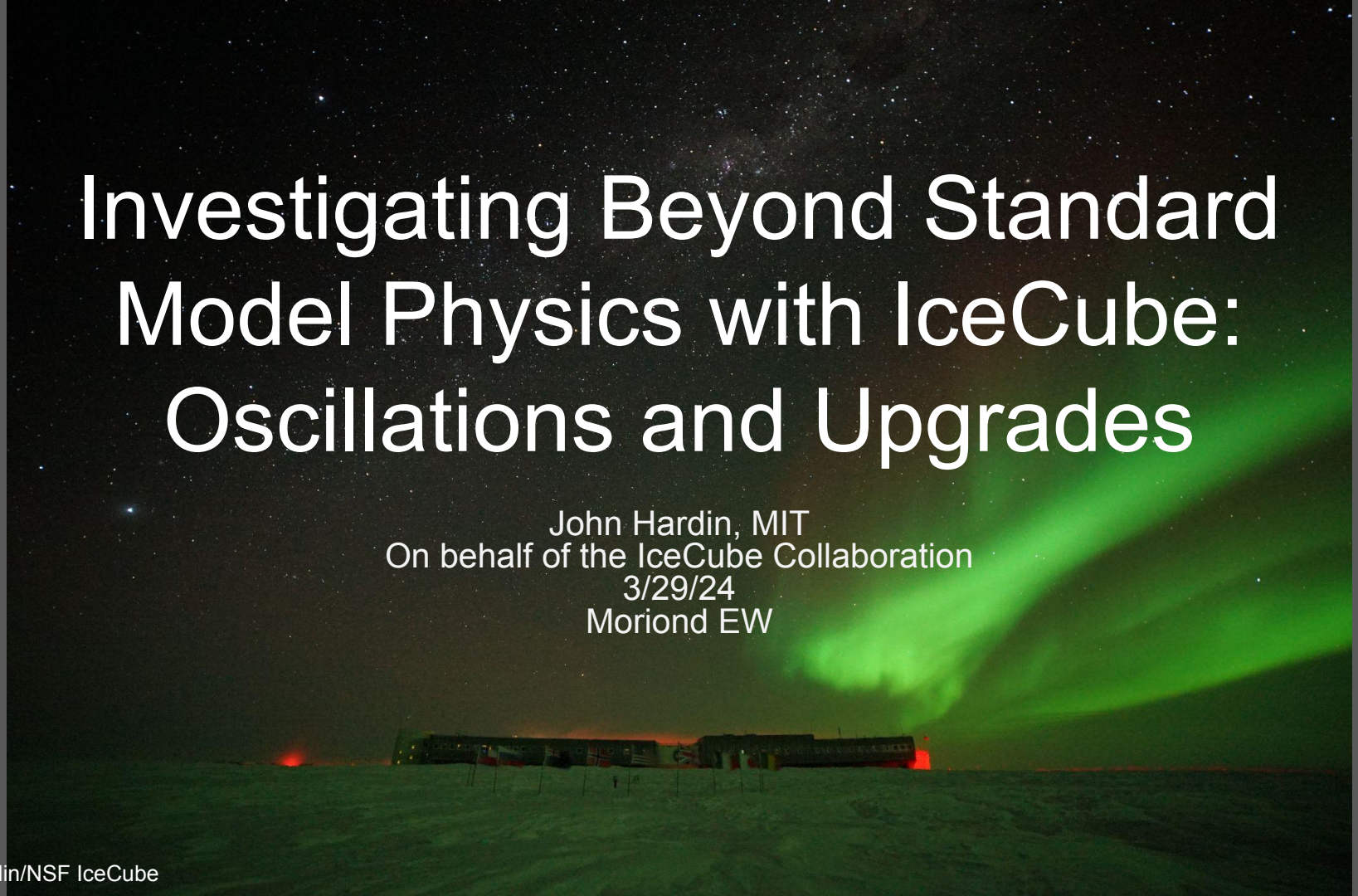


Investigating Beyond Standard Model Physics with IceCube: Oscillations and Upgrades

John Hardin, MIT
On behalf of the IceCube Collaboration
3/29/24
Moriond EW

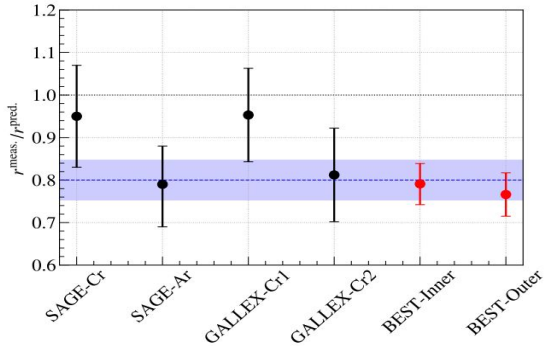
Outline

- What are Sterile Neutrinos, and why are we looking for them
- How does IceCube look for new physics
- Recent results on Sterile Neutrinos
- Other Beyond the Standard Model Results
- The IceCube Upgrade

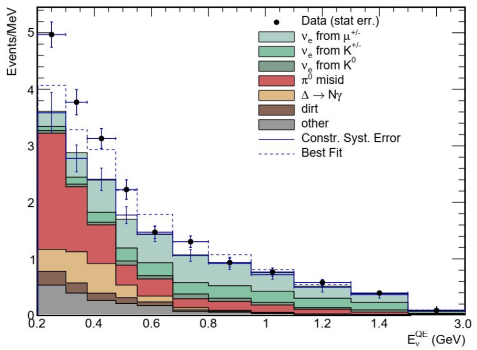
Sterile Neutrinos (3+1)

Something is Peculiar in the State Of Neutrinos

- 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
  - https://arxiv.org/abs/2211.02610

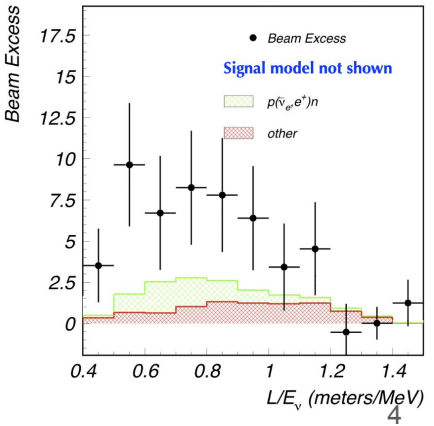


Phys Rev C, arxiv:2201.07364



Phys. Rev. Lett. 121 arxiv:1805.12028

Phys. Rev. D 64, 112007

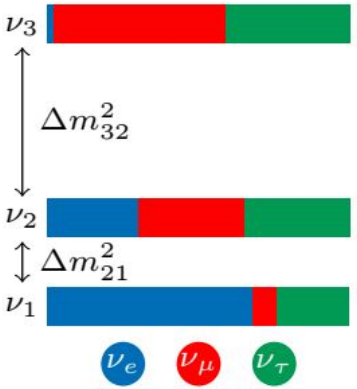


Arxiv: hep-ex/0104049

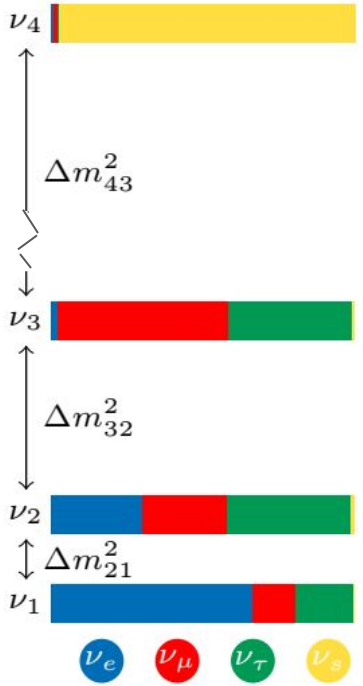
Which BSM: Sterile Neutrino(s)

- Proposed BSM particle
- Neutrino that does not interact weakly
- It can have a large mass splitting
- 2 Parameters: splitting and mixing (frequency and amplitude)
- IceCube detects this signal differently than other sterile searches

