NOvA: The NuMI Offaxis ν_e Appearance Experiment

A.Norman for the NOvA Collaboration

The NOvA Collaboration

180 Scientists & Engineers from 26 Institutions

Argonne National Laboratory
University of Athens
California Institute of Technology
University of California, Los Angeles
Fermi National Accelerator Laboratory
Harvard University
Indiana University
Lebedev Physical Institute
Michigan State University
University of Minnesota, Duluth
University of Minnesota, Minneapolis
The Institute for Nuclear Research, Moscow
Technische Universität München, Munich

State University of New York, Stony Brook
Northwestern University
University of South Carolina, Columbia
Southern Methodist University
Stanford University
University of Tennessee
Texas A&M University
University of Texas, Austin
University of Texas, Dallas
Tufts University
University of Virginia, Charlottesville
The College of William and Mary
Wichita State University

The NOvA Collaboration

ProtoType Detector Planes

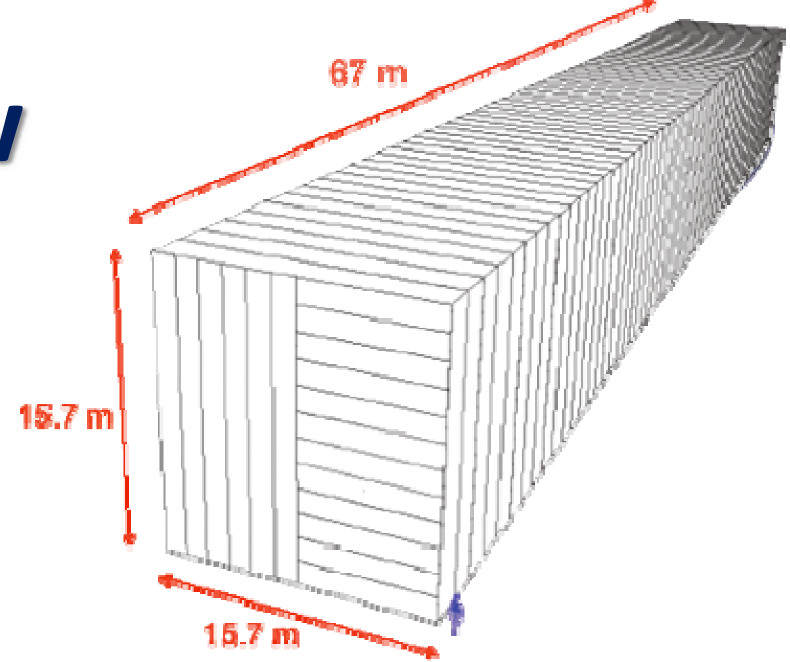
Argonne National Lab – April 25, 2009

NOvA Overview

- *NOvA* is a second generation accelerator based neutrino oscillation experiment, optimized for detection of the oscillations:

$$\nu_\mu \to \nu_e \quad \text{and} \quad \bar{\nu}_\mu \to \bar{\nu}_e$$

- *NOvA* is:
  - A 14 kton, "totally active", far site detector
  - A 222 ton near detector, utilizing an identical detector technology and geometry
  - An upgrade of the NuMI beam intensity from 320 kW to 700 kW
- Both detectors are "totally active", highly segmented liquid scintillator calorimeter designs
- The detectors are placed 14mrad off the primary beam axis to achieve narrow ν_μ energy spectrum, peaked at 2GeV.
- The far detect sits on a 810km baseline between Chicago and Northern Minnesota at the first oscillation maximum



Physics Motivations

NOVA SENSIVITIES

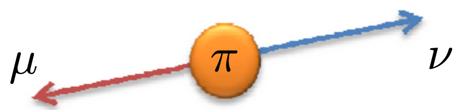
Questions for NOvA to Answer

- The NOνA experimental program addresses 7 of the 8 questions posed by the P5 strategic plan for neutrino physics :
  - ▶ What is the value of θ_{13} ?
  - ▶ Is θ_{23} maximal?
  - ▶ Do neutrinos violate CP?
  - ▶ What is the mass structure of the known neutrinos?
  - ▶ Are neutrinos their own anti-particles?
  - ▶ What can neutrinos tell us about physics beyond the standard model? Sterile Neutrinos?
  - ▶ What can we learn from the neutrino burst of a near galatic Supernova?

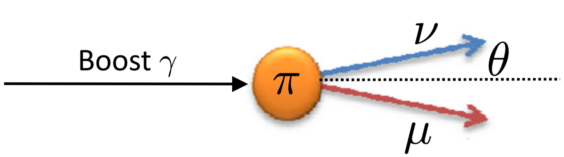
The Off-Axis Beam

The Off-Axis Effect

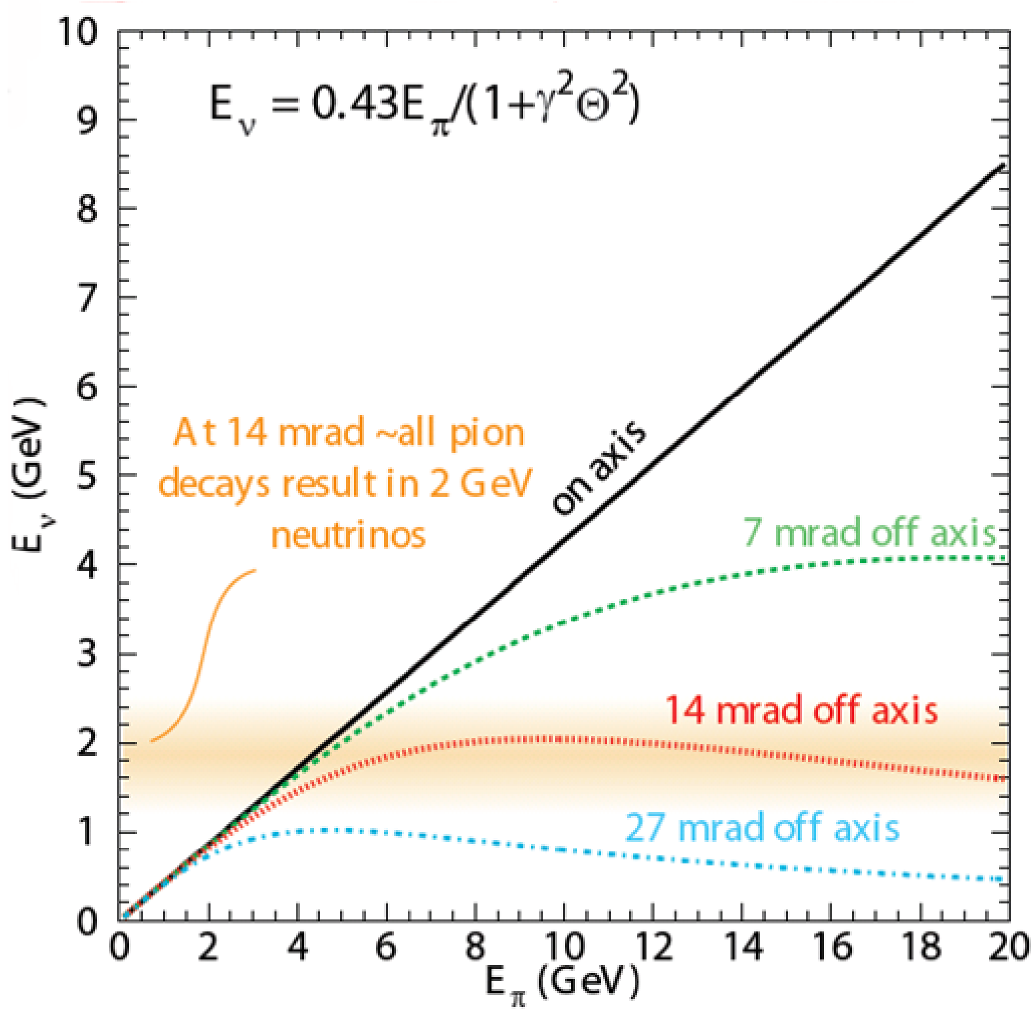
In the pion rest frame the kinematics are all completely determined for the decay



But when we boost into the lab frame the neutrino's energy depends on the angle relative to the boost direction.



This ends up projecting neutrino energy spectrum down till it's almost flat.



The Effect of Going Off-Axis

- By going off-axis, the neutrino flux from $\pi \rightarrow \mu + \nu$ is reduced at a distance z to:

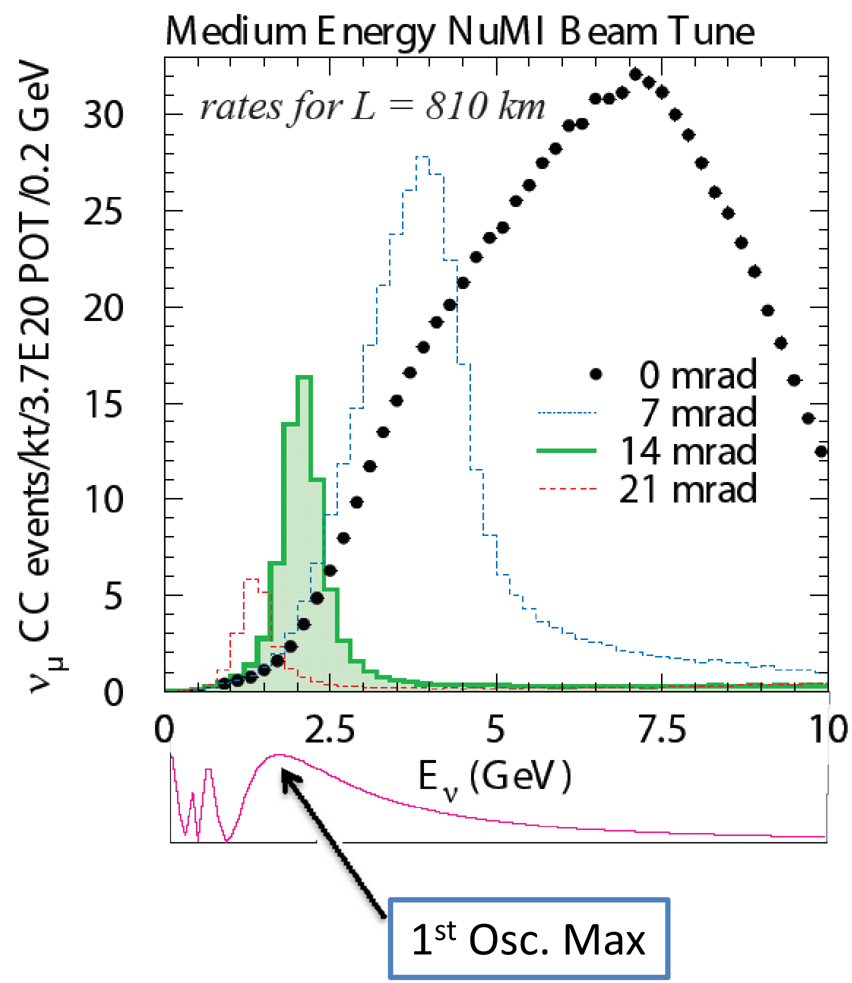
$$F = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

- But the energy narrows as θ^2:

$$E_\nu = \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

- For NOνA, moving 14 mrad off axis makes the NuMI beam energy
  - peak at 2 GeV
  - E_ν width narrows to 20%

- The detector is matched well to this narrow band beam with an energy resolution $\sim$ 4% for ν_μ CC events



