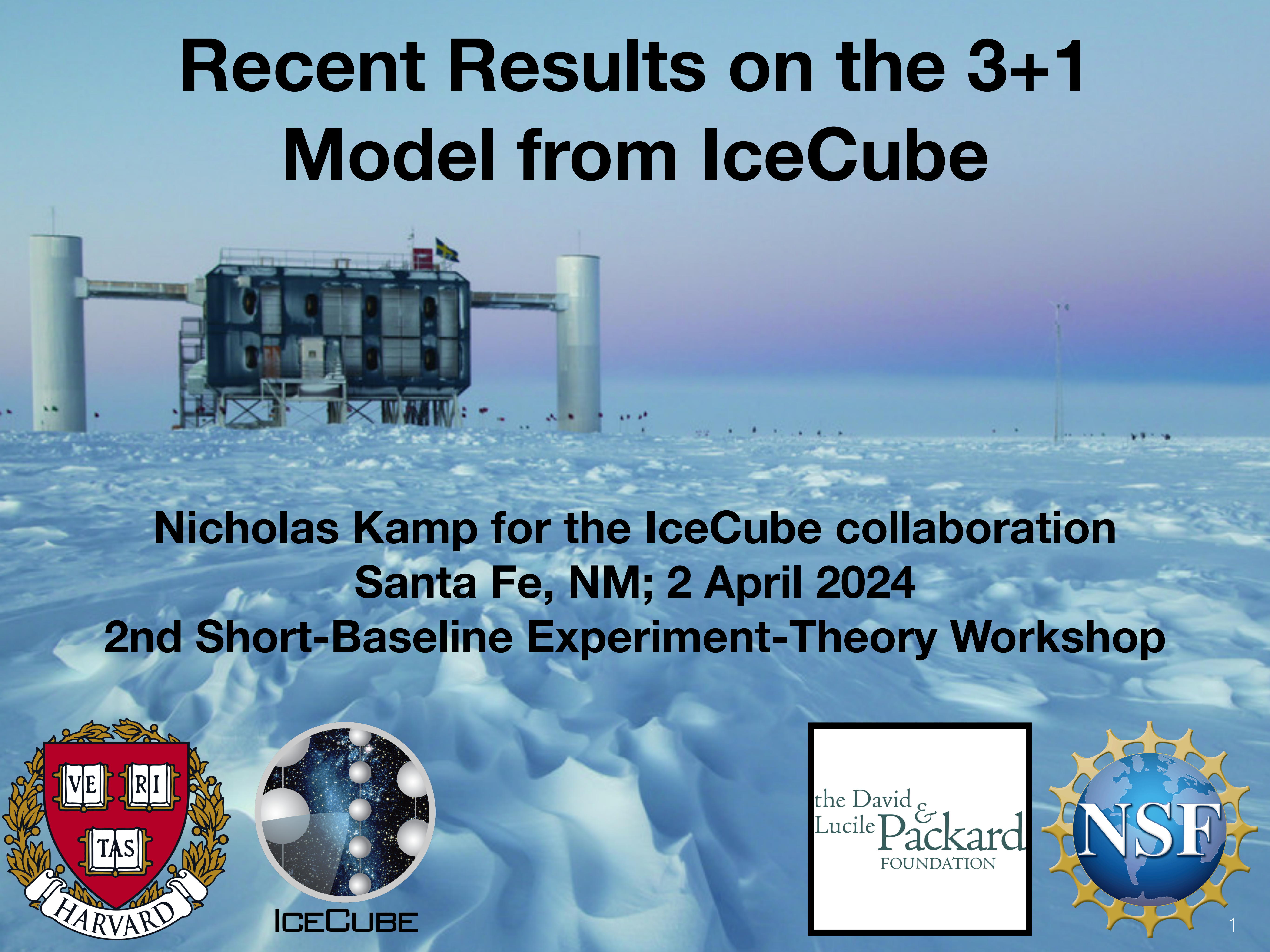
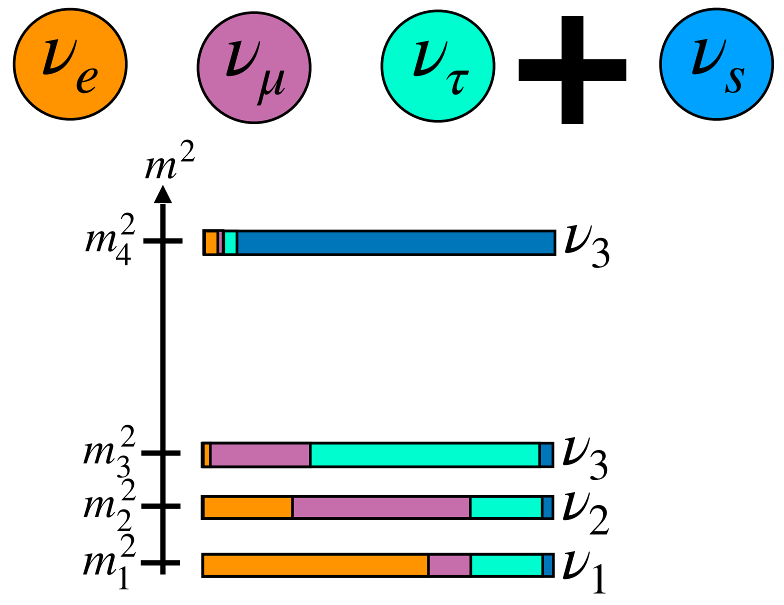


Recent Results on the 3+1 Model from IceCube

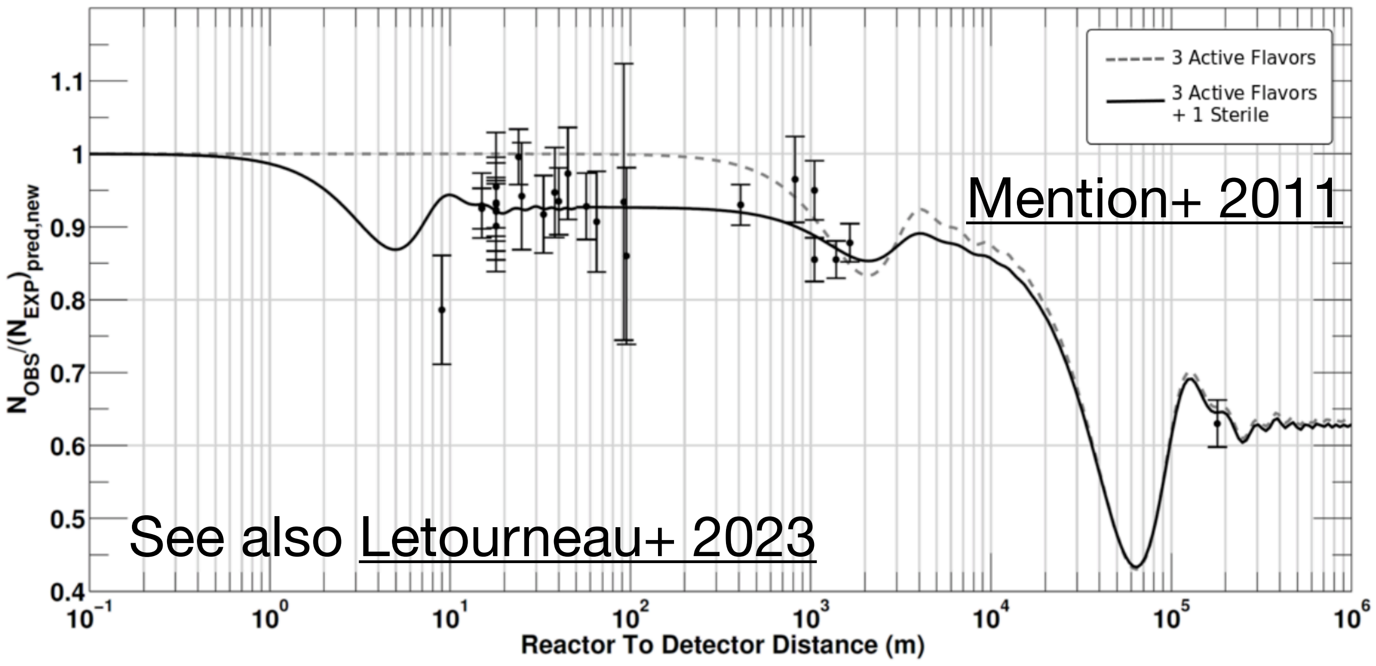
Nicholas Kamp for the IceCube collaboration
Santa Fe, NM; 2 April 2024
2nd Short-Baseline Experiment-Theory Workshop

Many Anomalies Hinting at 3+1



(Normal Ordering)

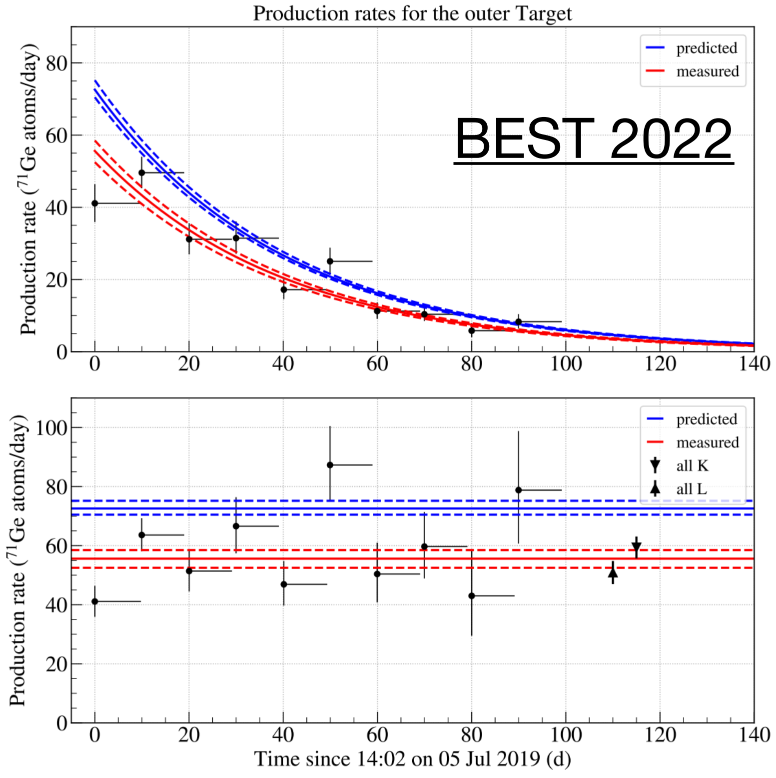
Reactor Antineutrino Anomaly



Mention+ 2011

See also Letourneau+ 2023

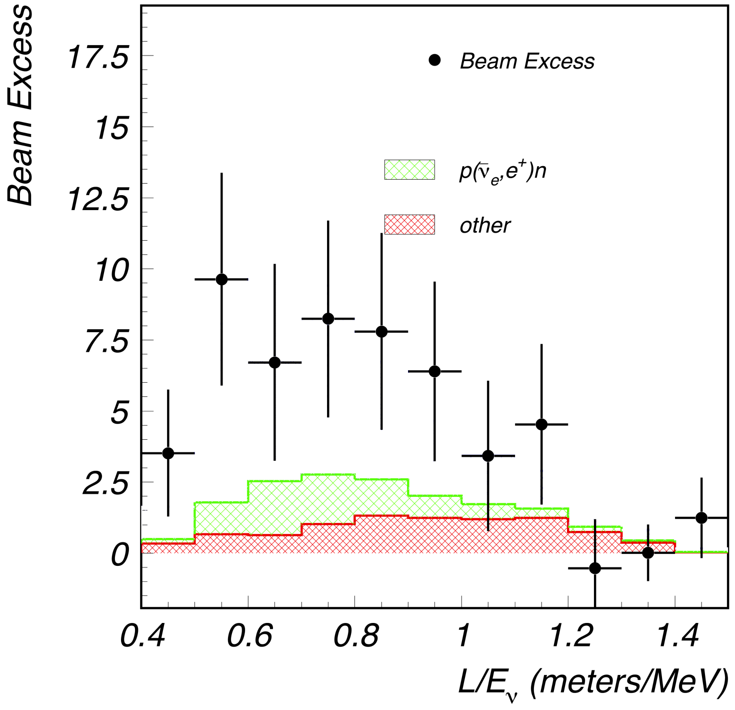
Gallium Anomaly



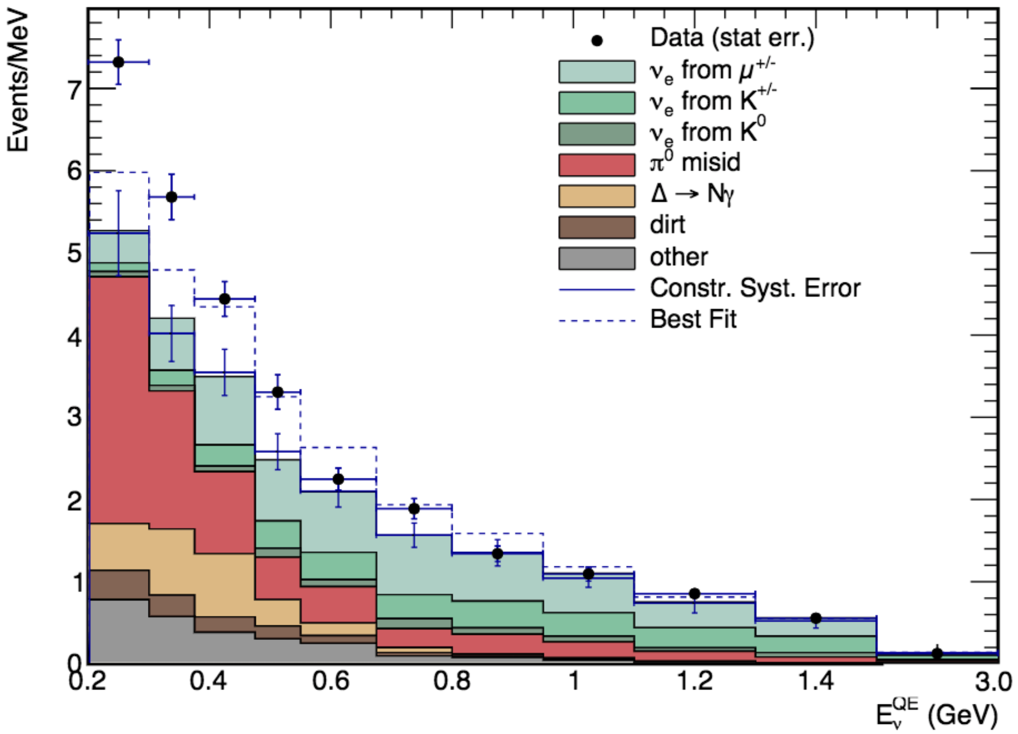
BEST 2022

Short Baseline Accelerator Anomalies

LSND 2001



MiniBooNE 2021



“Typical” 3+1 Experiment

Human-made neutrino source (e.g. accelerator, reactor, radioactive)

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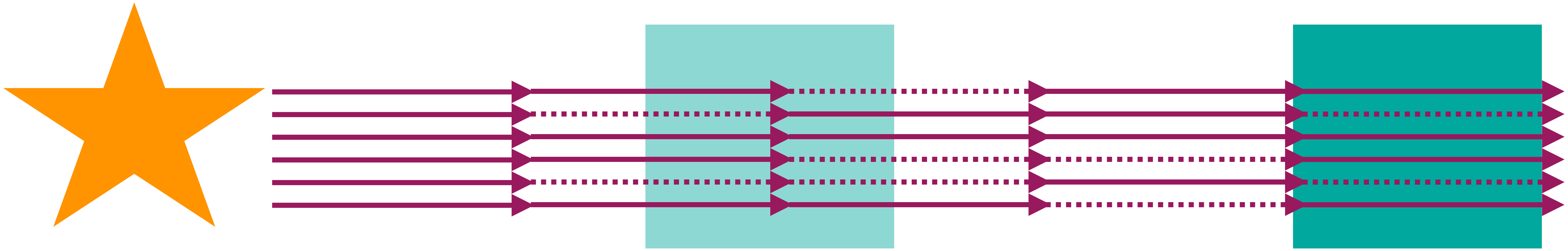
Observe neutrino interactions in one or two ton-scale detectors with fixed baseline

“Typical” 3+1 Experiment



Human-made neutrino source (e.g. accelerator, reactor, radioactive)

Search for anomalous (dis)appearance via vacuum oscillations induced by the new mass eigenstate

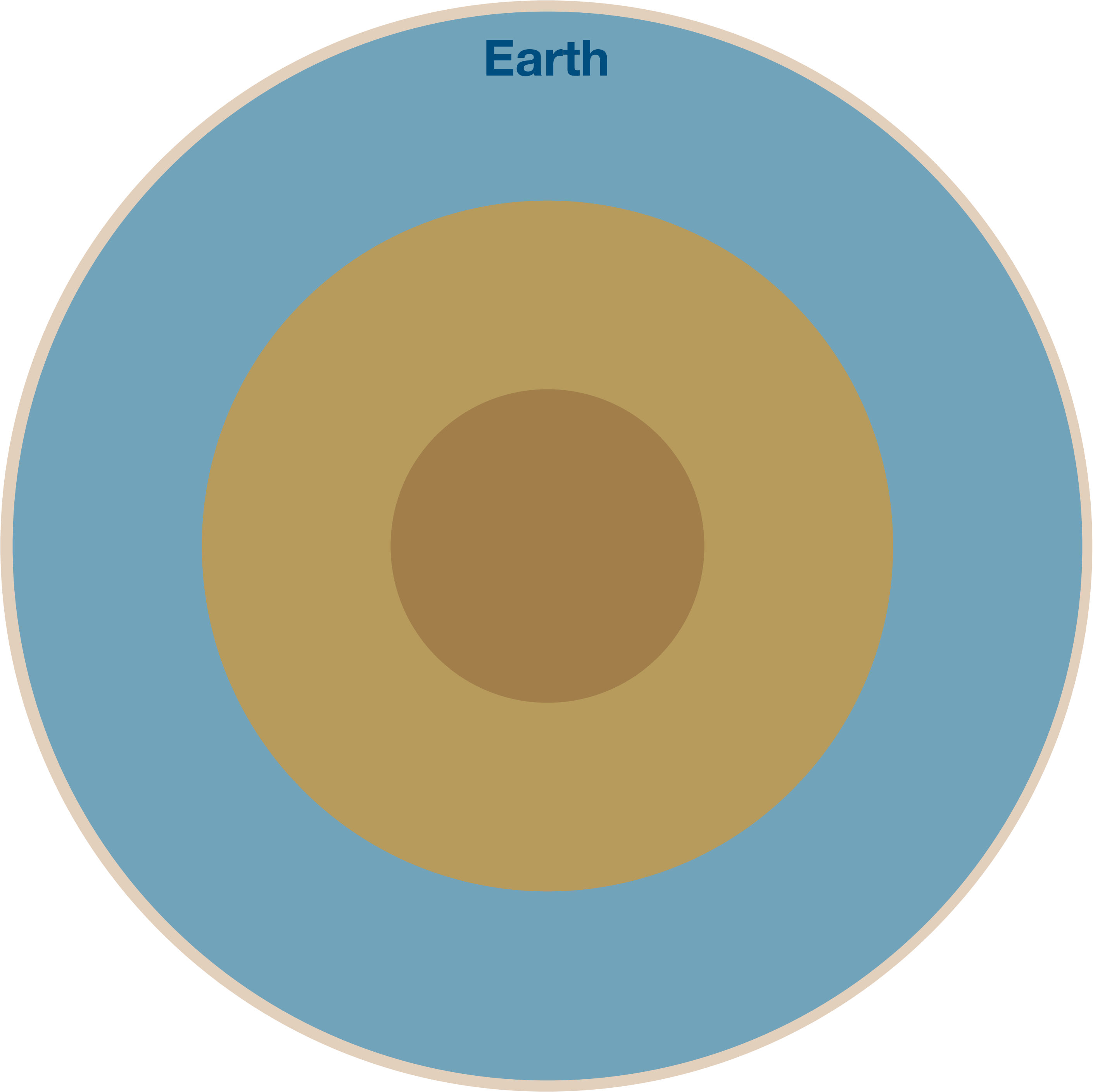
Observe neutrino interactions in one or two ton-scale detectors with fixed baseline

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e})\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$

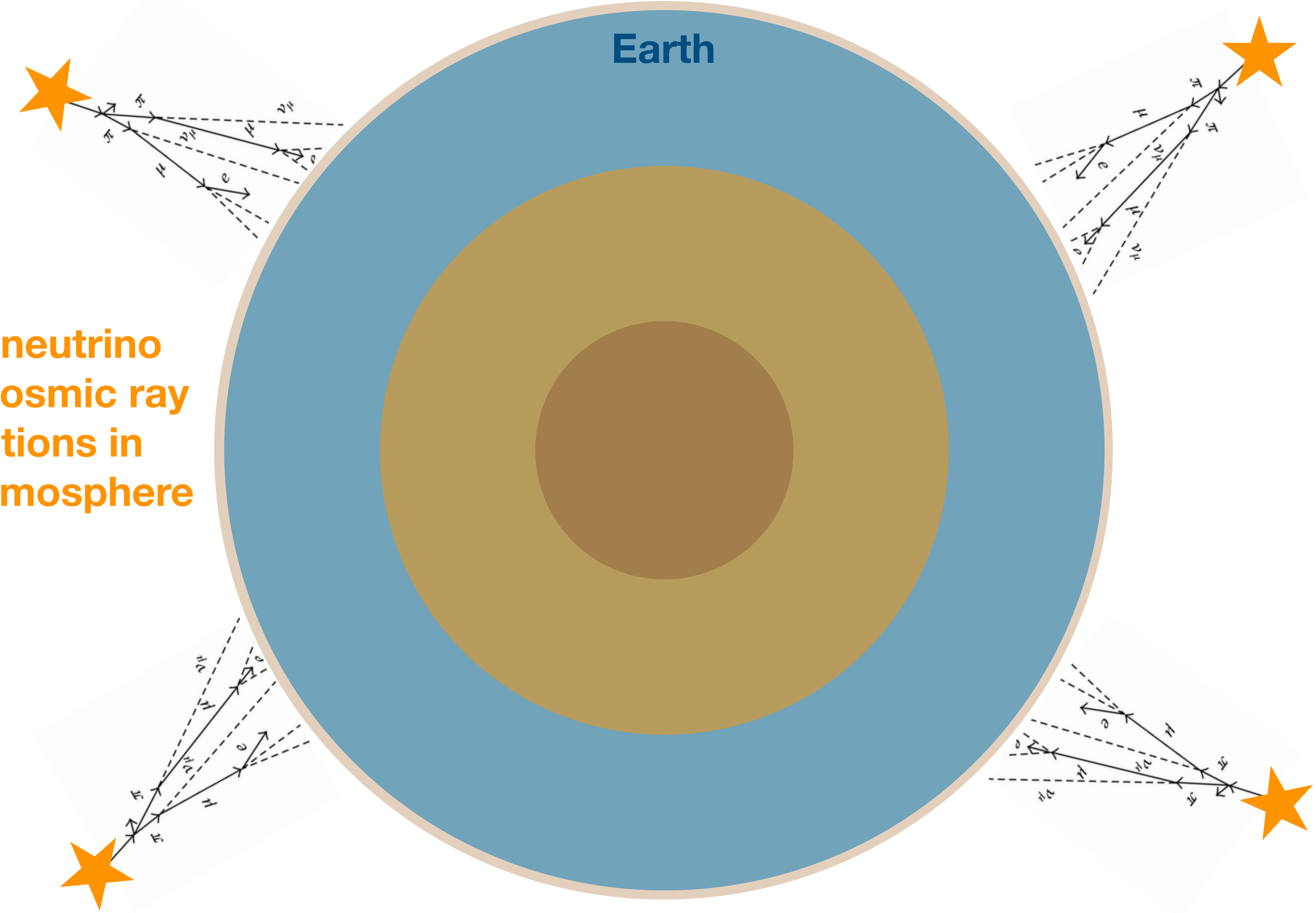
$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{ee})\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu})\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$

3+1 in IceCube

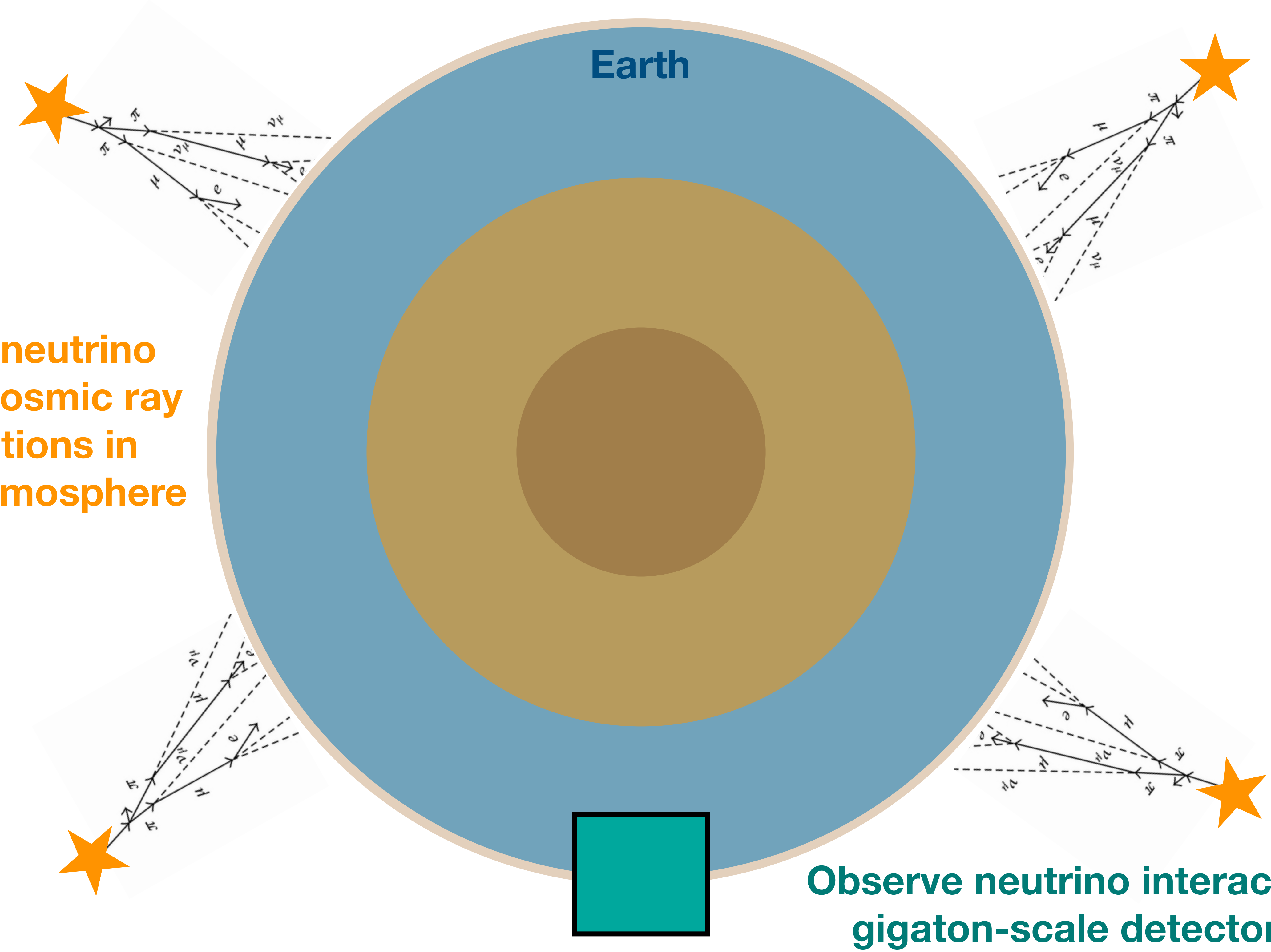


3+1 in IceCube



Natural neutrino source: cosmic ray interactions in Earth's atmosphere

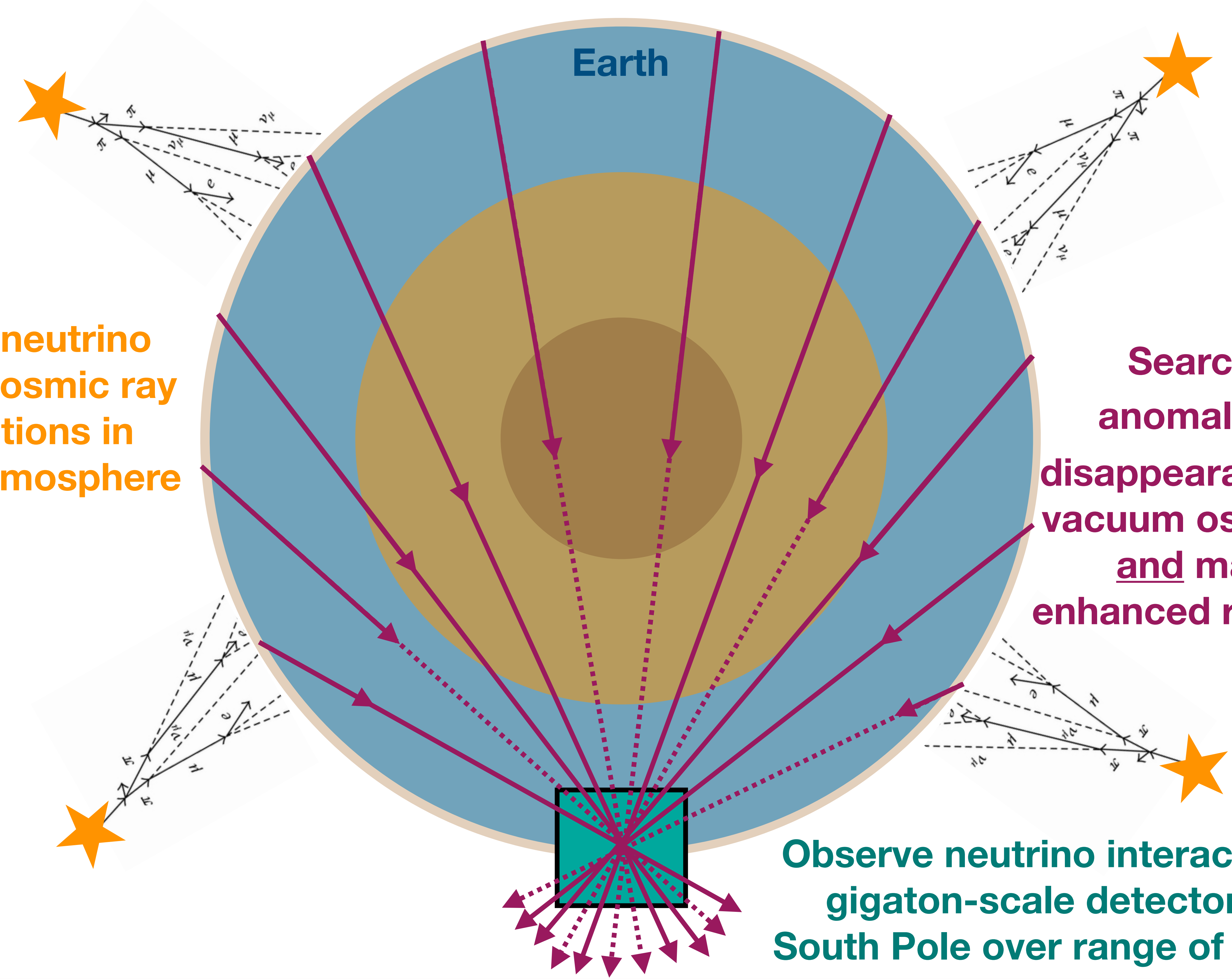
3+1 in IceCube



Natural neutrino source: cosmic ray interactions in Earth’s atmosphere

Observe neutrino interactions in a gigaton-scale detector at the South Pole over range of baselines

