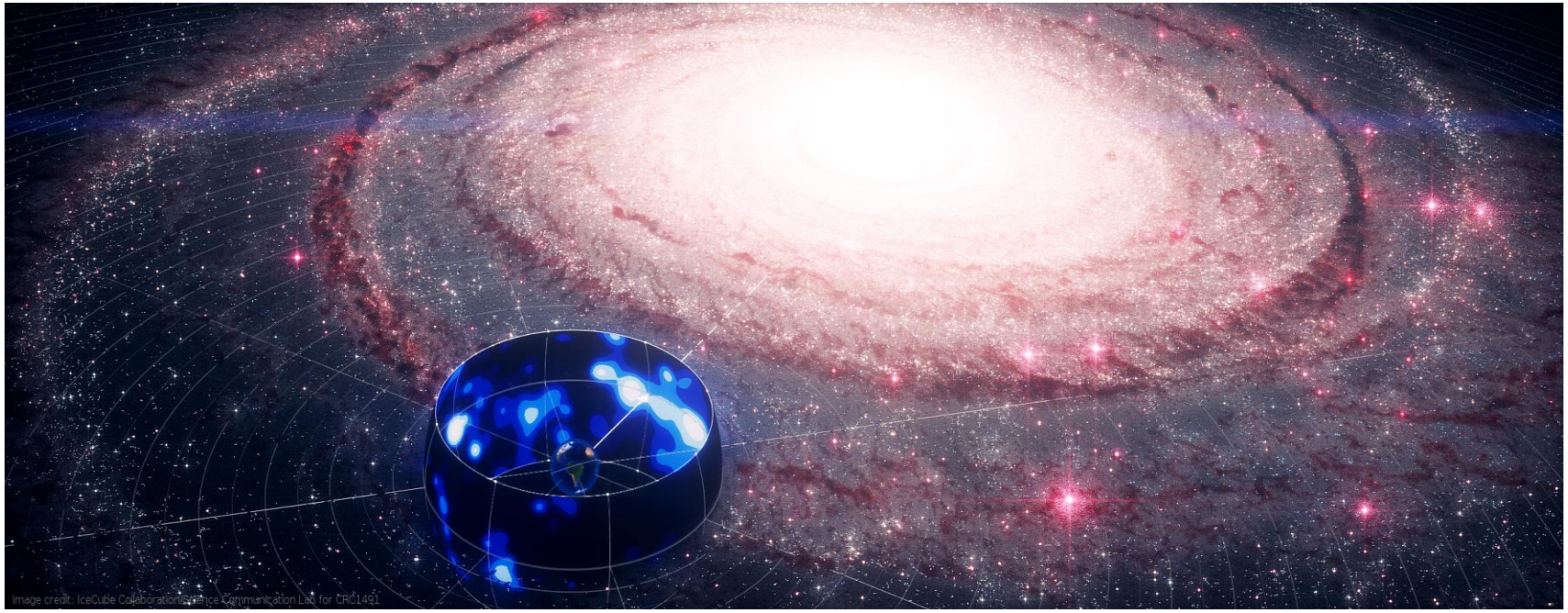
technische universität dortmund

IceCube Neutrino Observatory

SFB 876 Providing Information by Resource-Constrained Data Analysis

SFB1491



Evidence for high-energy neutrinos from the Galactic plane

Mirco Hünnefeld
mirco.huennefeld@tu-dortmund.de

SPONSORED BY THE
Federal Ministry of Education and Research

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

IRFU – CEA, Paris-Saclay
February 5th, 2024

Science – June 30, 2023

RESEARCH

RESEARCH ARTICLES

NEUTRINO ASTROPHYSICS

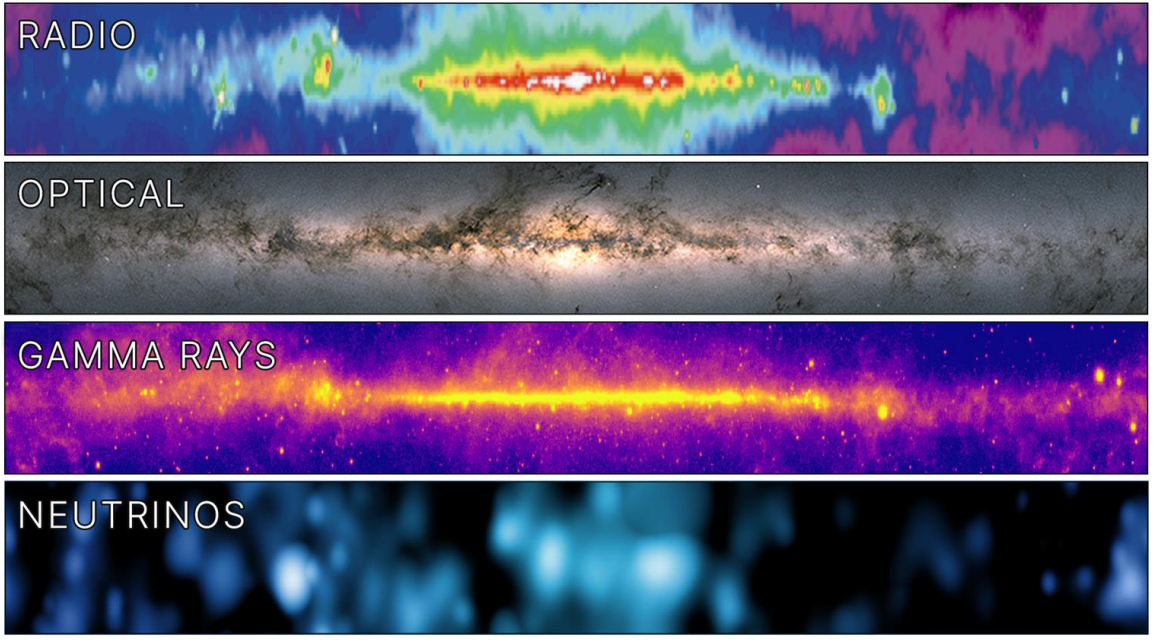
Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

DOI: 10.1126/science.adc9818

Stephen Sclafani

Mirco Hünnefeld



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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Image credit: DESY/Science Communication Lab

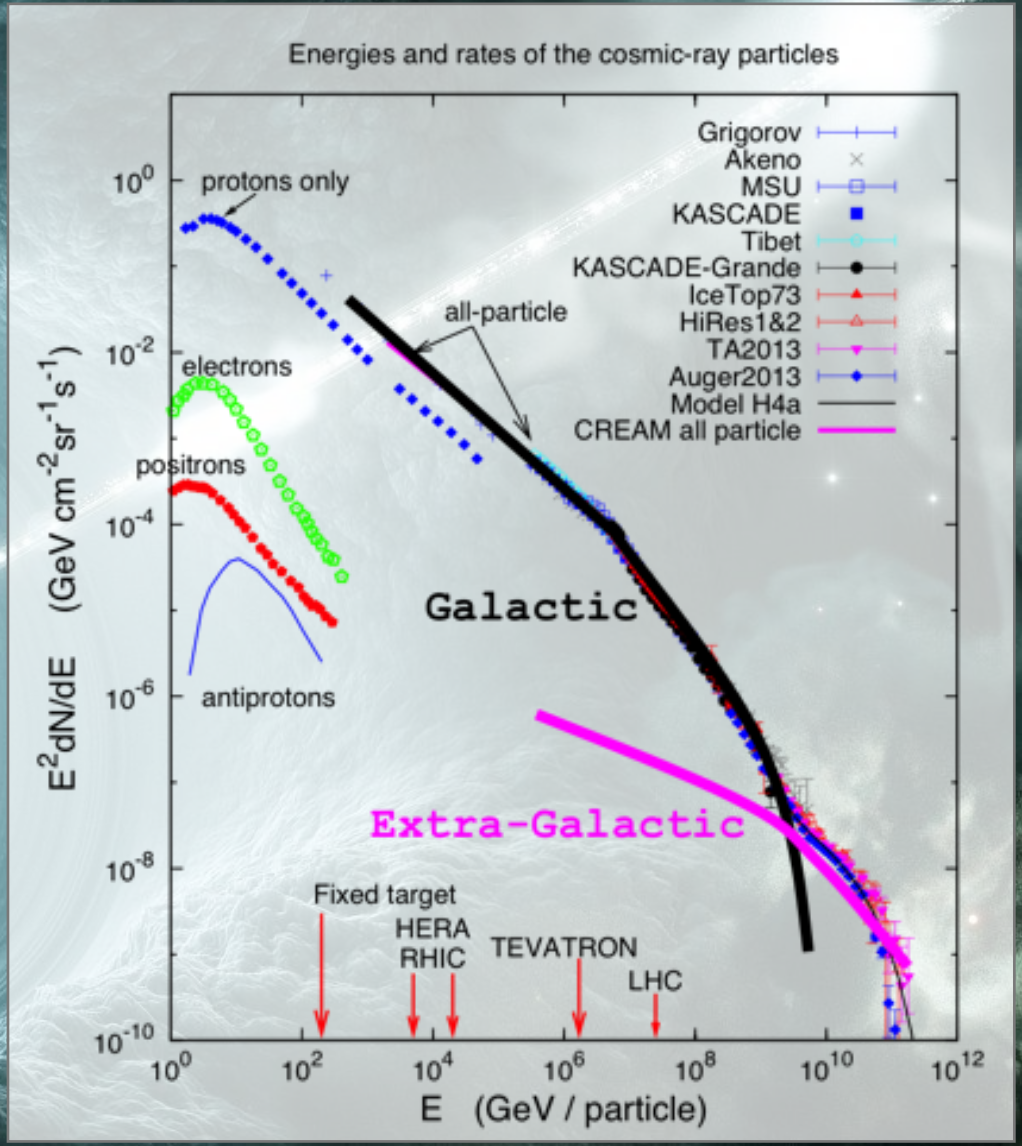
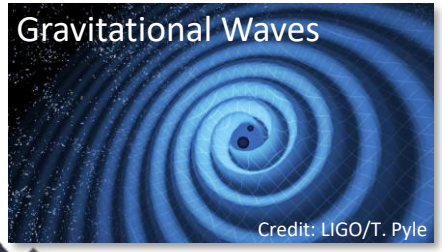


Image credit: DESY/Science Communication Lab

Neutrino Astronomy with IceCube



AGNs, SNRs, GRBs...

black holes

Gamma rays
They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

Neutrinos
They are weak, neutral particles that point to their sources and carry information from deep within their origins.

Cosmic rays
They are charged particles and are deflected by magnetic fields.

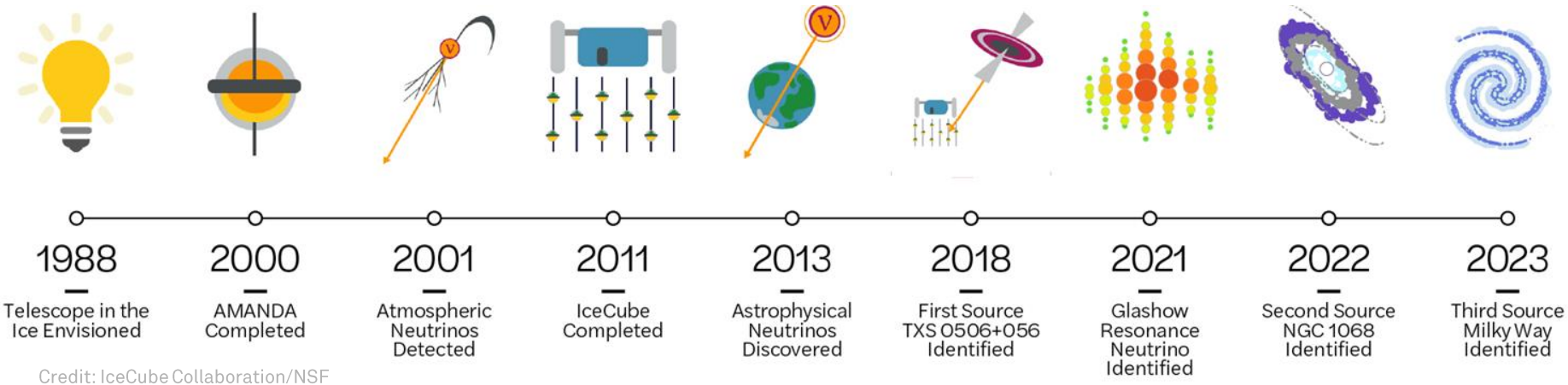
Earth

air shower

Credit: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Neutrino Astronomy – How far have we come?

A History of Neutrino Astronomy in Antarctica



Credit: IceCube Collaboration/NSF

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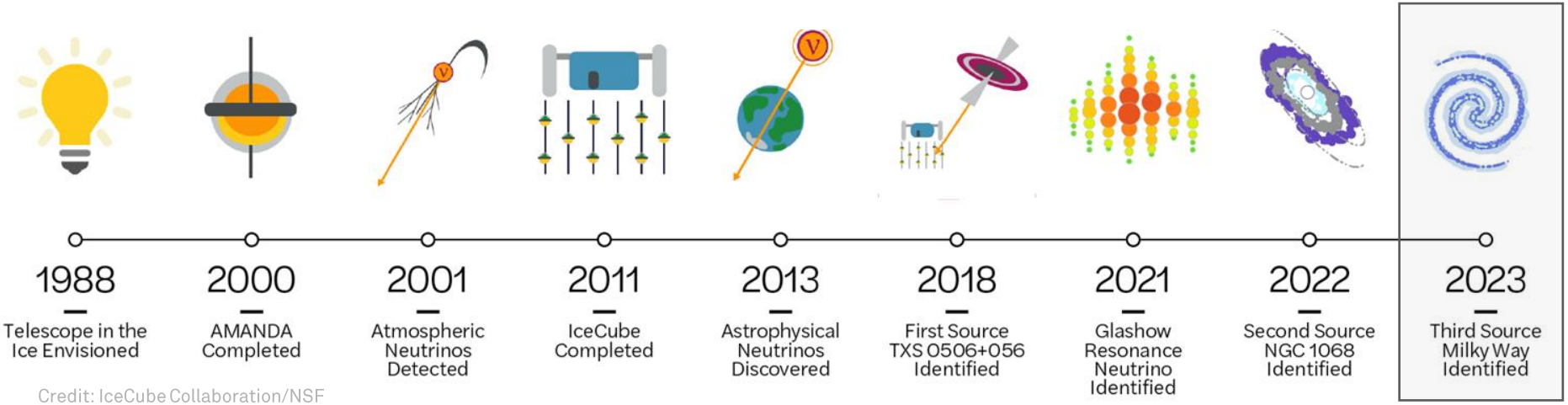
IceCube Neutrino Observatory NSF



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

BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

ITALY
University of Padova

JAPAN
Chiba University

NEW ZEALAND
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Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
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Academia Sinica

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University of Oxford

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Georgia Institute of Technology
Harvard University
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South Dakota School of Mines and Technology
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Stony Brook University
University of Alabama
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University of Kansas
University of Maryland
University of Rochester
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University of Utah
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University of Wisconsin–River Falls
Yale University

FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
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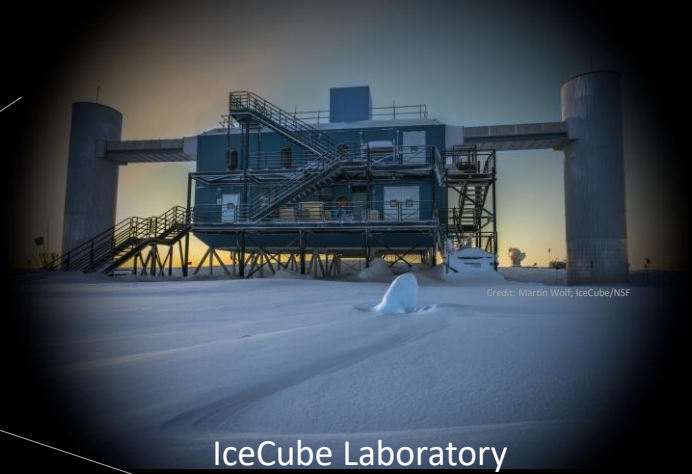
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