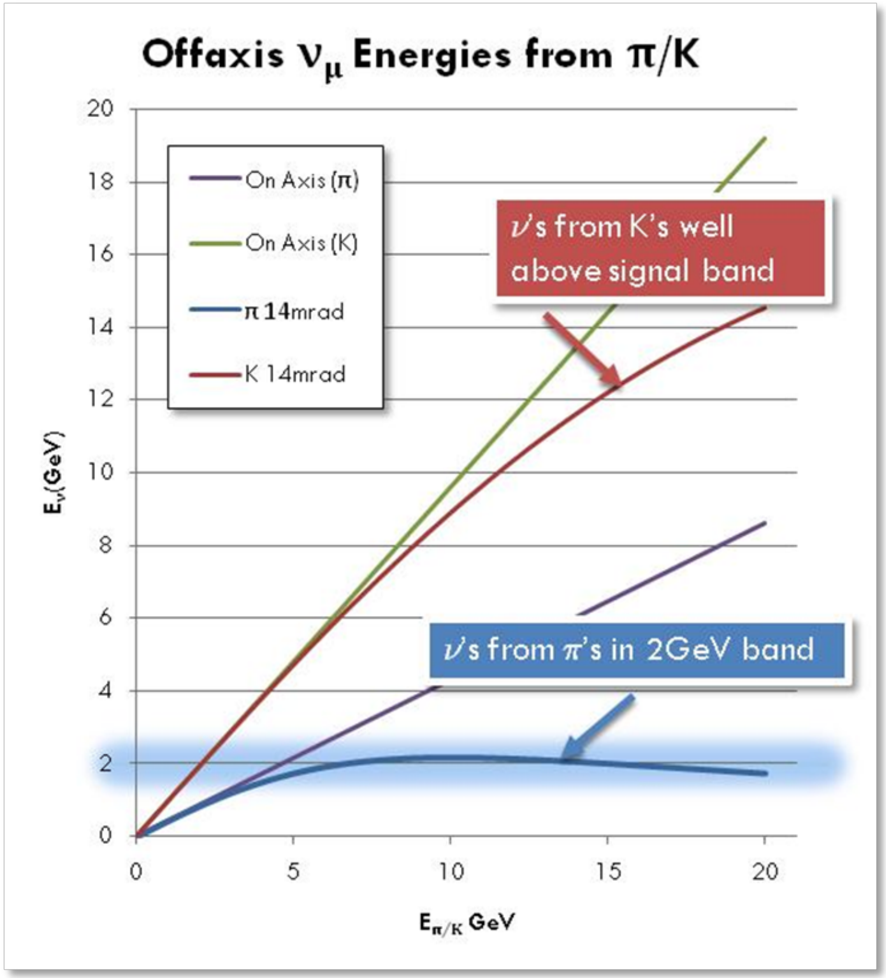
The Advantage of Going Off-Axis

- This suppresses the high energy tail (NC background)
- Significantly reduces the backgrounds from Kaons by shifting the neutrino energy

$$E_{\nu_K} = \frac{0.96 E_K}{1+\gamma^2\theta^2}$$

- Energy spectrum in the signal region becomes almost insensitive to the π/K ratio
- Results in neutrino peak primarily from π decays

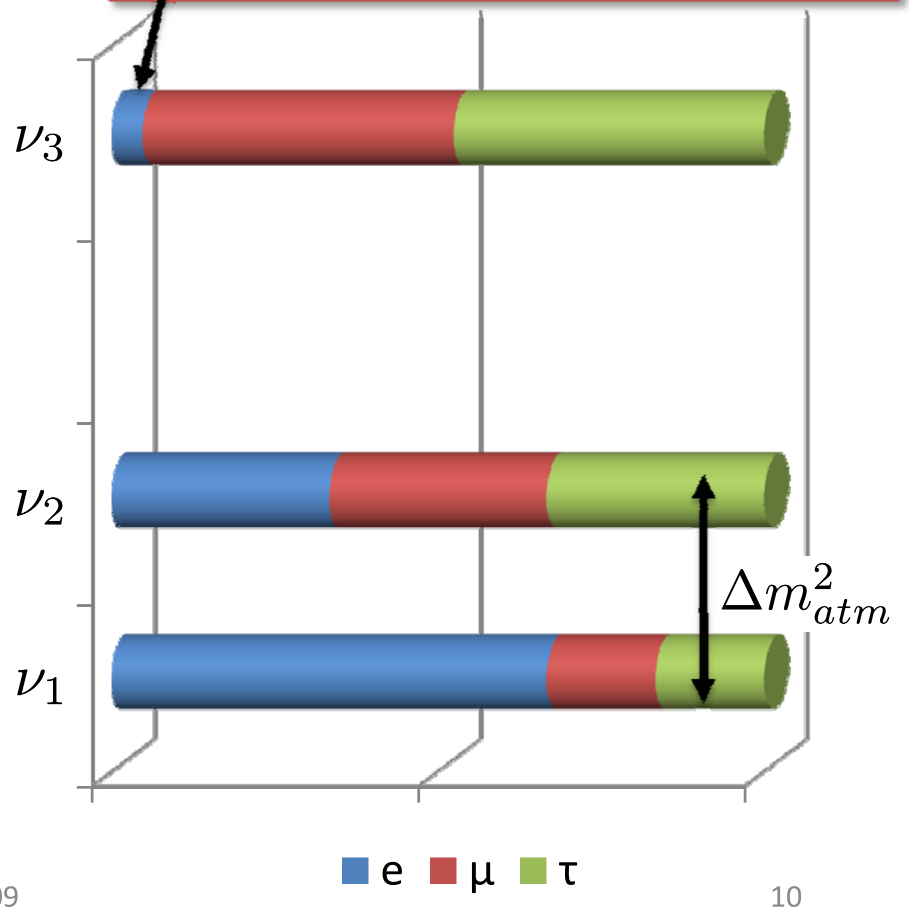
- Essential for making the high precision θ_{23} measurement



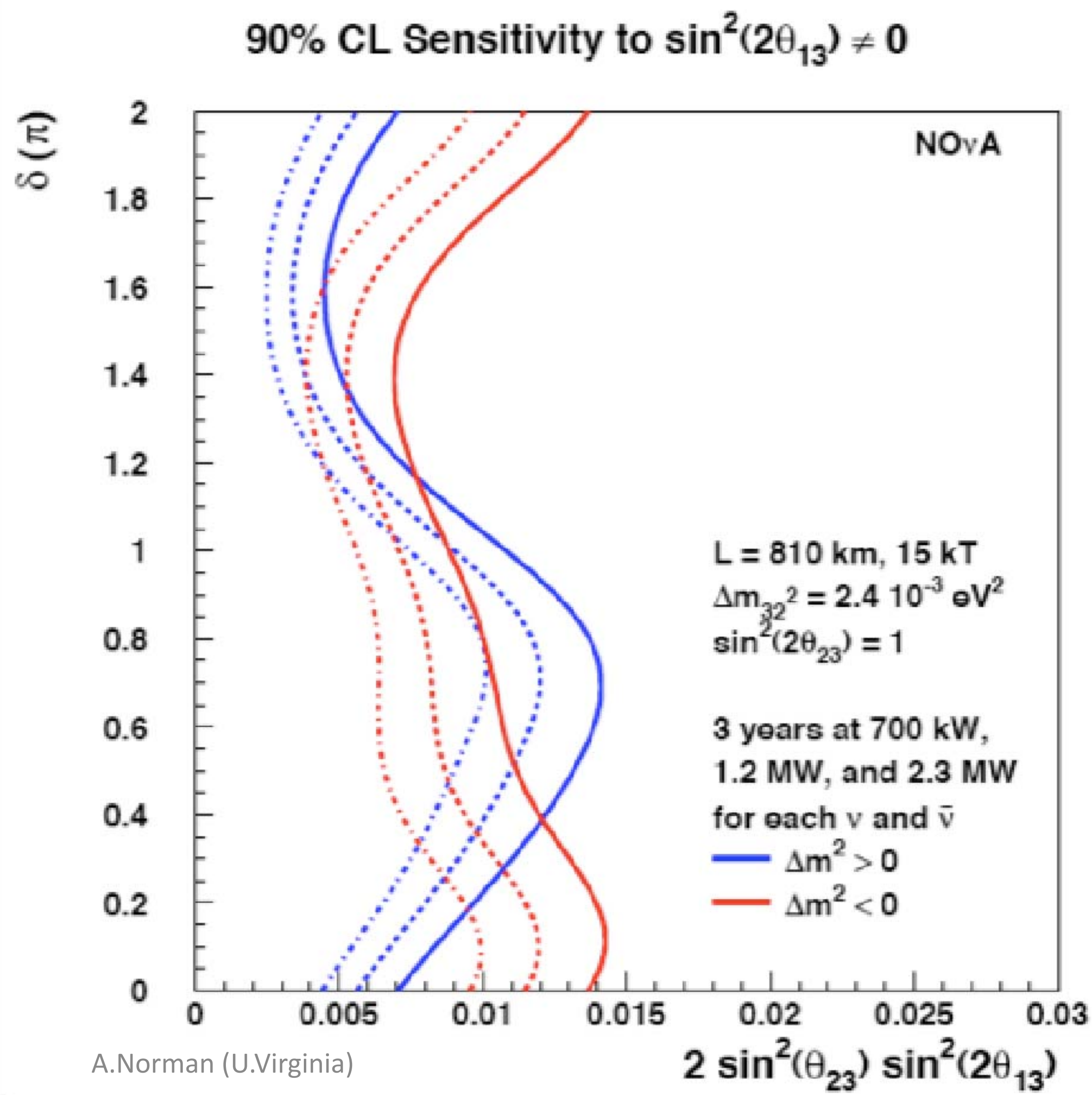
$P(\nu_\mu \to \nu_e)$ and U_{e3}

- Measuring ν_e appearance in the NuMI ν_μ beam will give evidence for $\nu_\mu \to \nu_e$ transitions and a non-zero U_{e3} component to Δm^2_{32}
- This is done through the ν_e CC channel
- The ν_μ NC is the dominant background,
- Controlled through the identification of initial vertex and displaced shower conversion point.
- NOνA's energy (2GeV) and baseline (810km) and segmentation (0.15X_0) are chosen to maximize the physics reach of accessing these transitions

The U_{e3} contribution to the third mass state is small, requiring a precision measurement of ν_e appearance



Sensitivity for θ_{13} from $\nu_\mu \rightarrow \nu_e$



- Nova is sensitive to electron neutrino appearance down to ∼0.01 at 90% CL
- The physics reach for θ_{13} is shown for 3 years of running each on ν and ν-bar.
- There are hints that θ_{13} may be large

Sensitivity for θ_{13} from $\nu_\mu \rightarrow \nu_e$

What we know about θ_{13}

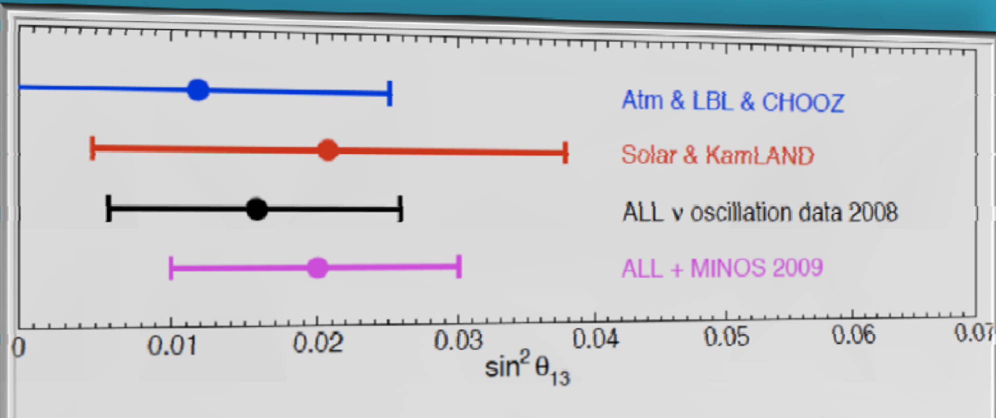


Figure 4: Hints of $\theta_{13} > 0$ from different data sets and combinations: 1σ ranges.