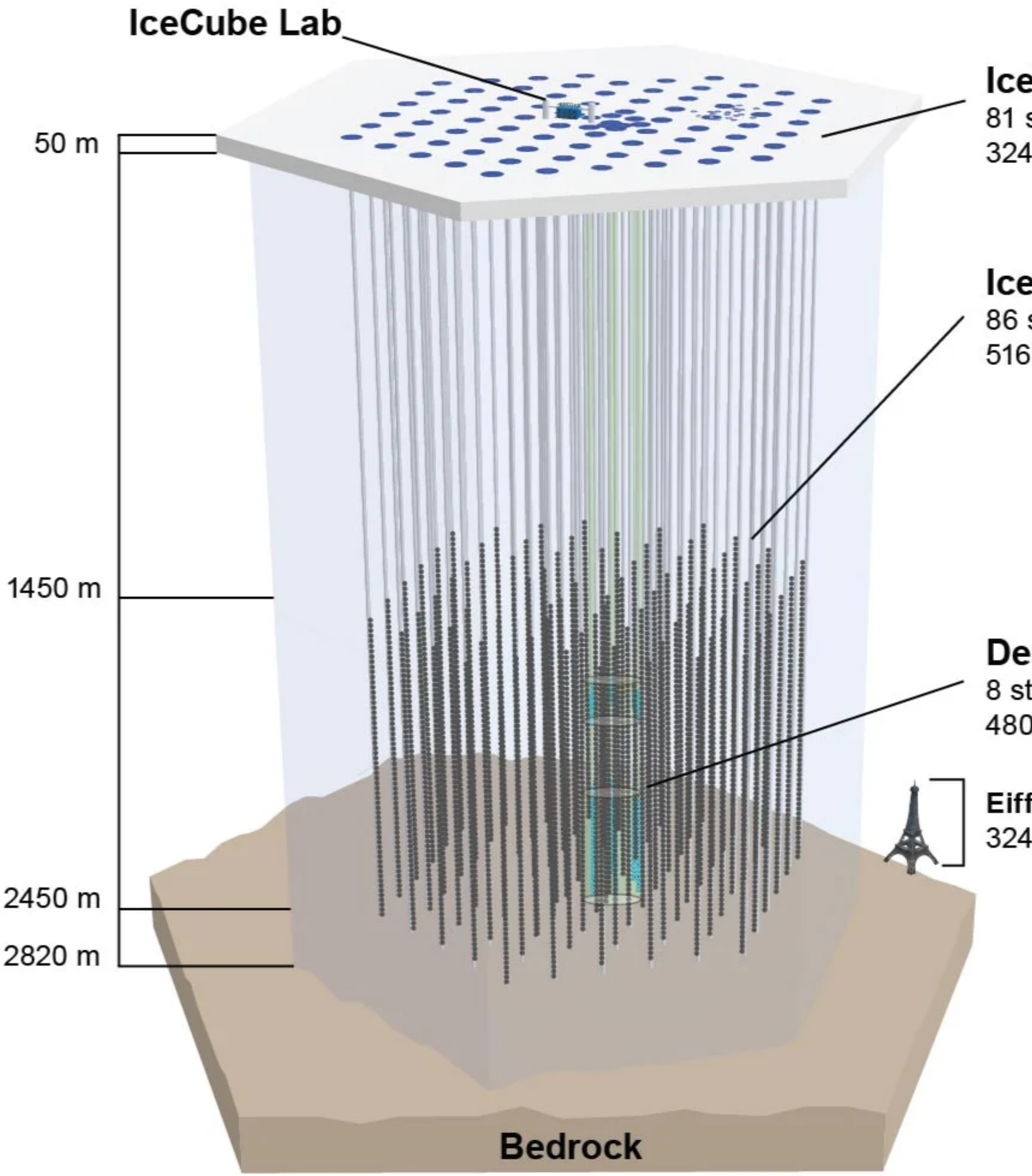
3+1 in IceCube



Natural neutrino source: cosmic ray interactions in Earth's atmosphere

Search for anomalous ν_μ disappearance from vacuum oscillations <u>and</u> matter-enhanced resonance

Observe neutrino interactions in a gigaton-scale detector at the South Pole over range of baselines



IceTop
81 stations
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors

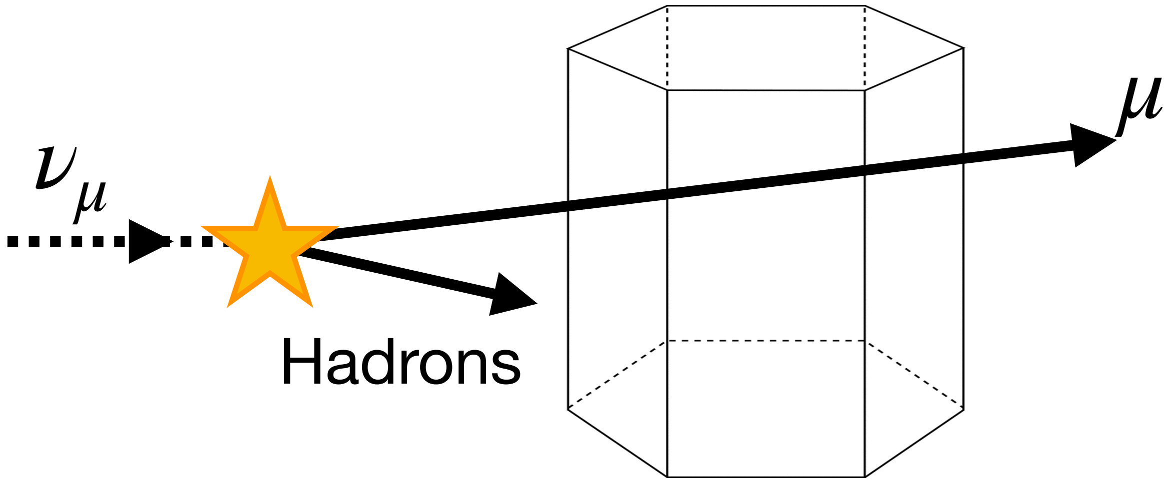
DeepCore
8 strings—spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m

~1 km^3 of South Pole ice instrumented with >5000 optical sensors!

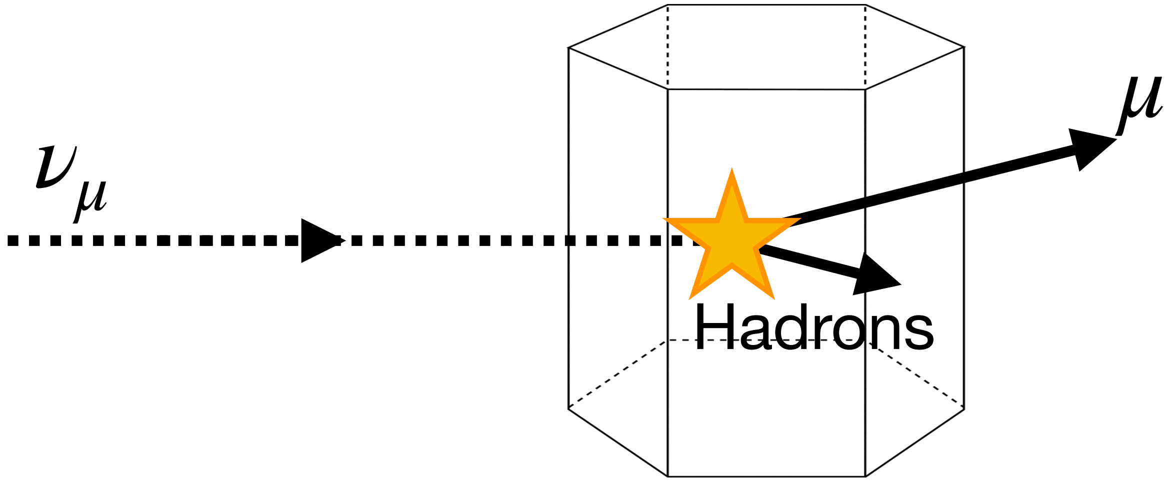
Quanta 2023

IceCube Event Types



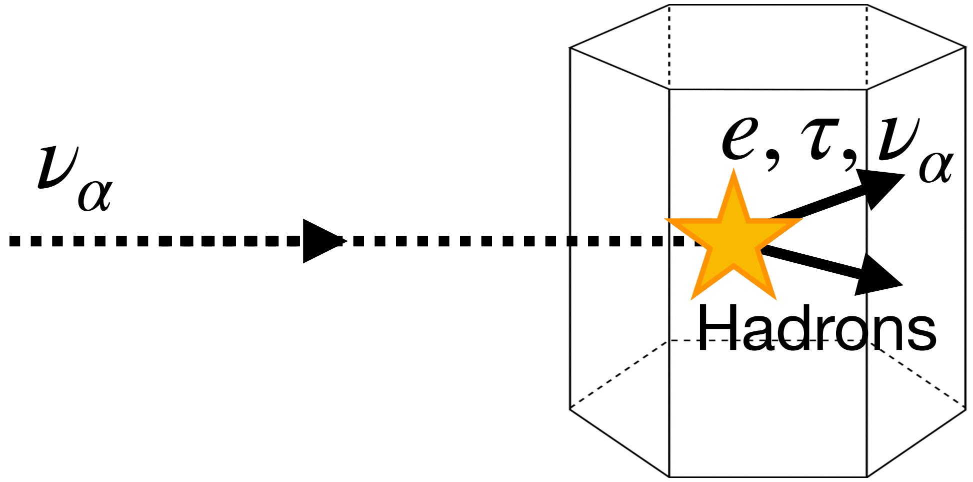
“Through-going track”

ν_μ charged-current DIS outside the active volume



“Starting track”

ν_μ charged-current DIS inside the active volume

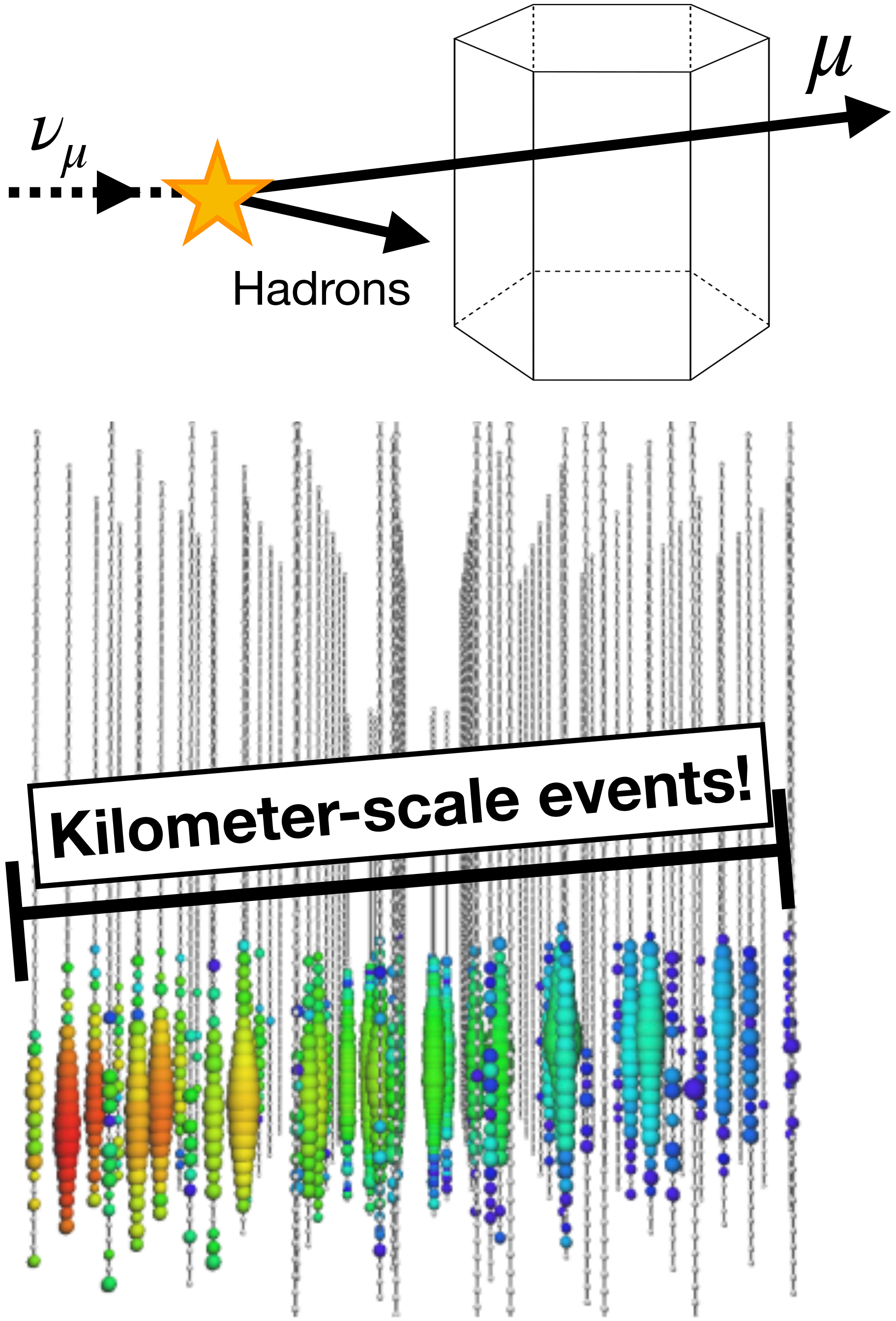


“Cascade”

$\nu_{e,\tau}$ charged-current DIS or ν_α neutral-current DIS inside the active volume

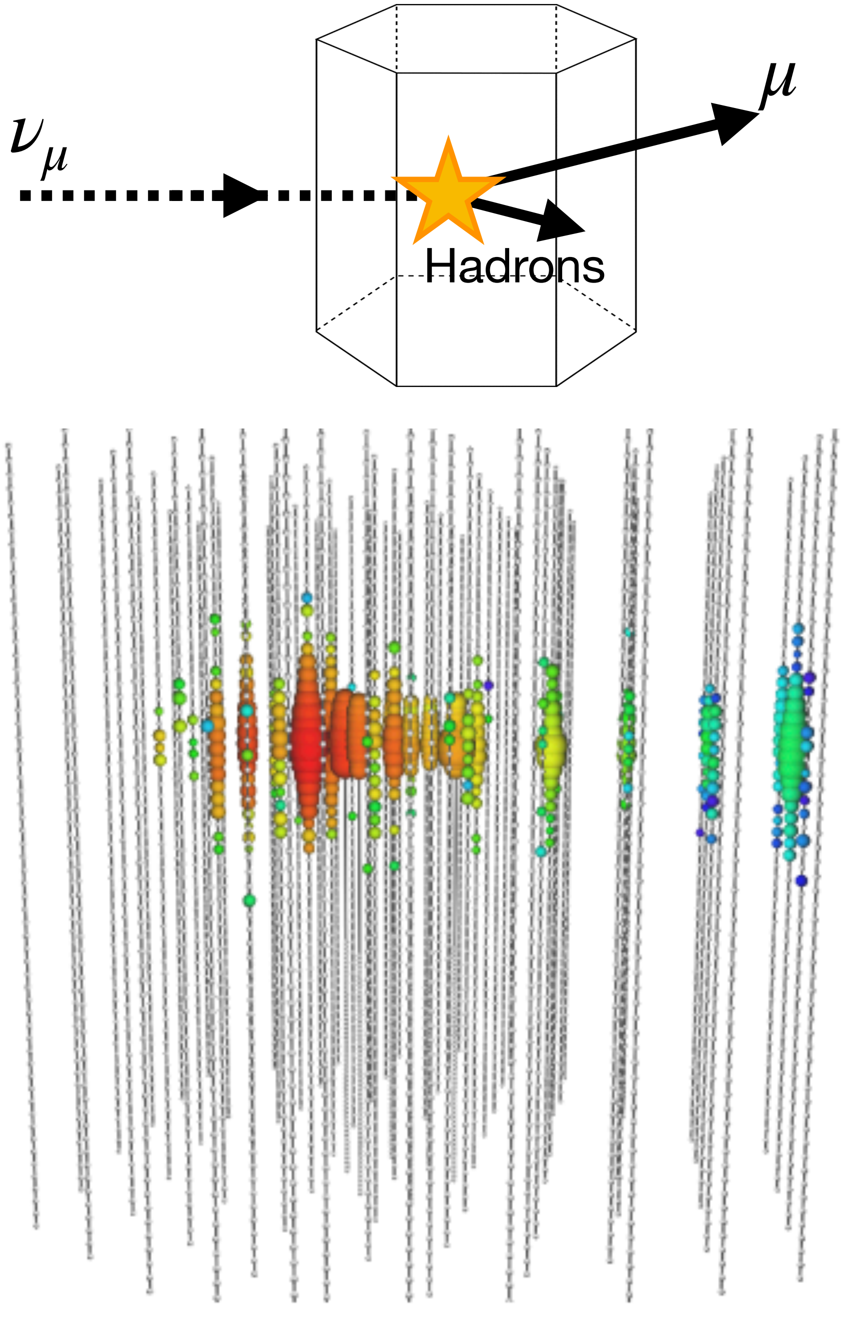
IceCube Event Types

Through-going track

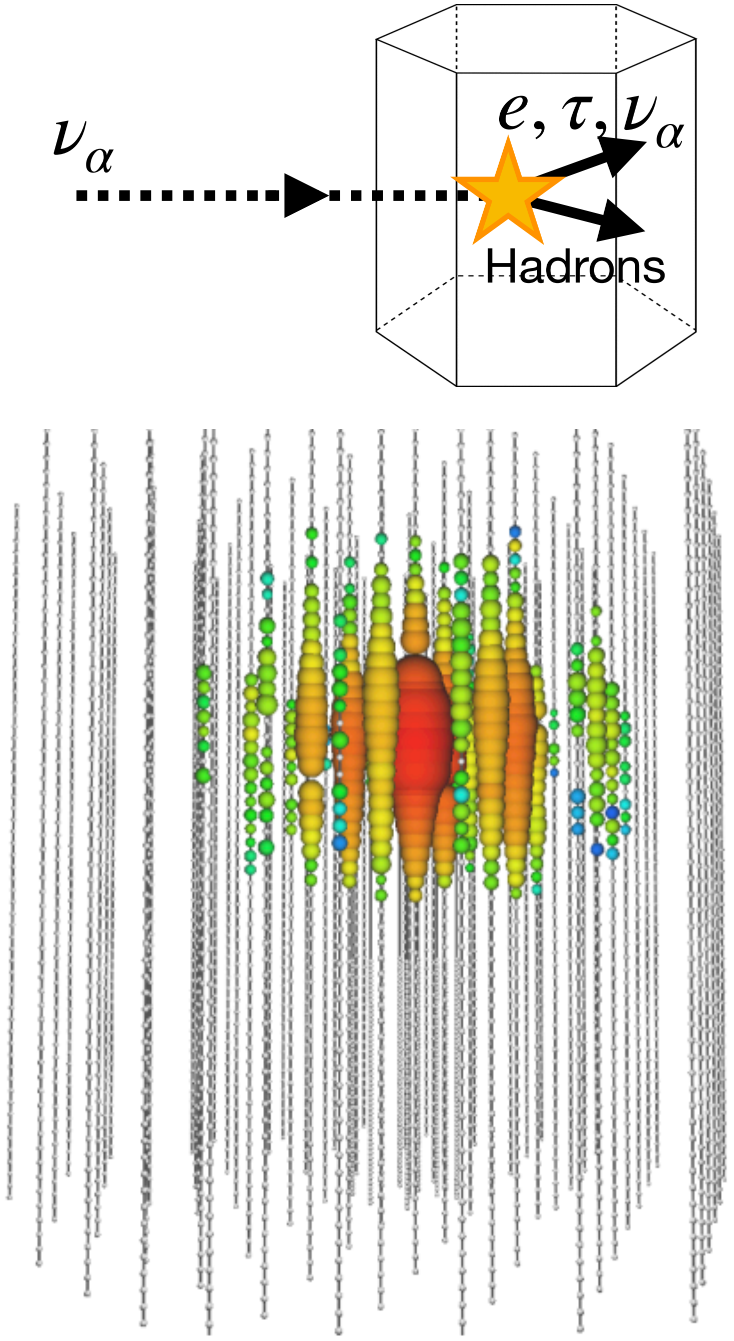


Kilometer-scale events!

Starting track



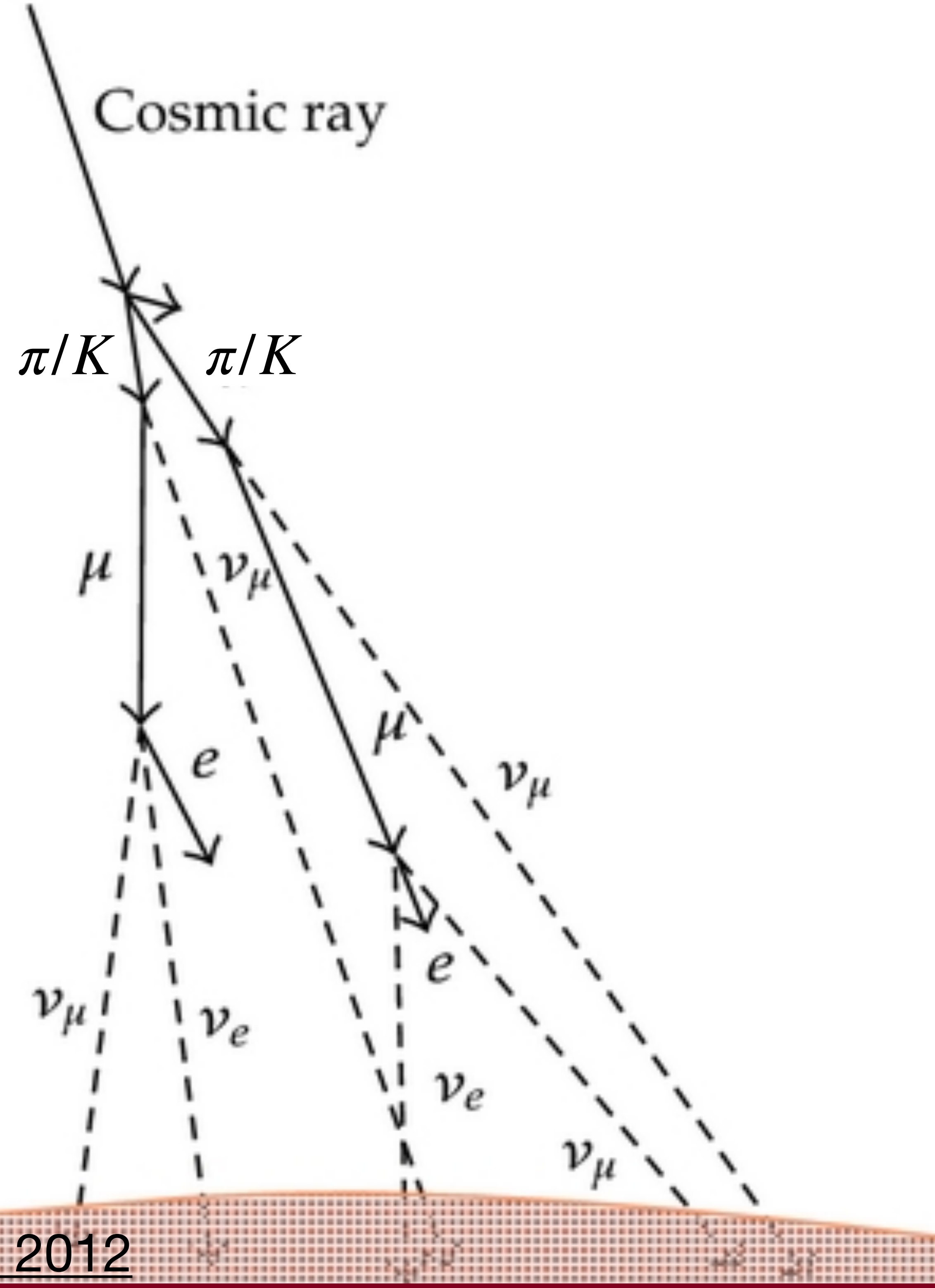
Cascade



Earliest photons 🟥🟨🟩🟦🟪 Latest photons

Atmospheric Neutrino Flux

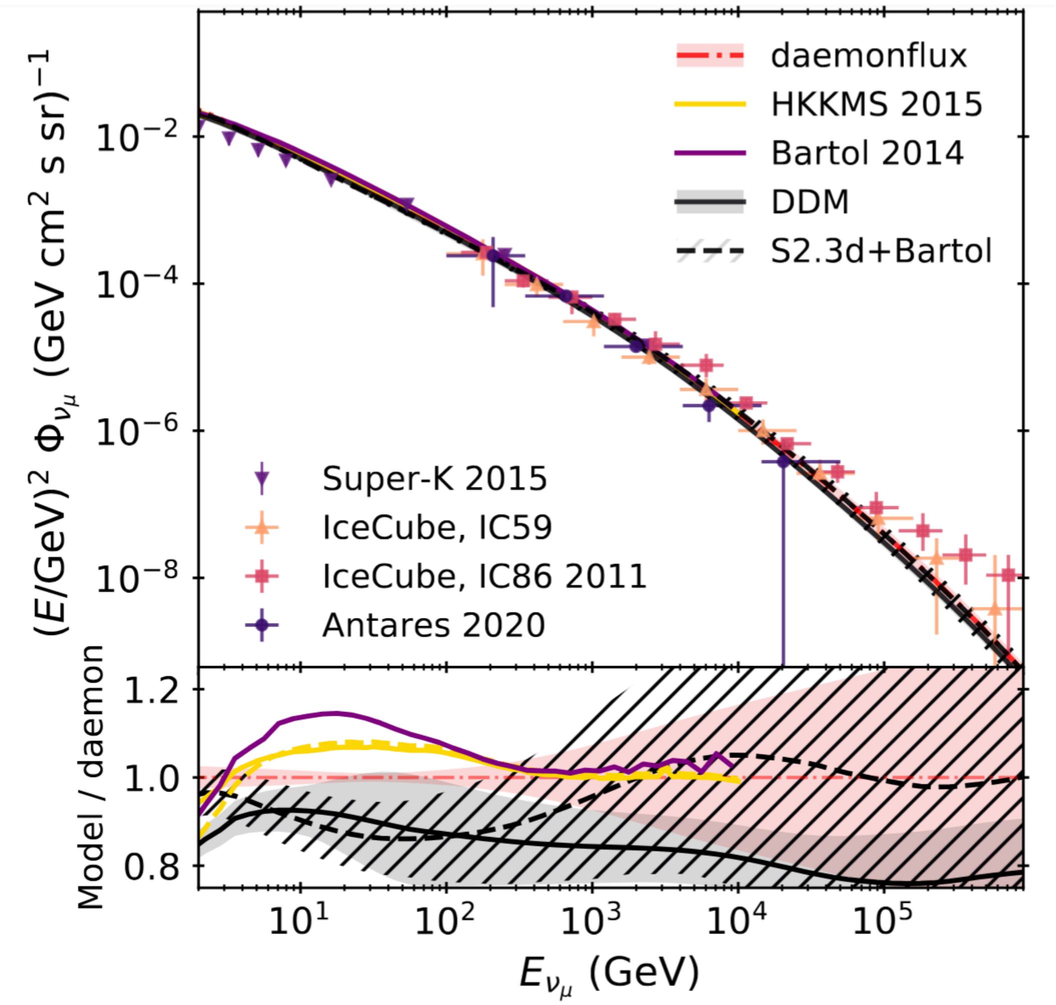
- We use the atmospheric neutrino flux as our $\nu_\mu/\overline{\nu}_\mu$ source
- Like accelerator neutrino sources, neutrinos generated by the decay of hadrons produced proton-nuclear collisions
- Unlike accelerator neutrino sources, flux predictions don't require modeling of complicated target hall geometry or magnetic fields of focusing horns

