Measuring Neutrino Mass Hierarchy with Atmospheric ν's

Alternatives to Accelerator-based Experiments

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Joint CPAD and Instrumentation Frontier Community Meeting

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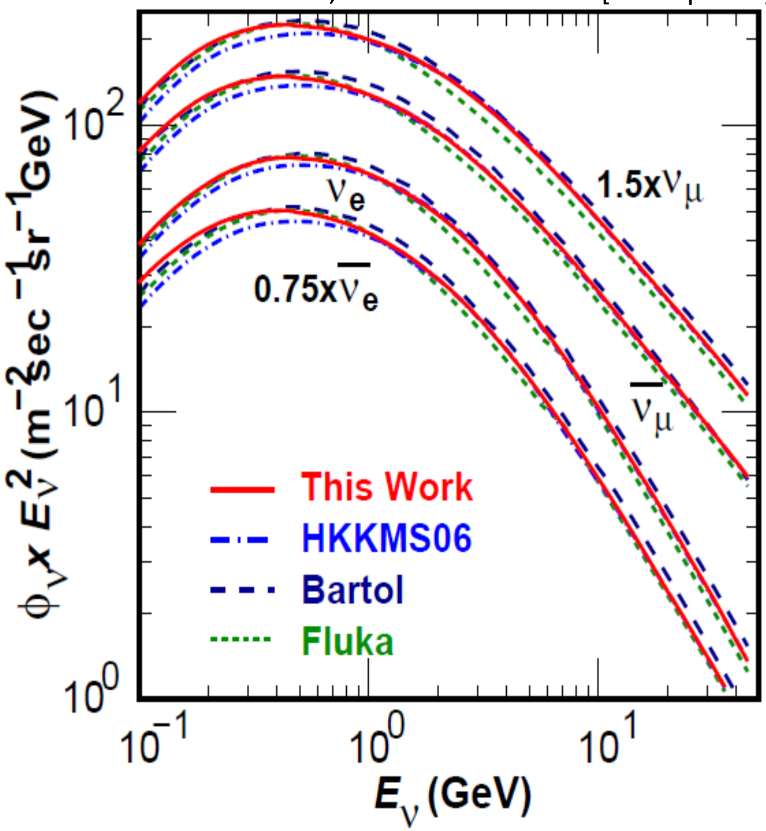
Atmospheric Neutrino Generation

M. Honda et al., arXiv:1102.2688v1 [astro-ph.HE]



- Cosmic rays strike air nuclei; decay of outgoing hadrons result in neutrinos

  $p + A \rightarrow N + \pi^+ + X$

  $\hookrightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Isotropic about Earth
  - Path length to detector spans ~10-10,000 km
- Large range of energies
  - ~100 MeV – many TeV+

Atmospheric Neutrino Generation

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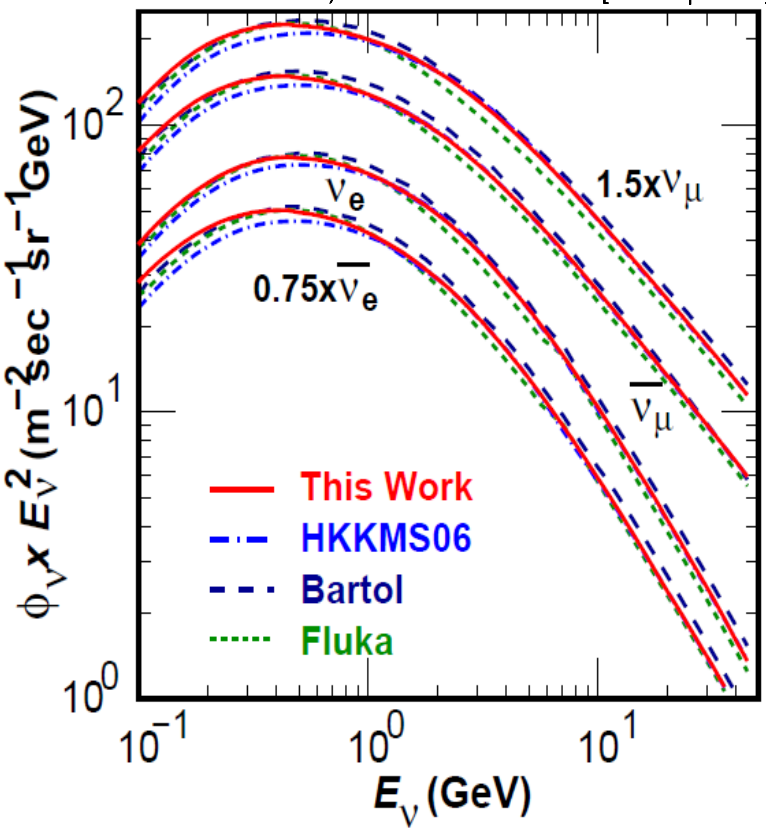
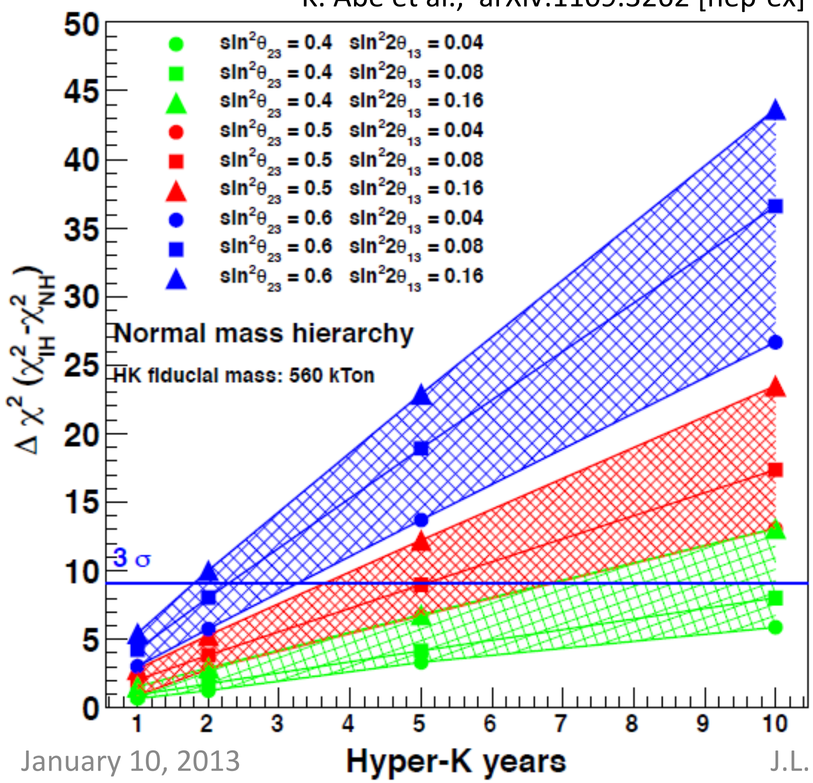


- Mass hierarchy affects neutrinos and anti-neutrinos differently
- Effects are present in both ν_e and ν_μ
  - Some detectors can see one, the other, or both
- Atmospheric neutrinos are free and contain both ν_e and ν_μ and antineutrinos
- Global neutrino program is using proven, well-understood technology for the most part

Why didn't we try to measure MH with atmospherics before?

- Size of matter effect scales with size of θ_{13} (value unknown until very recently), and sensitivity also depends on θ_{23} octant and true value of δ_{CP}.

K. Abe et al., arXiv:1109.3262 [hep-ex]



Hyper-K sensitivity for possible θ_{23} octants (green, red, blue) and range of θ_{13} values (indicated by band for each color).

