Oscillation Physics with DeepCore

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for the IceCube Collaboration

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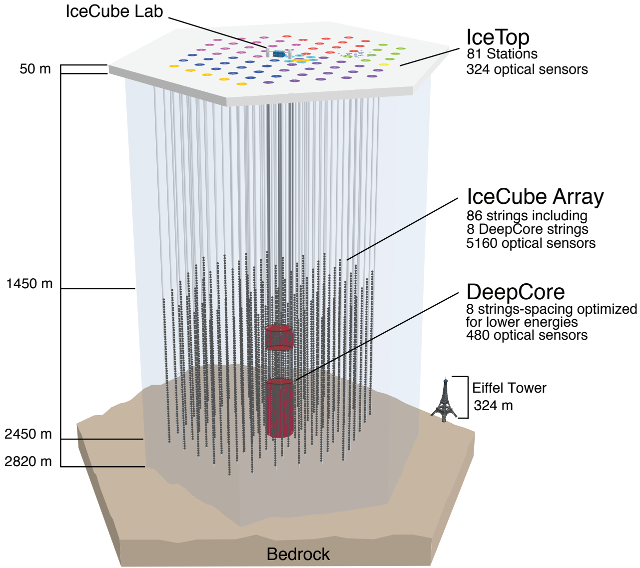
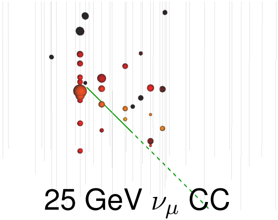
October 2nd, 2018

IceCube



- Instrumented 1 Gton of ice
- Optimized for TeV-PeV neutrinos
  - Astrophysical ν discovered!
- DeepCore
  - 10 Mton region with denser instrumentation
  - Pushes thresholds down to ≈ 5 GeV
  - Surrounding detector used as active veto against atmospheric μ

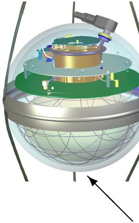
IceCube-DeepCore

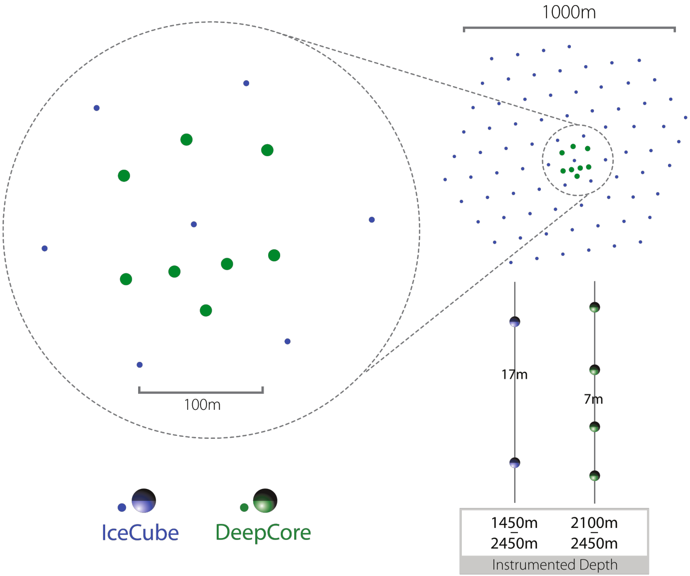


25 GeV ν_μ CC

color $\rightarrow$ hit time
size $\rightarrow$ hit charge

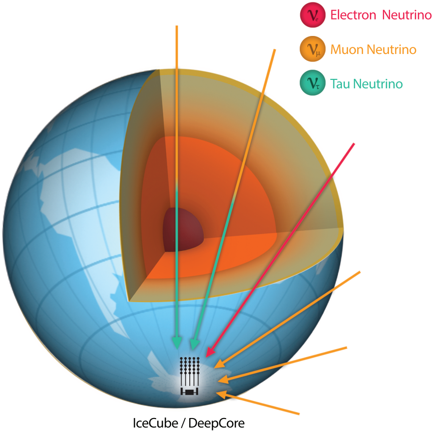
IceCube DOM





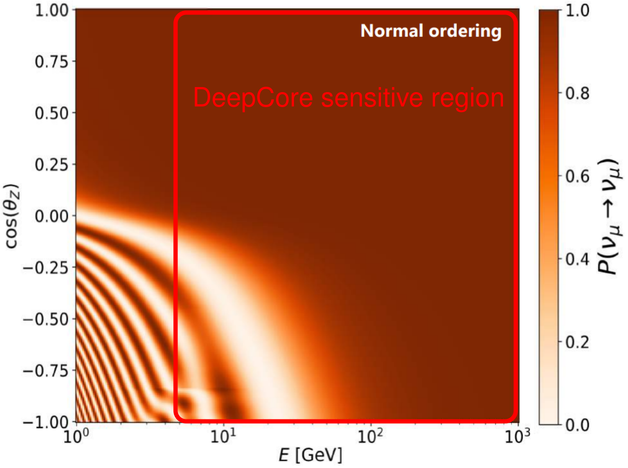
Analyses Strategy

- Atmospheric neutrinos allow for a very broad amount of physics to be done.
  - Wide range of energies from a few GeV to 100's of TeV
  - Many baselines observed up to 12,700 km
- Matter effects for Core-crossing neutrinos
- Can test standard oscillation picture
  - ν_μ disappearance, ν_τ appearance, mass ordering
- Broad spectrum of BSM oscillation physics probed
  - sterile neutrinos, NSI, decoherence, etc.



Oscillations in DeepCore

- Search for 3D distortions of events: [E, $\cos(\theta_{zenith})$, PID]
- ν_μ disappearance is dominant oscillation channel



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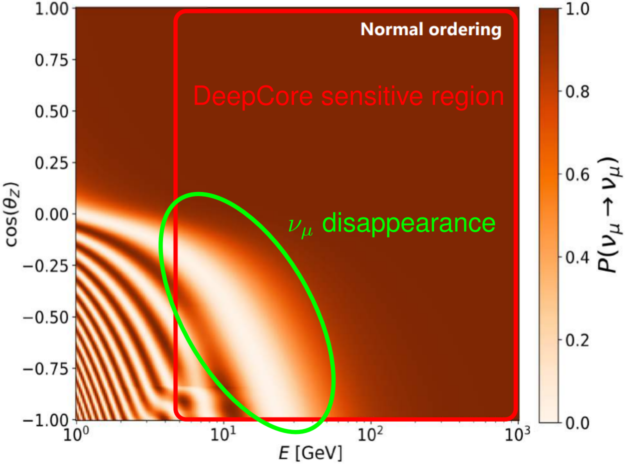

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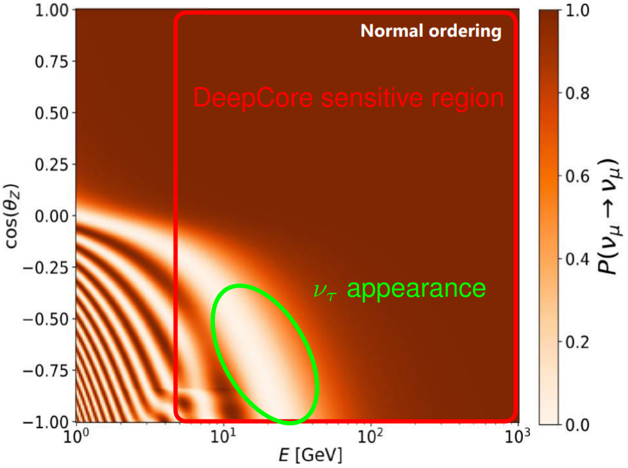

