KITP 2022

(Santa Barbara, US)

# Constraining BSM physics with atmospheric neutrinos at IceCube


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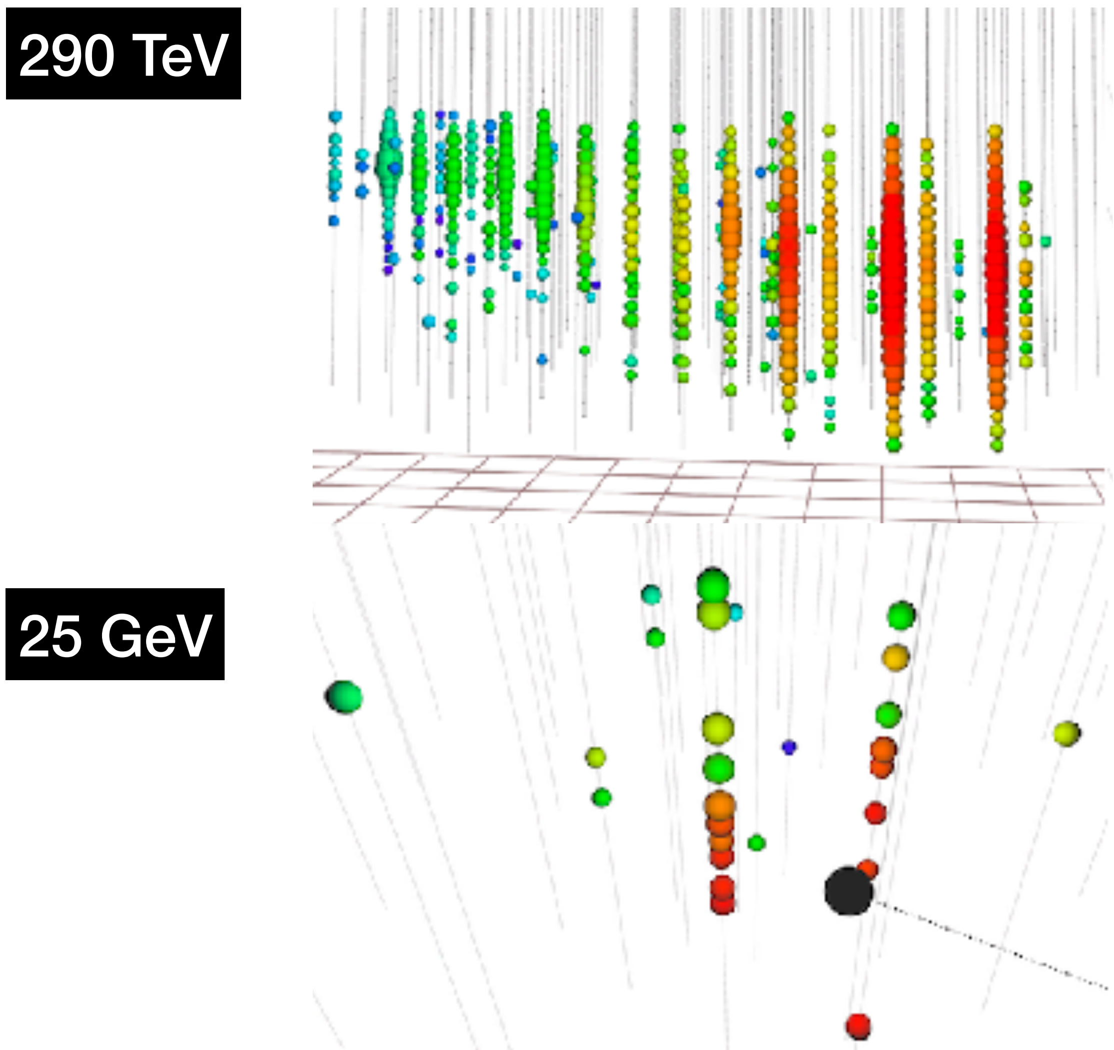
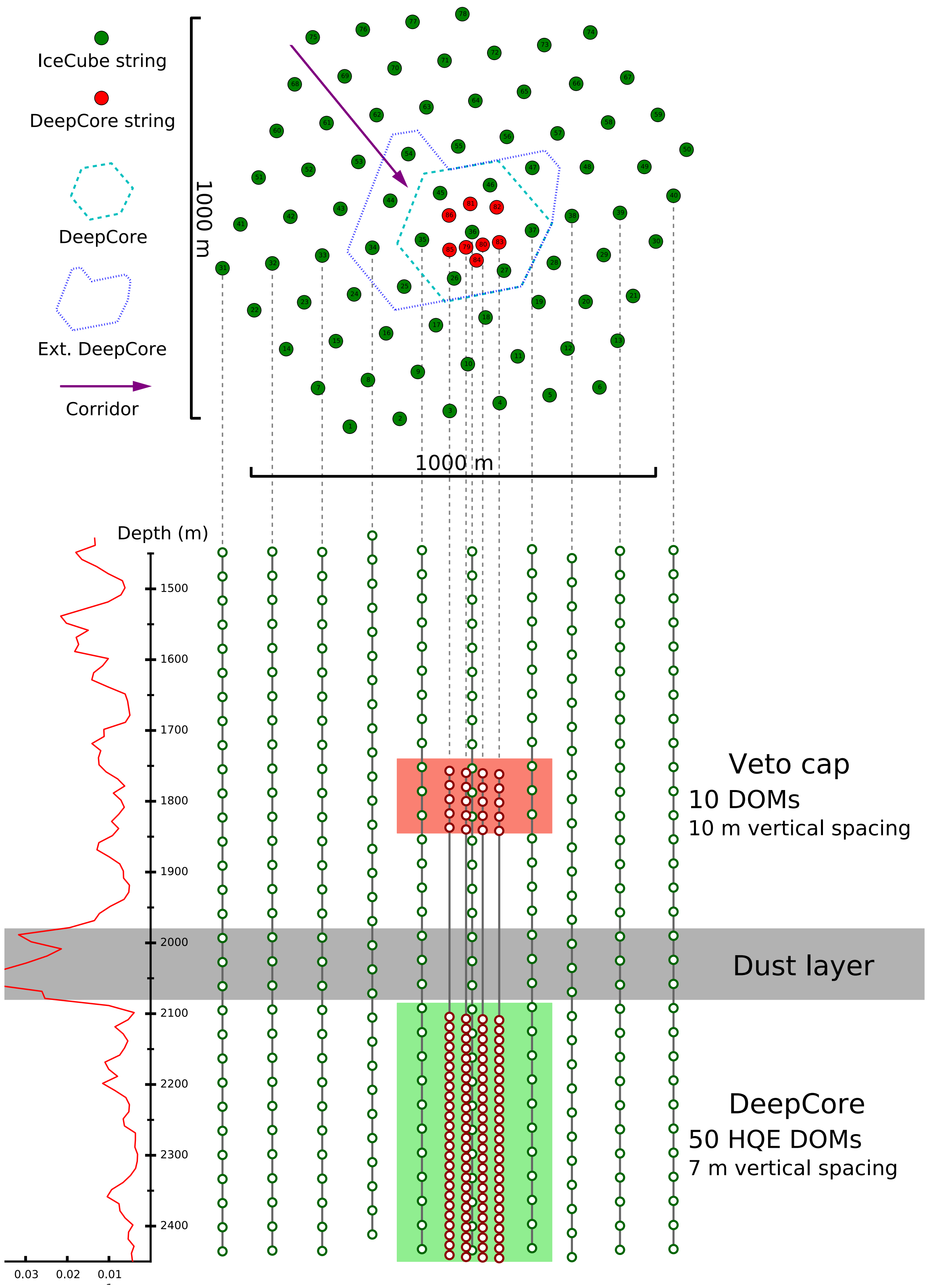
# IceCube

- Deep Core -> Low energy (5-100 GeV)
  - Challenges: triggering, reconstruction, PID.
- IceCube -> (1 TeV - 10PeV)
  - Challenges: statistics, reconstruction.

