UCLouvain seminar

(Louvain-la-neuve, Belgium)

IceCube's Latest Results in the Search for eV-scale Sterile Neutrinos

Phys. Rev. Lett. 133, 201804 (2024), 2405.08070
Phys. Rev. D 110, 092009 (2024), 2405.08077

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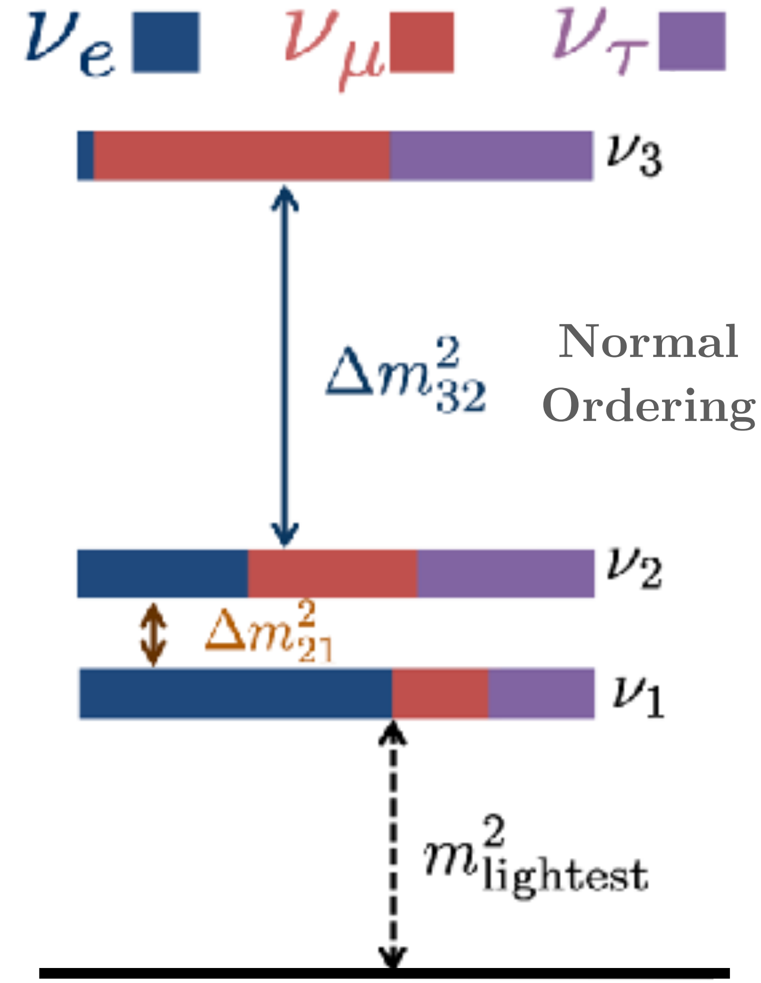
VEGA Valencia Experimental Group of Astroparticles

Neutrino oscillations



- Flavor states -> superposition of mass states
  - Parametrise with PMNS matrix
  - Measured most of the free parameters at percent level

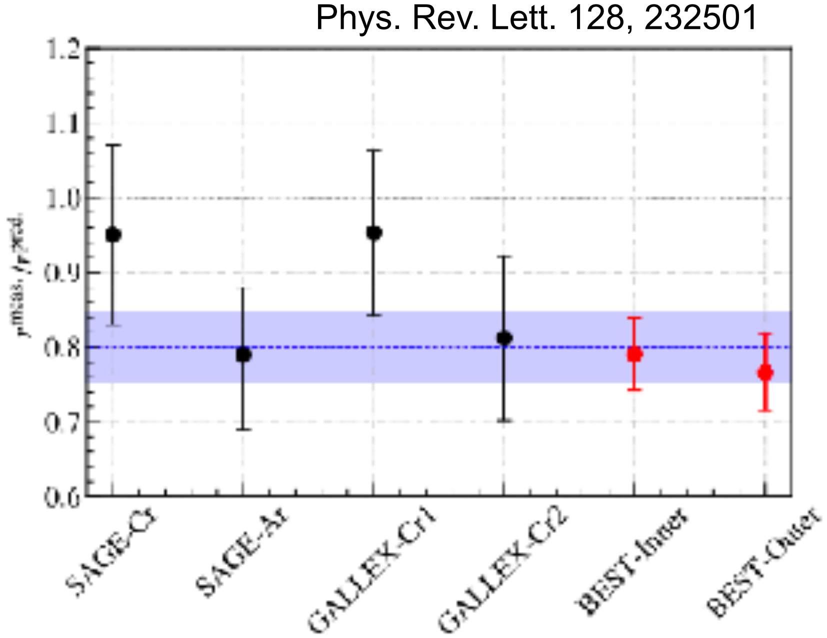
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospherics / Accelerators — Reactors / accelerator — Solar / reactors

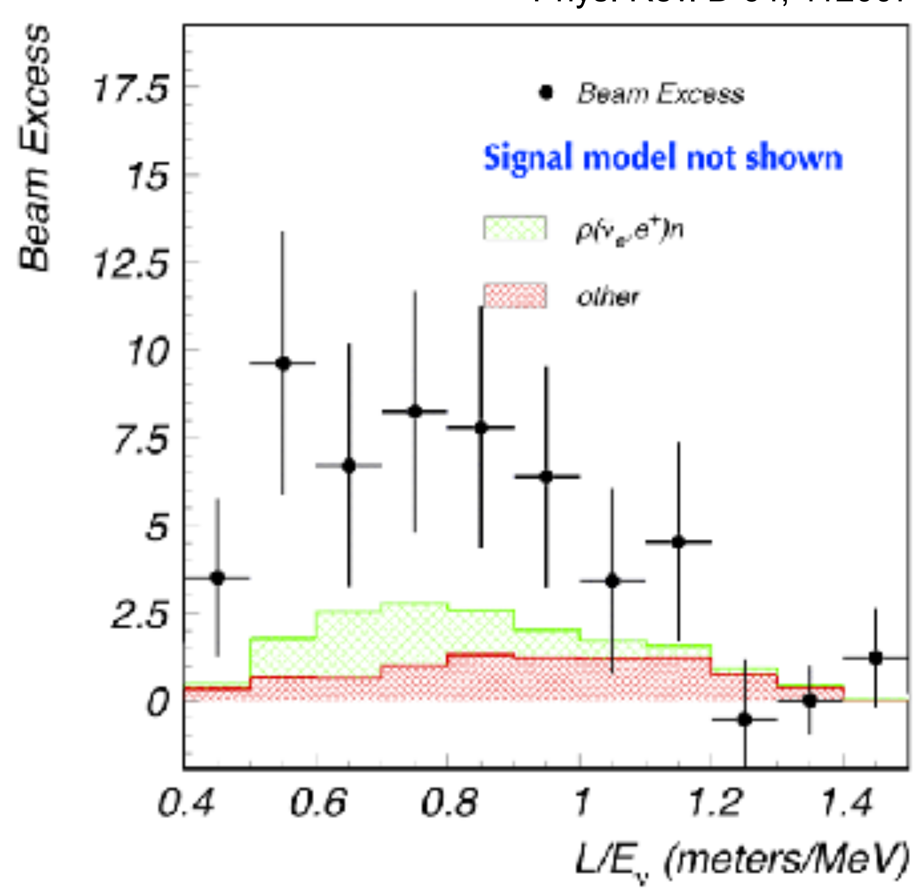
Anomalies

- Measurements in tension with standard oscillation (i.e. 3 states) at >3σ
  - Gallium anomaly -> less ν_e than expected
  - LSND -> more $\bar{\nu}_e$ than expected
  - MiniBoone -> more ν_e and $\bar{\nu}_e$ than expected

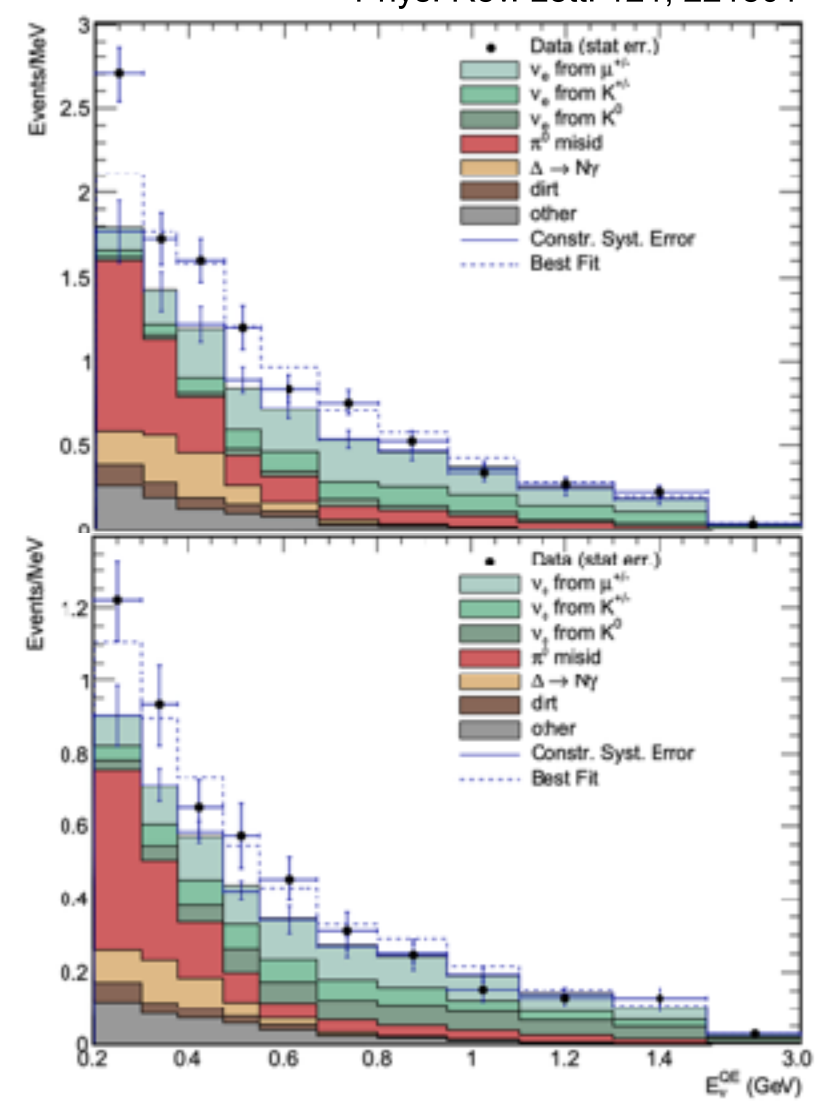
Phys. Rev. Lett. 128, 232501



Phys. Rev. D 64, 112007

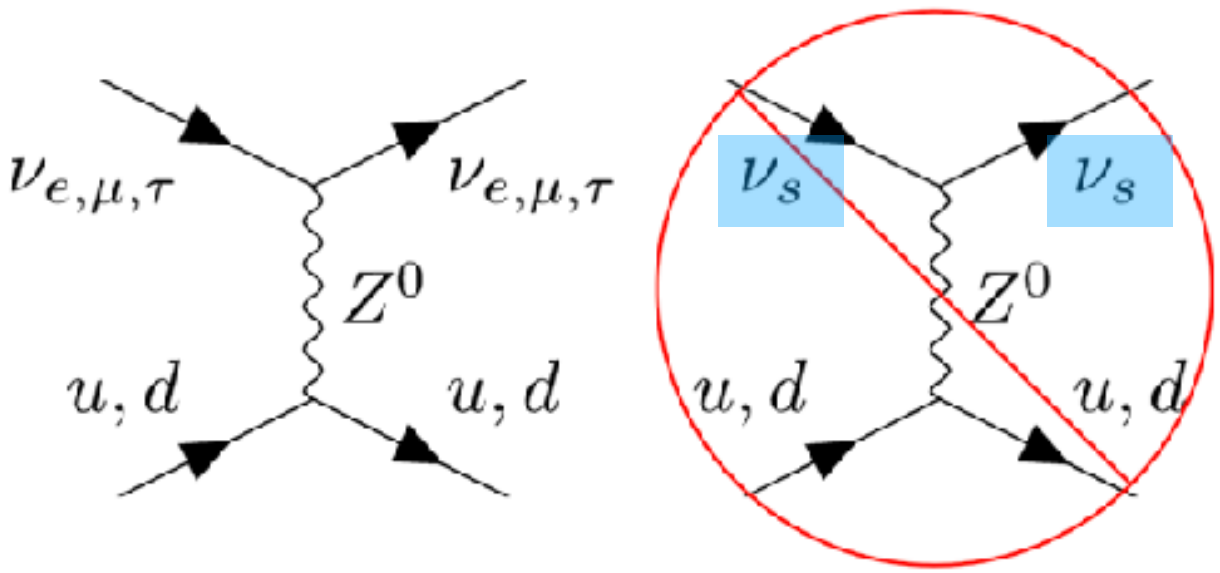


Phys. Rev. Lett. 121, 221801

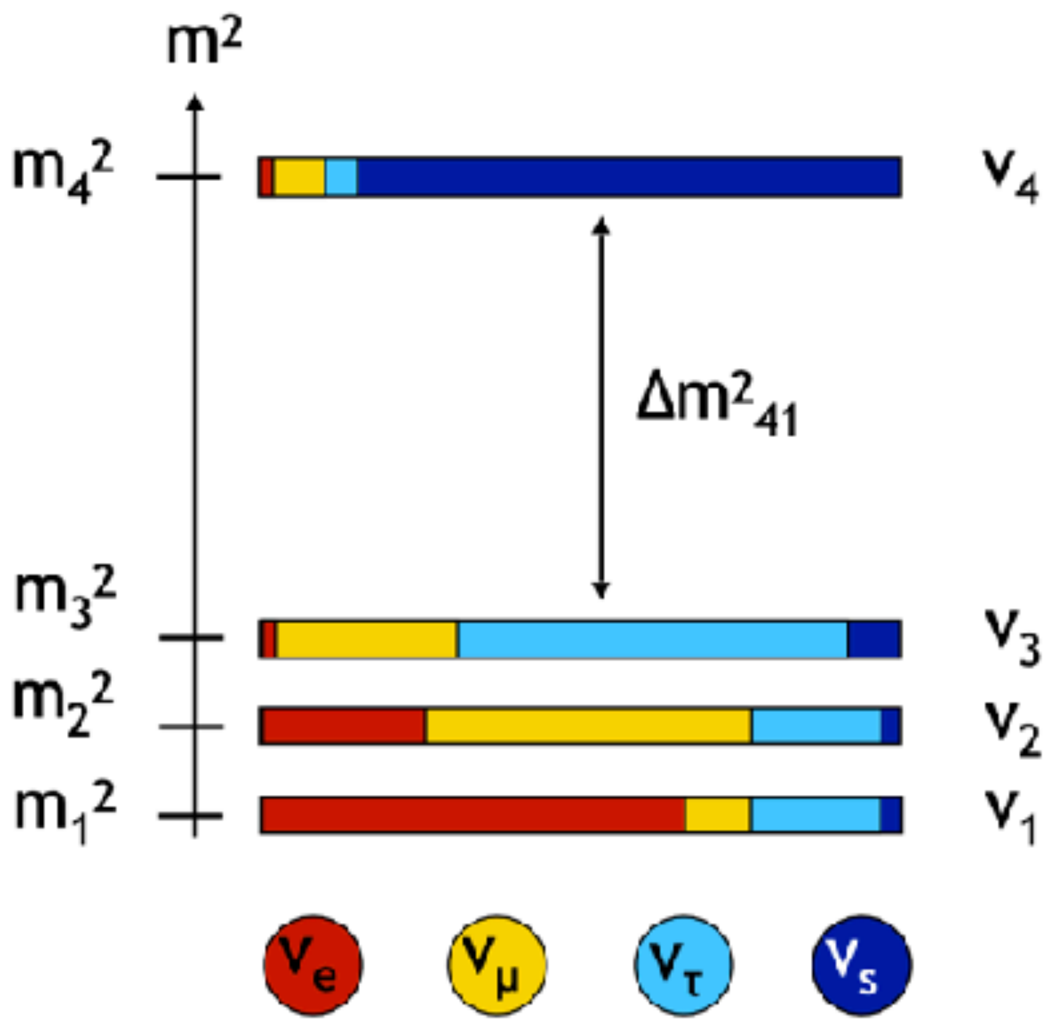


3+1 model

- Minimal extension -> new mass state that is blind to weak force
  - Alters standard oscillation probabilities
  - eV-scale sterile allows to explain "one by one" anomalies



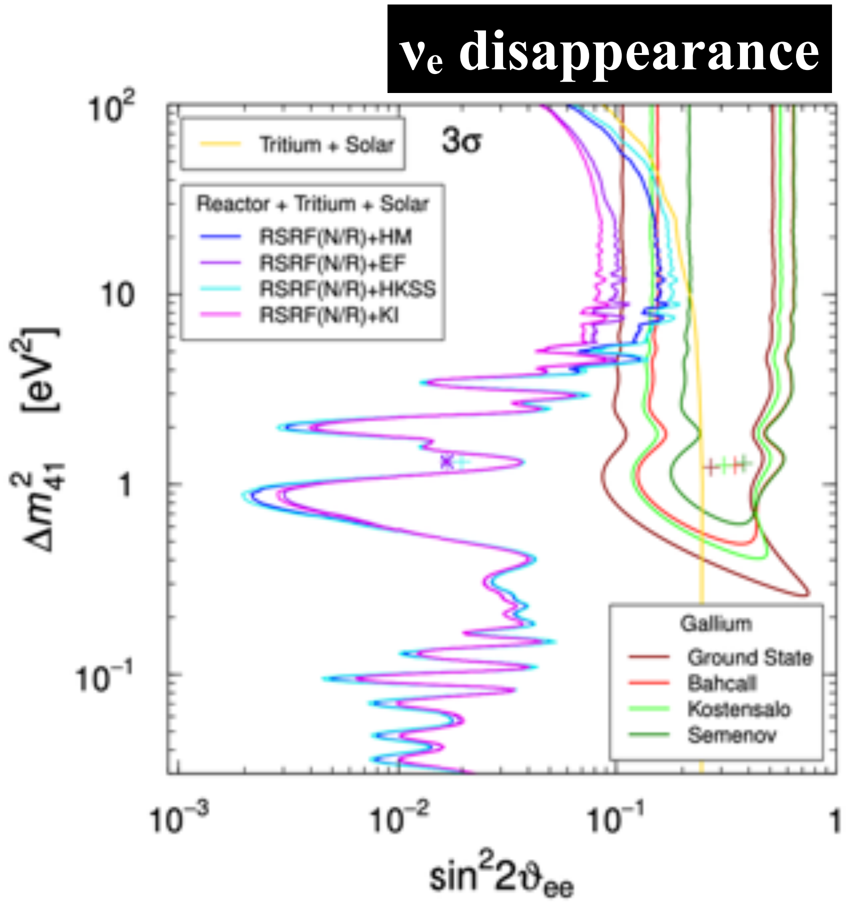
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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



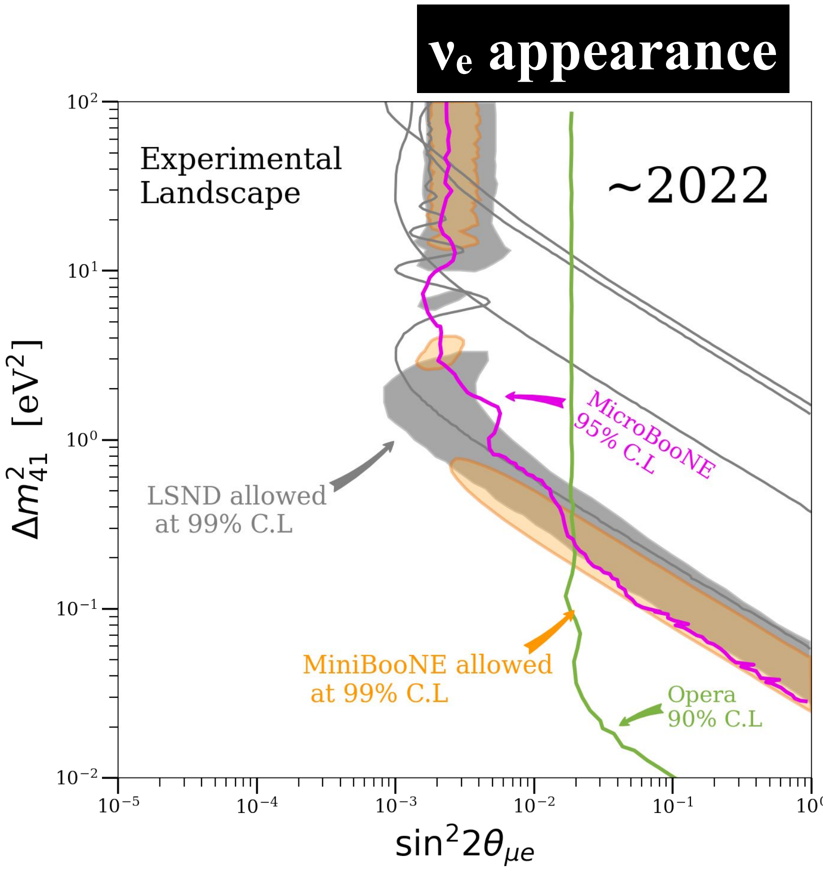
Normal ordering

3+1 puzzle

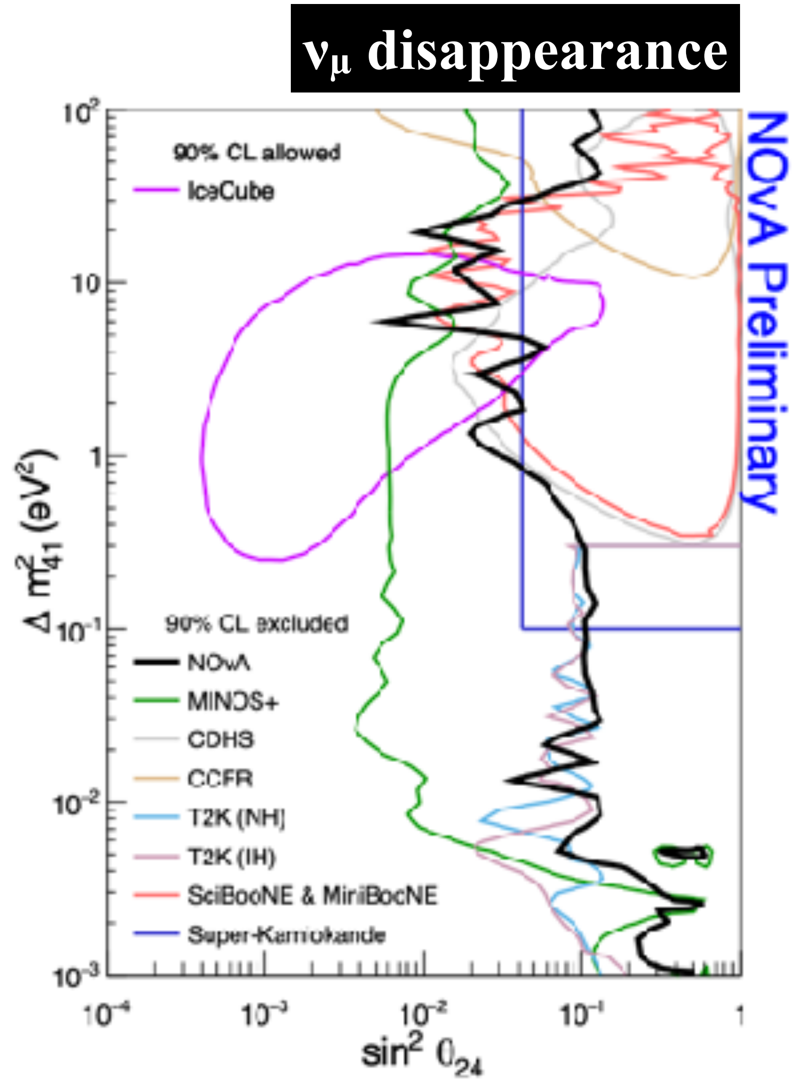
- 3+1 does not find a consistent picture when performing global fits
  - $\nu_\mu \rightarrow \nu_e$ appearance requires $\nu_\mu \rightarrow \nu_\mu$ disappearance



