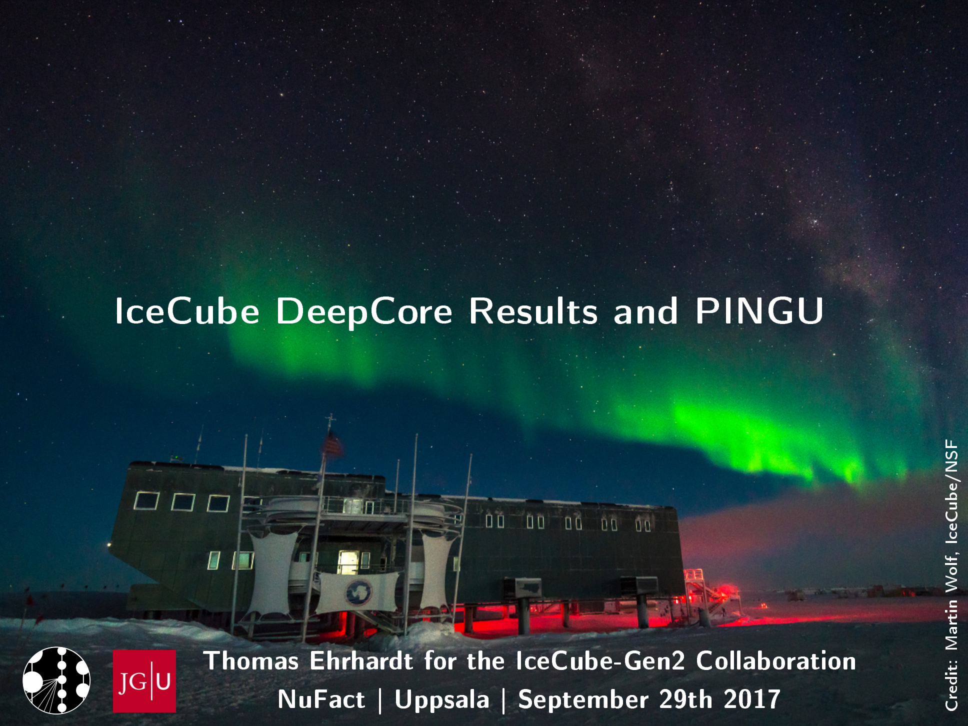


IceCube DeepCore Results and PINGU

Thomas Ehrhardt for the IceCube-Gen2 Collaboration

NuFact | Uppsala | September 29th 2017

Outline

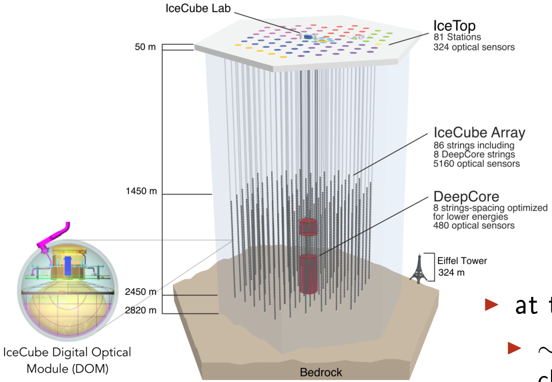
- IceCube DeepCore: recent results on neutrino oscillations

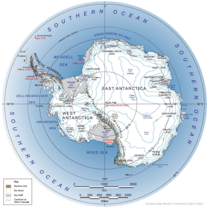
  arXiv:1707.07081

- Looking to the future with IceCube-Gen2 Phase 1 and PINGU

  as of this September: updated LoI at arXiv:1401.2046v2

IceCube Neutrino Observatory



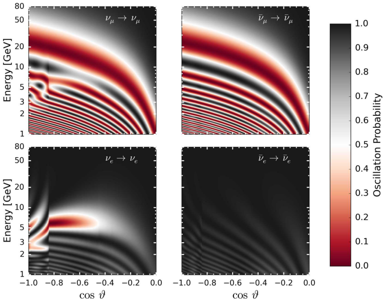


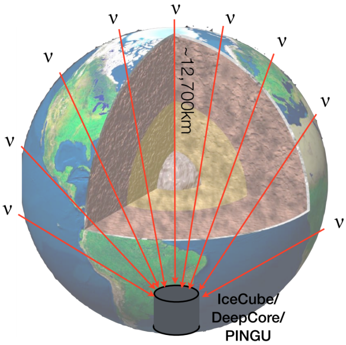
- 1 Gt of ice instrumented
- optimised for TeV–PeV range

