DOE/NSF-HEPAP/NSAC
Neutrino Scientific Assessment Group
“NuSAG”

Report to HEPAP

G. Beier, P. Meyers – July 13, 2007

- Goals of the next phases of neutrino oscillations
- The charge to NuSAG
- Off-axis and Wide Band Beam approaches
- Detector options
- Comparison of sensitivities (BNL/FNAL Study Group)
- Cost, schedule
- NuSAG recommendations

From the original charge to NuSAG:

…we ask the NuSAG to make recommendations on the specific experiments that should form part of the broad U.S. neutrino science program.

- September 1, 2005: **Recommendations to the Department of Energy and the National Science Foundation on a United States Program in Neutrino-less Double Beta Decay**
- February 28, 2006: **Recommendations to the Department of Energy and the National Science Foundation on a U.S. Program of Reactor- and Accelerator-based Neutrino Oscillation Experiments**

Members of NuSAG

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Ed Kearns (Boston University)
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Melvin Shochet (University of Chicago) *ex officio*
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HEP/nuclear, expt/theory, US/not, ν physics/not

Neutrino Oscillation Basics

The mixing matrix is:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Where: $c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

Atmospheric ν_μ | Reactor $\overline{\nu}_e$, Accelerator ν_μ | Solar ν_e | Majorana CP phases

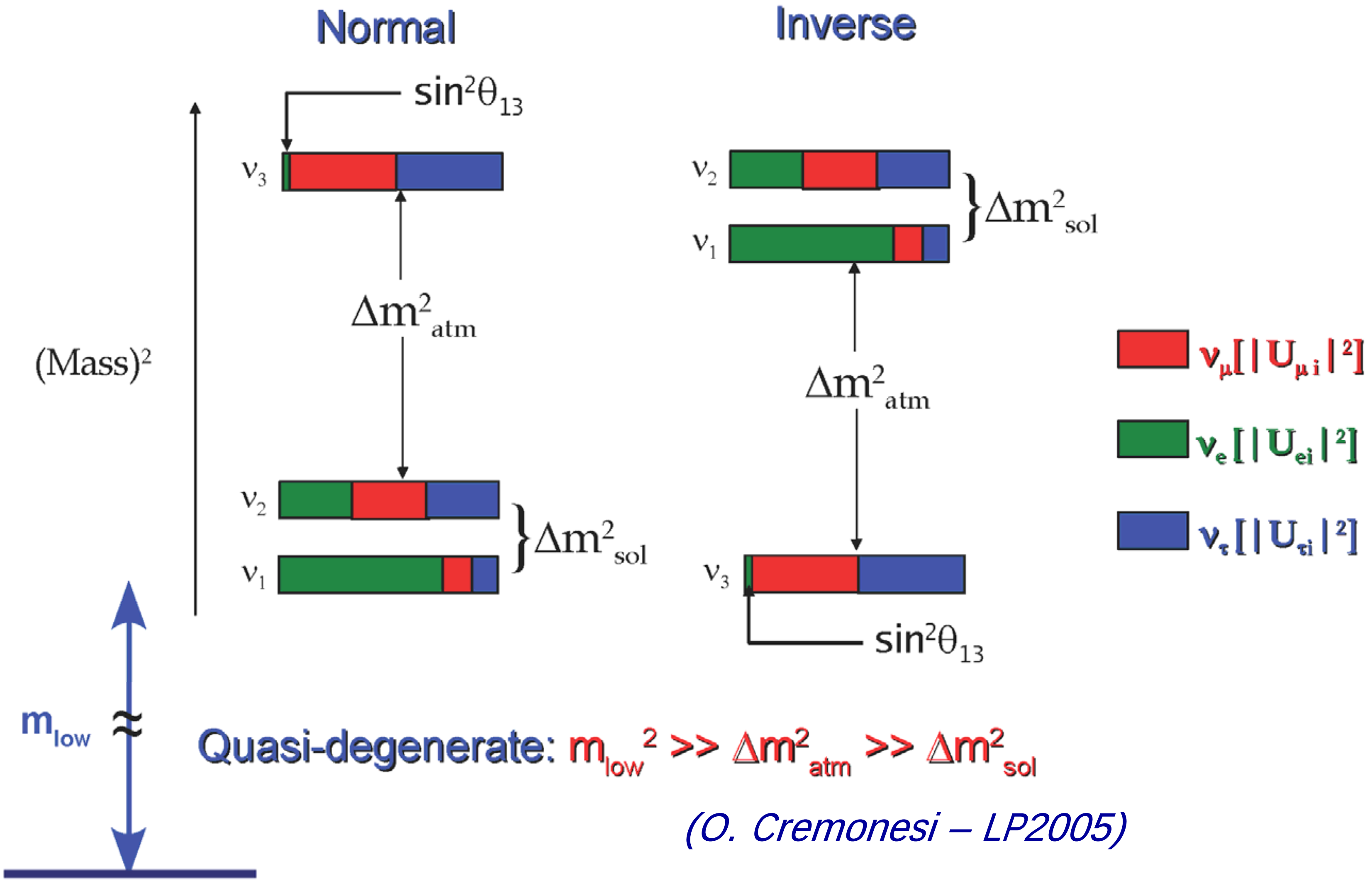
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\theta_{23} \approx \theta_{atm} \approx 45^\circ; \quad \theta_{12} \approx \theta_\odot \approx 34^\circ; \quad \theta_{13} \leq 12^\circ$$

δ *and* matter effects can lead to $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\overline{\nu}_\alpha \rightarrow \overline{\nu}_\beta)$

Majorana CP phases are not accessible through oscillation experiments

The possible mass hierarchies



(O. Cremonesi – LP2005)

Oscillations are sensitive only to Δm^2, not to the scale of m_ν

Goals of the next phases of the worldwide experimental program in neutrino oscillations

Fill out our understanding of 3-neutrino mixing and oscillations:

- What are the orderings and splittings of the neutrino mass states?
- What are the mixing angles?
- Is there CP violation in neutrino mixing?

A world-wide effort has laid out an ambitious program that can do ***all*** of this – subject to the values of the unknown parameters.

Goals of the next phases of the worldwide experimental program in neutrino oscillations

These are difficult experiments, requiring huge detectors and high-power beams:

100-500 kton detectors (Super-K: 22.5 kton)

1 MW beam (NuMI: 170 kW average)

Optimistic timescales run to 2030

Costs: $n \times \$100\text{M}$, with $n >$ (>>?) 3

To a good approximation, the probability $P(\nu_\mu \rightarrow \nu_e)$ for the neutrino oscillation is given by:

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 + \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4$$

Where $\alpha = \Delta m^2_{21} / \Delta m^2_{31}$ is the small (~1/35) ratio between the solar and atmospheric $(\text{Mass})^2$ splittings

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta)]}{(1-x)^2}$$

Atmospheric

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

Interference:

CP violating

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP conserving

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

Solar

And: $\Delta = \Delta m^2_{31} L / 4E_\nu$ **Kinematical oscillation phase**

$x = 2\sqrt{2} G_F N_e E_\nu / \Delta m^2_{31}$ **Matter effects: G_F = Fermi coupling**

N_e=electron density

Degeneracies: at fixed neutrino energy and baseline, $P(\nu_\mu \rightarrow \nu_e)$ depends on 3 (4) unknown parameters

- $\sin^2 2\theta_{13}$
- δ_{CP}
- $\text{sgn}(\Delta m^2_{31})$
- $(\sin^2\theta_{23})$ – if $\theta_{23} \neq 45°$ ($\sin^2 2\theta_{23}$ is measured)

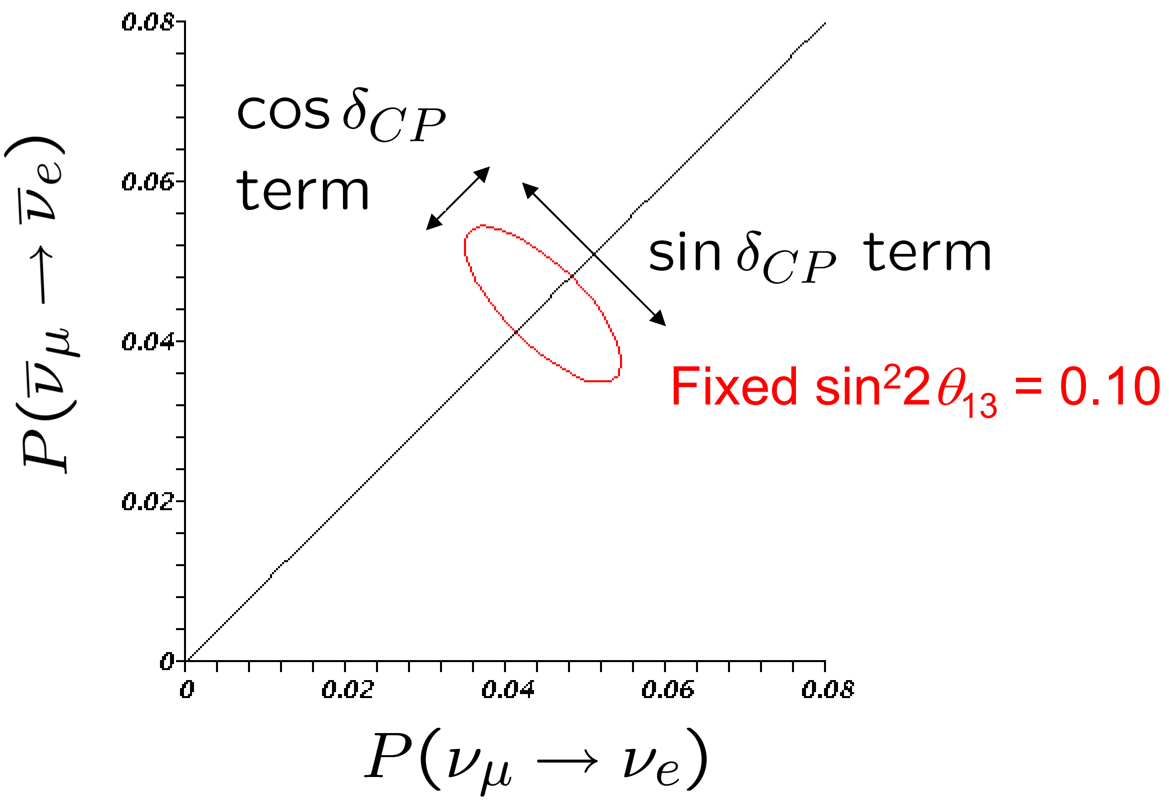
Strategies:

- More measurements
  - $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - multiple energies, multiple baselines
  - $\sin^2 2\theta_{13}$ from reactor experiments
- Longer baseline → higher E → larger matter effect
- Dumb luck

Bi-Probability Plot

E_ν=2.3 GeV, L=810 km - NOνA Parameters

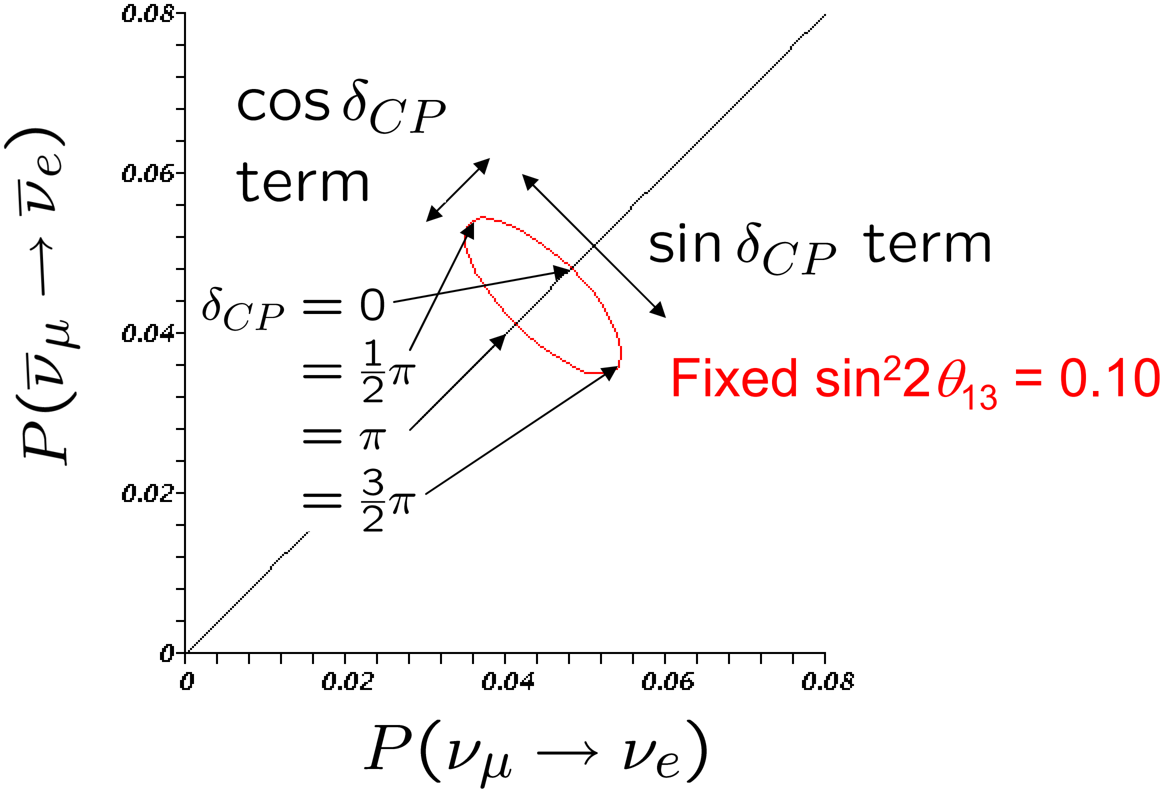
CP violation – vacuum oscillations



Bi-Probability Plot

E_ν=2.3 GeV, L=810 km - NOνA Parameters

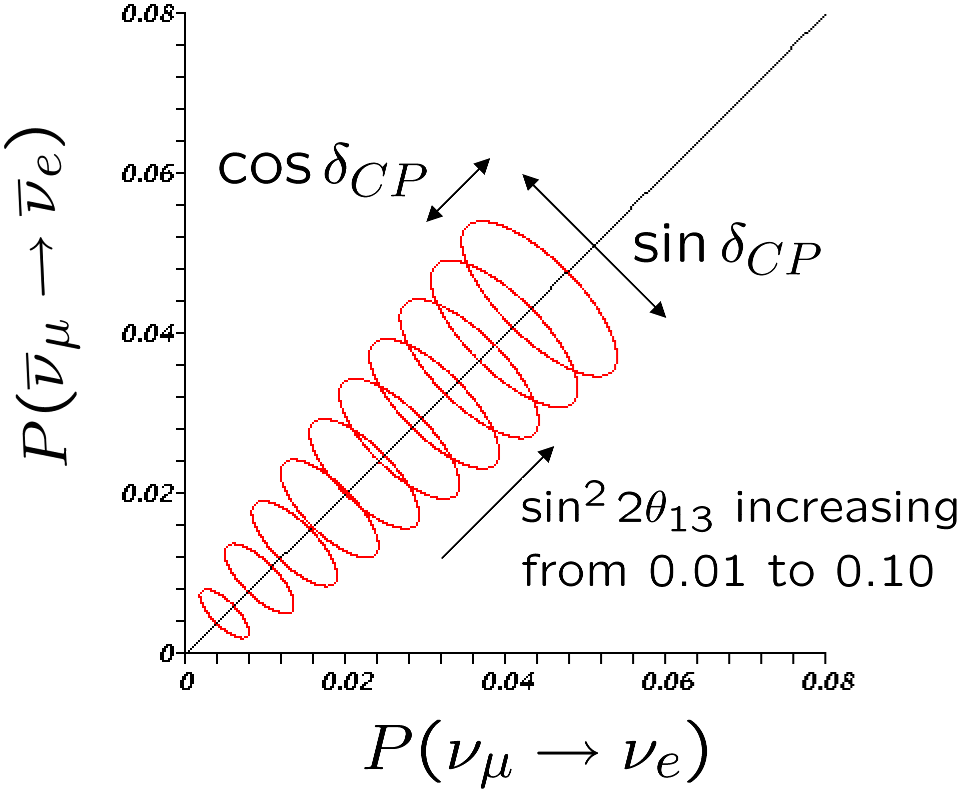
CP violation – vacuum oscillations



Bi-Probability Plot

E_ν=2.3 GeV, L=810 km - NOνA Parameters

CP violation – vacuum oscillations

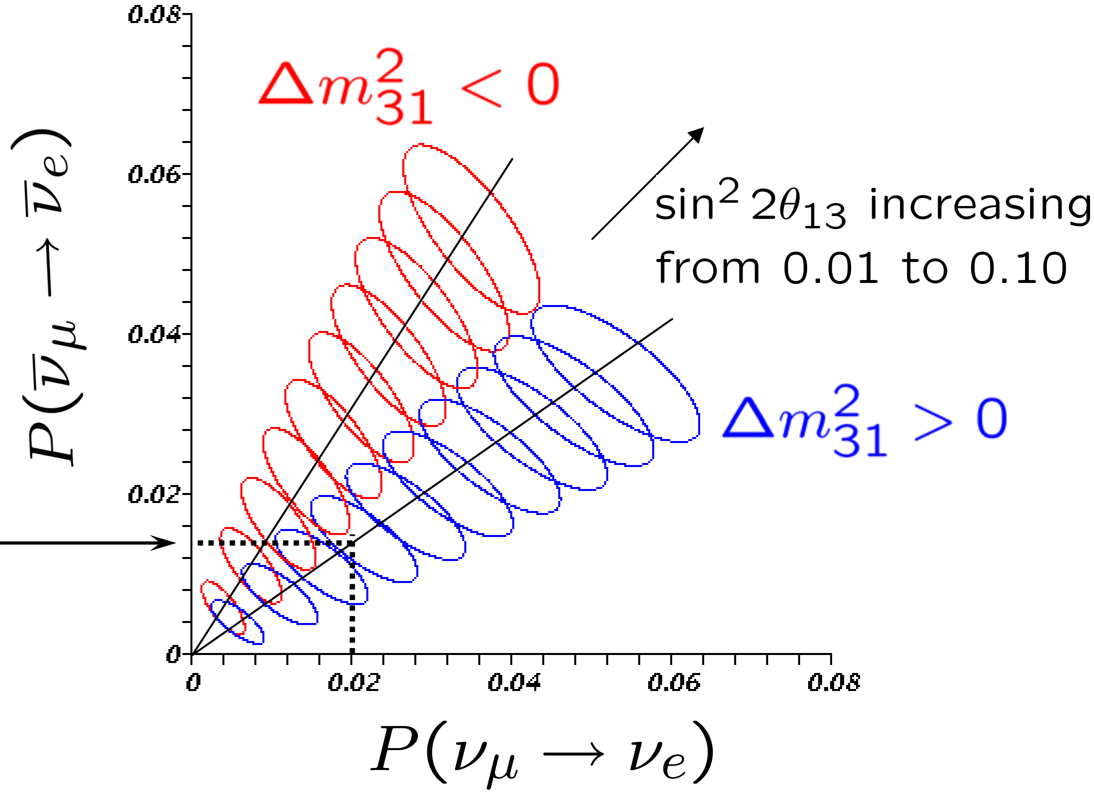


Bi-Probability Plot

E_ν=2.3 GeV, L=810 km - NOνA Parameters

CP violation – matter oscillations

Δm^2_{31}>0 and CP conserved or Δm^2_{31}<0 and max CP violation



Still assuming perfect measurements of P and $\overline{P}$!

