A U.S. Program of Long Baseline Neutrino Oscillations

Status Report to HEPAP

from the

Neutrino Science Assessment Group

Eugene W. Beier and Peter Meyers

July 6, 2006

Outline

- NuSAG and the charge
- The physics issues
- The measurements
  - Beam issues
  - Signal and background
  - Detector types
- International context
- NuSAG status

The Neutrino Scientific Assessment Group

- Formed by NSAC and HEPAP jointly
- Co-chaired by Gene Beier and Peter Meyers
- Three initial charges
  - Neutrino-less double beta decay
  - Reactor neutrino mixing
  - Accelerator neutrino mixing
- Reports delivered and approved by HEPAP and NSAC

NuSAG Members

- Eugene Beier (University of Pennsylvania and Co-Chair)
- Peter Meyers (Princeton University and Co-Chair)
- Leslie Camilleri (CERN)
- Boris Kayser (Fermi National Accelerator Laboratory)
- Ed Kearns (Boston University) New
- William Louis (Los Alamos National Laboratory) New
- Naomi Makins (University of Illinois)
- Tsuyoshi Nakaya (Kyoto University)
- Guy Savard (Argonne National Laboratory)
- Heidi Schellman (Northwestern University)
- Gregory Sullivan (University of Maryland)
- Petr Vogel (California Institute of Technology)
- Bruce Vogelaar (Virginia Tech)
- Glenn Young (Oak Ridge National Laboratory)
- Robert Tribble (Texas A & M) *ex-officio – NSAC* New
- Mel Shochet (University of Chicago) *ex-officio – HEPAP* New

Charge: ... 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*. ...

- **Scientific potential:** What are the important physics questions that can be addressed...?
- **Associated detector options:** What are the associated detector options...? What are the rough cost ranges...?
- **Optimal timeline:** What would be the optimal construction and operation timeline ... taking the international context into account?
- **Other scientific considerations:** What other scientific considerations, such as results from other experiments ... determine design parameters? What ... additional important physics questions can be addressed...?

Context for the Charge

APS study – The Neutrino Matrix - recommendation on neutrino oscillations:

We recommend ... a comprehensive US program ... to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos. This program should have the following components:

- An expeditiously deployed multireactor experiment...
- A timely accelerator experiment...
- *A proton driver in the megawatt class or above and neutrino superbeam with an appropriate very large detector capable of observing CP violation and measuring the neutrino mass-squared differences and mixing parameters with high precision.*

Context for Charge

Off-axis approach follows BNL P889 – produces narrow band beam at a particular energy. Limits highest energy neutrino flux at a fixed angle.

Off-axis approach adopted by NOνA, present effort is a follow on to NOνA.

Study of higher nodes of oscillation introduced by W. Marciano (hep-ph/0108181). Wide band beam can access mulitiple nodes simultaneously.

Multiple nodes require very long baselines – basis of proposal from BNL based collaboration.

Long Baseline Working Group

At approximately the time the NuSAG charge was issued, a

Workshop on Long Baseline Neutrino Experiments

was initiated by Brookhaven and Fermilab with a charge similar to the NuSAG charge and preliminary and final reports due July 15, 2006 and "before October" 2006, respectively.

NuSAG understands that parties interested in the NuSAG charge are engaged at the Long Baseline Workshop.

NuSAG Schedule

Charge delivered by HEPAP and NSAC – March, 2006.

Informational meeting held May 27-28 in Chicago

- Input from concerned parties
- Discussed areas where more information is needed

Questions/suggestions sent to Working Group June, 2006.

Next meeting probably September/October, 2006 – after Working Group report is received.

Reports to HEPAP and NSAC:

- Preliminary draft in December, 2006
- Final version February, 2007

Physics

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

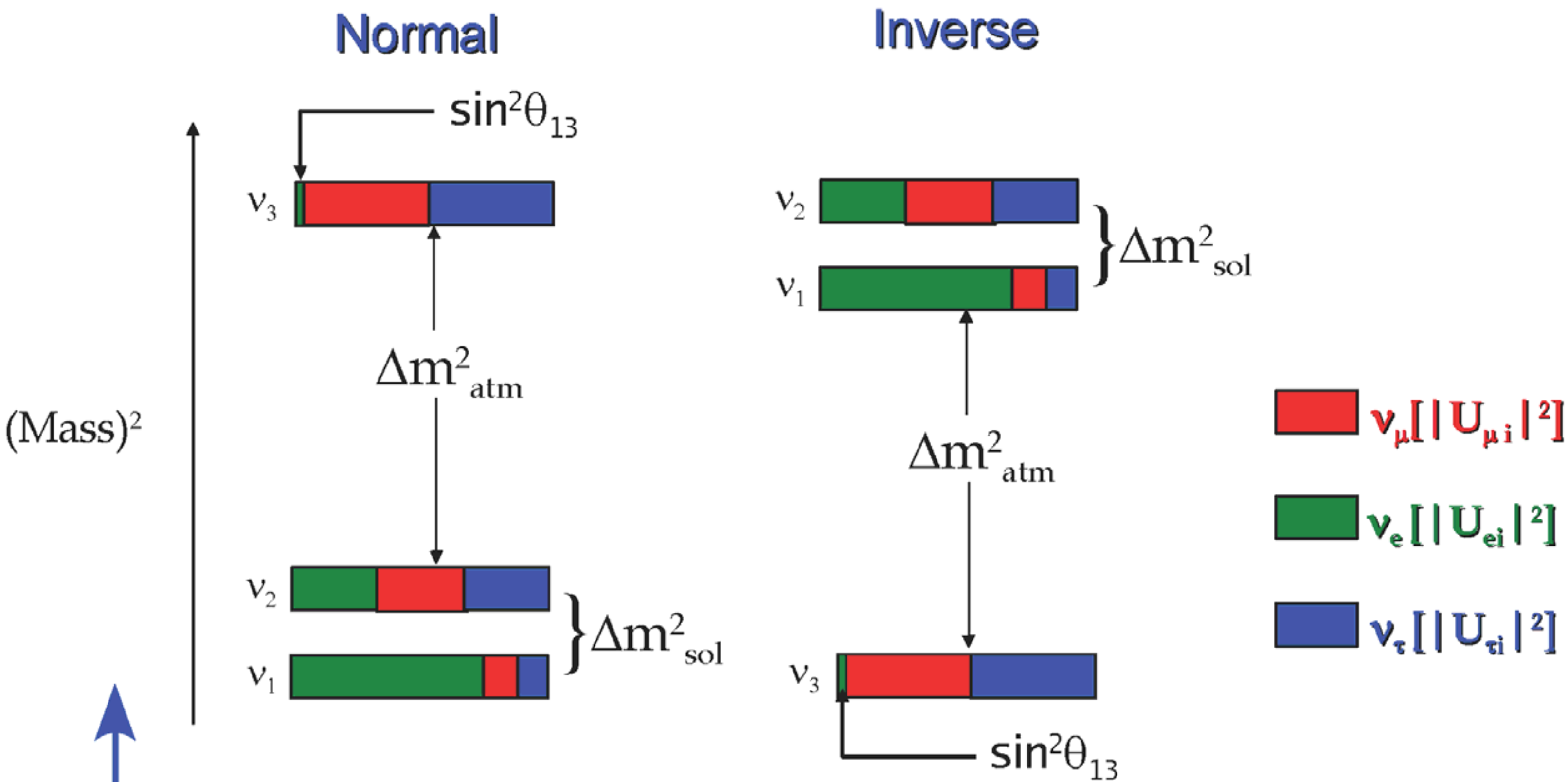
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix}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

