Latest Neutrino Oscillation Results from the Icecube Neutrino Observatory

Étienne Bourbeau* (on behalf of the IceCube Collaboration)

NuFACT, 27. August 2019

ICECUBE

centre for particle physics Discovery

KØBENHAVNS UNIVERSITET

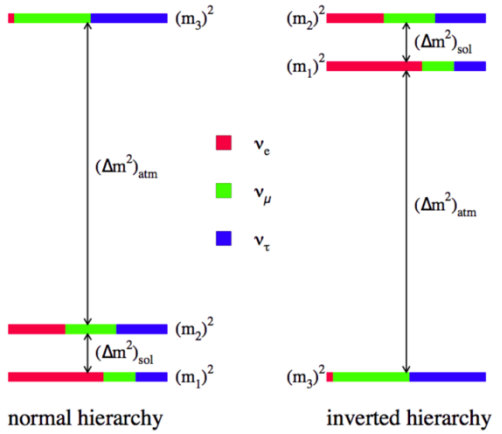
Why Study Neutrinos with IceCube?

- Many properties of the neutrino **have yet to be measured** (eg. mass ordering)

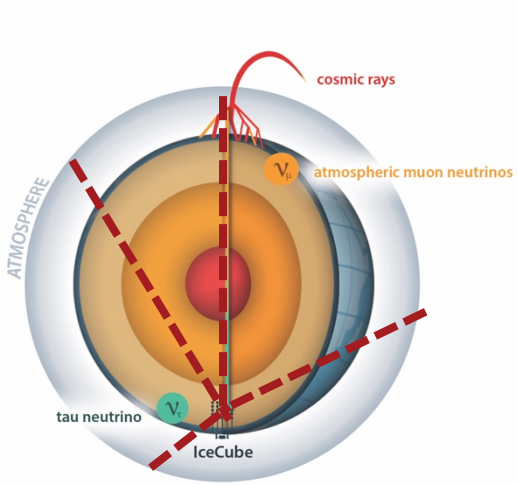
- **Neutrino oscillation** the only experimental evidence of non-conformity to the Standard Model (potential evidence for **new physics**)

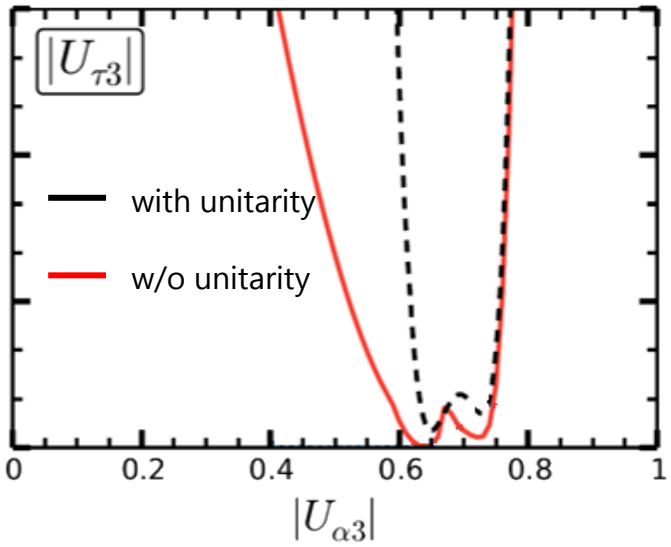
- PMNS **unitarity constraints** are **weakest for the third generation** of neutrinos, **an area where IceCube is highly sensitive**

- IceCube offers **high statistics + large range of baselines and energies**



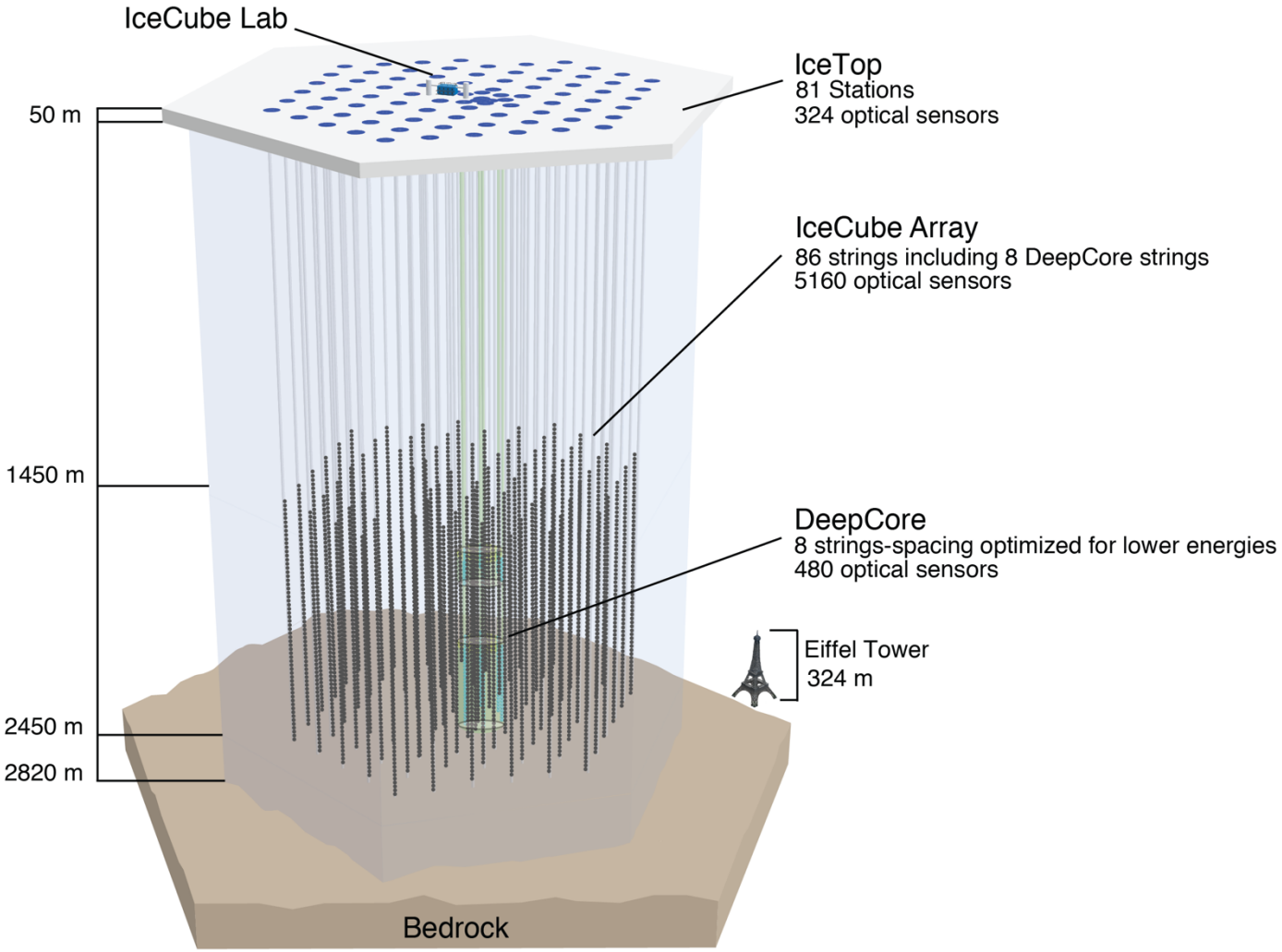
(from: arXiv:1205.2671)





(From 1508.05095)

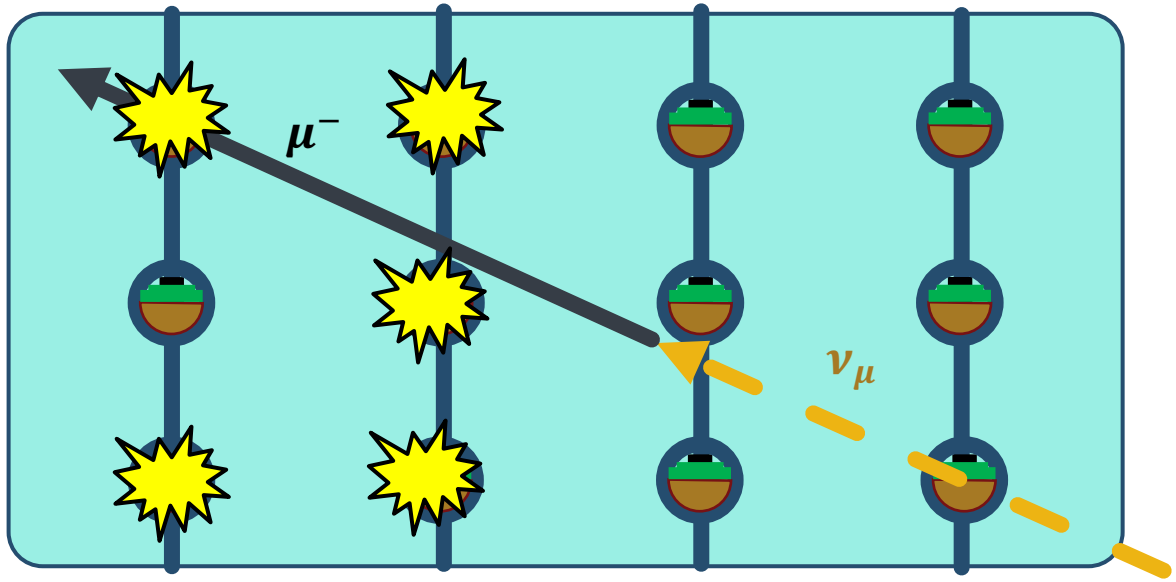
The IceCube Neutrino Telescope



- Deployed to detect neutrinos of astrophysical origin

- Optical Module (DOM): 30cm photomultiplier tube in pressured vessel
- Detect **Cherenkov radiation** from neutrino interactions in the ice

The IceCube Neutrino Telescope

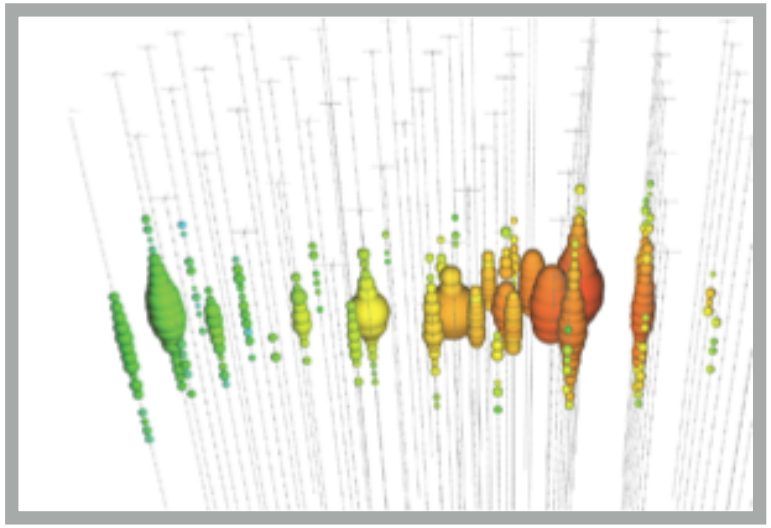


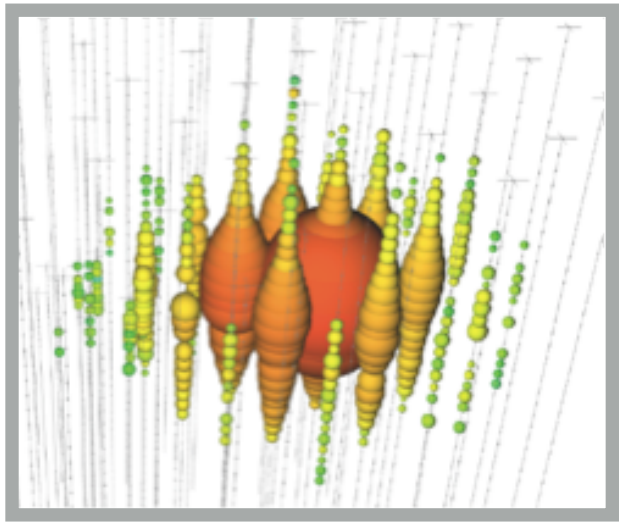
- Sensitive to different types of interactions:

Tracks

ν_μ^{CC}, ν_τ^{CC}(some of the time)

Worse Energy Resolution
Better Pointing accuracy





Cascades

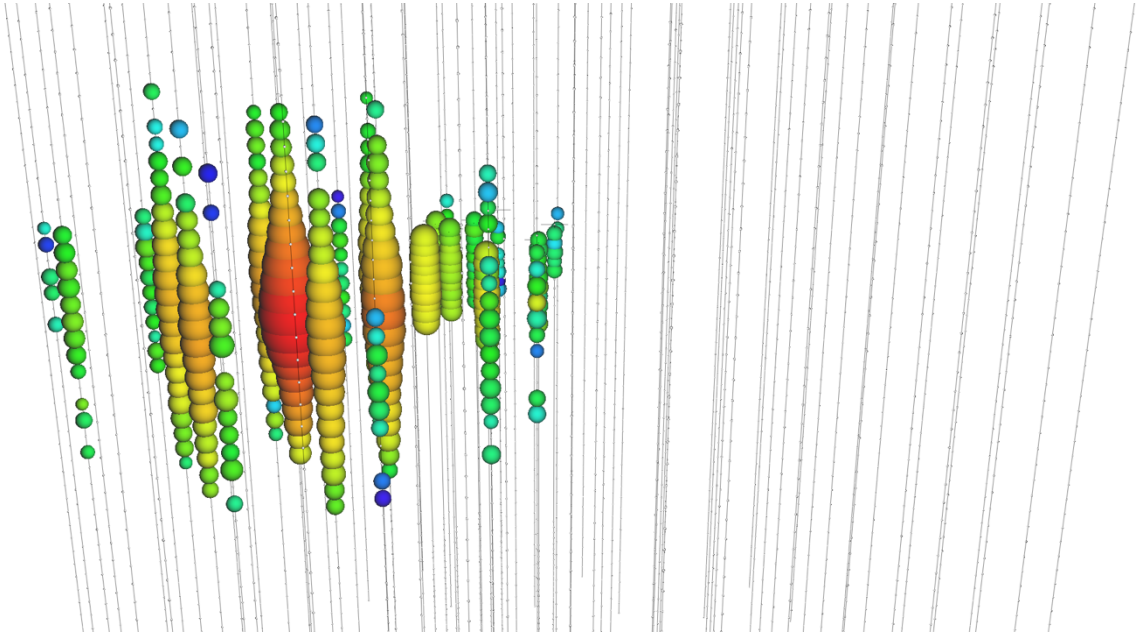
$\nu_{e,\mu,\tau}^{NC}$, ν_τ^{CC}(most of the time), ν_e^{CC}

