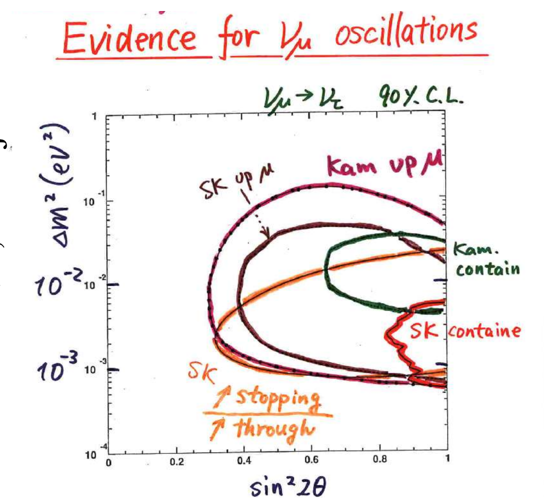
B.Fleming
DPF 2009
July 30, 2009

Experimental Overview of Neutrino Properties

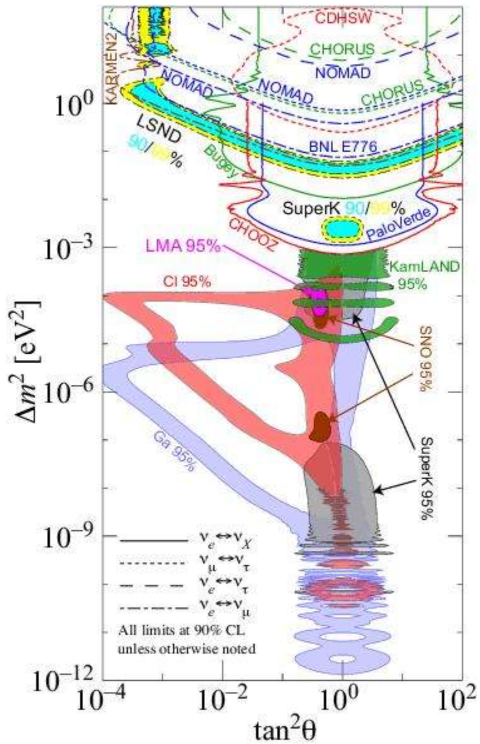
- What we know about neutrinos
- What we wish we knew about neutrinos
- Experimental program to find out

The last decade revolutionized neutrino physics

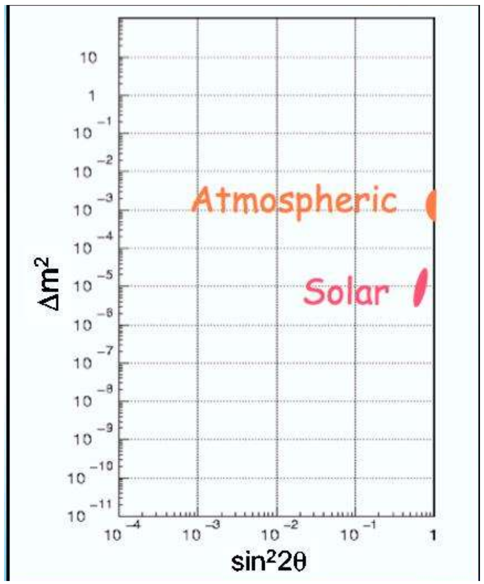
Neutrino '98, T. Kajita



1998



2004



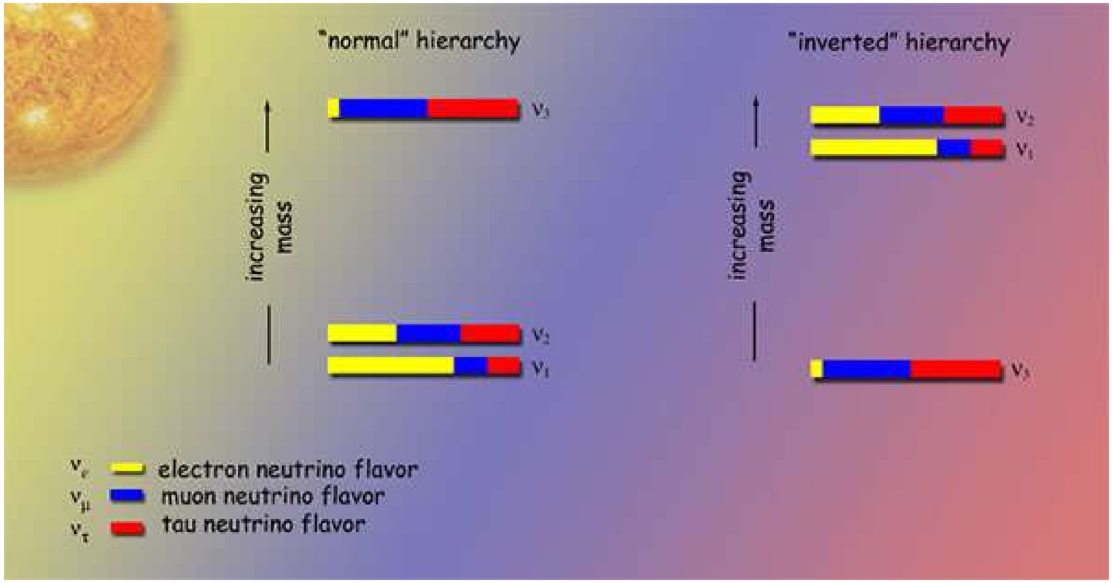
2008

Neutrino oscillation parameter space: Δm^2 vs $\sin^2 2\theta$

The Standard Model is incomplete.... Neutrinos mix and have mass!
Answering this question has opened up many more!

Open questions for running and future neutrino experiments

- What are the final unknowns in the mixing matrix (θ_{13})
- What is the mass hierarchy?
- Do neutrinos violate CP? (or, Are Neutrinos the Reason we Exist?)
- What is the absolute mass scale?
- What is the nature of the neutrino?
- What can the neutrino tell us about the sun and the cosmos?
- What unexpected properties of neutrinos might we find?



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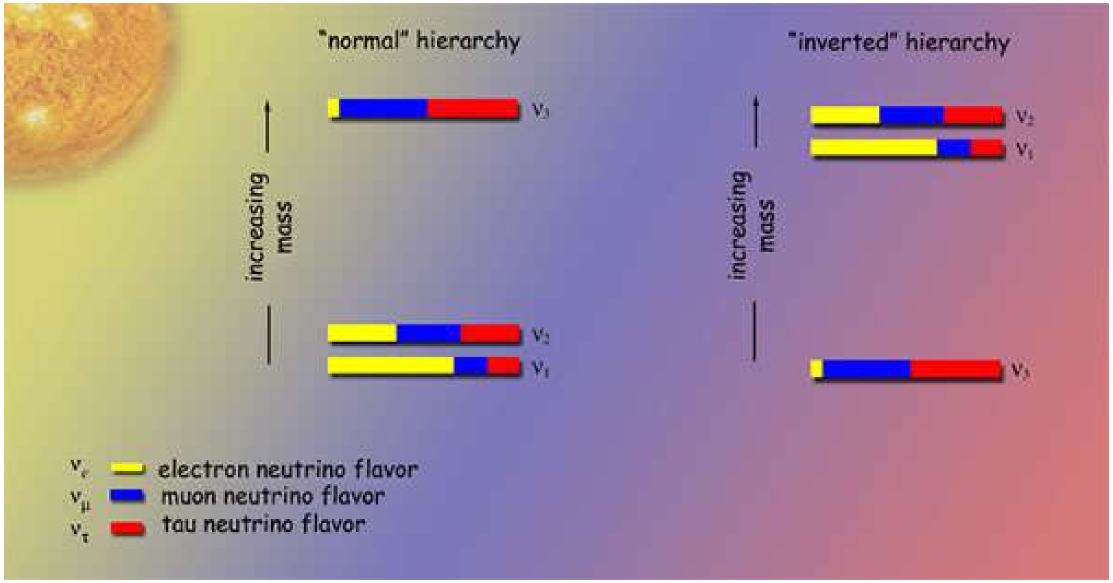

To much to say in 30 minutes

Focus on a few of these and highlighting ***New results!***

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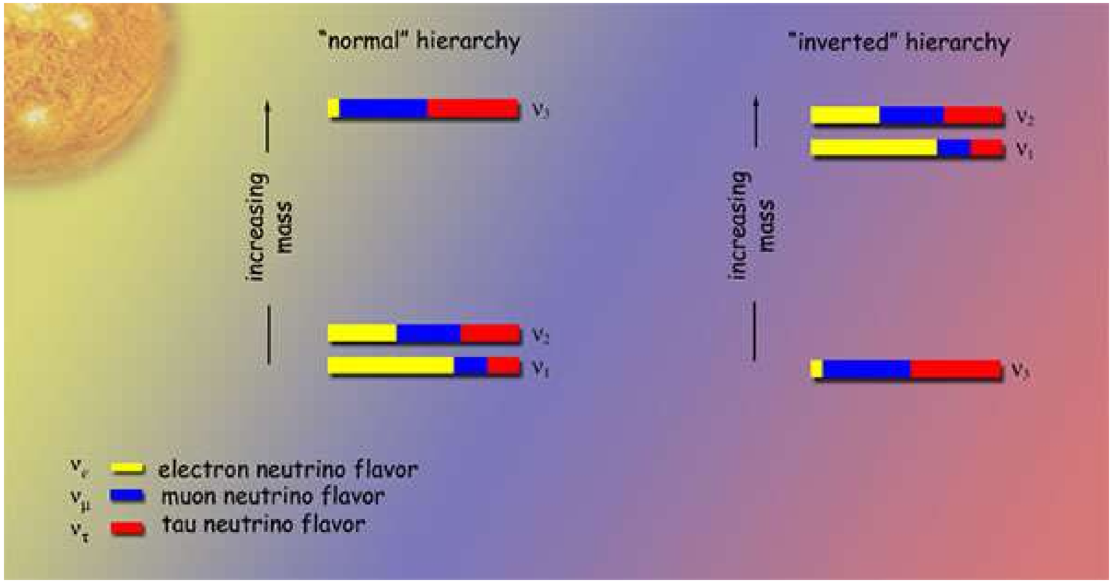
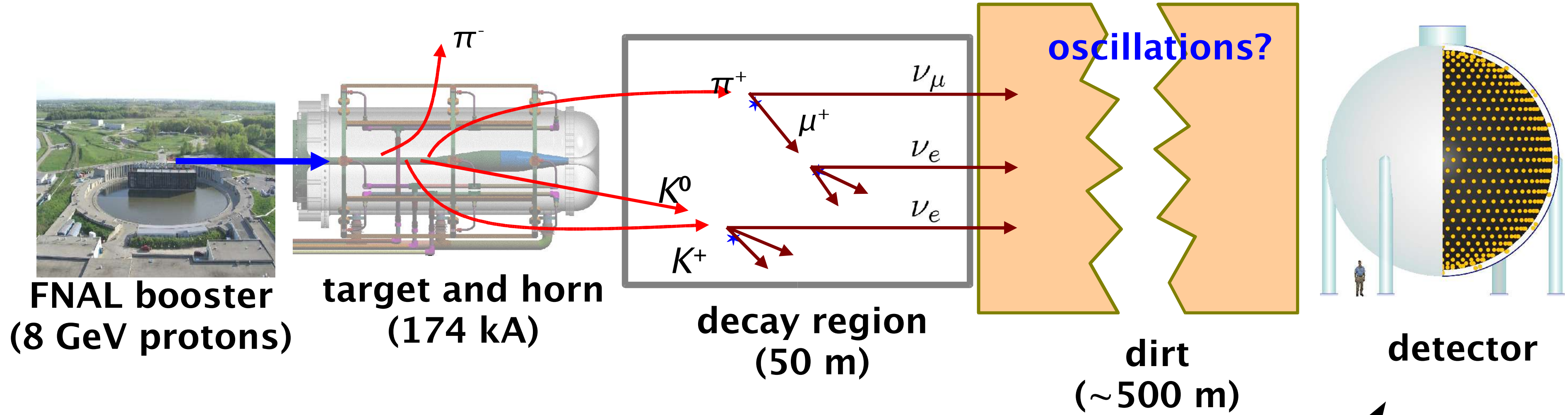
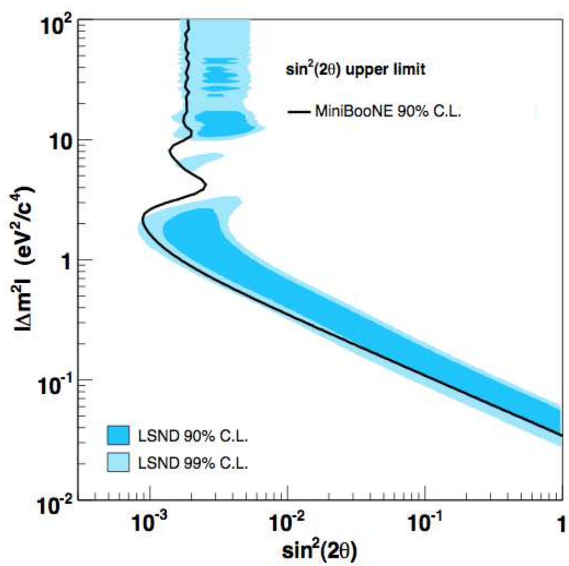


New results from MiniBooNE and MINOS

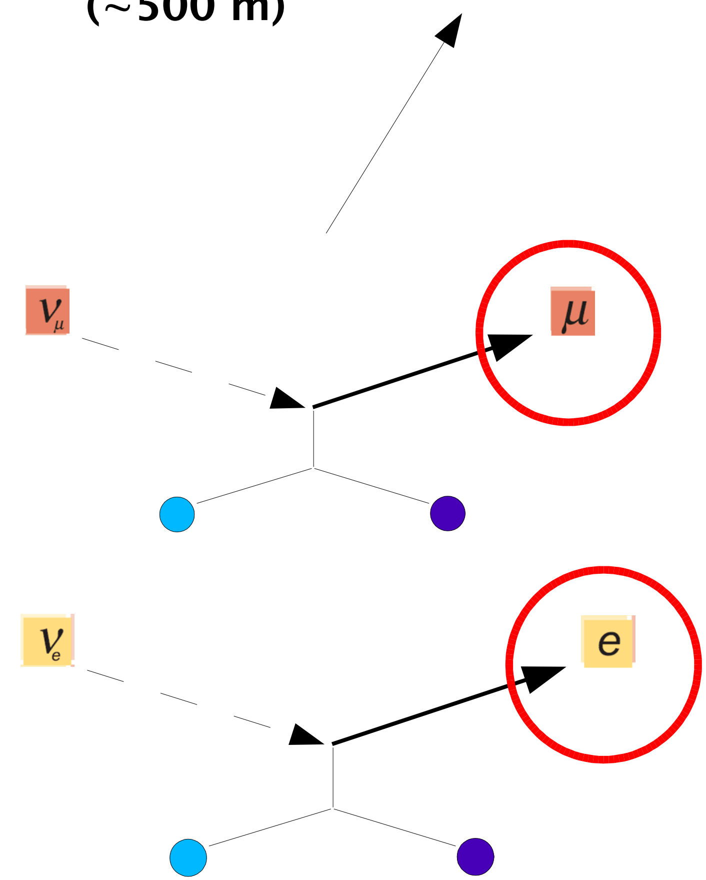
MiniBooNE: short baseline appearance measurement



