Searching for Quantum Decoherence in IceCube

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on behalf of the IceCube Collaboration
NBIA Summer School(7/7/2025)

Image credit: Yuya Makino, IceCube/NSF

Our current understanding of gravity breaks down at the Planck scale

Image Credit: Physics

How does spacetime behave at the Planck scale?

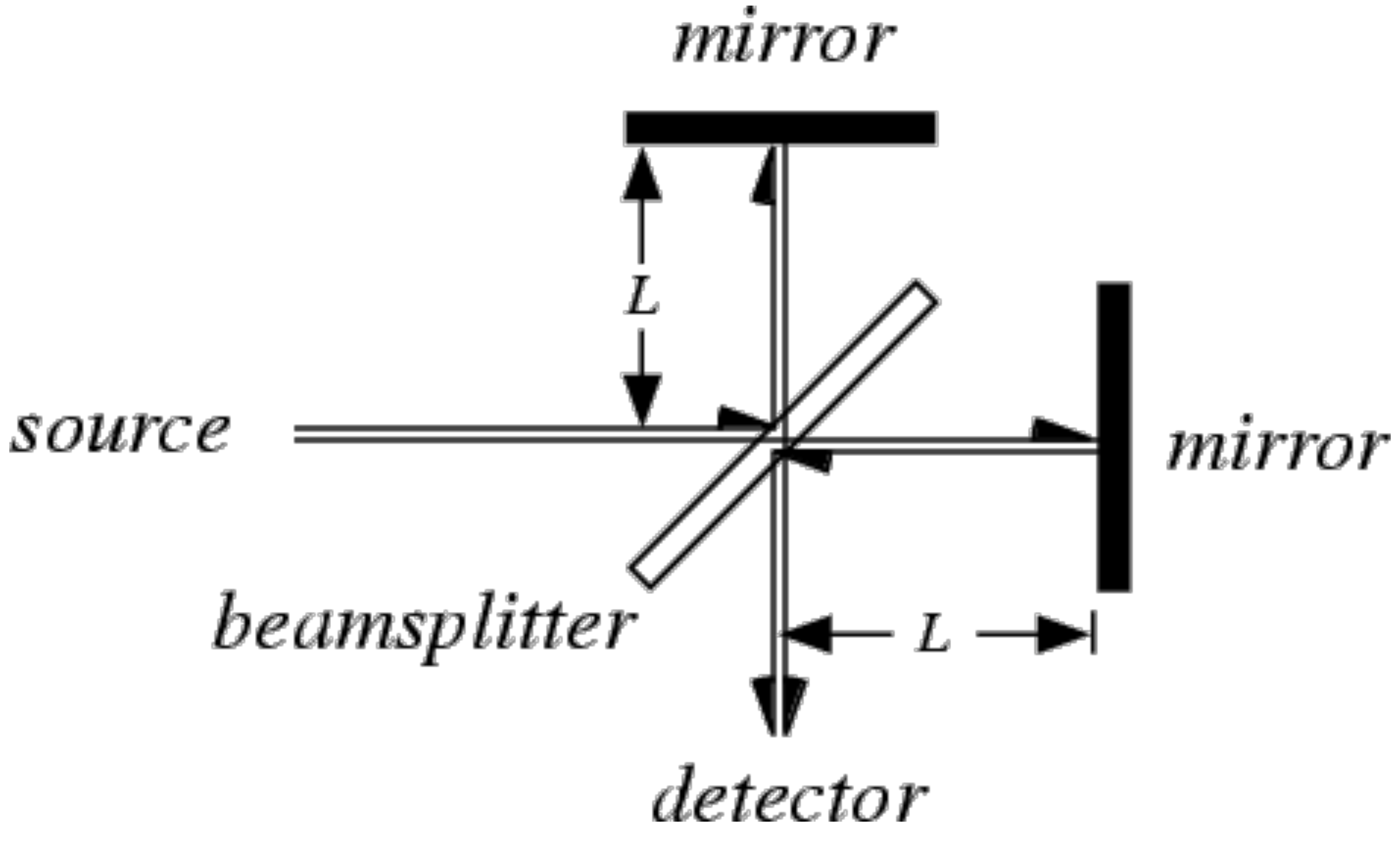
Image Credit: Physics

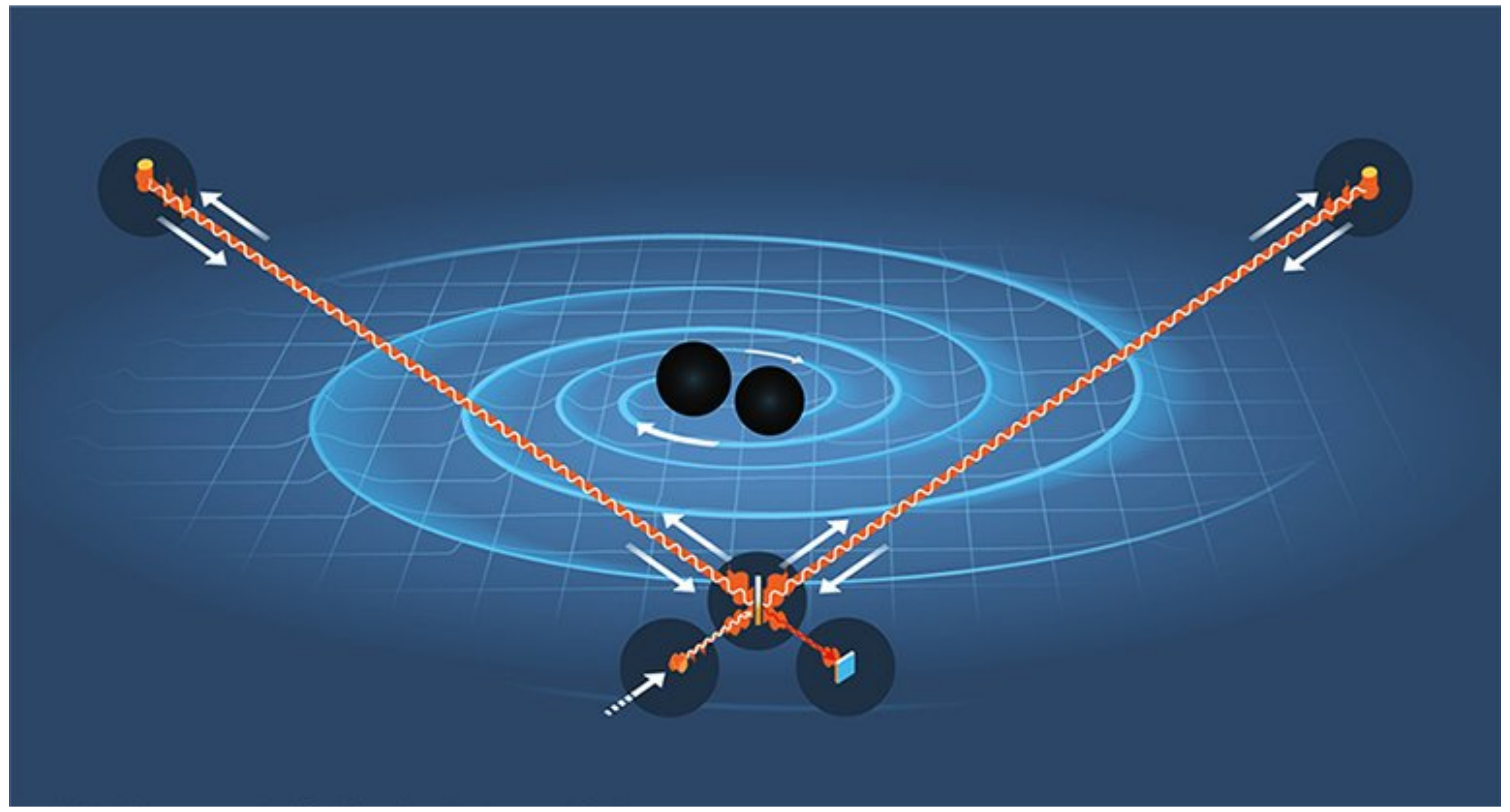
Neutrinos as interferometers

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

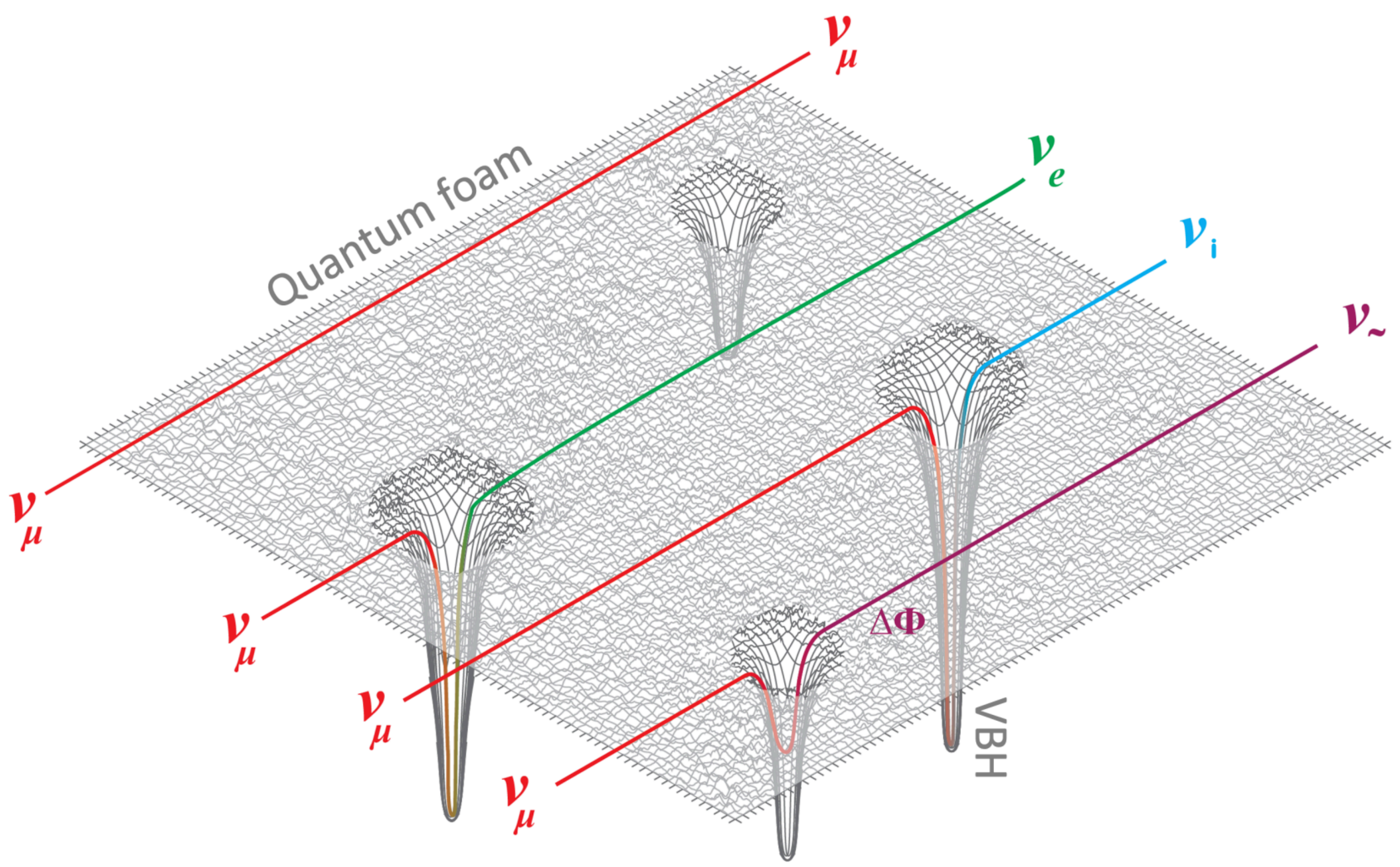
Gravitational wave interferometry to understand contraction of spacetime:

Neutrino interferometry to measure small-scale spacetime structure





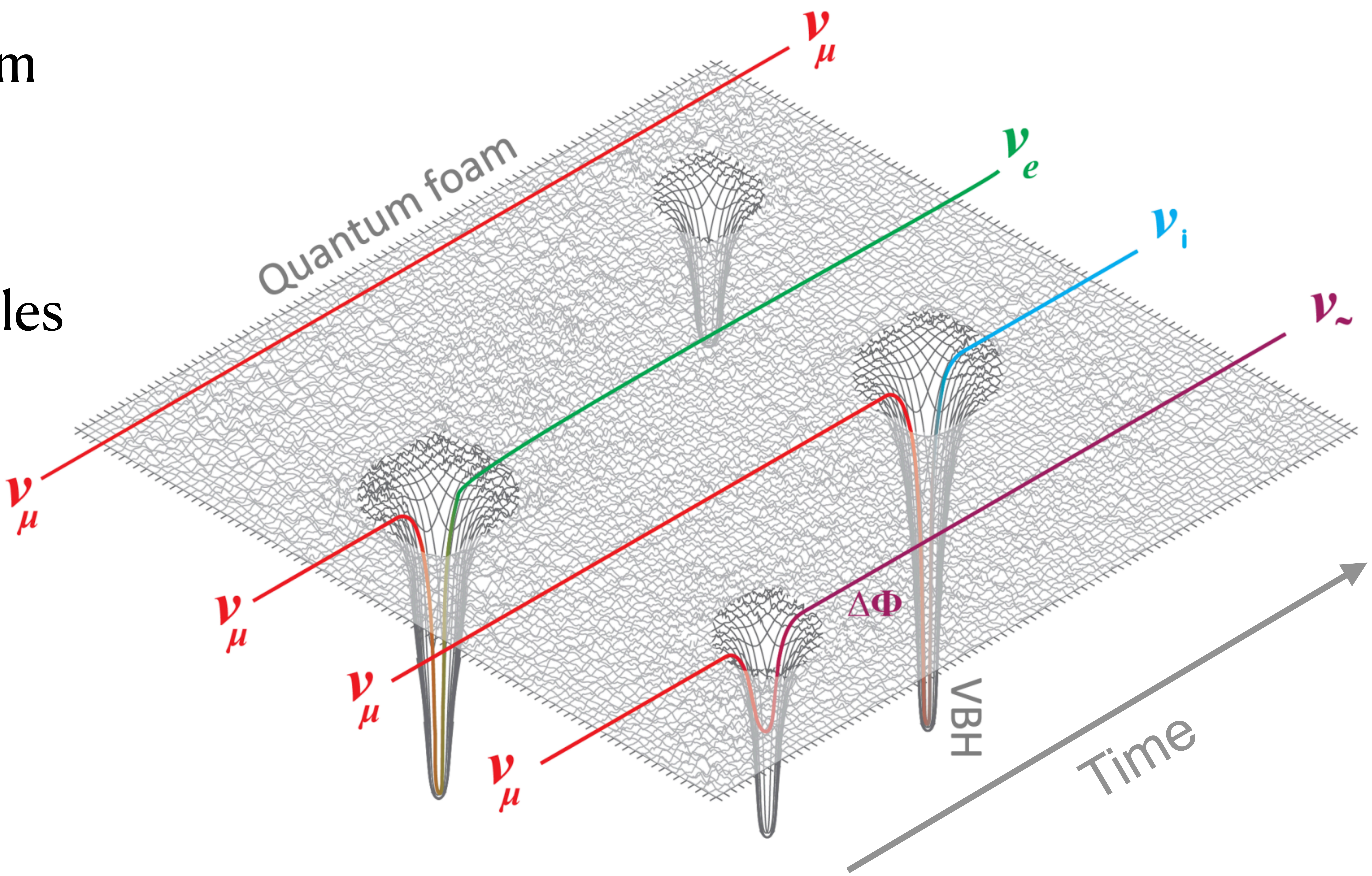
Credit: Johan Jarnestad/The Royal Swedish Academy of Sciences



IceCube Collaboration. Nature Physics 20, 913-920 (2024)

Decoherence Theory

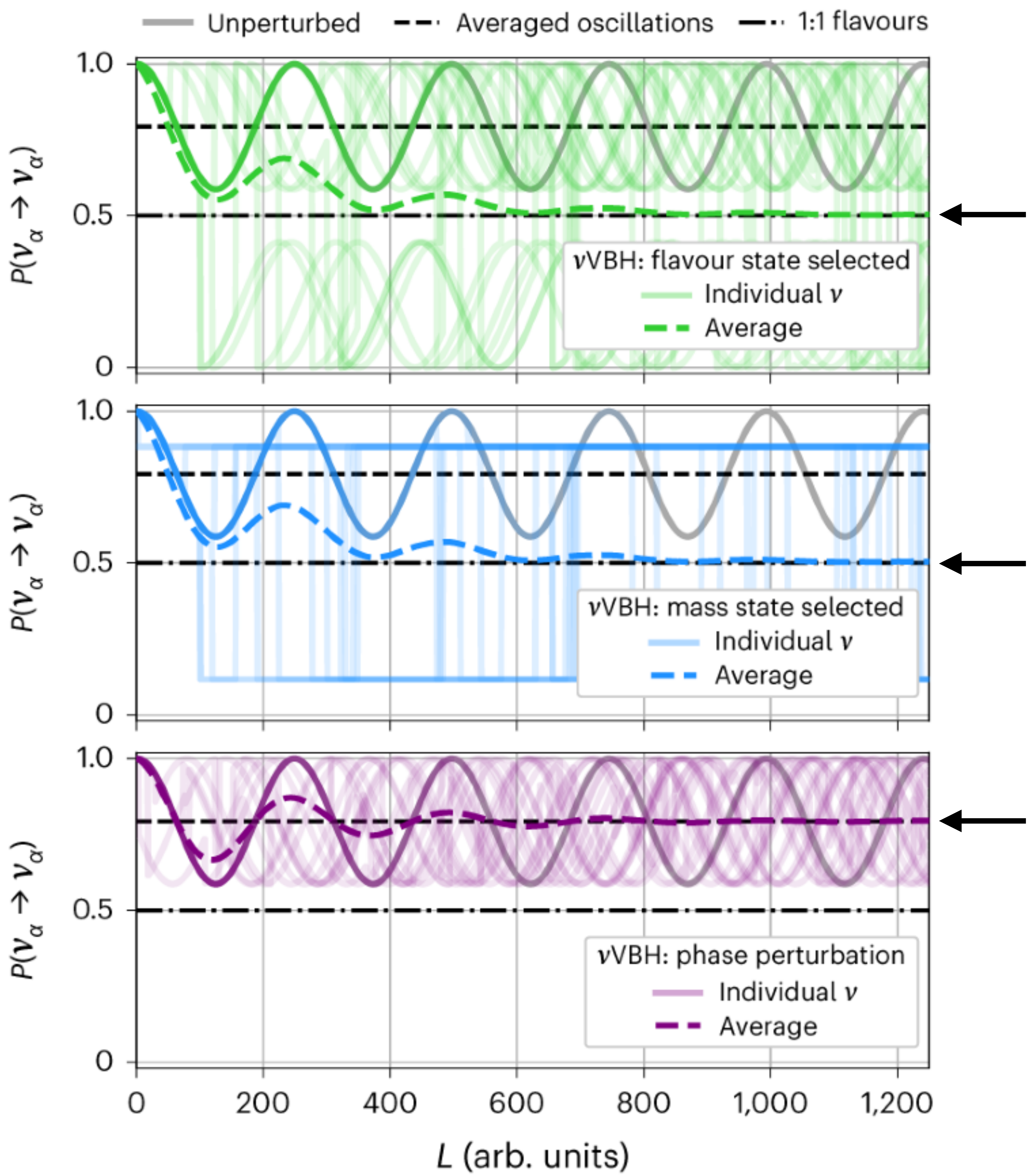
- Neutrinos can maintain quantum coherence over large distances
  - May be absorbed and re-radiated by Virtual Black Holes (VBHs)
- Two interaction modes:
  - State selection
  - Phase perturbation



T. Stuttard and M. Jensen. Phys. Rev. D 102 (2020) 115003.
IceCube Collaboration. Nature Physics 20, 913-920 (2024)

Decoherence Theory

- Neutrinos can maintain quantum coherence over large distances
  - May be absorbed and re-radiated by Virtual Black Holes (VBHs)
- Two interaction modes:
  - State selection
  - Phase perturbation
- Flavor distribution differs from expectation?



T. Stuttard and M. Jensen. Phys. Rev. D 102 (2020) 115003.
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How do we model this?

Lindblad Master Equation:

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

Standard unitary
time evolution

Non-unitary contributions
from quantum gravity

T. Stuttard and M. Jensen. Phys. Rev. D 102 (2020) 115003.
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How do we model this?

Decoherence Superoperator:

