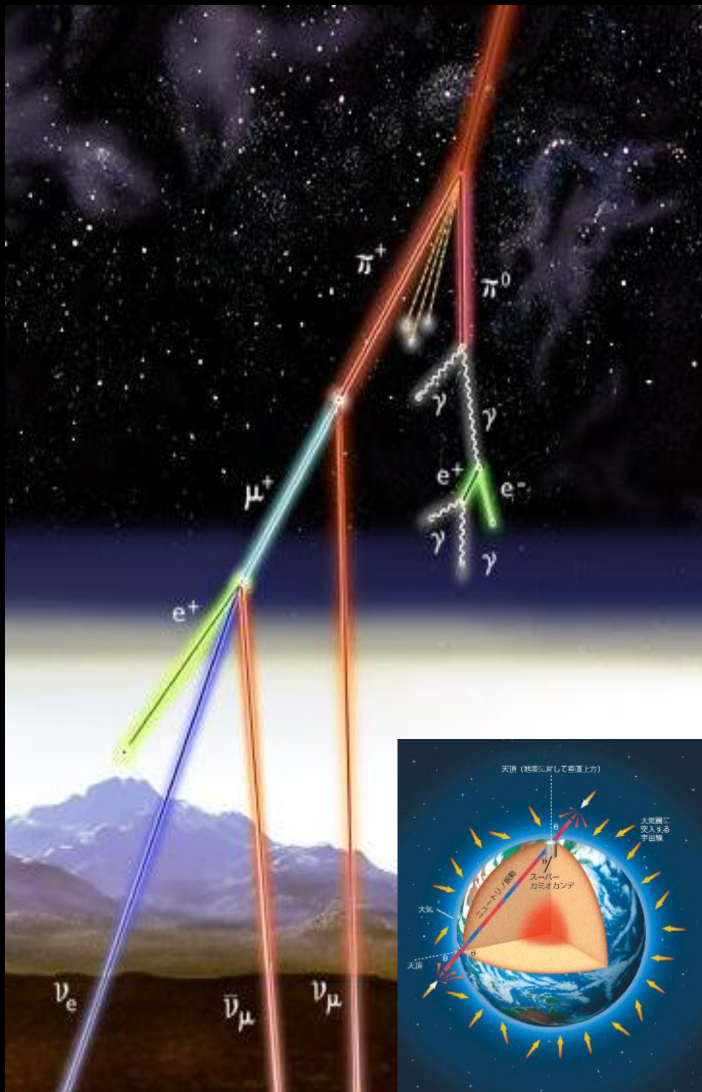
Atmospheric Neutrinos at the Intensity Frontier

Roger Wendell, Duke University

Intensity Frontier Workshop

2011.12.01

Atmospheric Neutrino Generation



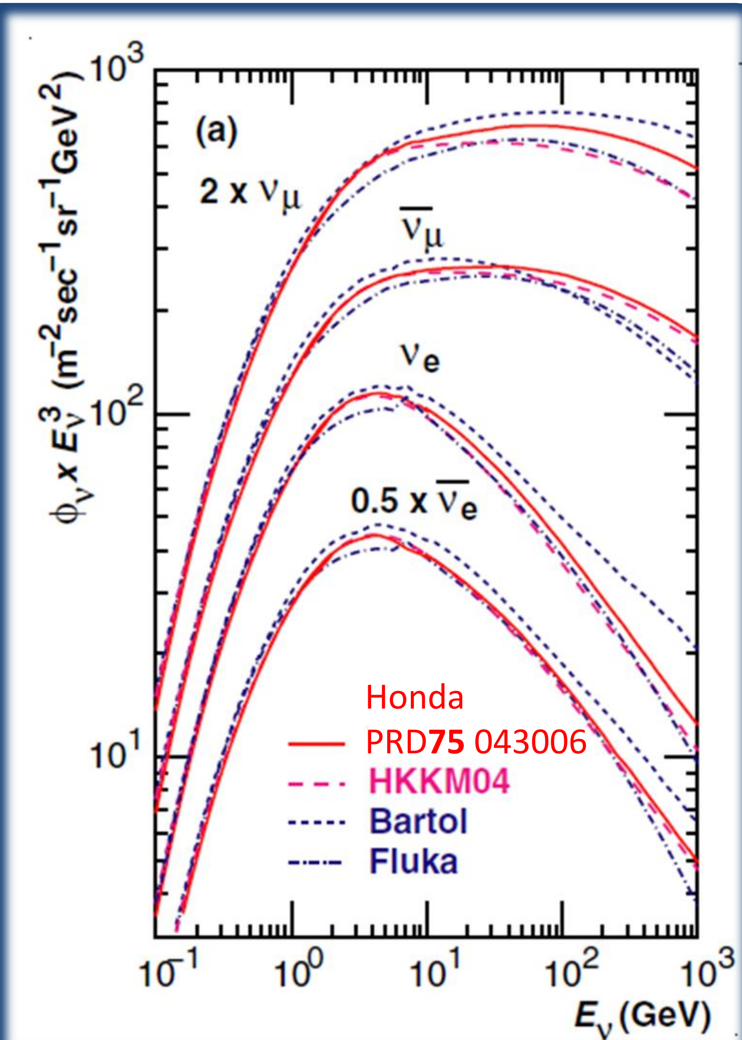
- Cosmic rays strike air nuclei and the decay of the out-going hadrons gives neutrinos

$$P + A \rightarrow N + \pi^{+} + x$$

$$\hookrightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu}$$

- Isotropic about the Earth
  - Path length to the detector spans 10 – 10,000 km
- Spans many decades in energy ~100 MeV – PeV+

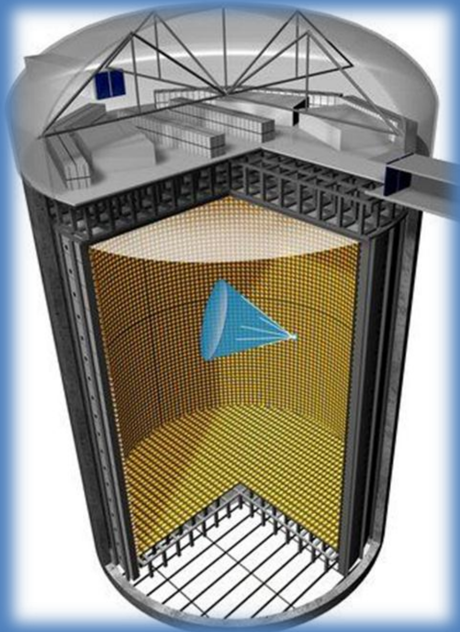
Atmospheric Neutrino Flux



Conventional Flux

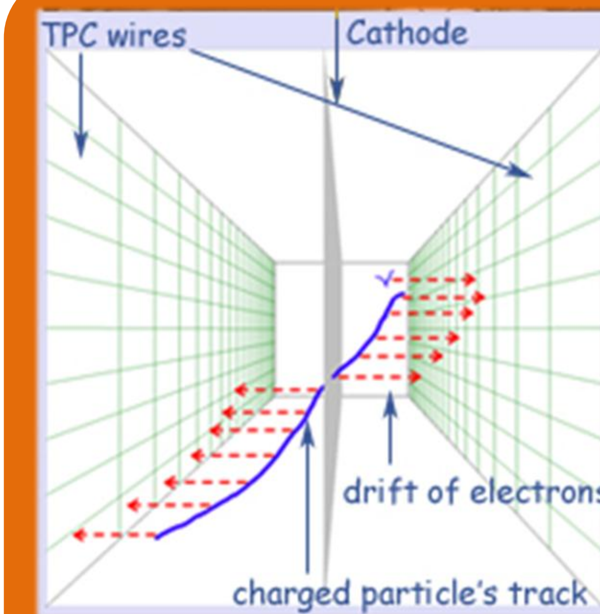
- Used to discover neutrino oscillations
  - Wide variation in L/E (Pathlength/Energy)
- Absolute flux known to ~20%
- Shape known to ~5-10%
- Up / Down Symmetric
  - → Uncertainties cancel

Technologies for Atmospheric Neutrino Experiments



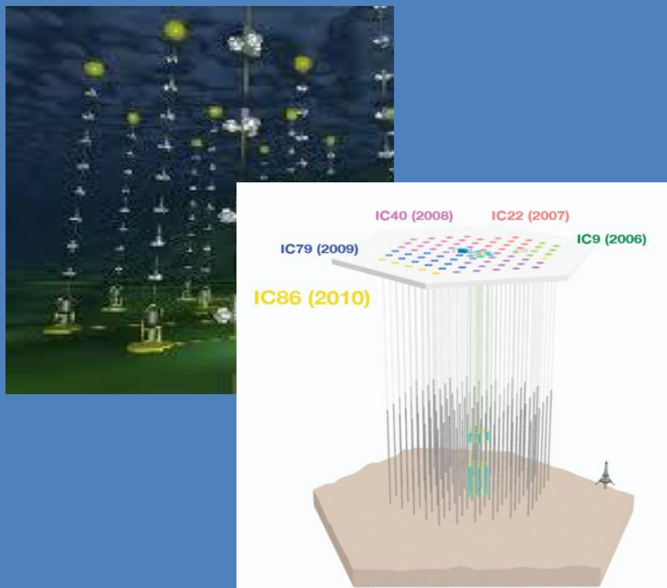
- Water Cherenkov
  - Super-K
  - Hyper-Kamiokande
  - LBNE $H_2 0$ Cherenkov
- Cheap, Proven, Lower E
- Good angular and momentum resolution
- Cherenkov threshold, ~MeV detector threshold

- Iron Calorimeters
  - Soudan, MINOS
  - ICAL at INO
- Charge sign discrimination with magnetization
- Good tracking, resolution
- Limited electron sensitivity, costly



- Liquid Argon (LAr)
  - ICARUS
  - GLACIER,
  - LBNE LAr20
  - Okinoshima
- Excellent resolution, efficiency, BG rejection
- Expensive to scale, unproven at kton scales

Technologies for Atmospheric Neutrino Experiments



- Neutrino Telescope
  - Antares, KM3NeT
  - Amanda, IceCube
- Huge detection volumes
- Sensitivity to very high energy neutrinos
- High energy threshold, challenging systematics

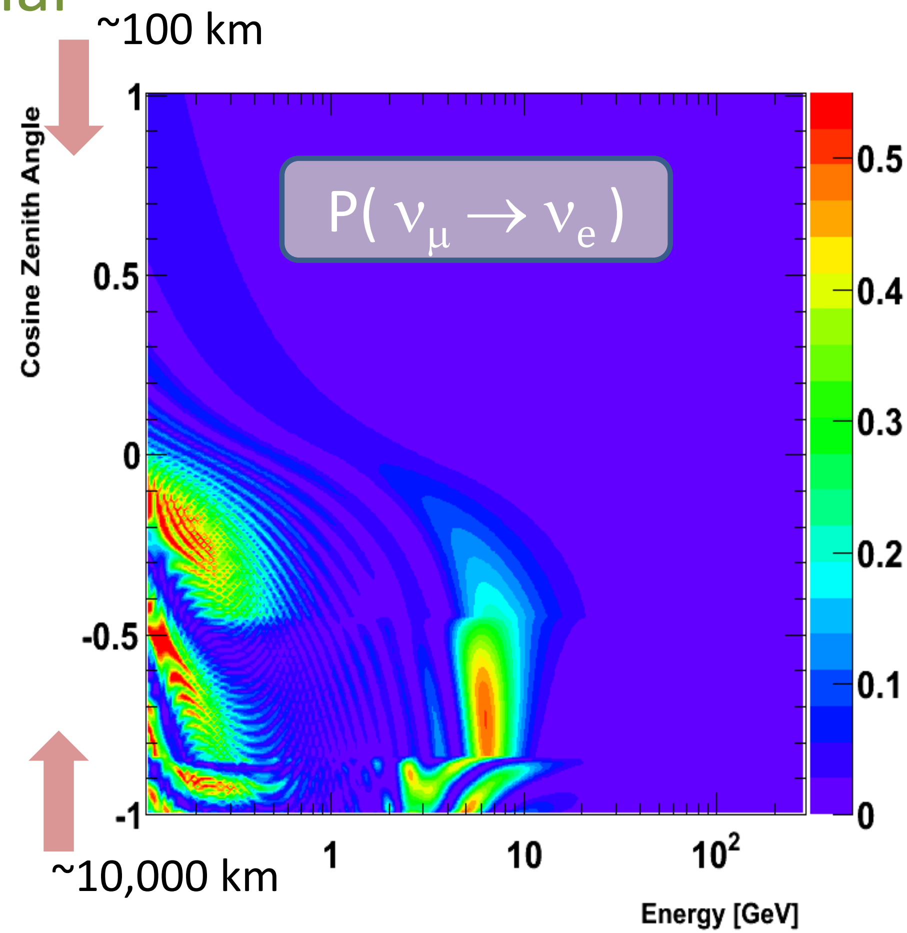
- Others
- Composite Trackers
  - MACRO
- Liquid Scintillator
  - LENA

