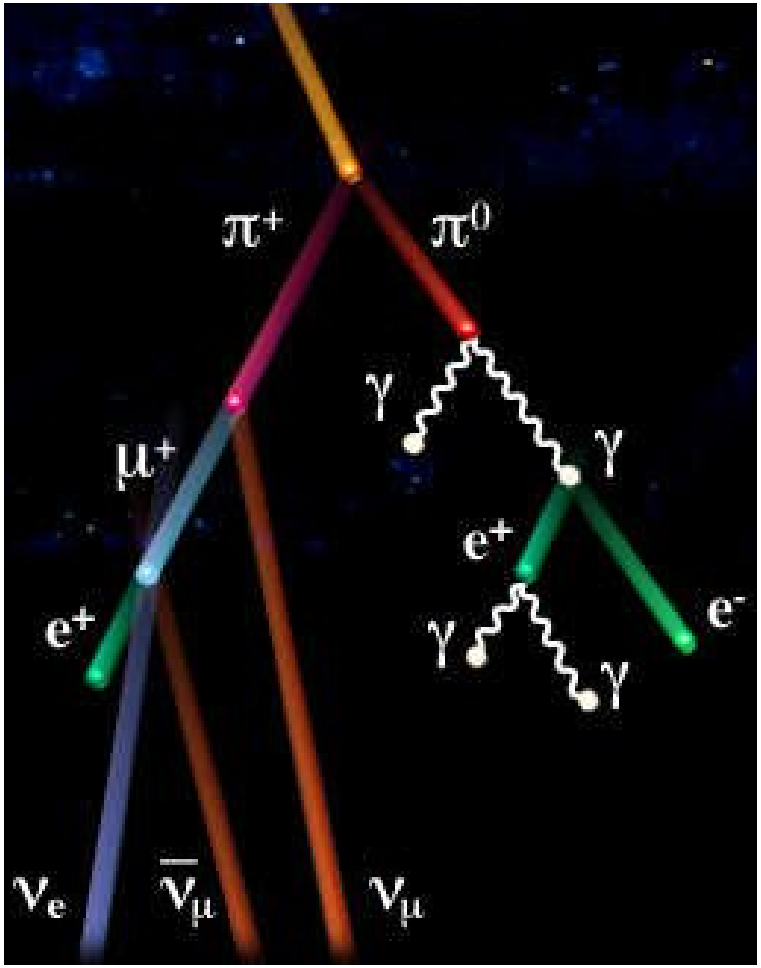
Atmospheric Neutrino Status and Prospects

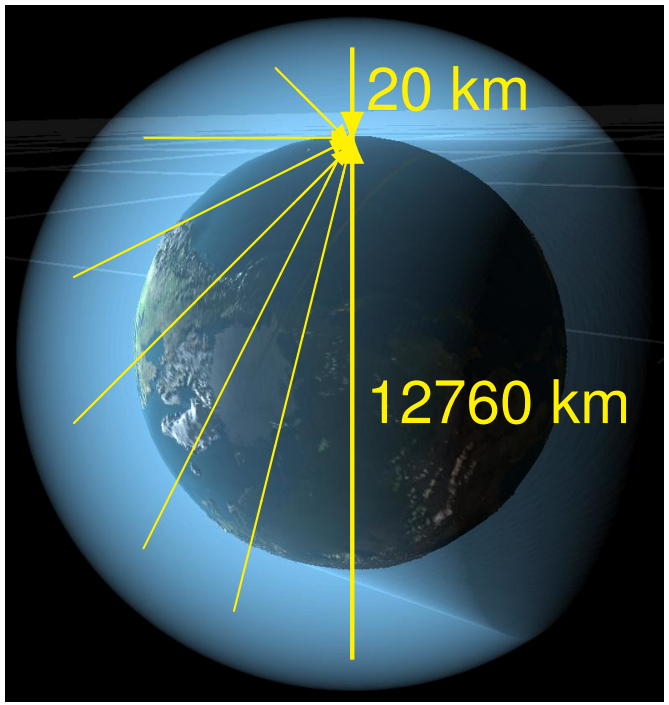
João Pedro Athayde Marcondes de André

MICHIGAN STATE UNIVERSITY

10 August 2015

Atmospheric neutrinos

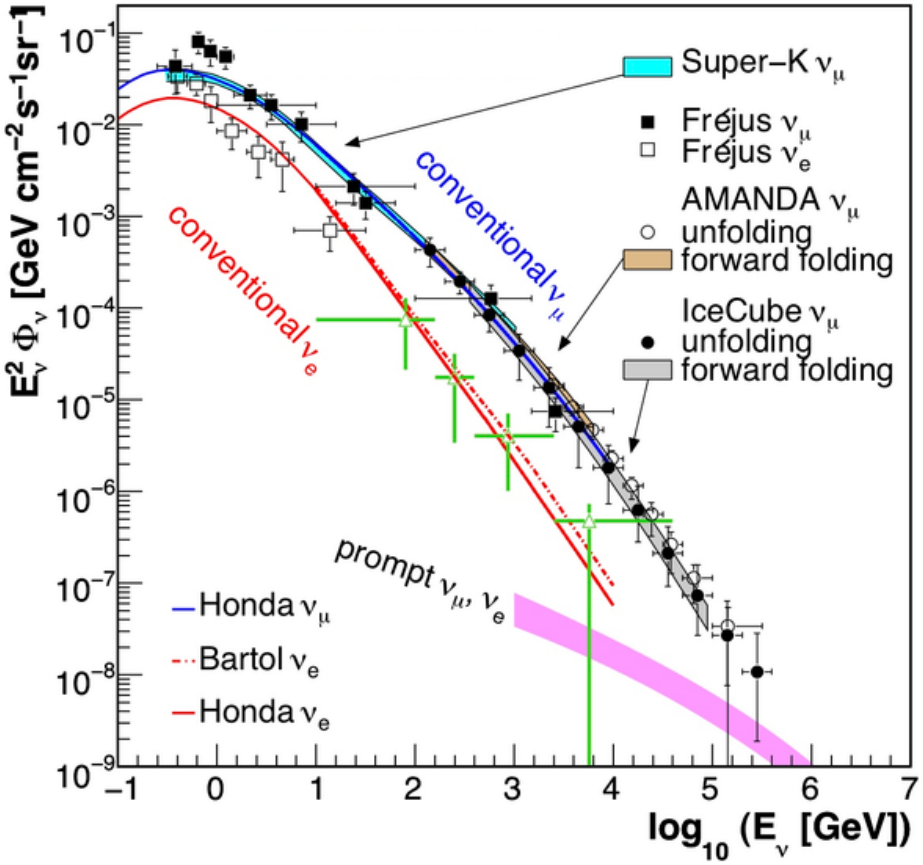


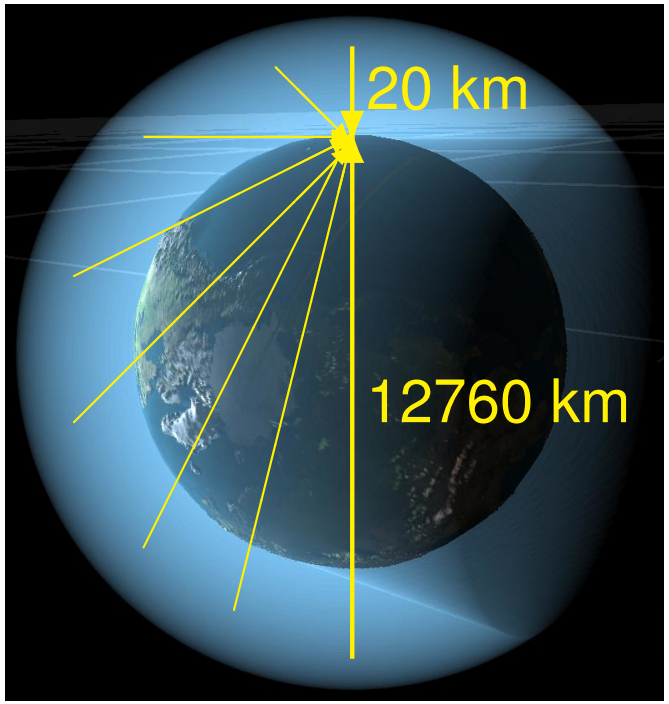


- 2:1 ratio between ν_μ:ν_e
- similar rate of ν and $\bar{\nu}$
  - however, x-sec for $\bar{\nu}$ half of ν

