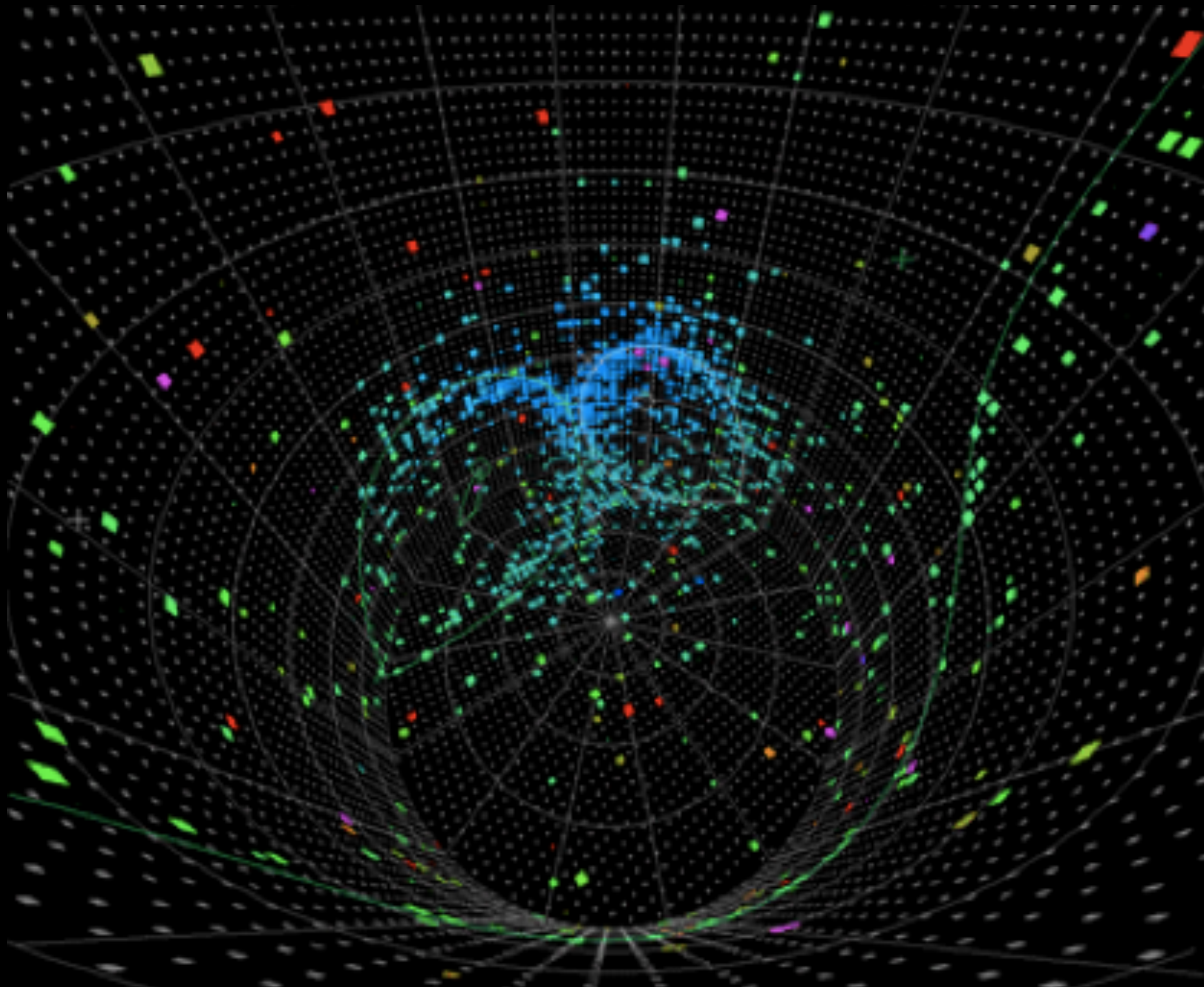
Future Long Baseline Experiments



Kate Scholberg, Duke University
Lownu 2011, November 2011

OUTLINE

Physics reach of next-generation long-baseline experiments

(standard 3-flavor oscillation context)

Possible future programs

- United States
- Europe
- Asia

The Glorious Past

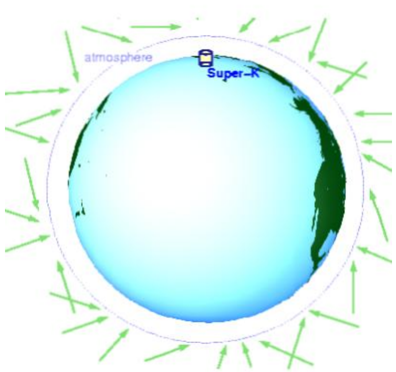
atmospheric **solar**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

First seen in atmospheric ν's, for which SK now has best mixing angle constraint

K2K was first long baseline confirmation

MINOS has best Δm^2_{23}



The Glorious Present

atmospheric **solar**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

More from SK atmospheric, MINOS on 2-3 mixing

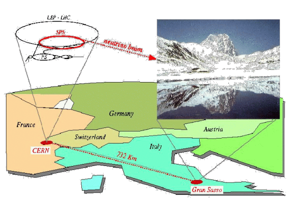
T2K making precision Δm^2_{23} measurement

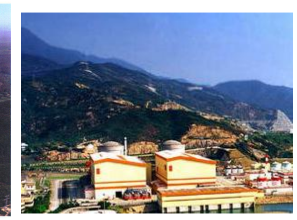
OPERA looking for explicit $\nu_\mu \rightarrow \nu_\tau$

First indications of non-zero θ_{13} from T2K, MINOS and Double Chooz

More soon from RENO, Daya Bay!

Next: NOνA





The Glorious Future

atmospheric **solar**

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Zoom in on CP δ,
and mass hierarchy

? ? ? ? ?

Getting at CP Violation

Observed for quarks; how about leptons?

phase δ in mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Compare transition probabilities for

$\nu_\mu \longrightarrow \nu_e$ **and** $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

But not simple to extract CP violating phase δ...
transition rates depend on all
MNS parameters, plus matter effects...

CP Violating Observables

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$

$$+\tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_\mp} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_\mp L}{2}\right) \cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

Non-CP terms

Changes sign for antineutrinos

CP violating

$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu}, \quad \tilde{B}_\mp \equiv |A \mp \Delta_{13}|, \quad A = \sqrt{2} G_F N_e$$

$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

A. Cervera et al., Nuclear Physics B 579 (2000)

More complicated...

Mass hierarchy affects nu/nubar via matter effects (need long L)

Need precision measurements of parameters....

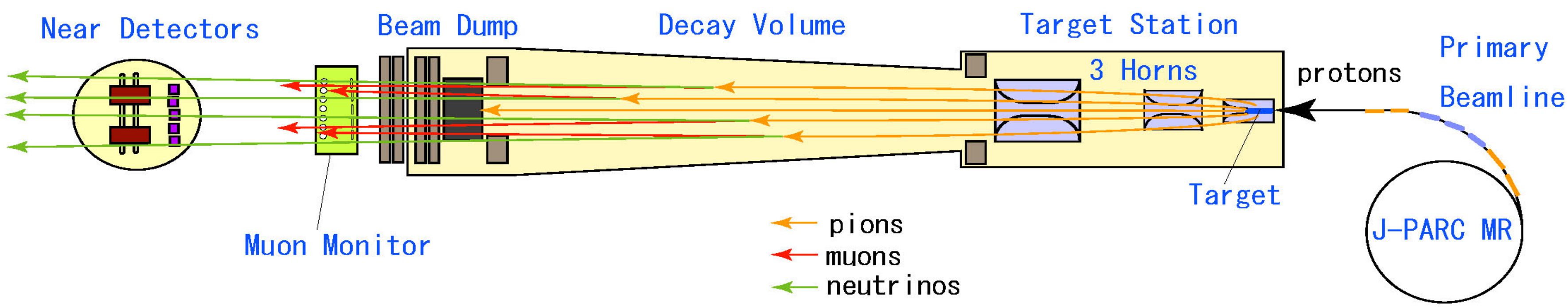
Multiple measurements **(ν's and $\bar{\nu}$'s) at different L, E needed to resolve intrinsic ambiguities**

