Al Mueller - BNL RHIC

Neutrinos: The Era of
Long Baselines
Large Detectors
Intense Beams

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Columbia University, NYC
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Pleasure to be back at Columbia

Occasion of Al's 70^{th} Birthday

Long, special relationship between BNL & Columbia

Phd MIT 1965 (BS. Iowa State '61)

BNL 1965 – 1971 Postdoc – Ass't Physicist

Exciting years in both

Weak Interactions, ν's, *V-A*

Strong Interactions – SU(3)

Al is part of the distinguished alumni group

Gary Feinberg

Mel Schwartz   '59 – '58

G.C. Wick   '57 – '64

Member of many advisory committees at BNL

High Energy & Nuclear Physics
(1)Program Advisory Committee 1988 – 1992
L. Truman Chair 1988 – 1991
M. Schwartz Chair 1991 – 1994
BSA – Science and Technology Board 1998 – 2006
RBRC Scientific Review Committee to Present

Unique Time:
RHIC – Construction 1990 – 1999
Call for Proposals ~ 1990
Under Mel – 11 Proposals Rejected 1991 – 1992
Subsequently 4 Approved
STAR, PHENIX, BRAHMS, PHOBOS

Large (STAR, PHENIX) Small (BRAHMS, PHOBOS)

A few words concerning RHIC

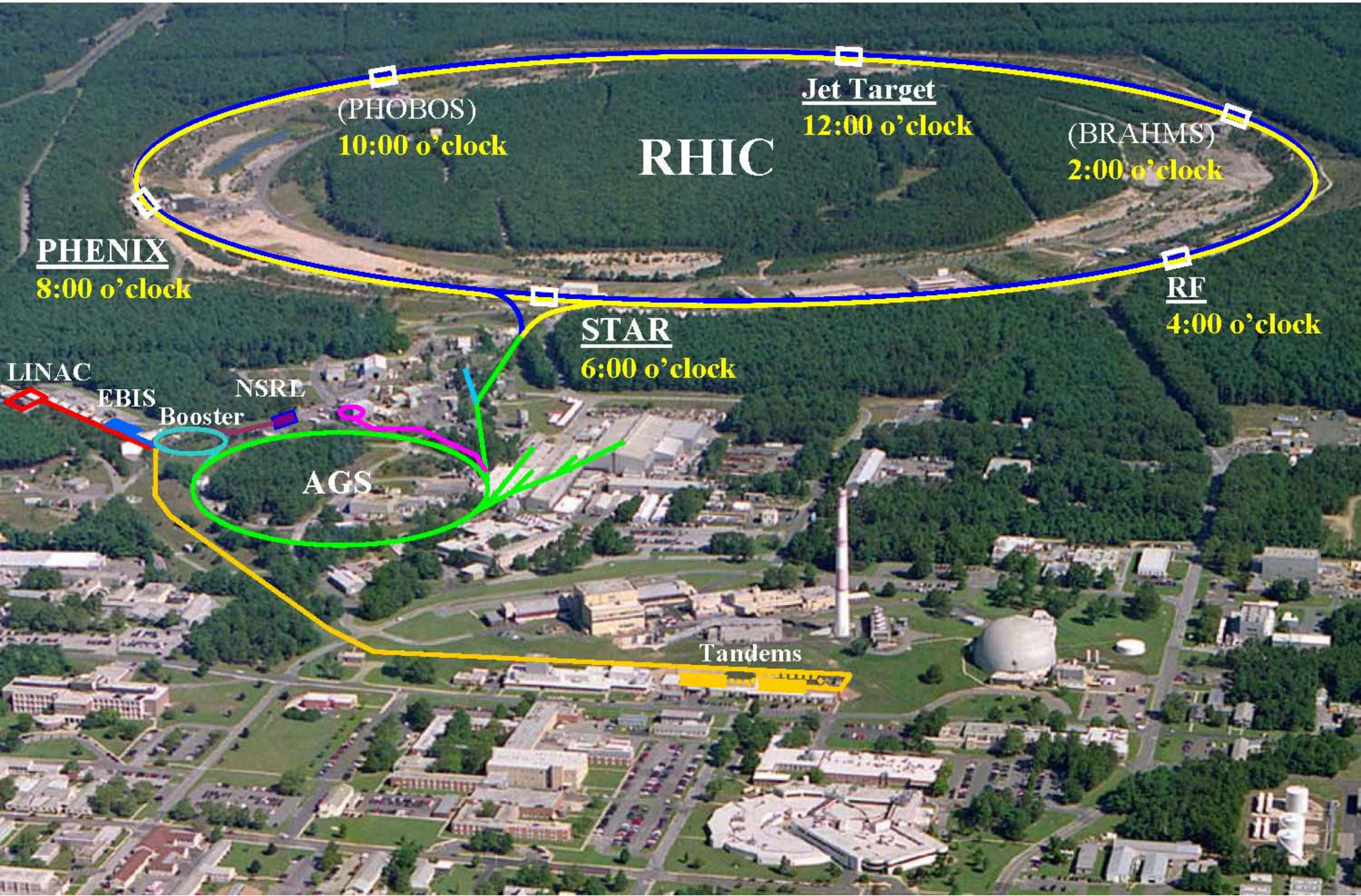
The preamble to the RHIC Conceptual Design Report of 1989 is especially Prophetic: I quote,

