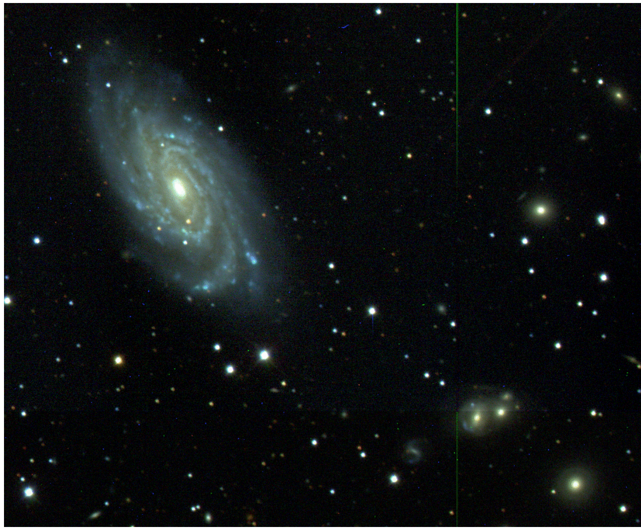
NOnA*: The Next Neutrino Oscillation Experiment

*NUMI Off-axis n_e Appearance experiment

Argonne, Athens, Caltech, UCLA, Fermilab, College de France, Harvard, Indiana, ITEP, Lebedev, Michigan State, Minnesota/Duluth, Minnesota/TC, Munich, Stony Brook, Northern Illinois, Ohio, Ohio State, Oxford, Rio de Janeiro, Rutherford, South Carolina, Stanford, TexasA&M, Texas/Austin, Tufts, Virginia, Washington, William & Mary

Ken Heller
University of Minnesota

The Issues



- **CP Violation in the Lepton Sector**
  - **Baryon Asymmetry of the Universe?**
- **Neutrino Mass Hierarchy**
- **The Lepton Mixing Matrix (Pontecorvo - Maki –Nakagawa - Sakata).**
  - **How big is q_{13}?**
- **Matter Effects in Neutrino Oscillations**

Mixing

CKM Quark Mixing Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} 0.97 & 0.22 & 0.003\,e^{i\delta} \\ -0.22 & 0.97 & 0.04 \\ 0.01 & -0.04 & 0.999 \end{pmatrix}$$

δ gives CP violation

$$\begin{pmatrix} 1 & 10^{-1} & 10^{-3} \\ 10^{-1} & 1 & 10^{-2} \\ 10^{-2} & 10^{-2} & 1 \end{pmatrix}$$

Small off-diagonal

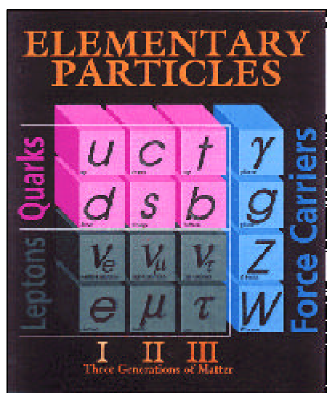
PMNS Lepton Mixing Matrix

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

$$\begin{pmatrix} 0.8 & 0.5 & < 0.2\,e^{i\delta}\,? \\ -0.5 & 0.5 & 0.7 \\ 0.5 & -0.5 & 0.7 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 1 & 10^{-?} \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

Big off-diagonal



3 neutrinos: LSND? Wait for MiniBOONE results

Neutrino Oscillation Measurements

Solar and Atmospheric Effects: $\Delta m_{12}^2, \theta_{12}, \Delta m_{23}^2, \theta_{23}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric: θ_{23} | **CP violation** | **Solar:** θ_{12}

Need to measure: ~~CP~~ **phase** δ , θ_{13} ($\nu_e \rightarrow \nu_\mu$), **Sign of** Δm^2_{32}

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

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

$\theta_{12} \sim 32^o$

$\theta_{23} \sim 45^o$

$?_{13} < 15^o$

Ignore Majorana phase

Measurements of n m ® n e and n̄ m ® n̄ e gives q 13 and d

$$P(n_\mu \text{ ® } n_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2(q_{23}) \sin^2(2q_{13}) \sin^2(1.27\ Dm_{23}^2\ L/E)$$

$$P_2 = \cos^2(q_{23}) \sin^2(2q_{12}) \sin^2(1.27\ Dm_{12}^2\ L/E)$$

$$P_3 = \mp J \sin(d) \sin(1.27\ Dm_{23}^2\ L/E)$$

$$P_4 = J \cos(d) \cos(1.27\ Dm_{23}^2\ L/E)$$

Matter Effect

P_1 x $(1 \pm 2E/E_R)$

P_3, P_4 x $(1 \pm E/E_R)$

E_R = 11 GeV (Earth)

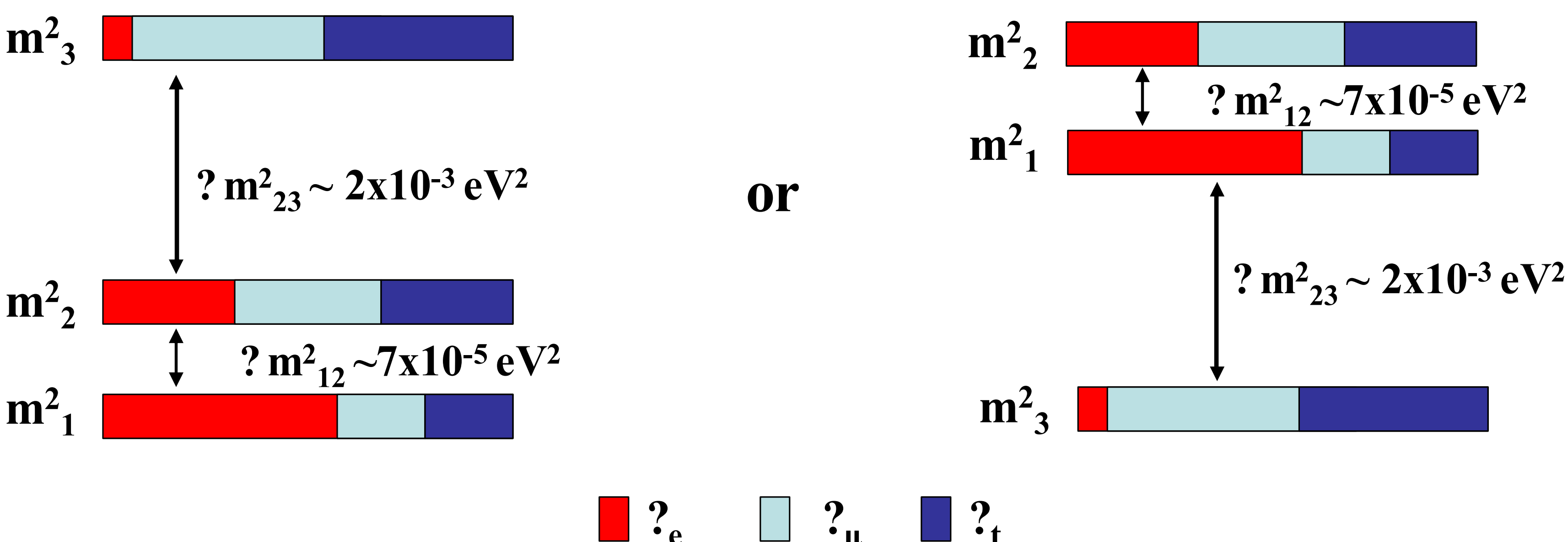
23% effect (10% T2K)

Enhancement for $Dm^2 > 0$

Suppression for $Dm^2 < 0$

$$J = \cos(q_{13}) \sin(2q_{12}) \sin(2q_{13}) \sin(2q_{23}) \sin(1.27\ Dm_{23}^2\ L/E) \sin(1.27\ Dm_{12}^2\ L/E)$$

Which Mass Hierarchy?

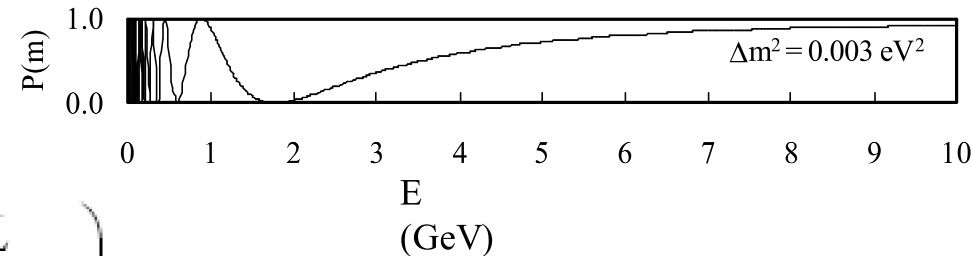


Expected Signal Size

Ignore matter effects, CP violation

P(n_m? n_e) ˜ P_1 = $\sin^2(q_{23})$ $\sin^2(2q_{13})$ $\sin^2(1.27\ Dm_{23}^{\ 2}$ L/E)

Peak of oscillation at



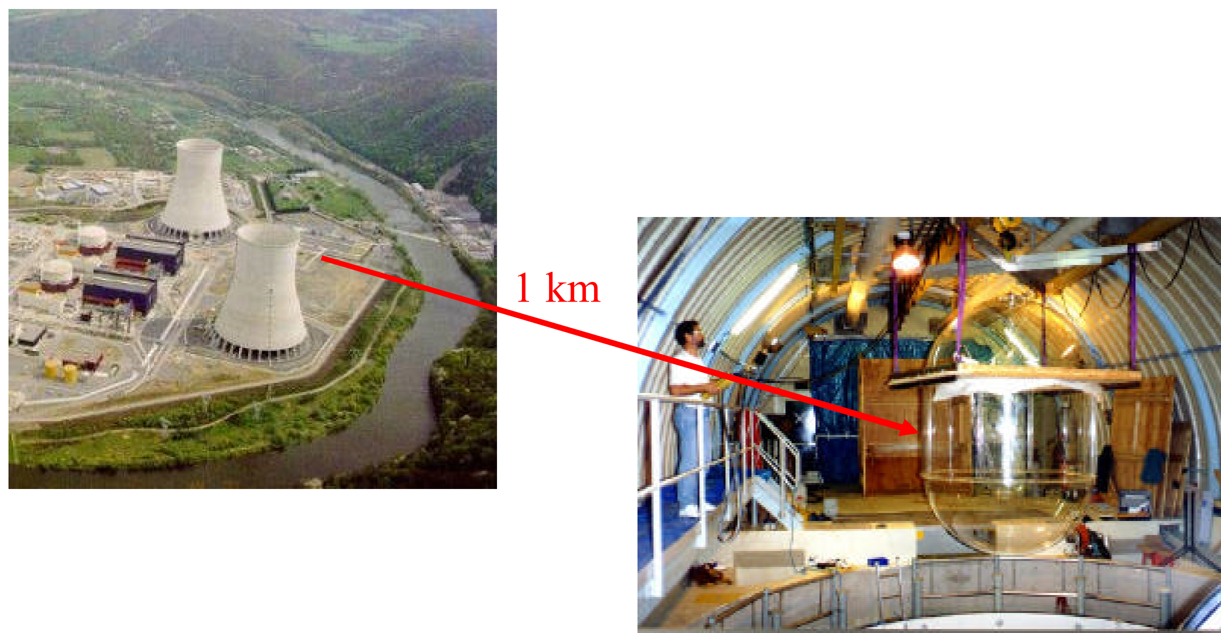
$$E = 1.7\ \text{GeV}\left(\frac{\Delta m_{32}^2}{2.5\times10^{-3}\,\text{eV}^2}\right)\left(\frac{L}{820\ \text{km}}\right)$$

P(n_m? n_e) ˜ ½ $\sin^2(2q_{13})$

Limit from CHOOZ:

$\sin^2 2q_{13}$ £ 0.2

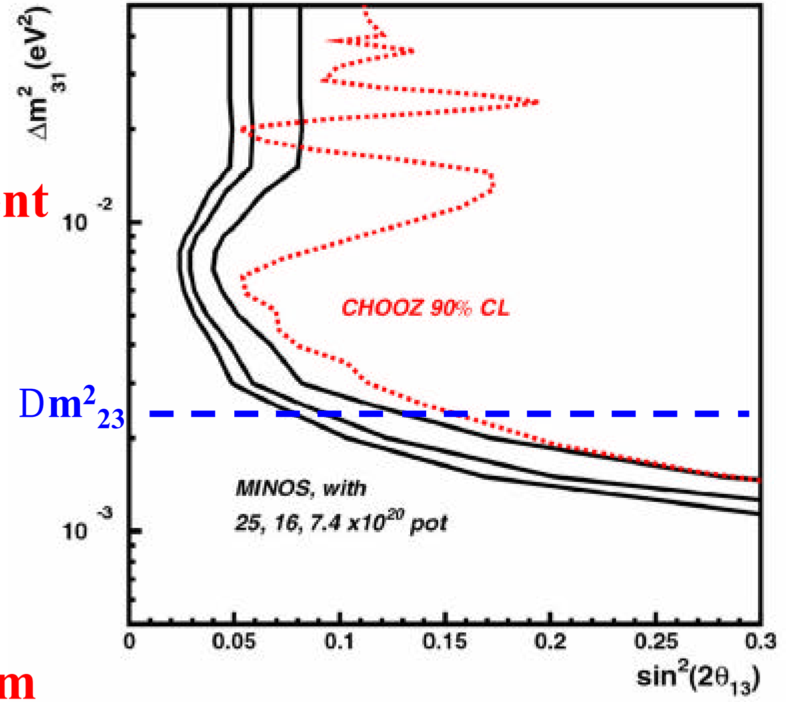
P(n_m? n_e) < 0.1



Program Goals

Primary Goals of NOnA

- Measure q_{13}
- Determine Mass Hierarchy
- Determine Needs for CP Violation Measurement



If q_{13} is large enough

- Find CP Violation

Need

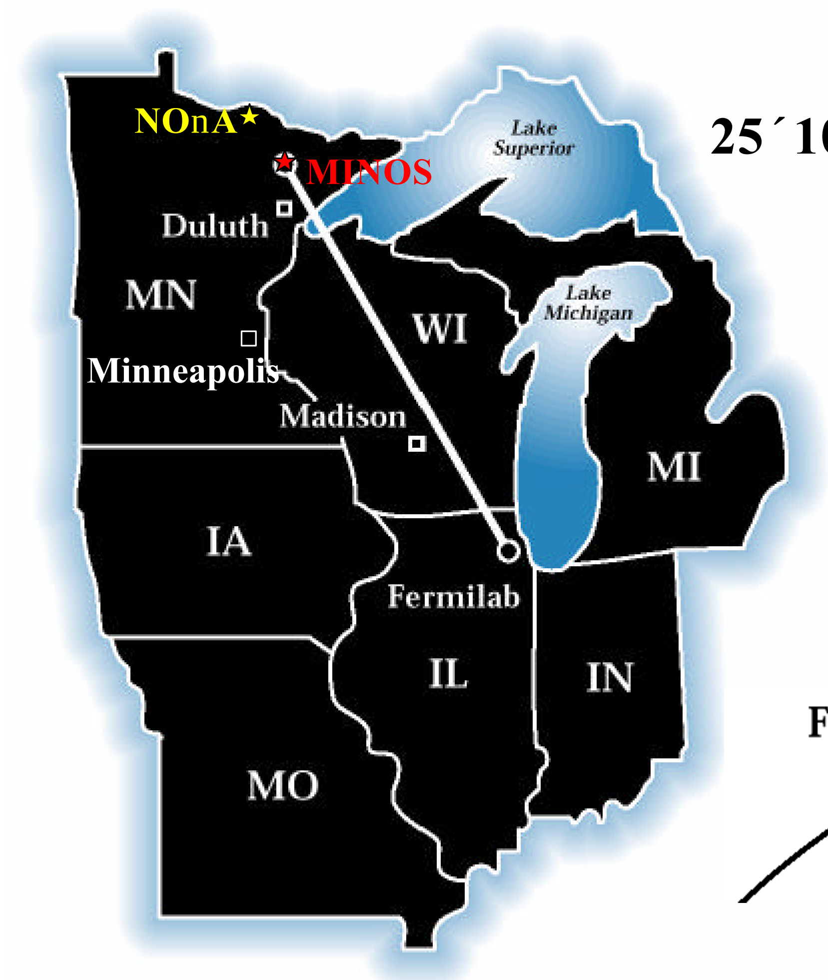
- Intense Muon Neutrino and anti-Neutrino beam
    - NUMI now, Proton Driver enhanced NUMI to come
- Detector With Good Electron ID
    - Large Mass
    - Small Cost/mass
    - Simple Operation at Remote Site with correct L/E

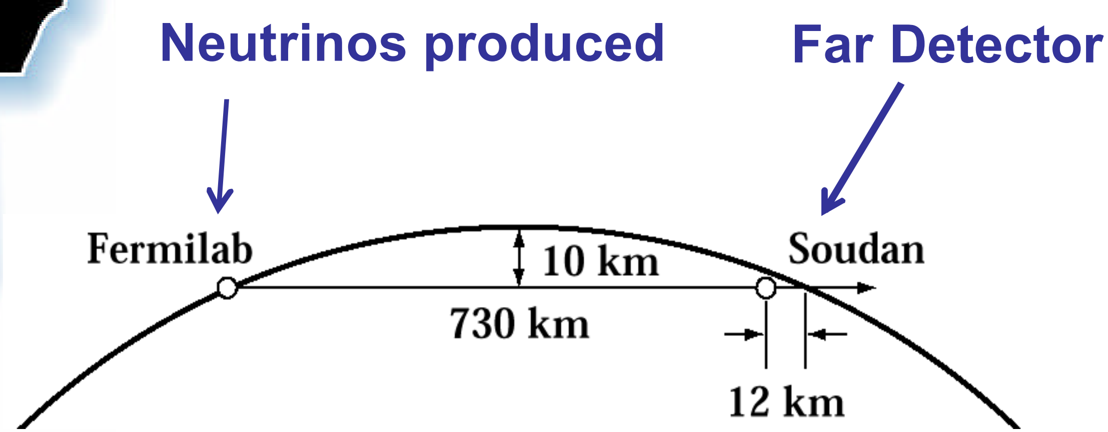
The NuMI Beam Exists

3.4 ´ 10^{20} protons/yr

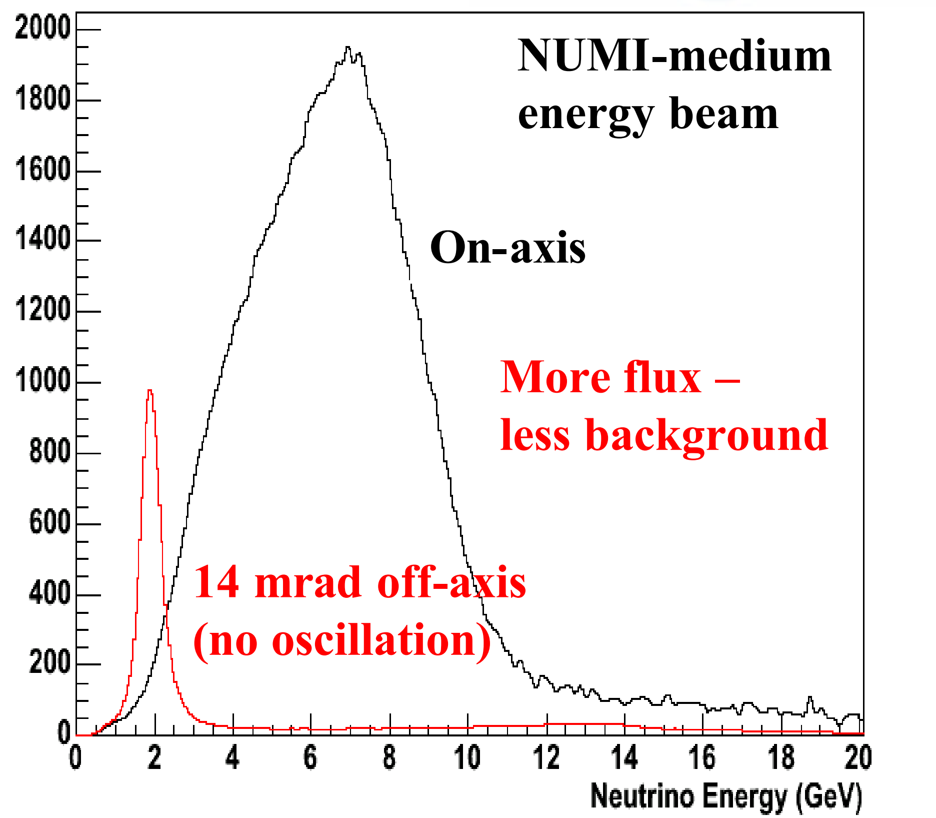
6.5 ´ 10^{20} protons/yr
post collider

25´ 10^{20} protons/yr
proton driver



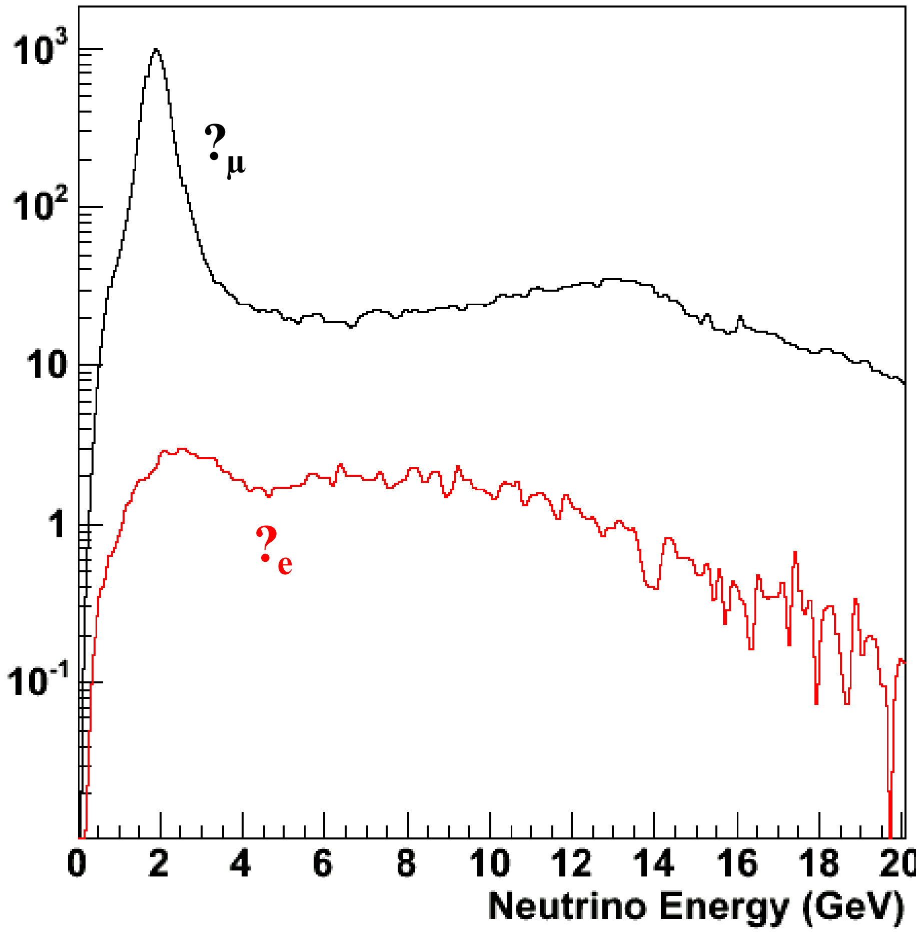


Use Off Axis Beam

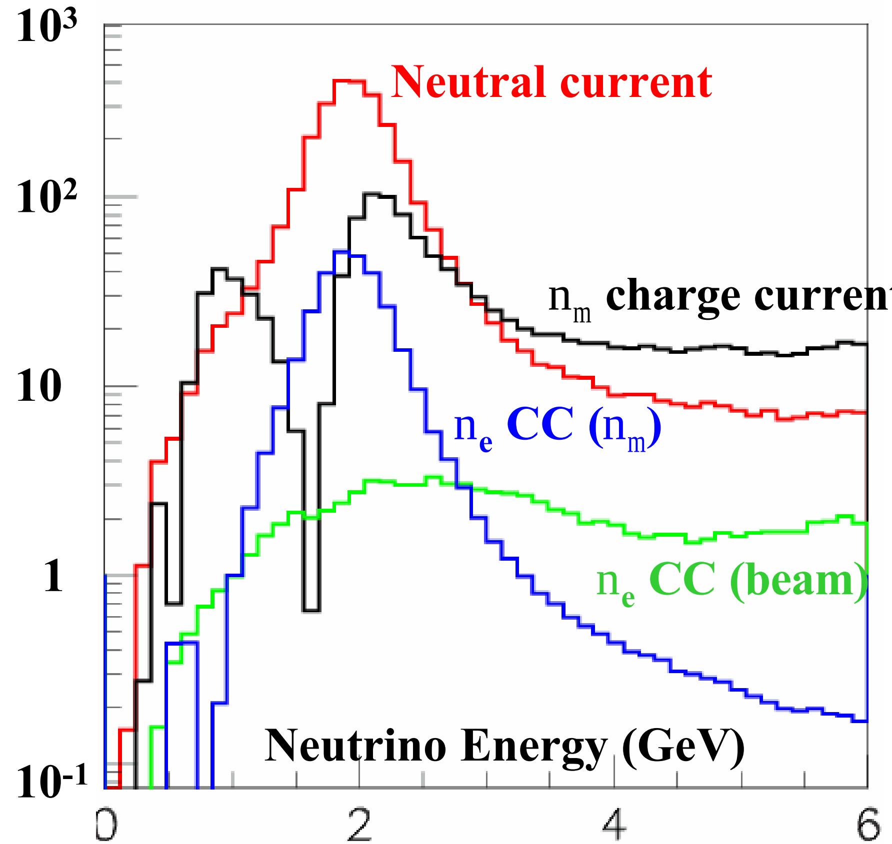


- Narrow energy distribution
- Higher Intensity at desired energy
- Suppressed high energy tail
  - Reduces NC contamination

