

## Observation of High-Energy Neutrinos from the Galactic Plane

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TeVPA 2023, Napoli  
September 11th, 2023

# Science – June 30, 2023

## RESEARCH

### RESEARCH ARTICLES

#### NEUTRINO ASTROPHYSICS

# Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration\*†

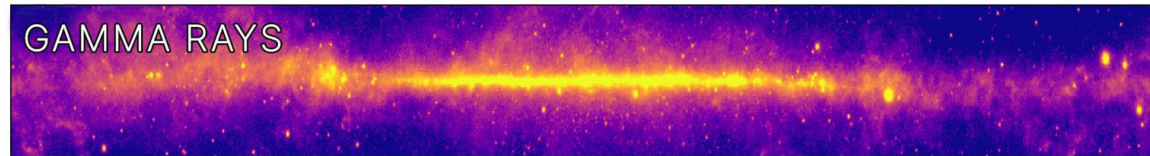
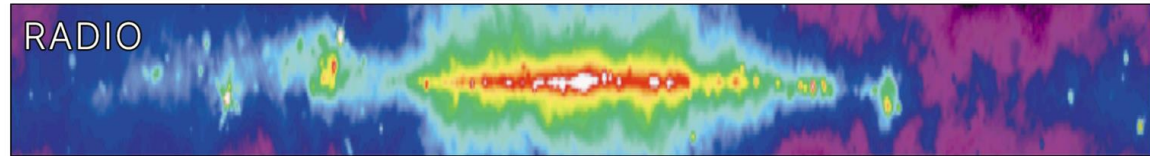
DOI: [10.1126/science.adc9818](https://doi.org/10.1126/science.adc9818)



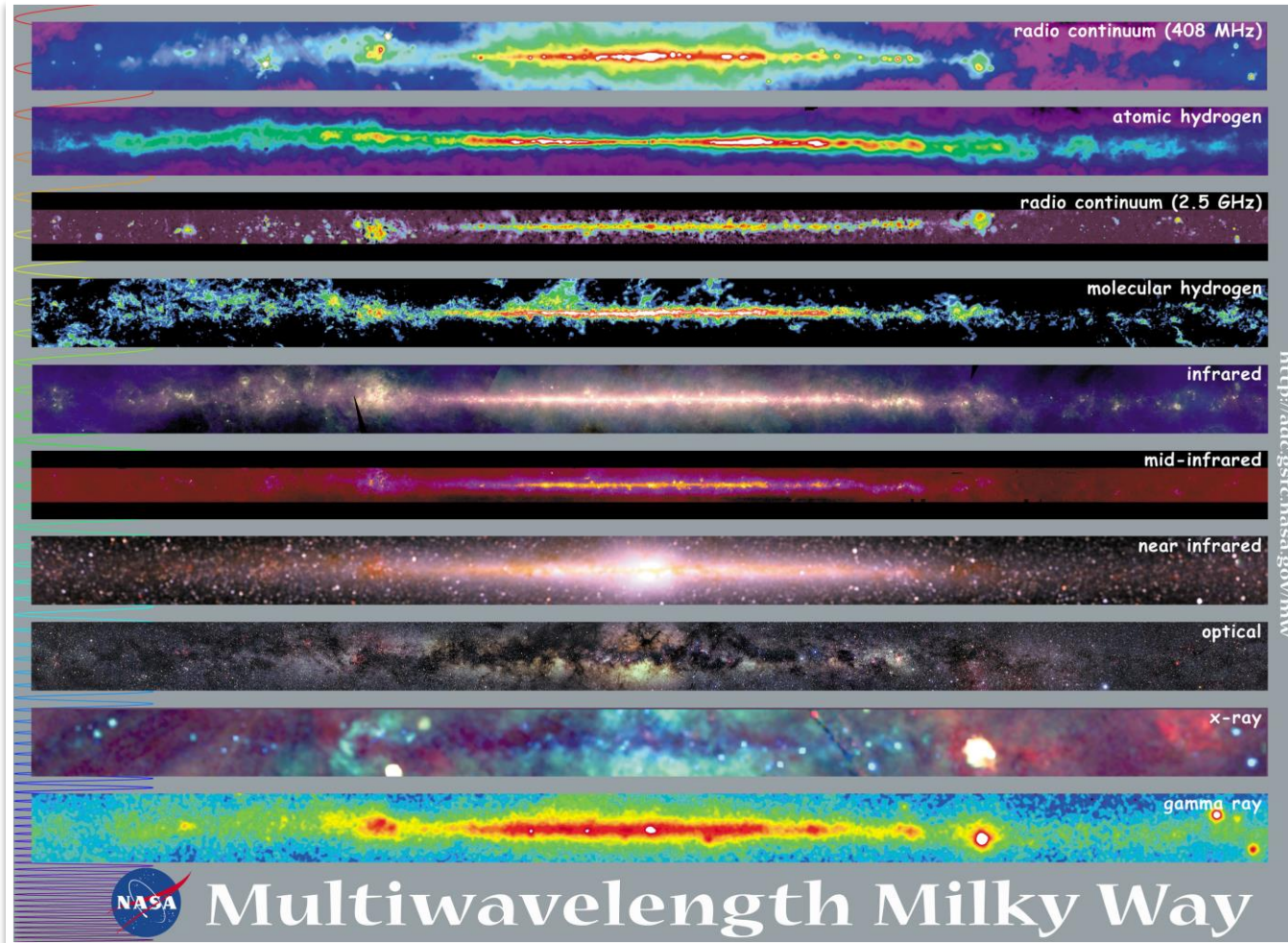
Stephen Sclafani



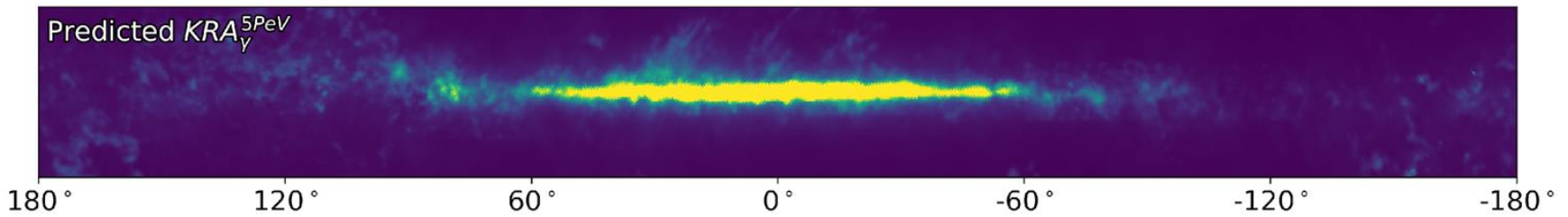
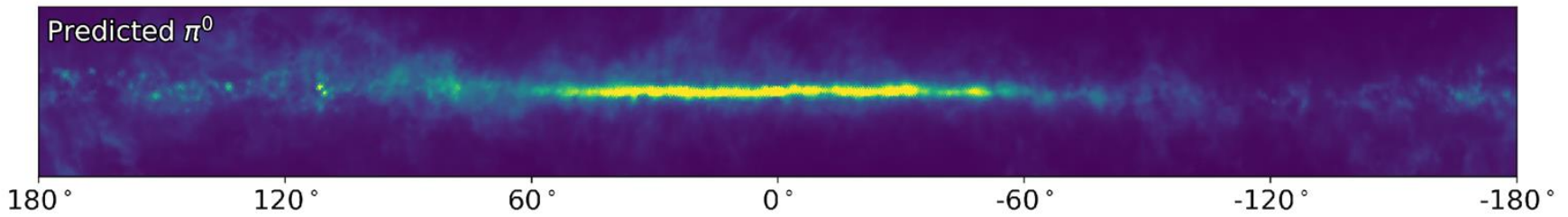
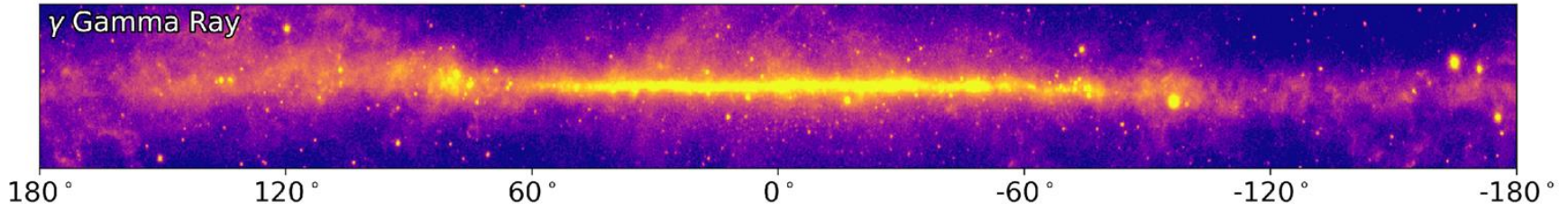
Mirco Hünnefeld



# The Multiwavelength Milky Way



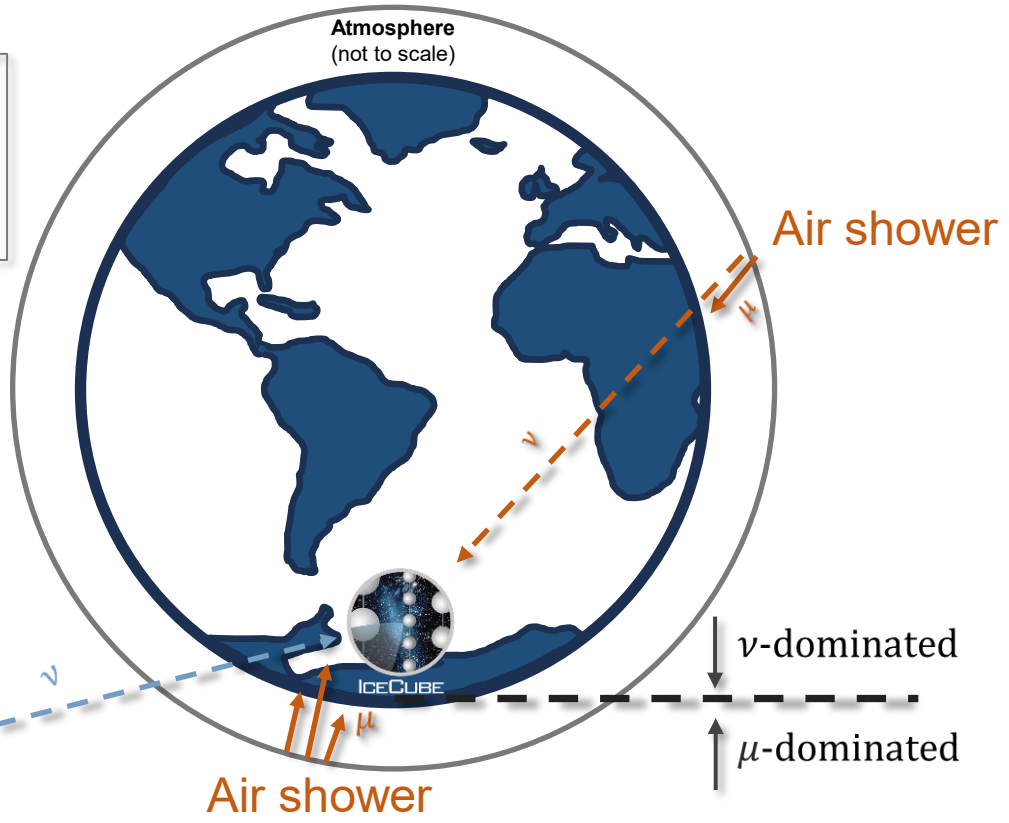
# Diffuse Neutrino Emission in the Galactic Plane