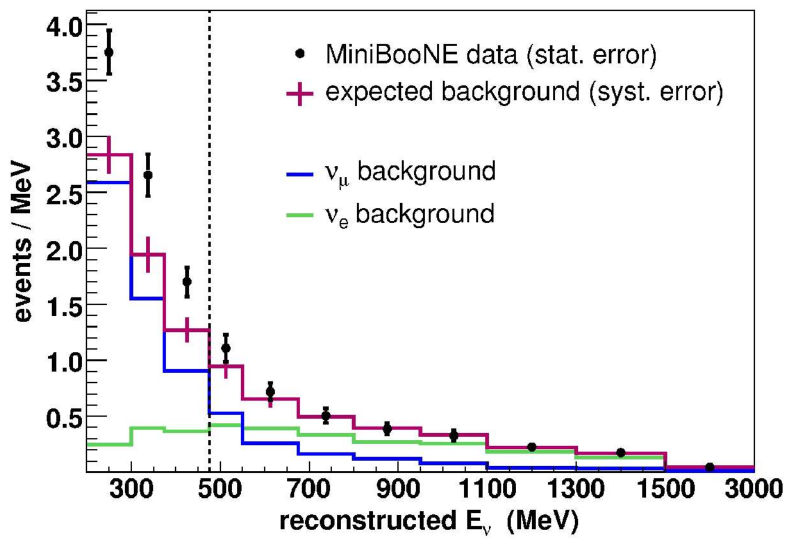
MiniBooNE Results: rules out 2 neutrino $\nu_\mu \to \nu_e$ oscillations (2007)

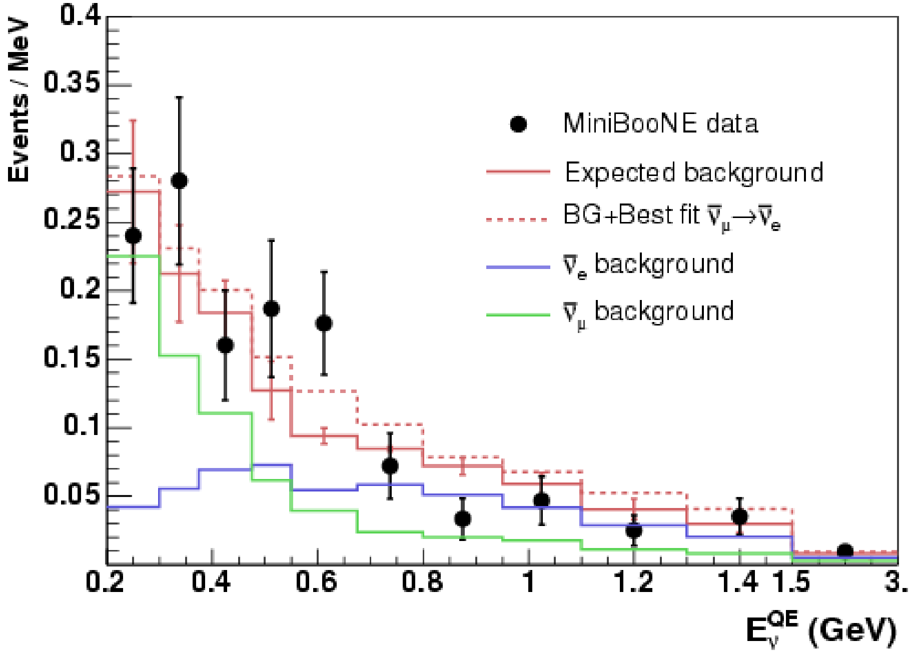


Incompatible with the LSND experiment at 98% CL.



Low energy excess neutrino and (new) anti-neutrino results...





Neutrinos

Low energy excess first reported in 2007.

After extensive review MiniBooNE continues to see excess at >3σ level

Anti-neutrinos

Data above 475 MeV is consistent with background 0.3σ excess

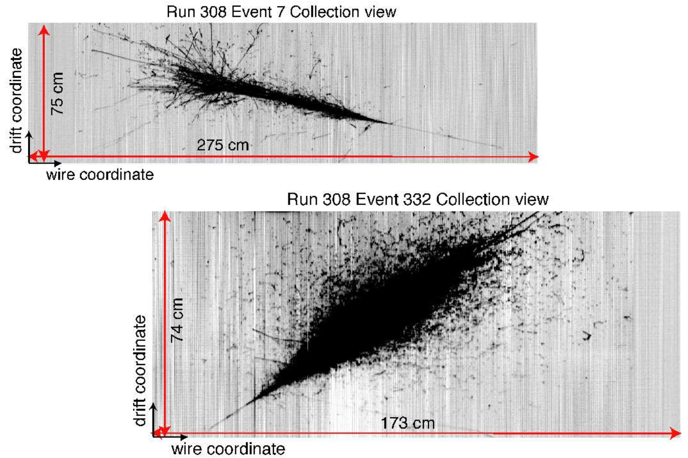
New results!

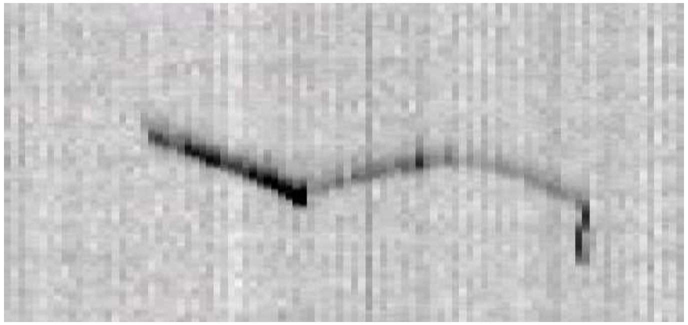
Data below 475 MeV No low energy excess observed..... -0.04σ excess

Need a new experiment to definitively identify excess...

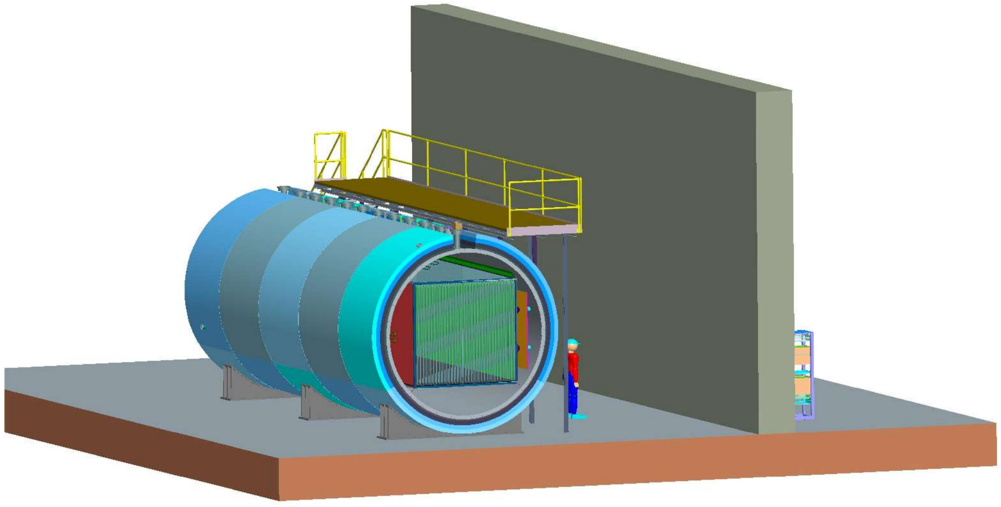
MicroBooNE LArTPC: new technique to address this physics

Capability to resolve particle interactions:
reduce backgrounds, identify and
improve signal





Liquid Argon Time Projection Chamber



Motivation

- ***Low energy excess***
- ***Neutrino xsecs***
- ***Physics R&D***
- ***Hardware R&D***

In a program en route to massive detectors...

- Stage 1 approval at FNAL in 2008
- Already partially funded through NSF MRI

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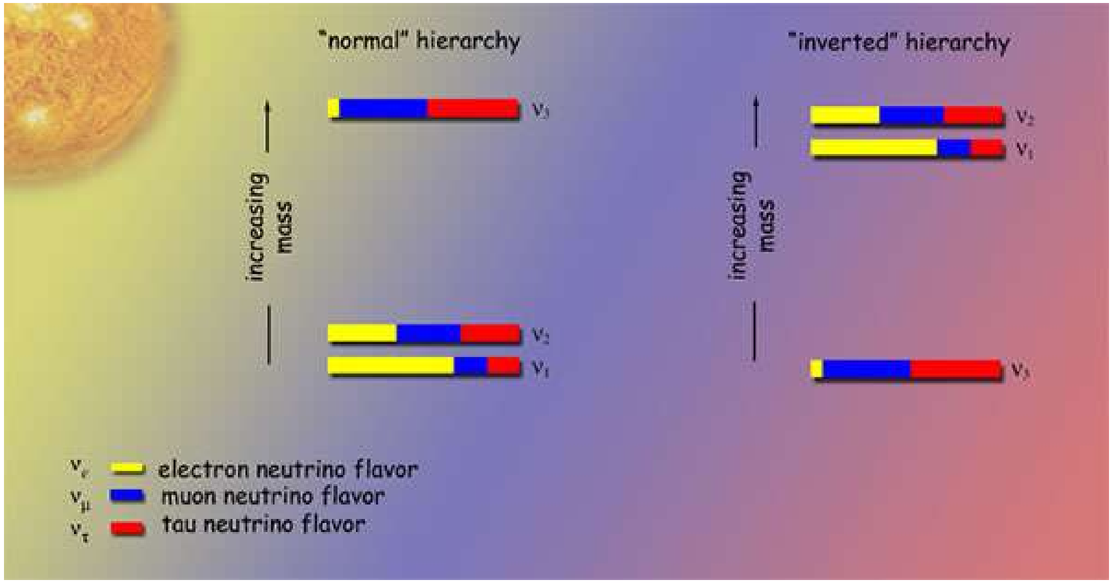
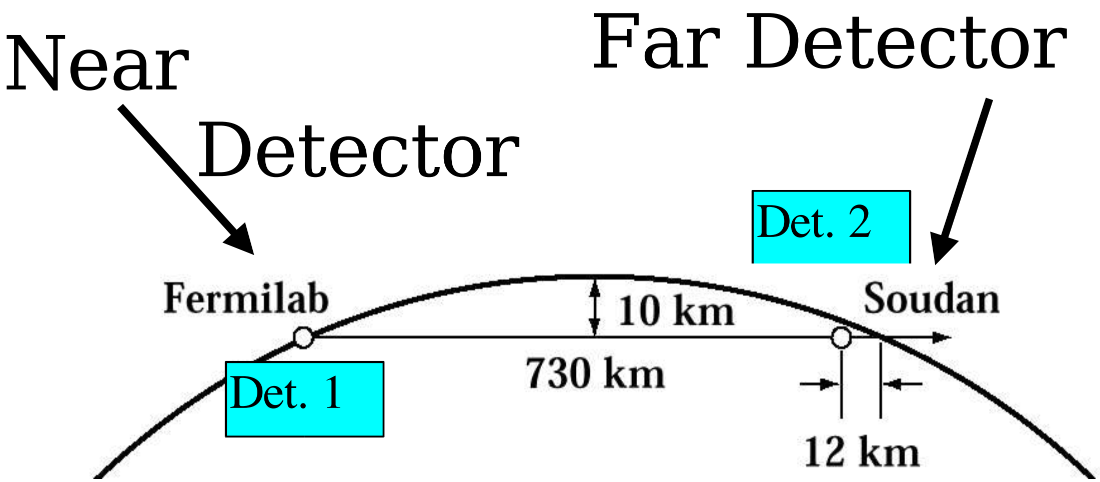


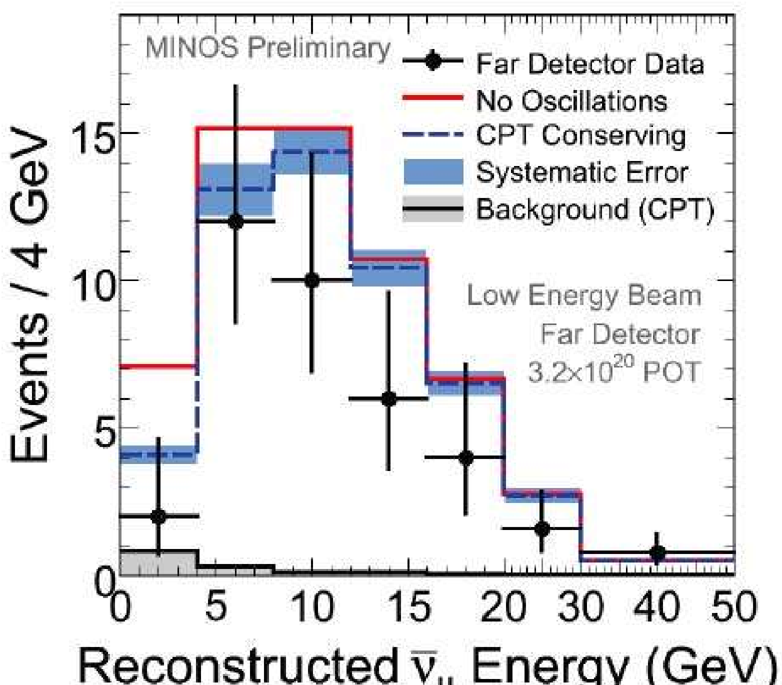
New results from MiniBooNE and MINOS

MINOS: Long baseline oscillation experiment



Magnetized detector can tag ν_μ and $\bar{\nu}_\mu$ interactions

New results!



Anti-neutrino appearance
$\nu_\mu \rightarrow \bar{\nu}_\mu$ appearance $<2.6\%$

Oscillation Search
Is $\Delta m^2 = \Delta\bar{m}^2$?
42 events detected
58.3 ± 8.4 expected

Open questions for running and future neutrino experiments

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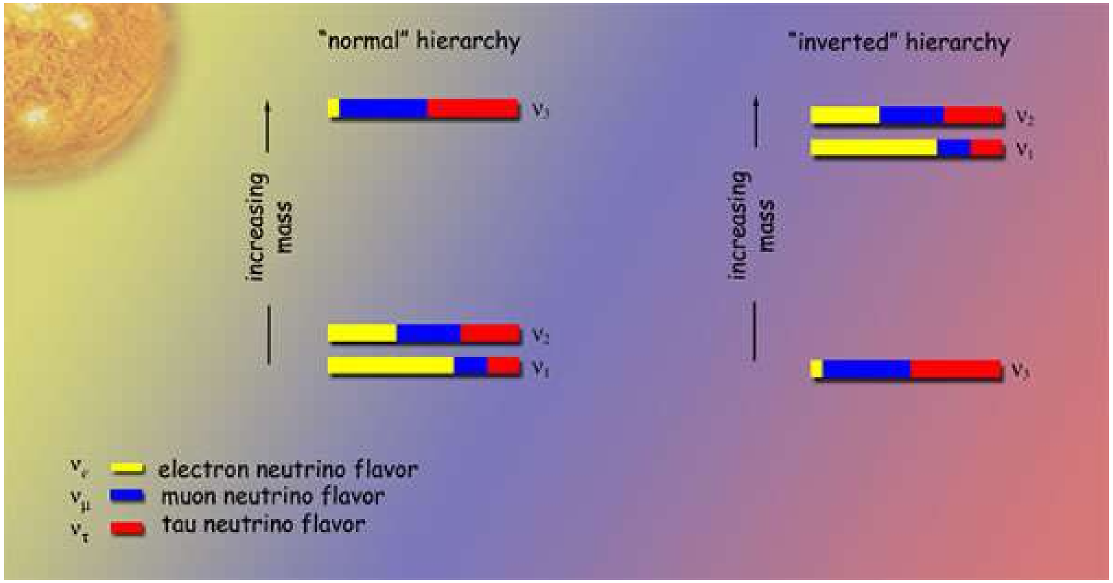

What we now know about neutrino mixing

The CP Violation Parameter

Three Neutrino Mixing Matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

Two independent mass splittings, Δm^2

The CP Violation Parameter

Long Baseline Oscillations...

