Accessing Particle/Astrophysics Measurements with the NOvA Detector

Designing a Data Driven Triggering & DAQ System for NOvA

Andrew Norman (U. Virginia)
HEP Seminar Argonne National Lab
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Galactic Center (Spitzer Space Telescope)

Seminar Outline

NOvA's Core Measurements

Neutrino Osc. Properties

θ_{13} θ_{23} δ_{CP} sign(Δm_{23})

The NOvA Detector

Basic Design as a

μ range-stack/ EM calorimeter

The DAQ & Triggering

Base Design and Redesign

Advantages &Limitations

Data Driven Triggering Model

Physics Triggering

Core Measurement

Supernova detection

Exotic Topologies

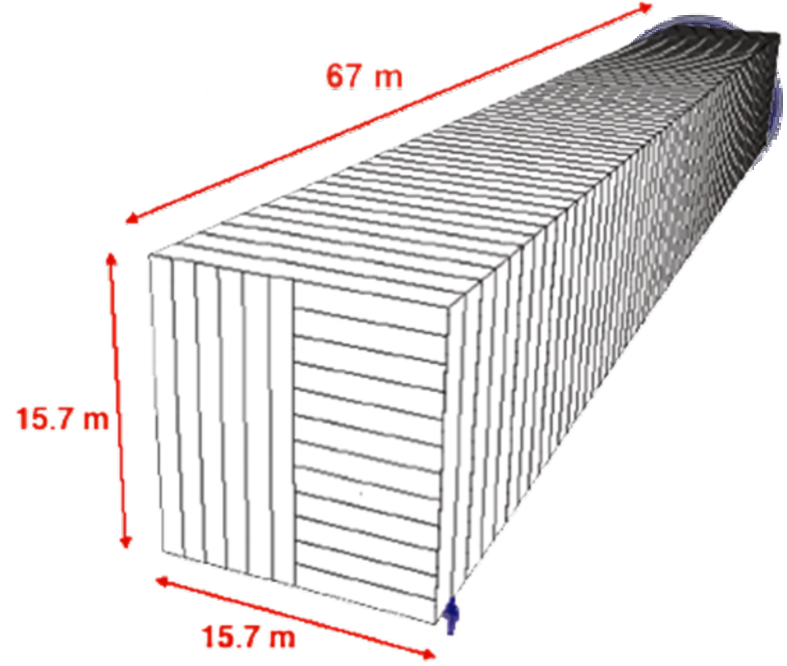
Directional triggers

High E ν's & cosmics

Neutrino Oscillations and Properties

NOVA CORE MEASUREMENTS

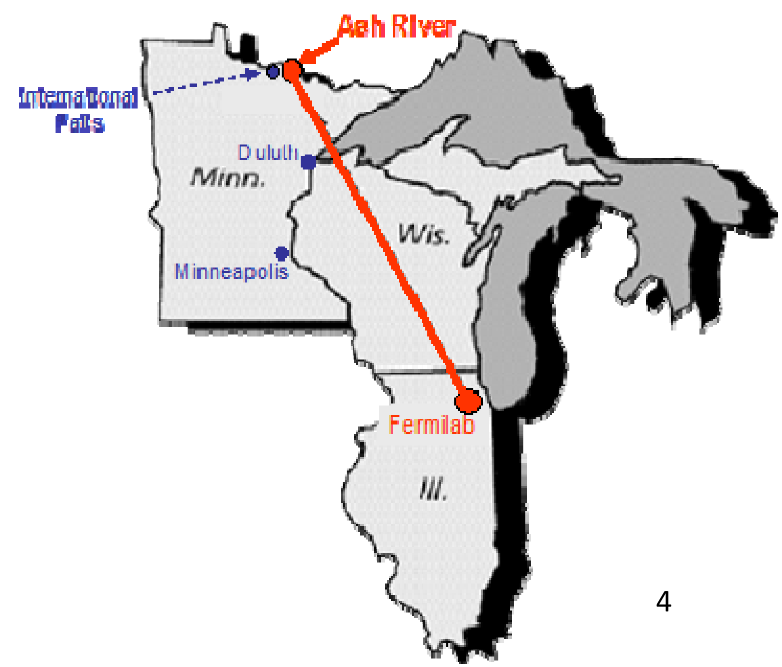
NOvA Overview



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

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

- *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



Neutrino Mixing

- We know from the Z width that there are three active (weak coupling) neutrino species
- We have observed oscillations between these which implies a mixing through the near degenerate mass eigenstates
- In analogy to CKM mixing we setup a mixing structure

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad \begin{pmatrix} u \\ c \\ t \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & \text{small} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \simeq \begin{pmatrix} 0.97 & 0.22 & 0.0036 \\ 0.22 & 0.97 & .041 \\ 0.0087 & 0.04 & 0.99 \end{pmatrix}$$

Very different structure

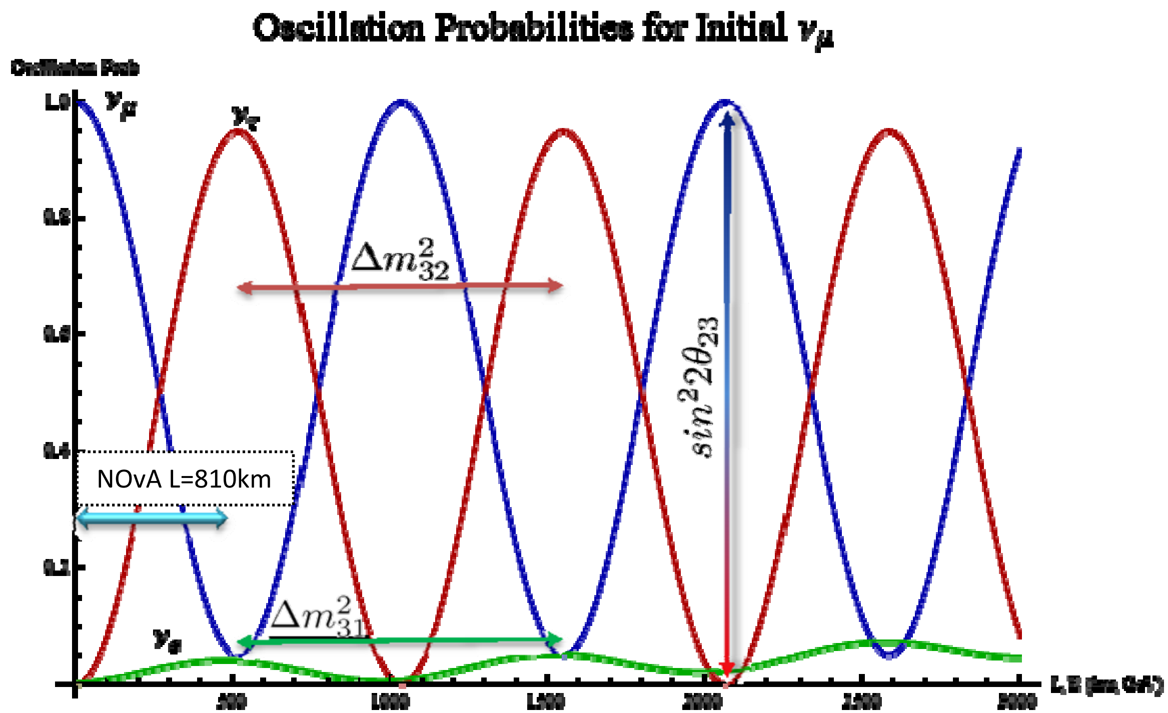
Near Unity

Neutrino Mixing

- Re-parameterize as a rotation in 3 angles and a phase

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- If we examine the oscillation probabilities it becomes clear how to read off PMNS parameters.



The NOvA Core measurements

eutrino Mixing

- Re-parameterize as a rotation in 3 angles and a phase

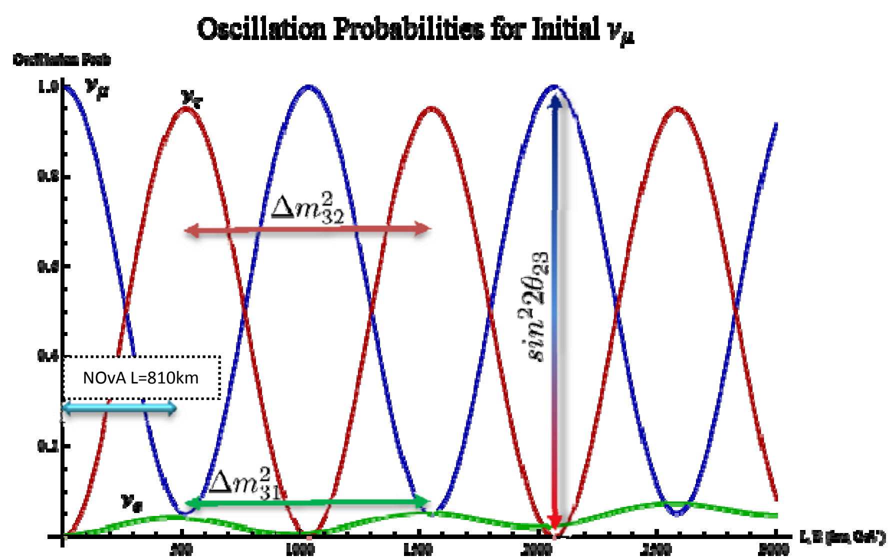
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric/Accelerator ν_μ disappearance

Accelerator $\nu_\mu \rightarrow \nu_e$ appearance
Reactor $anti\text{-}\nu_e$ disappearance

Solar ν_e and $anti\text{-}\nu_e$ disappearance

- If we examine the oscillation probabilities it becomes clear how to read off PMNS parameters.
- This leads to the classification of the mixing angles in terms of the characteristic L/E scale that is needed to view the oscillation



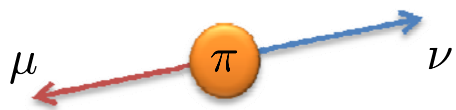
Core Questions for NOvA to Address

- 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 galactic Supernova?

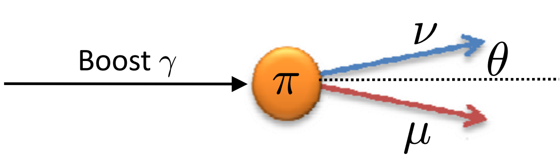
The Off-Axis Beam

The Off-Axis Effect

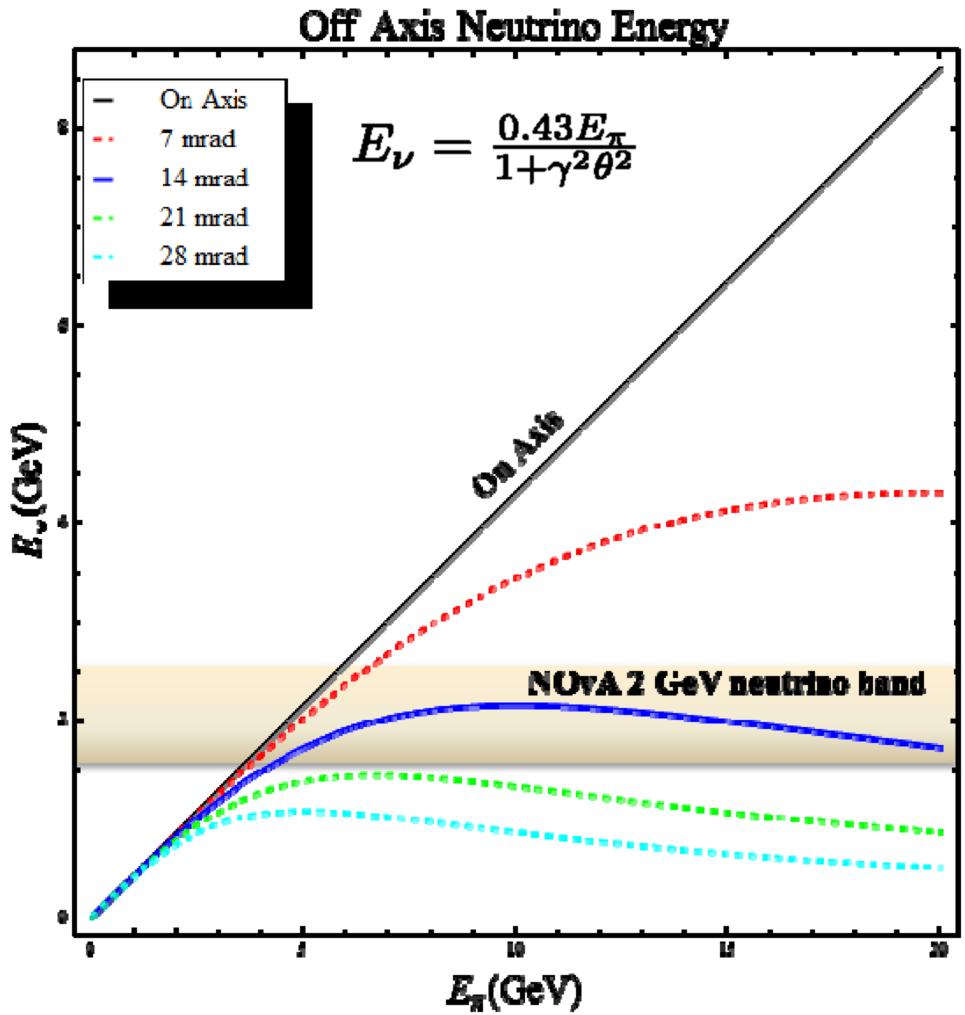
In the pion rest frame the kinematics are all completely determined for the decay



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 the neutrino energy spectrum down to be 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:

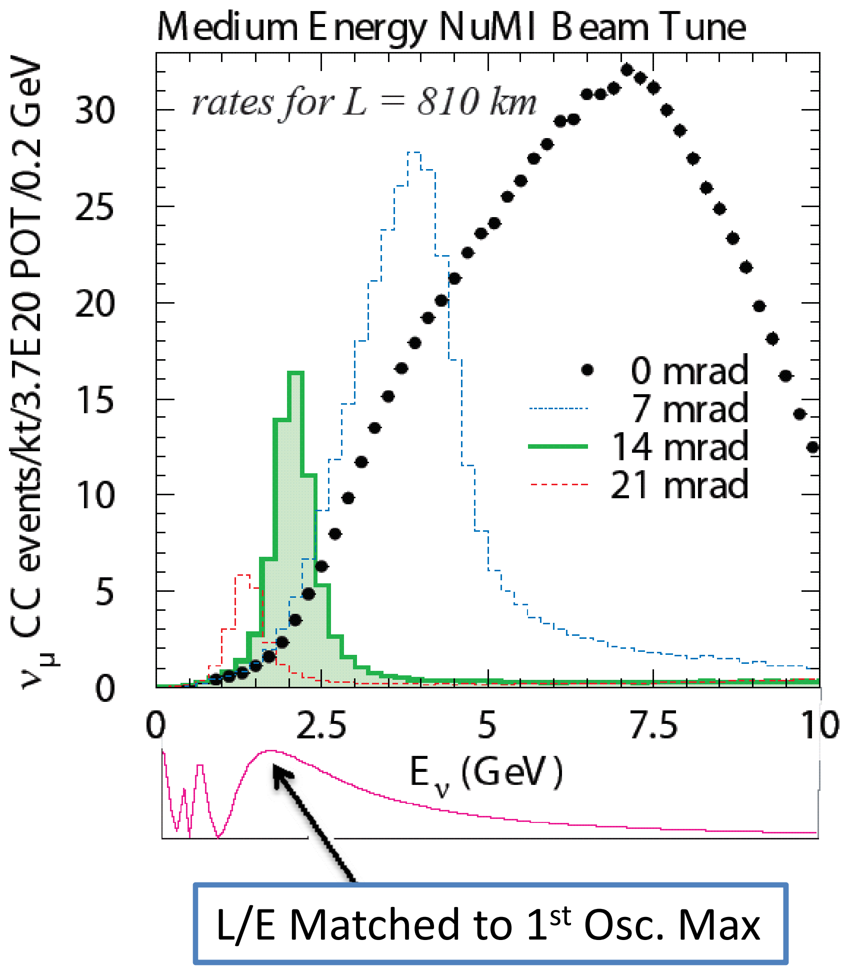
$$F = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

- But we narrow the ν energy spread:

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

- 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



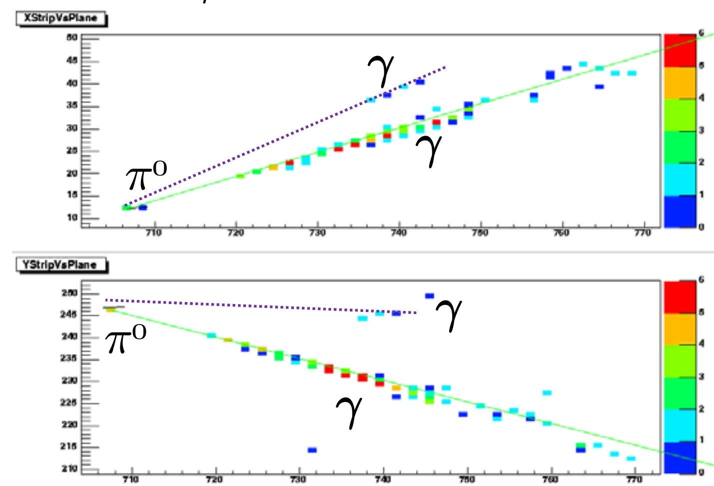
The Advantage of Going Off-Axis

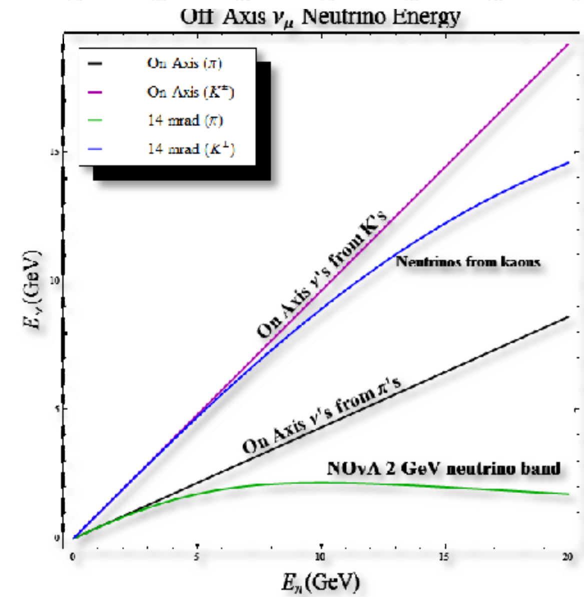
- To Make the ν_e appearance measurement you need to suppress backgrounds
  - Main background for the ν_e CC event topology is a ν_μ NC event with a π^o that is not fully reconstructed
  - Off-axis projection (narrow energy band) suppresses the high energy ν_μ NC tail
  - Other backgrounds are the intrinsic ν_e component of the beam ($K^\pm \to \pi^o e^\pm \nu_e$) which are small (but so is θ_{13}) which get projected off the energy band.
- To improve the θ_{23} disappearance measurement:
  - Significantly reduces the backgrounds from kaons ($K^\pm \to \mu^\pm \nu$) by shifting the neutrino energy to a different band

$$(E_{\nu_\mu})_K = \frac{0.96 E_K}{1+\gamma^2\theta^2}$$

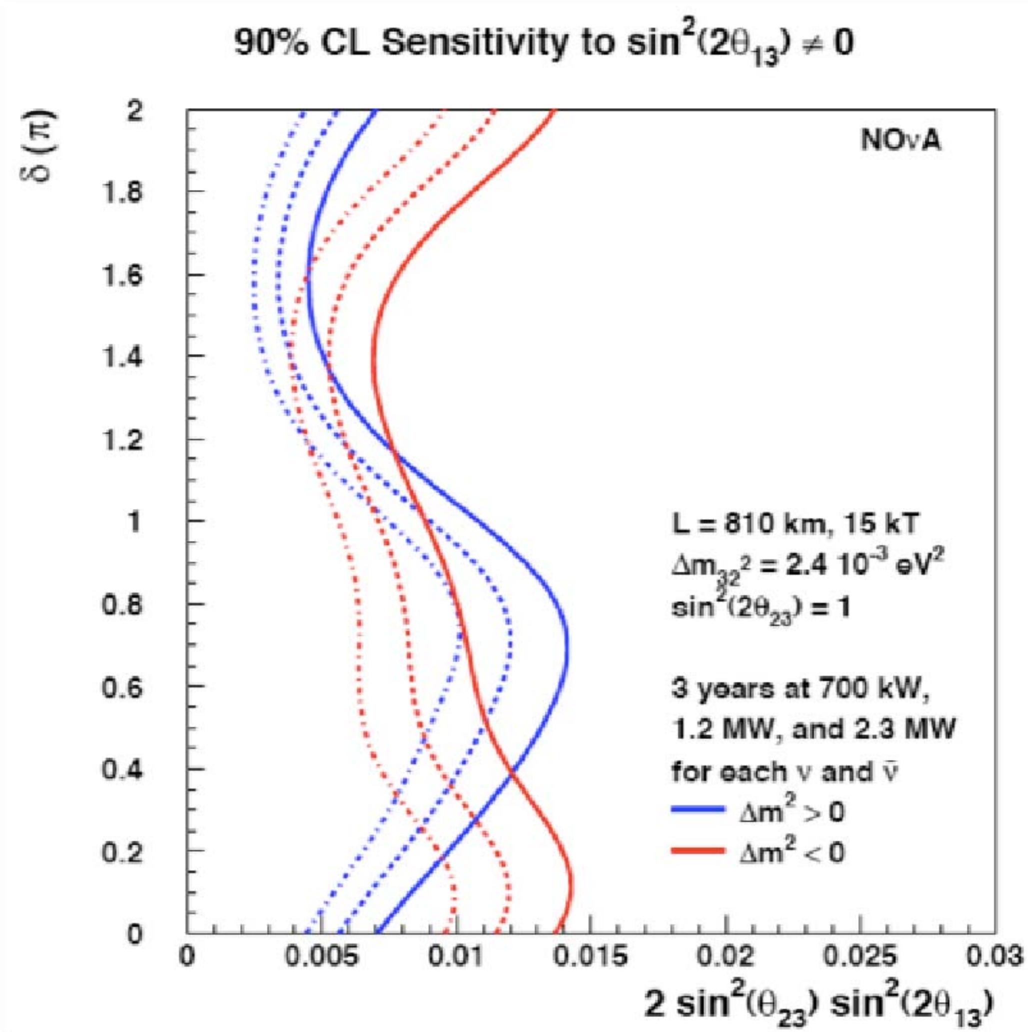
  - Neutrino peak is primarily from π decays
  - Energy spectrum in the signal region becomes almost insensitive to the π/K ratio