- various baselines available

Atmospheric neutrinos

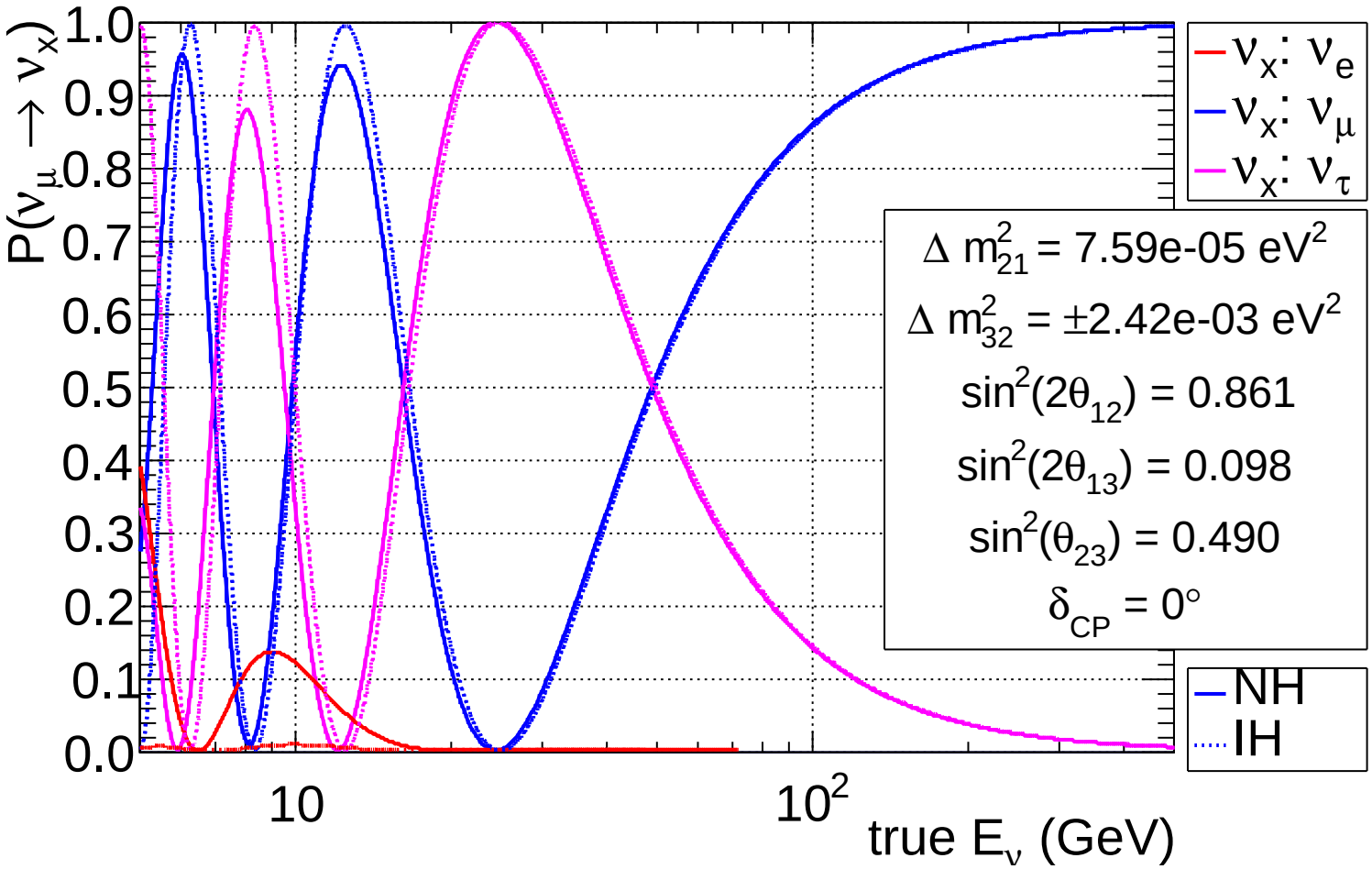




- ν energy over several orders of magnitude
- various baselines available

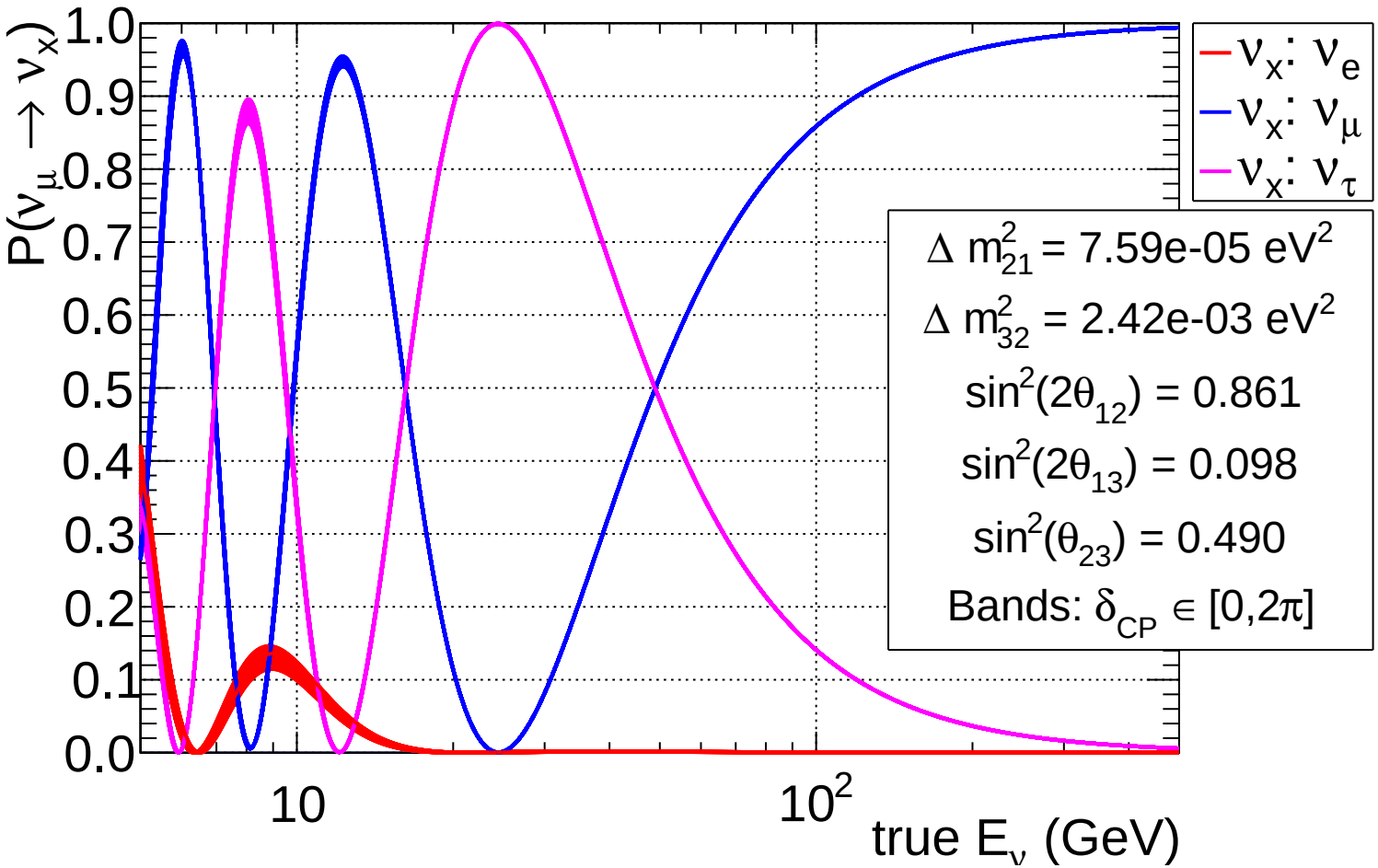
$\Rightarrow$ wide range of L/E available

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

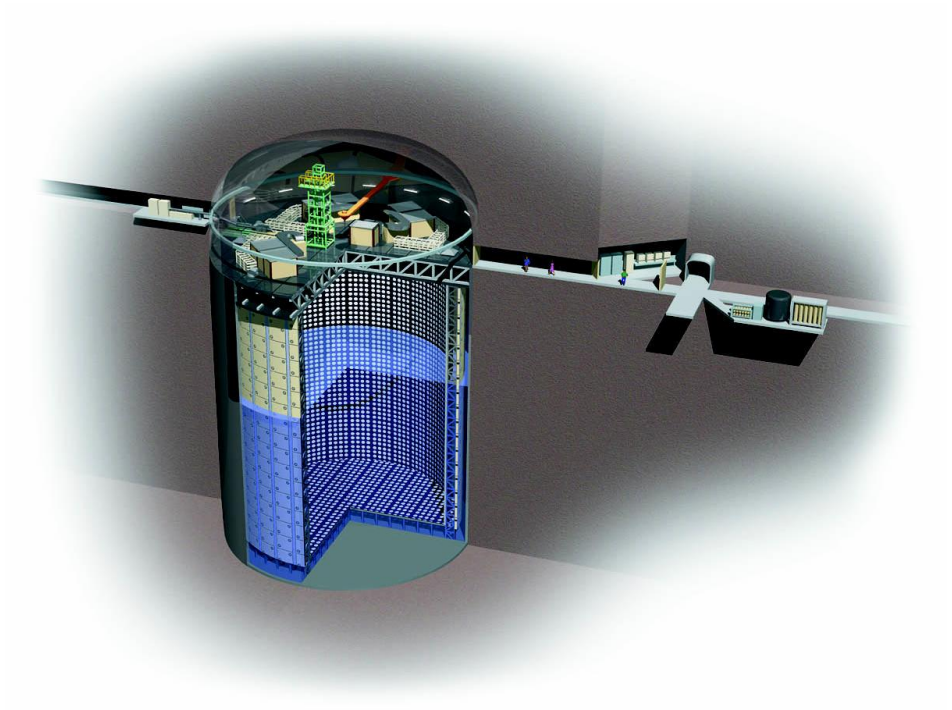
Atmospheric neutrinos oscillations



- 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

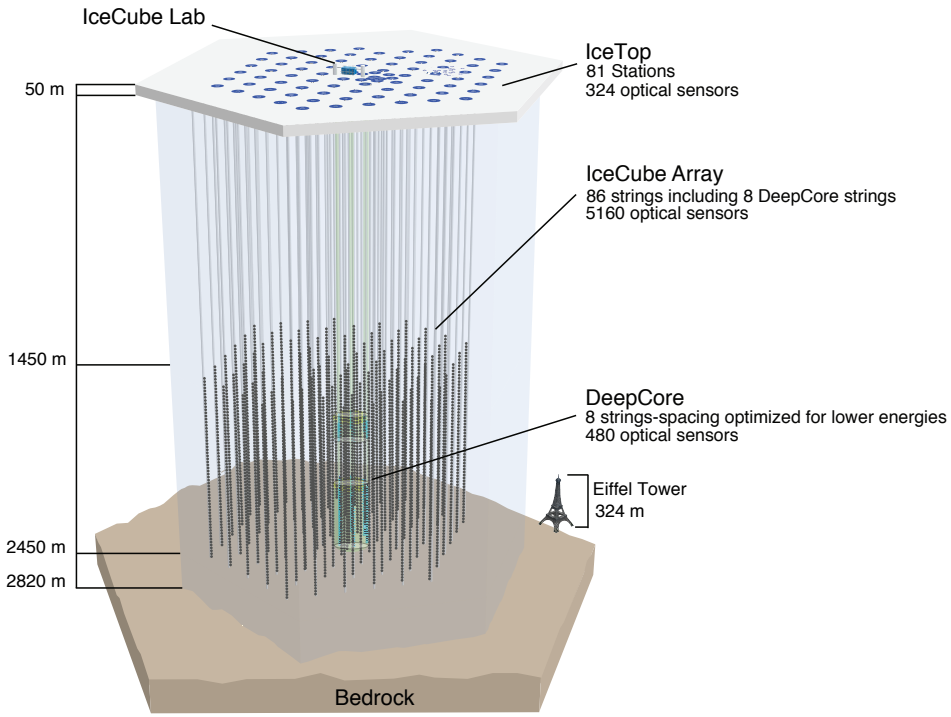
Current experiments

Super-Kamiokande



- Inner detector: 11129 PMTs
- Fiducial volume: 22.5 ktons
- Operation started in Apr. 1996

IceCube-DeepCore

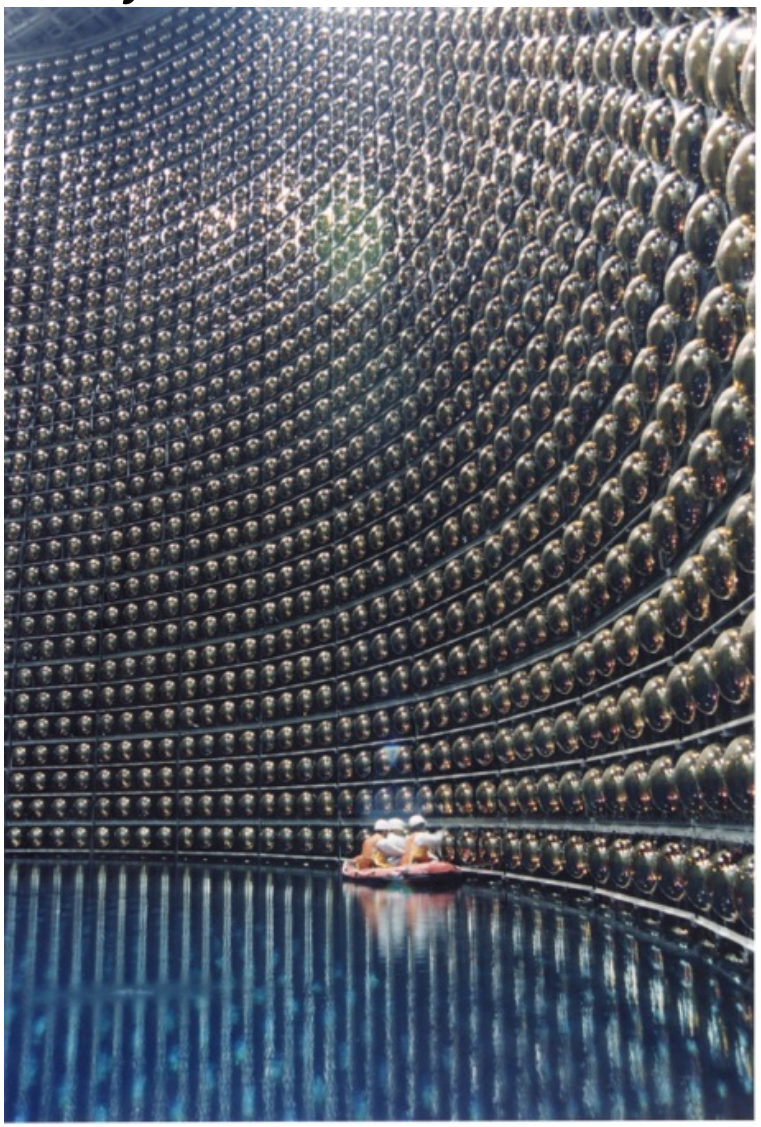


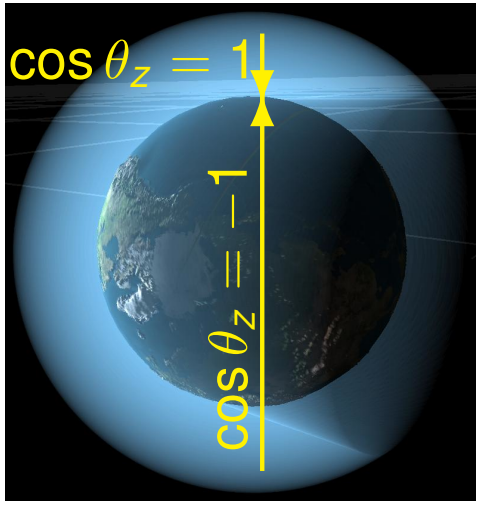
- In ice: 5160 PMTs
- Sparse array: 1 km^3 volume
- Denser OM volume: $\sim$ 6 Mtons
- Full detector: May. 2011

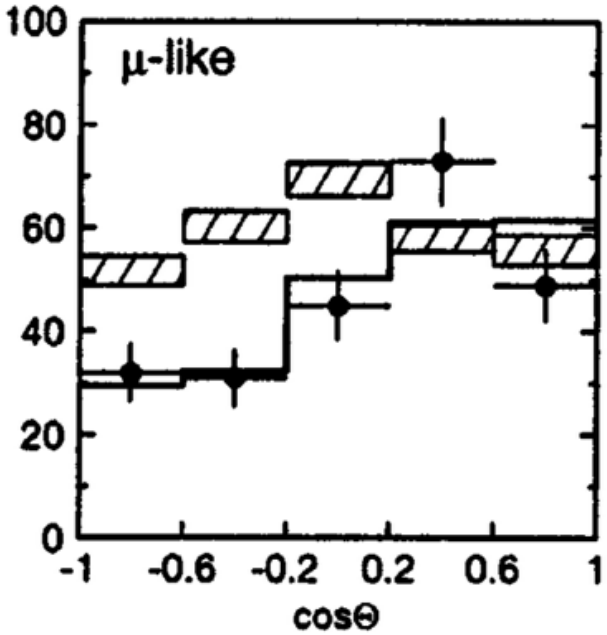
- Other experiments: far detectors of MINOS and NOνA, ANTARES, ...