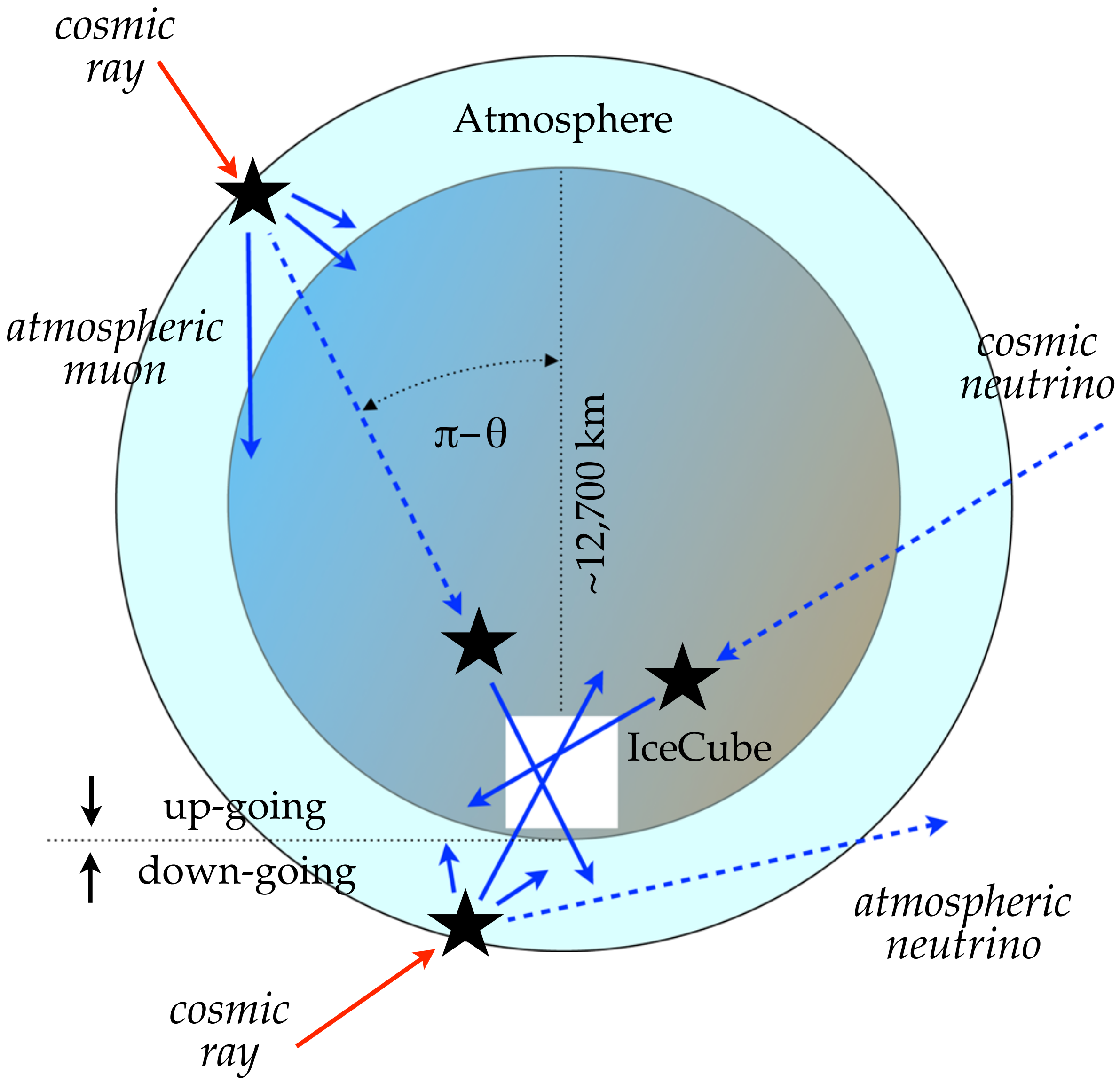


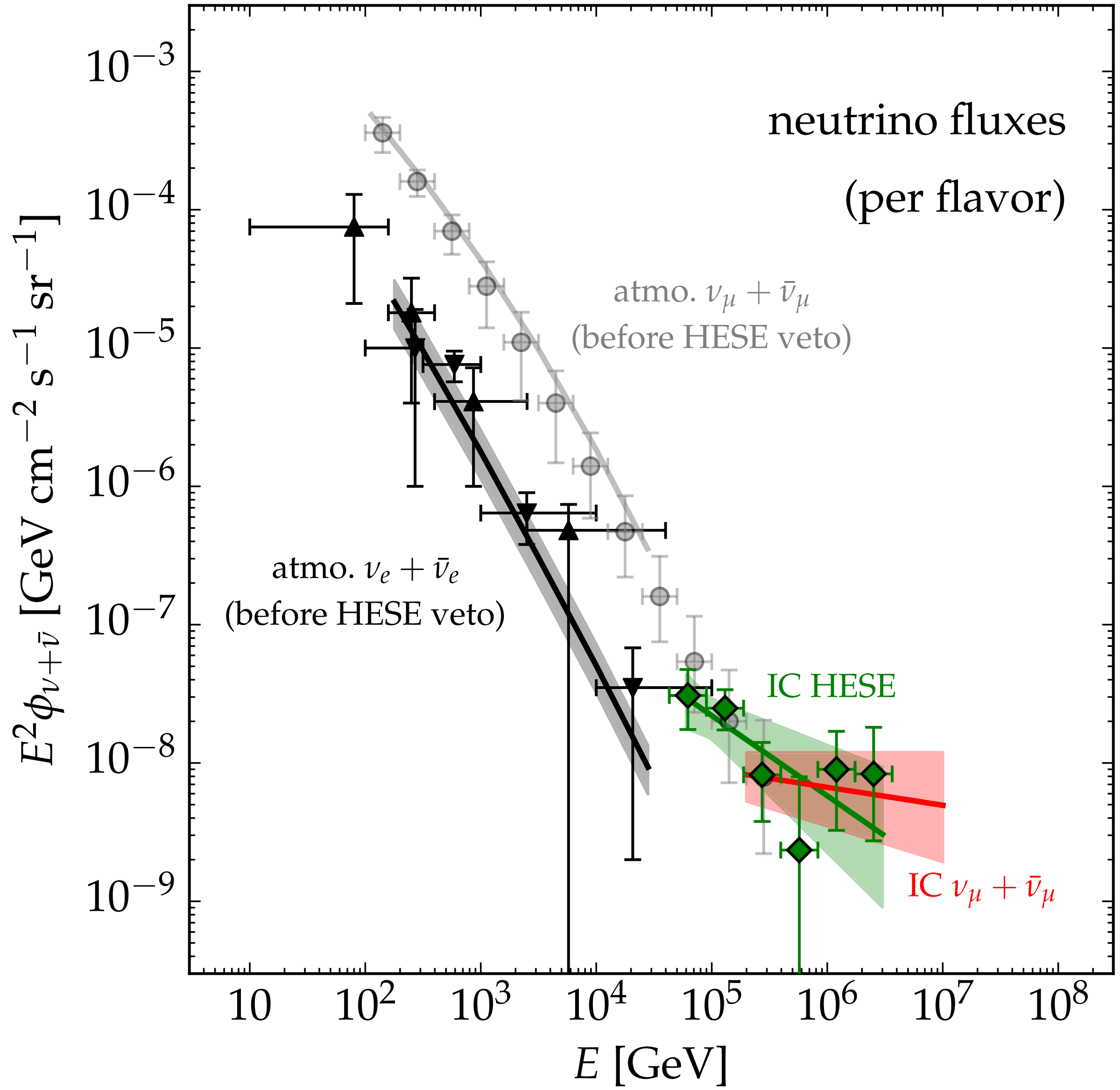



# Atmospheric neutrinos

- Dominant source of neutrinos in IceCube in the TeV regime.
- Two main channels are studied:
  - Upgoing tracks (~$\nu_\mu$-CC) and cascades (~$\nu_e$CC & $\nu_x$NC).

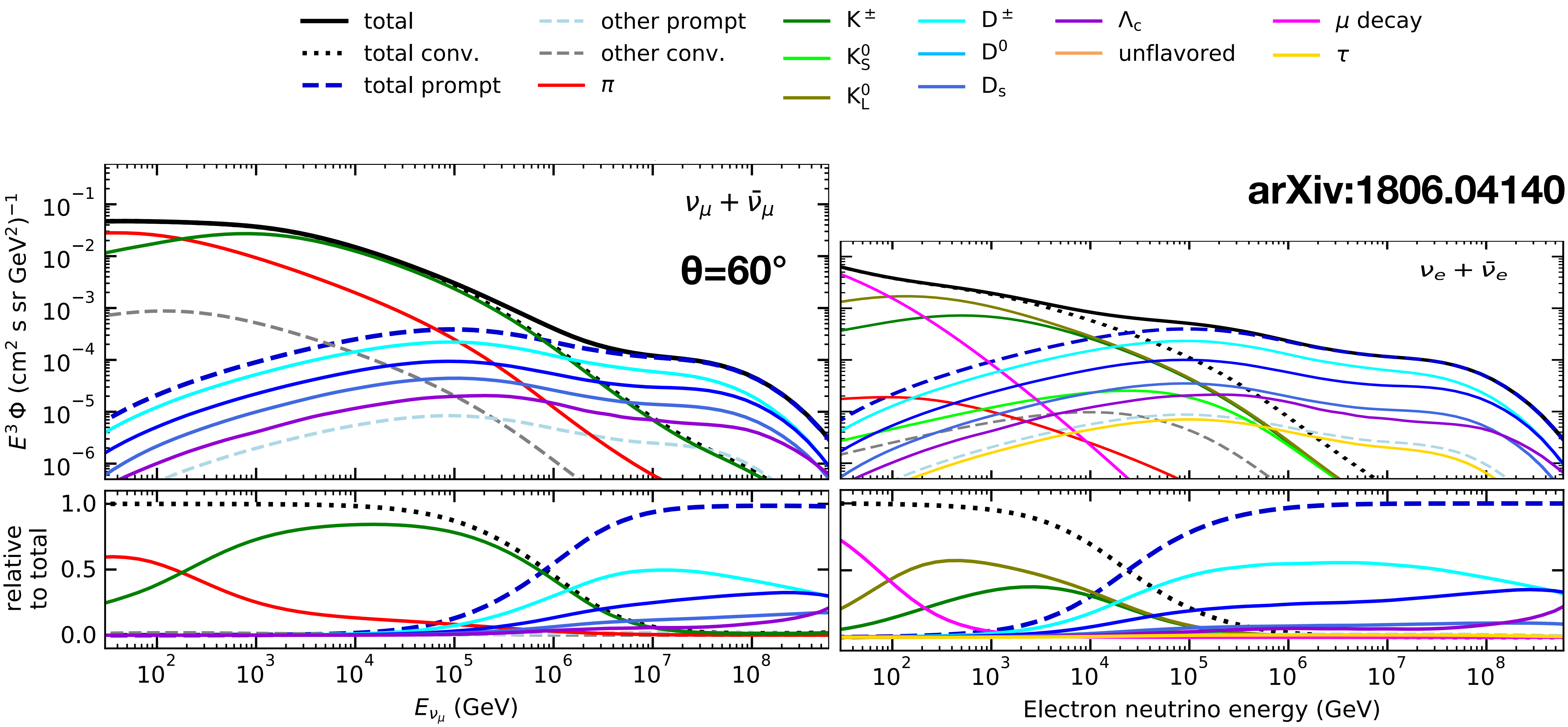
**arXiv:1806.05696**



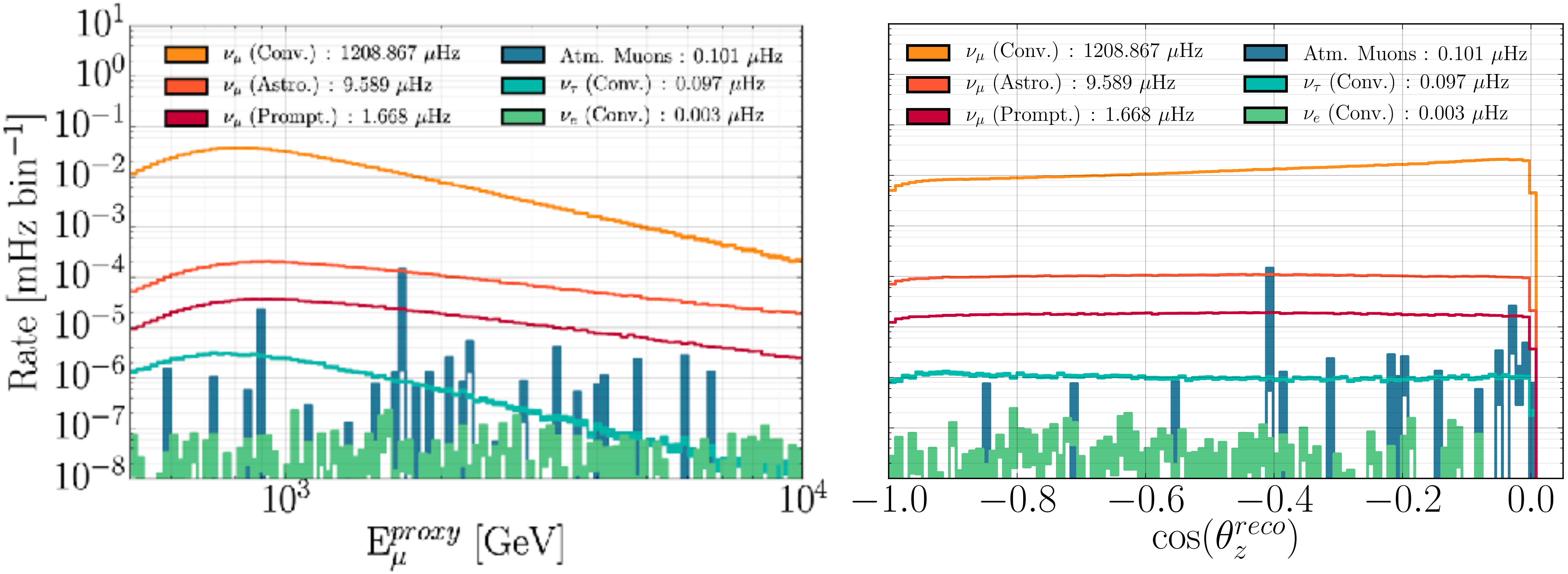
# Atmospheric neutrinos

- Mainly coming from Kaon decay in the TeV range.
- Prompt contribution expected to dominate for E>100TeV



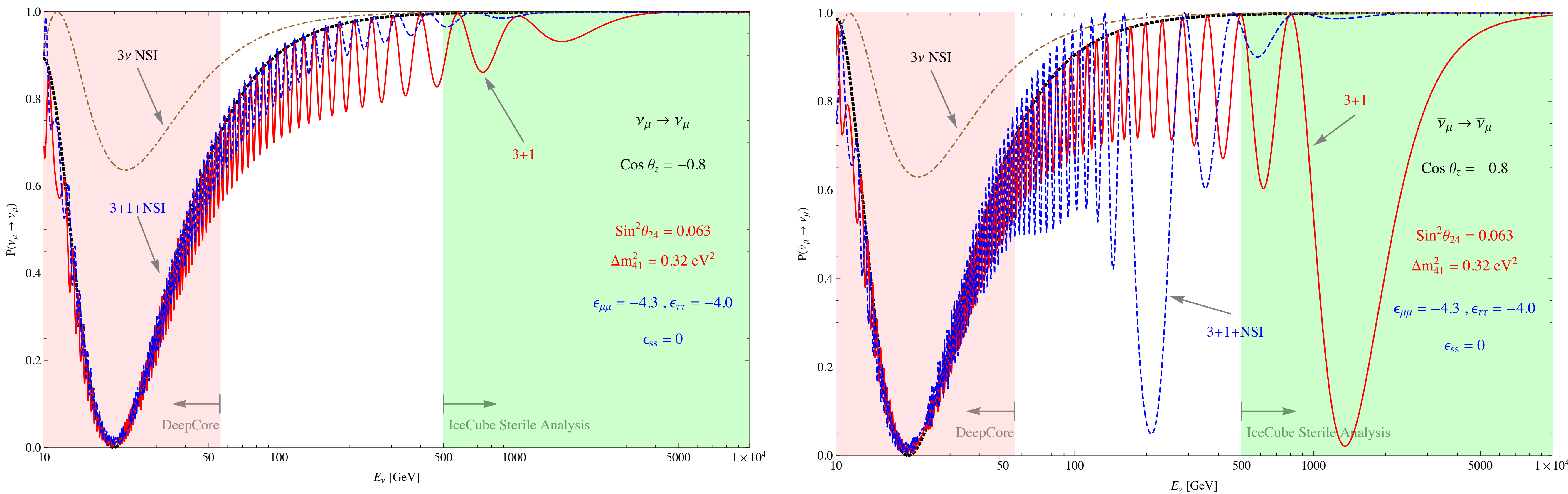
# Track selection

- Tight cuts to reduce atmospheric muon contamination.
- Thousands of TeV upgoing tracks every year with $\nu_\mu$ purity >99.9%!



