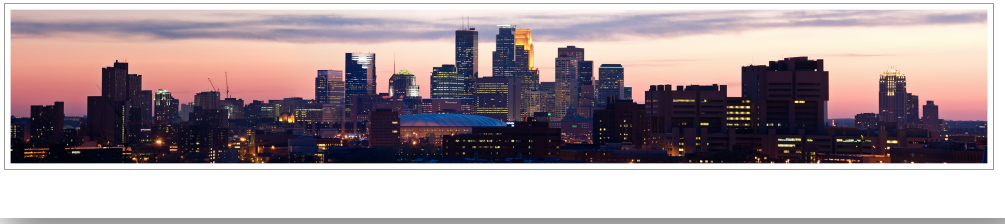
B. Fleming
SWAPS 2014
June 12th, 2014

The US-based Long Baseline Neutrino Program

- LBL goals
- LBNE -> LBNF – *comments from the US P5 report….*
- LBNF as part of a coherent, international SBL and LBL program

Snowmass on the Mississippi Summer 2013

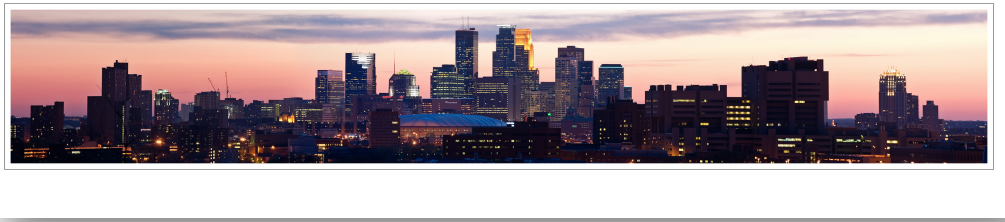


Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

- The Science Drivers:
  - **Use the Higgs boson as a new tool for discovery**
  - **Pursue the physics associated with neutrino mass**
  - **Identify the new physics of dark matter**
  - **Understand cosmic acceleration: dark energy and inflation**
  - **Explore the unknown: new particles, interactions, and physical principles**

Snowmass on the Mississippi Summer 2013



Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

5 science drivers

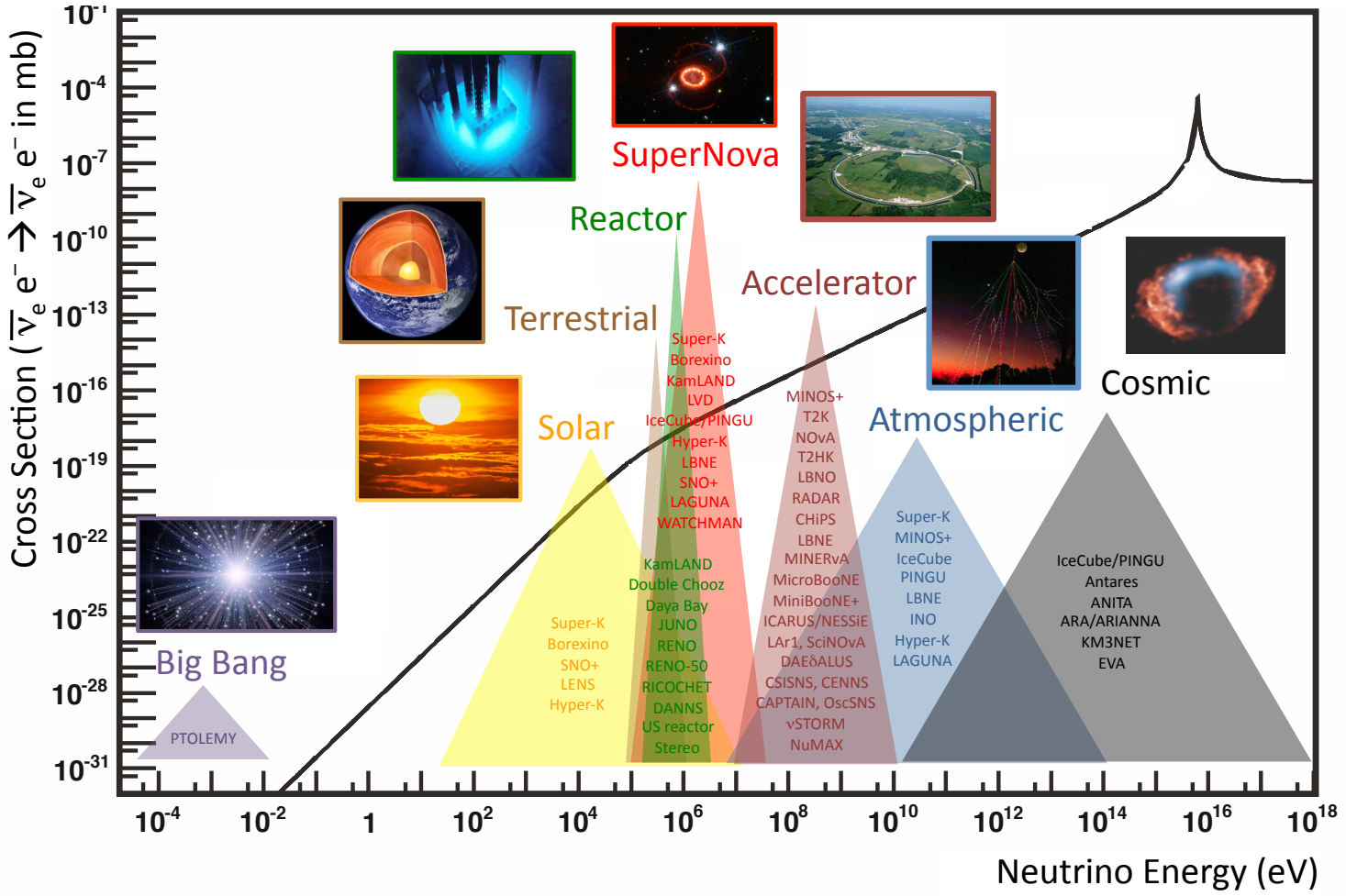
Particle Physics is Global

The United States and major players in other regions can together address the full breadth of the field's most urgent scientific questions if each hosts a unique world-class facility at home and partners in high-priority facilities hosted elsewhere.

- Hosting world-class facilities and joining partnerships in facilities hosted elsewhere are both essential components of a global vision.

Many Neutrinos over many different energies!
Tell us about neutrinos and about the universe…

Oscillations over broad range of distances and energies..



