

Searching for Quantum Decoherence in IceCube

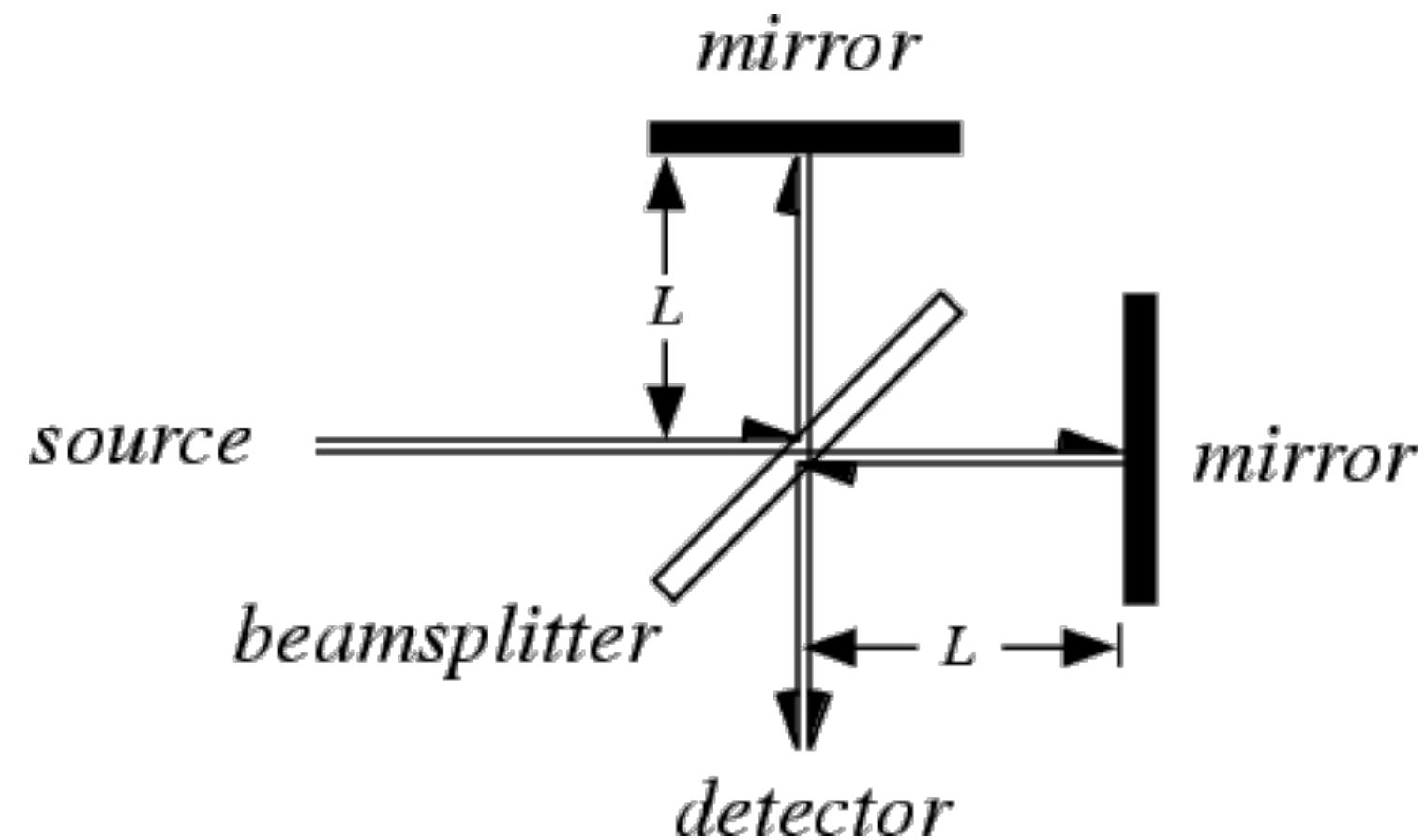
Tanvi Krishnan (tkrishnan@g.harvard.edu)
on behalf of the IceCube Collaboration
TeVPA 2026 (August 31, 2026)



How does spacetime behave at the Planck scale?

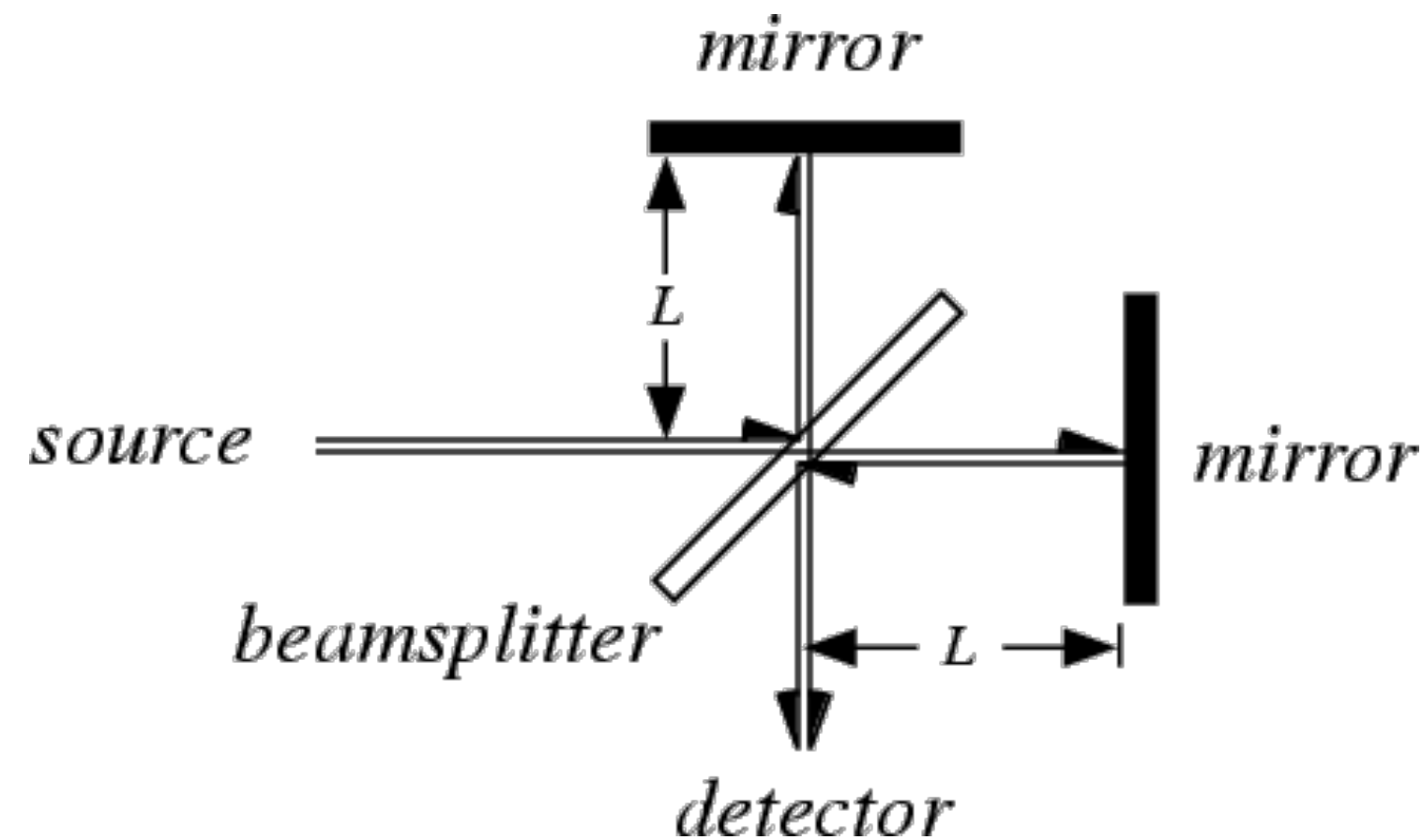
Neutrinos as interferometers

Interferometry to
understand structure of
vacuum (search for ether):

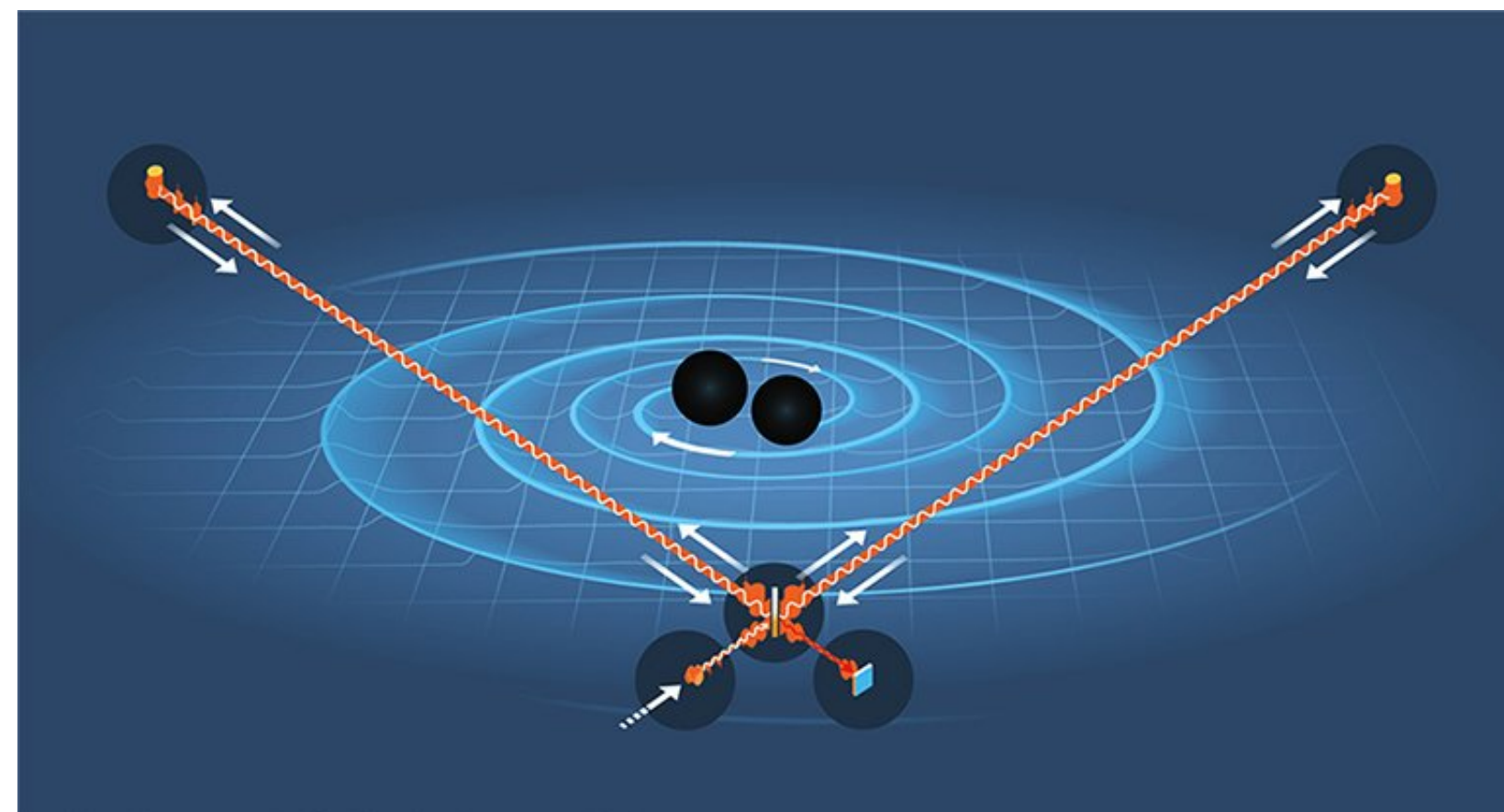


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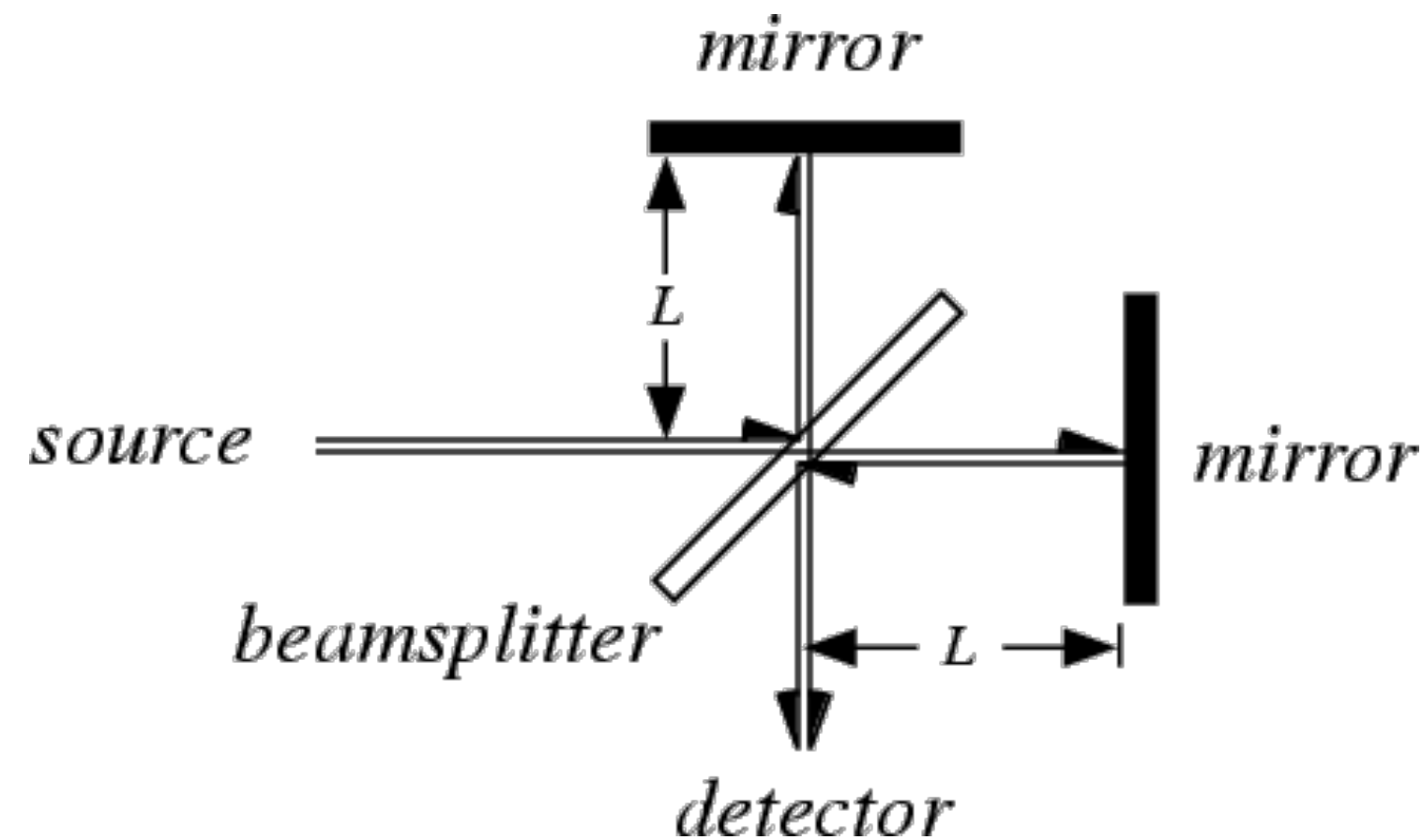
Gravitational wave
interferometry to
understand contraction of
spacetime:



