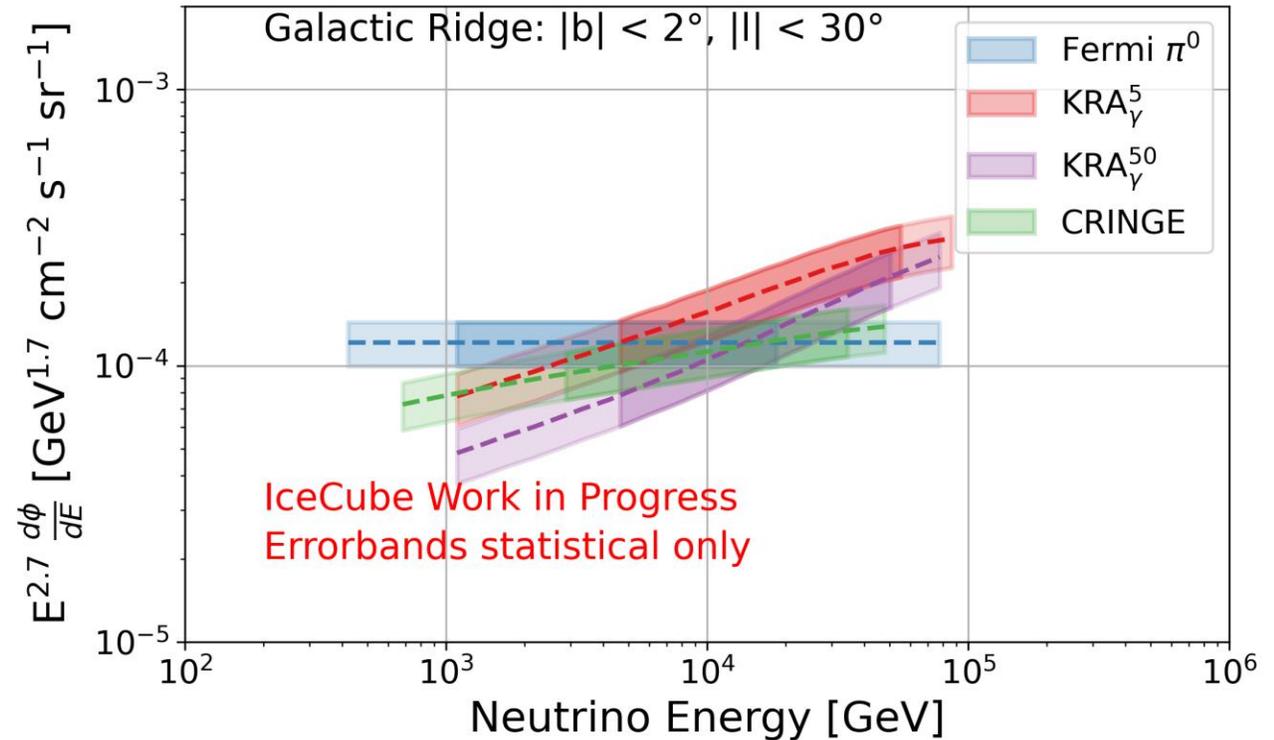
- The spatial TS distribution under the model template hypothesis shows most signal comes from the galactic center
- For Northern Tracks (the bigger of the two track samples) the galactic center is not in the field of view leading to a different distribution
- The fit is expected to match the models in the galactic center region



# Flux Measurement

- Model predictions are scaled to the best fit all-sky normalizations
- The sensitive energy range shown corresponds to the range contributing to 68% and 90% of the final TS (box and light shaded region)
- A spatial cut on the Galactic Ridge shows the fluxes in the region around the center, where the fit is the most sensitive