ν_μ NC BKG Topology



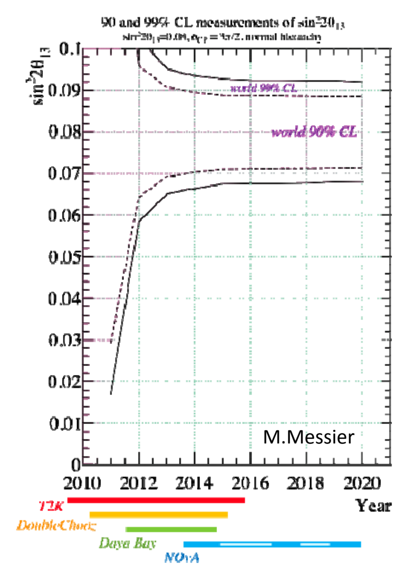


Sensitivity for θ_{13} from $\nu_\mu \rightarrow \nu_e$



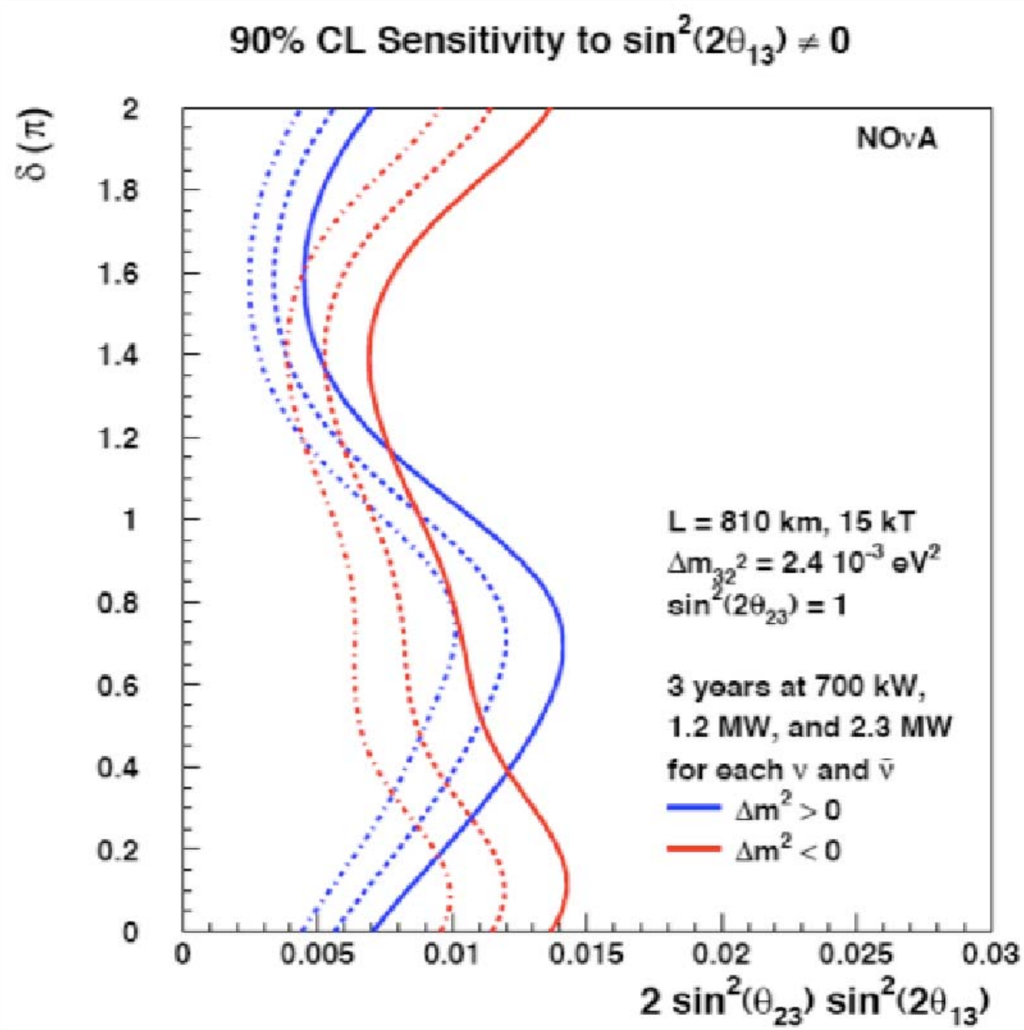
- Target Nova sensitive to electron neutrino appearance $\sim$0.01 at 90% CL

In an kind world θ_{13} is large
(T2K & DoubleChooz observe $\theta_{13} \neq 0$)



This opens up NOvA's access to measuring δ_{CP} and mass hierarchy resolution

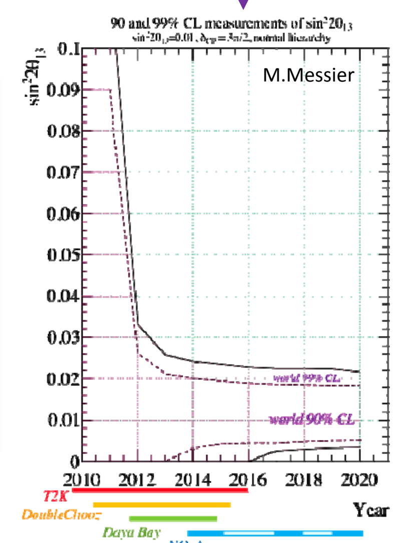
Sensitivity for θ_{13} from $\nu_\mu \rightarrow \nu_e$



- Target Nova sensitive to electron neutrino appearance $\sim$0.01 at 90% CL

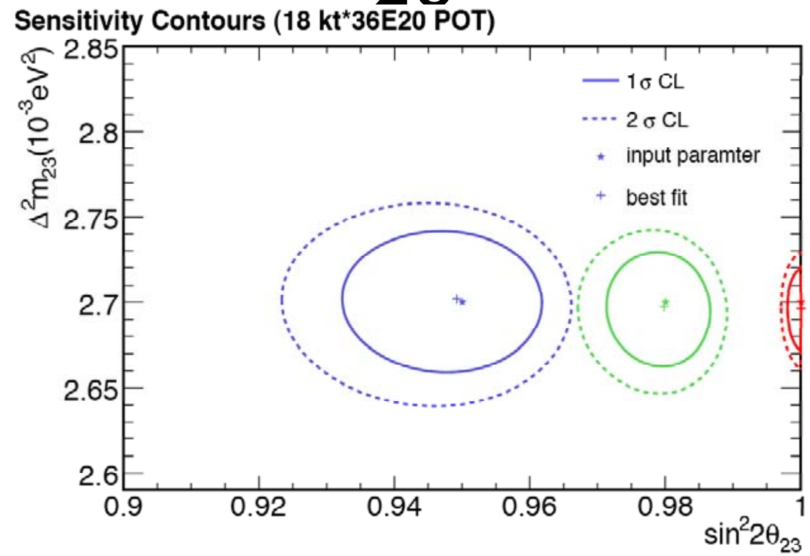
In a cruel world θ_{13} is small

This greatly reduces NOvA's access to δ_{CP} and mass hierarchy resolution

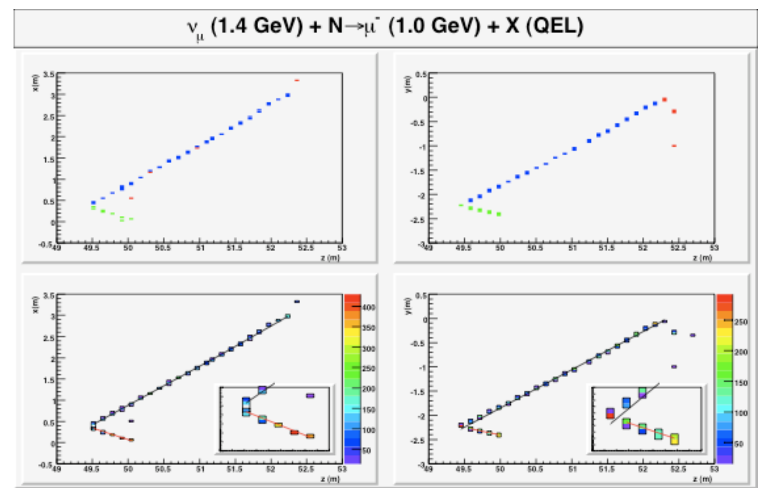


Sensitivity to $\sin^2(2\theta_{23})$

- The detector's energy resolution, allows NOνA to perform the disappearance measurement to 1%
- Typical 2GeV ν_μ CC-quasielastic event has $\sim$120 hit cells (dE/dx $\approx$ 12MeV/plane for MIPP)



- If $\sin^2(2\theta_{23})\neq 1$, we can then resolve the quadrant ($\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$,)
- Measure if ν_3 couples more to ν_μ or ν_τ



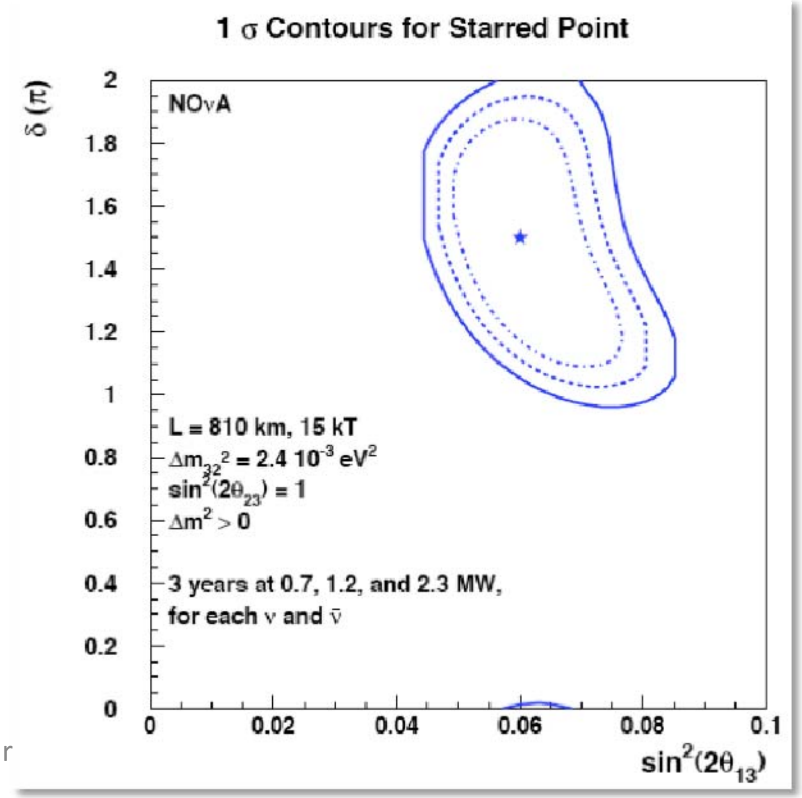
- If $\sin^2(2\theta_{23})=1$ then this is also interesting since it could be hint at a basic symmetry

CP Violation

- The Large Mixing Angle (LMA) solution gives sensitivity to δ_{CP} in the difference between the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions amplitudes.
- In vacuum, the transition probability is shifted with δ where at the first oscillation maximum the shift can be simplified to:

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

- For NOvA to measure δ_{CP} we must first observe a (large enough) non-zero $\nu_\mu \rightarrow \nu_e$ amplitude.
- But in matter, the ultimate sensitivity of NOνA for resolving the CP ambiguities depend on both the value of θ_{13} and δ

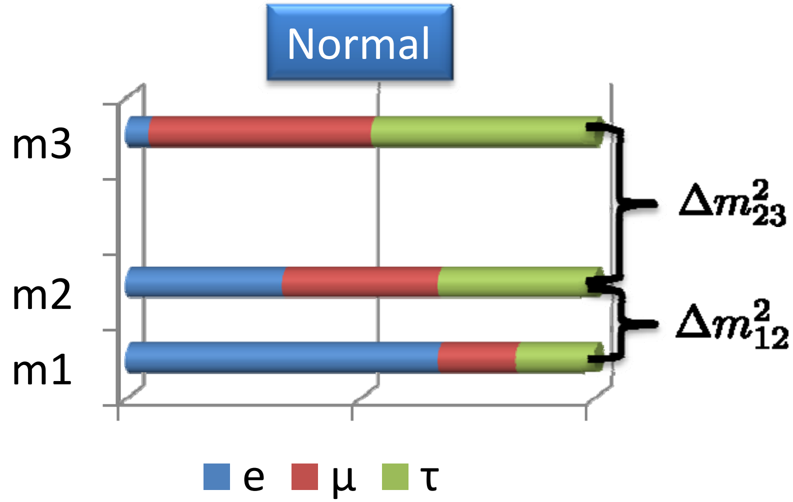


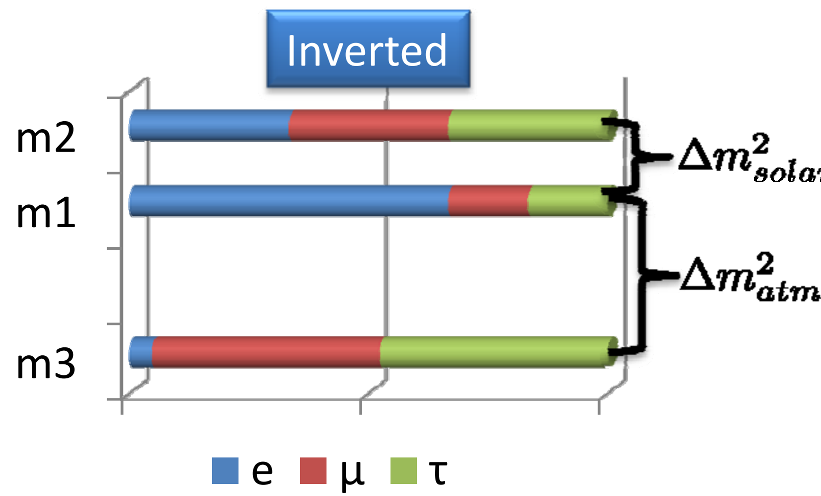
Mass Ordering

- 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



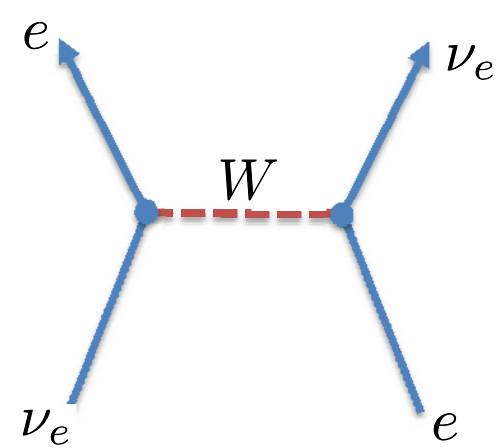


Matter Effect

- 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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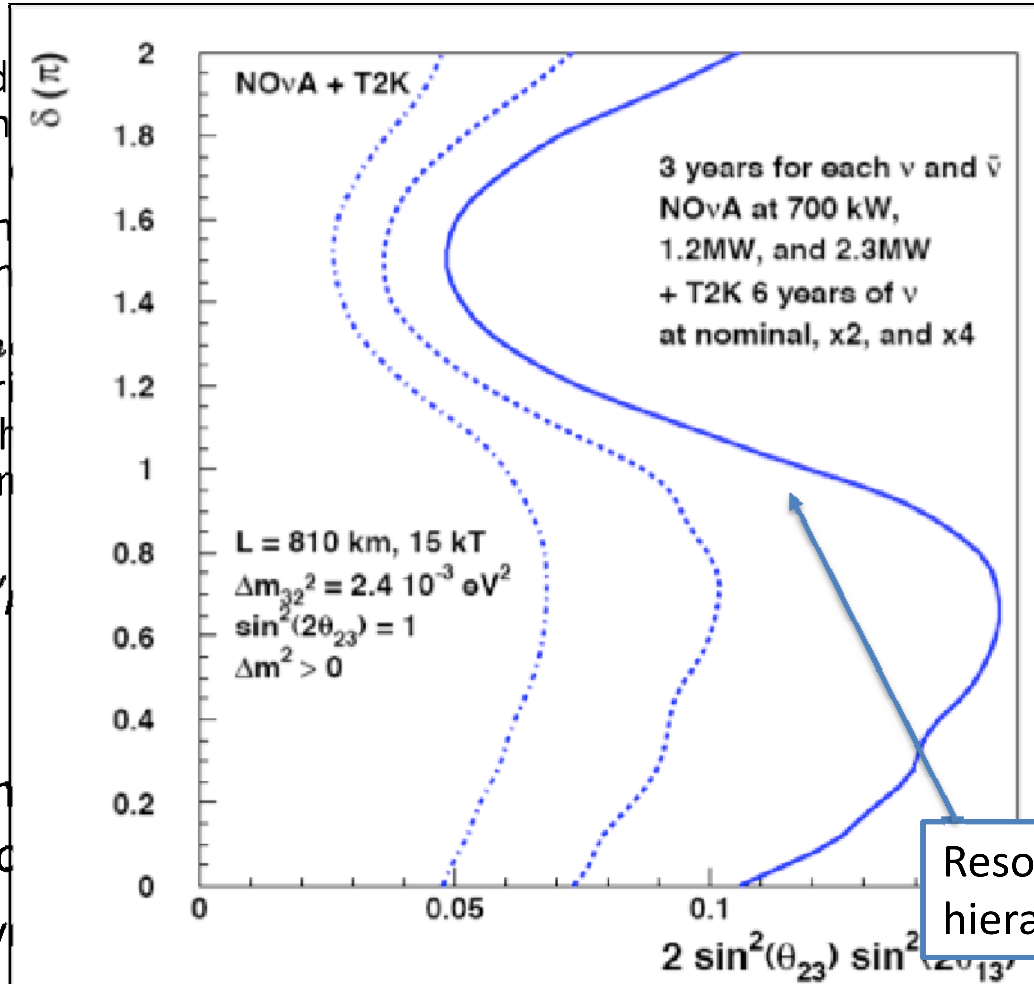

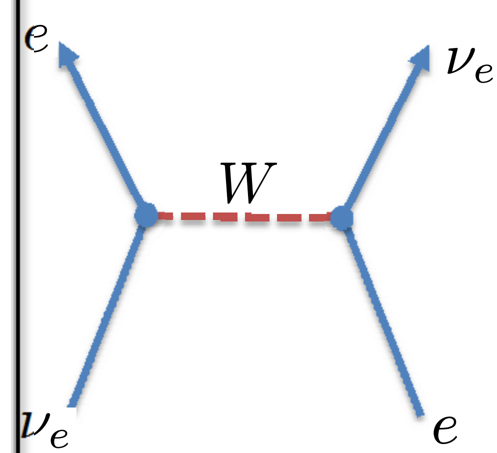

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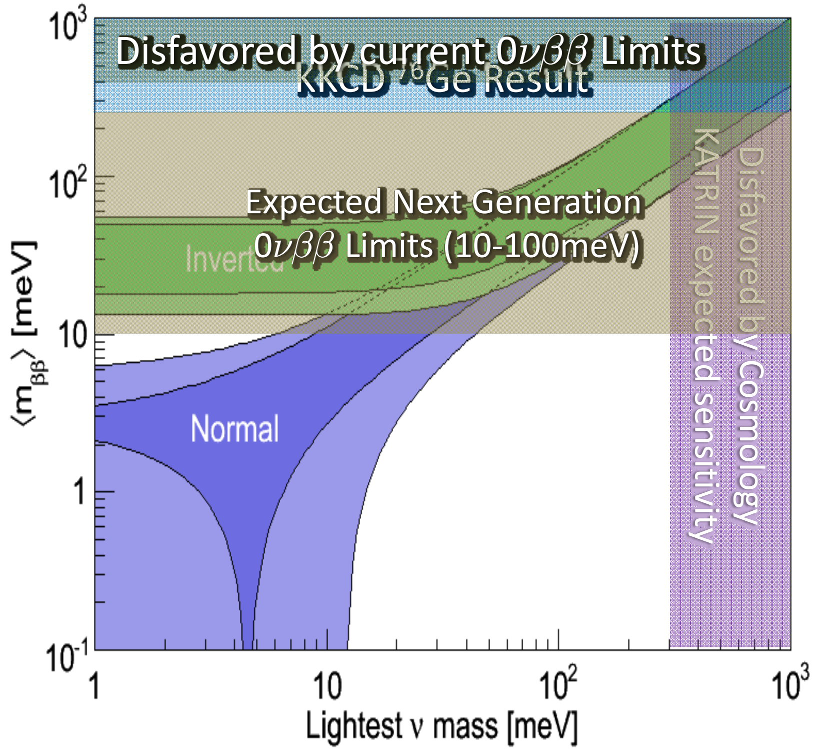
- For the 2 GeV neutrino beam used for NOνA, the matter effect gives a 30% enhancement/suppression in the transition probability.