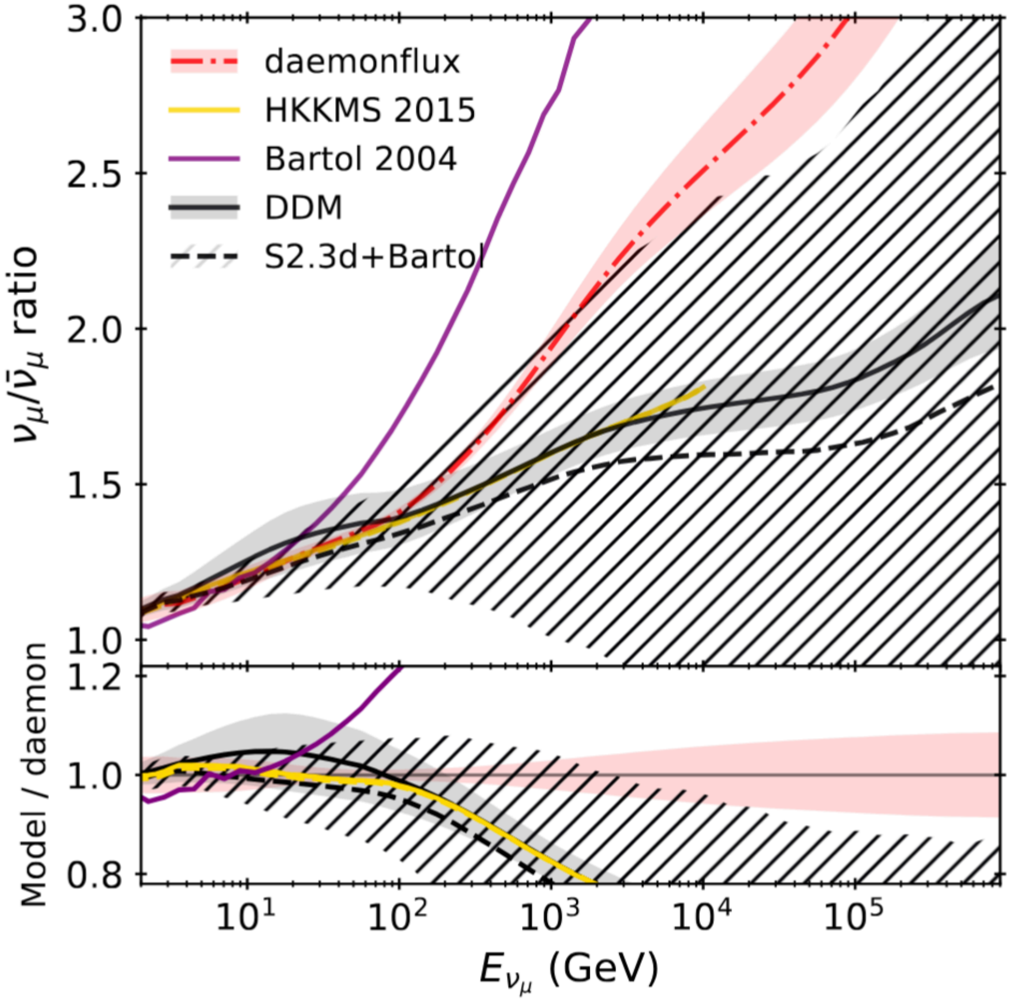


Kajita 2012

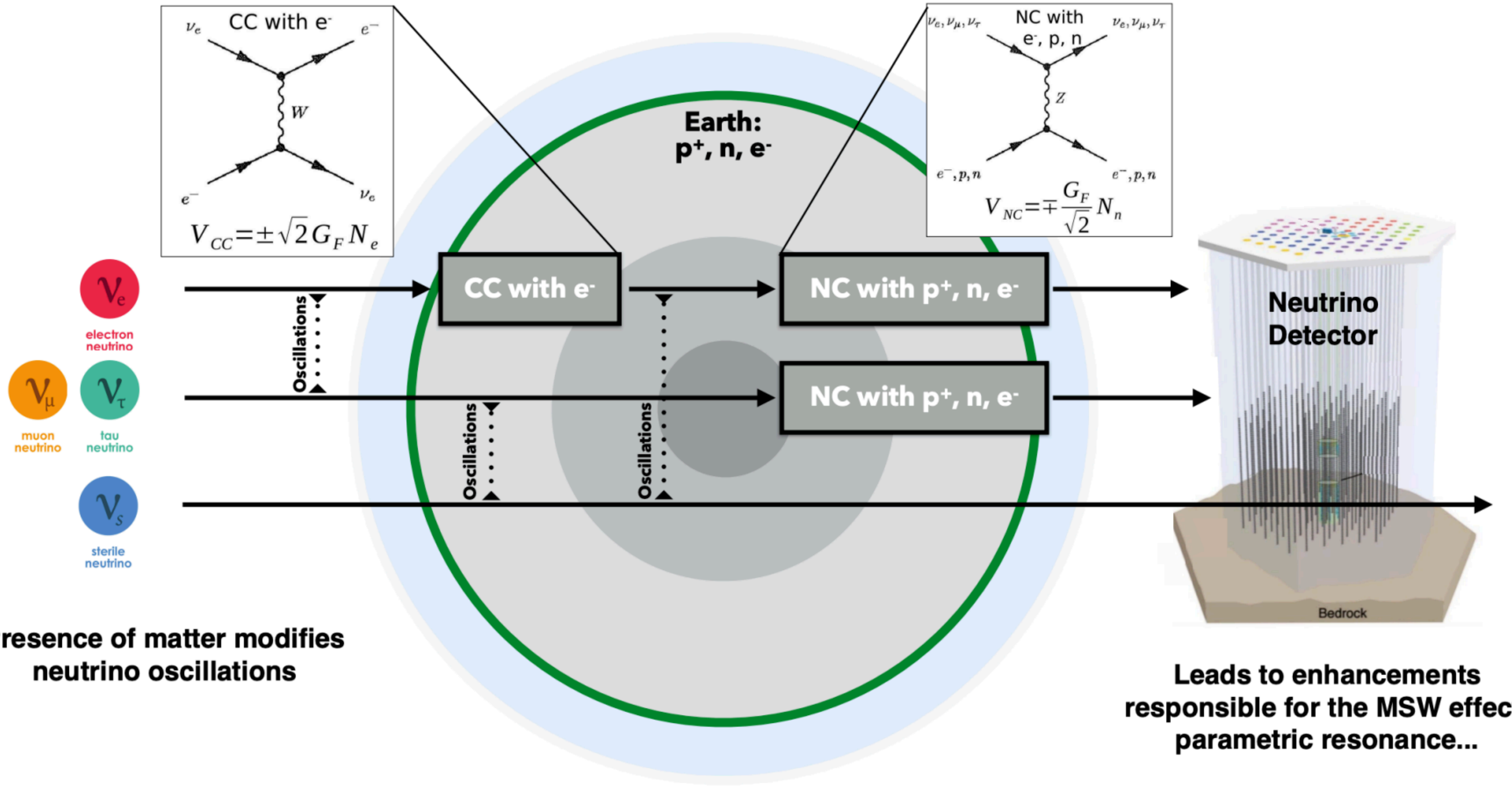
Atmospheric Neutrino Flux

- We use the updated DAEMONFLUX model (Yañez+ 2023)
- Based on measurements of cosmic muon fluxes and charge ratios as well as fixed target hadron cross sections
- Uncertainties account for cosmic ray nucleon flux, meson production cross sections, and detector-specific systematics





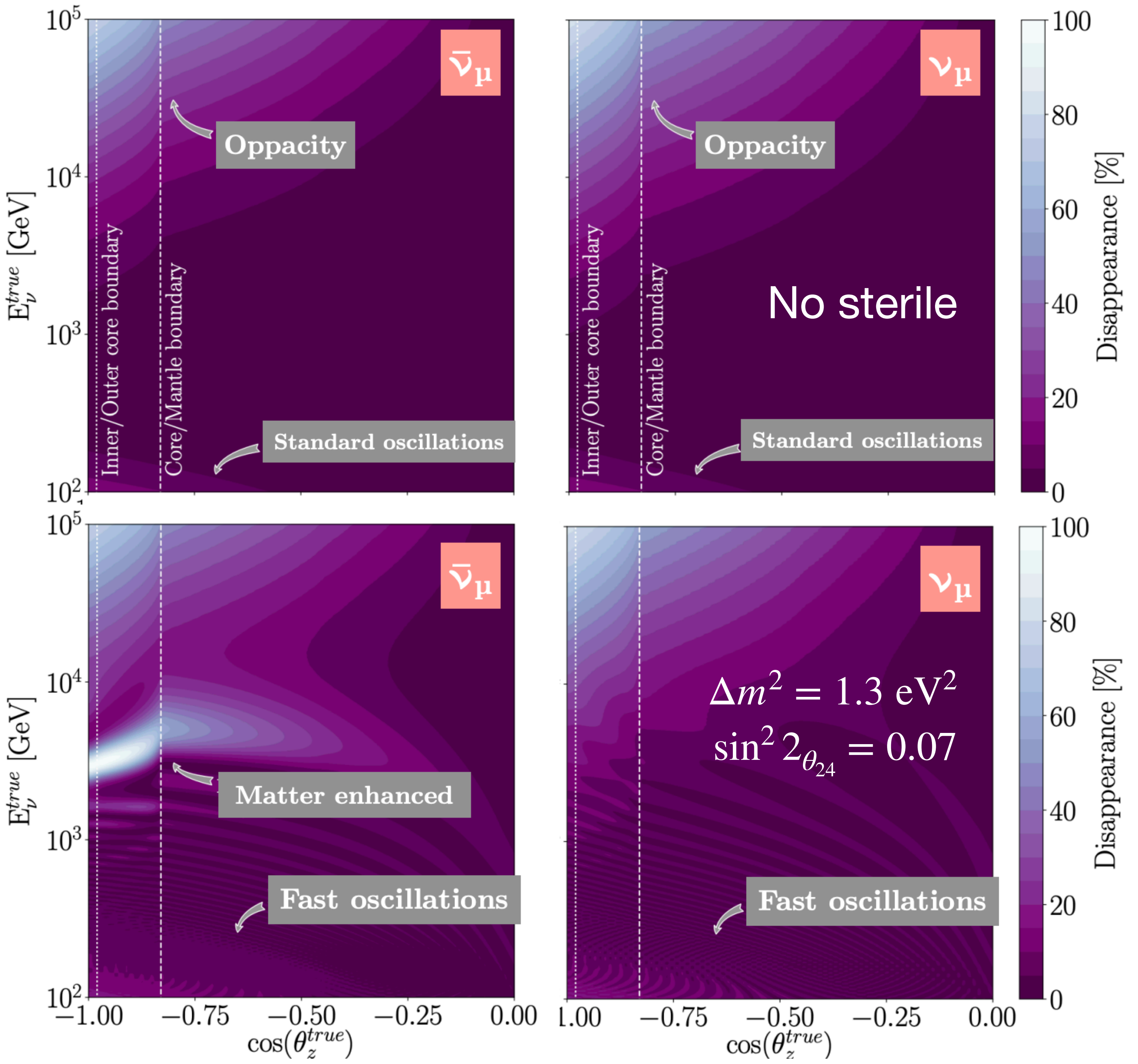
Sterile neutrinos in IceCube

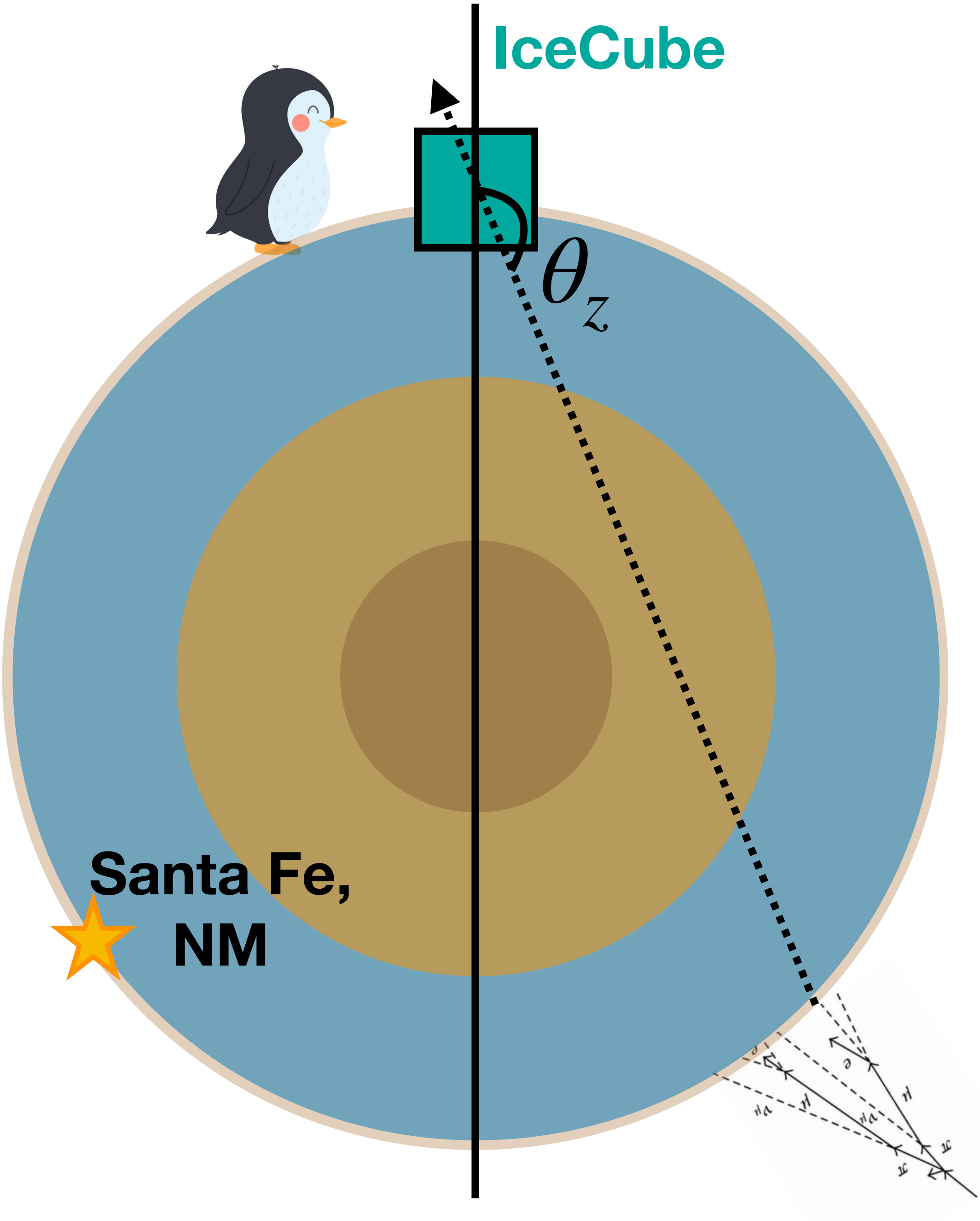


Presence of matter modifies neutrino oscillations

Leads to enhancements responsible for the MSW effect, parametric resonance...

Sterile neutrinos in IceCube

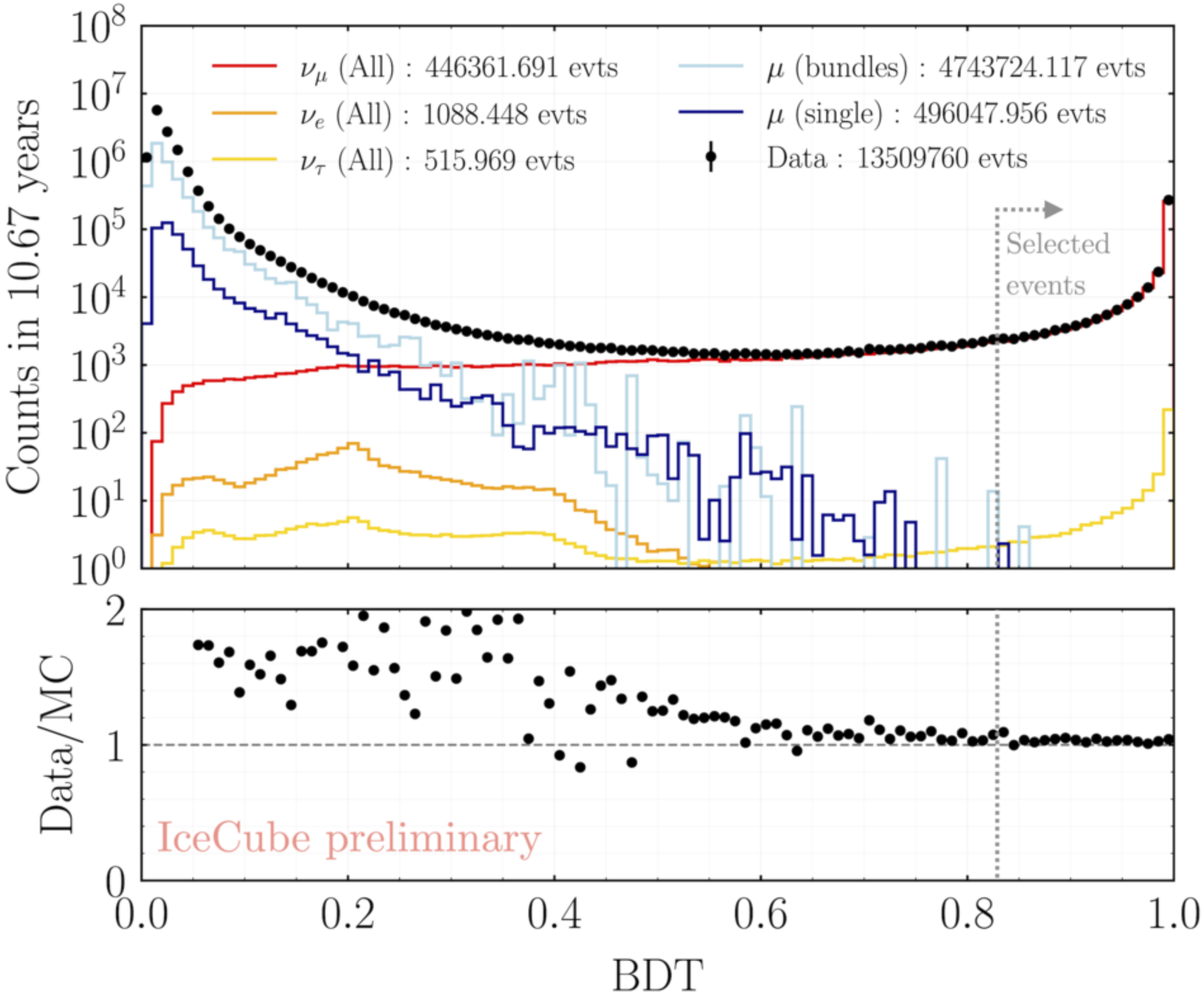


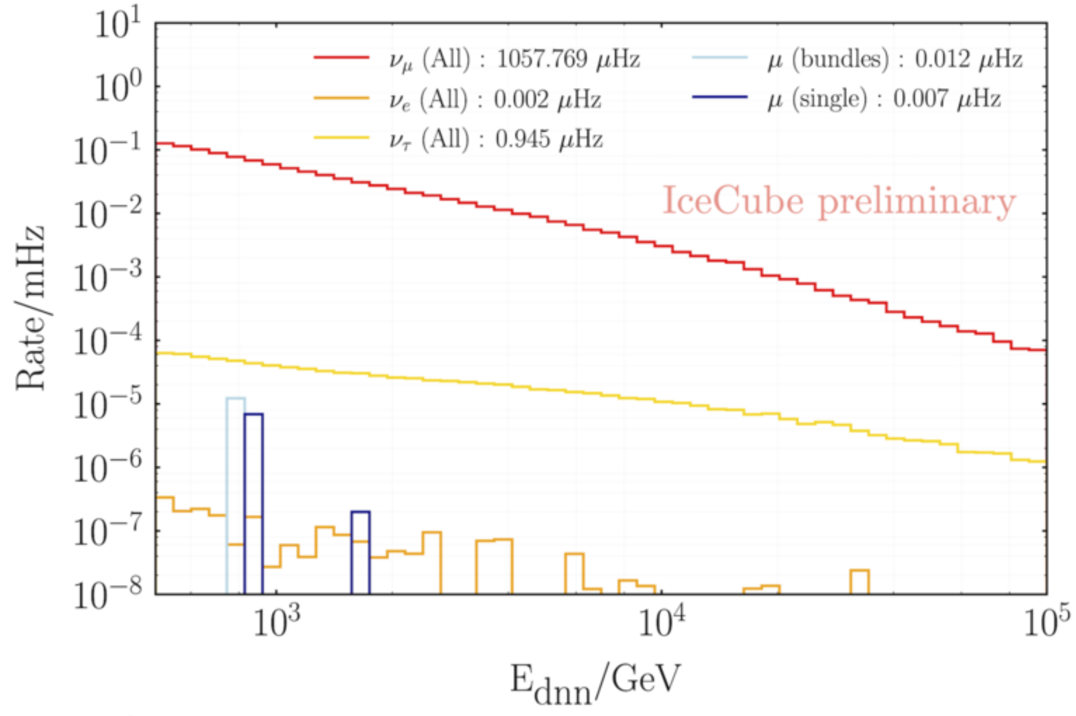


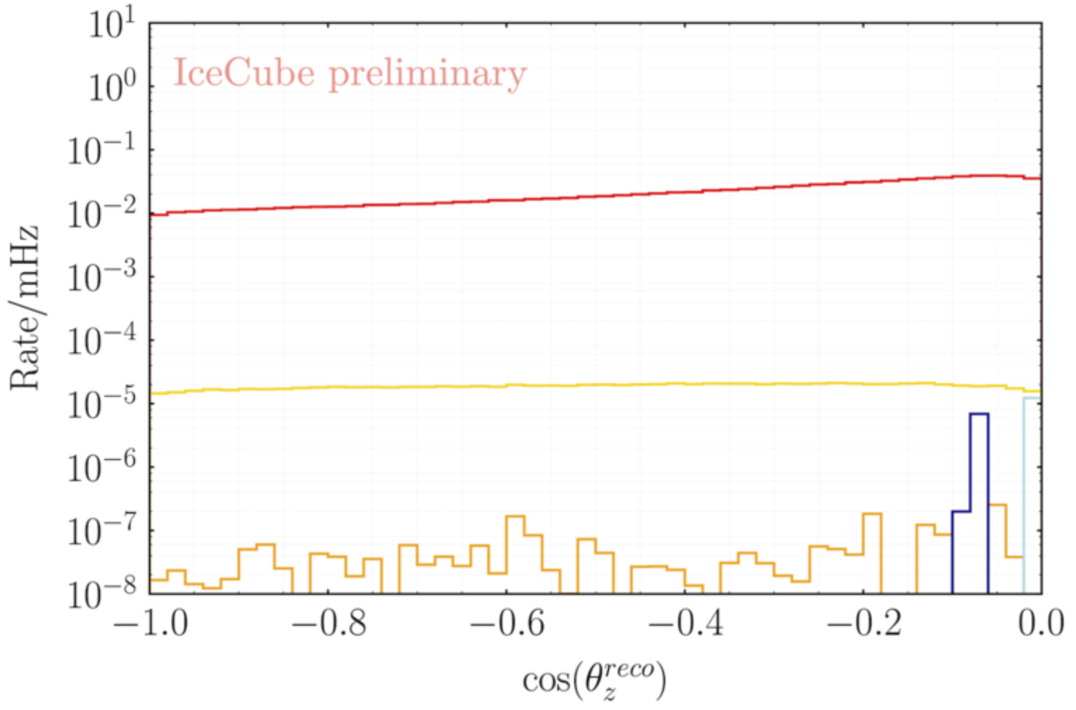
Simultaneous measurement of oscillated and un-oscillated component of neutrino flux