First measure of ν oscillations by Super-Kamiokande

- Evidence for oscillation of atmospheric neutrinos, *Phys.Rev.Lett.81 1562-1567*, 1998



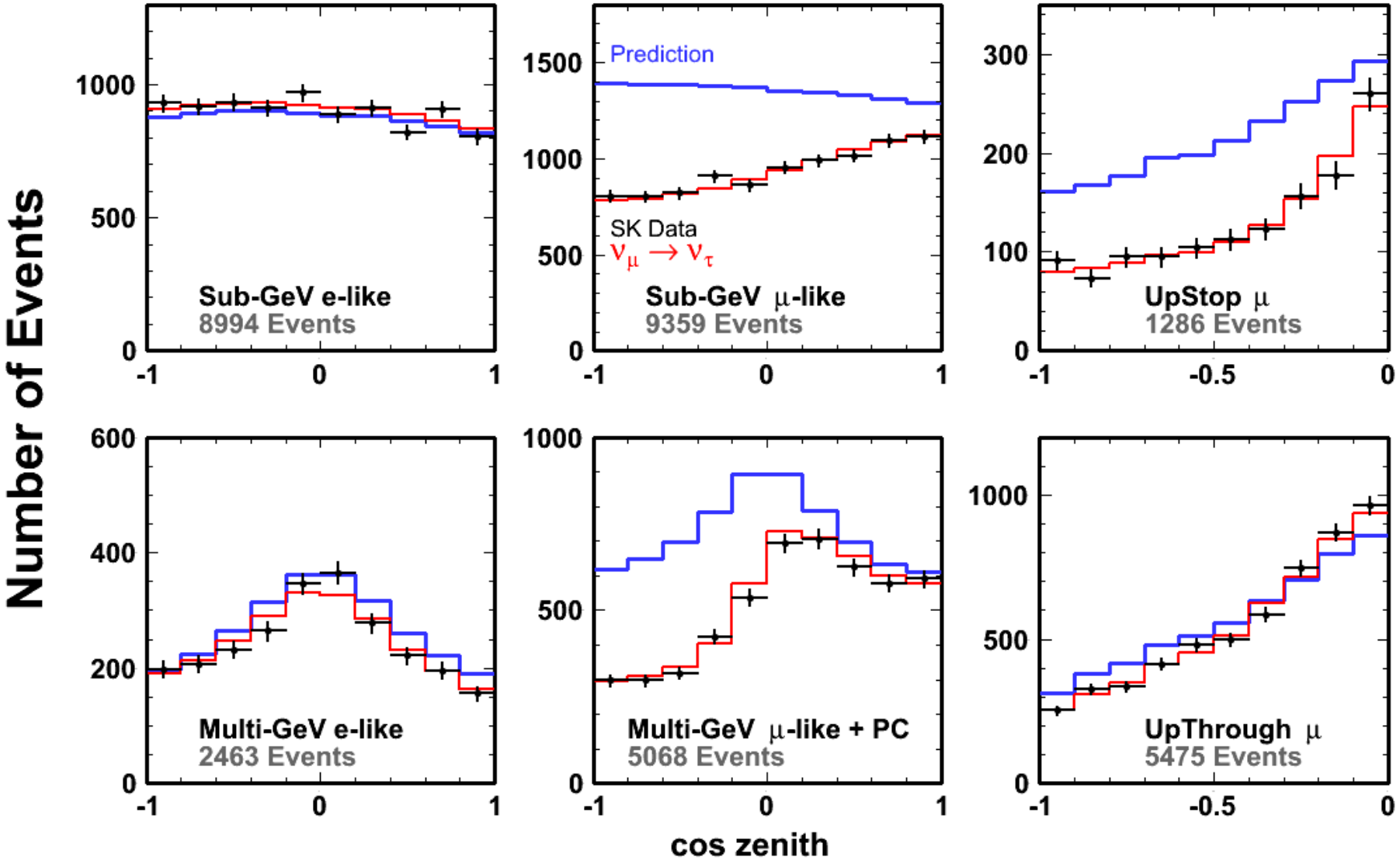




Recent results by SK

See presentation on WG1 parallel Tuesday by Jun Kameda

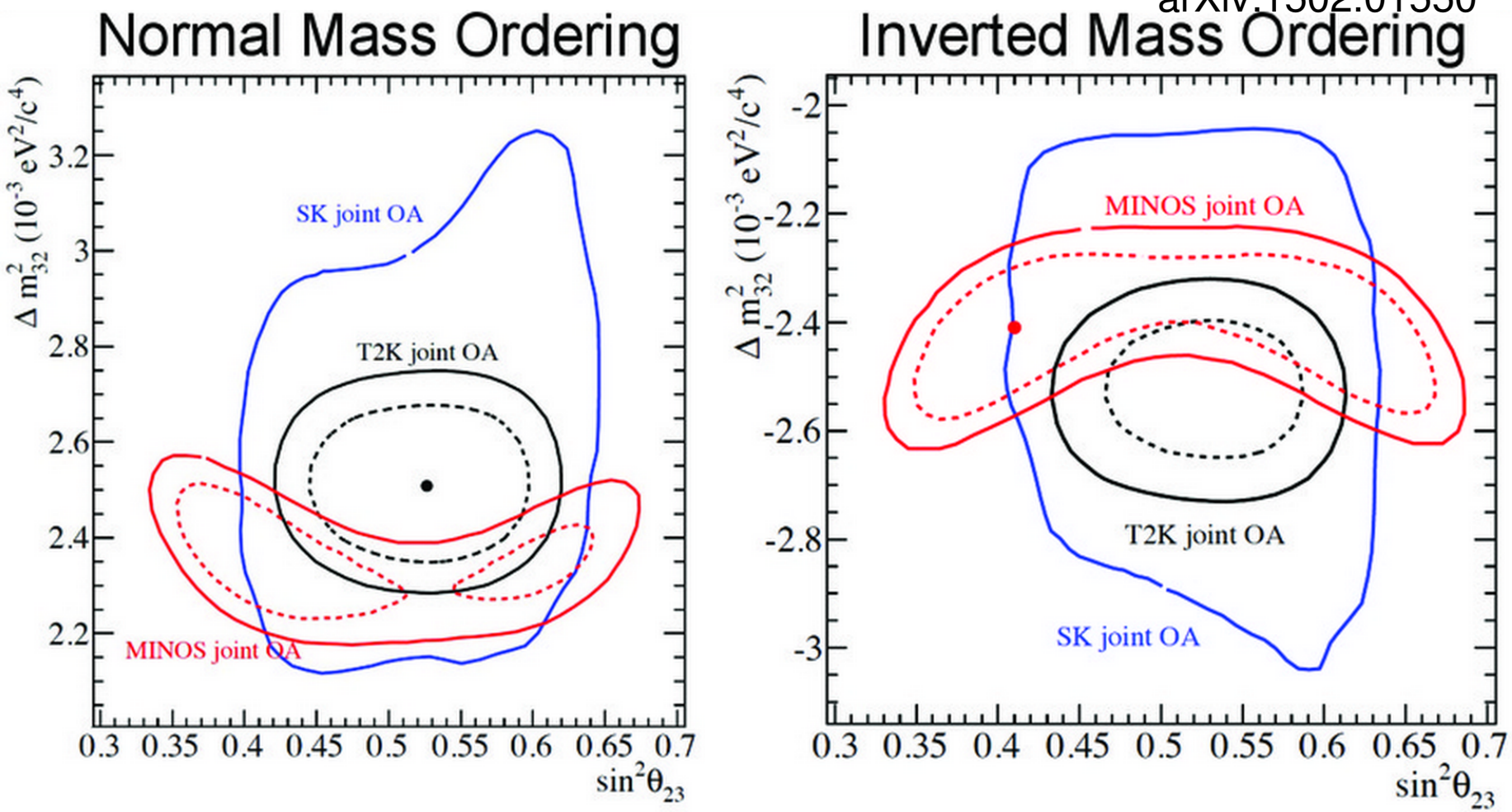
Hayato, WIN 2015



Recent results by SK: θ_{23} and Δm^2_{32}

See presentation on WG1 parallel Tuesday by Jun Kameda

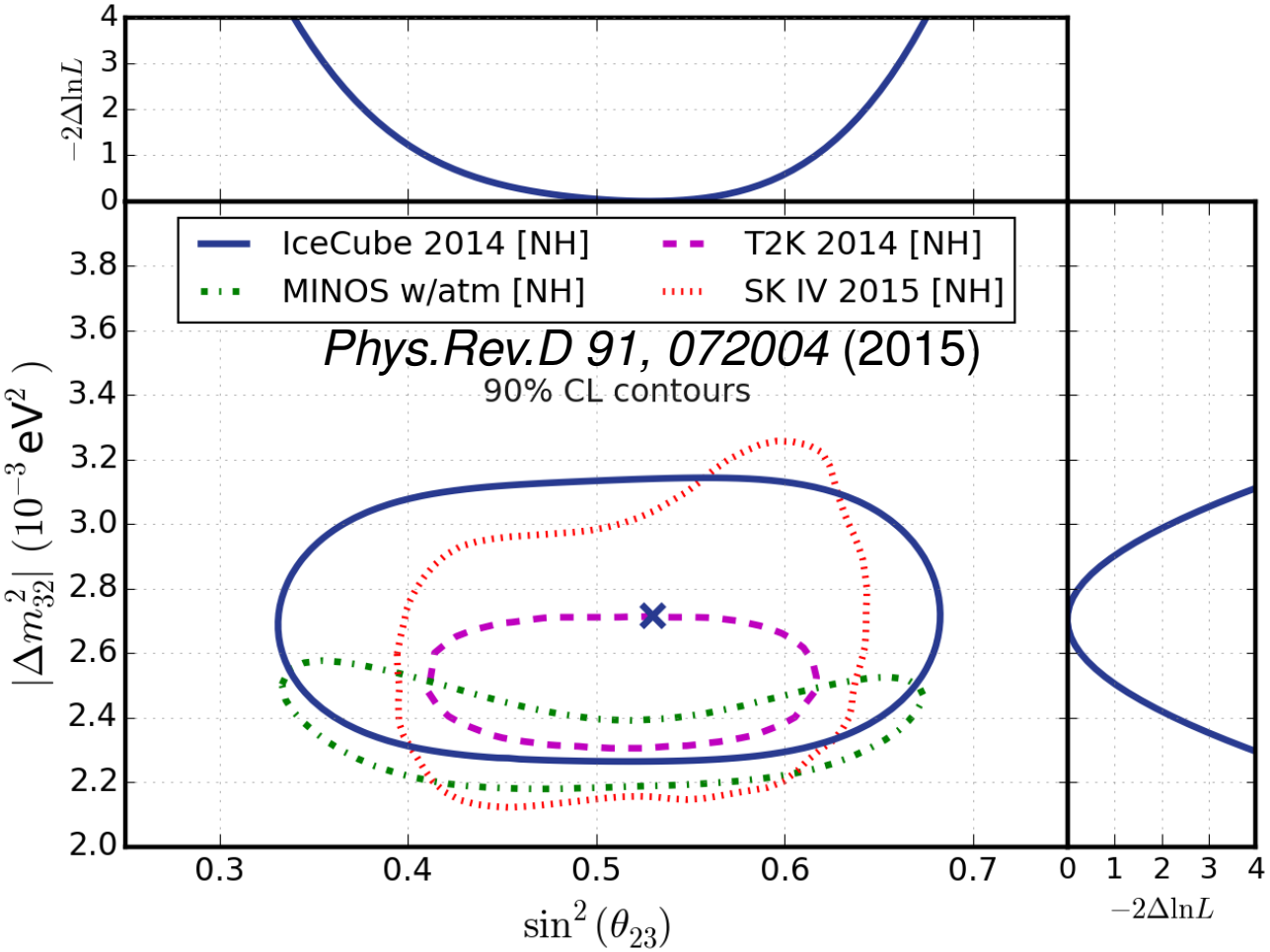
arXiv:1502.01550



- Long baseline accelerator experiments have overtaken atmospheric measurements in precision
- However, atmospheric experiments verify wide L and E ranges