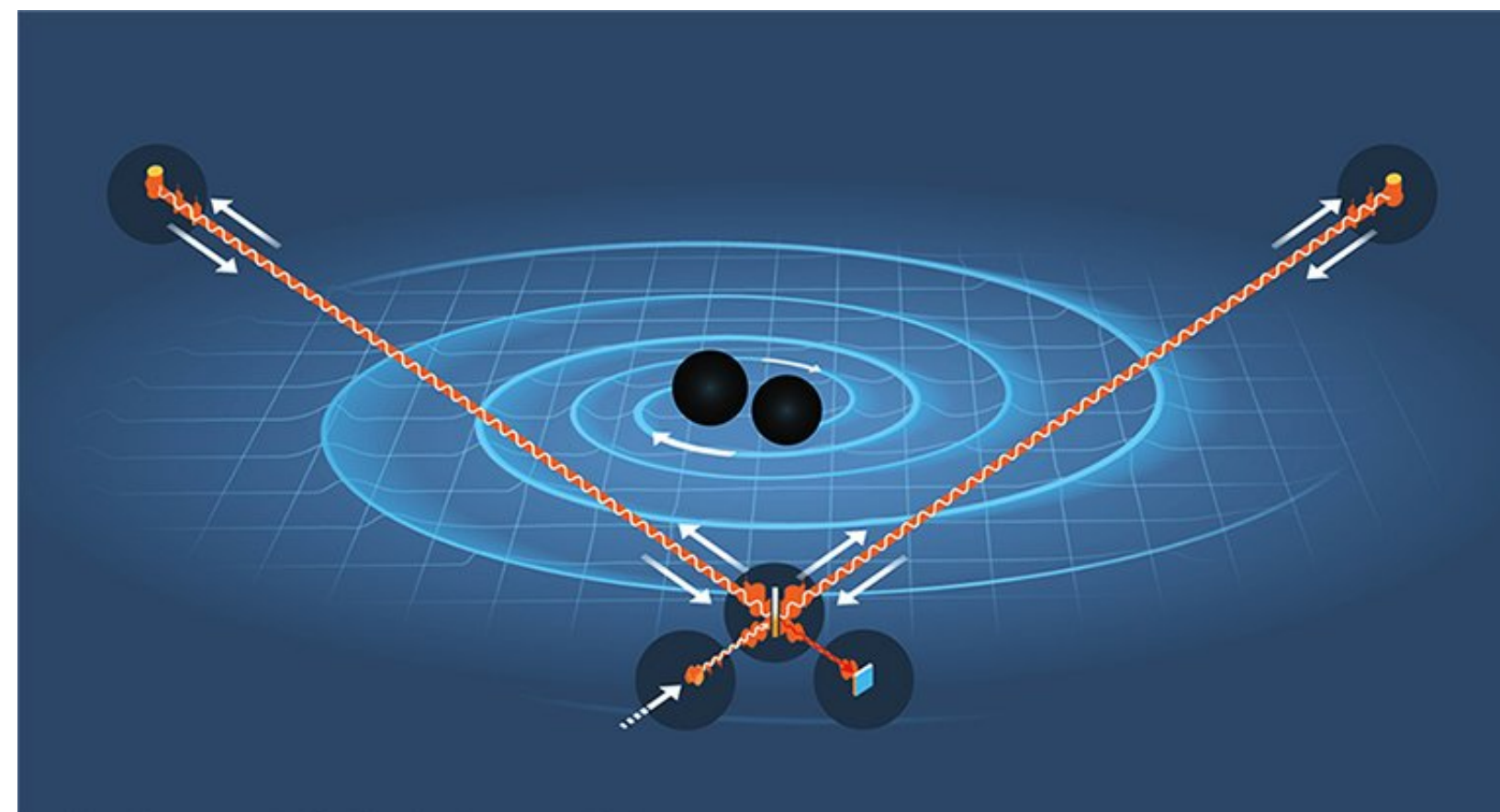
Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrinos as interferometers

Interferometry to understand structure of vacuum (search for ether):

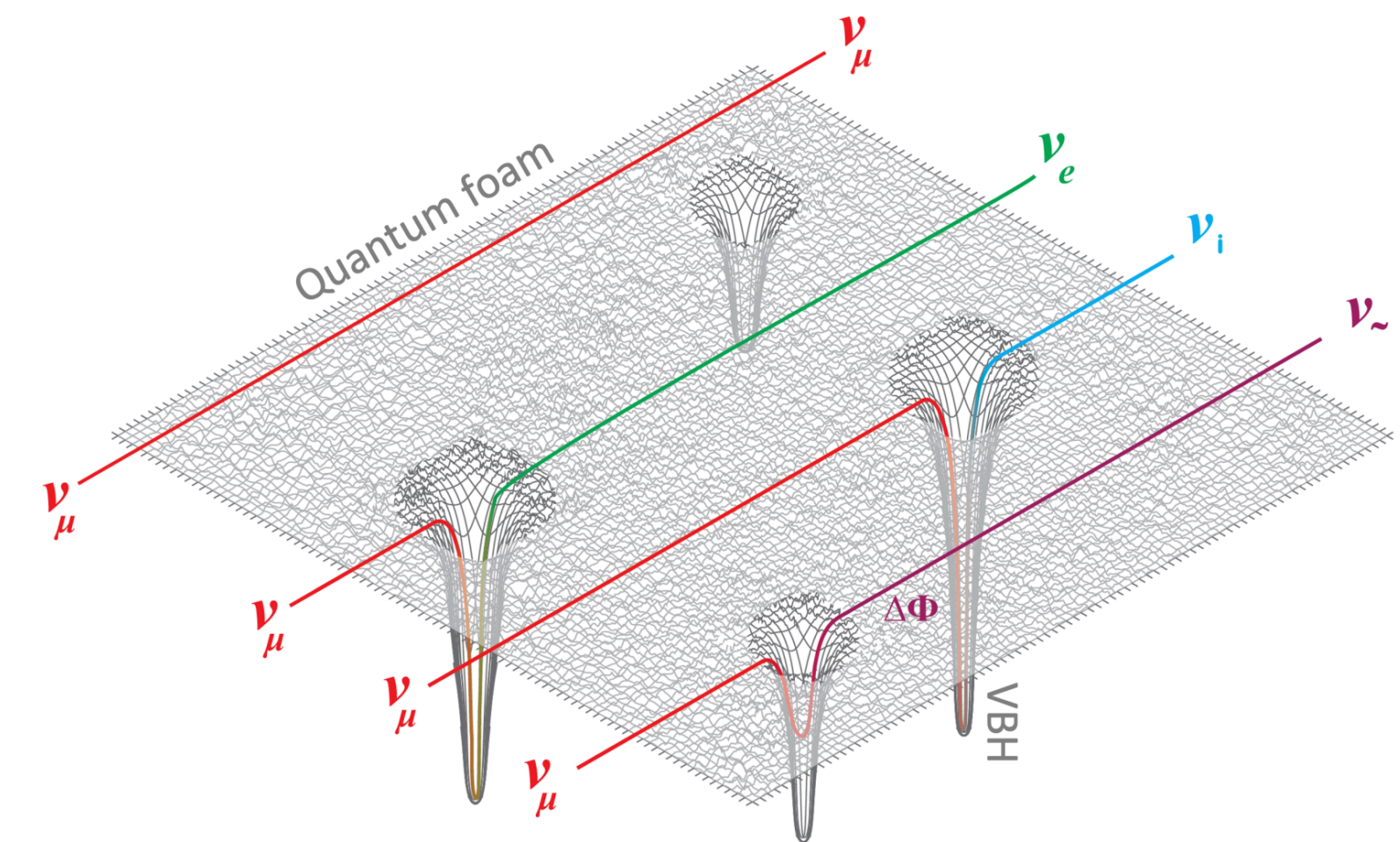


Gravitational wave interferometry to understand contraction of spacetime:



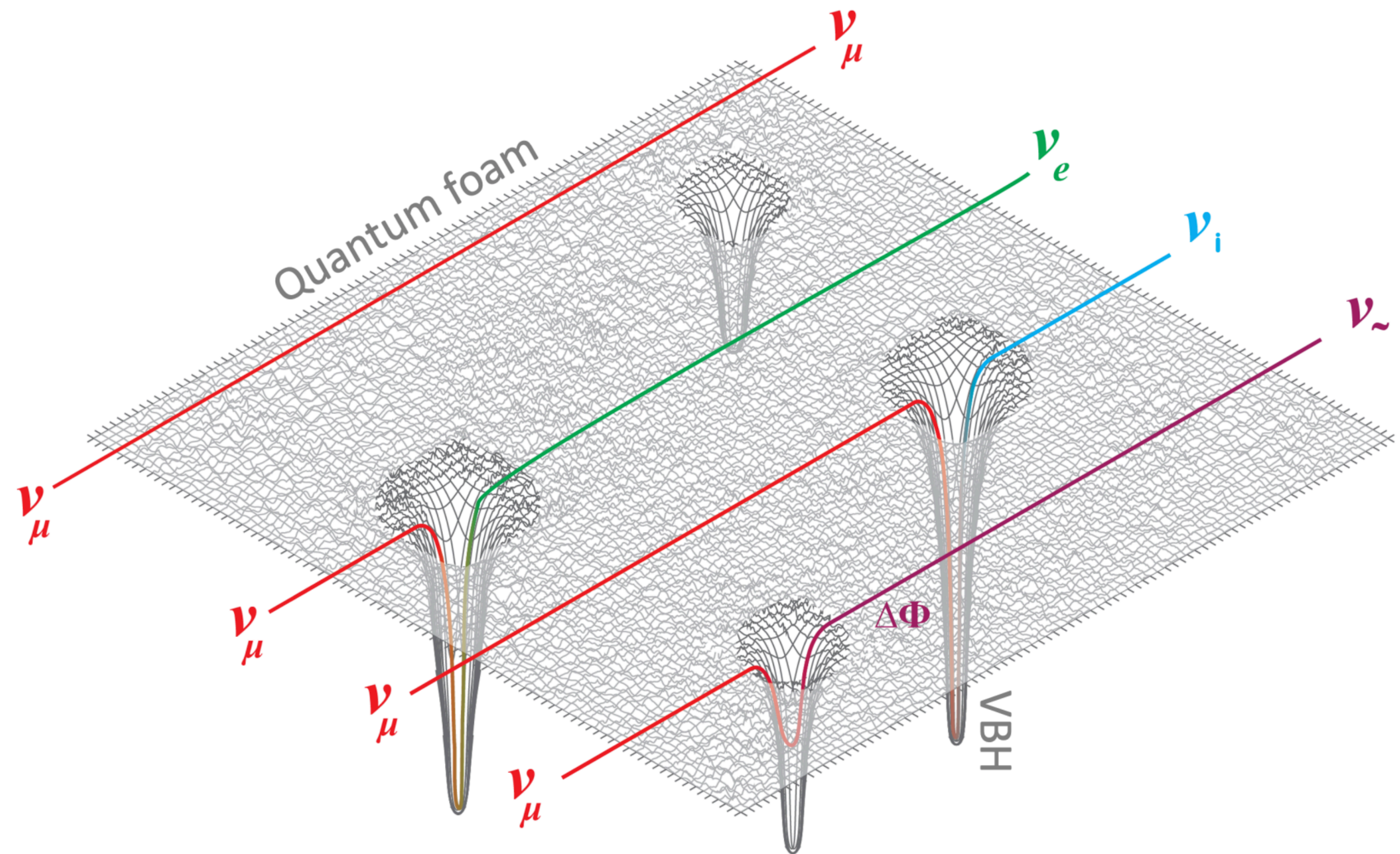
Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrino interferometry to measure small-scale spacetime structure



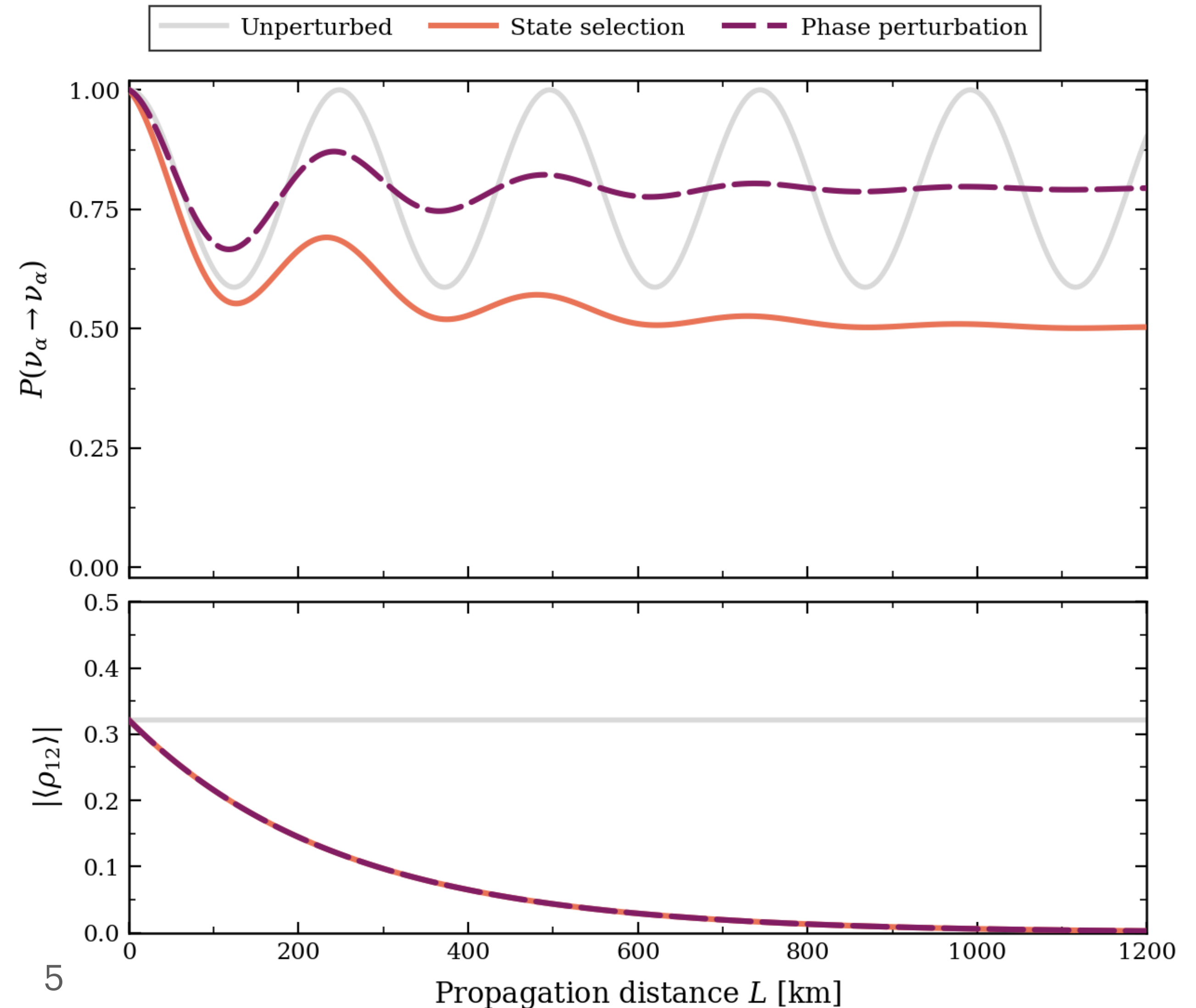
Decoherence Theory

- Neutrinos can maintain quantum coherence over large distances
- May probe Planck-scale spacetime fluctuations predicted by quantum-gravity models
 - i.e. absorption and re-radiation by virtual black holes (VBHs)



Decoherence Theory

- Two effective interaction modes considered:
 - State selection
 - Phase perturbation
- Can perturb flavor distribution from standard expectation



How do we model this?