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

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

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

$n =$ Energy dependance

$\Gamma_0 =$ Inverse of coherence length at E_0

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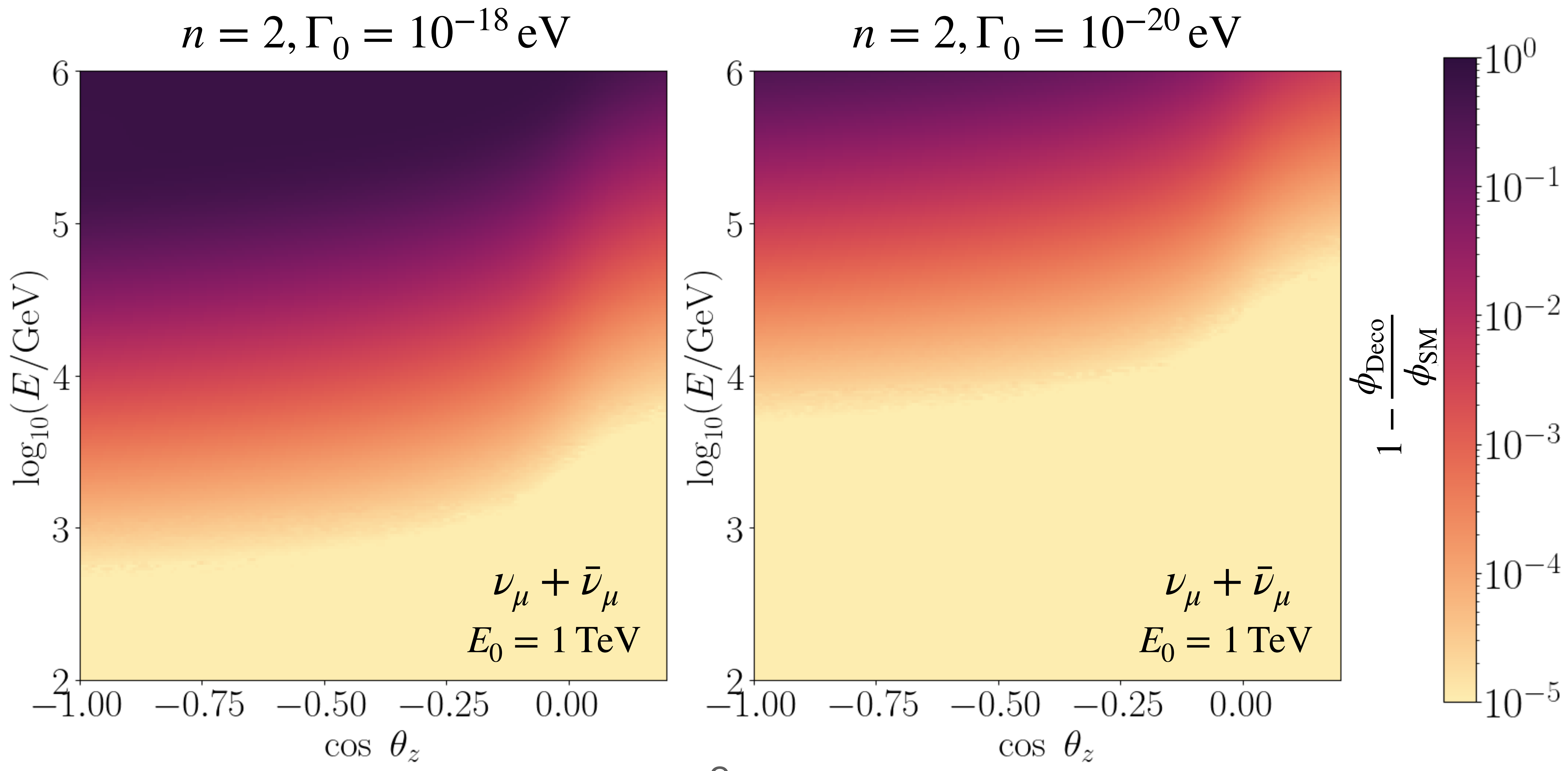
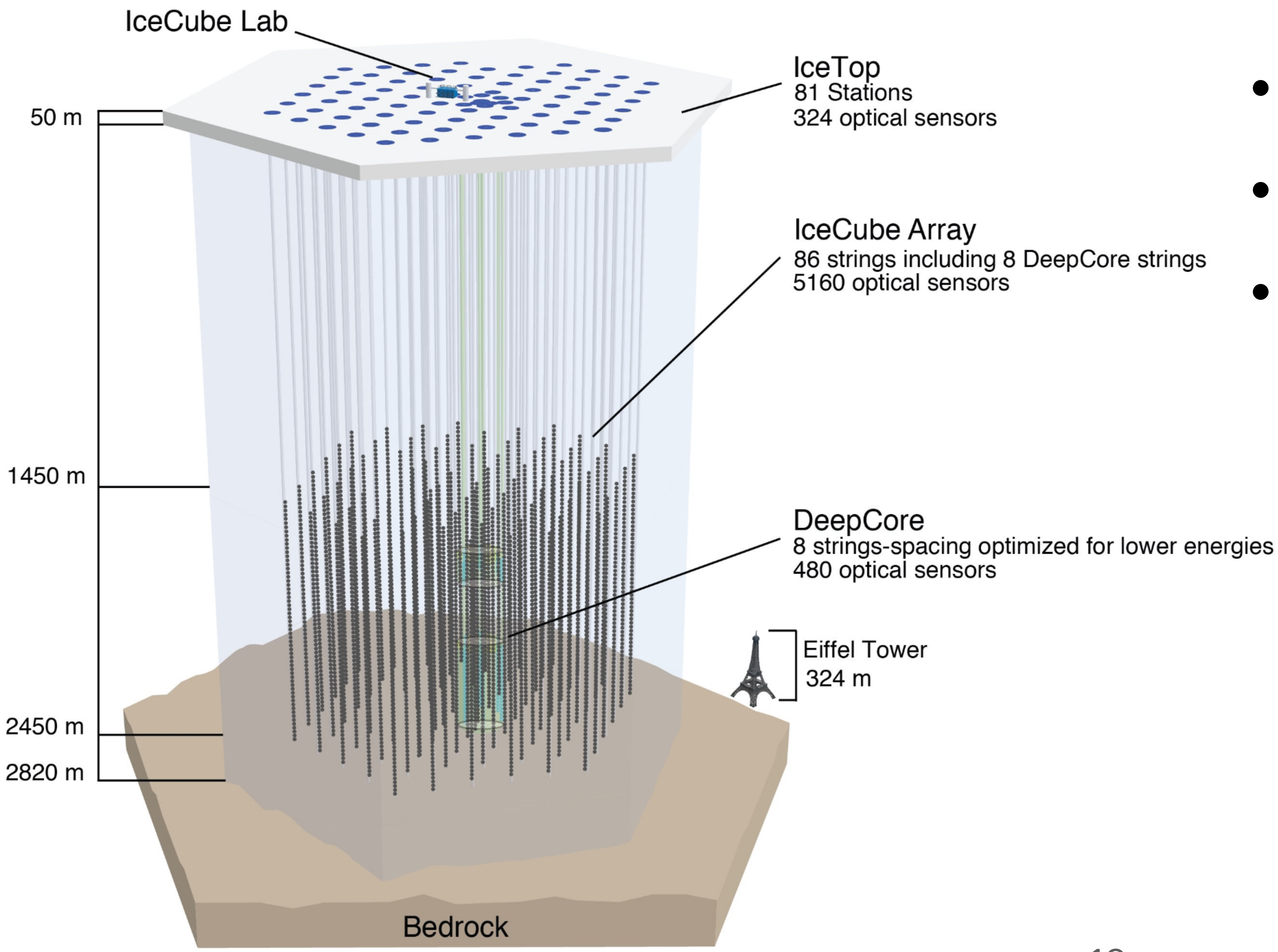
Decoherence Oscillograms

State selection

Probability of ν_μ disappearance:

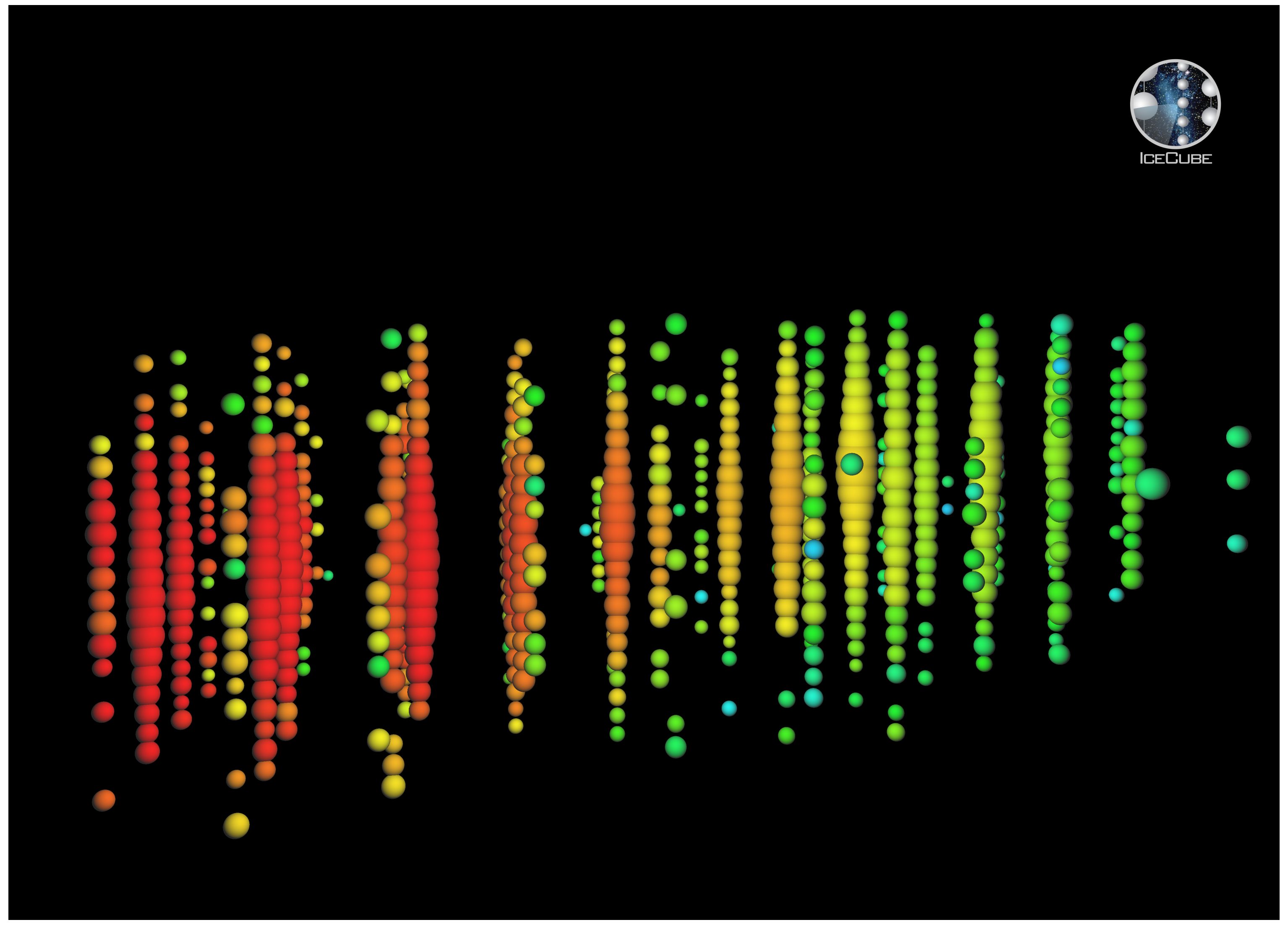


The IceCube Neutrino Observatory



Credit: IceCube Collaboration

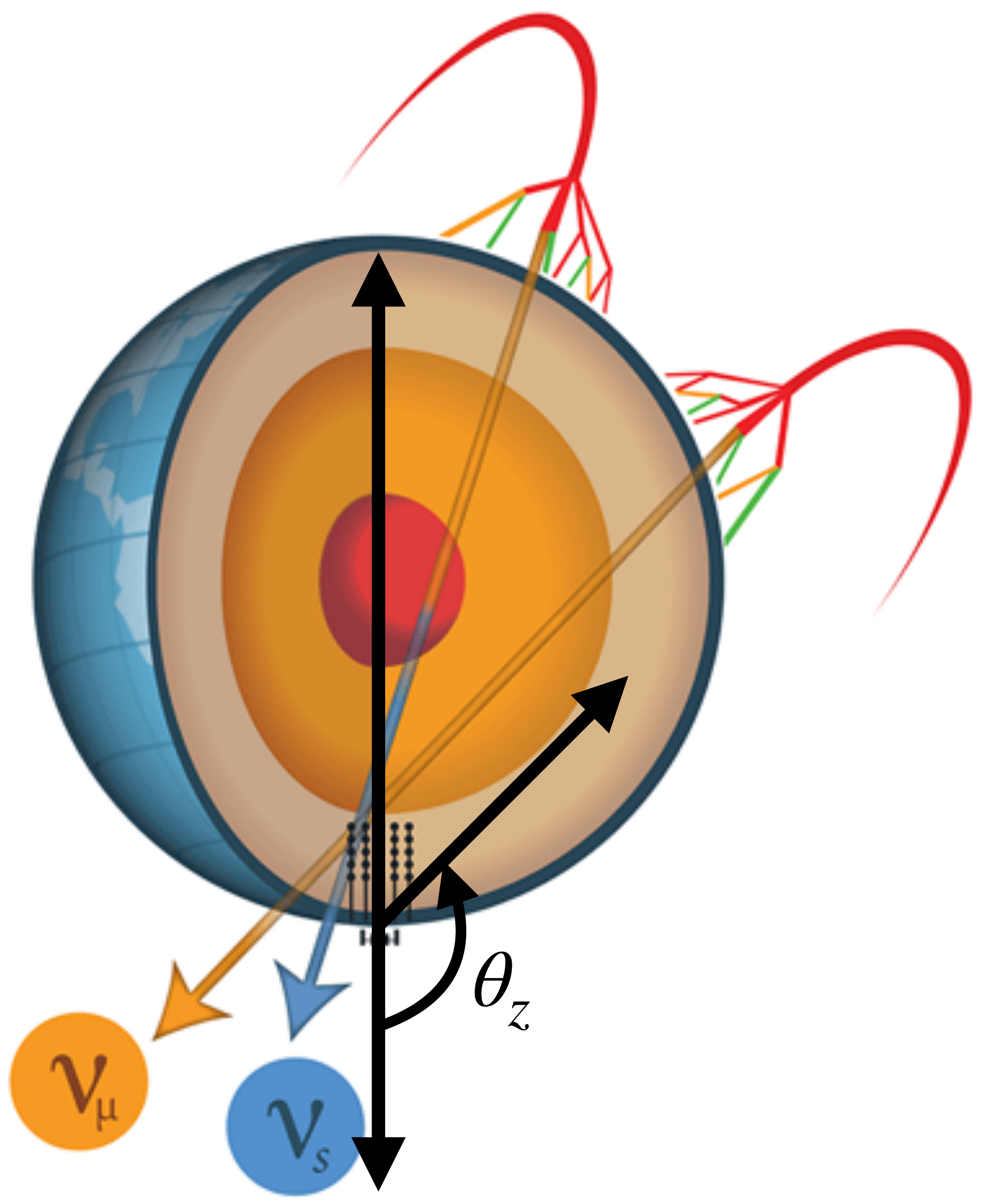
- World's largest neutrino telescope
- Located at the South Pole
- 5,160 Digital Optical Modules (DOMs) observe Cherenkov radiation in ice