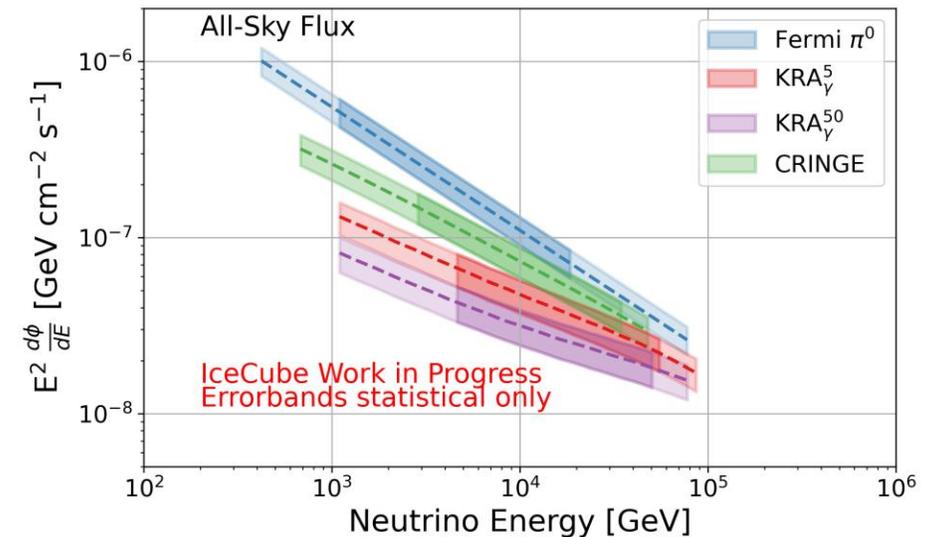
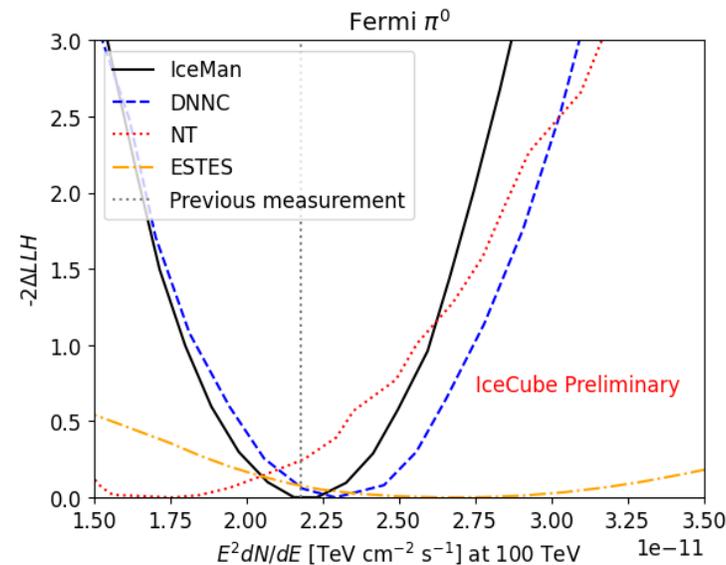
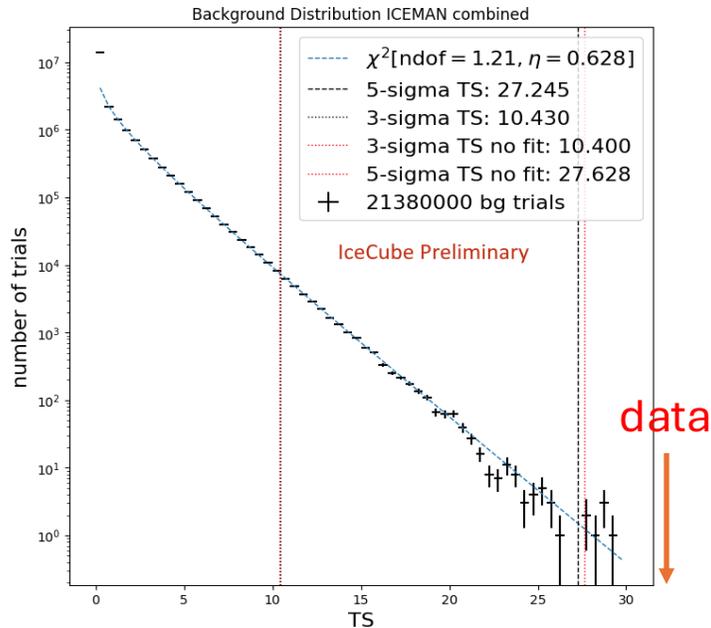
For model independent GP flux measurement see next talk #269 by Ludwig NESTE



Template	Pi0 [TeV/(s cm <sup>2</sup> ) ]	Kra5 (model norm)	Kra50 (model norm)	CRINGE (model norm)
Best fit (all-sky)	2.19e-11	0.53	0.37	0.91

# Conclusion and Outlook

- 5.7 sigma post trial significance with multi-flavor neutrinos from the galactic plane
- Flux measurements consistent between all sub data sets and the previous measurement
- This work represents IceCube's best knowledge of the neutrino signal from the galactic plane