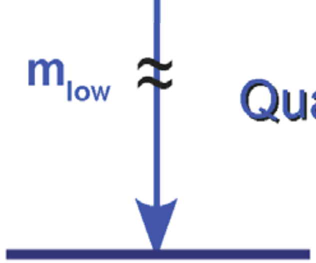
$$\theta_{23} \approx \theta_{atm} \approx 45^\circ; \quad \theta_{12} \approx \theta_\odot \approx 34^\circ; \quad \theta_{13} \leq 12^\circ$$

δ 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





Quasi-degenerate: $m_{low}^2 >> \Delta m^2_{atm} >> \Delta m^2_{sol}$

(O. Cremonesi – LP2005)

Oscillations are sensitive only to Δm^2

Oscillation Probability

In vacuum:

$$P(\nu_\mu(\overline{\nu}_\mu) \rightarrow \nu_e(\overline{\nu}_e)) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31}$$ Atmospheric

$$+ \sin 2\theta_{13} \cos \theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \times \sin \Delta_{31} \sin \Delta_{21} \cos(\Delta_{32} \pm \delta)$$ } Interference – CP effects

$$+ \sin^2 2\theta_{12} \cos^2 \theta_{23} \cos^2 \theta_{13} \sin^2 \Delta_{21}$$ Solar

where $\Delta_{ij} = 1.27 \Delta m^2_{ij}(eV^2) L(km)/E(GeV)$

and the CP violating term $\pm\delta$ has opposite signs for $\nu, \overline{\nu}$

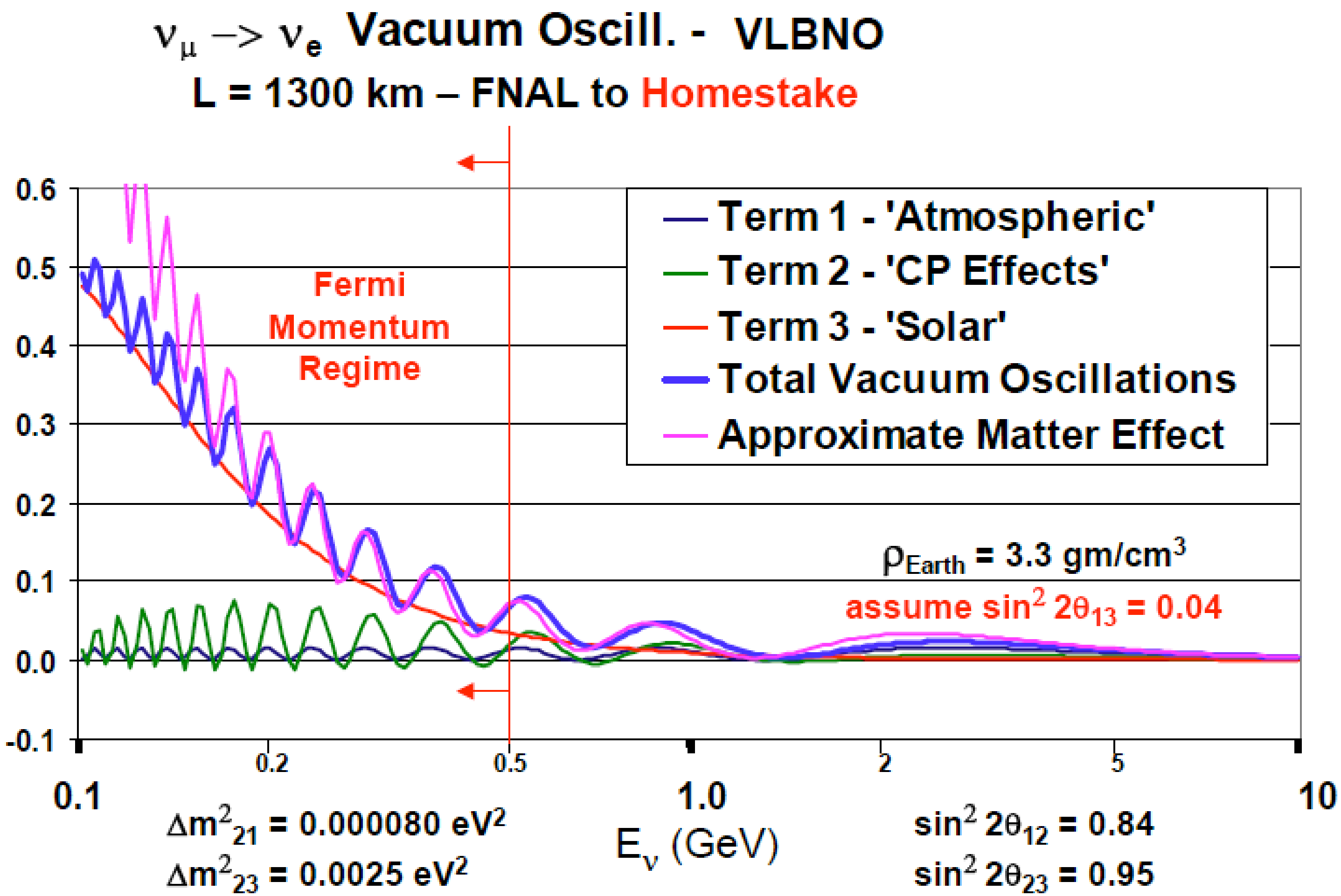
In matter: An appropriate analytic expansion has been given by Freund (hep-ph/0103300).

