BSM Physics with IceCube Tracks: Sterile Neutrinos and More

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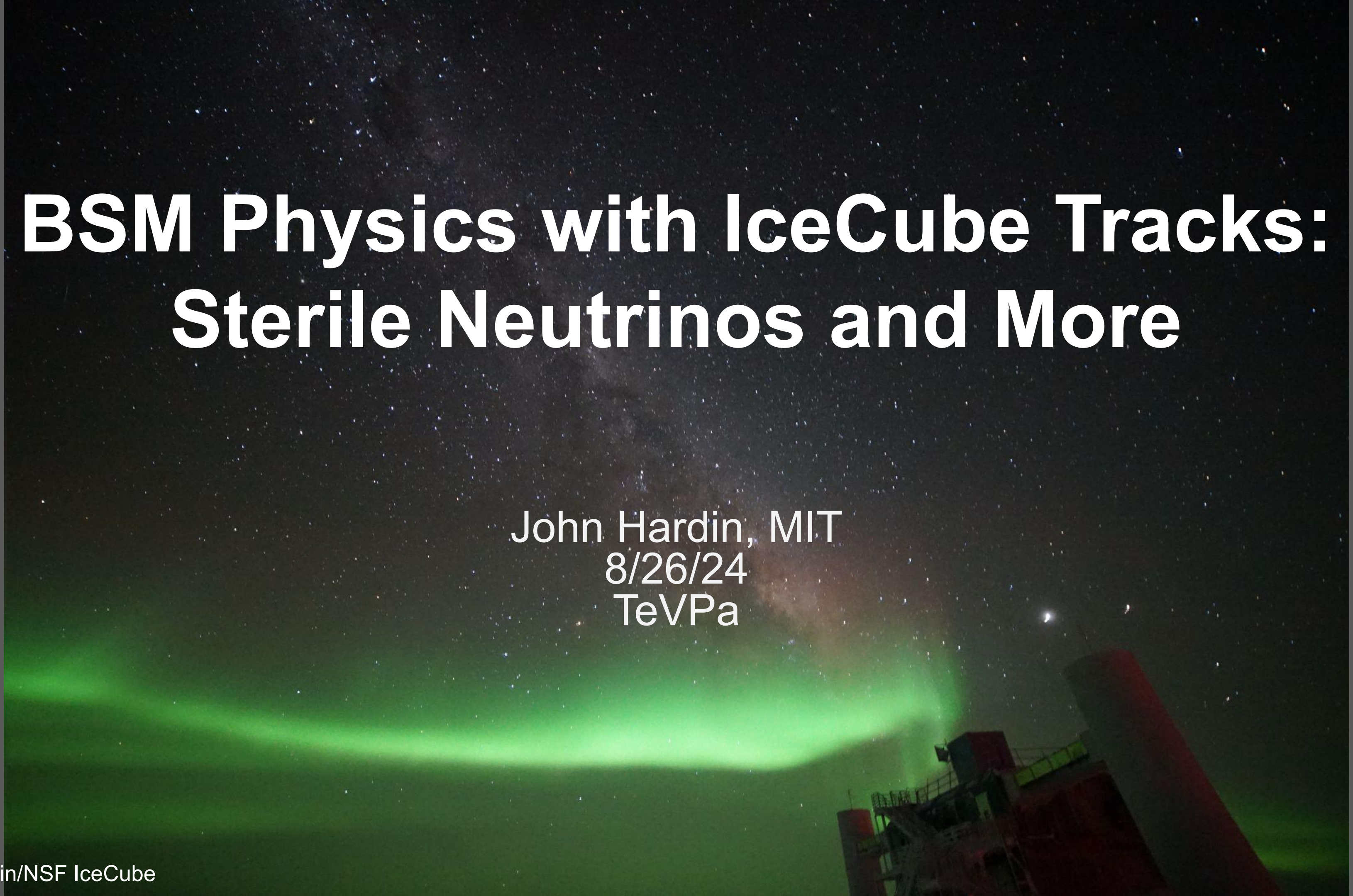
8/26/24
TeVPa



John Hardin/NSF IceCube

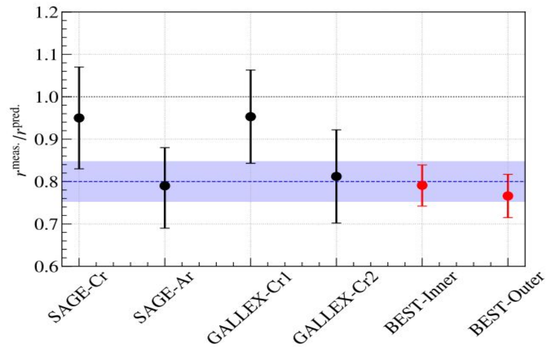
Outline

- What are Sterile Neutrinos, and why are we looking for them, a quick refresher
- Sterile Neutrinos in IceCube
- Other Machine learning in IceCube, and how it can help us look for galactic flavor ratios

Sterile Neutrinos (3+1) Quick Refresher

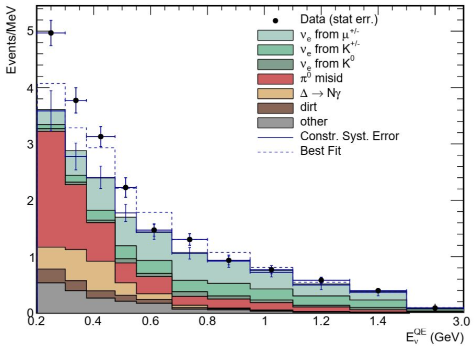
Anomalies remain in the 3 neutrino model

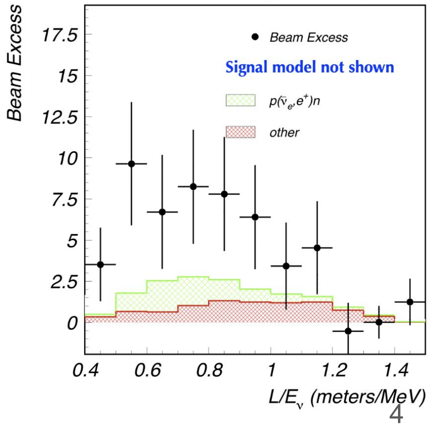
- Over the past 25 years we have developed a strong 3 neutrino model
- But anomalies remain
- Adding BSM physics could improve the global fit by ~7σ
  - Fitting ~20 experiments, including LSND, BEST, and MiniBooNE, and assuming Wilk's theorem
  - https://arxiv.org/abs/2211.02610



