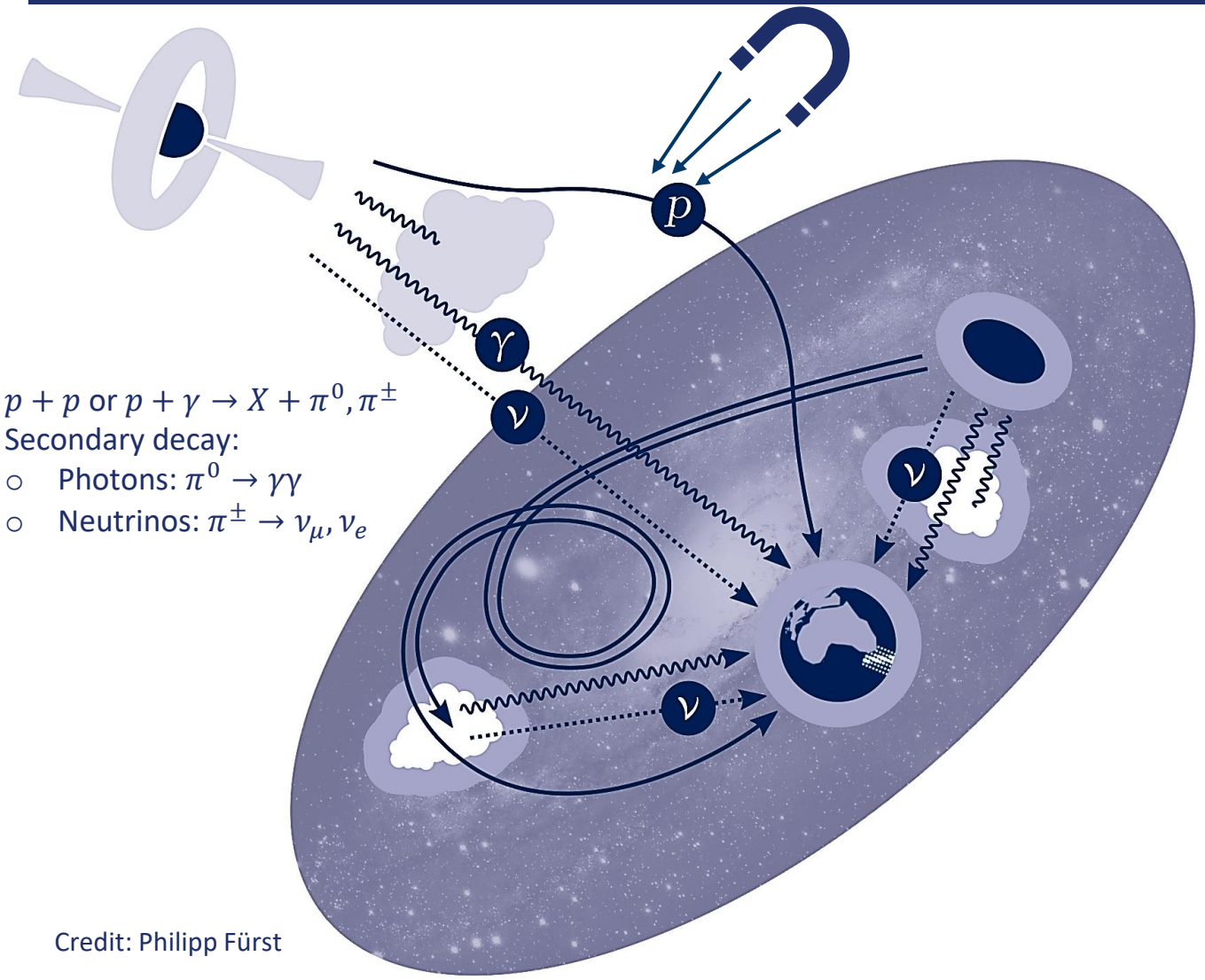
Recent IceCube results on the origin of cosmic neutrinos

Lisa Schumacher

for the IceCube Collaboration

ICHEP, Prague 2024

Neutrino astronomy in a nutshell



$p + p$ or $p + \gamma \rightarrow X + \pi^0, \pi^\pm$
Secondary decay:
- Photons: $\pi^0 \rightarrow \gamma\gamma$
- Neutrinos: $\pi^\pm \rightarrow \nu_\mu, \nu_e$

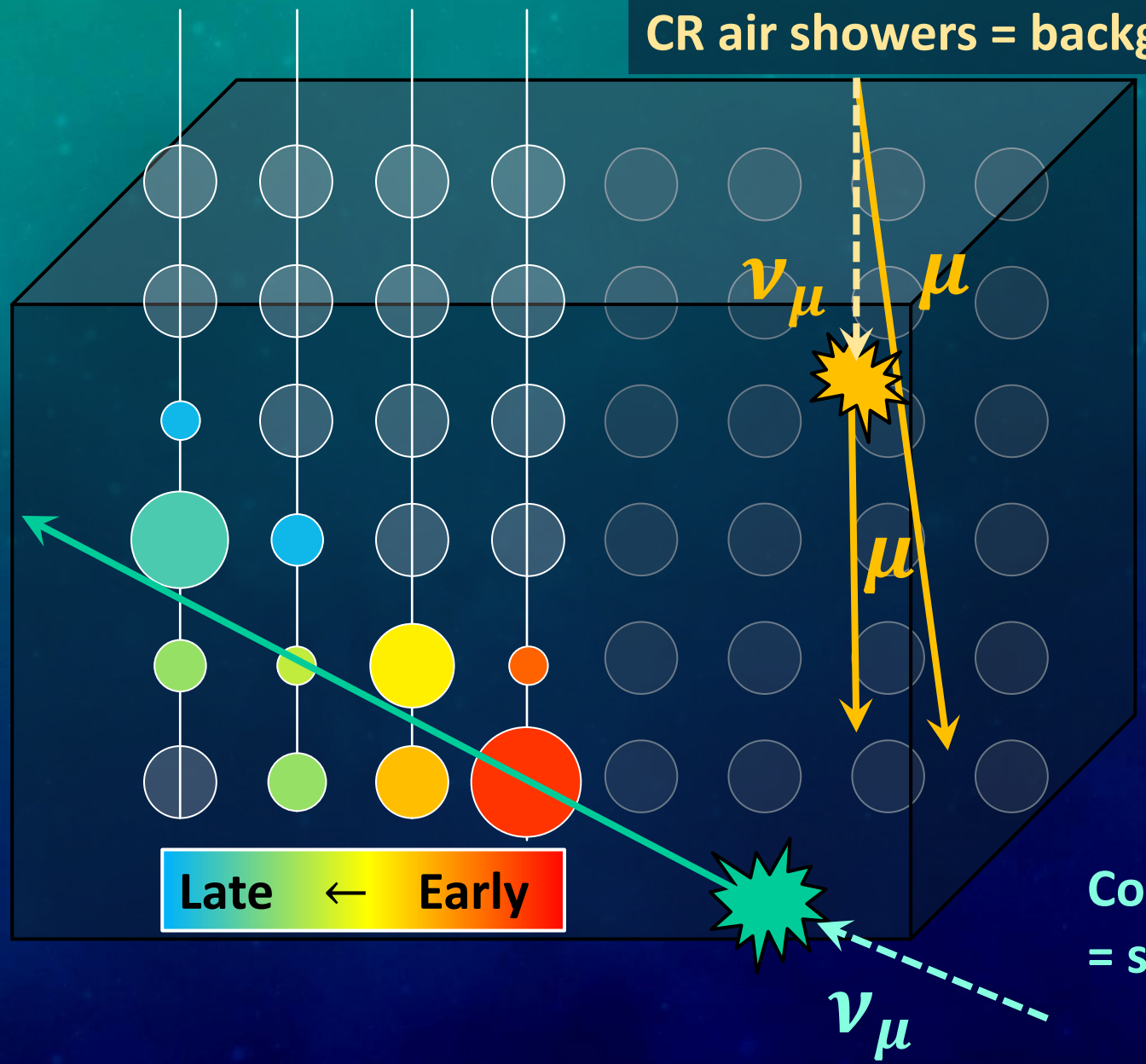
Credit: Philipp Fürst

What can these extreme environments tell us about particle physics at the highest energies?

Why are neutrinos interesting?

1) Neutrinos are unambiguous tracers of hadronic processes of CRs
2) Neutrinos can travel cosmological distances and through dense environments
3) Non-zero neutrino masses already point to physics beyond the standard model – what else are they hiding?

