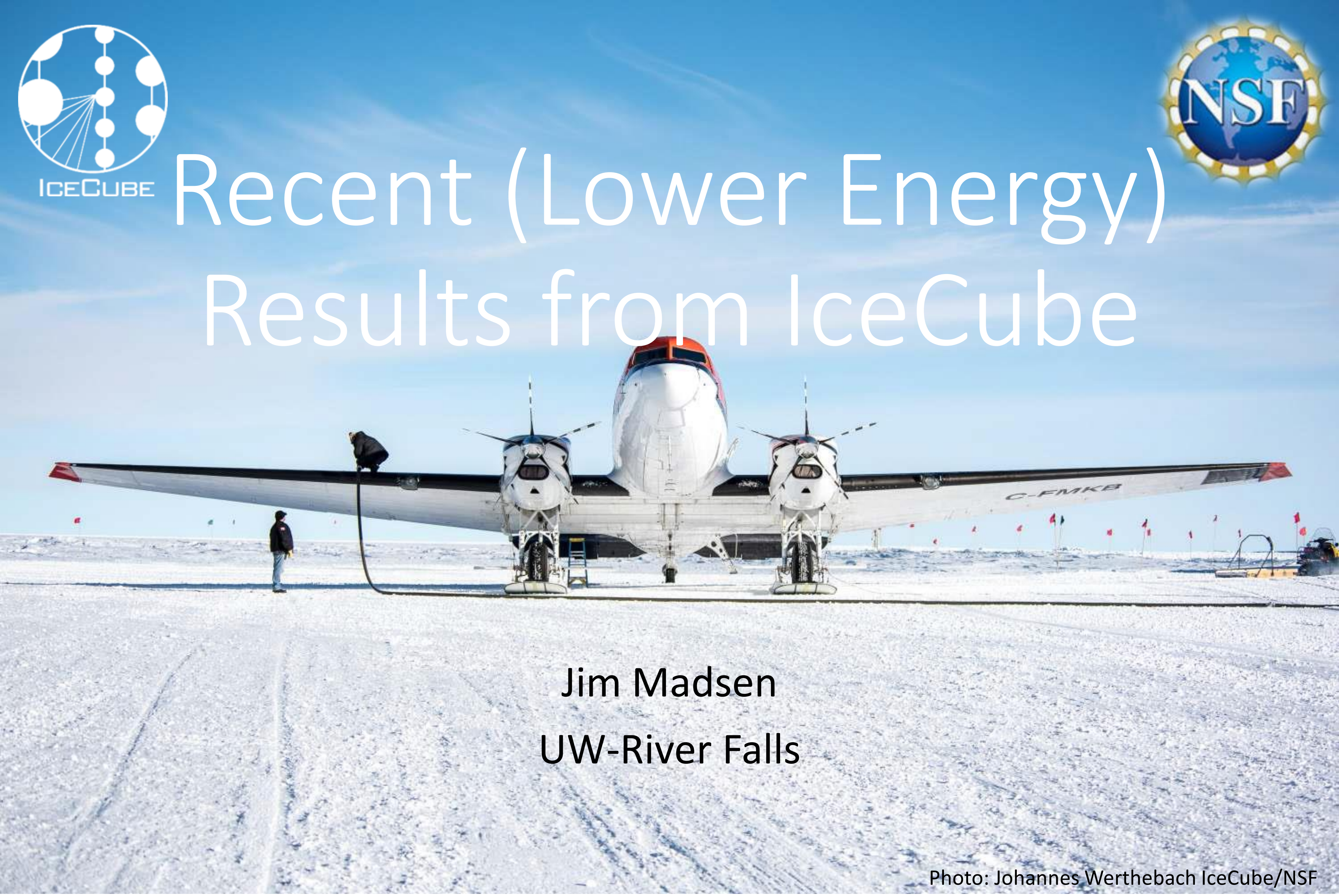
Recent (Lower Energy) Results from IceCube



Jim Madsen

UW-River Falls

Photo: Johannes Werthebach IceCube/NSF

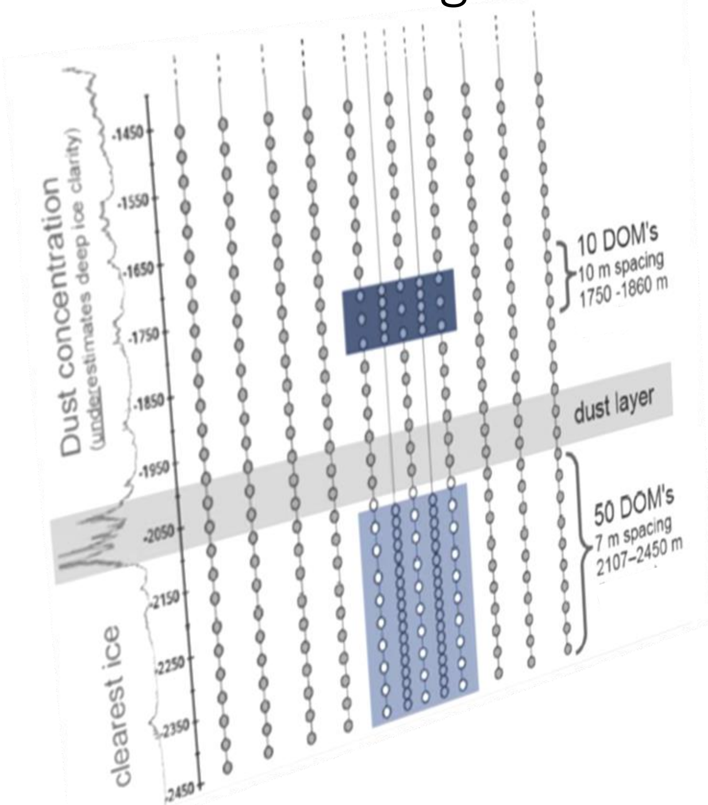
Outline

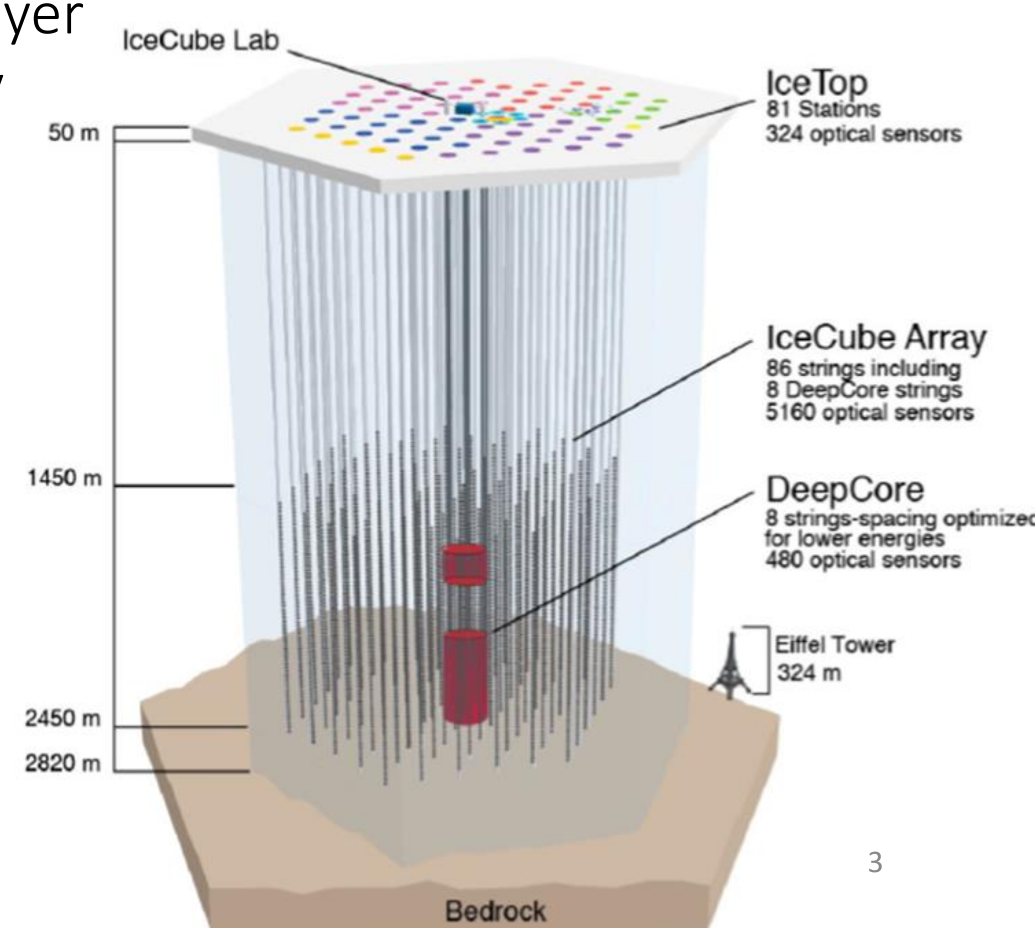
- IceCube/DeepCore
- Oscillations: Losing ν_μ and Finding ν_τ
- Sterile Neutrinos
- Nonstandard Neutrino Interactions
- Dark Matter Searches
- IceCube Upgrade
- Summary

Photo: Johannes Werthebach IceCube/NSF

IceCube DeepCore

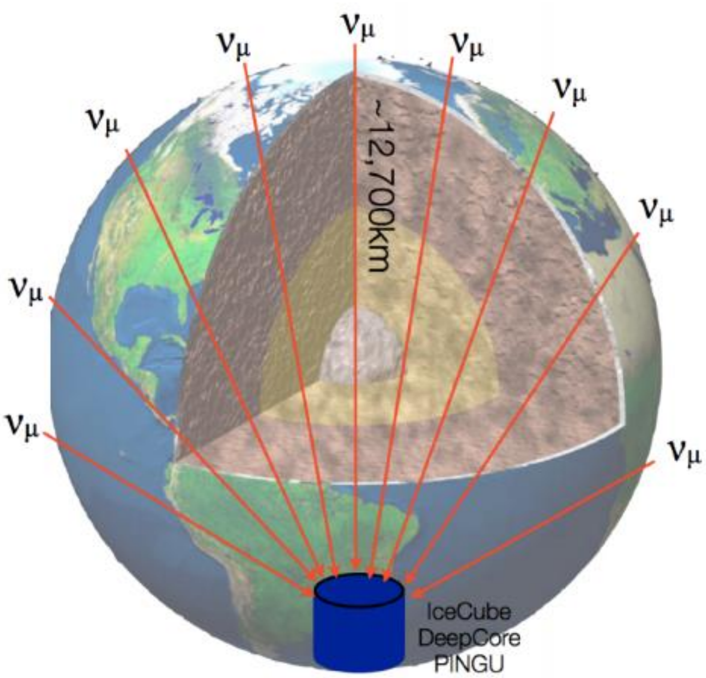
- 8 more densely spaced strings with high efficiency optical modules (DOMs)
  - Surrounded by IceCube strings (used as atm. muon veto)
  - In clearest Ice below dust layer
  - Neutrino energies > ~5 GeV