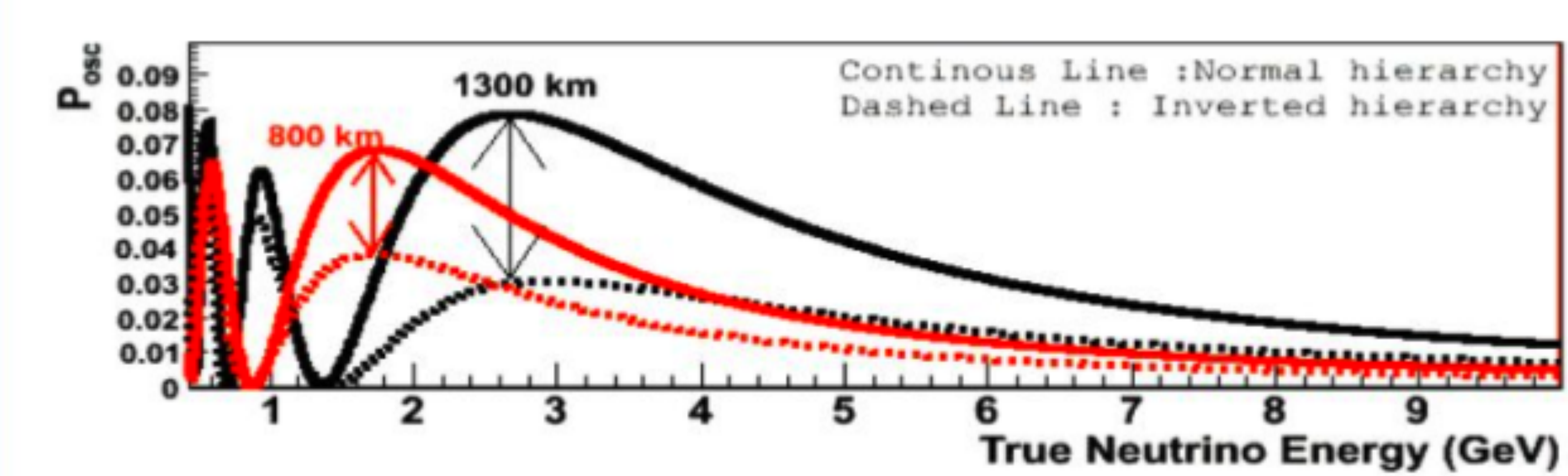
Next generation superbeams to access

θ_{13}, mass hierarchy, CP δ

Need ~1000 km, ~ few GeV energies

Basic technology is relatively well understood



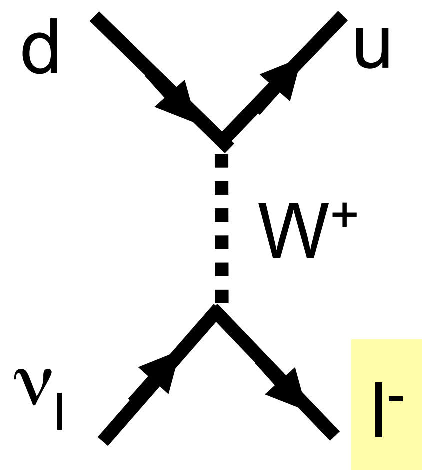


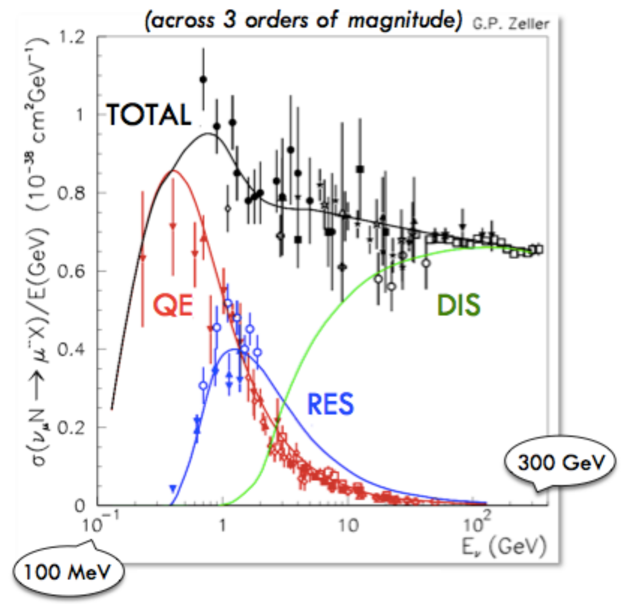
At far detector, for oscillation physics want:

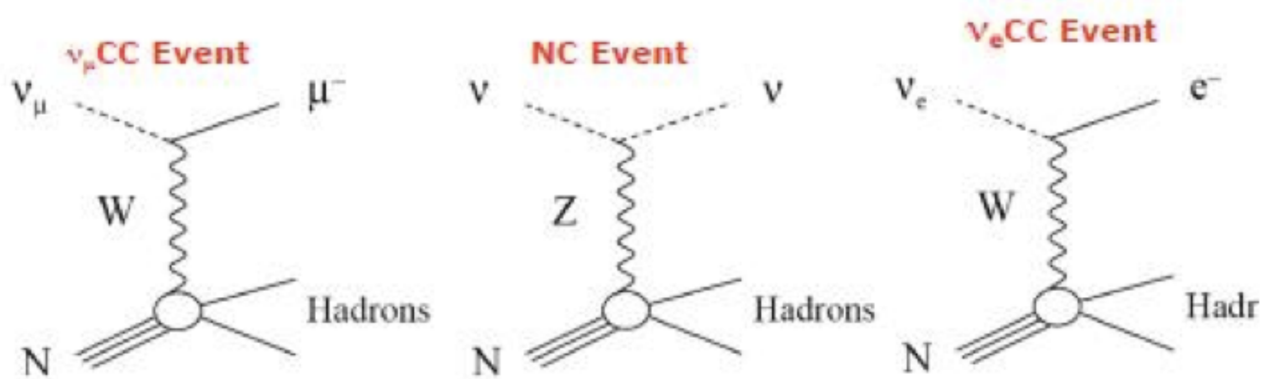
- flavor of the interacting neutrino
- interaction mode (CC, NC) & final state particle content
- energy resolution

$\nu_l + N \rightarrow l^{\pm} + N'$

charged-current quasi-elastic is the simple mode



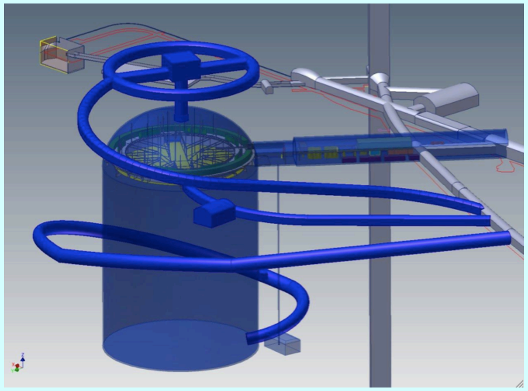


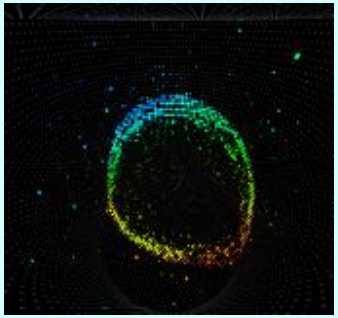


.. but at >~ GeV energies lots of other stuff comes out...

Possible large (multi-kton) detector technologies

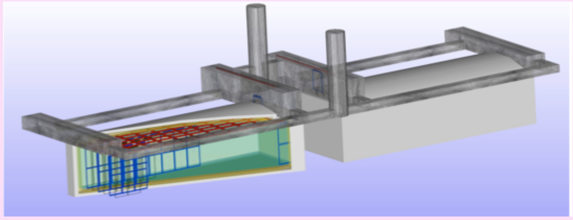
Water Cherenkov

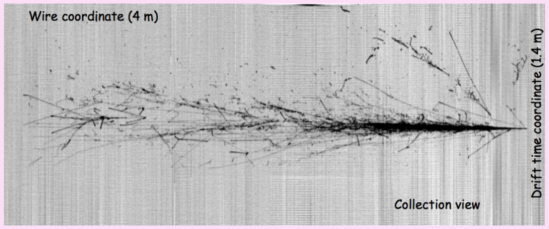




Cheap material, proven at very large scale

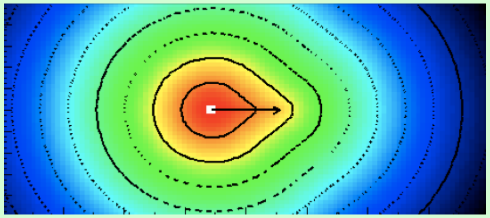
Liquid Argon





Excellent particle reconstruction

Liquid Scintillator



Low energy threshold

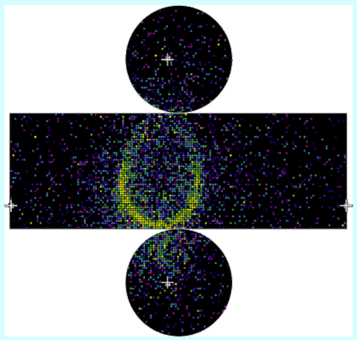
High energy reconstruction challenging

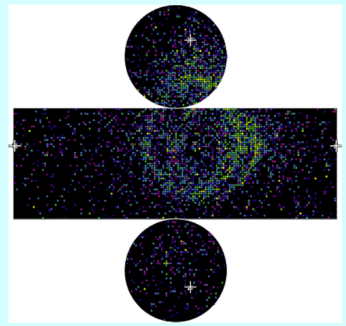
Detector choice issues for LBL physics

Need to reconstruct ~GeV neutrino interactions,
which often have multiple particles, complicated structure

Need to (for example) select ν_e from background

Water



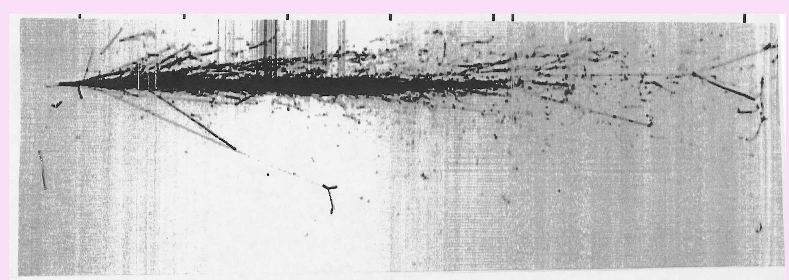


e.g. NC single pions
$\pi^0 \rightarrow \gamma\gamma$

Good efficiency & bg rejection shown w/T2K; likely possible to do better
Good photon collection, and possibly better timing,
may help: R&D for new photosensors underway

In principle, LAr can reconstruct entire interaction in detail

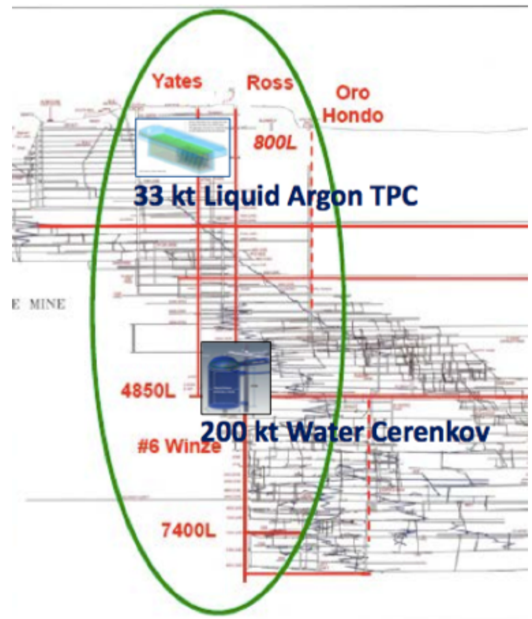
Efficiency higher,
so required detector mass
lower (factor ~6)

