Neutrino Experiment Physics Goals and Detector Challenges

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Fermilab
Workshop on Detector R&D
7-9 October 2010

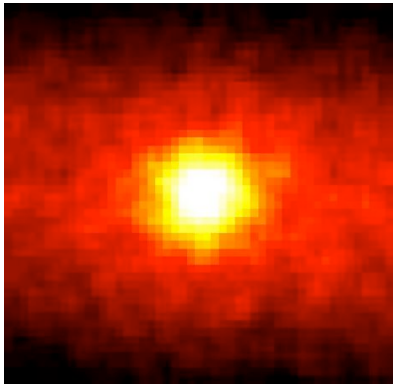
Elements of the Talk

- Review of the current state of detectors and upgrades
- What drives the upgrades?
  - Machine improvements?
  - Component degredation
  - Newer technologies?
- What are the "pie-in-the-sky" technology choices that would leverage qualitatively new physics? Is there effort in those directions?
- What are the time scales?
- What should be the focus now, in the near future and the far future to meet the experiment's goals

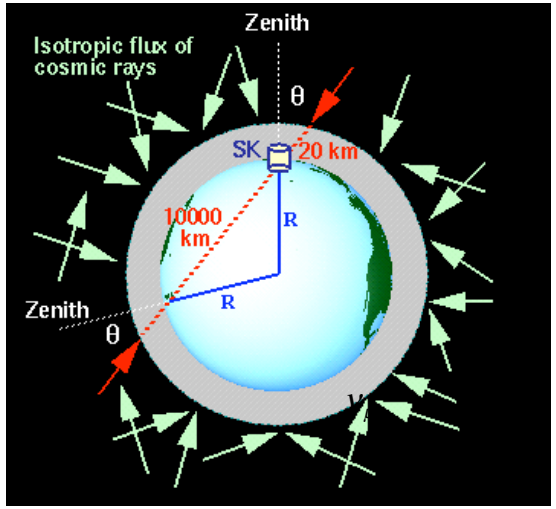
Outline

- Neutrino Overview
  - Broad range of neutrino energies ➔ lot's of detection techniques
  - Lot's of detectors that I don't have time to discuss
  - Focus on detectors for accelerator produced neutrinos
    - Past,present and future detectors
- Neutrino Challenges
  - Low event rates ➔ large detectors
  - Large detectors ➔ course granularity
  - Course granularity ➔ low efficiency, high background
  - High efficiency, low background ➔ $$$
- Detectors for LBNE ($\nu_\mu \rightarrow \nu_e$ FNAL➔DUSEL)
  - Physics goals
  - Favored technologies
  - Status of design, project status, timescale
  - Major Challenges

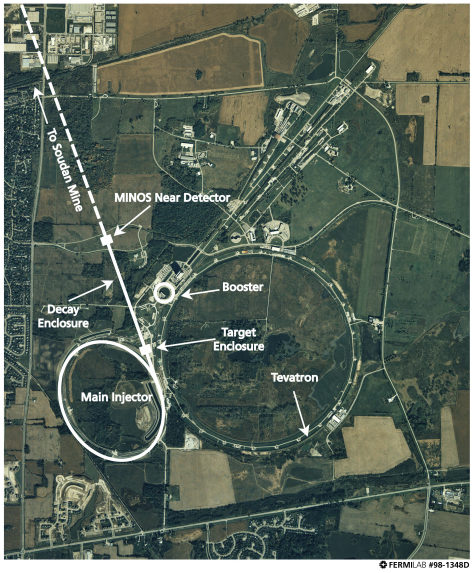
Diversity of Neutrino Physics



Solar neutrinos



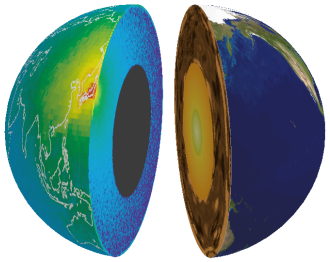
Atmospheric neutrinos



Accelerator neutrinos

Reactor neutrinos

Supernova neutrinos

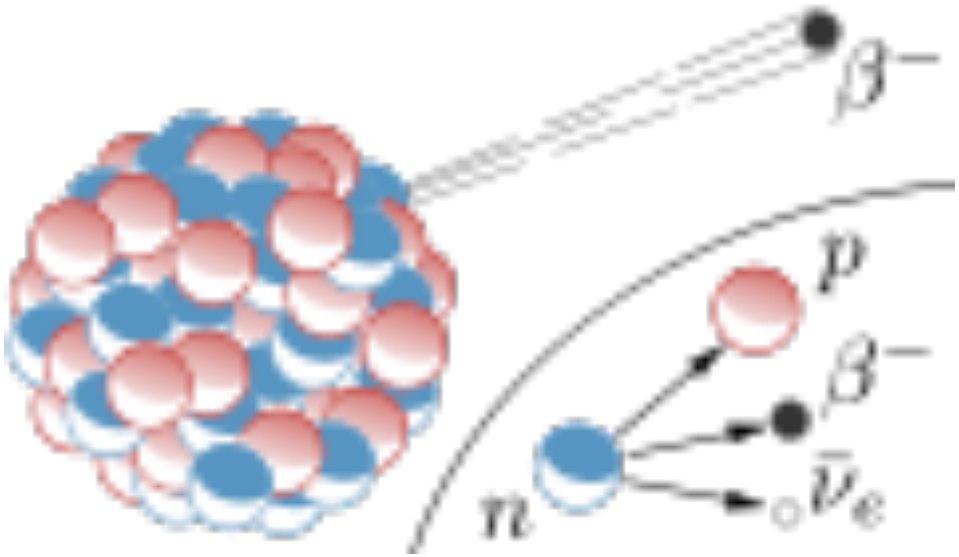


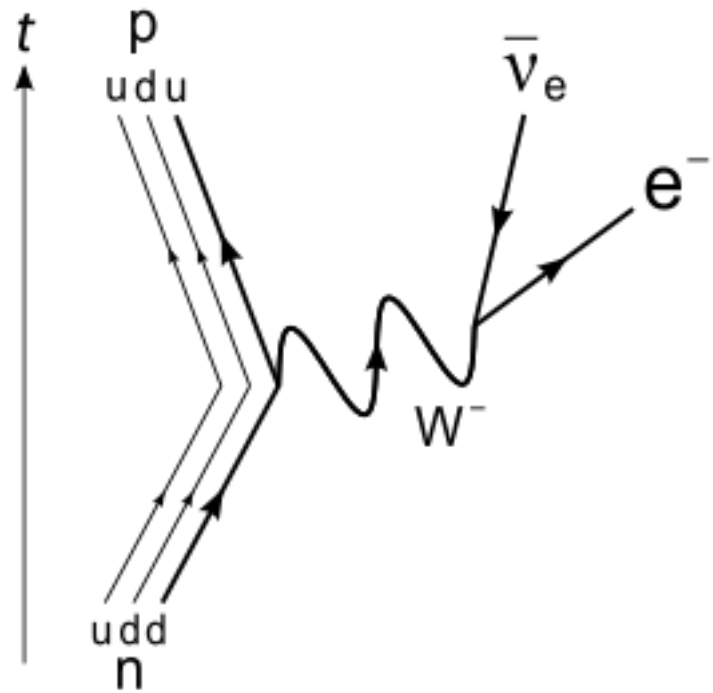
Geoneutrinos

Neutrino Energies

- These neutrinos have a broad range of energies
  - Geo : < 3.5 MeV
  - Reactor : 1 – 10 MeV
  - Solar : < 20 MeV
  - Supernova : 1 – 50 MeV
  - Atmospheric : 5 MeV - ~100 GeV
  - Accelerator : ~1 - ~100 GeV
  - UHE : 1 GeV – 100 PeV
- The neutrino energy dictates the ways the neutrinos will interact and hence become detectable

The Neutrino Interaction

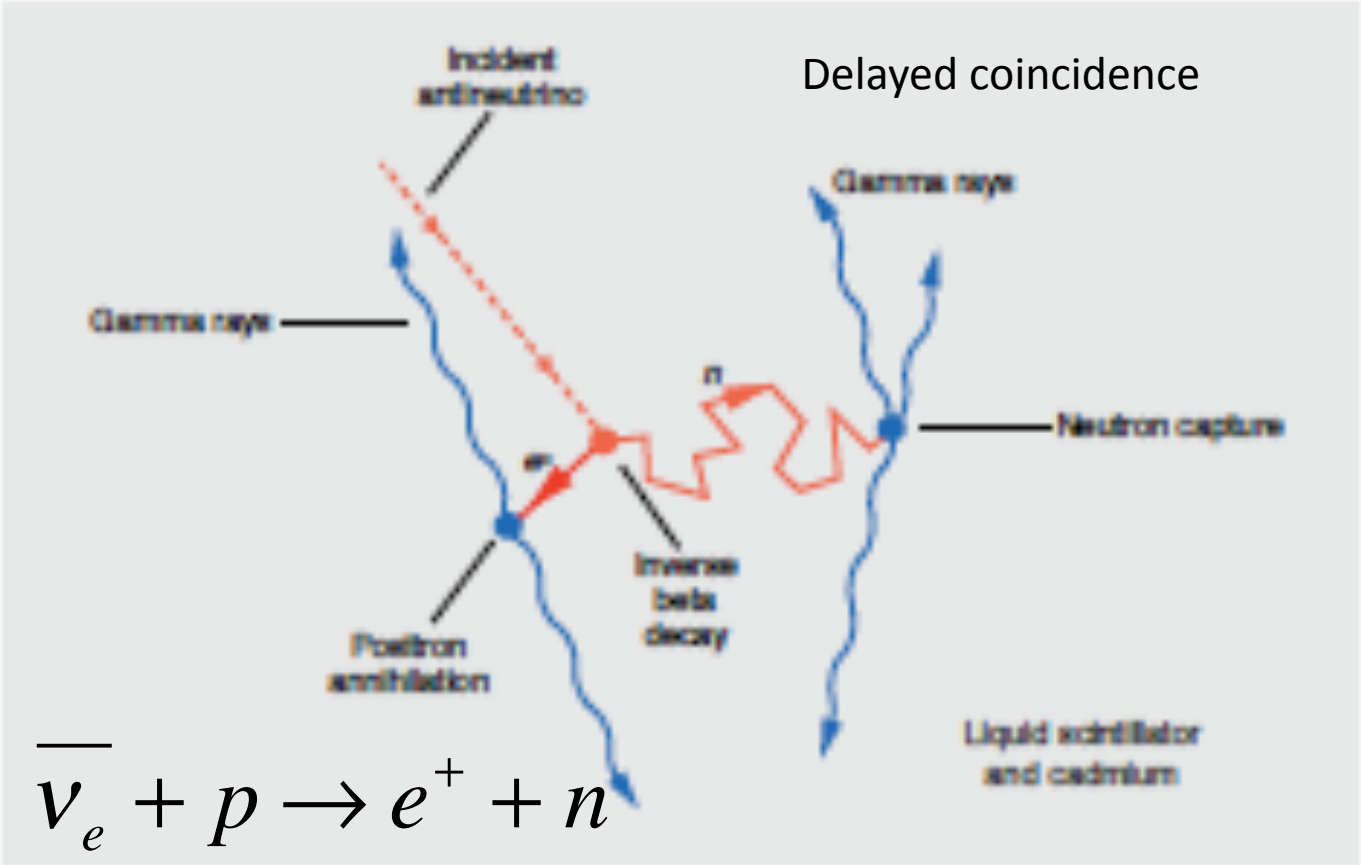




Invented to explain energy non-conservation in beta-decay

$$n \rightarrow p + e^{+} + \overline{\nu}_{e}$$

Neutrino Detection



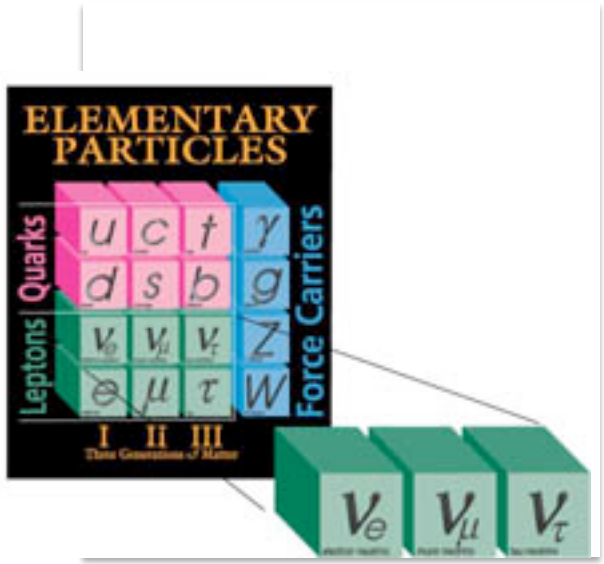
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

