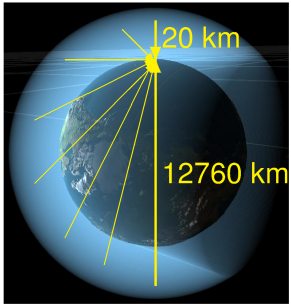
Recent Results from IceCube: ν oscillations

João Pedro Athayde Marcondes de André
for the IceCube Collaboration

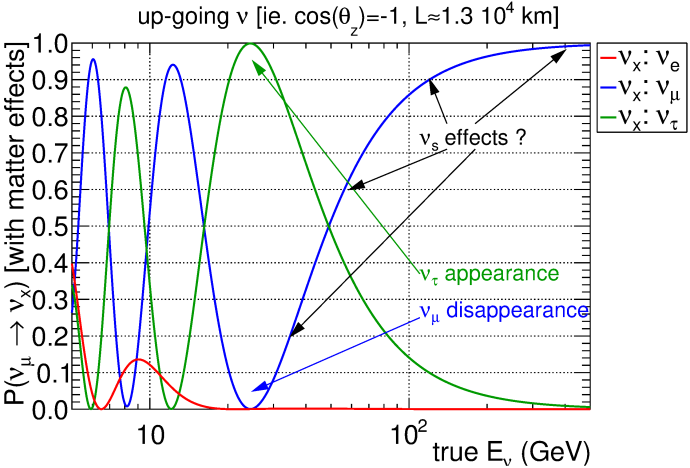
MICHIGAN STATE UNIVERSITY

24 March 2017

Neutrino oscillations with atmospheric neutrinos



- Several baselines available
  - L/E dependency on oscillation
  - Many orders of magnitude in E
- IceCube:
  - See clear ν_μ disappearance
  - Look for distortions in regular oscillations $\Rightarrow$ sterile neutrino searches

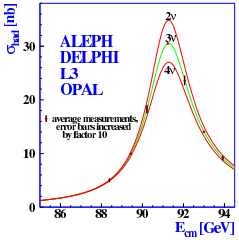


- IceCube not (very) sensitive to:
  - Neutrino mass ordering, δ_{CP}, ν_e appearance

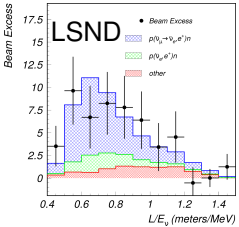
Sterile Neutrino

- From LEP: only 3 light ν couple with Z^0
- Many anomalies found in different experiments could be explained if there were more ν
  - Ga anomaly
  - LSND signal
  - MiniBOONE excess
  - Reactor anomaly
- At the same time other experiments didn't see anomalies in similar regions
- Need more data!

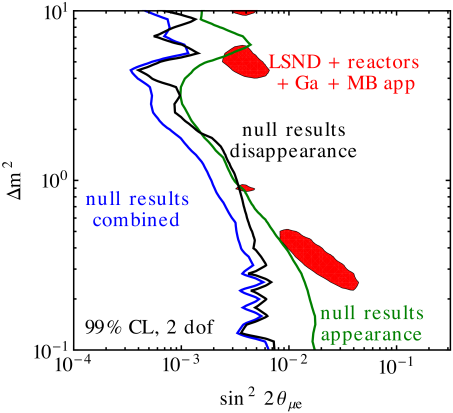
J.Phys.Rep. 427 257 (2006)



from arXiv:1204.5379

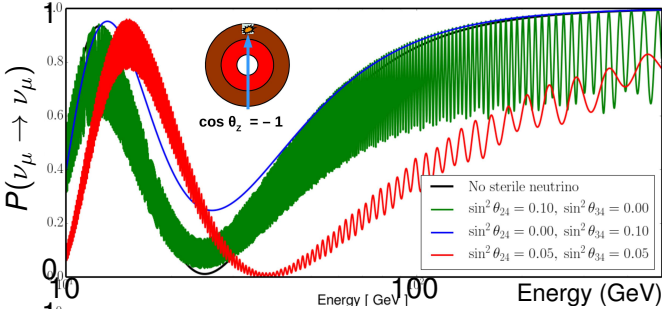


J. Kopp et al., JHEP 1305 (2013) 050

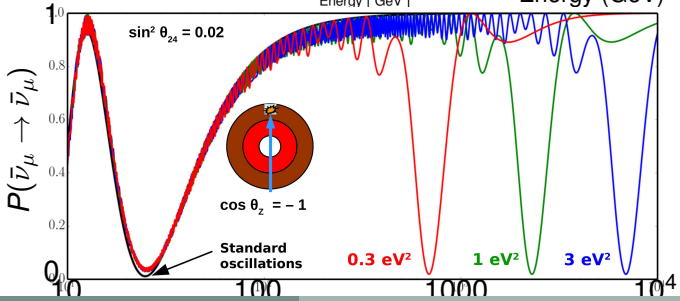


Sterile Neutrino Signatures in IceCube

- Signature LE: distortion in ν_μ disappearance
  - At 10-100 GeV
  - Sensitive to $\nu_\mu \leftrightarrow \nu_s \leftrightarrow \nu_\tau$
  - Not sensitive to Δm^2
    - ★ "Averaged out" effect

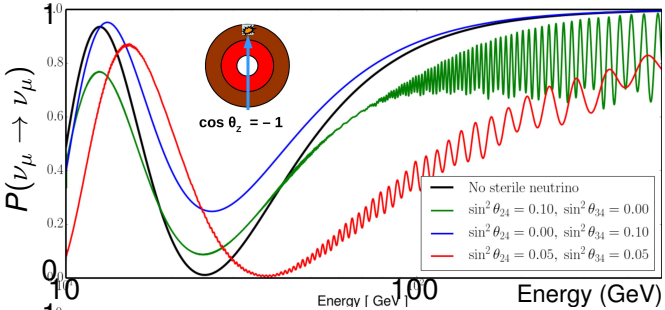


- Signature HE: new ν_μ disappearance maxima
  - At 0.5-10 TeV
  - Sensitive to $\nu_\mu \leftrightarrow \nu_s$
  - Sensitive to Δm^2
  - Resonant enhancement from matter effects
    - ★ highly sensitive to θ

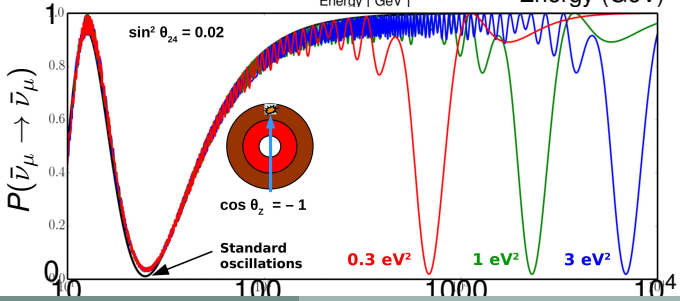


Sterile Neutrino Signatures in IceCube

- Signature LE: distortion in ν_μ disappearance
  - At 10-100 GeV
  - Sensitive to $\nu_\mu \leftrightarrow \nu_s \leftrightarrow \nu_\tau$
  - Not sensitive to Δm^2
    - ★ "Averaged out" effect