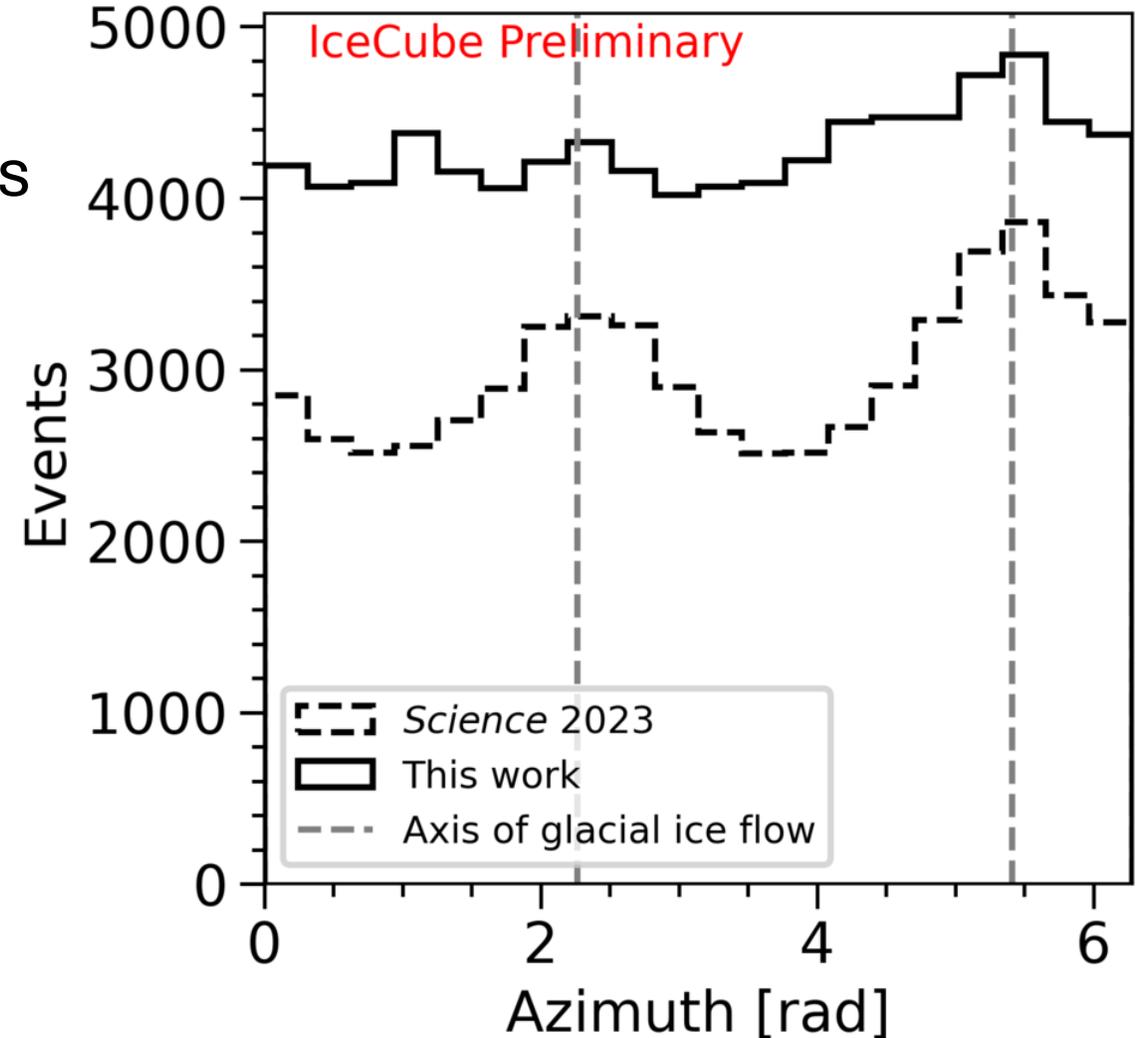




# Backup

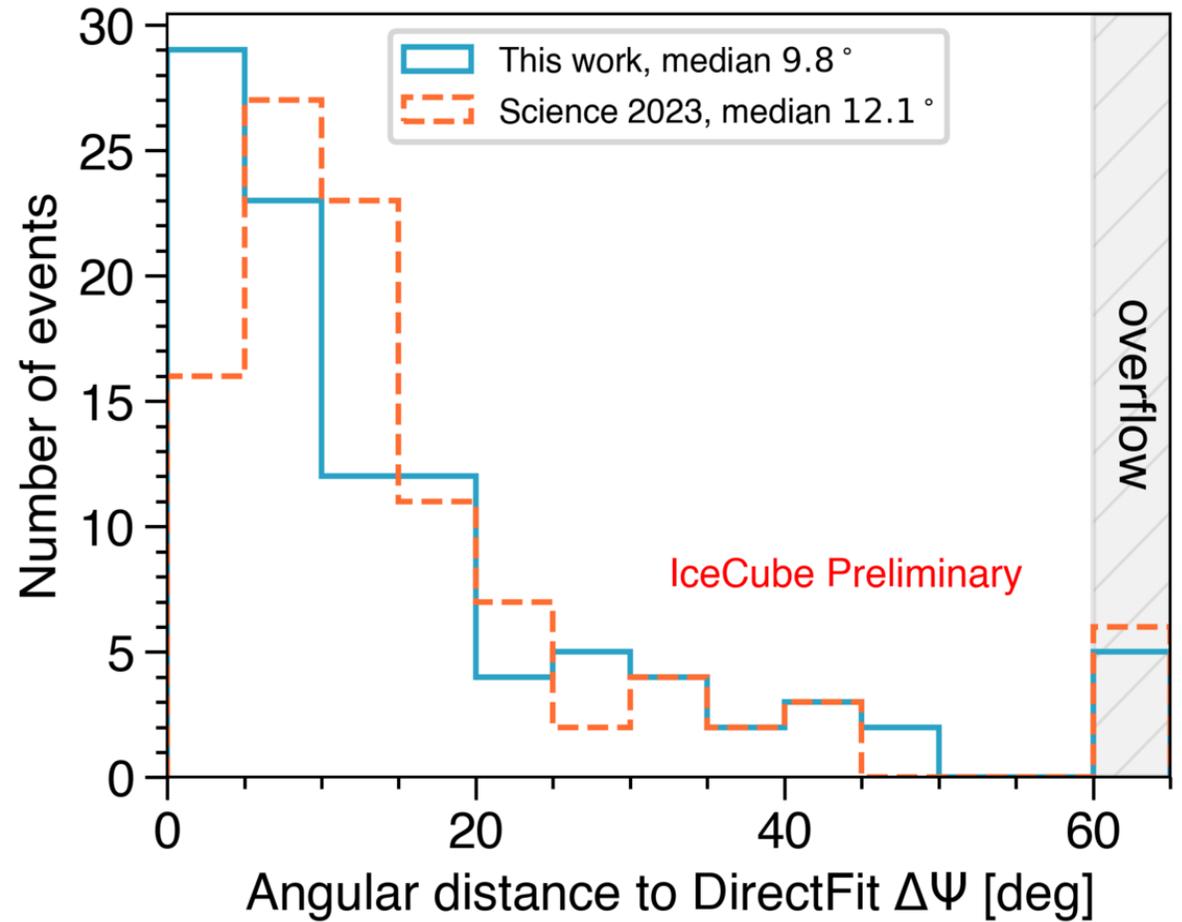
# Azimuth Bias Improvement by new Reconstruction