The three neutrino paradigm

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

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

neutrino mass states

Measured mass splittings and mixing angles

$\theta_{12} \approx 34°$

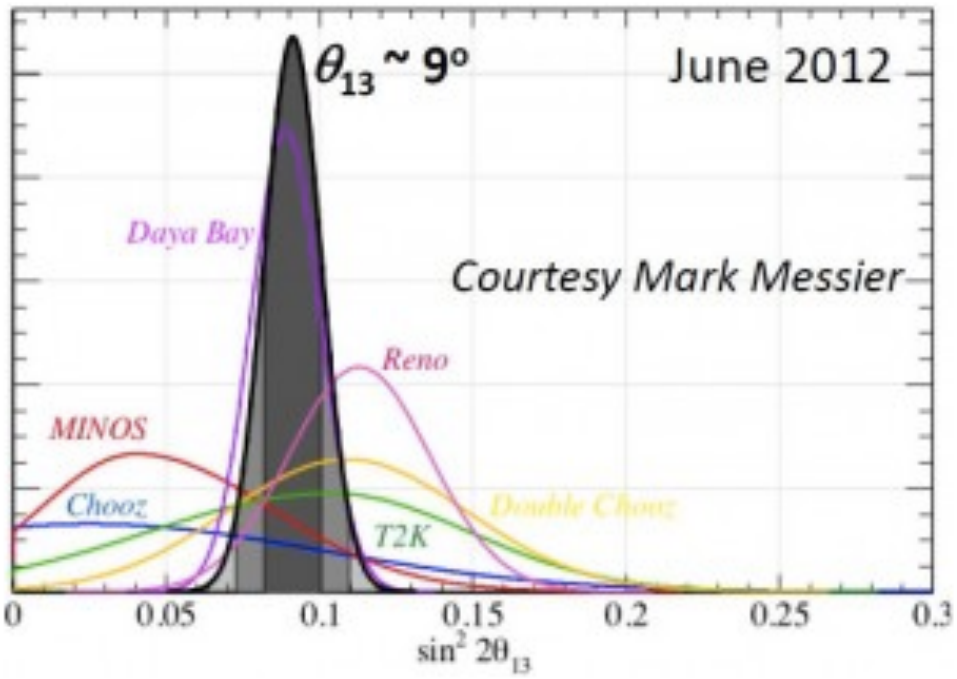
$\theta_{23} \approx 45°$

$\theta_{13} \approx 9°$

$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$

$|\Delta m^2_{31}| \approx 2.4 \times 10^{-3} eV^2$

$\delta_{CP} = \ ?$



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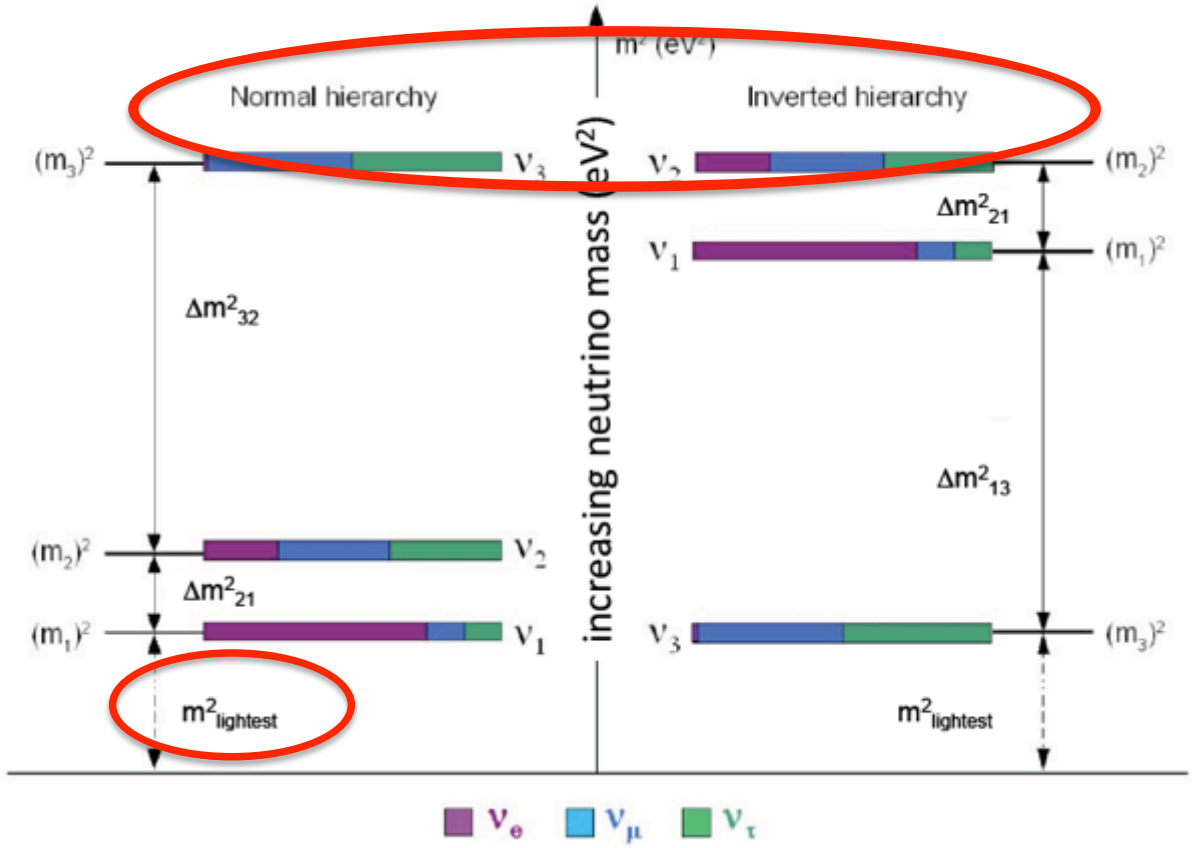

- what is the neutrino mass ordering?

$$\theta_{12} \approx 34^\circ$$

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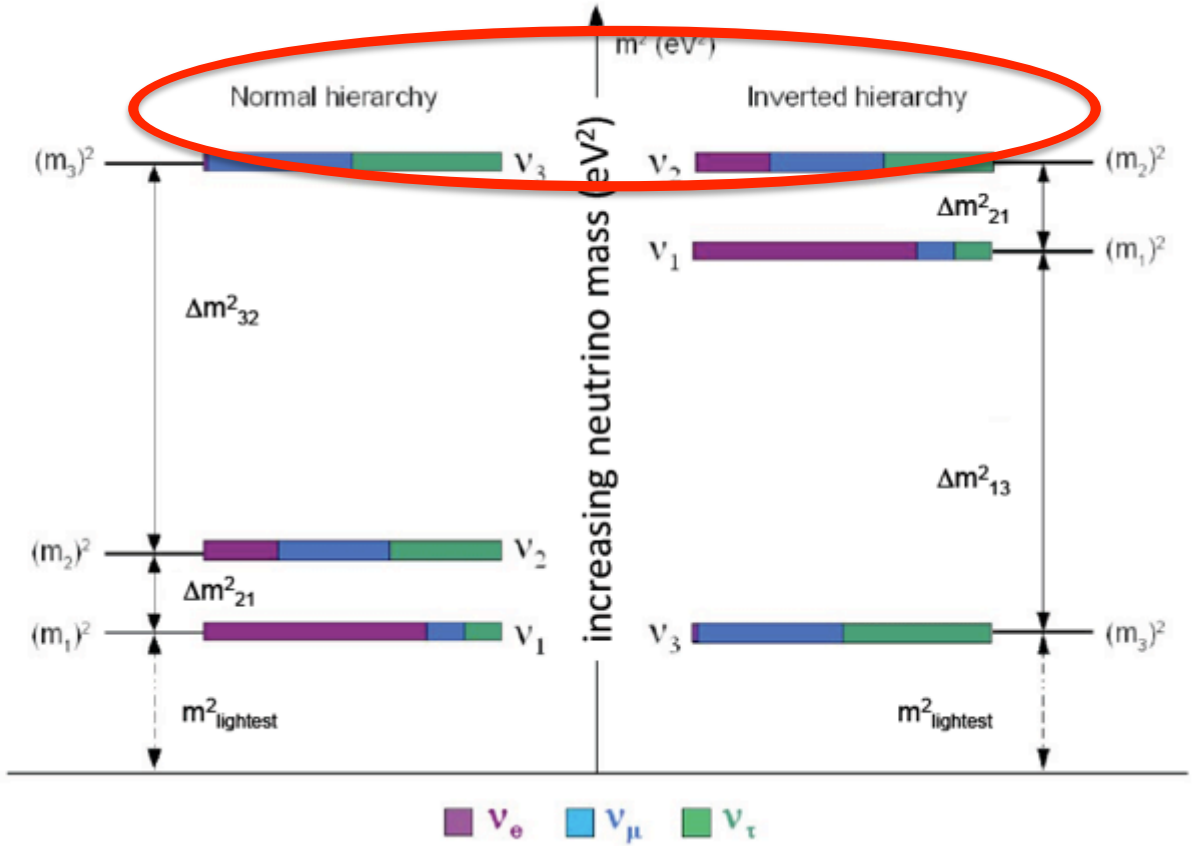


*- is **CP** violated in the neutrino sector?*

(do neutrinos oscillate at the same rate as anti-neutrinos?)

*- to what extent does the 3ν paradigm **describe nature**?*

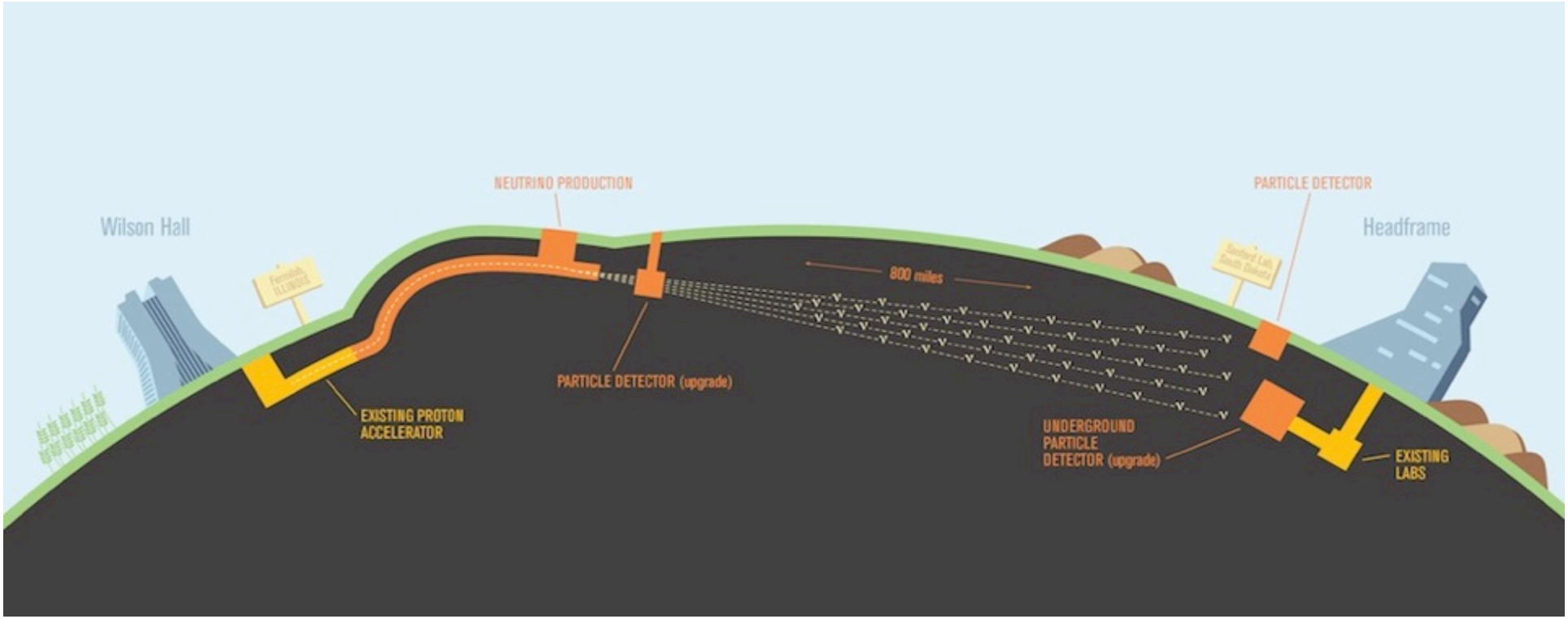
Pursue the physics associated with neutrino mass

