Tau Neutrino Appearance with 8 Years of IceCube Neutrino Data

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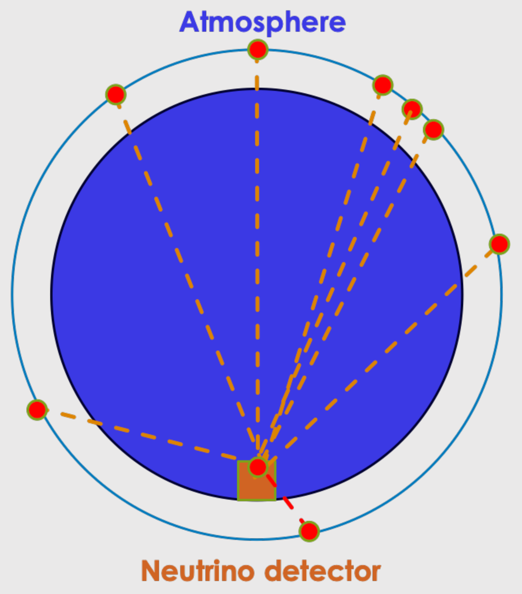
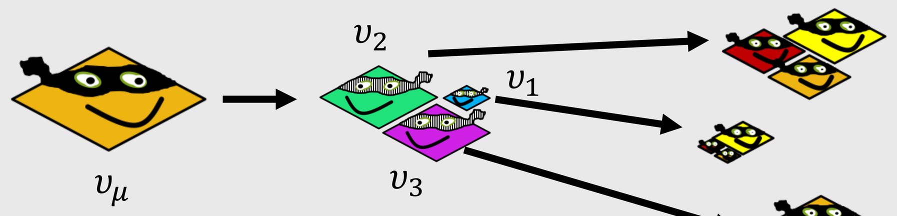
ICECUBE

Neutrino Oscillations in IceCube



Neutrinos from **cosmic-ray interactions** in the atmosphere are reconstructed with associated **energy** and **direction** (proxy for distance travelled). They allow IceCube to cover a **wide range of oscillation baselines (~10 to 10000 km, and 5 to 300 GeV)**

- Neutrino oscillations constitute **the only experimental evidence of non-conformity** to the Standard Model (potential evidence for **new physics**)
- It describes transitions between flavor states to mass states



Production (as ν_μ's)

Propagation (as superpositions of ν_1's, ν_2s and ν_3's)

Detection (as ν_e's, ν_μ's and ν_τ's)

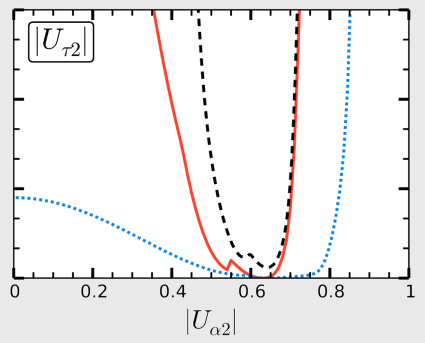
Unitarity

- PMNS **unitarity constraints** are **weakest for the third generation** of neutrinos, **an area where IceCube is highly sensitive [3]**
- **Non-unitarity** could indicate that **the 3x3 PMNS matrix** is a subset of a larger N x N mixing matrix
- IceCube operates in energy ranges were $\nu_{\tau,CC}$ **cross-section is much less kinematically suppressed** than in accelerator experiments