C. Giunti (2209.00916)



M. Ross (SnowMass 2022)

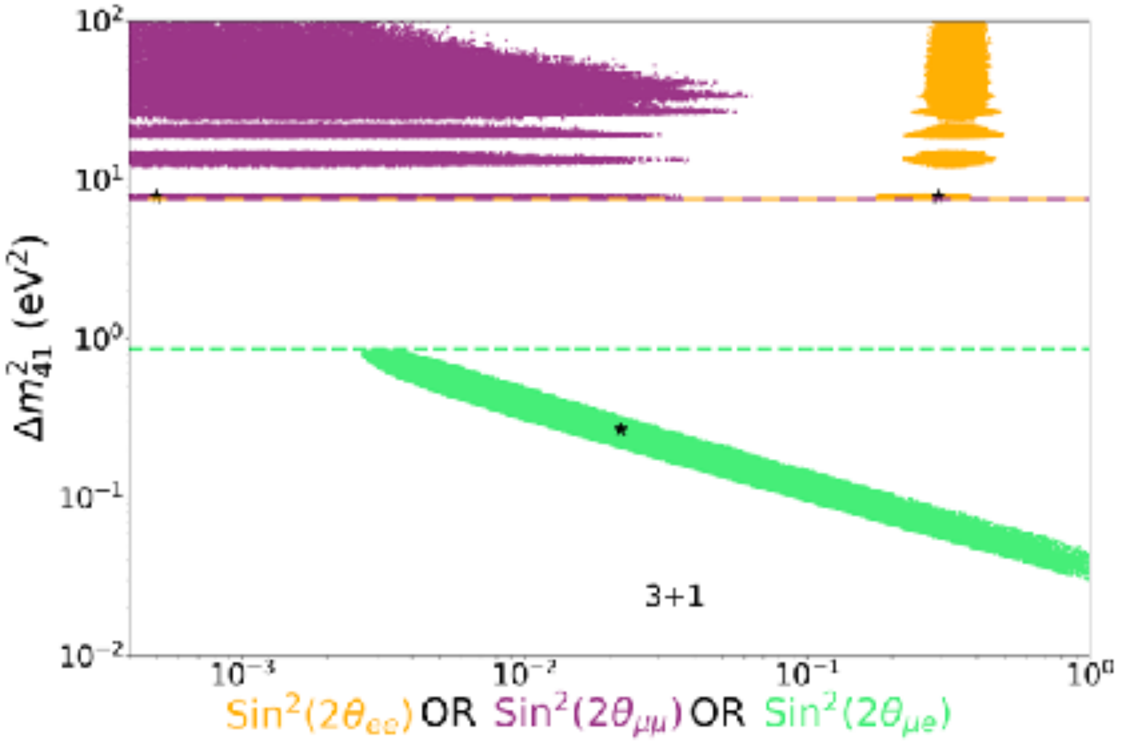


A. Sutton (NuFact 2023)

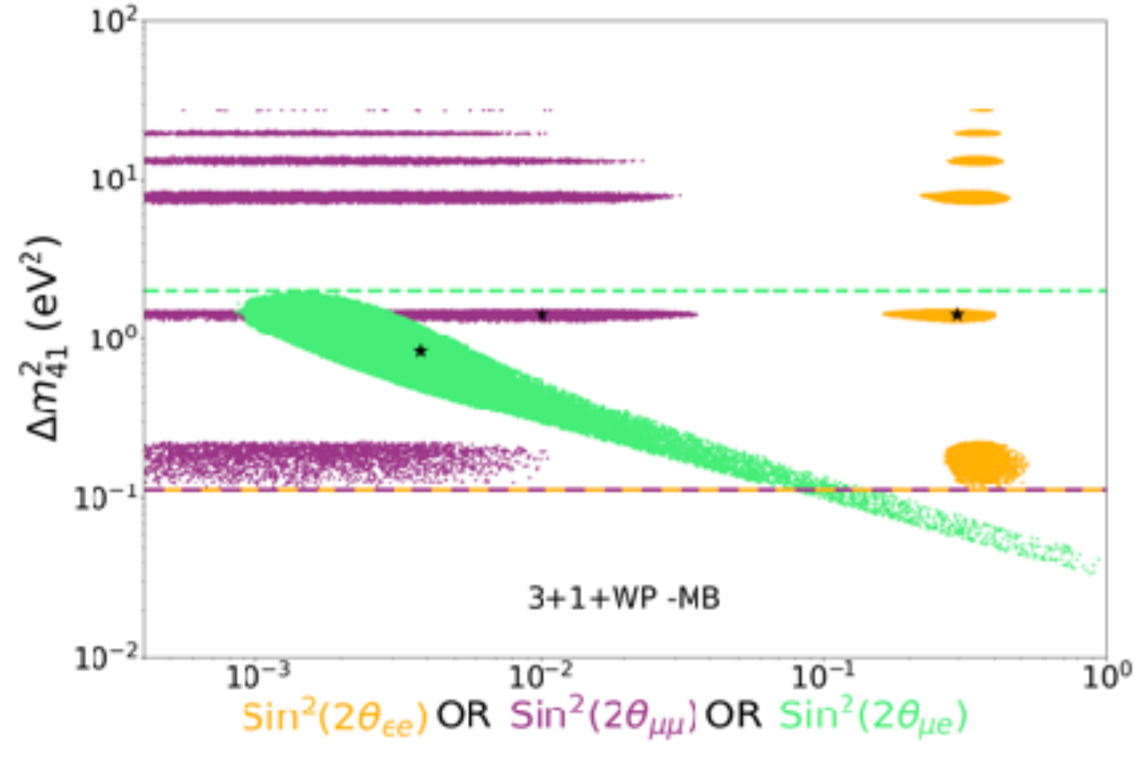
Ways to solve this puzzle

- More exotic scenarios might help reducing this tension
  - 3+1+decay, 3+1+Wavepacket, 3+X?

3+1 (4.5σ tension)



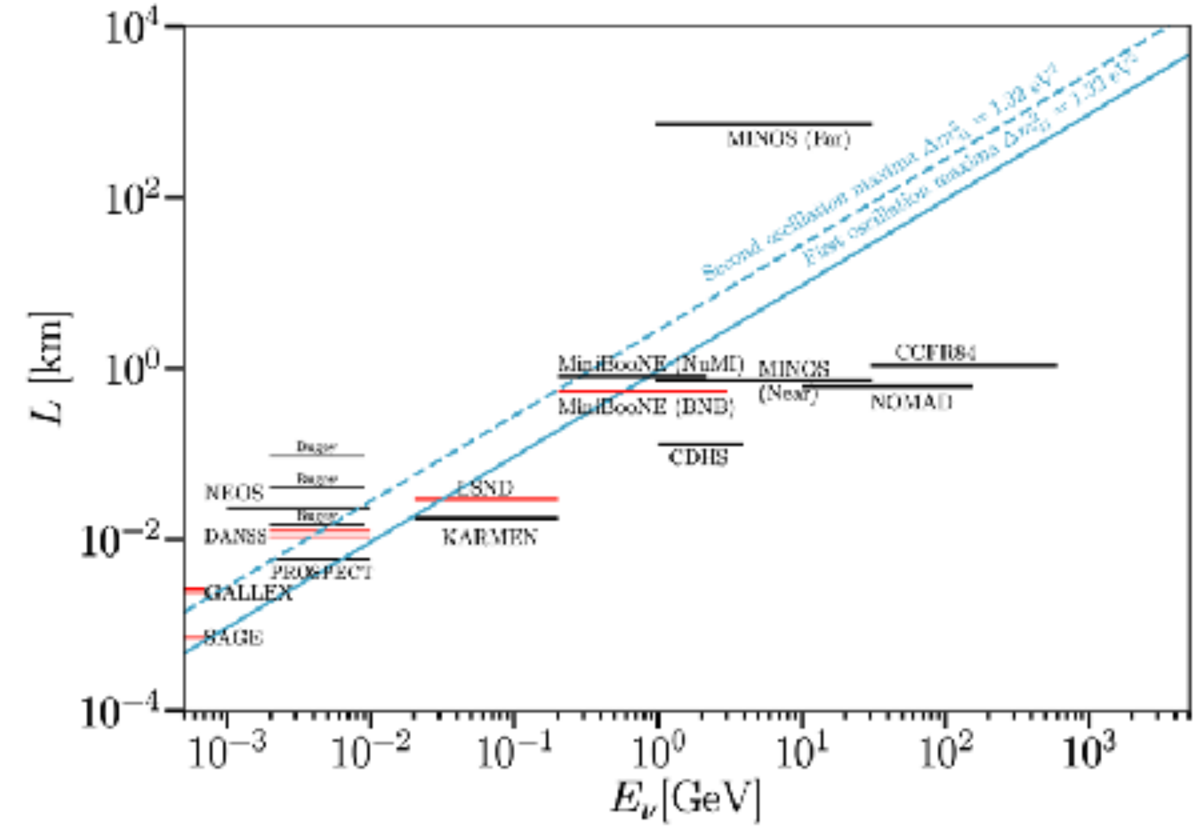
3+1+WP(noMB) (2.1σ tension)



JHEP 09 (2023) 058

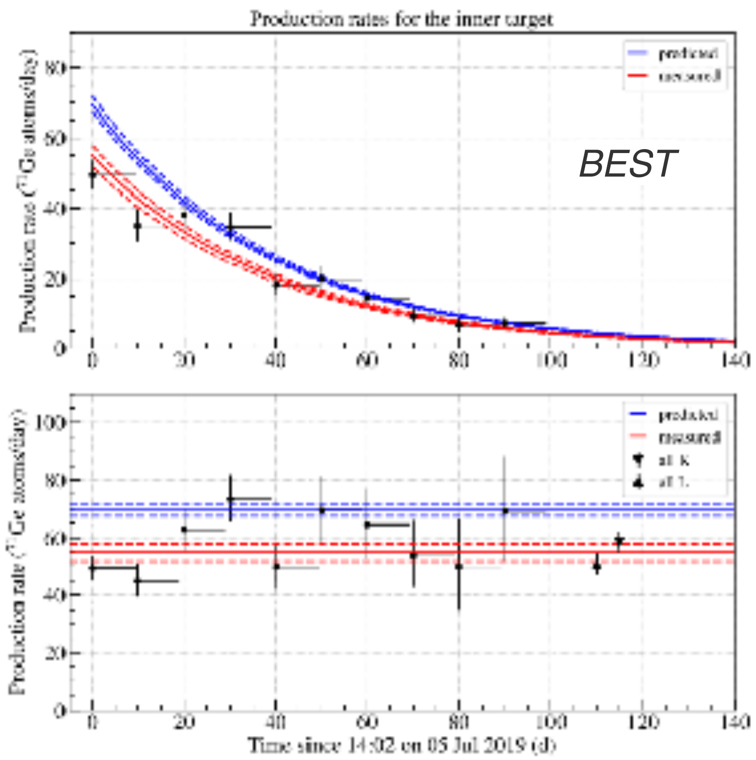
Wavepacket width of ~100fm
Too low according to theoretical calculations