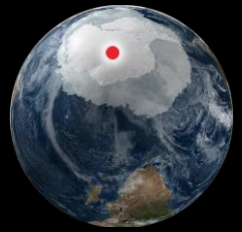
IceCube
South Pole Neutrino Observatory

icecube.wisc.edu

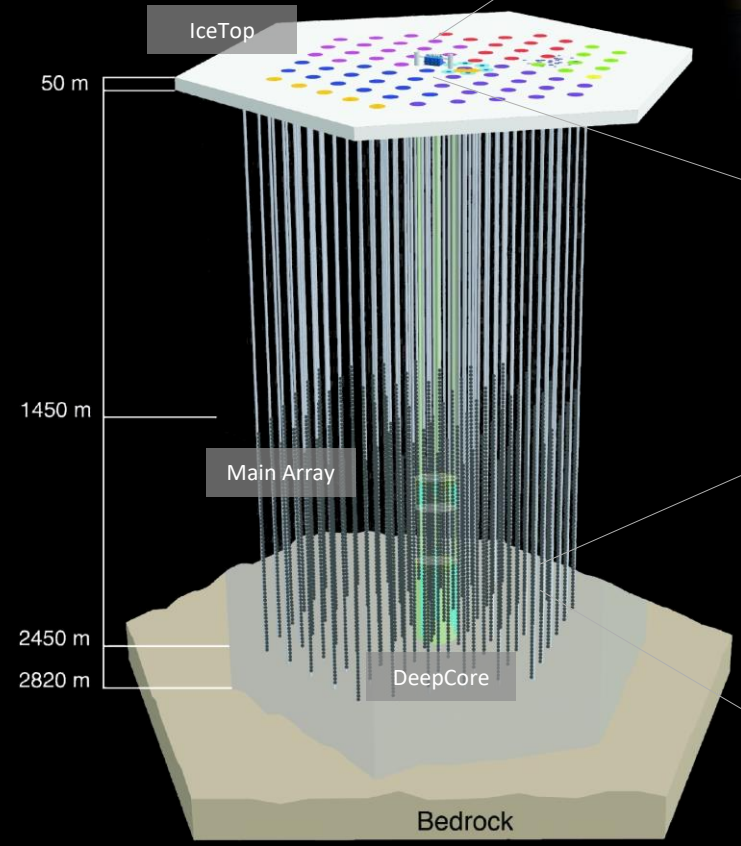
IceCube Neutrino Observatory

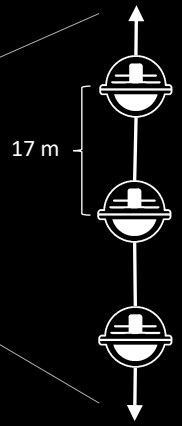


IceCube Laboratory

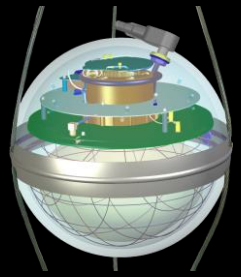


Amundsen-Scott South Pole Station, Antarctica



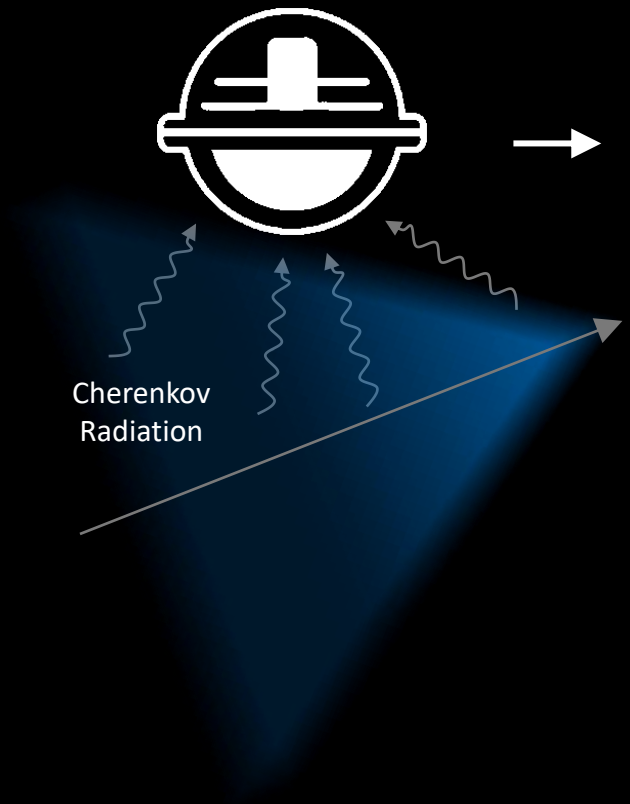


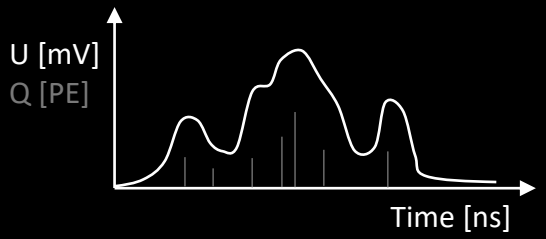
86 Strings:
78 Main Array
8 DeepCore



5160 Digital Optical Modules (DOMs)

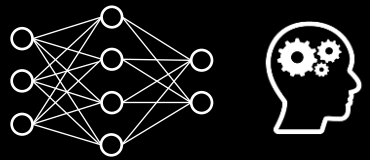
Detection Mechanism





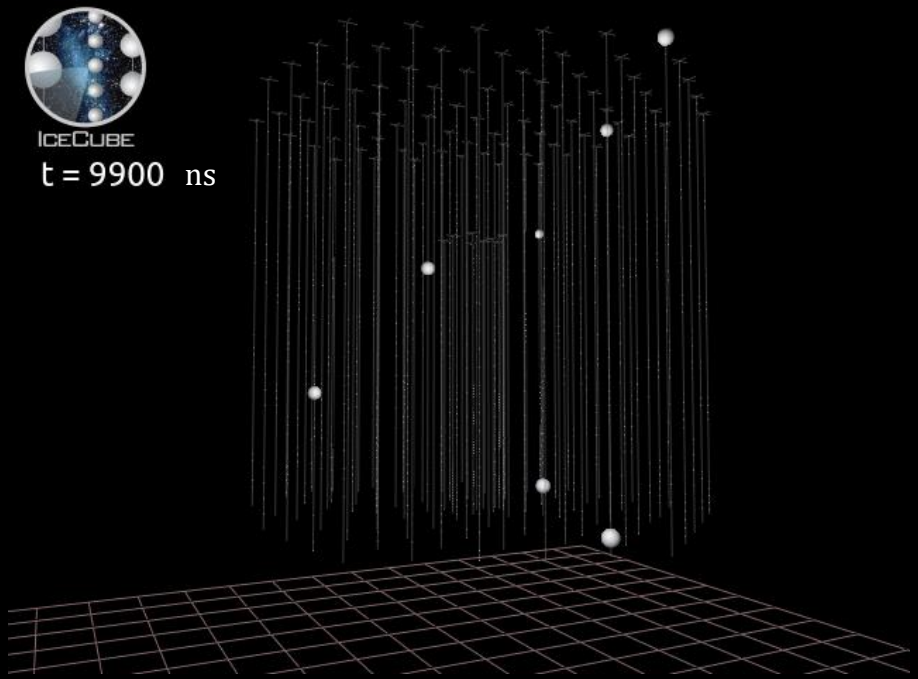
Pulse Series: (t_i, q_i)

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

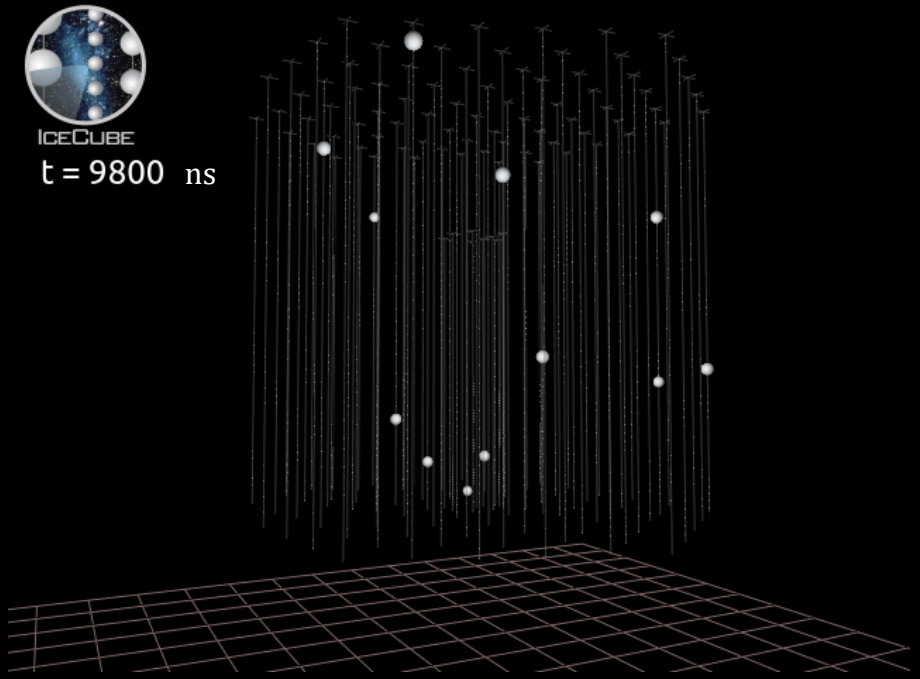


Event Topologies

Track Event



Cascade Event



① **Event Classification**
Topology? Neutrino?

② **Event Reconstruction**
Direction? Energy? Vertex?

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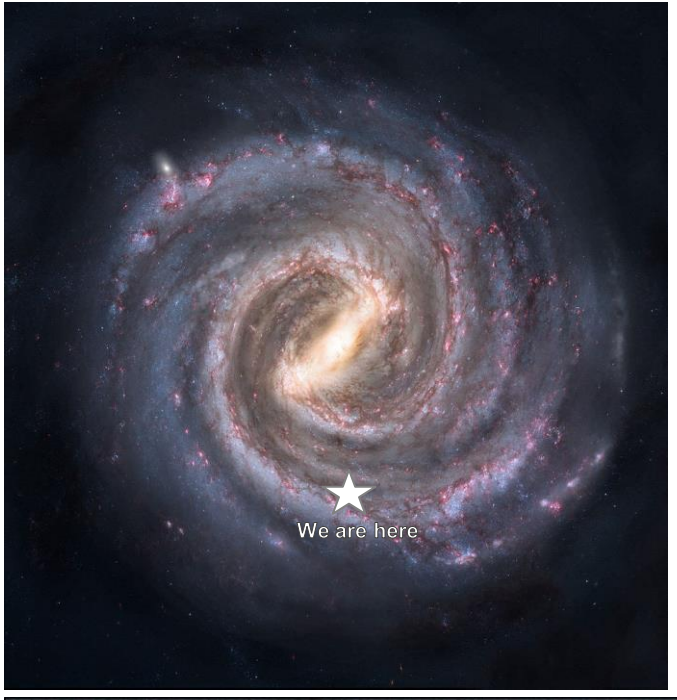
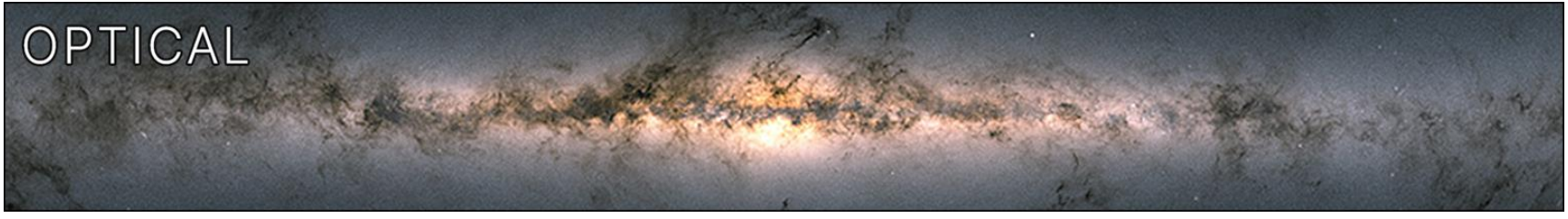
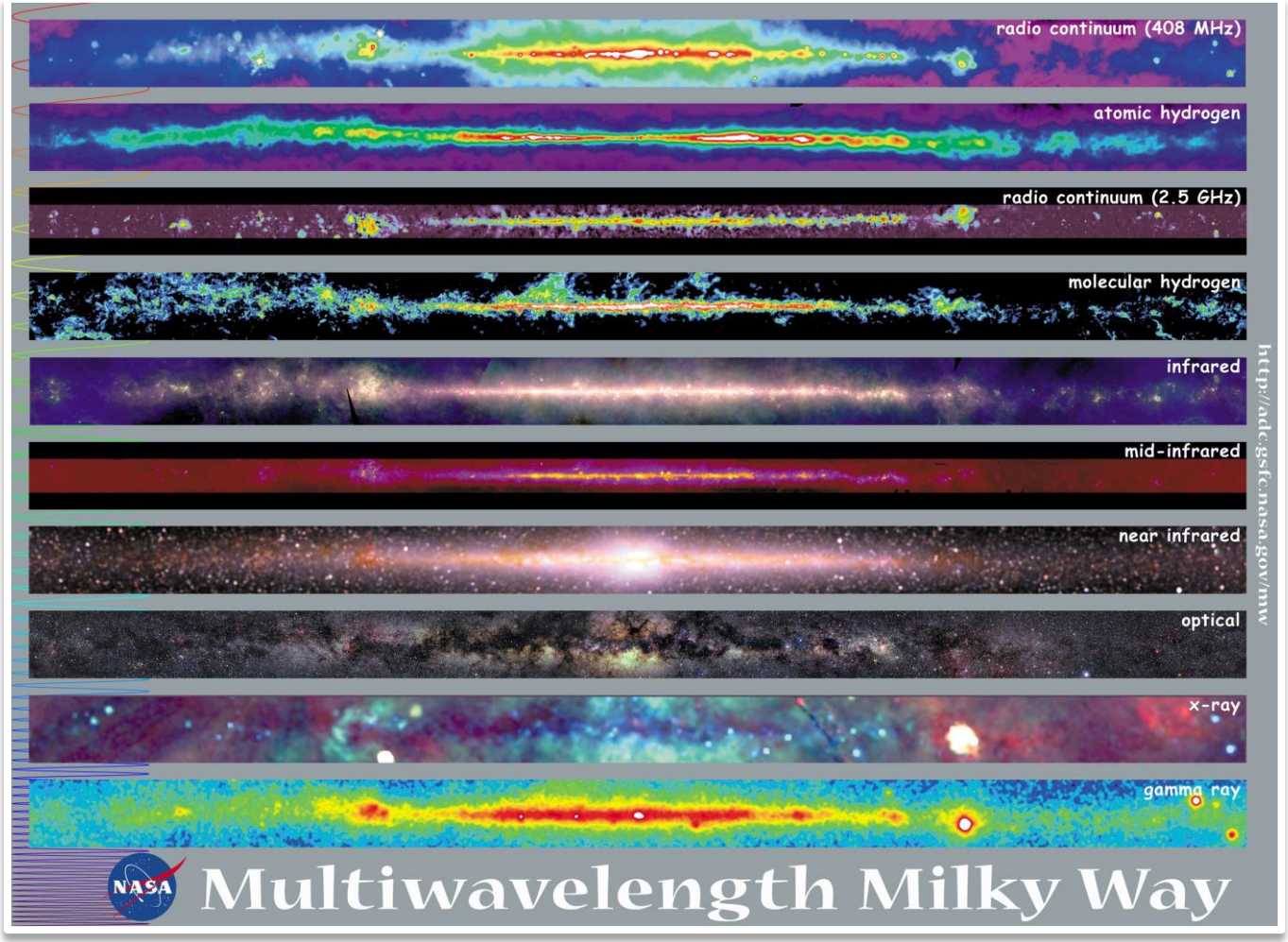
The plane of the Milky Way

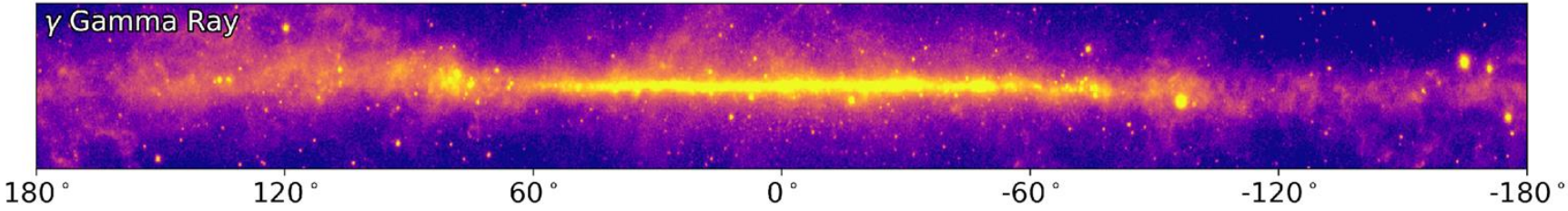




The Multiwavelength Milky Way

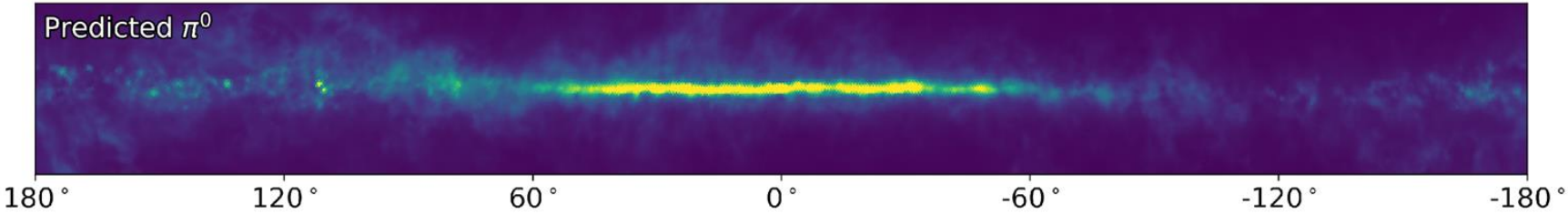


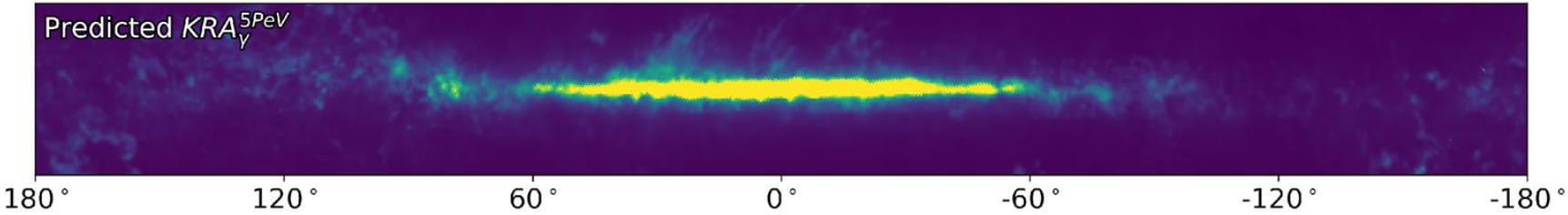
Models of Diffuse Neutrino Emission in the Galactic Plane



$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$$





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.