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

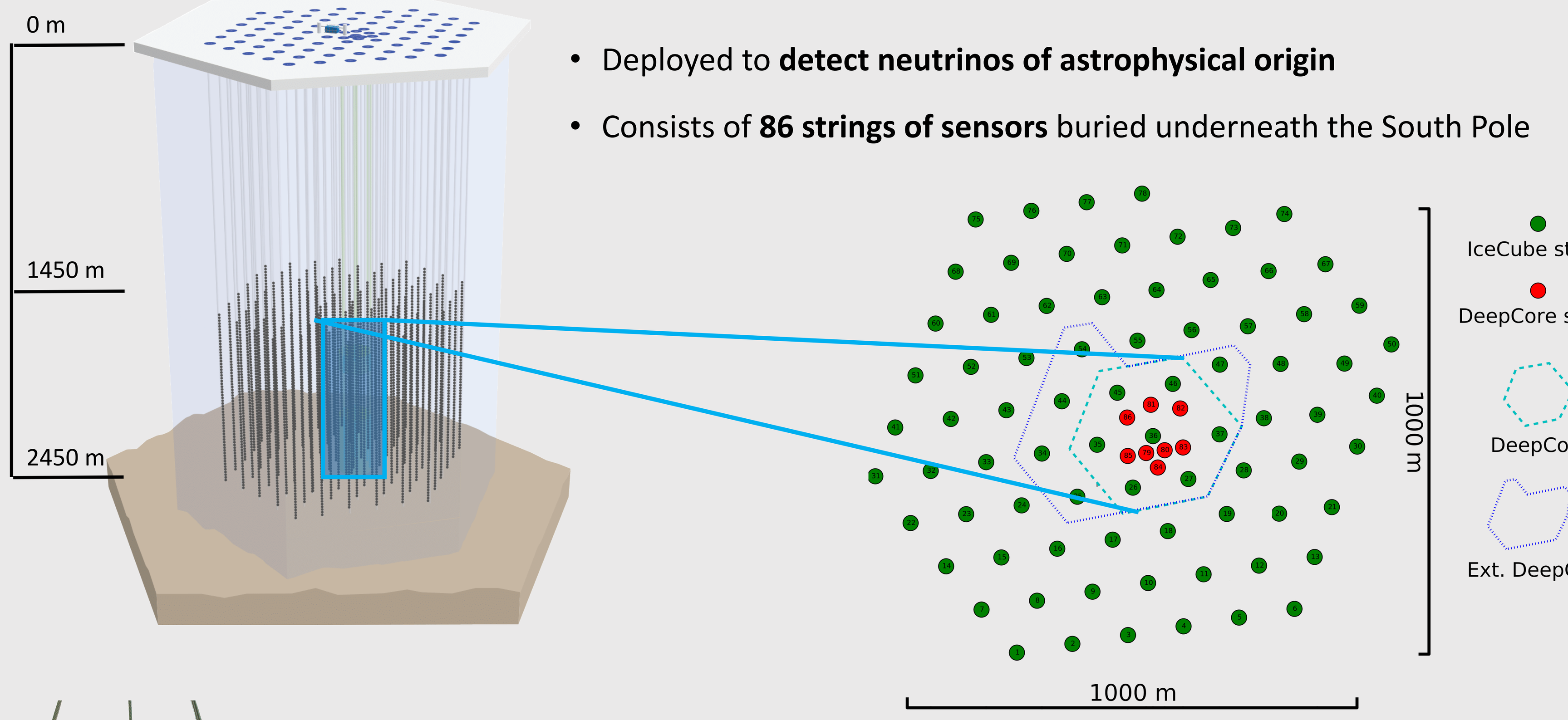
$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$; $|U_{e1}|^2 + |U_{\mu 1}|^2 + |U_{\tau 1}|^2 = 1$

Unitarity implies namely that rows and columns of the squared PMNS matrix sum up to 1.0



Constraint on matrix element $U_{\tau 2}$, assuming unitarity, without unitarity assumption (but assuming sterile neutrinos), and without unitarity and no sterile search / normalisation [1]

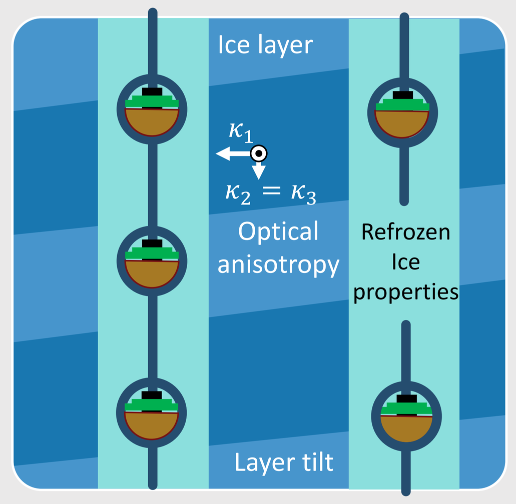
The IceCube and DeepCore Detectors

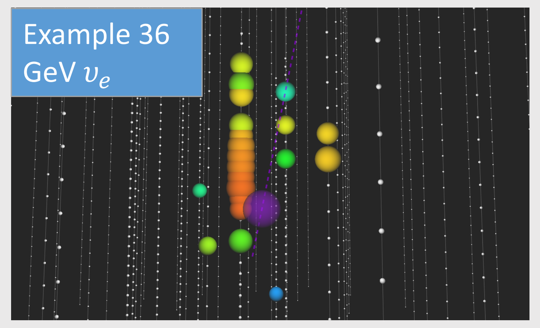


IceCube Neutrino Observatory [2]