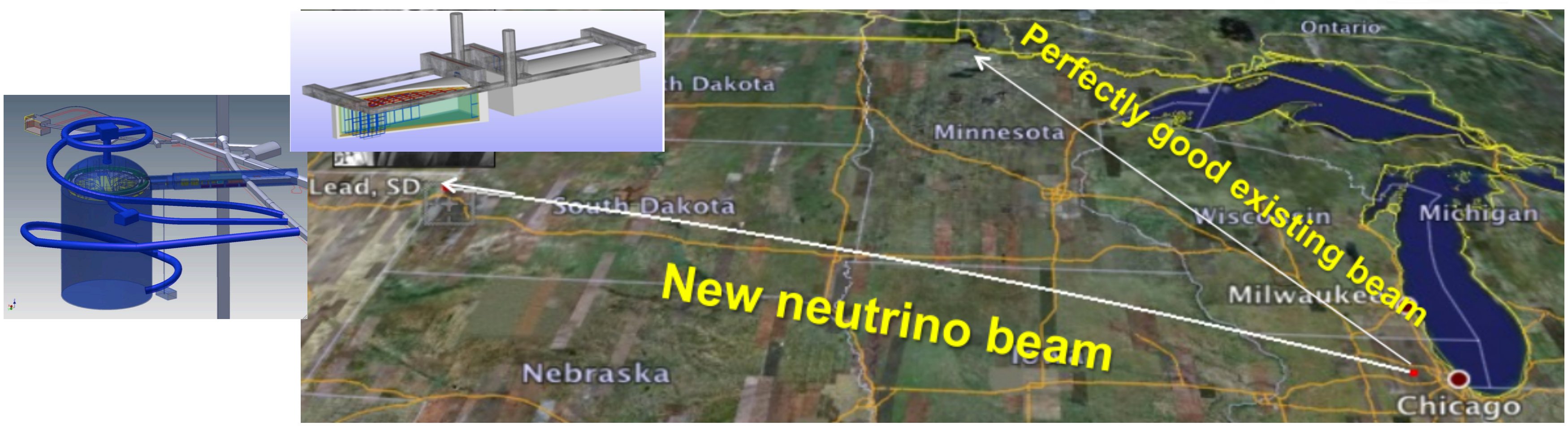


Future programs: United States

Long Baseline Neutrino Experiment (LBNE)

- Possible site: Homestake mine in South Dakota
- Under consideration:
  new 700 kW beam from FNAL with:
  200 kt water Ch. at 4850 ft
  OR 34 kton LAr TPC at 800 ft (or deeper)
- Longer term: Project X (2 MW)

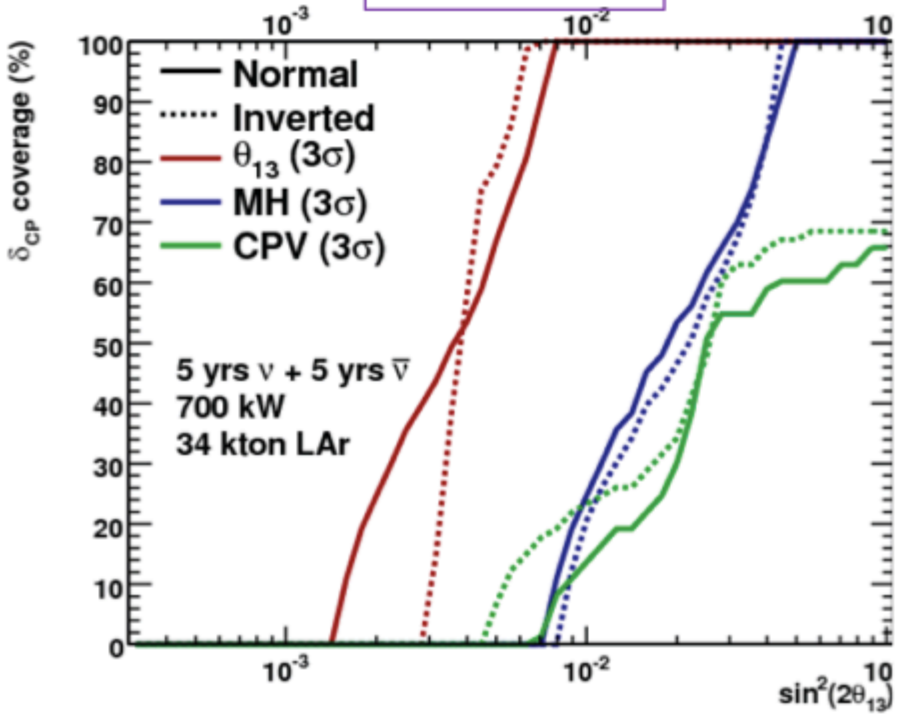




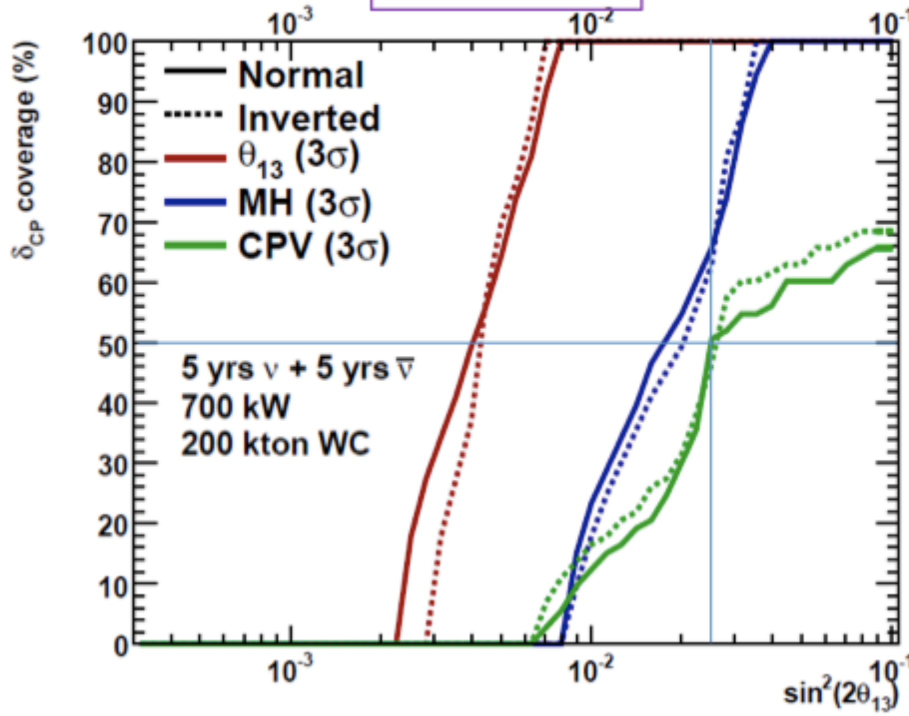
Example of sensitivity to oscillation parameters

LBNE sensitivity (1300 km baseline)

34 kt LAr TPC



200 kt WCD



Note: 34 kton LAr ~ 200 kt WCD because of better LAr efficiency

R. Wilson, NNN 11

- Fall 2010 NSF declined to pursue DUSEL as the primary agency
  - Set back LBNE at least 1 year
- DOE convened a committee to "Review of Options for Underground Science"
  - Consider viability and cost-effectiveness of Homestake as a DOE site for future particle and nuclear experiments specifically: LBNE, $0\nu\beta\beta$, Dark Matter (SNOLab to be considered as option for $0\nu\beta\beta$/Dark Matter)
  - Committee report to DOE June 2011: LBNE viable at Homestake
  - Recommended an early decision on far detector technology
  - We are waiting DOE decision on Homestake as the FD site
- Money set aside by NSF (FY11) and DOE (FY12) to continue dewatering and safety operations at Homestake
- July 2011: National Research Council committee report on DUSEL science was strongly supportive

Somewhat optimistic schedule:

Preconceptual Planning	*Conceptual Design*	*Preliminary Design*	*Final Design*	*Construction*	*Operations*

CD-0	CD-1	CD-2	CD-3	CD-4
Approve Mission Need	Approve Alternative Selection & Cost Range	Approve Performance Baseline	Approve Start of Construction	Approve Start of Operations or Project Completion
2010 Q2 (Actual)	2012 Q3	2014 Q1	2015 Q3	2022

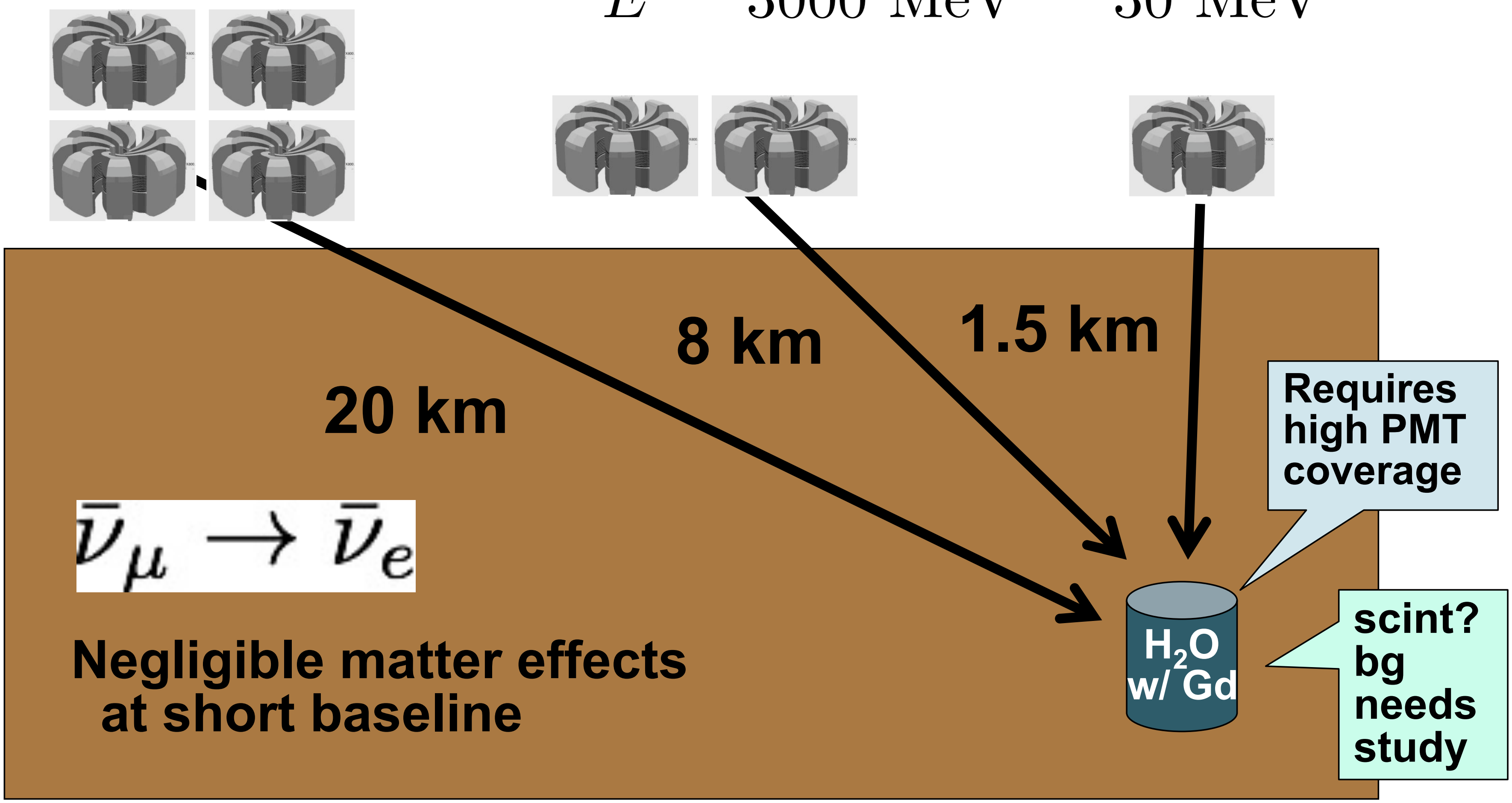
A different approach for ν CPV: DAEδALUS