Lindblad Master Equation:

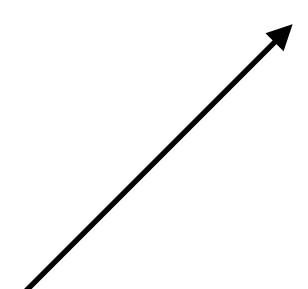
$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho]$$

How do we model this?

Lindblad Master Equation:

$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho]$$

Standard unitary
time evolution



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Lindblad Master Equation:

$$\dot{\rho} = -i[H, \rho] - \mathcal{D}[\rho]$$

Standard unitary
time evolution

Contributions from
quantum gravity

How do we model this?

Decoherence Superoperator:

$$\mathcal{D}(\rho) = (D_{\mu\nu} \rho^\nu) b^\mu$$

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$$D_{\text{state selection}} = \text{diag}(0, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma)$$

$$D_{\text{phase perturbation}} = \text{diag}(0, \Gamma, \Gamma, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0)$$

How do we model this?

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$$D_{\text{phase perturbation}} = \text{diag}(0, \Gamma, \Gamma, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0)$$

$$\Gamma(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{E_0} \right)^n$$

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Decoherence Superoperator:

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$$D_{\text{state selection}} = \text{diag}(0, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma)$$

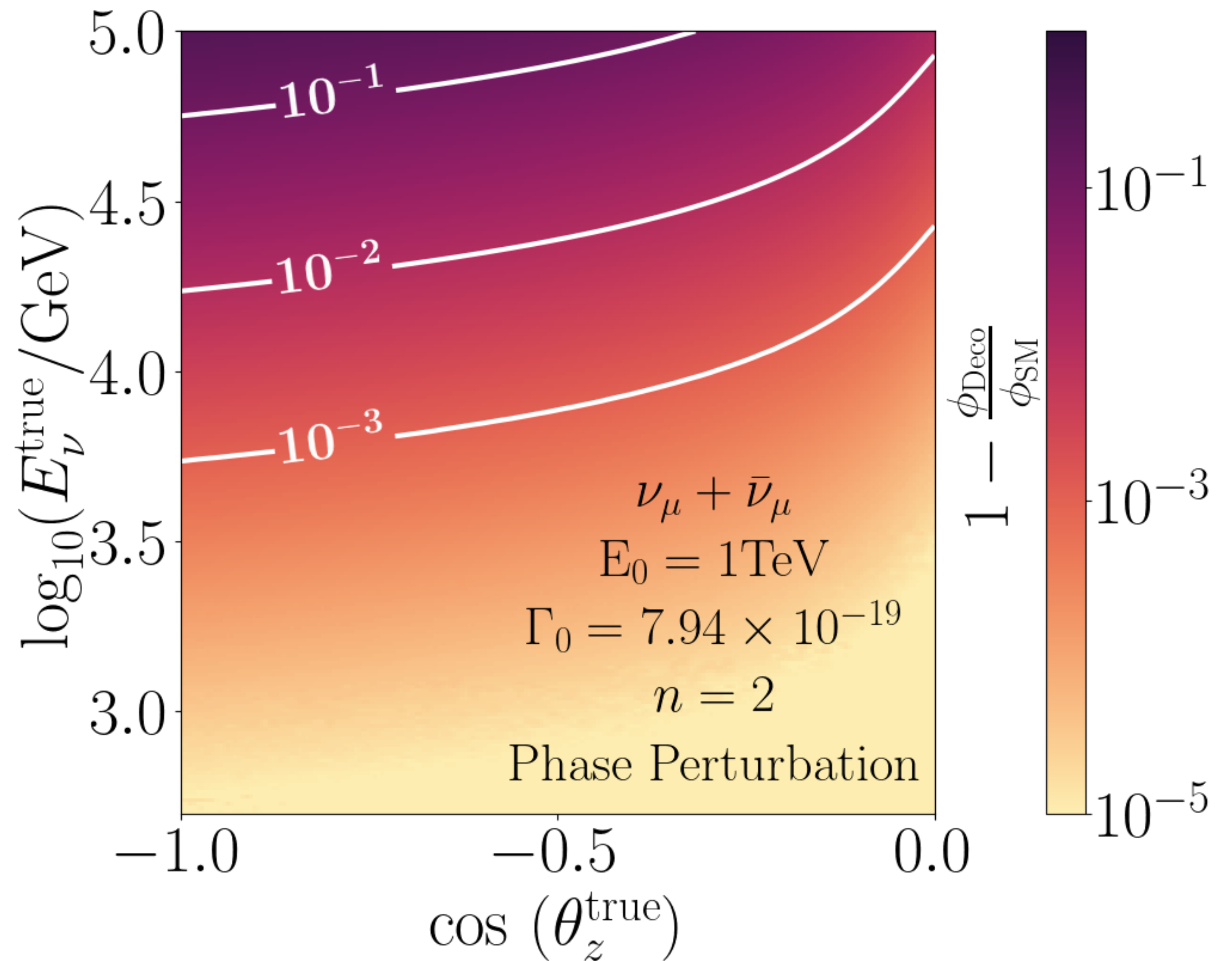
$$D_{\text{phase perturbation}} = \text{diag}(0, \Gamma, \Gamma, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0)$$

$$\Gamma(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{E_0} \right)^n$$

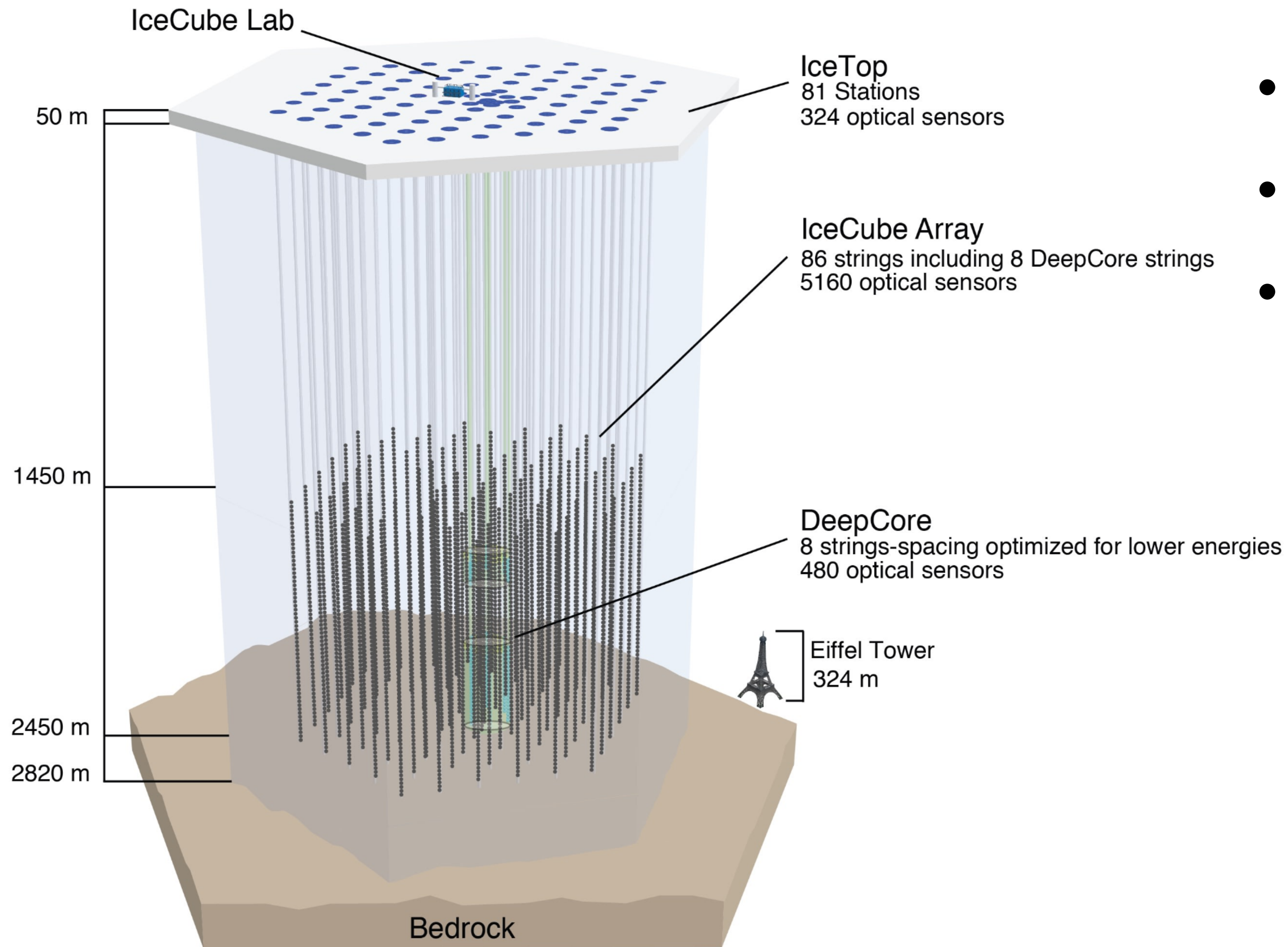
n = Energy scaling
 Γ_0 = Decoherence strength at $E_0 = 1$ TeV

