A Vision for Neutrino and Particle Physics at the South Pole

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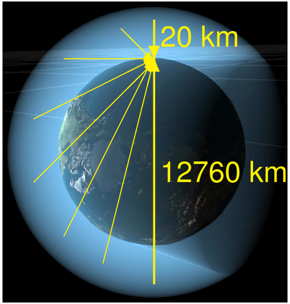
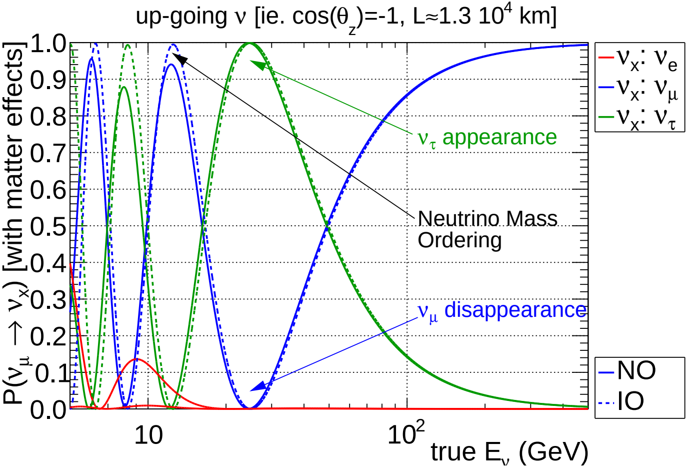
Neutrino oscillations with atmospheric neutrinos





- Several baselines available
  - L/E dependency on oscillation
- IceCube-DeepCore:
  - See clear ν_μ disappearance
  - Harder measurement of ν_τ appearance (on-going)
    - ★ low ν_τ x-sec
    - ★ missing energy from τ-decay

- Need next generation of experiments for:
  - Precision measurements of ν_τ appearance
  - Neutrino mass ordering

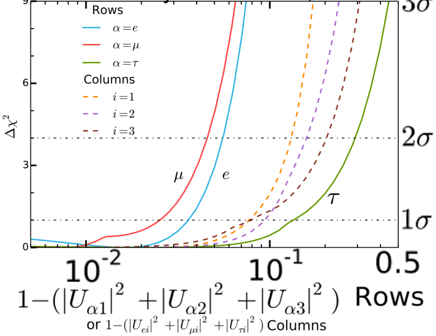
ν_τ appearance: testing unitarity of the mixing matrix U

- If we don't assume unitarity of mixing matrix $\rightarrow$ 9 parameters to be measured

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \quad \begin{matrix} \leftarrow \nu_e \text{ appearance and disappearance} \\ \leftarrow \nu_\mu \text{ disappearance and } \nu_e \text{ or } \nu_\tau \text{ appearance} \\ \leftarrow \nu_\tau \text{ appearance} \end{matrix}$$

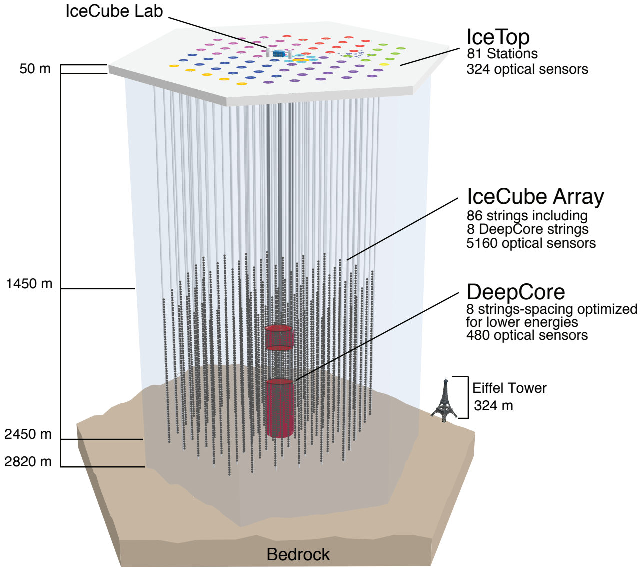
  - ν disappearance: sensitive to the absolute values of 1 row
  - ν appearance: sensitive to products between 2 rows

Phys. Rev. D 93, 113009



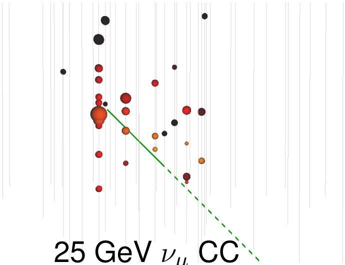
- Probing the τ-row: ν_τ appearance!
  - OPERA and SK measured that
  - in both cases saw too many ν_τ
    - ★ not statistically significant
      $\Rightarrow$ need precision measurements

IceCube



- Instrument 1 Gton of ice
- Optimized for TeV-PeV neutrinos
  - Astrophysical ν discovered!
- At it's center: DeepCore
  - $\sim$10 Mton region with denser instrumentation
  - $\Rightarrow$ lower E threshold
  - $\Rightarrow$ study neutrino oscillations
  - Surrounding detector used as active veto against atmospheric μ

