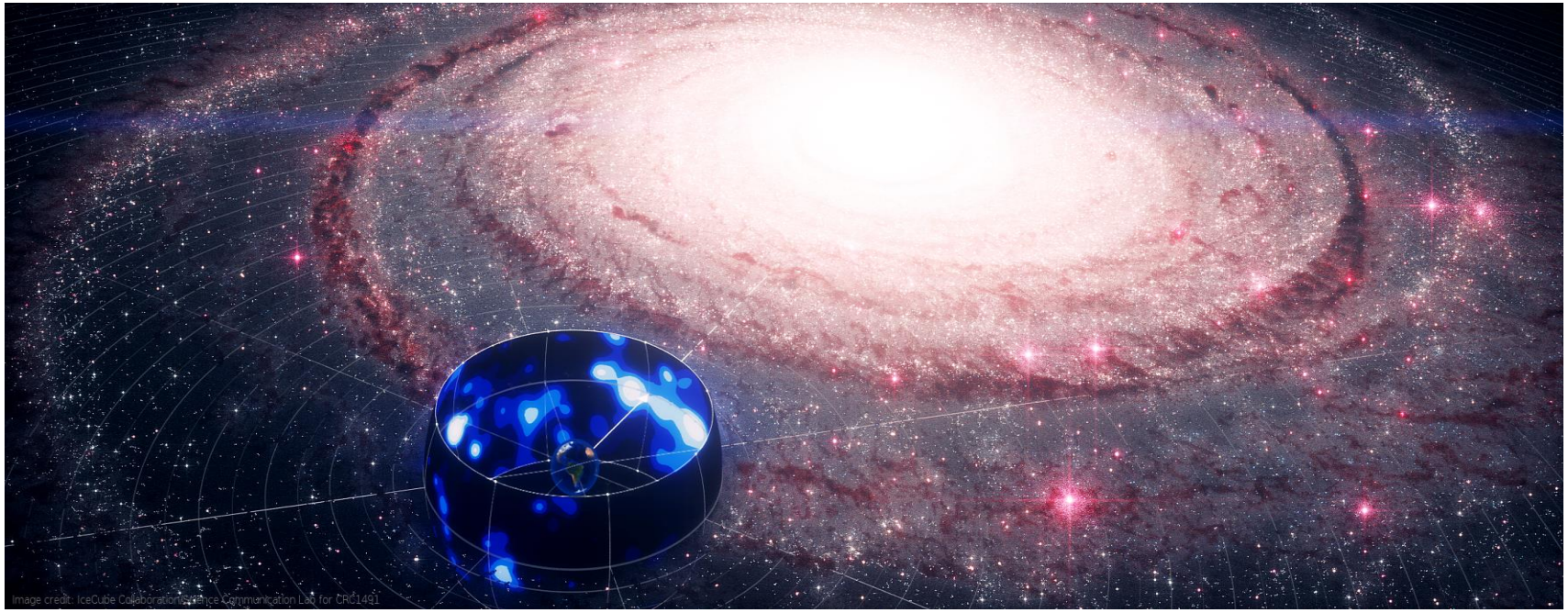
technische universität dortmund

IceCube South Pole Neutrino Observatory

SFB 876 Providing Information by Resource-Constrained Data Analysis

SFB1491



High-energy neutrinos from the Milky Way

Mirco Hünnefeld
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GSI-FAIR Summer Colloquium, Darmstadt
September 5th, 2023

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Federal Ministry of Education and Research

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DFG Deutsche Forschungsgemeinschaft
German Research Foundation

Science – June 30, 2023

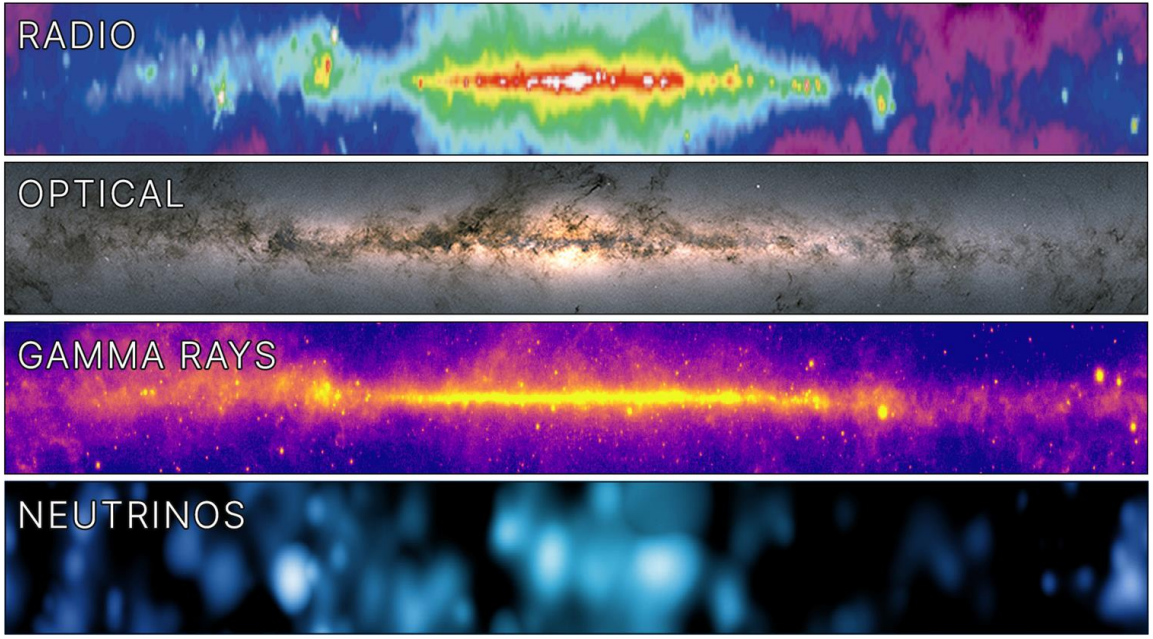
RESEARCH

RESEARCH ARTICLES

NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†



Talk Outline

Introduction to Neutrino Astronomy

The IceCube Neutrino Detector

- What is it and how does it work?

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Image credit: DESY/Science Communication Lab

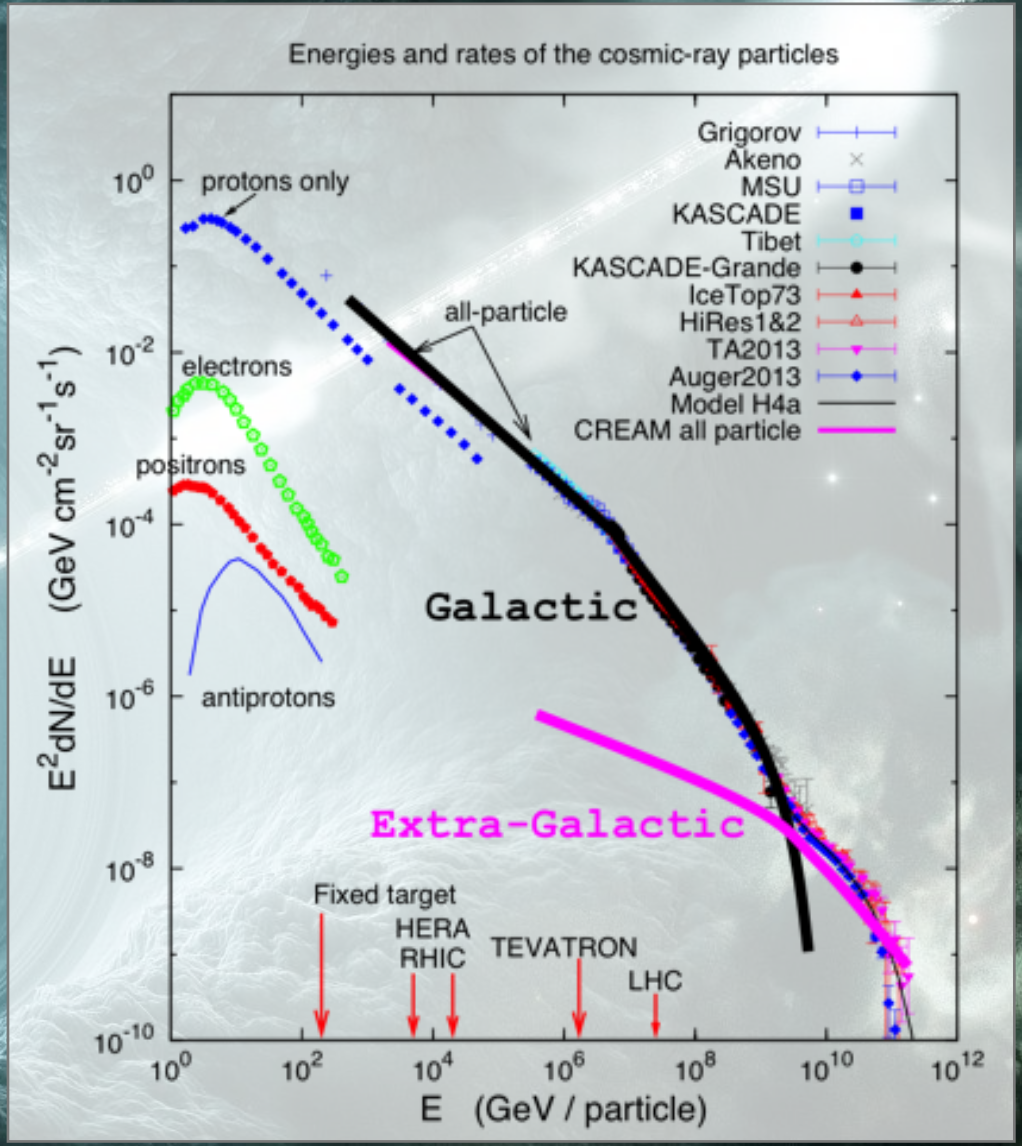
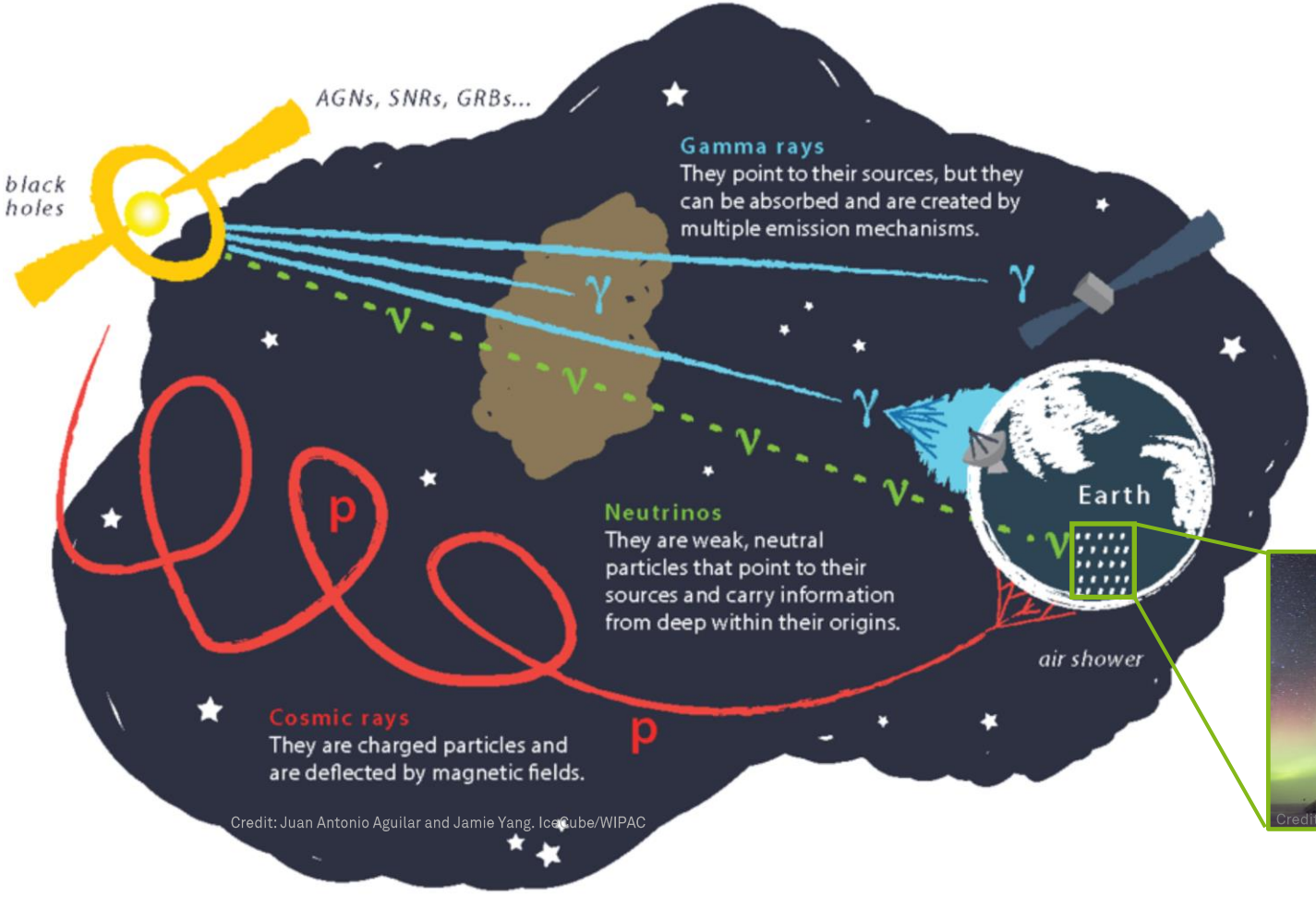


Image credit: DESY/Science Communication Lab

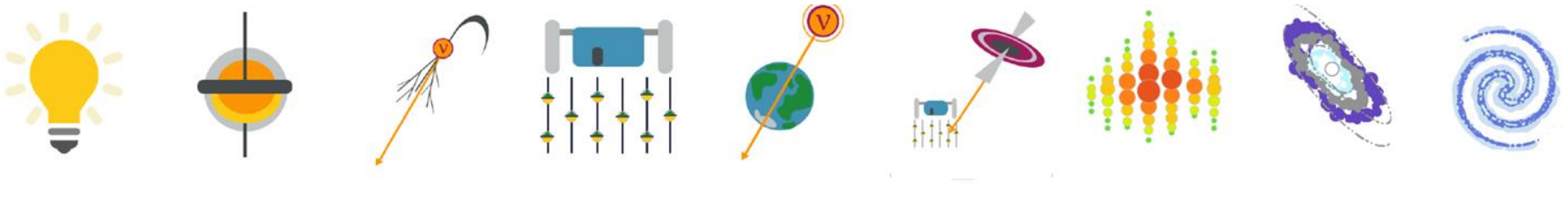
Neutrino Astronomy with IceCube



Neutrino Astronomy – How far have we come?