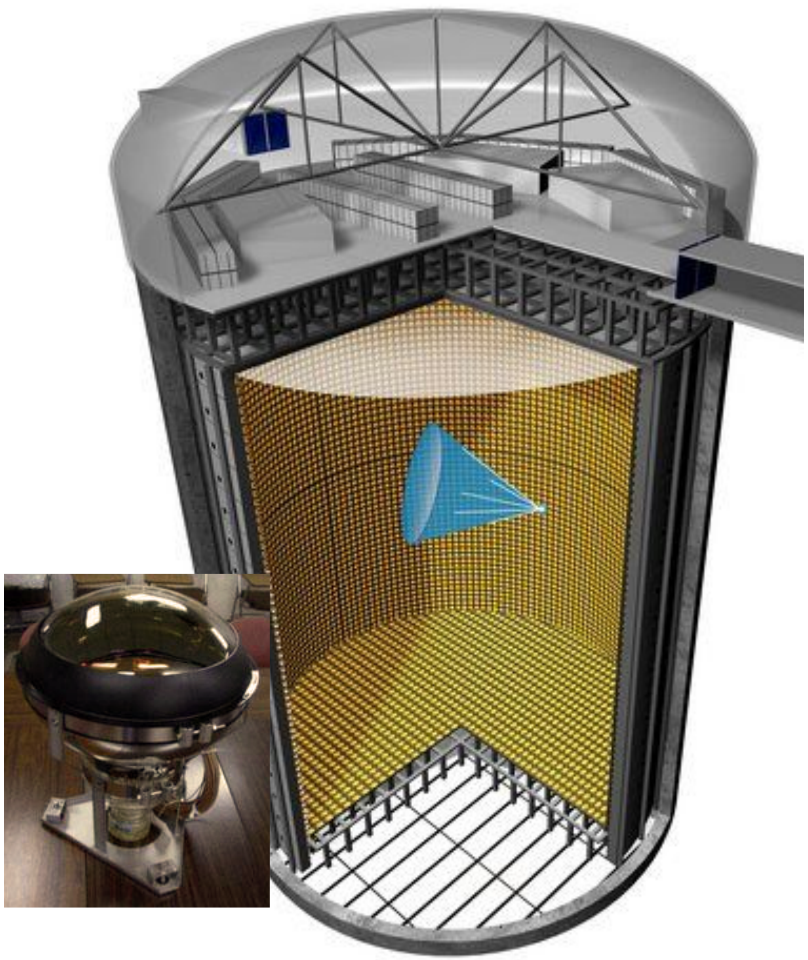
Effect of change in δ_{CP} not shown here.

If $\sin^2 2\theta_{13}$ had been < 0.01, it would take a very long time to measure this effect (but in principle, possible).

Now that θ_{13} is measured to be large…

- Existing experiments:
  - Super-Kamiokande (Water Cherenkov)
  - MINOS (magnetized steel-scintillator calorimeter)
- Future possible experiments:
  - Hyper-Kamiokande (Water Cherenkov)
  - ICAL @ INO (magnetized Iron Calorimeter)
  - PINGU @ IceCube (Ice Cherenkov)
  - LBNE *if underground and large enough* (LArTPC)
  - LBNO (LArTPC? Scintillator? WC?)

Super-Kamiokande

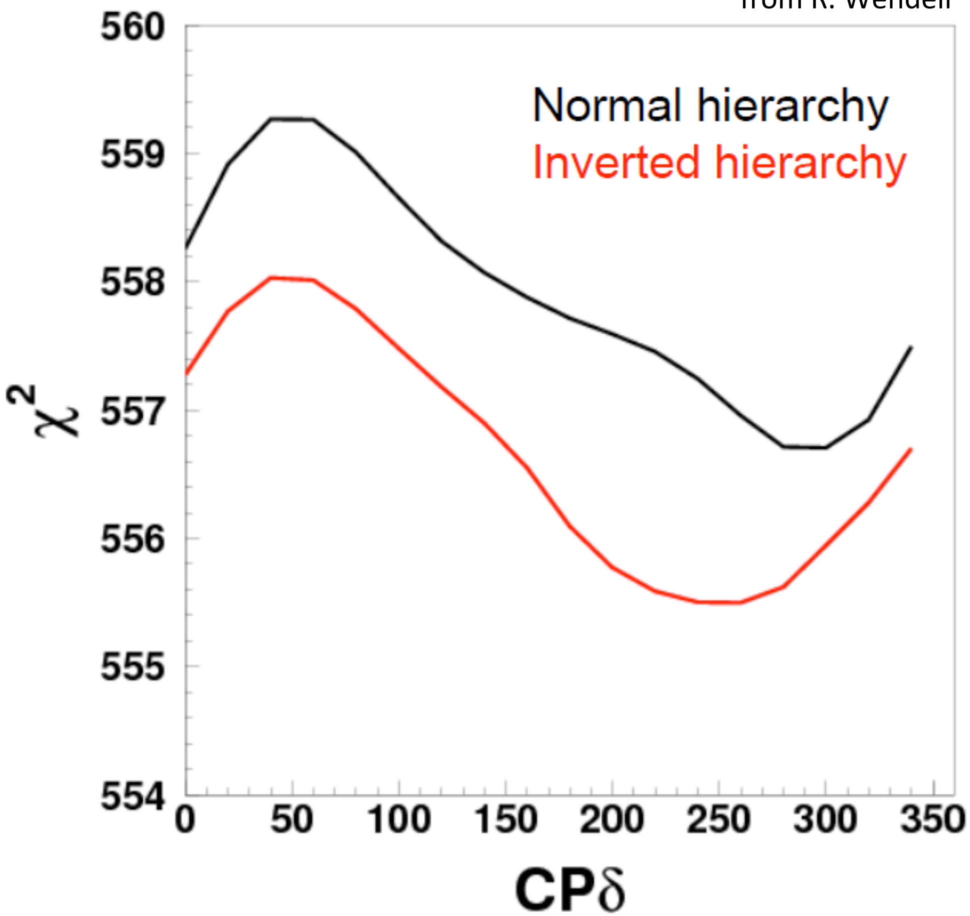


- 50 kton total volume (22.5 kt fiducial) Ring Imaging Water Cherenkov detector
  - Instrumented with 20” and 8” PMTs to form inner signal region and 4π veto, respectively
- Existing dataset 3903 days of atmospheric data (~34,000 events)
- Currently statistics limited

Probe mass hierarchy by looking for ν_e appearance.

So far, only a hint from SK…

from R. Wendell



Hierarchy	Fit Result
Normal	556.7 / 477 dof
Inverted	555.5 / 477 dof

χ^2_{min} (NH) - χ^2_{min} (IH) = 1.2

Expected sensitivity to inverted hierarchy is $\Delta\chi^2 = 0.9$

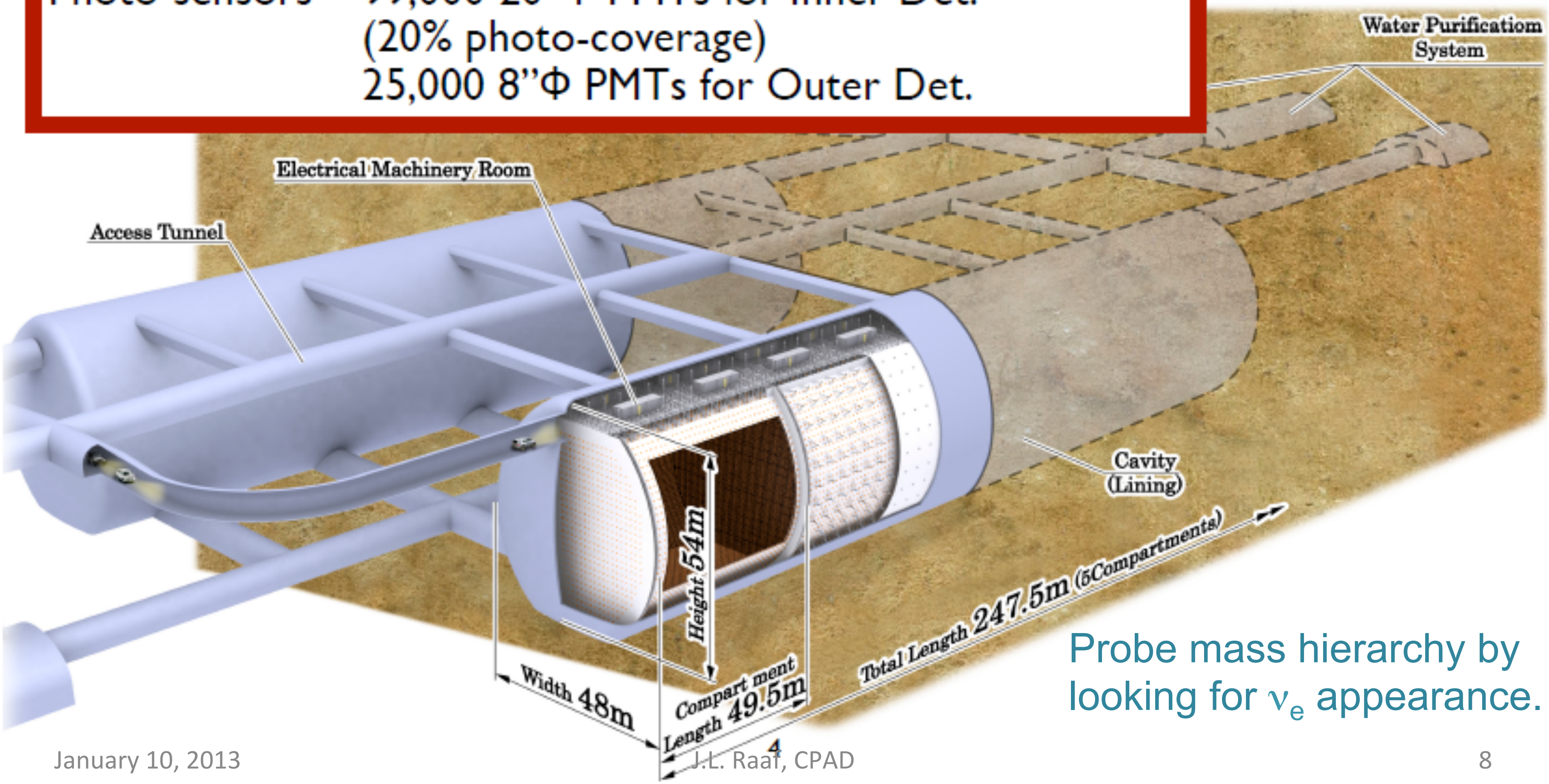
Data show 1σ preference for inverted hierarchy; not significant