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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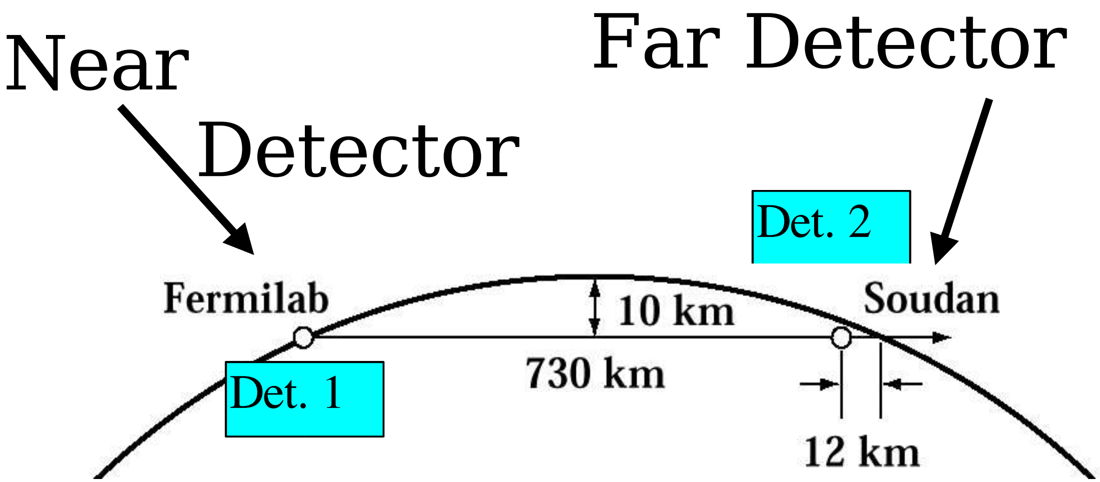
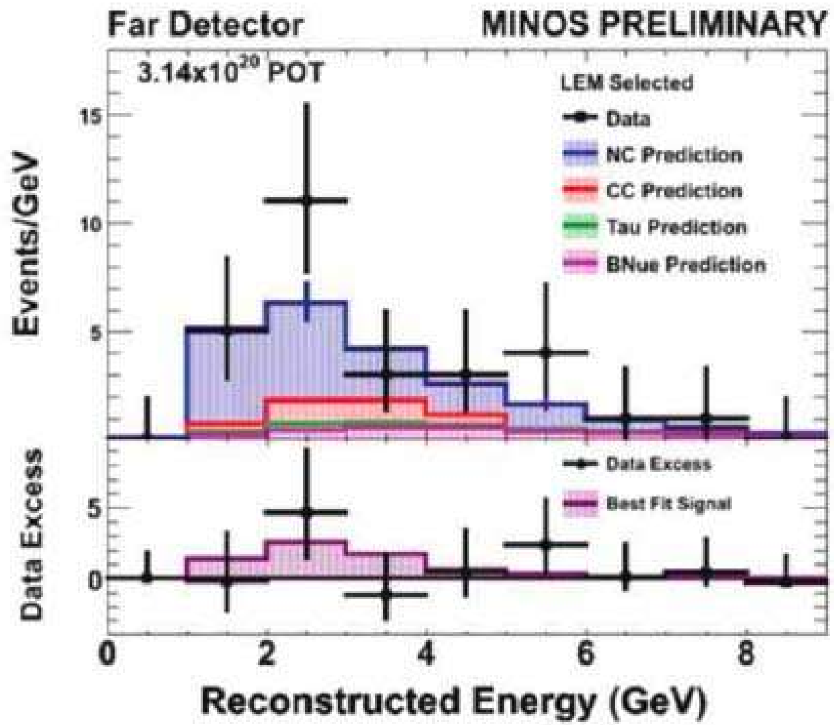
From Long Baseline Appearance Measurements

Goal is to be sensitive to
- Final unknown mixing angle, θ_{13}
- the CP violating phase, δ
- Mass hierarchy

Measurements of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

MINOS first ν_e appearance results





- Observed 35 events
- Expected 27±σ5(stat) ±2(sys)
- 1.5σ excess

New results!

Need next generation long baseline measurements…

Ingredients for Long Baseline Oscillation Physics

1) **lots of neutrinos**
2) lots of detector
3) fine-grained
 or specialized detectors

JPARC
(See K. Nishikawa talk)

High Intensity Neutrino Beams:

- JPARC (Japan)
- CNGS (Europe)
- NuMI/BNB (FNAL)

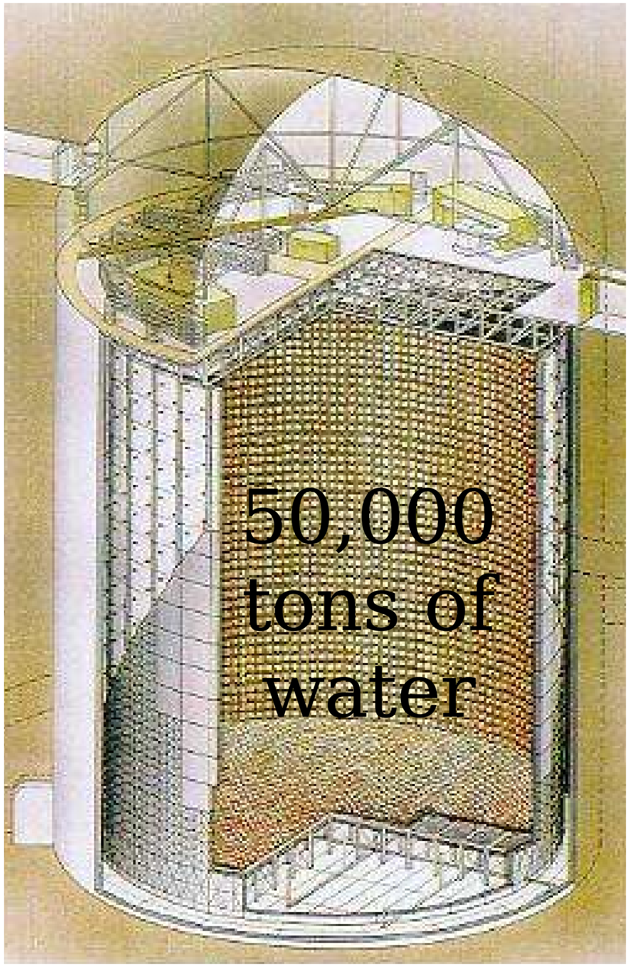
Even more Intense neutrino sources under consideration worldwide...

need lots of neutrinos to see a small oscillation probability

Ingredients for Long Baseline Oscillation Physics

1) lots of neutrinos
2) **lots of detector**
3) fine-grained
   or specialized detectors

Super-K



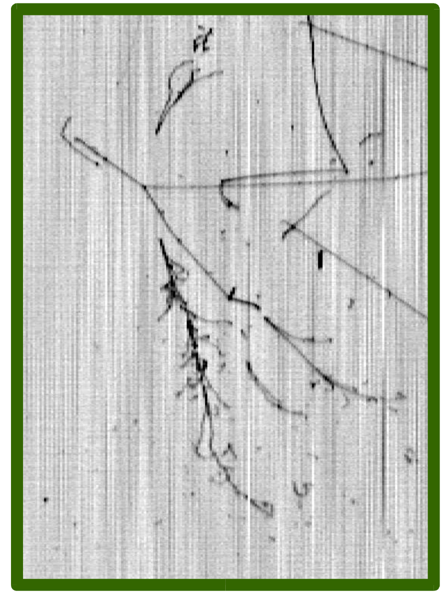
Conventional choice for
existing large detectors:
Cerenkov Imaging detector

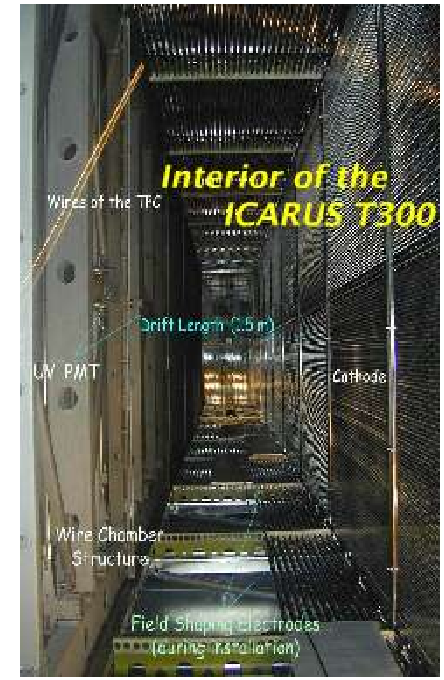
*need to stop as many neutrinos
as possible to see a small
oscillation probability*

Ingredients cont.

1) lots of neutrinos
2) lots of detector
3) **fine-grained**
   or specialized detectors

Fine-grained detectors have better signal efficiency and background rejection

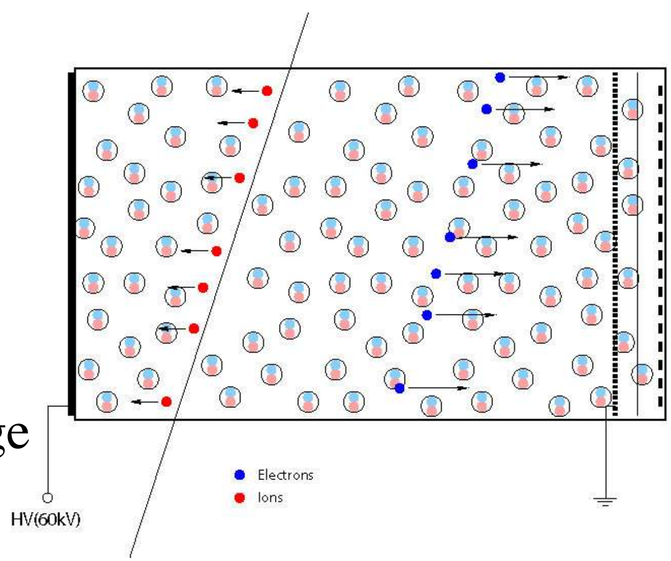




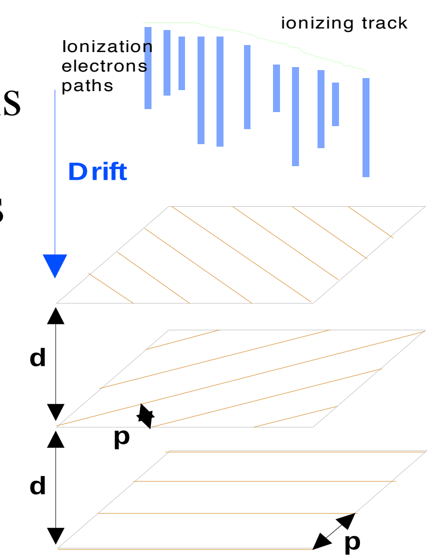
Liquid Argon
time projection chambers
(modern day bubble chambers)

Passing charged particle ionizes the Argon.

Ionization electrons drifted to the detector edge



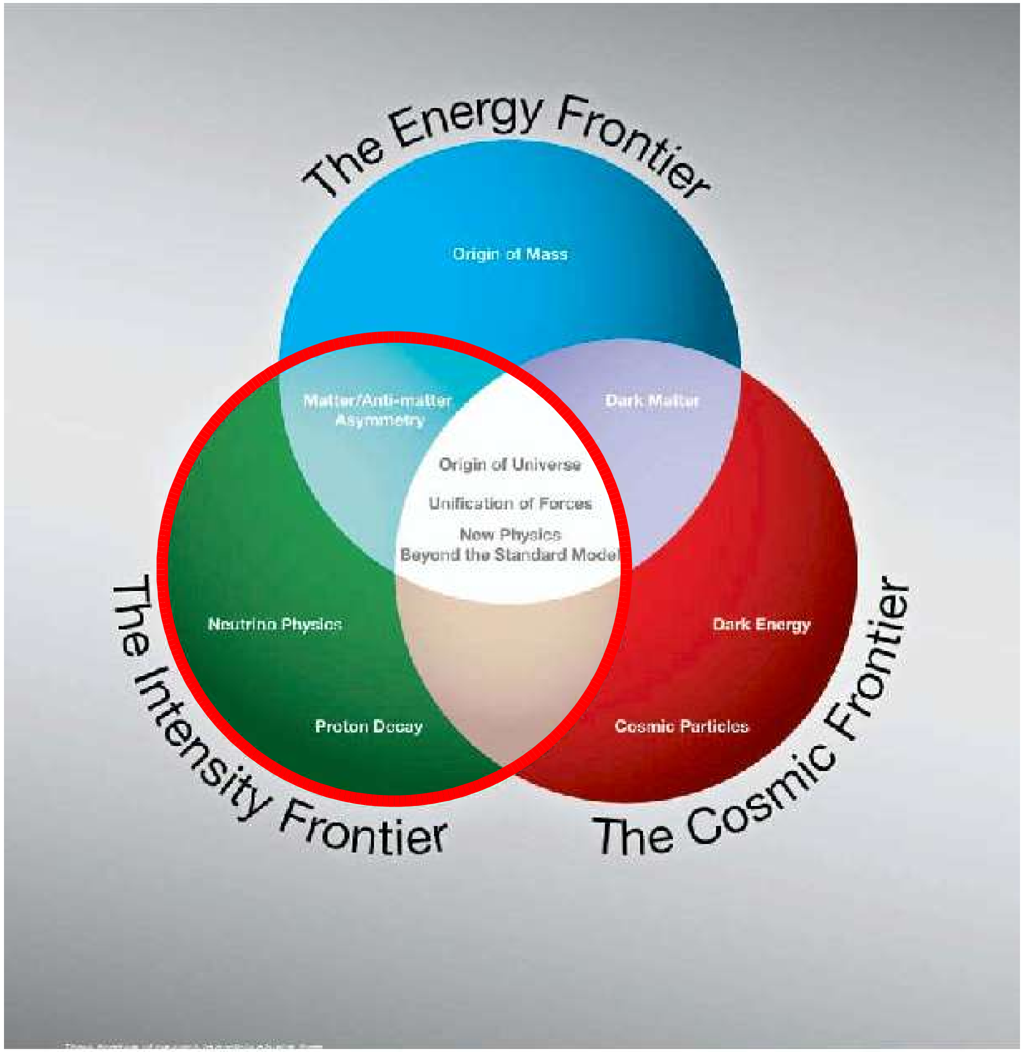
Ionization electrons drift through readout electrodes so charge is induced/collected on electrodes



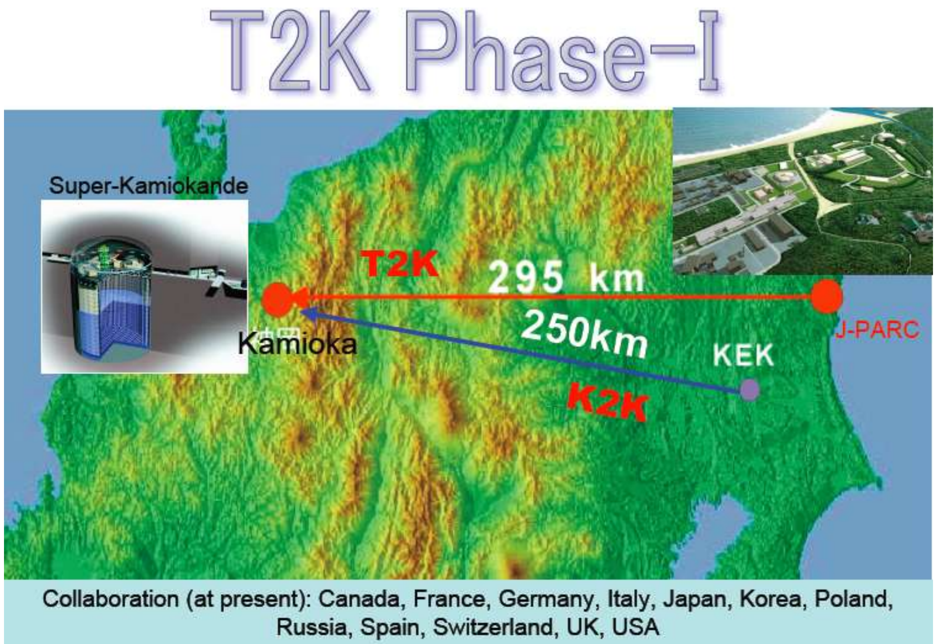
Detector technology pioneered by the ICARUS experiment over last 25 years