- at the core: **DeepCore**
  - $\sim$ 10 Mt of densely instrumented clear ice
  - lower energy threshold at few GeV
  - measurement of atmospheric neutrino oscillations (this talk), ν_τ appearance (talk by P. Eller)

Atmospheric Neutrinos

- steady ν flux available over large range of neutrino energies E_ν and oscillation baselines L
- for vertically upgoing ν_μ, first survival probability minimum at $E_\nu \sim 25$ GeV

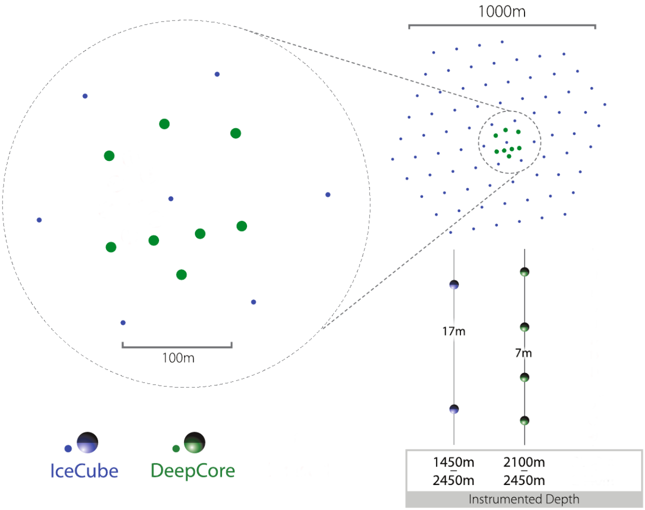




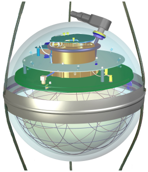
- Earth matter effects: characteristic modifications of oscillation probabilities below ~ 15 GeV, depending on neutrino mass ordering (NMO)

IceCube DeepCore

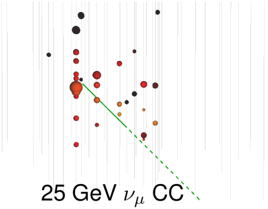
DeepCore



HQE IceCube DOM



10" PMT



25 GeV ν_μ CC

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

Recent Oscillation Analyses

DeepCore

IceCube 2014

Phys. Rev. D91, 072004 (2015)

- select "golden" ν_μ CC events
  - pronounced track-like topology
  - multiple unscattered photons
- restrict analysis to up-going region
  - reduction of backgrounds
- data-driven estimate of residual atmospheric muon background

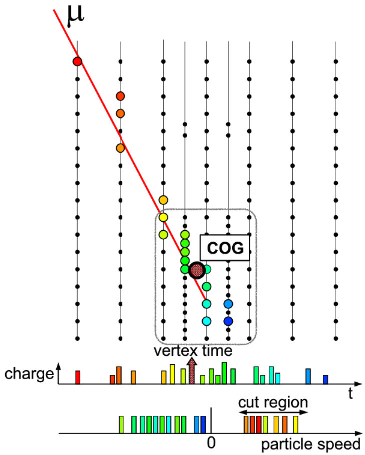
IceCube 2017

arXiv:1707.07081

- order of magn. statistics increase
  - include cascade- + track-like events
  - constrain systematics via inclusion of down-going events
- full likelihood event reconstruction
  - median resolutions at 20 GeV: 10° (16°) and 24 % (29 %) for track-like (cascade-like) events
- fits account for statistical uncertainty of expectation
- data-driven estimate of residual atmospheric muon background