Analysis Strategy

- BDT to isolate a pure sample of up-going tracks

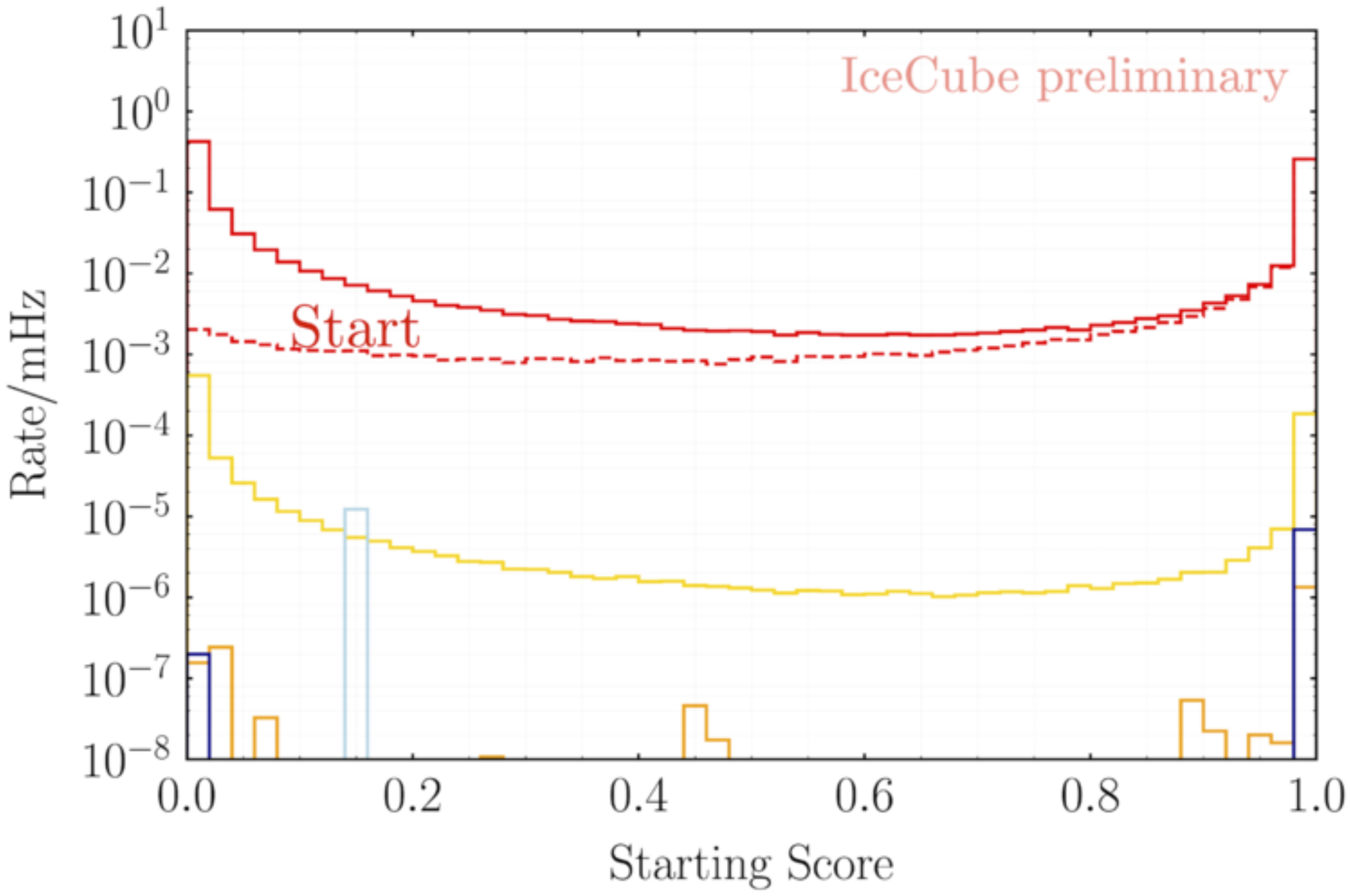


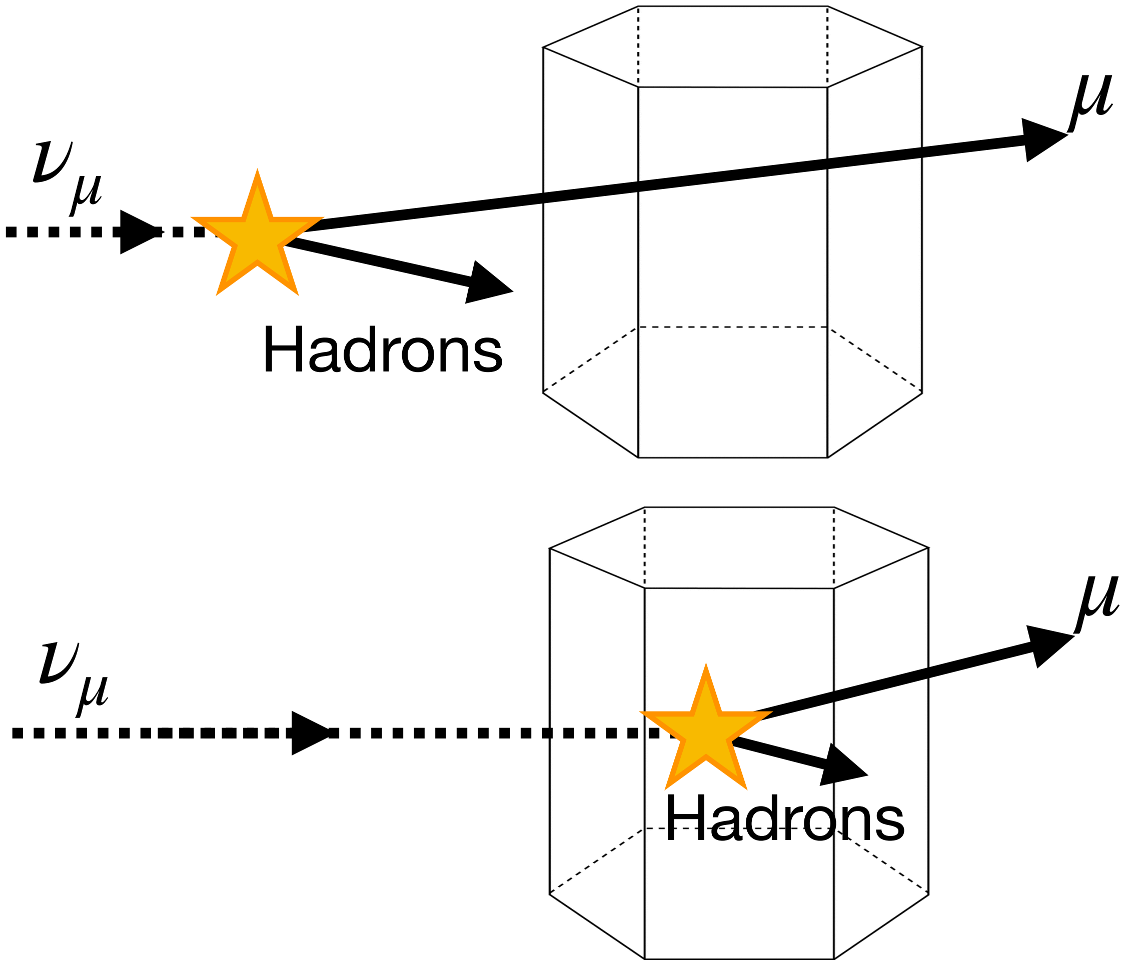




Analysis Strategy

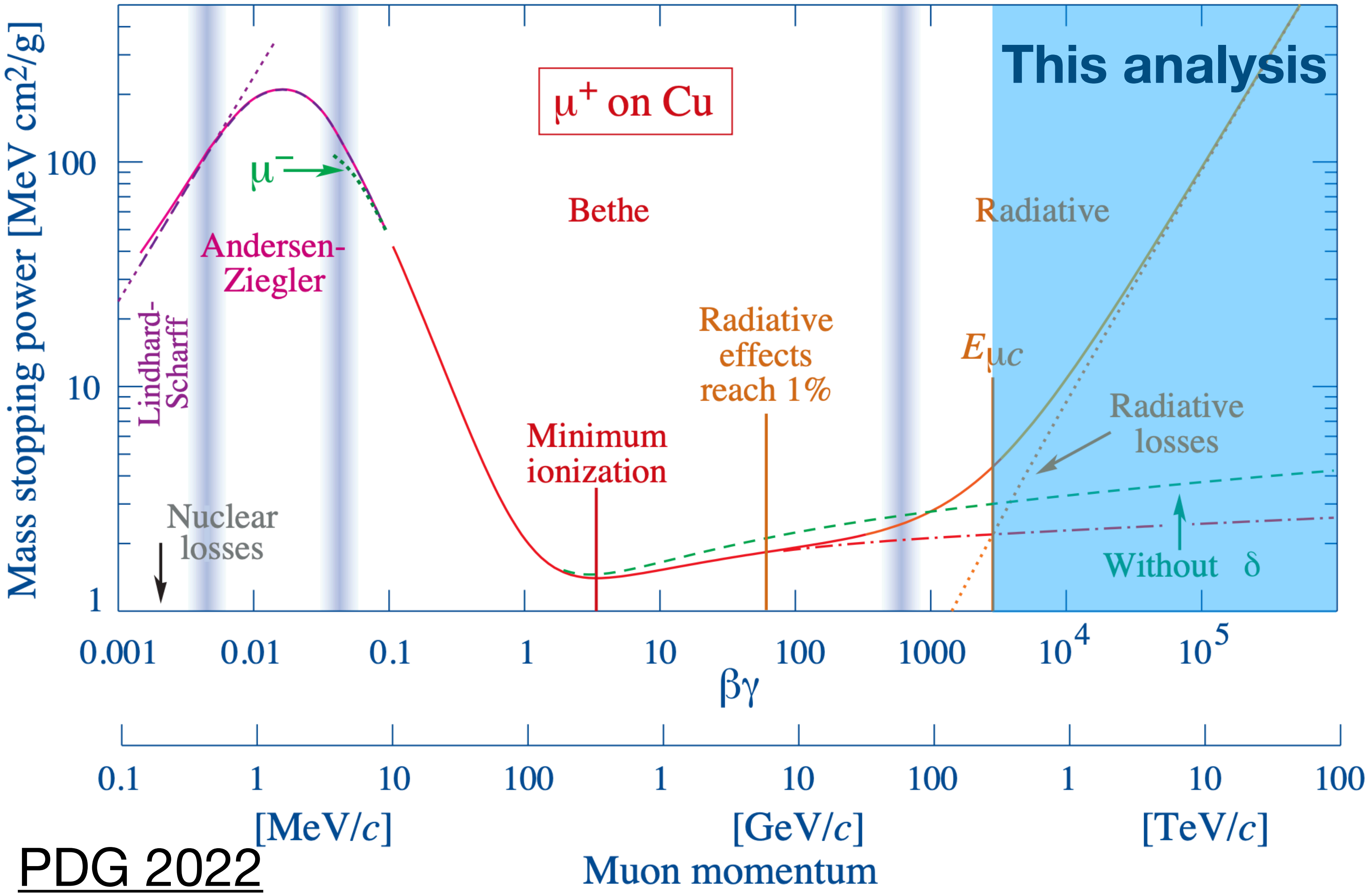
- BDT to isolate a pure sample of up-going tracks
- DNN to separate starting and through-going tracks



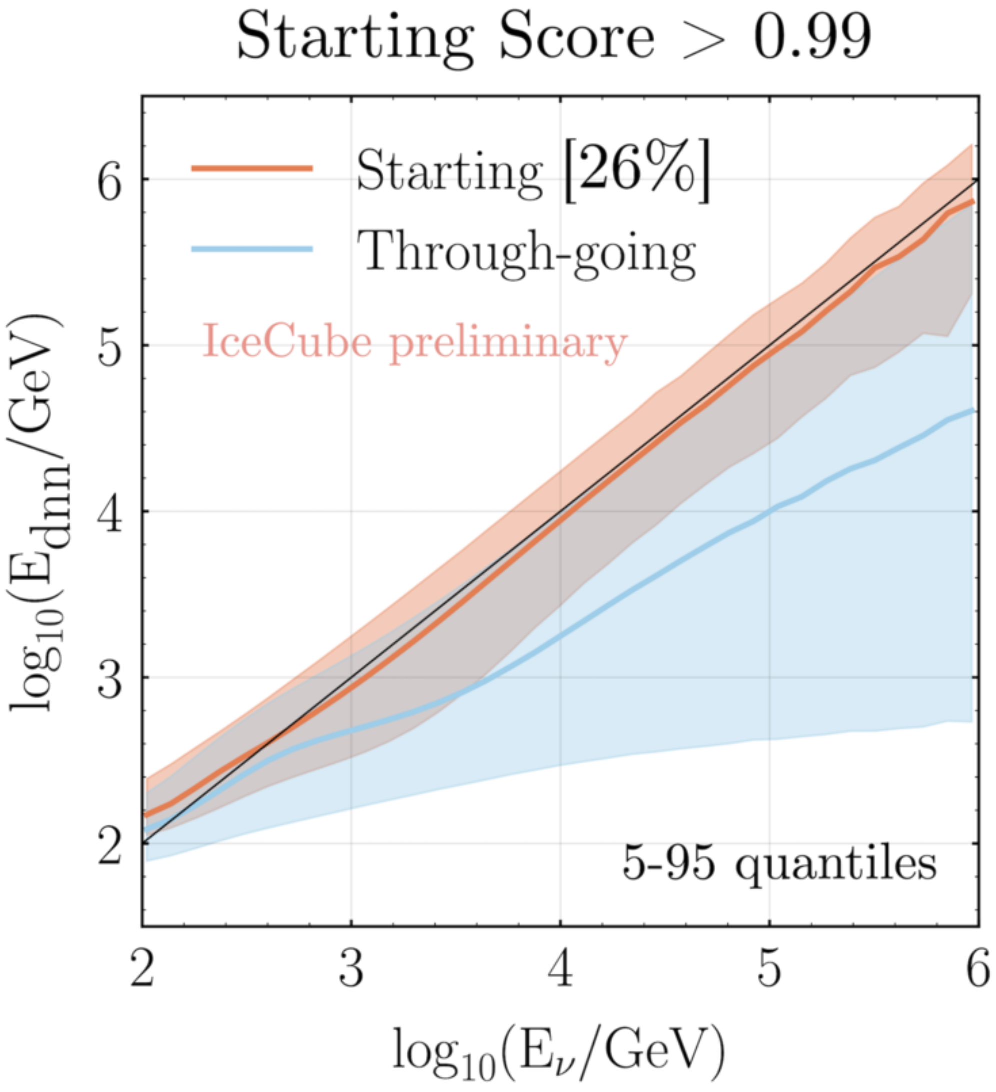


Analysis Strategy

- BDT to isolate a pure sample of up-going tracks
- DNN to separate starting and through-going tracks
- Another DNN to reconstruct the original neutrino energy



PDG 2022



Systematic Uncertainties

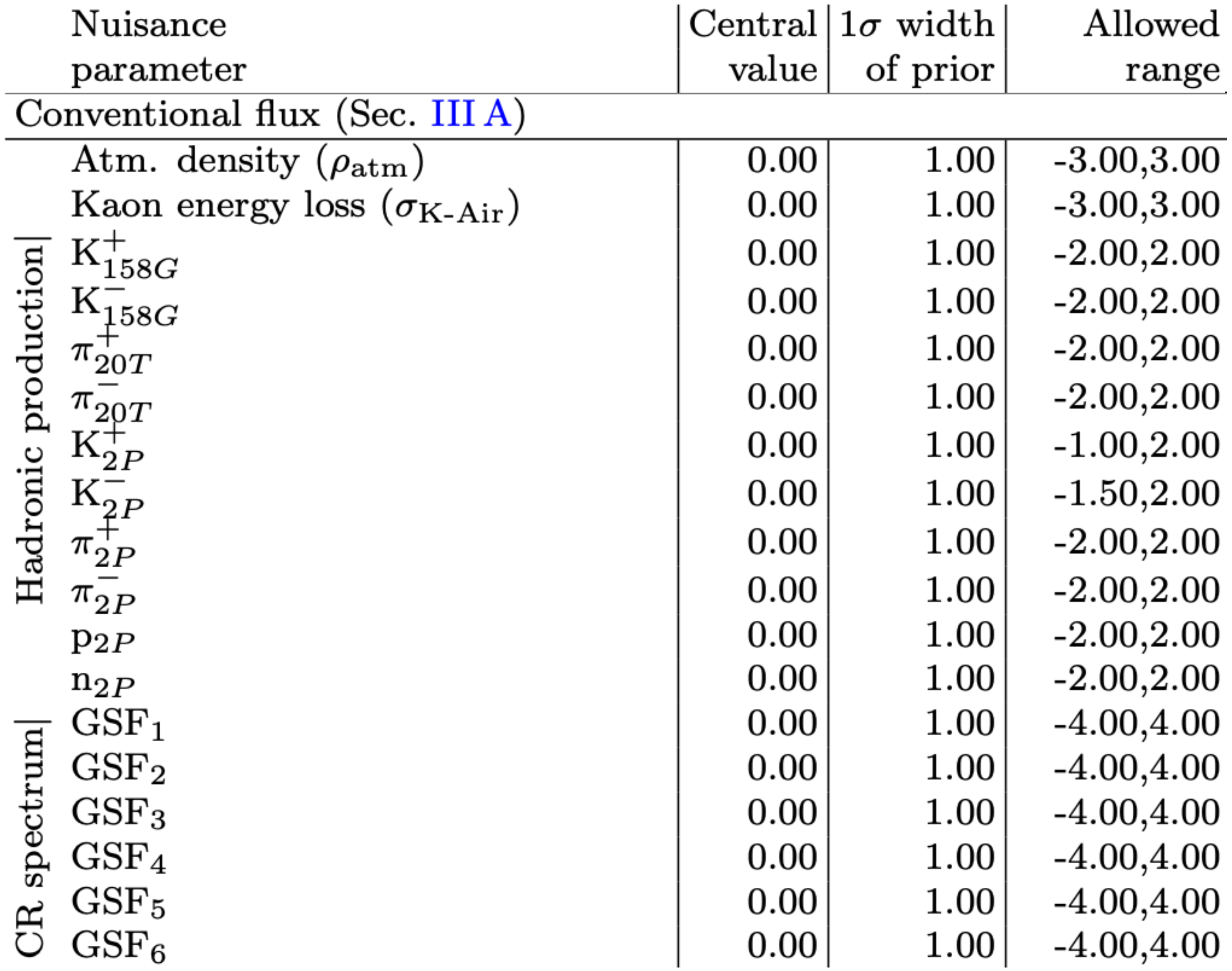
<u>6 major categories</u>

1. Conventional flux
2. Non-conventional flux
3. Bulk ice properties
4. Local DOM response
5. Neutrino attenuation
6. Overall normalization

Systematic Uncertainties

6 major categories

1. **Conventional flux**
2. Non-conventional flux
3. Bulk ice properties
4. Local DOM response
5. Neutrino attenuation
6. Overall normalization



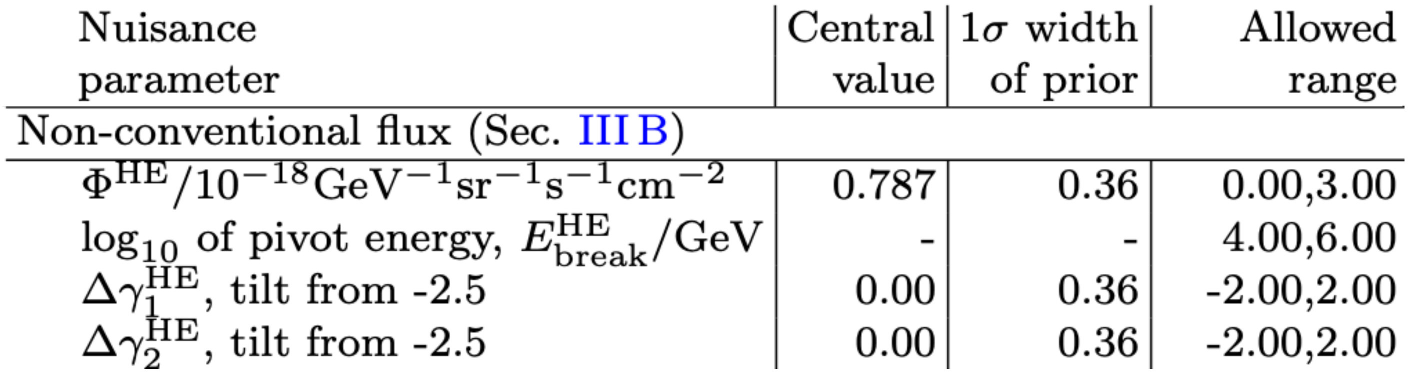
	Nuisance parameter	Central value	1σ width of prior	Allowed range
Conventional flux (Sec. III A)				
	Atm. density (ρ_{atm})	0.00	1.00	-3.00,3.00
	Kaon energy loss ($\sigma_{\text{K-Air}}$)	0.00	1.00	-3.00,3.00
Hadronic production	K^+_{158G}	0.00	1.00	-2.00,2.00
	K^-_{158G}	0.00	1.00	-2.00,2.00
	π^+_{20T}	0.00	1.00	-2.00,2.00
	π^-_{20T}	0.00	1.00	-2.00,2.00
	K^+_{2P}	0.00	1.00	-1.00,2.00
	K^-_{2P}	0.00	1.00	-1.50,2.00
	π^+_{2P}	0.00	1.00	-2.00,2.00
	π^-_{2P}	0.00	1.00	-2.00,2.00
	p_{2P}	0.00	1.00	-2.00,2.00
	n_{2P}	0.00	1.00	-2.00,2.00
CR spectrum	GSF_1	0.00	1.00	-4.00,4.00
	GSF_2	0.00	1.00	-4.00,4.00
	GSF_3	0.00	1.00	-4.00,4.00
	GSF_4	0.00	1.00	-4.00,4.00
	GSF_5	0.00	1.00	-4.00,4.00
	GSF_6	0.00	1.00	-4.00,4.00

DAEMONFLUX uncertainties + atmospheric density and meson energy losses in atmosphere

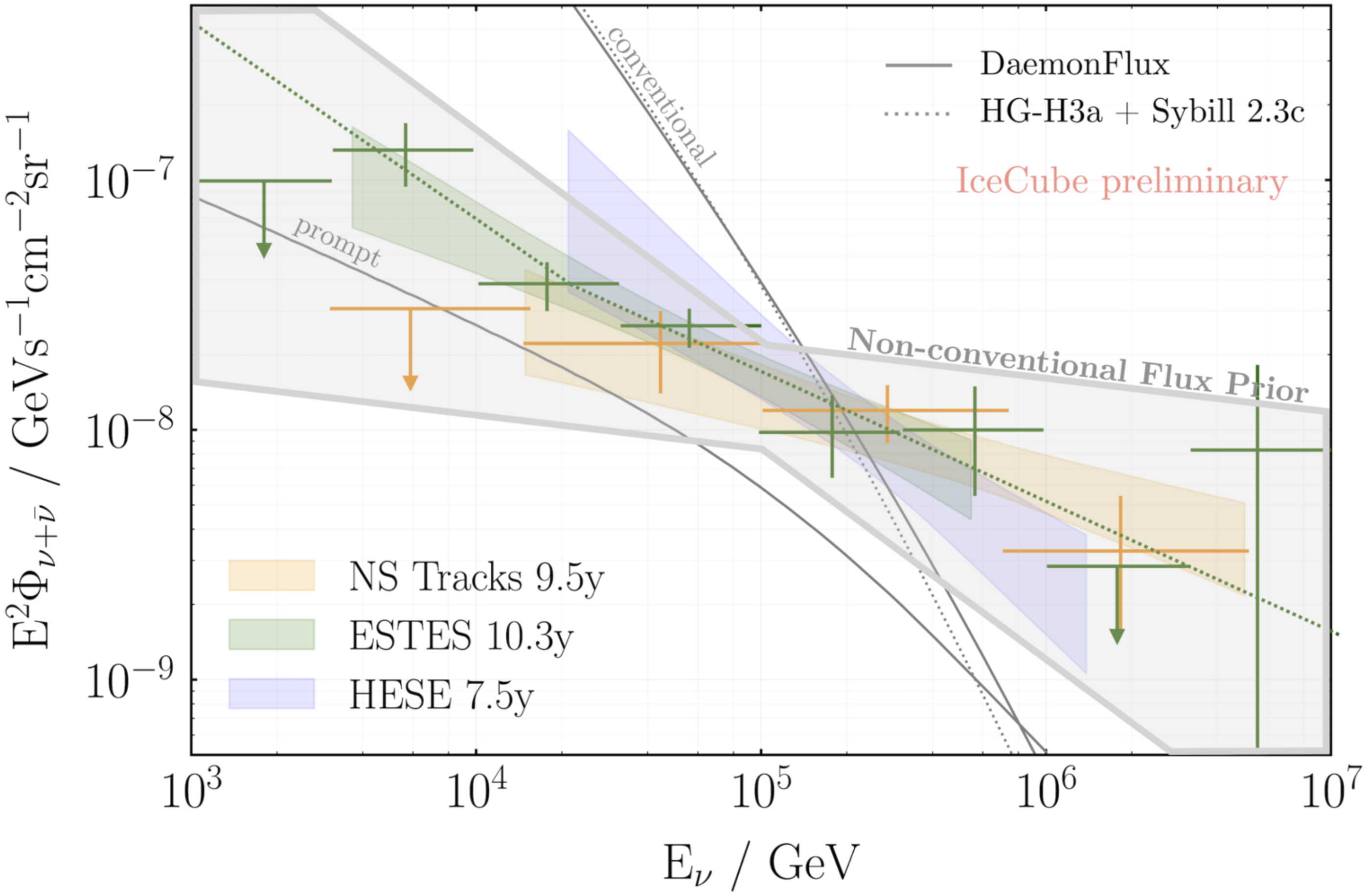
Systematic Uncertainties

<u>6 major categories</u>

1. Conventional flux
2. **<u>Non-conventional flux</u>**
3. Bulk ice properties
4. Local DOM response
5. Neutrino attenuation
6. Overall normalization



Nuisance parameter	Central value	1σ width of prior	Allowed range
Non-conventional flux (Sec. III B)			
$\Phi^{\mathrm{HE}}/10^{-18}\mathrm{GeV}^{-1}\mathrm{sr}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}$	0.787	0.36	0.00,3.00
$\log_{10}$ of pivot energy, $E^{\mathrm{HE}}_{\mathrm{break}}/\mathrm{GeV}$	-	-	4.00,6.00
$\Delta\gamma_1^{\mathrm{HE}}$, tilt from -2.5	0.00	0.36	-2.00,2.00
$\Delta\gamma_2^{\mathrm{HE}}$, tilt from -2.5	0.00	0.36	-2.00,2.00

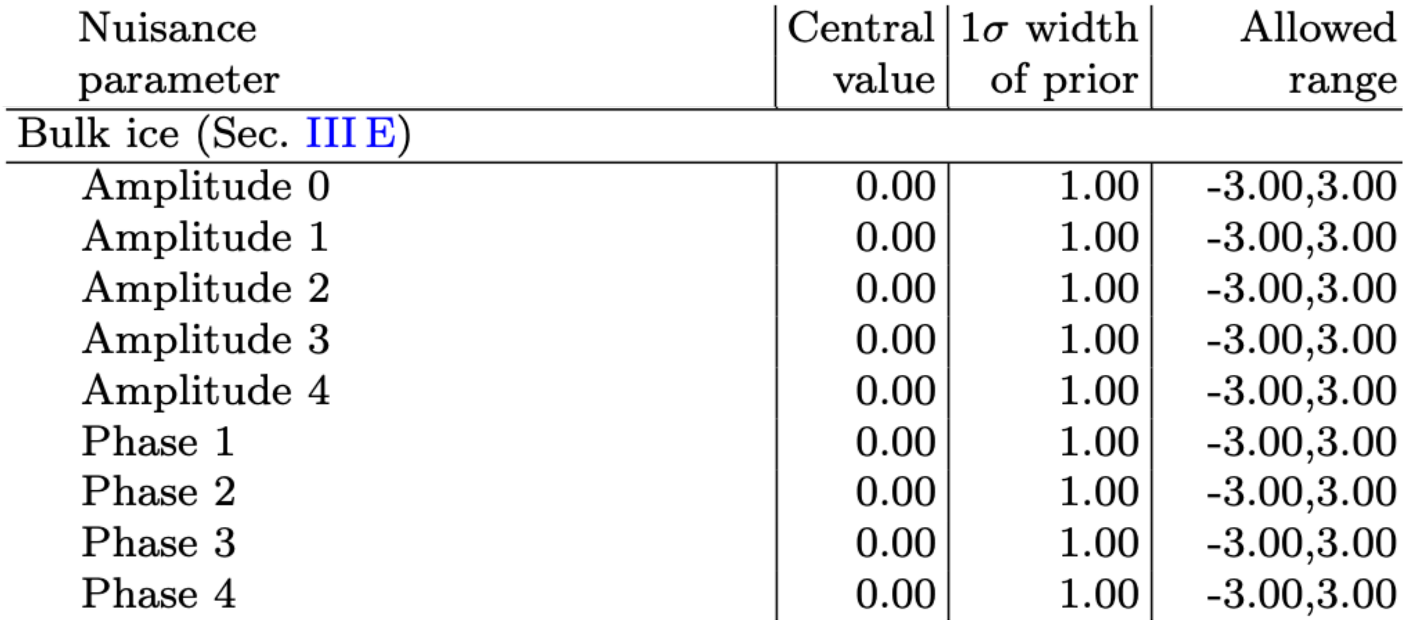


Broken power law to describe the prompt atmospheric + astrophysical flux

Systematic Uncertainties

<u>6 major categories</u>

1. Conventional flux
2. Non-conventional flux
3. **<u>Bulk ice properties</u>**
4. Local DOM response
5. Neutrino attenuation
6. Overall normalization



