TeVPA 2023

(Naples, Italy)

New Results for eV-scale Sterile Neutrino Searches with IceCube

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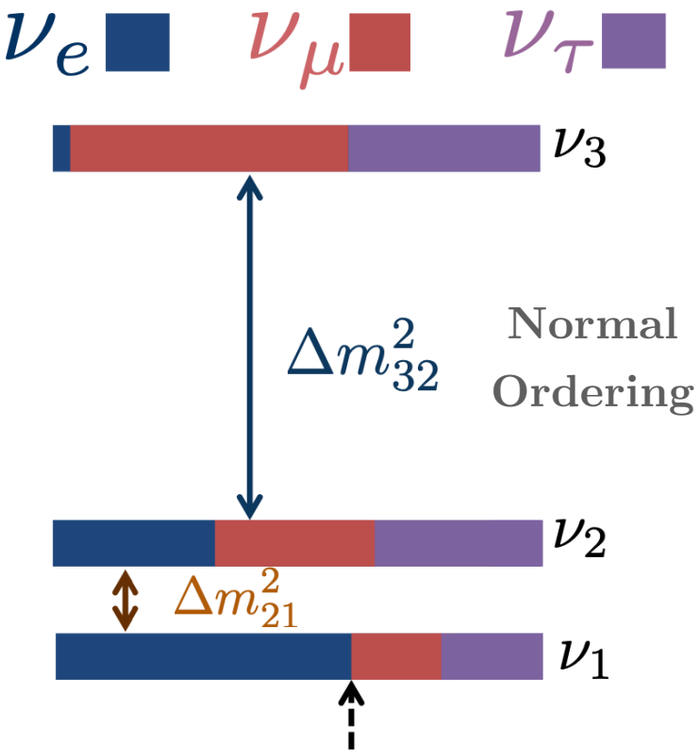
Neutrino oscillations

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

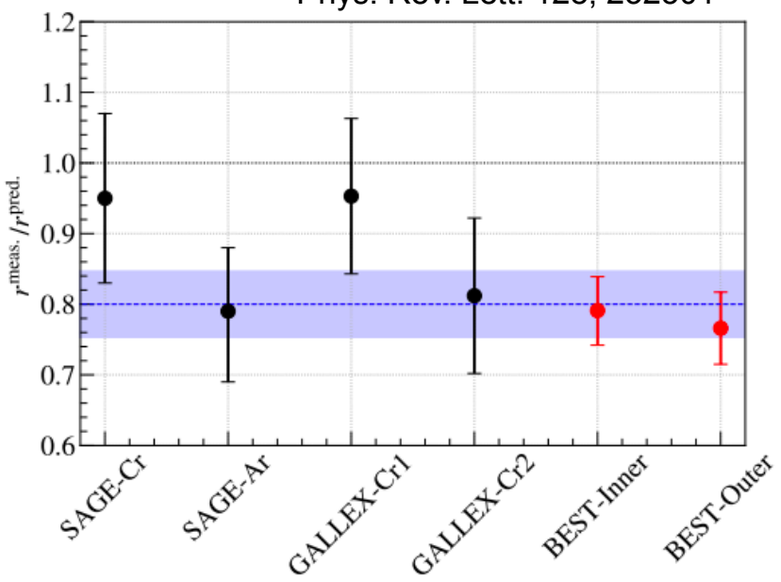


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospherics / Accelerators}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactors / accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar / reactors}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