Decoherence Oscillograms

- Expected amount of ν_μ disappearance across parameter space

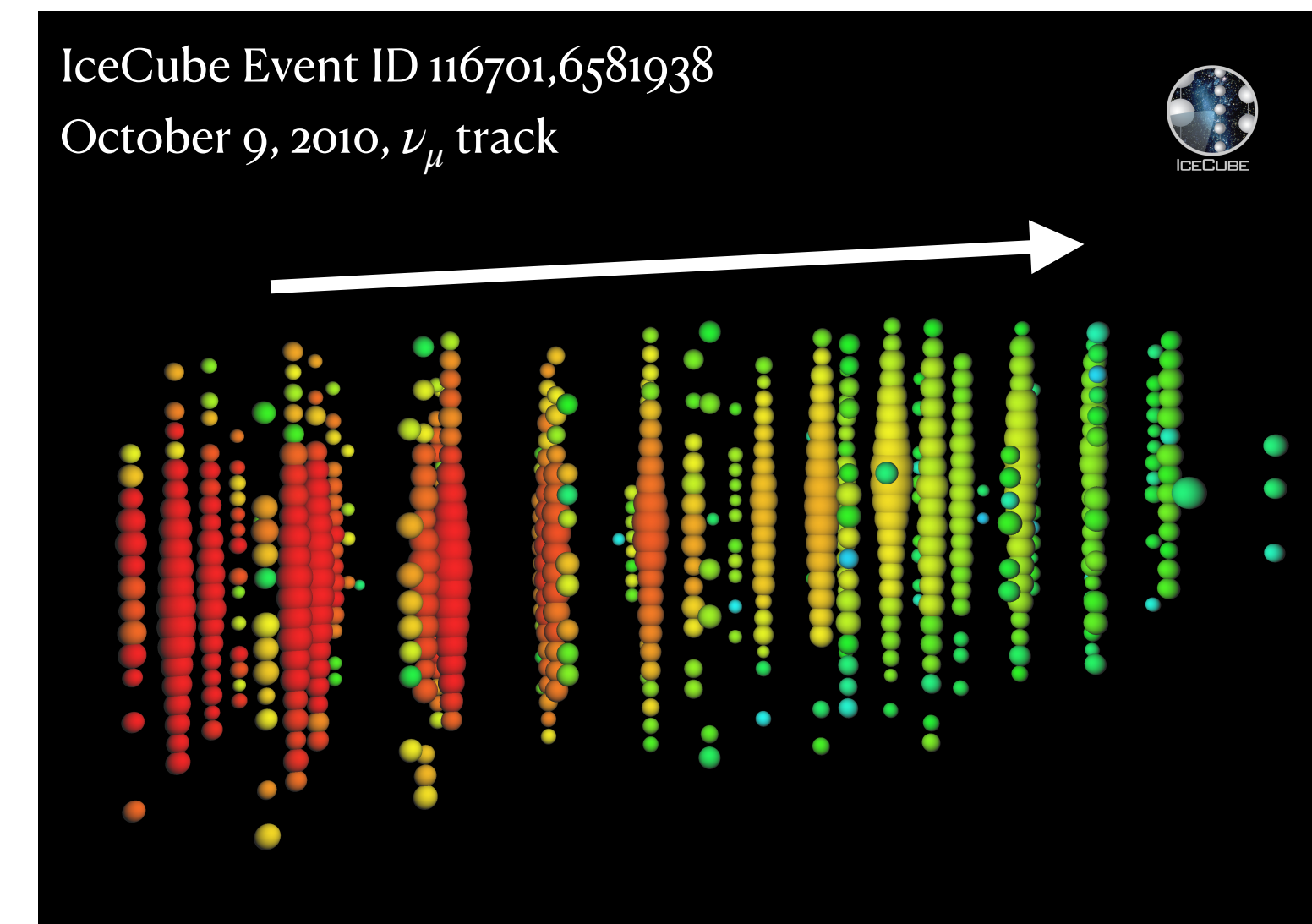


The IceCube Neutrino Observatory



Credit: IceCube Collaboration

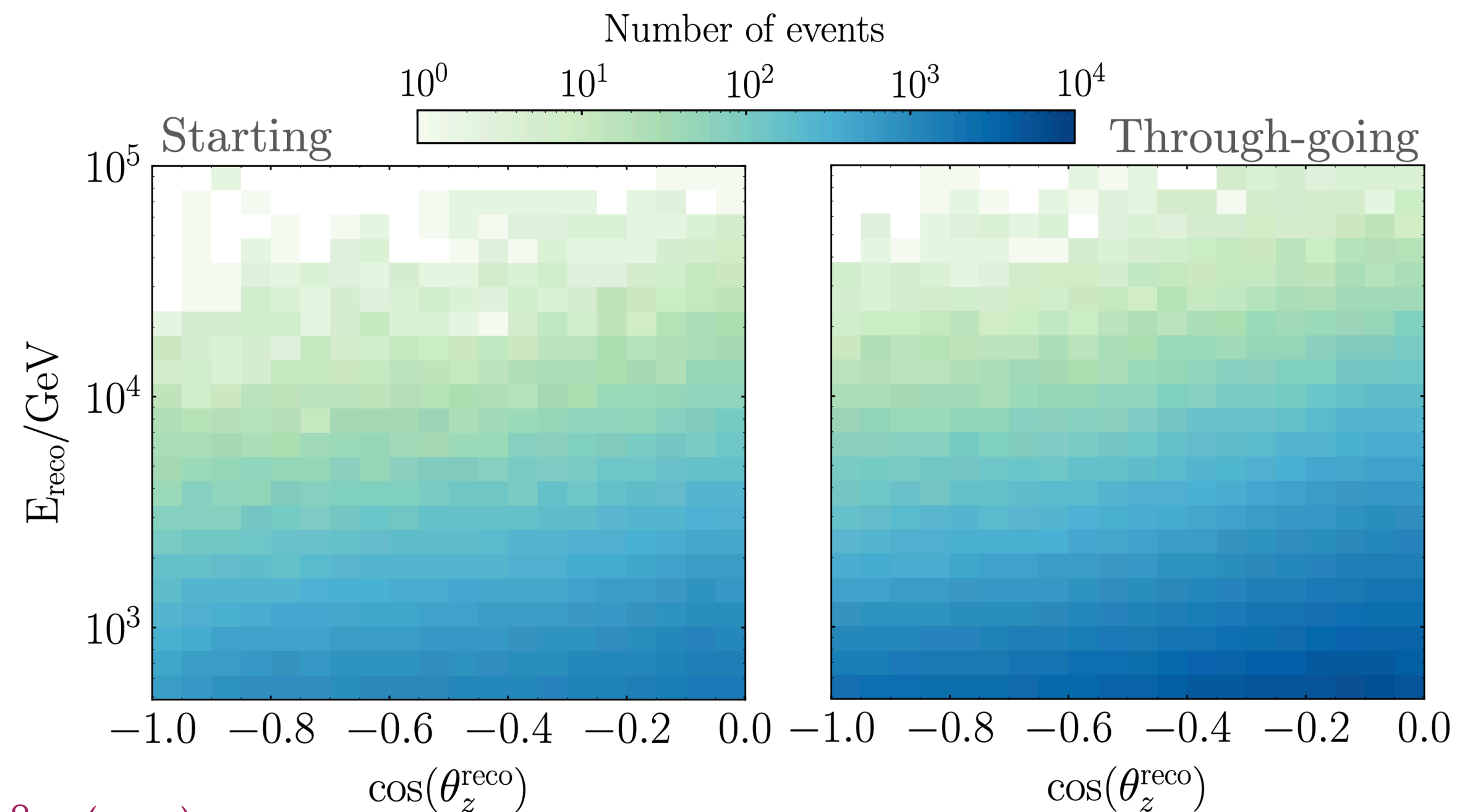
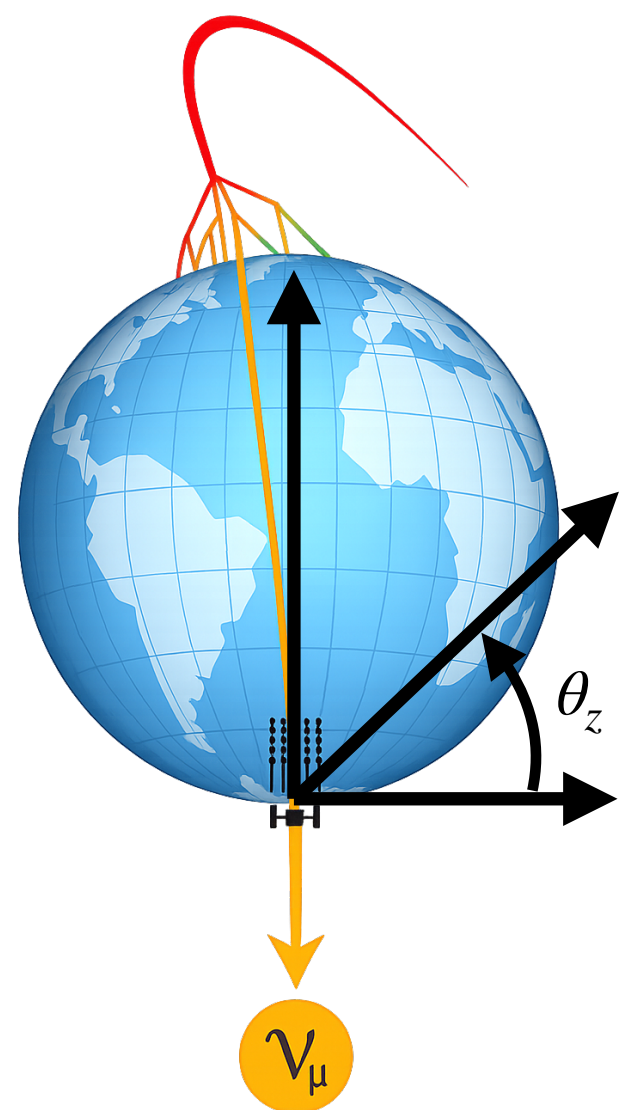
- Cubic-kilometer Cherenkov detector
- Located at the South Pole
- 5,160 Digital Optical Modules (DOMs) observe Cherenkov radiation in ice



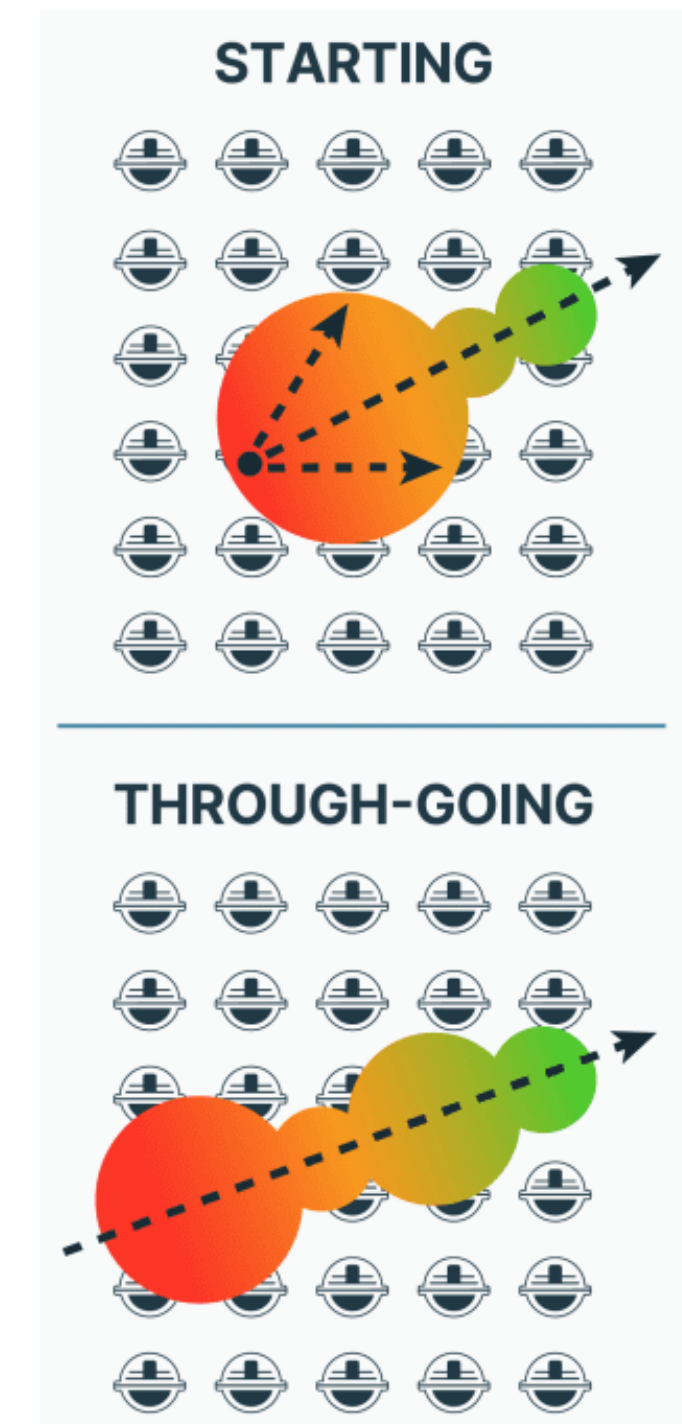
Credit: IceCube Collaboration

Analysis binning

- Uses 10.7 years of atmospheric neutrino tracks in IceCube
- Data + MC events are binned into 20 zenith, 22 energy and 2 morphology bins
- Uses GollumFit, an open-source framework for binned-likelihood neutrino telescope analyses
 - Perform a simultaneous likelihood fit of the decoherence parameters and 36 nuisance parameters to the data