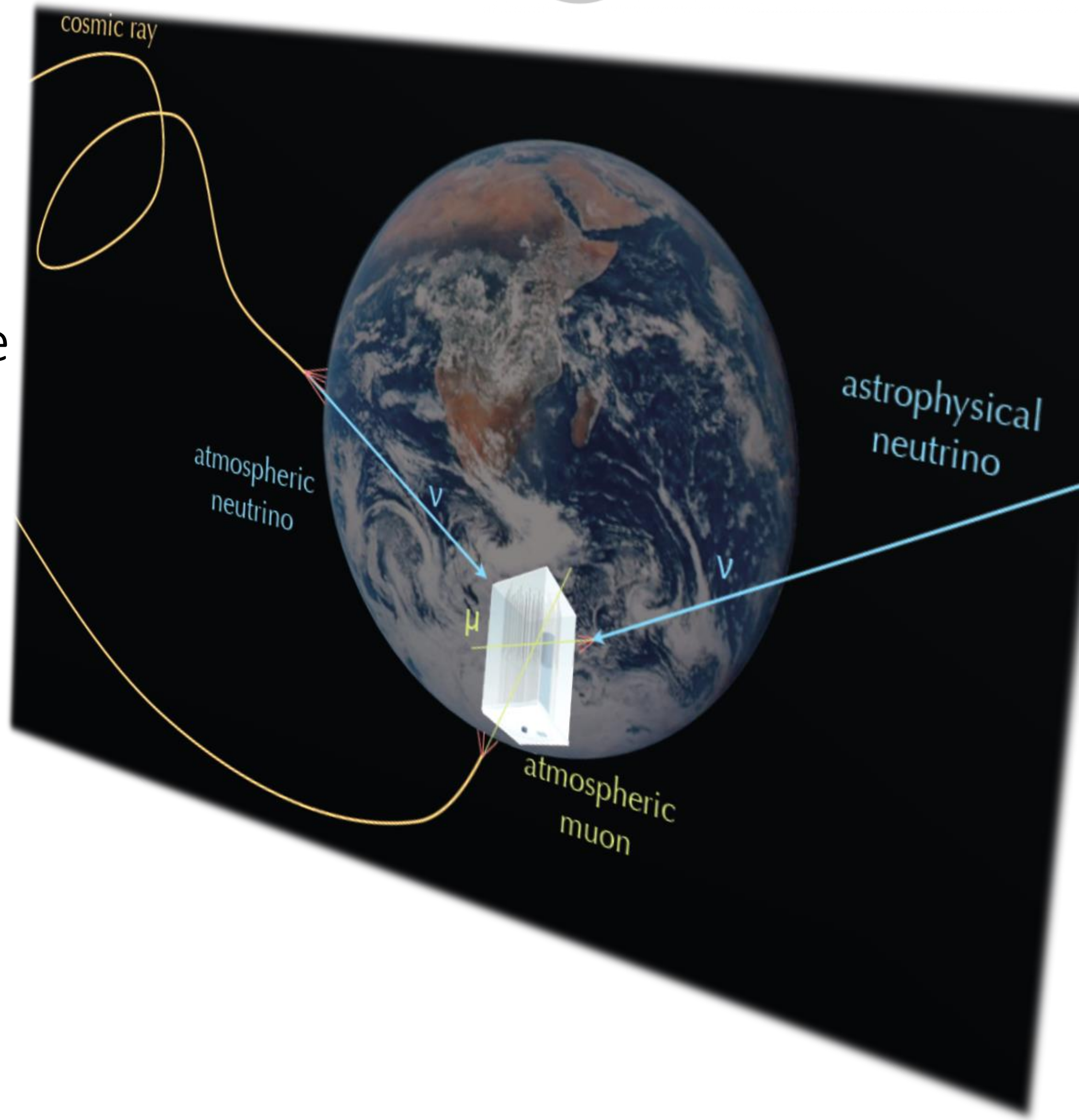




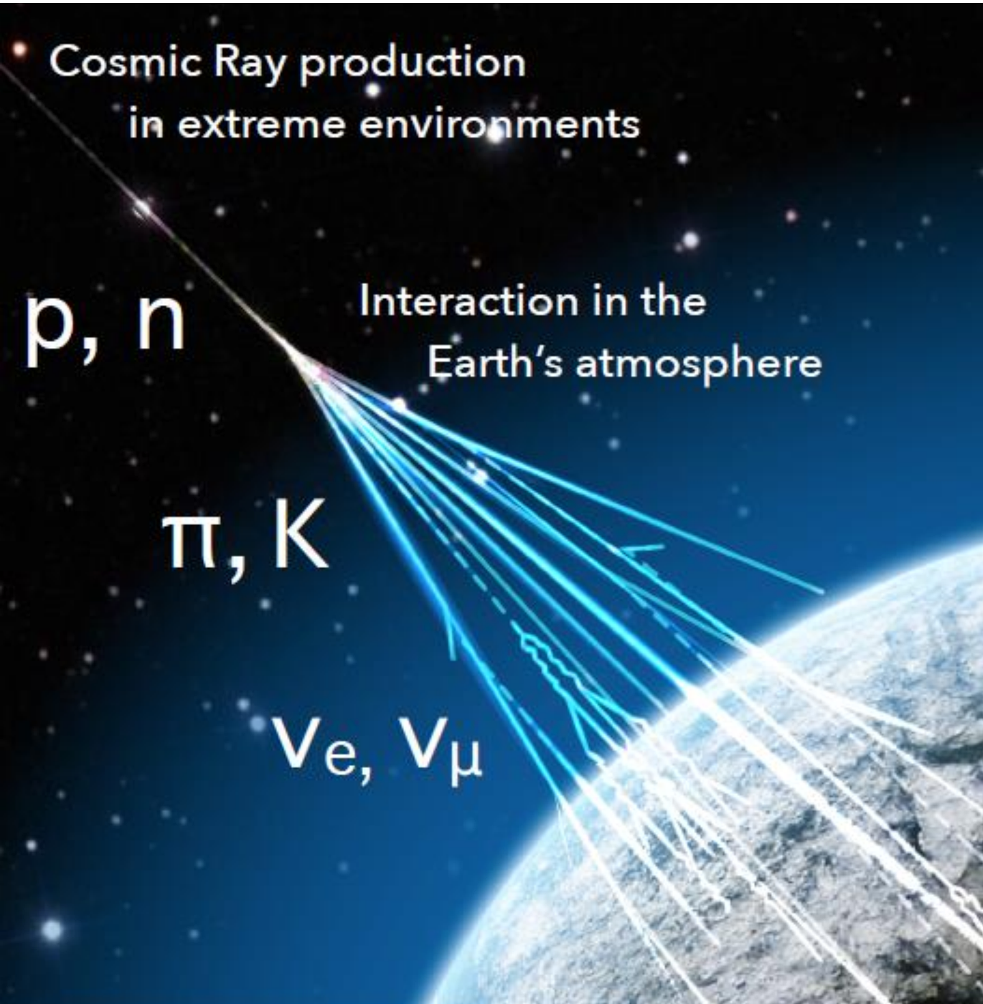
IceCube Signals

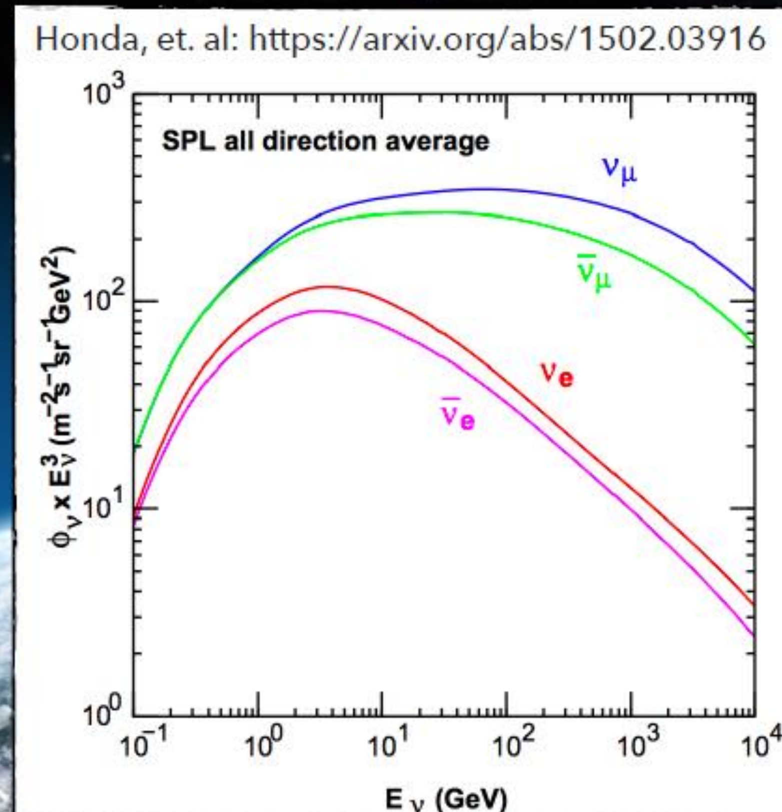
- Focus on atmospheric neutrinos
  - Cosmic Rays interact with Earth's atmosphere
  - Well known spectrum
  - ~10^5 events per year





Atmospheric Neutrinos





High statistics sample of neutrinos over large energy range and many baselines for FREE!

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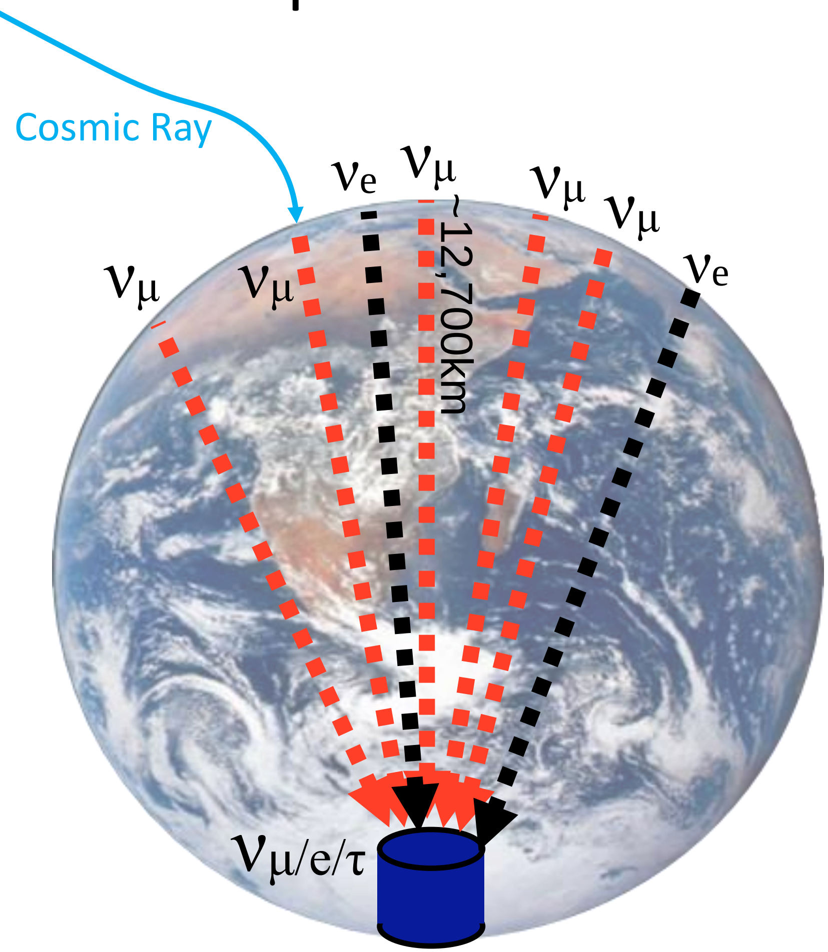
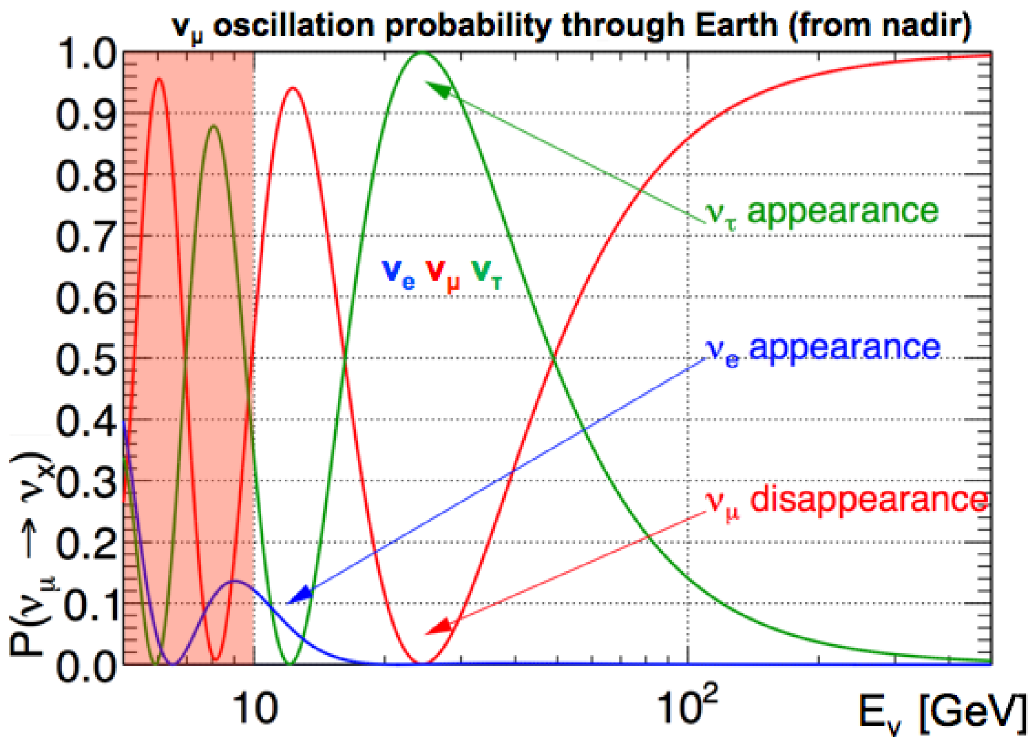
Atmospheric Neutrino Oscillation



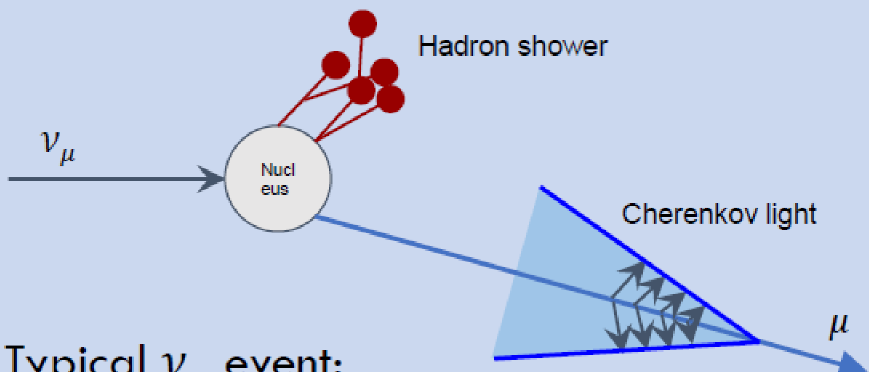


- DeepCore has a multi-megaton effective mass and probes large span of baselines and energy (L/E)

IceCube Event Signatures

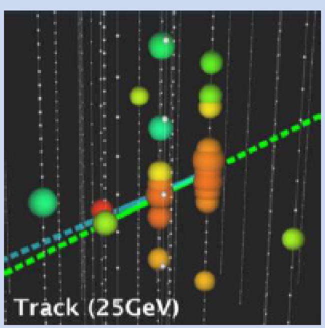
- Fully contained events inside DeepCore fiducial volume
- Reconstructed using a full Cascade + Track hypothesis
  - Position, direction, energy and PID (track or cascade like)