Ways to solve this puzzle

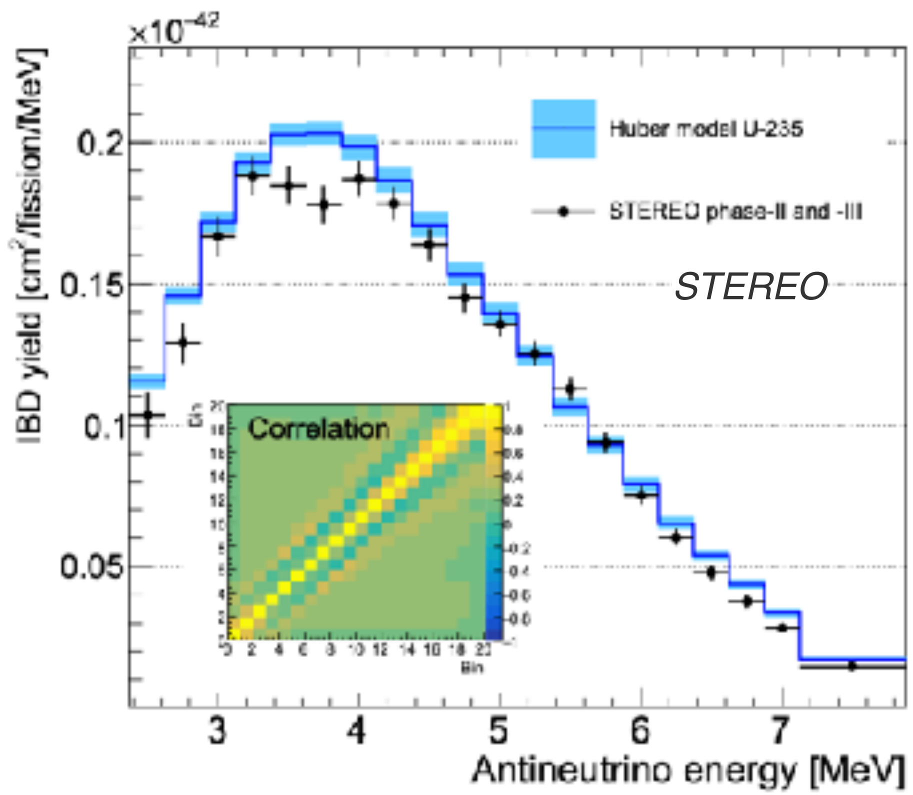


- What about data/systematics?
  - Collect more data with other experiments

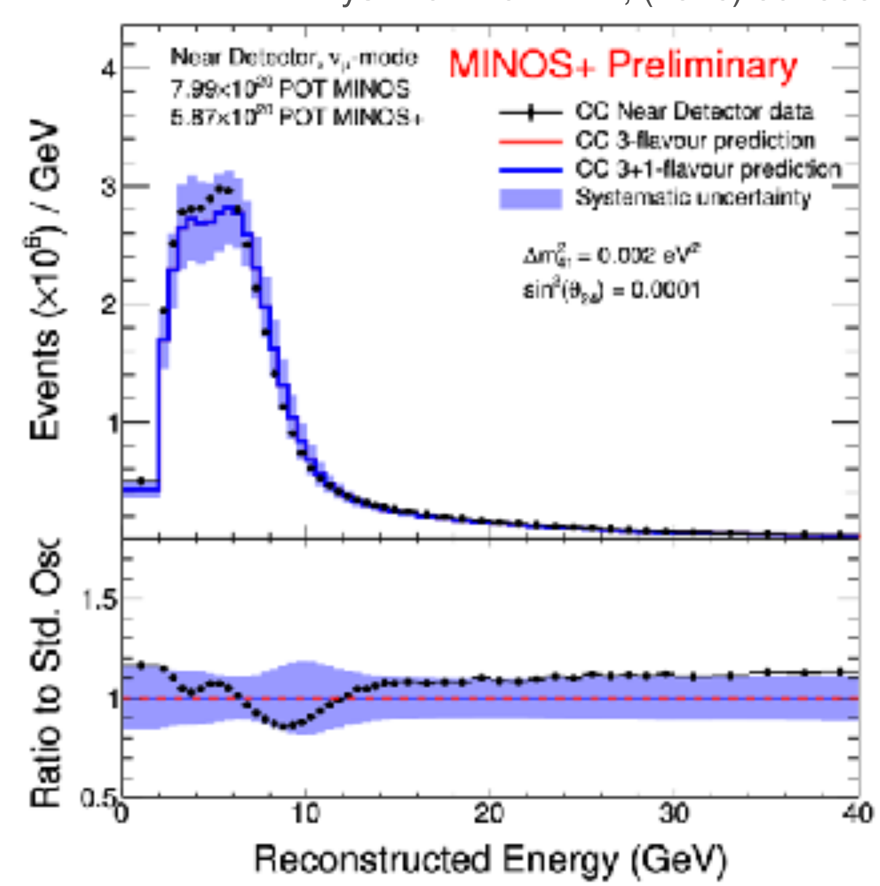
Phys.Rev.C 105 (2022) 6



Nature 613 (2023) 7943

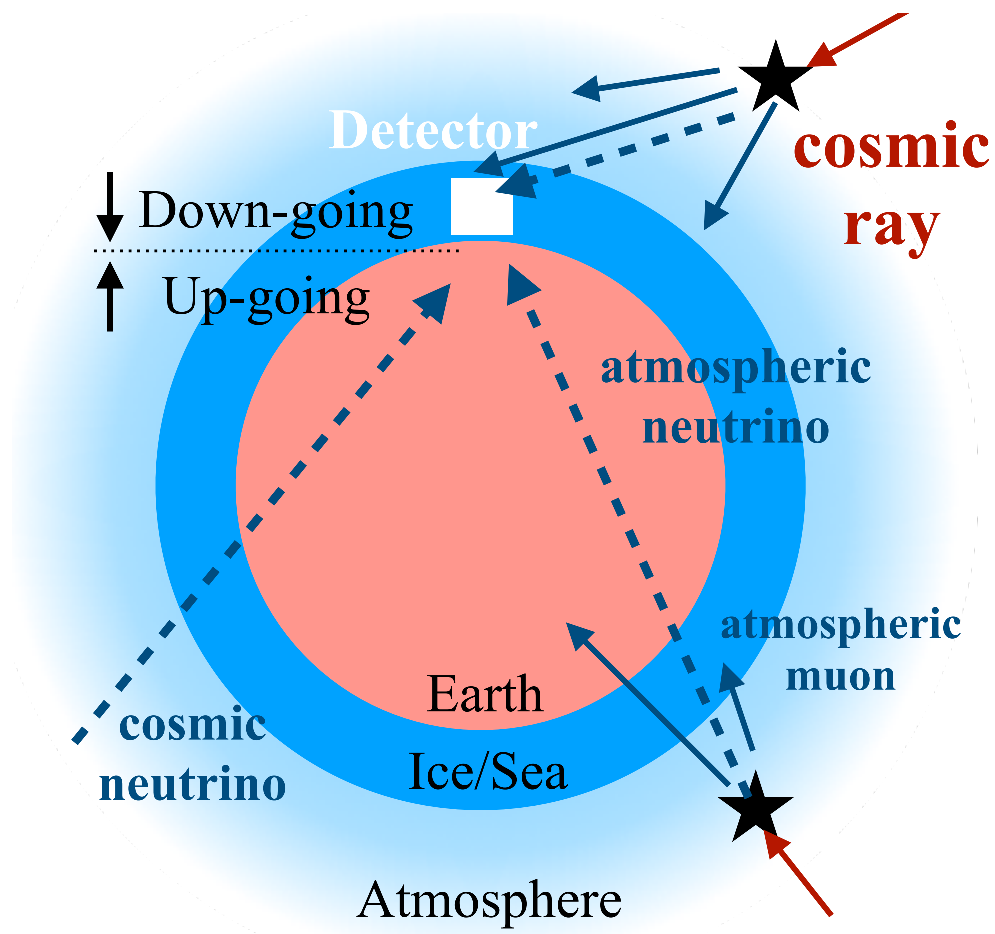


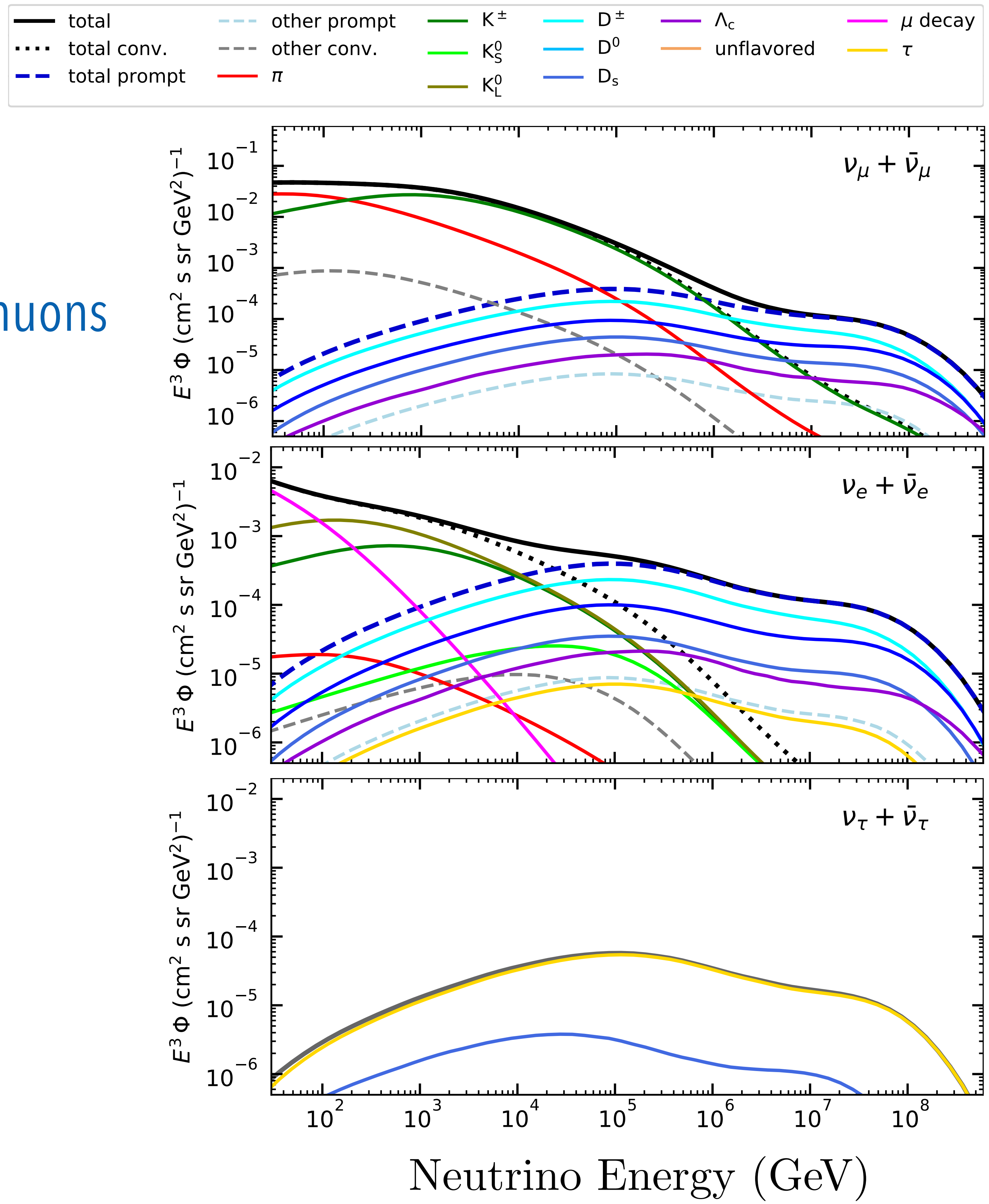
Phys. Rev. Lett. **122**, (2019) 091803



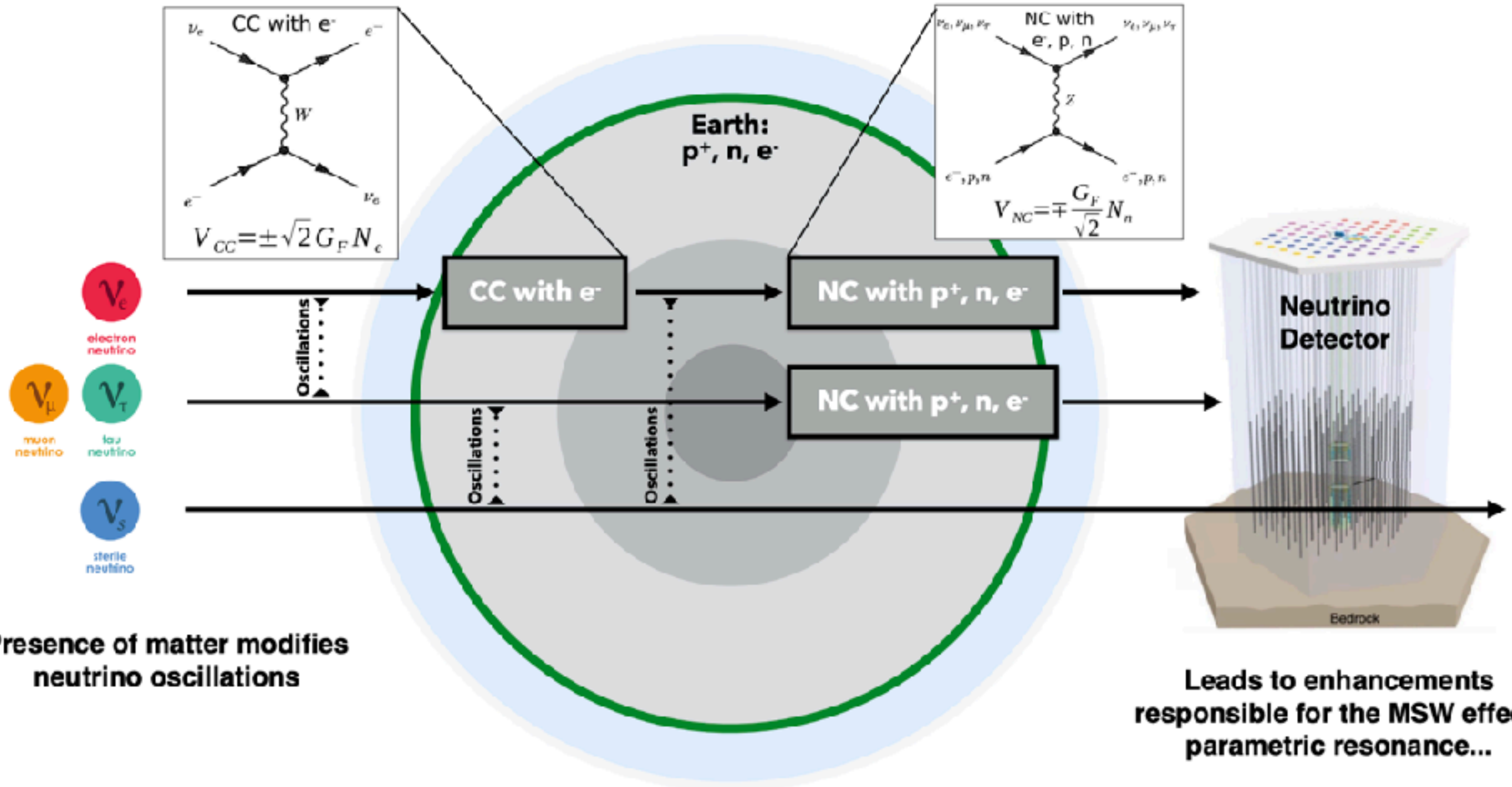
Atmospheric neutrinos

- Dominated by ν_μ from **kaon decay**
- Up-going -> shield for atmospheric muons





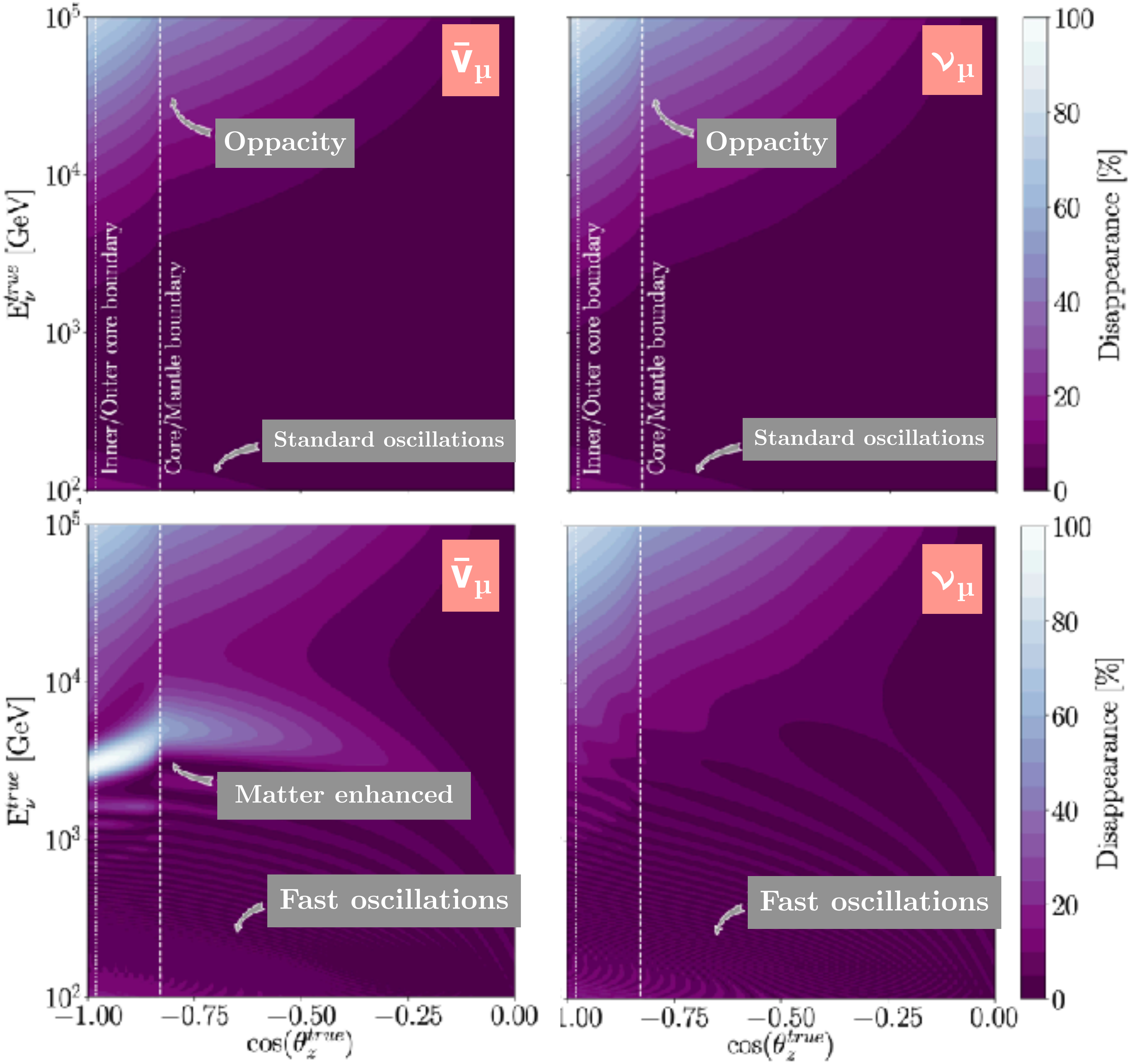
Matter enhanced oscillation



Presence of matter modifies neutrino oscillations

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

Matter enhanced oscillation

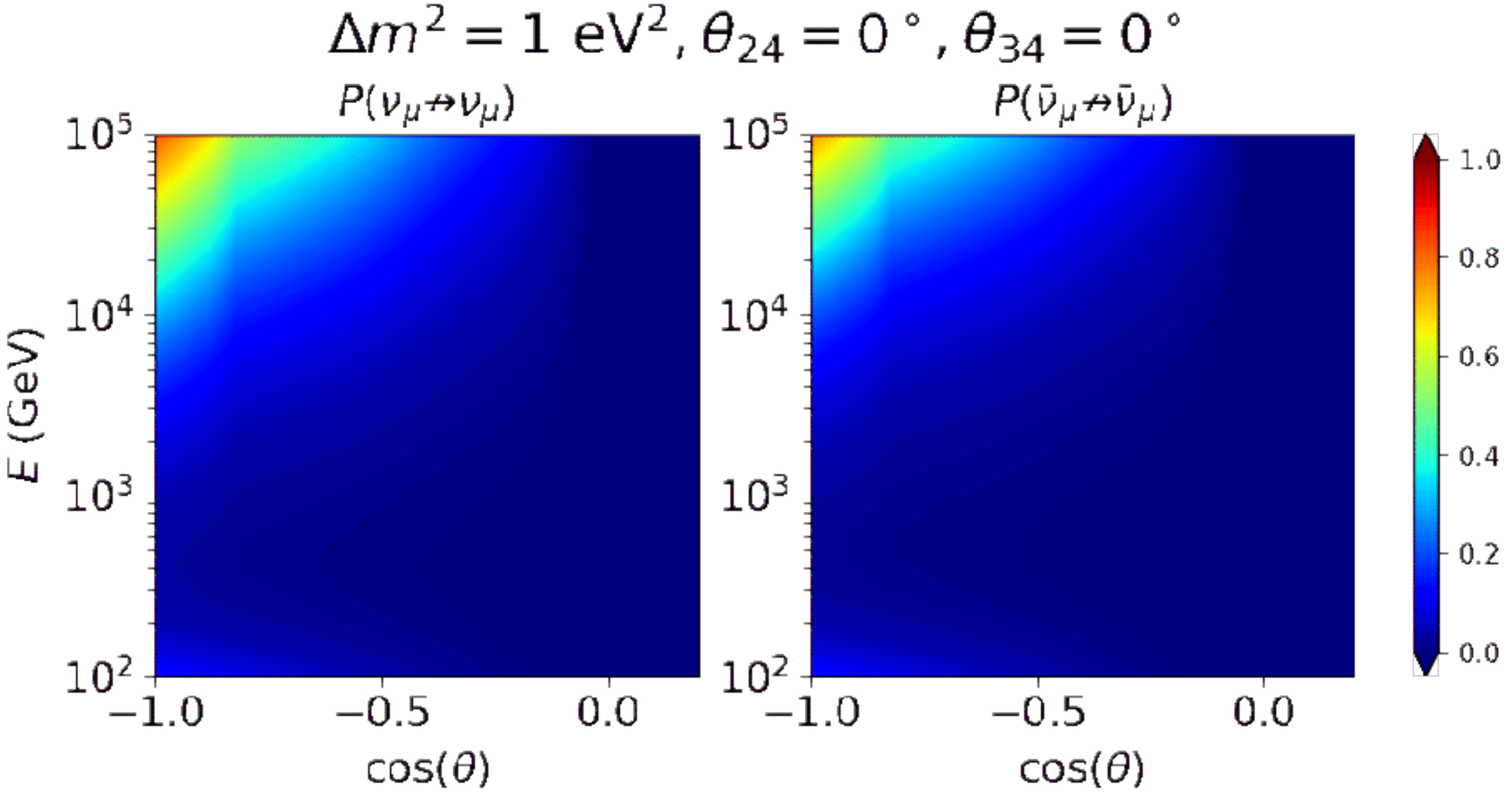


No Sterile

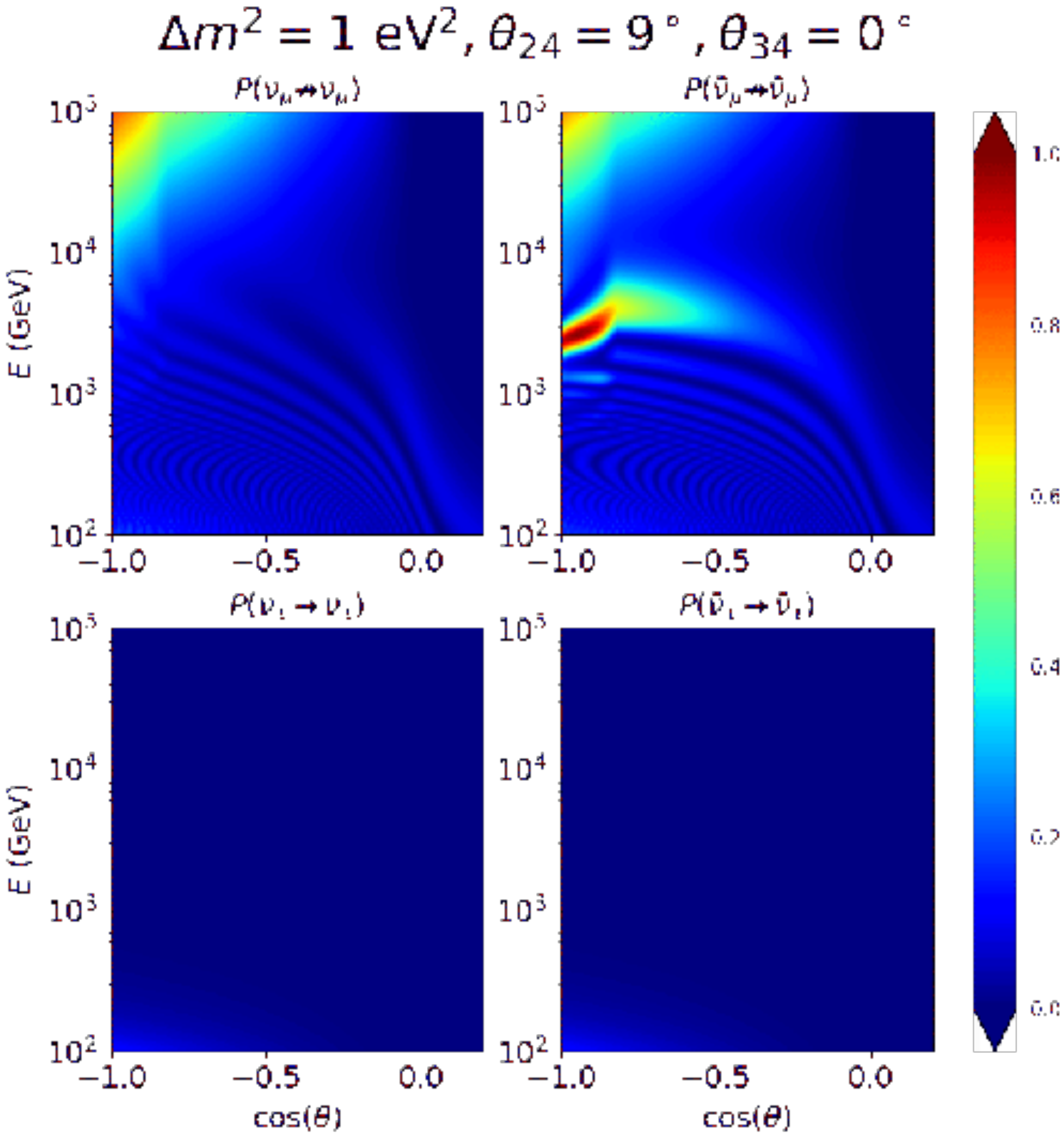
Sterile:
Δm^2_{41} = 1.3eV^2
$\sin(2\theta_{24})^2$ = 0.07

Unique
disappearance signature
(matter effects in $\bar{\nu}_\mu$)

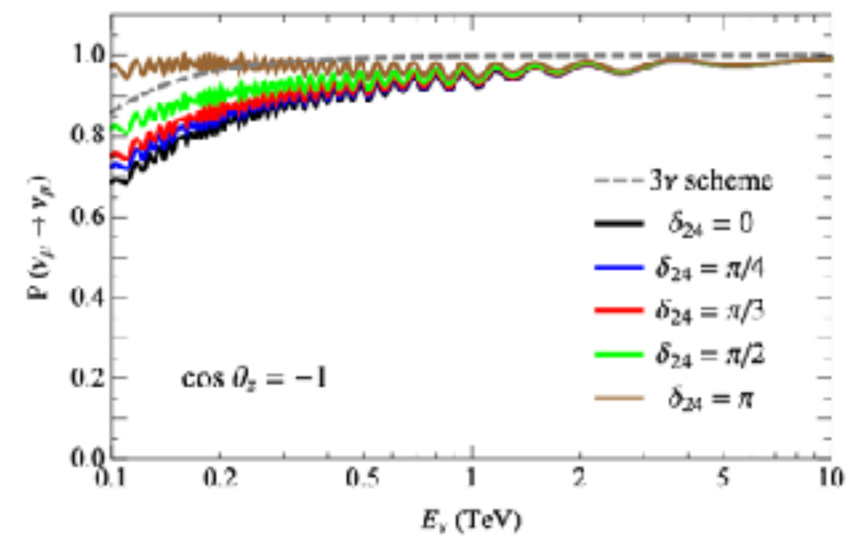
Matter enhanced oscillation – sample scenario