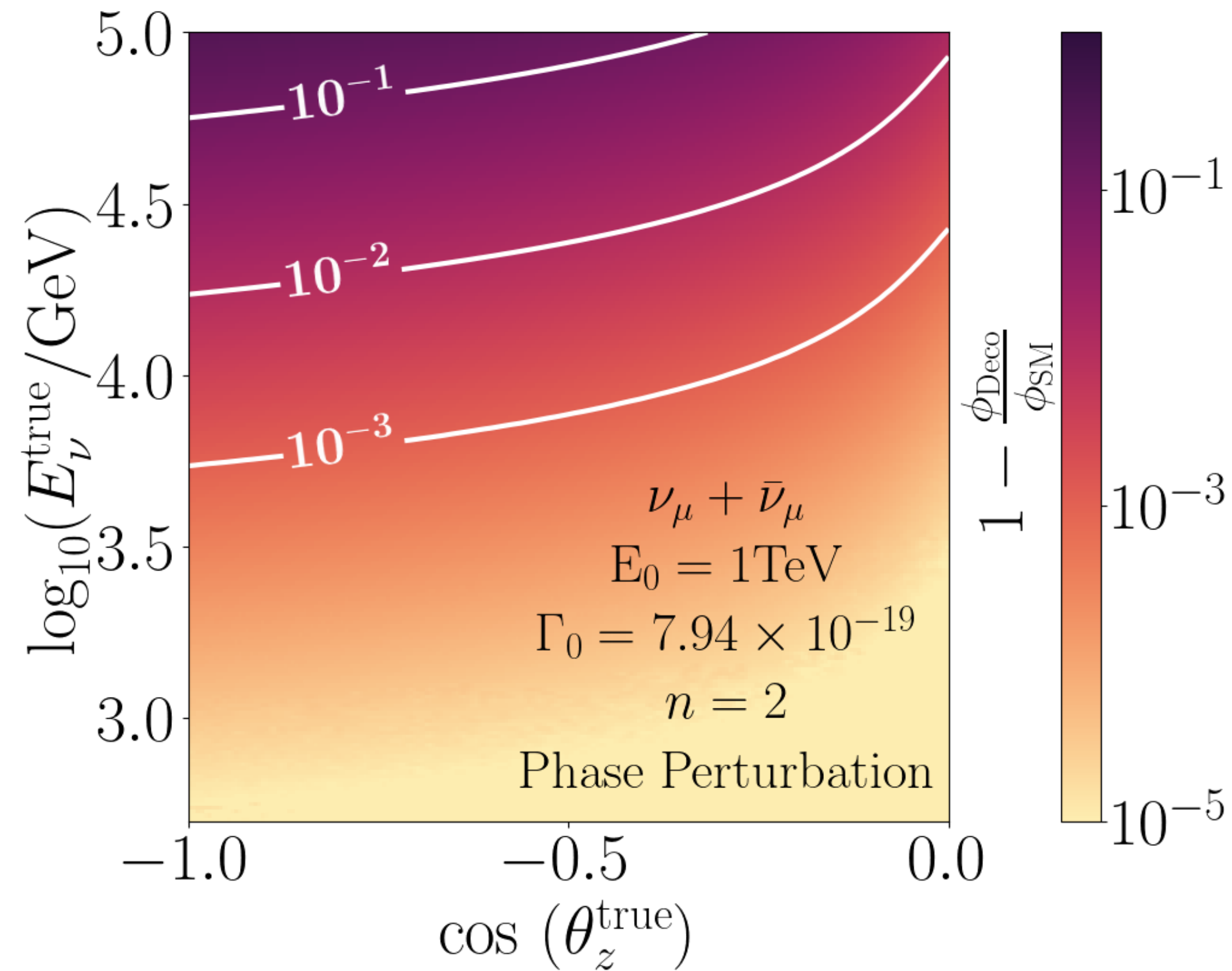


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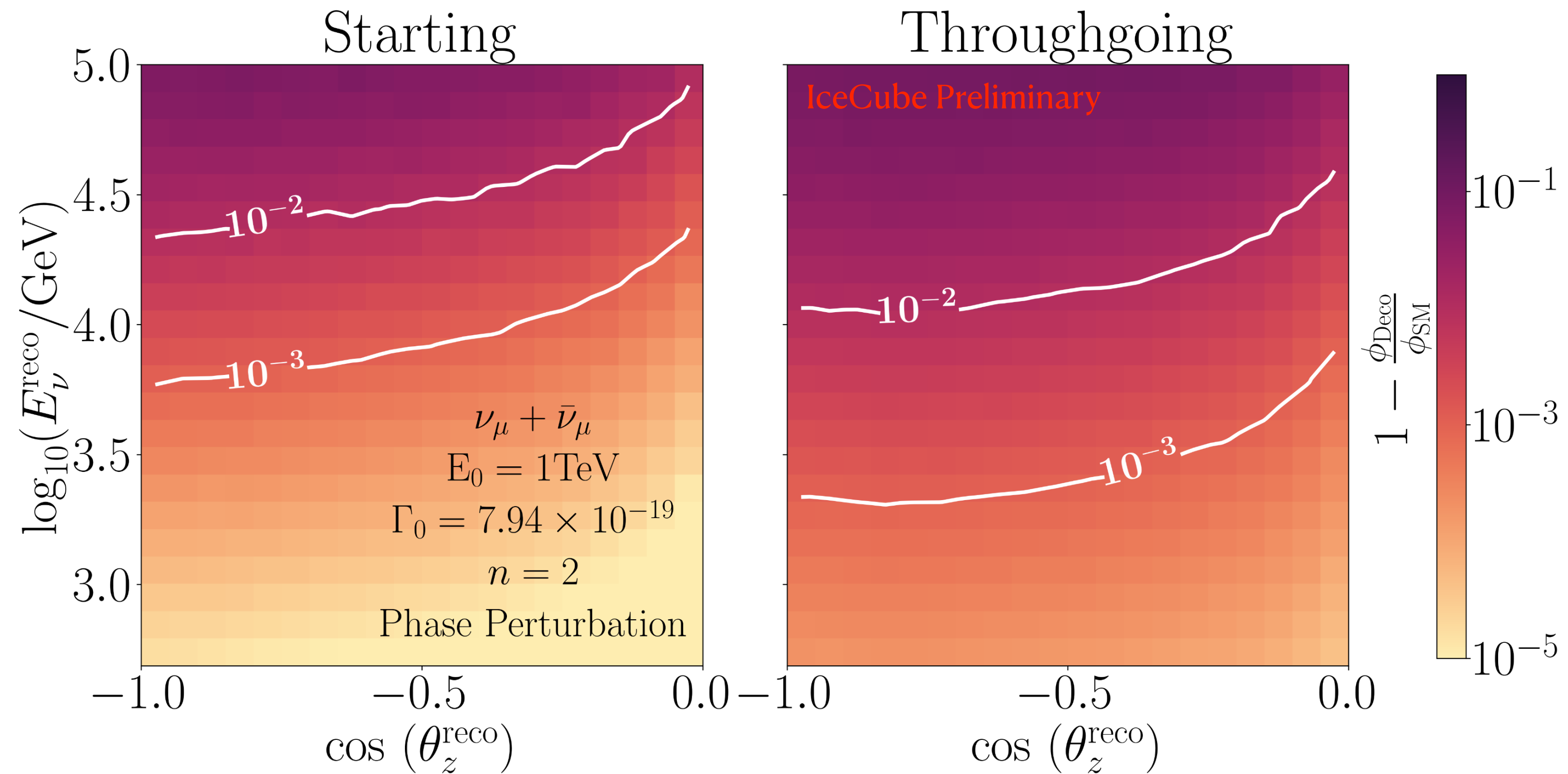


Reconstructed Oscillograms

Truth signature:

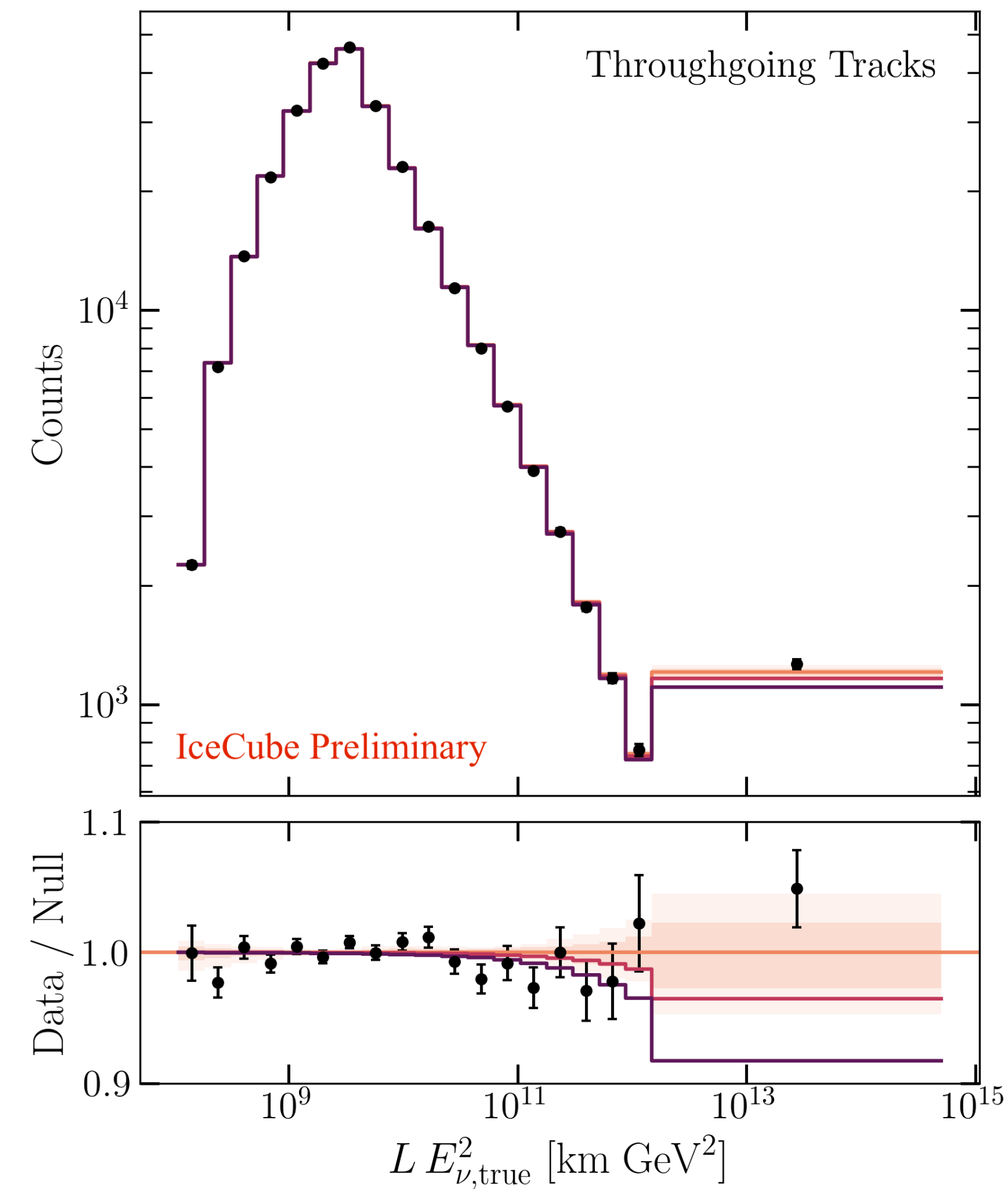
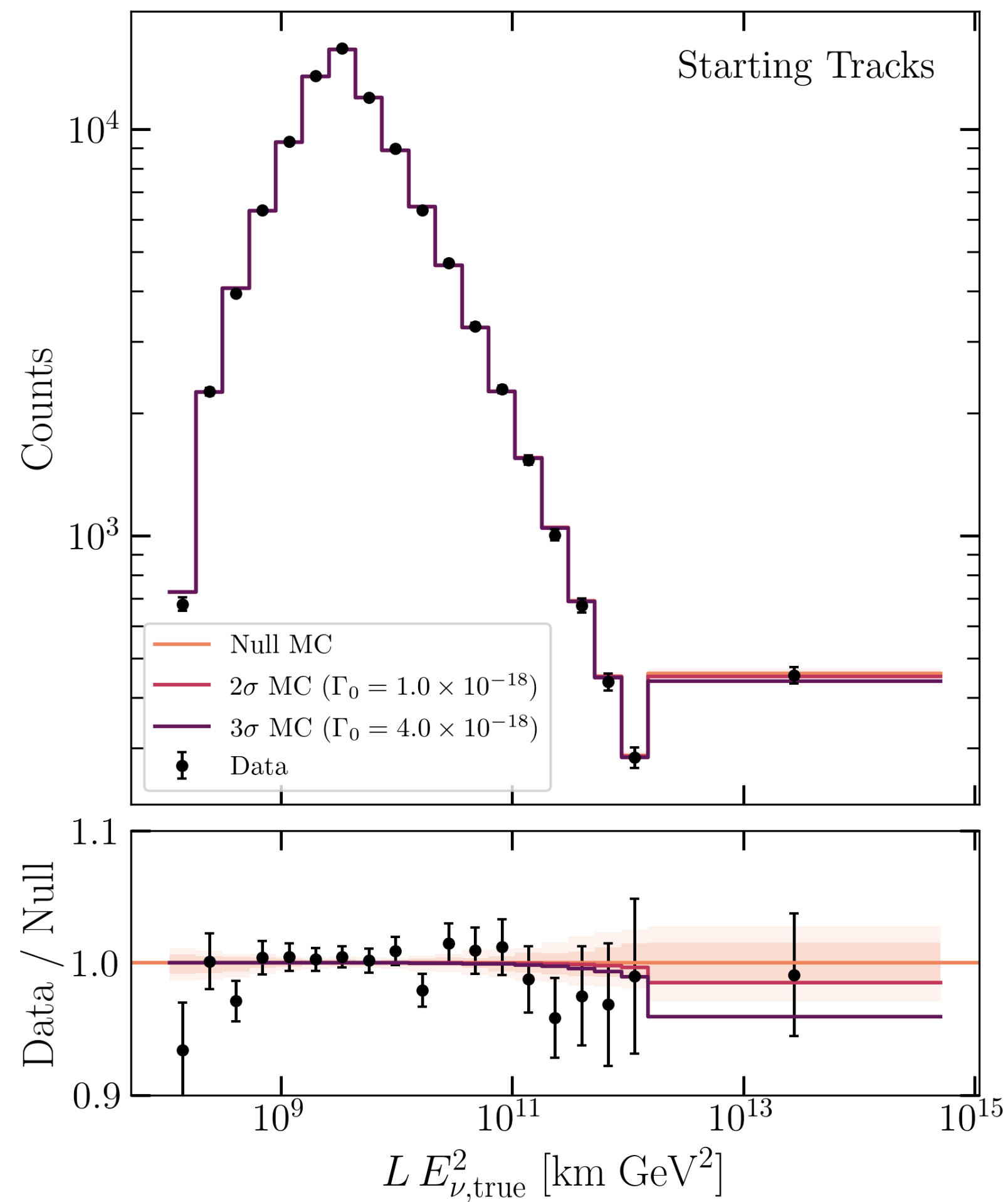


Reconstructed signature:



No evidence of Neutrino Decoherence

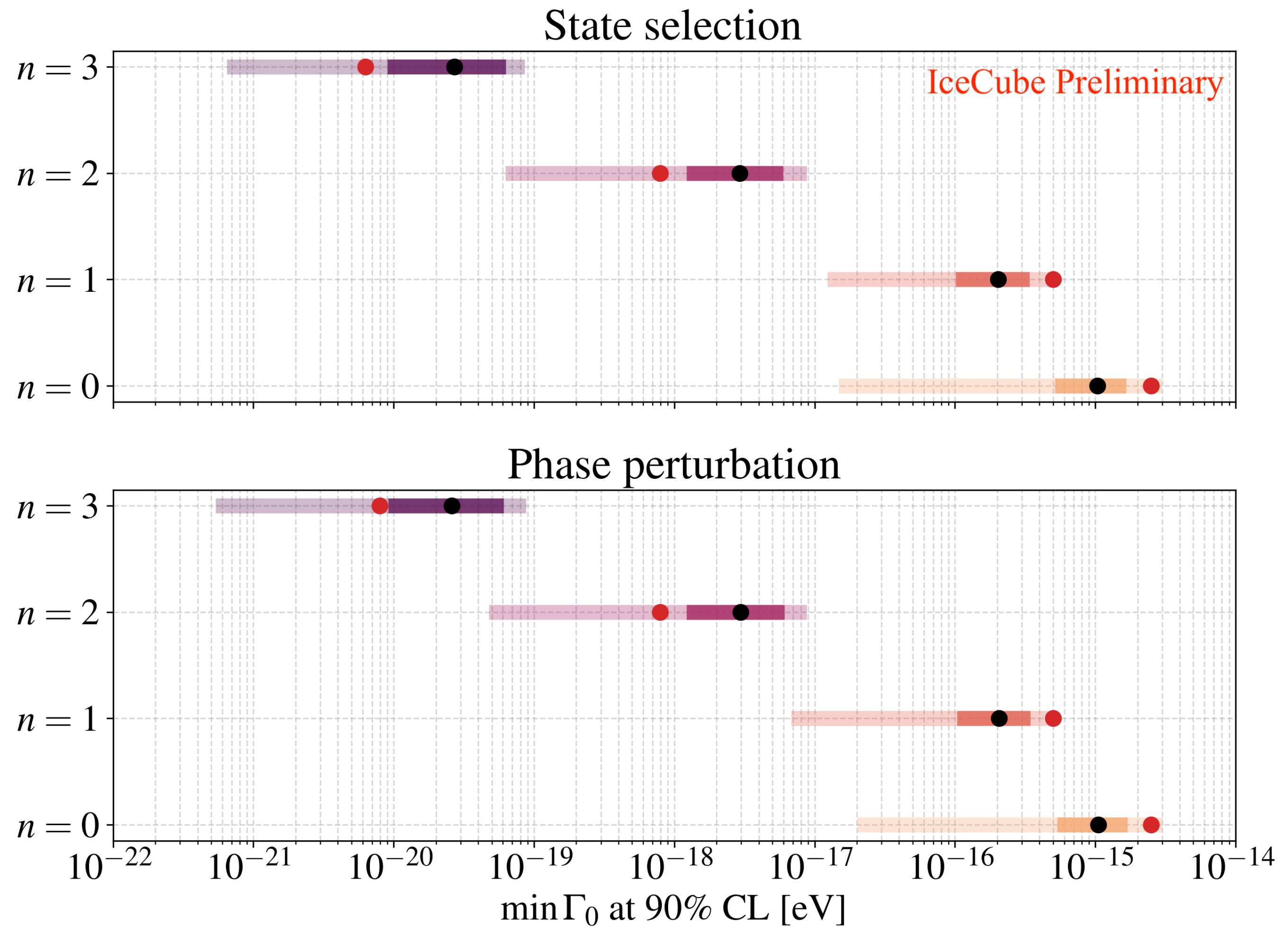
- No significant deviation from the Standard Model is observed
- Data favor the null (no-decoherence) hypothesis



