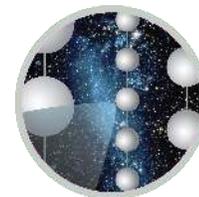


The Neutrino Universe

Highlights with IceCube

Thijs Juan van Eeden
Moriond 2026
Electroweak Interactions & Unified Theories

HELMHOLTZ



ICECUBE
NEUTRINO OBSERVATORY



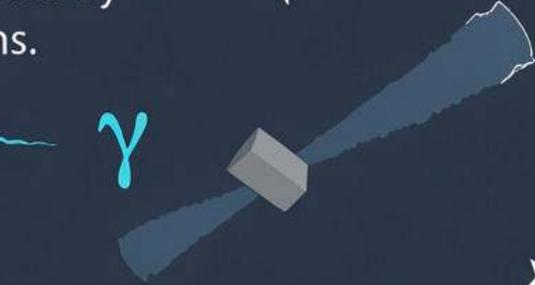
AGNs, SNRs, GRBs...

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.

air shower

p

p

Earth

γ

γ

γ

ν

ν

ν

ν

ν

Detect Cherenkov radiation from ν interaction products

Located at the South Pole

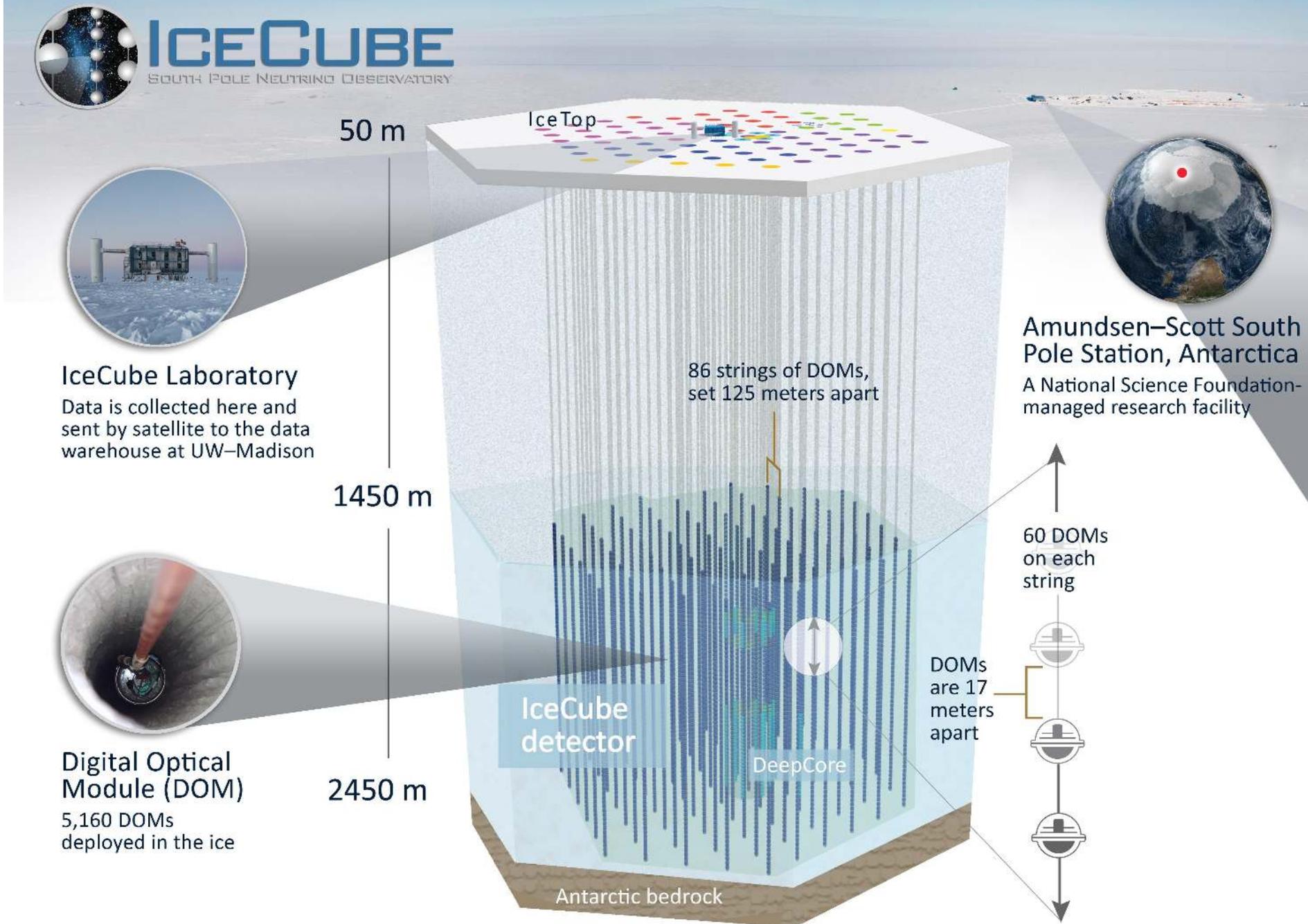
- 86 strings with 60 optical modules
- 6 denser strings targeting lower energy: DeepCore



IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW-Madison



Digital Optical Module (DOM)
5,160 DOMs deployed in the ice

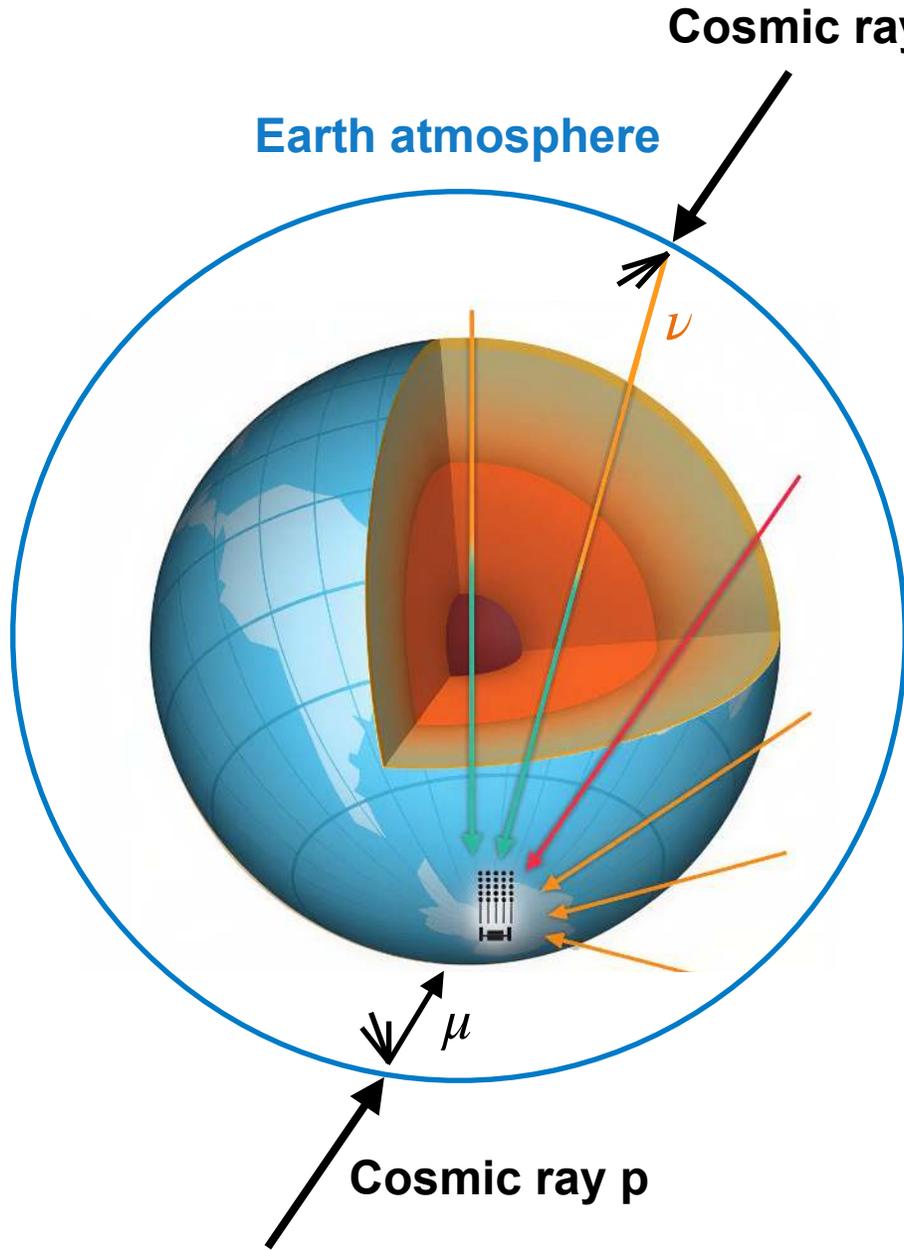


Atmospheric μ background

- Muons often reach the Earth surface before decaying

Suppressed by

- Earth filtering
—> Use upgoing events
- Veto regions
—> Reject when entering from detector boundary



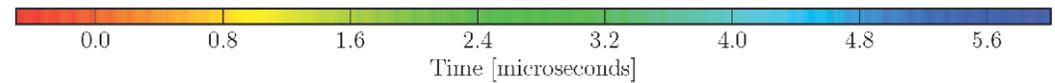
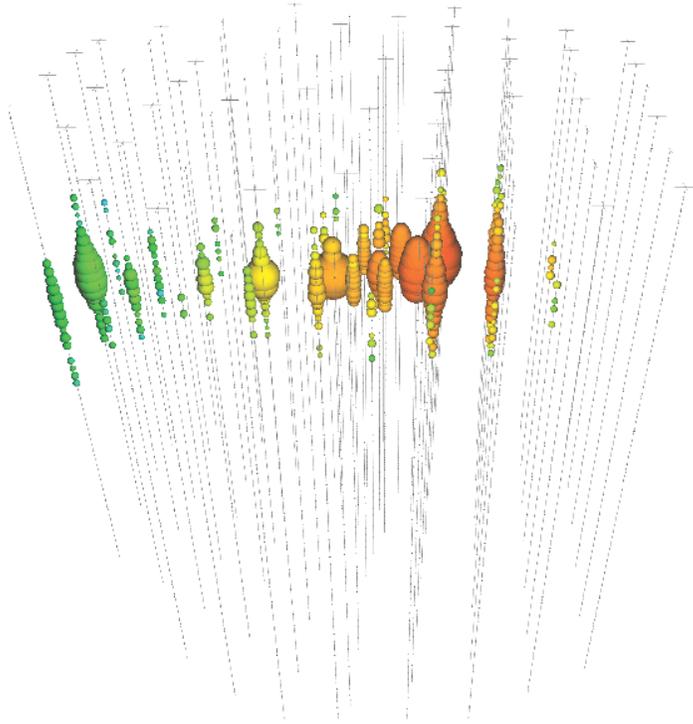
Atmospheric ν

- Conventional and prompt component from short lived charmed mesons

Detection signatures

Track

- μ from ν_{μ} CC
- Good angular resolution



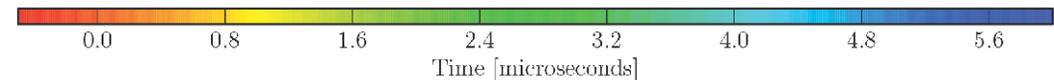
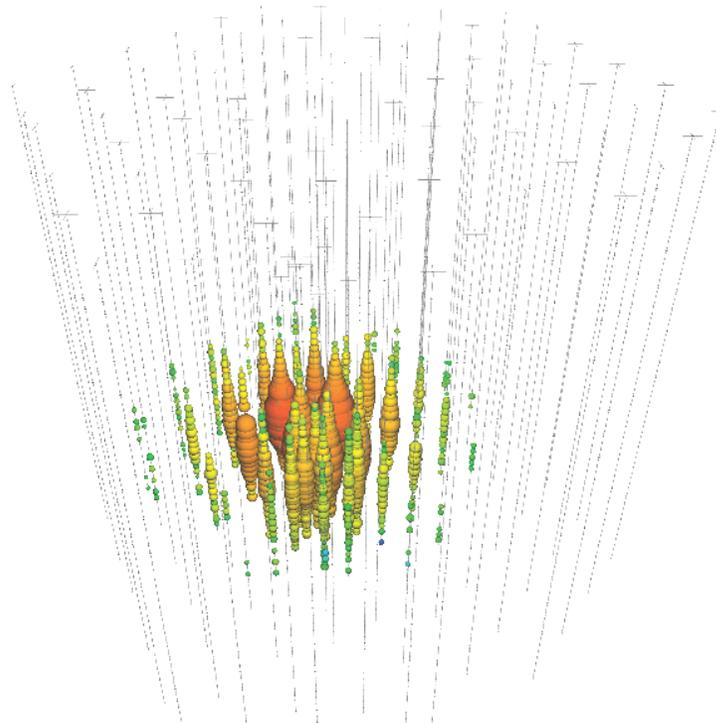
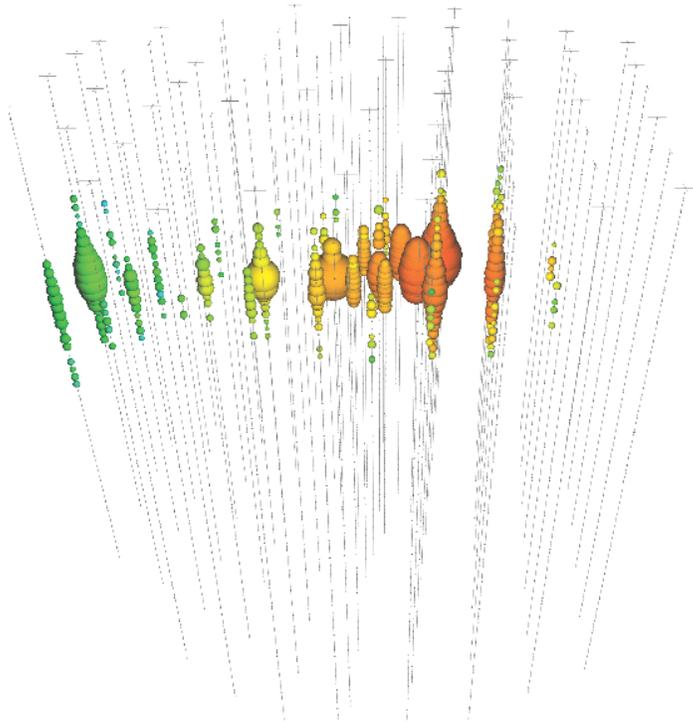
Detection signatures

Track

- μ from ν_μ CC
- Good angular resolution

Cascade

- ν NC and ν_e CC
- Good energy resolution



Detection signatures

Track

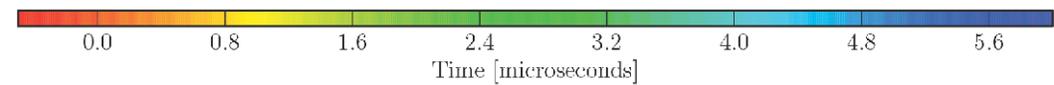
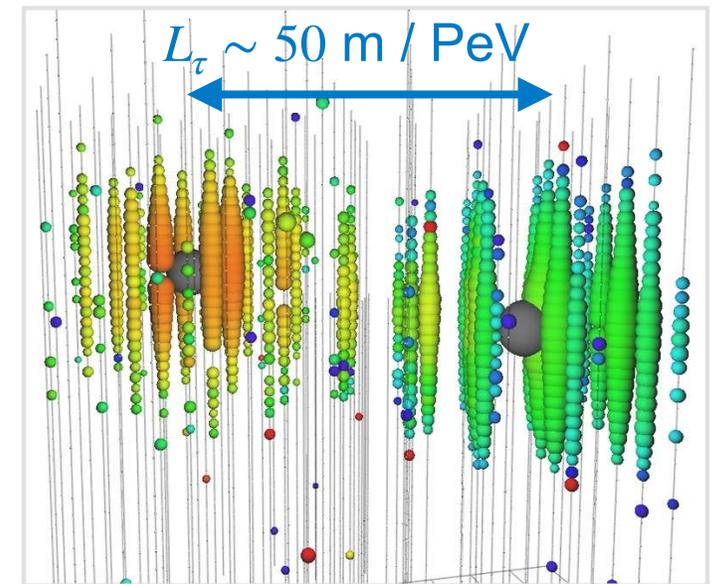
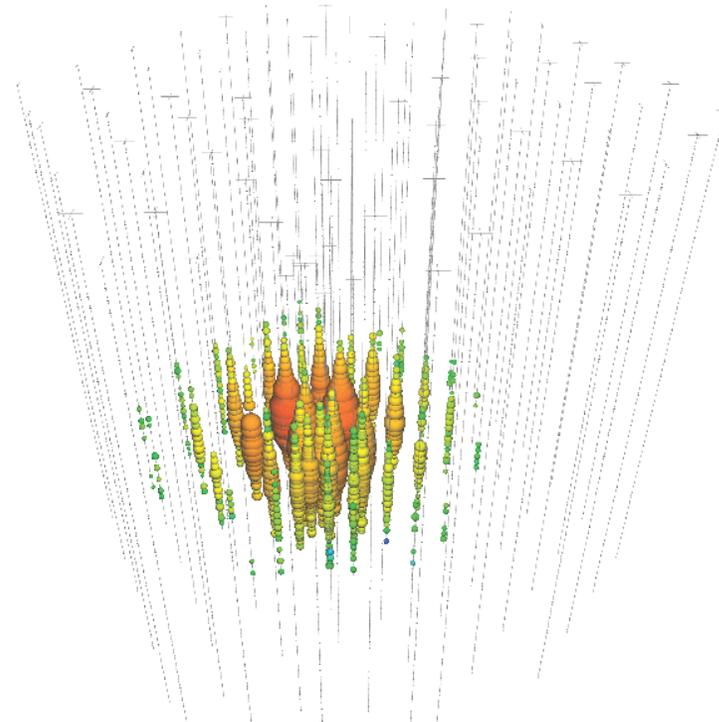
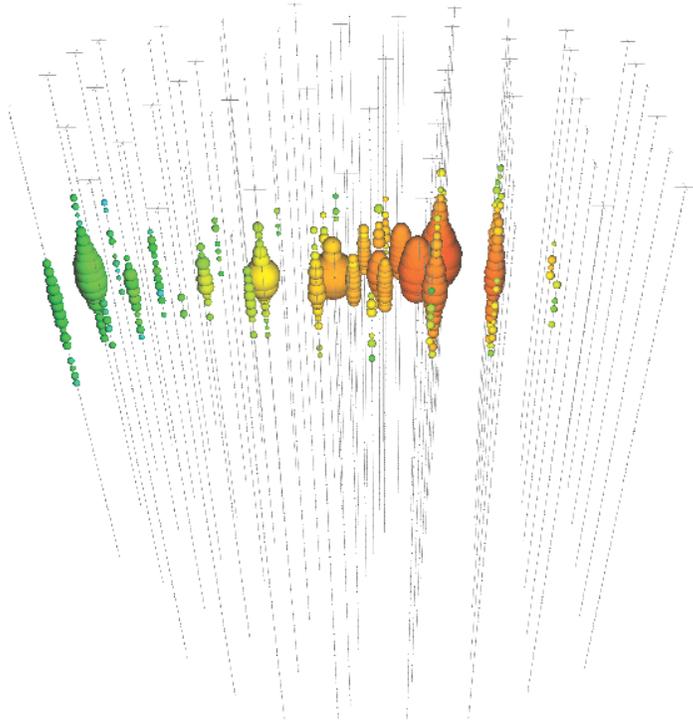
- μ from ν_μ CC
- Good angular resolution