Phys Rev C, arxiv:2201.07364

Phys. Rev. D 64, 112007



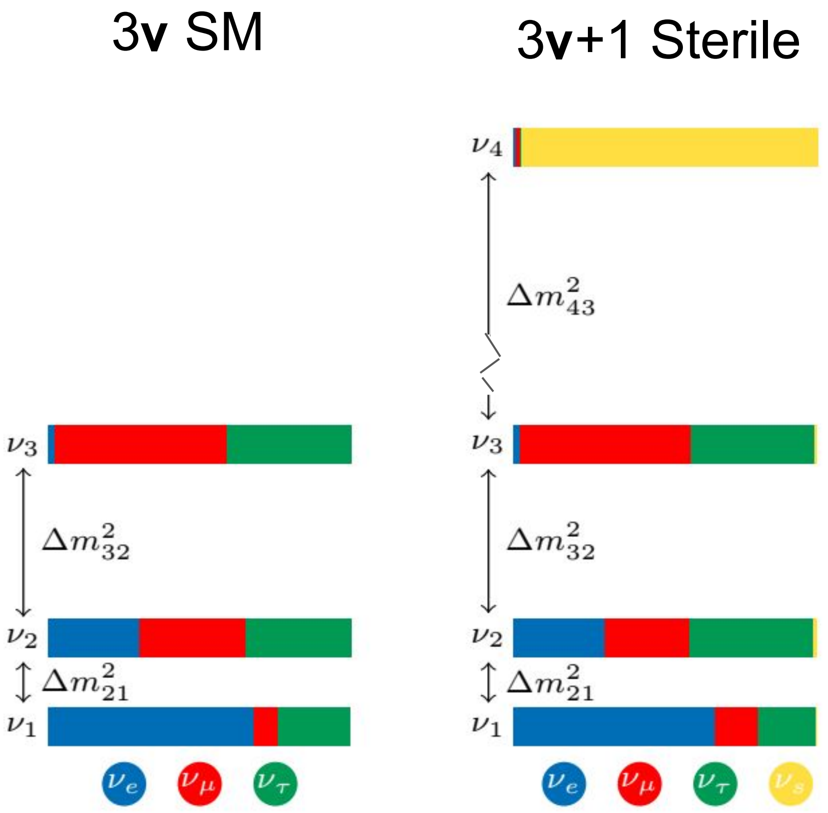


Phys. Rev. Lett. 121 arxiv:1805.12028

Arxiv: hep-ex/0104049

Sterile Neutrino(s) could explain them

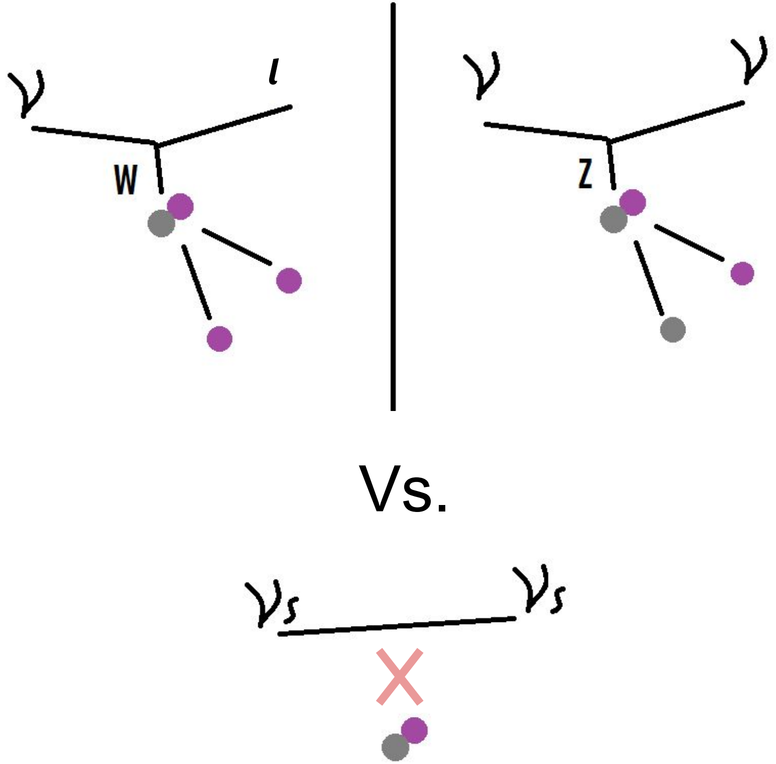
- Neutrino that does not interact weakly
- It can have a large mass splitting
- IceCube detects this signal differently than other sterile searches



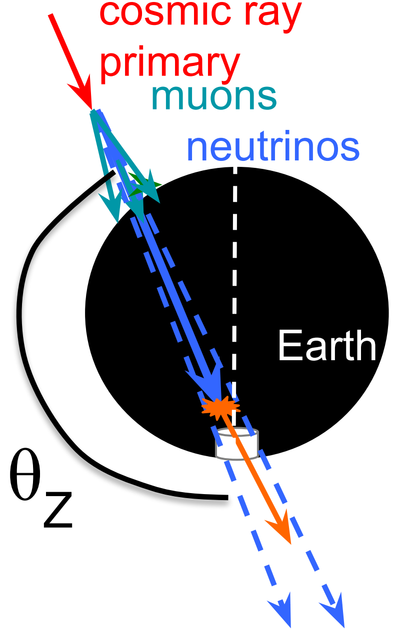
Phys. Rep. 884, arxiv:1906.00045

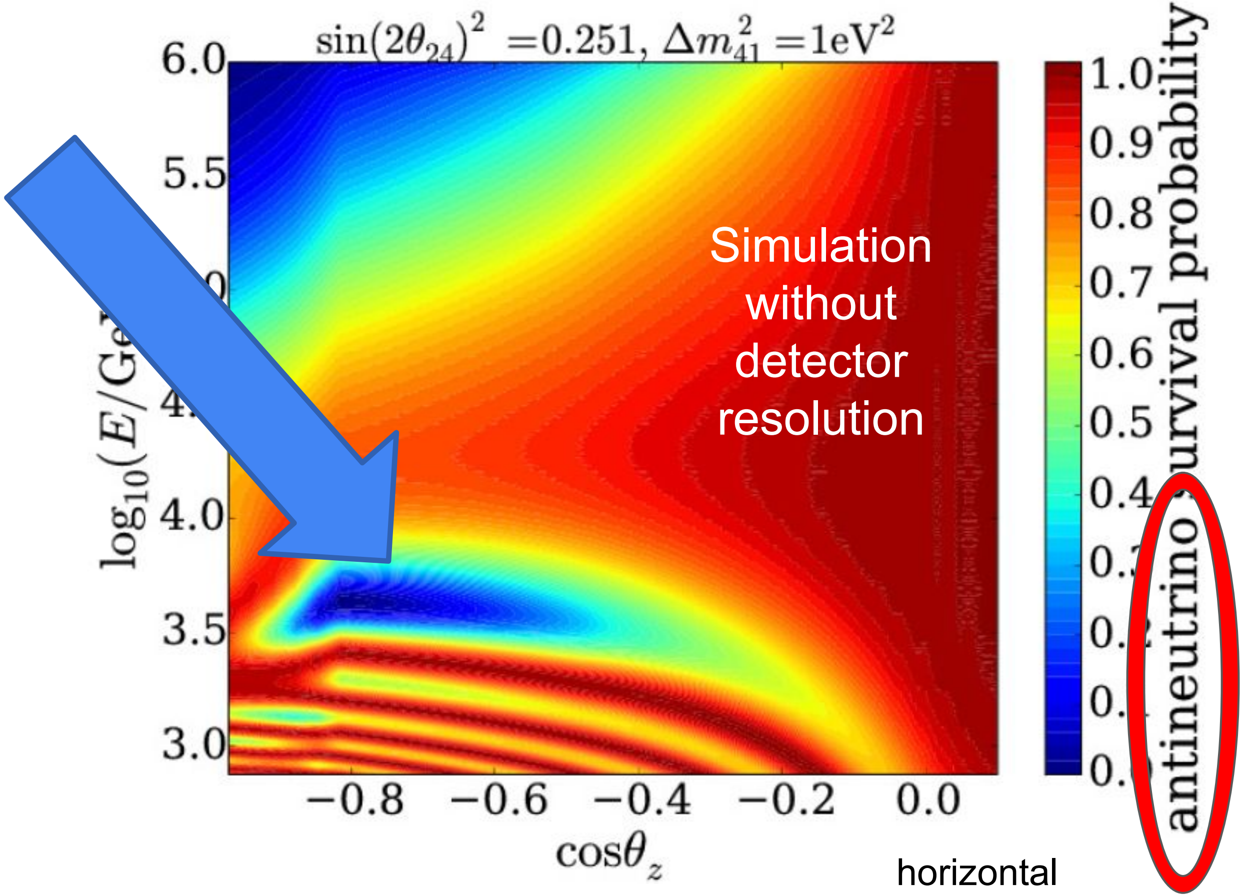
Sterile Neutrinos and the Earth in IceCube