Beam



At Far Detector

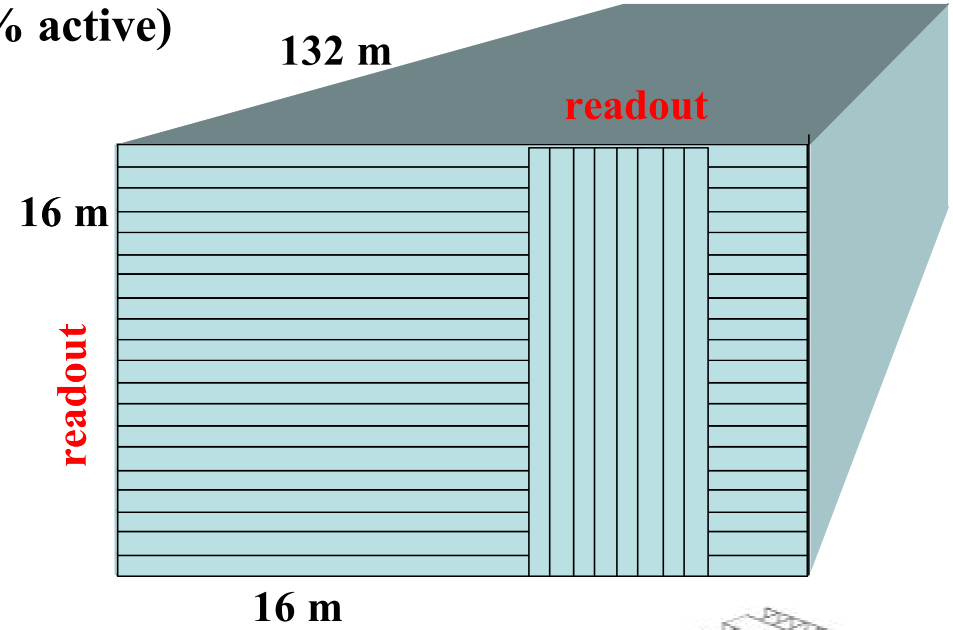


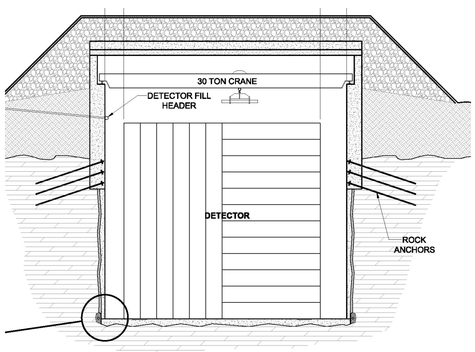
|– signal –|

At Chooz limit

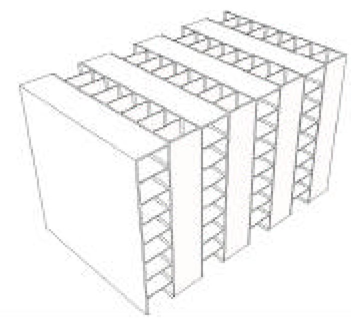
The NOnA Detector Design

- Large mass (30 kT)
- Good electron ID and energy resolution (80% active)
- Inexpensive parts
  - Active Element: Liquid Scintillator (24 kT)
  - Containment: PVC Extrusions (6 kT)
  - Photodetector: APDs (3/4 million pixels)
- No mine (full cosmic ray rate)
  - 8 through detector in a 10 msec spill
    (4 with overburden)

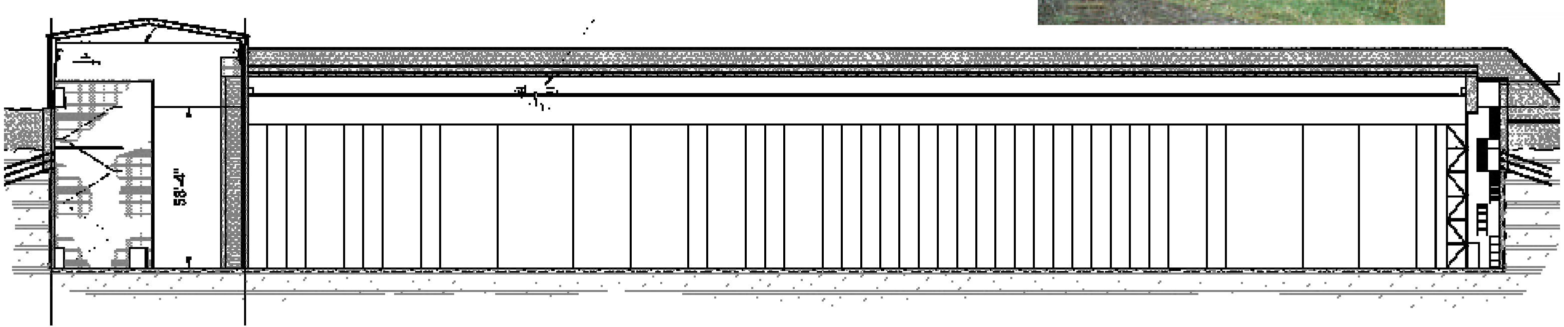




Sod house building design



1984 planes
761,856 cells

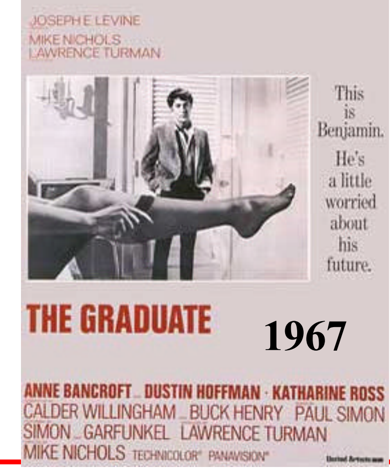


PVC Use in Construction

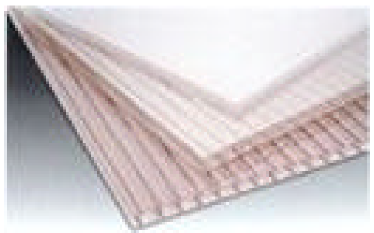
Deck Construction

Walls & Doors

Pipes

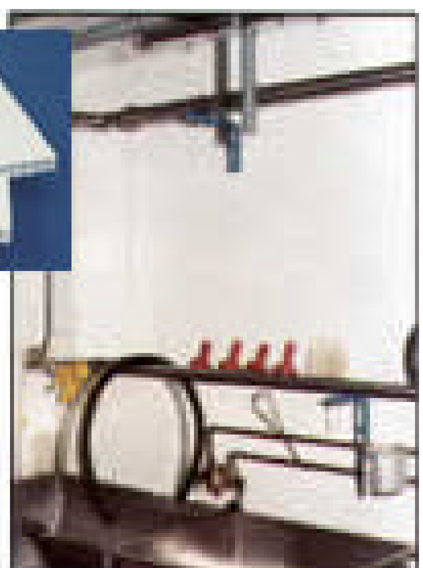


Mr. McGuire: I just want to say one word to you - just one word.
Ben: Yes sir.
Mr. McGuire: Are you listening?
Ben: Yes I am.
Mr. McGuire: 'Plastics.'
Ben: Exactly how do you mean?
Mr. McGuire: There's a great future in plastics.



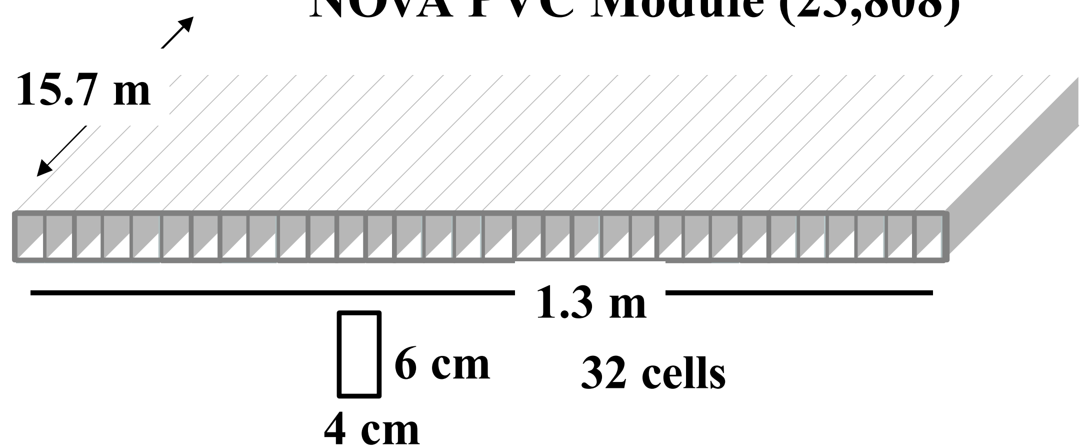
Standard Widths

980, 1050, 1220, 1250, 2100 mm

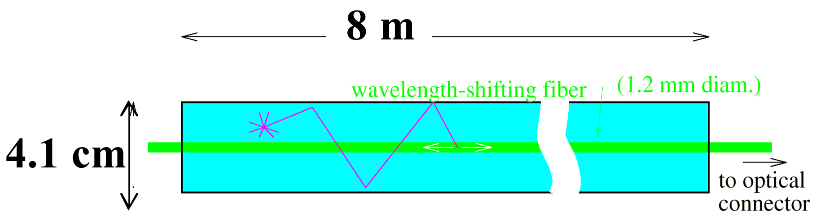


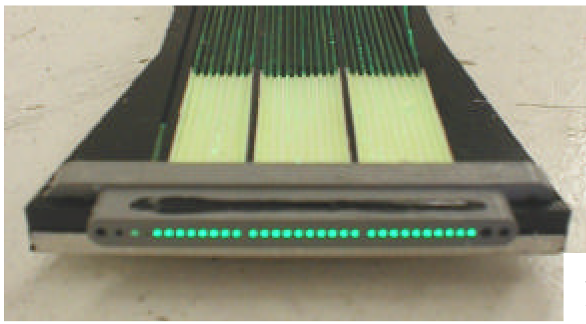
walls/celings
in milk houses

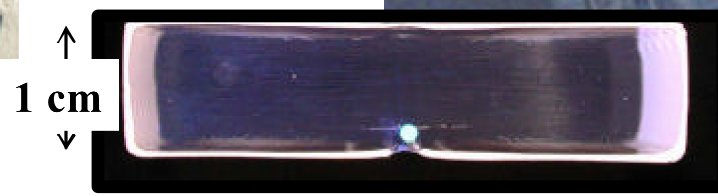
NOvA PVC Module (23,808)