Muons and muon neutrinos from CR air showers = background

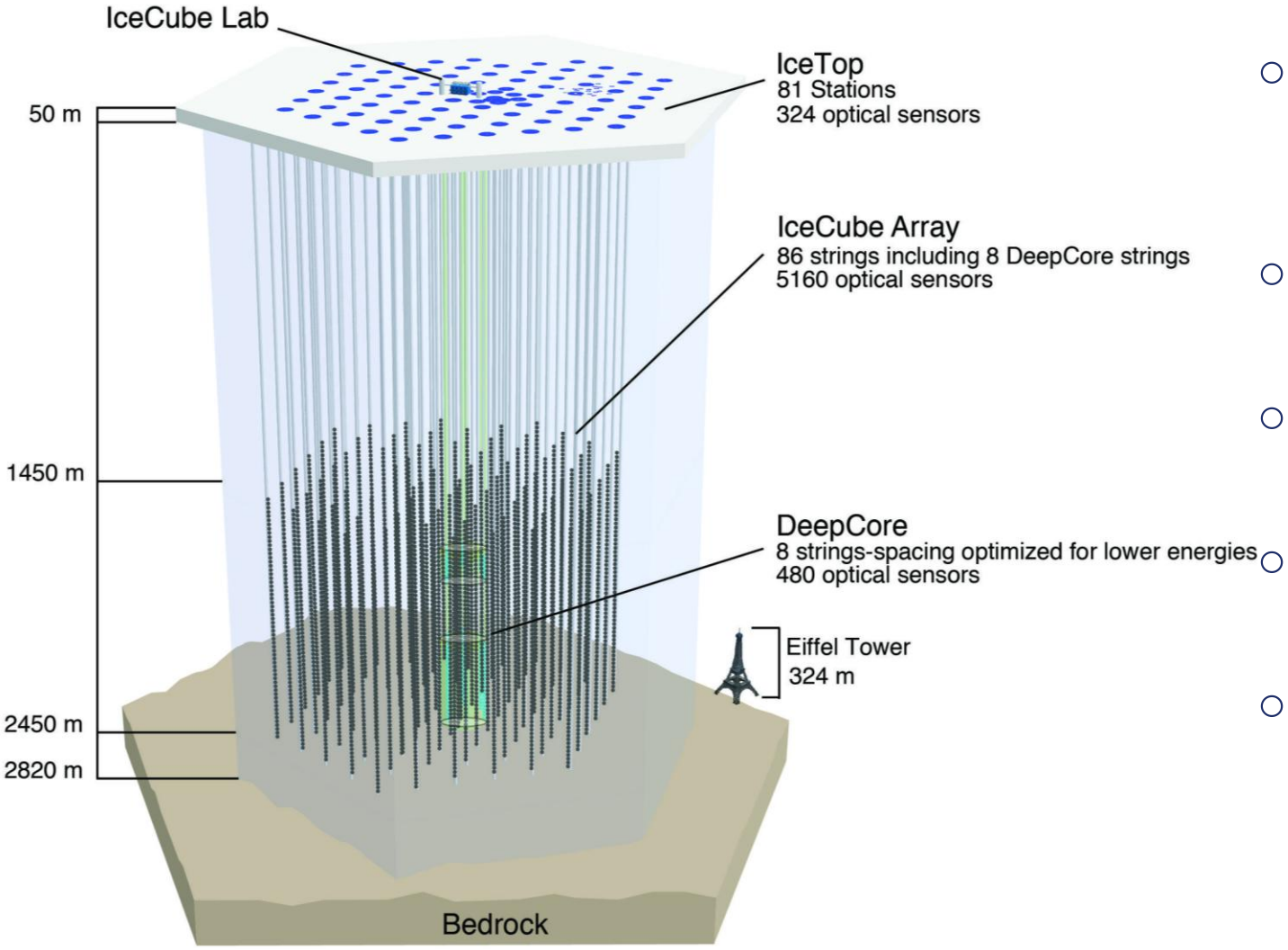


Detection medium: km^3 - volume of ice or water

3D array of optical modules

Cosmic neutrino = signal

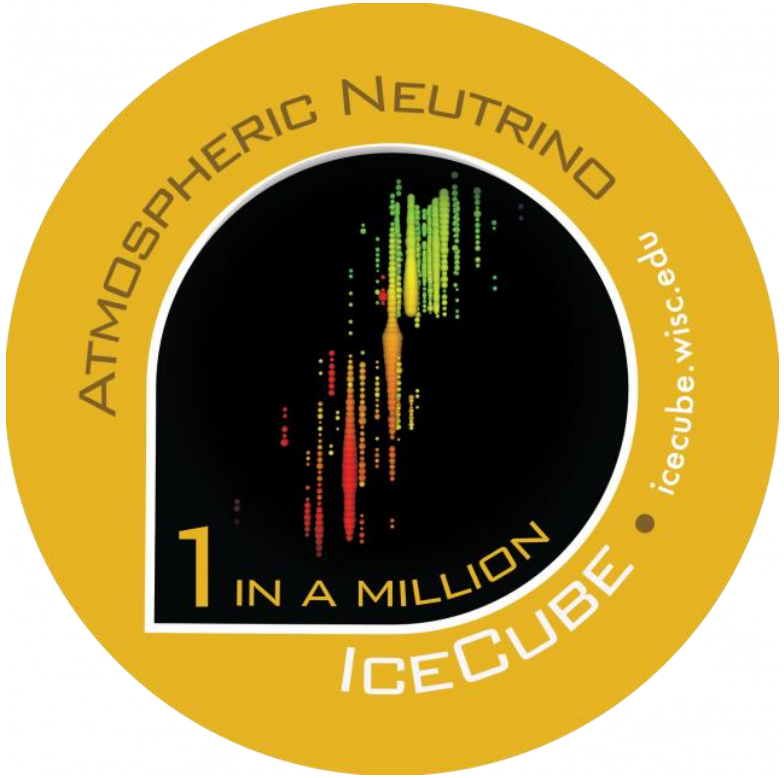
The IceCube Neutrino Observatory



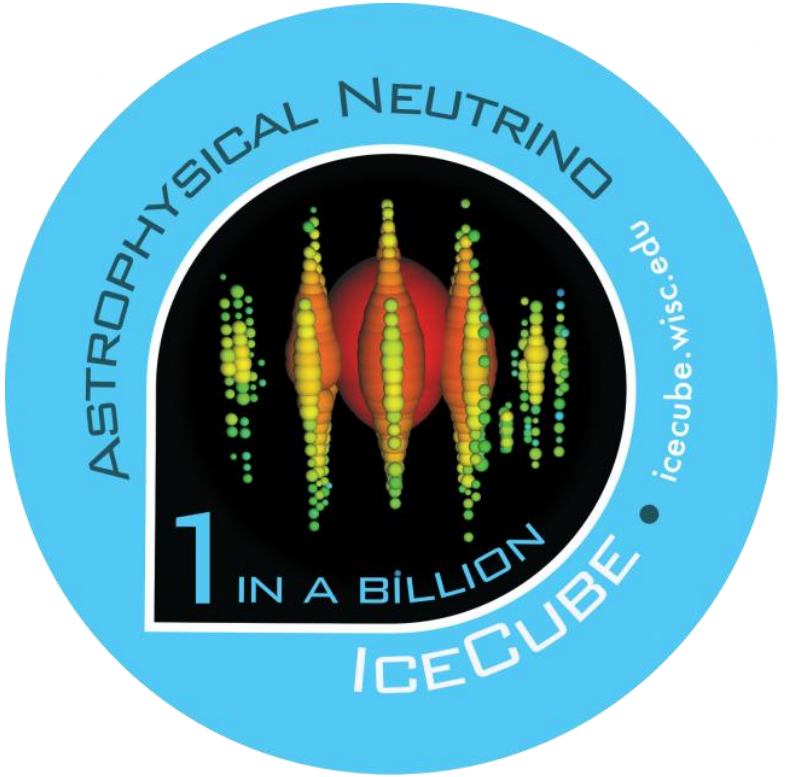
- Located at the geographic south pole 1.45-2.45 km deep in the ice with an instrumented volume of 1 km³
- 86 Strings with 60 Digital Optical Modules (DOMs) = 5160 DOMs in total
- Sparse instrumentation! 17m vertical & 125m horizontal spacing
- Full configuration running with >99% uptime since 2011
- Multi-purpose instrument for neutrino astronomy, neutrino physics, particle physics, physics beyond the standard model, …

Needle in a haystack

3000 atmospheric μ per second



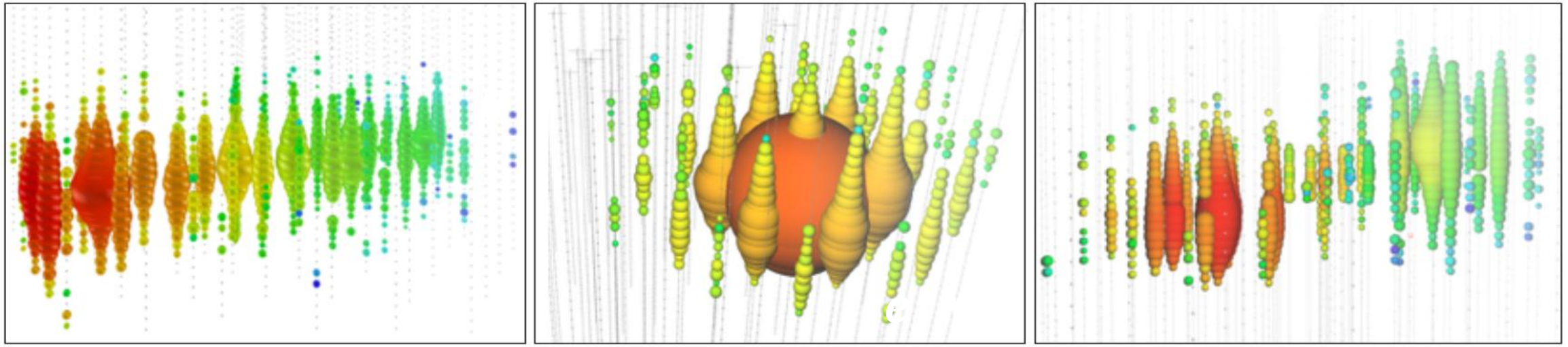
10 atmospheric ν per hour



100 astrophysical ν per year

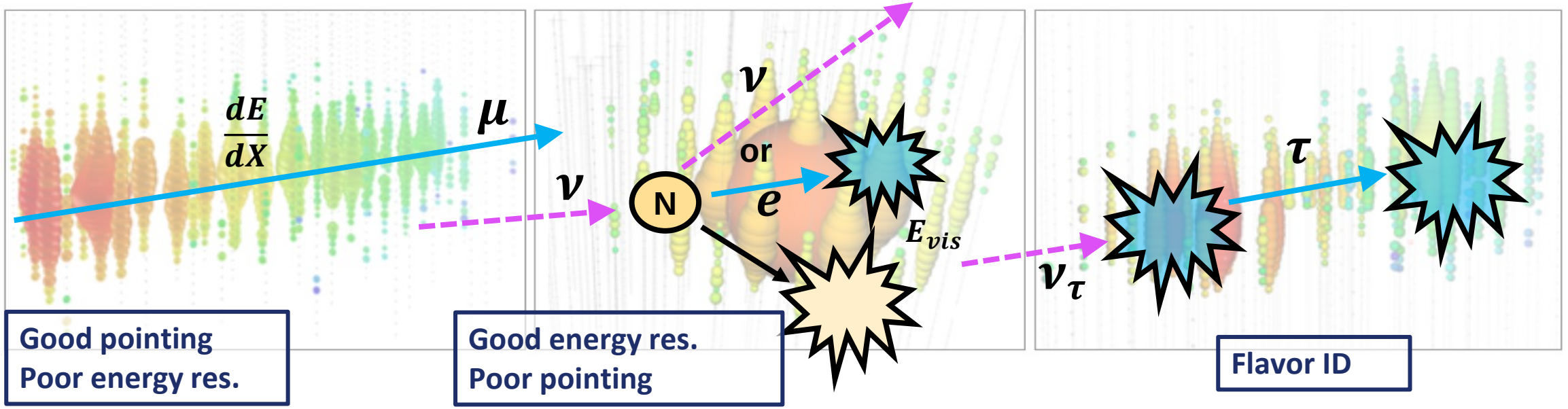
Neutrino signatures

IceCube-Gen2
arXiv:2008.04323v1



Neutrino signatures

IceCube-Gen2
arXiv:2008.04323v1



"**Tracks**":
- Good directional resolution $< 1°$
- Poor energy resolution via $\frac{dE}{dX}$ of muon

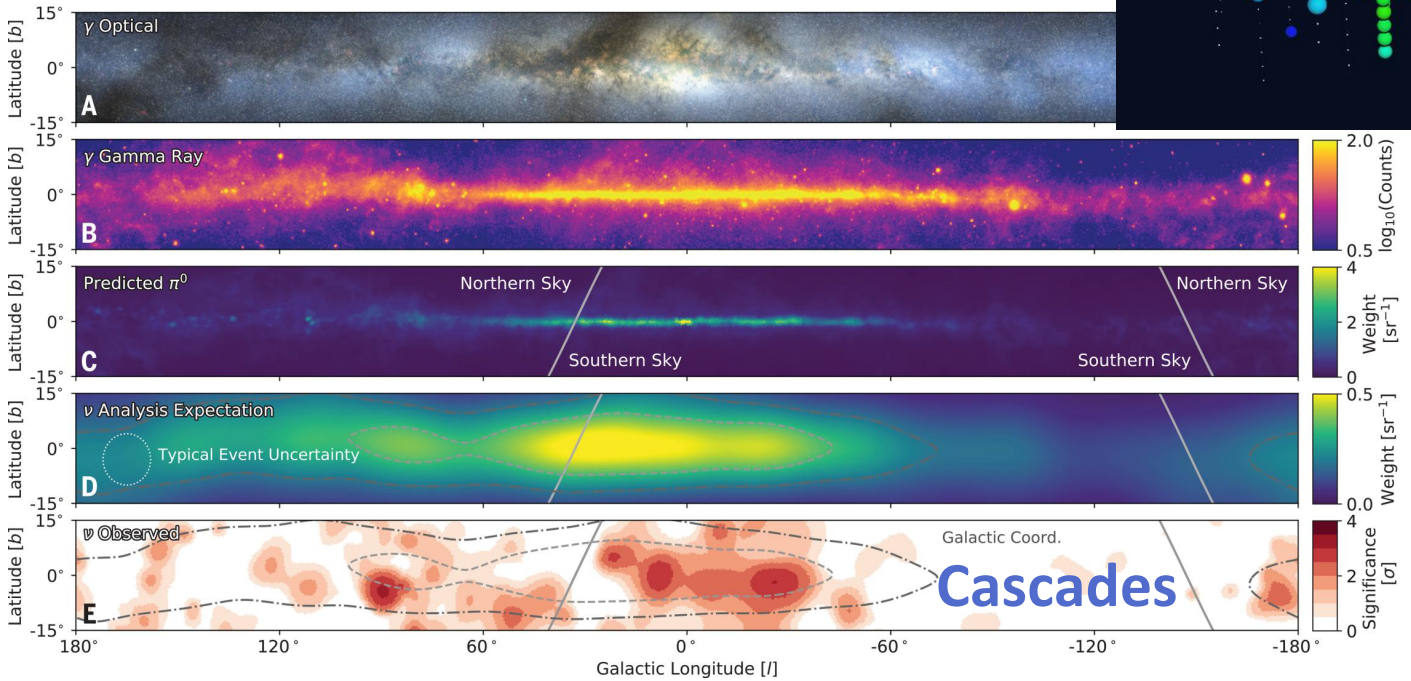
"**Cascades**":
- CC ν_e & ν_τ interactions + NC all-flavor
- Directional resolution $\sim 5 - 15°$
- Good resolution of visible energy: $\sim 10\%$ for CC ν_e

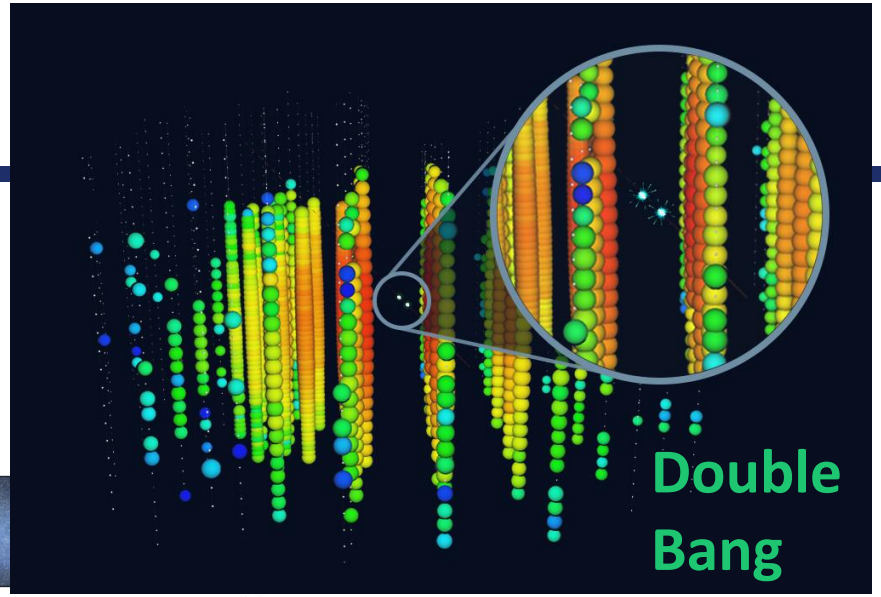
"**Double Bang**":
- CC ν_τ interactions + τ decay
- Only resolvable at high energies with distance between cascades