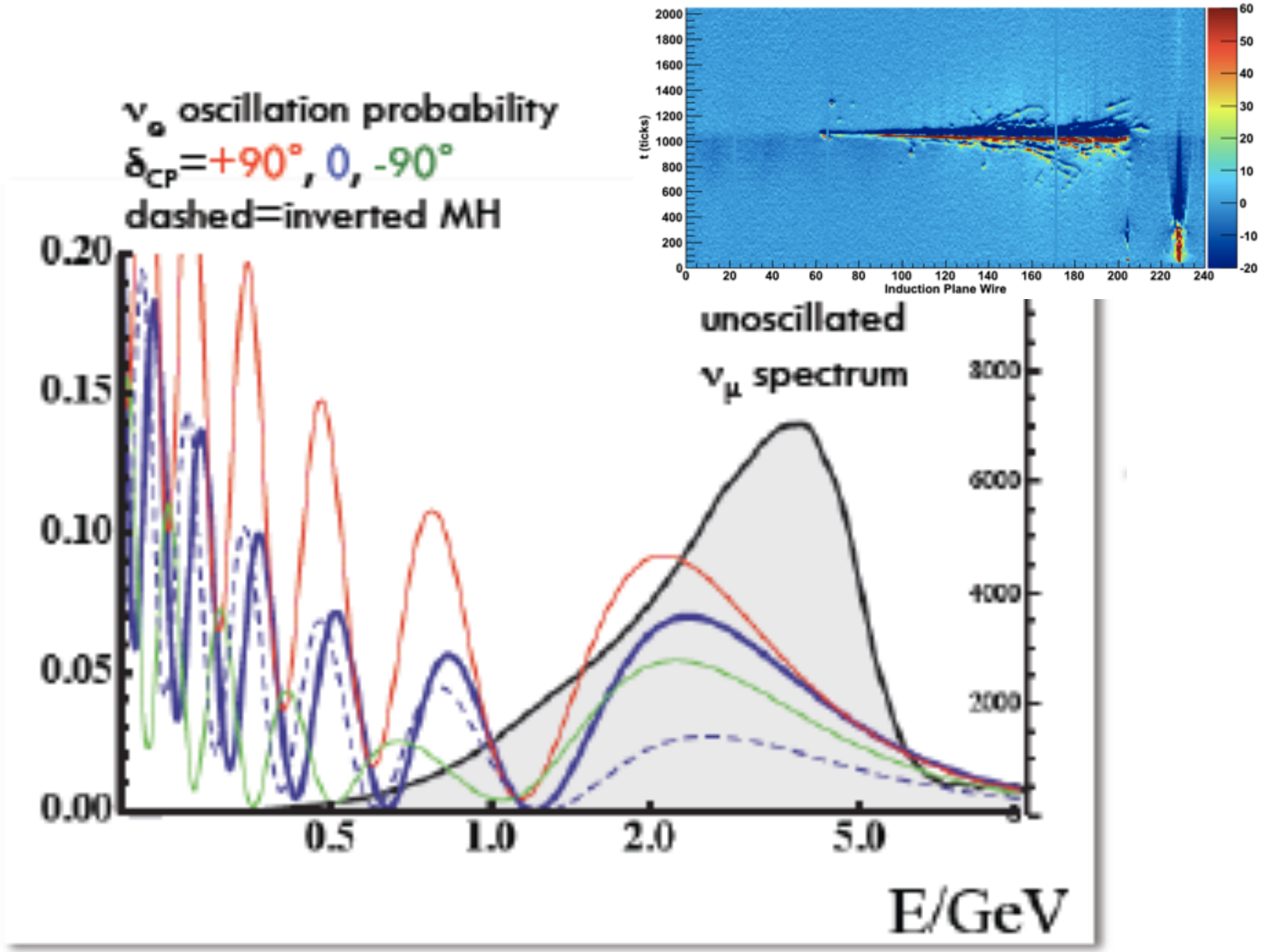
- Propelled by surprising discoveries from a series of pioneering experiments, neutrino physics has progressed dramatically over the past two decades, with a promising future of continued discovery.
- Many aspects of neutrino physics are puzzling. Powerful new facilities are needed to move forward, addressing:
  - *What is the origin of neutrino mass? How are the masses ordered (referred to as mass hierarchy)? What are the masses? Do neutrinos and anti-neutrinos oscillate differently? Are there additional neutrino types or interactions? Are neutrinos their own antiparticles?*

- **The U.S. is well positioned to host a world-leading neutrino physics program, which includes an optimized set of short- and long-baseline neutrino oscillation experiments**
  - The long-term focus is a **reformulated venture referred to here as the Long Baseline Neutrino Facility (LBNF), an internationally designed, coordinated, and funded program with Fermilab as host.**
  - LBNF would combine a high-intensity neutrino beam and a large-volume precision detector sited underground a long distance away to make accurate measurements of the oscillated neutrino properties. This large detector would also search for proton decay and neutrinos from supernova bursts.

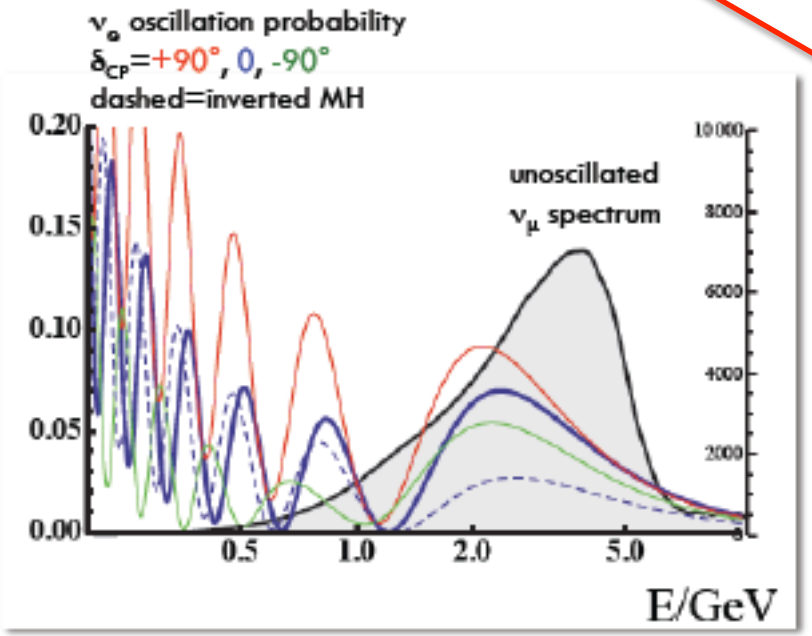
Long Baseline Neutrino Experiment (LBNE)

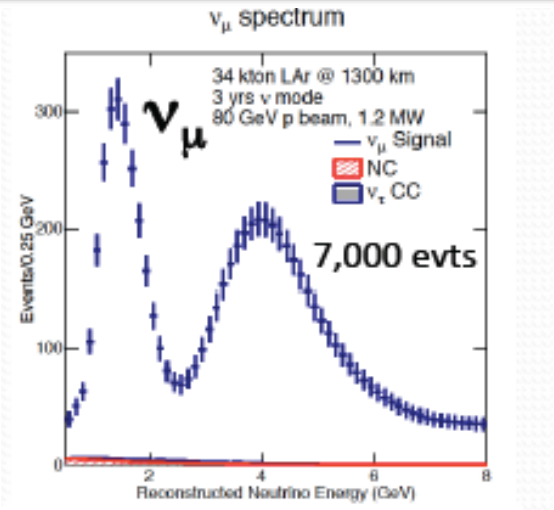
- Wide band beam – 0.5-10 GeV new neutrino beam at Fermilab
- Observe oscillation spectrum 0.5-10 GeV
- Baseline of 1300km from Fermilab to Homestake – lots of matter to observe mass hierarchy effects
- 34kton LArTPC far detector
- Determine mass hierarchy, Meausre CP Violation at the same time



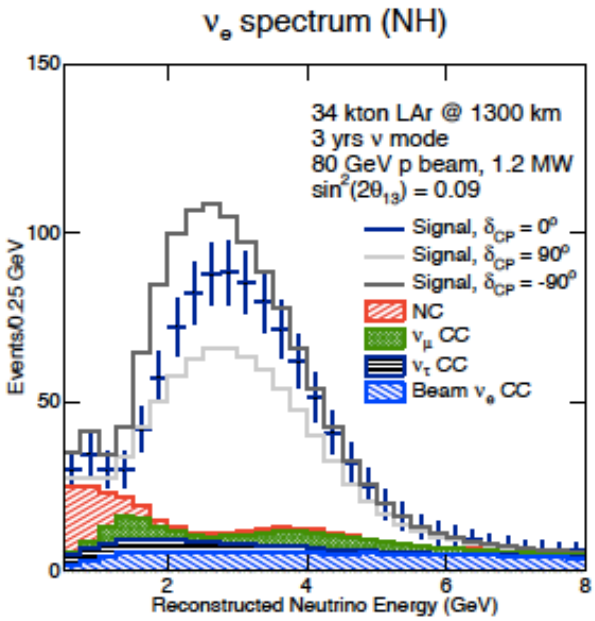

ν_e oscillation probability
δ_{CP}=+90°, 0, -90°
dashed=inverted MH
0.20
0.15
0.10
0.05
0.00
0.5
1.0
2.0
5.0
E/GeV
unoscillated
ν_μ spectrum
3000
6000
4000
2000
t (ticks)
Induction Plane Wire

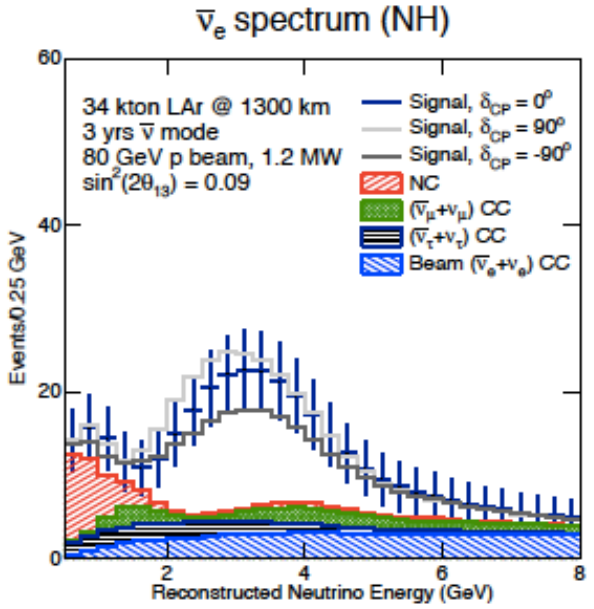
ν_e appearance for neutrinos and anti-neutrinos