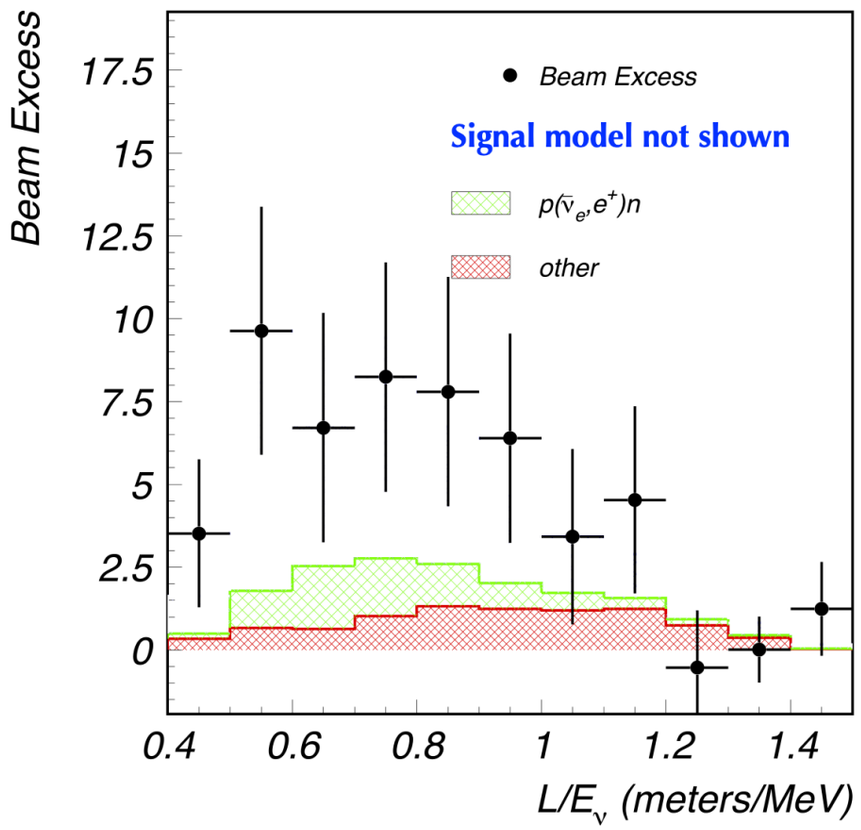
Anomalies

- 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

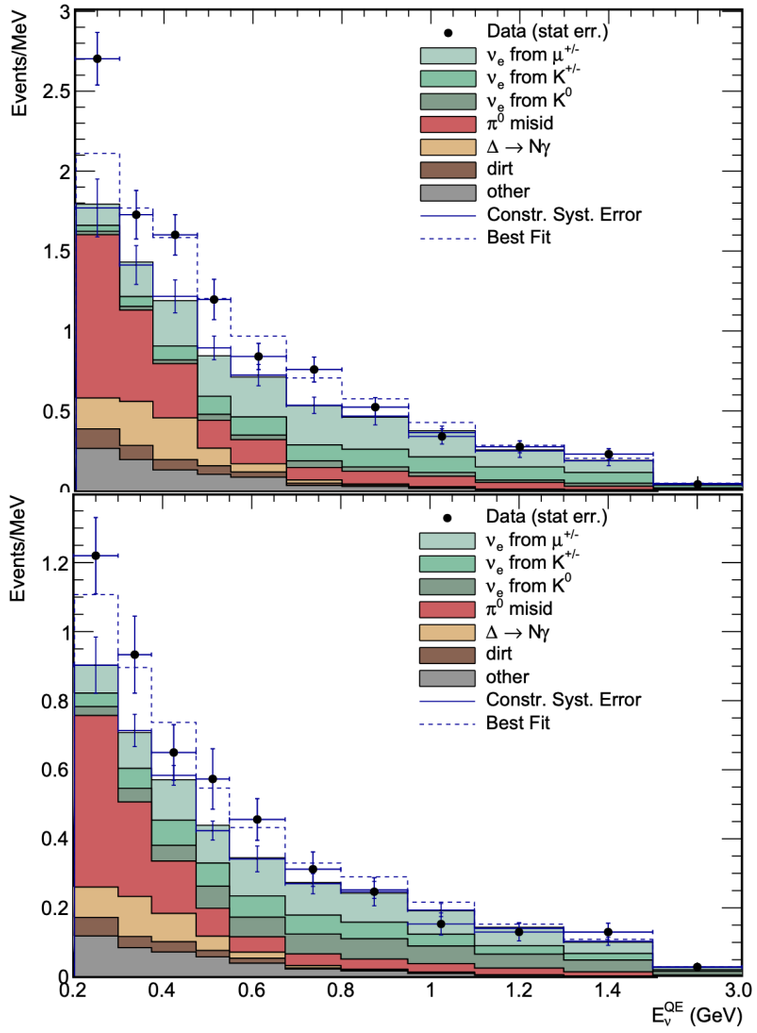
Phys. Rev. Lett. 128, 232501



Phys. Rev. D 64, 112007

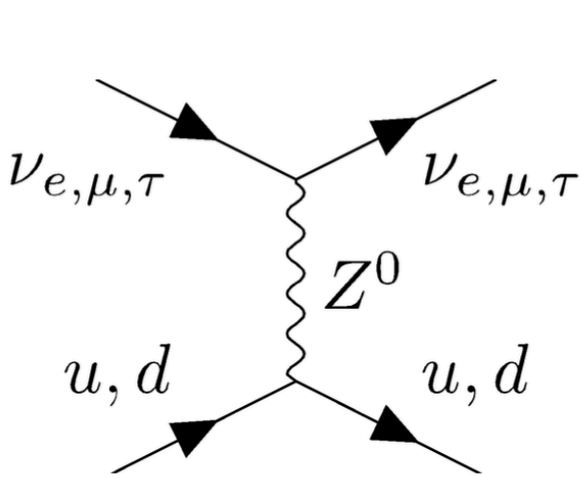


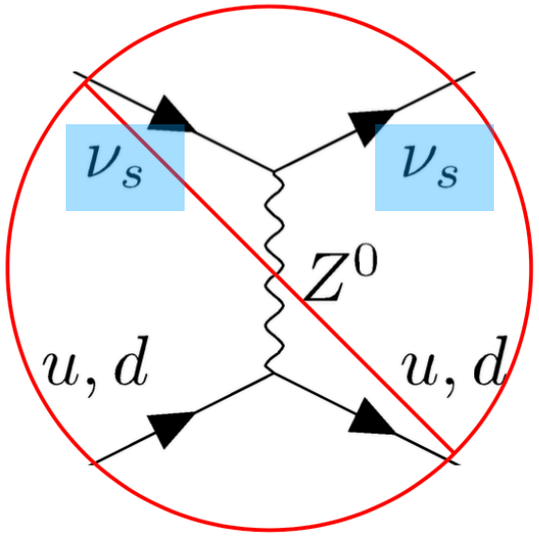
Phys. Rev. Lett. 121, 221801



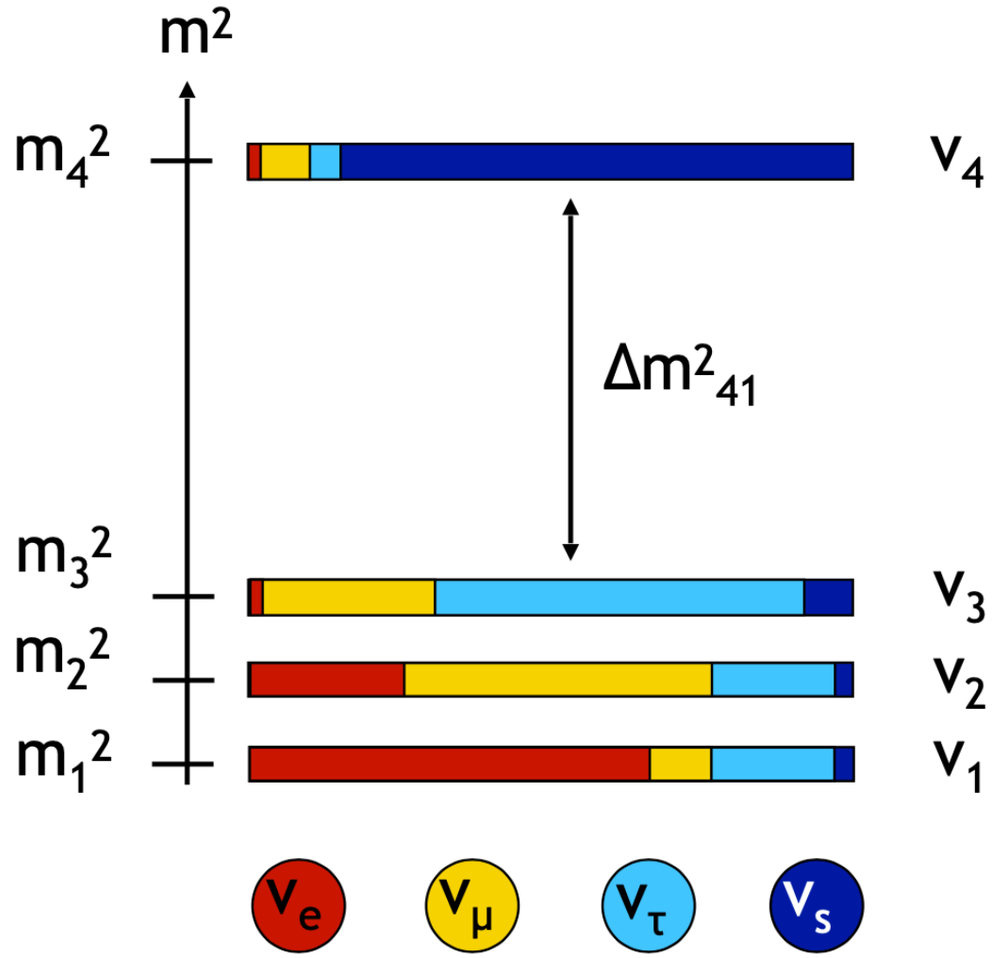
3+1 model

- 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





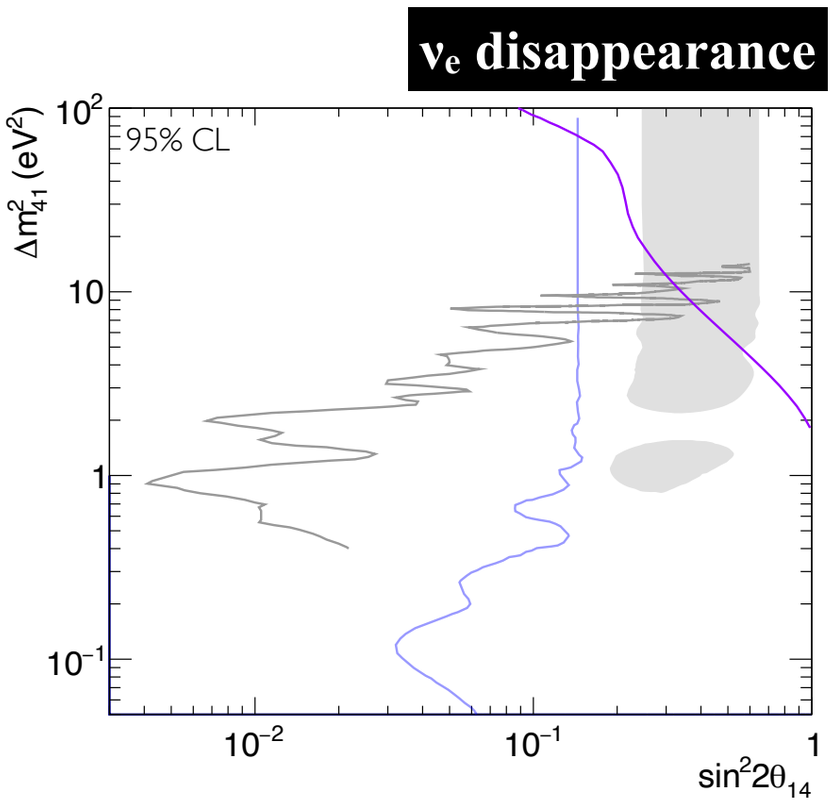
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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



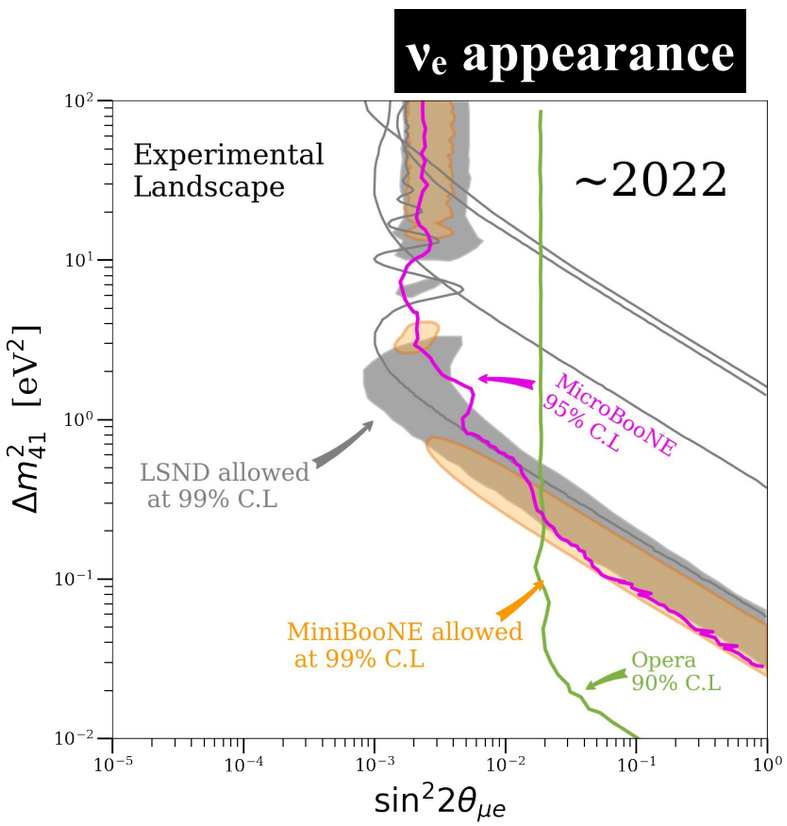
Normal ordering

3+1 puzzle

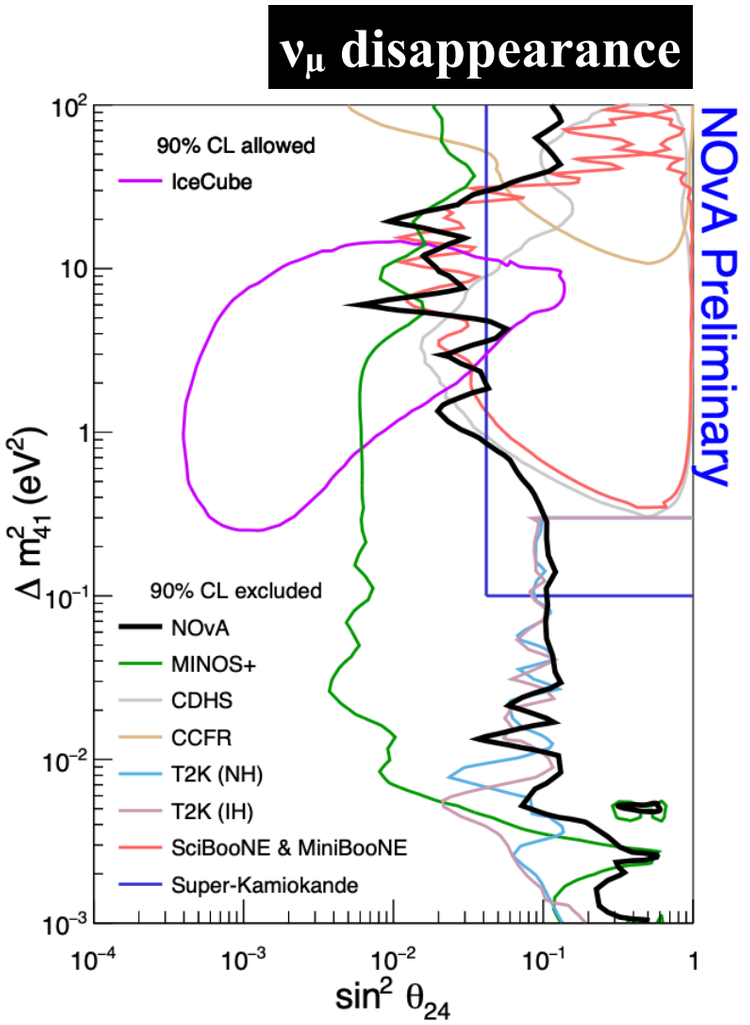
- 3+1 does not find a consistent picture when performing global fits
  - $\nu_\mu \rightarrow \nu_e$ appearance requires $\nu_\mu \rightarrow \nu_\mu$ disappearance



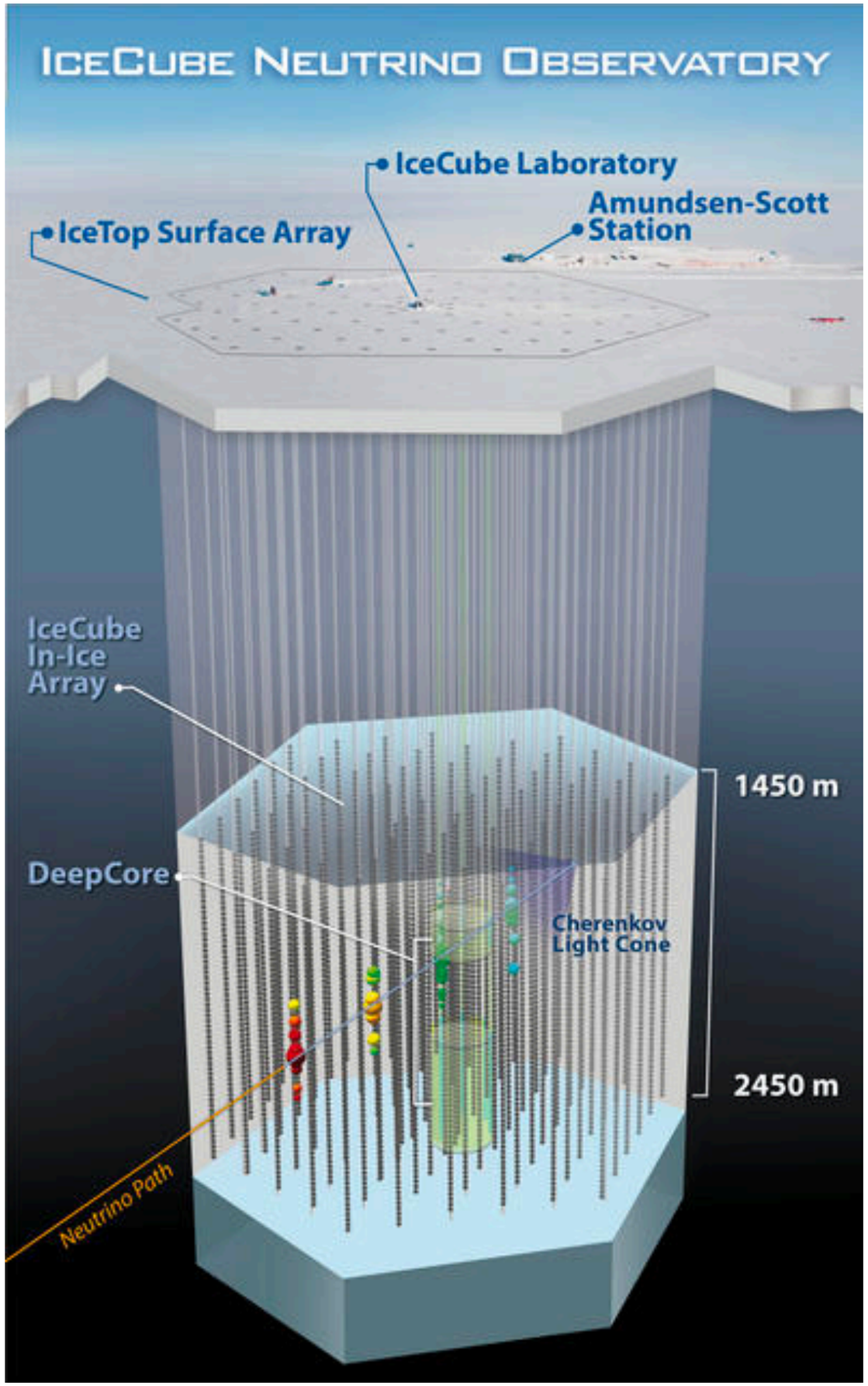
P. Teja (SnowMass 2022)



M. Ross (SnowMass 2022)



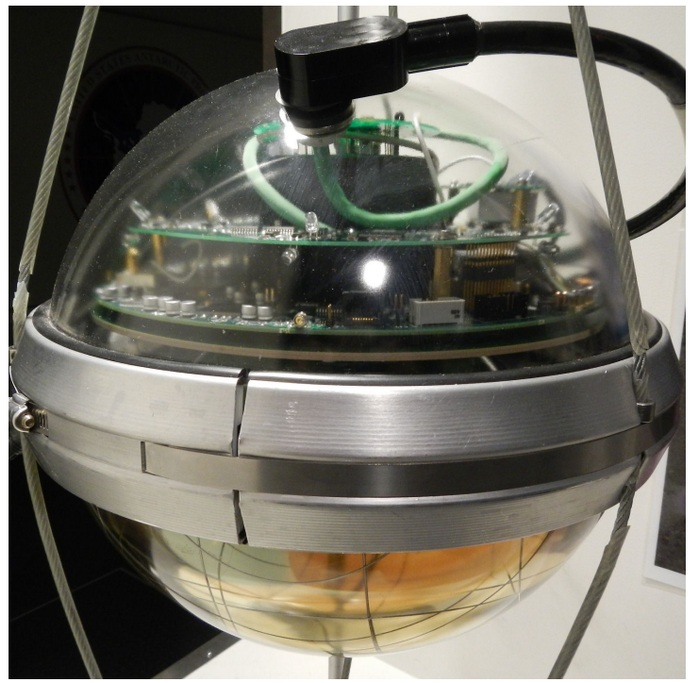
A. Sutton (NuFact 2023)