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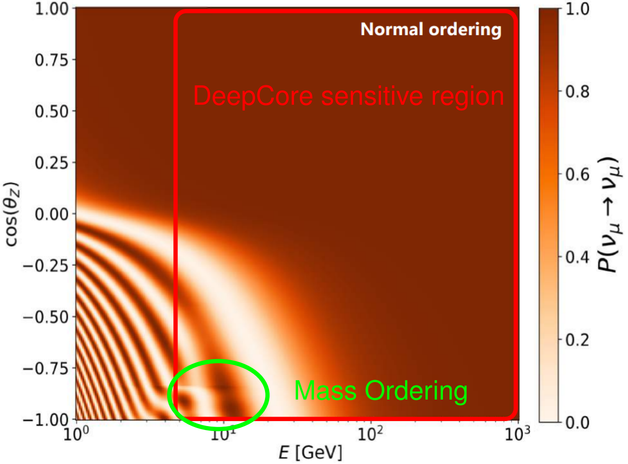

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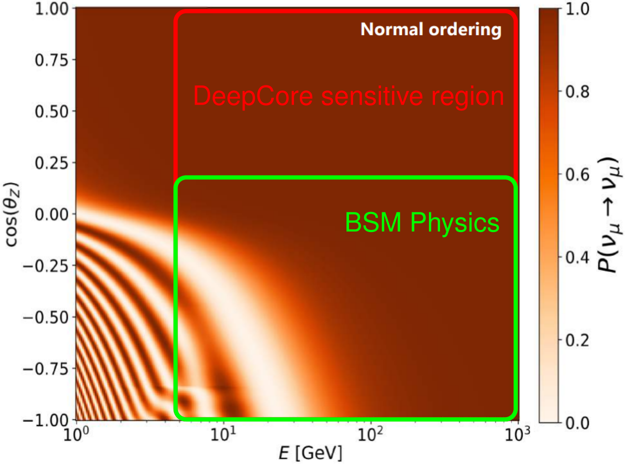
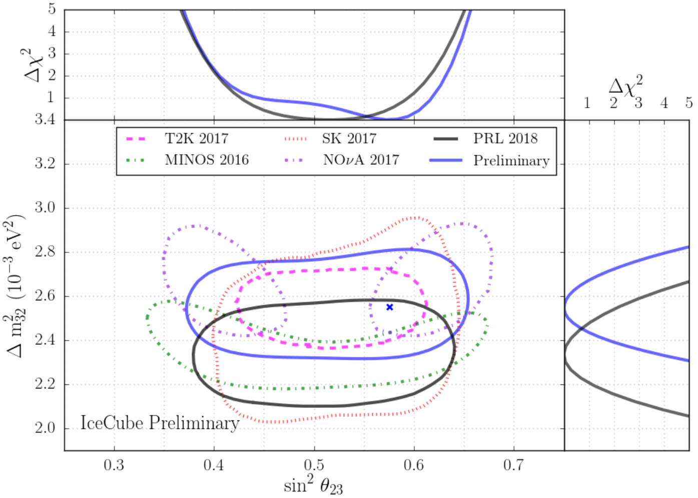


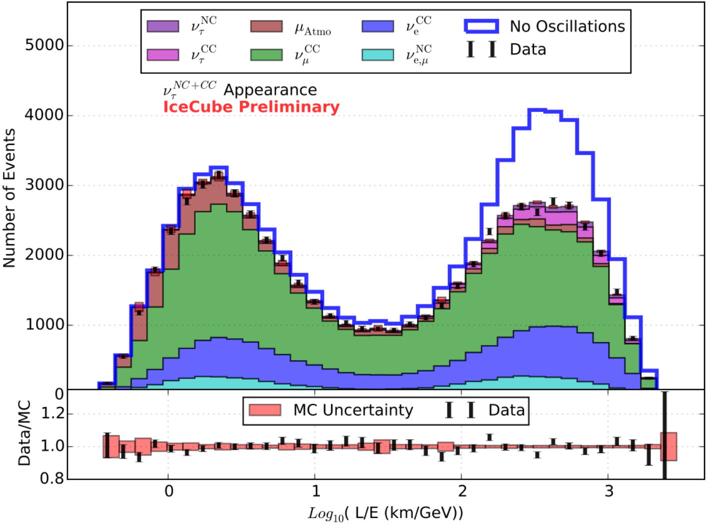
ν_μ Disappearance

- Two independent analyses have been performed on three years of data
  - 2018 PRL published, arXiv:1707.07081
  - New: 2018 high statistics sample
- Use different event selections, different reconstructions, and different PID metrics
- Samples largely non-overlapping

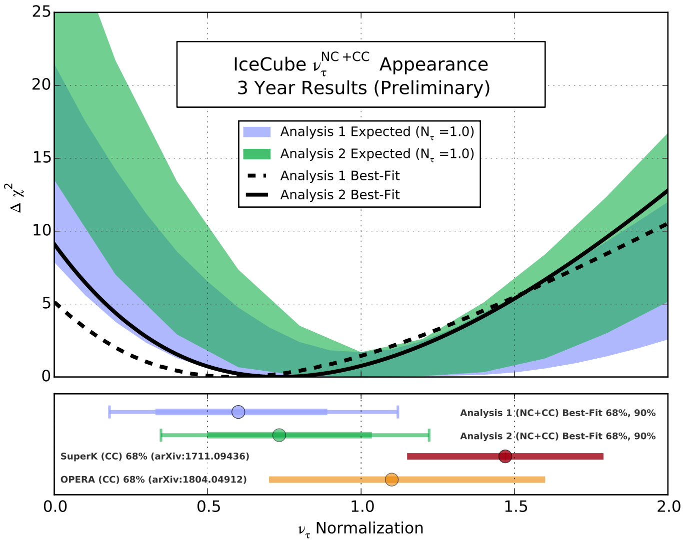


L/E

- Easier to visualize oscillation in L/E space
  - Actual analyses done in [E, $\cos(\theta_{zenith})$, PID]
- Can see clear disappearance of neutrinos at large L/E
- ν_τ appearance requires measuring a very small difference in the amount of oscillations