Track like

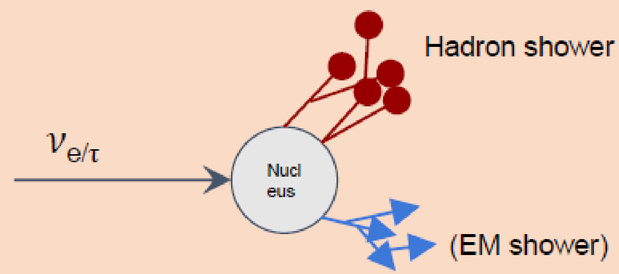


Typical ν_μ event:
Energy deposited in

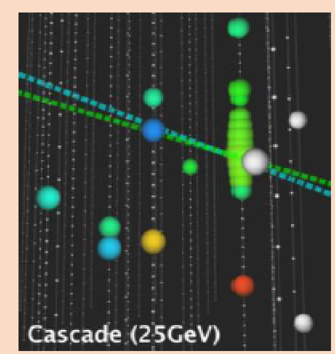
- Hadronic shower
  CC interaction
- Muon track
  (E ~ length)



Cascade like



Typical $\nu_{e/\tau}$ event:
All energy deposited in form of showers (hadronic and electro-magnetic)
Spatially more compact (no track)



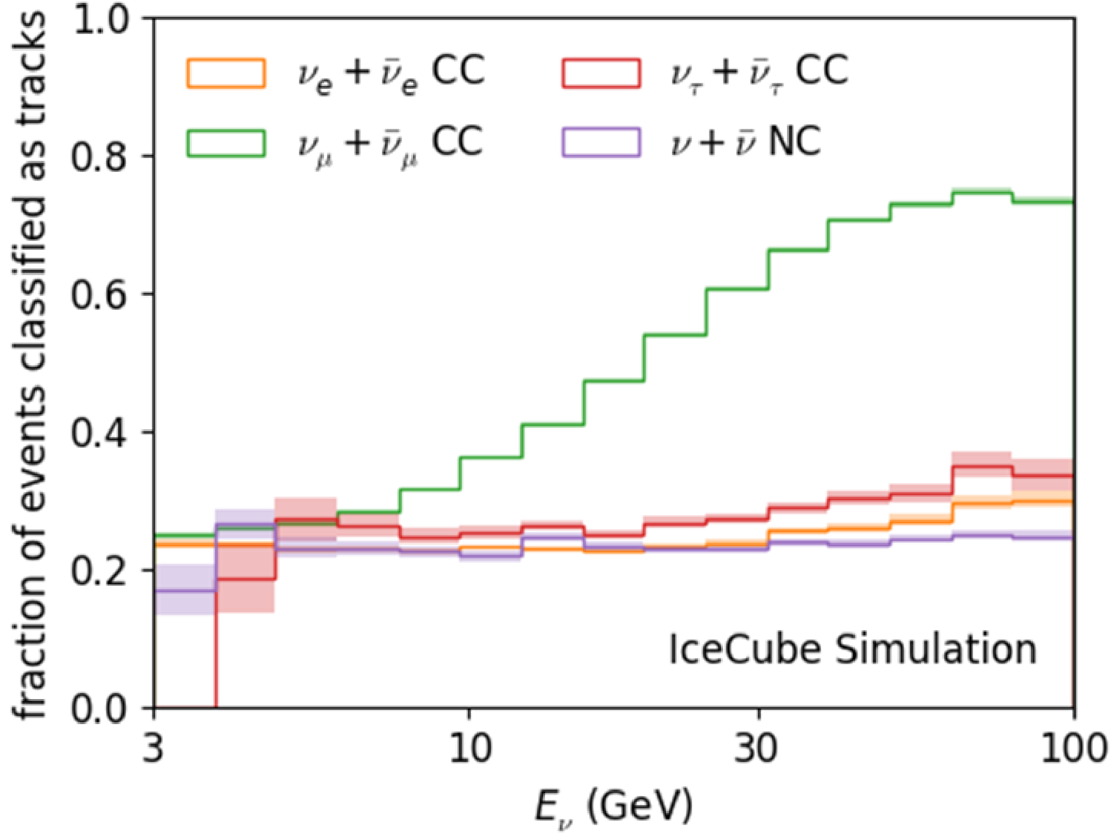
DeepCore Event

<u>9.28 GeV ν_μ:</u>

4.9 GeV muon
4.5 GeV cascade

Event Classification

- Ability to distinguish track and cascade events mainly depends on neutrino energy
  - Higher energy = longer muon tracks
- Separation based on additional reconstruction using cascade only (no track)
  - Utilizes difference in likelihood to the standard reconstruction as classifier



Measurement parameters

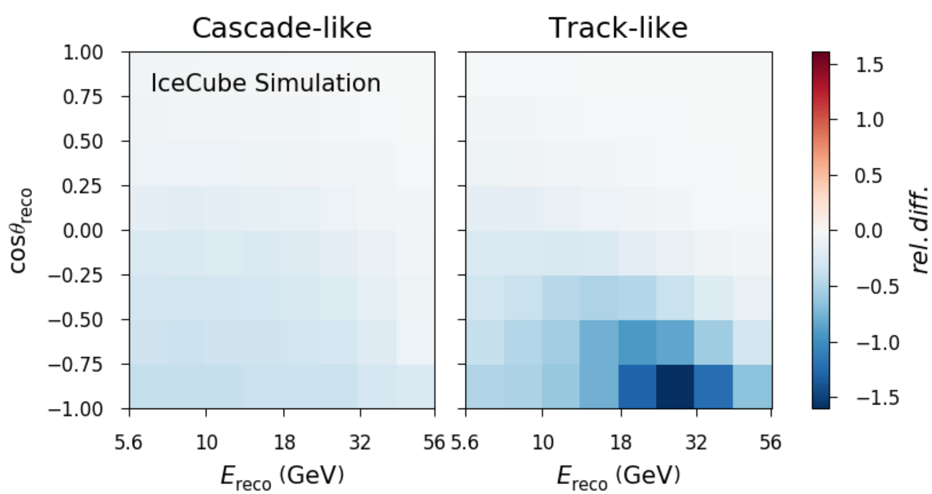
- ν_μ disappearance measurement:
  - Extracting two parameters:
    - θ_{23} : magnitude of disappearance
    - Δm^2_{31} : location of disappearance in terms of L/E

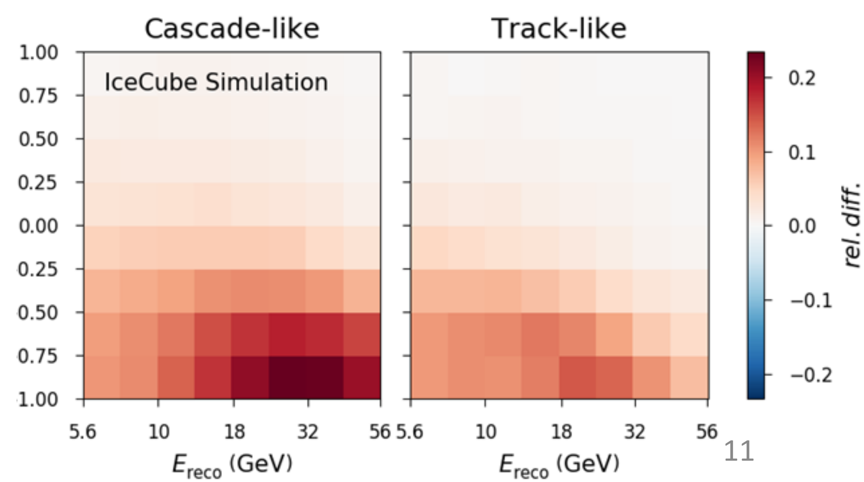
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$

- ν_τ appearance measurement:
  - same as disappearance, plus additional scale factor for tau neutrinos
    - ν_τ norm = 0: no tau neutrinos at all
    - ν_τ norm = 1: standard oscillation expectation
  - Scale factor can be applied to:
    - All ν_τ interactions (CC+NC)
    - Only (CC) ν_τ interactions (same as OPERA, Super-K)
    - We present results for both

Actual Signal

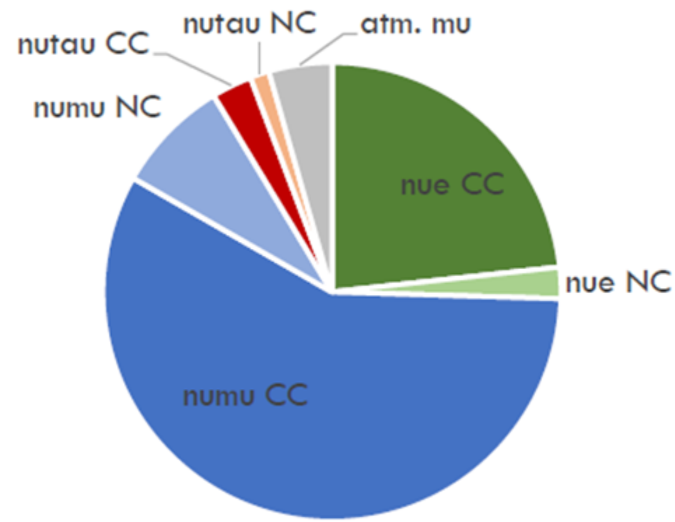
- ν_μ disappearance
  - Deficit of events compared to the no-oscillation case
  - Disappearance mostly visible in the track channel (relatively pure muon neutrino sample)
  - For upgoing events, concentrated around first oscillation maximum of ~25 GeV
- ν_τ appearance
  - Additional cascade channel events compared to no-appearance case
  - ~order of magnitude smaller effect than disappearance (due to suppressed CC cross section)
  - Slightly worse resolution for cascades than tracks





Data Set

- New DeepCore results are based on 3 years of data
  - Total of 41k events
    - 39k neutrinos (!)
    - 2k background events from atmospheric μ
  - Analysis in 8x8x2 bins:
    - Reconstructed neutrino energy (between 5.6 and 56 GeV)
    - Reconstructed zenith angle (covering the full sky from cos(zenith) -1 to +1)
    - Cascade and track-like event categories (PID)
- Median resolutions @ 20 GeV for tracks (cascades):
  - 10° (16°) zenith angle
  - 24% (29%) in energy



Type	Events	$\pm 1\sigma$
$\nu_e + \bar{\nu}_e$ CC	9530	24
$\nu_e + \bar{\nu}_e$ NC	904	9
$\nu_\mu + \bar{\nu}_\mu$ CC	23673	39
$\nu_\mu + \bar{\nu}_\mu$ NC	3313	17
$\nu_\tau + \bar{\nu}_\tau$ CC	1171	7
$\nu_\tau + \bar{\nu}_\tau$ NC	550	6
atmospheric μ	1821	44
total expected (best fit)	**40962**	**67**
observed	**40902**	**202**

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Systematic Uncertainties (ν_μ disappearance)

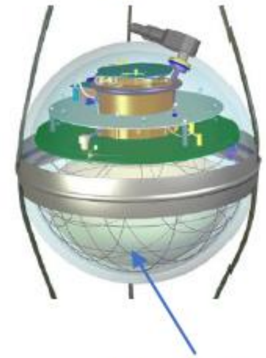
- Incorporating a variety of nuisance parameters in the measurement
- Covering uncertainties of:
    - Initial atmospheric neutrino flux
    - Interaction (cross sections)
    - Oscillation parameters
    - Detector uncertainties (efficiencies of optical modules and ice uncertainties)
    - Atmospheric muon background

Parameter	Prior	Best fit (CC+NC)	Best fit (CC)
Flux and cross sections			
ν_e/ν_μ-ratio	1.0 ± 0.05	1.03	1.03
ν_e up/hor-ratio (σ)	0.0 ± 1.0	-0.27	-0.27
$\nu/\bar{\nu}$-ratio (σ)	0.0 ± 1.0	-0.13	-0.09
$\Delta\gamma$ (spectral index)	0.0 ± 0.1	-0.050	-0.047
effective lifetime (y)	-	2.43	2.43
M_A (quasi-elastic) (GeV)	$0.99^{+0.248}_{-0.149}$	0.87	0.87
M_A (resonance) (GeV)	1.12 ± 0.22	0.84	0.84
ν NC Normalization	1.0 ± 0.2	1.23	1.25
Oscillation			
θ_{13} (°)	8.5 ± 0.21	8.5	8.5
θ_{23} (°)	-	45.9	45.9
Δm^2_{32} (10^{-3}eV^2)	-	2.33	2.34
Detector			
optical eff., overall (%)	100 ± 10	106	106
optical eff., lateral (σ)	0.0 ± 1.0	-0.38	0.40
optical eff., head-on (a.u.)	-	-1.30	-1.29
local ice model	-	-0.09	-0.03
Background			
Atm. μ fraction (%)	-	4.8	4.8
Measurement			
ν_τ appearance rate	-	0.75	0.62

Sensor Optical Efficiency

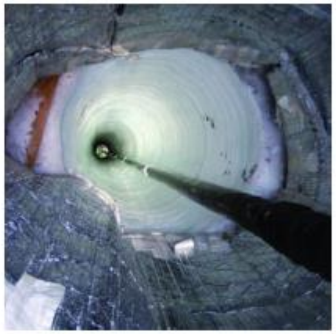
- Look closer at one of the most important sources of systematic uncertainty
  - Optical efficiency and angular acceptance of bare sensor modules known from lab measurements
  - After deployment in the ice and refreezing, zones of enhanced scattering (air bubbles) formed in ice
    - Causes an effective change in detection efficiency and acceptance
    - Effect studied with calibration LEDs and other methods
  - Multiple nuisance parameters allow for changes in the acceptance for our measurements