- Deployed to **detect neutrinos of astrophysical origin**
- Consists of **86 strings of sensors** buried underneath the South Pole

IceCube is not a perfect cube of ice. Absorption + scattering properties vary accross the glacier's depth. Constrained using **LED flashers** built in the DOMs





View of a typical neutrino event in DeepCore. **Color** represents photon arrival **time** (blue=early, red=late). Sphere **size represents the charge** collected

Systematics Uncertainties:
Analysis treats uncertainties as nuisance parameters in the fit:

- Neutrinos and muon spectral index
- Atmospheric Neutrino Flux ([4], [5])

} Production

- Quasielastic and resonant form factor
- Deep Inelastic scattering cross section
- Earth Model (neutrino propagation)

} Interaction

- Dom Efficiency
- Refrozen ice parametrisation
- Bulk Ice absorption & scattering

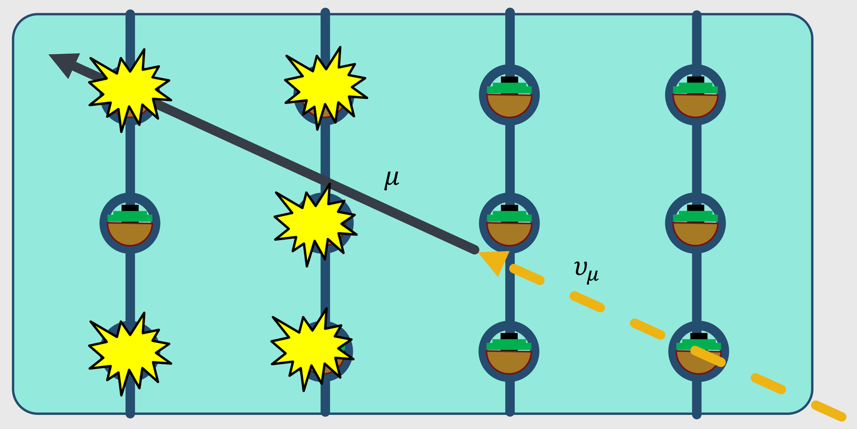
} Detection

Digital Optical Module (DOM)

- 30 cm photomultiplier tube + digitizer encapsulated in a pressure vessel
- Designed to detect **Cherenkov radiation** from particle interactions in the ice
- Elementary unit of the detector

The DeepCore Sub-Array

- 8 strings of **high quantum efficiency** DOMs
- **10 Mton fiducial volume**
- ~ **500 sensors** in closer spacing
- Rest of IceCube is used as a veto region

