An Improved Search for Unstable Sterile Neutrinos at IceCube

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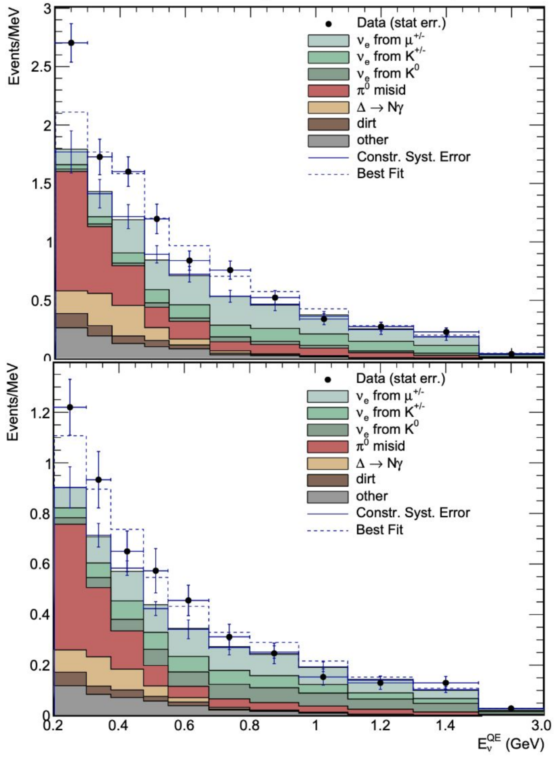
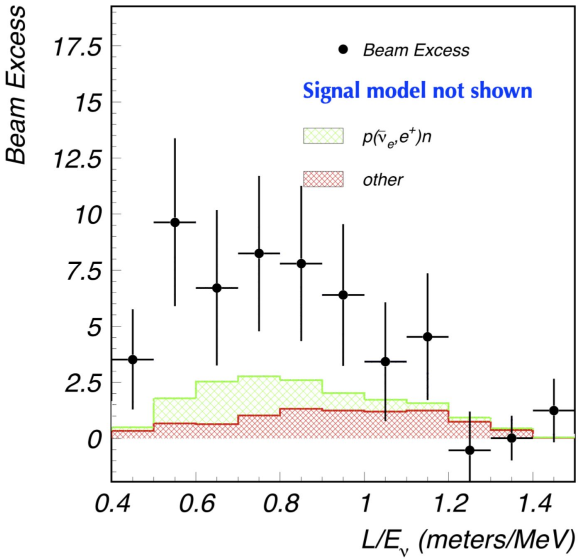
Neutrino Oscillation Anomalies

- Several unresolved anomalies in various neutrino experiments

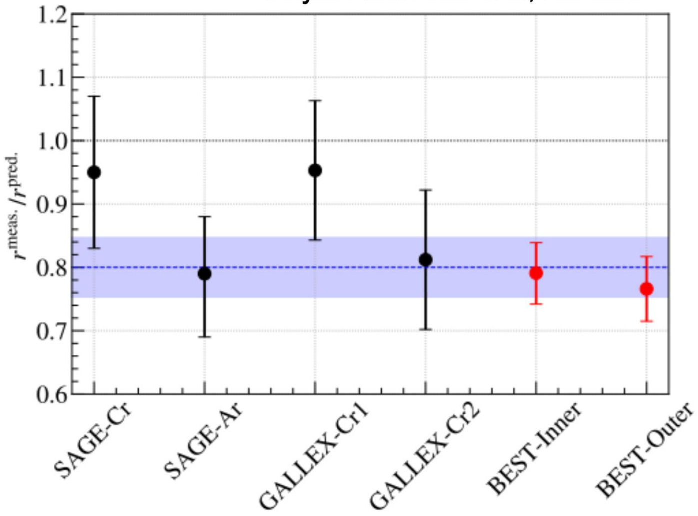
MiniBooNE Phys. Rev. Lett. 121, 221801



LSND Phys. Rev. D 64, 112007

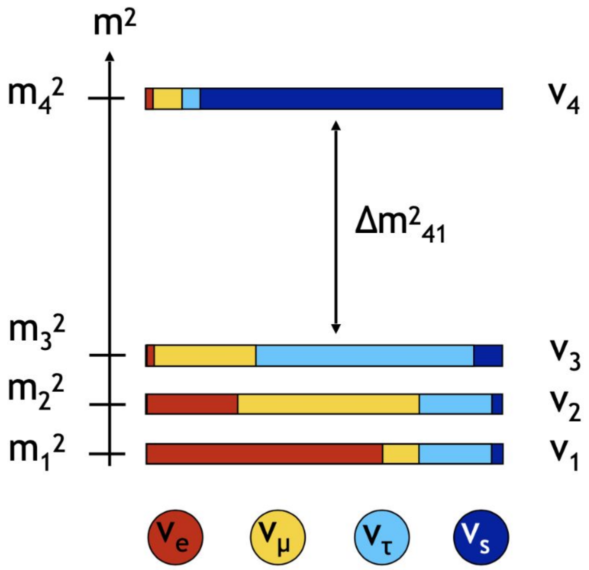


Gallium Phys. Rev. Lett. 128, 232501



3+1 Sterile Neutrino Model

- Anomalies in short baseline neutrino experiments could be explained by a sterile neutrino
  - Introduce a new flavor and mass state, append a row and column to the PMNS matrix
  - These states do not interact weakly → only accessible through oscillations

