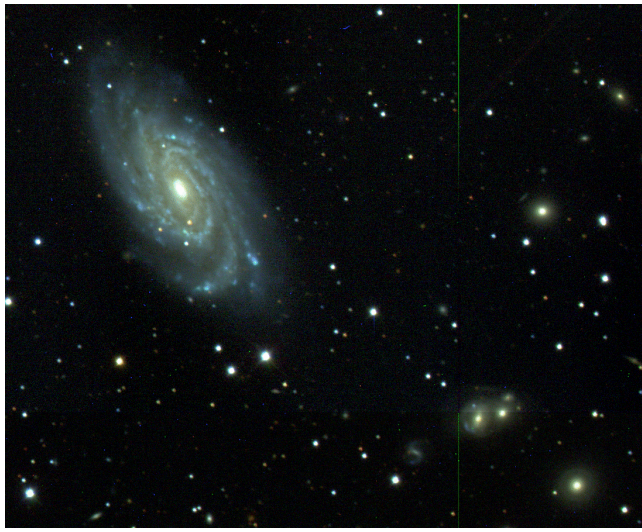
# NOnA*: The Next Neutrino Oscillation Experiment

***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

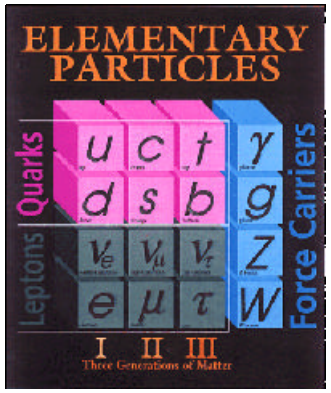
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} U_{ud} & U_{us} & U_{ub} \\ U_{cd} & U_{cs} & U_{cb} \\ U_{td} & U_{ts} & U_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

d 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

$$\begin{pmatrix} n_e \\ n_m \\ n_t \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{m1} & U_{m2} & U_{m3} \\ U_{t1} & U_{t2} & U_{t3} \end{pmatrix} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \end{pmatrix}$$

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

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

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:** $\theta_{23}$ | **CP violation** | **Solar:** $\theta_{12}$

**Need to measure: CP phase** $\delta$, $\theta_{13}$ ($\nu_e \to \nu_\mu$), **Sign of** $\Delta m^2_{32}$

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

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

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

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

$?_{13} < 15^o$

**Ignore Majorana phase**

# Measurements of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ gives $\theta_{13}$ and $\delta$

$$P(\nu_\mu \to \nu_e) = P_1 + P_2 + P_3 + P_4$$

$$P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m_{23}^2\, L/E)$$

$$P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\, \Delta m_{12}^2\, L/E)$$

$$P_3 = \mp J \sin(\delta) \sin(1.27\, \Delta m_{23}^2\, L/E)$$

$$P_4 = J \cos(\delta) \cos(1.27\, \Delta m_{23}^2\, L/E)$$

$$J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \sin(1.27\, \Delta m_{23}^2\, L/E) \sin(1.27\, \Delta m_{12}^2\, L/E)$$

**Matter Effect**

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

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

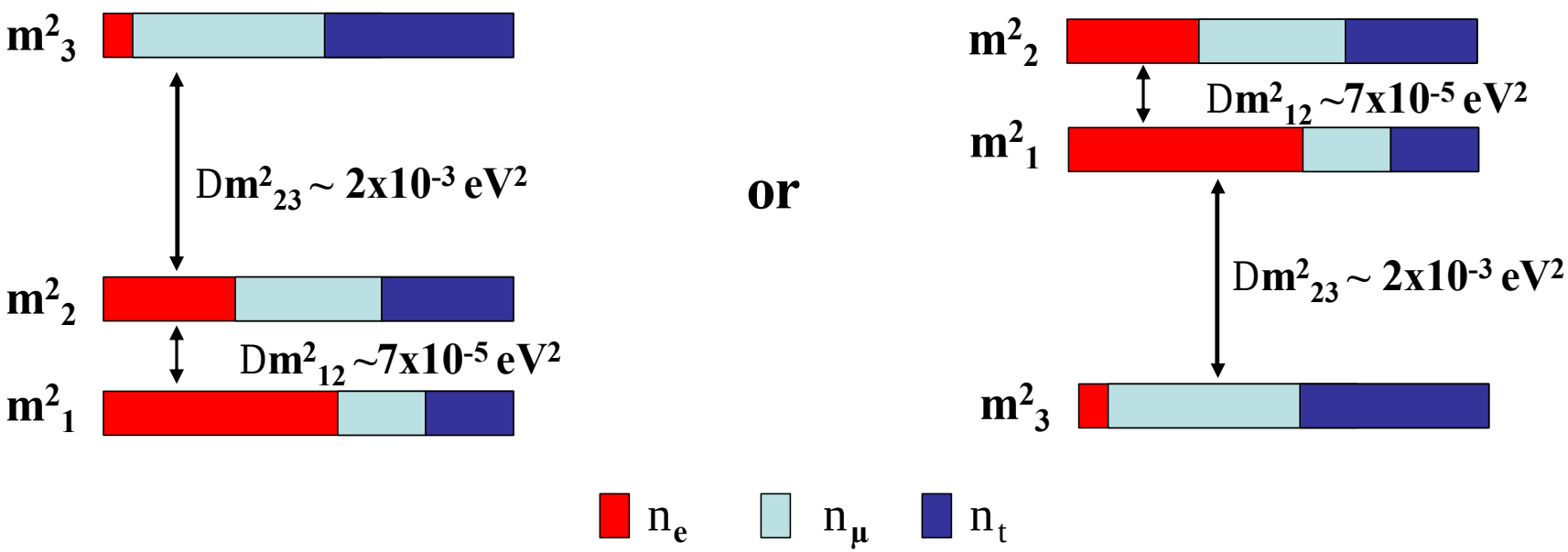
$E_R = 11$ GeV (Earth)

23% effect (10% T2K)

**Enhancement for $\Delta m^2 > 0$**

**Suppression for $\Delta m^2 < 0$**

## Which Mass Hierarchy?

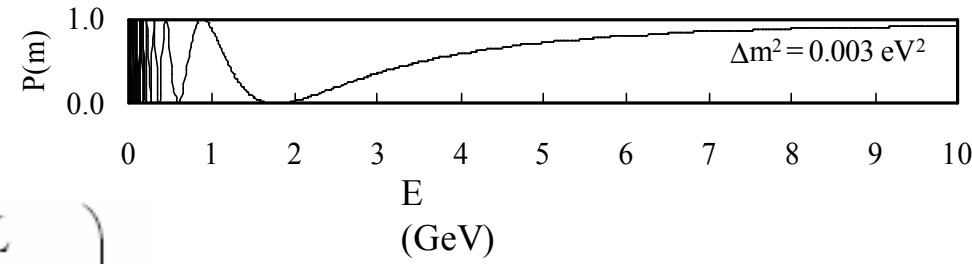


# Expected Signal Size

**Ignore matter effects, CP violation**

$$P(\nu_\mu \to \nu_e) \sim P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m_{23}^2\, L/E)$$

**Peak of oscillation at**




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

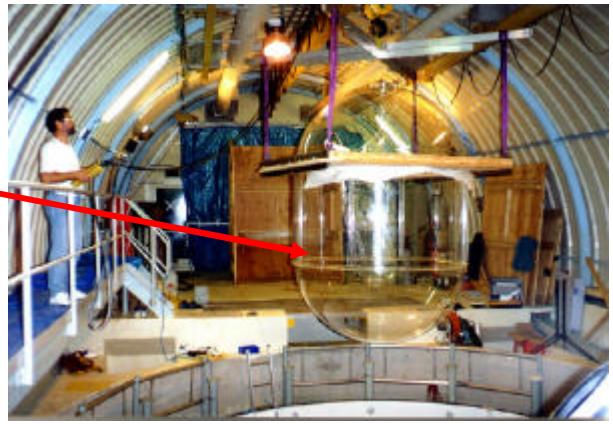
$$P(\nu_\mu \to \nu_e) \approx \tfrac{1}{2} \sin^2(2\theta_{13})$$

**Limit from CHOOZ:**

$$\sin^2 2\theta_{13} \leq 0.2$$

$$P(\nu_\mu \to \nu_e) < 0.1$$

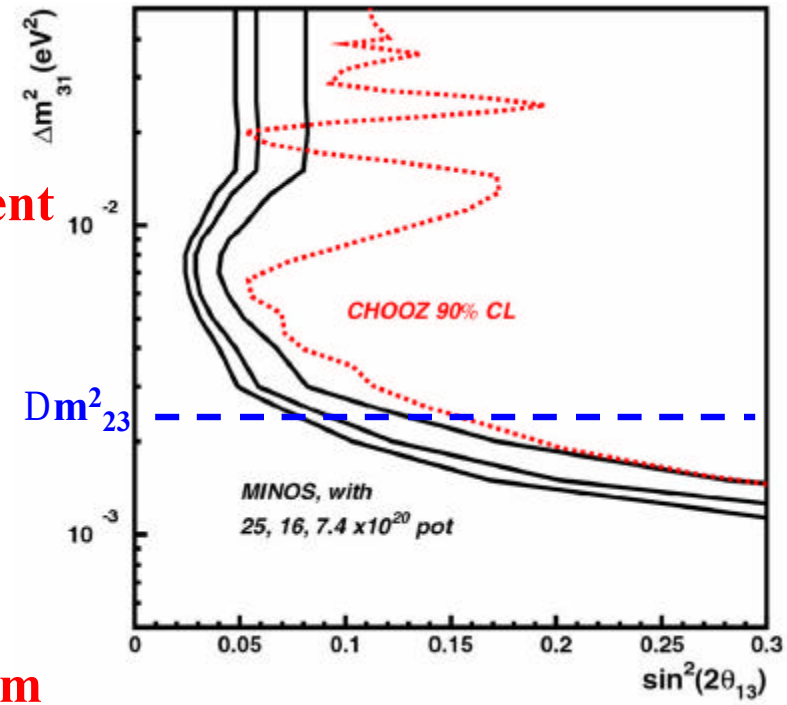
1 km



# 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

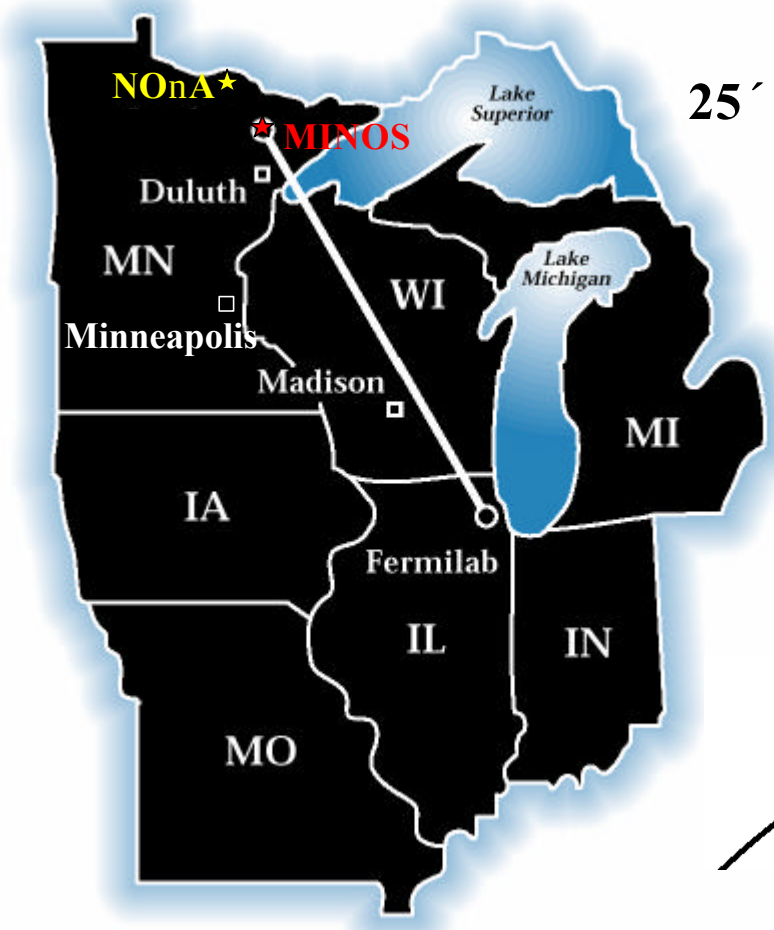
- Intense Muon Neutrino and anti-Neutrino beam
  - NUMI now, Proton Driver enhanced NUMI to come
- Detector With Good Electron ID
  - Large Mass
  - Small Cost/mass
  - Simple Operation at Remote Site with correct L/E

