Accelerator ν Experiments
Baselines
Detectors
Reactor ν Experiments
Atmospheric ν Experiments
Summary

Neutrino Oscillations Internationally

DURA Meeting, SLAC, 03/05/2013

Mary Bishai
Brookhaven National Laboratory

March 5, 2013

Outline

1 Accelerator ν Experiments
- Baselines
- Detectors

2 Reactor ν Experiments

3 Atmospheric ν Experiments

4 Summary

ACCELERATOR ν Experiments

Searching for CP Violation in Neutrino Oscillations

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Matter/anti-matter asymmetries in neutrinos are best probed using $\nu_\mu/\bar{\nu}_\mu \rightarrow \nu_e/\bar{\nu}_e$ oscillations (or vice versa):.

The charge-parity (CP) asymmetry is defined as

$$\mathcal{A}_{cp} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

$$\mathcal{A}_{cp} \sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{matter effects}$$

from Z. Parsa, BNL

The CP phase δ_{cp} is unknown. CP is violated when $\delta_{cp} \neq 0, \pi$

The 3 most important things to know about ν CPV

- $\mathcal{A}_{cp} \propto 1/\sin\theta_{13} \Rightarrow$ **Large θ_{13} makes CPV searches HARDER.**
- $\mathcal{A}_{cp} \propto 1/E_\nu \Rightarrow$ **CP asymmetries are larger at lower energies**
- $\mathcal{A}_{cp} \propto L \Rightarrow$ **CP asymmetries are larger at longer baselines**

Neutrino Interaction Cross-sections

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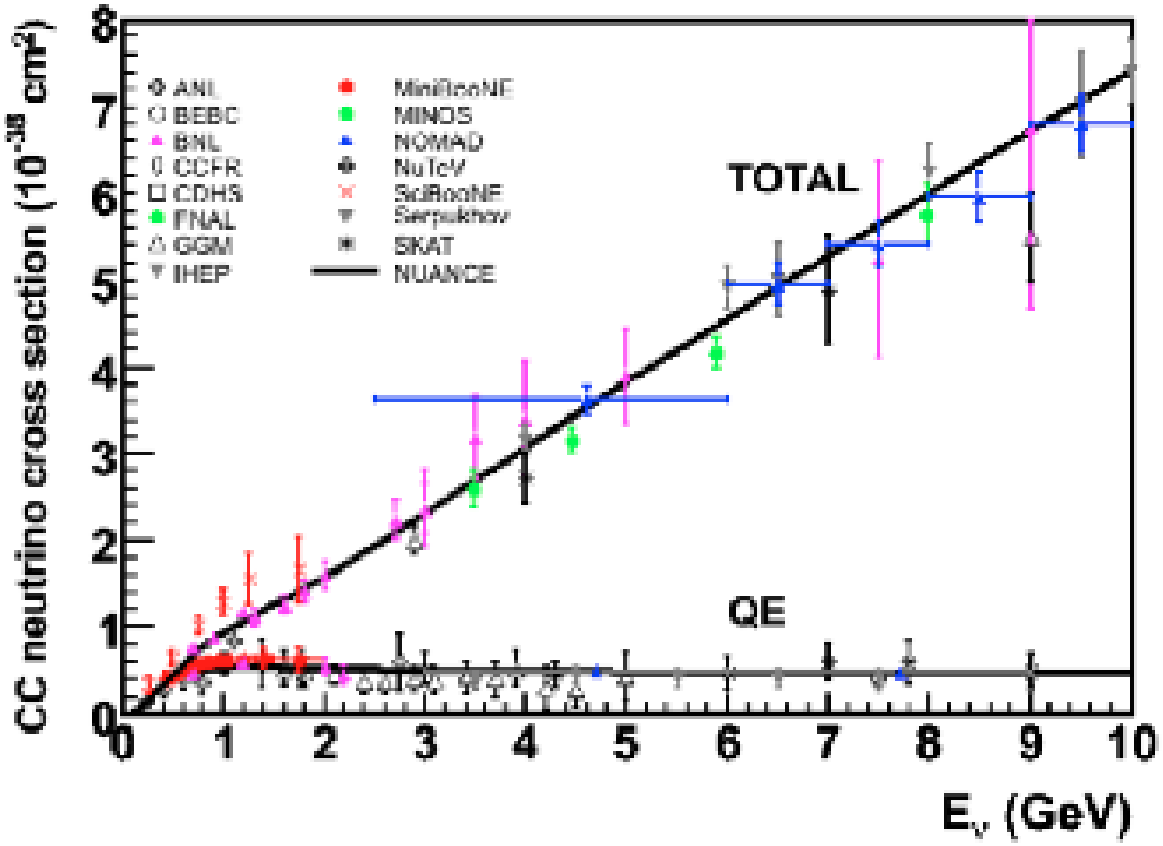
Neutrino CC cross-sections are very small and scale with energy:



Long baseline oscillations over 100's km and $\geq$ 200 MeV energies needed to probe CPV

Matter Effect on Neutrino Oscillation

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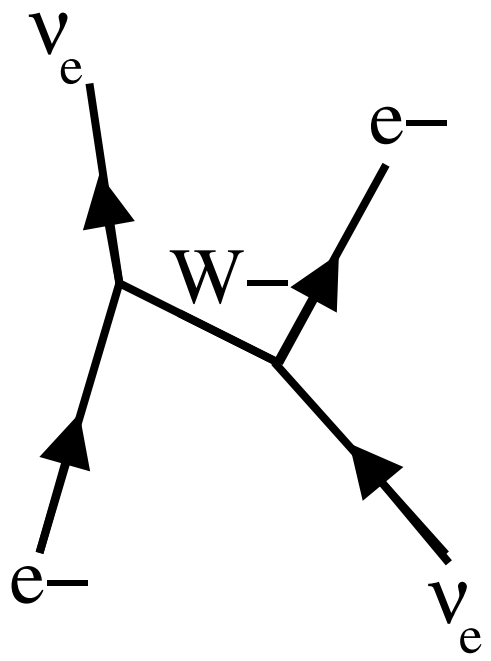
1978 and 1986: L. Wolfenstein, S. Mikheyev and A. Smirnov propose the scattering of ν_e on electrons in matter adds a coherent forward scattering amplitude to neutrino oscillation amplitudes. This acts as a refractive index $\Rightarrow$ neutrinos in matter have different effective mass than in vacuum.



The matter effect on ν_e scattering can be used to detect the unknown neutrino mass ordering using $\nu_x \rightarrow \nu_e$ oscillations through matter

Matter Effect on $\mathbf{P}(\nu_\mu \rightarrow \nu_\mathrm{e})$

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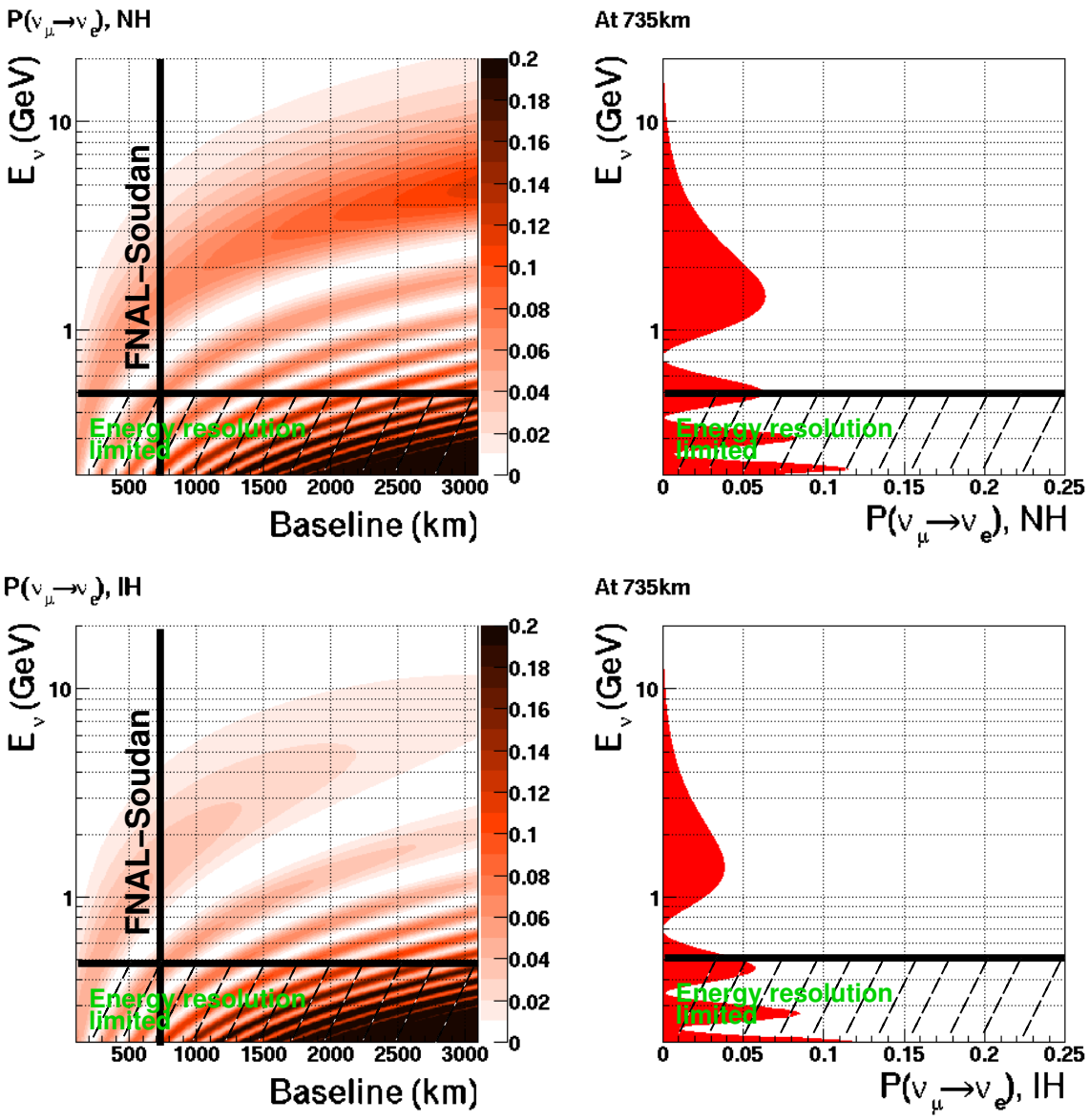

Matter Effect on $\mathbf{P}(\nu_\mu \rightarrow \nu_e)$

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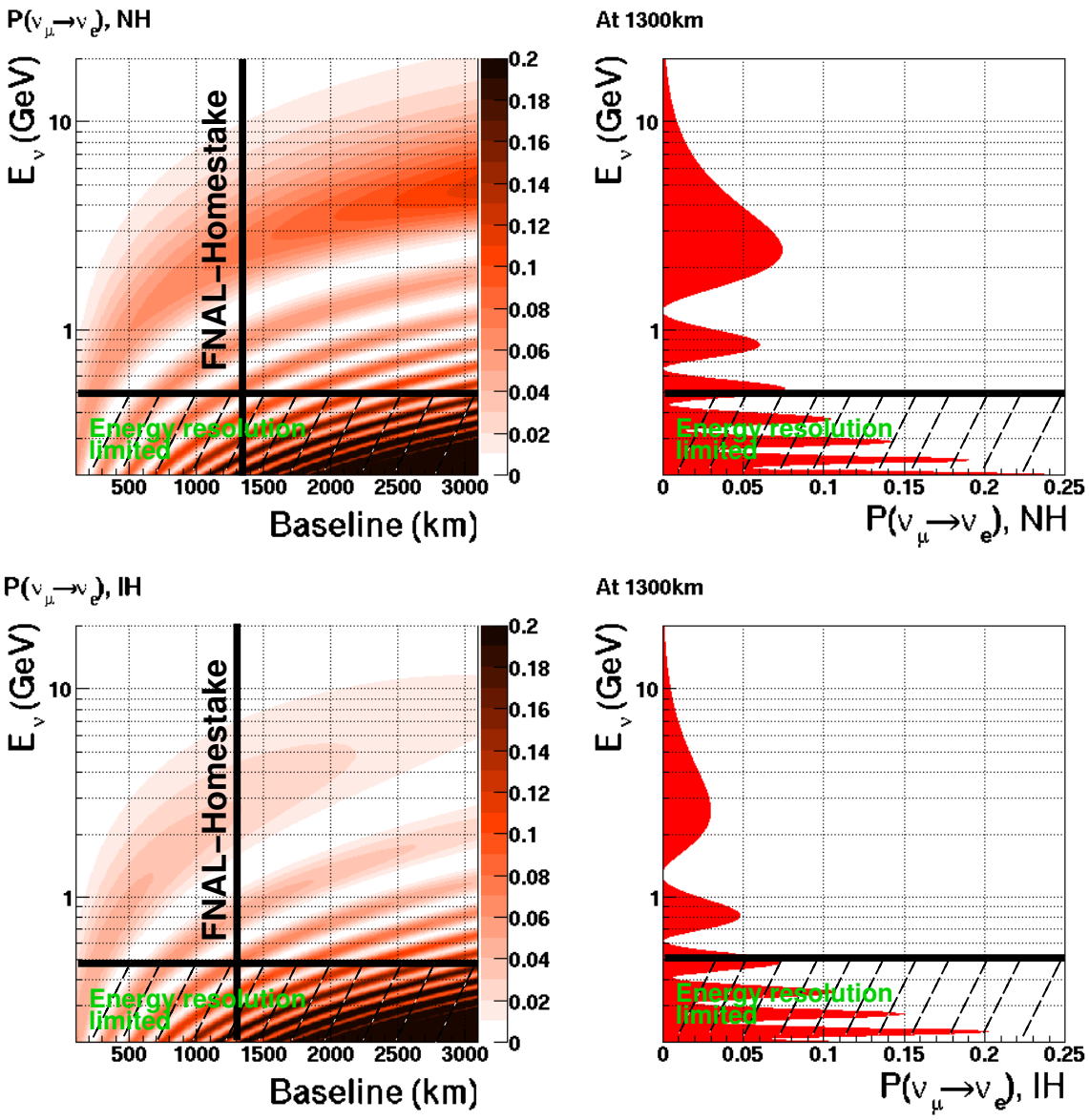