Measurement Strategy

- atmospheric μ background vetoed using IceCube array



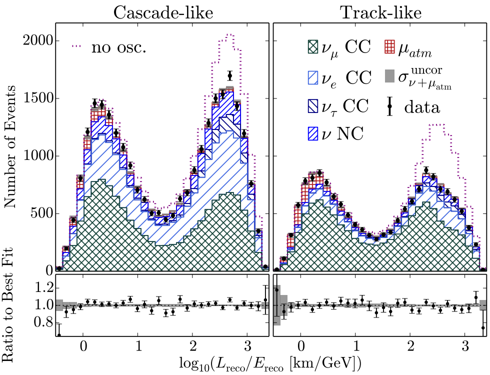
- further selection criteria and quality cuts: suppression of μ_{atm} by factor of $\sim 10^8$
- reconstruct ν energy E and zenith $\Rightarrow$ oscillation baseline (L) uniquely determined by zenith
- measure oscillations by fitting $L \times E \times$ event type distribution

Atmospheric Oscillation Measurement

arXiv:1707.07081

DeepCore

$\sim$ 41 k events from 2012–14 data sets – projected onto L/E **for illustration**



main sample contributions

- cascade-like sample:
  $\sim$ 48% ν_μ CC, $\sim$ 32% ν_e CC
- track-like sample:
  $\sim$ 68% ν_μ CC, $\sim$ 16% ν_e CC

best fit uncertainty from statistics and data-driven background shape

- binned χ^2 analysis with $8 \times 8 \times 2$ bins in $E \times L \times$ event type
  - $\chi^2/\text{n.d.f.} = 117/119$

Nuisance Parameter Fits

arXiv:1707.07081

DeepCore

Parameters	Priors	Best Fit NH	Best Fit IH
Flux and cross section parameters			
Neutrino event rate [% of nominal]	no prior	85	85
$\Delta\gamma$ (spectral index)	0.00±0.10	-0.02	-0.02
$\nu_e + \bar{\nu}_e$ relative normalization [%]	100±20	125	125
NC relative normalization [%]	100±20	106	106
$\Delta(\nu/\bar{\nu})$ [σ], energy dependent‡	0.00±1.00	-0.56	-0.59
$\Delta(\nu/\bar{\nu})$ [σ], zenith dependent‡	0.00±1.00	-0.55	-0.57
M_A (resonance) [GeV]	1.12±0.22	0.92	0.93
Detector parameters			
overall DOM efficiency [%]	100±10	102	102
relative DOM efficiency, lateral [σ]	0.0±1.0	0.2	0.2
relative DOM efficiency, head-on [a.u.]	no prior	-0.72	-0.66
Background			
Atm. μ contamination [% of sample]	no prior	5.5	5.6

‡: Following Barr, et al., *Phys. Rev.* D74, 094009

- no impact and thus fixed:

$$\Delta m^2_{21} = 7.53 \times 10^{-5}\,\text{eV}^2,\ \theta_{12} = 33.46^\circ,\ \theta_{13} = 8.47^\circ,\ \delta_{\text{CP}} = 0^\circ$$

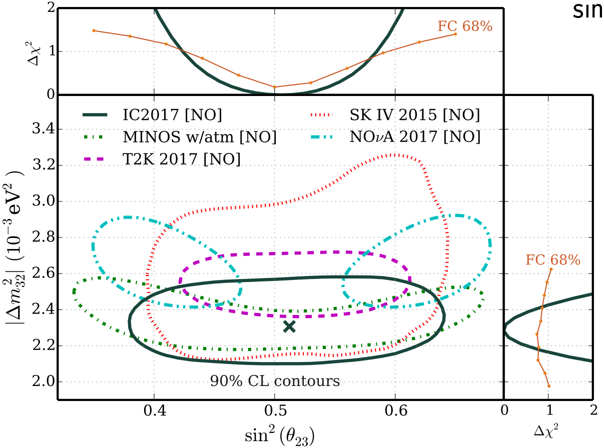
Atmospheric Oscillation Parameters

arXiv:1707.07081

DeepCore

best fit (normal ordering): $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\,\mathrm{eV}^2$,

$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$



- contours from Feldman-Cousins approach
- consistent with other dedicated experiments
- measurement still statistics-limited

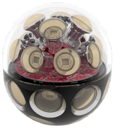
underway: follow-on analyses with this same + a higher-statistics data set