- A few points in common
- ~200 ev/kton/year atmospheric neutrinos
  - For future measurements we will need **large detector volumes**
  - with good angular and energy resolutions

Atmospheric Neutrinos As Signal

	Large lAr or H_20 Cherenkov	Iron Calorimeter	ν Telescope
"Atmospheric" and Neutrino Oscillations			
– Δm^2	■	■	■
– $\mathrm{Sin}^2\theta_{23}$, octant	■	■	
– $\mathrm{Sin}^2\theta_{13}$	■	■	■
– δ_{cp}	■		
– Mass Hierarchy	■	■	■
– Exotic Scenarios	■	■	■
– τ Appearance	■	■	■
Earth Radiography	■		■
Resolution of Parameter Degeneracy (+ beam)	■	■	■
Measurement of prompt flux			■

- Large lAr or H_20 Cherenkov
- Iron Calorimeter
- ν Telescope

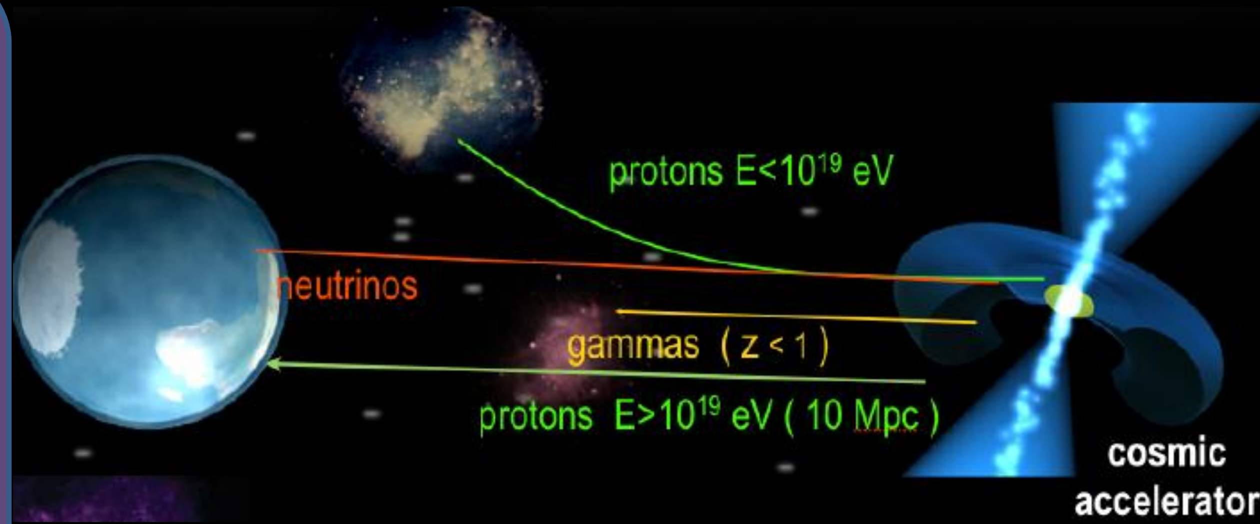


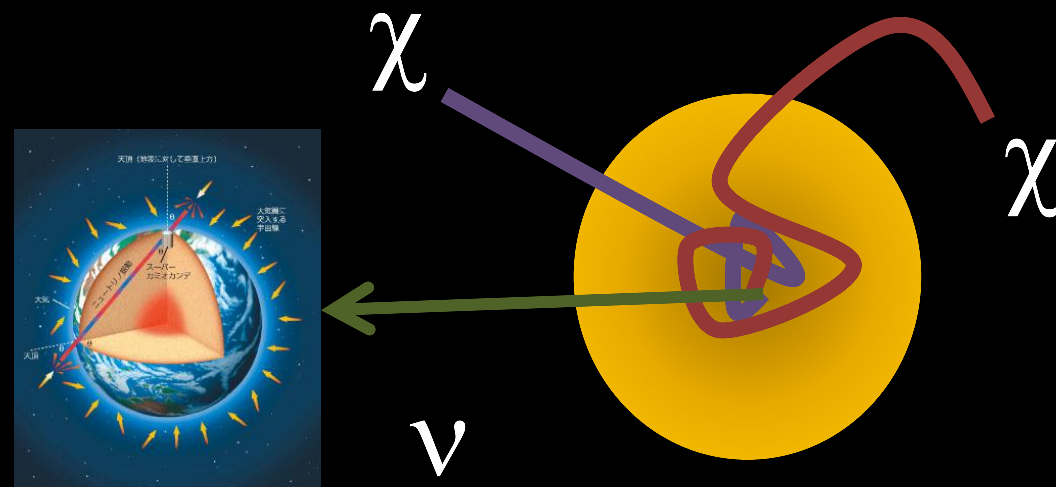
- Sensitive to three-flavor oscillations via matter effects
- Resonance exists for either ν or ν bar
  - $\rightarrow$ hierarchy
  - Strength coupled to θ_{13}
- At lower energies, oscillation probability is sensitive to $\sin^2\theta_{23}$

Atmospheric Neutrinos As Background

	Large lAr or H_2O Cherenkov	Iron Calorimeter	ν Telescope
☐ Proton Decay	■	■	
☐ Cosmogenic ν	■	■	■
☐ Point Sources			
☐ AGN			■
☐ GRB			■
☐ Solar Flares	■	■	
☐ Indirect Dark Matter	■	■	■
☐ Exotics			
☐ SUSY			
☐ CHAMPS			

- ■ Large lAr or H_20 Cherenkov
- ■ Iron Calorimeter
- ■ ν Telescope

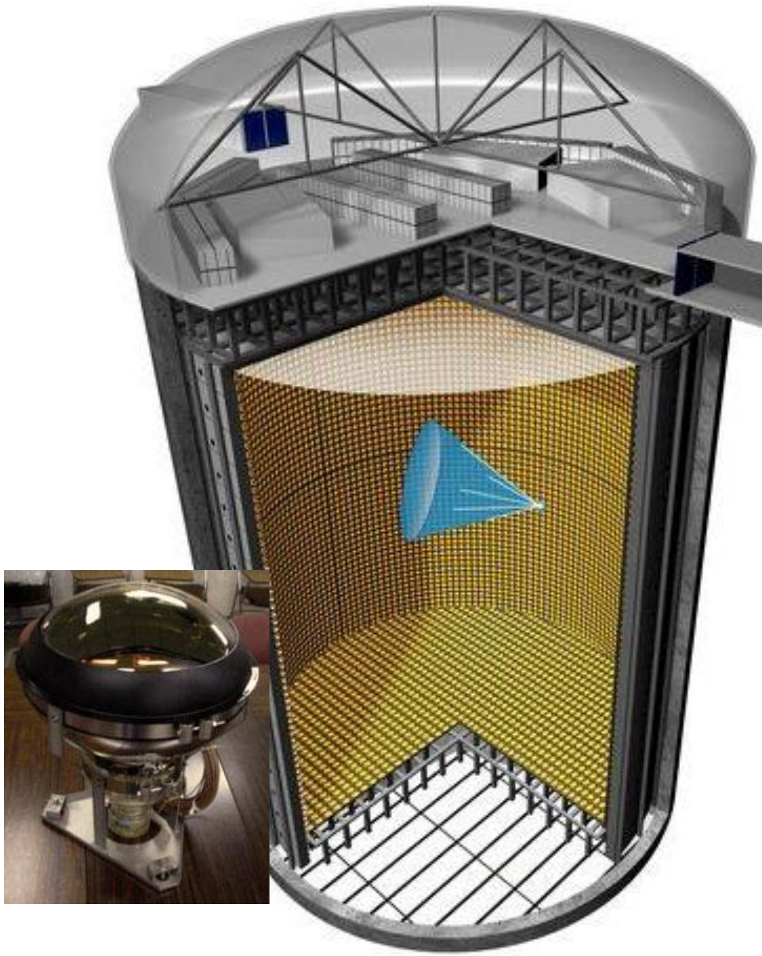


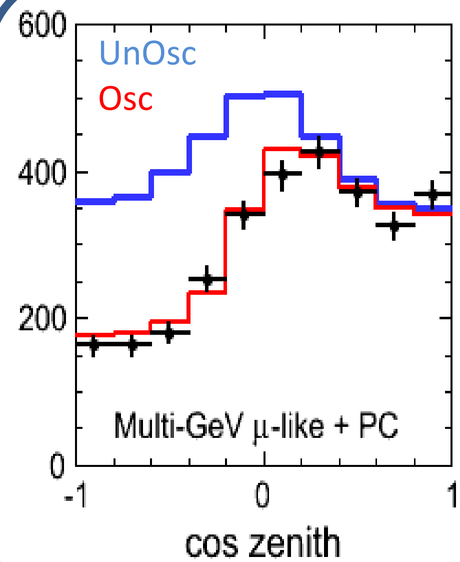


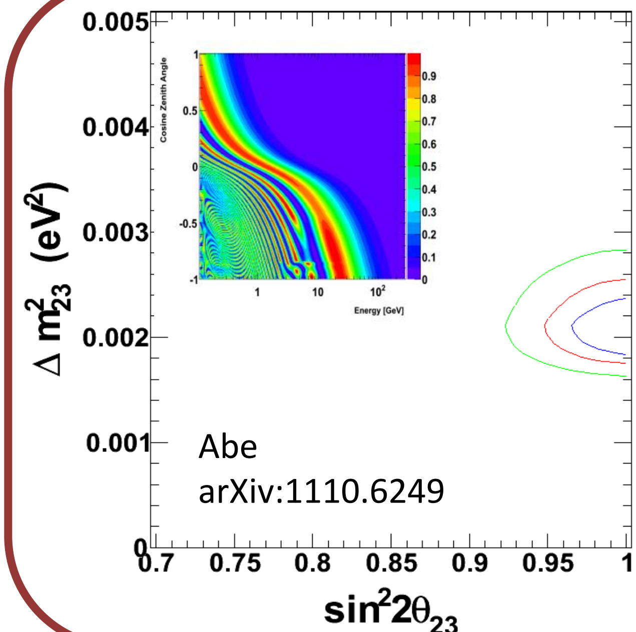
- ☐ Understanding and characterization of these backgrounds is key for future measurements

Super-Kamiokande : Not Yet Systematically limited

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2(1.27\, \Delta m^2_{23}\, L/E)$$



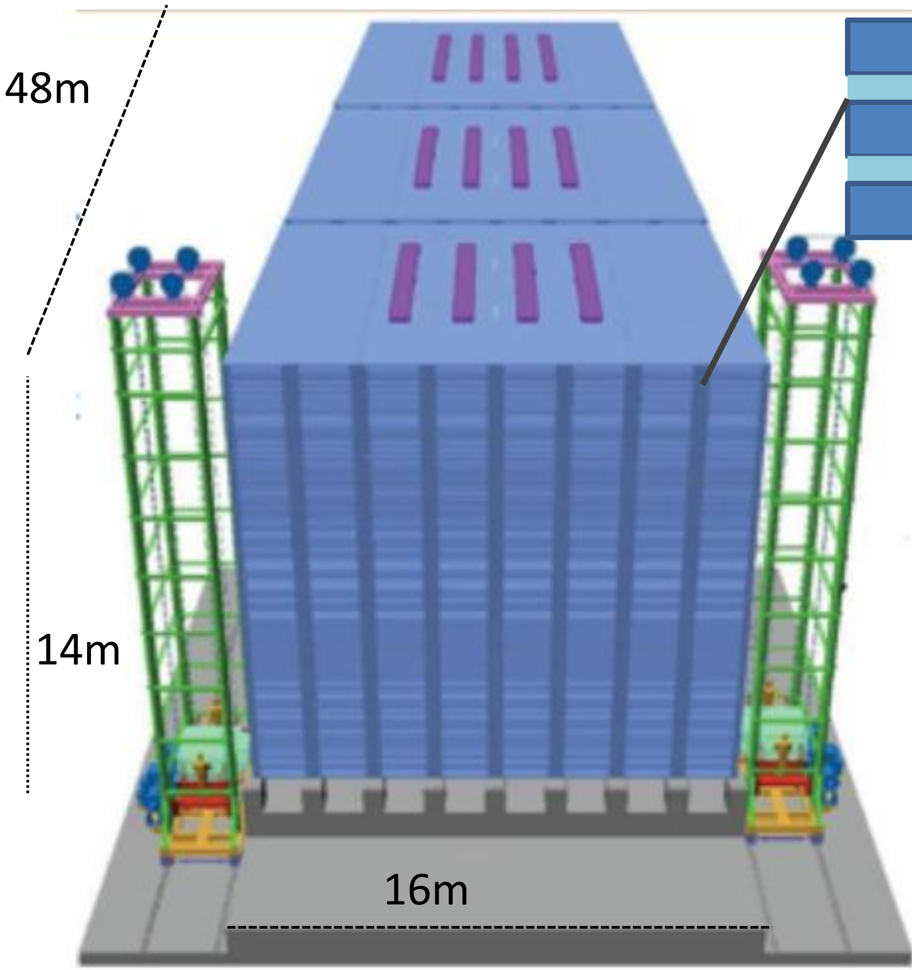


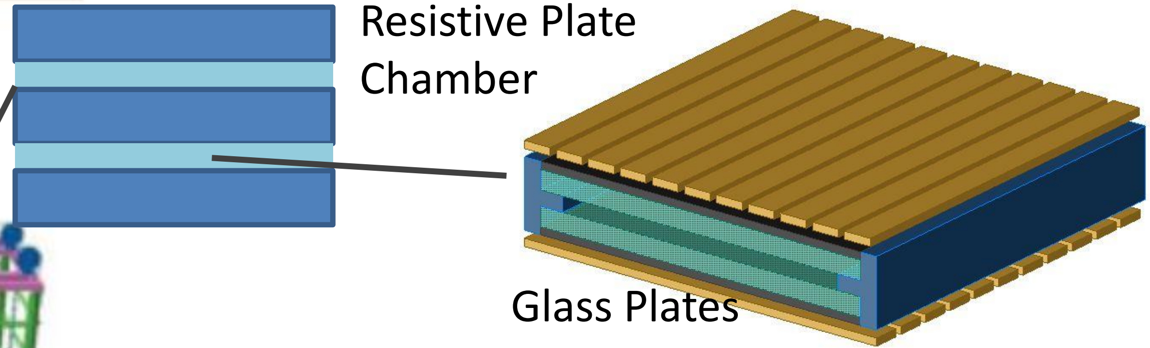


- 22.5 kton FV Volume
- Ring Imaging Water Cherenkov detector
- 11,1146 20" Phototubes
- Data taken over four periods since 1996