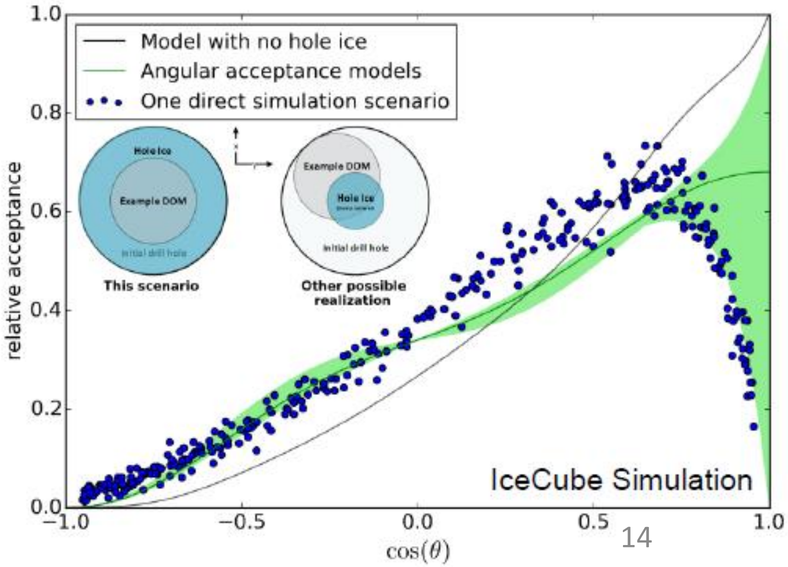
Digital Optical Module



Downward facing PMT

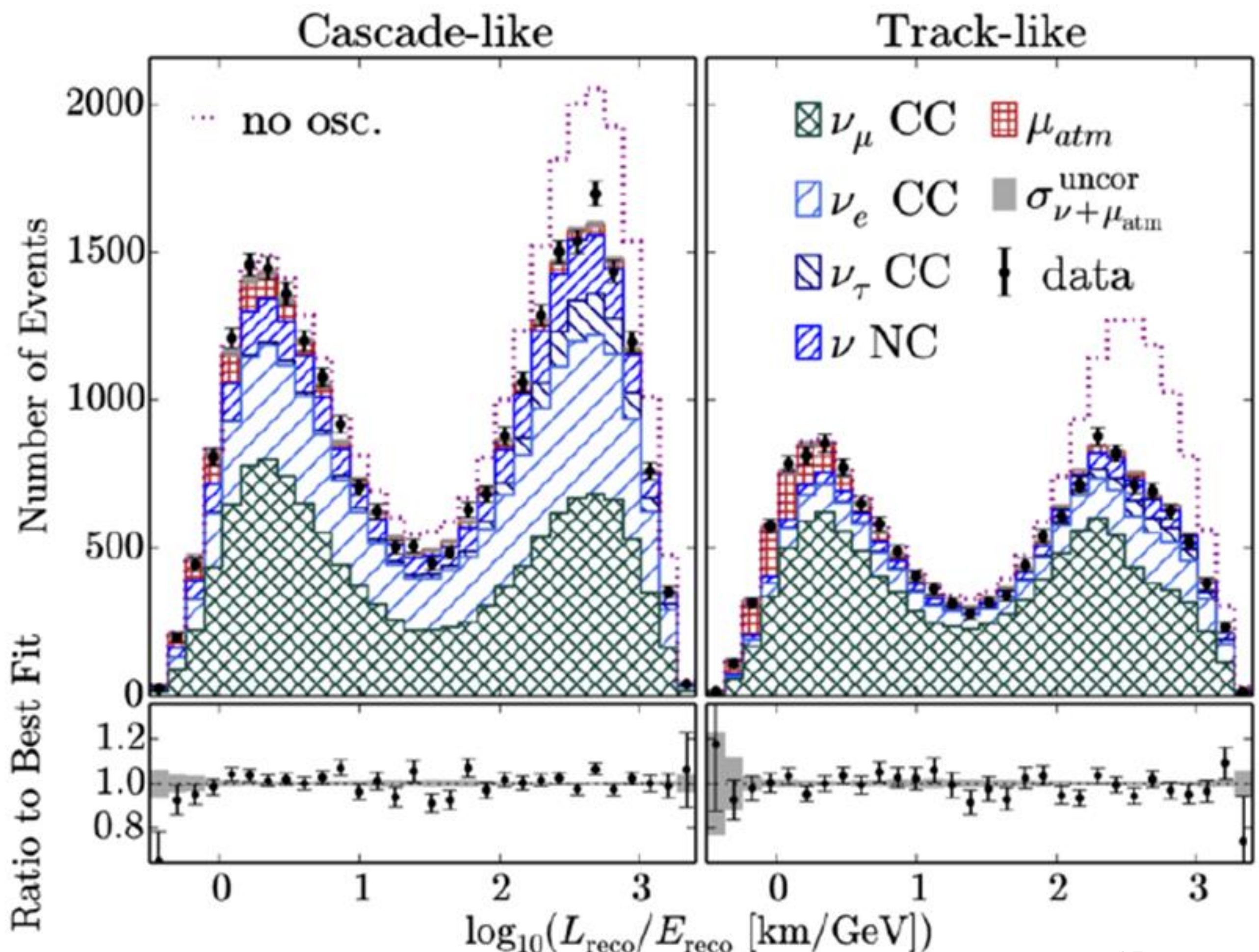
Borehole in the ice





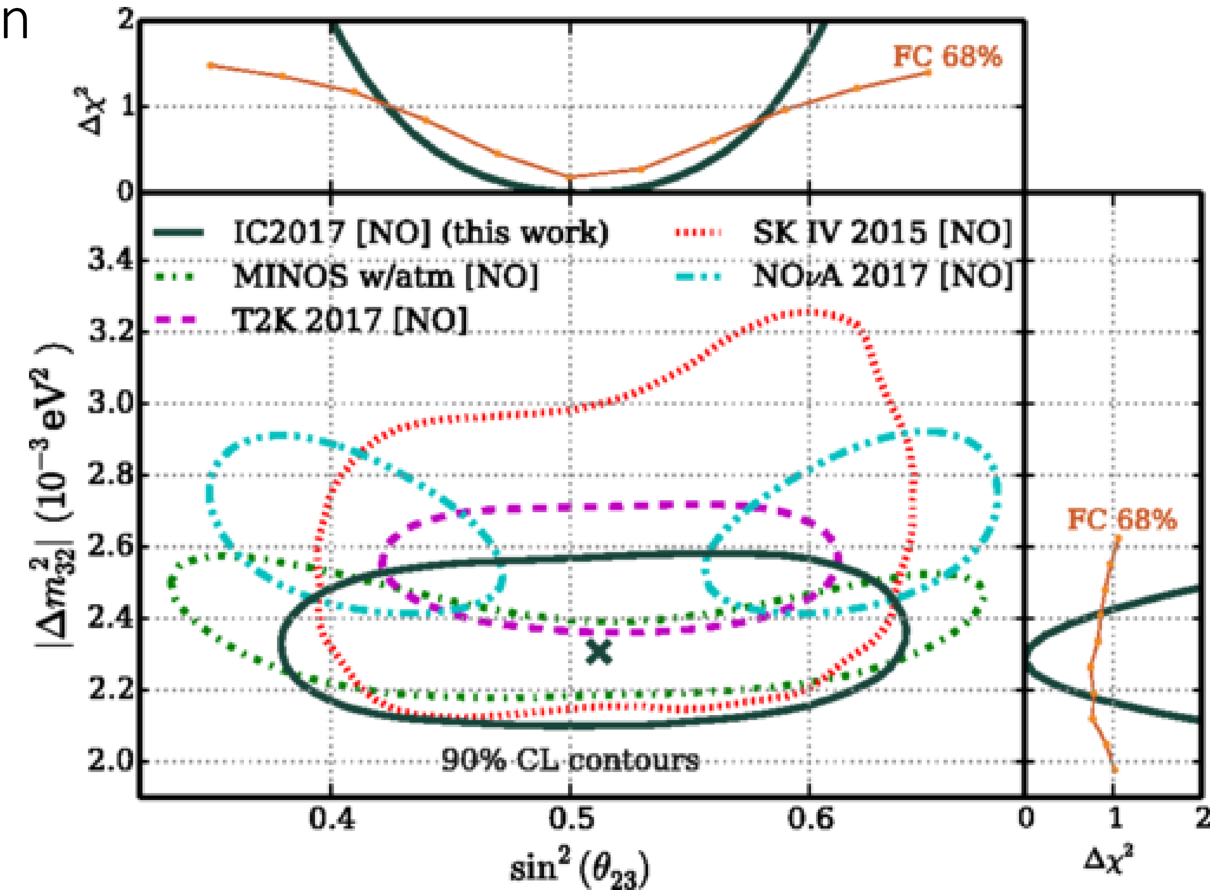
Event Distribution

- Projection of events onto the L/E axis
  - Peaks in events:
    - Down-going (left)
    - Up-going (right) are Earth crossing
  - Oscillation is clearly visible
  - Good data/MC agreement



ν_μ Disappearance Result

- Best-fit point preferring maximum mixing at
  - $\sin^2\theta_{23} = 0.51\ (+0.07, -0.09)$
  - $(\Delta m_{32})^2 = 2.31\ (+0.11, -0.13) \times 10^{-3}\ \mathrm{eV}^2$
  - Competitive precision with long baseline experiments