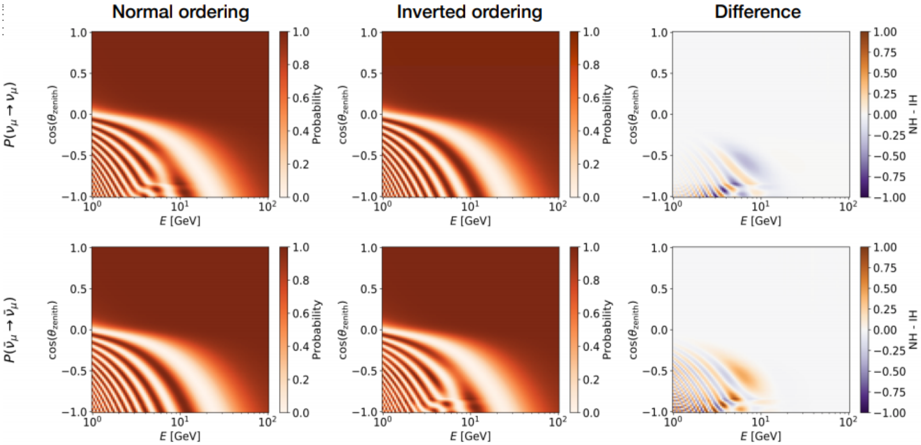


ν_τ Appearance



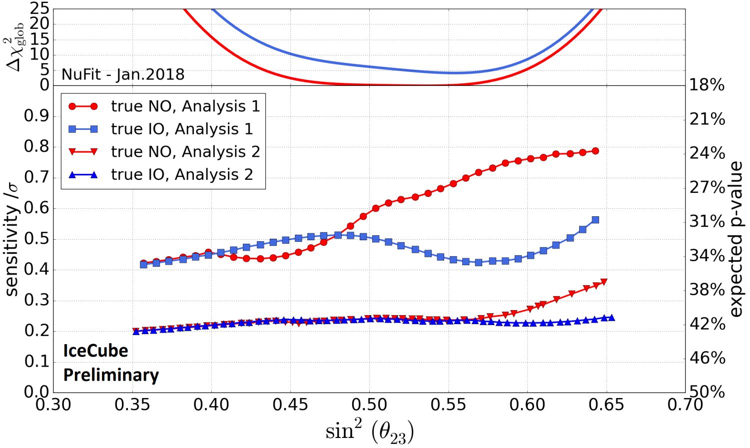
- Same two event samples as disappearance analysis
- Similar results and sensitivity
- Consistent with PMNS being unitary within 90% CL
- Paper in progress

Neutrino Mass Ordering



- NMO leads to matter induced transition for neutrinos (NO) or anti-neutrinos (IO)
  - Exploit the fact neutrinos and anti-neutrinos have different cross-sections

Neutrino Mass Ordering



- Matter effects appear just above energy threshold for current detectors
  - Need IceCube-Upgrade or PINGU to get better sensitivity

Conclusion

- IceCube/DeepCore can do a large breadth of oscillation physics
- Currently have world leading disappearance results from atmospheric neutrinos
  - Results competitive to dedicated LBL experiments
- We have made out first measurement of ν_τ appearance
- Shown proof of concept NMO results
  - Good stepping stone for Upgrade and Gen2 analyses
- Many great BSM oscillations results with no time to show
  - NSI, low energy sterile searched, decoherence ...
- Updated results with double the statistics currently underway!


THE ICECUBE COLLABORATION
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US National Science Foundation (NSF)
ICECUBE GEN2
icecube.wisc.edu

Backup

Neutrino oscillations

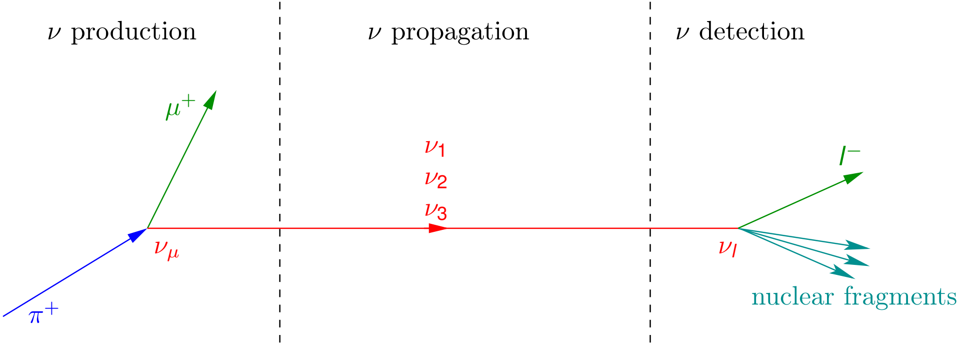
- 3 ν flavors: ν_e, ν_μ and ν_τ
- ν oscillation observed in various experiments since it's discovery
  - Implies that ν are massive particles $\rightarrow$ must also have 3 mass states: ν_1, ν_2, ν_3
- Projection between flavor $\leftrightarrow$ mass states via mixing matrix U:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

  - U is unitary if only 3-flavor mixing
- 6 parameters (Δm^2_{21}, Δm^2_{32}, θ_{12}, θ_{13}, θ_{23} and δ_{CP}) describe ν oscillations
  - possibility of a Majorana term, but does not effect oscillations
- Currently only δ_{CP} and mass ordering (sign of Δm^2_{32}) not measured

Neutrino oscillation – a schematic view



$|\nu_\mu\rangle = \sum_j U^*_{\mu j} |\nu_j\rangle$

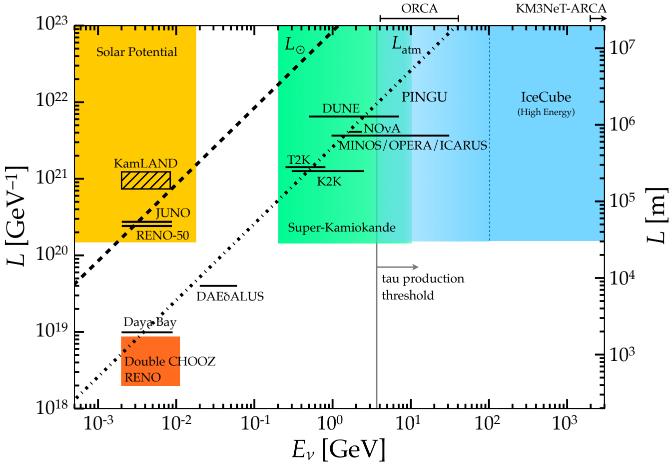
$|\nu_j\rangle \to e^{-iE_j t} |\nu_j\rangle$

$|\nu_j\rangle = \sum_l U_{lj} |\nu_l\rangle$

$$P(\nu_\mu \to \nu_l, t) = ||\langle \nu_l|\nu_\mu, t\rangle||^2 = \sum_{j,k} U_{lj} U^*_{\mu j} U^*_{lk} U_{\mu k} e^{-i(E_j - E_k)t} = \sum_{j,k} U_{lj} U^*_{\mu j} U^*_{lk} U_{\mu k} e^{-i\Delta m^2_{jk} \frac{L}{2E}}$$

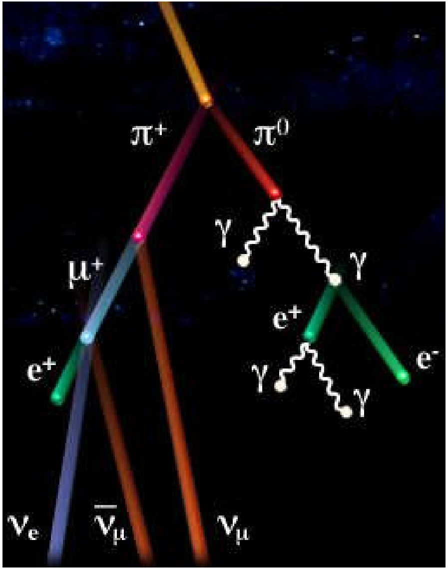
$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right) \sin^2 \left(\frac{\Delta m^2_{32} L}{4E}\right) \quad \text{for } \frac{L}{E} \lesssim 1000 \text{ km/GeV}$$

IceCube Upgrade: Oscillation Physics



IceCube probes oscillation physics at baselines and energies inaccessible to LBL or reactor neutrino experiments.