A History of Neutrino Astronomy in Antarctica

IceCube Neutrino Observatory · NSF



Credit: IceCube Collaboration/NSF

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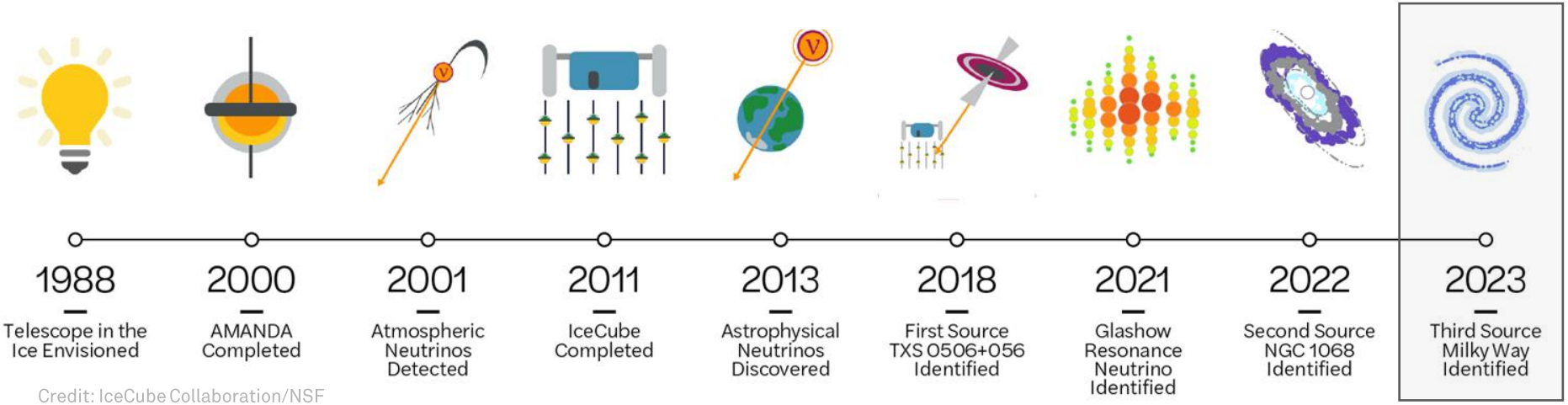

Credit: IceCube Collaboration/NSF

Milky Way In Neutrino Light

“The Milky Way in Neutrino Light” on YouTube

Credit: IceCube Collaboration / Science Communication Lab for CRC1491

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THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

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Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
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University of Alberta–Edmonton

DENMARK
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ECAP, Universität Erlangen-Nürnberg
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Karlsruhe Institute of Technology
Ruhr-Universität Bochum
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Pennsylvania State University
South Dakota School of Mines and Technology
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University of Rochester
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Fonds de la Recherche Scientifique (FRS-FNRS)
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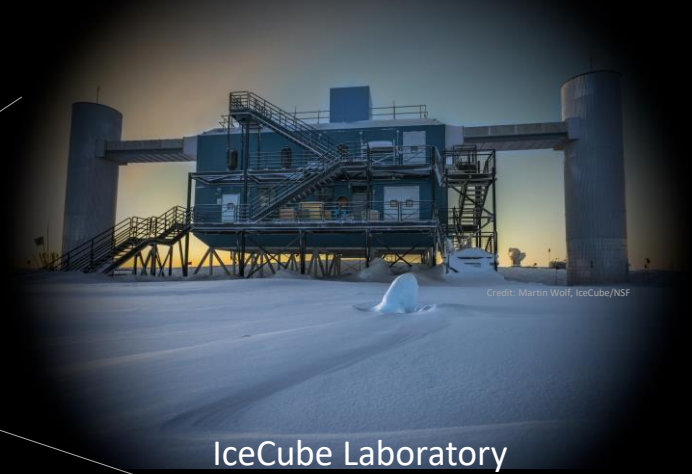
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

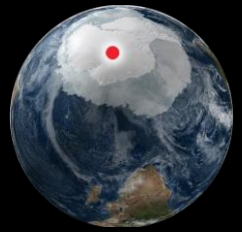
IceCube
South Pole Neutrino Observatory

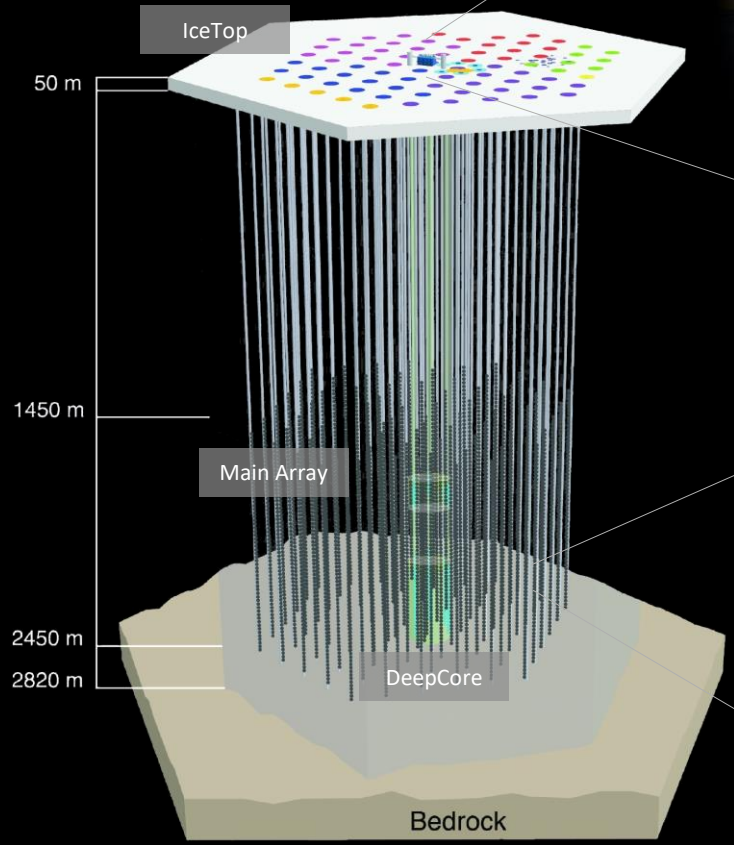
icecube.wisc.edu

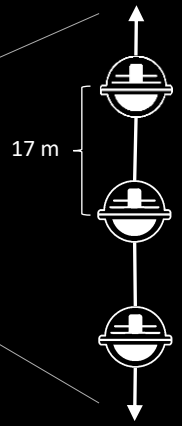
IceCube
SOUTH POLE NEUTRINO OBSERVATORY



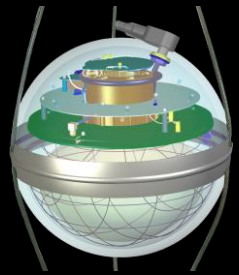
IceCube Laboratory


Amundsen-Scott South Pole Station, Antarctica

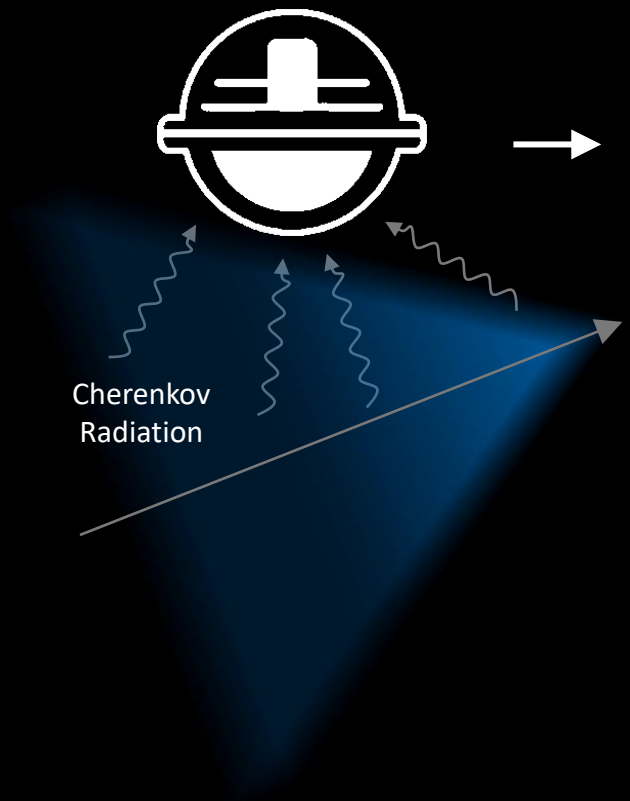


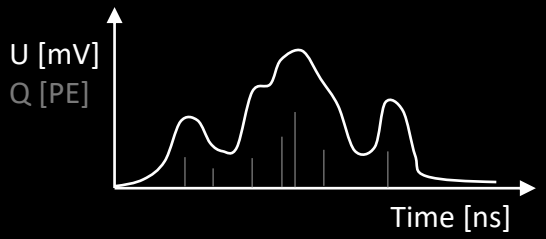


86 Strings:
78 Main Array
8 DeepCore

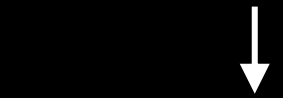

5160 Digital Optical Modules (DOMs)

Detection Mechanism

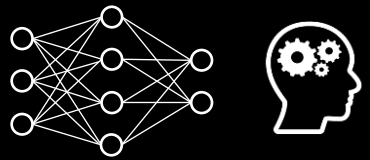




Pulse Series: (t_i, q_i)

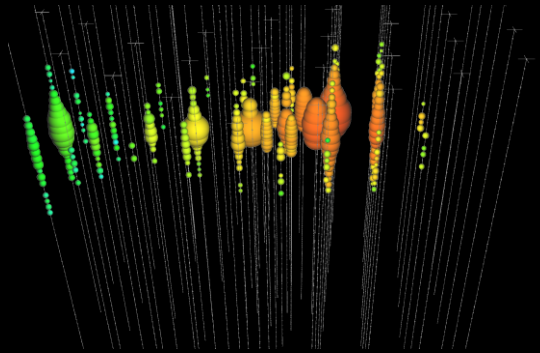


$$\mathcal{L}\left(\vec{x}\middle|\vec{\theta}\right) = \prod_i p(x_i|\vec{\theta})$$



Event Topologies

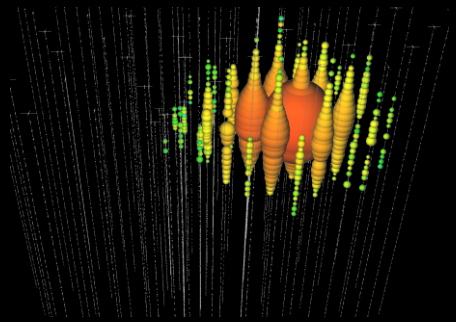
CC ν_μ



$\nu_\mu + N \rightarrow \mu + X$

Track
($< 1°$)

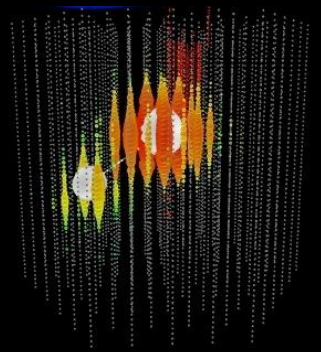
CC ν_e / NC ν_*



$\nu_e + N \rightarrow \mathrm{e} + X$
$\nu_* + N \rightarrow \nu_* + X$

Cascade
($\sim 10°$ at 10 TeV)