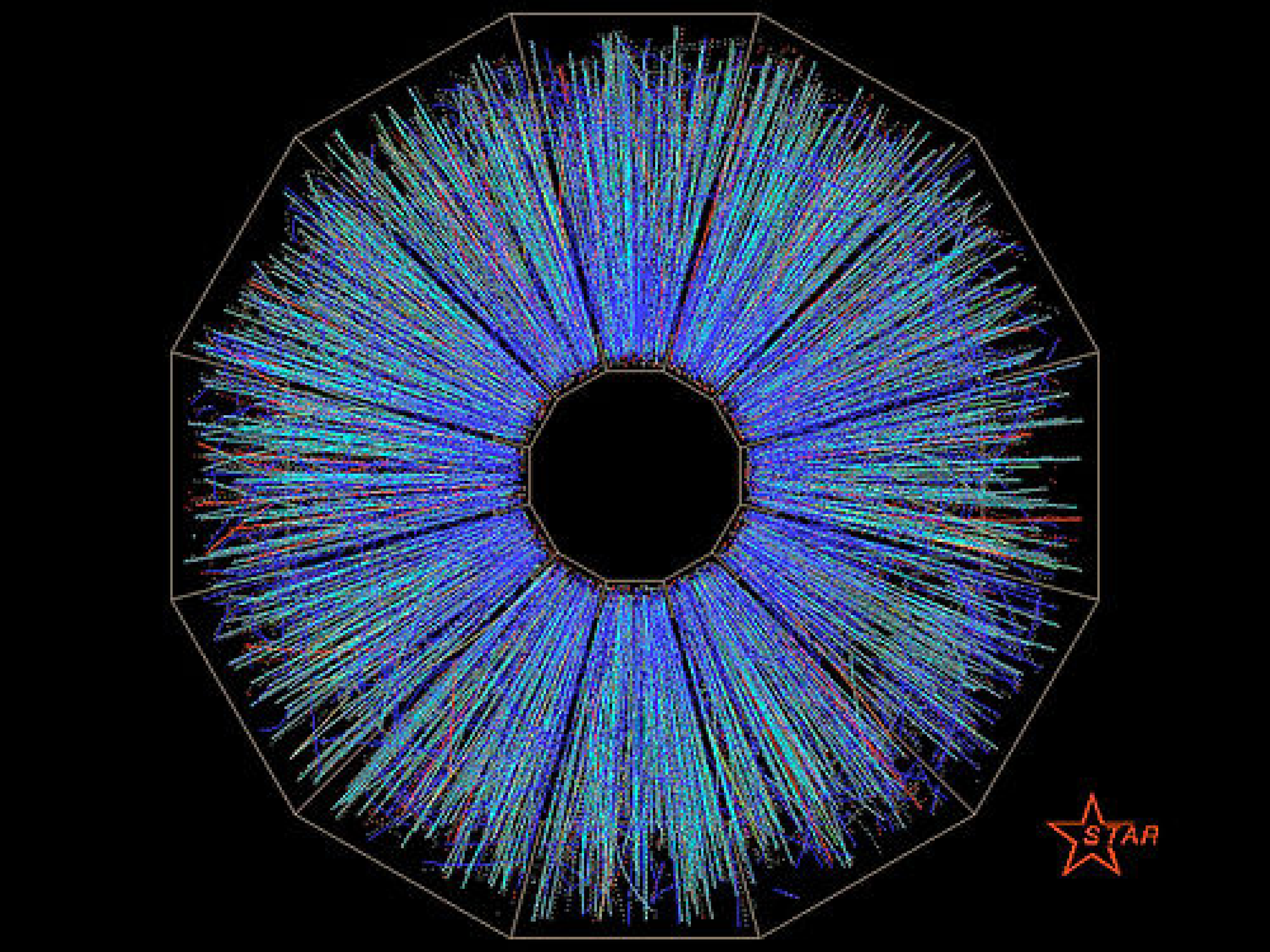
"The essential motivation for colliding nuclei at ultrarelativistic energies is the production of matter at extreme conditions of temperature and density: extended volumes of hadronic matter with energy densities greater than 10 times that of the nuclear ground state should be realizable. There is little direct knowledge about what to expect under such conditions. They have not been detected anywhere in the natural universe, and are just beginning to be approached through experiments with ion beams in experiments at Brookhaven and CERN. Thus the proposed facility represents a venture into an almost completely unknown regime for the study of basic properties of matter.
While this leap into the unknown is by itself compelling attraction for both experimenters and theorists, it is also true that very specific goals for discovery and exploration can be defined within the present understanding of Quantum Chromodynamics (QCD) – as developed from high energy collisions of elementary particles – and the low energy behavior of bulk nuclear matter. The parameters of the proposed machine complex will allow the experimenter to make contact with both regimes in the systematic study of new phenomenon"