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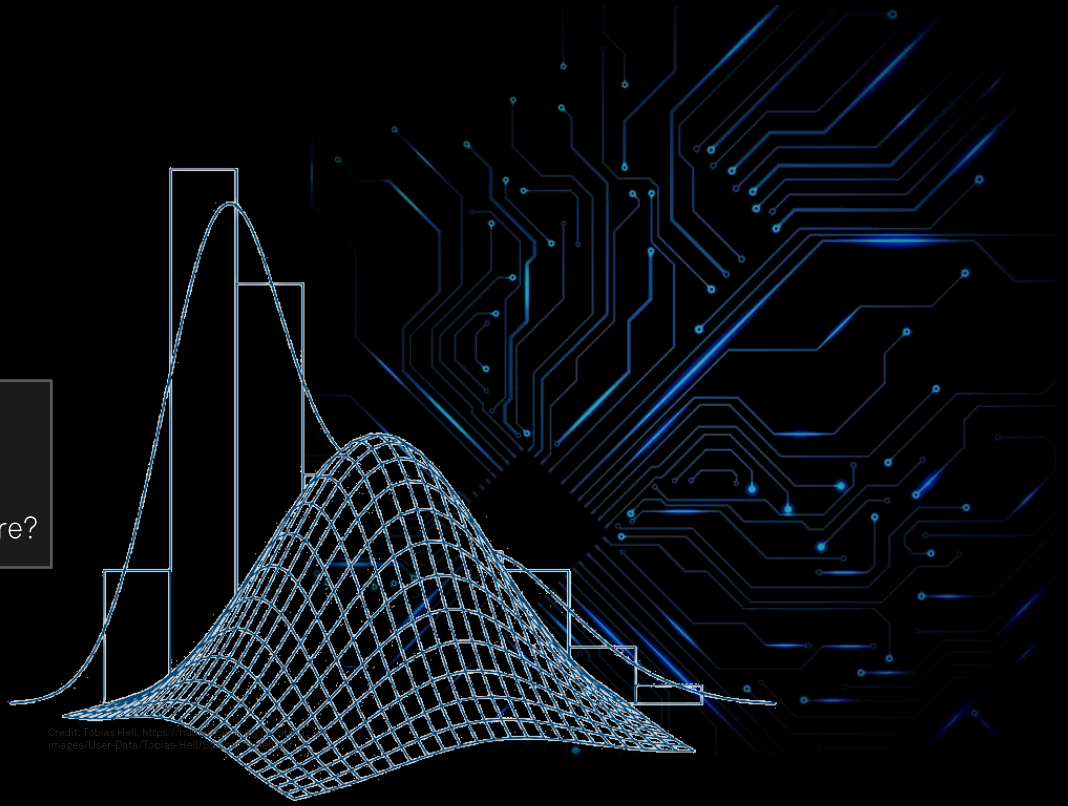


Neutrino Source Searches

Unbinned likelihood:

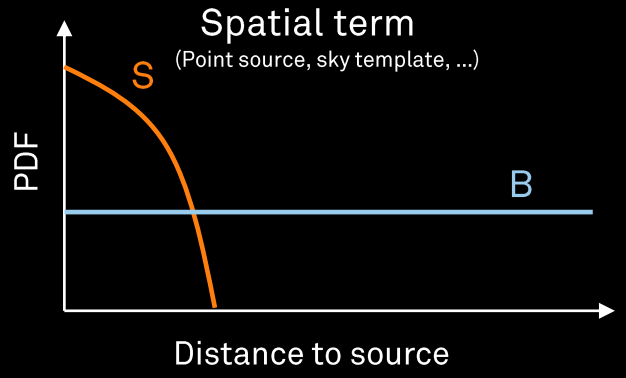
$$\mathcal{L} = \prod_i^N \left[\frac{n_s}{N} \cdot \boxed{S_i} + \left(1 - \frac{n_s}{N}\right) \cdot \boxed{B_i} \right]$$

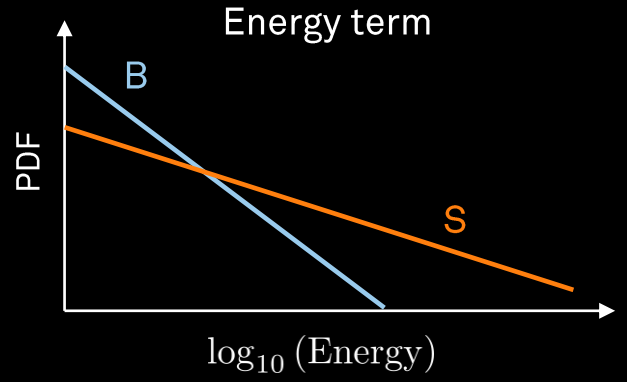
Signal
(Modeled by MC)

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:

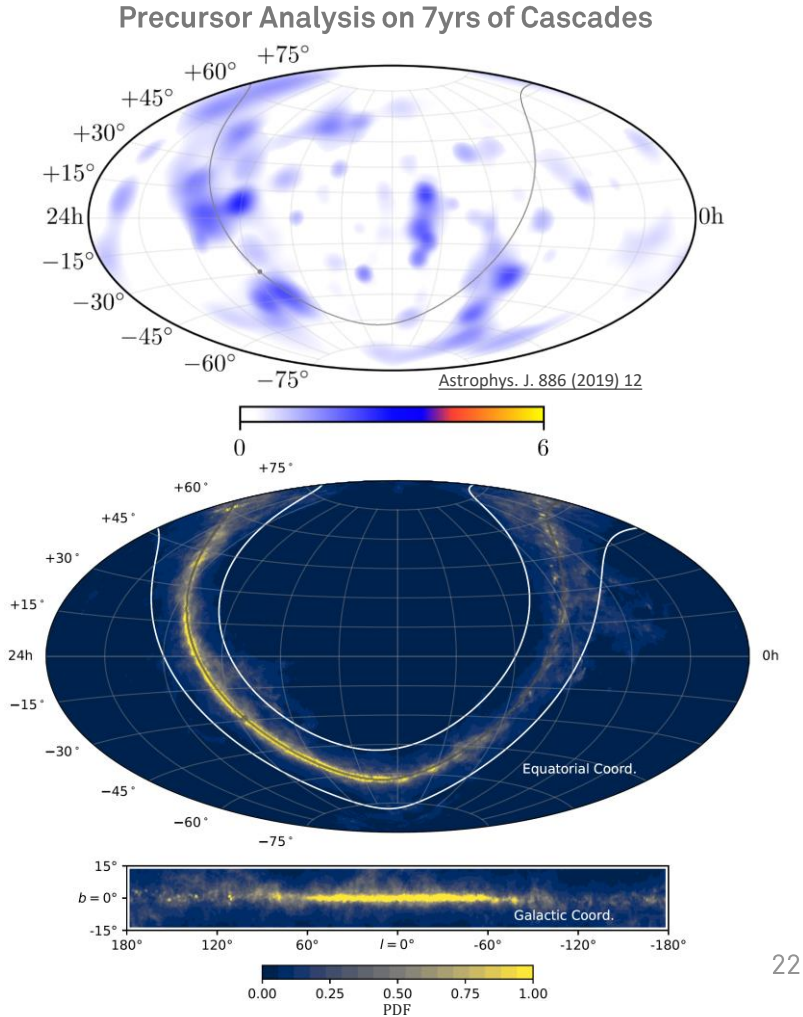
- Perform a point source search at every point in the sky
- Large trial factor due to high number of points tested

Stacked search

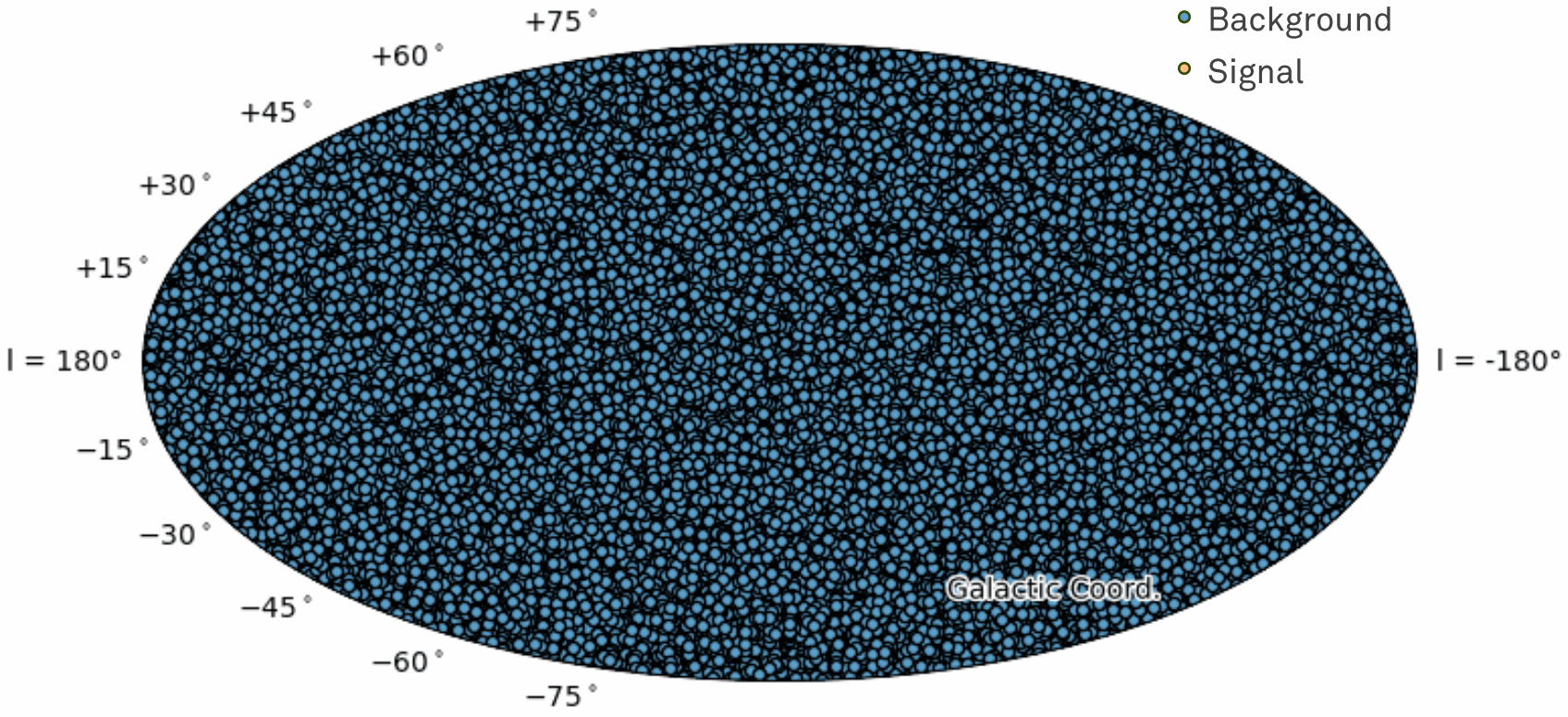
- Stack multiple point-like sources (with similar properties) “on top of” each other

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

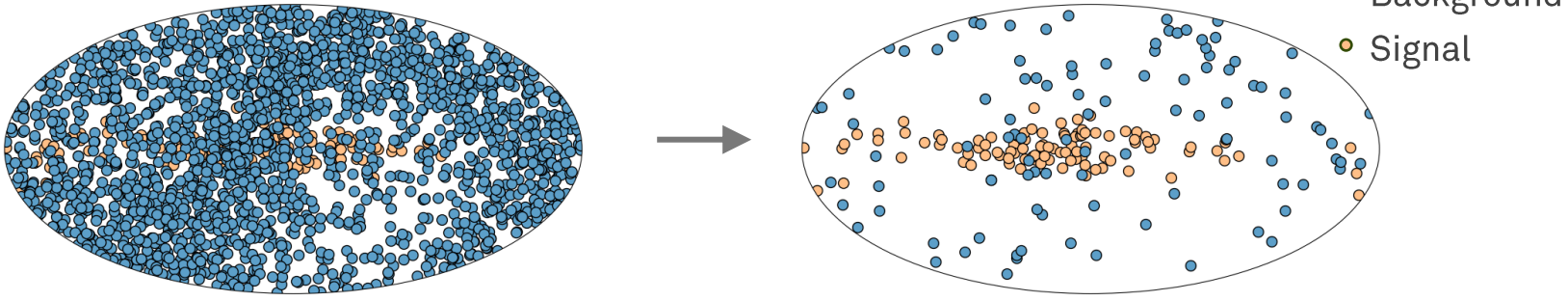


Challenges of Neutrino Source Searches

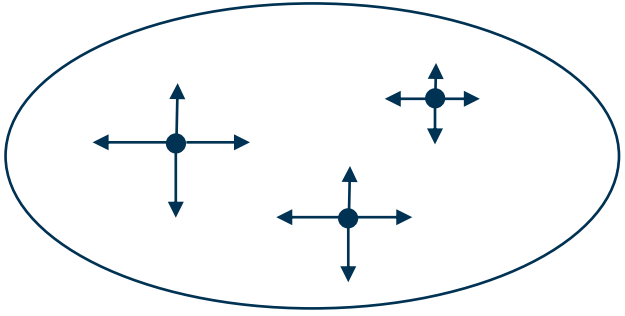


Combat Challenges with Machine Learning

- Event Selection



- Event Reconstruction



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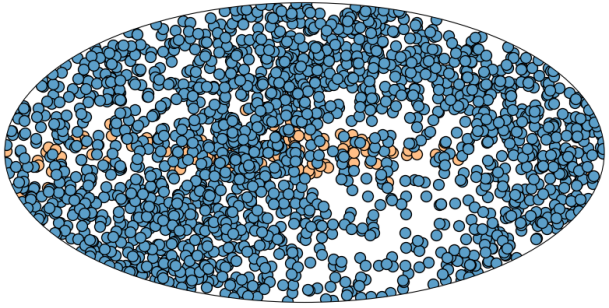