$$\sim 50\text{m} \cdot \left(\frac{E}{\text{PeV}}\right)$$

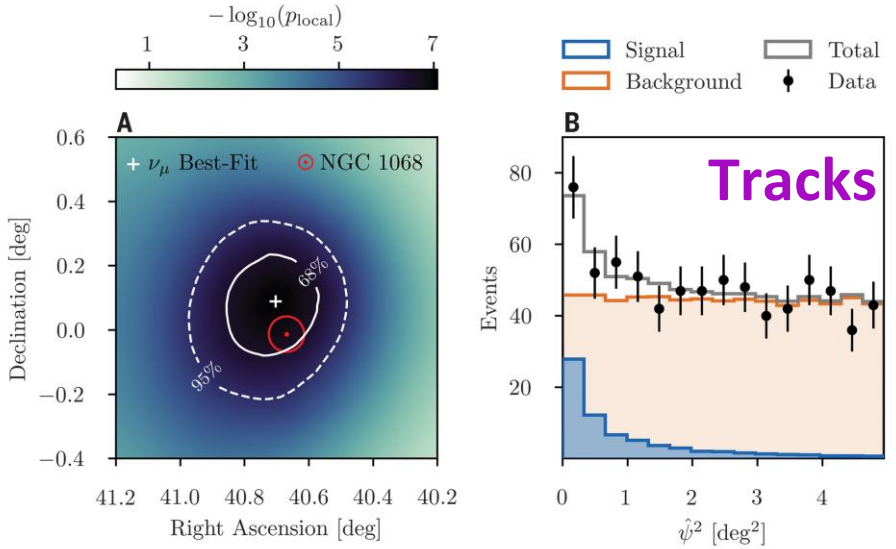
Recent highlights

Observation of high-energy neutrinos from the Galactic plane





Observation of Seven Astrophysical Tau Neutrino Candidates with IceCube

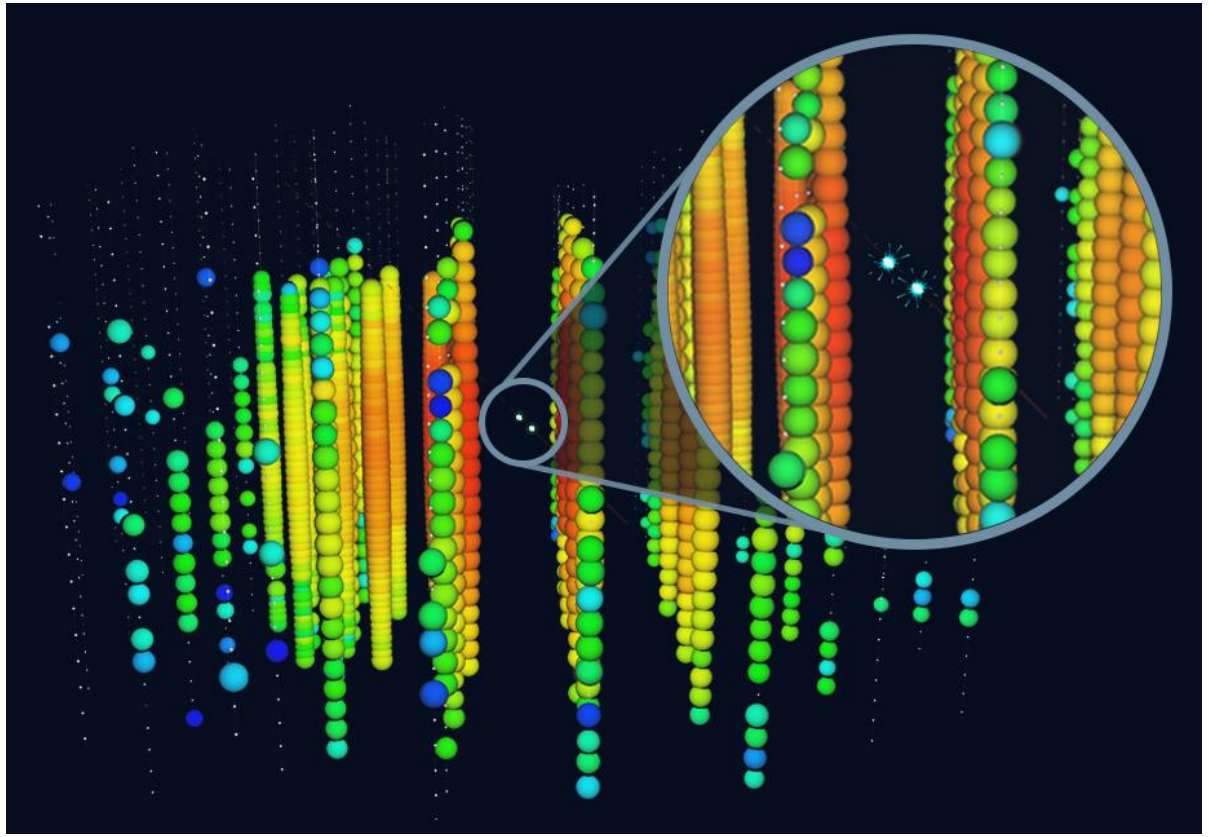


Evidence for neutrino emission from the nearby active galaxy NGC 1068

https://doi.org/10.1126/science.abg3395
https://doi.org/10.1126/science.adc9818
https://doi.org/10.1103/PhysRevLett.132.151001

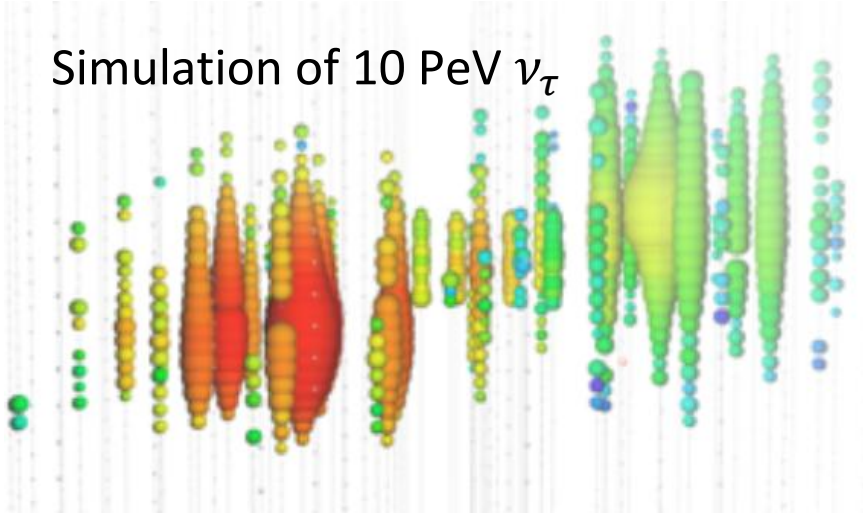
Tau neutrinos

https://doi.org/10.1103/PhysRevLett.132.151001

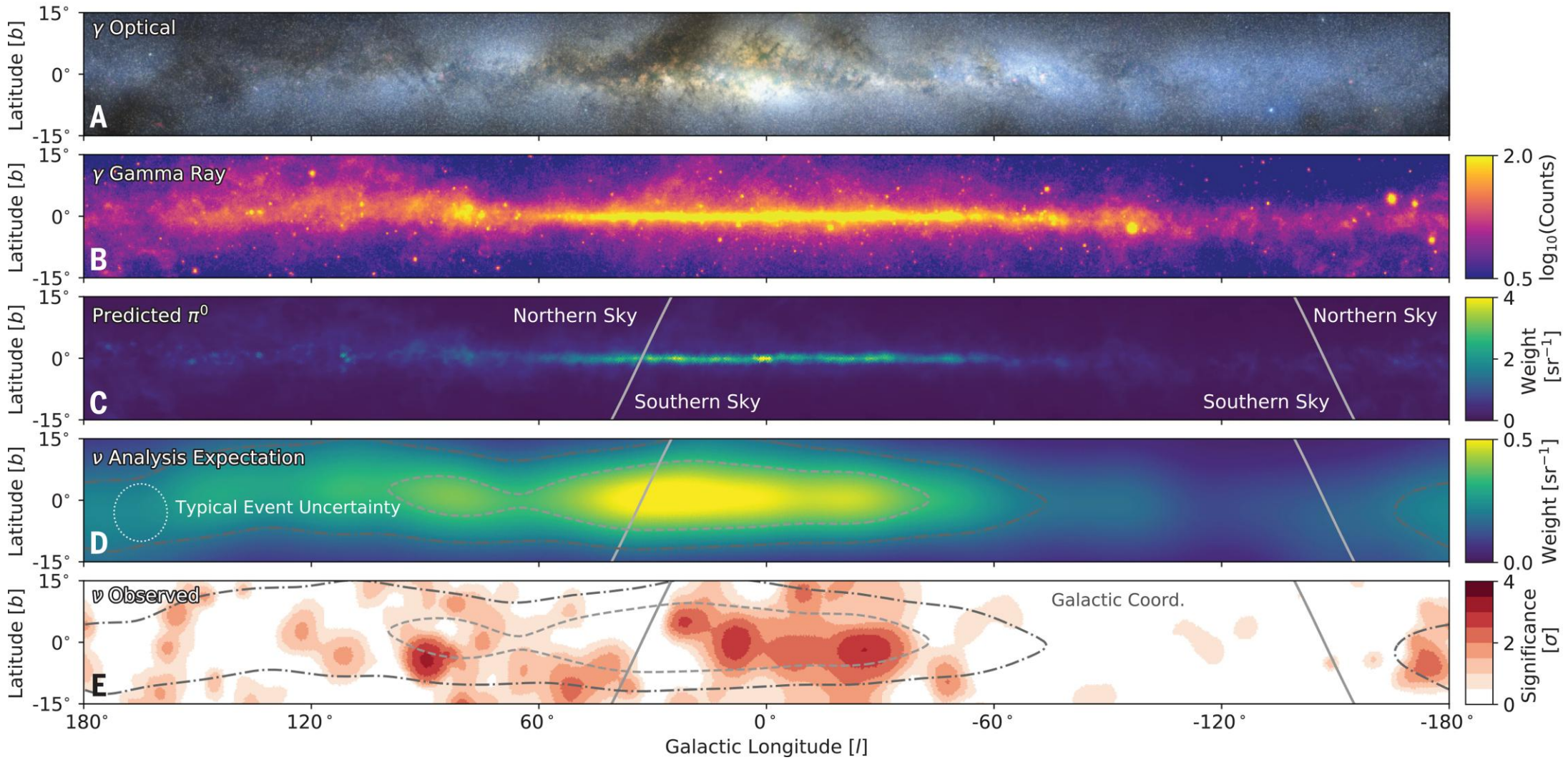


- Detected 7 tau neutrino candidates with novel image recognition methods based on CNNs (background expectation of 0.5 events)
  - Combined significance $> 5\sigma$
  - Independent confirmation of astrophysical neutrino flux