- Updated Reconstruction reduces azimuth bias along axis of glacial ice flow



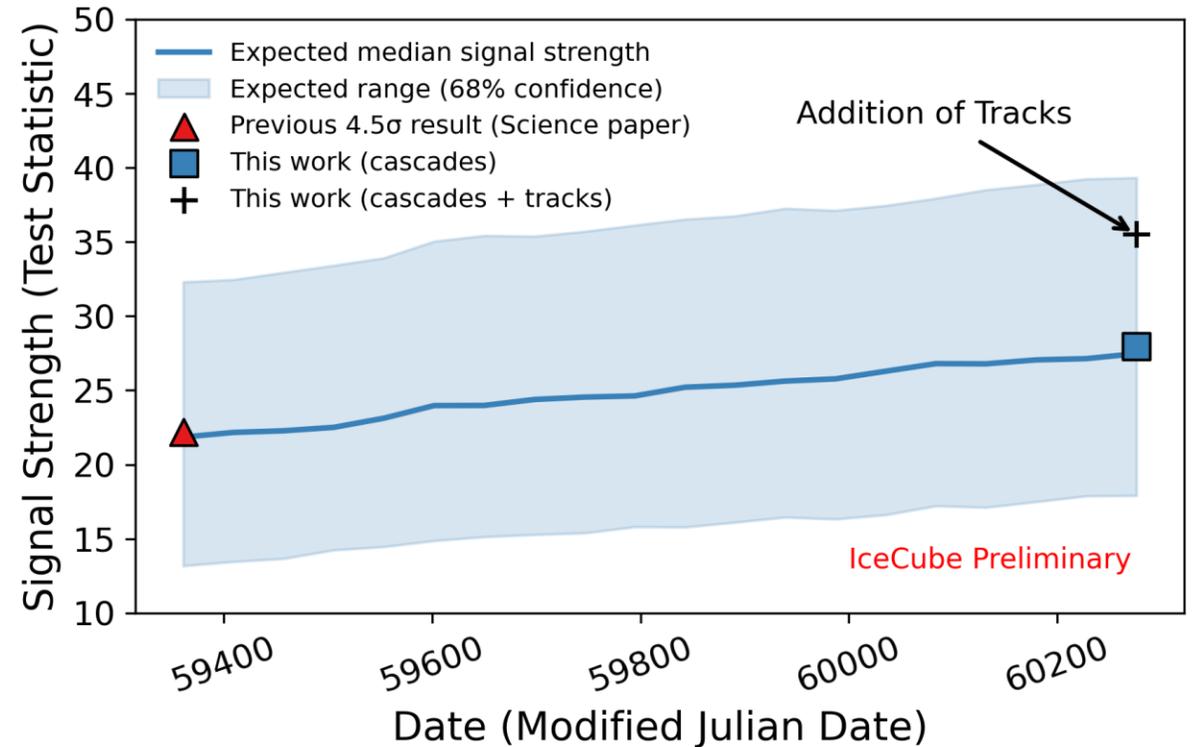
# Comparison with DirectFit

- DirectFit is an angular reconstruction in IceCube used (among others) for real time events
- It is more precise in the large N limit, but prohibitively expensive
- Comparison of the angular distance between the previous version of DNNC and this work shows the clear improvements from reconstruction and ice modelling



# Do we expect 5.7 sigma?

- Pseudo experiments are conducted at the new best fit with different livetimes
- Growth in TS in DNNC consistent with increase in livetime



# Best Fit Fluxes

- The best fit fluxes are shown for all four model and three sub-data sets
- The uncertainties include detector systematics

Channel	Fermi $\pi^0$ <sup>a</sup>	KRA $_{\gamma}^5$	KRA $_{\gamma}^{50}$	CRINGE
All flavours (IceMan)	$2.19^{+0.41}_{-0.39}$	$0.53^{+0.14}_{-0.12}$	$0.37^{+0.10}_{-0.09}$	$0.91^{+0.18}_{-0.17}$
Showers / cascades (DNNC)	$2.29^{+0.41}_{-0.40}$	$0.53^{+0.15}_{-0.13}$	$0.39^{+0.12}_{-0.10}$	$0.89^{+0.20}_{-0.18}$
Through-going muon tracks (NT)	$1.79^{+0.80}_{-0.80}$	$0.60^{+0.37}_{-0.36}$	$0.31^{+0.30}_{-0.22}$	$0.87^{+0.42}_{-0.39}$
Starting muon tracks (ESTES)	$2.74^{+1.97}_{-1.67}$	$0.33^{+0.37}_{-0.22}$	$0.25^{+0.29}_{-0.16}$	$1.22^{+0.86}_{-0.71}$