- SK discovered atmospheric neutrino oscillations exploiting the disappearance of upward-going muon events
- Currently **statistics limited**

ICAL at the India-based Neutrino Observatory (INO)



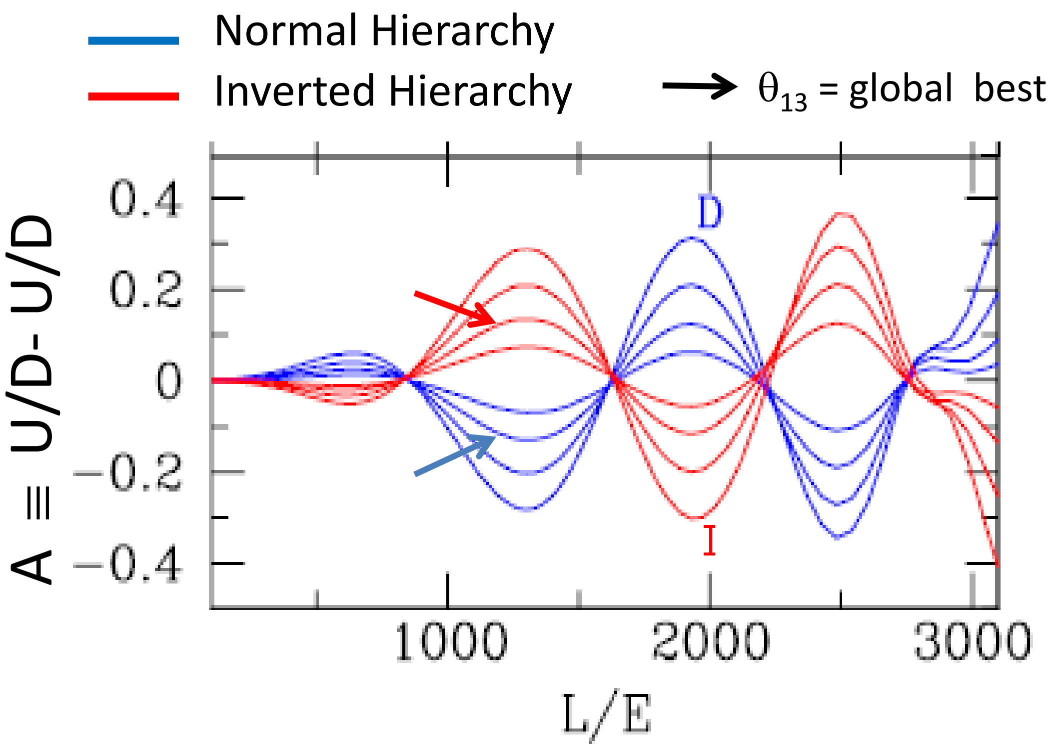


- 50 kton Iron Detector
- Magnetized to 1.5 Tesla
  - Charge sign discrimination means ν vs. $\bar{\nu}$ discrimination
- Efficient μ^+/μ^- discrimination power
  - No sensitivity to $e^{+,-}$

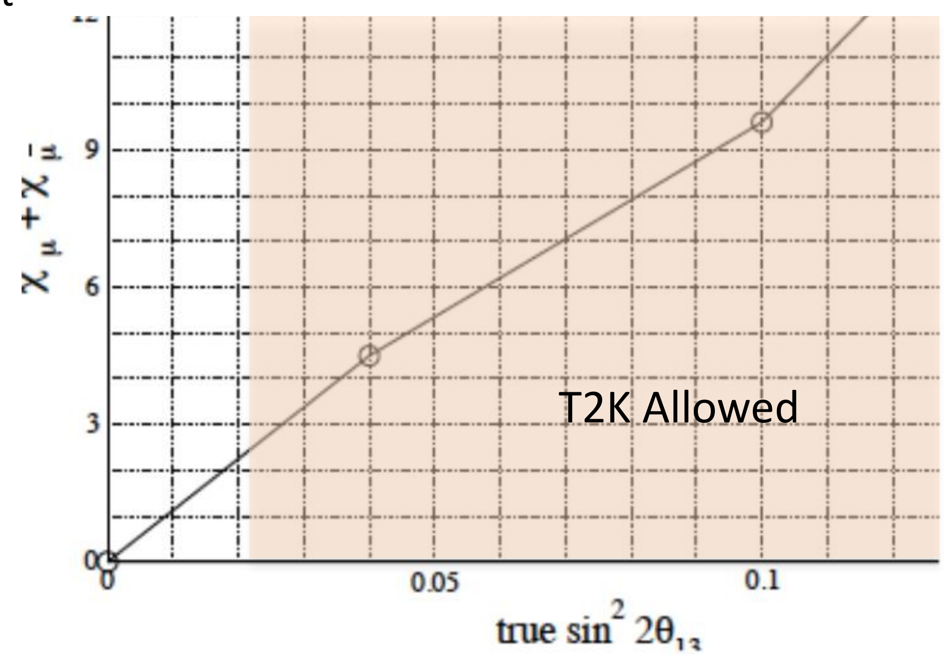
- 140 low carbon 60mm thick iron plates
- Resistive Plate Chambers (RPCs)

See R.Gandhi “INO Physics and Status”
Session 4

ICAL : Sensitivity to Hierarchy Through $\mu\pm$ asymmetry



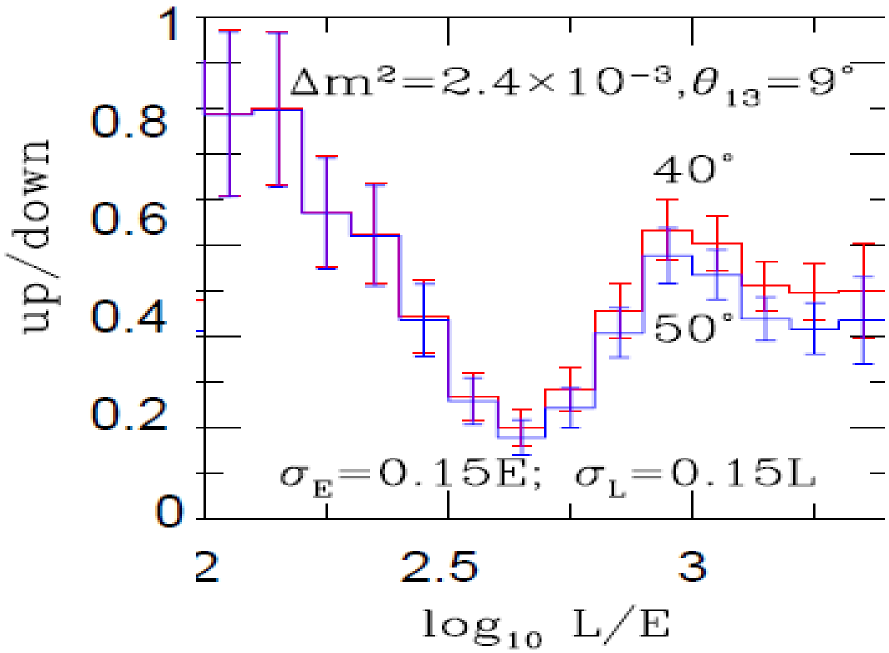
INO Project
Report 2006/01

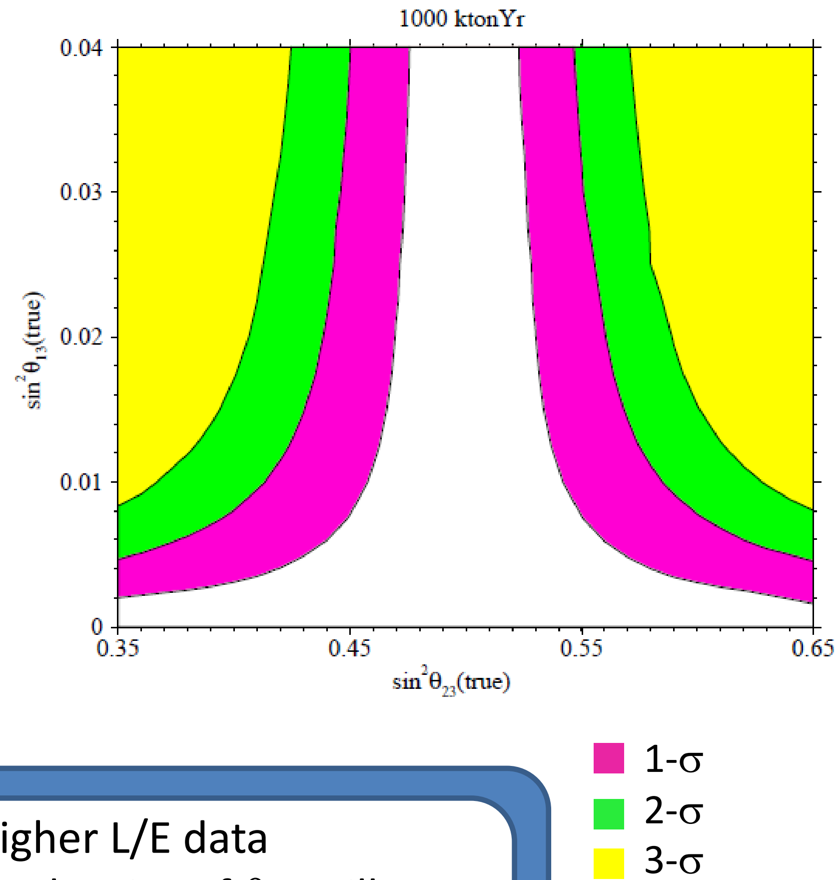


- Make use of asymmetric matter effects between ν_μ and $\bar{\nu}_\mu$ to discriminate hierarchy
- Sensitivity to hierarchy > 2σ if $\sin^2 2\theta_{13} > 0.05$
- 1 Mton • yr exposure

ICAL : Octant Ambiguity Resolving Power

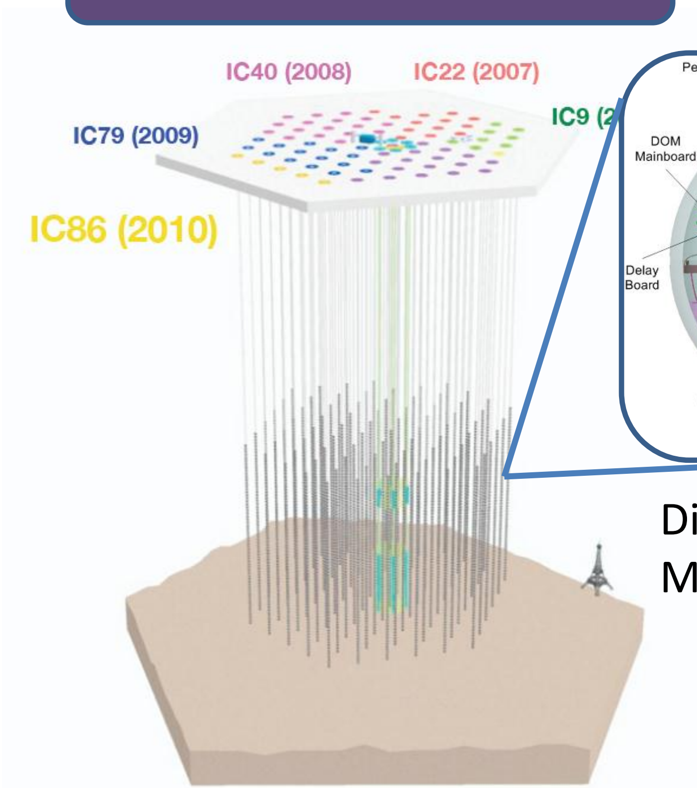
INO Project
Report 2006/01

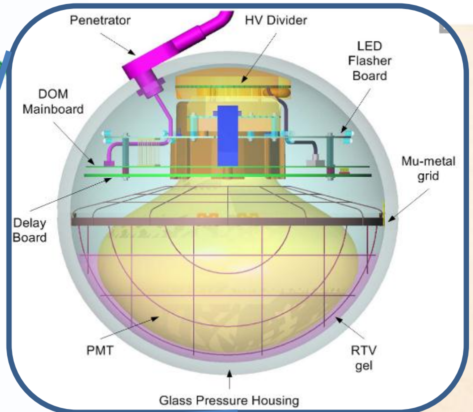




- ☐ Untangle the octant ambiguity using higher L/E data
- ☐ Inputs from external experiments about the size of θ_{13} will help
- ☐ Tests of ‘exotic’ physics as well:
  - ☐ CPT violation, Lorentz Invariance
  - ☐ ~1 eV^2 mass splittings -> MiniBooNE / LSND