Better Energy Resolution
Worse Pointing accuracy

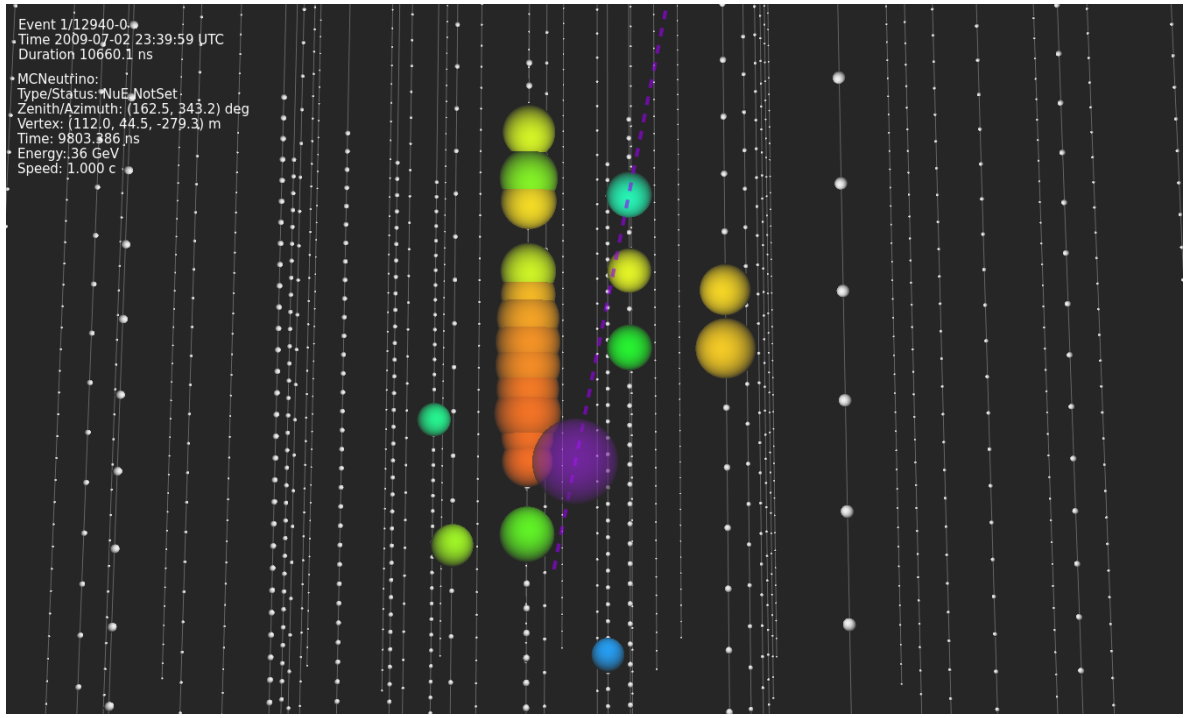
High Energy vs. Low Energy

- Oscillation measurements are made at GeV energies
- Significantly lower energy range than the astrophysical regime
- Dim events pose a challenge for reconstructions

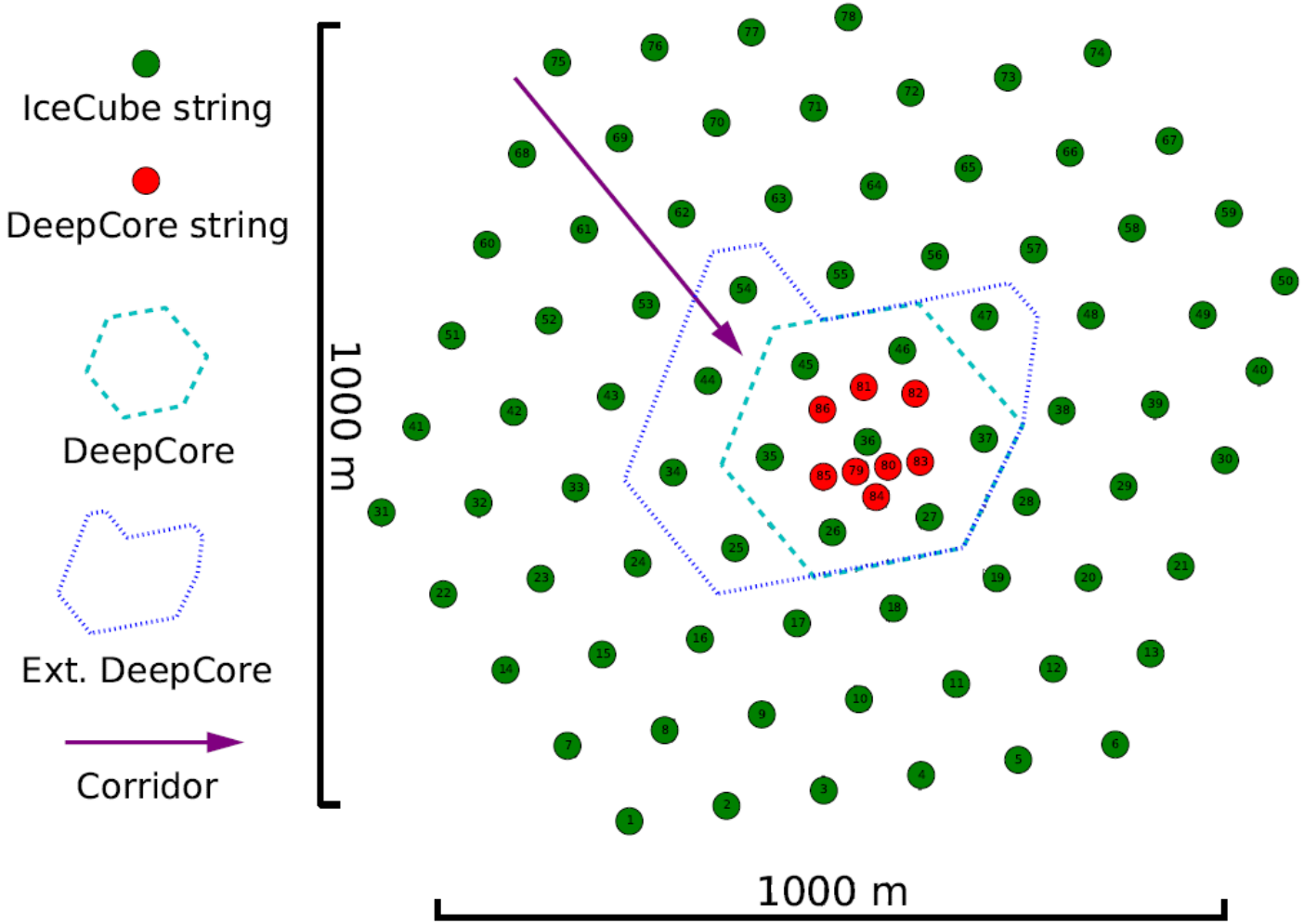
PeV cascade of astrophysical origin



30 GeV atmospheric neutrino



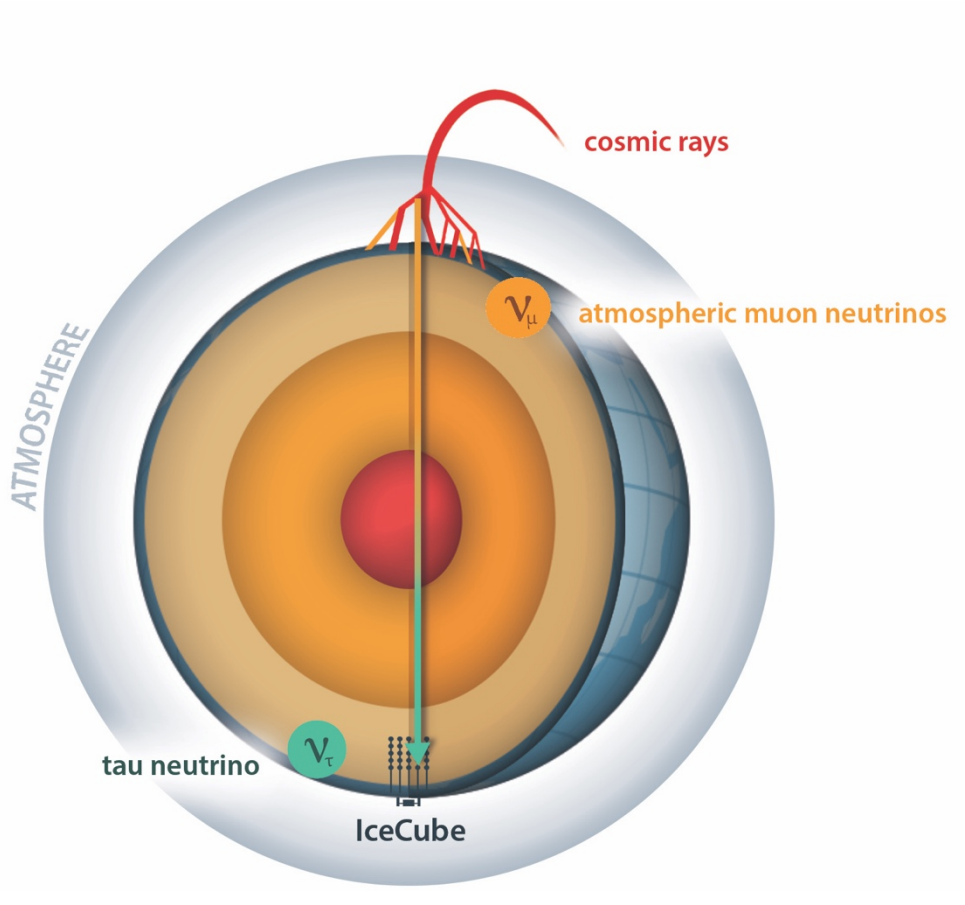
IceCube-DeepCore

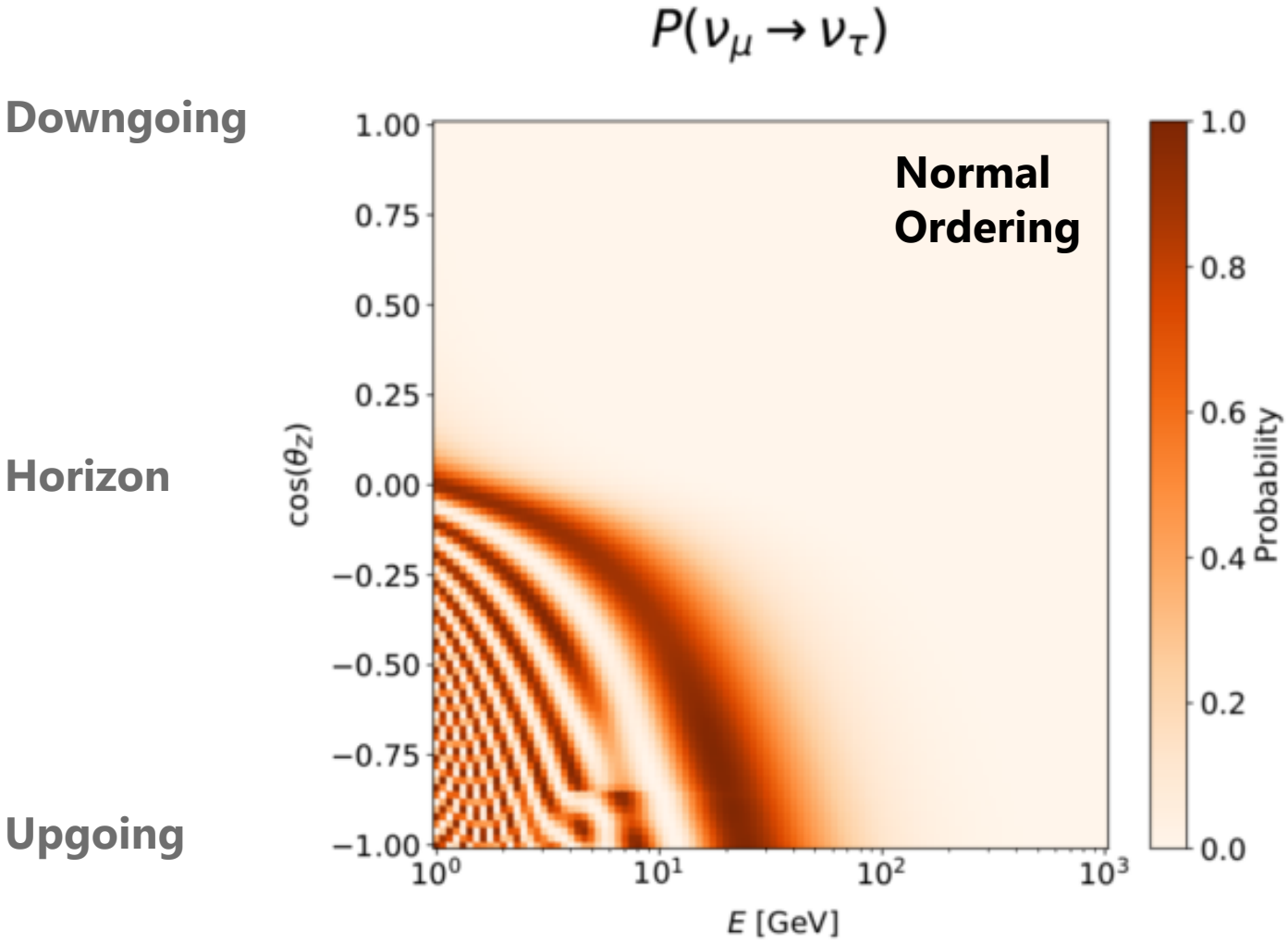


- Inset of the IceCube detector
- 8 strings of **high quantum efficiency** DOMs
- **10 Mton fiducial volume** (incl. neighbor IceCube strings)
- ~ **500 sensors** in closer spacing
- Rest of IceCube is used as a veto region