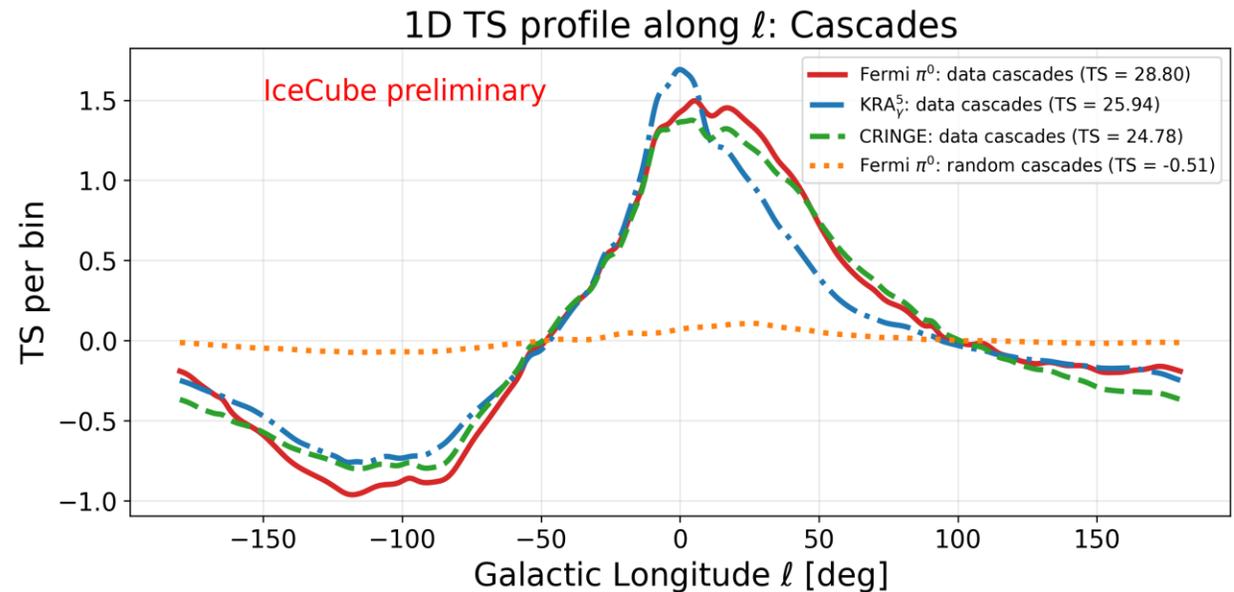
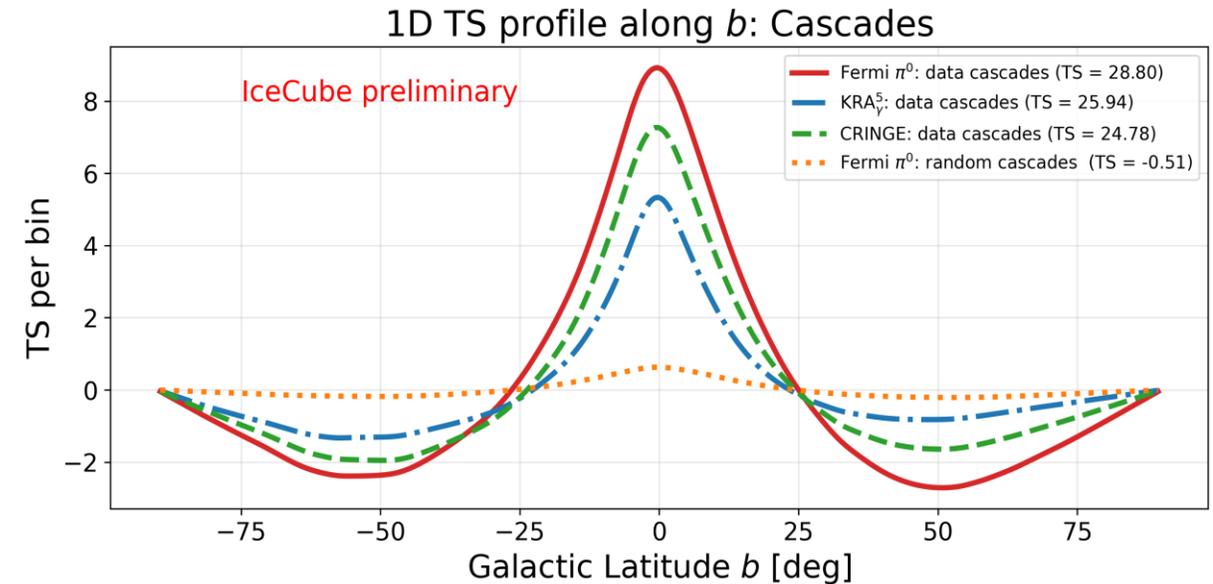
<sup>a</sup> Normalization reported at 100 TeV in units of  $10^{-11} \text{ TeV (s cm}^2\text{)}^{-1}$ .

Error bands account for detector systematics (nuisance parameters profiled in the likelihood).