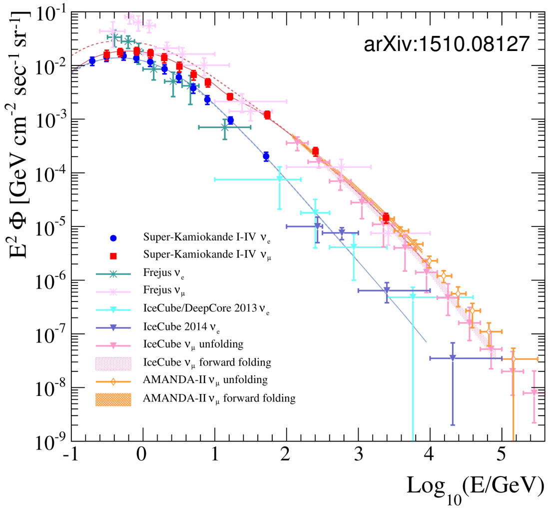
Atmospheric neutrinos



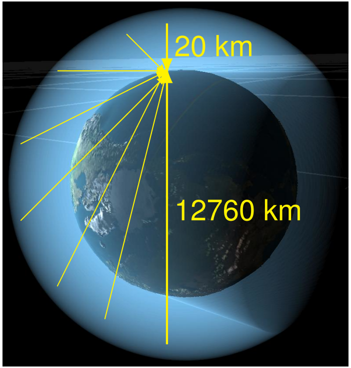
- Cosmic ray (CR) interact with atmosphere, producing hadronic shower
  - Decays produce ν
- ν_e:ν_μ:ν_τ produced at ≈1:2:0
- similar rate of ν and $\bar{\nu}$
  - however, cross-sections for $\bar{\nu}$ smaller than for ν

  $\Rightarrow$ at detection less $\bar{\nu}$ than ν

Atmospheric neutrinos



- ν energy over several orders of magnitude
- CR bombard Earth from all directions
  - $\Rightarrow$ neutrinos from all directions!



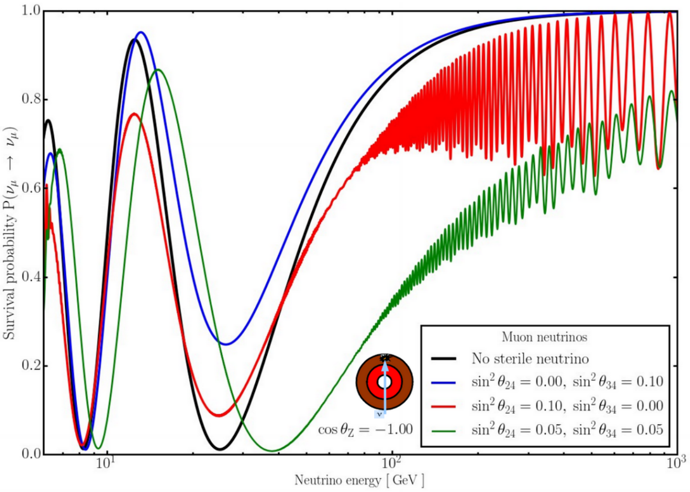
Typical Systematics Used in Analyses

Parameters	Priors
Flux and cross section parameters	
Neutrino event rate [% of nominal]	no prior
$\Delta\gamma$ (spectral index)	0.00 ± 0.10
$\nu_e + \bar{\nu}_e$ relative normalization [%]	100 ± 5
NC relative normalization [%]	100 ± 20
$\Delta(\nu/\bar{\nu})$ [σ], energy dependent‡	0.00 ± 1.00
$\Delta(\nu/\bar{\nu})$ [σ], zenith dependent‡	0.00 ± 1.00
M_A^{CCQE} [GeV]	$0.99^{+0.248}_{-0.149}$
$M_A^{resonance}$ [GeV]	1.12 ± 0.22
Detector parameters	
overall DOM efficiency [%]	100 ± 10
relative DOM efficiency, lateral [σ]	0.0 ± 1.0
relative DOM efficiency, head-on [a.u.]	no prior
Bulk ice, absorption [%]	100 ± 10
Bulk ice, scattering [%]	100 ± 10
Background	
Atm. μ contamination [% of sample]	no prior

$\ddagger$: Following Barr, et al., PRD74, 094009.

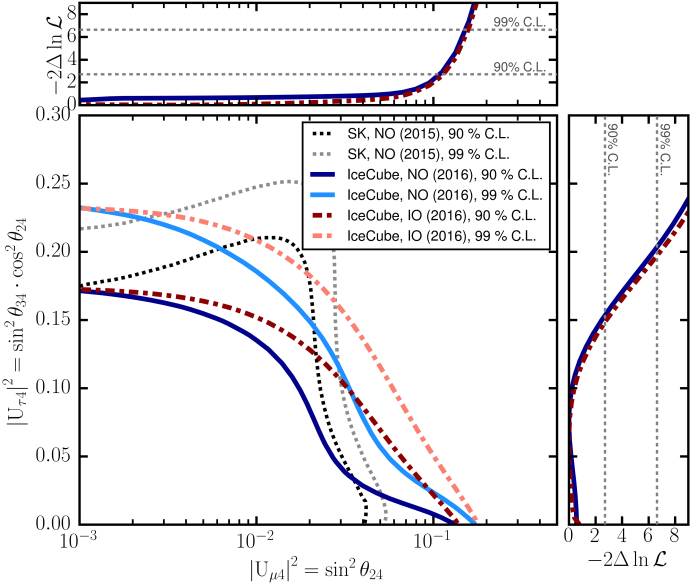
Sterile ν Search with DeepCore

- Effects of sterile neutrinos below 100 GeV
  - Modifies standard neutrino oscillations
  - Effect is proportional to amount of matter along neutrino path
- ν_μ disappearance minimum:
  - Change of depth
  - Shifts in energy
  - Independent of sterile neutrino mass (for $\Delta m^2_{14} > 0.3eV^2$)



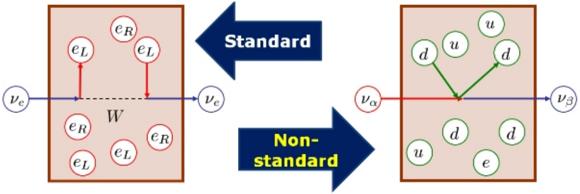
Results of Sterile ν Search with DeepCore

- Results based off three years of data
- Uses different event selection and reconstruction than “standard oscillation” results
- Probes $U_{\mu 4}$ and $U_{\tau 4}$ mixing to better than 10% for most of $0.1 eV^2 < \Delta m^2_{41} < 10 eV^2$ range



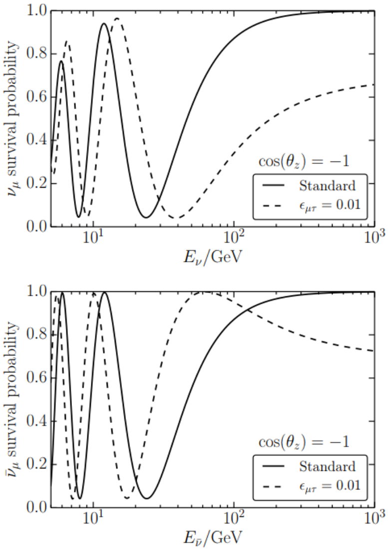
Non-Standard Interactions (NSI) in Matter

- Search for coherent forward scattering of neutrinos in matter due to some new mediator
- Additional effective matter potential that couples to u/d quarks