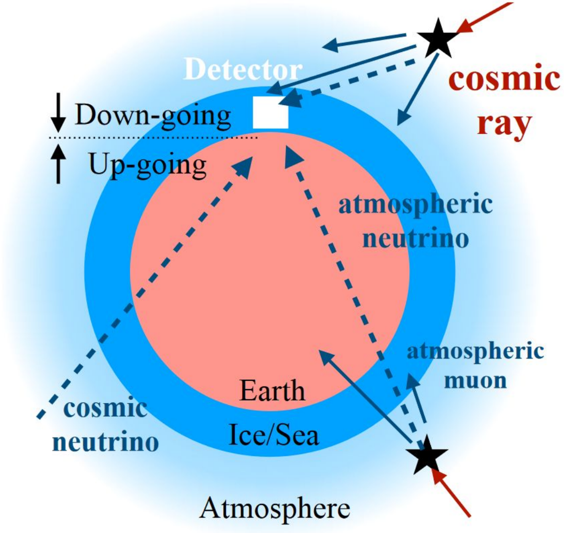


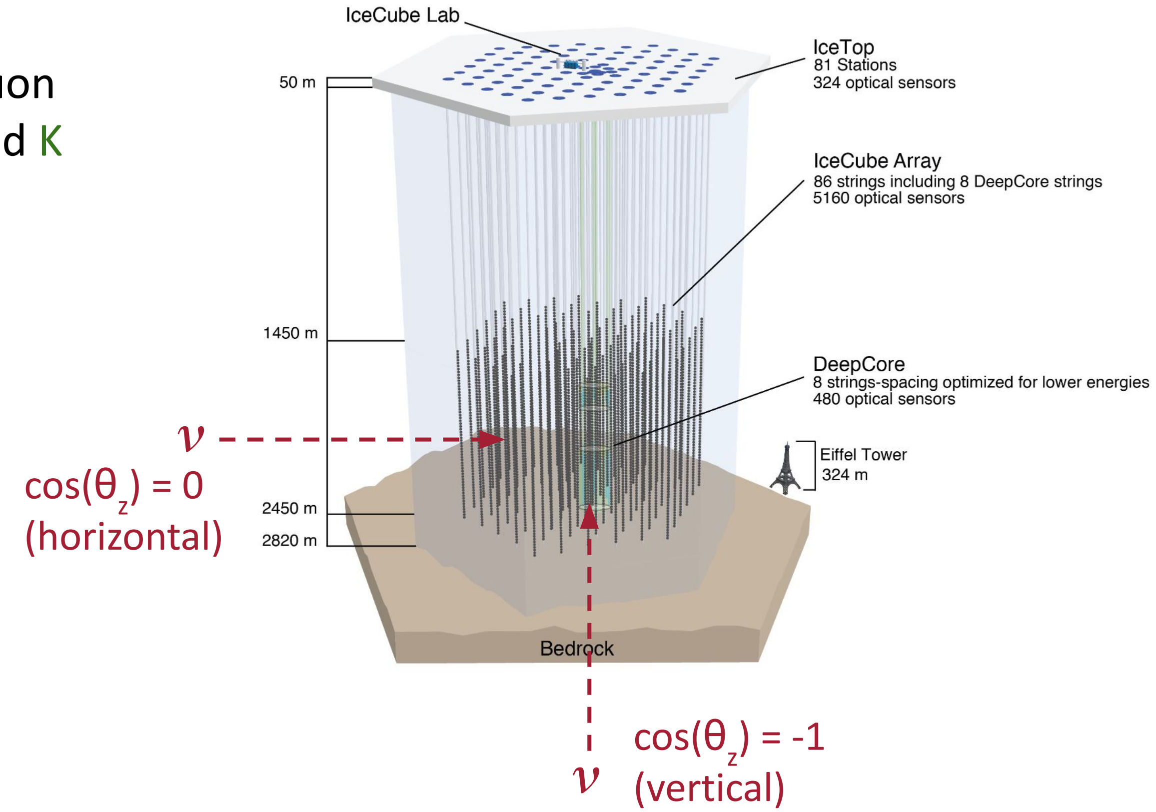
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4}\\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4}\\ U_{s1} & U_{s2} & U_{s3} & U_{s4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

$$|U_{e4}|^2 = \sin^2(\theta_{14})$$
$$|U_{\mu4}|^2 = \sin^2(\theta_{24})\cos^2(\theta_{14})$$
$$|U_{\tau4}|^2 = \sin^2(\theta_{34})\cos^2(\theta_{24})\cos^2(\theta_{34})$$

Atmospheric Neutrinos and IceCube

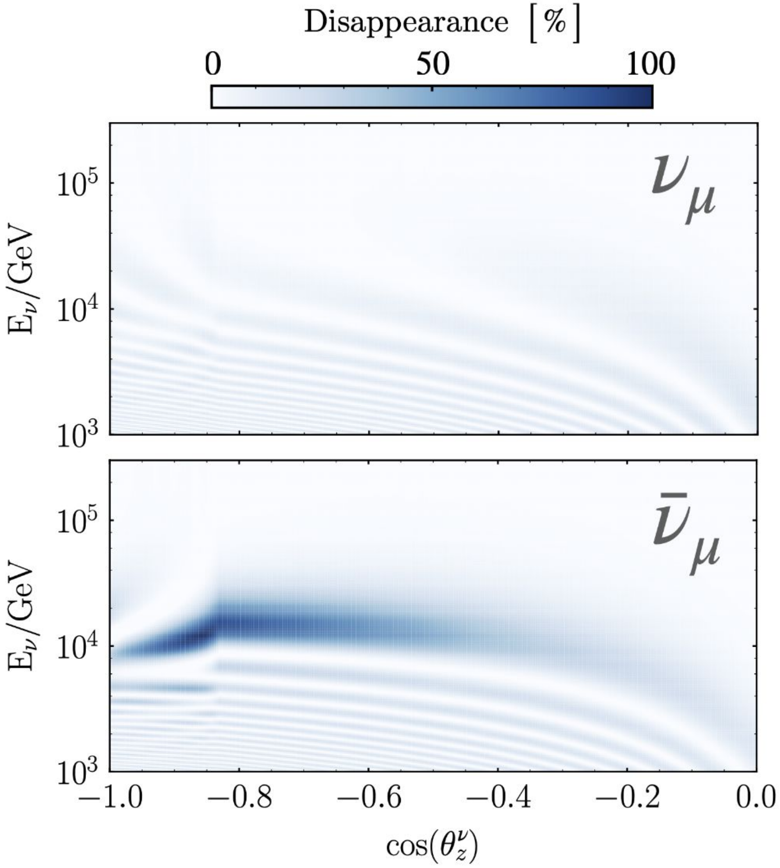
The conventional atmospheric muon neutrino flux originates from π and K decay-in-flight