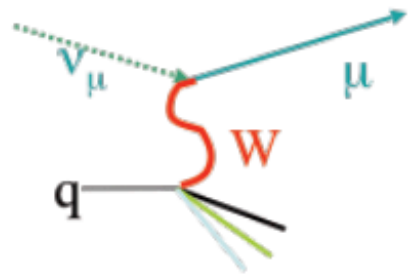
$$e^+ + e^- \rightarrow \gamma$$

$$n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{109}Cd + \gamma$$

$$\Delta t = 5\mu s$$

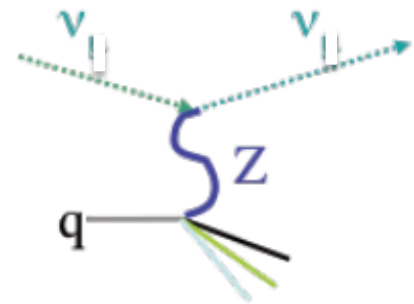
Neutrino Flavors & Interactions





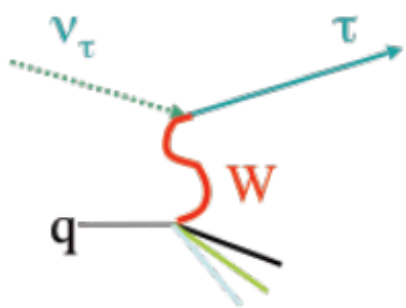
$\nu_\mu + N \rightarrow \mu^- + X$

Charged current



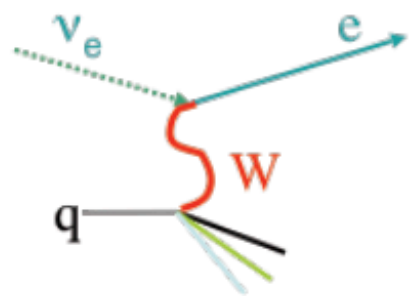
$\nu_\mu + N \rightarrow \nu_\mu + X$

Neutral current



$\nu_\tau + N \rightarrow \tau^- + X$

Tau Charged current



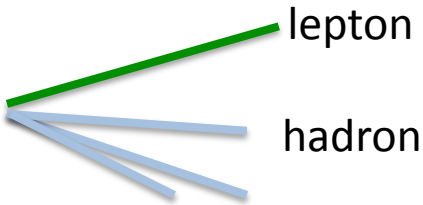
$\nu_e + N \rightarrow e^- + X$

Electron Charged current

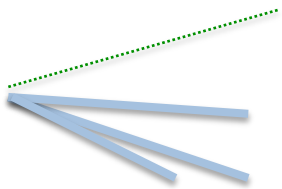
High Energy topologies

Deep Inelastic (DIS)

CC



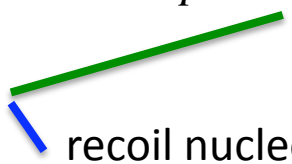
NC



Quasi-elastic (CCQE)

$$\nu_\mu + n \rightarrow \mu^- p$$

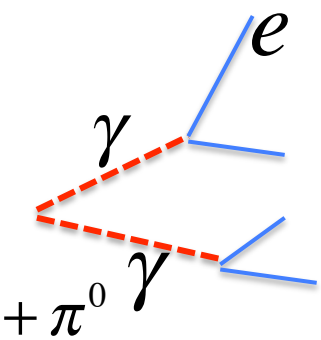
$$\nu_e + n \rightarrow e^- p$$



Neutral Current π^0(NC π^0)

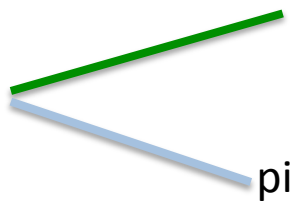
Resonant $\nu + N \rightarrow \nu + \Delta$

$$\Delta \rightarrow N + \pi^0$$



Coherent $\nu + A \rightarrow \nu' + A + \pi^0$

Single pion CC (CC)π



pion

The Challenge

Neutrino Cross sections are small

$$< 10^{-38} cm^2$$

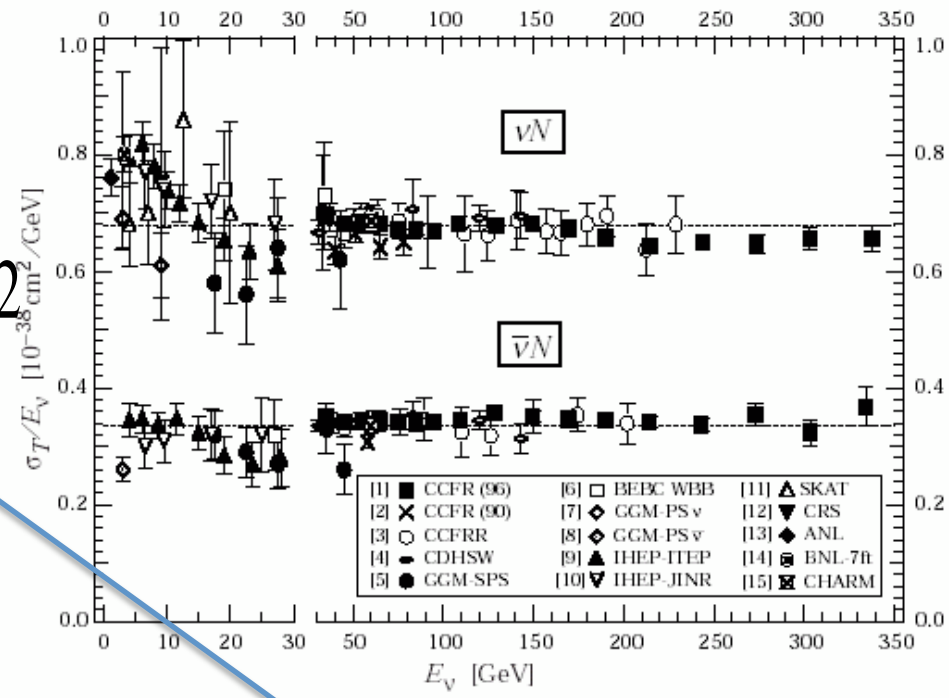
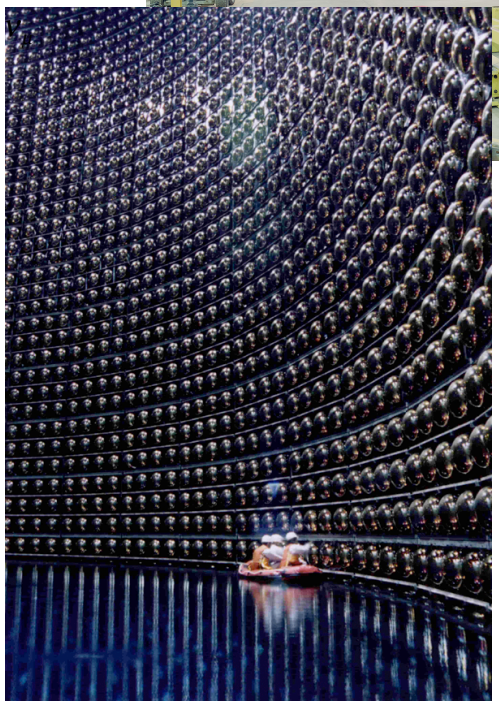


Figure 39.10: σ_T/E_ν, for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are the averaged values over all energies as measured by the experiments in Refs. [1–4]: $= 0.677 \pm 0.014$ $(0.334 \pm 0.008) \times 10^{-38}$ cm^2/GeV. Note the change in the energy scale at 30 GeV. (Courtesy W. Seligman and M.H. Shaevitz, Columbia University, 2001.)

$$N_\nu(E) = \Phi_\nu(E) \times \sigma_\nu(E) \times N_{tgt} \times \varepsilon(E)$$

Diversity of Neutrino Detectors

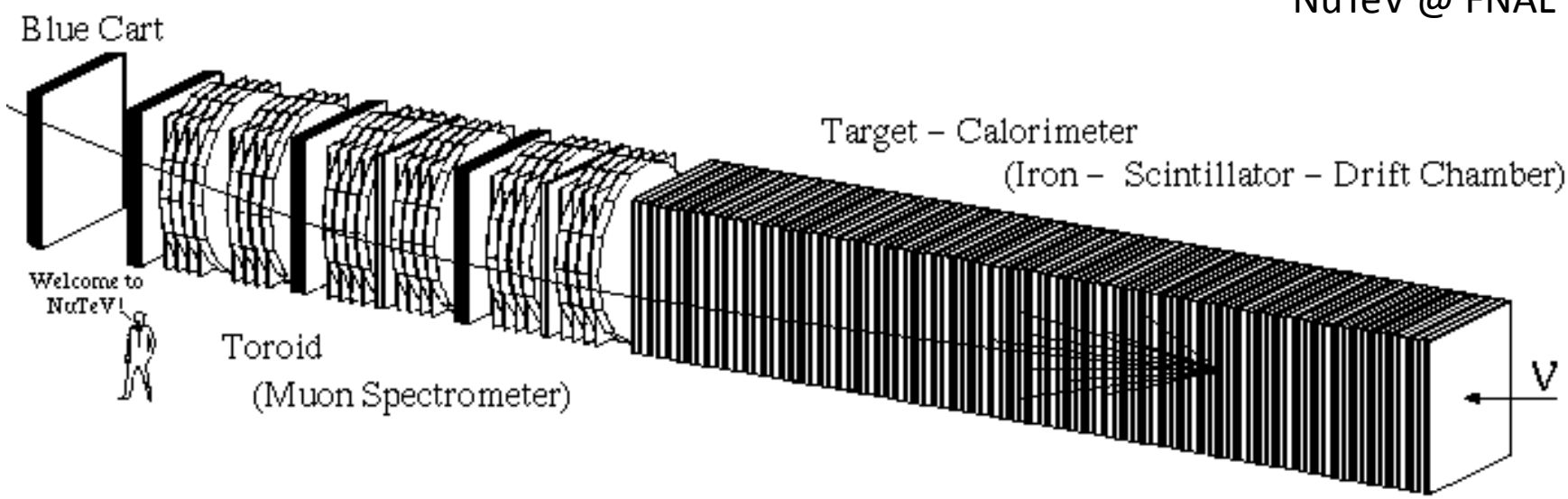


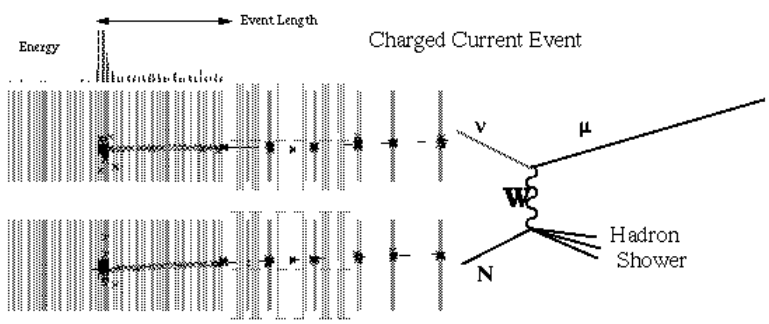
Neutrino Detectors

- Key Properties
  - Target Mass ➔ # of interactions *produced*
  - Particle ID, efficiency ➔ # of interactions *detected*
  - Energy, momentum measurement
  - Vertex resolution
- Key Feature
  - Monolithic
    - Generally a single target media and single detection technique
- Focus on those detectors that we build to see the direct by-products of the primary interactions
  - Not the indirect detection via cascades and delayed coincidence (i.e. Reines and Cowan)

Tracking Calorimeter
(+ Magnetic tracking)

NuTeV @ FNAL



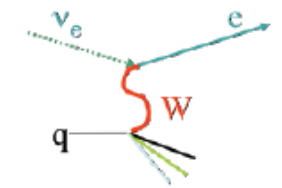


Newer detectors using this technique :
MINOS
Minerva

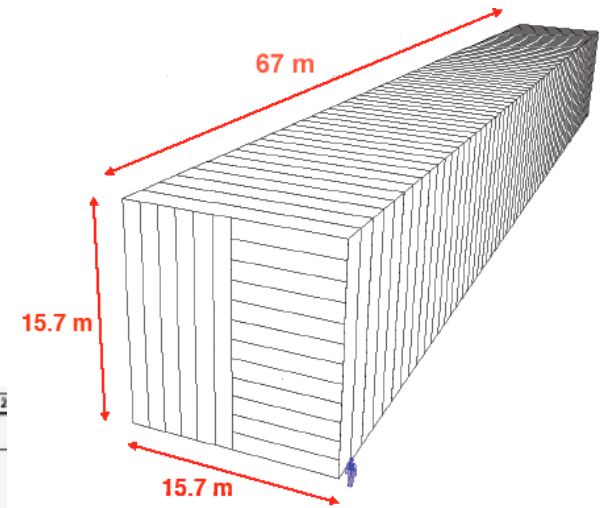
Proposed detectors to use this technique :
INO
Neutrino Factory Study

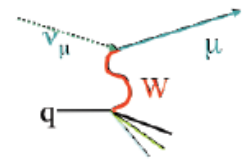
Liquid scintillator tracking calorimeter