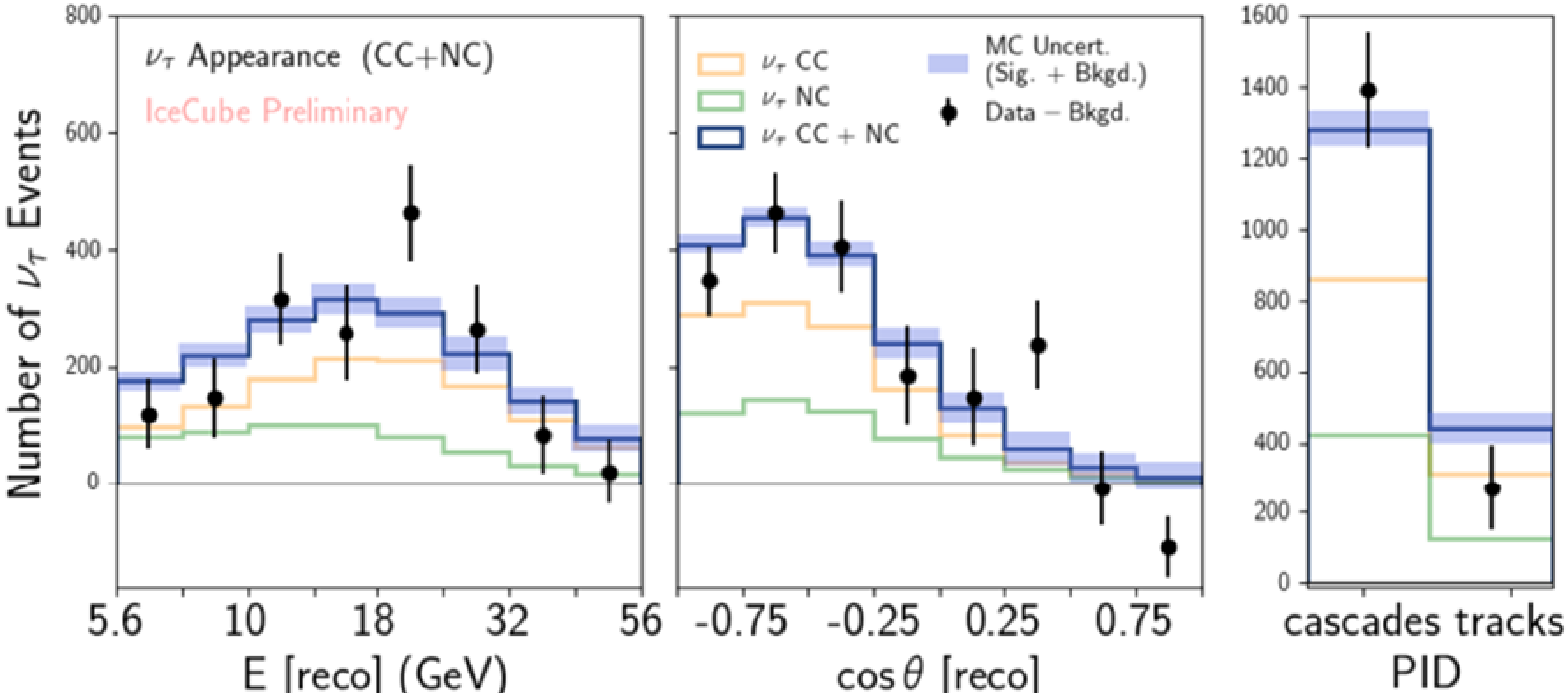


arxiv.org/abs/1707.07081

M. G. Aartsen et al. (IceCube Collaboration), Phys. Rev. Lett. 120, 071801 (2018)

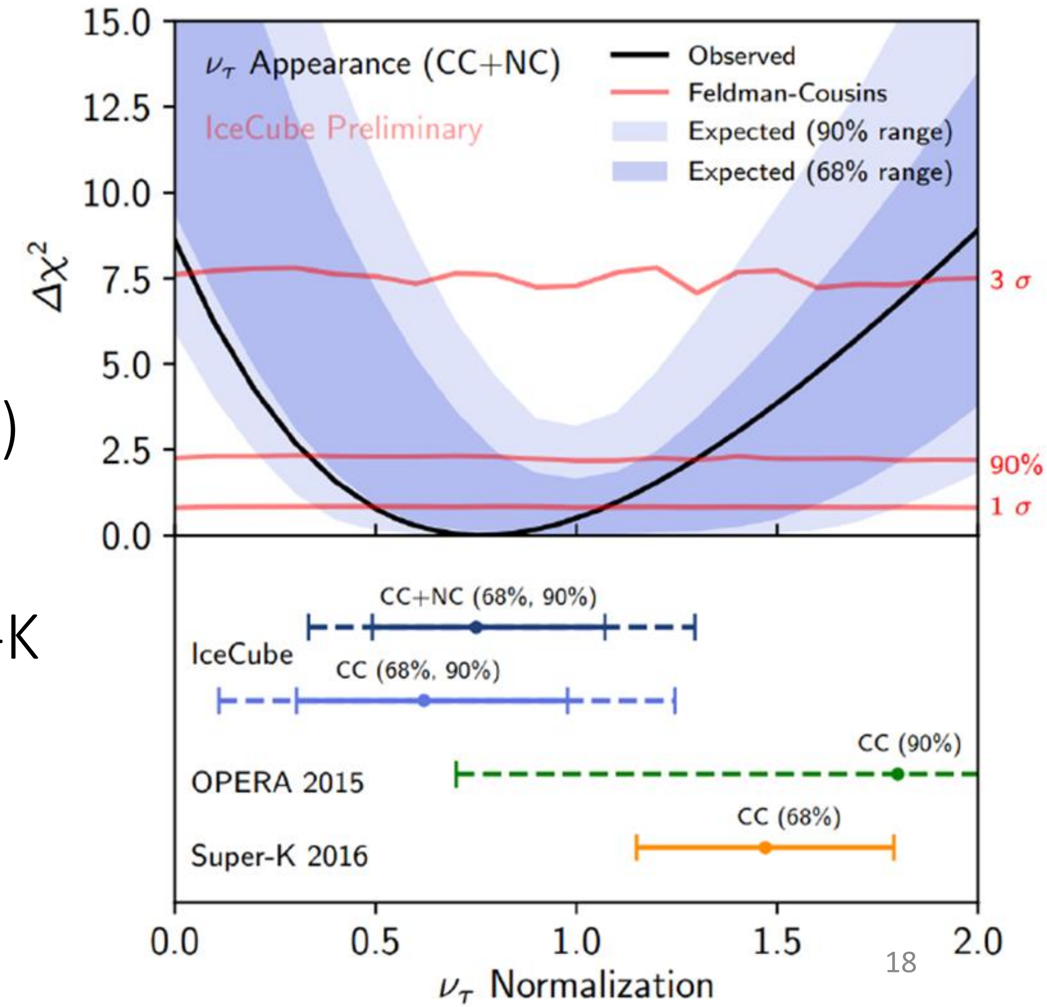
ν_τ Distributions

- Visible energies distributed around ~15 GeV,
  - Higher energy regime than the Super-K ν_τ analysis
  - ν_τ events appearing in upgoing (-1,0) (earth crossing trajectories)
  - Mostly classified as cascade PID
- Background subtracted data with best-fit ν_τ expectations



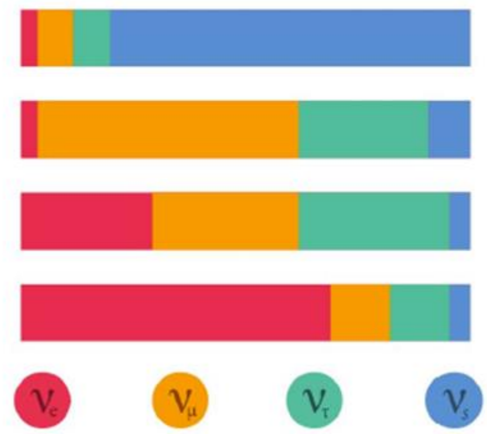
Preliminary ν_τ Appearance Result

- ν_τ normalization (with 68% C.I.)
  - CC+NC: 0.75 (+ 0.32, -0.26)
  - CC-only: 0.62 (+ 0.36, -0.31)
- ν_τ appearance significance (exclusion of no-appearance)
  - -CC+NC: 3.2 σ
  - -CC-only: 2.1 σ
- Precision on-par with Super-K



Sterile Neutrinos

- Are there only 3 neutrino mass states?
  - From Z decay width (LEP), only 3 active neutrinos
  - Additional states cannot couple to weak interaction, i.e. sterile
  - Massive sterile neutrinos can still oscillate with active states
- Additional (~eV scale) mass state could explain anomalies
  - short baseline (LSND/MiniBooNE)
  - reactor anti-neutrino flux
  - gallium
- IceCube DeepCore sensitive to $U_{\mu 4}$ and $U_{\tau 4}$ mixing elements



PMNS 3x3

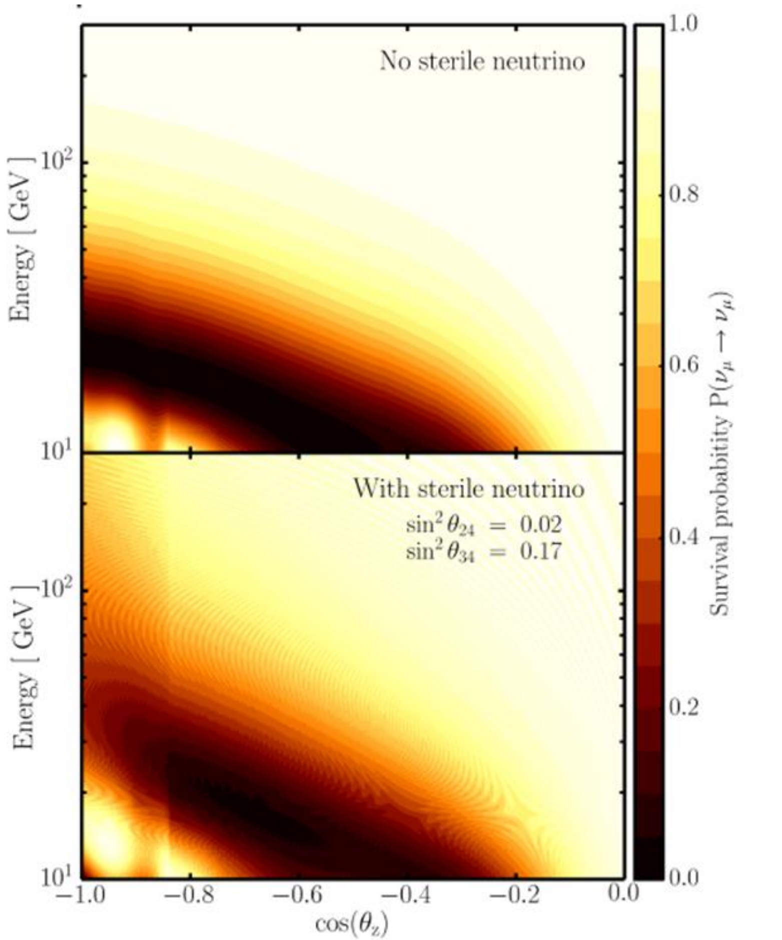
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2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

Conservative assumption: $\delta_{CP} = 0, \quad \theta_{14} = 0$

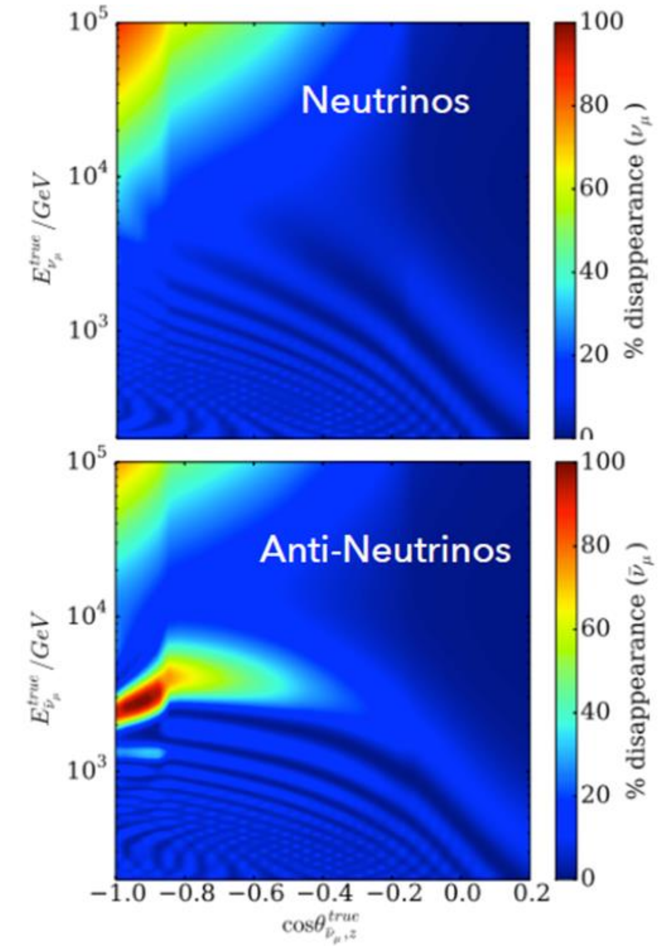
$$|U_{\mu 4}|^2 = \sin^2\theta_{24}$$
$$|U_{\tau 4}|^2 = \sin^2\theta_{34} \cdot \cos^2\theta_{24}$$

IceCube/DeepCore Sterile Neutrino Search

- For E_ν~10-100 GeV, smaller effective matter potential leads to less disappearance, and/or shift in minimum
- Independent of $(\Delta m_{41})^2$ for values > 0.3 eV^2

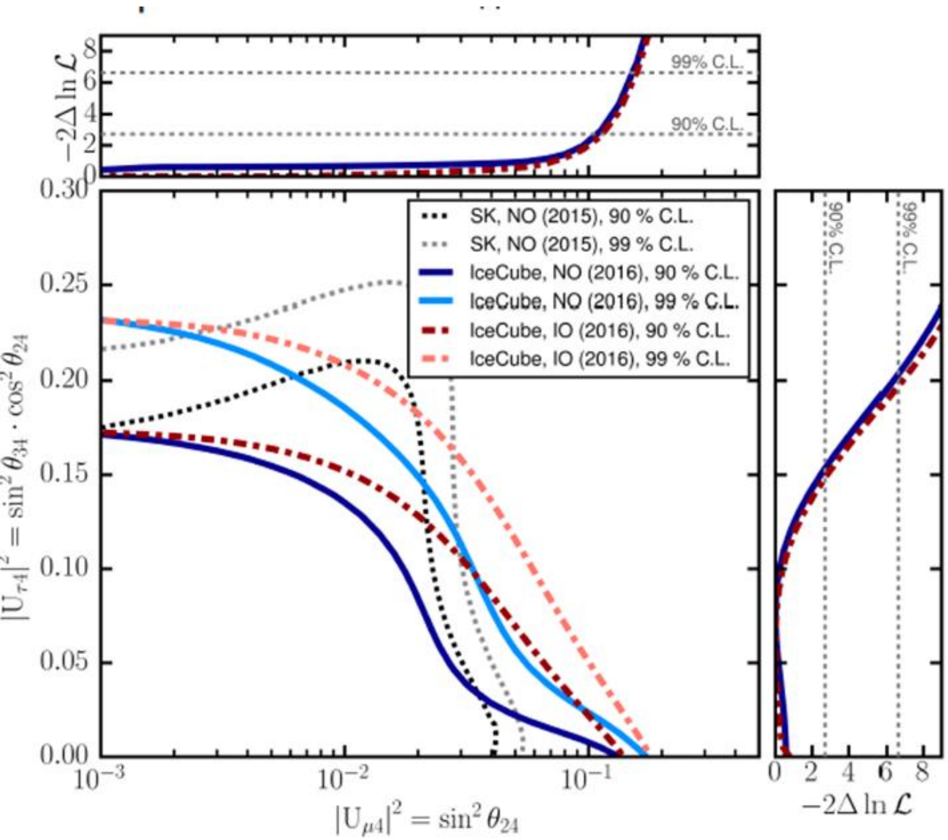


- For E_ν >100 GeV, matter potential leads to resonant enhancement of oscillations for antineutrinos
- Position of resonance proportional to $(\Delta m_{41})^2$