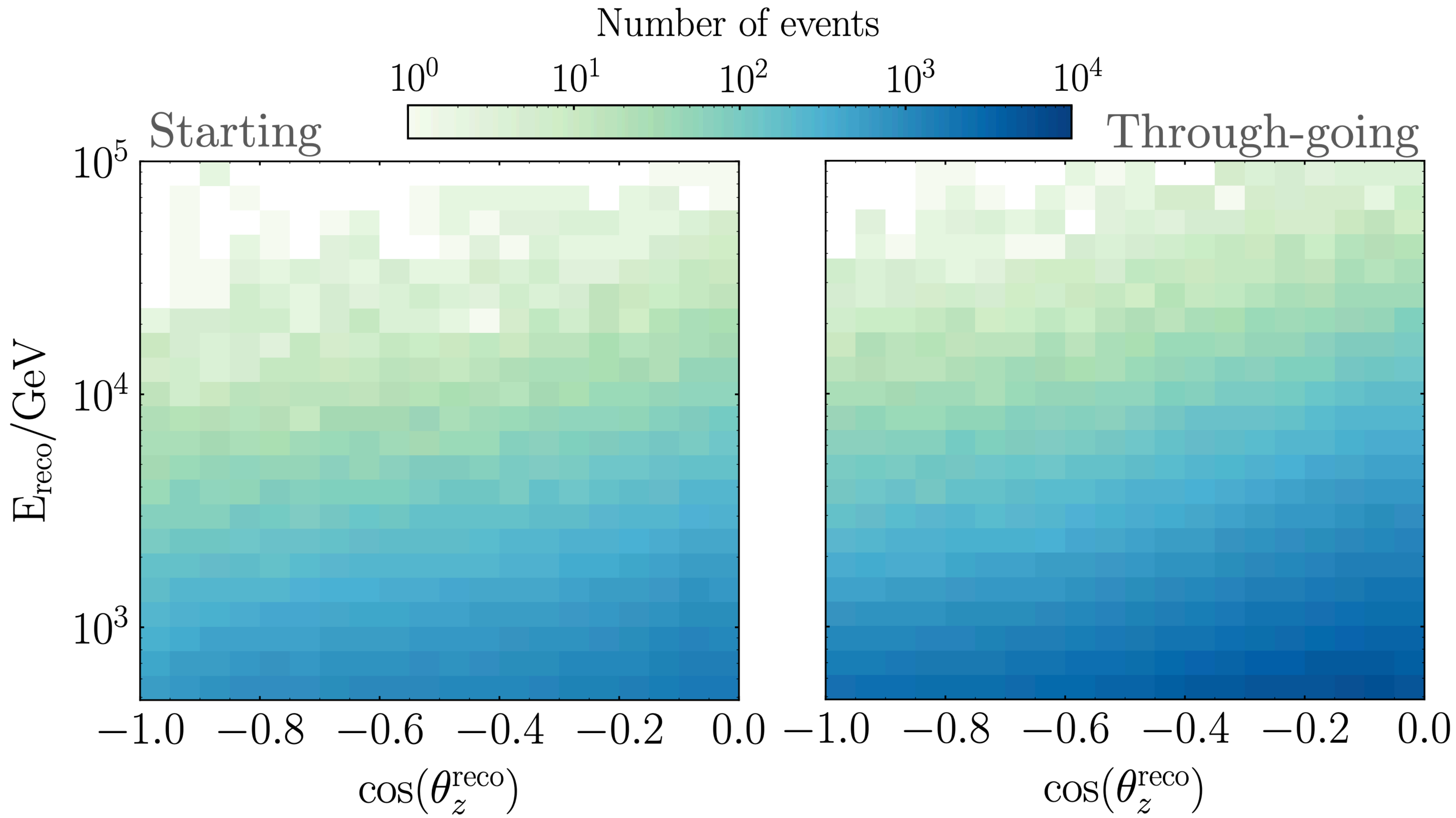


Credit: IceCube Collaboration

Analysis Binning

- We use 10.7 years of atmospheric neutrino events in IceCube
- Data + MC events are binned into 20 zenith, 22 energy and 2 morphology bins for the fit
- We use GollumFit, an open-source framework for binned-likelihood neutrino telescope analyses





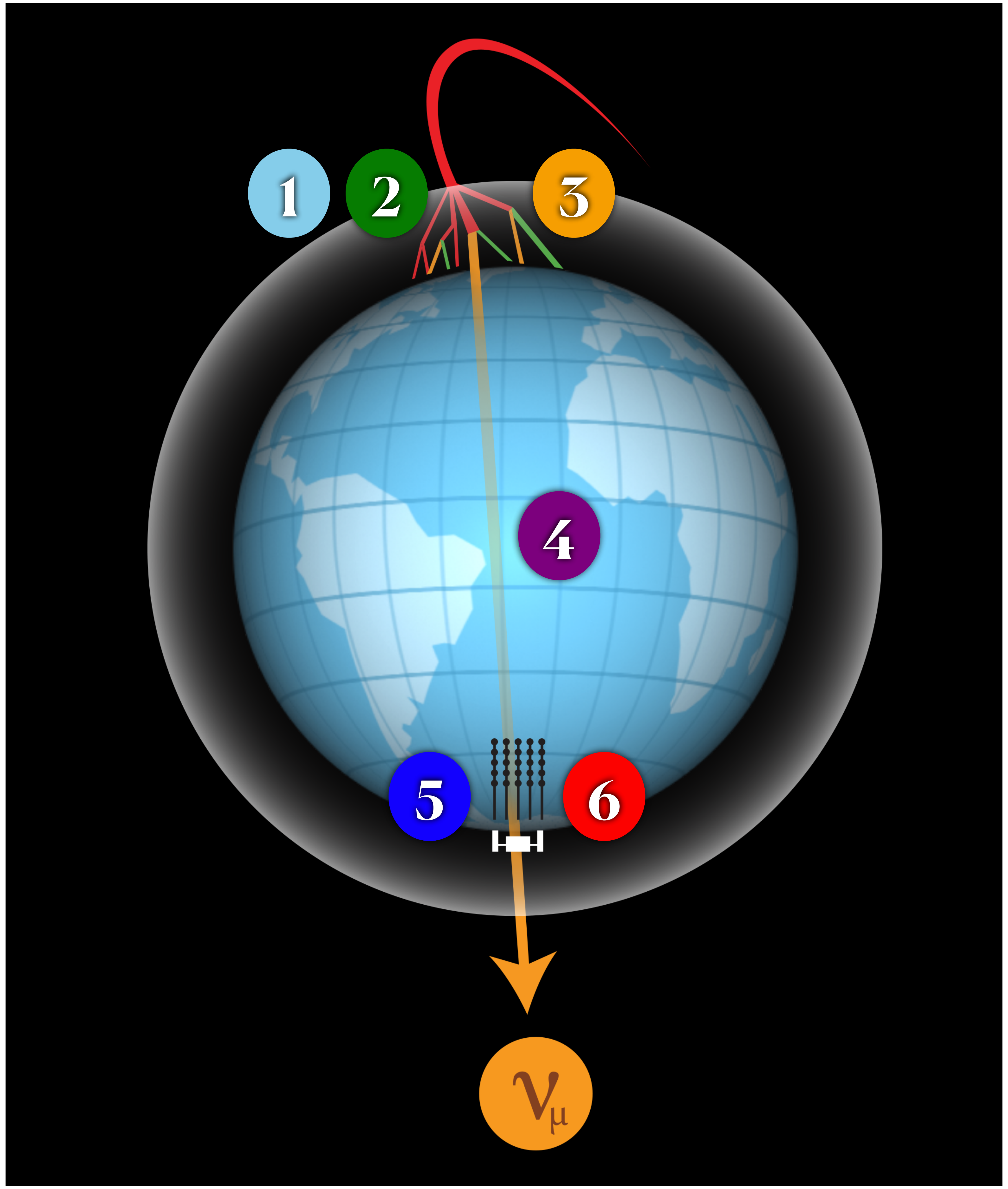
arXiv:2506.04491 Credit: IceCube Collaboration

IceCube Collaboration. Phys. Rev. Lett. 133, 201804 (2024)

Systematics

- Fit over 36 nuisance parameters in 6 categories

1. Cosmic ray spectrum properties
2. Hadronic production parameters
3. Astrophysical neutrino flux properties
4. Neutrino attenuation parameters
5. Overall normalization
6. Detector response