1. Ackermann et al. *The Astrophysical Journal* 750, no. 1 (April 2012): 3.
2. Gaggero et al *The Astrophysical Journal* 815, no. 2 (December 2015): L25.

# Challenges of Neutrino Source Searches

Rates:  
Atmospheric Muons:  $\sim 2700 / s$   
Atmospheric Neutrinos:  $\sim 1 / \text{hour}$   
Astrophysical Neutrinos:  $\sim 1 / \text{day}$



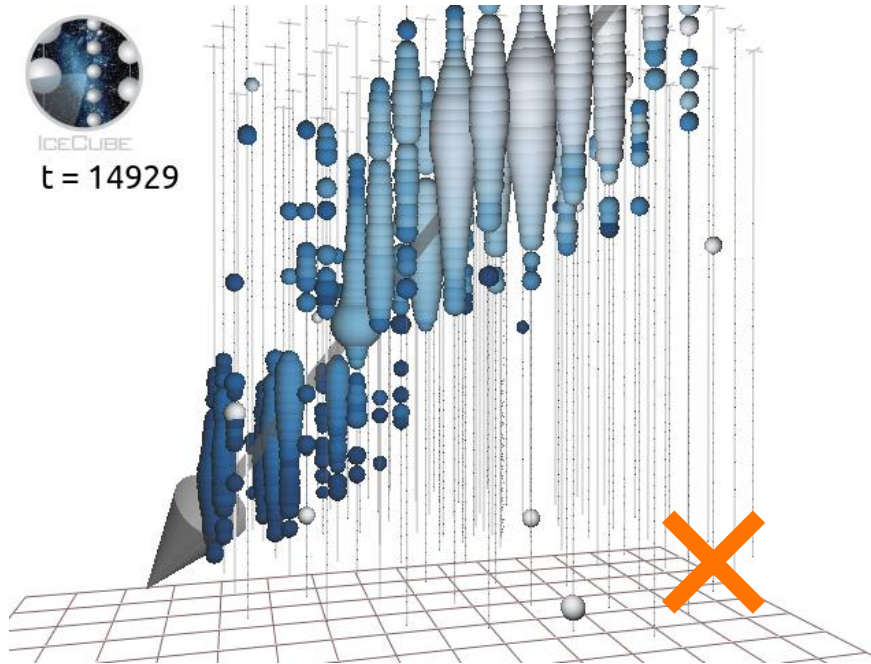
Astrophysical source (e.g., Milky Way)

→ Solved challenges with new tools based on deep learning

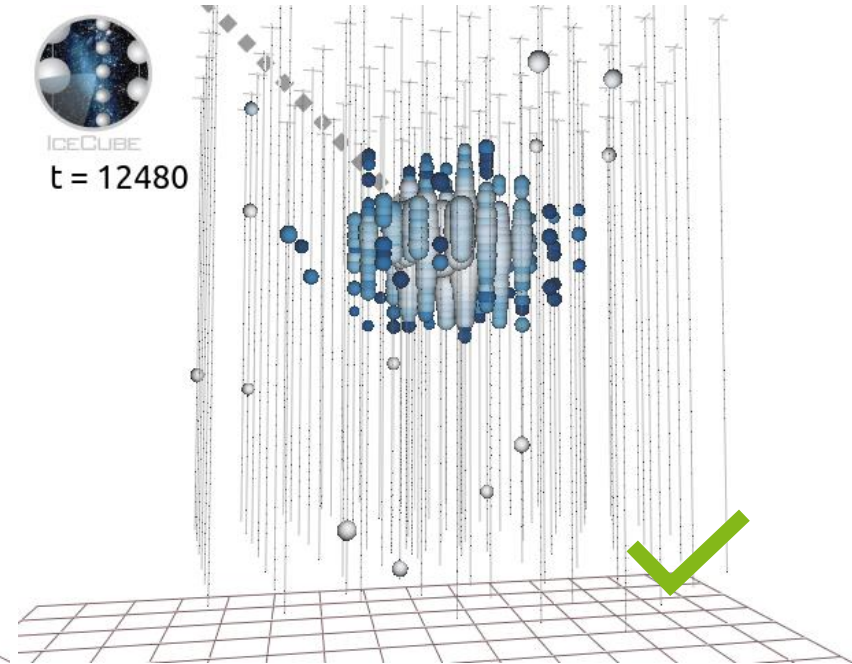


# Selection of Astrophysical Neutrinos

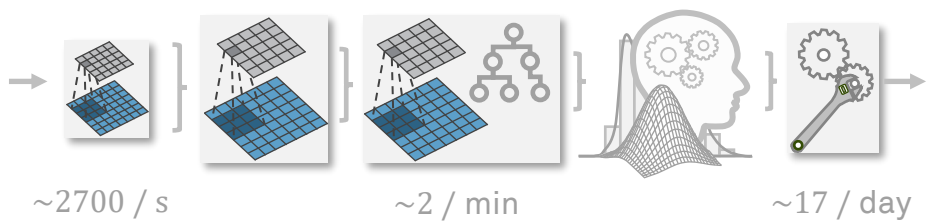
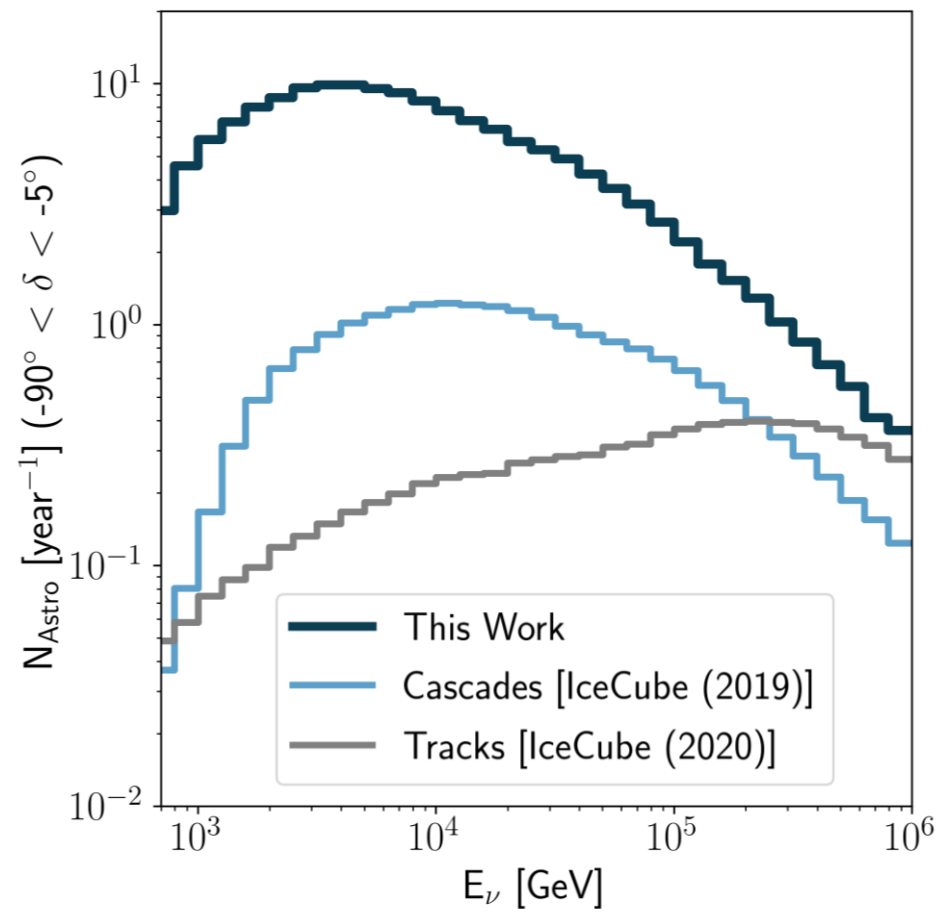
Entering  $\mu$