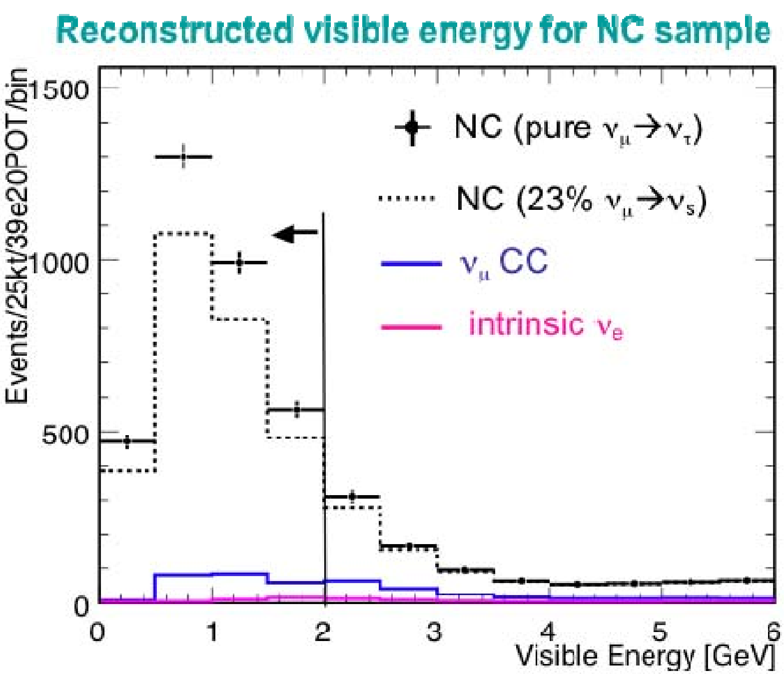
More NOvA Physics

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

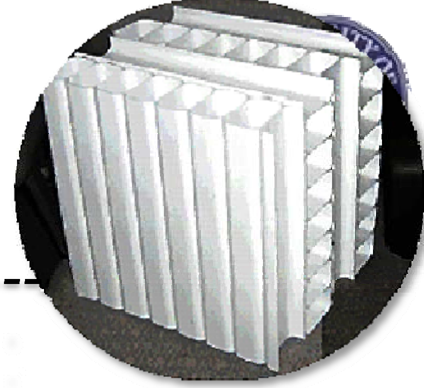


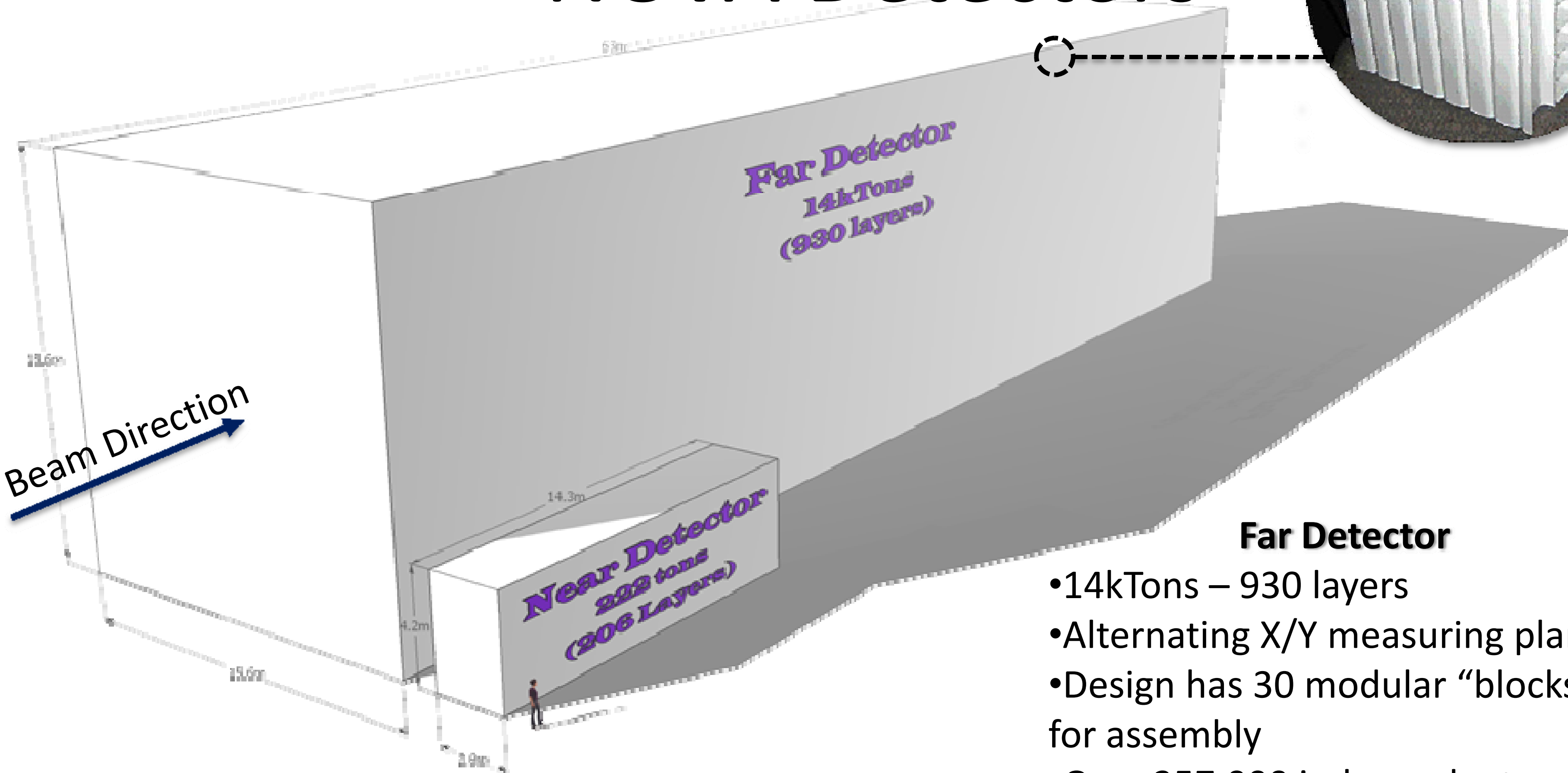
The high granularity of the NOvA detector makes clean measurements of the NC cross sections possible, and allows for Sterile neutrino searches

Design and Physics Parameters

THE NOVA DETECTOR

NOvA Detectors





Near Detector

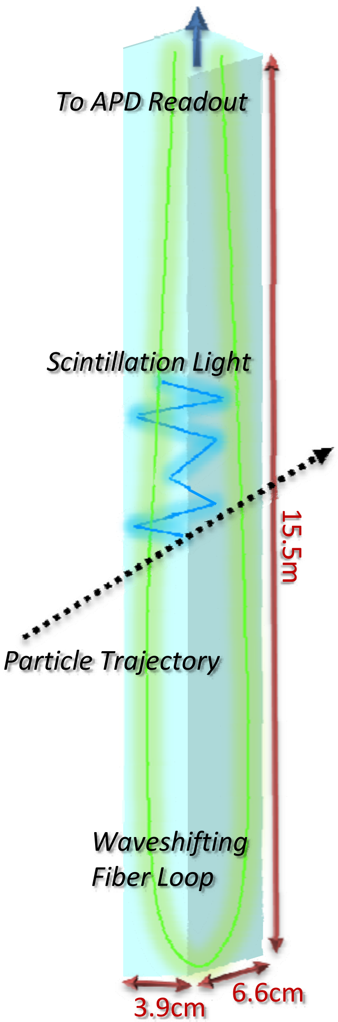
- 222 Tons – 206 layers
- 2 modules wide, six blocks deep
- Includes muon catcher for ranging out μ's
- Located 14mrad off axis in NuMI, next to MINOS cavern

Far 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

Detector Cell

Single Cell



There are 357,120 cells in NOvA

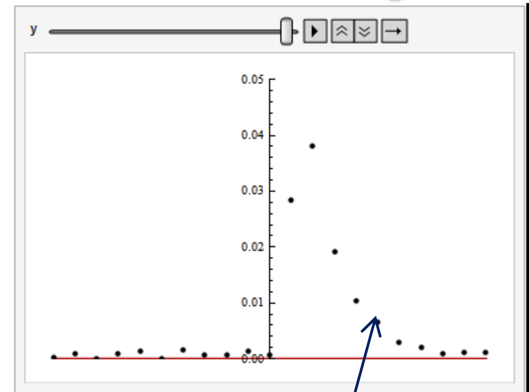
NOνA Detection Cell

- The base detector unit 3.9x6.6cm cell 15.7m long, filled with a mineral oil based liquid scintillator.
- Passage of MIPP through the cell (longitudinal to beam) results in dE/dx $\approx$12.9 MeV across the cell.
  - Roughly 10% of energy loss is in the PVC wall
  - Yields 10-12MeV of deposition in the scint.
- The measured light output is 30-38 p.e. from the far end of the cell into the APD readout
- Light yield gives a minimum Sig/Noise 10:1 (far end)

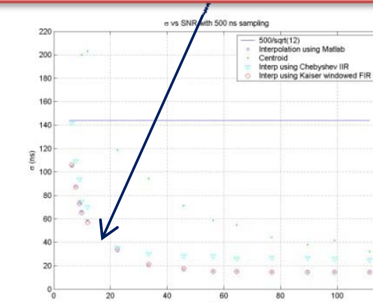
Zero Suppression

- Expected noise (electronic) 300e $\sim$ 3 p.e.
- Continuously digitizes w/ 500ns sampling
- Zero suppress (0.5-0.66) MIPP (15-20pe) depending on final light yields
- Results in a single cell, lower energy detection threshold of 6-8 MeV (far end)

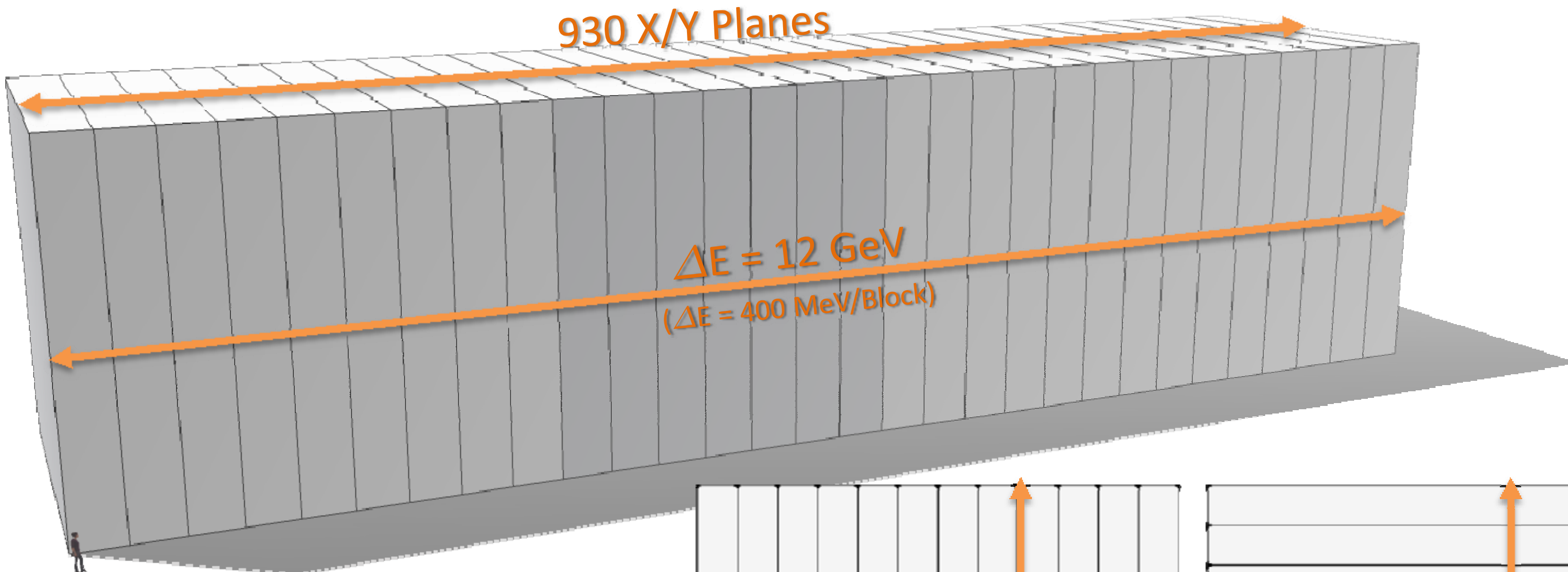
Matched Filtering



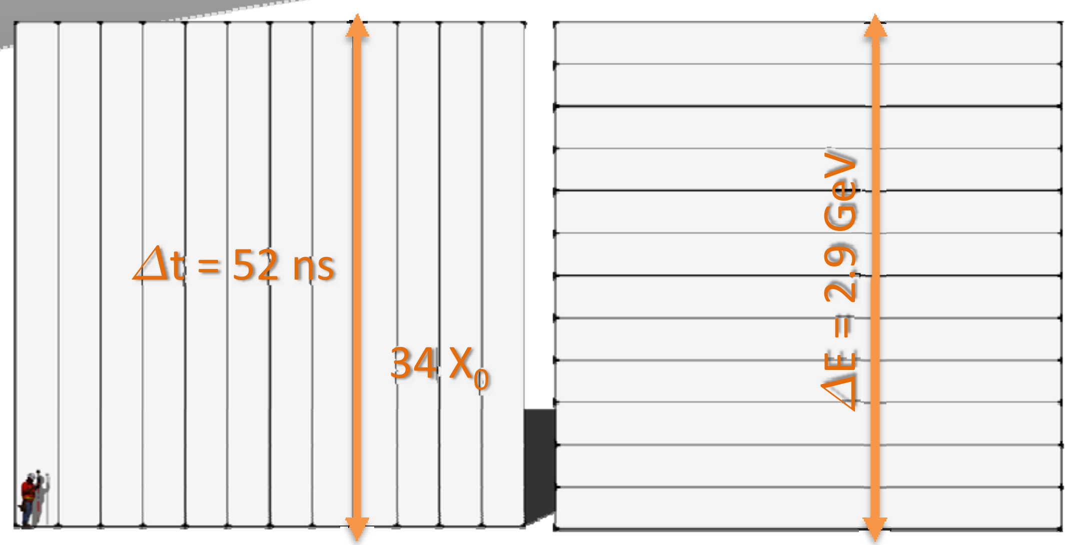
Raw data is matched to ideal response function in the FPGA, to extract pulse height and timing edge.
Timing resolution is a function of Sig/Noise (10:1 min) giving a timing resolution of < 30ns



Muon Range Stack



The detector can be though in the longitudinal direction as a 12GeV high segmented, low Z range stack. In the transverse direction a crossing $\approx$ 3GeV range with up to 384 sampling points



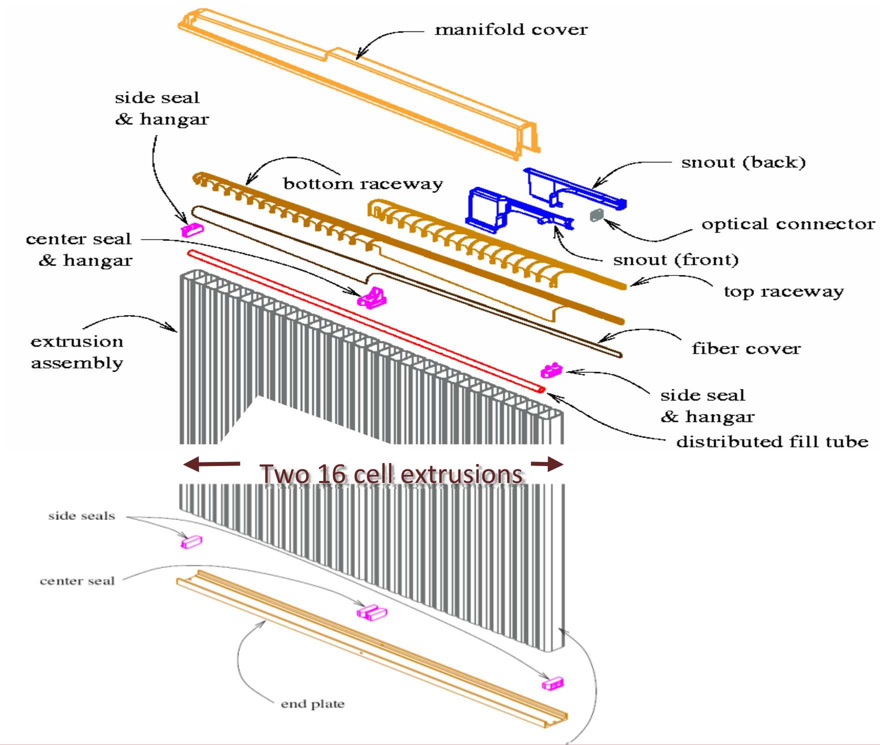
Detector Modules

NOνA Modules

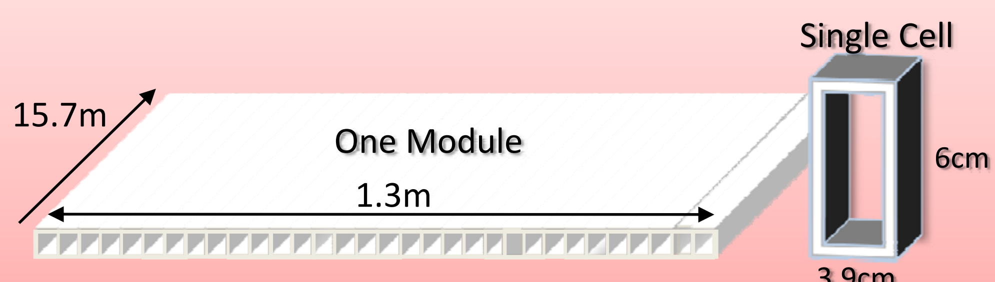
- The NOνA detector module forms the base unit for the detector.
- Each module is made from two 16 cell high reflectivity PVC extrusions bonded into a single 32 cell module
- Includes readout manifold for fiber routing and APD housing

- 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

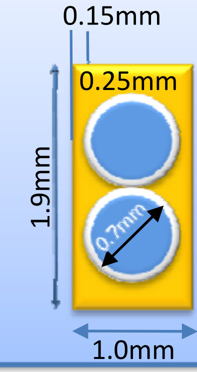
Avalanche Photodiodes – APDs

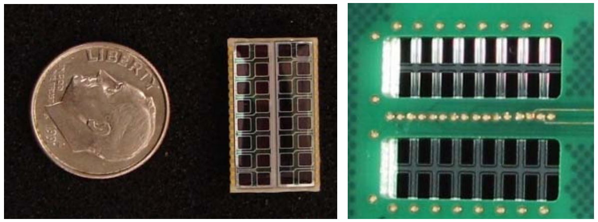
The NOνA Readout

- 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

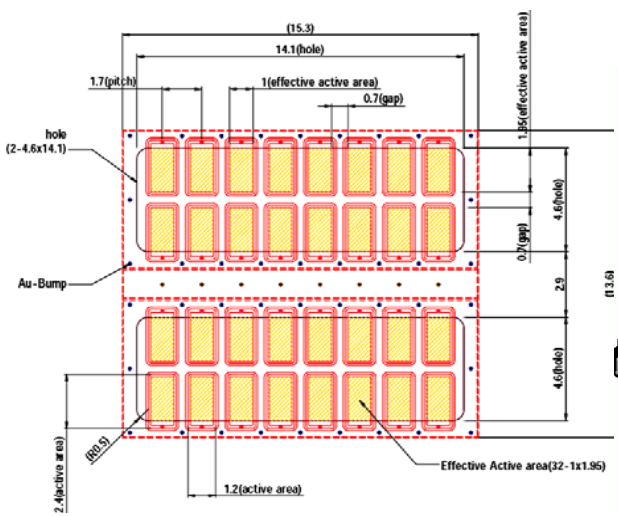
- Operated at gain of 100 for detection of 30-39 photon signal from far end readout
- Signal to noise at far end 10:1