Matter Effect on $P(\nu_\mu \rightarrow \nu_e)$

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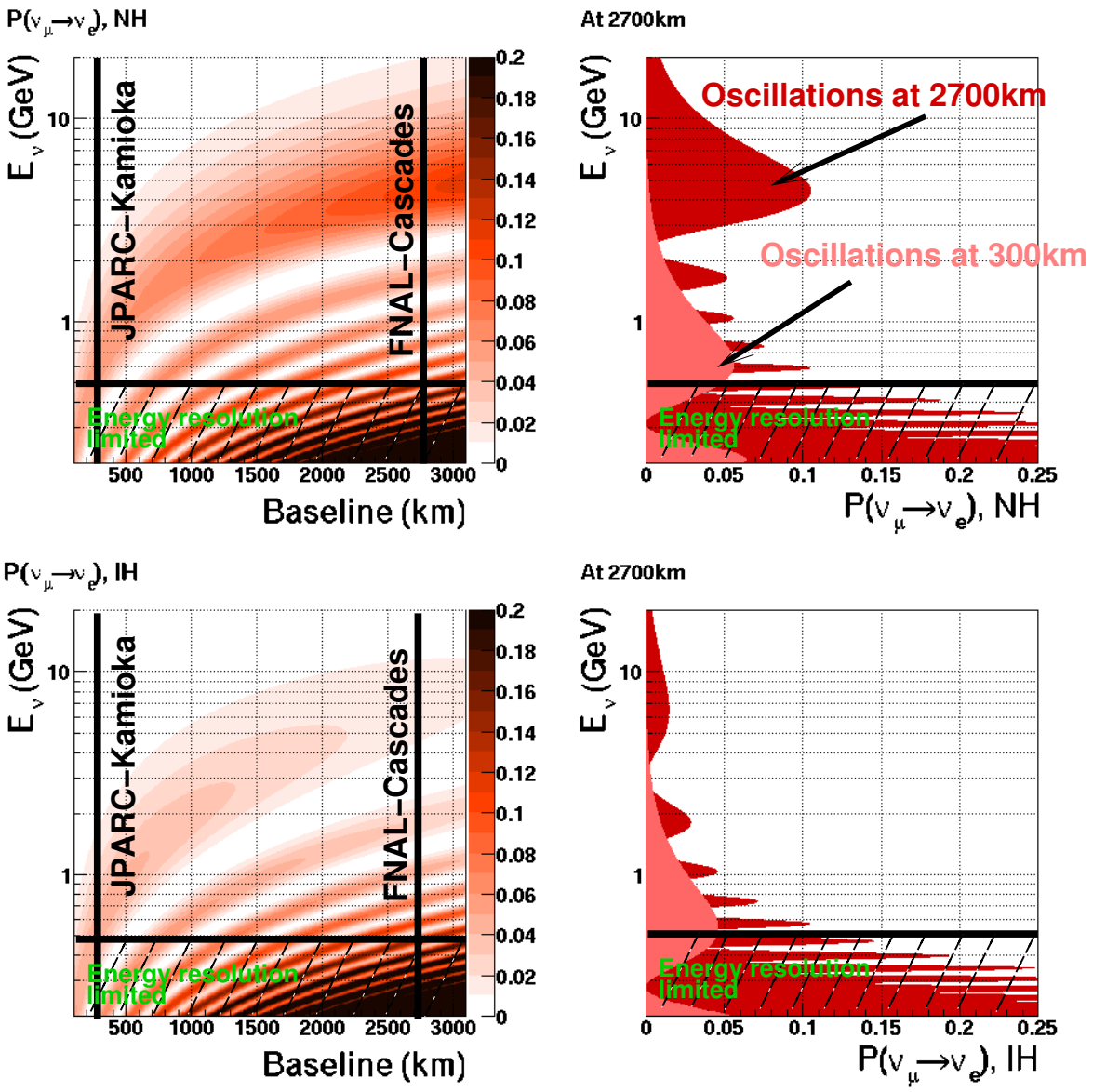

CP and Matter Asymmetries vs. Baselines for fixed L/E

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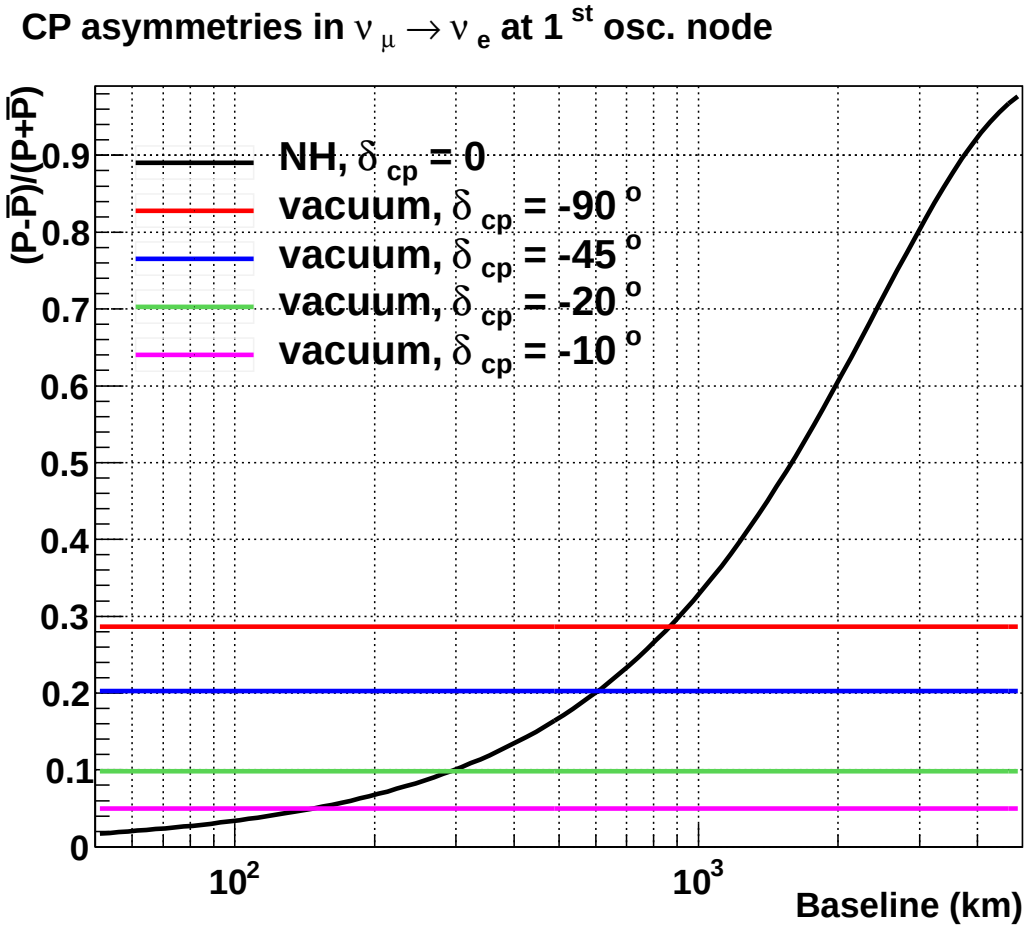

Impact of the mass hierarchy on asymmetry is very large in long baseline experiments

CP Asymmetries and the Mass Hierarchy

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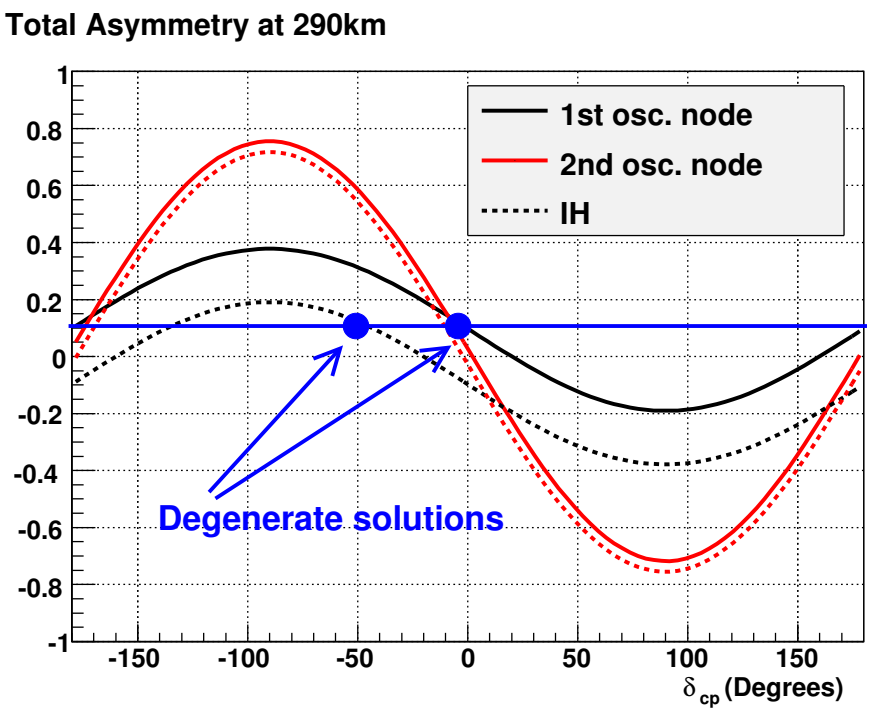
$\nu_\mu \longrightarrow \nu_e$ **oscillation maxima occur at**

$$E_\nu^n(\mathrm{GeV}) = \frac{2.5\Delta m_{32}^2(\mathrm{eV}^2)L(\mathrm{km})}{(2n-1)\pi} \quad n = 1, 2, 3...$$

L = 290km



At short baselines, irreducible degeneracies with MH,δ_{cp}

CP Asymmetries and the Mass Hierarchy

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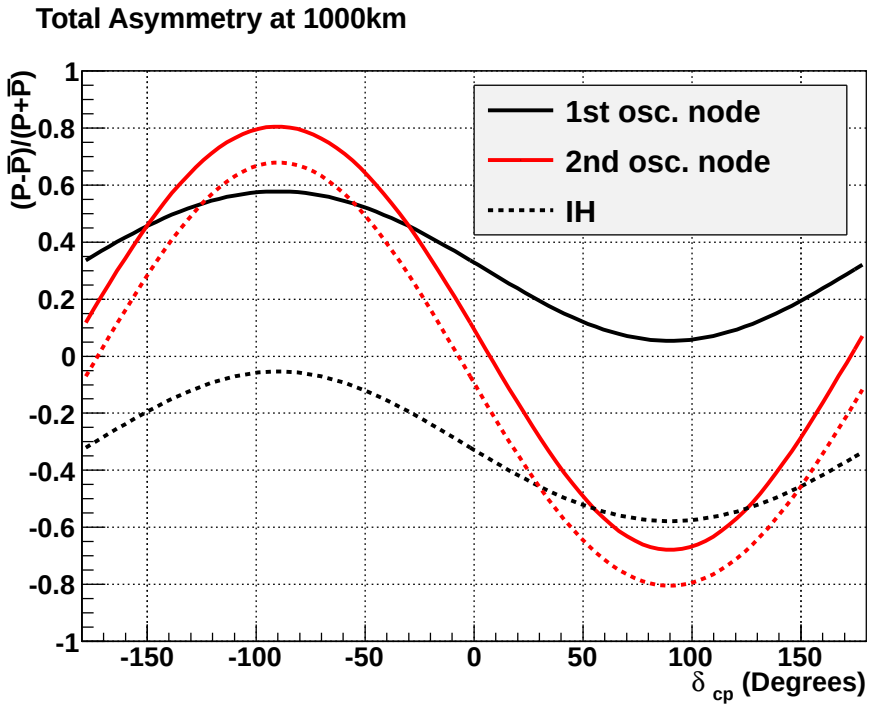
$\nu_\mu \longrightarrow \nu_e$ **oscillation maxima occur at**

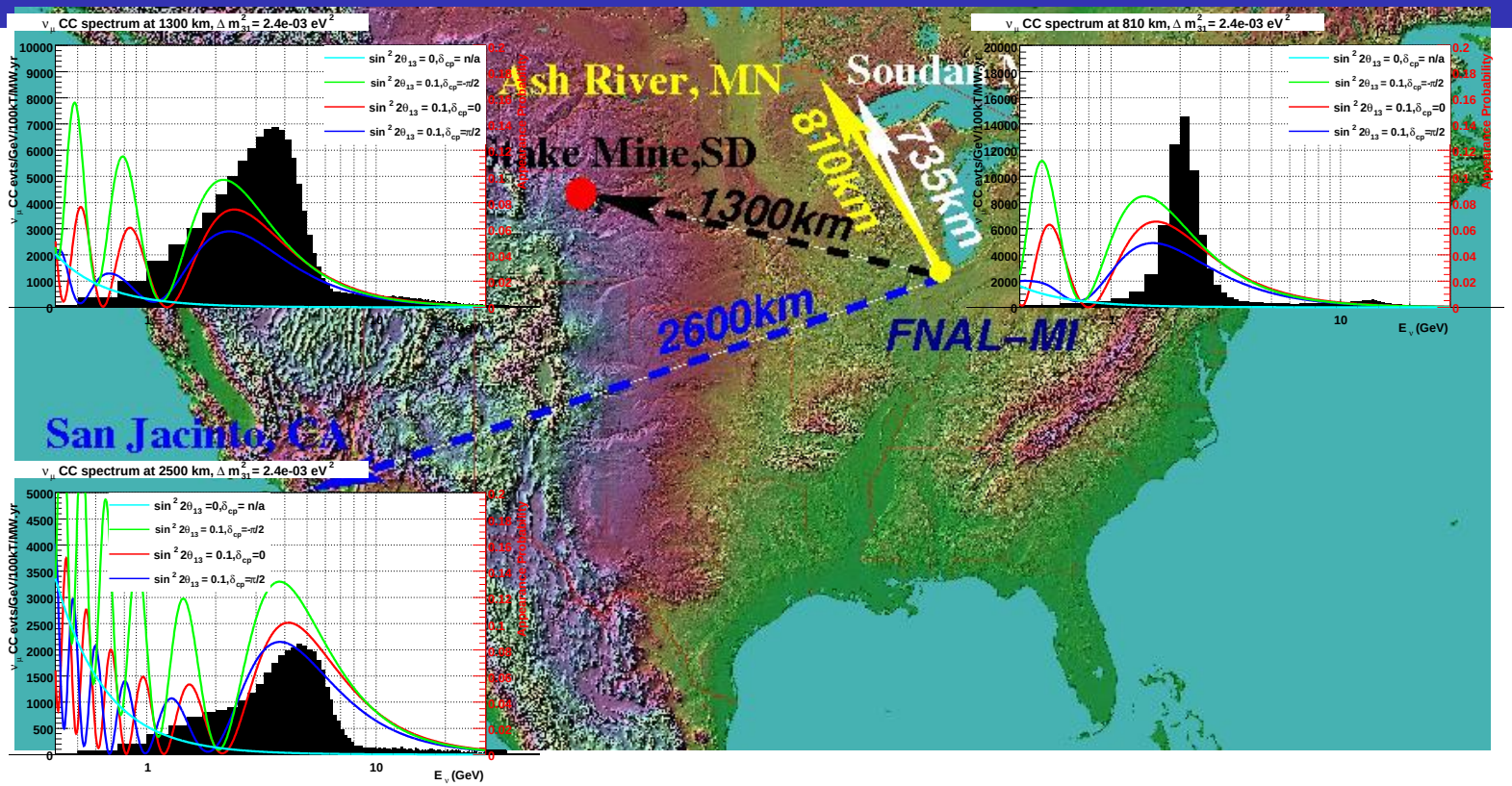
$$E_\nu^n(\mathrm{GeV}) = \frac{2.5\Delta m_{32}^2(\mathrm{eV}^2)L(\mathrm{km})}{(2n-1)\pi} \quad n = 1, 2, 3...$$

L = 1000km



A baseline > 1000km is needed separate MH from δ_{cp}

Superbeam Baselines in the U.S.