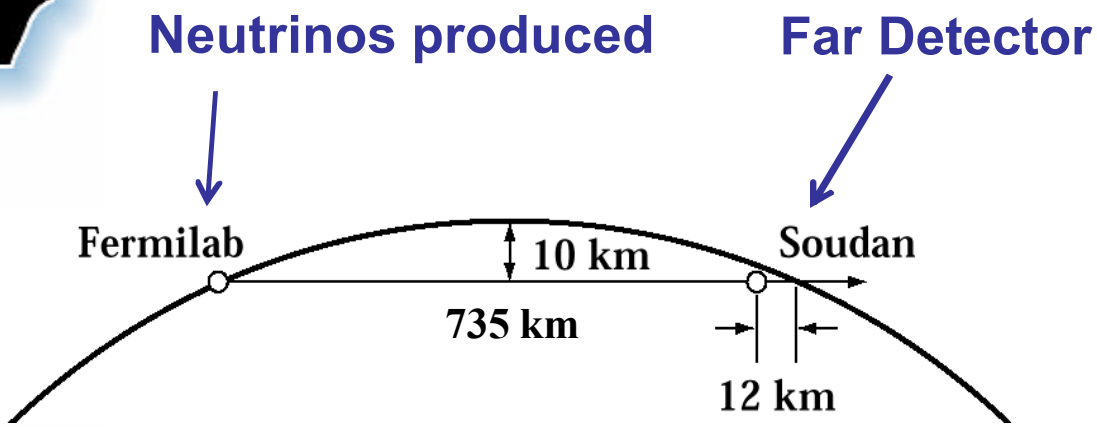
# The NuMI Beam Exists

3.4 ´ $10^{20}$ protons/yr

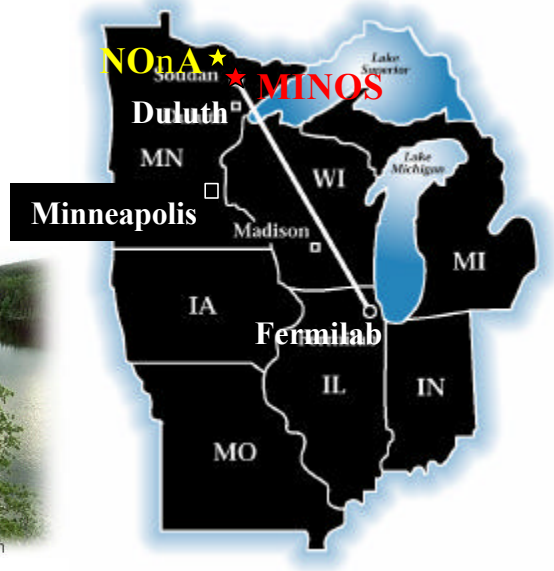
6.5 ´ $10^{20}$ protons/yr post collider

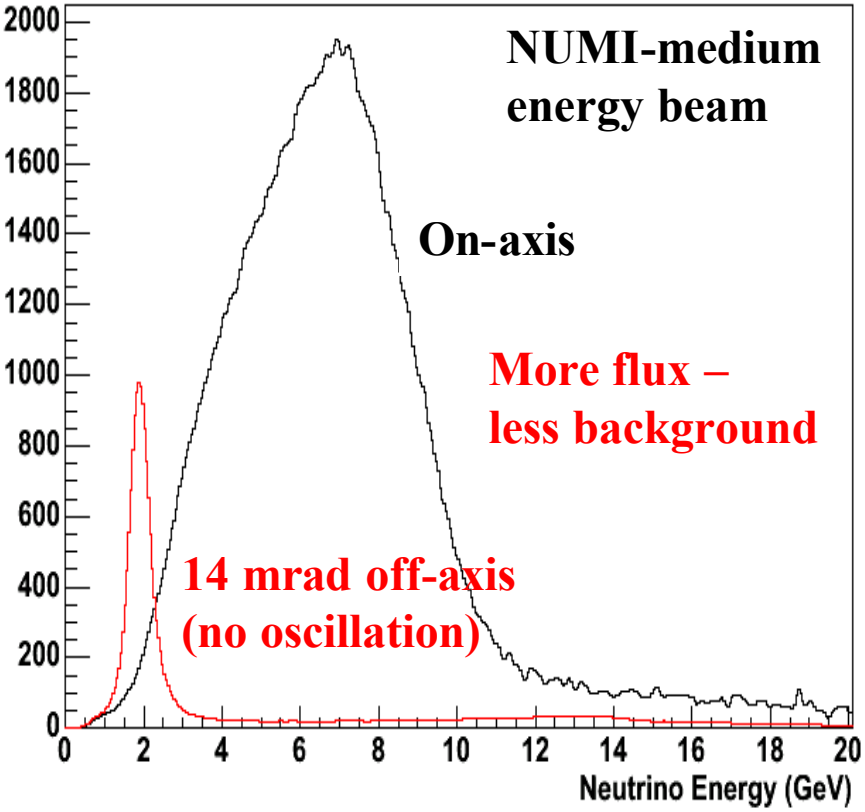
25´ $10^{20}$ protons/yr proton driver





# Use Off Axis Beam

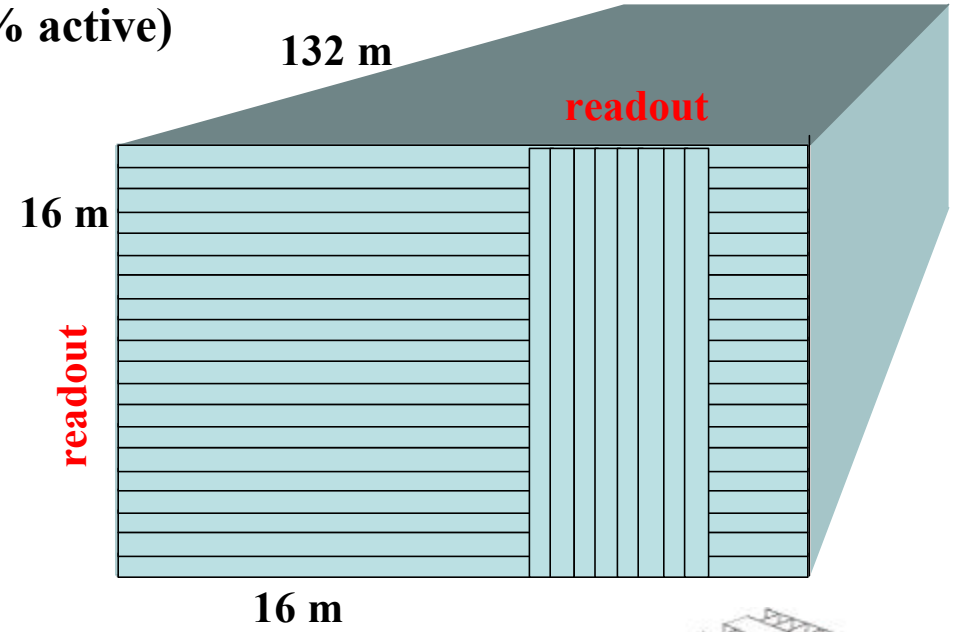


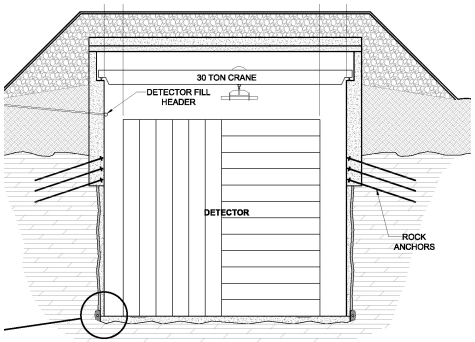




- Narrow energy distribution
- Higher Intensity at desired energy
- Suppressed high energy tail
  - Reduces NC contamination

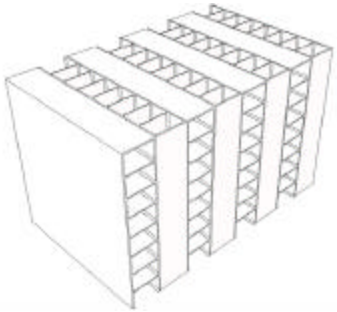
# The NOnA Detector Design

- 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)