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

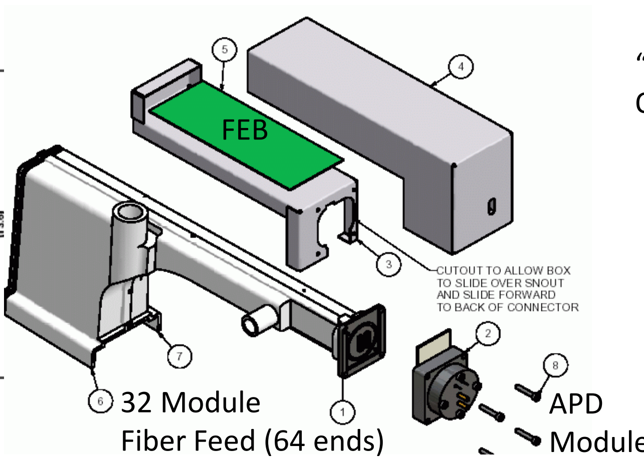




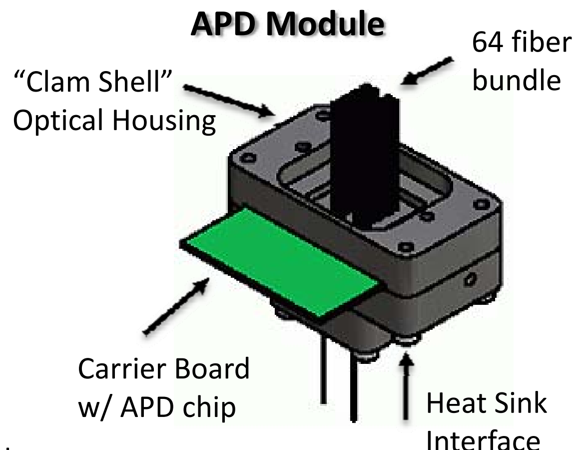
The bare APD is bonded to the carrier board to provide the optical mask and electrical interface



The 32 pixel APD array for the NOνA Readout System



APD Module



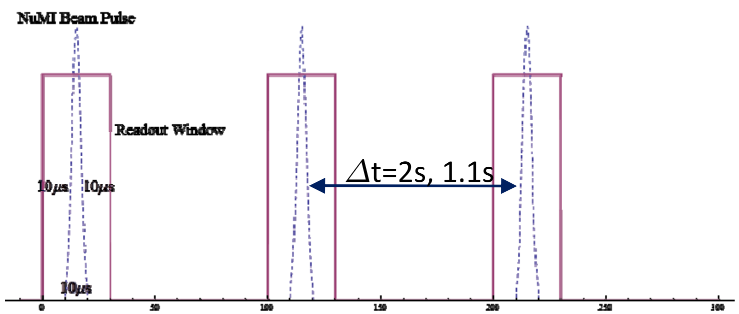
DAQ & Trigger

PHYSICS TRIGGERING

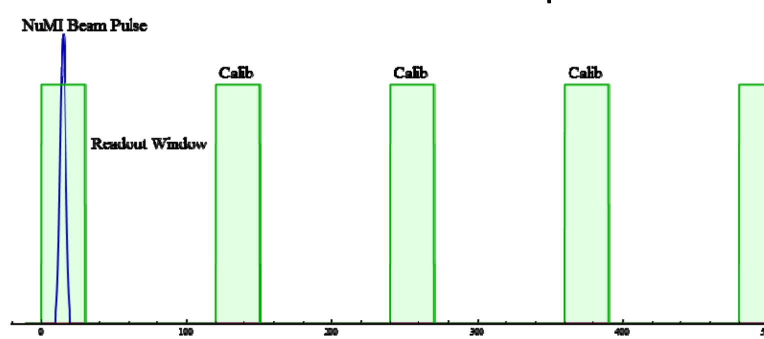
NOvA Core Measurements

- For all of the core NOvA physics topics— $\{\theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2\}$ the only triggers you need are:
  - Beam spill
  - Calibration pulser
- Both of these are completely open zero bias triggers. They impose no restrictions on the data and do not examine the event topologies.

- Beam Spill Trig
  - 30 \mu s window centered on GPS time of NuMI spill at FNAL



- Calibration Pulser
  - Random sampling of 30 μ s windows at 100 $\times$ beam period



Data & Noise Rates

Front End

- Raw single channel hit rate $\sim$ 100 Hz (noise + cosmics μ's)
- But < 30 Hz average noise hit rate per channel
- Rate into each DCM $\sim$ 2 MB/s
- Rate into buffer farm $\sim$ 360 MB/s (738 MB/s peak)

- All 200,000 time windows in a beam spill cycle are extracted to the buffer/trigger farm.

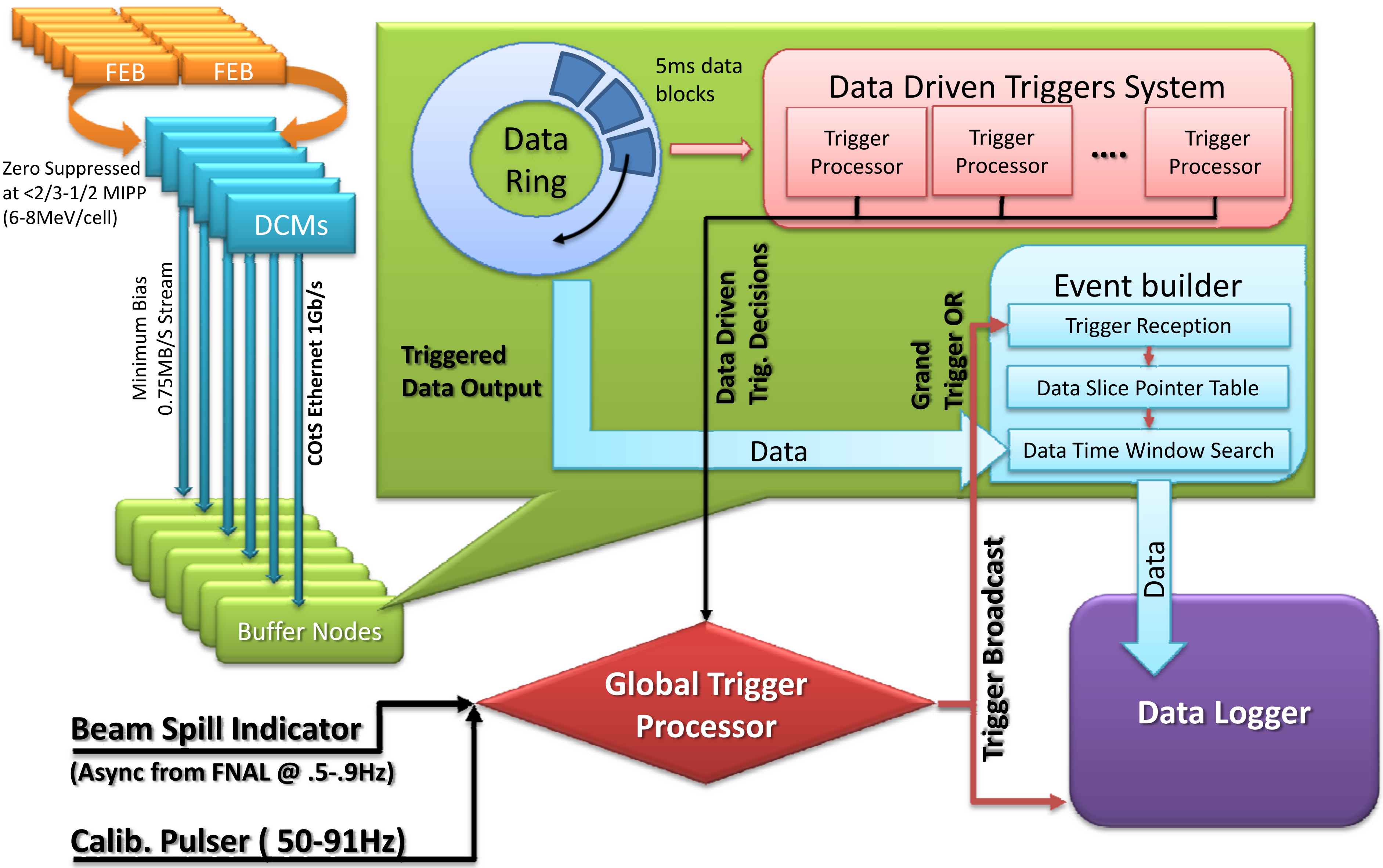
To Tape

- We write 303 of the 200,000 time windows per cycle to tape
  - The rest are lost

- Spill Trigger Data
  - \approx 12-23 kB/s
  - Only \sim 250 Gb/yr
  - 12 kB/s peak rate to storage

- Calibration Data
  - Manditory "Zero Bias" sample
  - 100x the spill window (3ms)
  - 1.1-2.3 MB/spill
  - 12-24 TB/yr

DAQ Data Flow and Triggering

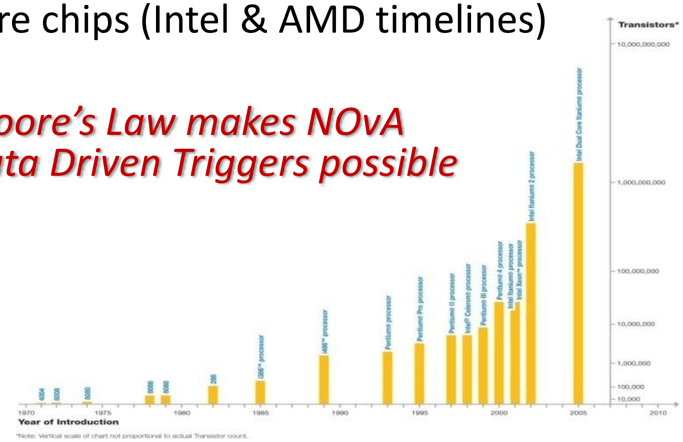


Buffer Farm (Trigger Farm)

- NOvA Uses ≈ 140 commodity class compute nodes as a long duration "buffer" for the raw data
- Number of buffer nodes is network I/O driven
  - With un-buffered switches need almost 1:1 mapping of DCM→BufferNode to handle total data throughput
  - Leads to 3-layer switch array and Round-Robin Data pattern
- Buffer depth is driven by latency for the "spill signal" to transit over the open Internet up to Ashriver
  - *MINOS Lore*: Latency <t>≈600ms, where 99% arrive within 5s (but there's a long tail)
  - Baseline NOvA design assumes maximum latency of 20s

Moore's Law Note:

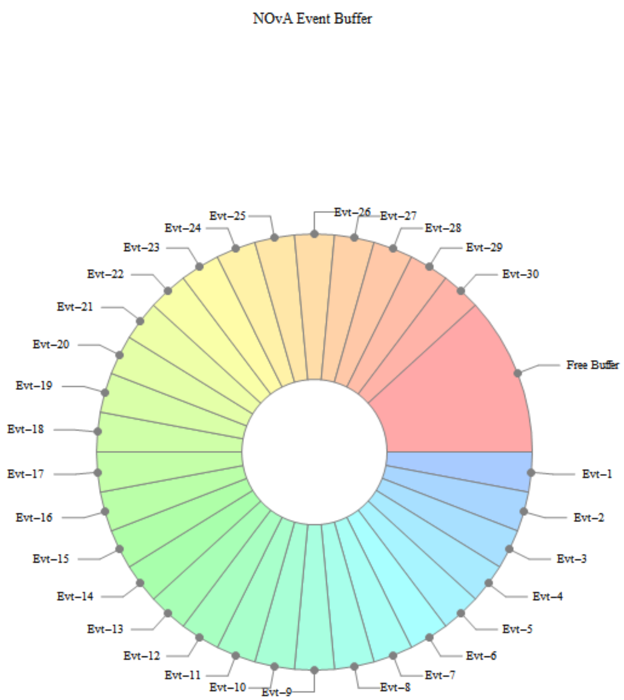
- When the DAQ buffer farm was first spec'd (2005) the first dual core chip was not yet introduced.
- The buffer farm was not envisioned to be able to handle the I/O requirements & derive topology based triggers
- Today the machines that are being bought for 2009/2010 are Dual 6 Core Boxes (12 processor cores per node)
- Projection for 2012 DAQ purchase are 16 core chips (Intel & AMD timelines)
- *Moore's Law makes NOvA Data Driven Triggers possible*



Data Driven Triggering

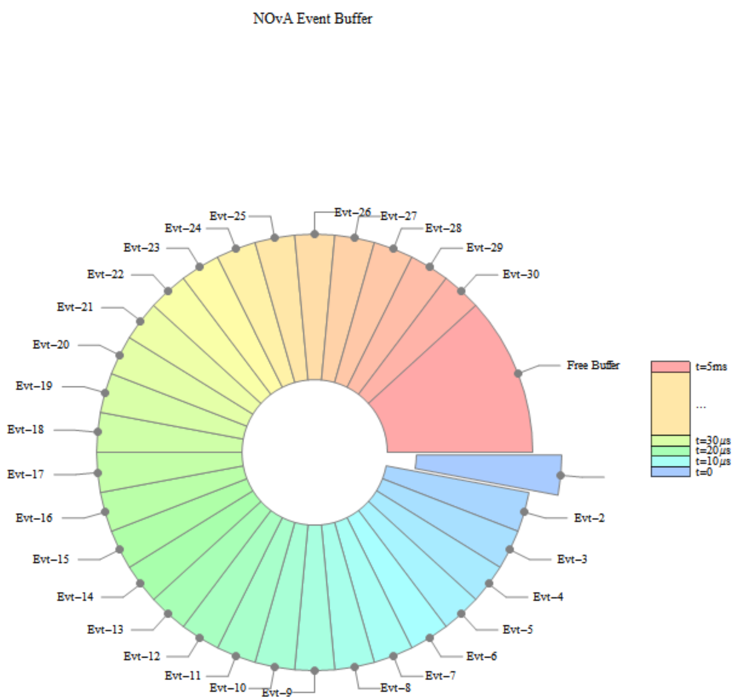
- Motivation:
  - Spill length is only 10μs with a 2s (1.33s) rep. rate.
    - Beam trigger is forced readout without prescale of 30 μs window (beam spill $\pm$ 10 μs buffer)
  - Means the detector is idle almost constantly
  - Total live time/yr $\approx$ 2.6 min
  - Total "beam spill" data rate is only 12-23kb/spill (250Gb/year max)

NOvA Event Buffer



- Each buffer node contains a single circular "Event Buffer"
- The buffer holds *raw* hit data from the entire detector, grouped in 5ms slices
- Buffer Size $\approx$ 30 slices deep (0.15s per node)
  - Gives system wide buffering of 20s of data
  - Actual size is roughly 115MB (30×3.8MB)

NOvA Event Buffer



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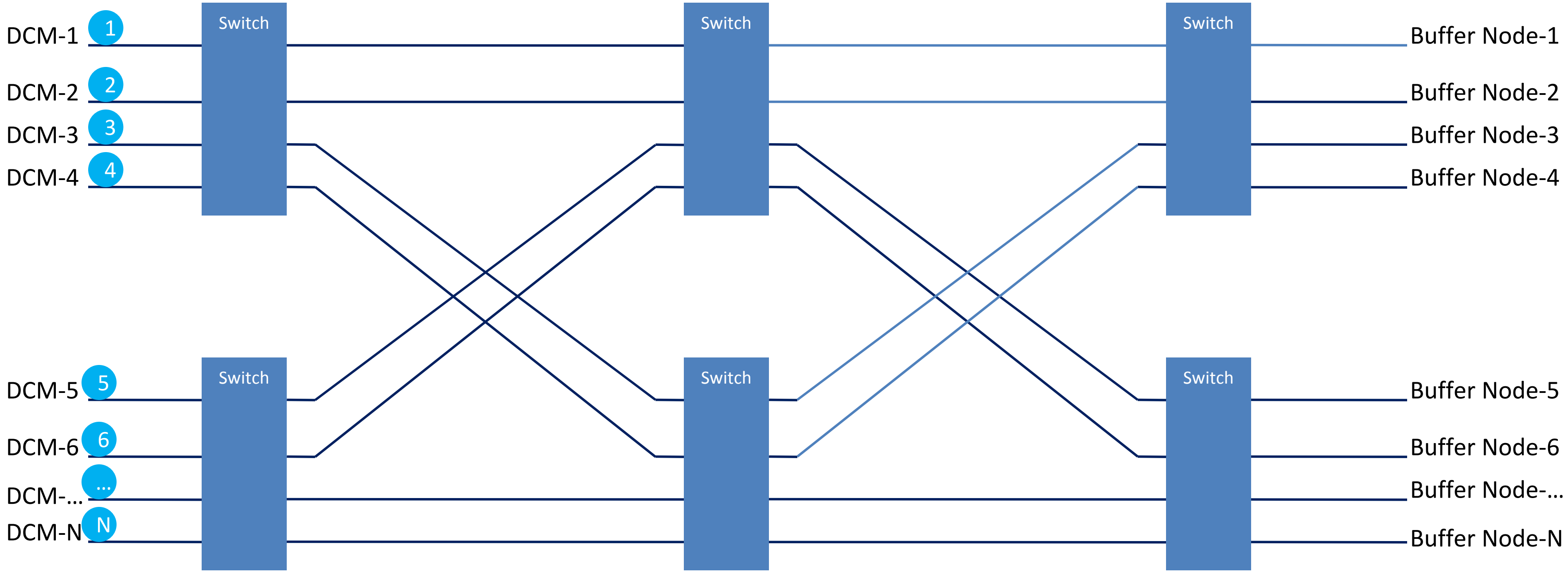
  - Actual size is roughly 115MB (30×3.8MB)

Network Data Routing

The Goal is to get the full data stream from the entire detector, for a given 5ms time slice out of the 180 data concentrator modules and into a single “buffer node” computer in the counting house.

But this is a continuous streamed readout, so there can be no network latency.
A “three layer” switch array is employed that maps equal number of input/output ports across switch layers forming a dedicated path between all start and end points



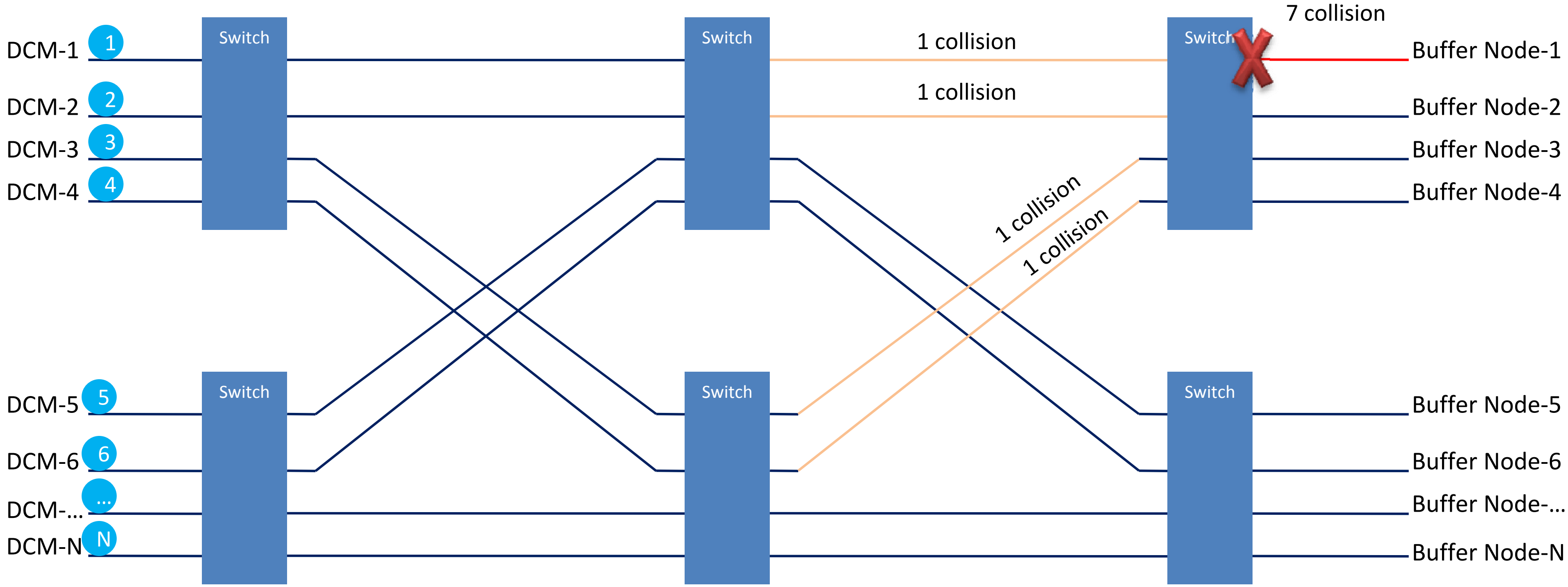
Data Routing

But what really happened:

1. 1 and 2 collided at the output of the 3rd layer switch, causing retransmission of 2
2. Actually 3 4 5 6 … N all had potential collisions at the third layer
3. Additionally 1 & 5 , 2 & 6 , 3 & … , 4 & N collide on the second layer

Each collision causes a delay (random with exponential backoff) and retransmission.