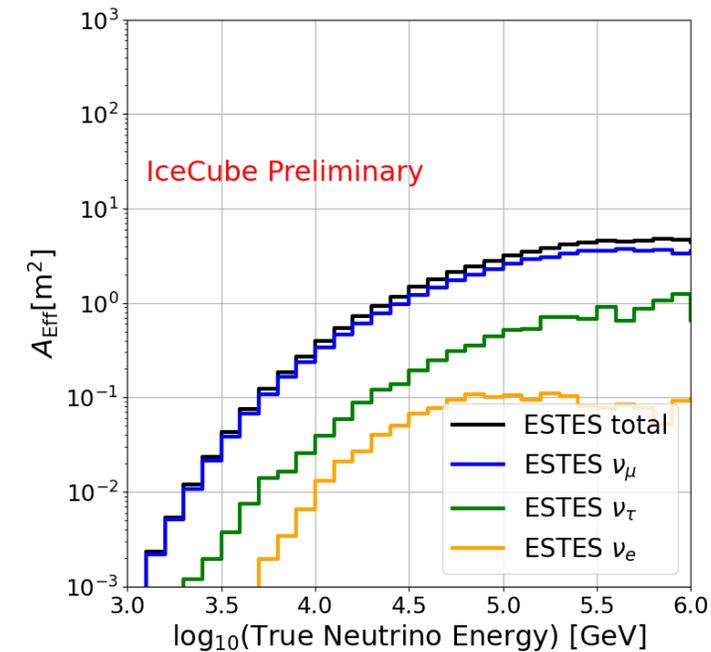
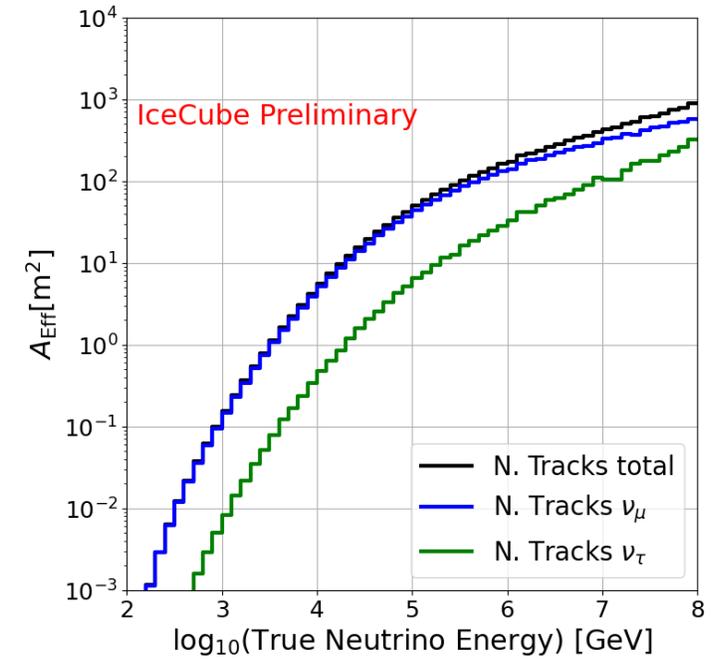
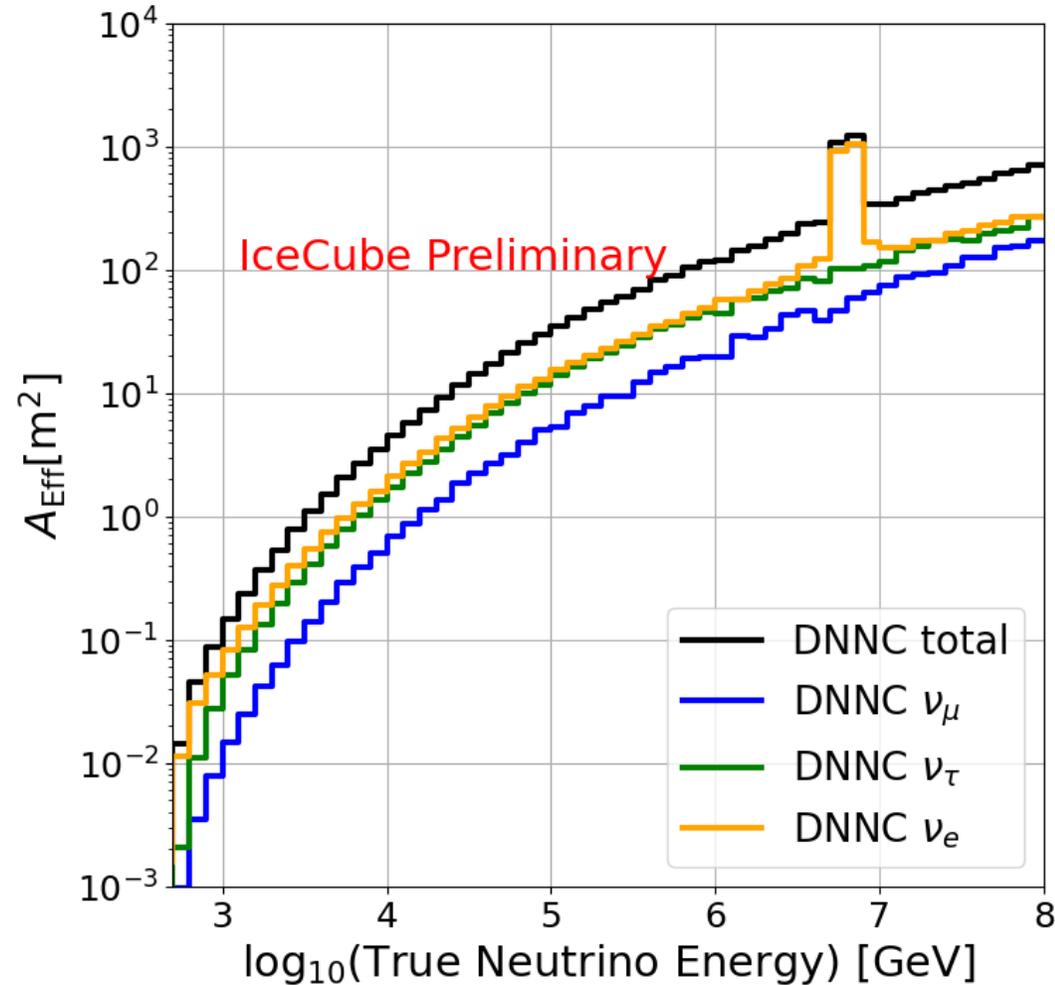
Overlaps among sub-datasets are *not* removed but removed for the combined all-flavours.