IceCube-Gen2 Phase 1

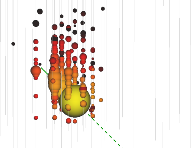
Phase 1

- 7 new strings instrumented with multi-PMT mDOMs in DeepCore region
- deploy set of novel calibration devices $\rightarrow$ take into account past and ongoing IceCube calibration efforts
- benefit high- and low-energy IceCube physics abilities
- dedicated detector + stepping stone towards PINGU

mDOM



24 × 3" PMTs



25 GeV ν_μ CC

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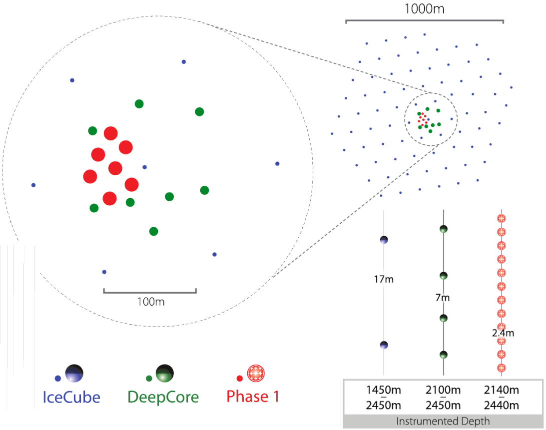
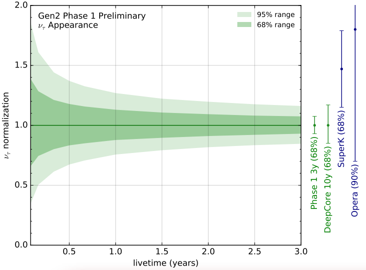


Phase 1 (Oscillation) Physics Goals

Phase 1



- tau neutrino appearance

  $< 10\,\%$ precision with 3 year sample

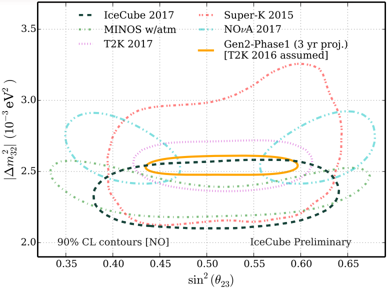
  probe unitarity of PMNS matrix

see P. Eller: ν_τ Appearance in IceCube

- maximal 2-3 mixing?

  consistent with IceCube & T2K, but disfavoured (2.6σ) by NOνA

- precision measurement of atmospheric mass splitting and (2-3) mixing angle



Phase 1 (Oscillation) Physics Goals

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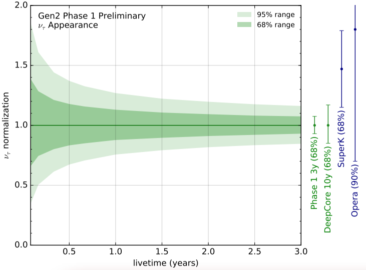

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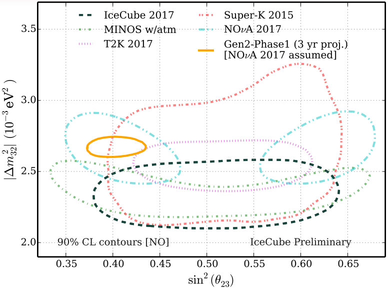
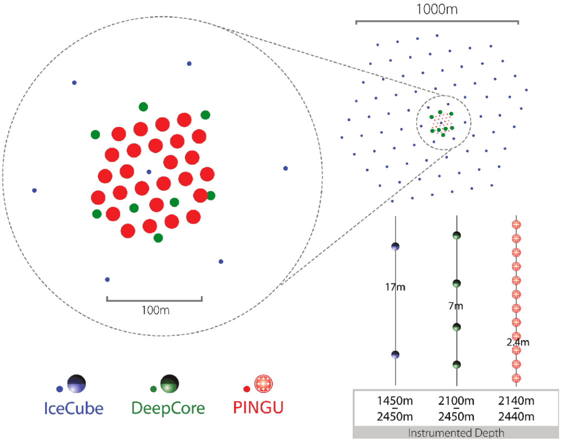