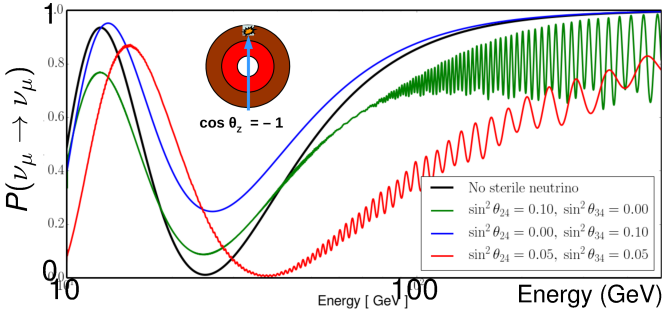


- Signature HE: new ν_μ disappearance maxima
  - At 0.5-10 TeV
  - Sensitive to $\nu_\mu \leftrightarrow \nu_s$
  - Sensitive to Δm^2
  - Resonant enhancement from matter effects
    - ★ highly sensitive to θ

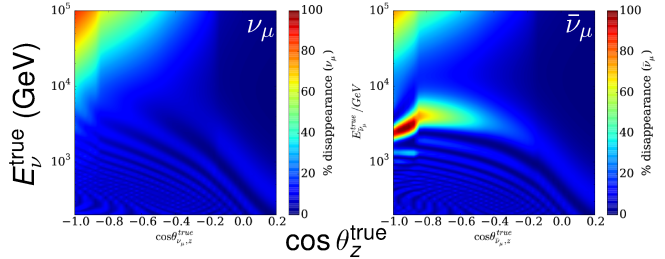


Sterile Neutrino Signatures in IceCube

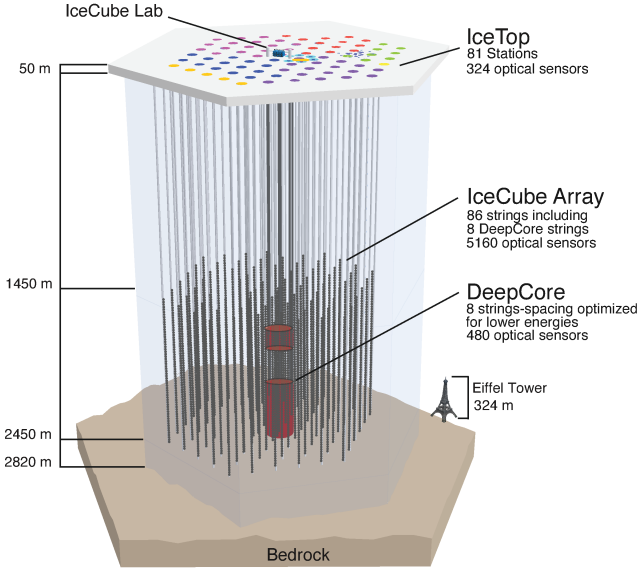
- Signature LE: distortion in ν_μ disappearance
  - At 10-100 GeV
  - Sensitive to $\nu_\mu \leftrightarrow \nu_s \leftrightarrow \nu_\tau$
  - Not sensitive to Δm^2
    - ★ "Averaged out" effect



- Signature HE: new ν_μ disappearance maxima
  - At 0.5-10 TeV
  - Sensitive to $\nu_\mu \leftrightarrow \nu_s$
  - Sensitive to Δm^2
  - Resonant enhancement from matter effects
    - ★ highly sensitive to θ



IceCube

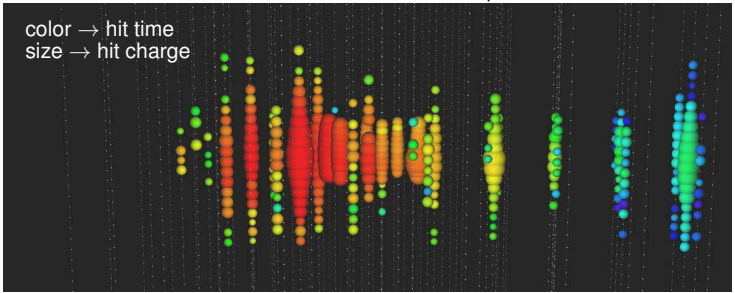


- Instrument 1 Gton of ice
- Optimized for TeV-PeV neutrinos
  - Astrophysical ν discovered!
  - Sensitive to the ν_s HE signature
- At it's center: DeepCore
  - $\sim$10 Mton region with denser instrumentation
  - $\Rightarrow$ lower E threshold
  - $\Rightarrow$ study neutrino oscillations
  - $\Rightarrow$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

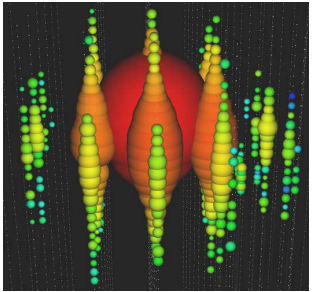
Events in IceCube

- μ produce long tracks in detector $\Rightarrow$ use that to categorize events
  - At high energy: 1° pointing accuracy for track-likes $\rightarrow$ know L well

Track-like events: mainly ν_μ CC events

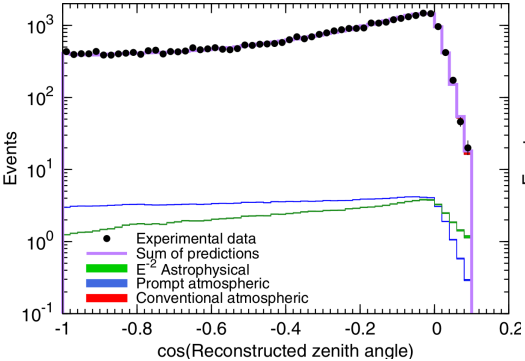


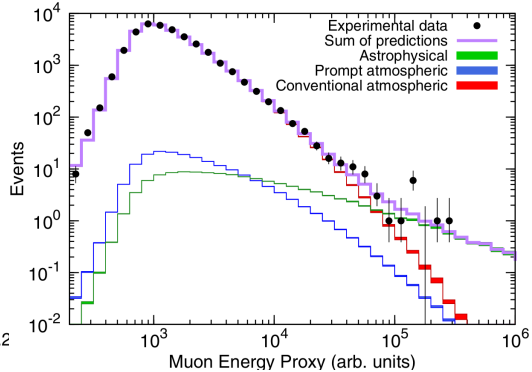
Cascade-like events



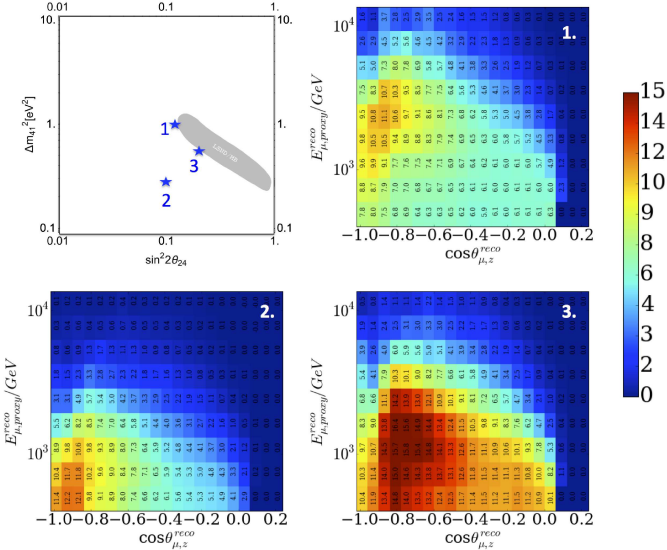
Searching for ν_s HE signature in IceCube

- Select through-going tracks (ν_μ events)
- Highest rate at $\sim$1 TeV
  - resonance condition for $\Delta m^2 \sim 1$ eV^2 $\rightarrow$ same as from LSND/MiniBoone anomalies