IceCube/DeepCore Sterile Neutrino Results

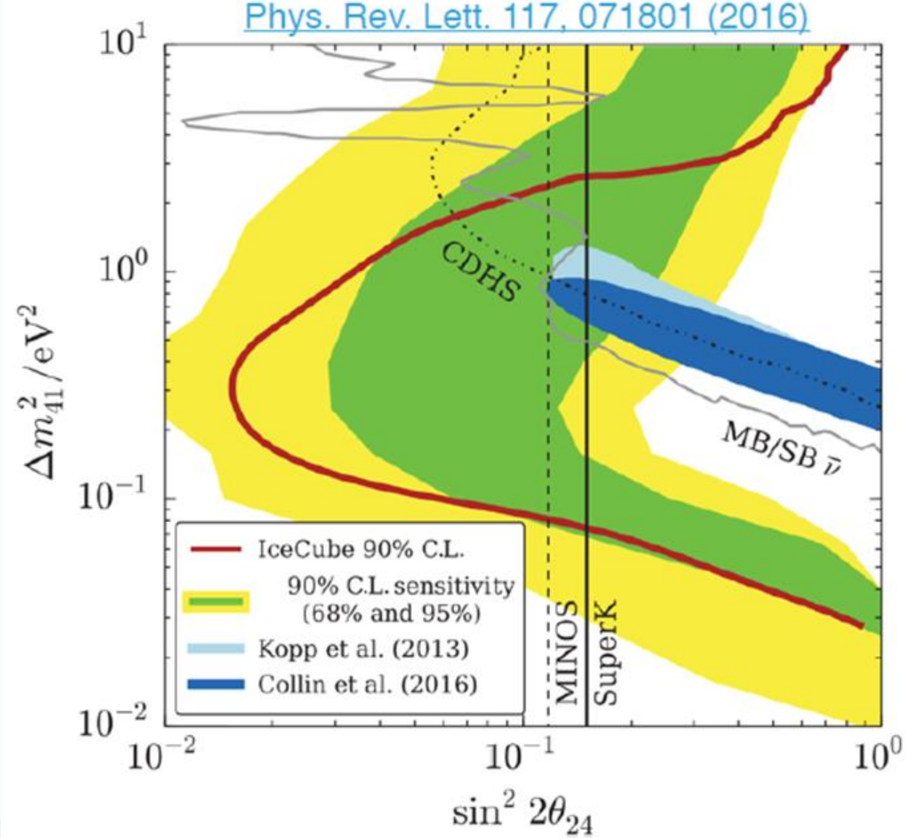
- E_ν ~10 - 100 GeV
- E_ν > 100 GeV



3 years of data, only up-going track-like events

Phys. Rev. D 95, 112002 (2017) arXiv:1702.05160

Phys. Rev. Lett. 117, 071801 (2016)



Only 1 year of data used

https://arxiv.org/abs/1605.01990

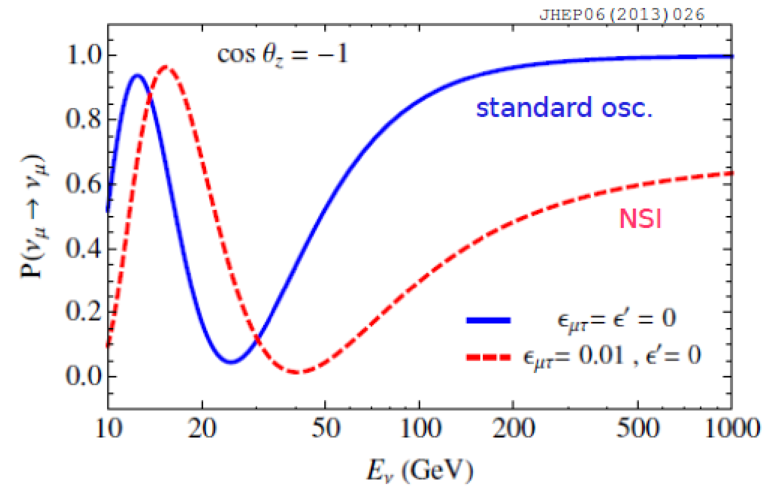
Nonstandard Neutrino Interactions

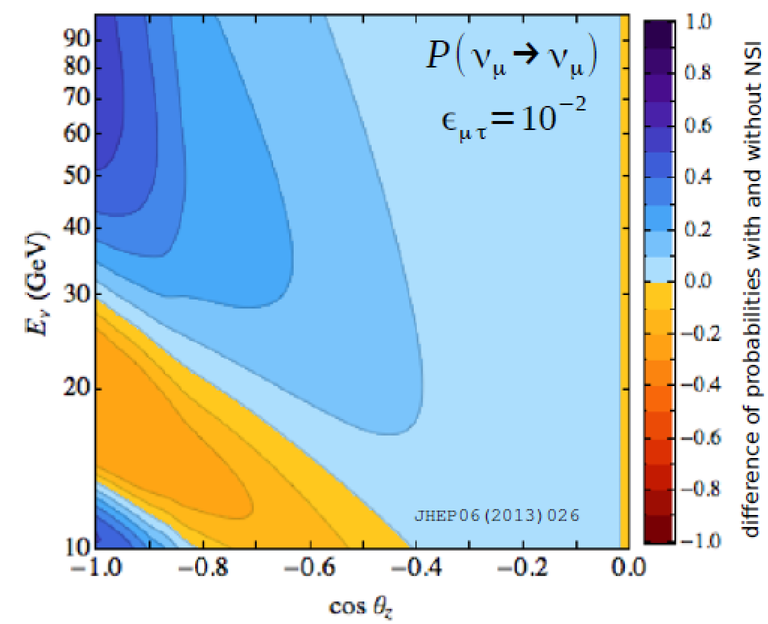
- Additional disappearance effect to MSW
- Mediated by non-SM bosons.

$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} (U^\dagger)_{k\beta} + V_{\mathrm{MSW}} + \sqrt{2} G_F N_f \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

standard MSW NSI

- → 9 additional "interaction terms"
- (6, if requirements of hermicity and unitarity are imposed)
- Modify the rate of neutrinos detected at different energies and angles
- Effect proportional to L*E





Nonstandard Neutrino Interactions Results

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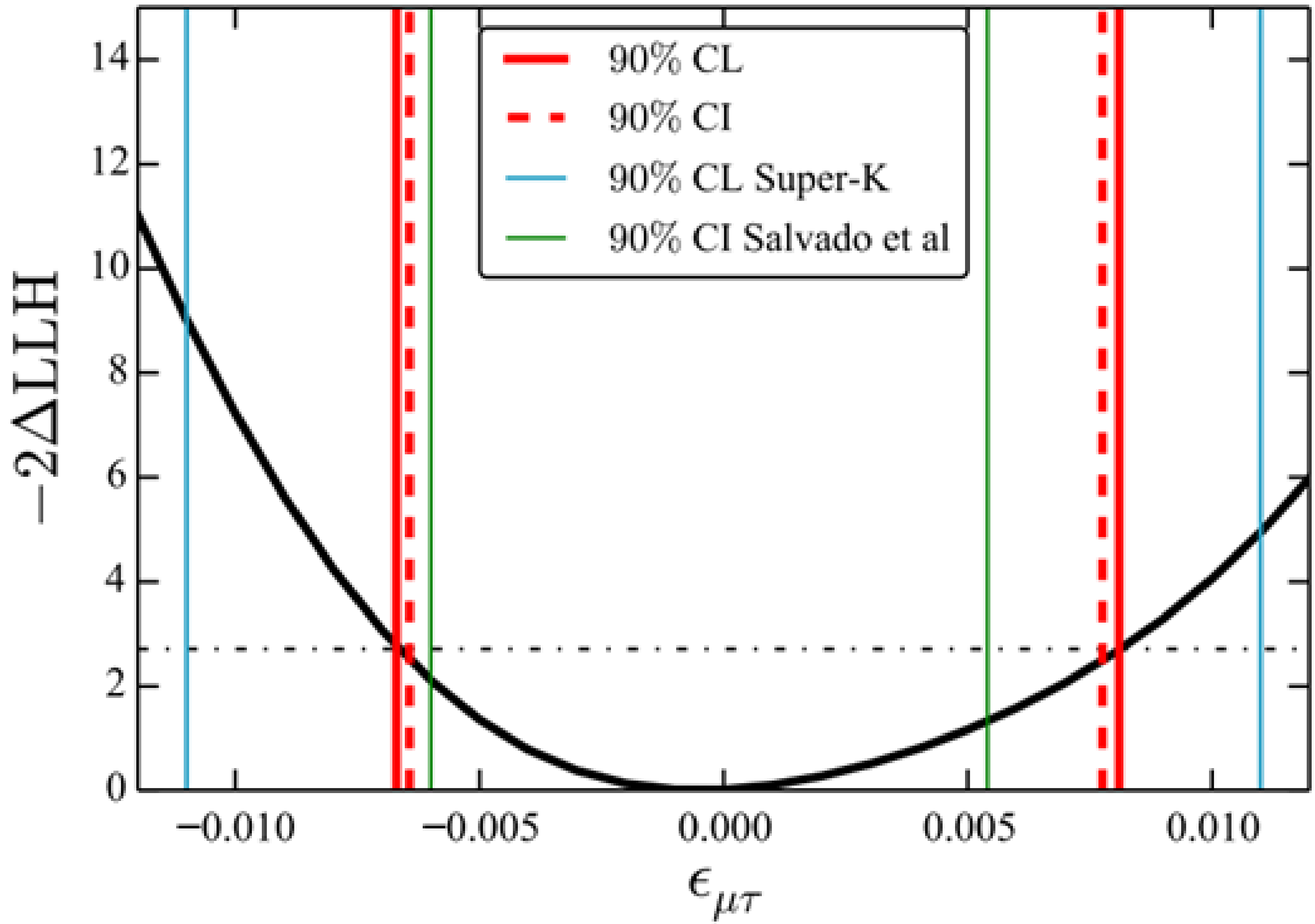
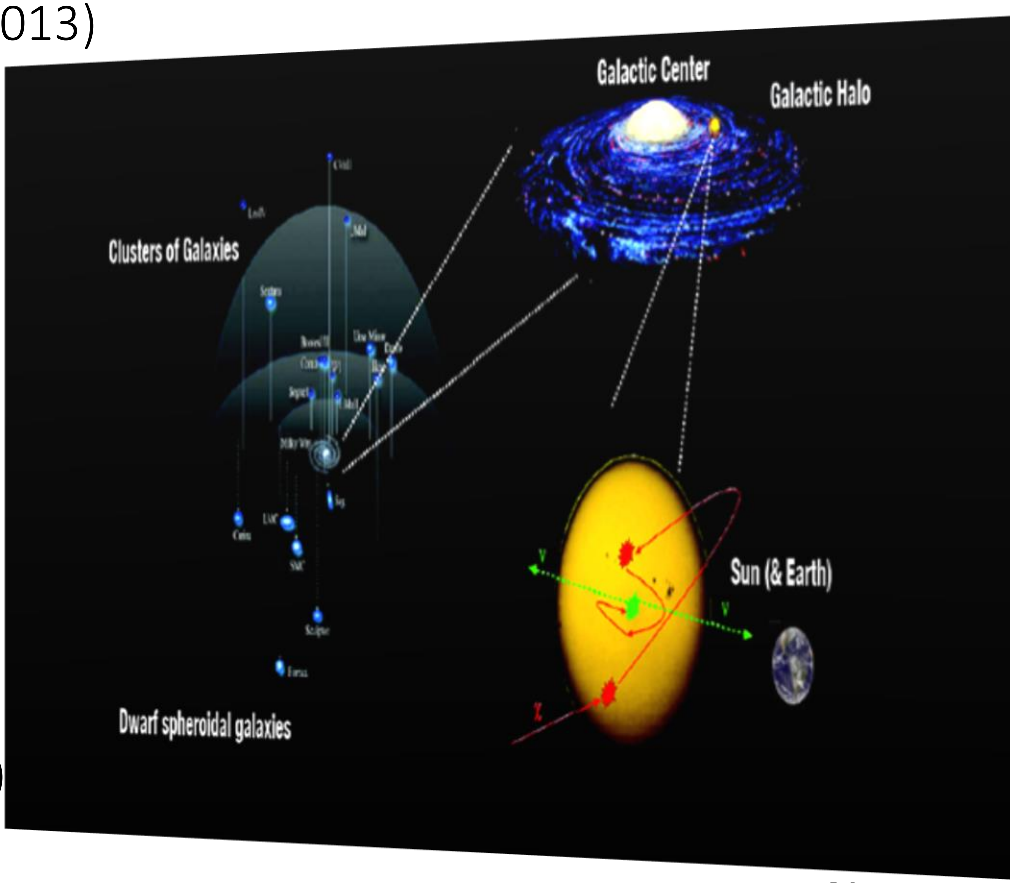
https://arxiv.org/abs/1709.07079



IceCube/DeepCore Low-Energy Dark Matter Searches

- Look for extra neutrinos from the
  - Sun:
    - Phys. Rev. Lett. 110, 131302 (2013)
    - Eur. Phys. J. C77, 146 (2017)
  - Earth:
    - Eur. Phys. J. C77, 82 (2017)
  - Galactic Center:
    - Eur. Phys. J. C75. 492 (2015)
    - Eur. Phys. J. C76. 531 (2016)
    - arXiv:1705.08103
  - Galactic Halo:
    - Eur. Phys. J. C75. 20 (2015)
  - Dwarf galaxies
    - Phys. Rev. D88, 122001 (2013)