3**ν** SM



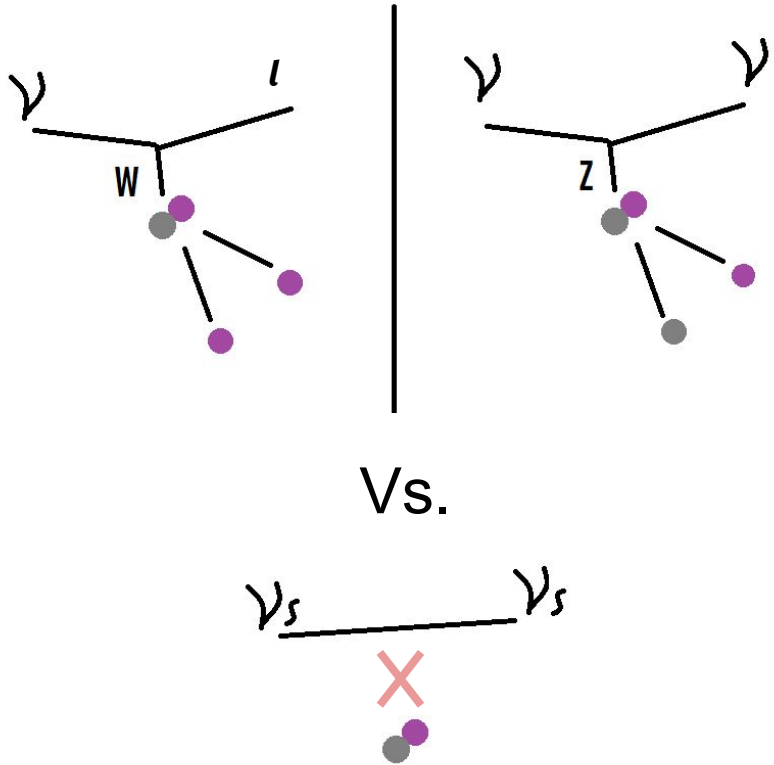
3**ν**+1 Sterile



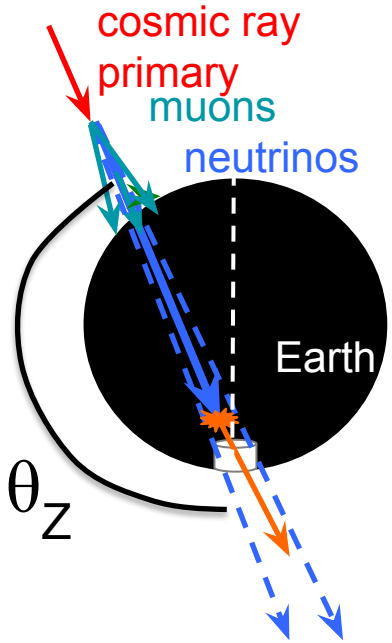
Phys. Rep. 884, arxiv:1906.00045

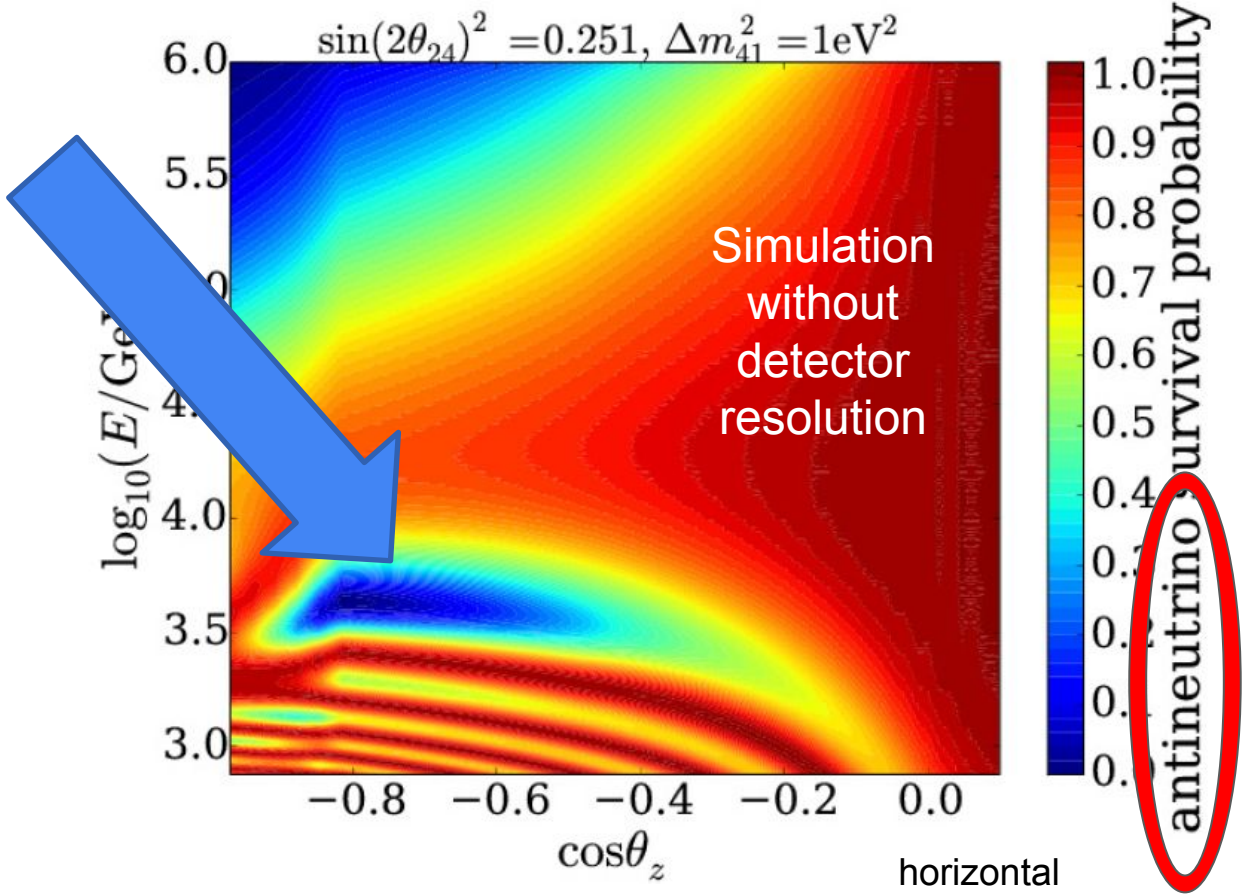
Sterile Neutrinos and the Earth in IceCube

- 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



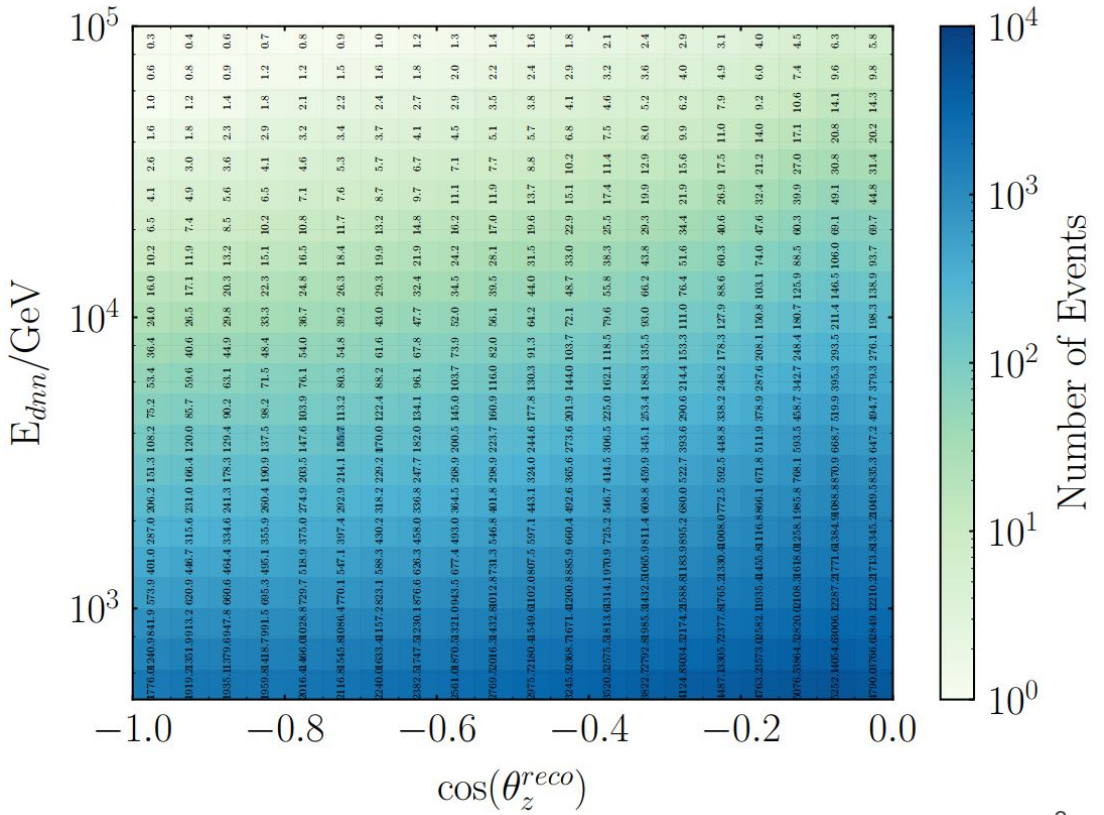
Matter effect on Sterile Neutrino:
Large disappearance of upgoing antineutrinos