Sterile Neutrino Oscillations in Matter

- To probe neutrino oscillations, IceCube can measure the energy and the zenith angle of the incoming neutrino
  - The zenith angle is a proxy for the baseline L, the distance that the neutrinos have traveled
- There are two main features in these oscillograms:



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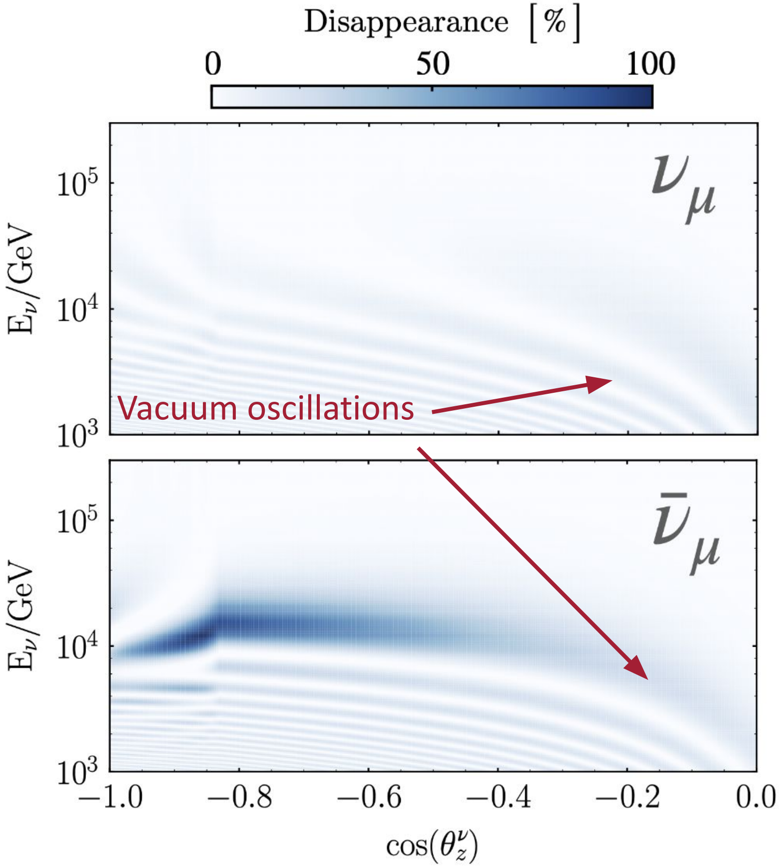

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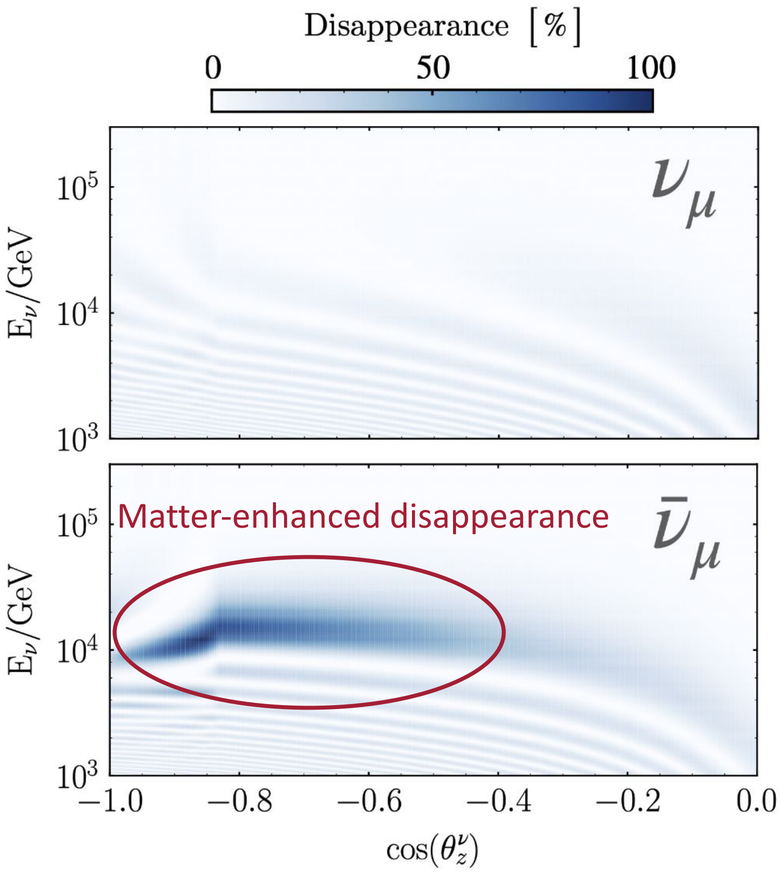
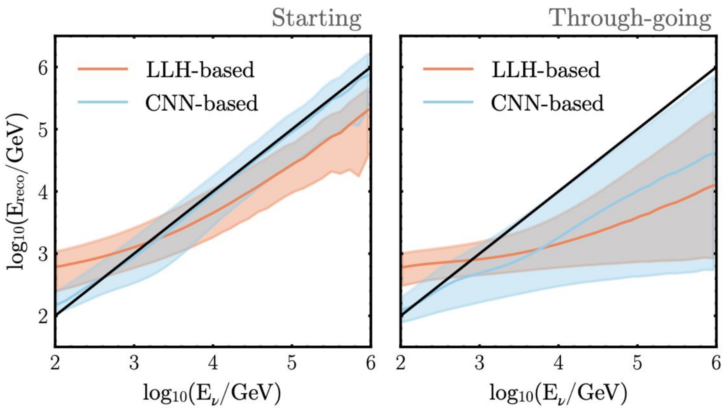
  - Vacuum (L/E) oscillations
  - A matter-enhanced resonant disappearance for antineutrinos that travel through most of the Earth