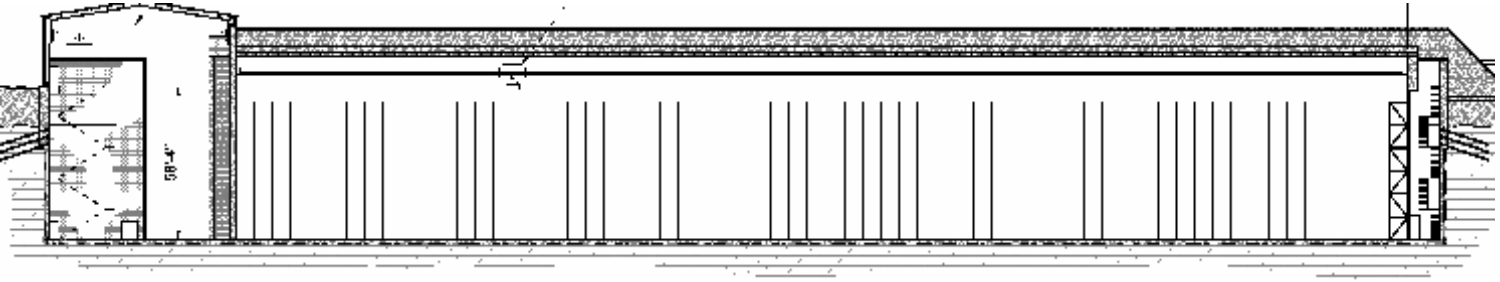



Sod house building design



1984 planes
761,856 cells

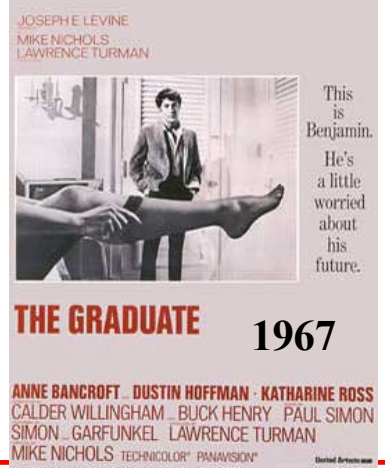


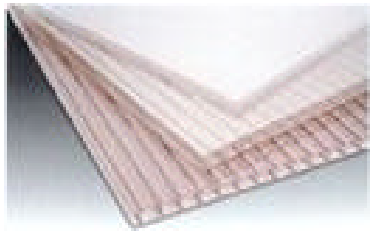
# PVC Use in Construction

Deck Construction

Walls & Doors

Pipes

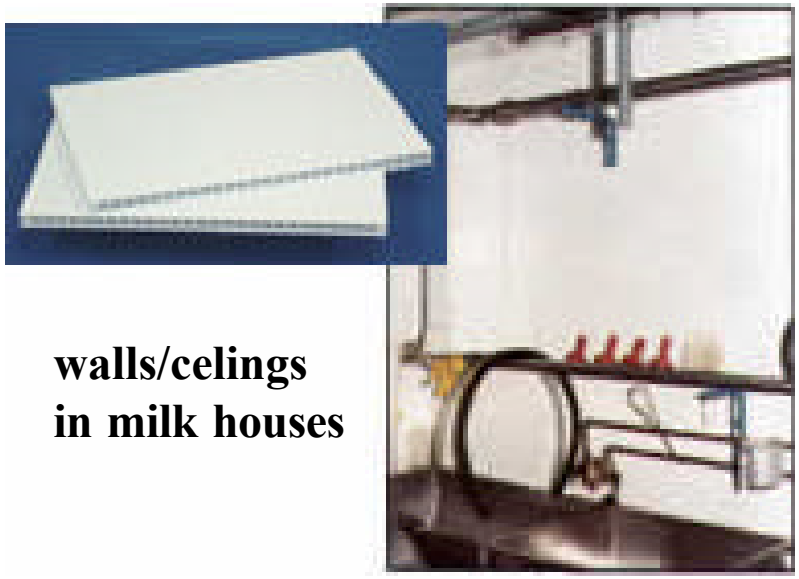


Standard Widths

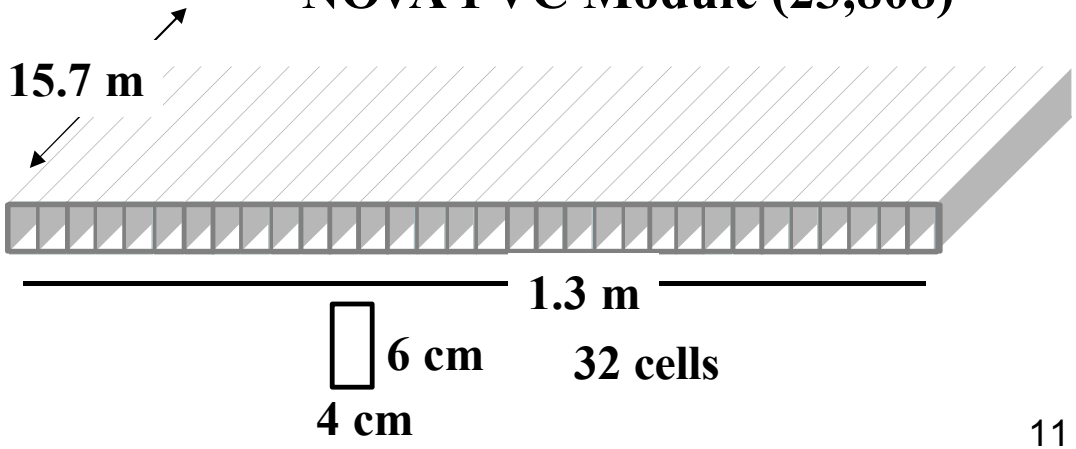
980, 1050, 1220, 1250, 2100 mm

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.

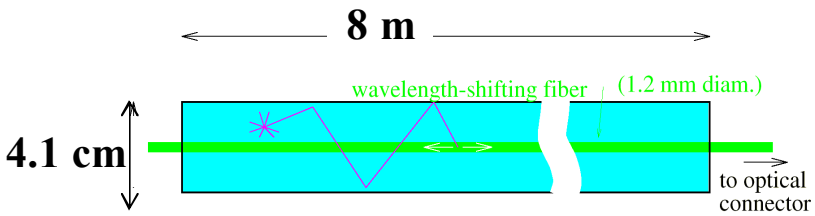


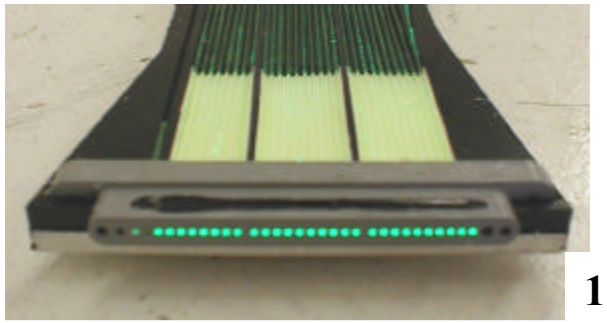
walls/celings in milk houses

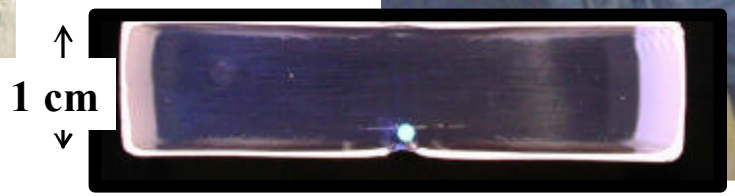
NOvA PVC Module (23,808)



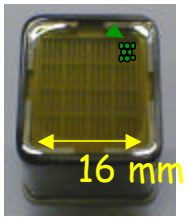
# Signal Collection Based on MINOS Active Detector



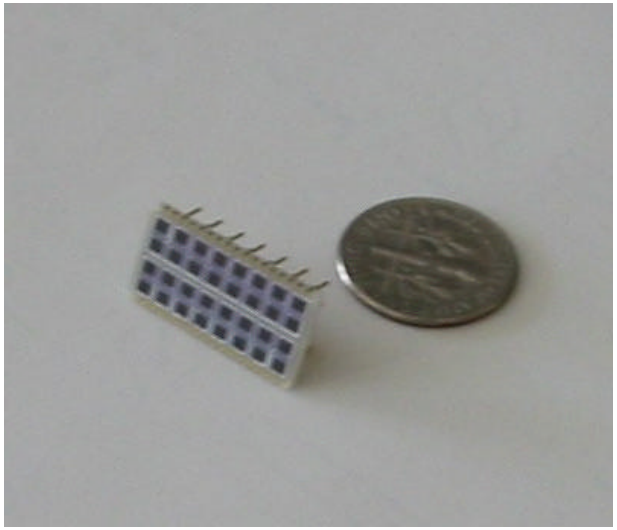


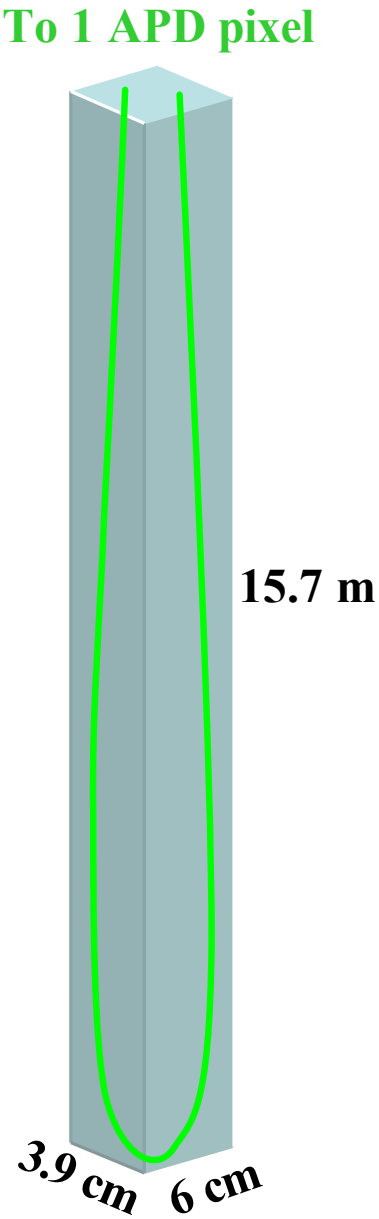
- Plastic Scintillator ® Liquid Scintillator
- 8 m length ® 15.7 m length
- 1 cm thick ® 6 cm thick
- 1.2 mm wavelength shifting fiber ® 0.8 mm wls fiber
- Straight fiber read out each side ® Looped fiber read out one side
- Hamamatsu multi-anode PMTs ® Hamamatsu multi-pixel Avalanche Photodiodes
- 8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