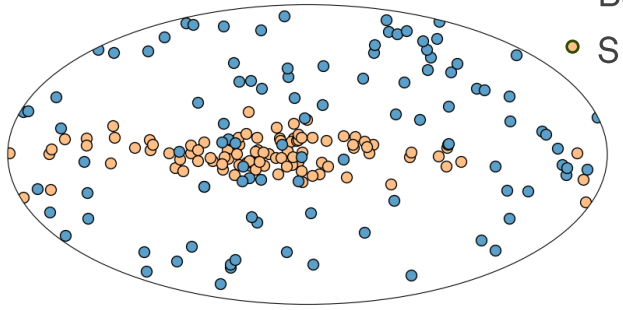

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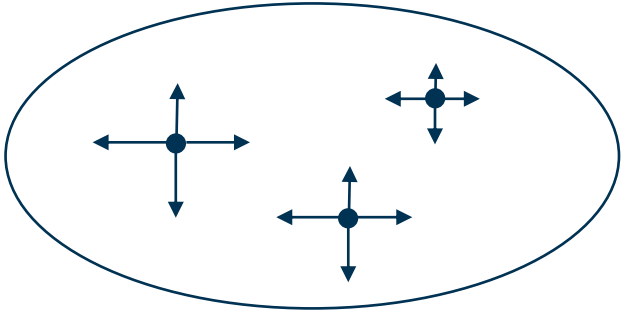


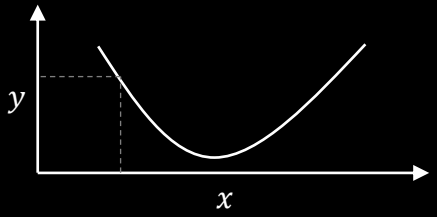
Utilize deep learning –
a field of Artificial Intelligence (AI)

Deep Learning (DL) in a Nutshell

1. DL performs a mapping from inputs to outputs

$$f : I \rightarrow O$$

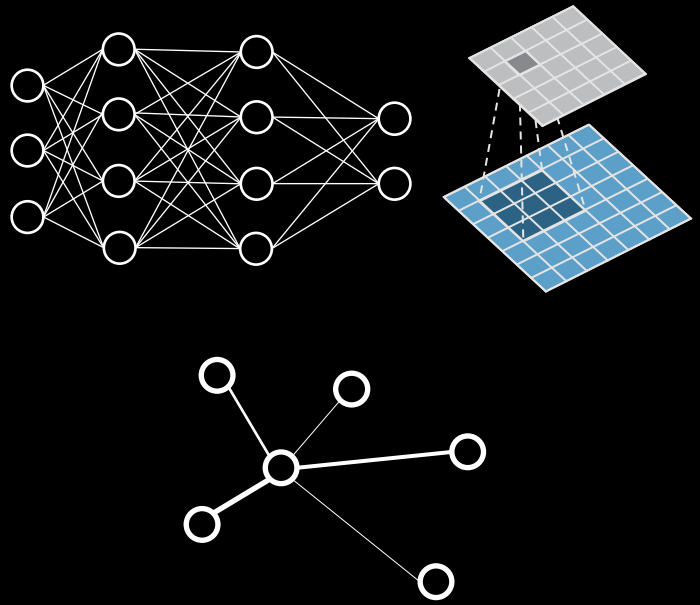
Input I	Output O
$x = 3$	$y = 12$



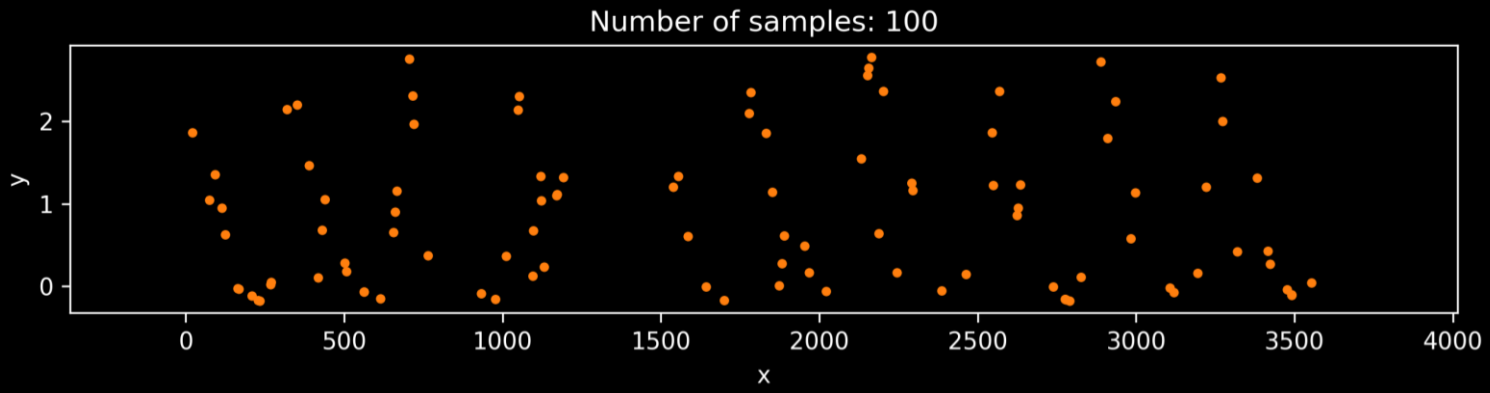
Can you explain deep learning in one sentence?

Deep learning is a subset of machine learning that uses artificial neural networks to model and understand complex patterns and relationships in data.

2. Different architectures utilize different symmetries and domain knowledge



Utilizing Domain Knowledge: Periodicity



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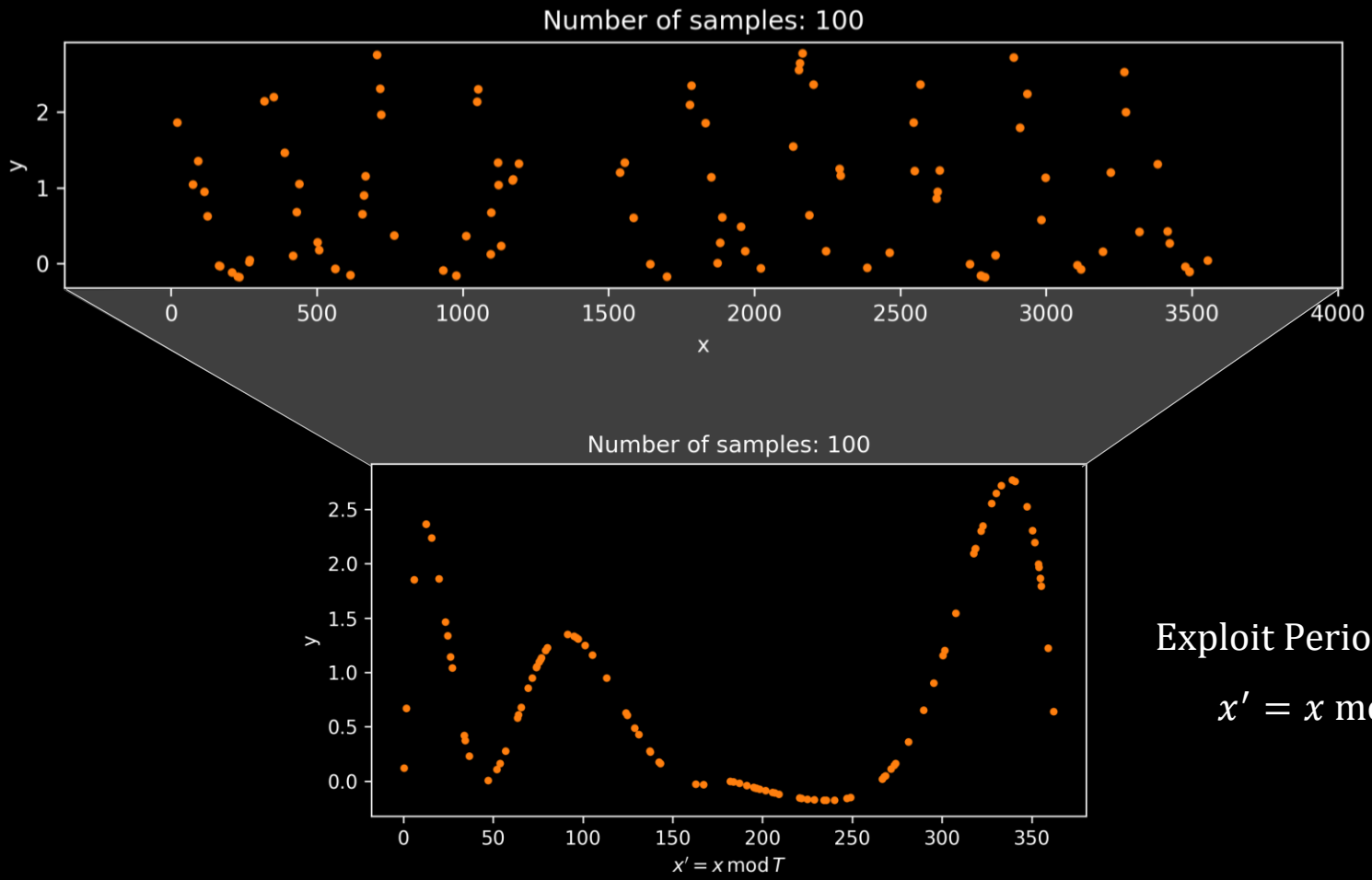
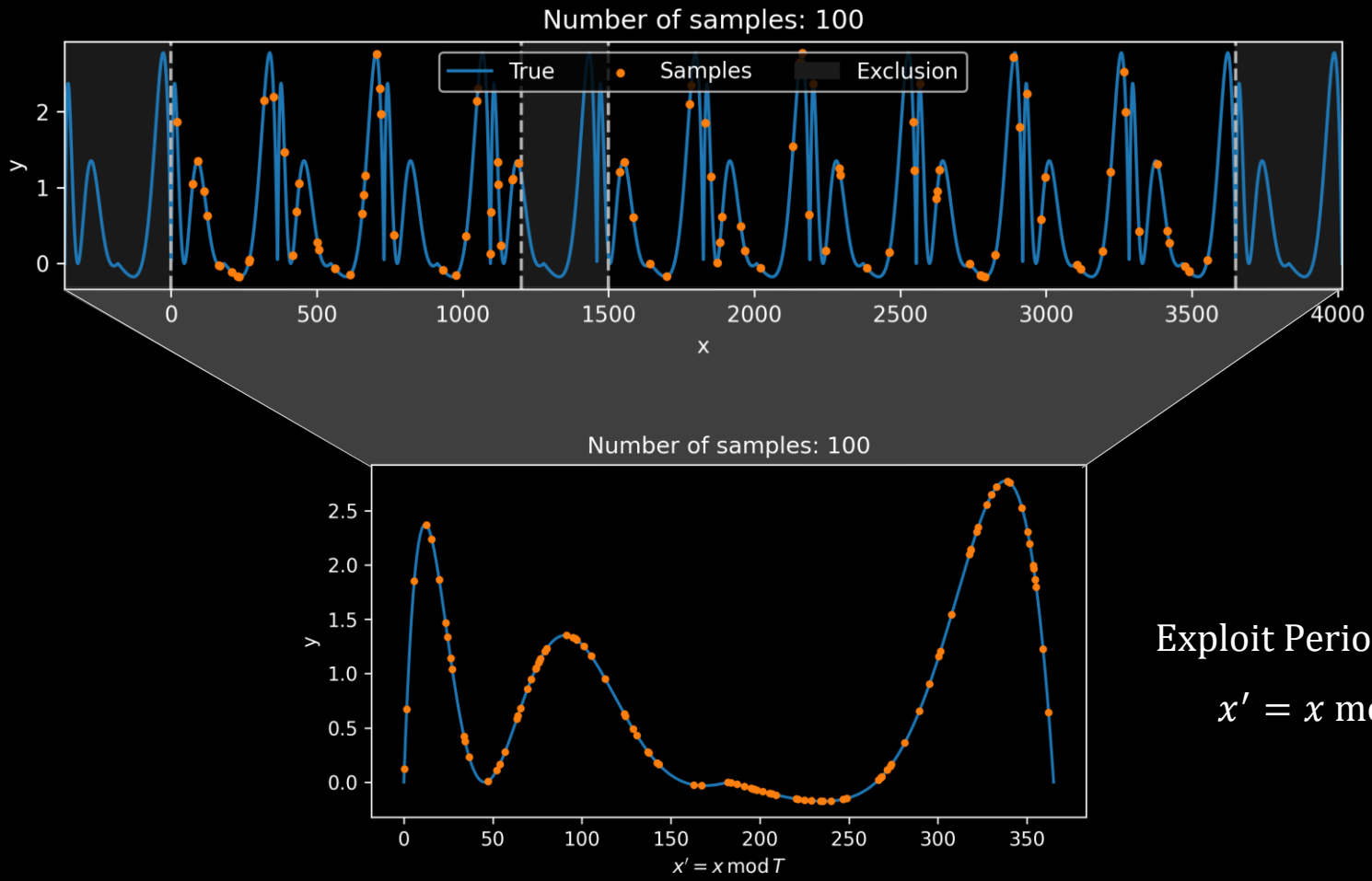


Exploit Periodicity:

$$x' = x \bmod T$$

Utilizing Domain Knowledge: Periodicity



Exploit Periodicity:

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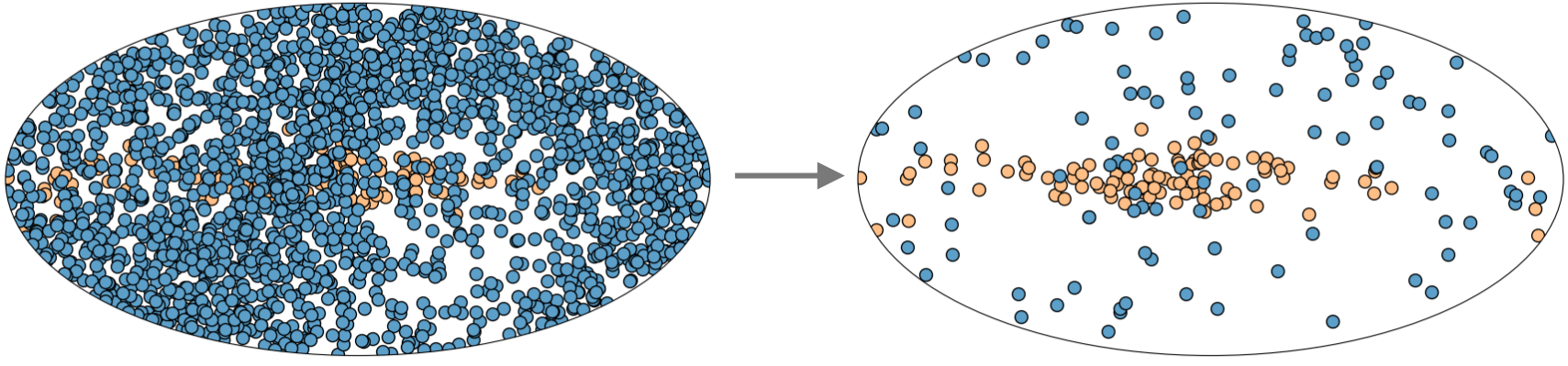
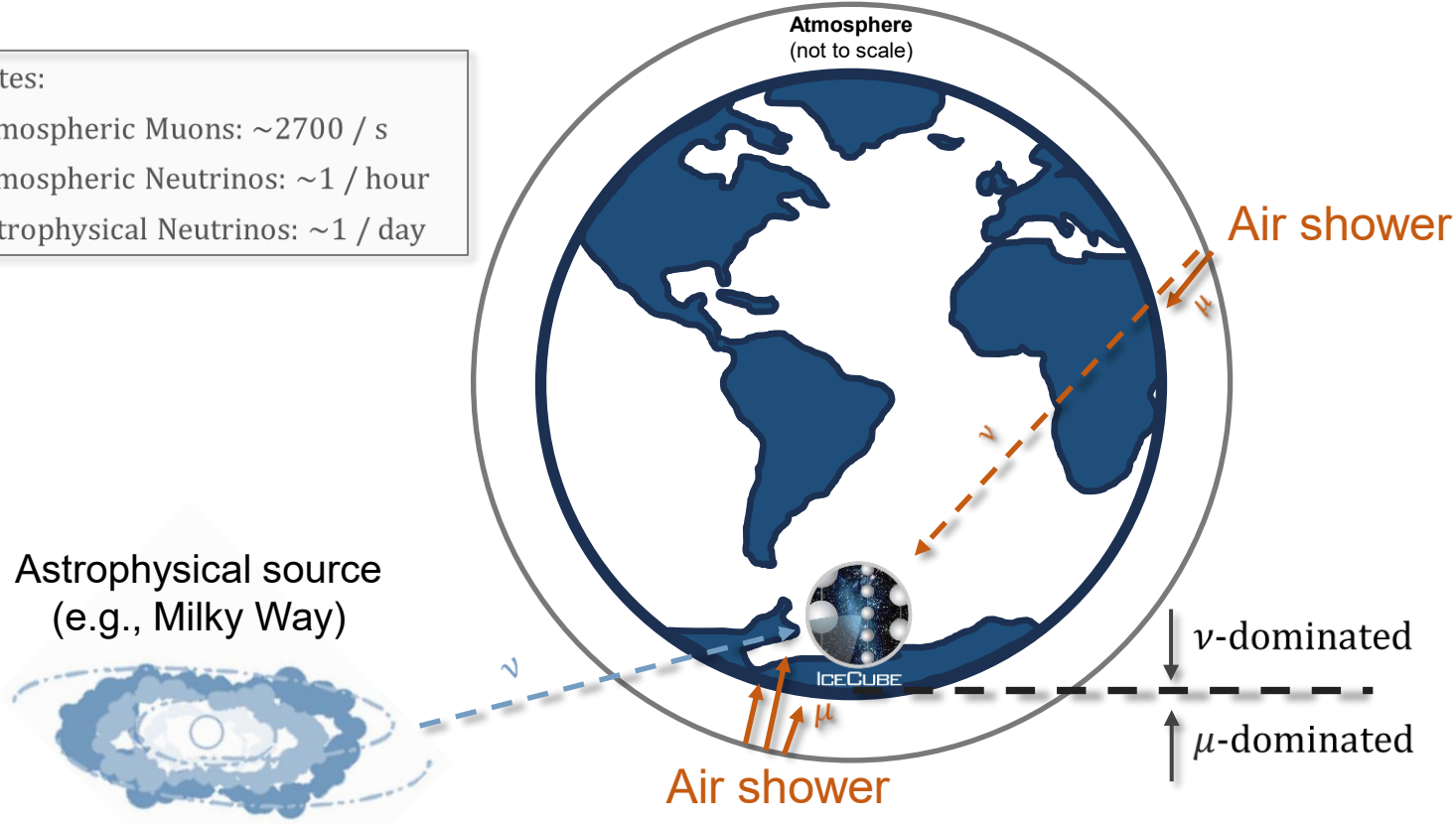
Event Selection