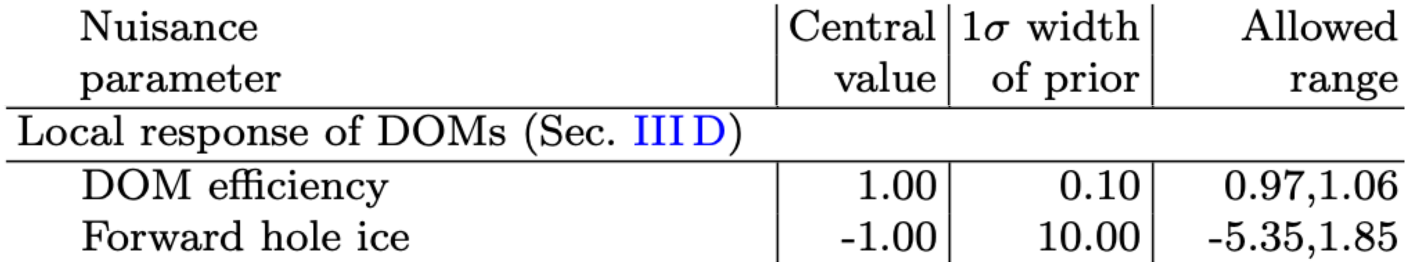
Nuisance parameter	Central value	1σ width of prior	Allowed range
Bulk ice (Sec. III E)			
Amplitude 0	0.00	1.00	-3.00,3.00
Amplitude 1	0.00	1.00	-3.00,3.00
Amplitude 2	0.00	1.00	-3.00,3.00
Amplitude 3	0.00	1.00	-3.00,3.00
Amplitude 4	0.00	1.00	-3.00,3.00
Phase 1	0.00	1.00	-3.00,3.00
Phase 2	0.00	1.00	-3.00,3.00
Phase 3	0.00	1.00	-3.00,3.00
Phase 4	0.00	1.00	-3.00,3.00

Variations in ice model characterized by correlated Fourier modes in energy and zenith space via the SnowStorm method (<u>IceCube 2019</u>). Ice properties are constrained by LED flasher data (<u>IceCube 2013</u>)

Systematic Uncertainties

6 major categories

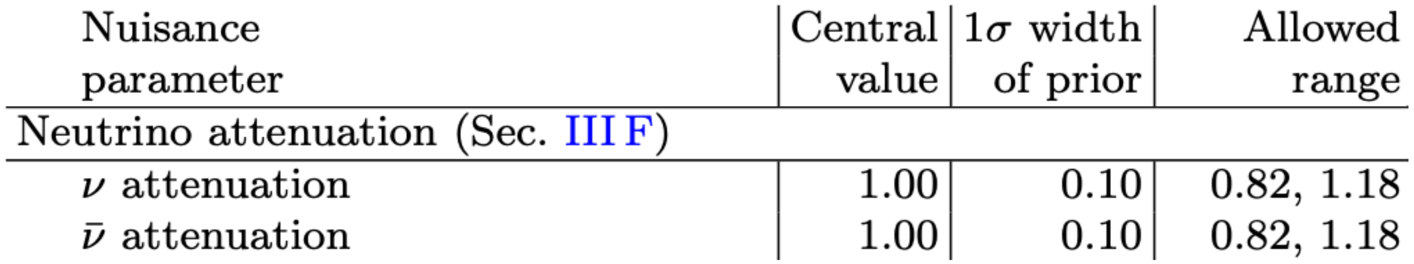
1. Conventional flux
2. Non-conventional flux
3. Bulk ice properties
4. **Local DOM response**
5. Neutrino attenuation
6. Overall normalization



Nuisance parameter	Central value	1σ width of prior	Allowed range
Local response of DOMs (Sec. III D)			
DOM efficiency	1.00	0.10	0.97,1.06
Forward hole ice	-1.00	10.00	-5.35,1.85

Captures photon detection efficiency of the DOMs as well as behavior of refrozen ice along strings

Systematic Uncertainties

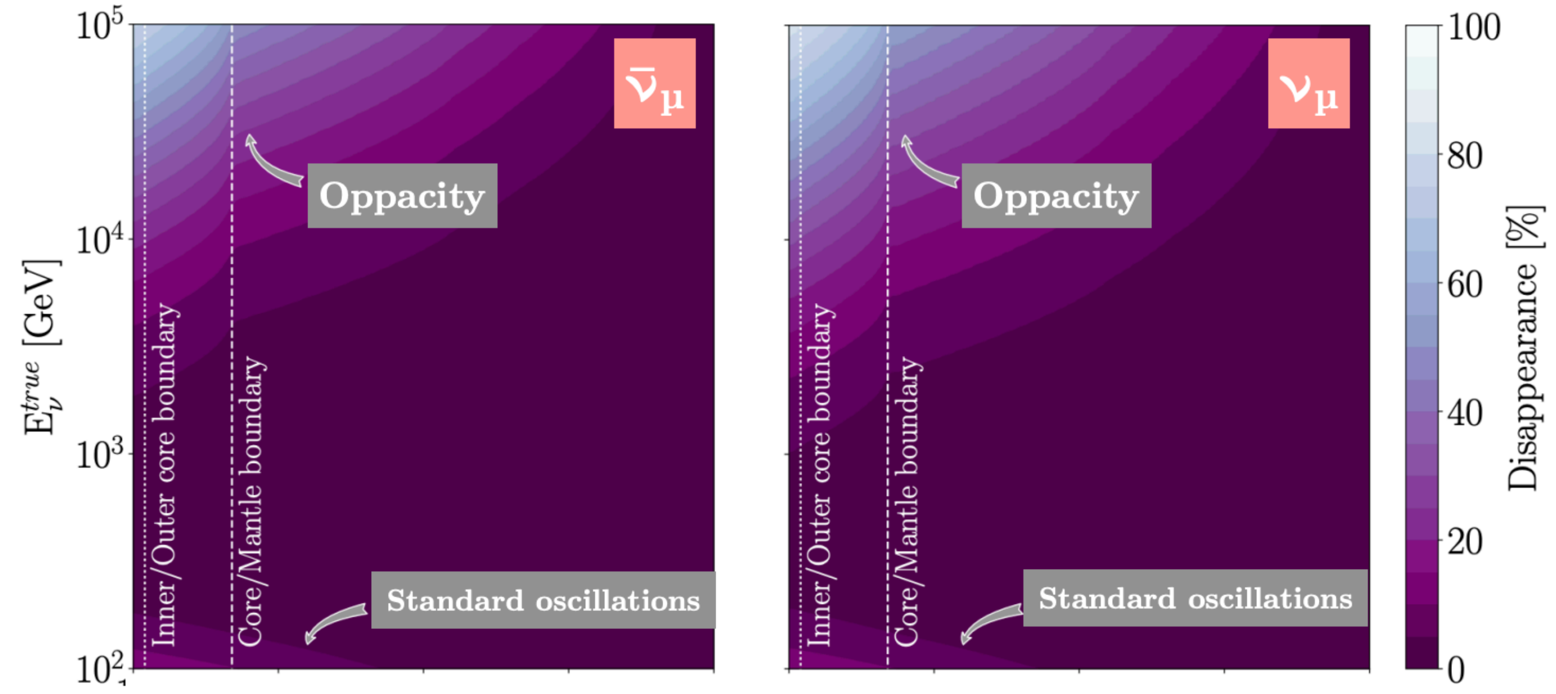


Nuisance parameter	Central value	1σ width of prior	Allowed range
Neutrino attenuation (Sec. III F)			
ν attenuation	1.00	0.10	0.82, 1.18
$\bar{\nu}$ attenuation	1.00	0.10	0.82, 1.18

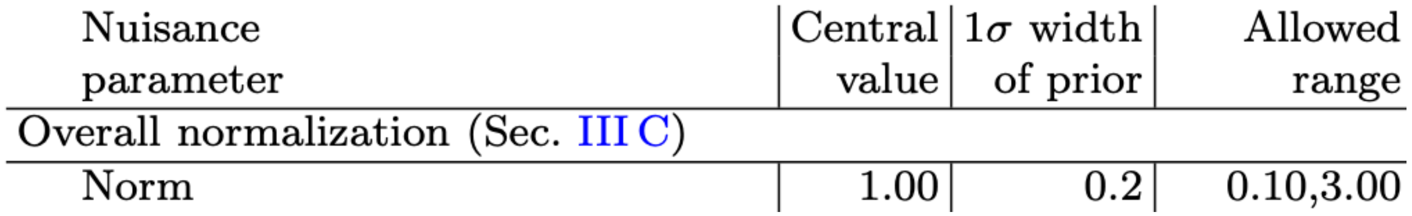
<u>6 major categories</u>

1. Conventional flux
2. Non-conventional flux
3. Bulk ice properties
4. Local DOM response
5. **<u>Neutrino attenuation</u>**
6. Overall normalization

Captures the attenuation of high-energy ($E_\nu \gtrsim 40$ TeV) neutrinos as they pass through the Earth



Systematic Uncertainties



Nuisance parameter	Central value	1σ width of prior	Allowed range
Overall normalization (Sec. III C)			
Norm	1.00	0.2	0.10,3.00

6 major categories

1. Conventional flux
2. Non-conventional flux
3. Bulk ice properties
4. Local DOM response
5. Neutrino attenuation
6. **Overall normalization**

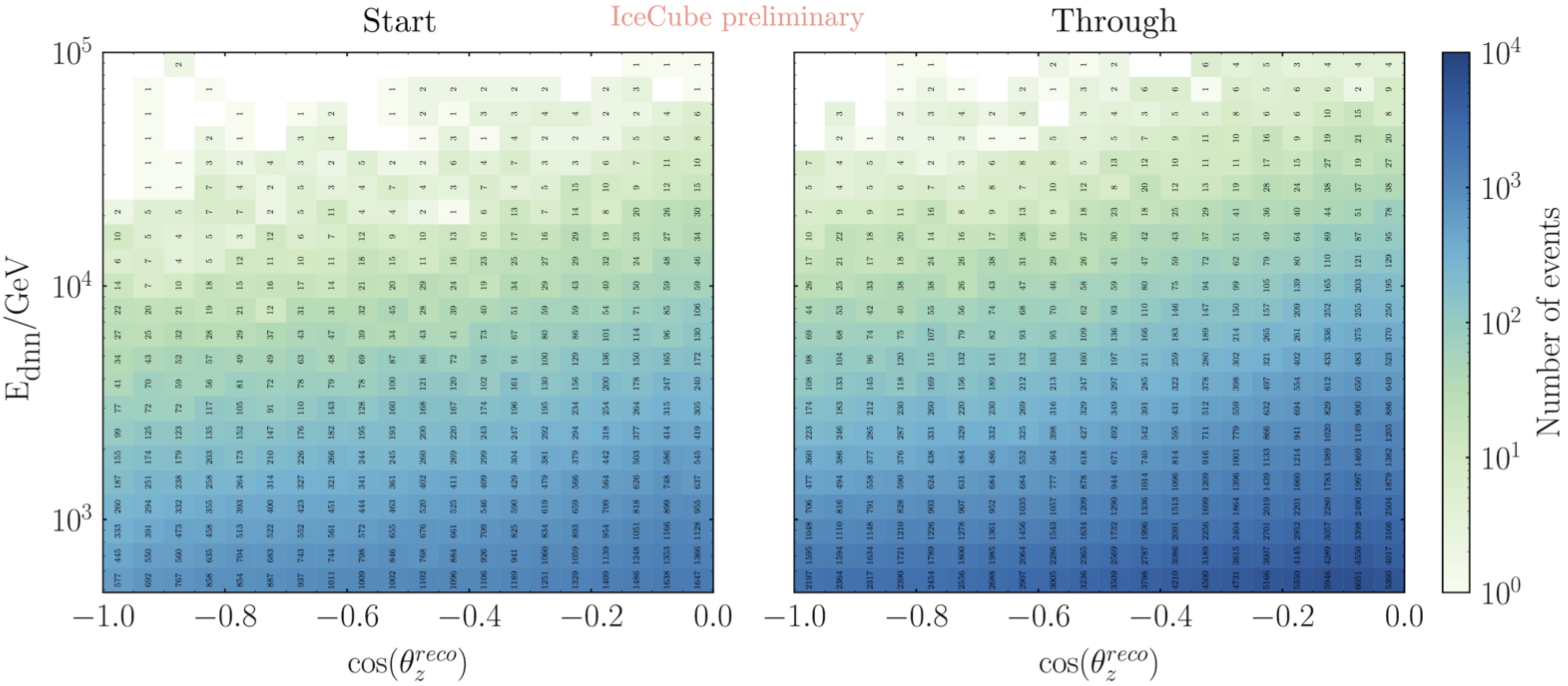
Captures uncertainties in overall flux normalization, total cross section, and muon energy loss in matter

Fit Strategy

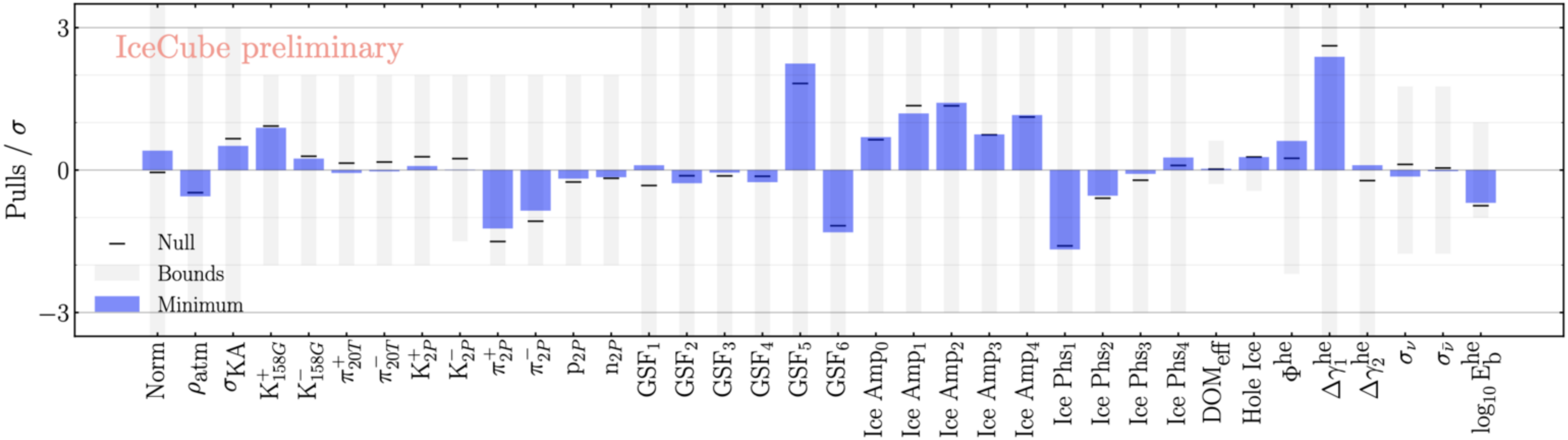
- Binned likelihood in $\{E_\nu^{\text{reco}}, \ \cos\theta_z^{\text{reco}}\}$
- Log-likelihood ratio test statistic marginalizing over the nuisance parameters with Gaussian priors
- Main result is a frequentist analysis with p-values computed assuming Wilks' theorem for two degrees of freedom
- Cross-checked with a Bayesian analysis
  - Not presented here, though results are consistent with the frequentist analysis

Data Sample

- Around 93K/270K starting/through-going ν_μ candidate events in 10.7 years

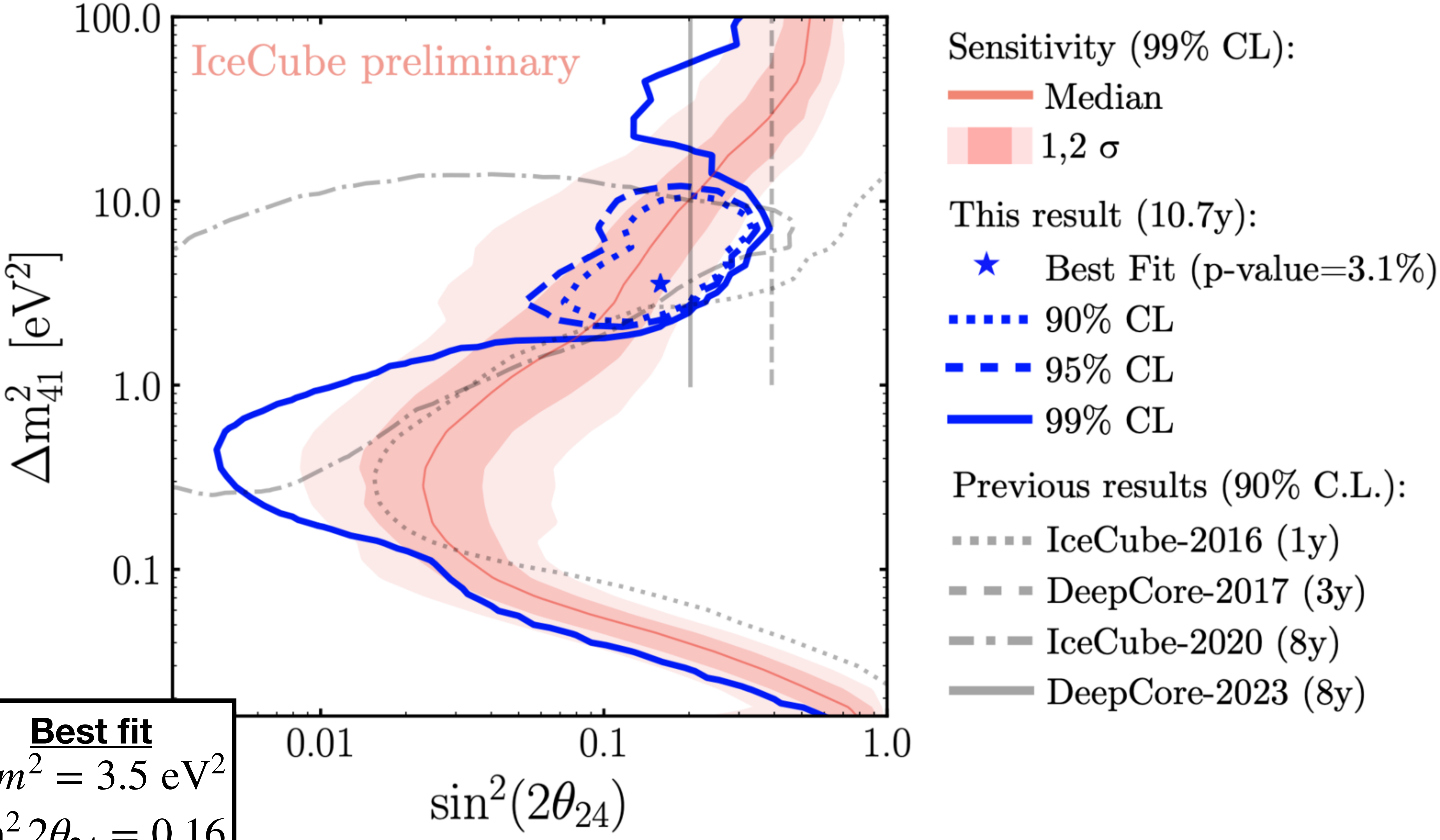


Post-fit systematics



Similar systematic pulls between best fit and null

Oscillation Fit Result

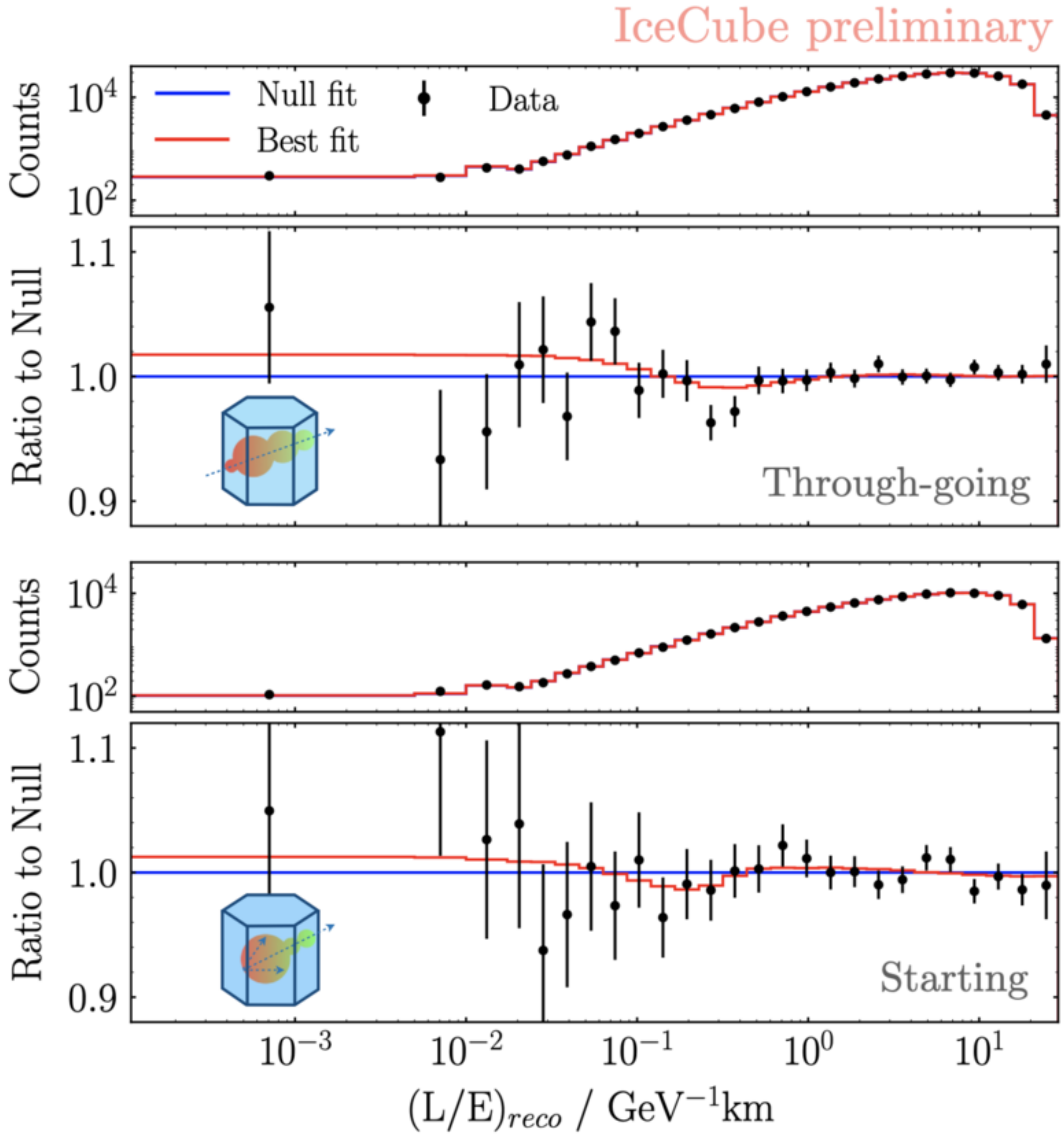


Best fit

$\Delta m^2 = 3.5$ eV^2

$\sin^2 2\theta_{24} = 0.16$

Oscillation Fit Result



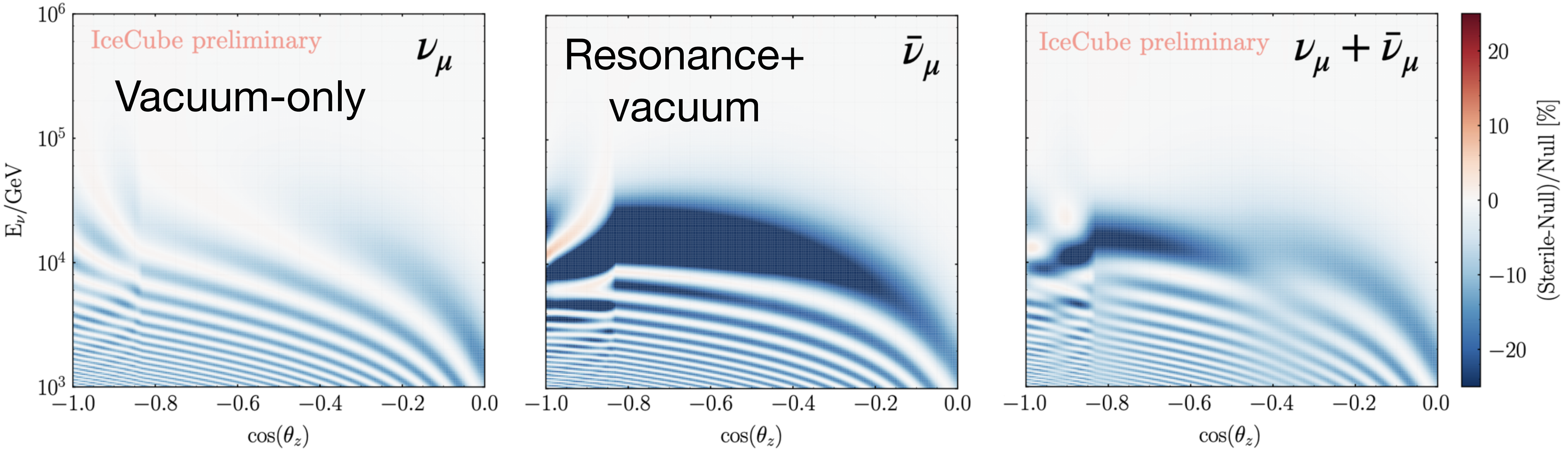
Best fit

$\Delta m^2 = 3.5\ \mathrm{eV}^2$

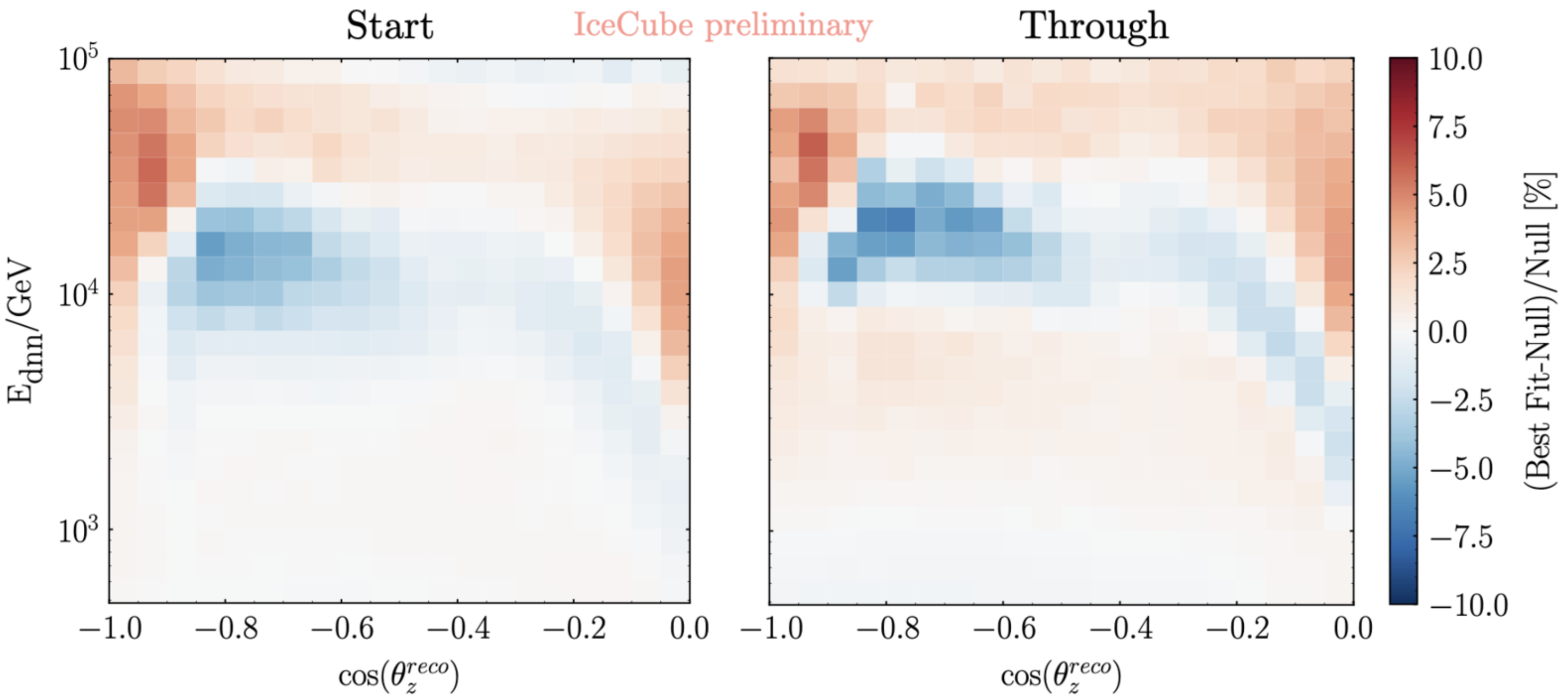
$\sin^2 2\theta_{24} = 0.16$

Where does our significance come from?