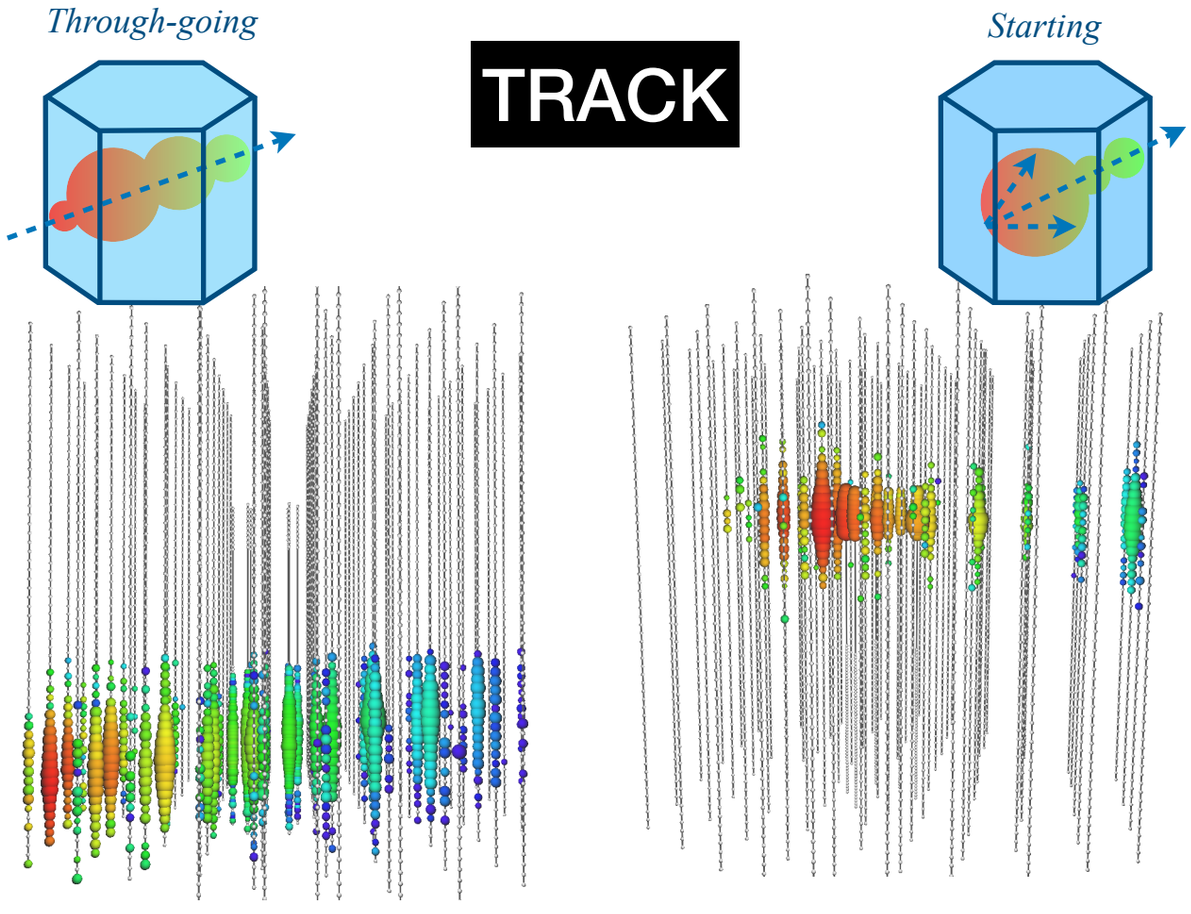


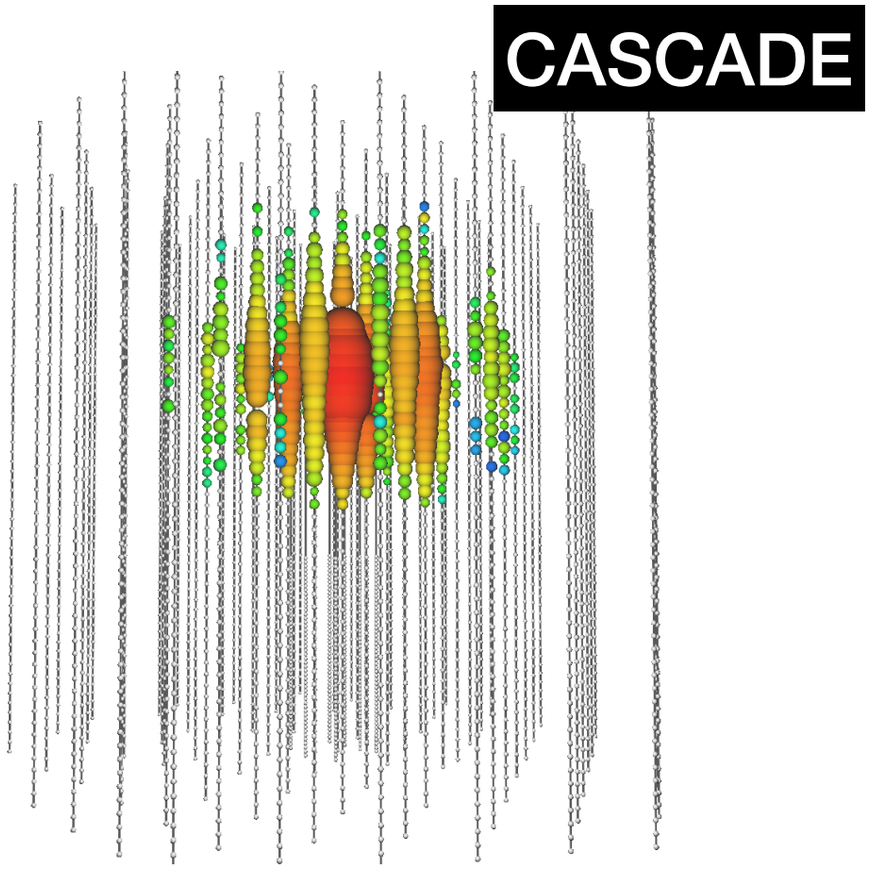
Largest neutrino detector on Earth!

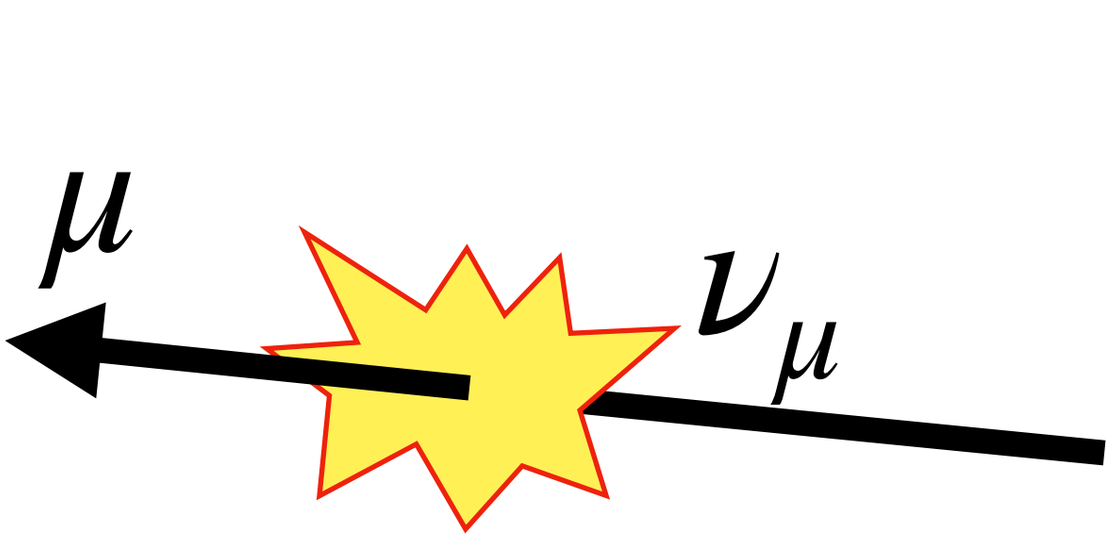
1km x 1km x 1km
Buried >2km under the ice