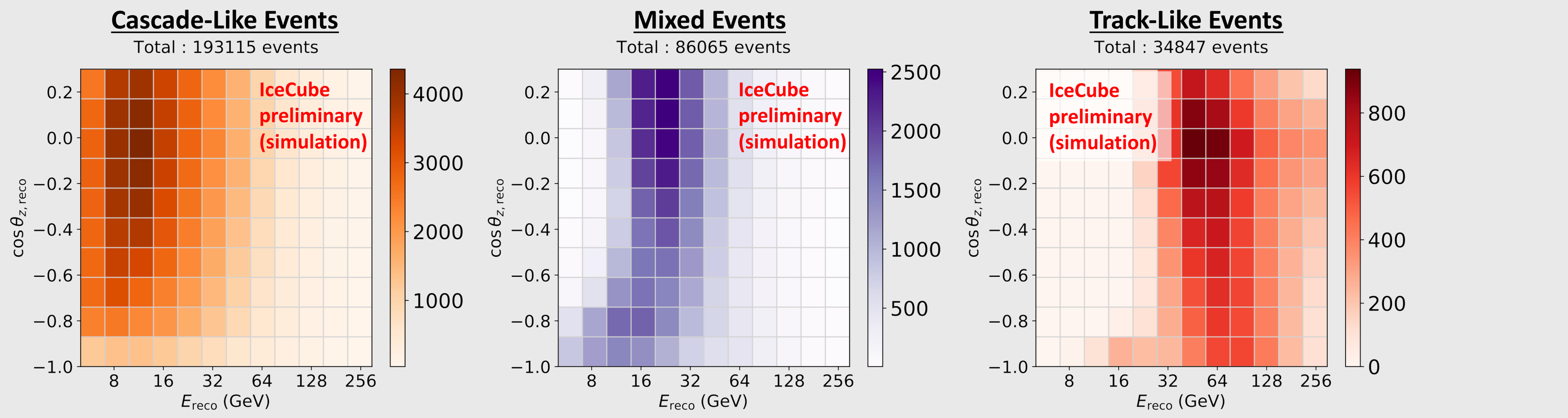


Reconstruction of neutrino events

- Charge and time of hits from all DOMs are fed into a likelihood-based event reconstruction algorithm
- $\nu_{\mu,CC}$ **interactions have mostly track-like** profiles, while $\nu_{e,CC}$, $\nu_{\tau,CC}$ **and all** ν_{NC} **interactions produce point-like (ie cascade)** profiles

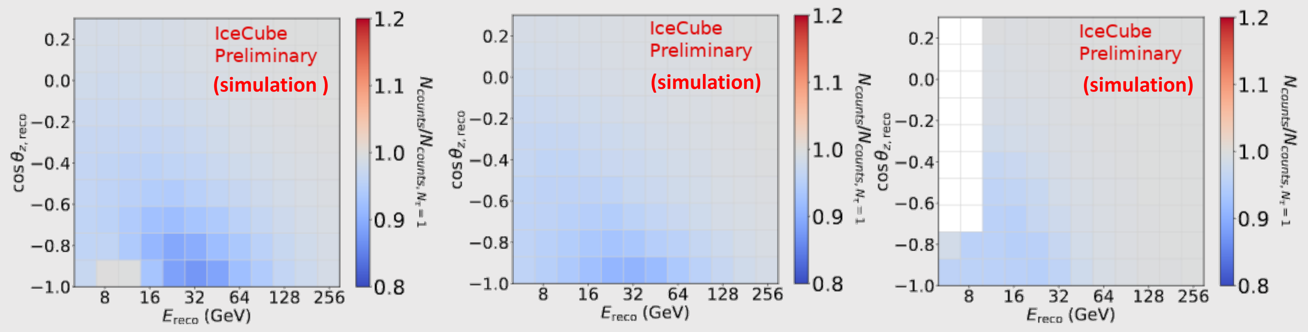
Analysis Principle

- We count the number of neutrinos detected per particle ID (ie flavor), energy and zenith bins
- We then compare the result to our expectations from standard oscillation
- Tau neutrino fraction is **fit as a statistical excess of events** in non-track events (ie we don't identify individual tau neutrino events)



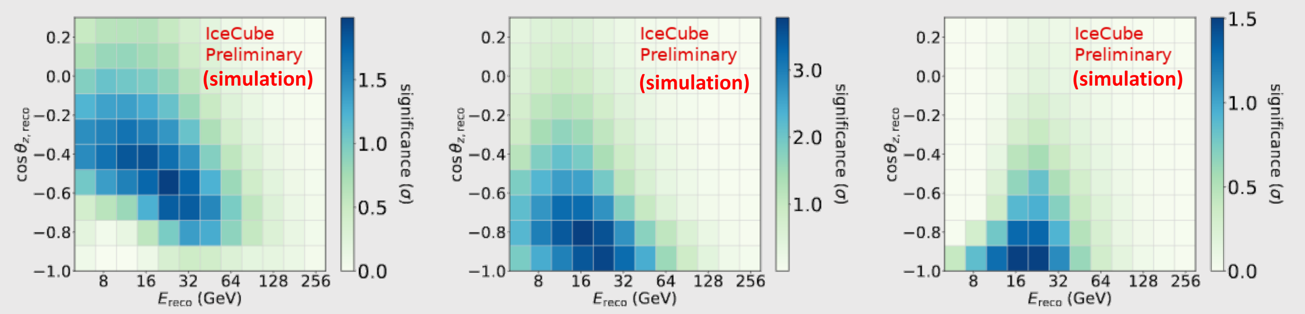
- We perform a **multi-dimensional fit of a Monte-Carlo template to our data**. The fit includes both physical (Δm^2_{32}, θ_{23}, **tau normalization** N_τ) and nuisance parameters to handle systematics.

