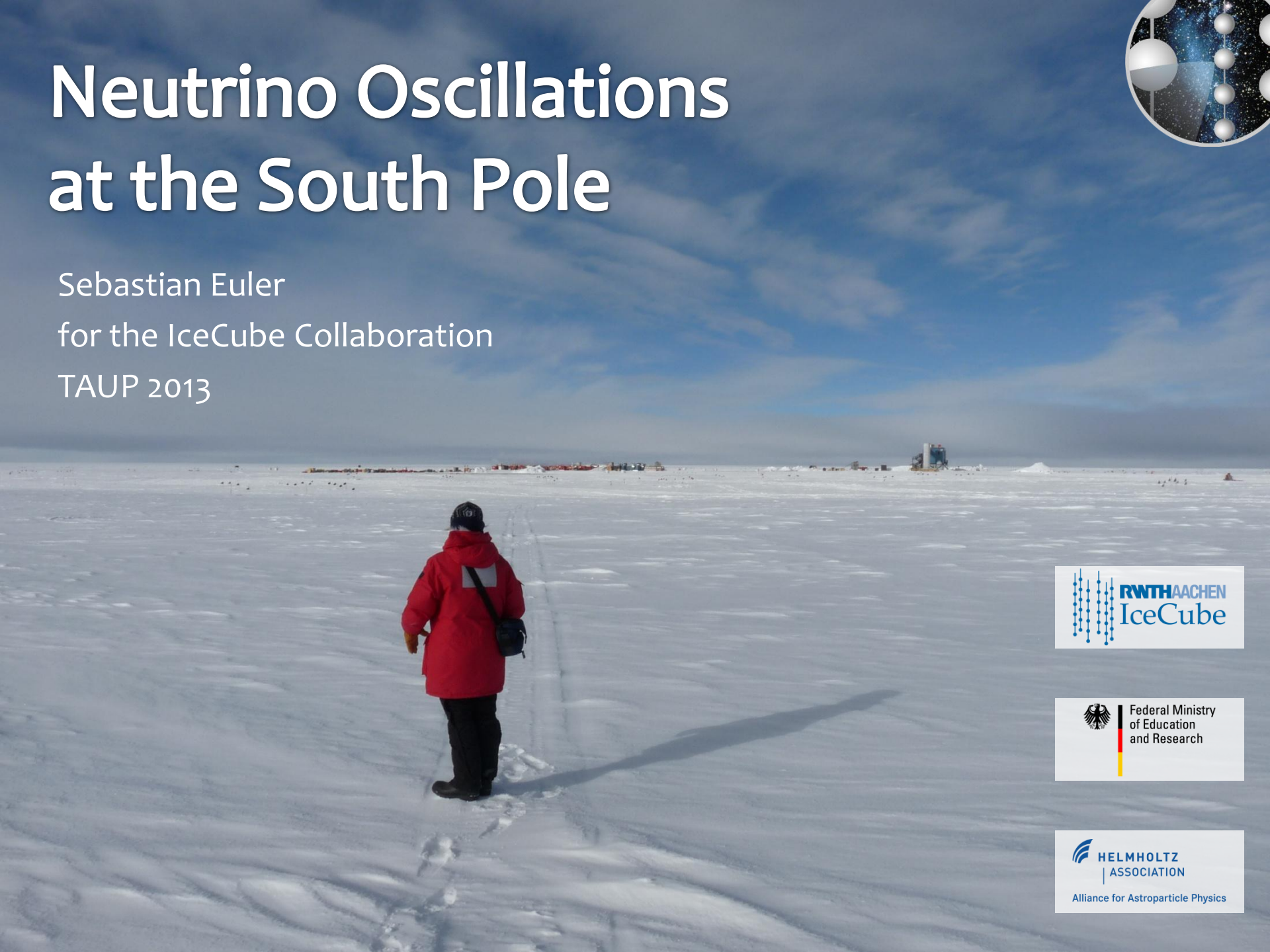
Neutrino Oscillations at the South Pole

Sebastian Euler
for the IceCube Collaboration
TAUP 2013



RWTH AACHEN IceCube

Federal Ministry of Education and Research

HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

Overview

- Atmospheric Neutrino Oscillations
- The IceCube Neutrino Observatory

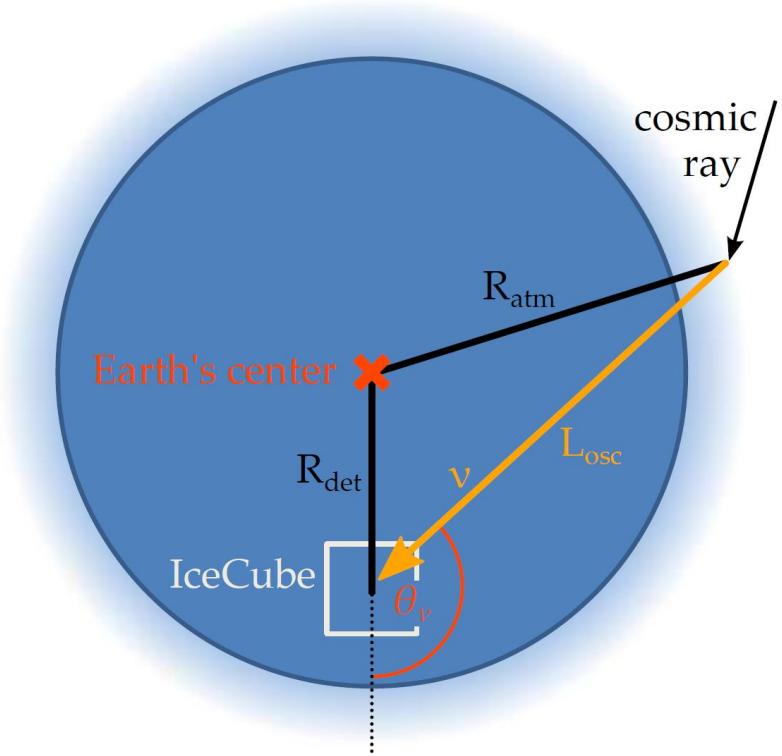
- IC-79 – first analysis
  - only zenith angle
  - χ^2
  - traditional event selection

just published:
Phys. Rev. Lett. 111, 081801 (2013)

- IC-79 – second analysis
  - zenith angle and energy
  - likelihood
  - newly developed event selection, classical reconstruction methods

- IC-86
  - zenith angle and energy
  - likelihood
  - newly developed reconstruction methods

Atmospheric neutrino oscillations



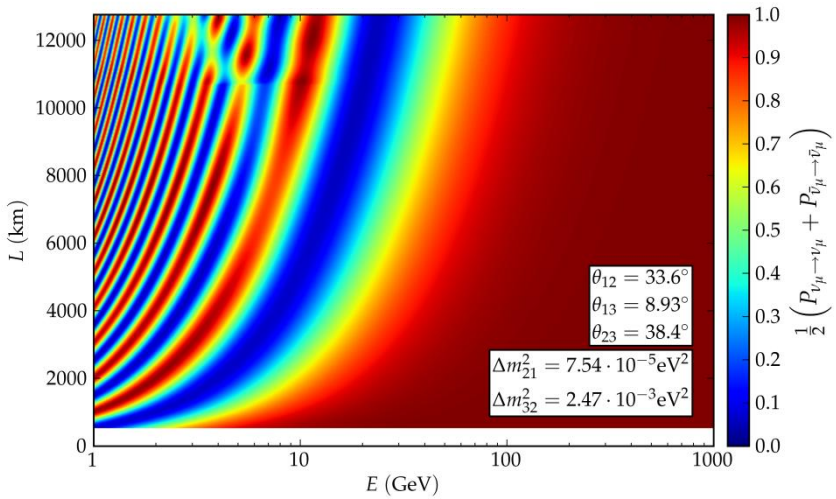
- approximation used throughout this talk:
  pure two-flavor oscillations $\nu_\mu \rightarrow \nu_\tau$
- oscillation probability depends only on
  - oscillation parameters
    Δm^2 and $\sin^2(2\theta_{23})$
  - oscillation length L
    ($\leftrightarrow$ zenith angle θ_ν)
  - neutrino energy E_ν

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{atm}) \cdot \sin^2\left(1.267 \cdot \Delta m^2_{atm}/\mathrm{eV}^2 \cdot \frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$