Global Fit by Fogli et al. (arXiv:0905.3549)

- $\theta_{13} = 0$ disfavored by almost 2σ
- Central Value of fit:

$$\sin^2 \theta_{13} = 0.02$$

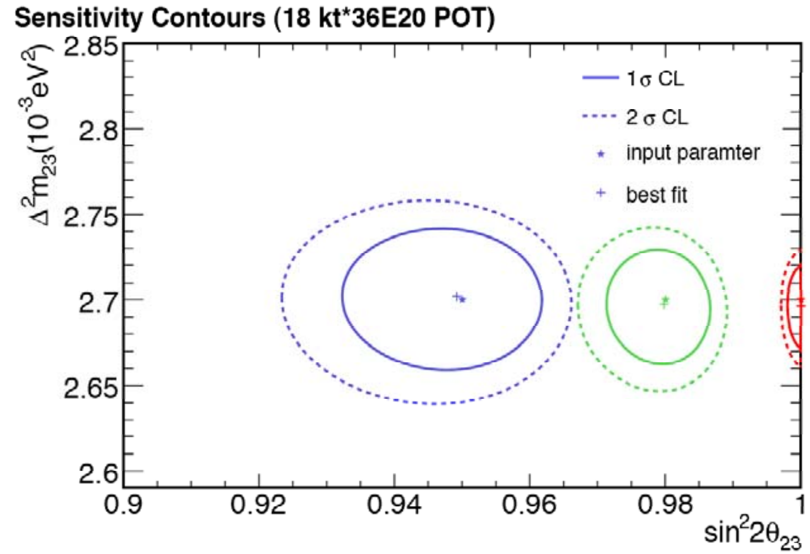
or

$$\sin^2 2\theta_{13} = 0.08$$

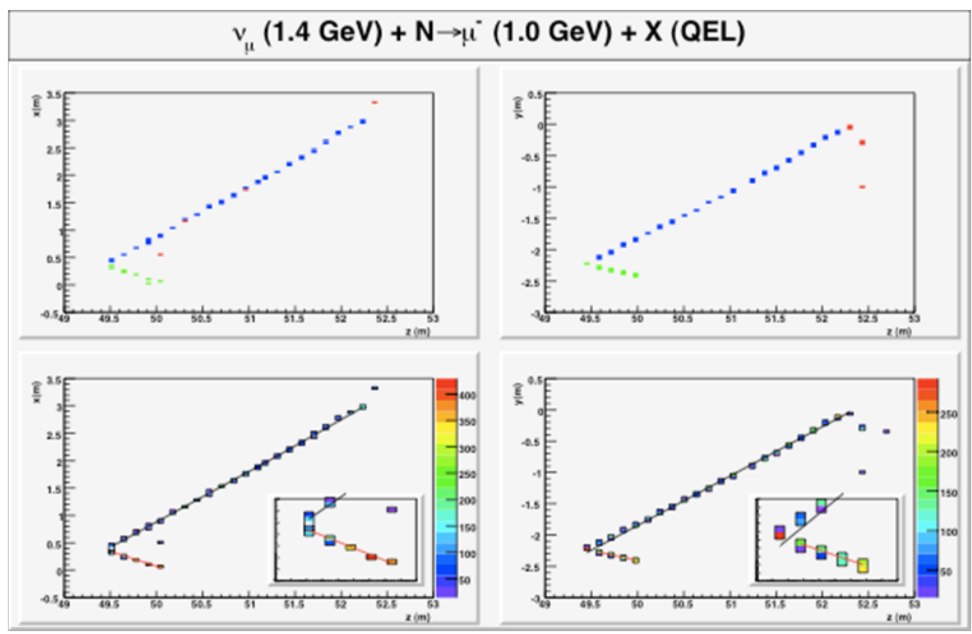
- Nova is sensitive to electron neutrino appearance down to $\sim$0.01 at 90% CL
- The physics reach for θ_{13} is shown for 3 years of running each on ν and ν-bar.
- There are hints that θ_{13} may be large

Sensitivity to $\sin^2(2\theta_{23})$

- The detector's excellent energy resolution, allows NOνA to perform the disappearance measurement to 1%
- Typical 2GeV ν_μ CC-quasielastic event has $\sim$120 hit cells



- If $\sin^2(2\theta_{23}) \neq 1$, we can then resolve quadrant of the mixing ($\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$,)
- Measure if ν_3 couples more to ν_μ or ν_τ
- If $\sin^2(2\theta_{23}) = 1$ then this could be a new basic symmetry

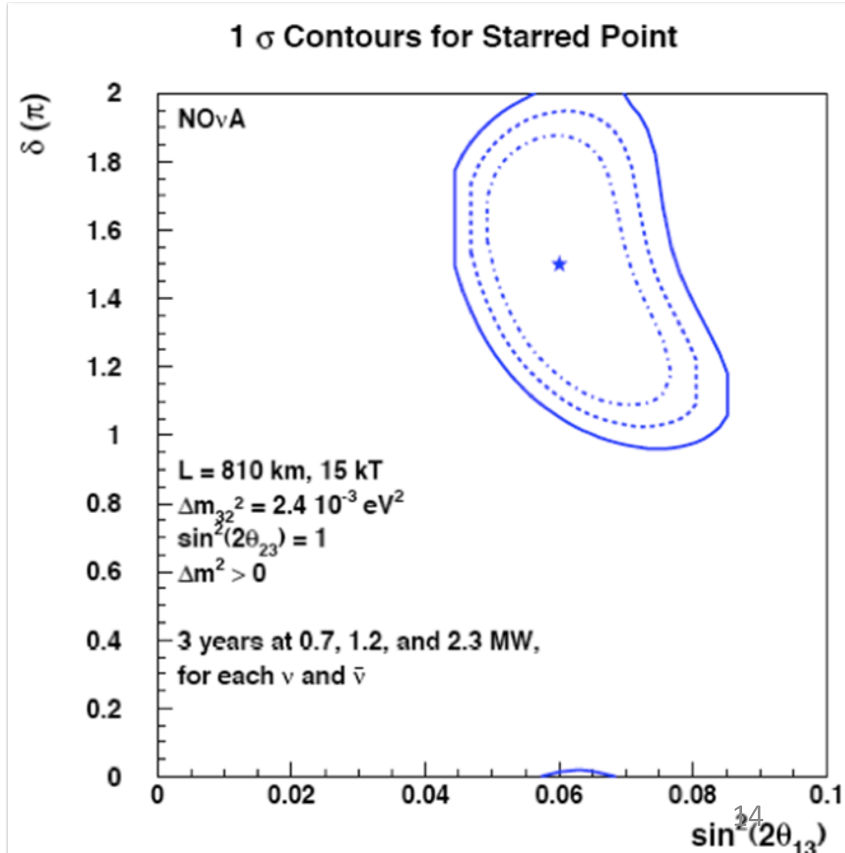


CP Violation

- NOvA gives us our first access to CP violation in the neutrino sector
- The Large Mixing Angle (LMA) solution gives sensitivity in $\nu_\mu \to \nu_e$ transitions to the CP violating phase δ.
- In vacuum, the transition probability is shifted with δ. At the first oscillation maximum the shift is:

$$|\Delta P_\delta(\nu_\mu \to \nu_e)| \sim 0.06\% \sqrt{\frac{sin^2 2\theta_{13}}{0.05}}$$

- Since the shift is proportional to $\sqrt{sin^2 2\theta_{13}}$ the importance of the sub-leading terms grow, as $sin^2 2\theta_{13}$ gets small.
- In matter, the ultimate sensitivity of NOνA for resolving the CP ambiguities depend on both θ_{13} and δ

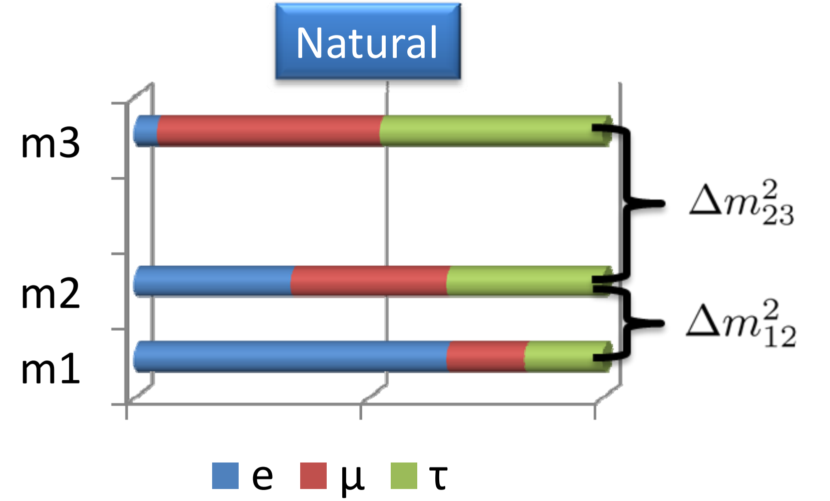


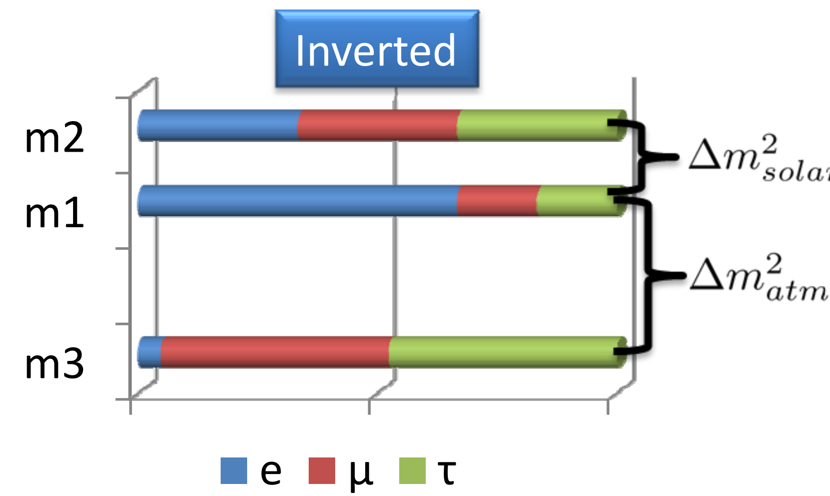
Mass Ordering

- From solar and atmospheric data we know:

$$m_1 < m_2$$
$$\Delta m^2_{12} < \Delta m^2_{23}$$
$$\Delta m^2_{23} \approx 2 \times 10^{-3} eV$$

- This leads to two possible mass hierarchies
  - A "normal" order which follows the charged lepton mass ordering
  - An "inverted" order where m_3 is actually the lightest
- NOνA can solve this by measuring the sign of m_{23} using the MSW effect over the 810km baseline



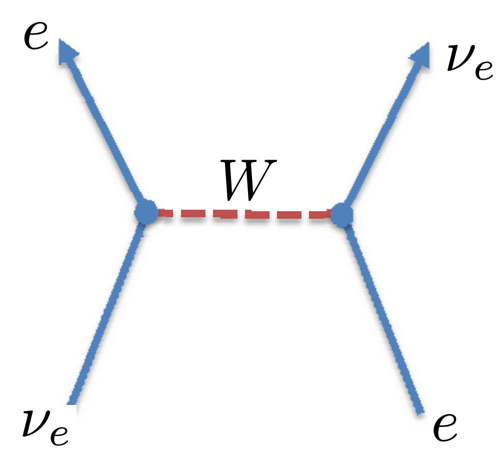


Matter Effect

- The forward scattering amplitudes for neutrinos and anti-neutrinos through normal matter differ due to the inclusion of the extra diagram for interactions off electrons
- This difference breaks the degeneracy in the neutrino mass spectrum and modify the oscillation probability

$$P_{mat}(\nu_\mu \rightarrow \nu_e) \neq P_{mat}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- If the experiment is performed at the first peak in the oscillation then the matter effects are primarily a function of the beam energy and approximated by:



$$P_{mat}(\nu_\mu \rightarrow \nu_e) \approx (1 + \frac{E}{E_R}) P_{vac}(\nu_\mu \rightarrow \nu_e)$$

$$E_R = \frac{\Delta m^2_{23}}{2\sqrt{2} G_F N_e} \approx 11 GeV$$

- In the normal hierarchy this matter effect enhances the transition probability for neutrinos and suppresses the probability for antineutrinos transitions
- With an inverted hierarchy the effect is reversed
- For the 2 GeV neutrino beam used for NOνA, the matter effect gives a 30% enhancement/suppression in the transition probability.