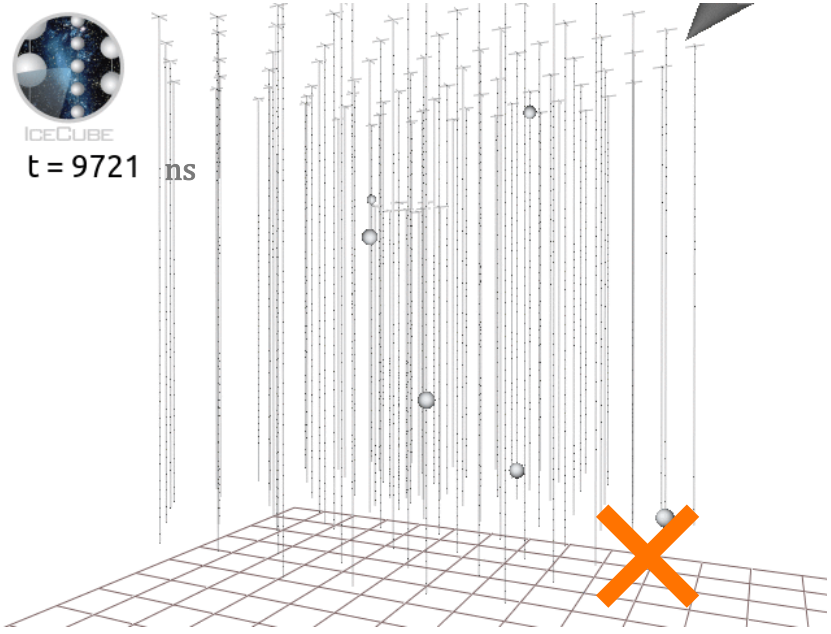
Selection of Astrophysical Neutrinos

Rates:
Atmospheric Muons: ~2700 / s
Atmospheric Neutrinos: ~1 / hour
Astrophysical Neutrinos: ~1 / day

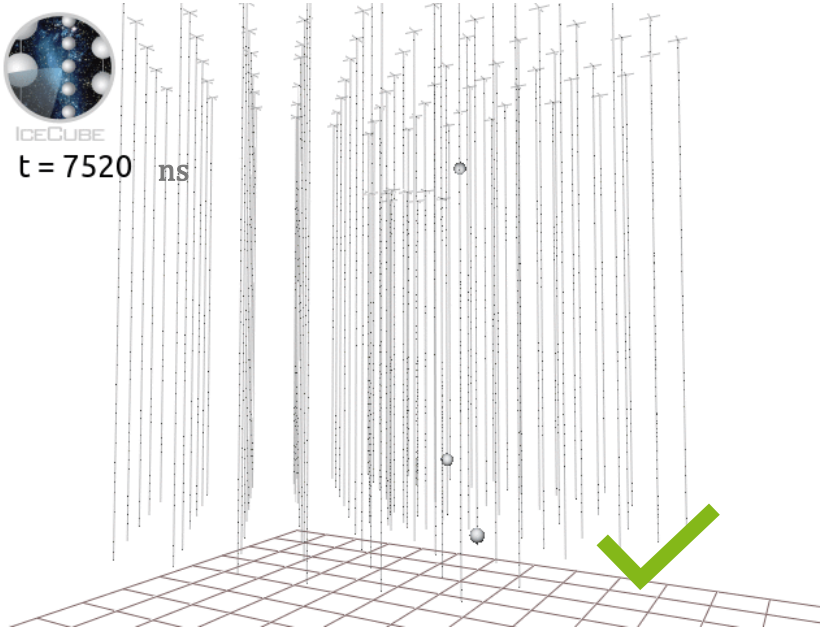


Selection of Astrophysical Neutrinos

Entering μ



Cascade Event



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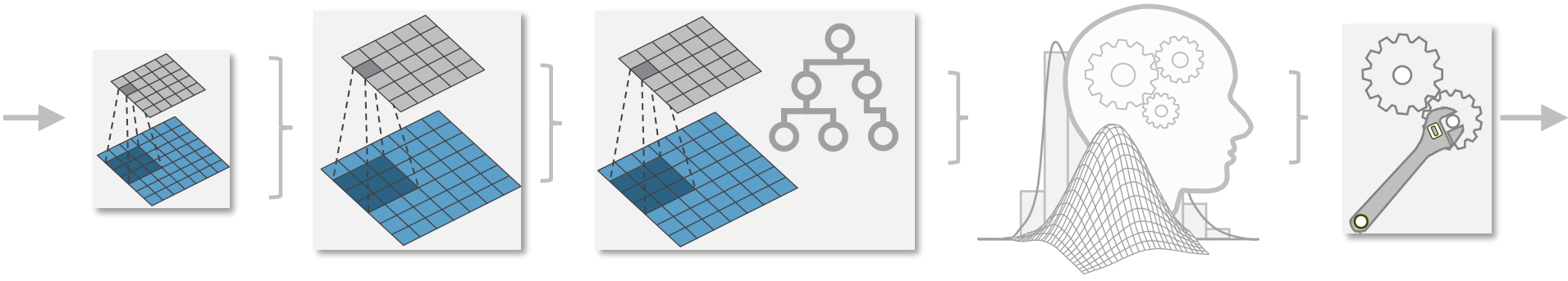
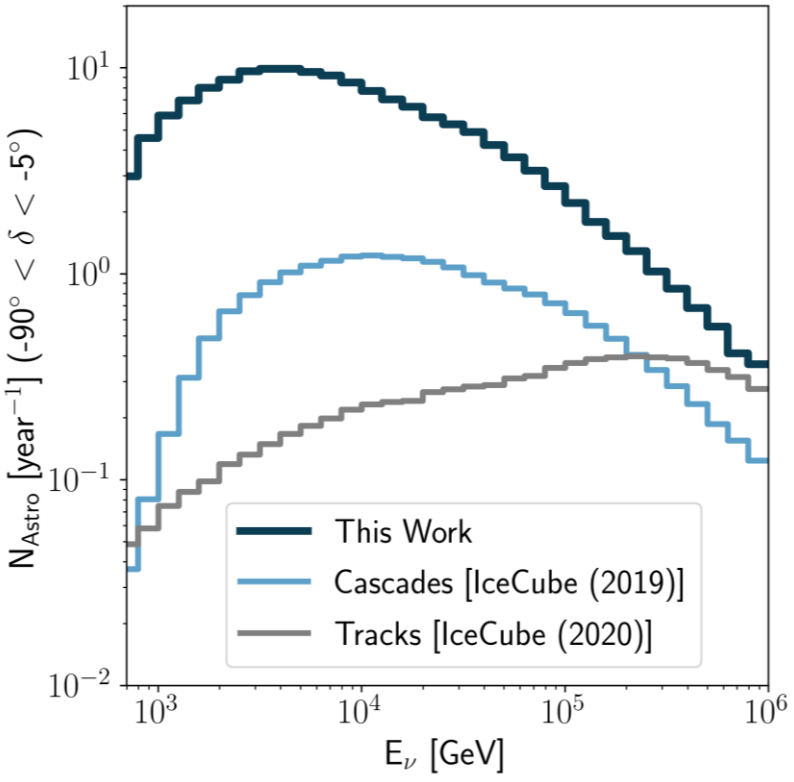


~2700 / s ~2 / min ~17 / day

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

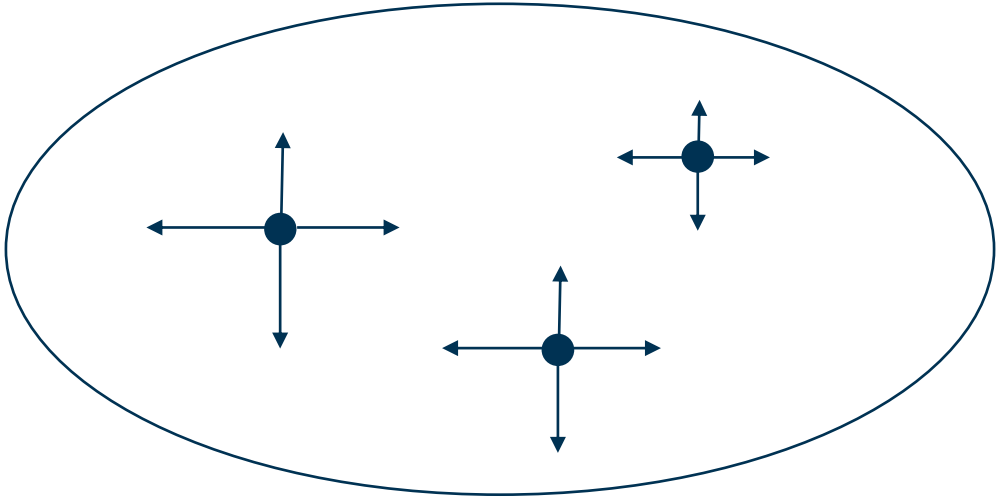
Selection of Astrophysical Neutrinos



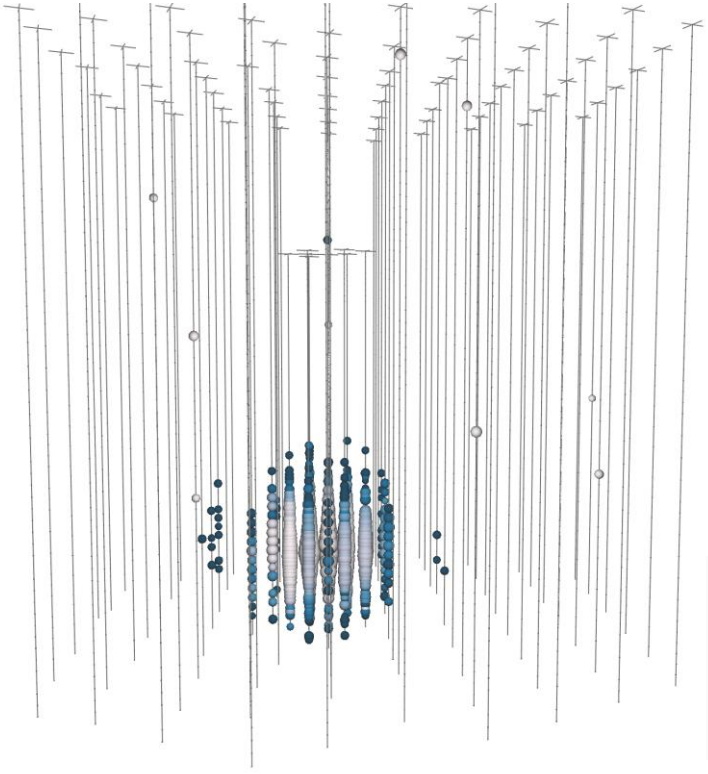
Event selection:

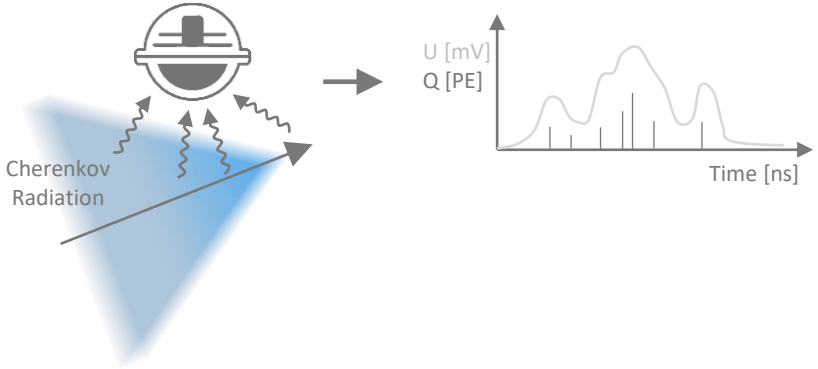
- Background reduced by almost 8 orders of magnitude
- 30 times as many events as precursor analysis

Event Reconstruction



Reconstructing Event Properties

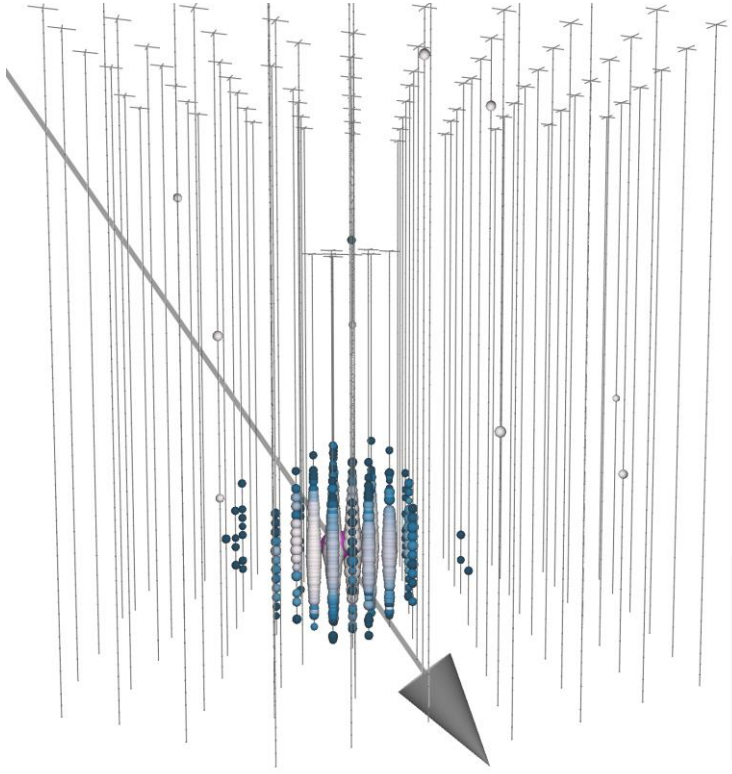


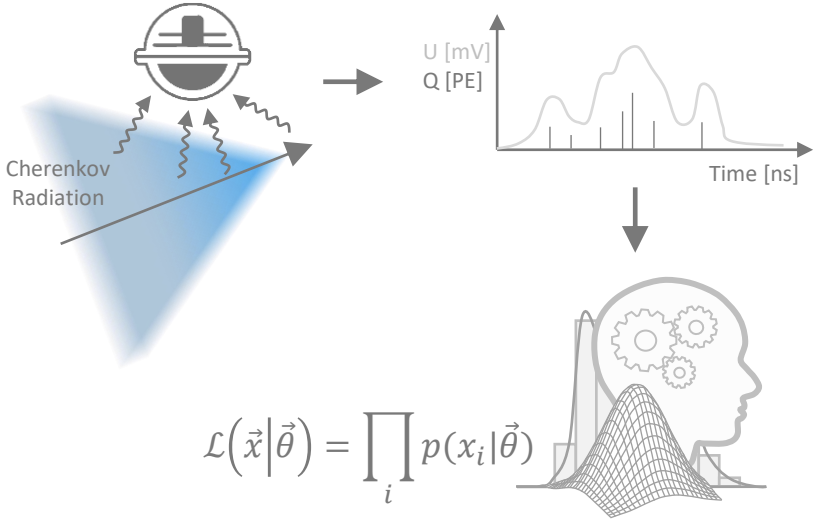


Event reconstruction:

- 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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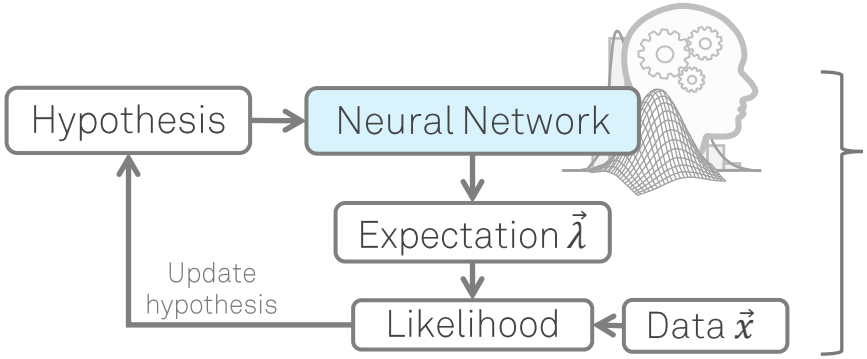
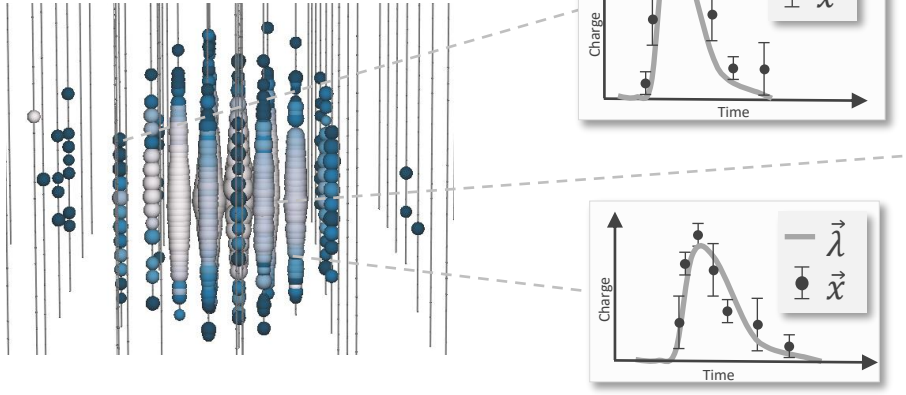
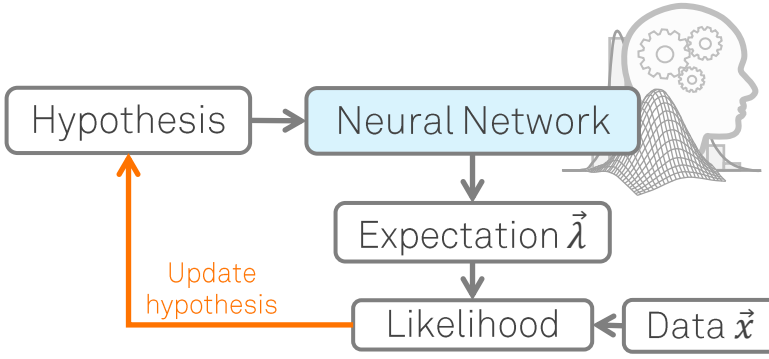


Hybrid reconstruction method:

- 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**



Reconstructing Event Properties



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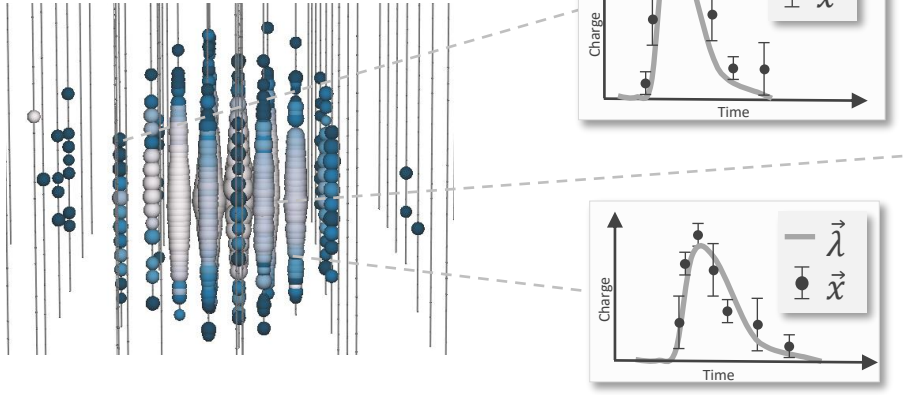
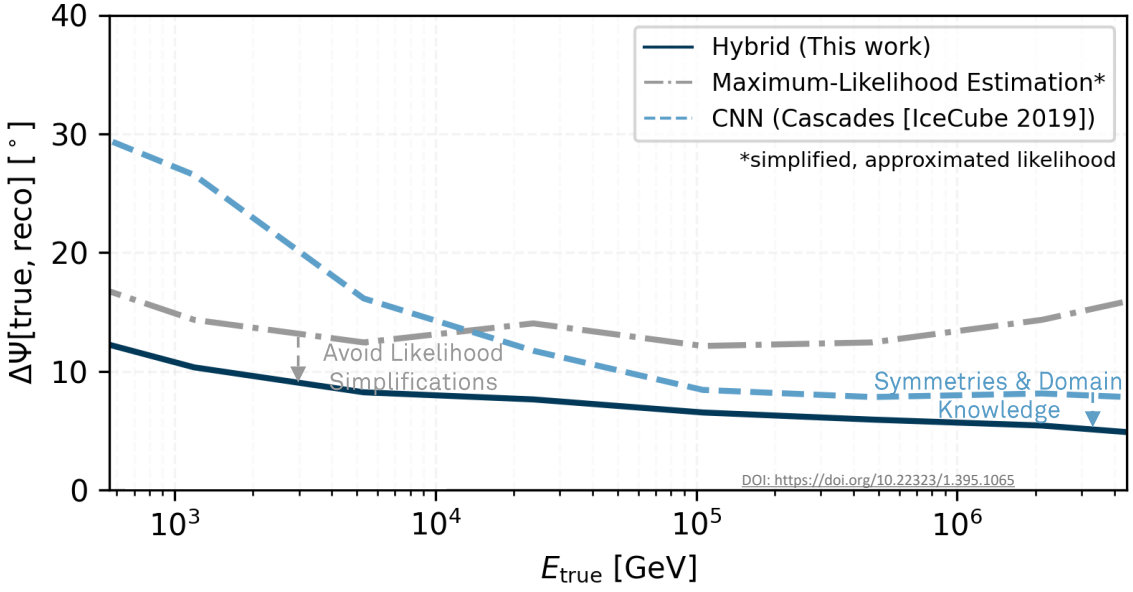


Improvements by novel methods



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

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

Search for Galactic Neutrino Emission

- 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”

zoom


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?

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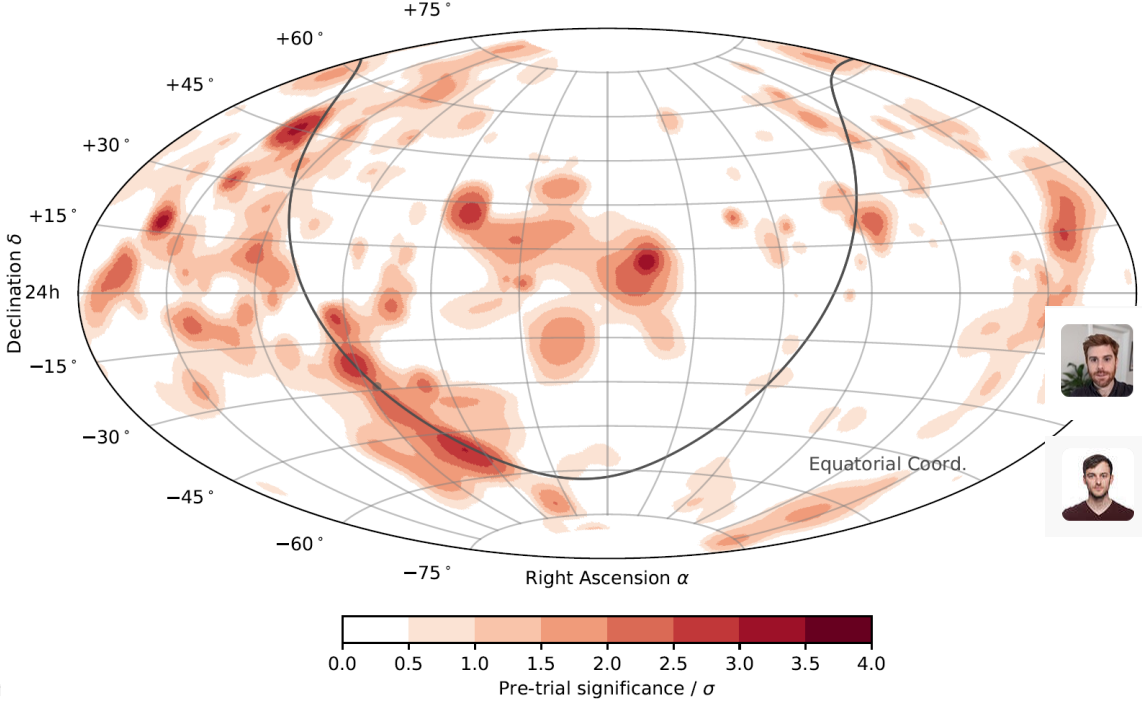

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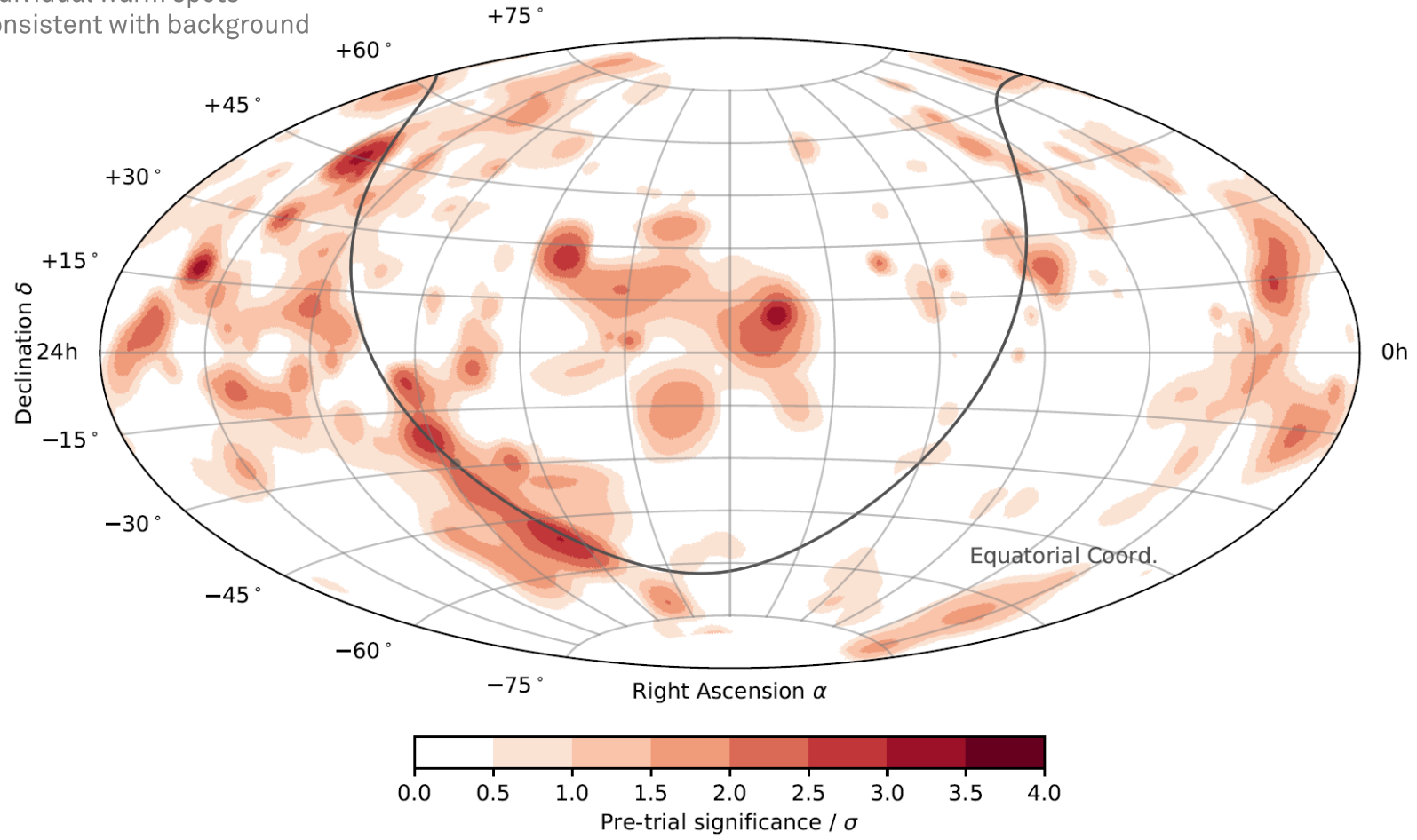
Results from All-Sky Search

Individual warm spots consistent with background



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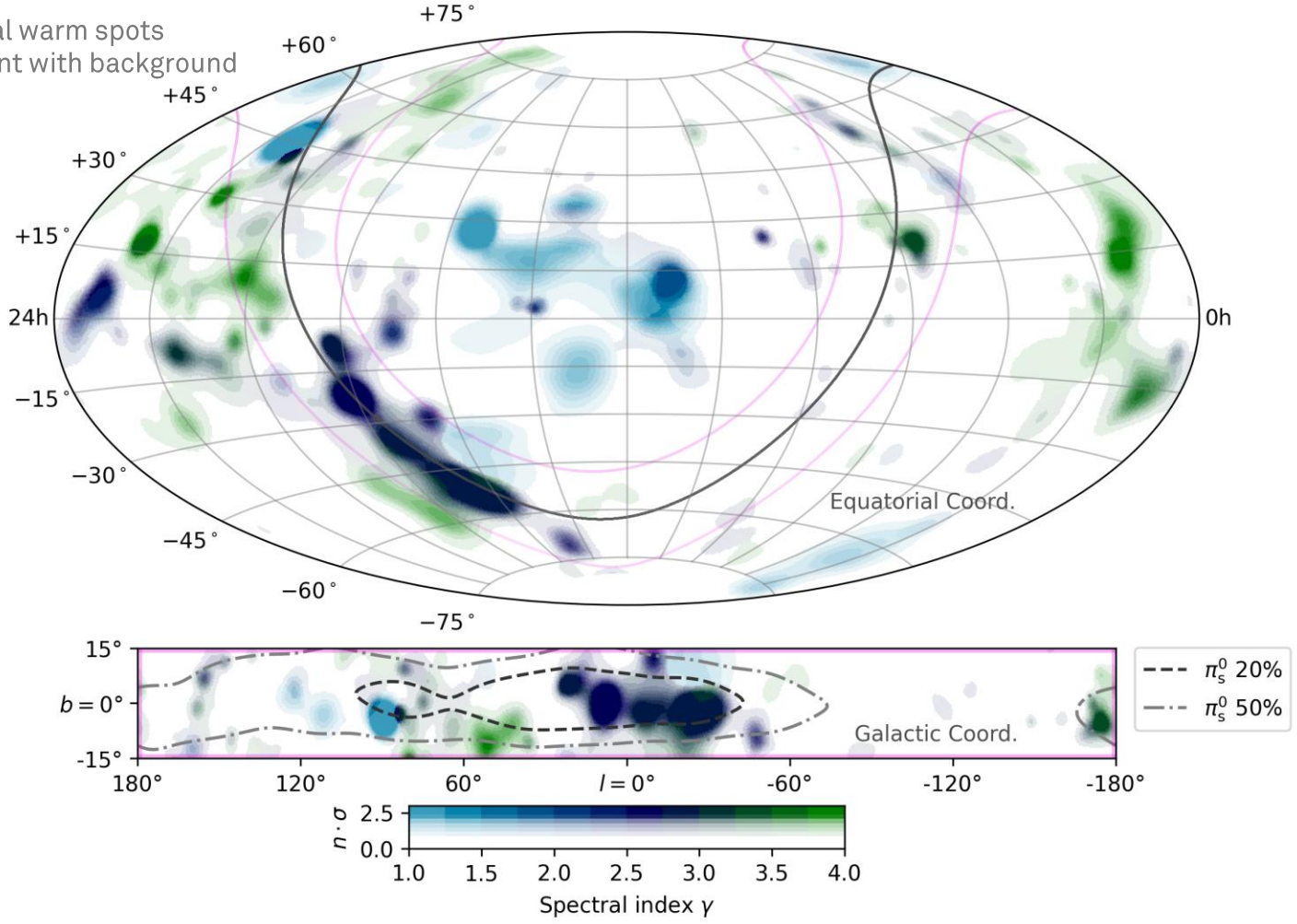