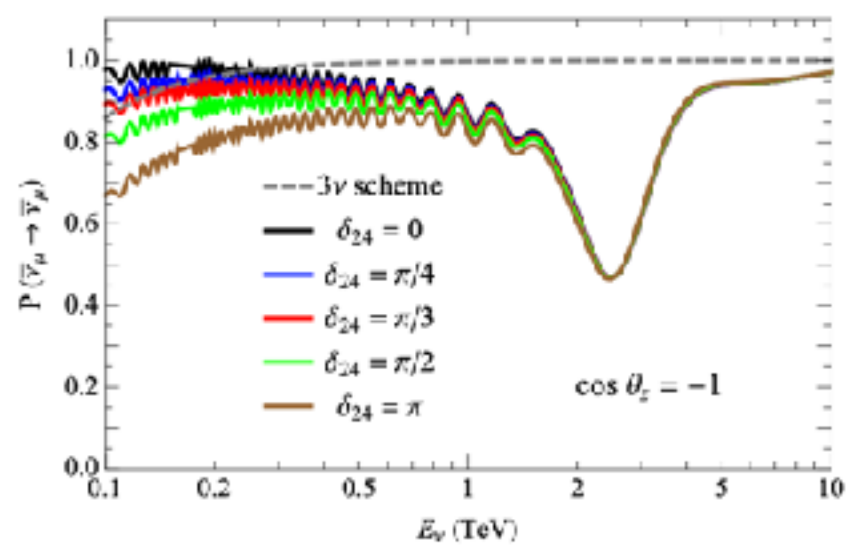


Matter enhanced oscillation - more complex scenarios



Important if θ_{34}!=0 and E<500GeV

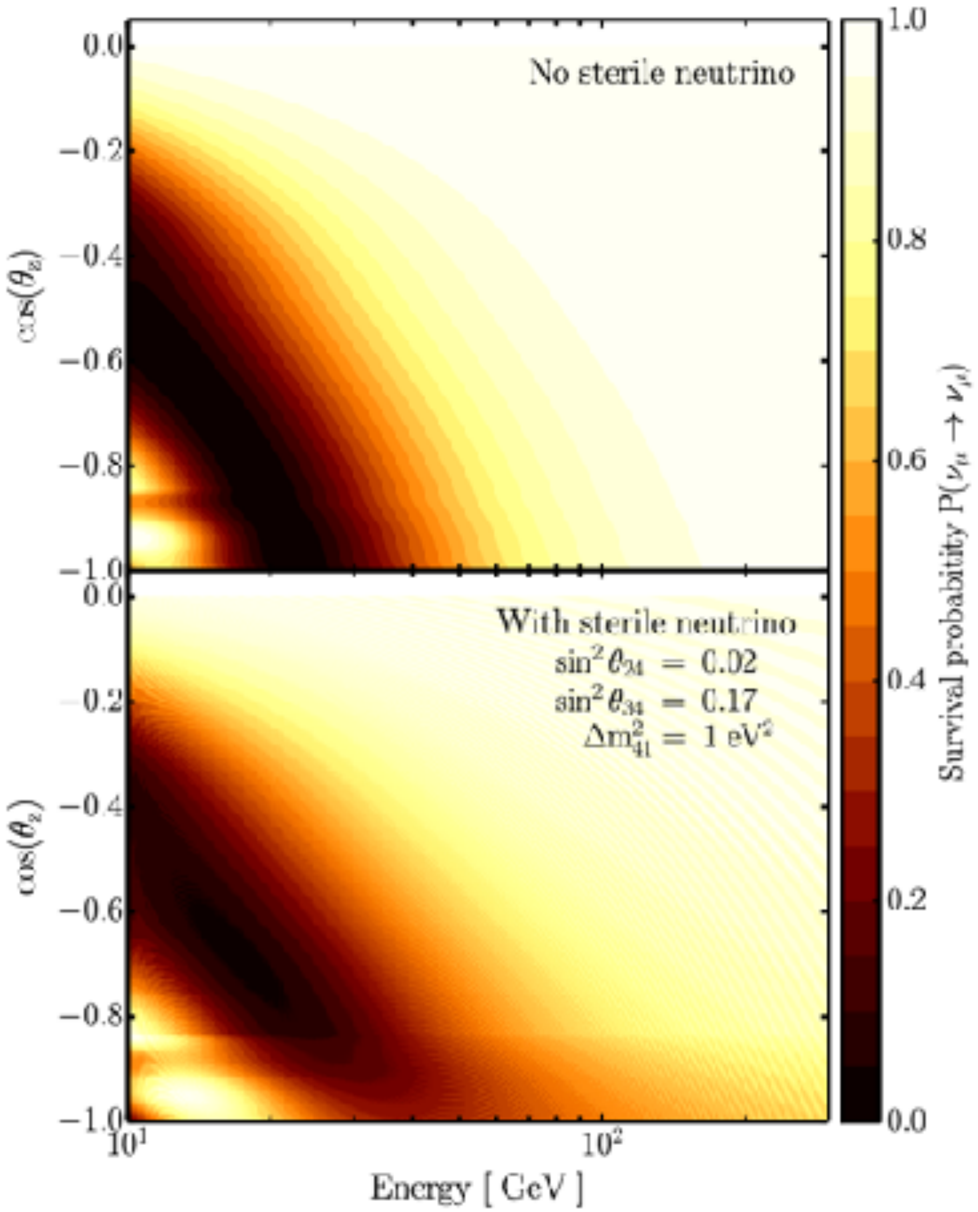


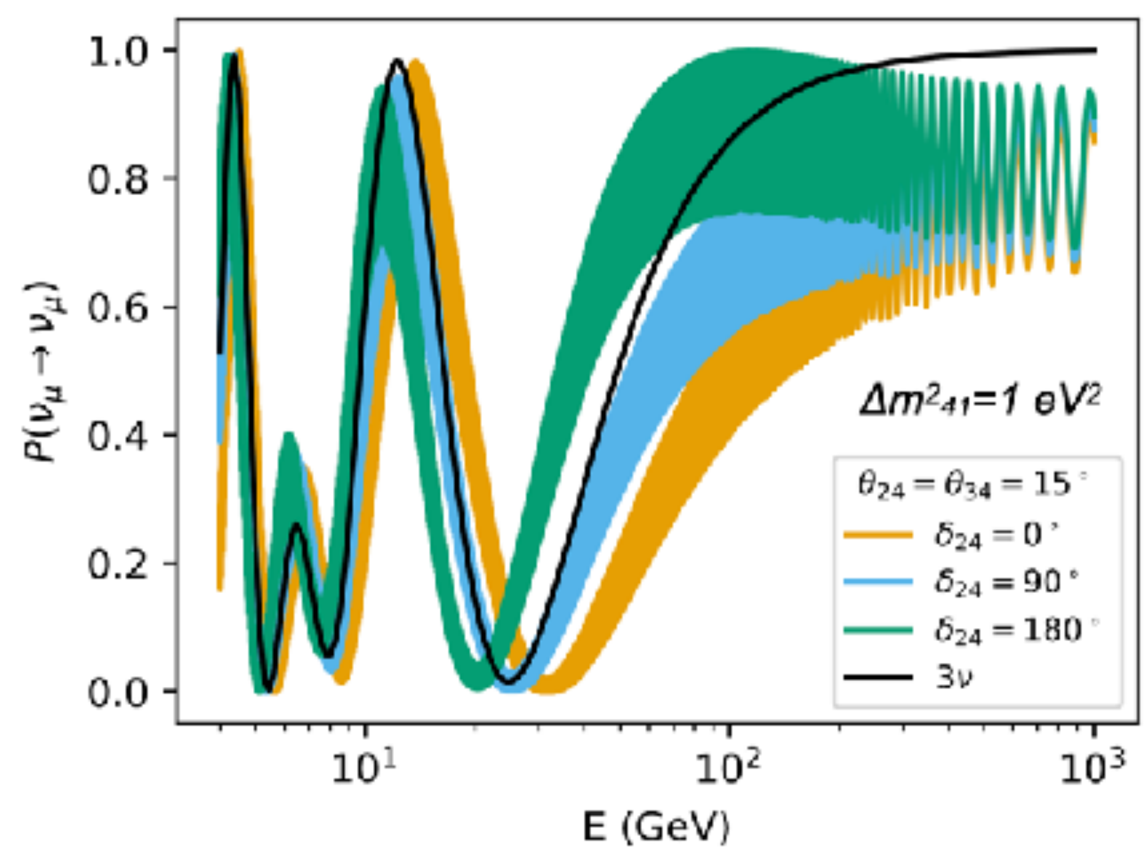


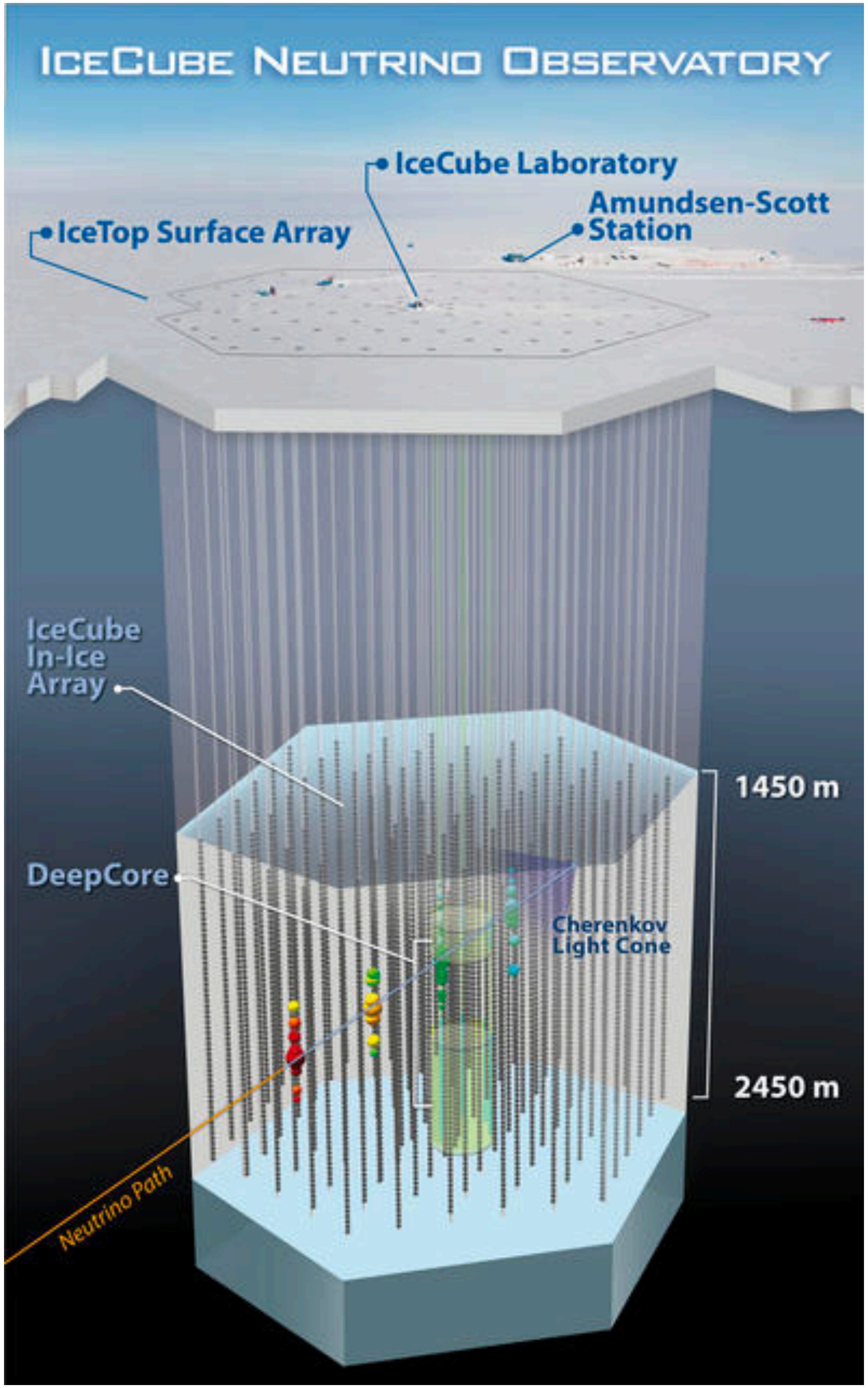
A. Esmaili, A. Smirnov (1307.6824) -> We show that the case with $U_{\tau 4} = \delta_{24} = 0$ leads to the weakest IceCube signal and therefore should be used to bound $U_{\mu 4}$.

Oscillations in the GeV regime

- For mass splitting >1eV^2, rapid oscillations -> average
- Some degeneracy with standard oscillation parameters but resolvable



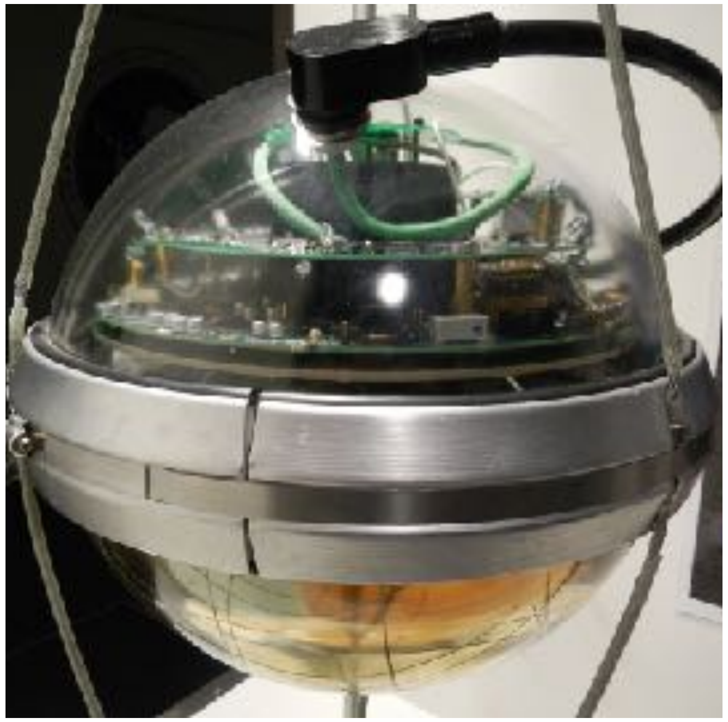




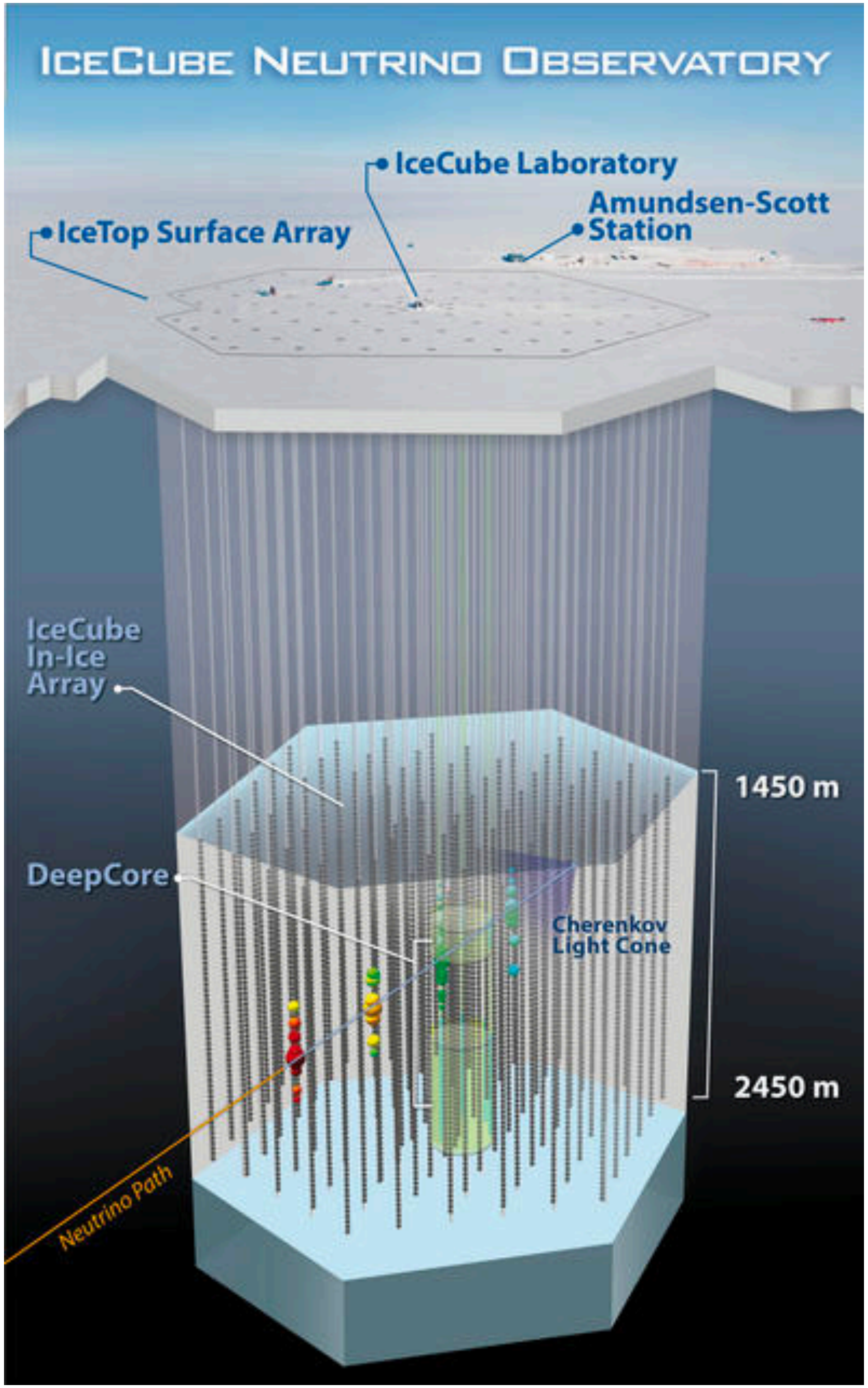
Largest neutrino detector on Earth!

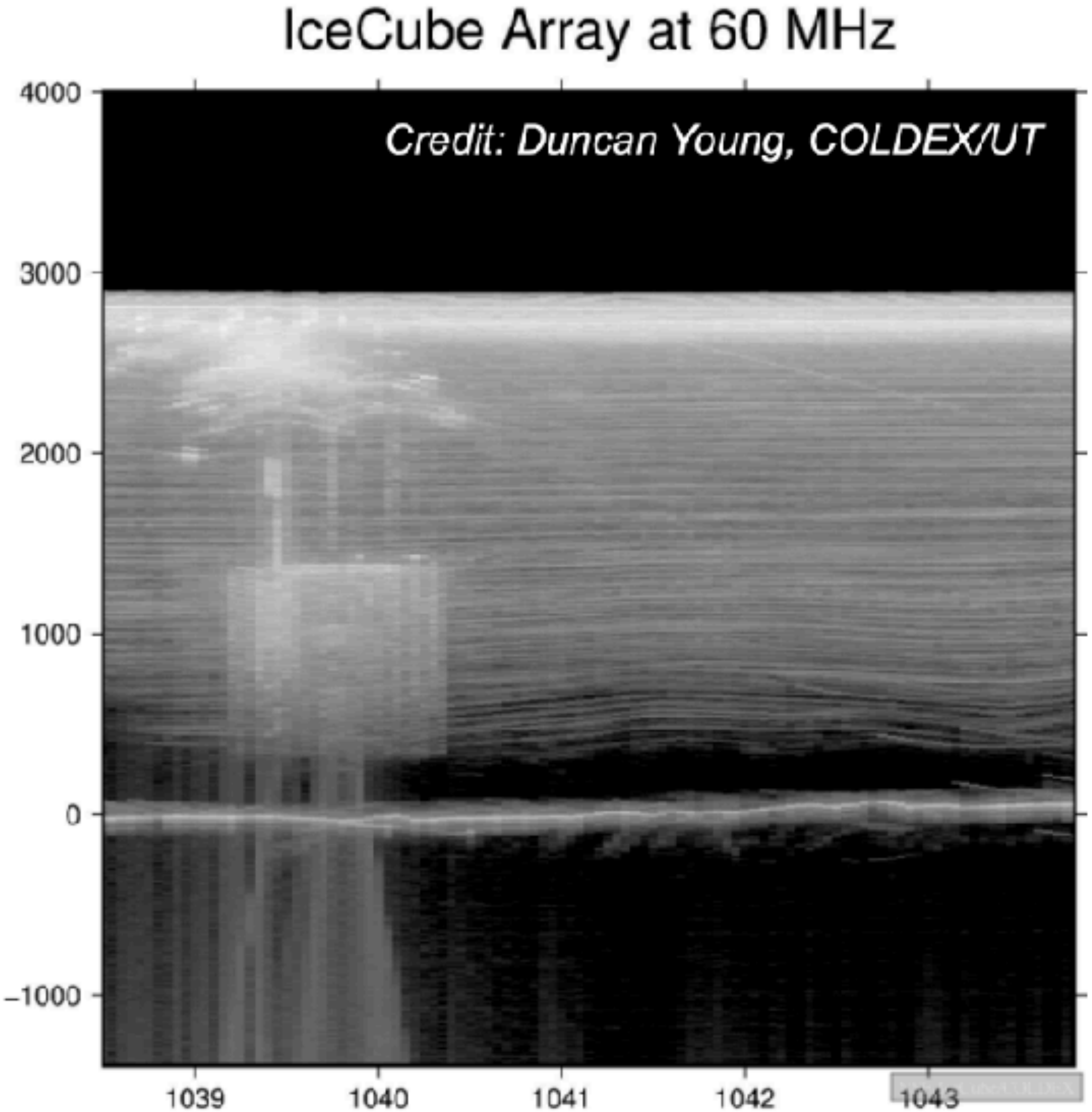
1km x 1km x 1km
Buried >2km under the ice