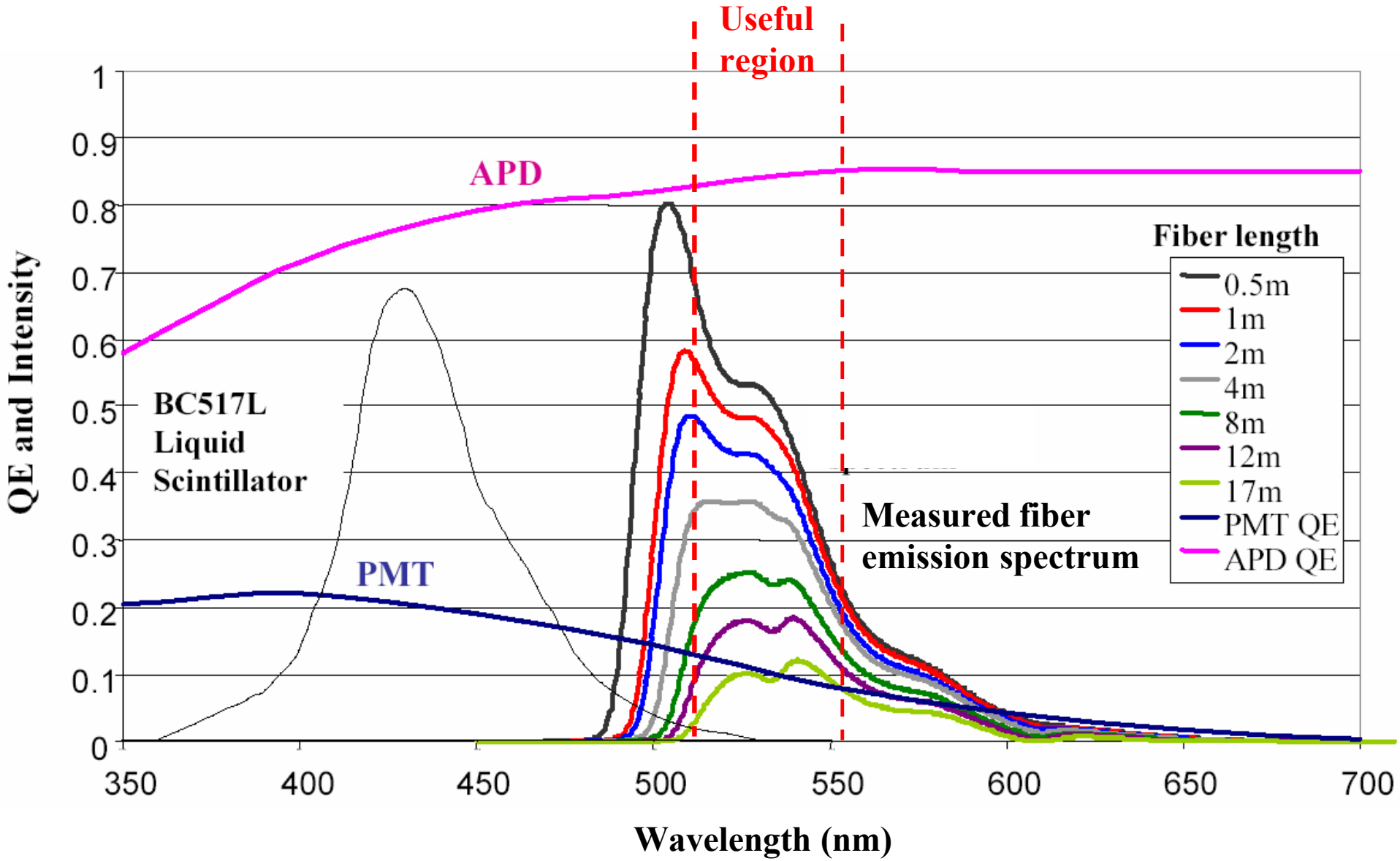
# Active Detector

- **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



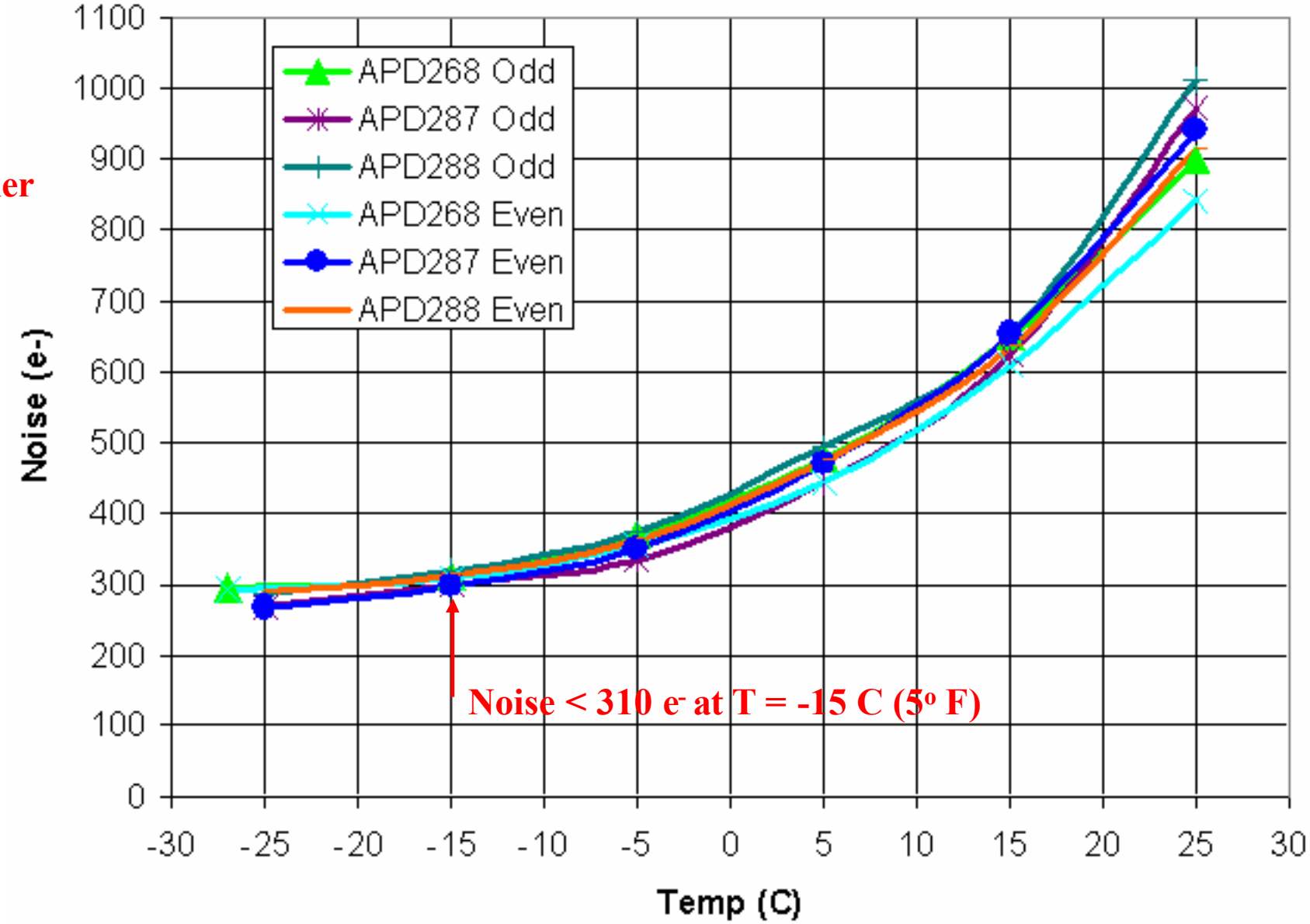


# Quantum Efficiency and Fiber Emission



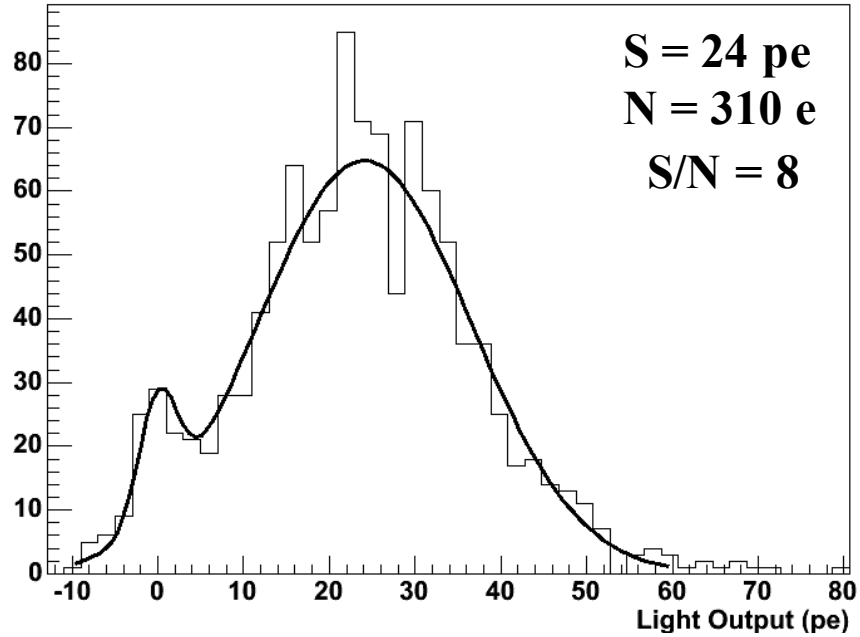
# Noise vs. Temperature at Gain = 100

APD + Amplifier Noise



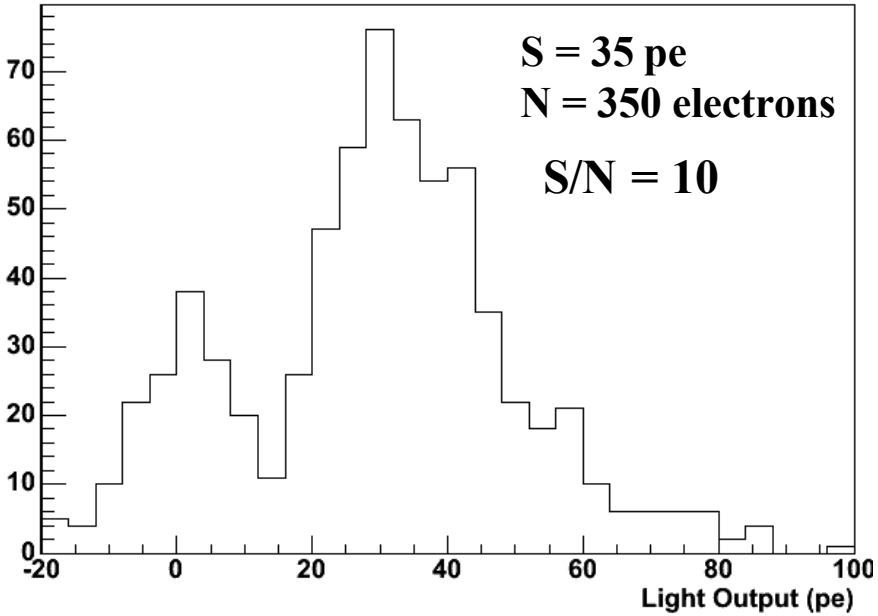

Noise to 250 e with correct amplifier capacitance

# Full Cell at Full Length

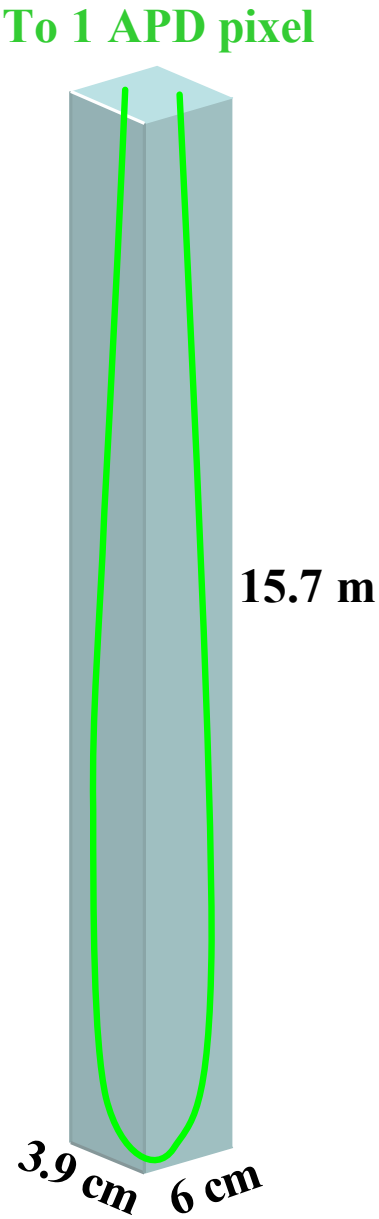



**Measurement 1 MIP**
**Using cosmic ray muons**

**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

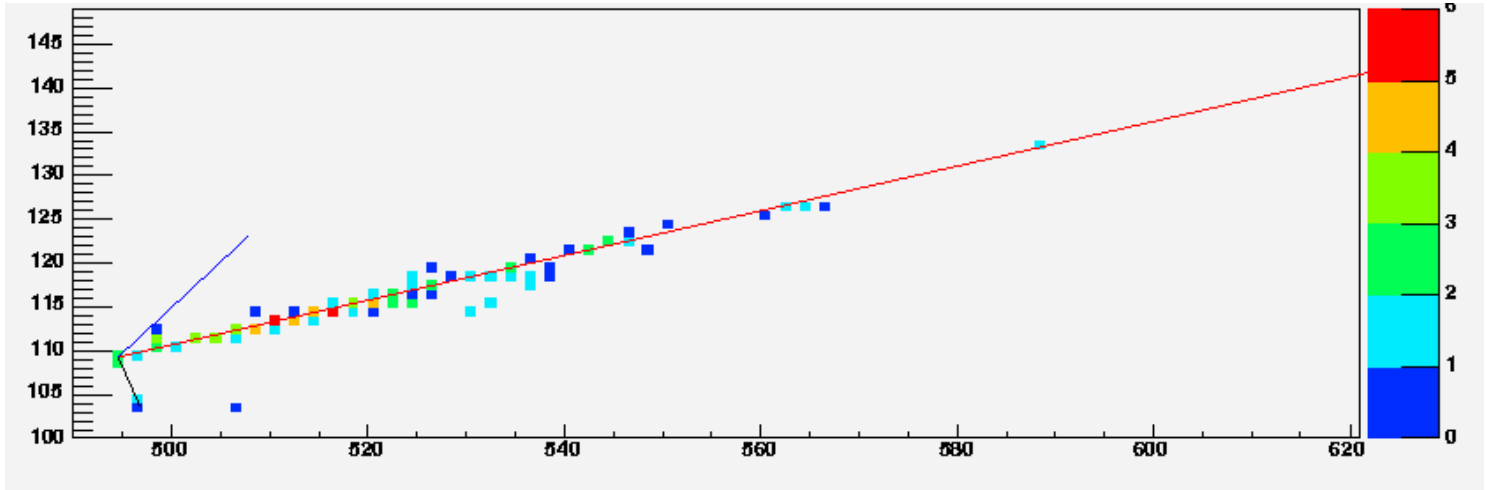
$n_e$ p ® $e^-$ p $p^+$

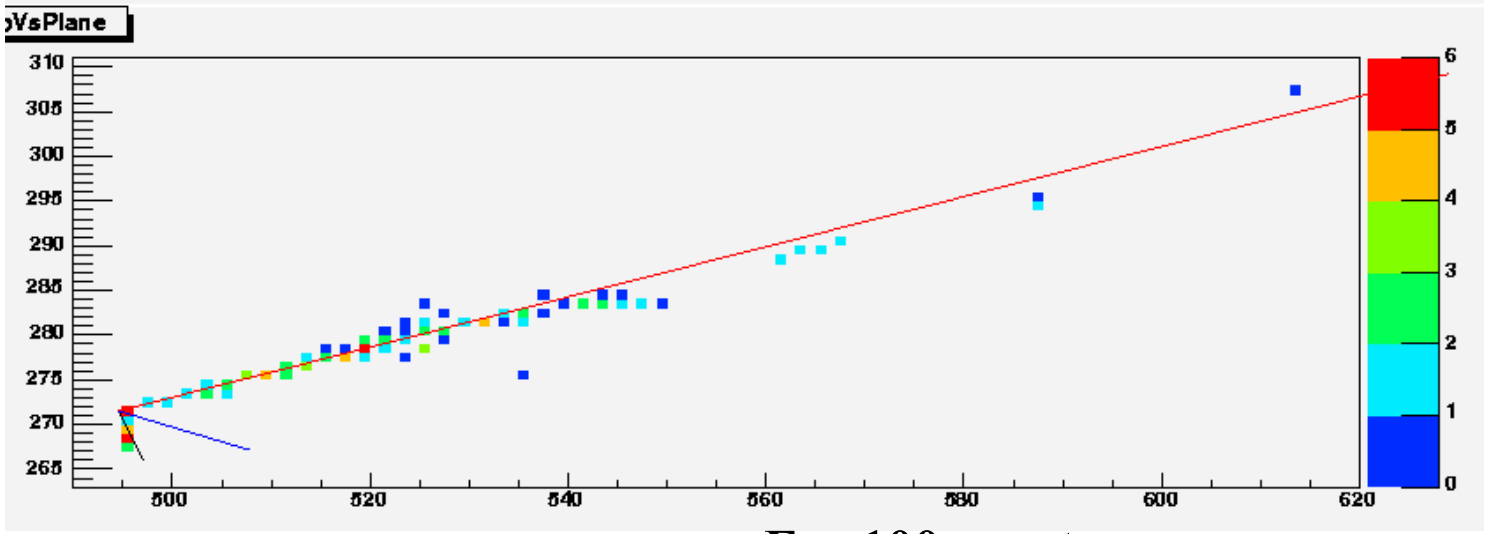
$E_n$ = 2.5GeV

$E_e$ = 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 | $7.1 \times 10^{-4}$ | 1 event |
| Rejection n nc | $1.3 \times 10^{-3}$ | 6 events |
| Rejection beam $n_e$ cc | $6.6 \times 10^{-2}$ | 7 events |