RHIC has indeed created a new state of hot dense matter however behaving more like a liquid than a gas, the sQGP.

I would say that this dream envisioned for RHIC has been fulfilled

RHIC – a High Luminosity (Polarized) Hadron Collider Entering Its Scientific Prime




STAR

Neutrino History

- 1930 Existence – Postulated by Pauli
- 1956 Discovered
- 1962 Two Neutrinos
- 1970-91 Solar deficiency
- 1991 Three Neutrinos
- 2000's Neutrino Oscillations and Mass
  - Kamiokande
  - Super Kamiokande
  - Sudbury
  - Kamland
  - KEK
  - Minos and Others

Neutrino Parameters

Mass Differences

$$\Delta m_{32}^2 = m_3^2 - m_2^2 = \pm 2.3(2)\times 10^{-3}\,\mathrm{ev}^2$$

$$\Delta m_{21}^2 = m_2^2 - m_1^2 = +7.6(2)\times 10^{-5}\,\mathrm{ev}^2$$

Mixing Angles

$$\theta_{23} \sim 45^\circ \quad \sin^2 2\theta_{23} = 1.0$$

$$\theta_{12} \sim 34^\circ \quad \sin^2 2\theta_{12} = 0.87$$

$$\theta_{13} < 11^\circ \quad \sin^2 2\theta_{13} < 0.15$$

To be determined

Value of θ$_{13}$

Mass hierarchy – sign of

CP violation Δm^2_{32}

Precision Measurement of

Δm^2_{32} Δ^2_{21} θ_{23} θ_{12}

Why?

Comparison with Quark mixing parameters

Matter-Antimatter asymmetry

Leptogenisis – Baryogenesis

Other Benefits

Proton Decay

Supernovae

Oscillations: 3 Flavors

Quark Sector CKM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} .97 & .23 & (2-3i)10^{-3} \\ -.23 & .97 & .04 \\ (7-3i)10^{-3} & -.04 & .99 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$J = 3.1 \times 10^{-5} \qquad \delta = 57^{o}$$

Lepton Sector

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} .81 & .51 & s_{13}e^{-i\delta} \\ -.4-.6\,s_{13}e^{i\delta} & .6-.4\,s_{13}e^{i\delta} & .7 \\ .4-.6\,s_{13}e^{i\delta} & -.6-.4\,s_{13}e^{i\delta} & .7 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$s_{13} \equiv \sin\theta_{13} \quad \leq 0.2$$

$$J = .11 \sin 2\theta_{13} \ \sin\delta$$

How?