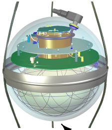
IceCube-DeepCore

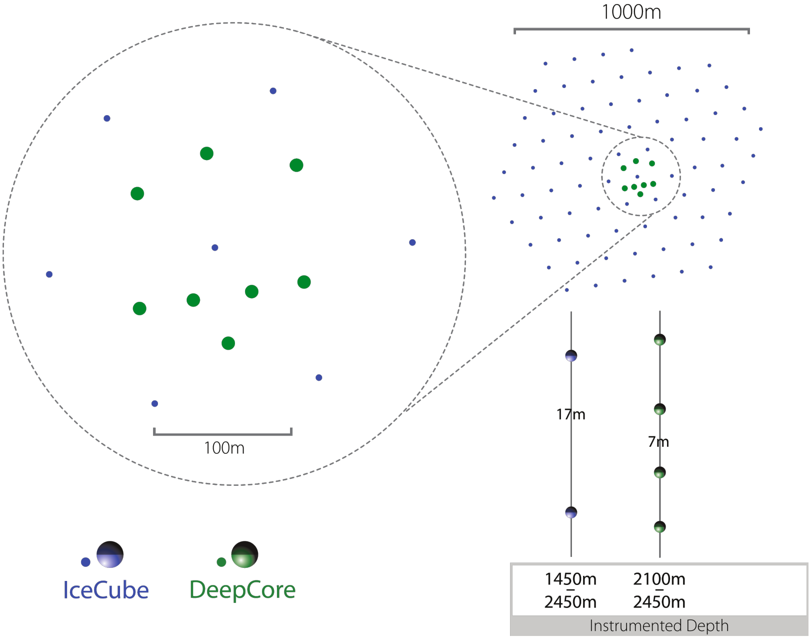


25 GeV ν_μ CC

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

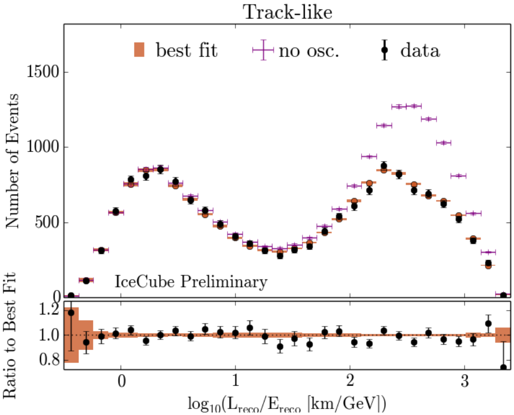
IceCube DOM

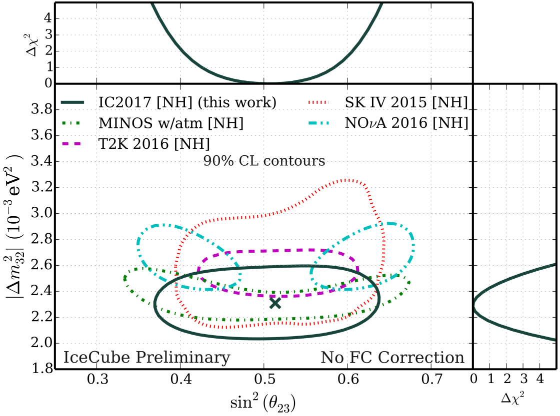




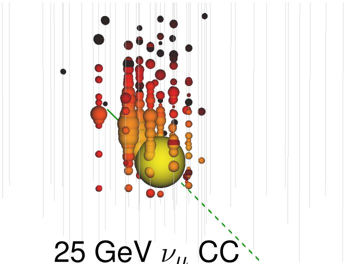
IceCube-DeepCore: ν_μ disappearance measurement

- Brand new results (first shown at Feb 2017) with improved analysis on 3 year sample
- Fitting done in 3D space (E,cos θ_z, PID) $\rightarrow$ projected in L/E for illustration
- Consistent & competitive results to accelerator based measurements
  - Different *E* range (and baselines) than for accelerator based studies





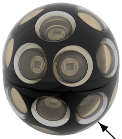
IceCube-Gen2 Phase1



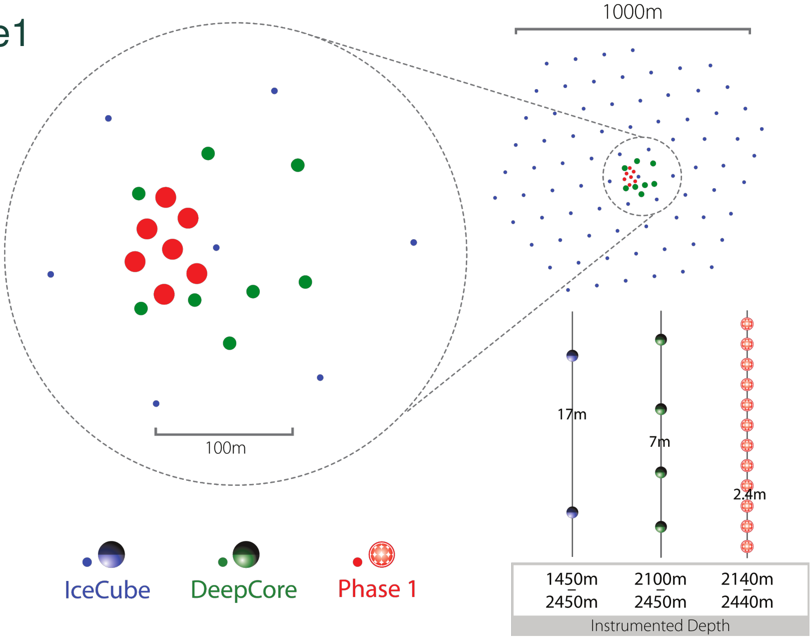
25 GeV ν_μ CC

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

mDOM

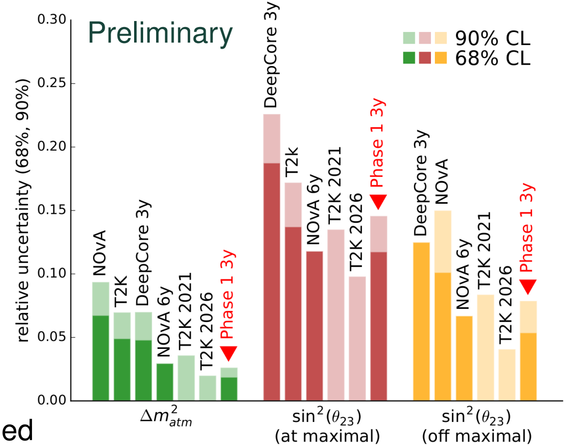


24 $\times$ 3” PMTs



IceCube Gen2 Phase1 analysis goals

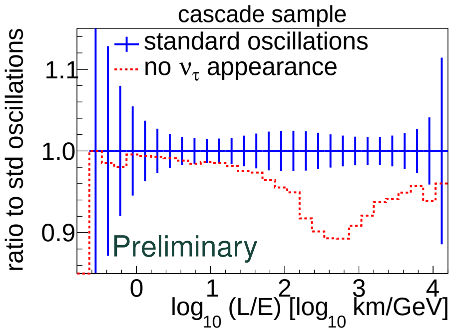
- ν_τ appearance analysis
- Sensitivity to θ_{23} and Δm^2_{31} complementary to dedicated LBL experiments ⟶
- Octant/Maximal mixing (3σ in 3 years for NOνA best fit θ_{23})
- Neutrino mass ordering (1.5-2σ in 3 years)
- Improvements on eV sterile ν searches, solar WIMP searches, . . .
- New calibration devices will also be installed
  - ⇒ Better ice description and calibration
  - ⇒ Improvements in reconstruction resolutions
  - ⇒ Improvement to neutrino astronomy