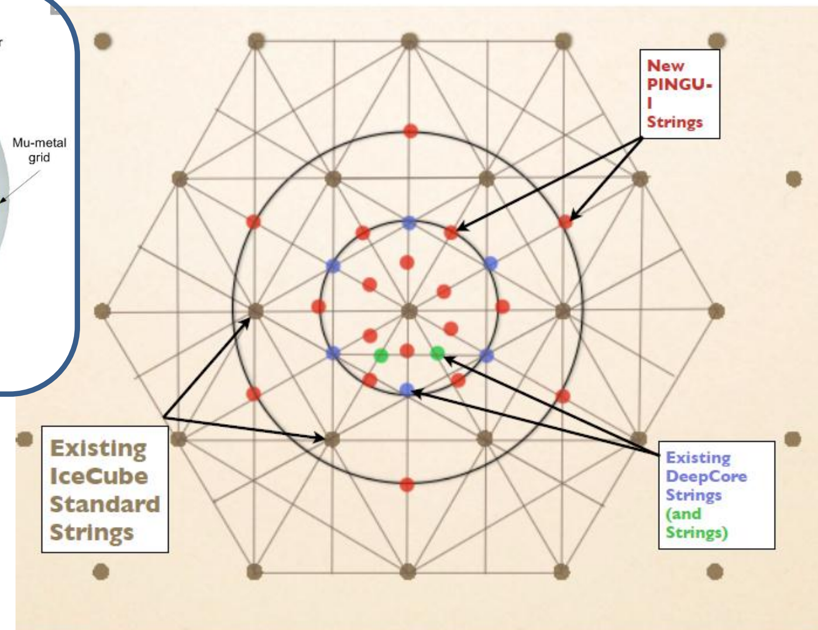
IceCube + DeepCore





Digital Optical Module (DOM)

PINGU



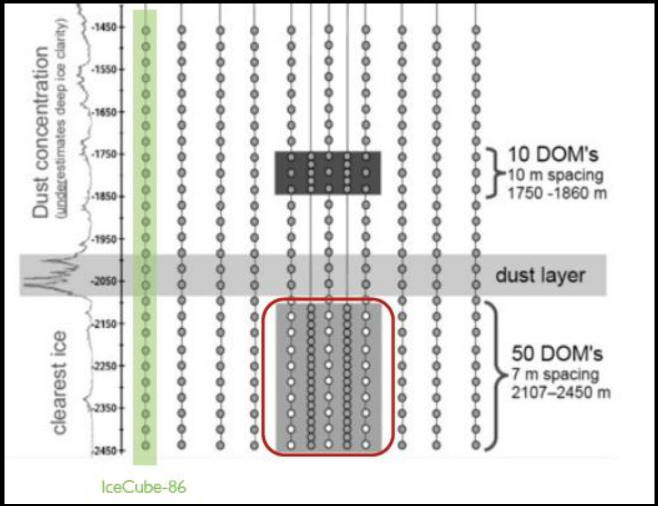
- Higher phototube densities lower the energy threshold of the detector
- Less densely instrumented volume can be used as a veto

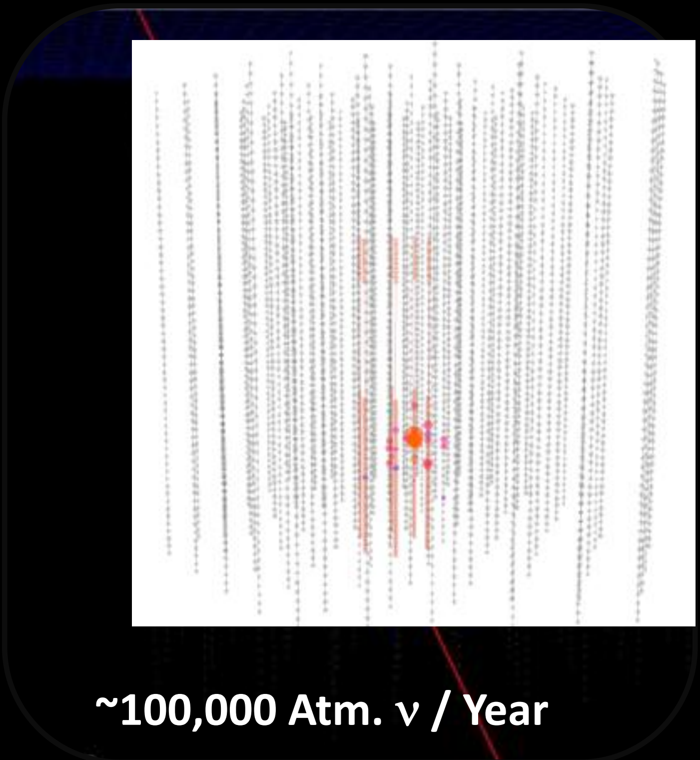
IceCube	DeepCore	PINGU	PINGU-II
PMT density			
Energy Threshold			
~100 GeV	~10 GeV	~1 GeV	~100 MeV

Oscillation sensitivity →

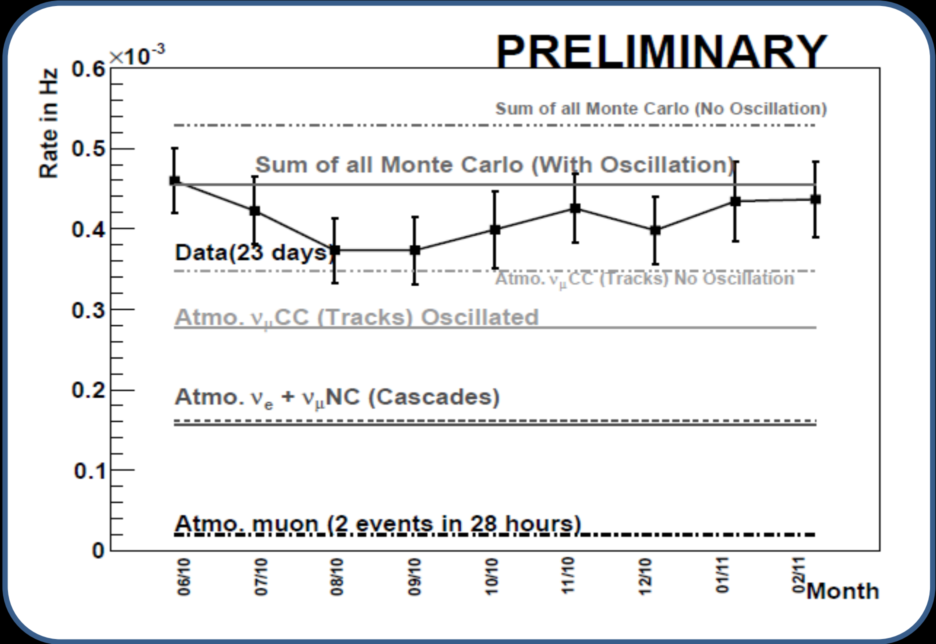
IceCube + DeepCore December 2010+

ICRC 2011



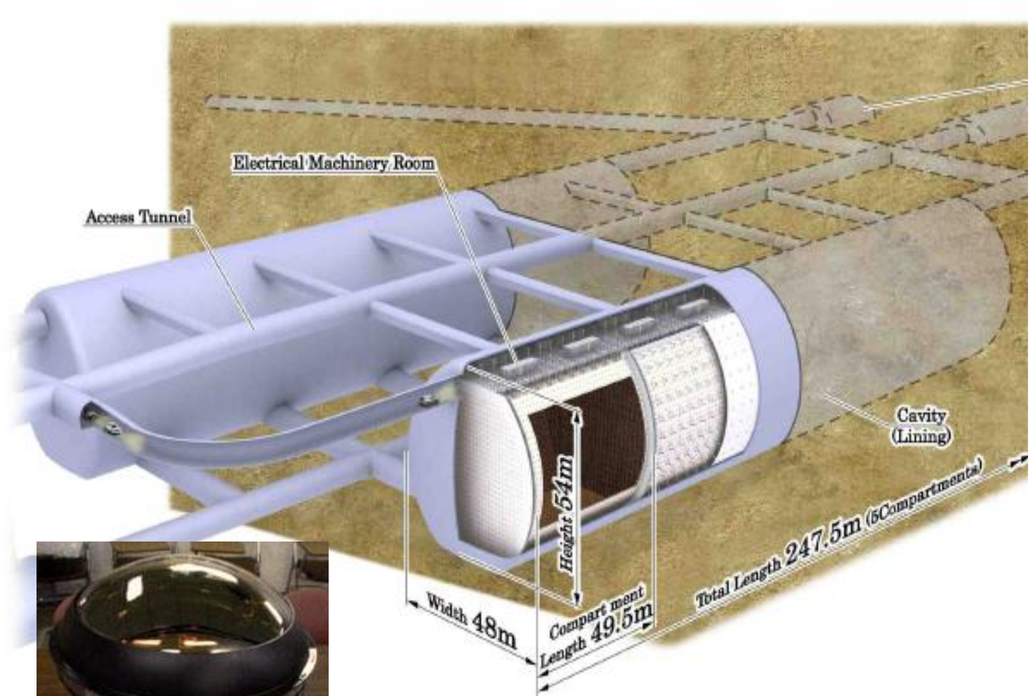


~100,000 Atm. ν / Year



- Observation of 'cascade' (ν_e, ν_τ, NC) events
  - Proof of DeepCore principle
- Consistent with expectation from atmospheric MC
- Also sensitive to:
  - Oscillations , $\nu_\mu \rightarrow \nu_\tau$
  - ν_τ appearance
- See also D.Cowen, "IceCube Upgrades" Session 4

Hyper-Kamiokande



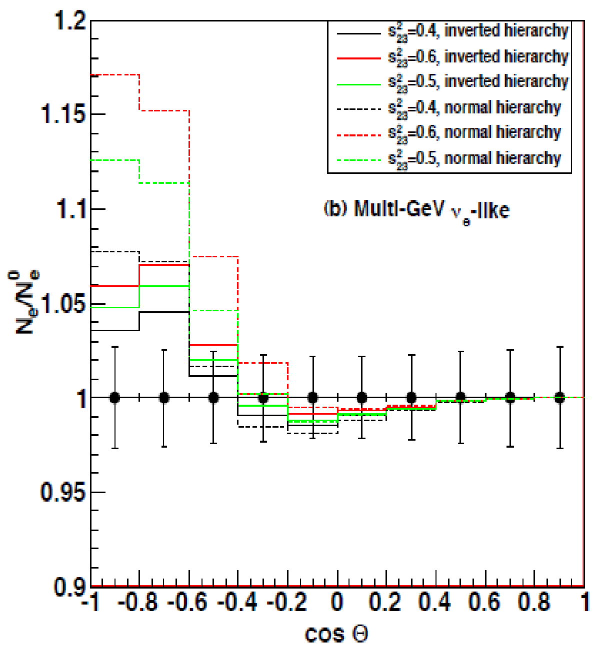
- 1,750 m.w.e Rock Overburden
- 990 kton Total Volume
  - 560 kton Fiducial Volume
- Inner and Outer Detectors
  - ID : 99,000 20” PMTS (25% Coverage)
  - OD: 25,000 8” PMTS