Muon survival probability

- oscillation probability in dependence of neutrino energy E and

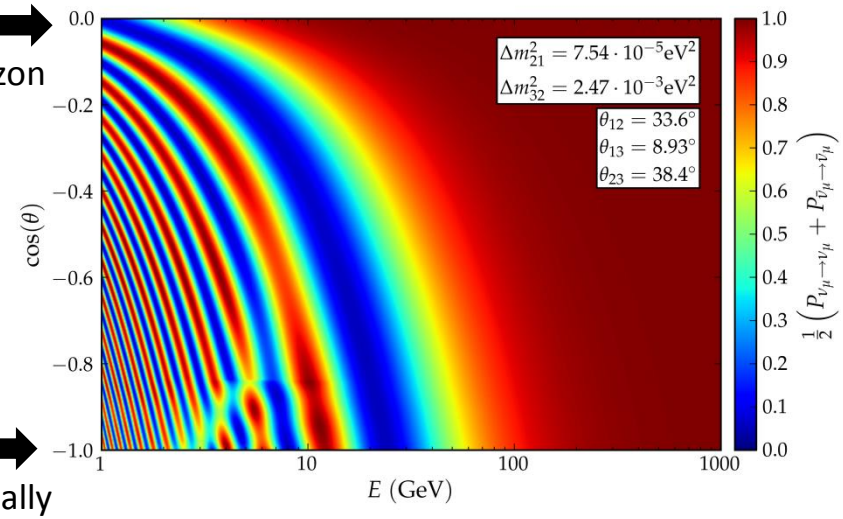
oscillation length L



zenith angle θ

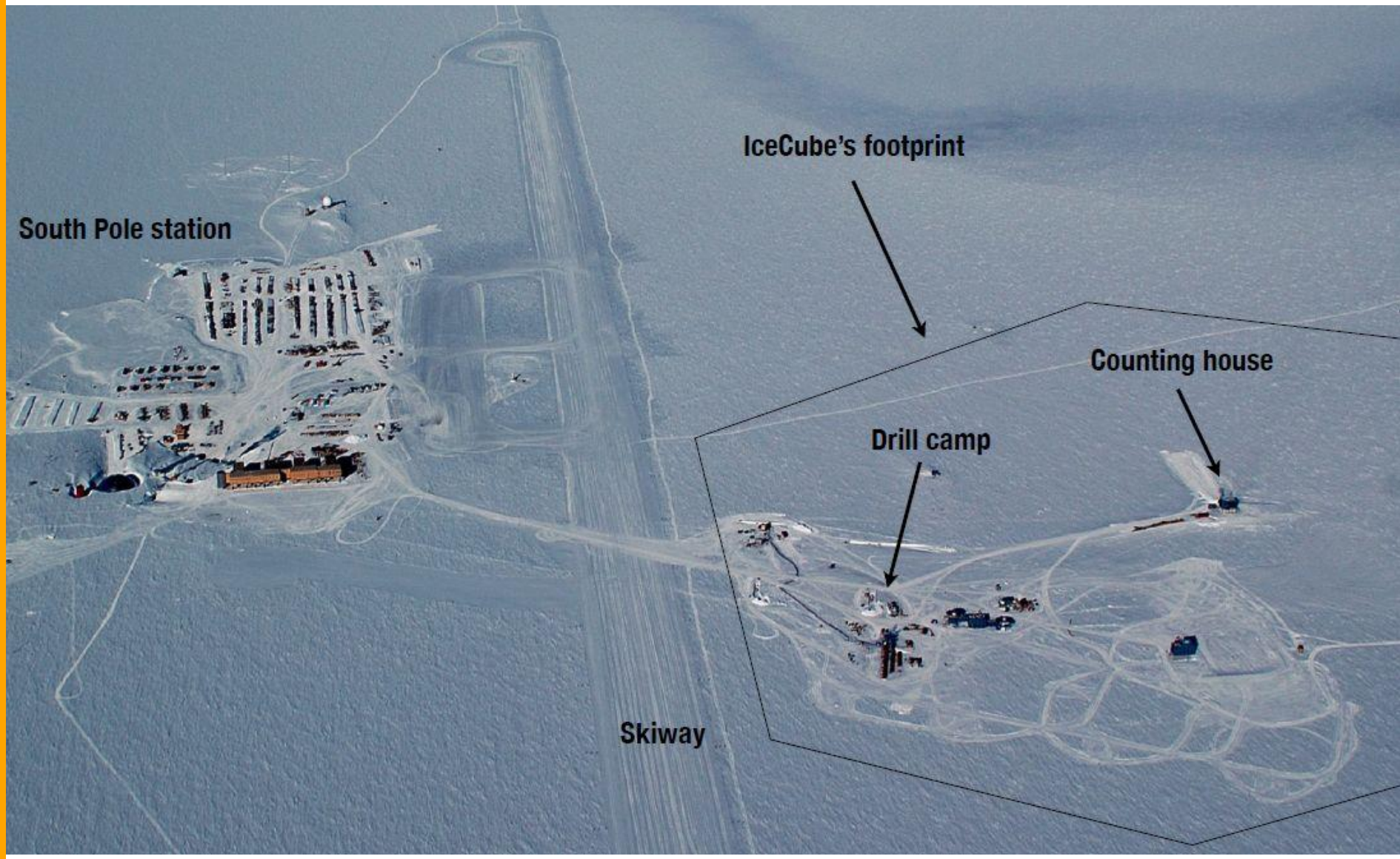
horizon

vertically upwards



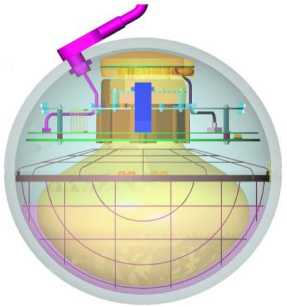
- goal of all these analyses: first oscillation minimum at ~25 GeV
- require threshold of ~10 GeV
- no effect at high energies → constrain systematics

The IceCube Neutrino Observatory



The IceCube Neutrino Observatory

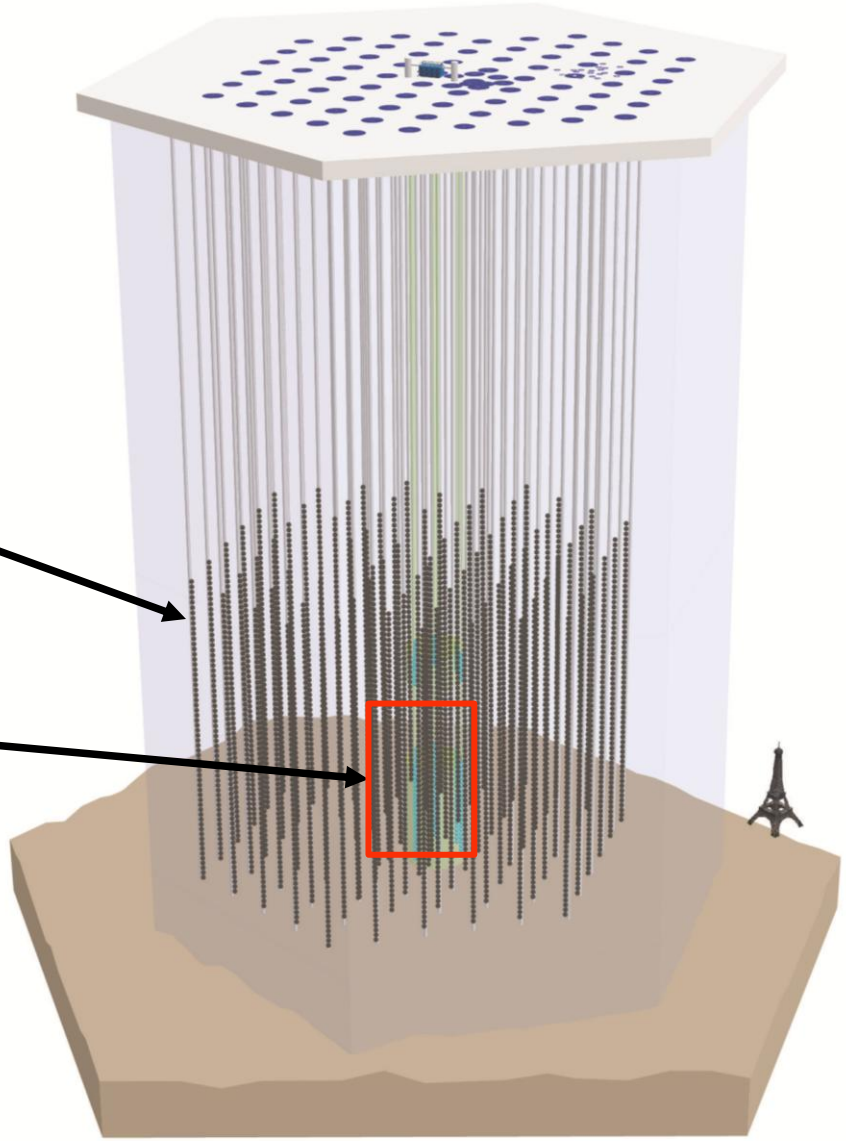
- 5160 PMTs buried in the clear Antarctic ice
- in depths of 1450 m – 2450 m
- 1km^3 instrumented volume



Digital
Optical
Module

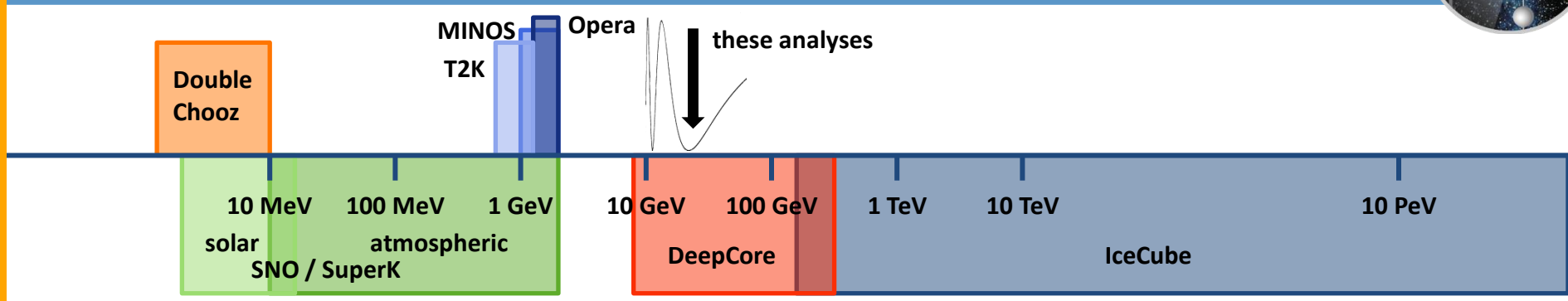
- completed December 2010

- innermost part: **DeepCore**
  - most clear ice
  - more densely instrumented
  - PMTs with higher quantum efficiency
  - dedicated trigger

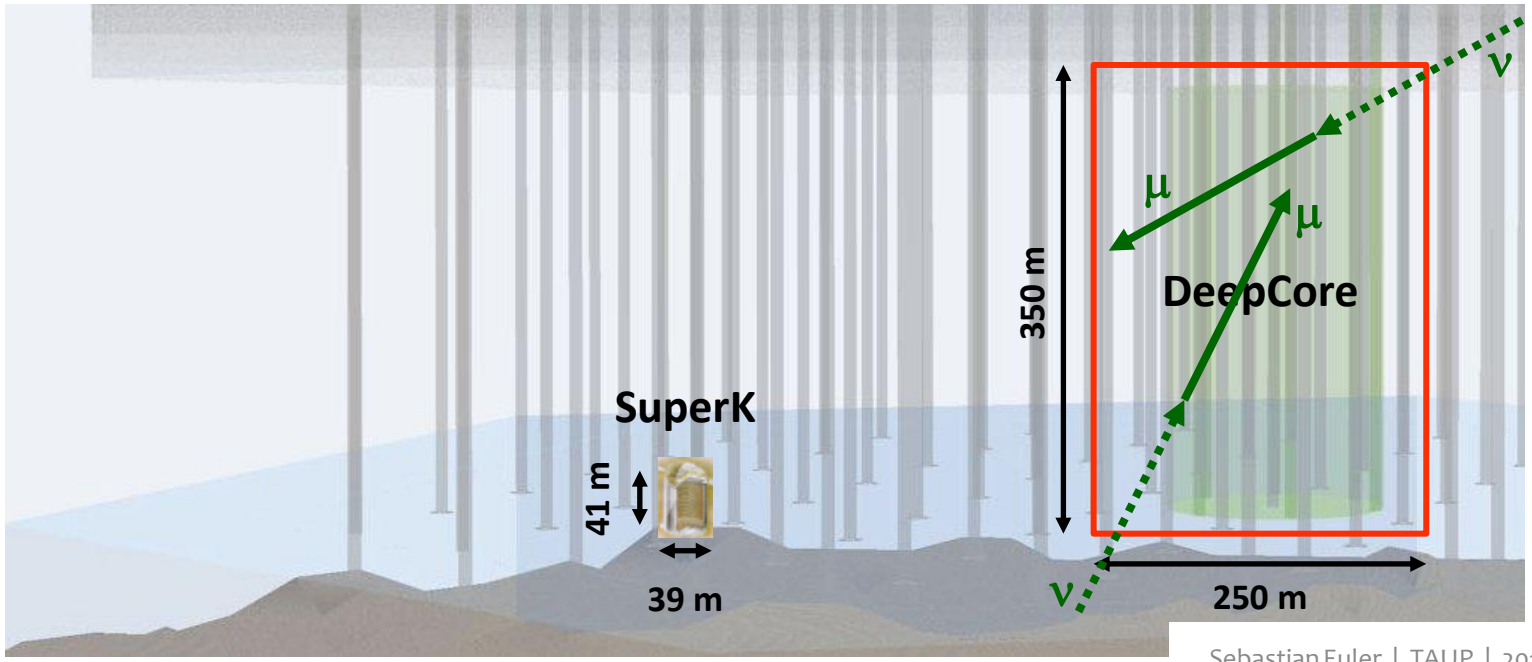


➡ **energy threshold ~ 10 GeV**

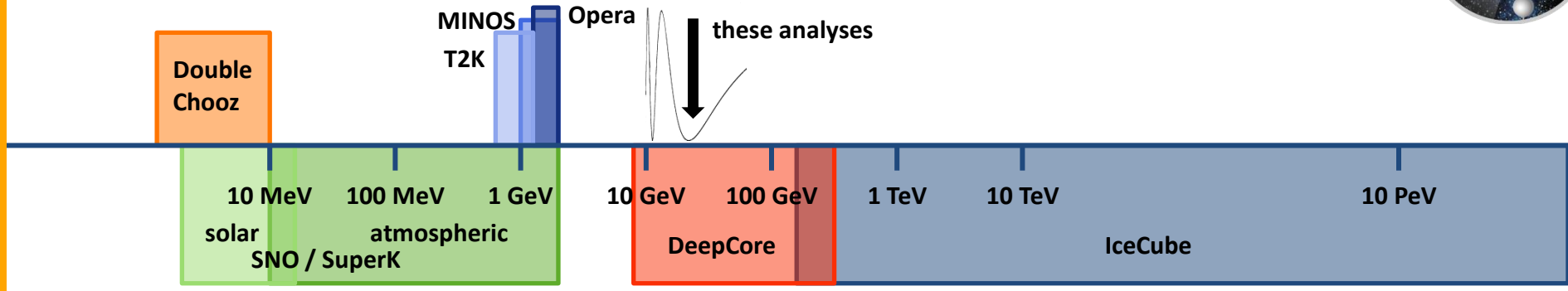
DeepCore as a neutrino oscillation detector