# Oscillations

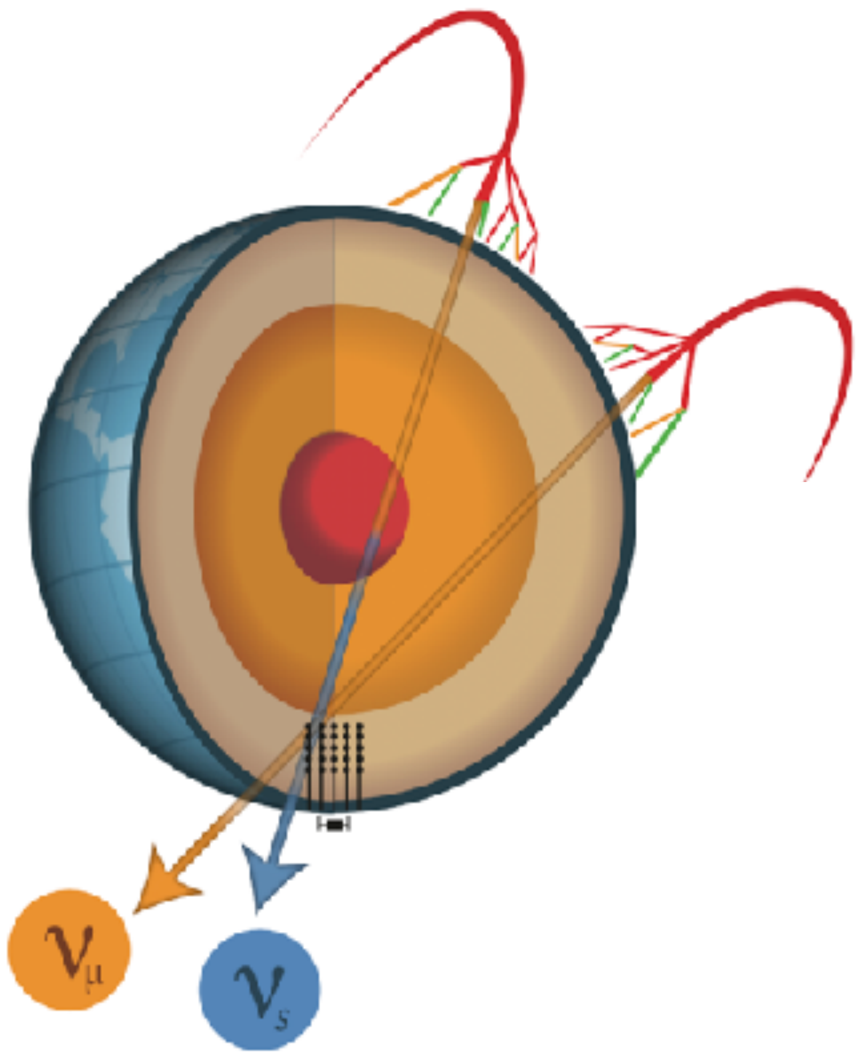
- Standard oscillations are subdominant above 100 GeV.
- NSI and sterile neutrinos distort anti-neutrino oscillation probabilities.
  - Look for dips in the atmospheric muon neutrino spectrum.




arXiv:1810.11940

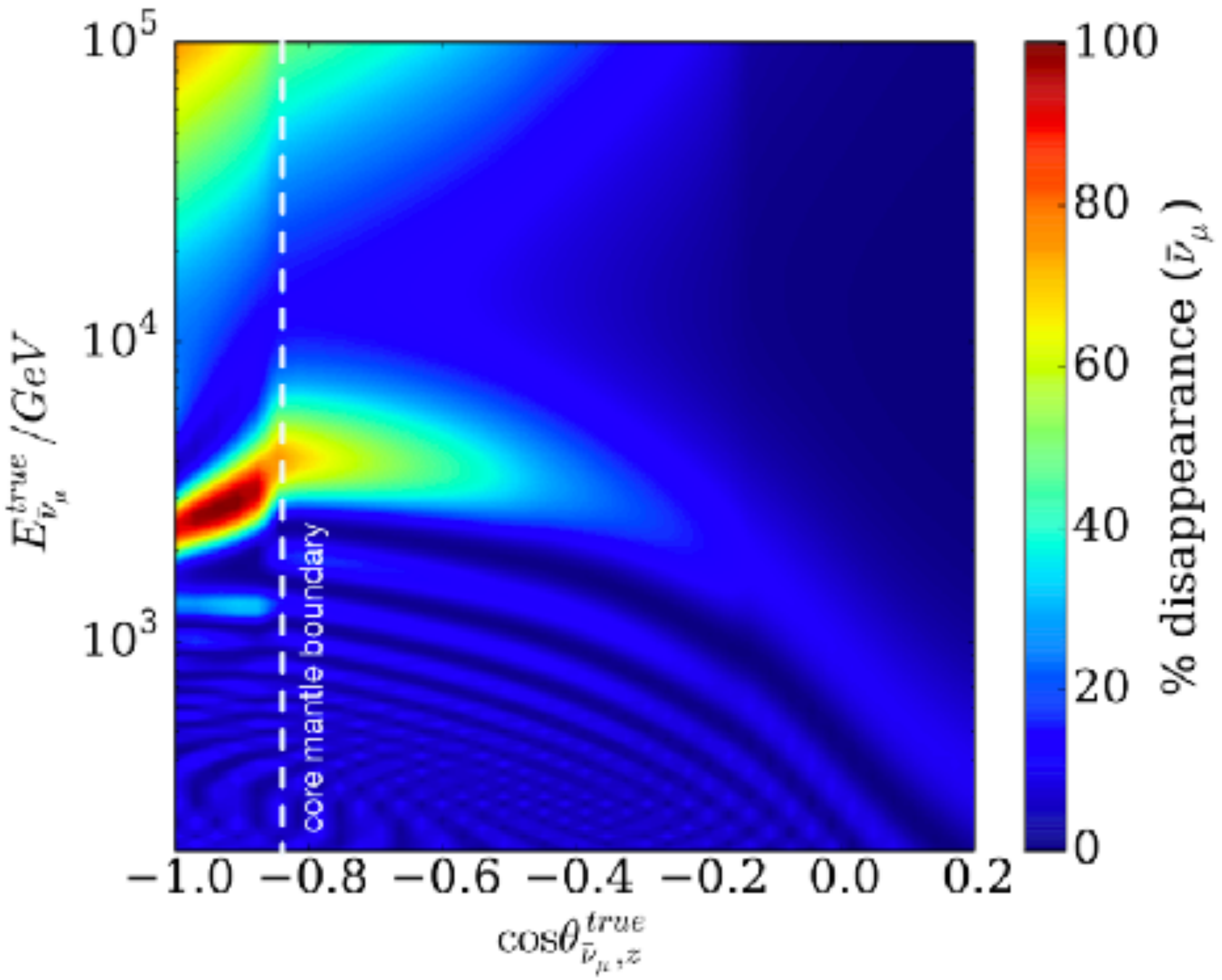
# List of BSM analyses

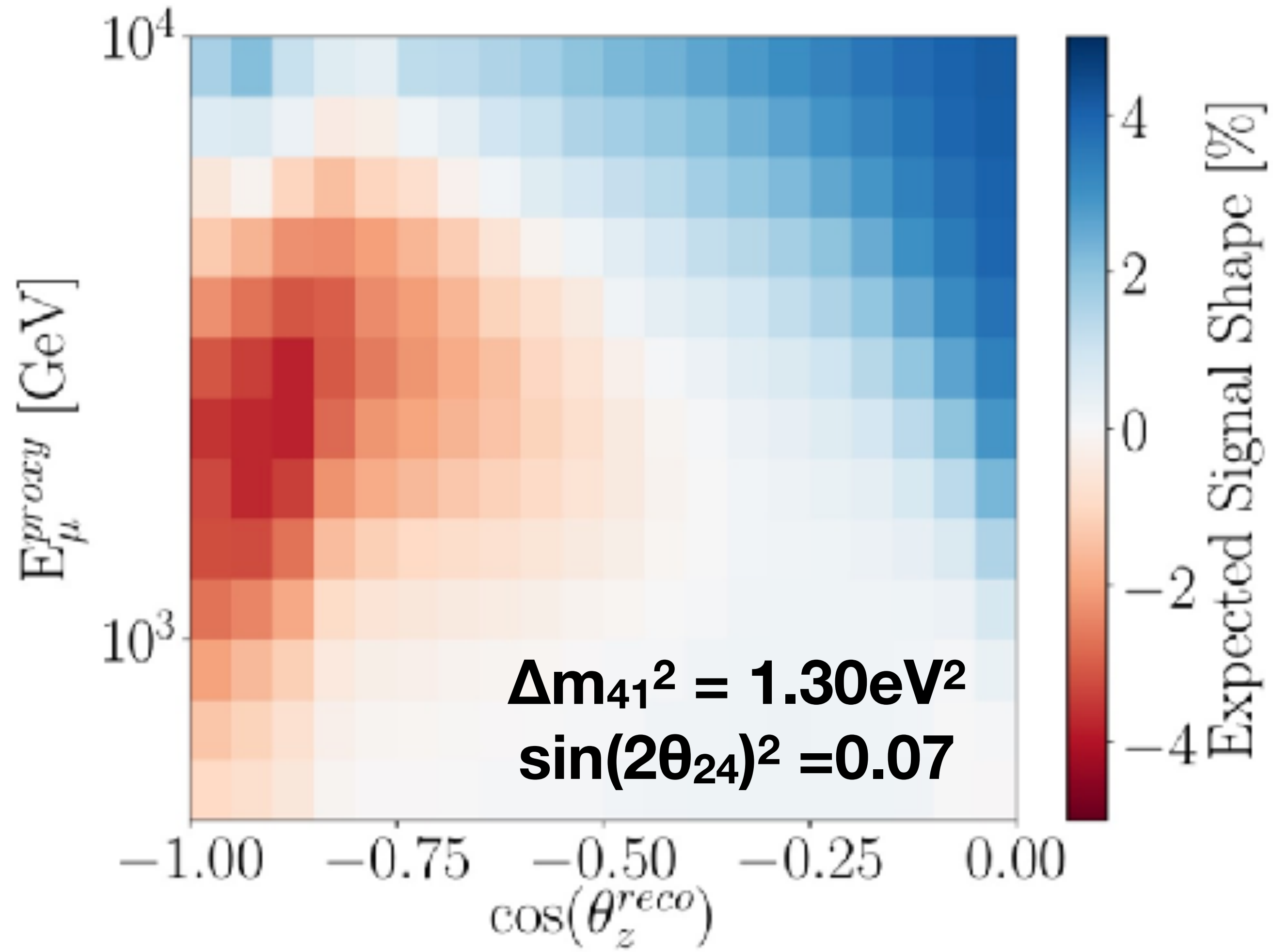
- Several analyses have been published using this sample:
  - 8 years NSI.
    - arXiv:2201.03566 (2022).
  - 8 years Sterile+Decay.
    - arXiv:2110.02351 (2021).
  - 8 years Sterile neutrinos.
    - Phys. Rev. Lett. 125, 141801 (2020)
    - Phys. Rev. D 102, 052009 (2020).
  - 3 years Sterile neutrinos.
    - Phys. Rev. Lett. 117, 071801 (2016).



# Sterile neutrinos

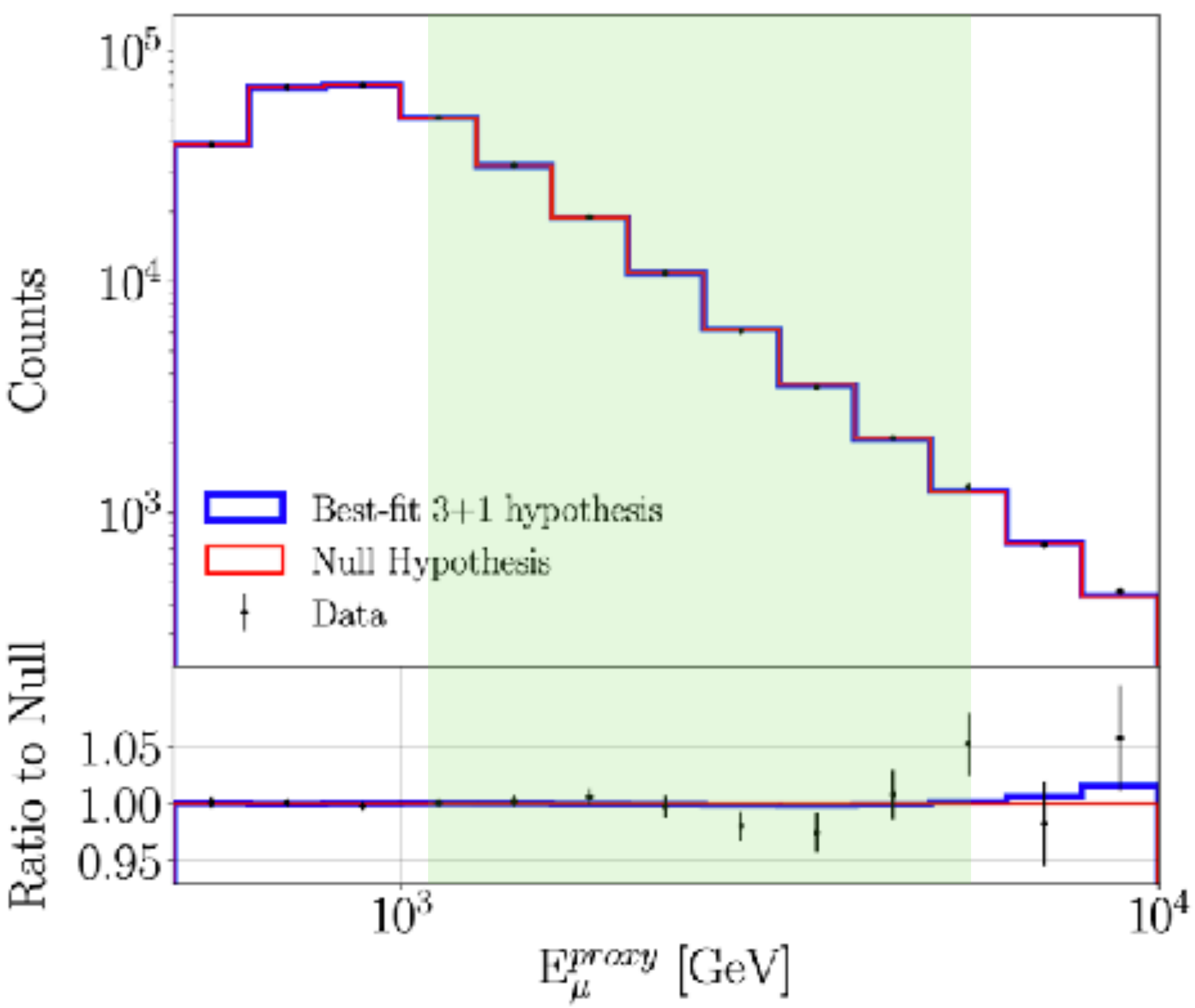
- Minimal extension:
  - Only two free parameters ($\Delta m_{41}^2$ and $\theta_{24}$, $\theta_{34}=0$, $\theta_{14}=0$).
  - Clear shape differences with respect to null hypothesis (SM oscillations).