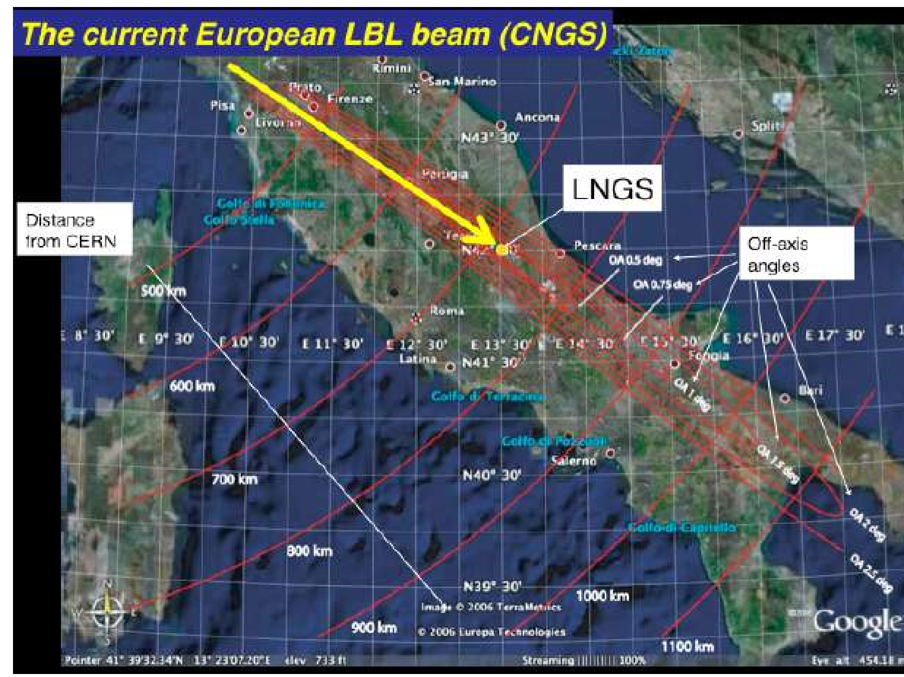
Growing interest in long baseline oscillation programs here and abroad

HEPAP's P5 panel report (2008) included this program as a key component of the US program

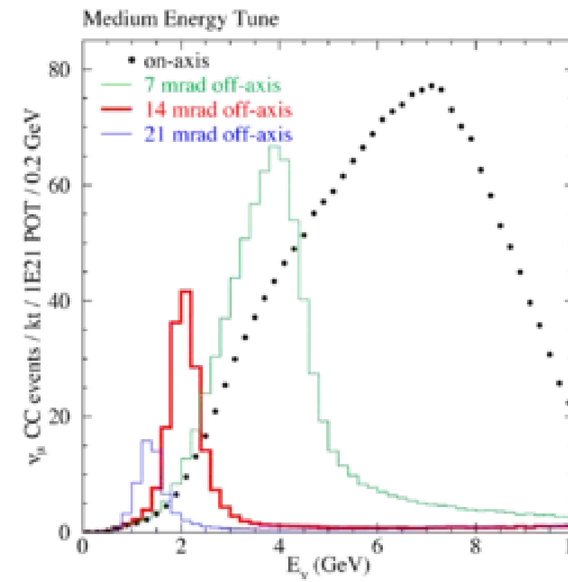


A number of programs worldwide
in the planning....
Asia and Europe

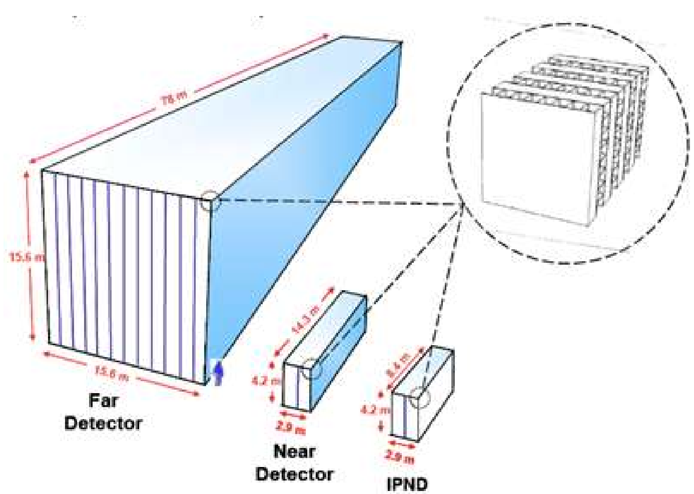




US Based program: NOVA



2 GeV neutrino beam



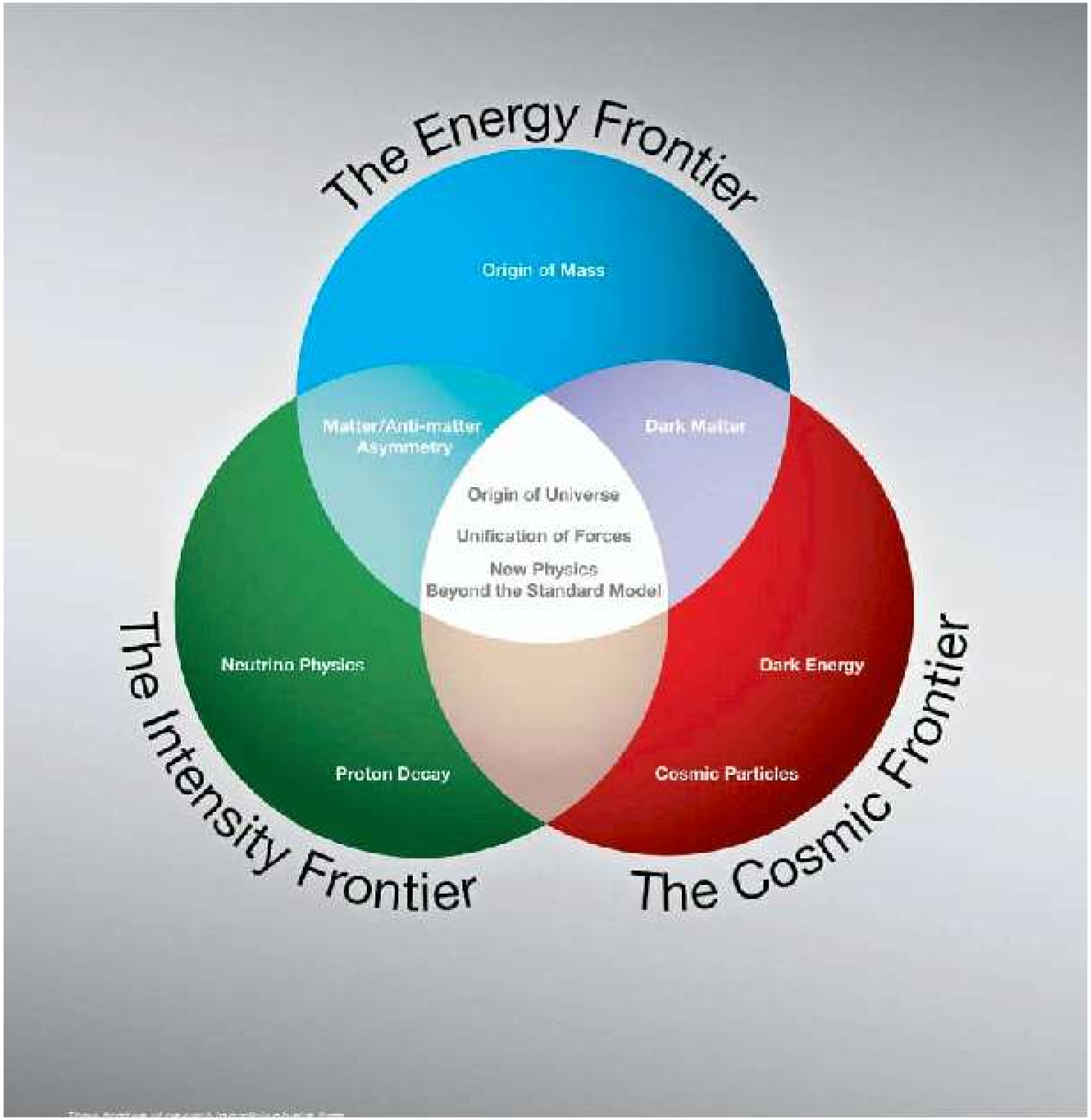
Segmented liquid scintillator detector

NOvA will look for ν_e appearance in a ν_μ beam

- improve reach in theta_13
- measure the mass hierarchy

Program beyond NOvA.....

Recommendations from the Report of the P5 Panel for particle physics, May 29, 2008



Recommendations from the Report of the P5 Panel for particle physics, May 29, 2008

At the Intensity Frontier:

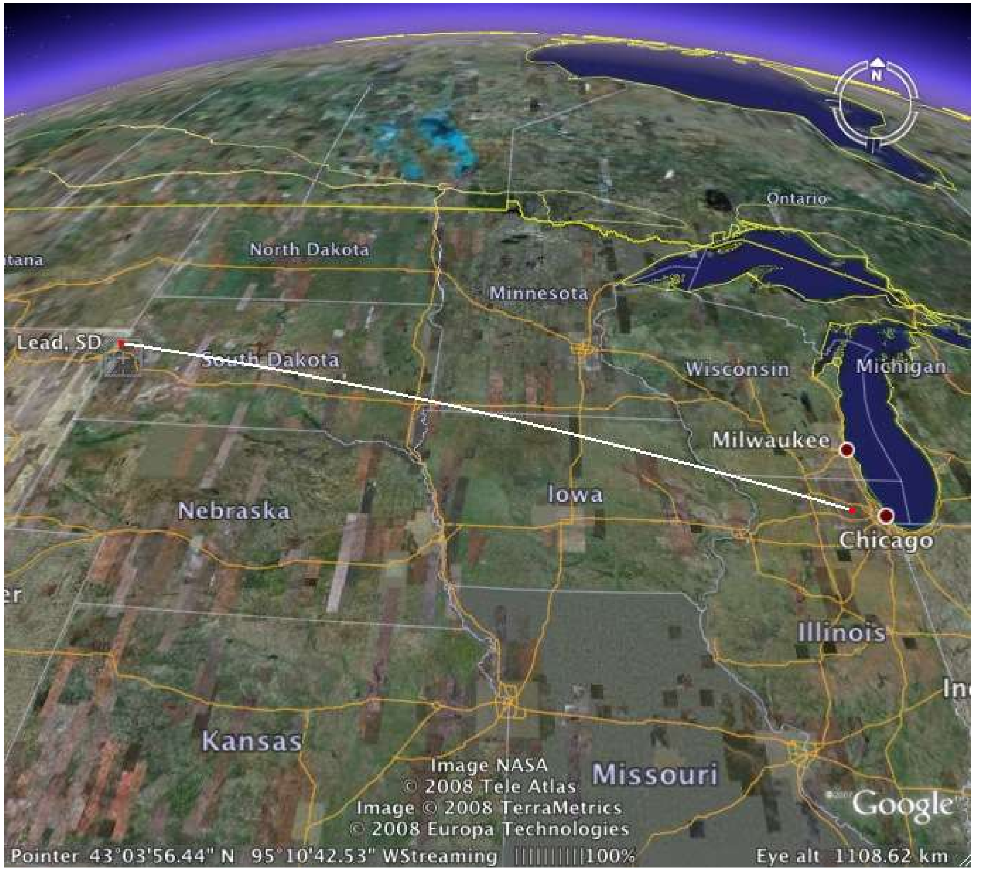
The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL laboratory and a high-intensity neutrino source at Fermilab

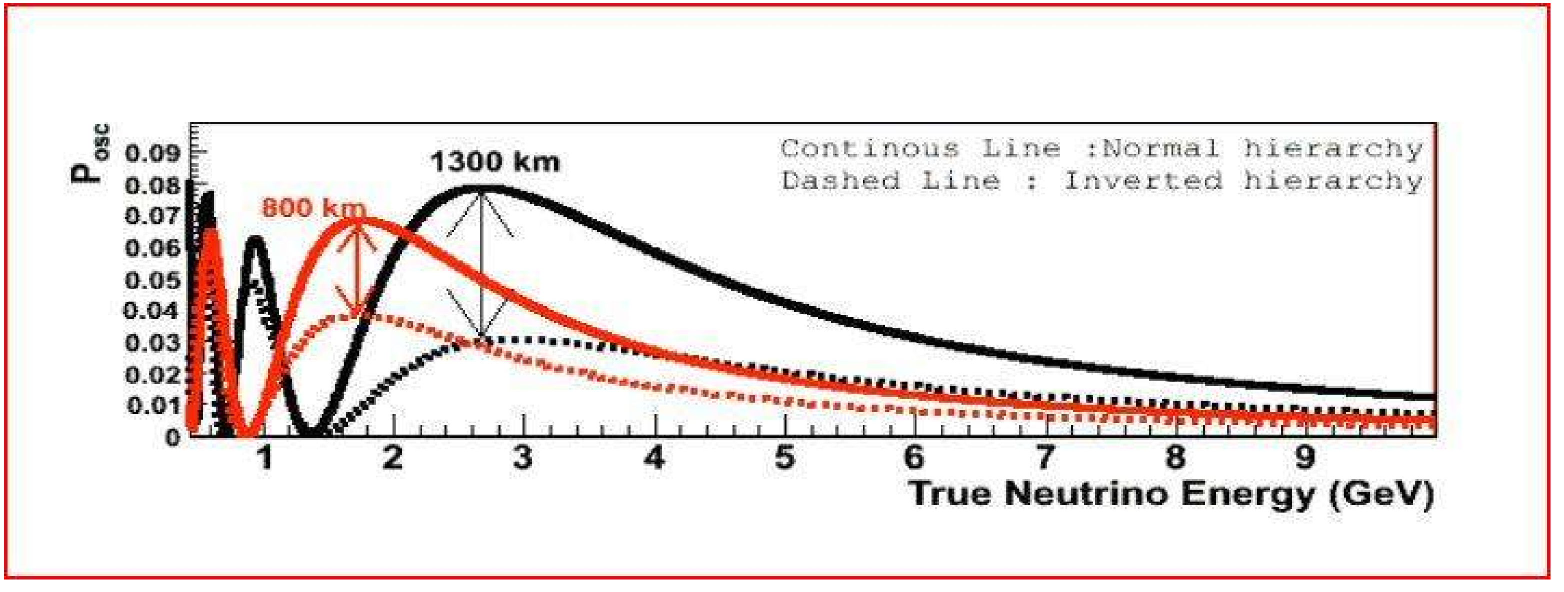
The panel recommends proceeding now with an R&D program to design a multi-megawatt proton source at Fermilab and a neutrino beamline to DUSEL and recommends carrying out R&D in the technology for a large detector at DUSEL.

The panel recommends support for a vigorous R&D program on liquid argon detectors and water Cerenkov detectors in any funding scenario considered by the panel. The panel recommends designing the detector in a fashion that allows an evolving capability to measure neutrino oscillations and to search for proton decays and supernovae neutrinos.

