Neutrino Oscillation Physics with IceCube/DeepCore and PINGU

NNN 2013 Conference
November 12th 2013
Kashiwa, Japan

Andreas Groß
for the
IceCube/PINGU Collaboration

TECHNISCHE UNIVERSITÄT MÜNCHEN

Outline

- Introduction IceCube/DeepCore
- Measurements of Neutrino Oscillations with IceCube and DeepCore
- Outlook for improvements with IceCube/DeepCore
- The PINGU detector for precision oscillation measurements including neutrino mass hierarchy
- The MICA conceptual detector for supernova neutrinos and proton decay

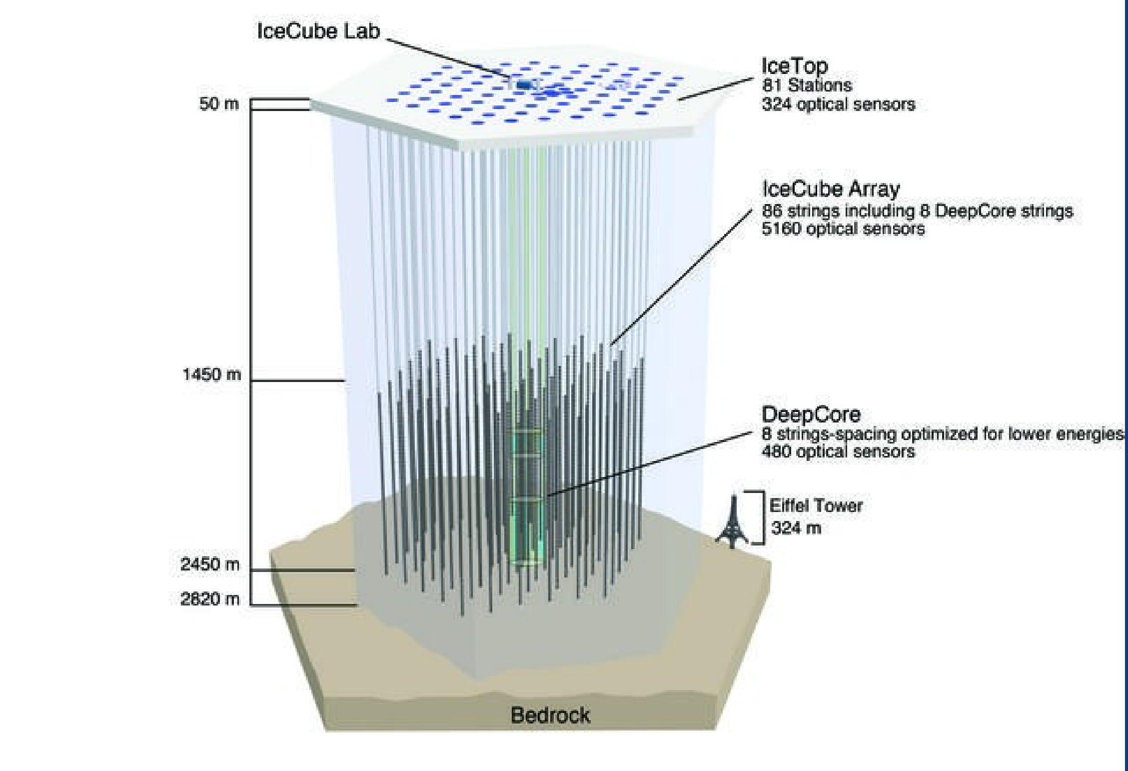
The IceCube Collaboration & PINGU

International 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)
Inoue Foundation for Science, Japan
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)

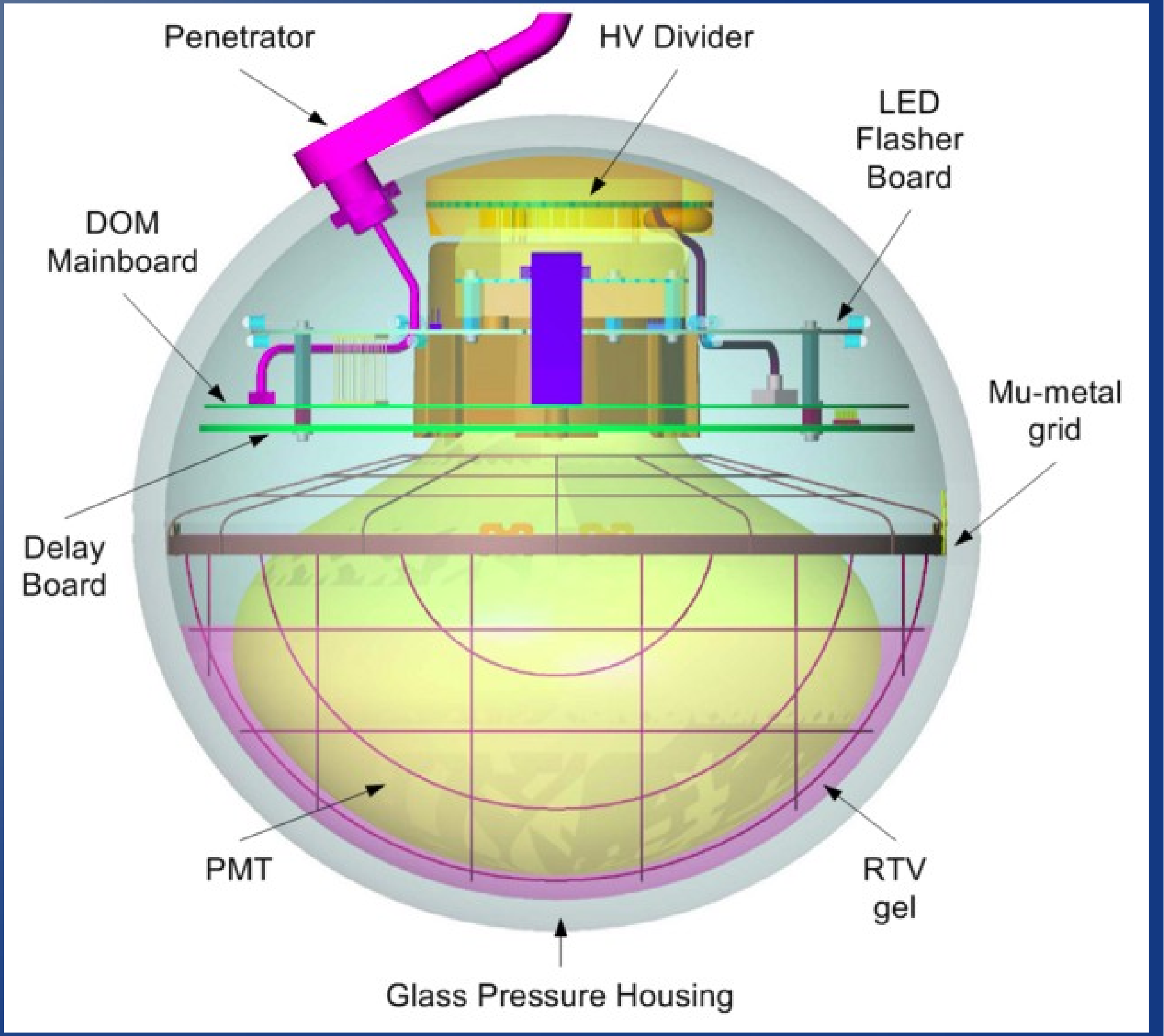
The IceCube Neutrino Observatory and it's DeepCore subdetector

- 86 strings, >5000 PMTs
- IceCube optimized for TeV – PeV energies, 125 m string spacing, ~17 m vetical spacing
- DeepCore sub-detector: 8 dedicated strings with 40-70 m string spacing, 7 m vertical PMT spacing plus 7 adjacent IceCube strings
- IceCube serves as a muon veto for DeepCore