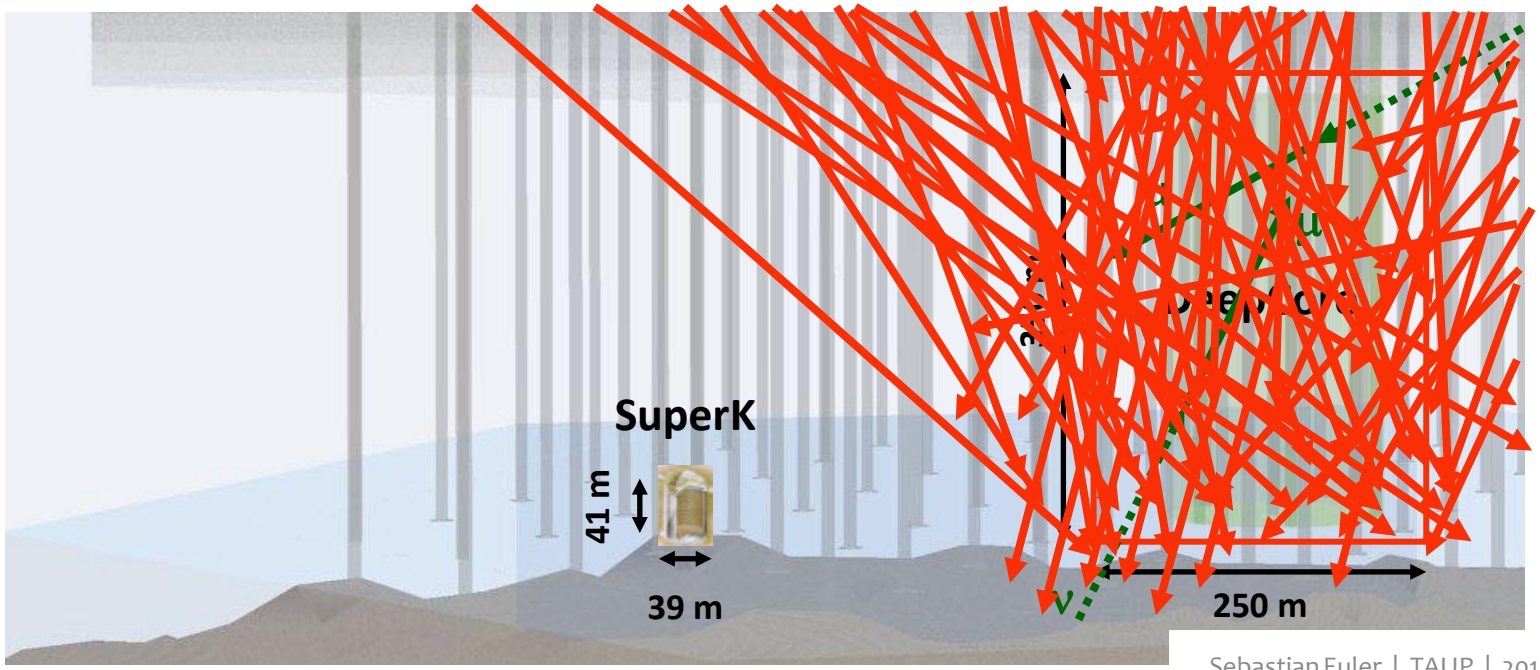
- measure oscillations at higher energies than reactor and accelerator experiments
- huge volume ➡ excellent statistics (~150.000 atm. ν_μ per year)



DeepCore as a neutrino oscillation detector

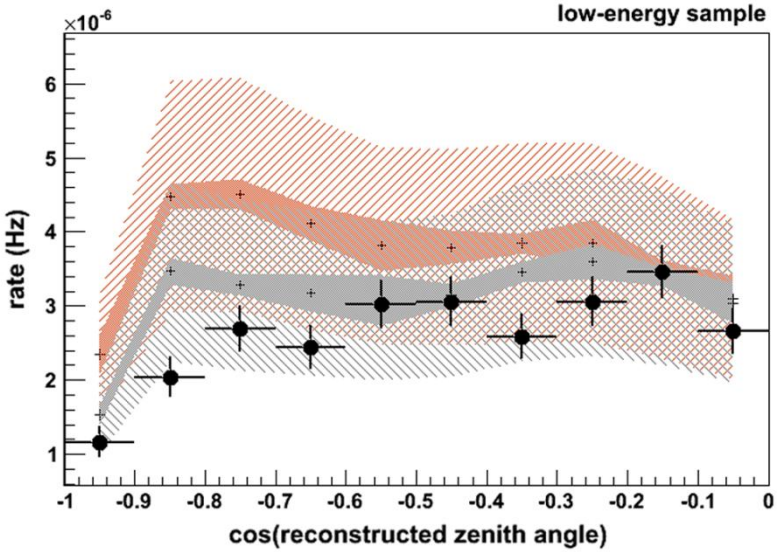


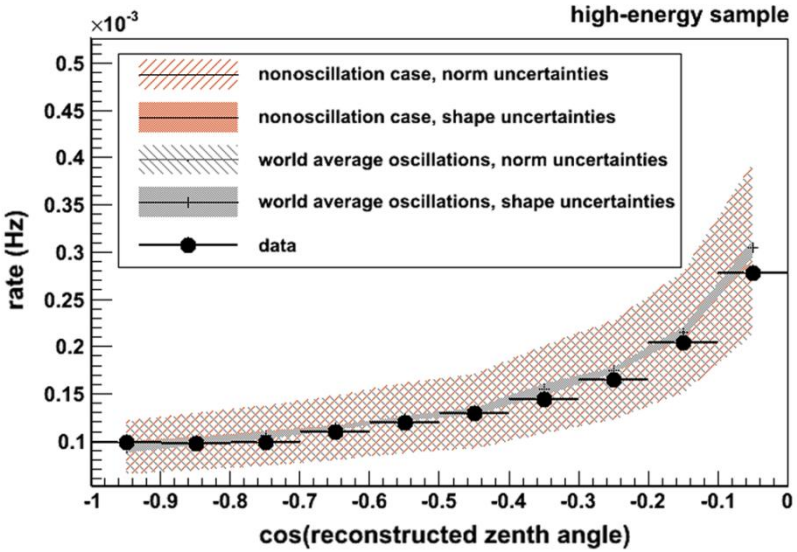
- measure oscillations at higher energies than reactor and accelerator experiments
- huge volume ➡ excellent statistics (~150.000 atm. ν_μ per year)
- … but also some 10^9 atm. μ!



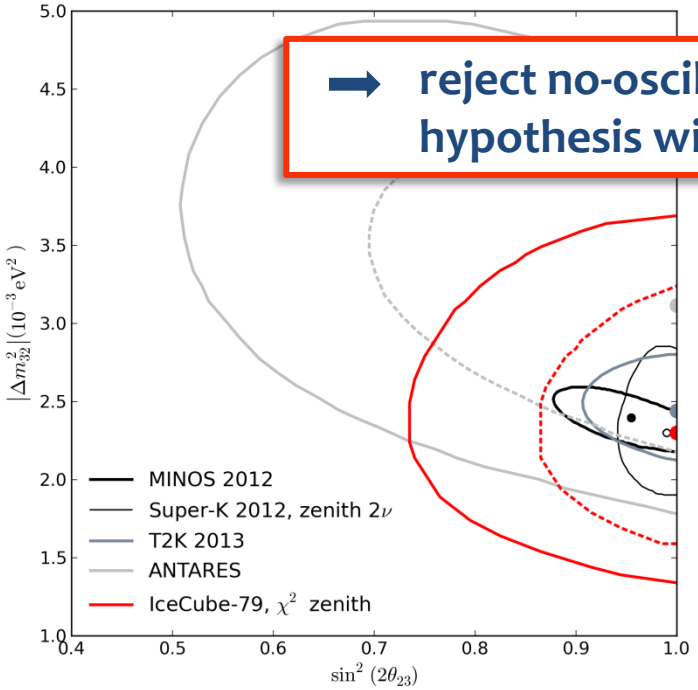
IC79 – first analysis

Phys. Rev. Lett. 111, 081801 (2013)





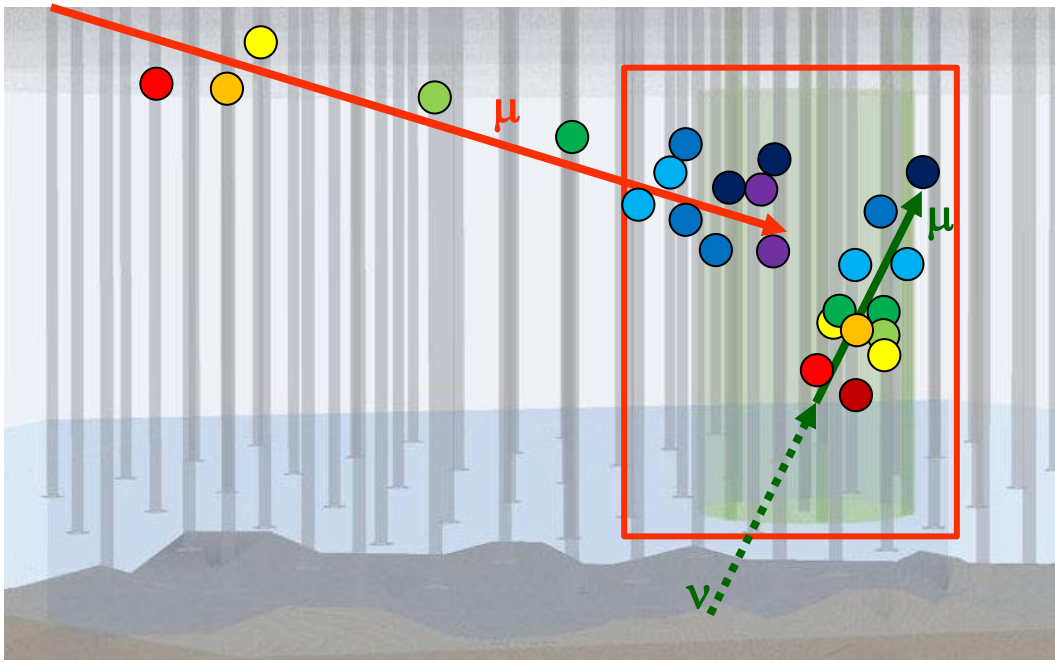
- event selection based on event quality
- low-energy sample:
  - 719 events
  - expect large oscillation effects
- high-energy sample:
  - unaffected by oscillations
  - constrain systematics