Long baseline neutrino program:

- Intense neutrino and anti-neutrino beams from Fermilab
  - Start with 700 kW beam
  - Upgrade with high intensity proton machine (Project X) to 2MW
- Baseline of > 1000 km
- Very massive detectors in a deep underground lab in Lead, SD (Homestake/DUSEL)

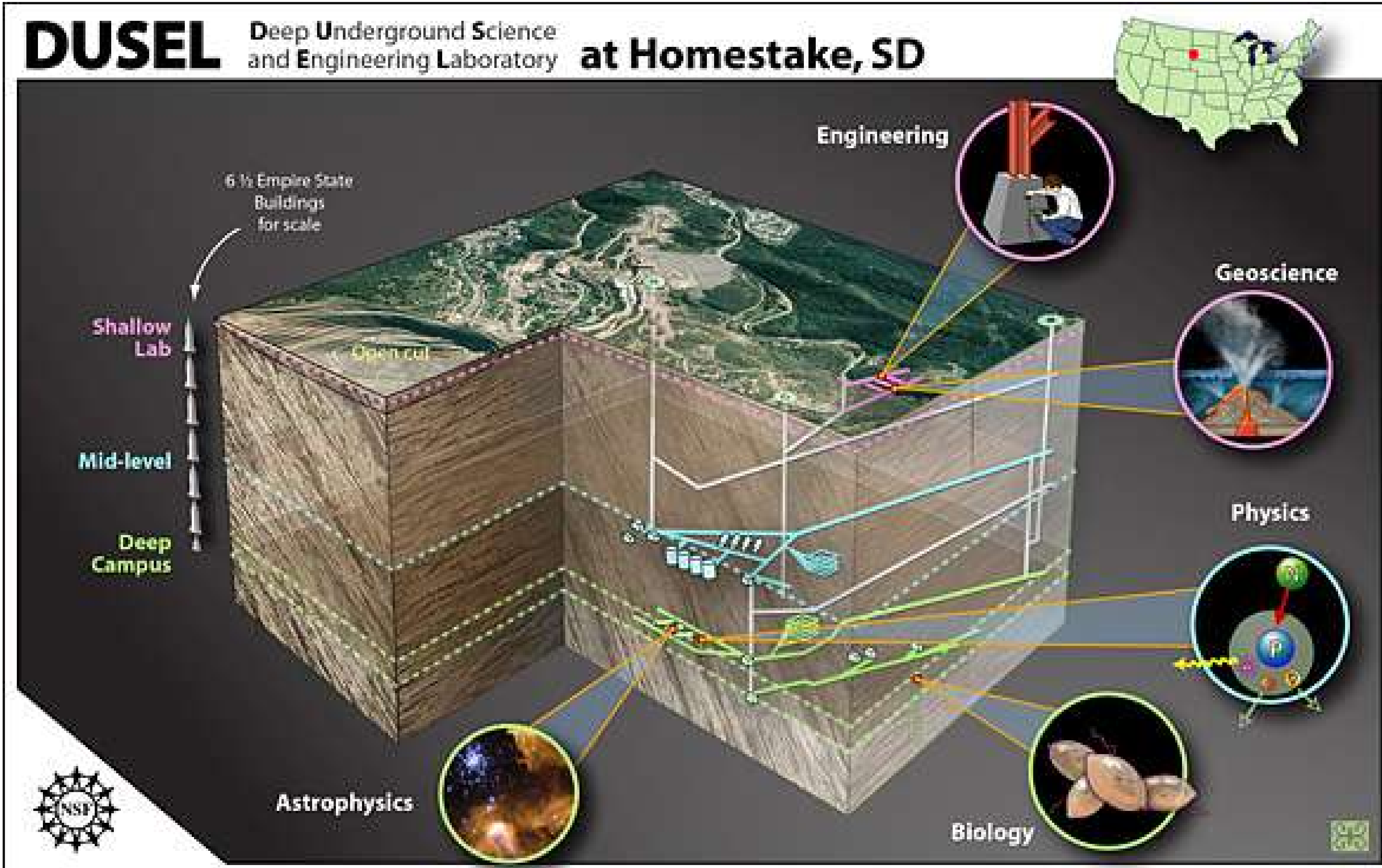




L = 1300 km (more matter effect in the oscillations

Broad band beam can cover 1st and

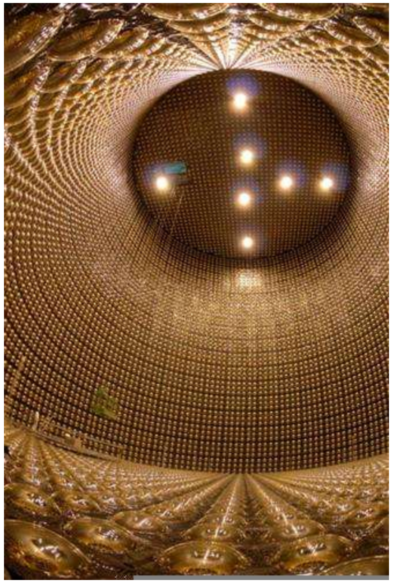
2nd maximum


DUSEL
Deep Underground Science and Engineering Laboratory
at Homestake, SD
Engineering
6 ½ Empire State Buildings for scale
Geoscience
Shallow Lab
Open cut
Mid-level
Physics
Deep Campus
Astrophysics
Biology
NSF

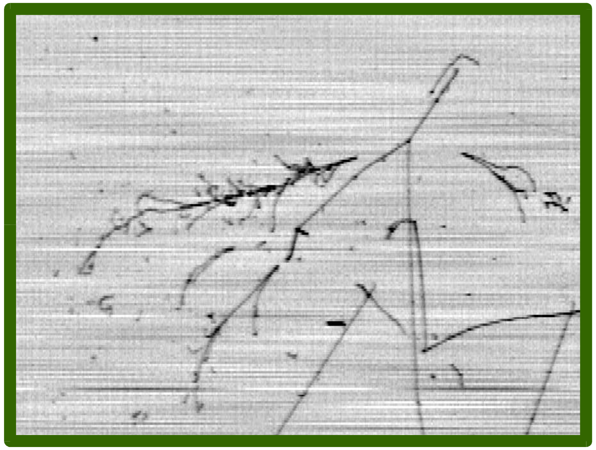
Massive detectors for long baseline program

Options under consideration:
50-100 kt LAr, 300-500 kton WC,
or some combination of the two technologies

Water Cerenkov
Imaging detectors



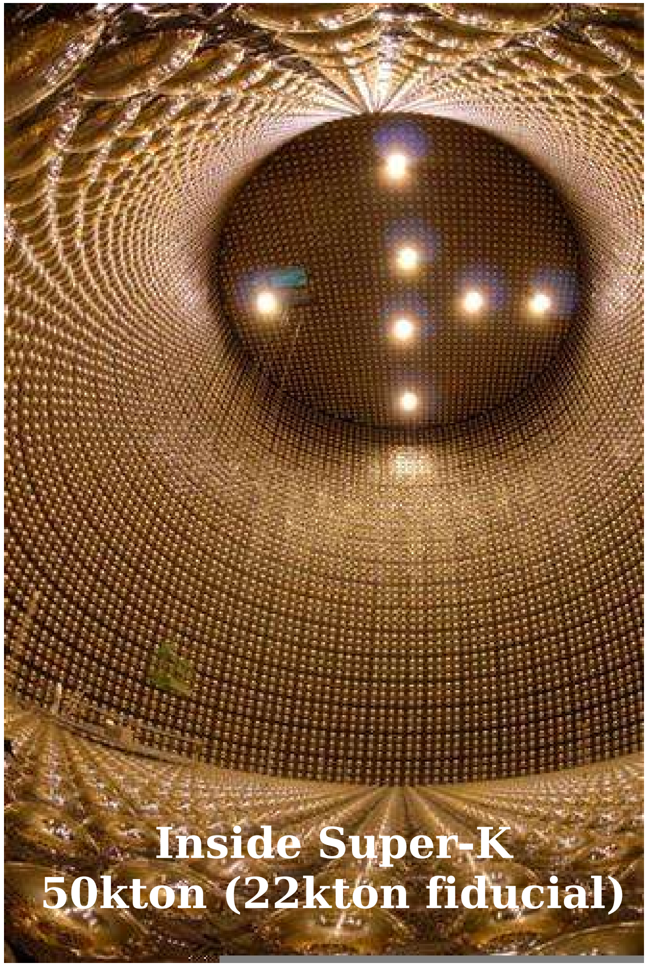
Liquid Argon TPCs



Siting deep underground shields the experiments from cosmic ray showers

Water Cerenkov

100kton fiducial volume water detector modules



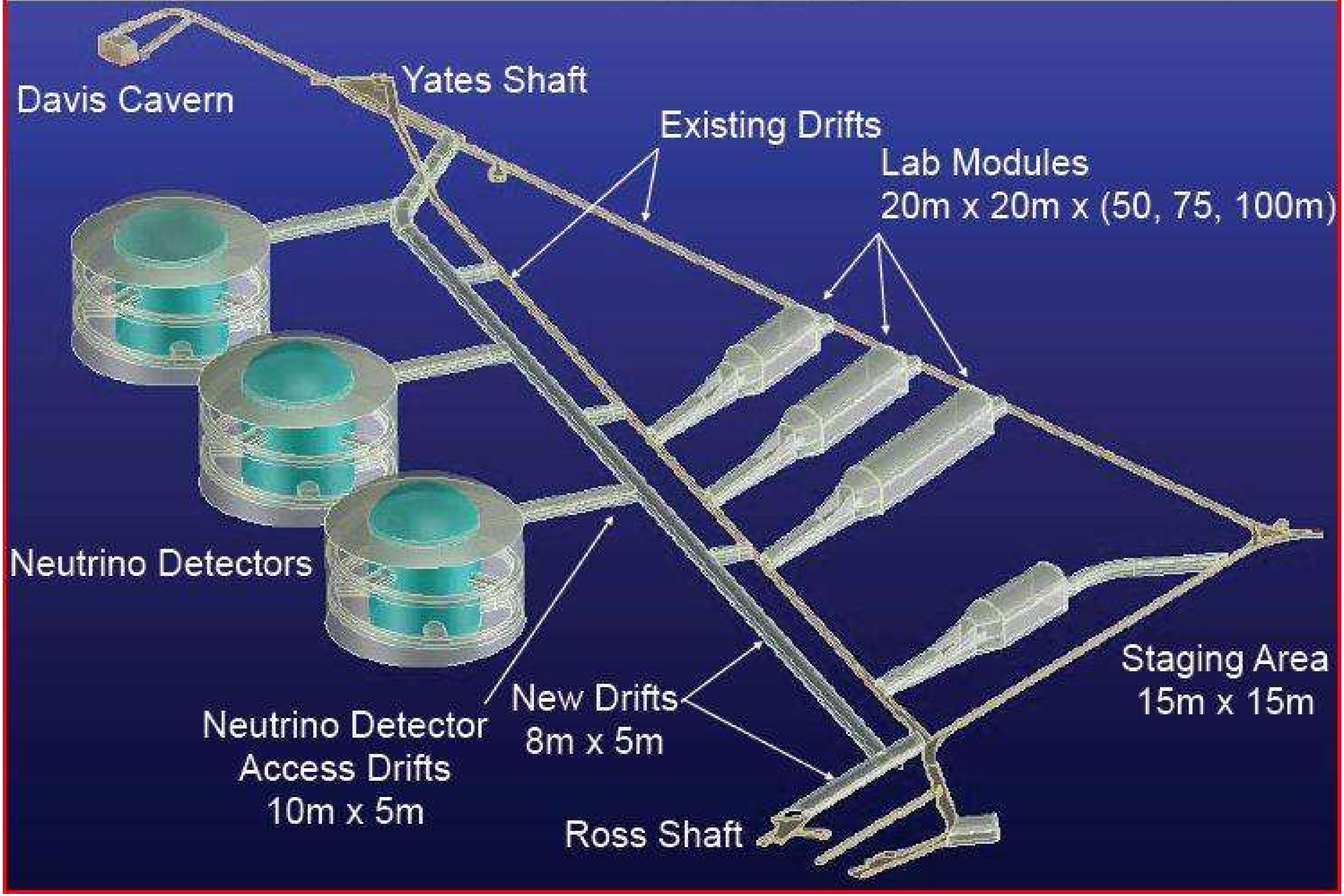
- Cerenkov Imaging detector
  - Long baseline appearance
  - Proton decay
  - SN and solar neutrino

- 50,000 PMTs per module
- 10% photocathode coverage
- Located at 4850 ft level

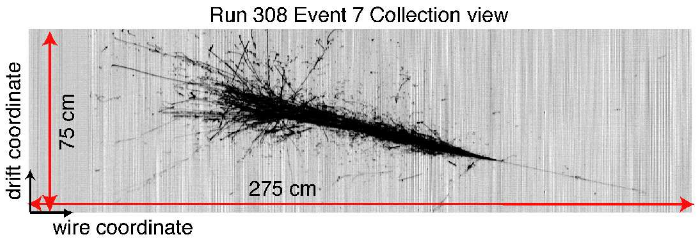
To compensate for poor signal efficiency and background detection, detector sizes are ~6 times larger than LArTPCs

Large detectors but known technology

4850 Level Conceptual Layout



Liquid Argon TPCs

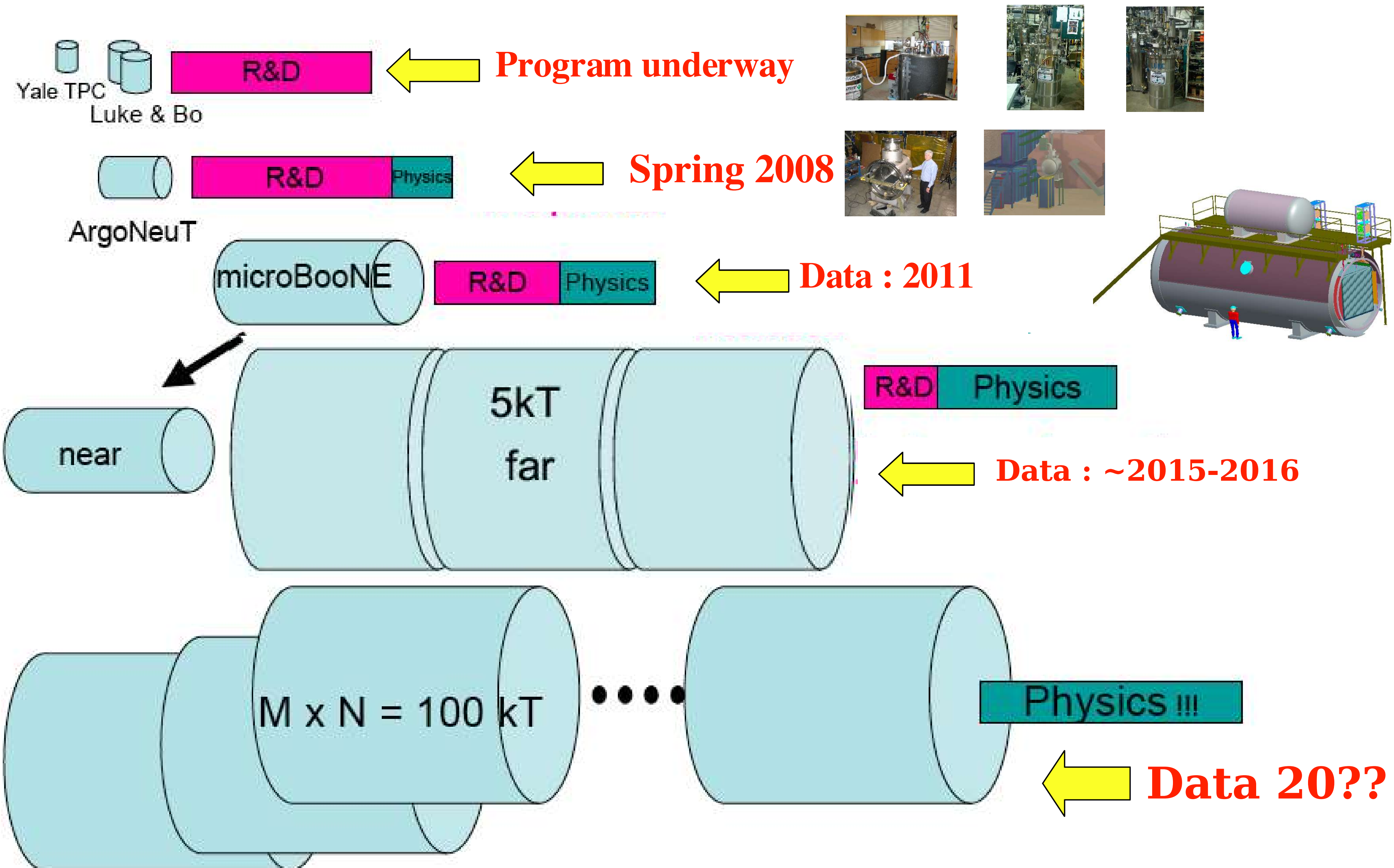


Unique Detectors
⇒ precision measurements in neutrino physics
⇒ appear scalable to large volumes

- Neutrino oscillation physics: significantly more sensitive than WC detectors.
  (~6 times more sensitive than WC technology
  translates into smaller volumes for same physics reach)
  ν_e appearance is difficult. Need powerful LAr detectors.....
- Proton decay searches
  - sensitive to $p \rightarrow \nu\, k$
  - Extend sensitivity beyond SK limits with detectors larger than 5kton
- Supernova and solar neutrinos

Beautiful detectors, but can they be built on large scales?