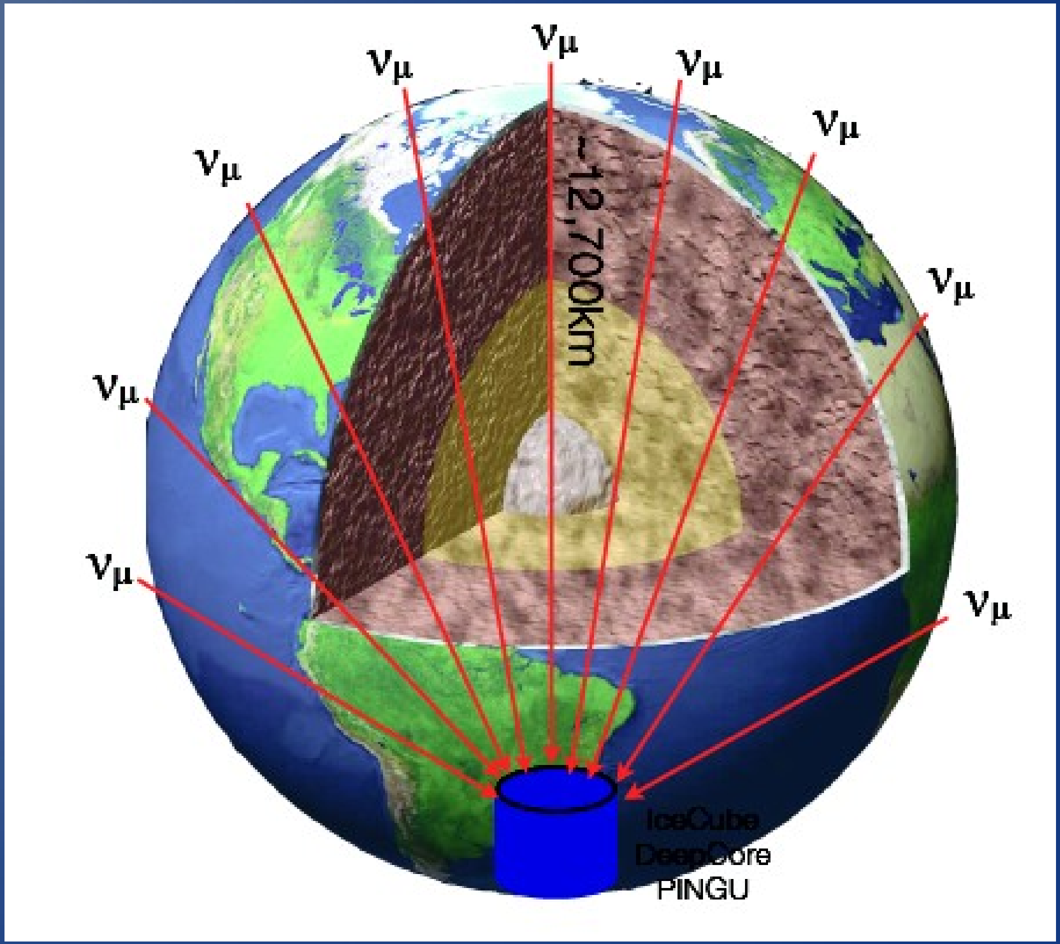
IceCube Digital Optical Modules (DOMs)

- PMT
- In-ice high voltage generation
- In-ice digitization of waveforms (ATWD, FADC)
- Coincidence check with 4 (next-to-)nearest neighbors (hard local coincidence)
- Flasherboard with 12 LEDs as calibraton light source



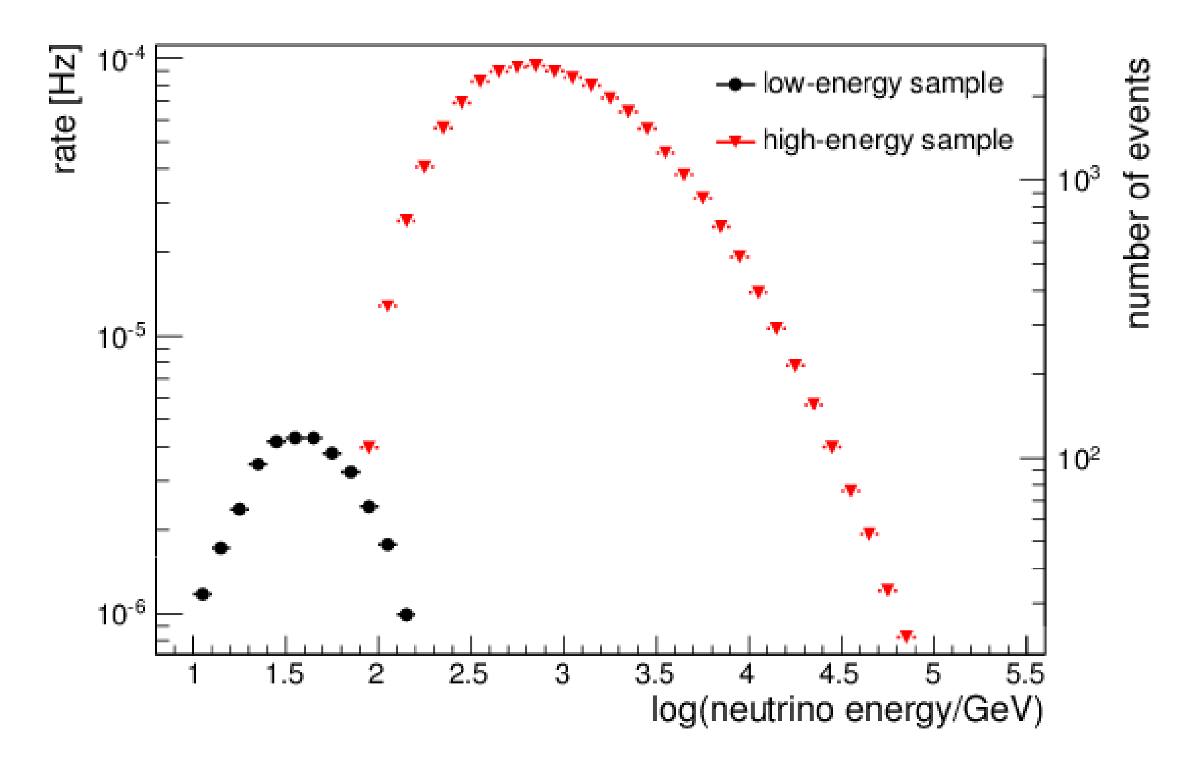
Oscillatons of atmospheric neutrinos

- Cosmic Ray interactions in the atmosphere provide high flux of neutrinos from all directions at a large range of enegies (sub-GeV to tens of TeV)
- Variation of direction (zenith angle) and energy results in direction- and energy dependent oscillation effects
- First minimum of muon neutrino oscillation curve around 25 GeV for vertical events