Analysis technique

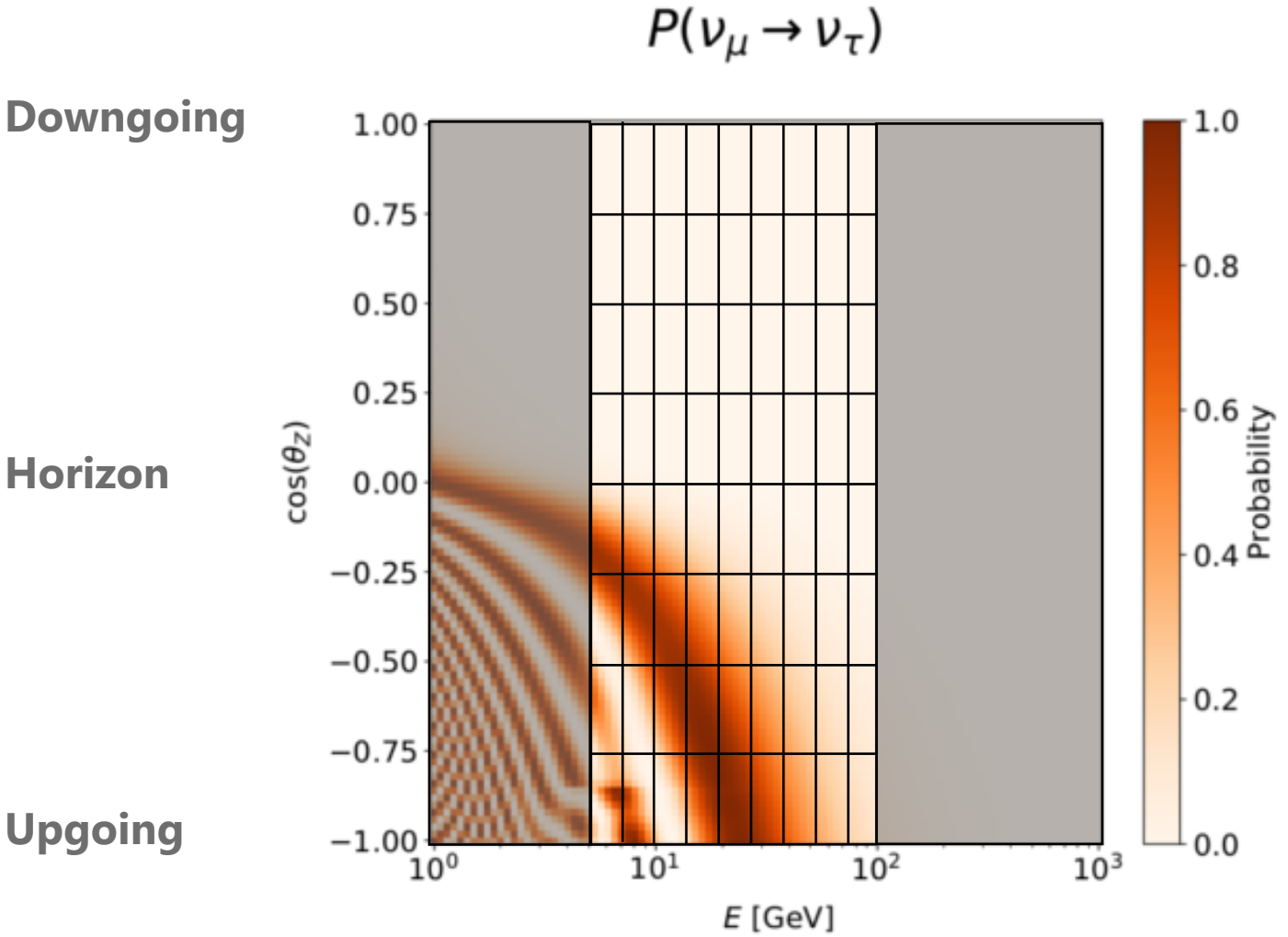
- **Wide range of L/E ratios covered** with DeepCore: O(1km, 10 000km) and O(GeV, TeV)





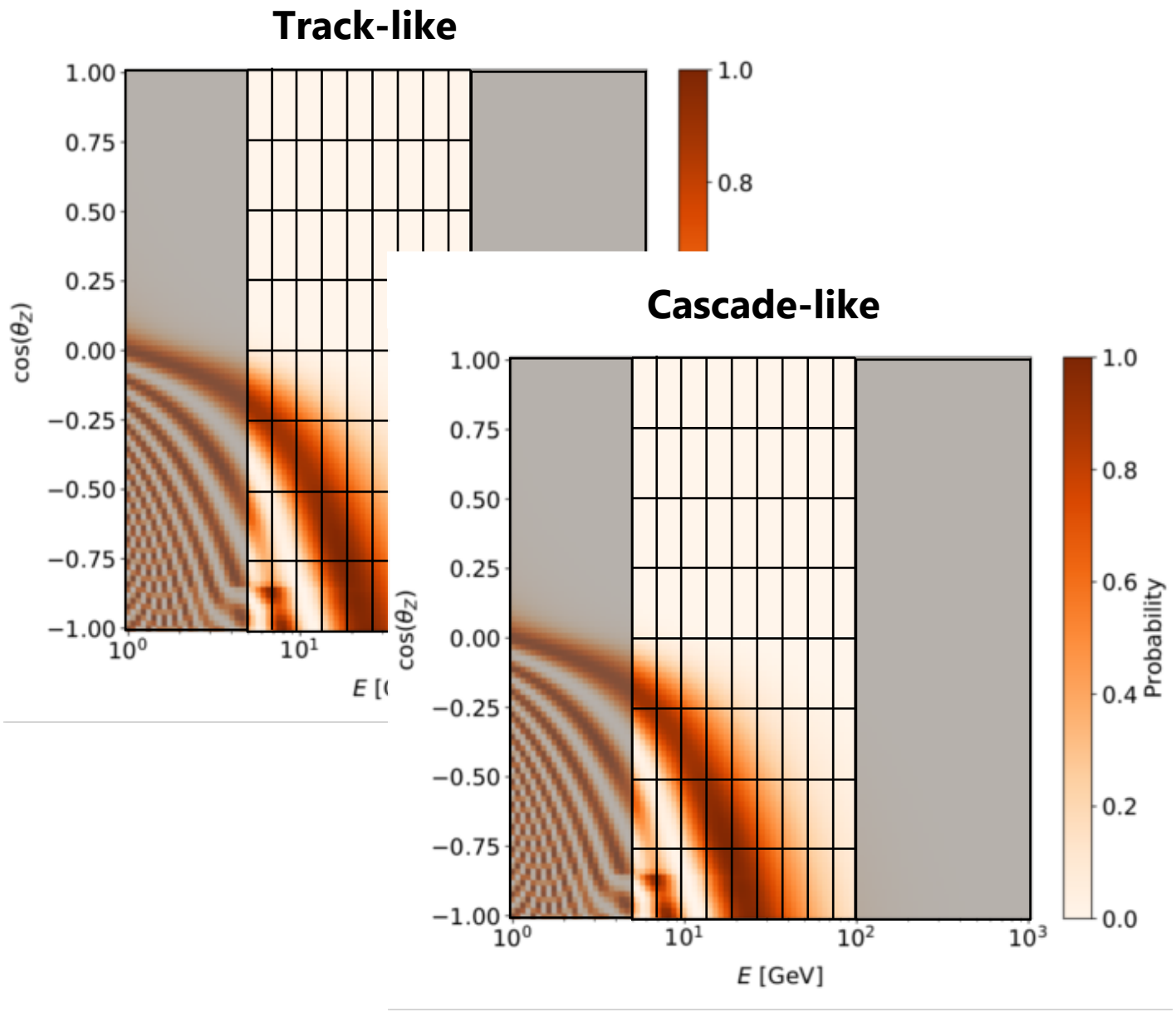
Analysis technique

- Sample divided into **zenith + energy bins**



Analysis technique

- Sample divided into **zenith + energy bins**
- **Particle ID** (PID) to separate track-like from cascade-like (sensitive to different channels)



Analysis technique

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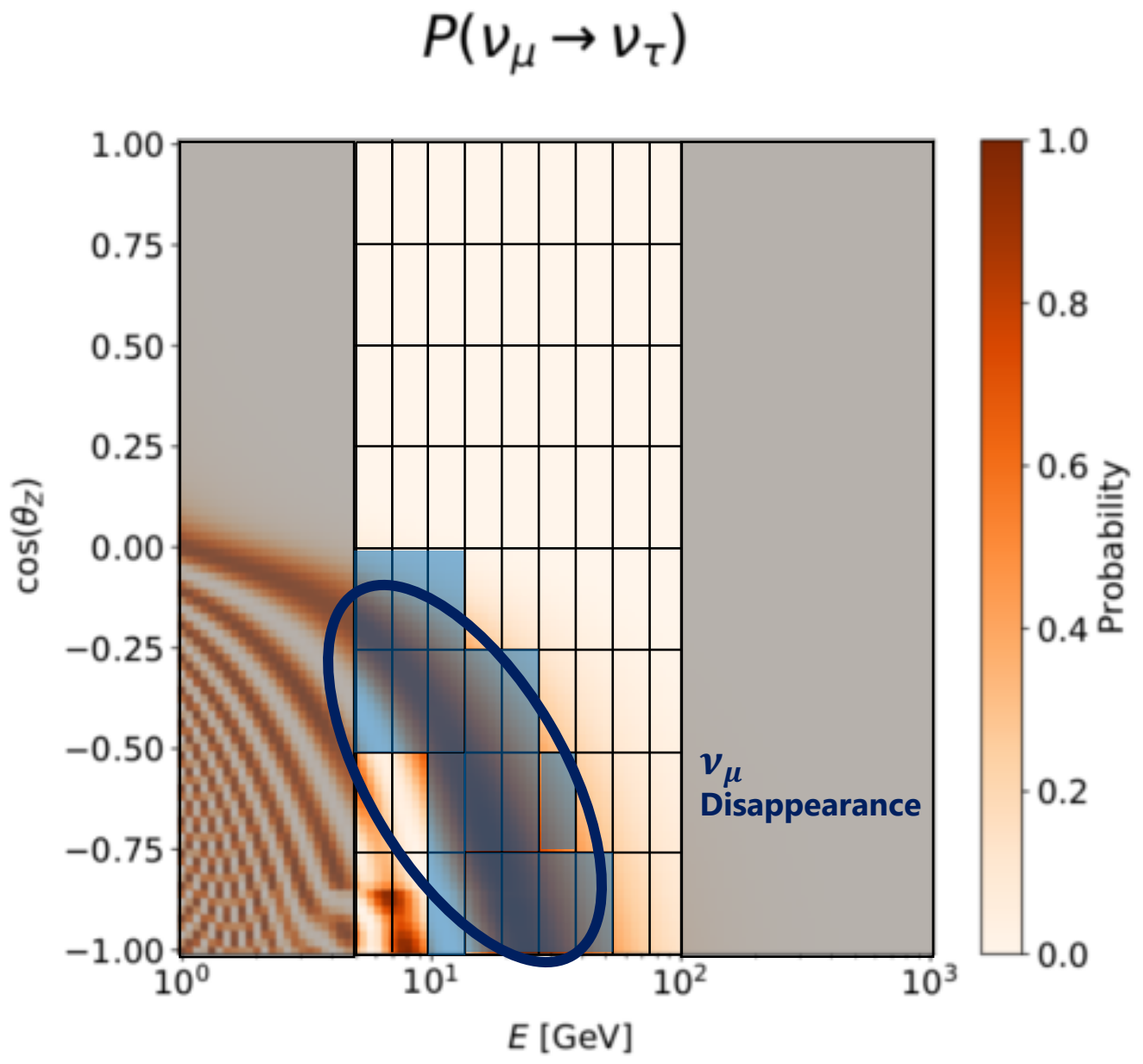
- Look for **changes in the shape of these distributions,** induced by oscillation



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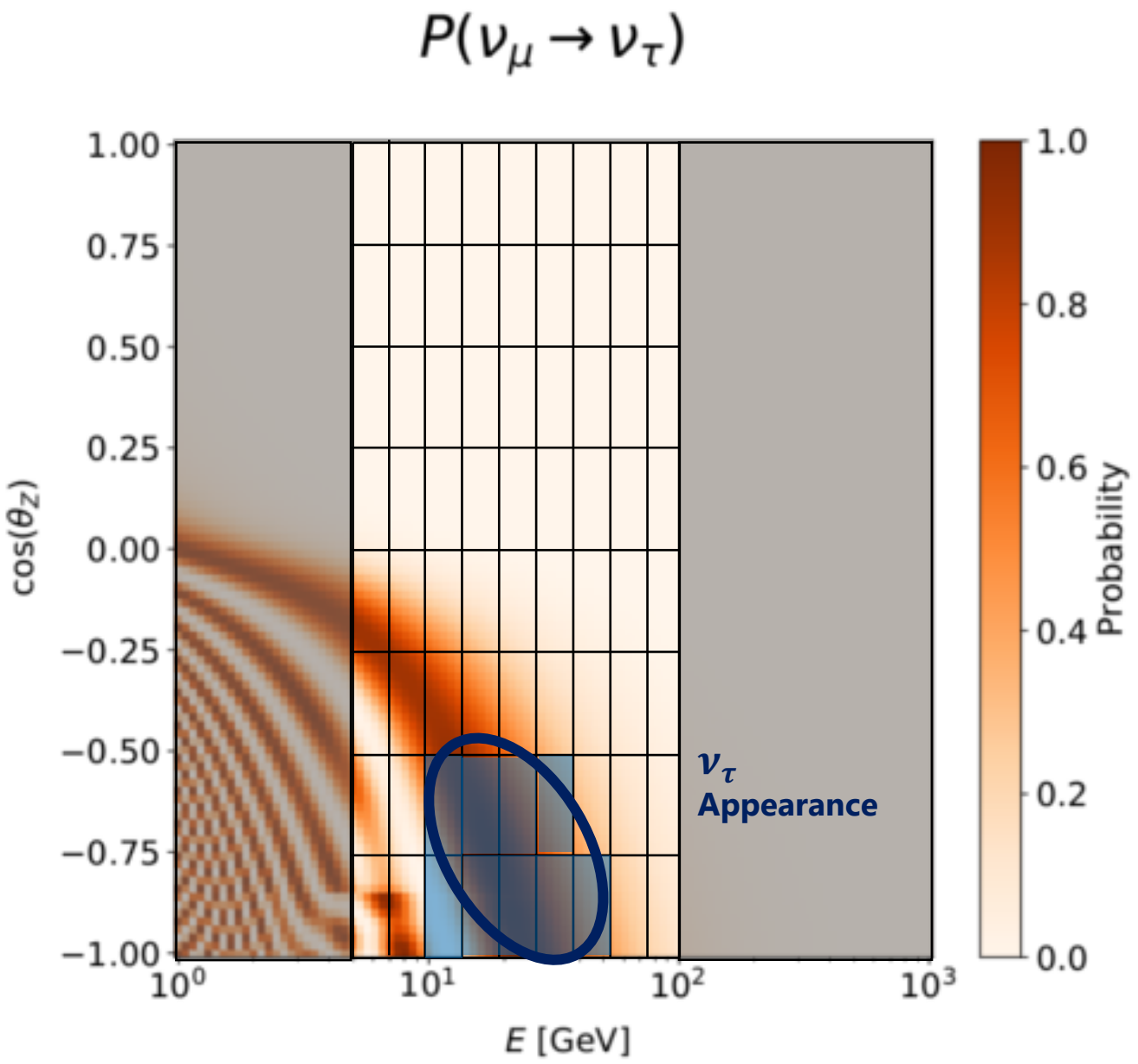