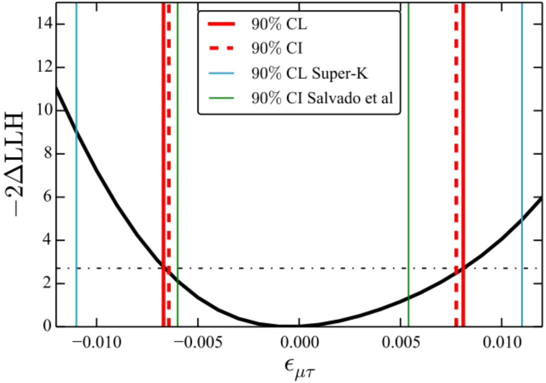


$$H_{\alpha\beta} = \frac{1}{2E_\nu} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger_{k\beta} + V_{MSW} + \sqrt{2} G_F N_f \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

DeepCore NSI Results

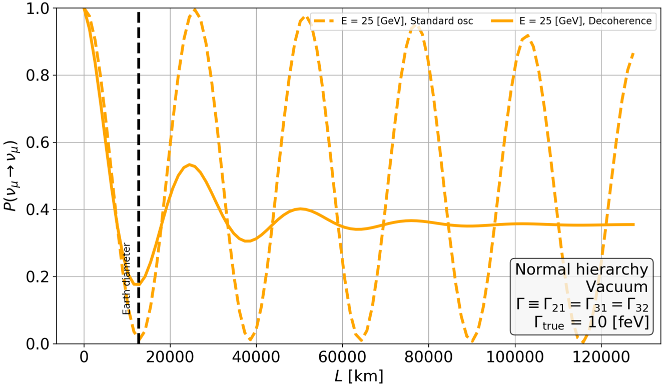


- NSI in matter modulates the normal 3-flavor oscillation pattern
  - Effect different for ν and $\bar{\nu}$
- $\epsilon_{\mu\tau}$ measured (modifies ν_μ disappearance) using sterile neutrino event sample



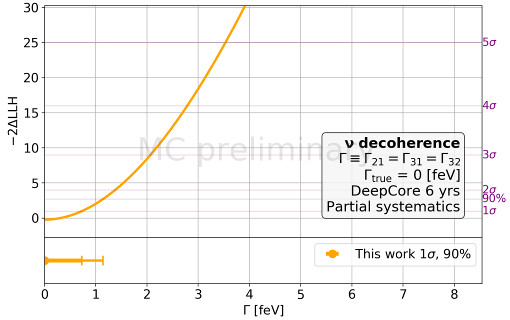
Decoherence

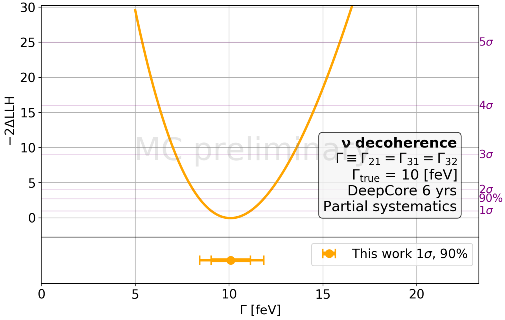
- Weak coupling between neutrino and environment causes decoherence
- Dampens oscillation probability over distance/time
- Introduces three effective damping parameters, Γ_{ij}
  - Could be energy dependent



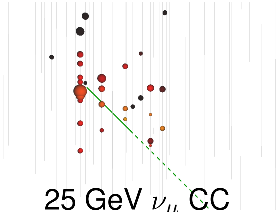
Decoherence

- DeepCore analysis underway
- Expect to put limits of *Gamma* < 1 feV at 1σ





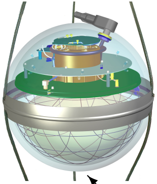
IceCube Upgrade



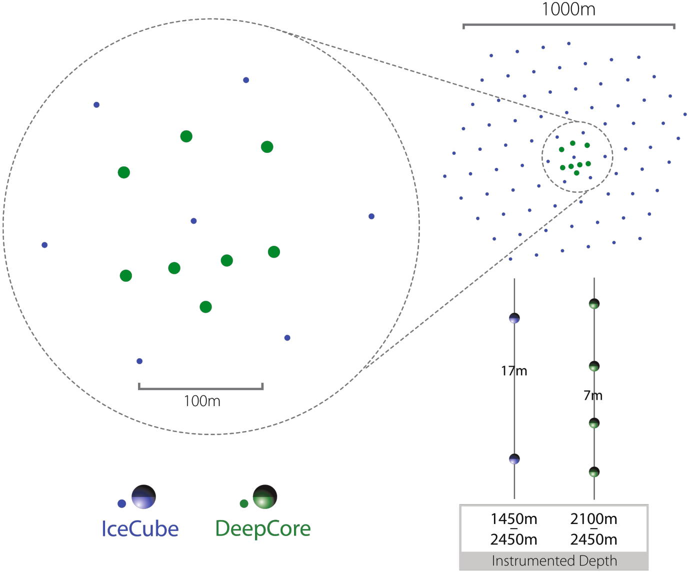
25 GeV ν_μ CC

color $\rightarrow$ hit time
size $\rightarrow$ hit charge

IceCube DOM



10” PMT



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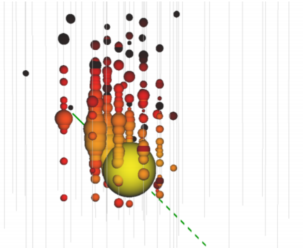

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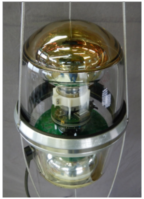
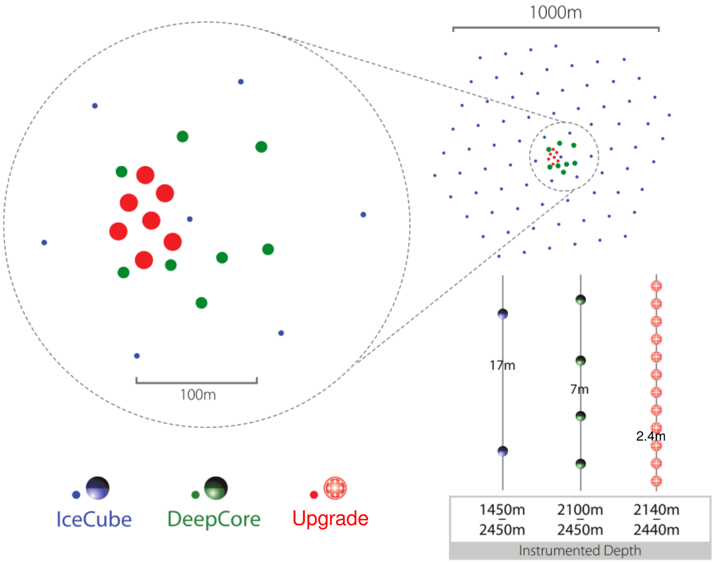