Simulation of 10 PeV ν_τ

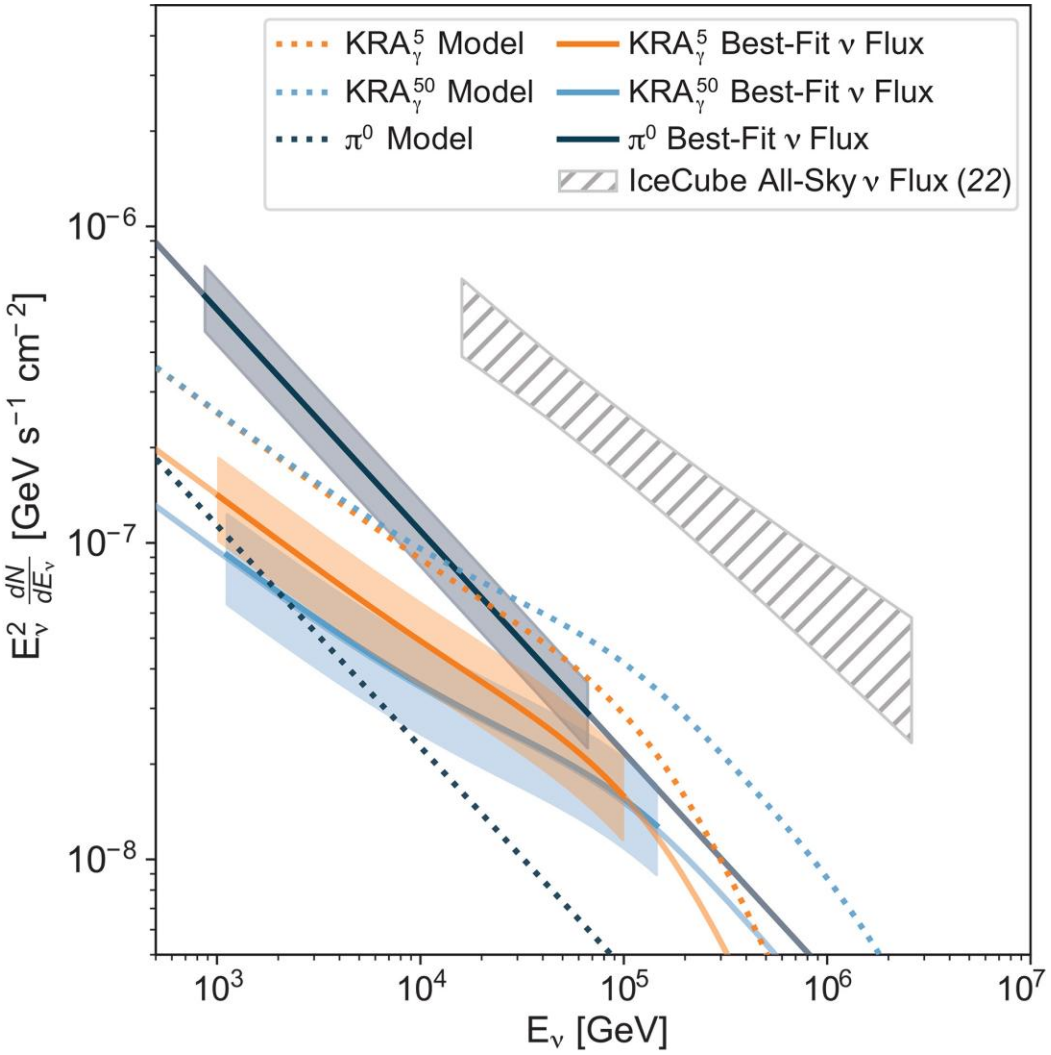


Galactic neutrinos



Galactic plane – diffuse emission

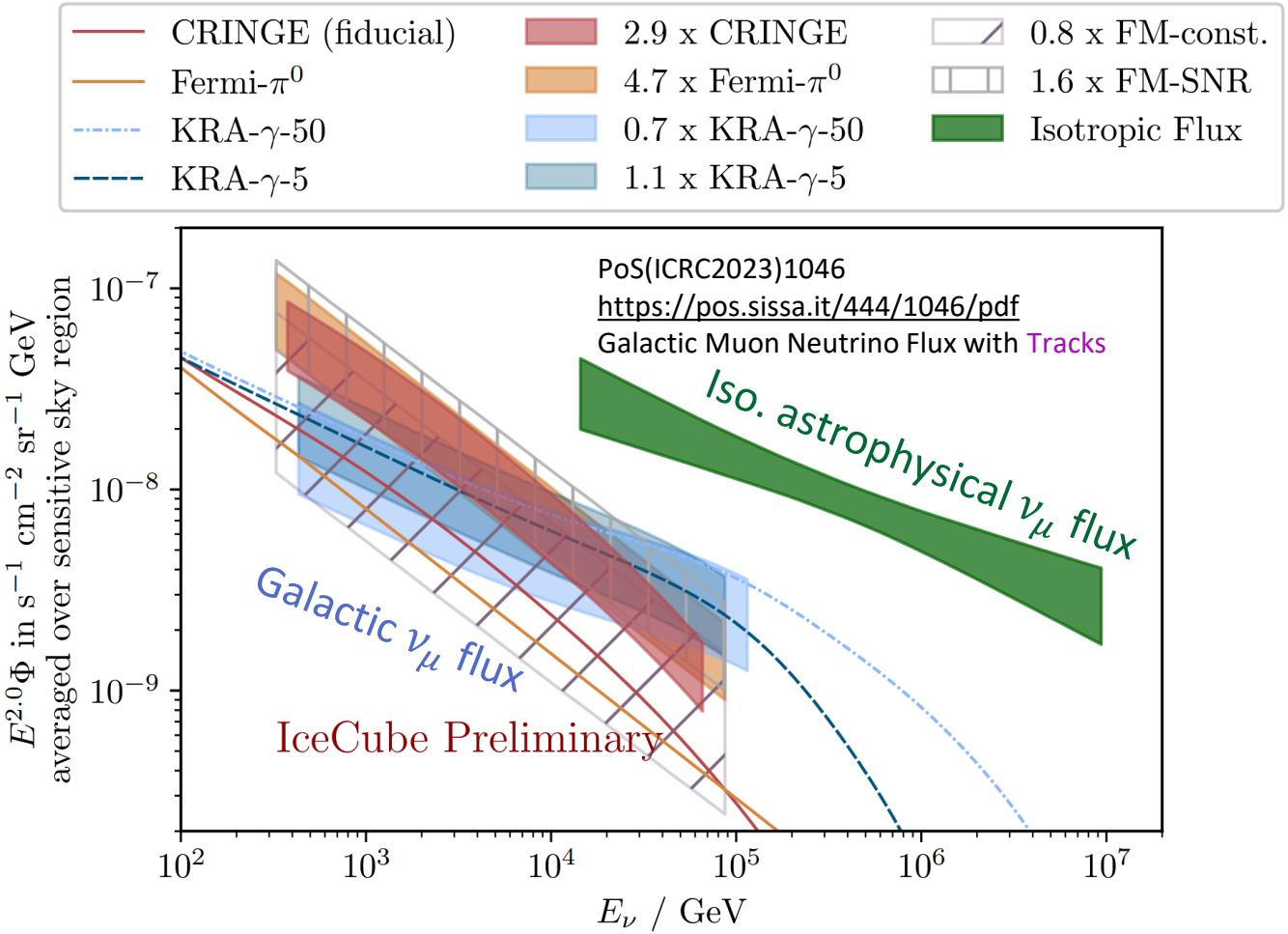
https://doi.org/10.1126/science.adc9818



- Observation of Neutrinos from the Galactic Plane with a novel machine-learning reconstruction of Cascades - **Significance: 4.5σ**
- Galactic Muon Neutrino Flux with Tracks **Significance: 2.7σ**
- View of our Galaxy at highest energies & complementary to Fermi and LHAASO gamma rays
- Results using tracks are not yet significant, but are compatible with cascades
- Work ongoing for combining these independent data sets

What we (don't) know

http://dx.doi.org/10.3847/1538-4357/acc1e2 CRINGE as baseline model



Tested models differ in underlying model assumptions
-> different energy spectrum & spatial distribution

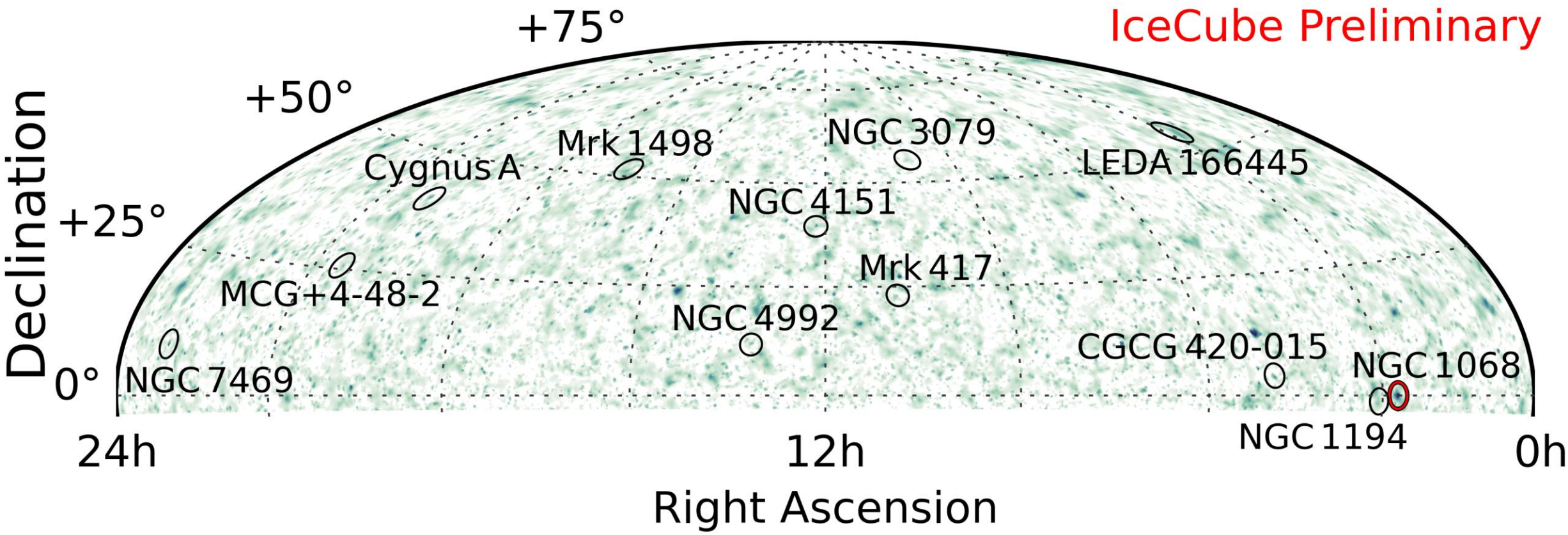
Galactic Muon Neutrino Flux with Tracks
Significance: 2.7σ

✓ About 6-13% of total astrophysical neutrino flux comes from GP (based on simultaneous fit of both components)

❑ Multiple diffuse neutrino emission models were tested, but no clear preference yet

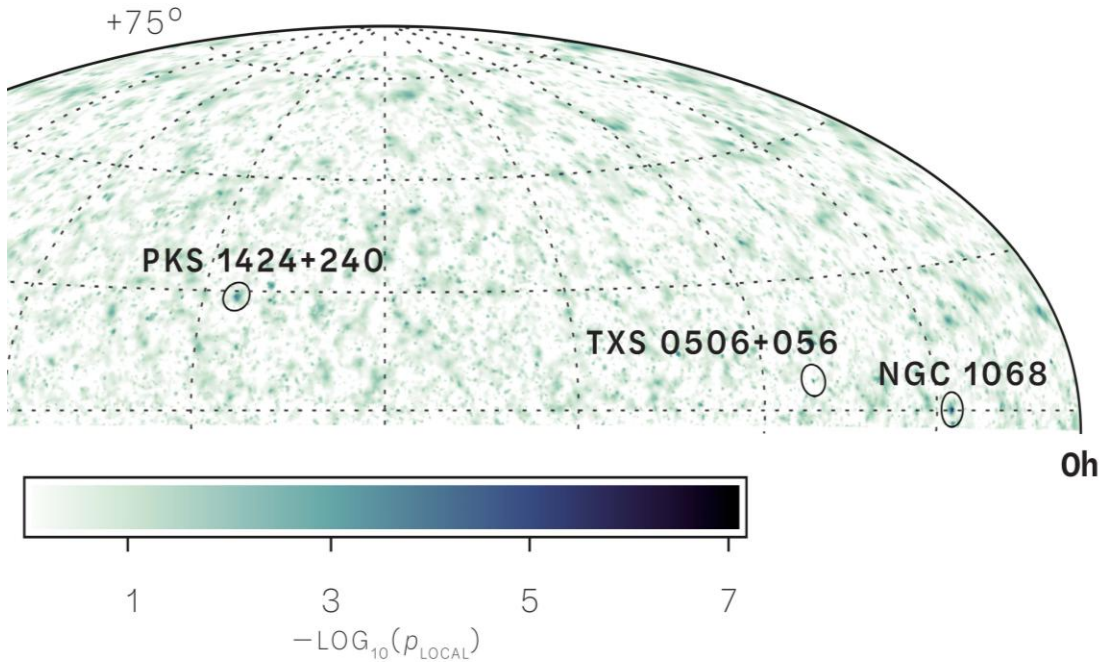
❑ Normalization larger than expected could hint at sources in addition to diffuse emission, but still speculative

Extragalactic neutrinos



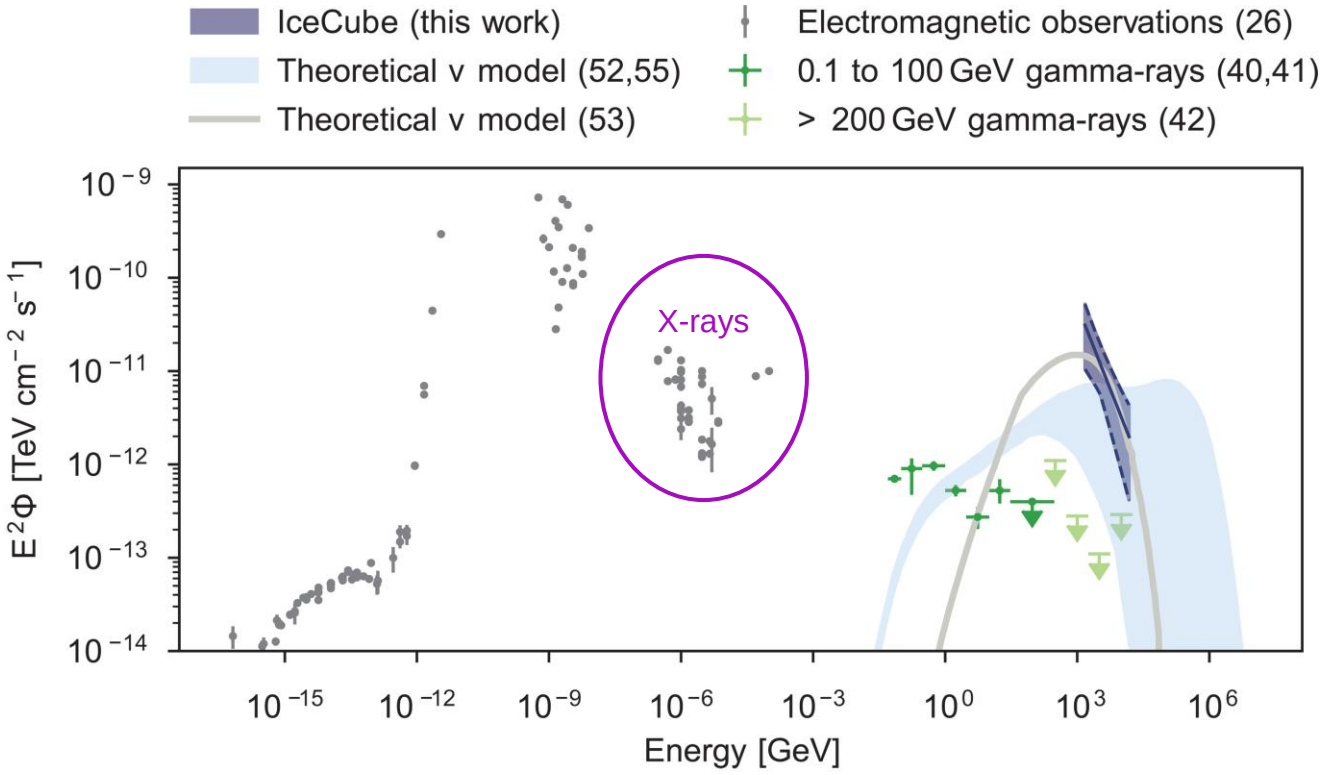
NGC 1068

- Evidence for neutrino emission from NGC 1068 with significance of 4.2σ using tracks
- Significance based on pre-defined list of 110 gamma-ray sources – local significance $> 5\sigma$