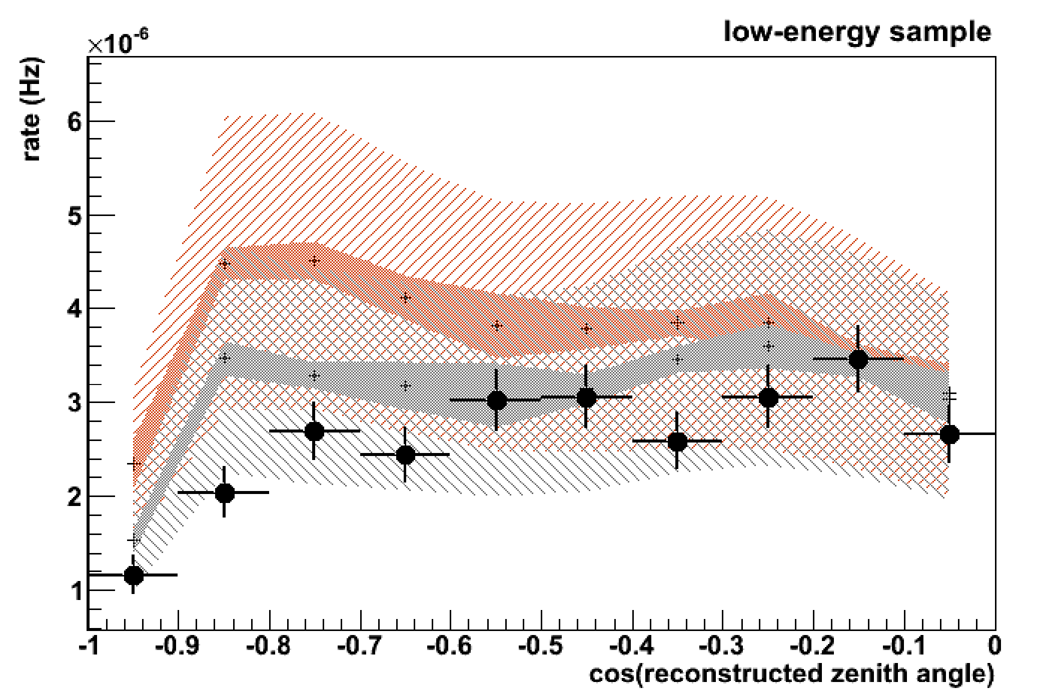


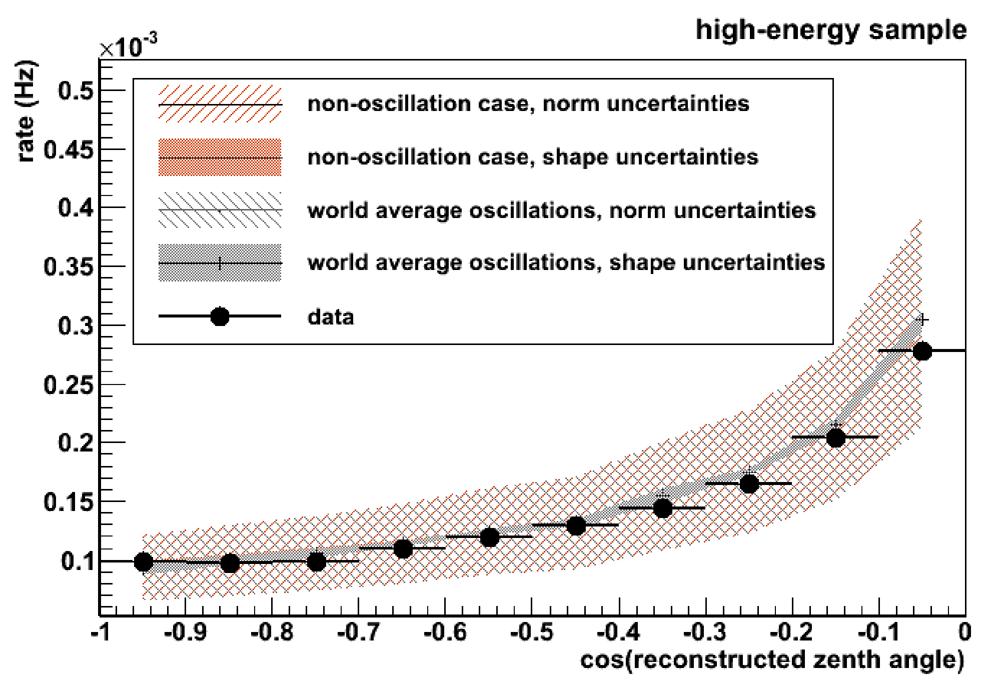
Muon disappearance in IceCube - first analysis -

- PRL 111 (2013) 081801
- Reconstructions from IceCube
- Low-energy (20-100 GeV) event selection with low efficiency, but selecting well-reconstructed events
- Additional standard high-energy (>100 GeV) IceCube event selection for reduction of systematic uncertainties



Data and MC expectation

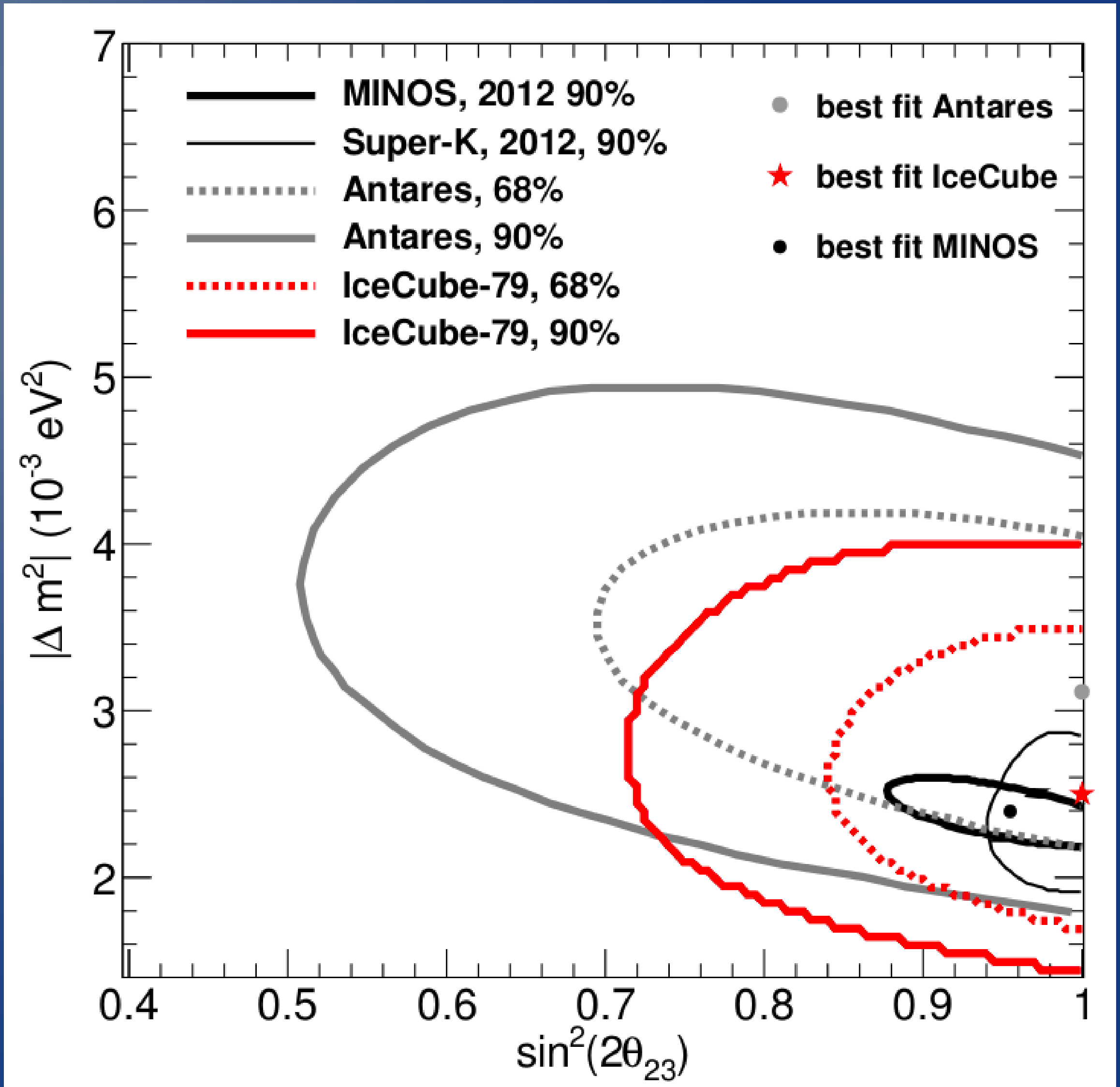




- Statistically significant angle-dependent suppression at low energy, high-energy sample provides constraint on uncertainties in simultaneous fit
- Shaded bands show range of uncorrelated systematic uncertainties; hatched regions show overall normalization uncertainty

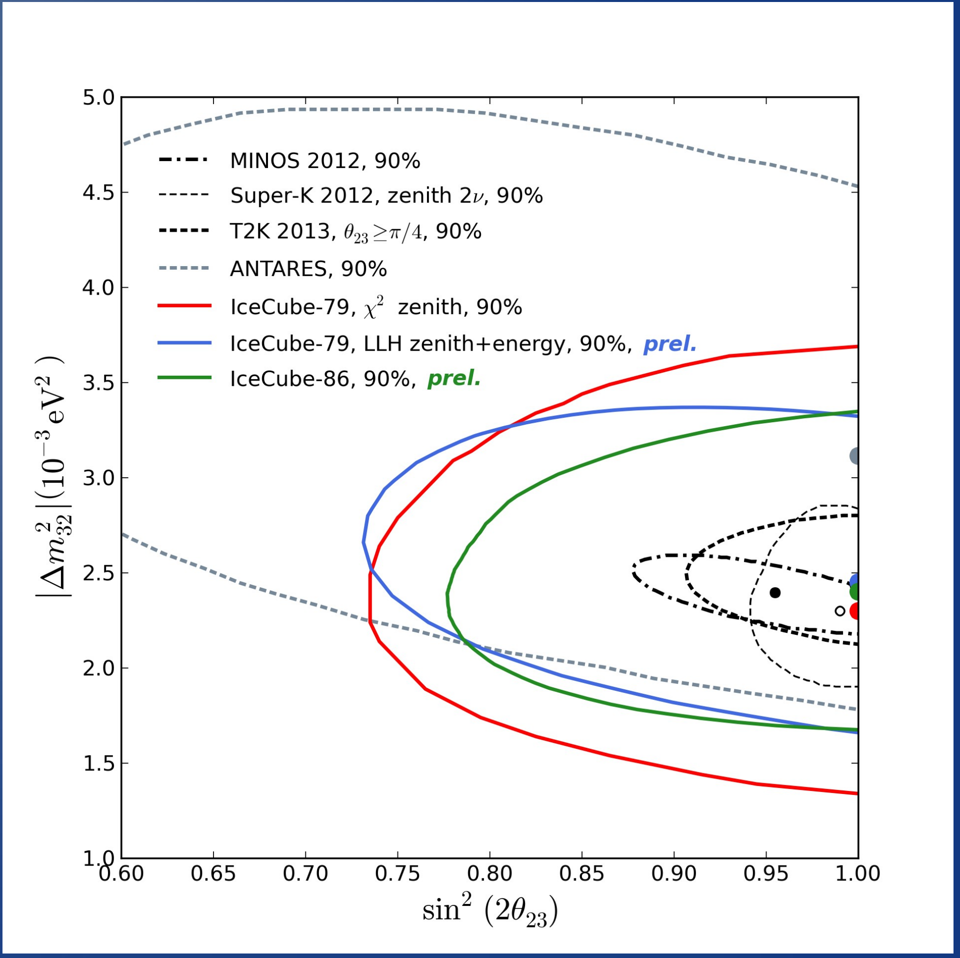
Muon disappearance in IceCube - first result -