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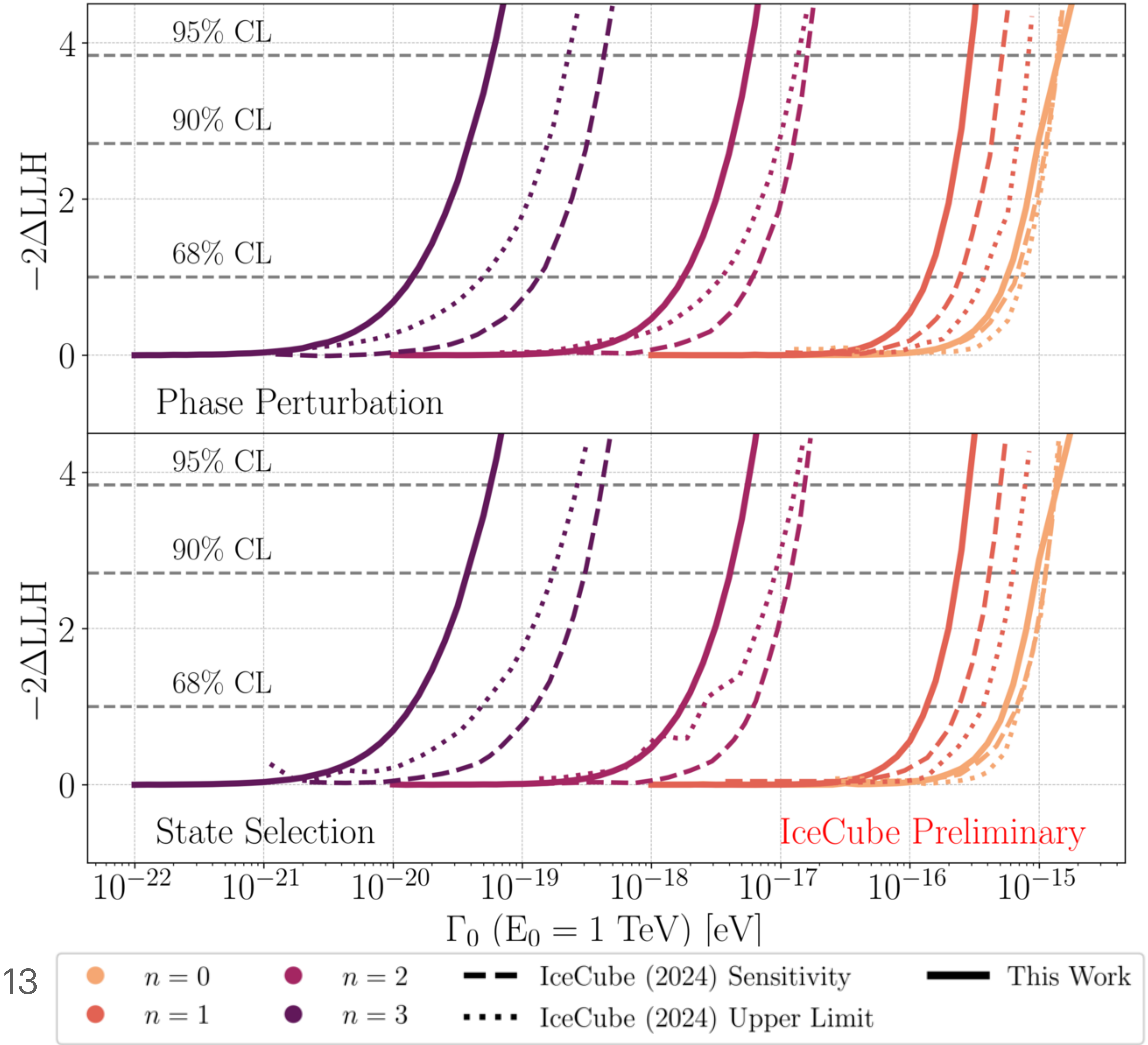
Significant Gain in Sensitivity

Stronger constraint

- Most significant improvement for models with strong energy dependance



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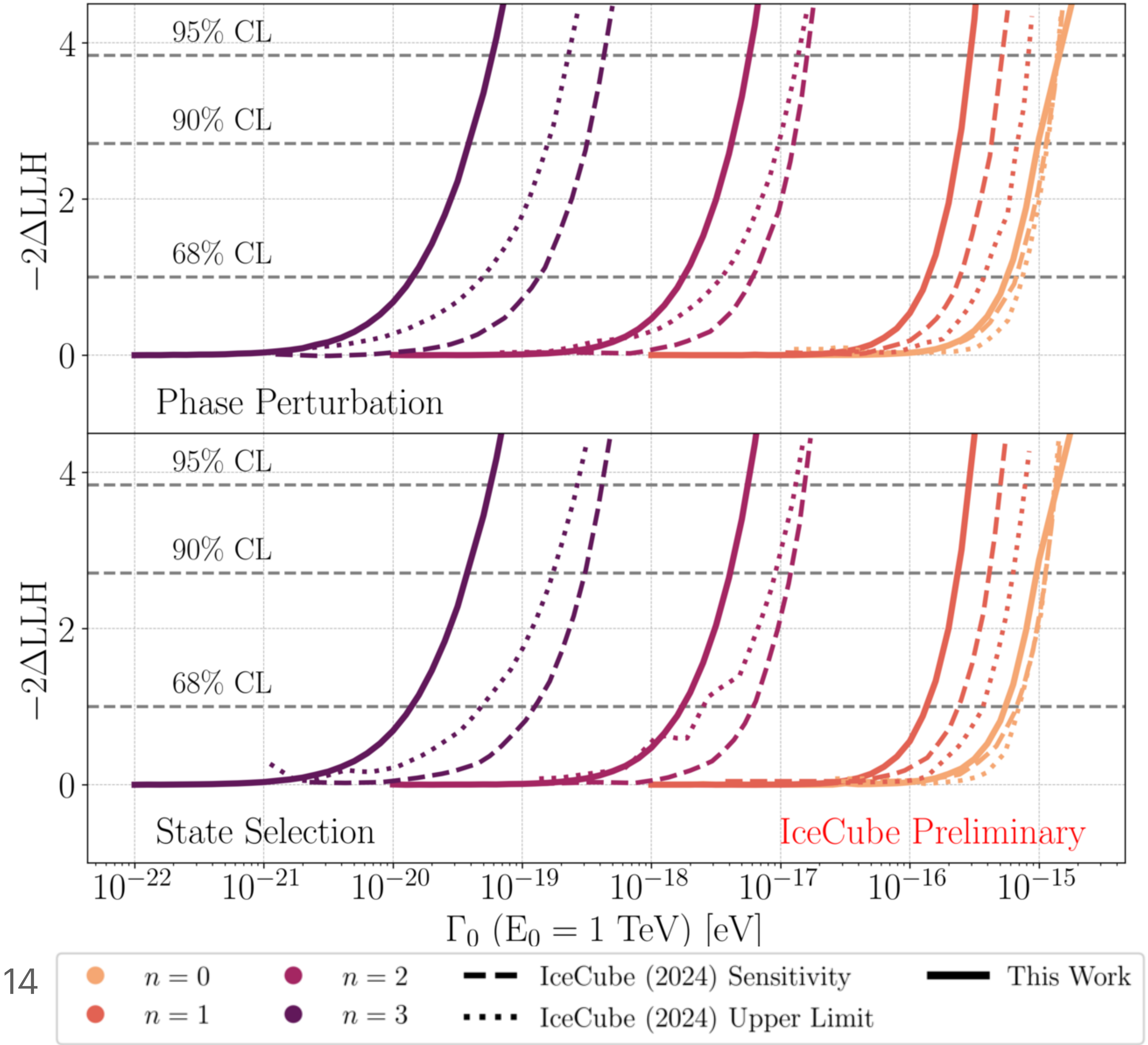
Significant Gain in Sensitivity

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



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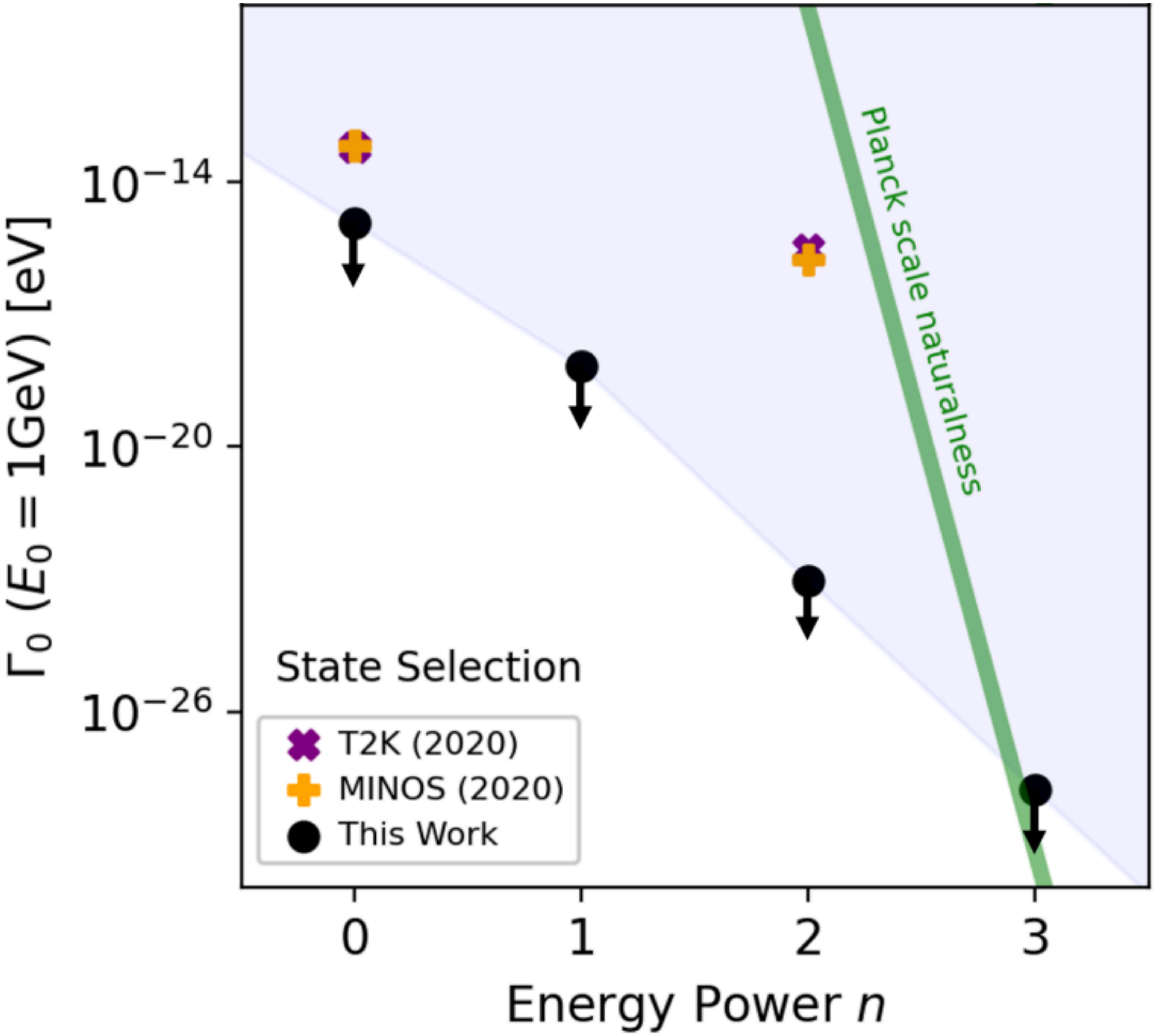
Probing the Planck Scale

- Naturalness: Expect $\mathcal{O}(L_P)$ coherence length for neutrinos with energies $\mathcal{O}(E_P)$
- Our analysis is sensitive to Planck-scale physics below natural expectation for $n = 0, 1, 2$
  - $n = 2$ motivated by probing quantum decoherence effects in string theory models
- Approach Planck-scale natural expectation for $n = 3$

IceCube 2024 constraints:



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

[T. Stuttard and M. Jensen. Phys. Rev. D 102 (2020) 115003.](#)

Conclusion

- This analysis searches for neutrino decoherence due to quantum gravity using 10.7 years of atmospheric muon neutrino events from IceCube
- We obtain a significant sensitivity boost from previous IceCube world-leading constraints
- Unblinded results coming soon!