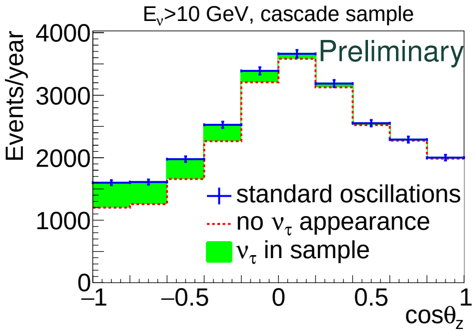


Proposal submitted to NSF

Signal for ν_τ appearance in IceCube-Gen2 Phase1

- Appearing ν_τ events usually classified as cascades
  - There is no clear μ track
- Our signal: ν_τ events at specific L/E region in cascade channel
  - Measurement done in 3D: $\cos\theta_z \times E \times PID$ space
  - 1D projection of $\cos\theta_z$ shown below for simplicity





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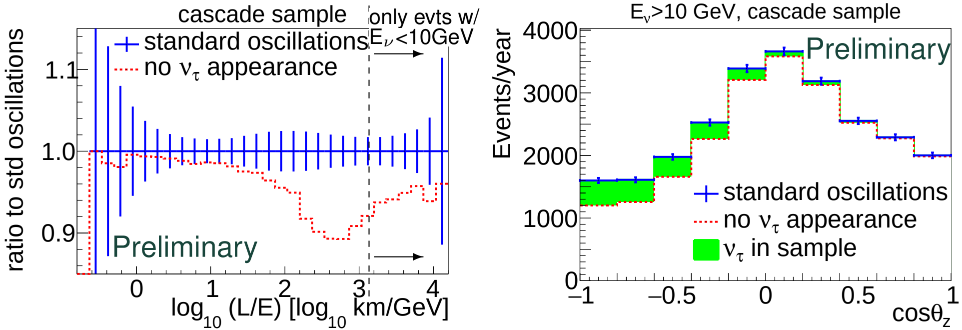


Systematic errors

Parameter	Priors
Atmospheric ν flux parameters	
$\Delta\gamma$ (spectral index)	0.00±0.10
ν_e normalization	1.00±0.20
ν NC normalization	1.00±0.20
$\Delta(\nu/\bar{\nu})$, energy dependent‡	$0 \pm 1\sigma$
$\Delta(\nu/\bar{\nu})$, zenith dependent‡	$0 \pm 1\sigma$
Cross section parameters (from GENIE)	
M_A (resonance) [GeV]	1.12±0.22
M_A (quasi-elastic) [GeV]	$0.99^{+0.25}_{-0.15}$

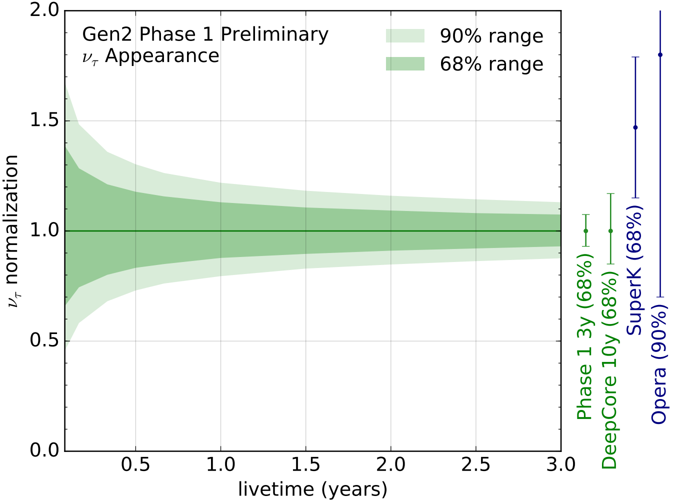
‡: Following Barr, et al., PRD 74, 094009.

Parameter	Priors
Standard mixing parameters	
Δm^2_{32}	no prior
$\sin^2\theta_{23}$	no prior
Detector parameters	
Hole ice scattering*	from calibration
DOM efficiency* [%]	100±10

*: Systematic change studied for IceCube-DeepCore used here.

- In general same systematics used for IceCube-DeepCore analysis
  - θ_{13}, DIS x-sec uncertainties tested and observed to be irrelevant
- Impact of systematics limited in result due to different $L \times E$ dependency to signal
- New calibration devices with IceCube-Gen2 Phase1 ⇒ improve detector systematics
- Leading systematics for ν_τ appearance: $\Delta(\nu/\bar{\nu})$, zenith dependent

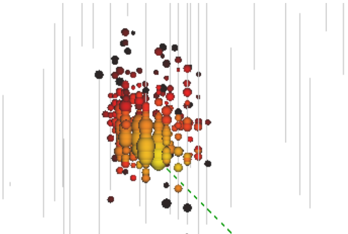
Sensitivity to ν_τ appearance in IceCube-Gen2 Phase1



* Projected DeepCore sensitivity using same sample as in pg 6.

- $<$ 7% precision in the ν_τ normalization after 3 years of data
- Not many experiments can do this measurement!