Plan is to continue collecting data for the next 10+ years.
Can expect ~1-2σ sensitivity to MH in the next 5 years.

Hyper-Kamiokande

Total Volume	0.99 Megaton
Inner Volume	0.74 Mton
Fiducial Volume	0.56 Mton (0.056 Mton × 10 compartments)
Outer Volume	0.2 Megaton
Photo-sensors	99,000 20"Φ PMTs for Inner Det. (20% photo-coverage) 25,000 8"Φ PMTs for Outer Det.

20x SK volume



Probe mass hierarchy by looking for ν_e appearance.

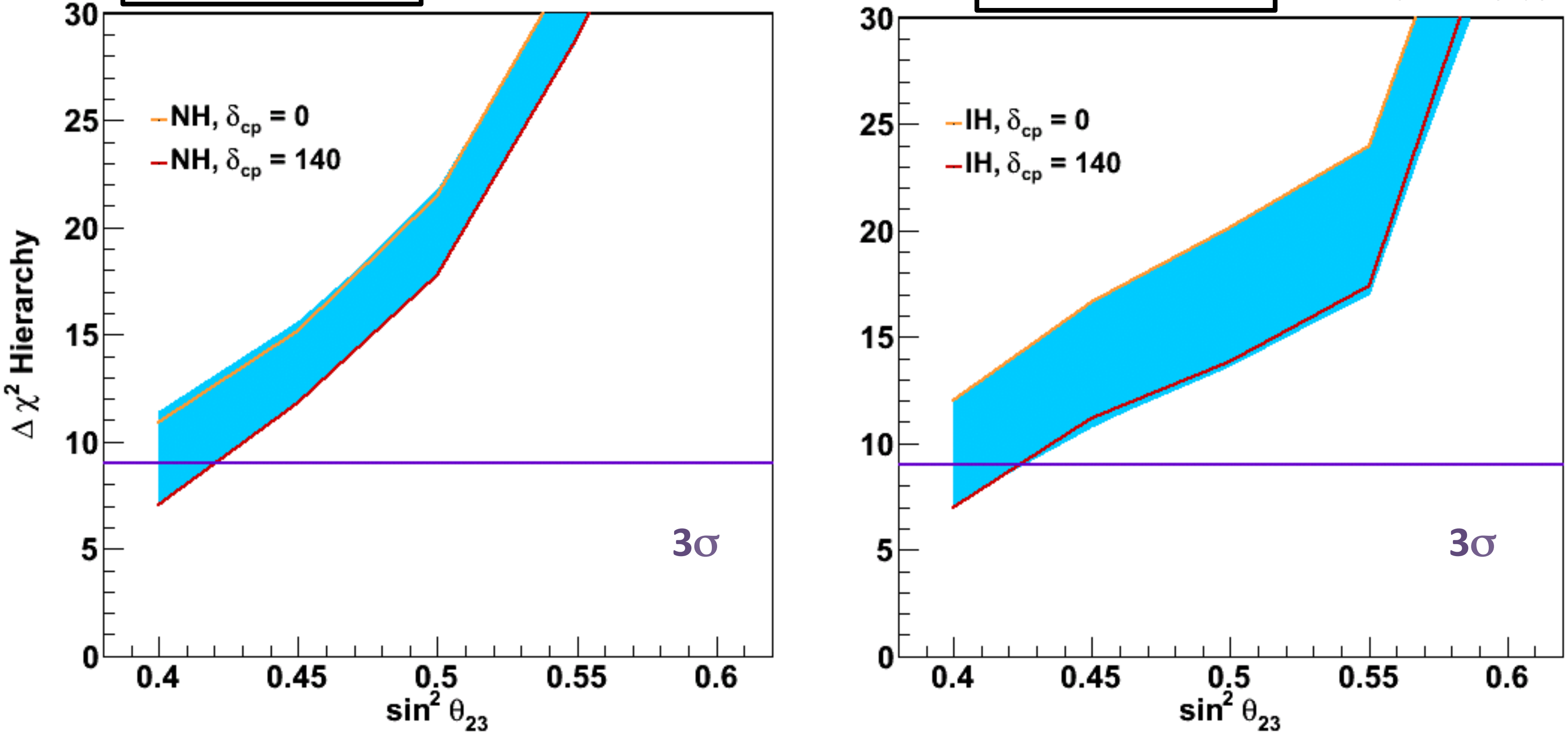
HK sensitivity w/10 yrs atmospheric data

True NH

θ_{13} fixed; $\sin^2 2\theta_{13} = 0.10$

True IH

from R. Wendell



- Thickness of band corresponds to uncertainty from δ_{cp}
- Weakest sensitivity overall in the tail of the first θ_{23} octant

Challenges: scaling to larger detectors, PMTs are expensive. Want higher efficiency photodetectors at lower cost (Mayly's talk later in this session).