NEW

Multiple stopped-pion neutrino sources:

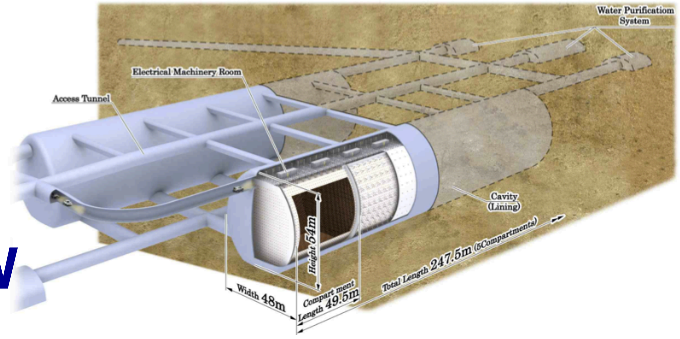
L~1.5-20 km
E ~10-50 MeV

$$\frac{L}{E} \sim \frac{1000\ \mathrm{km}}{3000\ \mathrm{MeV}} \sim \frac{10\ \mathrm{km}}{30\ \mathrm{MeV}}$$



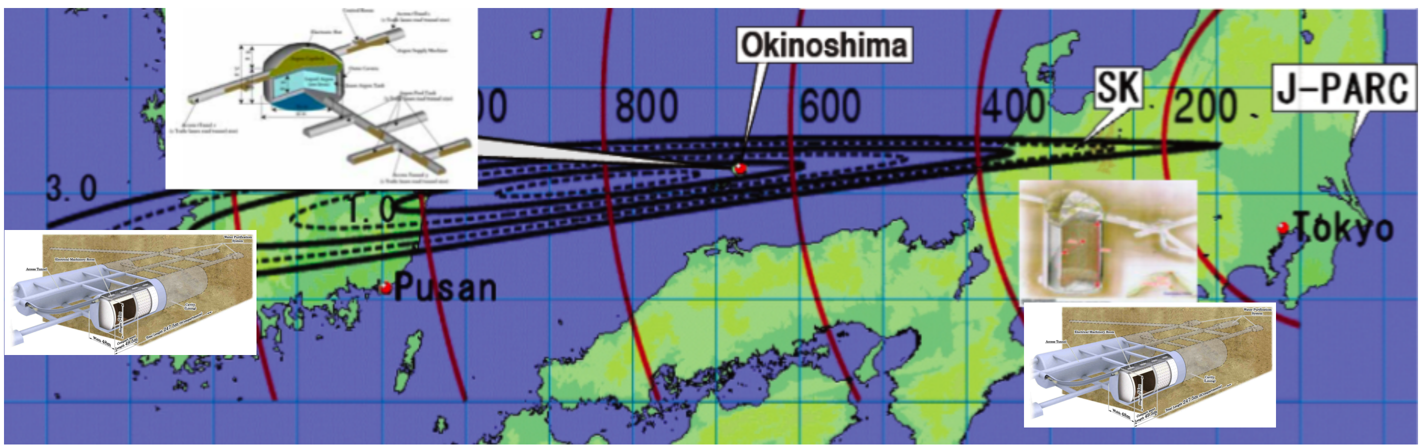
J. Conrad & M. Shaevitz, Multiple Cyclotron Method to Search for CP Violation in the Neutrino Sector, arXiv:0912.4079, Phys. Rev. Lett. 104, 141802 (2010)

Future programs: Asia

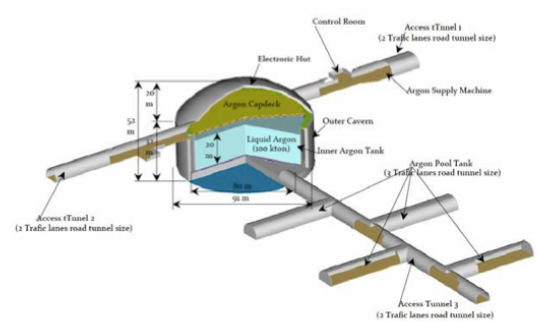


Hyper-Kamiokande

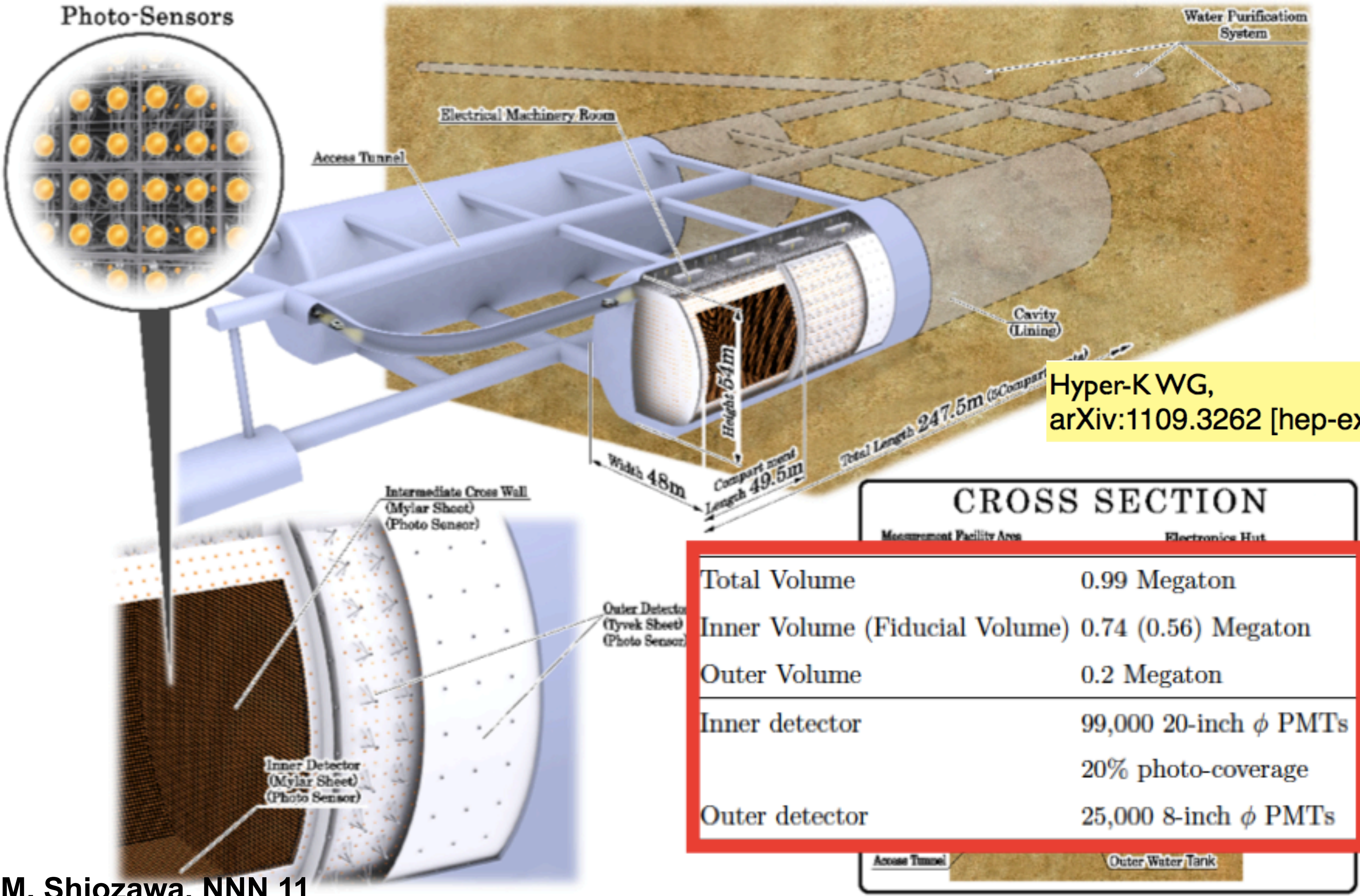
- Tochibora mine, near Kamioka;
  sites under study (1500-1750 mwe)
- 560 ktons (25 x SK)
- eventual upgrade to T2K beam to 1.7 MW
- LOI posted to arXiv: data start ~2018



Also, ideas for 100 kton LAr
at Okinoshima island
(R&D program started at KEK)