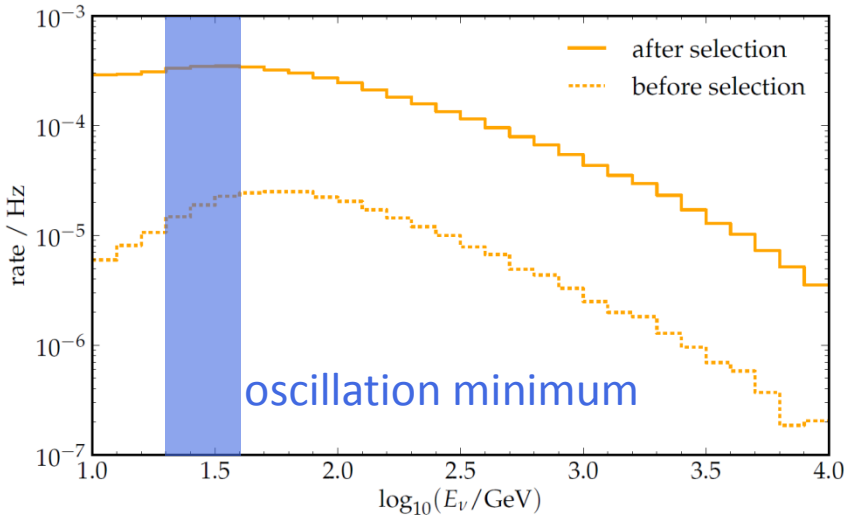
➡ **reject no-oscillation hypothesis with > 5σ**

IC79 – second analysis

- new ideas:
  - single consistent data selection based on IceCube as veto
  - factor 10 improved statistics
  - global 2-dim. likelihood fit of zenith angle & energy
  - constraining systematic uncertainties by including them as nuisance parameters



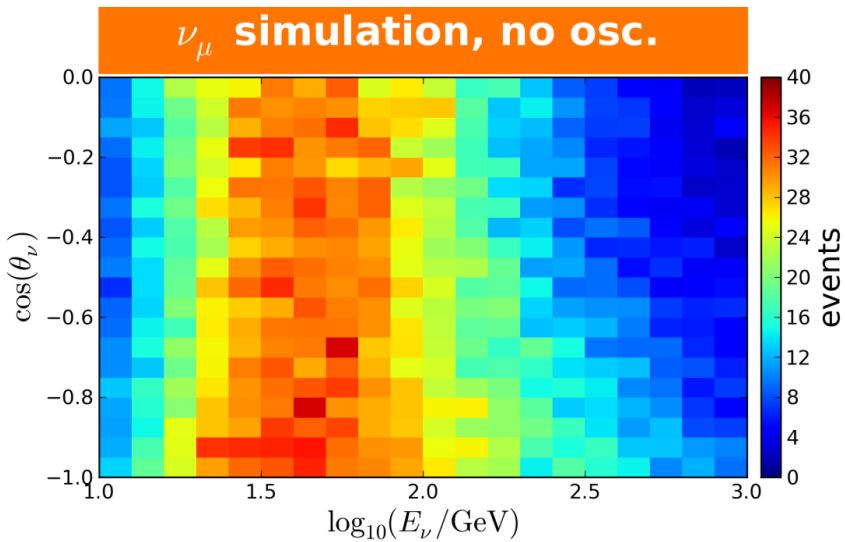
- energy spectrum and event rates:

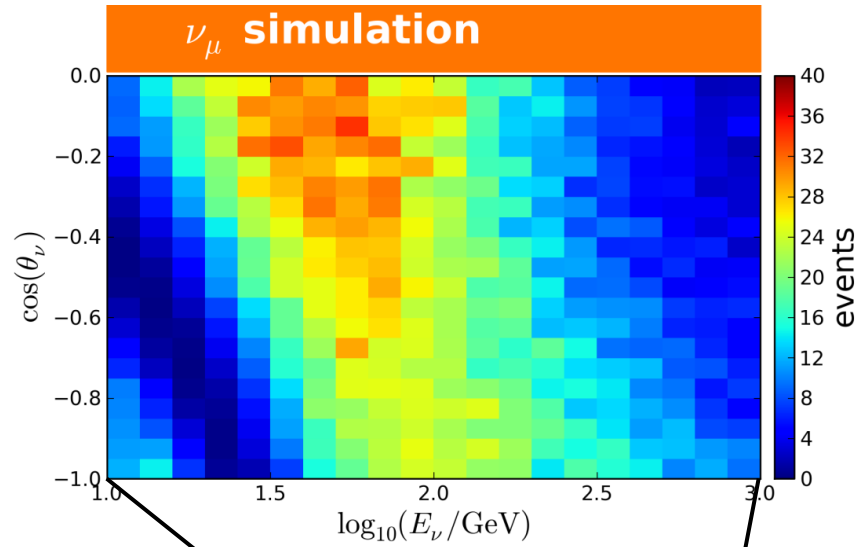


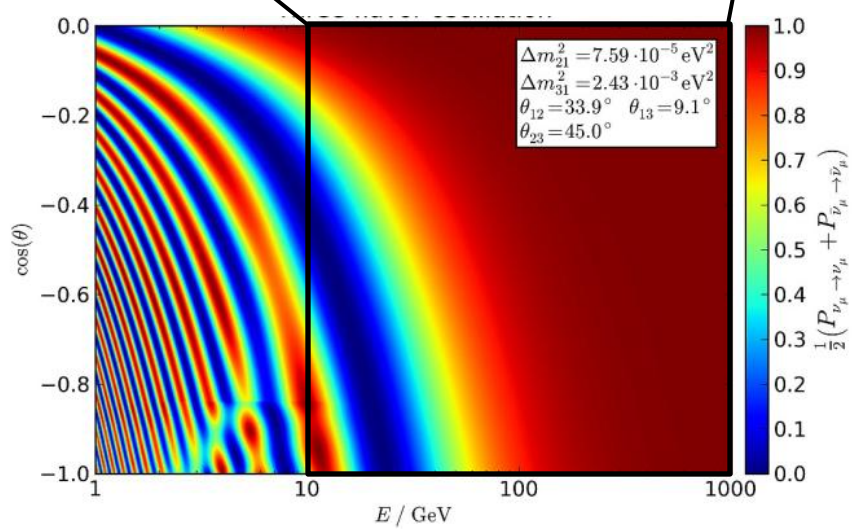
Expected and observed event numbers 312 d livetime (May 2010 – May 2011)	
ν_μ	6668
ν_e	1102
ν_τ	230
atm. μ	145
exp. data	**8117**

Effect of oscillations on event sample

- true MC zenith angle and energy



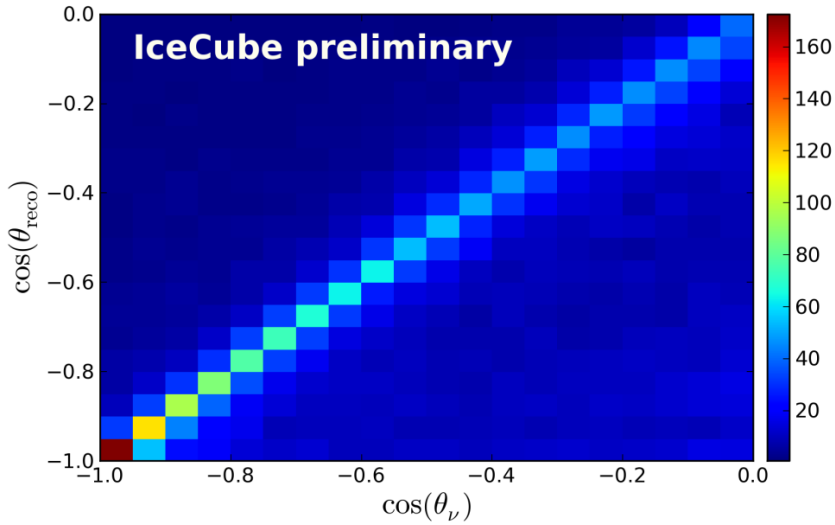




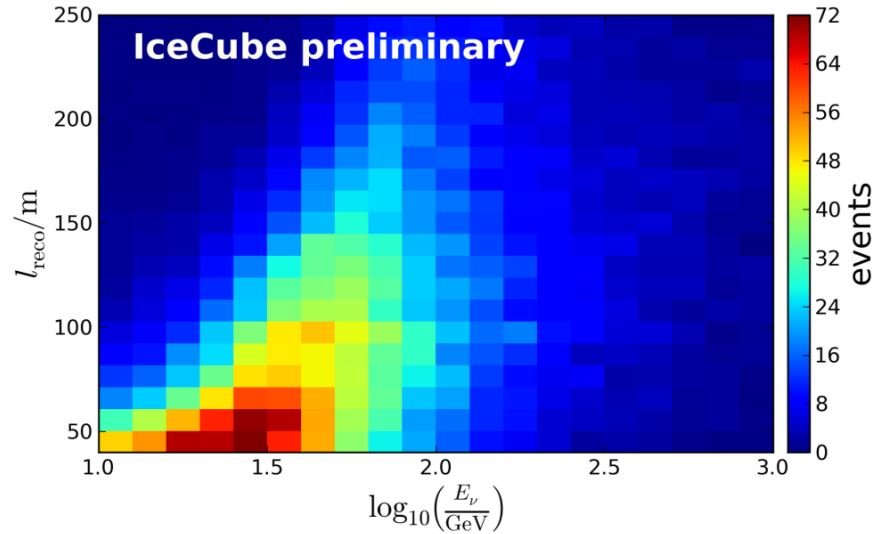
- distinct signature!
- … before reconstruction