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

Image credit: Yuya Makino, IceCube/NSF

Backup Slides

Image credit: Yuya Makino, IceCube/NSF

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

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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
- Thru/starting track separation
- New BDT selection for final-level cuts

→ **larger, higher purity sample**

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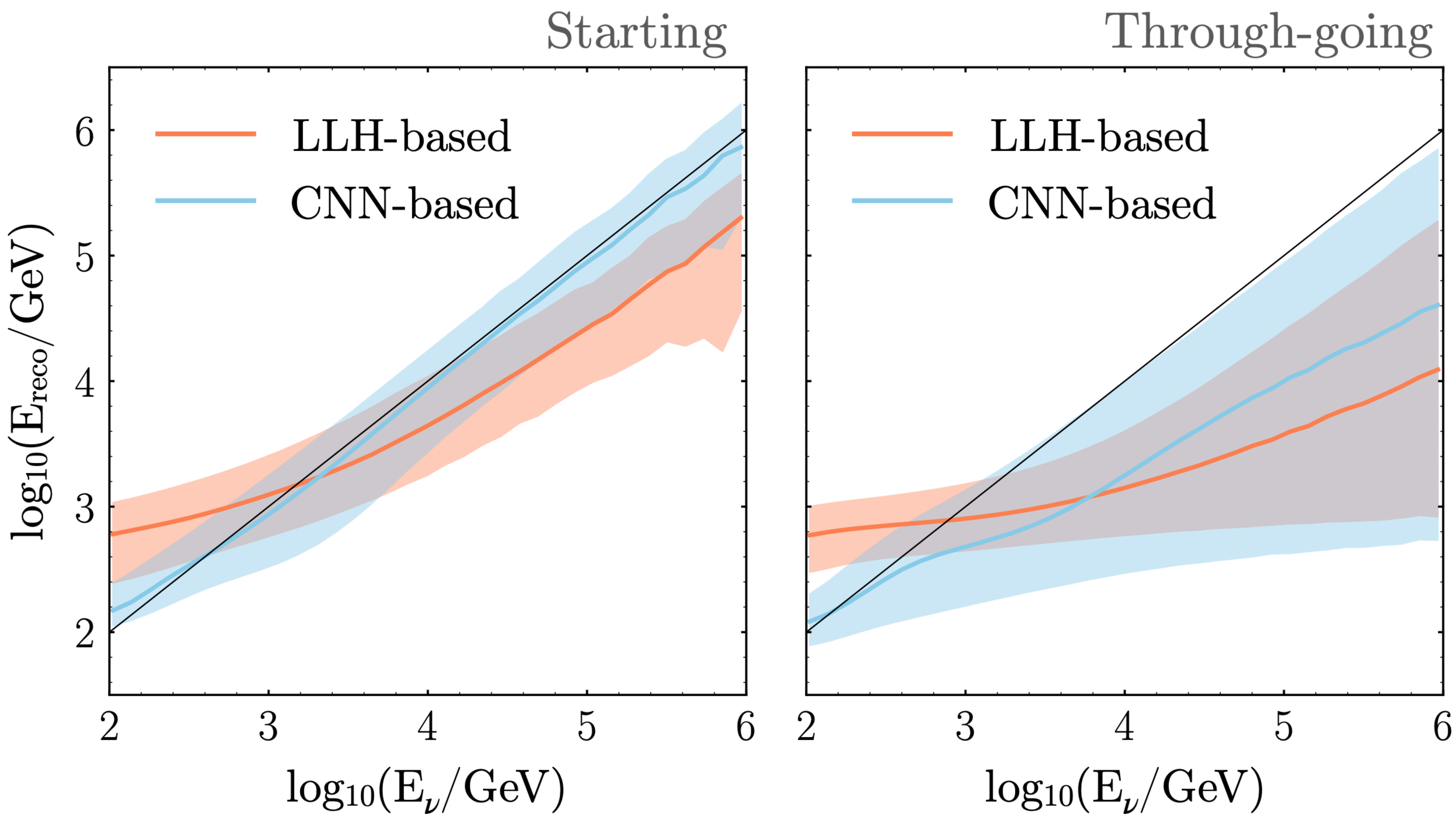
Energy Resolution



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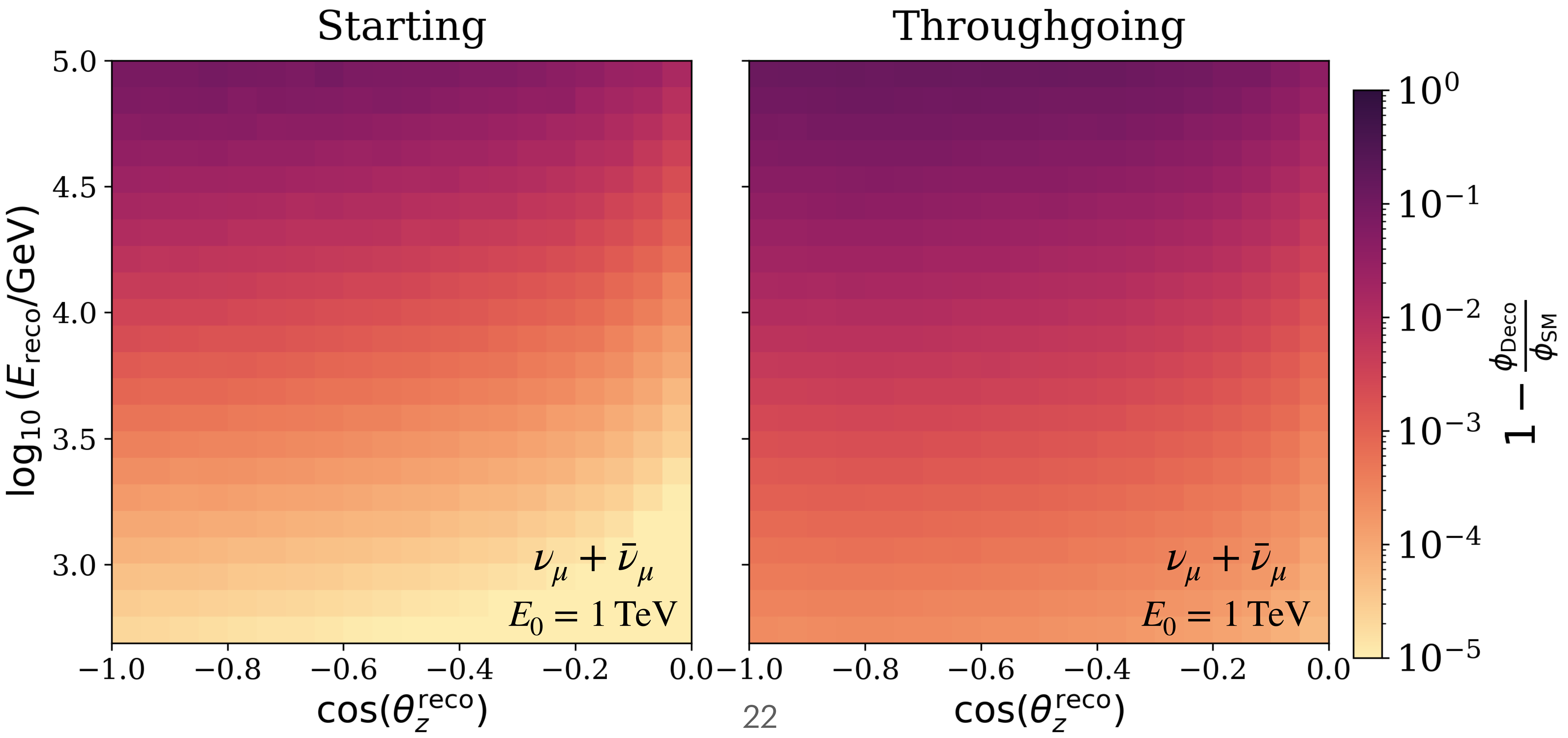
Reconstructed Oscillograms