>5k optical sensors

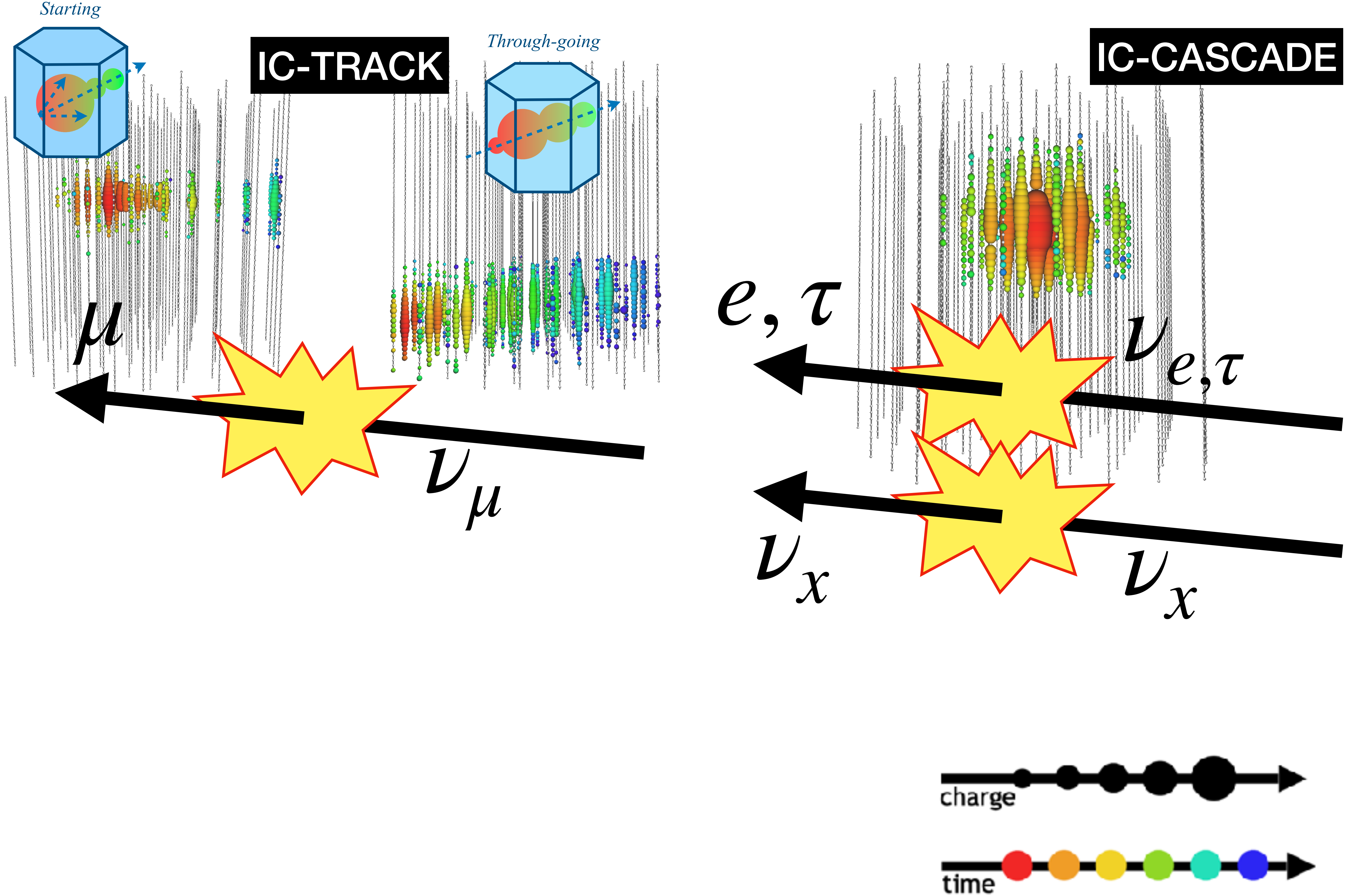


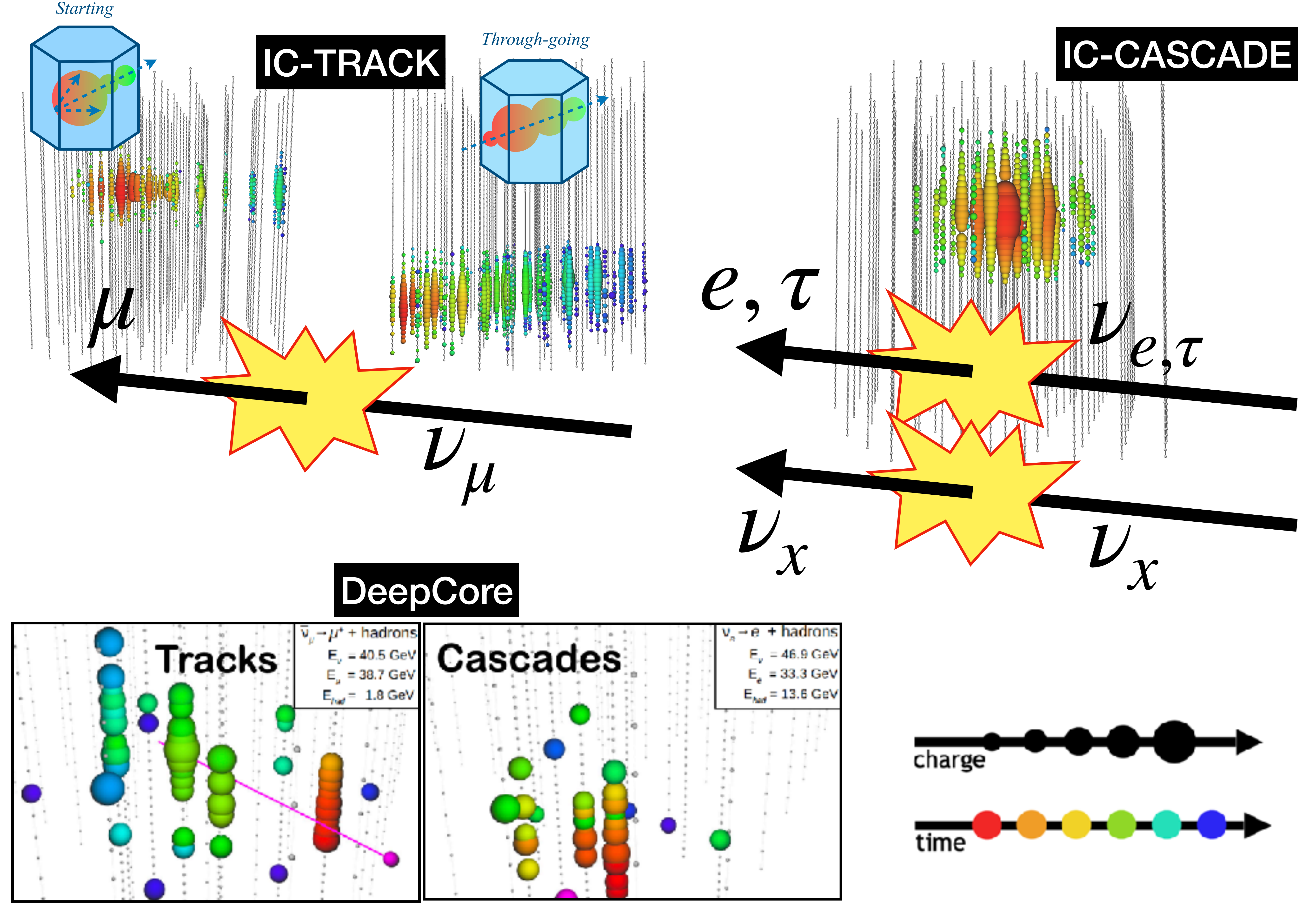
	Horizontal (m)	Vertical (m)	$E_{threshold}$ (GeV)
IceCube	125	17	~100
DeepCore	~50	7	~5





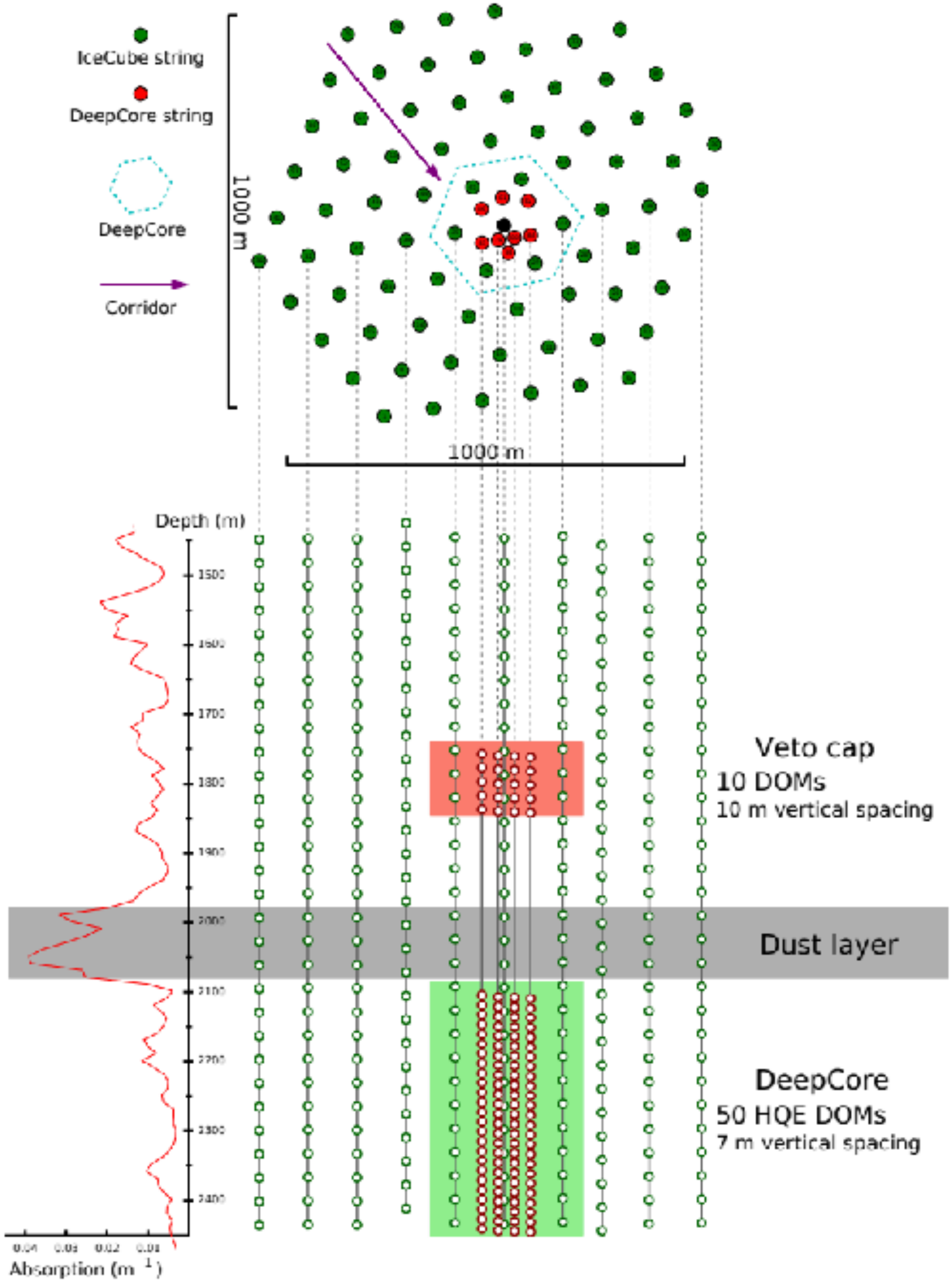
A ground-penetrating radar capture of the IceCube detector deployed in the ice.


Starting
IC-TRACK
Through-going
IC-CASCADE
μ
ν_μ
e, τ
$\nu_{e,\tau}$
ν_x
ν_x
charge
time

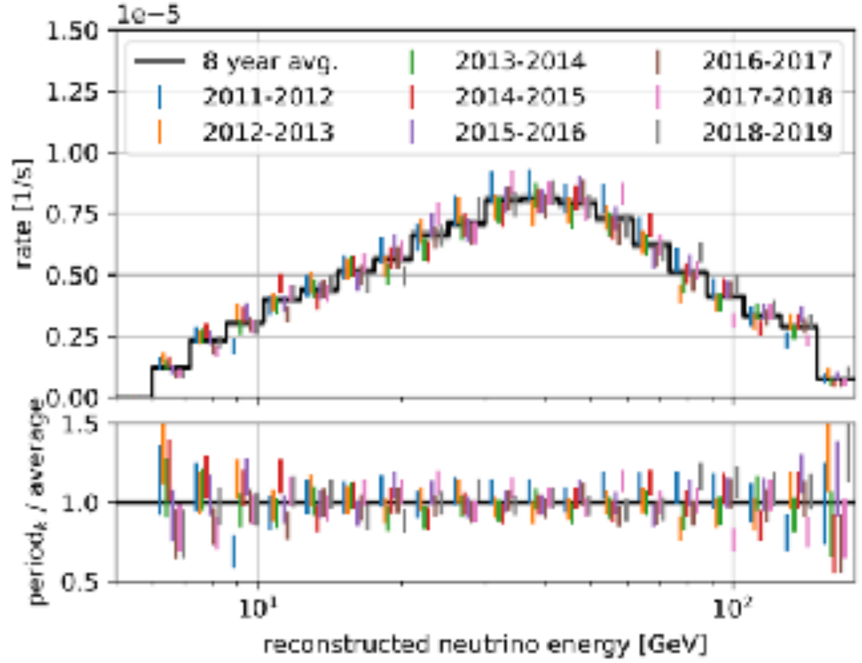


Starting
IC-TRACK
Through-going
IC-CASCADE
μ
ν_μ
e, τ
$\nu_{e,\tau}$
ν_x
ν_x
DeepCore
Tracks
$\bar{\nu}_\mu \rightarrow \mu^+$ + hadrons
E_ν = 40.5 GeV
E_μ = 38.7 GeV
E_{had} = 1.8 GeV
Cascades
$\nu_e \rightarrow e$ + hadrons
E_ν = 46.9 GeV
E_e = 33.3 GeV
E_{had} = 13.6 GeV
charge
time

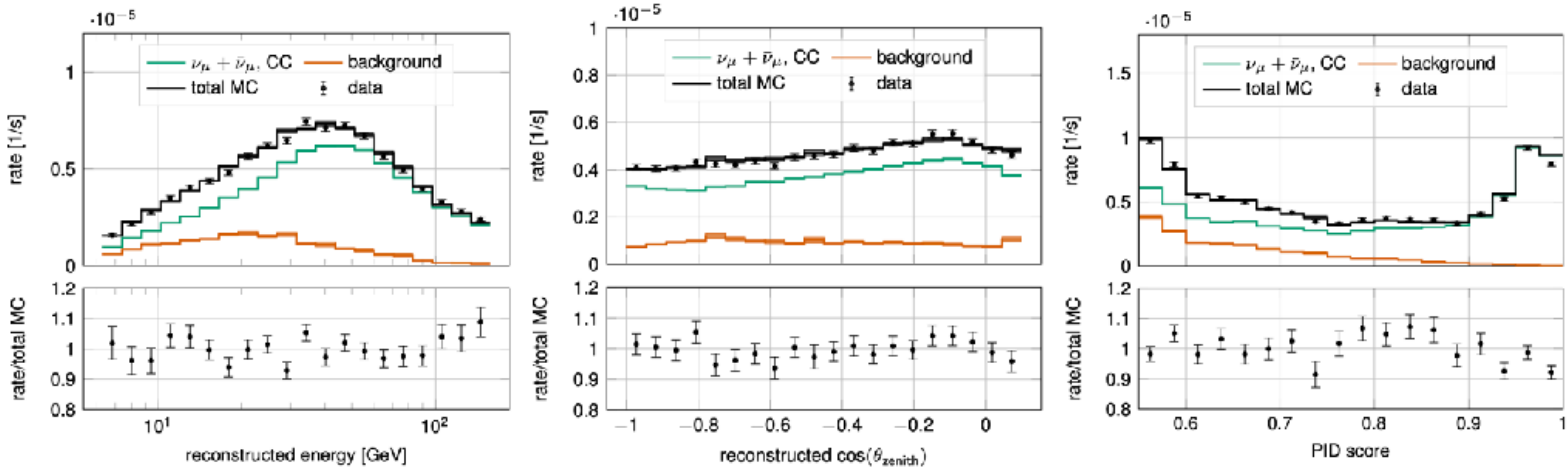
Low Energy Analysis



Select upgoing tracks

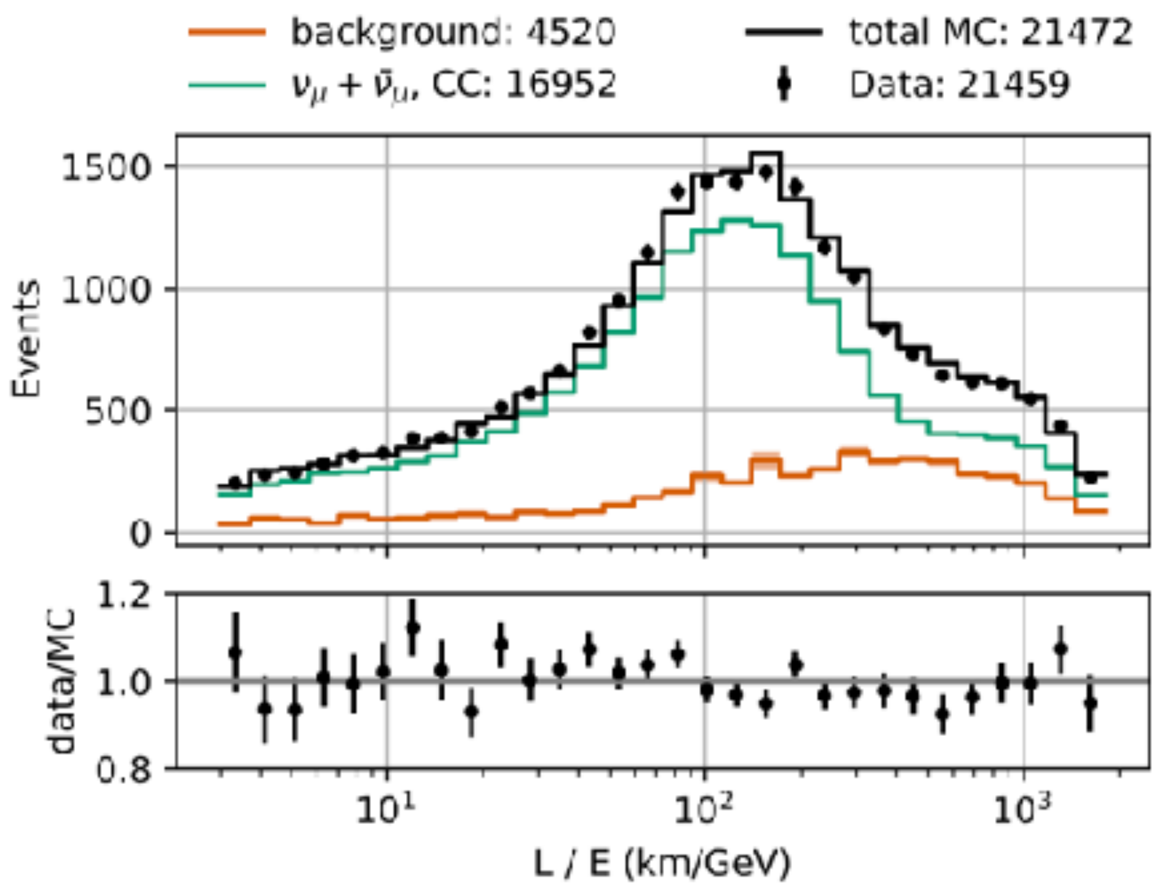


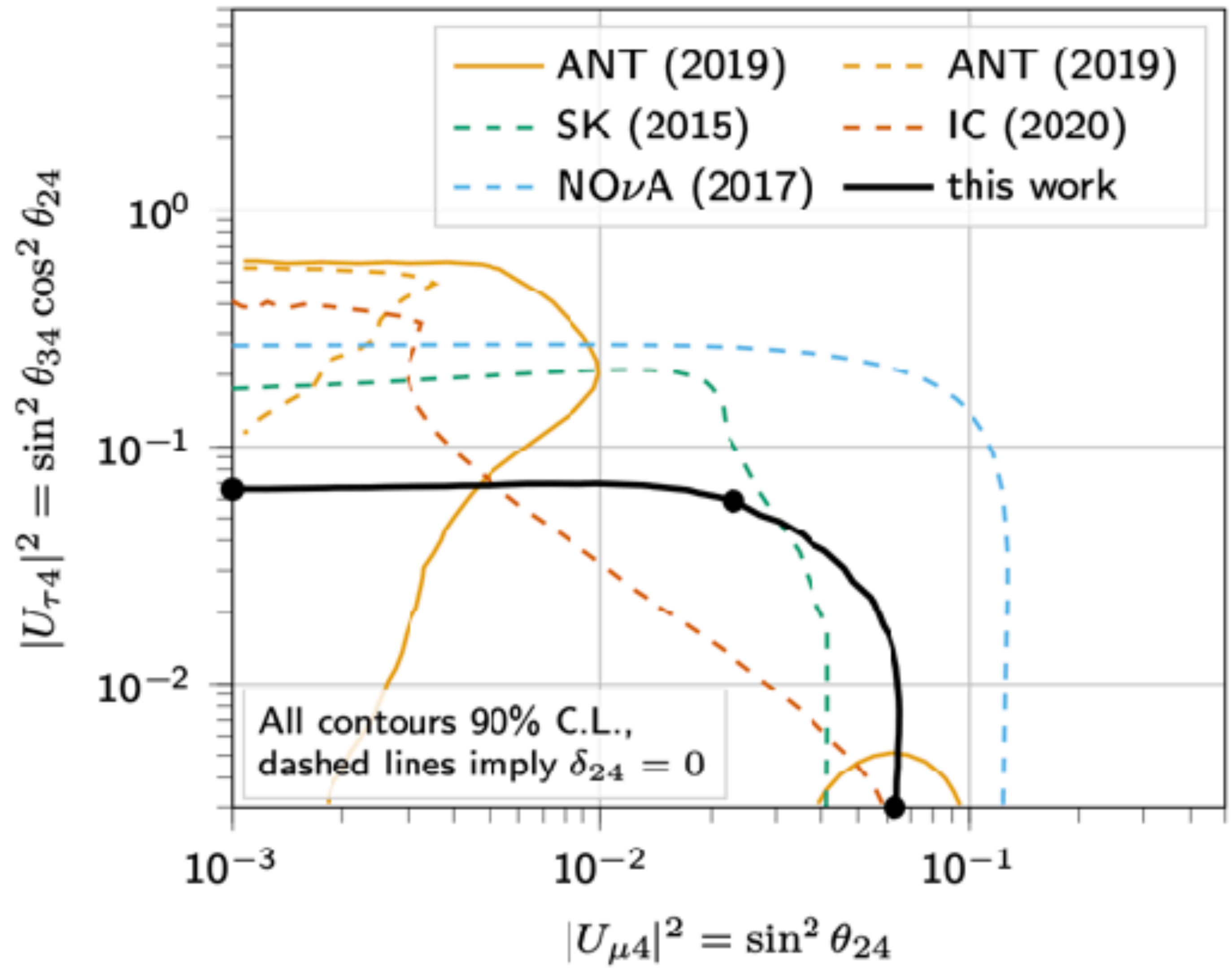
- 8 years of lifetime
- Good data/MC (goodness of fit ~25%)
- ν_μ CC purity >80%



Select upgoing tracks

- Very competitive constraints in $U_{\tau 4}$!