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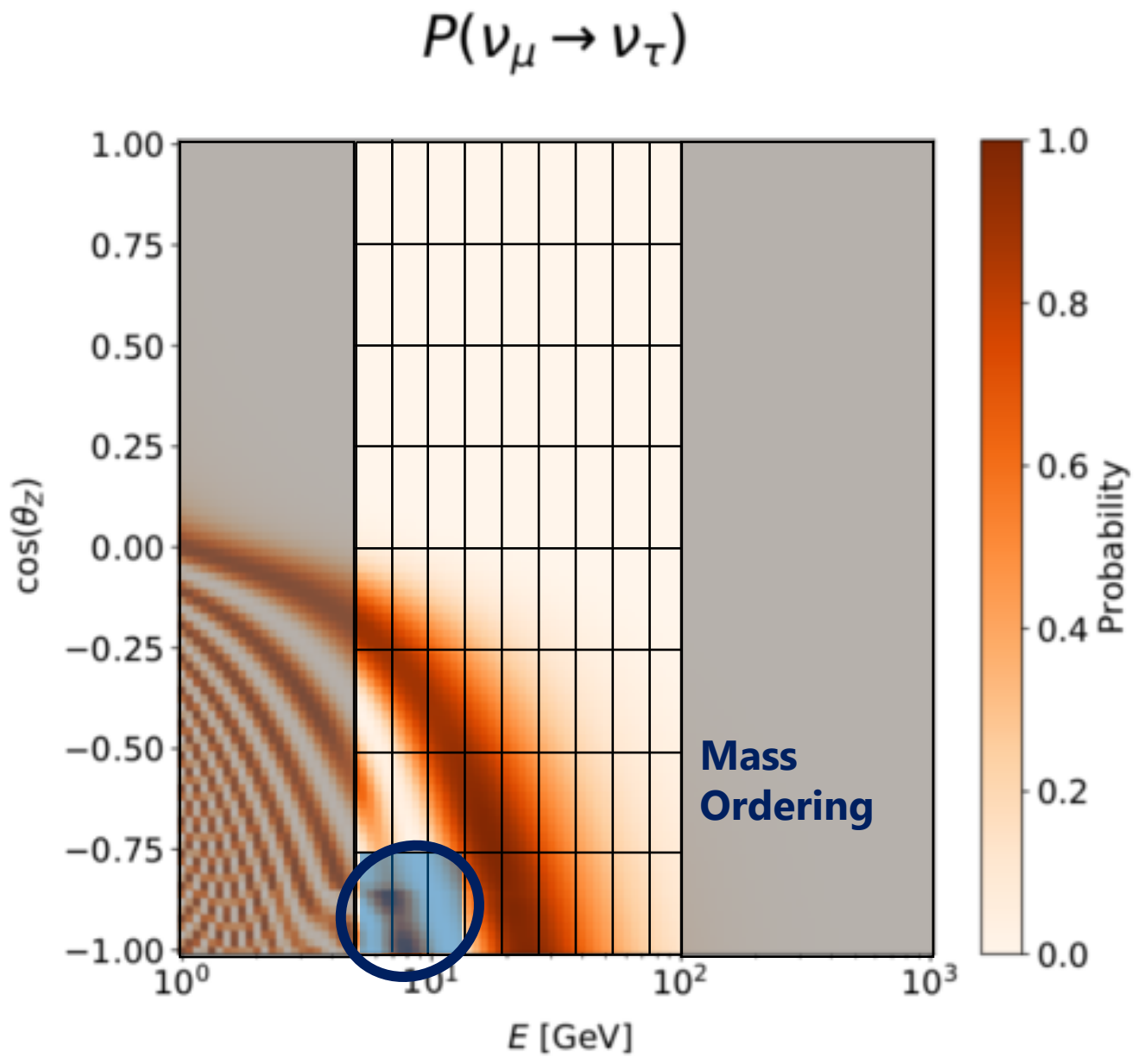
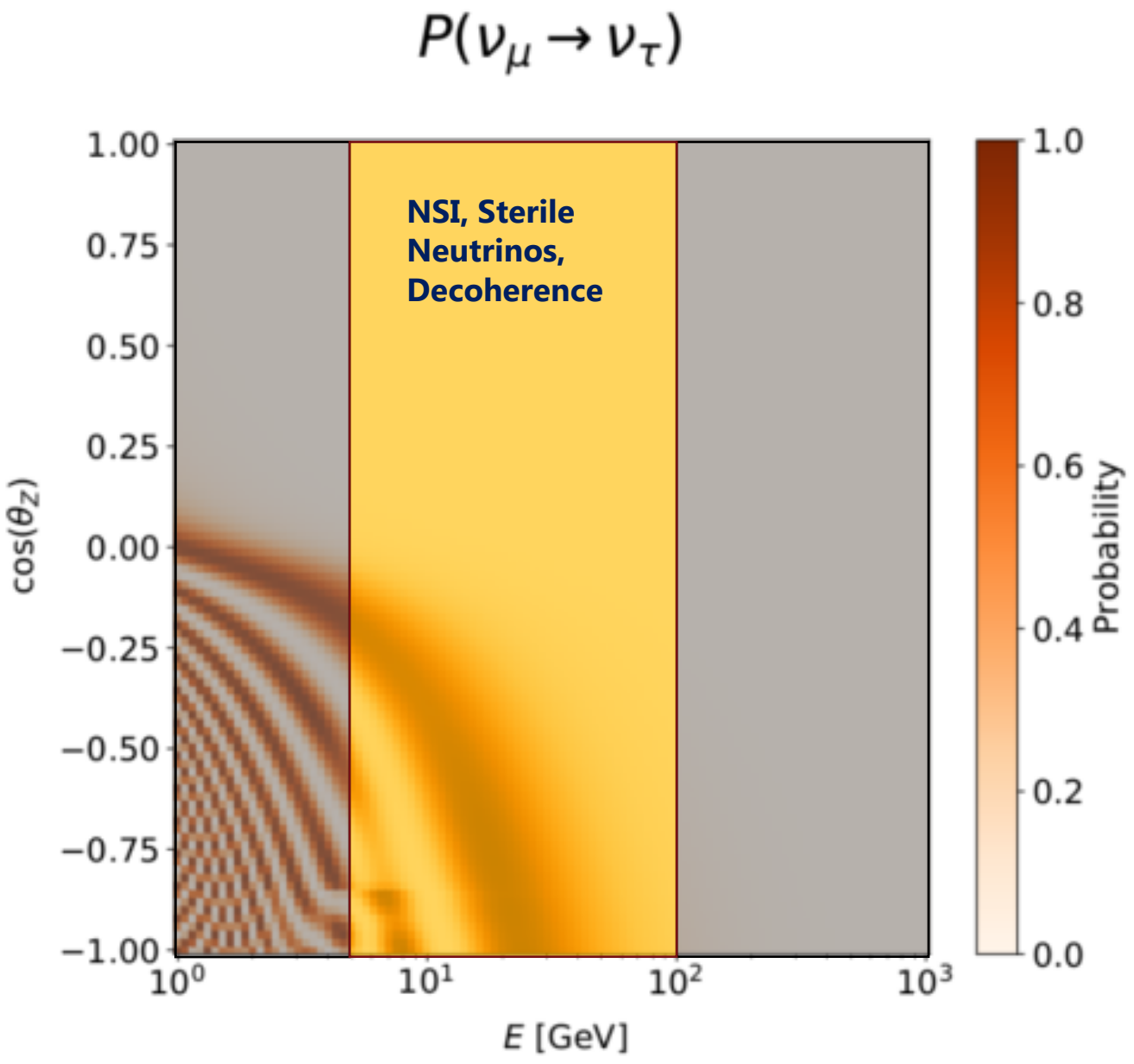


Analysis technique

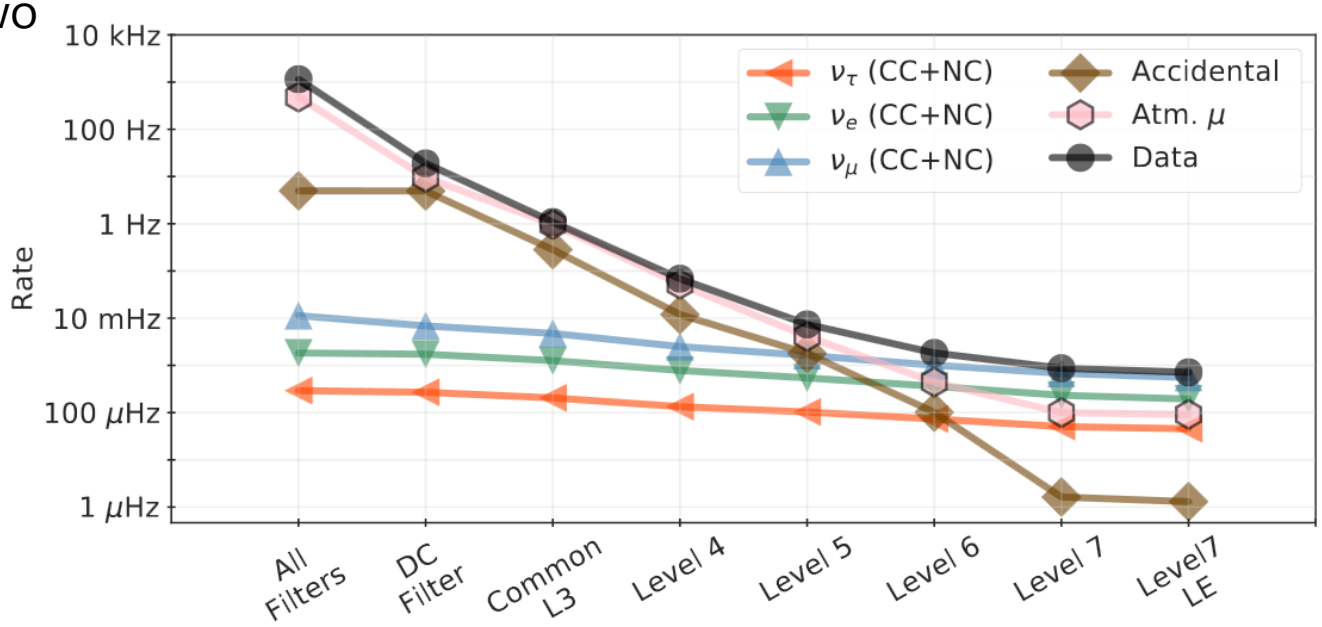
- Sample divided into **zenith + energy bins**
- **Particle ID** (PID) to separate track-like from cascade-like (sensitive to different channels)
- Look for **changes in the shape of these distributions,** induced by oscillation
- Large parameter space to **probe for new physics**



Data Samples

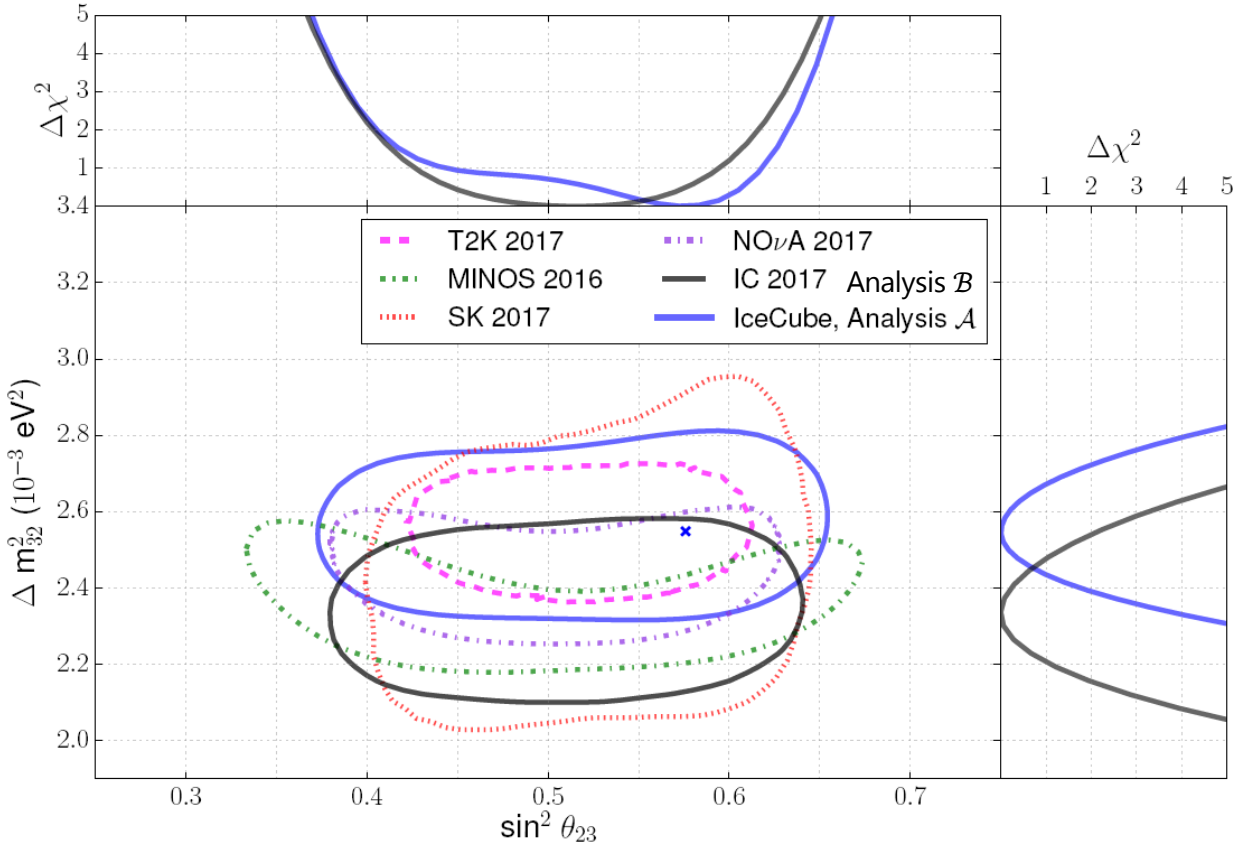
- **Two analyses samples** were produced on **~3 years of data**
  - **Analysis sample $\mathcal{A}$**: Simulated muon background, large statistical sample, additional systematics treatments
  - **Analysis sample $\mathcal{B}$**: Data-driven background estimation, medium-sized statistical sample
- **Extensive cross-checks** performed between the two