https://doi.org/10.1126/science.abg3395

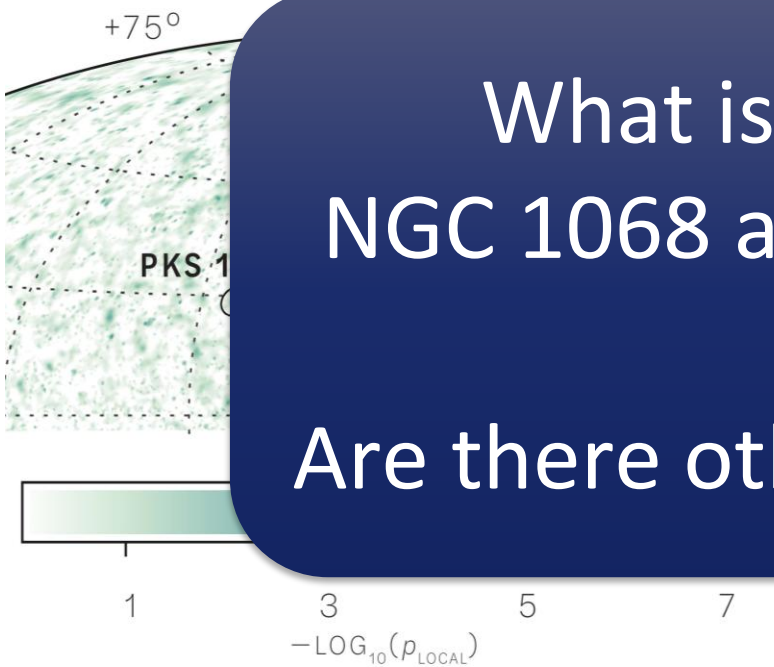
- Seyfert II galaxy at a distance of 14.4 Mpc (very close by!) with Compton-thick AGN
- X-Ray corona around accretion disk may enable neutrino production & gamma-ray absorption



NGC 1068

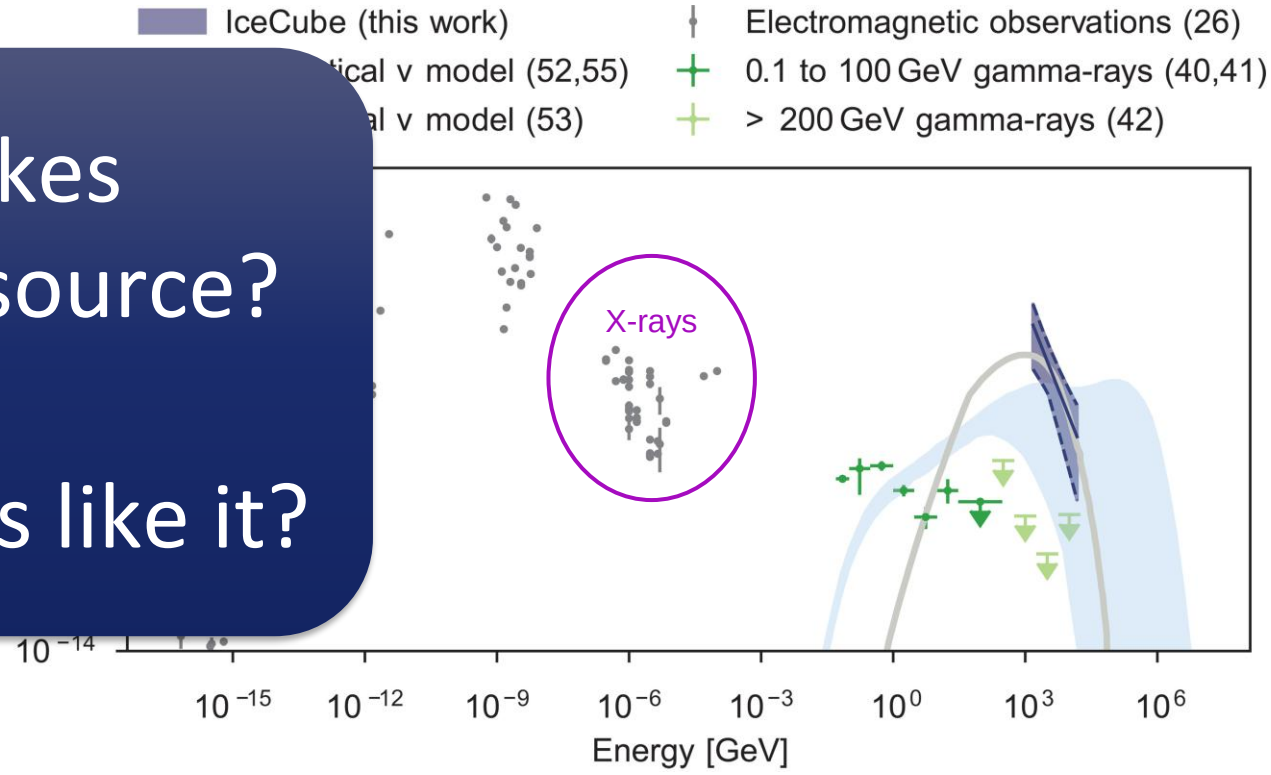
- Evidence for neutrino emission from NGC 1068 with significance of 4.2σ using tracks
- Significance based on pre-defined list of 110 gamma-ray sources – local significance $> 5\sigma$

- Seyfert II galaxy at a distance of 14.4 Mpc (very close by!) with Compton-thick AGN
- X-Ray corona around accretion disk may enable neutrino production & gamma-ray absorption



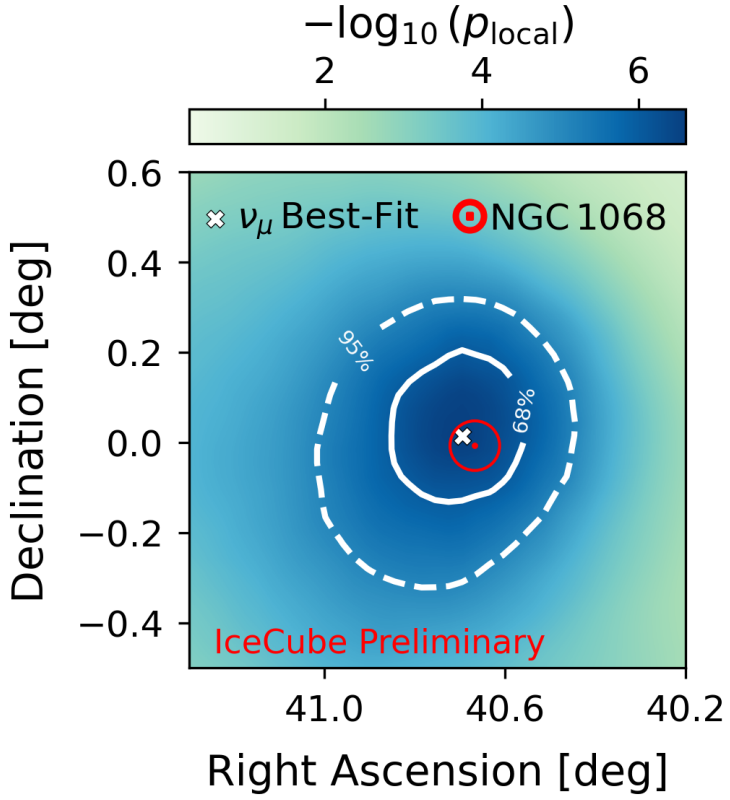
What is it that makes NGC 1068 a neutrino source?

Are there other sources like it?



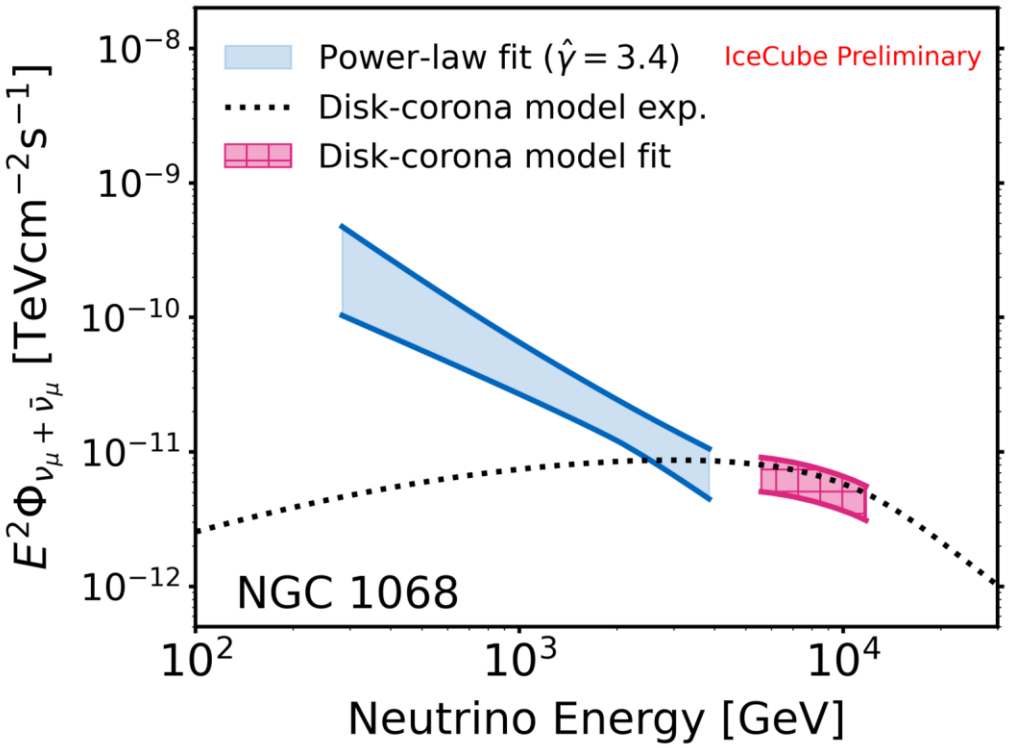
https://doi.org/10.1126/science.abg3395

New results on NGC 1068



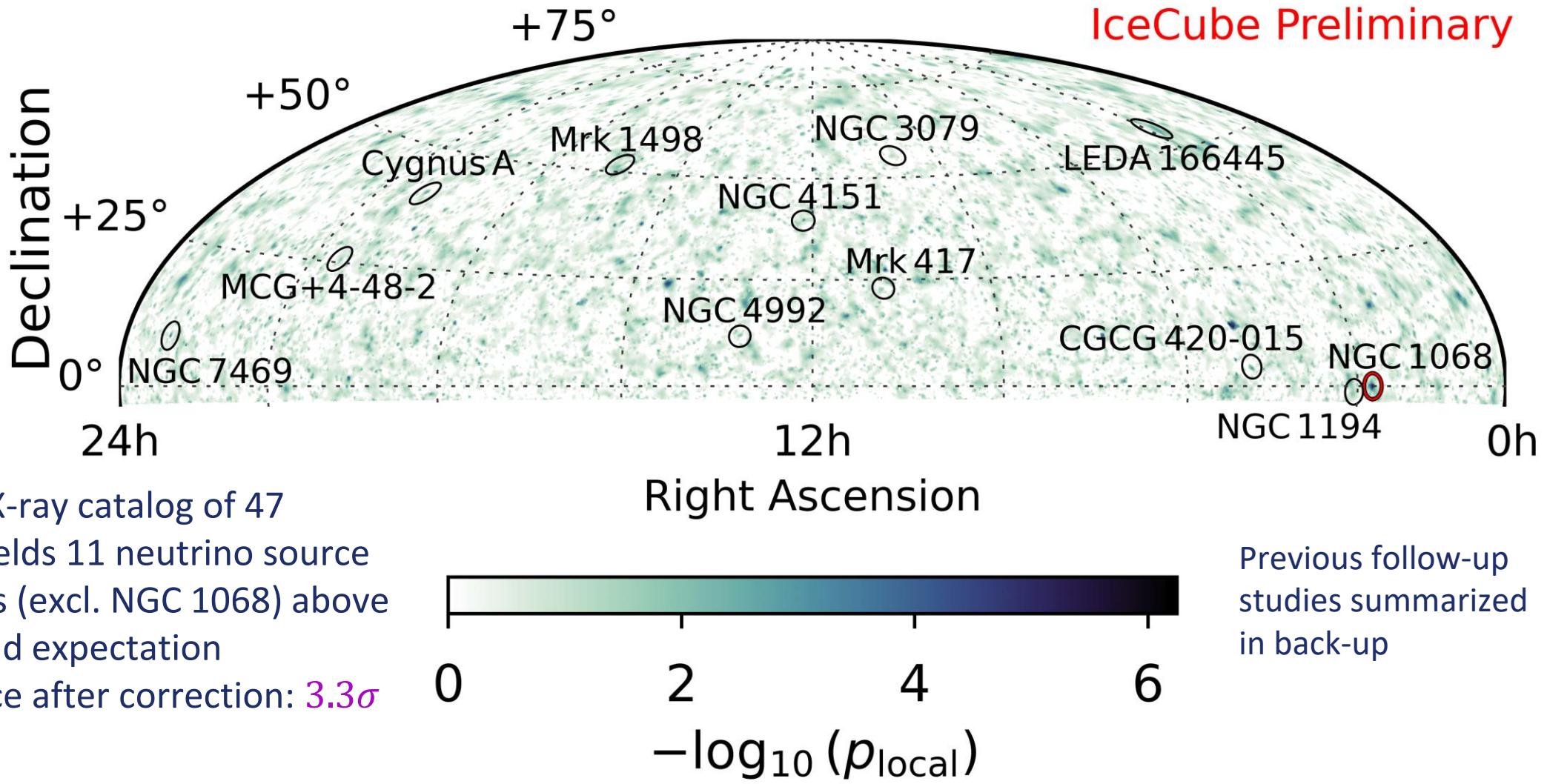
- 9 → 13 years of data
- Significance: 4σ

Disk-corona model based on
https://doi.org/10.3847/1538-4357/ac1c77



- Spectrum became softer - $\mathrm{E}^{-\gamma}$ with $\gamma = 3.2 \rightarrow 3.4$
- Model prediction similarly significant, but fundamentally different spectral shape – further investigations needed!