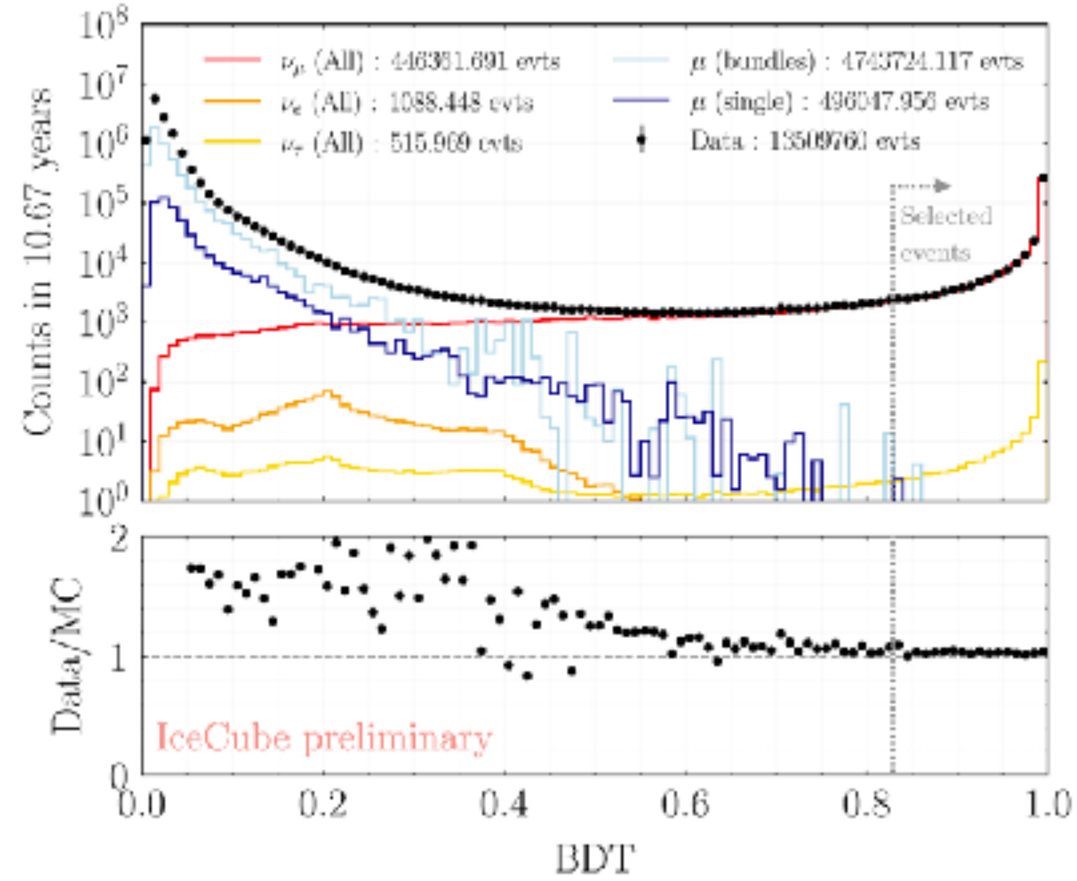


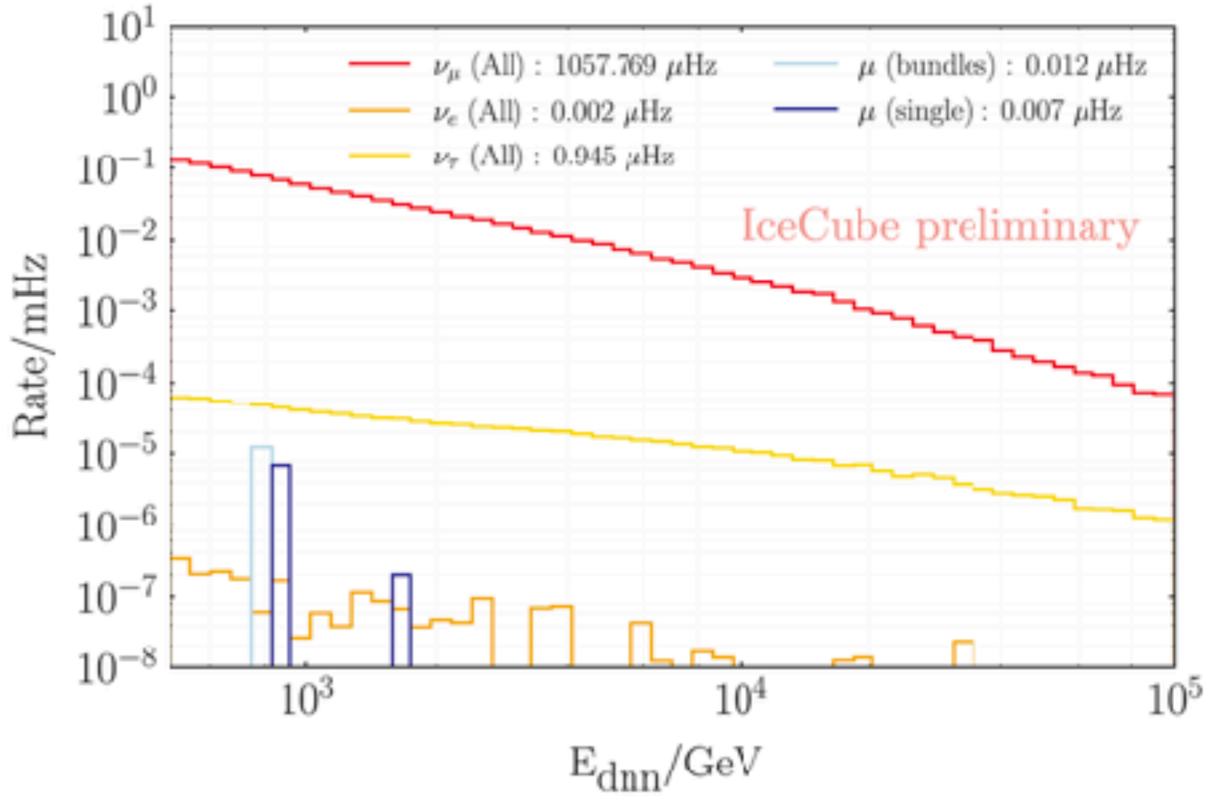


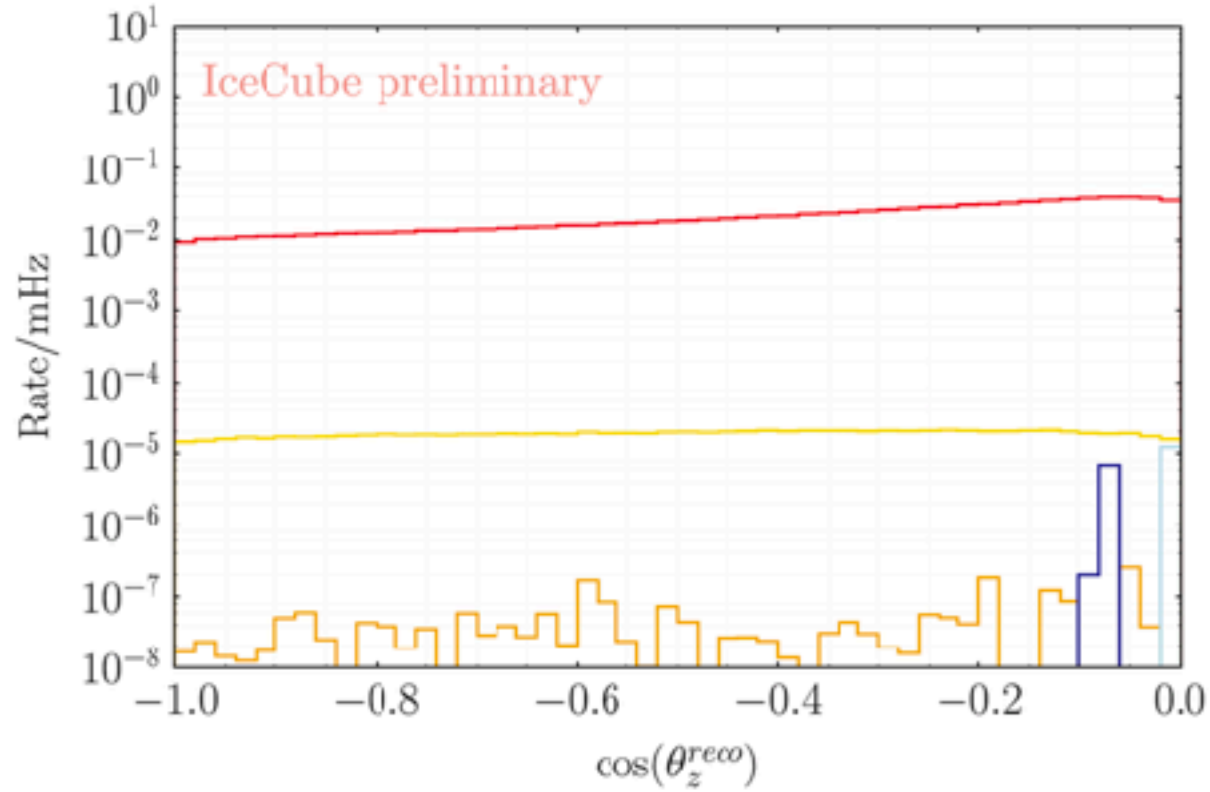
High Energy Analysis

Select upgoing tracks

- Moving from simple cuts to BDTs
  - Reduce the contamination of muons (<2.5evt/y)
  - Higher muon neutrino efficiency (factor 1.4)

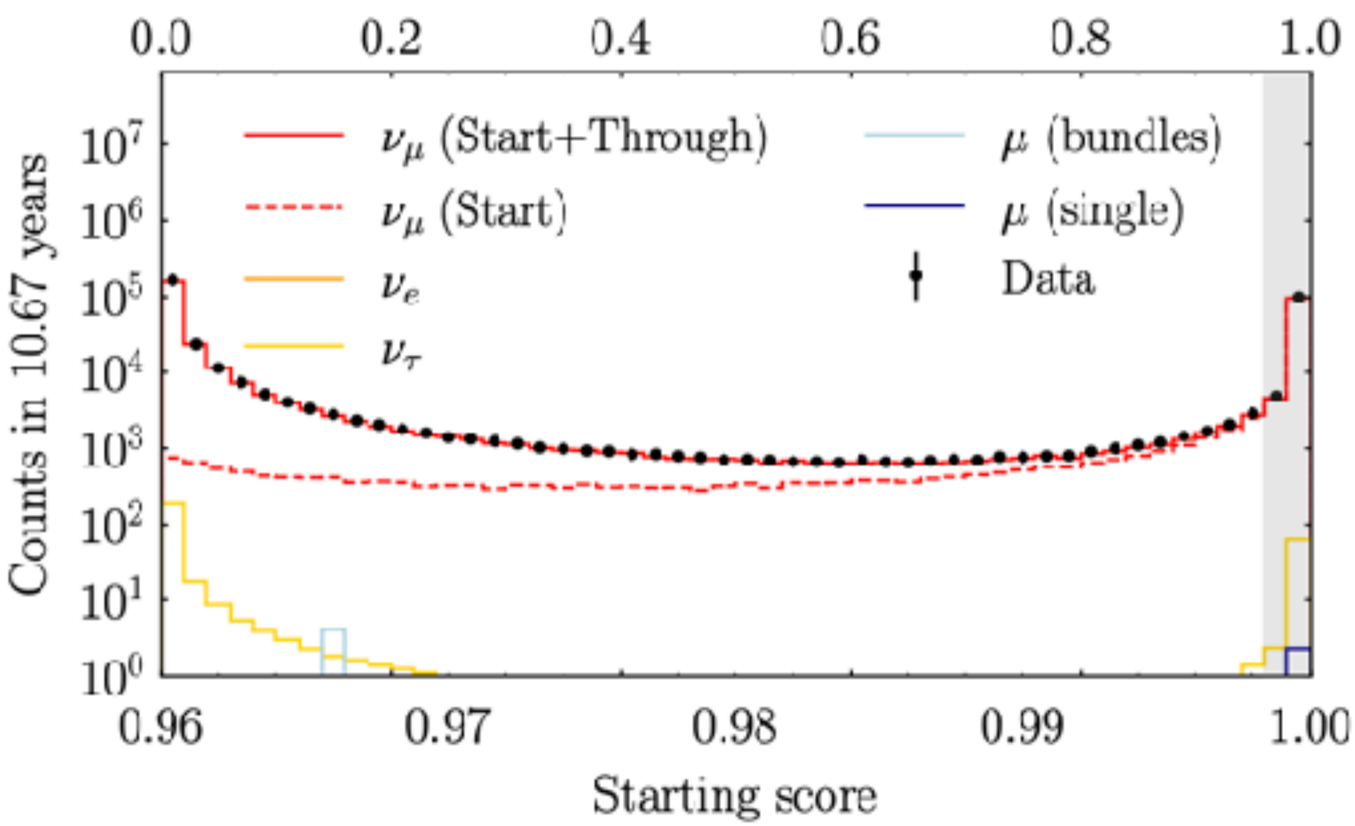


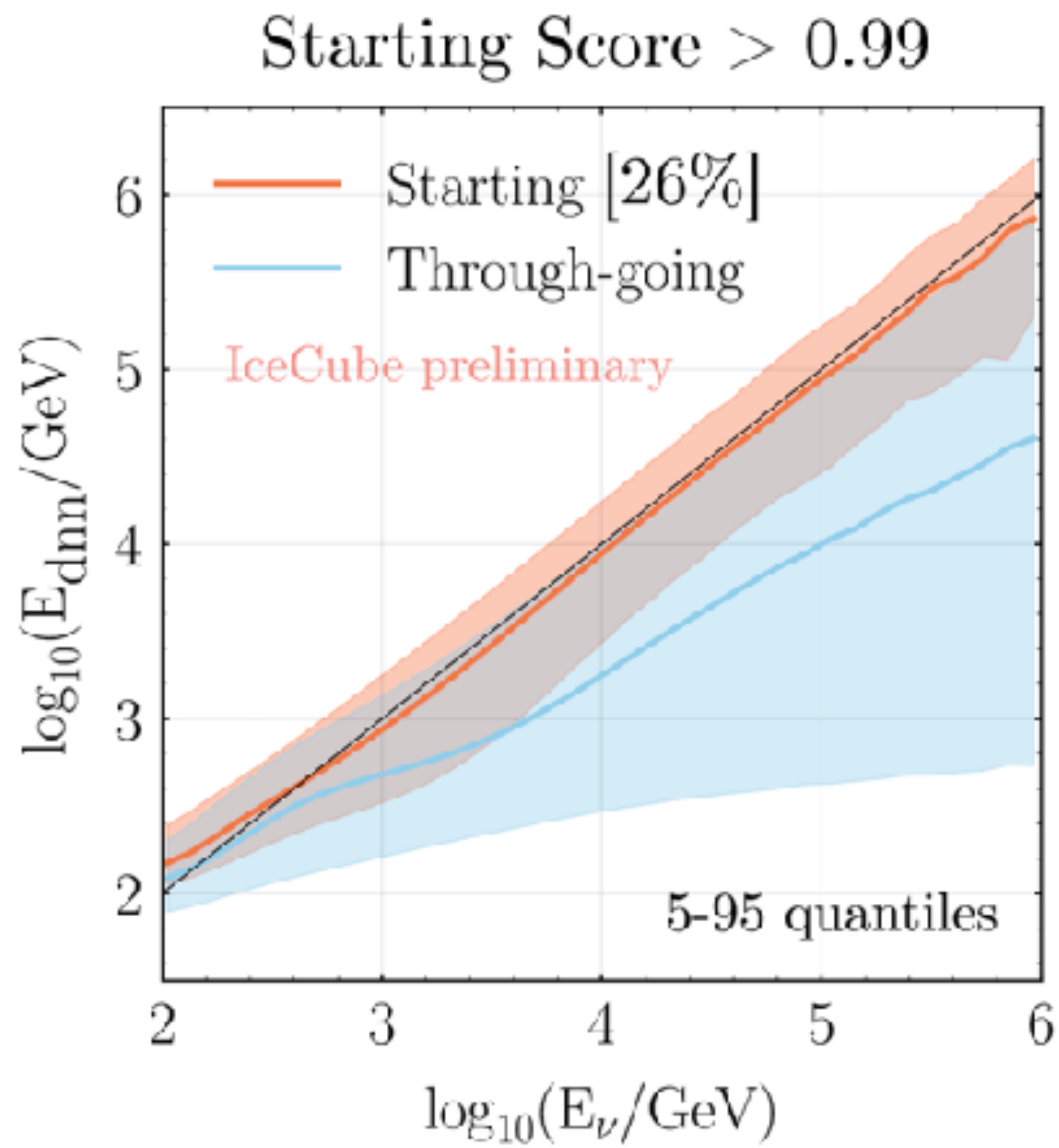




Energy estimator

- New energy reconstruction using NN
  - Dedicated event selection for starting events -> better proxy from neutrino energy





Systematics

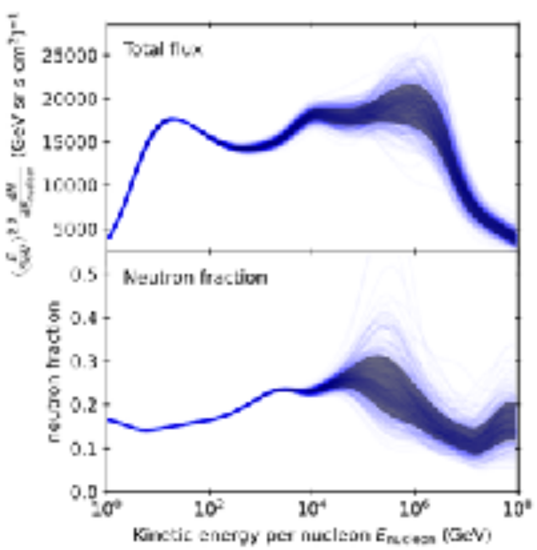
- Main changes with respect to previous analysis
  - Bulk ice -> moving to energy+zenith dependence
  - Conventional flux -> new treatment using DAEMONFLUX (PRD107, 123037)
  - Non-conventional flux -> Using broken power law

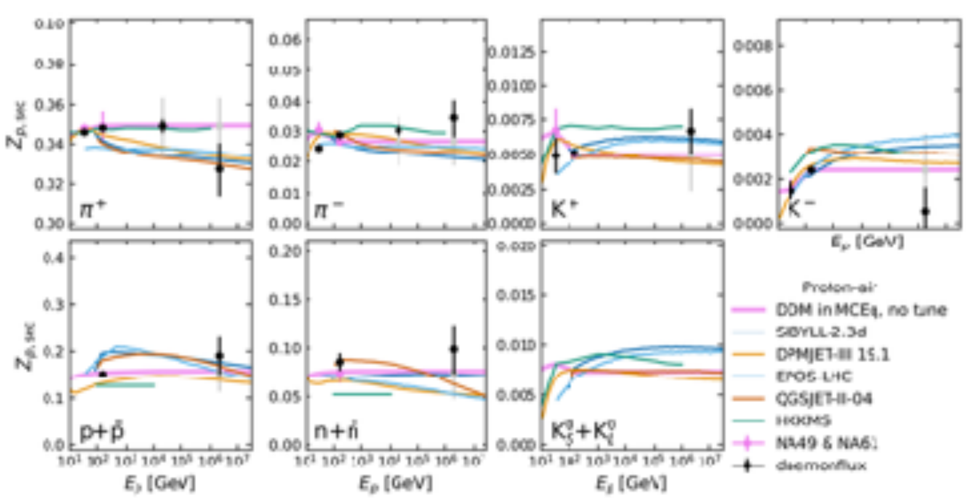
Detector Parameters	Central Value	1σ Prior Width
Normalization	1.0	±0.4
DOM efficiency	1.27	±10%
Ice Amplitude 0	0.0	±1.0
Ice Amplitude 1	0.0	±1.0
Ice Amplitude 2	0.0	±1.0
Ice Amplitude 3	0.0	±1.0
Ice Phase 1	0.0	±1.0
Ice Phase 2	0.0	±1.0
Ice Phase 3	0.0	±1.0
Ice Phase 4	0.0	±1.0
Forward Hole Ice	-1.0	±10
Cross-section Parameters		
ν cross section	1.0	±0.1
$\bar{\nu}$ cross section	1.0	±0.1
High-energy Flux Parameters		
Normalization	0.787	±0.36
$\Delta\gamma_1$, tilt from -2.5	0.0	±0.36
$\Delta\gamma_2$, tilt from -2.5	0.0	±0.36
Pivot energy in log10	-	-