Recent results by IceCube: θ_{23} and Δm^2_{32}

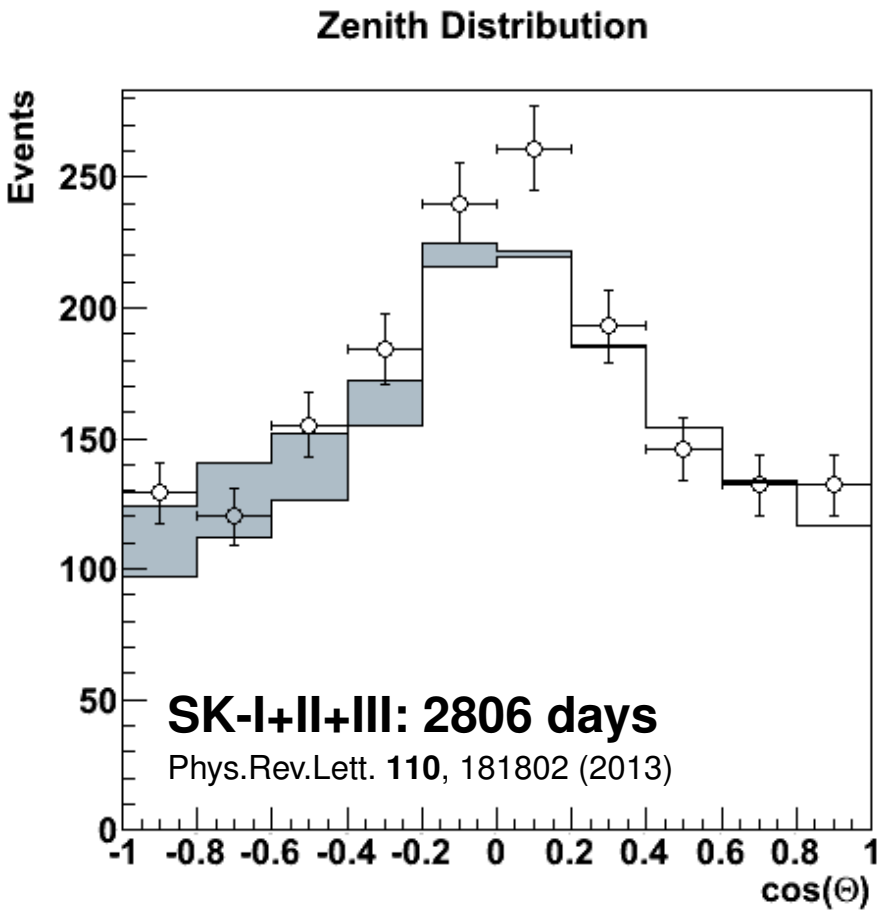
See presentation on WG1 parallel Tuesday by João Pedro A M de André



- New atmospheric ν experiments starting to appear in the picture

Recent results by SK: ν_τ appearance

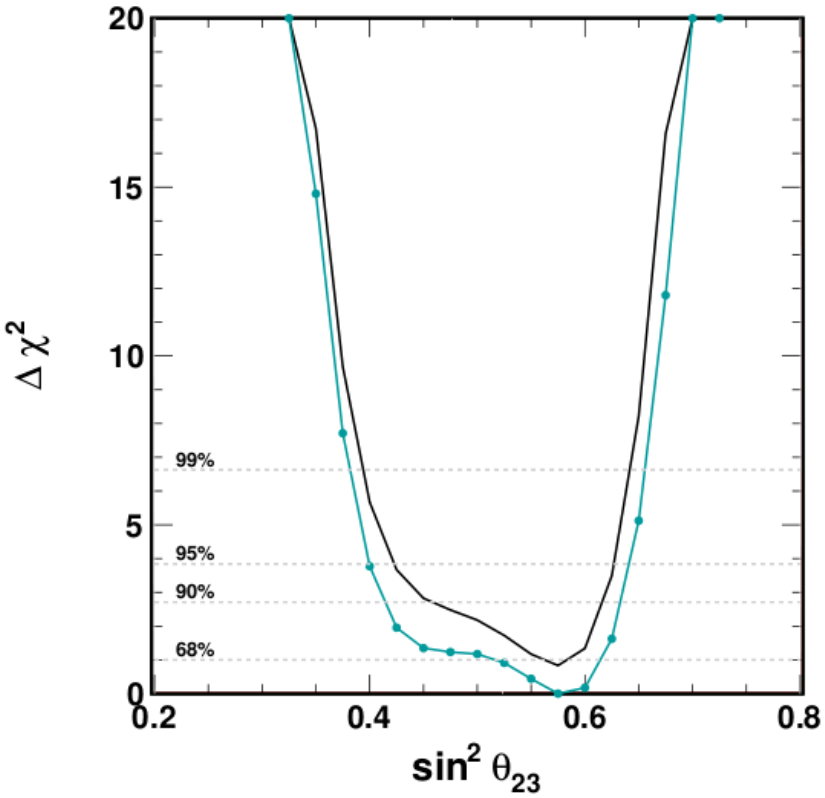
See presentation on WG1 parallel Tuesday by Jun Kameda

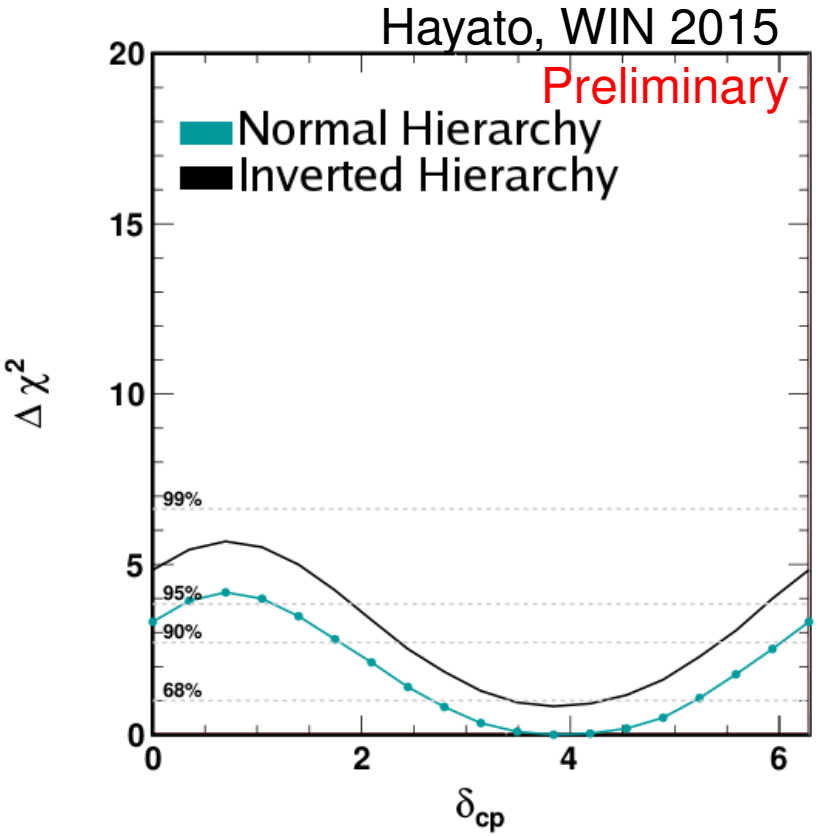


- Search for hadronic decays of τ in SK
- Measured ν_τ normalization 1.42±0.35 (stat)
  - 3-flavour oscillation exp: 1
  - if no ν_τ appearance: 0
- Total: $180 \pm 44^{+18}_{-15} \nu_\tau$ events
  - 3.8σ observation of ν_τ appearance

Recent results by SK: NMH, octant, δ_{CP}

See presentation on WG1 parallel Tuesday by Jun Kameda

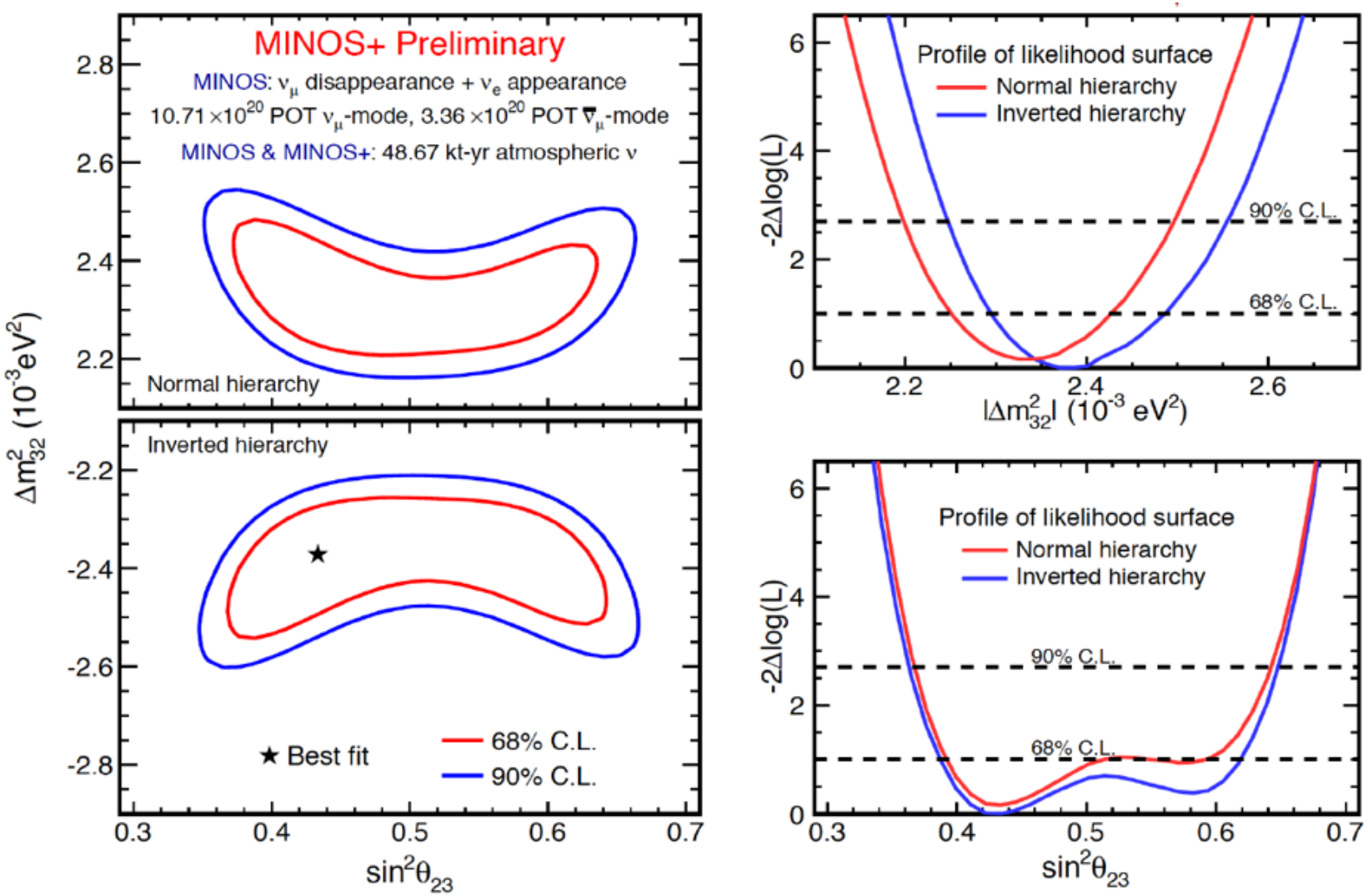




- Slight ($\sim 1\sigma$) preference for:
  - normal mass hierarchy
  - 2nd octant
  - $\pi < \delta_{CP} < 2\pi$