Schematic View of the Hyper-Kamiokande



Total Volume	0.99 Megaton
Inner Volume (Fiducial Volume)	0.74 (0.56) Megaton
Outer Volume	0.2 Megaton
Inner detector	99,000 20-inch ϕ PMTs
	20% photo-coverage
Outer detector	25,000 8-inch ϕ PMTs

Hyper-K WG, arXiv:1109.3262 [hep-ex

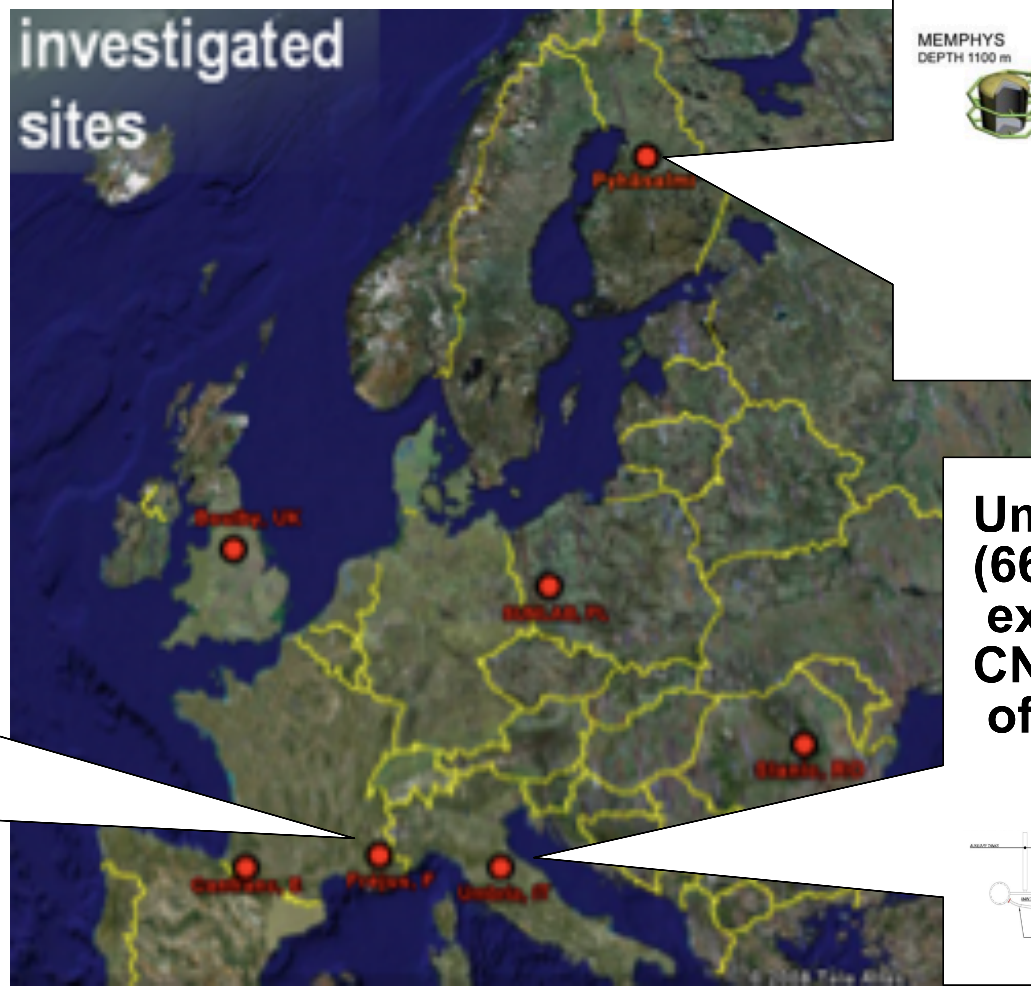
M. Shiozawa, NNN 11

Future programs: Europe

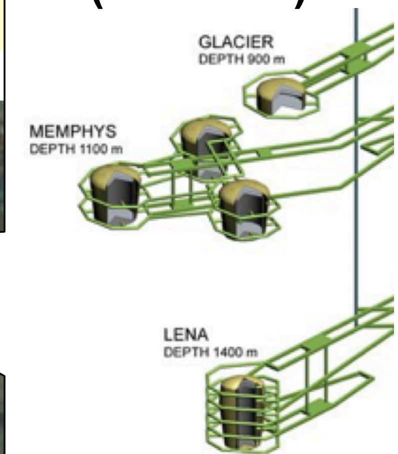
LAGUNA-LBNO

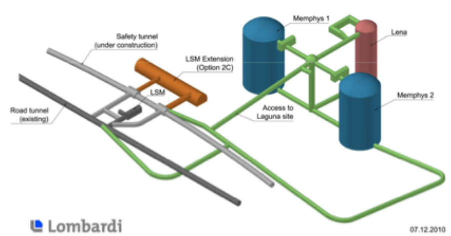
MEMPHYS: 0.5 Mt water
GLACIER: 100 kt LAr
LENA: 50 kt scintillator

0.4-1.2 MW beam from CERN, 130-2300 km (Future: β beam, ν factory)



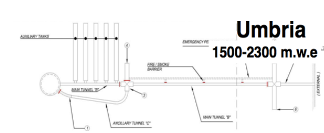
Pyhäsalmi (2300 km)



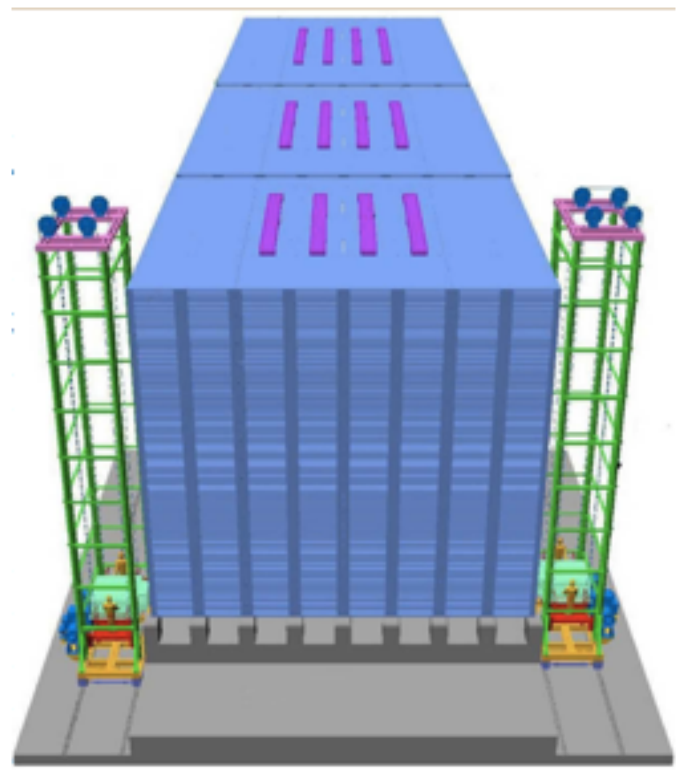


Fréjus (130 km)

Umbria (665 km, existing CNGS beam, off-axis)



Also: INO India-based Neutrino Observatory



Focus on atmospheric neutrinos
w/magnetized 50 kt iron calorimeter ICAL
(get charge sign, nu vs nubar);

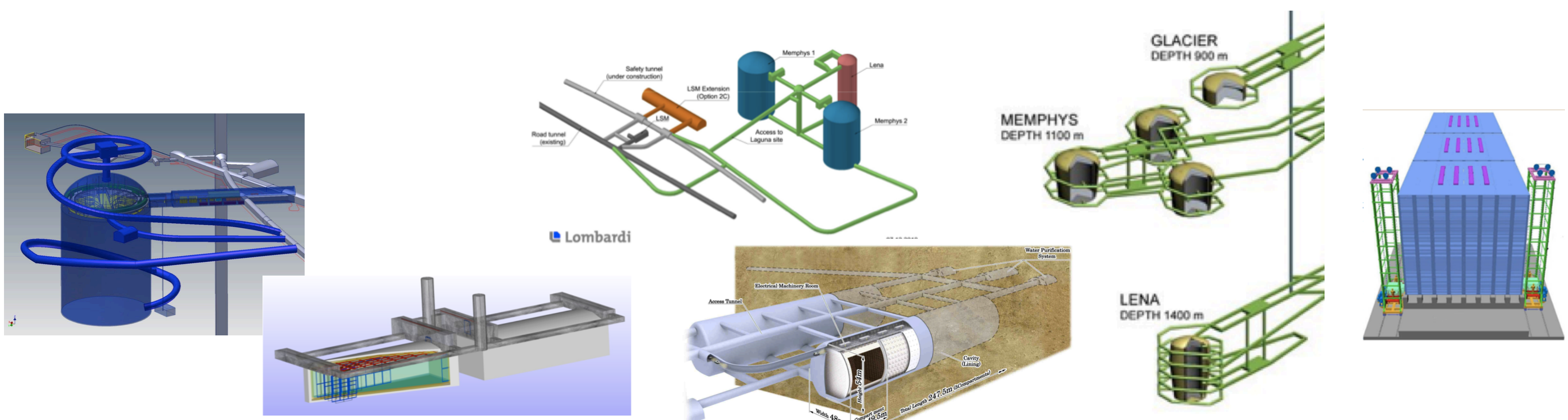
Possibly ~7000 km long baseline to CERN or J-PARC
in long term future?