- This analysis in IceCube doesn’t look for standard oscillations
- The sterile portion (if any) does not interact in the earth
- Different matter potential for sterile and non-sterile neutrinos
- Produces a resonant (!) term



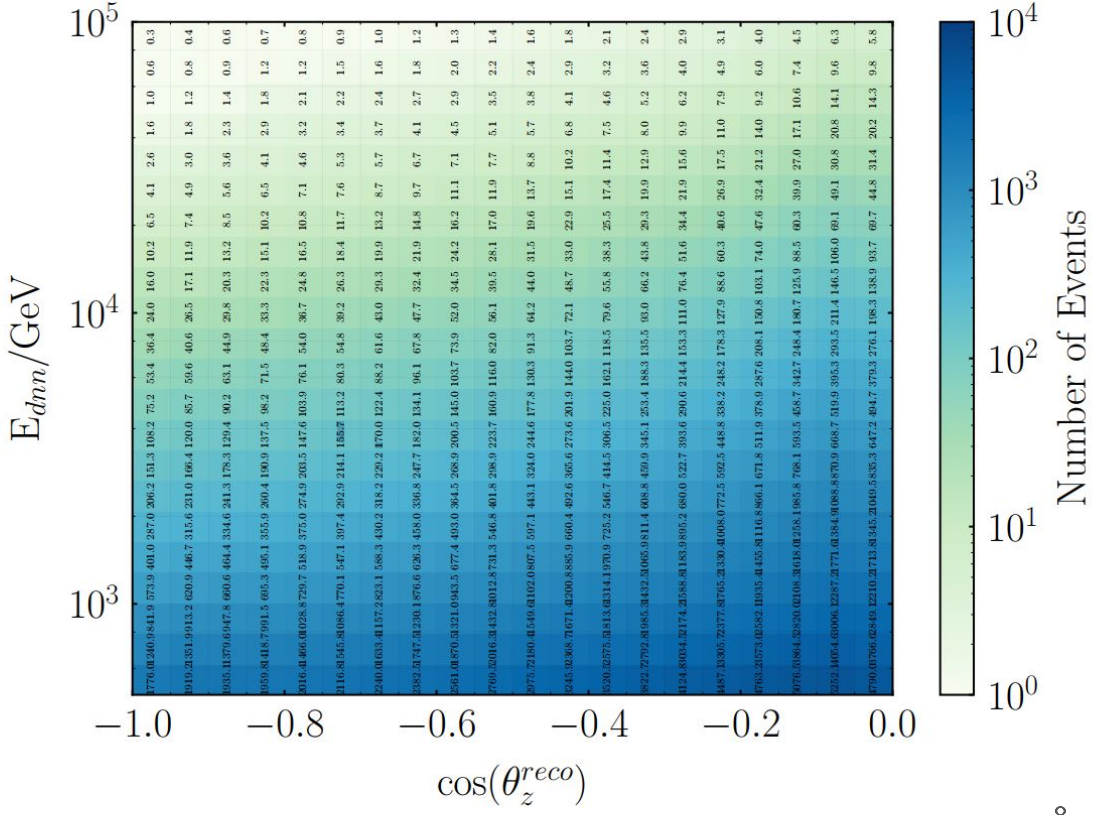
Matter effect on Sterile Neutrino:
Large disappearance of upgoing antineutrinos





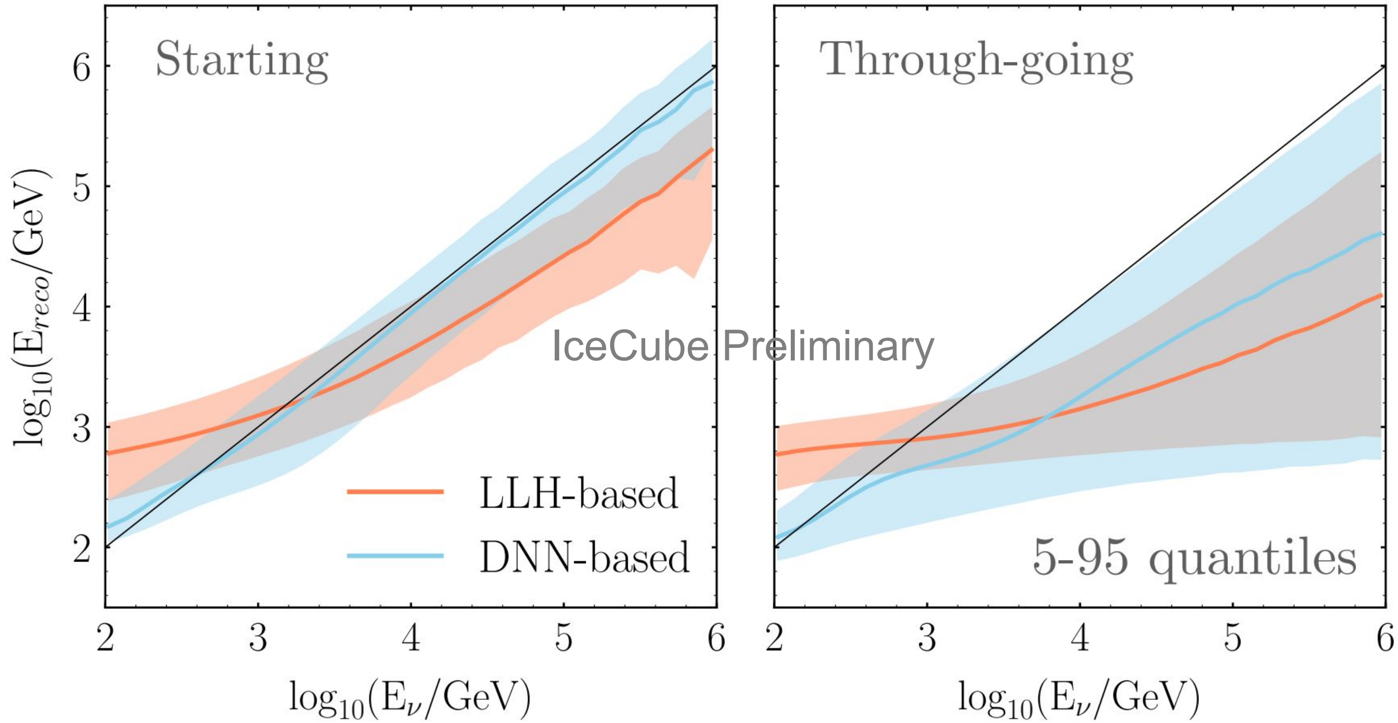
How does IceCube look for this deficit?