# Background m CC event

$n_m n \circledR m^- n p^+ p^o$

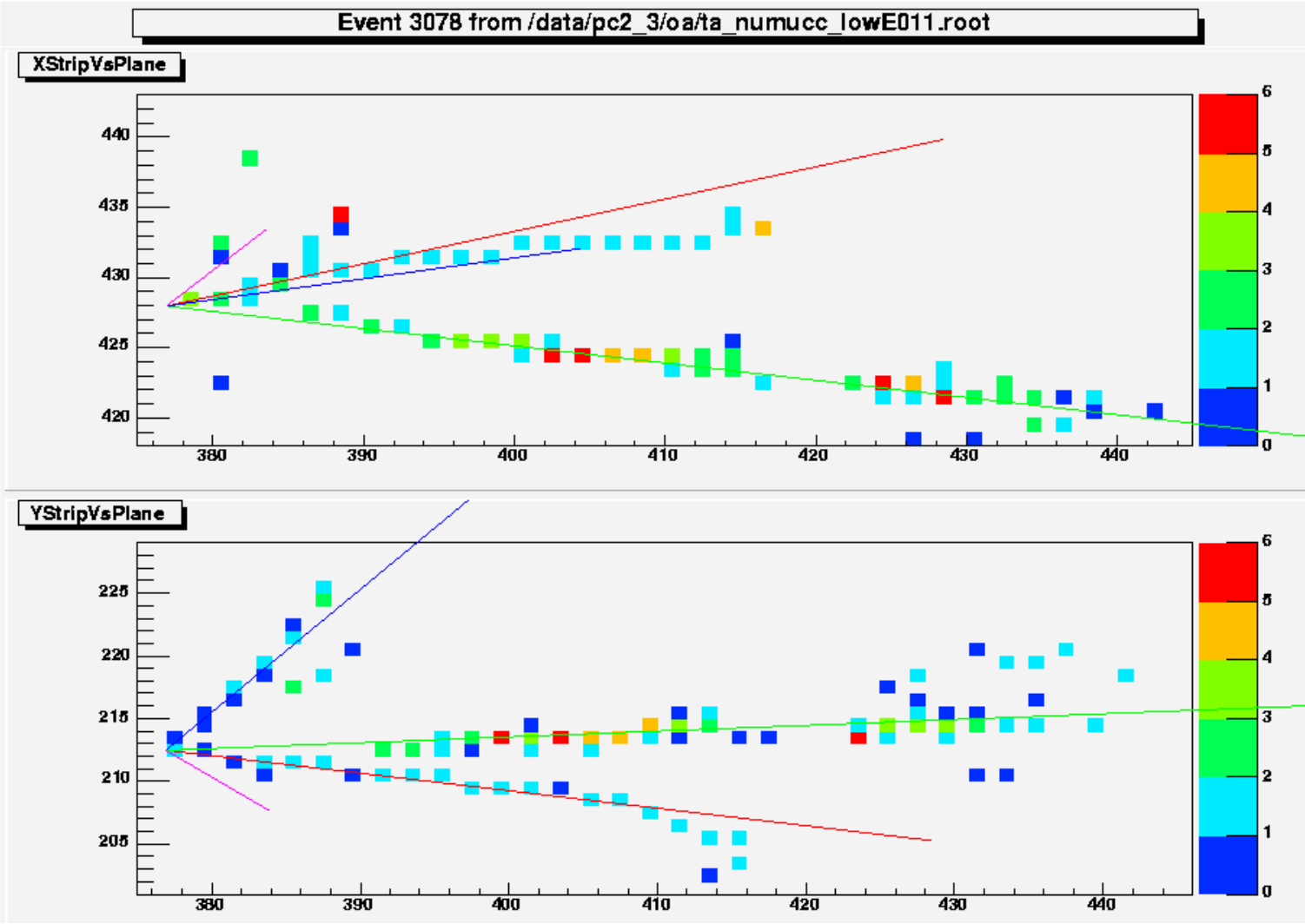
$E_n$=2.8 GeV

$E_m$=0.5GeV

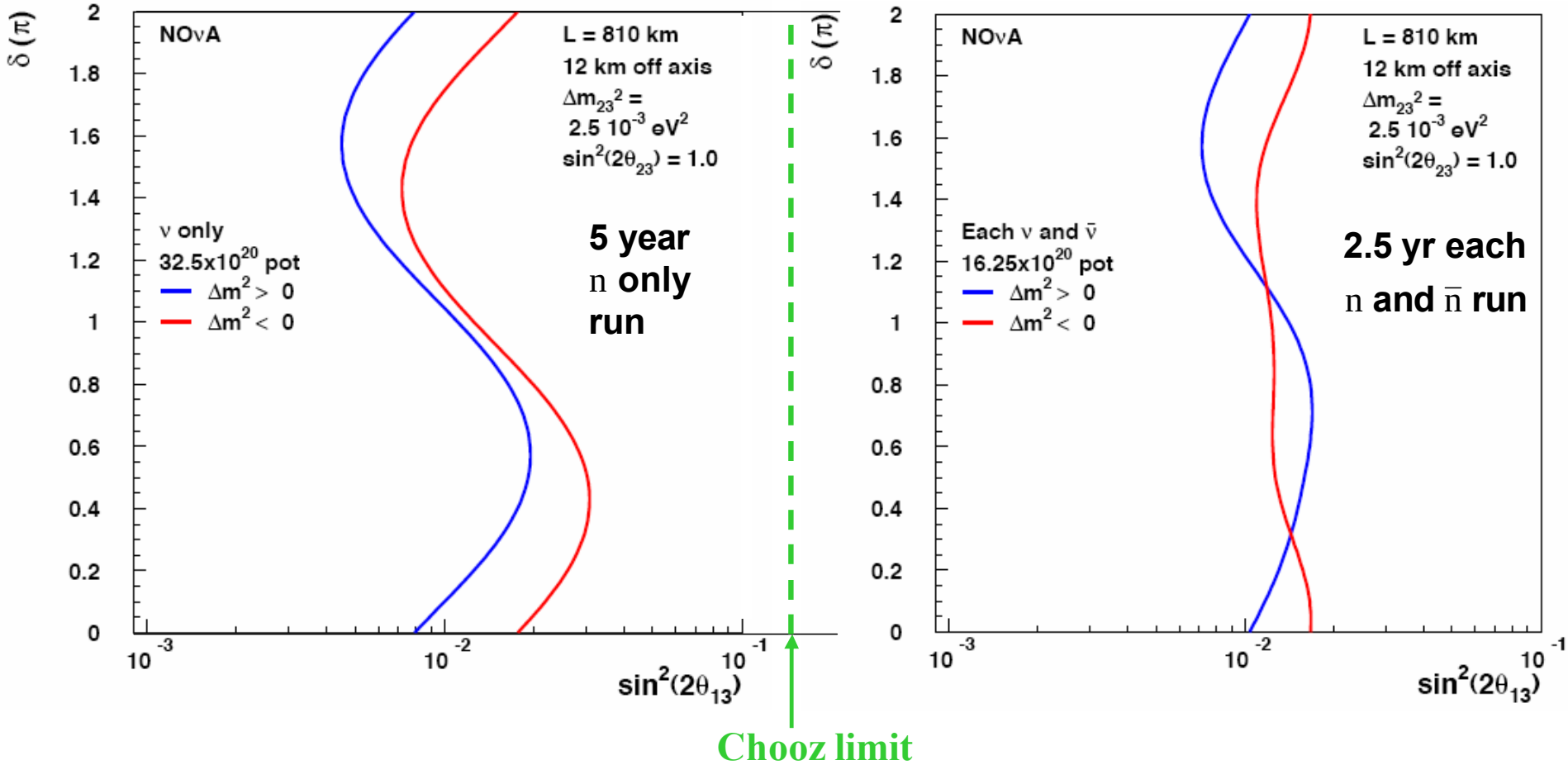
$E_n$=1.0GeV

$E_{p+}$=0.4GeV

$E_{po}$=1.8GeV



# 3 s Discovery Potential for $\nu_\mu \to \nu_e$



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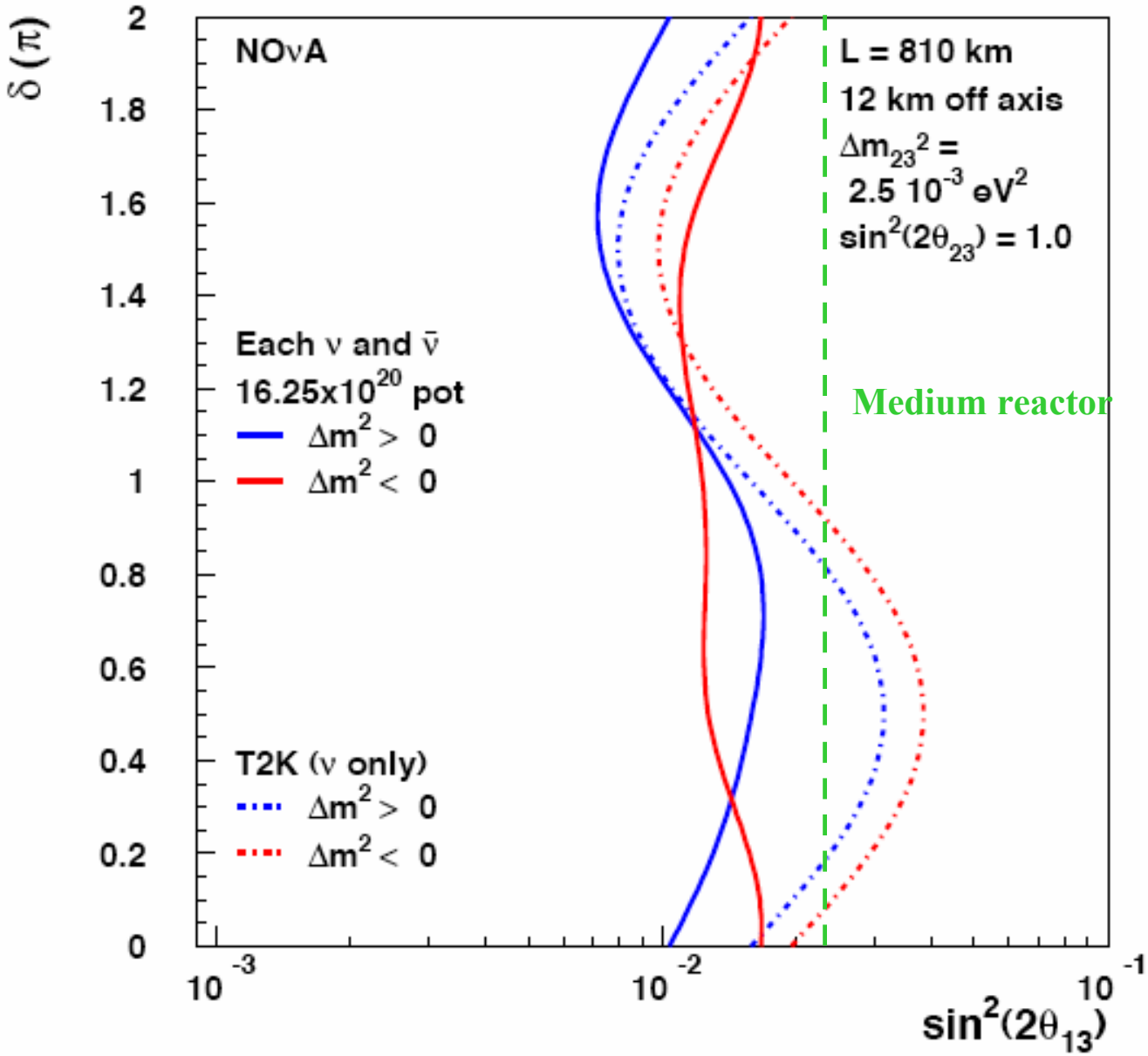
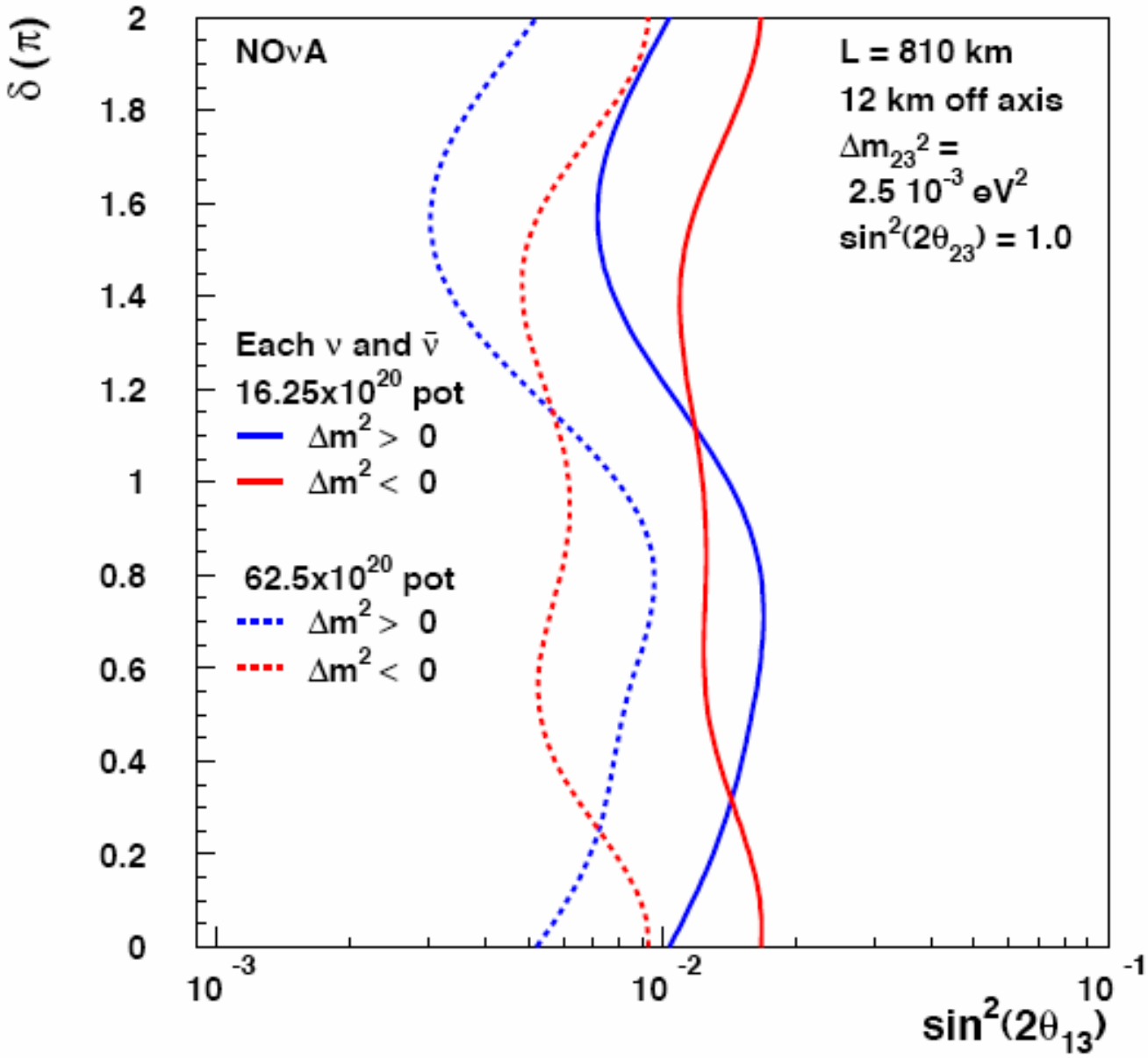


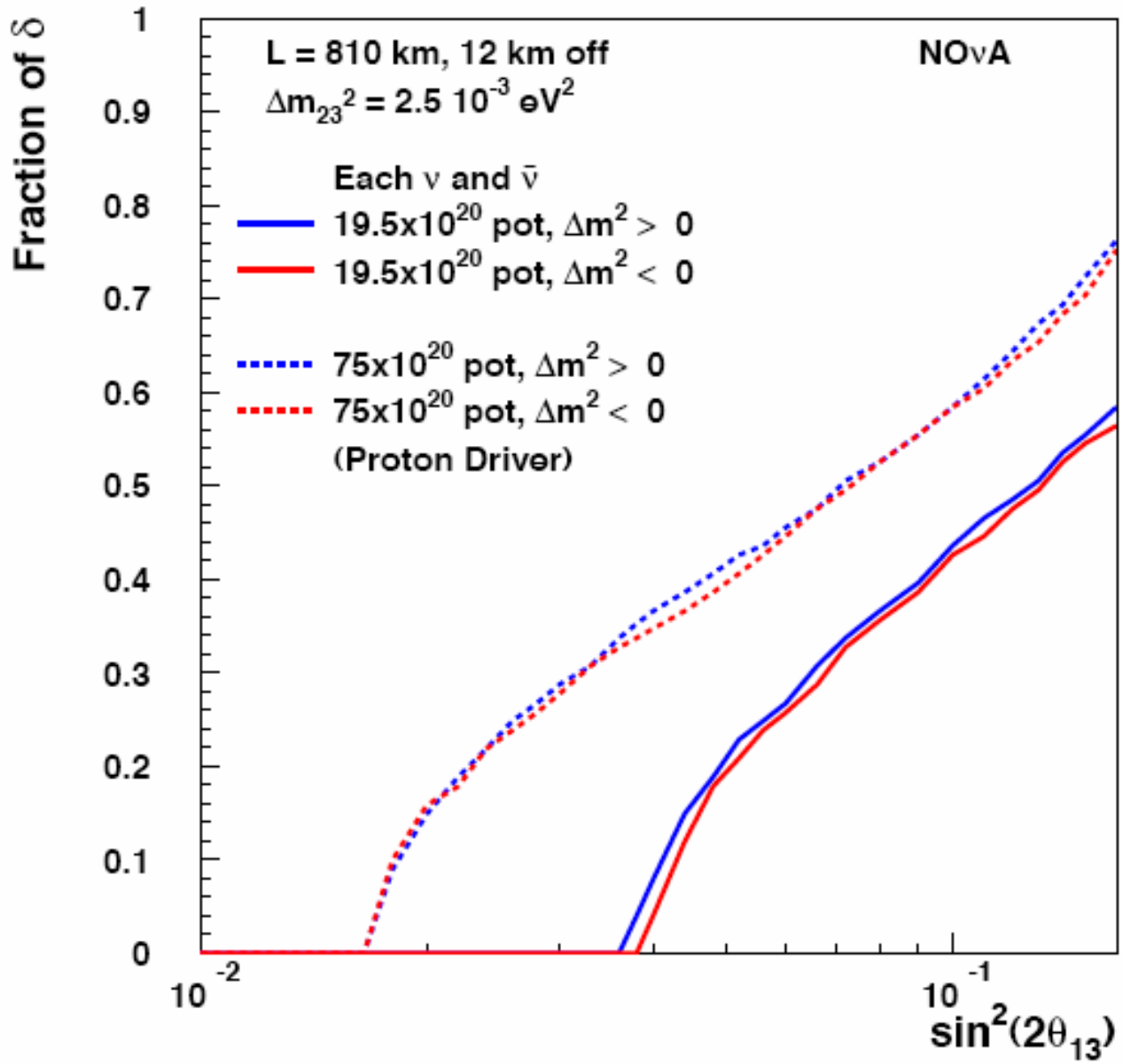
# 3 s Discovery Potential for $\nu_\mu \to \nu_e$