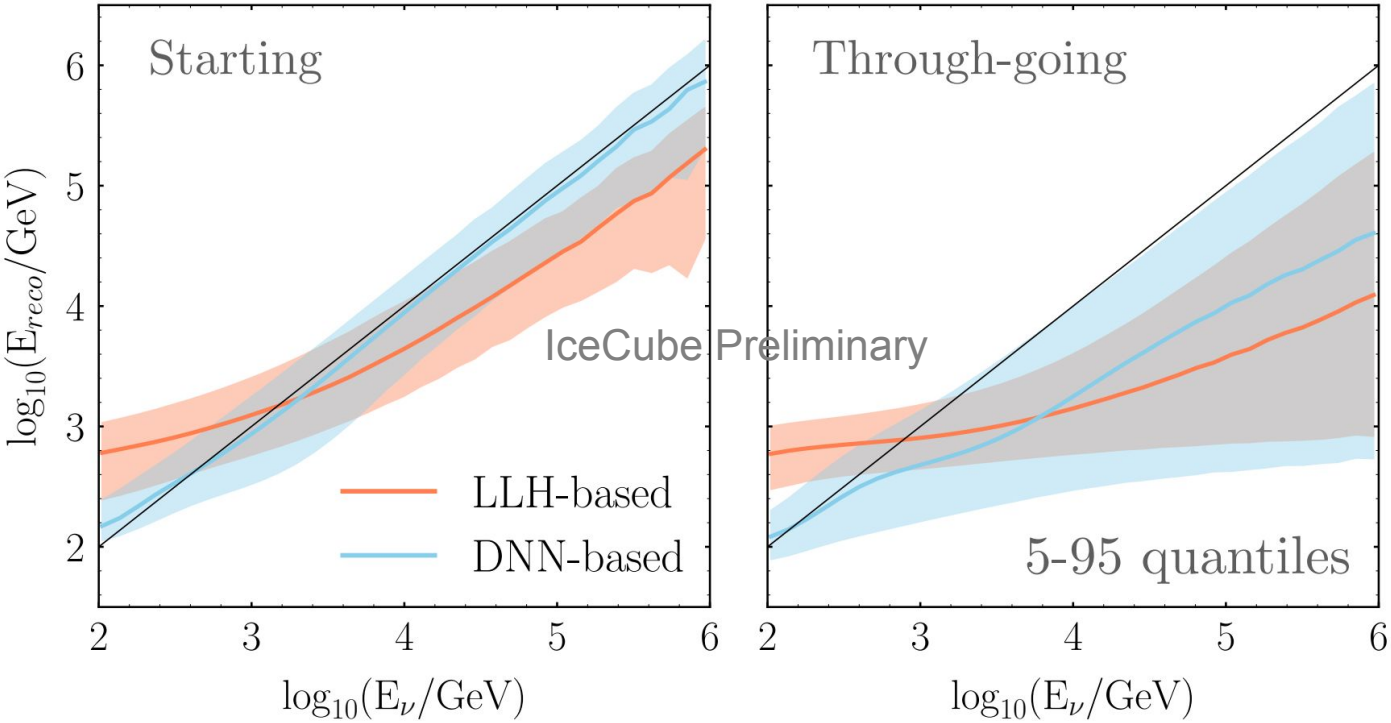
How does IceCube look for this deficit?

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



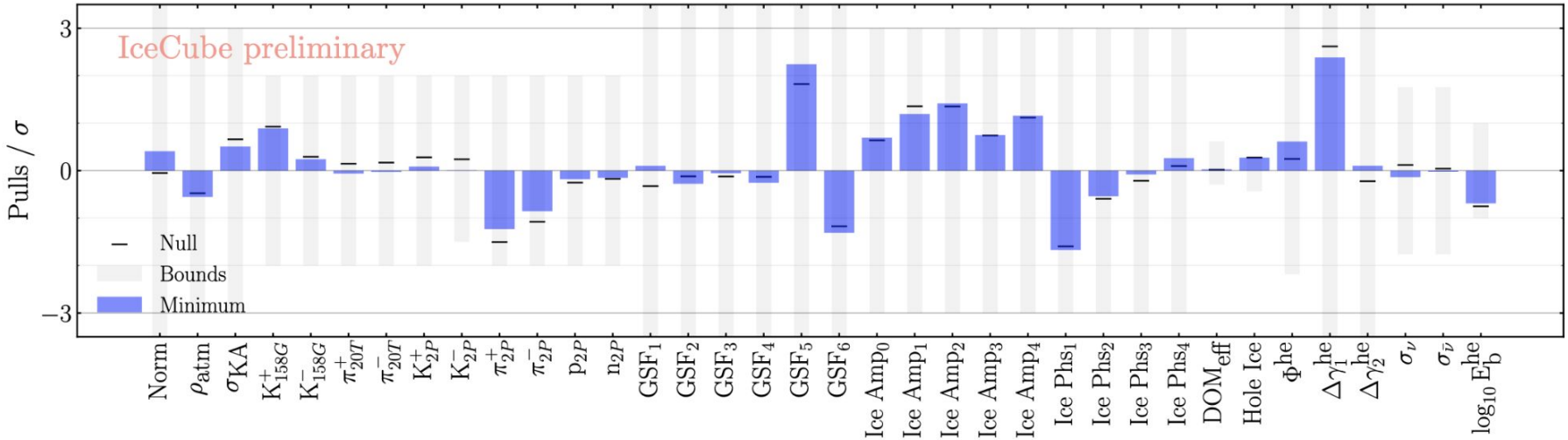
Improvements:

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



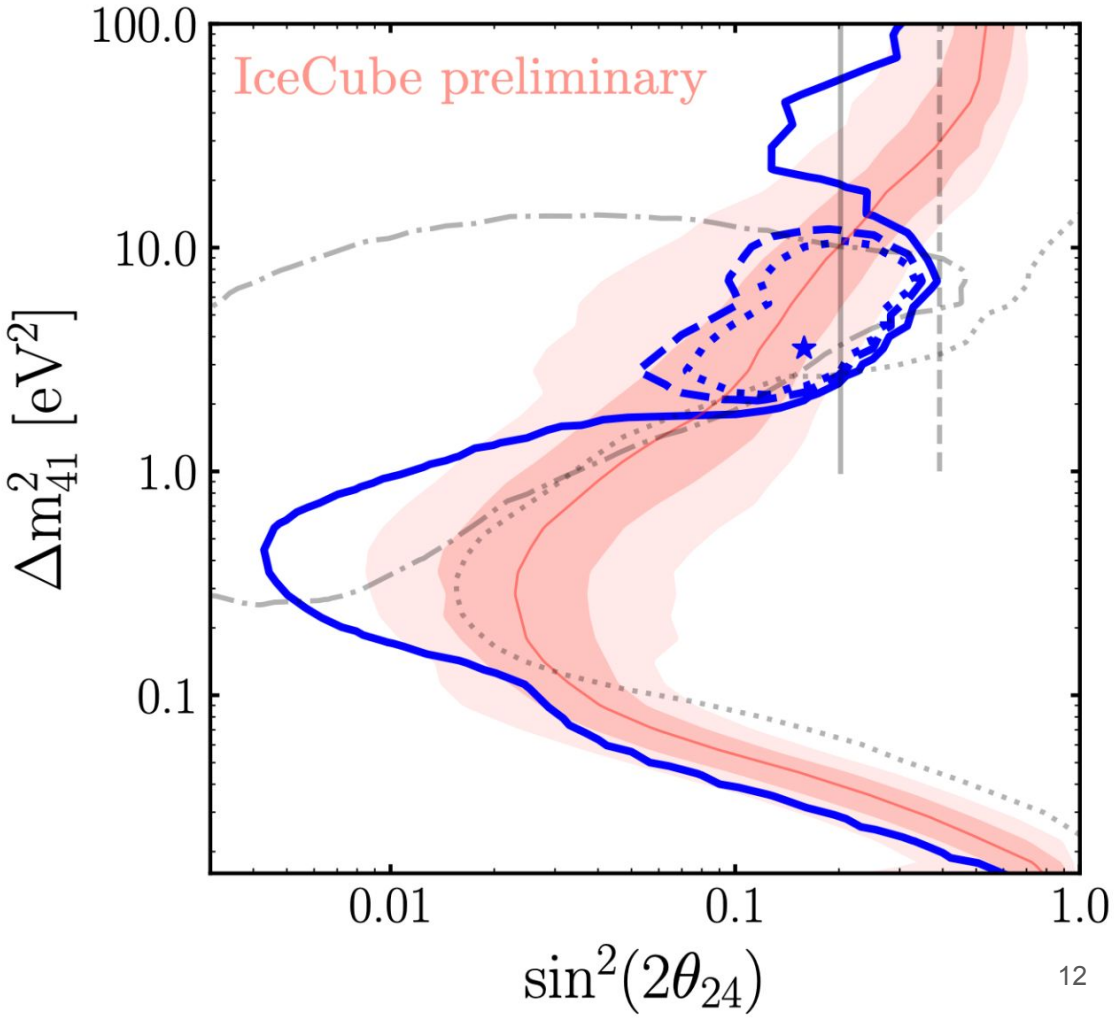
Results

First: The Systematics

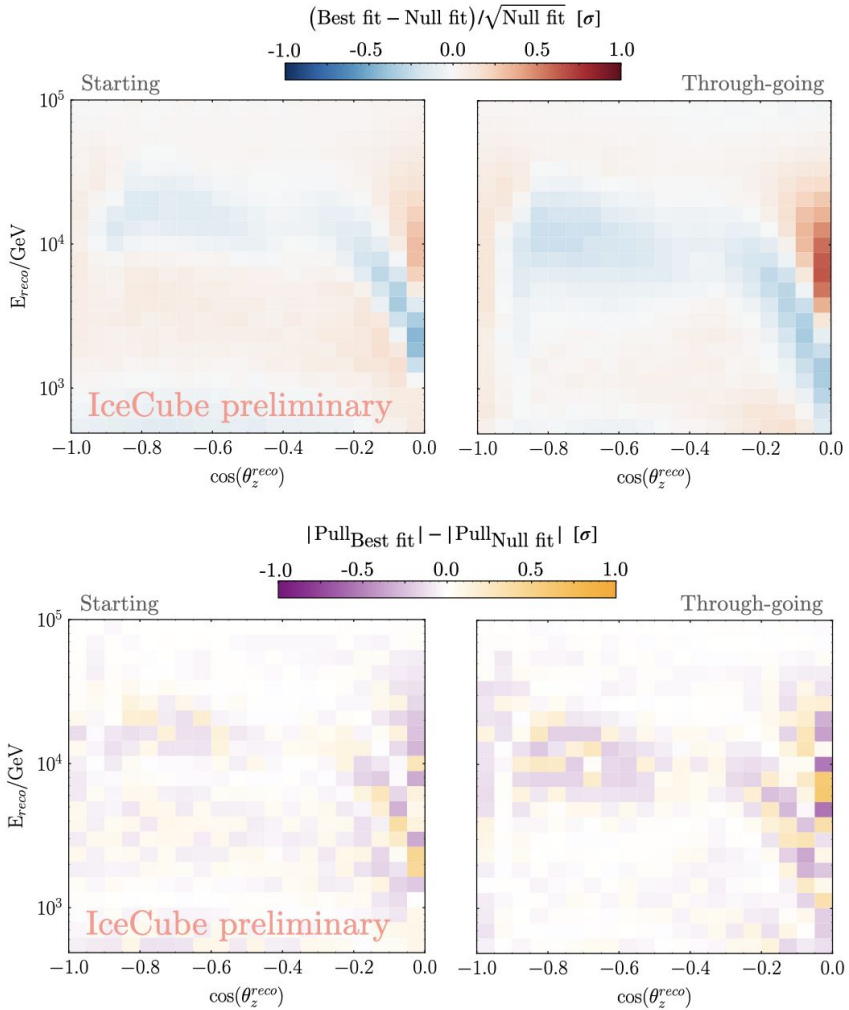


Result

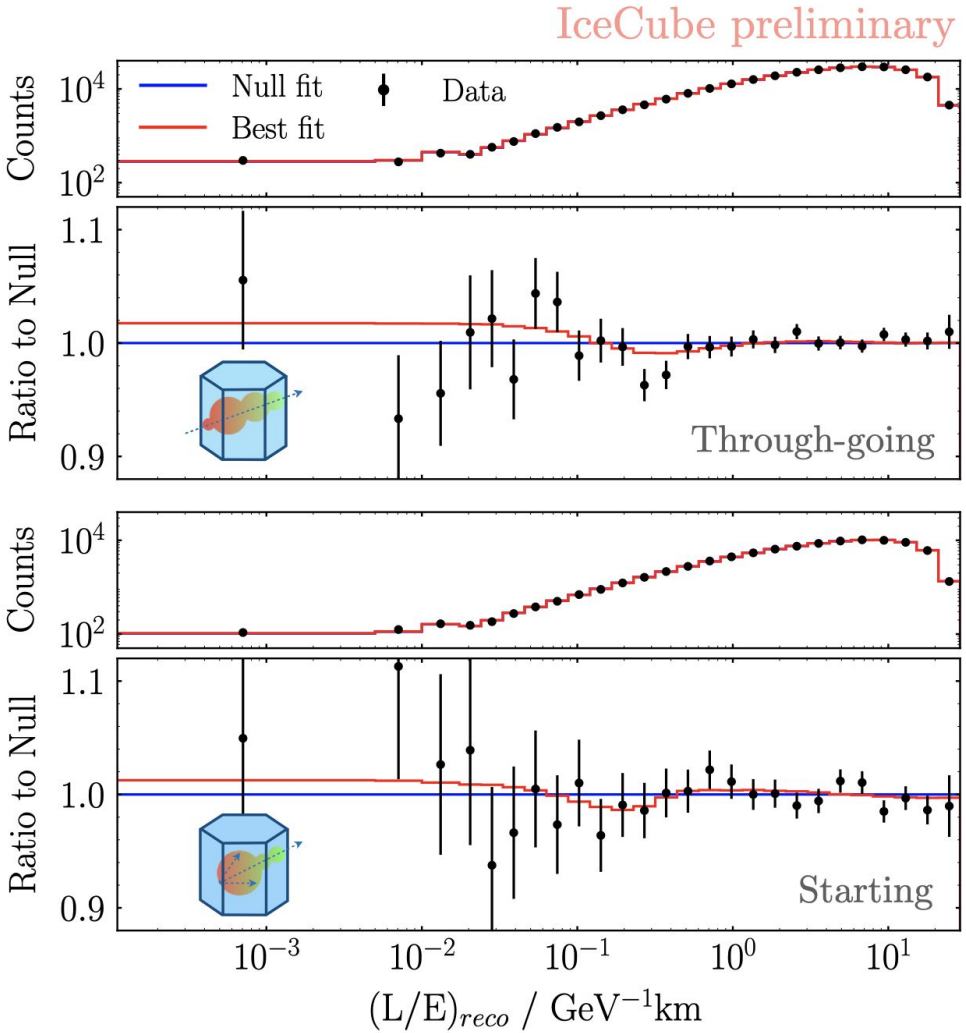
- $\Delta m^2 = 3.5 eV^2$
- $\sin^2(2\theta_{24}) = 0.16$
- $p_{null} = 3.1\%$