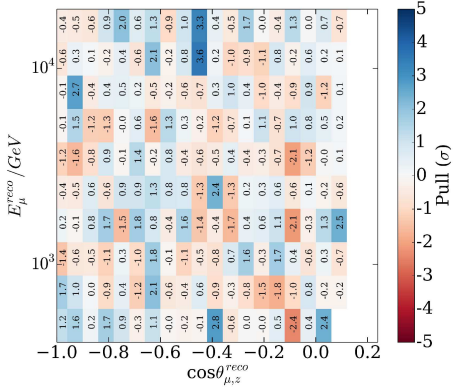




What possible signals would look like…



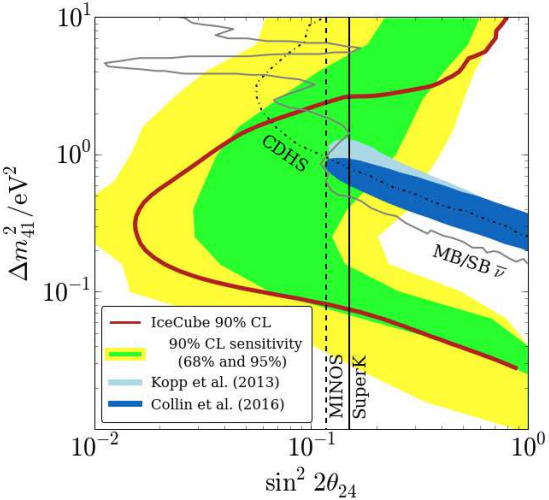
and what we measured



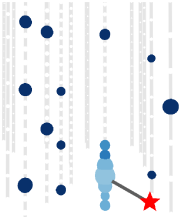
Statistical pulls from data at no-sterile best fit

Results from HE sterile search

- Result compatible with no-sterile hypothesis ⇒ set new limit
  - Only using 1 year of data, statistics limited → more to come



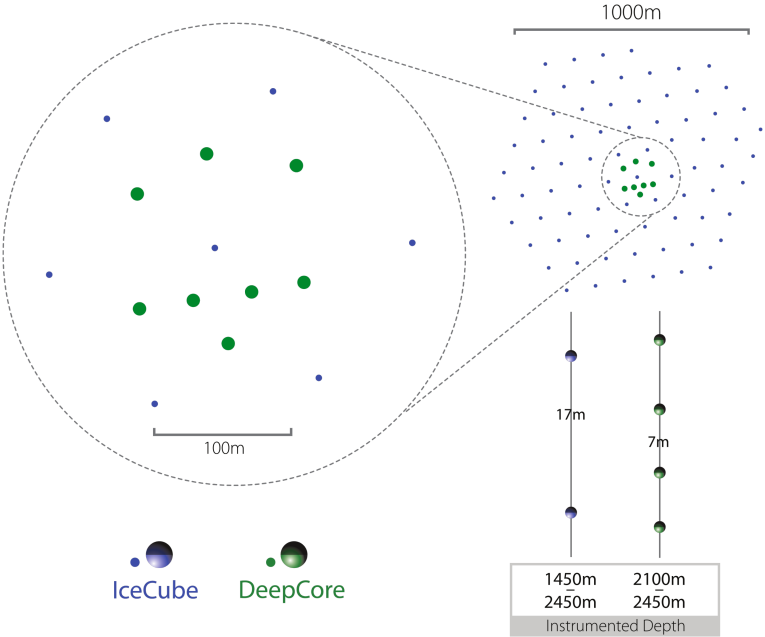
IceCube-DeepCore



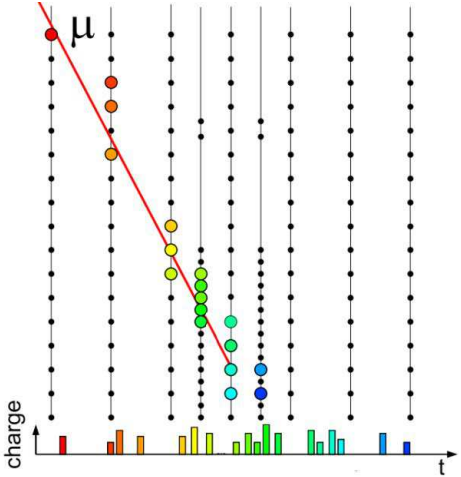
12 GeV ν_μ CC

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

- Denser instrumentation
- needed for ν oscillation
- needed for LE ν_s search



General Low-Energy Measurement Strategy



- Main background is atmospheric μ
  - Use IceCube as veto to reject atm μ events
- Reconstruct ν energy and direction
  - oscillation distance (L) given by zenith
- Measure oscillation by fitting $L \times E$ distribution

Samples used for Low-Energy Analyses

LE ν_s search

- Used in ν_μ disappearance "IC2014": PRD 91, 072004 (2015)
- Focus on ν_μ CC "golden events"
  - Clear μ tracks
  - Several non-scattered photons
- Use only up-going events

Similarities in both analyses

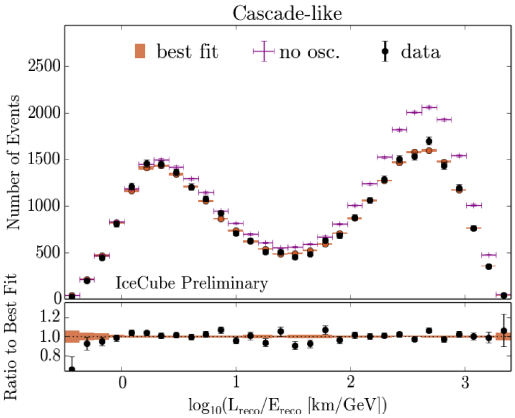
- Atmospheric μ background shape estimated from data
- ν reconstruction resolution similar
- 3 year data sets
- Similar set of systematics

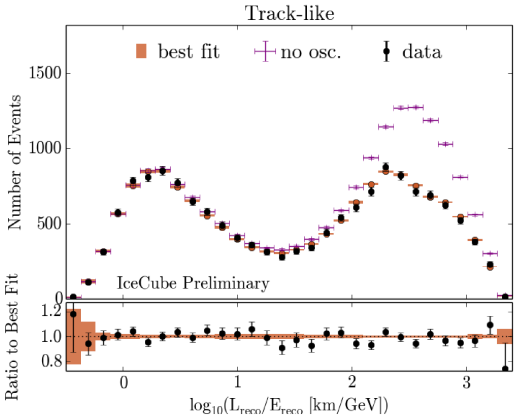
ν_μ disappearance

- Reconstruction fits full event topology with LLH-based method
  - Can fit events with scattered photons
  - Can reconstruct all ν types
- Order of magnitude more in statistics
- Full sky analysis
  - Better control of systematics
- PID variable separates sample in two:
  - Track: ν_μ CC enriched sample
  - Cascade: mix of all ν flavors
- Fitting includes term accounting for statistical uncertainty from prediction
- Brand new result: first shown Feb-2017

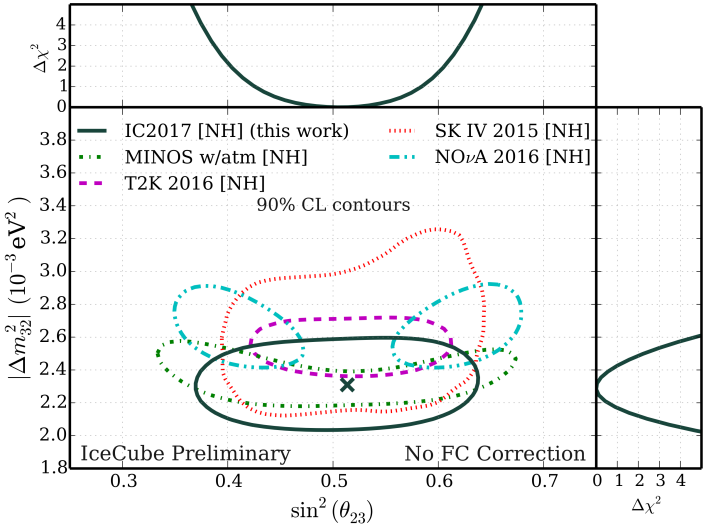
IceCube-DeepCore: ν_μ disappearance measurement