Cascade Event



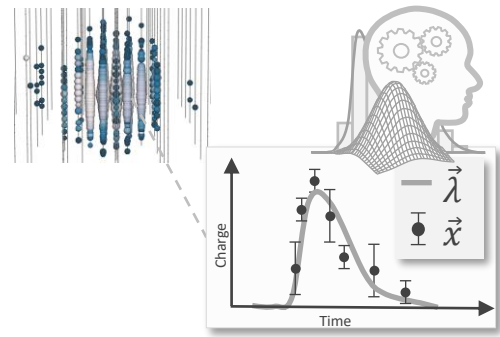
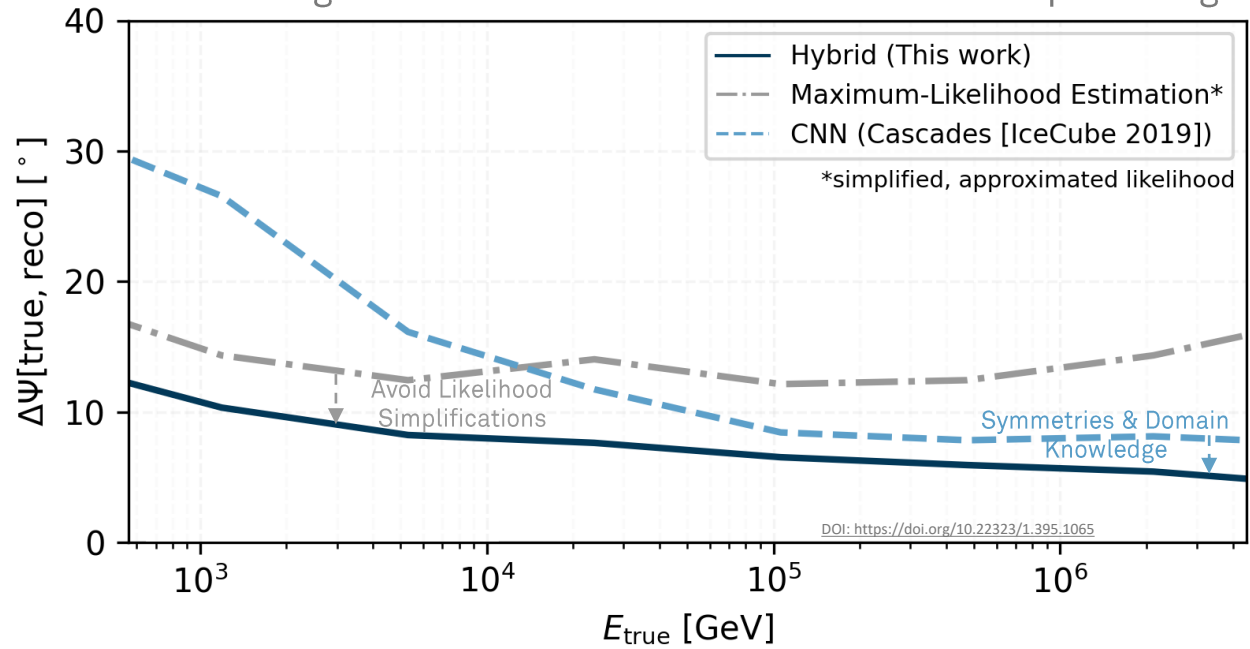
# Selection of Astrophysical Neutrinos



- Event selection:**
- Employs series of convolutional neural networks (CNNs) and boosted decision trees
  - Background reduced by almost 8 orders of magnitude
  - 30 times as many events as precursor analysis

# New hybrid reconstruction method utilized

Combining maximum-likelihood estimation with deep learning



Improvements due to novel methods:

- Improved reconstruction resolution over entire energy range
- 30 times as many events
- Analysis sensitivity improved by a factor of 3

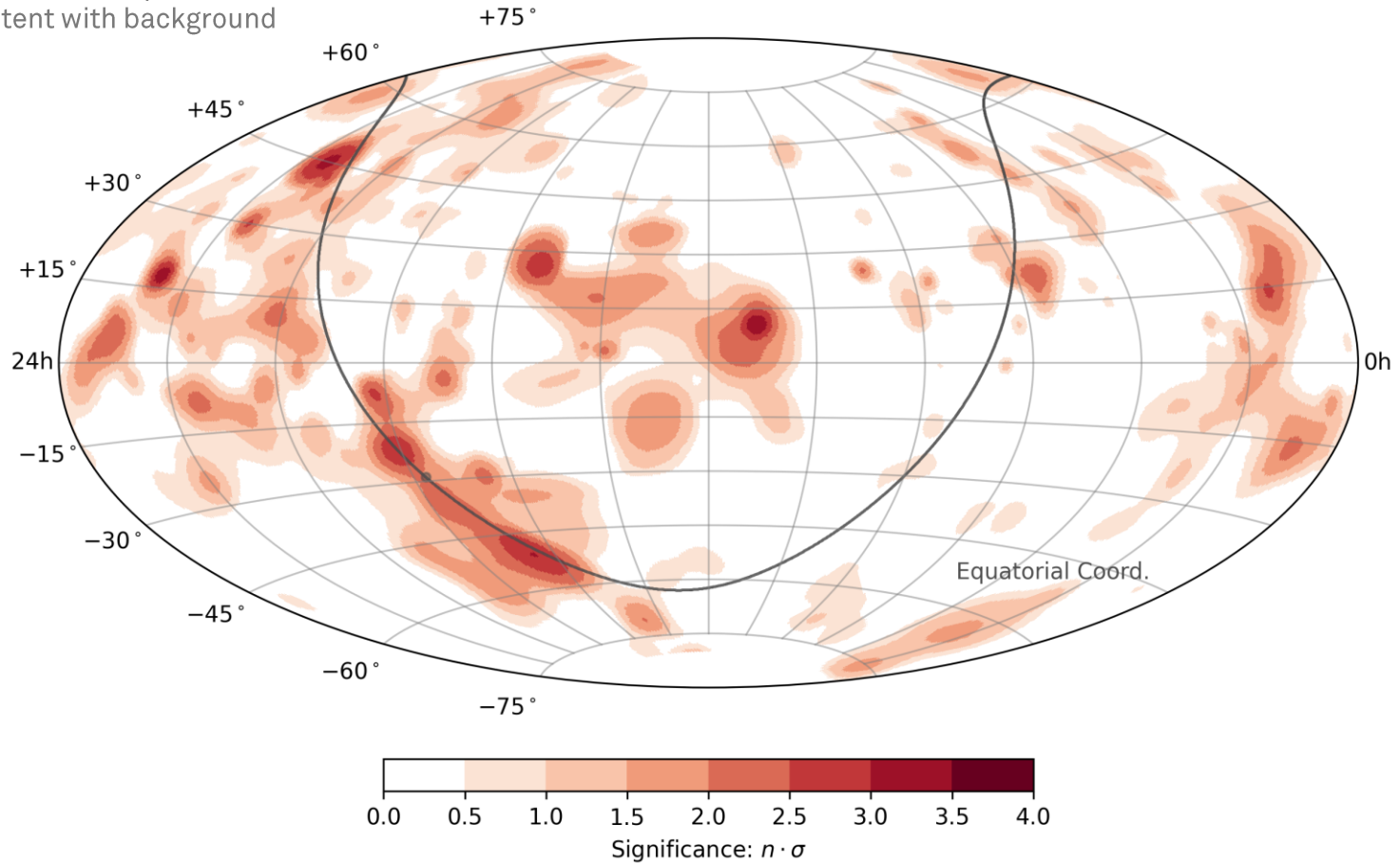
Equivalent to savings of 75 years of detector livetime and > \$500 million





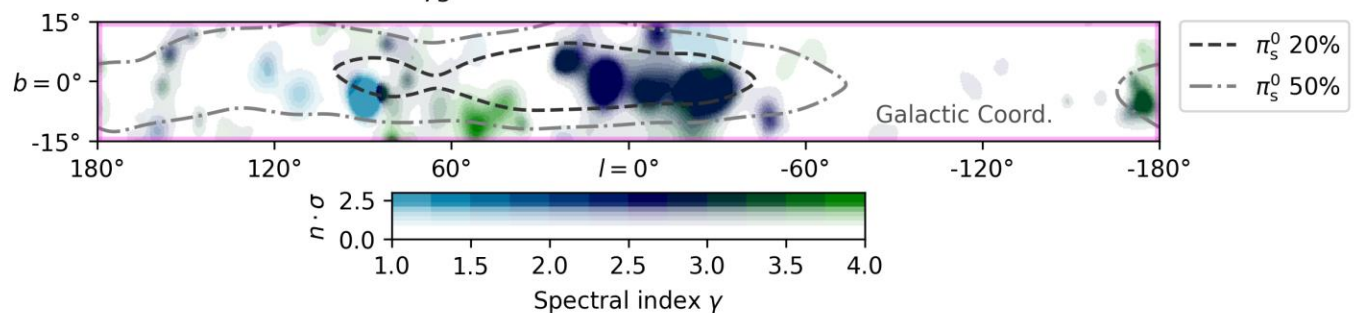
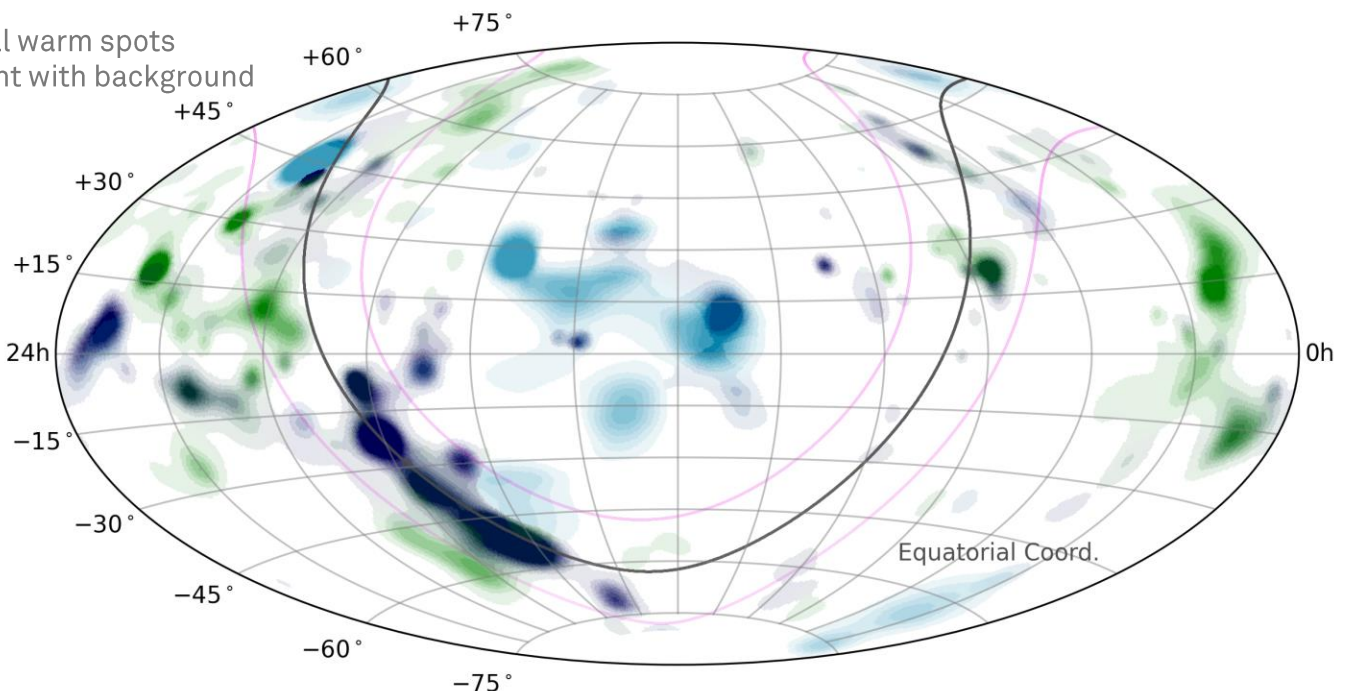
# Results from All-Sky Search