- PRL 111 (2013) 081801
- High-energy IceCube event reconstructions applied to DeepCore
- Oscillation parameters fit to zenith distribution
- Systematics included
- Excellent agreement to world average measurments
- Large uncertainties in the IceCube measurement



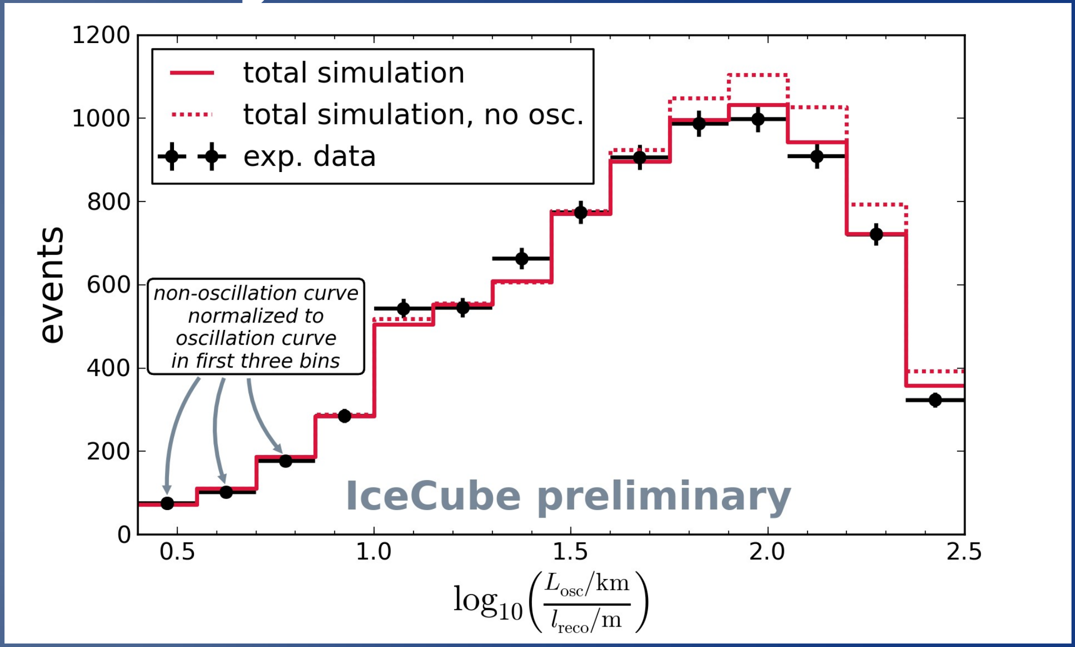
Further IceCube ν_μ disappearance results so far

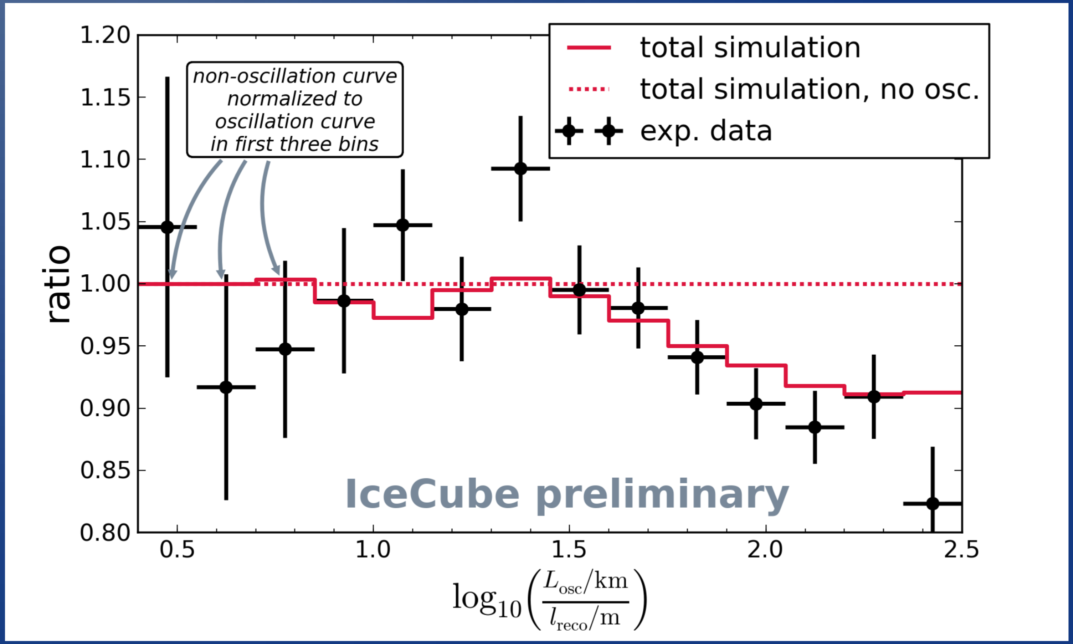
- All analyses 1 year of data
- Focus on technique development
- Inclusion of energy observable, 2D fit (zenith, energy)
- Improvement mainly for the mass splitting



IC79 second analysis results

- Focus: efficiency improvement
- Highest event selecion efficiency reached so far
- L/E visualizes the oscillation effects

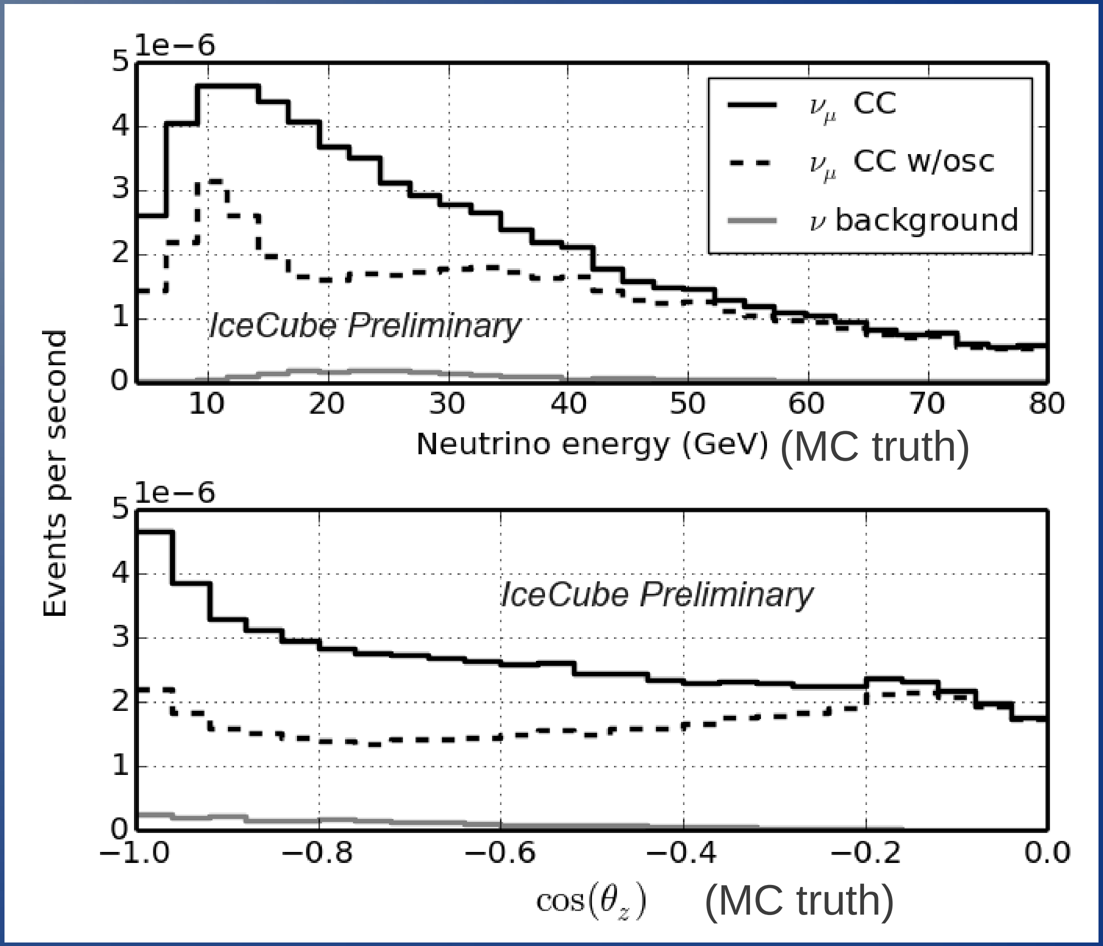




33rd ICRC conference, contribution 0848 included in arxiv:1309.7008

IC86 oscillation results

- Focus: new reconstruction techniques using unscattered photons
- Good angular resolution at lowest energies
- Highest event rates at ~10 GeV