- Fitting done in 3D space (E,cos θ_z, PID) $\rightarrow$ projected in L/E for illustration
- Analysis donw with $E_{\text{reco}} \in [5.6, 56]$ GeV
  - Different E range (and baselines) than for accelerator based studies





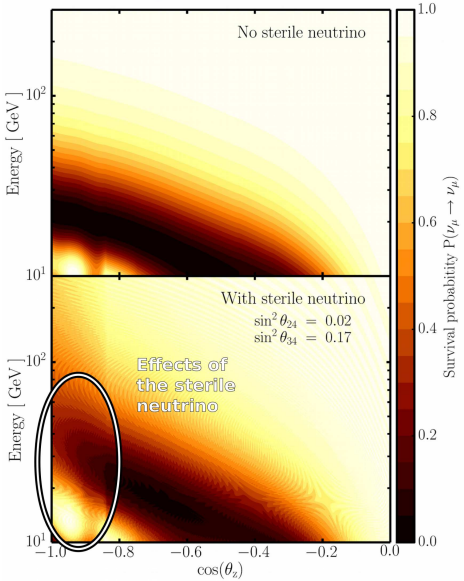
IceCube-DeepCore: ν_μ disappearance measurement



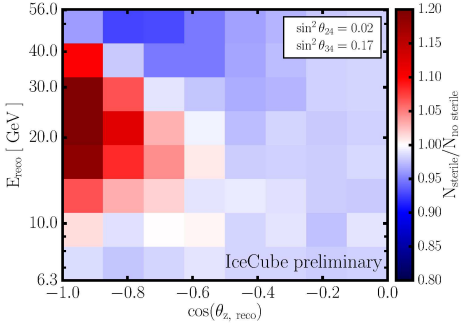
$$\frac{\chi^2}{ndf} = \frac{123}{119}$$

- Consistent & competitive results to accelerator based measurements

IceCube-DeepCore: Sterile Neutrino effect in sample

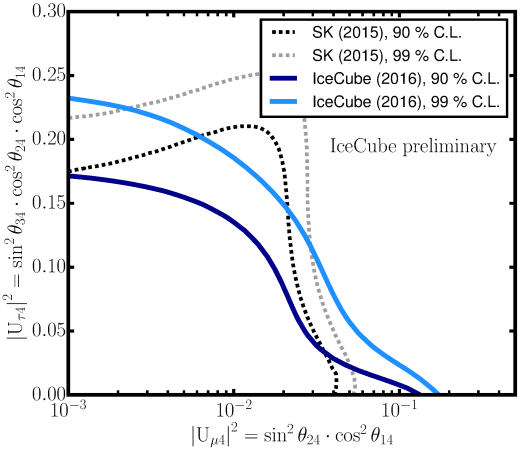


- ν_s effect stronger if more matter $\rightarrow$ was produced by the HE resonant effect
- Clear "averaged" effect of ν_s
  - Different $L \times E$ dependency than regular oscillation



IceCube-DeepCore: LE Sterile Neutrino result

- Result compatible with no-sterile hypothesis
- Limits comparable to those of SK
  - Strong limits on $|U_{\tau 4}|^2$, not accessible from HE ν_s search

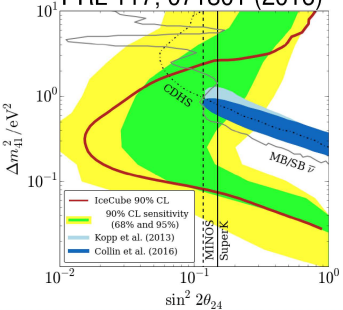


Submitted to journal and to arXiv:1702.05160

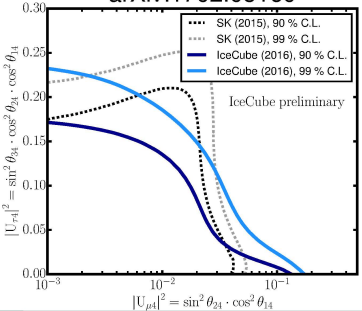
Summary

- Using IceCube data to test sterile neutrino hypothesis:
  - HE and LE analysis consistent with 3-flavor ν oscillations
  - Strong (complementary) limits placed with both analyses
  - Currently work on-going on both analyses to improve sensitivity (new cuts, new data)
- Recent progress also made in ν_μ disappearance analysis
  - Significant reduction in θ_{23} and Δm^2_{32} ranges
    - ★ Preference for maximal mixing, like T2K
  - Other measurements with this sample are under way!

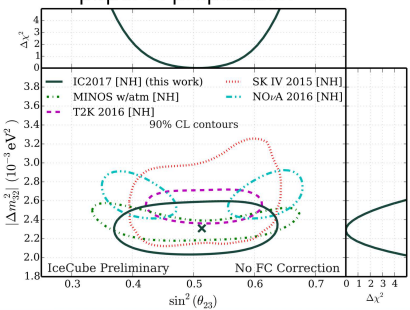
PRL 117, 071801 (2016)



arXiv:1702.05160



paper in preparation



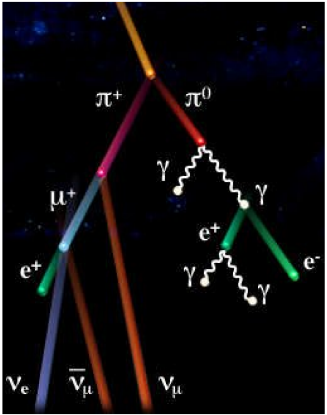
The IceCube Collaboration

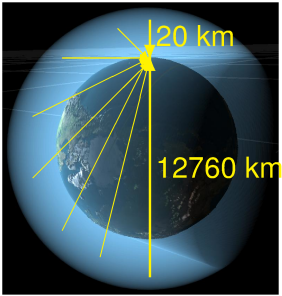
Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Backup slides

Atmospheric neutrinos

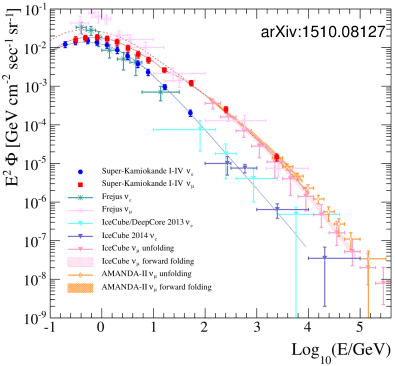


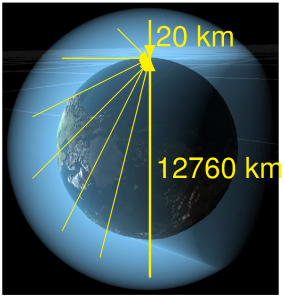


- 2:1 ratio between ν_μ:ν_e
- similar rate of ν and $\bar{\nu}$
  - however, x-sec for $\bar{\nu}$ half of ν