NOvA



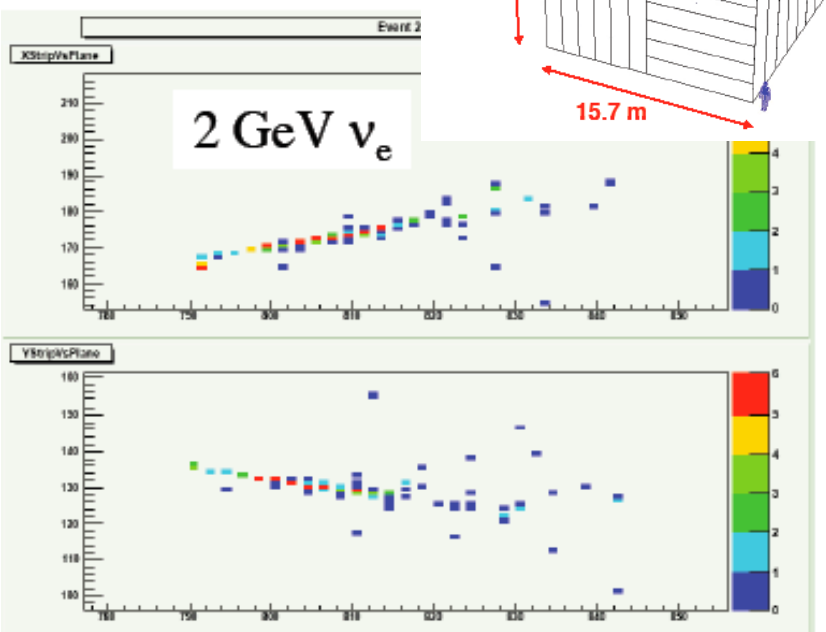
$\nu_e + N \rightarrow e^- + X$

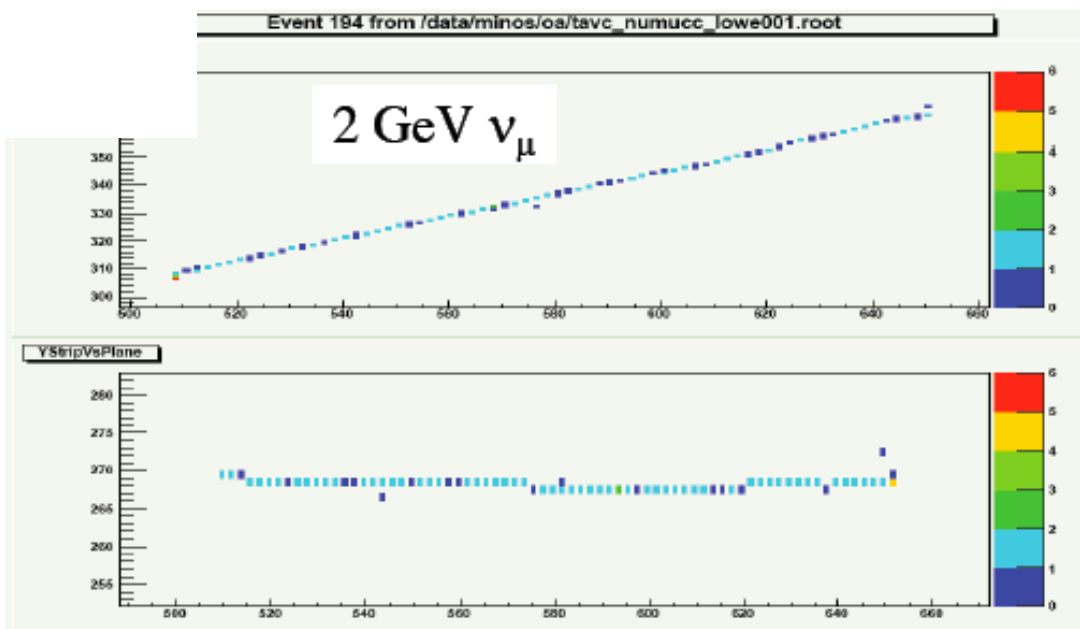




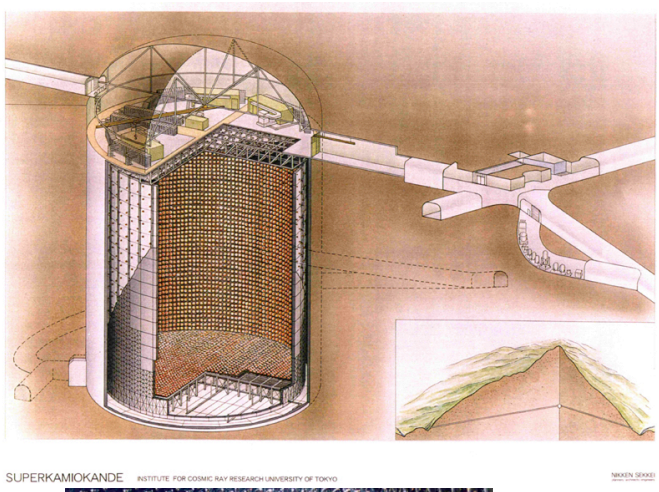
$\nu_\mu + N \rightarrow \mu^- + X$

A 2-GeV muon is 60 planes long.