CC event rates per 100kt.MW.yrs (1 MW.yr= 1×10^{21} p.o.t) for $\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$, NH:

Expt	ν_μ CC	ν_μ CC osc	ν_μ NC	ν_e beam	$\nu_\mu \to \nu_e$	$\nu_\mu \to \nu_\tau$
Ash River 810km	18K	7.3K	3.6K	330	710	TBD
Hmstk 1300km	29K	11K	5.0K	280	1100	TBD
CA 2500km	11K	2.9K	1.6K	85	760	TBD

Need MW beams and 100 kton detectors regardless of baseline!

Superbeam/Neutrino Factory/Beta Beam Baselines in Europe

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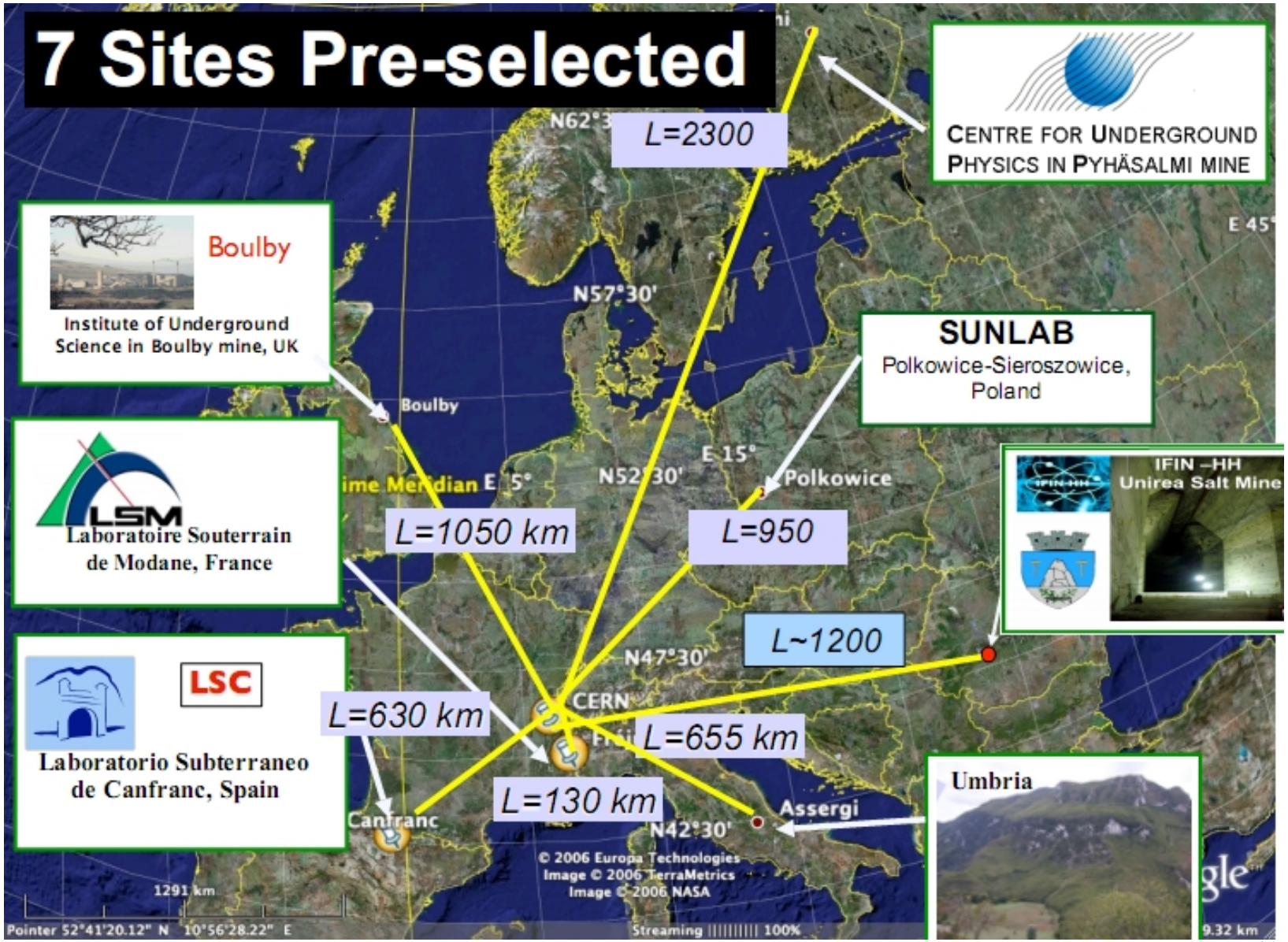

European Strategy in Neutrino Physics Draft Report 2013

2013 Proposed Update of the European Strategy for Particle Physics (Draft): CERN should develop a neutrino programme to pave the way for a substantial European role in future long baseline experiments. Europe should explore the possibility of major participation in leading neutrino projects in the US and Japan"
`https://indico.cern.ch/getFile.py/access?resId=0&materialId=0&confId=217656`

Neutrino Oscillation Baselines in Japan

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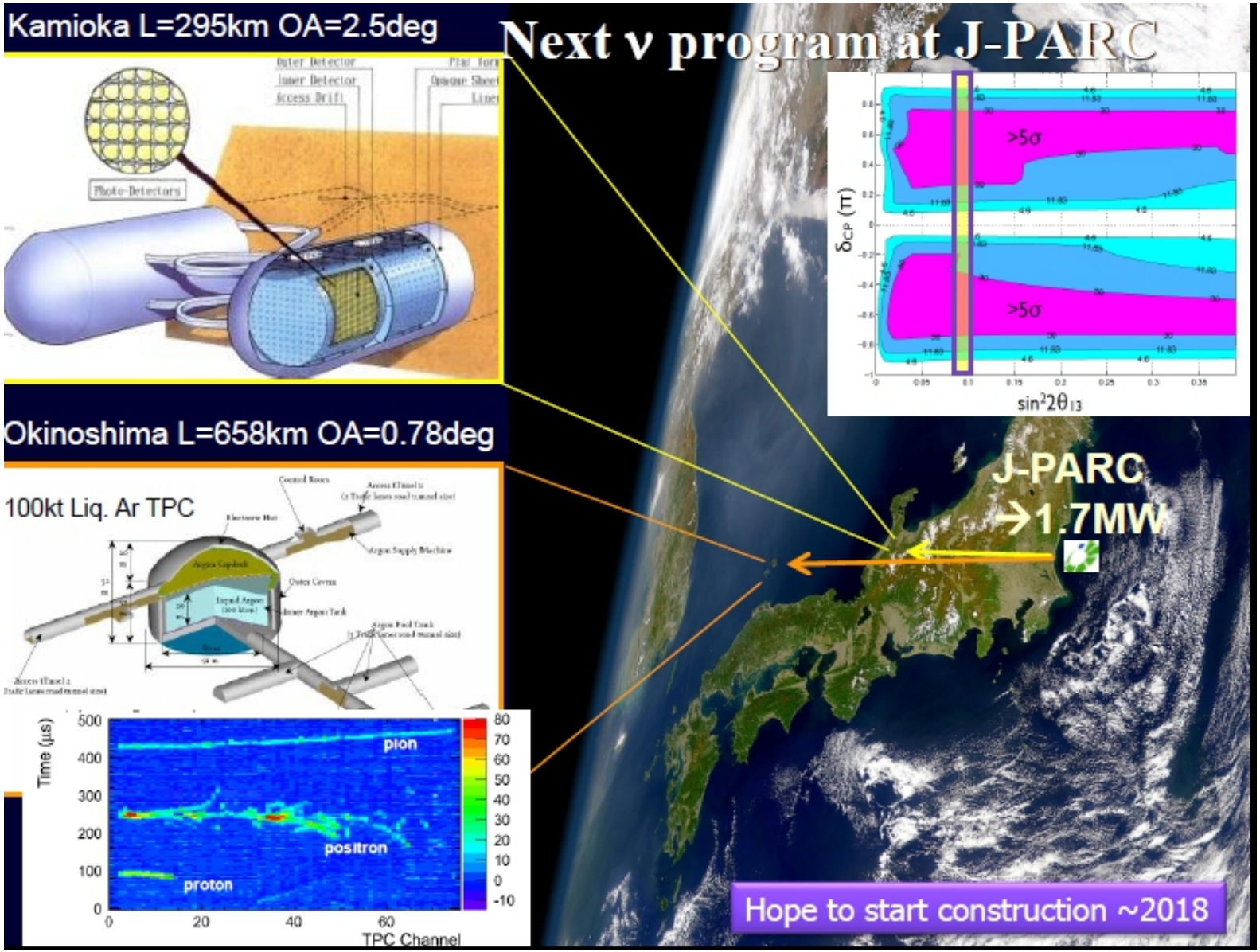

Massive Neutrino Detectors: The LBNE LAr-TPC (USA)

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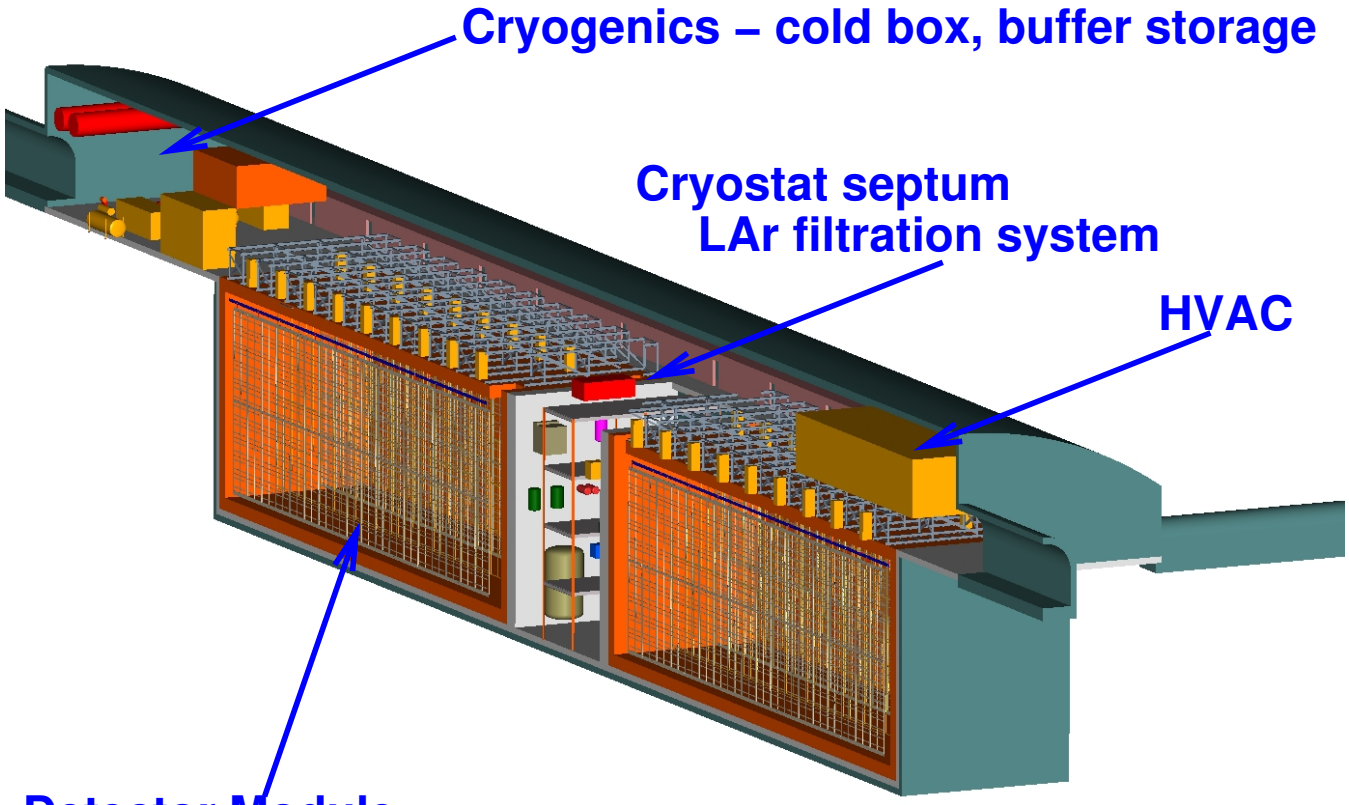
U.S. technology decision 2012: massive LAr-TPC

A 35 kton fiducial Liquid Argon Time-Projection-Chamber:



Detector Module
2 high x 3 wide x 18 long drift cells x 2 modules
216 APAs, 224 CPAs

35 kton (underground) : $\sim$ 660$M FY10$ (incl. 40% contingency)

Massive Neutrino Detectors: Hyper-Kamiokande (Japan)

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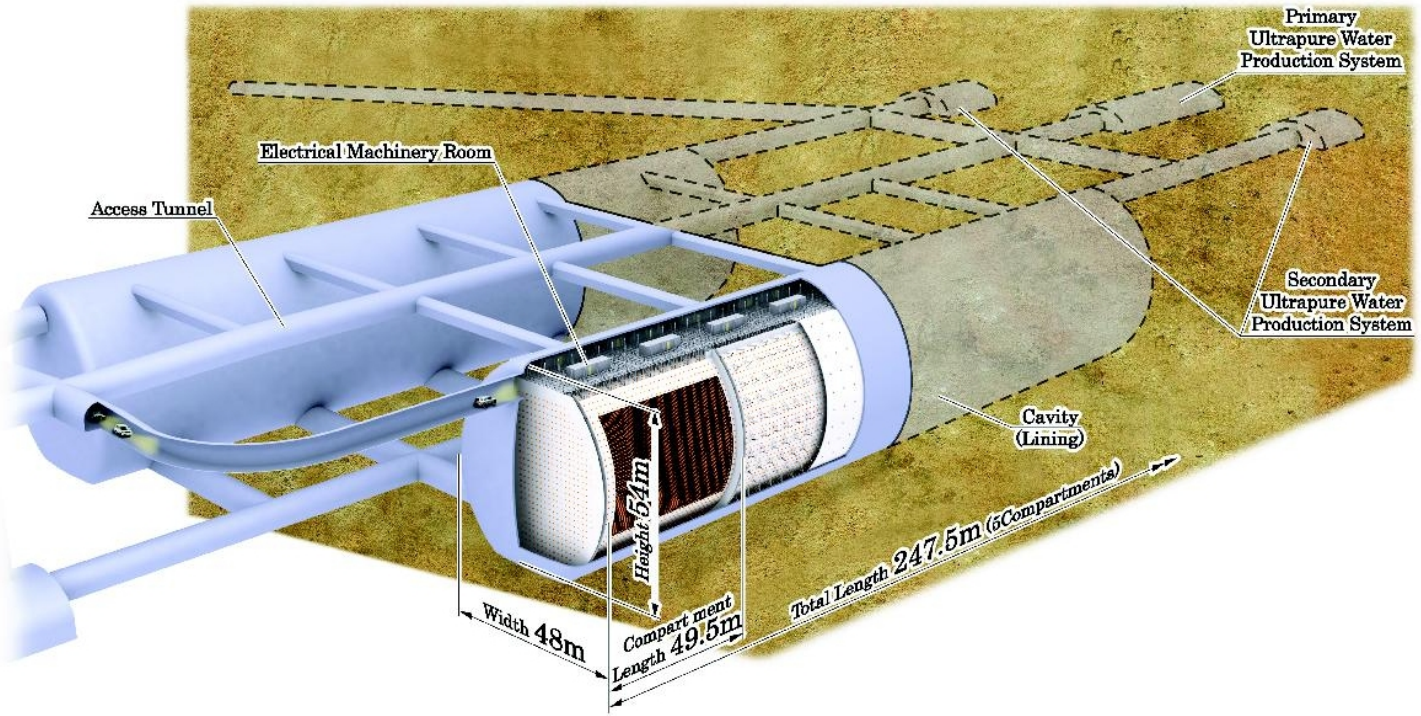
Japanese technology decision 2013: massive water Cherenkov