- various baselines available

Atmospheric neutrinos

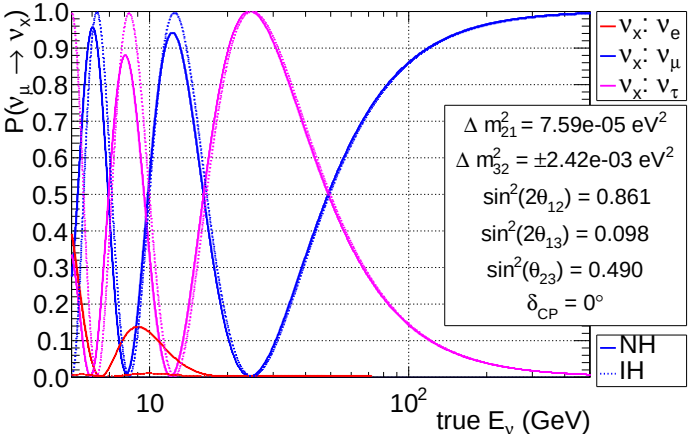




- ν energy over several orders of magnitude
- various baselines available

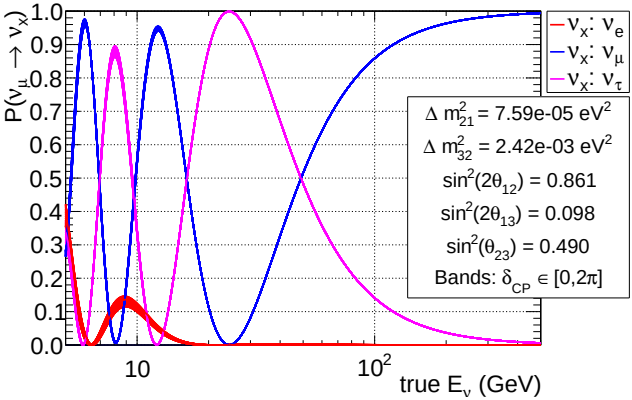
$\Rightarrow$ wide range of L/E available

Atmospheric neutrinos oscillations



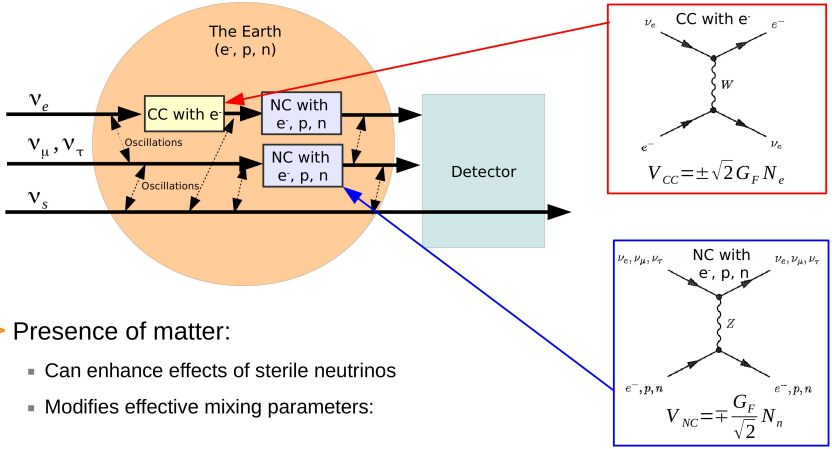
- Largest baseline (L=12760 km, $\cos\theta_z = -1$) has:
  - First oscillation maxima at $\sim$ 25 GeV
  - Matter effects below $\sim$ 12 GeV
  - Potential for ν_e appearance at 8 GeV

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: schema



> Presence of matter:

- Can enhance effects of sterile neutrinos
- Modifies effective mixing parameters:

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 \pm \frac{2 E V_{\text{int}}}{\Delta m^2 \cos 2\theta}}$$

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta \pm 2 E V_{\text{int}})^2 + (\Delta m^2 \sin 2\theta)^2}$$

Matter effects: oscillation enhancement

$$\tan 2\theta_M = \frac{\tan 2\theta}{1 - \frac{2EV_{\text{int}}}{\Delta m^2 \cos 2\theta}}$$

$$\Delta m_M^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2EV_{\text{int}})^2 + (\Delta m^2 \sin 2\theta)^2}$$

At resonance

$$E_R = \frac{\Delta m^2 \cos 2\theta}{2V_{\text{int}}}$$

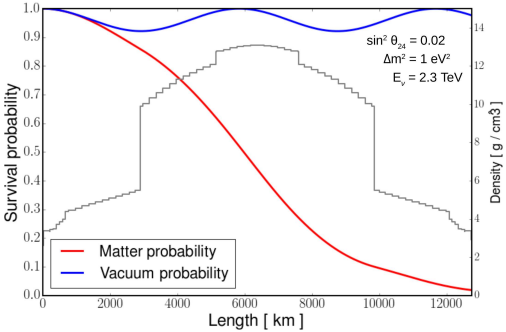
Maximal mixing:

$$\theta_M = \frac{\pi}{4}$$

$$\Delta m_M^2 = \Delta m^2 \sin 2\theta$$

Maximal oscillations length

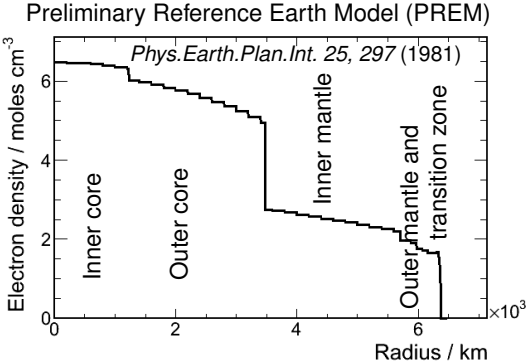
> Matter can enhance sterile neutrino signal

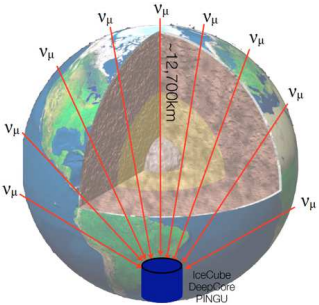


> Parametric resonance (NOLR):

- Resonant enhancement of oscillations magnitude
- Oscillation length in core ~2 core sizes
- Resonant disappearance of muon anti-neutrinos
- Resonance energy ~ TeV

Matter Effects





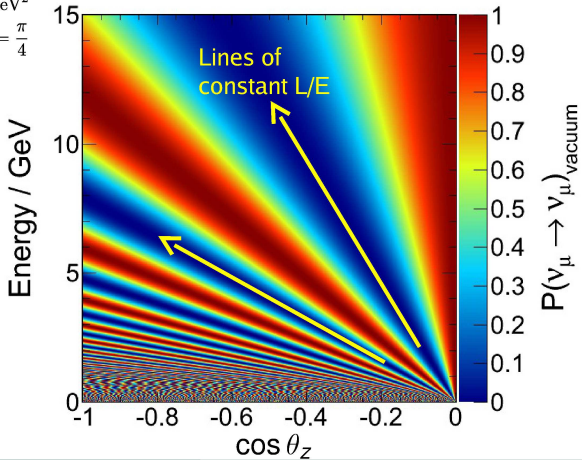
- MSW effect alter oscillation probabilities of ν (NH) or $\overline{\nu}$ (IH)
  - Sharp changes in density between zones produce visible effects in oscillation probabilities
- Different paths "see" different mass patterns $\Rightarrow$ can be probed by measuring the zenith of the neutrino