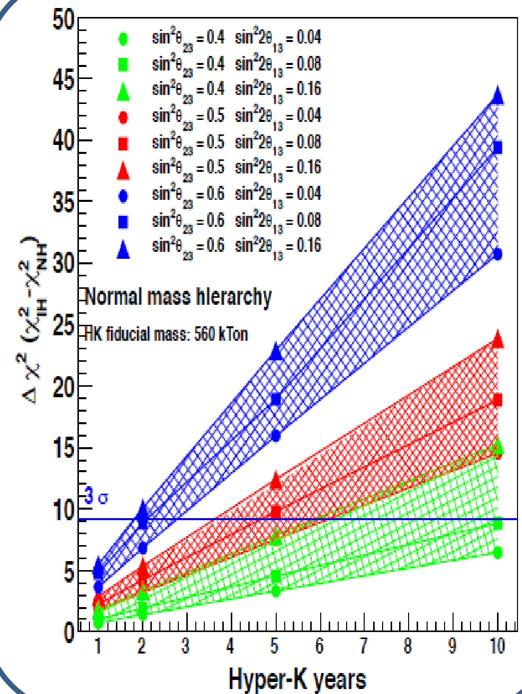
- Next generation water Cherenkov detector
- Well understood technology
- 2.5 degrees off T2K beam axis
- ~kms away from Super-K

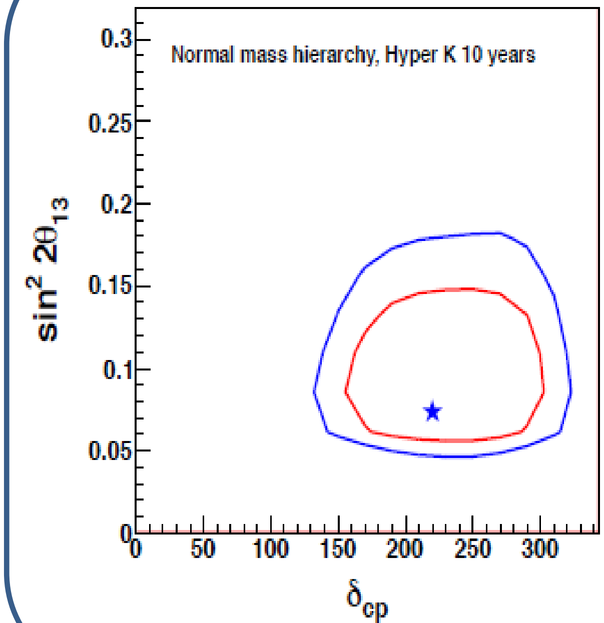
See M. Yokoyama “Hyper-K Detector and Plans” Session 4

Hyper-Kamiokande : Atmospheric ν physics reach

Abe
arXiv:1109.3262

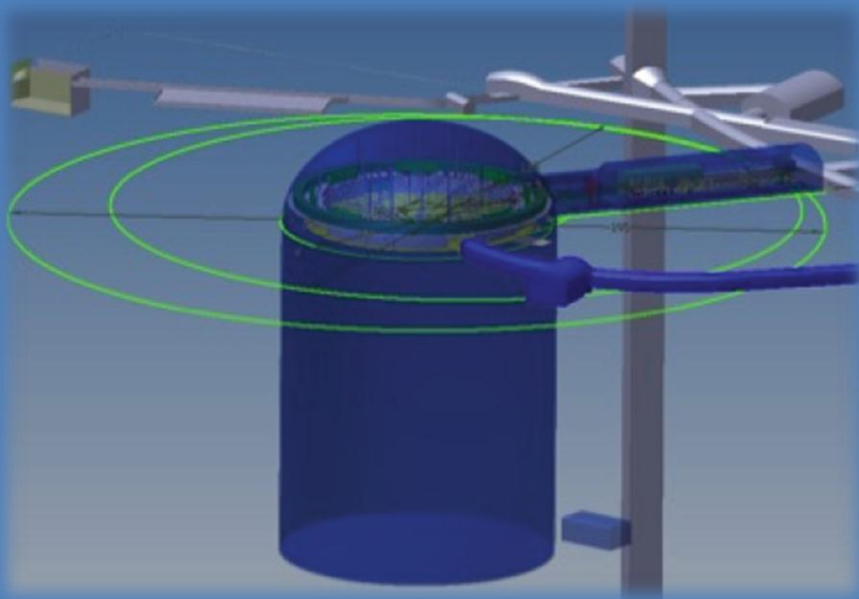






- Can determine mass hierarchy for a variety of values of atmospheric mixing within 10 years .
- For values of θ_{13} near the T2K observation, can constrain about 50% of CP space
- Can determine the octant of θ_{23} if $\sin^2 2\theta_{23} < 0.99$

LBNE : Water Cherenkov or LAr

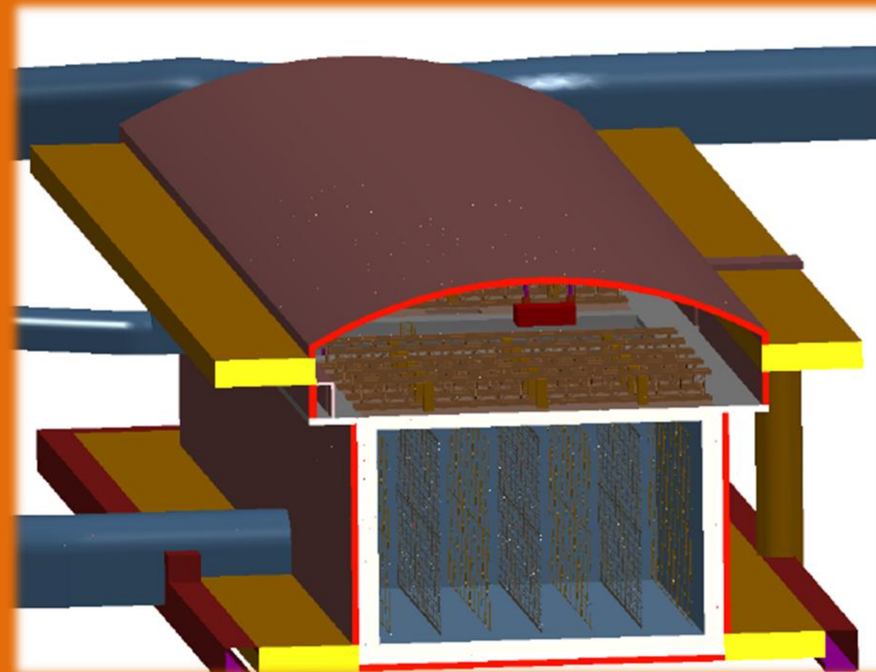


100 kton modules

- 1, 2, or 3
- 10” High quantum efficiency PMTs
- 15% or 30% coverage

- 4850 ft level
- Gadolinium?

See B.Svoboda’s talk in Session 4

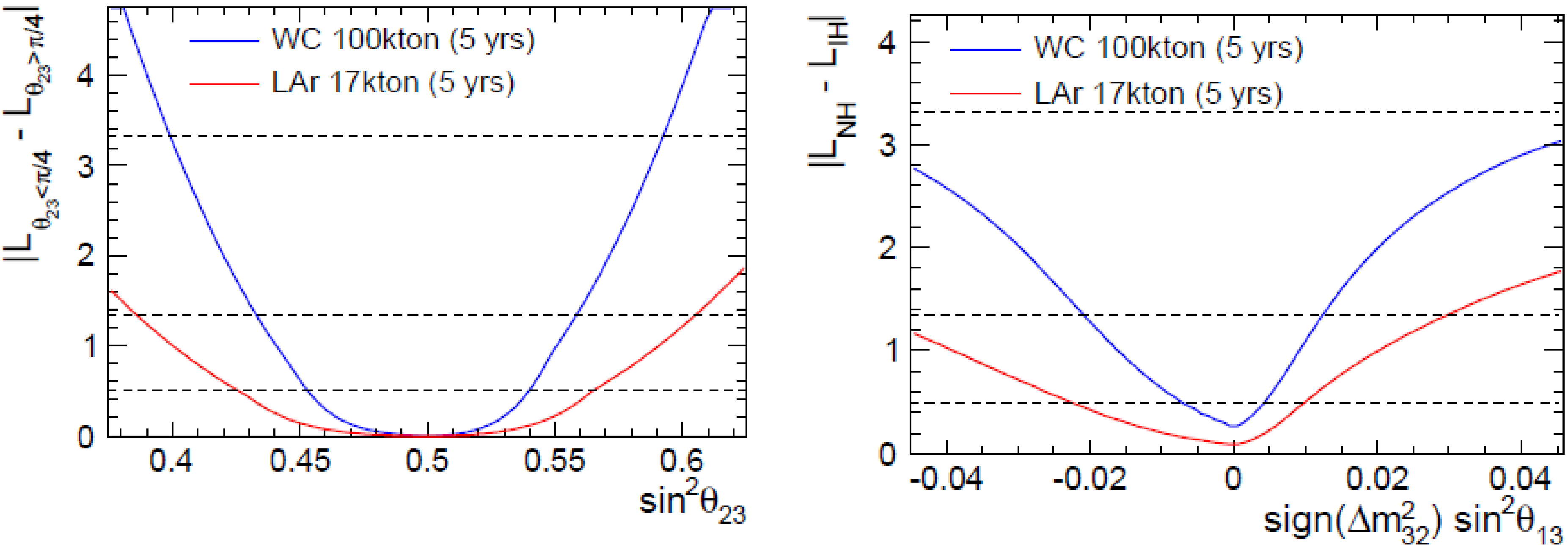


- 17kton LAr modules
  - 2 or 3
- 800 ft. level or 300 ft. level
- With or without a muon veto

See B.Fleming’s talk in Session 4

LBNE : Physics Sensitivity with Atmospheric

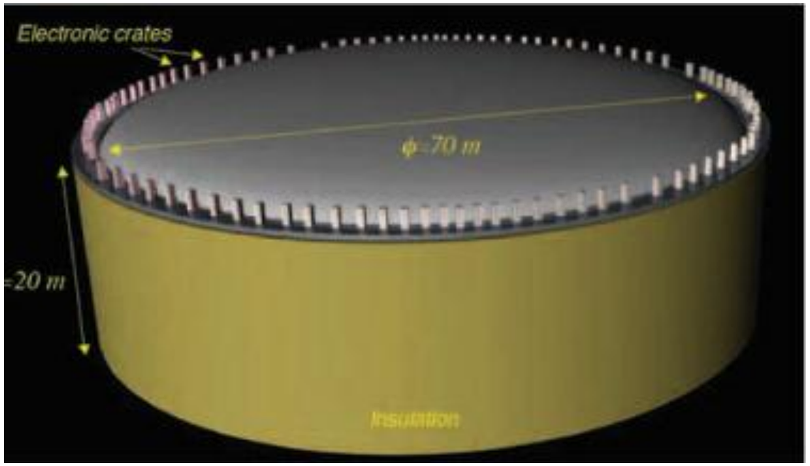
Akiri
arXiv:1110.6249

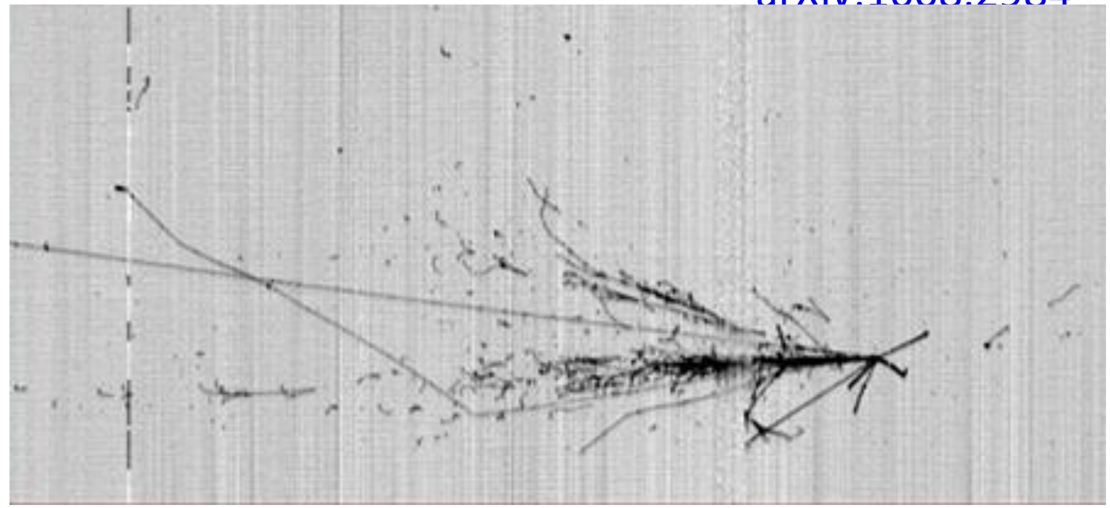


- With minimal configuration
  - Sensitivity to hierarchy for modest values of θ_{13}
  - And to θ_{23} octant
- Expect better performance with more FV
- LAr analysis can likely be improved using and L/E technique