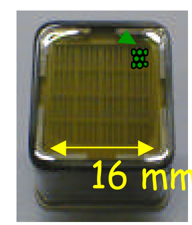


Signal Collection Based on MINOS Active Detector





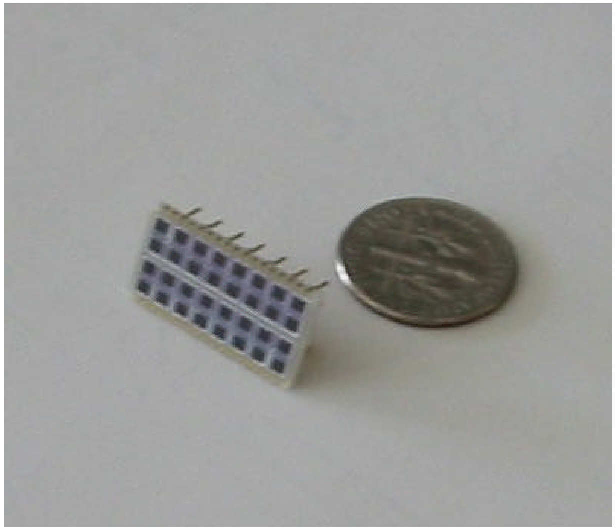


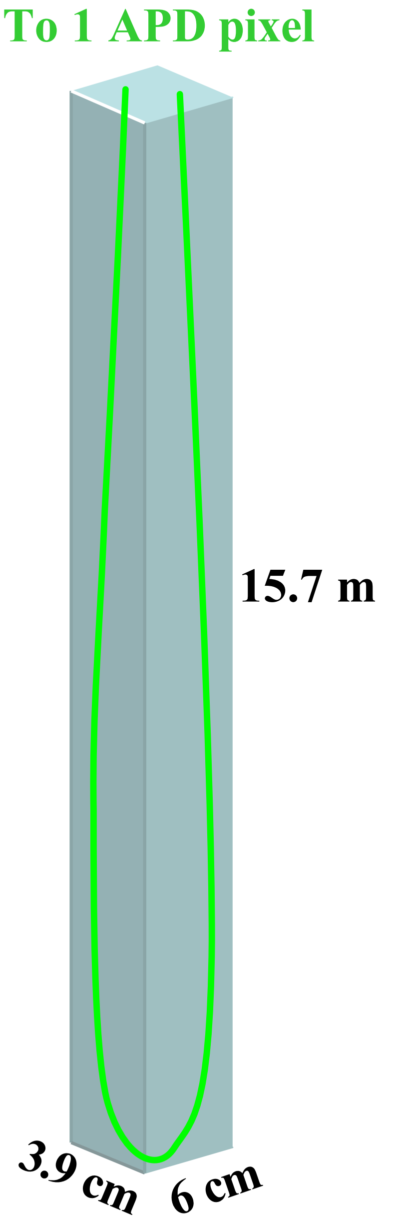


- Plastic Scintillator ? Liquid Scintillator
- 8 m length ? 15.7 m length
- 1 cm thick ? 6 cm thick
- 1.2 mm wavelength shifting fiber ? 0.8 mm wls fiber
- Straight fiber read out each side ? Looped fiber read out one side
- Hamamatsu multi-anode PMTs ? Hamamatsu multi-pixel Avalanche Photodiodes
- 8 cells/pixel multiplexing ? 1 cell/ pixel

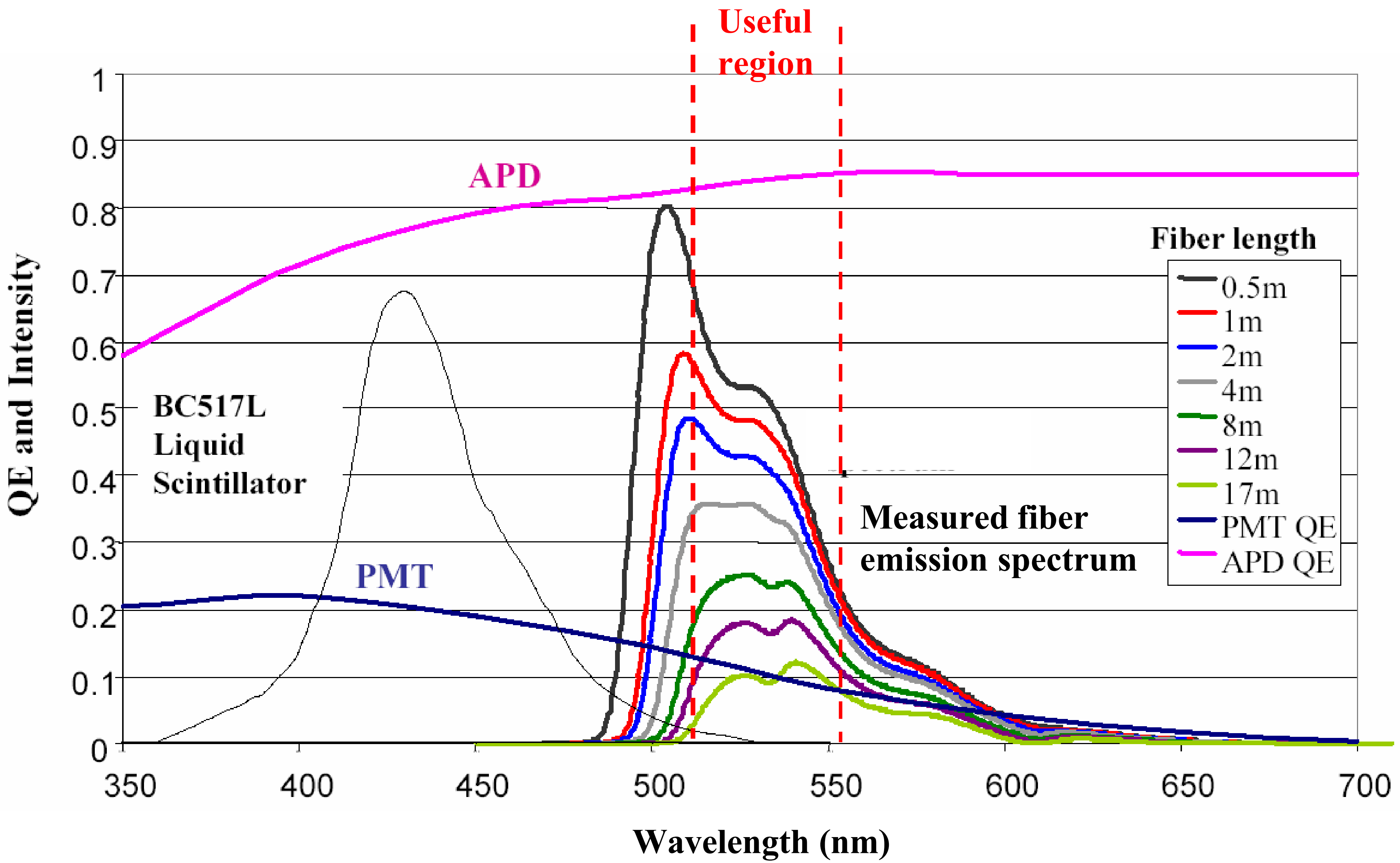
Active Detector

- **Scintillator Element Length 15.7 m**
  - **Sufficient light output with single ended readout (U loop)**
  - **Good shipping length**
  - **Approximately 4 cm wide 6 cm deep**
- **Scintillator Material**
  - **Liquid equivalent to**
    - **Bicron 517L**
- **Multiclad WLS Fiber**
  - **Kuraray 0.8 mm diameter**
  - **U loop**
- **Photodetector**
  - **APD**
  - **¾ million pixels**



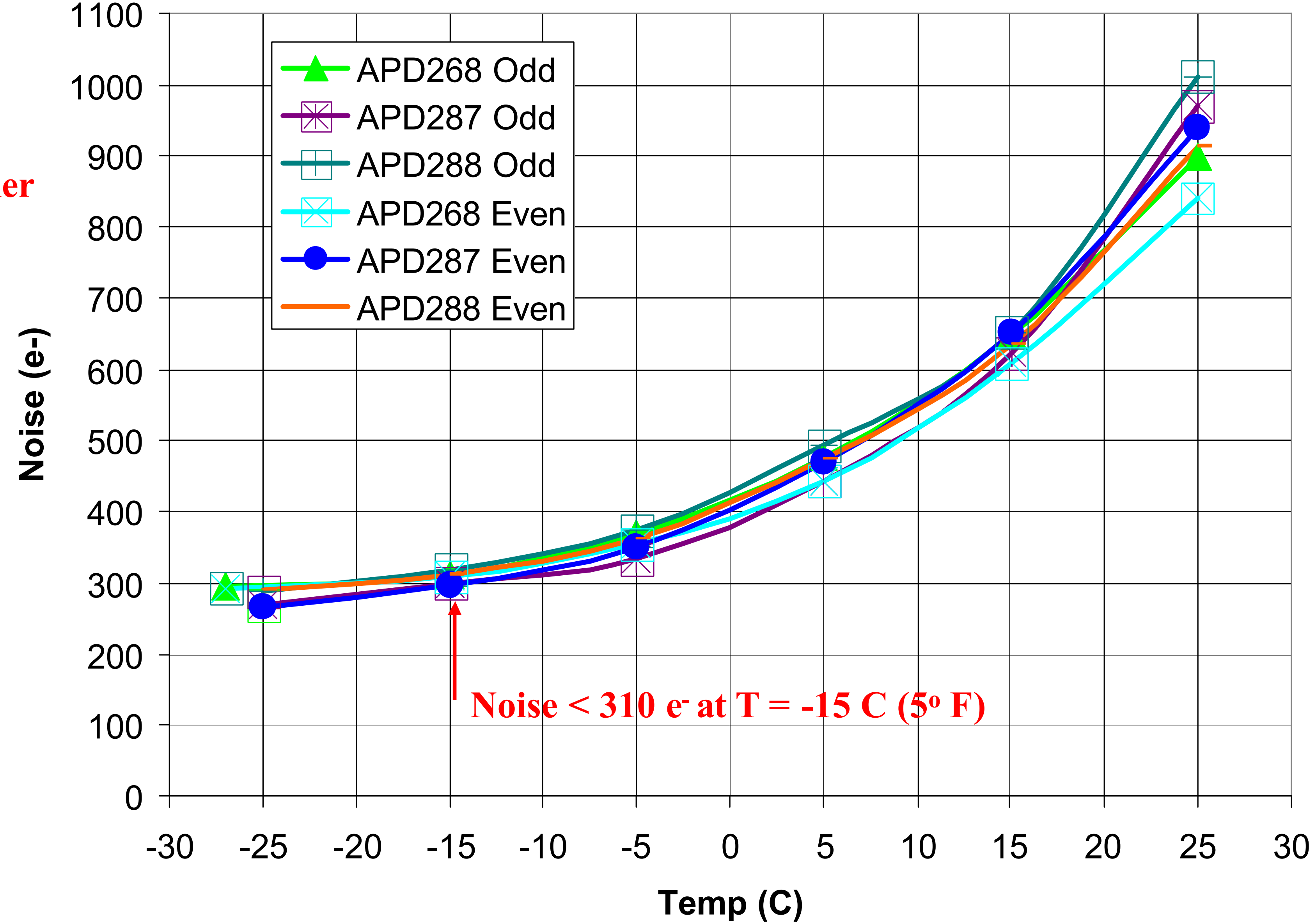


Quantum Efficiency and Fiber Emission



Noise vs. Temperature at Gain = 100

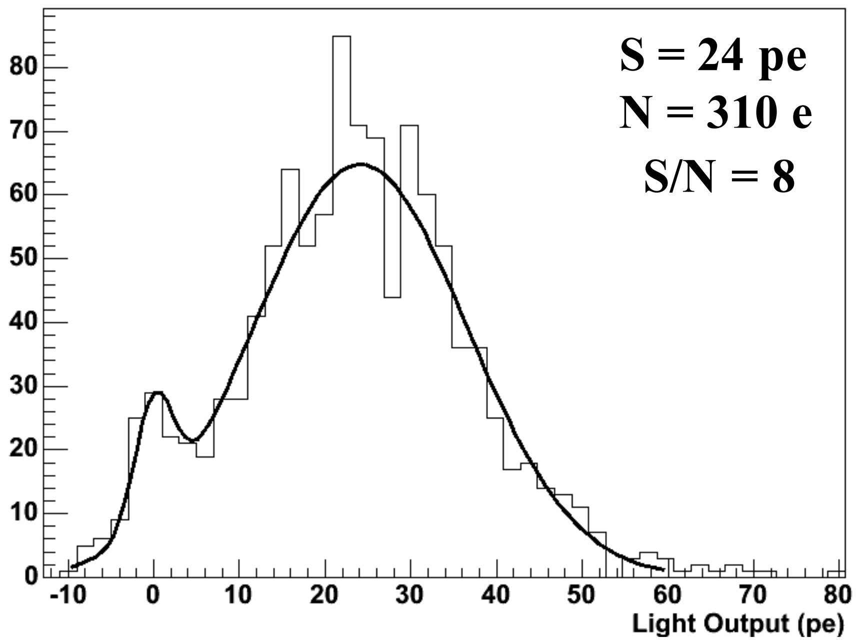
APD + Amplifier Noise



Noise < 310 e^- at T = -15 C (5^o F)