Cascade

- ν NC and ν_e CC
- Good energy resolution

Double cascade

- ν_τ CC, $\tau \rightarrow$ hadrons, electron
- Most important signature for ν_τ



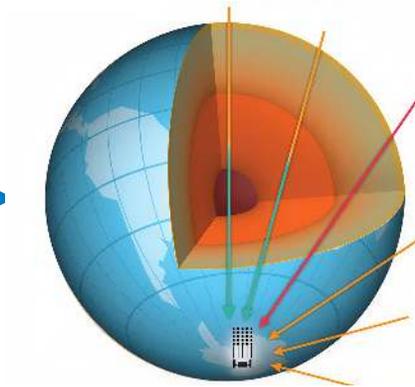
Neutrino source searches

IceCube

Search for excess in the sky or from known sources in catalogs (blazars, active galaxies, tidal disruption events, ..)



ν



Neutrino source searches

IceCube



2013

.....●.....
**ASTROPHYSICAL
NEUTRINOS**
DISCOVERED



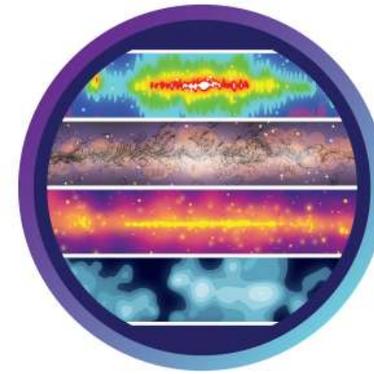
2018

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2022

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2023

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2024

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Neutrino source searches

IceCube



2013

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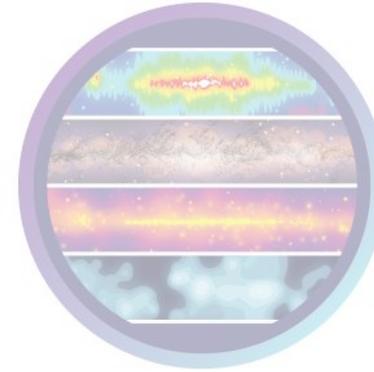
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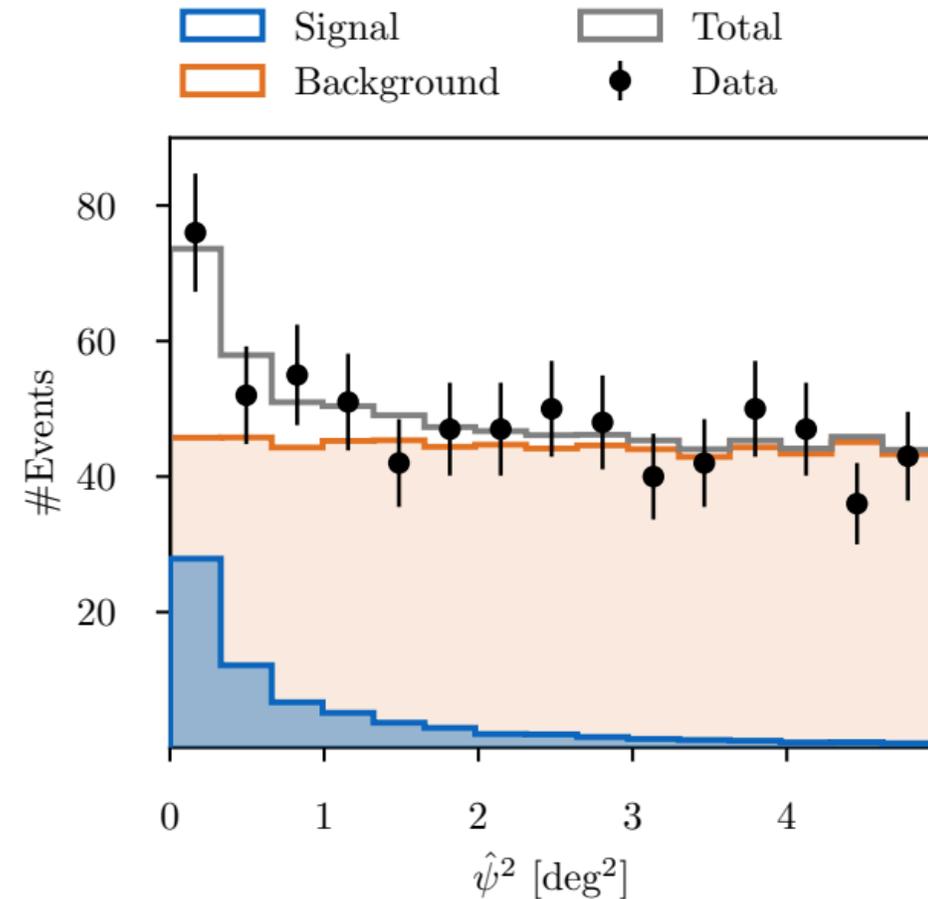
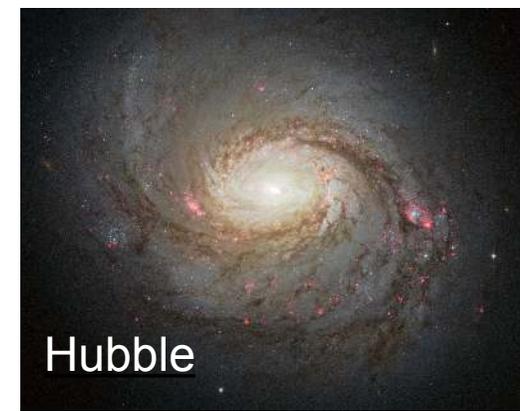
2024

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Source searches

Nearby active galaxies

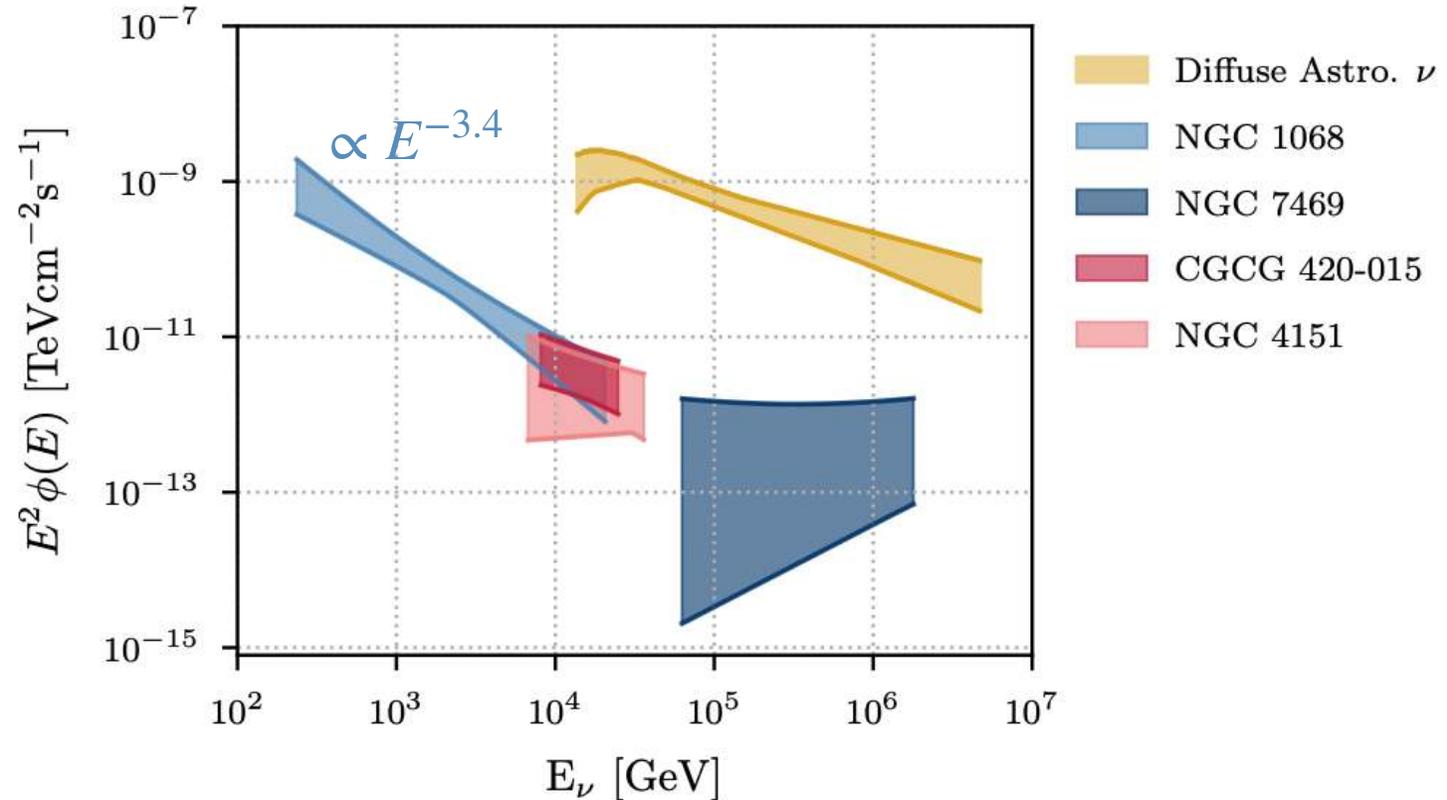
- Neutrino emission from nearby active galaxy
NGC 1068: [Science, 378\(6619\), 538-543](#)
- No γ at similar energy
- X-ray brightest active galaxy in sky



Source searches

Nearby active galaxies

- Neutrino emission from nearby active galaxy NGC 1068: [Science, 378\(6619\), 538-543](#)
- Follow-up on 47 bright X-ray sources
 - Submitted to ApJL: [arXiv.2510.13403](#)
 - NGC 1068: 4σ
 - Soft spectrum: $\gamma = 3.4$
 - Much higher ν flux than γ
 - 3.3σ when stacking 11 sources, excluding NGC 1068



Flavor composition

IceCube



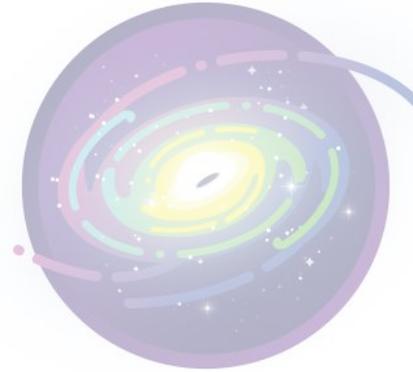
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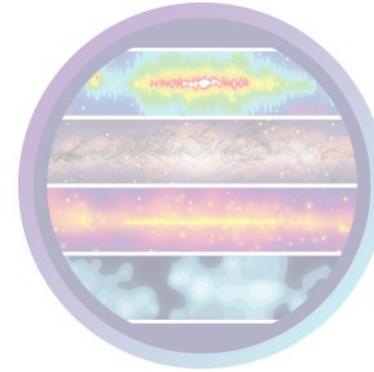
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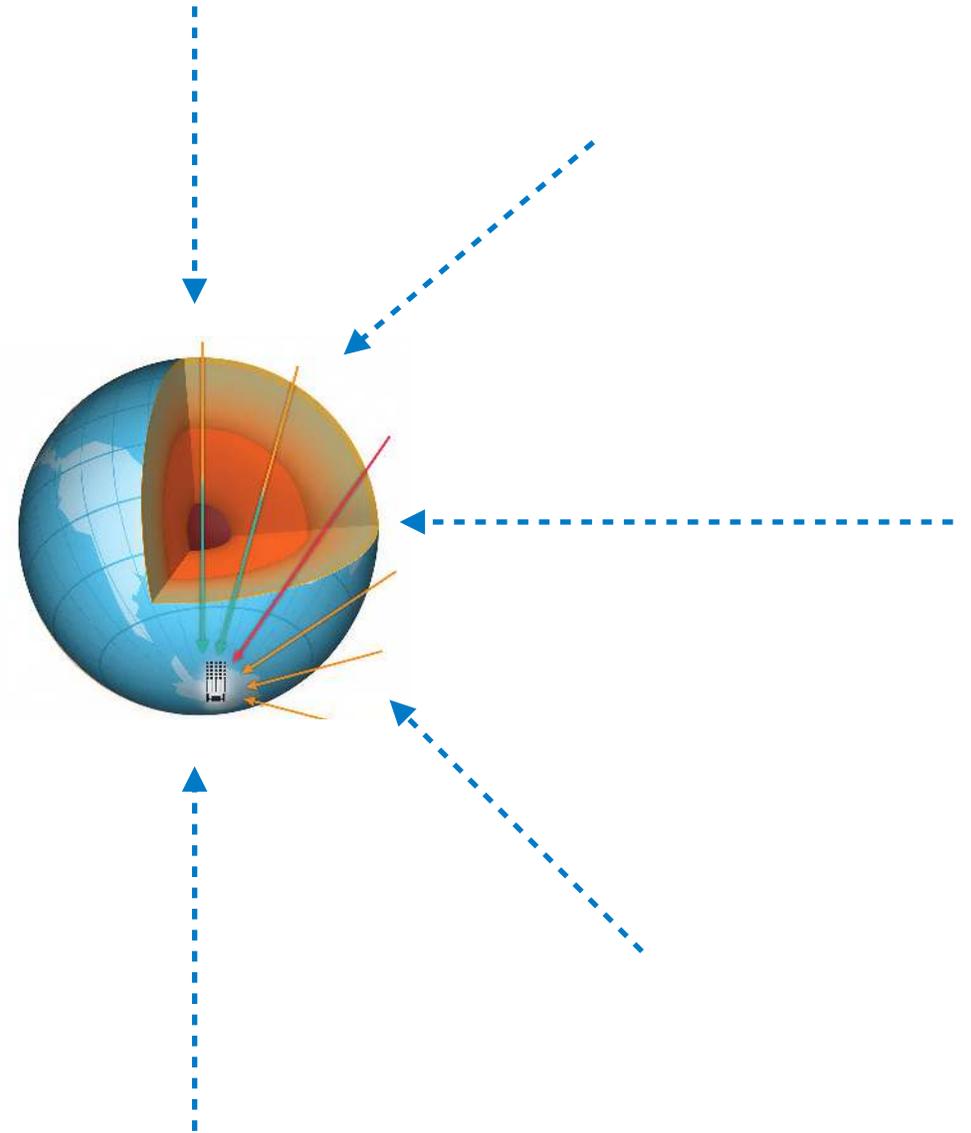
Diffuse neutrino studies

IceCube

- Characterise ν energy spectrum
 - Measure flavor composition
- > Probe cosmic ray acceleration and source environment