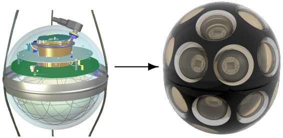
IceCube-Gen2 PINGU



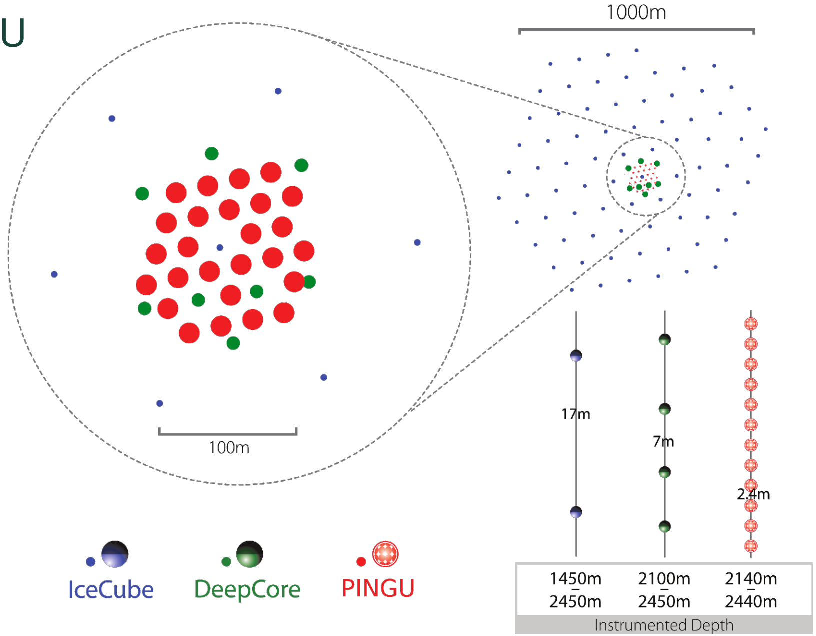
12 GeV ν_μ CC

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

IceCube DOM → mDOM

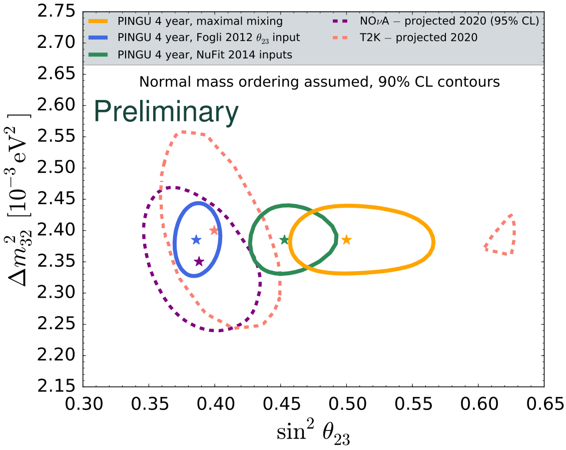


in LoI — plan to use



IceCube Gen2 PINGU analysis goals

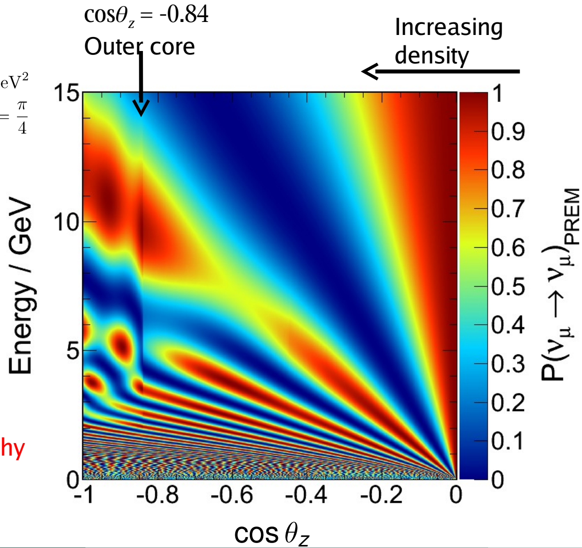
- Improves on IceCube-Gen2 Phase1 sensitivies across the board
- ν_τ appearance analysis:
  - in 6 months reach 10% precision
- Improved sensitivity to θ_{23} and Δm^2_{31} $\rightarrow$
- Neutrino mass ordering
- ...