IceCube Upgrade: Hardware

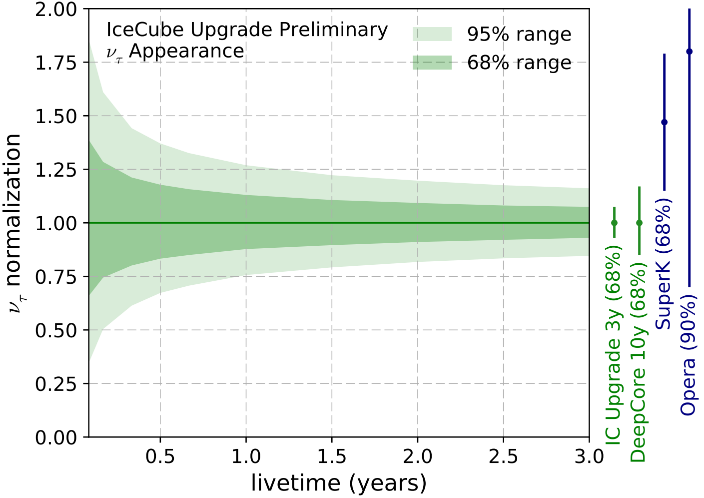
- Seven new strings in DeepCore with inter-string space of $\sim$22m
- Three primary DOM designs:
  - pDOMs almost identical to DOMs currently used in IceCube with updated electronics
  - multi-PMTs mDOMs
  - Dual optical sensor in an Ellipsoid Glass for Gen2 (D-Egg)
- Will include new calibration devices to help better understand the ice
  - Onboard LEDs with wider range of angles accessible, including vertically
  - New camera for local ice calibration
- Stand alone calibration devices
  - Isotropic light sources
  - Collimated light sources

IceCube Upgrade: Science Goals

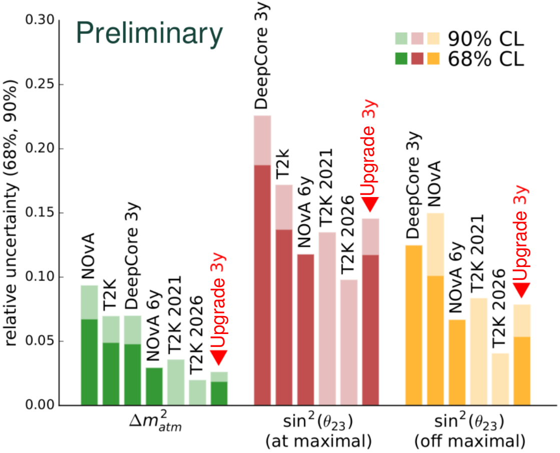
- ν_τ appearance analysis
  - PMNS unitarity tests
- Precision measurements of $\sin^2(\theta_{23})$ and Δm^2_{32}
  - Octant/Maximal mixing
  - Complementary to LBL experiments
- Neutrino mass ordering at 1.5-2σ in 3 years
- Improvement on eV sterile ν searches, NSI, solar dark matter searches, and other BSM searches
- Better neutrino astronomy at high energies
  - Improved angular resolution and veto performance
  - ν_τ identification
  - Multi-messenger astronomy

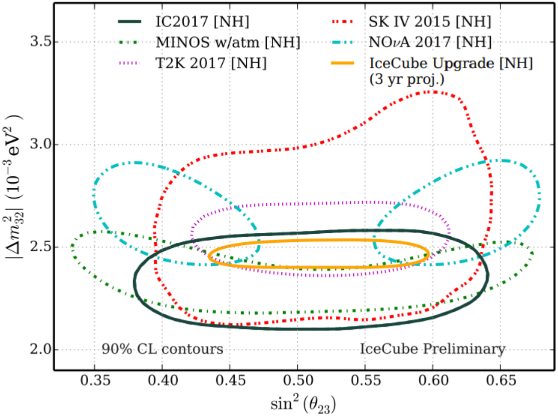
IceCube Upgrade: ν_τ Appearance

- $<$ 7% precision on the ν_τ normalization after 3 years of data.
- $\sim$ 10% precision needed for real tests of the unitarity of the PMNS mixing matrix.
- Very few experiments can do this measurement!



IceCube Upgrade: ν_μ Disappearance

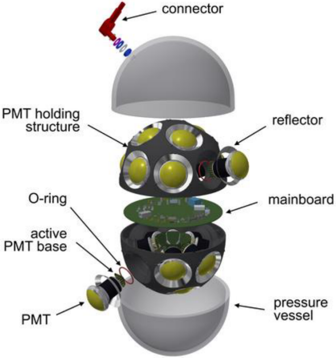




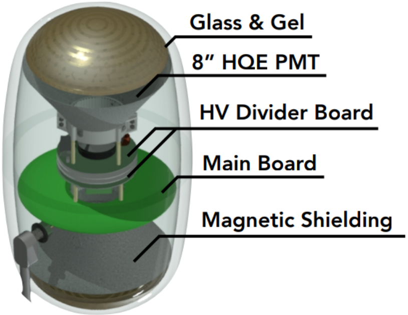
Projected limits on $\sin^2(\theta_{23})$ and Δm^2_{32} competitive with dedicated LBL experiments.

IceCube Upgrade: Hardware

- multi-PMTs mDOMs
  - 24 × 3" PMTs housed in a 14" DOM
  - Double the photocathode area of IceCube DOMs
  - Provides extra directional information of photons



- D-Egg
  - Two 8" PMTs facing back-to-back
  - Ellipsoid glass, optimal shape for glass transparency
  - Single ADC with wide dynamic range

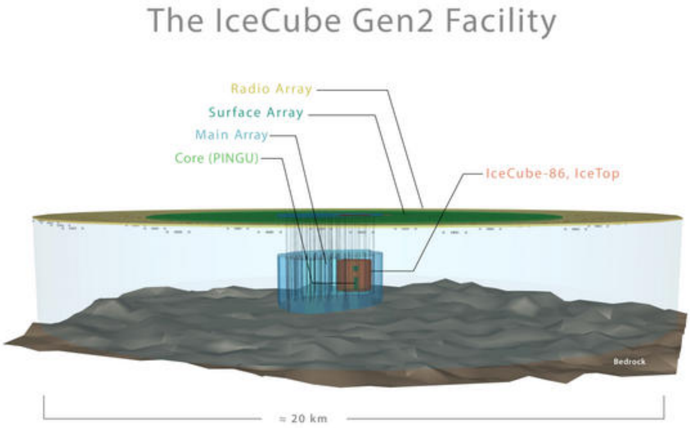


IceCube Upgrade Timeline

- Project timeline:
  - 2019-Q1: Preliminary Design Review; drill recon season at Pole
  - 2019: Preparation for final design; long lead procurement
  - 2020-Q1: Final Design Review
  - 2020-2021: Drill generators ship to Pole; refurbish drill structures at Pole
  - 2021-2022: Firn drilling
  - 2022-2023: Deploy 7 strings

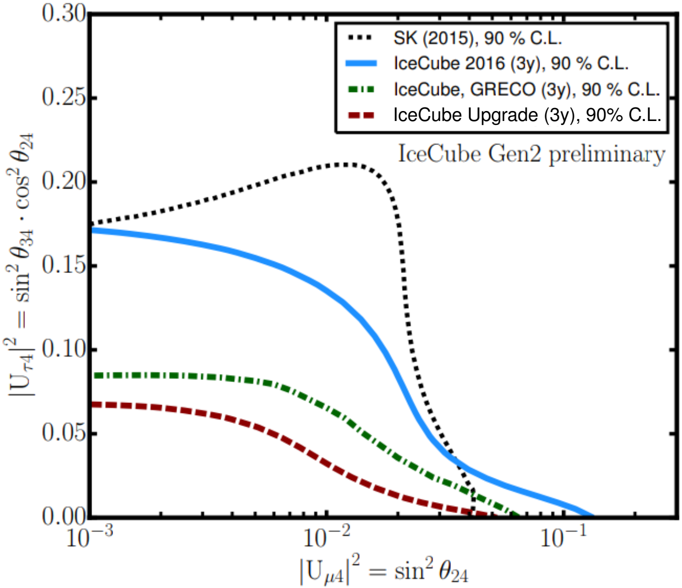
IceCube-Gen2

- IceCube-Gen2 is a versitile facility for future South Pole physics
- Radio Array
- Surface Array
- High Energy Array
  - 120 strings $\times$ 90 sensors/string
  - $\sim$ 8 km^2 area with wider string spacing
- PINGU
  - Low energy infill
  - 17 strings $\times$ 125 sensors + Upgrade strings
  - 24m inter-string spacing

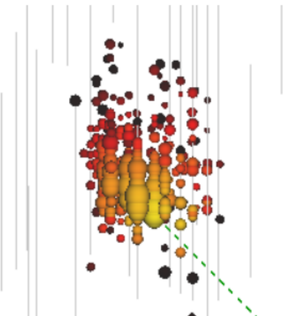


IceCube Upgrade: Sterile Neutrinos

- Higher precision event reconstructions increase sensitivity considerably.
- Upgrade should produce similar improvements in searches for non-standard neutrino interactions (NSI), dark matter, and other BSM physics - under current investigation.