CC ν_τ

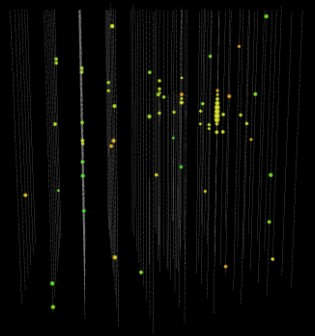


$\nu_\tau + N \rightarrow \tau + X$

Cascade / Track /
Double-Cascade

Event Topologies

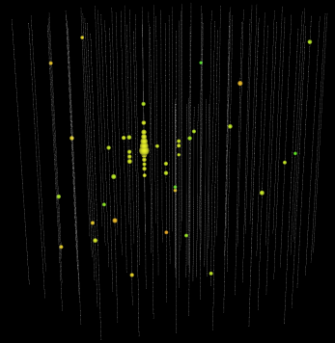
CC ν_μ



$\nu_\mu + N \rightarrow \mu + X$

Track

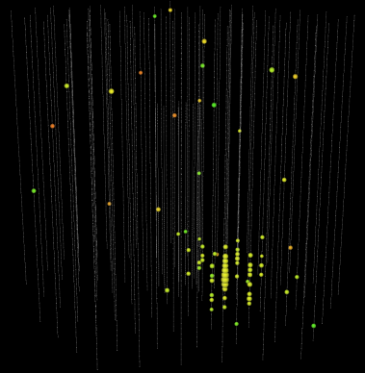
CC ν_e / NC ν_*



$\nu_e + N \rightarrow \mathrm{e} + X$
$\nu_* + N \rightarrow \nu_* + X$

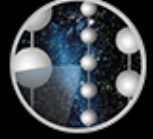
Cascade

CC ν_τ



$\nu_\tau + N \rightarrow \tau + X$

Cascade / Track / Double-Cascade



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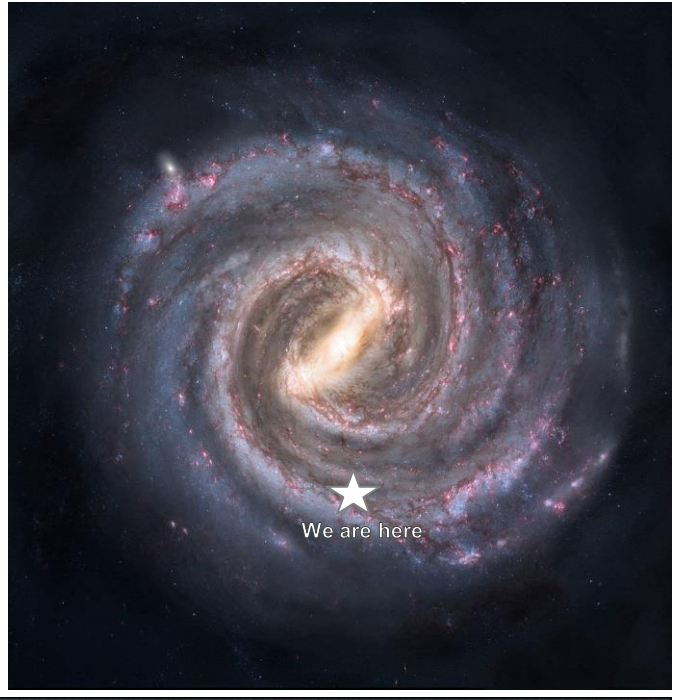
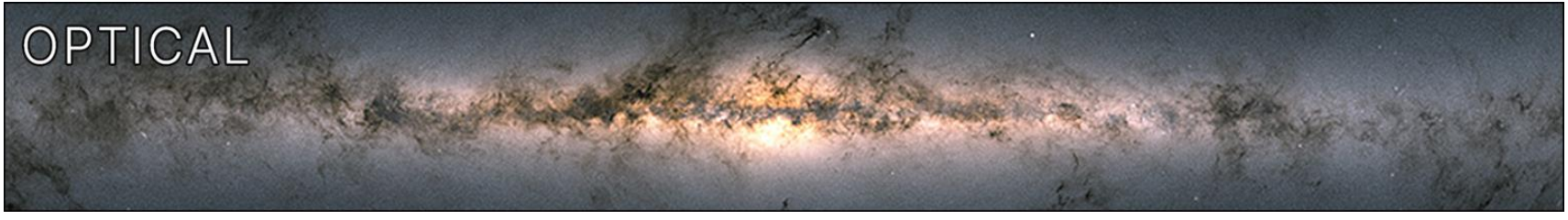
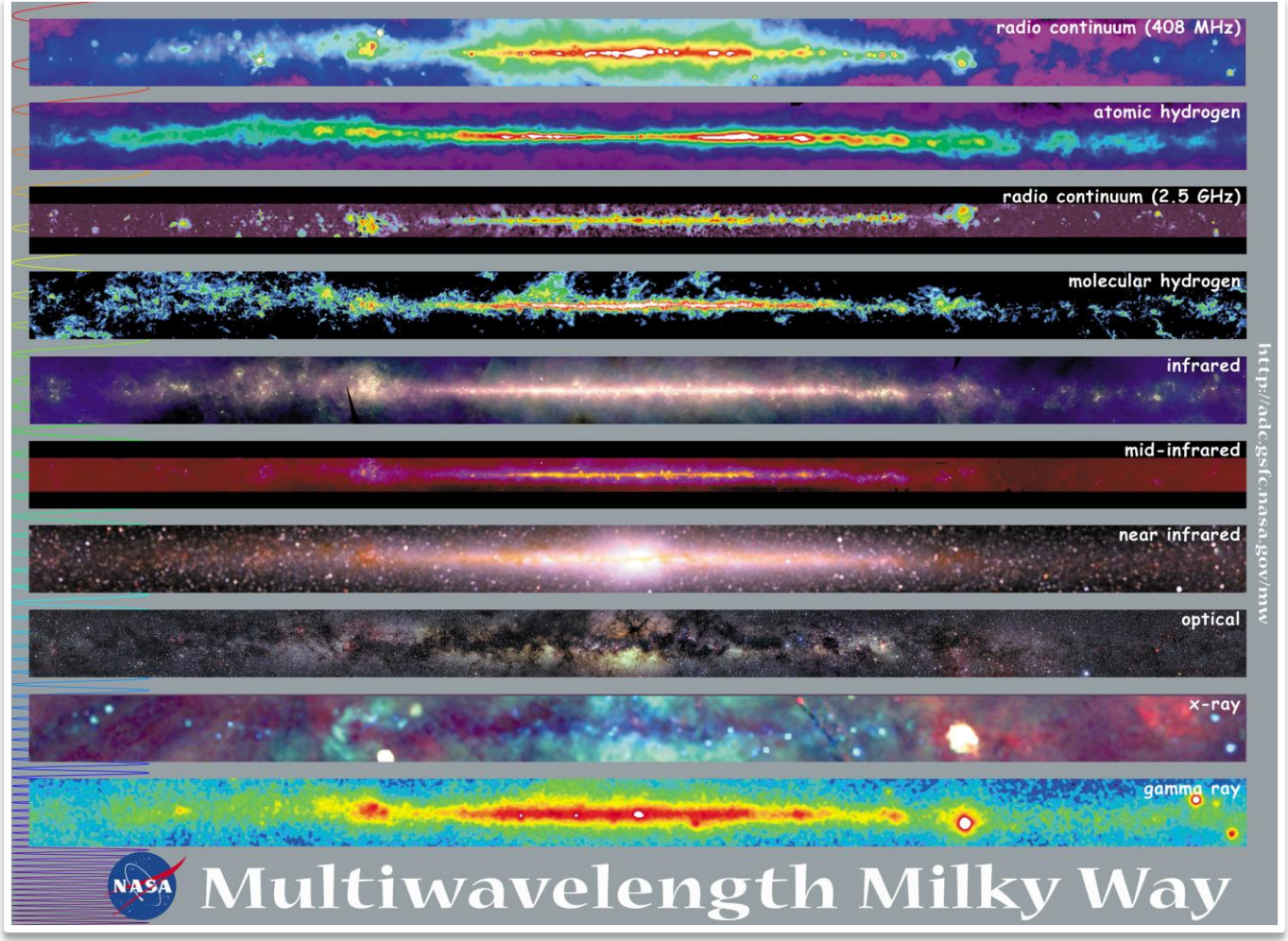
The Galactic Plane



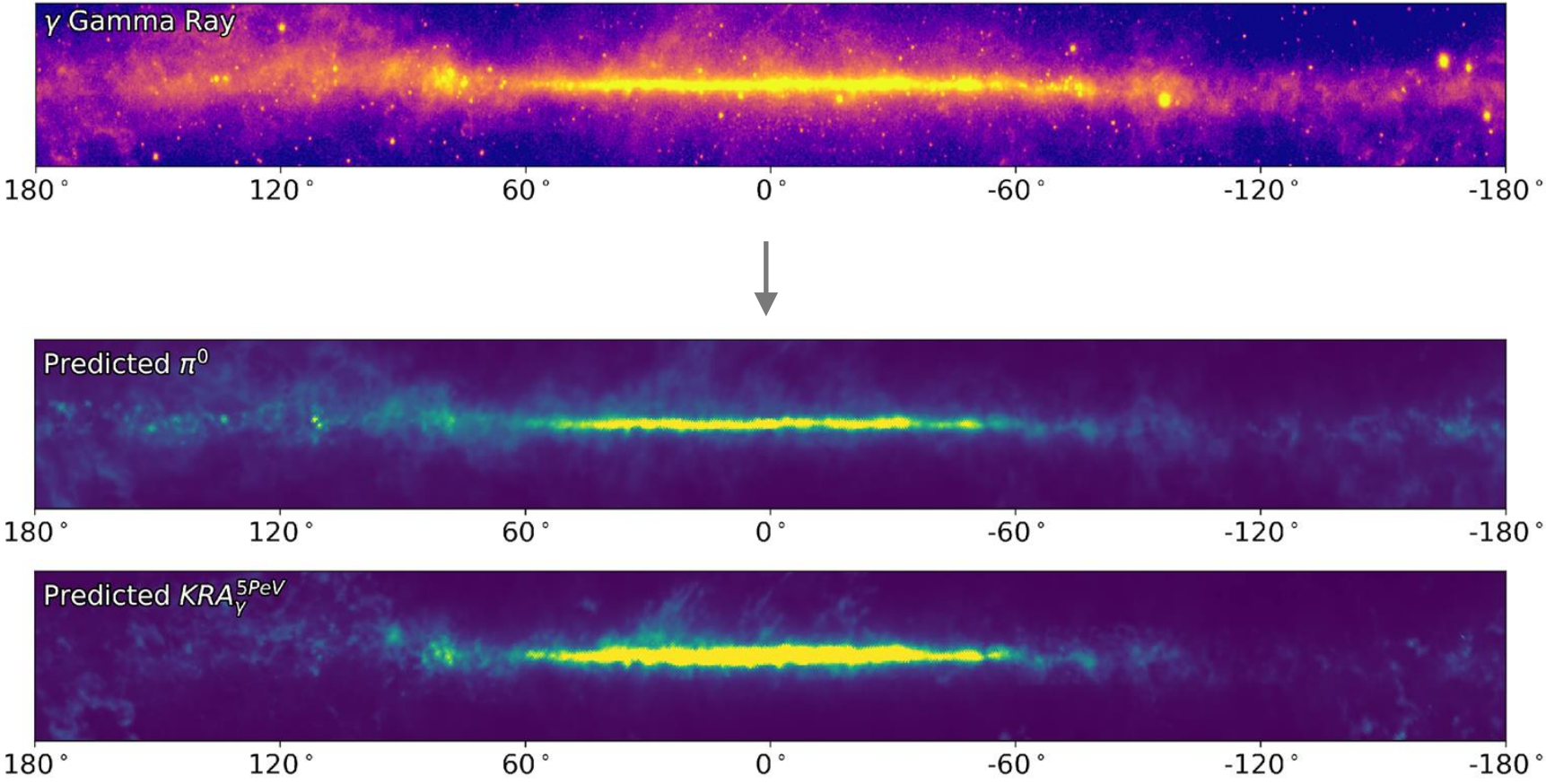


Slide credit: Naoko Kurahashi Neilson

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.

Slide credit: Steve Sclafani

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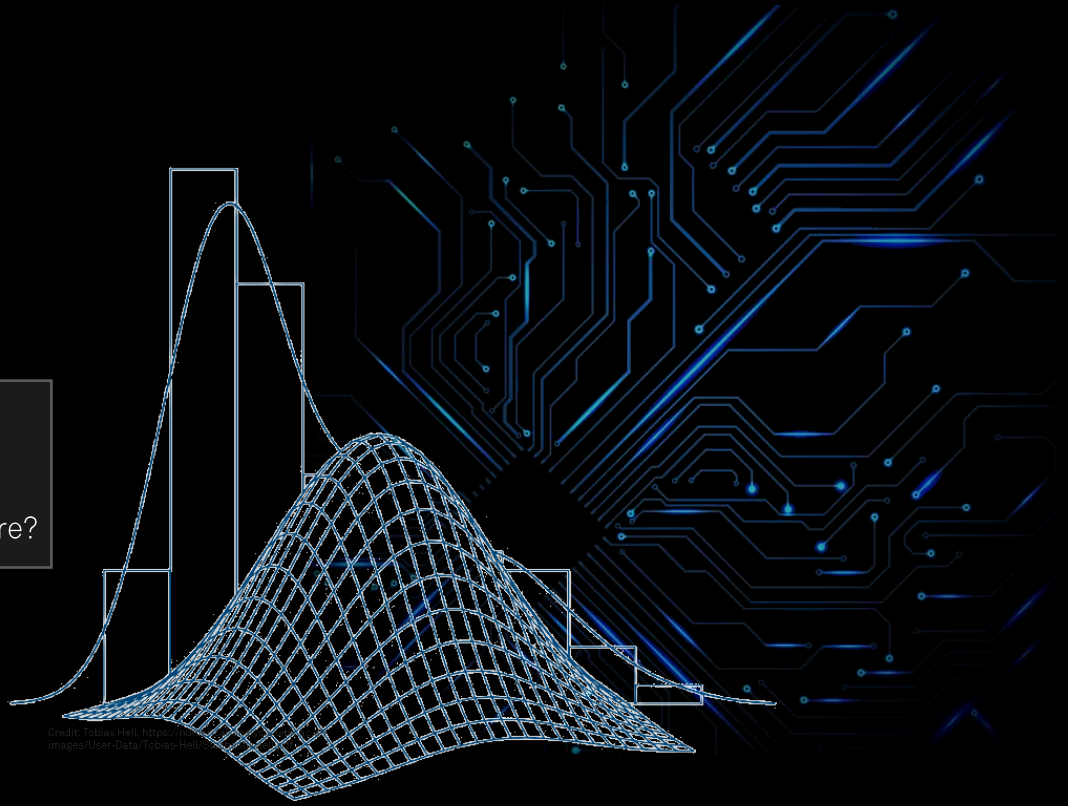


Neutrino Source Searches

Unbinned likelihood:

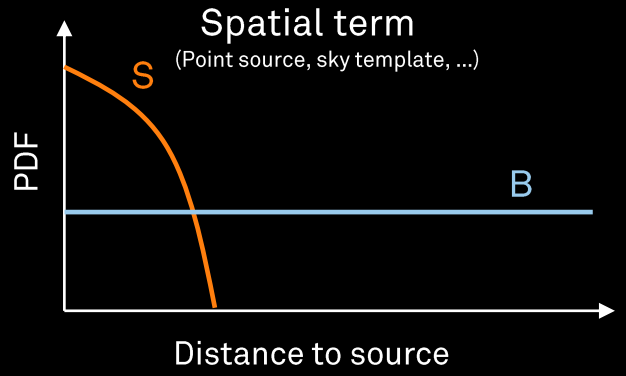
$$\mathcal{L} = \prod_i^N \left[\frac{n_s}{N} \cdot \boxed{S_i} + \left(1 - \frac{n_s}{N}\right) \cdot \boxed{B_i} \right]$$