Matter Effect

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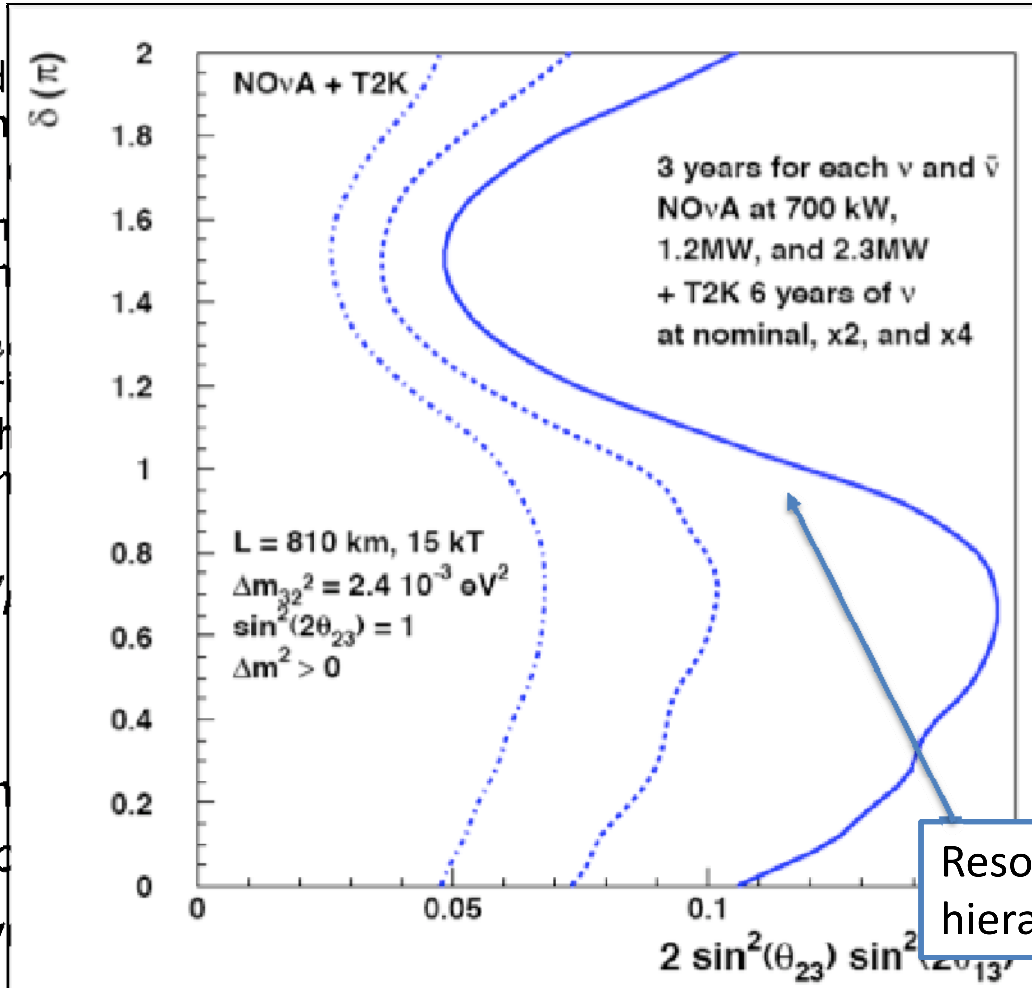

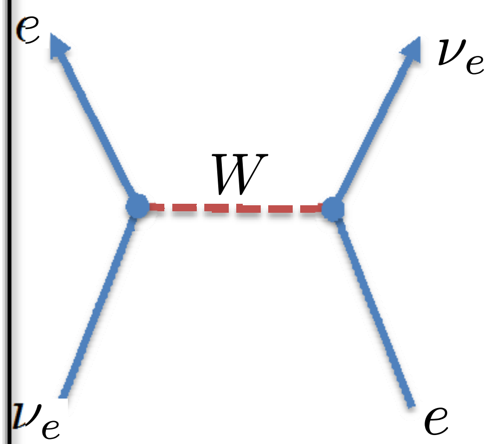

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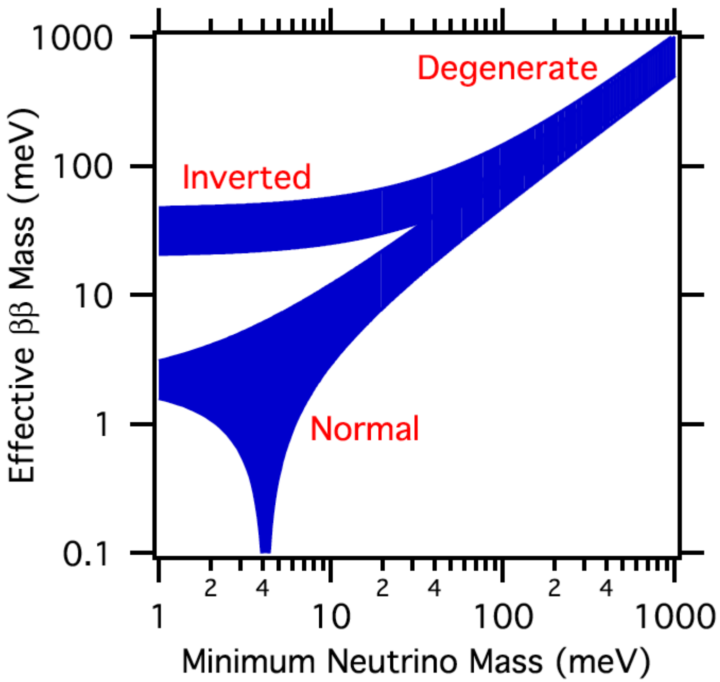
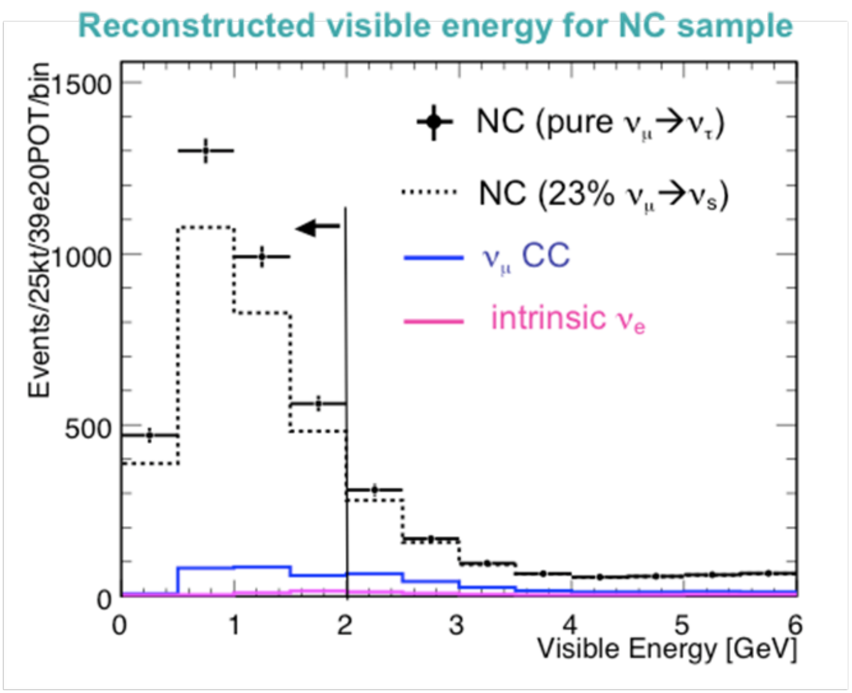
More NOvA Physics

Dirac/Majorana



If NOvA can establish the inverted mass hierarchy, then the next generation of neutrinoless double-β decay experiments should see a signal, else it is highly likely that neutrinos are Dirac in nature.

Sterile Neutrinos



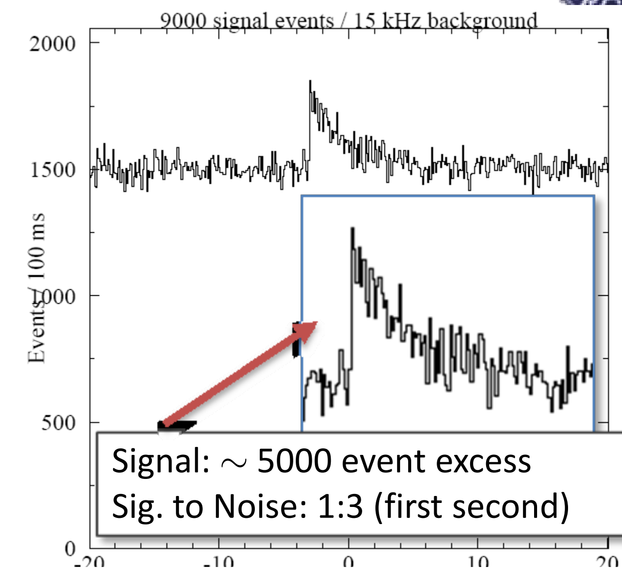
The high granularity of the NOvA detector makes clean measurements of the NC cross sections possible, and allows for Sterile neutrino searches

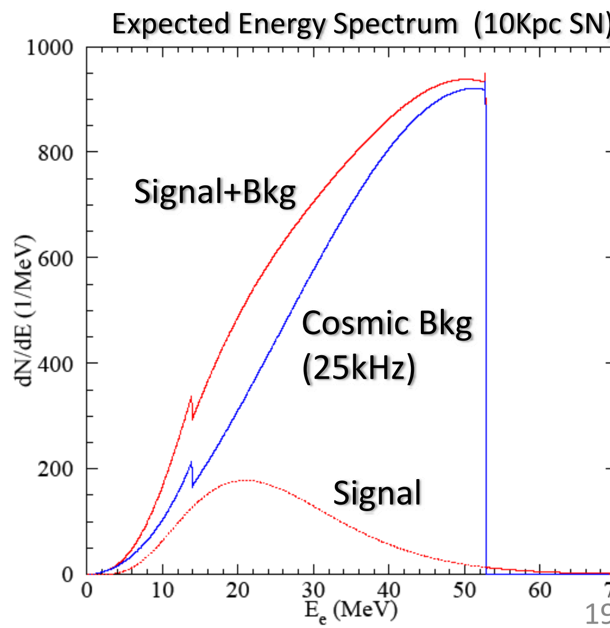
SuperNOνA Detection

- Primary SuperNOνA Signal:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- For a supernova at 10kpc the total signal is expected to contain:
  - 5000 total interactions over a time span of $\approx$ 10s
  - Half the interactions in the first second
  - Energy peaks at 20MeV and falls off to $\sim$ 60MeV
- Challenge is triggering in real time
  - Need data driven open triggering
  - Long event buffering ($\sim$ 30sec)
  - Time window correlation & merging
- NOνA – farm 180 trigger/buffer PCs (min 30s total event buffering)