Expectation vs Data

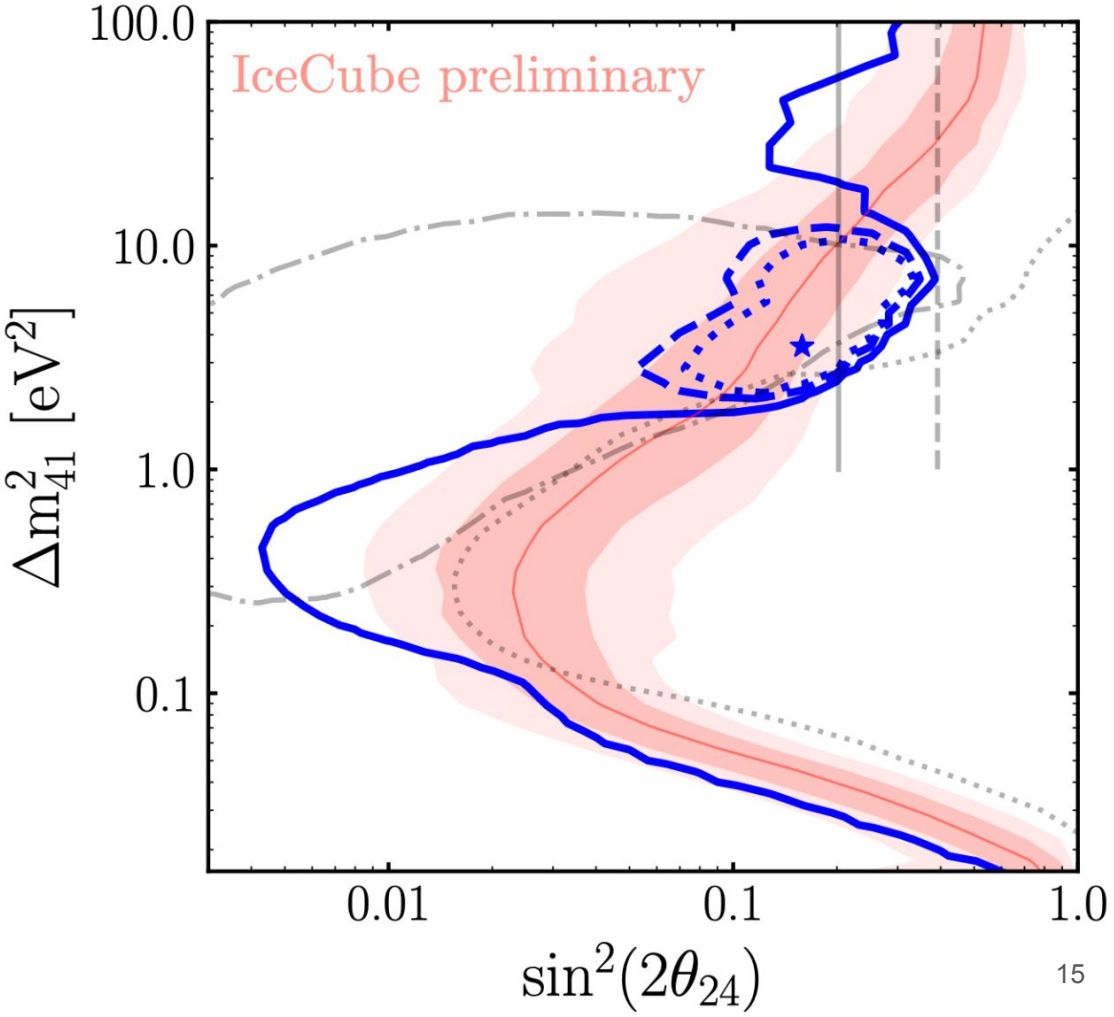


1 Dimension: L/E



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

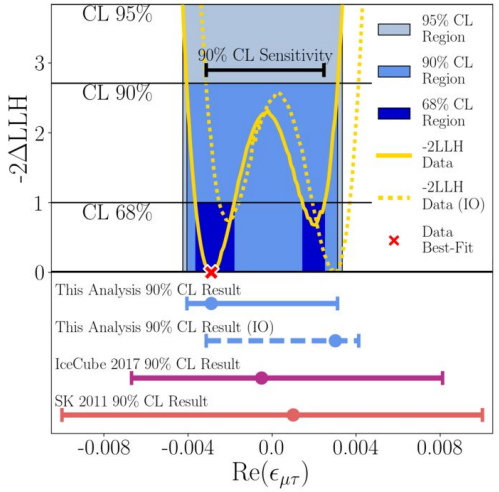


Beyond Sterile Neutrinos

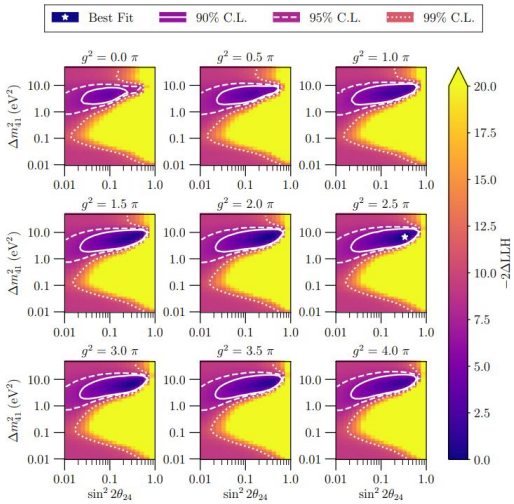
John Hardin/NSF IceCube

Sensitivity to a wide variety of SM and BSM Physics

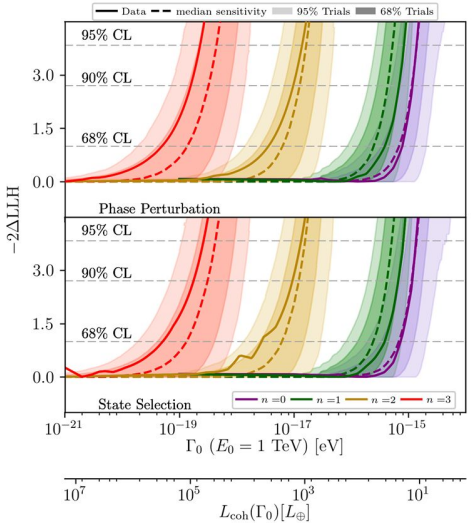
NSI



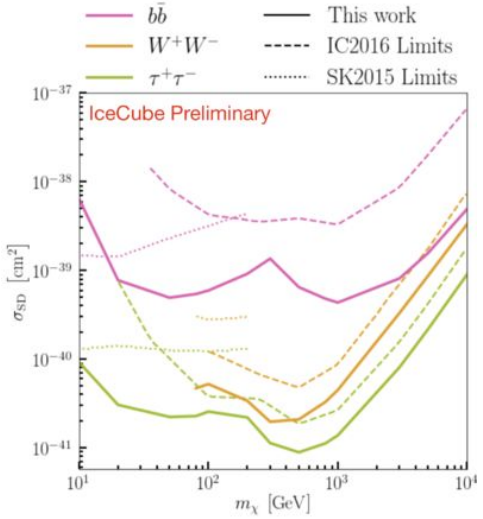
Sterile Decay



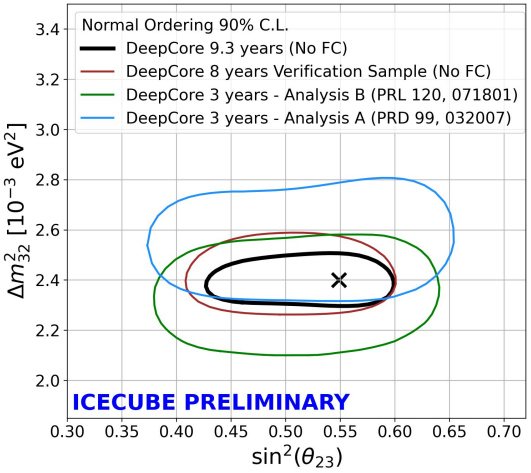
Decoherence



Solar WIMP



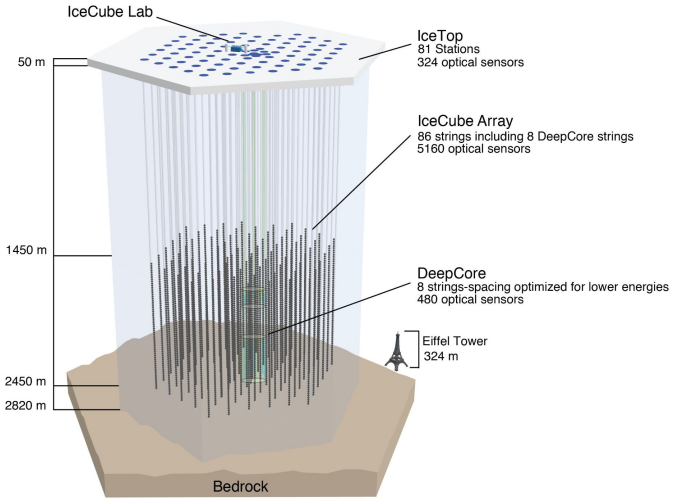
Standard Oscillations

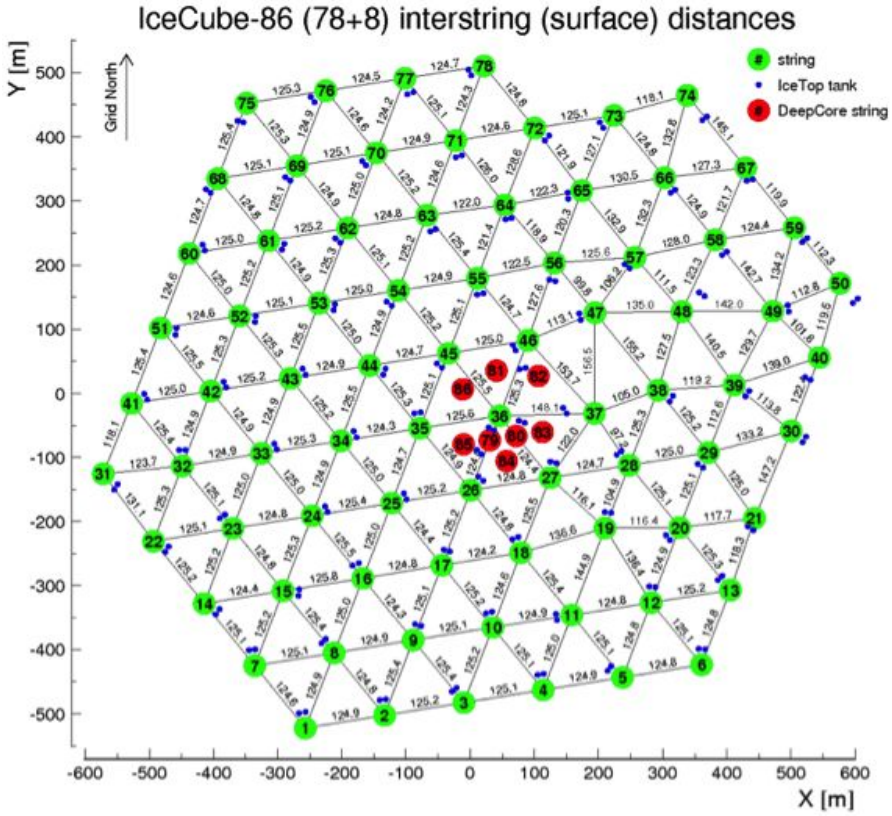


IceCube is Improving

The IceCube Upgrade

- IceCube is divided into the large regular grid of strings and a denser core
  - Higher acceptance vs lower energy threshold