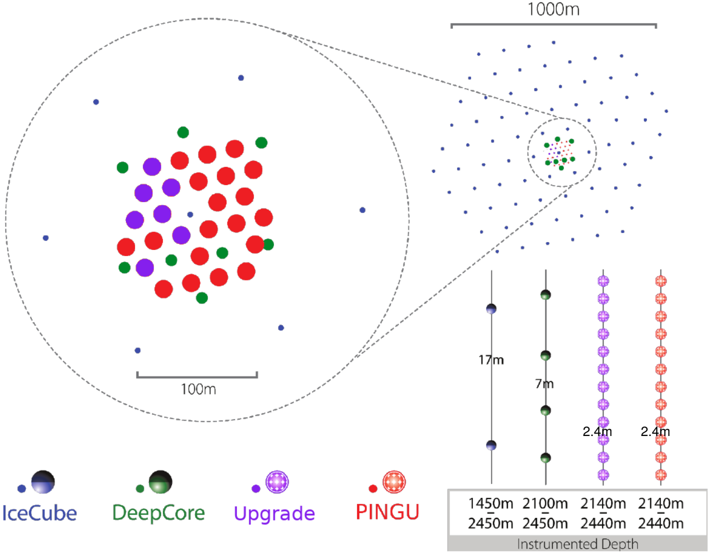


PINGU



12 GeV ν_μ CC

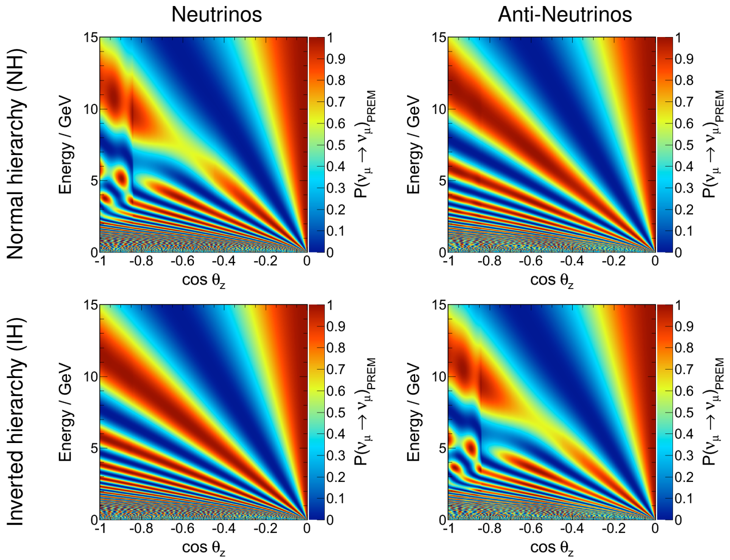
color $\rightarrow$ hit time
size $\rightarrow$ hit charge



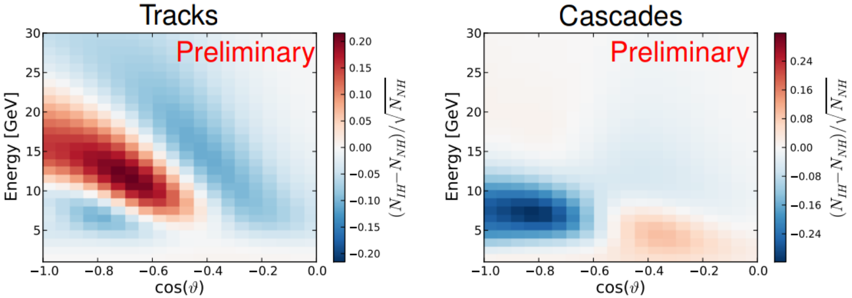
PINGU: Science Goals

- Augmenting the low-energy program of the upgrade.
  - $\sim$ 70k up-going atmospheric neutrinos per year
- Neutrino mass ordering
- ν_τ appearance
- $\sin^2(\theta_{23})$ octant sensitivity
- Wide breadth of other science:
  - Dark matter searches
  - Earth tomography
  - SN
  - ...

PINGU: Neutrino Mass Ordering

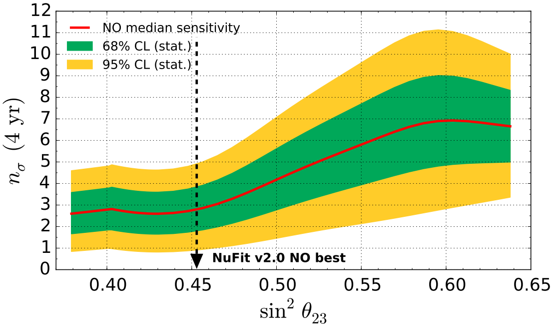


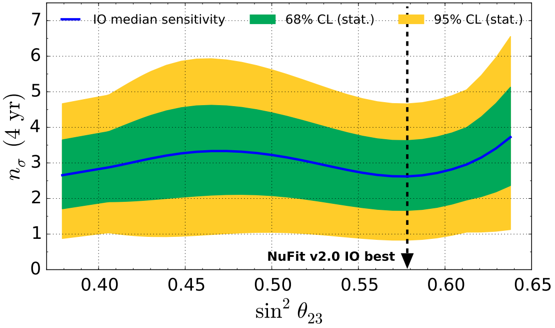
PINGU: Neutrino Mass Ordering



- PINGU cannot differentiate ν and $\bar{\nu}$: rely on difference in flux and cross-section
  - Large statistical samples: $\sim$33k ν_μ + $\bar{\nu}_\mu$ CC per year, $\sim$25k ν_e + $\bar{\nu}_e$ CC per year
- Distinct ordering dependent signatures for tracks (mostly ν_μ CC) and cascades
  - Intensity is statistical significance of each bin with 1 year data
  - Particular expected “distortion pattern” helps mitigate impact of systematics

PINGU: Neutrino Mass Ordering

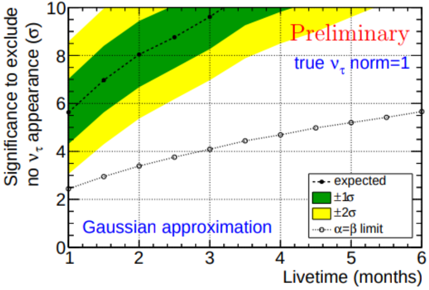


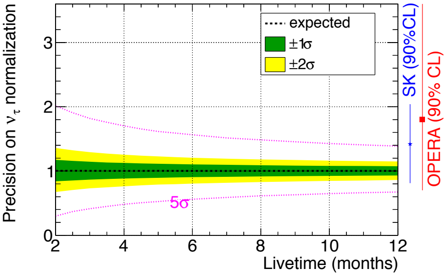


- Sensitivities calculated with 2 different methods (LLR and $\Delta\chi^2$) in agreement
- NMO sensitivity strongly depends on true $\sin^2(\theta_{23})$
- Median sensitivity of $\sim 3\sigma$ with 4 years of data for current best-fit values
  - Current global best fit close to sensitivity minimum for both orderings!