Neutrino oscillations in vacuuum

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

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

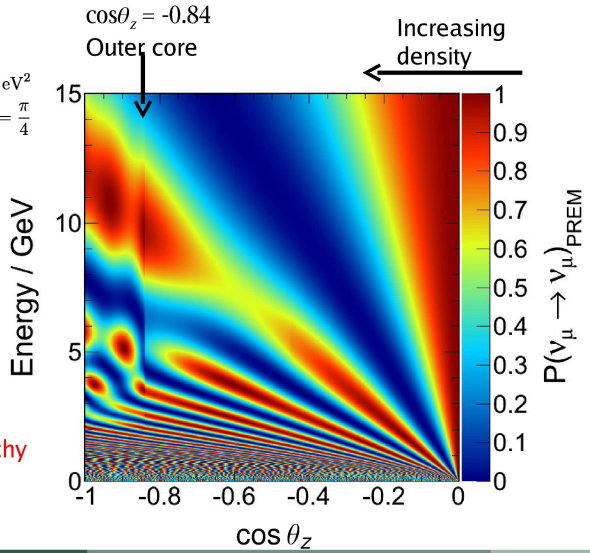
$\sin^2(2\theta_{23}) = \frac{\pi}{4}$



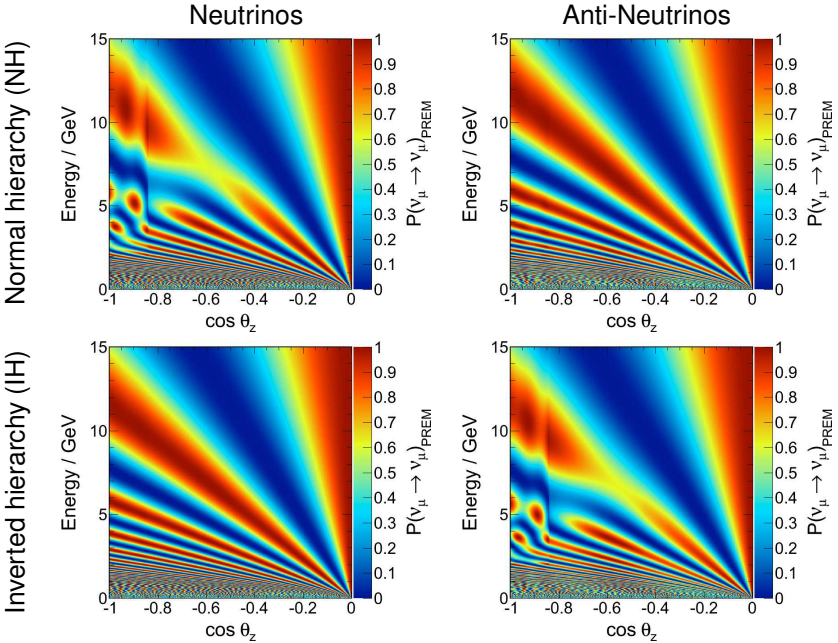
Neutrino oscillations in matter

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

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

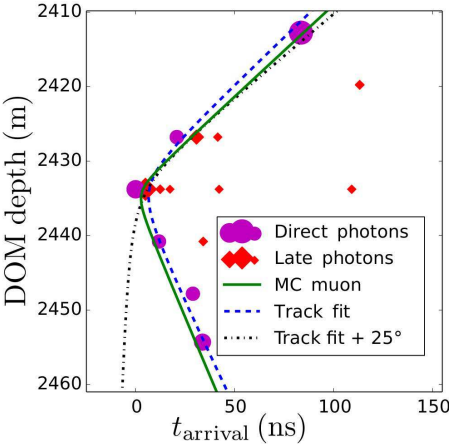


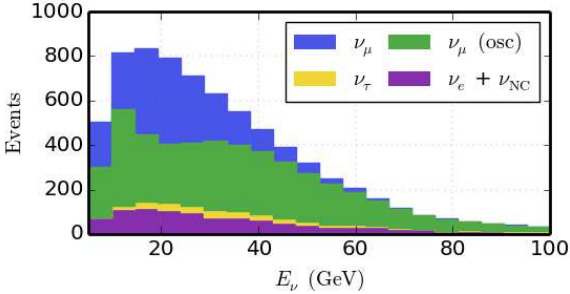
Neutrinos
Normal hierarchy


Neutrinos
Anti-Neutrinos
Normal hierarchy (NH)
Inverted hierarchy (IH)
Energy / GeV
cos θz
P(νμ → νμ)PREM
15
10
5
0
-1
-0.8
-0.6
-0.4
-0.2
0
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

“golden events”

- Clear μ tracks
  - Reduce contamination of cascades (primarily ν NC and ν_e CC)

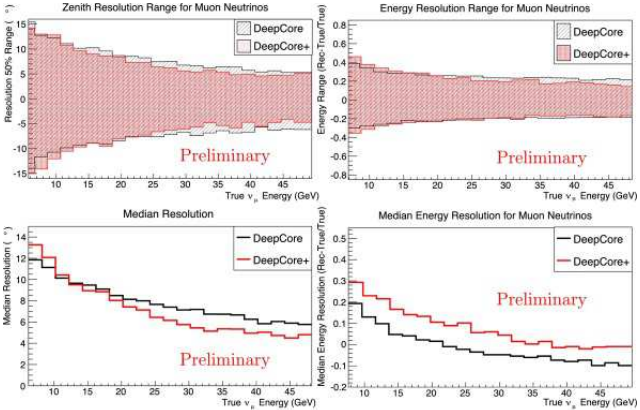




- Require several non-scattered γ
- select events “easy” to reconstruct
  - 10° resolution in neutrino zenith
  - 25% resolution in neutrino energy

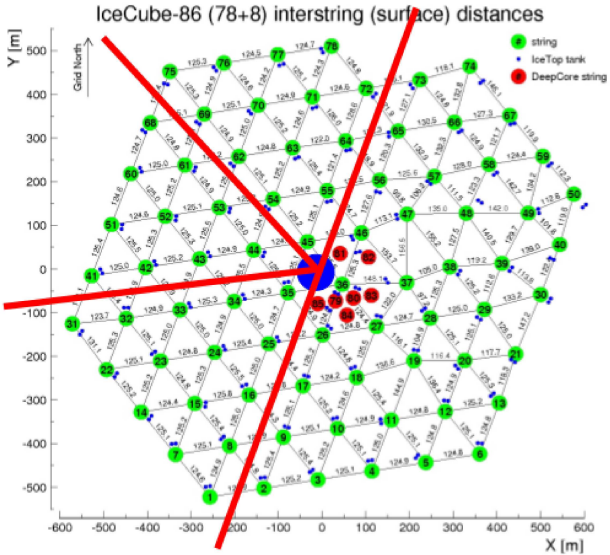
LH-based reconstruction using MultiNest

- MultiNest is an implementation of nested-sampling algorithm
  - alternative approach to Markov Chain MC
  - designed to work efficiently in multi-modal likelihood spaces
- We use it in place of a “minimizer”
  - Reconstruct 8 parameters describing low-energy ν_μ CC (HybridReco)
    - ★ (x,y,z,t) + (zenith, azimuth) + (track length, cascade energy)
  - If used while fixing track length at 0 m ⇒“cascade fit”
  - Use the likelihood function defined in Millipede (Poisson)