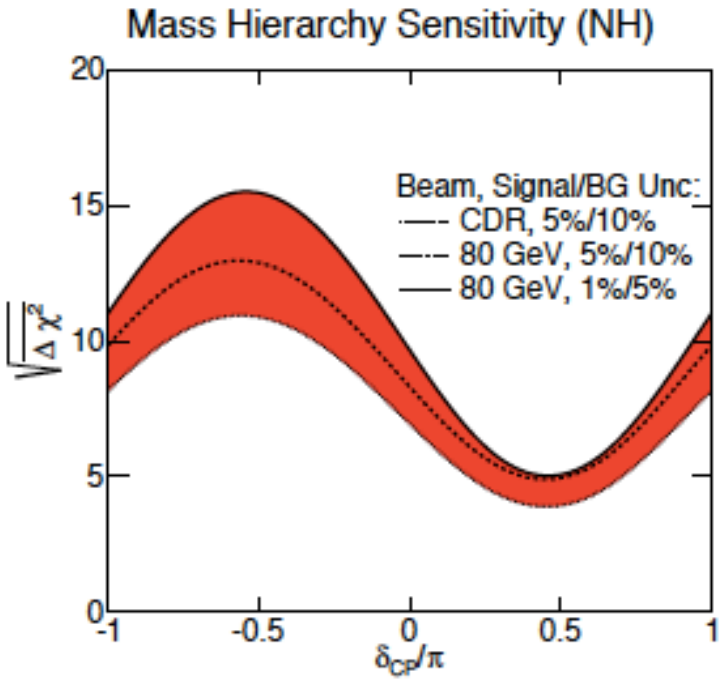


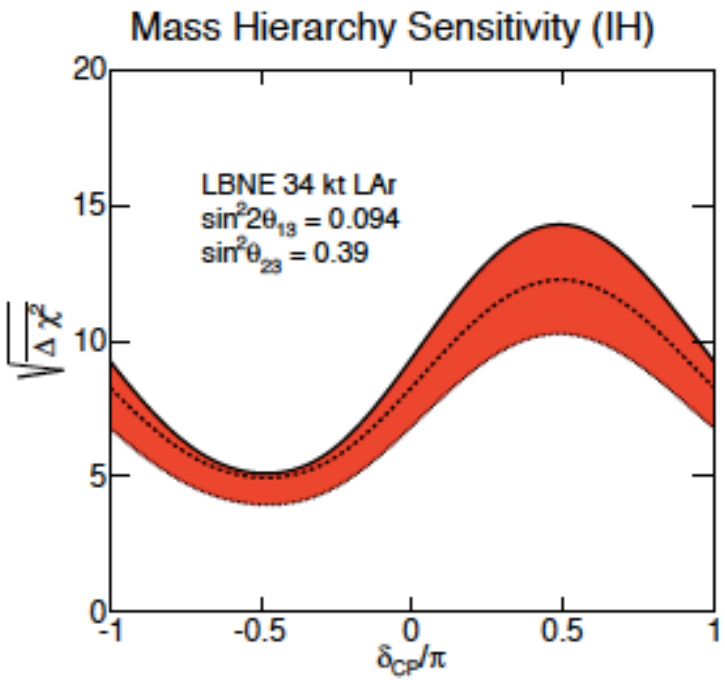
ν_μ dis-appearance

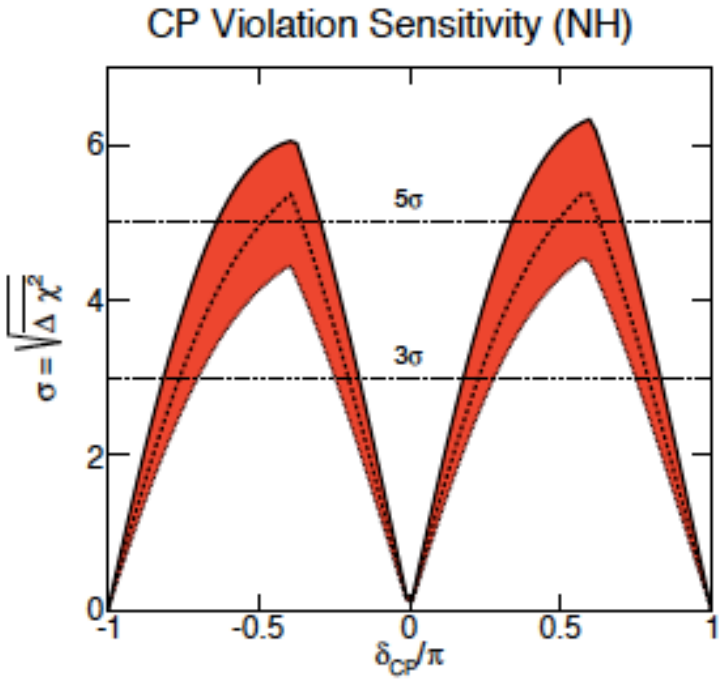


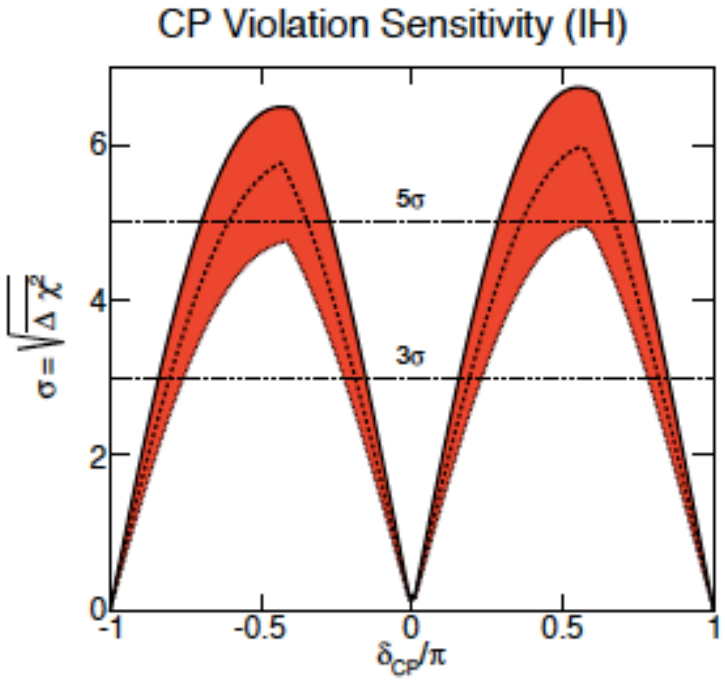


Translates to sensitivity for Mass Hierarchy and CP Violation









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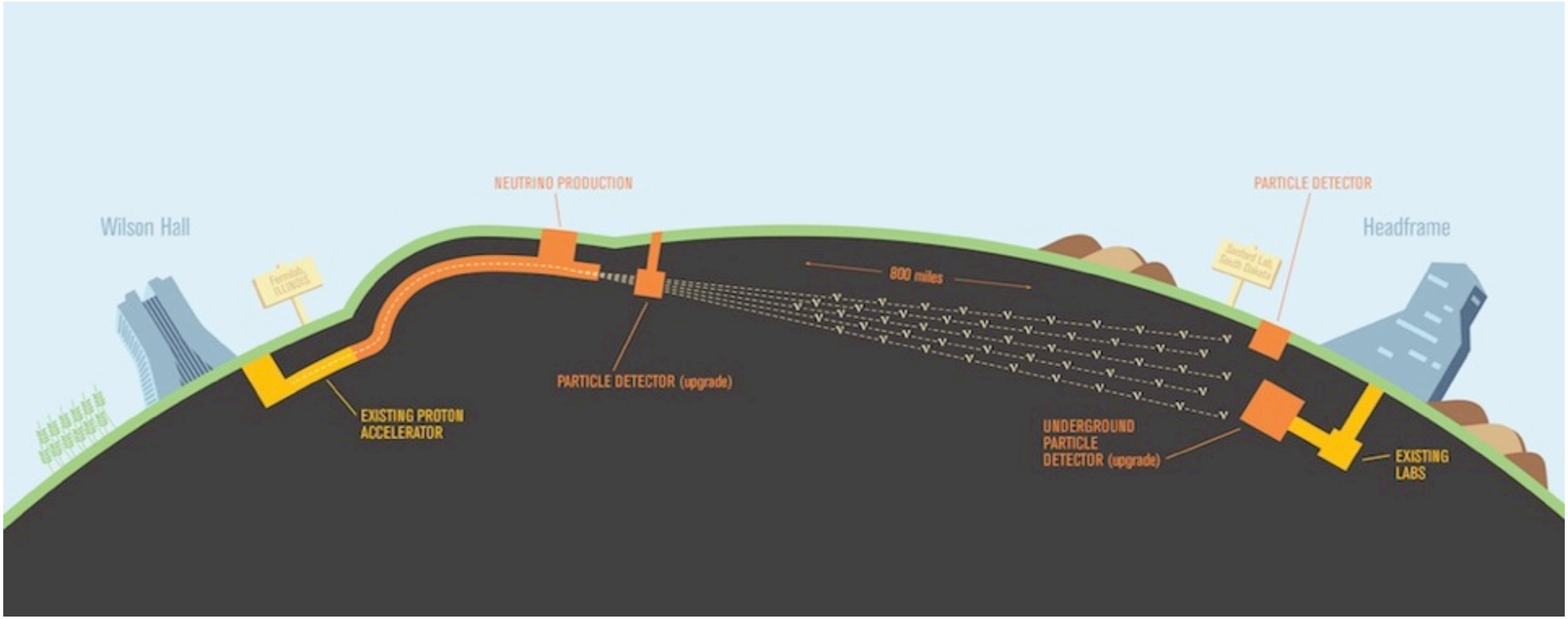
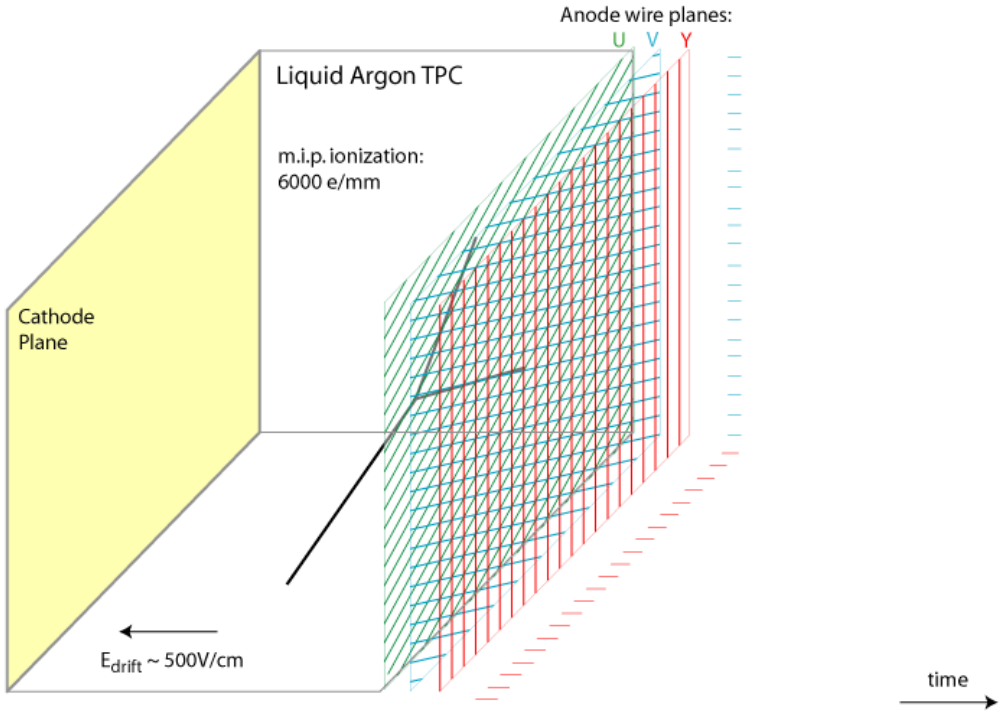