For experiments under consideration, matter effects are maximum at $E_\nu \approx$ 6 GeV, and the CP asymmetry goes as $A_{CP} \sim 1/E_\nu$.

Oscillation Measurement Goals

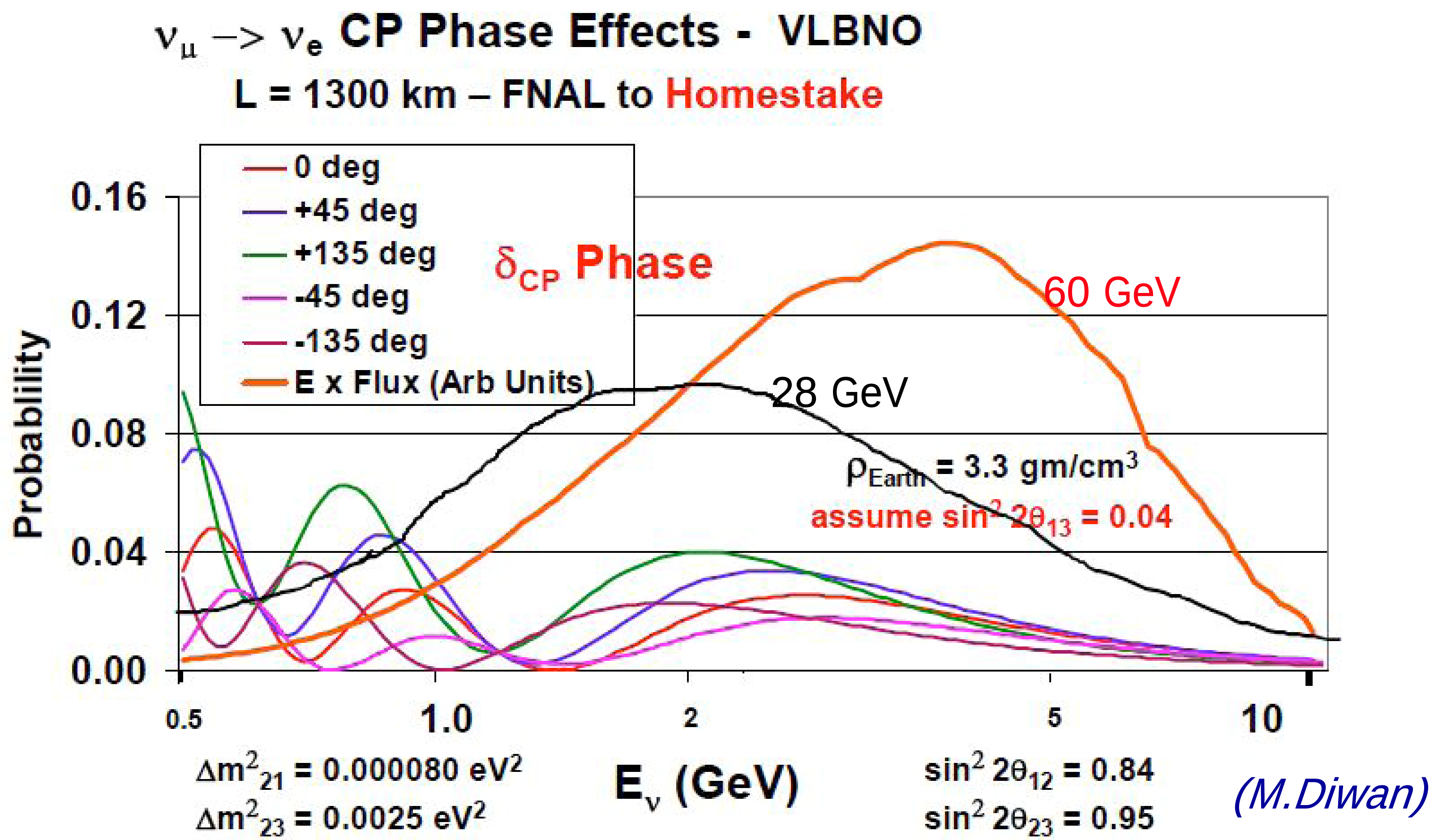
- U_{e3} magnitude – is $\sin\theta_{13}$ large enough to see interference effects?
- Measure δ – is CP violation present?
- Resolve mass hierarchy – sign of Δm^2_{13}.
- θ_{23} degeneracy – is θ_{23} less than or greater than 45°?

Illustration of Oscillation Probability



(M. Diwan)

Illustration of Oscillation Probability



Off-axis experiment counts events at “fixed” energy.

WBB experiment measures spectral distortion.

Measurement Requirements

- Intense neutrino (ν_μ) source.
- Long or very long baseline.
- Large detector:
  - Signal is CC ν_e interaction from $\nu_\mu \rightarrow \nu_e$ oscillation.
  - Backgrounds:
    - ν_e in beam.
    - NC π^0 production identified as electron.
    - Other CC interactions.
    - "Wrong-sign" backgrounds from anti-neutrinos

Overview of OA vs. WB Beam

	Off-axis	Wideband
Requires:	$\sim$ 1 MW source NOνA+Big 2nd detector Greenfield, near surface site Mods to NUMI beam	$\sim$ 1 MW source Very big detector Underground lab New beam
Advantages:	Increment on existing beam and detector	Measure full energy spectrum Broad physics program Detector technology
Challenges:	Statistics Detector technology	π^0 rejection at higher energies

Proton Source

Modifications to FNAL accelerator complex *(A. Marchionni)*

- **Booster:** repetition rate upgrade to 15 Hz
- **Main Injector:** RF and shielding upgrades
- **Recycler:** new injection and extraction transfer lines, RF systems
- **Accumulator:** new injection and extraction lines, new RF systems
- **NuMI:** upgrade primary proton line, new target and horn, target chase cooling, installation of Helium bags, work cell upgrade