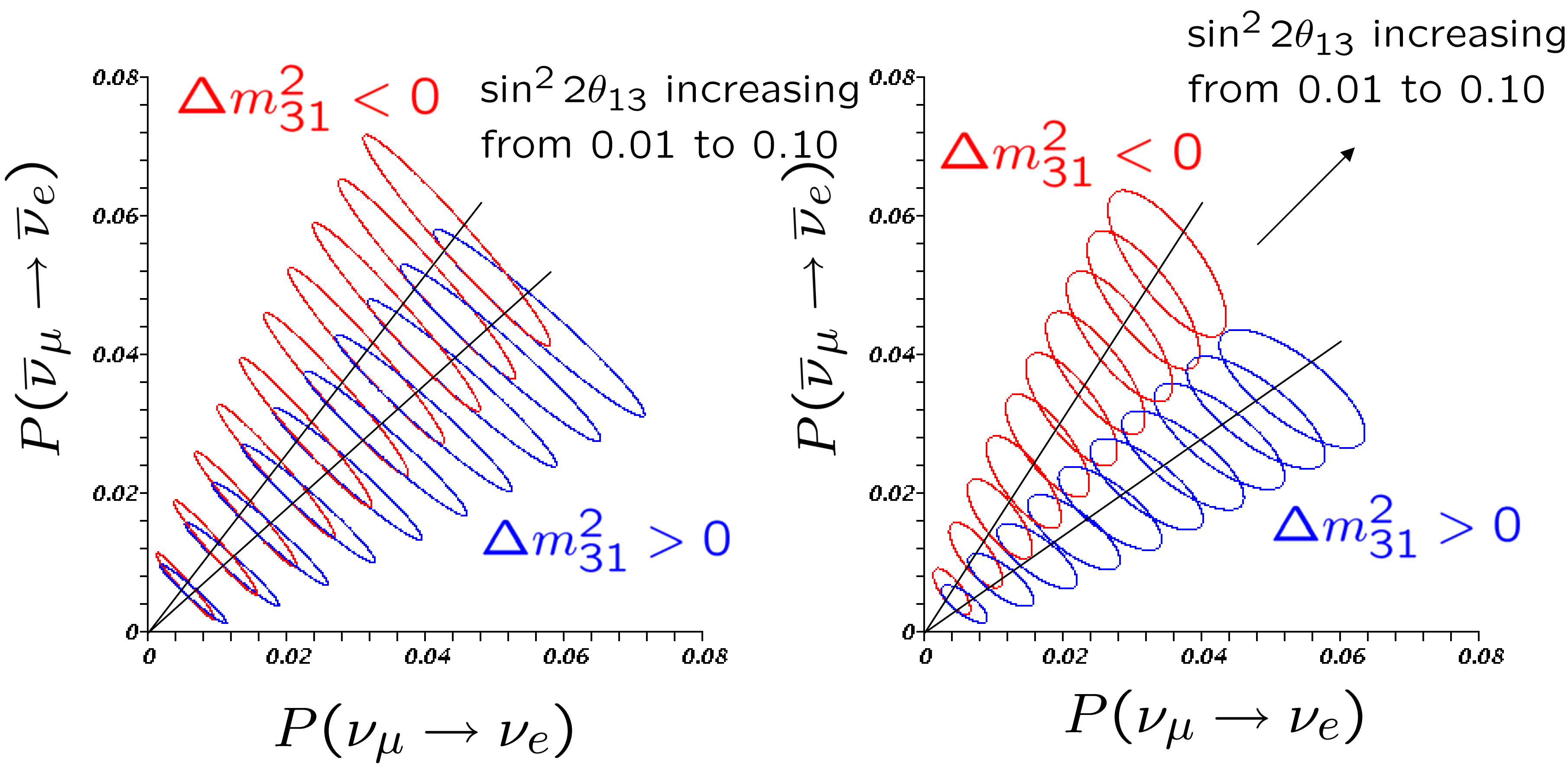
Bi-Probability Plot

E_ν=0.6 GeV, L=295 km

T2K Parameters

E_ν=2.3 GeV, L=810 km

NOνA Parameters



For $\Delta m_{31}^2<0$ and δ_{CP} near $\pi/2$

Or $\Delta m_{31}^2>0$ and δ_{CP} near $3\pi/2$ - Solution may be unique

"Phase 1": currently approved or planned

Reactor experiments

- Double Chooz: 3σ sens $\sin^2 2\theta_{13} \sim 0.05$ by late 2012
- Daya Bay: 3σ sens $\sin^2 2\theta_{13} \sim 0.02$ by 2013

Accelerator experiments (with currently planned beam power)

- T2K: 90%CL sens $P(\nu_\mu \rightarrow \nu_e) \sim 0.01$ by late 2012
- NOvA: 3σ sens $\sin^2 2\theta_{13} \sim 0.02$ by 2014; ~0.01 by late 2017
- NOvA+T2K: some sensitivity to mass hierarchy at the highest currently allowed θ_{13}'s

"Phase 2": NuSAG's current charge

- Next round of accelerator experiments to extend mass-hierarchy and CP violation sensitivity to $\sin^2 2\theta_{13} \sim 0.01$ – seems to be about the max reach with conventional beams

From NuSAG's second charge letter:

"Assuming a megawatt class proton accelerator as a neutrino source, please answer the following questions for accelerator-detector configurations including those needed for a multi-phase off-axis program and a very-long-baseline broad-band program."

The questions:

- Scientific potential
- Associated detector options, including rough cost
- Optimal timeline, including international context
- What other scientific inputs are needed?
- What additional physics can be addressed?

Historical context (c.2005-6) and the BNL/FNAL Study Group

• T2K and NOvA use "off-axis" neutrinos to create narrow-band beams, and both lay out potential programs including upgraded accelerator power, beams, and detectors.
• Meanwhile, an alternate approach using a "wide-band beam" proposed (originally by Brookhaven groups).

These are the approaches NuSAG is charged to evaluate.

Concurrently, BNL and FNAL convened a Study Group spanning both approaches – **NuSAG's major input.**

General consensus: **FNAL Main Injector would be the proton source** for either approach in the U.S.

Accelerator $\nu_\mu \rightarrow \nu_e$ appearance experiments

Signature:

• Electrons from ν_e Charged Current (CC) events

• Quasi-elastic (CCQE) cleanest and allow reconstruction of ν energy (smeared by Fermi motion)

Backgrounds:

• "Intrinsics": ν_e from μ and K decay, not oscillation

• "π^0":

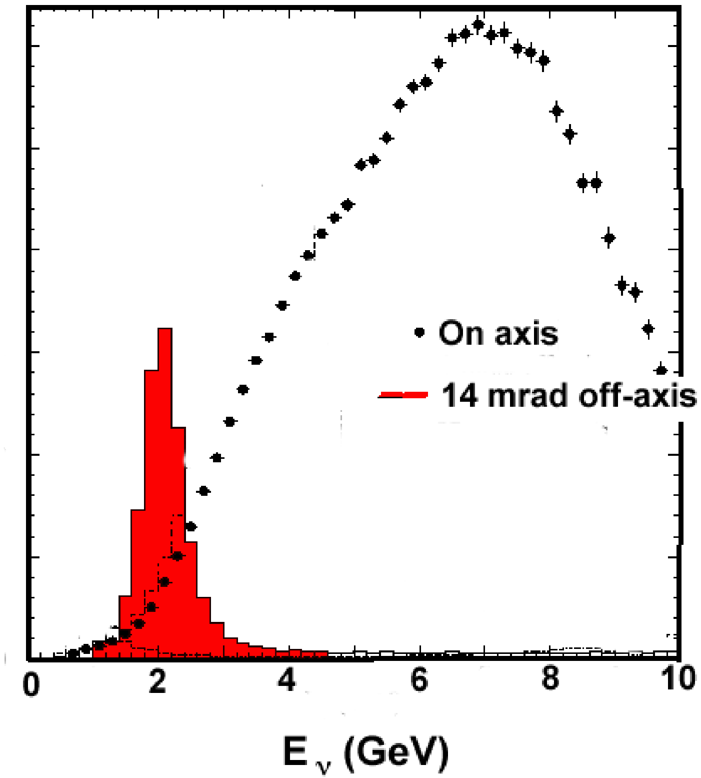
  • produced in higher-energy ν interactions
  • can resemble electrons if gammas merged or low energy gamma missed
  • Neutral Current (NC) π^0 most insidious

Off-axis approach

- At a fixed angle from π beam direction, π's of **all** energies give ν's of about the **same** energy – a narrow-band beam
- Lose flux, but loss of HE flux decreases NC π^0 background at beam energy
- ν_e from K at different energy
- Use upgraded NuMI beam
- No deep sites available