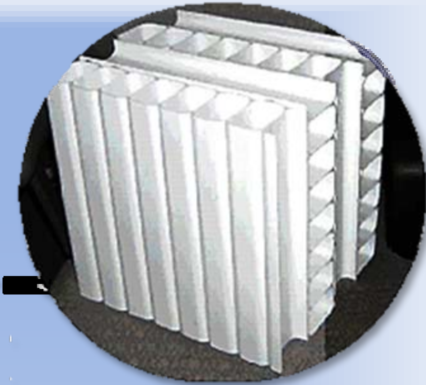


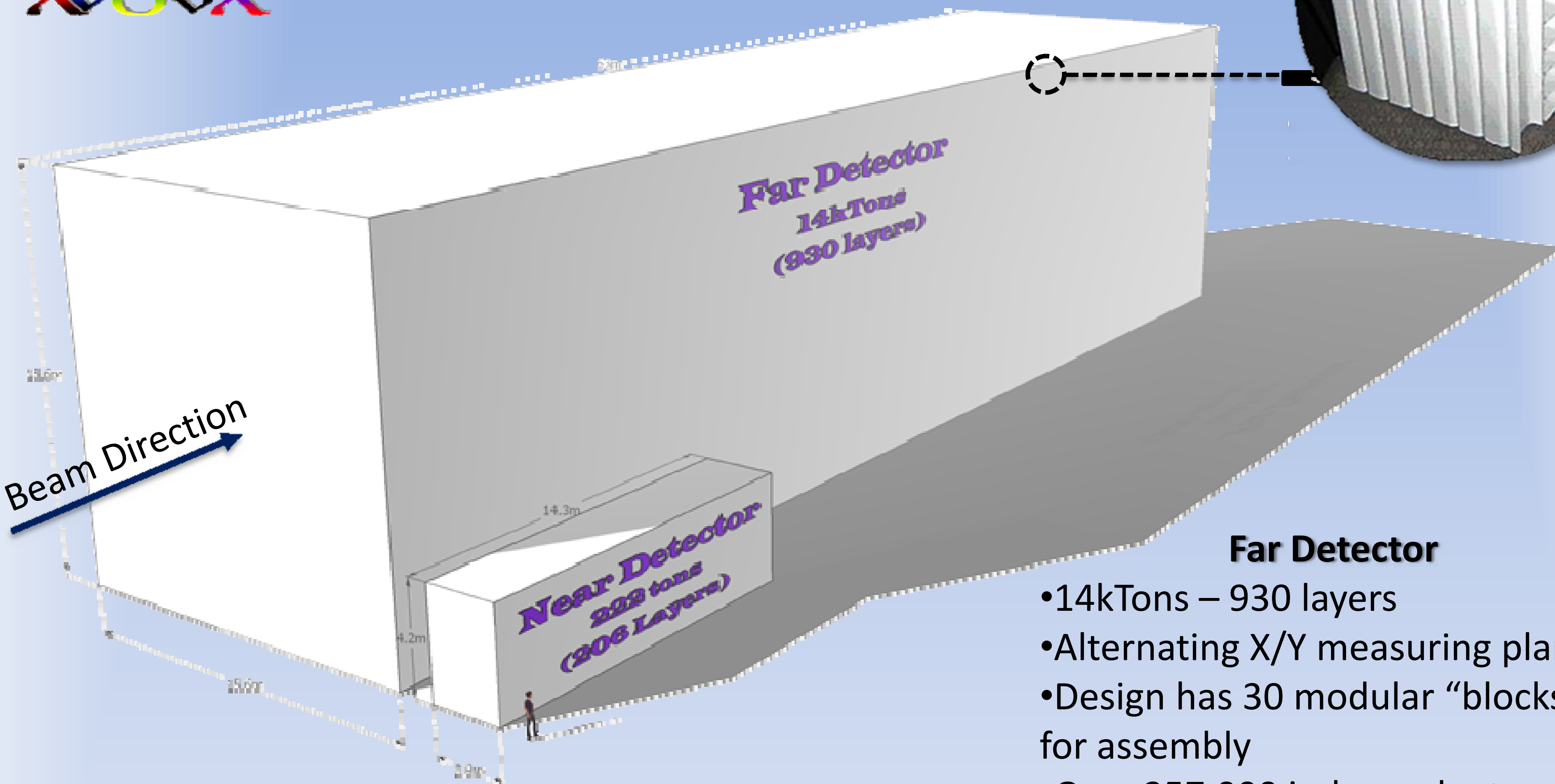


The Experiment

THE NOVA DETECTOR

NOvA Detectors





Far Detector

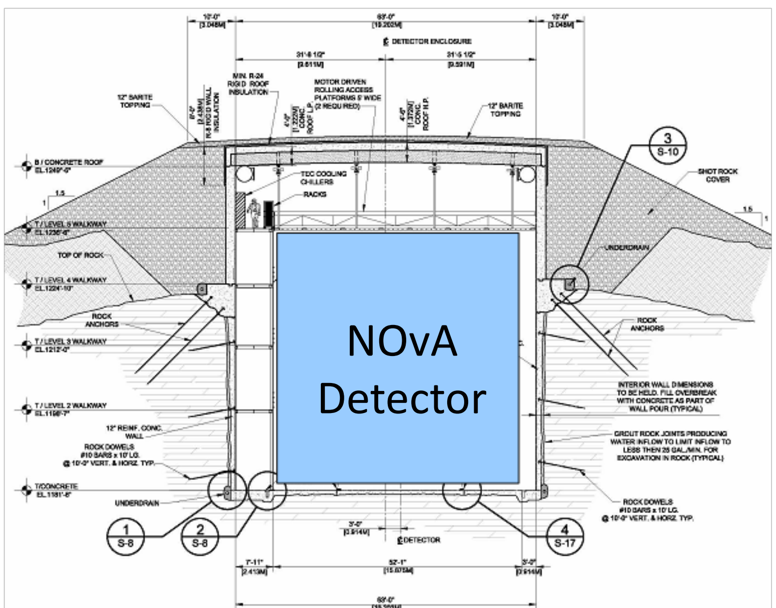
- 14kTons – 930 layers
- Alternating X/Y measuring planes
- Design has 30 modular "blocks" for assembly
- Over 357,000 independent measurement cells
- > 70% of total mass is active
- Located 14mrad off axis
- 810km baselines

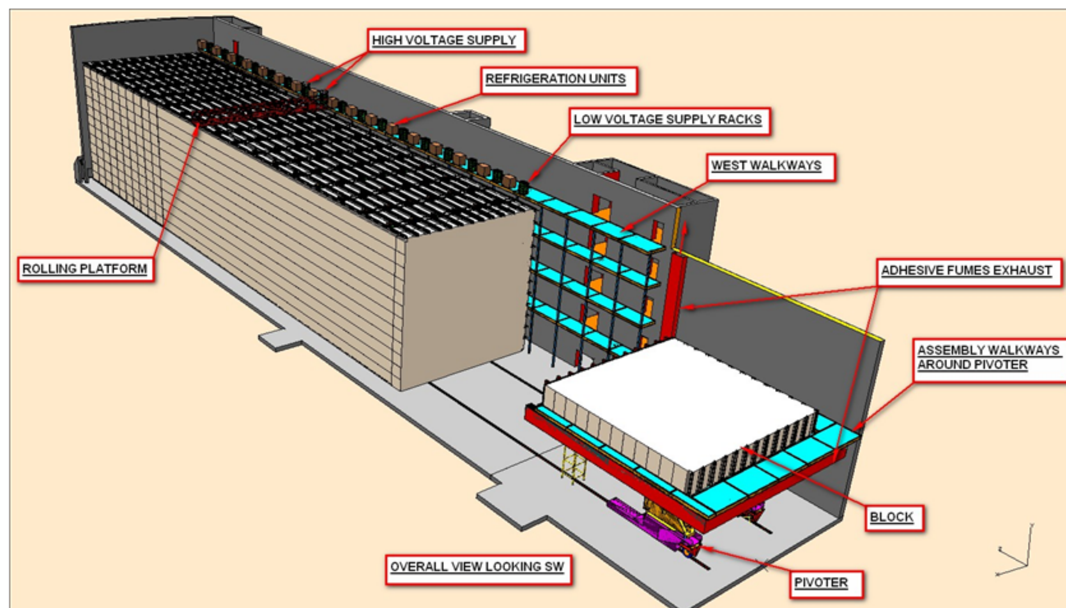
Near Detector

- 222 Tons – 206 layers
- 2 modules wide, six blocks deep
- Includes muon catcher for ranging out μ's
- Located 14mrad off axis in NuMI, next to MINOS cavern

Far Site (Ash River)

- The Ash River site:
  - Provides 810km baseline
  - Sits 11.8 km (14.5 mrad) off the NuMI beam axis
  - Is the most northern site in the United States that was accessible by road (and we had to build an extra 3.6miles of road to get there)
- Detector Hall
  - Designed for up to an 18kt detector
  - Detector is build in place using modules blocks which are assembled and raised.
  - Production physics data collection can start after commissioning of the first few blocks



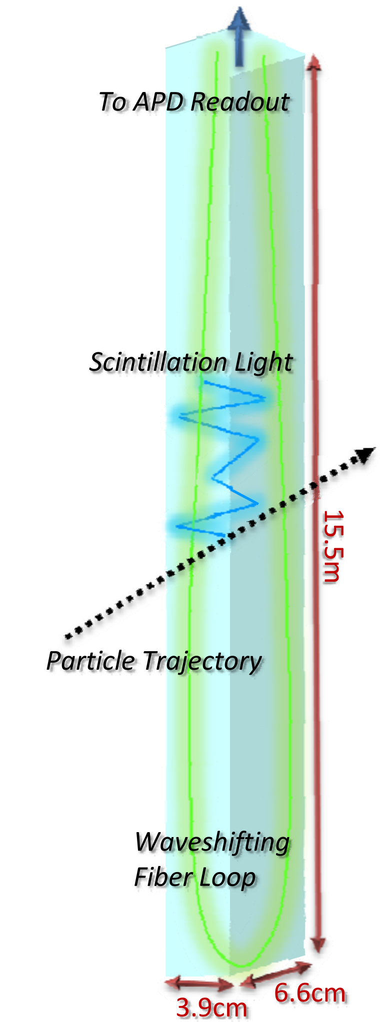


Far Site (Ash River)

Far Site – First Blast

Detector Cell
Fiber and Scintillator

Single Cell



There are 357,120 cells in NOνA

NOνA Detection Cell

- The base detector unit 3.9x6.6cm cell 15.7m long, filled with a mineral oil based liquid scintillator.
- High reflectivity PVC gives $\sim$8 reflections for emitted light before capture in a wave shifting fiber
- 0.7mm wave shifting fiber loop captures the light and transports it up the cell
- Both fiber ends are read out by a single pixel of the APD.