Other Giant LAr Tricks : LBNE, GLACIER, Okinoshima

arXiv:1008.2984

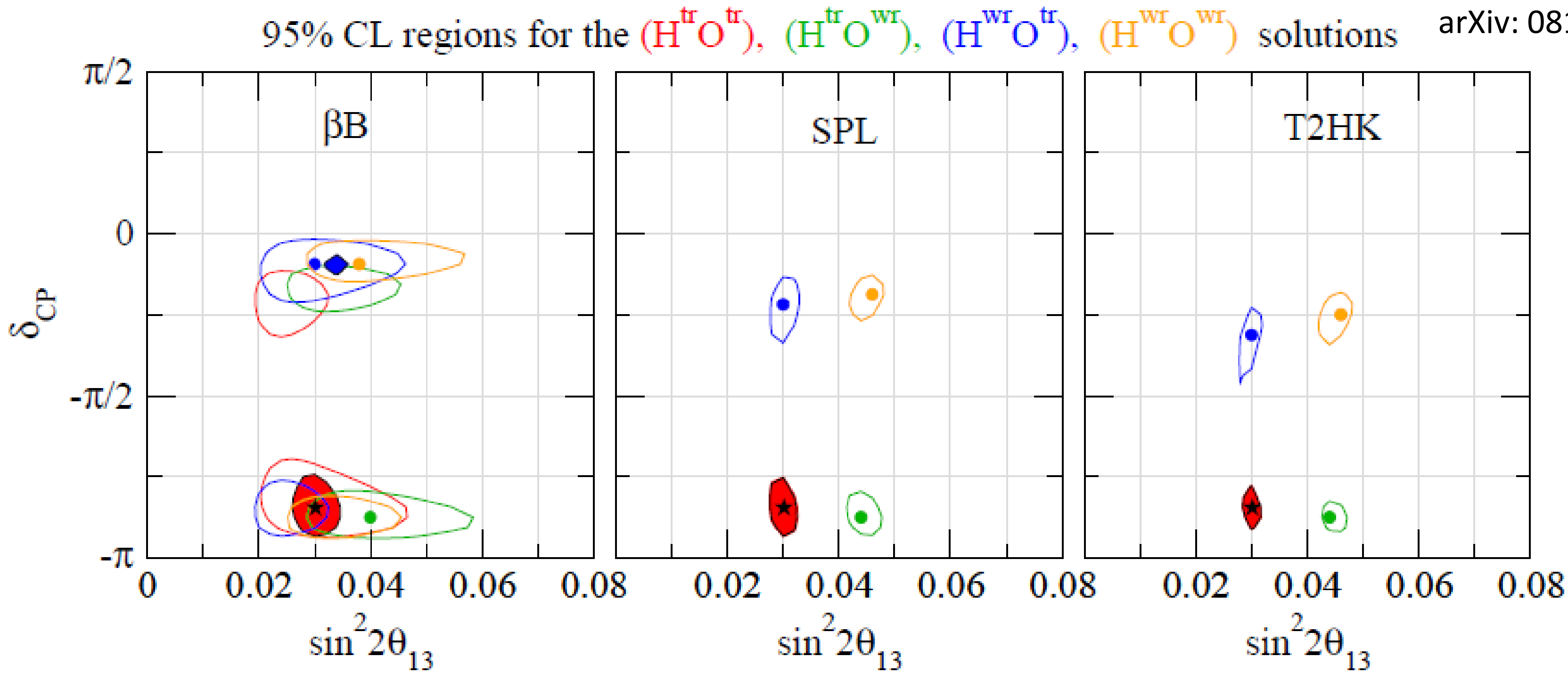




- Statistical identification of τ via hadronic decay modes
  - Gains from charged and neutral pion identification (~100% efficient)
  - No Cherenkov threshold effects
- 100 kton • yr exposure
  - 77 τ , 46 w/ $\pi \rightarrow$ > 4 σ significance
- Observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations
- Measurement of ν_τ cross section

Complementarity of Beam and Atmospheric ν

Schwetz
arXiv: 0812.2392



- Most of the planned detectors have a beam component
- Inputs from accelerator experiments can pin down the values of the atmospheric mixing parameters and θ_{13}
- Combined with atmospheric neutrino data the wrong (degenerate) solutions to beam data can be eliminated

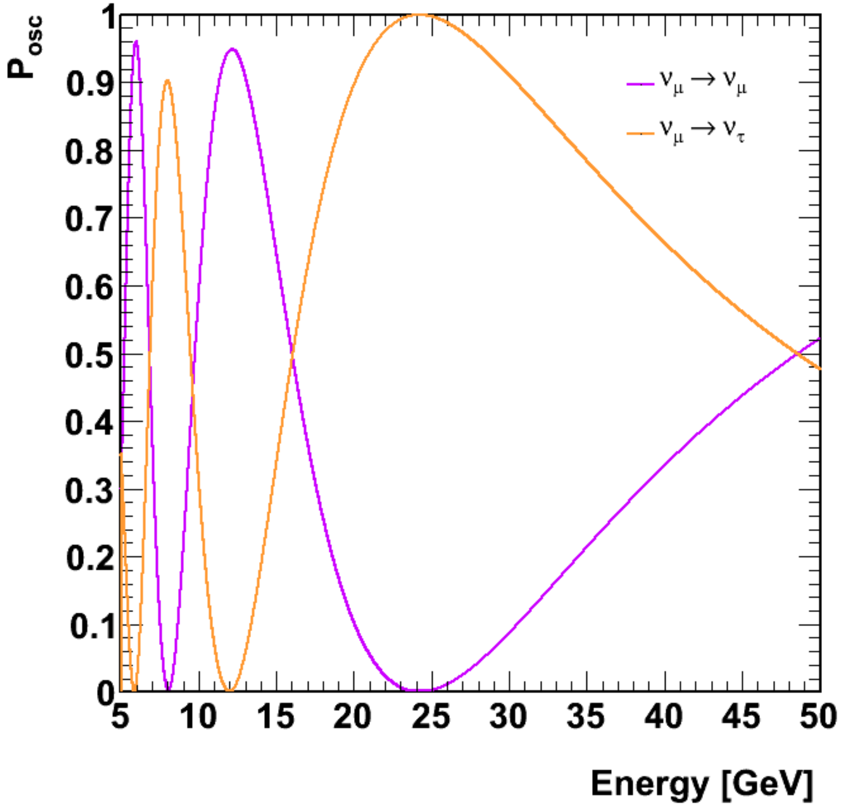
Summary

- Atmospheric Neutrinos still have a lot to offer
  - Understanding their flux as a background to exotic particle searches important for future measurements
  - By themselves can provide constraints on neutrino oscillation parameters
  - Coupled with long-baseline measurements can help resolve parameter degeneracies

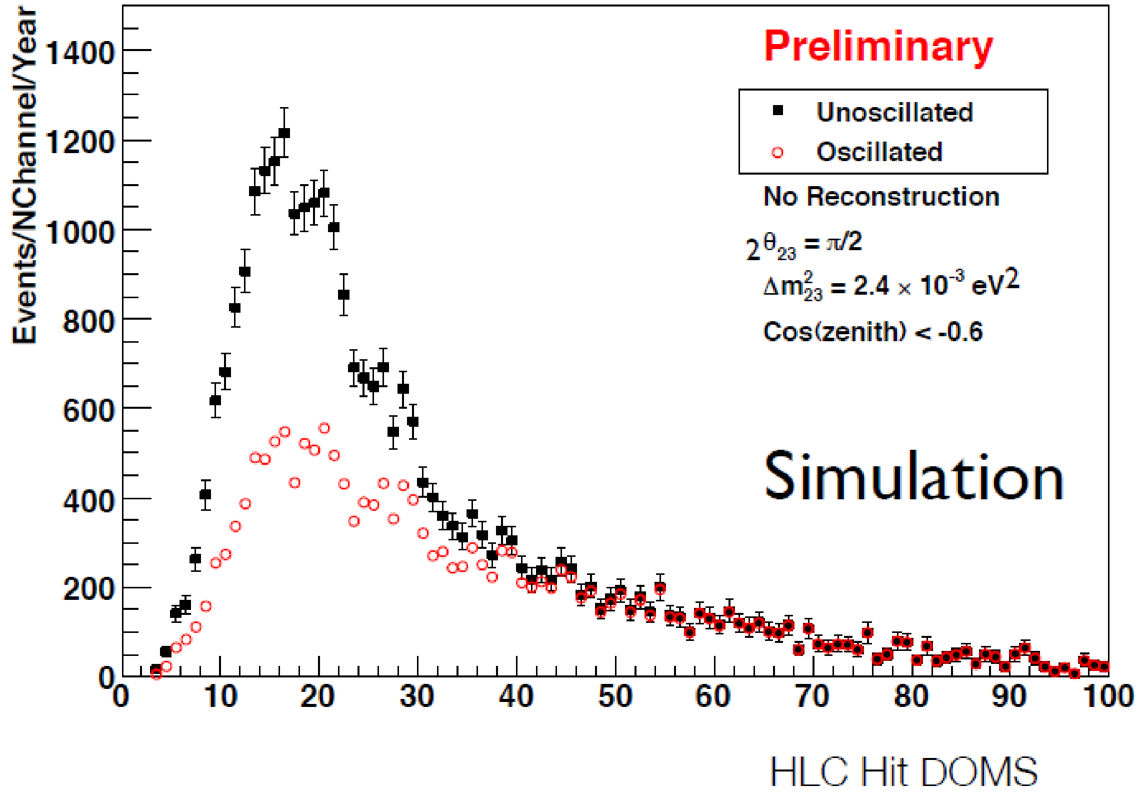
- Please continue to enjoy atmospheric neutrinos

Back Pocket

PINGU-I (and Beyond)

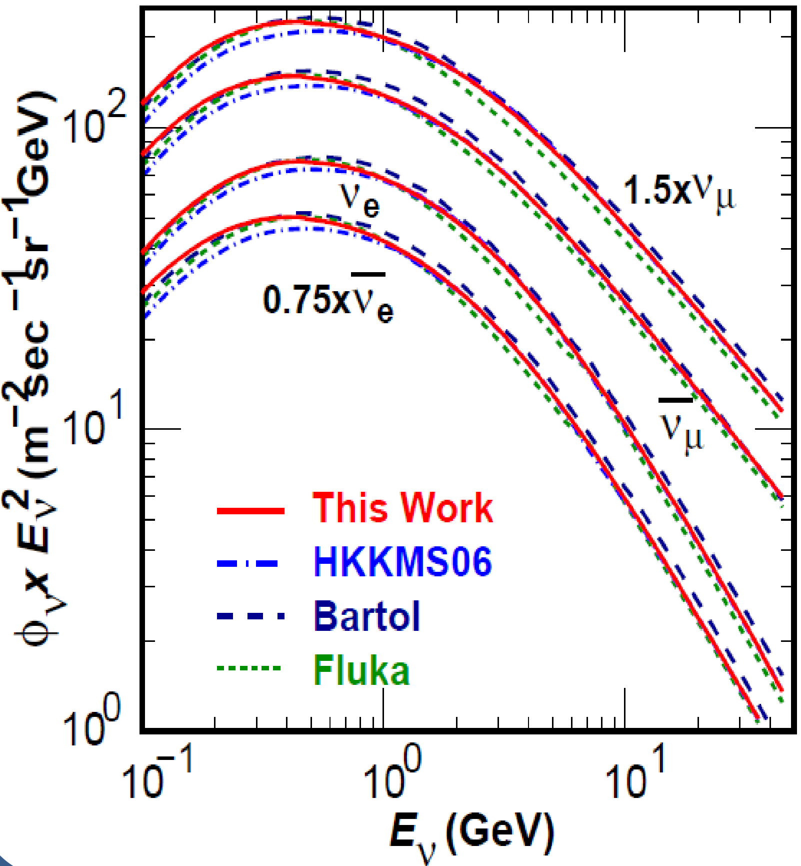


arXiv:XXXX

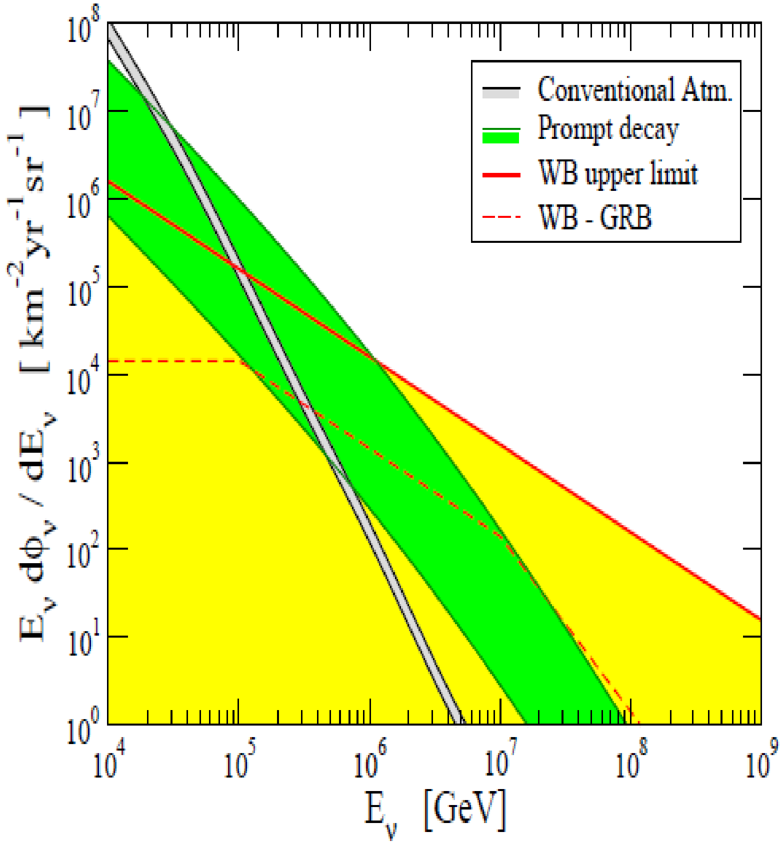


- Lower energy threshold improves sensitivity to oscillations
  - Reduced ν_e flux at relevant energies
- With high statistics better access to second oscillation maximum
  - Better handle of hierarchy and θ_{13}
  - Nail down Δm^2