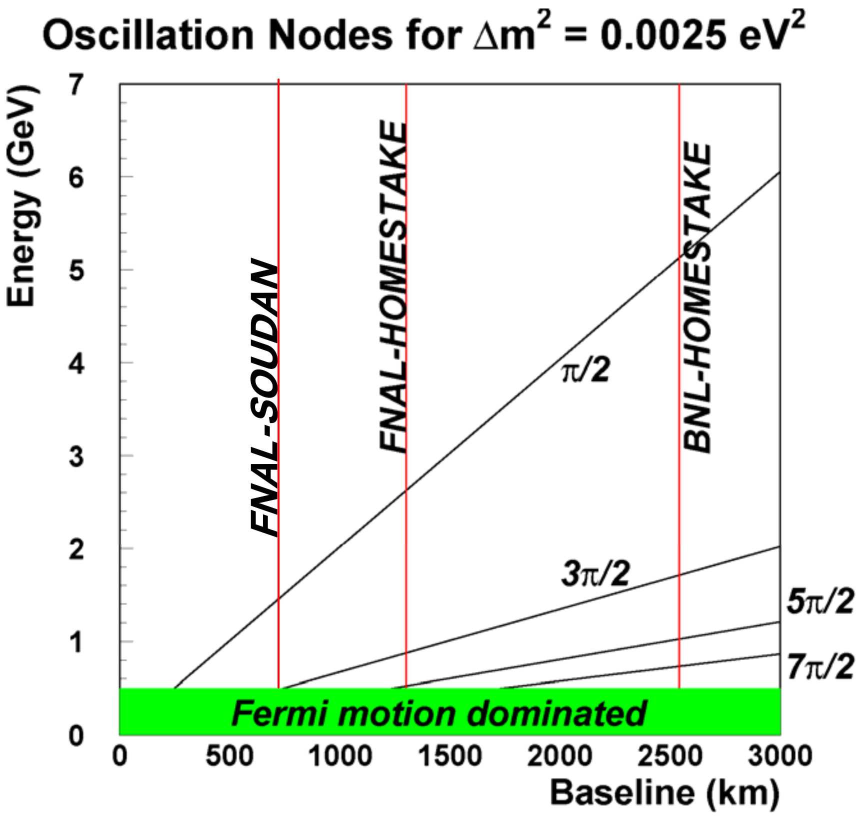
Estimated Costs: 700 kW - 9900 K$

1 MW – 32000 K$ additional

(Includes M&S only, no inflation, no contingency)

Baselines

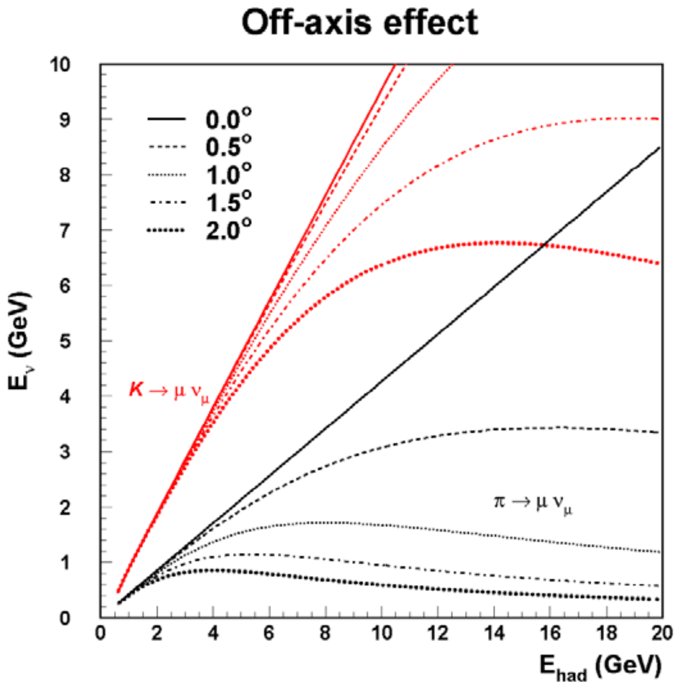
- Fermilab to Soudan accesses one appearance node
- Longer baselines such as Fermilab to Homestake access multiple nodes