- Extremely pure (>99.9%) sample of upgoing (Northern) tracks (Muon Charged Current)
- Primarily looking at atmospheric neutrinos
- Energy Range of 500 GeV - 100 TeV
- ~360k events
- Improved from previous analyses stopping at 10 TeV



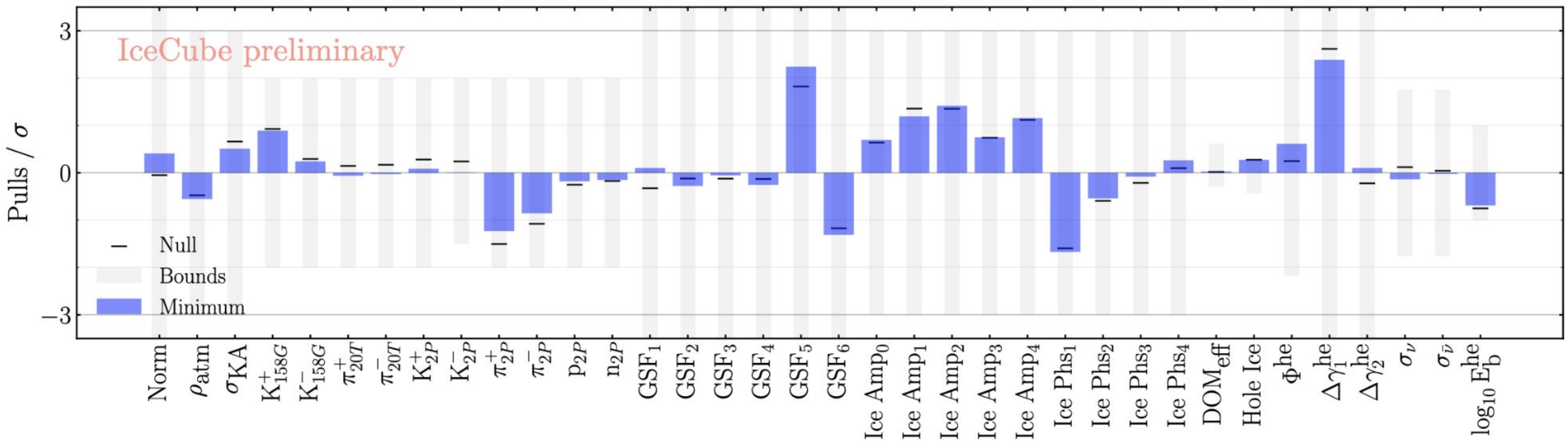
Improvements:

- BDT based selection
- Starting vs Throughgoing separation
- DNN Based Energy Reconstruction:



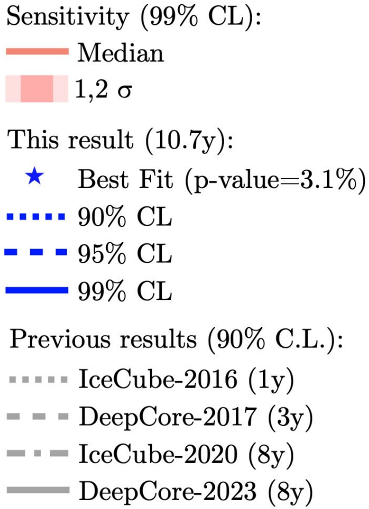
Results

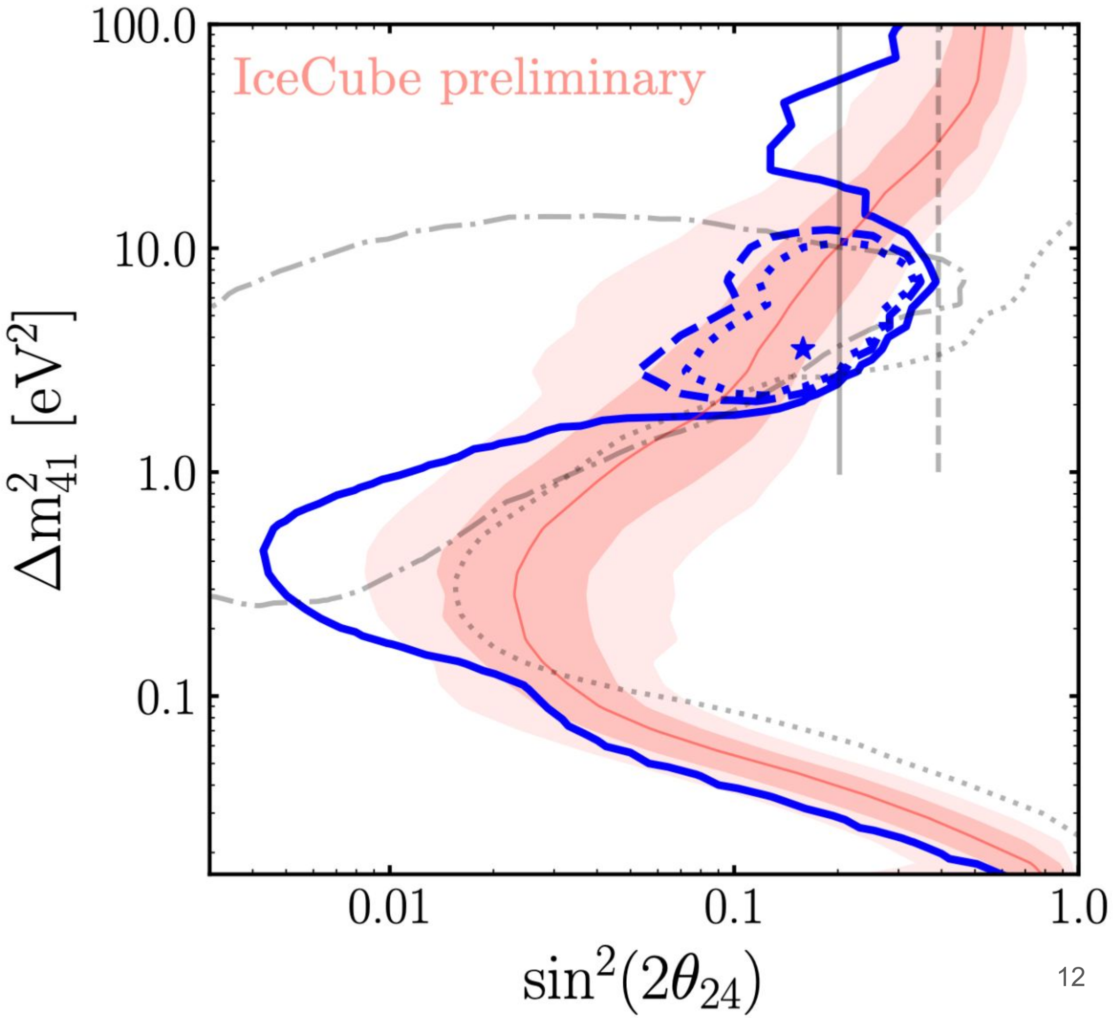
First: The Systematics



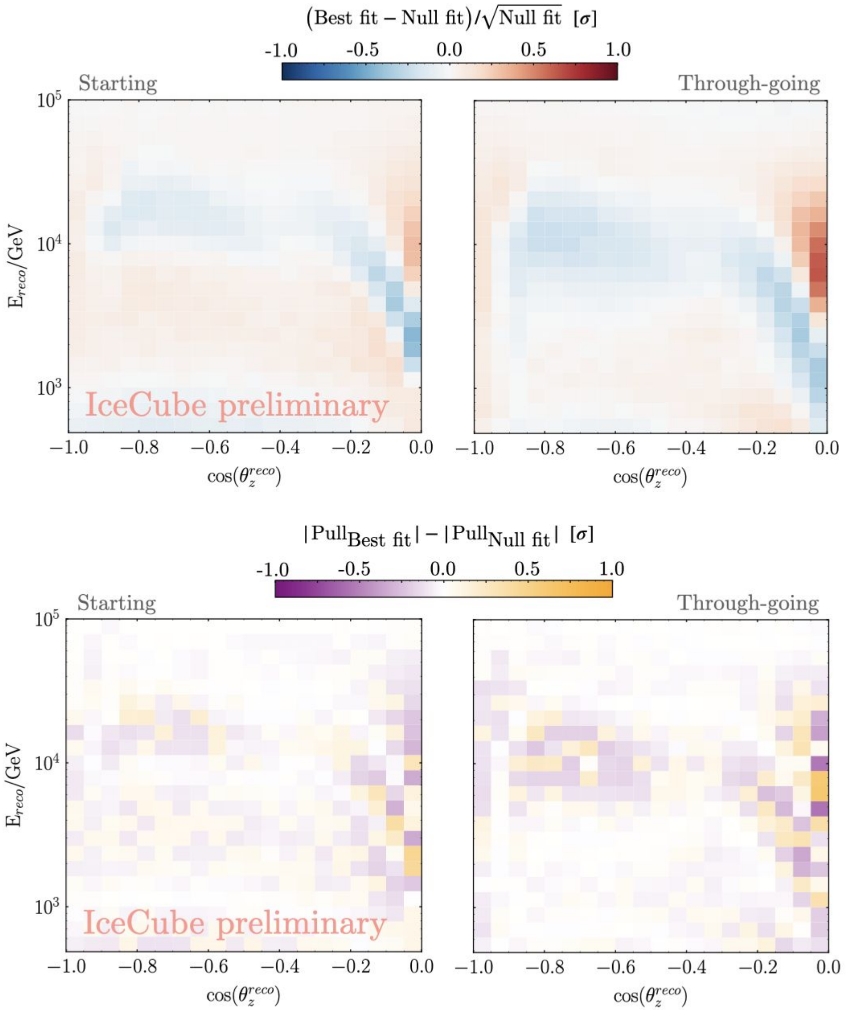
Result

- $\Delta m^2 = 3.5 eV^2$
- $\sin^2(2\theta_{24}) = 0.16$
- $p_{null} = 3.1\%$

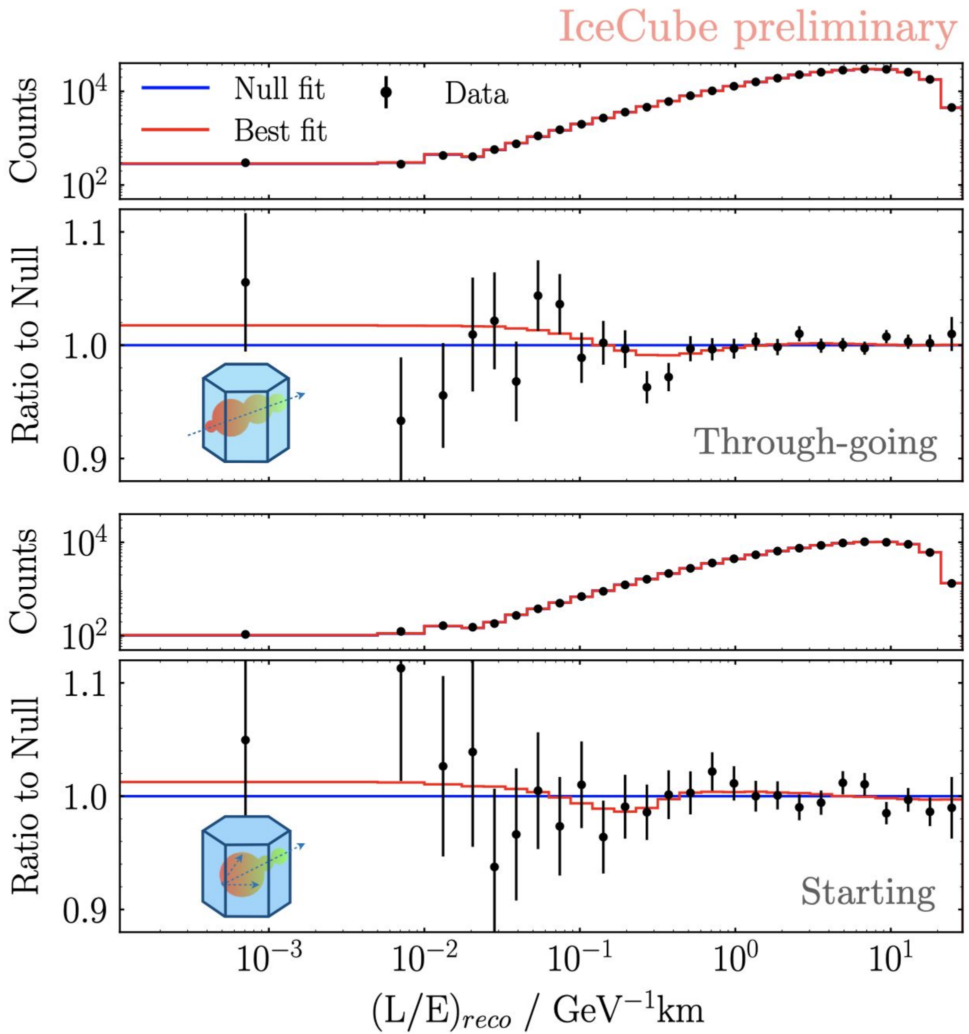




Expectation vs Data

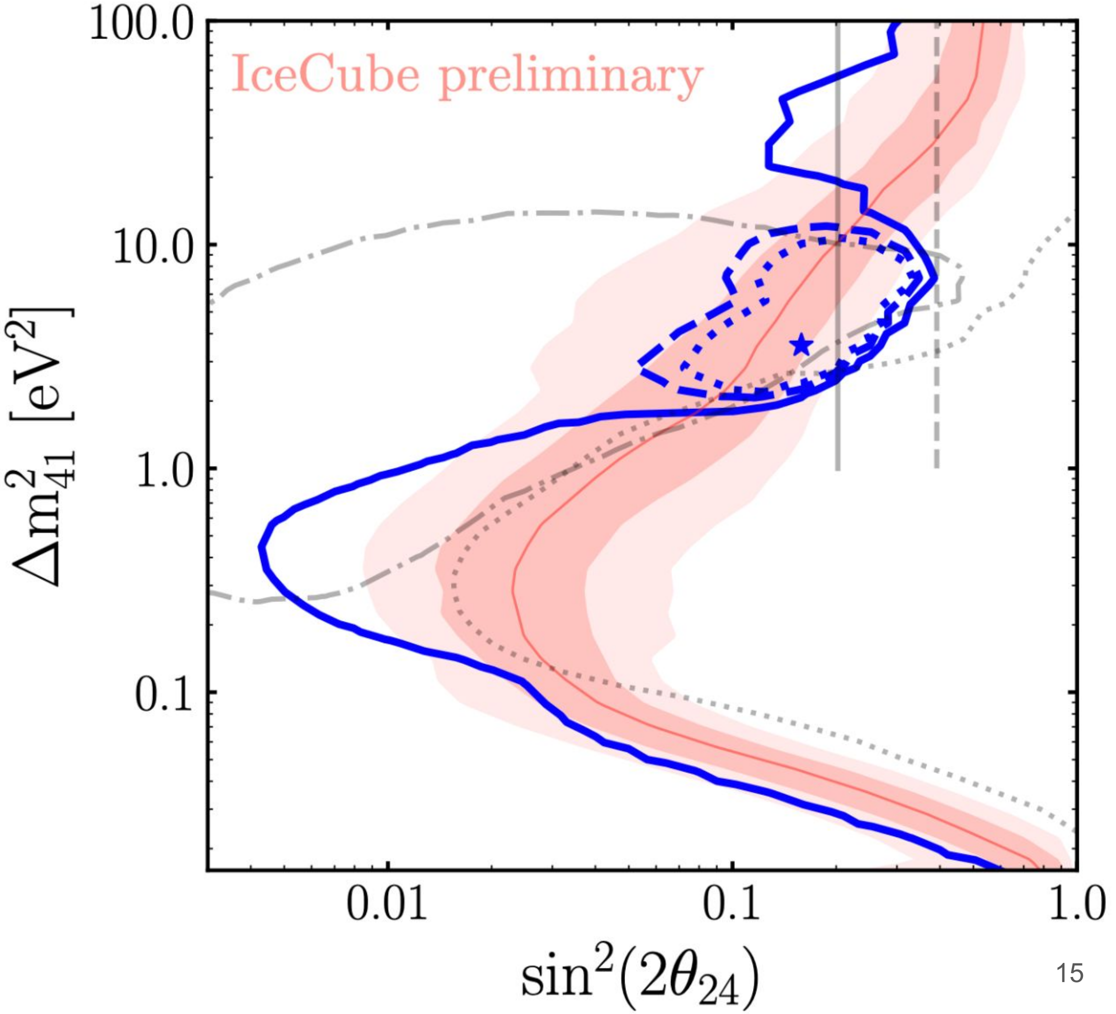


1 Dimension: L/E



Conclusions

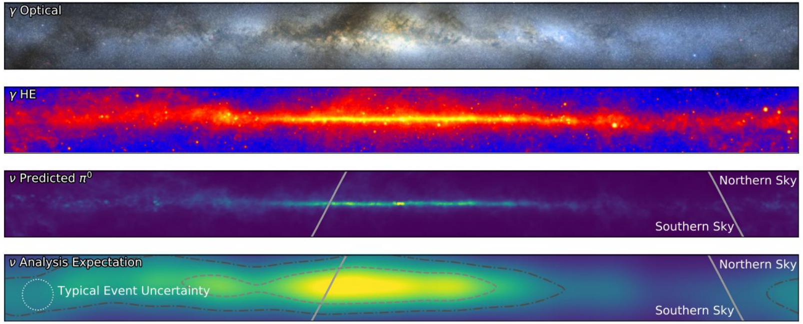
- The p-value for the null hypothesis of sterile neutrinos in the muon disappearance channel is 3.1%
- Does not rise to evidence
- Contributes to our understanding of the neutrino landscape

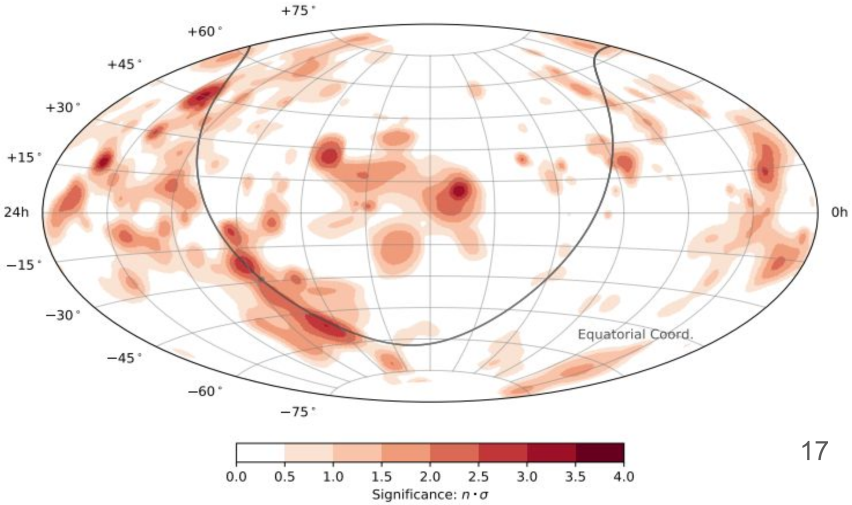


Machine Learning Opens up More Analyses with IceCube Data

Most Famously: The Galactic Plane