Without detector effects



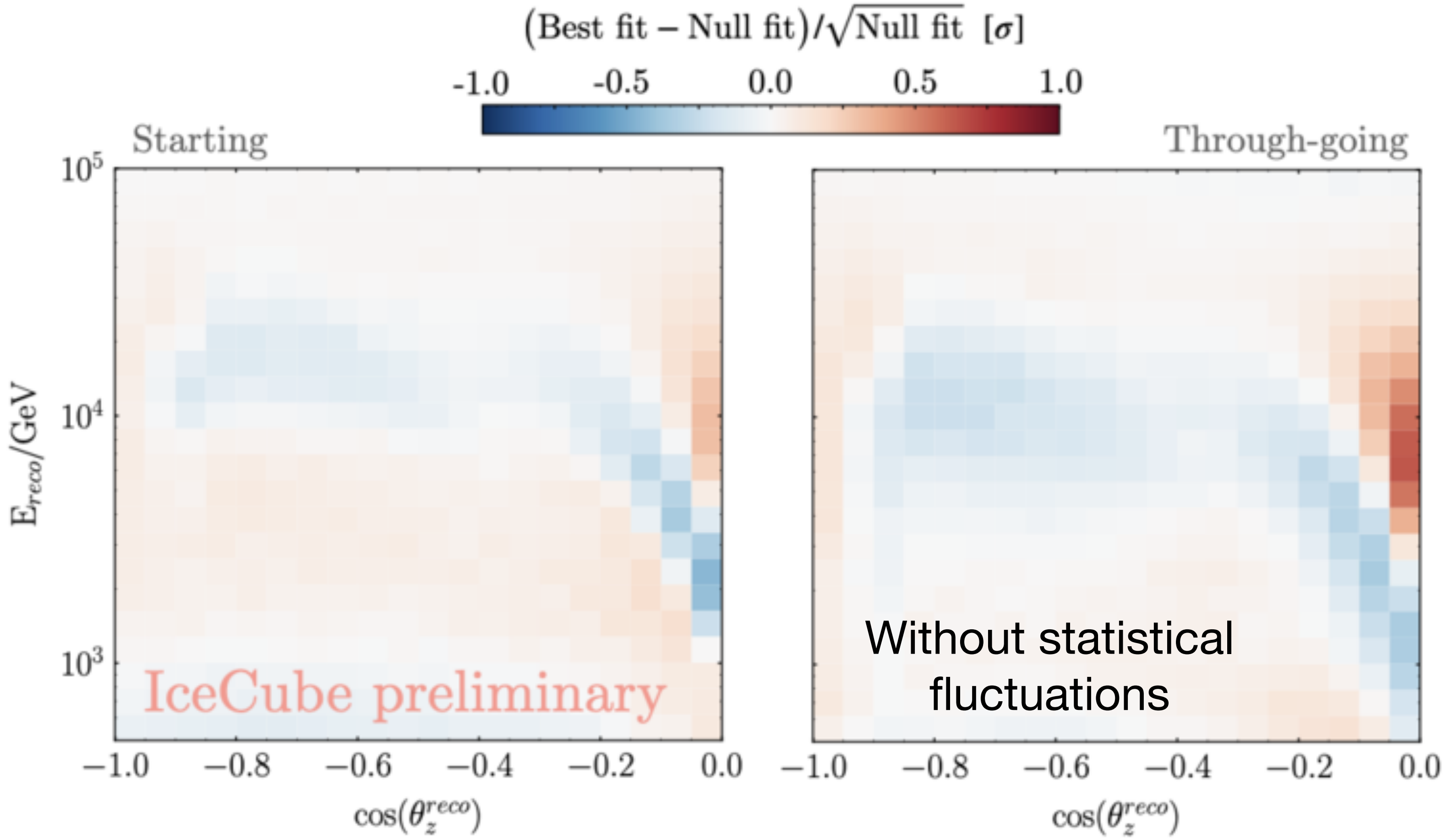
With detector effects, without statistical fluctuations



$$\text{Pull} \equiv \frac{\text{Best fit} - \text{Null fit}}{\sqrt{\text{Null fit}}}$$

Red: excess in best fit v.s. null

Blue: deficit in best fit v.s. null

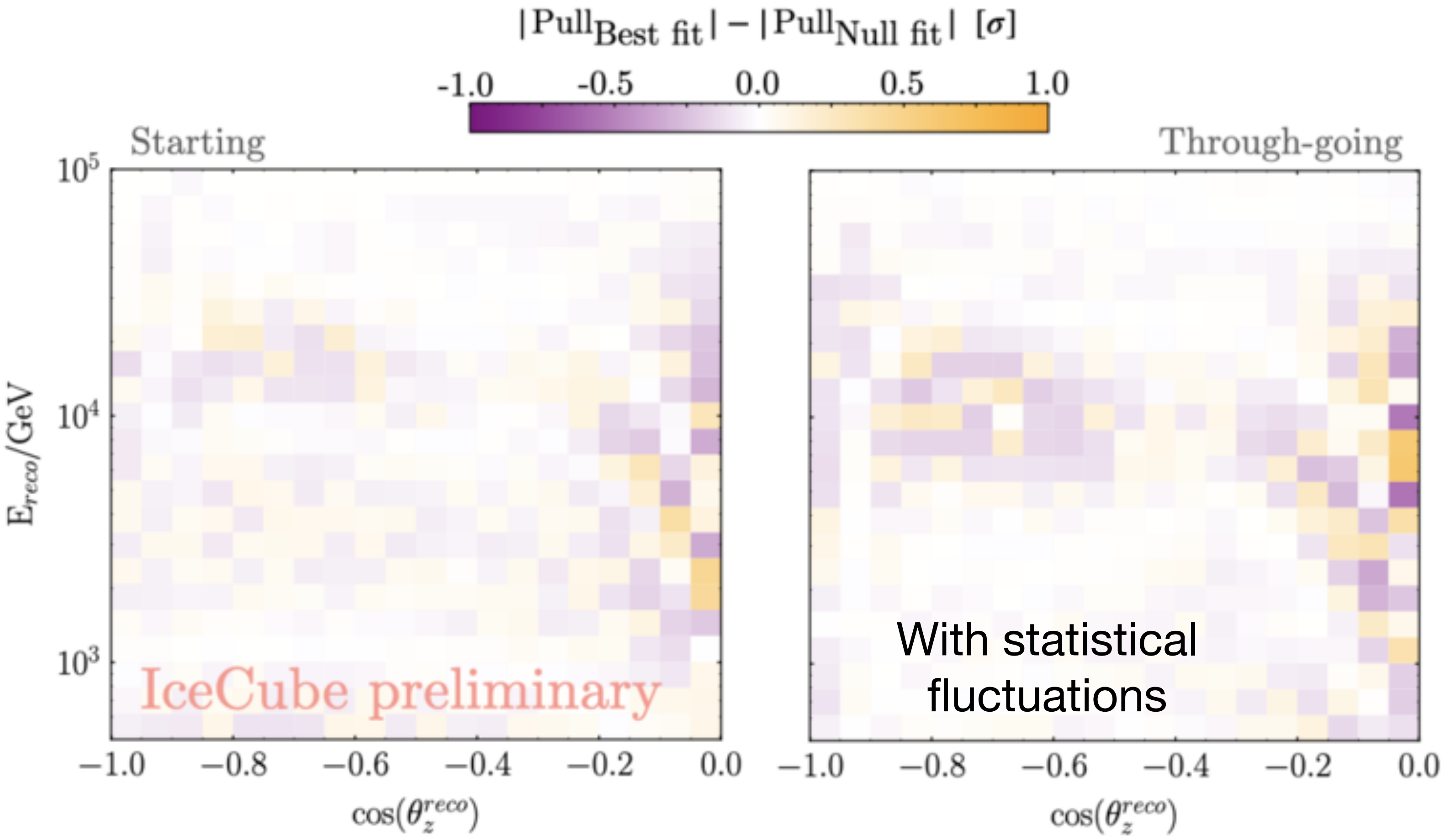


Without statistical fluctuations

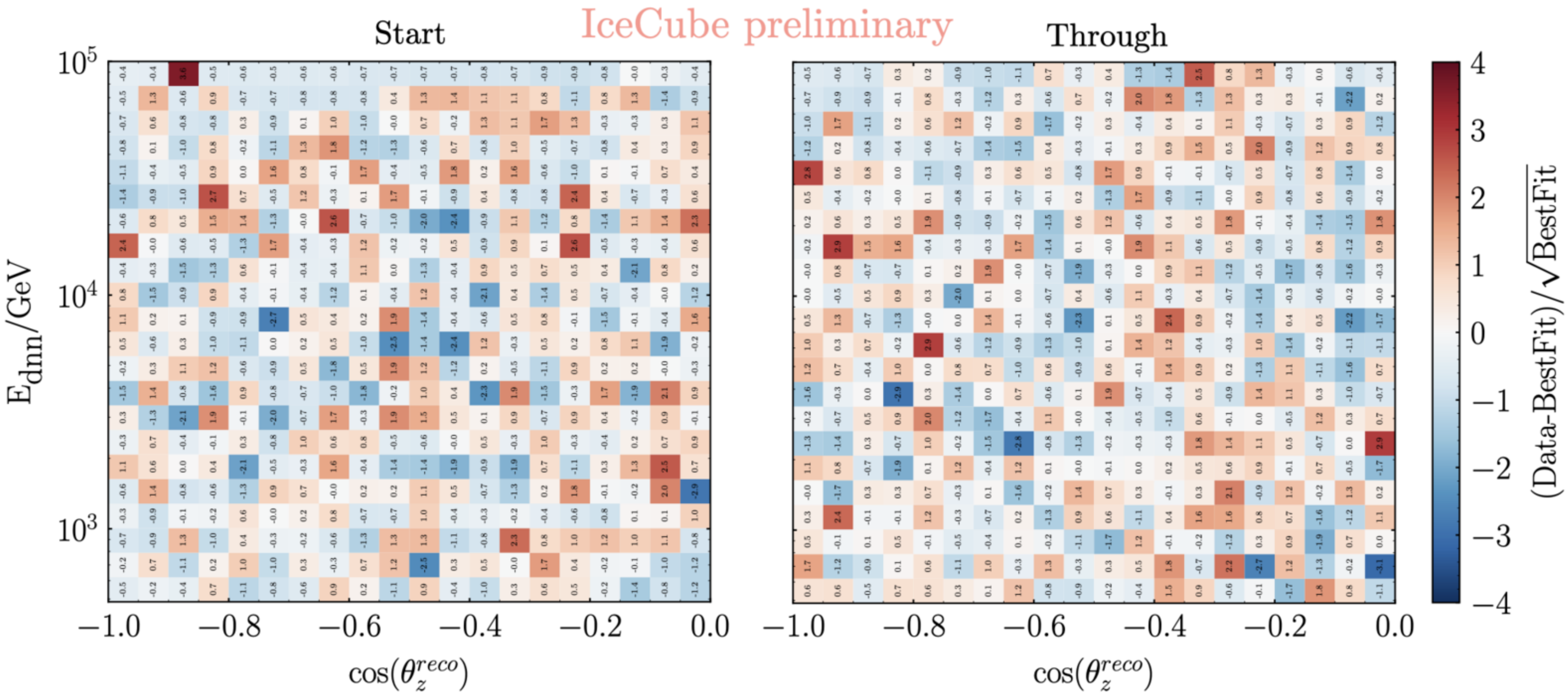
$$\text{Pull} \equiv \frac{\text{Data} - \text{Fit}}{\sqrt{\text{Fit}}}$$

Yellow: data prefers null fit

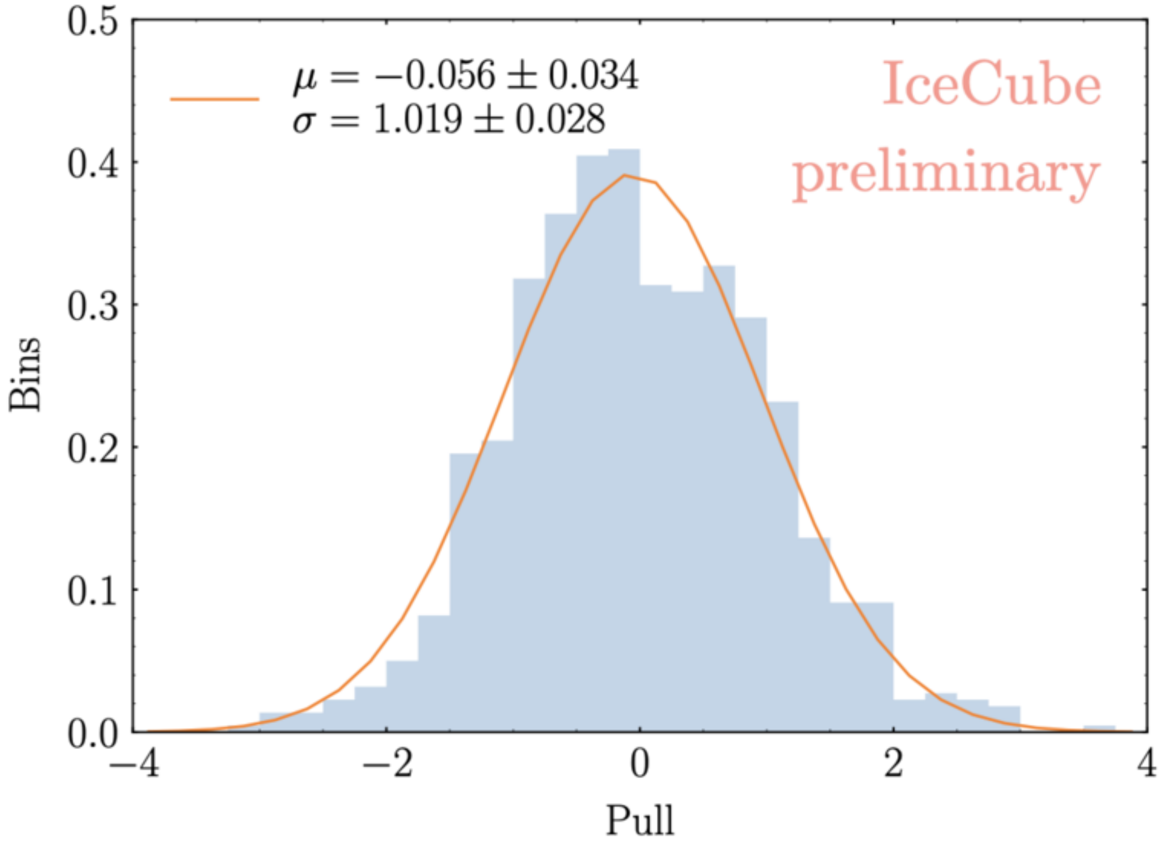
Purple: data prefers oscillation fit



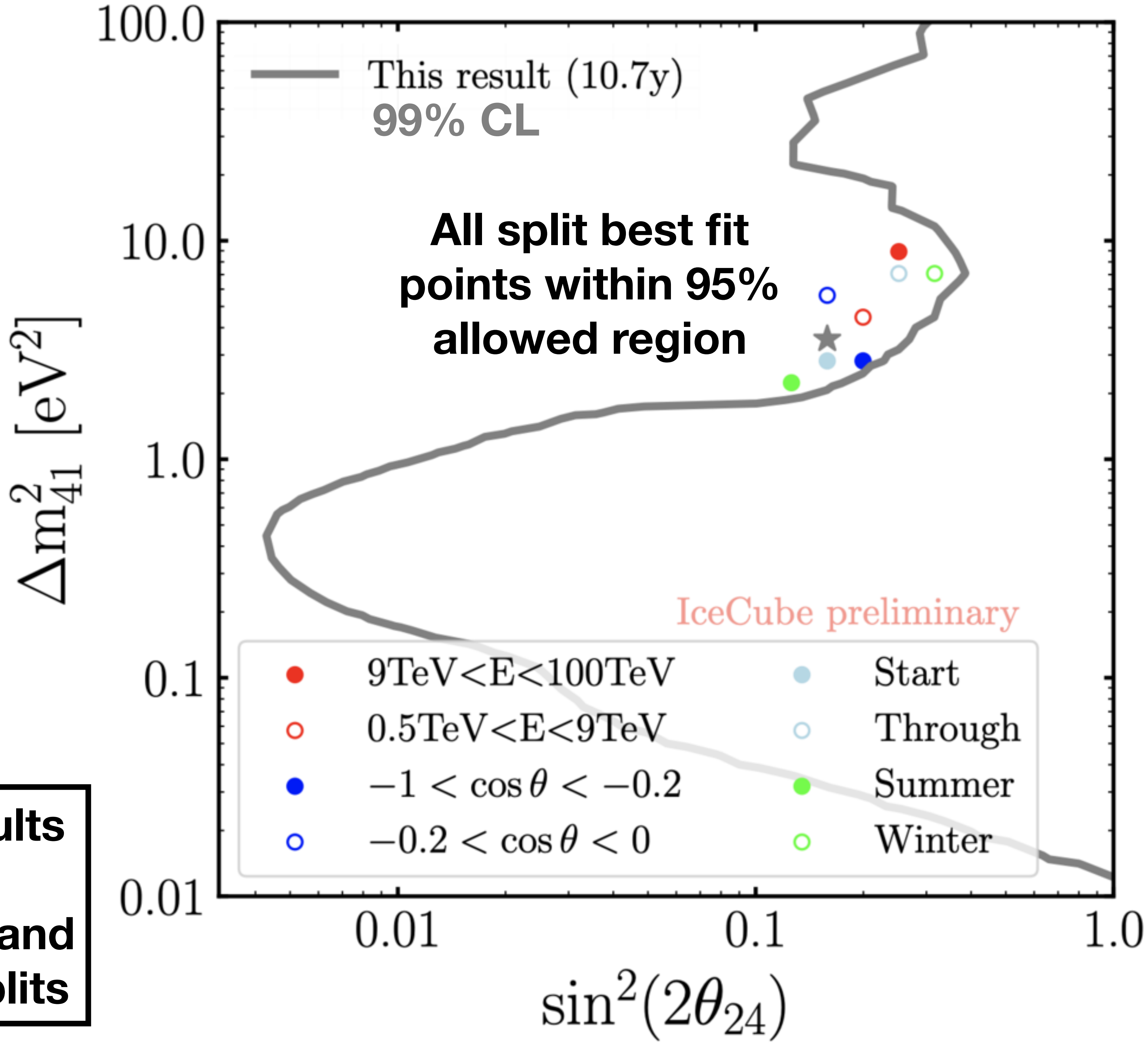
With statistical fluctuations



Good agreement between data and MC at best fit (goodness of fit p-value ~12%)



Post-unblinding checks

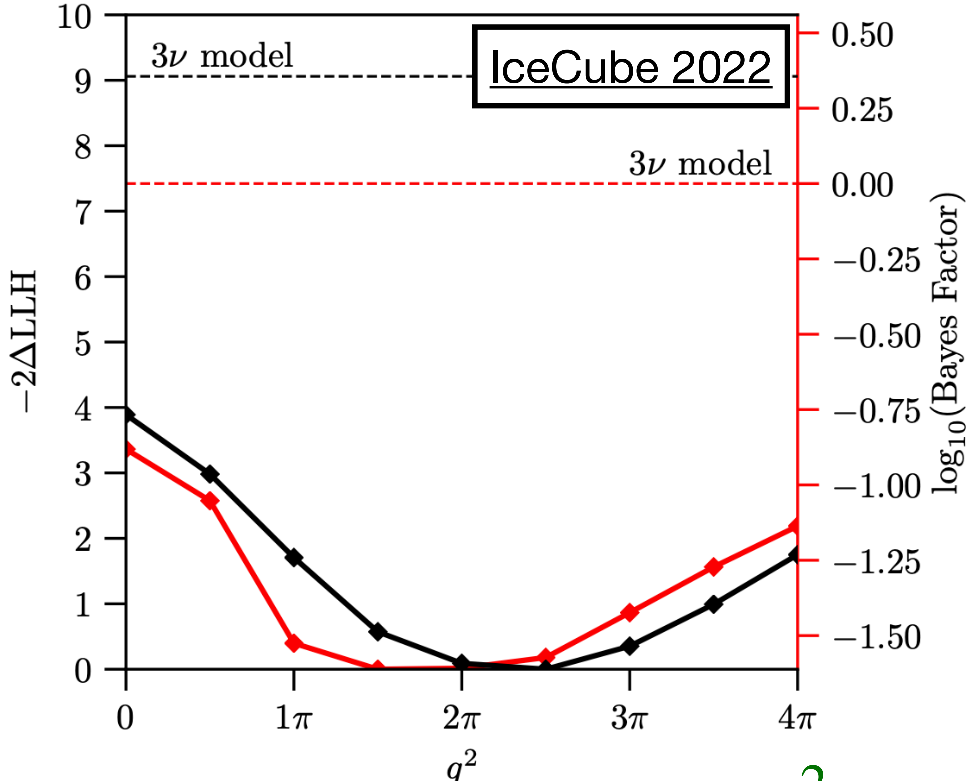


All split best fit points within 95% allowed region

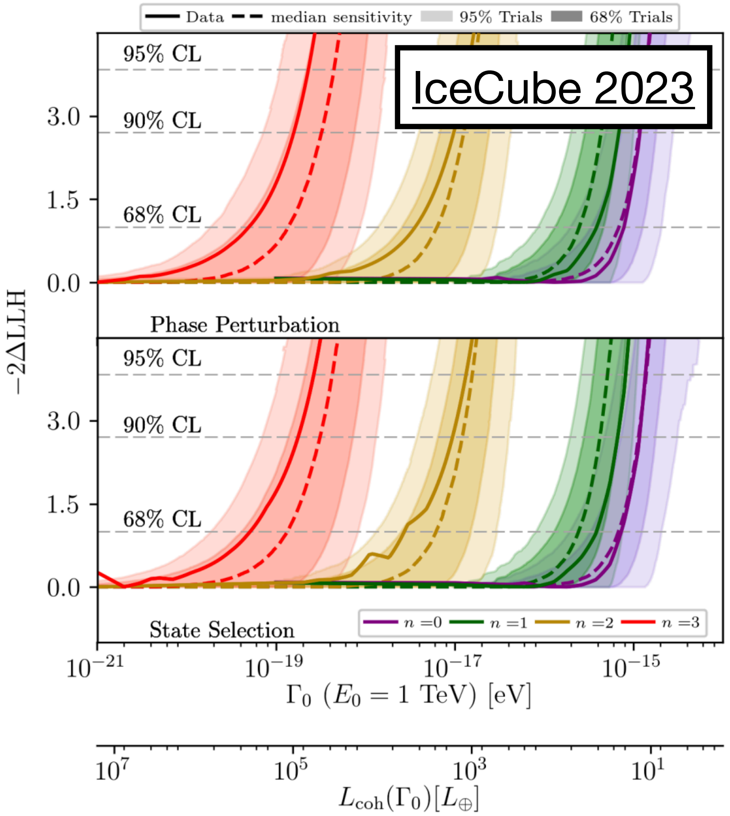
Consistent results in azimuthal direction splits and year-by-year splits

Related Work in IceCube

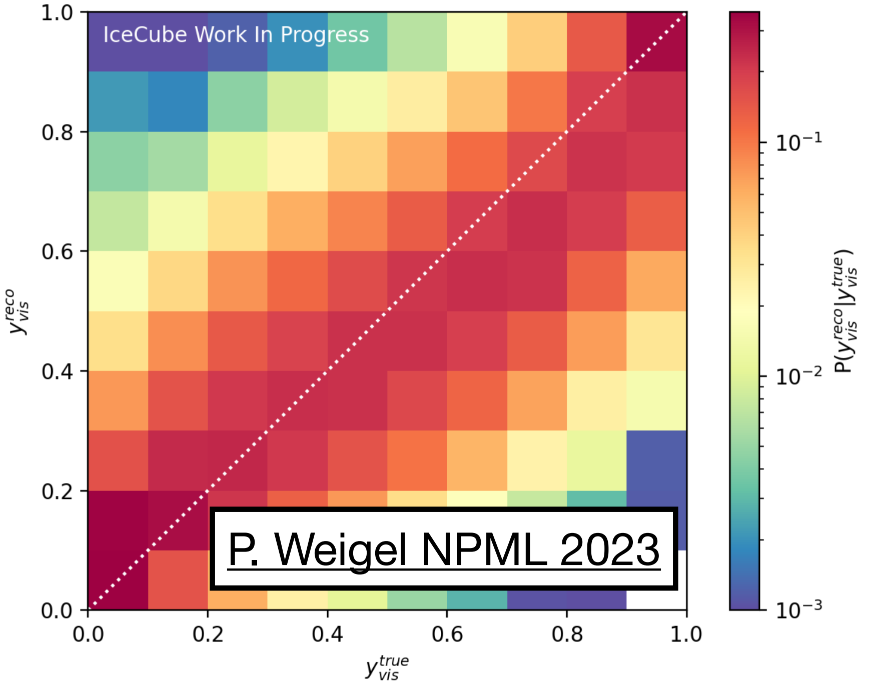
3+1 with decay



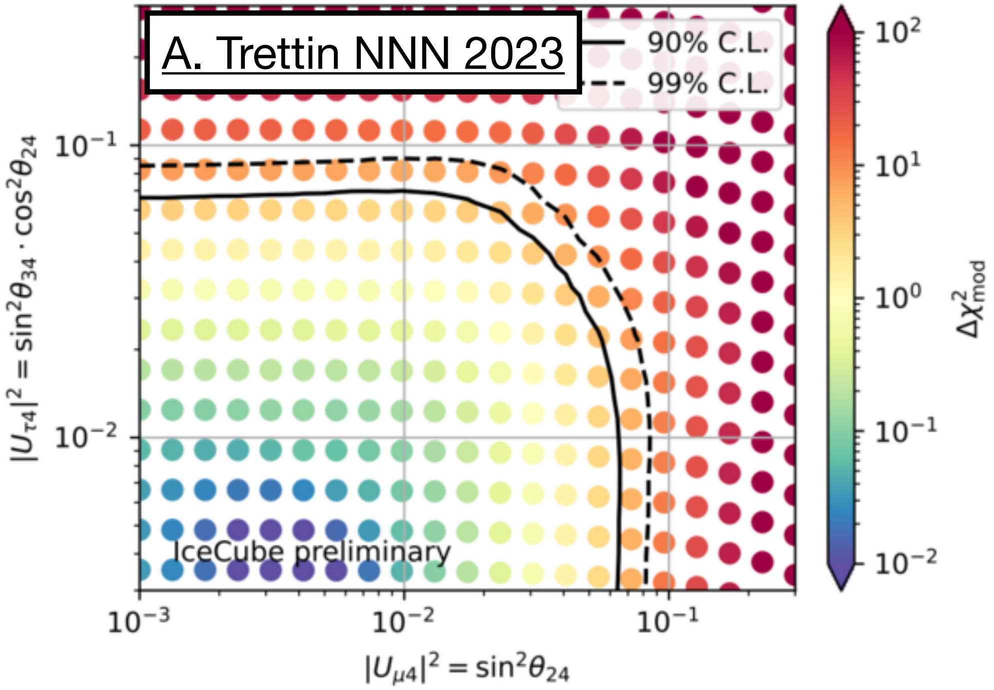
Decoherence



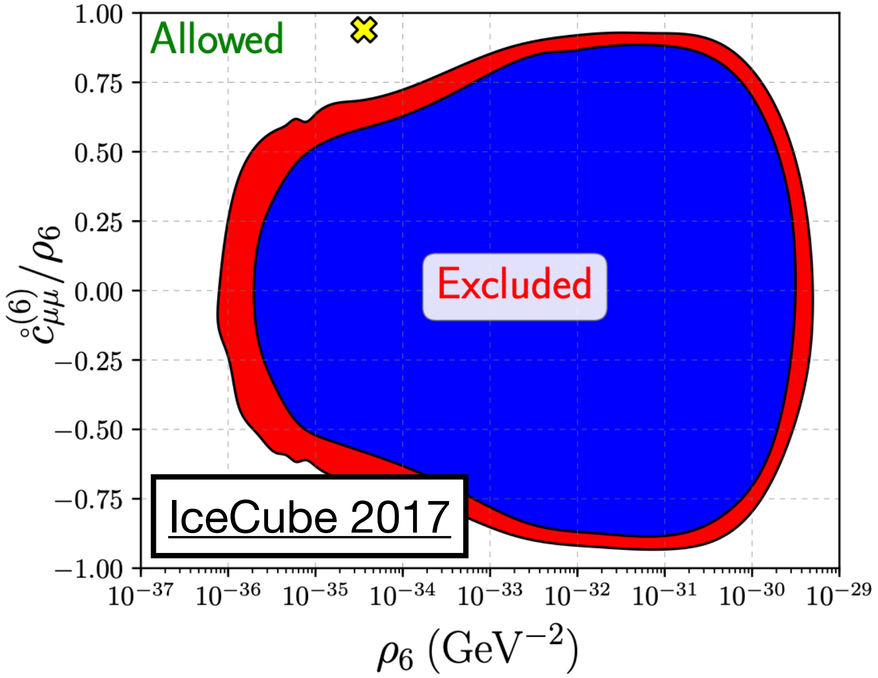
3+1 w/ Inelasticity



3+1 w/ nonzero $|U_{\tau4}|^2$



Lorentz Violation



Updated analyses coming soon!