Large Detectors

Water Cereknov $\geq$ 300 Ktons.

(50 Kton)

Liquid Argon $\geq$ 50 Ktons

(.6 kton)

Intense Proton Beam

I $\geq$ 1 Mwatt (.3 Mwatt)

Long Baseline

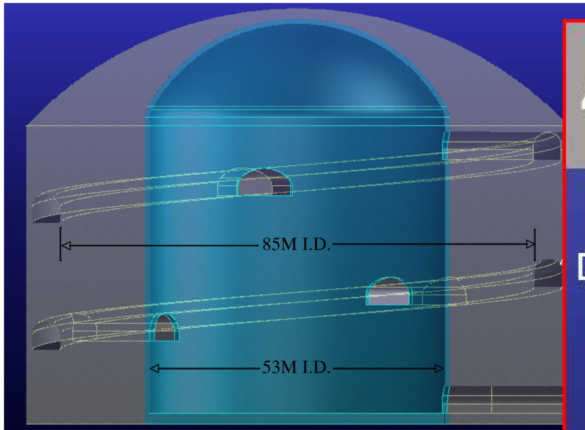
L $\geq$ 1,000 km (750 km)

Wide Band Neutrino Beam .5 – 5 GeV

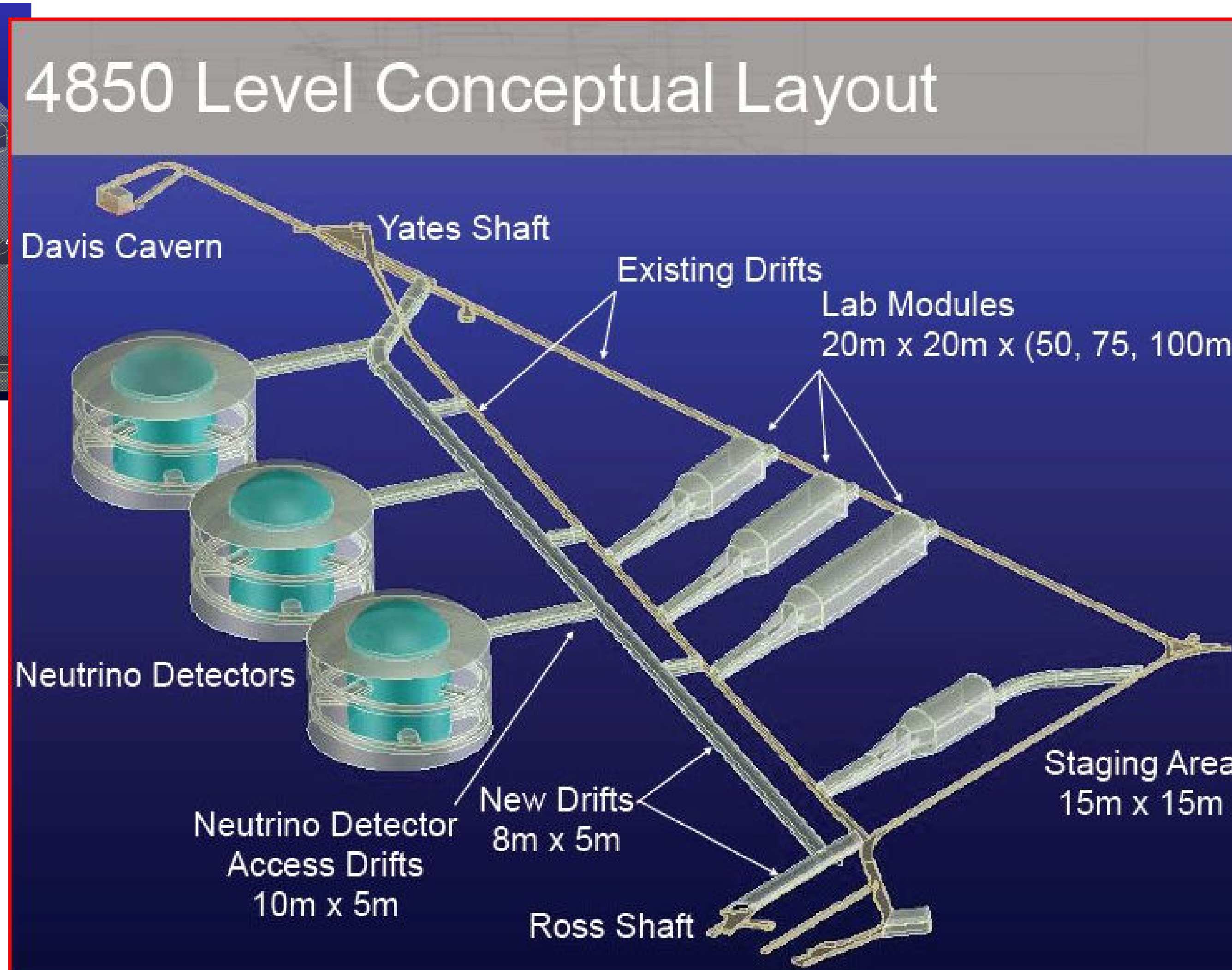
Appearance exp't $\nu_\mu \rightarrow \nu_\mu$; Disappearance exp't $\nu_\mu \rightarrow \nu_e$