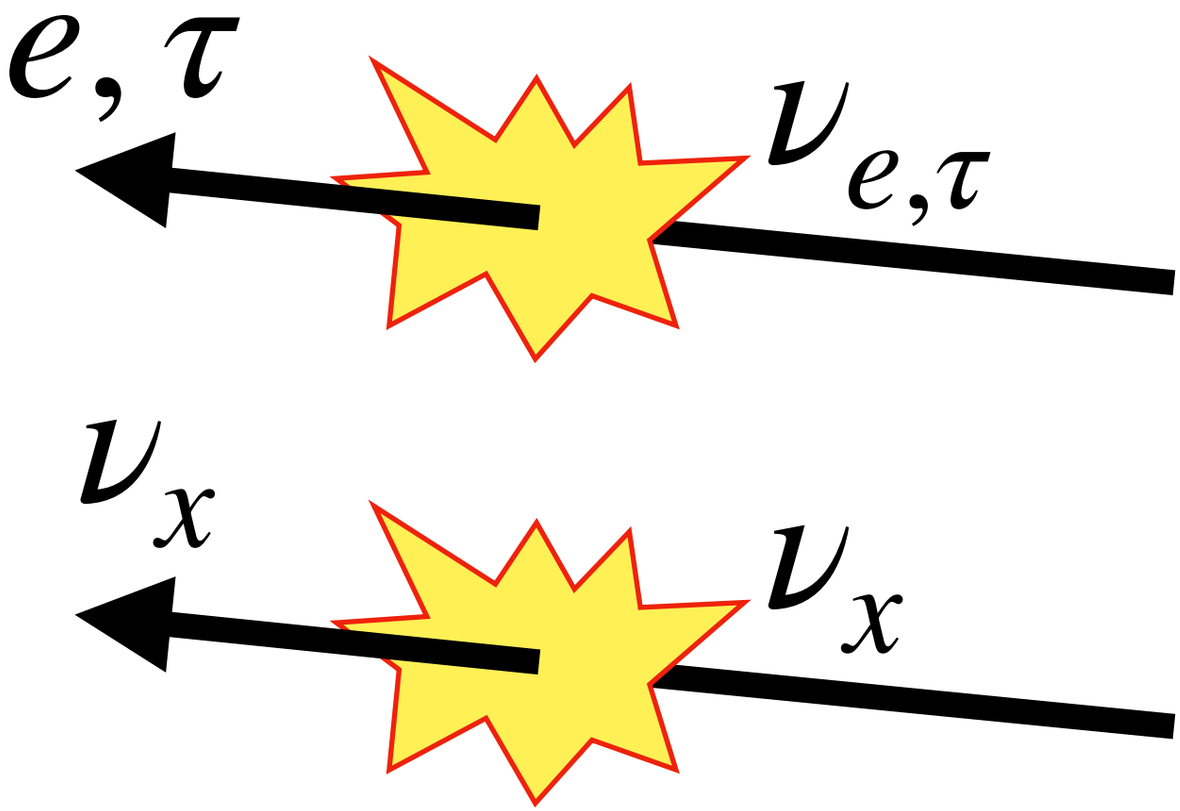
>5k optical sensors




Through-going
Starting
TRACK

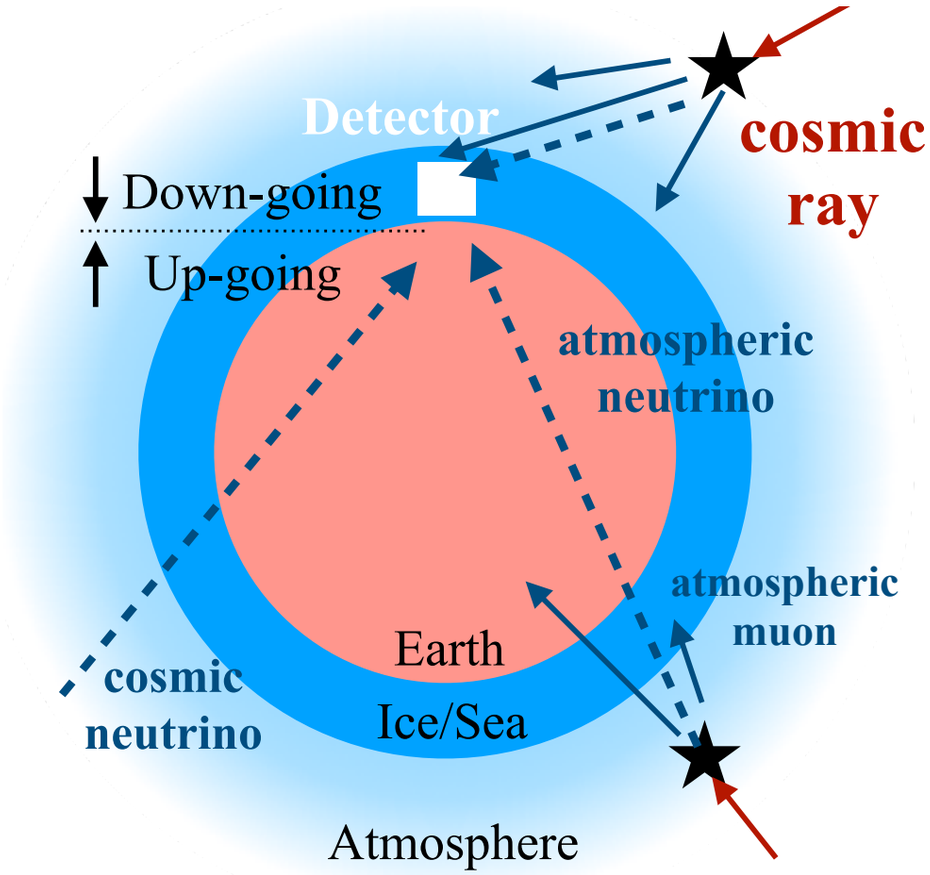

CASCADE

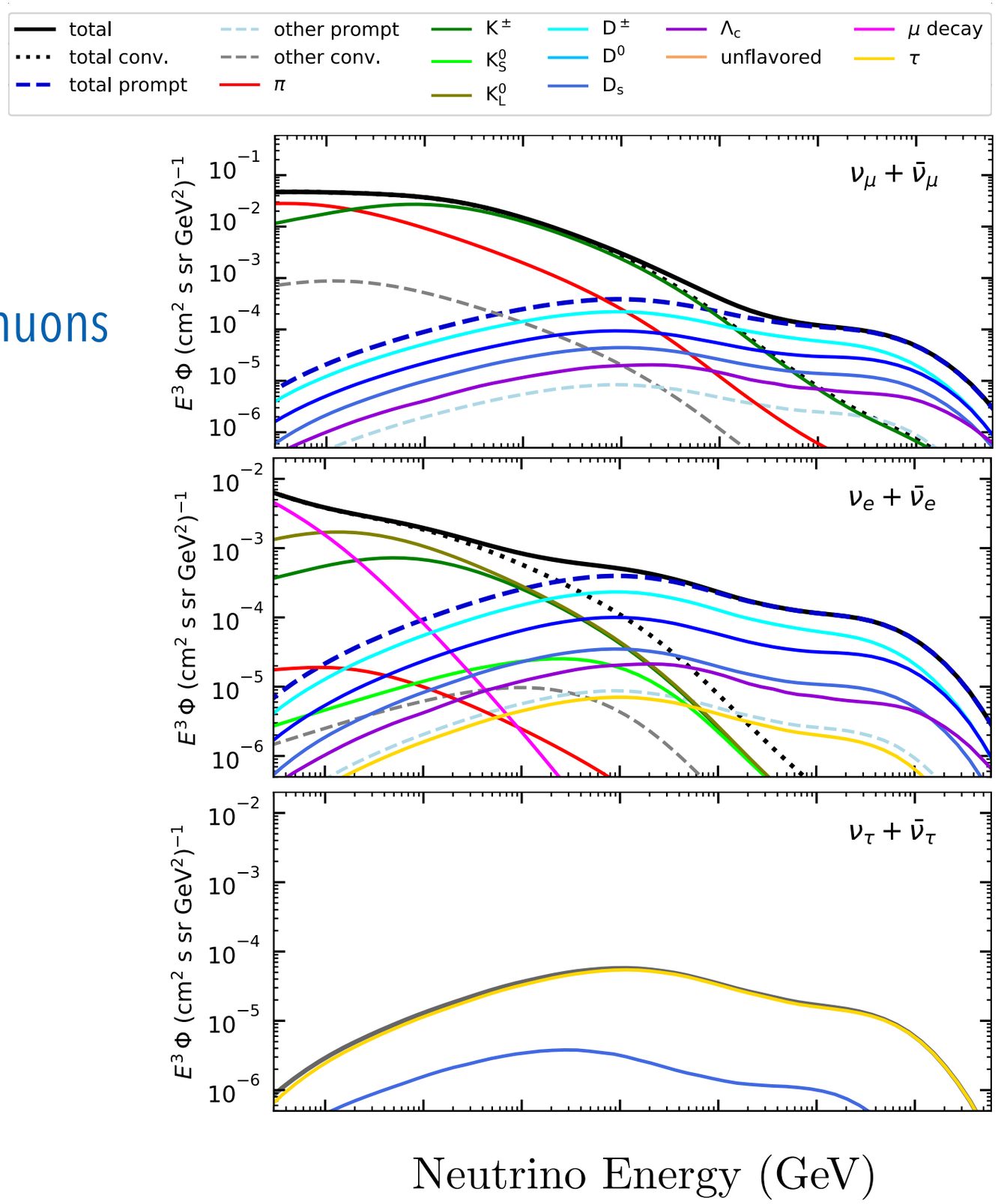

μ
ν_μ


e, τ
$\nu_{e,\tau}$
ν_x
ν_x

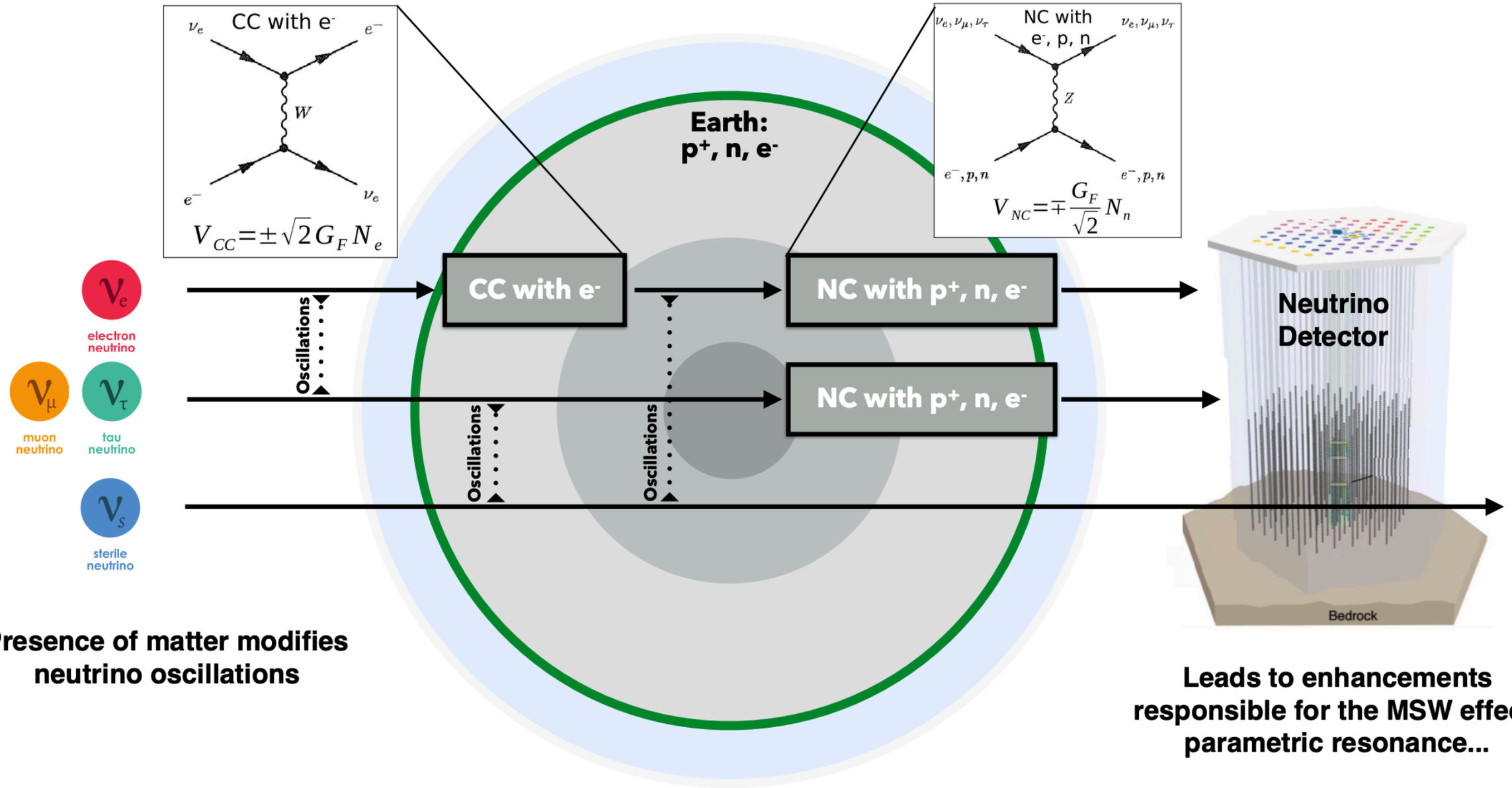
Atmospheric neutrinos

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





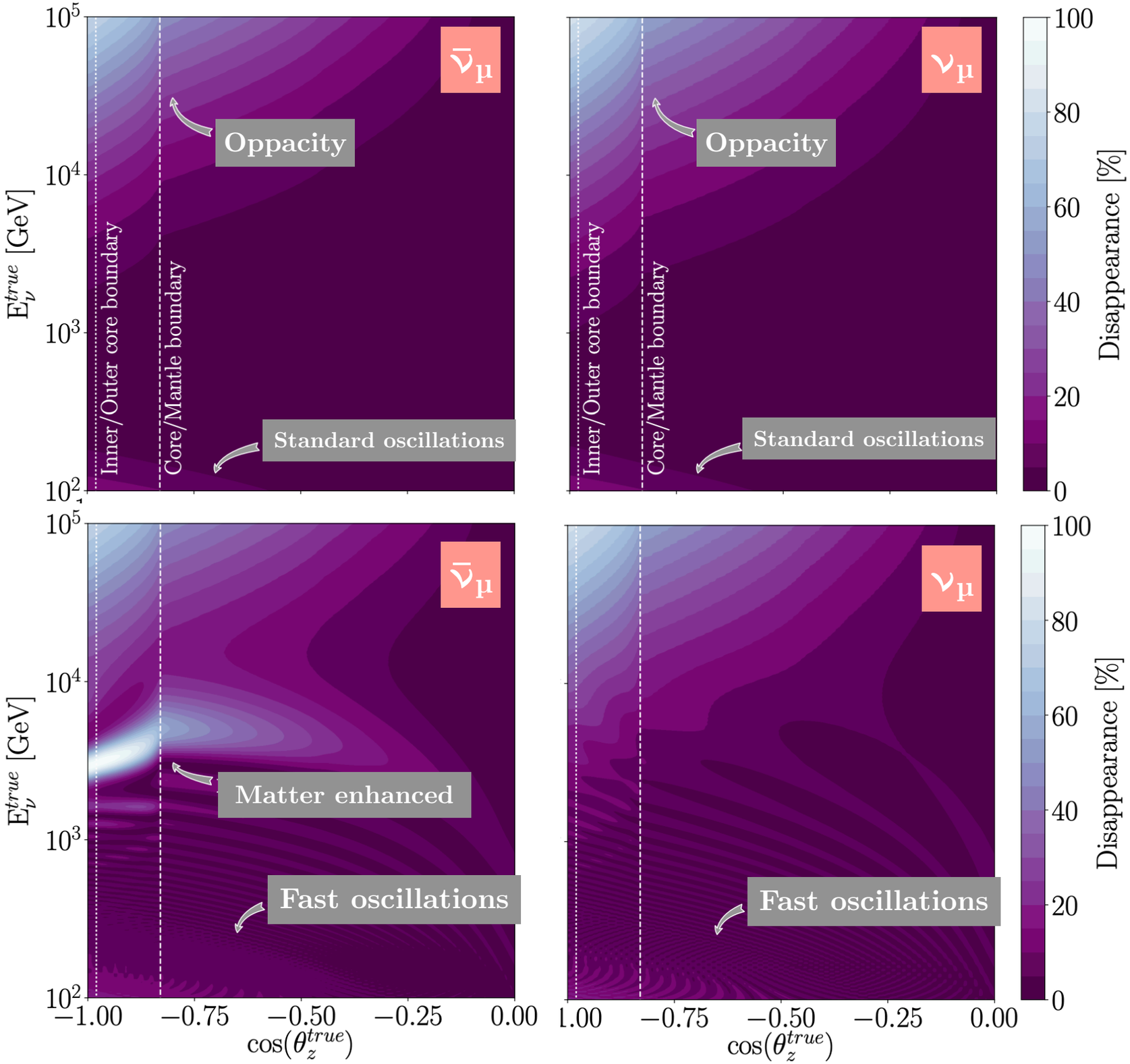
Matter enhanced oscillation



Presence of matter modifies neutrino oscillations