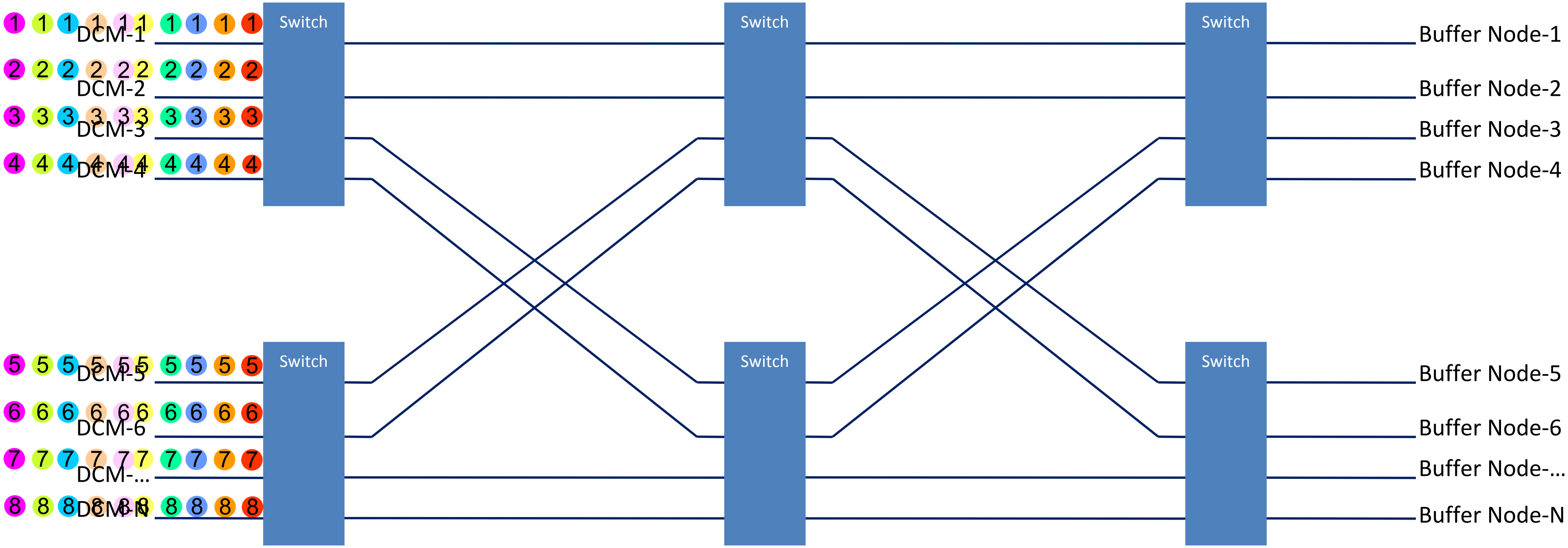
This has the potential to break the DAQ stream



Ethernet Switch Array (Startup)

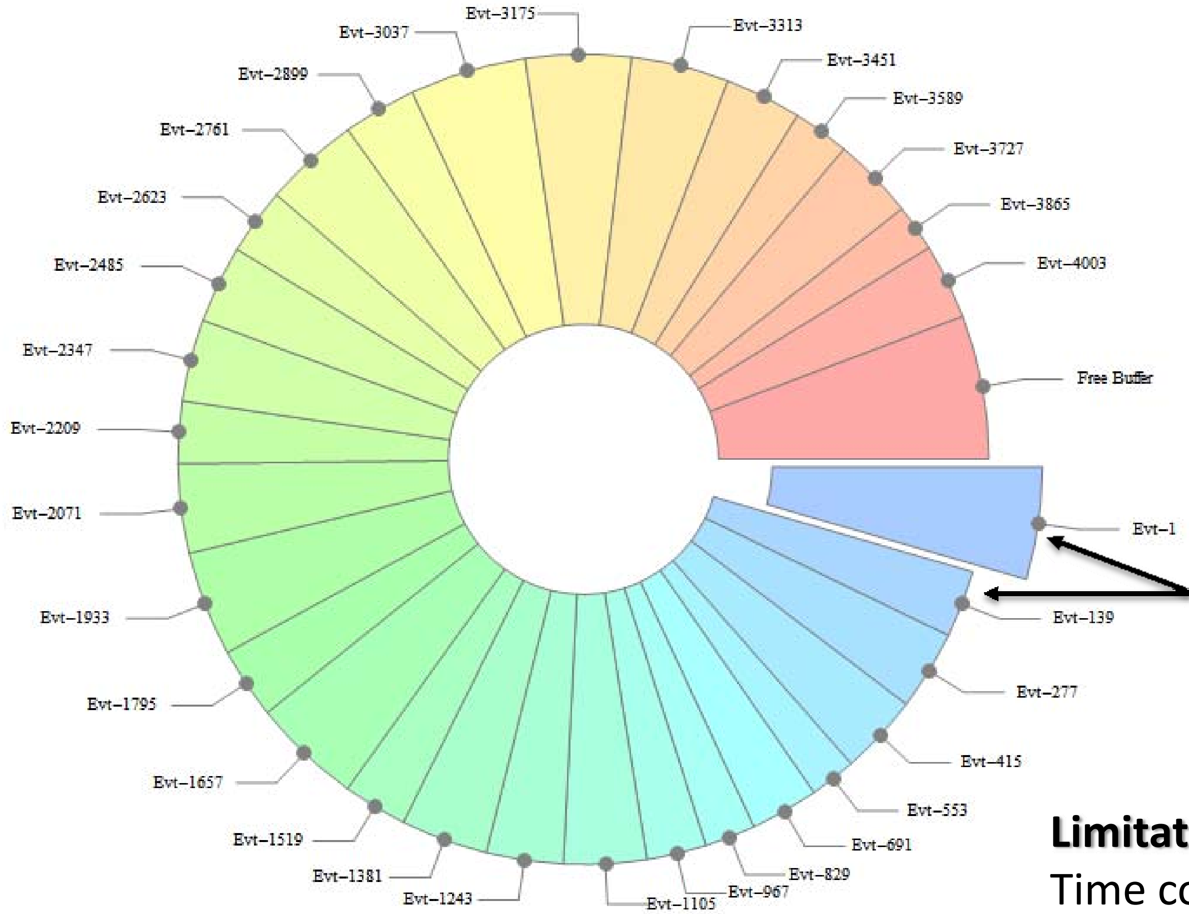
One solution is to "stagger" the transmission of packets out of the Data Concentrators and force each successive time window into a different Buffer Node.
This results in data pattern that is free of collisions and utilizes the full aggregated bandwidth of the three layers.

But….if the staggering becomes de-synchronized, the system is prone to collisions and the time to fill a single node is $N_{buffer} \times t_{slice}$



"Round Robin" Buffering

NOvA Round Robin Event Buffer
(138 Buffer Node Model)



Adjacent time windows are offset by the size of the buffer farm

For 140 node farm this means a 0.7s offset between adjacent slices

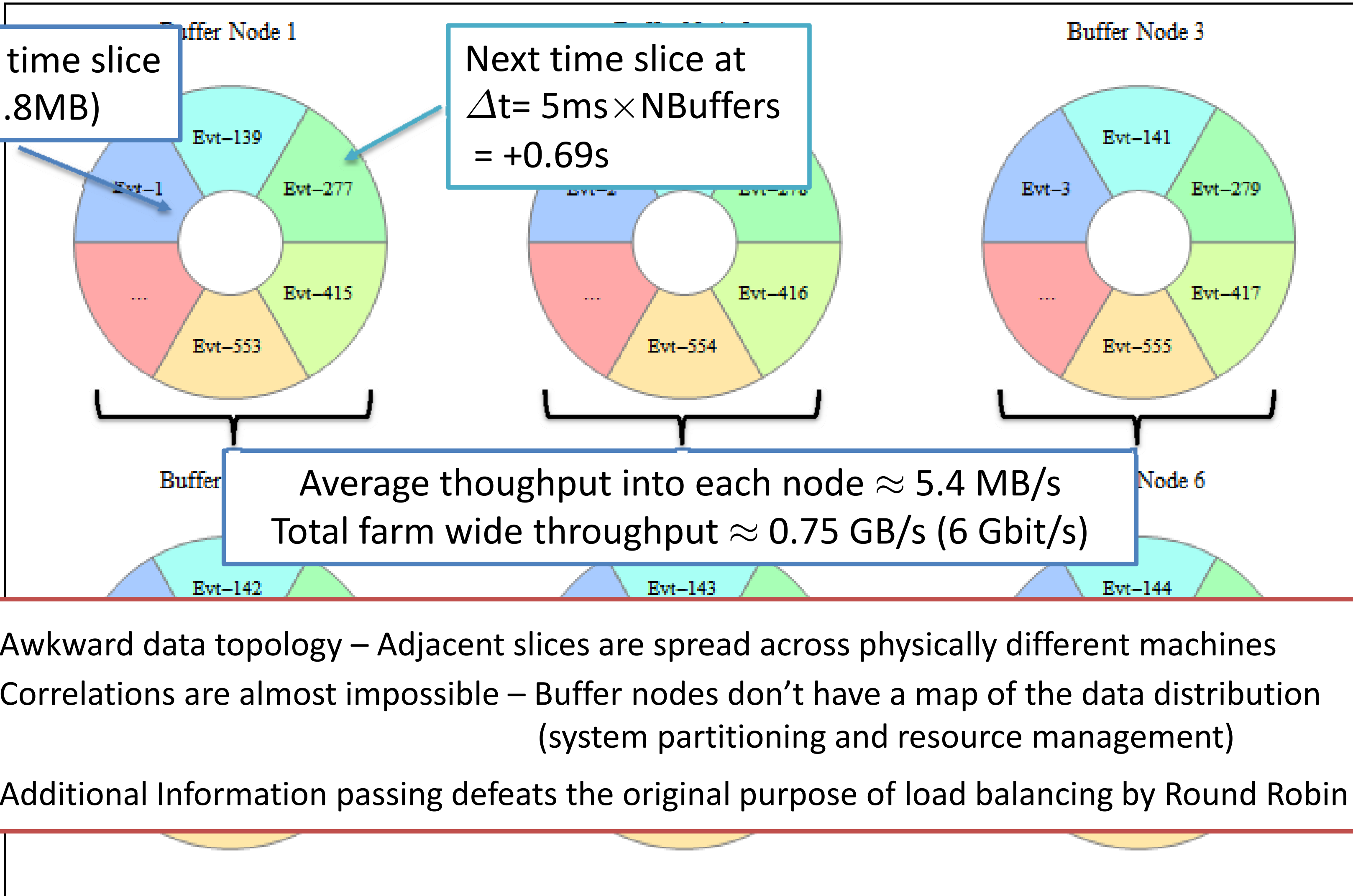
Why Round Robin?

In 2005, commercial off the self network switch technology didn't provide the buffered throughput to accommodate the streaming NOvA data rate out of the Data Concentrator Modules. The solution was to distribute the bandwidth across multiple physical switch/buffer nodes paths. This results in the Round Robin pattern.

Limitation:

Time correlations across MilliSlice windows are difficult. $\Delta t_{ave} \approx 2.5\text{ms}$.

“Round Robin” Buffering



5ms time slice
(≈ 3.8MB)

Next time slice at
$\Delta t = 5\text{ms} \times \text{NBuffers}$
= +0.69s

Average thoughput into each node ≈ 5.4 MB/s
Total farm wide throughput ≈ 0.75 GB/s (6 Gbit/s)

Awkward data topology – Adjacent slices are spread across physically different machines

Correlations are almost impossible – Buffer nodes don’t have a map of the data distribution (system partitioning and resource management)

Additional Information passing defeats the original purpose of load balancing by Round Robin

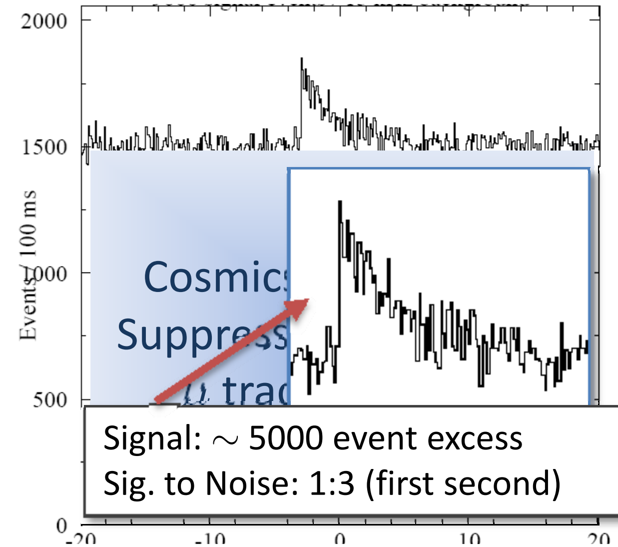
TRIGGER TYPES

SuperNOνA Detection

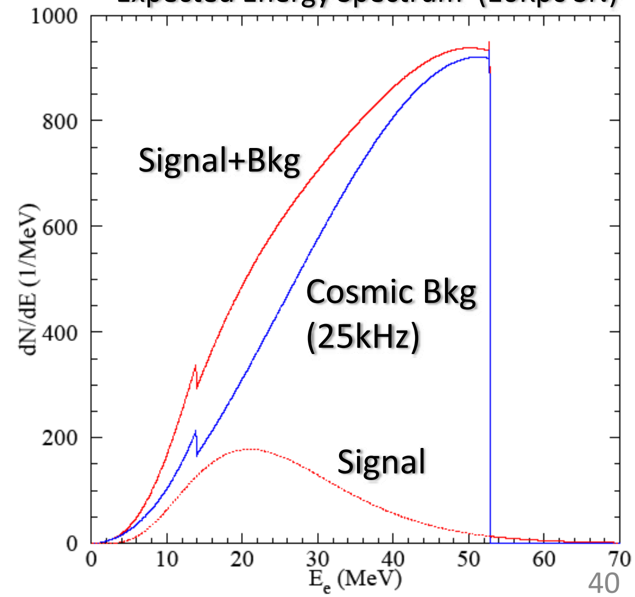
- Primary SuperNOνA Detection Signal is the inverse beta decay reaction:

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

- 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 ($\sim$ 20sec)
  - Time window correlation, merging
- On successful trigger requires a 300 fold spike in rate to tape to dump the entire buffer

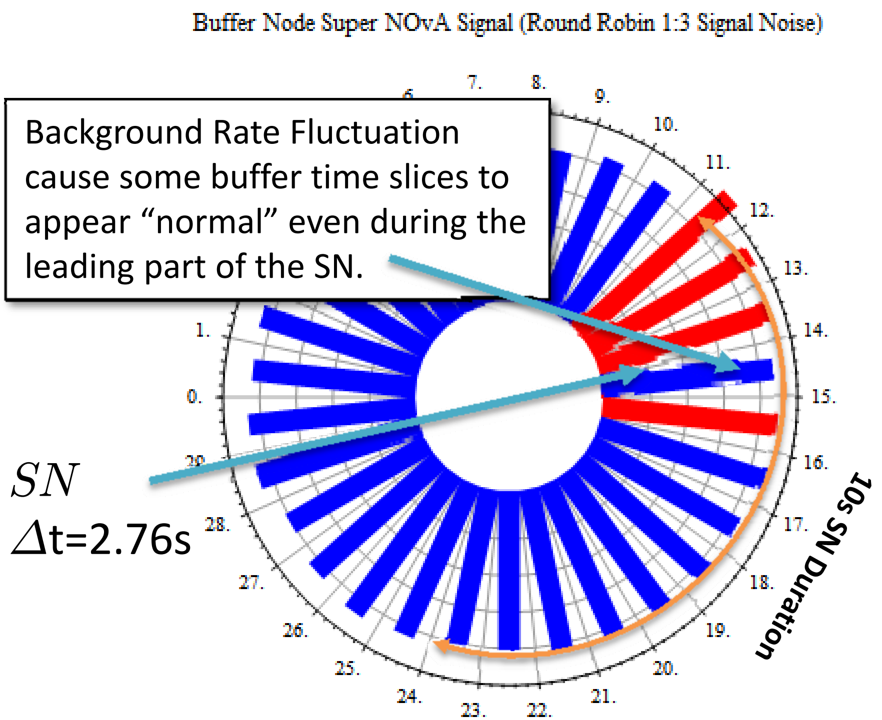


Expected Energy Spectrum (10Kpc SN)

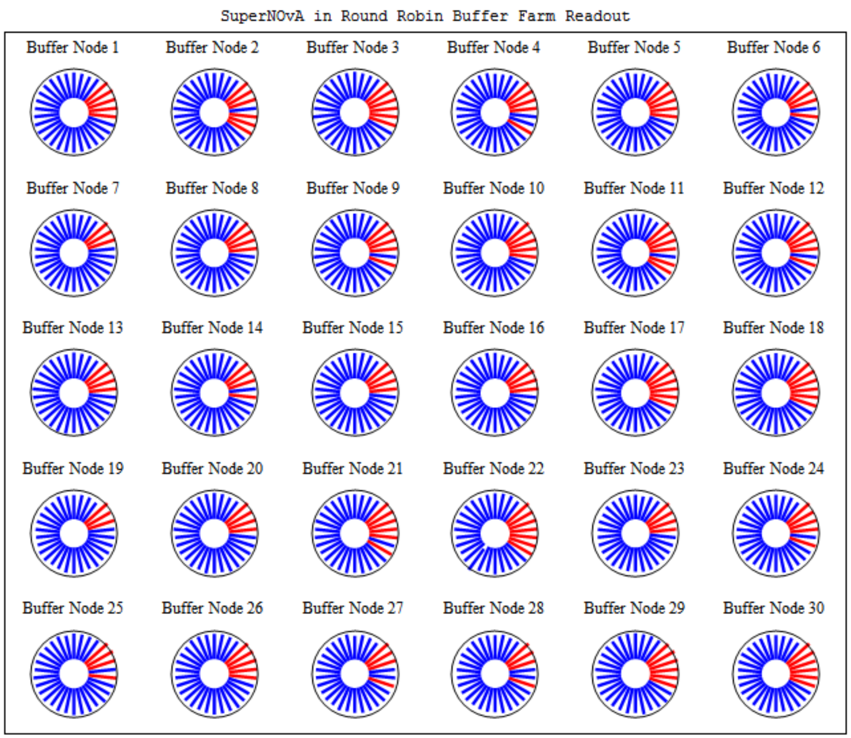


Supernova Detection & Triggering

Round Robin Buffer Farm Topology (138 nodes)



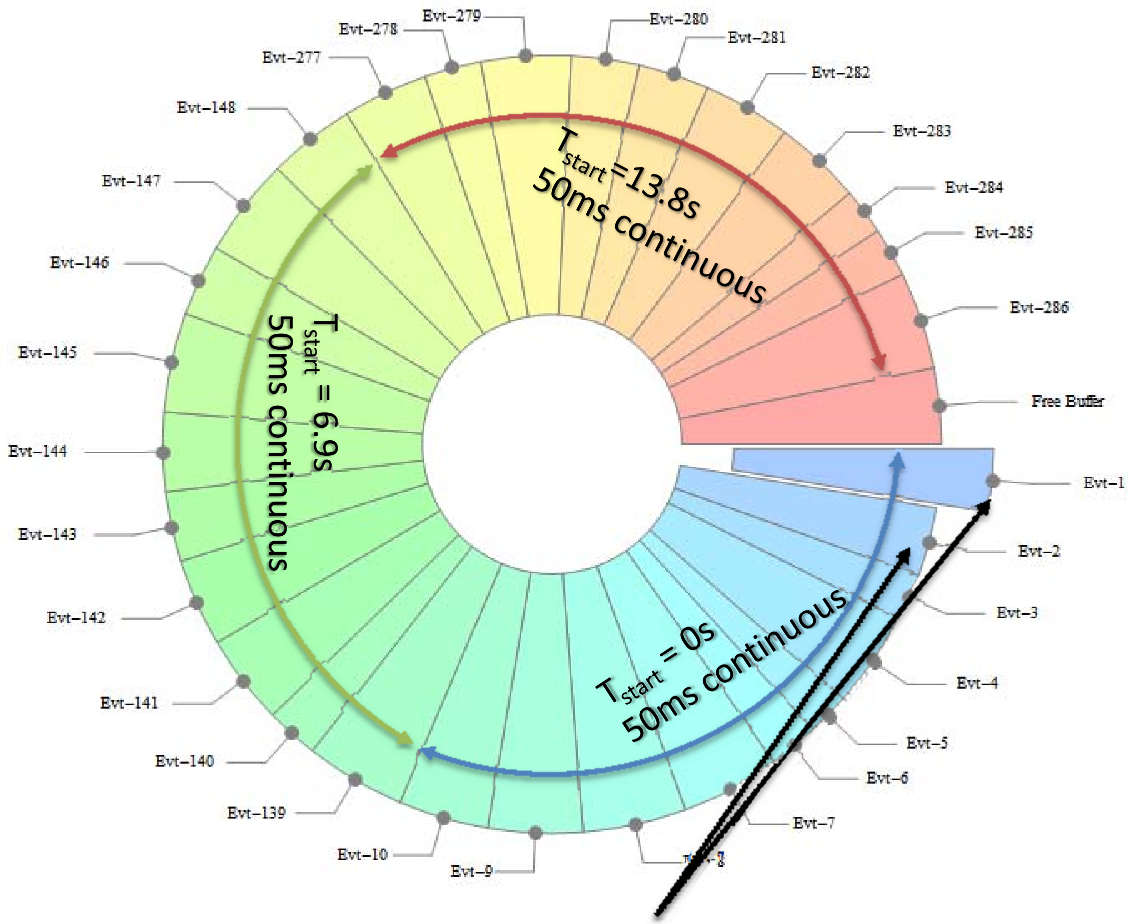
Simulated buffer occupancies assuming SN leading edge at buffer occurred at t=6.9s. Integrated single to noise is assumed at 1:3 in the first 1s. Buffers with: $R/R_{Bkg} \geq 1.1$ coded red.