Liquid Argon TPC R&D must evolve to massive scales



US program

Main challenges for massive LArTPCs

- **Purification Issues: large, industrial vessels**
  - Test stand measurements
  - Purification techniques for non-evacuable vessels
  - Purity in full scale experiment
- **Cold, Low Noise Electronics and signal multiplexing**
  - Test stand measurements
  - Plan for R&D towards cold electronics
- **Vessels: design, materials, insulation**
  - Learn as we go in designing MicroBooNE
- **Vessel siting underground: safety, installation …**
- **Understanding costs of these detectors**

US program to address these is moving along rapidly!
Ongoing R&D and plans for what more needs to be done….

ArgoNeuT

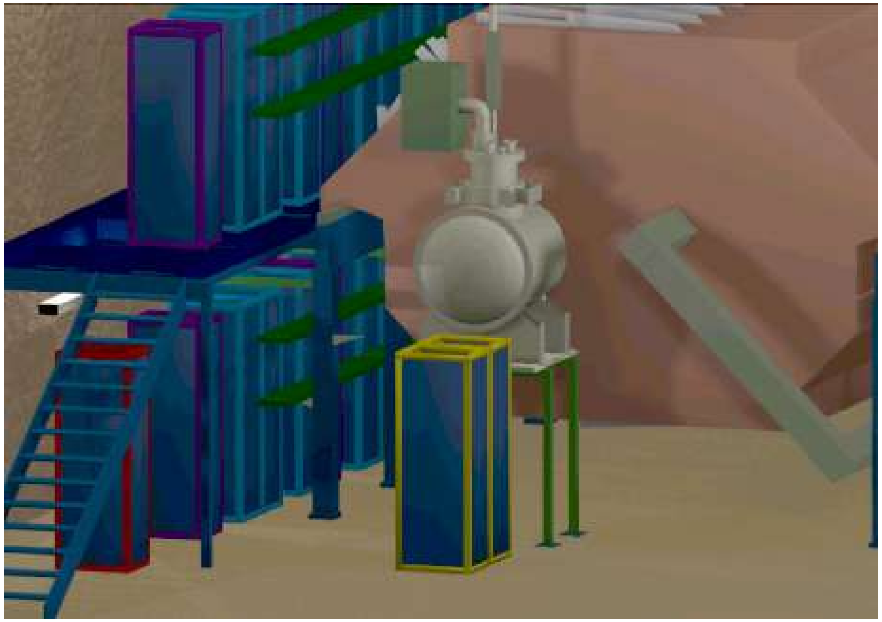
First US detector to see neutrinos

Joint NSF/DOE project

0.3 ton active volume

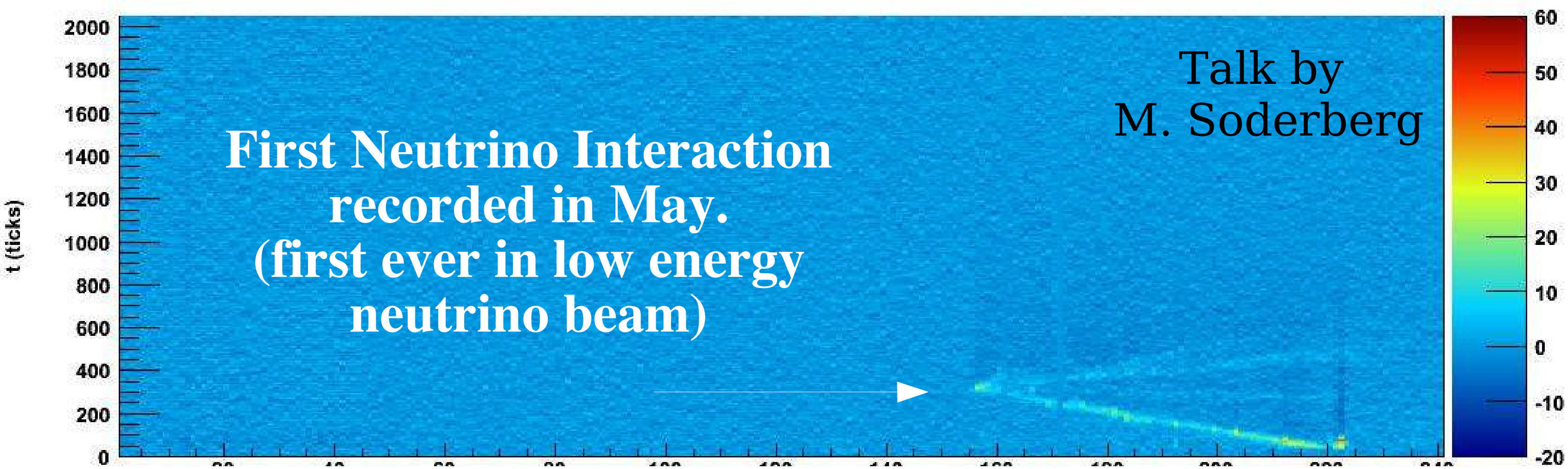
0.5 x 0.5 x 1.0 m^3 TPC; 500 channels

- See neutrino interactions (~150 evts/day)
- Long term running conditions
- Underground siting issues



Collaboration: University of L'Aquila, Fermilab, Gran Sasso Lab, Michigan State, University of Texas at Austin, Yale

Going underground early 2009

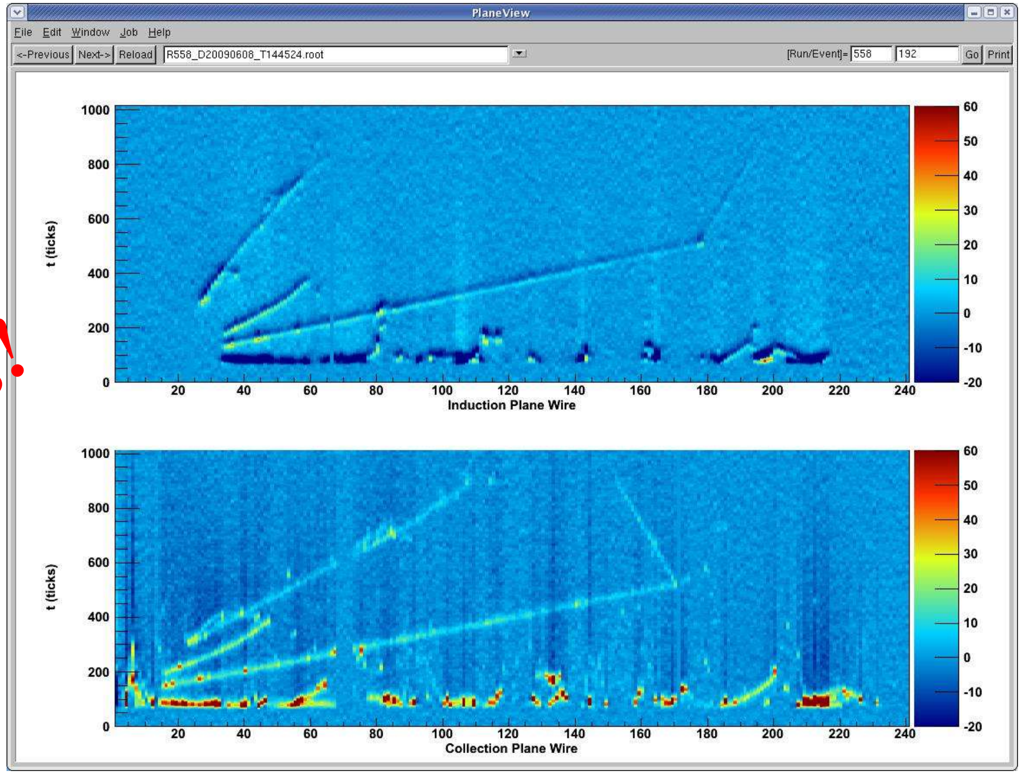


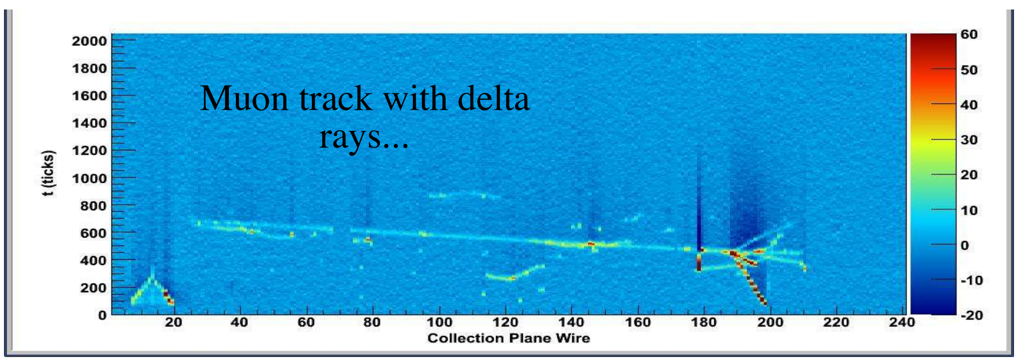
New results!