Oscillating ν



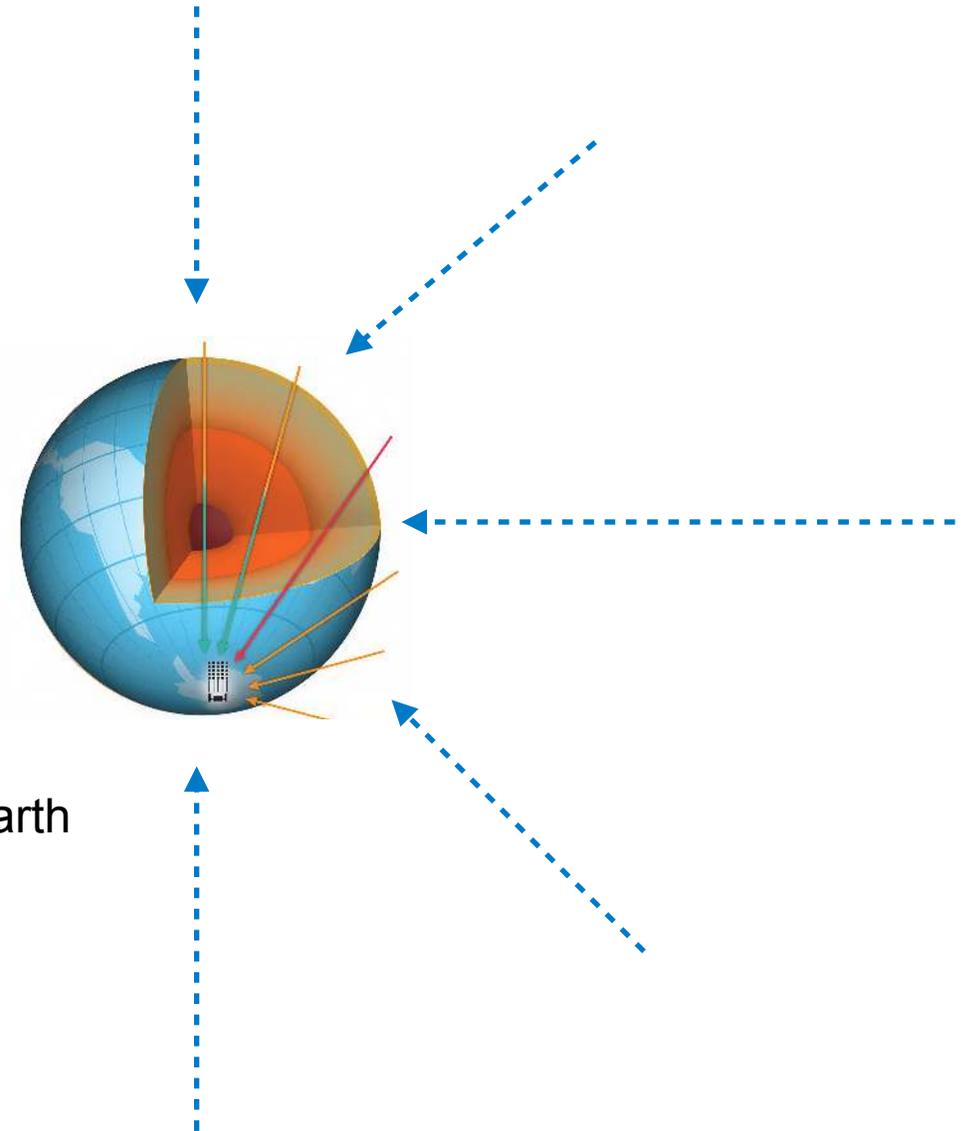
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Oscillating ν



Flavor composition at the source

● $f_e : f_\mu : f_\tau = 1 : 2 : 0$

Measured flavor composition at Earth

$f_e : f_\mu : f_\tau$

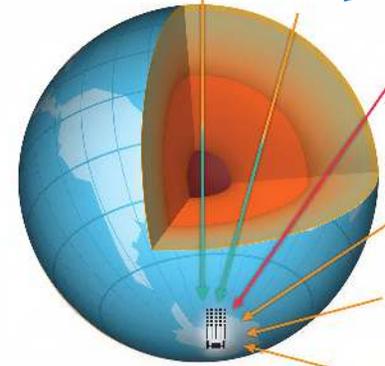
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$f_e : f_\mu : f_\tau$

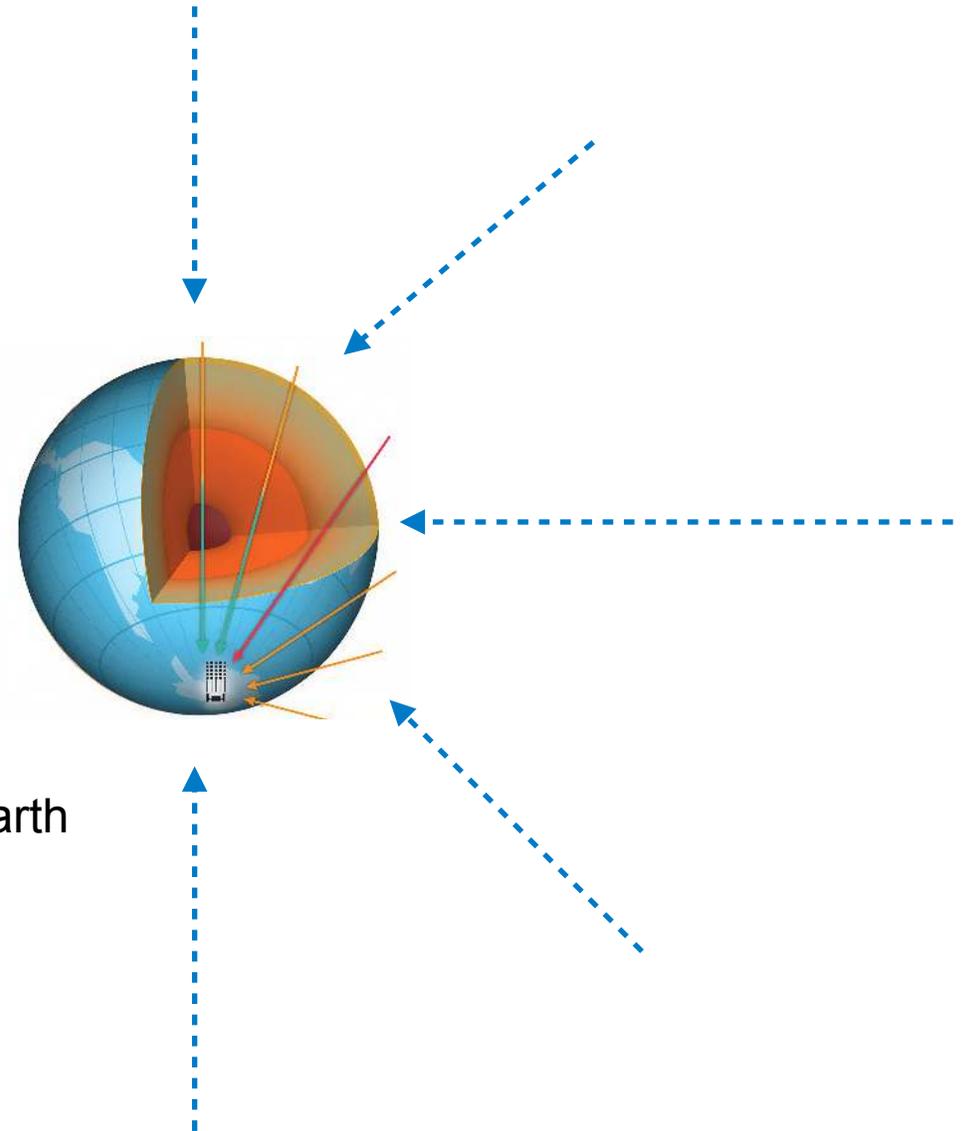
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▲ $f_e : f_\mu : f_\tau = 1 : 0 : 0$

Measured flavor composition at Earth

$f_e : f_\mu : f_\tau$

Astrophysical flavor composition

With IceCube

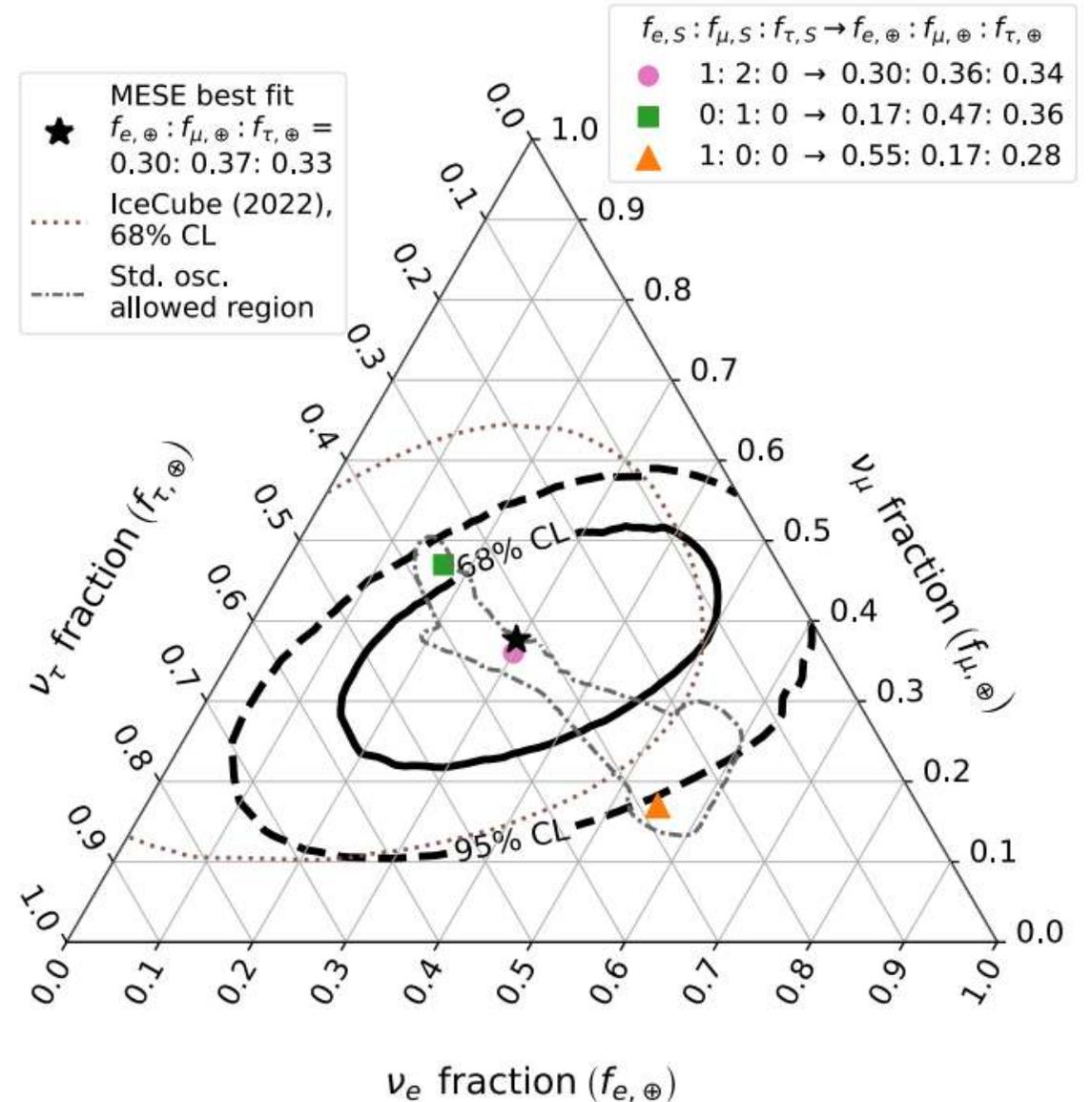
- 11.4 years of IceCube starting events with lower energy threshold: 5 - 10 TeV
 - Starting events sensitive to all neutrino flavors
- Best-fit flavor composition

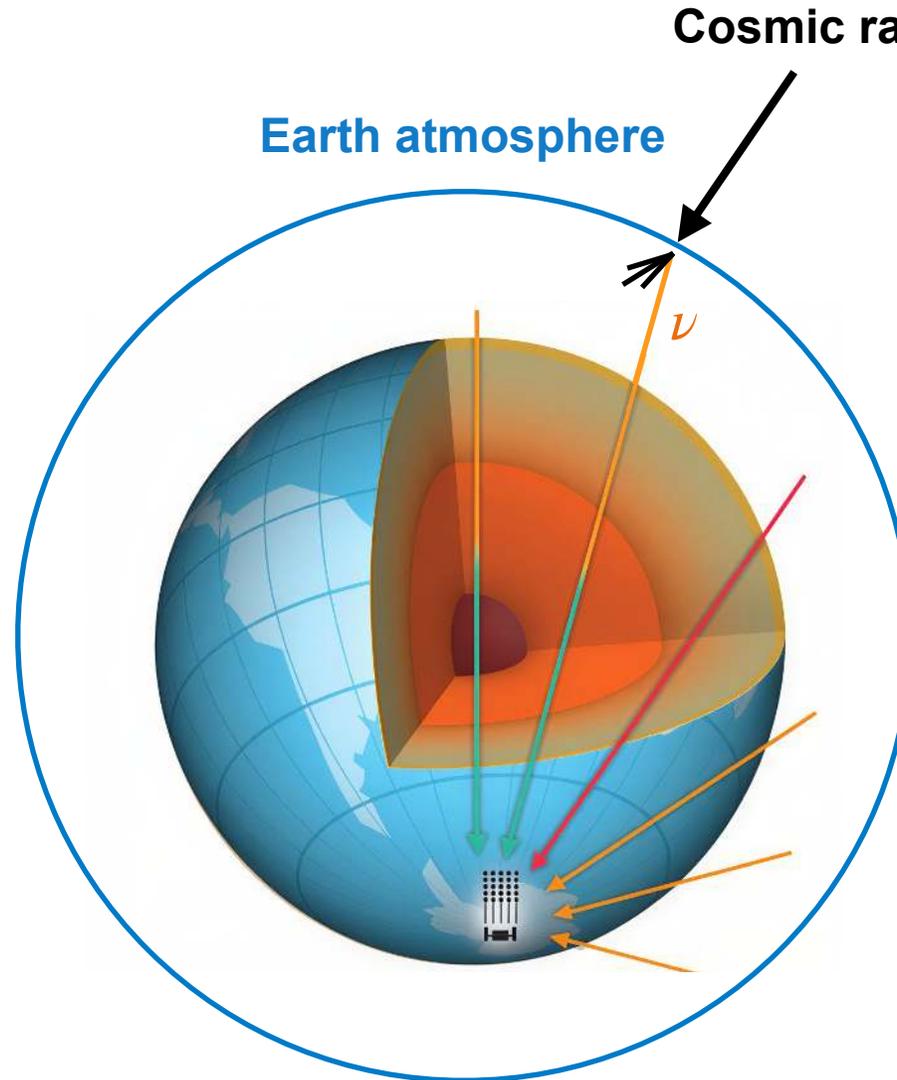
$$f_{\nu_e} : f_{\nu_\mu} : f_{\nu_\tau} = 0.30 : 0.37 : 0.33$$
- Submitted to PRL: [arXiv.2510.24957](https://arxiv.org/abs/2510.24957)