- **Two cylindrical tanks lying side-by-side. Each tank 48 (W) X 54 (H) X 250 (L) m.**
- **The total fiducial mass is 0.99 (0.56) million metric tons $\equiv$ 20 (25) X Super-K.**
- **The inner region viewed by 99,000 20-inch PMTs (20% coverage).**

Massive Neutrino Detectors: GLACIER/LENA/MEMPHYS (EUROPE)

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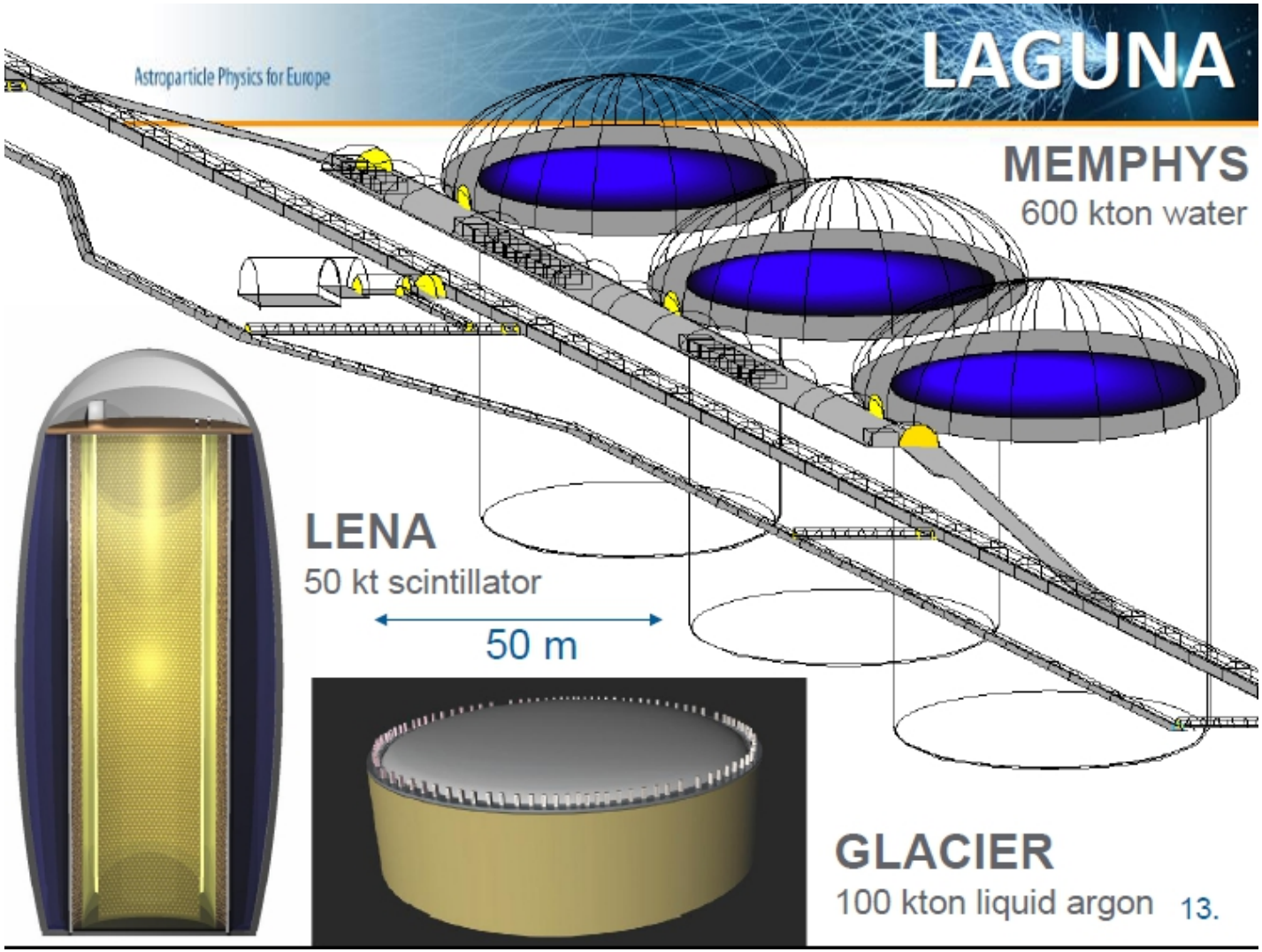

Christian Spiering, DESY, ESPP12

Comparison of Underground Detector Locations

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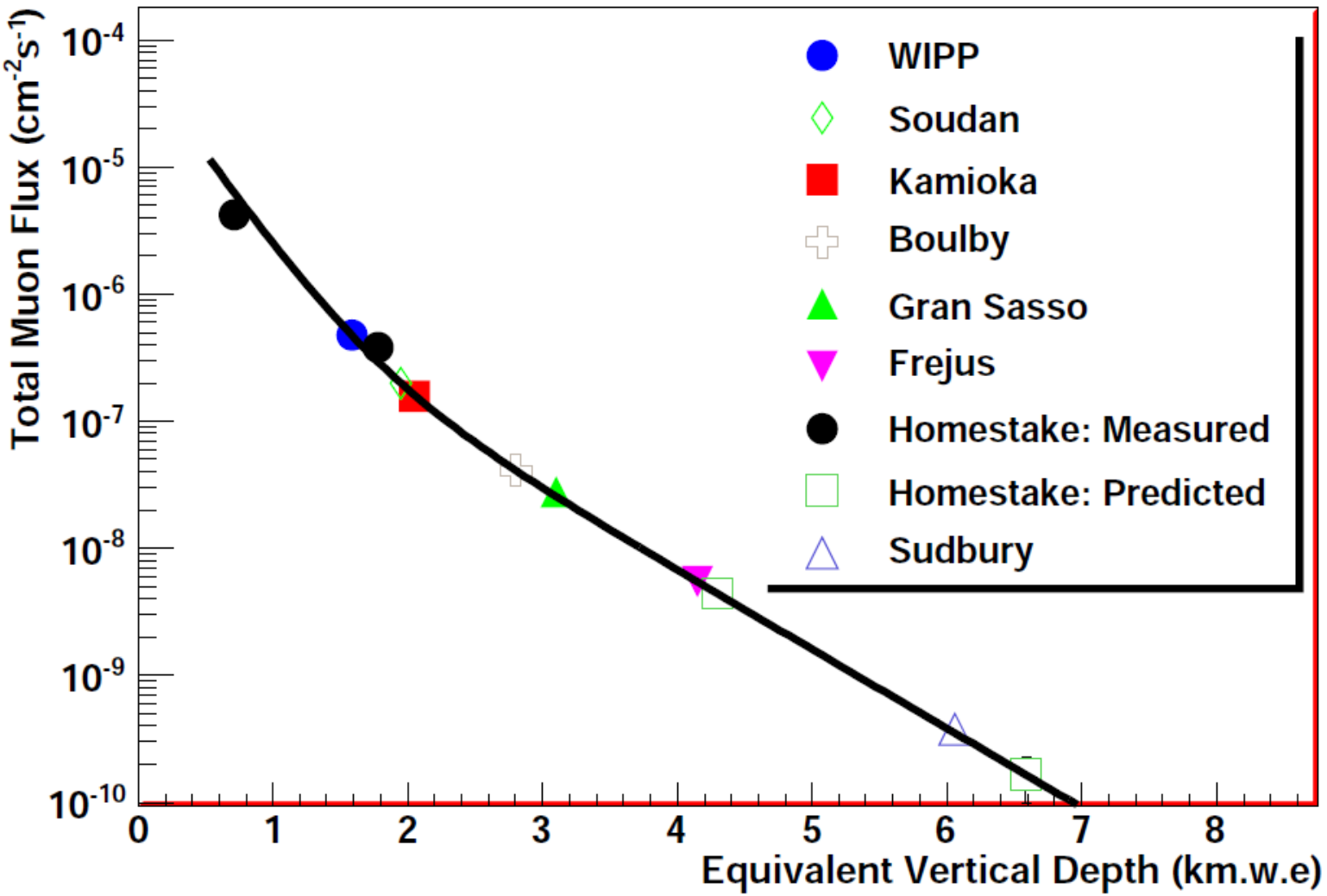

Physics Potential with Different Underground Detectors

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Physics potential of the 3 types of detectors for proton decay and neutrino astrophysics *

Topics	GLACIER (50 kt)	LENA (50 kt)	MEMPHYS (500 kt)
proton decay, sensitivity(10 years) $e^+\pi^0$ anti-ν K^+ (**)	2.5×10^{34} 5×10^{34}	- 4×10^{34}	15×10^{34} 2.5×10^{34}
SN at 10 kpc, # events CC NC ES Elastic scatt. P	~ 19,500 0.8×10^4 (ν_e) 1.1×10^4 0.4×10^3 (e) -	~16,000 1.3×10^4 (anti-ν_e) 1.0×10^3 6.2×10^2 (e) 2.6×10^3 (p)	~250,000 2.5×10^5 (anti-ν_e) - 1.3×10^3 (e) -
Diffuse SN #Signal/Background events (10 years)	~50/30	~60/10	~120/100 (1 module with Gd)
Solar neutrinos # events, 1 year	^{8}B ES : 1.5×10^4 Abs: 0.5×10^5 (dependent on the achievable threshold)	^{7}Be: 3.6×10^6 pep: 1.0×10^5 ^{8}B: 2.9×10^4 CNO: 7×10^4	^{8}B ES: 1.2×10^5
Atmospheric ν # events, 1 year	5×10^3	5×10^3	5×10^4
Geo-neutrinos # events, 1 year	Below threshold	1.5×10^3	Below threshold

* some numbers strongly depend on model assumptions and give a qualitative rather than an exact quantitative comparison.
** this channel is particularly prominent in SUSY theories. Indications for SUSY at the LHC would boost its importance.

Christian Spiering, DESY, ESPP12

Sensitivities vs Baseline - Superbeams

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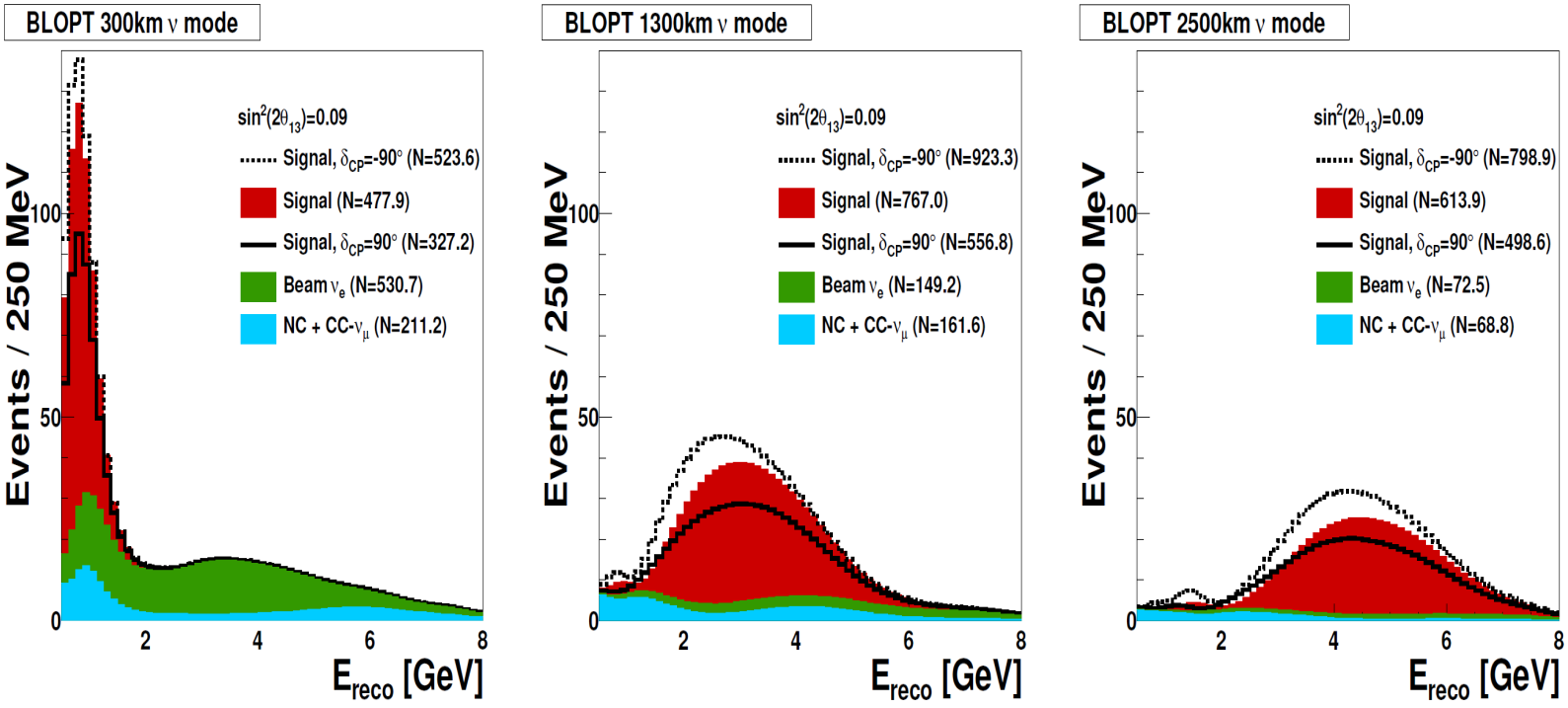
Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. For 35 kTon LAr-TPC.