Newest addition to x-ray/neutrino puzzle

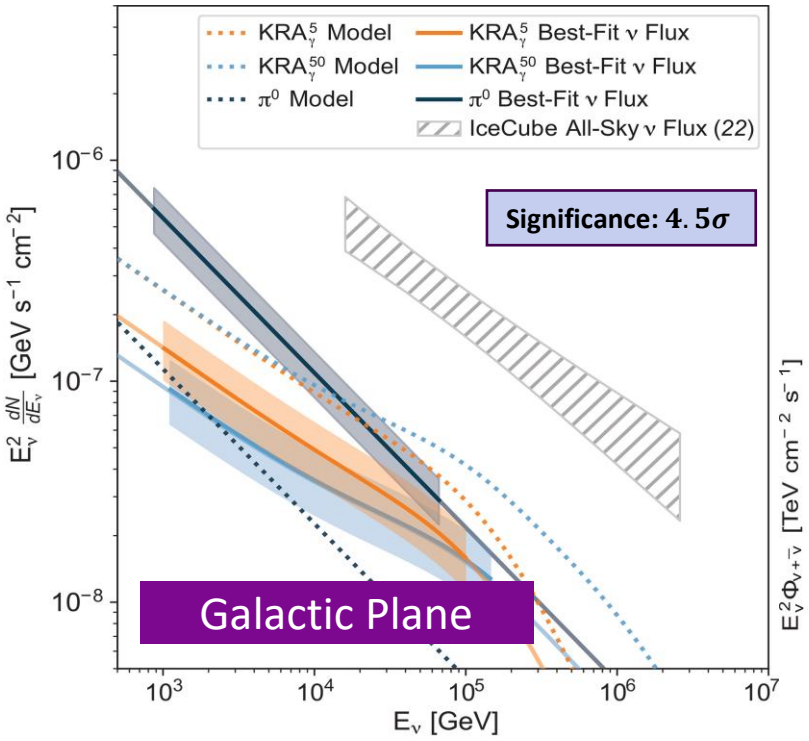


- Seyfert – X-ray catalog of 47 sources yields 11 neutrino source candidates (excl. NGC 1068) above background expectation
- Significance after correction: 3.3σ

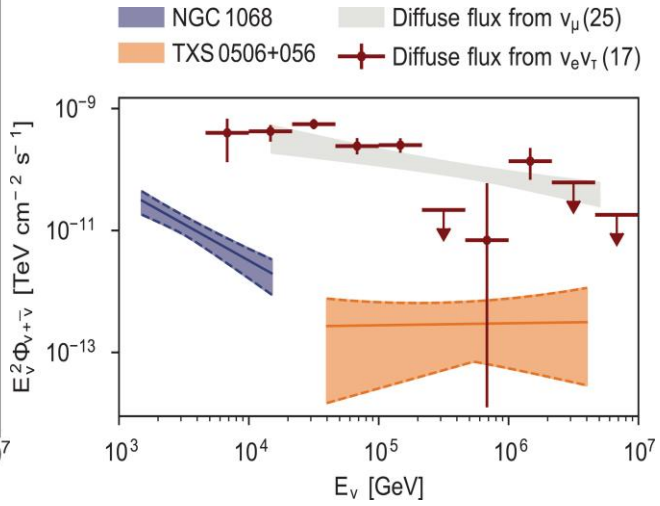
Previous follow-up studies summarized in back-up

The bigger picture

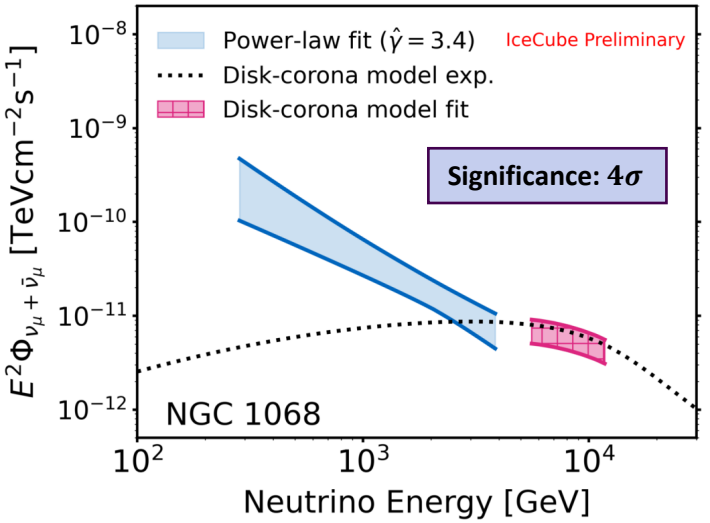
- Galactic & extragalactic neutrino associations are emerging
- Significant proportion of overall neutrino flux not yet accounted for

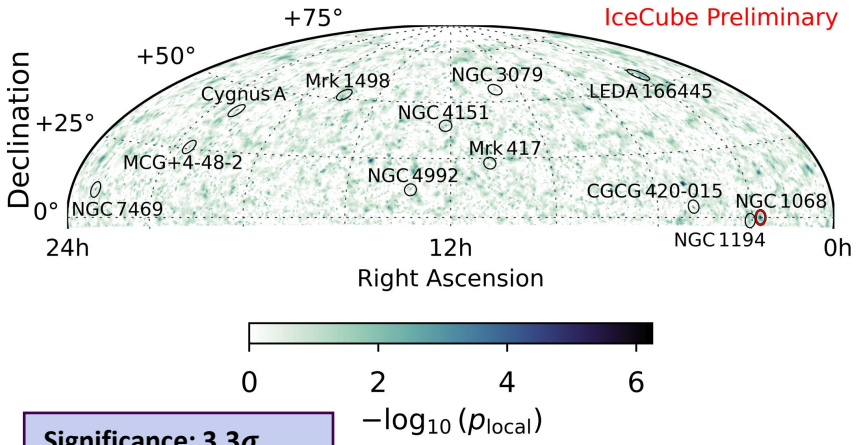


NGC 1068 & TXS 0506+056



NGC 1068 (new)



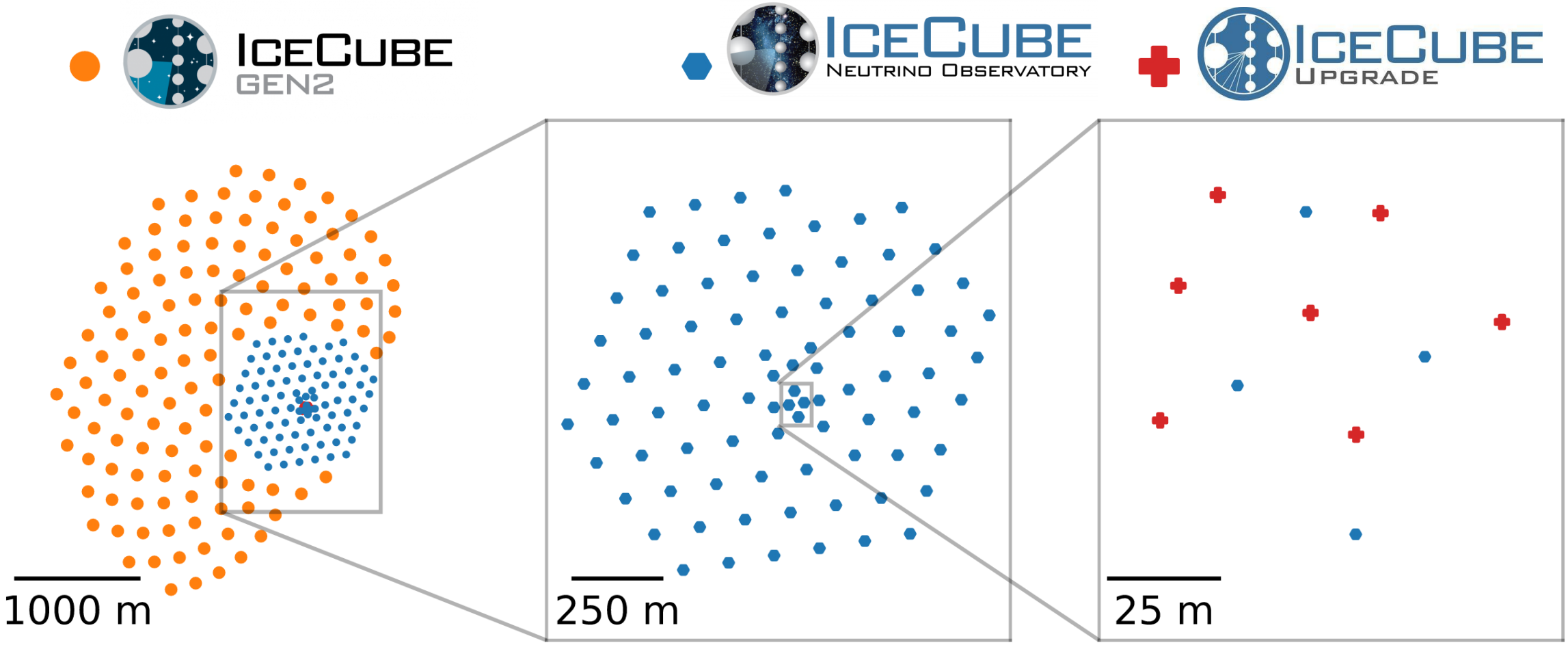


Significance: 3.3σ

Seyfert/X-Ray AGN

What’s next?

Extending to higher and lower energies



Extending to higher and lower energies

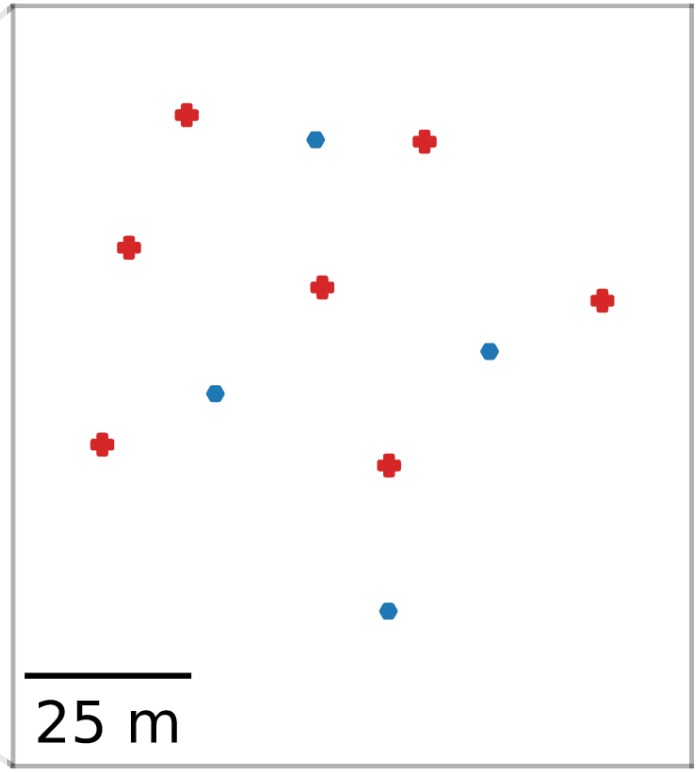
IceCube GEN2

IceCube Neutrino Observatory

+ IceCube Upgrade

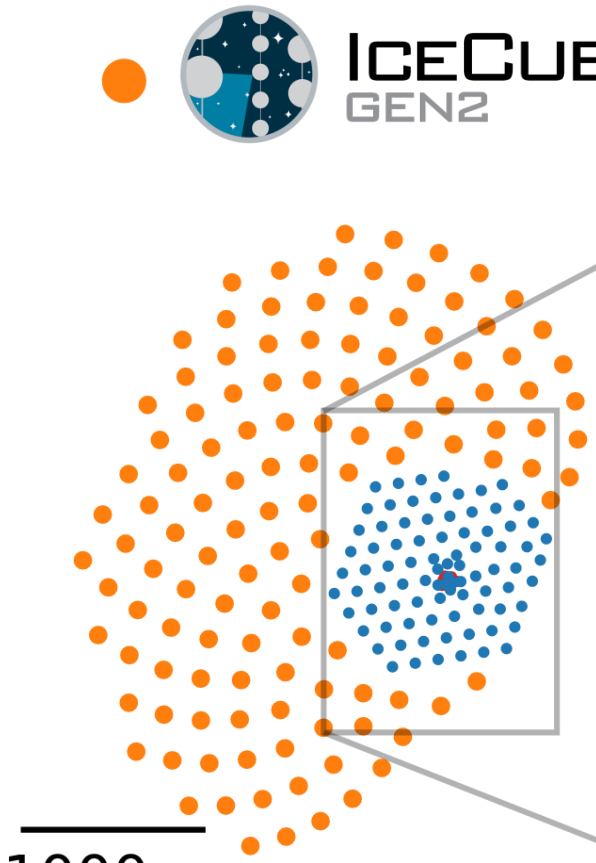
IceCube Upgrade

- Extending sensitivity at lower energies for calibration & atmospheric neutrino oscillation
- Re-processing of >TeV data to include new calibration
- Deployment of new photosensors in winter 2025/26