- Ratio of a scenario with $N_\tau = 0.5$ w.r.t standard oscillation paradigm



- Significance based on likelihood Test Statistic :

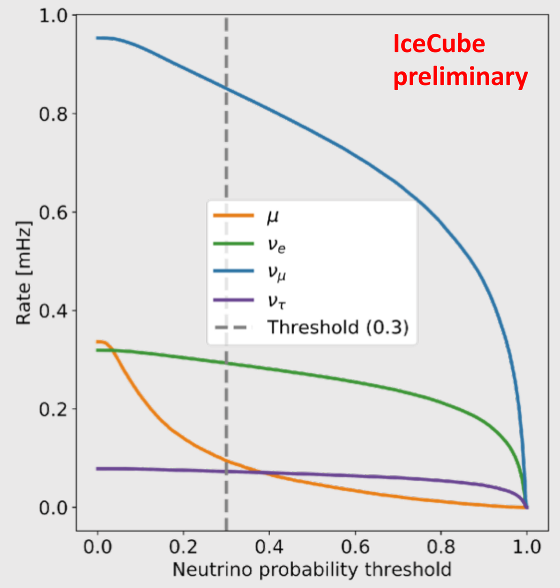
$$-2\frac{LLH_{Best-fit}}{LLH_{N_\tau=1}}$$



- Very good signal-to-background ratio in the key signal region (**low-energy** (<50 GeV), **upward-going events**)

Event Selection

- Consists of **eight years of detector data** (mid-2011 to mid-2019)
- Several cuts applied to eliminate **atmospheric muons** and **self-triggered noise** events (our main backgrounds)
- Use of **new machine-learning classifiers** (boosted decision trees) to perform final-level muon rejection + PID classification
- Yields a **large statistics sample** of neutrinos that well suited for ν_μ **disappearance** (see poster #547), or for **non-standard interactions** (see poster # 364)



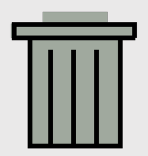
Rate of various particle types as a function of the cut applied to classifier output. Multi-variate techniques allow us to efficiently reduce the muon background while keeping most neutrinos

The Sample in Numbers

	ν_e	ν_μ	ν_τ
Final Level Rates:	0.343 mHz	1.02 mHz	0.0704 mHz
# of events:	~88000	~263000	~18000