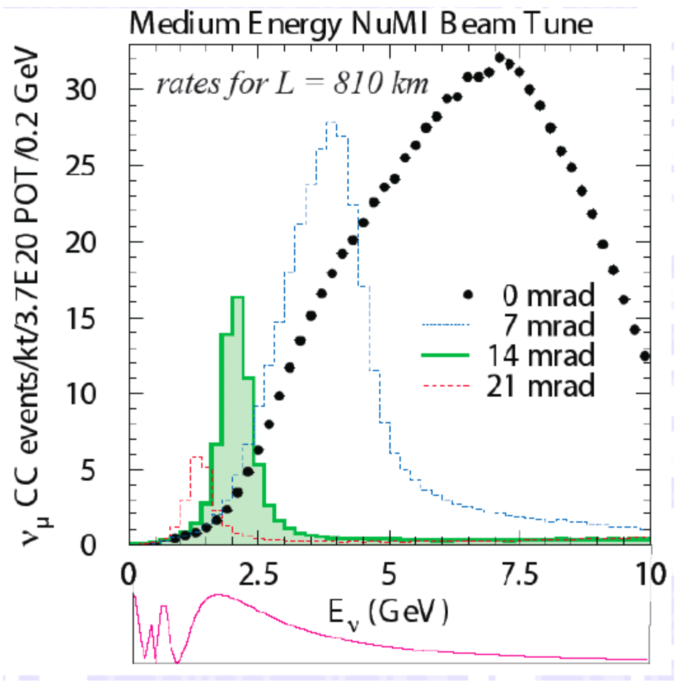
Off-Axis and Wide Band Beams

Off-Axis: Match maximum flux to appearance maximum

WBB: Cover multiple nodes – use different L/E of nodes

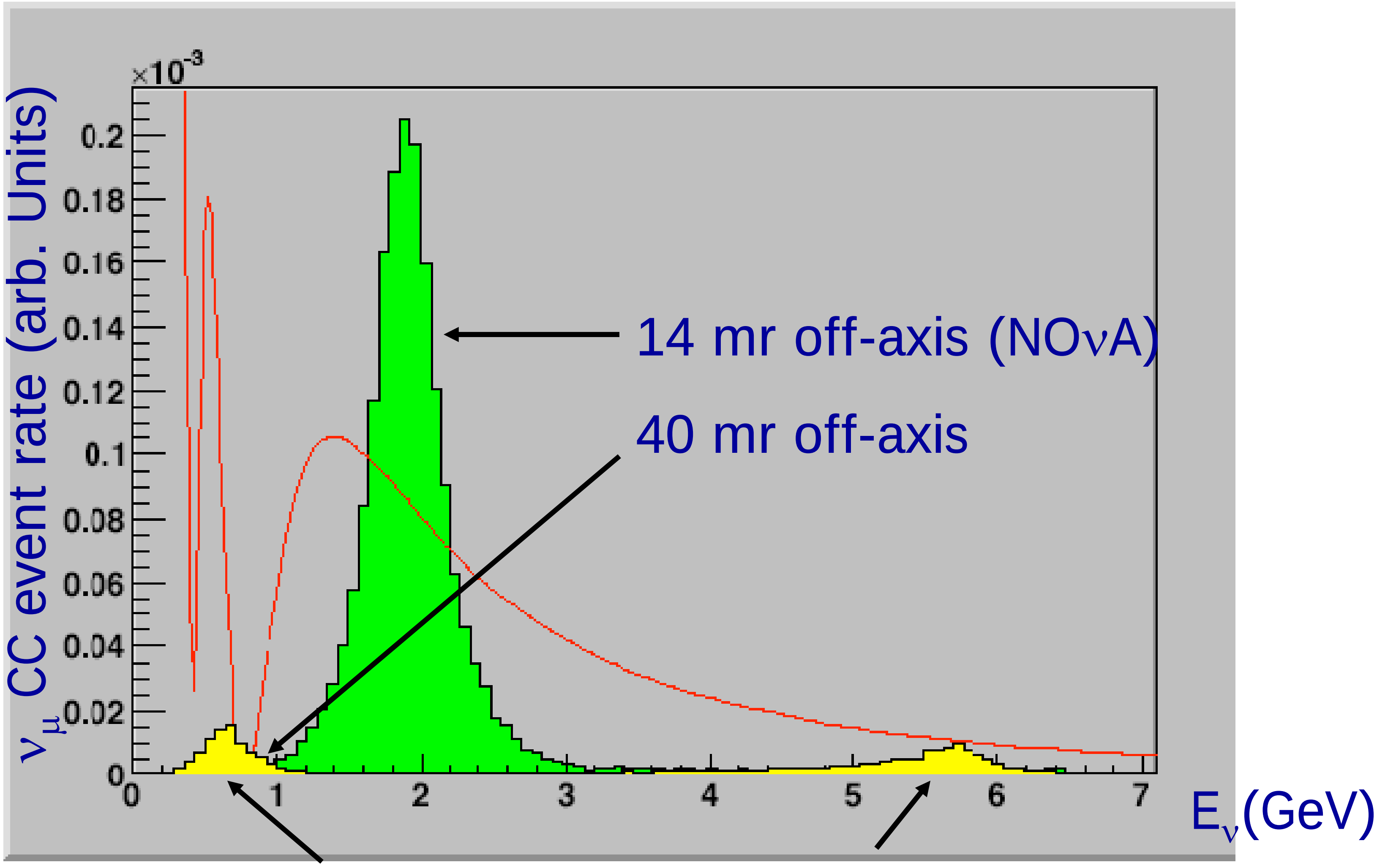


(B. Viren)



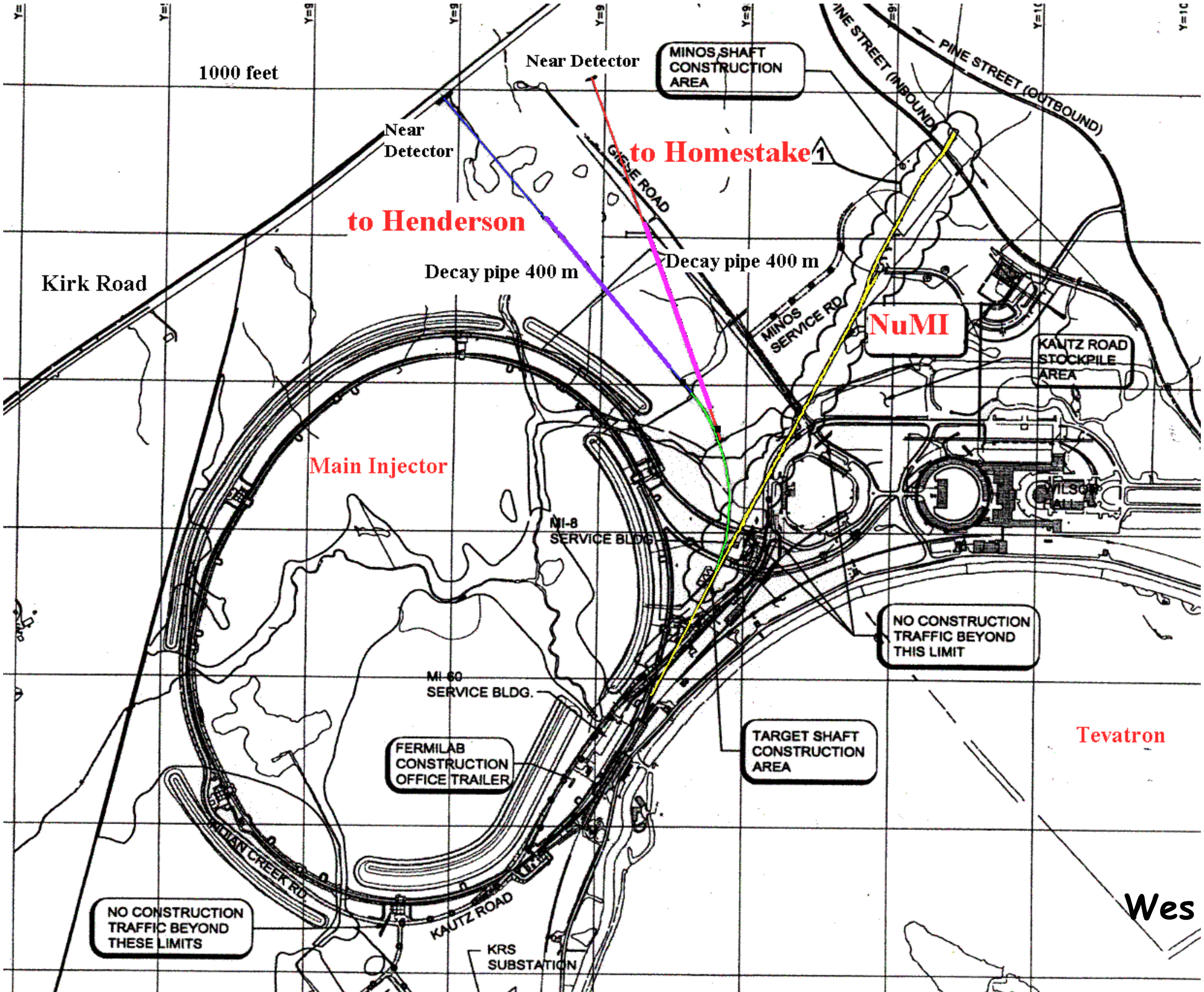
(G. Feldman)