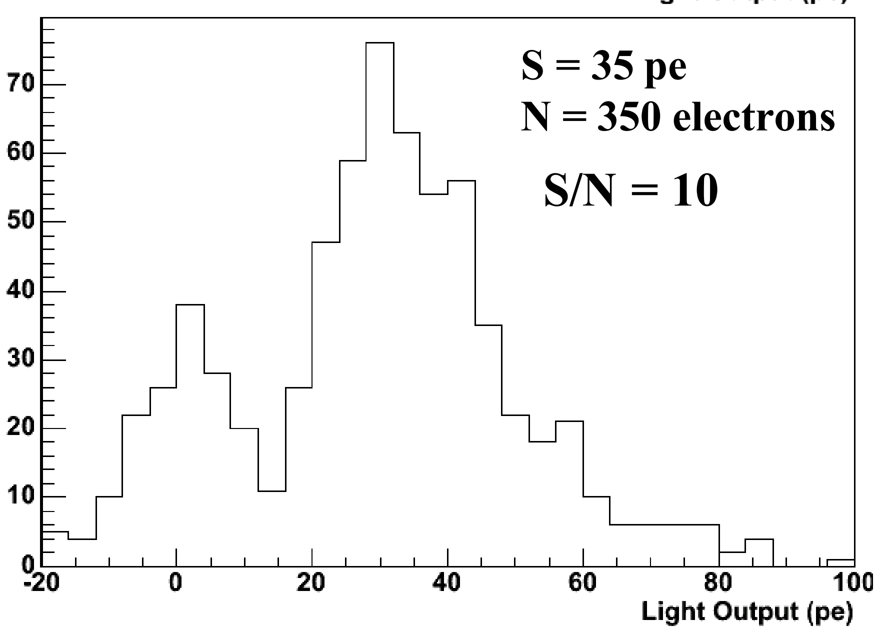
Noise to 250 e with correct amplifier capacitance

Full Cell at Full Length

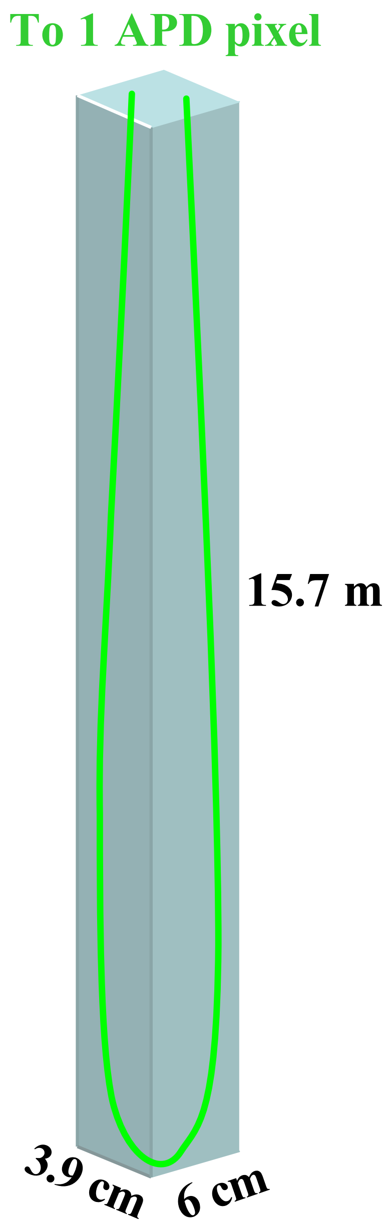


Measurement 1 MIP
Using cosmic ray muons

4 cm x 6 cm cell –
12% TiO_2 in PVC
(not optimal reflectivity)



With matched amplifier and designed reflectivity expect S/N > 10



Event Simulations

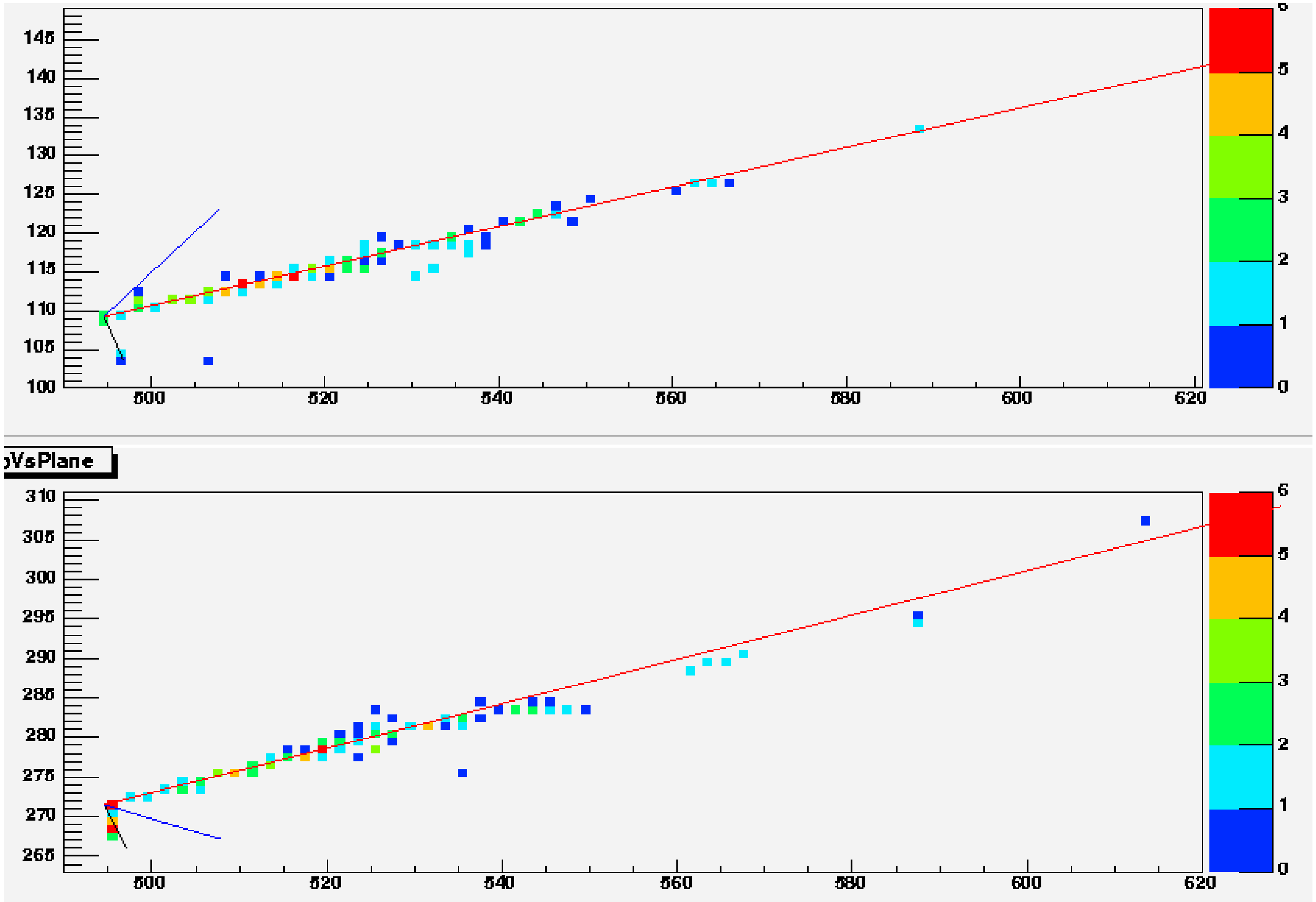
n_e **p** ® **e**$^-$ **p** p^+

E_n = 2.5GeV

E_e = 1.9GeV

E_p = 1.1GeV

E_p = 0.2GeV



		For 100 events
Efficiency oscillation n_e cc	0.23	86 events
Rejection n_m cc	7.1 x 10^{-4}	1 event
Rejection n nc	1.3 x 10^{-3}	6 events
Rejection beam n_e cc	6.6 x 10^{-2}	7 events