Recent results by MINOS/MINOS+: NMH, octant

See presentation on WG1 parallel Wednesday by João Coelho



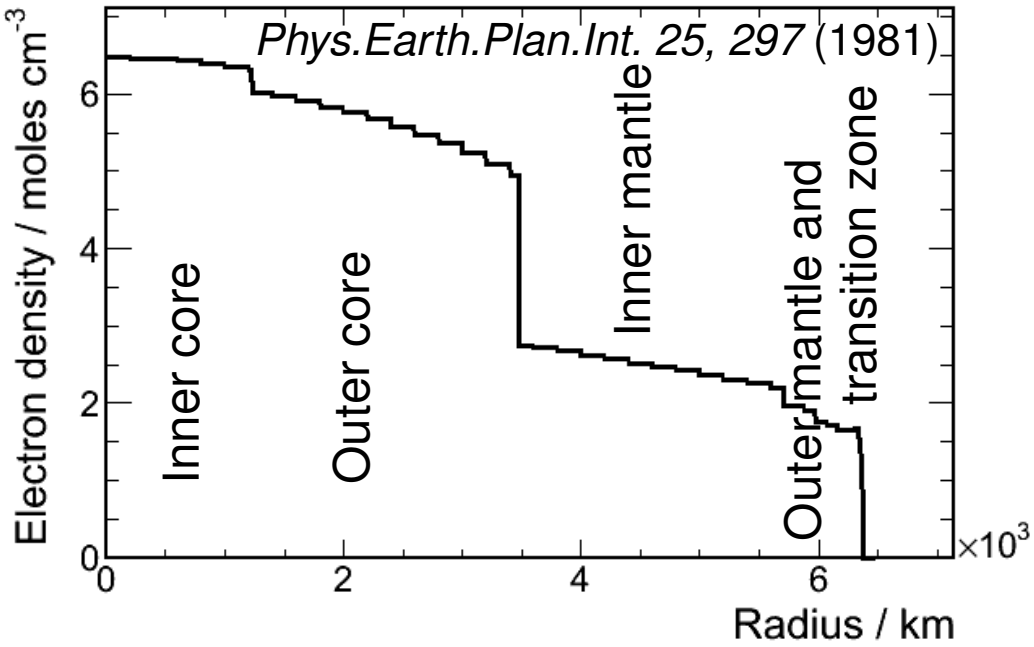
A.P. Schreckenberge, WIN 2015

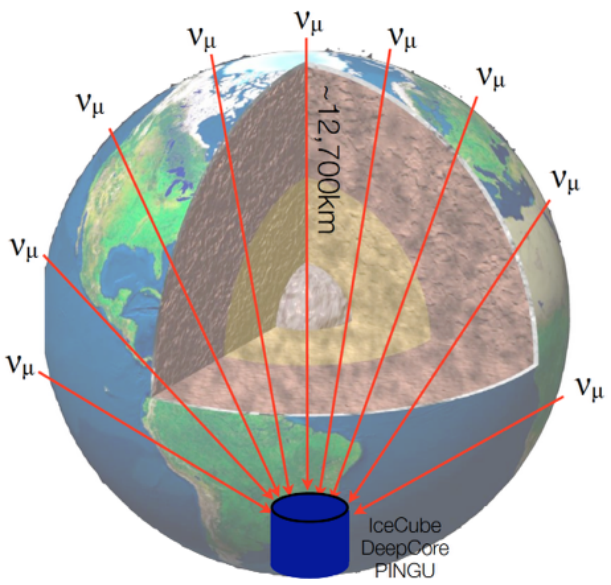
- Joint ν beam and atmospheric ν measurement
- Slight preference for octant and hierarchy opposed to SK

Measuring the ν Mass Hiearachy with atmospheric ν

Matter Effects

Preliminary Reference Earth Model (PREM)





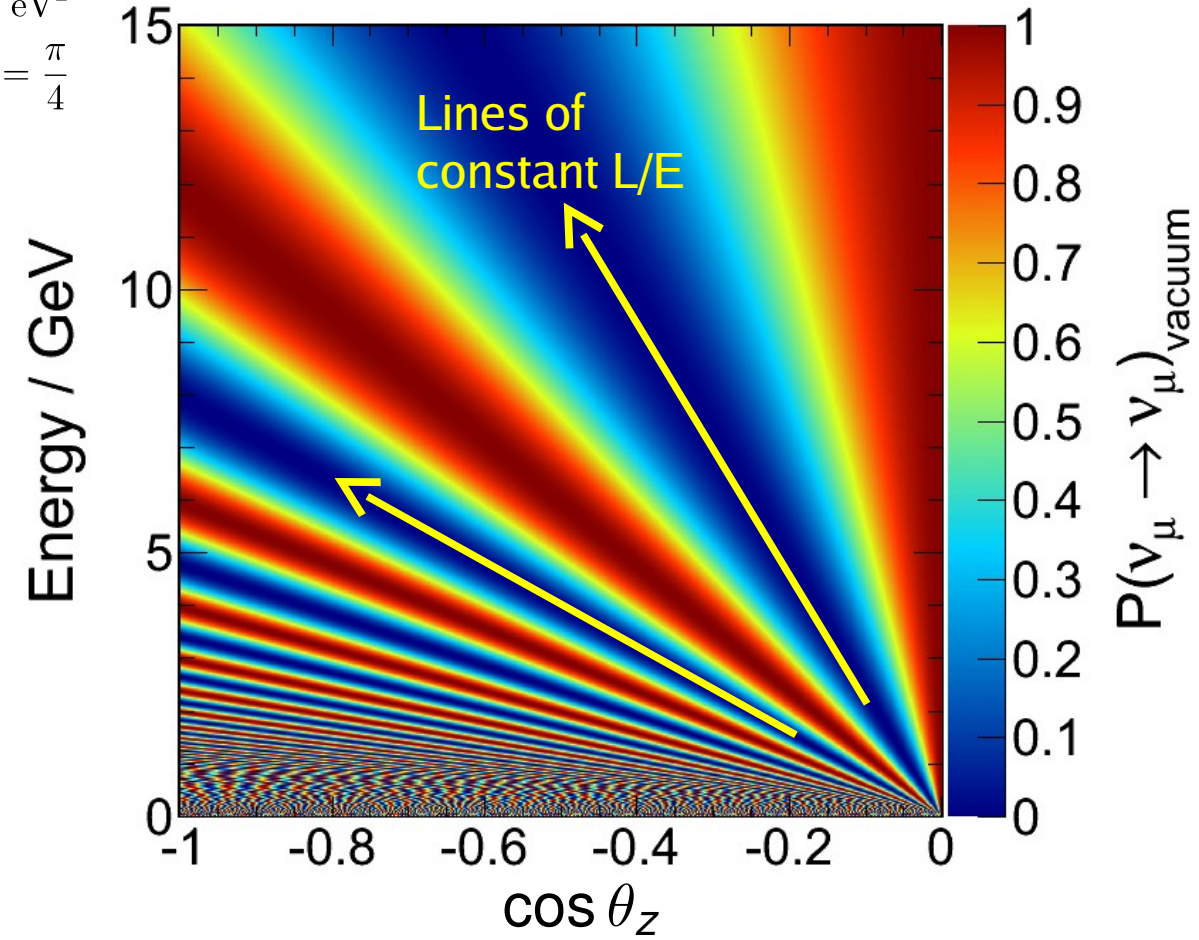
- MSW effect alter oscillation probabilities of ν (NH) or $\overline{\nu}$ (IH)
  - Sharp changes in density between zones produce visible effects in oscillation probabilities
- Different paths "see" different mass patterns $\Rightarrow$ can be probed by measuring the zenith of the neutrino