Off-axis approach-NUMI beam at 810km



(G. Rameika)

Possible WB beams to distant DUSEL sites:



Wes Smart

Detector Options

- Liquid scintillator
  - Not presented to NuSAG; needs to be much larger than NOνA
- Liquid Argon
  - Presented in off-axis context, may be applicable for WBB approach
- Water Cherenkov – monolithic or modular
  - Must be underground to limit cosmic rays
  - Does it require DUSEL? Could it work at Soudan?

Liquid Argon Detector

Good signal efficiency, good π^0 rejection

Neutral current event with 1 GeV π^0

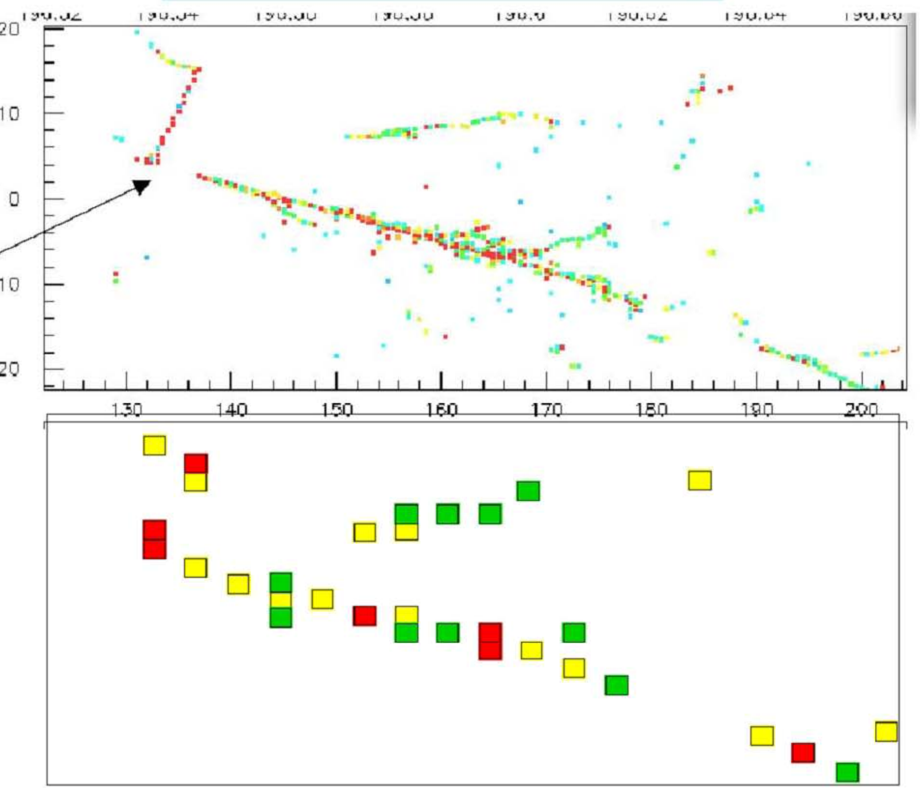
$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$