Ongoing efforts to combine high-energy starting events with tracks and cascades

—> Same treatment of systematics

—> Perform combined flavor composition measurement





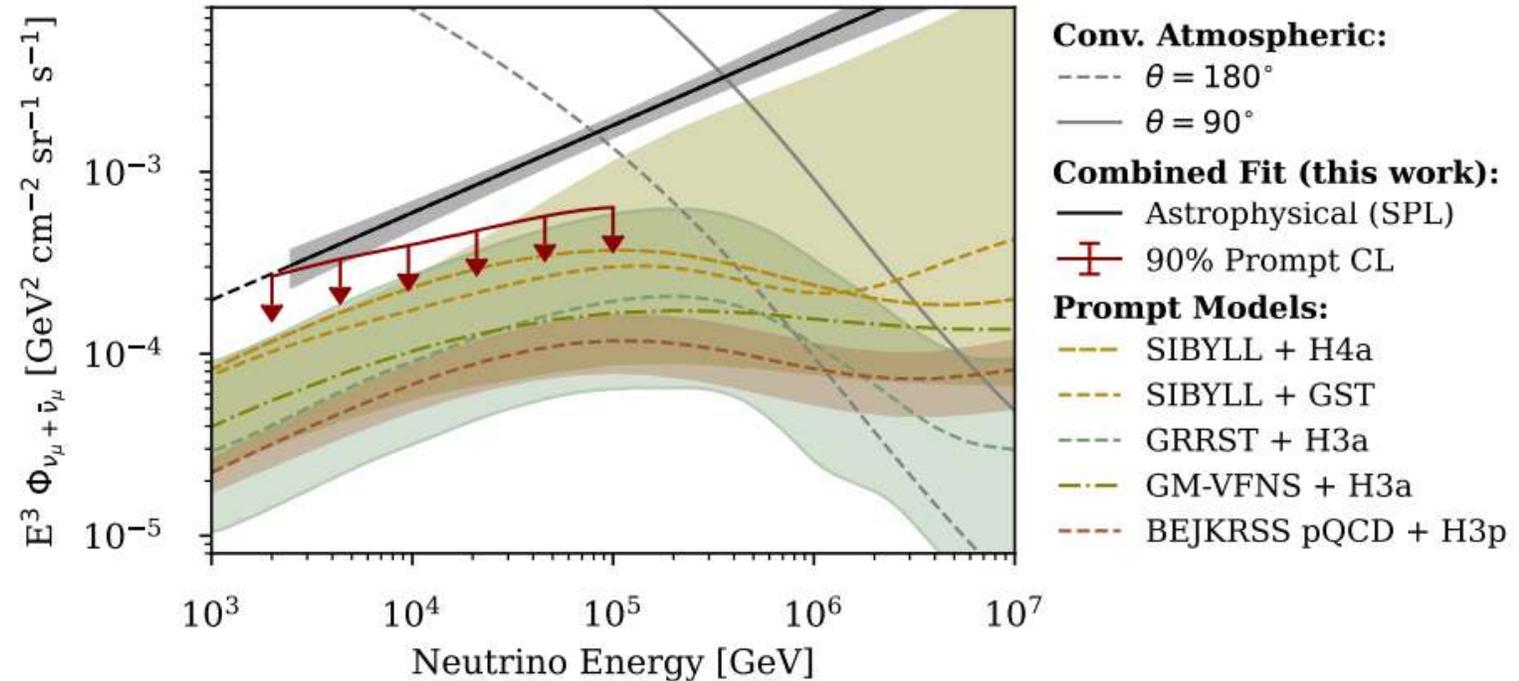
Atmospheric ν

- Conventional component:
 - $K^+, \pi^+ \rightarrow \nu_\mu + \mu^+$
 - $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
- Dominates < 100 TeV
- $dN/dE \sim E^{-3.7}$
- Prompt component from short lived charmed mesons
 - Dominates > 100 TeV
 - $dN/dE \sim E^{-2.7}$

Prompt neutrinos

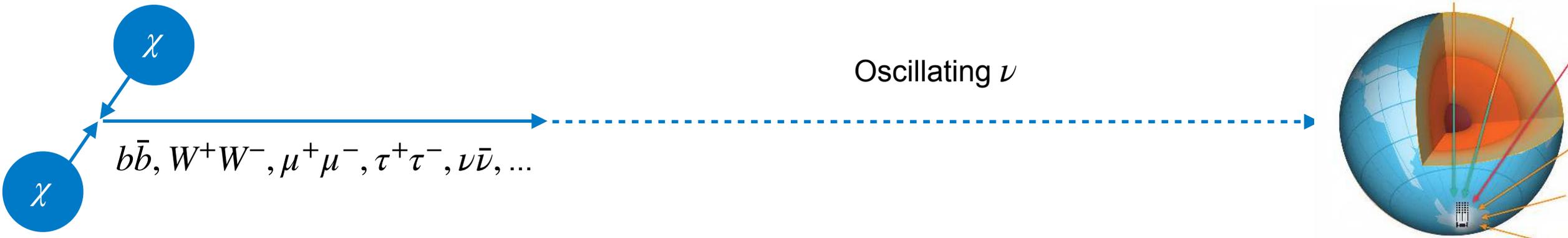
With IceCube

- Understanding hadronic interactions in cosmic ray air showers
- Improves astrophysical neutrino studies
- Not observed yet in separate track and cascade analyses
 - Hidden by astrophysical neutrinos
- Combined analysis: non-zero best-fit
 - Consistent with null hypothesis: 1σ
- Submitted to EPJ-C: [arXiv.2512.17760](https://arxiv.org/abs/2512.17760)



Searches for WIMPs

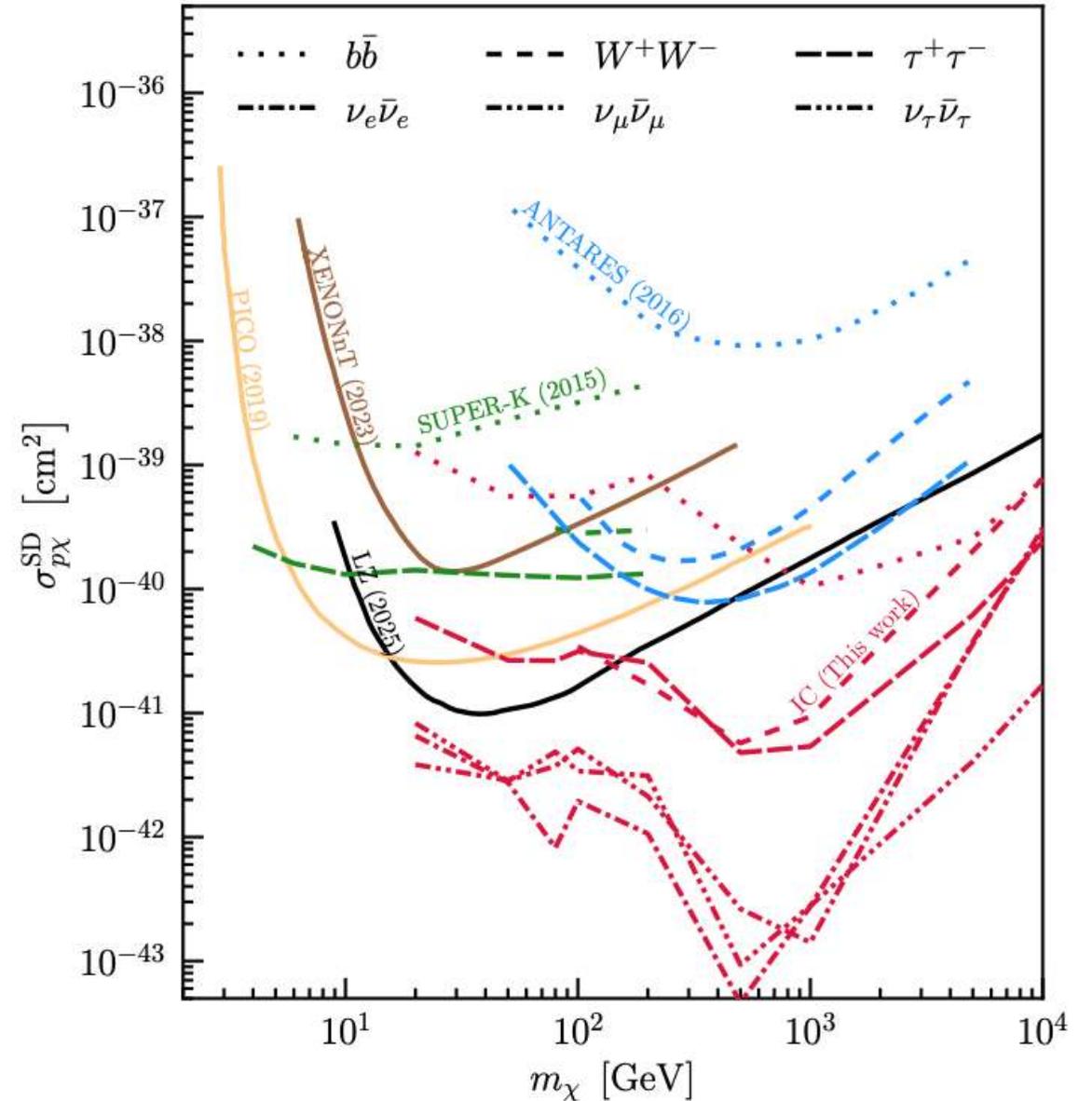
Indirect detection



Searches for WIMPs

The Sun

- DM scatters on nuclei in sun
 - > Gravitationally bound
 - > Capture and annihilation in equilibrium
- World-best limits spin-dependent DM-proton scattering cross section
- Complementarity between the different mass regimes
 - Accelerators can target even lower masses
 - Direct detection performs better for spin-independent cross section
- Submitted to PRL: [arXiv.2507.08457](https://arxiv.org/abs/2507.08457)



What's next?

IceCube



2013

.....●.....
**ASTROPHYSICAL
NEUTRINOS**
DISCOVERED



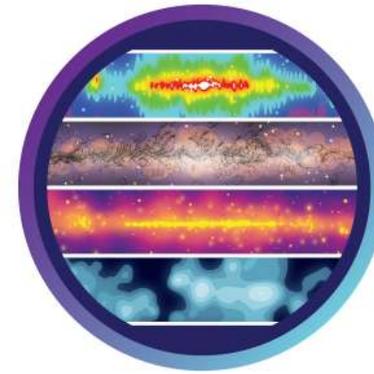
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2024

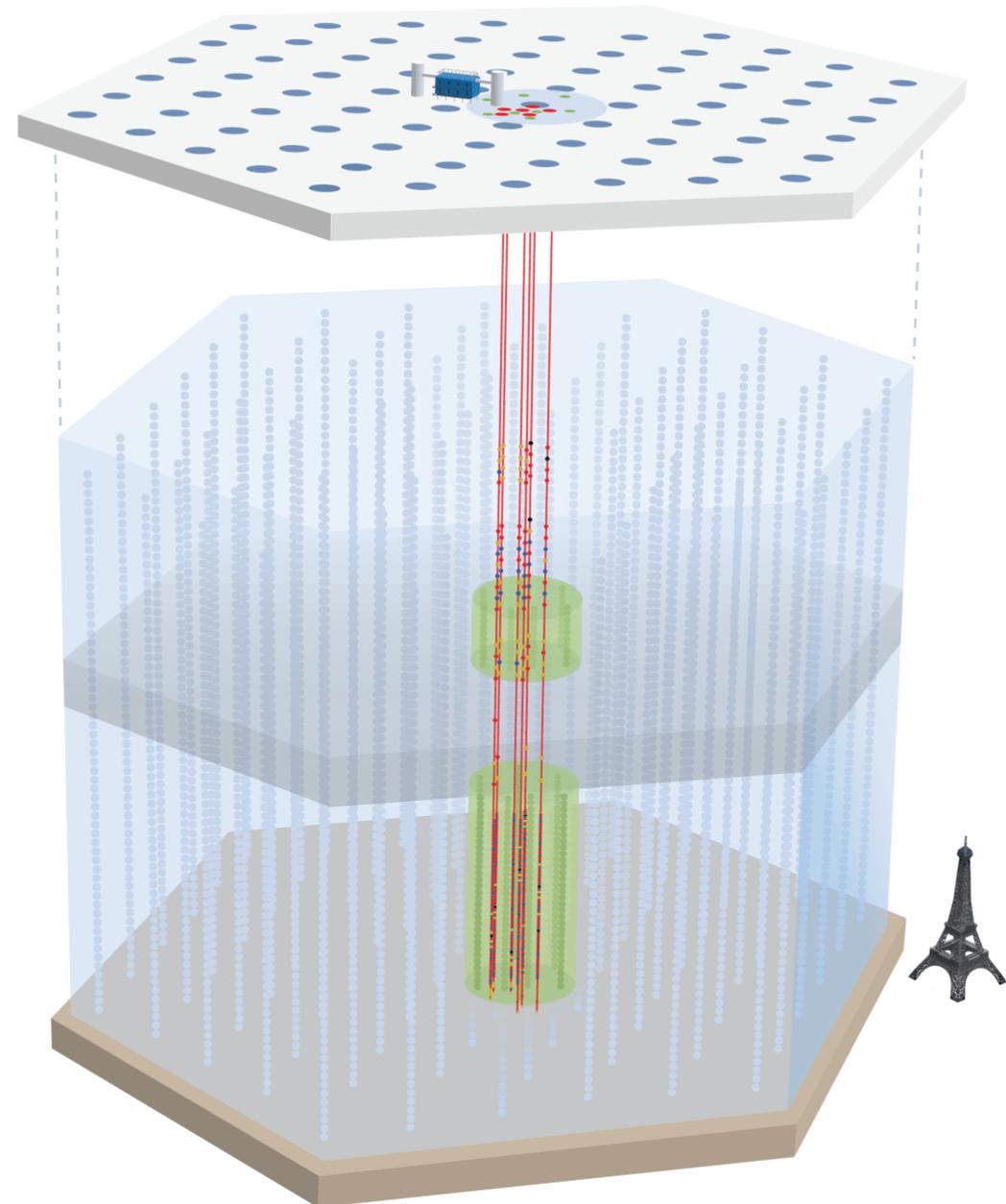
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**ASTROPHYSICAL
TAU NEUTRINOS**
IDENTIFIED

The IceCube Upgrade

Deployed this season

6 densely instrumented strings with > 600 improved optical modules and calibration devices: [press release](#)

- Extend energy range to lower energies
 - Improved oscillation and WIMP sensitivities
- Special devices for studying ice properties
 - Improve calibration throughout whole detector



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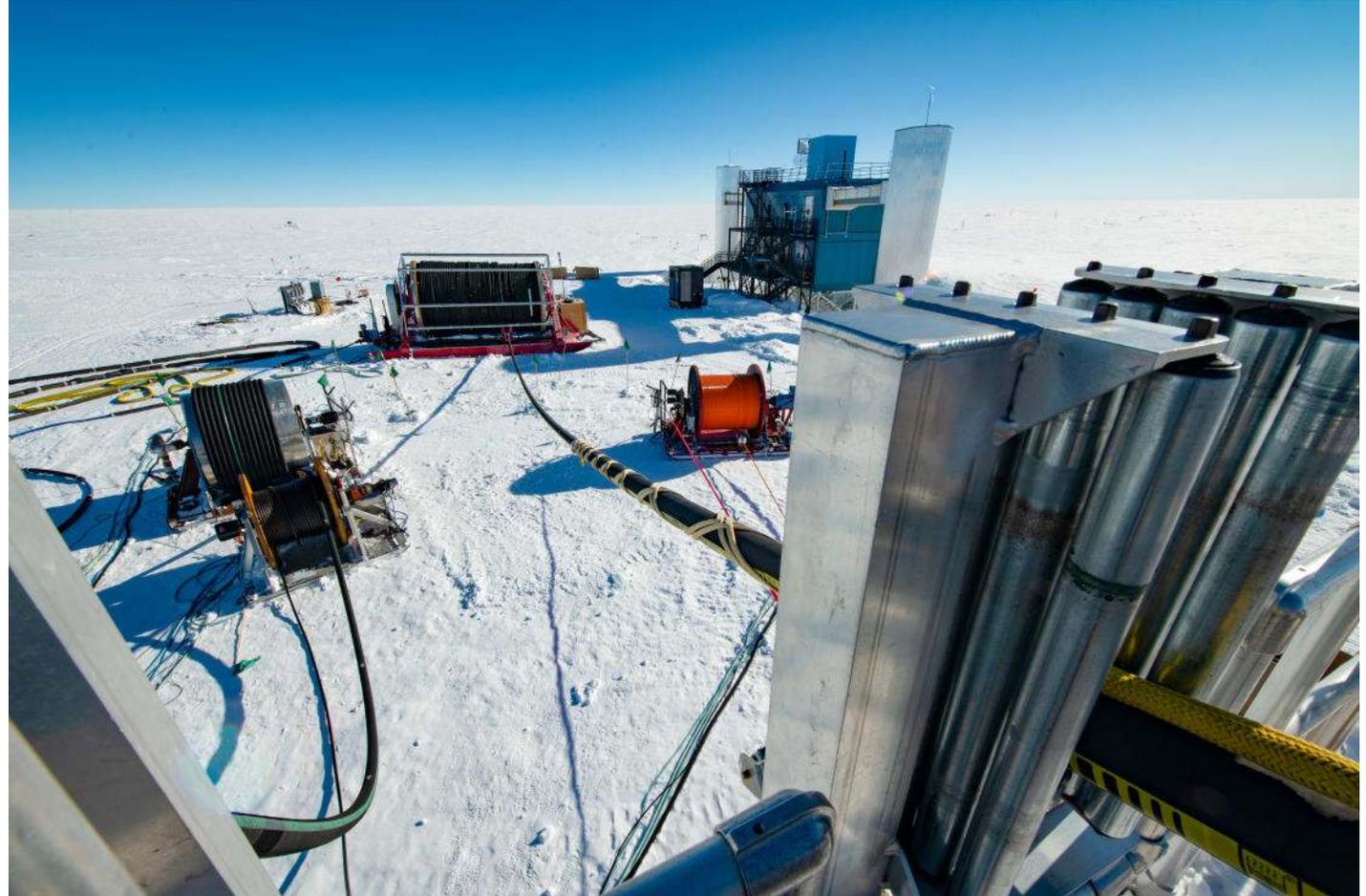