Neutrino oscillations in vacuum

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

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

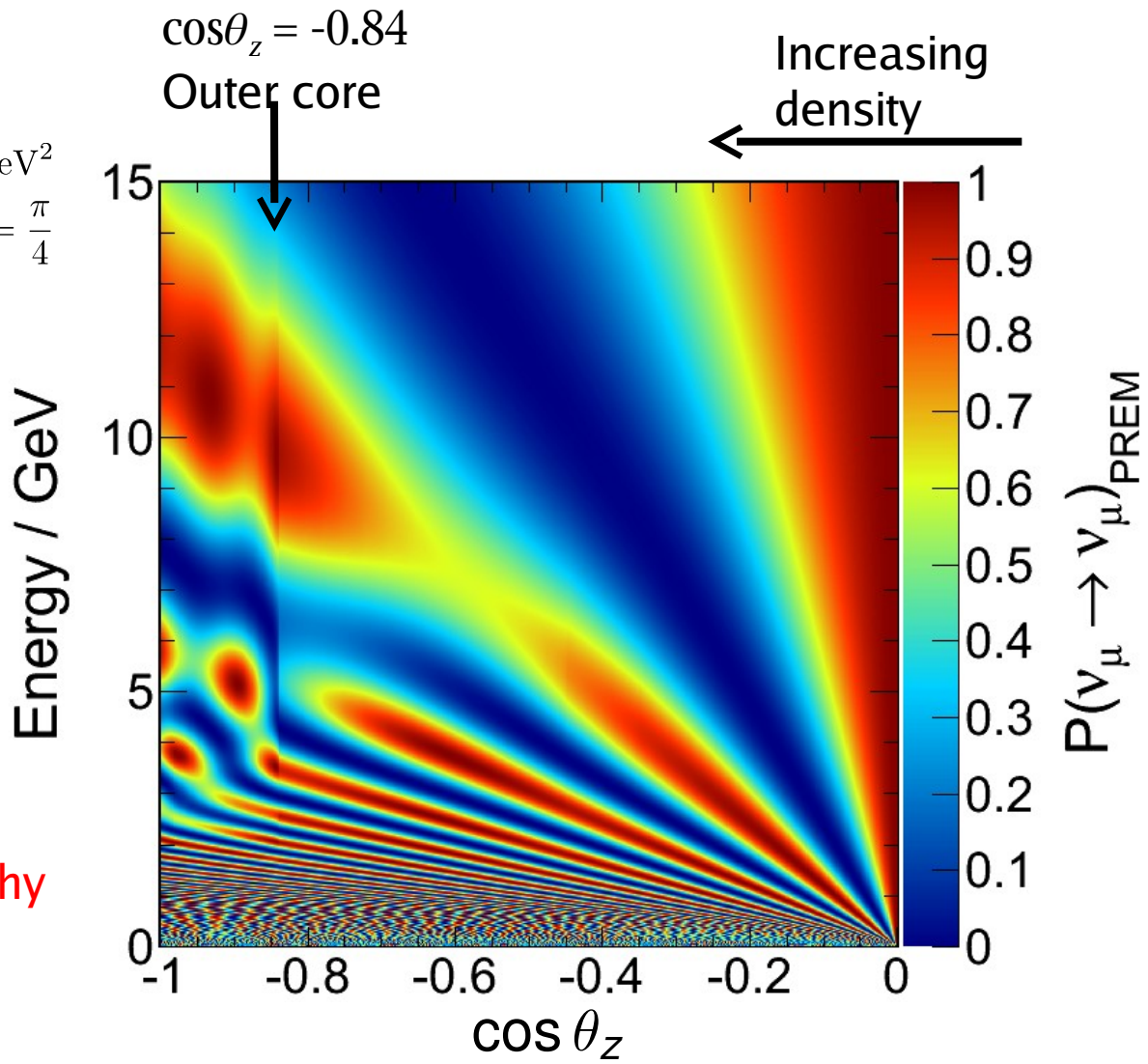
$\sin^2(2\theta_{23}) = \frac{\pi}{4}$



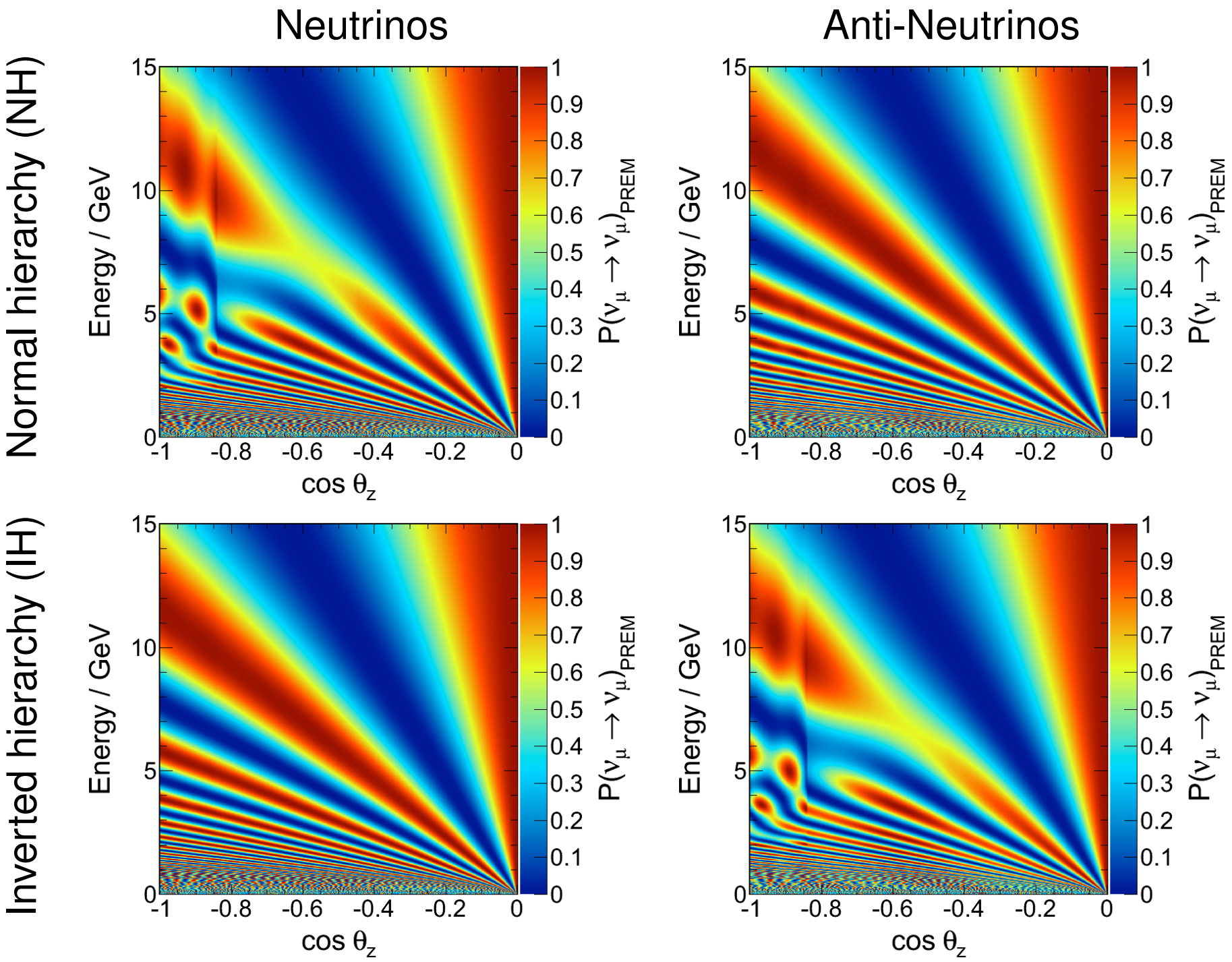
Neutrino oscillations in matter

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

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



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

Why are ν and $\bar{\nu}$ behave differently?

+ for neutrinos
- for antineutrinos

CC interactions of ν_e with matter

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}=\begin{pmatrix}-\frac{\Delta m^2}{4E}\cos(2\theta)\pm\sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin(2\theta)\\ \frac{\Delta m^2}{4E}\sin(2\theta) & \frac{\Delta m^2}{4E}\cos(2\theta)\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_x\end{pmatrix}$$

Matter potential modifies neutrino mixing $\rightarrow$ effective mixing angles in matter:

$$\tan(2\theta_m)=\frac{\frac{\Delta m^2}{2E}\sin(2\theta)}{\frac{\Delta m^2}{2E}\cos(2\theta)\mp\sqrt{2}G_F N_e}$$

$+$ if NH
$-$ if IH

- for neutrinos
+ for antineutrinos

$\Rightarrow$ Resonance condition for ν if NH and $\bar{\nu}$ if IH

The future of atmospheric ν detectors

PINGU: Proposed Icecube Next Generation Upgrade

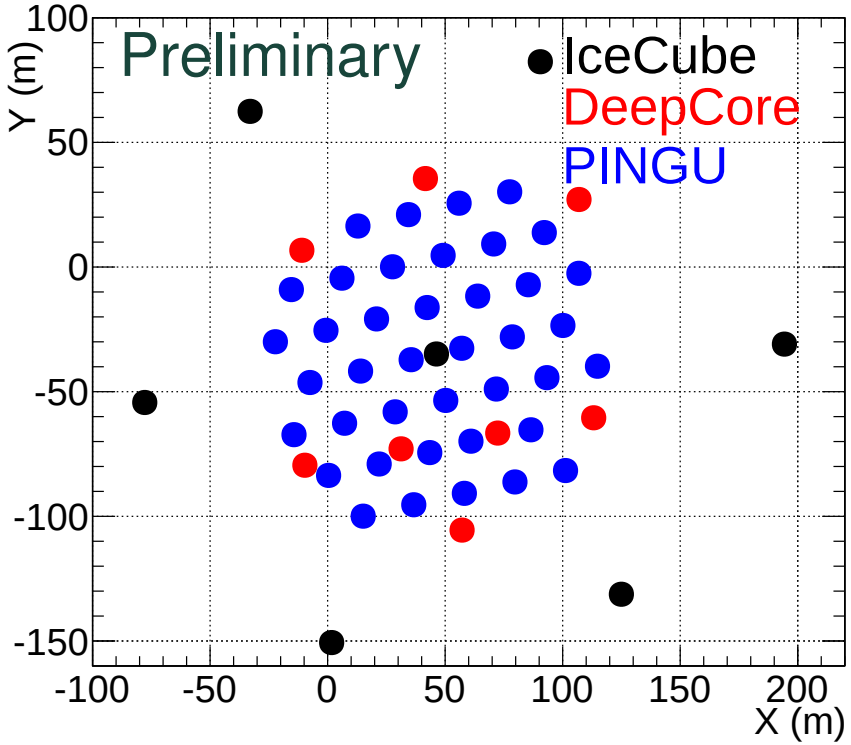
See presentation on WG1 parallel Tuesday by João Pedro A M de André

- 78 strings, 125 m string spacing
- 17 m modules z-spacing

- 8 strings, 75 m string spacing
- 7 m modules z-spacing

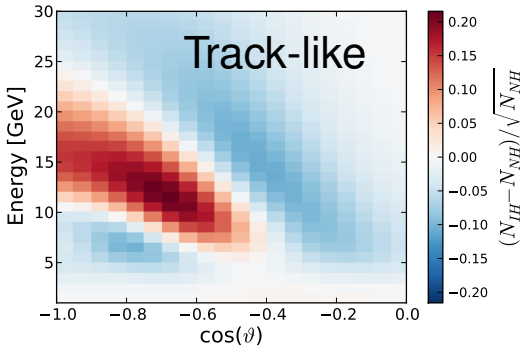
- 40 strings, 22 m string spacing
- 3 m modules z-spacing
  - all optical modules in clearest ice
  - 15× higher photocathode density

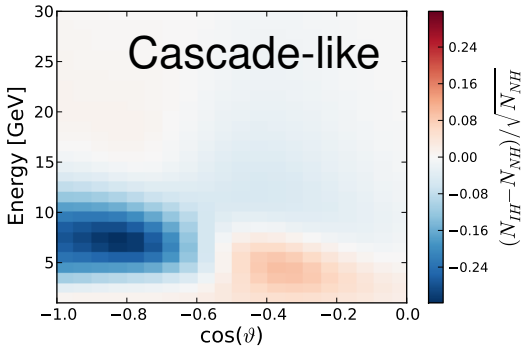
Top view of the PINGU new candidate detector



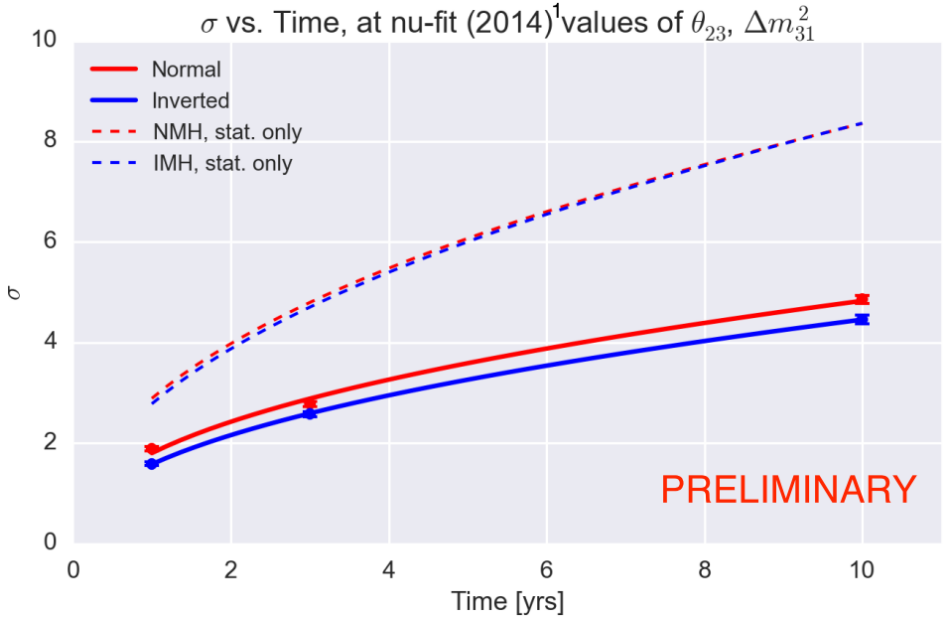
PINGU: measuring NMH

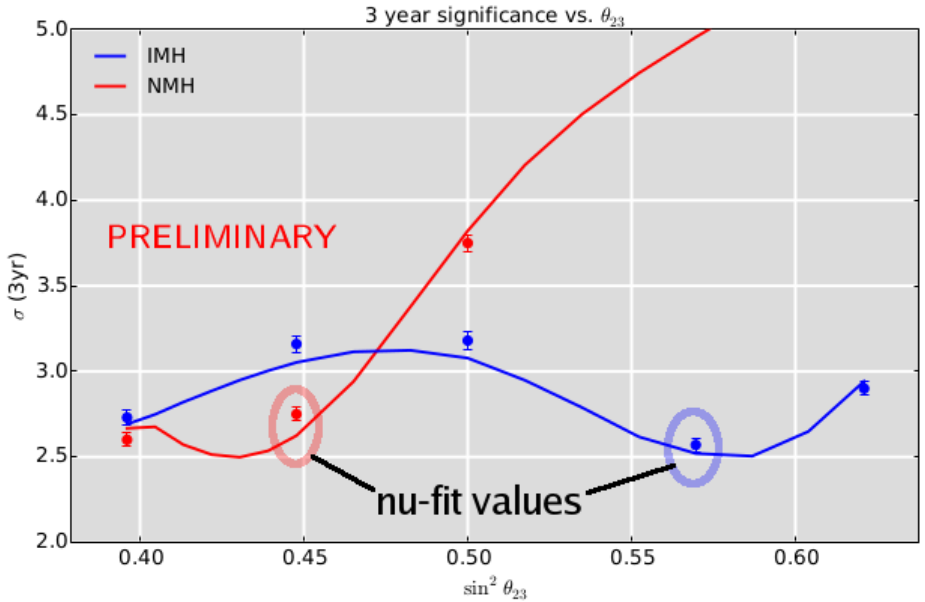
See presentation on WG1 parallel Tuesday by João Pedro A M de André





- Includes detector effects
- Dominant systematics are oscillation parameters
- nu-fit θ_{23}: 42° NH; 49° IH