$f(\Delta m^2$, θ's, L/E, earth matter)

Water Cherenkov Detector



1 module fid:
100 kT

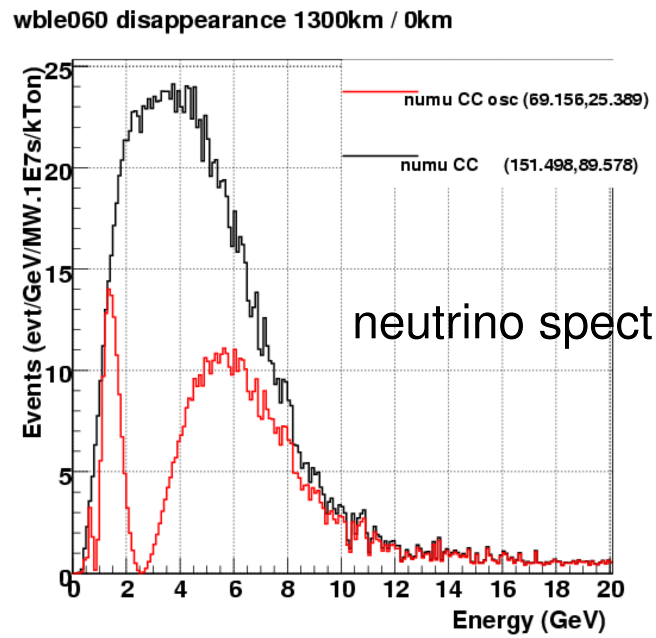


300 kT

Event rate

Evt rate: 1 MW for 3 yrs ★

Event type	300kT, 120 GeV 0.5 deg.	300kT, 60 GeV 0 deg.
Numu CC no osc	161820	272693
Numu CC with osc	68220	124479



neutrino spectrum

High precision $\sin^2 2\theta_{23}$, Δm^2_{31}

- **Important (esp. θ23 ~ 45 deg.) with possibility of new physics.**
- **Either 120 GeV or 60 GeV beam can be used: two oscillation nodes.**
- **Measurement dominated by systematics (see hep/0407047) (~1%)**