Buffer Farm Snap Shot

SN Data extends over all buffer nodes (138 different computers)

Serial Buffering



Adjacent data blocks are now continuous in time,

How?

In 2009, serial buffering is possible because network traffic shaping switches are now available with large aggregated bandwidths and deep port buffers.

Advantages:

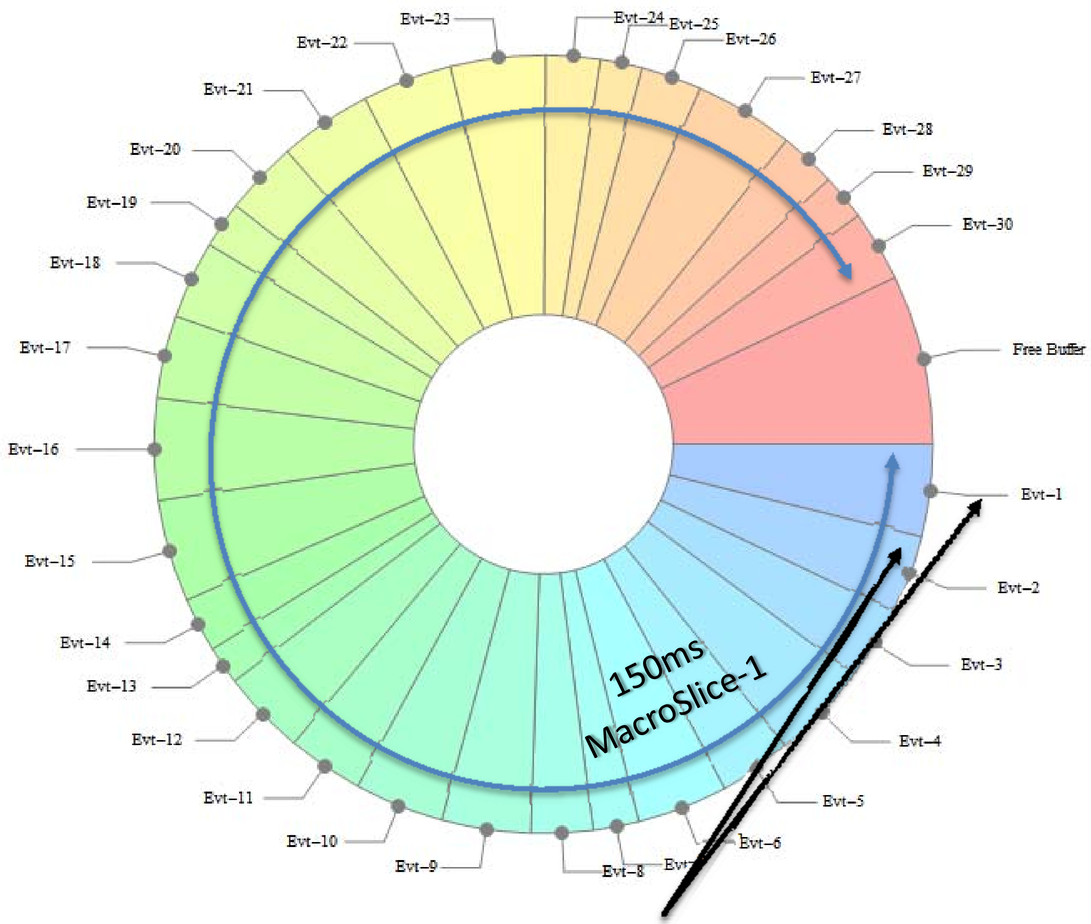
Time correlations across MilliSlice windows are easy. $\Delta t_{max} \approx 150$ms.

Certain physics triggers are more "natural" in this topology, less prone to false positives

No synchronized offsetting of DCM transmission times is required

The a prob of having a spill window straddle buffer nodes drops from $\sim$1.2% to 0.04% for 150ms grouping.

Serial Buffering



Adjacent data blocks are now continuous in time, and MacroSlice can, extend the entire buffer depth

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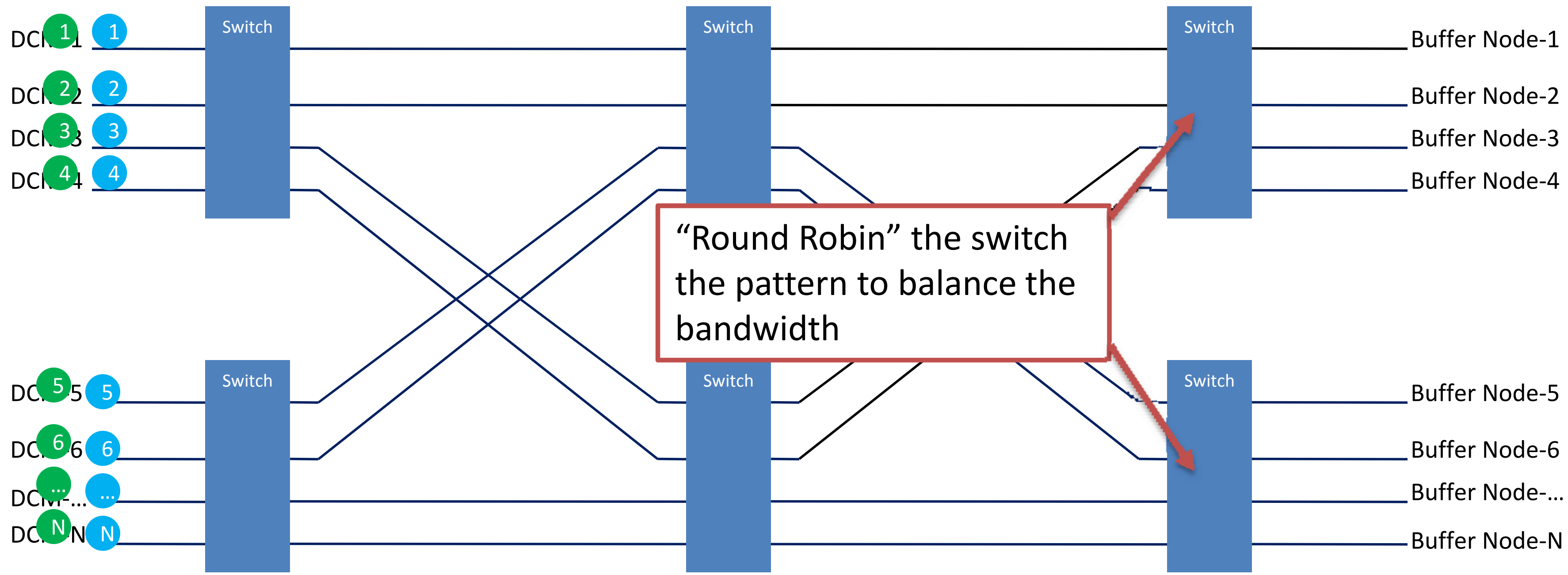
Buffered Data Routing

Matches a 0.15s NOvA data buffer,
With overhead to scale events buffers
comfortably by a factor of 3-4

- Collisions prevented by switch buffer
- Efficient high bandwidth "stream" to node with beneficial data topology

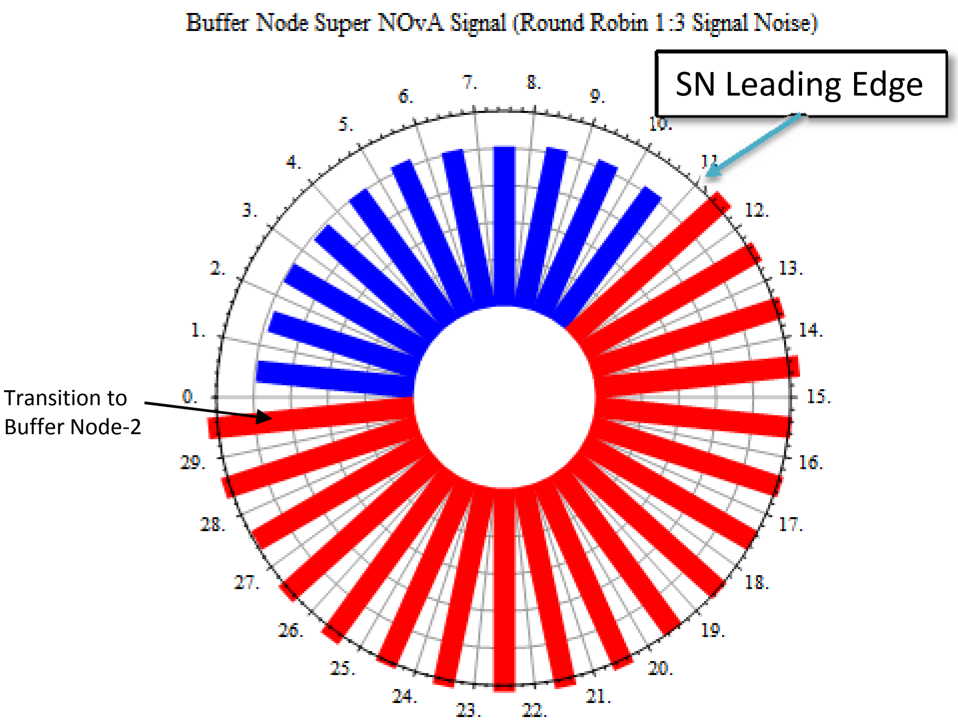
Modern Buffered Switches

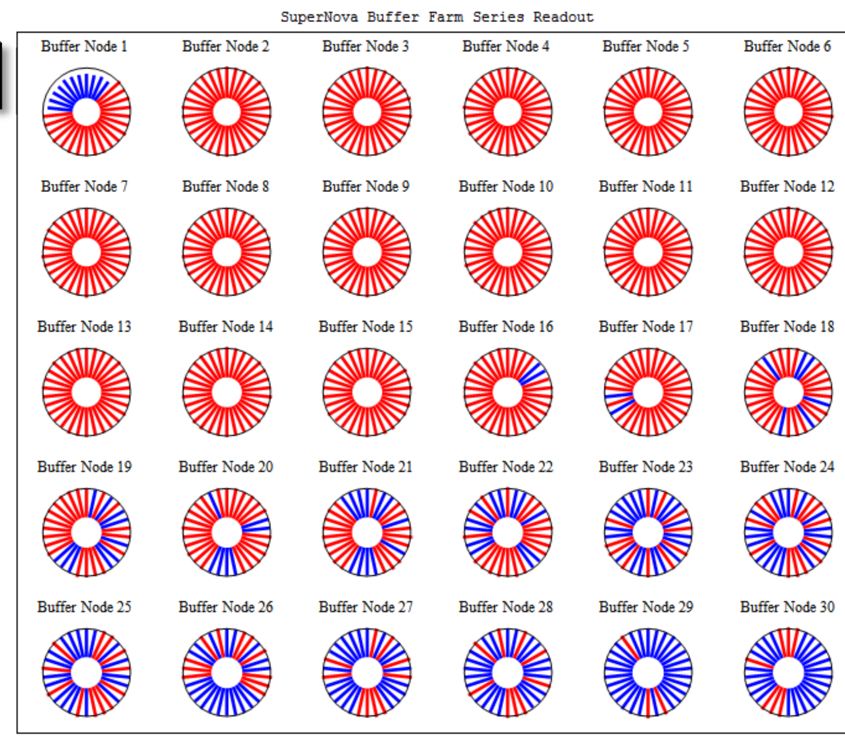
- Designed to handle and shape "burst data patterns"
- Internal 510mb-1Gb data buffer
- Aggregated bandwidths > 320Gbs



Supernova Detection & Triggering

Serial Buffer Farm Topology (138 nodes)



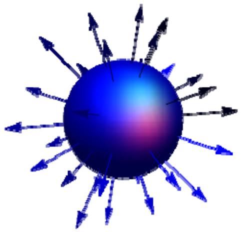


Simulated buffer occupancies assuming SN leading edge at buffer occurred at t=0.05s. Integrated single to noise is assumed at 1:3 in the first 1s.

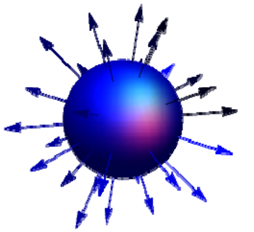
Buffers with: $R/R_{Bkg} \geq 1.1$ coded red.

Buffer Farm Snap Shot

- SN Data extends over 68 sequential nodes.
- Strong triggering signal is first 3rd



Exotic Topologies: Magnetic Monopoles



Properties

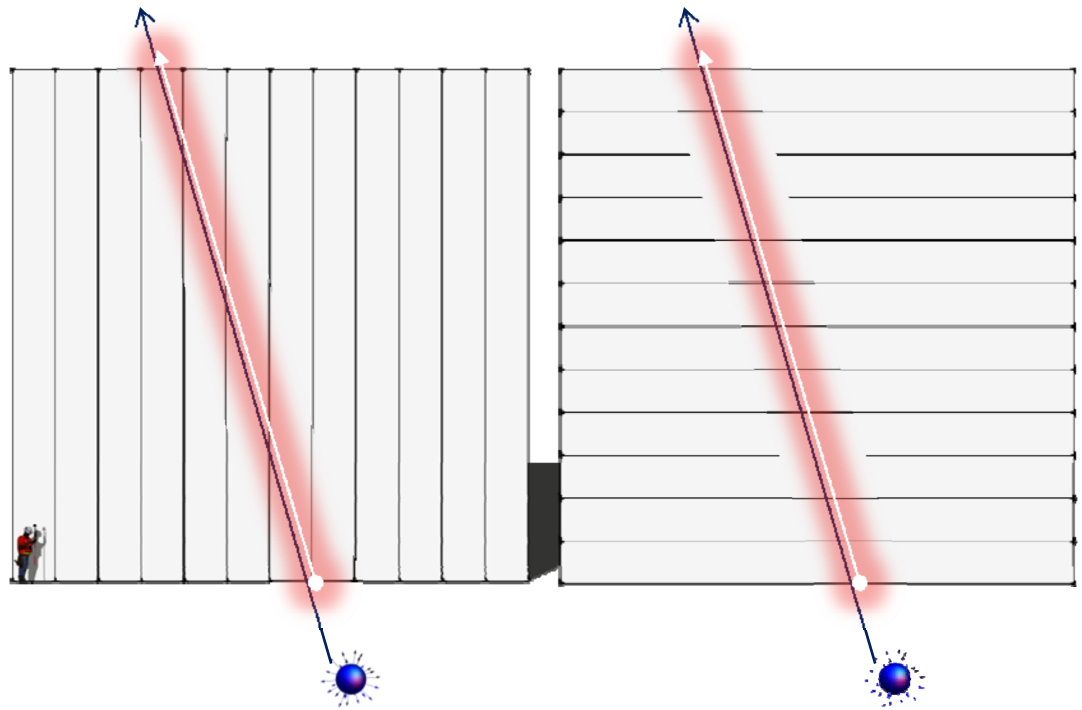
- Natural result of grand unified gauge theories
- GUTs predictions for:
  - Super-massive point like objects $m \sim 10^{17}$ GeV/c^2
- Wide Velocity range
  - Galactic Bound $v \simeq 10^{-3}$ c
  - Solar Bound $v \simeq 10^{-5}$ c
  - Earth Bound $v \simeq 10^{-6}$ c

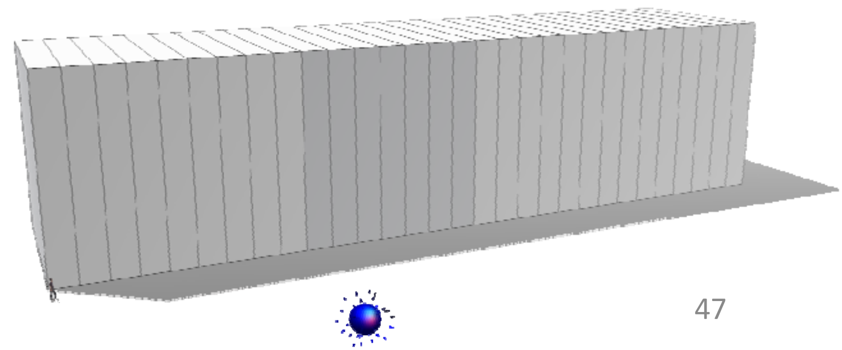
Upper Limits

- Parker Bound
  - Required so that MM do not "short circuit" galactic field faster than galactic dynamo-regeneration mechanism
  - $O(10^{-15})$ cm^{-2} s^{-1} sr^{-1}
- Extended Parker Bound
  - 1.2×10^{-16} cm^{-2} s^{-1} sr^{-1}
- Current Limit from MACRO
  - 1.4×10^{-16} cm^{-2} s^{-1} sr^{-1}
  - Mass/Velocity Dependent

Magnetic Monopole Signature

- Extremely slow, highly ionizing, highly penetrating track, traversing the detector volume.
- Leave distinct signature in either $\perp$ or $\|$ orientation
- Transit times:
  - Transverse
    - $\beta = 10^{-3}c$, $\Delta t \approx 52\mu s$
    - $\beta = 10^{-4}c$, $\Delta t \approx 520\mu s$
    - $\beta = 10^{-5}c$, $\Delta t \approx 5$ ms
  - Longitudinal
    - $\beta = 10^{-3}c$, $\Delta t \approx 225\mu s$
    - $\beta = 10^{-4}c$, $\Delta t \approx 2.2$ ms
    - $\beta = 10^{-5}c$, $\Delta t \approx 22$ ms
- These times are well matched to NOvA's detector geometry and readout
  - Even with a $\beta = 10^{-1}$ you would expect a transverse transit of >500 ns across 350+ cells each with 30ns timing resolution