Individual warm spots consistent with background



# Results from All-Sky Search

Individual warm spots consistent with background



# Results from Diffuse Galactic Plane Searches

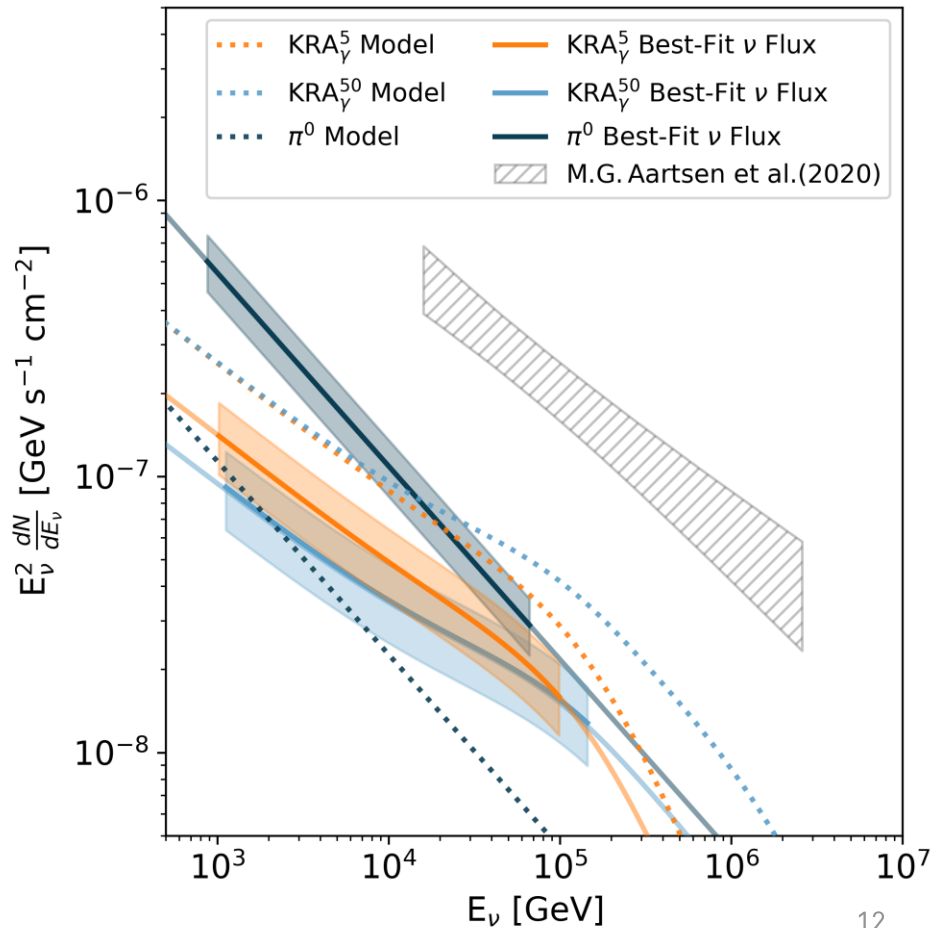
After trial-correction:  $4.5\sigma$

Model	Signal Events	Pre-trial p-value ( $N\sigma$ )
$\pi^0$	748	$1.26 \times 10^{-6}$ ( $4.71\sigma$ )
$KRA_\gamma^5$	276	$6.13 \times 10^{-6}$ ( $4.37\sigma$ )
$KRA_\gamma^{50}$	211	$3.72 \times 10^{-5}$ ( $3.96\sigma$ )

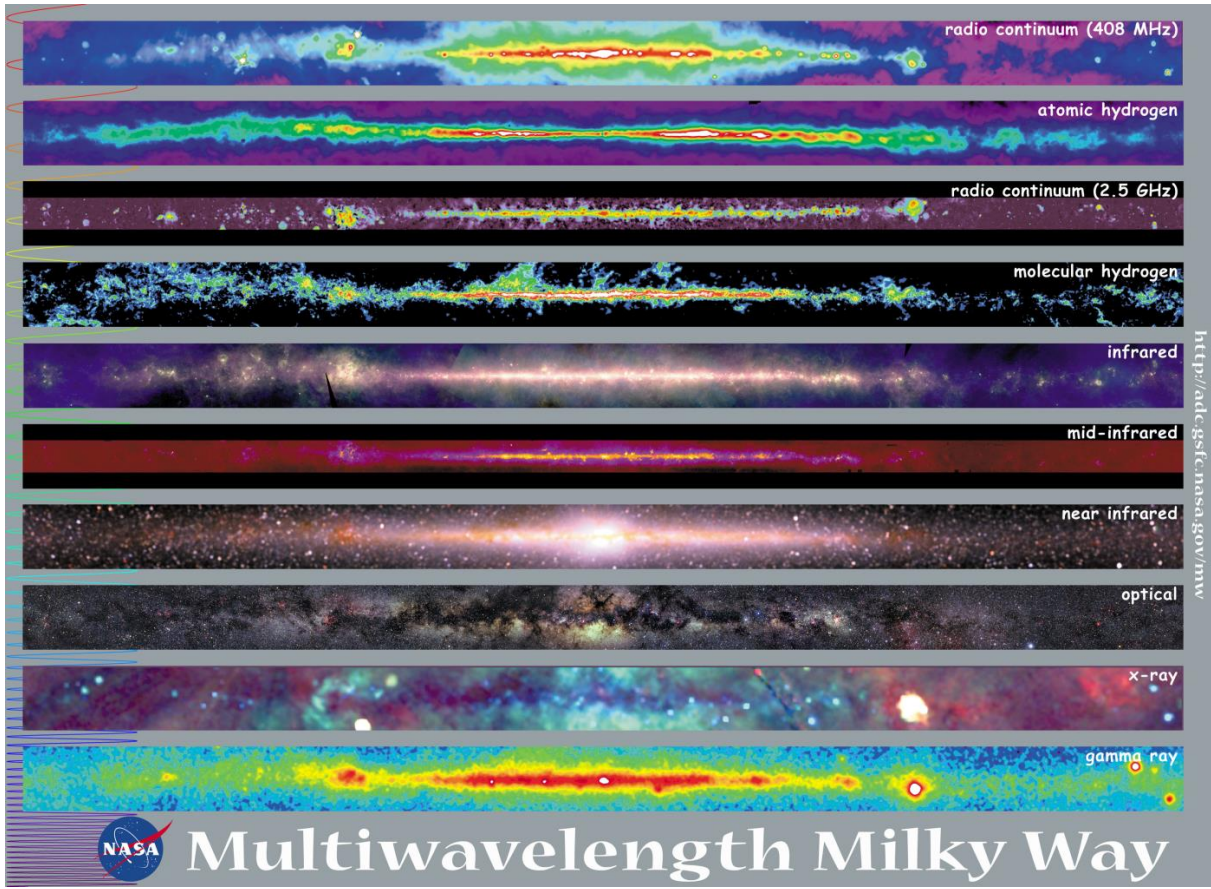
$\pi^0$ : based on Fermi-LAT gamma-ray measurements (DOI:10.1088/0004-637X/750/1/3)

$KRA_\gamma^{50}$ : based on Gaggero et. al (DOI:10.1088/2041-8205/815/2/L25)

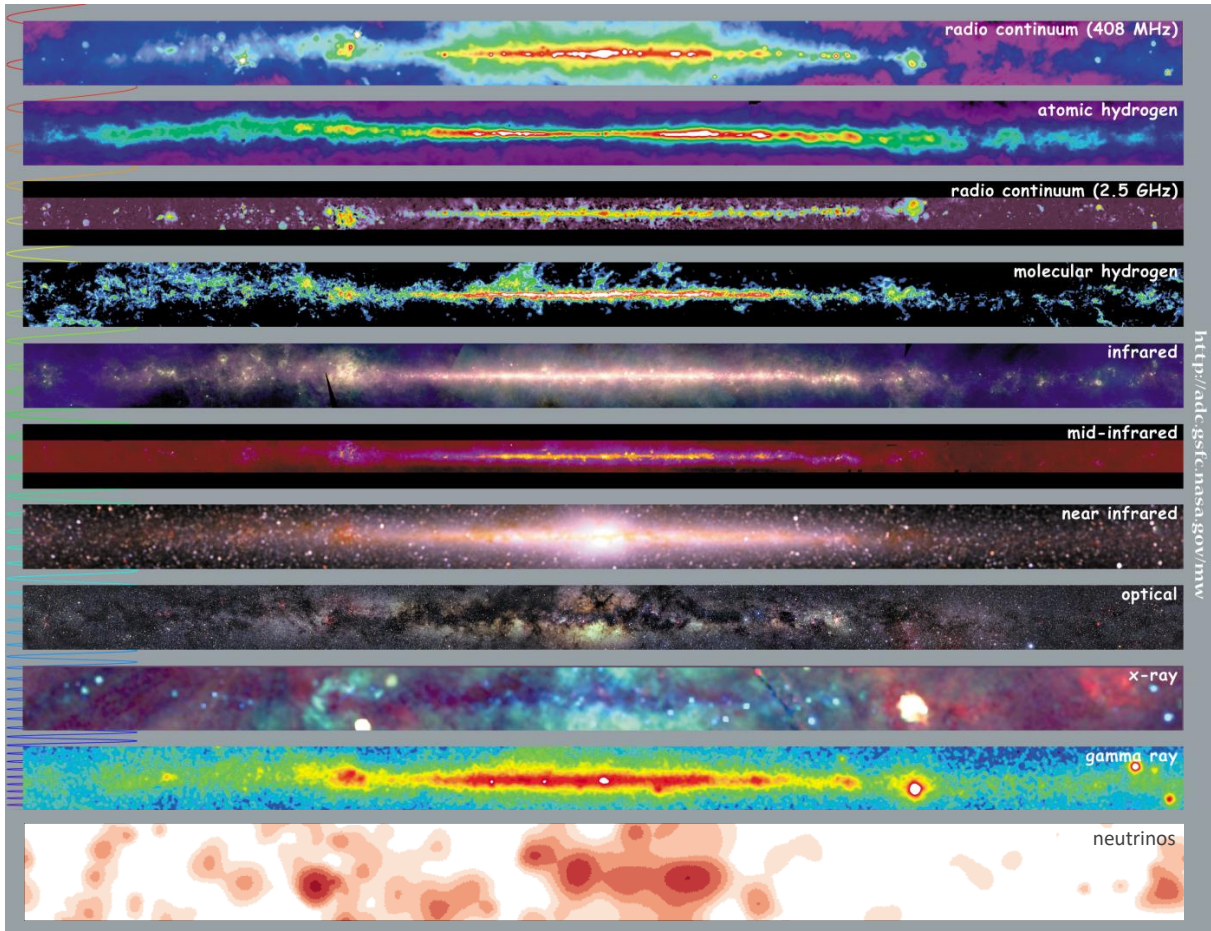
- Shaded regions depict energy ranges that contribute most to the significance
- Galactic flux may explain up to ~10% of astrophysical flux
- Relative model contributions depend on location on the sky