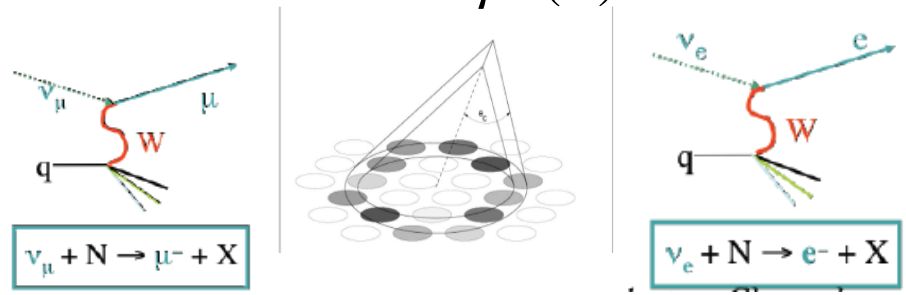


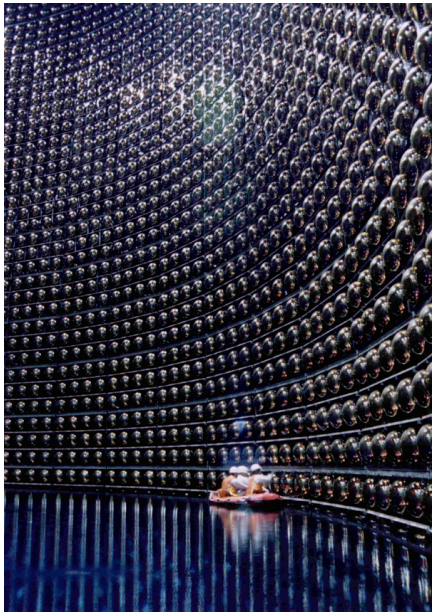


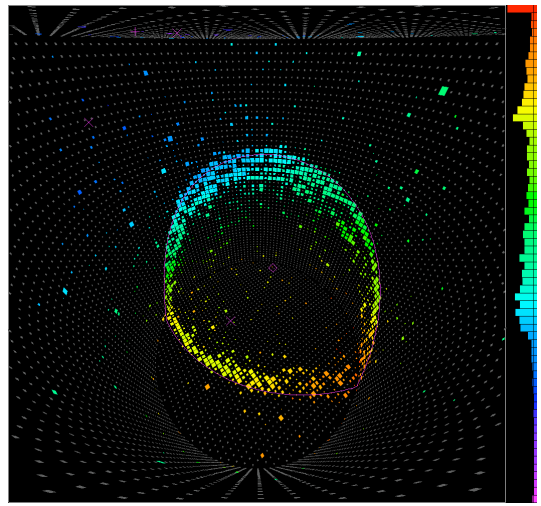
Ring imaging particle ID

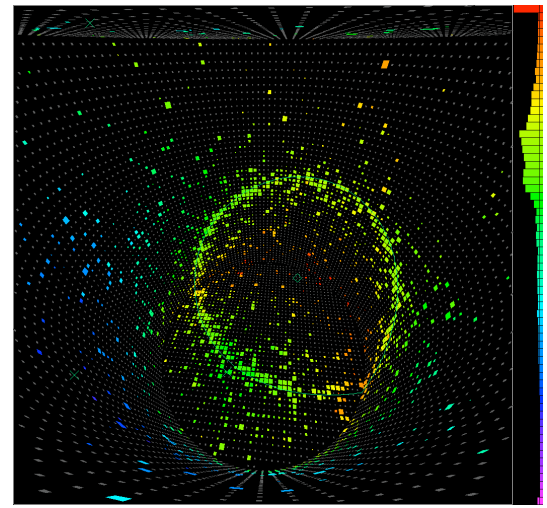


$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$





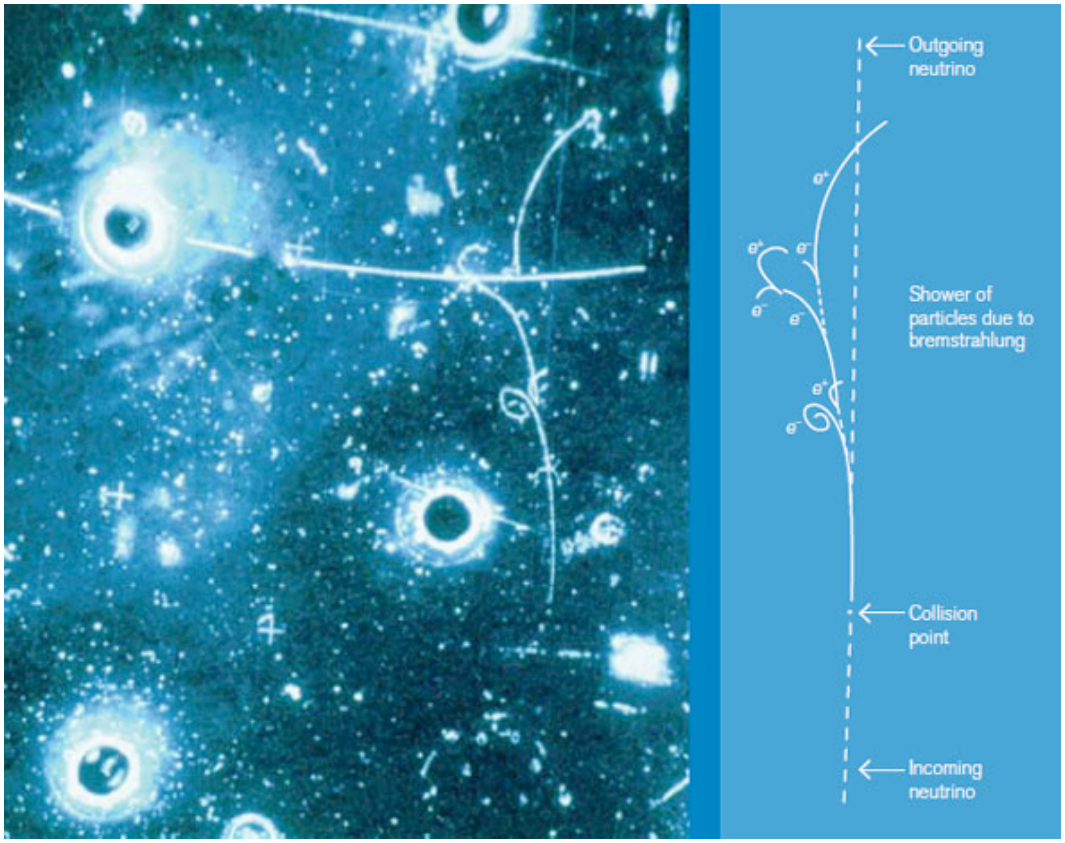




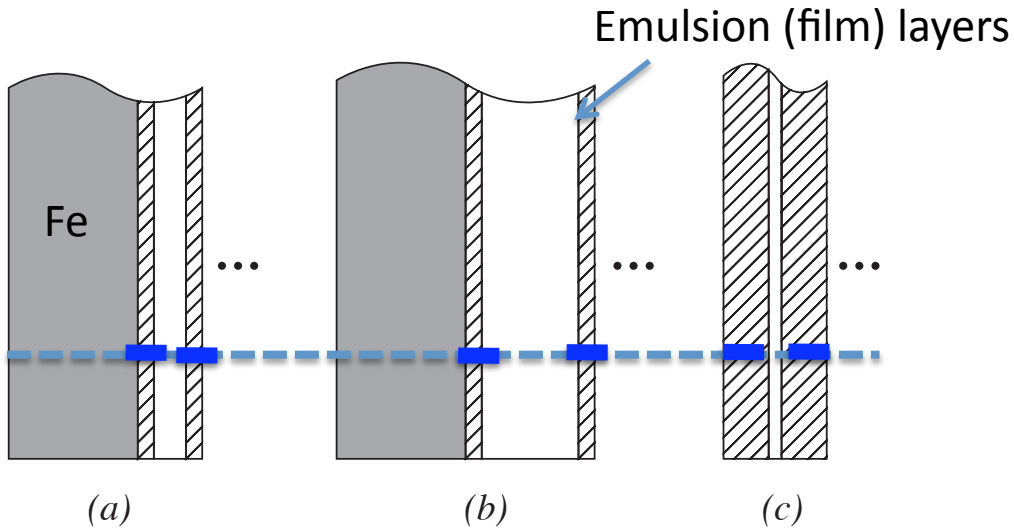
3-d imaging : Bubble chamber

Gargamelle Bubble Chamber

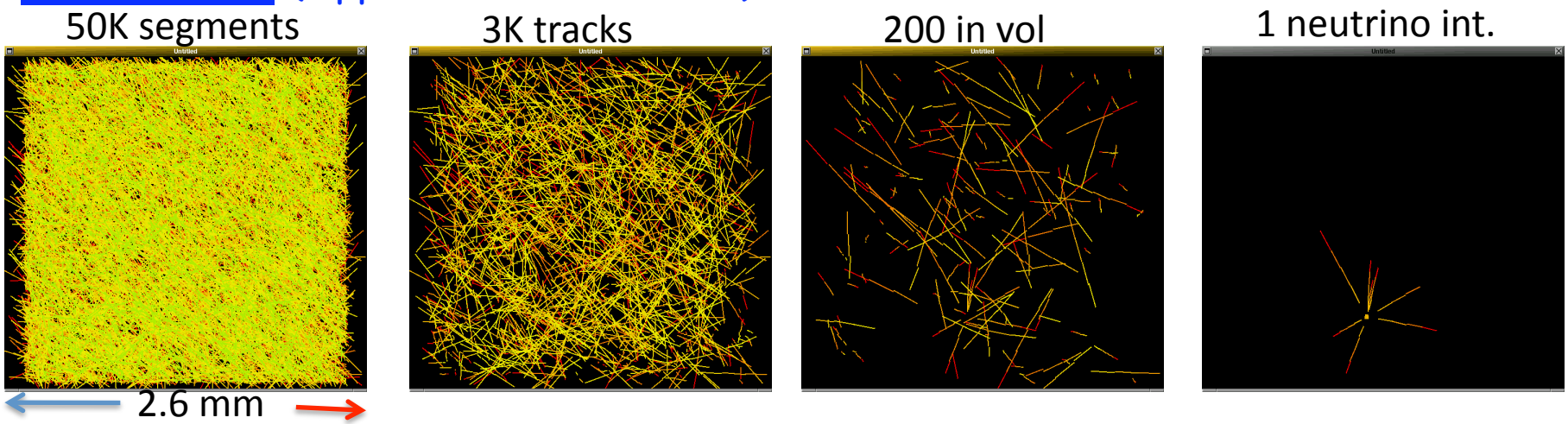
1st detection of a NC interaction



3-d imaging : Emulsion

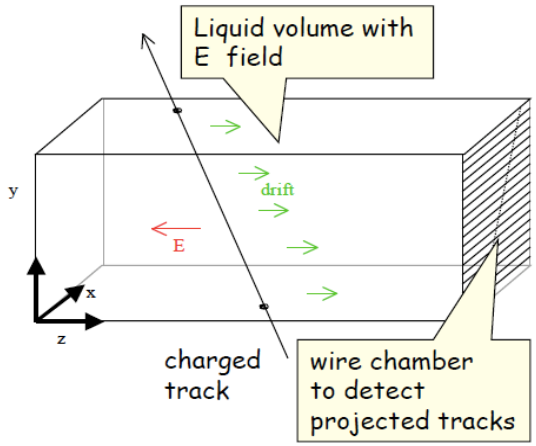


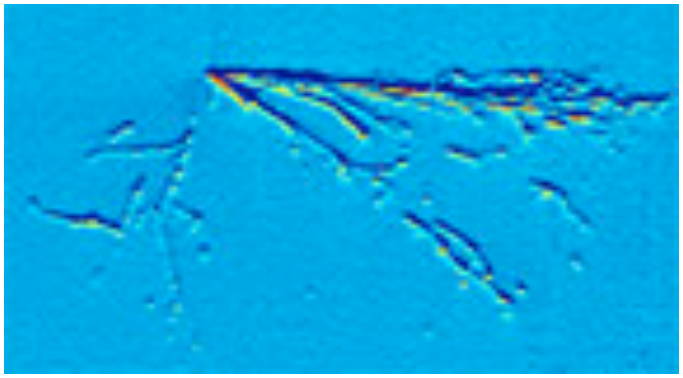
NET-scan (Application to DONUT)

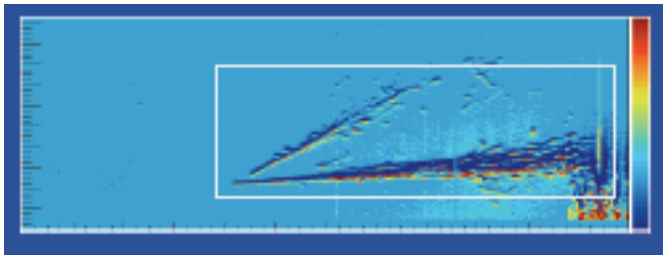


Detection Technique for OPERA

3-d imaging : Liquid Argon

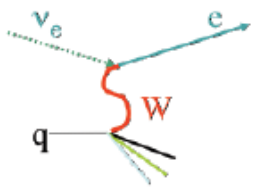




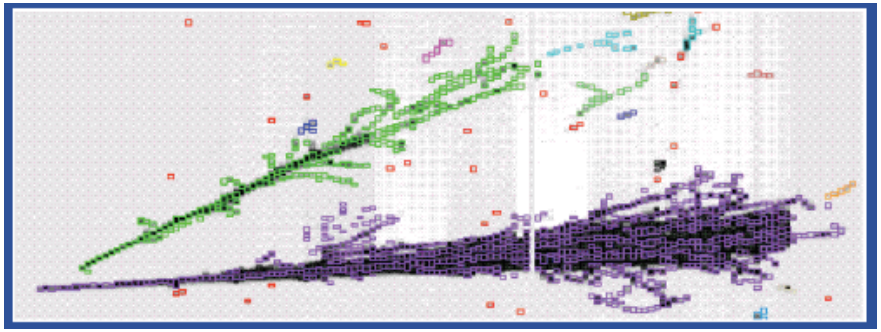


ArgoNeuT

Location: Fermilab
Active volume: 0.0003 kton
Year of first tracks: 2008
First neutrinos: June 2009



$$\nu_e + N \rightarrow e^- + X$$



Detector Summary

- Tracking Calorimeters
  - Target material
    - Steel
    - Carbon,lead, scint,water,He…
  - Tracking detectors
    - Gas tubes
    - Liquid scintillator
    - Solid scintillator
- Ring Imaging
  - Target materials
    - Water
    - Scintillator
    - Mineral Oil
  - Active detectors : PMT's
- 3-d Imaging
  - Bubble Chambers
  - Emulsion
  - Liquid Argon

Common characteristics : Simple, monolithic Target Material and Radiation Detectors

Where we've been
and
where we're going

Neutrino History

- 1956 – 1st detection of $\overline{\nu}_e$ via delayed coincidence in liquid scintillator
- 1962 – detection of ν_μ in an Fe-spark chamber tracking detector
- 1973 – discovery of neutral currents in the Gargamell bubble chamber
- 1987 – detection on neutrinos from SN1987a in water cherenkov detector
- 1998 – detection of ν_τ in emulsion
- 1998 – discovery of neutrino oscillations in water cherenkov detector

World Tour 2010

- US - Fermilab
  - MINOS, Minerva : solid scintillator-Tracking calorimeters
  - MiniBooNE : Mineral Oil Ring Imaging
- Europe - Gran Sasso Lab
  - Opera (3d-emulsion+spectrometer)
  - ICARUS (3d-liquid argon)
- Japan – JPARC/Kamioka
  - Super-K/T2K : Water Cherenkov Ring imaging
  - T2K near : fine grained trackers, water target
- South Pole
  - Ice Cube : Large area tracking with PMTs

Apologies if I missed an experiment……

Near Term
Commissioning, construction, design

- US/Canada
  - NOvA : 15-kT scale, liquid scintillator, WLS fiber/ apd readout
  - MicroBooNE : 100-ton scale, liquid argon, TPC's
  - SNO+: kiloton scale, liquid scintillator, PMT's
- Europe and Asia
  - Double Chooz
  - Daya Bay
  - Reno

Reactor Experiments
For theta13
Scintillator/PMT based-
delayed coincidence techniques

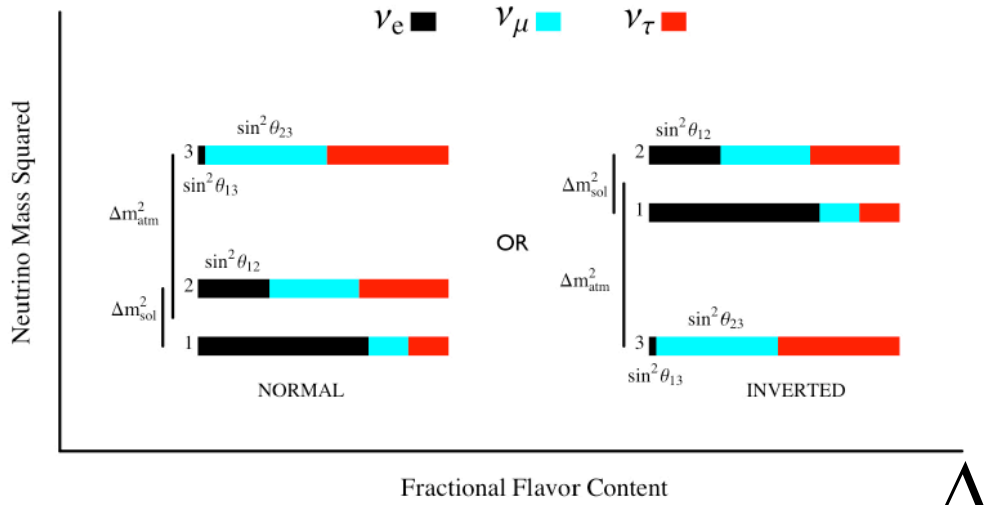
What are the current physics questions being addressed by present and future neutrino experiments?

- Neutrino Mass and Mixing
  - What is the value of the third mixing angle, θ_{13}
  - If $\theta_{13} \neq 0$, what is the value of δ_{CP}
  - What is the neutrino mass ordering
  - Precision Measurements of θ_{23} *and* Δm^2_{23}
  - Is θ_{23} maximal

What are the current physics questions being addressed by present and future neutrino experiments?

- Neutrino Anomalies
  - Low energy excess of electron-like events in MiniBooNE
  - $\overline{\nu}_e$ appearance in MiniBooNE anti-neutrinos
  - $\nu_\mu \; and \; \overline{\nu_\mu}$ differences in MINOS
- Supernova Watch

Current state of knowledge



$$\Delta m^2_{12} << \Delta m^2_{23}$$

?

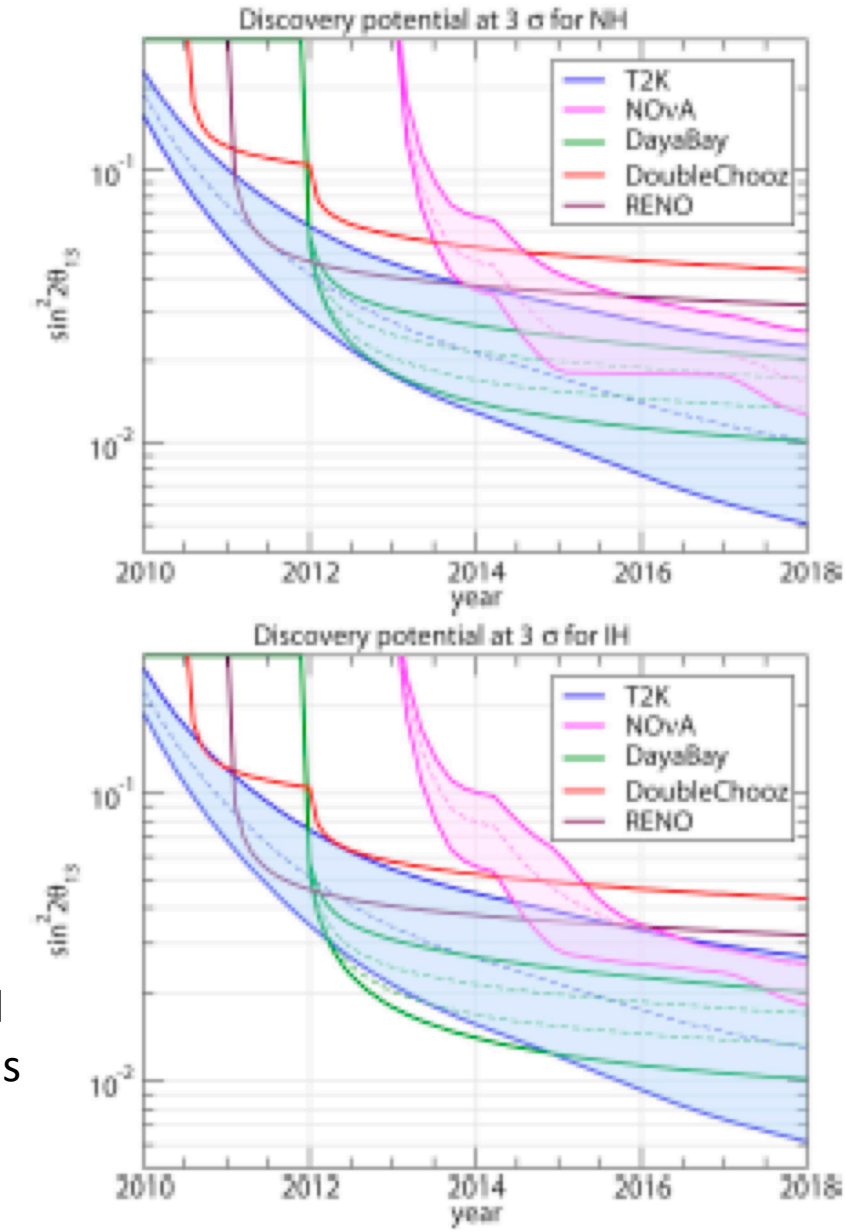
$$\Delta m^2_{13} \approx \Delta m^2_{23}$$

$$m_1 < m_2$$

Δm^2_{12}	$7.59 \pm 0.02 \times 10^{-5} eV^2$
Δm^2_{23}	$2.43 \pm 0.13 \times 10^{-3} eV^2$
$\sin^2 2\theta_{12}$	0.87 ± 0.03
$\sin^2 2\theta_{23}$	> 0.92
$\sin^2 2\theta_{13}$	$< 0.19 \quad (90\% CL)$

θ_{13} Experiments

- Reactors
  - Double Chooz
  - Daya Bay
  - Reno
- Accelerator Beams
  - T2K
  - NOvA



θ_{13}: phenomenology, present status and prospect", Mauro Mezzetto and Thomas Schwetz, ArXiv:1003.5800v1 [hep-ph] 30Mar2010