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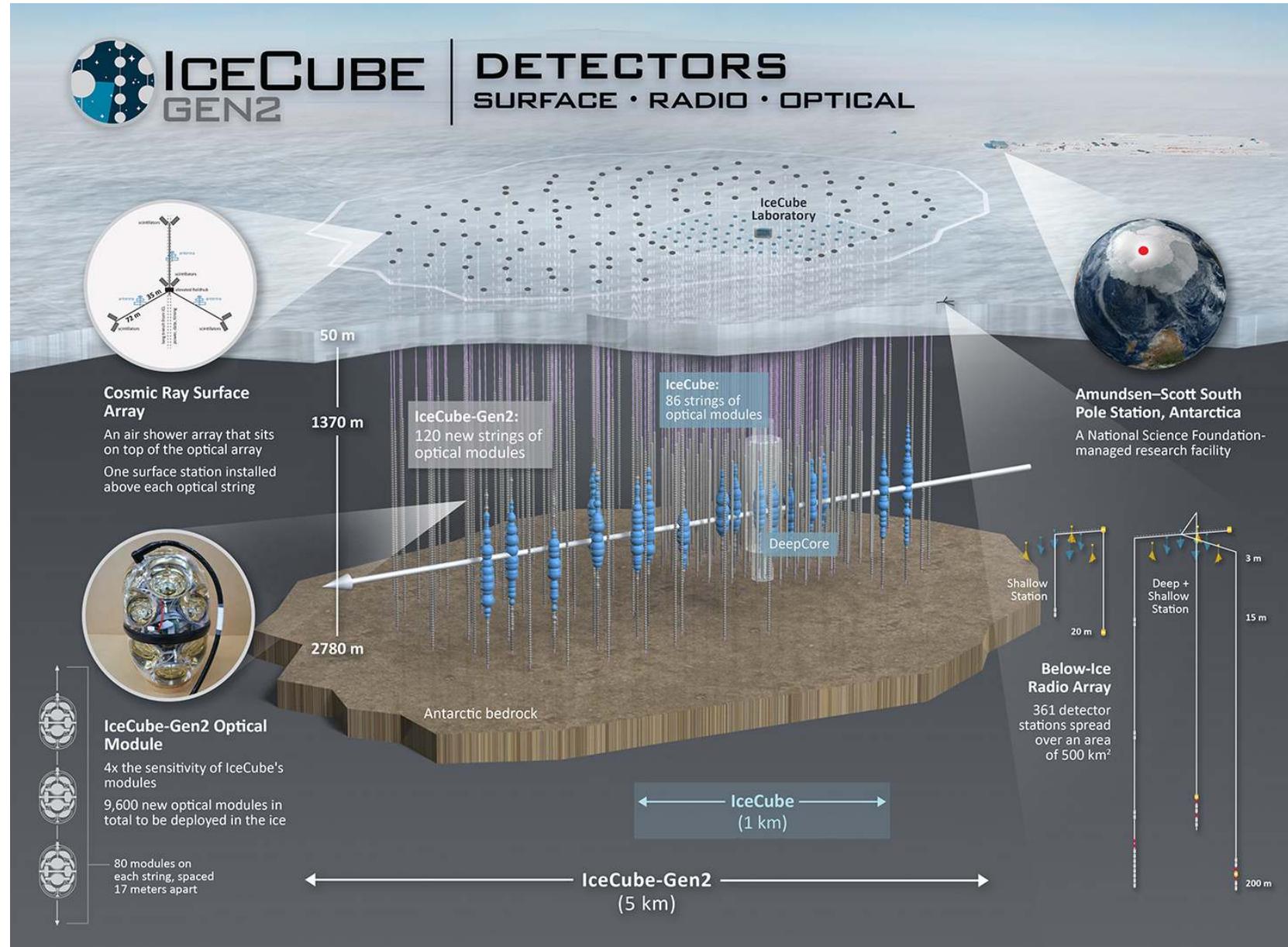
IceCube-Gen2

Future

- Increase optical array from 1 to 8 km³
- Radio array to detect ν via Askaryan effect

Extend sensitivity beyond 1 EeV

On German national roadmap



Summary

- IceCube detects neutrinos over a large energy range

Outlook

- Improved calibration for new and archival data due to the IceCube Upgrade
- Probing extremely high-energy neutrinos with IceCube-Gen2

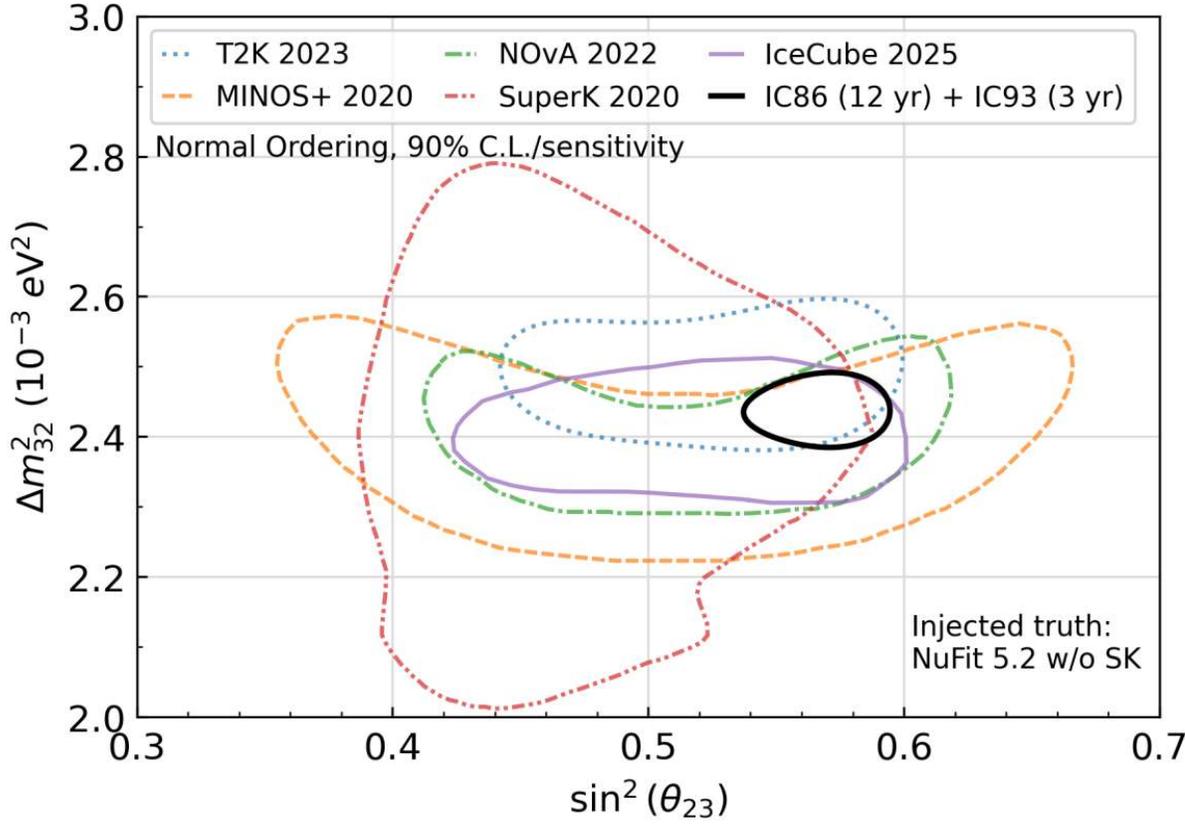
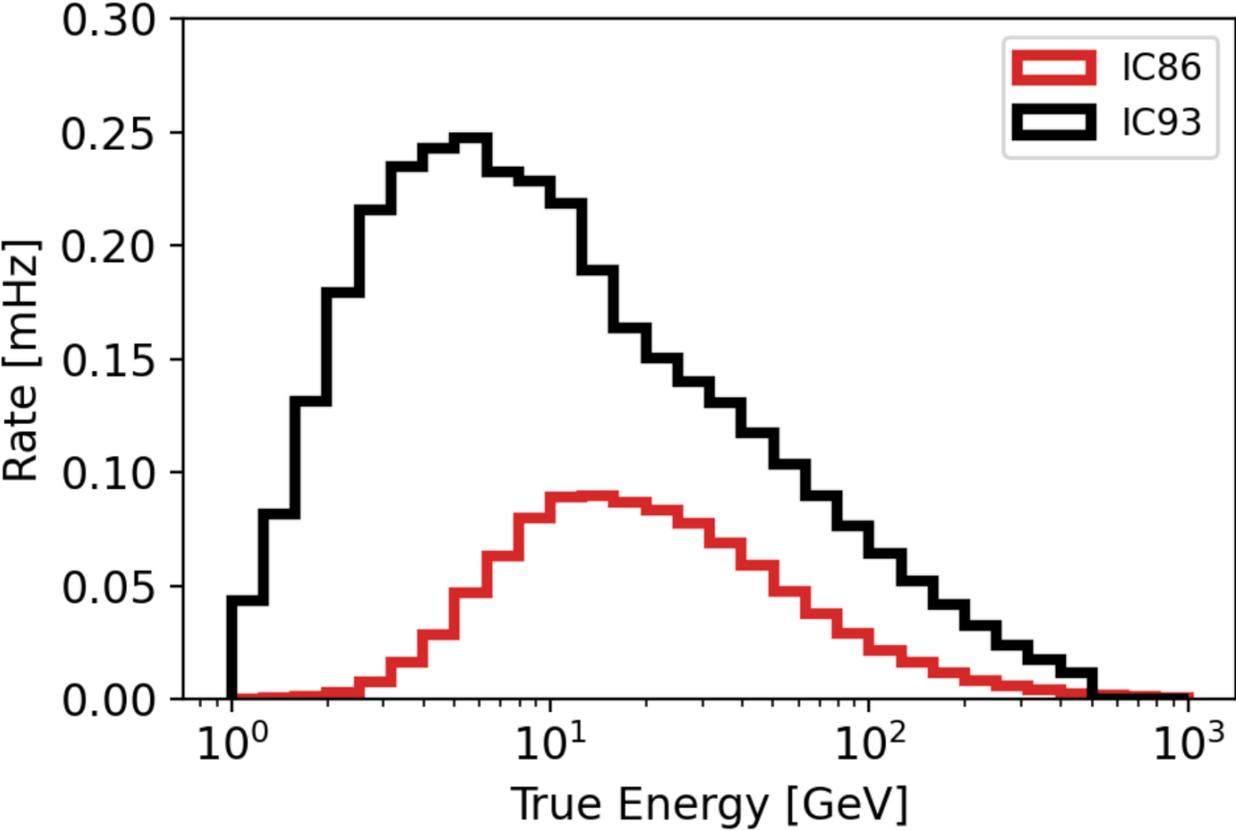


Backup

IceCube Upgrade

Physics potential

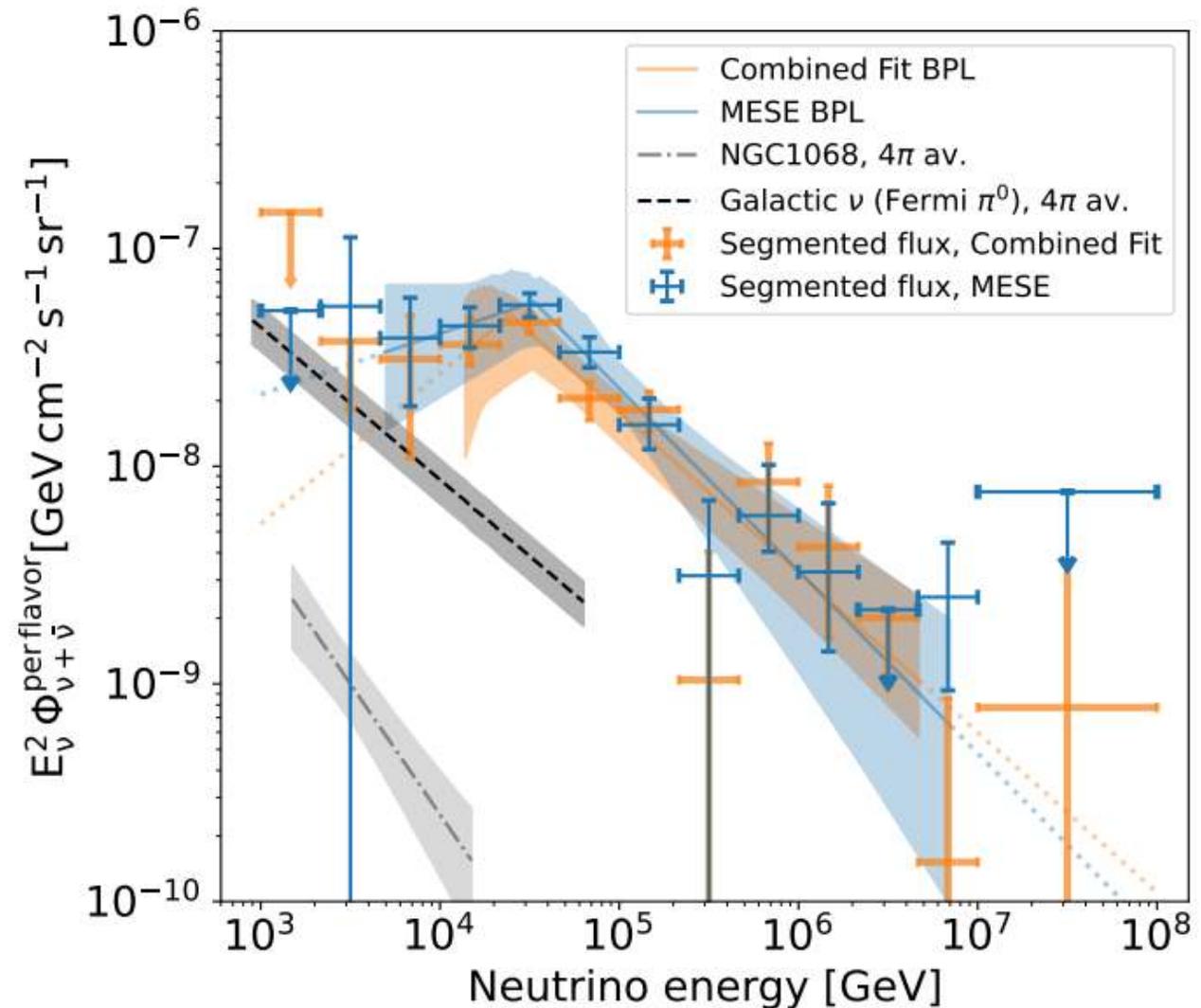
• [arXiv.2509.13066](https://arxiv.org/abs/2509.13066)



Diffuse astrophysical neutrinos

With IceCube

- Combined track and cascade analysis shows first evidence in break of spectrum (30 TeV)
 - Confirmed by separate event selection with starting events
- Broken power law preferred over single power law with $>4\sigma$
- Spectral break could indicate changes in source population or mechanism for neutrino production
- Submitted to PRL: [arXiv.2507.22233](https://arxiv.org/abs/2507.22233)

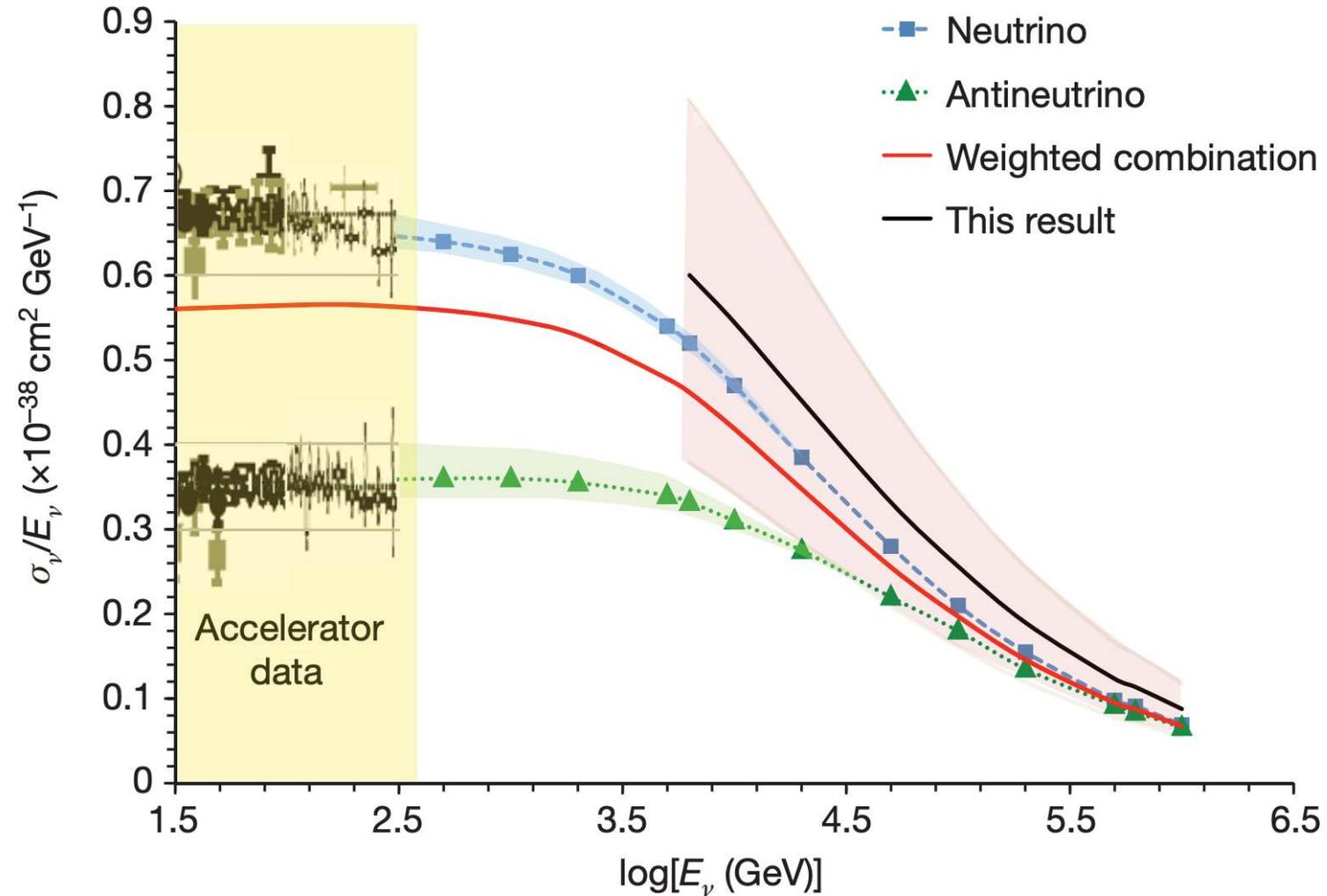


Cross sections

With IceCube

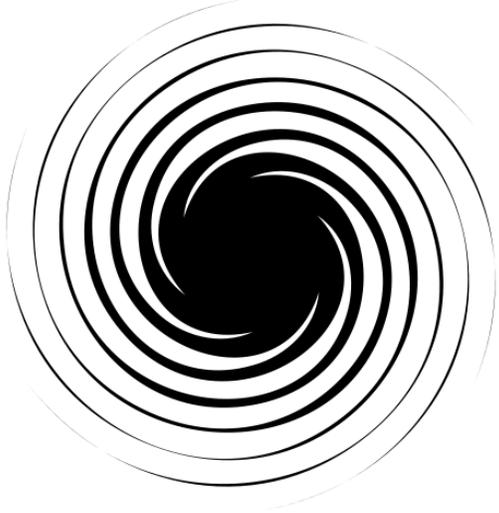
- Cross section measurement above 40 TeV
 - 1.3 times prediction SM, but within uncertainties
- Use attenuation in the Earth
- Neutrino beam at accelerators reach ~ 0.4 TeV
 - Energy gap being filled by Faser