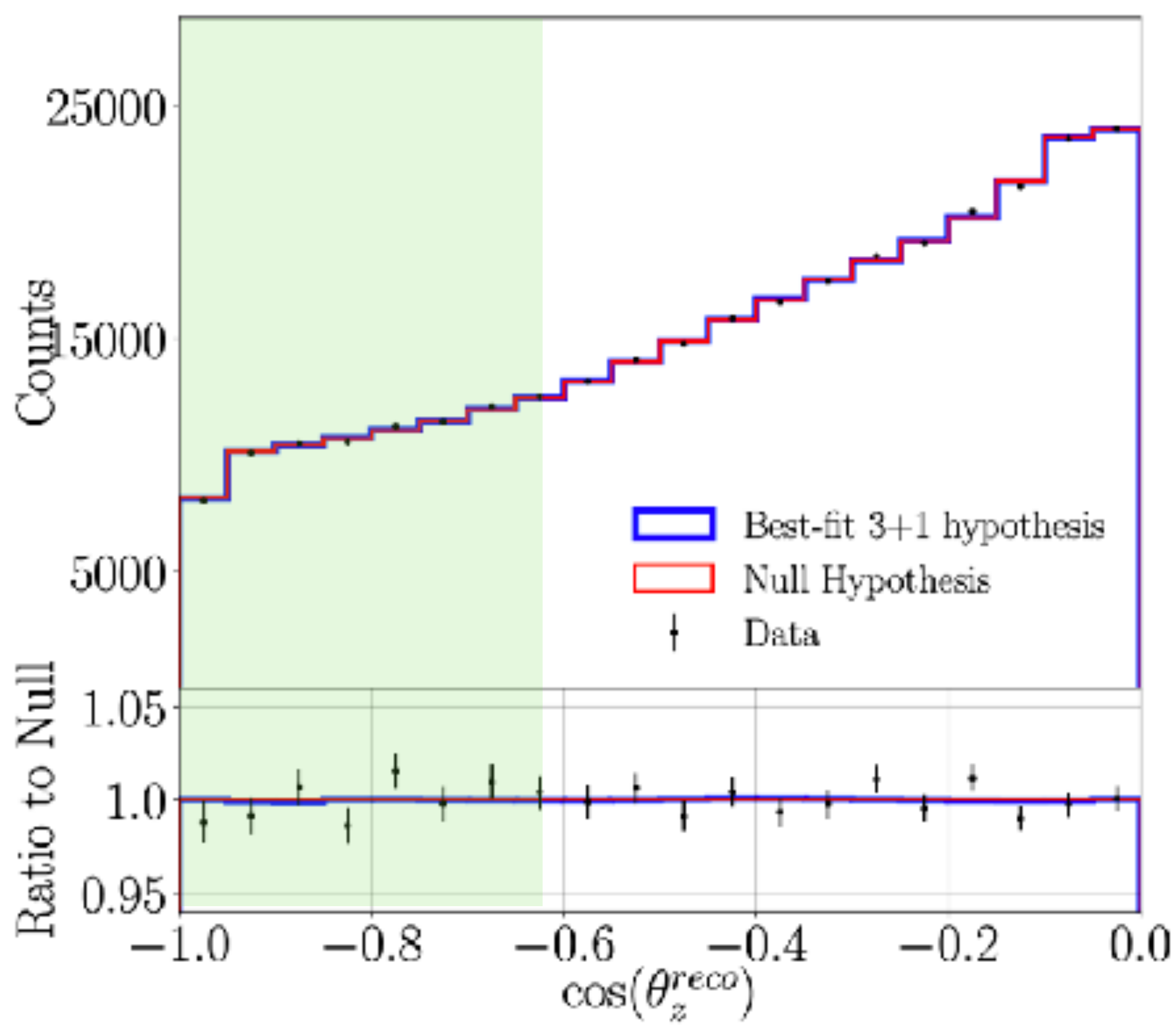


# Results

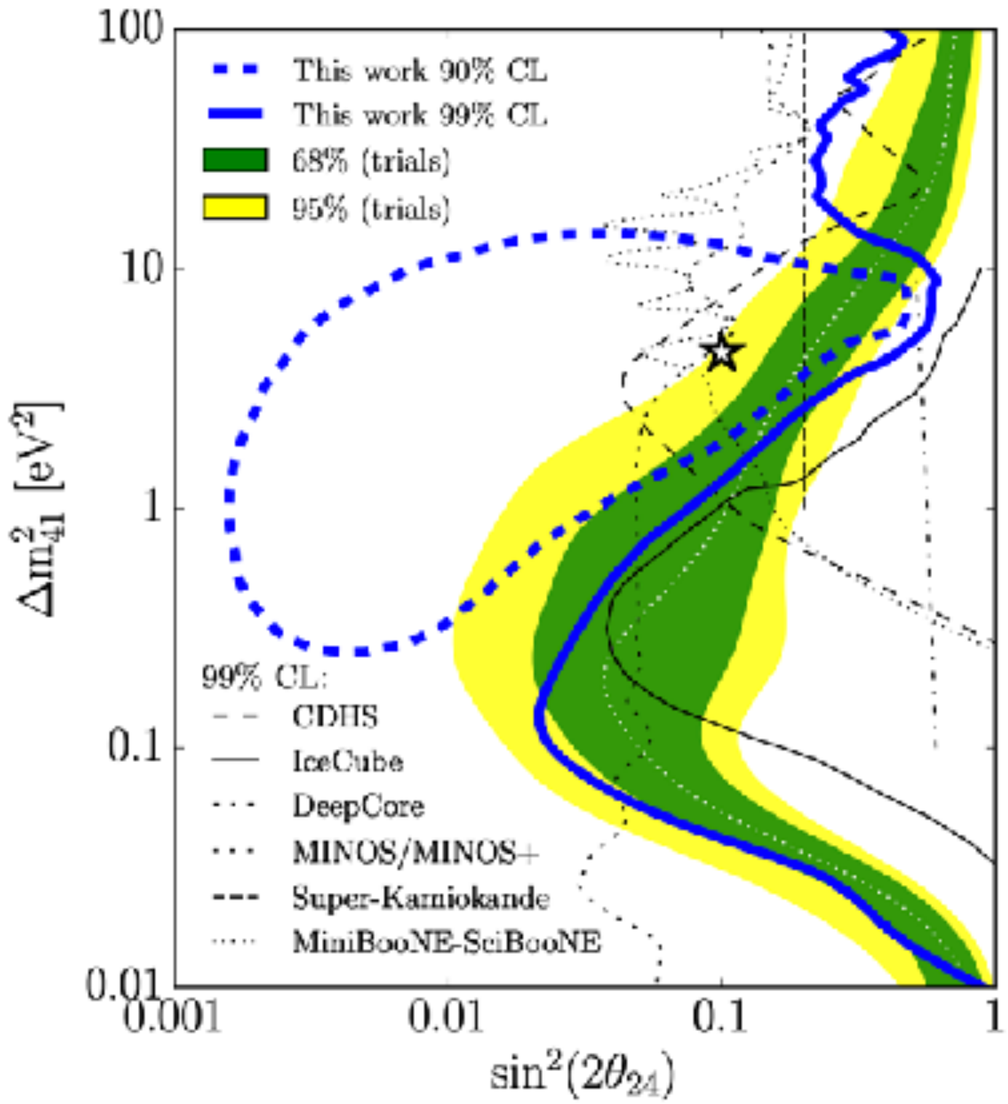
- Using 8 years of data -> 300k $\nu_\mu+\bar{\nu}_\mu$ events!!!
  - Look for a dip in the shaded area.

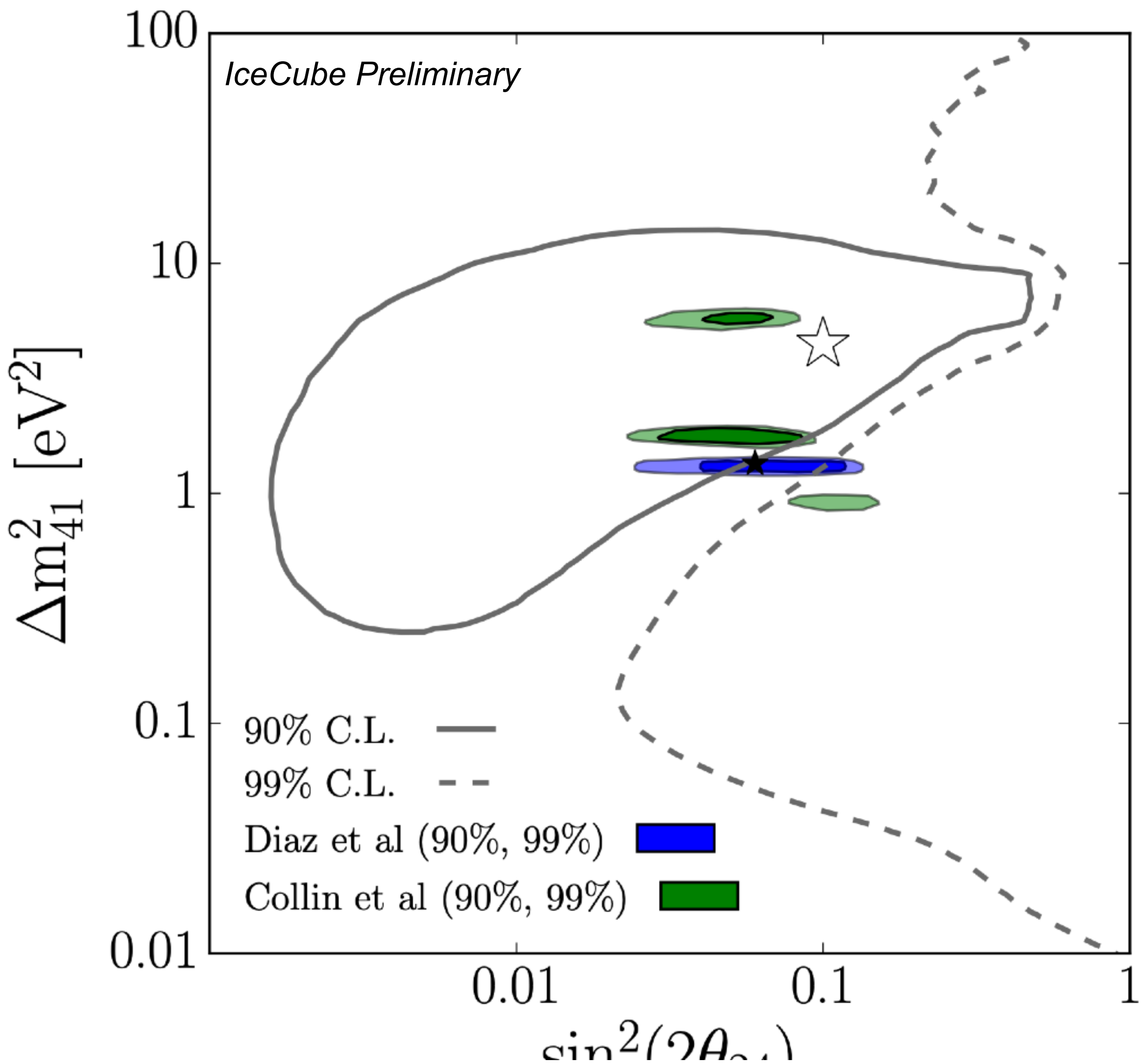


# How it compares to others?

- Leading constraints in some regions of the phase space!
  - Best fit point remains stable for different time periods.
  - It lies in a very interesting region of the phase space.
  - Null is rejected at 8% p-value.

