Neutrino Physics, Current Status and Opportunities

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Seminar CEA Saclay

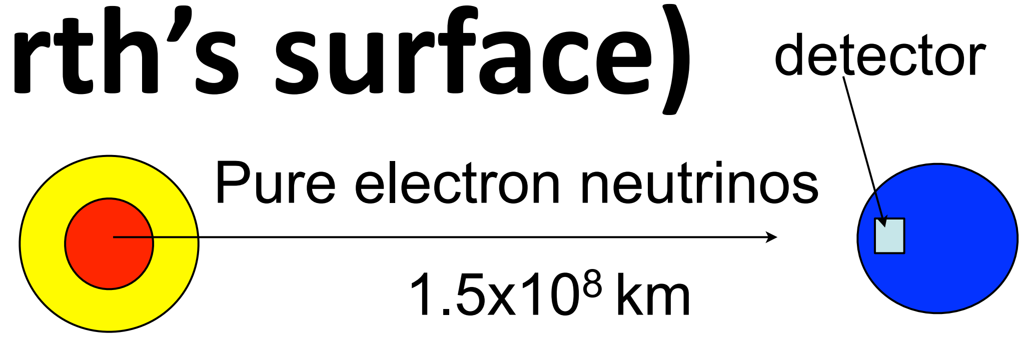
June 25, 2014

Outline

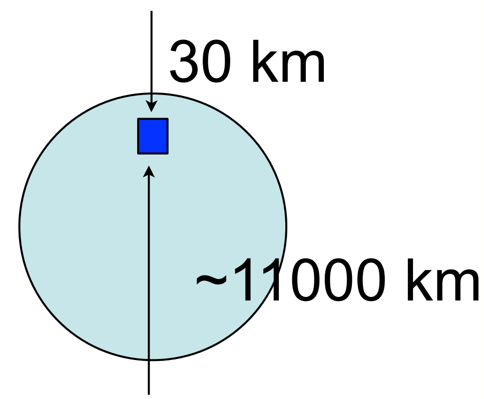
- **Brief review of neutrino properties.**
- **Brief review of natural and manmade sources and detectors.**
- **Current status of data from oscillations with emphasis on the recent measurement of θ_{13}**
- **Benefits of θ_{13} and the scientific case for a new accelerator experiment.**
- **Description and Status of implementing the Long-Baseline Neutrino Facility and status of the current scientific collaboration.**

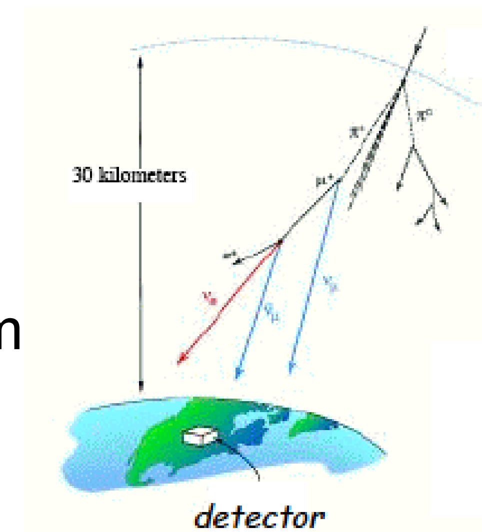
I will move from basic to technical explanation in the talk.

Neutrino Sources (at Earth's surface)



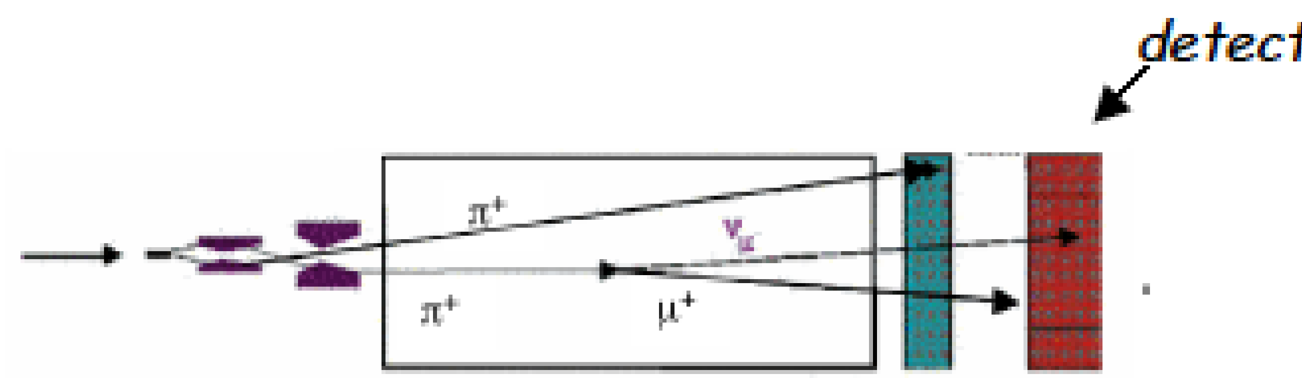
- **The Sun**
  - **<0.5 MeV, 10^{11} /cm^2 s**
  - **3-14 MeV, 3 x 10^6 /cm^2 s**
- **Cosmic rays hitting Atmosphere**
  - **~1 GeV, ~5000/m^2/sec**
- **Radioactive decays in the Earth**
  - **<3 MeV, 10^6-10^7 /cm^2/sec**
- **Supernova. 99% of the energy of the explosion goes into neutrinos of all types. ~10 MeV, 20 seen in 1987.**
- **CMB nus. 300 cm^{-3} @ 2.7 K. (not detectable as yet).**
- **Nuclear reactors.**
  - **<10 MeV, 6x10^{20} /3GW(th)**
- **Accelerator Beam (10-120 GeV proton)**
  - **1-100 GeV, 10^{17}/m^2/GeV/MW*yr @1 km.**