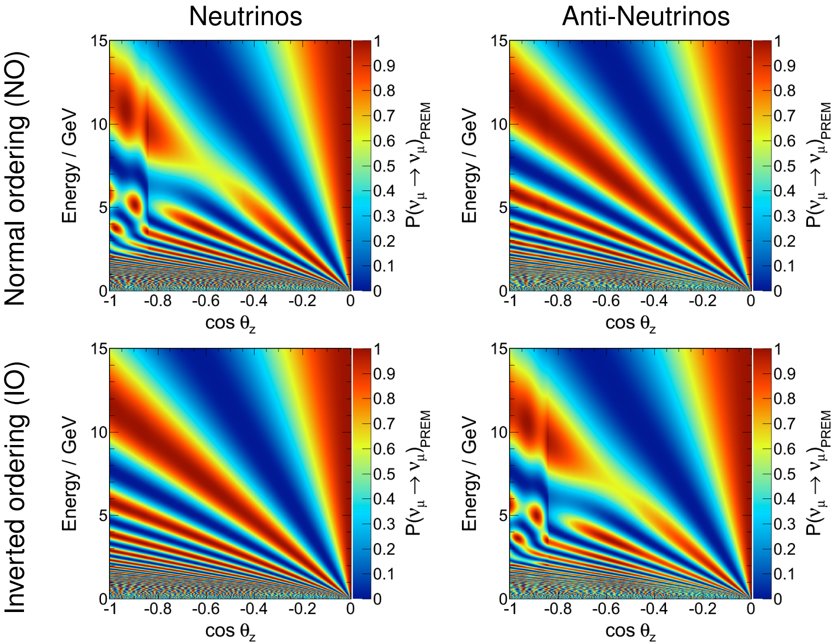
Neutrino oscillations in matter

$\Delta m^2_{32} = 2.32 \times 10^{-3}\,\text{eV}^2$

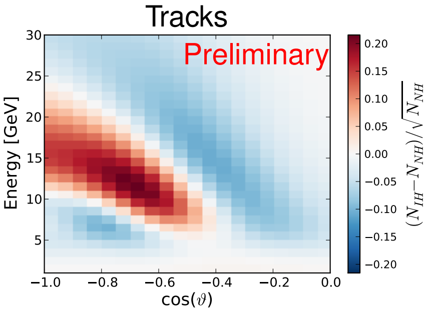
$\sin^2(2\theta_{23}) = \frac{\pi}{4}$

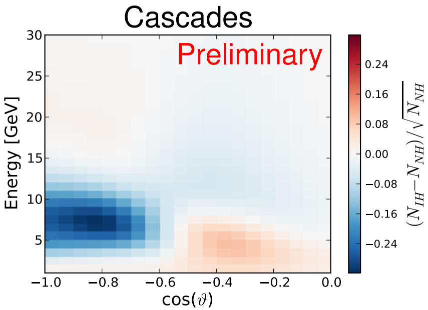


Neutrinos
Normal hierarchy


Neutrinos
Anti-Neutrinos
Normal ordering (NO)
Inverted ordering (IO)
Energy / GeV
cos θ_z
$P(\nu_\mu \rightarrow \nu_\mu)_{PREM}$

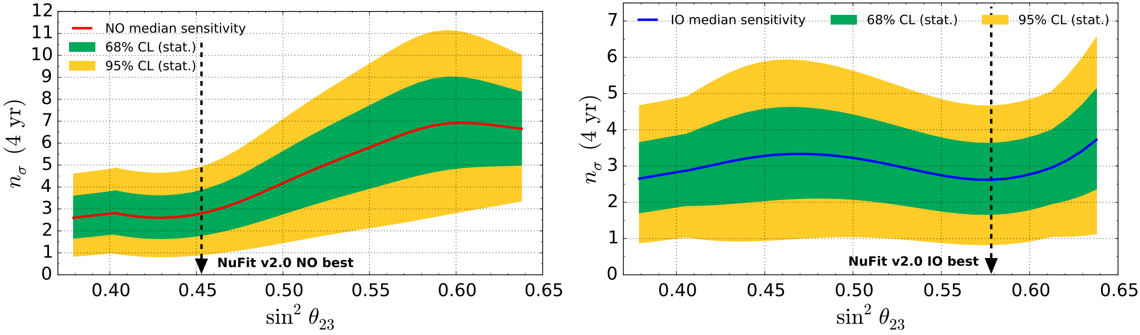
Neutrino Mass Ordering effect observable on PINGU





- PINGU cannot differentiate ν and $\bar{\nu}$: rely on difference in flux and cross-section
  - Large statistical samples: $\sim$33k $\nu_\mu + \bar{\nu}_\mu$ CC per year, $\sim$25k $\nu_e + \bar{\nu}_e$ 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

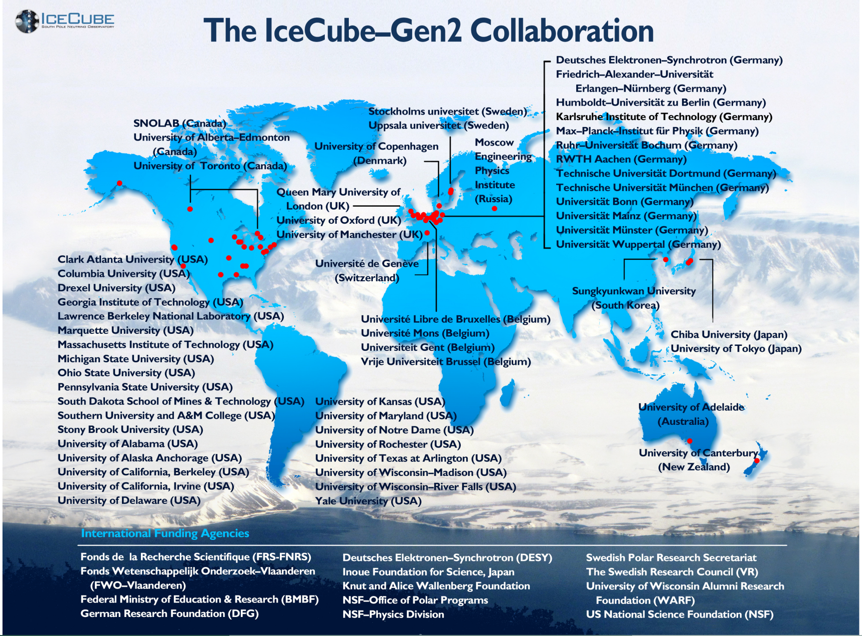
IceCube-Gen2 PINGU sensitivity to Neutrino Mass Ordering



- Sensitivities calculated with 2 different methods (LLR and $\overline{\Delta\chi^2}$) in agreement
- NMO sensitivity strongly depends on true θ_{23}
  - θ_{23} uncertainty also has large effect in precision: synergy with other efforts!
- 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

Summary

- IceCube-DeepCore detector: good performance to measure neutrino oscillations
  - Latest θ_{23} and Δm^2_{32} measurement of similar precision to those from accelerators
- IceCube-Gen2 Phase1: proposal submitted to NSF
  - First step towards full IceCube-Gen2 program
  - Very good sensitivity to ν_τ appearance: expected precision better than 7% after 3 years
  - Improvements in wide range of measurements expected
    - ⋆ including improvements to neutrino astronomy via improvement in calibrations!
- IceCube-Gen2 PINGU: going beyond IceCube-Gen2 Phase1
  - Potential low-energy extension within IceCube-Gen2
  - Essential to measure Neutrino Mass Ordering
  - Other improvements in broad physics program (ν oscillation, WIMPs, SNs, . . .)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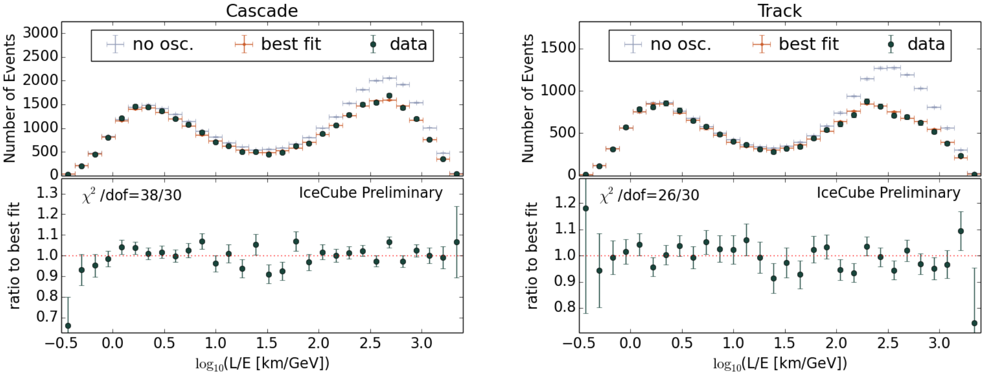
Backup slides