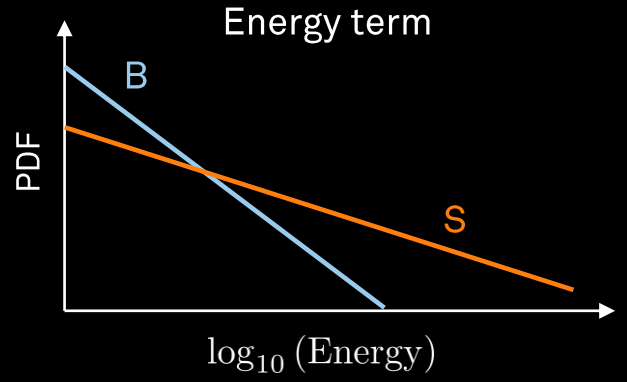
Signal
(Modeled by MC)

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

Test-statistic:

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





Neutrino Source Searches

Point source search:

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

All-sky search:

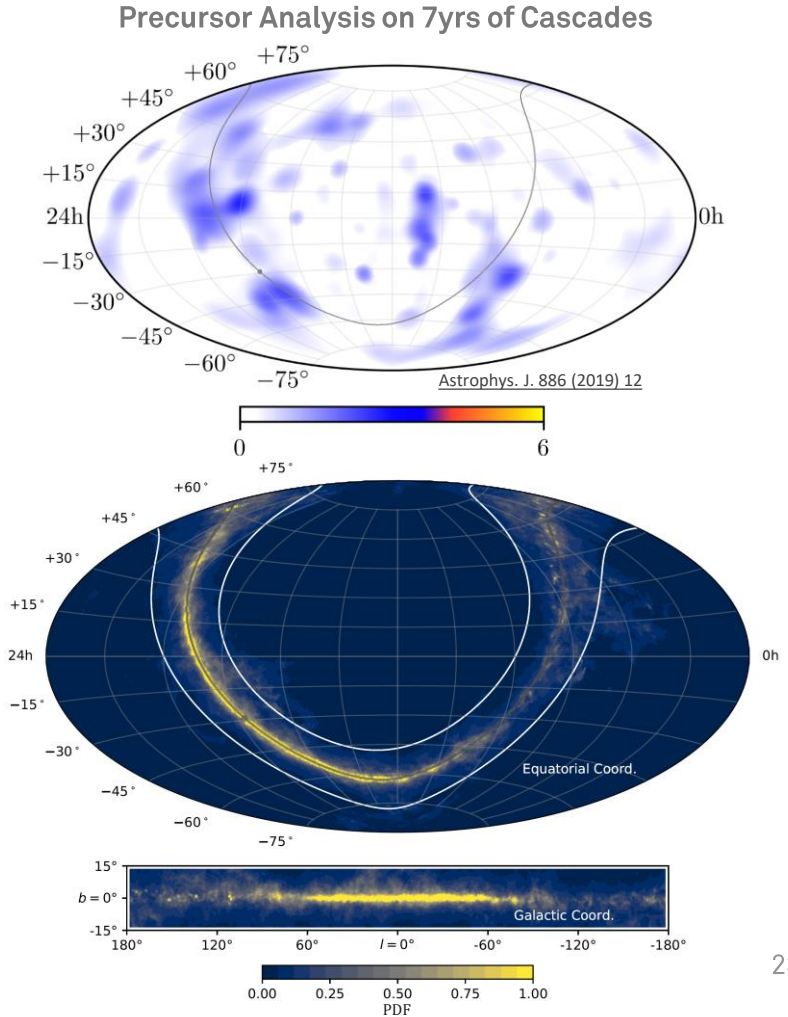
- Perform a point source search at every point in the sky
- Large trial factor due to high number of points tested

Stacked search

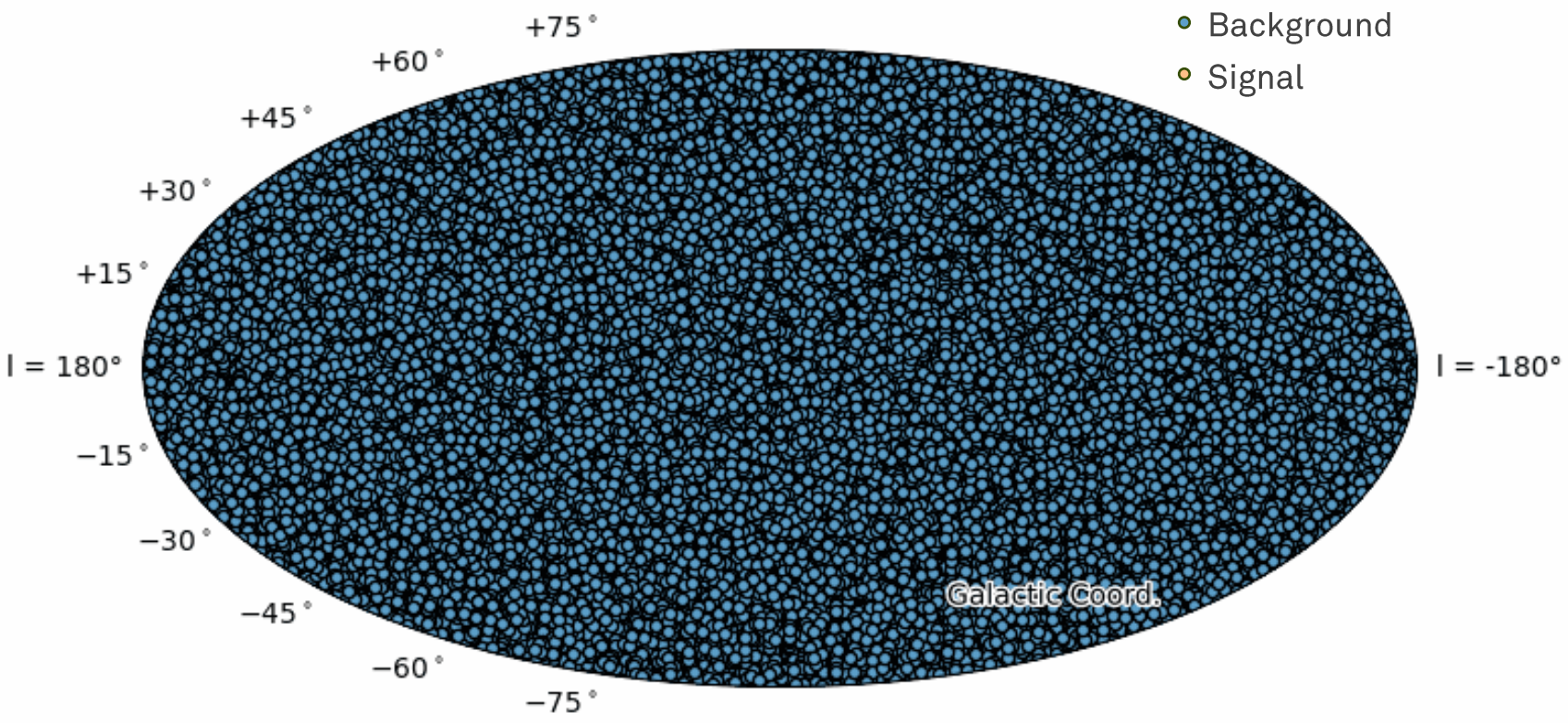
- Stack multiple point-like sources (with similar properties) “on top of” each other

Template Searches

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

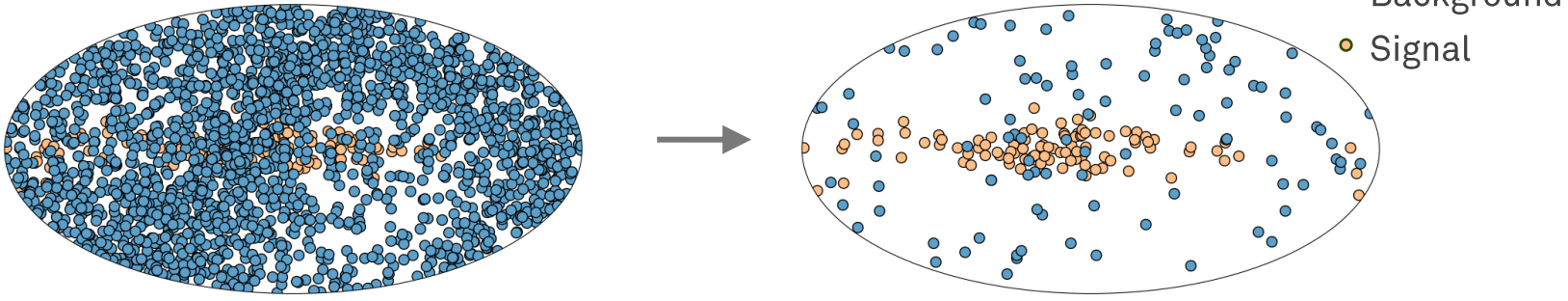


Challenges of Neutrino Source Searches

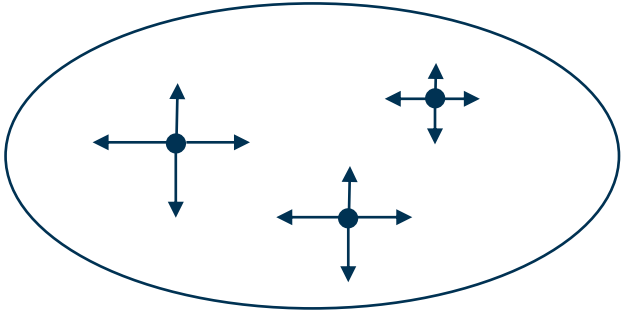


Combat Challenges with Machine Learning

- Event Selection



- Event Reconstruction



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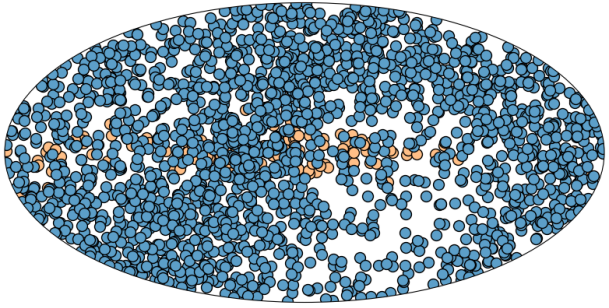

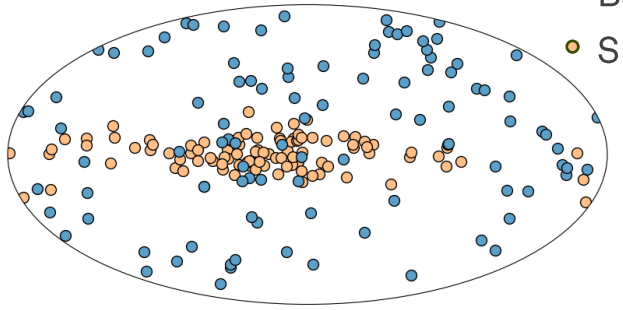

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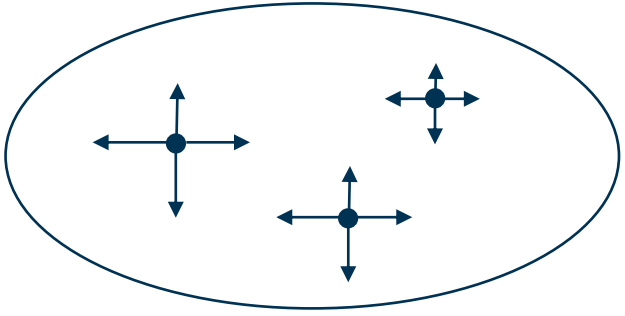
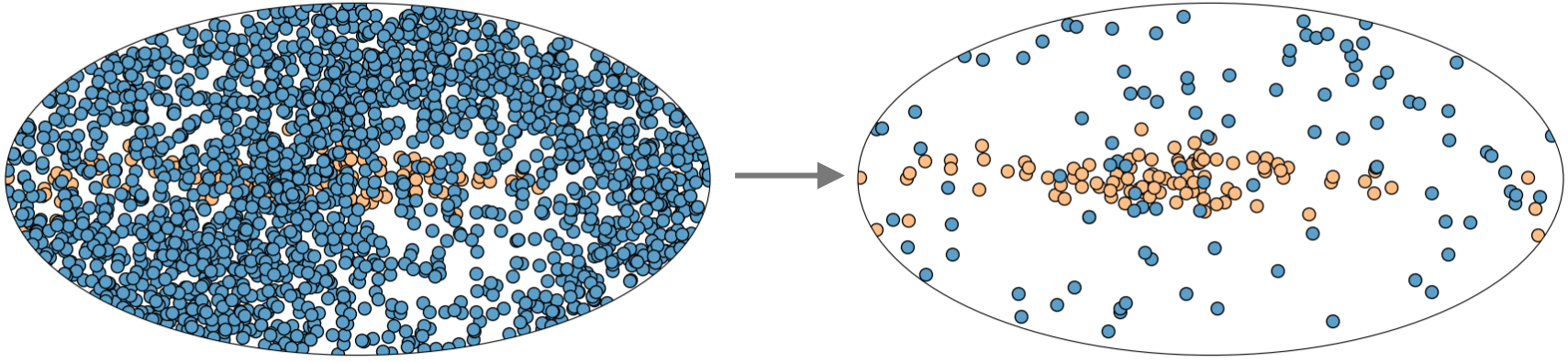


Utilize machine learning –
a field of Artificial Intelligence (AI)