Reconstruction of zenith and energy

zenith angle

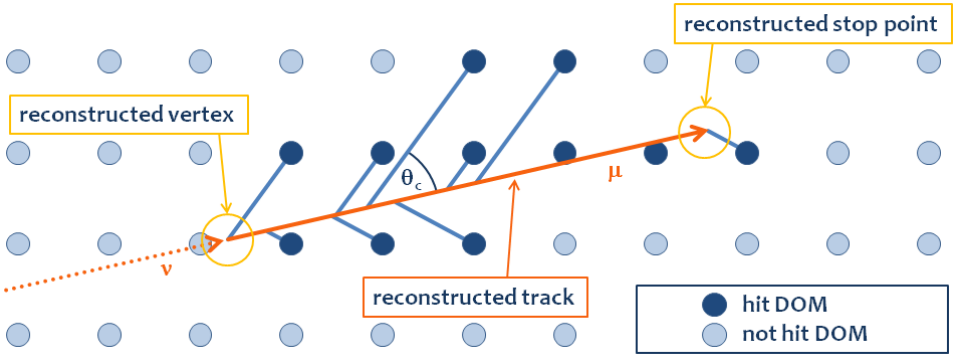


track length

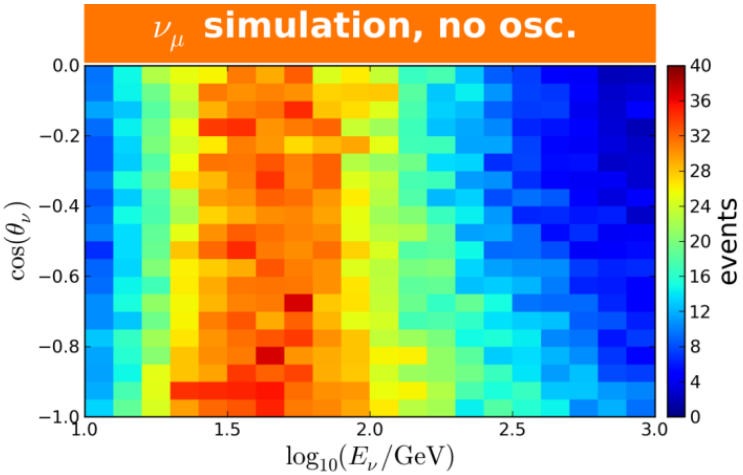


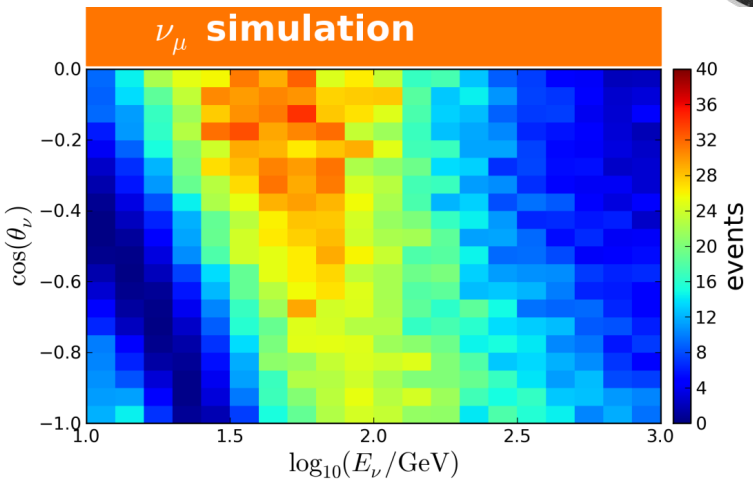
- reconstruction of low-energy events is challenging
- median angular resolution ~4° – 8°
- median length resolution ~60m
- sufficient because of high statistics

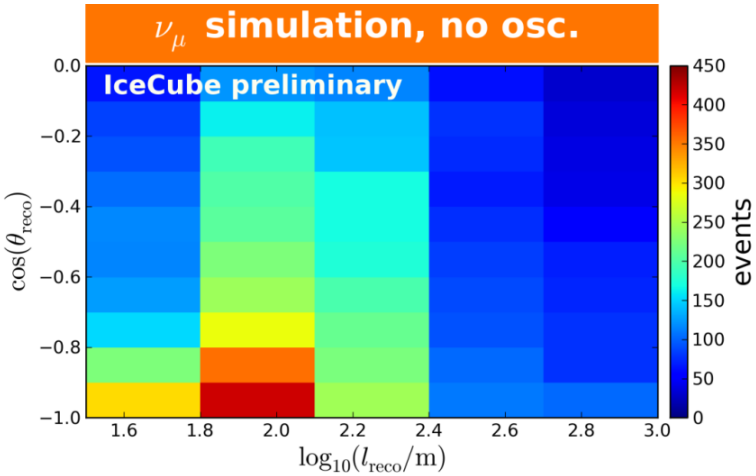
track length reconstruction

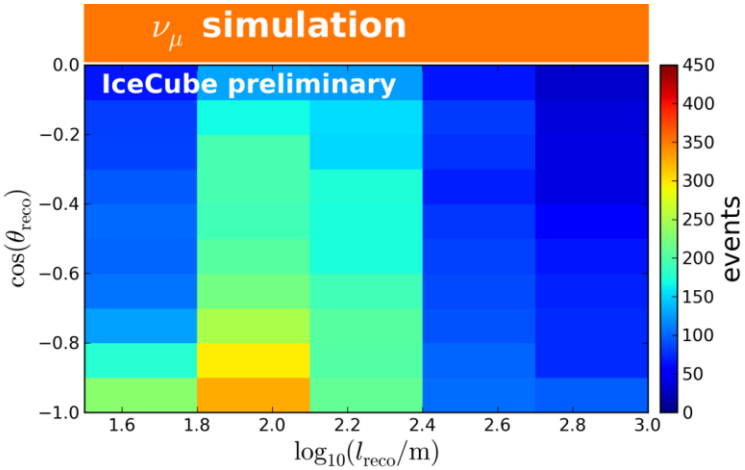


Effect of oscillations – after reconstruction

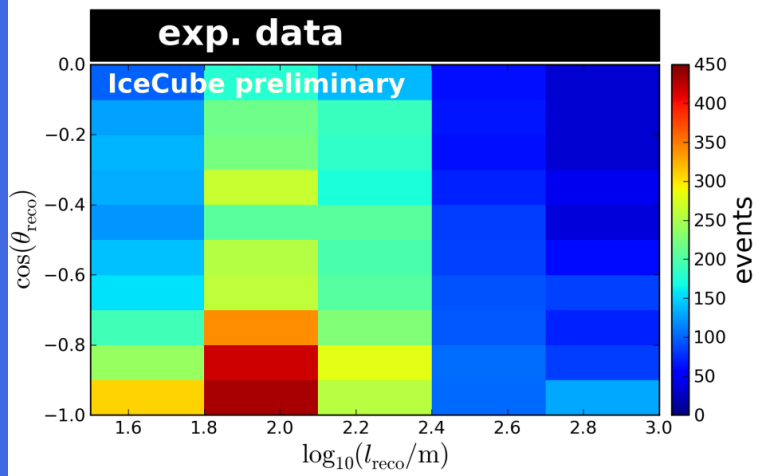






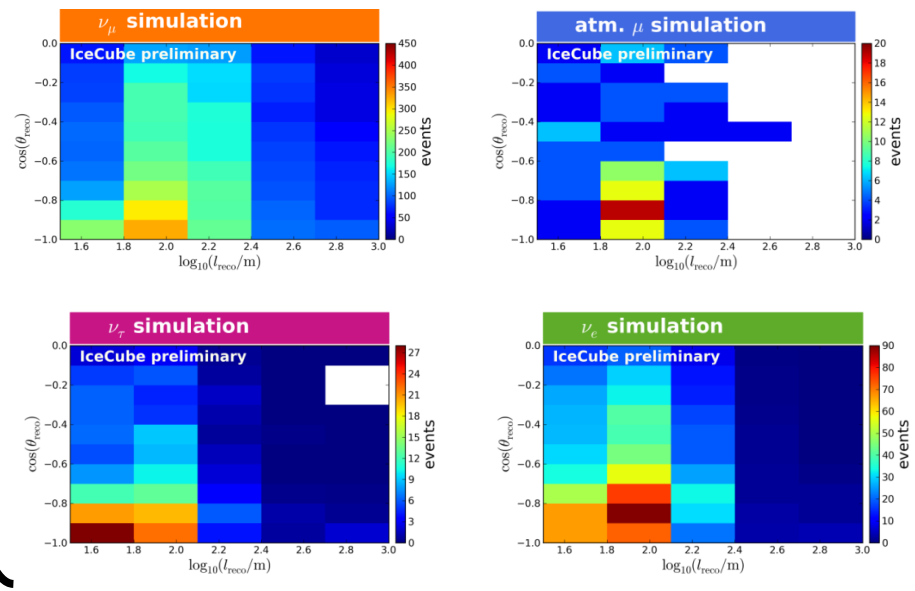


Likelihood method

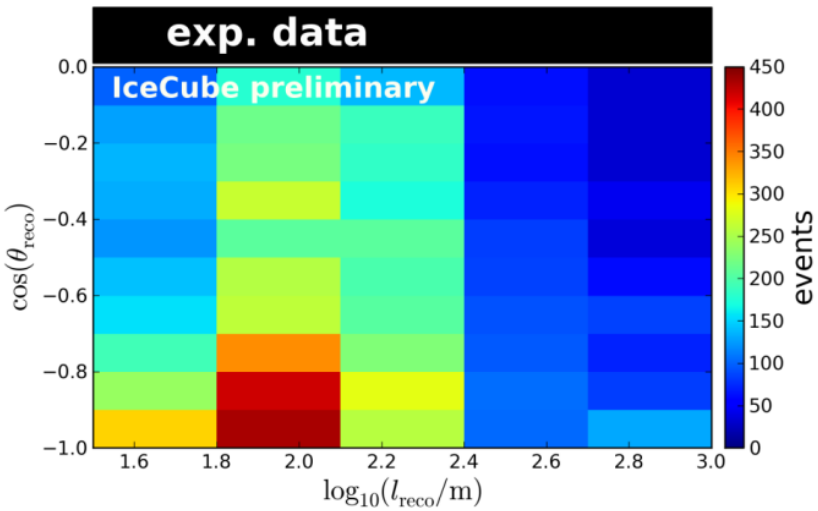


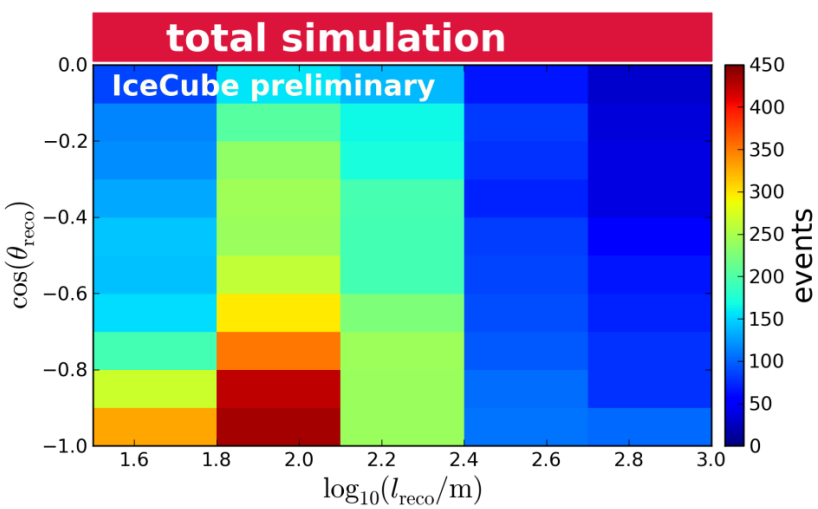
- binwise comparison of experimental data with the expectation for the sum of signal and backgrounds
- based on Poisson likelihood
- global fit
  - oscillation parameters Δm^2_{32} & $\sin^2(2\theta_{23})$
  - model & detector uncertainties incorporated as nuisance parameters

$$= \sum \left(\begin{array}{cc} \nu_\mu \text{ simulation} & \text{atm. } \mu \text{ simulation} \\ \nu_\tau \text{ simulation} & \nu_e \text{ simulation} \end{array} \right)$$