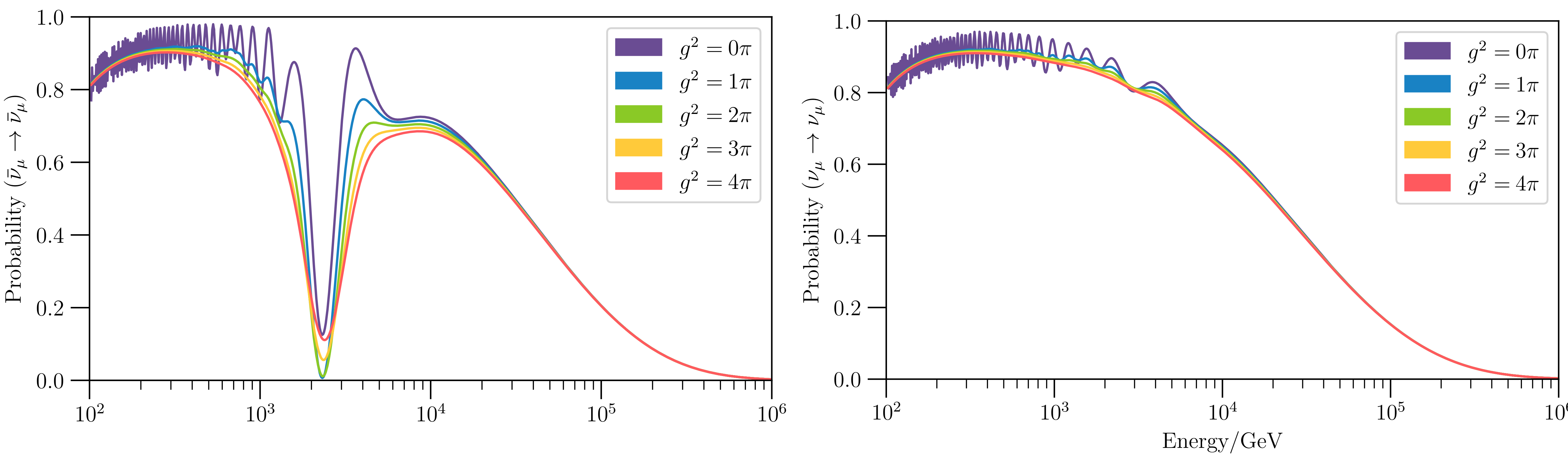


# Sterile neutrinos + Decay

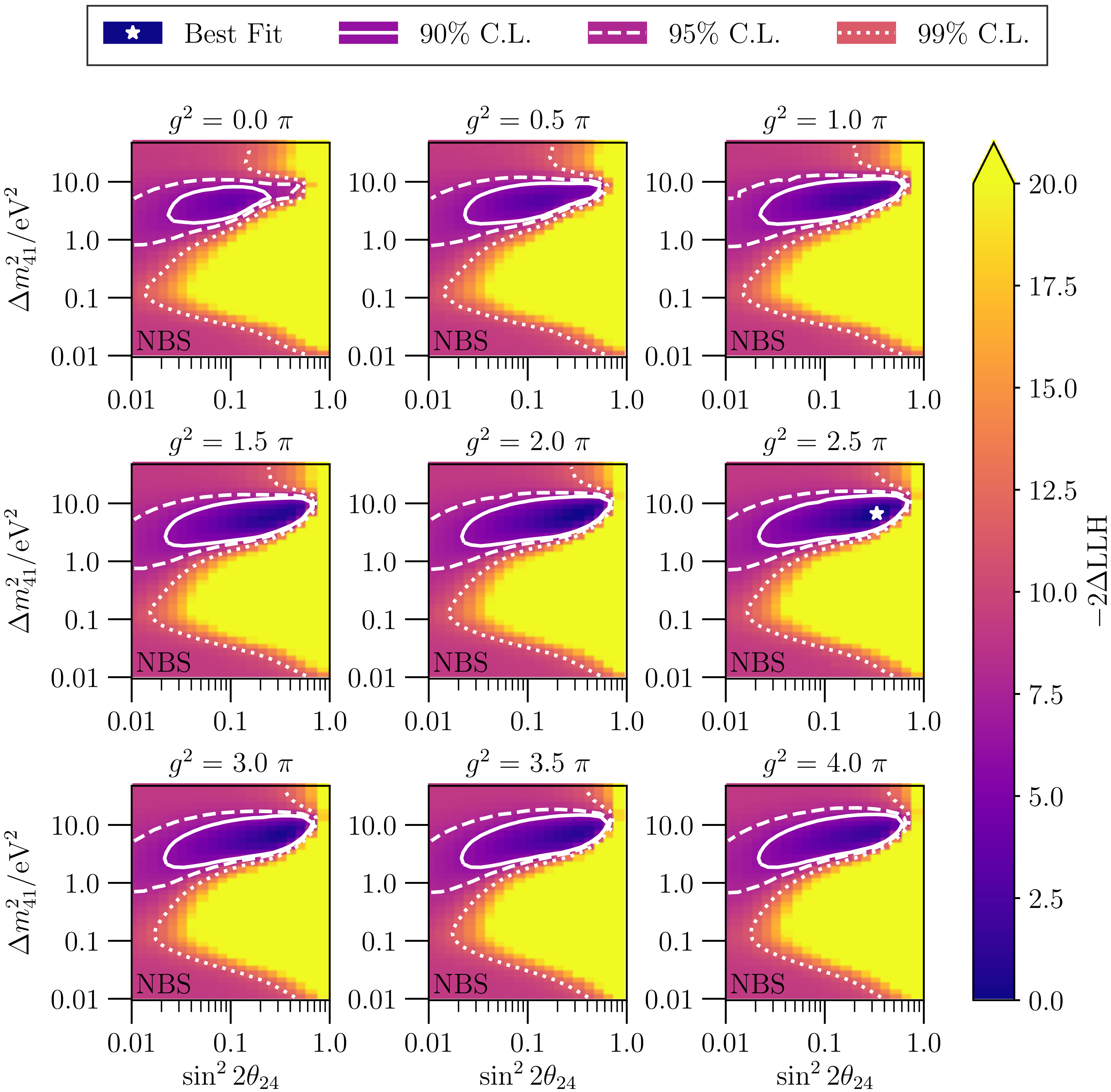
arXiv:hep-ph/0505216
arXiv:1711.05921
arXiv:1911.01447
arXiv:1911.01427

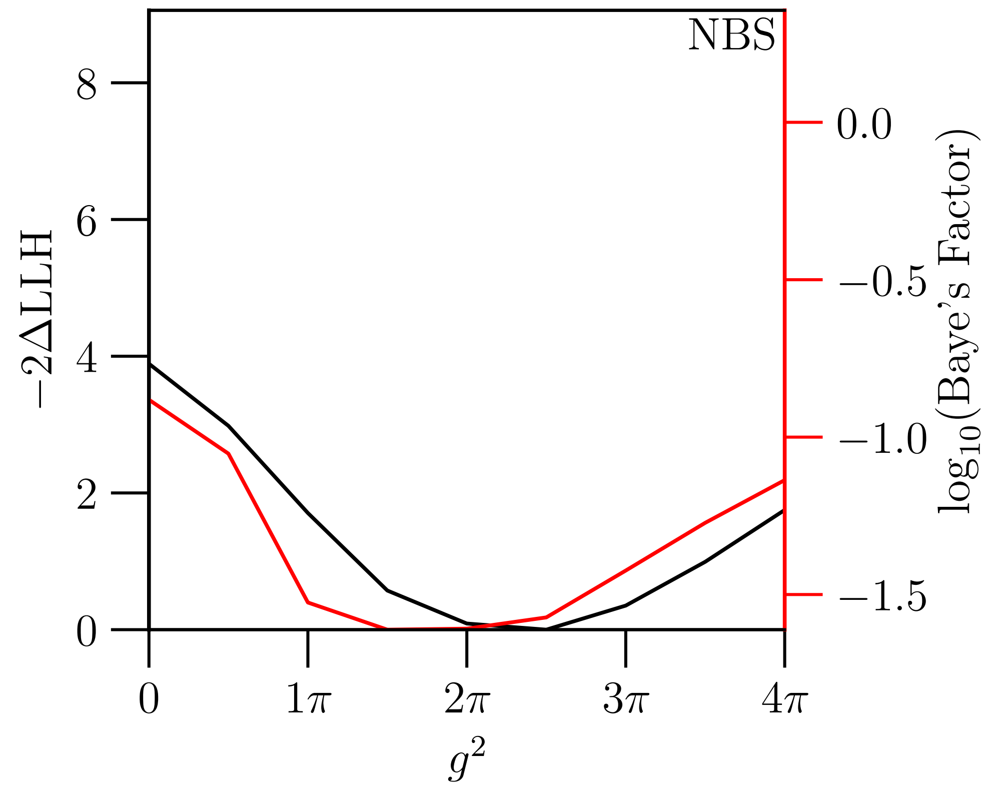
- Add additional degrees of freedoms
  - Alleviate tension between $\nu_e$ appearance and $\nu_\mu$ disappearance searches.
- Visible decay:
  - $\nu_s \rightarrow \nu_x \phi$
  - Lifetime proportional to $g^{-2}$



# Sterile neutrinos + Decay

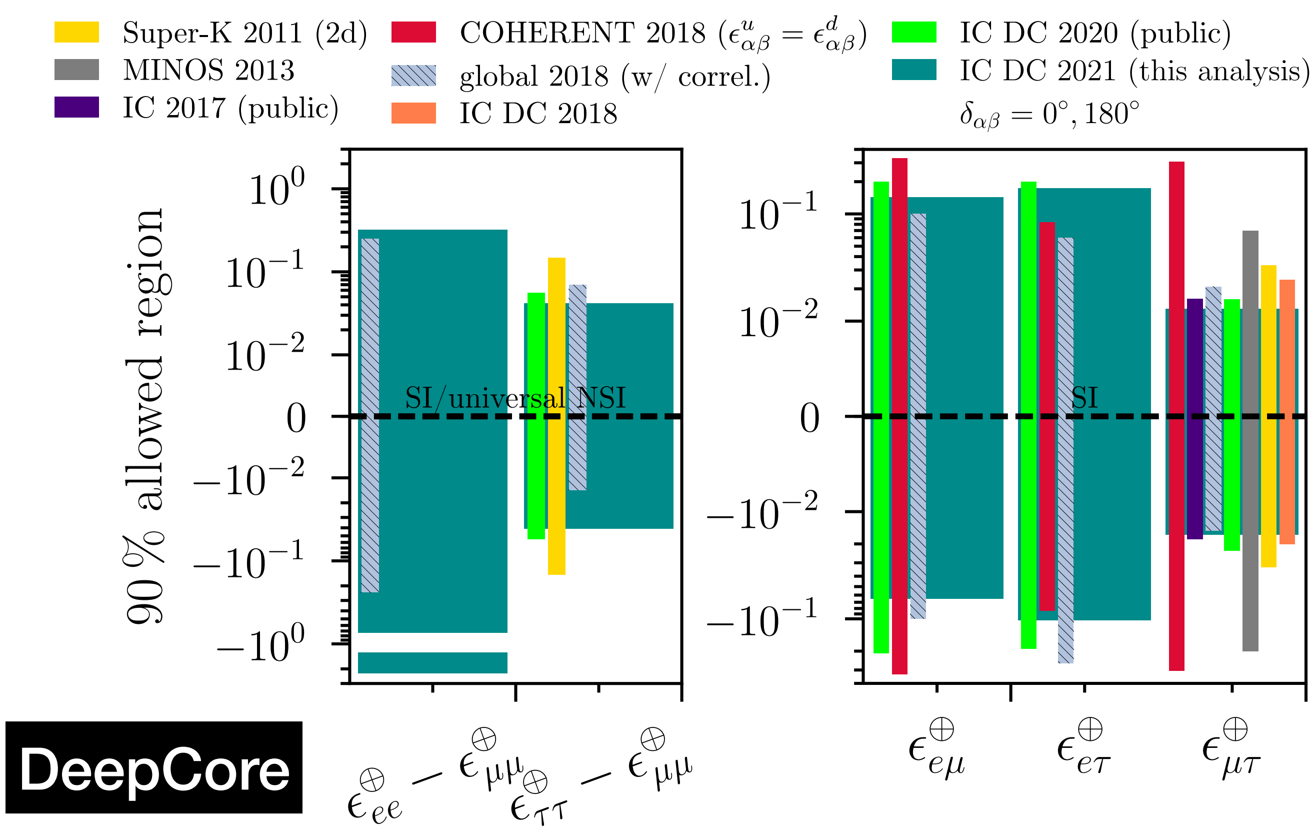
- IceCube data ‘prefers’ the 3+1 decay hypothesis.