• [Nature 551, 596–600 \(2017\)](#)



Neutrino flavor composition

Oscillations



Neutrino oscillations

- > Diffuse neutrino flux from multiple unresolved sources with different distances
- > Sensitive to average flavor-transition probabilities
- > Only depends on mixing angles and CP violation phase



$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha \rangle|^2 = \left| \sum_i U_{\alpha i}^* U_{\beta i} e^{-i \frac{m_i^2 L}{2E}} \right|^2$$

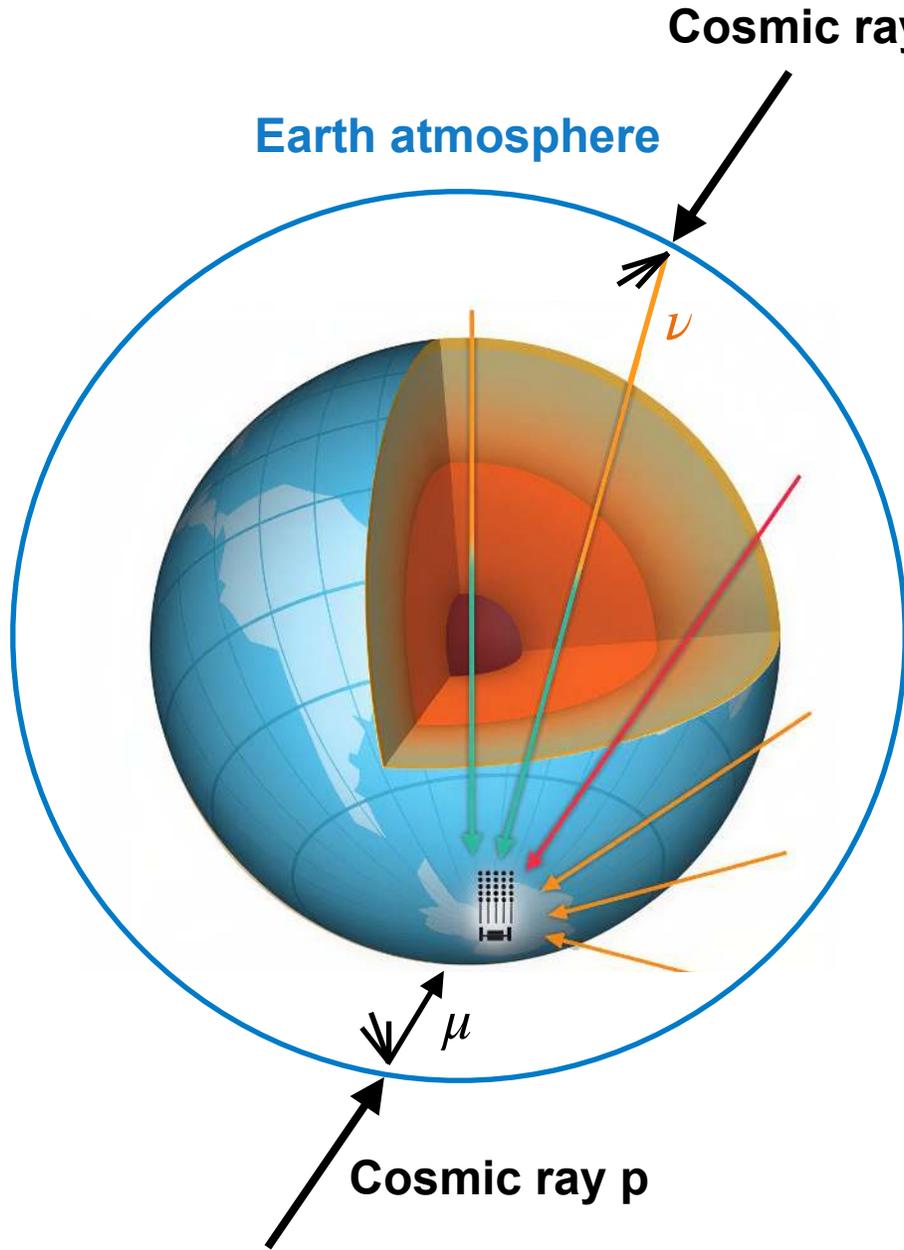
Average over L 

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Suppressed by

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- Veto regions
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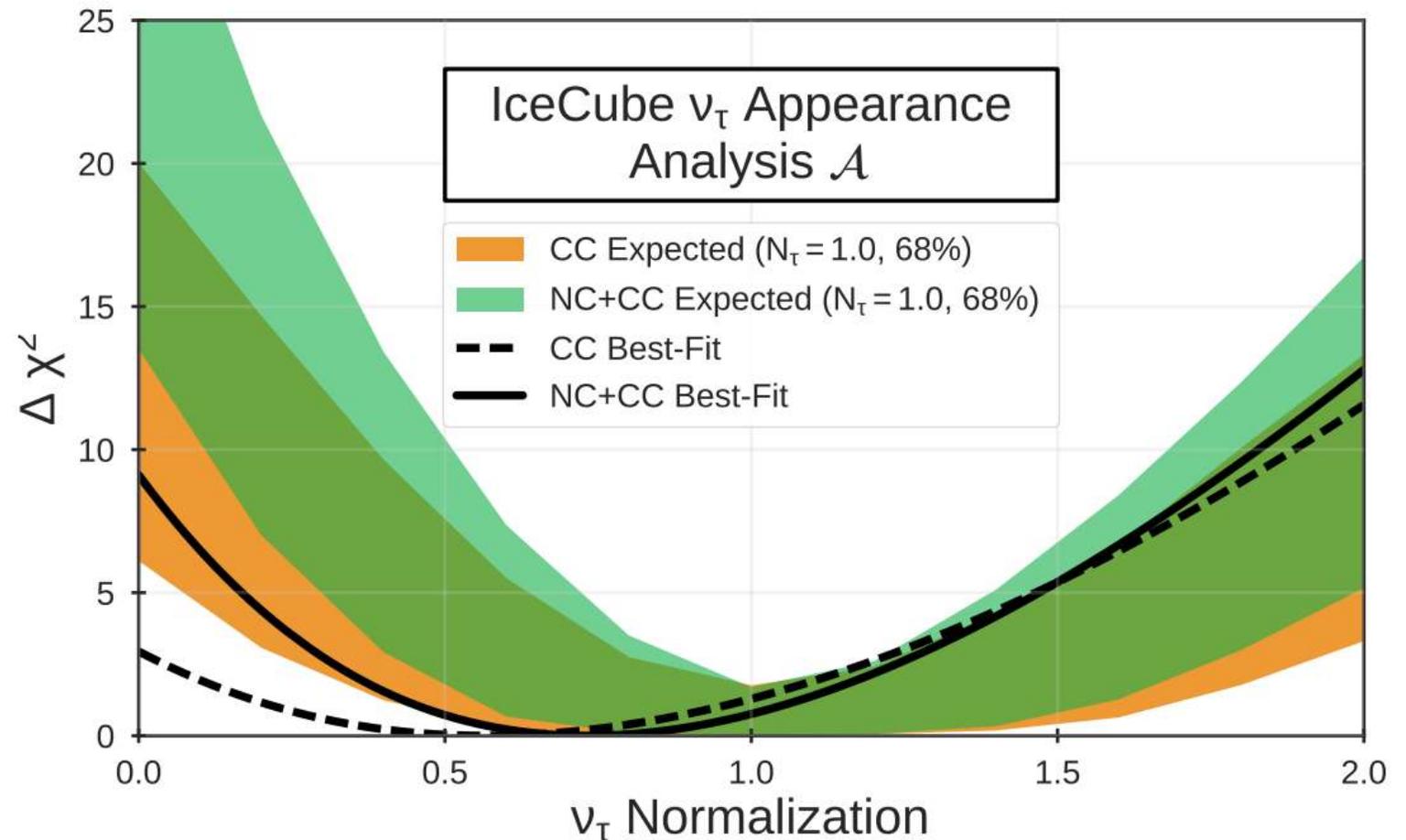
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 - $dN/dE \sim E^{-3.7}$
- Prompt component from short lived charmed mesons
 - Dominates > 100 TeV
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Atmospheric tau neutrino appearance

With DeepCore

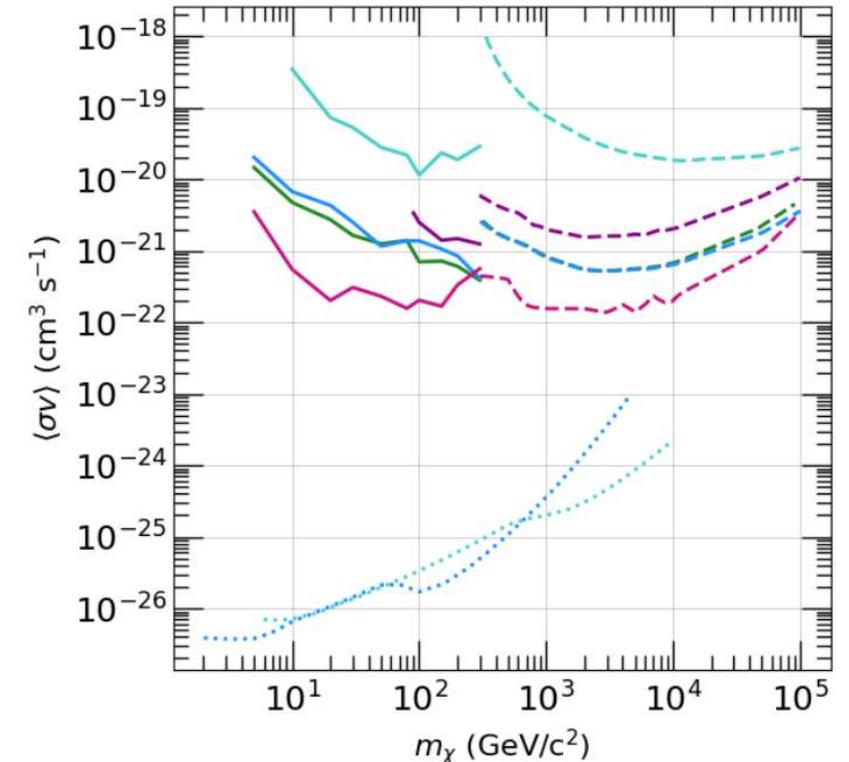
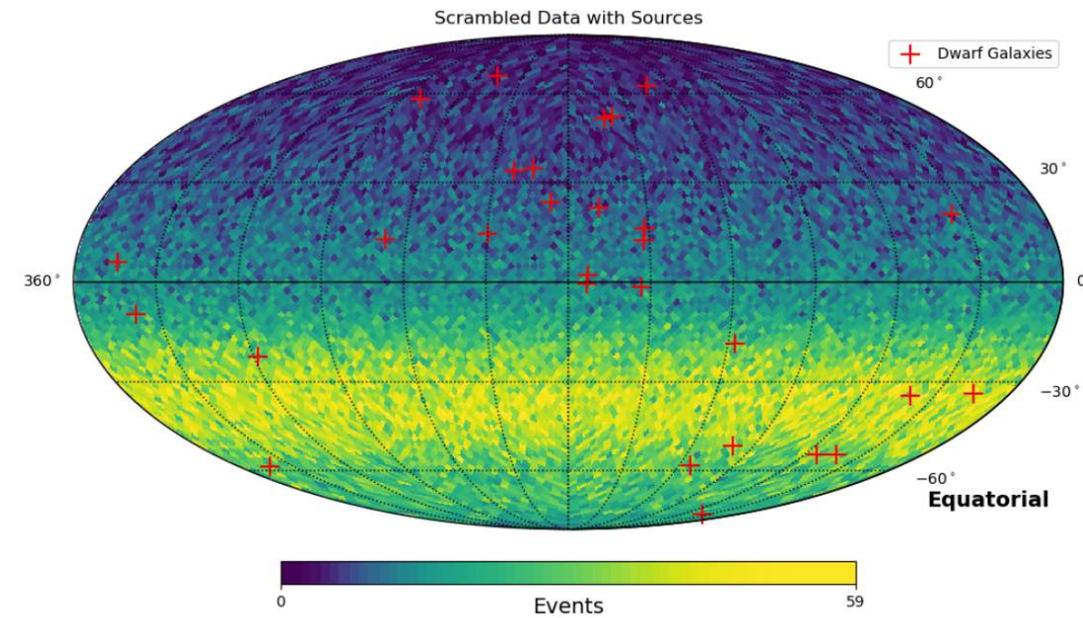
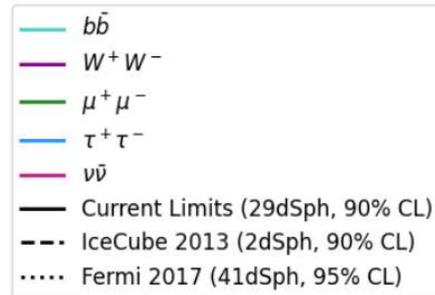
- Virtually not produced in cosmic ray air showers
—> Neutrino oscillation
- Tau neutrino normalization: $0.73^{+0.30}_{-0.24}$
- Absence of ν_τ oscillations: 3.2σ
- [Phys. Rev. D 99, 032007 \(2019\)](#)



Searches for WIMPs

Dwarf spheroidals

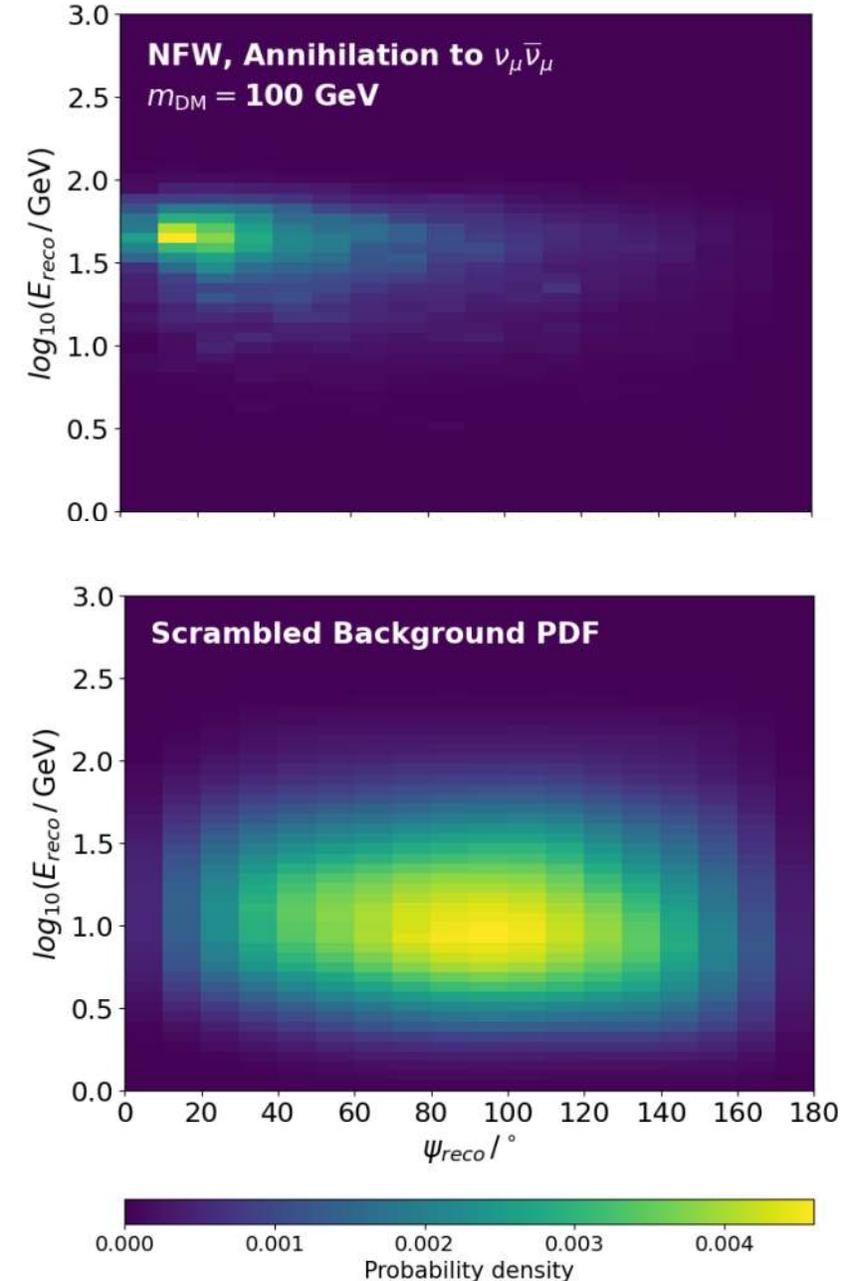
- Most DM-dominated structures known
- Little high-energy astrophysical activity
- Dark matter masses: $< 300 \text{ GeV}$
- Upper limit on velocity averaged annihilation σ
- Stacked analysis for 29 objects using 7 years of DeepCore data
Submitted to PRD: [arXiv.2511.19385](https://arxiv.org/abs/2511.19385)