$\nu_\mu \longrightarrow \nu_e$ Appearance. Normal Hierarchy



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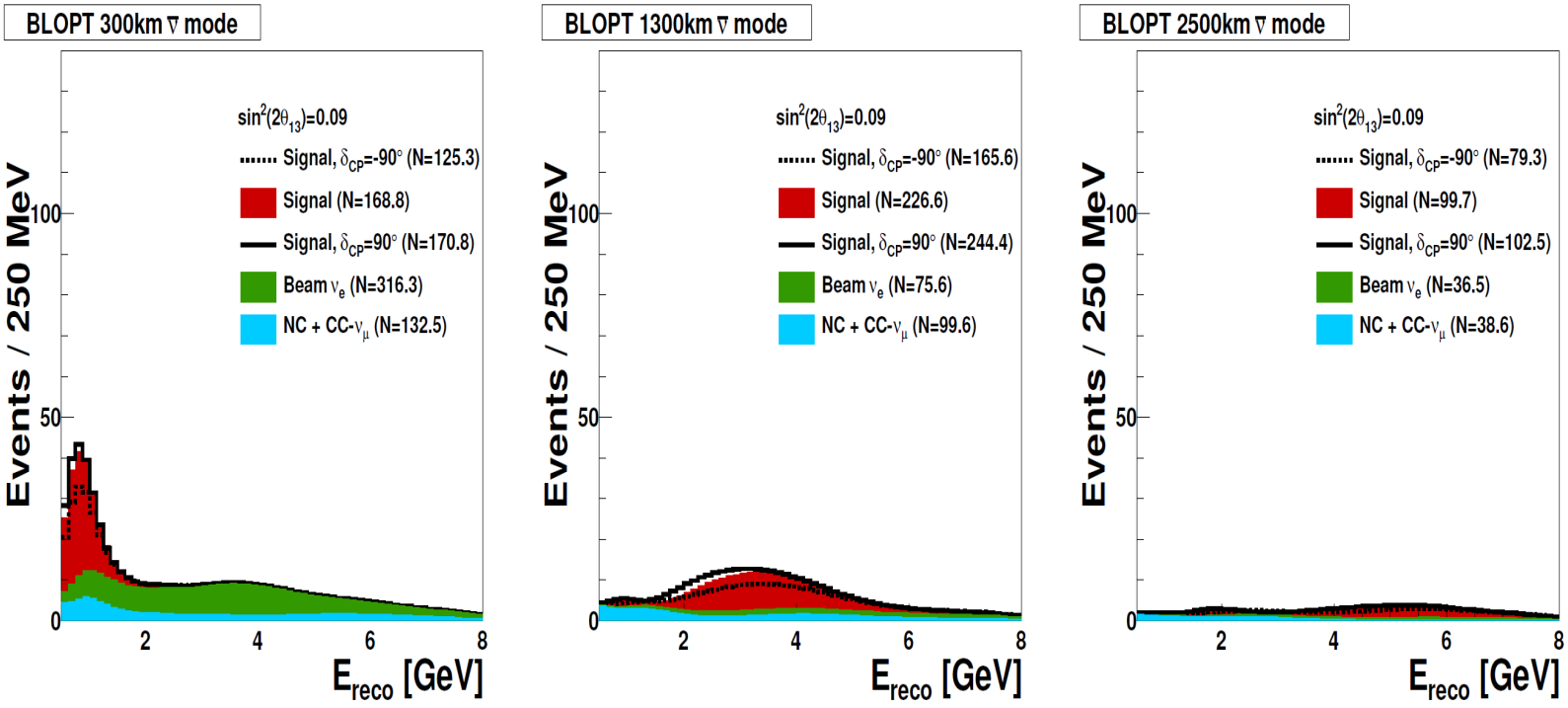
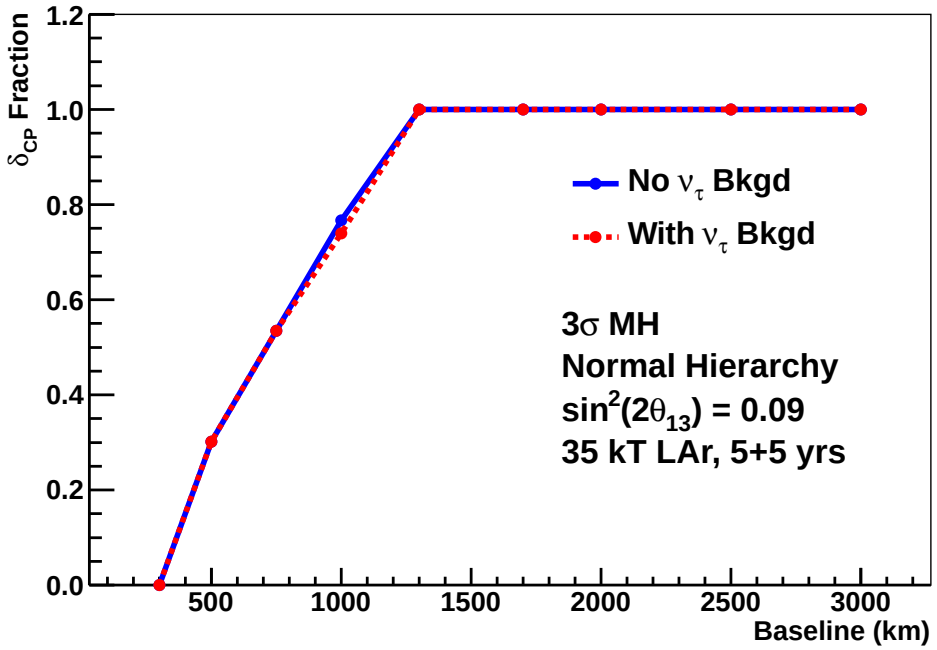


Sensitivities vs Baseline - Superbeams

Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. For 35 kTon LAr-TPC.

Mass hierarchy senstivity at $\geq 3\sigma$

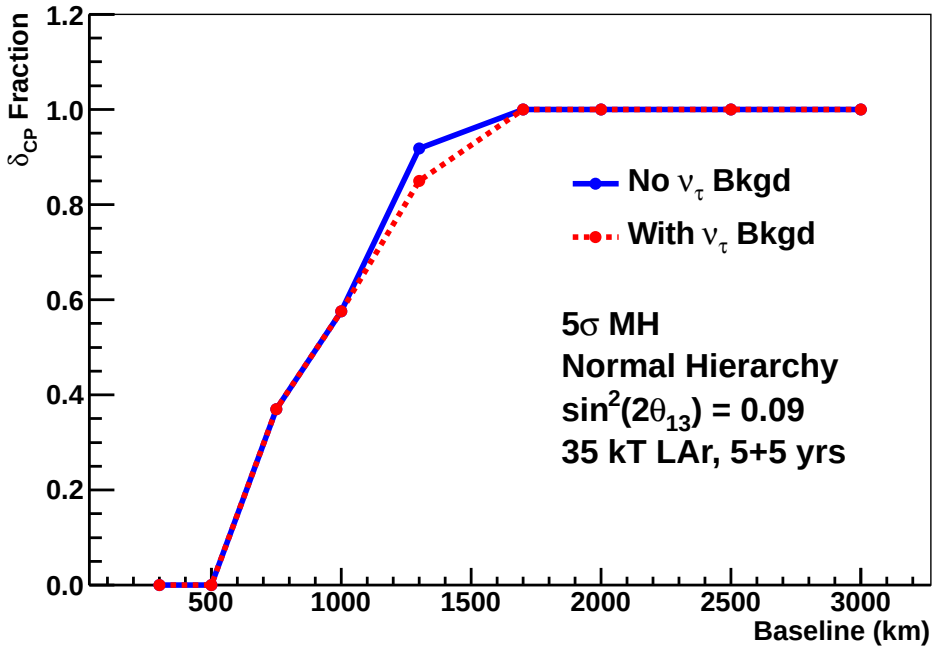


Baselines of 1300-1500km sufficient to resolve MH at 3σ

Sensitivities vs Baseline - Superbeams

Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. For 35 kTon LAr-TPC.

Mass hierarchy senstivity at $\geq 5\sigma$

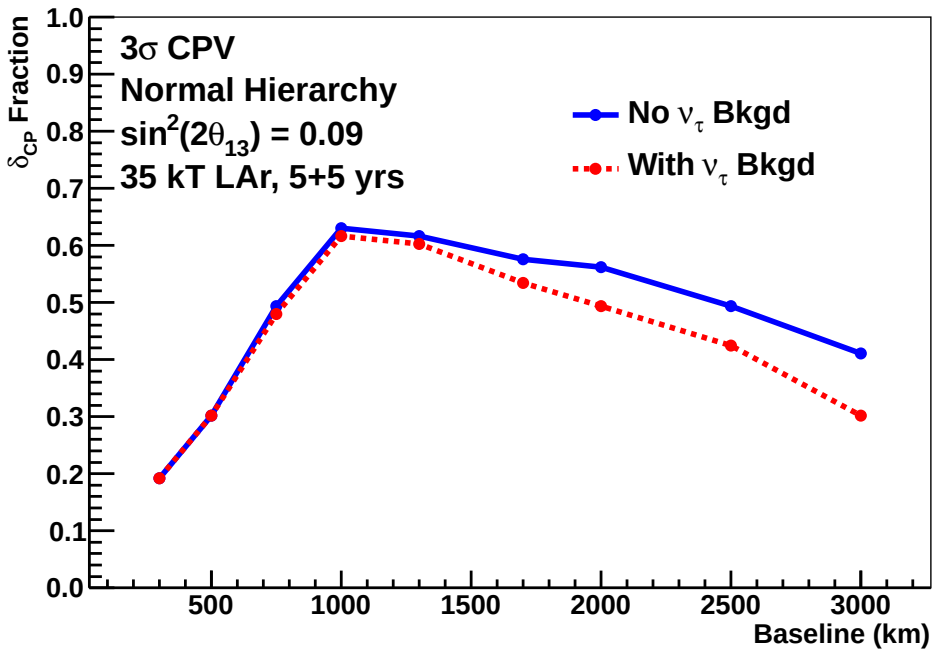


Baselines of 1500-1700km sufficient to resolve MH at 5σ

Sensitivities vs Baseline - Superbeams

Starting from the MI 120 GeV, we produced an optimized horn focused beam based on NuMI designs for each baseline. For shorter baselines we used off-axis angles. For 35 kTon LAr-TPC.

CP violation sensitivity at 3σ



Baselines of 1000-1500km best CPV sensitivity for superbeams

CPV in Short vs. Long Baseline Accelerator ν

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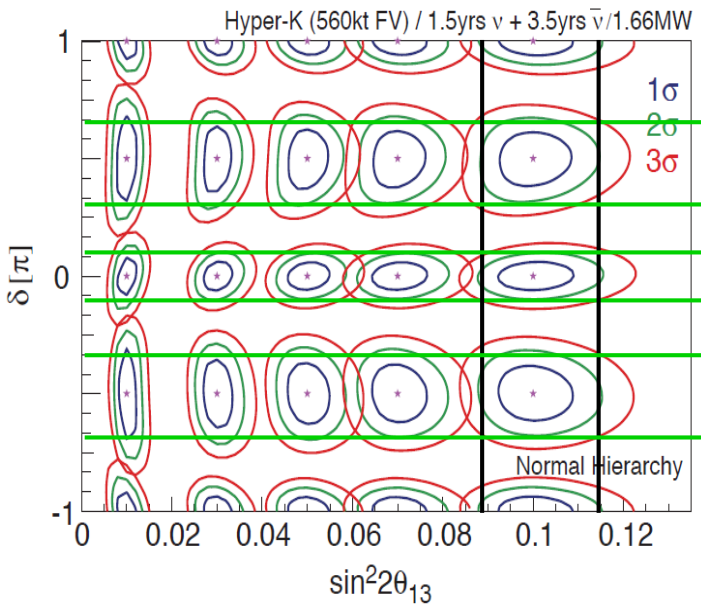
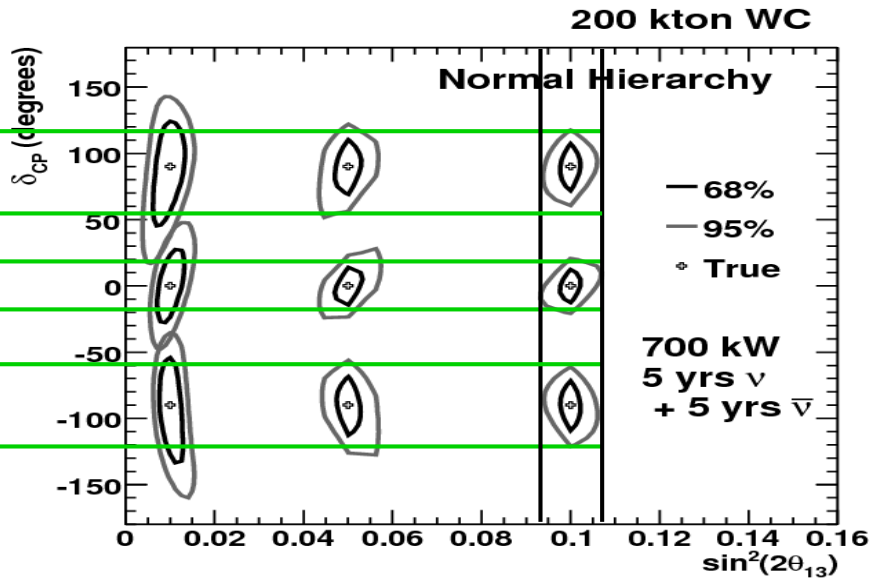
Assuming the MH is already determined:

290km, 1.66MW, 560kton WCD T2HK



1300km, 700kW, 200kton WCD LBNE



Smaller detectors are needed in mid-range baselines (1000-1500km)

Optimization of NF Baseline and μ Energy (P.A. Huber)

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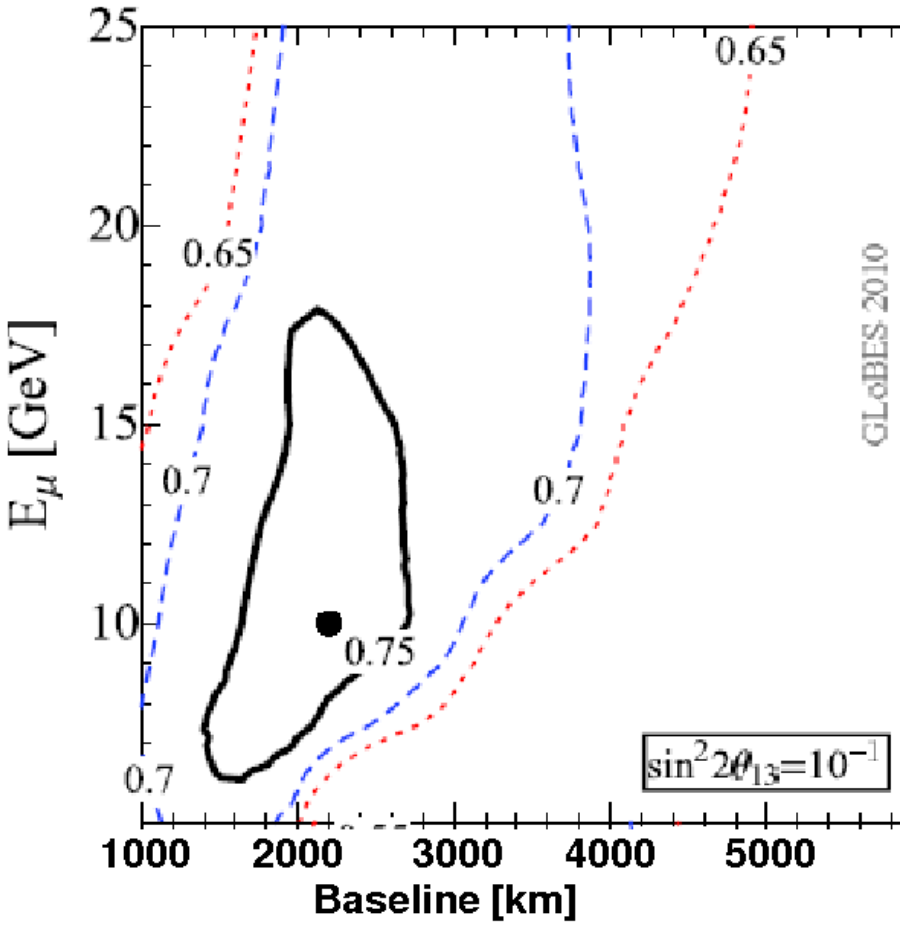

Using MIND (Magnetized Iron Neutrino Detector) and a single baseline:

The optimal range is 1400-2600km for E_μ from 7 - 15 GeV.