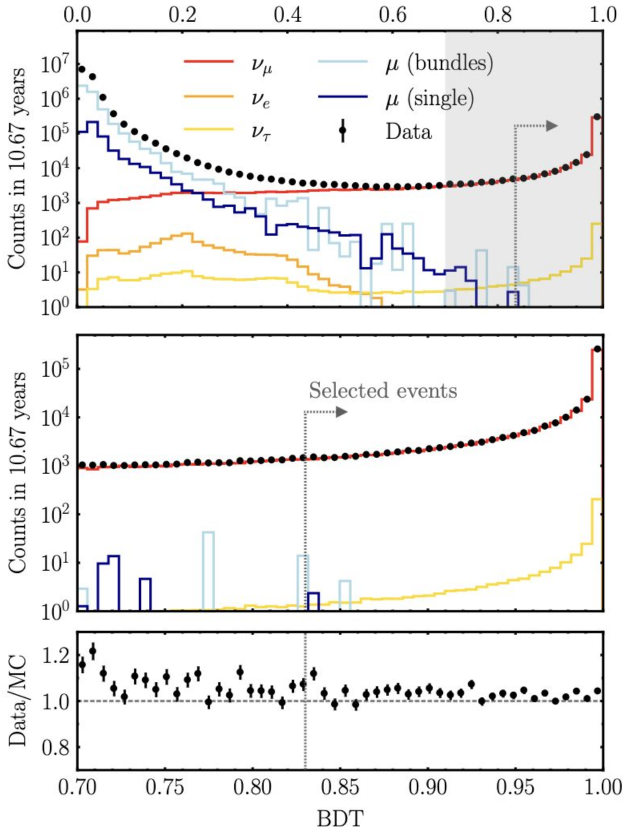
$$E_{res} = \mp \frac{\Delta m^2 \cos(2\theta)}{\sqrt{2} G_F N_n}$$



Improvements to Event Selection and Analysis

- To search for sterile neutrinos, we leverage the large flux of atmospheric muon (anti)neutrinos observed in IceCube
- Major improvements since the previous search:
  - BDT for removing atmospheric muon backgrounds
  - DNN-based energy reconstruction and classifier
  - More detailed ice systematic treatment
  - Improved atmospheric flux systematics
  - Broken power law for astrophysical flux



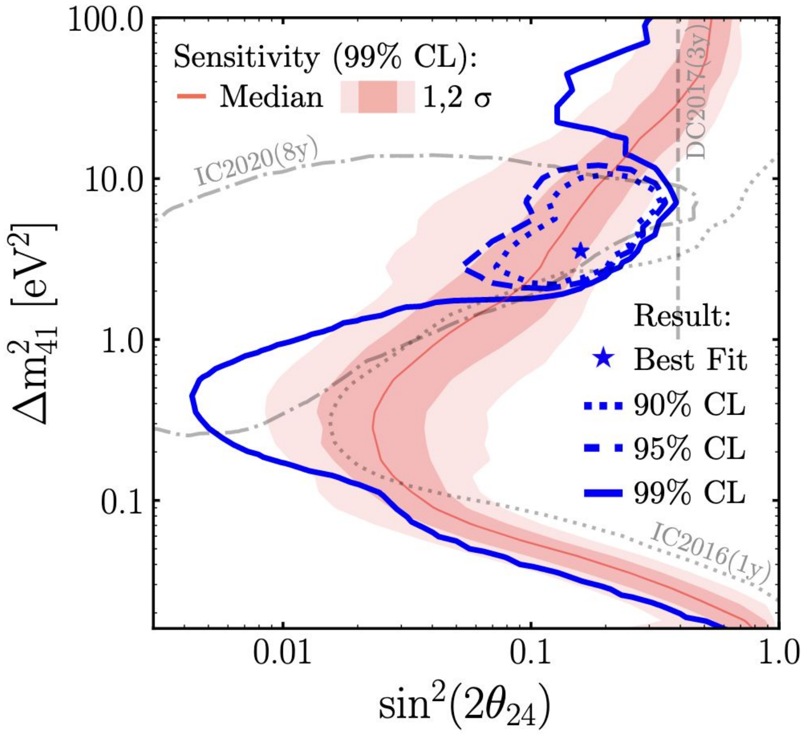


Latest 3+1 Sterile Neutrino Results

- Best Fit:

$$\Delta m^2_{41} = 3.5\ \mathrm{eV}^2$$
$$\sin^2(2\theta_{24}) = 0.16$$
$$\text{p-value} = 3.1\% \longrightarrow 2.2\sigma$$

- Consistent with the previous sterile analyses in IceCube
- These results appeared on the arXiv **today**! See: arXiv:2405.08070