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

Matter enhanced oscillation



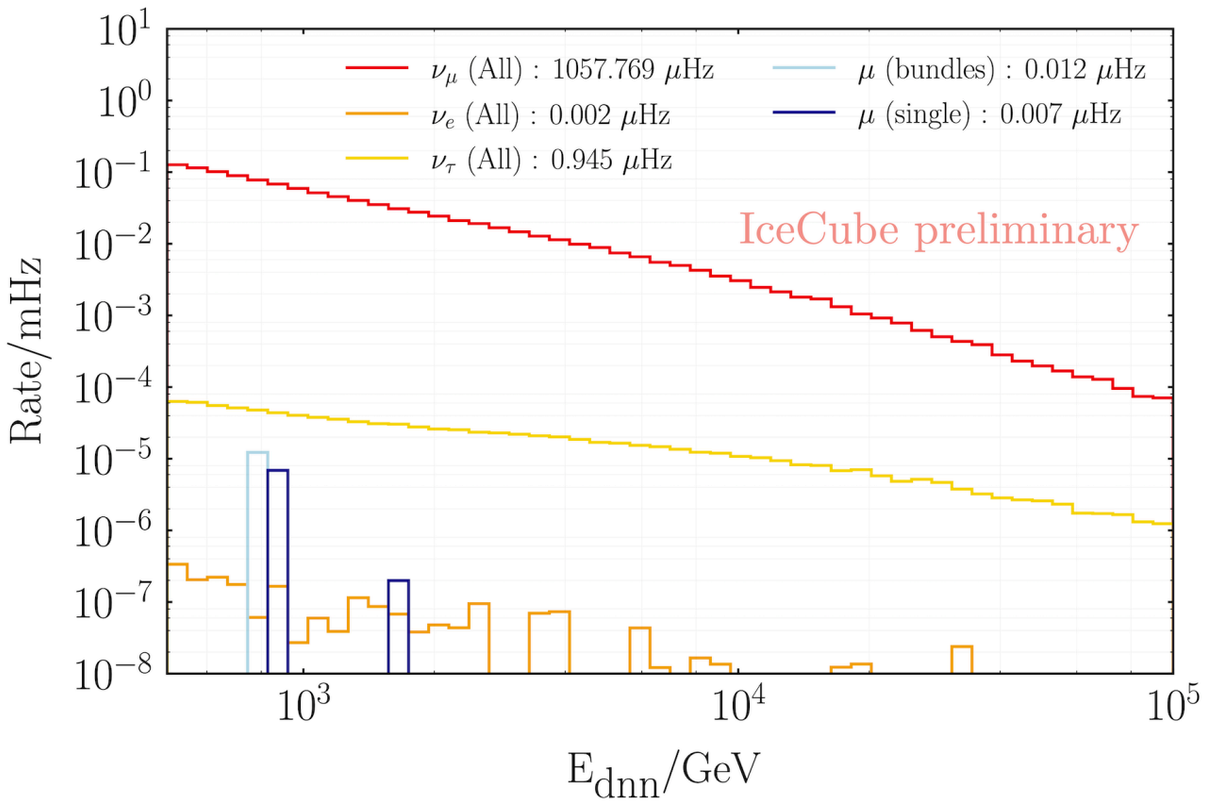
No Sterile

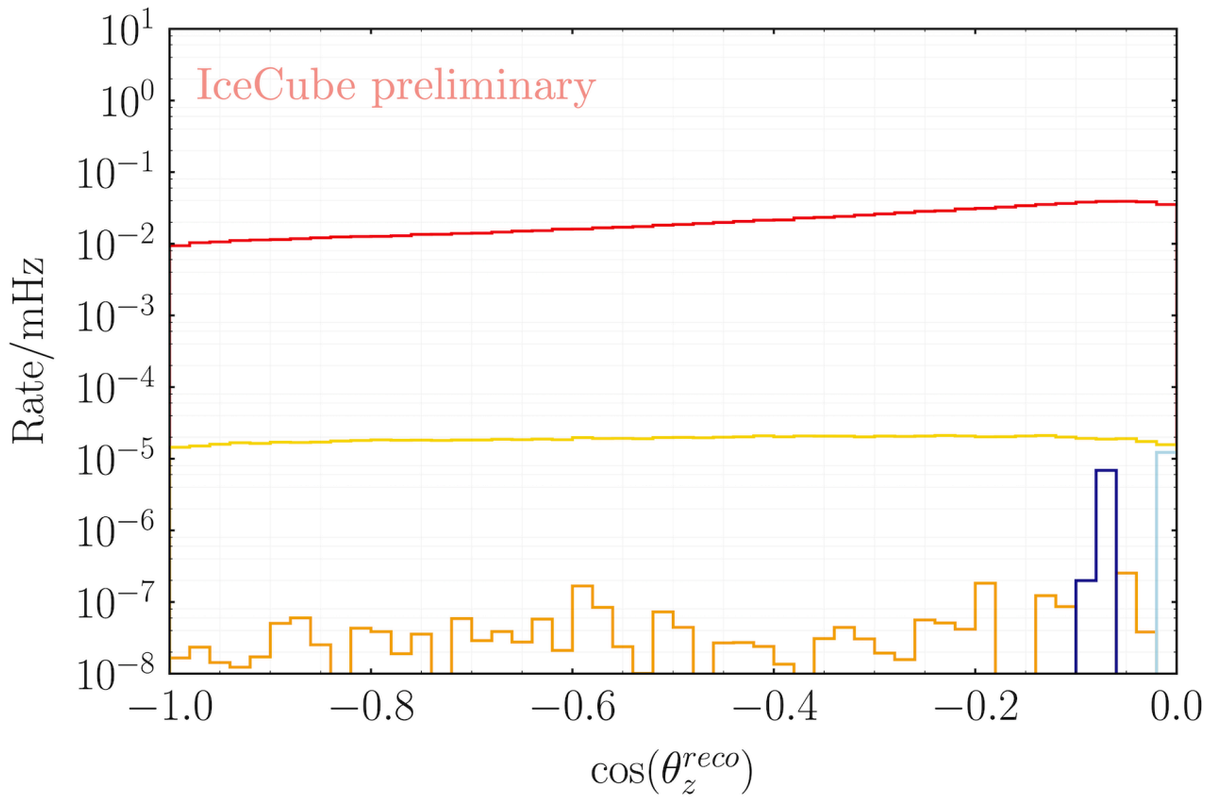
Sterile:
$\Delta m^2_{41} = 1.3 eV^2$
$\sin(2\theta_{24})^2 = 0.07$

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

Select upgoing tracks

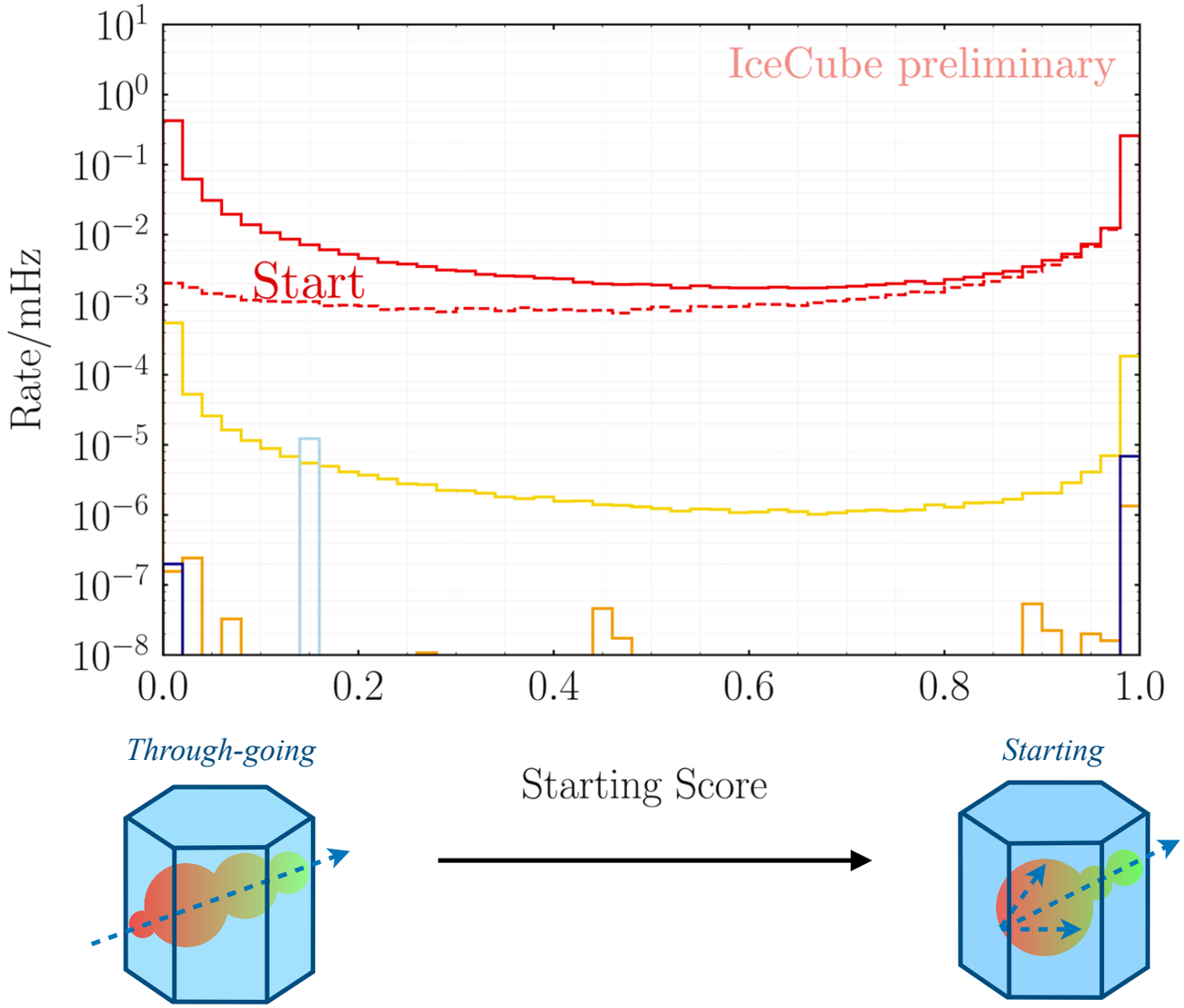
- Moving from simple cuts to BDTs
  - Reduce the contamination of atmospheric muon (<2.5 events/y)
  - Higher muon neutrino efficiency (factor 1.4)