Data reduction chart (Analysis sample $\mathcal{A}$):



ν_μ Disappearance

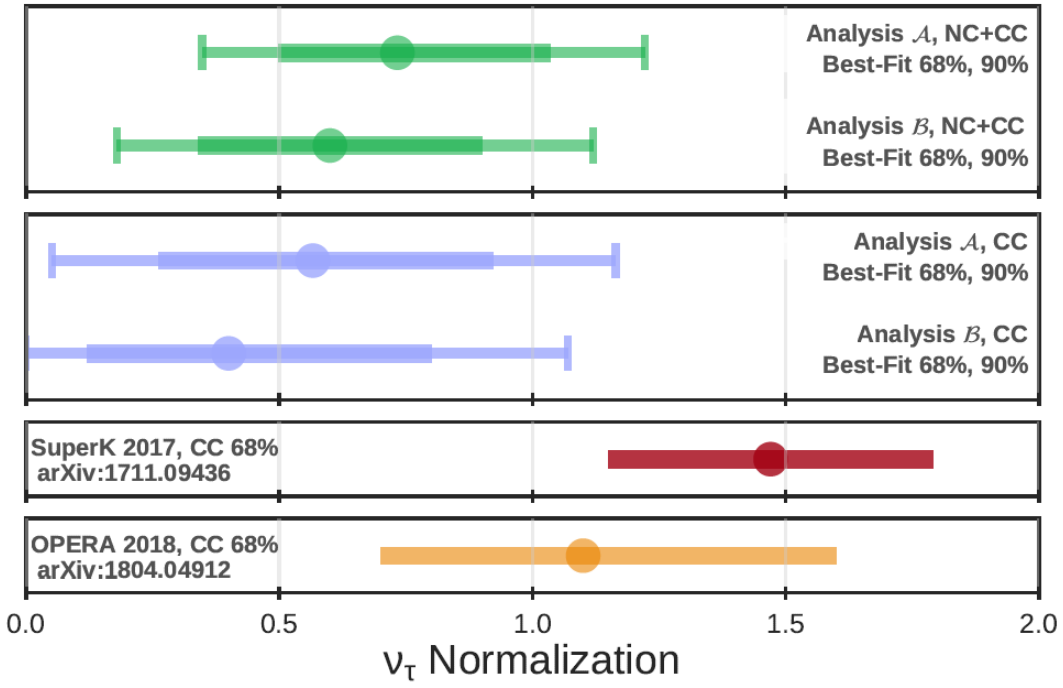
1707.07081



- **Strongest oscillation channel** in IceCube
- Compare data with expectation of standard neutrino oscillation
- Fit histograms to oscillation **frequency (Δm^2_{32})** and **strength ($\sin^2(\theta_{23})$)**
- Both analyses **show large agreement** with each other, and other experiments

ν_τ Appearance

1901.05366



- Separate fit on the predicted number of tau neutrinos in the data (called the tau normalization N_τ)
- $N_\tau \neq 1$ can indicate **departure from unitarity** (*provided the cross-section is known)
- **2000+ tau neutrinos** in sample $\mathcal{A}$
- Complementary to muon disappearance channel

$$N_i^{sim} = \boldsymbol{N_\tau} \cdot A_i \left(F_i^{\nu_e} P_{\nu_e \to \nu_\tau} + F_i^{\nu_\mu} P_{\nu_\mu \to \nu_\tau} \right)$$

Nutau normalization
($N_\tau = 1$ → 3-flavour osc.)

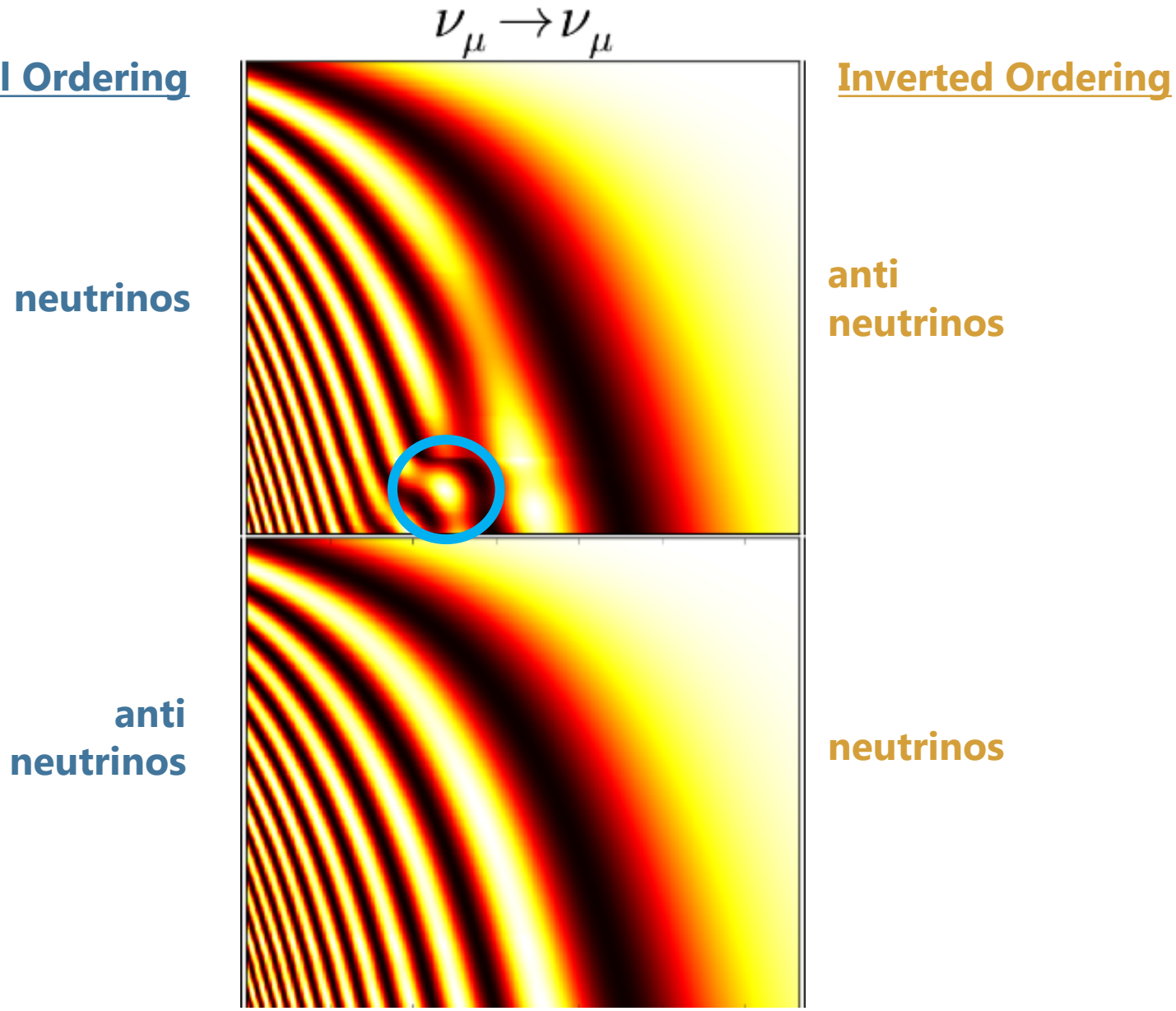
Detector response

Oscillated atmospheric flux

Mass Ordering

1902.07771

- Vacuum oscillations perturbed by the presence of **matter** in the Earth
- Various matter effects induce **distortions in the oscillogram**
- Mass Ordering affects **the type of particle** experiencing the distortion (neutrinos vs. antineutrinos)

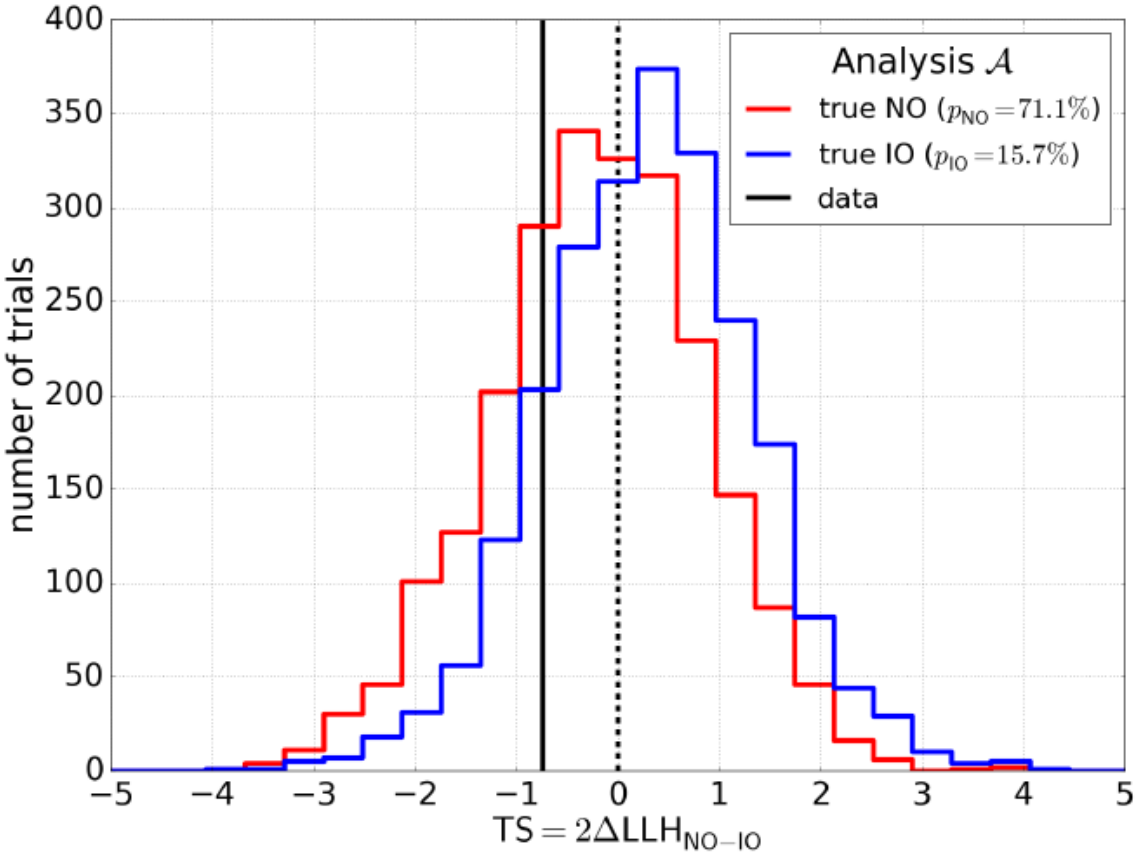


Mass Ordering

1902.07771

- **Weak signature** in IceCube, driven by difference in neutrino / antineutrino flux + cross-section
- Shown: Test statistic quantifying **likelihood of favouring normal ordering**
- **Proof-of-concept** for the IceCube Upgrade