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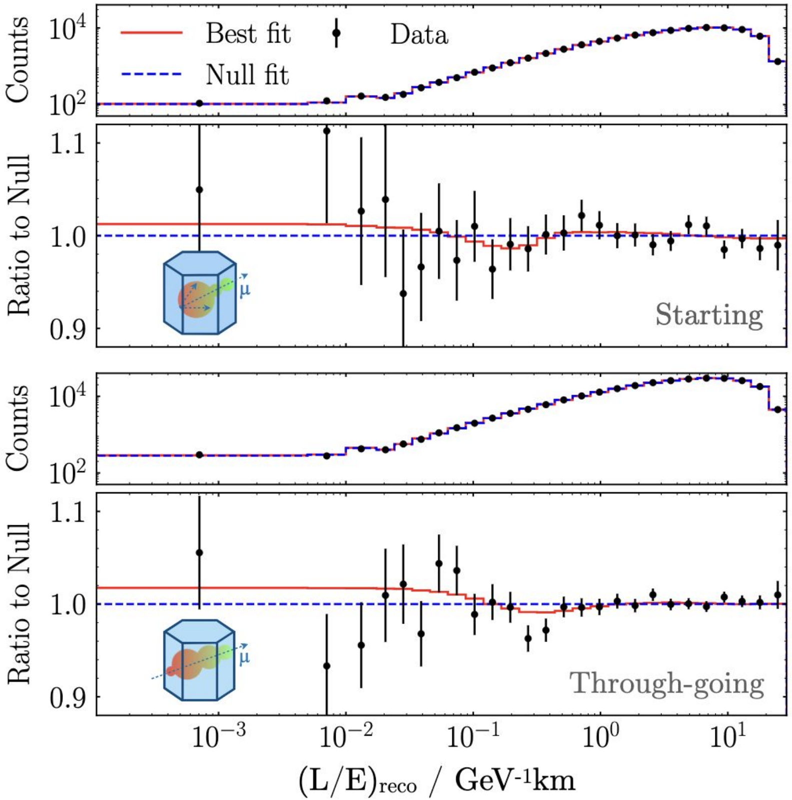
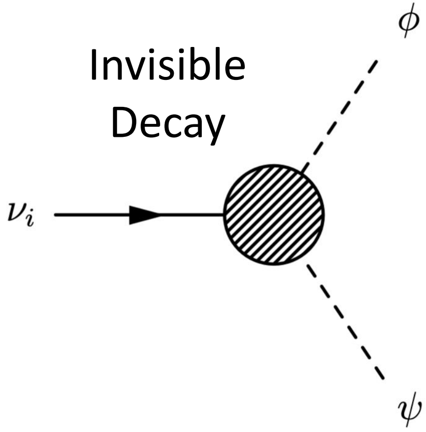
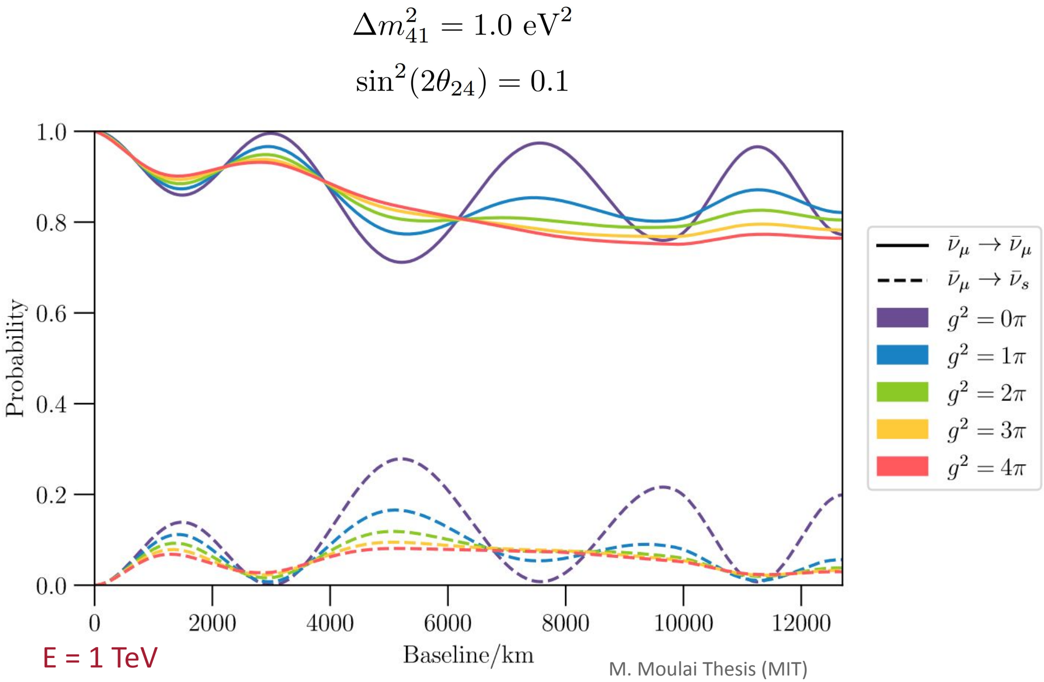


Invisible Sterile Neutrino Decay



Adding a decay mechanism[1] dampens the sterile oscillation signature, which is preferred in the global fits[2]