No evidence of Neutrino Decoherence

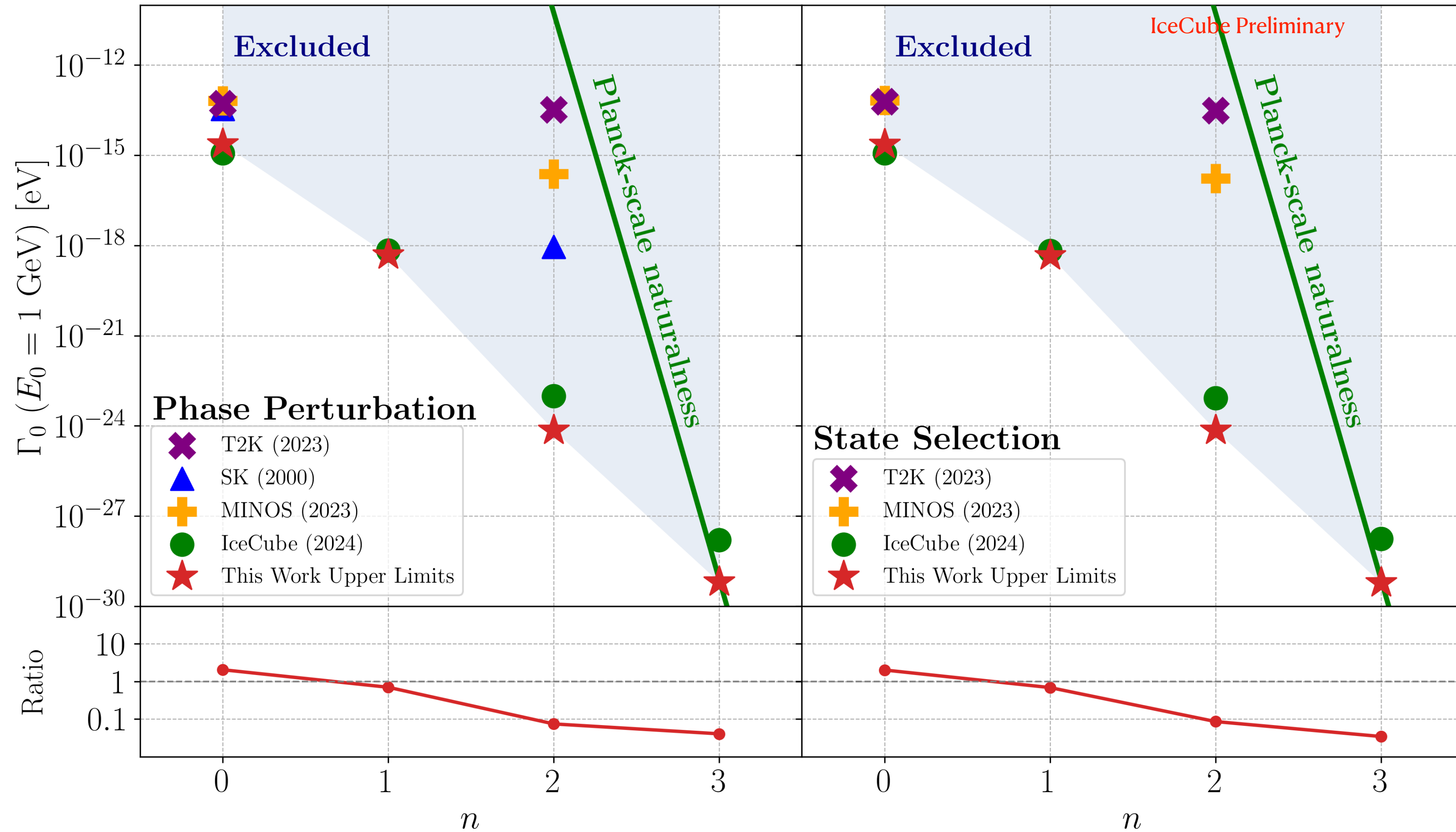
- 90% CL upper limits (red) are consistent with expected sensitivity from null pseudoexperiments (shaded bands)

n	State Selection Γ_{90} (eV)	Phase Perturbation Γ_{90} (eV)
0	2.36×10^{-15}	2.41×10^{-15}
1	4.58×10^{-16}	4.80×10^{-16}
2	7.26×10^{-19}	7.26×10^{-19}
3	6.05×10^{-21}	6.37×10^{-21}



Comparison with Past Results

- Over 10x improvement over previous IceCube limits for $n = 2$ and 3
- Sensitivity extends beyond simple Planck-suppressed expectation for $n = 3$
 - By naturalness, expect $\mathcal{O}(L_P)$ coherence length for neutrinos with energies $\mathcal{O}(E_P)$



[IceCube Collaboration. Nature Physics 20, 913-920 \(2024\)](#)

[E. Lisi, A. Marrone, and D. Montanino. Phys. Rev. Lett. 85, 1166 \(2000\)](#)

[A. L. G. Gomes, R. A. Gomes, and O. L. G. Peres. J. High Energ. Phys. 2023, 35 \(2023\).](#)

Conclusion

- This analysis is a follow-up to the prior IceCube 7.6 year Decoherence search
- Uses the same selection and fitting techniques as the recent IceCube eV-scale sterile search and nearly unchanged systematics
- Sets world-leading constraints on VBH-induced neutrino decoherence
- Substantially narrows viable parameter space for Planck-scale Markovian decoherence effects in neutrino oscillations

Speaker acknowledges support from the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research, Department of Energy Computational Science Graduate Fellowship

The background of the slide is a composite image. The upper portion shows a dark night sky filled with stars and the Milky Way galaxy, which appears as a bright, hazy band of light. Below the sky, a green aurora borealis (northern lights) is visible, stretching horizontally across the frame. In the foreground, a snowy, flat landscape is shown. On the left side of the landscape, there is a structure illuminated with bright red lights, possibly a research station or a small building. Several small, dark flags or markers are visible in the snow across the foreground.

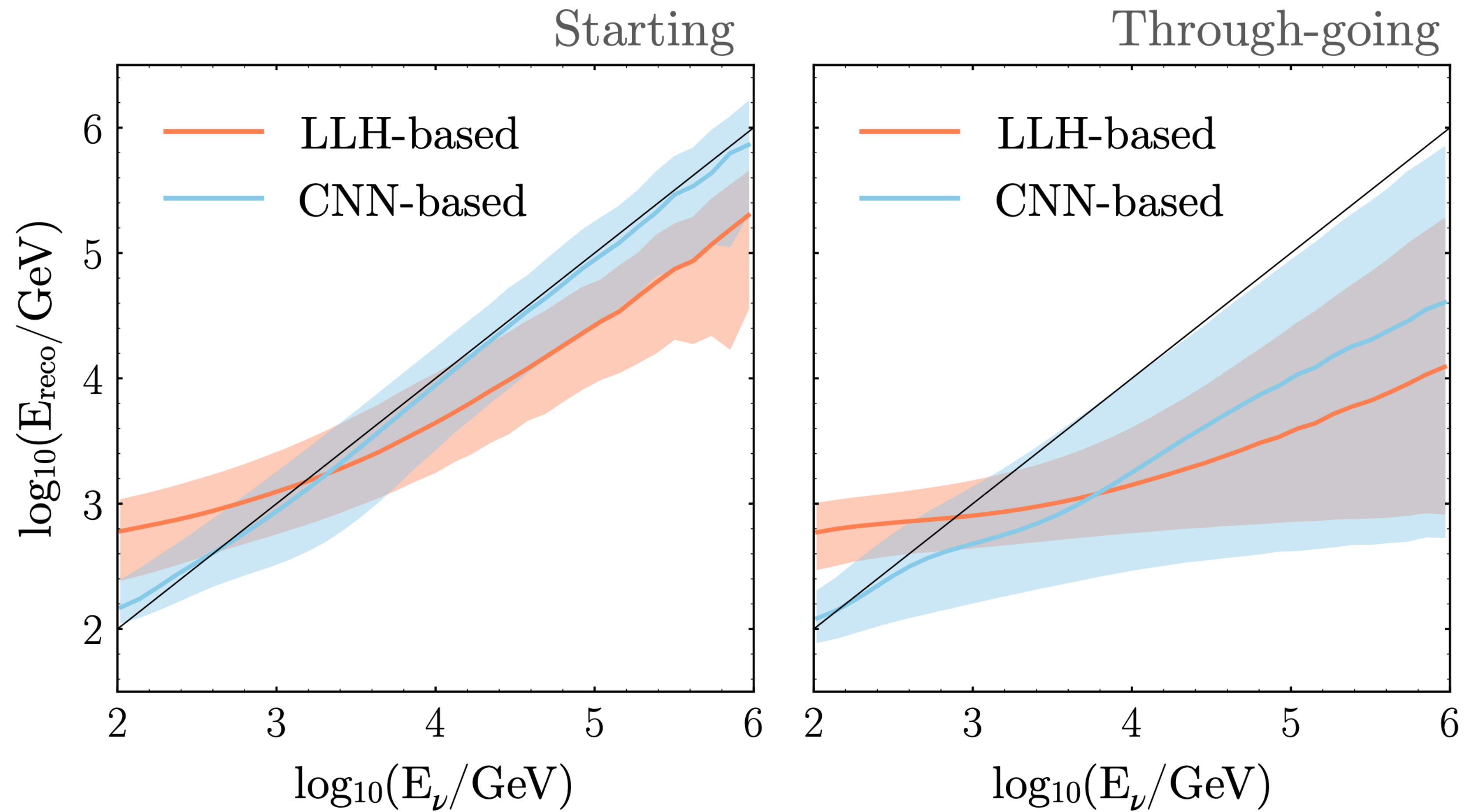
Thank you!
Any questions?

Backup Slides

MEOWS: Matter-Enhanced Oscillations with Steriles

- Dataset originally developed for sterile neutrino analyses
- Very pure, well-understood dataset of atmospheric neutrino tracks
 - Also used for other analyses, including an eV-scale sterile neutrino search (PRL 2024)
- Multiple iterations of dataset:
 - Previous IceCube Decoherence search (Nature Physics, 2024): 7.6 years
 - This work: 10.7 years

Energy Resolution



Systematics

- Fit over 36 nuisance parameters in 6 categories
 1. Overall Normalization
 2. Detector response
 3. Bulk ice properties
 4. Conventional flux (hadronic + cosmic ray)
 5. Non-conventional (astrophysical) flux
 6. Neutrino attenuation

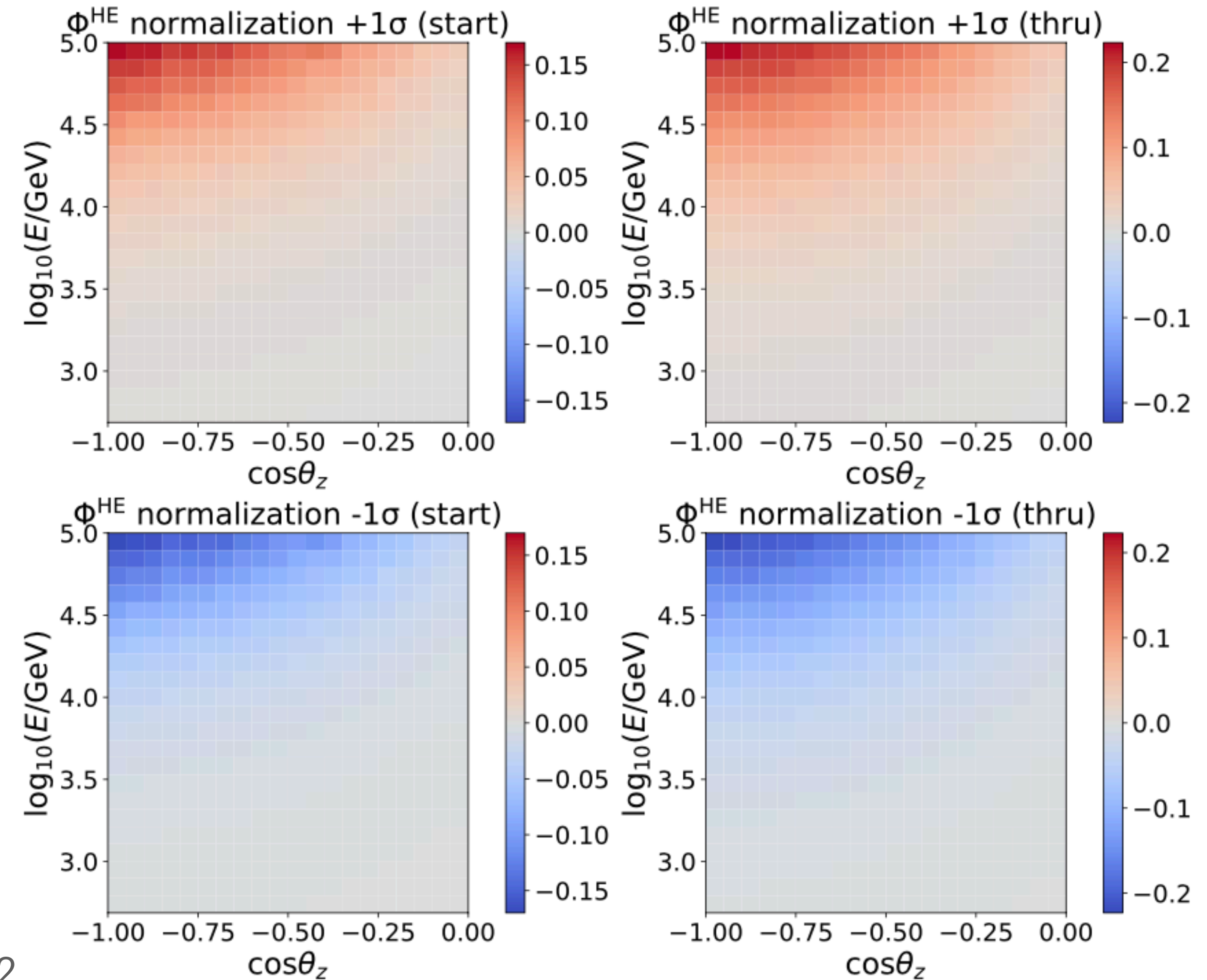
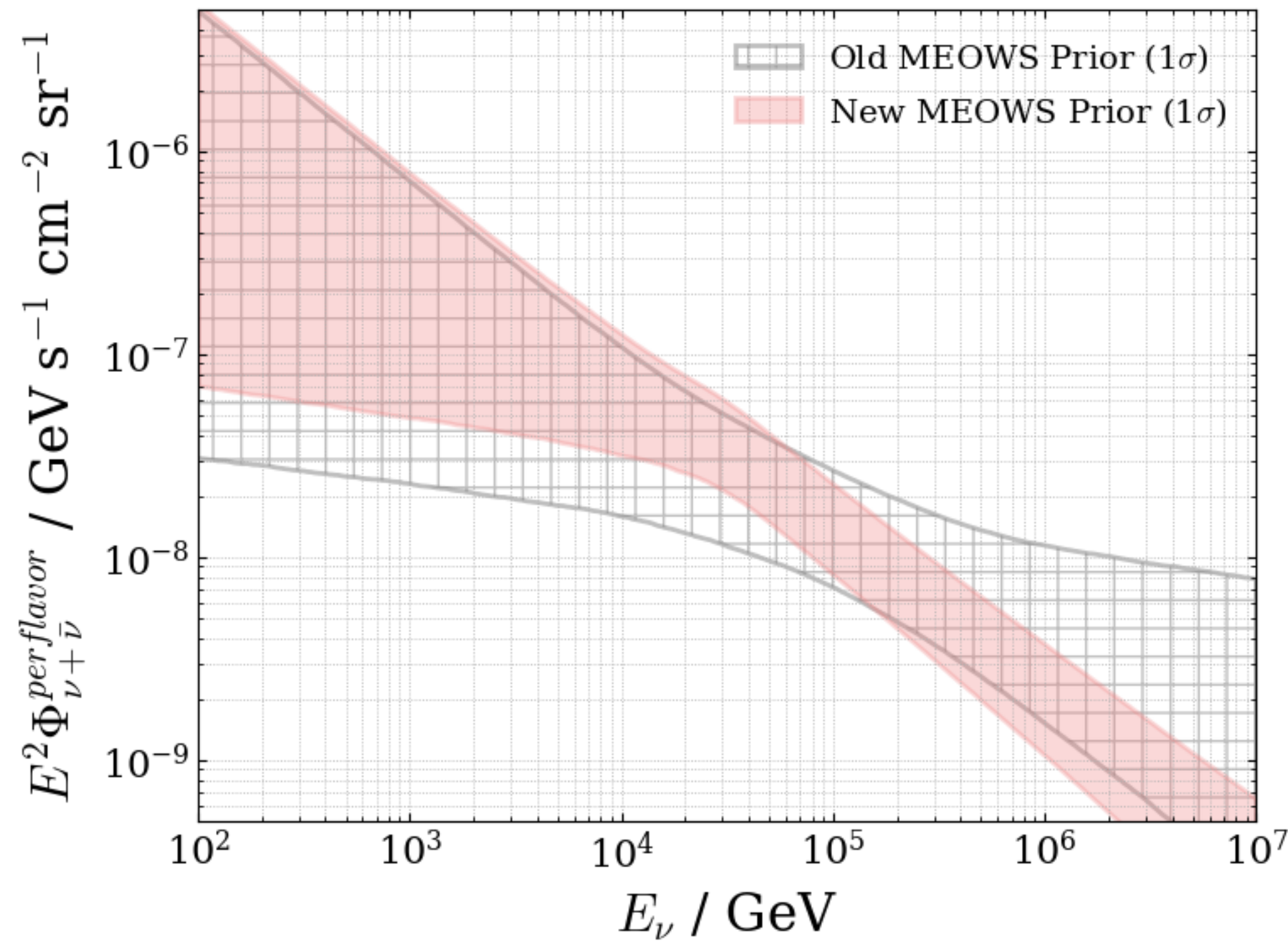
Systematics