IceCube-DeepCore L/E

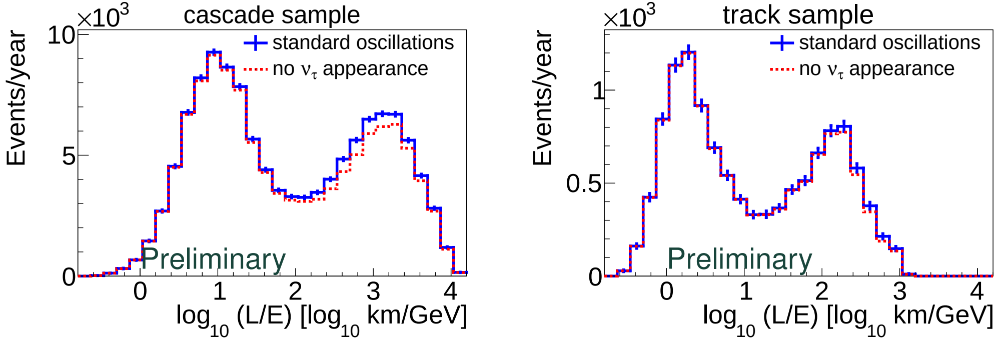


IceCube-DeepCore ν_μ disappearance result systematics

Parameter	Priors	Best fit NH	Best fit IH
Standard neutrino mixing parameters			
Δm^2_{32} [10^{-3} eV^2/c^4]	no prior	$2.31^{+0.12}_{-0.14}$	$-2.32^{+0.12}_{0.13}$
$\sin^2\theta_{23}$	no prior	$0.51^{+0.08}_{-0.08}$	$0.51^{+0.08}_{-0.07}$
Atmospheric neutrino flux parameters			
$\Delta\gamma$ (spectral index)	0.00±0.10	-0.02	-0.02
ν_e normalization	1.00±0.20	1.24	1.24
ν NC normalization	1.00±0.20	1.05	1.05
$\Delta(\nu/\bar{\nu})$, energy dependent	‡	-0.56σ	-0.60σ
$\Delta(\nu/\bar{\nu})$, zenith dependent	‡	-0.53σ	-0.55σ
Cross section parameters (from GENIE)			
M_A (resonance) [GeV]	1.12±0.22	0.91	0.92
Detector parameters			
DOM lateral sensitivity (hole ice)	0.020±0.010	0.022	0.022
DOM forward sensitivity (hole ice)	no prior	-0.76	-0.70
DOM efficiency [% of nominal]	100±10	103	103
Background			
Atm. μ contamination [%]	no prior	5.2	5.2

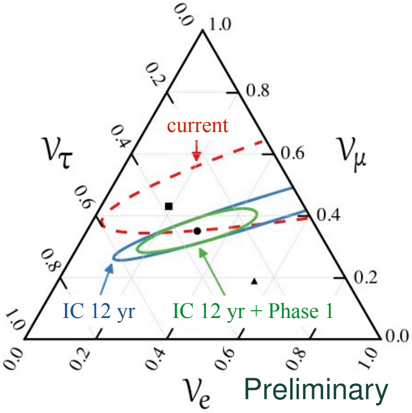
‡: Following Barr, et al., PRD74, 094009.

IceCube-Gen2 Phase1 L/E



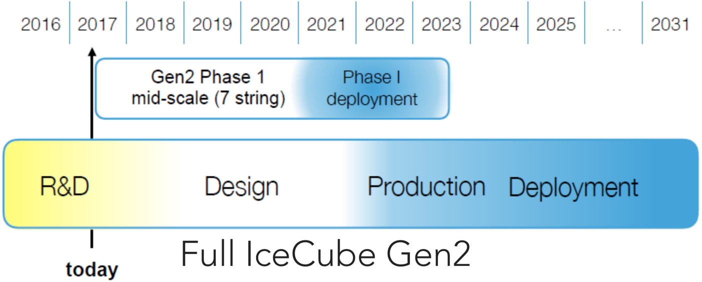
IceCube-Gen2 Phase1 impact in neutrino astronomy

- Better understanding of ice and calibration ⇒ improve reconstruction resolutions/PID
- Use better reconstructions to re-analyse existing IceCube data

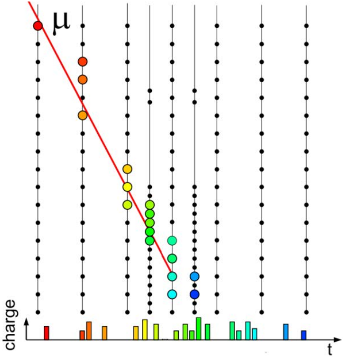


IceCube-Gen2 Phase1 timescale

- Proposals for Gen2 Phase I submitted to NSF and foreign partners
  - Seven strings of new instrumentation in the center of IceCube – tau physics and improved calibration to enable reanalysis with improved sensitivity