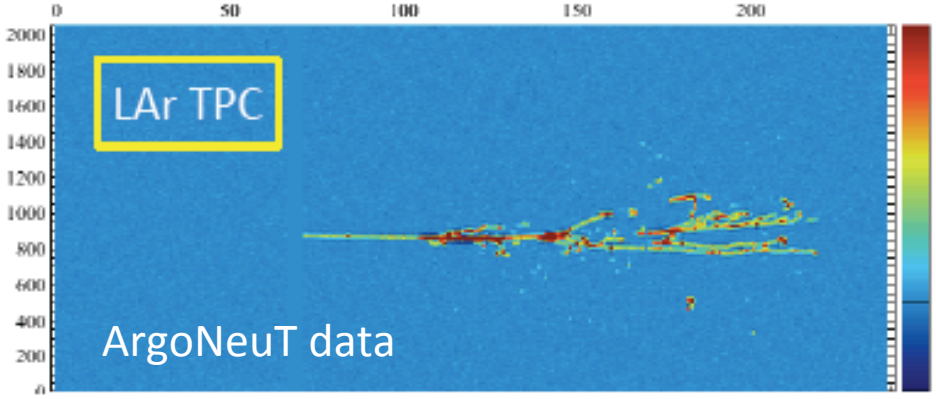
LArTPCs

- Passing charged particles ionize Argon
- Electric fields drift electrons meters to wire chamber planes
- Induction/Collection planes image charge, record dE/dx

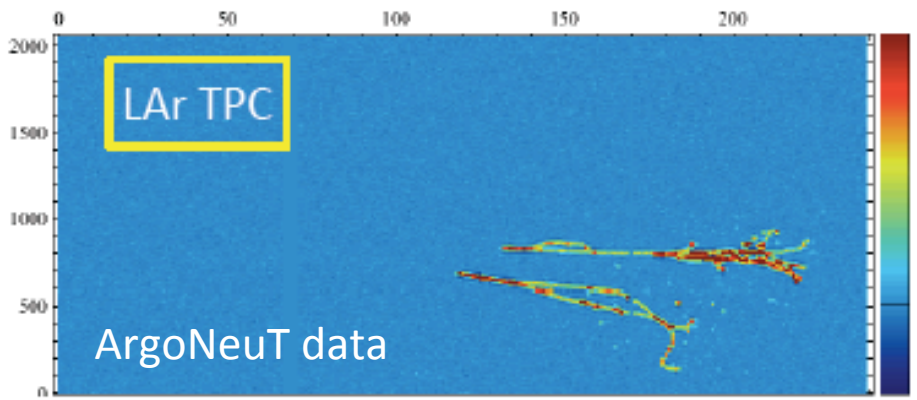


Electron/photon Separation with LAr TPCs

1 GeV electron shower



Decay of a 1 GeV π^0 to two photons.

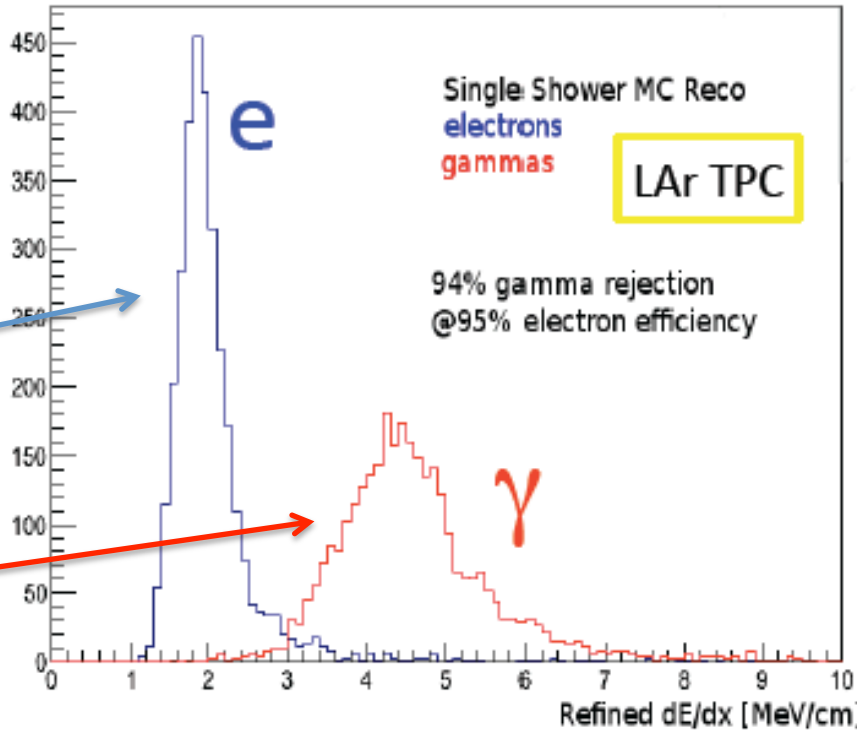


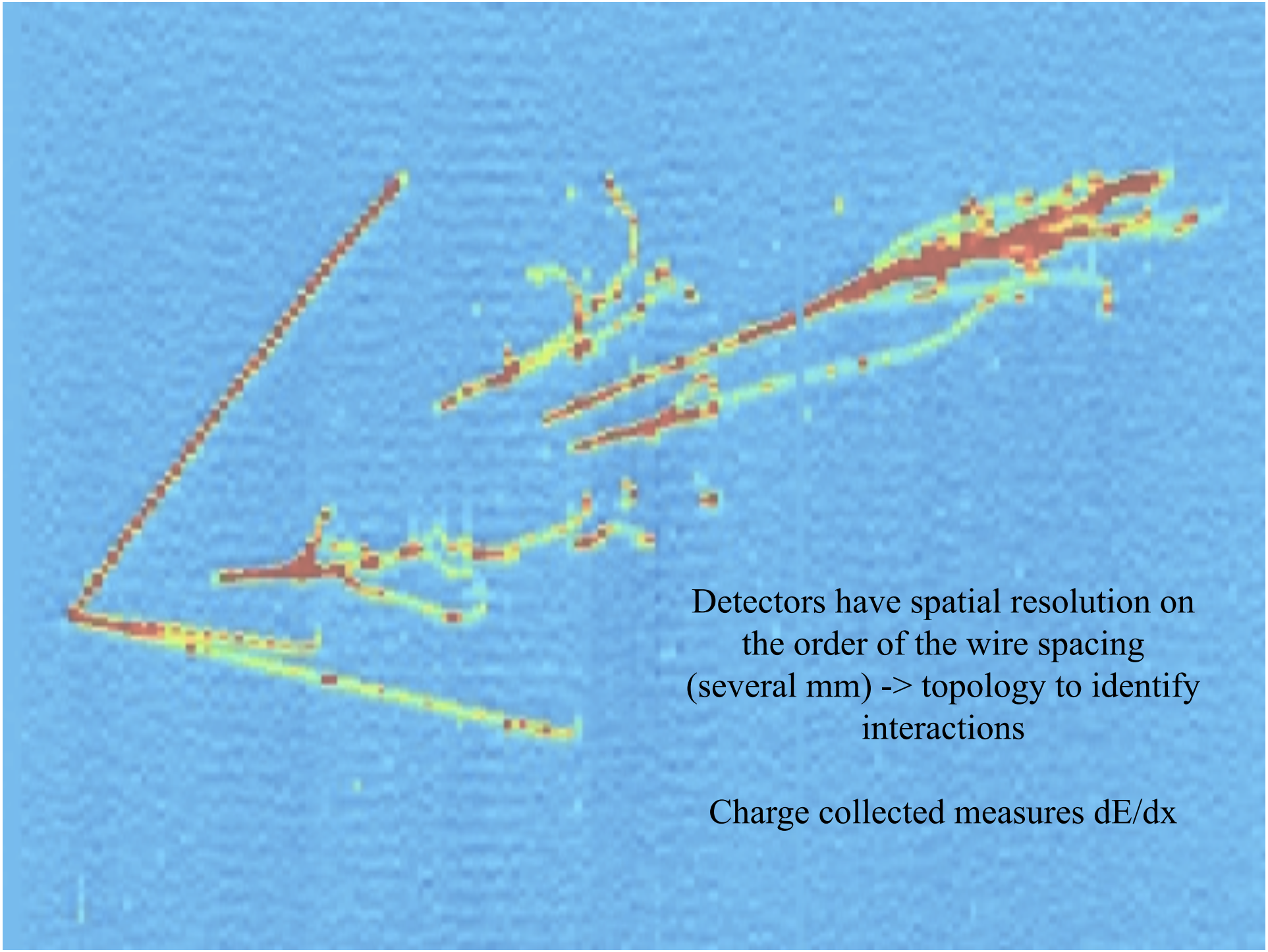
Beautiful images of events to use topology to differentiate event classes