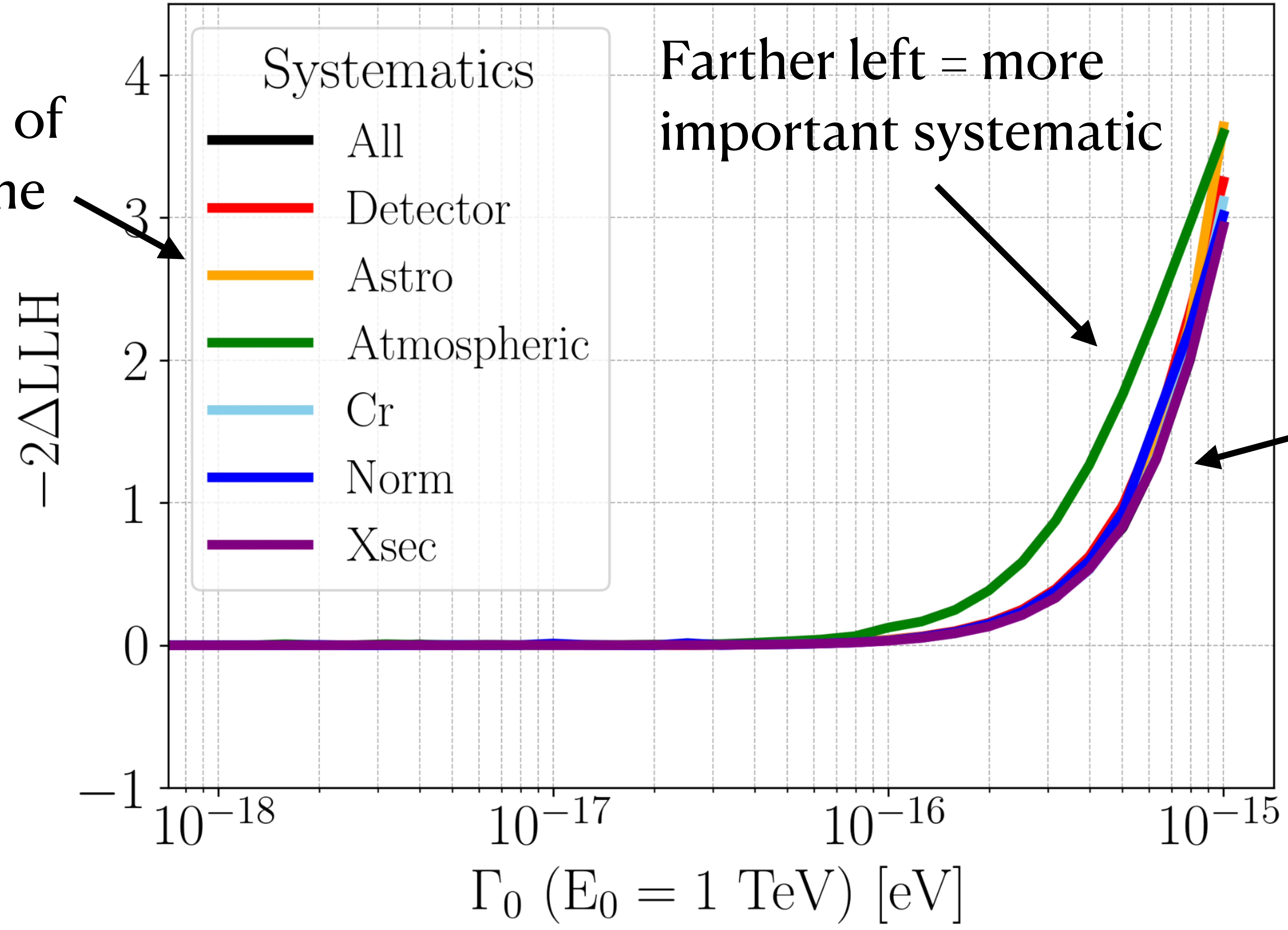
State selection

$n = 2, \Gamma_0 = 10^{-18}$



Systematic Impacts

Remove one group of systematics at a time

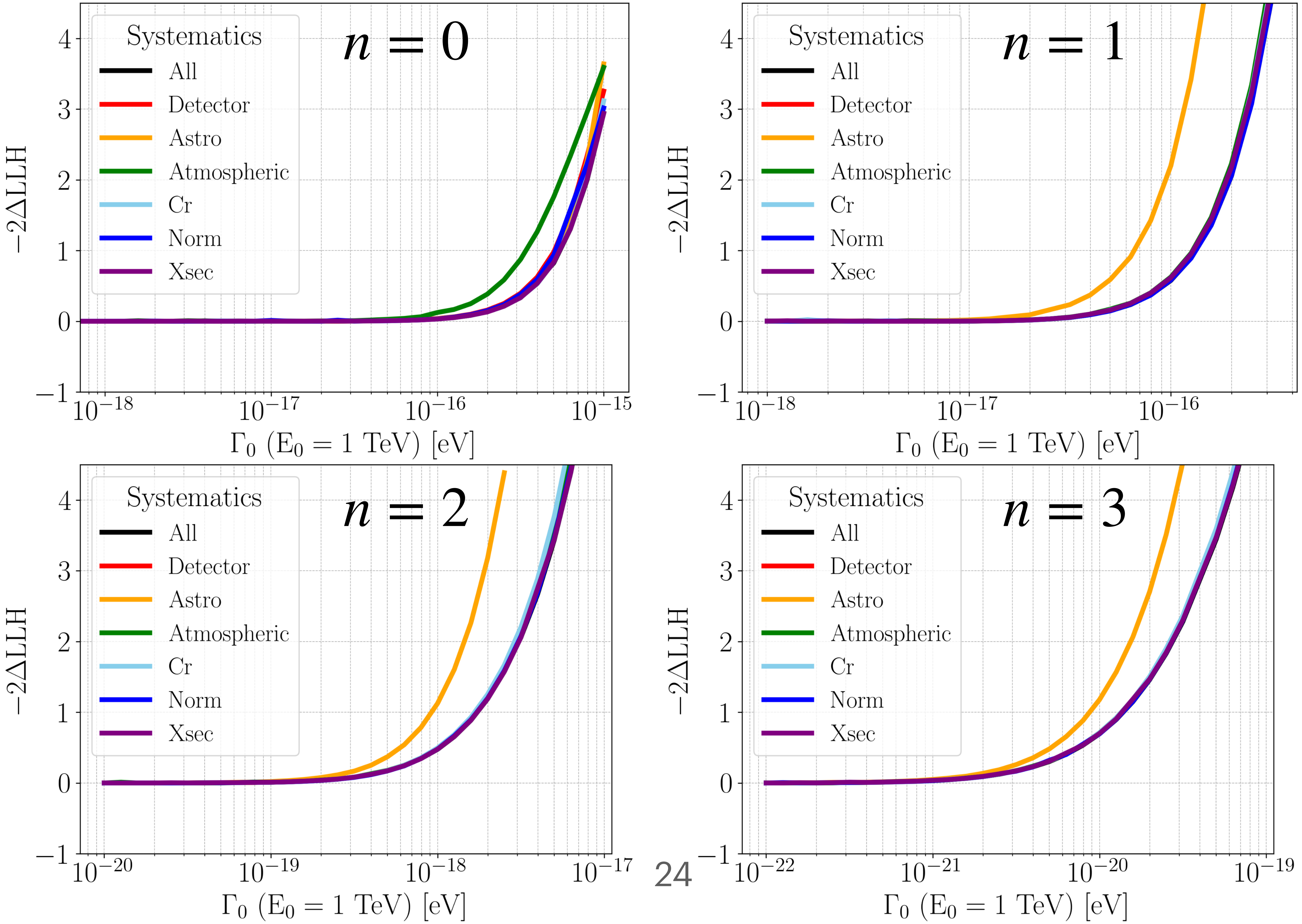


Farther left = more important systematic

See how it changes sensitivity

Systematic Impacts

State selection



Systematics

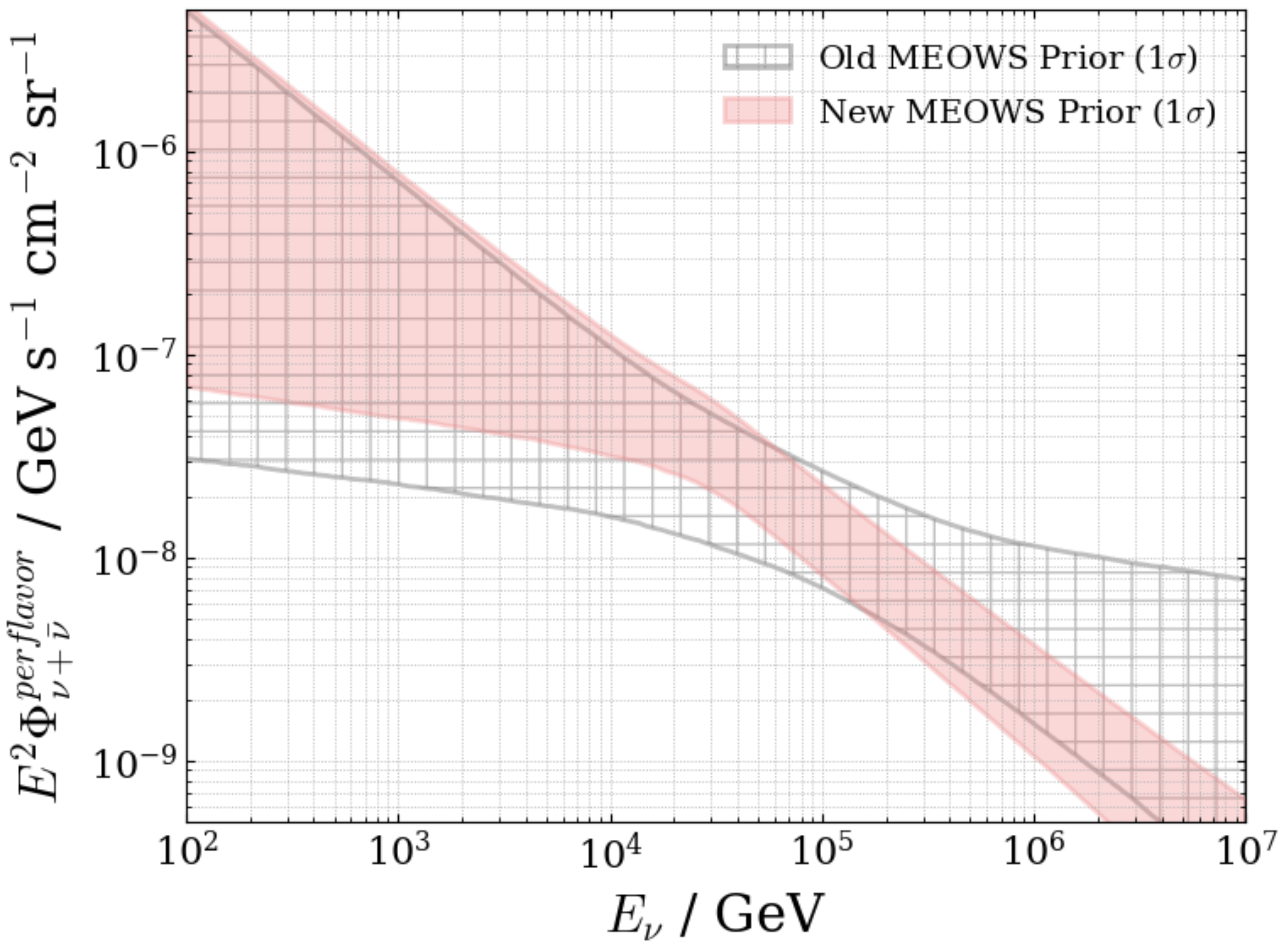
36 nuisance params used in this analysis

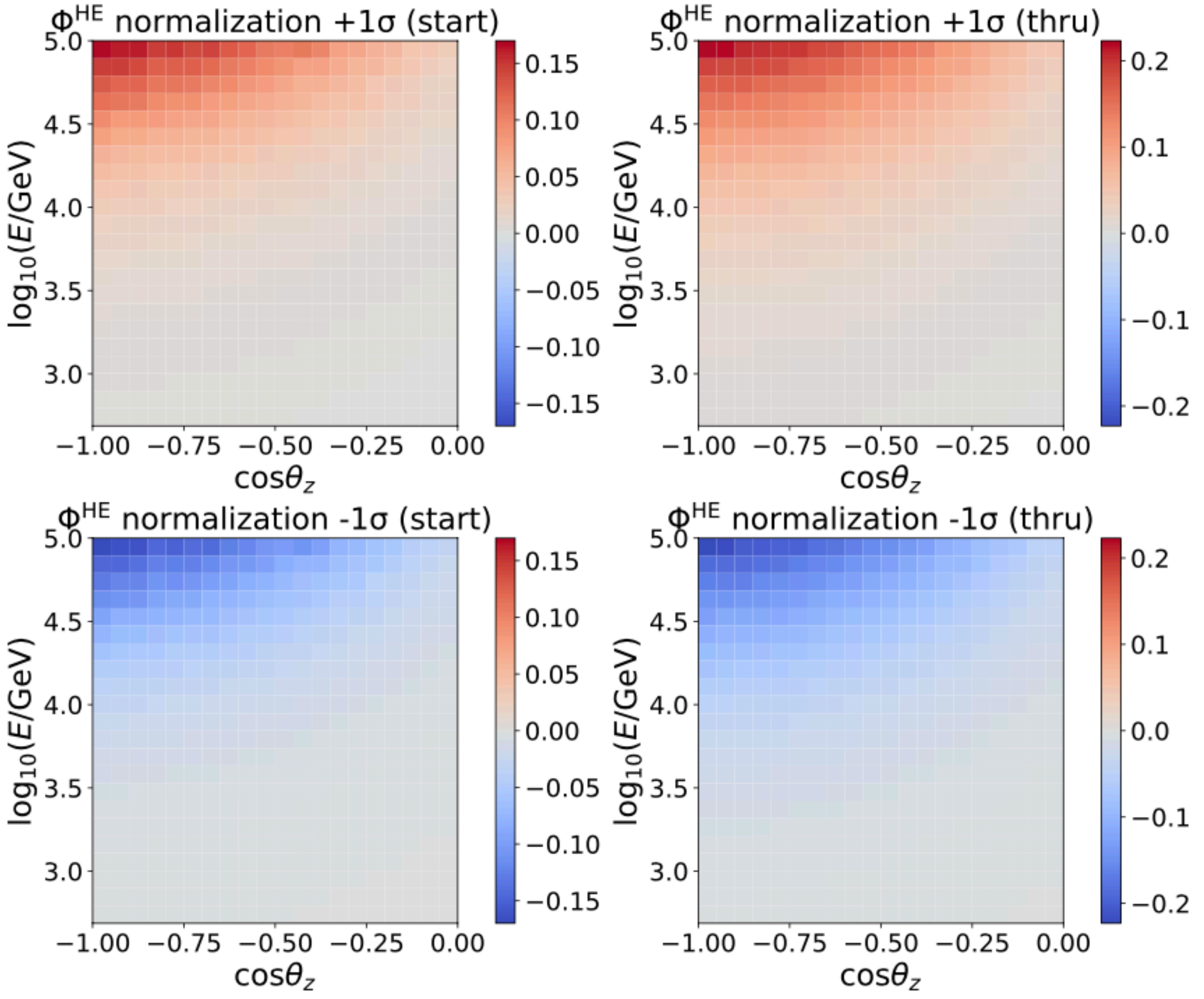
Systematic	Central	Prior (1σ)	Range	Implementation
Detector Parameters				
Normalization	1.0	± 0.2	[0.1,3]	
DOM efficiency	1.27	$\pm 10\%$	[1.234, 1.346]	6 support points
Ice Amplitude 0	0.0	± 1.0	[-3,3]	Correlation (see Fig. 19)
Ice Amplitude 1	0.0	± 1.0	[-3,3]	"
Ice Amplitude 2	0.0	± 1.0	[-3,3]	"
Ice 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]	"