  →detector must work at/near surface

  →cannot use Water Cherenkov



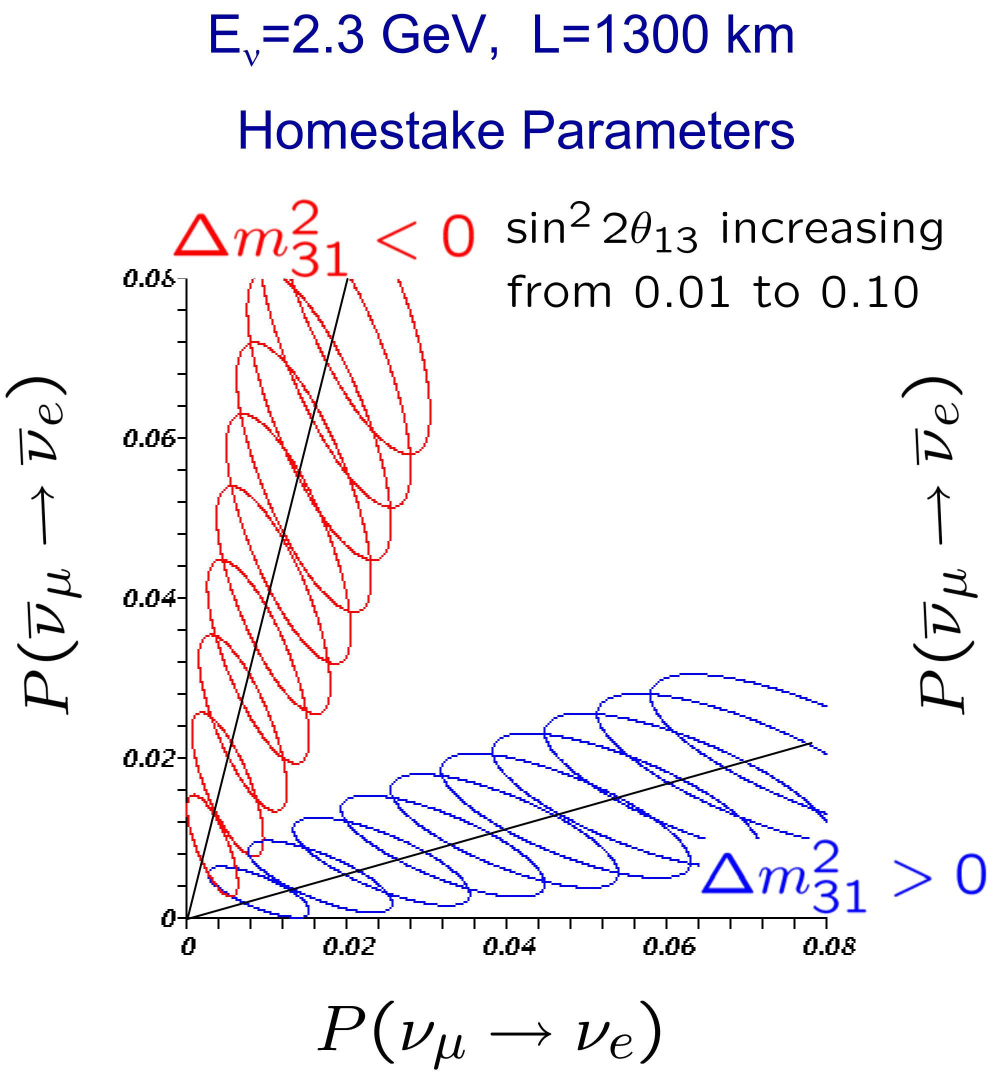
Wide-band Beam approach

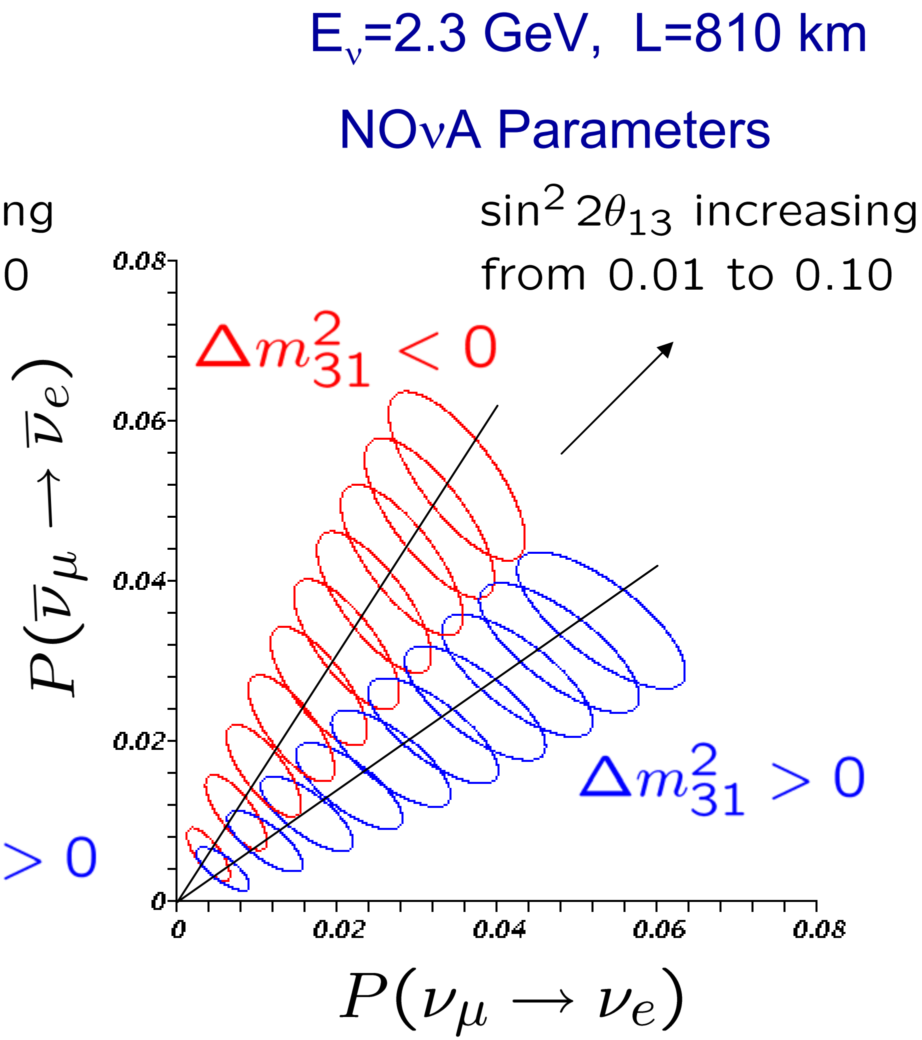
- Energy dependence lifts degeneracies
  (uses primarily spectrum across 1st max, as counting rate is low at 2nd)
- On-axis beam maximizes flux for long baselines
- Long baselines enhance matter effect

but:

- High energy component brings π^0 background
- Use small off-axis angle to suppress

Bi-Probability Plot





Monoenergetic neutrinos – the effect of matter and distance

U.S. experimental scenarios using these approaches

All start with Fermilab Main Injector

- Max achieved beam power: 315 kW @ 120 GeV
- Initial upgrade plan to 700 kW – part of NOvA project
- Possible longer-term upgrade to 1.2 MW (or even 2 MW)
- Less beam power at lower energies

Off-axis

- ~100 kton of Liquid Argon TPC
- Use existing/upgraded NuMI beam
- Deploy all at NOvA site, or split with "2^{nd} max", or other

Wide-band beam, very long baseline

- ~300-500 kton of water Cherenkov (or ~100 kton LArTPC)
- In DUSEL
- New neutrino beam

Detector technologies

Water Cherenkov

- Known, successful technology for ν osc and p decay
- Must be underground: DUSEL
- R&D on large caverns
- PMT's drive cost and construction time
- R&D for new light sensors
- WBB application needs good π^0 rejection