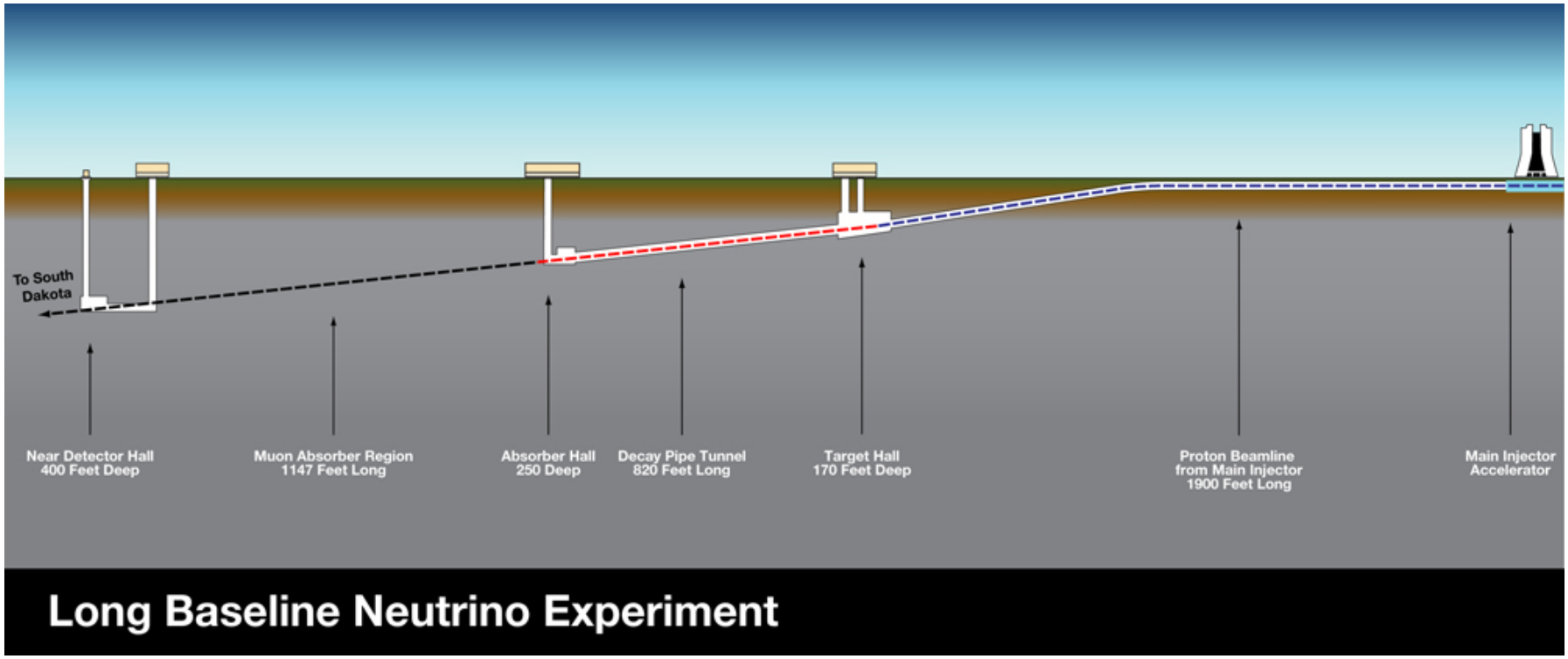
Beyond θ_{13}

- If is not too small ($\sin^2 2\theta_{13} \cong 0.01$) or larger a next generation of experiments can tackle some new questions in the neutrino sector
- This next generation of experiments have been discussed in the US, Japan and Europe
- All require upgraded beam capabilities and massive detectors

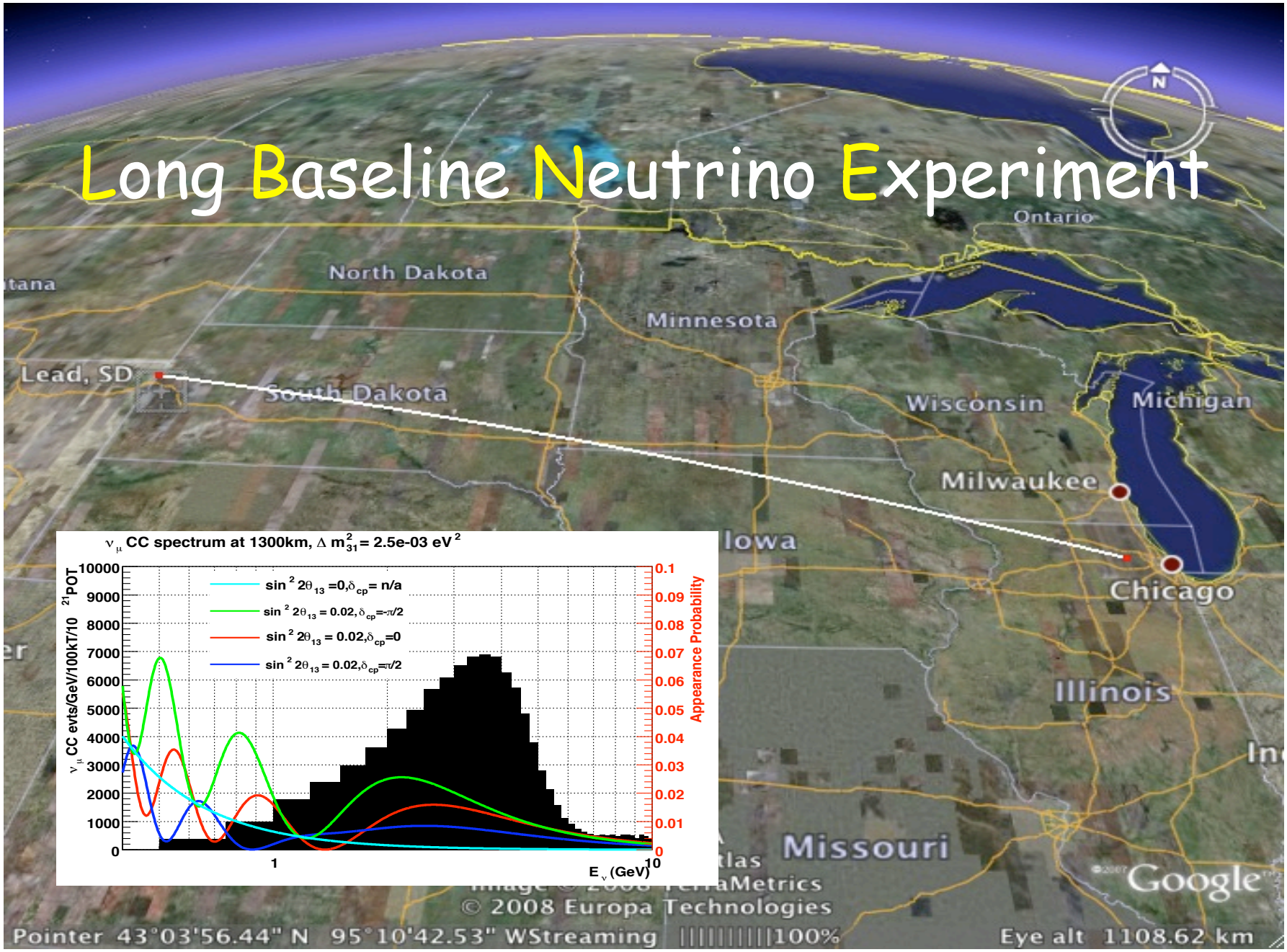
Beyond θ_{13}

- In 2008 initiated the process of preparing CD-0 (Mission Need) documentation for a Long-baseline neutrino experiment in the US
- A CD-0 for LBNE was issued in January 2010
- An analysis of alternatives for source and detector lead to the development of the conceptual design of the LBNE project