CPV coverage with Different Experiments (P.A. Huber)

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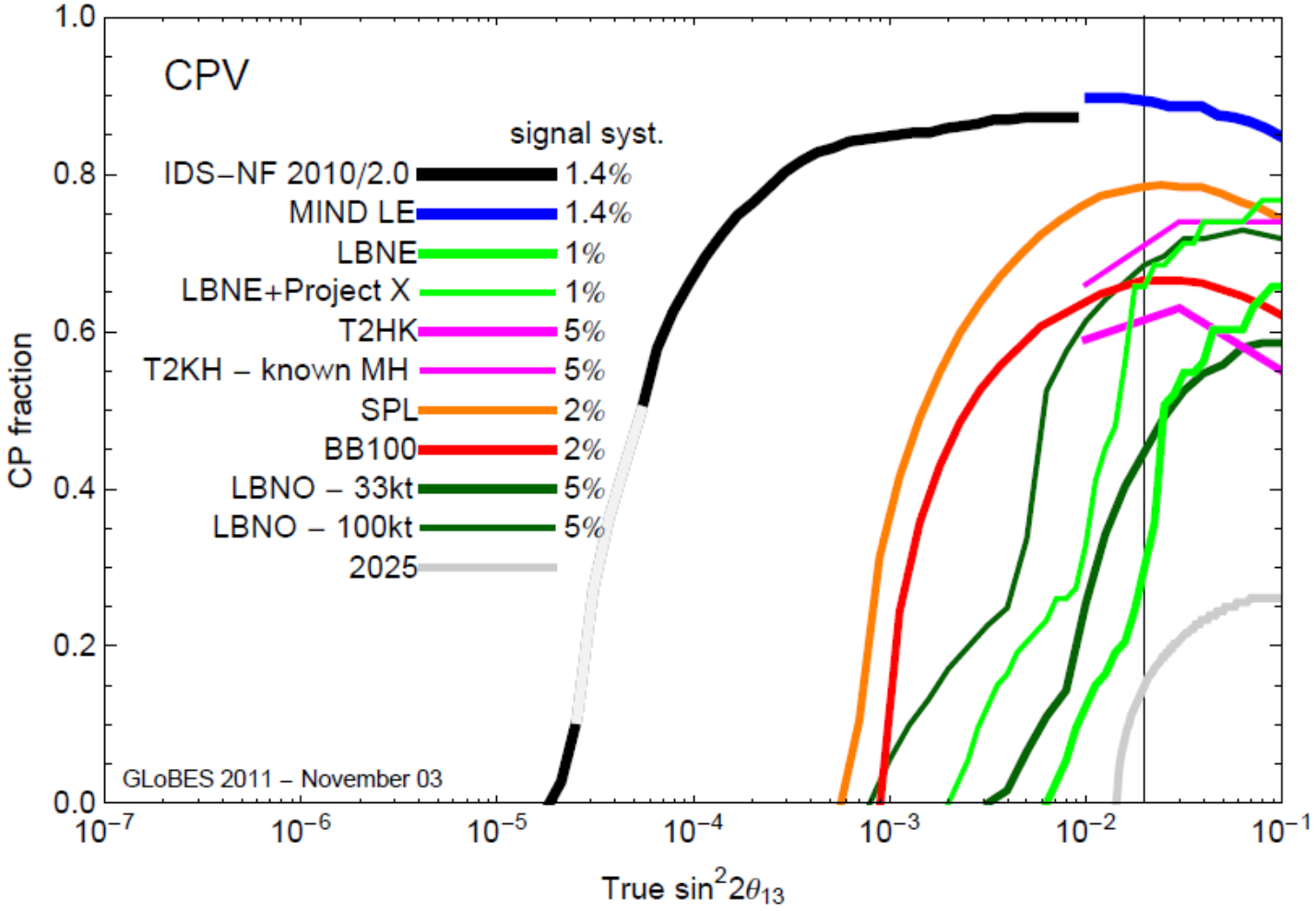

Neutrino factories can determine CPV for values of δ_{cp} close to 0 and π

Precision Measurements of CP Violation Phase (P.A. Huber)

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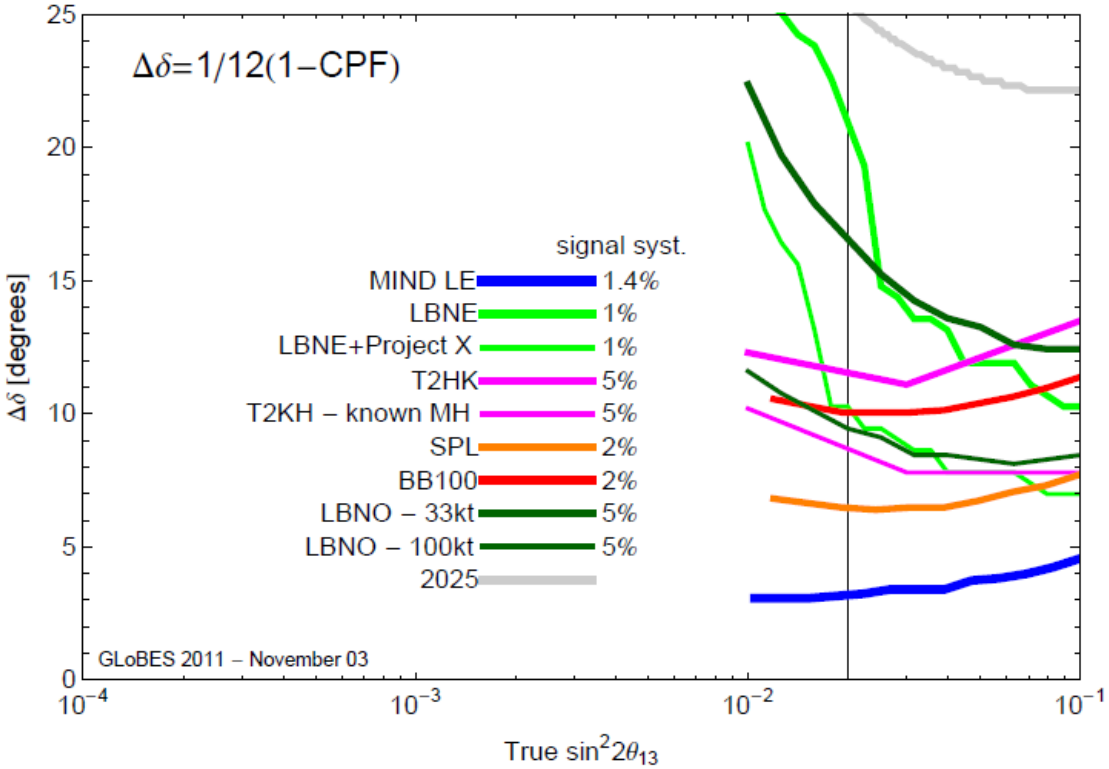
Sensitivity to physics beyond 3-flavor mixing REQUIRES high precision measurements of PMNS



Comparison not very accurate because of different assumptions of expt. uncertainties

Reactor ν Experiments

Reactor $\bar{\nu}_e$: Precision Measurement of Two Mixing Angles

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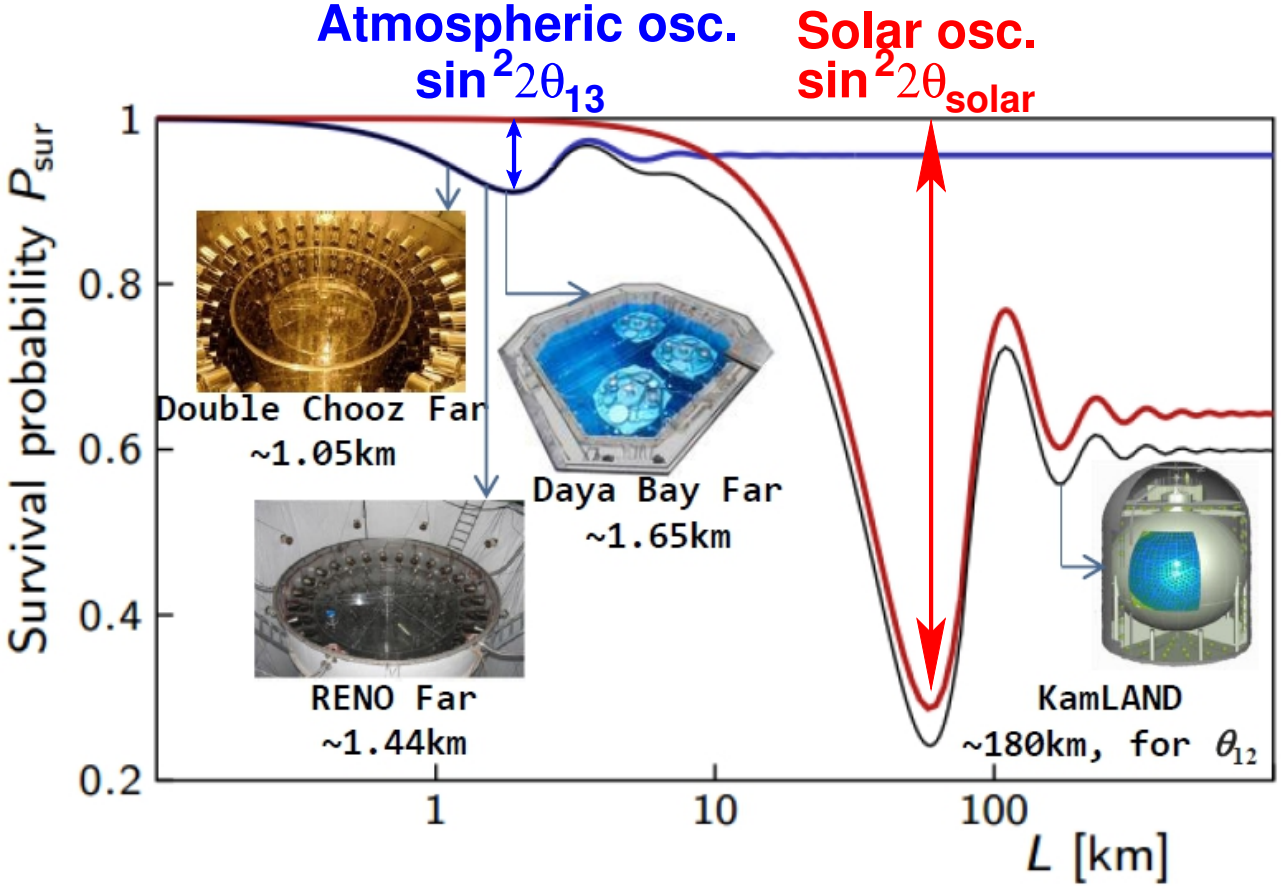

In 2012: Measurement of a 3rd mixing amplitude:

$$\sin^2\theta_{13} = 0.0241 \pm 0.0025$$

Much smaller than $\sin^2\theta_{solar}$ and $\sin^2\theta_{atm.}$

The Daya Bay II Experiment (China)

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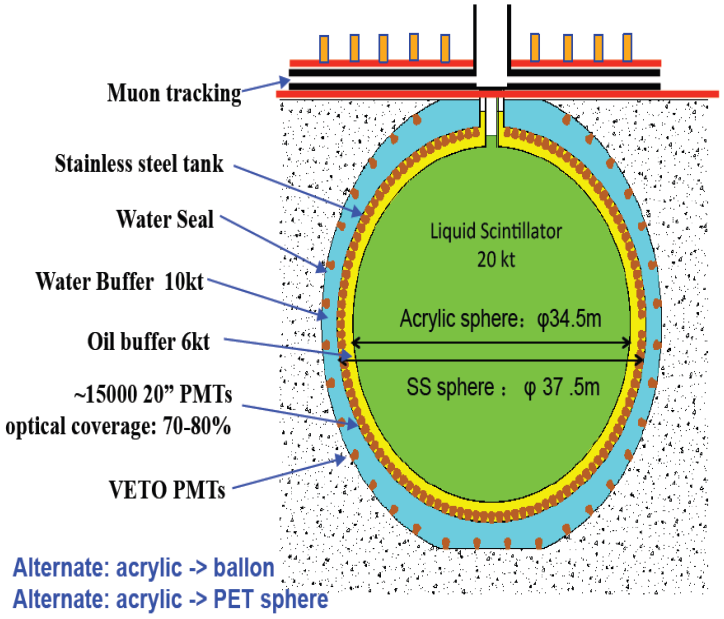