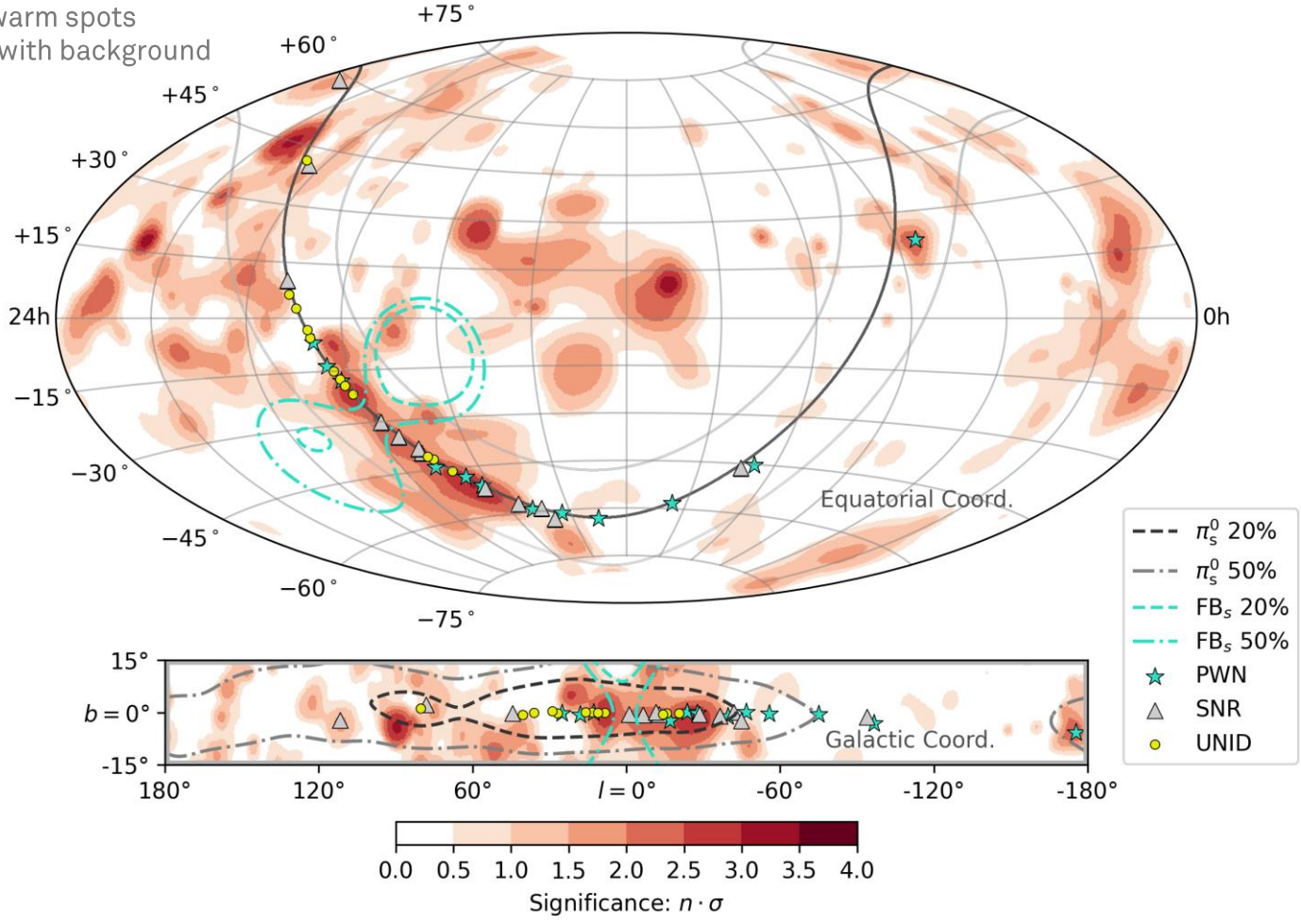
Analysis Results

	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.

Analysis Results

Individual warm spots consistent with background



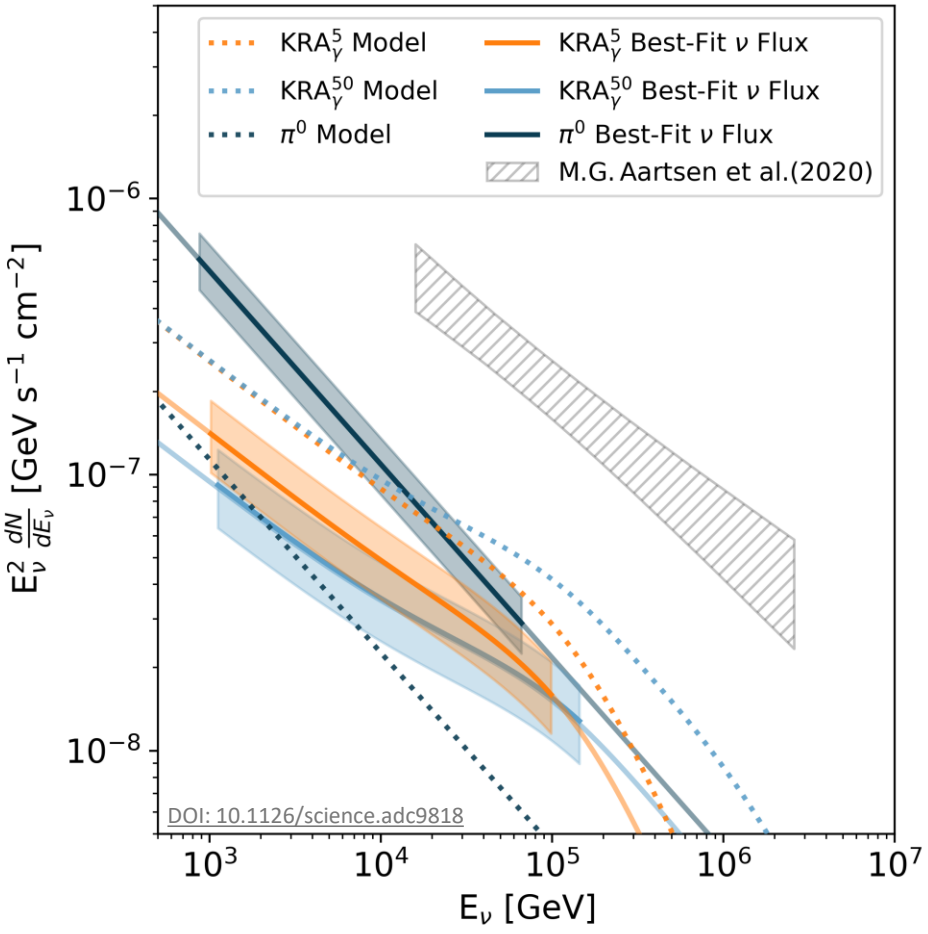
Results from Diffuse Galactic Plane Searches

After trial-correction: 4.5σ

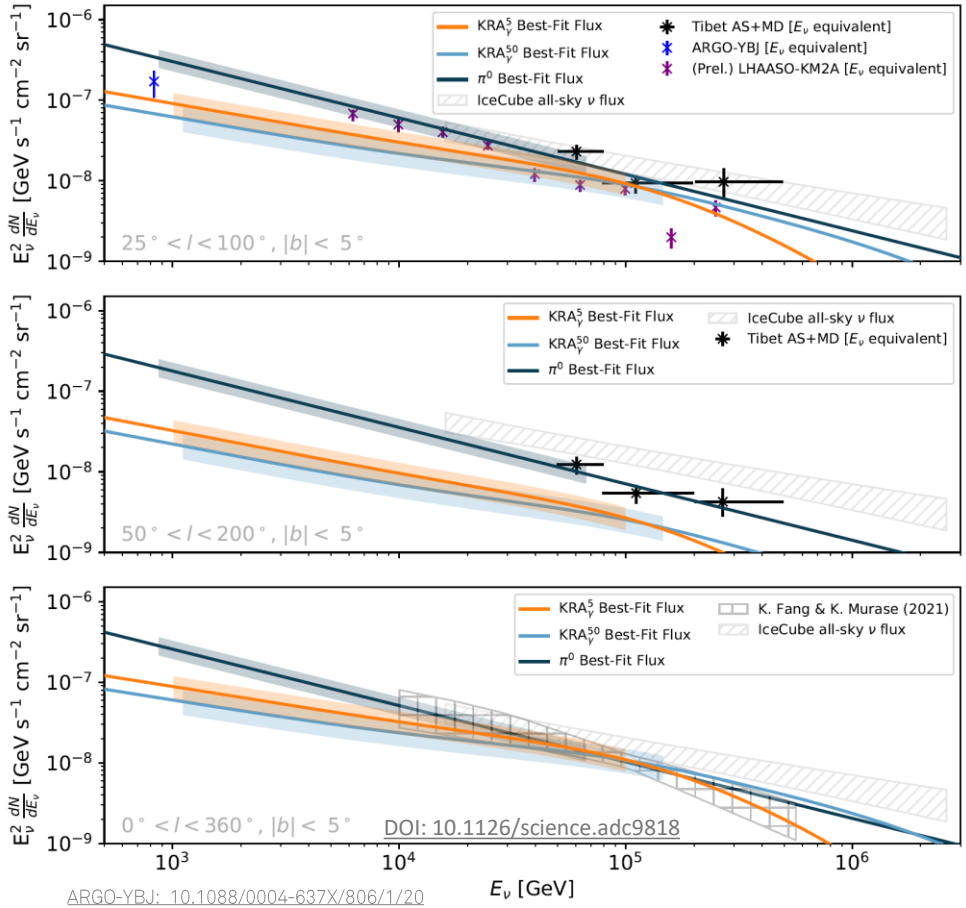
Model	Signal Events	Pre-trial p-value ($N\sigma$)
π^0	748	1.26×10^{-6} (4.71σ)
KRA_γ^5	276	6.13×10^{-6} (4.37σ)
KRA_γ^{50}	211	3.72×10^{-5} (3.96σ)

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
- Note that the analysis only fits the model normalization; spectrum is kept fixed to model prediction

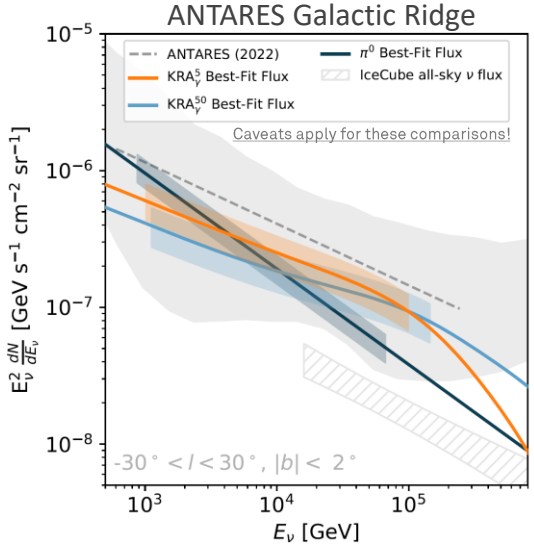


Comparisons to other measurements are challenging



ARGO-YBJ: 10.1088/0004-637X/806/1/20
(Prel.) LHAASO-KM2A: 10.22323/1.395.0859
Tibet AS+MD: 10.1103/PhysRevLett.126.141101

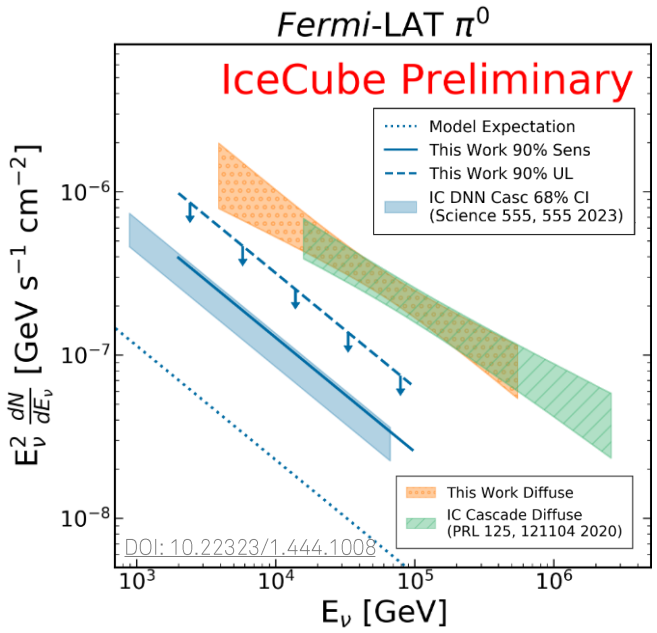
- Conversion of gamma ray measurements assumes pp scenario without attenuation
- Caveats apply for these comparisons!
  - IceCube measurement is over entire sky: separate measurements for individual sky regions are required for comparisons
  - Only normalization is fit for, not spectrum



ANTARES (2022): 10.1016/j.physletb.2023.137951

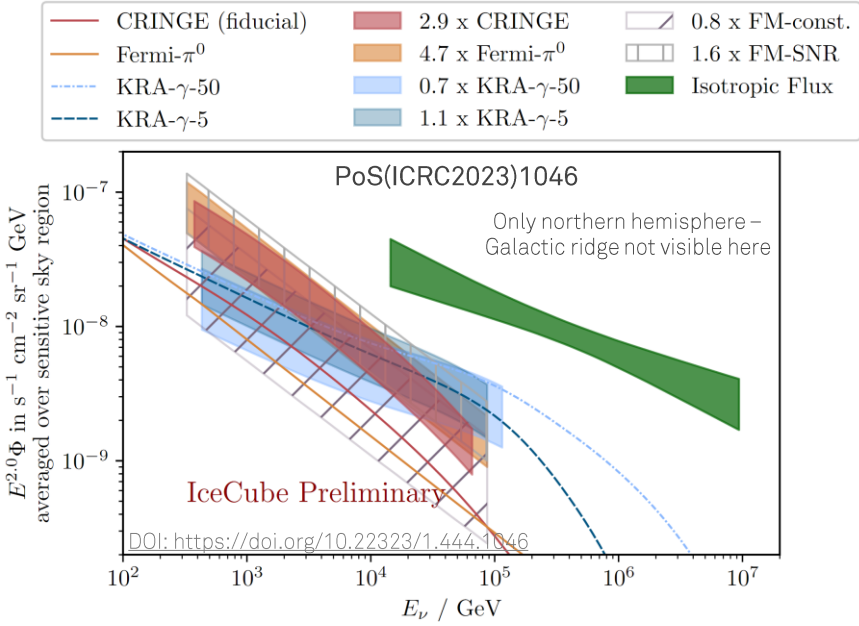
Follow-up Measurements of the GP Neutrino Signal

IceCube starting tracks (1.5σ for GP)[1]



IceCube northern tracks (2.7σ for GP)[2]

CRINGE Model: DOI 10.3847/1538-4357/acc1e2



A future analysis:

- Measure flux in regions along GP in a model independent approach
- Align regions to gamma-ray measurements to better enable comparisons