- DNN Based reconstruction has improved energy resolution of another type of IceCube event “Cascades”
- This has improves sensitivity to the point that IceCube has seen the Galactic Plane in Neutrinos
- Specifically, it has seen the Galactic Plane in Cascades
    - In Science: https://www.science.org/doi/10.1126/science.adc9818

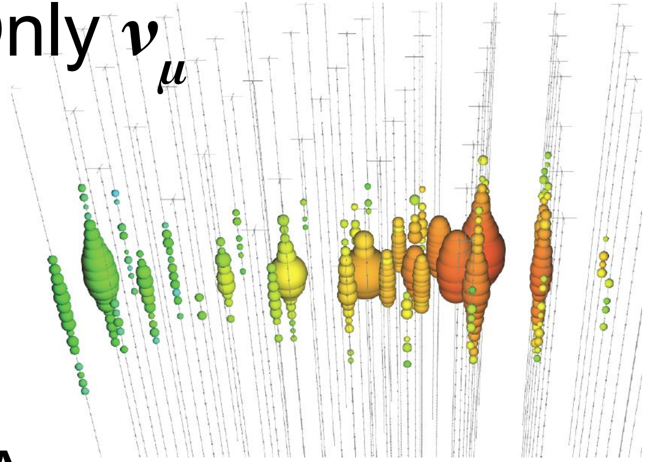




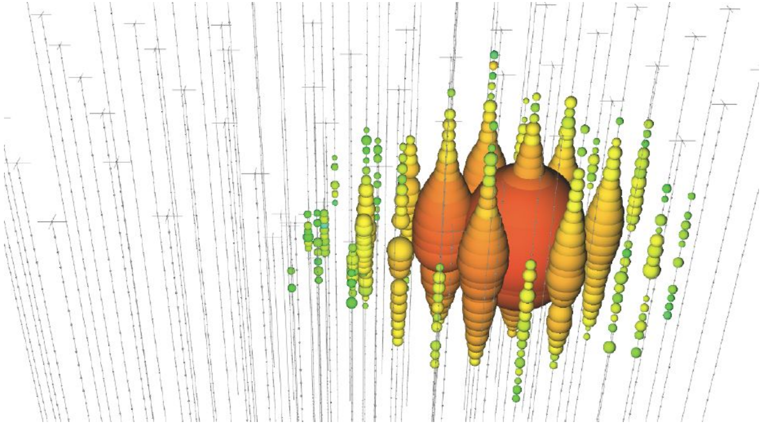
Tracks vs Cascades

- Our tracks can only be produced by muon neutrinos
    - Long, with excellent angular and poor energy resolution
- The cascades can be produced by any type of neutrino
    - Good energy resolution, but poor angular resolution
- Note that the two types of events have a differential flavor sensitivity