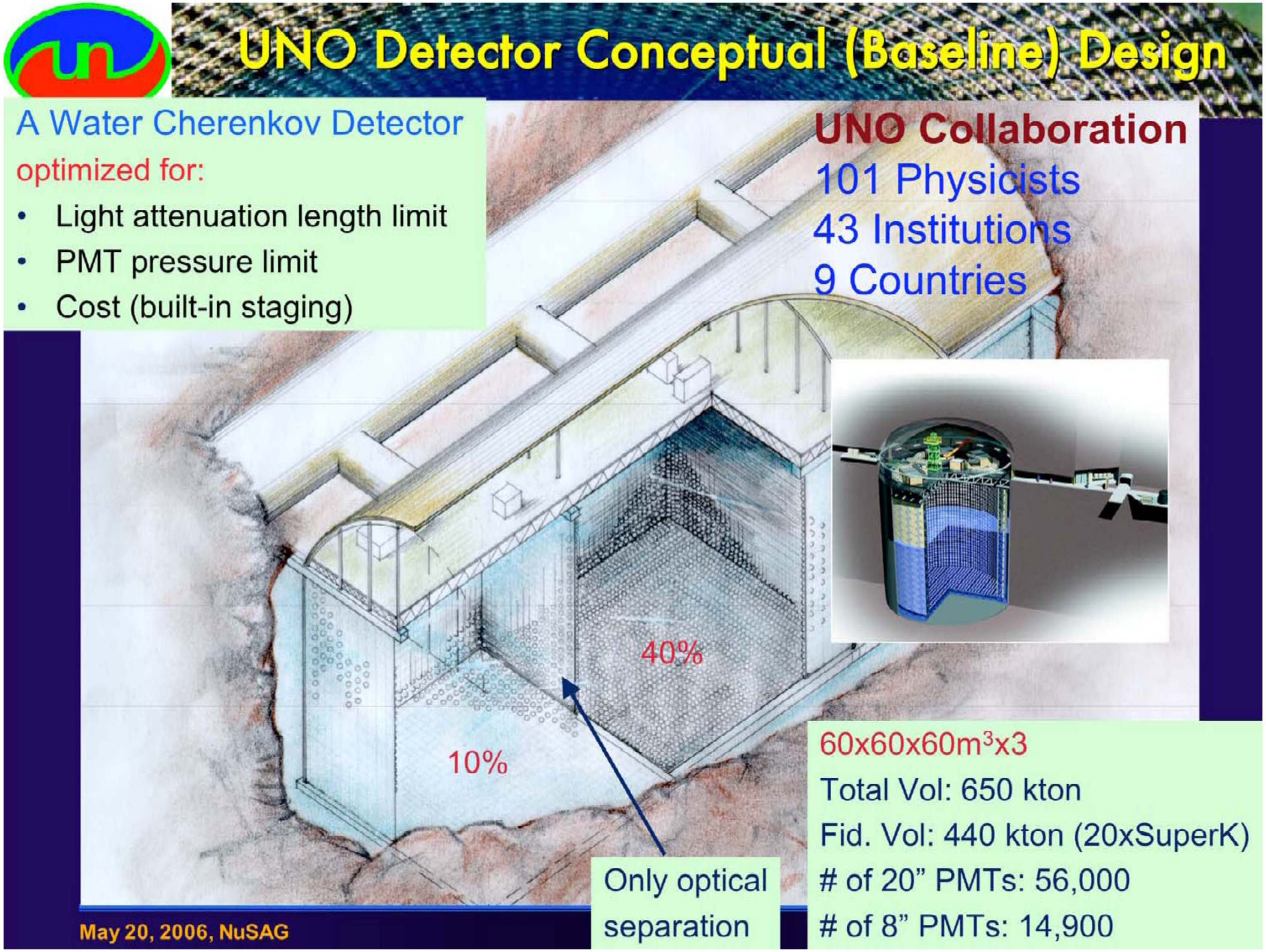
  new algorithms appear to be good enough

  efficiency ~15-20%

  recent development!

Two versions under study in U.S.

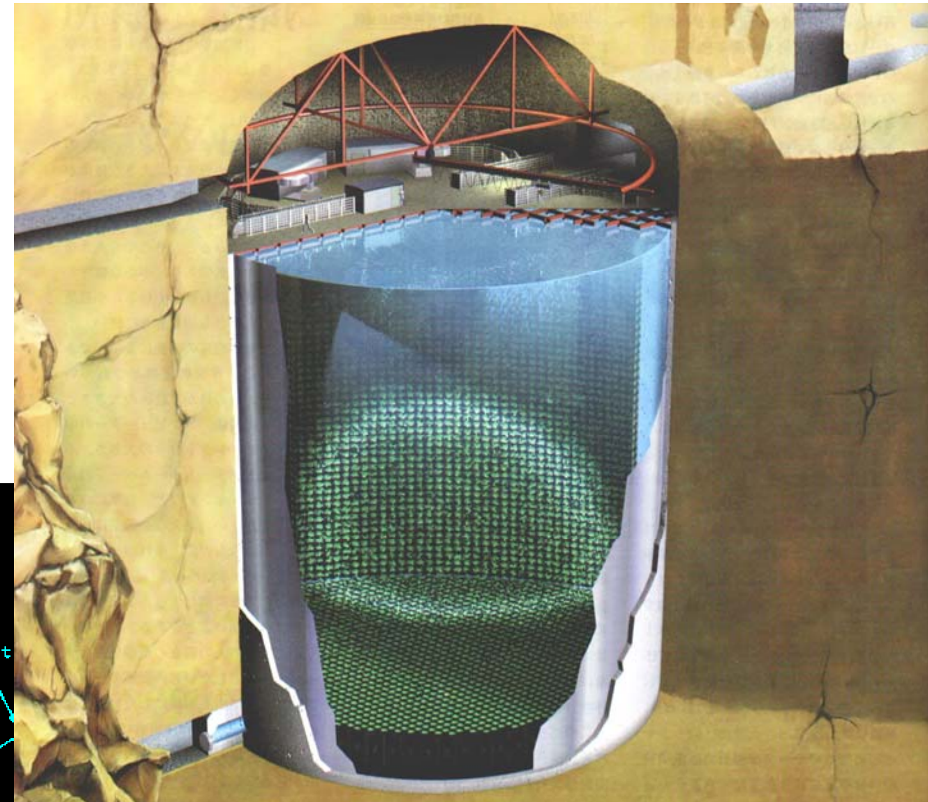
Monolithic Water Cherenkov Detector

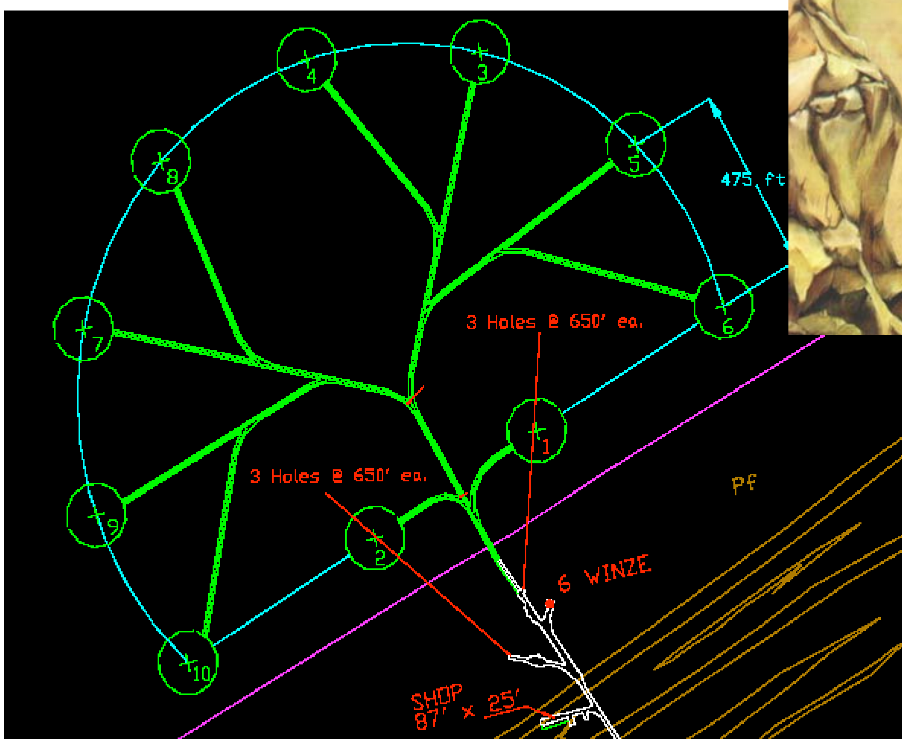


(C.-K. Jung)

Modular Water Cherenkov Detector

Build three 100 kton detector modules – each looks like a scaled up Super-Kamiokande, but with less PMT coverage.