# The Multiwavelength Milky Way



# The Multiwavelength **Multimessenger** Milky Way



# Summary & Outlook

Strong evidence for neutrino emission from the Galactic plane

- Background-only hypothesis rejected at  $4.5\sigma$
- Emission from Galactic plane may explain up to  $\sim 10\%$  of astrophysical flux observed by IceCube
- Independent hints in IceCube track channels ( $\sim 2.7\sigma$ )<sup>1</sup> and in ANTARES<sup>2</sup> ( $\sim 2\sigma$ )

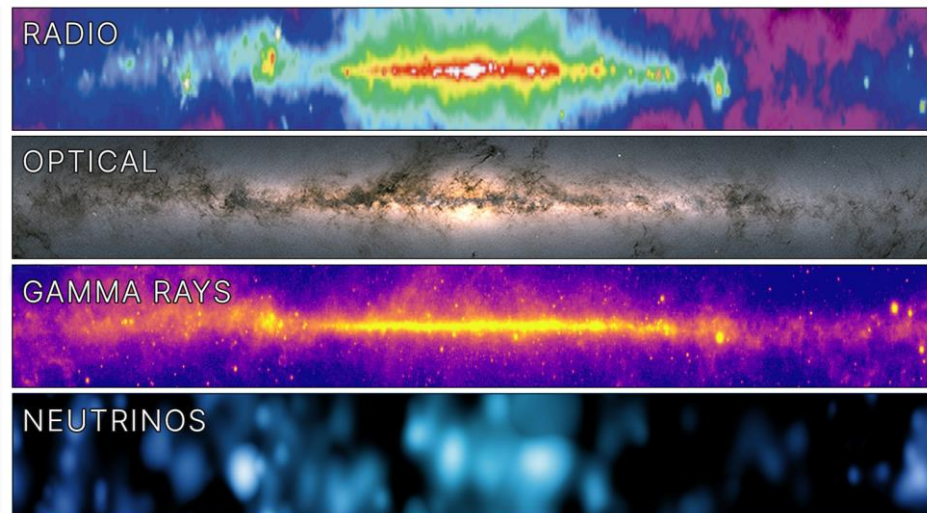
Observation enabled by new tools based on Deep Learning

- 30 times as many events than precursor selection
- Improved reconstruction resolution by up to 50%
- Analysis sensitivity improved by a factor of 3

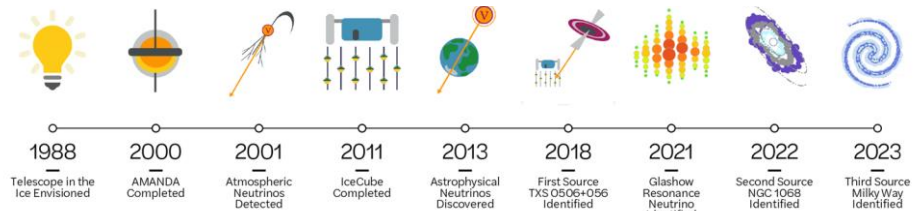
This result leads to many new questions:

- Diffuse or unresolved? Origin of CRs? Galactic structure? ...
- Ongoing studies, future upgrades, and combination with other neutrino detectors will help to shed light on these

➔ We have arrived in the era of neutrino astronomy!



## A History of Neutrino Astronomy in Antarctica



Credit: IceCube Collaboration/NSF

Achieved milestones have picked up in pace in recent years!

<sup>1</sup> DOI: 10.22323/1.444.1046

<sup>2</sup> DOI: 10.1016/j.physletb.2023.137951

# THE ICECUBE COLLABORATION

 **AUSTRALIA**  
University of Adelaide

 **BELGIUM**  
UCLouvain  
Université libre de Bruxelles  
Universiteit Gent  
Vrije Universiteit Brussel

 **CANADA**  
SNOLAB  
University of Alberta–Edmonton

 **DENMARK**  
University of Copenhagen


 **GERMANY**  
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ECAP, Universität Erlangen–Nürnberg  
Humboldt–Universität zu Berlin  
Karlsruhe Institute of Technology  
Ruhr-Universität Bochum  
RWTH Aachen University  
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and Technology  
Southern University  
and A&M College  
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University of Kansas

University of Maryland  
University of Rochester  
University of Texas at Arlington  
University of Utah  
University of Wisconsin–Madison  
University of Wisconsin–River Falls  
Yale University

## FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)  
Fonds Wetenschappelijk Onderzoek-Vlaanderen  
(FWO-Vlaanderen)

Federal Ministry of Education and Research (BMBF)  
German Research Foundation (DFG)  
Deutsches Elektronen-Synchrotron (DESY)

Japan Society for the Promotion of Science (JSPS)  
Knut and Alice Wallenberg Foundation  
Swedish Polar Research Secretariat

The Swedish Research Council (VR)  
University of Wisconsin Alumni Research Foundation (WARF)  
US National Science Foundation (NSF)





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# Backup

# Neutrino Source Searches

Unbinned likelihood:

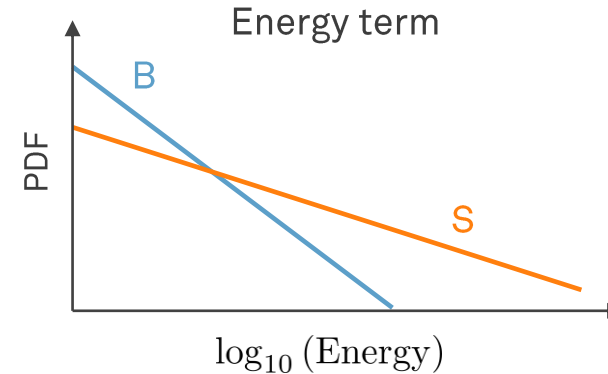
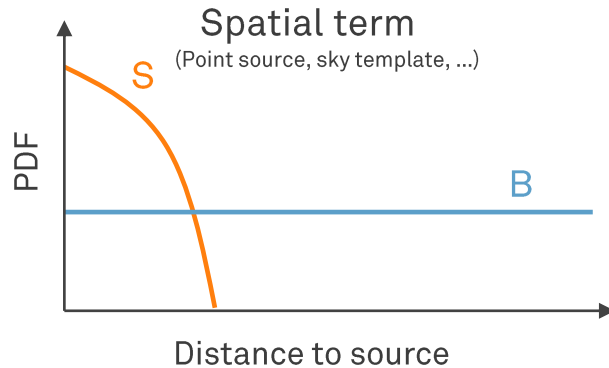
$$\mathcal{L} = \prod_i^N \left[ \frac{n_s}{N} \cdot \boxed{S_i} + \left(1 - \frac{n_s}{N}\right) \cdot \boxed{B_i} \right]$$

Signal  
(Modeled by MC)

Background  
(modeled by scrambling experimental data, with signal subtraction modification)

Test-statistic:

$$TS = -2 \log \left[ \frac{\mathcal{L}(n_s=0 | \text{Data})}{\mathcal{L}(\hat{n}_s, \hat{\gamma}_s | \text{Data})} \right]$$



# Neutrino Source Searches

## Point source search:

- Assume a single point-like neutrino source
- Spatial PDF via von Mises-Fisher distribution
- Fit for flux ( $\propto n_s$ ) and spectral index ( $\gamma_s$ )

## All-sky search:

- Perform a point source search at every point in the sky
- Large trial factor due to high number of points tested

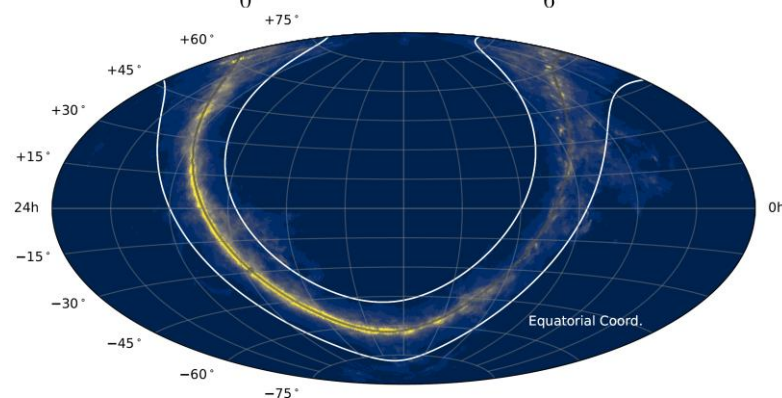
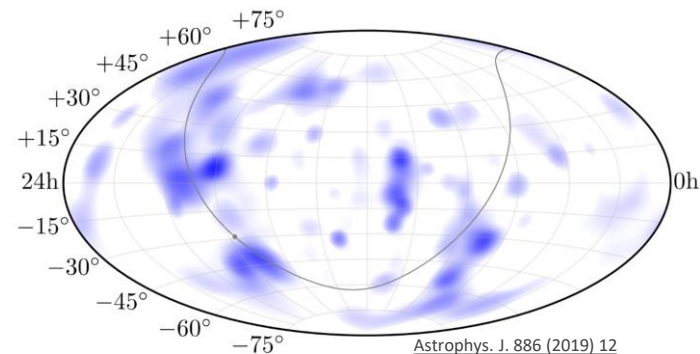
## Stacked search