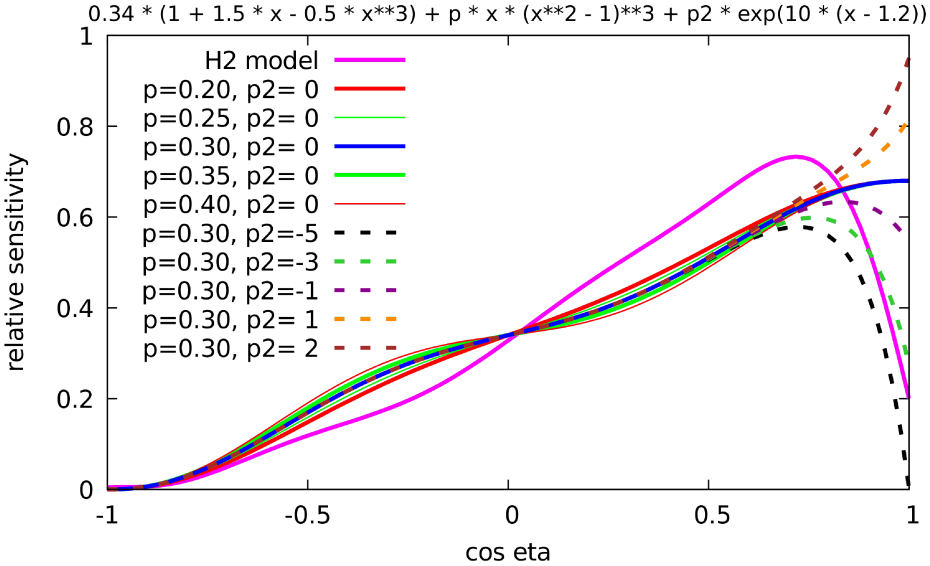


(a) Zenith resolution. (b) Energy resolution.

Inverted Corridor Cut



DOM sensitivity: parametrizing the hole ice column effect



HE ν_S search

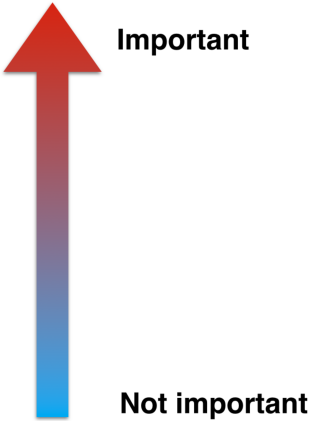
from C. Arguelles @ICHEP2016

Systematics!

Systematics are super important; *some are more than others*.
These are the systematics we considered:

- *DOM efficiency*
- *Flux continuous parameters*
  - *spectral index*
  - *π/K ratio*
  - *$\nu/\bar{\nu}$ ratio*
- Air shower hadronic models
- Primary cosmic ray fluxes
- Hole ice
- Neutrino cross sections
- Bulk ice scattering/absorption
- Earth model

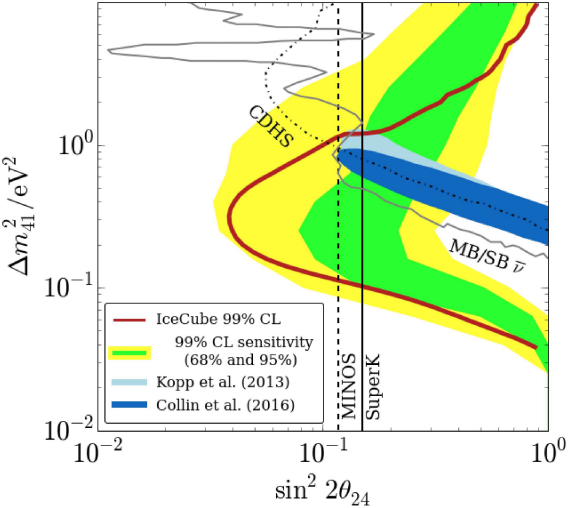
continuous systematics
discrete systematic

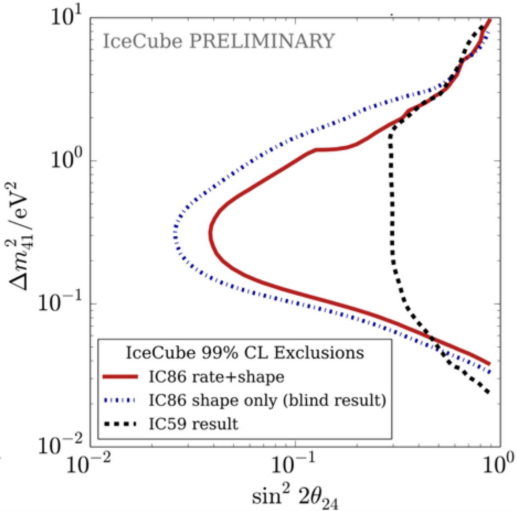


35

99% CL

✤We unblinded one year of data which had ~ 20 000 neutrino events.





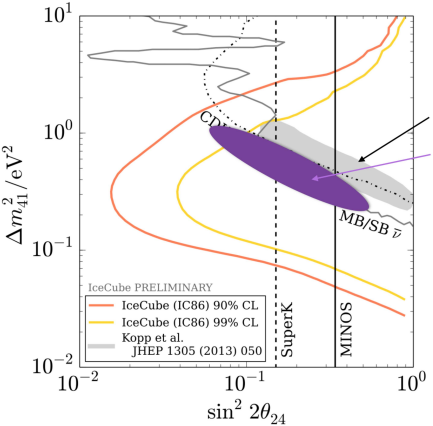
Correspondence between angles being measured

$$
\begin{aligned}
\sin^2 2\theta_{ee} &= \sin^2 2\theta_{14} \\
\sin^2 2\theta_{\mu\mu} &= 4\cos^2\theta_{14}\,\underline{\sin^2\theta_{24}}\left(1-\cos^2\theta_{14}\sin^2\theta_{24}\right) \\
\sin^2 2\theta_{\mu e} &= \sin^2 2\theta_{14}\,\underline{\sin^2\theta_{24}} \\
\sin^2 2\theta_{e\tau} &= \sin^2 2\theta_{14}\cos^2 2\theta_{24}\sin^2\theta_{34} \\
\sin^2 2\theta_{\mu\tau} &= \underline{\sin^2 2\theta_{24}}\cos^4\theta_{14}\sin^2\theta_{34}
\end{aligned}
$$

from C. Arguelles @ICHEP2016

Relationship with other angles

- $\sin^2 2\theta_{ee} \equiv 4|U_{e4}|^2(1-|U_{e4}|^2)$: reactor experiments.
- $\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu4}|^2(1-|U_{\mu4}|^2)$: MINOS, SK. (**this analysis**)
- $\sin^2 2\theta_{\mu e} \equiv 4|U_{\mu4}|^2|U_{e4}|^2$: LSND, MB, KARMEN, NOMAD.



BF: $|U_{e4}|^2 = 0.023$

3σ: $|U_{e4}|^2 = 0.048$

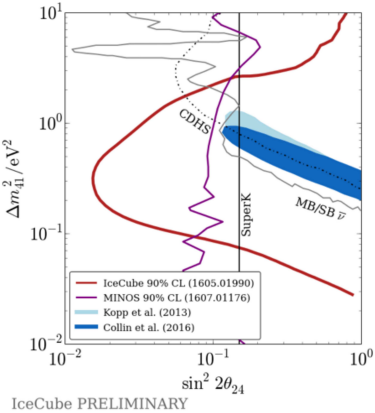
(Kopp et al. arXiv:1303.3011)