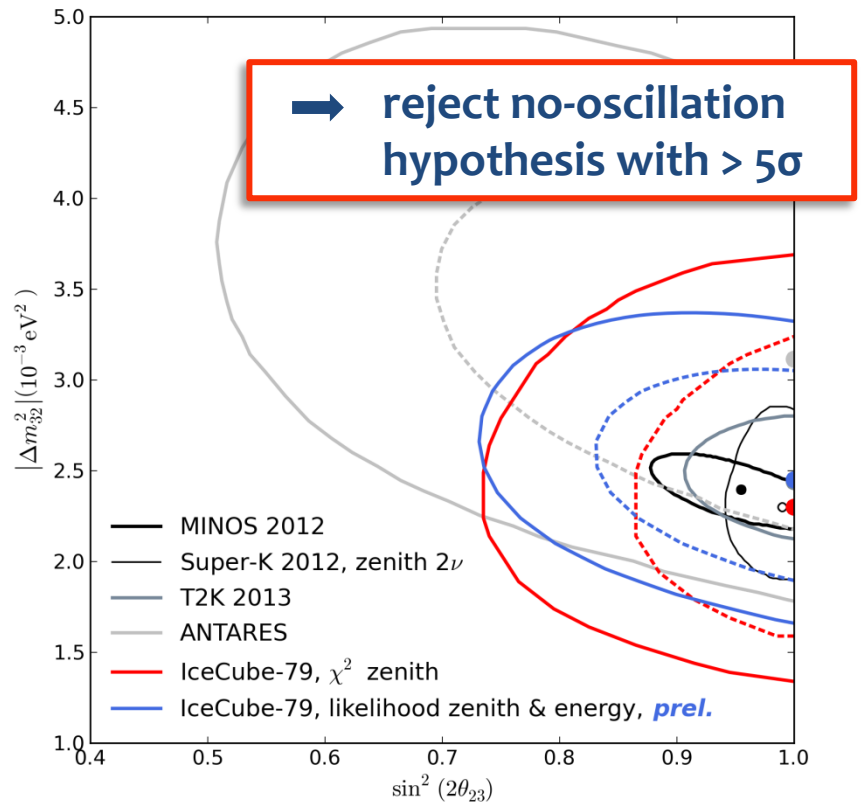


Fit result

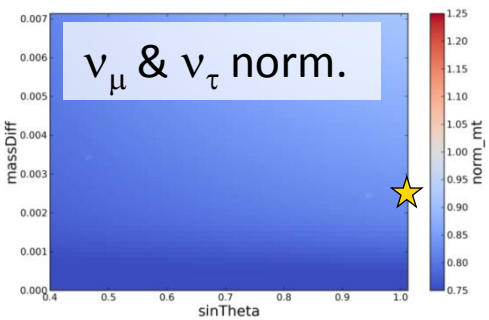


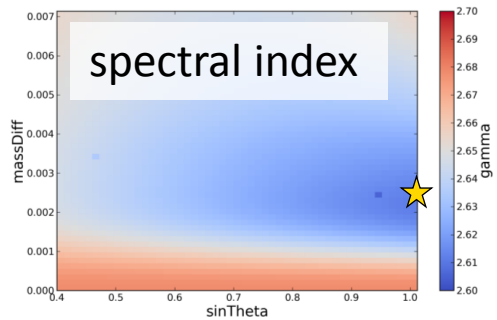


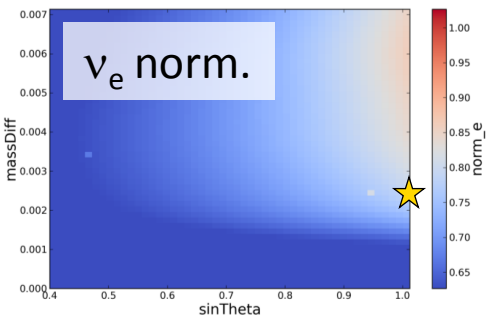
- Experimental data well described by sum of simulations
- best fit:
  - $\Delta m^2_{32} = 2.45 \cdot 10^{-3}\,\mathrm{eV}^2$
  - $\sin^2(2\theta_{23}) = 1.0$

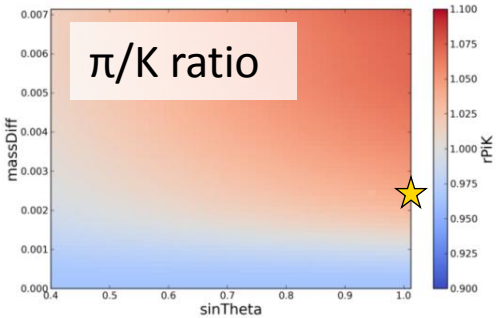


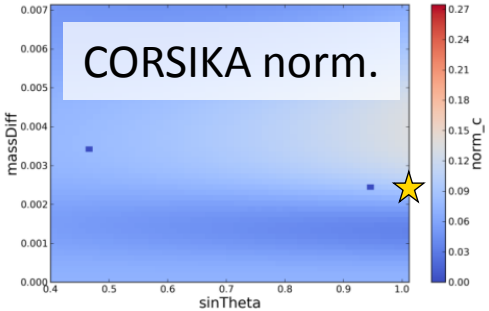
Fitted nuisance parameters









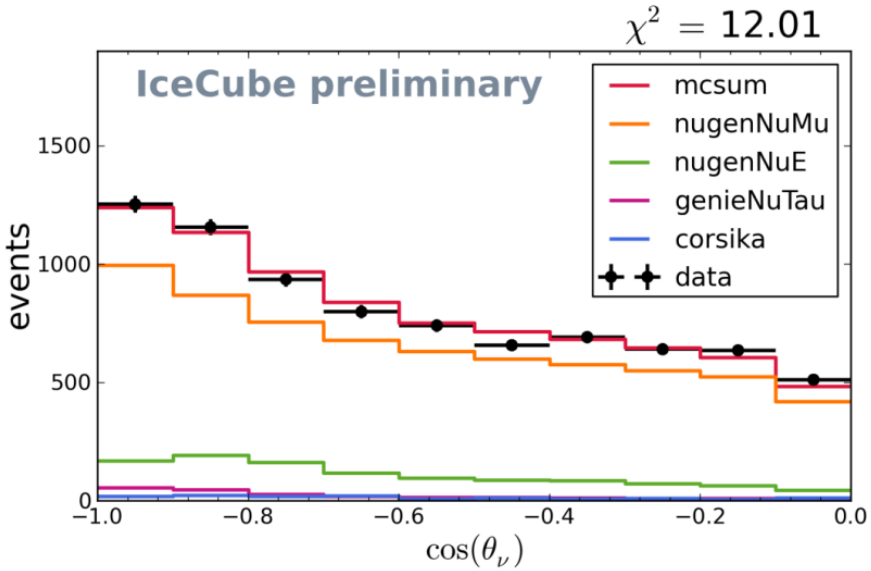


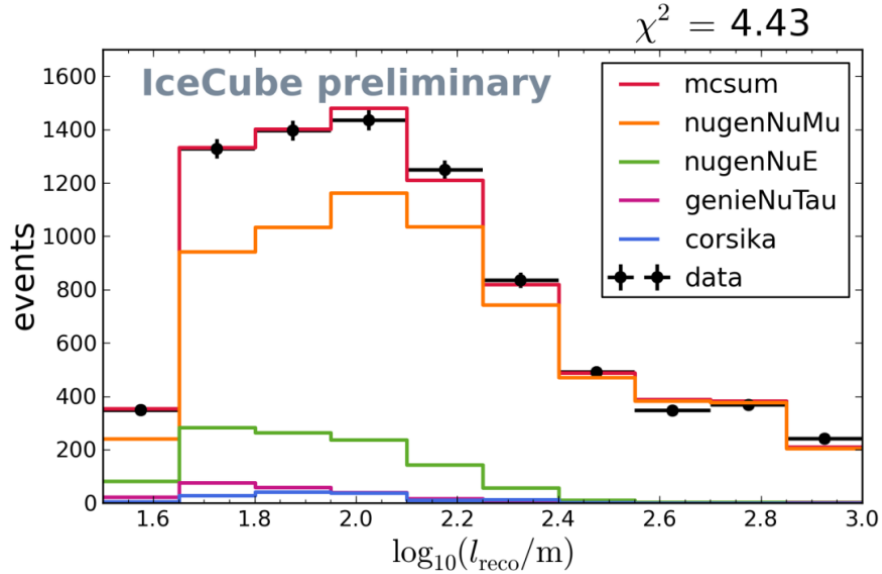
Color range corresponds to the 2σ range of assumed systematic uncertainties

- Systematic uncertainties implemented as nuisance parameters:
  - normalizations of individual components
  - primary cosmic ray spectral index
  - π/K ratio
- ice properties & optical efficiency taken care of in separate fits

Best-fit projections for zenith and length

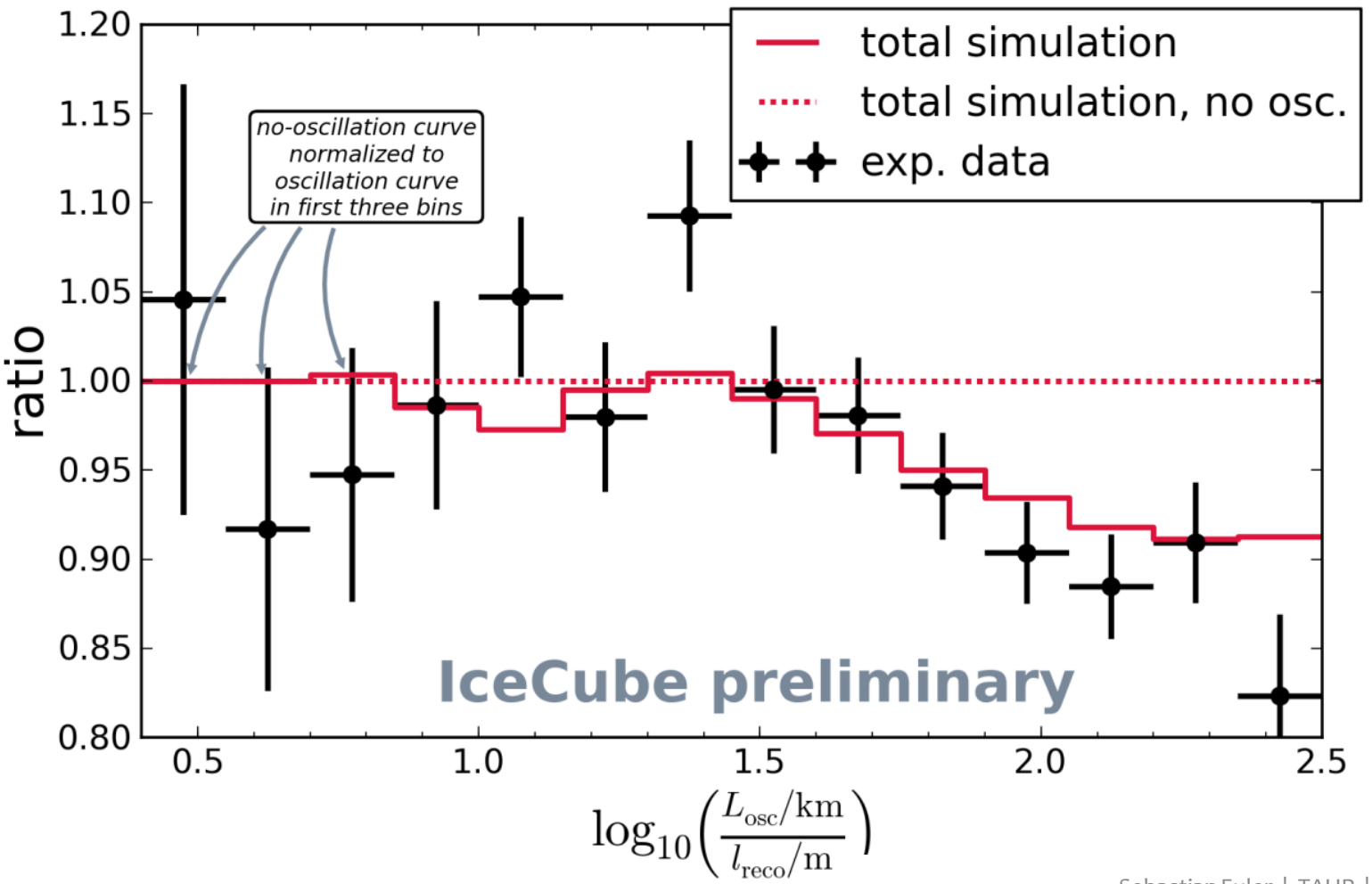
- Analysis is not performed on these distributions!
- Projections of best fit matches well experimental data within uncertainties
- Note: systematic uncertainties are optimized by the fit procedure and not drawn