Background m CC event

$n_m\mathbf{n} ® m^-\mathbf{n}p^+p^o$

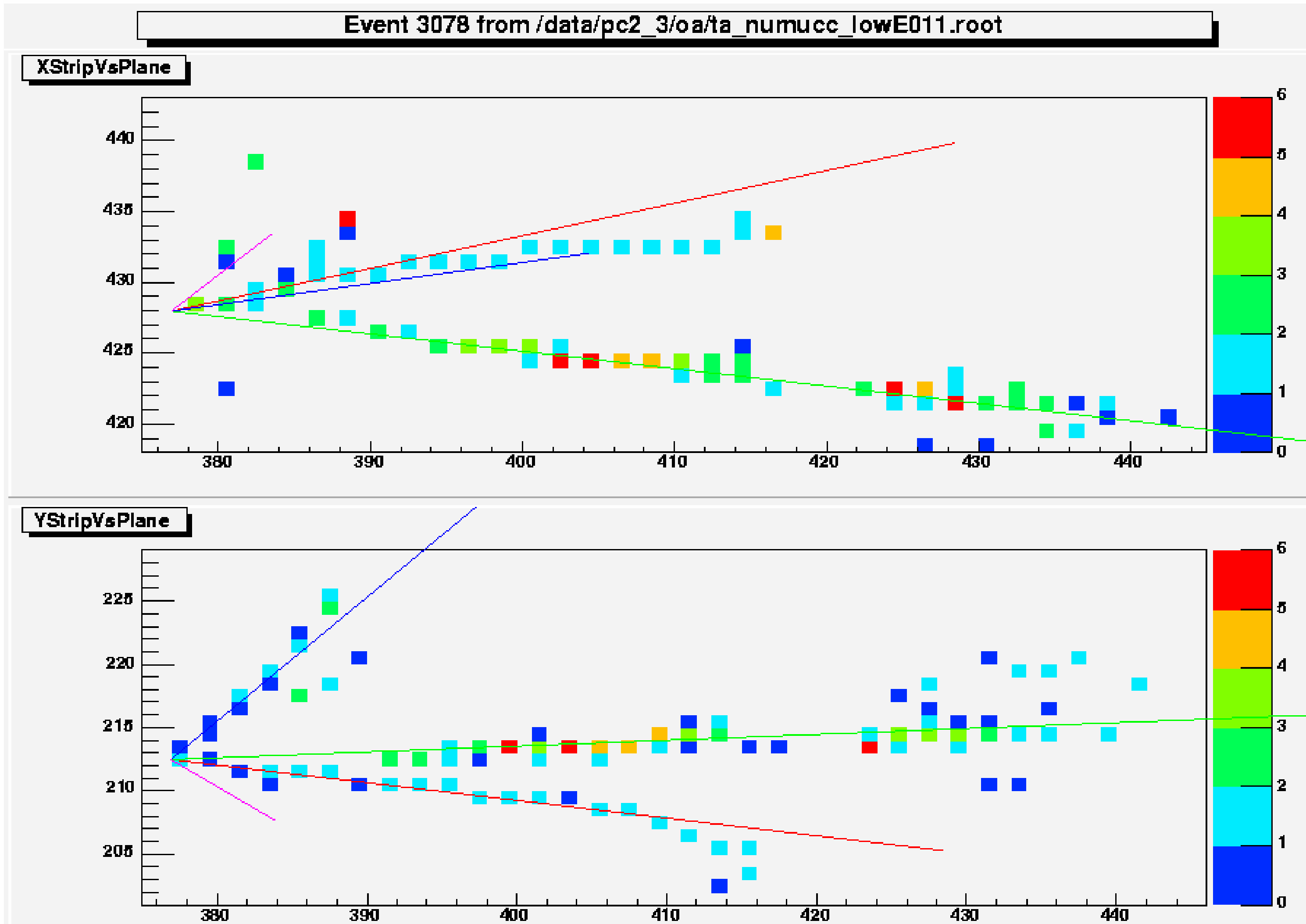
E_n=2.8 GeV

E_m=0.5GeV

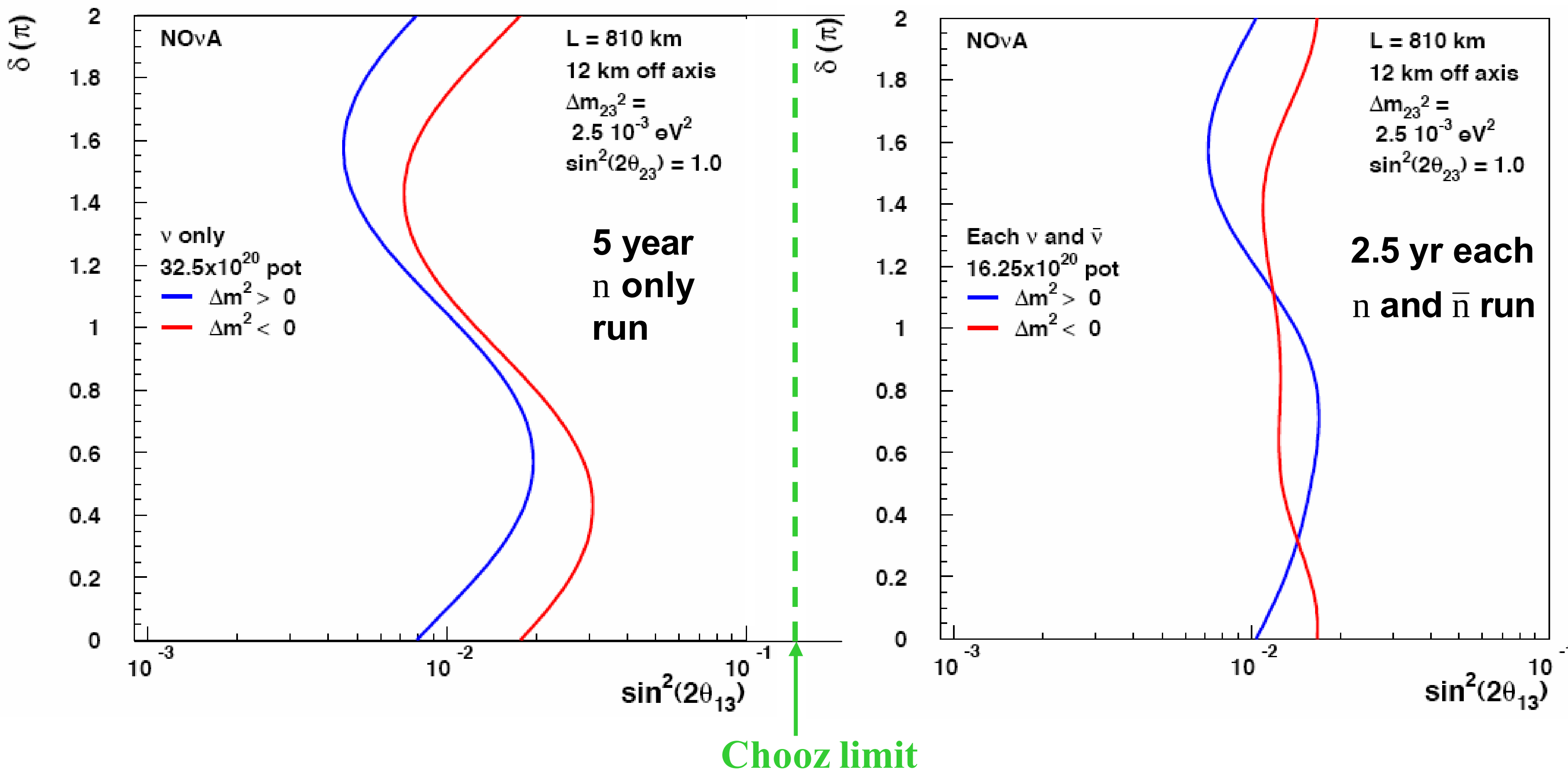
$E_\mathbf{n}$=1.0GeV

E_{p+}=0.4GeV

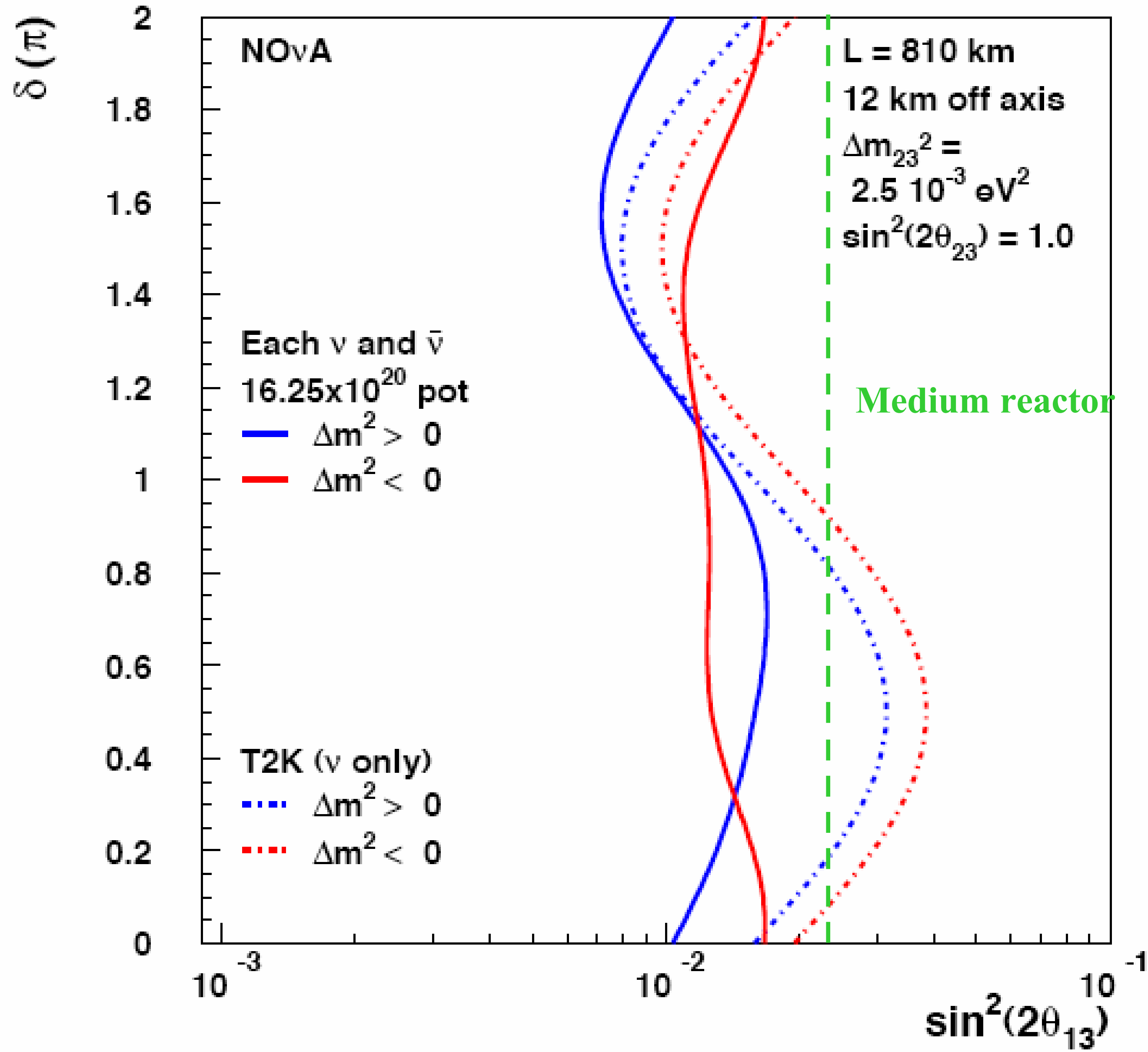
E_{po} =1.8GeV



3 s Discovery Potential for n_m ® n_e

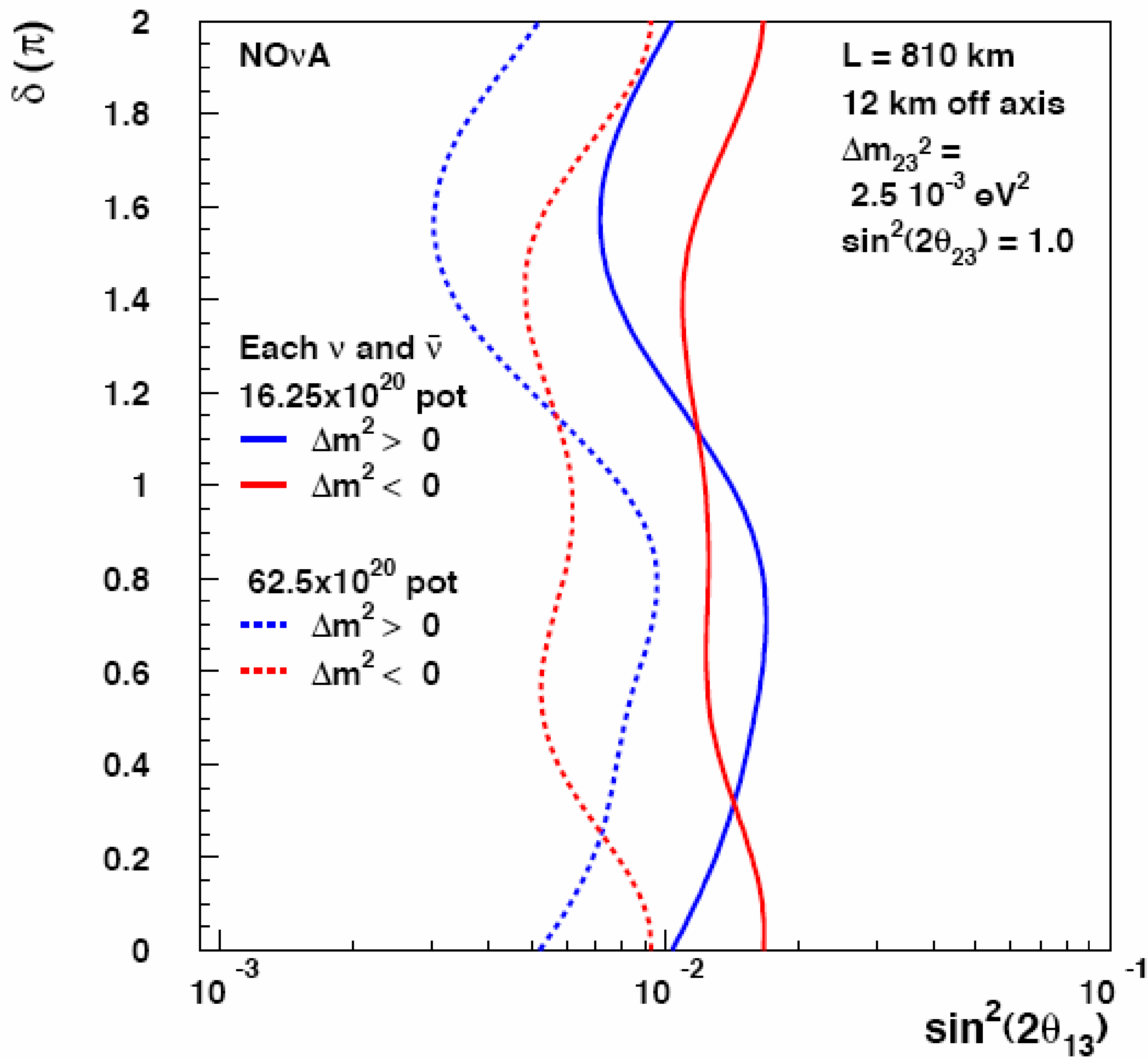


3 s Discovery Potential for n_m ® n_e



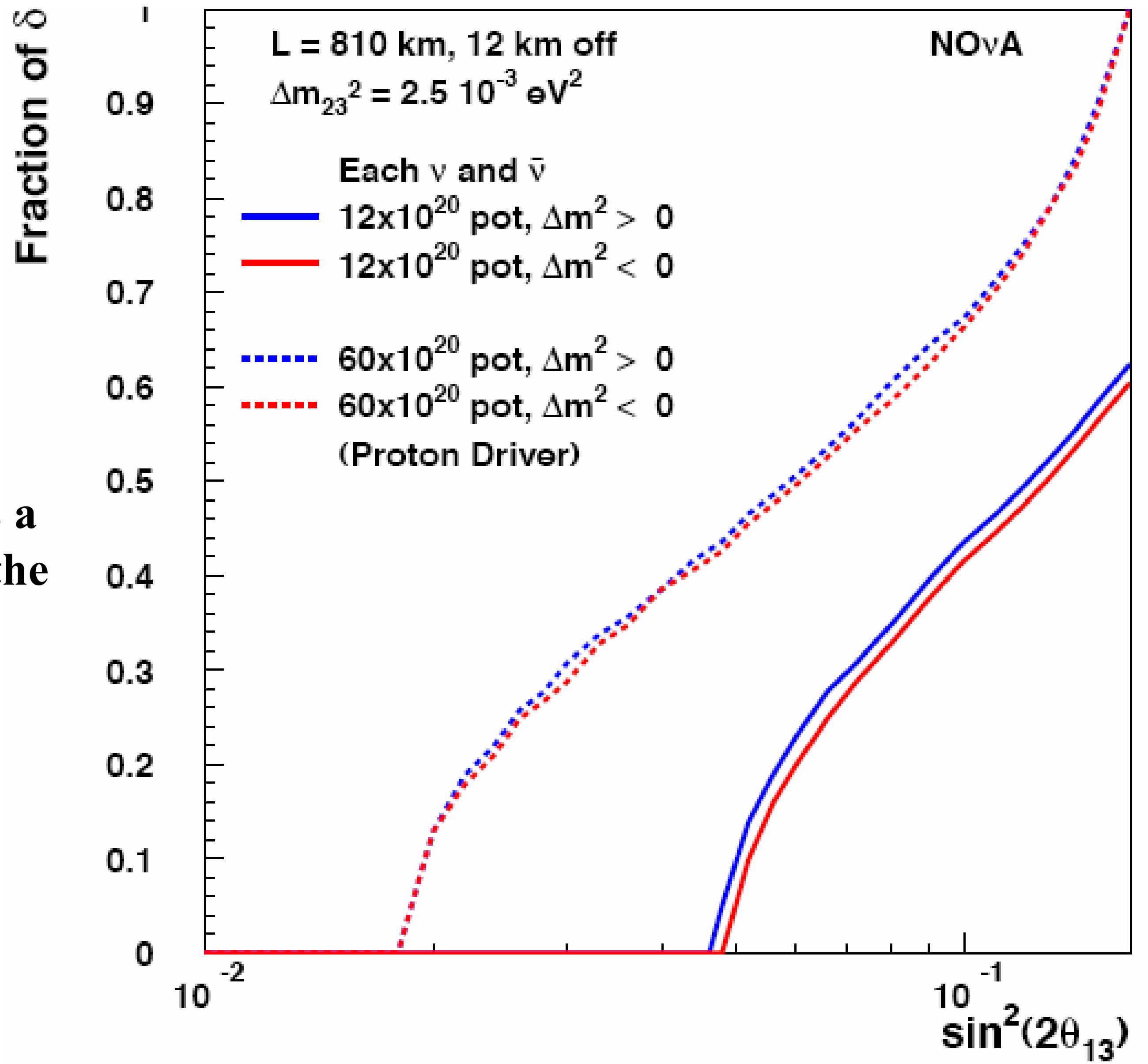
3 s Discovery Potential for n_m ® n_e