Searches for WIMPs

Galactic Center

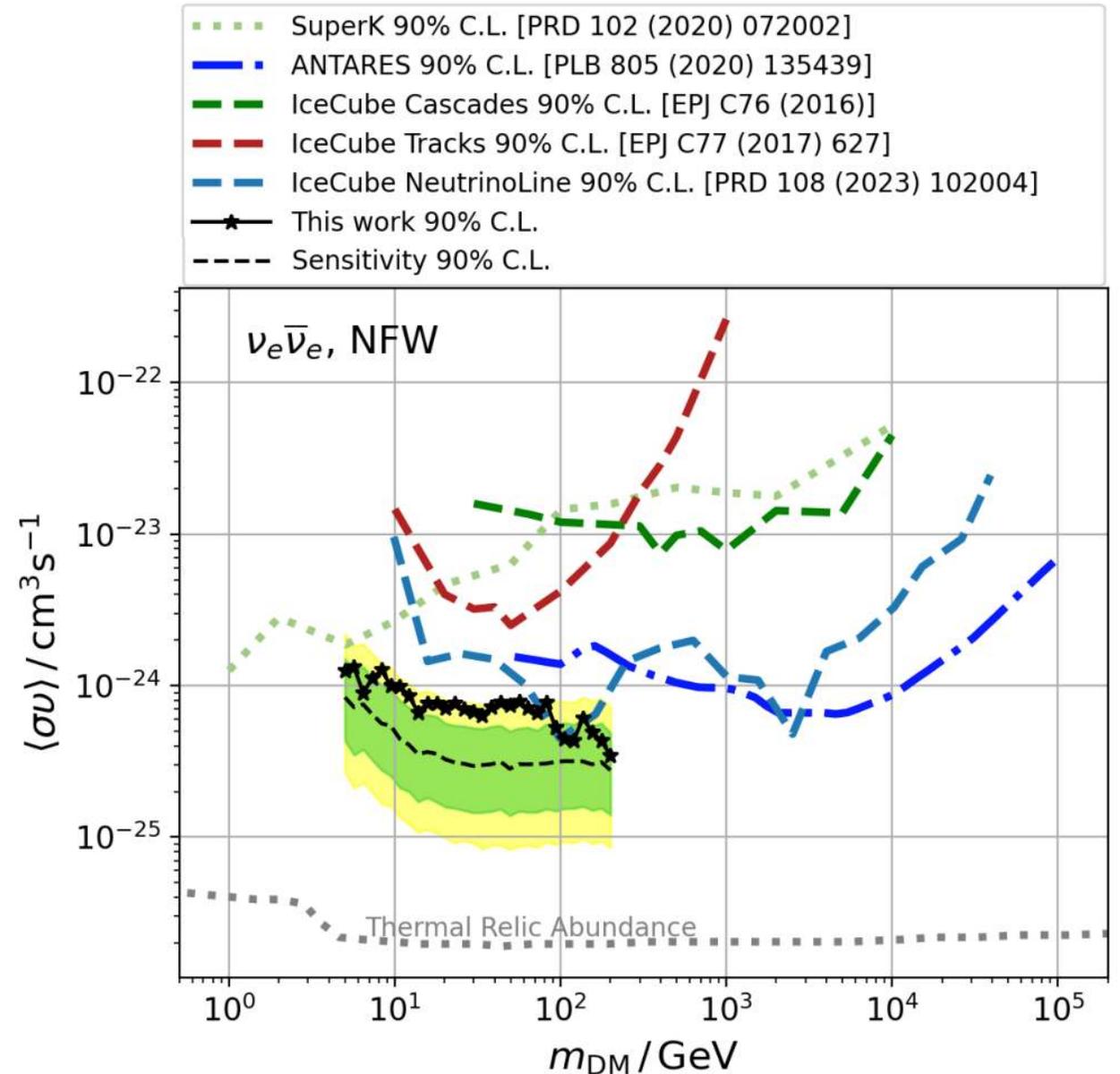
- Dark matter masses: 15 GeV - 18 TeV
- No significant excess found
 - Most significant Post-trial: 1.08σ
 $M_{\text{DM}} = 201.6 \text{ GeV}, \chi\chi \rightarrow b\bar{b}$
- Upper limit on velocity averaged annihilation σ
- 9 years of DeepCore data
Submitted to PRD: [arXiv.2511.00918](https://arxiv.org/abs/2511.00918)



Searches for WIMPs

Galactic Center

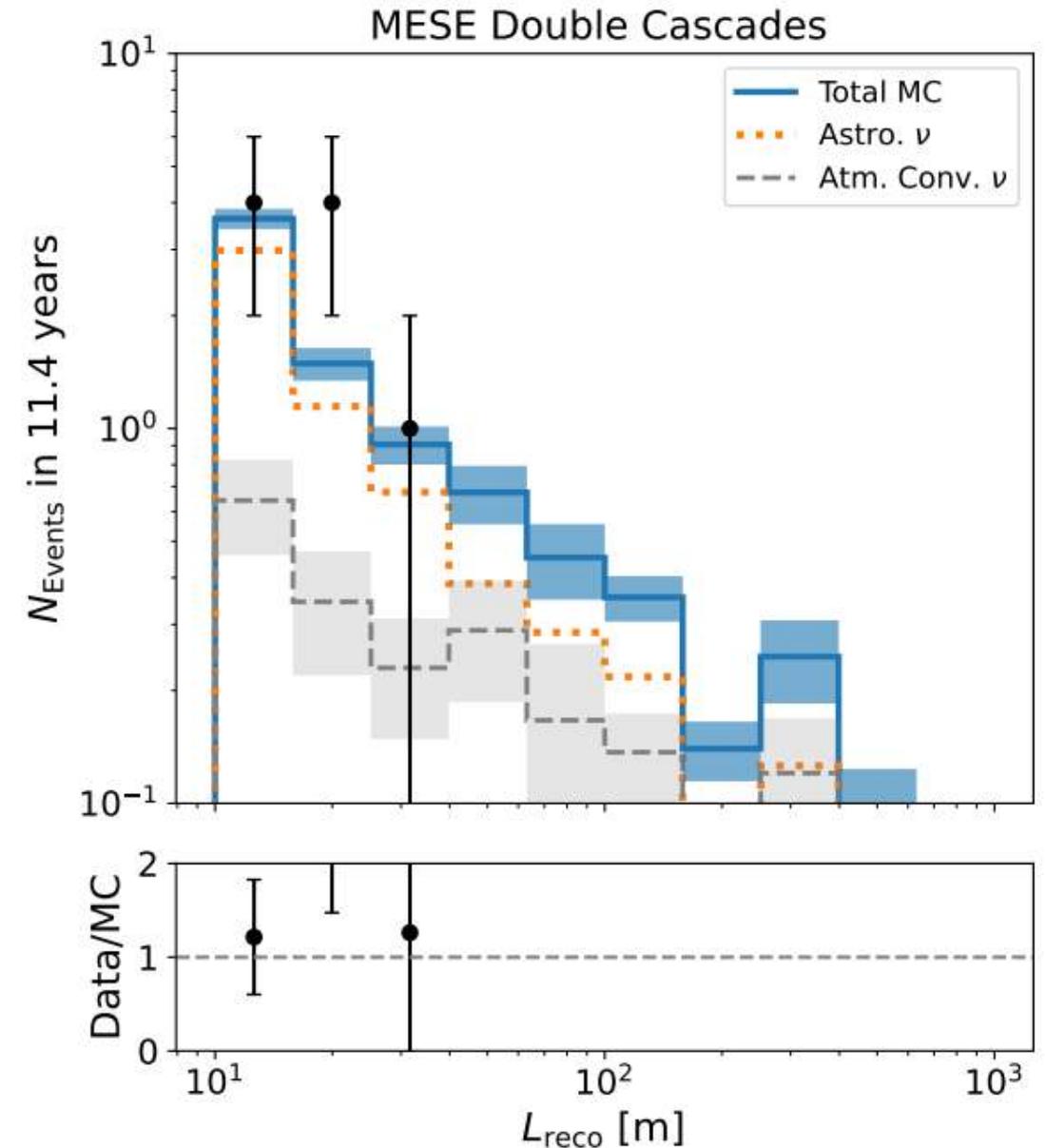
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- No significant excess found
 - Most significant Post-trial: 1.08σ
 $M_{\text{DM}} = 201.6 \text{ GeV}, \chi\chi \rightarrow b\bar{b}$
- Upper limit on velocity averaged annihilation σ
- 9 years of DeepCore data
Submitted to PRD: [arXiv.2511.00918](https://arxiv.org/abs/2511.00918)



Flavor composition analysis

Starting events

- 9 double cascade candidate events
- 11.4 years of IceCube starting events from 5 - 10 TeV
- Best-fit flavor composition
 $f_{\nu_e} : f_{\nu_\mu} : f_{\nu_\tau} = 0.30 : 0.37 : 0.33$
- Submitted to PRL: [arXiv.2510.24957](https://arxiv.org/abs/2510.24957)

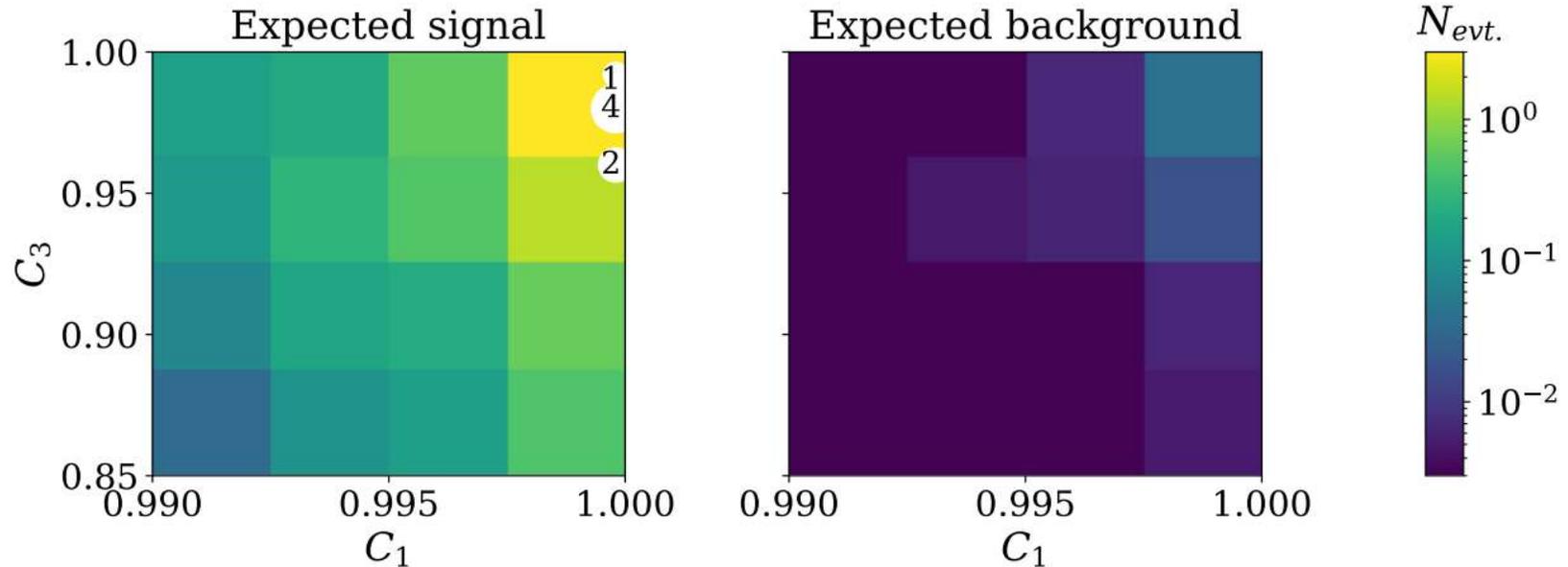
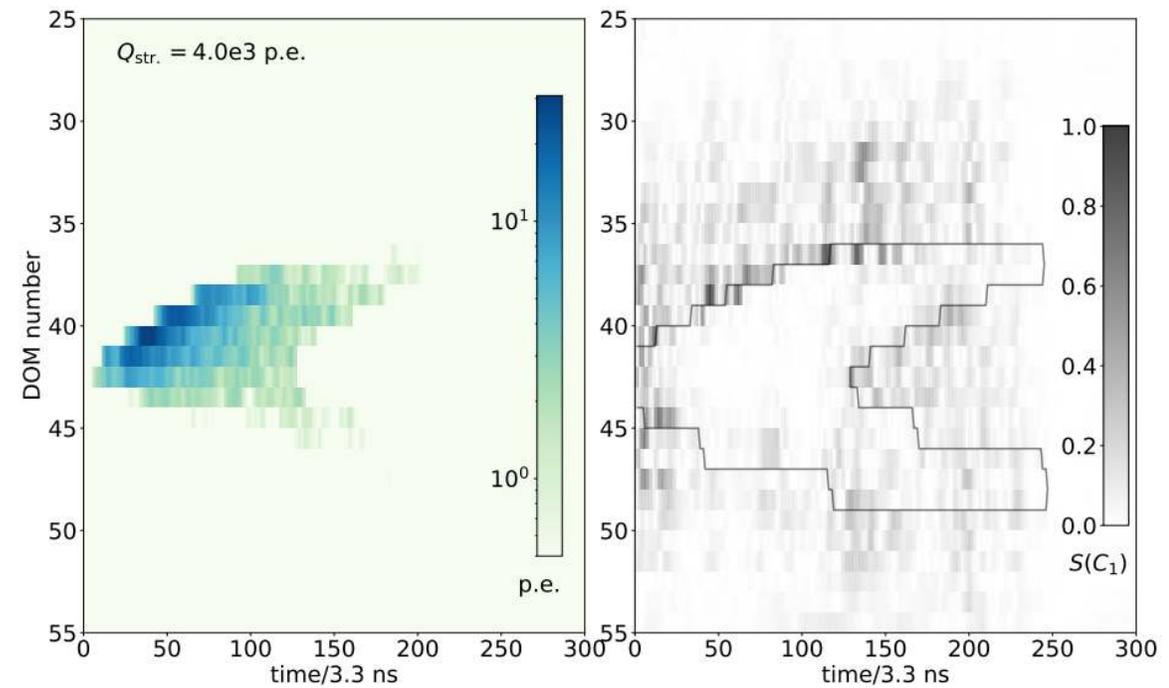


Diffuse astrophysical neutrinos

CNNs

- CNNs trained on images derived from simulated events
- 7 candidate ν_τ in 9.7 years of data
 - Between 20 TeV and 1 PeV
- Absence of ν_τ ruled out with 5σ
 - Caveat: backgrounds from prompt atmospheric muons, charm, and shower-to-shower fluctuations not included

• [Phys. Rev. Lett. 132, 151001](#)