**Proton Driver**



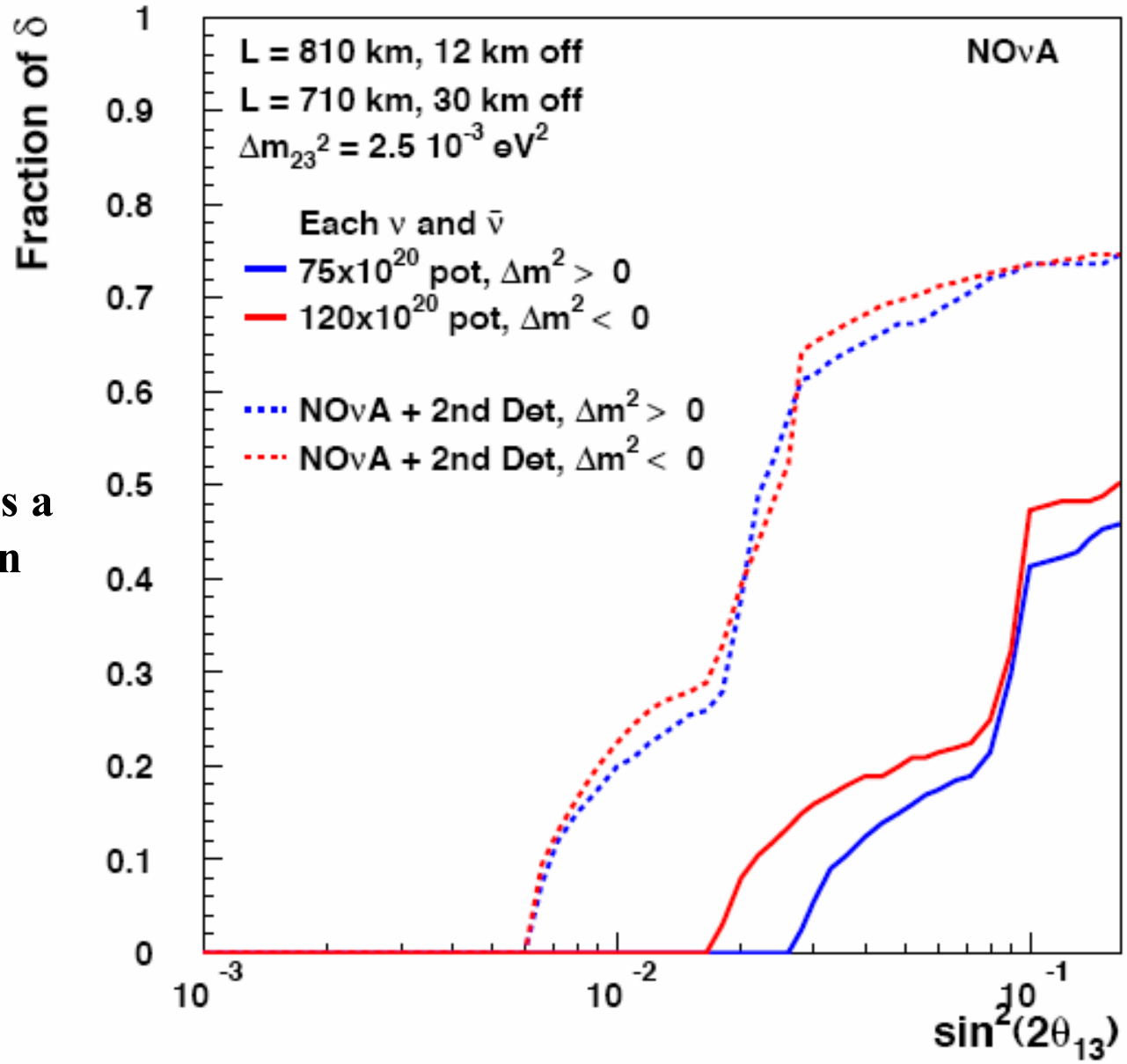
# 95% CL Resolution of the Mass Hierarchy