Take advantage of calorimetry to tag electrons vs gammas using dE/dx before electromagnetic shower evolves

Electron

Converted γ: e^+e^-



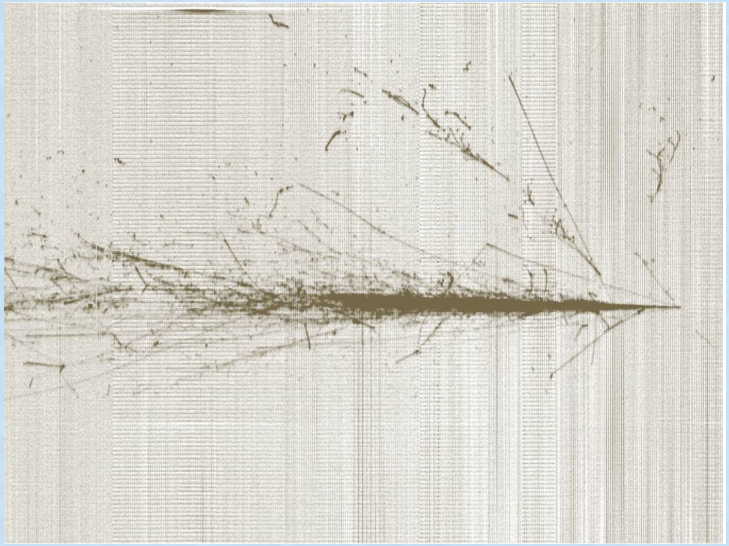


Detectors have spatial resolution on the order of the wire spacing (several mm) -> topology to identify interactions

Charge collected measures dE/dx

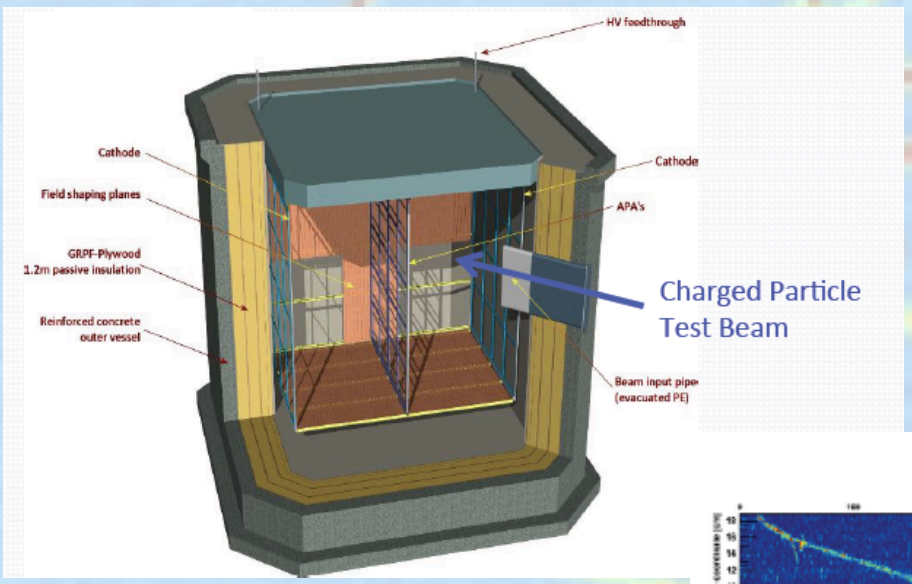
Liquid Argon TPC development: very briefly….

- Early R&D in the US in the 1970s
  - Willis and Radeka: electrodes in LAr
  - Chen: first prototypes of small detectors
- Pioneered by European neutrino physics Community
  - ICARUS prototypes
  - Surface run of the T300 ICARUS detector in 2001
  - Successful running of ICARUS underground 2010-2013



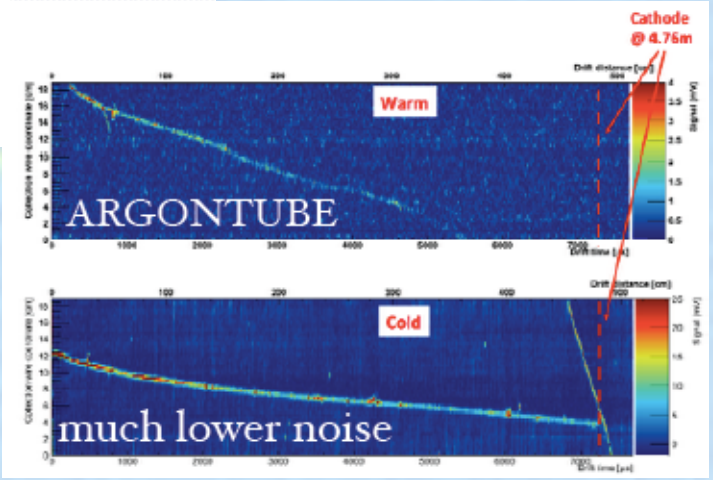
Liquid Argon TPC development, cont.

- Extensive continued R&D towards next generation LArTPC detectors
  - ArgonTube, electronics testing and development, HV studies, at BERN
  - Double phase detectors at ETHZ/CERN
  - Growing R&D program at CERN with WA104, WA105, ARGONCUBE



WA105

ArgonTube
Long Drift Test
Cold Electronics Test



Liquid Argon TPC development: cont.

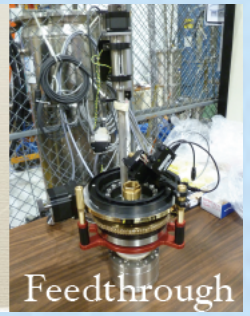
Renewed interest in the US in LArTPC development

- First tracks in small prototype: 2007
- Materials Test stand at FNAL: 2007-present
- ArgoNeuT data taking in the NuMI beam 2008-2009

MicroBooNE construction (Thomas Strauss, BERN PD)

Materials Test Stand: FNAL

ArgoNeuT



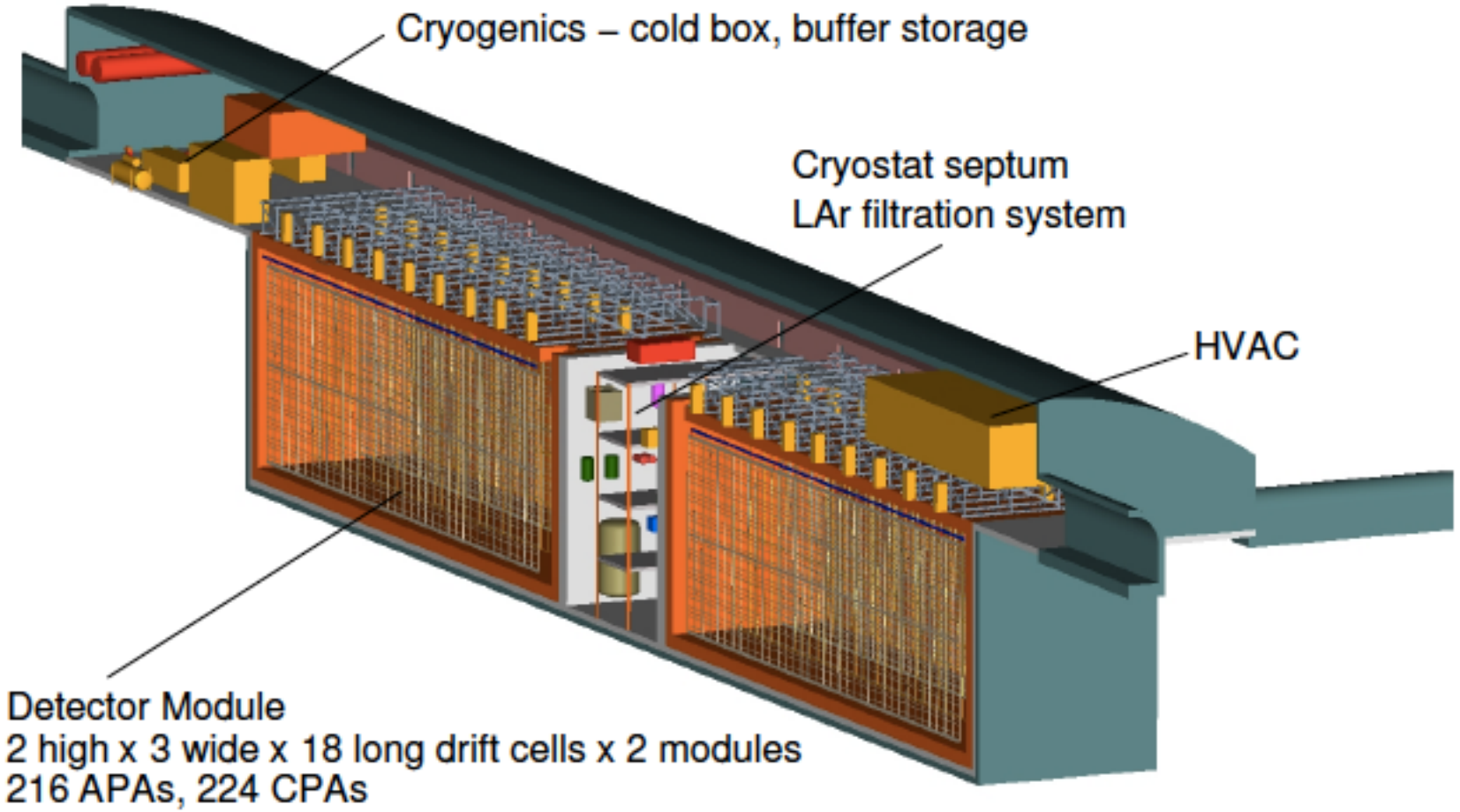
MicroBoone laser System from BERN

- Now many tests and experiments underway
  - LAPD test
  - 35 ton prototype
  - MicroBooNE -> LAr1-ND -> ICARUS on the BNB
  - ArgoNeuT -> LArIAT calibration experiment
  - CAPTAIN calibration experiment
  - Small prototypes to address specific questions (ie: light collection)
- LArTPC chosen for the far detector technology for LBNE in 2012