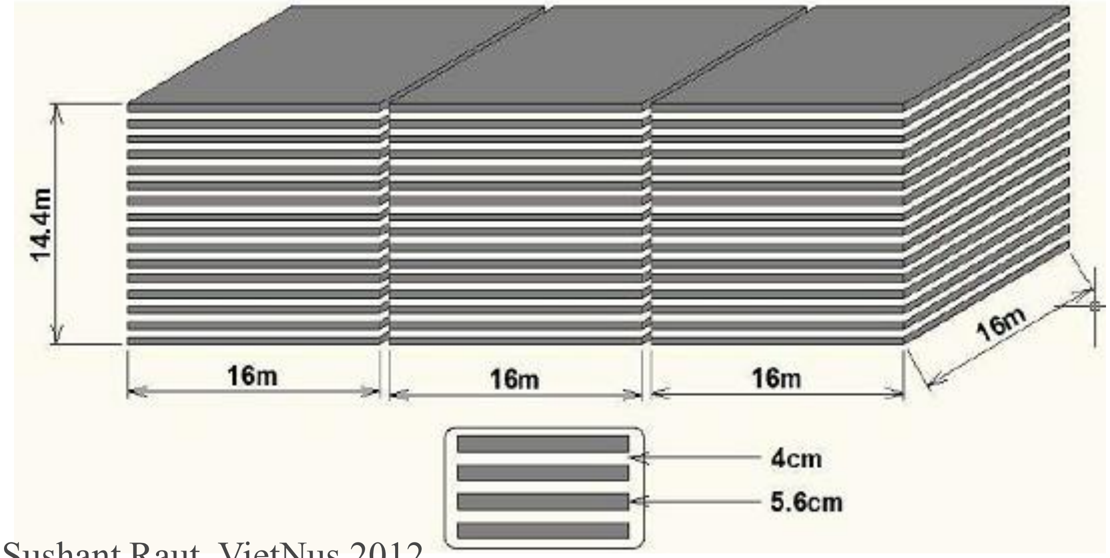
ICAL @ INO

50 kton magnetized iron calorimeter

- 150 layers of iron & glass RPCs

Good L & E resolution
Charge discrimination

Lots of experience from past experiments

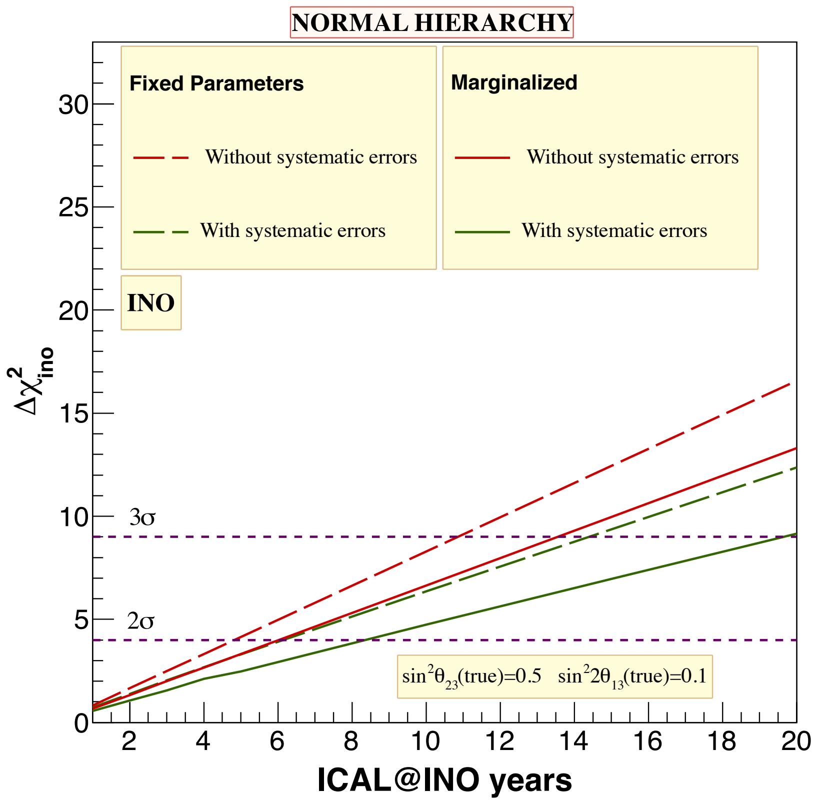


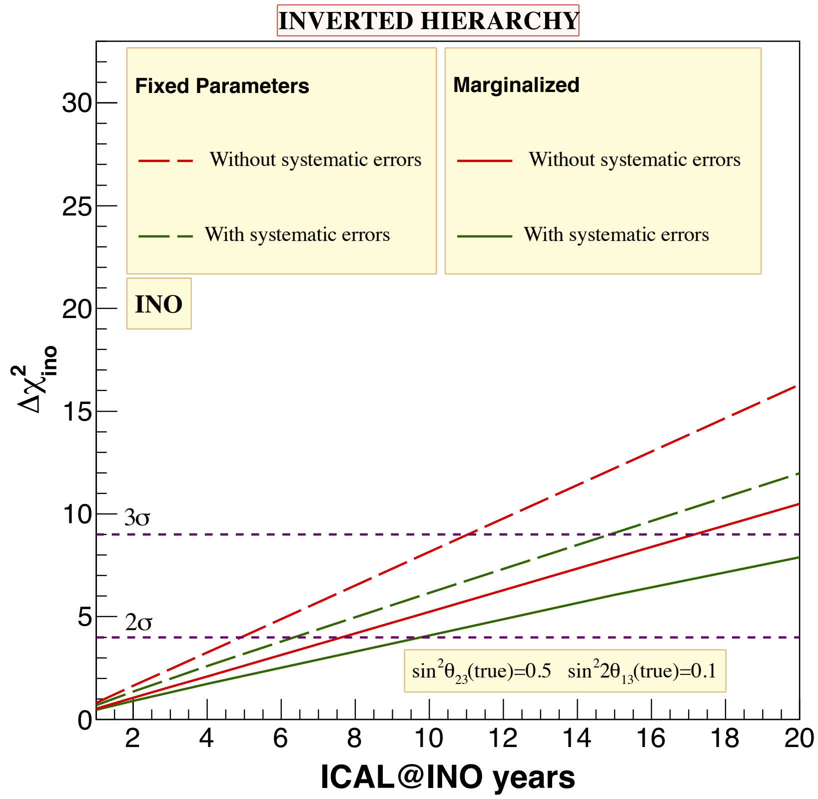
Sushant Raut, VietNus 2012

Probe mass hierarchy by looking for ν_μ disappearance.

Note that sensitivity to MH could increase if reconstruction of e-like events is also made possible in this detector.

ICAL @ INO Sensitivity to MH

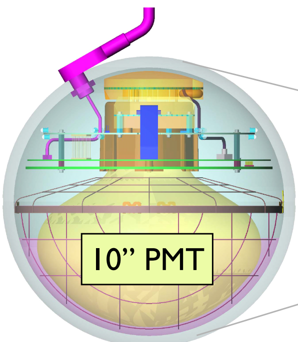




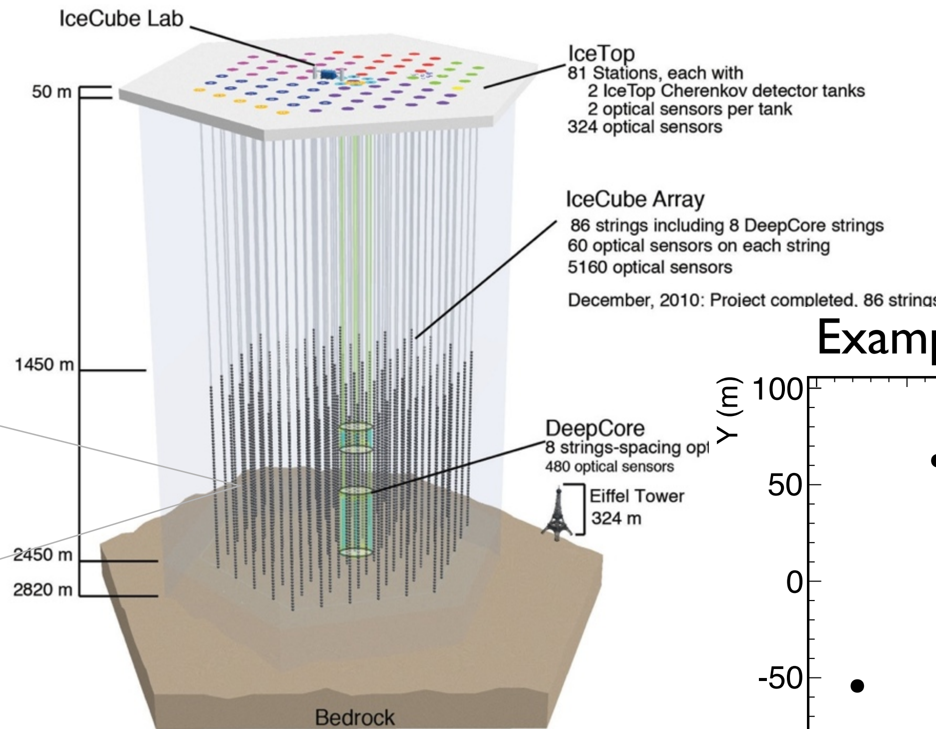
Challenges:

- Improve angular resolution of neutrinos (by improving hadron direction reconstruction)
- Need to lower energy threshold

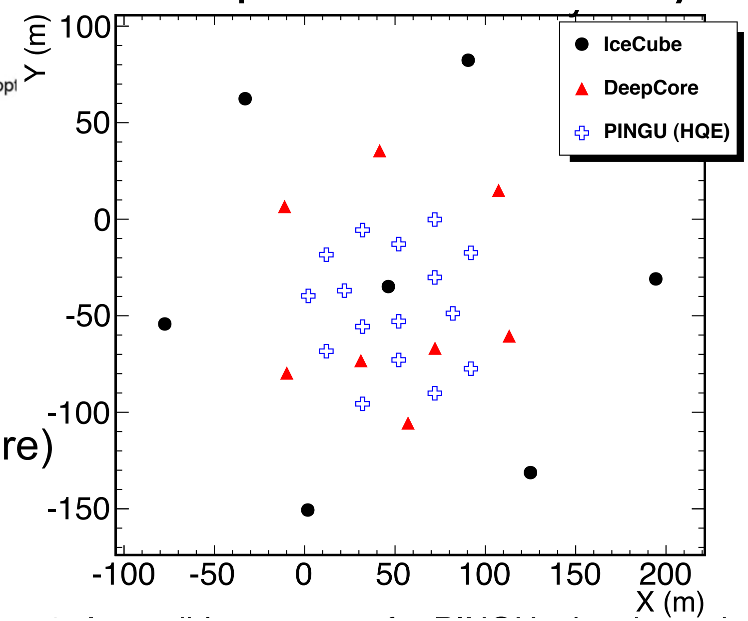
PINGU @ IceCube



Digital Optical Module (DOM)