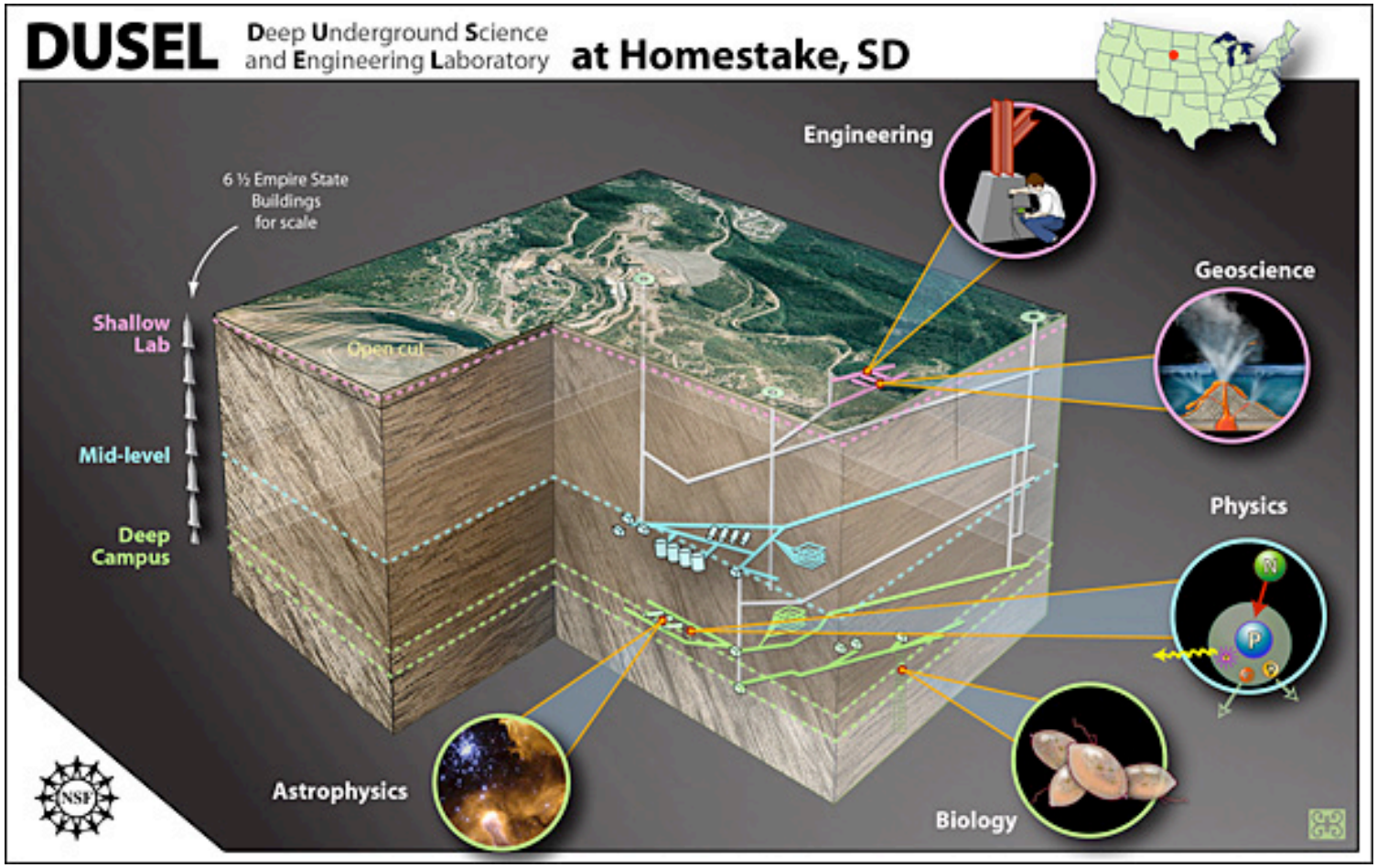
A new neutrino beam at Fermilab



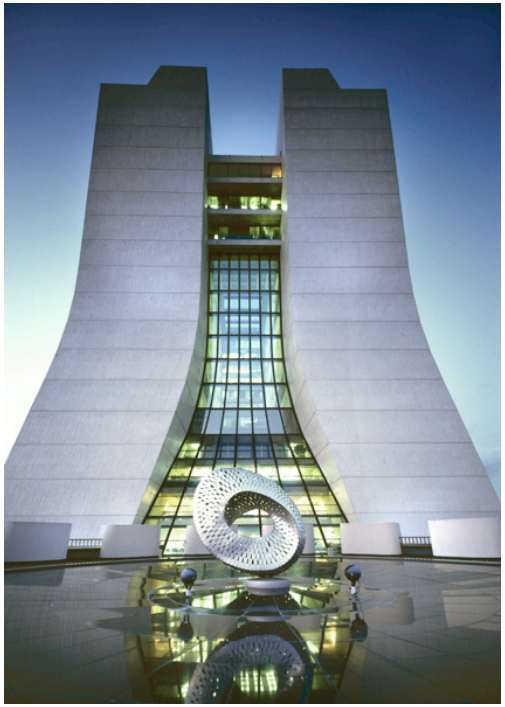
Long Baseline Neutrino Experiment

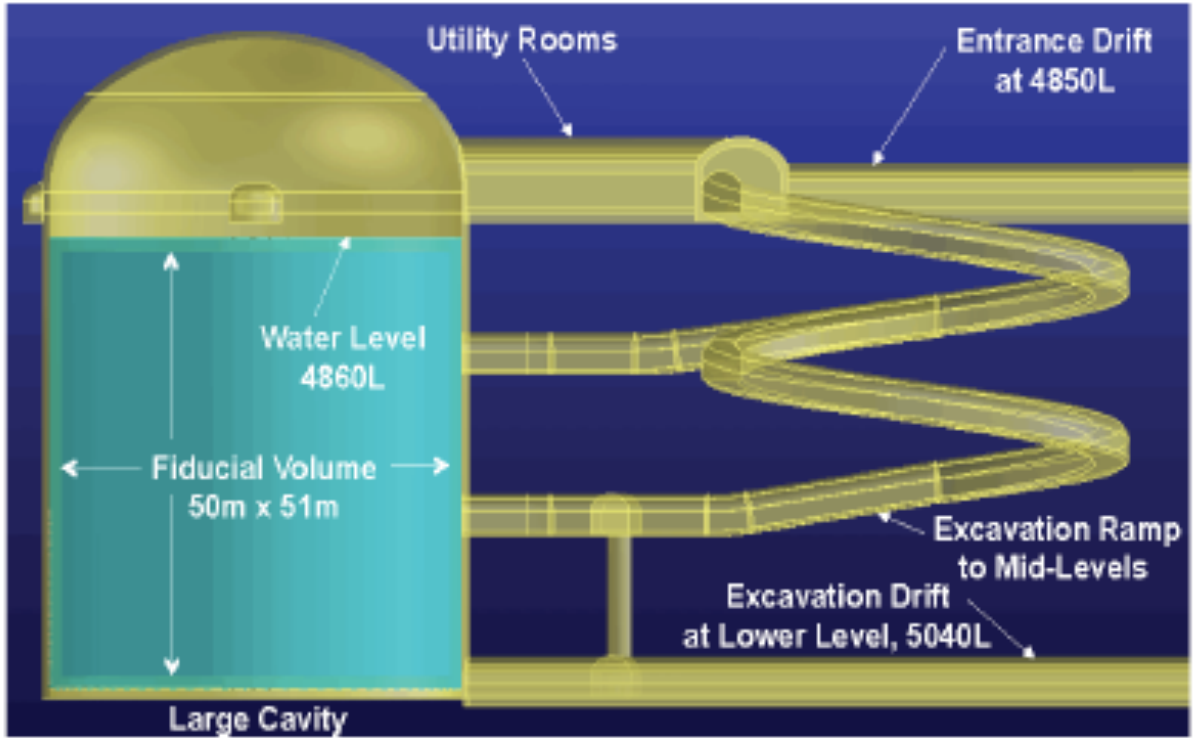


A deep underground laboratory

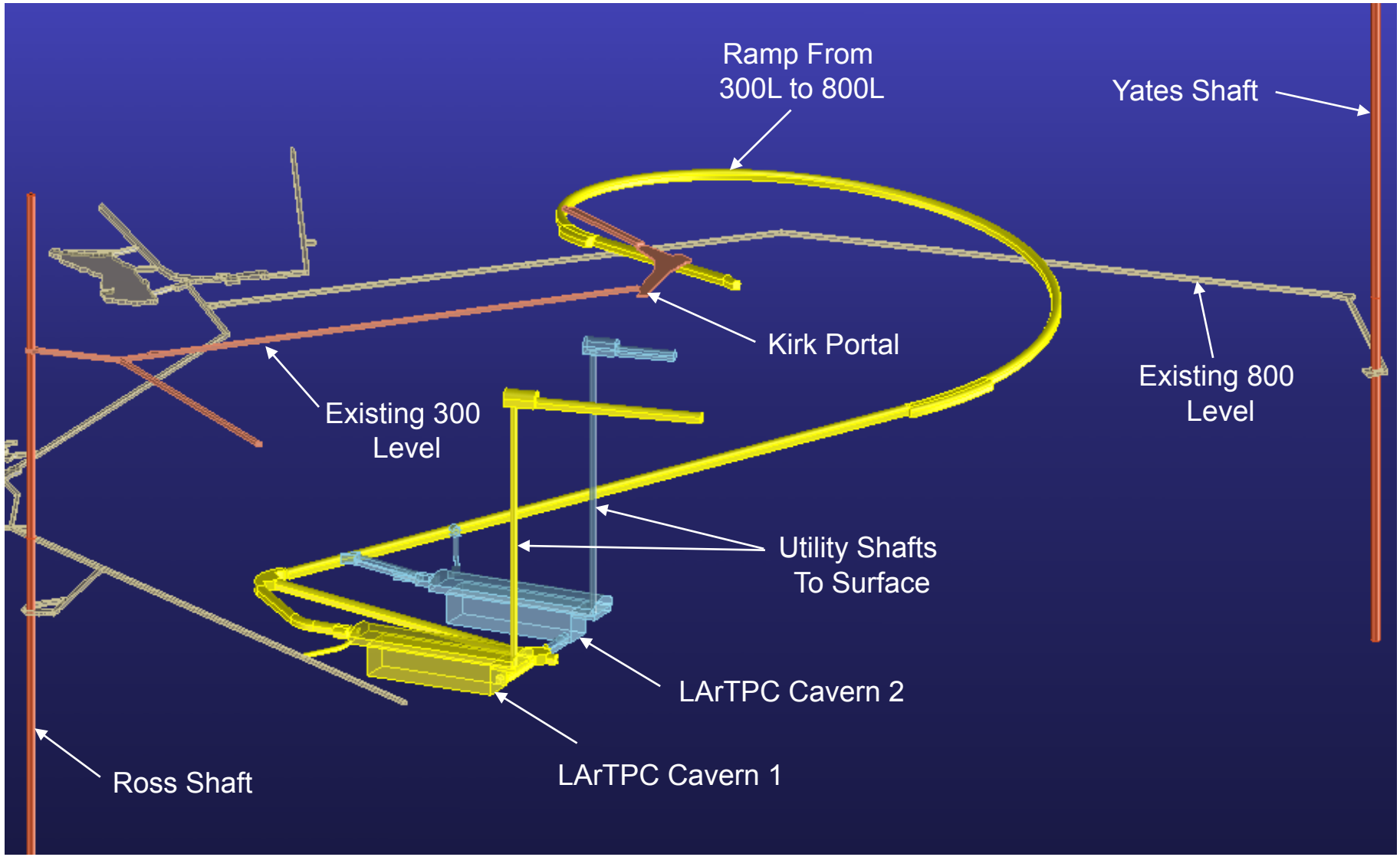


Very Large Detectors

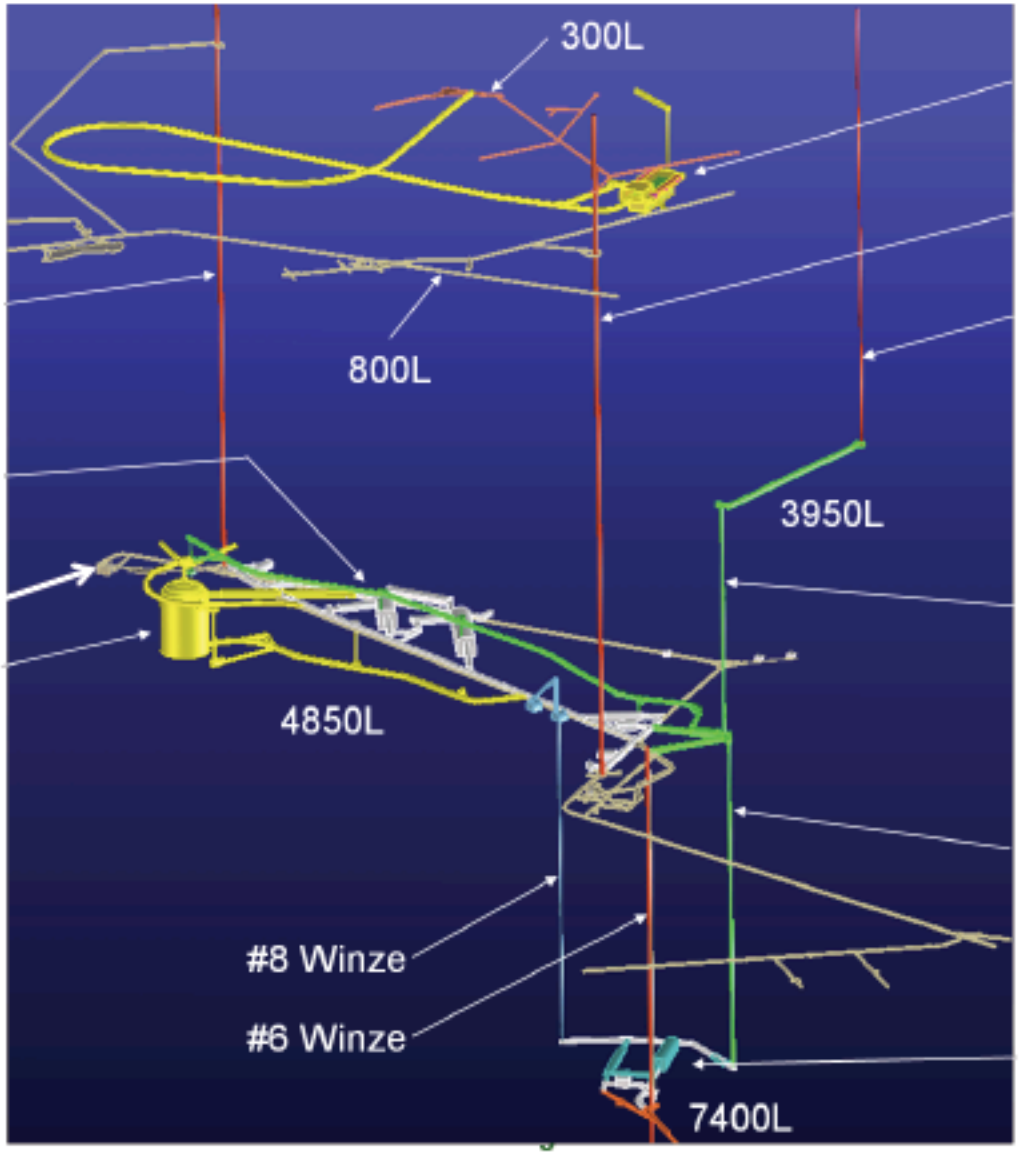




LBNE, LArTPC, 300L – 800L Plan

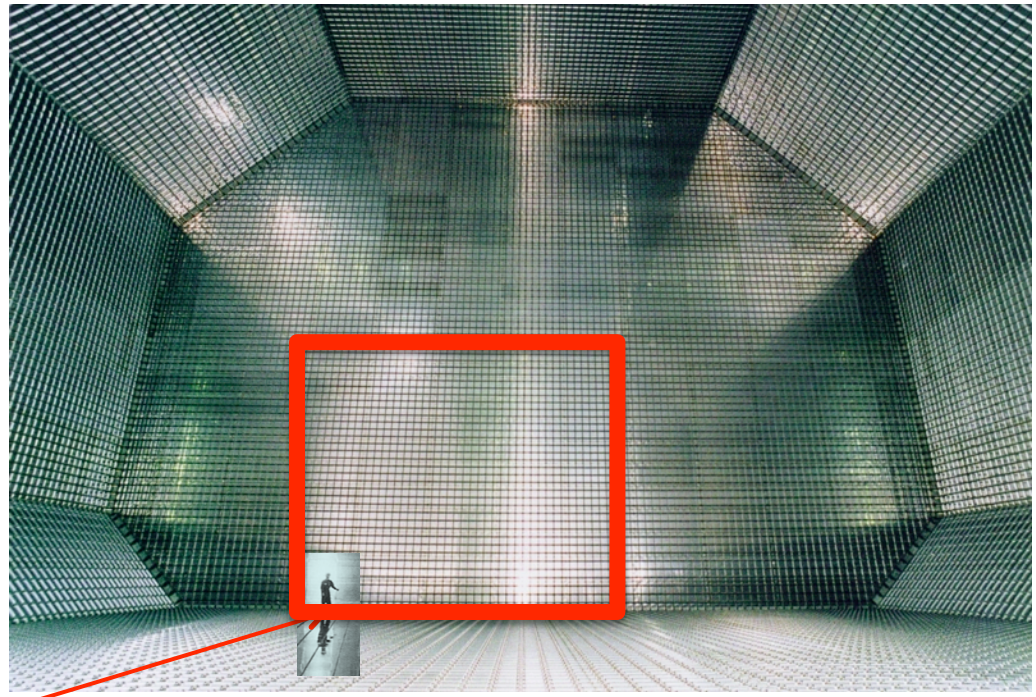


Underground Physics Lab Layout



LAr20 Membrane Cryostat interior

Figure. Roof nozzle penetration



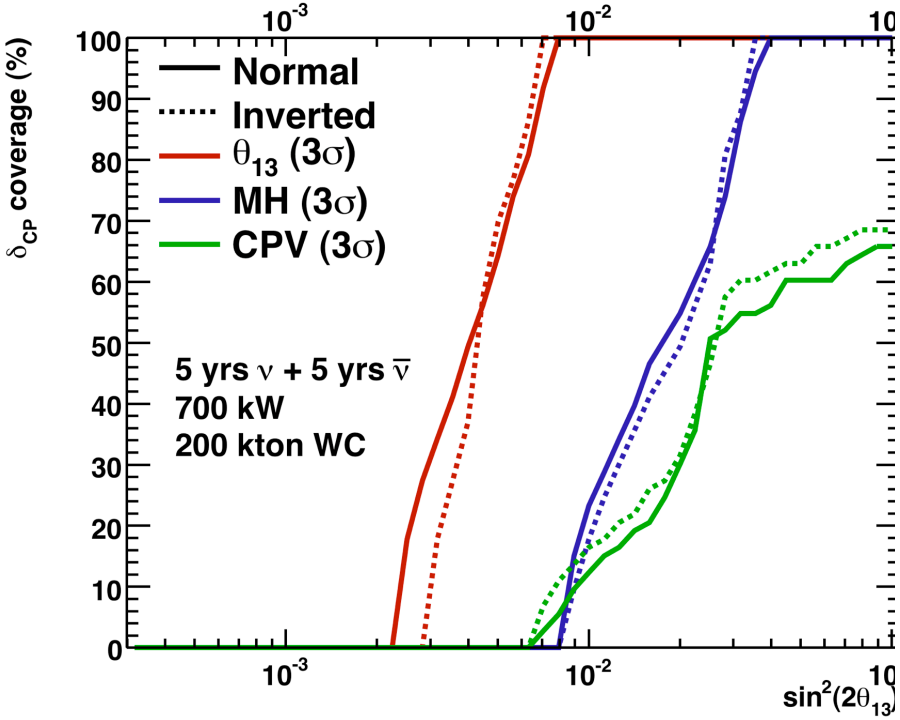
Person scale

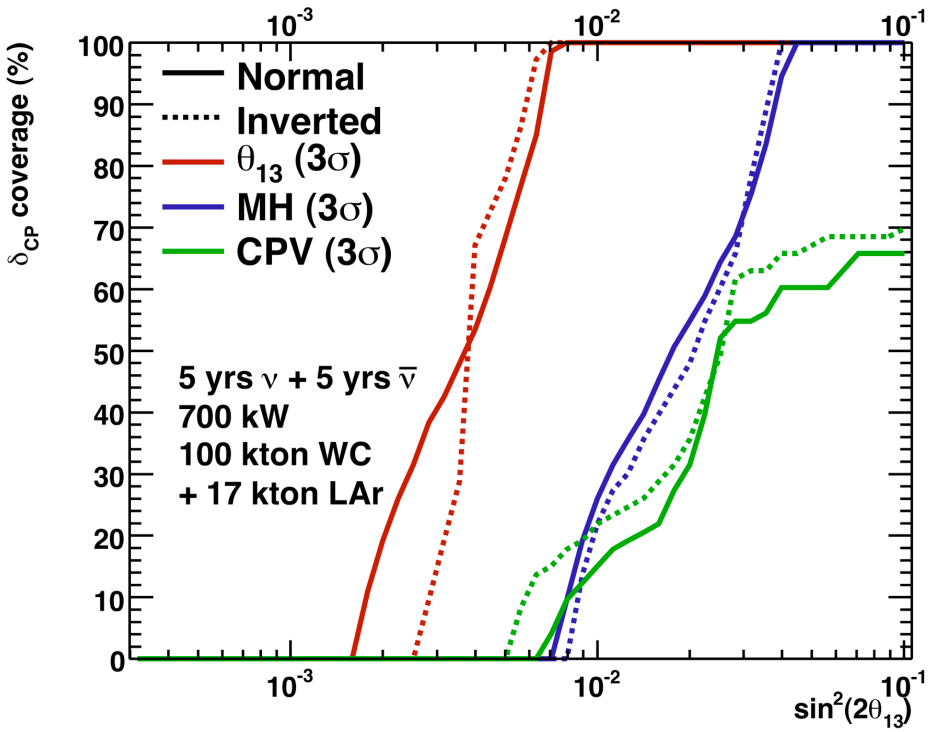
Figure. Membrane Cryostat for LNG ship tanker. This tank is 35 m high x ~45 m wide, 40,000 m^3. LAr20 will be 16 m high x 16 m wide x 74 m long 19,000 m^3.