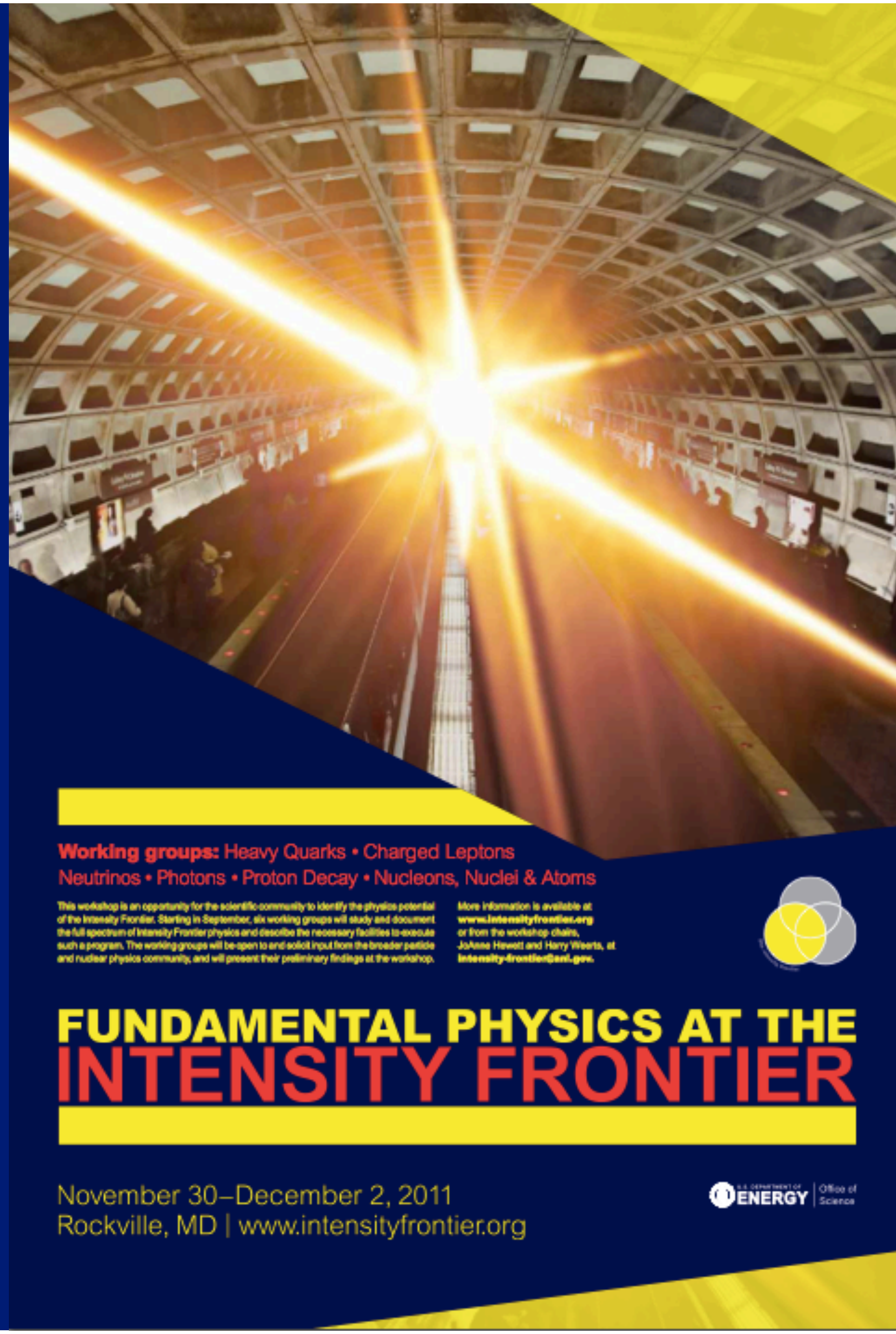
The Glorious Future

Let's hope for a diverse one, with breadth of approaches and physics!

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

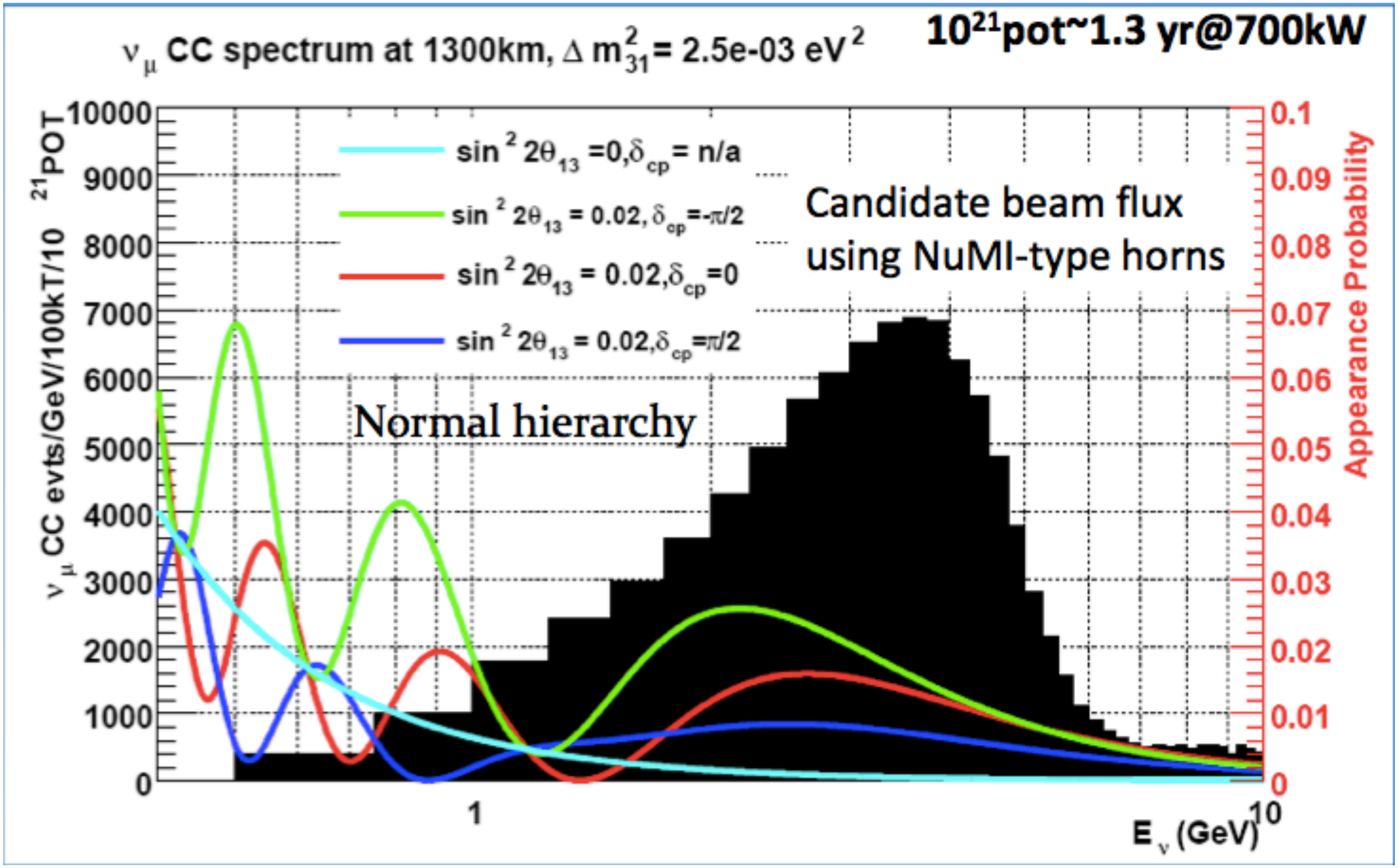
Zoom in on CP δ, and mass hierarchy





Working groups: Heavy Quarks • Charged Leptons
Neutrinos • Photons • Proton Decay • Nucleons, Nuclei & Atoms
This workshop is an opportunity for the scientific community to identify the physics potential of the Intensity Frontier. Starting in September, six working groups will study and document the full spectrum of Intensity Frontier physics and describe the necessary facilities to execute such a program. The working groups will be open to and solicit input from the broader particle and nuclear physics community, and will present their preliminary findings at the workshop.
More information is available at www.intensityfrontier.org or from the workshop chairs, JoAnne Hewett and Harry Weerts, at intensity-frontier@anl.gov.
FUNDAMENTAL PHYSICS AT THE
INTENSITY FRONTIER
November 30–December 2, 2011
Rockville, MD | www.intensityfrontier.org
ENERGY | Office of Science

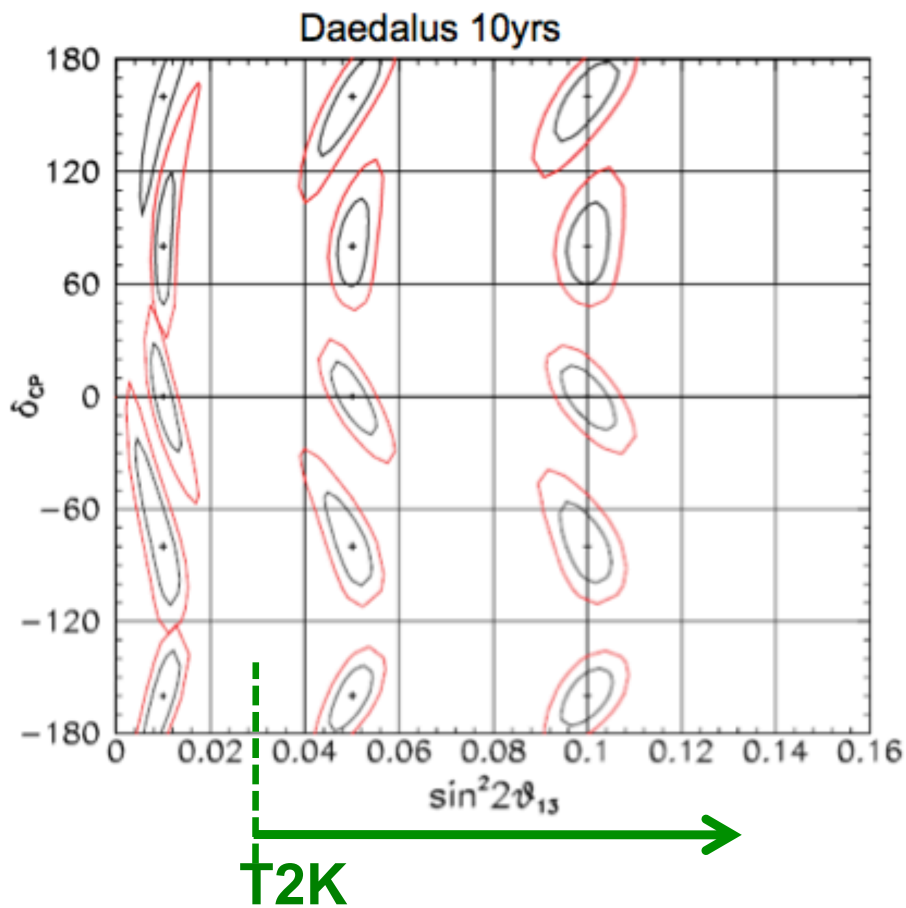
LBNE event spectrum and oscillation probabilities