- Stack multiple point-like sources (with similar properties) “on top of” each other

## Template Searches

- Spatial and energy PDF given via a template over the sky
- Fit for flux ( $\propto n_s$ ) only, since spectral index is often part of the model template

## Precursor Analysis on 7yrs of Cascades



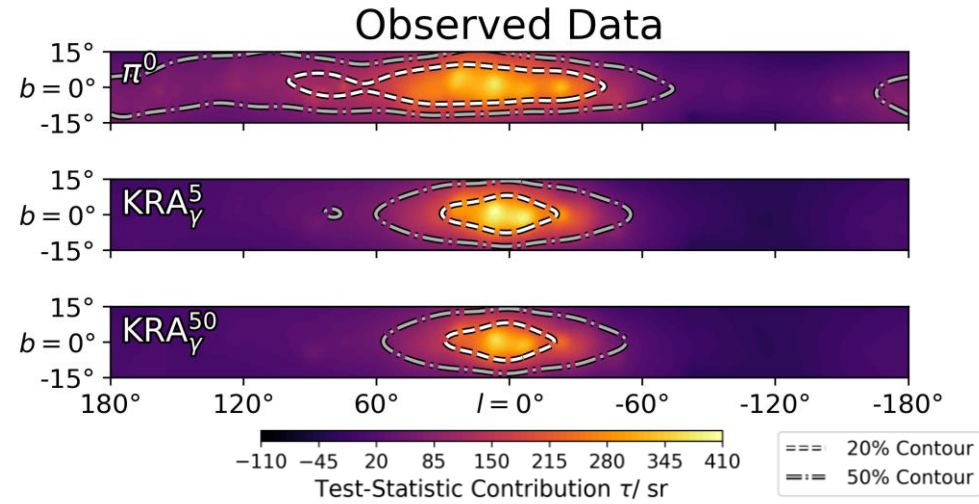
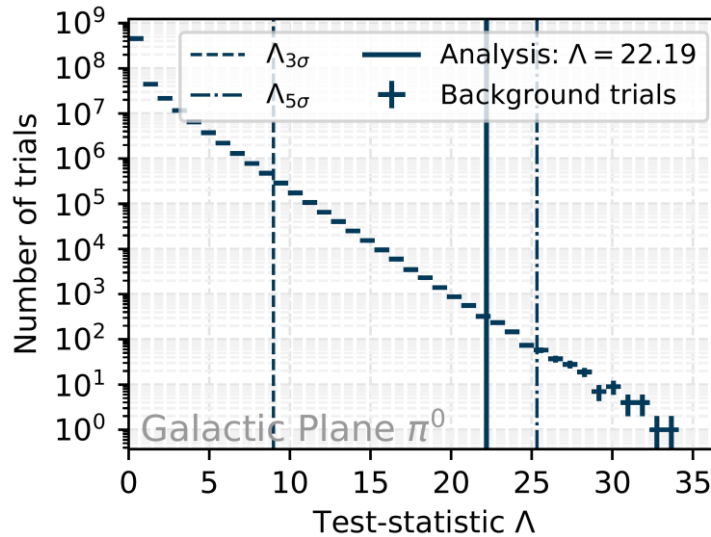
# Analysis Results

	Flux sensitivity $\Phi$	$P$ value	Best-fitting flux $\Phi$
<i>Diffuse Galactic plane analysis</i>			
$\pi^0$	5.98	$1.26 \times 10^{-6}$ (4.71 $\sigma$ )	$21.8^{+5.3}_{-4.9}$
$KRA_{\gamma}^5$	$0.16 \times MF$	$6.13 \times 10^{-6}$ (4.37 $\sigma$ )	$0.55^{+0.18}_{-0.15} \times MF$
$KRA_{\gamma}^{50}$	$0.11 \times MF$	$3.72 \times 10^{-5}$ (3.96 $\sigma$ )	$0.37^{+0.13}_{-0.11} \times MF$
<i>Catalog stacking analysis</i>			
SNR		$5.90 \times 10^{-4}$ (3.24 $\sigma$ )*	
PWN		$5.93 \times 10^{-4}$ (3.24 $\sigma$ )*	
UNID		$3.39 \times 10^{-4}$ (3.40 $\sigma$ )*	
<i>Other analyses</i>			
Fermi bubbles		0.06 (1.52 $\sigma$ )	
Source list		0.22 (0.77 $\sigma$ )	
Hotspot (north)		0.28 (0.58 $\sigma$ )	
Hotspot (south)		0.46 (0.10 $\sigma$ )	

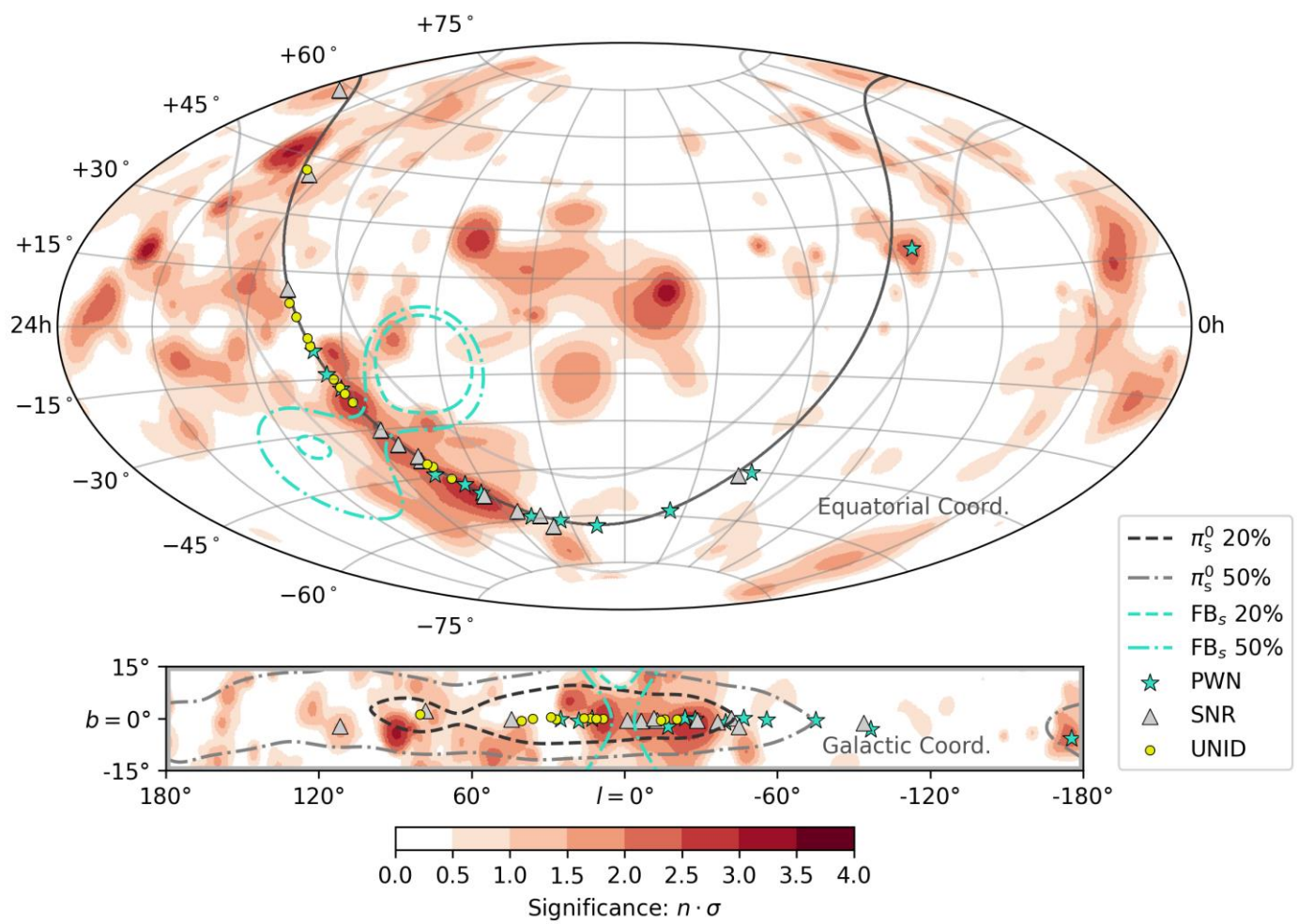
\*Significance values that are consistent with the diffuse Galactic plane template search results.