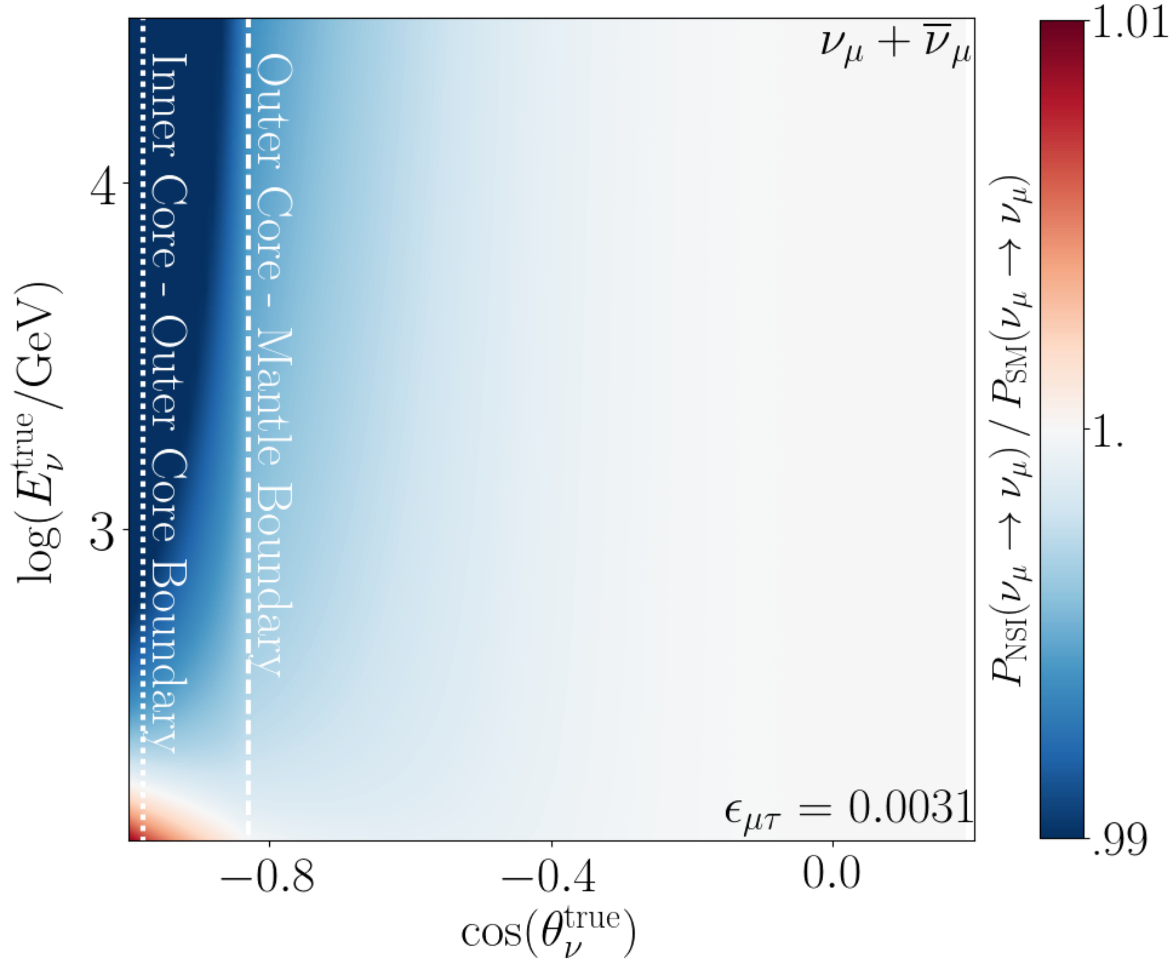


# NC-NSI

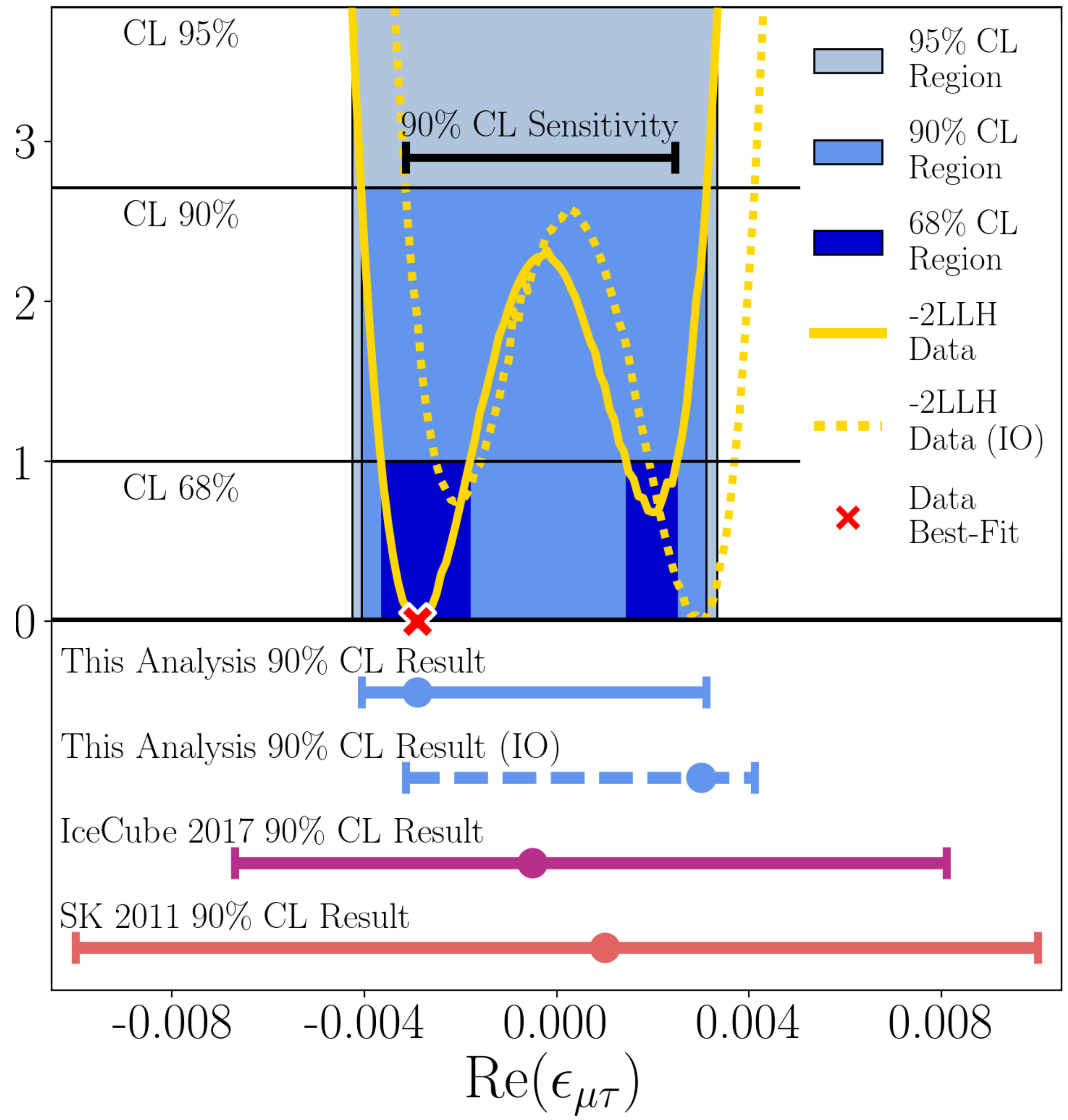
- If $\varepsilon_{\mu\tau}>0$ we expect less vertically upgoing TeV tracks in IceCube.
  - Effect of other $\varepsilon_{xx}$ subdominant.
- Standalone constrain on $\varepsilon_{\mu\tau}$ using TeV atmospheric muon neutrinos.