Normal-like ← → **Inverted-like**



Non-Standard Interactions

Publication in preparation

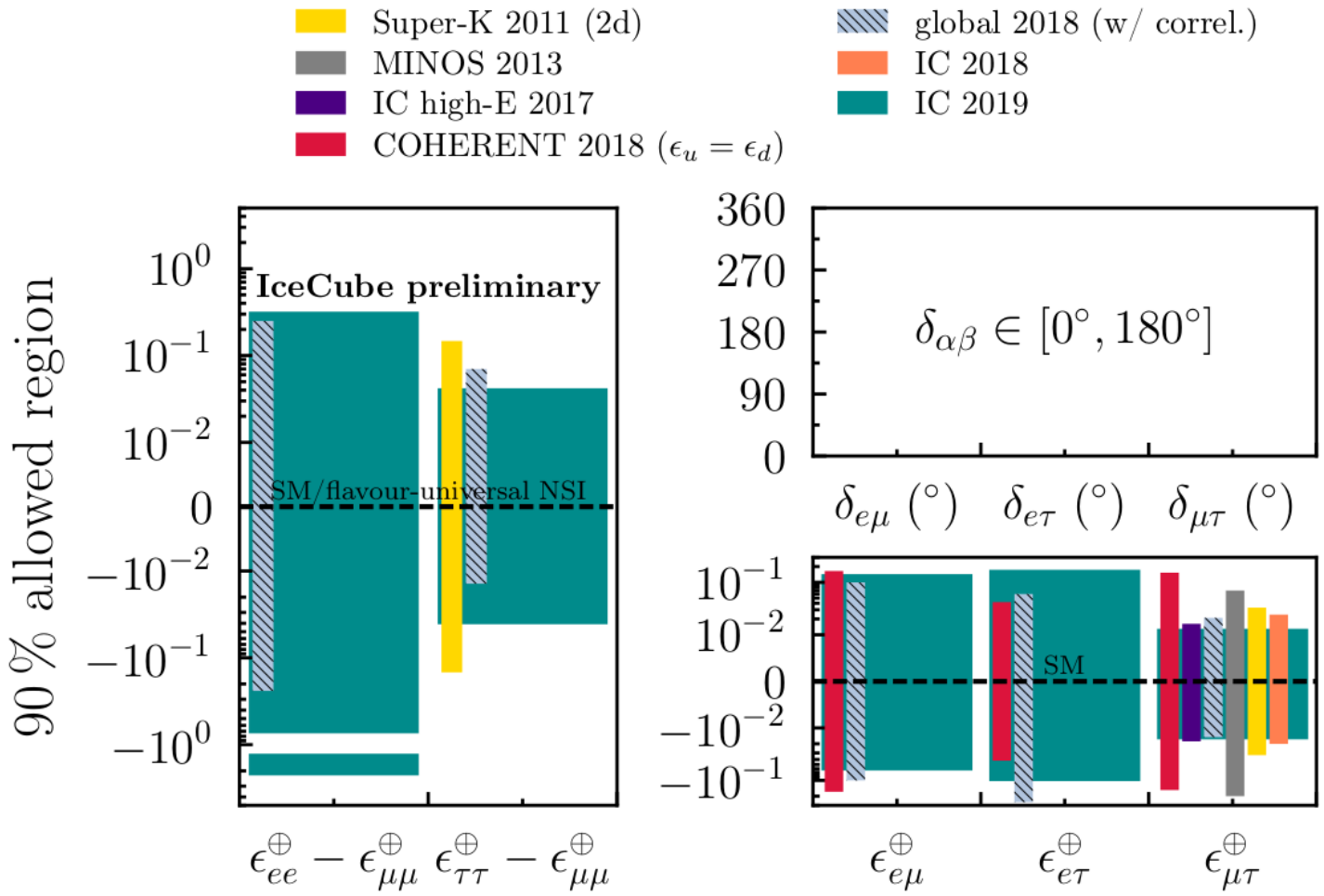
- Search for **additional physics scales** / light mediators acting on neutrino **while they propagate**
- Effect can be parametrized by an **effective Hamiltonian**: $H_{\mathrm{mat}} = \sqrt{2} G_F N_e(r) \begin{pmatrix} 1+\epsilon^{\oplus}_{ee} & \epsilon^{\oplus}_{e\mu} & \epsilon^{\oplus}_{e\tau} \\ \epsilon^{\oplus *}_{e\mu} & \epsilon^{\oplus}_{\mu\mu} & \epsilon^{\oplus}_{\mu\tau} \\ \epsilon^{\oplus *}_{e\tau} & \epsilon^{\oplus *}_{\mu\tau} & \epsilon^{\oplus}_{\tau\tau} \end{pmatrix}$
- $\epsilon^{\oplus}_{\alpha\beta}$: relative strength of coupling w.r.t strength of the weak interaction
- Explores a **richer variety of coupling strength parametrizations** than previous results:
  - ❑ 2 searches for **non-universal** interactions } **Single, real parameter fits**
  - ❑ 3 searches for **flavour-changing** interactions } **Single, complex parameter fits**
  - ❑ 1 search exploring an **effective vacuum parametrization** } **3 parameter fits (less model-dependent)** 1805.04530

Non-Standard Interactions

Publication in preparation

Results are for Normal Ordering

Individual coupling strength fits:

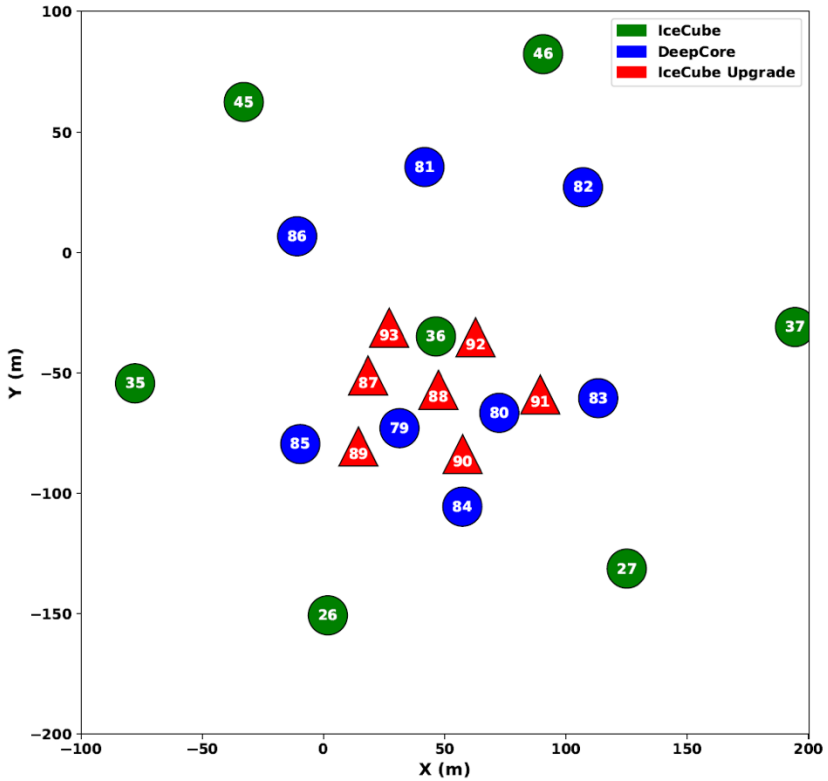


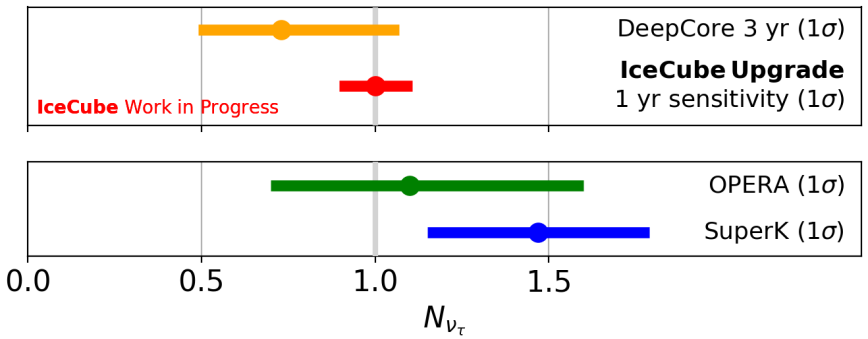
- **No NSI discovered**
- Results are **independent of the scale** of new physics
- **Improves / set new limits** on multiple parameters
- Complements searches using **non-oscillation-based** experiments

Next Generation of analyses

- **4 additional years of data** available (total of 7.5 years)
- **Improved characterization** of ice properties + PMT charge response
- New **machine learning tools** for refined classification
- **Better treatment** of atmospheric flux systematics
- Improved **event reconstructions**
- **Expanded searches for new physics**

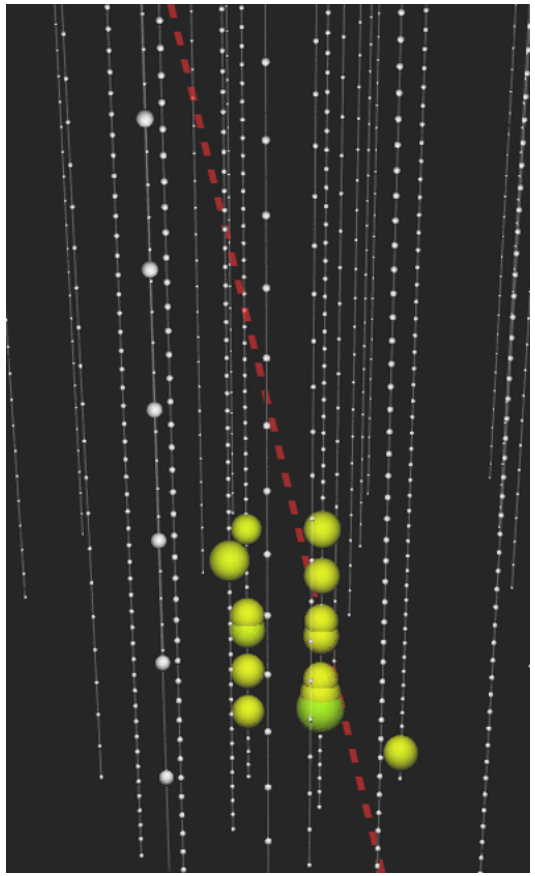
IceCube Upgrade (deployment in 2022-2023)



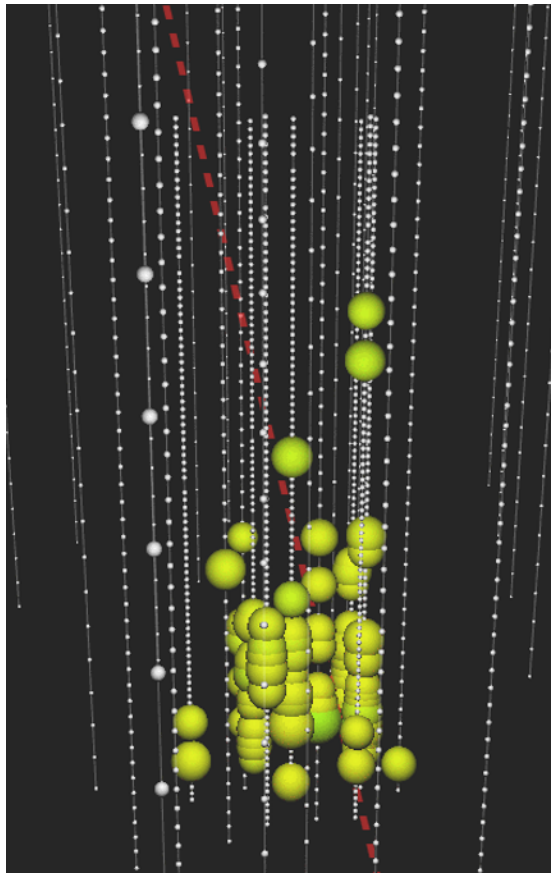


21 GeV Tau Neutrino

In DeepCore



In the Upgrade



- Will be able to reconstruct 1 GeV events

Conclusion

- New set of results on three years of data now complete
- All results agree with the standard 3-flavour oscillation paradigm
- Not covered here: Sterile Neutrino Search (see J. Hignight's talk on Friday)
- 7 years results coming soon
- The Upgrade will be awesome

Backup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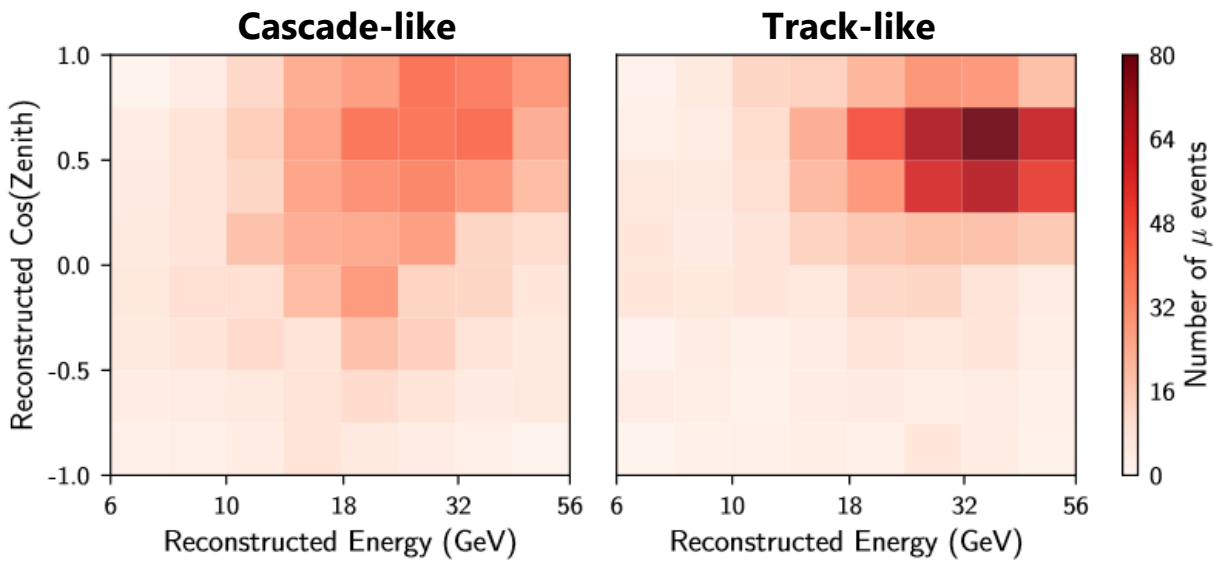
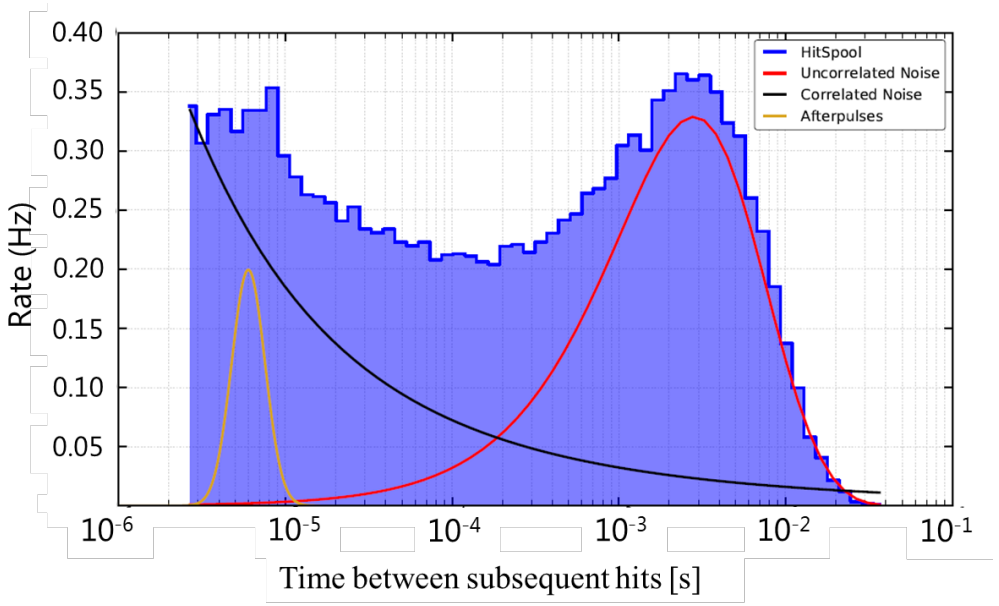
Backup - Analysis technique - Backgrounds