36 nuisance params used in this analysis

Systematic	Central	Prior (1σ)	Range	Implementation
Normalization Parameters				
Normalization	1	± 0.2	[0.1,3]	
Detector Parameters				
DOM efficiency	1.27	$\pm 10\%$	[1.234, 1.346]	6 support points
Ice Amplitude 0	0.0	± 1.0	[-3,3]	Correlation
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 Amplitude 4	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				
Zenith Correction	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
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	[-2, 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]	"
Cosmic Ray Parameters				
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]	"
Non-Conventional (Astrophysical) 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	0.34	± 0.11	[-2,2]	
Pivot energy in log10	4.52	± 0.11	[4,6]	
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]	"

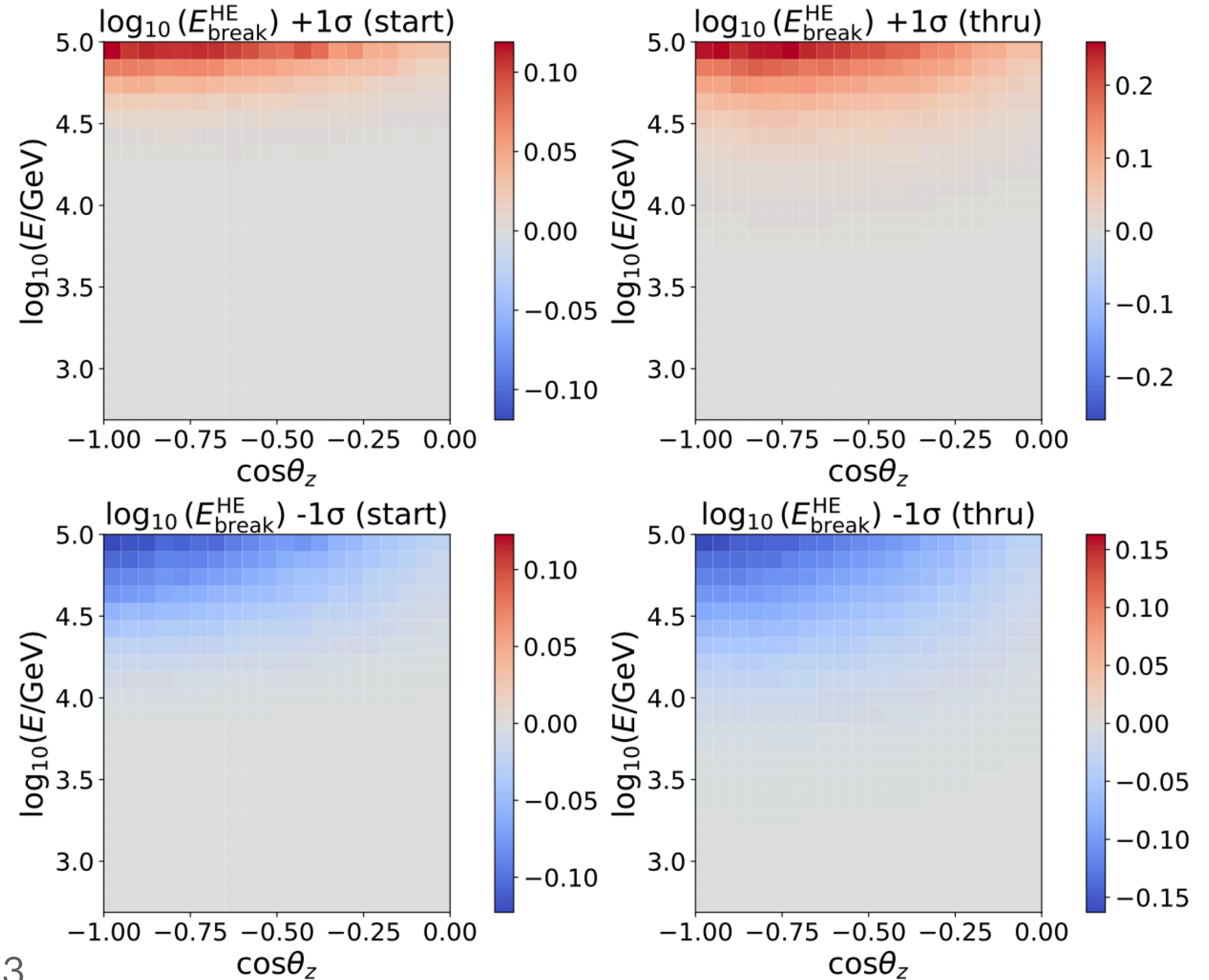
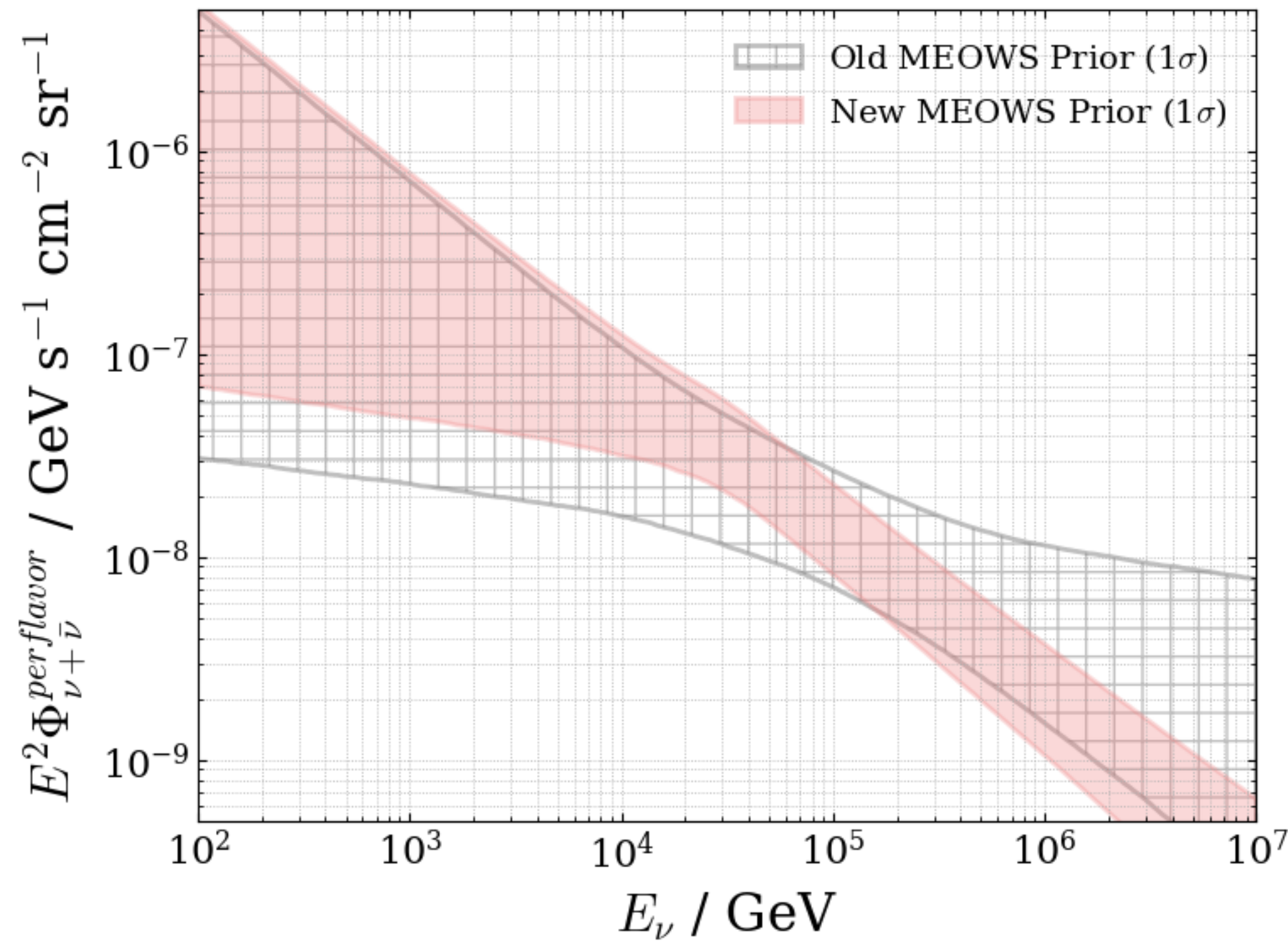
Systematic Effects