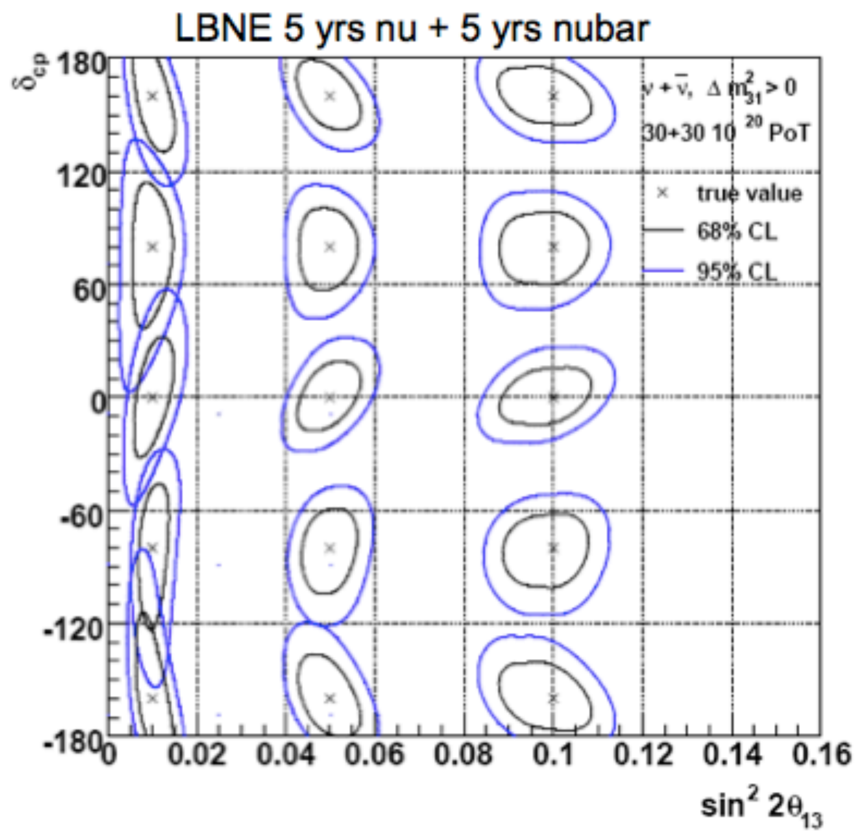


R. Wilson, NNN 11

DAEδALUS CP sensitivity

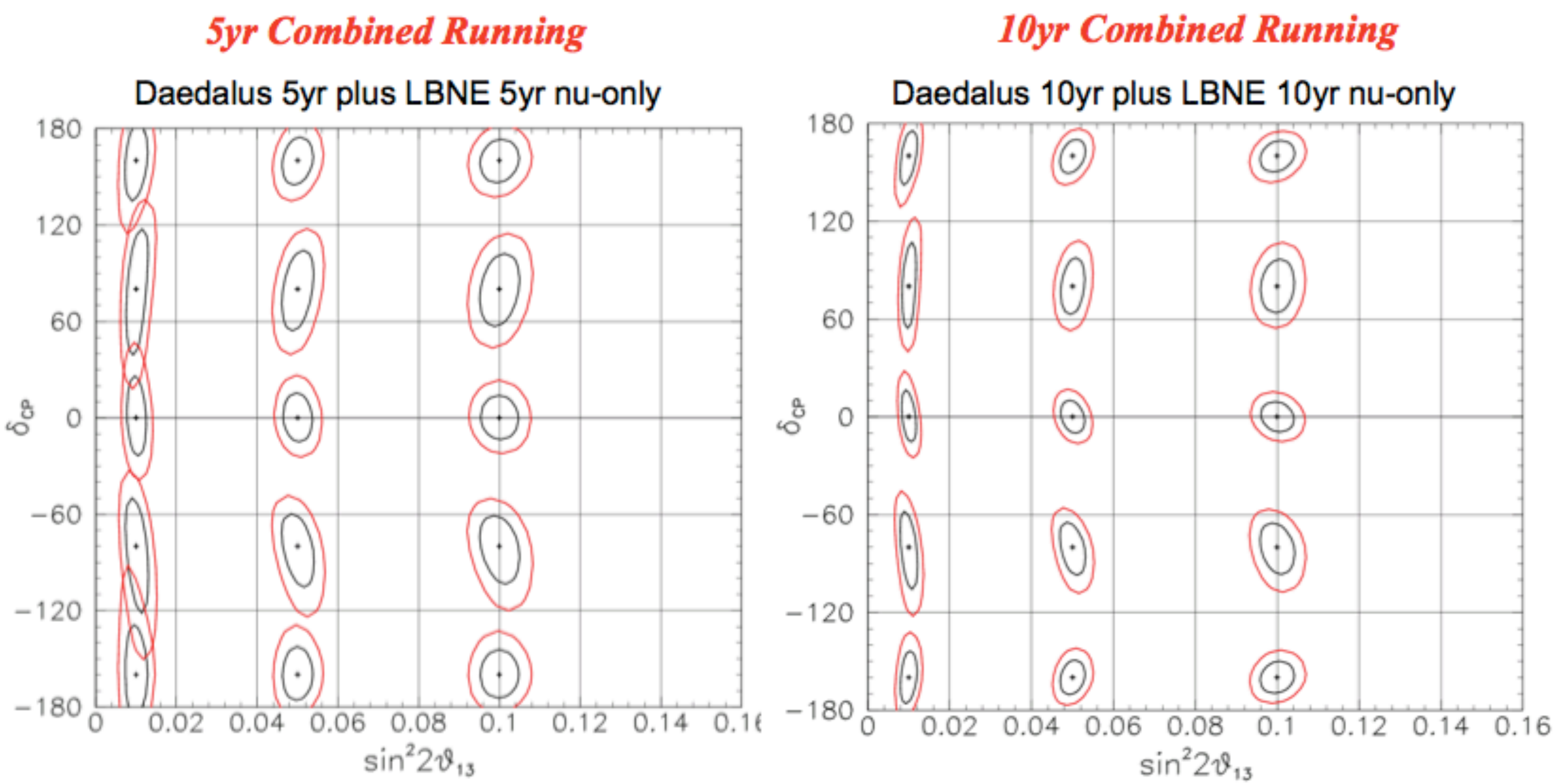
(assumes 300 kt WC, normal hierarchy)





Combining with LBNE

(assumes 300 kt WC)