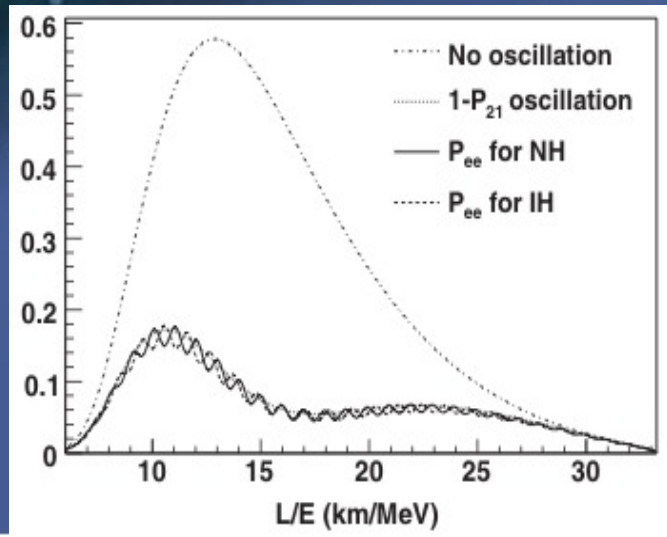

Locate experiment at 60km from reactors - where solar osc. is max

Observe subdominant atm. osc

DYBII Challenge 1: Energy Resolution

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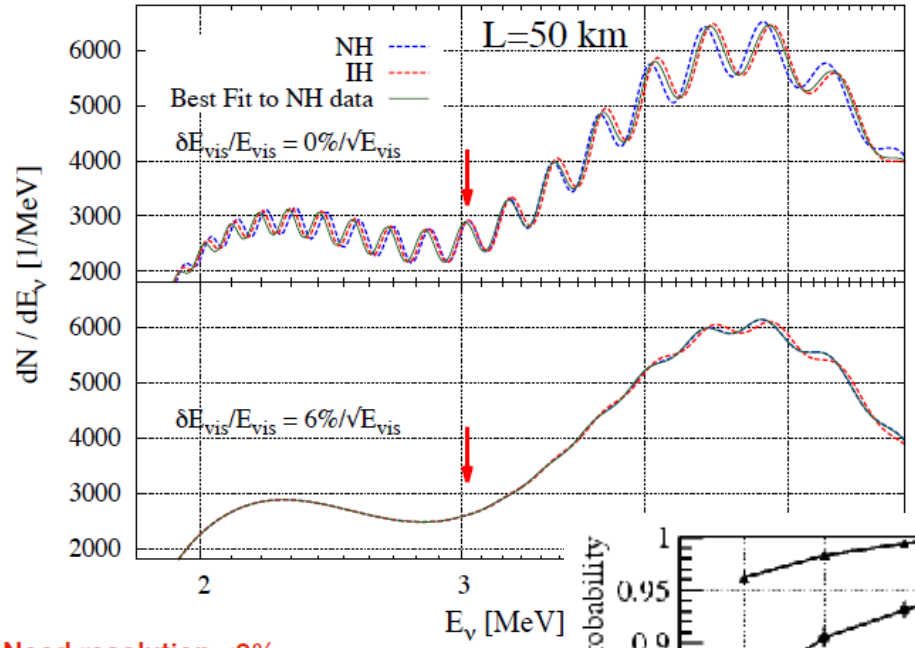
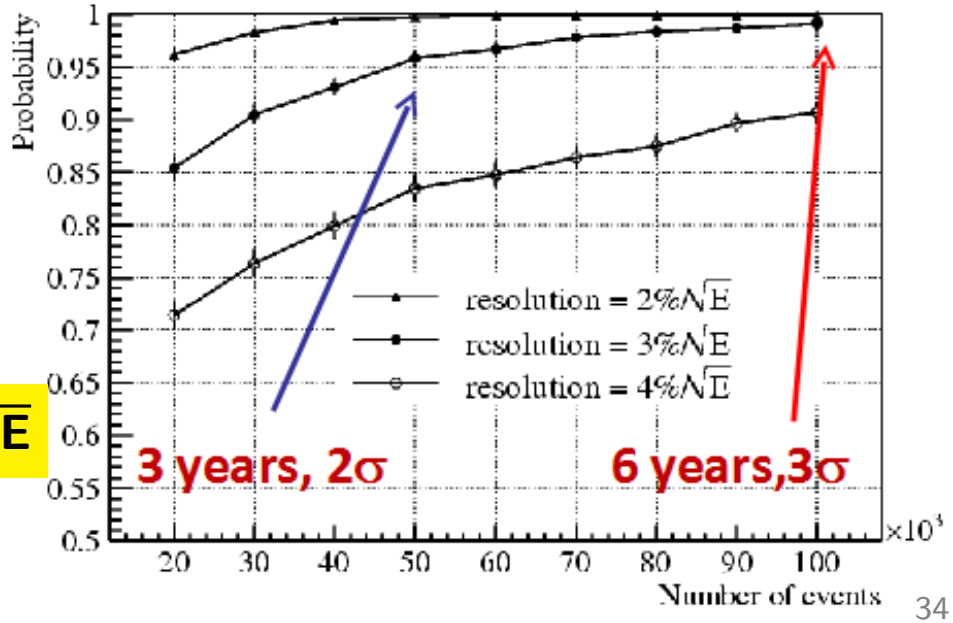


- Need resolution <3%



Need resolution $\leq 3\%/\sqrt{E}$

DYBII Challenge 2: Energy Non Linearity

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- Experimentally measured is essentially the reconstructed energy based on the light collection, which may not be linear to the real energy of the particle
  - Quenching of the scintillator
  - Cherenkov contribution
  - Position dependence
  - Electronics
- With certain non-linearity, the IH could behave like the NH, and vice versa

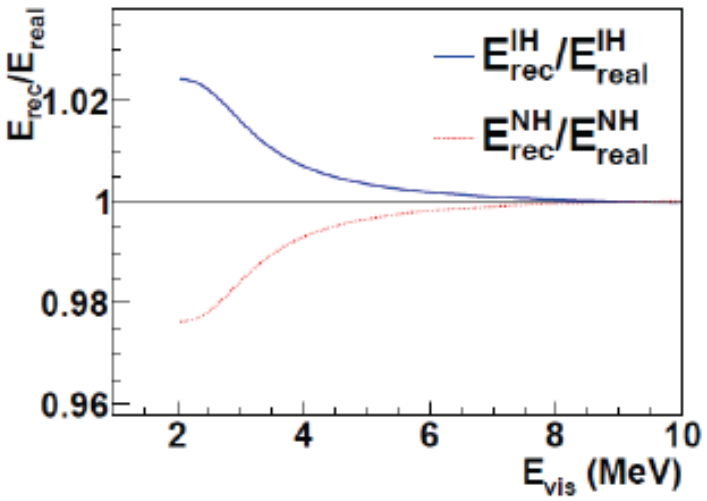
IH: $$\cos\left((2|\Delta m^2_{32}| - \Delta m^2_{\phi}(E_{\bar{\nu}}, L))\frac{L}{E_{real}}\right)$$

$$=$$

NH: $$\cos\left((2|\Delta' m^2_{32}| + \Delta m^2_{\phi}(E_{\bar{\nu}}, L))\frac{L}{E_{rec}}\right)$$

Assuming a non-linearity function

$$E_{rec} = \frac{2|\Delta' m^2_{32}| + \Delta m^2_{\phi}(E_{\bar{\nu}}, L)}{2|\Delta m^2_{32}| - \Delta m^2_{\phi}(E_{\bar{\nu}}, L)} E_{real} \ .$$



Need to know the non-linearity to <1%

X. Qian et.al. arXiv: 1208.1551

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RENO 50km

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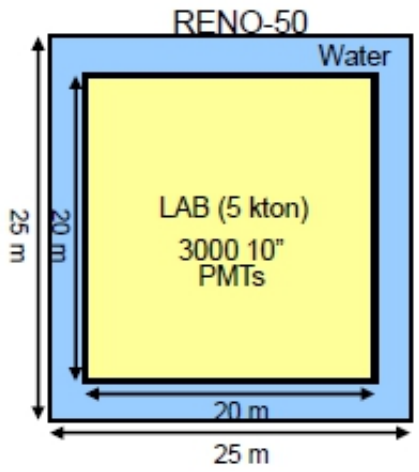
RENO-50

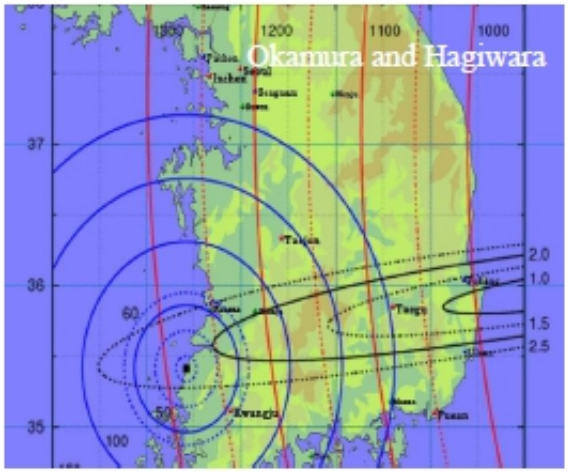
- Measure large θ_{12} neutrino oscillation with 5kton liquid scintillator at L~50 km
- RENO can be used as near detectors.
- 2018 ~



Physics goal of RENO-50

- Precise measurement of θ_{12}
  $\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} \sim 1.0\%(1\sigma)$ in a year ← current accuracy : 5.4%
- Determination of mass hierarchy Δm^2_{13}
- Neutrino burst from a Supernova in our Galaxy :
  ~1500 events (@8 kpc)
- Detection of T2K beam : ~120 events/year
- Test of non-standard physics :
  sterile/mass varying neutrinos

J-PARC neutrino beam direction



Atmospheric ν Experiments

MSW Effect in Atmospheric ν Oscillations

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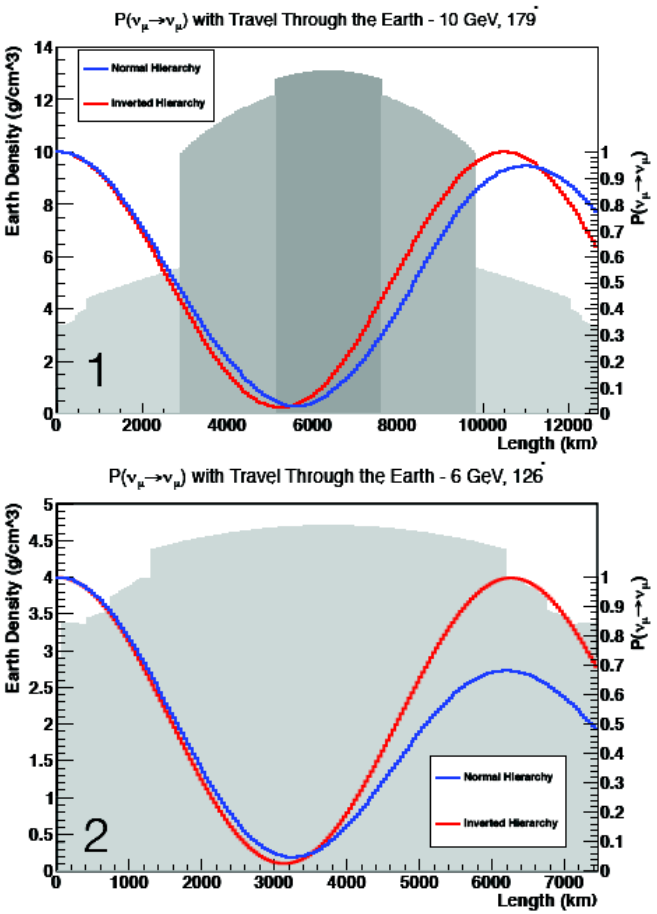

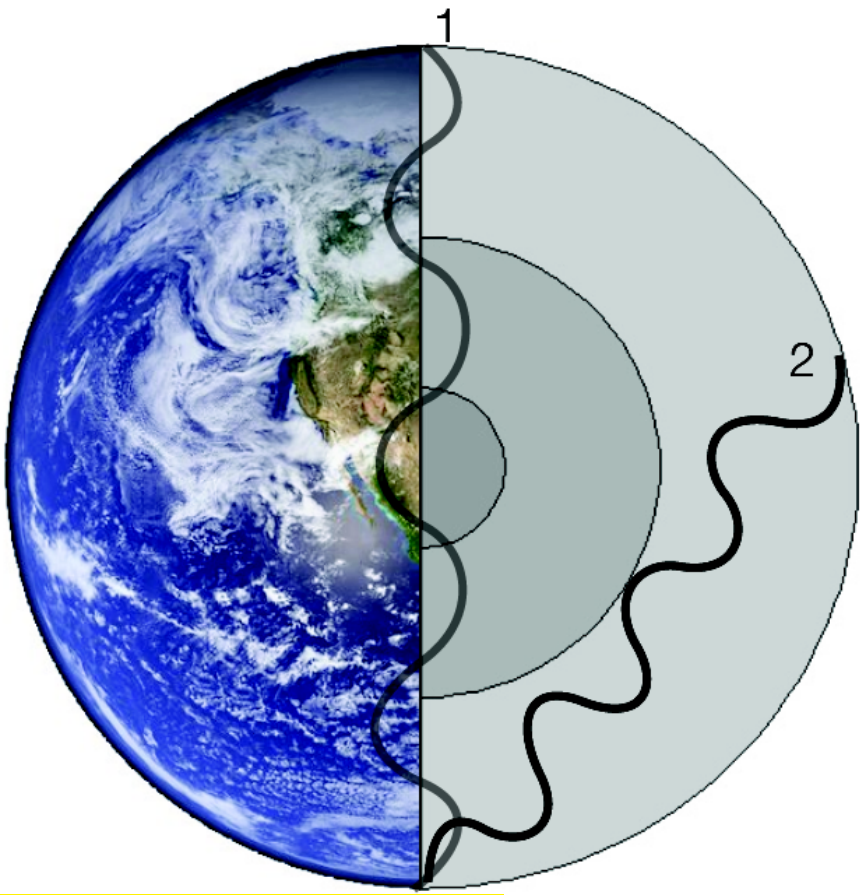

MSW effect sensitive to sign of Δm^2_{32} (atmospheric)

Normal hierarchy (NH): $\Delta m^2_{32} > 0$
Inverted hierarchy (IH): $\Delta m^2_{32} < 0$