- Effect of shifting systematics by $\pm 1\sigma$



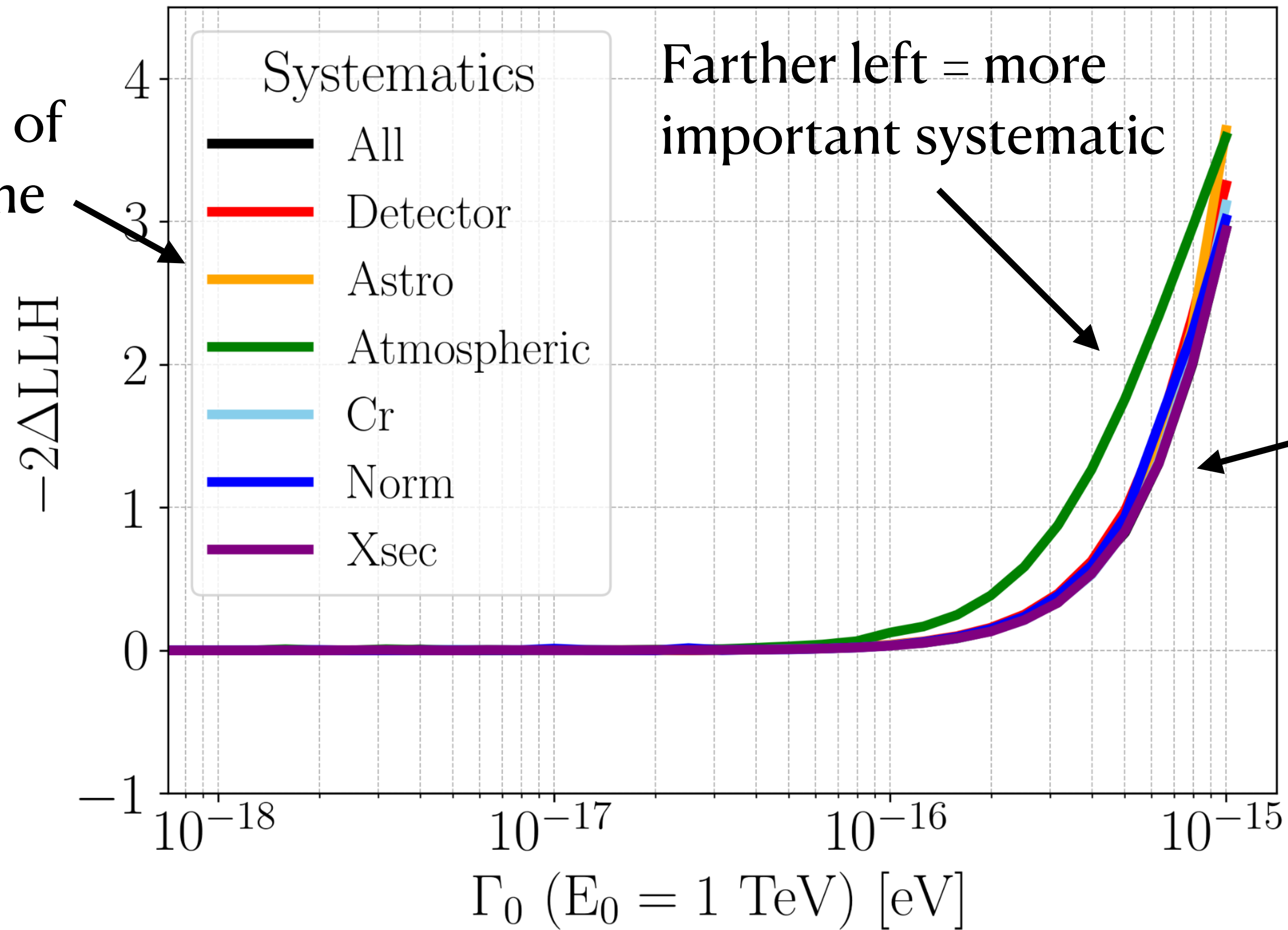
Systematic Effects

- Effect of shifting systematics by $\pm 1\sigma$



Systematic Impacts

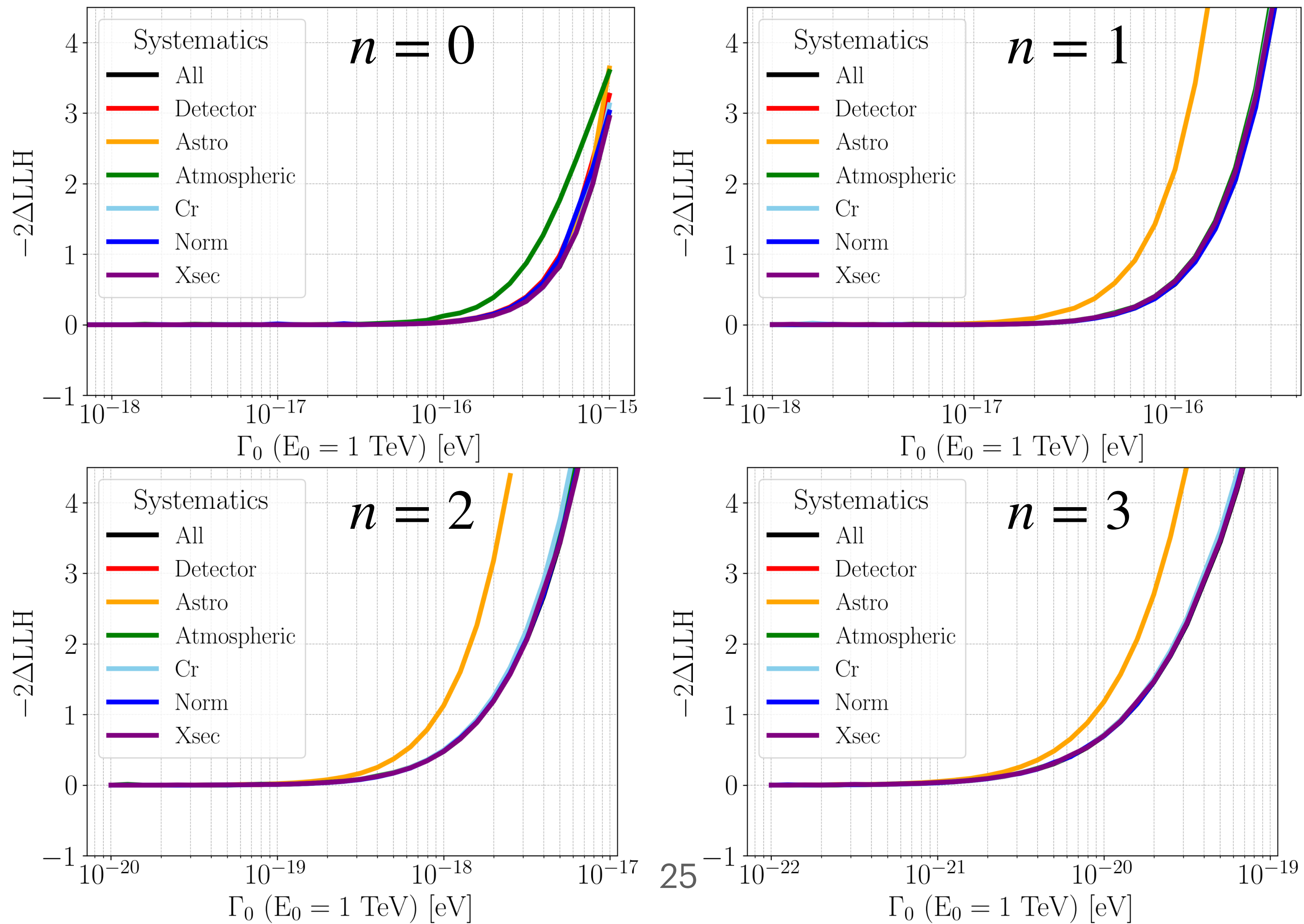
Remove one group of systematics at a time



See how it changes sensitivity

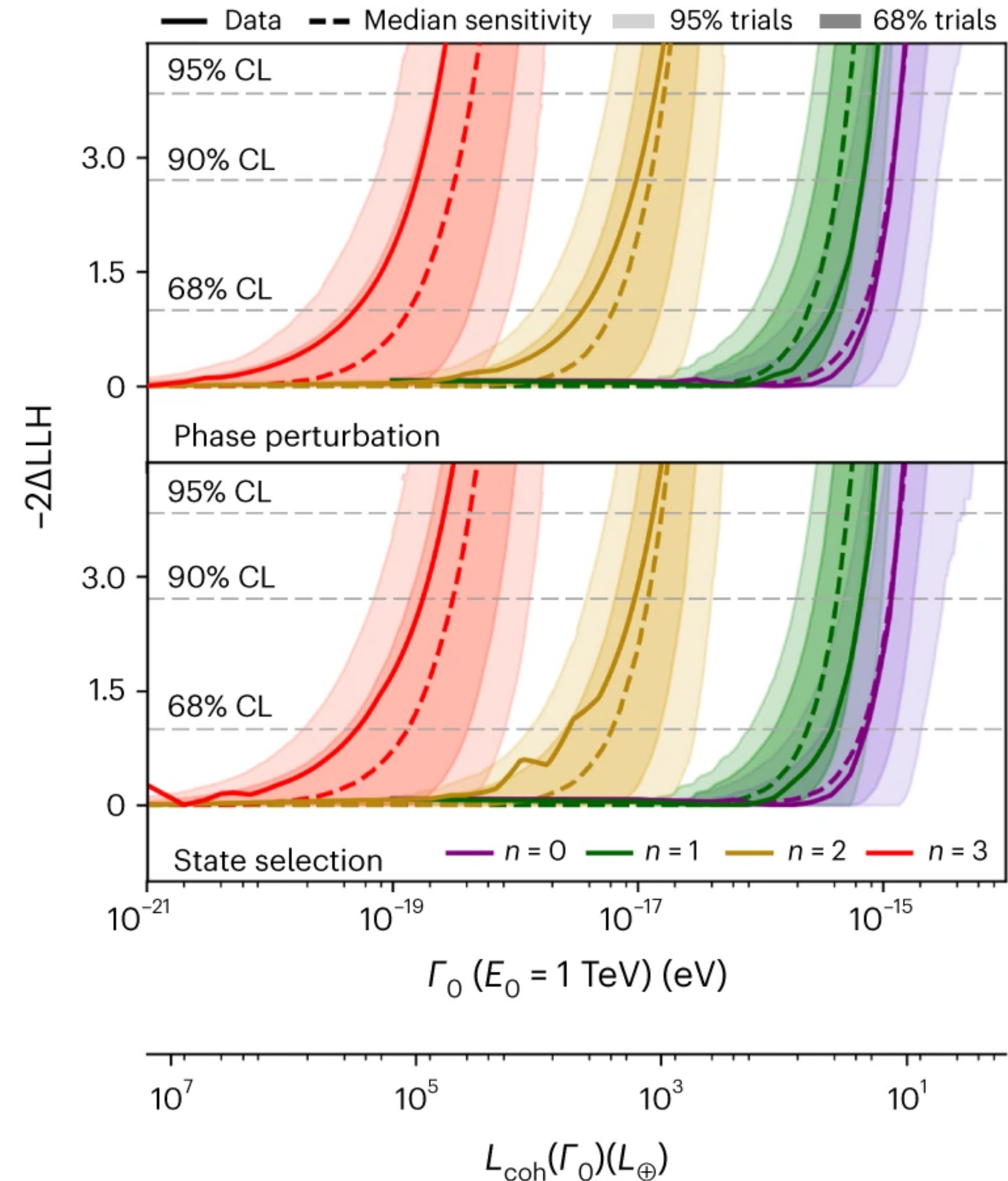
Systematic Impacts

State selection



Previous IceCube Constraints

- World's strongest limits on neutrino decoherence from quantum gravity
 - 30-50 times more sensitive for $n=0$
 - 6-8 orders of magnitude more sensitive for $n=2$



What has been improved?

	Previously:	This work:
Events:	305, 735 events	368, 071 events
Years:	7.634 years	10.669 years
Reco Energies:	500 GeV to 10 TeV	500 GeV to 100 TeV

Also:

- New energy estimator
- Through/starting track separation
- New selection for final-level cuts

→ **larger, higher purity sample**

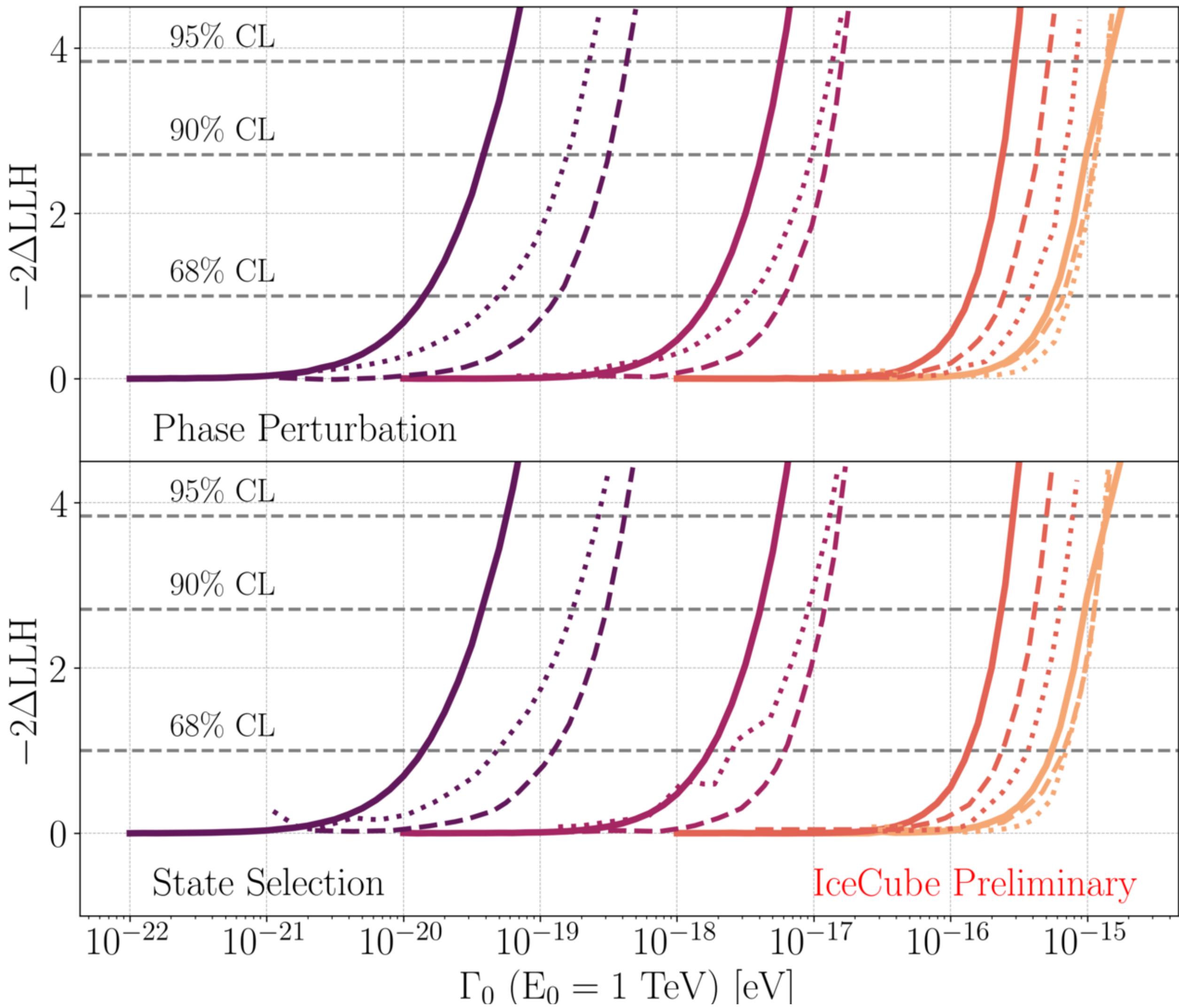
Significant Gain in Sensitivity

Stronger constraint



- Most significant improvement for models with strong energy dependance
- Factor of improvement of my sensitivities compared to previous analysis:

n	Phase	State selection
0	1.18x	1.20x
1	1.79x	1.79x
2	2.98x	2.98x
3	8.20x	8.20x



Comparison of Upper Limits

Experiment	Model	$n = 0$	$n = 1$	$n = 2$	$n = 3$
IceCube (this work)	State Selection	2.36×10^{-15}	4.58×10^{-19}	7.26×10^{-25}	6.05×10^{-30}
	Phase Perturbation	2.41×10^{-15}	4.80×10^{-19}	7.26×10^{-25}	6.37×10^{-30}
IceCube (Nature Physics 2024)	State Selection	1.17×10^{-15}	6.67×10^{-19}	9.48×10^{-24}	1.77×10^{-28}
	Phase Perturbation	1.18×10^{-15}	6.89×10^{-19}	9.80×10^{-24}	1.58×10^{-28}
MINOS (JHEP 10 (2023) 035)	State Selection	6.8×10^{-14}	—	1.7×10^{-16}	—
	Phase Perturbation	6.5×10^{-14}	—	2.4×10^{-16}	—
T2K (JHEP 10 (2023) 035)	State Selection	6.2×10^{-14}	—	3.1×10^{-14}	—
	Phase Perturbation	5.2×10^{-14}	—	3.3×10^{-14}	—
Super-K (PRL 85, 1166)	Phase Perturbation	3.5×10^{-14}	—	0.9×10^{-18}	—

[IceCube Collaboration. Nature Physics 20, 913-920 \(2024\)](#)
[E. Lisi, A. Marrone, and D. Montanino. Phys. Rev. Lett. 85, 1166 \(2000\)](#)
[A. L. G. Gomes, R. A. Gomes, and O. L. G. Peres. J. High Energ. Phys. 2023, 35 \(2023\).](#)

Split Sample Post-Unblinding Check

- Can draw vertical lines intersecting all lines on each subplot
 - Shows agreement within 2σ
- Test passes for all 8 models tested