IceCube-Gen2 PINGU

PINGU

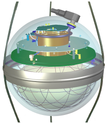
- in total 26 additional strings in DeepCore region

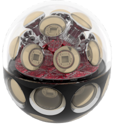


Significantly updated Letter of Intent as of this September

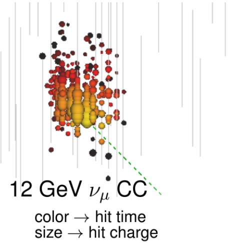
arXiv:1401.2046v2

LoI: HQE IceCube DOM





envisaged: mDOM



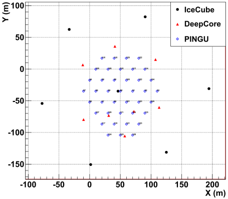
PINGU Geometry Summary

PINGU

early geometries:

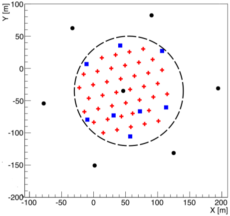
arXiv:1401.2046**v1**

- 40 strings w/ 60 DOMs each
- 20 m horizontal spacing
- 5 m DOM-DOM spacing



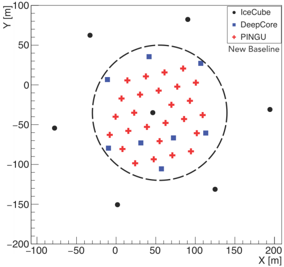
various conferences

- 40 strings w/ 96 DOMs each
- 22 m horizontal spacing
- 3 m DOM-DOM spacing



now (arXiv:1401.2046**v2**):

- 26 strings w/ 192 DOMs each
- 24 m horizontal spacing
- 1.5 m DOM-DOM spacing



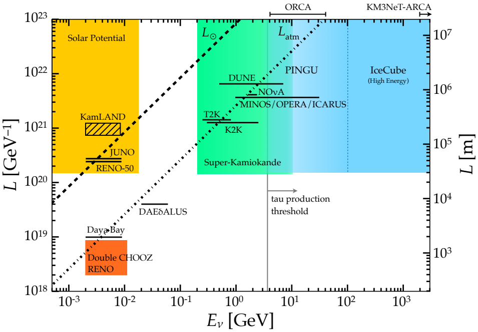
- reduced no. of holes to drill
- higher photocathode density
- **performance just as good!**

Analysis Goals

arXiv:1401.2046v2

PINGU

- improve on Phase 1 sensitivities across the board
- around 70k upgoing atmospheric neutrinos per year
- neutrino mass ordering and θ_{23} octant sensitivity
- tau neutrino appearance



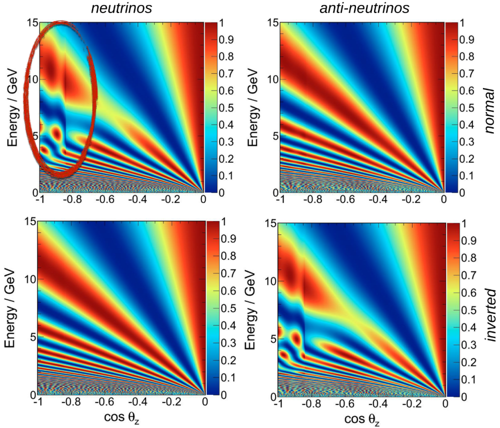
- + additional science (WIMP dark matter, Earth tomography, SNe)

NMO Measurement Principle

PINGU

- up to few 10 % differences in oscillation probabilities, depending on which NMO realised
- effect to 1st order symmetric w.r.t. flip of NMO & $\nu \leftrightarrow \bar{\nu}$

ν_μ survival



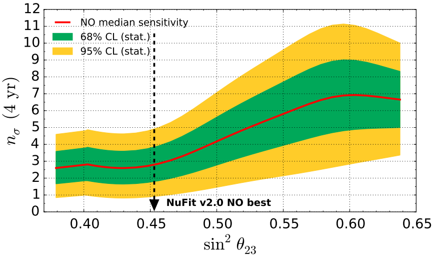
but:

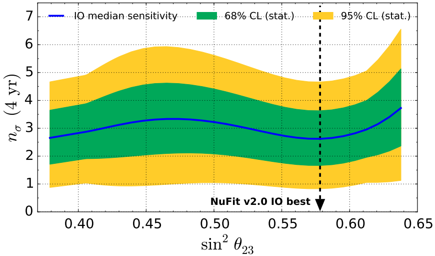
- atmospheric flux $\Phi_\nu / \Phi_{\bar{\nu}} \sim 1.3$
- x-sections $\sigma_{\nu N} / \sigma_{\bar{\nu} N} \sim 2$

$\Rightarrow$ few percent residuals even w/o ν vs. $\bar{\nu}$ discrimination

- massive O(Mton) detector required for sufficient event statistics

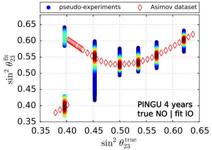
NMO Sensitivity





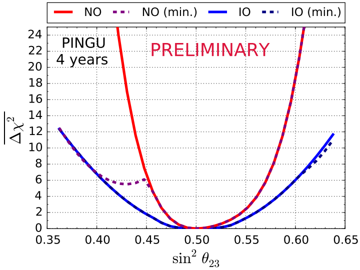
- good agreement between Asimov and pseudo-data ensemble studies
- sensitivity strongly dependent on true value of θ_{23}

  synergy potential: profit from better knowledge of θ_{23}

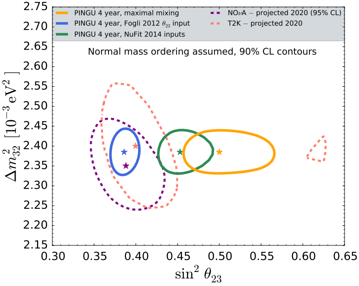


- projected median sensitivity $\sim 3\sigma$ in 4 years for recent global best fit values (close to sensitivity minima)

Atmospheric Oscillation Parameters



- 4-year octant sensitivity $\gtrsim 3\sigma$ if
  - IO: $\sin^2\theta_{23} \lesssim 0.38$ or $\gtrsim 0.62$
  - NO: $\sin^2\theta_{23} \lesssim 0.38$ or $\gtrsim 0.58$
- for true first octant and NO, profit greatly from knowing the NMO

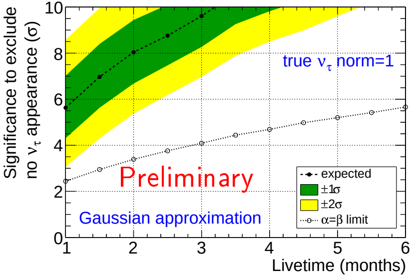


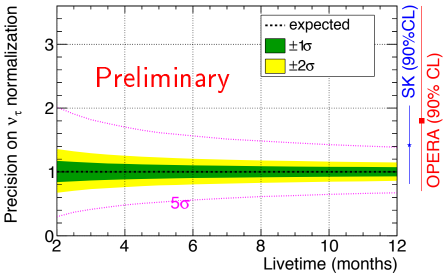
- precision of $\sin^2\theta_{23}$ and Δm^2_{32} measurement for different true $\sin^2\theta_{23}$ and NO
- compared to projected accelerator constraints

Tau Neutrino Appearance

with expected ν_τ appearance from standard 3-flavour oscillations:

- expect to reach 5σ exclusion of no ν_τ appearance with a month of data
- expect better than 10 % precision after one year of measurement





Summary

- IceCube DeepCore
  - new data set: significantly enhanced measurement of atmospheric oscillation parameters Δm^2_{32} & $\sin^2\theta_{23}$, maximal mixing preferred
  - follow-on studies underway
- planning for IceCube-Gen2 in progress
  - Phase 1 as stepping stone, with substantial improvements to both high energy neutrino astronomy and low energy neutrino physics
- PINGU
  - going beyond Phase 1: potential low energy extension within IceCube-Gen2
  - crucial in determination of NMO
  - multifaceted physics reach, e.g., atmospheric oscillations, WIMPs, SNe
  - **updated Letter of Intent available at arXiv:1401.2046v2**