300 000+ neutrinos with the energy range [5,300] GeV

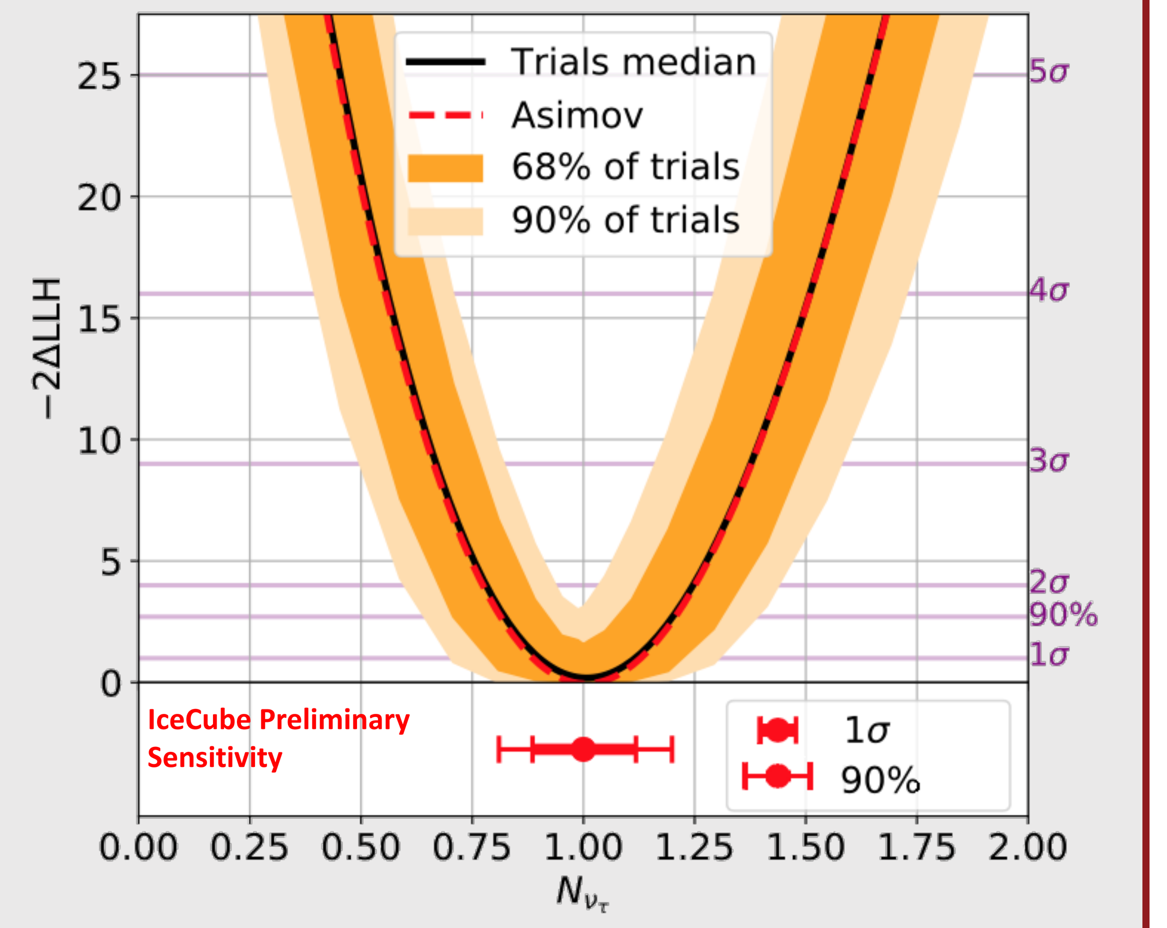
Muons: 0.0554 mHz, ~14000

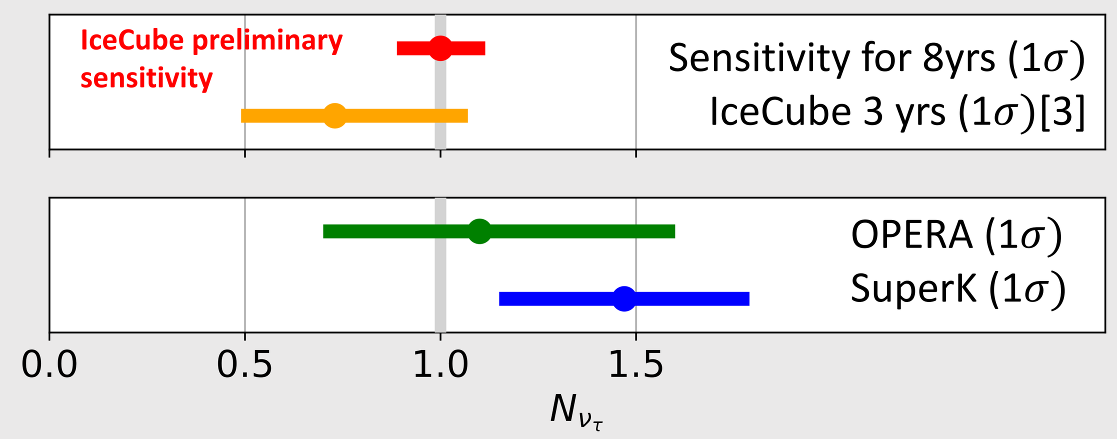


Noise: 0.0305 mHz, ~8000

Sensitivity Projections

- Right: Expected change in the measured test-statistic for a range of injected tau normalization
- In red: Variation expected from injecting the same nominal MC template (Asimov data challenge)
- In orange: Variation of the test statistic for multiple pseudo-experiments with poisson-fluctuated templates





- **Left: 68% uncertainty on the tau normalization,** compared to the previous IceCube results [3]
- **11 % precision** will make this the world-leading measurement

References

[1] S. Parke, M. Ross-Lonergan. Phys. Rev. D, 93, 113009 (2016) [arXiv:1508.05095]
[2] Aartsen et al (IceCube Collaboration). JINST 12 P03012 (2017) [arXiv: 1612.05093]
[3] Aartsen et al (IceCube Collaboration). Phys. Rev. D, 99 032007 (2019)
[4] A. Fedynitch. Matrix Cascade Equation. https://github.com/afedynitch/MCEq
[5] G.D. Barr et al. Phy. Rev. D, 74, 094009 (2006) [arXiv: astro-ph/0611266]

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