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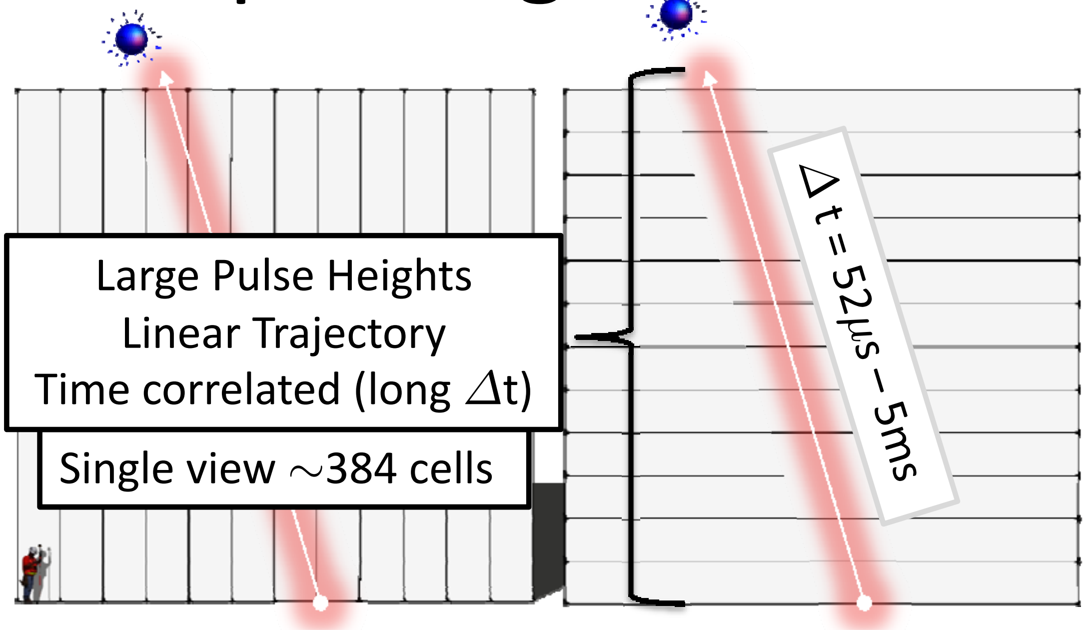
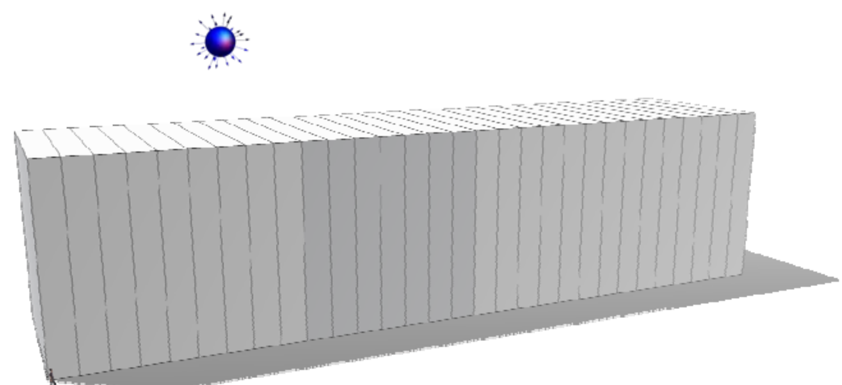
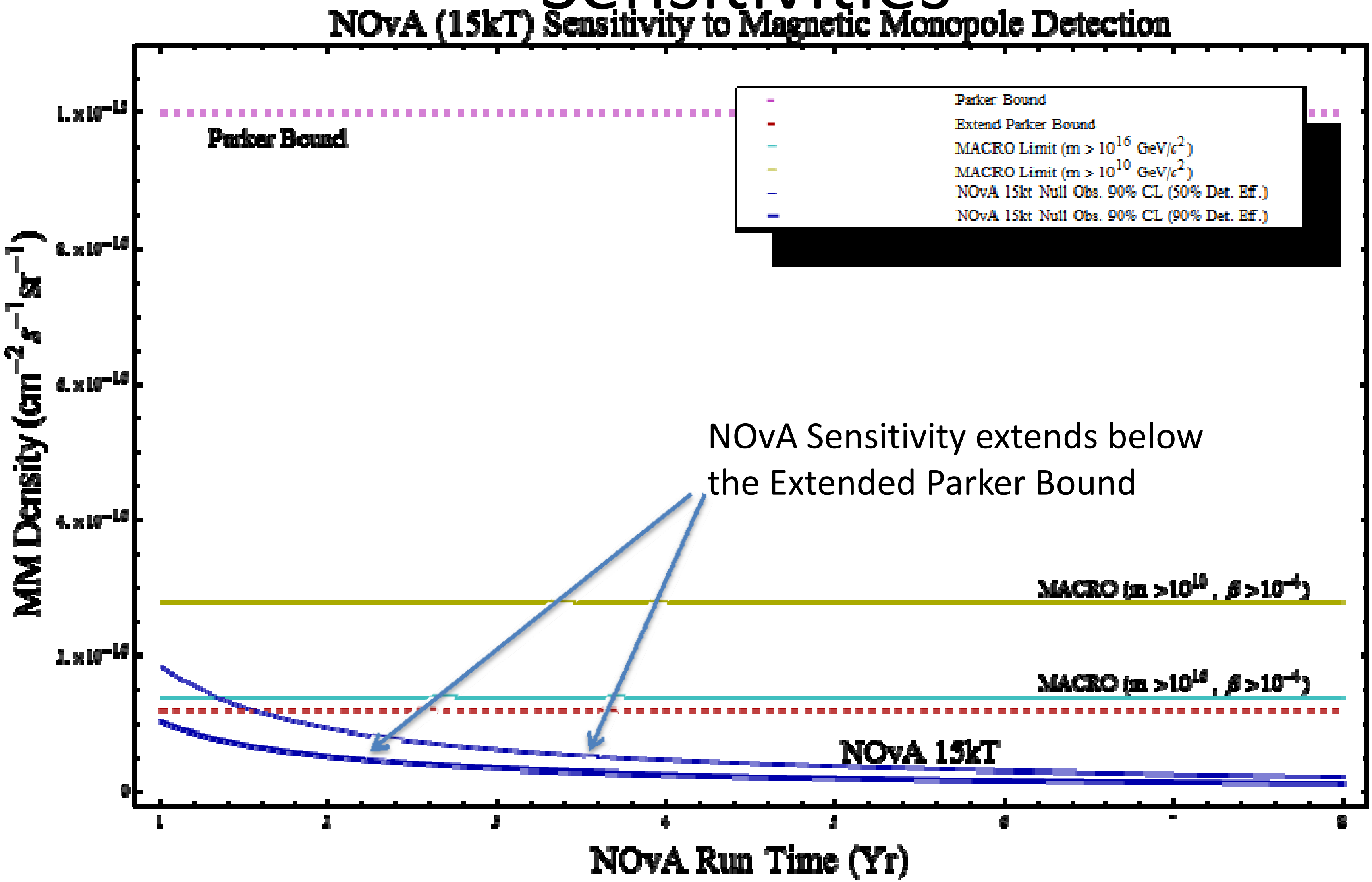




Monopole Triggering

- The "rare" nature of having a monopole cross the detector requires a data driven trigger
- Without a trigger NOvA's sensitivity reaches at most $\sim 2.3\times10^{-14}$ cm^{-2} s^{-1} sr^{-1}
- But…with a simple trigger –
  linear tracking, Δ timing, dE/dx
  - NOvA can push below the Extended Parker Bound
  - And can cover a wider range in MM $\beta = (10^{-1} - 10^{-5})$ than previous results
- A 100% efficient NOvA detector would reach 1.5×10^{-17} cm^{-2} s^{-1} sr^{-1} over six years of running

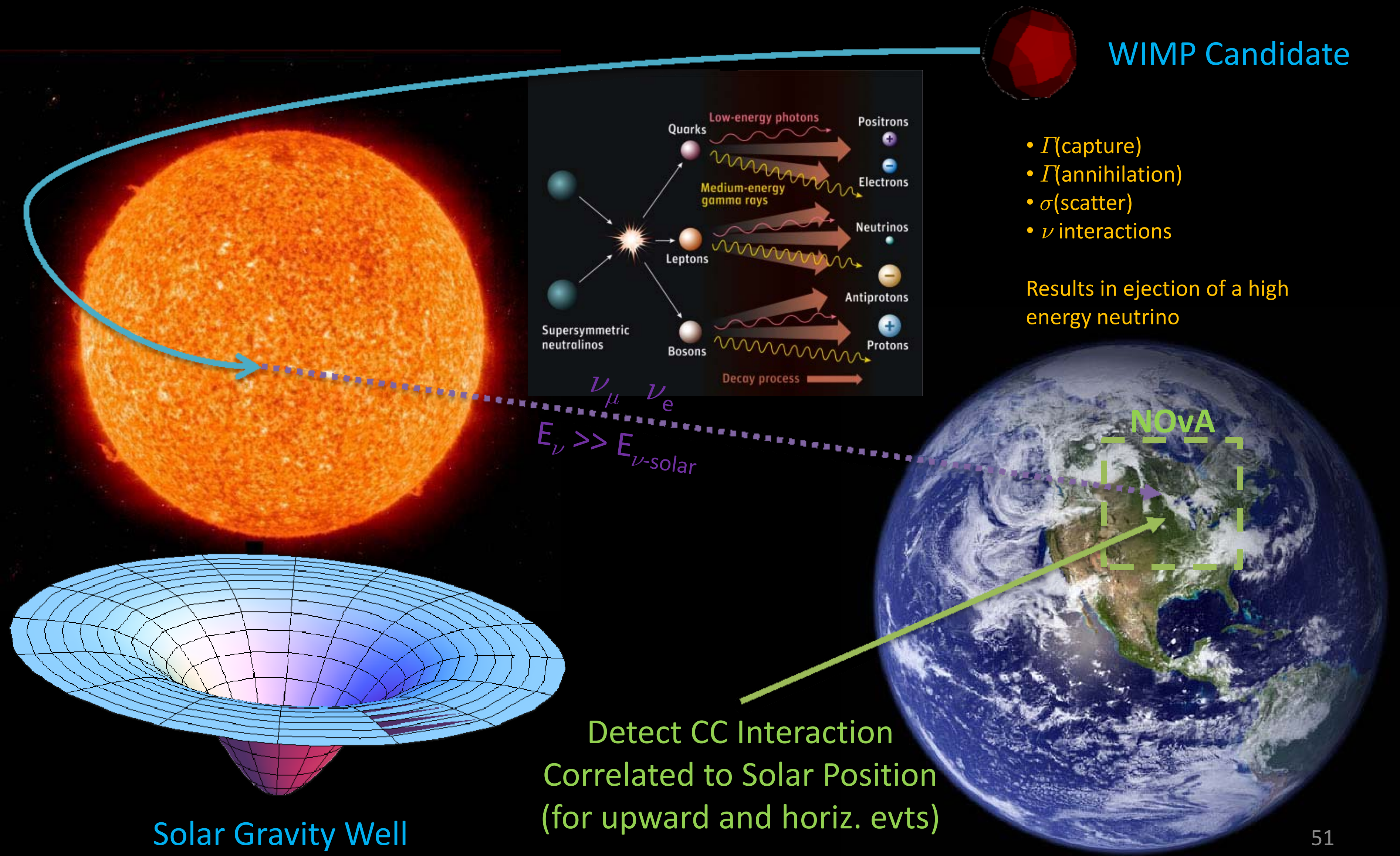
Magnetic Monopole Sensitivities



A.Norman (U.Virginia)

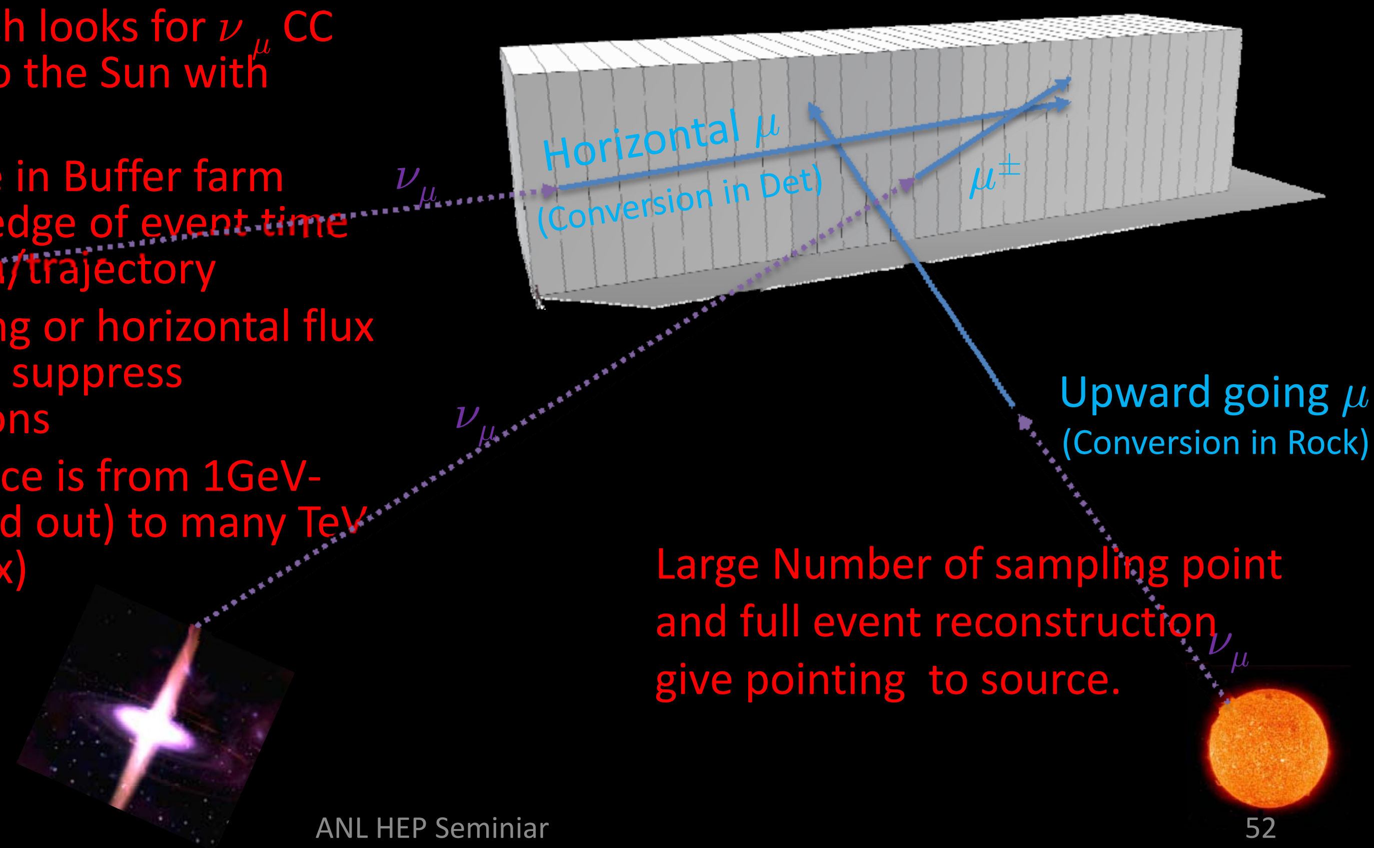
MACRO –Ref: M.Ambrosio et al. (2002) Eur.Phys.J. C25, 511-522 (2002)

WIMP Detection



WIMP Detection

- NOvA is all but insensitive to the Solar ν flux
- Simple energy threshold is enough to completely suppress the ^8B ν's
- Solar WIMP search looks for ν_μ CC events pointing to the Sun with Energy >> E_{low}
- Triggering is done in Buffer farm which has knowledge of event time and solar position/trajectory
- Only Upward going or horizontal flux are considered to suppress Atmospheric muons
- General acceptance is from 1GeV-10GeV (μ's ranged out) to many TeV (muon E via dE/dx)



Large Number of sampling point and full event reconstruction give pointing to source.

NOvA WIMP Triggers

Solar Tracking – ν_μ

- ν_μ Requires:
  - Reconstructed ν_μ CC muon track (upward or horizontal)
    - Allows conversion in the rock or atmosphere while keeping cosmic ray background to a minimum
  - Track pointing requirement ($\pm$ 5 degrees to solar)
  - Track Energy >> E_{solar}

Solar Tracking – ν_e

- ν_e Requires:
  - Reconstructed ν_e CC EM shower shape (upward or horizontal)
    - Interaction point required within the detector
    - Pre-veto of ranged muon in shower origination area
  - Shower pointing requirement
  - Total shower energy >> E_{solar}

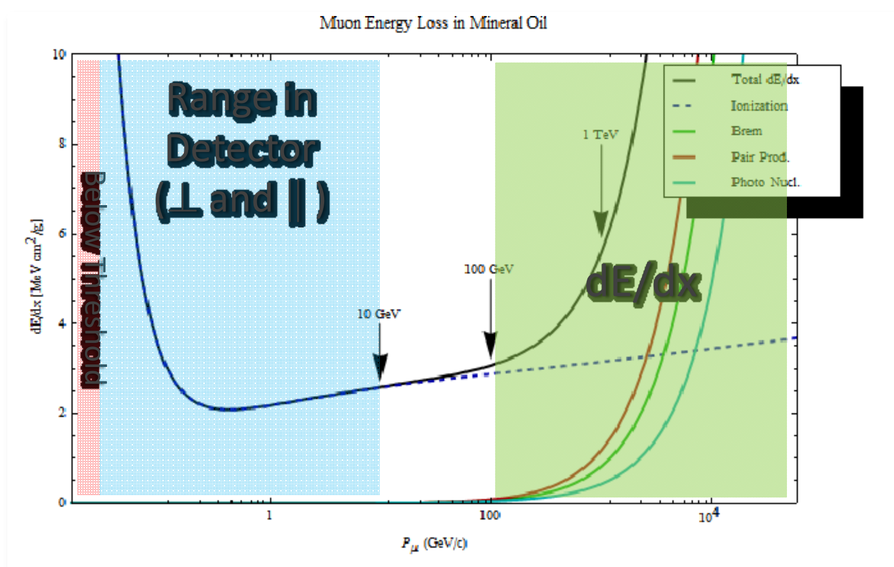
WIMPS and High Energy ν's

ATM ν's & Galactic WIMP

- Doubles as High E ATM ν trigger
- Requires:
  - Reconstructed ν_μ or ν_e CC event (upward or horizontal)
  - Δt (bottom/top)
    - Timing resolution 30ns
  - Higher E threshold to suppress false positives from atm cosmics
- Sky survey and source correlation is done offline

Energy Range

- For upward/horizontal ν_μ the available range is from sub-GeV to >> TeV with E_μ from dE/dx

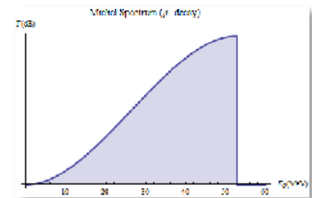


Delayed Coincidence Triggering

- Many processes of interest have a signature which includes a delayed component
  - Muon decay (ordinary Michel spectrum, for calibration)

$$\mu^- \to e^- \nu_\mu \bar{\nu}_e$$

$$\boxed{E_{e^-} = \text{Michel Spectrum}}$$



  - Low energy Neutrino/Anti-neutrino CC events (Supernova Source)

$$\nu_e + {}^{12}C \to e^- + {}^{12}N \hookrightarrow e^+ + {}^{12}C \qquad \boxed{E_{e+} = 16.4\text{MeV}\ , \tau = 11\text{ms}}$$

$$\bar{\nu}_e + {}^{12}C \to e^+ + {}^{12}B \hookrightarrow e^- + {}^{12}C \qquad \boxed{E_{e+} = 13.4\text{MeV}\ , \tau = 19\text{ms}}$$

Triggering on Delayed Coincidences

- Easy if the coincidence is short (i.e. less than buffer window)
  - And if the signal is also well localized
- Hard if time window is long
  - Singles rate limits purity of trigger
    - Base singles rate $\sim$ 100 Hz (noise + cosmic μ's)
    - Reduced singles rate $\sim$ 30 Hz (elec. noise only)
- Not possible without pre-rejection of cosmics

Summary & Conclusions

NOvA is unique:

- It accesses a set of fundamental measurements that are vital to understanding neutrinos
- But the detector that has been designed is much more versatile due to its size and fine sementation
- There are opportunities to explore topics in cosmic ray & astrophysics over wide energy ranges and at sensitivities that make NOvA very complimentary to other experiments

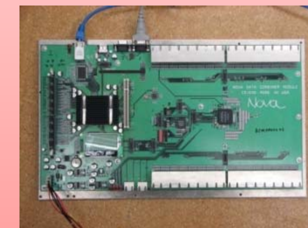
All that is required is some creativity and a trigger!