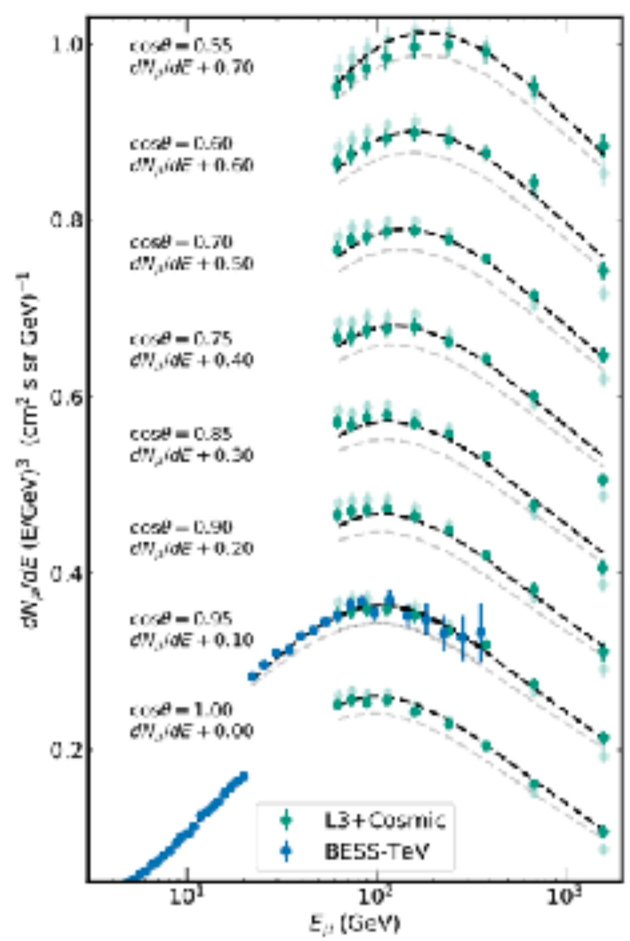
Conventional Flux Parameters			
Atm. Density	0	±1.0	
Kaon energy loss	0.0	±1.0	
K^+_{158G}	0.0	±1.0	Hadronic production
K^-_{158G}	0.0	±1.0	Hadronic production
π^+_{20T}	0.0	±1.0	Hadronic production
π^-_{20T}	0.0	±1.0	Hadronic production
K^+_{2P}	0.0	±1.0	Hadronic production
K^-_{2P}	0.0	±1.0	Hadronic production
π^+_{2P}	0.0	±1.0	Hadronic production
π^-_{2P}	0.0	±1.0	Hadronic production
p_{2P}	0.0	±1.0	Hadronic production
n_{2P}	0.0	±1.0	Hadronic production
GSF_1	0.0	±1.0	Cosmic ray
GSF_2	0.0	±1.0	Cosmic ray
GSF_3	0.0	±1.0	Cosmic ray
GSF_4	0.0	±1.0	Cosmic ray
GSF_5	0.0	±1.0	Cosmic ray
GSF_6	0.0	±1.0	Cosmic ray

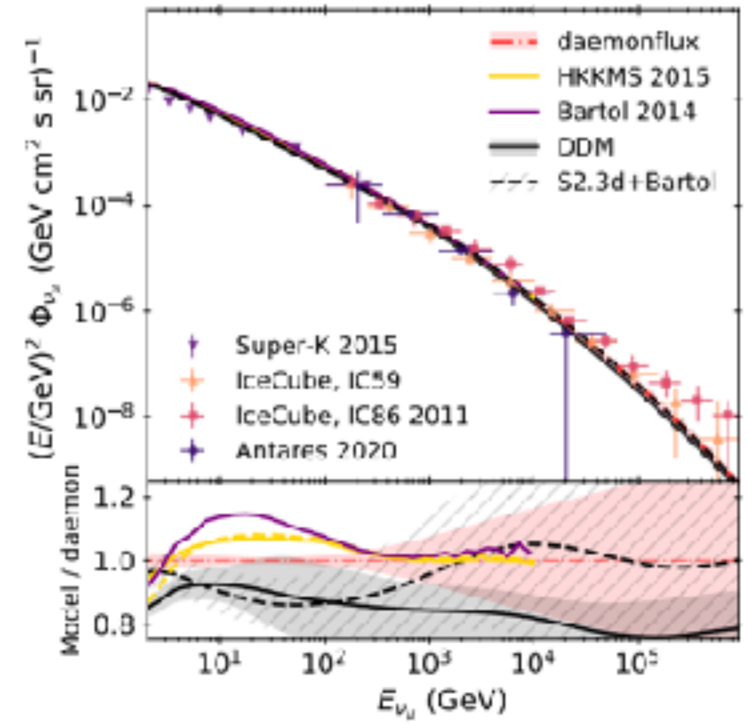
Daemonflux

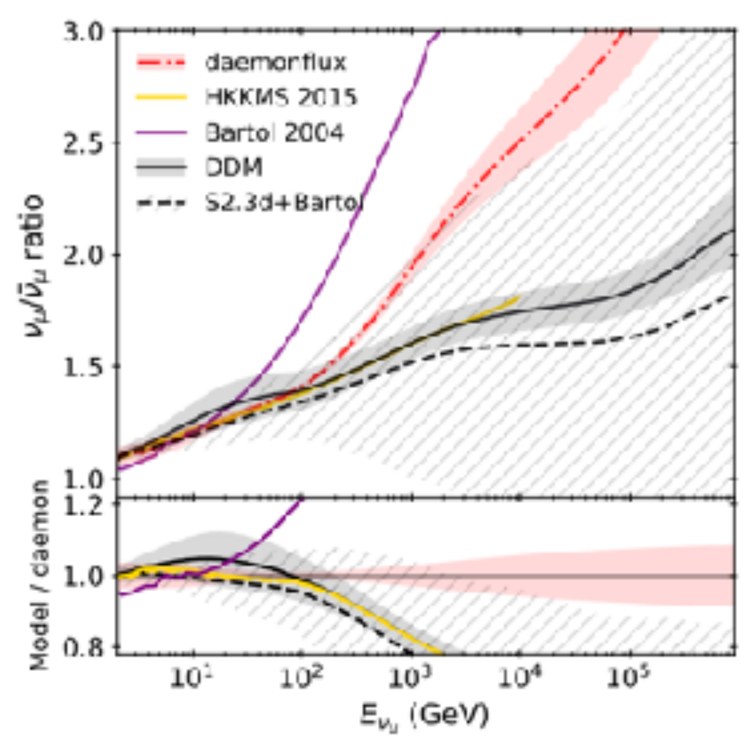
- New prediction of neutrino fluxes:
  - Calibrated using muon measurements at Earth surface.
  - Treatment of systematics -> cosmic ray and hadronic yields.





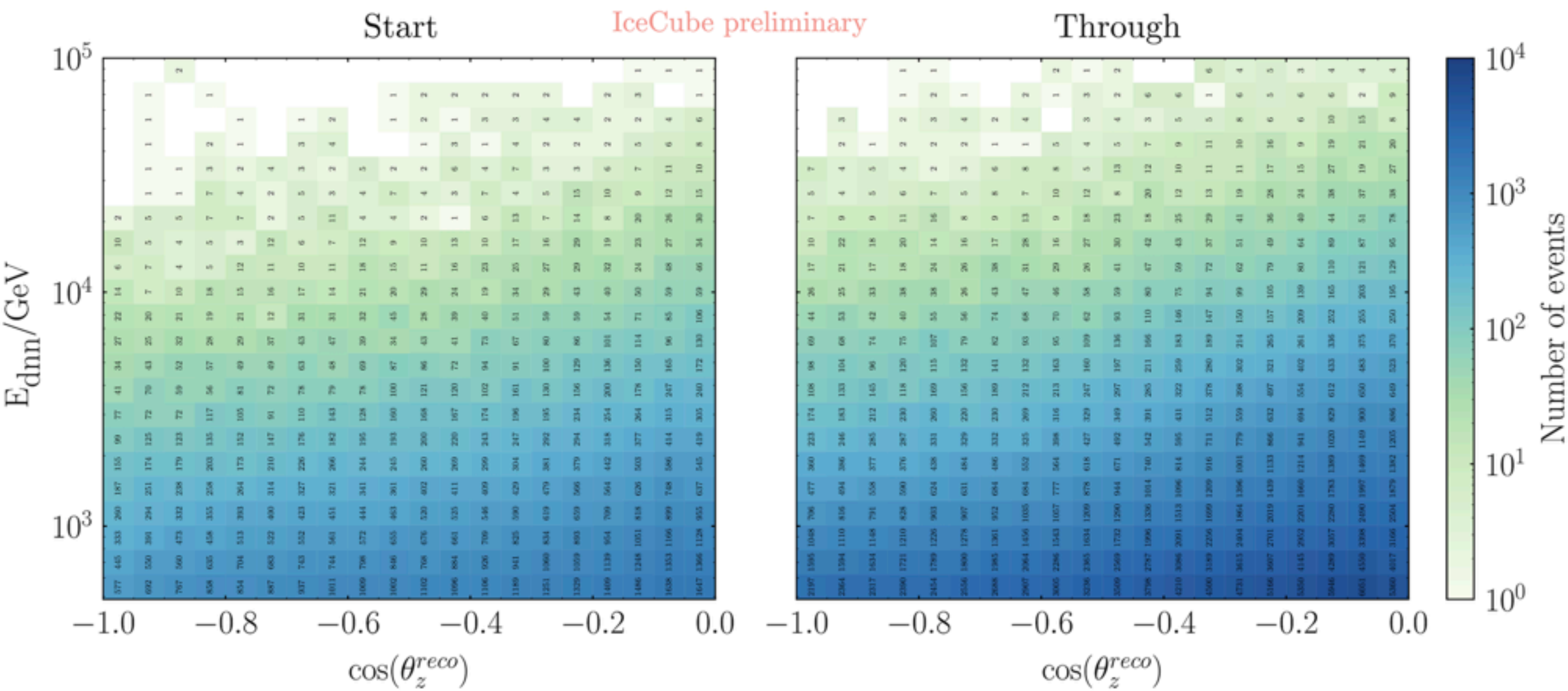






Data Sample

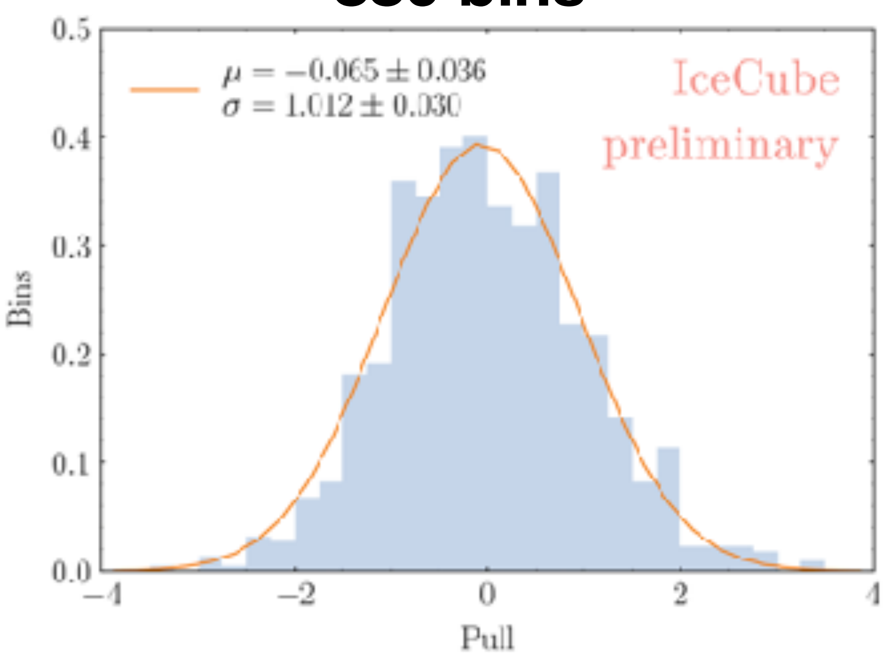
- Unblinded 10.7 years -> ~400k tracks

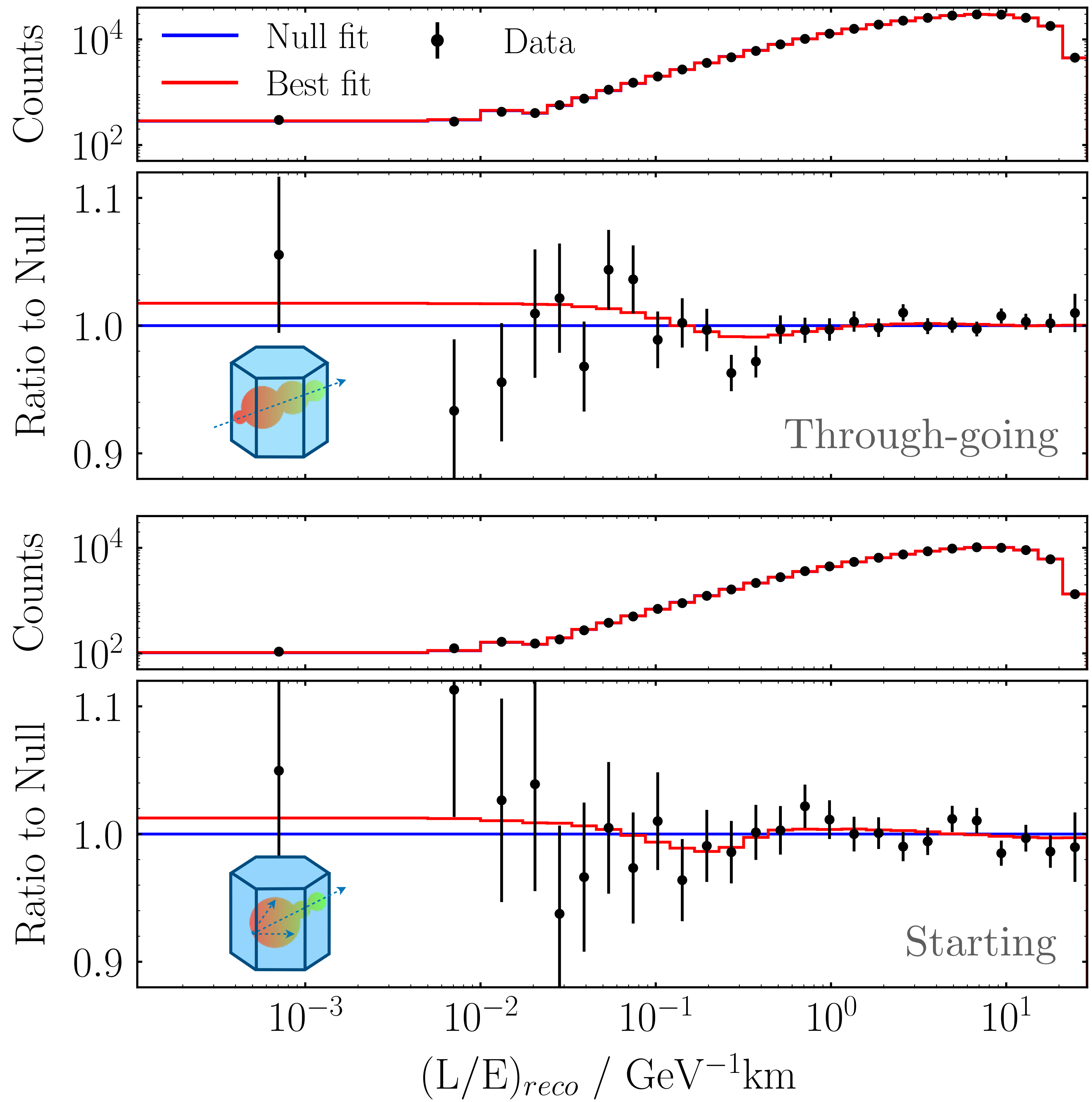


Results

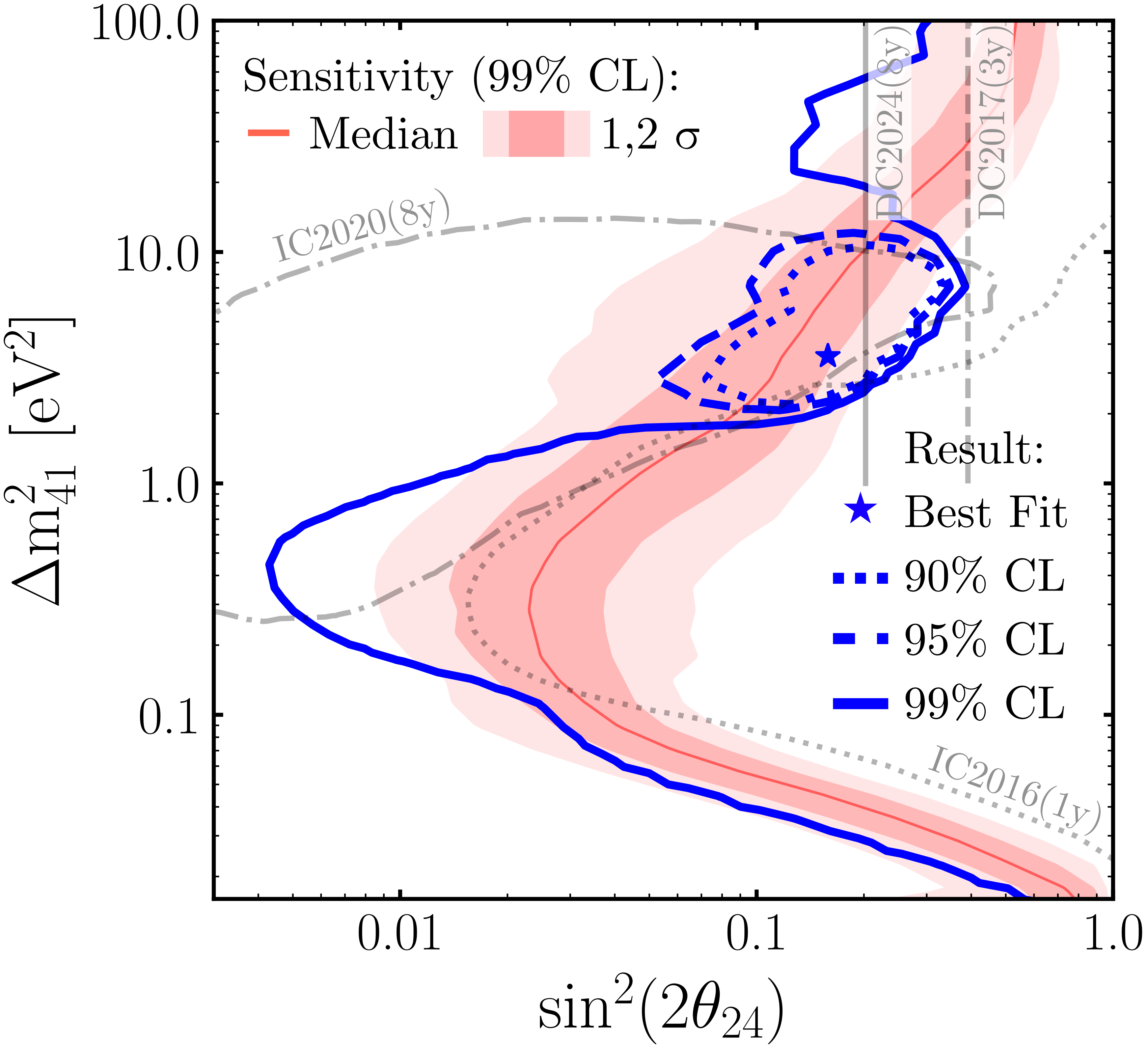
- Goodness-of-fit with p value=12%

880 bins





Results

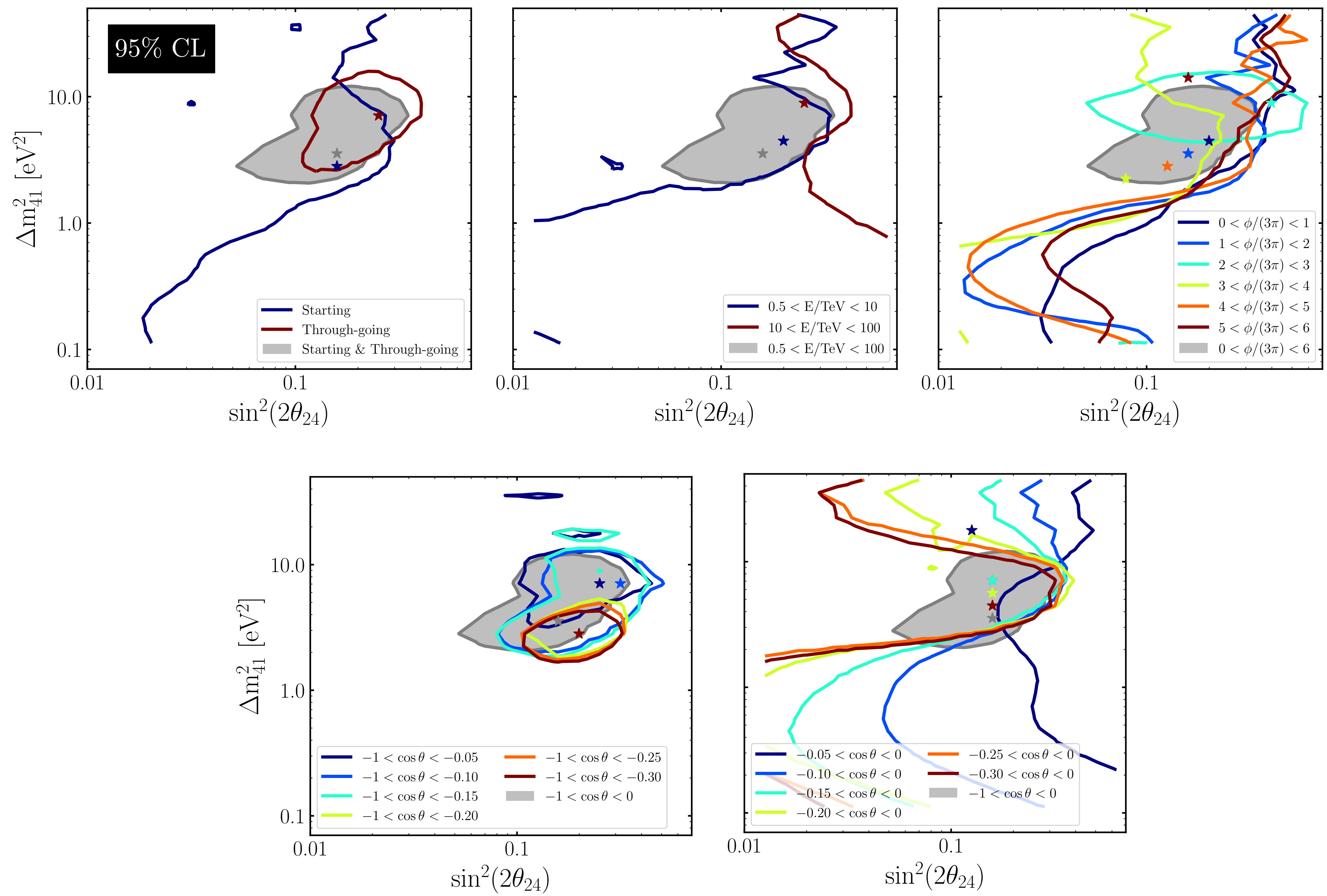


Best fit:
Δm^2_{41} = 3.5 eV^2
θ_{24} = 12°

- Goodness-of-fit with p-value=12%
- Compatible with previous IC analysis.
- Null rejection p-value=3.1% (**2.2σ**)