Example PINGU Geometry



IceCube: 1km^3 ice Cherenkov detector (30 Mton DeepCore)

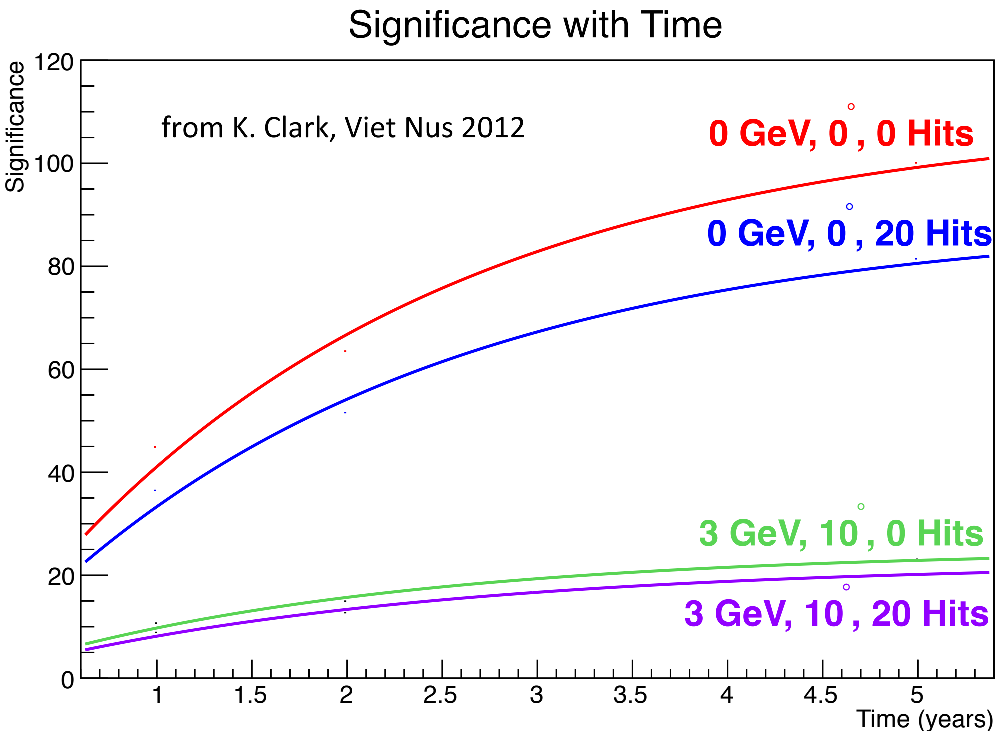
PINGU: region of increased photosensor density

aim for ~few GeV threshold

Probe mass hierarchy by looking for ν_μ disappearance.

If *e* PID is developed (to distinguish from NC & τ), greater sens to MH here too.

PINGU MH significance



NB: This significance calculation is different than that shown for other experiments. Do not compare directly.

Caveats:

Considers ν_μ disappearance only

No systematic effects

No misreconstruction of downgoing ν_μ

This option is actually not very expensive… Estimated at ~$50M.

Challenges:

- Need to demonstrate reconstruction capabilities
- Need to understand effect of systematics

LBNE or LBNO, but only if underground!

- Can't study atmospheric neutrinos on the surface
- If LArTPC, detector will have excellent tracking/reconstruction/PID capabilities

Challenges:

Haven't built LArTPCs on this scale yet, although we're heading in the right direction

Need to demonstrate reconstruction/PID

And by the way..

- If your detector is underground AND it's a giant detector, your physics portfolio is greatly enhanced
  - Searches for proton decay
  - Supernova neutrino detection
  - Solar neutrinos

Summary

- Measuring δ_{CP} requires knowledge of mass hierarchy. Mass hierarchy will be measured by at least one of these options.
- For the most part, all options involve well-understood detector technologies; no need to develop new, but possibly may improve old…
  - Light detection in Cherenkov detectors (want higher efficiency, lower cost)
  - Calorimeters (RPCs well-understood)
  - LArTPCs (demonstrated on small scale, need to go bigger)
- Atmospheric neutrinos are free
  - Make sure the next generation experiments are underground so we can use this source
    - Other interesting physics are then accessible too!