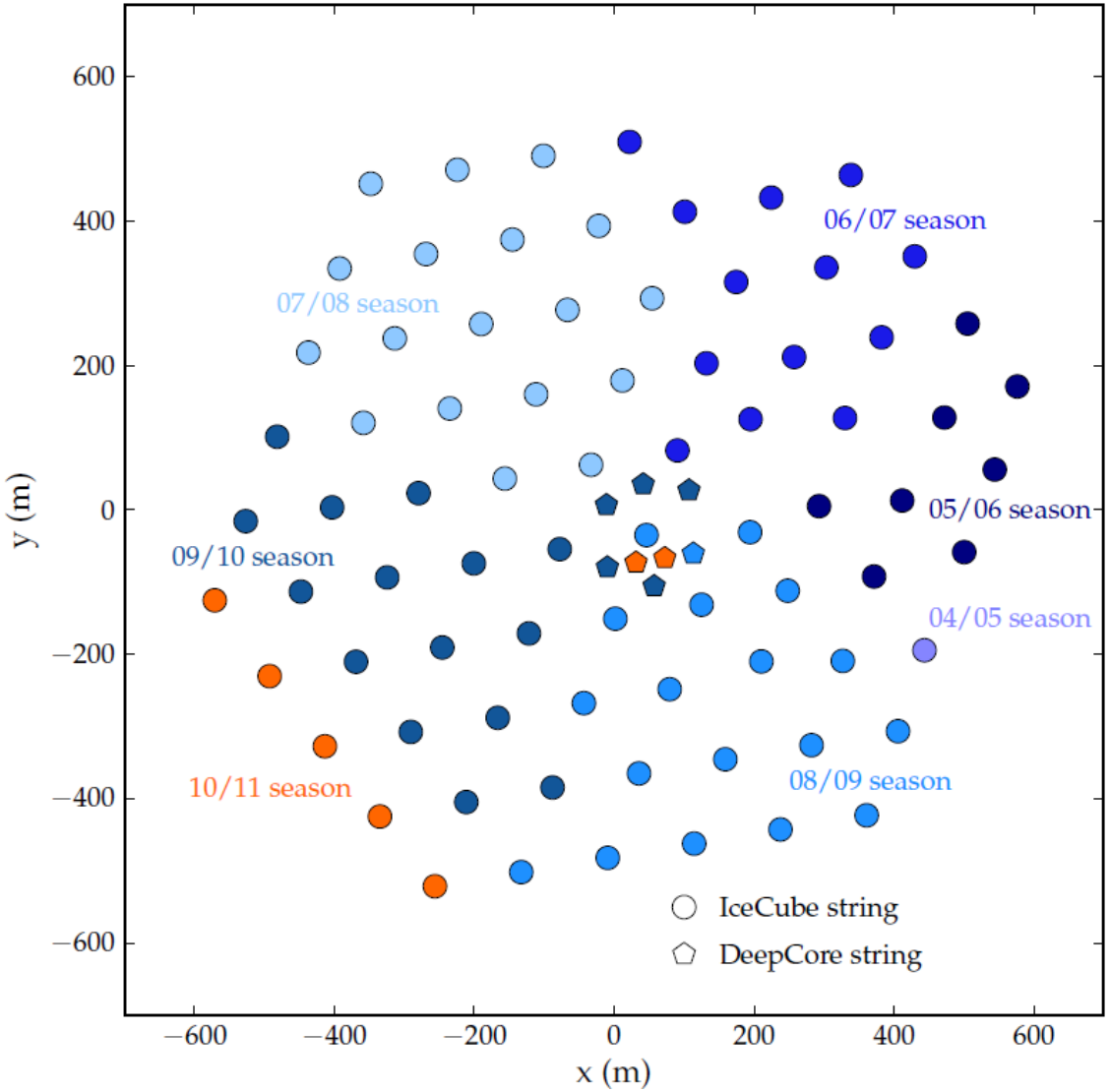
Measured L/E distribution

- L_{osc} / l_{reco} , proportional to L/E



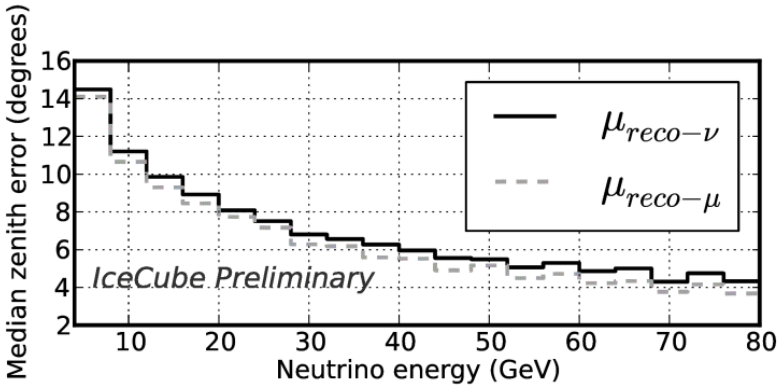
IC86 analysis – new developments

- two more DeepCore strings
  – improves sensitivity for lowest energies
- similar event selection based on IceCube as an active veto
- new energy reconstruction
- new zenith reconstruction

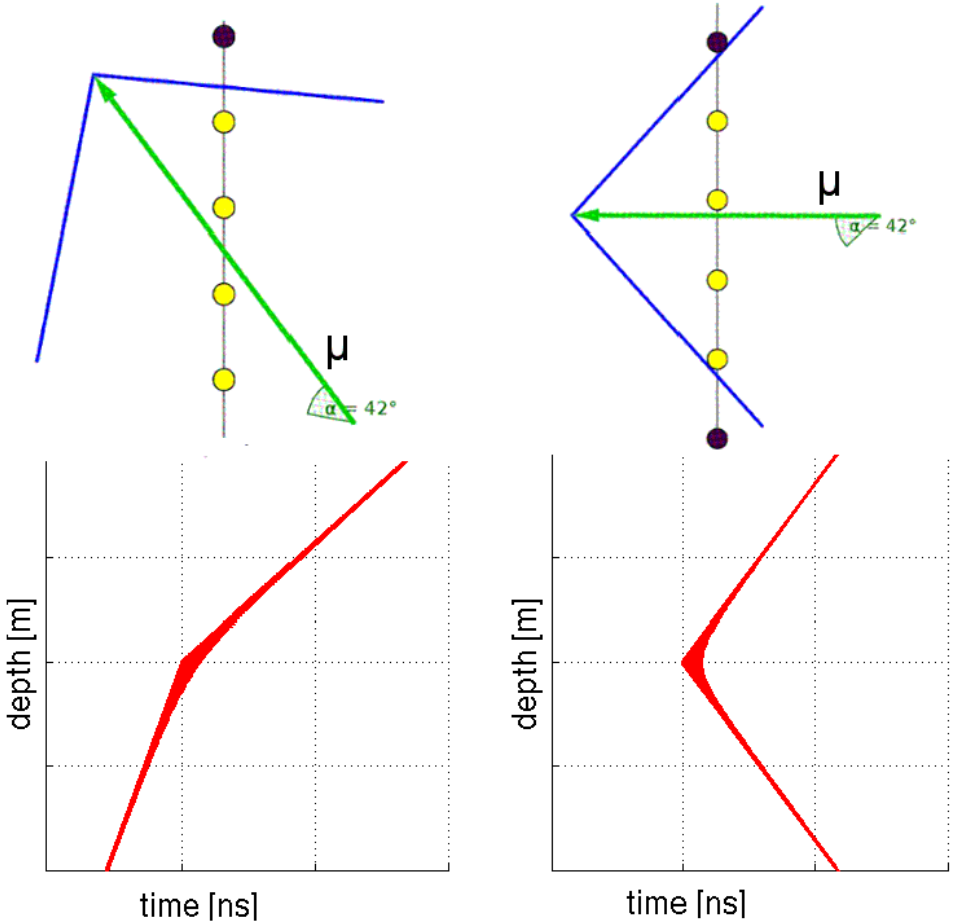


IC86 analysis – new zenith reconstruction

- new zenith reconstruction:
  - muon produces cone of Cherenkov light
  - intersects strings → hyperbolas
- events selected if hyperbolas are found
- removing scattered photons → reduce influence of ice-related systematics
- resolution ~10°

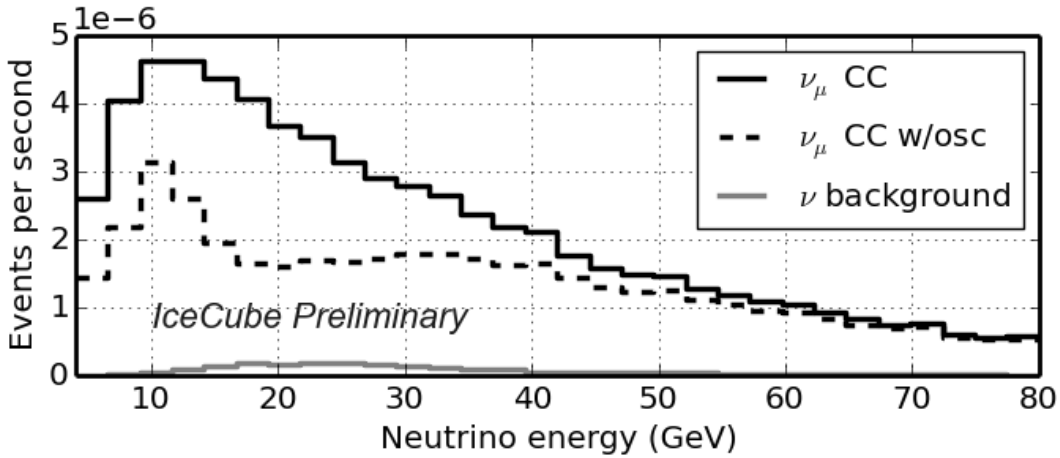


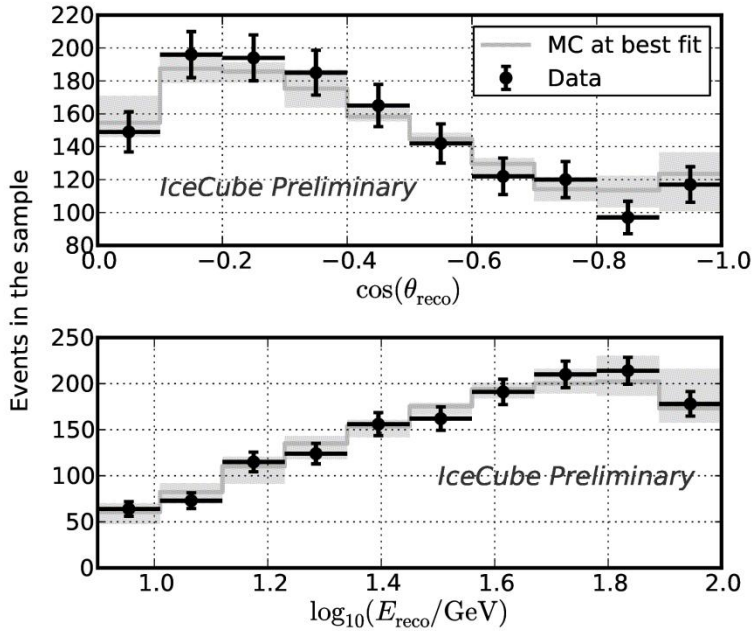
SANTA zenith reconstruction
(based on ANTARES idea)