Event Selection



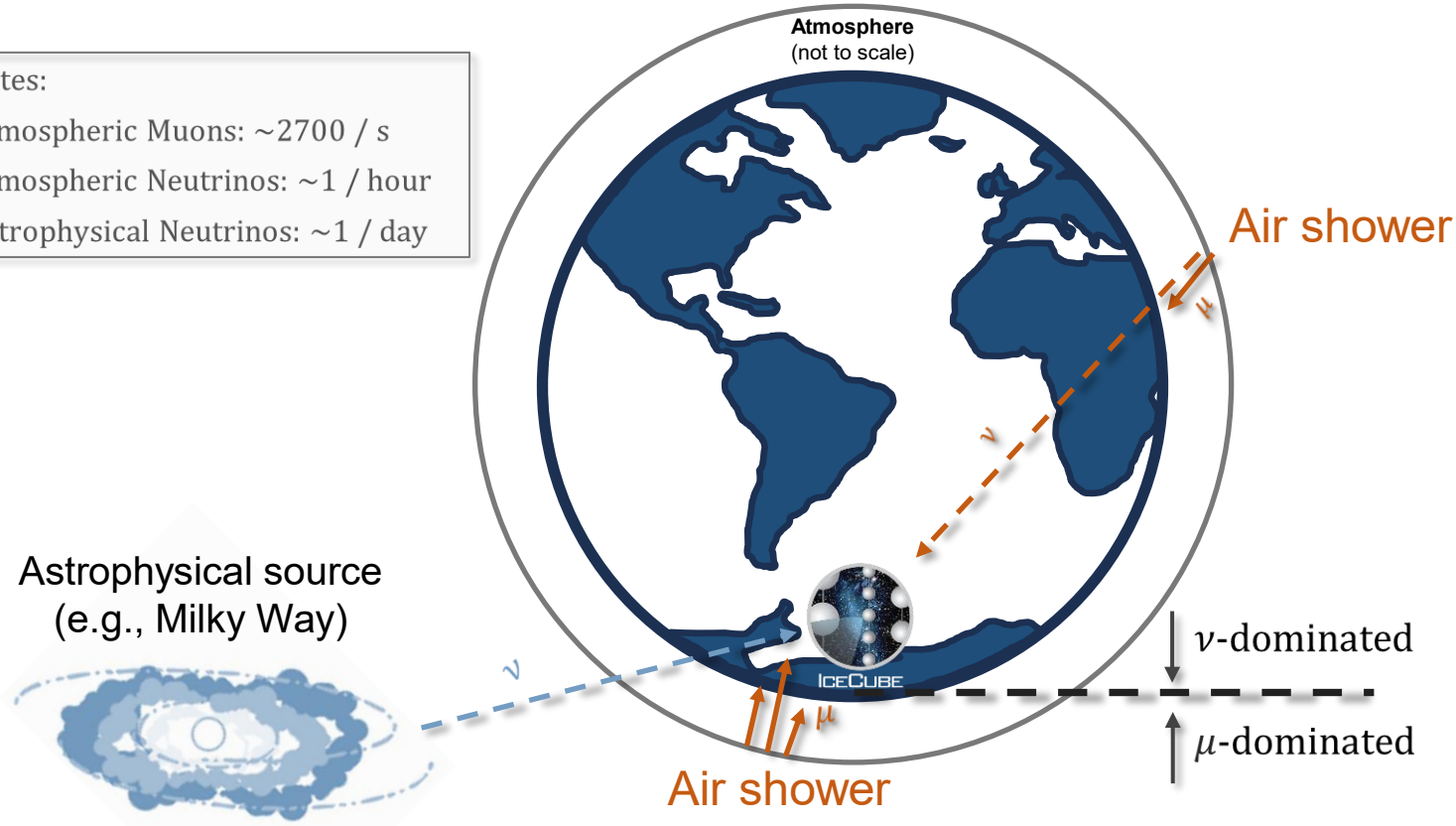
Selection of Astrophysical Neutrinos

Rates:

Atmospheric Muons: ~2700 / s

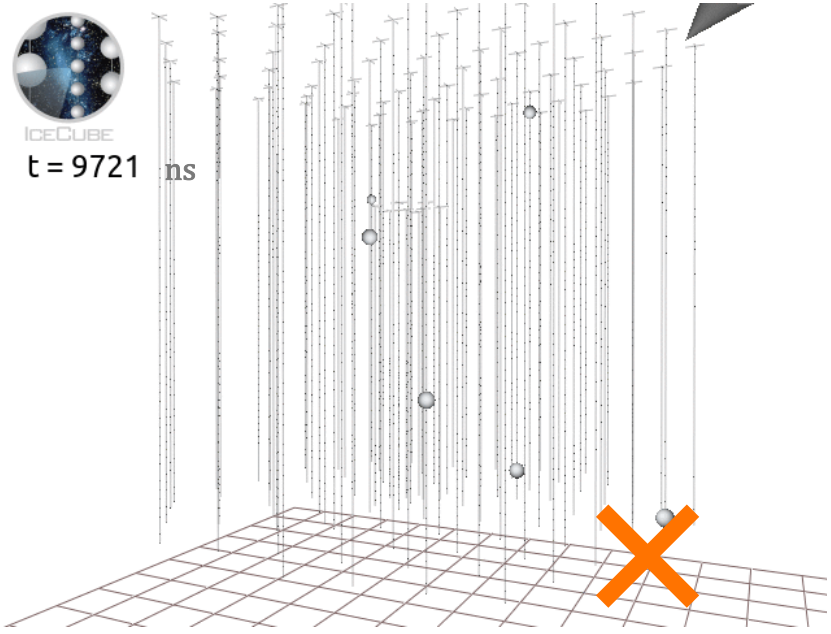
Atmospheric Neutrinos: ~1 / hour

Astrophysical Neutrinos: ~1 / day

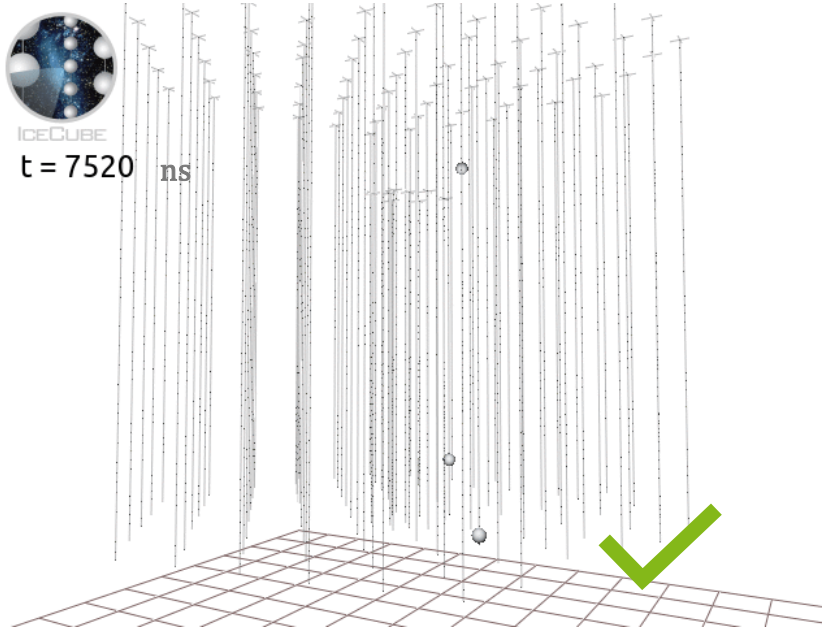


Selection of Astrophysical Neutrinos

Entering μ

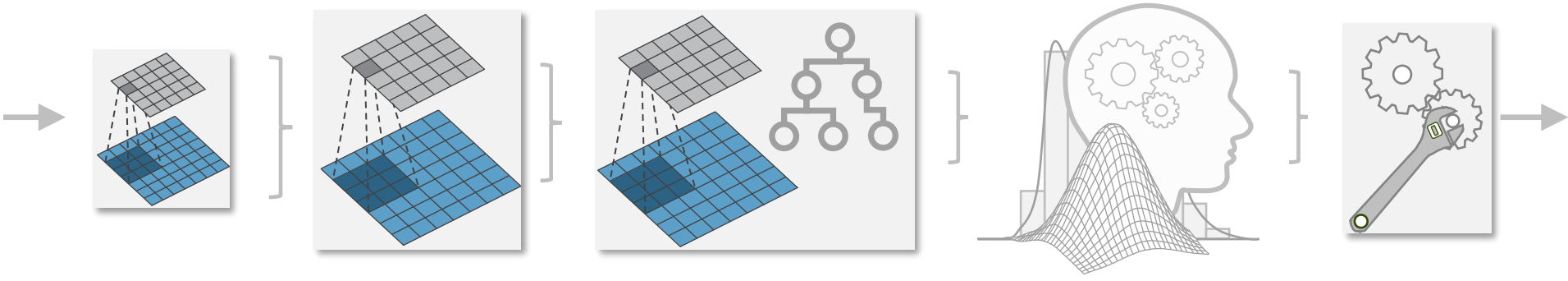


Cascade Event



IceCube South Pole Neutrino Observatory · SFB1491 · SFB 876 Providing Information by Resource-Constrained Data Analysis · Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation · Federal Ministry of Education and Research

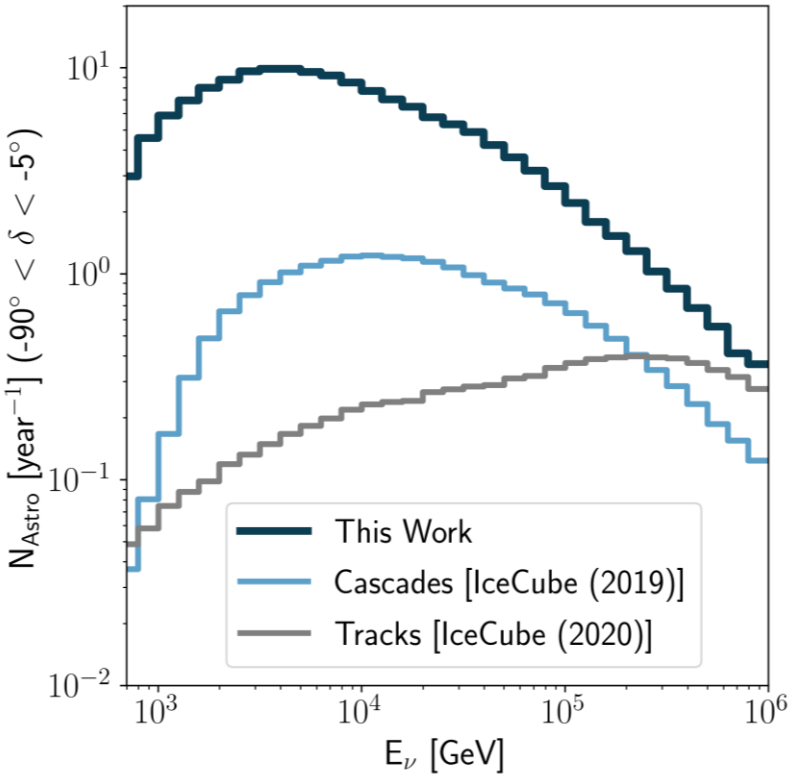
Selection of Astrophysical Neutrinos



~2700 / s ~2 / min ~17 / day

- Series of convolutional neural networks (CNNs)
- Final step via boosted decision trees (BDTs)

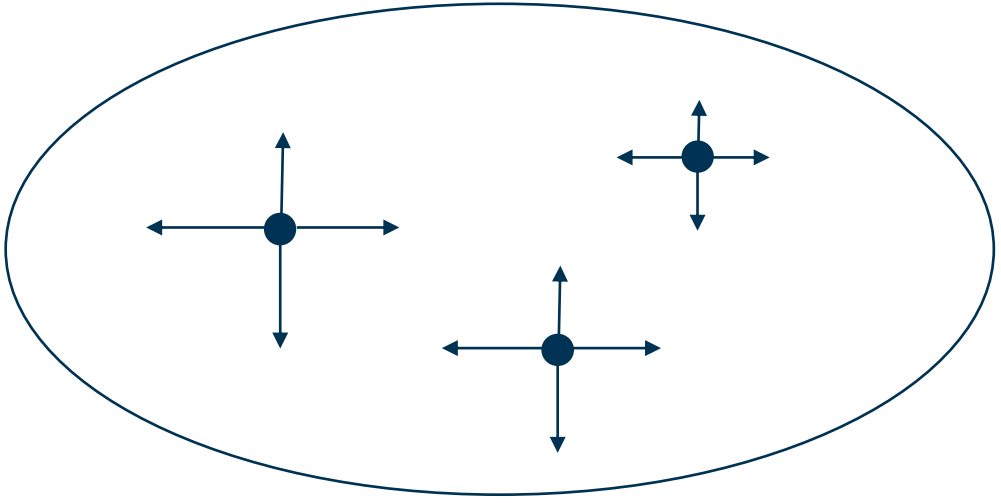
Selection of Astrophysical Neutrinos



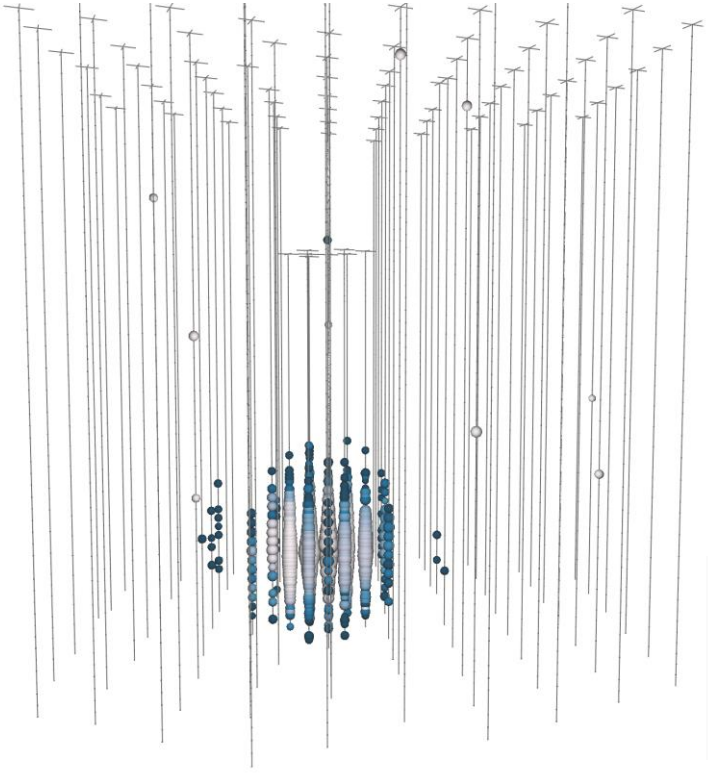
Event selection:

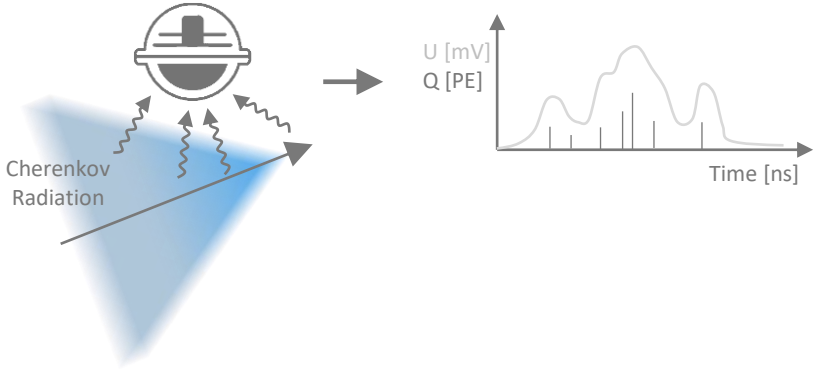
- Background reduced by almost 8 orders of magnitude
- 30 times as many events as precursor analysis

Event Reconstruction



Reconstructing Event Properties

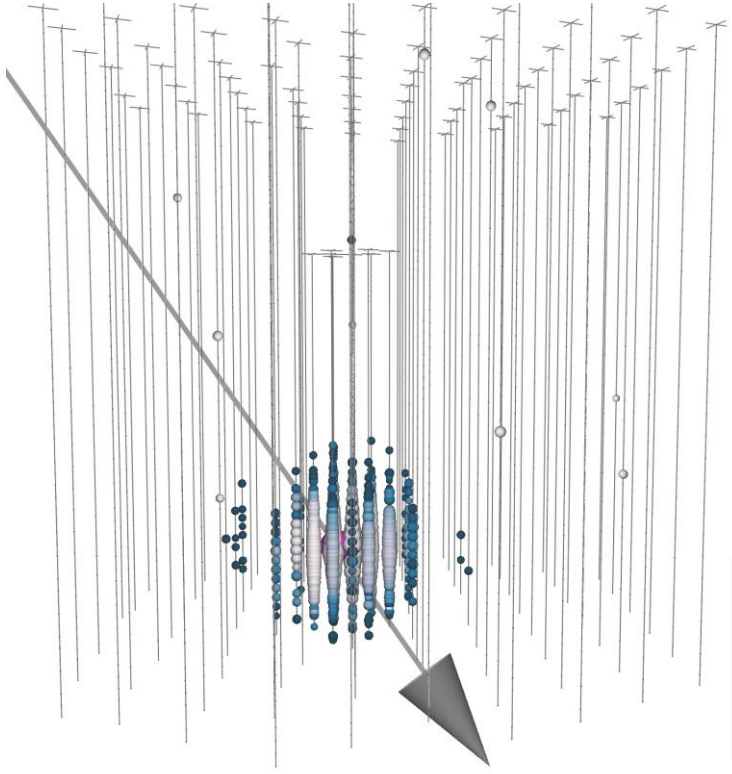


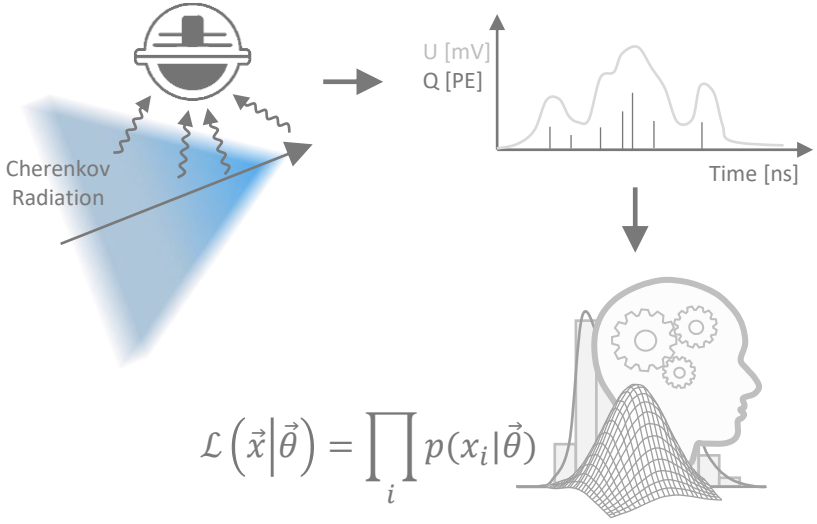


Event reconstruction:

- Neutrino events are characterized by their energy and direction
- Properties are inferred from observed light pattern in detector

Reconstructing Event Properties





$$\mathcal{L}\left(\vec{x}\middle|\vec{\theta}\right) = \prod_i p(x_i|\vec{\theta})$$

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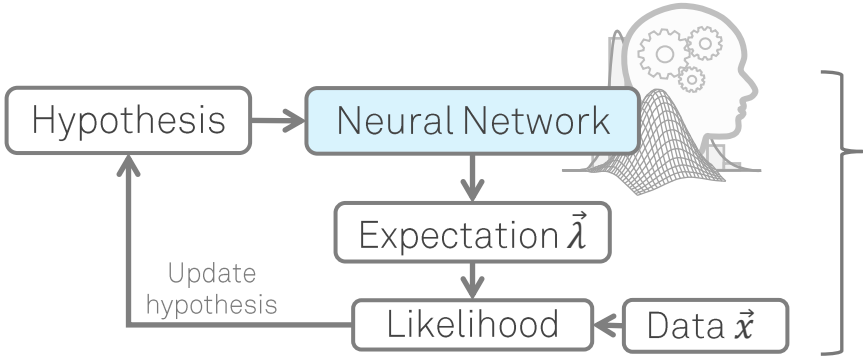
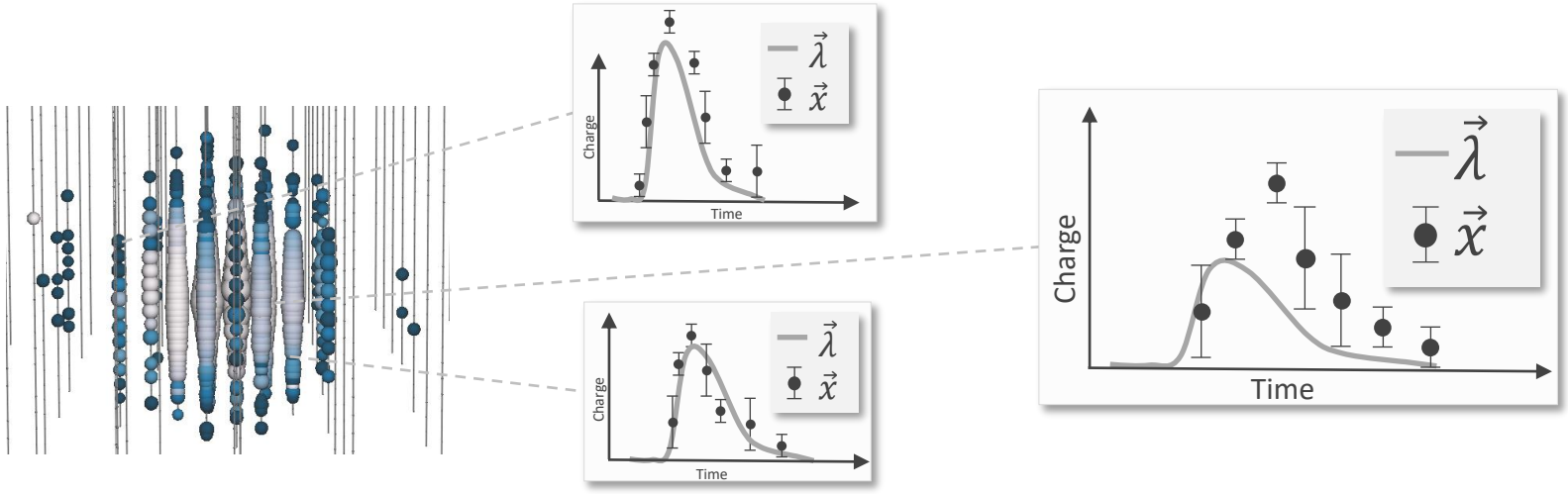
Reconstructing Event Properties



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**



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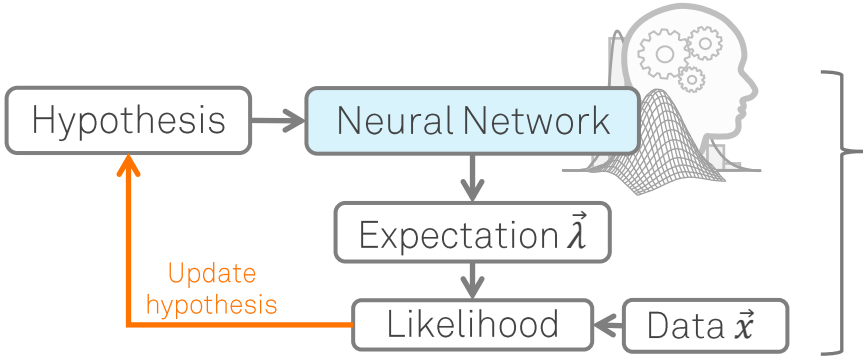

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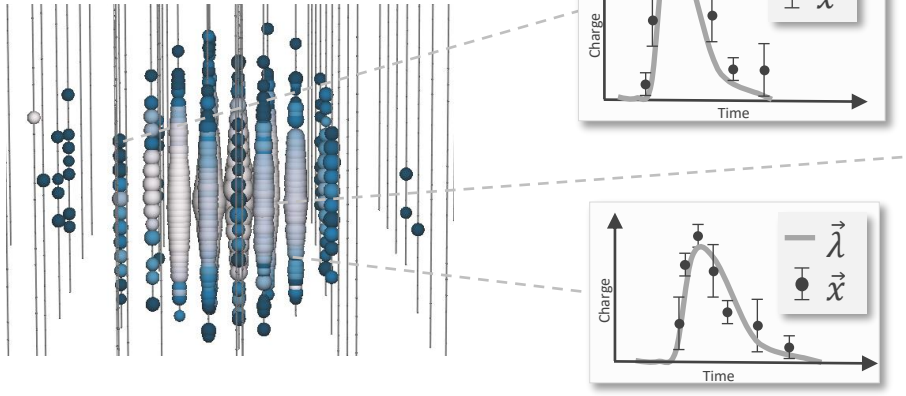
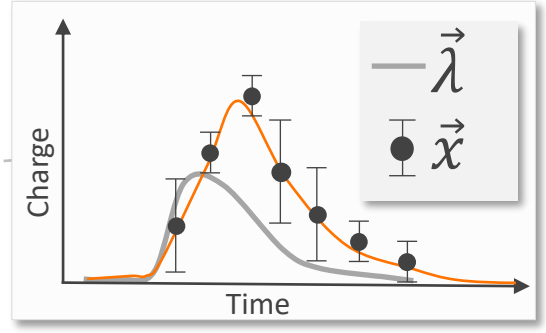
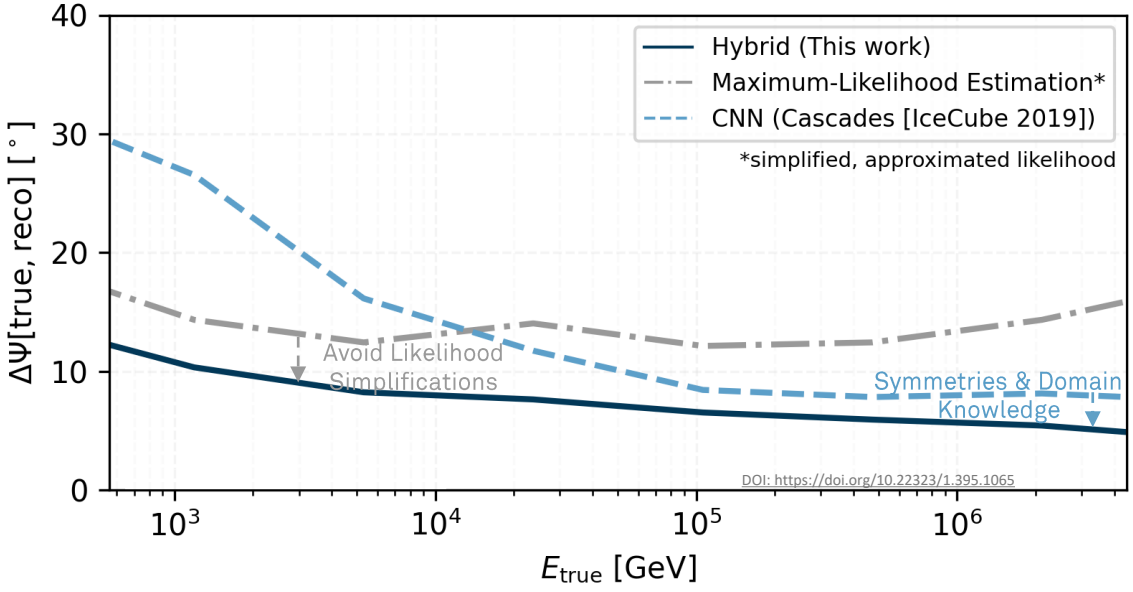




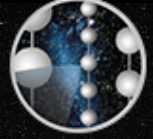
Improvements by novel methods



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



Talk Outline

Introduction to Neutrino Astronomy

The IceCube Neutrino Detector

- What is it and how does it work?