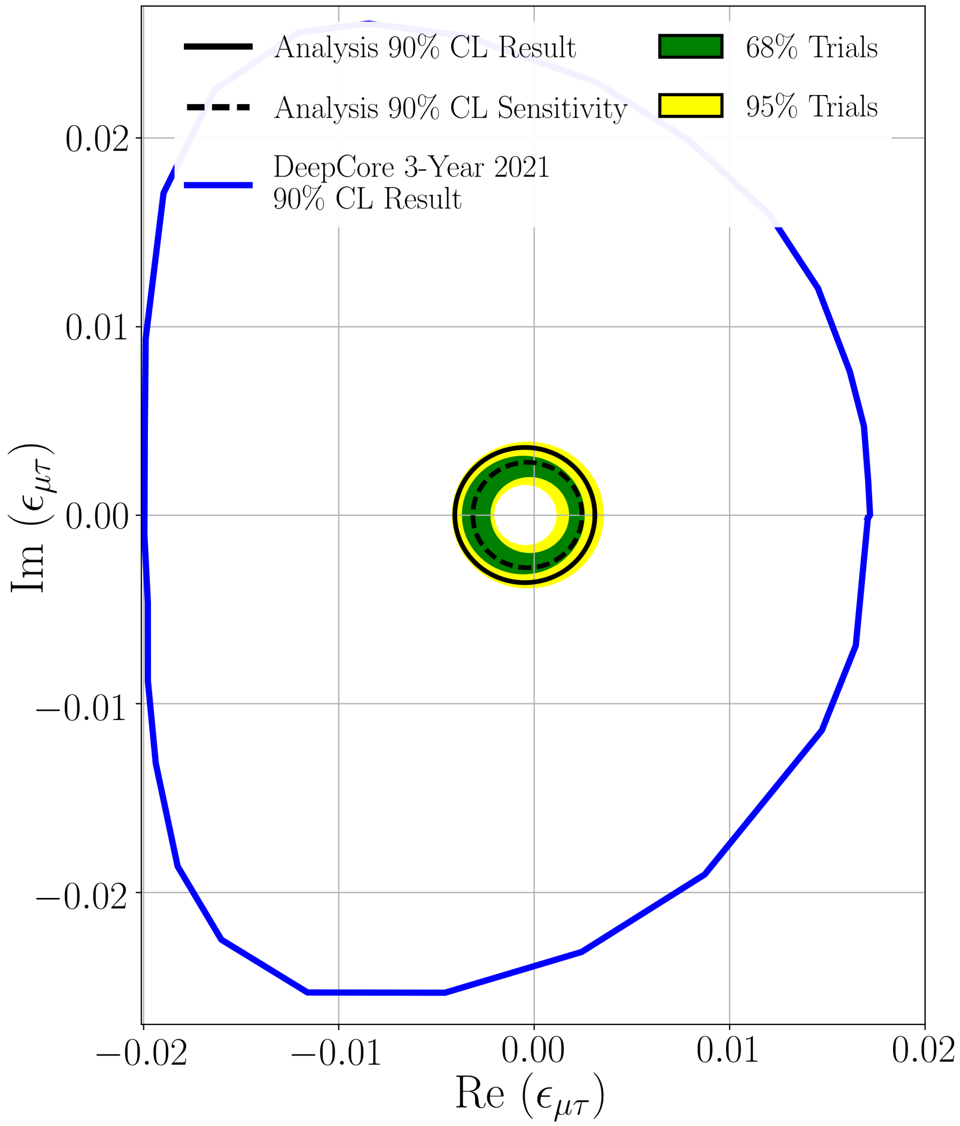


# NC–NSI

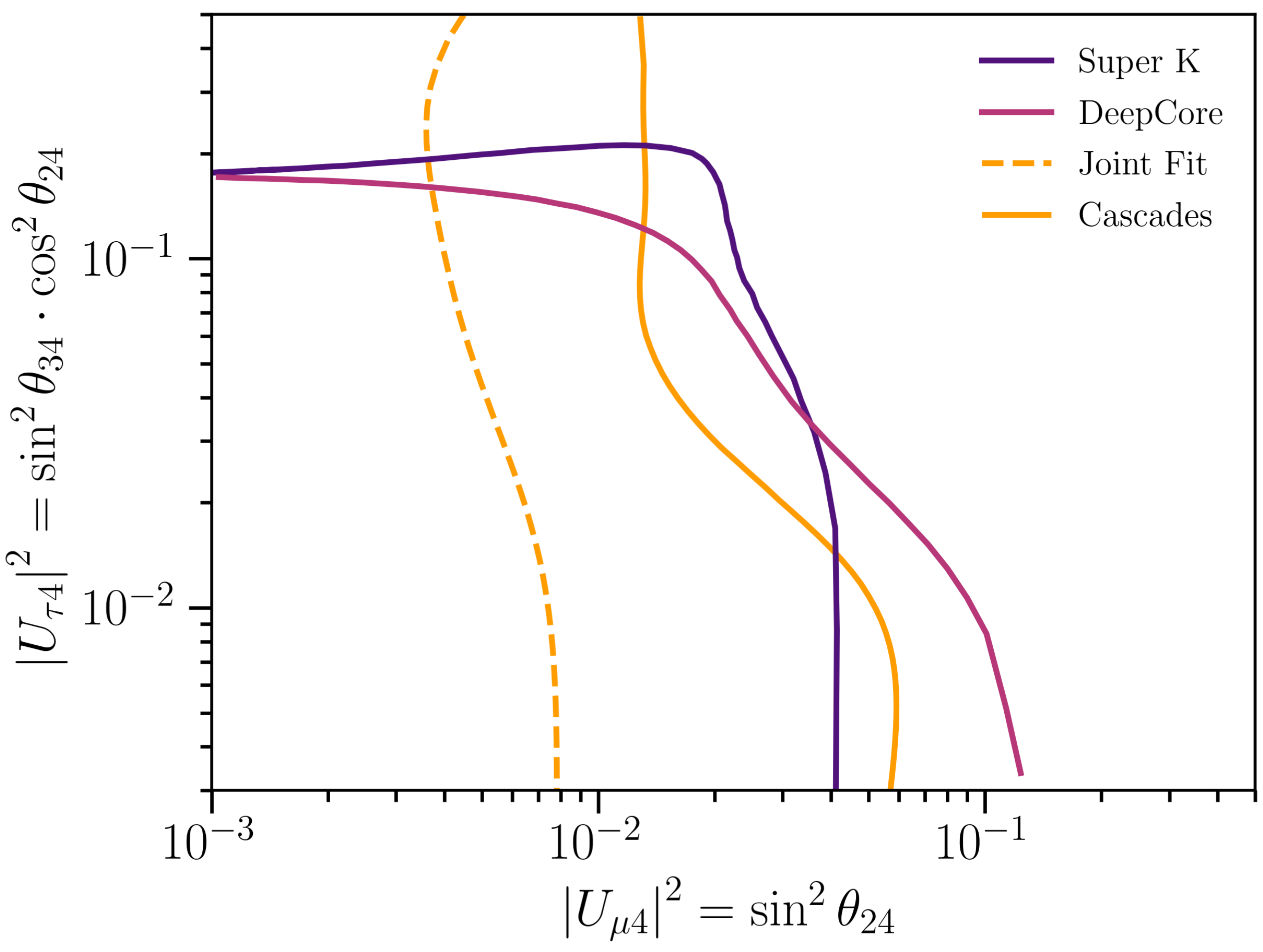
- World leading constraints in $\varepsilon_{\mu\tau}$.
- Results are consistent with no NSI at a p-value of 25.2%.

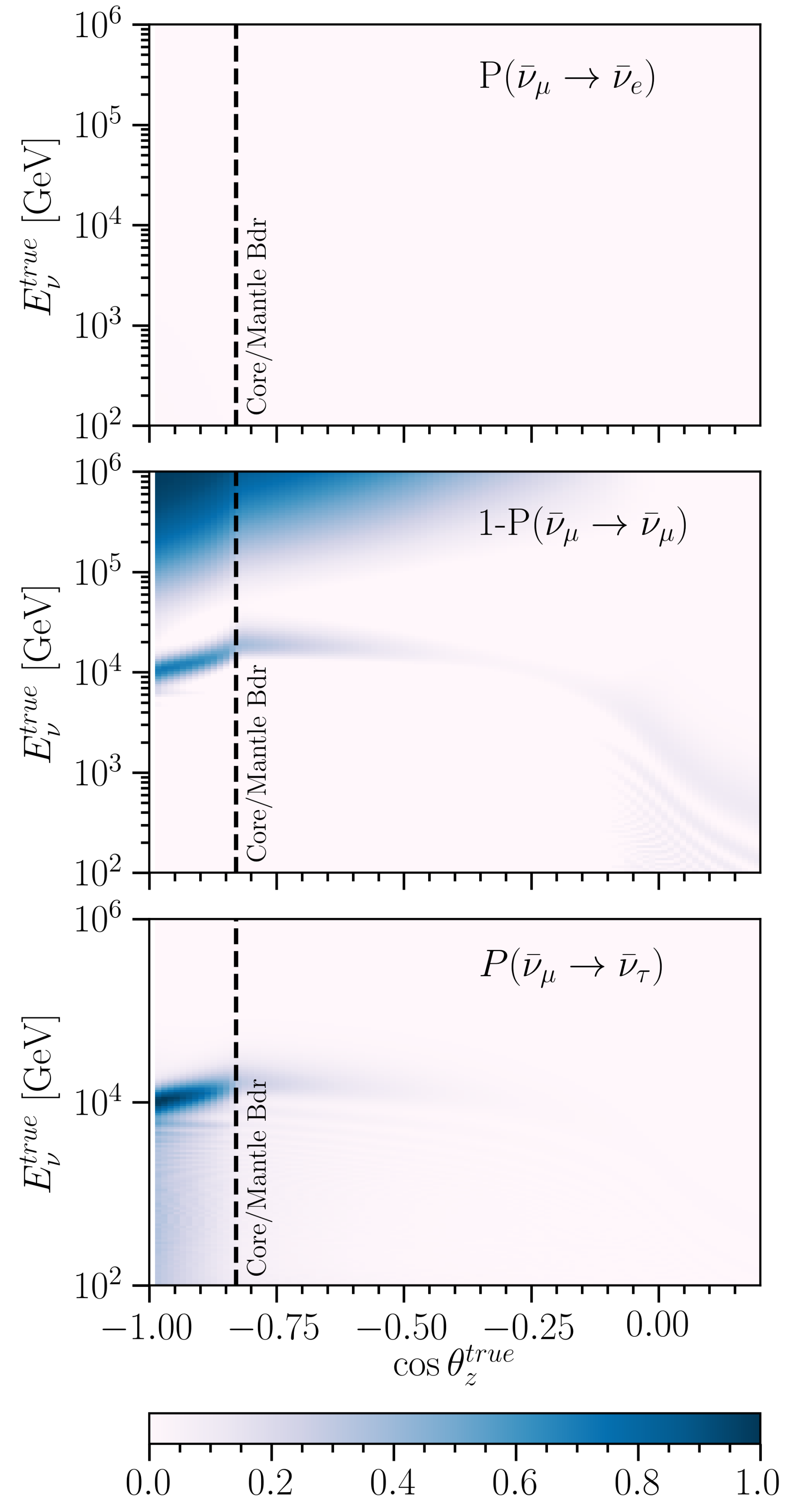


# Prospects

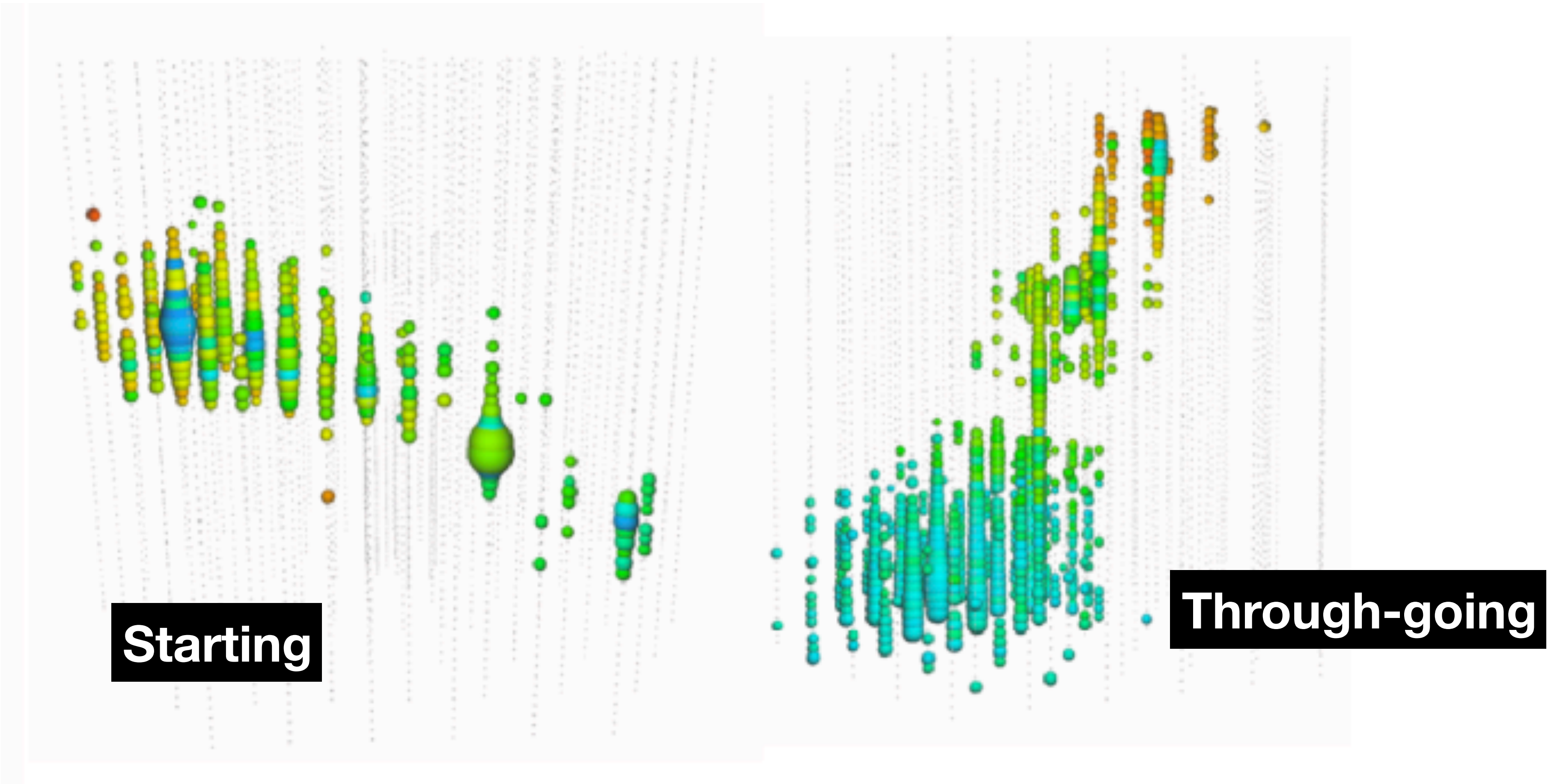
- Non-zero $\theta_{24}$ and $\theta_{34}$ parameter:
  - Widens the resonance disappearance.
  - Increment of upgoing TeV cascades ($\nu_\tau$).
  - Can probe BEST regions if $\theta_{24}>0$.



# Prospects

- New event selection and reconstruction undergoing.
  - Simple cuts -> MVA.
  - Likelihood reconstruction -> DNN.
  - Upgoing tracks -> Starting + Through going tracks