★ **yr~2x10^7 sec**

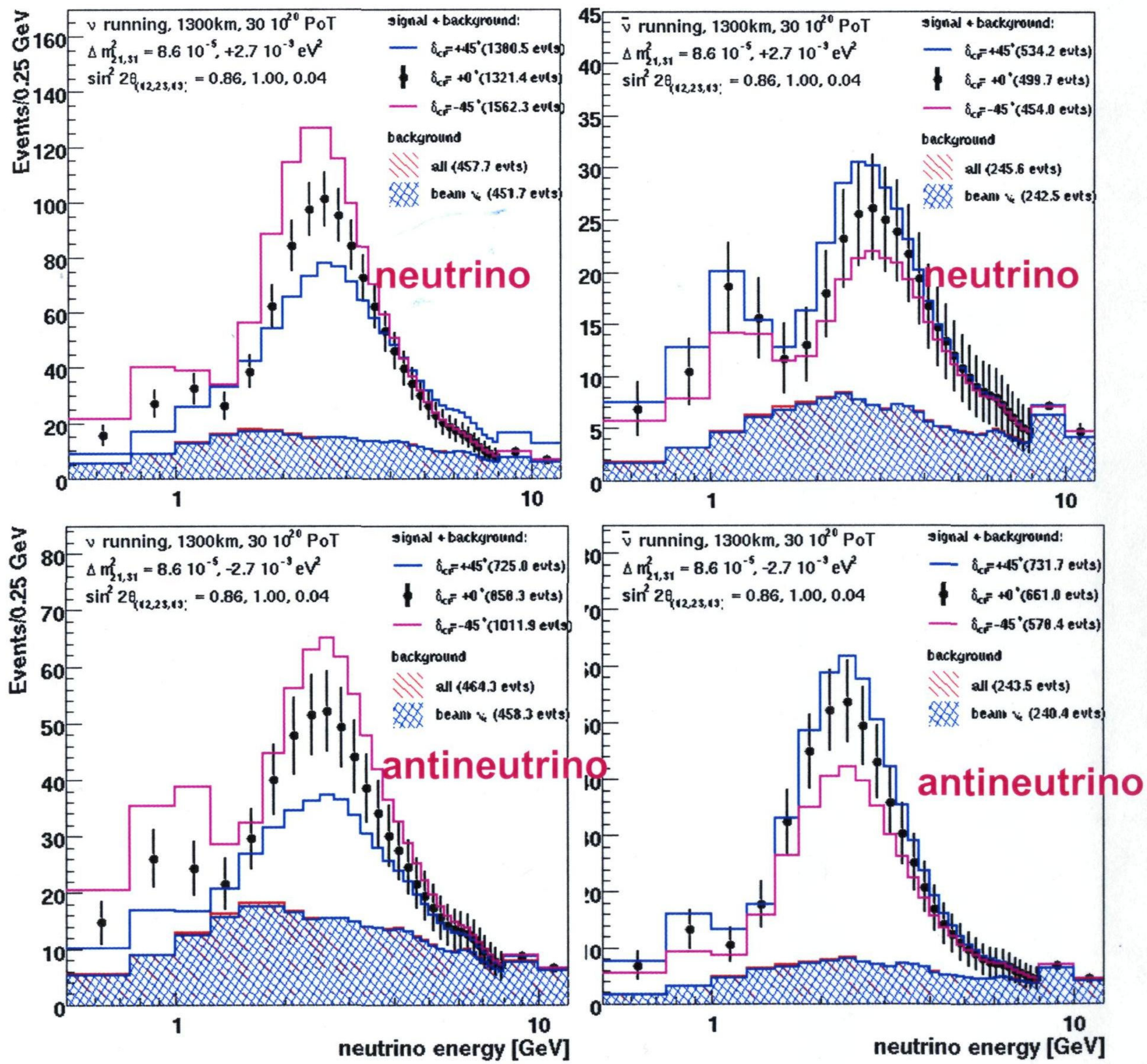
Electron neutrino appearance spectra

$\sin^2 2\theta_{13} = 0.04$, **100kT LAr.**, WBLE 120 GeV, 1300km, 30E20 POT.