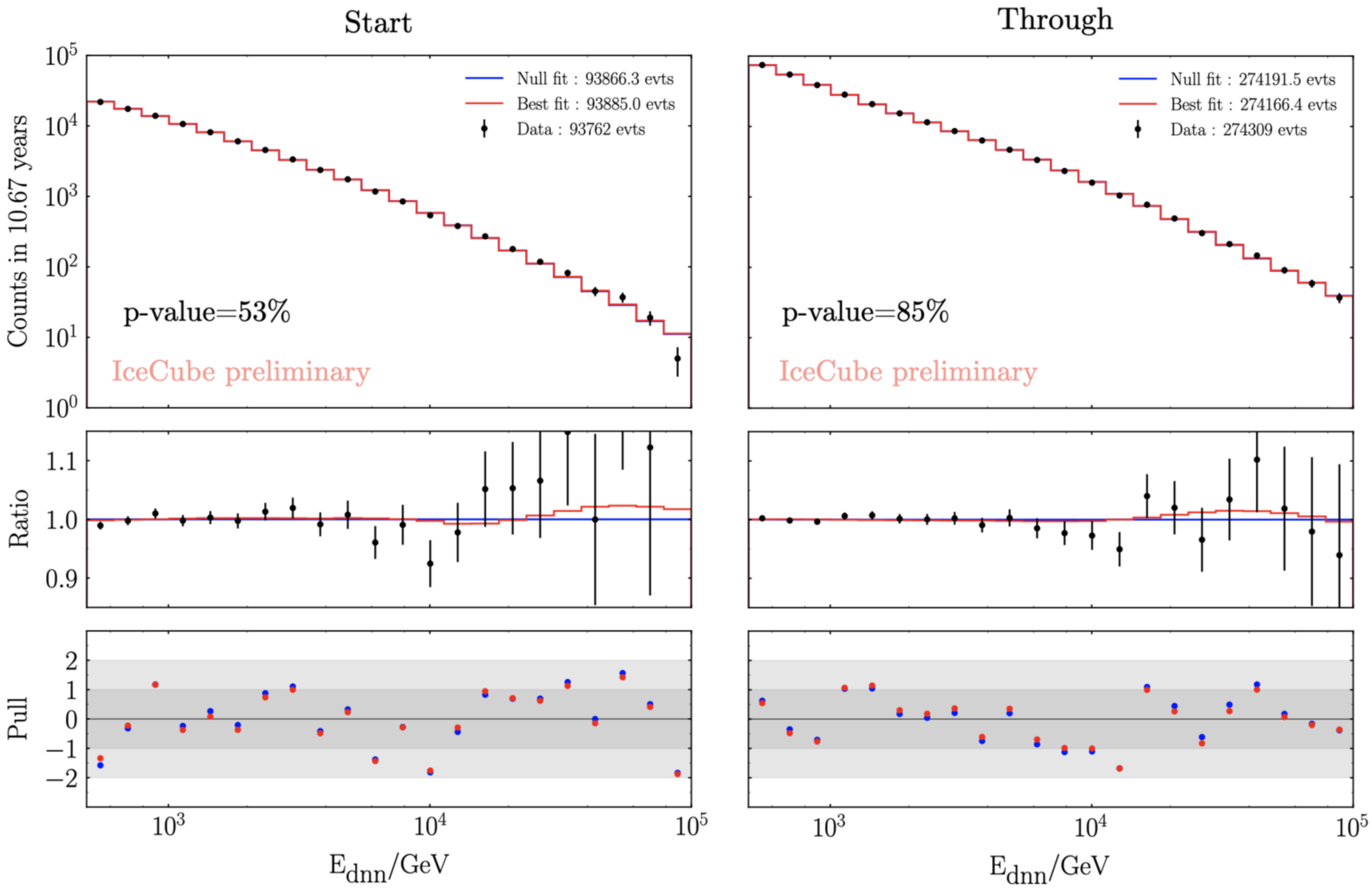
Conclusion

- IceCube has performed a search for sterile neutrino oscillation imprints in 10.7 years of atmospheric muon neutrino data
  - Sensitivity from matter-enhanced resonance
  - Improvements to event selection, reconstruction, and systematic treatment
- Best fit at $\Delta m^2 = 3.5\ \mathrm{eV}^2,\ \sin^2 2\theta_{24} = 0.16$
  - Consistent with best fit (null) at 12% (3.1%)
- Results from related analyses on the way
- **Data release for the 8-year version of this analysis available here: https://dataverse.harvard.edu**

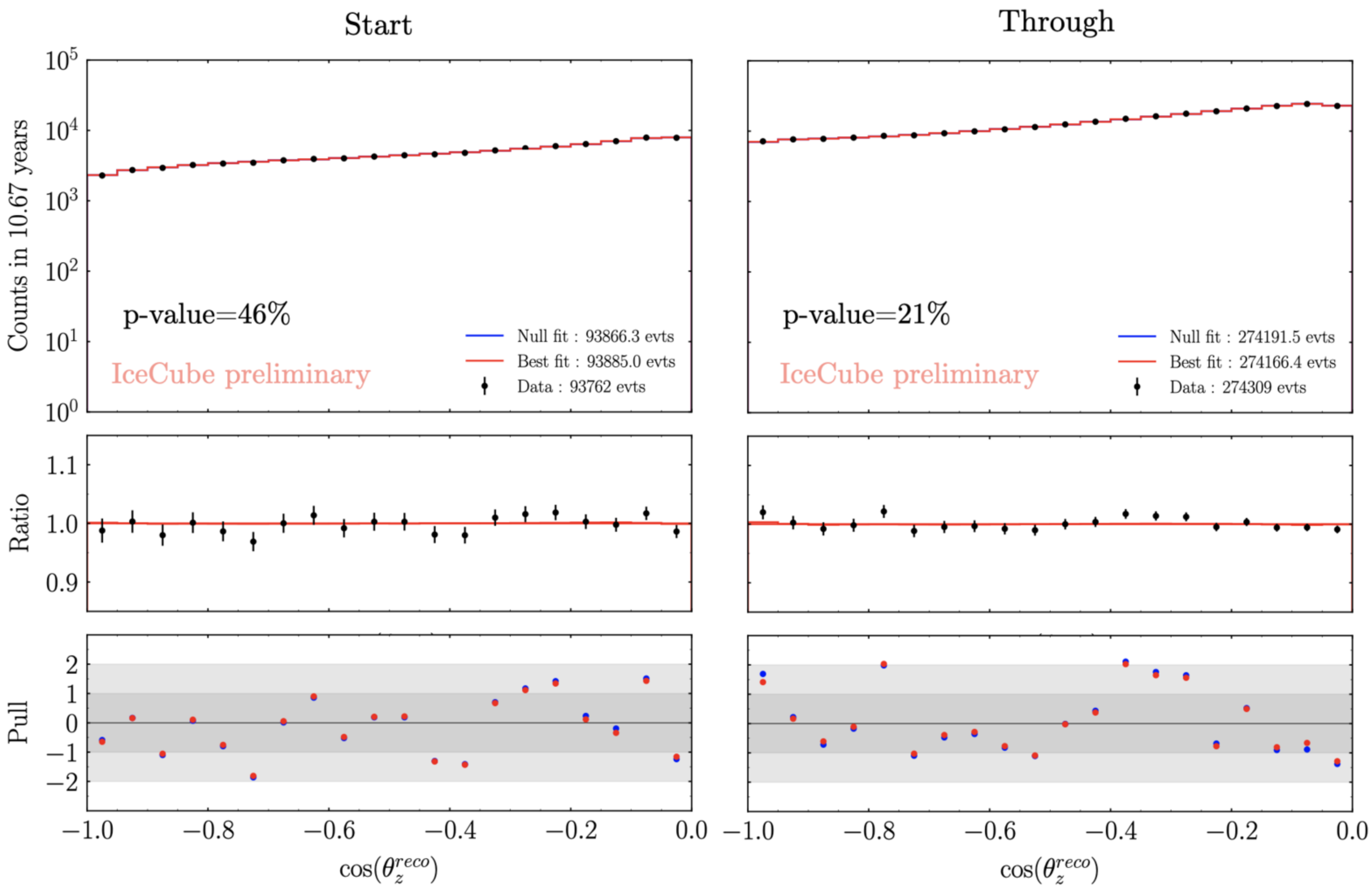
Thank you!

Backups

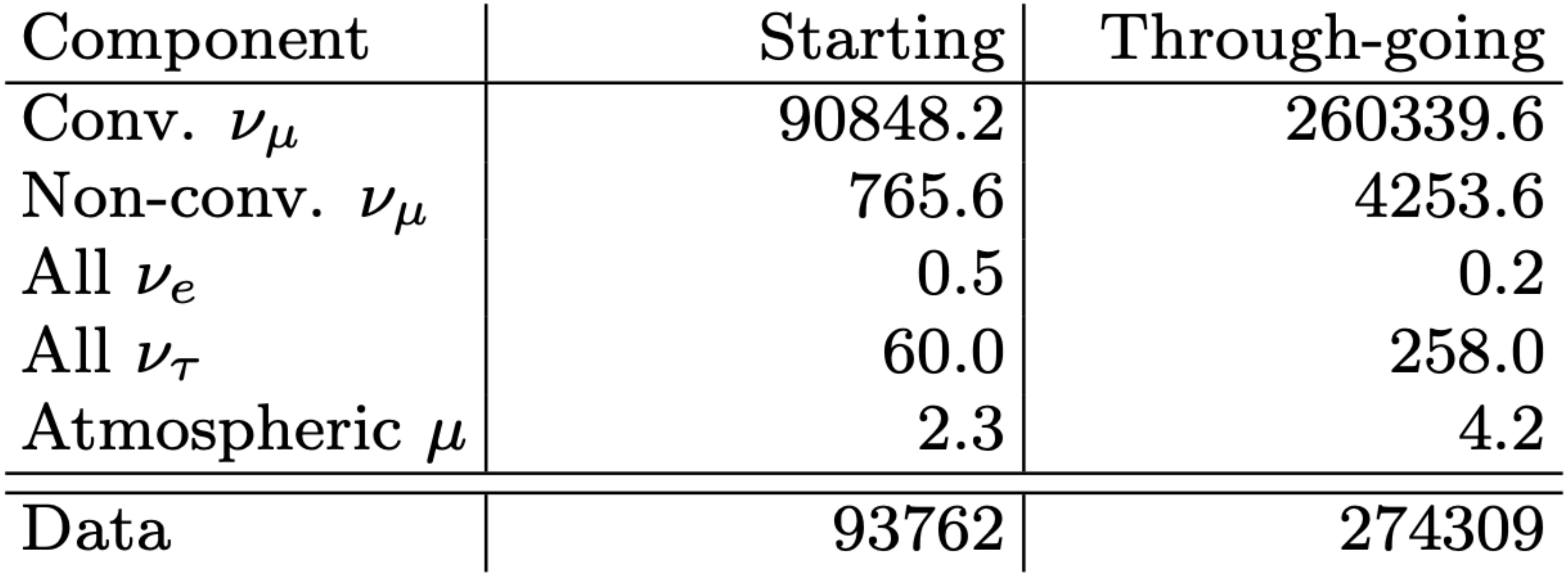
1D Distributions



1D Distributions

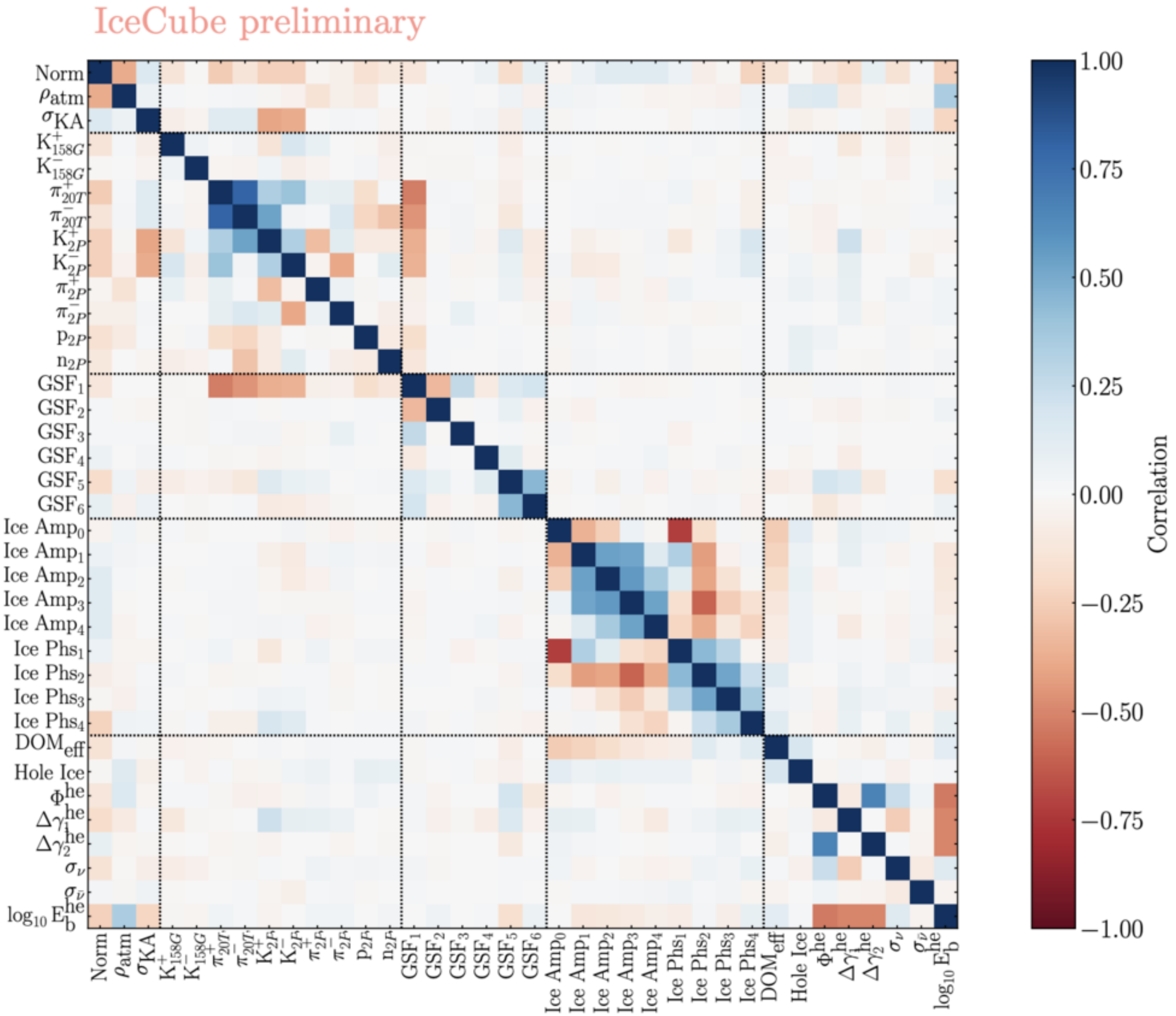


Data Rates

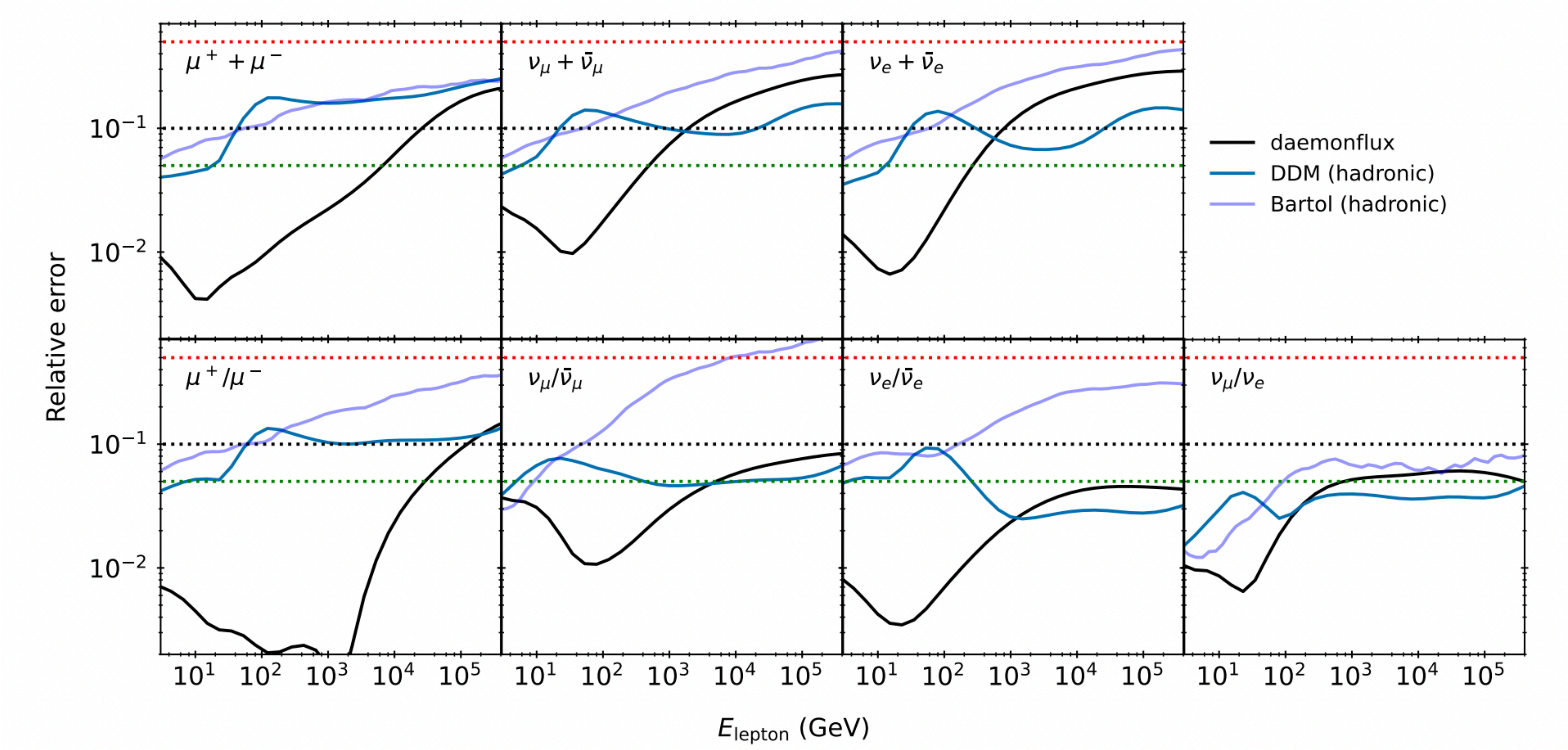


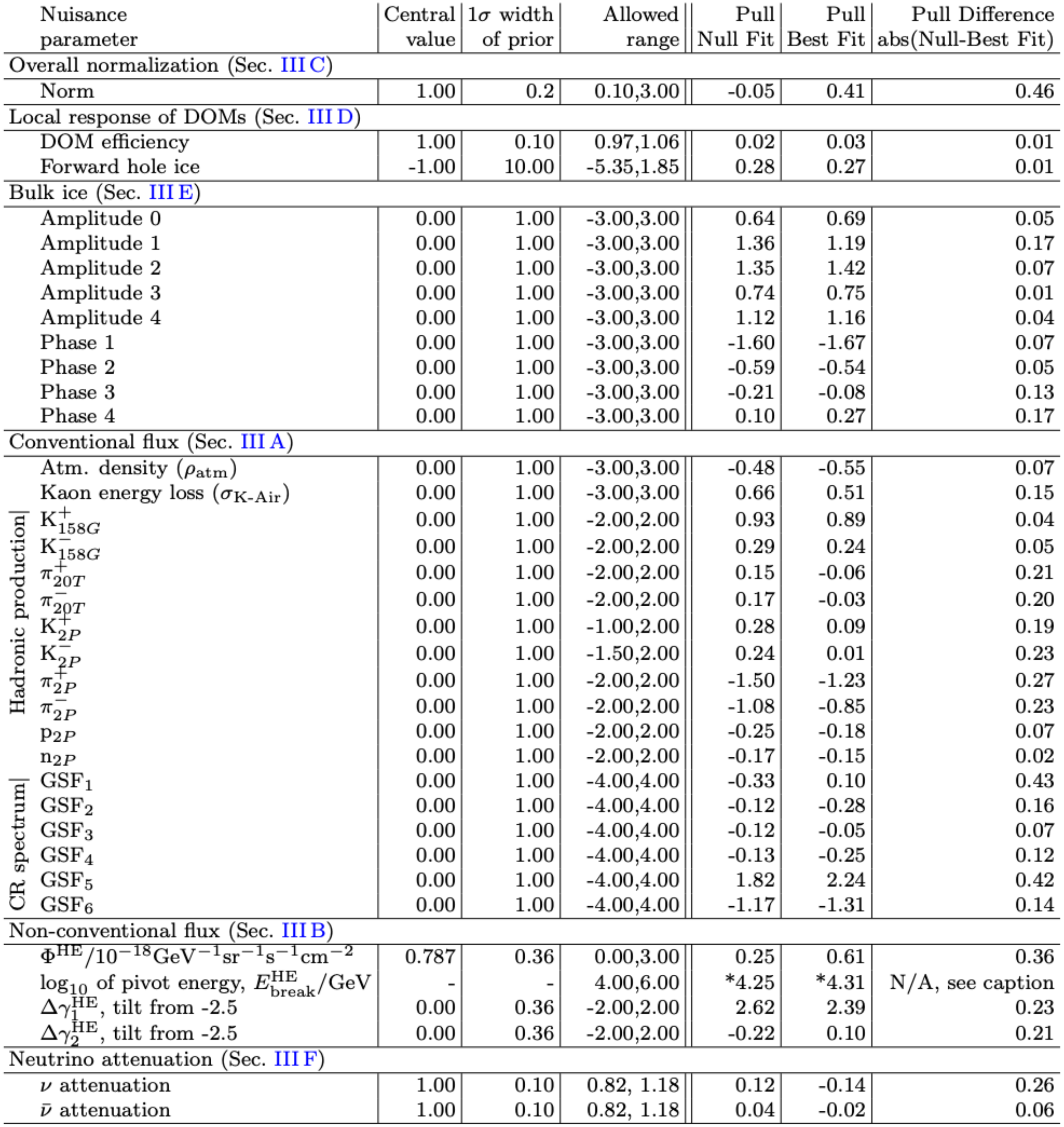
Component	Starting	Through-going
Conv. ν_μ	90848.2	260339.6
Non-conv. ν_μ	765.6	4253.6
All ν_e	0.5	0.2
All ν_τ	60.0	258.0
Atmospheric μ	2.3	4.2
Data	93762	274309