Source searches

TXS 0506+056

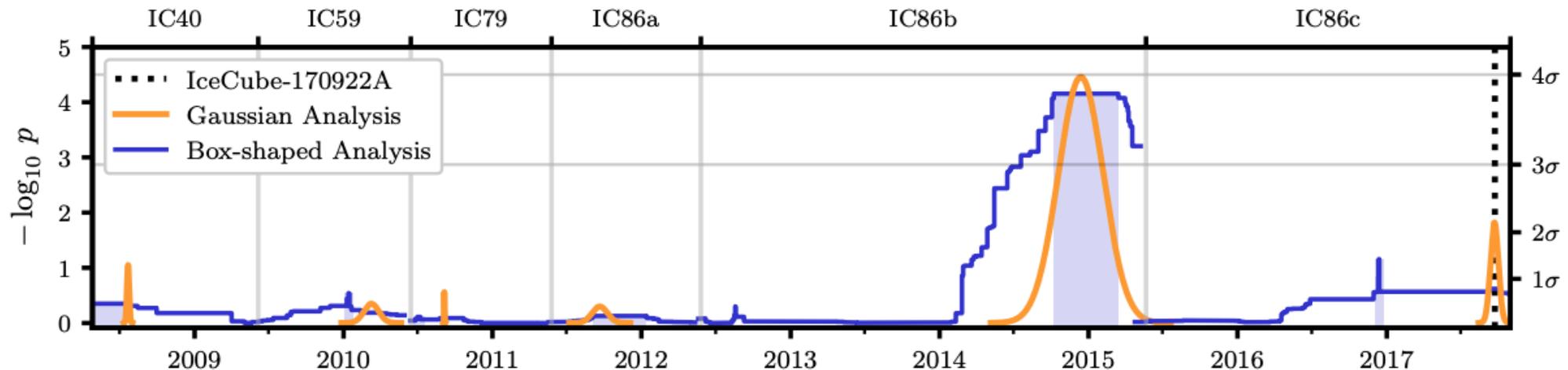
- High-energy ν detected on 22 September 2017 coincident with a gamma-ray flare from blazar

- [Science 361, no. 6398 \(2018\): 147-151](#)

- Retrospectively: excess of events between September 2014 and March 2015

- 3.5σ

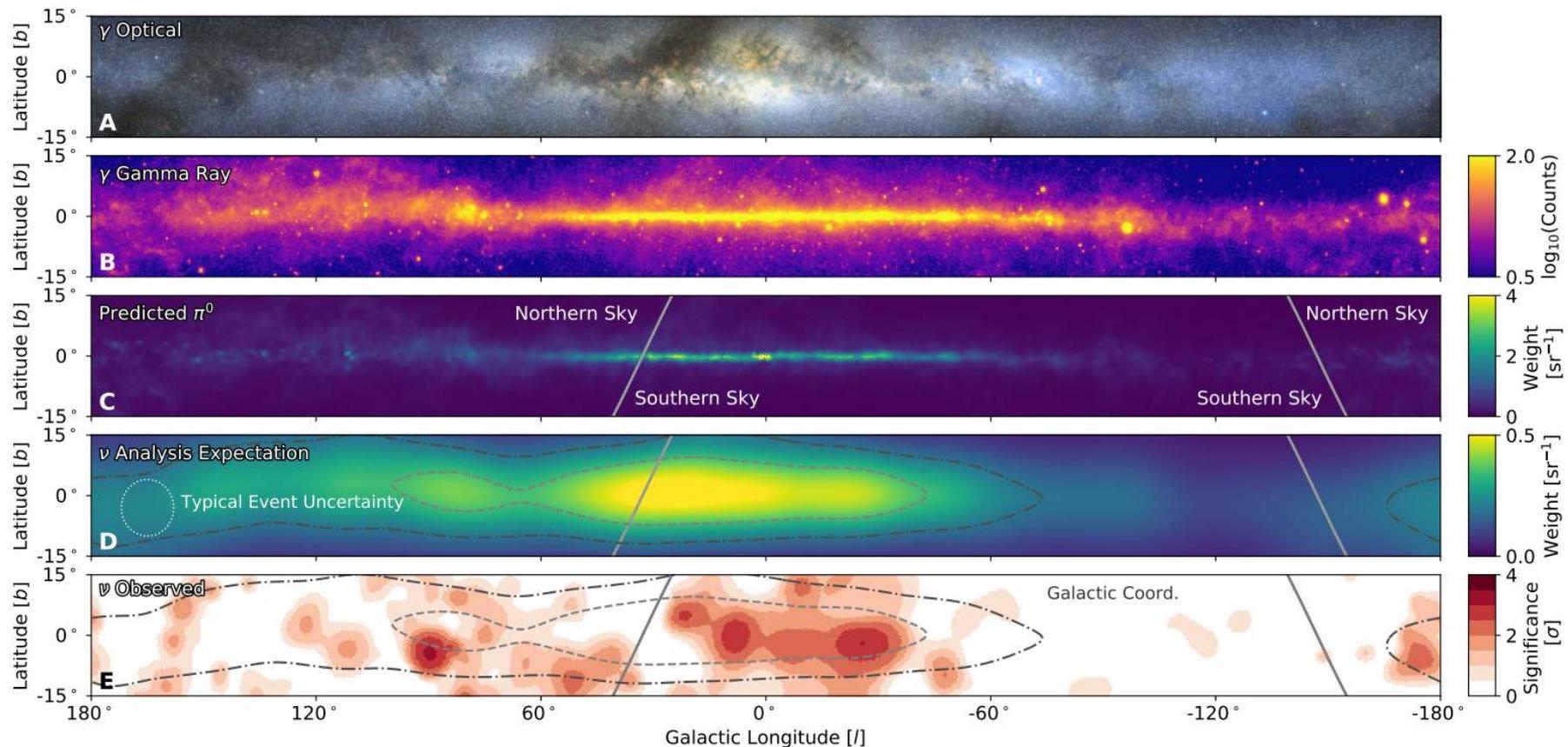
- 1% of diffuse flux

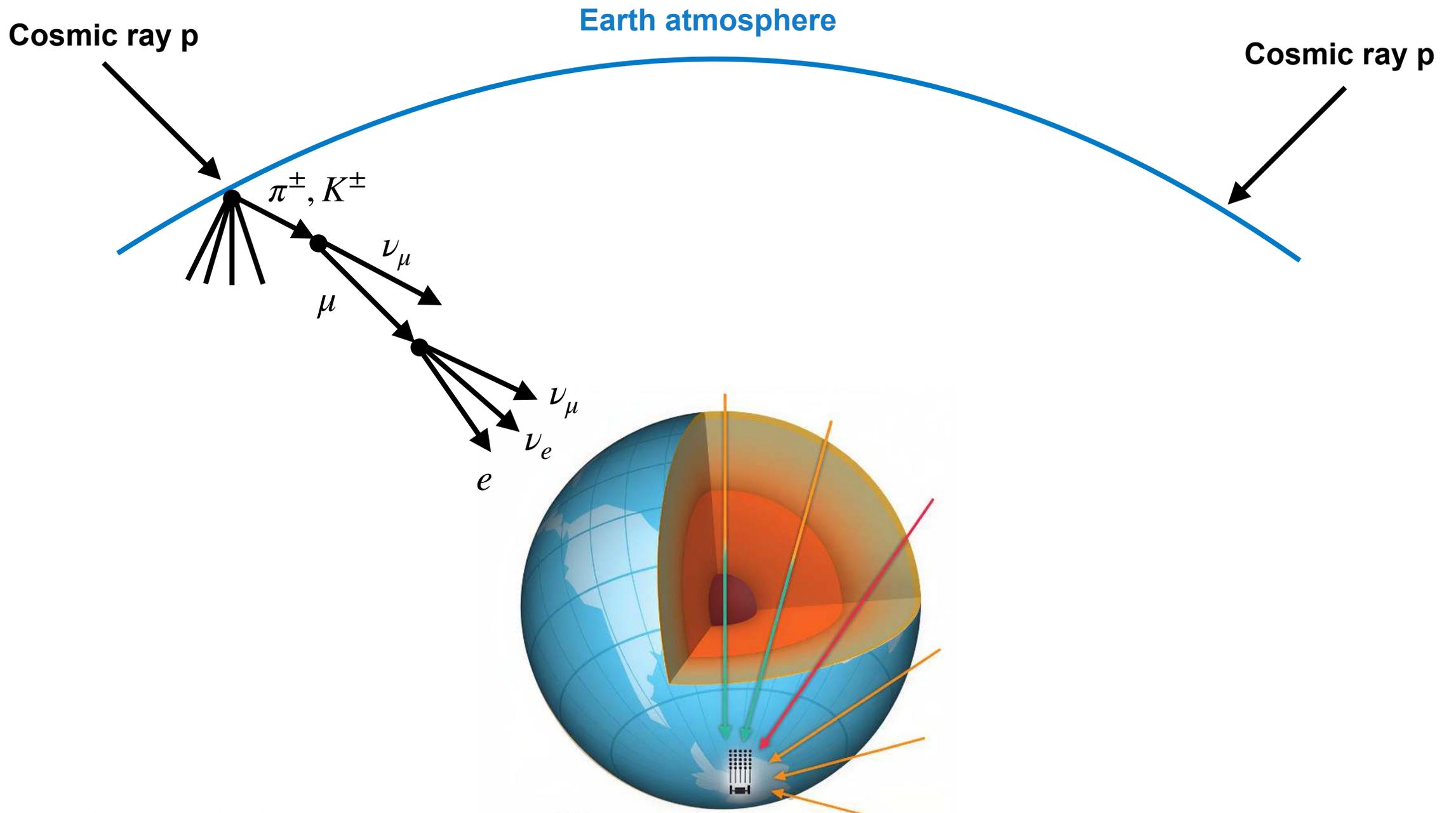


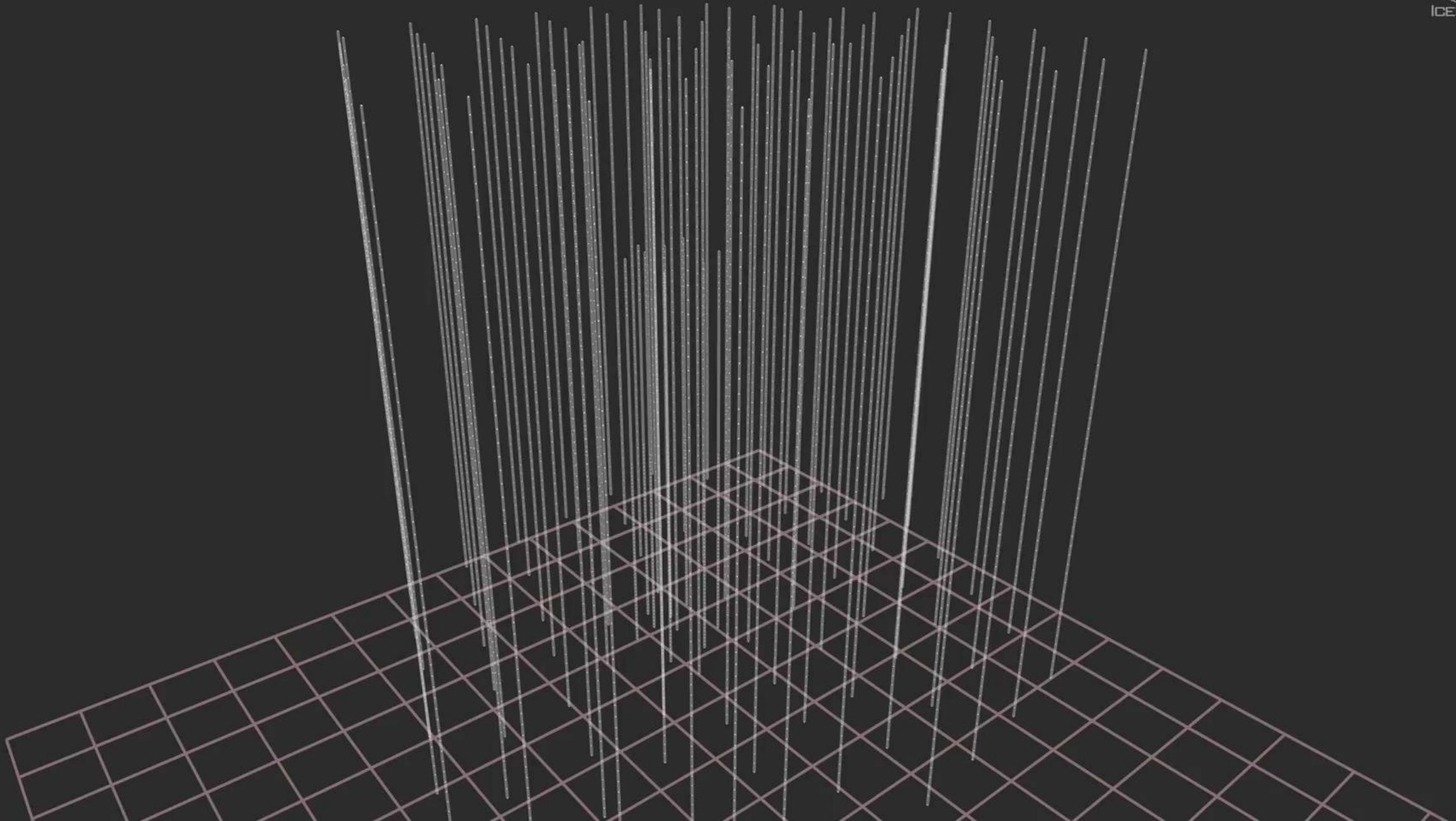
Source searches

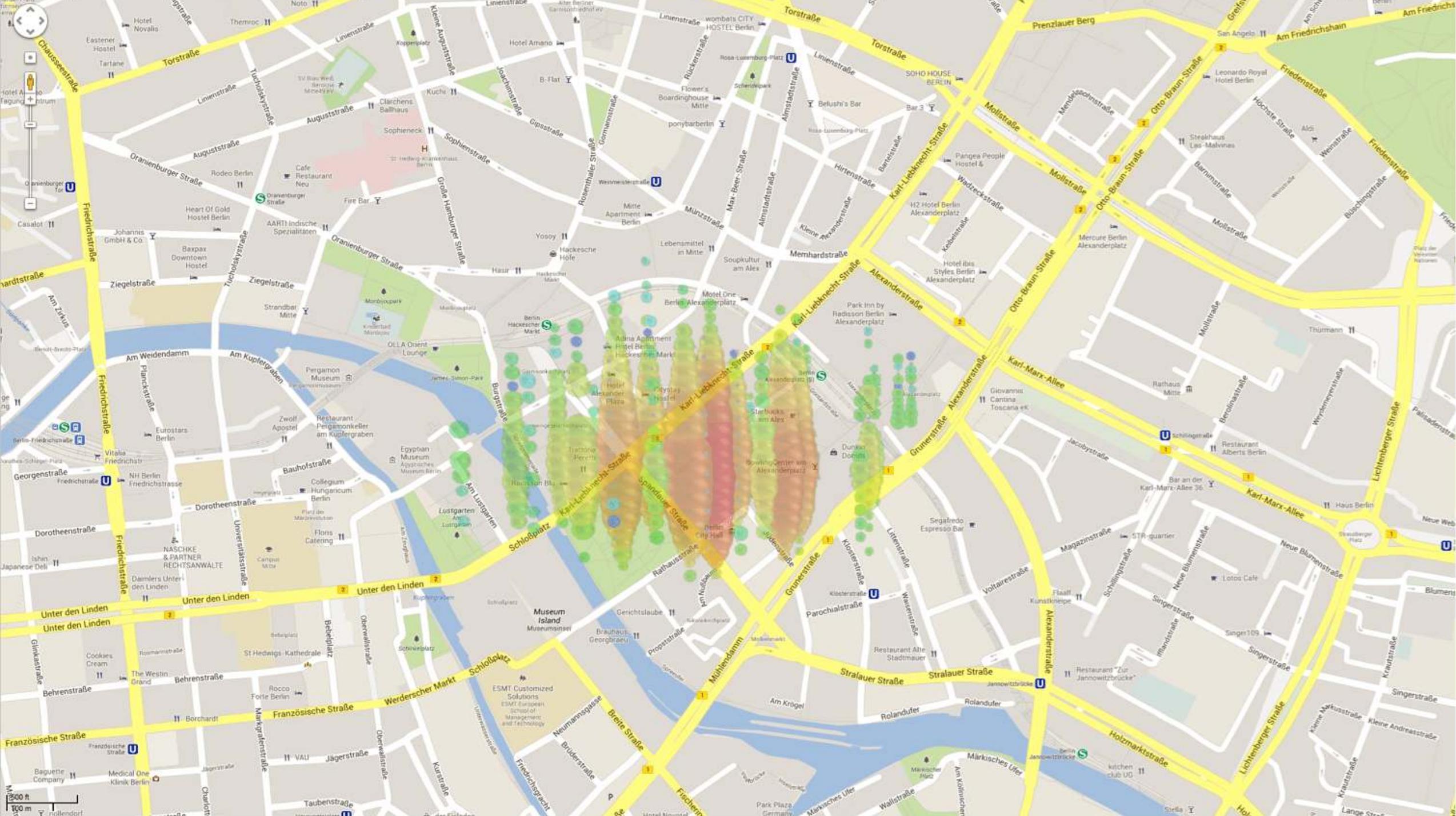
Galactic plane

- Diffuse neutrino emission from our Galaxy: [Science, 380\(6652\), 1338-1343](#)
 - Could also arise from unresolved point sources
- Significance to 5σ : [arXiv.2507.08753](#) (paper in preparation)









500 ft
100 m

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