Proton Driver

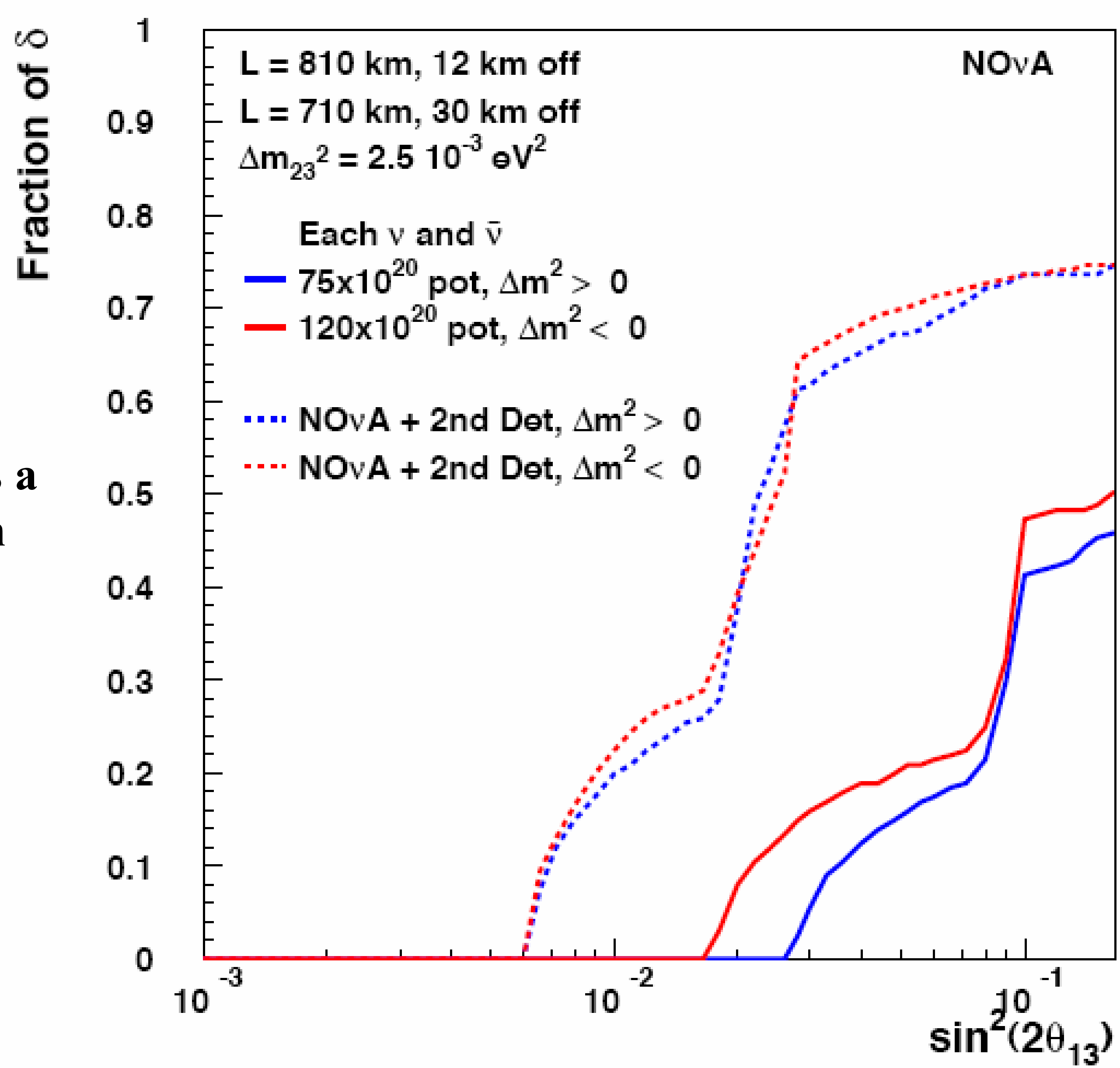


95% CL Resolution of the Mass Hierarchy

Fraction of possible d values for which there is a 95% C.L. resolution of the mass hierarchy

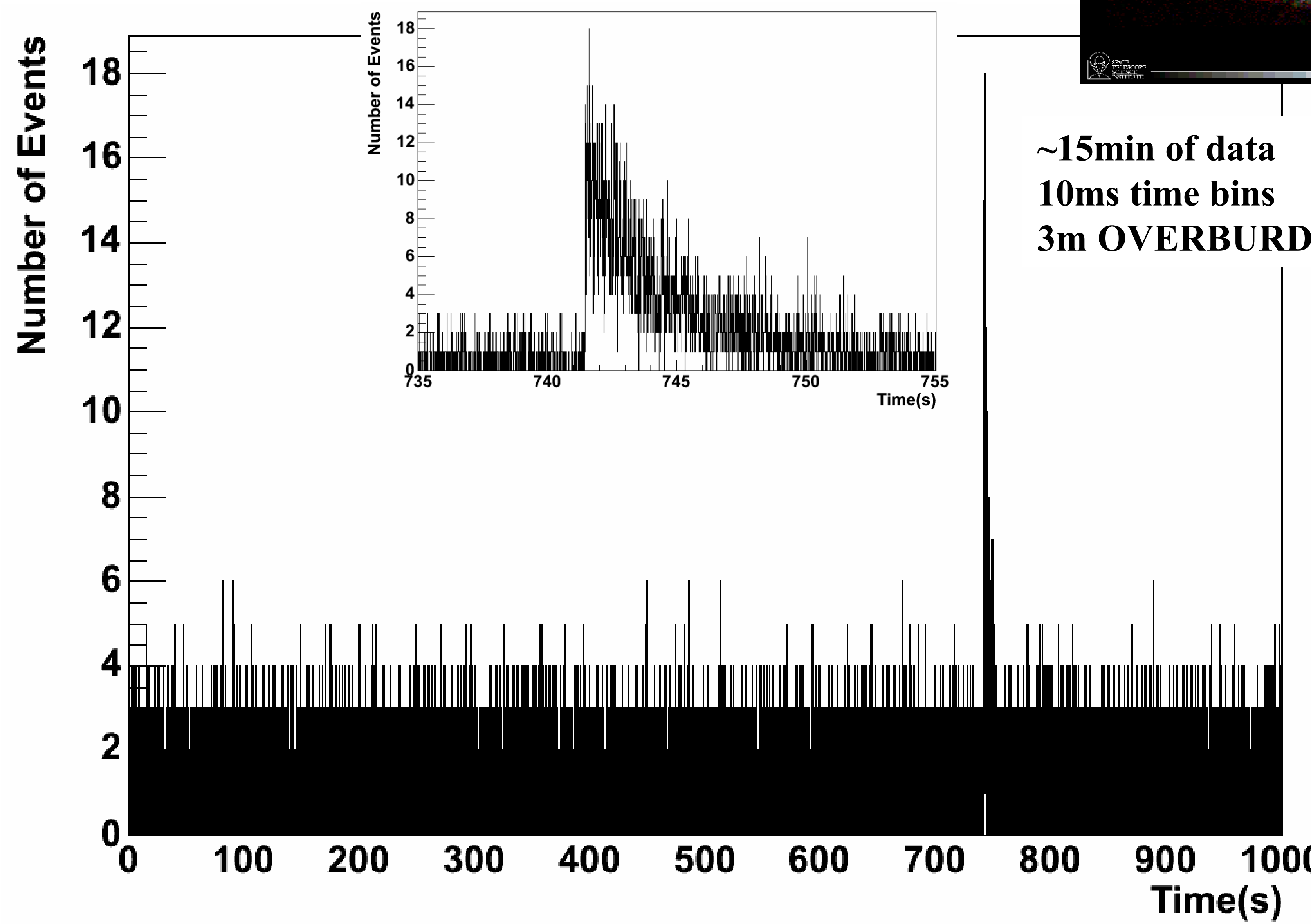


3 s Determination of CP Violation



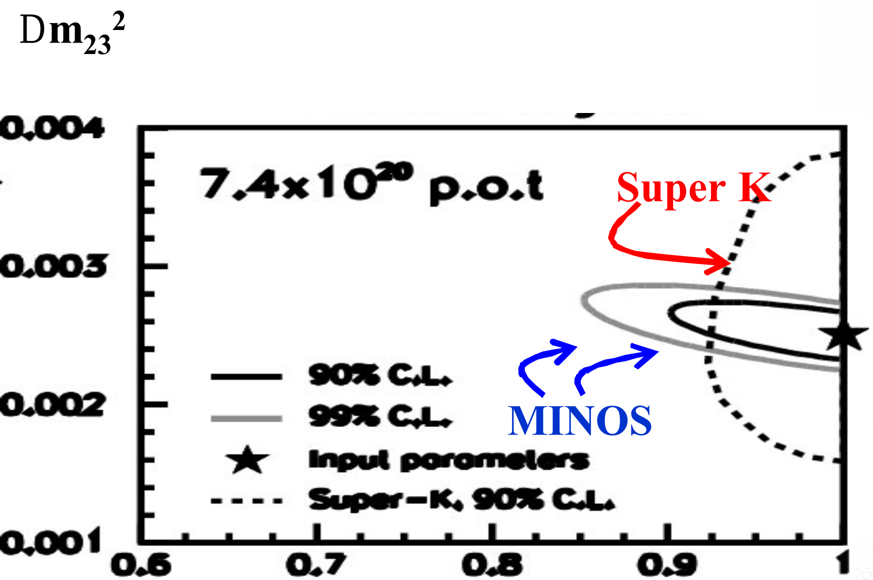
Fraction of possible d values for which there is a 95% C.L. determination that CP is violated for both mass orderings