Best-fit systematic correlations



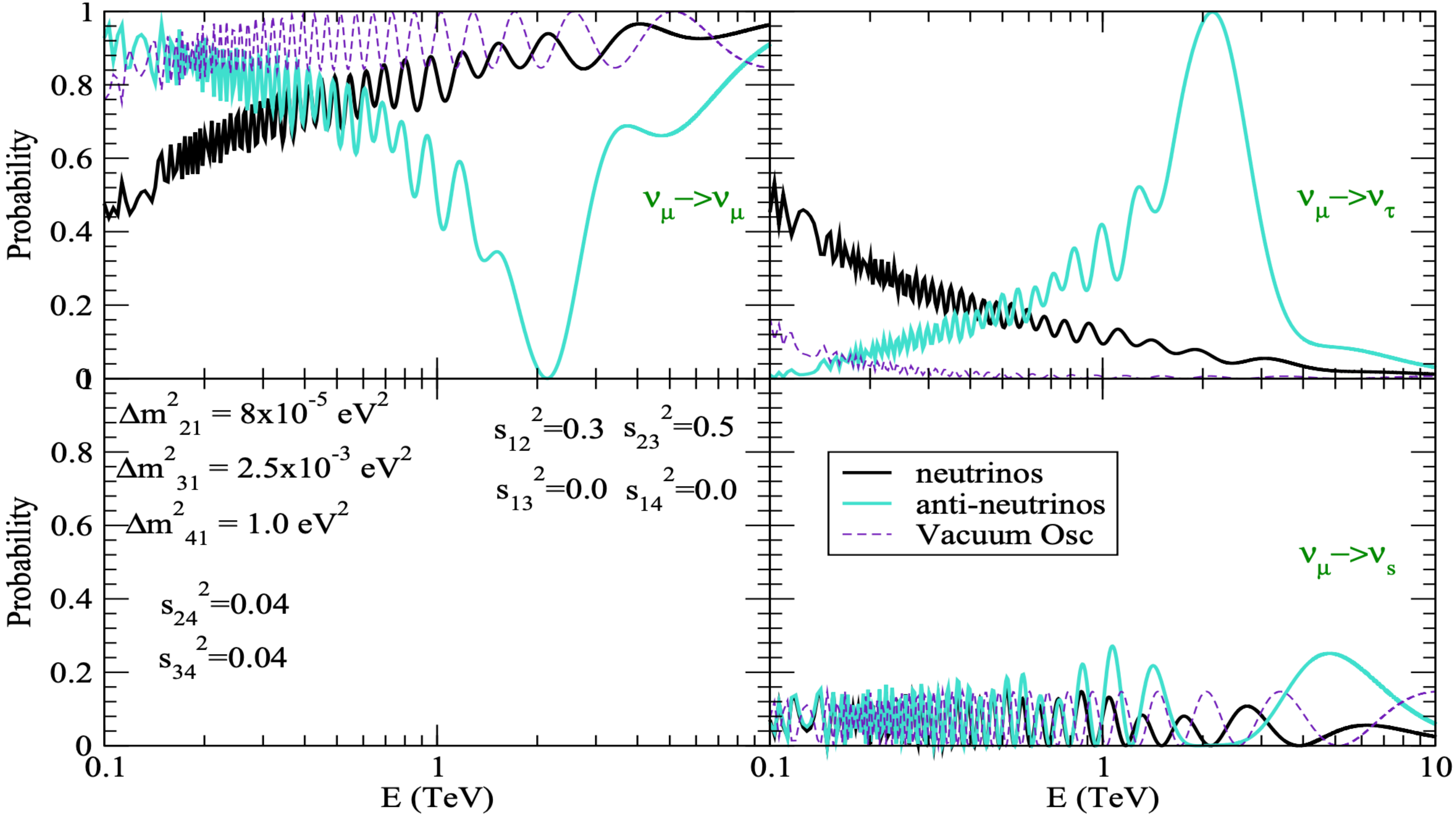
Daemonflux high energy uncertainties



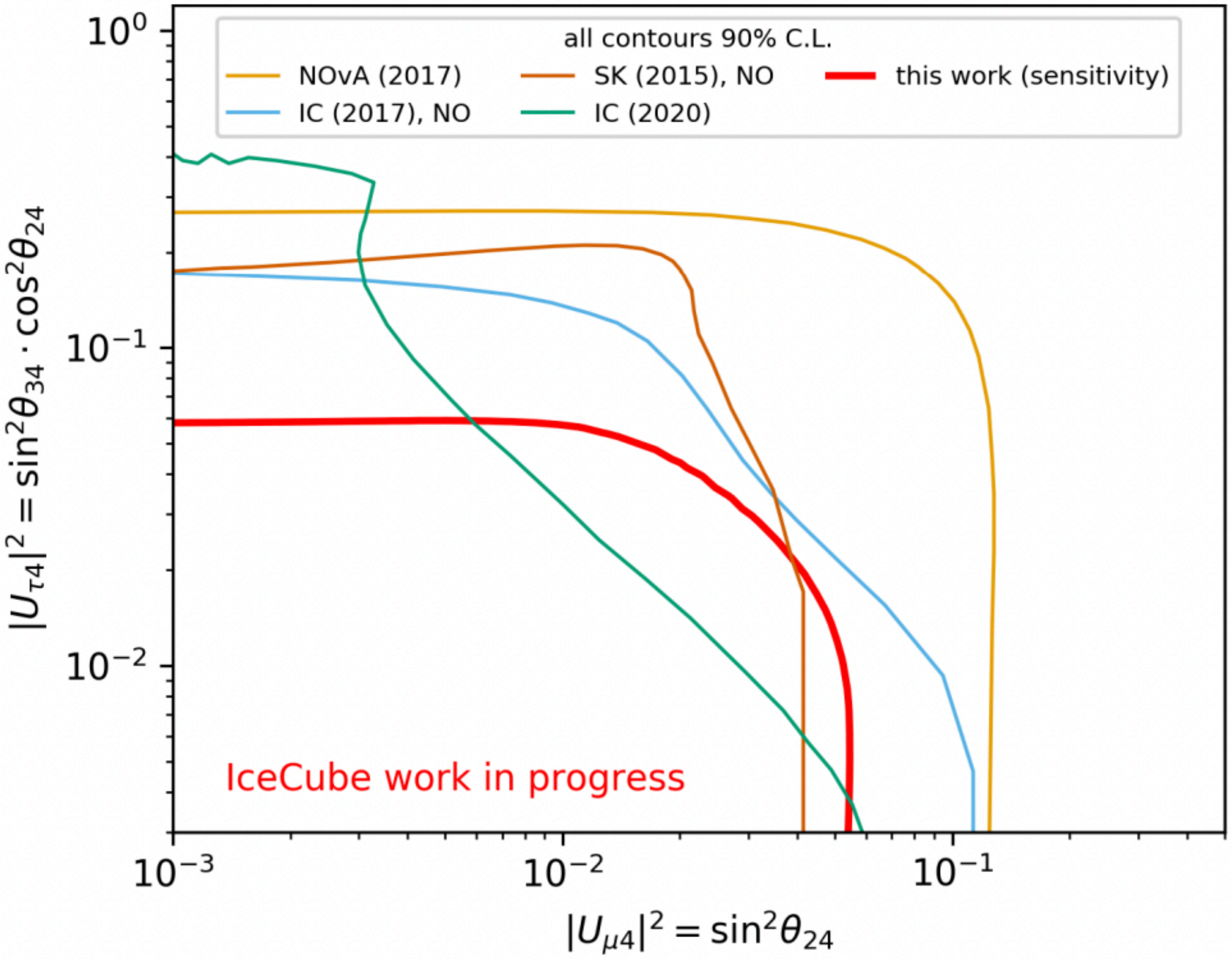


	Nuisance parameter	Central value	1σ width of prior	Allowed range	Pull Null Fit	Pull Best Fit	Pull Difference abs(Null-Best Fit)
Overall normalization (Sec. III C)							
	Norm	1.00	0.2	0.10,3.00	-0.05	0.41	0.46
Local response of DOMs (Sec. III D)							
	DOM efficiency	1.00	0.10	0.97,1.06	0.02	0.03	0.01
	Forward hole ice	-1.00	10.00	-5.35,1.85	0.28	0.27	0.01
Bulk ice (Sec. III E)							
	Amplitude 0	0.00	1.00	-3.00,3.00	0.64	0.69	0.05
	Amplitude 1	0.00	1.00	-3.00,3.00	1.36	1.19	0.17
	Amplitude 2	0.00	1.00	-3.00,3.00	1.35	1.42	0.07
	Amplitude 3	0.00	1.00	-3.00,3.00	0.74	0.75	0.01
	Amplitude 4	0.00	1.00	-3.00,3.00	1.12	1.16	0.04
	Phase 1	0.00	1.00	-3.00,3.00	-1.60	-1.67	0.07
	Phase 2	0.00	1.00	-3.00,3.00	-0.59	-0.54	0.05
	Phase 3	0.00	1.00	-3.00,3.00	-0.21	-0.08	0.13
	Phase 4	0.00	1.00	-3.00,3.00	0.10	0.27	0.17
Conventional flux (Sec. III A)							
	Atm. density (ρ_{atm})	0.00	1.00	-3.00,3.00	-0.48	-0.55	0.07
	Kaon energy loss ($\sigma_{\text{K-Air}}$)	0.00	1.00	-3.00,3.00	0.66	0.51	0.15
Hadronic production	K^+_{158G}	0.00	1.00	-2.00,2.00	0.93	0.89	0.04
	K^-_{158G}	0.00	1.00	-2.00,2.00	0.29	0.24	0.05
	π^+_{20T}	0.00	1.00	-2.00,2.00	0.15	-0.06	0.21
	π^-_{20T}	0.00	1.00	-2.00,2.00	0.17	-0.03	0.20
	K^+_{2P}	0.00	1.00	-1.00,2.00	0.28	0.09	0.19
	K^-_{2P}	0.00	1.00	-1.50,2.00	0.24	0.01	0.23
	π^+_{2P}	0.00	1.00	-2.00,2.00	-1.50	-1.23	0.27
	π^-_{2P}	0.00	1.00	-2.00,2.00	-1.08	-0.85	0.23
	p_{2P}	0.00	1.00	-2.00,2.00	-0.25	-0.18	0.07
	n_{2P}	0.00	1.00	-2.00,2.00	-0.17	-0.15	0.02
CR spectrum	GSF_1	0.00	1.00	-4.00,4.00	-0.33	0.10	0.43
	GSF_2	0.00	1.00	-4.00,4.00	-0.12	-0.28	0.16
	GSF_3	0.00	1.00	-4.00,4.00	-0.12	-0.05	0.07
	GSF_4	0.00	1.00	-4.00,4.00	-0.13	-0.25	0.12
	GSF_5	0.00	1.00	-4.00,4.00	1.82	2.24	0.42
	GSF_6	0.00	1.00	-4.00,4.00	-1.17	-1.31	0.14
Non-conventional flux (Sec. III B)							
	$\Phi^{\text{HE}}/10^{-18}\text{GeV}^{-1}\text{sr}^{-1}\text{s}^{-1}\text{cm}^{-2}$	0.787	0.36	0.00,3.00	0.25	0.61	0.36
	$\log_{10}$ of pivot energy, $E^{\text{HE}}_{\text{break}}/\text{GeV}$	-	-	4.00,6.00	*4.25	*4.31	N/A, see caption
	$\Delta\gamma^{\text{HE}}_1$, tilt from -2.5	0.00	0.36	-2.00,2.00	2.62	2.39	0.23
	$\Delta\gamma^{\text{HE}}_2$, tilt from -2.5	0.00	0.36	-2.00,2.00	-0.22	0.10	0.21
Neutrino attenuation (Sec. III F)							
	ν attenuation	1.00	0.10	0.82, 1.18	0.12	-0.14	0.26
	$\bar{\nu}$ attenuation	1.00	0.10	0.82, 1.18	0.04	-0.02	0.06

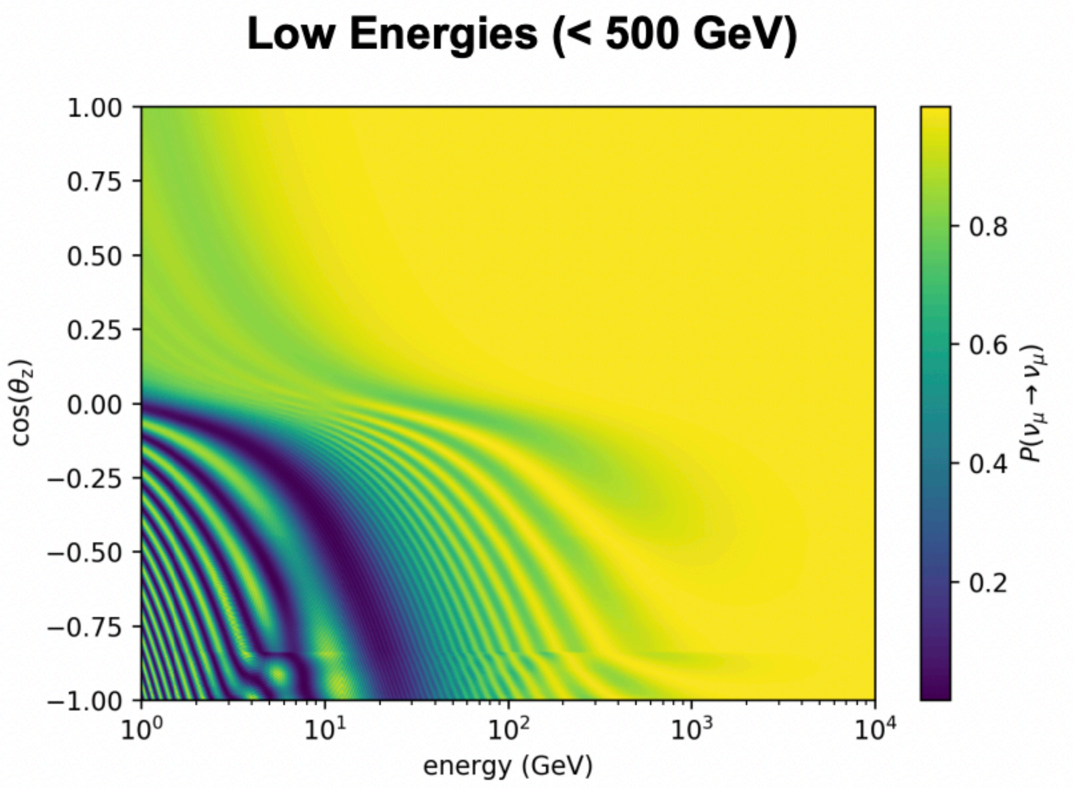
Choubey 2007



DeepCore Sterile Analysis



This Talk



> fast oscillations overlaid on standard three-flavor oscillation pattern

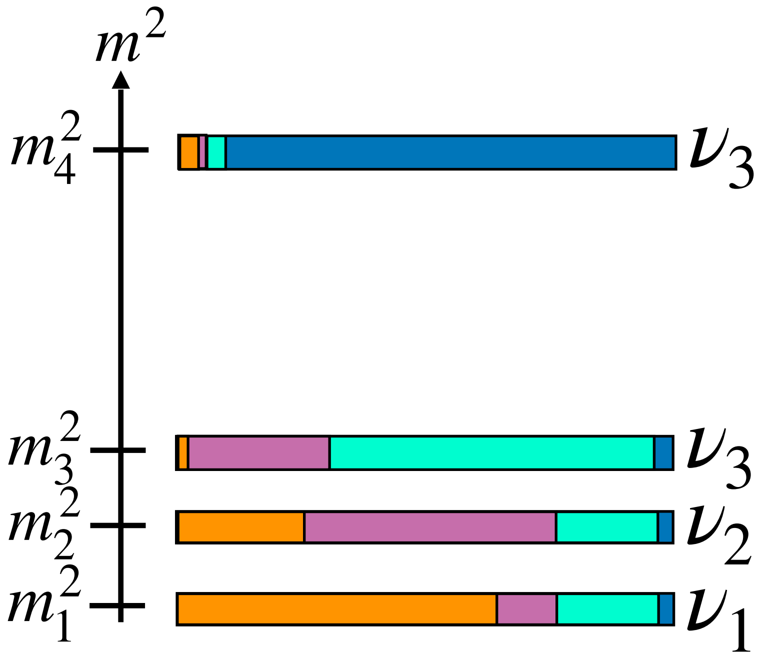
Credit: A. Trettin VLVnT 2021

The 3+1 Model

- Most common explanation: new eV-scale mass eigenstate
- Invisible Z width measurements mean this state must be mostly sterile
- Facilitates oscillations at shorter baseline than those involving active neutrinos

ν_e ν_μ ν_τ $+$ ν_s

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{\mu 1} & U_{\tau 1} & U_{s1} \\ U_{e2} & U_{\mu 2} & U_{\tau 2} & U_{s2} \\ U_{e3} & U_{\mu 3} & U_{\tau 3} & U_{s3} \\ U_{e4} & U_{\mu 4} & U_{\tau 4} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$



(Normal Ordering)

Tension in Global Fits

$$P(\nu_\mu \to \nu_e) = 4|U_{e4}|^2|U_{\mu4}|^2\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$

SBL Accelerator

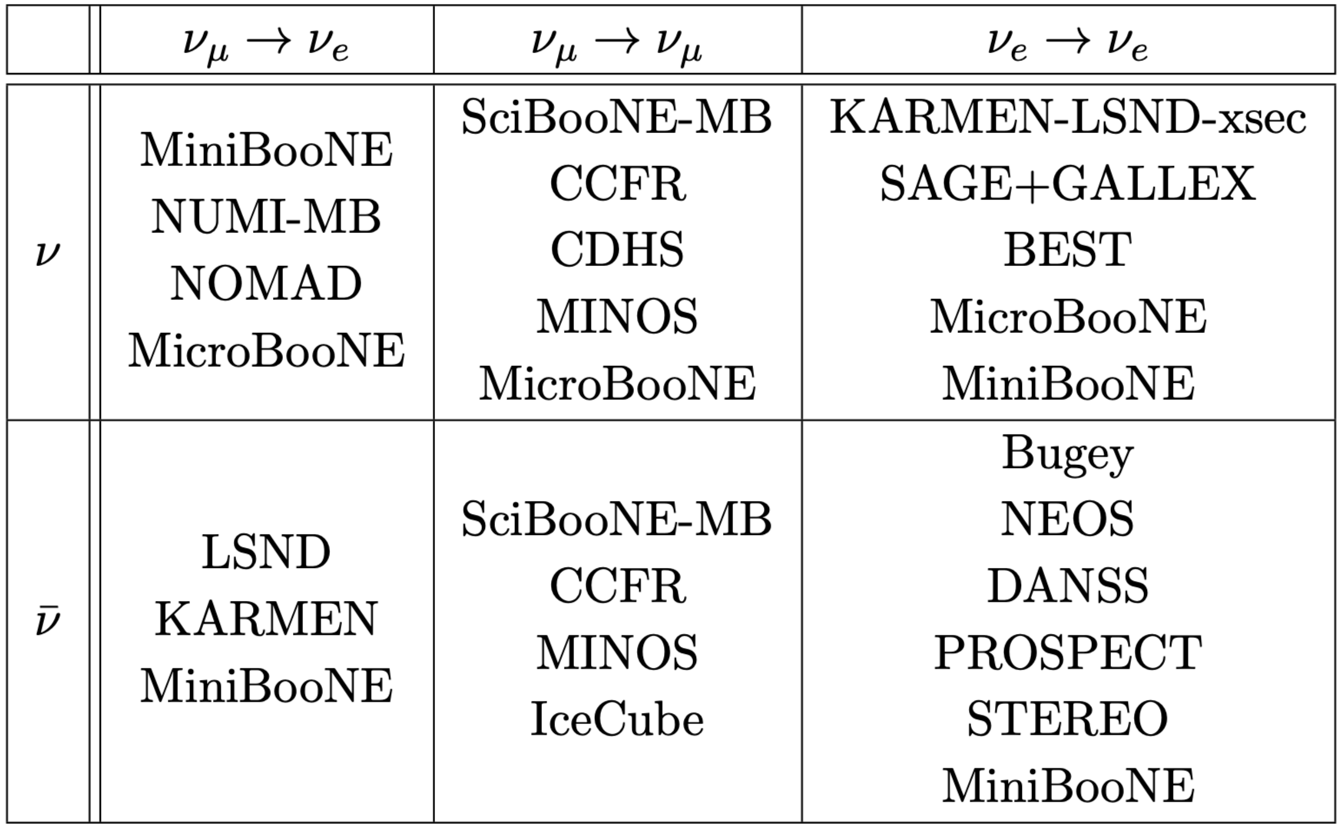
$$P(\nu_e \to \nu_e) = 1 - 4|U_{e4}|^2(1-|U_{e4}|^2)\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$

SBL Gallium/Reactor

$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)\sin^2\left(1.27\Delta m^2\frac{L}{E}\right)$$

LBL Accelerator/Atmospheric

Hardin+ 2022



	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
ν	MiniBooNE NUMI-MB NOMAD MicroBooNE	SciBooNE-MB CCFR CDHS MINOS MicroBooNE	KARMEN-LSND-xsec SAGE+GALLEX BEST MicroBooNE MiniBooNE
$\bar{\nu}$	LSND KARMEN MiniBooNE	SciBooNE-MB CCFR MINOS IceCube	Bugey NEOS DANSS PROSPECT STEREO MiniBooNE

Tension in Global Fits

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e})\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

SBL Accelerator

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{ee})\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

SBL Gallium/Reactor

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu})\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

LBL Accelerator/Atmospheric

Hardin+ 2022

	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\mu$	$\nu_e \to \nu_e$
ν	MiniBooNE NUMI-MB NOMAD MicroBooNE	SciBooNE-MB CCFR CDHS MINOS MicroBooNE	KARMEN-LSND-xsec SAGE+GALLEX BEST MicroBooNE MiniBooNE
$\bar{\nu}$	LSND KARMEN MiniBooNE	SciBooNE-MB CCFR MINOS IceCube	Bugey NEOS DANSS PROSPECT STEREO MiniBooNE

Tension in Global Fits

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{\mu e})\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

SBL Accelerator

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{ee})\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

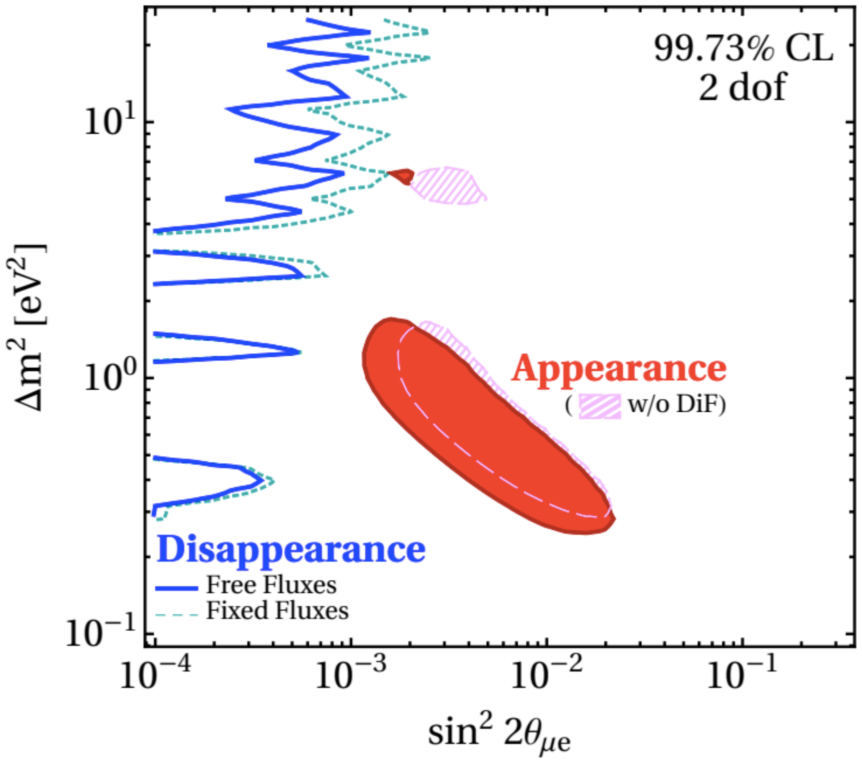
SBL Gallium/Reactor

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu})\sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

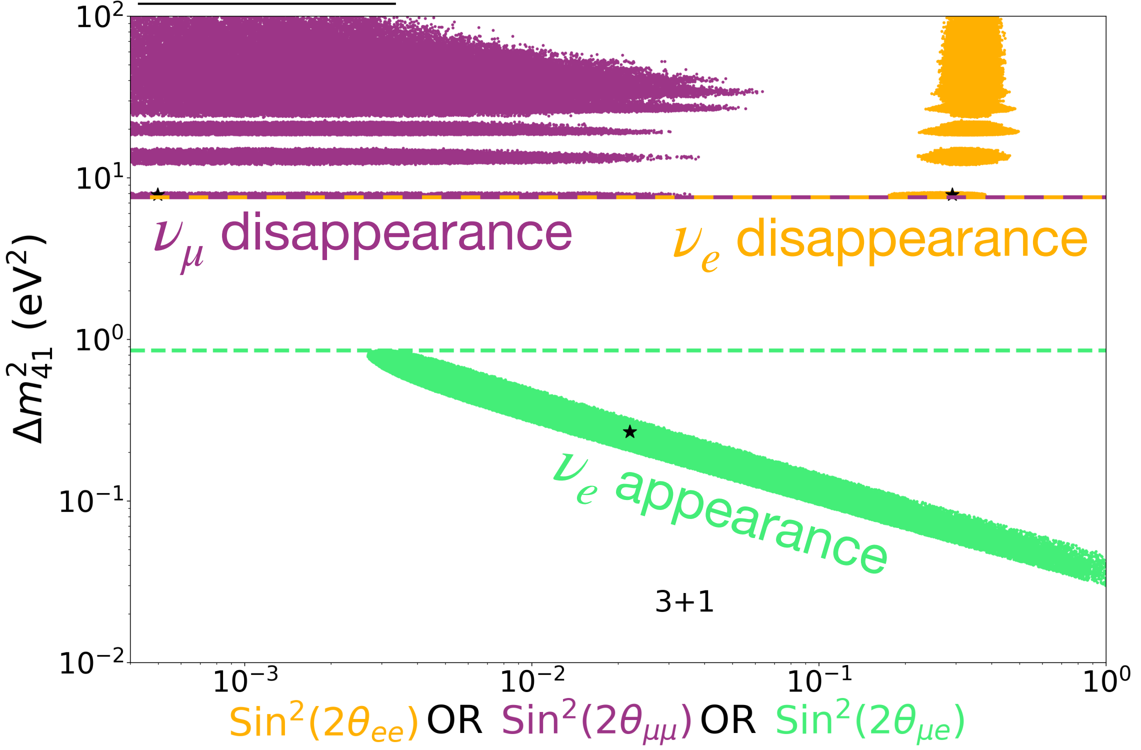
LBL Accelerator/Atmospheric

Lack of clear muon neutrino disappearance in tension with electron neutrino appearance/disappearance anomalies at the 4.9σ level (Hardin+ 2022)

Dentler+ 2018



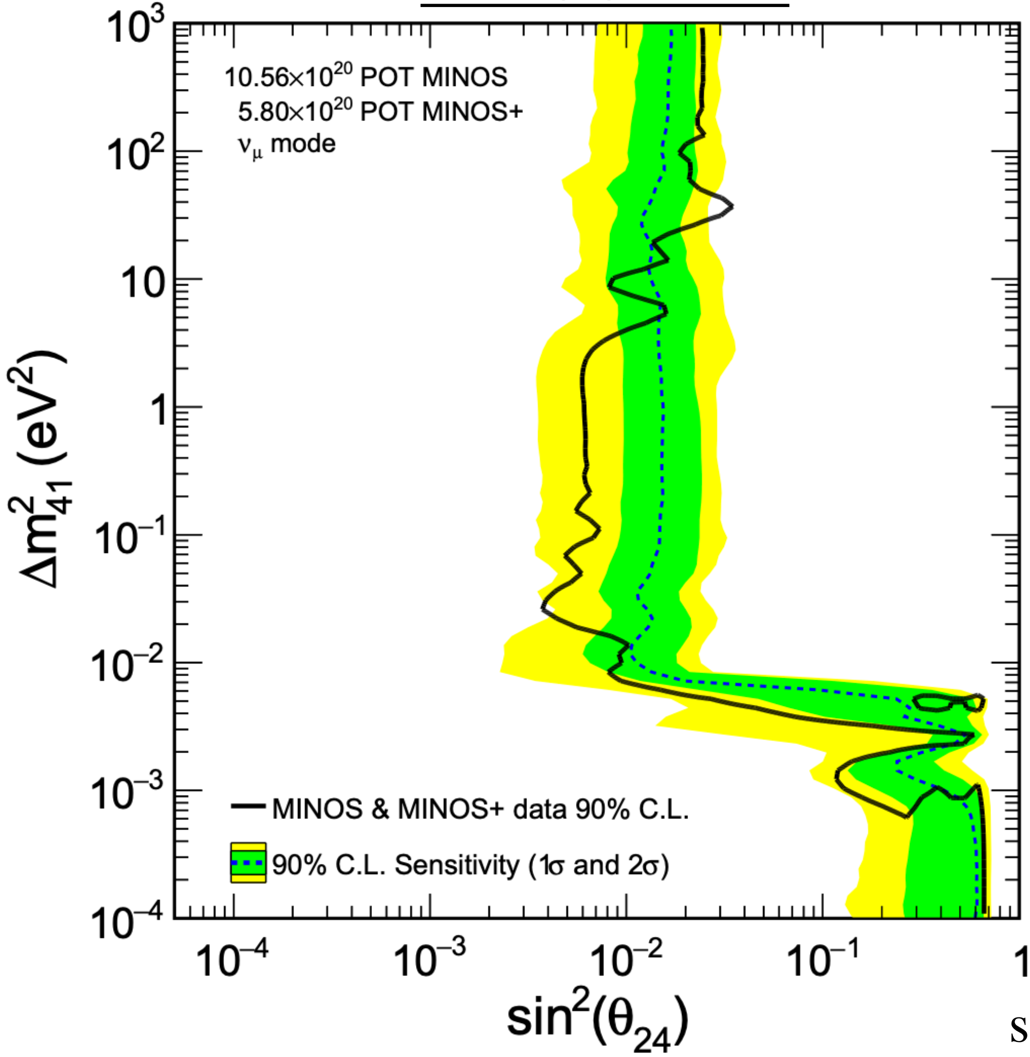
Hardin+ 2022



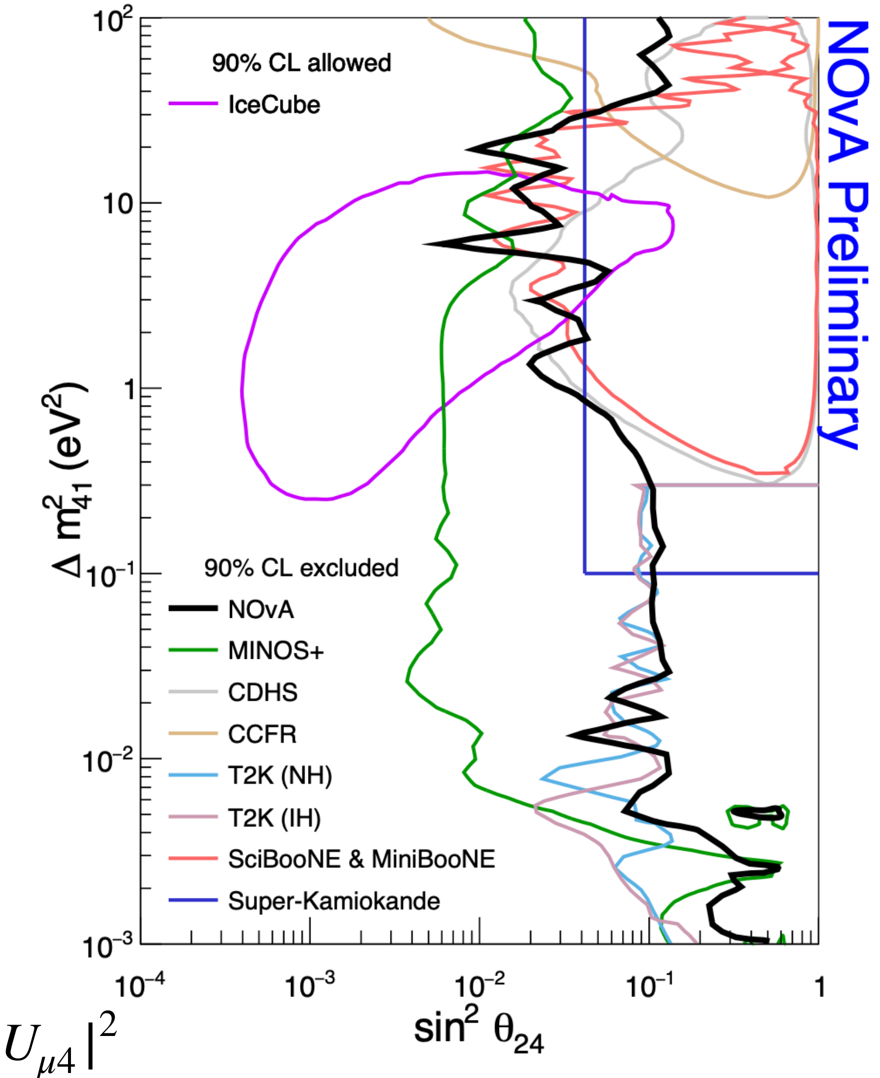
Muon Neutrino Disappearance

- Strongest constraints on ν_μ disappearance at $\Delta m^2 \sim 1\ \mathrm{eV}^2$ typically come from long baseline accelerator experiments
- **Can we explore this channel in a complementary way?**

MINOS 2017



A. Sutton NuFACT 2023



$\sin^2\theta_{24} \approx |U_{\mu 4}|^2$