Updated to better match recent measurements

Systematic Effects

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





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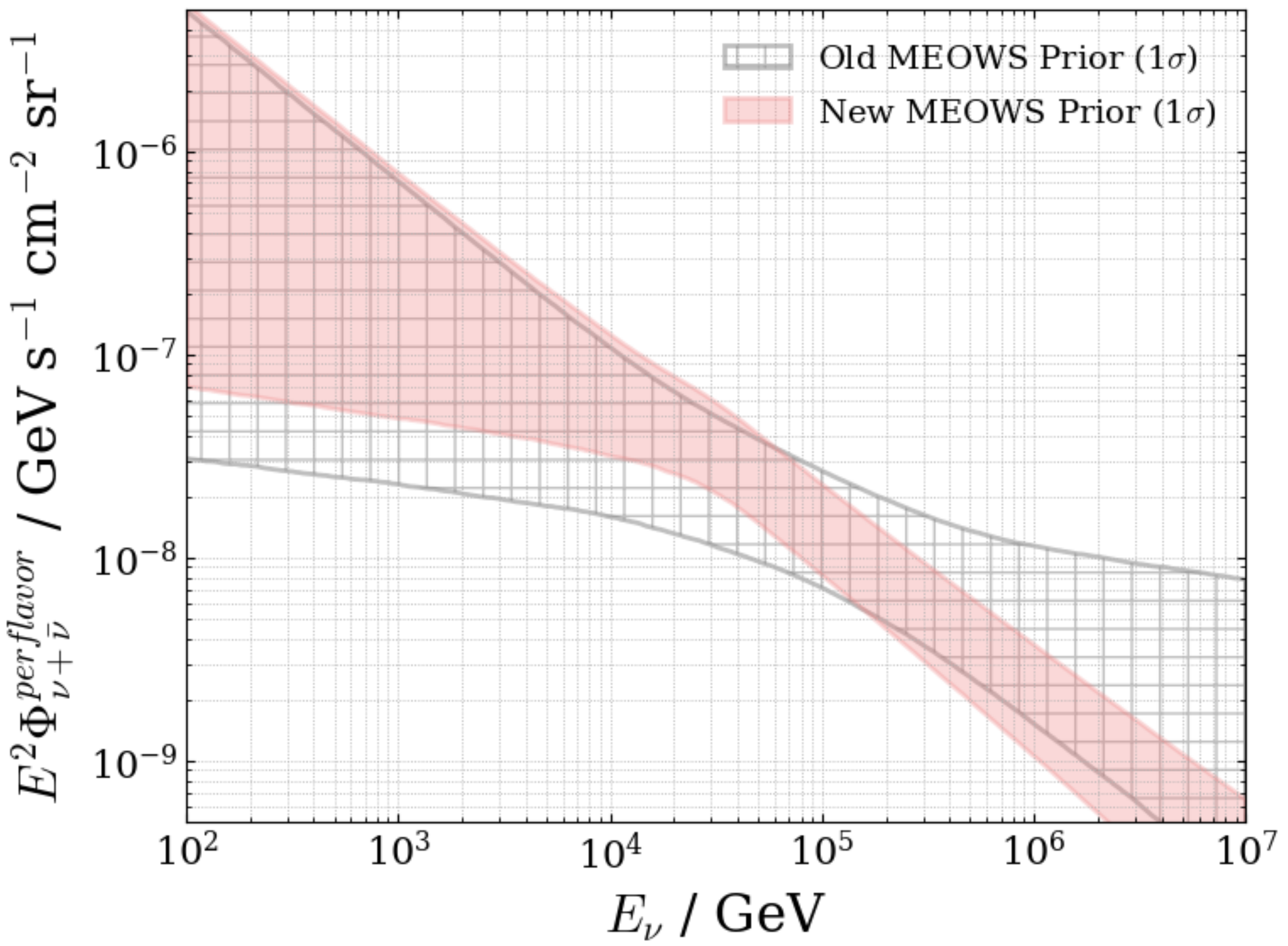
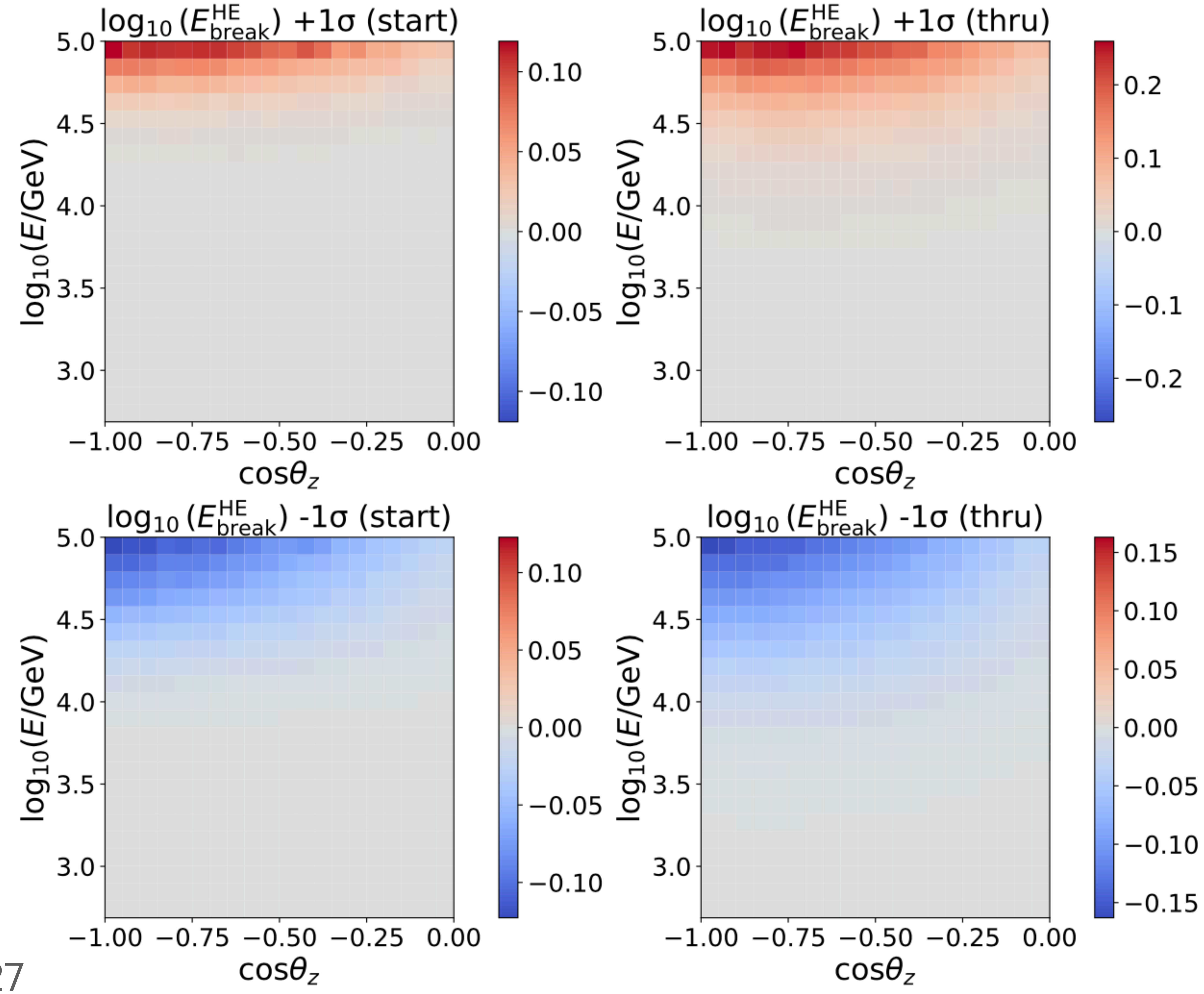
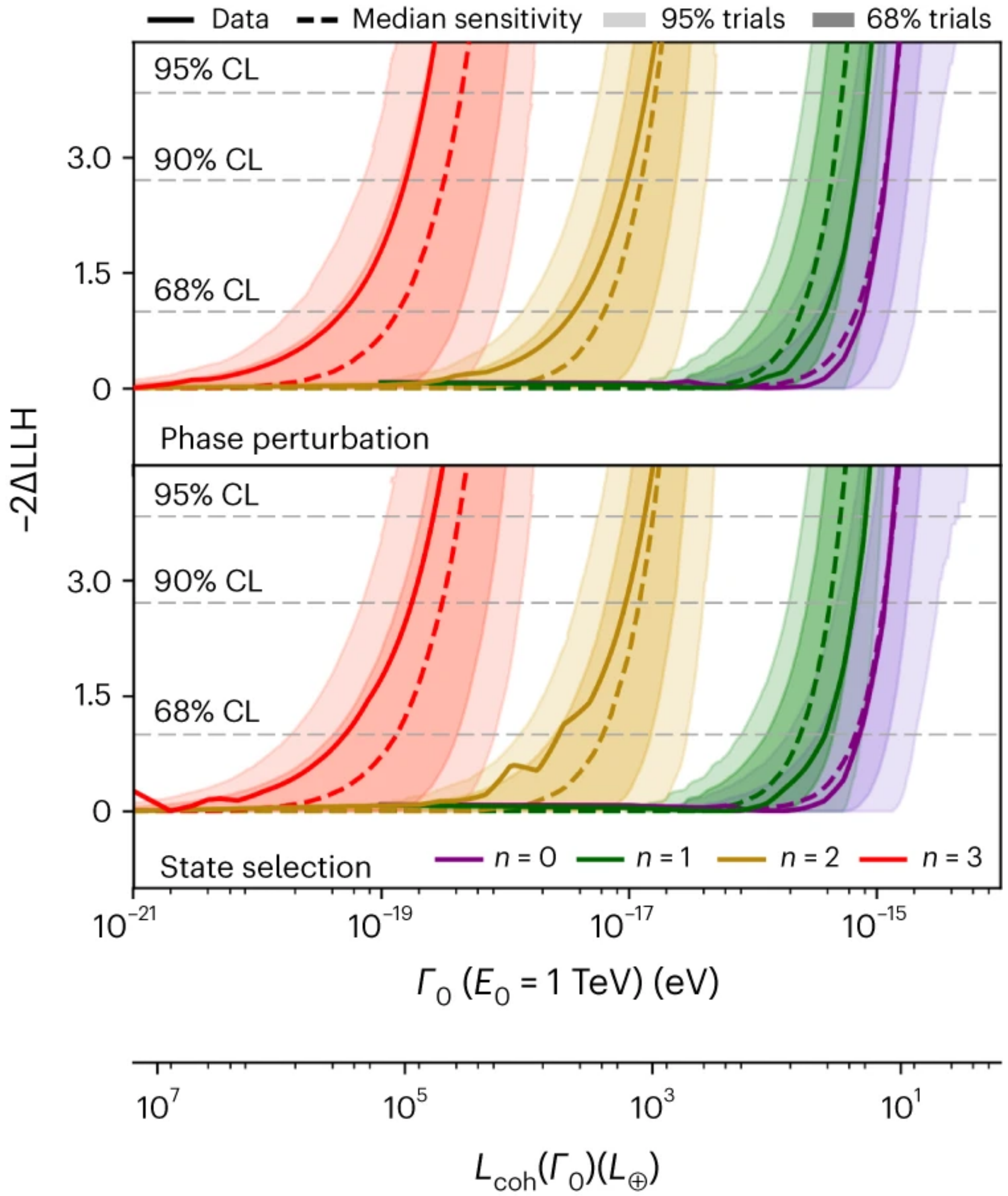




Previous IceCube Constraints

- 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



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