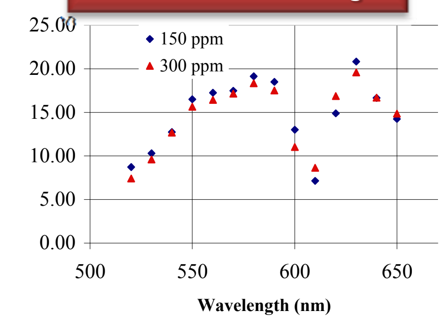
Light Collection

- The scintillator/fiber detection cell is measured to delivers 30-39 p.e. for a muon traversing the far end of the cell
- NOνA uses over 14,000km of fiber

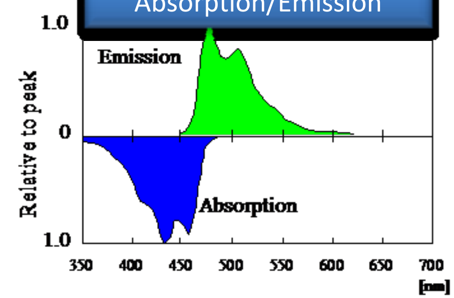
Fiber

The fiber is a double clad 0.7mm fiber doped with 300ppm of a K27 fluorescent dye. The fiber exhibits a long attenuation length for the peak emission spectrum with tests at 300ppm of dye concentration over 15m for the 550nm peak of the spectrum.

Fiber Attenuation Length



Absorption/Emission



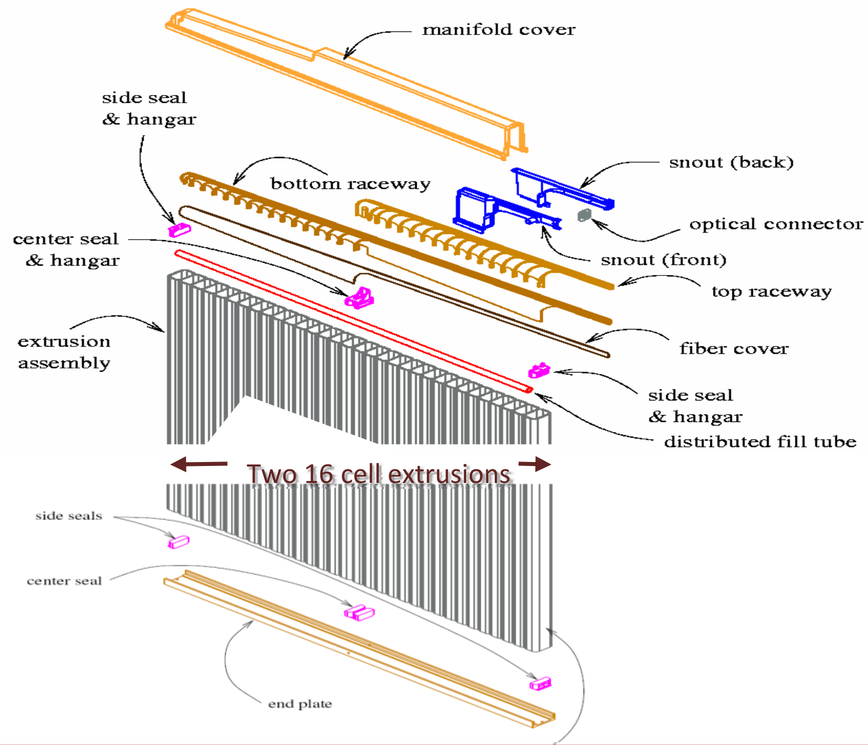
Detector Modules

NOνA Modules

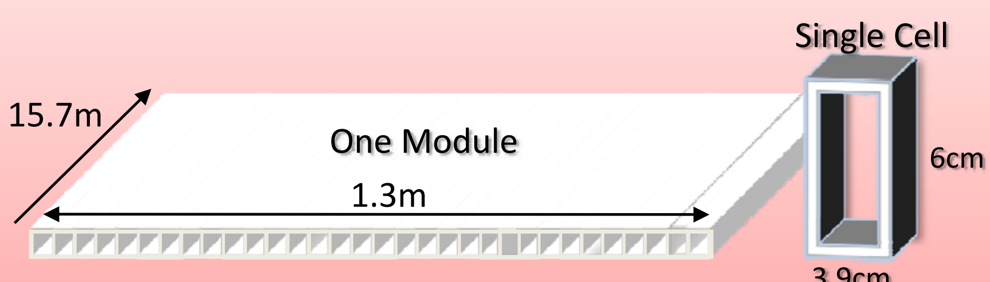
- The NOνA detector module forms the base unit for the detector.
- Each module is made from two 16 cell high reflectivity PVC extrusions bonded into a single 32 cell module
- Includes readout manifold for fiber routing and APD housing

- Combined 12 module wide X or Y measuring planes.
- Each module is capped, and filled with the liquid scintillator.
- These are the primary containment vessel for the 3 million gallons of scintillator material.

- There are 11,160 detector modules with a total of 357,120 separate detection cells in the NOνA Far Detector.



PVC Extrusions



Each extrusion is a single 15.7m (51.5ft) long set of 6x3.9cm cells.
Two extrusions are joined to form a single 1.3m wide module

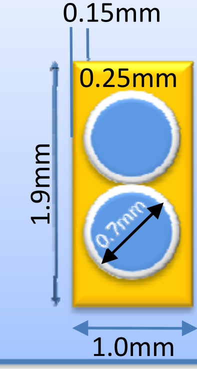
Avalanche Photodiodes – APDs

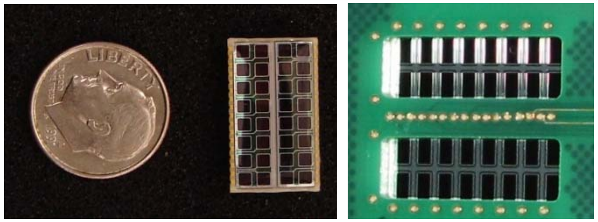
The NOνA Readout

- Require 357,120 optical readout channels
- Custom designed 32 channel APD *(Hamamatsu)*
- High 85% Q.E. above 525nm
- Cooled to -15° to achieve noise rate < 300 electrons

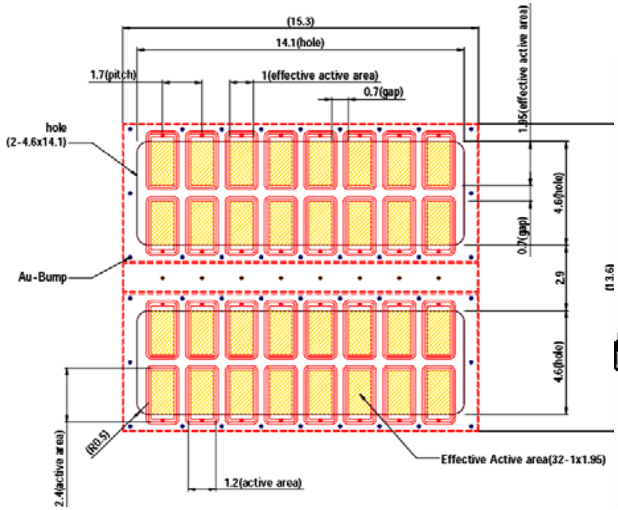
- Operated at gain of 100 for detection of 30-39 photon signal from far end readout
- Signal to noise at far end 10:1

Pixel Geometry
Each pixel is designed to have an active area 1.0mm by 1.9mm to accommodate the aspect ratio of the two 0.7mm fiber ends from a single cell

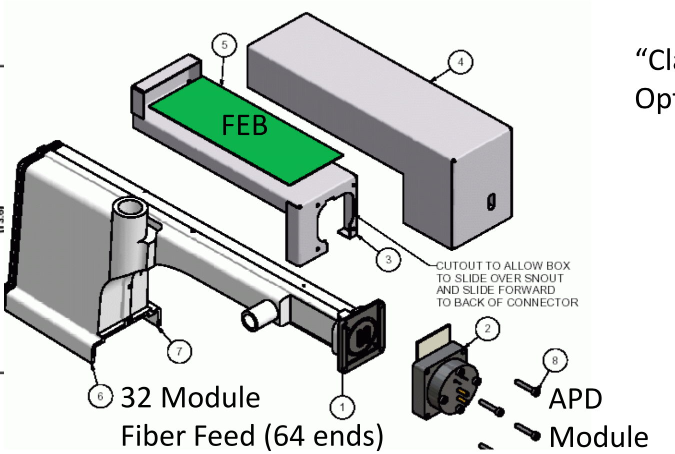




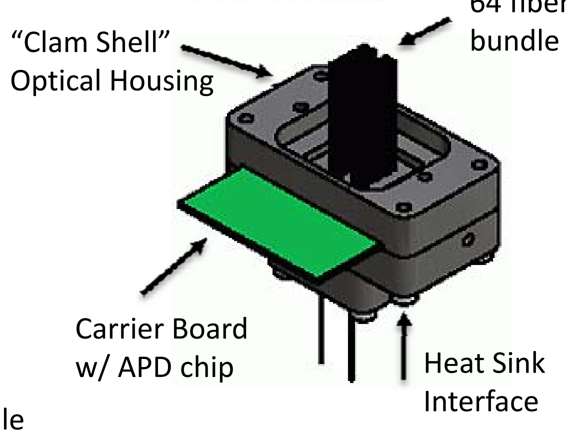
The bare APD is bonded to the carrier board to provide the optical mask and electrical interface



The 32 pixel APD array for the NOνA Readout System

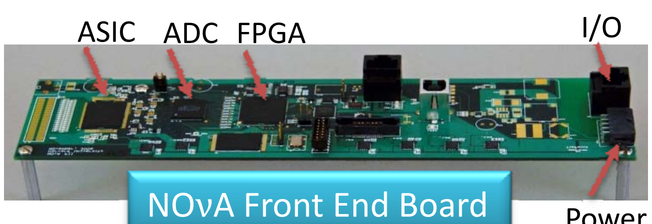


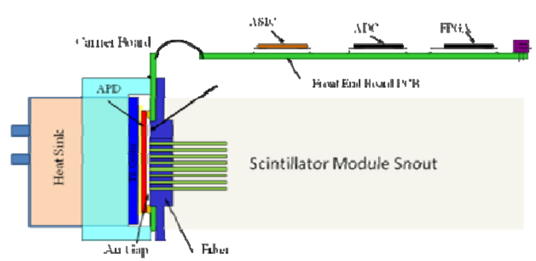
APD Module



Front End Electronics

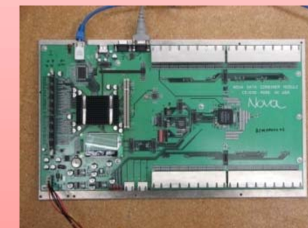
- Use a continuous digitization and readout scheme
- APDs are sampled at a 2MHz and a dual correlated sampling procedure is used for signal recognition/zero suppresion
- Done real time on the FPGA, the signals are then dispatched to Collector nodes as "time slices"
- Data Concentrator Modules assemble/order the data and dispatch macro time windows to a "buffer farm" of 180 compute nodes
- Provides minimum 30sec full data buffer for trigger decision
- Dead-timeless system with software based micro/macro event triggering





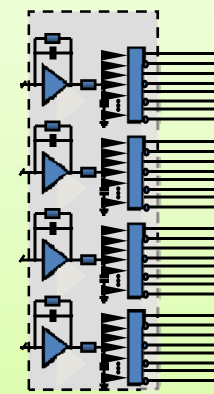
Data Concentrators (DCM)

The digitized data streams from 64 front end boards are broadcast over 8B/10B serial links to an associated data concentrator module which orders, filters and buffers the data stream, then repackages the data into an efficient network packet and rebroadcasts it to a specific buffer node for trigger decisions.