Detector technologies

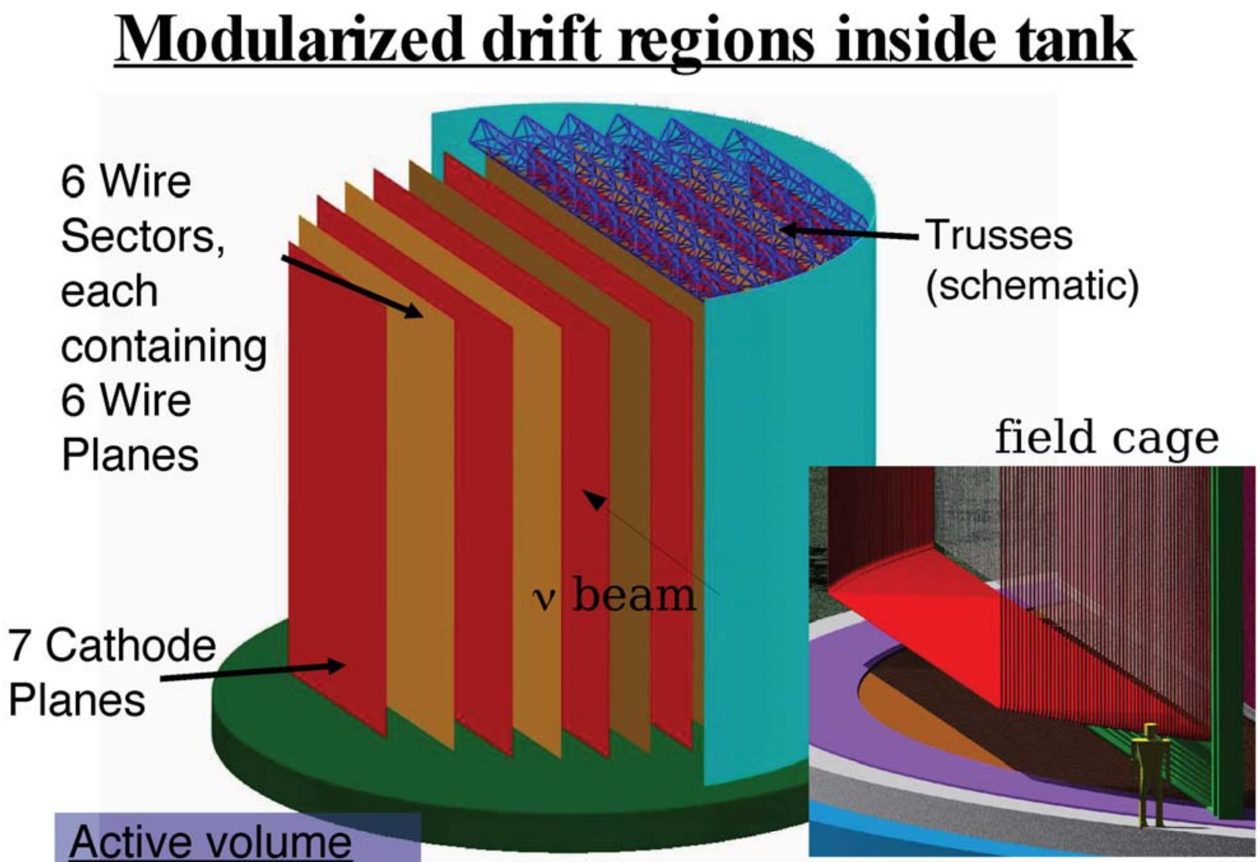
Liquid Argon TPC

- Ability to reconstruct events in detail → excellent π^0 rejection and ~80% efficiency, ~4-5×Water Cherenkov
- If underground, good for $p \rightarrow K^+\nu$, a possibly favored proton decay mode
- Existence proof: ICARUS T600 (two 300 ton modules)
- Aggressive R&D needed to prove feasibility at 50-100 kton scale
- Must drastically reduce costs (<1/10 per-ton of T600)
- Plausible that it can work at surface – proof needed

R&D leading to demonstration of substantial detector in NuMI beam

Liquid Argon Detector

Still early in conceptual design and R&D



Active volume
Diameter: 40m
Height: 30m

(B. Flemming)

Scalable → 15-50 kTons
4 - 6 wire planes

Other Physics

Nucleon decay

- Water Cherenkov detector 15 times Super-K fiducial volume
  excellent general purpose detector

- Liquid argon TPC – excellent for SUSY preferred decay $p \rightarrow K^+ \nu_\tau$ due to good tracking

- Could become high priority if Super-K sees candidates

Low energy neutrino astrophysics

- Neutrino burst from galactic supernova

- Diffuse supernova neutrino background

- Some solar neutrino physics

Other physics may increase costs (e.g. more PMT's for Low E)

Sensitivity calculations by BNL/FNAL Study Group

Options presented (many others looked at):

1. Off axis, 100 kton LAr at NOvA site
2. Off axis, 50 kton LAr at NOvA site + 50 kton LAr at 2nd max
3. Wide-band, 300 kton Water Cherenkov at Homestake
4. Wide-band, 100 kton LAr at Homestake

Note: rule of thumb was LAr ~ 3×WaterC, hence

300 kton WaterC ←→ 100 kton LAr

but under the assumptions developed for the calculations, the factor is more like ×4-5

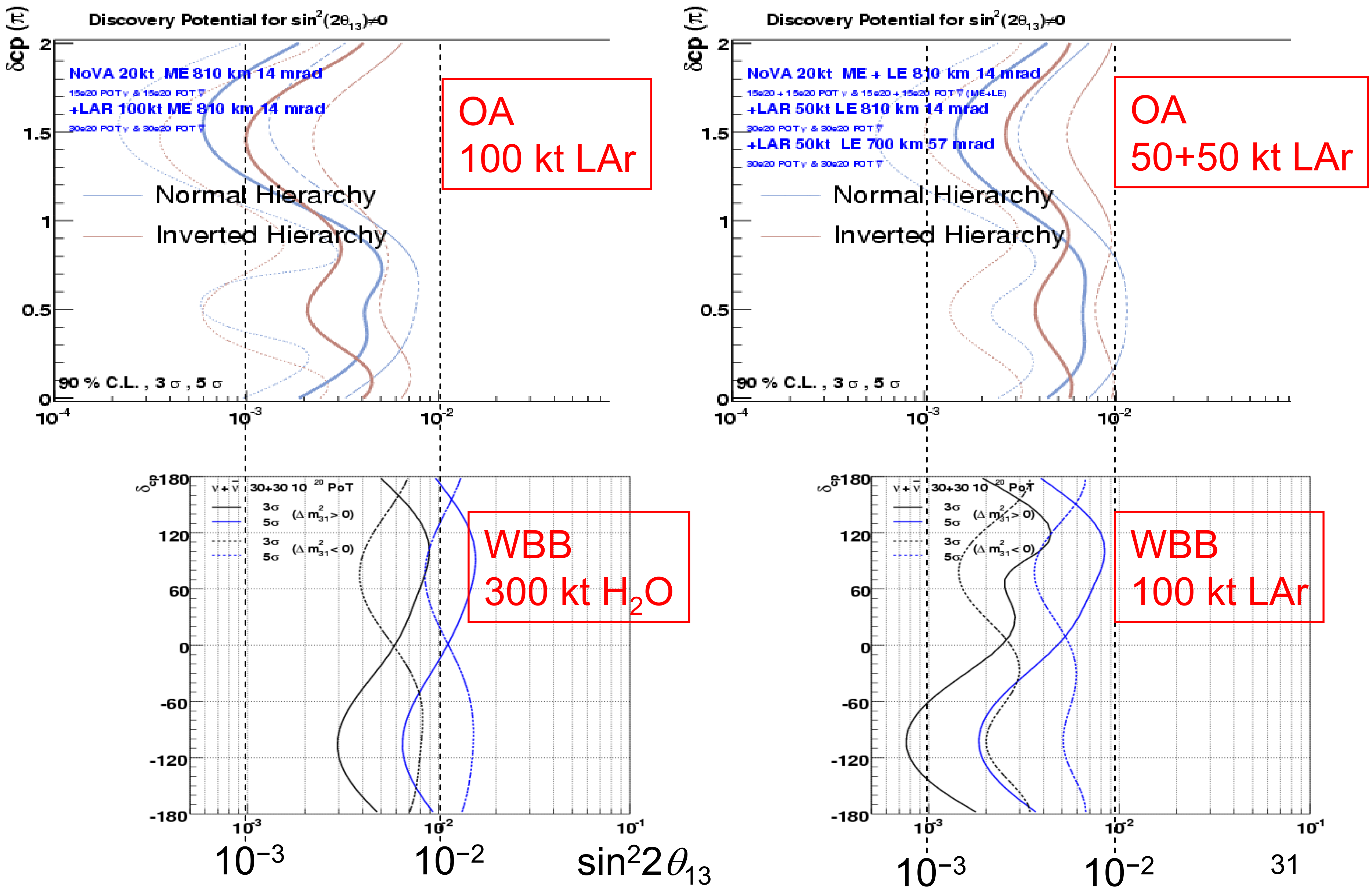
Sensitivity calculations by BNL/FNAL Study Group

NuSAG's criteria:

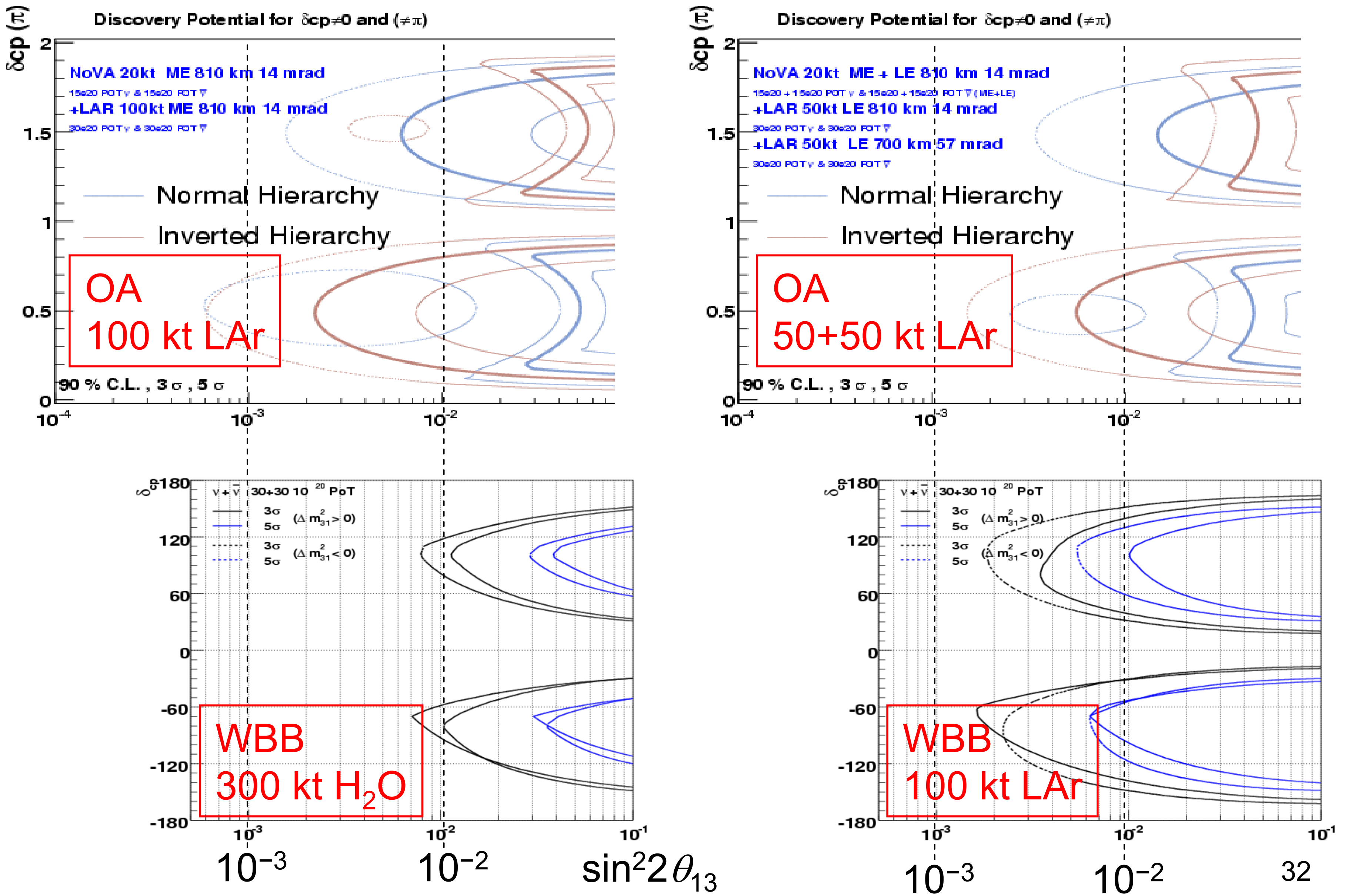
- Establish $\theta_{13} \neq 0$: At what $\sin^2 2\theta_{13}$ is $\sin^2 2\theta_{13}=0$ rejected at 5σ for all values of δ_{CP}?
- Determine the mass hierarchy: At what $\sin^2 2\theta_{13}$ is the wrong mass hierarchy rejected at 5σ for all values of δ_{CP}?
- Find CP violation: At what $\sin^2 2\theta_{13}$ are $\delta_{CP}=0$ and π rejected at 5σ for 50% of the values of δ_{CP}?