Credit: Martin Wolf, IceCube/NSF

The IceCube–Gen2 Collaboration

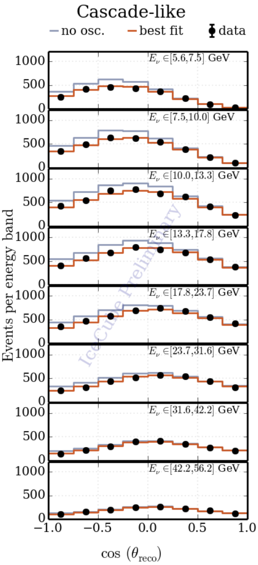
International Funding Agencies

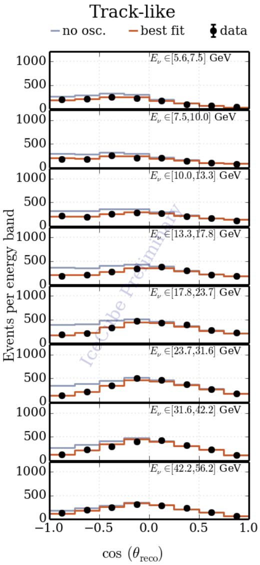
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation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

BACKUP

Data and Best Fit in Analysis Binning

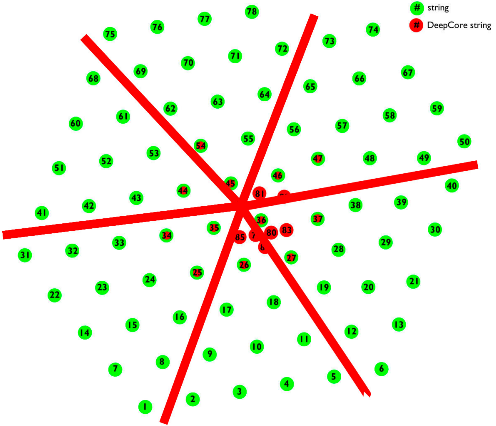
DeepCore (Backup)





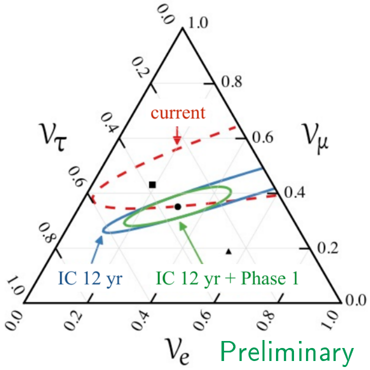
Atmospheric Muon Background Estimate

"Inverted Corridor Cut"



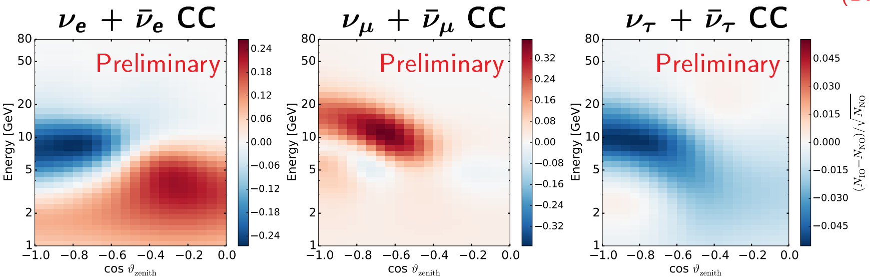
Phase 1: Impact on Neutrino Astronomy

- improved knowledge of ice and calibration will benefit reconstruction, flavour ID
  - gain by re-analysing decade of IceCube data



PINGU: NMO Signature

PINGU (Backup)



- expect $\sim$ 33k $\nu_\mu + \bar{\nu}_\mu$ CC + $\sim$ 25k $\nu_e + \bar{\nu}_e$ CC per year
- distinct spectral features depending on NMO
- intensity: projected statistical significance per bin for 1 year of data
- perfect flavour ID only for illustration