Atmospheric Muons



- Main Background component
- Affect mostly downgoing region

Detector Noise

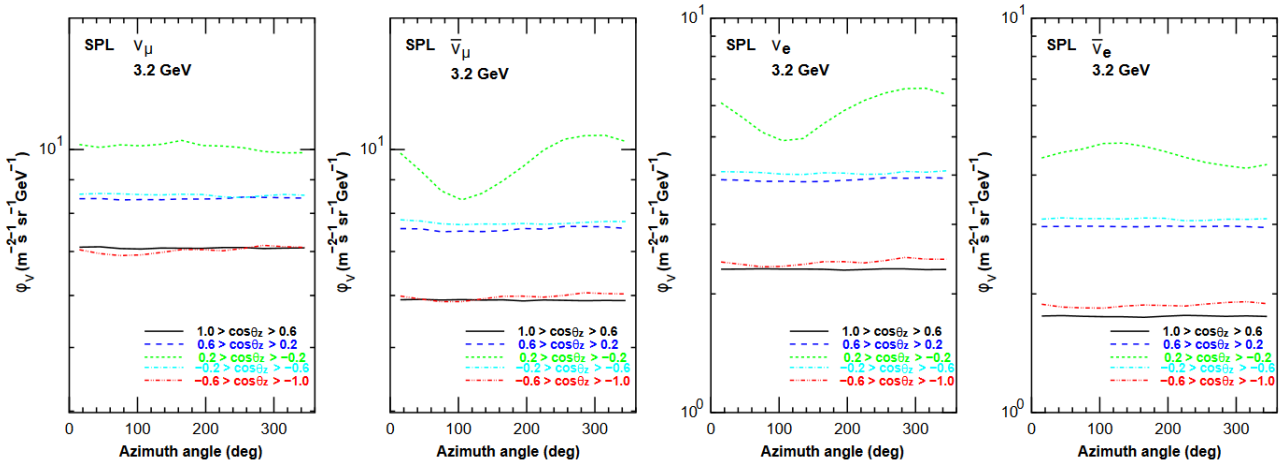


- Light from scintillation in the DOM glass
- Complex time structure
- Minimal effect at final level

Backup – IceCube sensitivity to anti-neutrinos

Neutrino Flux directionality:

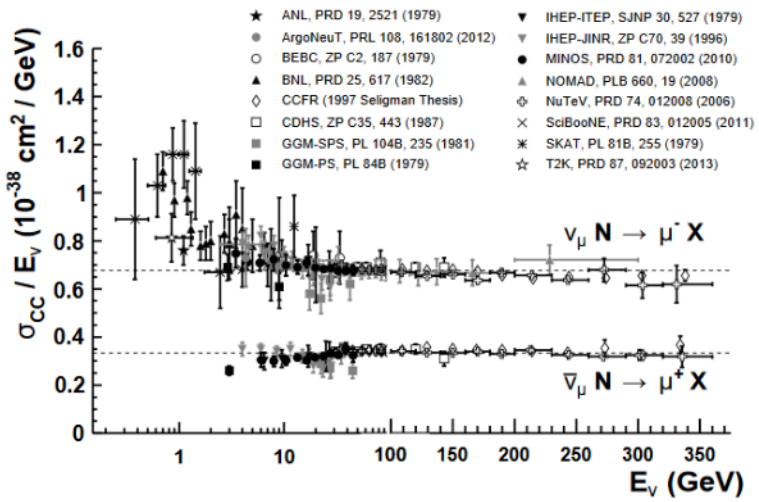
(1502.03916)



inelasticity?

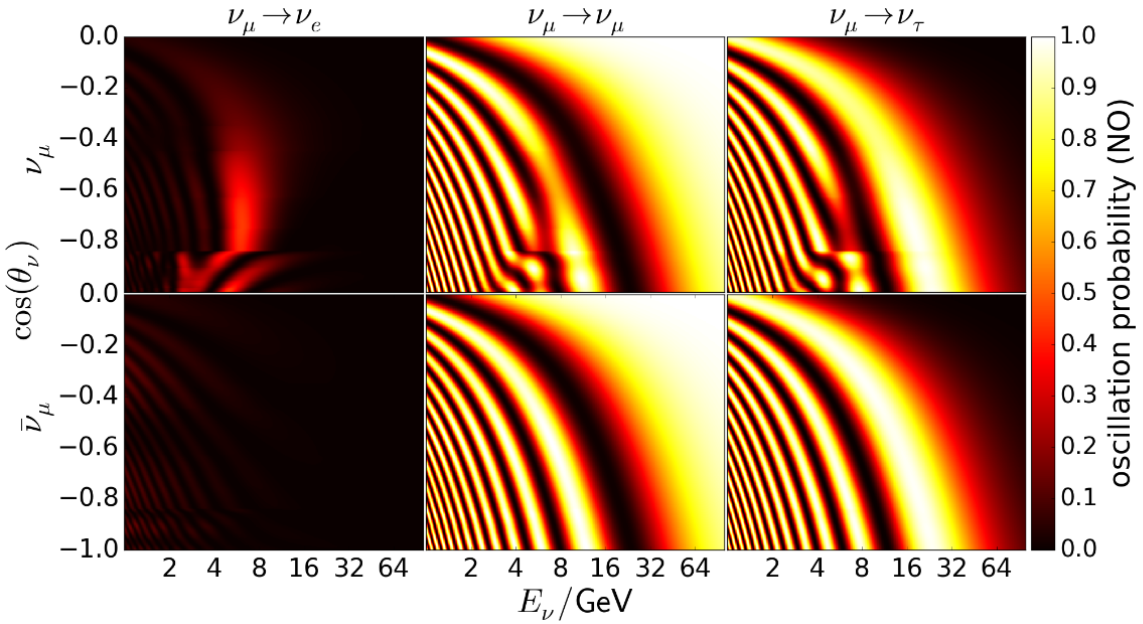
Cross-Section:

(PDG Review)



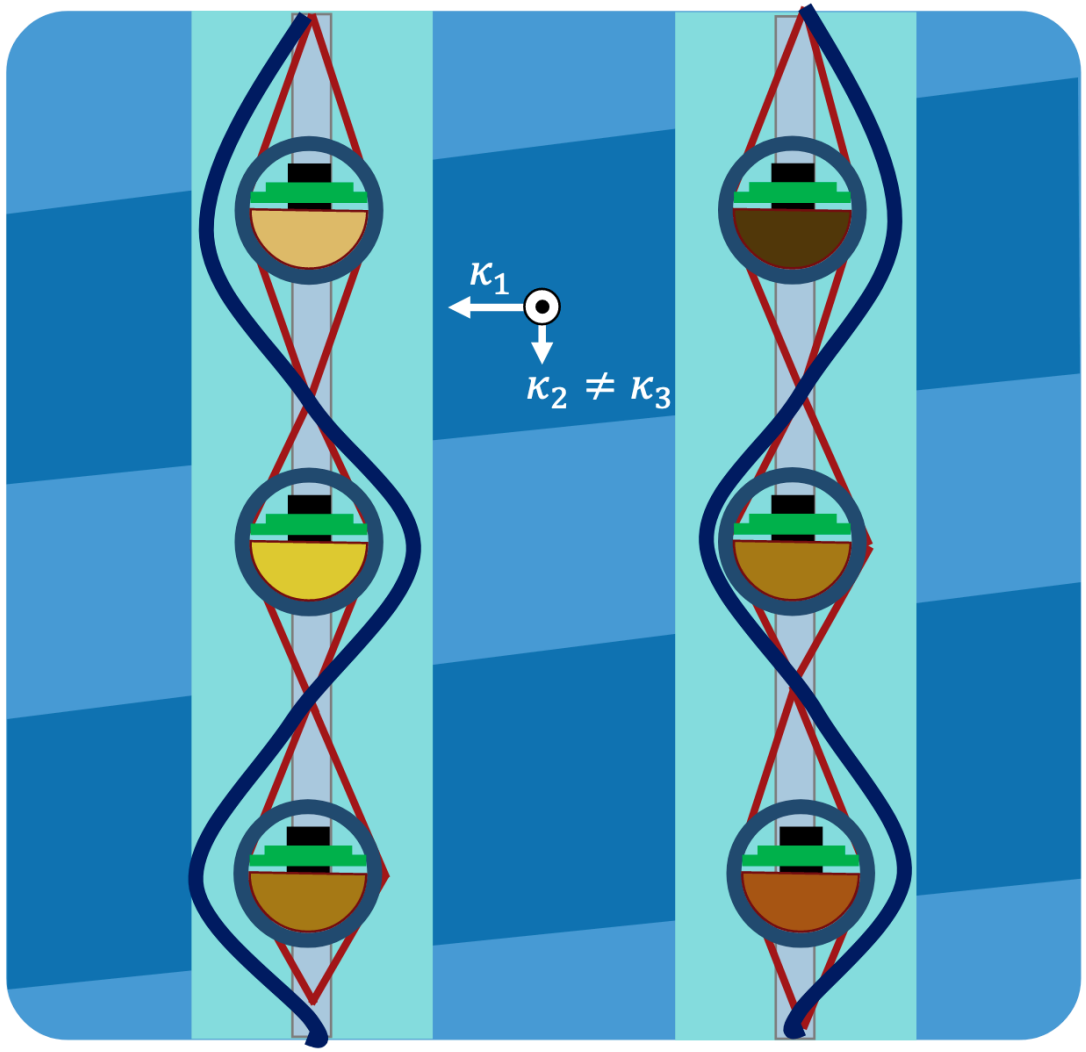
Matter effects in the Earth:

(1902.07771)



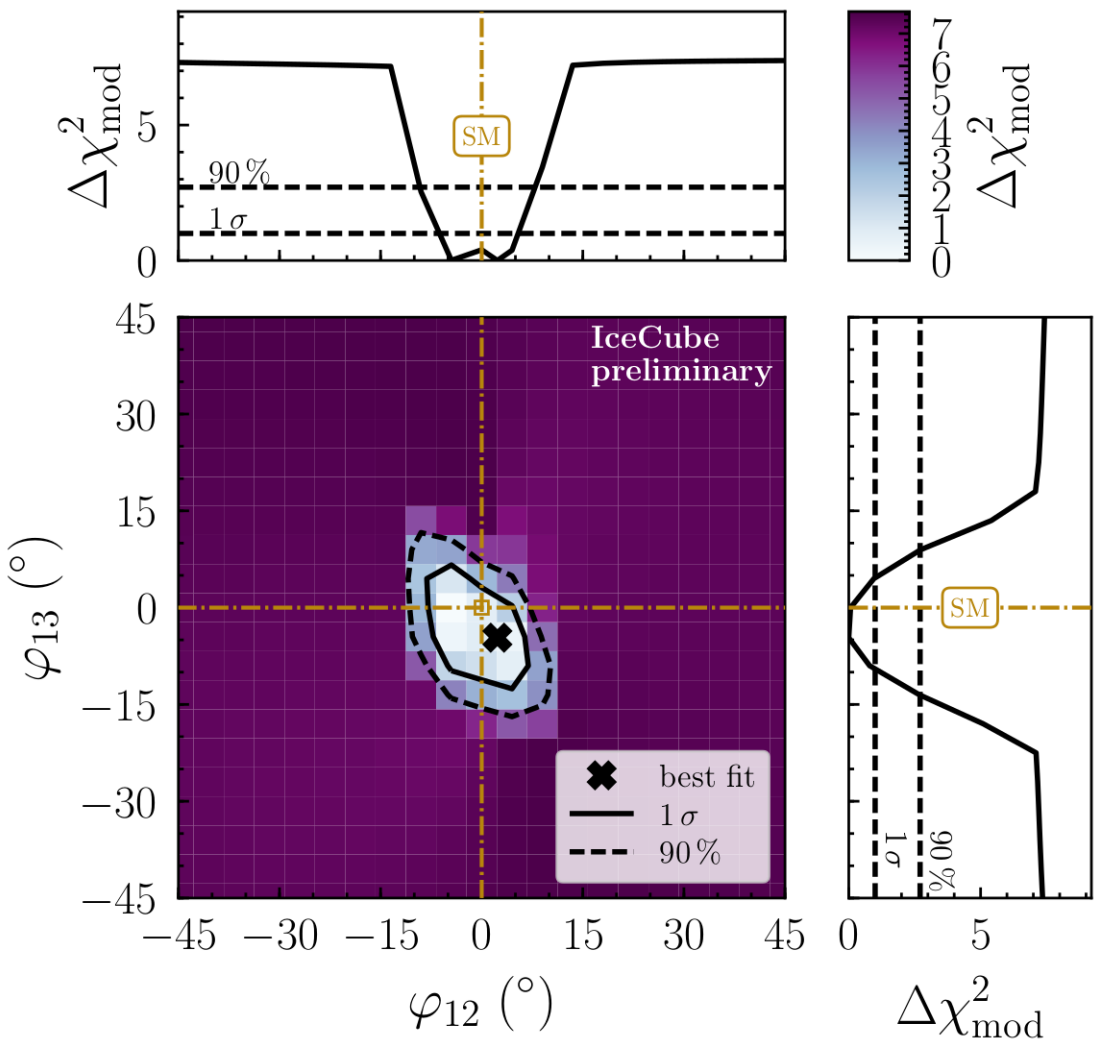
Backup - Analysis technique (Systematics)