33rd ICRC conference, contribution 0450 included in arxiv:1309.7008

IC86 oscillation results

- Focus: new reconstruction techniques using unscattered photons
- Good angular resolution at lowest energies
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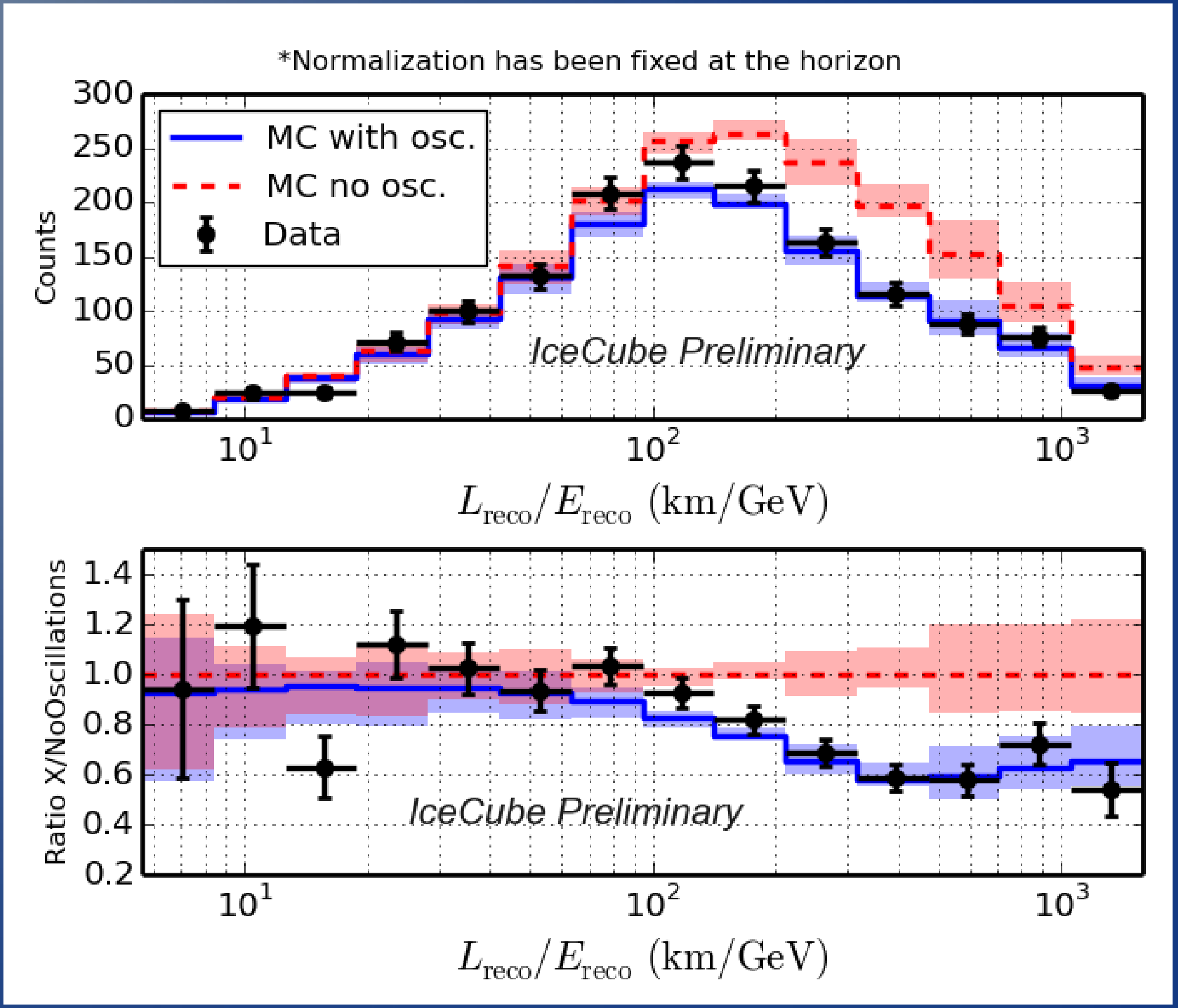

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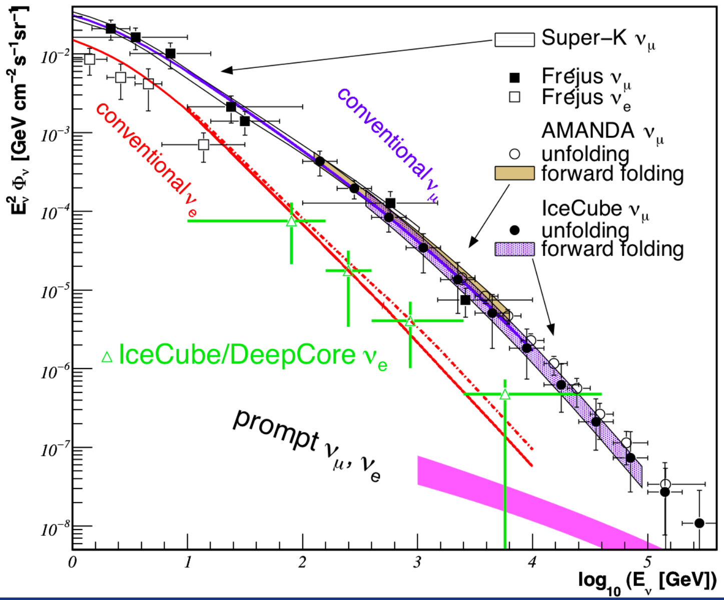
Status of oscillation analyses with DeepCore

- First result published
- Second generation analyses use 2D parameter scan (θ_{rec} and E_{rec})
- Transition to multi-year analyses soon, combining the strengths of the different approaches

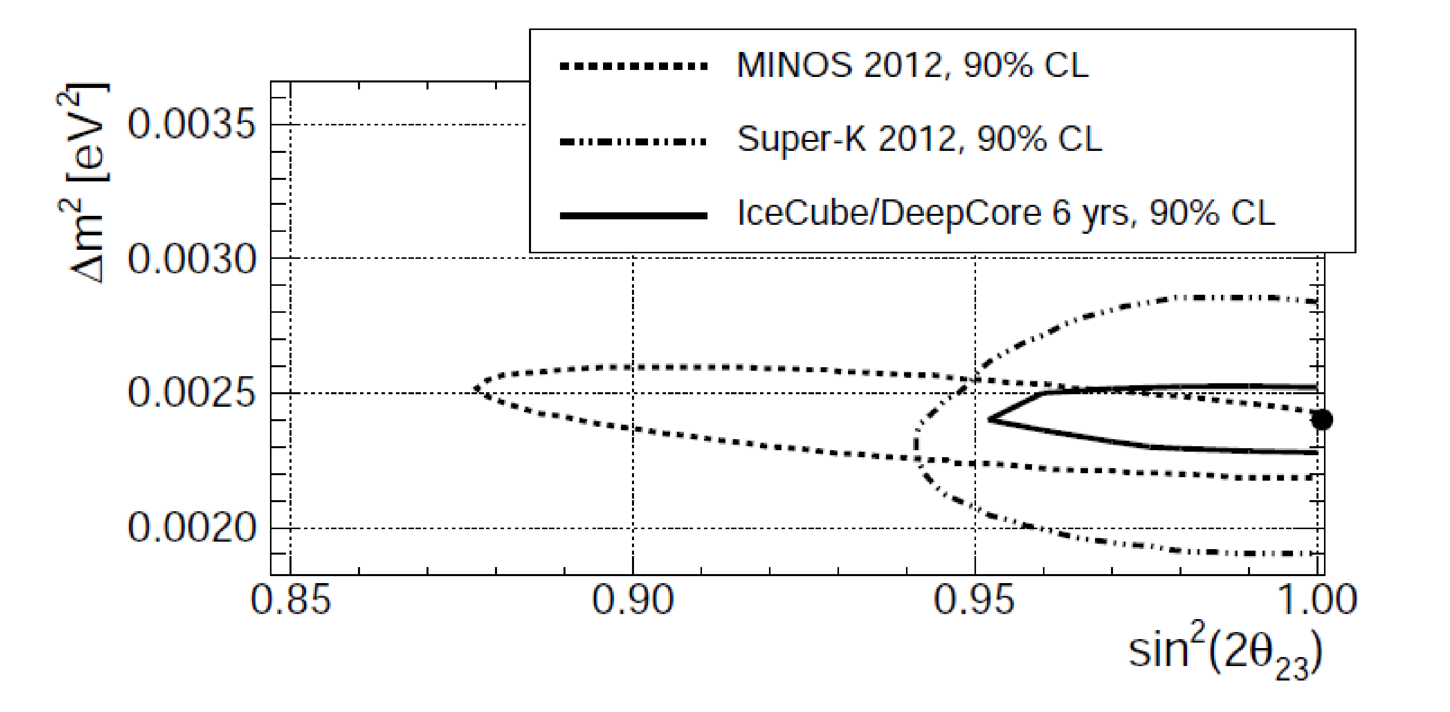
Note: DeepCore has detected electron neutrinos at energies from 80 GeV to 6 TeV (cascade channel), see PRL 110 (2013) 151105