IC86 analysis – sample

- 343 d livetime
- 1487 neutrino events
- at even lower energies (peak at ~10 GeV)

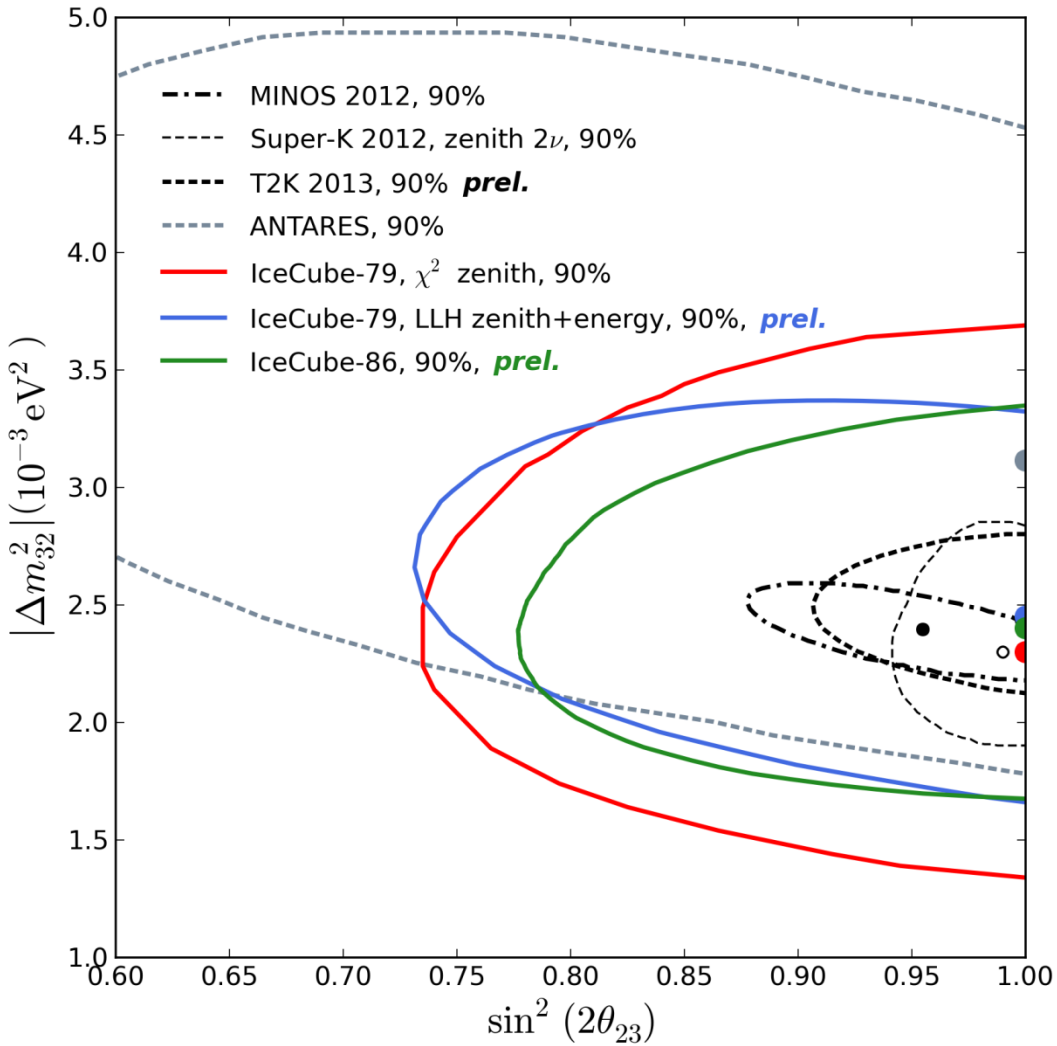




- good agreement between experimental data and best-fit MC
- χ^2 = 48.8 / 54 d.o.f.

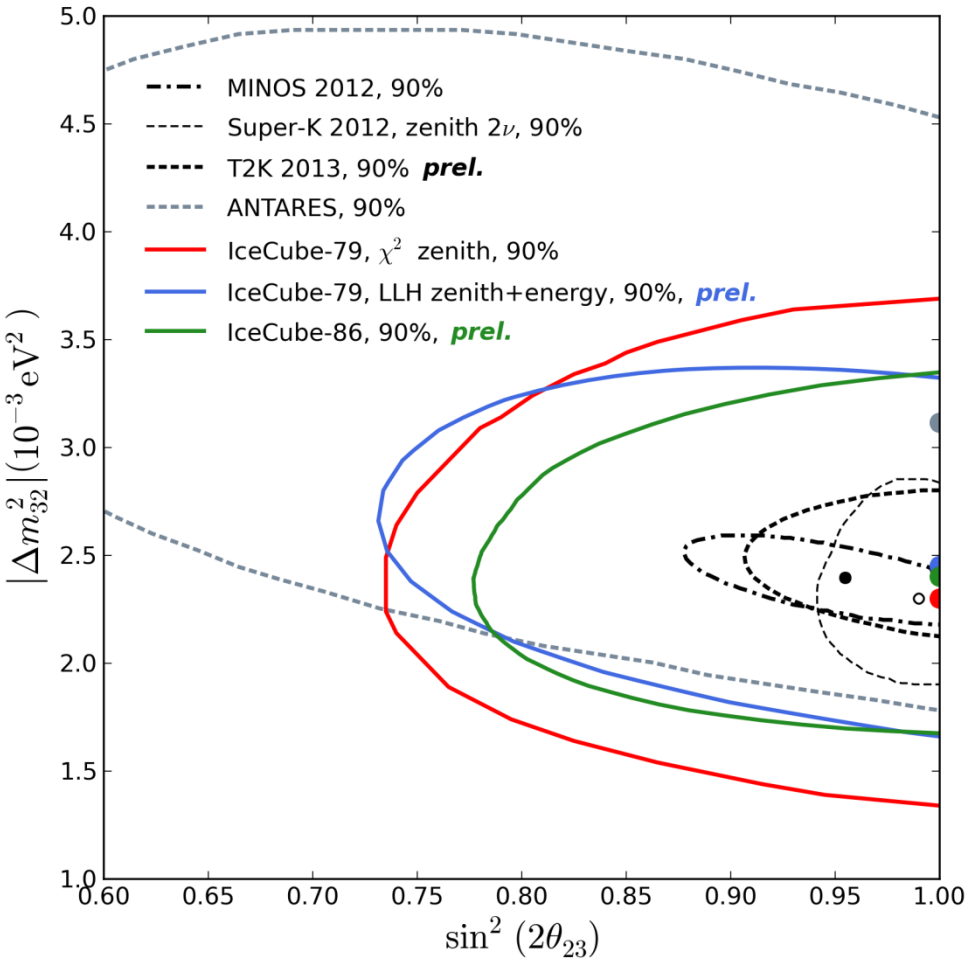
IC86 analysis – 90% contours

- $\sin^2(2\theta_{23}) = 1$
  (> 0.93 at 68% C.L.)
- $|\Delta m^2_{32}| = 2.4 \pm 0.4 \cdot 10^{-3}\ \mathrm{eV}^2$
- improved sensitivity to mixing angle
- rejection of no-oscillation hypothesis by 6σ



Conclusions

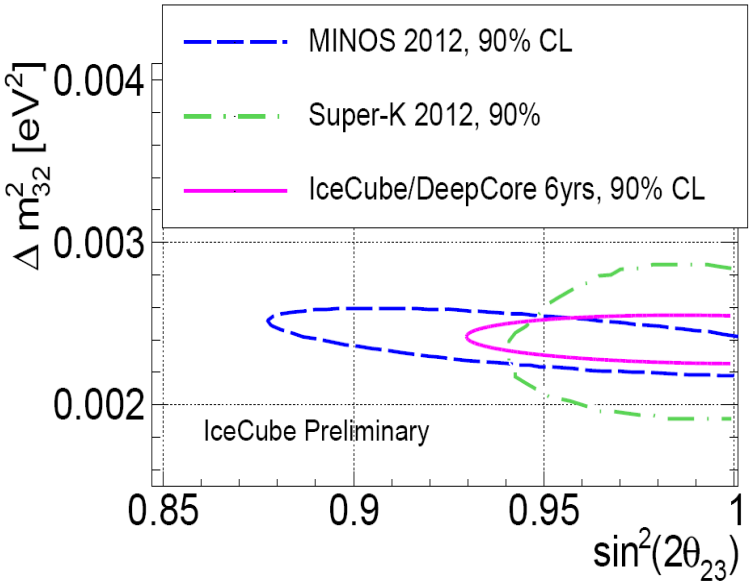
- IceCube has successfully demonstrated its ability to study atmospheric neutrino oscillations
- measured parameters in good agreement with other experiments



- Near-future improvements
  - further improve reconstruction algorithms
  - better low-energy simulations
  - better understanding of systematics
  - full 3-flavor oscillation treatment
  - 2 more years of data waiting to be analyzed (IC-86)

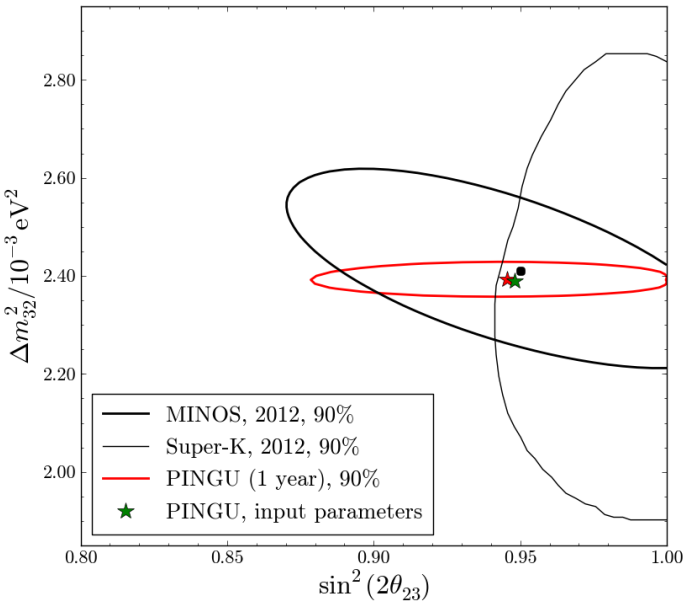
Outlook

- anticipated IceCube performance after 6 years of operation



- DeepCore will allow a competitive measurement of the oscillation parameters

- anticipated PINGU performance after 1 year



- further improvement with planned PINGU detector