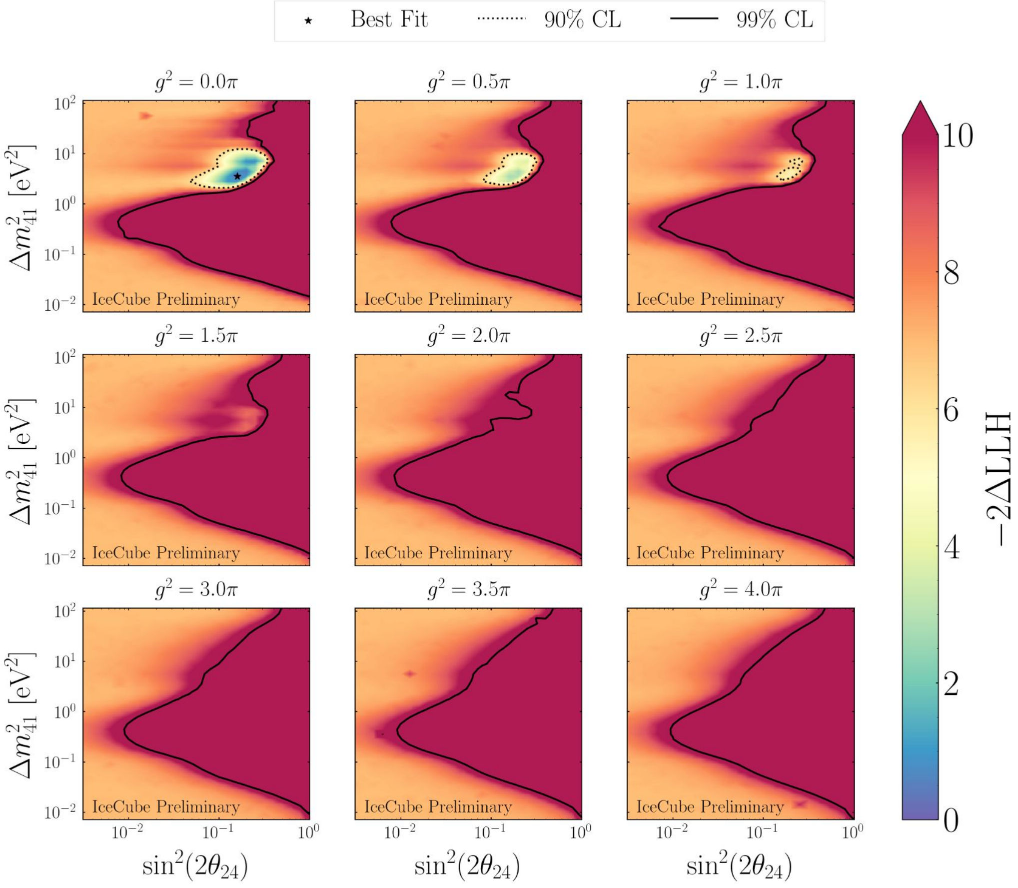
$$\tau = \frac{1}{\Gamma} = \frac{16\pi}{g^2 m_4}$$



[1]*Phys. Rev. D 97, 055017*
[2]*J. High Energ. Phys.* **2023**, 58 (2023)

Results for 3+1+decay

- The best fit for the 3+1+decay search is the no-decay scenario
  - Best fit at $g^2 = 0$
  - p-value = 7.4% (3 dof)



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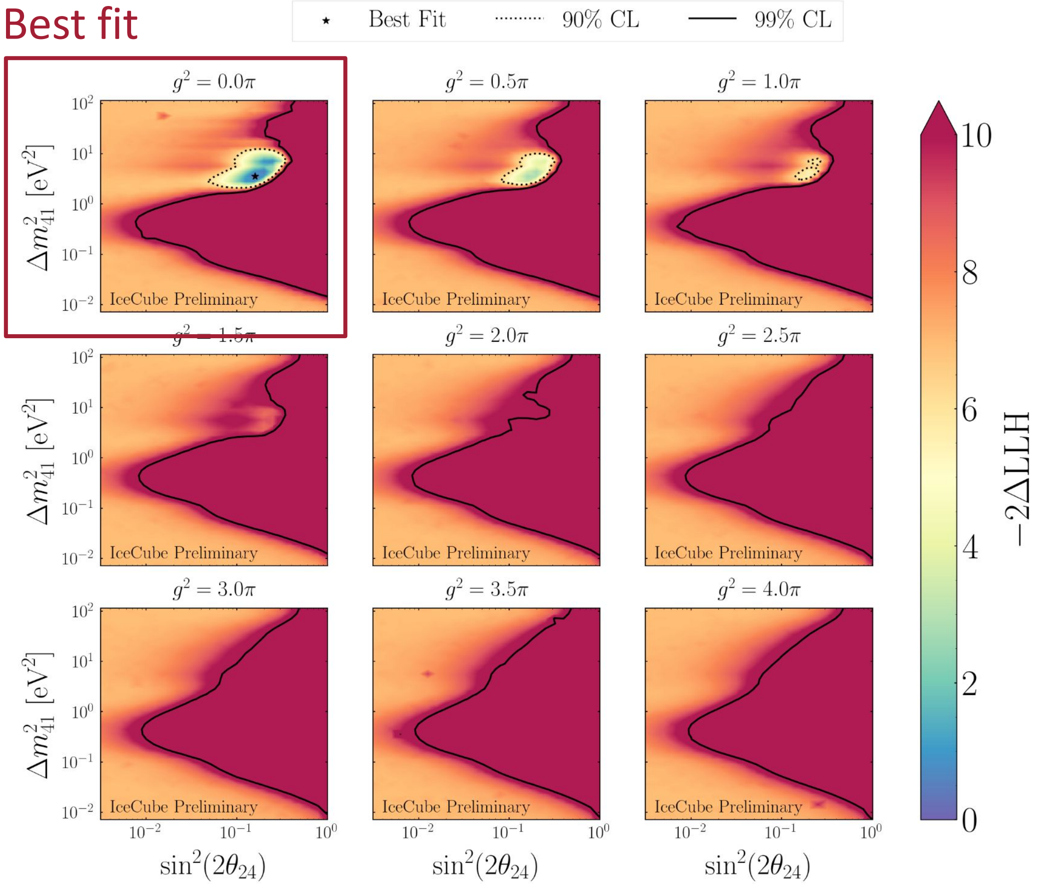