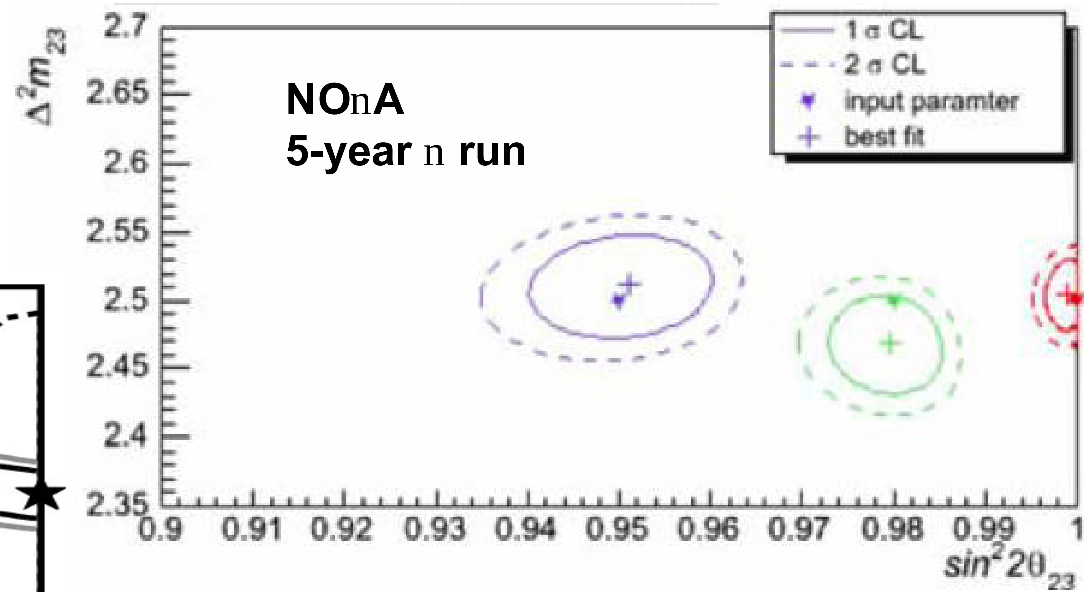
Typical supernova signal

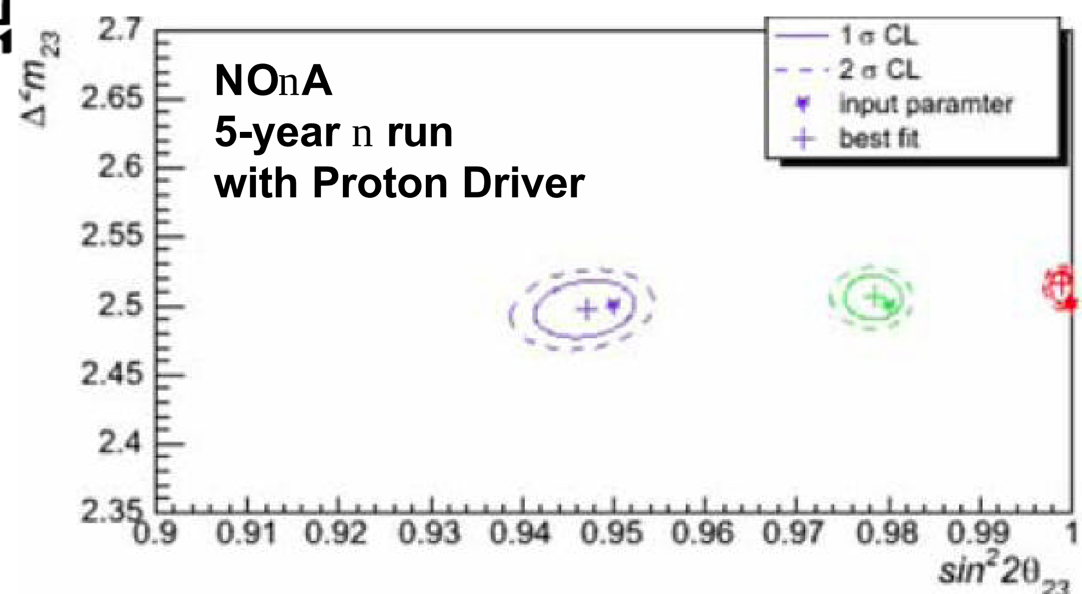


~15min of data
10ms time bins
3m OVERBURDEN

Measurement of Dm_{32}^2 and $\sin^2(2q_{23})$

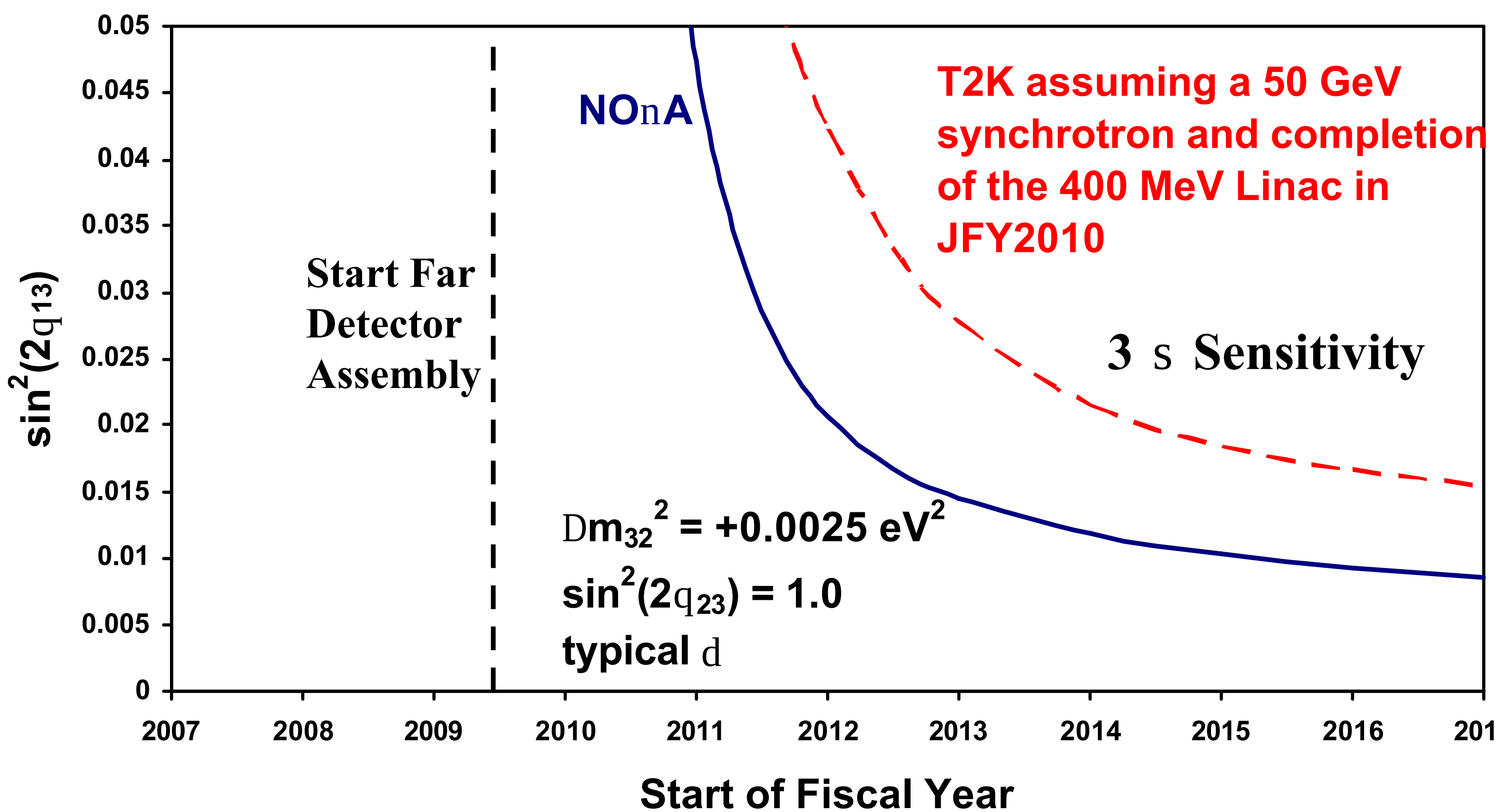






Proposed Schedule

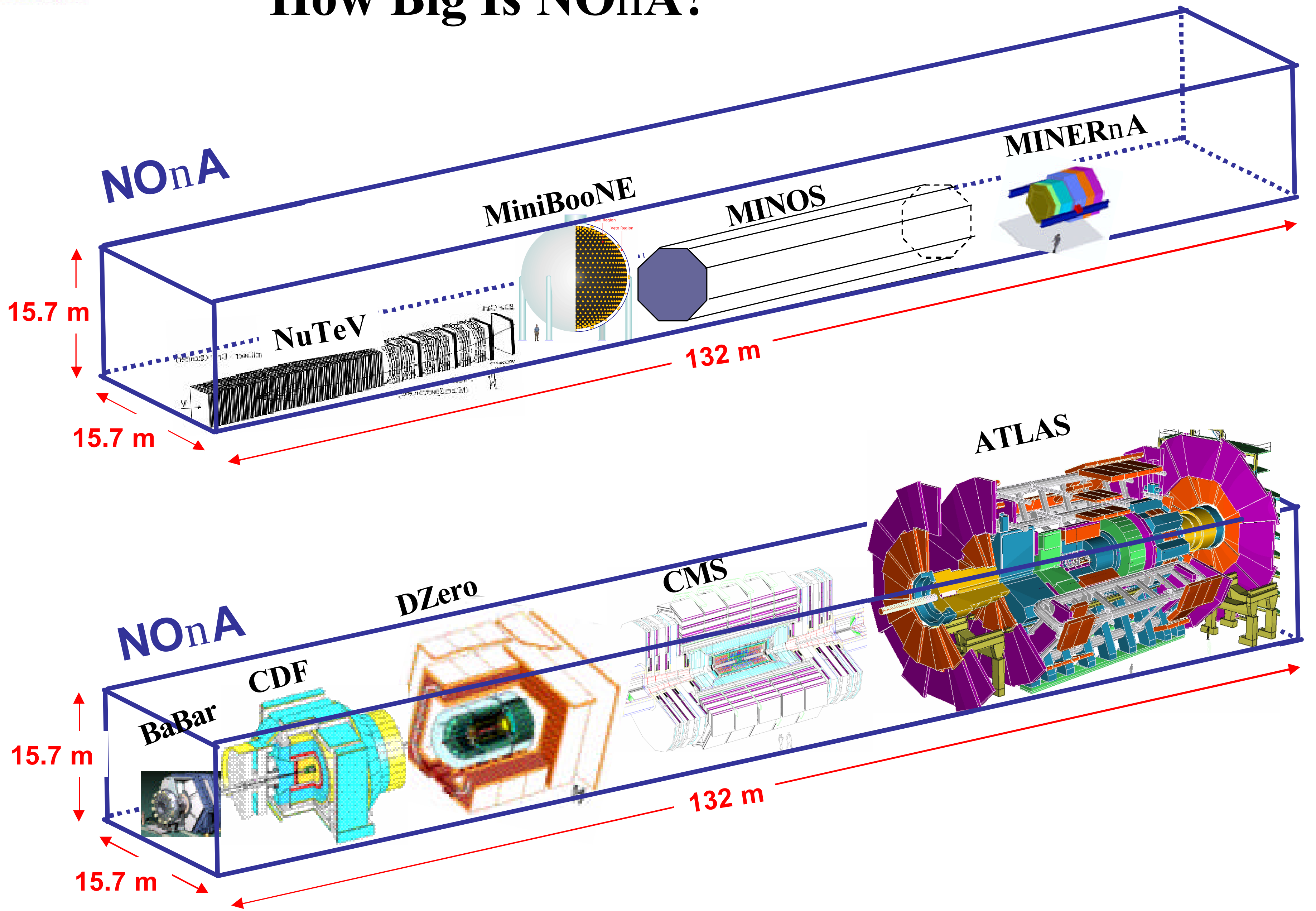
Project start	Oct 2006
Start Far Detector Building construction	Jul 2007
Start extrusion module factories	Oct 2007
Start construction of Near Detector	Dec 2007
Start operation of Near Detector	Jul 2008
Start Far Detector assembly	May 2009
First kiloton operational	Oct 2009
Full 30 kilotons operational	Jul 2011



Conclusions

- The NOnA experiment provides a program to investigate some of the most important issues in physics. It has Stage 1 approval.
- The NOnA experiment can be built now using existing and well-proven technology. Near detector construction and measurements can start sooner.
- The NOnA experiment can access interesting regions of possible lepton CP violation with the Proton Driver.
- The NOnA experiment is open to new collaborators.

How Big Is NOnA?



NOnA has about the same mass as the 5 collider detectors combined