BACKUP SLIDES

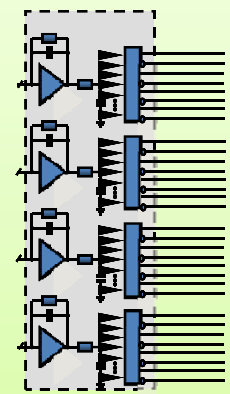
Front End Electronics

- 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

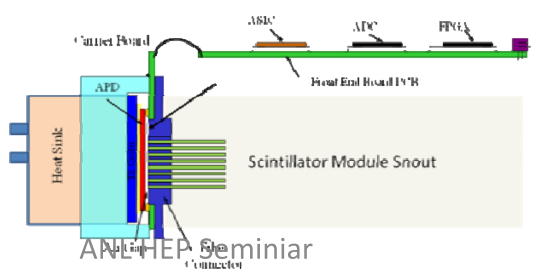
Data Concentrators (DCM)
The digitized data streams from 64 front end boards are broadcast over 8B/10B serial links to an associated data concentrator module which orders, filters and buffers the data stream, then repackages the data into an efficient network packet and rebroadcasts it to a specific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



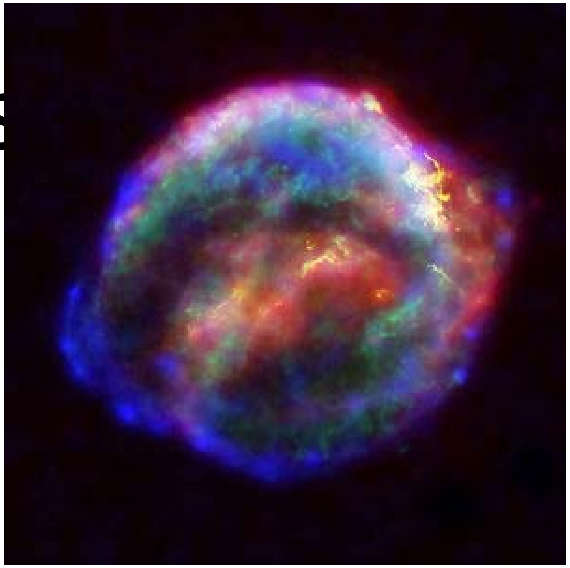
FEB ASIC
The custom designed ASIC is an integrator/shaper with multiplexer running at 16MHz. The channels are Muxed at 8:1 and sent to a 40MHz quad ADC for digitization. For the higher rate near detector the channels are muxed at 2:1 and sent to 4 quad ADCs. ASIC is a low noise device with expected noise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



NOvA Front End Board



Supernova Neutrinos

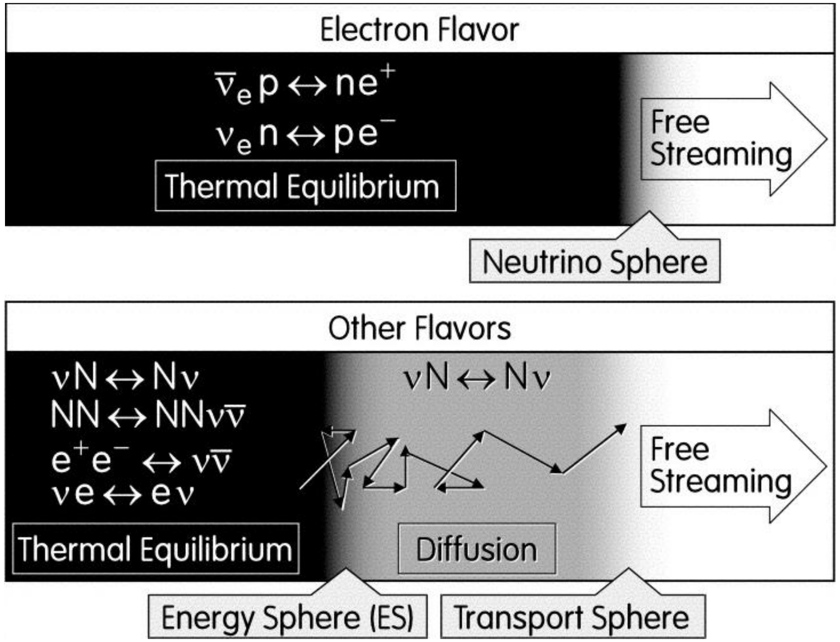


- Neutrinos and Antineutrinos are produced via:

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

- 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



Reactor anti-ν_e detection

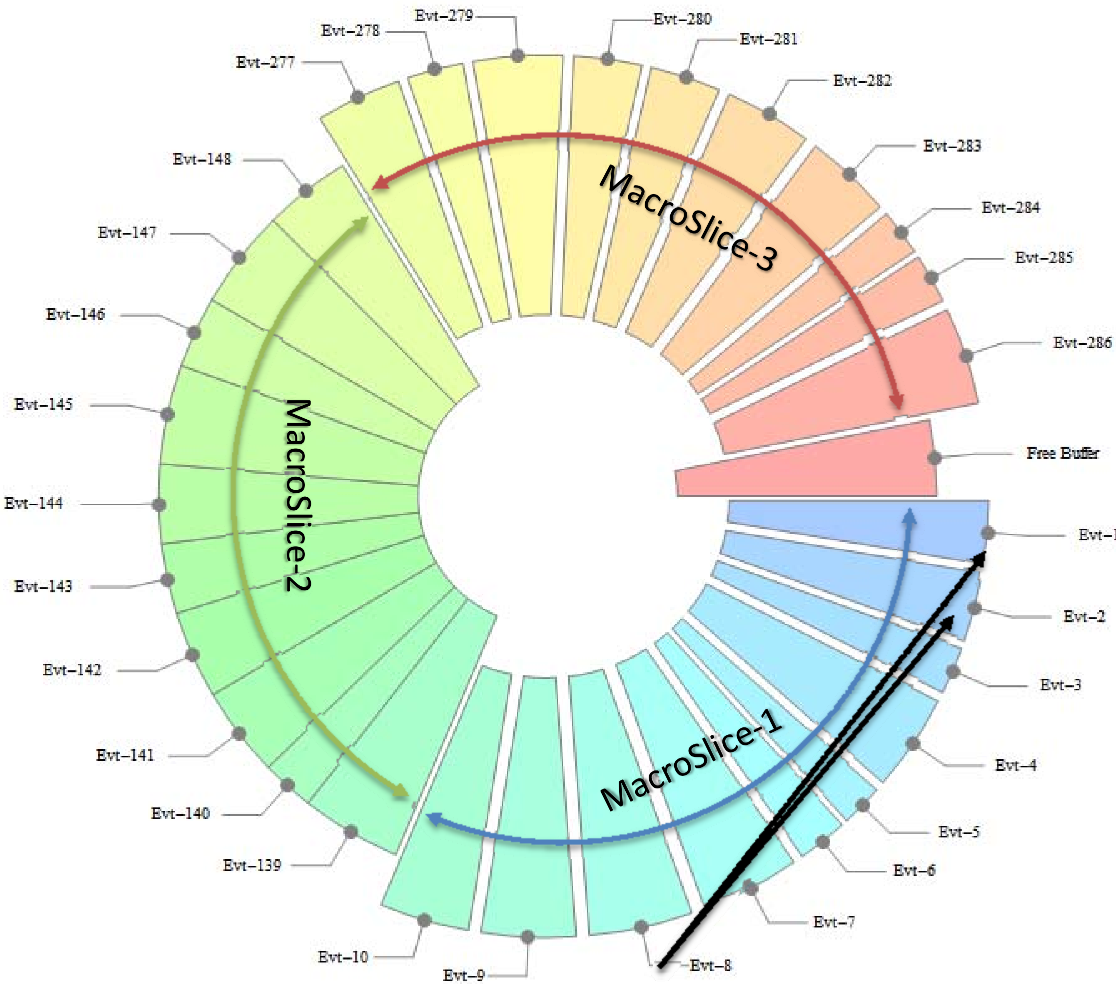
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$e^+ + e^- \rightarrow \gamma\gamma(\text{2x } 0.511 \text{ MeV } + \text{ T}_\text{e})$$

$$n + p \rightarrow D + \gamma(8.8 \text{ MeV}, \tau \sim 180\mu\text{s}, \sigma = 0.3\text{b})$$

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma' s(8\text{MeV}, \tau \sim 28\mu\text{s}, \sigma = 5 \times 10^4\text{b})$$

Serial Buffering



Adjacent data blocks are now continuous in time, and MacroSlice can be defined

How?

In 2009, serial buffering is possible because network traffic shaping switches are now available with large aggregated bandwidths and deep port buffers.

Advantages:

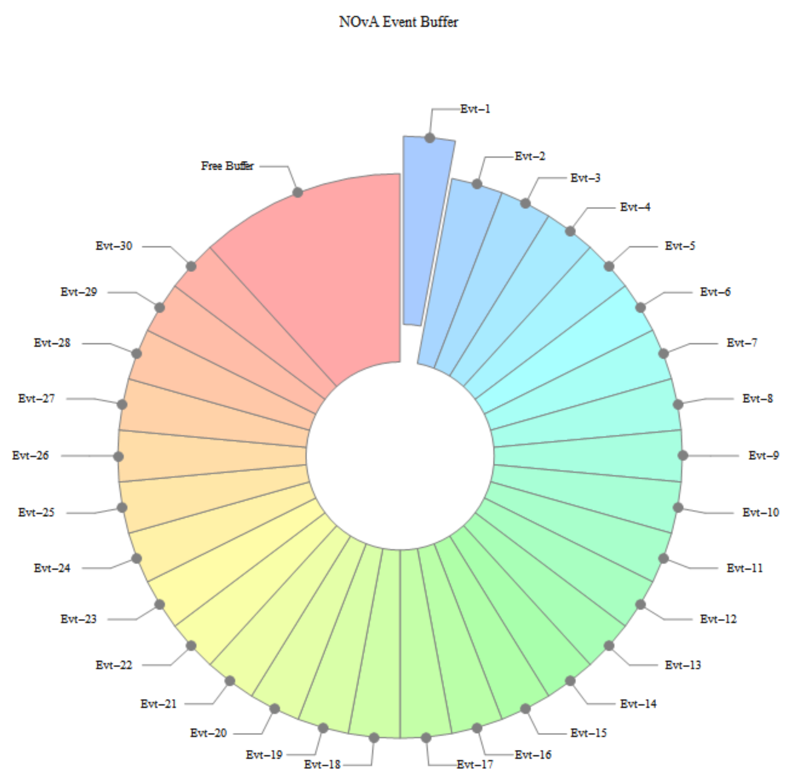
Time correlations across MilliSlice windows are easy. $\Delta t_{max} \approx 150$ms.

Certain physics triggers are more "natural" in this topology, less prone to false positives

No synchronized offsetting of DCM transmission times is required

The a prob of having a spill window straddle buffer nodes drops from $\sim$1.2% to 0.04% for 150ms grouping.

NOvA Event Buffer



- Each buffer node contains a single circular "Event Buffer"
- The buffer holds ***raw*** hit data from the entire detector, grouped in 5ms slices
- Buffer Size $\approx$ 30 slices deep (0.15s per node)
  - Gives system wide buffering of 20s of data
  - Actual size is roughly 115MB (30$\times$3.8MB)

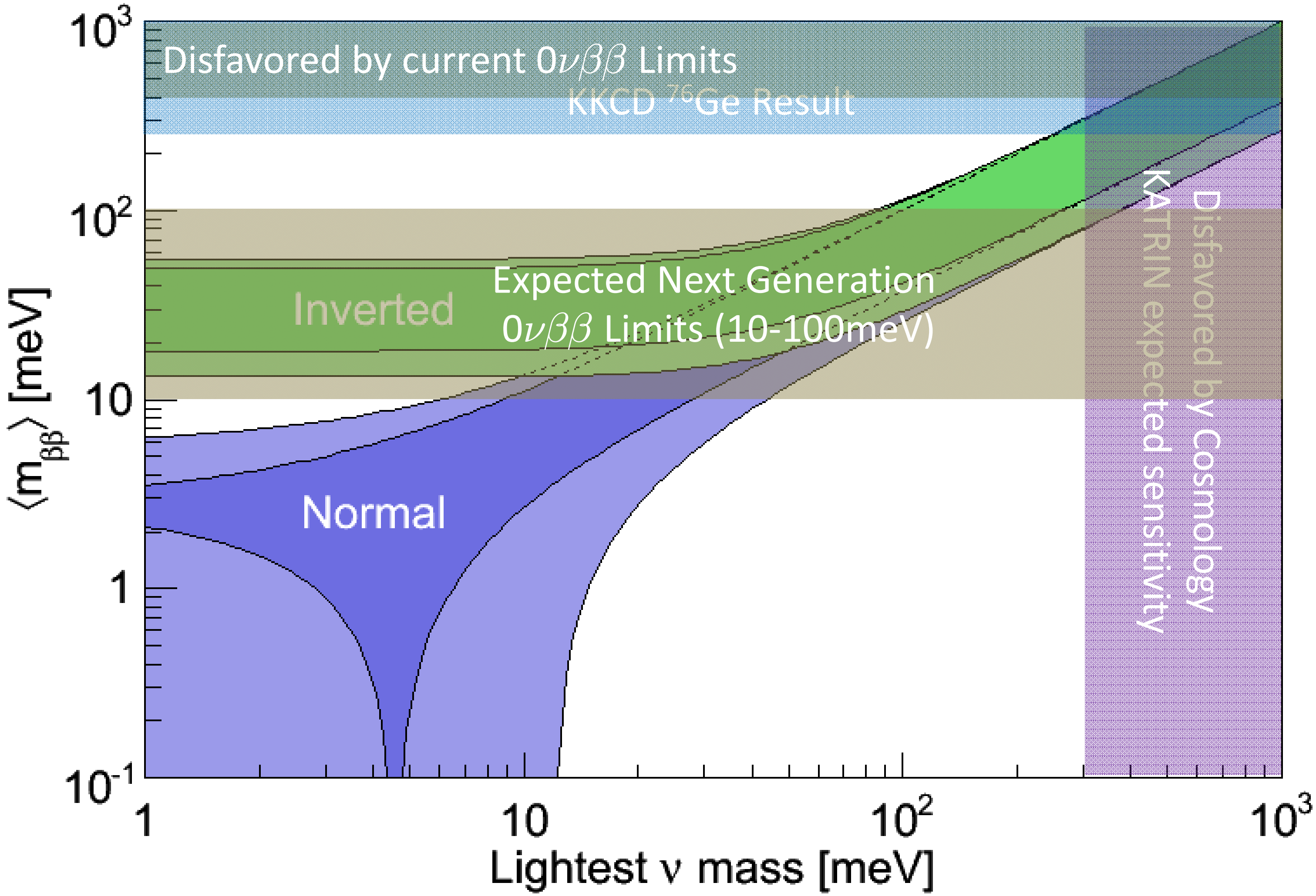
My Involvement & Bias

- UVA Became involved with NOvA in the fall of 2005
  - We concentrated on the CD-1/2/3 designs for:
    - Power Distribution Systems
    - Detector Controls & Monitoring (slow controls)
- From 2005-Present, NOvA has become the primary focus of our group (and my time) – Our involvement has evolved substantially
- Currently I serve as the L3 manager for two task trees
  - Detector Control Systems (x.7.4)
  - DAQ Software Integration (x.7.3) (part of 2009 DAQ reorganization)
- Additional responsibilities in:
  - DAQ Hardware→Software Interfaces (DCM embedded software/cntrl)
  - DAQ Software & triggering design
  - Detector Infrastructure (power distribution, mechanical support, routing, etc…)

General Philosophy

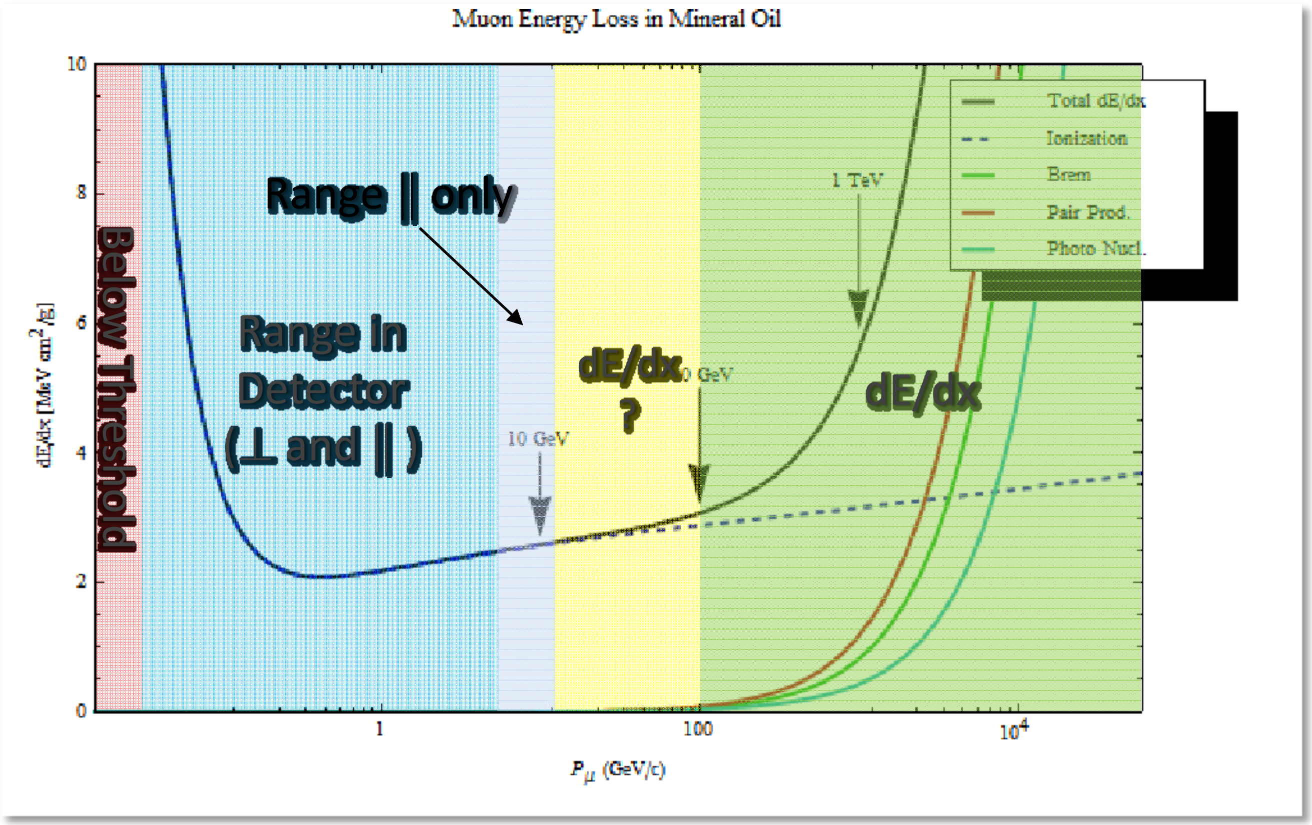
It's important to understand where the data comes from in order to understand what you can do with it.

DAQ, Triggering & Electronics



Klapdor-Kleingrothaus, Krivosheina, Dietz and Chkvorets, *Phys. Lett. B* ***586* 198 (2004).**

Muon Detection
MeV to TeV μ's



Motivation for this talk:

I get this question (a lot recently):

"Can NOvA…… θ_{13} θ_{23} δ_{CP} sign(Δ m$_{31}$)"

see a Supernova?

detect dark mater?

find sources of (very) high energy neutrinos?

measure (high E) cosmic fluxes?

measure σ_{NC} from the beam?

from the atm?

see monopoles?

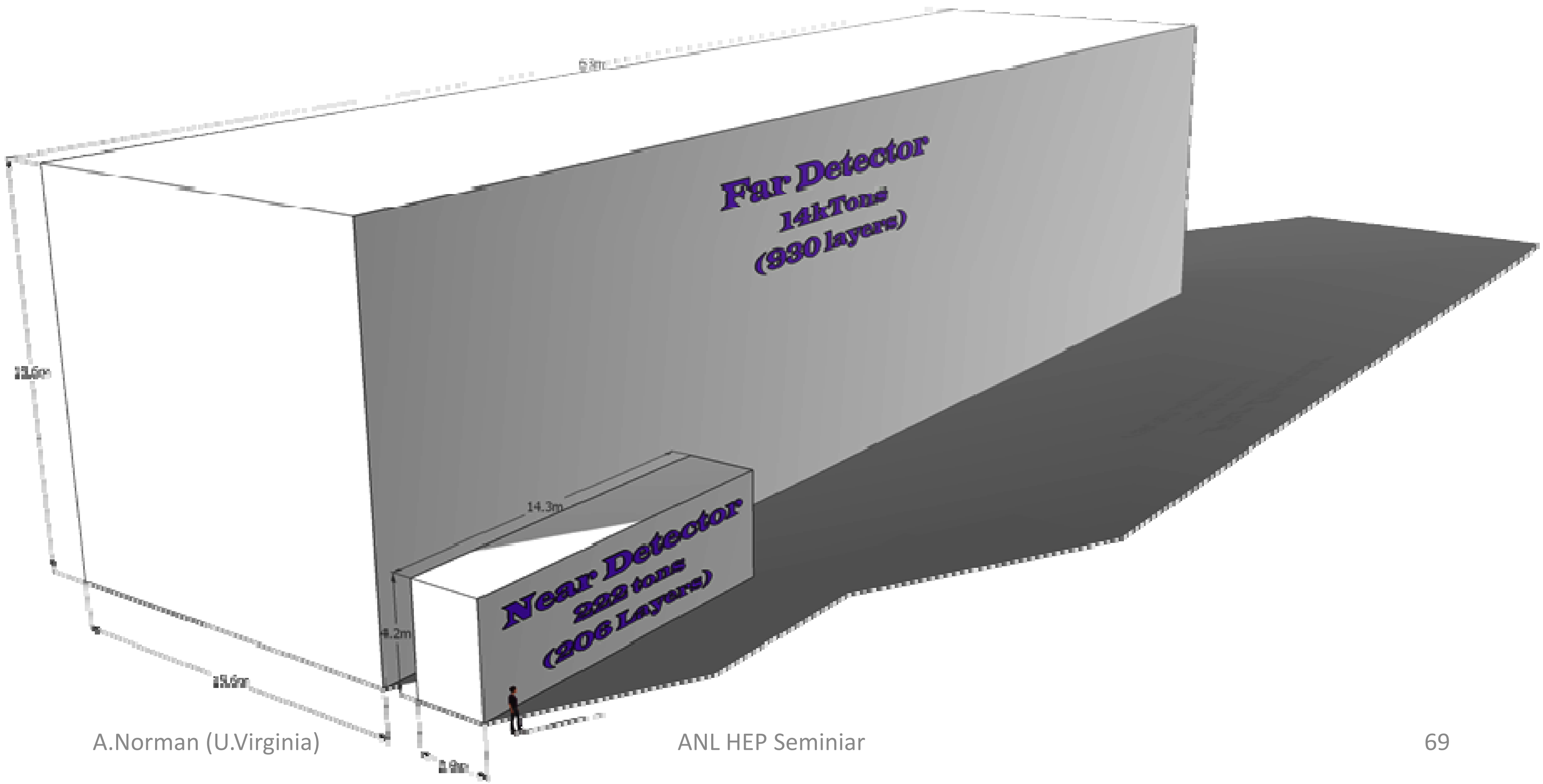
And I answer:

"Well….."

"Maybe….."

"It depends on the trigger."

"We're working on redesigning the triggers."


Far Detector
14kTons
(930 layers)
Near Detector
222 tons
(206 Layers)
14.3m

Mixing Matrices

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

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

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.5 & \text{small} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad U_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.02 & 1 & .04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}$$