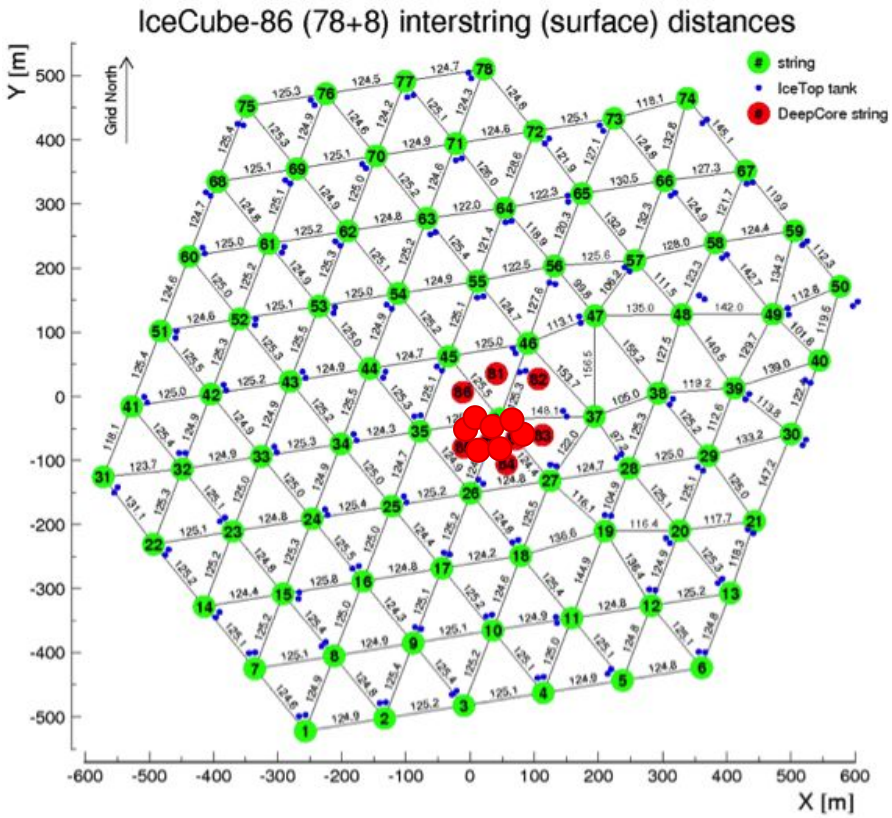




Credit: IceCube

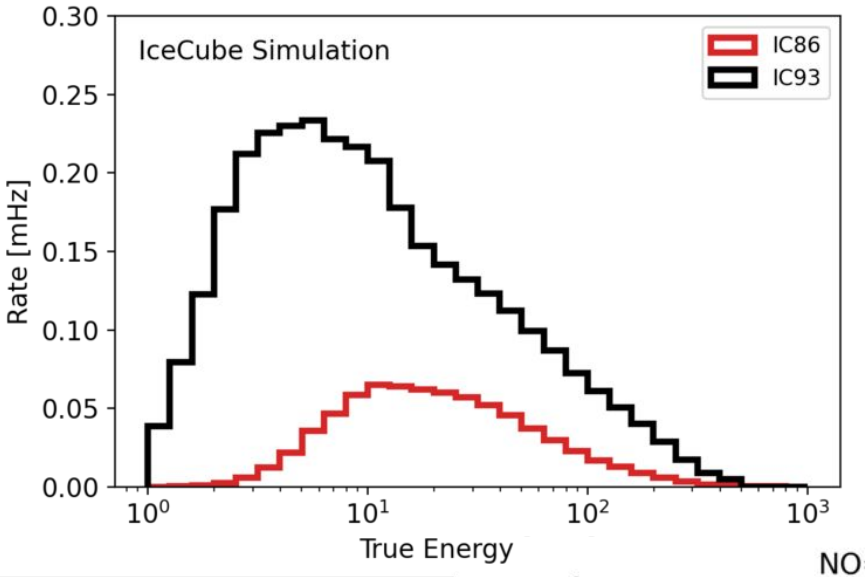
The IceCube Upgrade

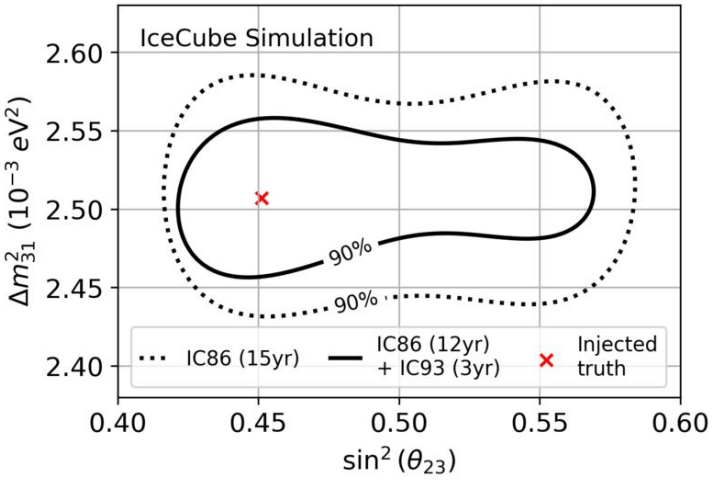
- IceCube is divided into the large regular grid of strings and a denser core
  - Higher acceptance vs lower energy threshold
- Upgrade is expected to go into operation in early 2026
- Even denser - lower energy thresholds

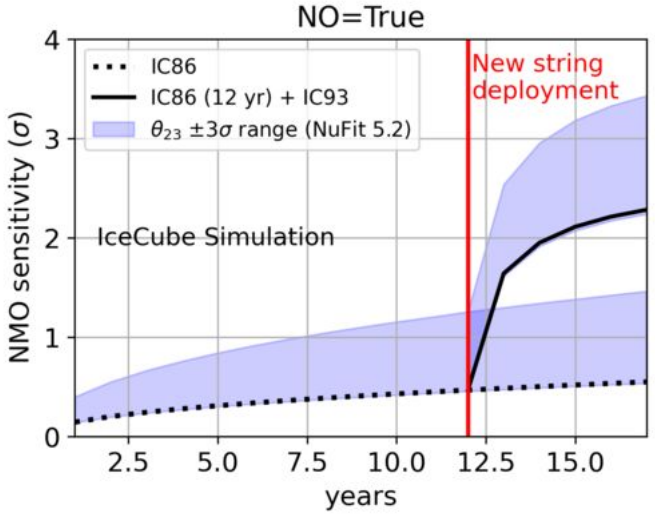


Credit: IceCube

Upgrade Expectations







Conclusions

- IceCube observes a 3.1% statistical agreement with a no-sterile neutrino model in the muon disappearance channel
- IceCube has access to a wide variety of BSM Physics
- The IceCube upgrade will push us past current statistical limitations
- Stay Tuned

John Hardin/NSF IceCube

John Hardin/NSF IceCube

Backup

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	±10%	[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]	"

Sterile Neutrinos: Global picture

- We know that something is happening in the global data
  - Either a systematic or new physics
- But tension tells us that simple 3+1 doesn't appear to be the answer
- IceCube's analysis is a unique contribution to this picture

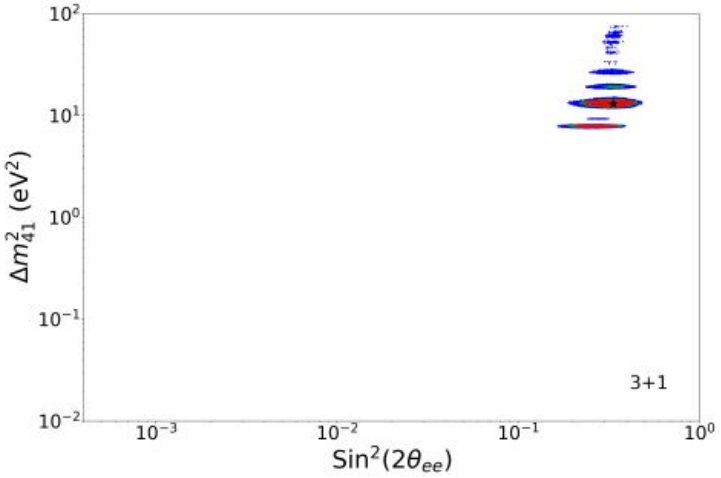
The data are anomalous:

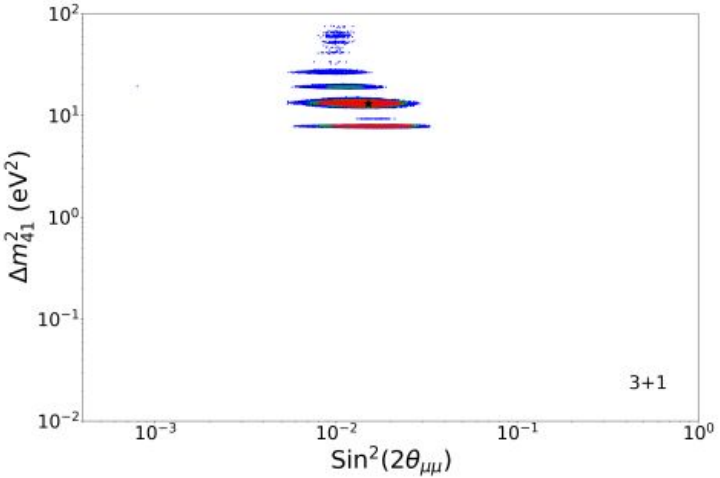
But there is tension in 3+1:

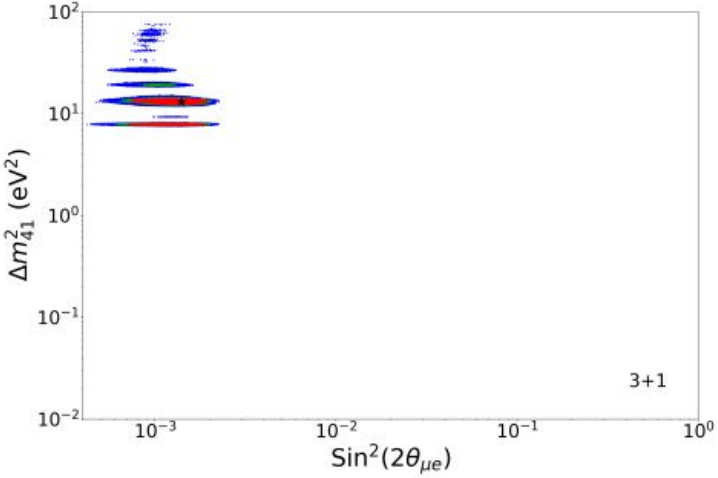
Fit type:	3+1	3+2	3+3	3+1+WP	3+1+dk
(Null vs Sterile) $N\sigma$	6.2	6.2	6.1	7.1	7.0
(3+1 vs Other) $N\sigma$		2.1	2.4	3.8	3.8
(PG Test) $N\sigma$	4.9	5.3	4.1	3.4	3.7