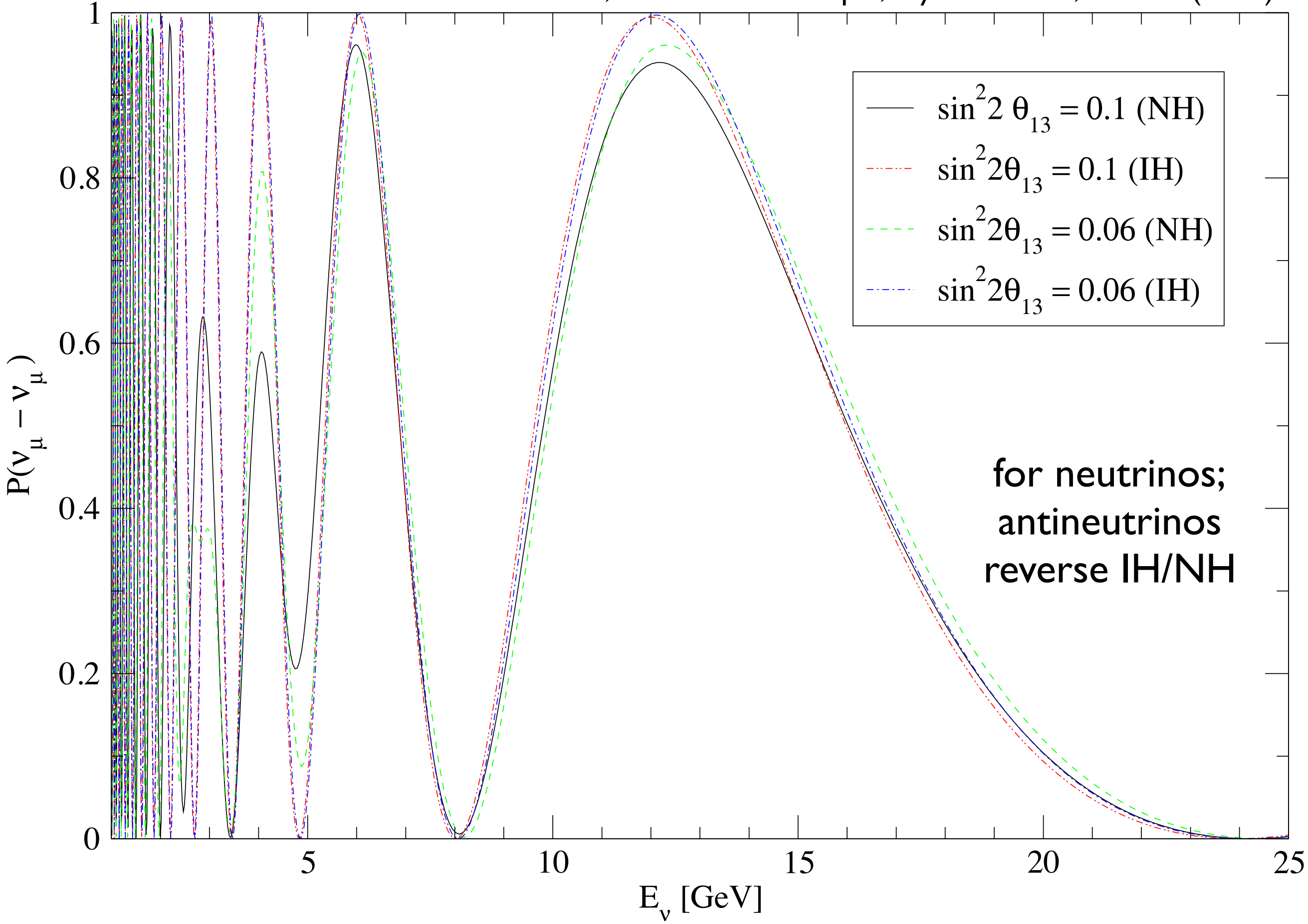
Questions

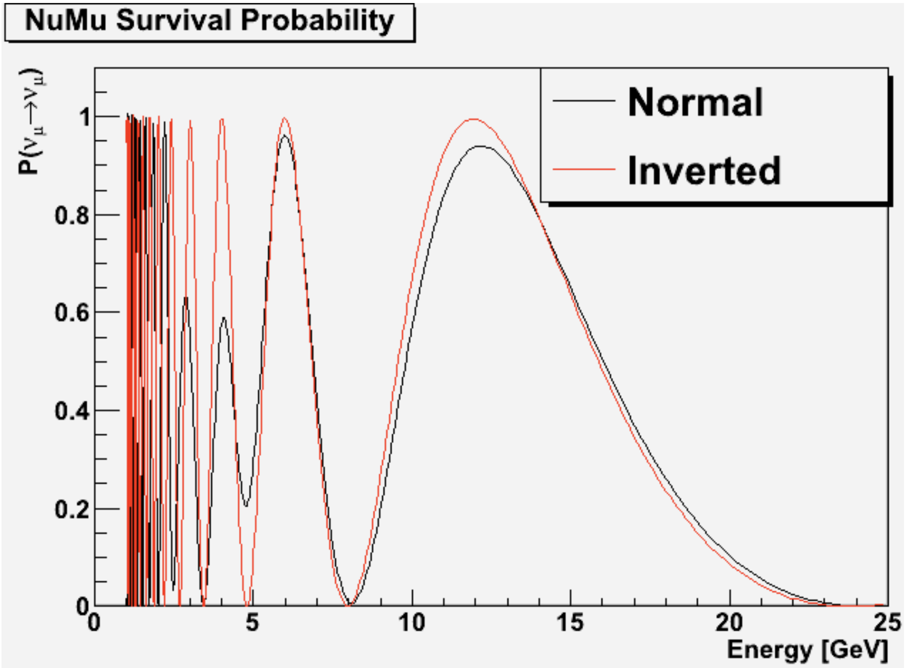
On what timescale can we expect a mass hierarchy measurement? At what cost?

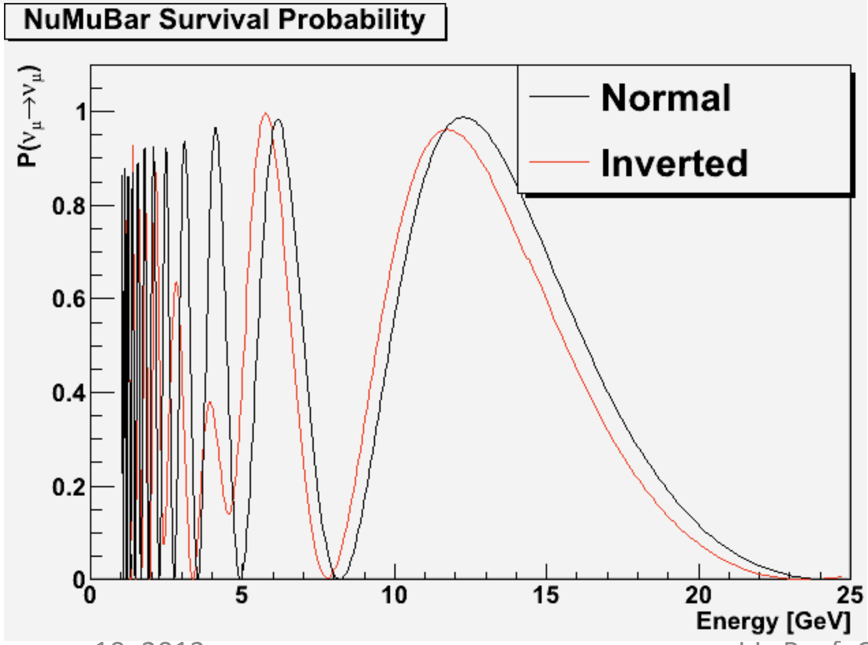
- What are the largest systematics?
- What other challenges will we need to address?

Extras

Mena, Mocioiu & Razzaque, *Phys. Rev.* D78, 093003 (2008)




NuMu Survival Probability
$P(\nu_\mu \to \nu_\mu)$
Normal
Inverted
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
Energy [GeV]


NuMuBar Survival Probability
$P(\nu_\mu \to \nu_\mu)$
Normal
Inverted
0
0.2
0.4
0.6
0.8
1
0
5
10
15
20
25
Energy [GeV]

MINOS

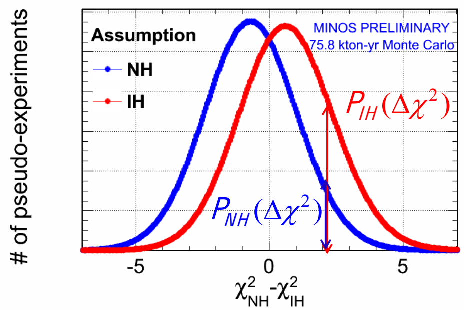
Studies ongoing.

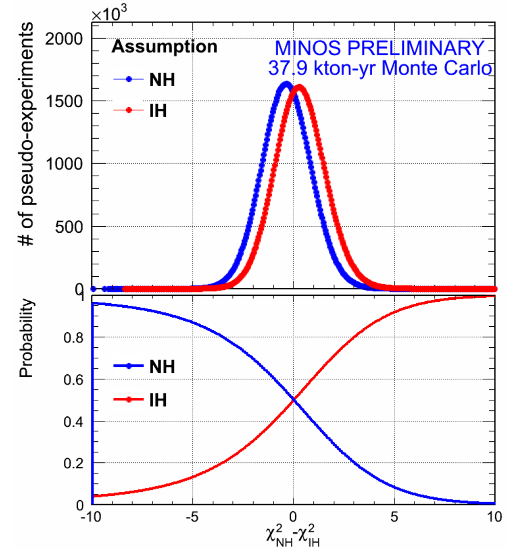
5.4kton detector

Measurement of the Mass Hierarchy

A statement may be made after the data sample is looked at, on "the probability to be normal mass hierarchy or inverted mass hierarchy" once $\chi^2_{NH} - \chi^2_{IH}$ is measured based on the Bayes' theorem.

$$P(IH \mid \Delta\chi^2) = \frac{P(\Delta\chi^2 \mid IH)}{P(\Delta\chi^2 \mid IH) + P(\Delta\chi^2 \mid NH)}$$





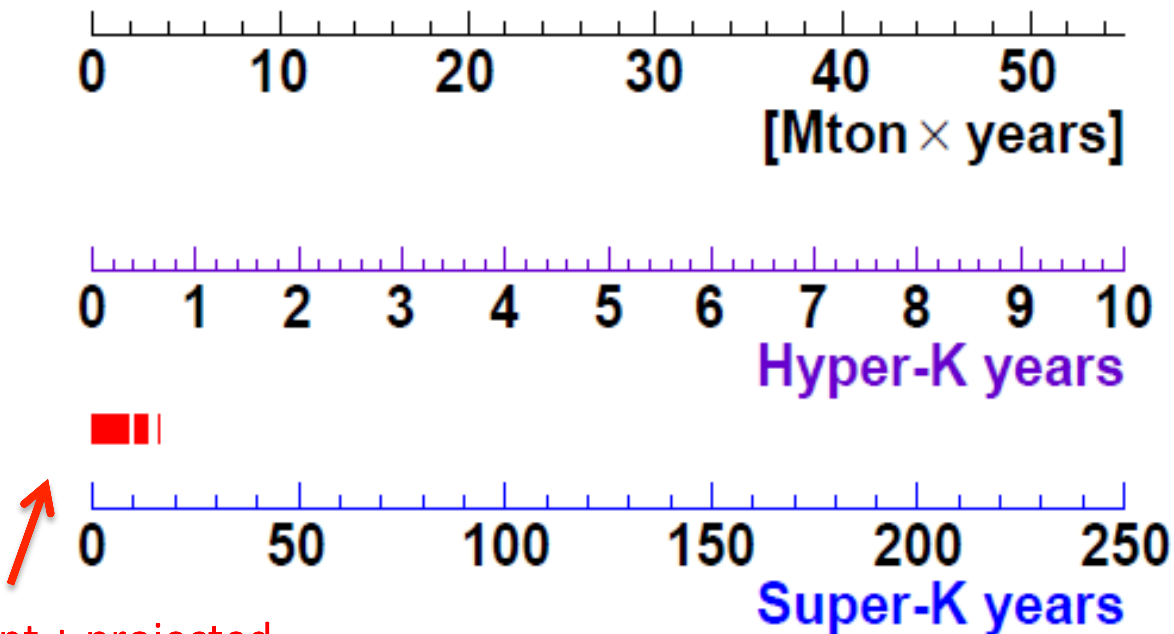
Current and Future Sensitivity

The probability to determine the *correct* mass hierarchy

Exposure (kton-years)	Normal Mass Hierarchy	Inverted Mass Hierarchy	Average
37.9	61.3%	59.7%	60.5%
75.8	65.6%	63.9%	64.7%
379	80.6%	79.1%	79.8%