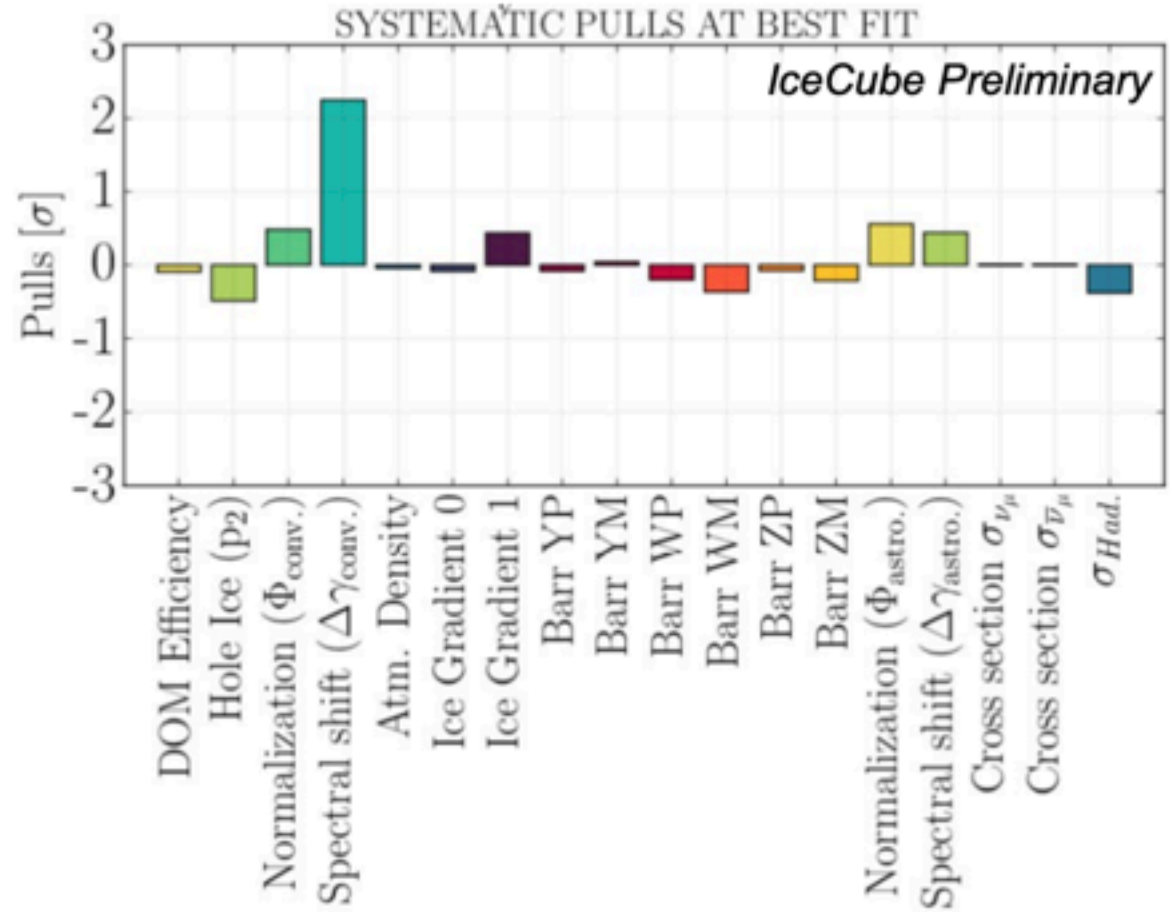


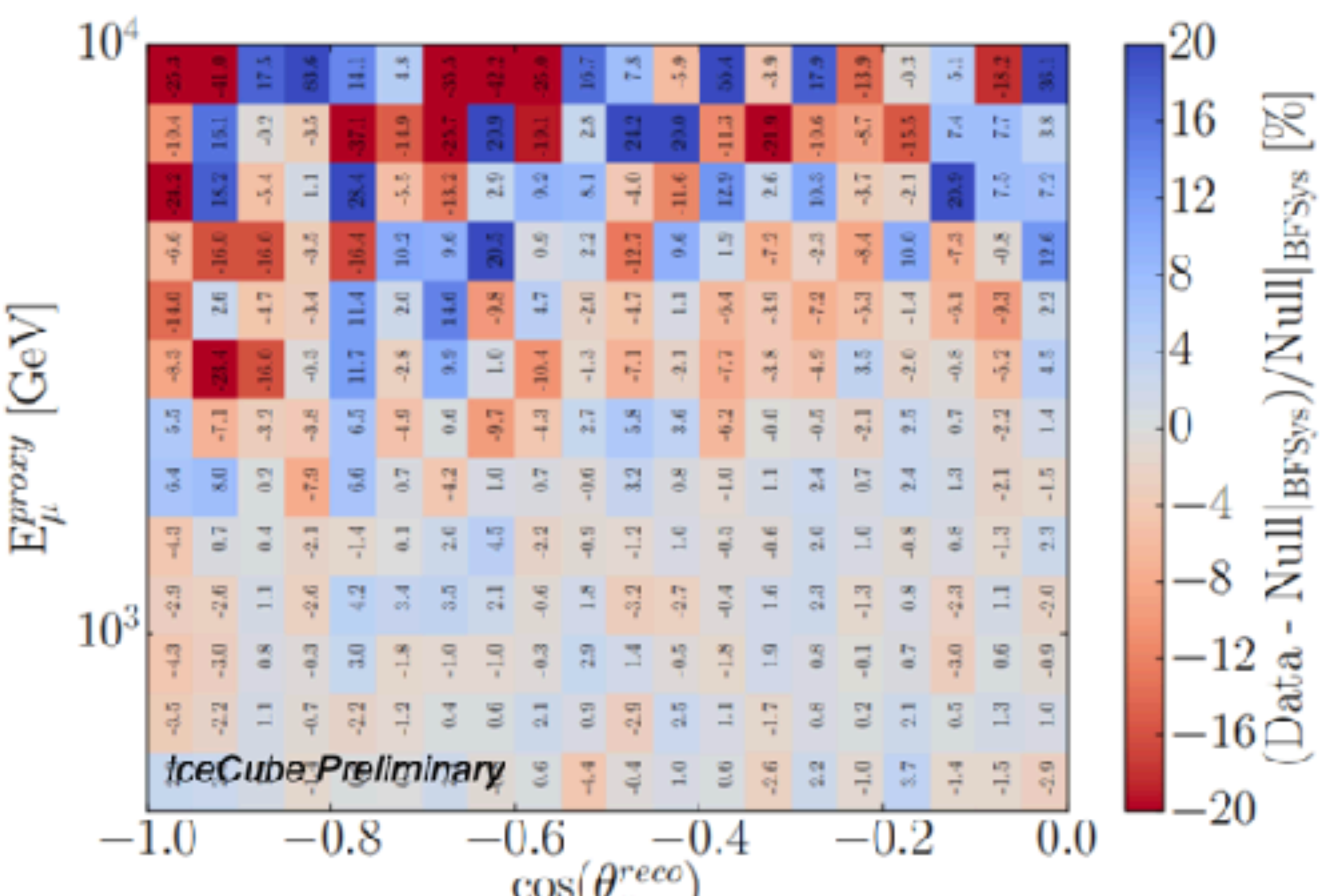
# Conclusions

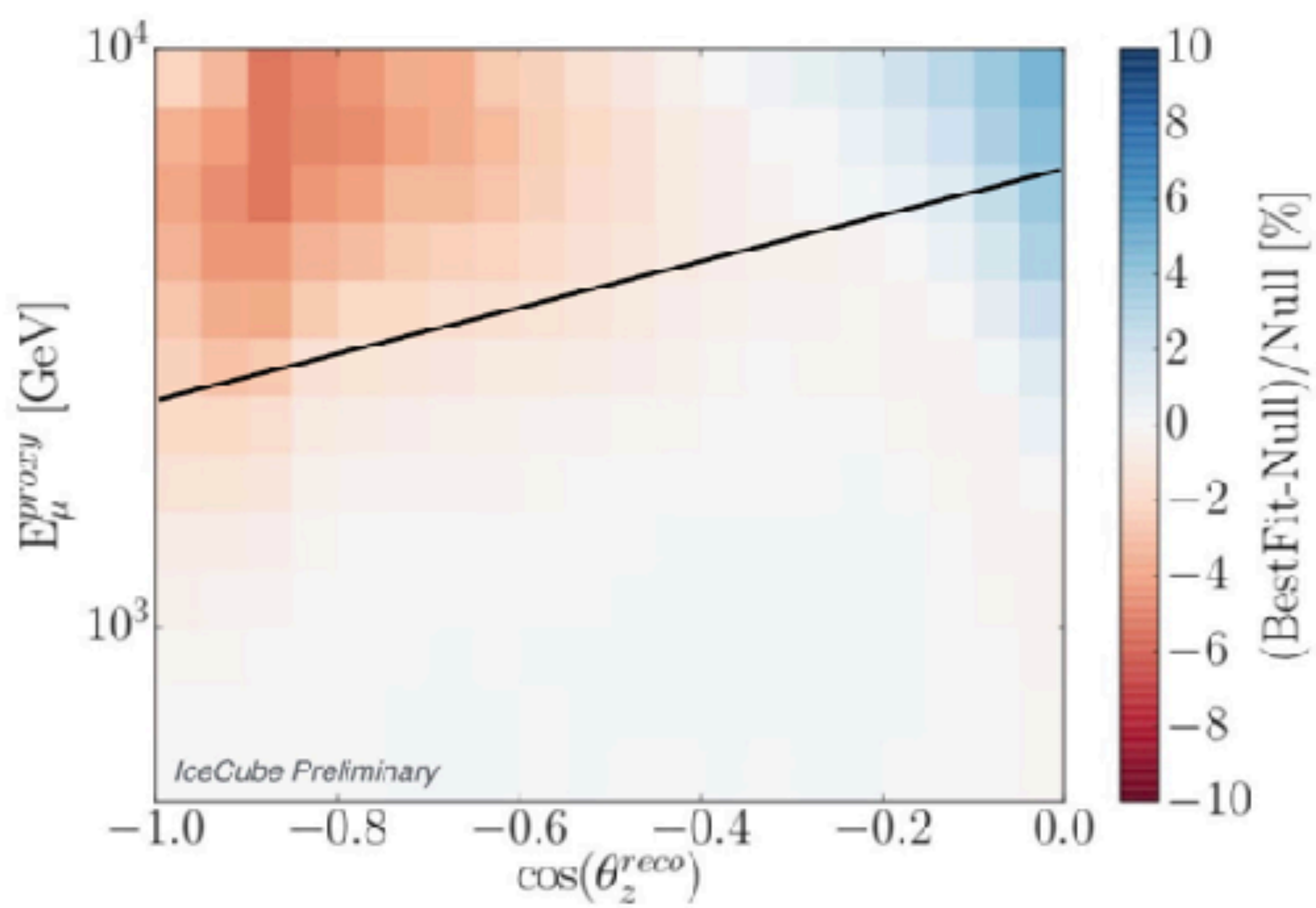
- Neutrino telescopes offer a rich program for BSM searches.
- TeV atmospheric neutrinos have become one of the main probes to study hot topics in the BSM community:
  - Non standard interactions.
  - Sterile neutrinos.
- World leading constraints in some of these analysis.
  - Expect to further improve them in the upcoming years.

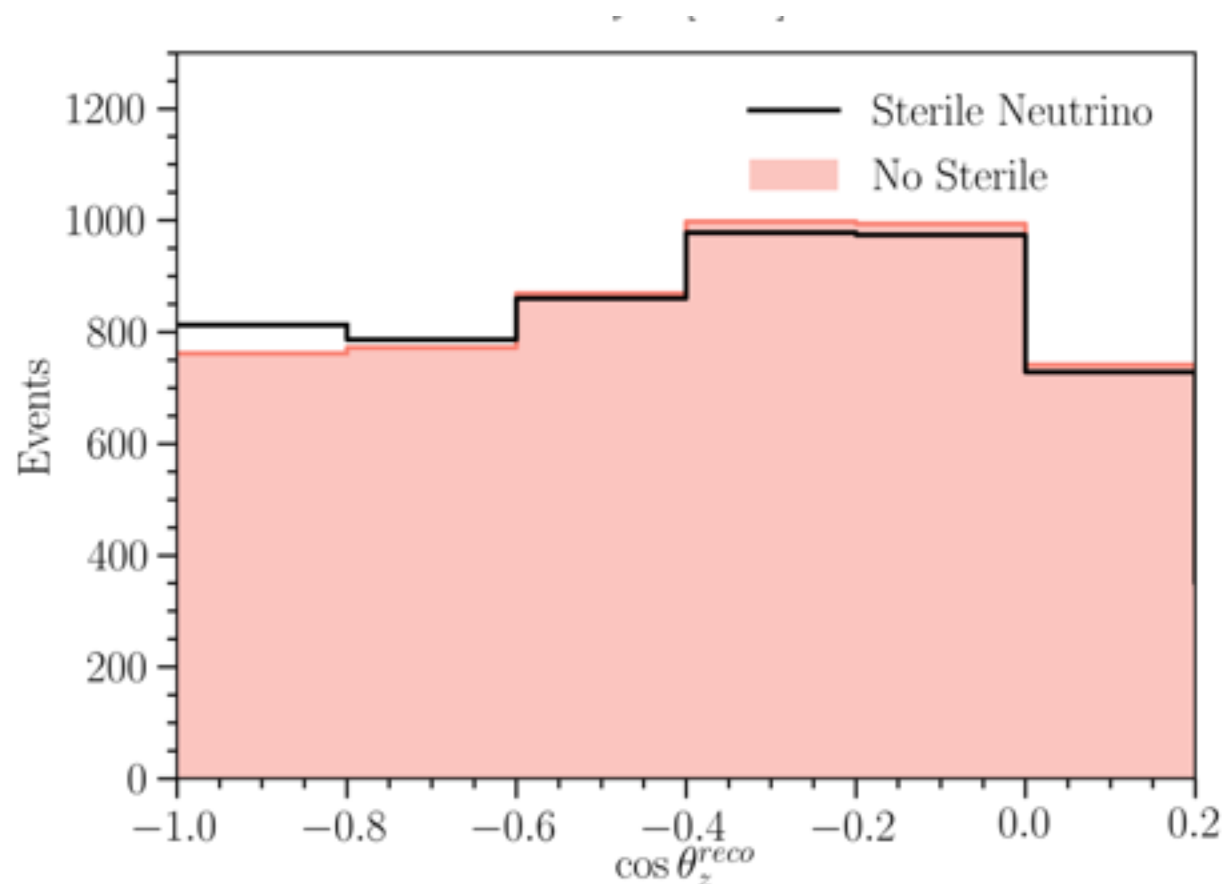
$$\Delta m^2_{41} = 4.47^{+3.53}_{-2.08}\,\mathrm{eV}^2$$

$$\sin^2(2\theta_{24}) = 0.10^{+0.10}_{-0.07}$$





Sterile Neutrino
No Sterile
Events
0
200
400
600
800
1000
1200
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
$\cos\theta_z^{reco}$