$$(1\ \mathrm{GeV})\ \pi^0 \rightarrow \gamma + \gamma$$

3.5% X_0 samples

in all 3 views

4 cm gap



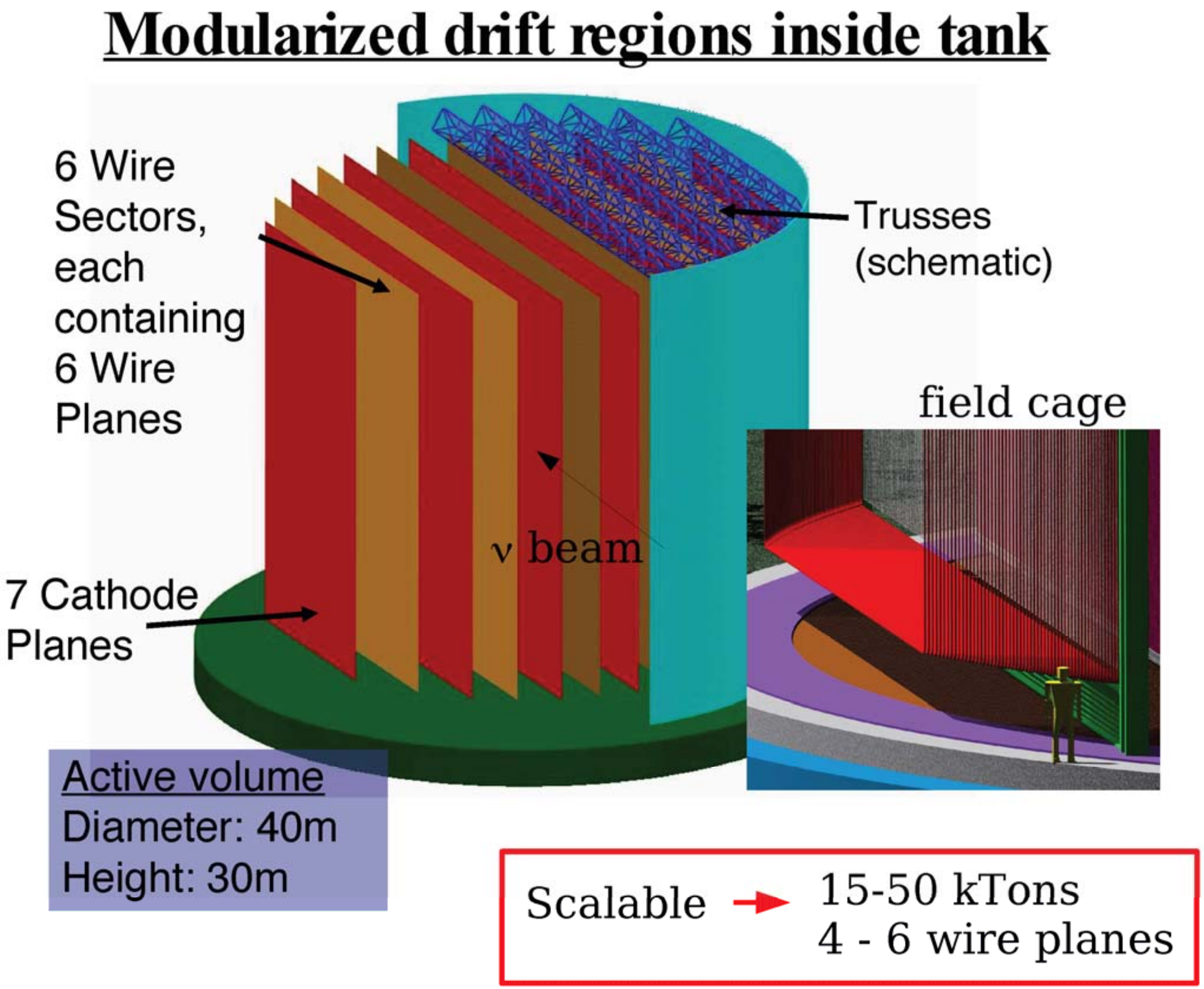
12% X_0 samples

alternating x-y

(B. Flemming)

Liquid Argon Detector

What is time scale for R&D, construction?

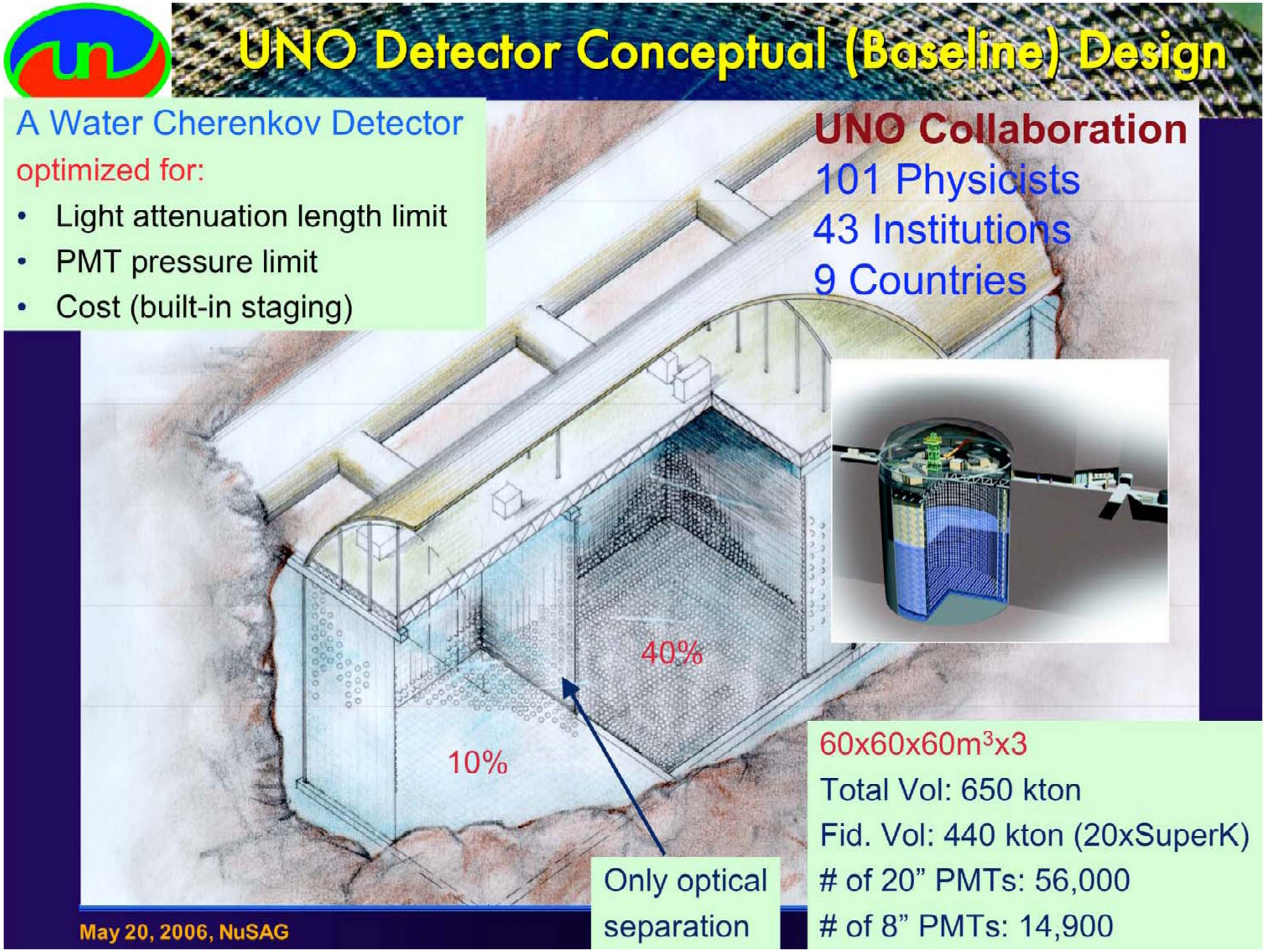


(B. Flemming)

Water Cherenkov Detectors

- Needs to be underground to reduce triggers from cosmic ray μ's.
- Proponents want to be more than 1000km from source to see multiple nodes and improve CP sensitivity.
- Two techniques proposed:
  - Monolithic detector: UNO – better fiducial to total volume, fewer PMTs
  - Modular detector: 3M, MEMPHYS – established technology, only build what is needed.