The "discrimination power" to determine the *correct* mass hierarchy

Exposure (kton-years)	Normal Mass Hierarchy	Inverted Mass Hierarchy
37.9	24.2%	19.1%
75.8	31.4%	27.6%
379	61.3%	57.5%



Current + projected
Accumulated Data

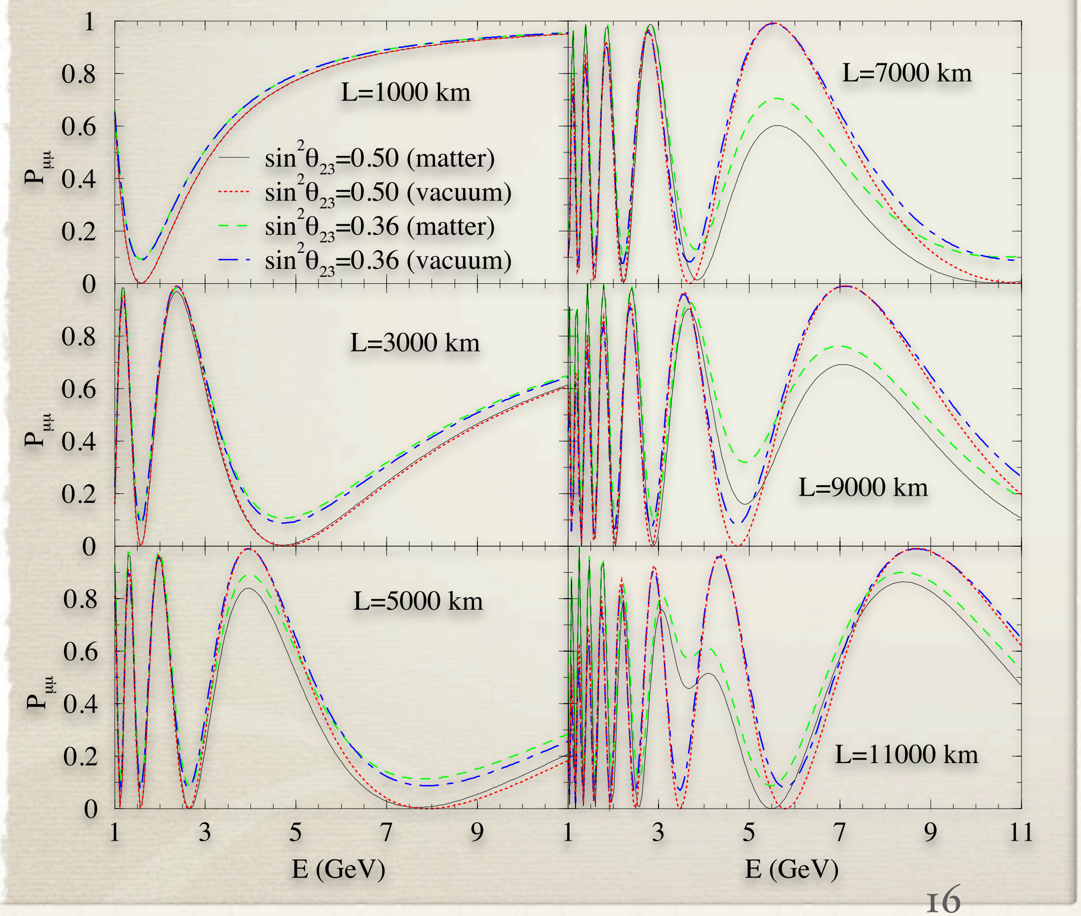
- Currently there are 0.24 Mton•yrs SK data on hand
- In another 10 years we will have about 85% of 1 HK year

- Super-K oscillation analysis has been updated to include constraints from global information on θ_{13}
- No decisive indication of the mass hierarchy, θ_{23} octant, or value of δ_{cp} yet …

Sensitivity (σ)	$\sin^2\theta_{23}$	SK Current	SK + 10 years
Hierarchy	0.4	0.70	0.98
	0.6	1.50	2.10
Octant	0.4	2.00	2.60
	0.6	1.61	2.10

- The Future
  - Still statistics limited
  - Constraints from external data may help focus the sensitivity of atmospheric neutrinos
    - Analysis incorporating global data underway
  - At Hyper-K exposures the sensitivity to oscillations can address many of the current unknowns (and all in combination with beam data)

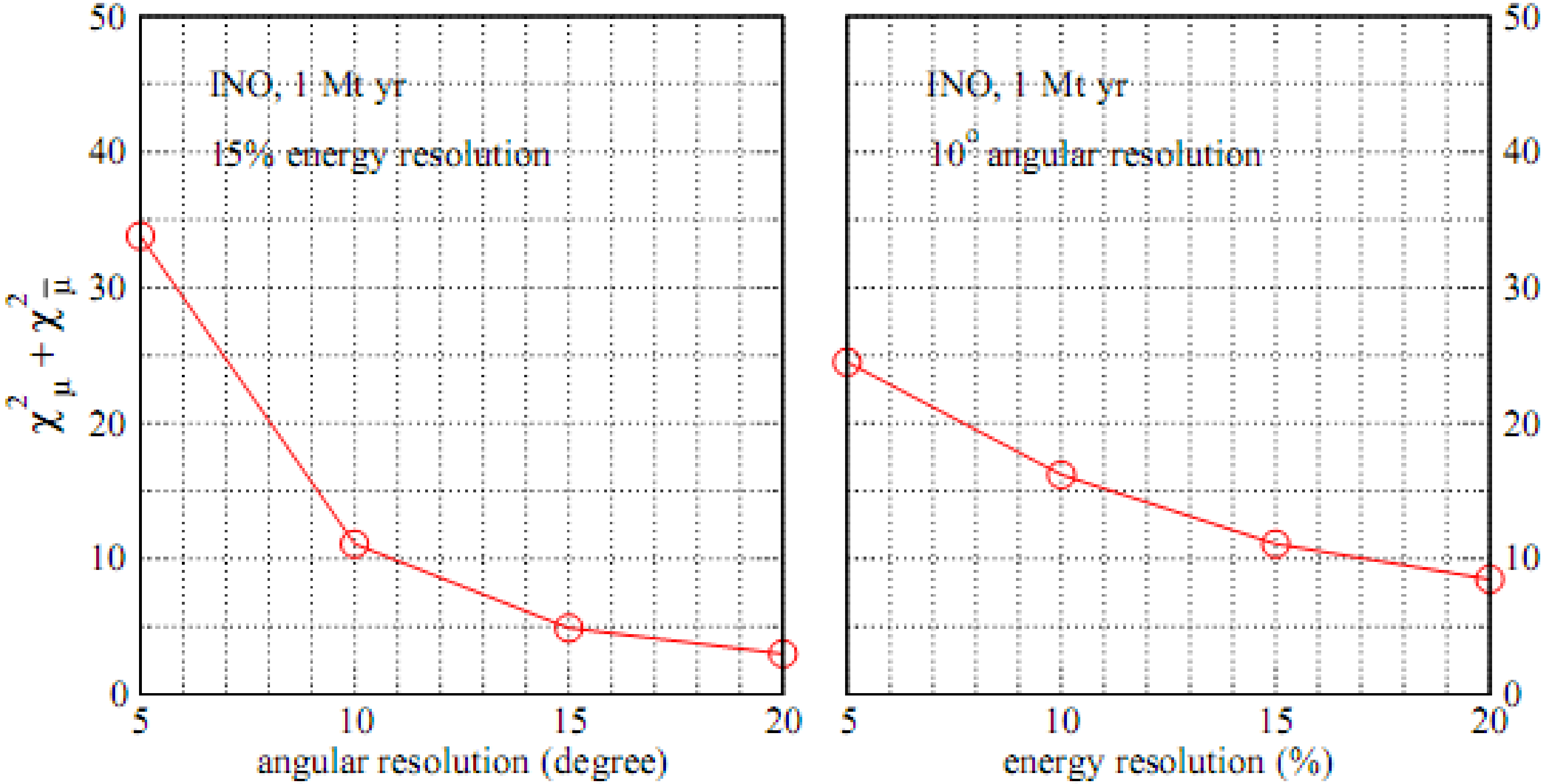
Large Matter Effects in ν_μ Survival Probability