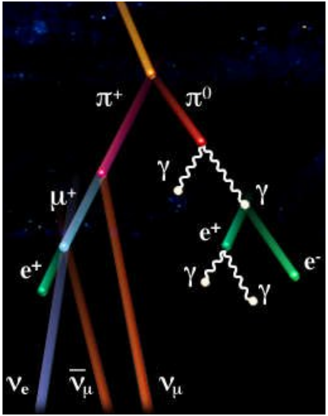


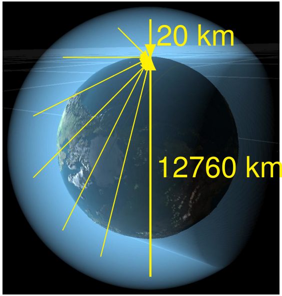
Measurement strategy



- Main background is atmospheric μ
  - Use IC as veto to reject atm μ events
- Reconstruct ν energy and direction
  - oscillation distance (L) given by zenith
- Do oscillation measurement!
- Same concept from DeepCore works on Gen2 Phase1

Atmospheric neutrinos

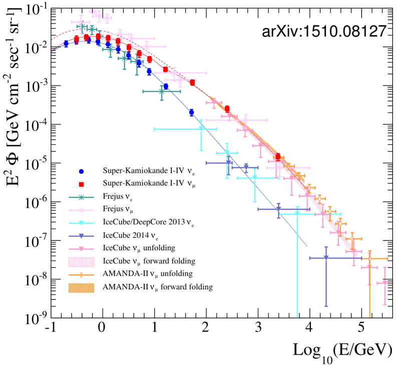


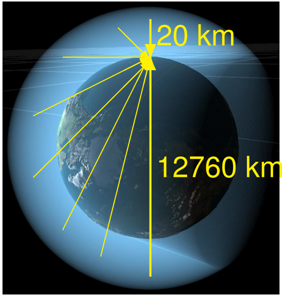


- 2:1 ratio between ν_μ:ν_e
- similar rate of ν and $\bar{\nu}$
  - however, x-sec for $\bar{\nu}$ half of ν

- various baselines available

Atmospheric neutrinos

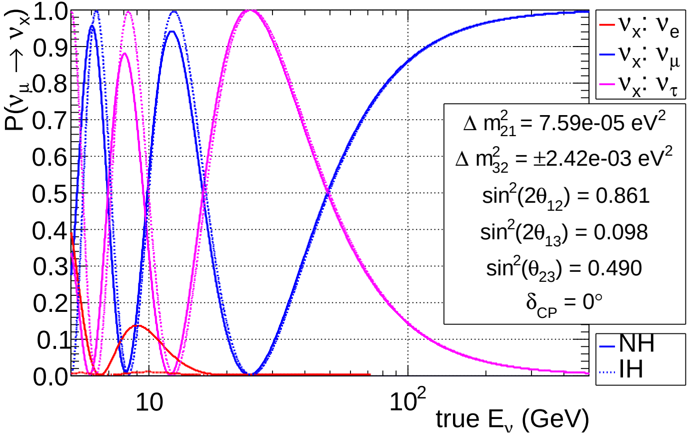




- ν energy over several orders of magnitude
- various baselines available

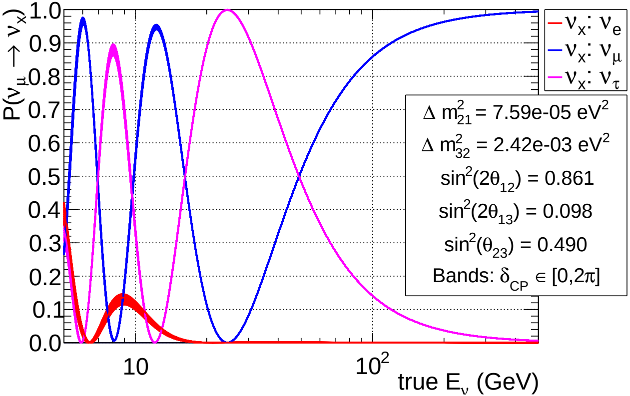
$\Rightarrow$ wide range of L/E available

Atmospheric neutrinos oscillations



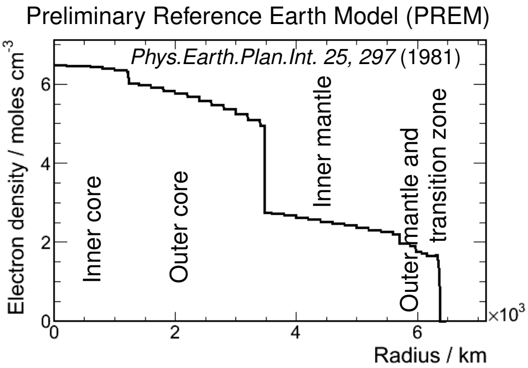
- Largest baseline (L=12760 km, cos $\theta_z = -1$) has:
  - First oscillation maxima at $\sim$ 25 GeV
  - Matter effects below $\sim$ 12 GeV
  - Potential for ν_e appearance at 8 GeV

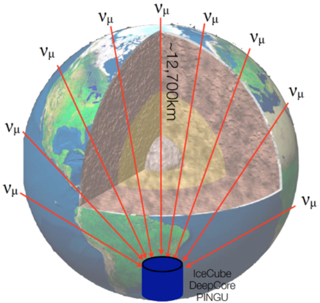
Atmospheric neutrinos oscillations



- Largest baseline (L=12760 km, cos $\theta_z = -1$) has:
  - First oscillation maxima at $\sim$ 25 GeV
  - δ_{CP} below $\sim$ 12 GeV
    - but matter effects dominate that region
  - Potential for ν_e appearance at 8 GeV

Matter Effects





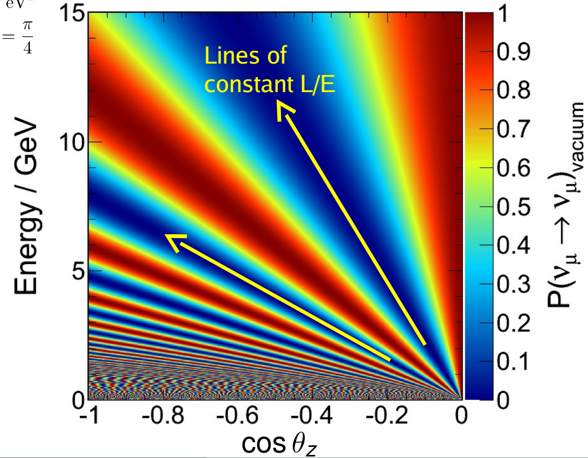
- MSW effect alter oscillation probabilities of ν (NH) or $\overline{\nu}$ (IH)
  - Sharp changes in density between zones produce visible effects in oscillation probabilities
- Different paths "see" different mass patterns $\Rightarrow$ can be probed by measuring the zenith of the neutrino