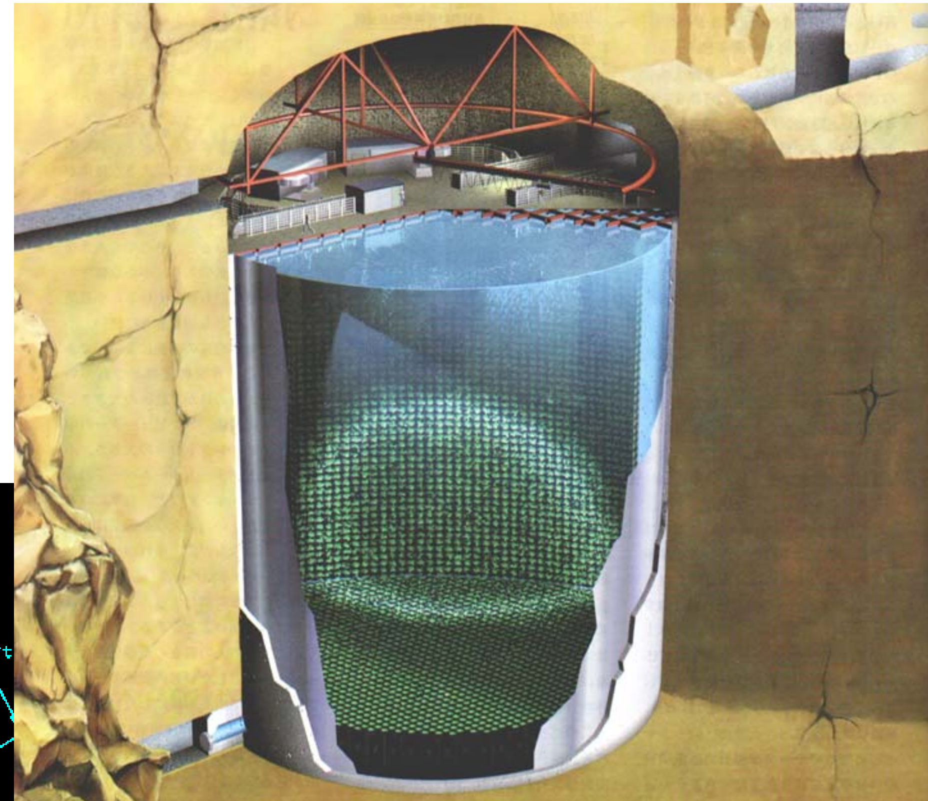
Monolithic Water Cherenkov Detector

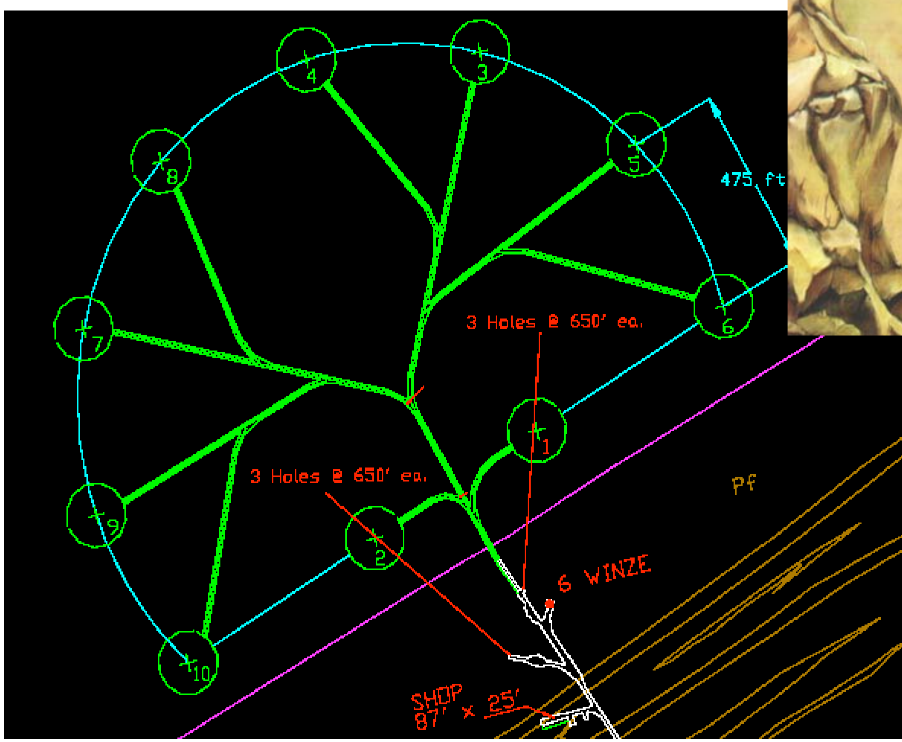


(C.-K. Jung)

Modular Water Cherenkov Detector

Build ten 100 kton detector modules – each looks like a scaled up Super-Kamiokande, probably with fewer PMTs.





NuSAG presentation proposes starting with three modules.

International Context

After NOνA, T2K-I and Daya Bay, CHOOZ II:

- International Scoping Study
  – Look at Superbeams, β-Beams, and ν-Factory
- Europe
  – CERN Superconducting Proton Linac to Frejus
  – β-Beam to Frejus
  – Need ν-Factory if $\sin^2 2\theta_{13} < 0.01$
- Asia
  – T2K-II – Increase JPARC beam intensity (4MW?)
  – T2HK – Build Hyper-Kamiokande multi-kton detector
  – Possiblity for half of HK in mainland Asia – T2KK (Korea)?

These ideas generally utilize multi-MW beams – beyond the immediate NuSAG study.

Present NuSAG Status

- 16 “suggestions” sent to Working Group – NuSAG awaits WG Interim Report.
  - Use consistent assumptions and methodologies...
  - Give enough detail that results can be understood with a hand calculator...
  - Specify level of simulation in current sensitivity estimates...
  - Compare sensitivities to NOνA and T2K.
  - Many more suggestions, some specific to water Cherenkov or LAr technology.