# Analysis Results

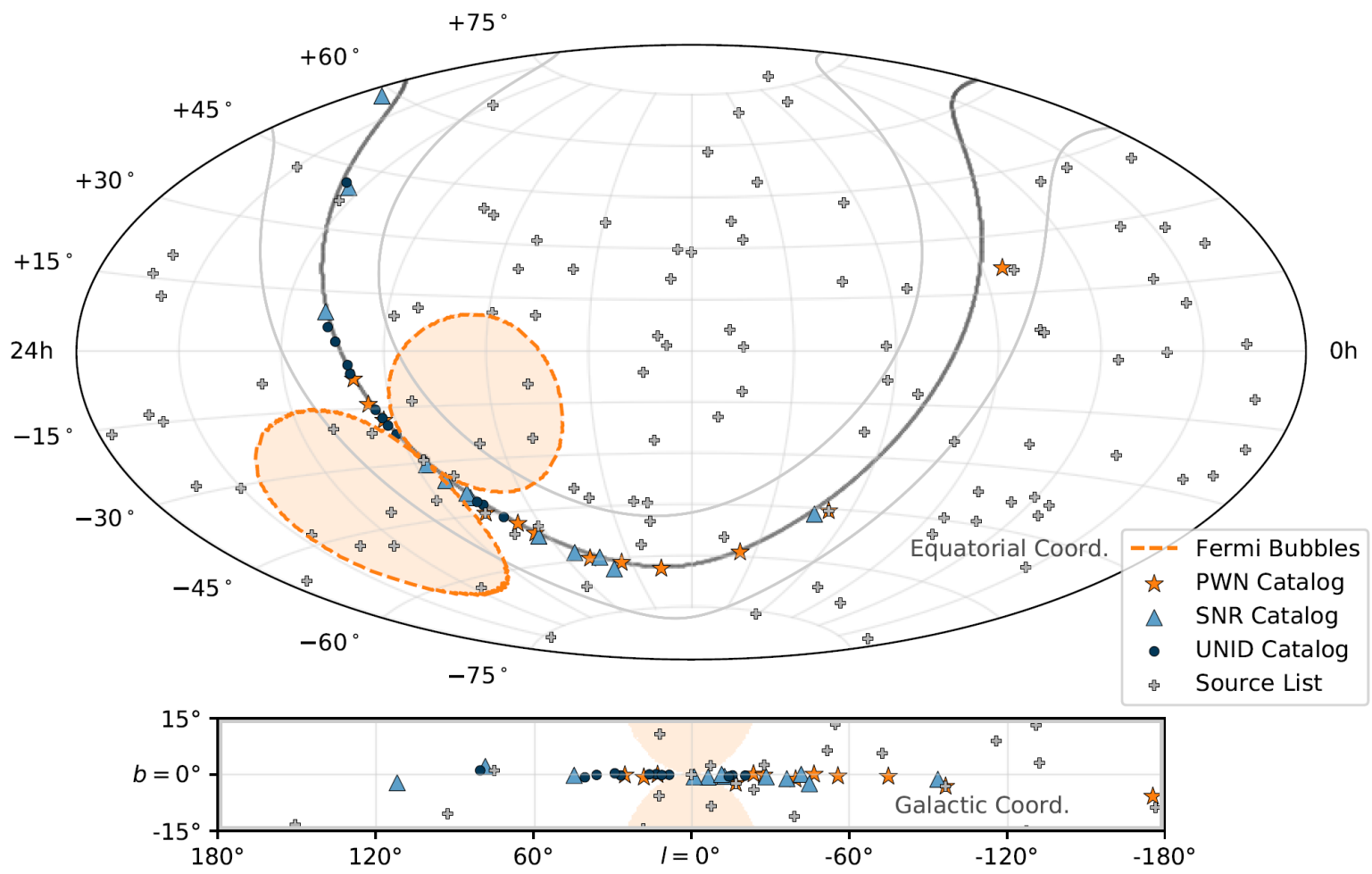
Global significance:  $4.5\sigma$



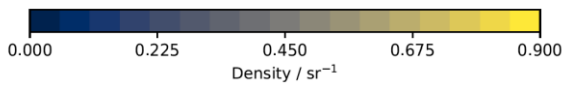
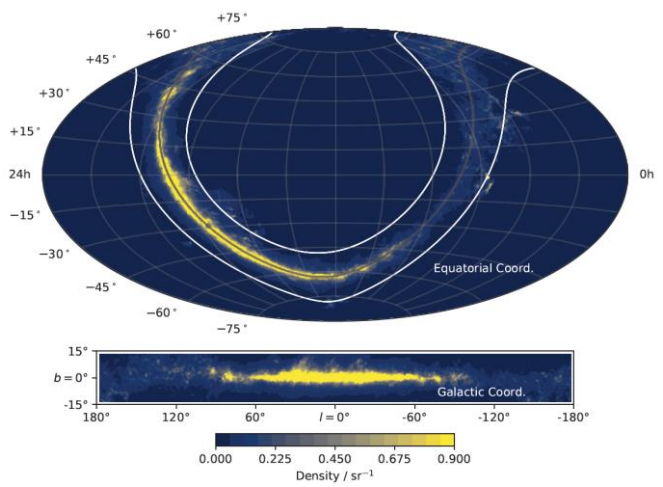
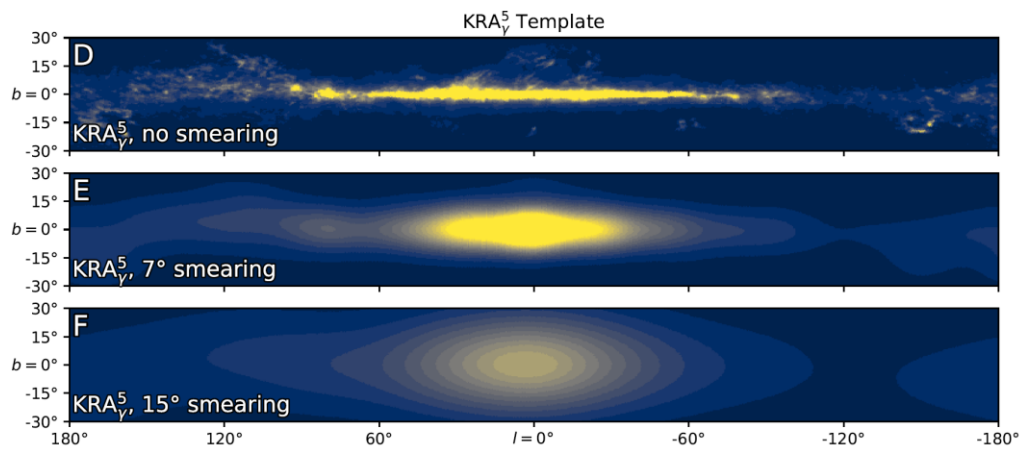
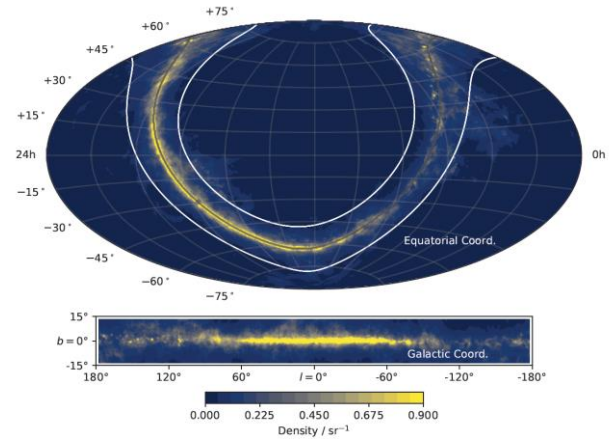
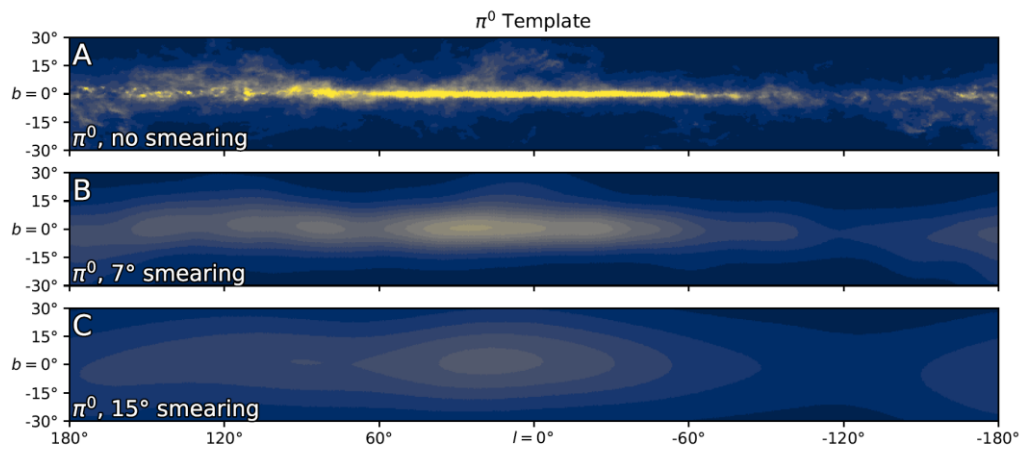
# Analysis Results



# Performed Searches

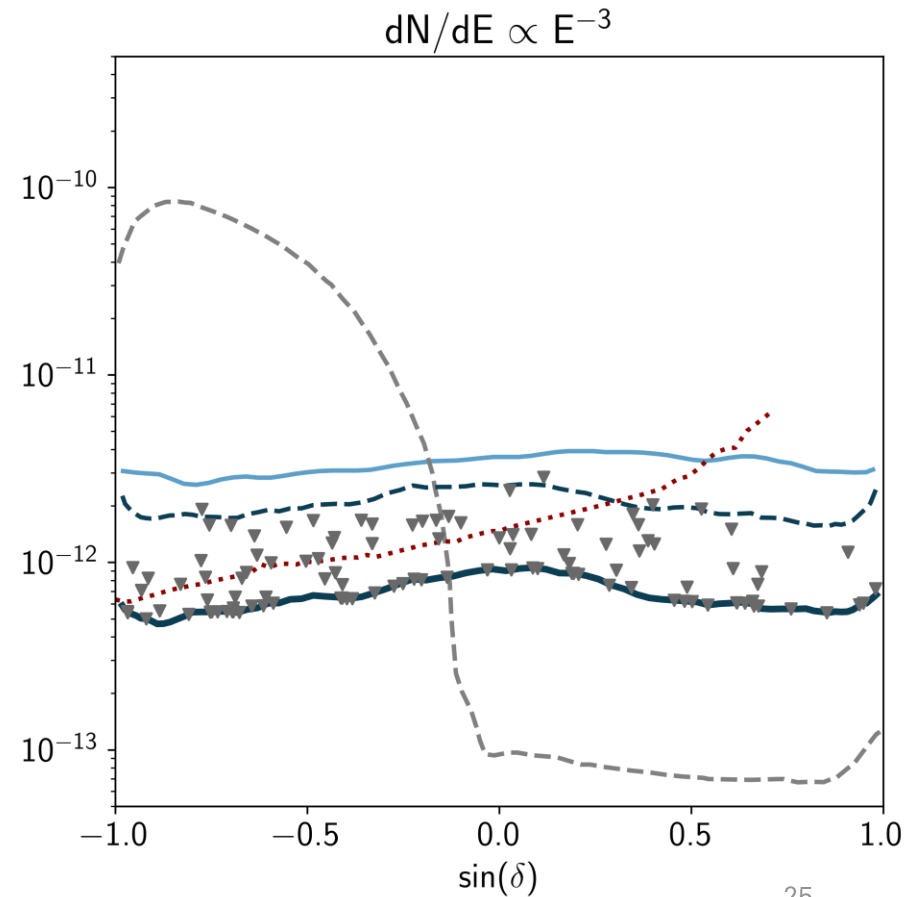
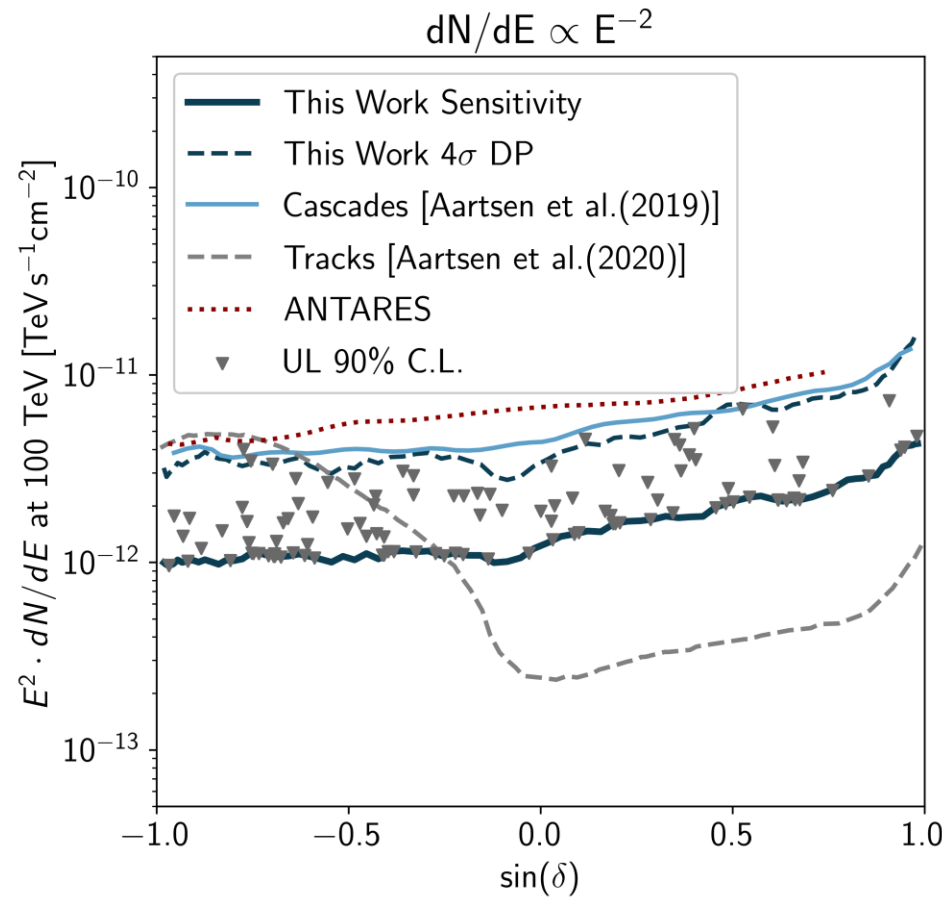