# DNNC binned TS

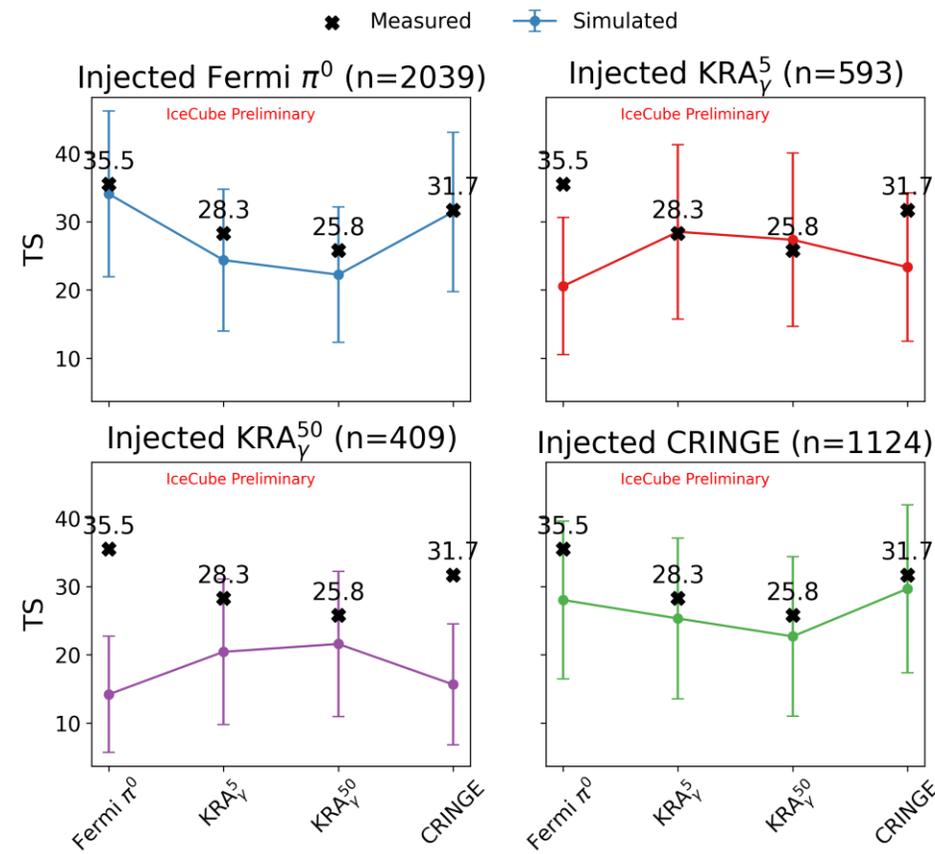
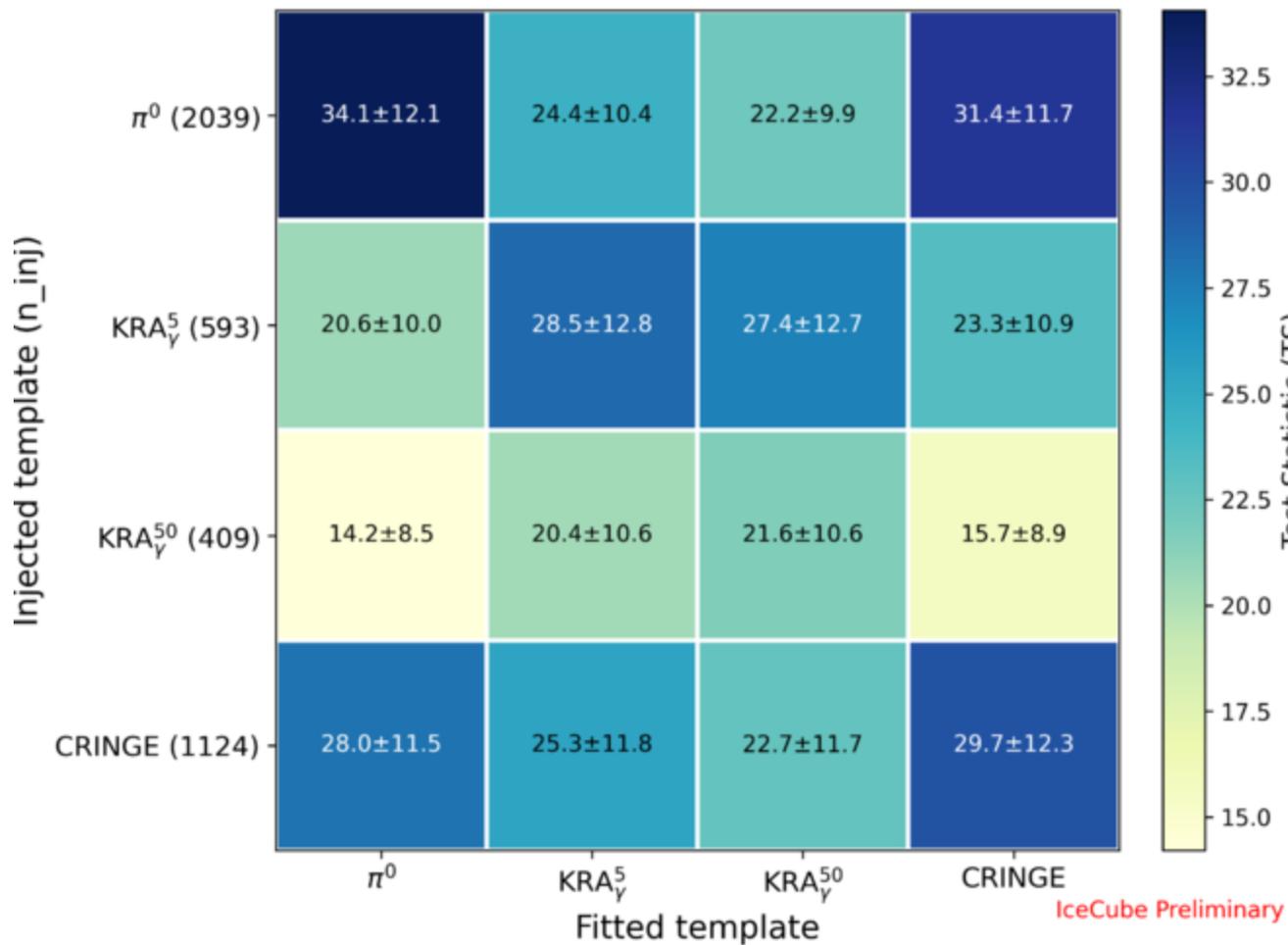
- Shown is the binned TS of the combined best fit along galactic latitude and longitude