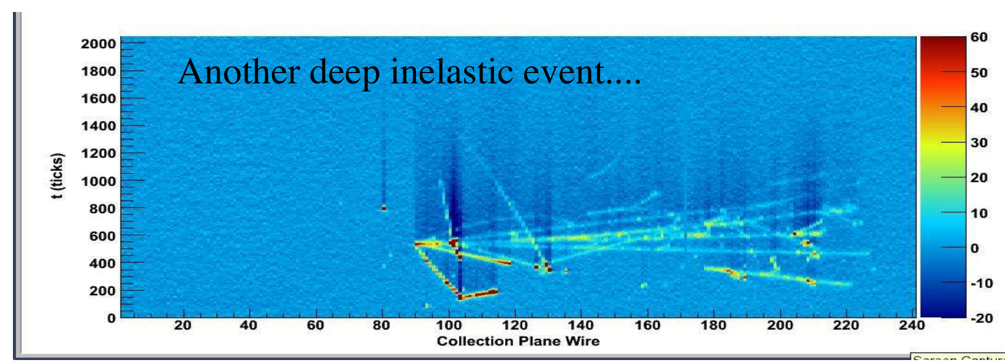
Deep Inelastic event

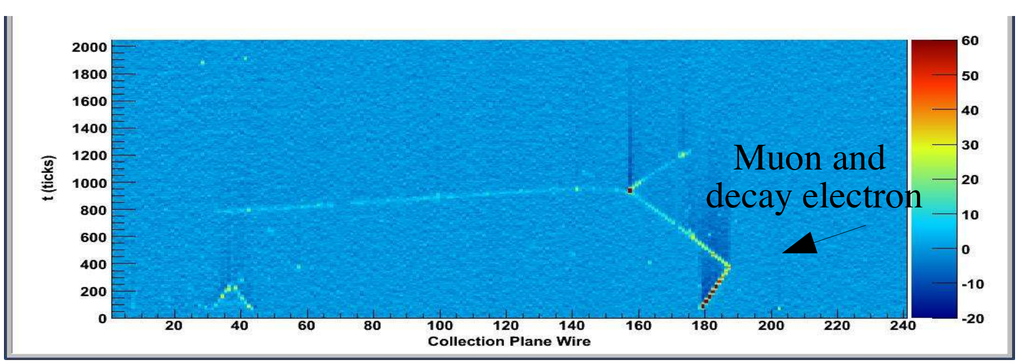
Induction plane

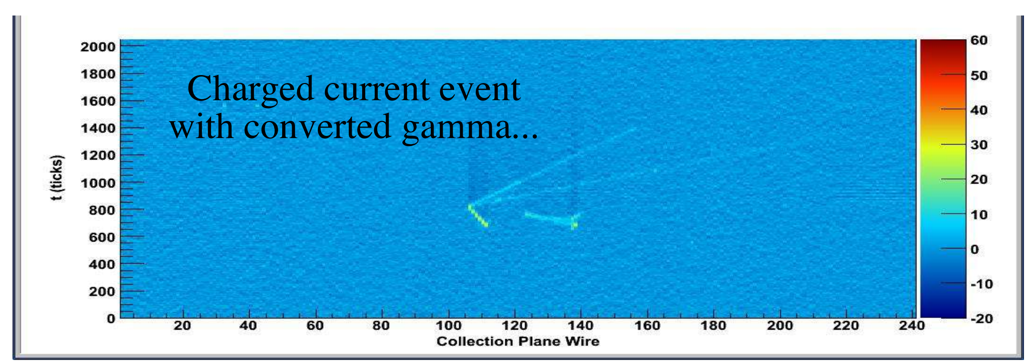
Collection plane



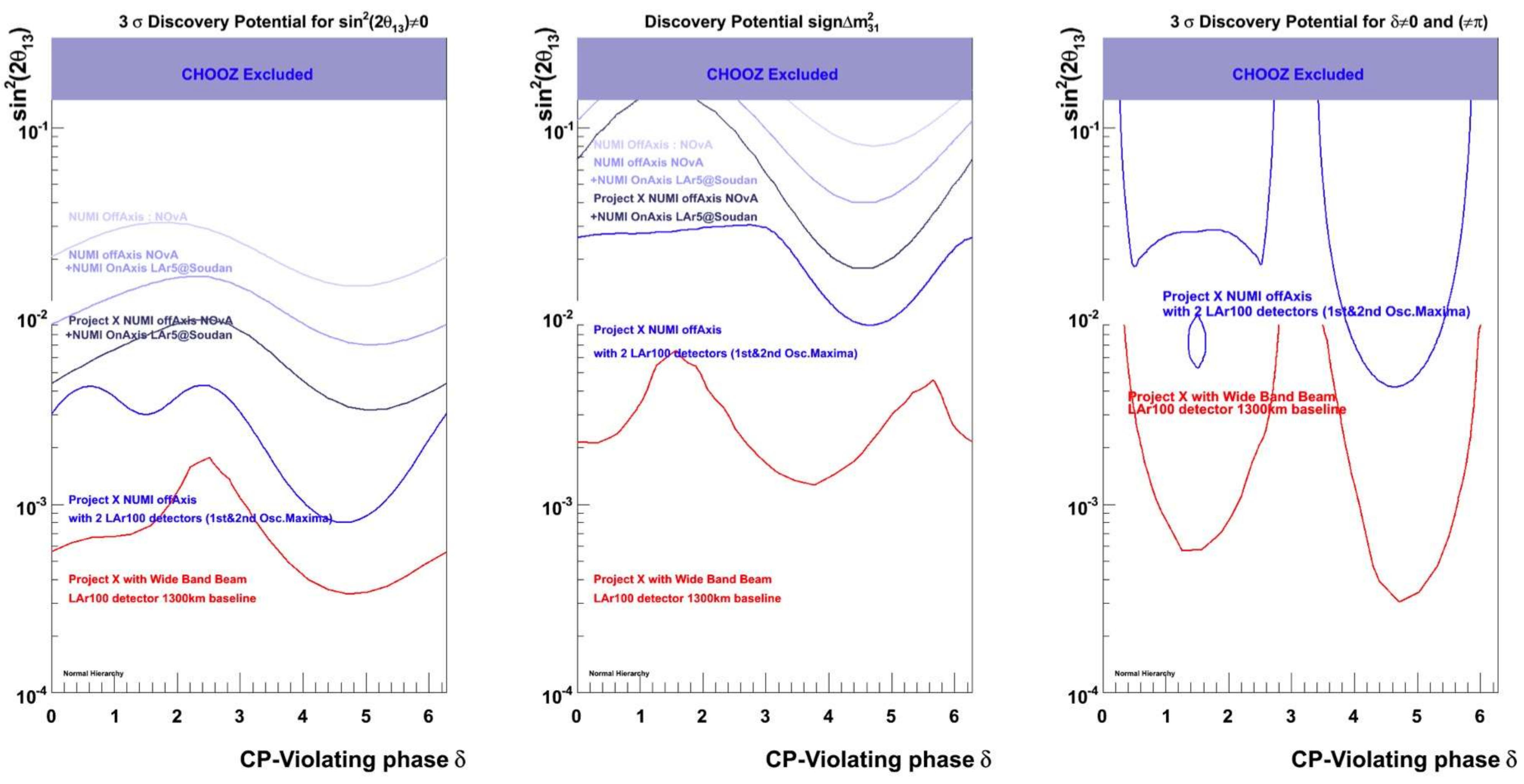




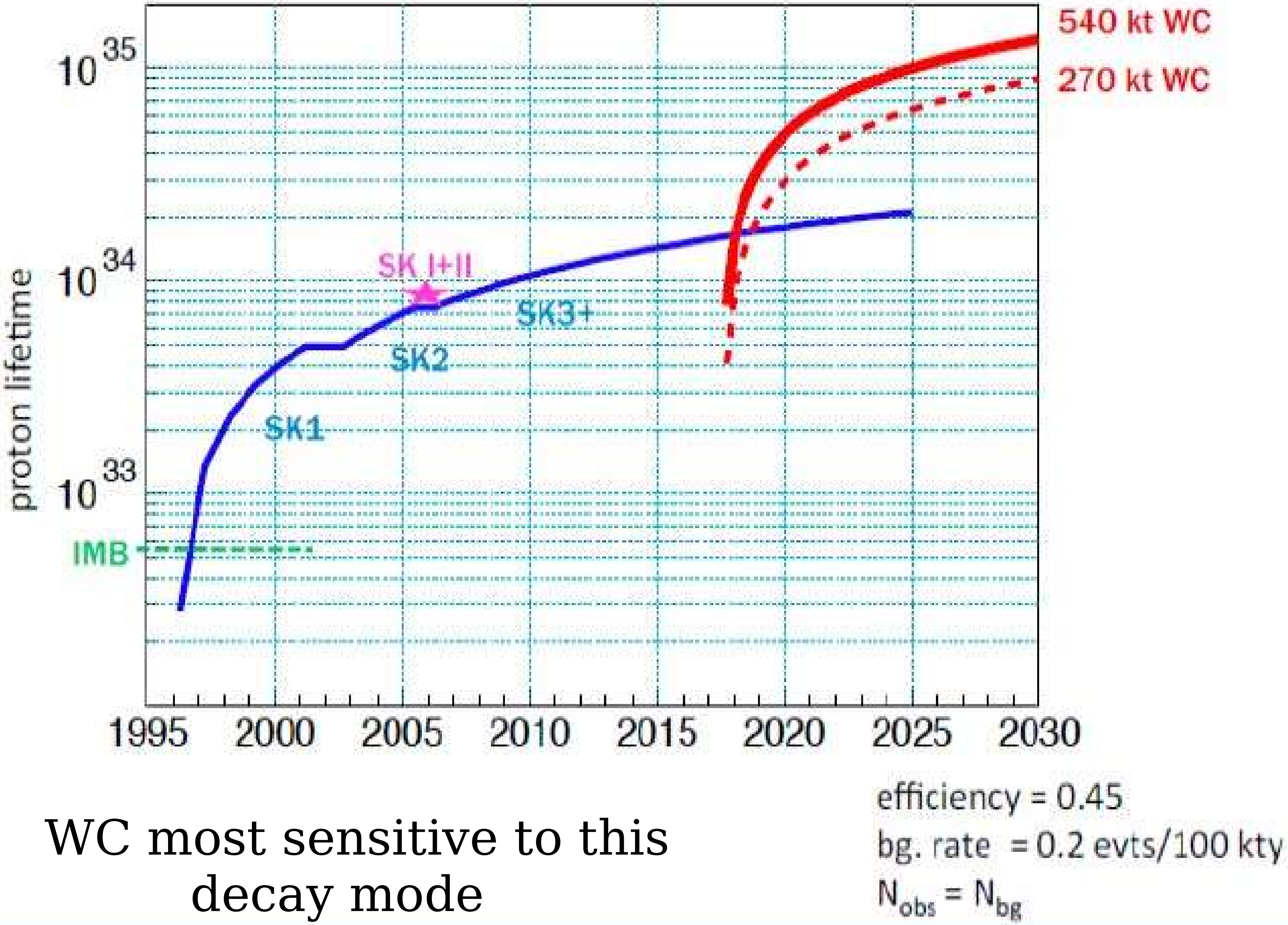




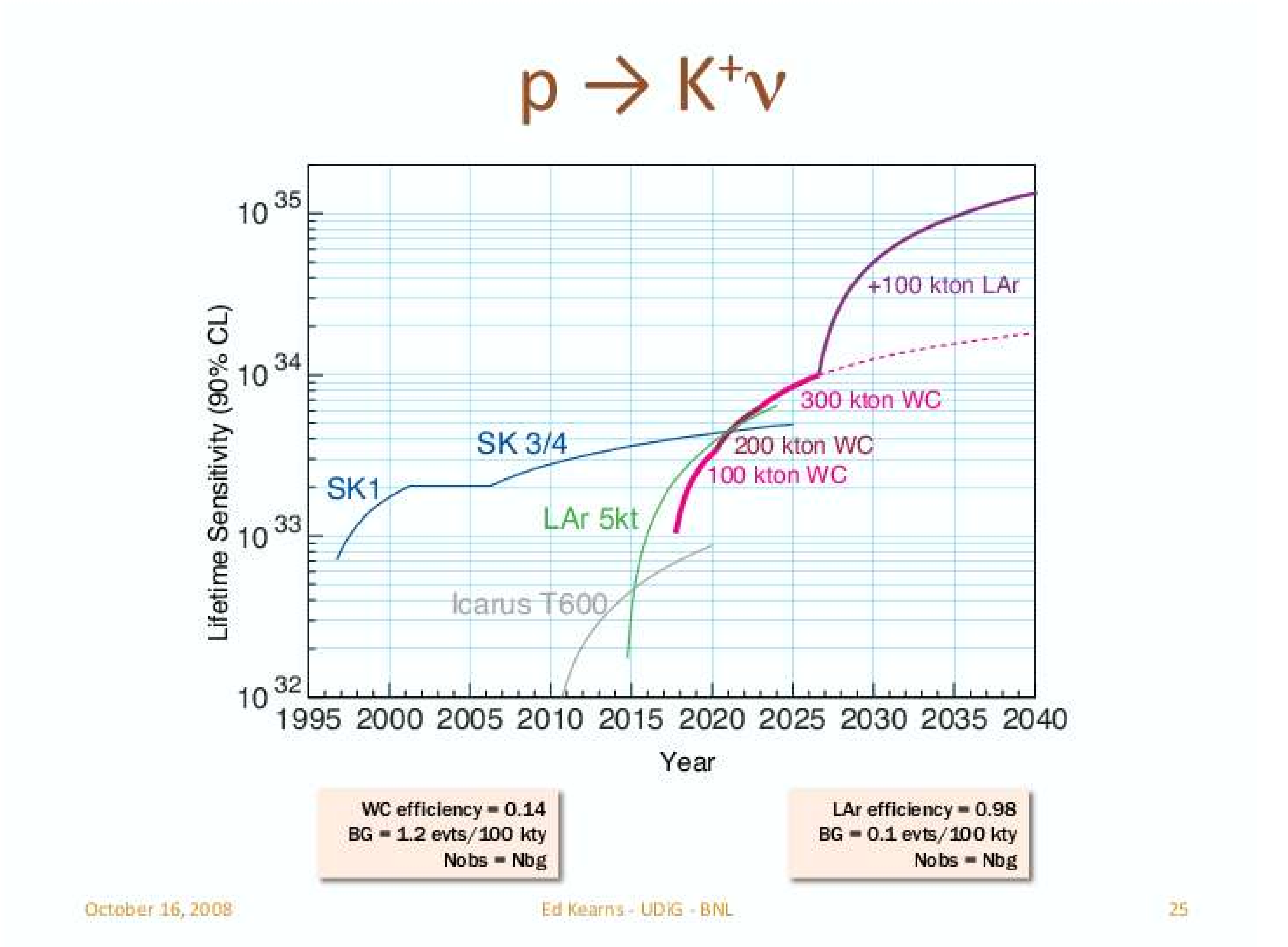
Impressive physics reach for CP Violation search



$$p \rightarrow e^+ \pi^0$$



WC most sensitive to this decay mode



LArTPCs most sensitive to this decay mode

Supernova neutrino reactions in WC and Lar are sizable
and complementary in reaction type and signal shape

H_2O

$\overline{\nu}_e + p \rightarrow n + e^+$ (88%/89%) ,
$\nu_e + e^- \rightarrow \nu_e + e^-$ (1.5%/1.5%) ,
$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$ (< 1%/ < 1%)
$\nu_x + e^- \rightarrow \nu_x + e^-$ (1%/1%) ,
$\nu_e + ^{16}O \rightarrow e^- + ^{16}F$ (2.5%/ < 1%)
$\overline{\nu}_e + ^{16}O \rightarrow e^+ + ^{16}N$ (1.5%/1%) , an
$\nu_x + ^{16}O \rightarrow \nu_x + O^*/N^* + \gamma$ (5%/6%) ,

LAr

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$$
$$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Cl}^* + e^+$$
$$\nu_\alpha + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{Ar}^* + \nu_\alpha$$
$$\hookrightarrow {}^{40}\mathrm{Ar} + \gamma_1 + \ldots \gamma_n$$
$$\nu_e + e^- \rightarrow \nu_e + e^-$$
$$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$$
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

100 kt H_2O, SN@10 kpc

Interaction	Rates ($\times 10^4$)
$\overline{\nu}_e + p \rightarrow n + e^+$	2.3
$\nu + e \rightarrow \nu + e$	0.1
$\nu_x + ^{16}O \rightarrow ^{16}O + \nu_x$	0.05
$\nu_x + ^{16}O \rightarrow ^{16}F + e$	0.2

100 kt of LAr, SN @ 10 kpc

Interaction	Rates ($\times 10^4$)
ν_e CC (^{40}Ar, ^{40}K*)	2.5
ν_x NC (^{40}Ar*)	3.0
ν_x ES	0.1
anti–ν_e CC (^{40}Ar, ^{40}Cl*)	0.054

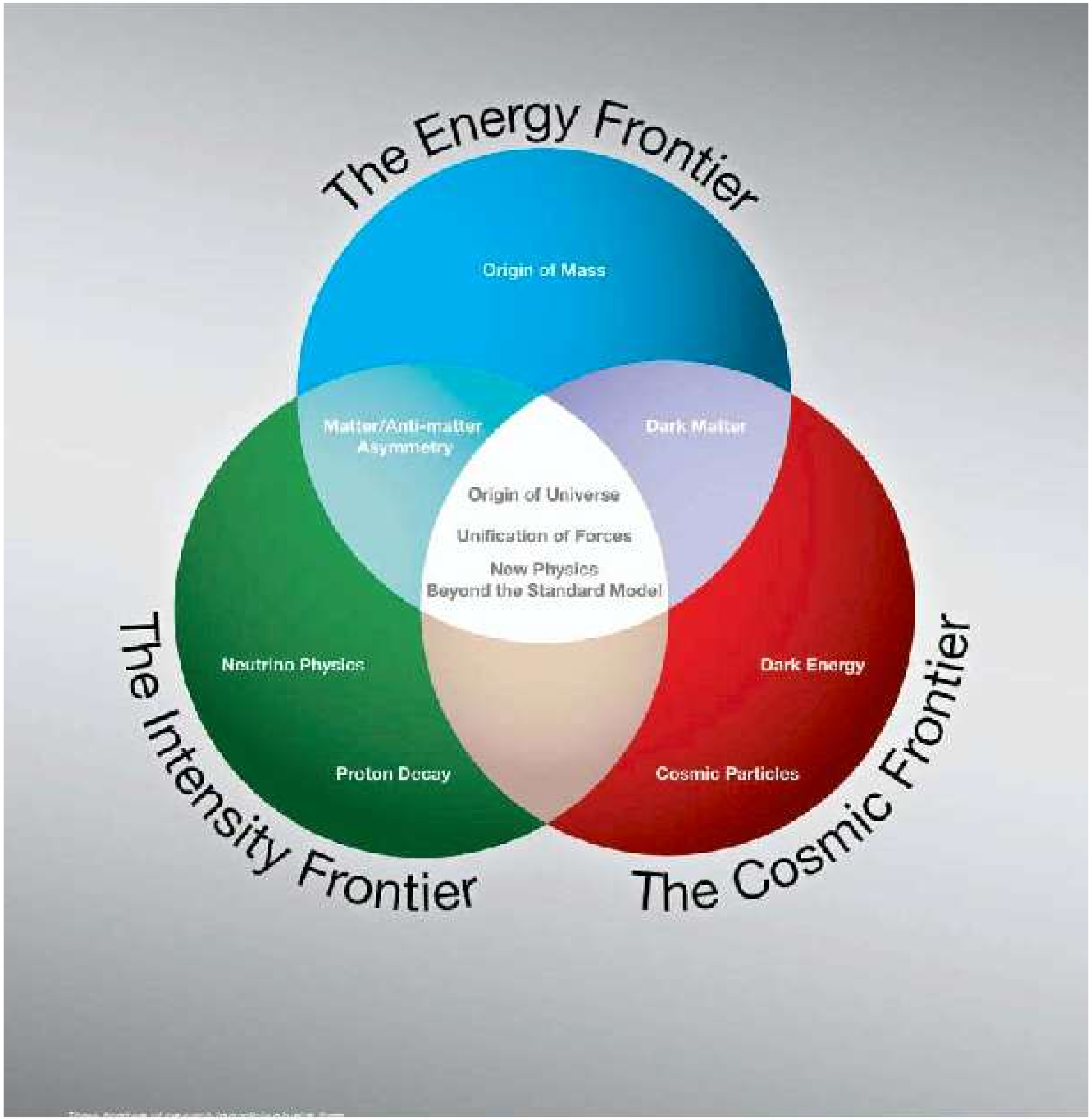
A. Bueno NP2008, via K.Scholberg

SuperNoVA relic searches also possible...