# Template Searches

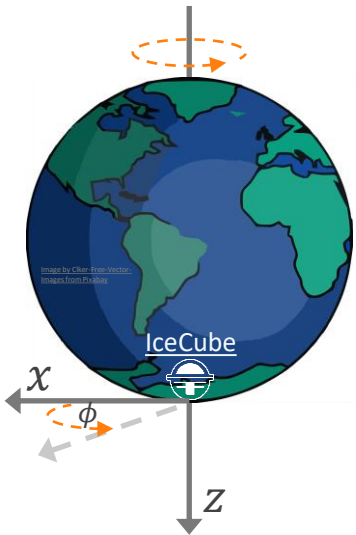




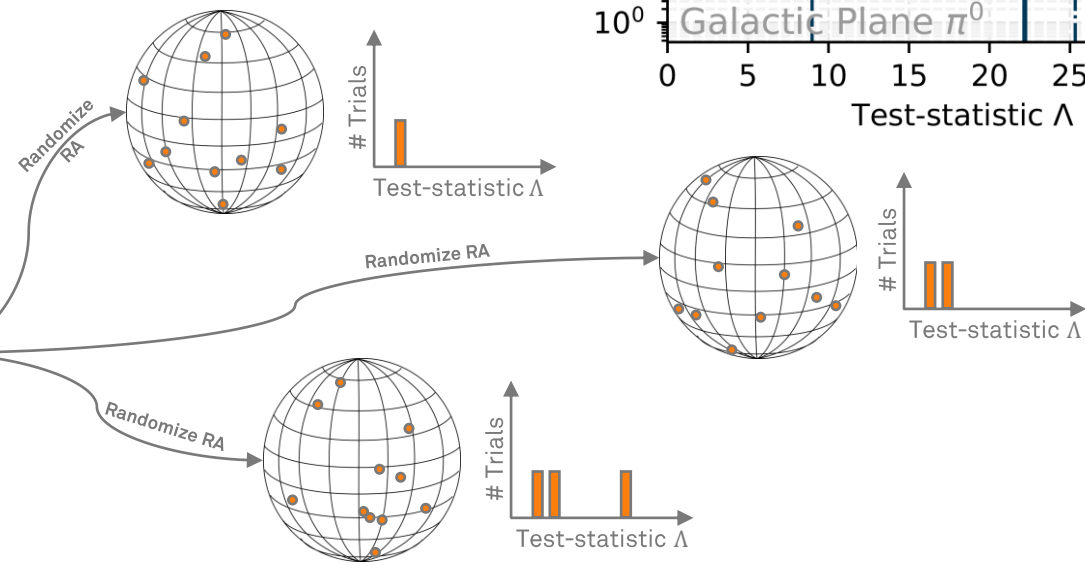
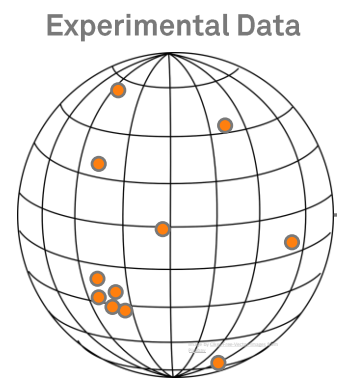
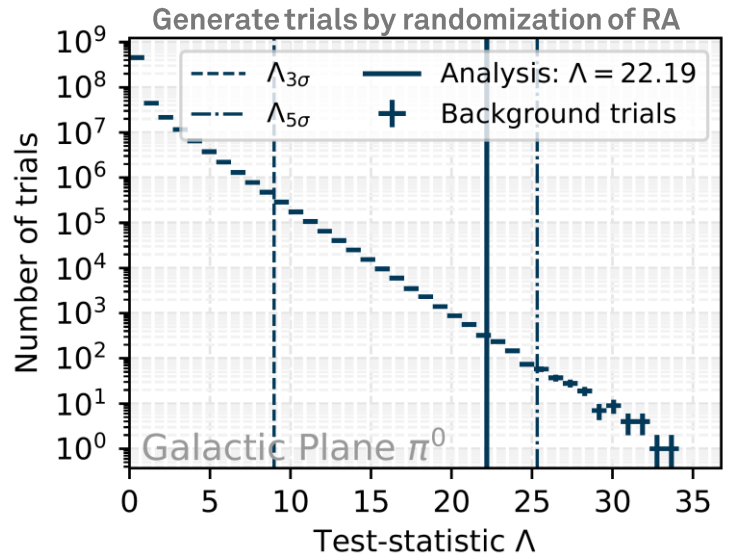
# Point Source Sensitivity



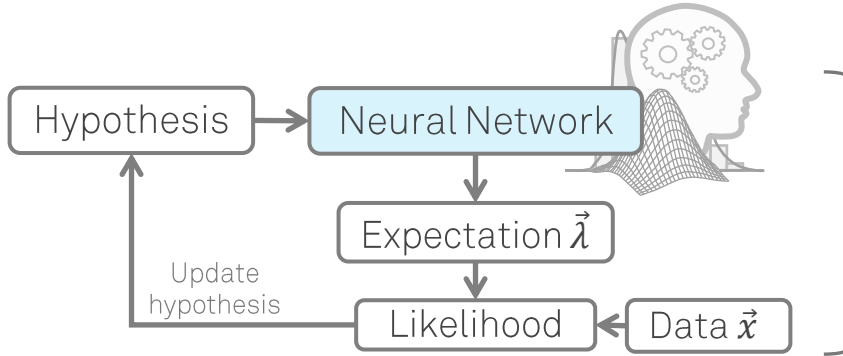
# Data-driven Search Method



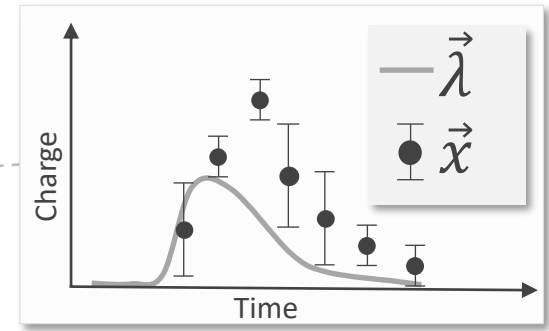
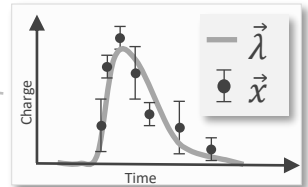
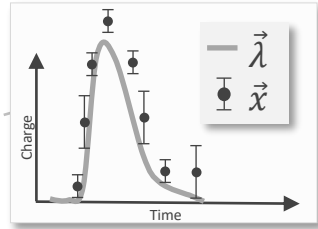
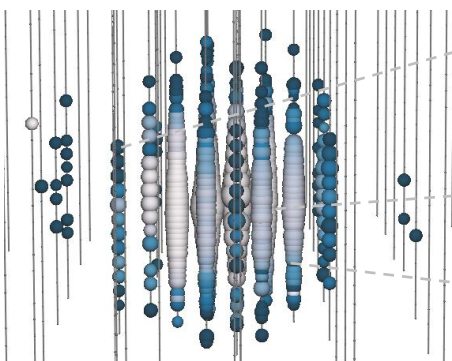
- Backgrounds are independent of current orientation of Earth
- Backgrounds are modelled in **data-driven** approach by randomizing experimental data
- Randomization of events in Right Ascension (RA) only modifies extra-terrestrial properties of data



# Reconstructing Event Properties



- Hybrid reconstruction method:
- Combines maximum-likelihood estimation with deep learning
  - Modeling of high-dimensional PDFs via neural networks
  - Exploits available information and symmetries
  - Improved resolution over entire energy range**



DOI: <https://doi.org/10.22323/1.395.1065>