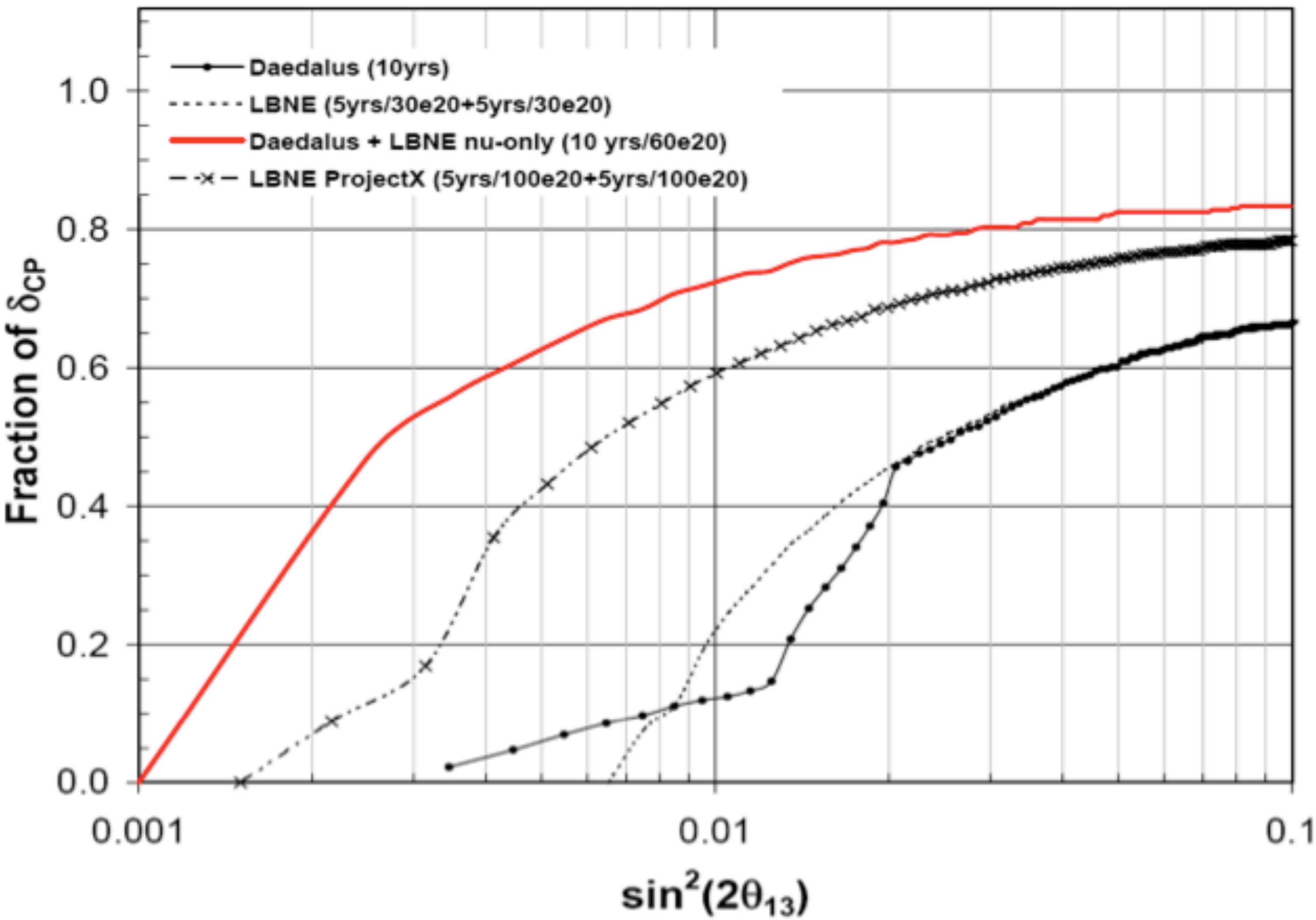


1 and 2 σ contours

Studies show that
5 LBNE + 5 DAEδALUS is better than
10 LBNE or 10 DAEδALUS

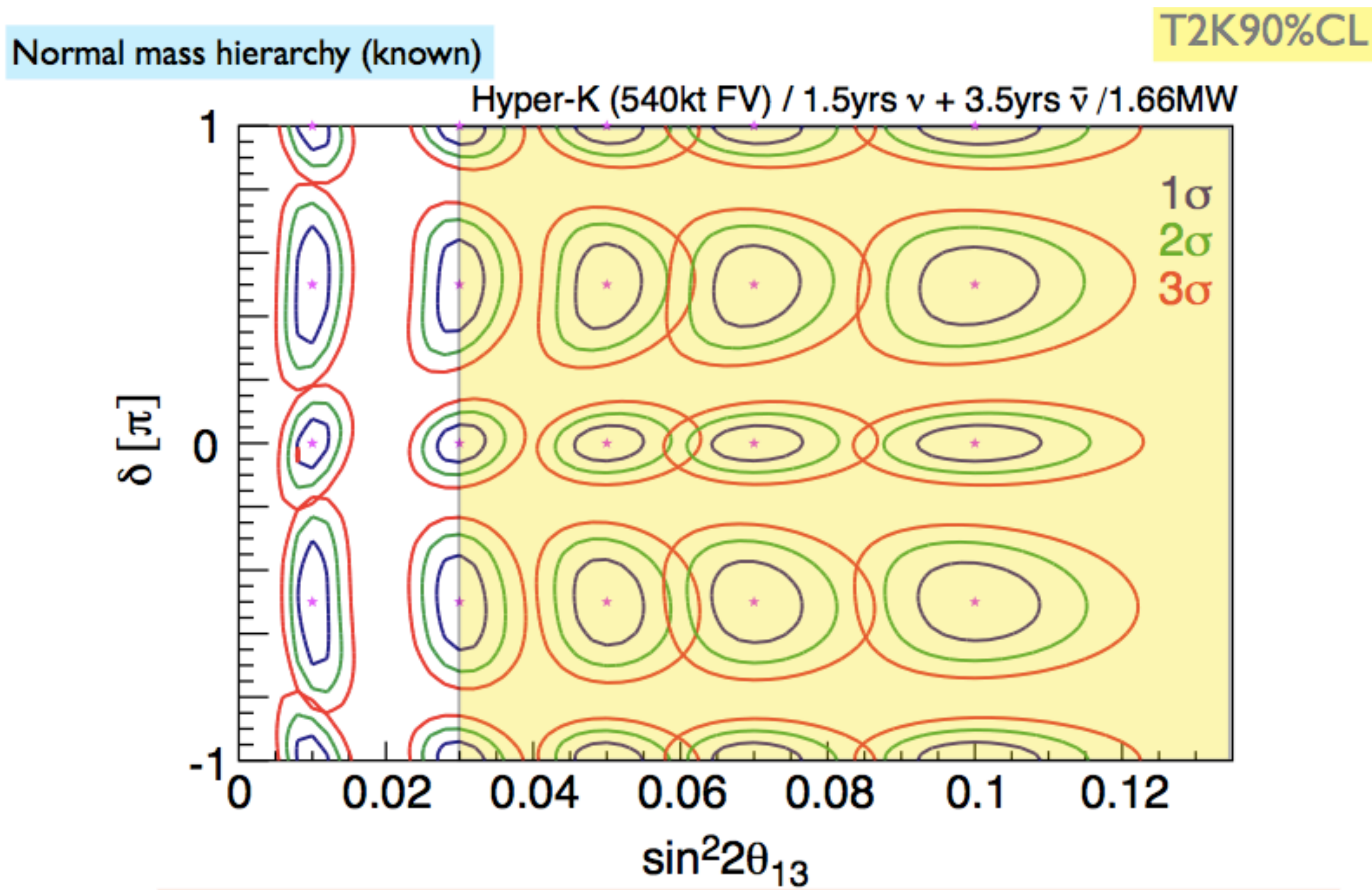
- **A Study of Detector Configurations for the DUSEL CP Violation Searches Combining LBNE and DAEδALUS, arXiv:1008.4967**

Combining with LBNE



(Recent preprint has similar conclusions:
Agarwalla,Huber,Link,Mohapatra - http://arxiv.org/abs/1005.4055)

Hyper-K CP Contours



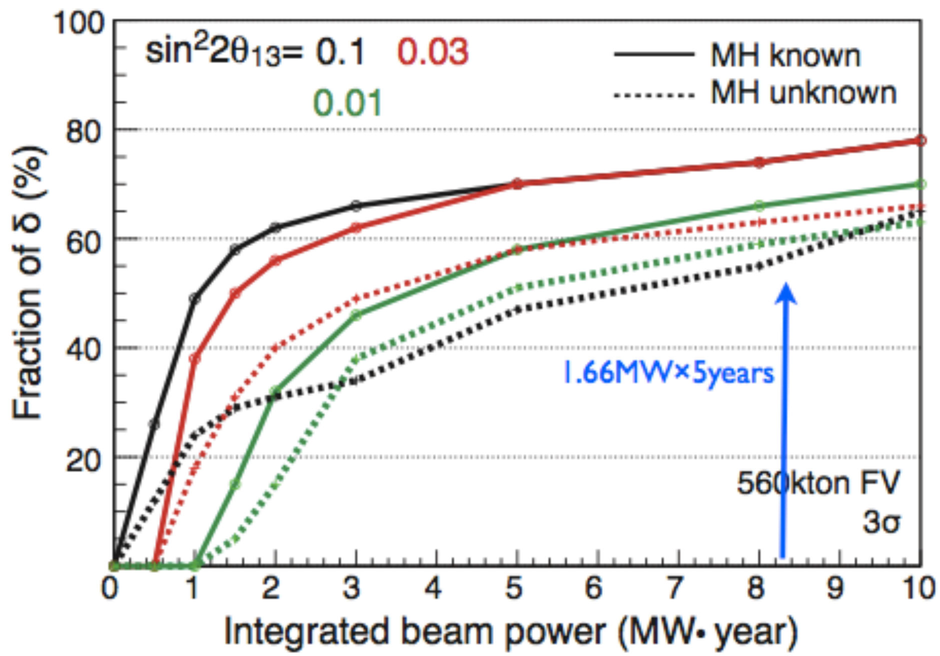
Good sensitivity in whole T2K's θ_{13} allowed region!

M. Shiozawa, NNN 11

Fraction of δ (%) for CPV discovery

Fraction of δ in % for which expected CPV ($\sin\delta \neq 0$) significance is $>3\sigma$

		mass hierarchy known	mass hierarchy unknown
$\sin^2 2\theta_{13}$	0.1	74	55
	0.03	74	63
	0.01	66	59

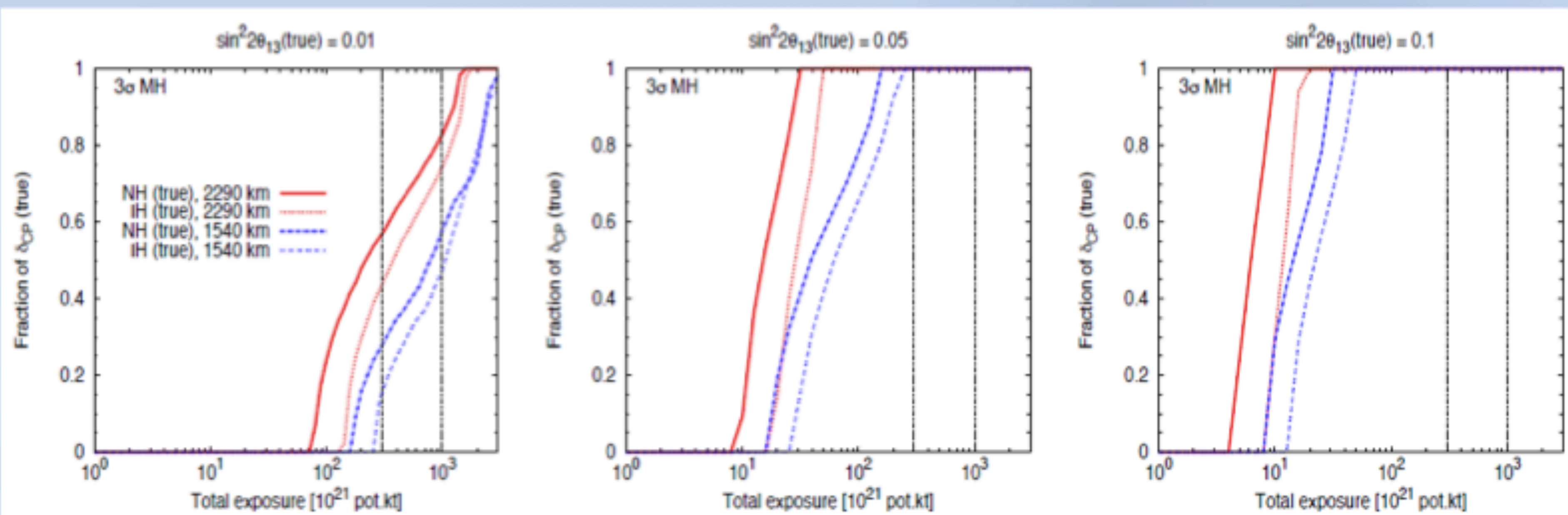


CP violation can be observed with >3σ for 74% of the δ param. space.
Effect of unknown MH is limited (~70% coverage down to ~60%).

M. Shiozawa, NNN 11

Physics with a CNPY beam

Example from 1109.6526 [hep-ph], Agarwalla, Li, Rubbia (HP-PS2: 50GeV protons, 3×10^{21} pot/y (1.6MW))



C. Touramanis, NNN 11