PINGU: ν_τ Appearance

- Expected to reach 5σ exclusion of no ν_τ appearance with a month of data
  - Can even reach 5σ exclusion of no ν_τ appearance within a year if ν_τ normalization is 0.6.
- Can reach Upgrade precision with less than 1 year of data.

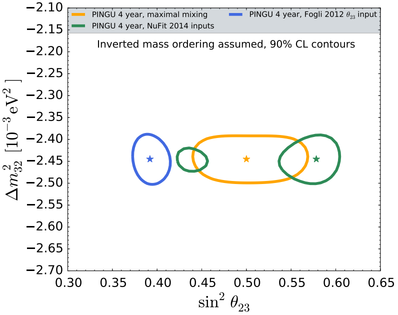


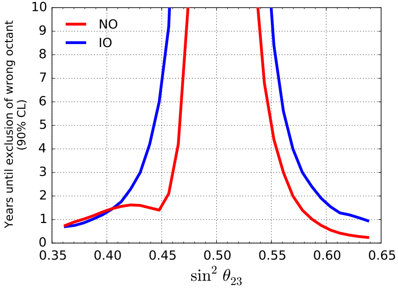


PINGU: ν_μ Disappearance

- Precision of $\sin^2(\theta_{32})$ and Δm^2_{32} measurement is as good as LBL experiments

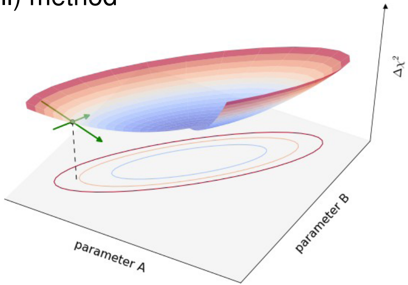
- 4 year octant sensitivity $\gtrsim 3\sigma$ if:
  - NO: $\sin^2(\theta_{32}) \lesssim 0.38$ or $\gtrsim 0.62$
  - IO: $\sin^2(\theta_{32}) \lesssim 0.38$ or $\gtrsim 0.58$



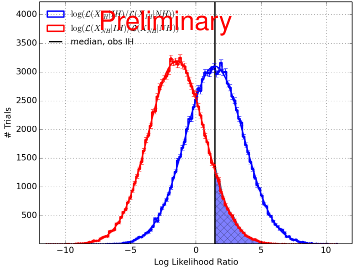


Methods for estimating sensitivity to the NMH

χ^2 (pull) method



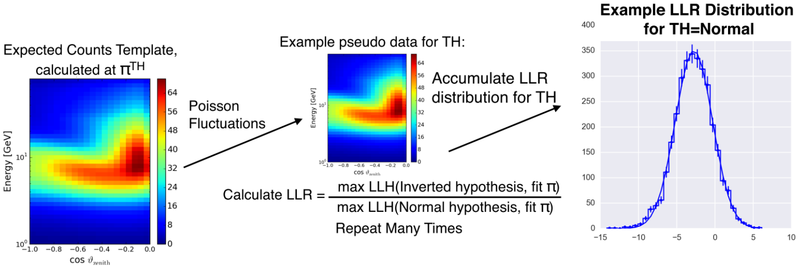
Likelihood Ratio



- Currently two methods used: the χ^2 method and Likelihood Ratio
  - Output of full simulation and reconstruction parametrized and used
  - Analysis done in $E_\nu \times \cos(\text{zenith})$ space in 2 PID bins
  - χ^2 method: Relatively fast evaluation by scanning nonlinear parameters and propagating error for linear parameters and minimizing the $\Delta\chi^2$
  - Likelihood Ratio: Full analysis from pseudo data sets. While method is slower it does not pre-suppose any shapes

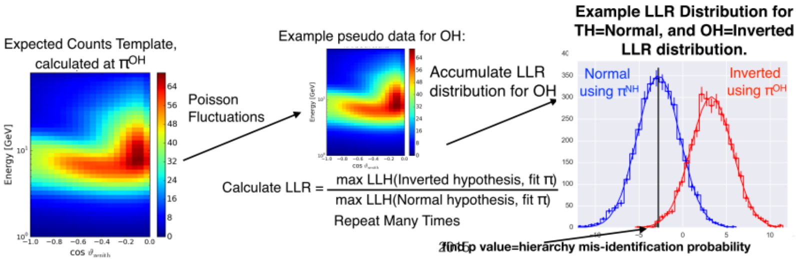
LLR method

- Greatly improved statistical analysis method since LoI
  - Ability to include many more systematics (from 2 → ~10) by using a minimizer to find optimal LLH fit rather than grid scan
  - Run optimizer twice to search for solutions in both octants of θ_{23}.
- To test for significance of true hierarchy (TH)/rejection of other hierarchy (OH)
  - pull pseudo data from template of TH, with parameters:
    $\pi^{TH} = (\Delta m^2_{31}|^{TH}, \theta_{23}|^{TH}, \theta_{13}|^{TH},$ *all other params at nominal*)
  - Then following procedure is performed:



LLR method

- Greatly improved statistical analysis method since LoI
  - Ability to include many more systematics (from 2 → ~10) by using a minimizer to find optimal LLH fit rather than grid scan
  - Run optimizer twice to search for solutions in both octants of θ_{23}.
- To test for significance of true hierarchy (TH)/rejection of other hierarchy (OH)
  - Next: parameters in OH that fit best to TH are found: $\pi^{OH} = (\Delta m^2_{31}|^{OH}, \theta_{23}|^{OH})$
  - Find LLR distribution at these parameters, π^{OH}, to find probability of mis-identifying OH as TH.
    - p value then converted to significance of rejecting OH.



Systematics for PINGU Studies

	LLR	$\overline{\Delta\chi 2}$	
Oscillation	$*$	$*$	$\Delta m^2_{31} = 2.46 \times 10^{-3}\,\mathrm{eV}^2,\ -2.37 \times 10^{-3}\,\mathrm{eV}^2$ [47]
	$*$	$*$	$\theta_{23} = 42.3°,\ 49.5°$ [47]
	$*$	$*$	$\theta_{13} = 8.5° \pm 0.2°$ [47]
		†	$\delta_{\mathrm{CP}} = 0°$
Flux & Cross Section	$*$	$*$	Event rate = nominal
	$*$	$*$	ν_e/ν_μ flux ratio = nominal $\pm$ 3% [53]
	$*$	$*$	$\nu/\overline{\nu}$ flux ratio = nominal $\pm$ 10% [53]
	$*$	$*$	Atmospheric spectral index = nominal $\pm$ 0.05 [53]
		†	Air-shower interactions [53]
		†	Neutrino cross-section (see Sec. Appendix B)
Detector	$*$	$*$	Energy scale = $1.0 \pm 10\%$ († $\pm 0.5\%$)
		†	Individual module efficiency = nominal $\pm 10\%$
			Ice properties