The cost, effort, and time required demand that the program's discovery potential be held to high standards.

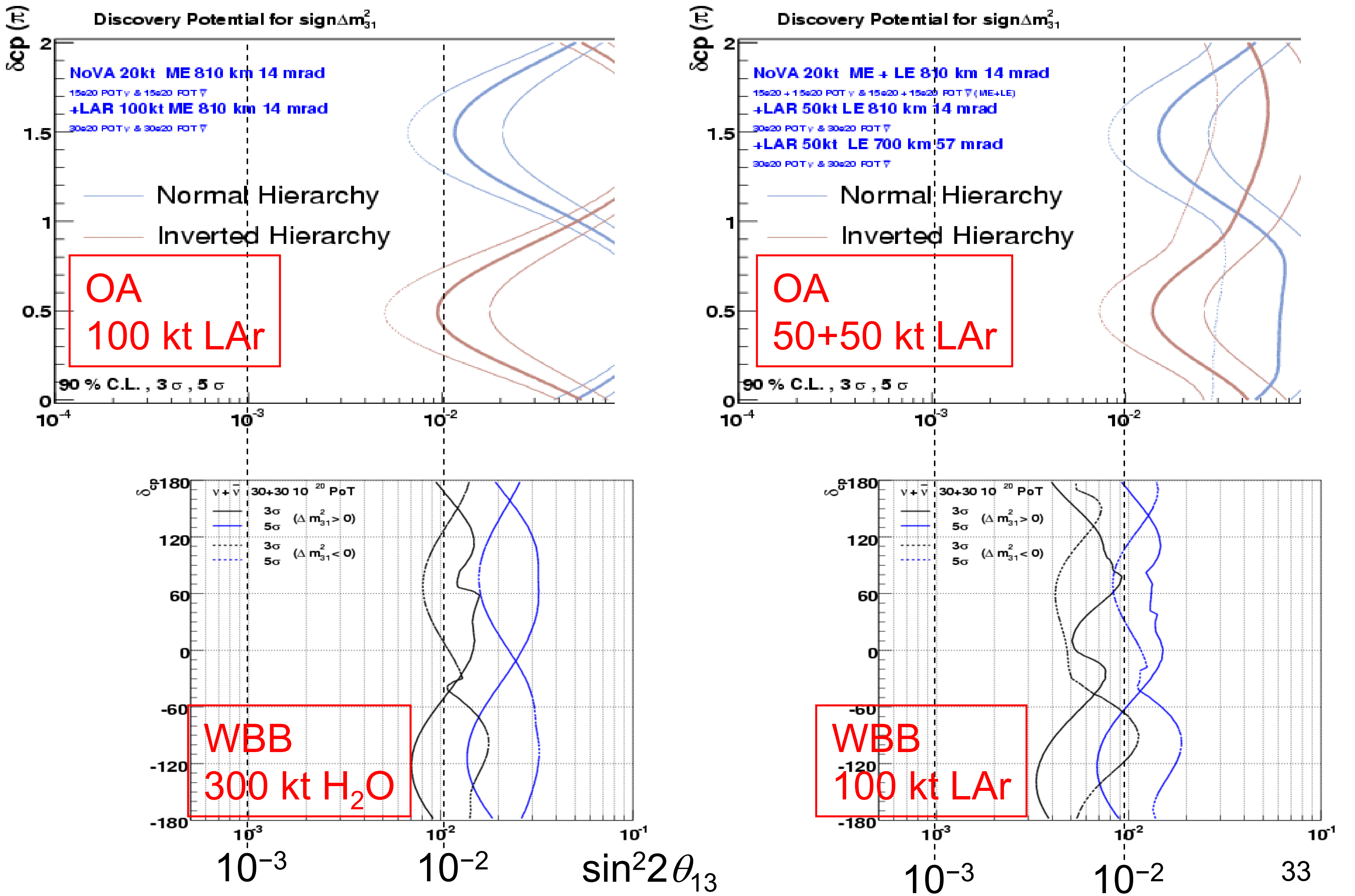
Sensitivity to $\sin^2 2\theta_{13}>0$



Sensitivity to CP violation



Sensitivity to mass hierarchy



30×10^{20} p.o.t neutrino + 30×10^{20} p.o.t antineutrino
≈ 3-5 years neutrino + 3-5 years antineutrino

Option	$\sin^2 2\theta_{13}$ 5σ, all δ_{CP}	CPV 5σ,50% δ_{CP}	$\mathrm{sgn}(\Delta m^2_{13})$ 5σ, all δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.008	0.08	0.18
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.011	>0.10	0.15
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.015	>0.10	0.032
4) WBB 0.5° 100 kt LAr, 1300 km	0.008	0.035	0.019

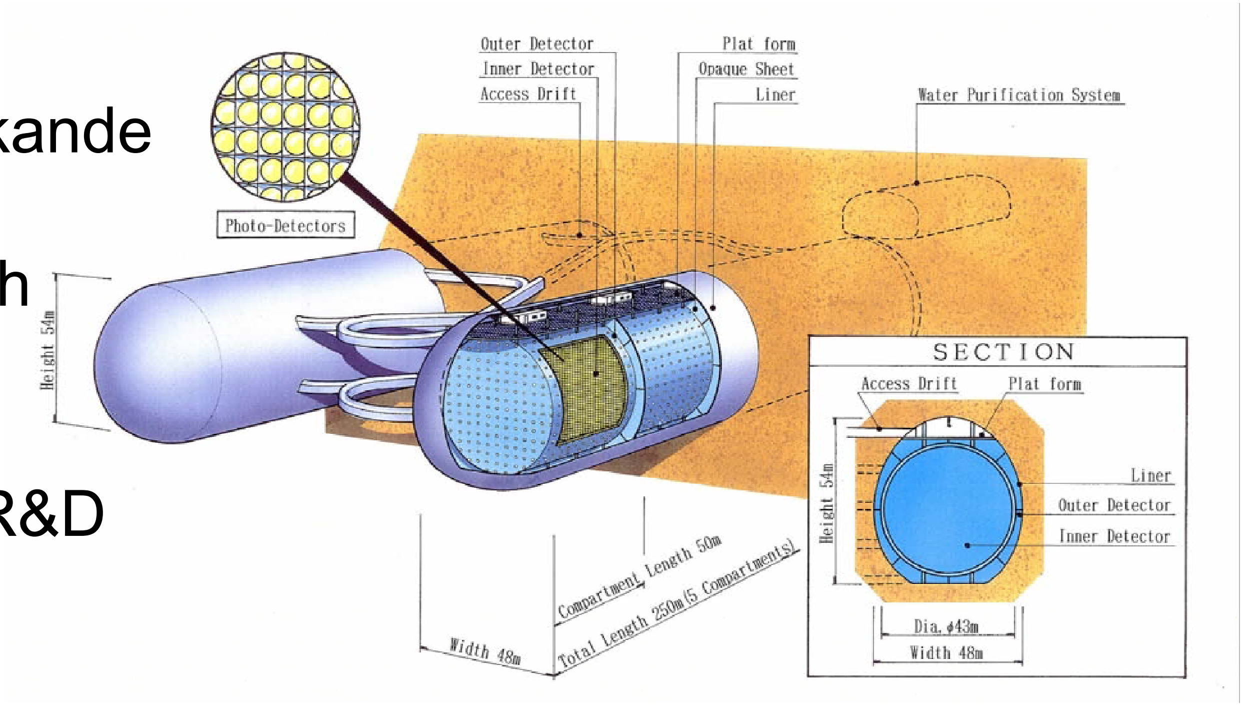
Option	$\sin^2 2\theta_{13}$ 5σ, all δ_{CP}	CPV 5σ,50% δ_{CP}	$\mathrm{sgn}(\Delta m^2_{13})$ 5σ, all δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.008	0.08	0.18
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.011	>0.10	0.15
2A) 100/100 kt LAr	0.009	0.08	0.08
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.015	>0.10	0.032
3A) 60×10^{20} p.o.t. each	0.012	0.08	0.022
4) WBB 0.5° 100 kt LAr, 1300 km	0.008	0.035	0.019