[1] DOI: 10.22323/1.444.1008 [2] DOI: 10.22323/1.444.1046

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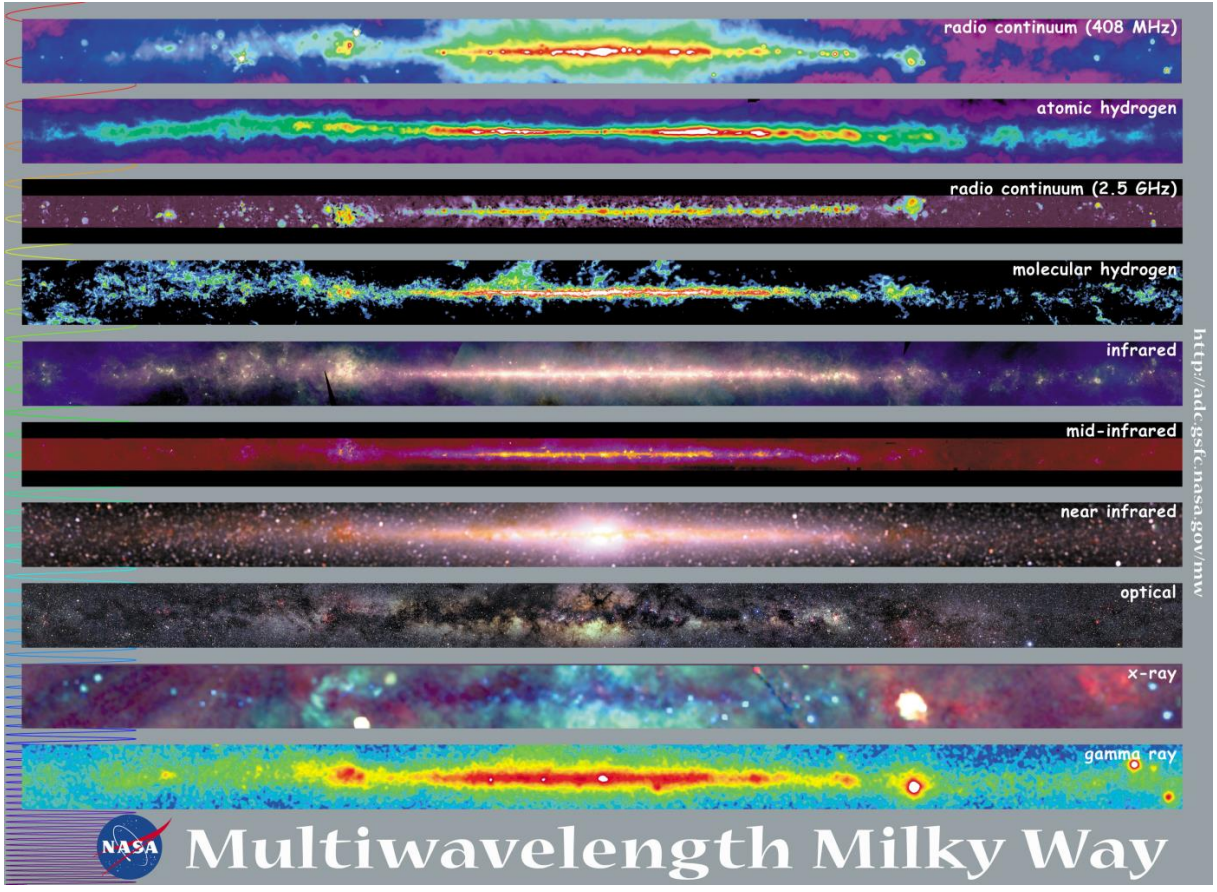
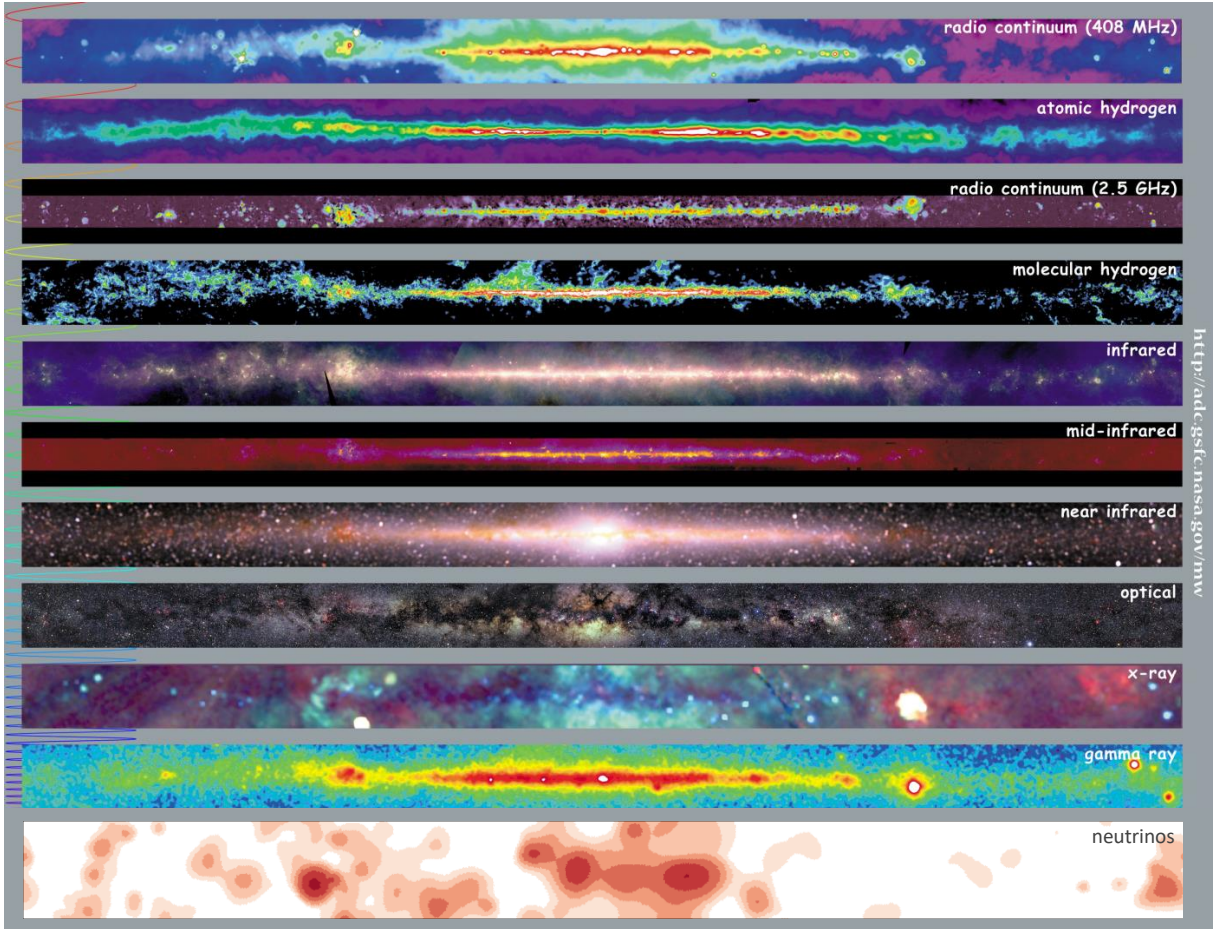


The ~~Multiwavelength~~ Multimessenger Milky Way



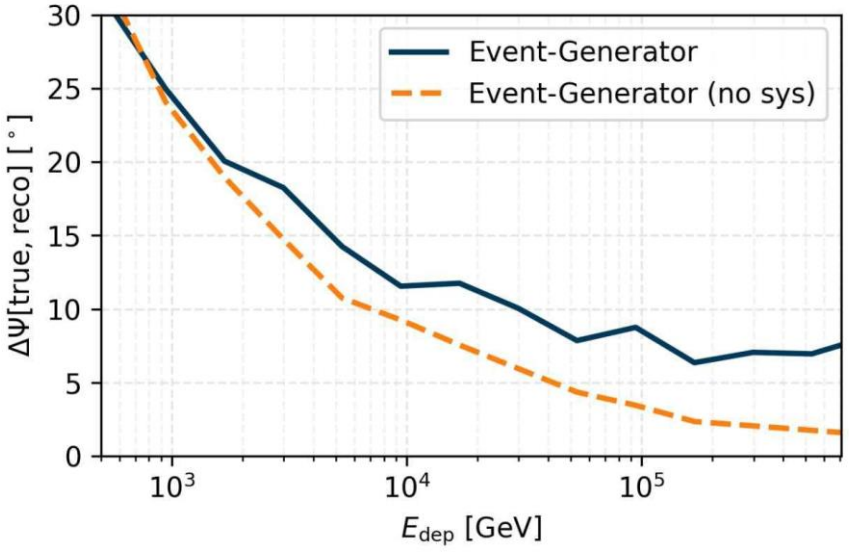
A bright future for Neutrino Astronomy

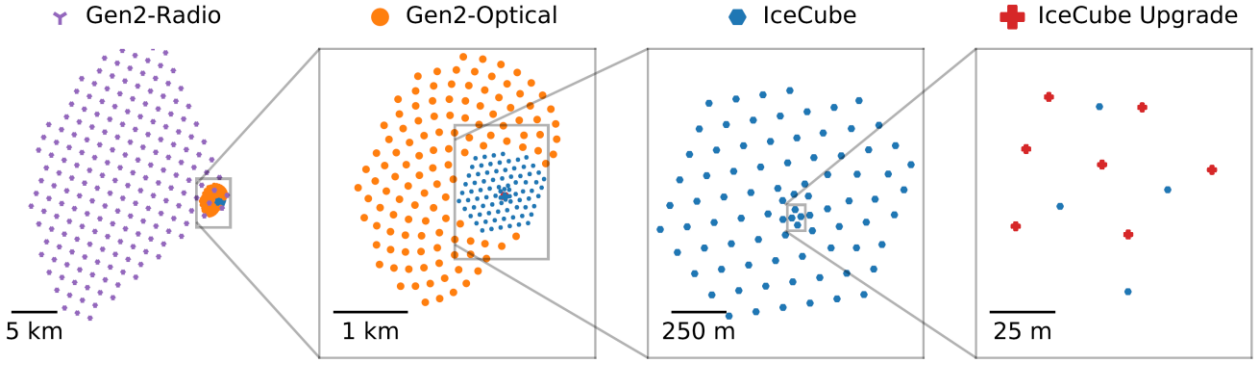
IceCube Extensions

- IceCube Upgrade: low-energy infill + calibration
- IceCube Gen2: high-energy extension

Future Neutrino Telescopes

- Under construction: KM3Net, Baikal GVD
- Site exploration/prototyping: P-ONE, TRIDENT





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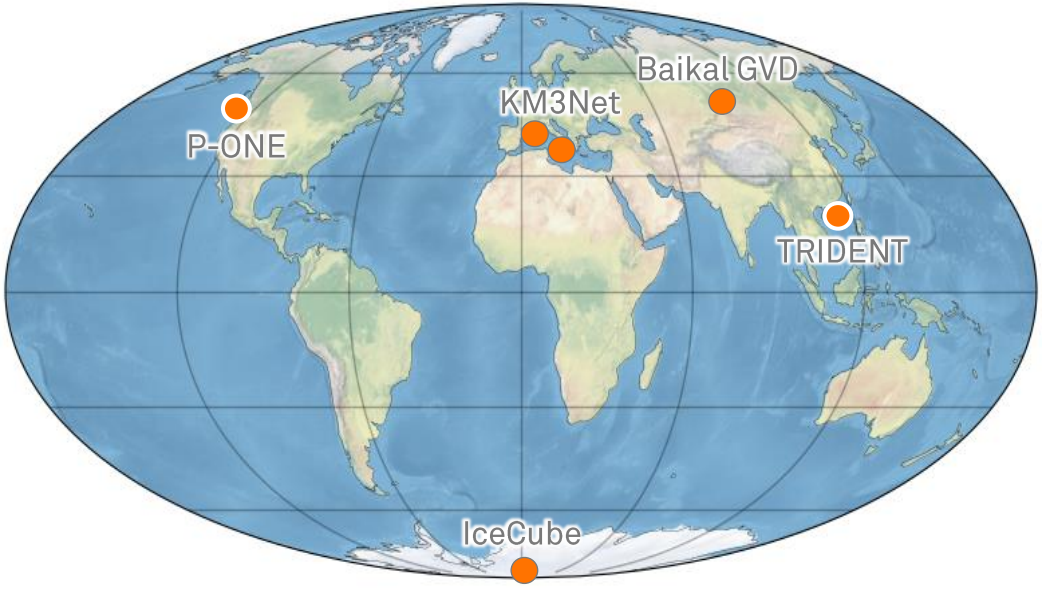
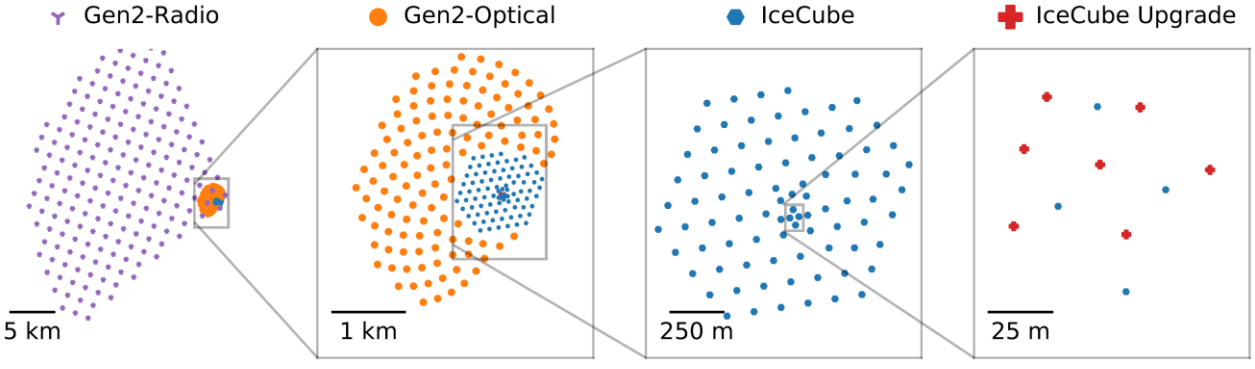




Summary & Outlook

Strong evidence for neutrino emission from the Galactic plane

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

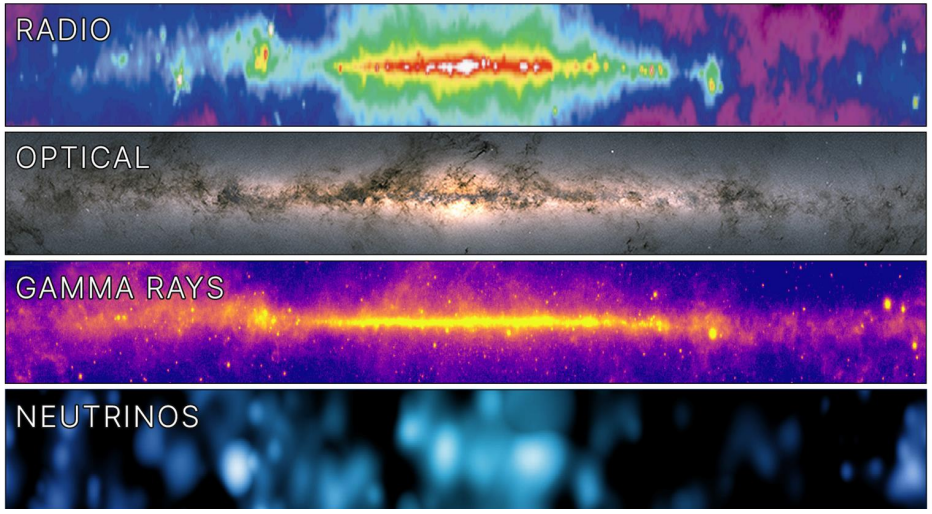
Observation enabled by new tools based on Deep Learning

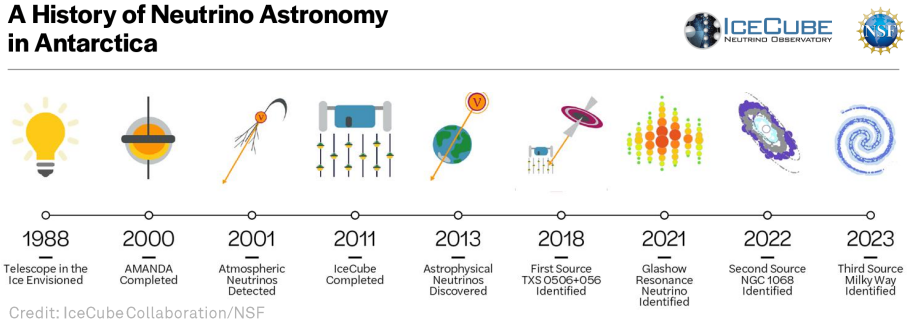
- 30 times as many events than precursor selection
- Improved reconstruction resolution by up to 50%
- Analysis sensitivity improved by a factor of 3

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!





Achieved milestones have picked up in pace in recent years!

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

Thank you!