Only ν_μ



Any ν

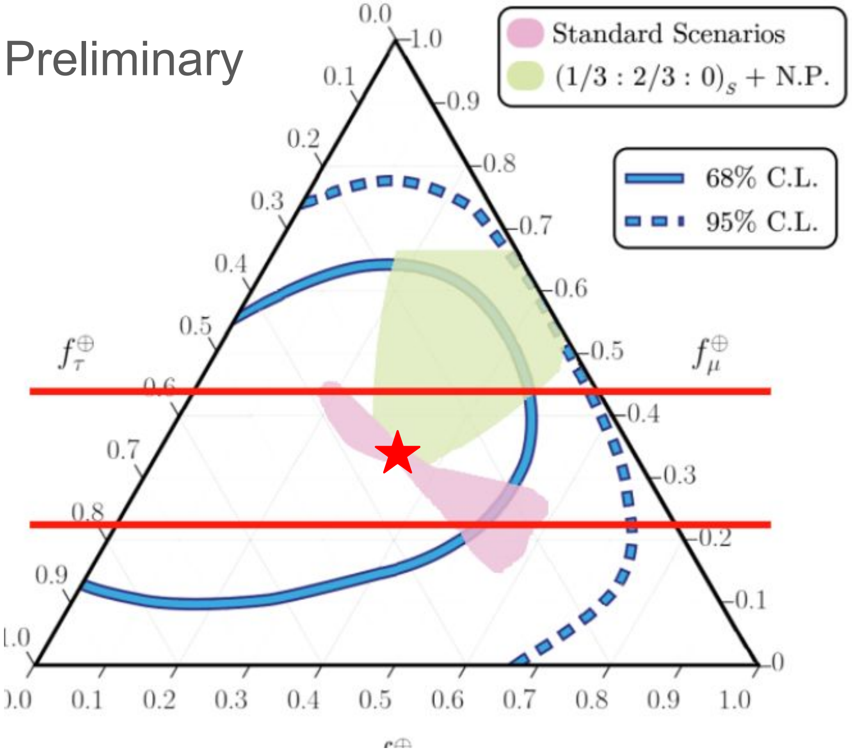


We can leverage this difference

- We expect that astrophysical neutrinos will arrive at the earth in a 1:1:1 mixture of flavors
- This holds true for neutrinos from the galaxy
- By comparing the intensity of the tracks over background to cascades over background, we can estimate the flavor composition of neutrinos from the galactic plane

Preliminary Sensitivities

- If we restrict to 1 dimension, we expect to be able to measure the fraction of muon flavor neutrinos to 0.12 (at the 1:1:1 starred point)
  - Red lines are to guide the eye for expected 1 dimensional flavor error
- This would be a new and independent test of standard oscillations with galactic neutrinos
- We are planning to do a full 3 flavor fit
- Unblinding soon!



Conclusions

- IceCube observes a 3.1% statistical agreement with a no-sterile neutrino model in the muon disappearance channel
- The IceCube observation of the Galactic Plane has opened up a new angle to look at astrophysical flavor ratios
- Machine learning based reconstruction has improved the sensitivity of existing analyses and opened up new possible analyses, including galactic flavor ratios
- Stay Tuned!

Thank You

John Hardin/NSF IceCube

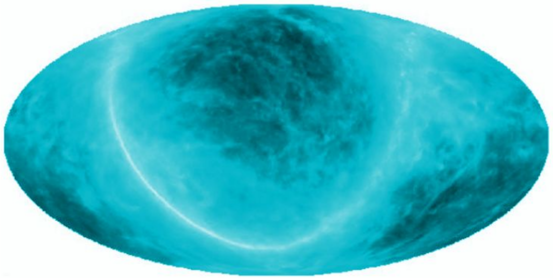
Backup

MEOWS

- Track sample
- High Purity
- Northern Sky
- Starting Separation
- DNN based reconstruction

Sensitivity to:

- Muon Neutrinos
- Some Tau Neutrinos

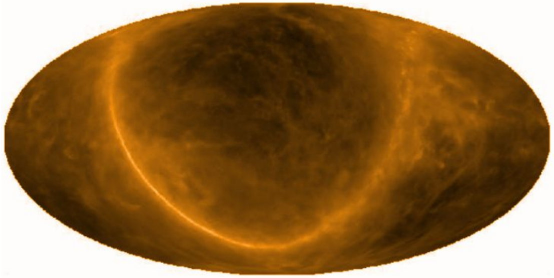


DNN Cascades

- Cascade Sample
- High Energy resolution
- All Sky
- DNN based reconstruction

Sensitivity to:

- All Flavors



Look at both samples with the same template

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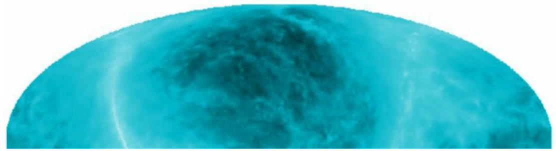

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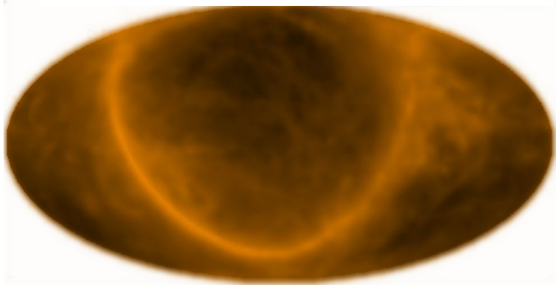

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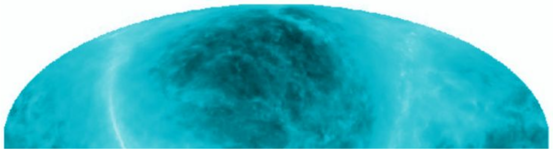

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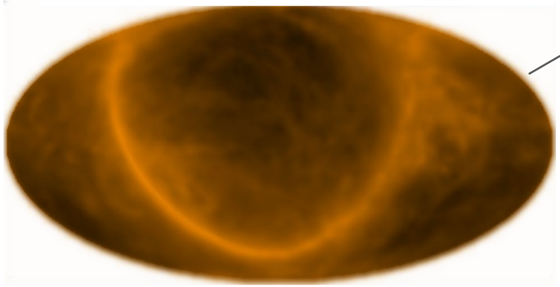