32

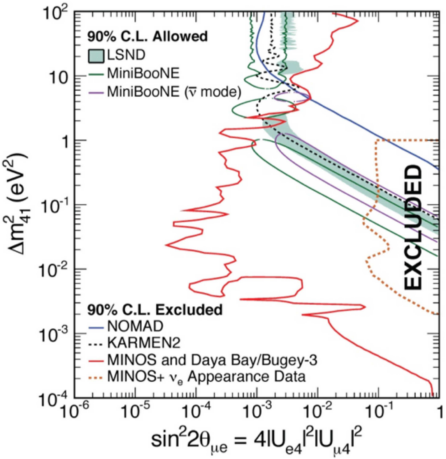
from C. Arguelles @ICHEP2016

Other new results from *Neutrino2016*

MINOS



MINOS+Daya Bay

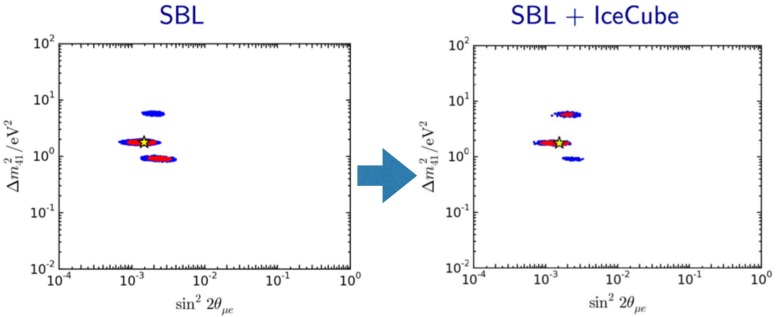


arXiv:1607.01176,1607.01177

27

from C. Arguelles @ICHEP2016

A new global fit with IceCube



3+1	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu 4}\rvert$	$\lvert U_{\tau 4}\rvert$	N_{bins}	χ^2_{min}	χ^2_{null}	$\Delta\chi^2$ (dof)
SBL	1.75	0.163	0.117	-	315	306.81	359.15	52.34 (3)
SBL+IC	1.75	0.164	0.119	0.00	524	518.59	568.84	50.26 (4)
IC	5.62	-	0.314	-	209	207.11	209.69	2.58 (2)

G.Collins, C.A., J. Conrad, M. Shaevitz (arXiv:**1602.00671** and arXiv:**1607.00011**)[33]

LE ν_S search

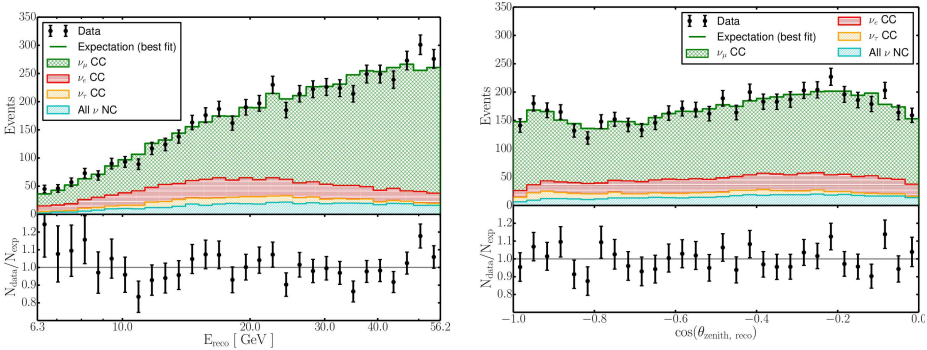


FIG. 8. Event rates shown as a function of (top) E_{reco} and (bottom) $\cos\theta_{z,reco}$. The various different neutrino components from Monte Carlo simulation used in the fit are shown as stacked histograms. The total expected event rate is in good agreement with the observed data, shown as black points.

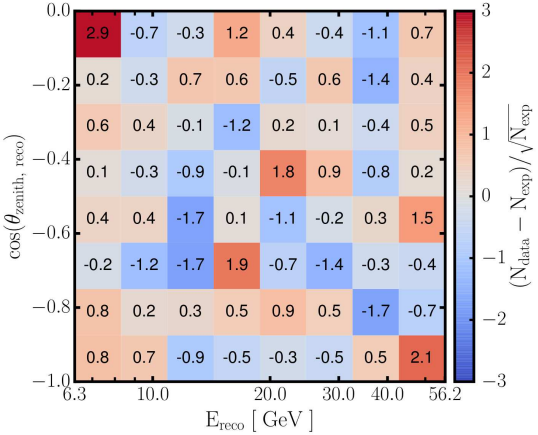


FIG. 7. Statistical pulls between data and expectation for the best fit point.

TABLE I. A list of the nuisance parameters, priors (if used) and their best fit point obtained in the analysis.

Parameter	Priors	Best fit
Standard mixing parameters		
$\lvert\Delta m^2_{32}\rvert$ [$10^{-3}\mathrm{eV}^2$]	no prior	2.52
$\sin^2\theta_{23}$	no prior	0.541
Flux parameters		
γ	no prior	−2.55
ν_e normalization	1 ± 0.05	0.996
$\Delta(\nu/\bar{\nu})$, energy dependent	$0 \pm 1\sigma$	0.19σ
$\Delta(\nu/\bar{\nu})$, zenith dependent	$0 \pm 1\sigma$	0.19σ
Cross section parameters		
M_A (resonance) [GeV]	1.12 ± 0.22	1.16
M_A (quasi-elastic) [GeV]	$0.99^{+0.25}_{-0.15}$	1.03
Detector parameters		
Hole ice scattering [cm^{-1}]	0.02 ± 0.01	0.021
DOM efficiency [%]	100 ± 10	101
Background		
Atm. μ contamination [%]	no prior	0.01

IceCube-DeepCore ν_μ disappearance

Fitting Function used in this analysis

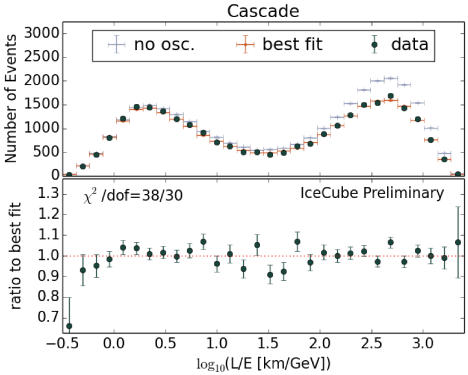
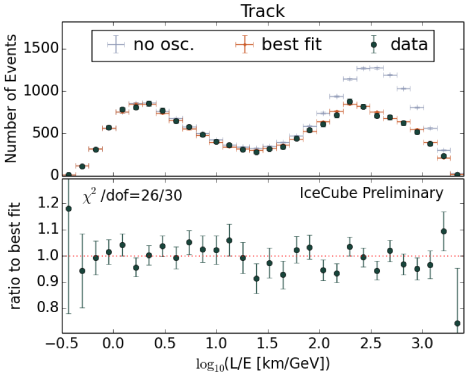
- 30 years of MC for ν components and several systematic variants
- We use a sideband from data to measure the atmospheric μ background shape
  - Similar method used in PRD sample
- Need to account for uncertainty in prediction, especially for background muons
- Our solution is to fit a χ^2 function instead of a $\mathcal{L}$ function.

$$\chi^2 = \sum_{i \in \{\text{bins}\}} \frac{(n_i^{pred} - n_i^{data})^2}{(\sigma_i^{pred})^2 + (\sigma_i^{data})^2} + \sum_{j \in \{\text{syst}\}} \frac{(s_j - \hat{s}_j)^2}{\hat{\sigma}_{s_j}^2}$$

  - n_i^{pred}, n_i^{data}: number of events in bin i for prediction (ν MC + μ sideband) and data
  - σ^{data}: statistical uncertainty in the data for bin i
  - σ_i^{pred}: statistical uncertainty in prediction with additional shape uncertainty in μ sideband
  - $\hat{s}_j$, $\hat{\sigma}_{s_j}$: central value and sigma of a Gaussian prior of systematic s_j
- All bins have large enough number of events a Gaussian distribution approximates well a Poisson distribution

Systematics used in analysis and best fit

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-DeepCore L/E