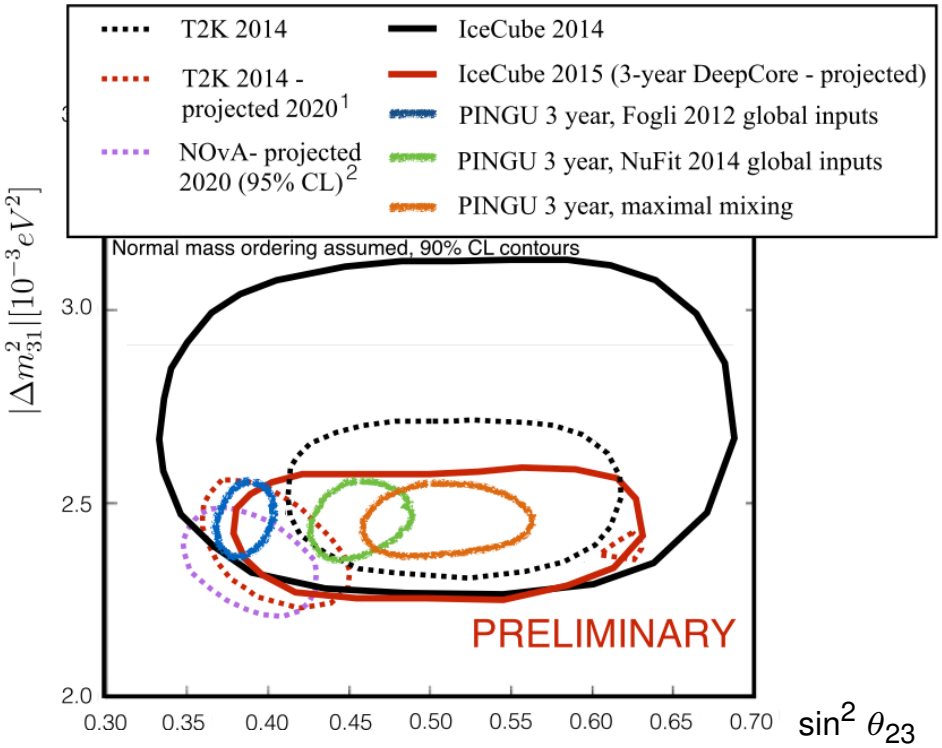




PINGU: other ν oscillation measurements

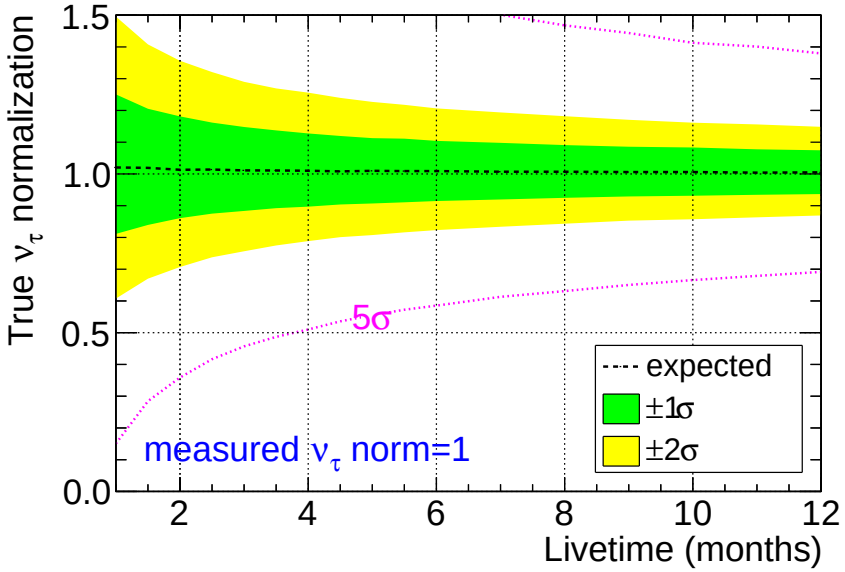
See presentation on WG1 parallel Tuesday by João Pedro A M de André

Measure of θ_{23} and Δm^2_{32}



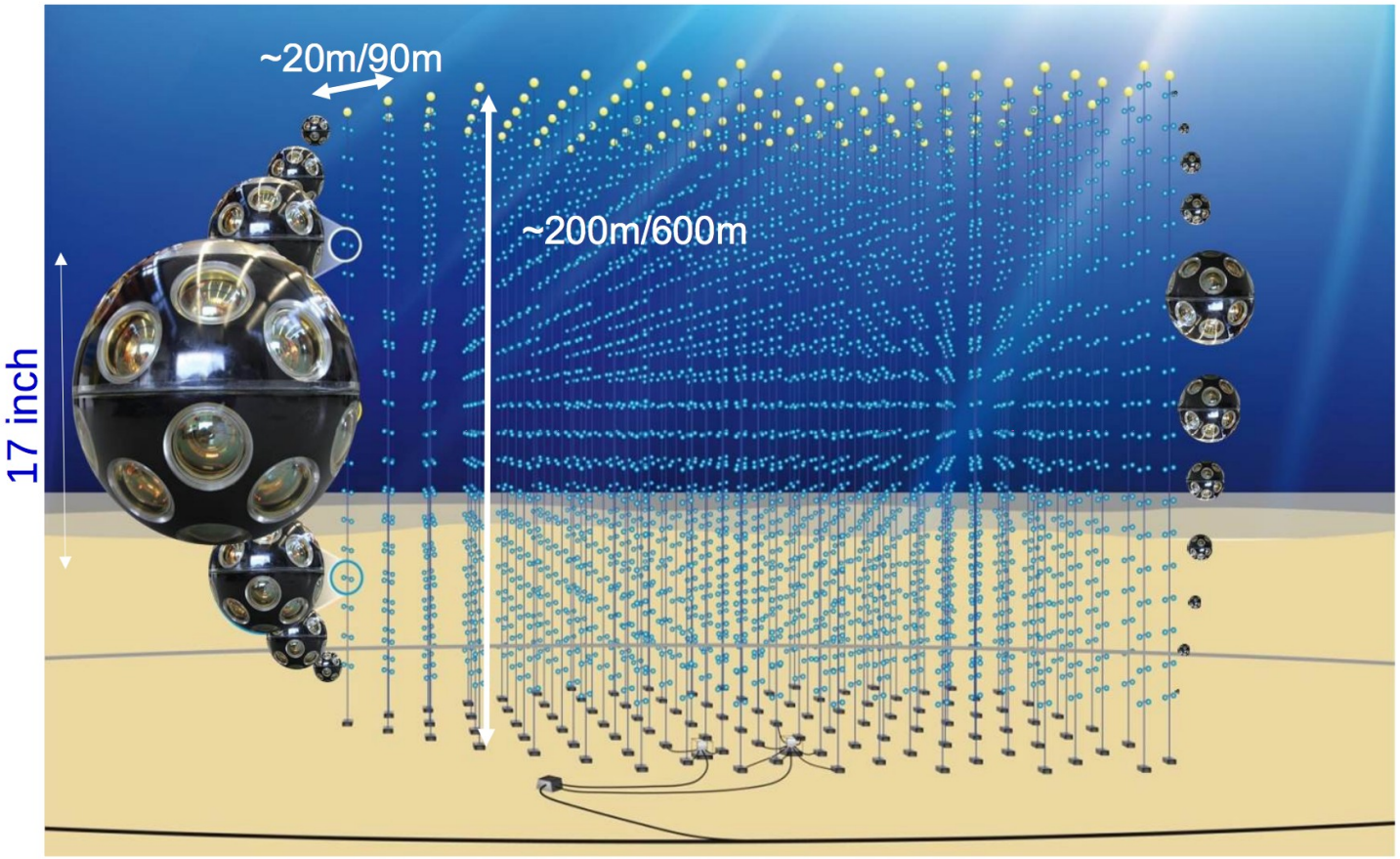
- Expected constraints of precision comparable to NOνA and T2K (projected)

Measure of ν_τ appearance



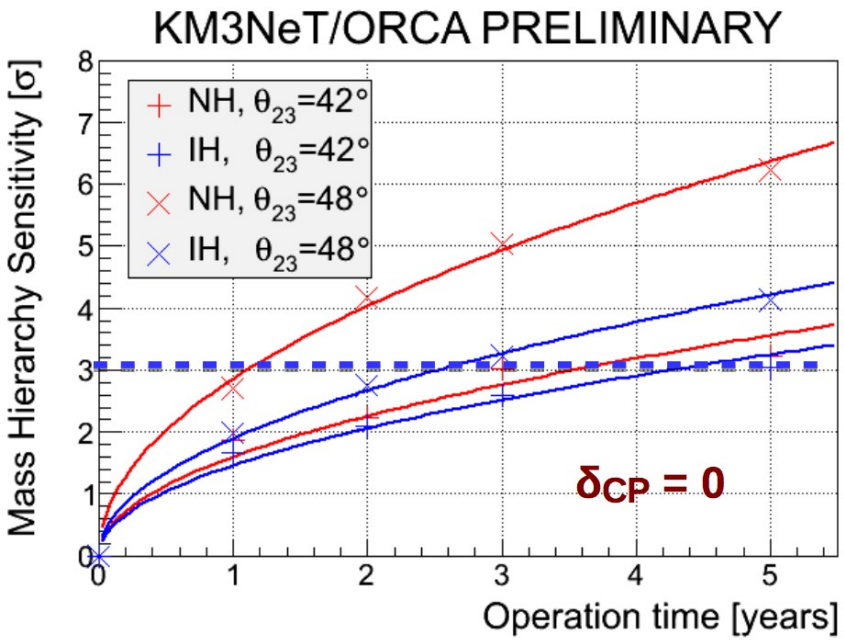
- 5σ exclusion of no ν_τ appearance after 1 month
- 10% precision in the ν_τ normalization after 6 months

ORCA

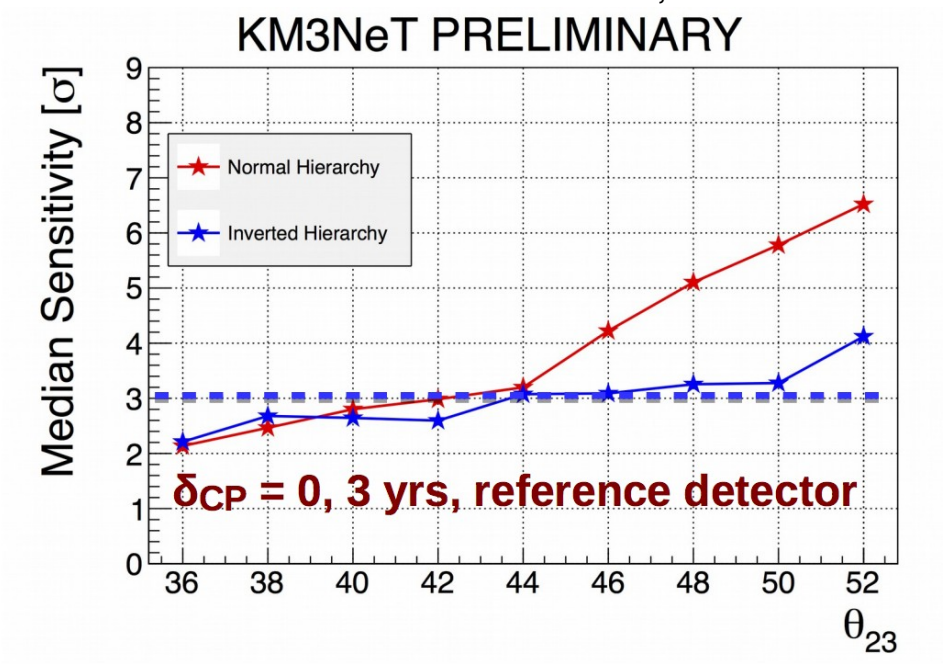


- Proposed upgrade of ANTARES
  - 115 strings, 20 m spacing, 18 OMs/string
  - Currently installing 6-string demonstrator