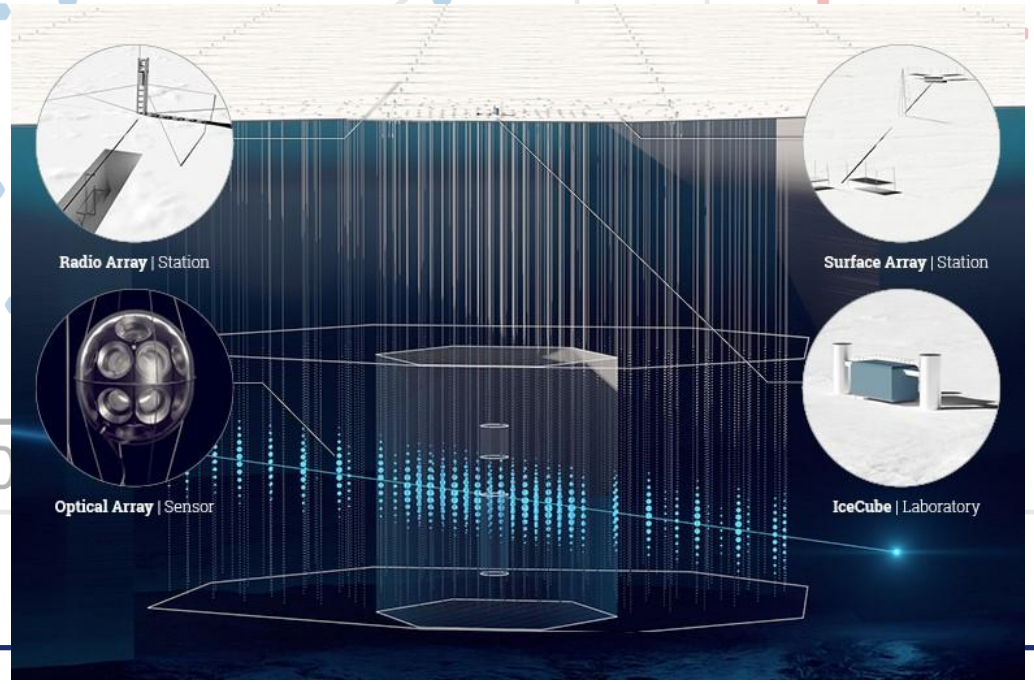
1000 m

Extending to higher and lower energies

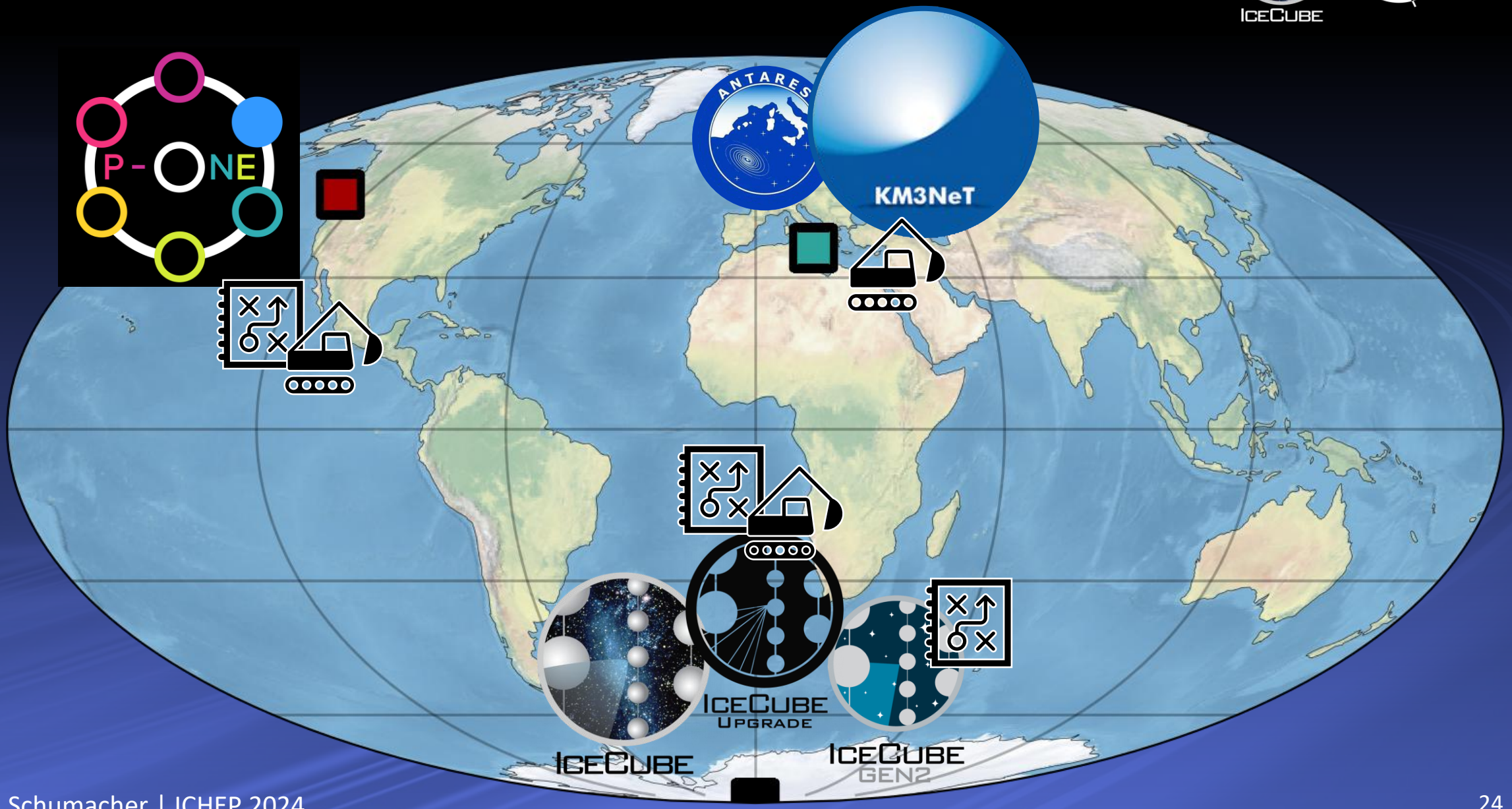


IceCube-Gen2

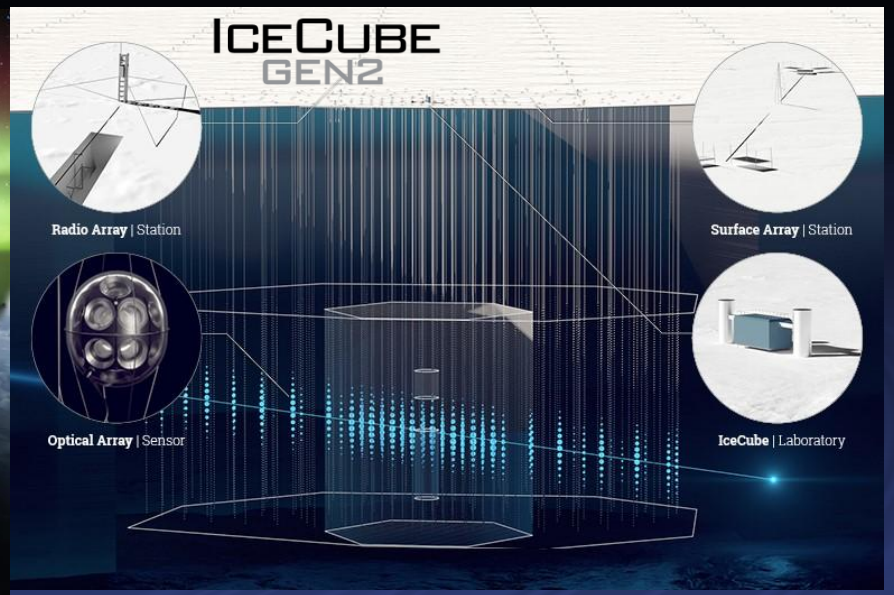
- In Ice:
  5x larger effective area and 2x better pointing for highest-energy tracks
- Other components:
  large radio array & surface CR detectors



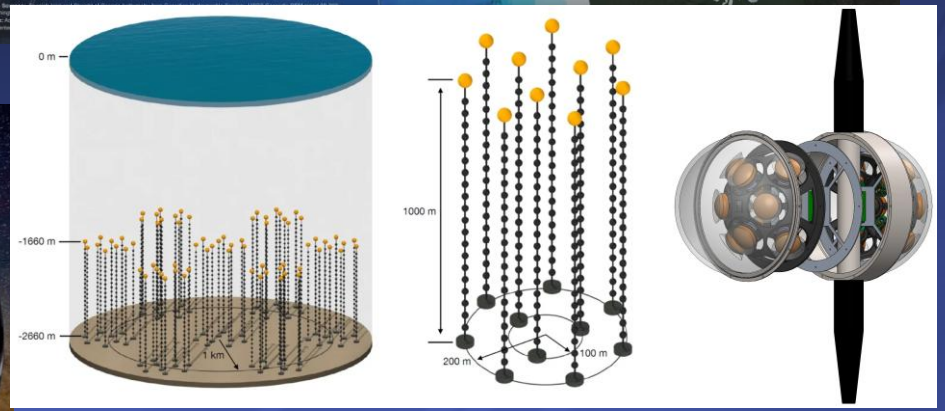
The global picture

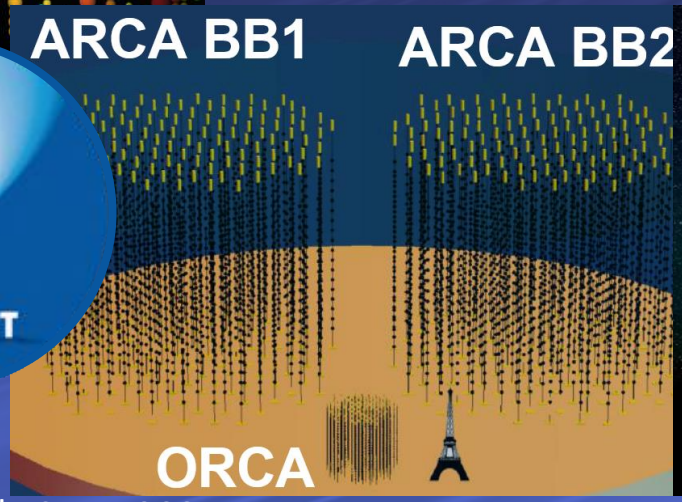


The global picture



Pacific Ocean Neutrino Experiment





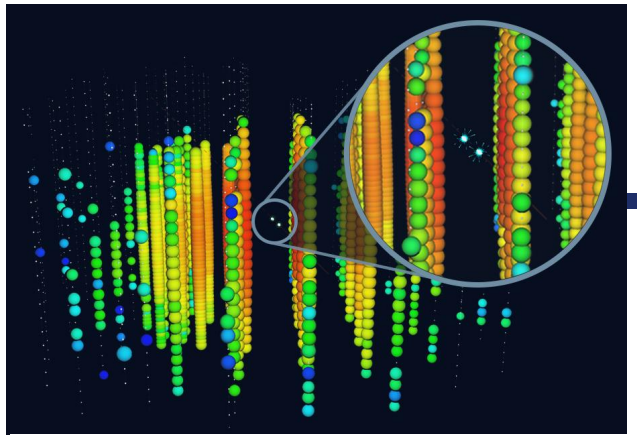
João Coelho – Neutrino 2024

+ TRIDENT, HUNT, Baikal-GVD, TAMBO, …


Thanks for listening!
THE ICECUBE COLLABORATION
AUSTRALIA
University of Adelaide
BELGIUM
UCLouvain
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel
CANADA
Queen's University
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
University of Canterbury
REPUBLIC OF KOREA
Chung-Ang University
Sungkyunkwan University
SWEDEN
Stockholms universitet
Uppsala universitet
SWITZERLAND
Université de Genève
TAIWAN
Academia Sinica
UNITED KINGDOM
University of Oxford
UNITED STATES
Clark Atlanta University
Columbia University
Drexel University
Georgia Institute of Technology
Harvard University
Lawrence Berkeley National Lab
Loyola University Chicago
Marquette University
Massachusetts Institute of Technology
Mercer University
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Nevada, Las Vegas
University of Rochester
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)
IceCube Neutrino Observatory
icecube.wisc.edu