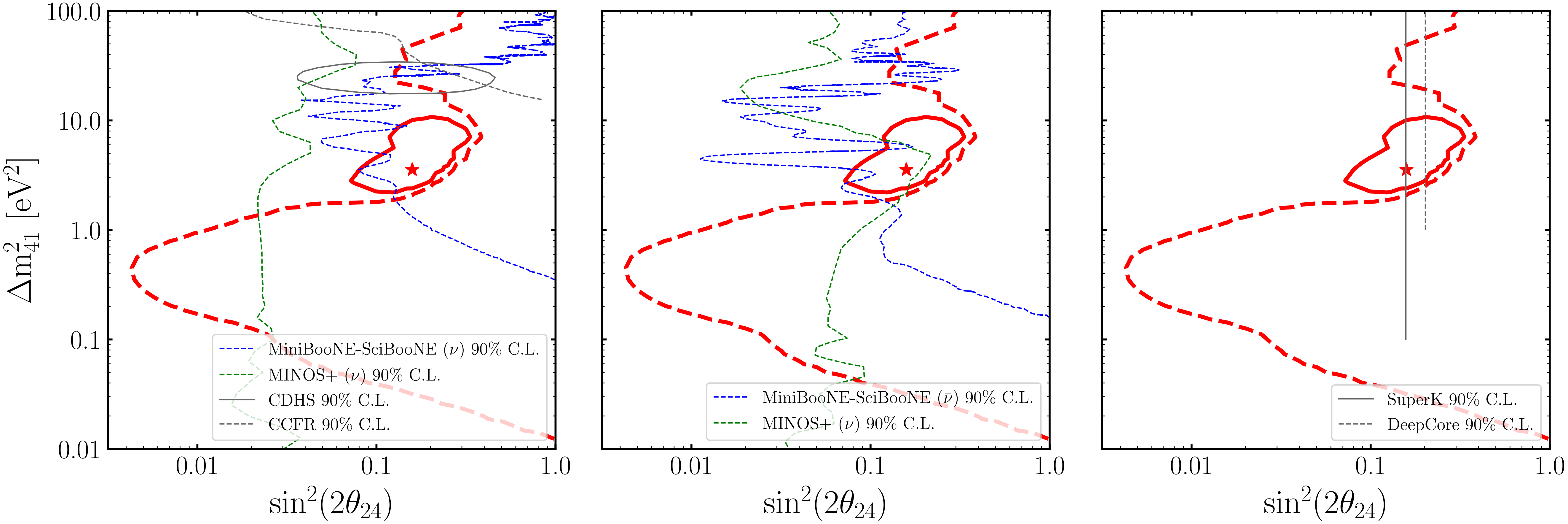
Compatibility Tests

- Checks to understand result
  - Splits in different region of the reconstructed phase space



Compared with world data

- Best-fit in tension with other numu disappearance measurements

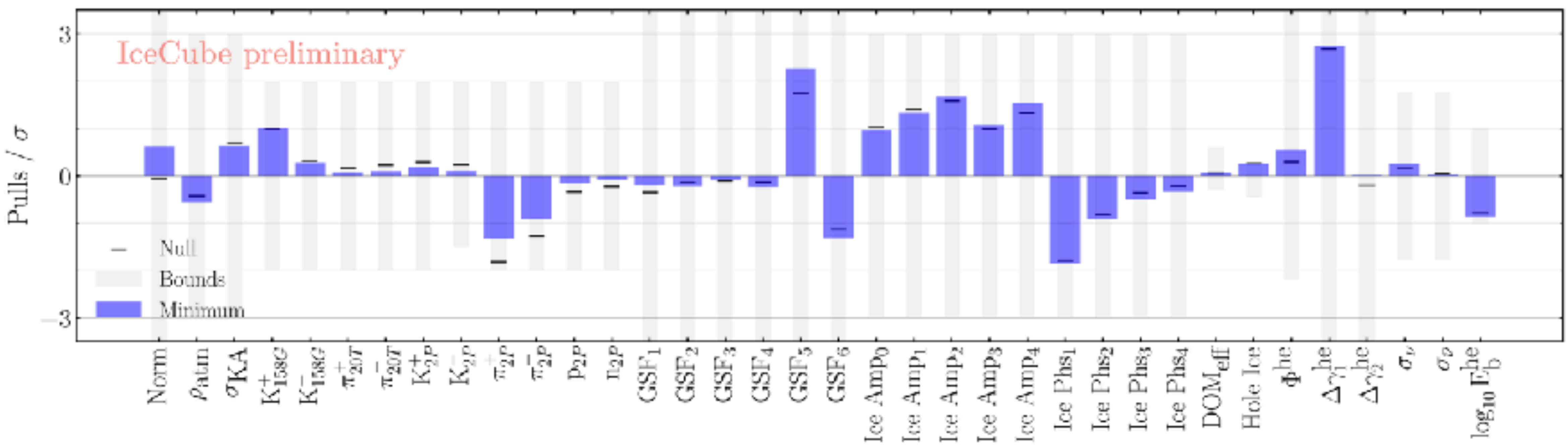


Conclusions

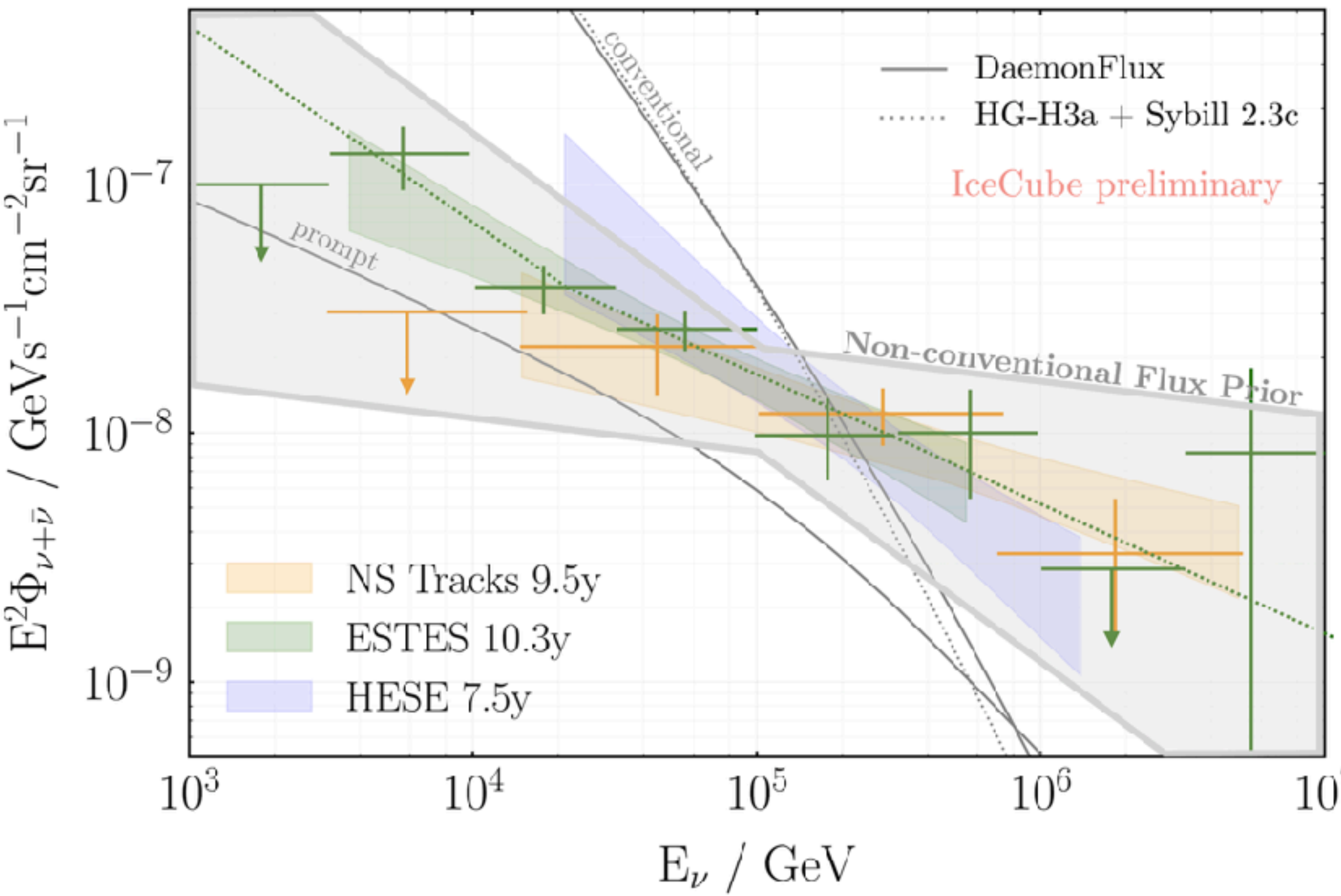
- Unique sterile searches
  - Different energy range (systematics) to any other experiment
  - Signal mainly driven by different oscillations regimes
- New analyses with major changes
  - Event selection
  - Energy reconstruction
  - Flux treatment
- Unblinded 10.7 and 8 years of data with IC and DeepCore
  - Consistent with previous IC analyses
  - Ongoing tests to quantify the significance of the result
- Mild tension with other experiements -> What can we do?
  - Continue improving our understanding of detector
  - Develop analysis with other neutrino telescopes
  - More complex scenario than vanilla 3+1

Fit quality

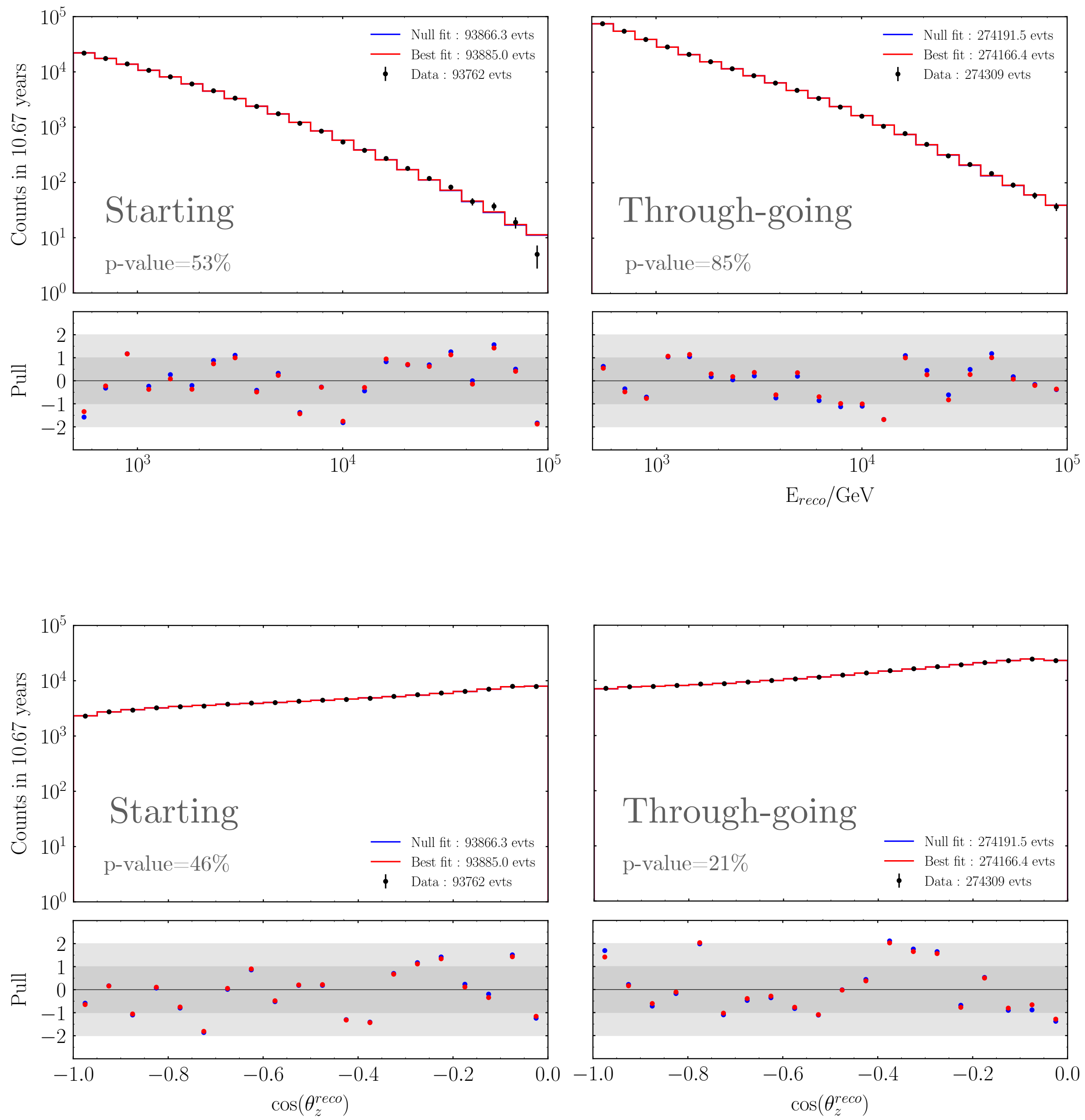
- Goodness-of-fit with p-value~10%
- Bin-wise pulls normally distributed
- Nuisance parameters within allowed ranges



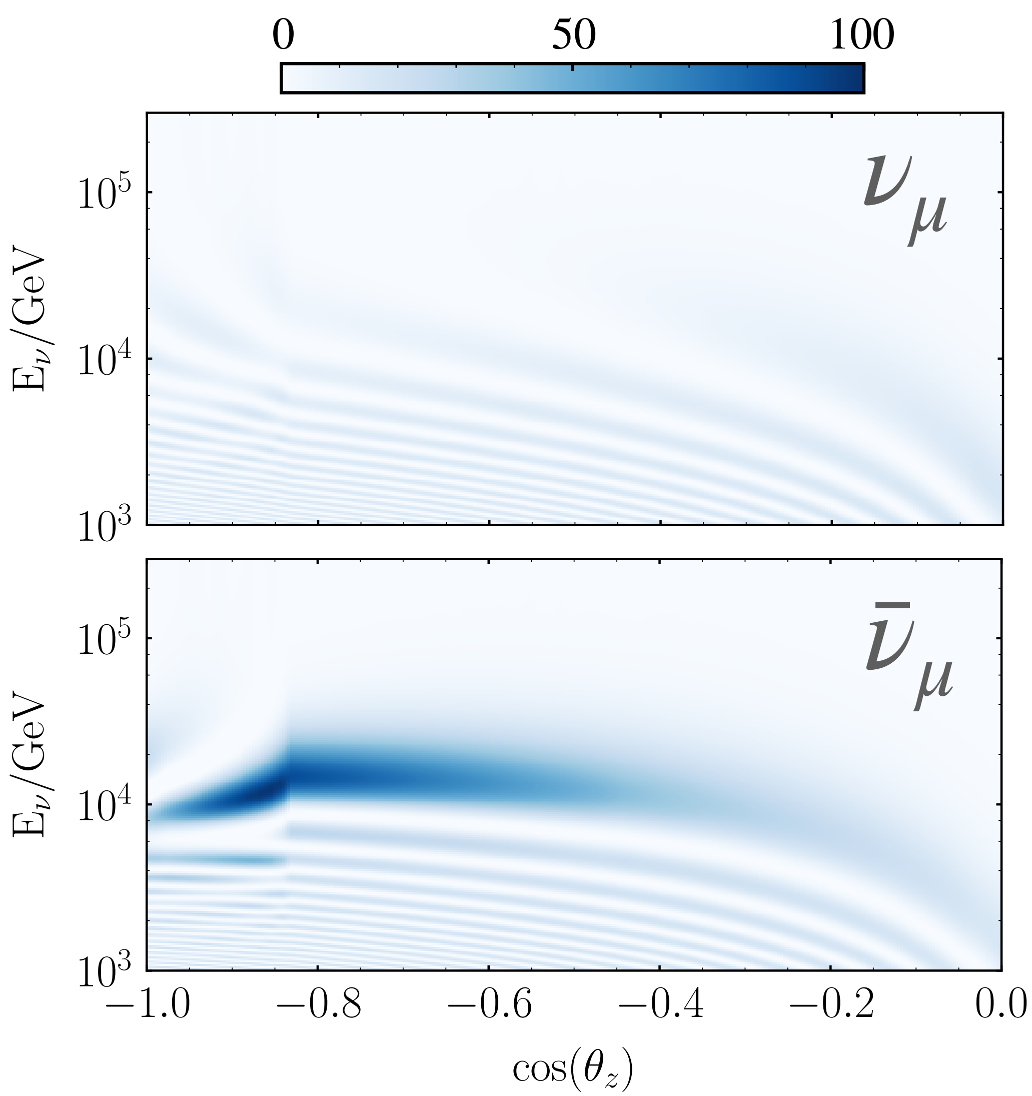
Non-conventional priors

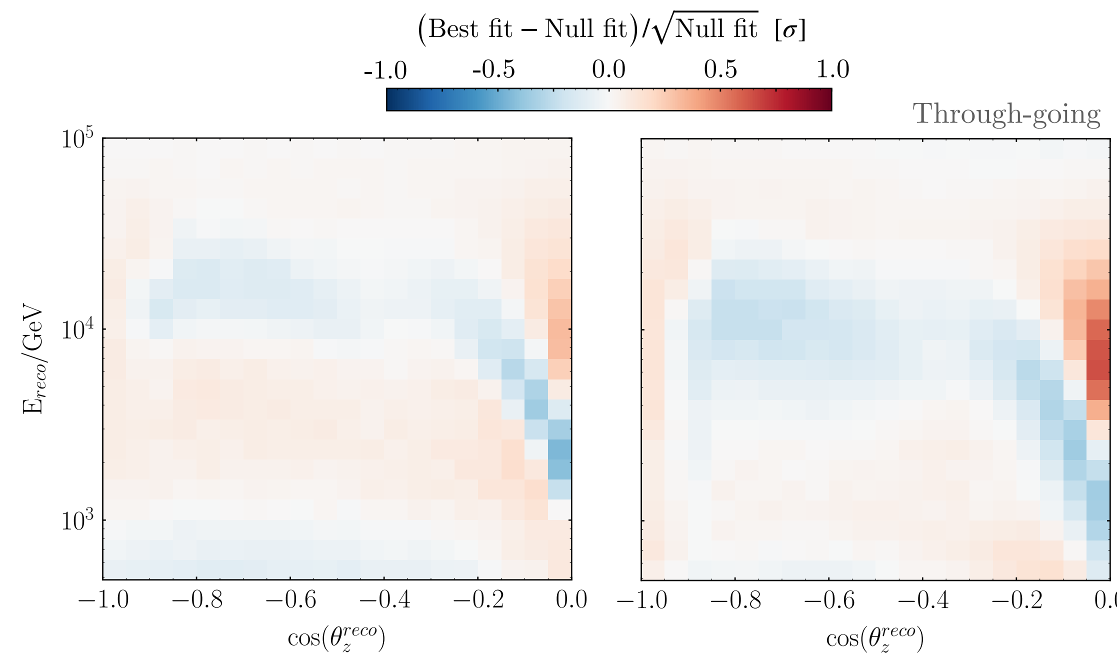


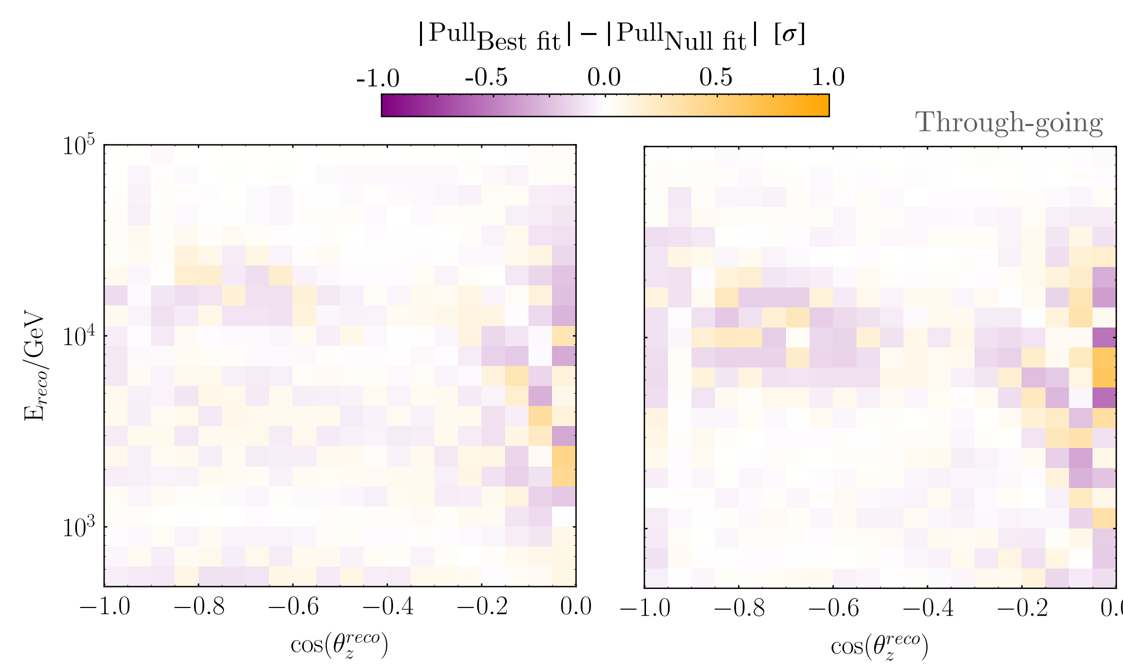
1D distributions



Best-fit vs null flux







Other new results

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- $U_{\mu 4}$ and $U_{\tau 4}$ free