ORCA: measuring NMH

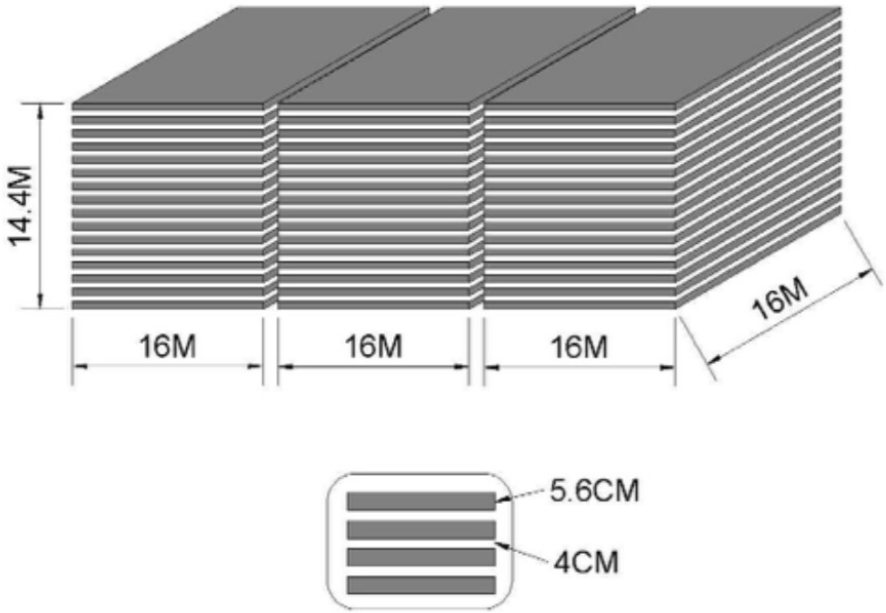


J. Brunner, ICRC 2015



INO

See presentation on WG1 parallel Tuesday by Sanjeev Kumar Verma



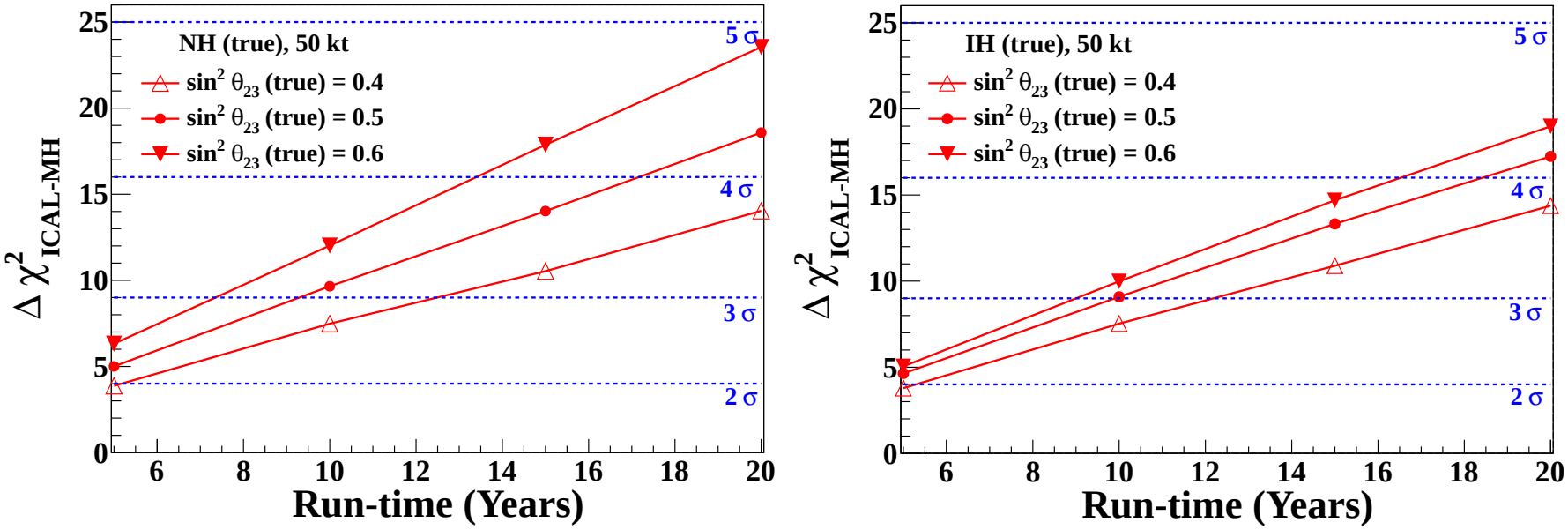
- Magnetised iron calorimeter
  - 52 kton
  - 1.5 T at center

$\Rightarrow$ ability to separate ν_μ and $\bar{\nu_\mu}$ interactions

INO: measuring NMH

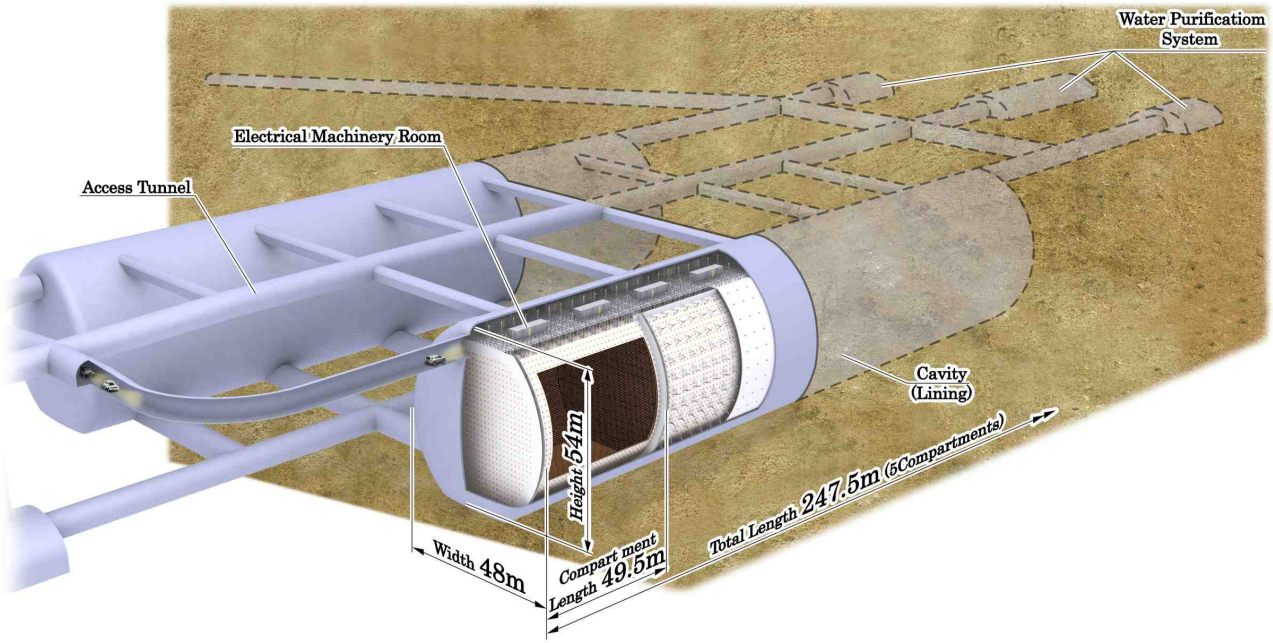
See presentation on WG1 parallel Tuesday by Sanjeev Kumar Verma

arXiv:1406.3689v1



Hyper-Kamiokande

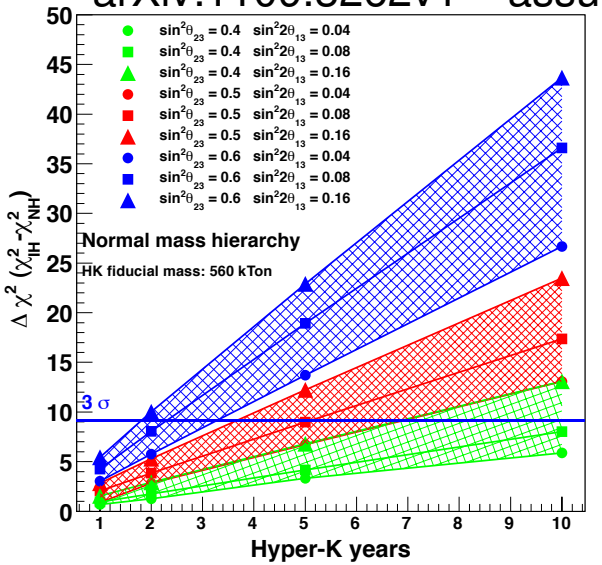
See presentation on WG1 parallel Monday by Tom Feusels

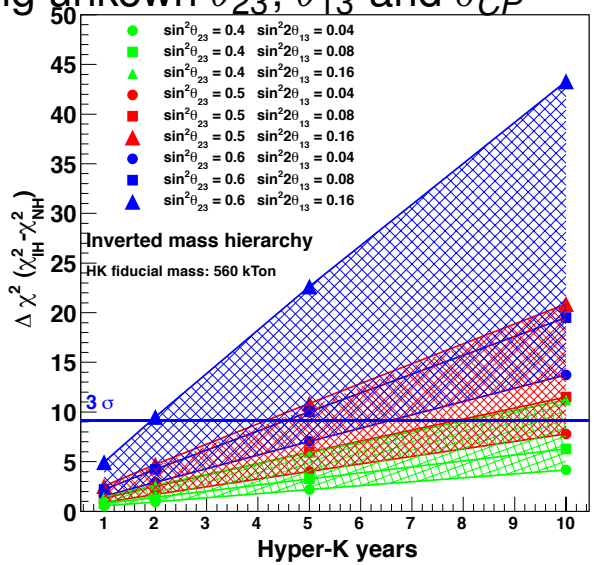


- 25× Super-Kamiokande
- Fiducial volume: 0.56 Mton (total volume: 0.99 Mton)
- 99000 PMTs in inner detector
- also to be used with current T2K beam

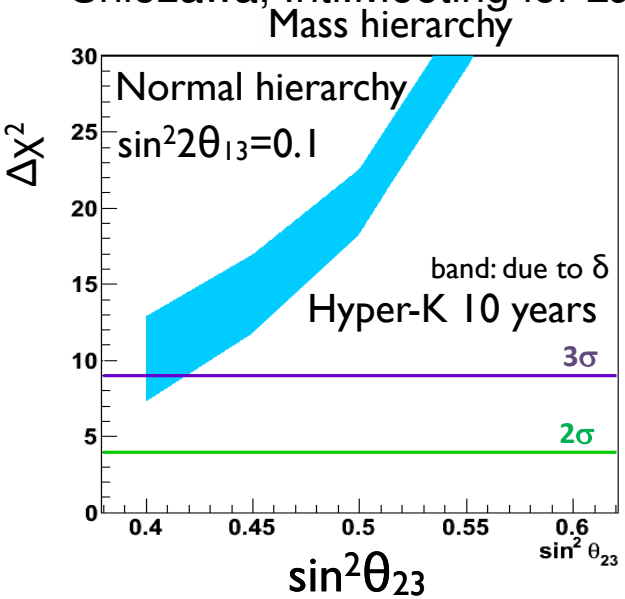
Hyper-Kamiokande: measuring NMH and octant

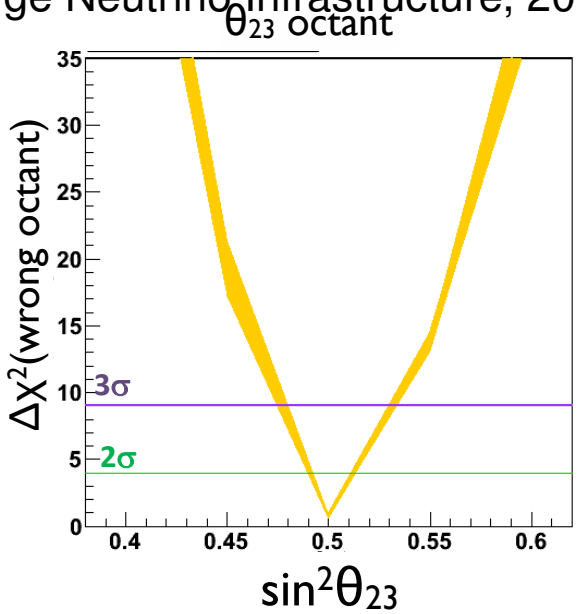
arXiv:1109.3262v1 – assuming unkown θ_{23}, θ_{13} and δ_{CP}





Shiozawa, Intl.Meeting for Large Neutrino Infrastructure, 2015





Summary

- Atmospheric neutrinos have and continue to provide quality measurements of ν oscillations
  - First evidence of ν oscillations
  - Precise measurements of Δm^2_{32} and θ_{23}
  - ν_τ appearance measurement
- The next generation of experiments will improve on current measurements and aim for measuring the NMH
  - PINGU and ORCA can reach 3 σ CL in 3-4 years from built detector
- Very complementary to accelerator-based experiments
  - Explore wide range of baselines and energies at once
- And that is not all physics reach of these detectors
  - Published/possible searches for sterile neutrinos, dark matter, ...