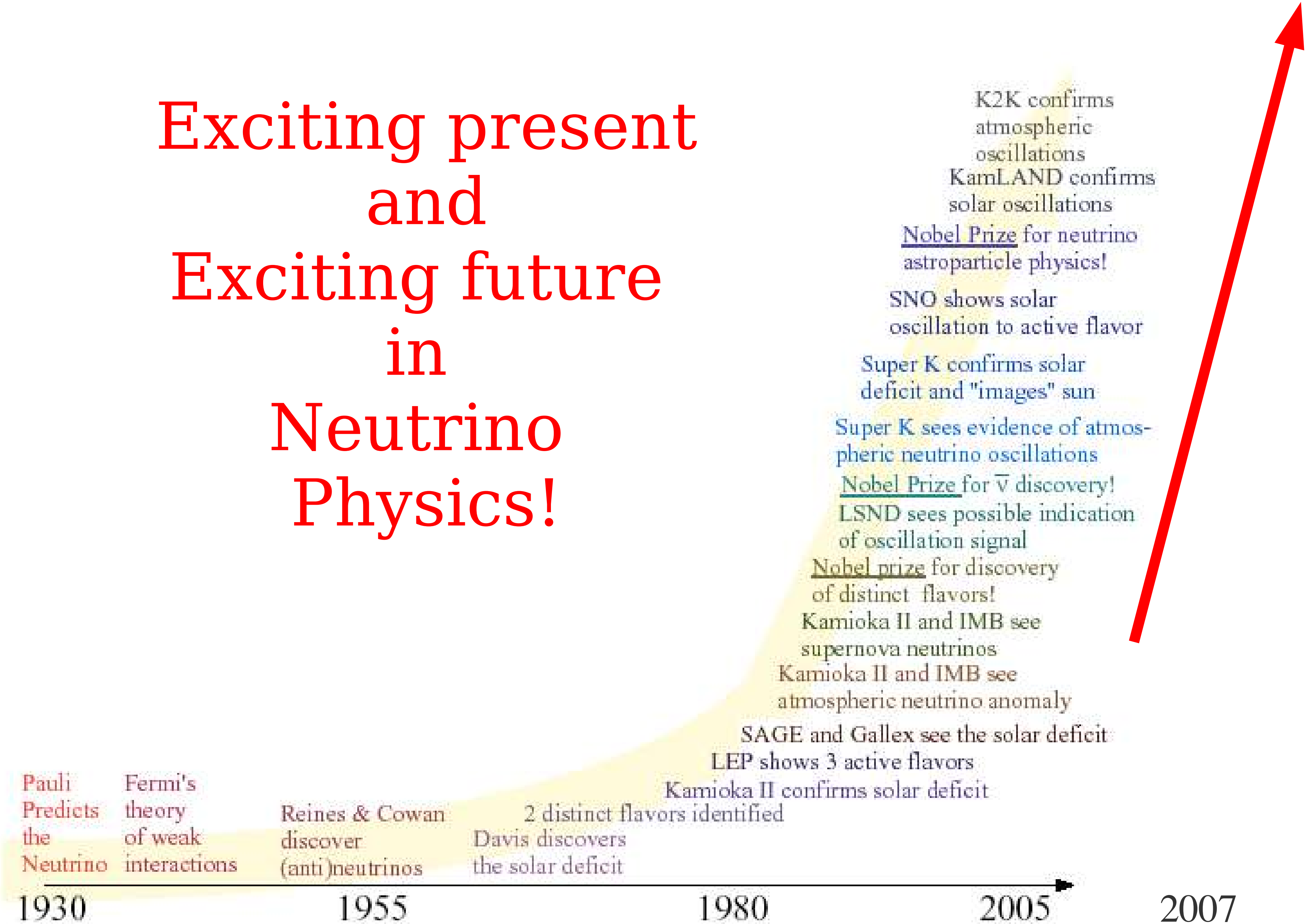
While there are many challenges ahead in building these detectors sited deep underground…

the physics is so compelling

And at the Intersections…



Exciting present and Exciting future in Neutrino Physics!

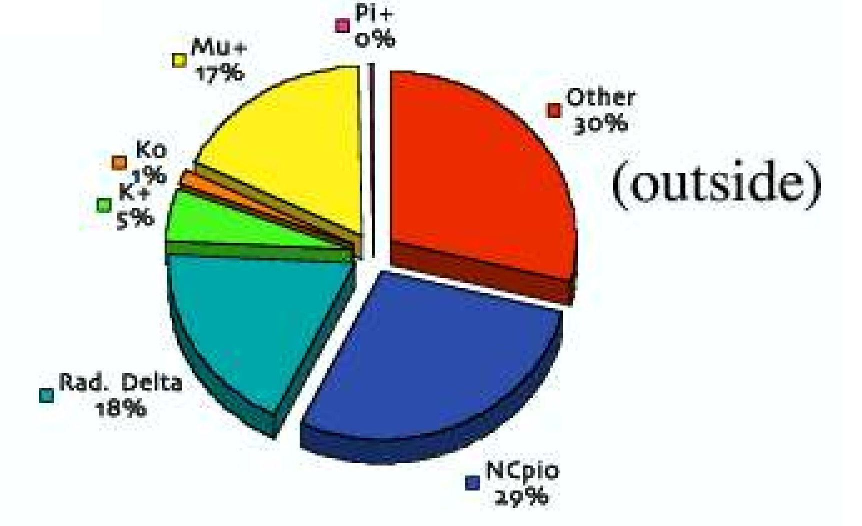


Backups

MicroBooNE's LArTPC detection technique extremely powerful

- e/γ separation capability removes ν_μ induced single γ backgrounds
- electron neutrino efficiency: ~x2 better than MiniBooNE
- sensitivity at low energies (down to tens of MeV compared to 200 MeV on MiniBooNE)

MiniBooNE low E backgrounds



Translates to 5σ sensitivity if excess is ν_es

3σ if excess is γs

Inability to identify excess as ν_es or γs illustrates the need for the best detectors for ν_e appearance physics

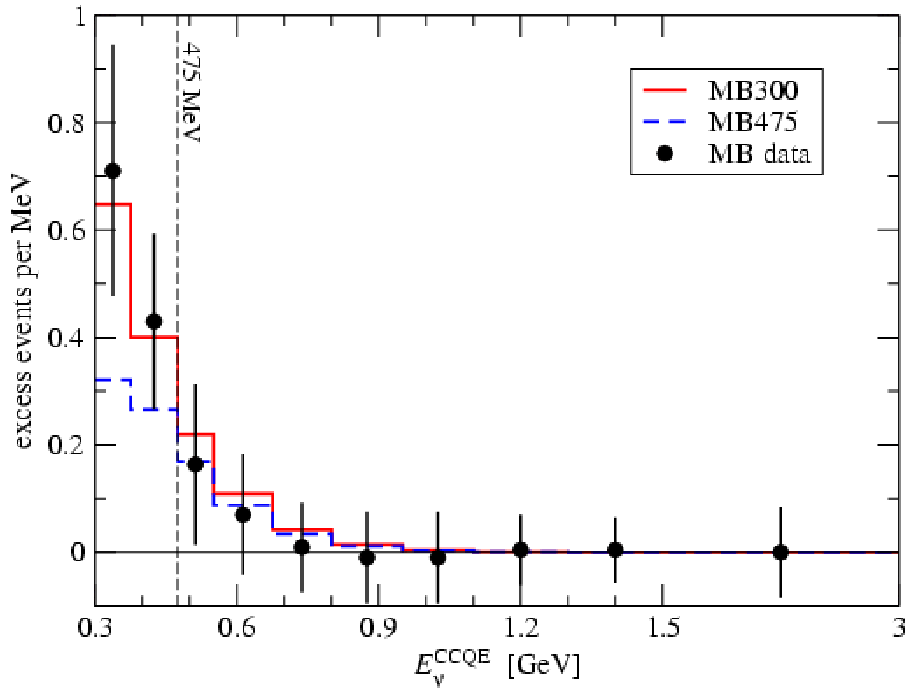
→ the strength of the LAr detection technique

Interpretation as electron neutrinos

Oscillations to Sterile νs

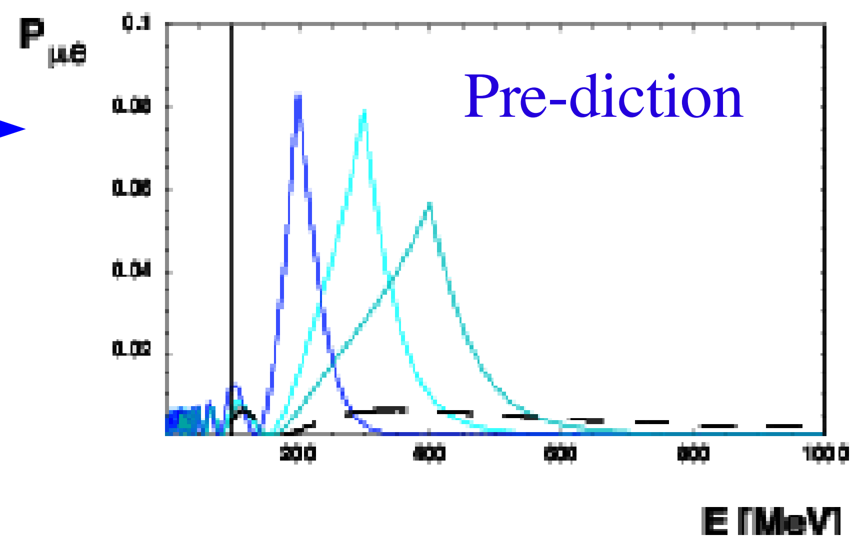
- hep-ph/0705.0107v1

Maltoni and Schwetz 3+2 CPV model fits MiniBooNE and LSND excesses. Tension with NSBL.



- hep-ph/0706.1462
- hep-ph/0710.28985
- hep-ph/0702049
- hep-ph/0504096

Pakvasa, Pas, Weiler: Sterile neutrinos that can travel in extra dimensions oscillate with SM neutrinos



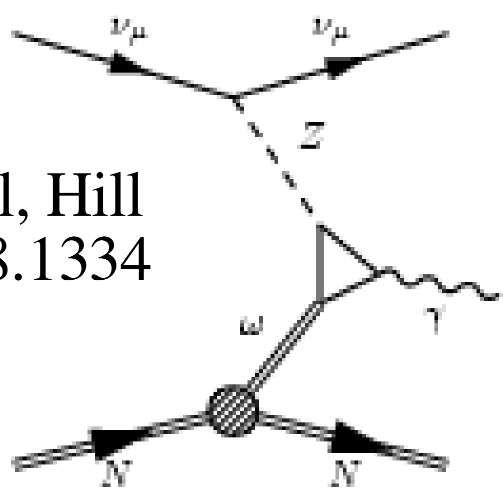
Neutrino decay, Lorentz Violation, ...

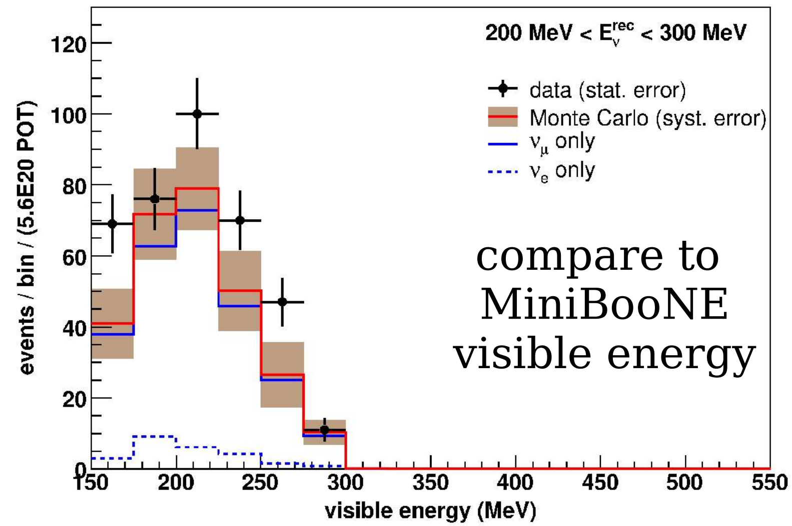
- hep-ph/0707.4953
- hep-ph/0606154
- hep-ph/0602237
- hep-ph/0707.2285

Interpretation as photons

Standard Model process with potentially big implications....

Harvey, Hill, Hill
hep-ph/0708.1334

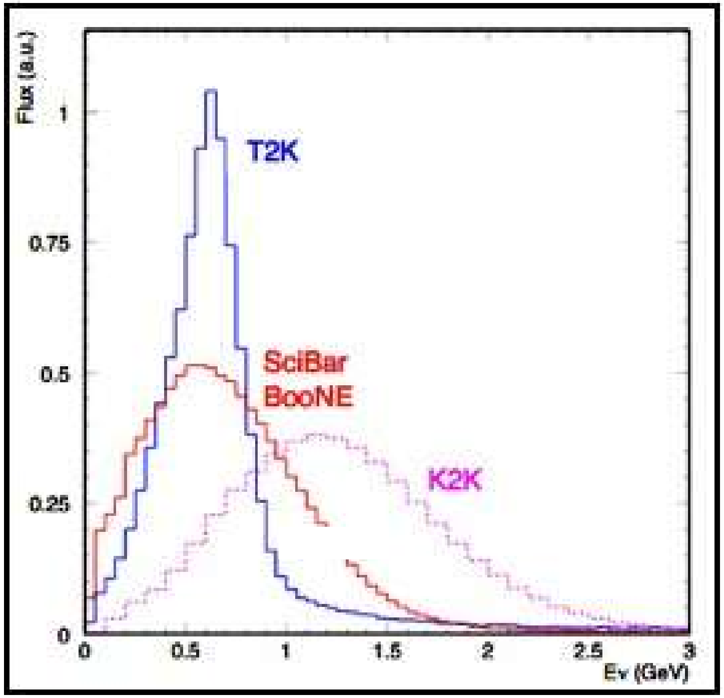




Disfavored with no excess in anti-neutrino mode...

Impact on Broader program

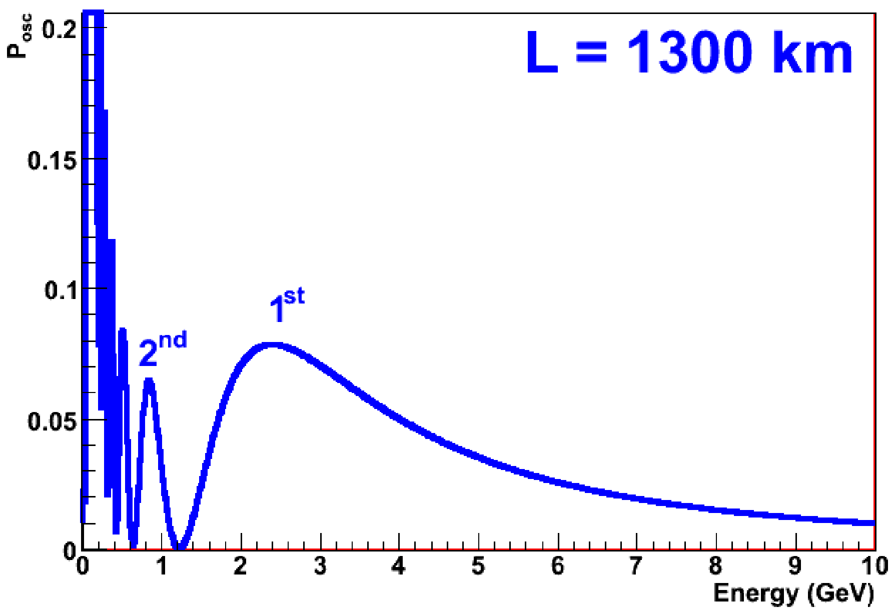
Regardless of interpretation, excess must be understood for next generation ν_e appearance measurements.



T2K experiment:

- Similar energy spectrum
- Cerenkov detection technique

DUSEL Long Baseline Program:
Low energy excess in region of 2^{nd} oscillation maxima



The CP Violation Parameter

Long Baseline Oscillations...

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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

From Long Baseline Appearance Measurements

Goal is to be sensitive to
- Final unknown mixing angle, θ_{13}
- the CP violating phase, δ
- Mass hierarchy

Measurements of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$