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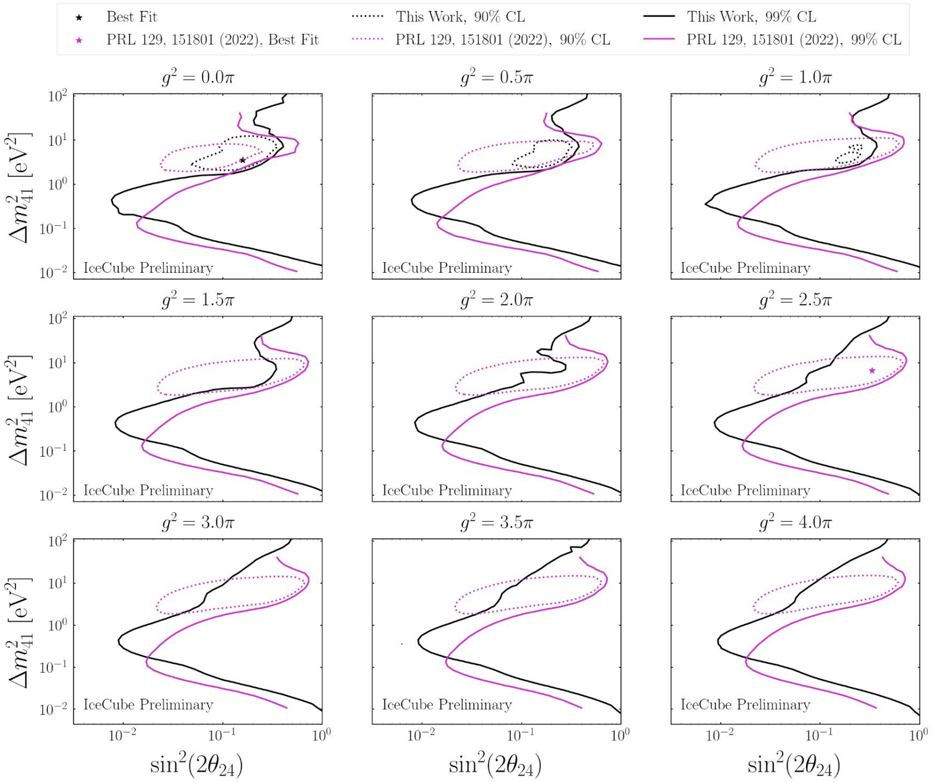
  - Previous best fit is excluded, but the LLH space was quite shallow so there is overlap



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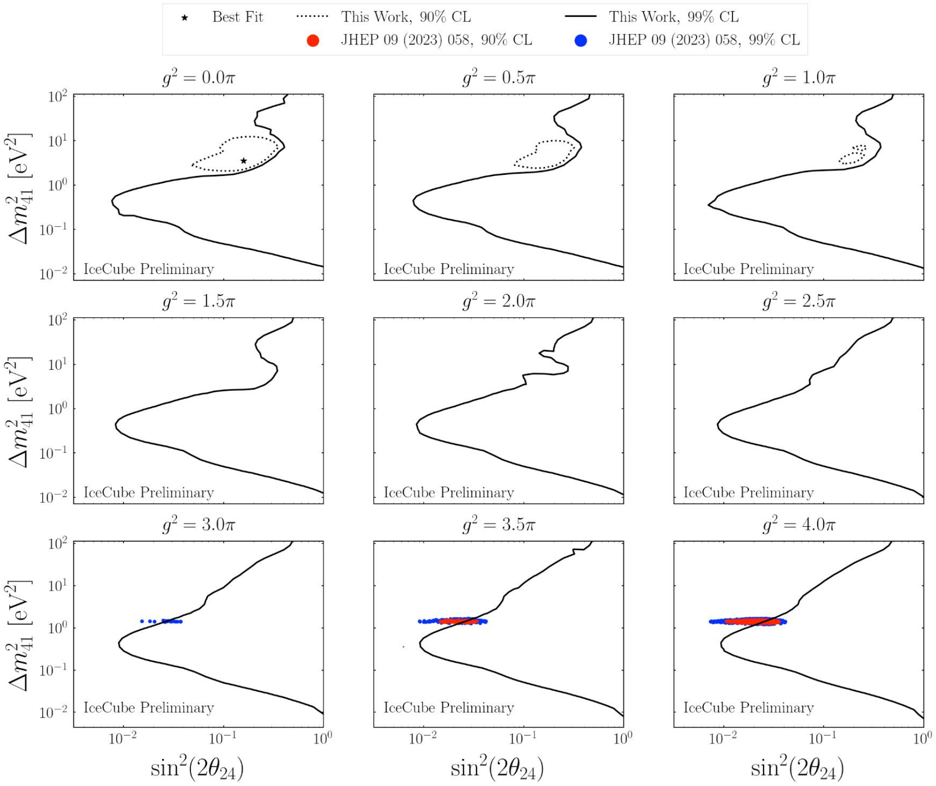
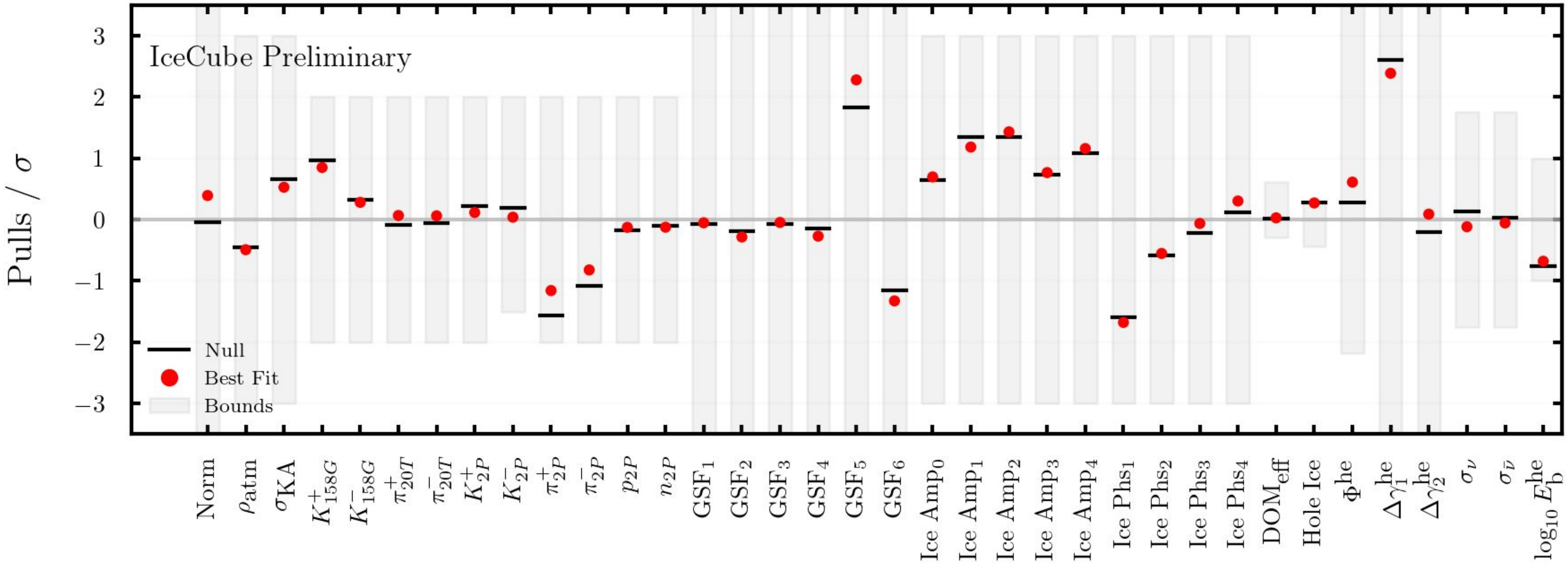
- Regions from the global fits to SBL experiments are excluded
  - Partially excluded at 99% CL
  - Mostly excluded at 95% CL