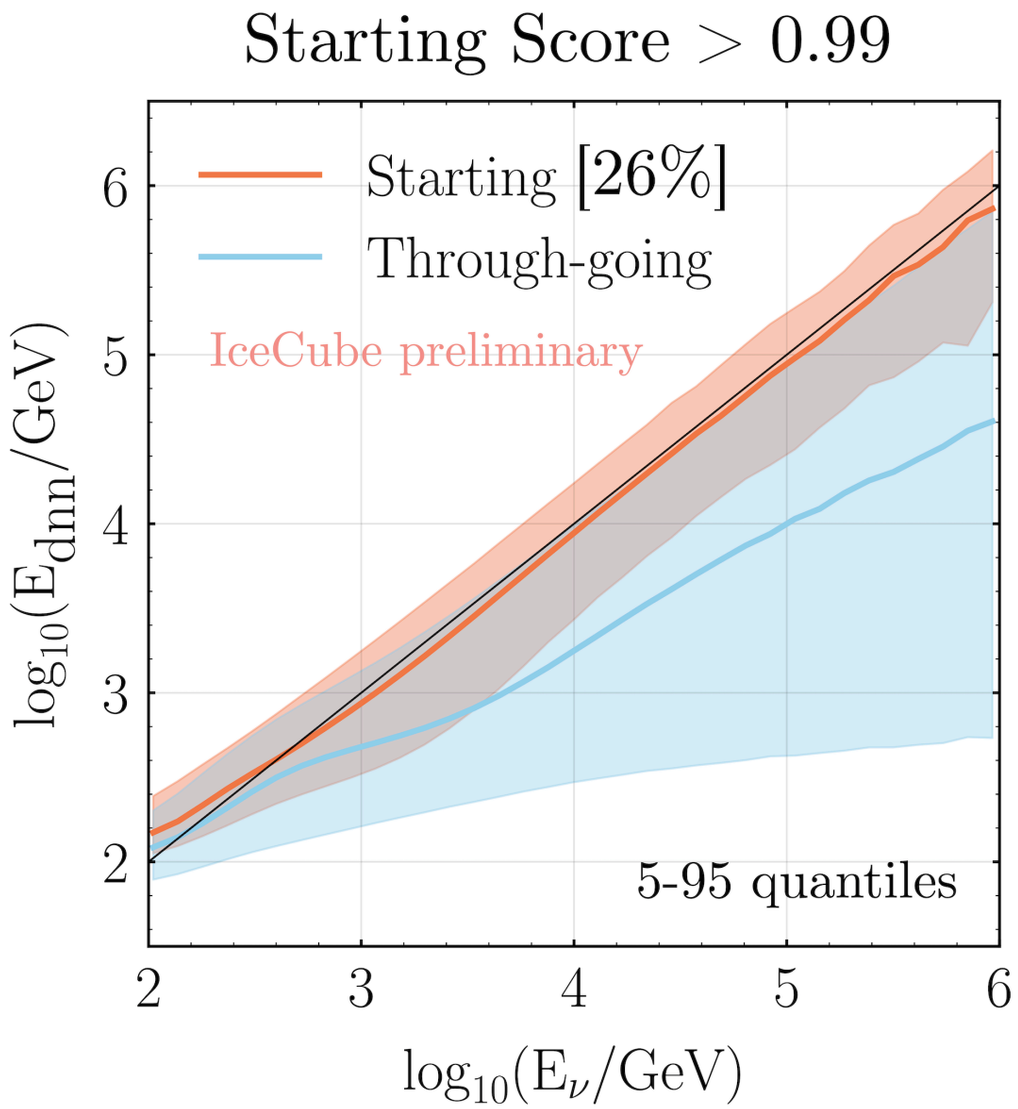




Energy estimator

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





Systematics

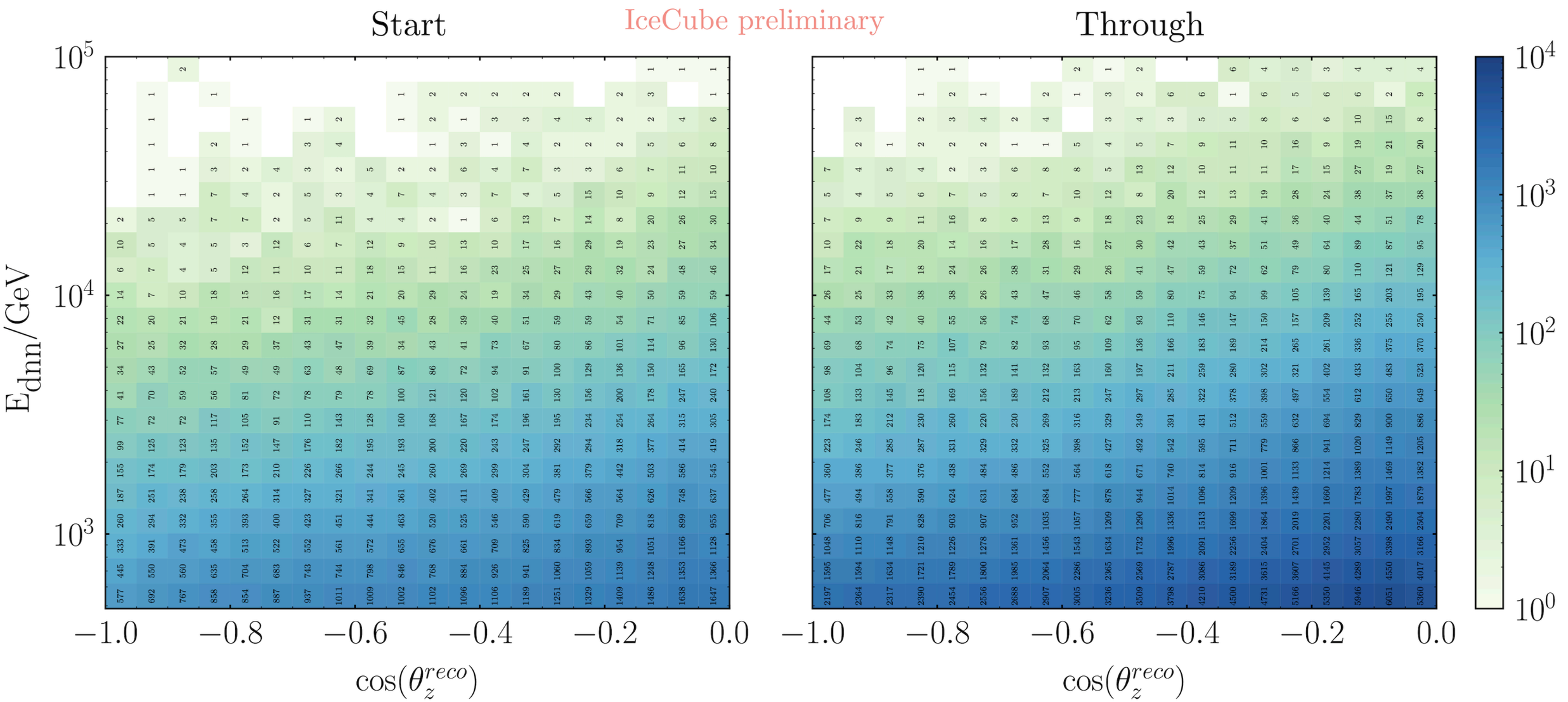
- Main changes with respect to previous analysis
  - Bulk ice -> moving to energy+zenith dependence
  - Conventional flux -> new treatment using DAEMONFLUX (PRD107, 123037)
  - Non-conventional flux -> Using broken power law

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	
π^+_{20T}	0.0	±1.0	
π^-_{20T}	0.0	±1.0	
K^+_{2P}	0.0	±1.0	
K^-_{2P}	0.0	±1.0	
π^+_{2P}	0.0	±1.0	
π^-_{2P}	0.0	±1.0	
p_{2P}	0.0	±1.0	
n_{2P}	0.0	±1.0	
GSF_1	0.0	±1.0	Cosmic ray
GSF_2	0.0	±1.0	
GSF_3	0.0	±1.0	
GSF_4	0.0	±1.0	
GSF_5	0.0	±1.0	
GSF_6	0.0	±1.0	

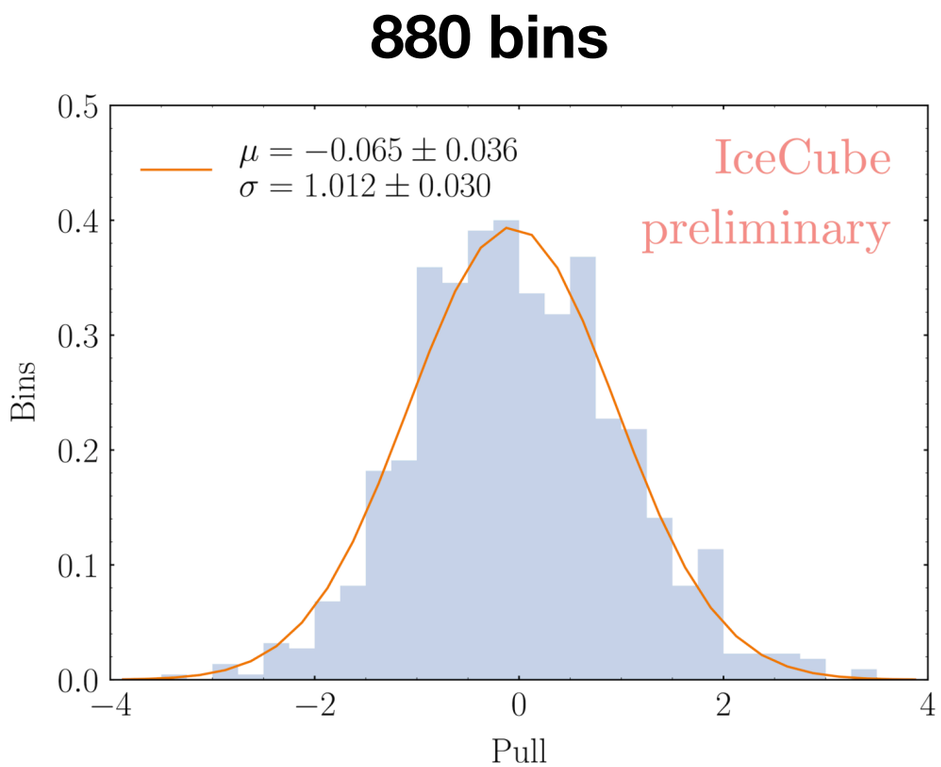
Data Sample

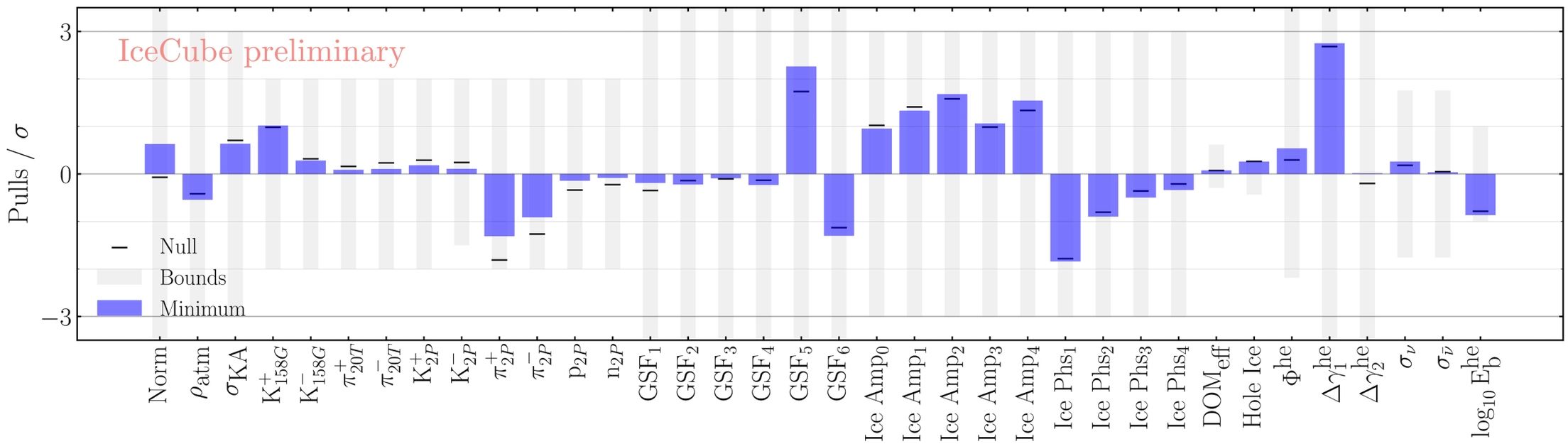
- Unblinded 10.7 years -> ~400k tracks



Fit quality

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

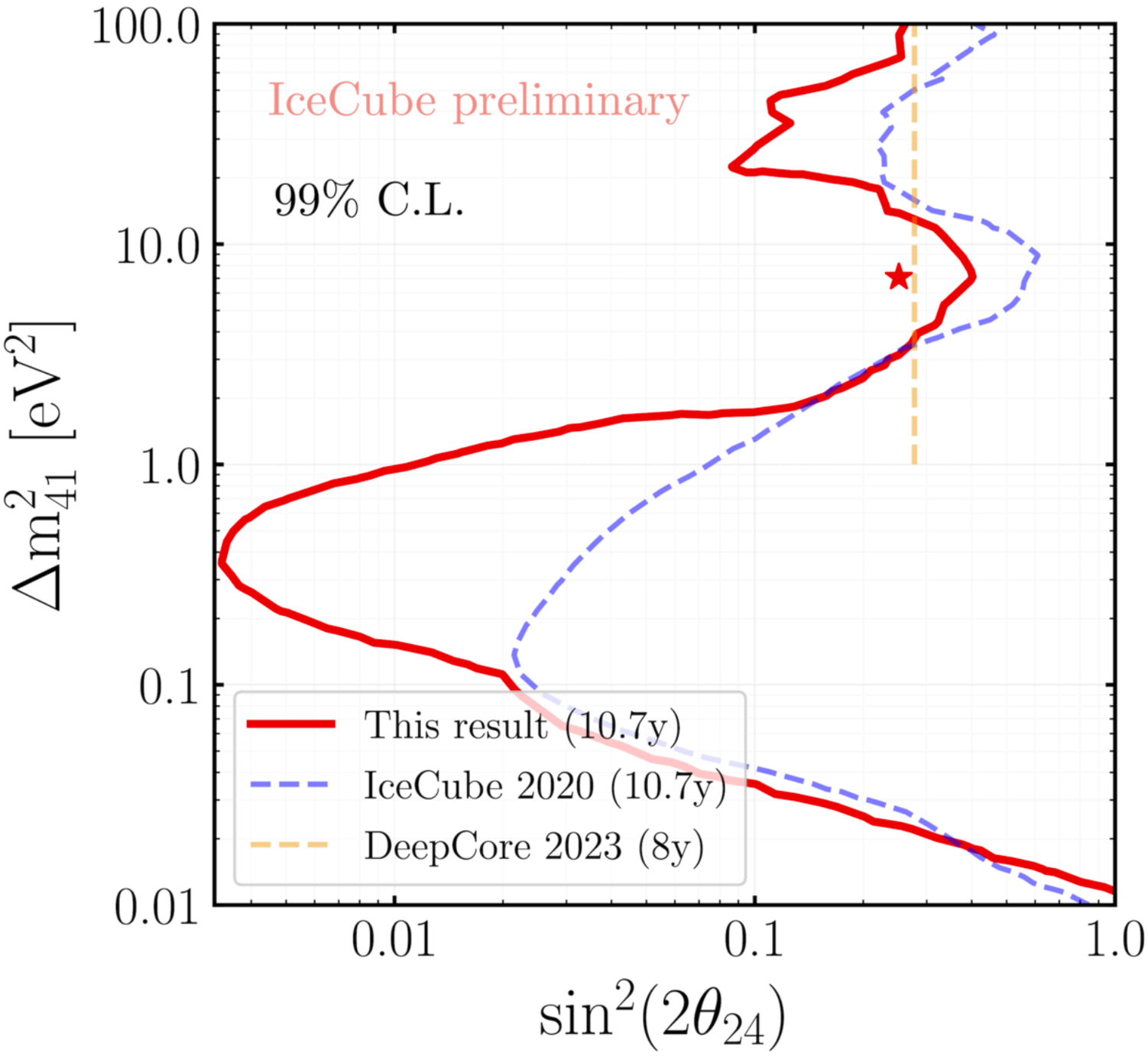




Results

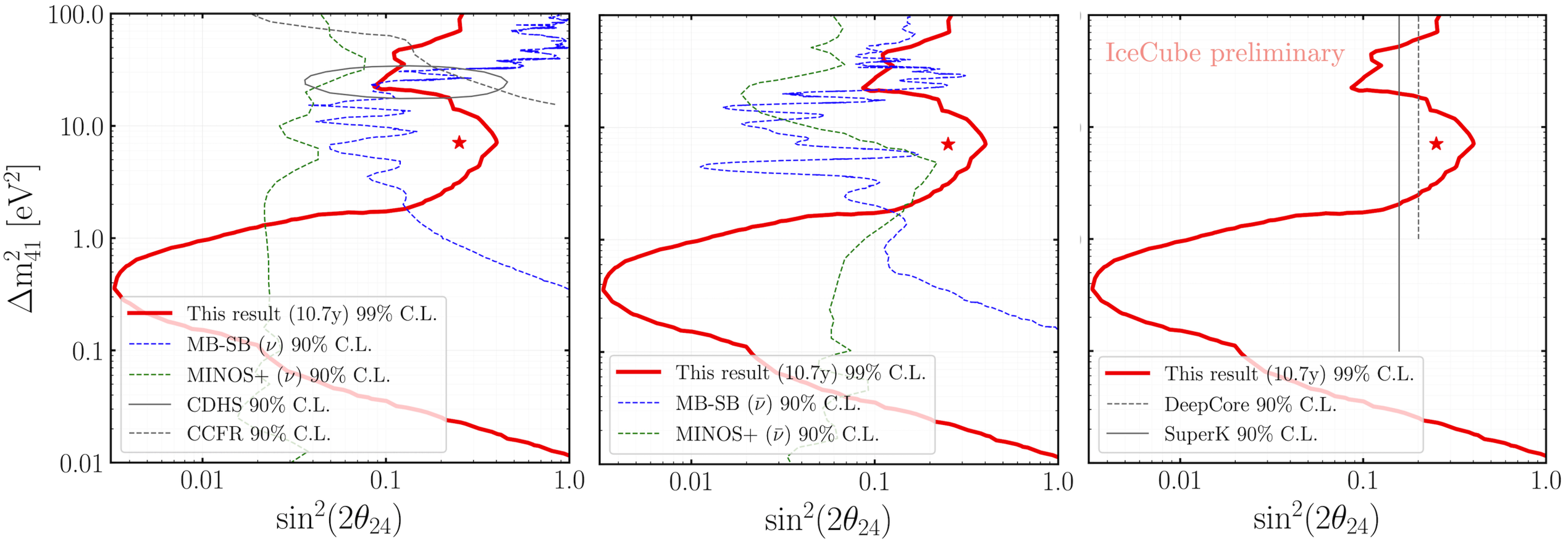
Best fit:
$\Delta m^2_{41} = 7.1 eV^2$
$\theta_{24} = 15°$