Atm. ν_μ Oscillations and Mass Hierarchy

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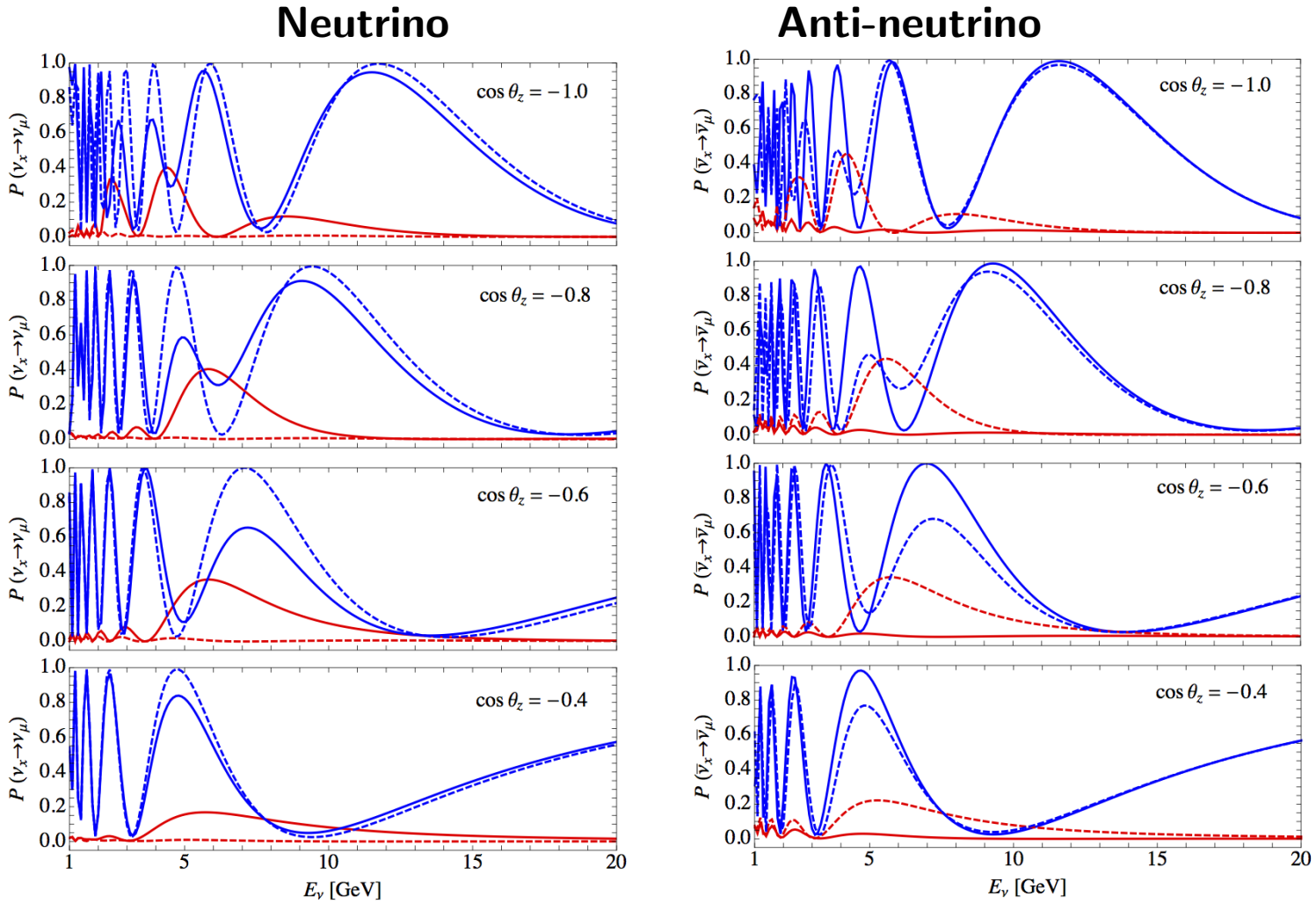

$\nu_e \to \nu_\mu$ $\nu_\mu \to \nu_\mu$ --- NH ($\Delta m^2_{atm} > 0$) - - - IH ($\Delta m^2_{atm} < 0$)

Effects are largest in the 3-10 GeV range

Atm. ν_μ Oscillations and Mass Hierarchy

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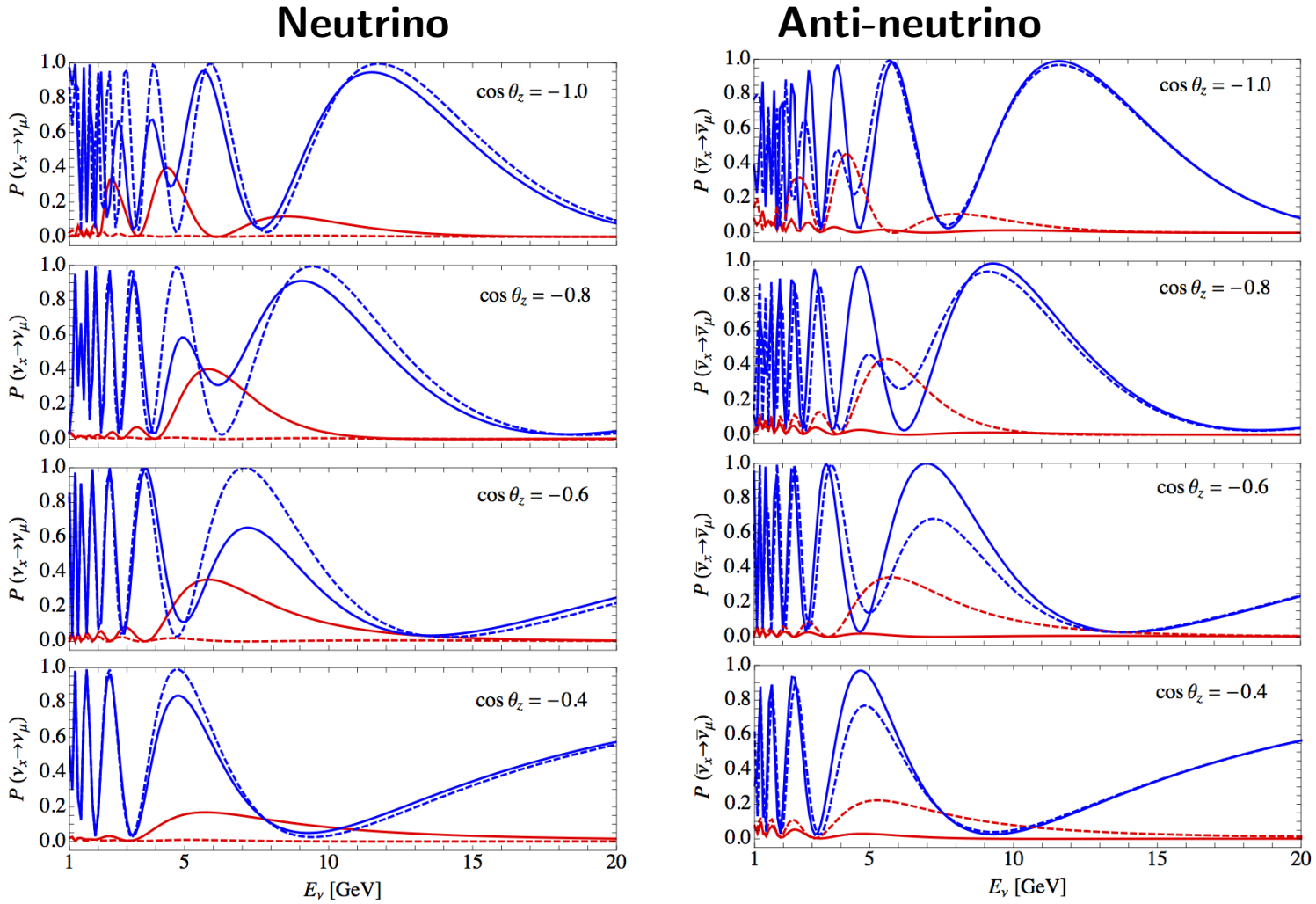


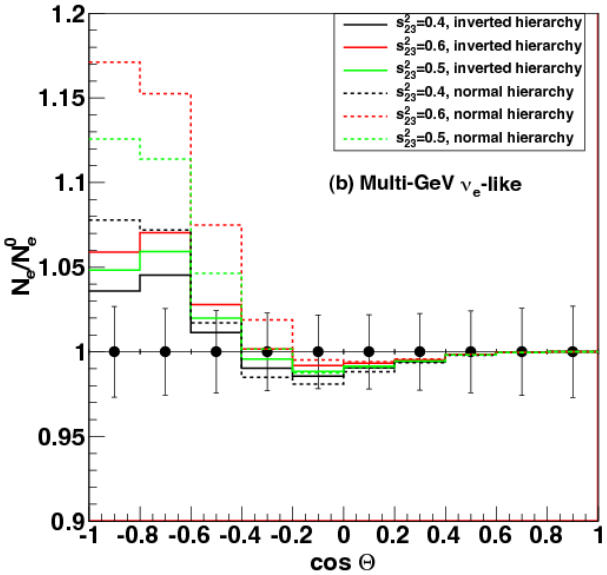
$\nu_e \to \nu_\mu$ $\nu_\mu \to \nu_\mu$ --- NH ($\Delta m^2_{atm} > 0$) - - - IH ($\Delta m^2_{atm} < 0$)

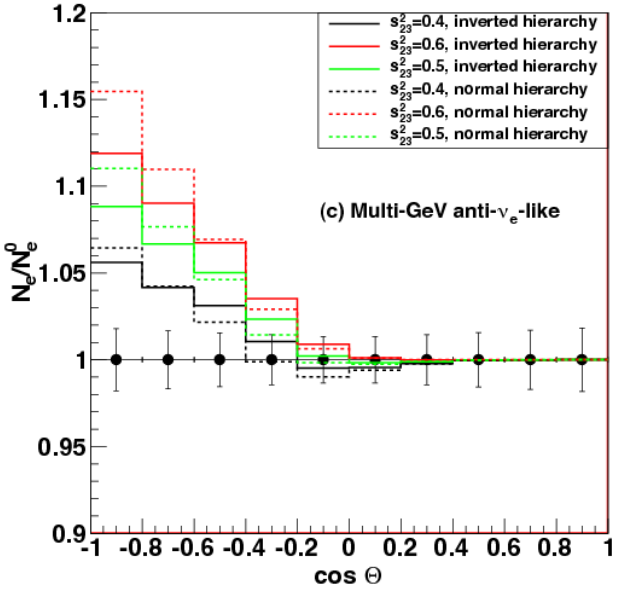
Effects are largest in the 3-10 GeV range

Hyper-Kamiokande Atmospheric ν and MH

TABLE XII. Expected number of ν_e-like and $\bar{\nu}_e$-like events in 10 Hyper-K years for each interaction component.

	CC ν_e	CC $\bar{\nu}_e$	CC $\nu_\mu + \bar{\nu}_\mu$	NC	Total
ν_e-like sample	15247	2831	3731	4792	26601
- single-ring	6356	1086	1682	1740	10864
- multi-ring	8891	1745	2049	3052	15737
Percentage (%)	57.3	10.6	14.0	18.0	100.0
$\bar{\nu}_e$-like sample	28309	17255	1232	4559	51355
- single-ring	20470	13401	444	2496	36811
- multi-ring	7839	3854	788	2063	14544
Percentage (%)	55.1	33.6	2.4	8.9	100.0





Hyper-Kamiokande MH Sensitivities with Atmospheric ν

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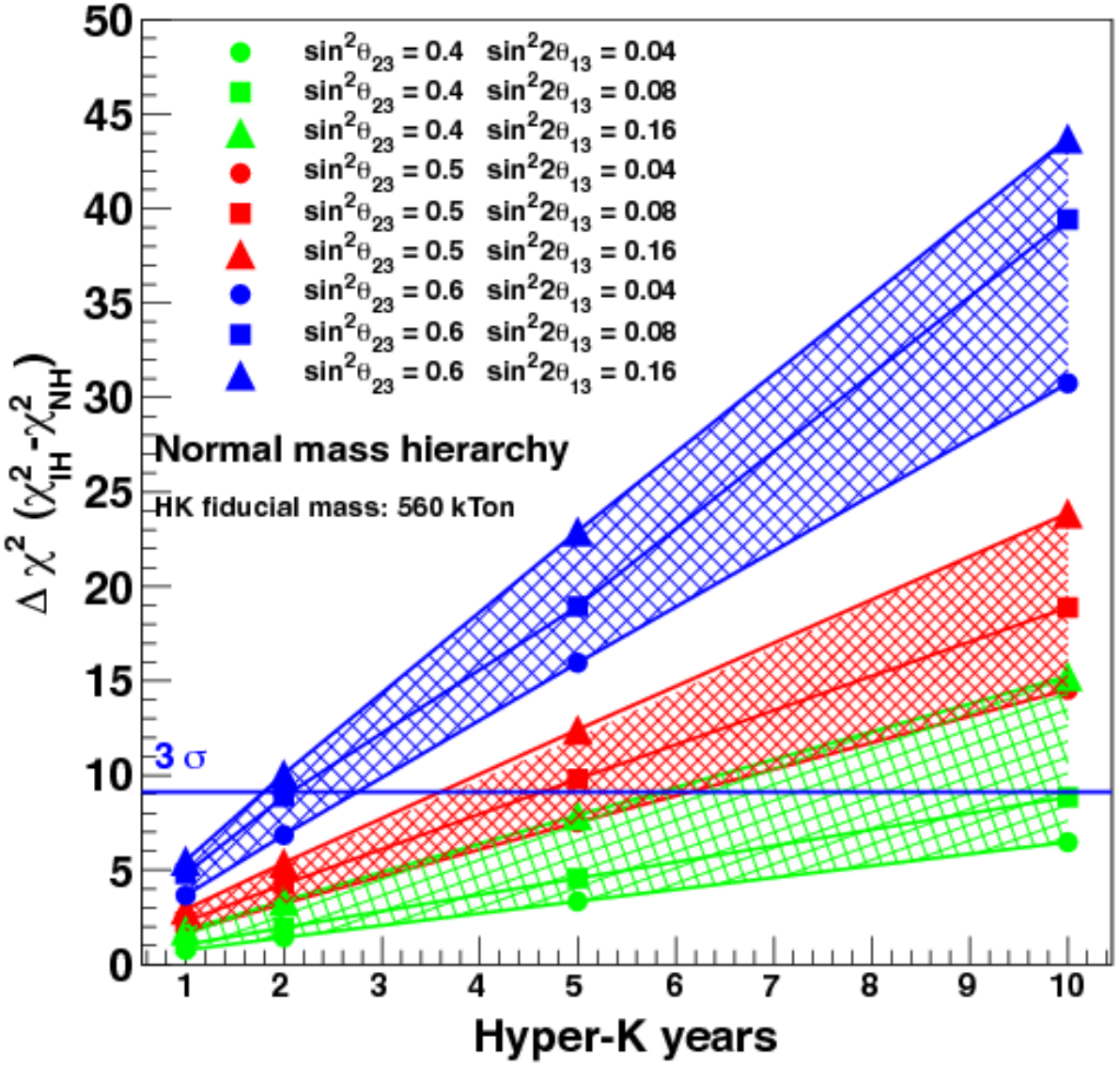

Summary

Neutrino Oscillations Internationally

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Summary

The 3 flavor framework for neutrino oscillations is well established

- **Experiments have identified 2 very different mass scales and 3 mixing amplitudes.**
- **The mass ordering (hierarchy) of the 1 and 3 mass states is still unknown.**
- **The mass hierarchy can be probed using the matter effect in long baseline accelerator $\nu_\mu \rightarrow \nu_e$ (US, Europe), long baseline reactor $\bar{\nu}_e$ disappearance (China, Korea), using atmospheric ν (Japan, US, Europe).**
- **Discovering ν CPV requires many 100kt .MW .yr exposures in a very long baseline experiment. Larger detector masses and independent MH determination are required at shorter baselines.**