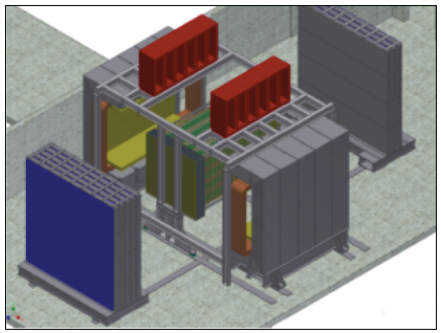
Many of these programs include International Collaboration and Swiss collaborators

Large to

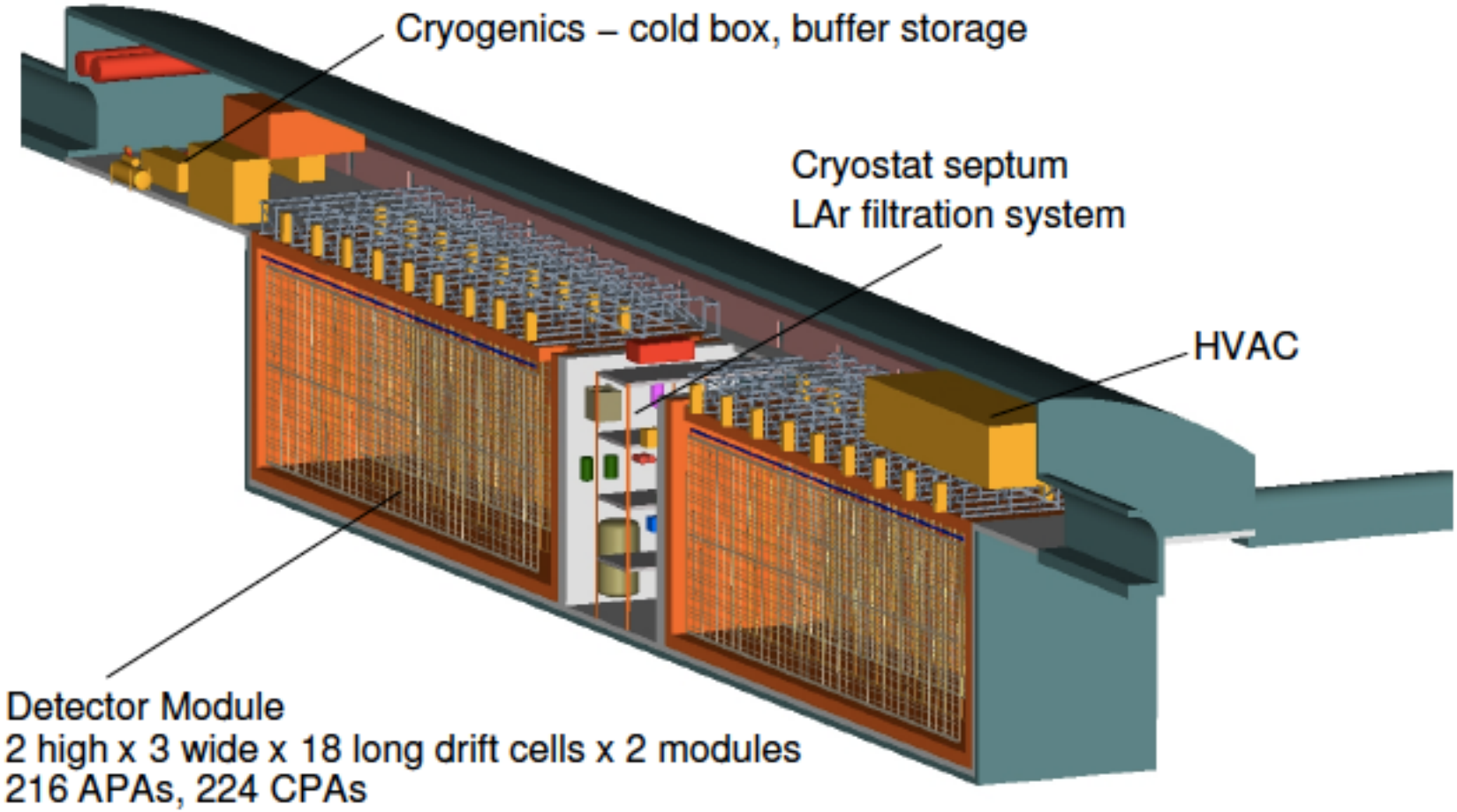
Huge



LBNE detector design concept
34ktons total fiducial volume,
modularized, and sited deep
underground



Near Detector Concept



Neutrino Oscillation Experiments (Long Baseline)

- For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward**, we set as the goal a mean sensitivity to CP violation of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}.**
  - By current estimates, this corresponds to an exposure of 600 kt*MW*y assuming systematic uncertainties of 1% and 5% for the signal and background, respectively**. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector.**
- The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.

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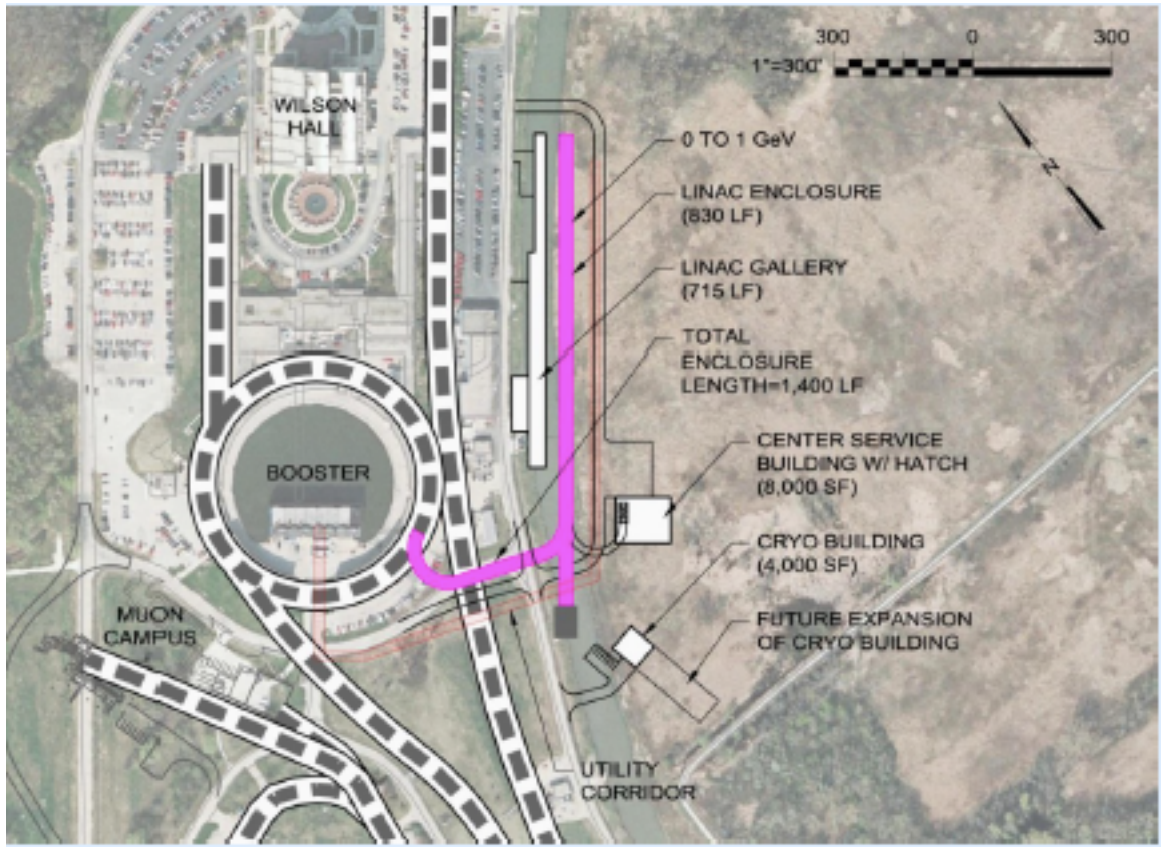
PIP-II

- 800 MeV SC pulsed LINAC
- Higher energy injection into Booster
- **>1MW by 2025**
- Upgradeable to 2.3 MW