DeepCore potential under optimistic assumptions

- Improved accuracy on systematic uncertainties (50%)
- Improved reconstruction (reach better accuracy for highly efficient event selection)
- 6 years of data

33rd ICRC conference, contribution 0460 included in arxiv:1309.7008

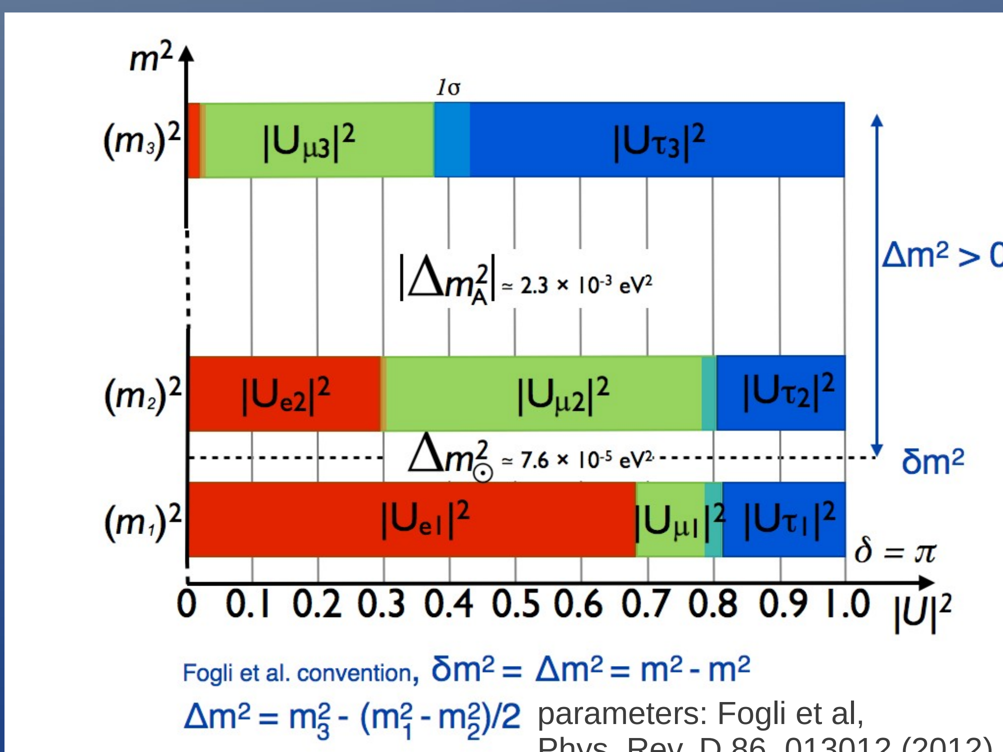


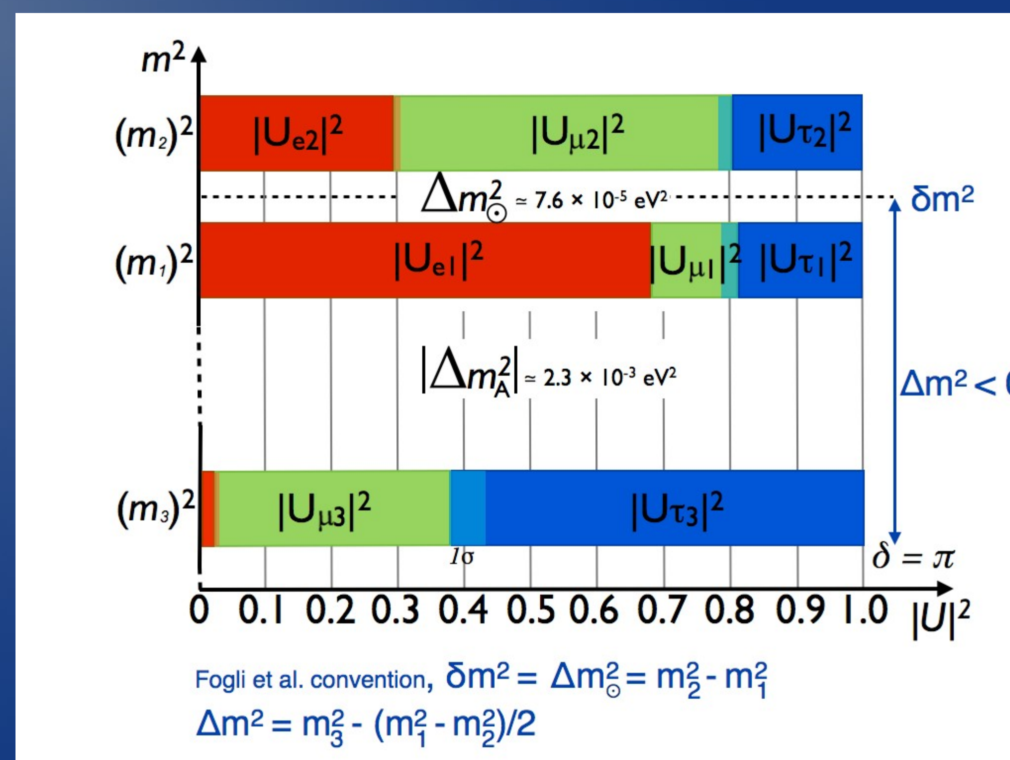
The concept of PINGU

- PINGU (Precision IceCube Next Generation Upgrade) is a potential extension of IceCube/DeepCore to energies below 10 GeV
- Baseline geometry is 40 additional strings with a 20m spacing, 60 DOMs per string
- Better control of systematics due to new calibration devices, denser instrumentation
- Primary goal: Measurement of the neutrino mass hierarchy
- Timeline: 2-3 years needed for construction at South Pole, deployment could start as early as 2016/17

Neutrino Mass Hierarchy

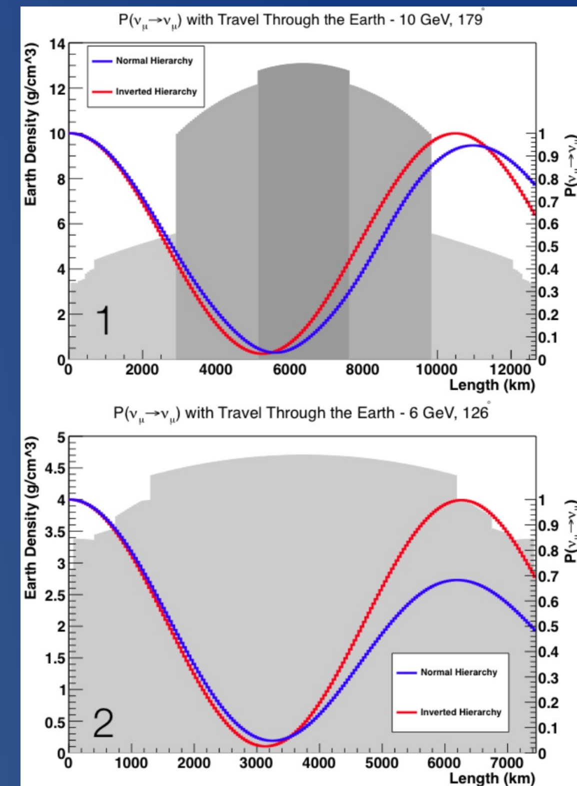
- Known parameters in neutrino oscillation physics:
  - mixing angles; absolute mass differences; mass ordering of ν_1 and ν_2
- Unknown parameters:
  - Complex phase δ
  - Mass ordering: is ν_3 the lightest or the heaviest neutrino?

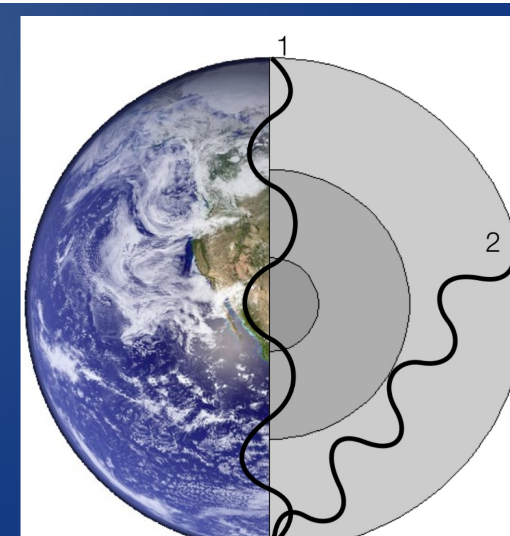




How do we want to measure it?