Neutrinos from the Galactic Plane

- The Multiwavelength Milky Way
- Diffuse Neutrino Emission

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- How do we search for this emission?
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Conclusions and Outlook

20th of January 2022: Analysis Unblinding

Analysis Unblinding:

- Analysis is developed in a blinded fashion
- Once review and checks have been cleared, unblinding approval is granted
- This is the “moment of truth”


Stephen Sclafani


Mirco Hünnefeld


Michael Richman


Naoko Kurahashi Neilson

```
mhuennefeld@cobalt08:~
(venv) mhuennefeld@cobalt08 ~ $ python unblind.py unblind-gp --TRUTH pi0
```

```
================================================
=== Results for GP template: pi0
================================================
    Number of Background Trials: 549500000
    TS: 22.189
    ns: 748.043
    p-value: 1.261e-06
    n-sigma: 4.71
    --> Found evidence for a source!
================================================
```


sclafani 4:12 PM
@mrichman Approved for unblinding


mhuennefeld 5:16 PM
showtime 🙂 What zoom room are we using?

20th of January 2022: Analysis Unblinding

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zoom


Stephen Sclafani


Mirco Hünnefeld


Michael Richman


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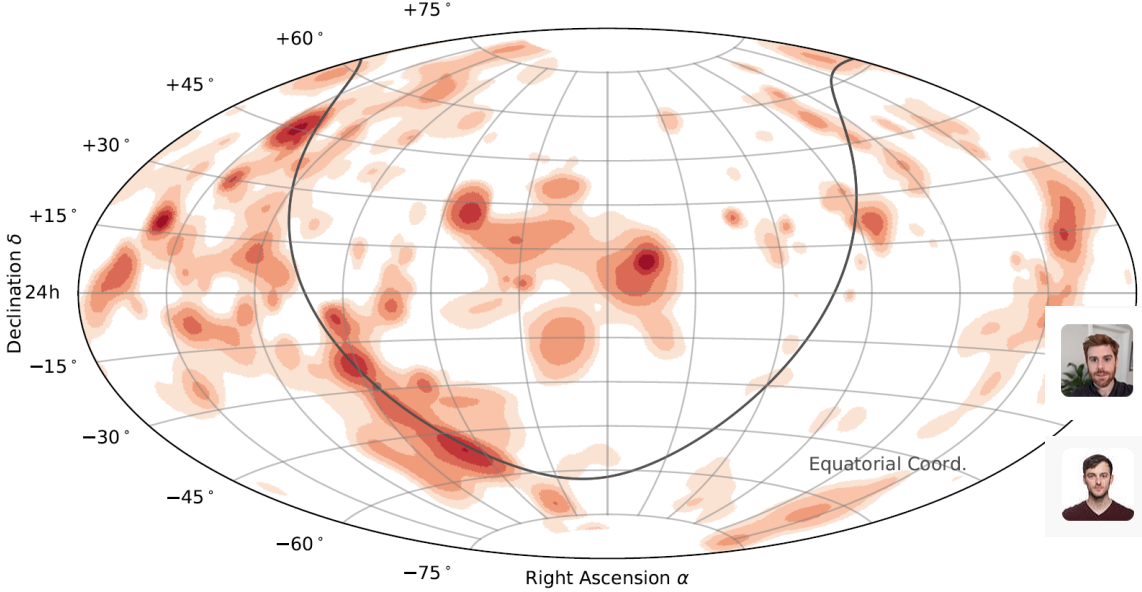

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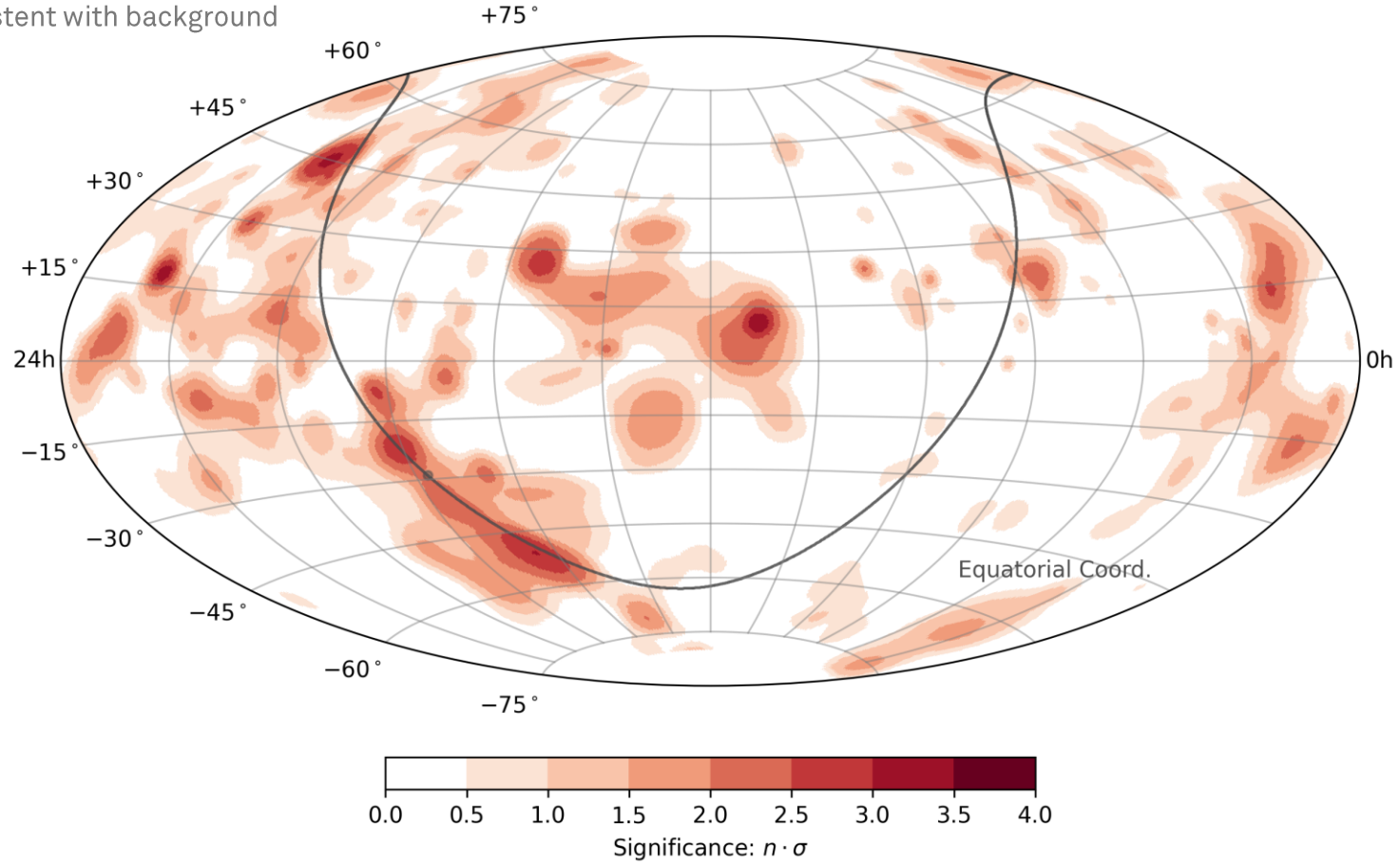
Results from All-Sky Search

Individual warm spots
consistent with background



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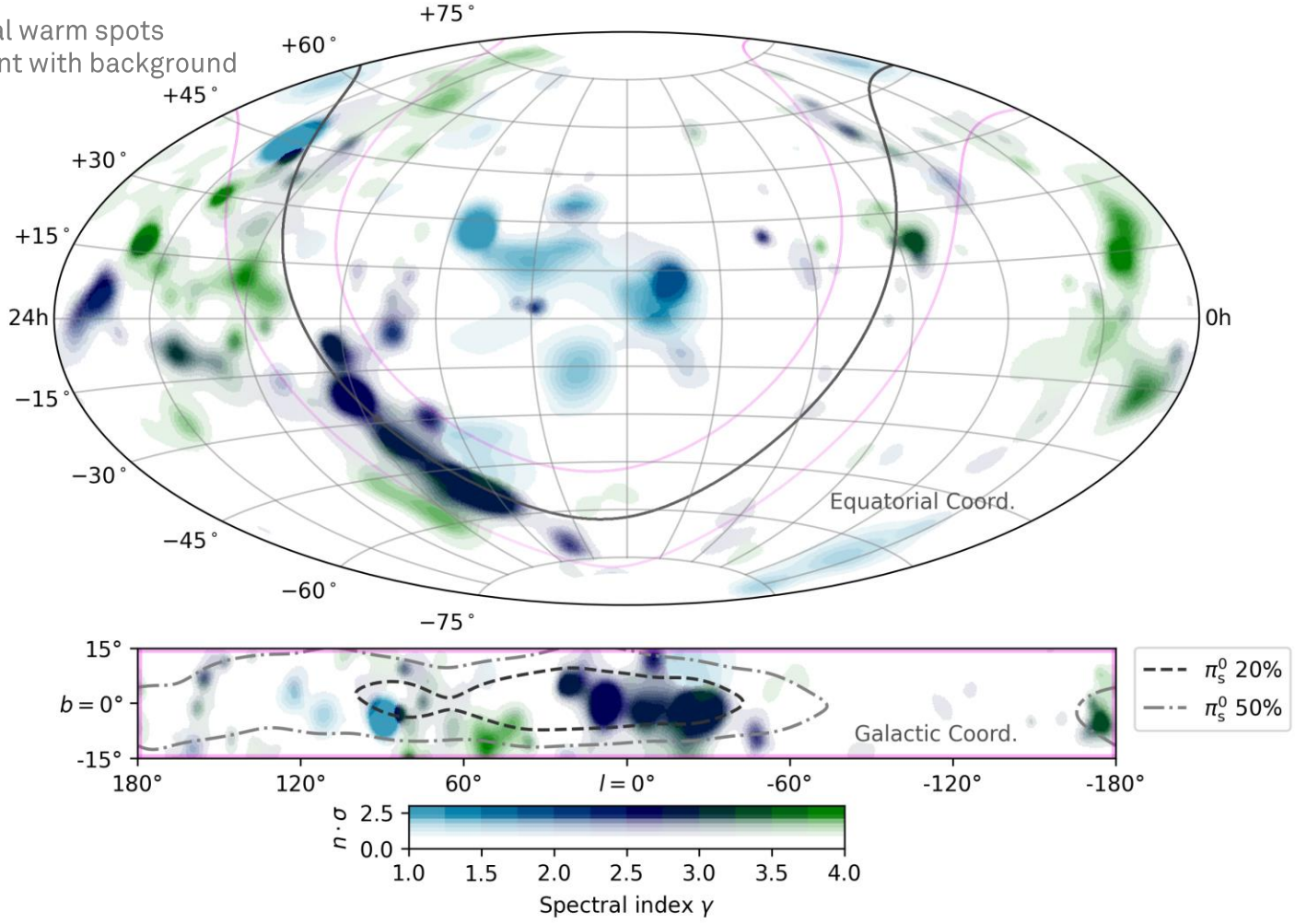


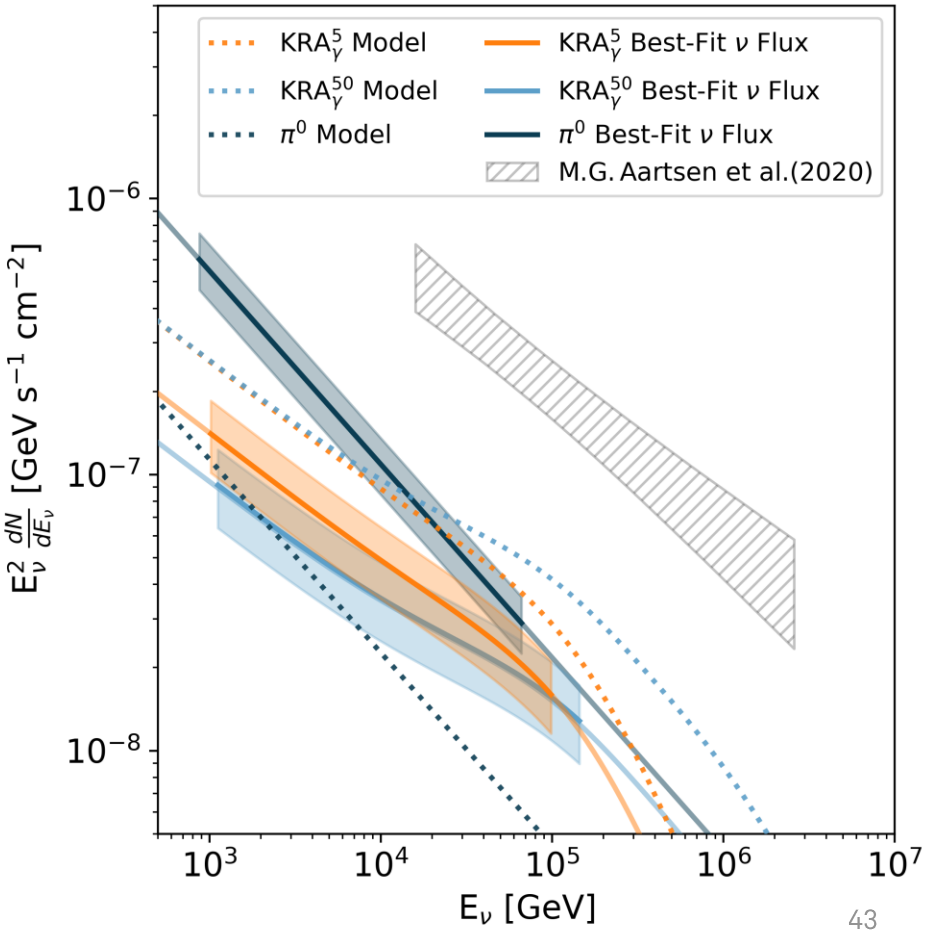
Results from Diffuse Galactic Plane Searches