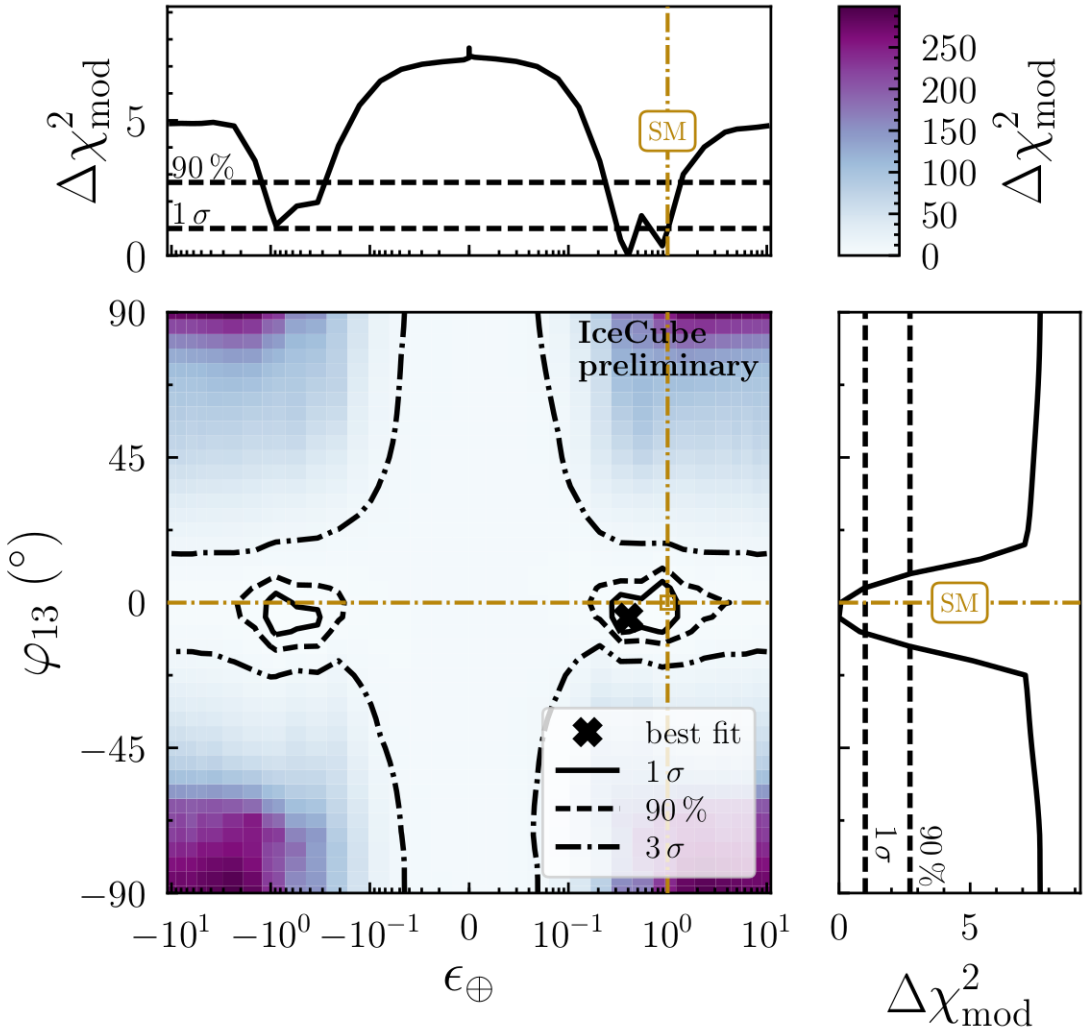
- Low energy means low light yield, and therefore higher sensitivity to systematics
- **Ice properties**
- **Instrumental response** of the DOM
- Additional uncertainties from theoretical modeling of:
  - Atmospheric air showers
  - nuclear cross-sections



Backup – Additional NSI Results

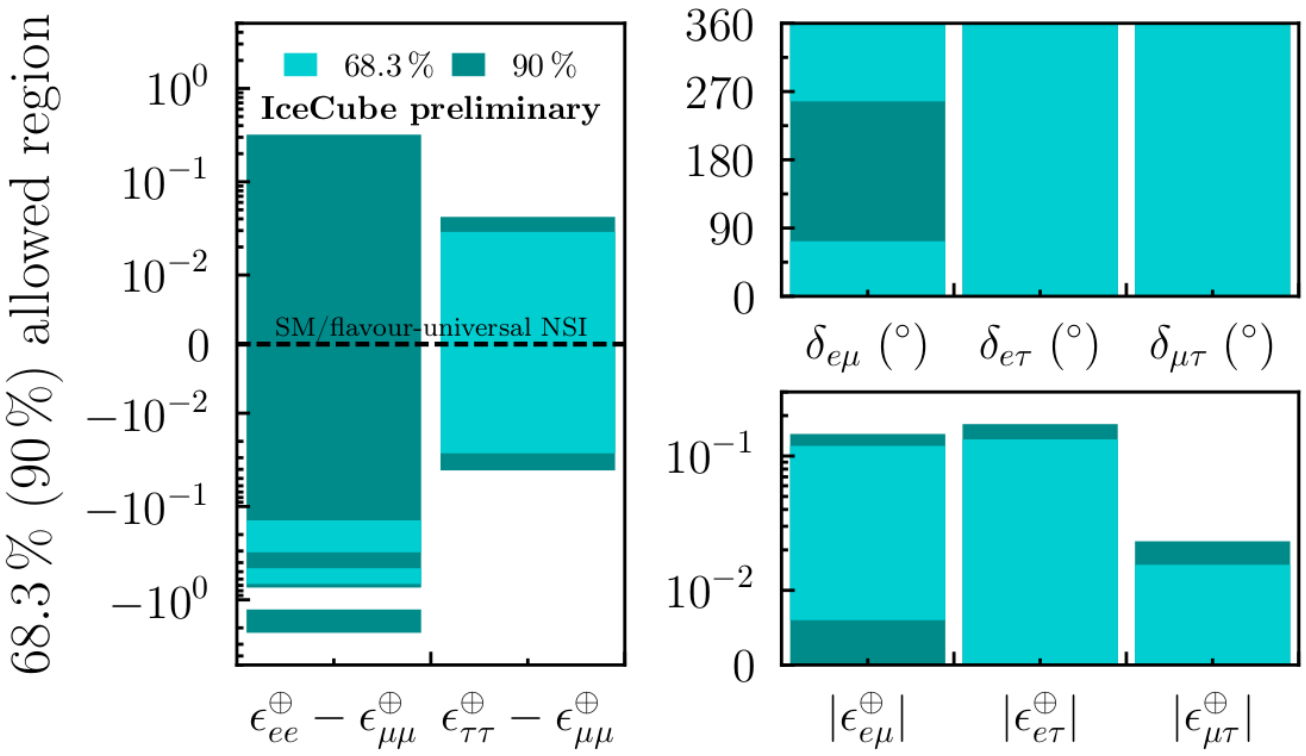
Effective Vacuum Parametrization results:





Backup – Additional NSI Results

Single-parameter searches (assuming complex phases):



Measuring Neutrino Oscillations

- Neutrino wavefunction after travelling a distance L: $|\nu_i(L)\rangle = e^{-i\frac{m_i^2 L}{2E}}|\nu_i(0)\rangle$
- The probability of measuring flavour state α as state β at that distance is given by :

$$P_{\alpha\to\beta} = \left|\langle\nu_\beta(L)|\nu_\alpha\rangle\right|^2 = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right) + 2\sum_{i>j} Im\left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*\right)\sin\left(\frac{\Delta m_{ij}^2 L}{2E}\right)$$

Oscillation experiments measurements therefore depend on:

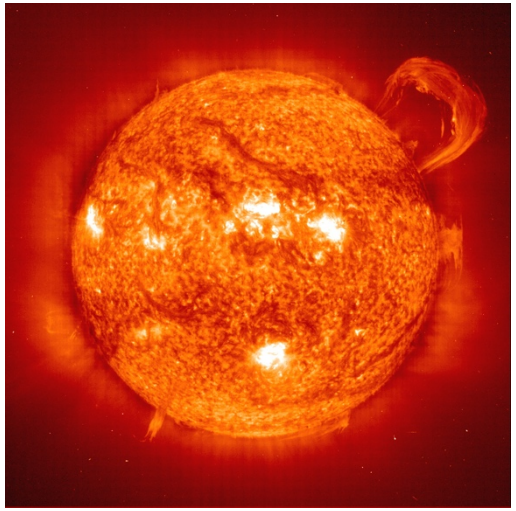
- **Mixing elements** $\boldsymbol{U_{\alpha i}}$
- **Squared mass differences** $\boldsymbol{\Delta m_{ij}^2}$
- **Baseline-to-energy ratio** $\boldsymbol{L/E}$

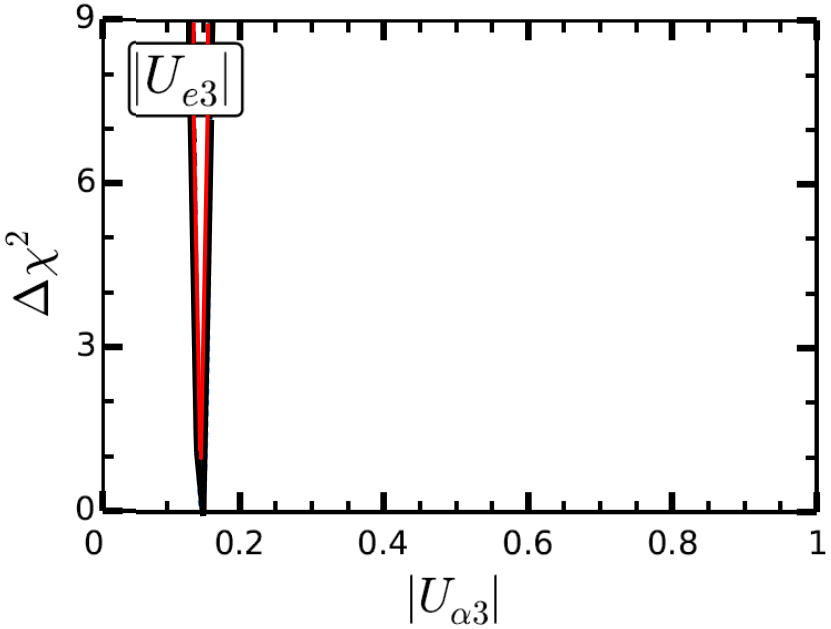
Constraints on mixing matrix elements

For ν_e's:

- ~ 10^{10} neutrinos / s / cm^2 (solar neutrinos)
- ~ 10^8 anti-neutrinos / s / cm^2 (2 km away from nuclear reactor)
- First direct detection (Cowan + Reines) : 3 neutrinos / hour

Large wealth of data can constrain ν_e mixing to ~1% level





— with unitarity

— w/o unitarity

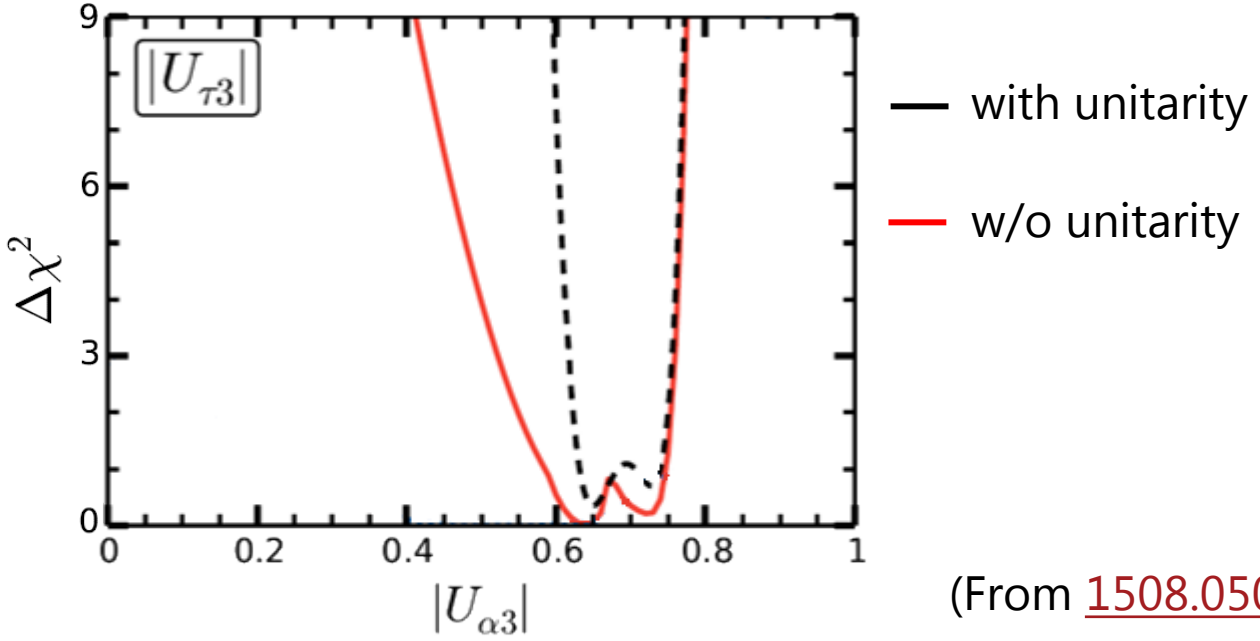
(From 1508.05095)

Constraints on mixing matrix elements

For ν_τ's:

- ~ 10^{-10} Prompt neutrinos / cm^2 / s (undiscovered)
- Since their discovery (2000): **<10 direct detections** (using accelerators)

Mixing parameters for ν_τ weakly constrained, especially if one removes unitarity requirements



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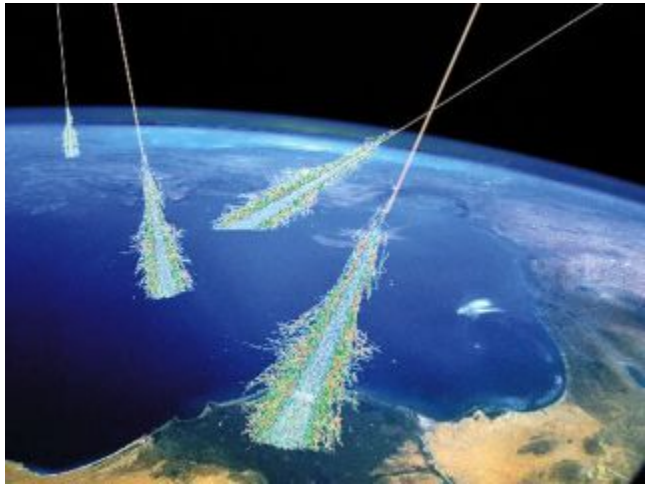

What do we mean by unitarity?

- Probabilities must be conserved
- This implies that $\boldsymbol{U}^\dagger \boldsymbol{U} = \boldsymbol{I}$
- Departure from unitarity could imply **additional dimensions** (sterile neutrinos) or **non-standard interactions**

Normalisation of ν_e

Normalisation of ν_1

$$\begin{bmatrix} U_{e1}^2 & + & U_{e2}^2 & + & U_{e3}^2 \\ + & U_{\mu 1}^2 & U_{\mu 2} & & U_{\mu 3} \\ + & U_{\tau 1}^2 & U_{\tau 2} & & U_{\tau 3} \end{bmatrix} = 1$$

$$= 1$$

Unitarity triangles

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}^* \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$