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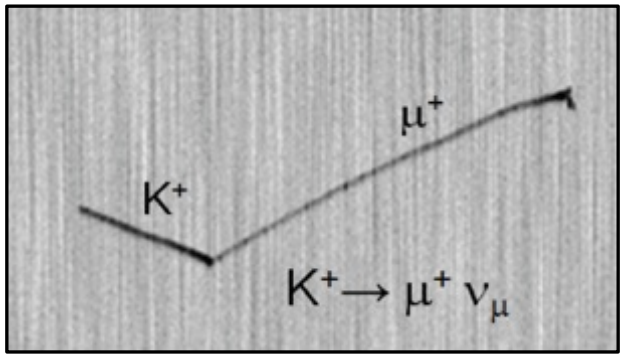
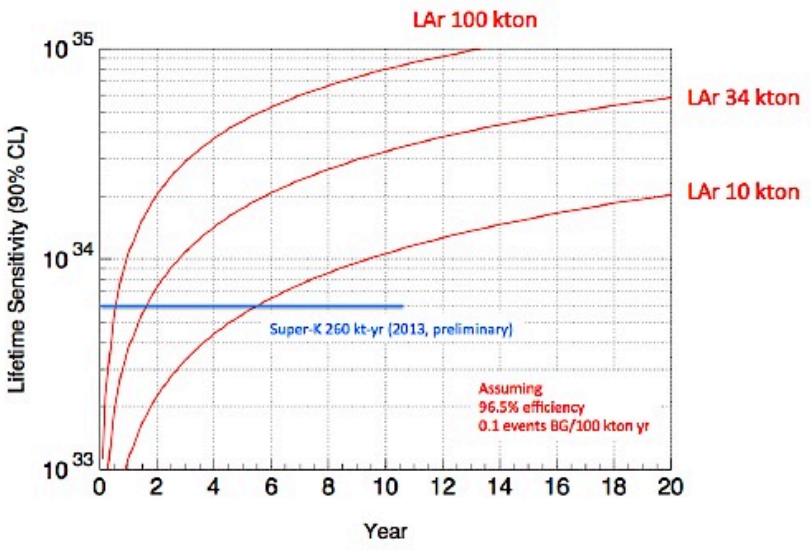
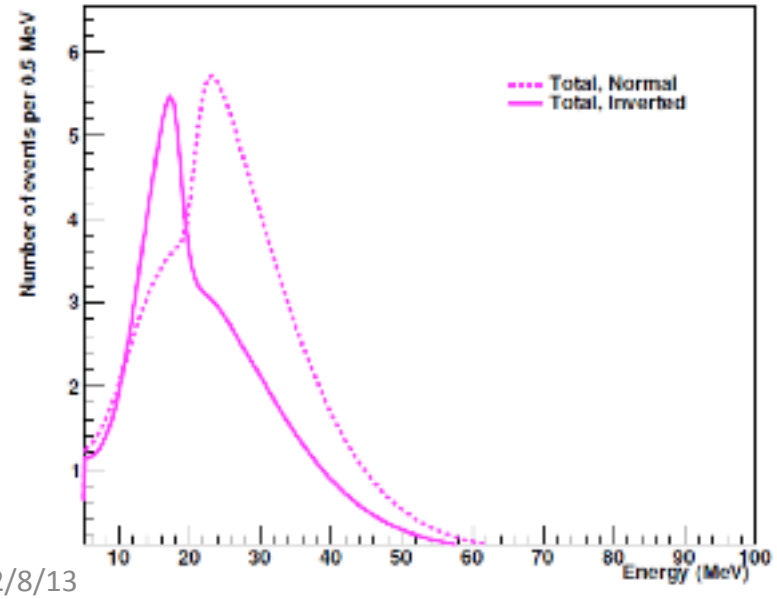
Large Underground LArTPC can search for **Proton Decay**

- Light collection for t_0
- Charge collection for event signature



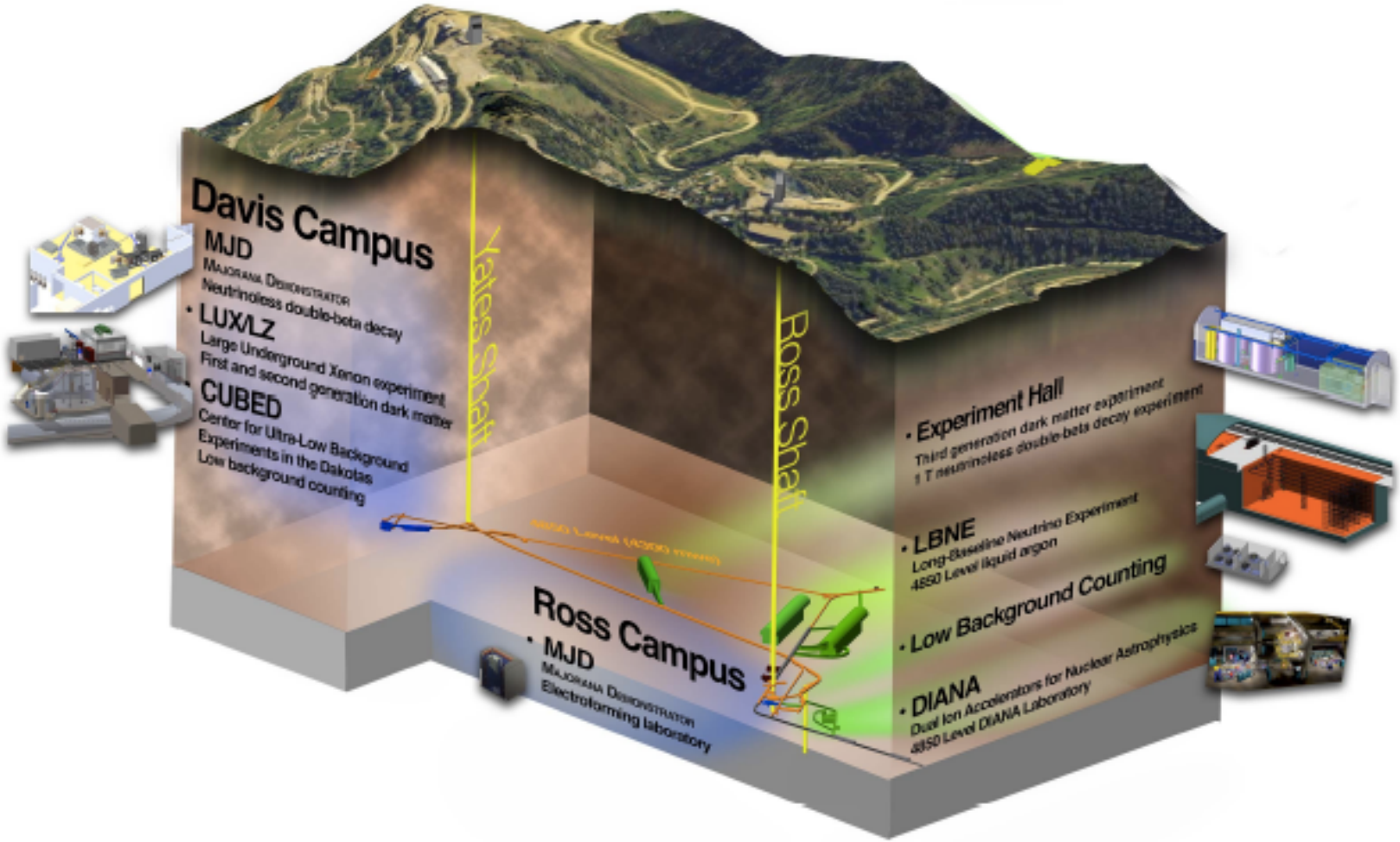




Sensitive to **Supernova Burst**

- Initial burst of neutrinos most sensitive to neutrino properties
- Several thousand events for a galactic supernova in LAr34kton
- Signature: low energy electrons

Far site – SURF facility in Lead, SD



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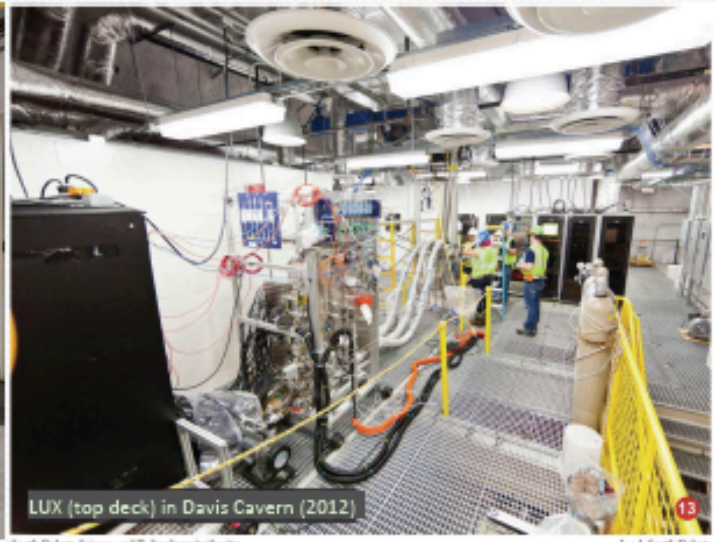

Neutrino Oscillation Experiments (LBNF)

- A more ambitious long-baseline neutrino facility has also been urged by the Snowmass community study and in expressions of interest from physicists in other regions.

- To address even the minimum requirements specified above, **the expertise and resources of the international neutrino community are needed.**

- **A change in approach is therefore required**: The activity should be reformulated under the auspices of a new international collaboration, as an internationally coordinated and internationally funded program, with Fermilab as host. There should be international participation in defining the program's scope and capabilities. The experiment should be designed, constructed, and operated by the international collaboration. The goal should be to achieve, and even exceed if physics eventually demands, the target requirements through the broadest possible international participation.

Neutrino Oscillation Experiments (LBNF)

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Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. *LBNF is the highest-priority large project in its timeframe.*

- To addr… …**tise and resourc…**
- **A chang…** …rmulated under th… …onally coordina… …. There should b… …d capabilit… …ated by the inte… …n exceed if physics eventually demands, the target requirements through the broadest possible international participation.

Neutrino Oscillation Experiments (Program)

- There is a vibrant international neutrino community invested in pursuing the physics of neutrino oscillations.
- The U.S. has unique accelerator capabilities at Fermilab to provide neutrino beams for both short- and long-baseline experiments, with some experiments underway, and a long-baseline site is available at the Sanford Underground Research Facility in South Dakota.
- Many of these current and future experiments and projects share the same technical challenges. Interest and expertise in neutrino physics and detector development of groups from around the world combined with the opportunities for experiments at Fermilab provide the essentials for an international neutrino program.

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

Summary

- The U.S. is well positioned to host a world-leading neutrino physics program.
- LBNF is the highest-priority large project in its timeframe.
- The far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power

The activity should be reformulated under the auspices of a new international collaboration, as an internationally coordinated and internationally funded program, with Fermilab as host.