Atmospheric Neutrino Fluxes



- "Conventional" flux used to discover neutrino oscillations
  - Wide variation in L/E
- Absolute flux known to ~20%
- Shape known to ~5-10%

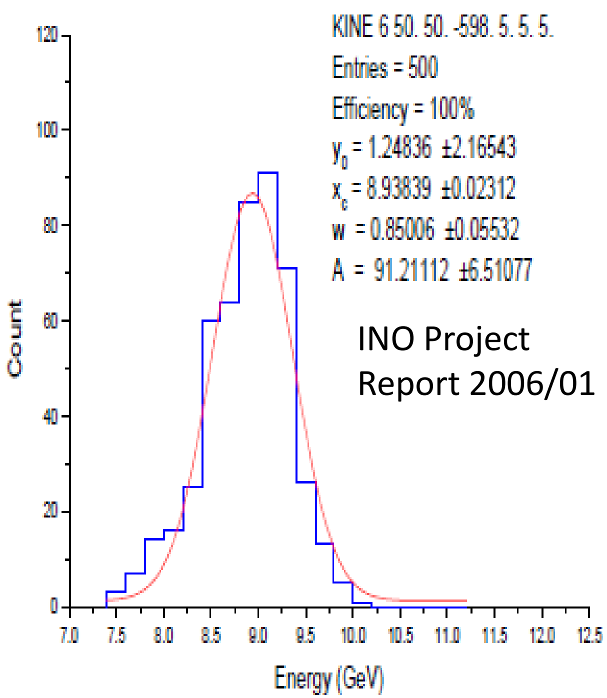


- "Prompt" Flux from the production and decay of charmed mesons:
- Currently unmeasured

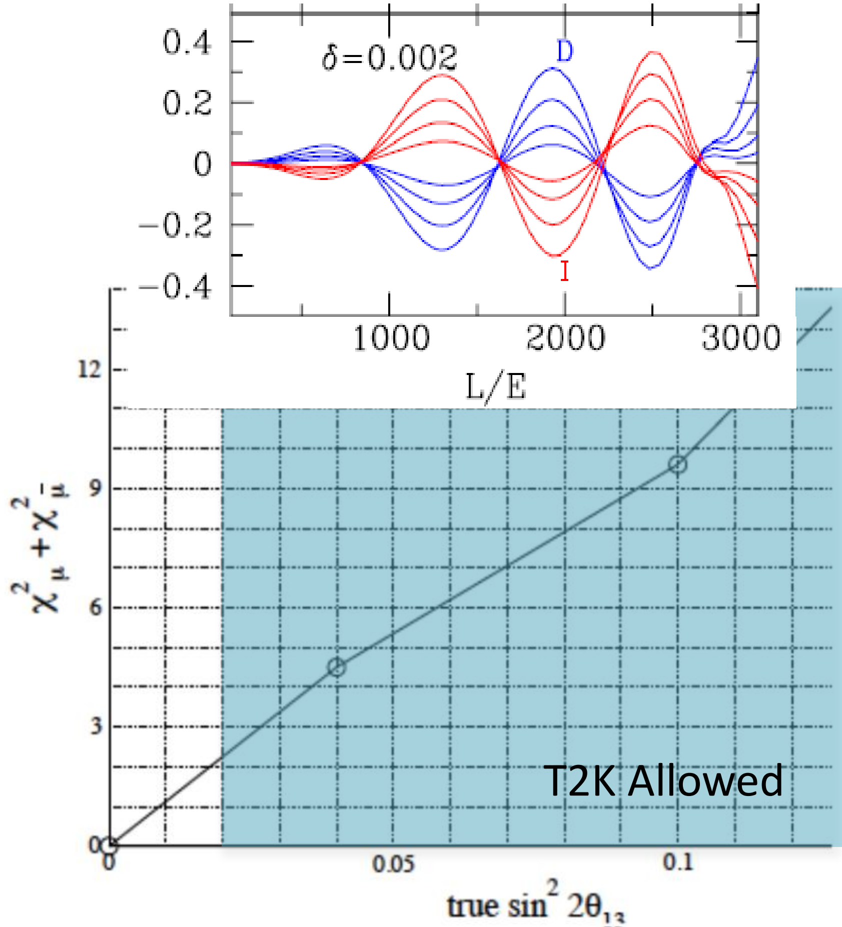
ICAL : Sensitivity to Hierarchy Through μ± asymmetry

INO Project Report 2006/01

- Efficient μ^+/μ^- discrimination power
  - No sensitivity to $e^{+,-}$
- Good Resolution expected:
  - Angular ~10 degrees
  - Energy ~15% (E > 1 GeV)

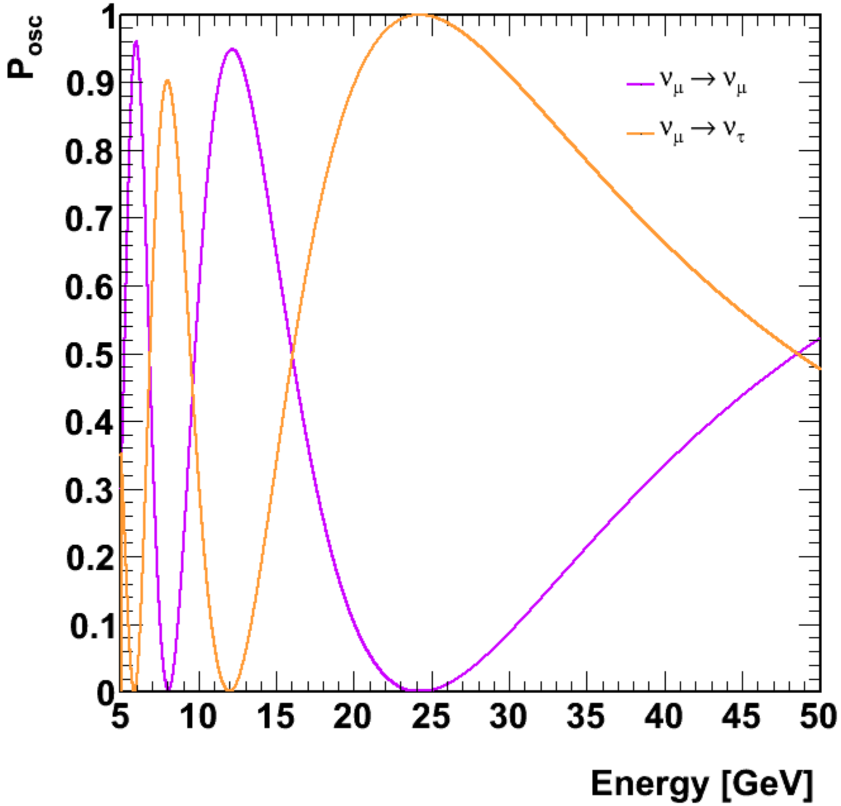


INO Project Report 2006/01

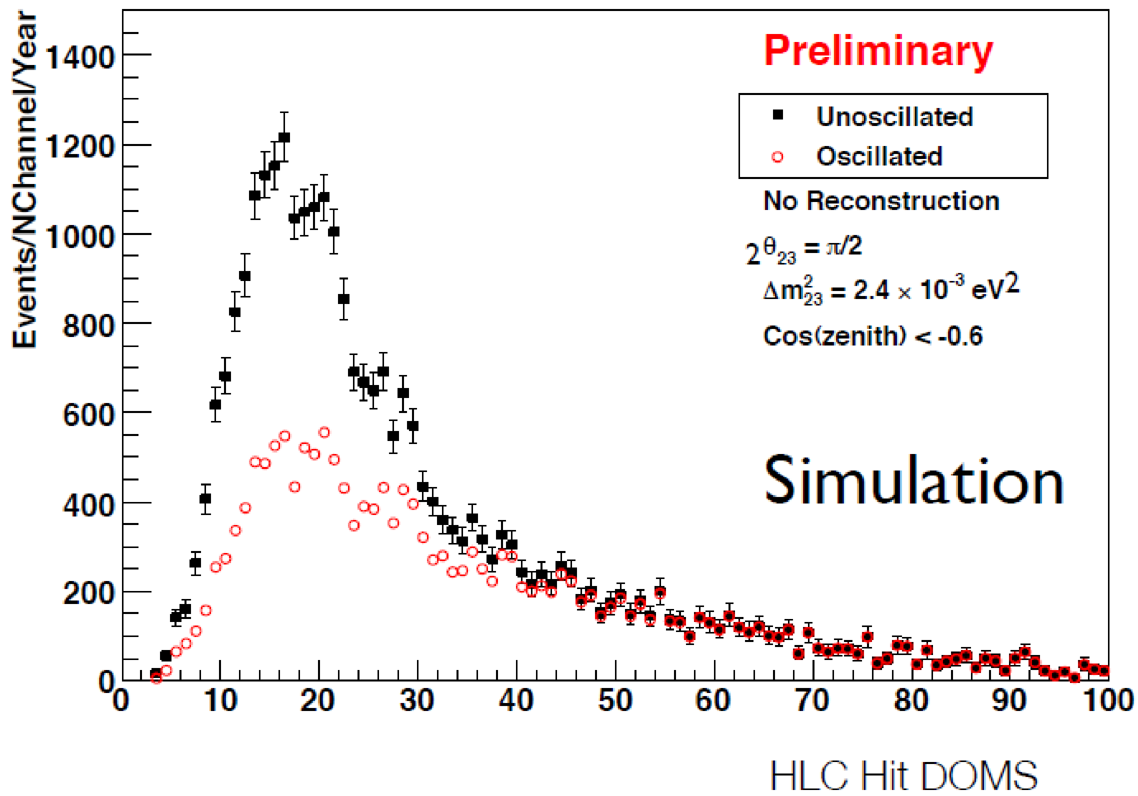


- Make use of asymmetric matter effects between ν and ν to discriminate hierarchy
- Sensitivity to hierarchy > 2 s if $\sin^2 2\theta_{13} > 0.05$
- 1 Mton . yr exposure

PINGU-I (and Beyond)



arXiv:XXXX



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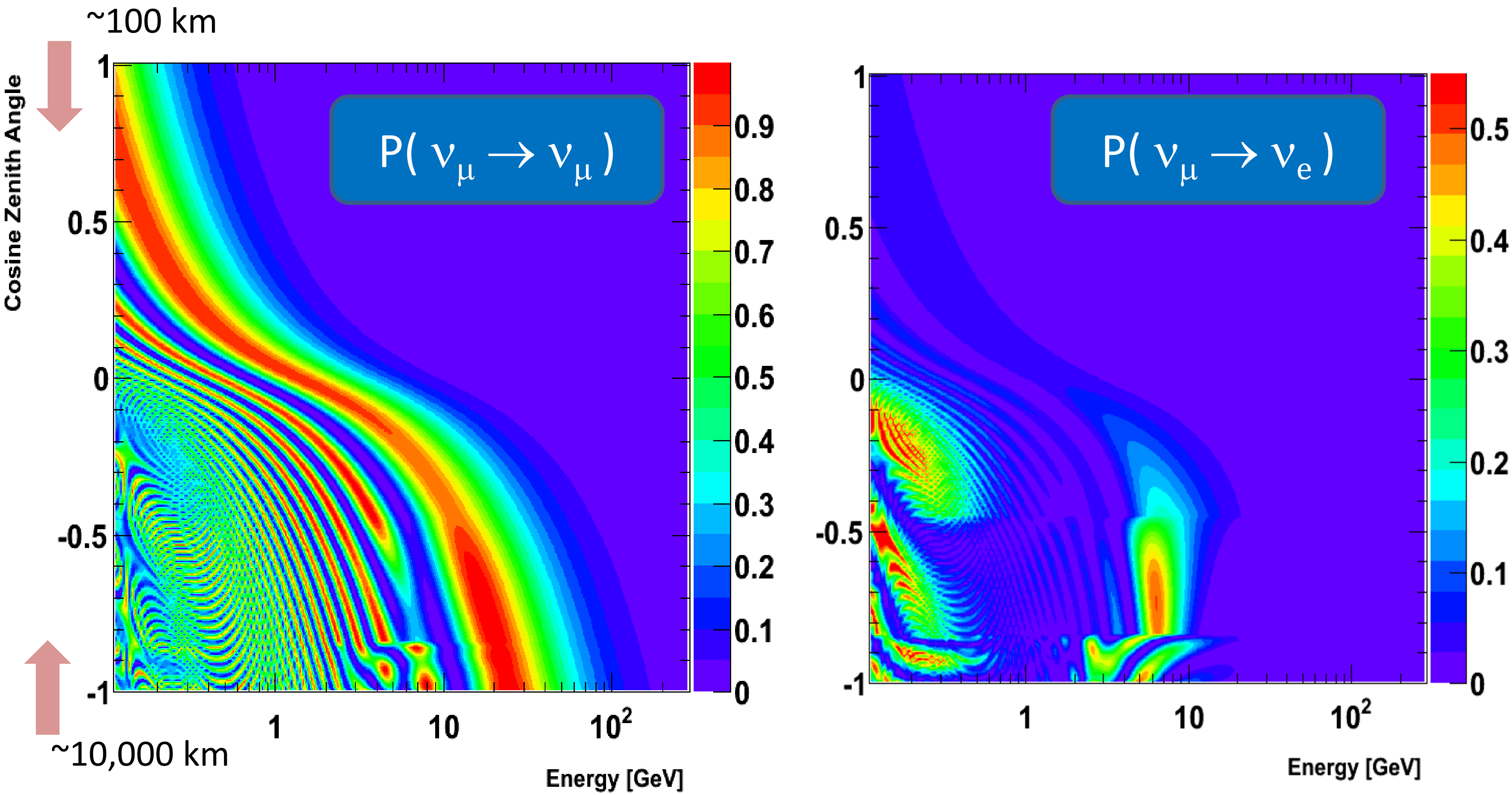
Atmospheric Neutrinos as Signal