After trial-correction: 4.5σ

Model	Signal Events	Pre-trial p-value ($N\sigma$)
π^0	748	1.26×10^{-6} (4.71σ)
KRA_γ^5	276	6.13×10^{-6} (4.37σ)
KRA_γ^{50}	211	3.72×10^{-5} (3.96σ)

π^0: based on Fermi-LAT gamma-ray measurements (DOI: 10.1088/0004-637X/750/1/3)
$\mathrm{KRA}_\gamma^{5/50}$: based on Gaggero et. *al* (DOI 10.1088/2041-8205/815/2/L25)

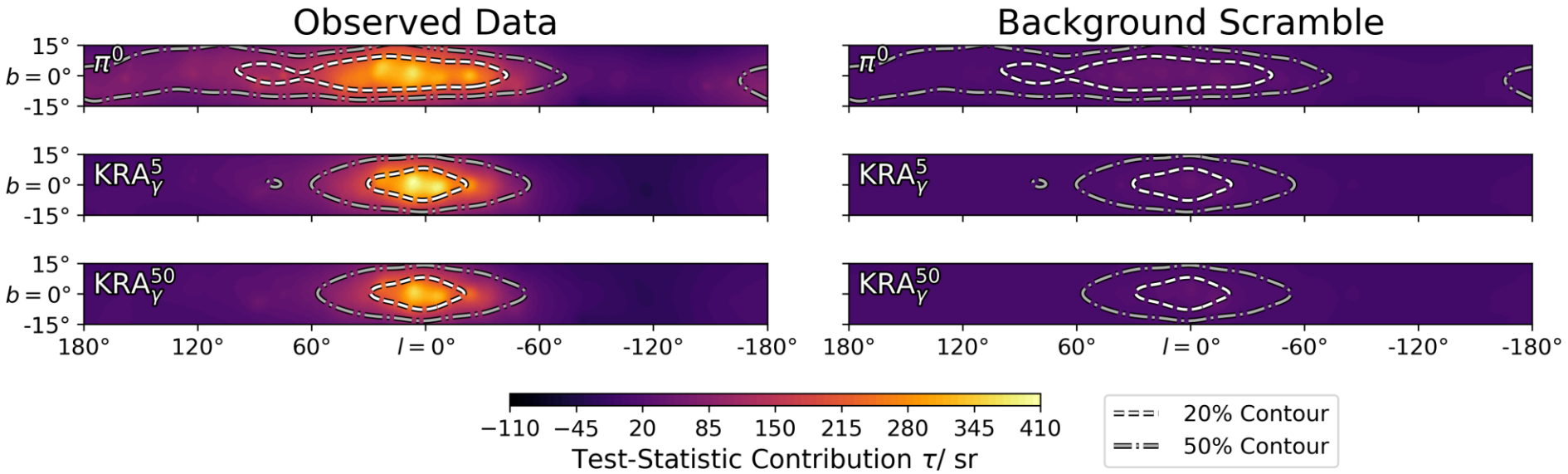
- Shaded regions depict energy ranges that contribute most to the significance
- Galactic flux may explain up to ~10% of astrophysical flux
- Relative model contributions depend on location on the sky



IceCube South Pole Neutrino Observatory · SFB1491 · SFB 876 Providing Information by Resource-Constrained Data Analysis · Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation · Federal Ministry of Education and Research

Analysis Results

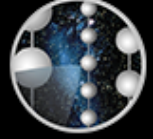
Global significance: 4.5σ



Analysis Results

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

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



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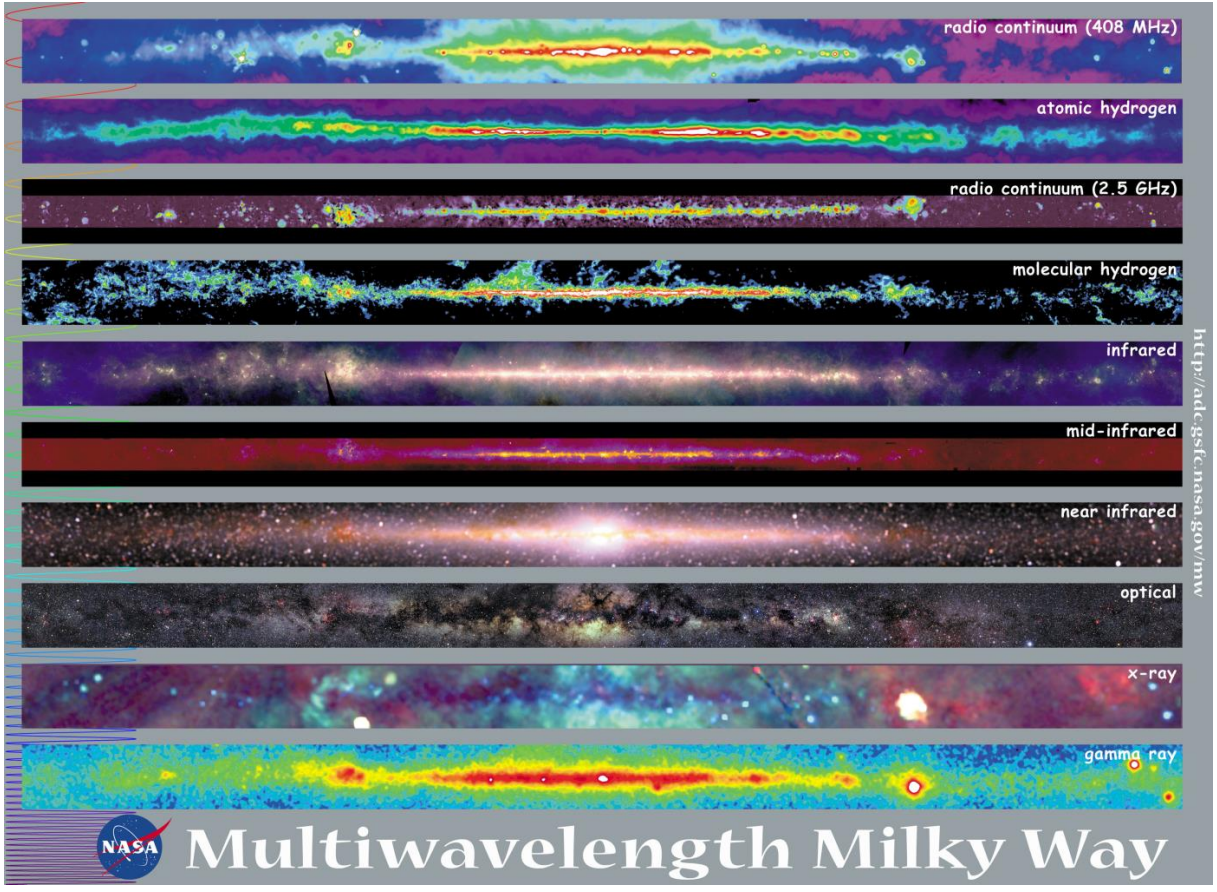
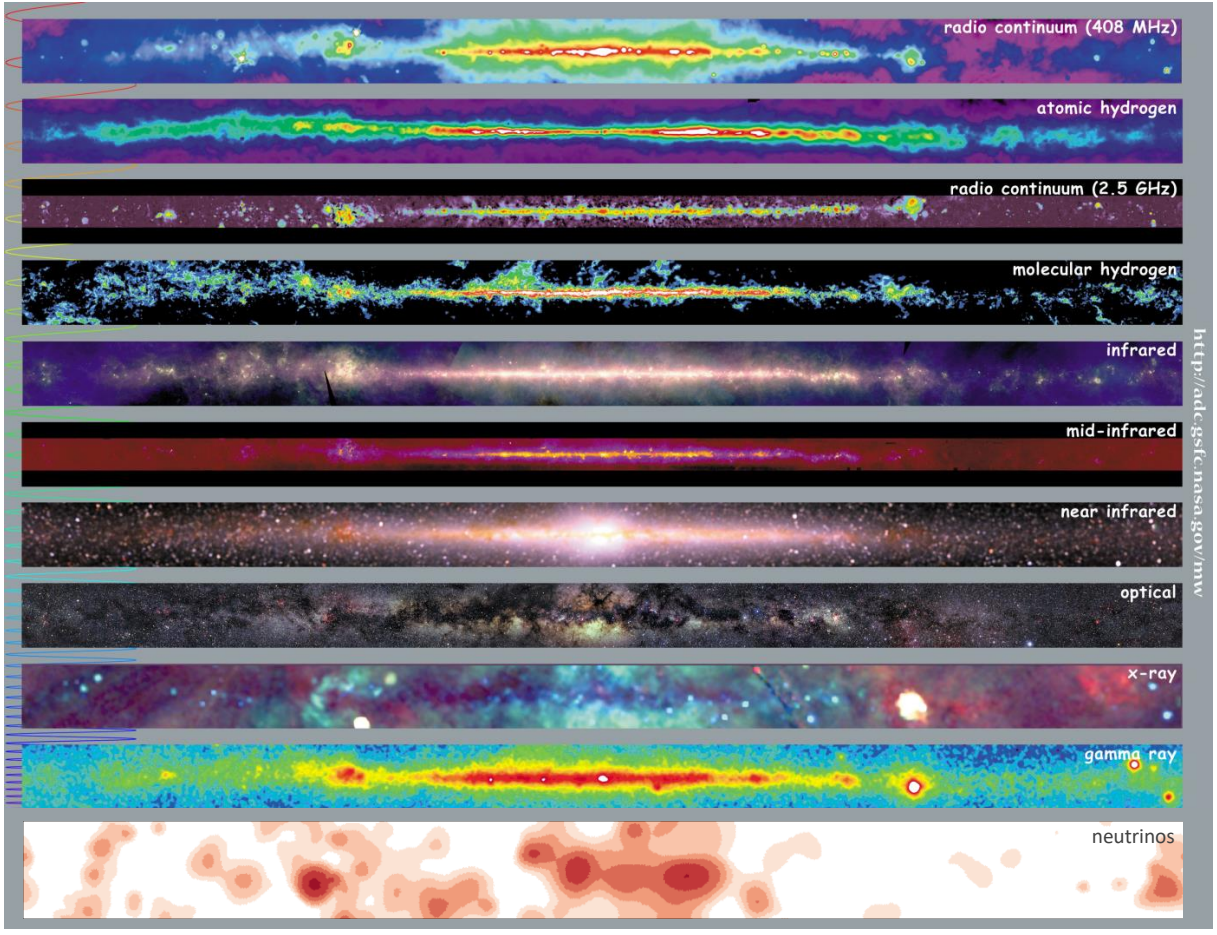
The Multiwavelength Milky Way



The ~~Multiwavelength~~ Multimessenger Milky Way



Summary & Outlook

Strong evidence for neutrino emission from the Galactic plane

- Background-only hypothesis rejected at 4.5σ
- Emission from Galactic plane may explain up to ~10% of astrophysical flux observed by IceCube
- Independent hints in IceCube track channels (~2.7σ)[1] and in ANTARES[2] (~2σ)

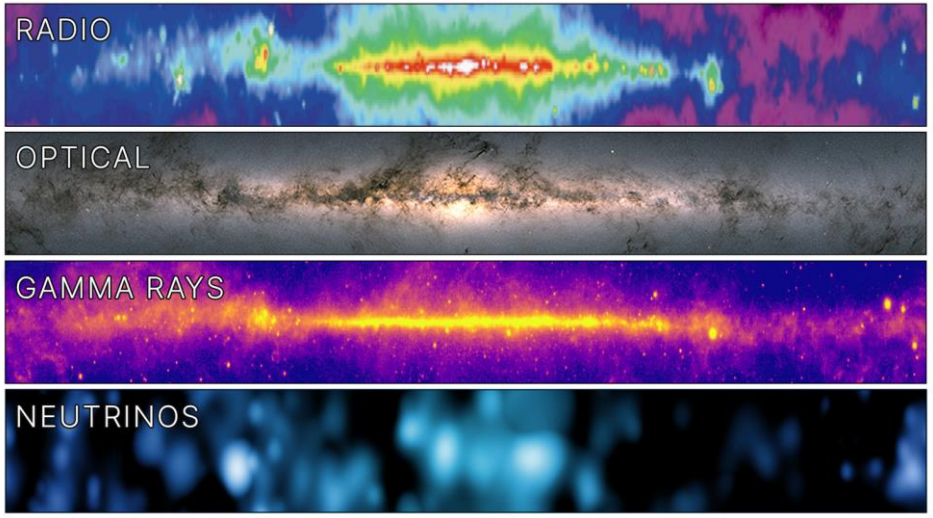
Observation enabled by new tools based on Deep Learning

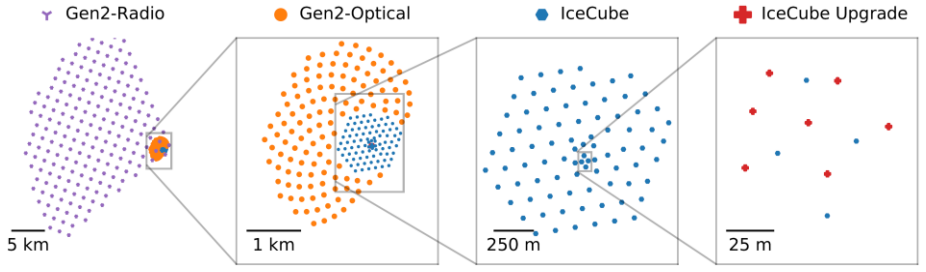
- 30 times as many events than precursor selection
- Improved reconstruction resolution by up to 50%
- Analysis sensitivity improved by a factor of 3

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!





[1] DOI: 10.22323/1.444.1046
[2] DOI: 10.1016/j.physletb.2023.137951