Neutrino oscillations in vacuum

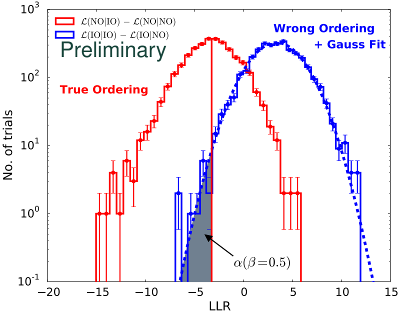
$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$\Delta m^2_{32} = 2.32 \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2(2\theta_{23}) = \frac{\pi}{4}$



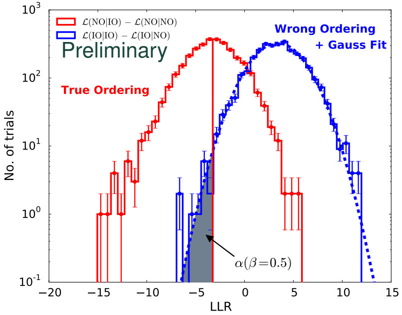
Estimating sensitivity to the NMO: Log Likelihood Ratio



1. Generate pseudo-data trial in analysis binning
   - True physics and systematics kept fixed for generation
2. Fit assuming NO and IO
3. Calculate log likelihood ratio between IO and NO

- Advantages of the method:
  - Can account for any systematic given
  - Does not pre-suppose shape of ΔLLH distribution
- Disadvantages of the method:
  - The significance “limited” by number of trials
    - ★ If Gaussian can provide approximate significances
  - Since each trial is a full fit (and given lots of trials needed) having large number of systematics can became prohibitively time consuming

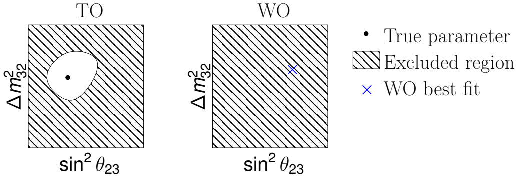
Median sensitivity



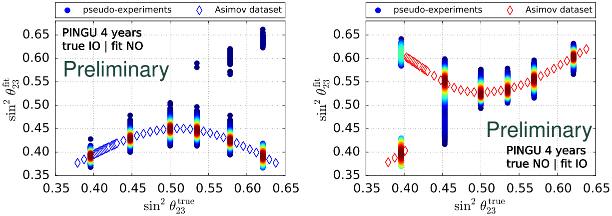
- For quantifying significance to measure ordering usually use median sensitivity
  - Widely used in literature
- “Median sensitivity” will mean that 50% of the time we can do better and 50% of the time we can do worse
- “Median sensitivity” calculated by integrating shade region under wrong ordering assumption
  - If distribution fits well Gaussian, integrate area under Gaussian curve instead of trial distribution

Excluding an ordering

- To say we measure the true ordering (TO) at a given CL we want to be able to exclude the wrong ordering (WO) for any value of the oscillation parameters



- Testing every point of the WO parameter space too costly
  - WO best-fit gives parameters of “maximum confusion” (used to get WO trial distribution)

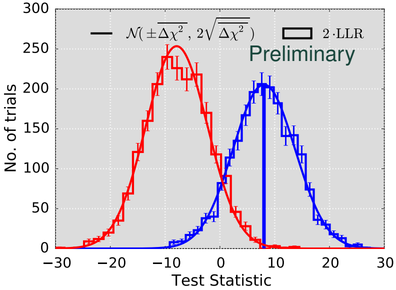


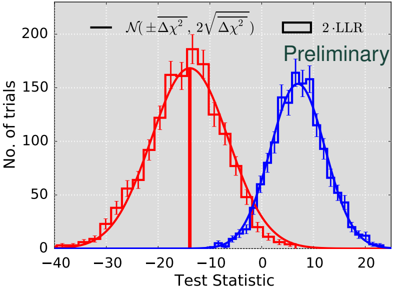
Estimating sensitivity to the NMO: $\Delta\chi^2$ method

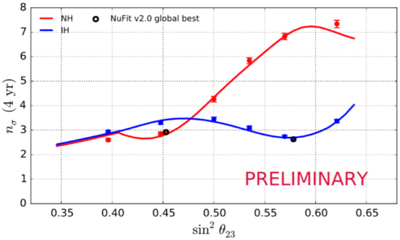
1. Get expected number of events in analysis binning
   - True physics and systematics kept fixed as in LLR method
   - But, no Poisson fluctuations applied
2. Calculate minimal $\overline{\Delta\chi^2}$ for the WO
   - $\overline{\Delta\chi^2} = \min_{p \in WO} \sum_i \left(\frac{\mu_i^{TO}(p_0) - \mu_i^{WO}(p)}{\sigma_i} \right)^2$
   - $\Delta\chi^2$ is Gaussian distributed with mean $\pm\overline{\Delta\chi^2}$ and sigma $2\sqrt{\overline{\Delta\chi^2}}$
3. Evaluate distribution of $\Delta\chi^2$ for NO and IO
   $\Rightarrow$ correspond to the LLR trial distribution

- Advantages of the method:
  - Linear systematics are extremely fast to be computed
  - Even with non-linear systematics still much faster than LLR
- Disadvantage of the method:
  - Intrinsic assumption of gaussianity of final distribution
  - Not possible to include non-centered priors
    - ★ cannot include prior on θ_{23} due to “maximum confusion” method

Comparing Test Statistic of LLR and $\Delta\chi^2$







- Good agreement between TS

$\Rightarrow$ sensitivities in agreement
  - lines from $\Delta\chi^2$
  - points from LLR