- Compatible with previous IC analysis
- Null rejection <3σ



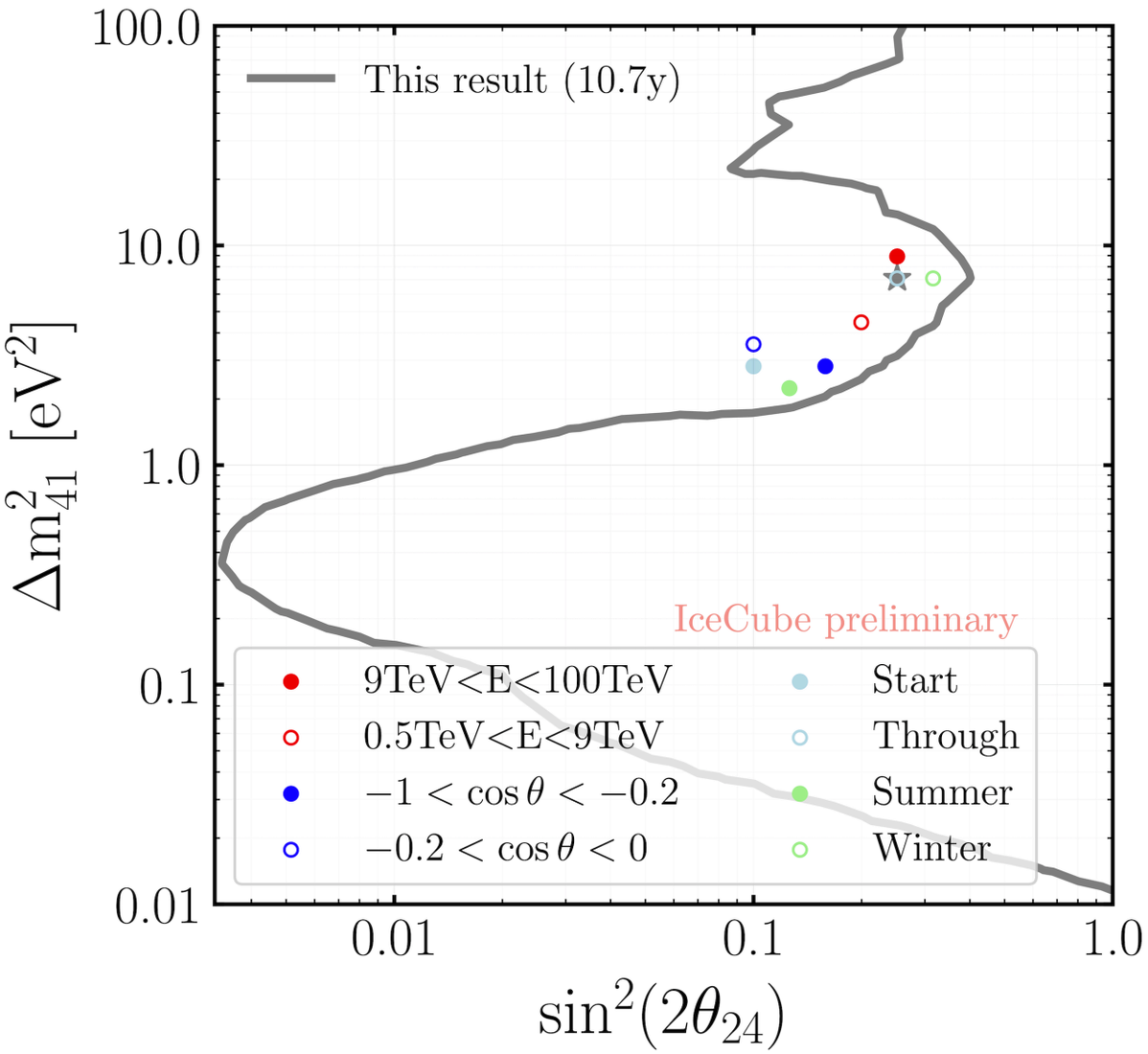
Compared with world data

- Best-fit in tension with other numu disappearance measurements



Compatibility Tests

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



Conclusions

- Unique sterile search
  - Different energy range (systematics) to any other experiment
  - Signal mainly driven matter enhanced oscillations

- New analysis with major changes
  - Event selection
  - Energy reconstruction
  - Flux treatment

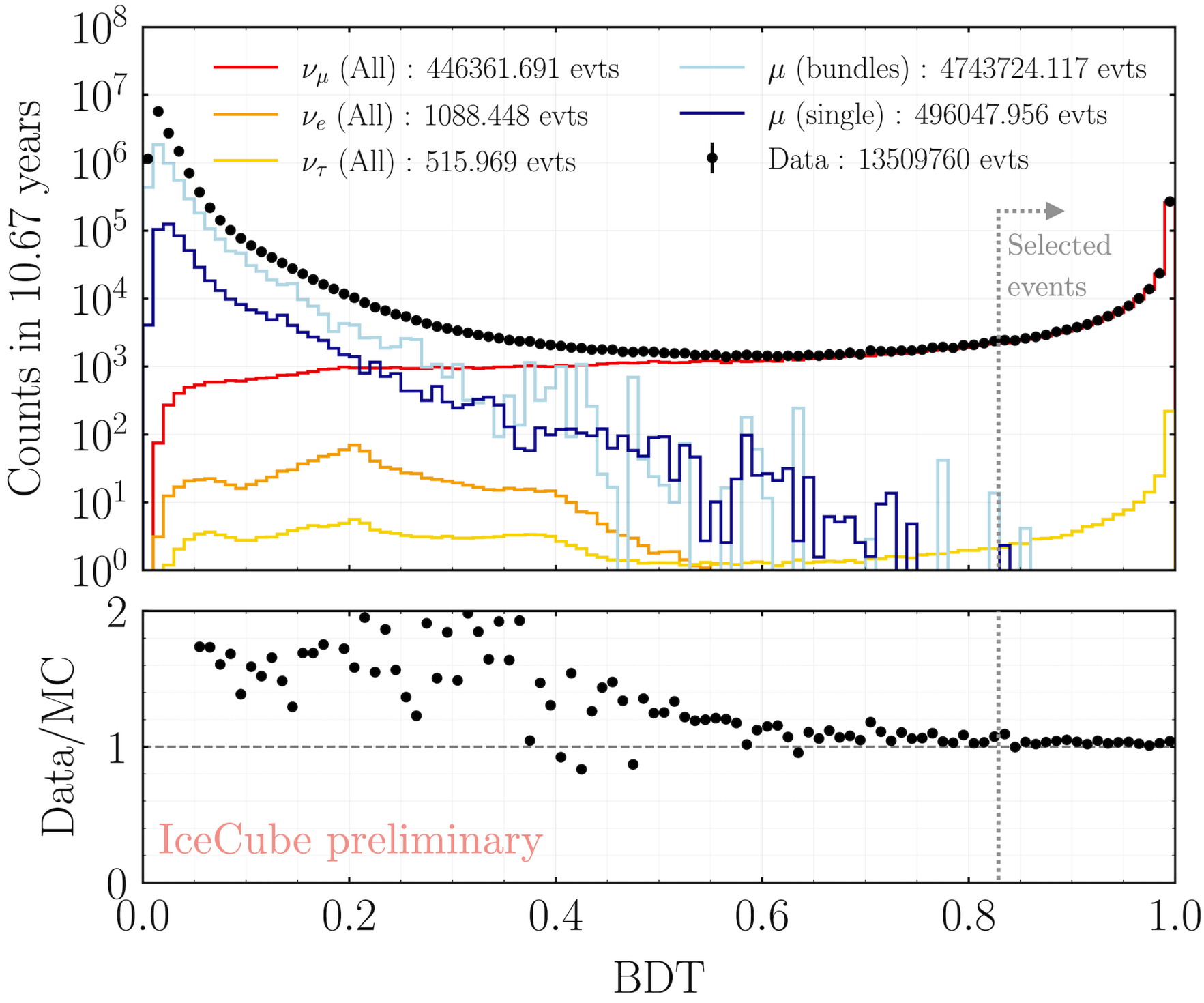
- Unblinded 10.7 years of data
  - Consistent with previous IC analyses
  - Tension with other experiments

- Ongoing tests to quantify the significance of the result

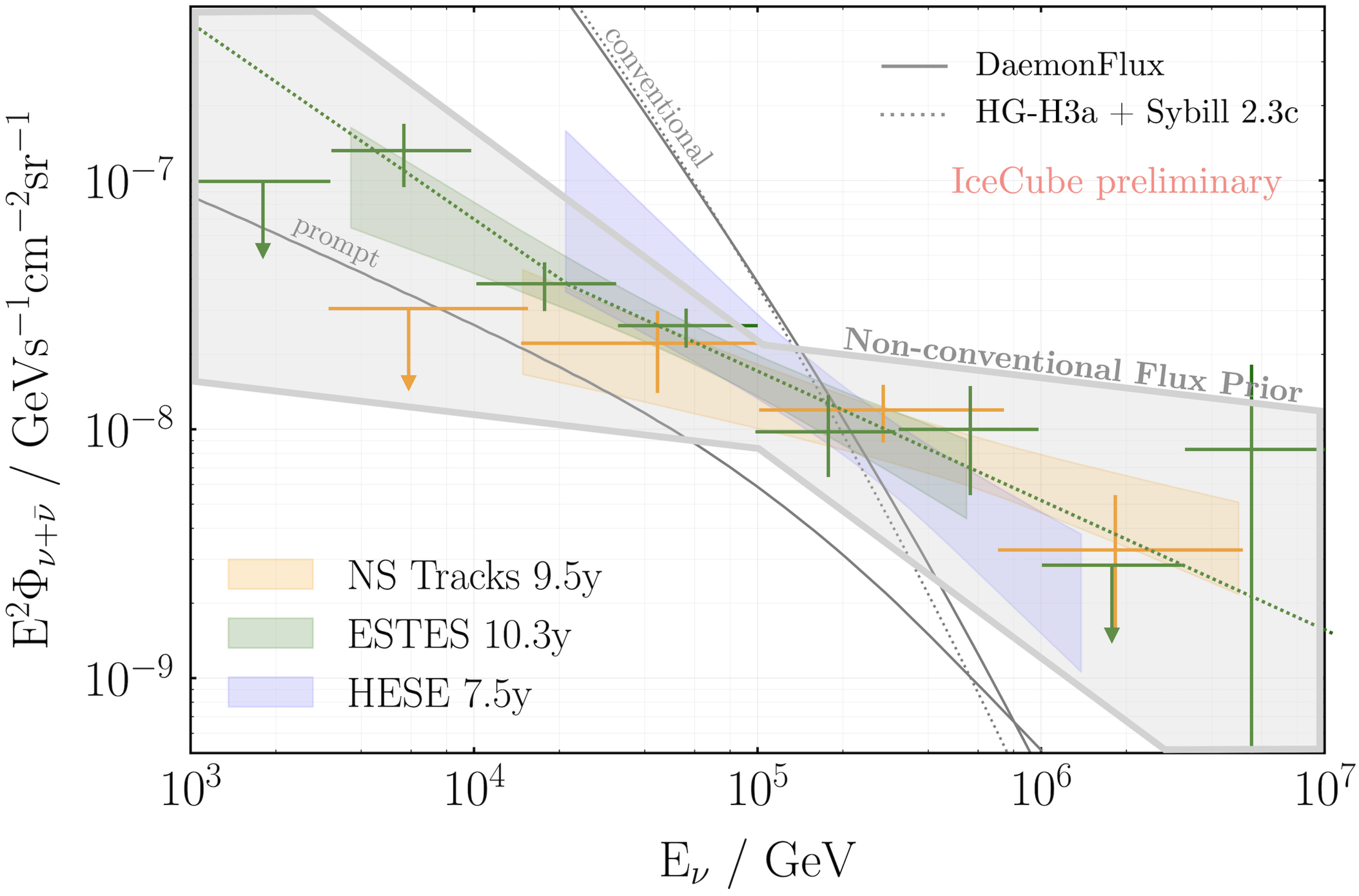
Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 101025085.