Systematic pulls



For details of the systematic treatment, see: [arXiv:2405:08077]

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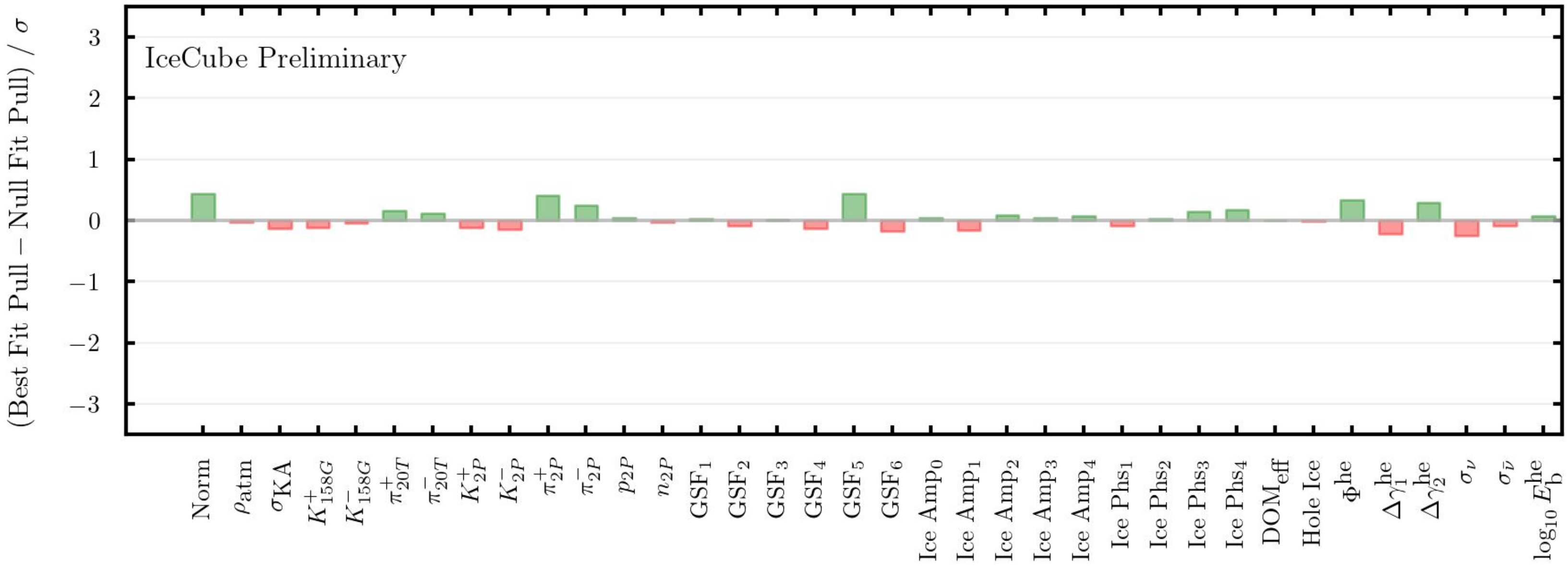

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Conclusion

- IceCube has performed an improved search for unstable eV-scale sterile neutrinos using 10.7 years of muon neutrino data
  - Probed the invisible decay case, which is preferred over the ordinary 3+1 in the global fits
- No preference for decay was found, best fit point at $g^2 = 0$
  - Results are consistent with previous analysis from 2021, but the previous best fit point is now excluded at >99% CL
  - This result puts constraints on the preferred region of the SBL experiments

Thank you for listening!