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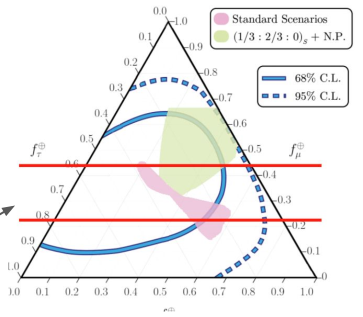
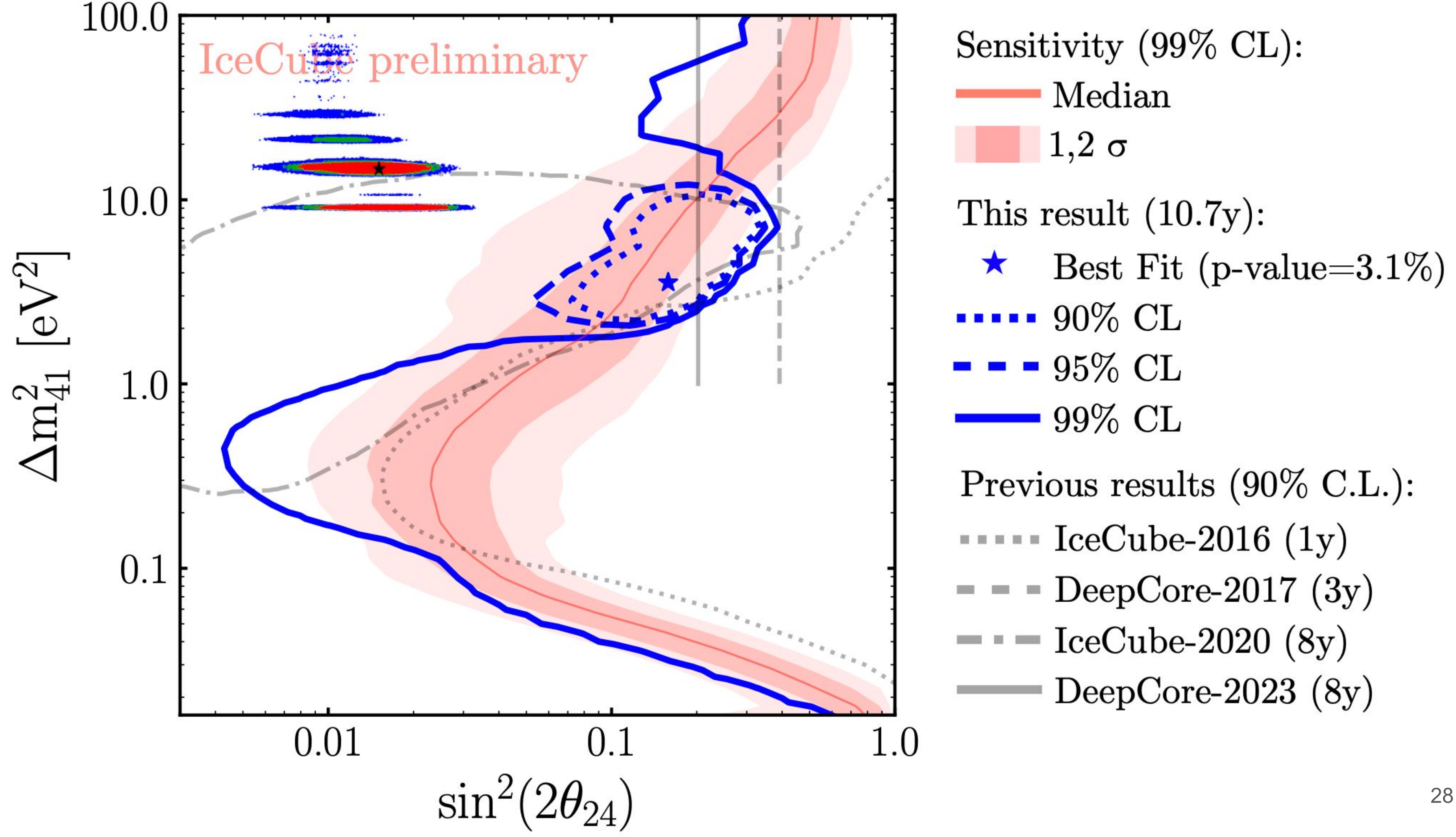


Extract Flavor Ratios

Improvements to the Sterile Search

- For the sterile analysis, the systematic treatment was improved
- Updated (conventional) atmospheric flux modeling
    - Arxiv:2205.14766
    - Updated Cosmic Ray Modeling
    - Updated Hadronic Modeling
- Updated astrophysical modeling
    - Specifically, a broken power law

Systematic	Central	Prior (1σ)	Range	Implementation
Detector Parameters				
Normalization	1.0	±0.2	[0.1,3]	
DOM efficiency	1.27	$\pm10\%$	[1.234, 1.346]	6 support points
Ice Amplitude 0	0.0	±1.0	[-3,3]	Correlation (see Fig. 19)
Ice Amplitude 1	0.0	±1.0	[-3,3]	"
Ice Amplitude 2	0.0	±1.0	[-3,3]	"
Ice Amplitude 3	0.0	±1.0	[-3,3]	"
Ice Phase 1	0.0	±1.0	[-3,3]	"
Ice Phase 2	0.0	±1.0	[-3,3]	"
Ice Phase 3	0.0	±1.0	[-3,3]	"
Ice Phase 4	0.0	±1.0	[-3,3]	"
Forward Hole Ice	-1.0	±10	[-5.35, 1.85]	5 support points
Conventional Flux Parameters				
Atm. Density	0	±1.0	[-3,3]	Spline
Kaon energy loss	0.0	±1.0	[-3,3]	Spline
K^+_{158G}	0.0	±1.0	[-2, 2]	Correlation (see Fig. 24)
K^-_{158G}	0.0	±1.0	[-2, 2]	"
π^+_{20T}	0.0	±1.0	[-2, 2]	"
π^-_{20T}	0.0	±1.0	[-2, 2]	"
K^+_{2P}	0.0	±1.0	[-1, 2]	"
K^-_{2P}	0.0	±1.0	[-1.5, 2]	"
π^+_{2P}	0.0	±1.0	[-2, 2]	"
π^-_{2P}	0.0	±1.0	[-2, 2]	"
p_{2P}	0.0	±1.0	[-2, 2]	"
n_{2P}	0.0	±1.0	[-2, 2]	"
GSF_1	0.0	±1.0	[-4, 4]	"
GSF_2	0.0	±1.0	[-4, 4]	"
GSF_3	0.0	±1.0	[-4, 4]	"
GSF_4	0.0	±1.0	[-4, 4]	"
GSF_5	0.0	±1.0	[-4, 4]	"
GSF_6	0.0	±1.0	[-4, 4]	"
High-energy Flux Parameters				
Normalization	0.787	±0.36	[0,3]	
$\Delta\gamma_1$, tilt from -2.5	0.0	±0.36	[-2,2]	
$\Delta\gamma_2$, tilt from -2.5	0.0	±0.36	[-2,2]	
Pivot energy in log10	-	-	[4,6]	Uniform prior
Cross-section Parameters				
ν cross section	1.0	±0.1	[0.824, 1.176]	30 support points
$\bar{\nu}$ cross section	1.0	±0.1	[0.824, 1.176]	"


IceCube preliminary
100.0
10.0
1.0
0.1
Δm²₄₁ [eV²]
0.01
0.1
1.0
sin²(2θ₂₄)
Sensitivity (99% CL):
Median
1,2 σ
This result (10.7y):
Best Fit (p-value=3.1%)
90% CL
95% CL
99% CL
Previous results (90% C.L.):
IceCube-2016 (1y)
DeepCore-2017 (3y)
IceCube-2020 (8y)
DeepCore-2023 (8y)