- Max effect for L~7000 km and E~6 GeV [E(spmax) = E(res)]
- P_{μ_μ} decreases (increases) at the spmax (spmin) due to matter effects
- sign of earth matter effects depend on both L and E
- matter effects depend on the value of θ_{13}
- matter effects also depend on the value of θ_{23}
- most imp is to choose proper bins in both E and L

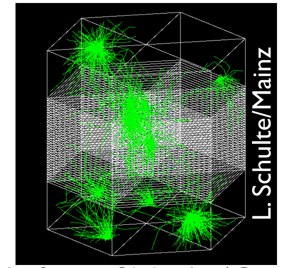
Mass hierarchy determination

- Impact of resolutions



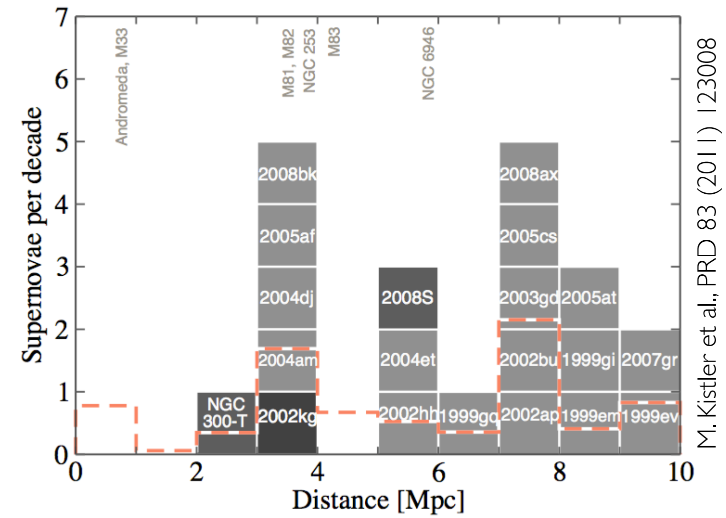
Gandhi et al: 0707.1723;
Also see
Petcov, Schwetz: hep-ph/0511277

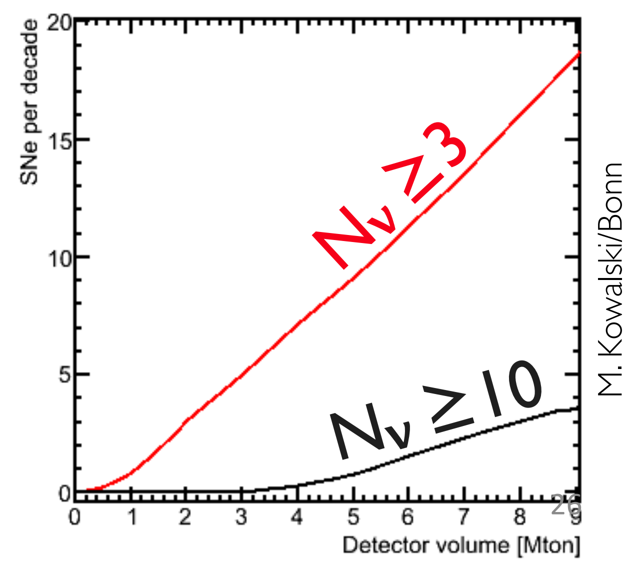
MICA: Supernovae



γ's from SN ν's (Geant4)

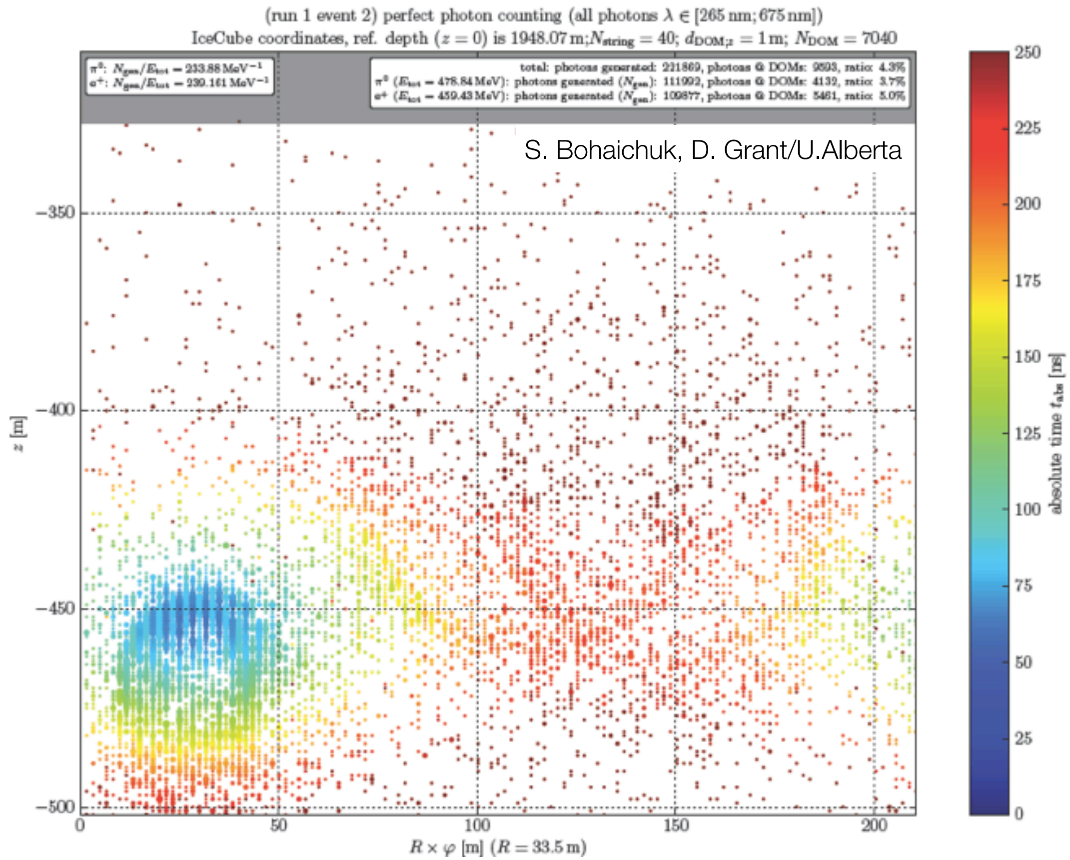
- SN neutrinos at 10-20 MeV would produce 2000-4000 Cherenkov photons:
  - Even few percent photocathode coverage enough to see a single SN neutrino
  - A burst of >=3 neutrinos in 1-10s would be above atmospheric neutrino background
    - Have not yet looked at spallation daughters
  - A ~5 MTon detector could see to ~10Mpc
    - Roughly annual supernova neutrino detection!
  - Other benefits:
    - Early triggers for optical telescopes
    - ...and gravitational wave detectors: bkgd. reduction ~10^6; signal enhancement ~1000x
  - Caveats: LOTS of uncertainties (reconstruction, particle ID, spallation rejection...)





MICA: Proton Decay

- Very challenging. To beat backgrounds from atmospheric neutrinos and muon spallation products one needs:
  - energy (momentum) resolution
  - particle ID via Cherenkov ring reconstruction
  - high photocathode area
- Simulations just starting



$p \rightarrow \pi^0 + e^+$

Idealized

1.5 MTon (5×10^{35} protons),
10 MeV threshold,
240 photons/MeV,
5% photons detected,
NO scattering