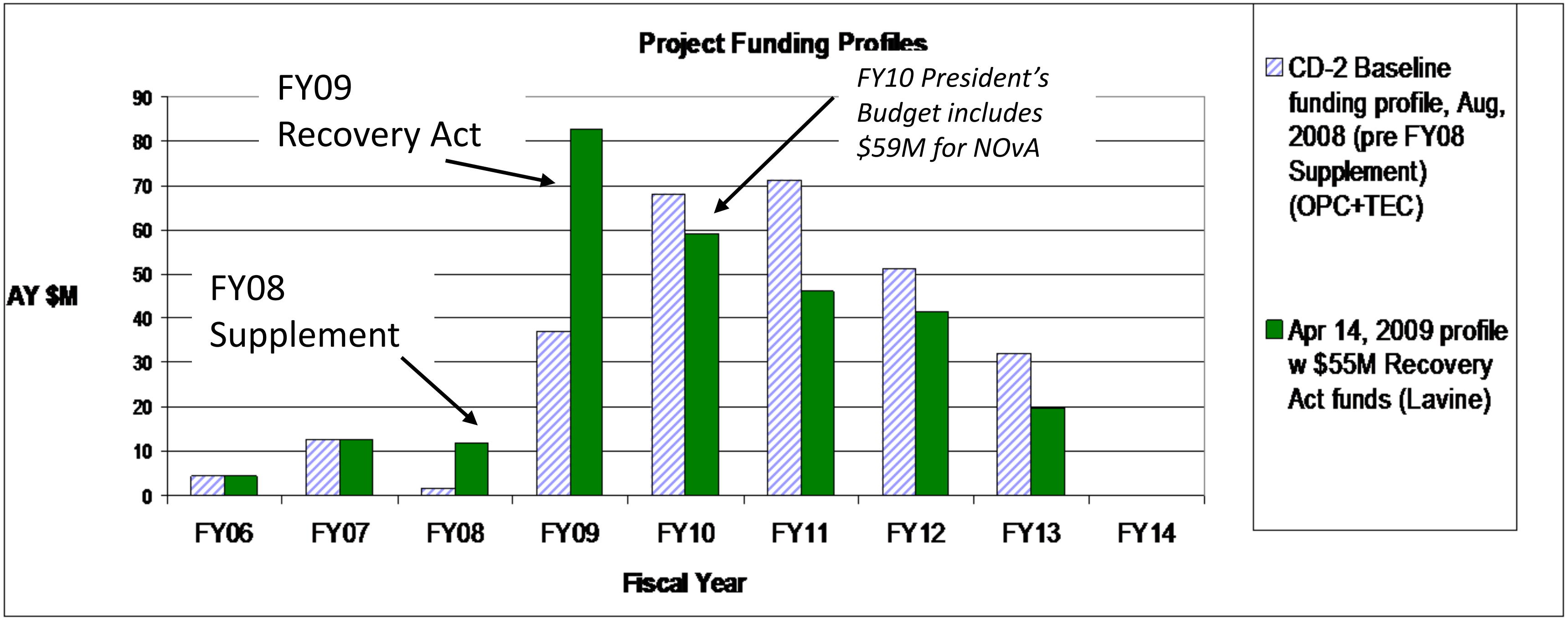
FEB ASIC

The custom designed ASIC is an integrator/shaper with multiplexer running at 16MHz. The channels are Muxed at 8:1 and sent to a 40MHz quad ADC for digitization. For the higher rate near detector the channels are muxed at 2:1 and sent to 4 quad ADCs. ASIC is a low noise device with expected noise < 200 e. rms.



NOvA Status & Funding

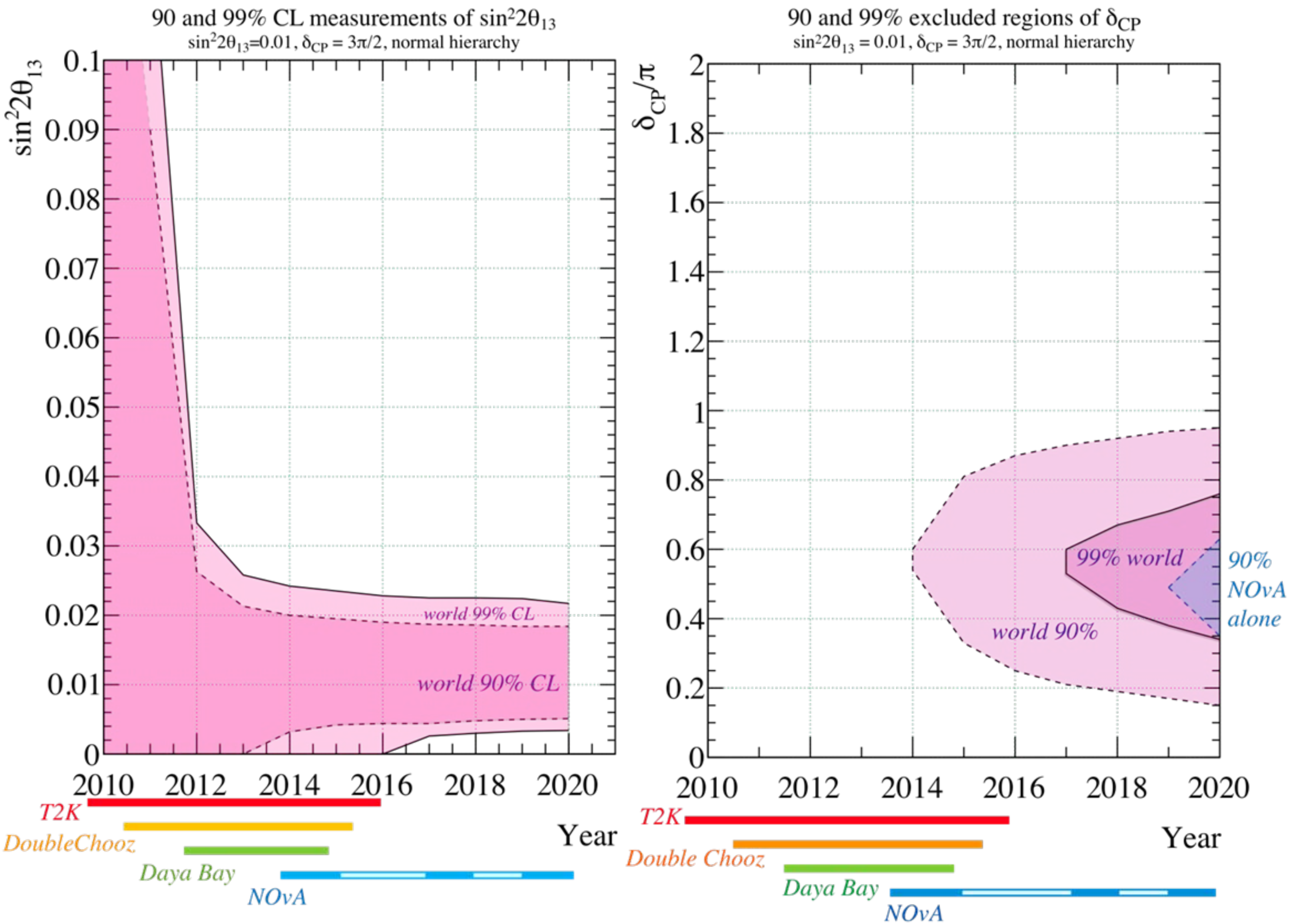
- NOvA Received 55M$ in American Recover & Reinvestment Act funding
- Ground was broken on the far site May 1st 2009
- NOvA under went a CD-3b review last week
- NOvA will attempt to use the dramatic change in funding to advance the project schedule
- Near detector is now schedules for construction & commissioning on the surface in spring/summer 2010



Additional Materials

BACKUP SLIDES

Moving towards θ_{13} & δ_{CP} (World Data)



- T2K+ Daya Bay can push the upper limit on $\sin^2 2\theta_{13}$ to 0.01.
- NOvA pushes the non-zero discovery past 99% CL.
- NOvA's sensitivity to δ_{CP} can cover half the δ_{CP} space

M.Messier (NOvA CD-3b Review)

ν_μ Neutral Current Background

Event Parameters

Reaction:

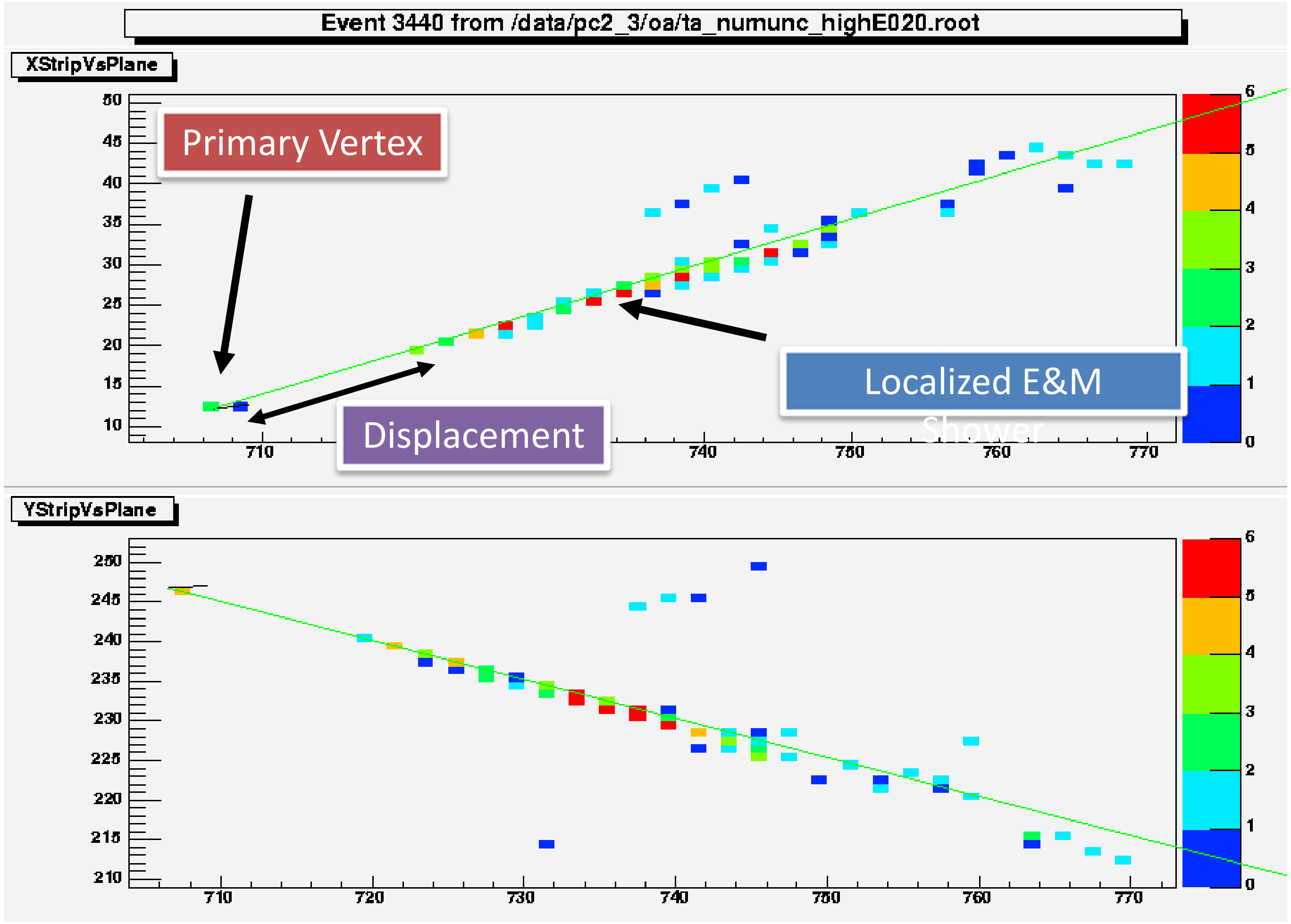
$$\nu_e N \rightarrow p\pi^0\nu_\mu$$

E_ν = 10.6GeV

E_p = 1.04GeV

E_π = 1.97GeV

Suppressed by vertex/shower displacement identification



ν_e Charged Current Channel

Event Parameters

Reaction:

$$\nu_e p \rightarrow p \pi^+ e^-$$

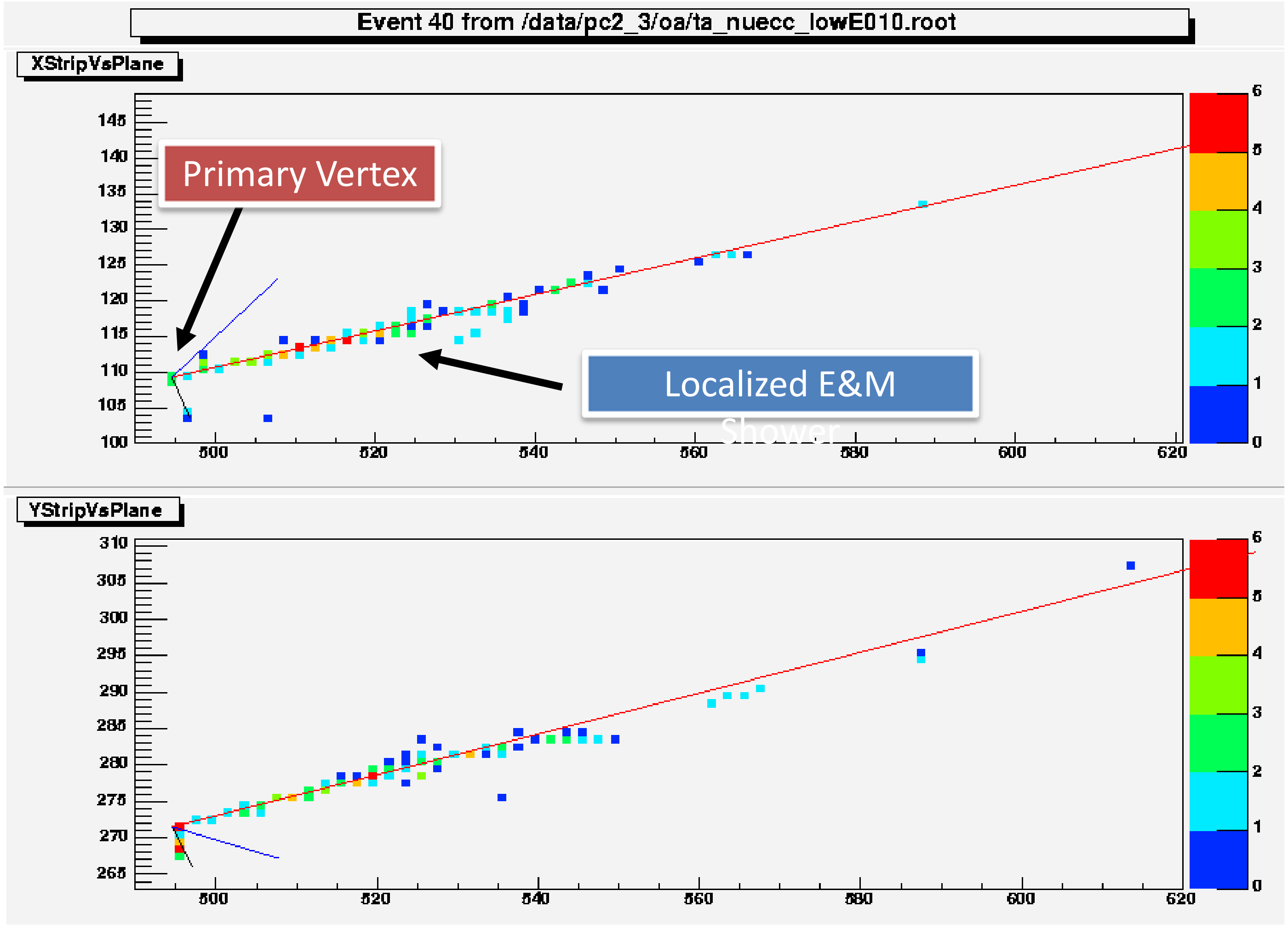
E_ν = 2.5GeV

E_p = 1.1GeV

E_π = 0.2GeV

E_e = 1.9GeV

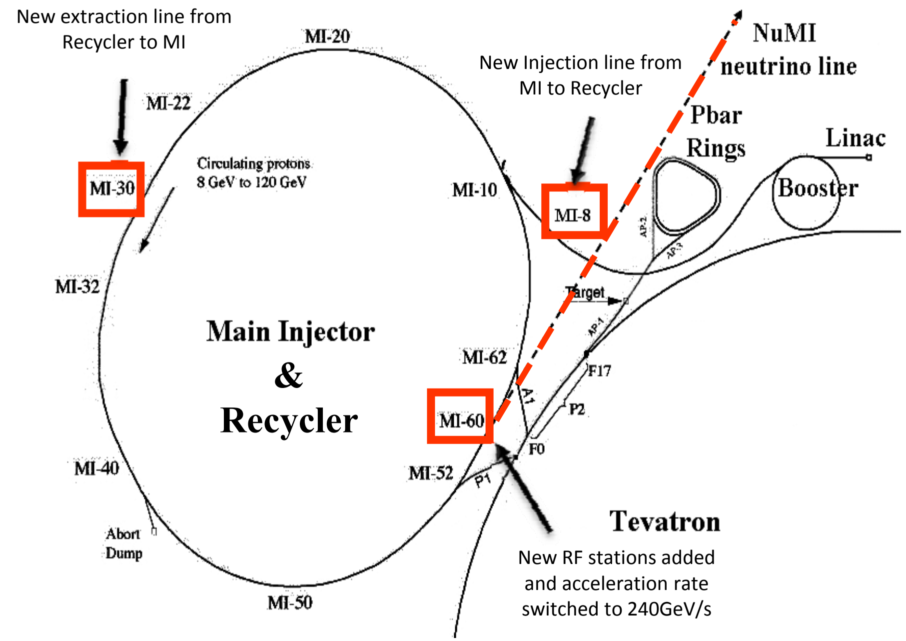
Shower spans ~65 of the 1178 planes

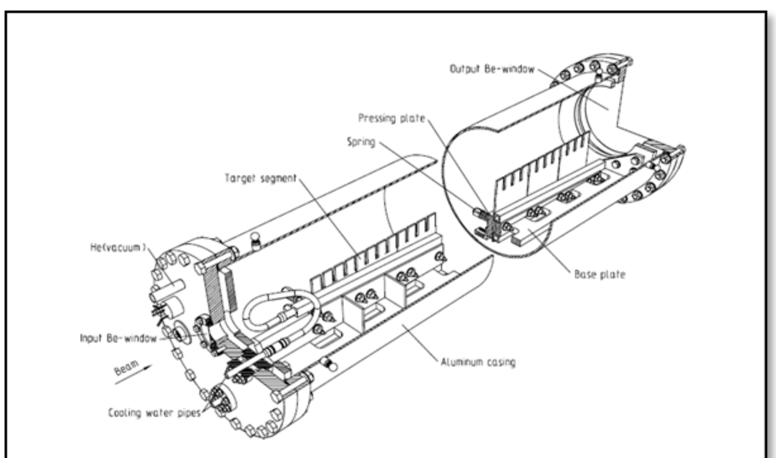


NuMI Accelerator Upgrade

Beamline Upgrade

- Proton source upgraded from 320kW to 700kW
- NuMI will deliver 4.9×10^{12} protons per pulse
- 1.33s rep-rate.
- This results in 6×10^{20} pot/yr.





Changes

- Recycler runs proton not anti-protons
- New injection/extraction lines for Recycler to Main Injector transfers
- Main Injector cycle time reduced from 2.2s to 1.5s (stack in the recycler)
- Cycle time reduced again to 1.33s with 2 more RF stations at MI-60 and with transition of the MI from 204 GeV/s to it's design acceleration rate of 240 GeV/s.
- NuMI target redesign for high flux

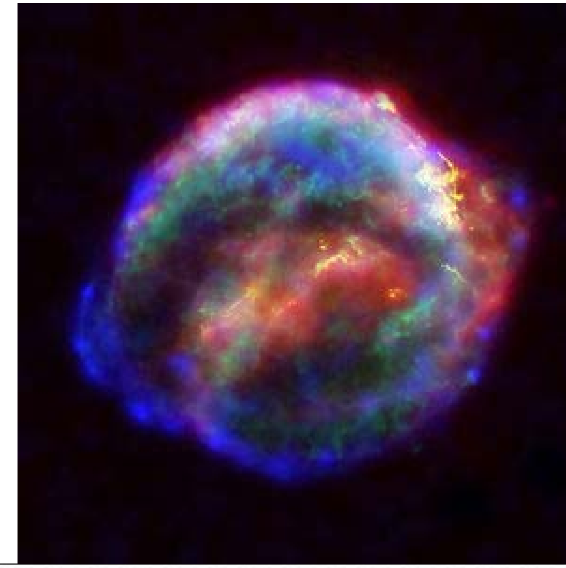
Supernova Neutrinos

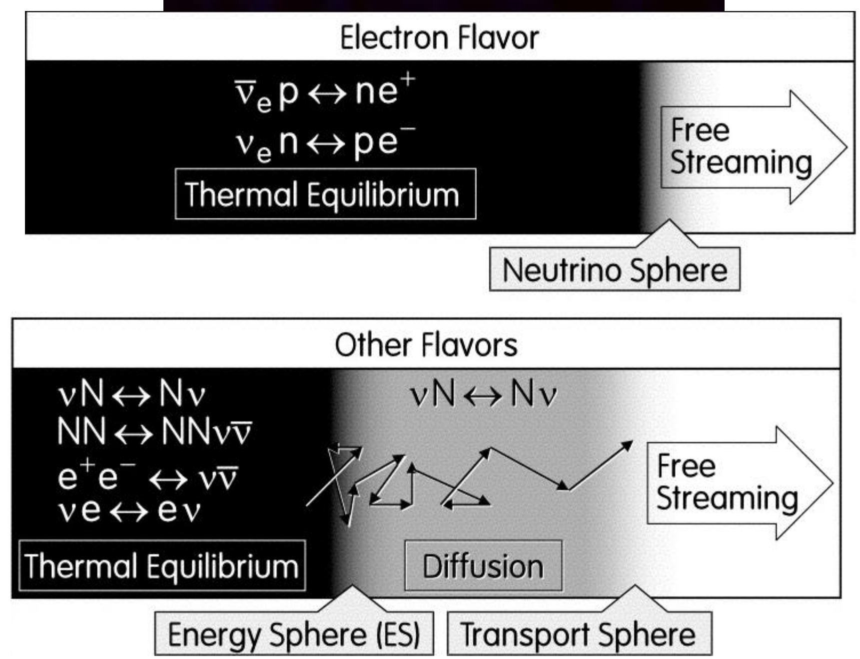
- Neutrinos and Antineutrinos are produced via:

$$NN \to NN\nu\bar{\nu}, \quad e^{+}e^{-} \to \nu\bar{\nu}, \ldots.$$

- The neutrinos are trapped in core collapse, reach thermal equilibrium and then escape in a burst
- Duration of the neutrino burst: 1-10s
- The neutrino luminosity is upwards of 100 times greater than the optical luminosity
- Neutrino flash proceeds primary photons by 5-24 hours.

- Each flavor takes away the same energy fraction
- Different neutrino temperatures are due to allowed reaction channels





DAQ and Trigger