$(-\delta_{cp} = -45°, -\delta_{cp} = +45°)$

Normal **Reversed**

- **LAR assumptions**
- **80% efficiency on electron neutrino CC events.**
- **sig(E)/E = 5%/sqrt(E) on quasielastics**
- **sig(E)/E = 20%/sqrt(E) on other CC events**



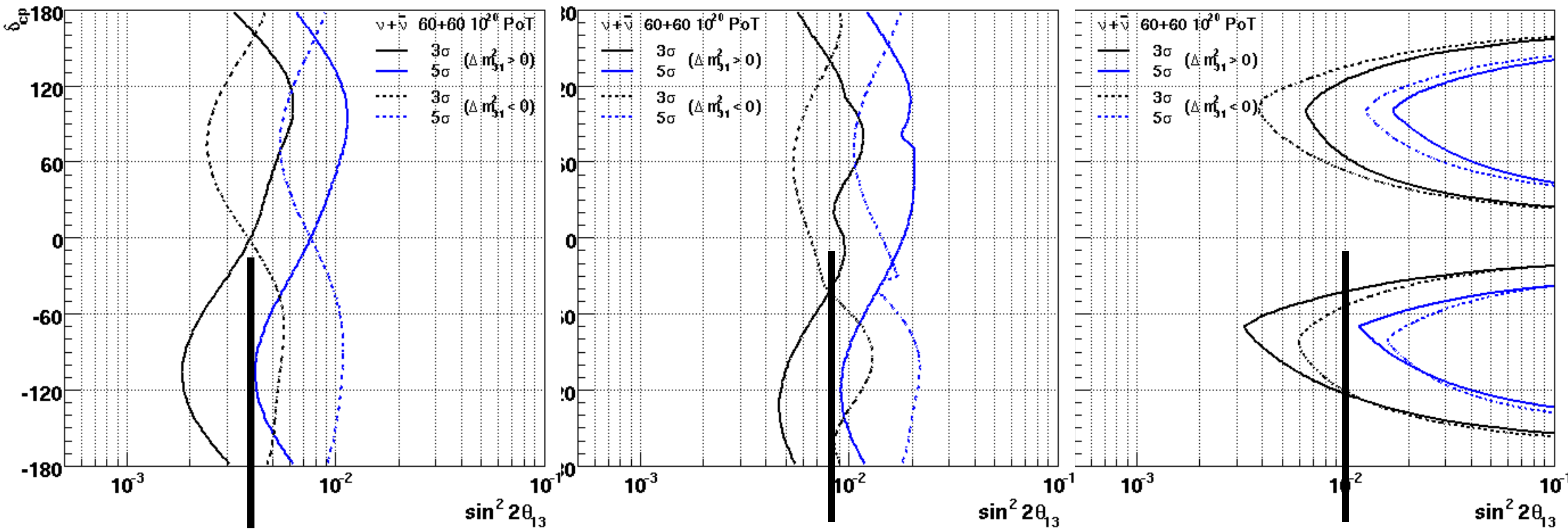
Spectra and sensitivity is the work of M. Bishai, Mark Dierckxsens, Patrick Huber + many helpers

WBLE to DUSEL(1300km) 3sig, 5sig discovery regions.