arxiv:arxiv:2211.02610

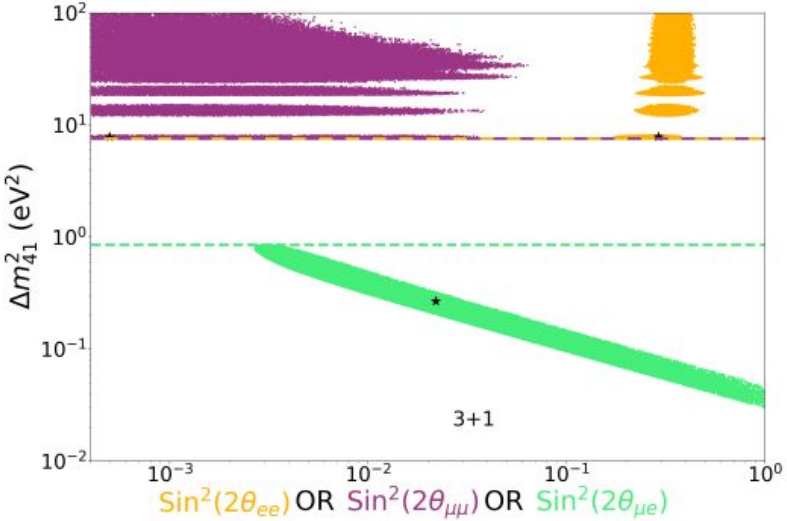
World results

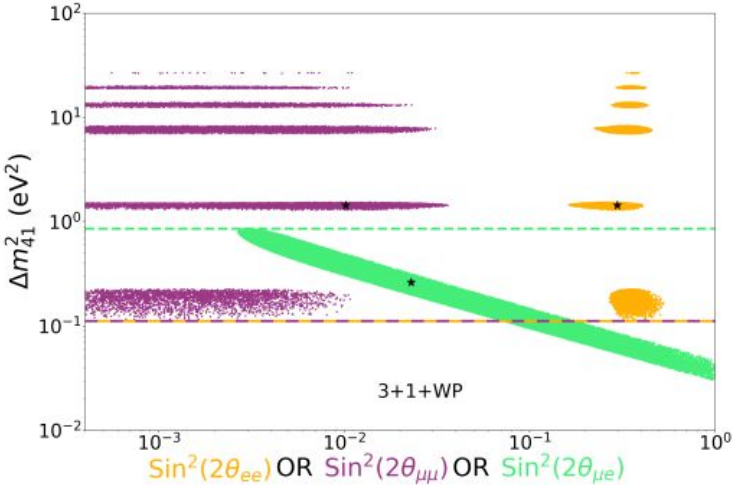


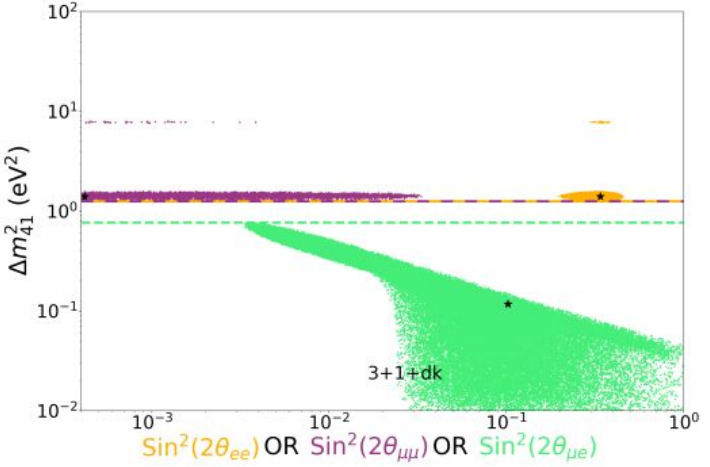


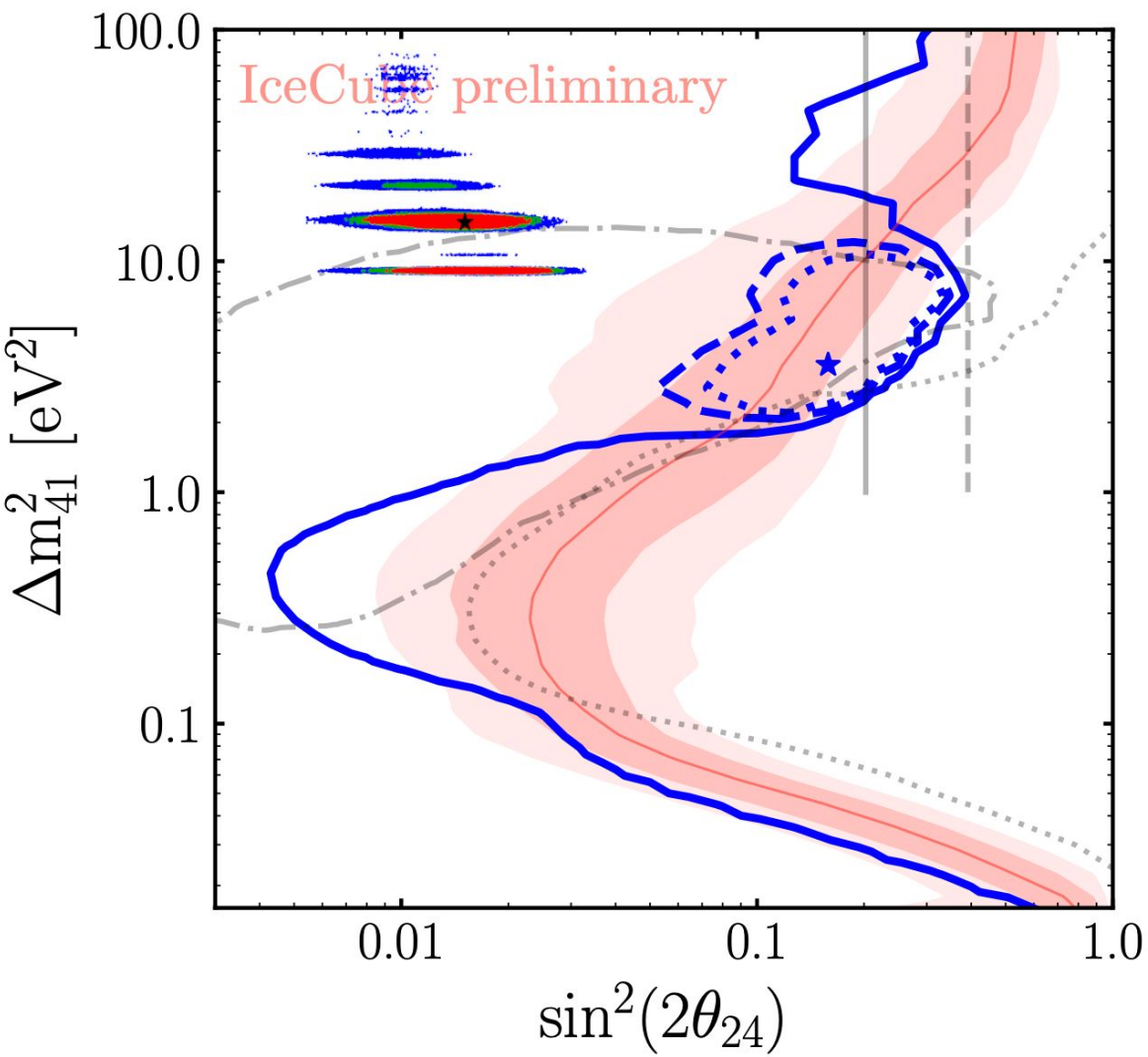


World tension







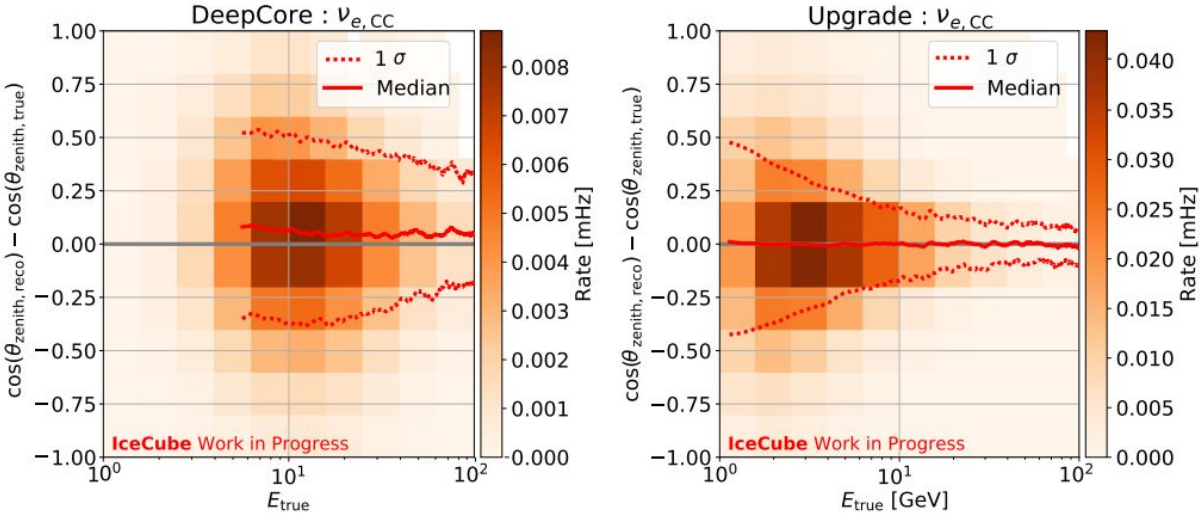


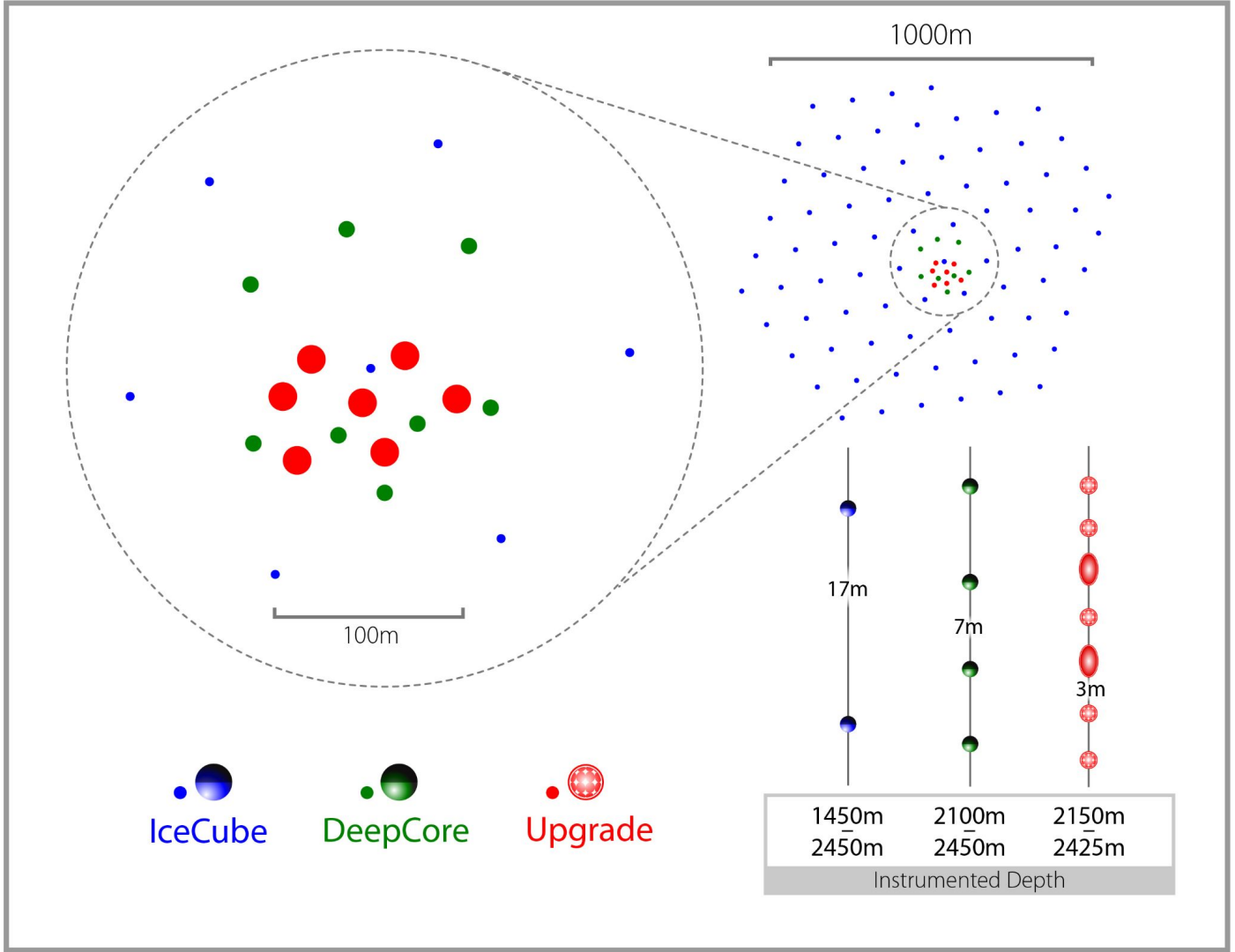
Sensitivity (99% CL):
- Median
- 1,2 σ

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)

Fit type:	3+1	3+2	3+3	3+1+WP	3+1+dk
(Null vs Sterile)					
$\Delta\chi^2$	46.5	56.9	67.4	61.1	60.6
Δdof	3	7	12	4	4
p-value	4.4E-10	6.3E-10	9.8E-10	1.7E-12	2.2E-12
$N\sigma$	6.2	6.2	6.1	7.1	7.0
(3+1 vs Other)					
$\Delta\chi^2$		10.1*	20.6*	14.6	14.1
Δdof		4	9	1	1
p-value		3.9E-2	1.5E-2	1.3E-4	1.7E-4
$N\sigma$		2.1	2.4	3.8	3.8
(PG Test)					
χ^2_{app}	148.2	131.8	131.1	148.2	146.8
N_{app}	2	5	9	2	3
χ^2_{dis}	639.8	626.1	625.2	638.4	641.4
N_{dis}	3	6	9	4	4
χ^2_{glob}	816.1	796.2	785.7	801.5	807.5
N_{glob}	3	7	12	4	4
χ^2_{PG}	28.1	38.4	29.5	14.9	19.3
N_{PG}	2	4	6	2	3
p-value	7.9E-07	9.3E-08	4.9E-05	5.8E-04	2.4E-4
$N\sigma$	4.9	5.3	4.1	3.4	3.7


DeepCore : $\nu_{e,\mathrm{CC}}$
1 σ
Median
IceCube Work in Progress
$\cos(\theta_{\mathrm{zenith,reco}}) - \cos(\theta_{\mathrm{zenith,true}})$
E_{true}
Rate [mHz]
Upgrade : $\nu_{e,\mathrm{CC}}$
1 σ
Median
IceCube Work in Progress
$\cos(\theta_{\mathrm{zenith,reco}}) - \cos(\theta_{\mathrm{zenith,true}})$
E_{true} [GeV]
Rate [mHz]


1000m
100m
17m
7m
3m
IceCube
DeepCore
Upgrade
1450m
2450m
2100m
2450m
2150m
2425m
Instrumented Depth