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

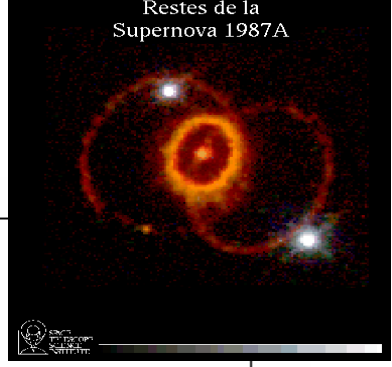


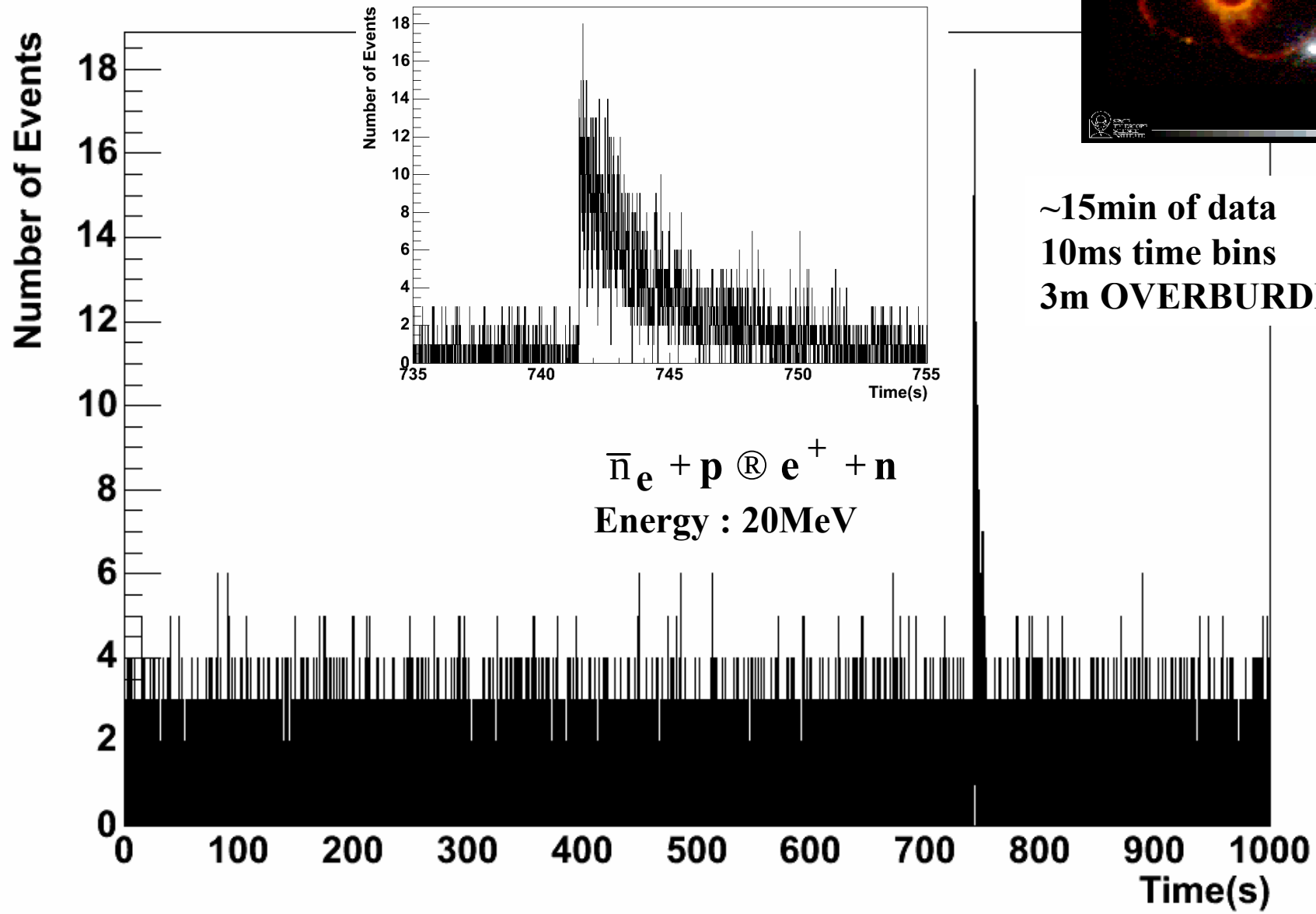
# 3 s Determination of CP Violation

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

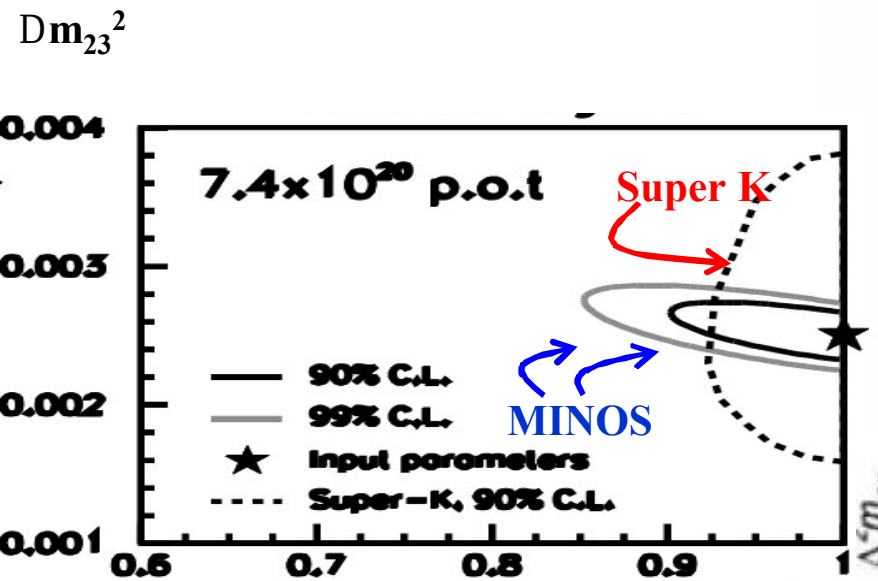


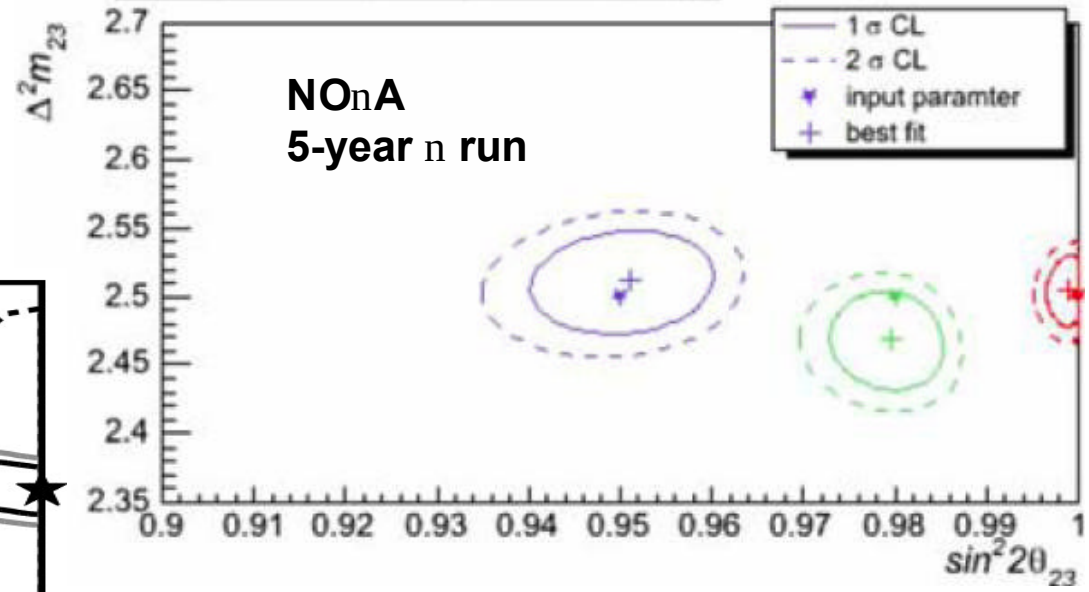
# Typical supernova signal

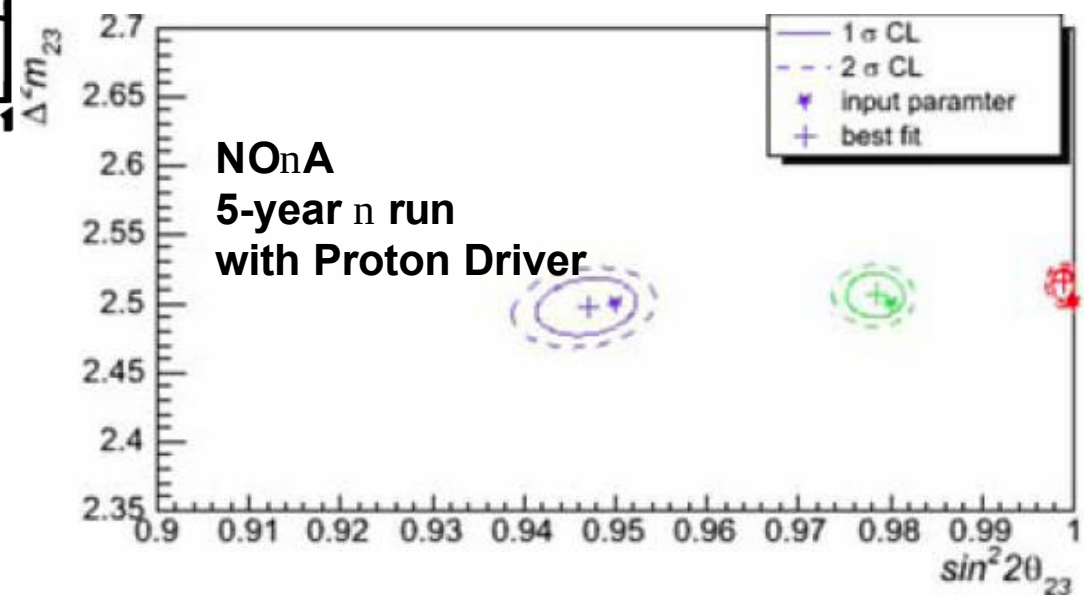