30×10^{20} p.o.t neutrino + 30×10^{20} p.o.t antineutrino
≈ 3-5 years neutrino + 3-5 years antineutrino

Option	$\sin^2 2\theta_{13}$ 3σ,50% δ_{CP}	CPV 3σ,50% δ_{CP}	$\mathrm{sgn}(\Delta m^2_{13})$ 3σ,50% δ_{CP}
1) NuMI-ME 0.9° 100 kt LAr, 1st max	0.002	0.02	0.05
2) NuMI-LE 0.9°/3.3° 50/50 kt LAr, 1st/2nd max	0.004	0.05	0.04
3) WBB 0.5° 300 kt H_2O Ch, 1300 km	0.006	0.02	0.01
4) WBB 0.5° 100 kt LAr, 1300 km	0.002	0.005	0.006

International context for Phase 2

Japan:
- Hyper-Kamiokande
- 2×270 kton
- T2K beam with upgraded power
- Light sensor R&D underway



Plan: continue R&D until physics case solidifies – evidence that θ_{13} big enough for CP violation search or of proton decay.

Baseline too short for independent mass hierarchy.

International context for Phase 2

Europe:

- Focused mostly on new neutrino source technology that would be needed if $\sin^2 2\theta_{13}$~0.02 or below: Beta beams, neutrino factory.
- Not usually considered competitive with Phase 2, but may have to be reconsidered.
- Considering same detector options: 500 kton WaterC, LArTPC.

Cost estimates/considerations

Physicist's estimates, not reviewed

- Monolithic Water Cherenkov: 440 kton
  $500M based on scaling Super-K
  PMTs are 40% of cost
- Modular Water Cherenkov: 3×100 kton
  $335M estimate
  PMTs are 60% of cost
- Wide-band beam: FNAL to DUSEL
  NuMI cost $109M
  F2D is shorter, wider, steeper
  Guess: $100-200M?

Cost estimates/considerations – 2

- Liquid Argon TPC: 100 kton
  No idea yet
  LAr is ~$1M/kton
  50 kton tank ~$18M
  No estimate yet for: electronics, refrigeration, purification, safety,…

None of these include:
  Main Injector upgrades: 700 kW → ≥1 MW
  Near detector + hall

Timeline

A. Decision/approval

NuSAG advocates learning size of $\sin^2 2\theta_{13}$ from Phase 1 experiments before proceeding with Phase 2

- Double Chooz: 3σ sens $\sin^2 2\theta_{13} \sim 0.05$ by late 2012
- Daya Bay: 3σ sens $\sin^2 2\theta_{13} \sim 0.02$ by 2013
- T2K: 90%CL sens $P(\nu_\mu \rightarrow \nu_e) \sim 0.01$ by late 2012
- NOvA: 3σ sens $\sin^2 2\theta_{13} \sim 0.02$ by 2014; ~0.01 by late 2017

NuSAG conclusion: 2012 at earliest

Project approval process: 3-4 years

Timeline – 2

B. Construction

Water Cherenkov: 7-10 years, limited by PMT production

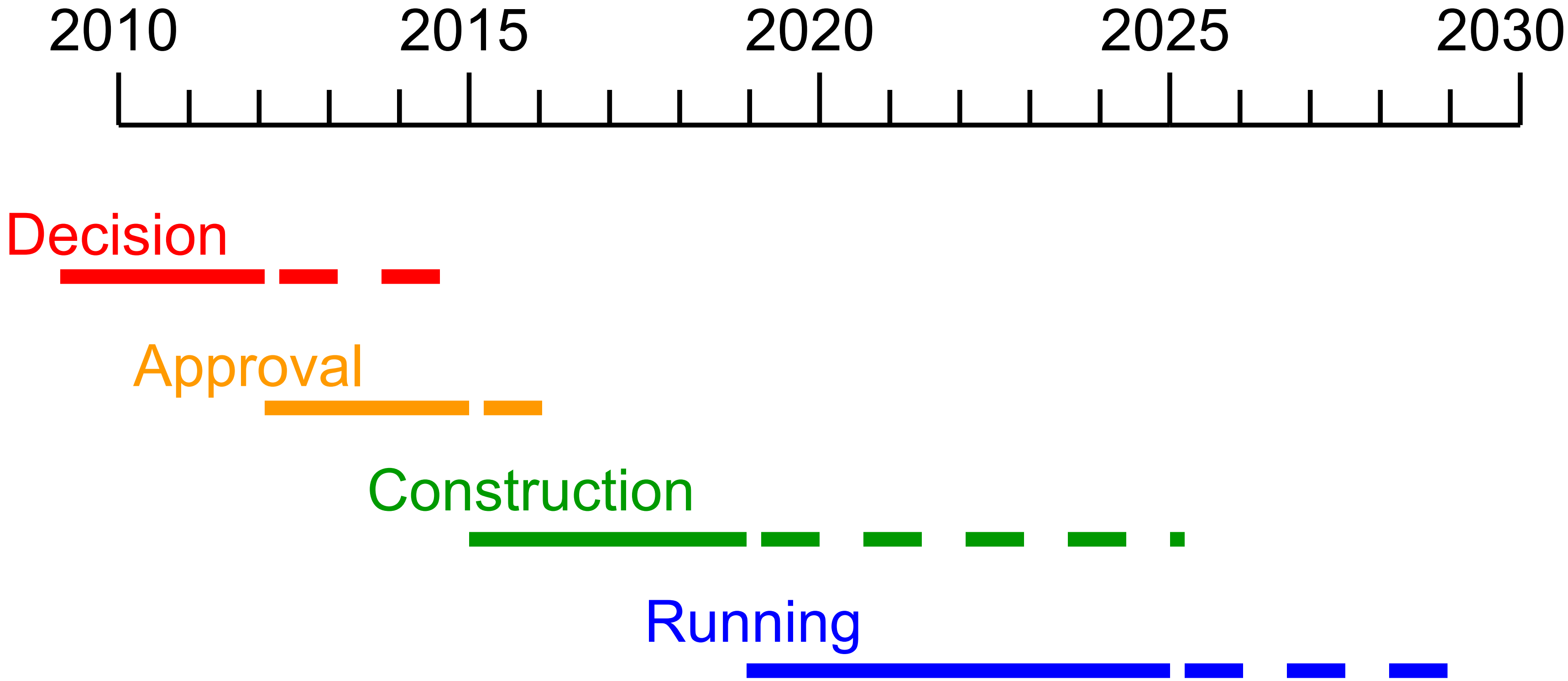
– decrease by more suppliers? (cash flow issue)

LArTPC: not known – guess 4-6 years??

If in DUSEL, ready for occupancy when?

C. Running

Sensitivity plots assumed 6-10 years @ 1 MW


2010
2015
2020
2025
2030
Decision
Approval
Construction
Running

Summary

• Plausible extrapolations of existing technology will allow 5σ searches for CP violation in the neutrino sector and 5σ determinations of the mass hierarchy down to $\sin^2 2\theta_{13} \sim 0.03$, with substantial sensitivity to ~ 0.01.

These are important physics goals!

• The large detectors needed for such measurements can also extend the sensitivity of searches for proton decay and neutrinos from astrophysical sources.

Draft report: **Recommendations to the Department of Energy and the National Science Foundation on a Future U.S Program in Neutrino Oscillations**

To HEPAP and NSAC June 11, 2007

Comments received, clarifications incorporated into text

Recommendation 1. The US should prepare to proceed with a long baseline neutrino oscillation program to extend sensitivity to $\sin^2 2\theta_{13}$, to determine the mass ordering of the neutrino spectrum, and to search for CP violation in the neutrino sector. Planning and R&D should be ready for a technology decision and a decision to proceed when the next round of results on $\sin^2 2\theta_{13}$ becomes available, which could be as early as 2012. A review of the international program in neutrino oscillations and the opportunities for international collaboration should be included in the decision to proceed.

Recommendation 2. Research and development towards an intense, conventional neutrino beam suitable for these experiments should be supported. This may be in the form of intensity upgrades to the existing NuMI beam, as well as development of a new beam directed towards DUSEL, which would likely employ the wide-band beam approach.

Recommendation 3. Research and development required to build a large water Cherenkov detector should be supported, particularly addressing questions of minimum required photocathode coverage, cost, and timescale.

Recommendation 4. A phased R&D program with milestones and using a technology suitable for a 50-100 kton detector is recommended for the liquid argon detector option. Upon completion of the existing R&D project to achieve purity sufficient for long drift times, to design low noise electronics, and to qualify materials, construction of a test module that could be exposed to a neutrino beam is recommended.

NuSAG's thanks to the BNL/FNAL Study Group

Convened by: Sally Dawson, Hugh Montgomery

Chaired by: Gina Rameika, Milind Diwan

My thanks to the members of NuSAG and to Gene Beier