Source: GTT & Russ Rucinski

Why 2 technologies?

Detector options for LBNE





LAr mass is chosen to match the performance of the WC

Physics goals would like to require 2 100kT WC EQUIVALENT detectors

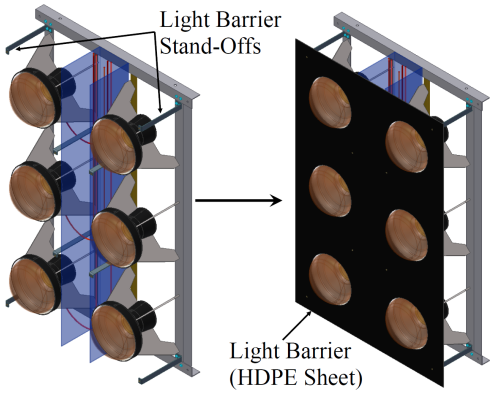
Plots by Lisa Whitehead, Brookhaven National Lab

Detector Comparisons

- Water Cherenkov
  - Proven technology
  - Needs to be deep (>1000m w.e. for beam)
  - Low efficiency for e (~10-20%) in the few GeV region (to keep NCpi0 background low)
    - Leads to the large mass requirement
- Liquid Argon
  - Developing technology
  - Should be able to operate at shallow depth
  - High efficiency for e (70-80%), good (excellent?) background rejection for e/pi0
    - Allows for the smaller mass requirement

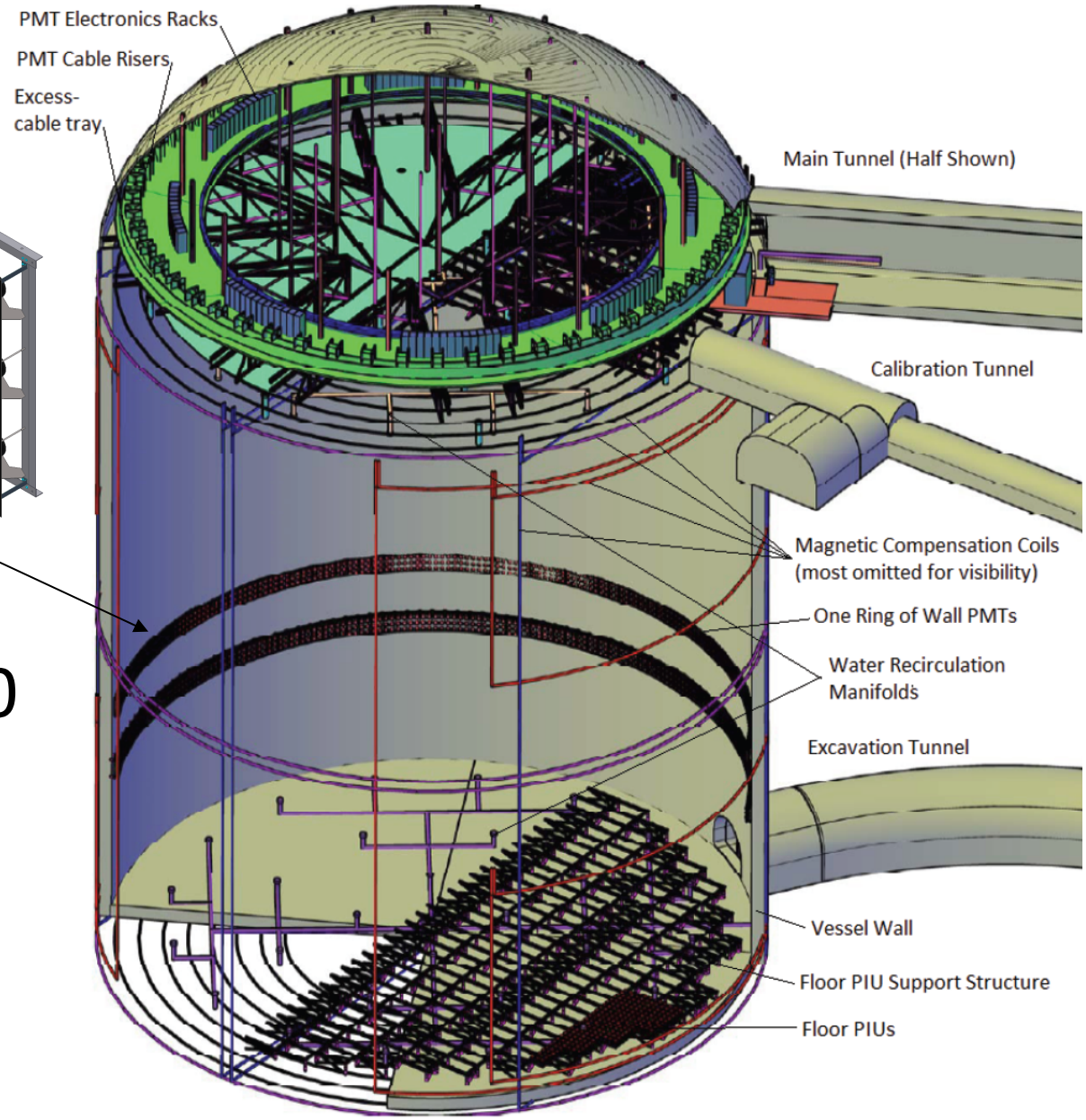
Major Challenges

- Water Cherenkov
  - Very Large
    - Unprecedented civil construction
    - Unprecedented PMT procurement
    - Depth ➔ pressure on PMTs ➔ glass strength or protection….
  - High Cost
    - Conventional Construction
    - PMTs
- Liquid Argon
  - Achieving purity in LAr
    - Large volume ➔ long drift
    - Would like to not have to evacuate the large volume cryostat
  - Developing low cost, low noise electronics (650K channels)
  - Understanding the cost
    - Appears to be less expensive than water (for equivalent physics) but needs to be proven
    - Driven by smaller caverns

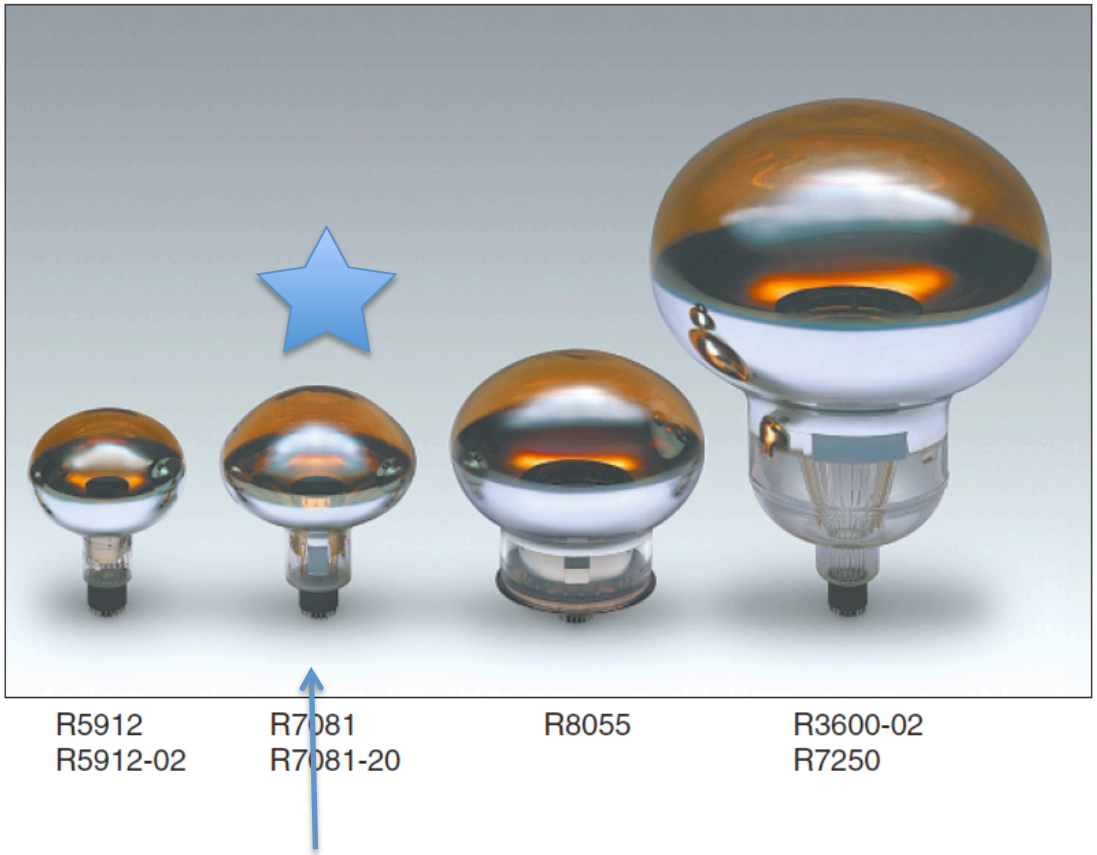


Wall PIU

Need 50,000



PMT's



50,000 10" High Q.E. tube; standard QE tube ➔ ~65,000
Cost-benefit analysis

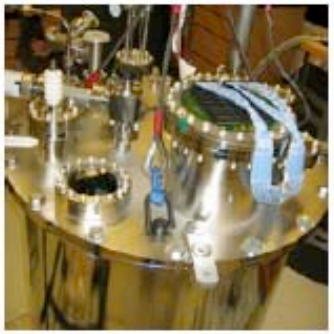
Unit cost ~ $1 – 2 K

Liquid-Argon Time Projection Chambers

Status of R&D Program in the US

The first TPCs in the United States:

Yale TPC



Location: Yale University
Active volume: 0.00002 kton
Year of first tracks: 2007

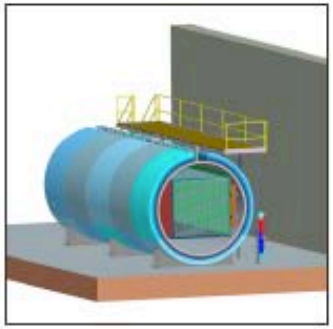
Bo

Location: Fermilab
Active volume: 0.00002 kton
Year of first tracks: 2008

ArgoNeuT

Location: Fermilab
Active volume: 0.0003 kton
Year of first tracks: 2008
First neutrinos: June 2009

MicroBooNE



Location: Fermilab
Active volume: 0.1 kton
Start of construction: 2010

Test stands to improve liquid-argon technology:

Luke

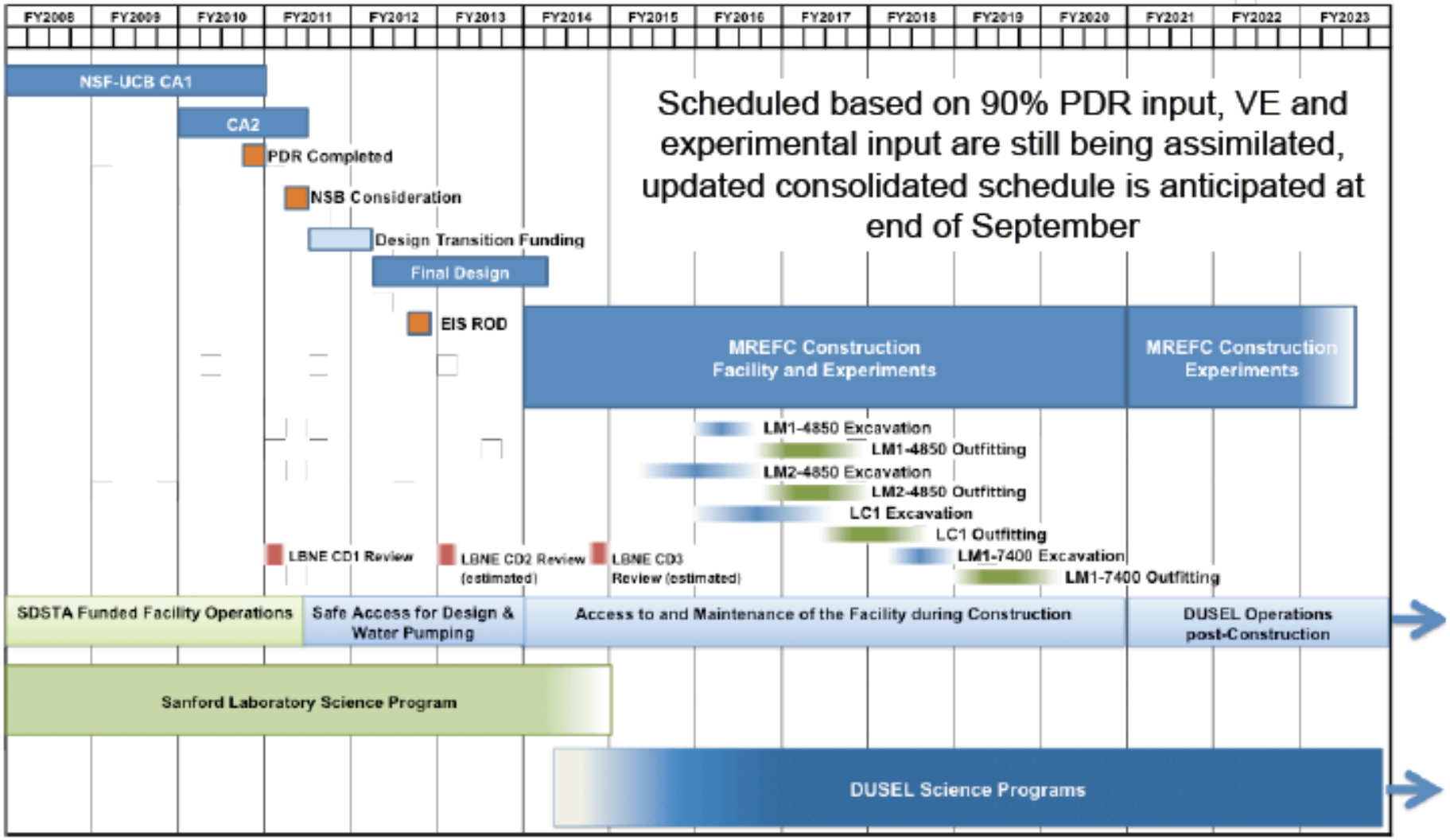
Location: Fermilab
Purpose: materials test station
Operational: since 2008

LAPD

Location: Fermilab
Purpose: LAr purity demo
Operational: 2010

What to do NEXT to prove that we can build a 20kT module?

Project Milestone Schedule through Construction



Scheduled based on 90% PDR input, VE and experimental input are still being assimilated, updated consolidated schedule is anticipated at end of September

LBNE Milestones/Timeline

- Department of Energy CD-0
  - January 2010
- CD-1 Review and Approval
  - January-May 2011
- CD-2 (Cost and Schedule Baseline)
  - 2013
- CD-3 : Start Construction!
  - 2015
- CD-4 : Start Operations !
  - 2020-2021 (if all goes well)

Timing Dilemmas

- We need cost estimates and resource loaded schedules for CD-1 ➔ NOW
- Puts pressure on the project teams to do a technology selection as soon as possible
  - Difficult to demonstrate capability and feasibility of LAr
- Long lead procurement (6-8 yr delivery schedules) ➔ we would need to place orders for PMT's shortly after CD-2
  - ➔difficult to imagine a scenario of waiting for a newer, cheaper technology

Considerations about detector development/evolution

- We need to make technology choices for our program than we will be running in the 2020 decade
- We are planning to make a ~$1B investment in this program
- We expect it to operate, in some fashion, for >> 10 years
- Investment in new technologies for detection of neutrinos and other rare phenomena should be a high priority

Conclusions

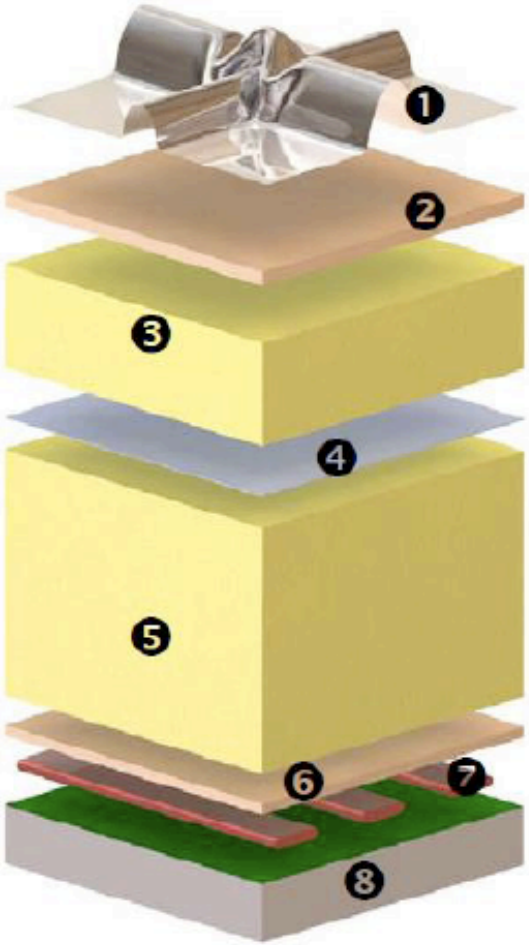
- Neutrino physics employs a diverse suite of detector technologies
- Future accelerator based neutrino detectors need to be large
  - High detection efficiency can mitigate the size
- For some physics topics the size shouldn't be compromised, so cost reduction of the instrumentation is key

Backup Slides

A quick lesson in “Project Speak”

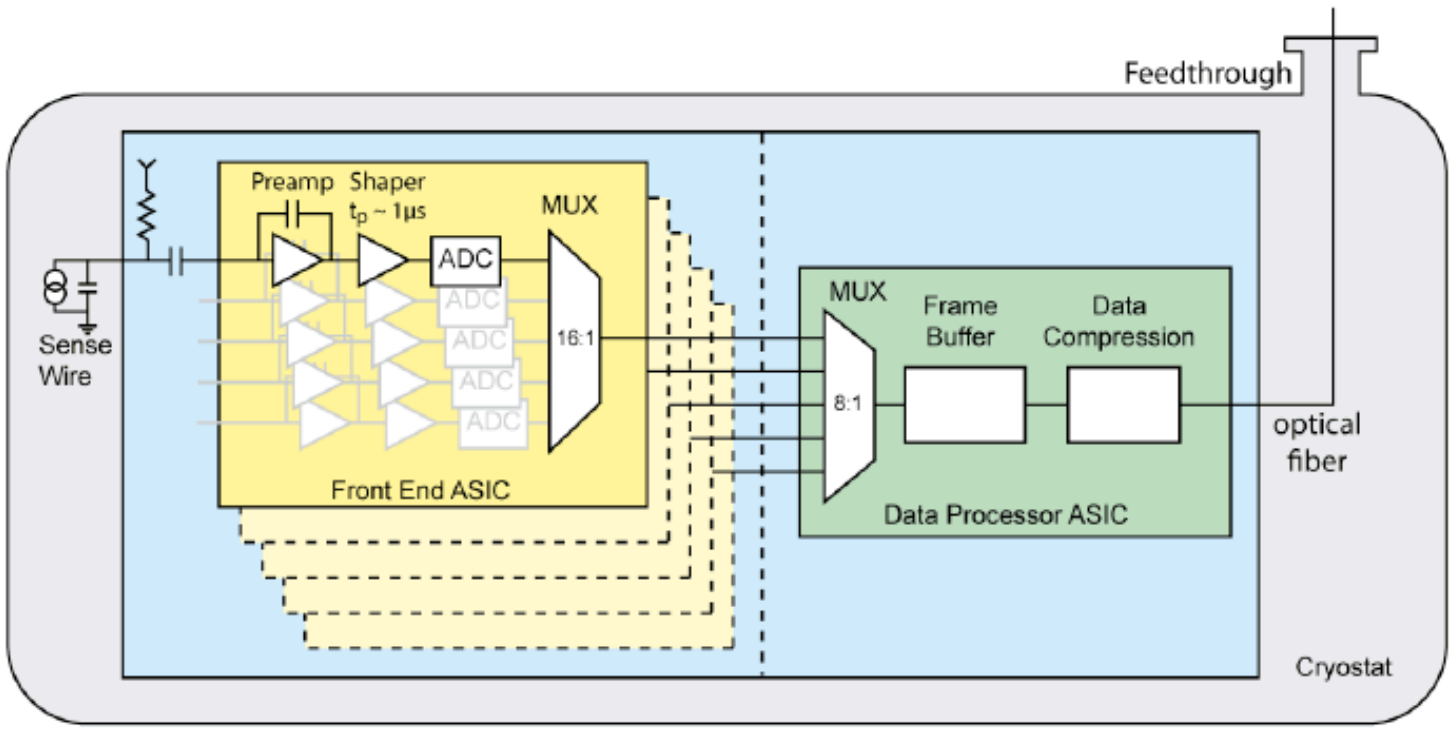
- New Department of Energy Project’s must pass through a “Critical Decision” process : CDs
- CD-0
  - Approval to do conceptual design
- CD-1
  - What can you do, and for how much $$? When could you do it?
- CD-2
  - How much does it *really* cost and how long will it *really* take?
- CD-3
  - What are you really going to build and are you really ready to build it?
- CD-4
  - Does it work? Did we get what we paid for?

Membrane Cryostat



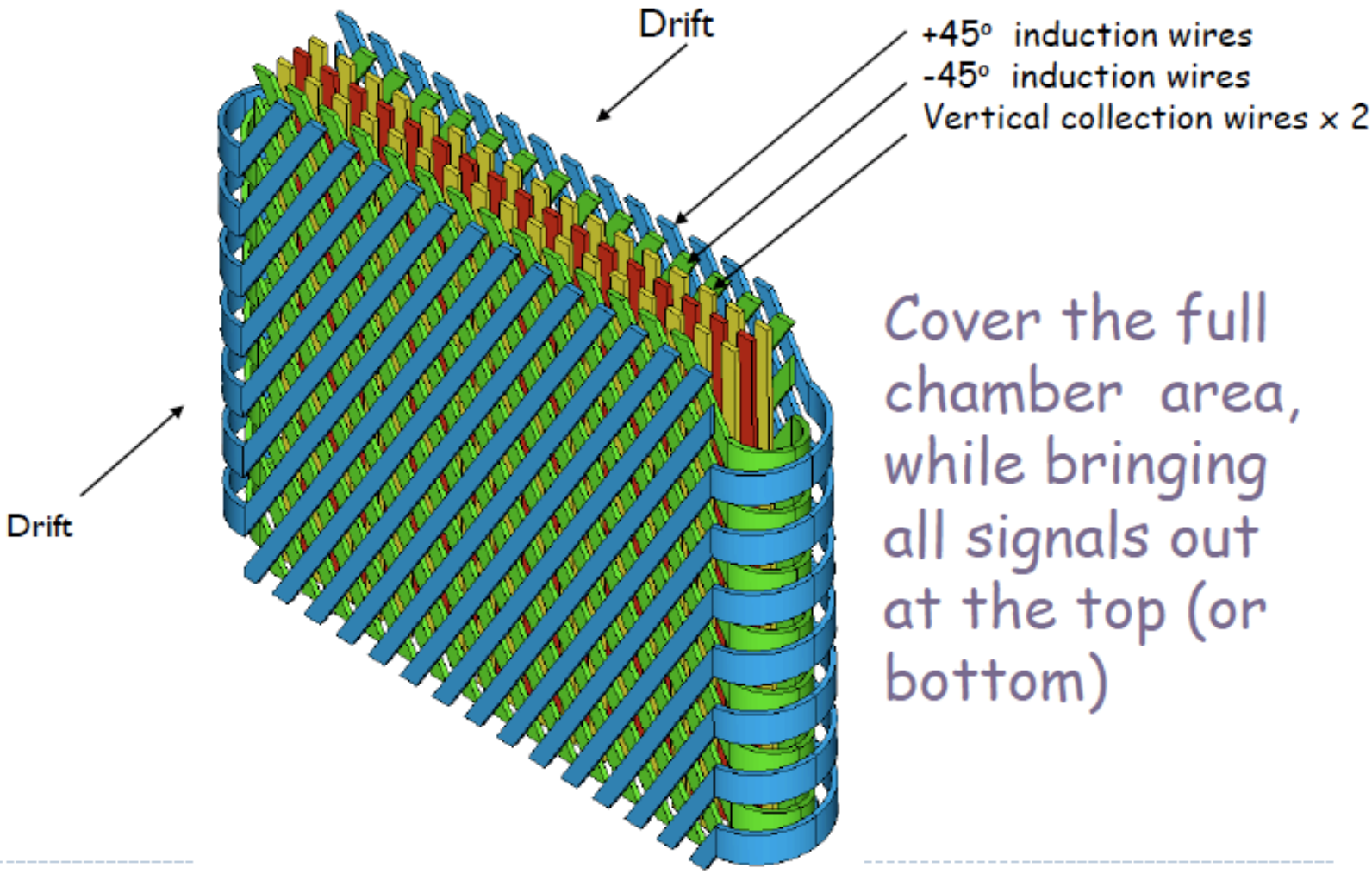
1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Concrete covered with moisture barrier

Cold Electronics



Power ~ 10mW/channel
Cost = $3.5M design & prototyping + $5/channel (including ASICs, boards, feedthroughs)

Anode Plane Assembly (APA)



Cover the full chamber area, while bringing all signals out at the top (or bottom)