Solar Dark Matter Summary

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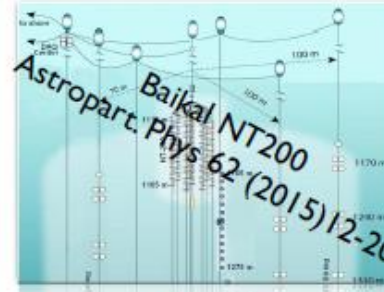
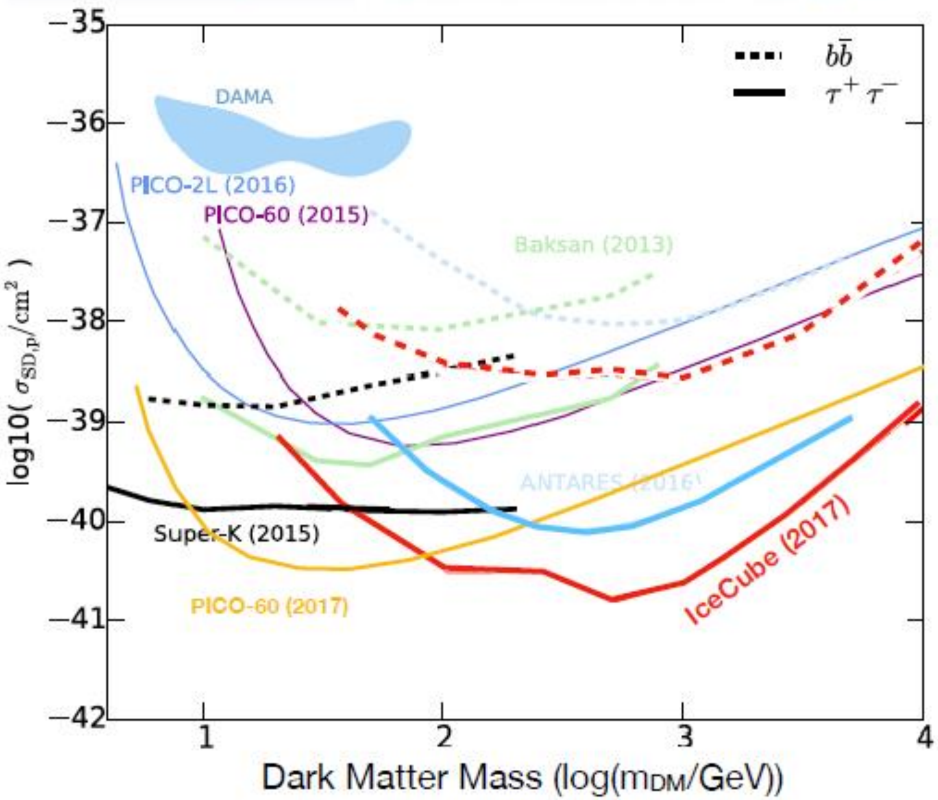
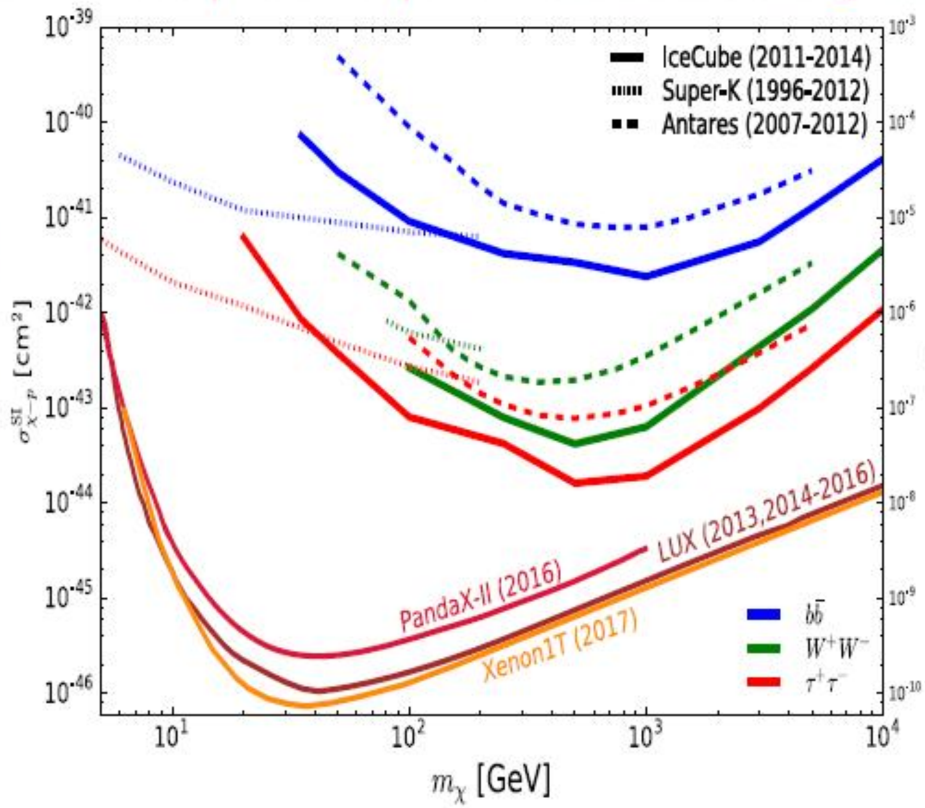


Spin-dependent scattering

Spin-independent scattering



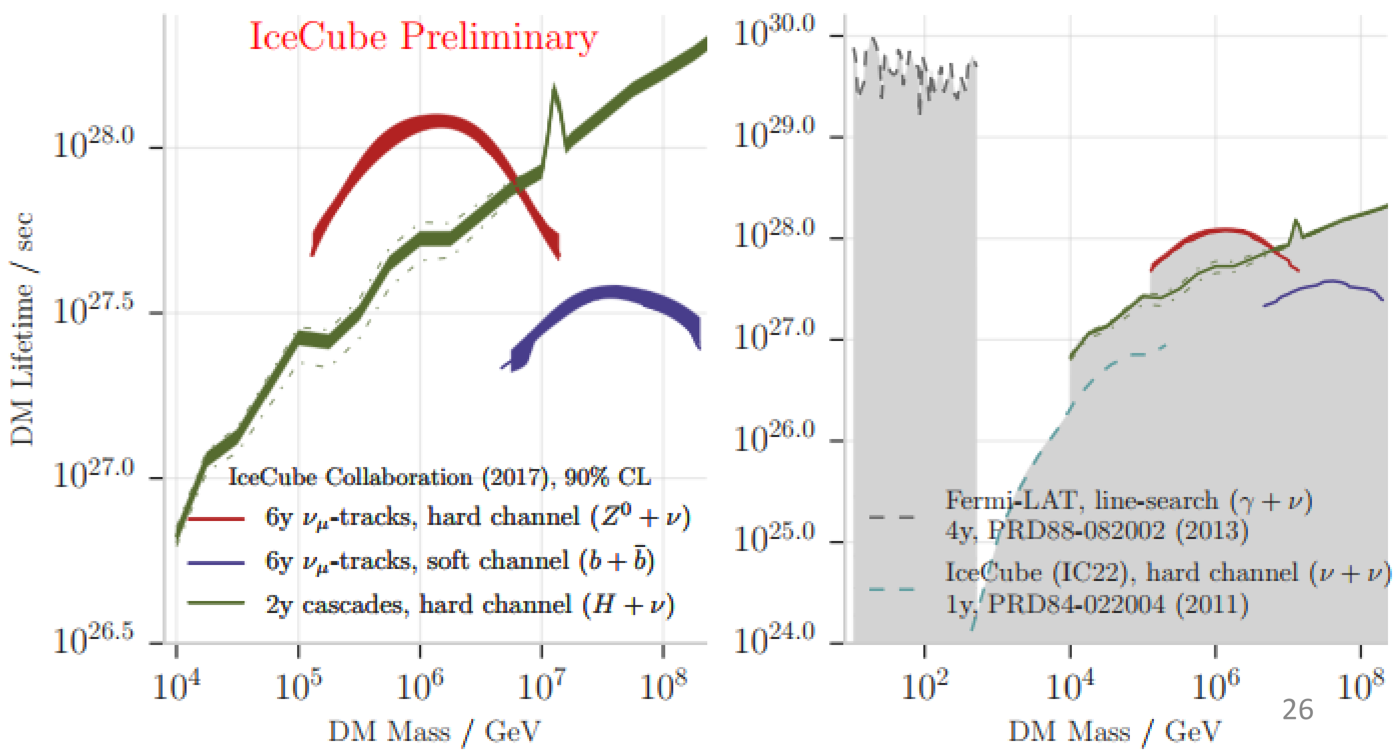


Provided by Carsten Rott

Heavy Dark Matter Decay Searches

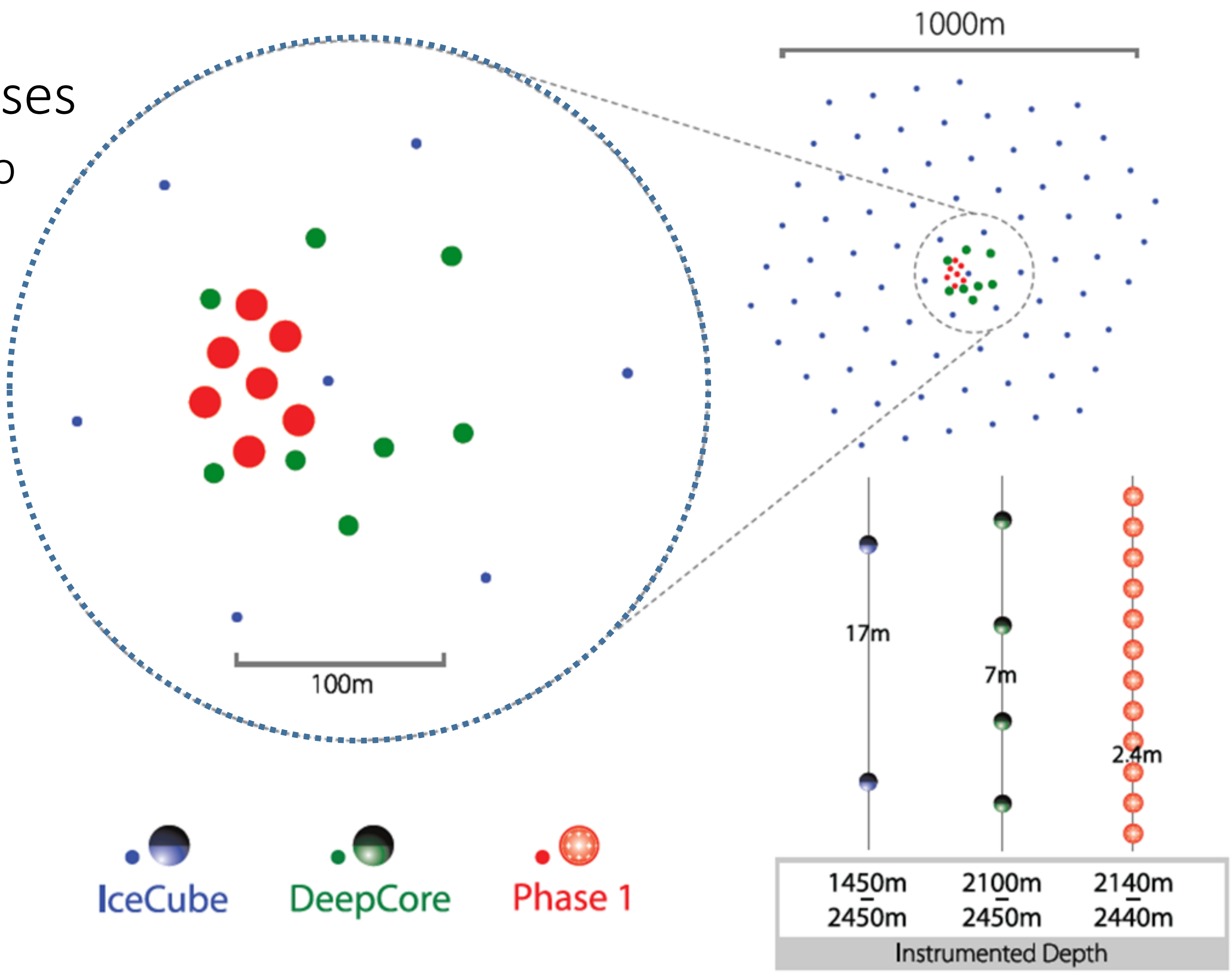
https://pos.sissa.it/301/923/pdf

- Look for neutrino flux in addition to atmospheric and diffuse astrophysical
- Distinguished by its distinctive features in the energy spectrum
  - Cut-off at half the mass of the DM-particle
  - Asymmetry of the arrival directions due to the DM halo of our galaxy



IceCube Upgrade (Proposed)

- Three primary purposes
  - High impact neutrino physics
  - In-situ R&D of new photon sensor technologies
  - Deployment of new calibration devices
- First steps toward IceCube Gen2