ICAL

2004
- R&D
- Site Selection

2011
- Construction of INO
- Prototyping of ICAL

2017
- ICAL Physics Data

Later
- ICAL As far detector for a β beam etc.

IceCube

2010+
- IceCube
- 89 Strings
- 125m separation
- 17m DOM spacing
- ~100+ GeV ν

2014/5
- DeepCore
- 8 DC + 12 IC Strings
- 72m separation
- 17m HQE DOM spc.
- ~10+ GeV ν

- PINGU-I
- +~20 DC Strings
- Denser Design
- ~1+ GeV ν

2018/9
- PINGU-II
- New Photo Sensor
- Proton Decay , SN ν
- ~100+ MeV ν

Hyper Kamiokande

2011
- Letter of Intent

201X
- Funding and construction

~2019
- Physics Data starts

LBNE

- **2011**: Technology Decision
- **201X**: Funding + Construction
- **2020**: Physics data start

Resolutions

Hyper-Kamiokande

Resolution		$e^{+,-}$	$\mu^{+,-}$
Δp	500 MeV	5.6%	3.6%
	5 GeV	2.0%	1.6%
Δpid	500 MeV	98.5%	99.0%
	5 GeV	99.8%	100.0%
Δvtx	500 MeV	28 cm	23 cm
	5 GeV	27 cm	32 cm

ICAL-INO

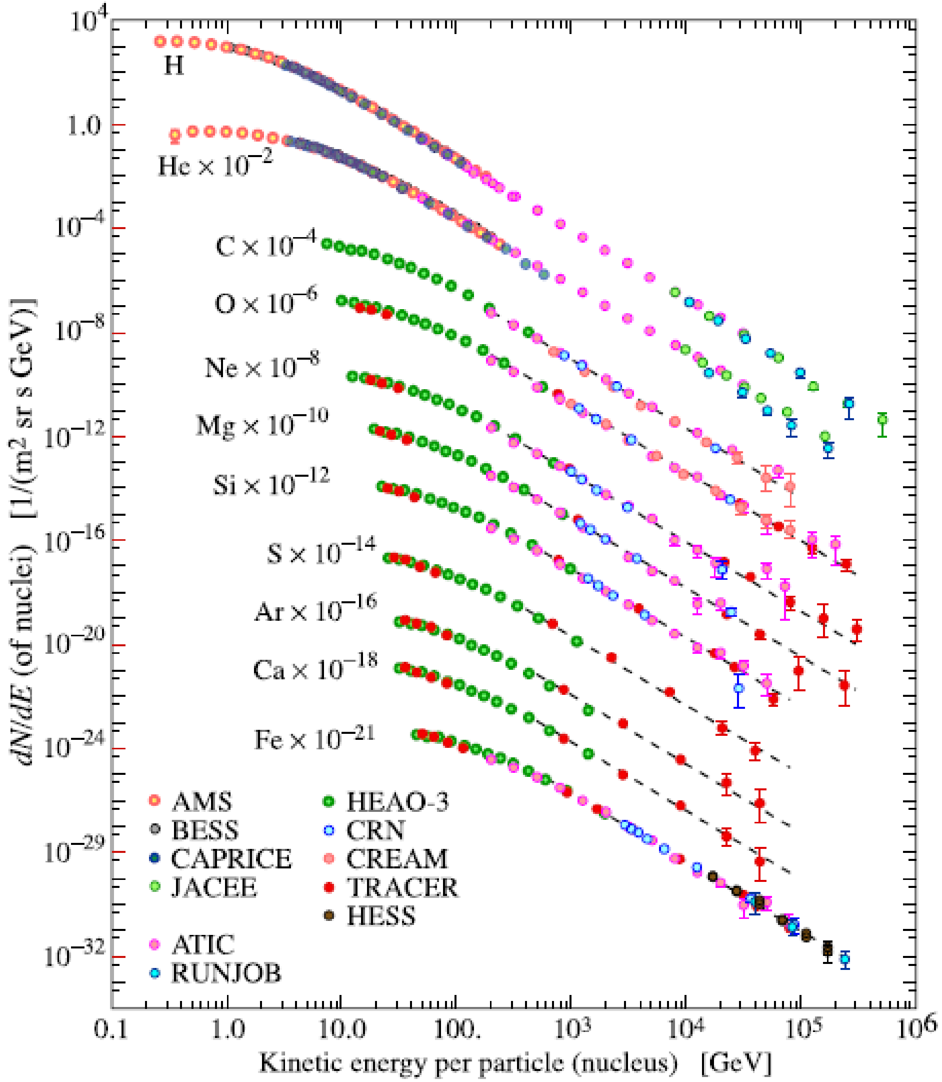
- Good Resolution expected:
  - Angular ~10 degrees
  - Energy ~15% (E > 1 GeV)

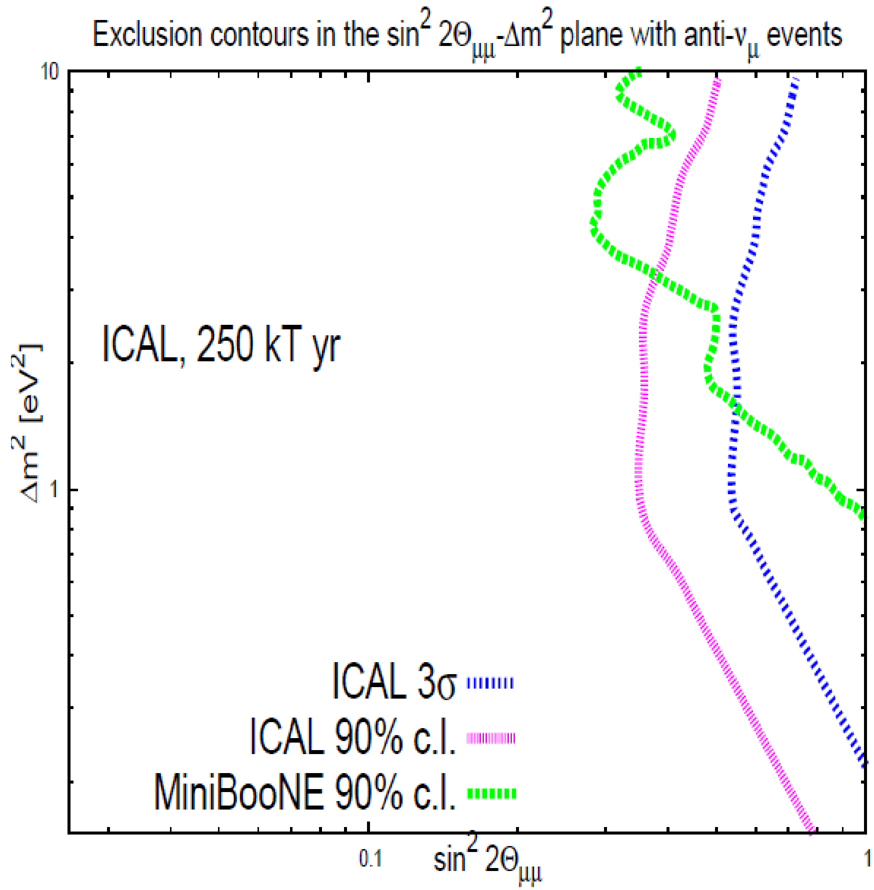
LBNE

Recon.		WC	lAr
FC	lept. E	2+2 / √E %	2+2 / √E %
	lept. Dir	2°	2°
PC	lept. E	50 %	50%
	lept. Dir	2°	2°
Hadron	E	30+30 / √E %	30 / √E %
	Dir	45° + 15° /√E	10°

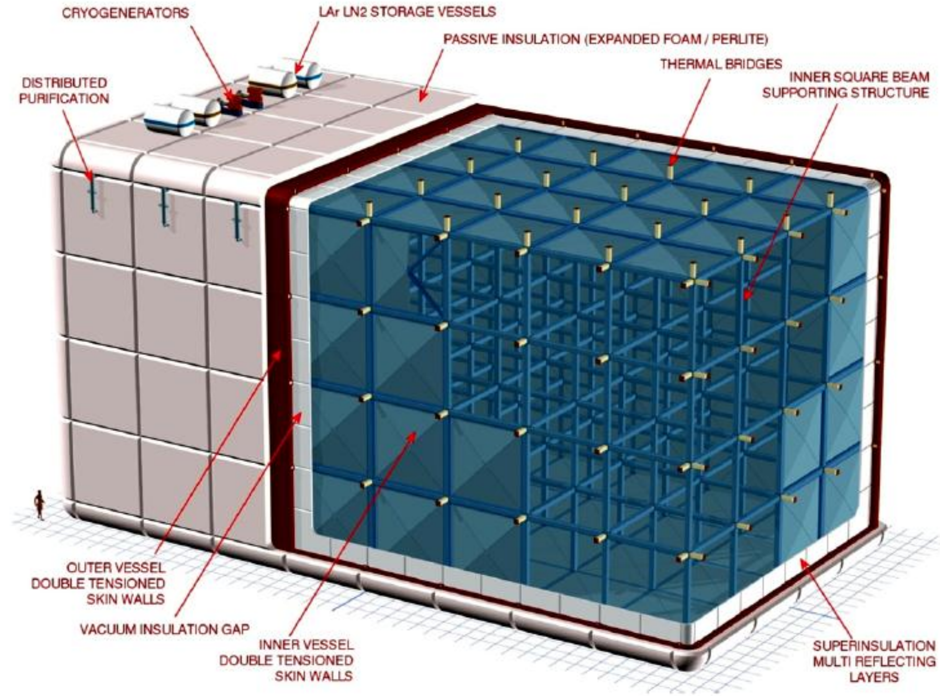
Recon.	lAr
Energy	15%
Zenith Angle	10°
Particle ID	**100%**

Primary Cosmic Ray Flux + ICAL





The Ideal Detector



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top

13:30->*18:20* **Session 1**

13:30	Aspects of Neutrino Theory (20')	Joachim Kopp (*FNAL*)
13:50	Overview on Neutrino Mass Models and their Predictions (20')	Mu-Chun Chen (*Univ. California, Irvine*)
14:10	The Connection between Neutrino CP Violation and Leptogenesis (20')	Boris Kayser (*FNAL*)
14:30	Discussion	
14:40	Directions for Neutrino Physics in Europe (20')	Alain Blondel
15:00	Directions for Neutrino Physics in Asia (20')	Masato Shiozawa (*Univ. Tokyo*)
15:20	Discussion	
15:30	Coffee Break	
16:00	Intensity Frontier Physics Research at the Sanford Underground Research Facility (Homestake) (20')	Kevin Lesko (*Univ. California, Berkeley*)
16:20	Future Long-Baseline Neutrino Physics in the U.S. (20')	Regina Rameika (*FNAL*)
16:40	Discussion	
16:50	Future Atmospheric Neutrino Experiments (20')	Roger Wendell
17:10	Neutrino Physics in India (20')	Brajesh Choudhary (*Delhi Univ., India*)
17:30	Future Solar Neutrino Experiments (20')	Josh Klein
17:50	The SNOLAB Physics Program (20')	Nigel Smith
18:10	Discussion	
18:20	Adjourn	

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