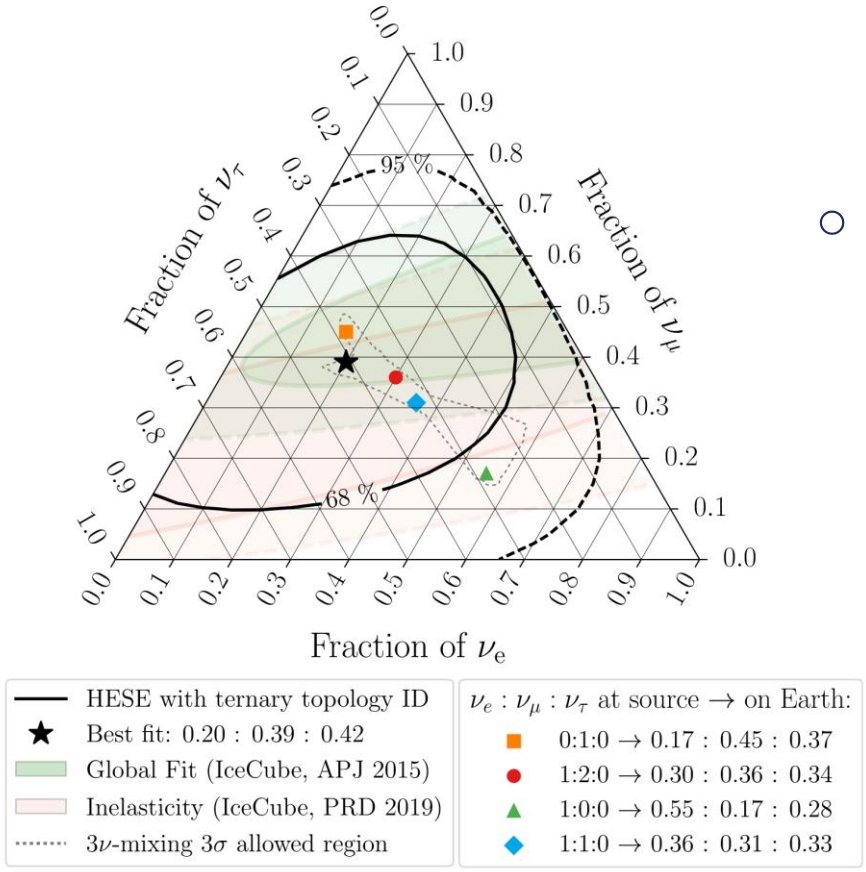
Back up

Tau neutrinos & Flavor



https://doi.org/10.1103/PhysRevLett.132.151001

- Found 7 tau neutrino candidates with novel image recognition methods based on CNNs (background expectation of 0.5 events)
  - Combined significance $> 5\sigma$
  - Independent confirmation of astrophysical neutrino flux
- Related other works:
  - Flavour measurement of astrophysical neutrino flux to constrain production scenarios
  - Glashow resonance - $\overline{\nu_e}$ detection (2021)
    https://www.nature.com/articles/s41586-021-03256-1
  - New analyses and publications in progress!



HESE: high-energy starting events - high purity astro neutrinos (2022)
https://doi.org/10.1140/epjc/s10052-022-10795-y

Galactic sources?

- Through-going tracks: no significant evidence for extended sources in the Galactic Plane, but 2.6σ significance at region of unidentified TeV gamma-ray source 3HWC J1951+266

  https://doi.org/10.3847/1538-4357/acf713

- Cascades: $> 3\sigma$ significance for correlation with TeV-gamma ray sources in GP, cannot be disentangled from the diffuse GP emission due to large angular uncertainty of cascades

  https://doi.org/10.1126/science.adc9818
  Same cascade data as used for GP analysis

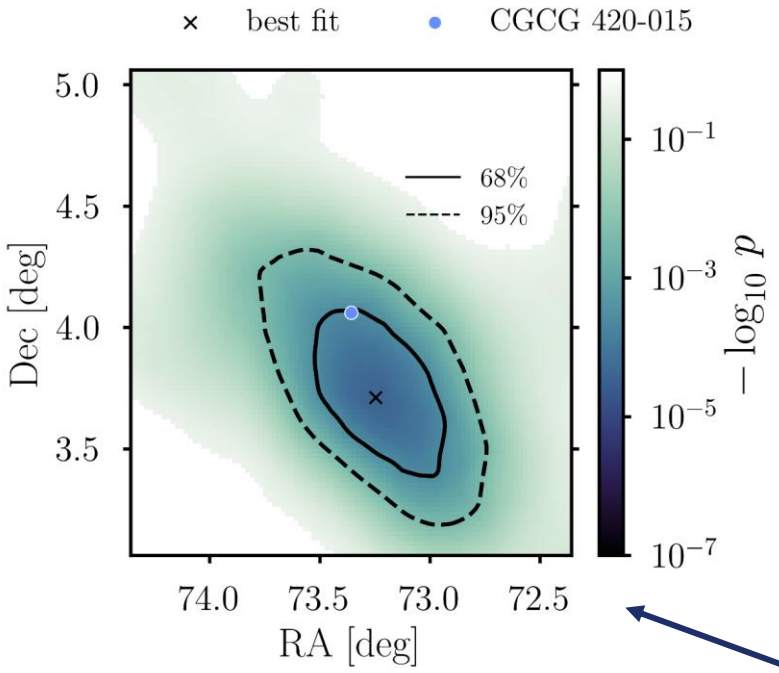
- Upcoming publication: Search for joint multimessenger signals from potential Galactic PeVatrons with HAWC and IceCube – no correlation found, starting to constrain hadronic production scenarios of HAWC sources

  https://doi.org/10.48550/arXiv.2405.03817
  Submitted to ApJ

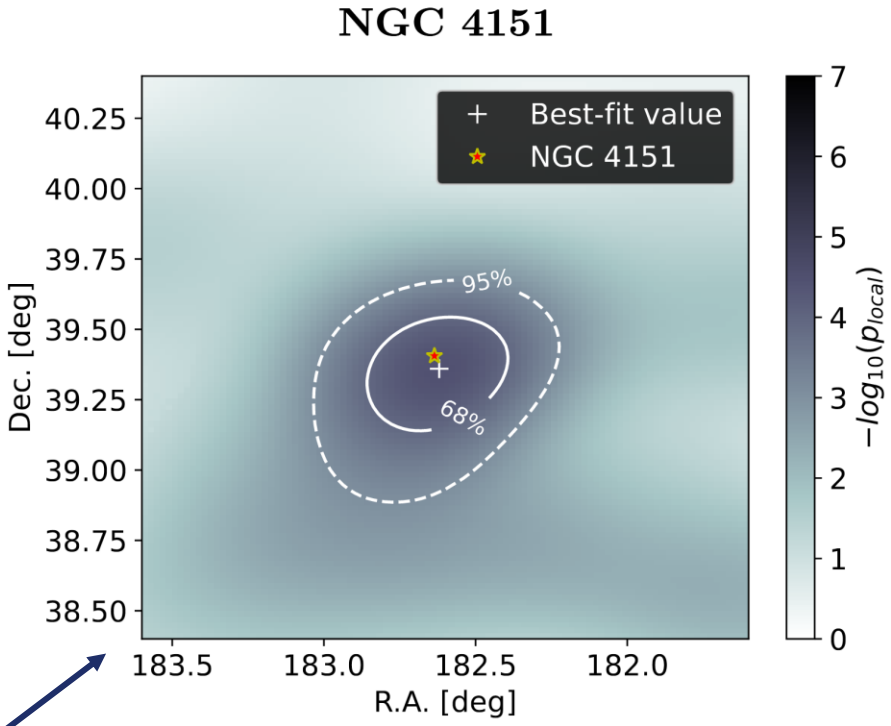
We start to see the (diffuse) neutrino emission of the plane, but individual sources cannot be resolved yet

Seyfert Galaxies & X-ray bright AGN

- Excess of neutrinos associated with two sources, NGC 4151 and CGCG 420-015 @ 2.7σ significance
- Results constrain the collective neutrino emission from chosen source catalogue



- Search for high-energy neutrino emission from hard X-ray AGN
- Confirmed emission of NGC 1068 and found NGC 4151 @ 2.9 σ significance



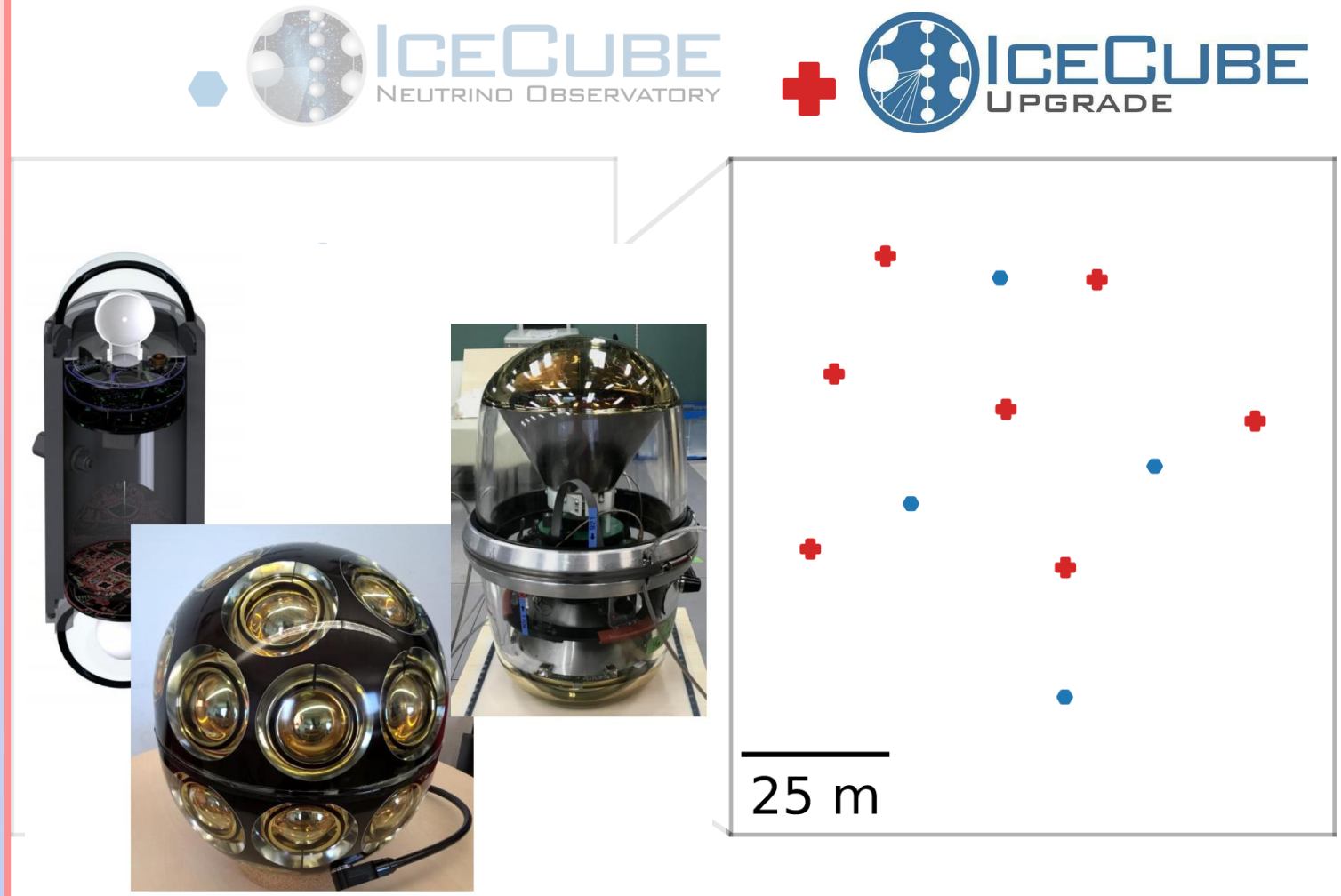
- Overlapping data sets and source catalogues → not independent results
- Open questions remain about neutrino production mechanism in source candidates
- Further studies on-going!

Publications submitted to ApJ:
https://arxiv.org/abs/2406.07601
https://arxiv.org/abs/2406.06684

Extending to higher and lower energies

IceCube Upgrade

- Better efficiency and reconstruction at low energies with significantly increased photodetection area
- Improved calibration of ice, reduced systematic uncertainties
- Deployment of new photosensors in winter 2025/26
- Goals:
  - Precision measurement of atmospheric neutrino oscillations
  - Re-processing of >TeV data to include new calibration



Extending to higher and lower energies

IceCube-Gen2

- In Ice:
  5x larger effective area and 2x better pointing for highest-energy tracks -> significant improvement expected for detection of highest-energy sources
- Other components:
  large radio array & surface CR detectors