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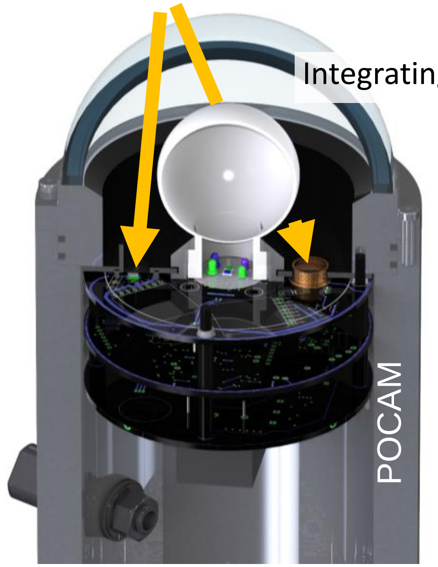
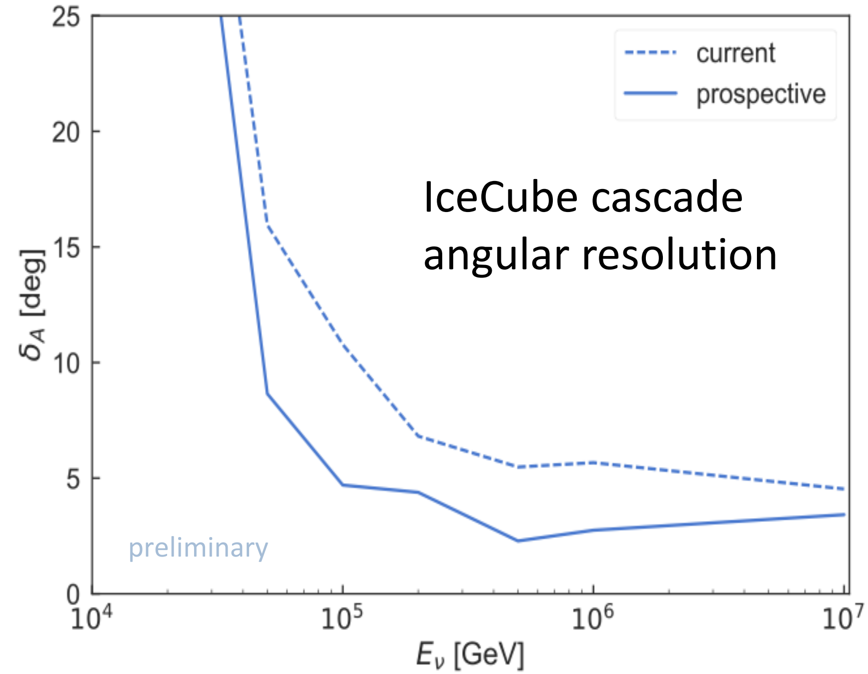
Calibration Devices

- Precision Optical Calibration Module (POCAM)
  - Prototype is being tested w/ collaboration from Baikal-GVD
  - Isotropic, nanosecond pulsed, self-calibrating source
  - Better ice modeling = better reconstruction resolution
- Low-power cameras (mobile phones)
  - Deploy on many modules
  - Observe local variation of ice properties and refrozen 'hole' ice

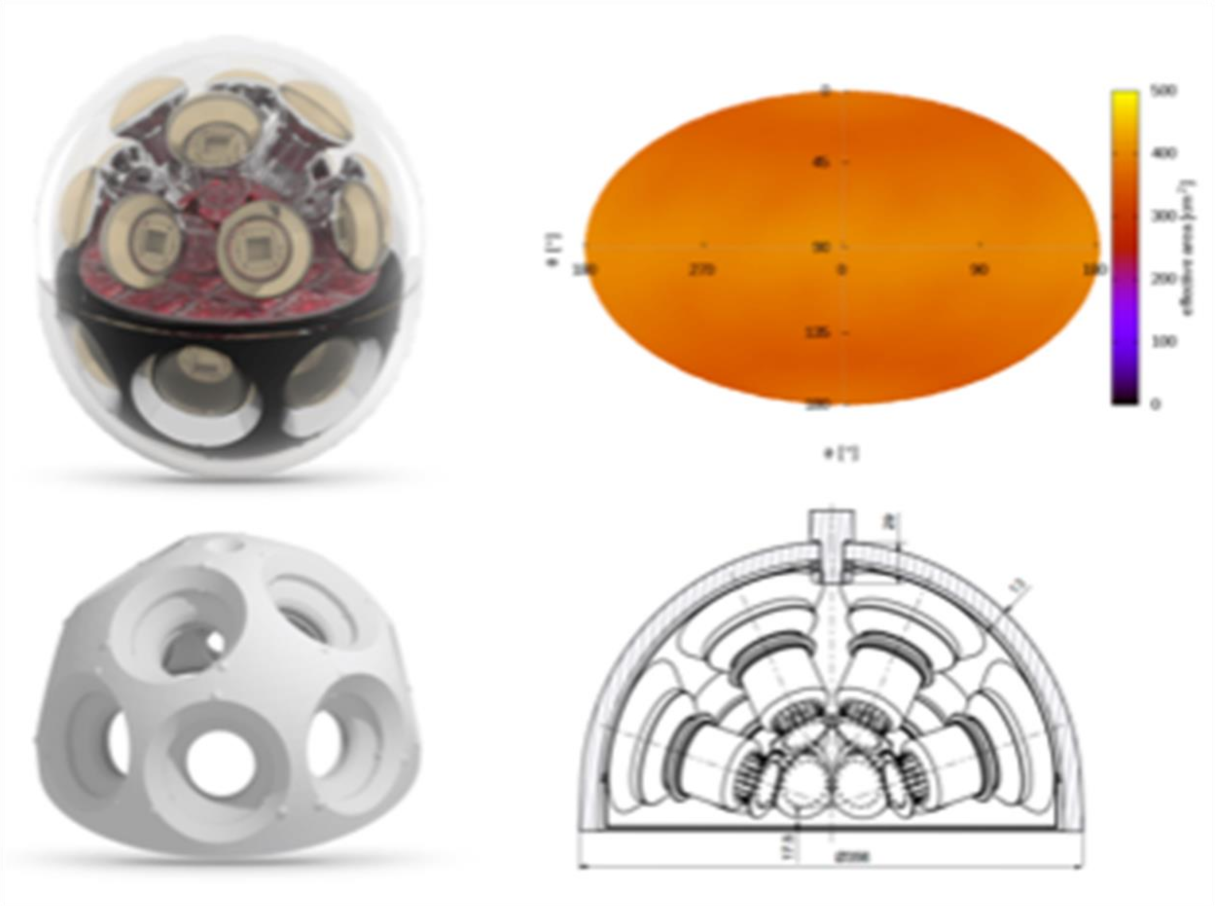




*T. Yuan, TeVPA2017

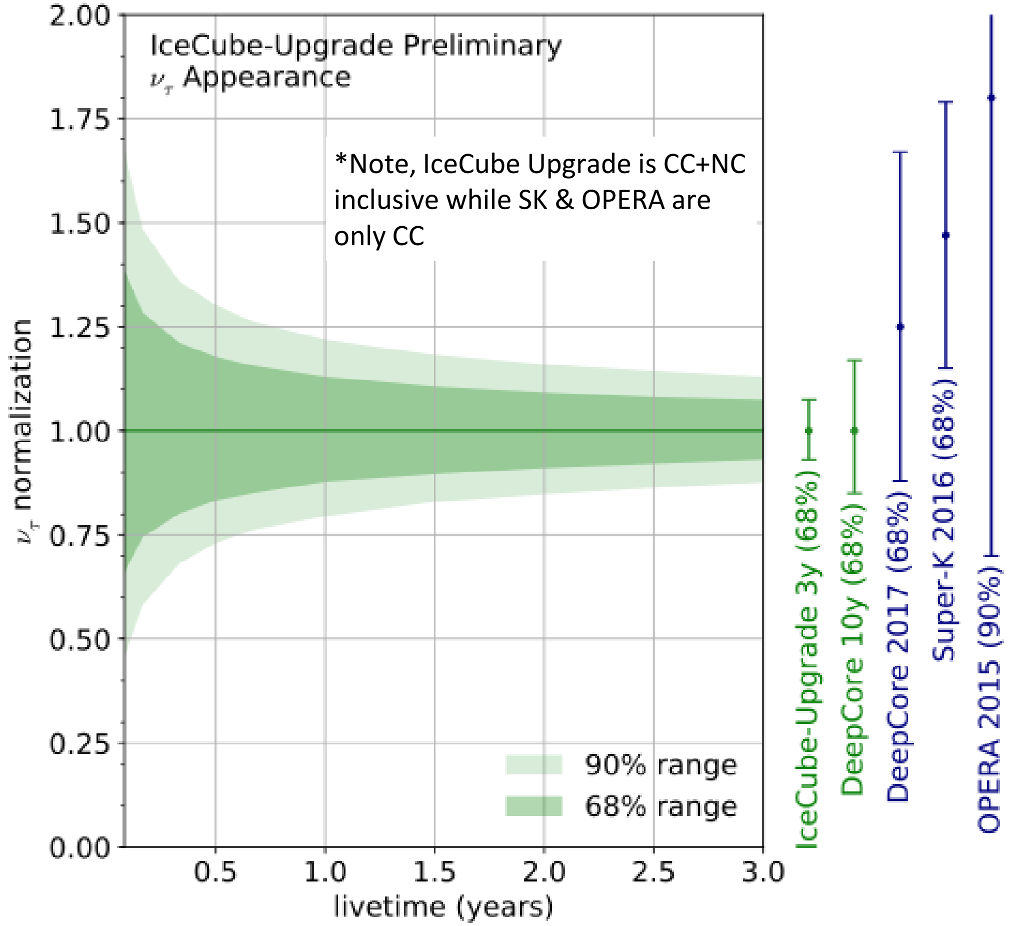
Sensor Design

- Several sensor designs under continuous study
- PINGU and IceCube Upgrade are focused on multi-PMT modules
  - 24x 3” PMTs
  - Isotropic photon acceptance
  - Use of directional information



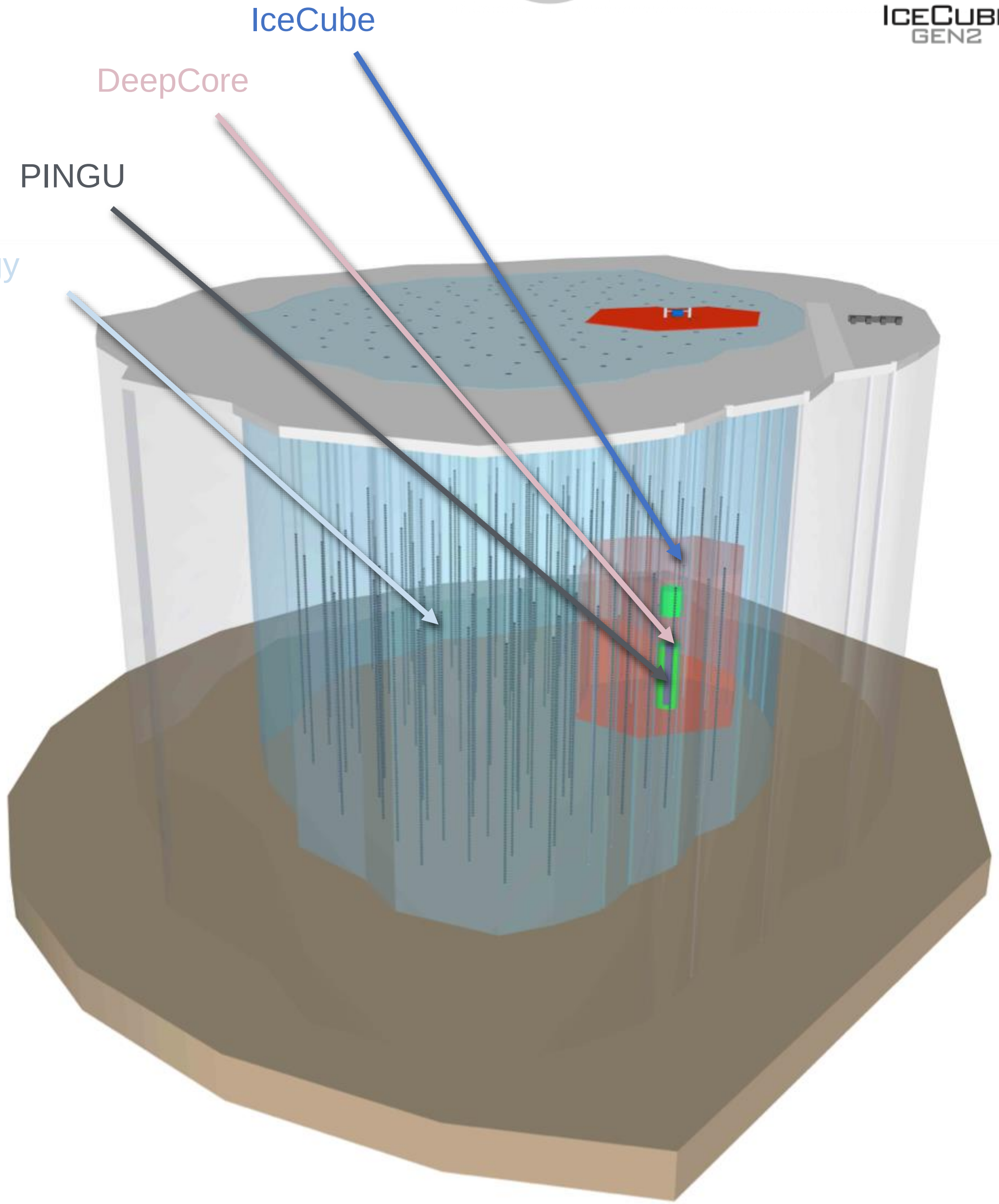
ν_τ Appearance for IceCube Upgrade

- Similar to DeepCore measurement
  - Direct measure of $|U_{\tau 3}|^2$
  - Energy and zenith angle excess in cascade channel



IceCube-Gen2

- PINGU
  - 26 total strings
  - Low energy infill
  - mDOM sensors
- High Energy Array
  - 120 new strings
  - 80 sensors/string
  - ~8 km^3 volume
  - 240m string-string (120m for IceCube)
- Investigating a Surface Array



Summary

- IceCube is a multipurpose facility
  - Competitive and improving atmospheric neutrino oscillations results
  - Best limits on NSI and eV sterile neutrinos
  - Leading limits in some dark matter sectors
- Still digging through new and archival data to improve analyses
- IceCube upgrade will significantly enhance ν_τ capabilities, point way for next generation IceCube
- Exciting times for Astroparticle and Astrophysics

Photo: Johannes Werthebach IceCube/NSF

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