300 kT WCh

60 10^20 POT for each nu and anu

Stat+syst th13 — mass ordering — CP violation

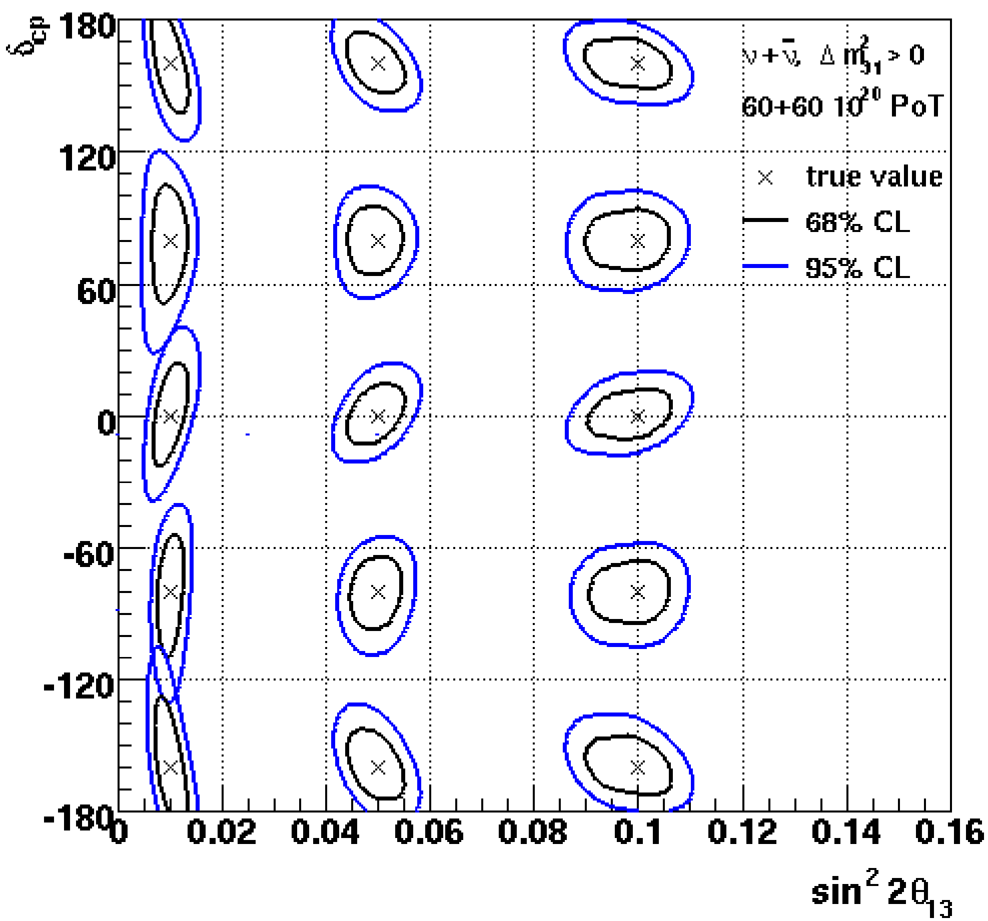


0.004 — 0.008 — 0.01

CP Fraction: Fraction of the CP phase (0-2pi) covered at a particular confidence level.

Report the value of th13 at the 50% CP fraction.

- Program should lead to measurement of 3-generation parameters without ambiguities.
- CP measurement is approximately independent of θ13 if not background limited. Need large detector independent of θ13 value.



300 kT water Cherenkov detector @DUSEL Measurement of CP phase and $\sin^2 2\theta_{13}$ at several points. All ambiguities and mass hierarchy are resolved.

Proton Decay

Early Experiments

IMB, Kolar Gold Mine, Homestake, Soudan, Frejus

Recent Experiments

Kameokande, Superkameokande

Theory:	$p \rightarrow e^{+}\pi^{o}$	$p \rightarrow k^{+}\nu$
SU(5) Minimal	**10^{29}-10^{30} yrs**	**10^{28}-10^{30} yrs**
SUSY GUT		
SU(5)		
SO(10)	**2 x 10^{35} yrs**	**10^{34}yrs**
Exp. Limits	**8.2 x 10^{33}yrs**	**>2.8x 10^{33}yrs**

SuperK 141 kton yrs

Next Order of Magnitude

Again Need very large detectors

Supernova Neutrinos

SN87A IMB
Kameokande 19 Events

Core Collapse of Supernova
Supernova Dynamics
Fundamental Neutrino Properties, including θ_{13} and mass hierarchy

Galactic Supernovae
~ 1 in 30 years $(\bar{\upsilon} + p \rightarrow n + e^{+})$
~ 100,000 events in 10 kpc

Diffuse (Relic) Supernova
$\bar{\nu} e$ and νe
Continuous flux

Measure Neutrino
Number
Energy 0 – 40 MeV
Time seconds

Need many Large Detectors

Conclusions

New Era:

Large Scale detectors	**300 Kton Water Cerenkov; 50 Kton liquid argon**
Intense Beams	**1 – 2 Mwatts**
Long distances	**1300 Km Fermilab – Homestake**

First Proposed (2003)

Very Long Baseline Neutrino Oscillation

Experiment for Precise Measurement of mixing Parameters and CP Violating Effects

M. Diwan, W. Marciano et. al. Phys. Rev. D 68, 12002 (2003)

Grand opportunity:

- **Greatly improve accuracy of atmospheric and solar neutrino parameters**
- **Resolve value of Theta 13, mass hierarchy and possibly observe CP violation**
- **Observe Supernova**
- **Possibly observe proton decay**
- **DOE,NSF, Fermilab actually pursing such a neutrino program**