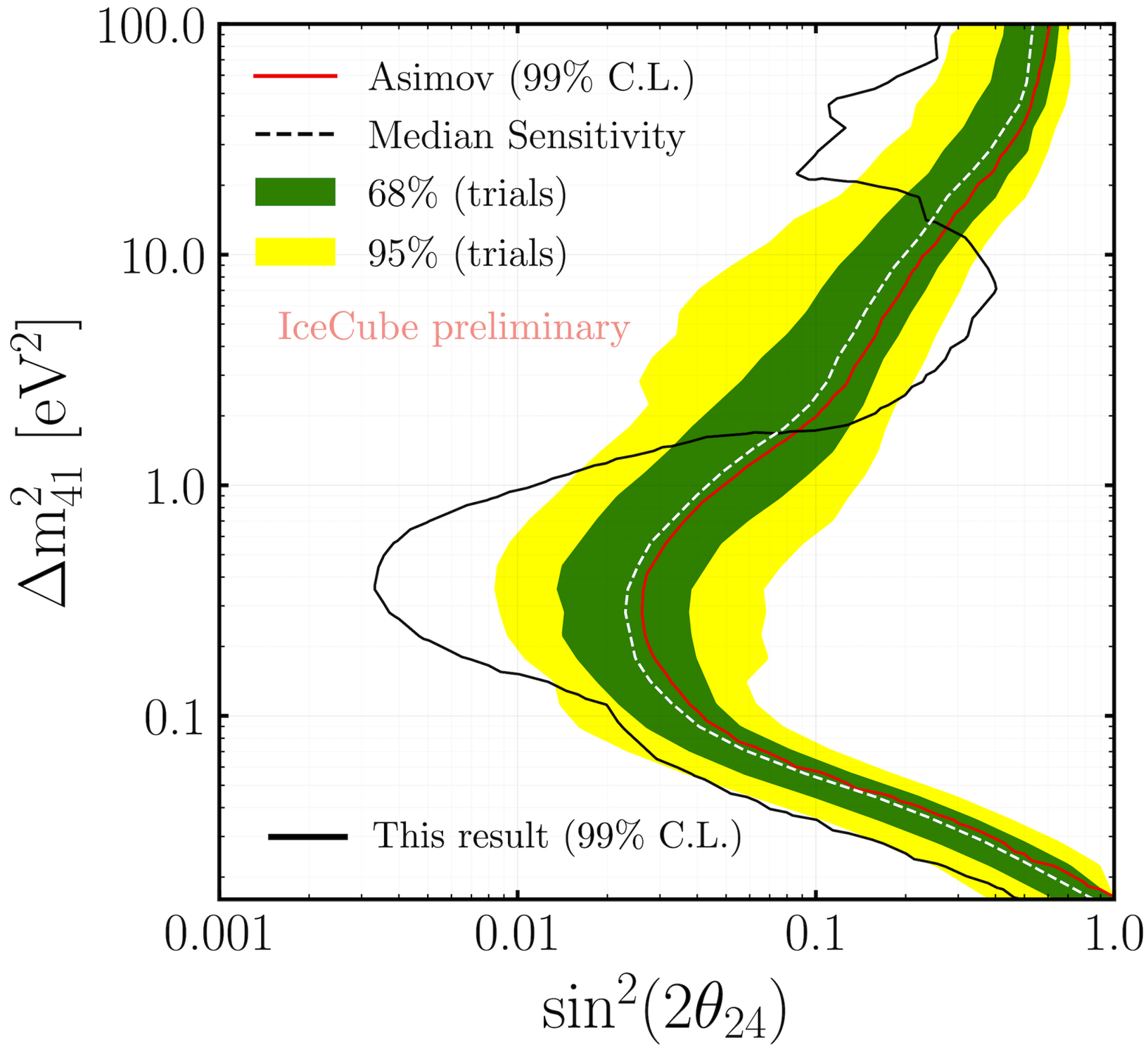
BDT distribution



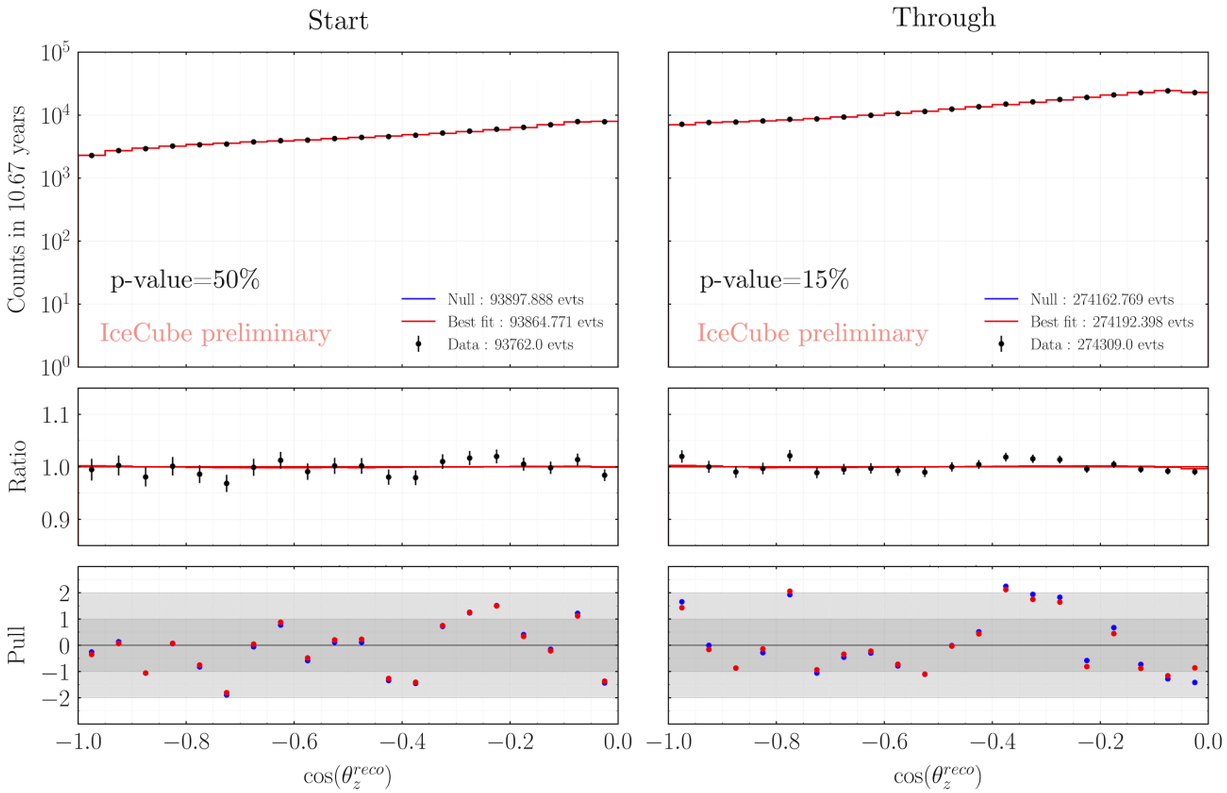
Non-conventional priors

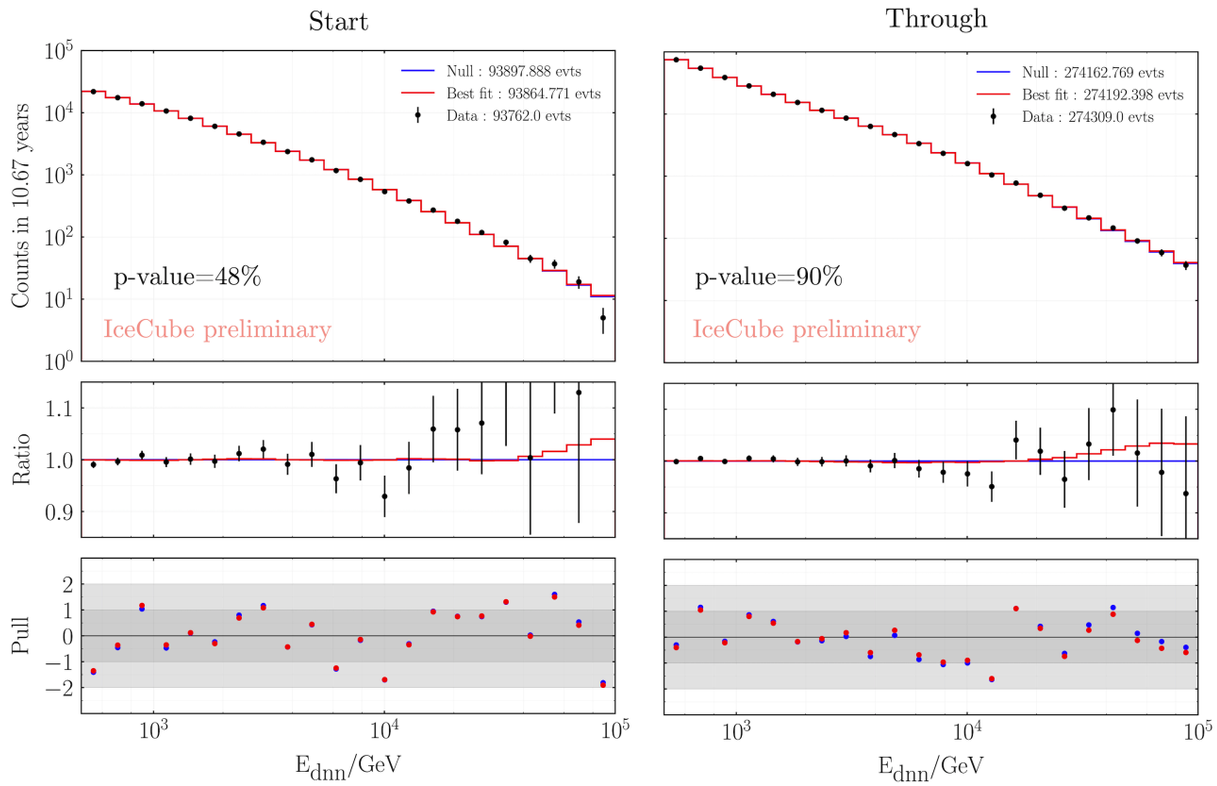


Sensitivity

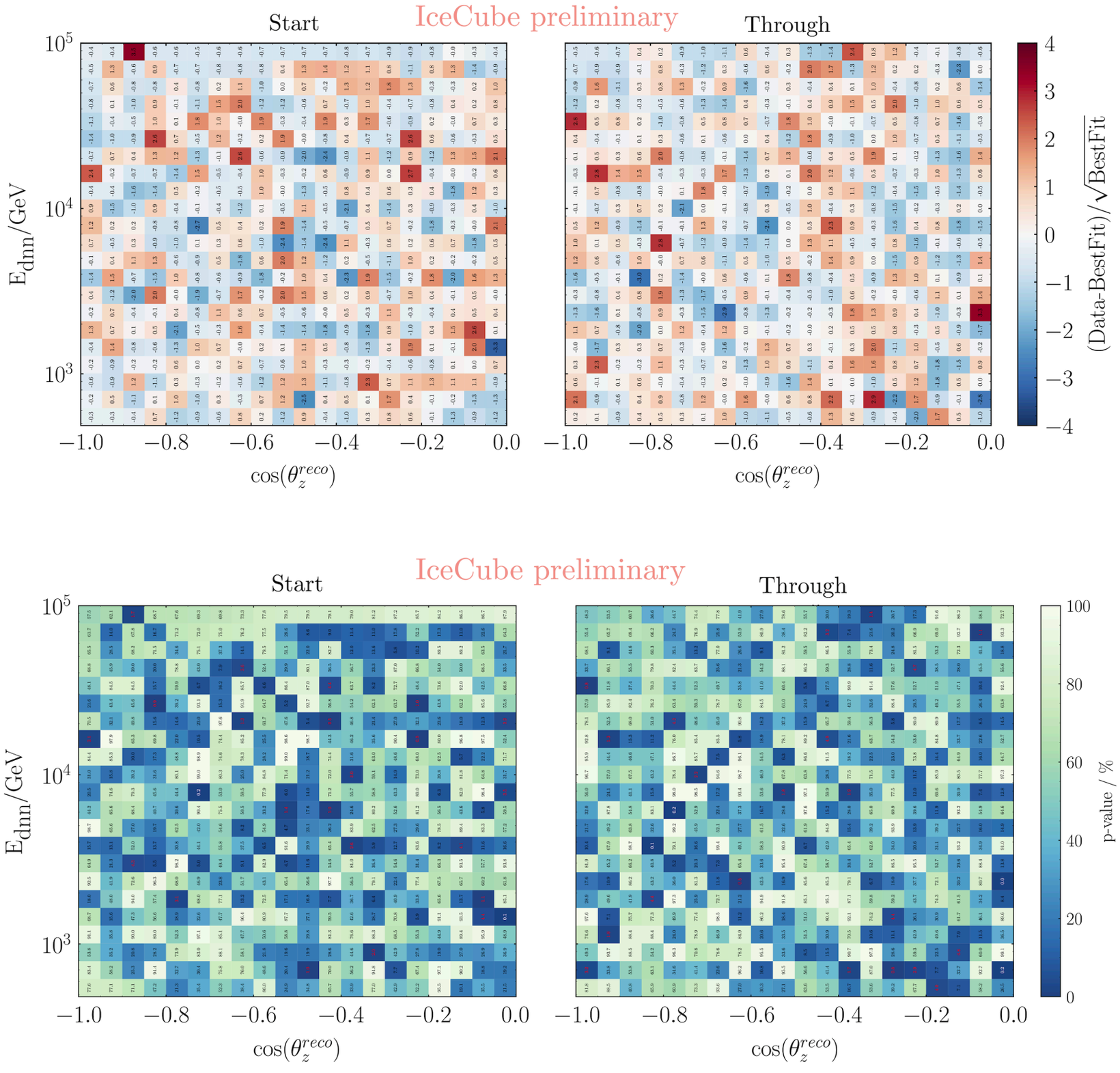


1D distributions





2d pulls



1k pseudoexp. at best-fit point

Best-fit vs null flux