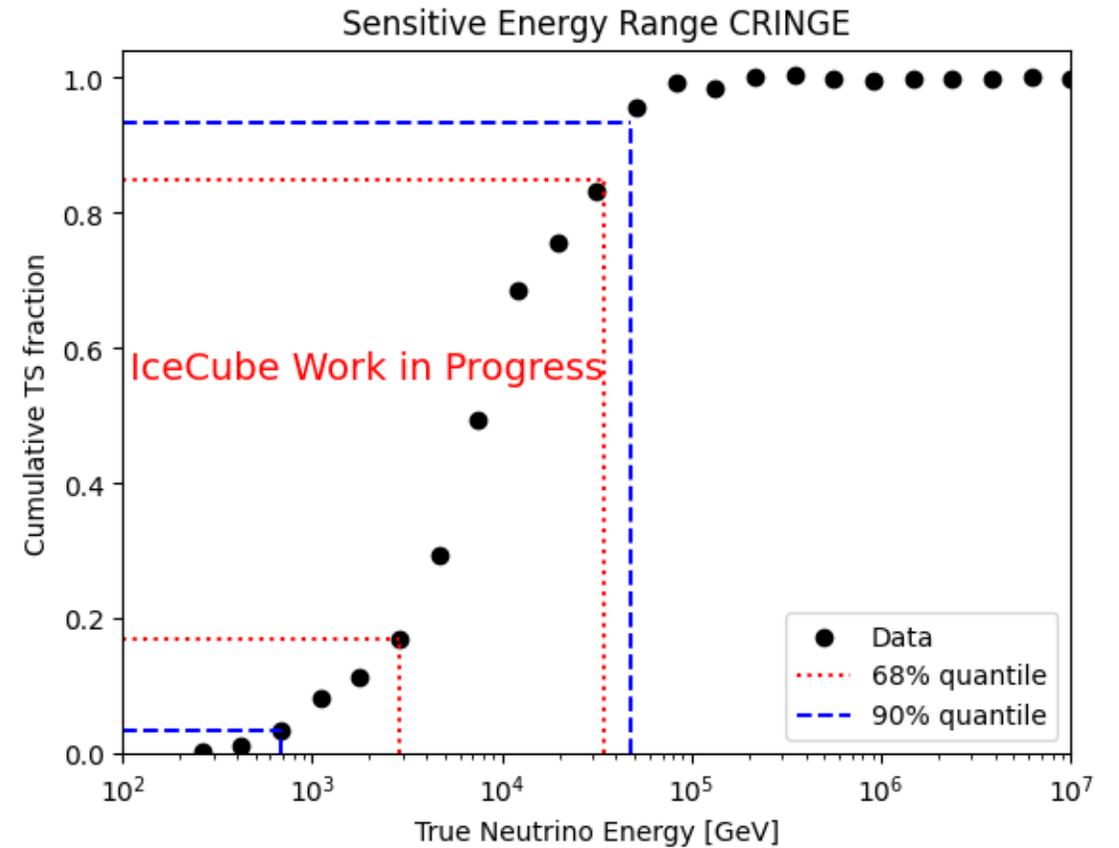
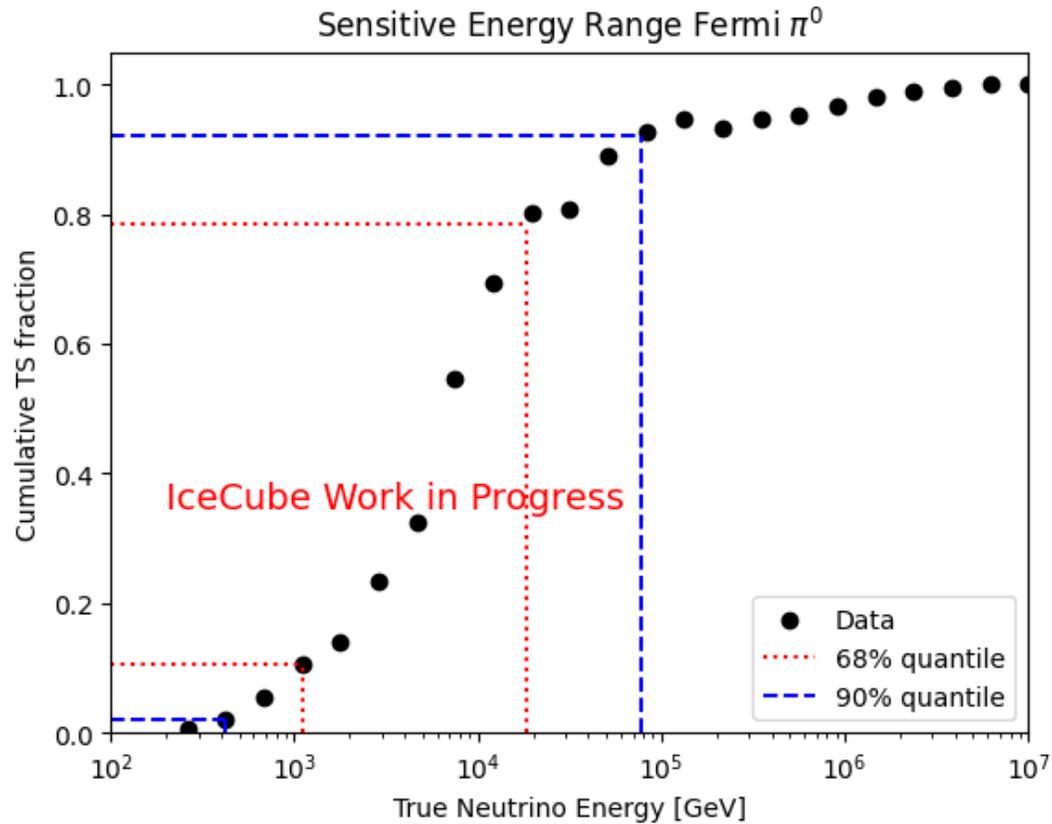
# Effective Area per Dataset



# Pseudo Experiments



# Sensitive Energy Range Method



# Signal Subtraction

- Show is the signal subtraction template for different models acceptance weighted with the ESTES data set
- The template accounts for the contamination of the background distribution by signal