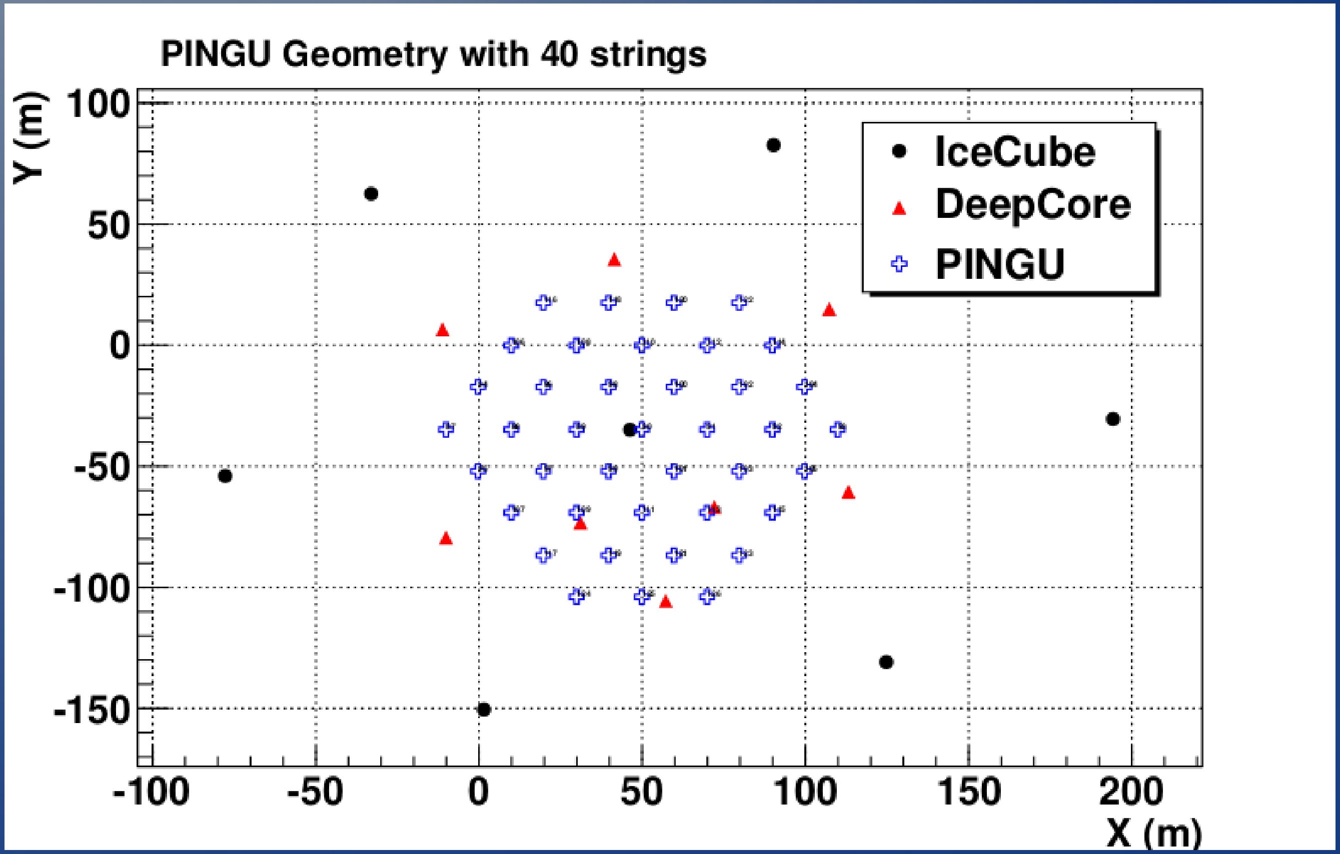
- MSW effect: neutrino oscillations in matter differ from vacuum
  - strongest effects in the range of ~5-15 GeV
- MSW effect depends on hierarchy
- Atmospheric neutrinos: CR interaction in the atmosphere, pion, kaon decay
- Need high statistics of events below 10 GeV
  - This is achievable for ice Cherenkov detectors
    - Use denser instrumentation than for IceCube/DeepCore, ANTARES
    - Instrument a larger volume than for Super-K





Potential design of PINGU

- Design goal: Measurement of the neutrino mass hierarchy, reach >2 sigma after 1 year



Baseline geometry (various others are studied)

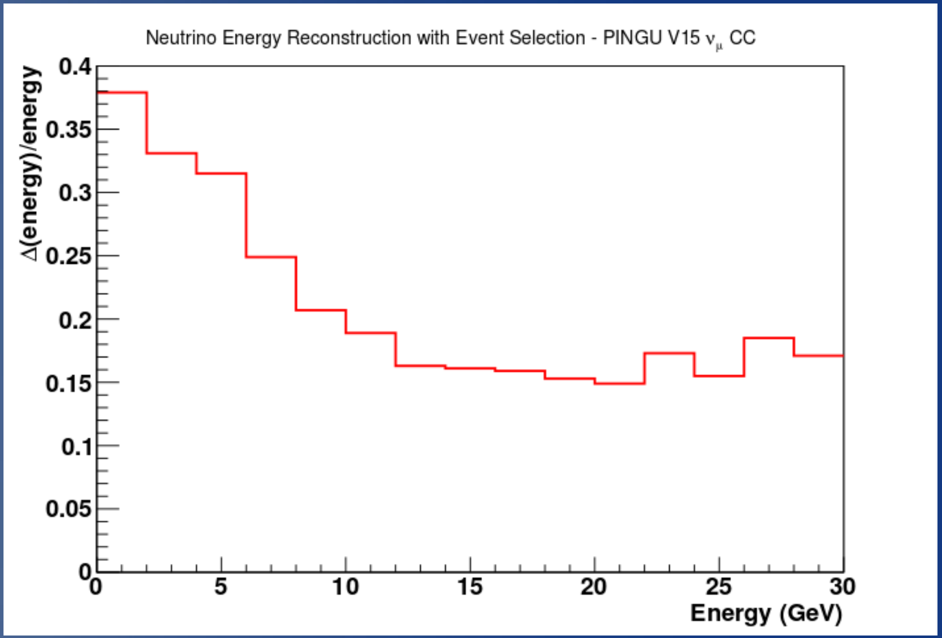
Event reconstruction and background rejection

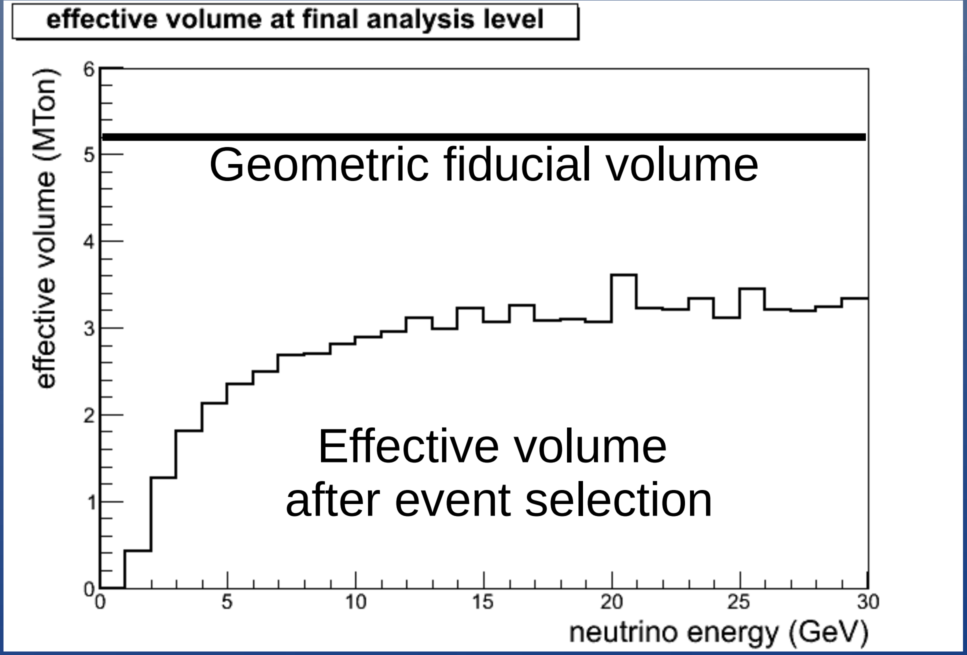
- Second generation of low-energy reconstruction
  - multi-dim LLH fit reconstructing cascade and track simultaneously (parameters: interaction vertex, cascade energy, neutrino direction, muon energy)
- Event selection:

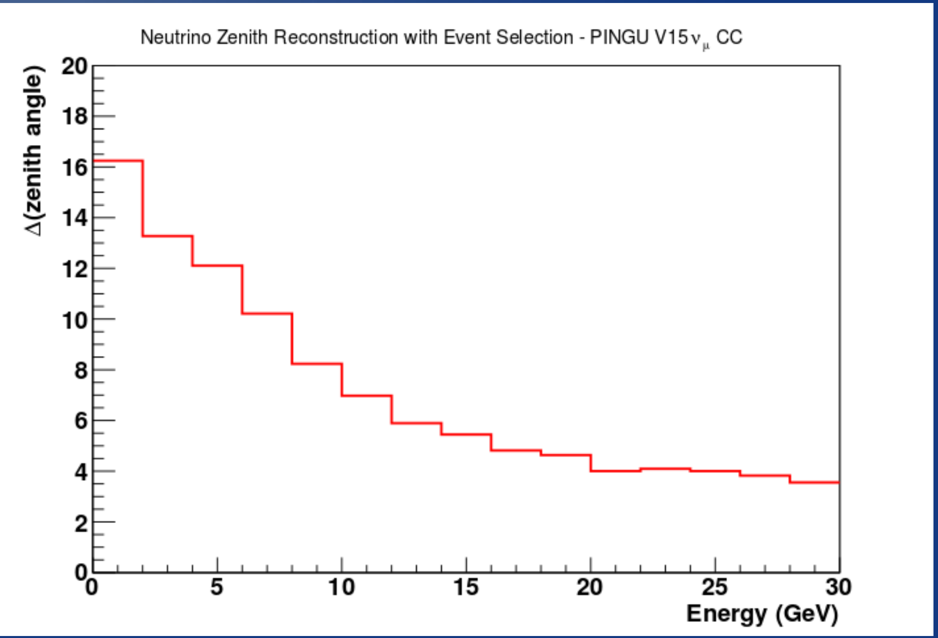
  Muon background signature differs from low-energy neutrinos:
  - Require the reconstructed vertex to be in the fiducial volume
  - Require the reconstructed energy to be within 0.5-80 GeV (energy region of interest)
  - Require the reconstructed direction to be upwards going

PINGU performance

- Fiducial volume defined by a cylinder with 75 m radius and 320 m height







Sensitivity to Neutrino Mass Hierarchy

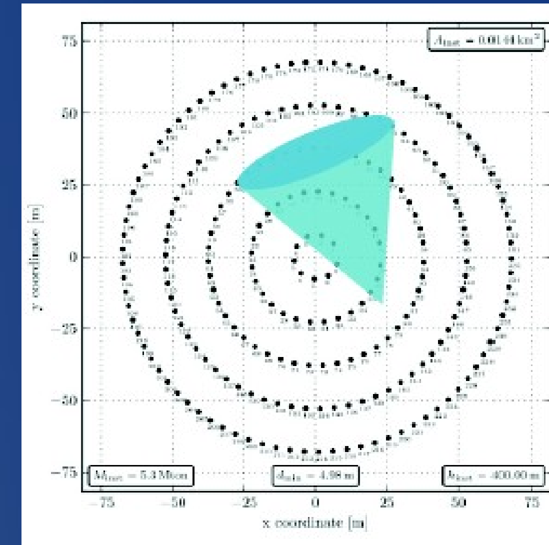
- Analysis currently under collaboration review
- Letter of Intent to be released very soon
- Marginalization over uncertainties in Δm^2_{13} and $\sin^2(\theta_{23})$
- Detector systematics considered:
  - Energy scale uncertainty
  - Uncertainty in flux normalization and spectral index
  - Uncertainty in effective area

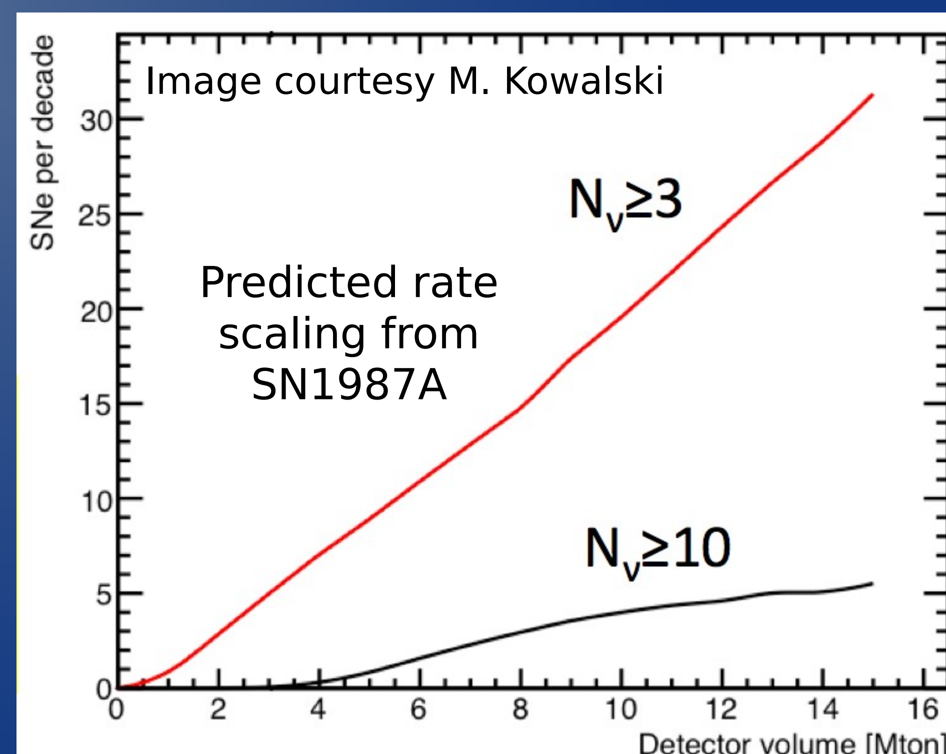
Summary PINGU

- PINGU as a further infill array within the DeepCore volume could lower the energy threshold from 10 GeV to a few GeV
- Main goal: determination of the neutrino mass hierarchy (design goal: >2 sigma after 1 year)
- Further potential in neutrino oscillations: maximum 23 mixing? If not, in which octant is θ_{23}?
- Non-oscillation physics: dark matter searches, supernova neutrinos

MICA

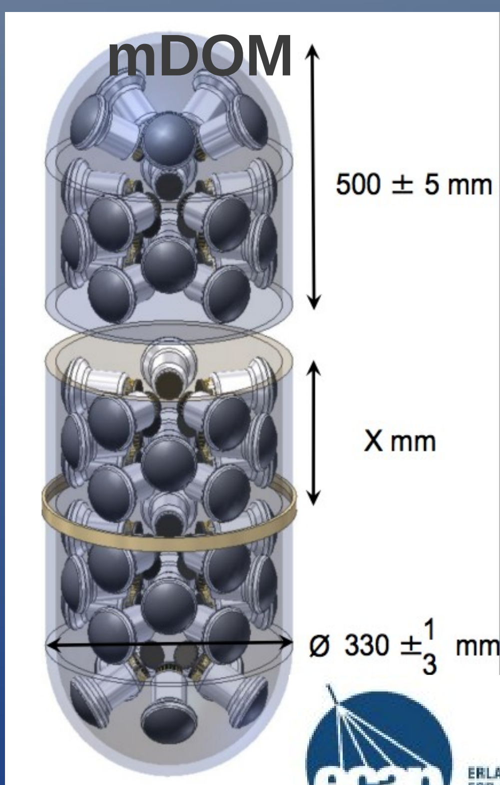
- Densest instrumentation
- O(few hundred) strings within DC volume
- Linear photon detectors
- R&D with PINGU (WOM)
- Supernova detection, up to ~ 10 MPc
- O(10 MeV) threshold for bursts, O(50 MeV) for single events
- Might be sensitive to proton decay (backgrounds)
- Cherenkov ring imaging?



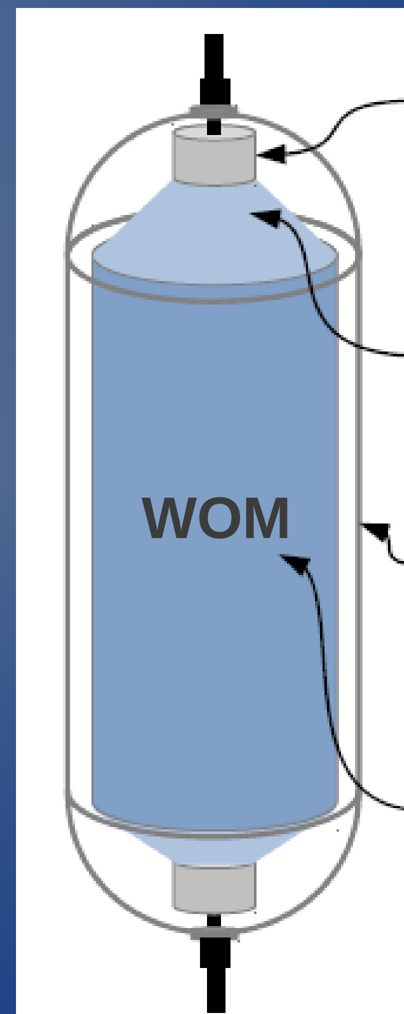


R&D for MICA with PINGU

- Goal: deploy potential MICA detectors with PINGU for test purposes
- Variuos designs persued



Multi-PMT DOM based on km3NET design



Conclusions

- Large volume neutrino telescopes entered the field of neutrino oscillation physics
- First results form available
- Additional statistics and improved methods will allow to achieve similar precision with the existing DeepCore detector as current leading experiments after a few more years
- PINGU can improve the performance for energies below 10 GeV and it can measure the neutrino mass hierarchy