# Measurement of $Dm_{32}^2$ and $\sin^2(2q_{23})$

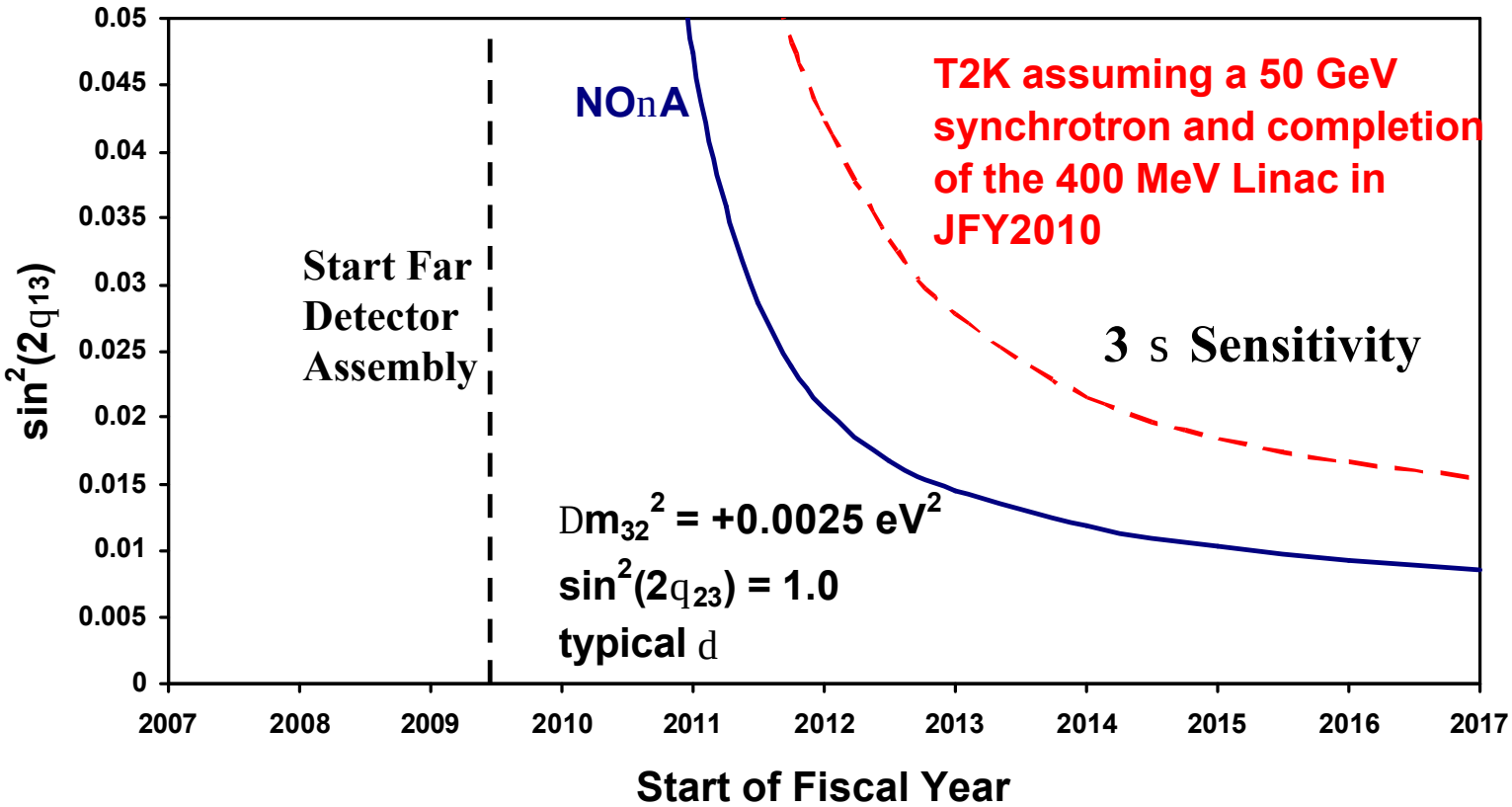


# Proposed Schedule

| 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 |

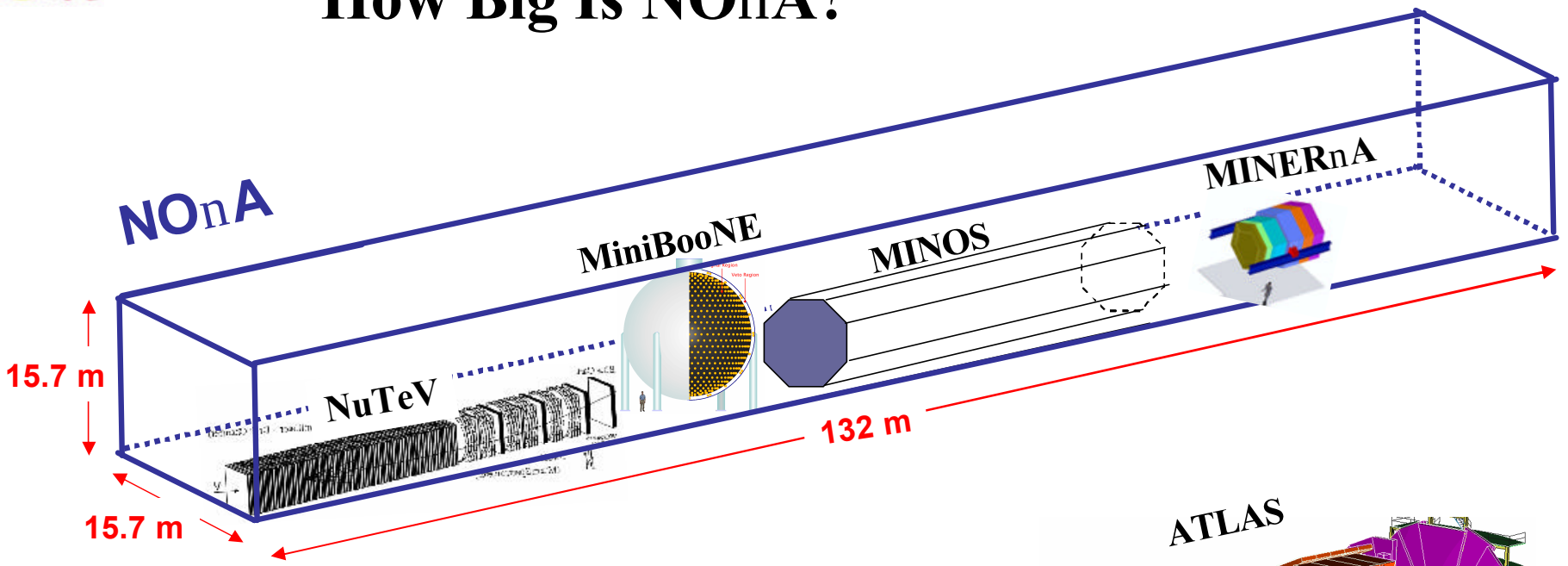


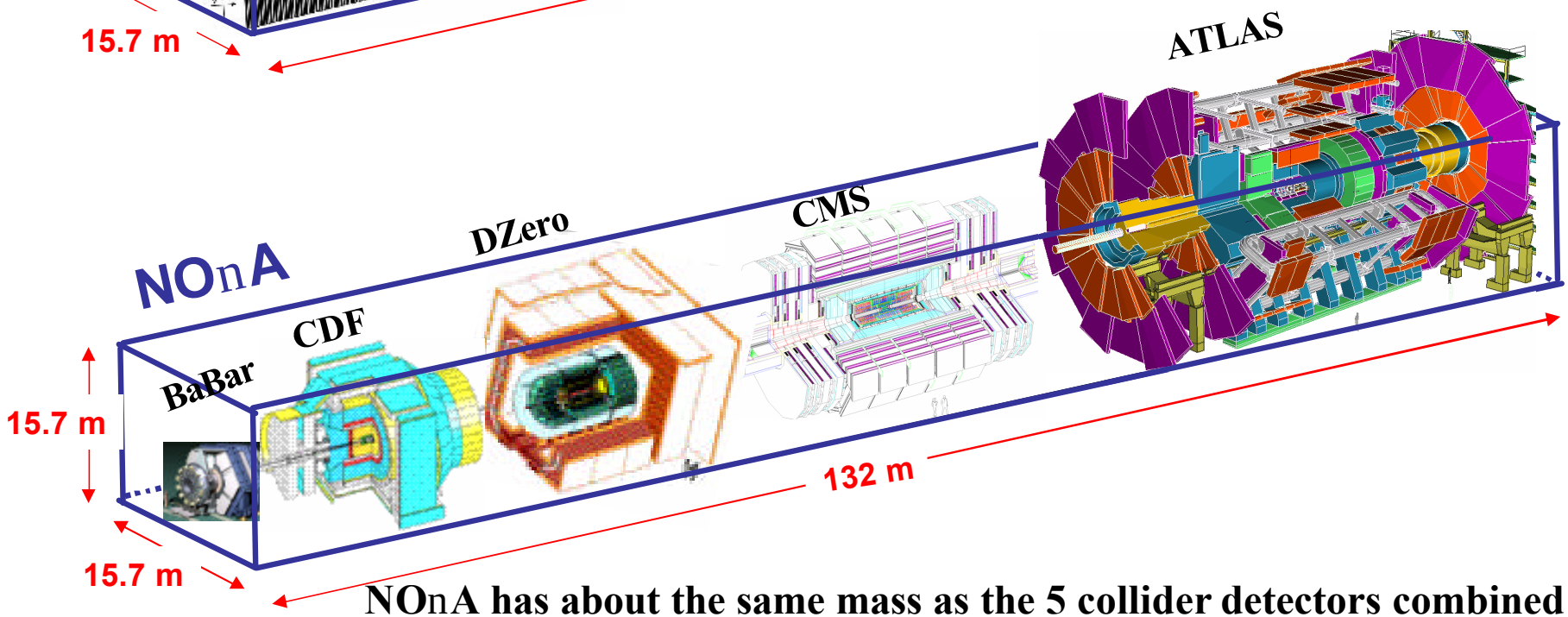
# Conclusions

- 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.

The NOnA Detectors

# How Big Is NOnA?




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