mix of muon and electron types

Pure electron anti-neutrino source. Isotropic (4Pi) beam.

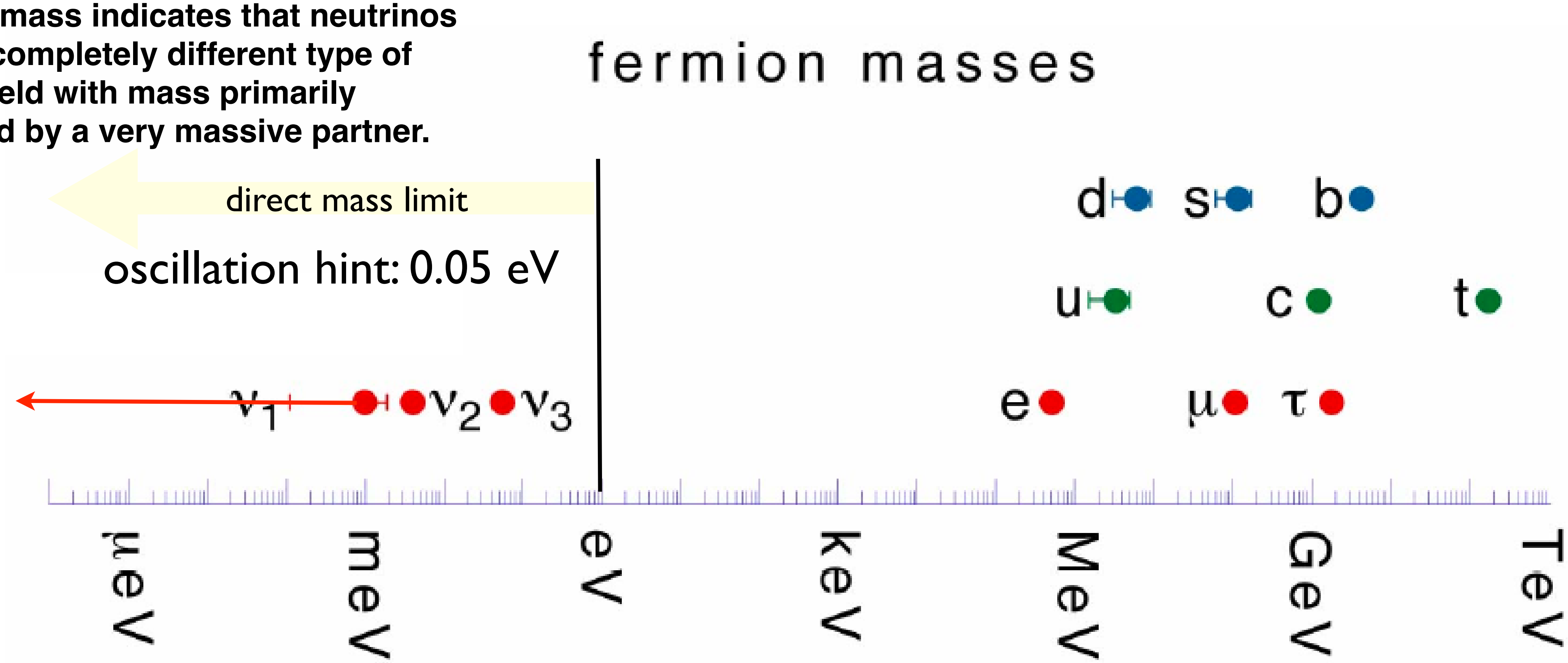


Pure muon neutrino (antinu) source, pulsed, directed

What else do we know and how do we know it ?

- Neutrinos are definitely massive with extremely small mass - from the existence of oscillations.
- Neutrino is the most abundant particle of matter with probably only 3 active types - cosmology and precision EW.
- Neutrino mass and mixing is completely different compared to quarks. I will review backwards for simplicity.

The small mass indicates that neutrinos may be a completely different type of massive field with mass primarily determined by a very massive partner.



If neutrinos have mass; the massive states need not be the same as the Weak interaction states. A neutrino could be in a classic superposition of states.

This will lead to interference effects

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2t} - e^{-iE_1t}|^2 \end{aligned}$$

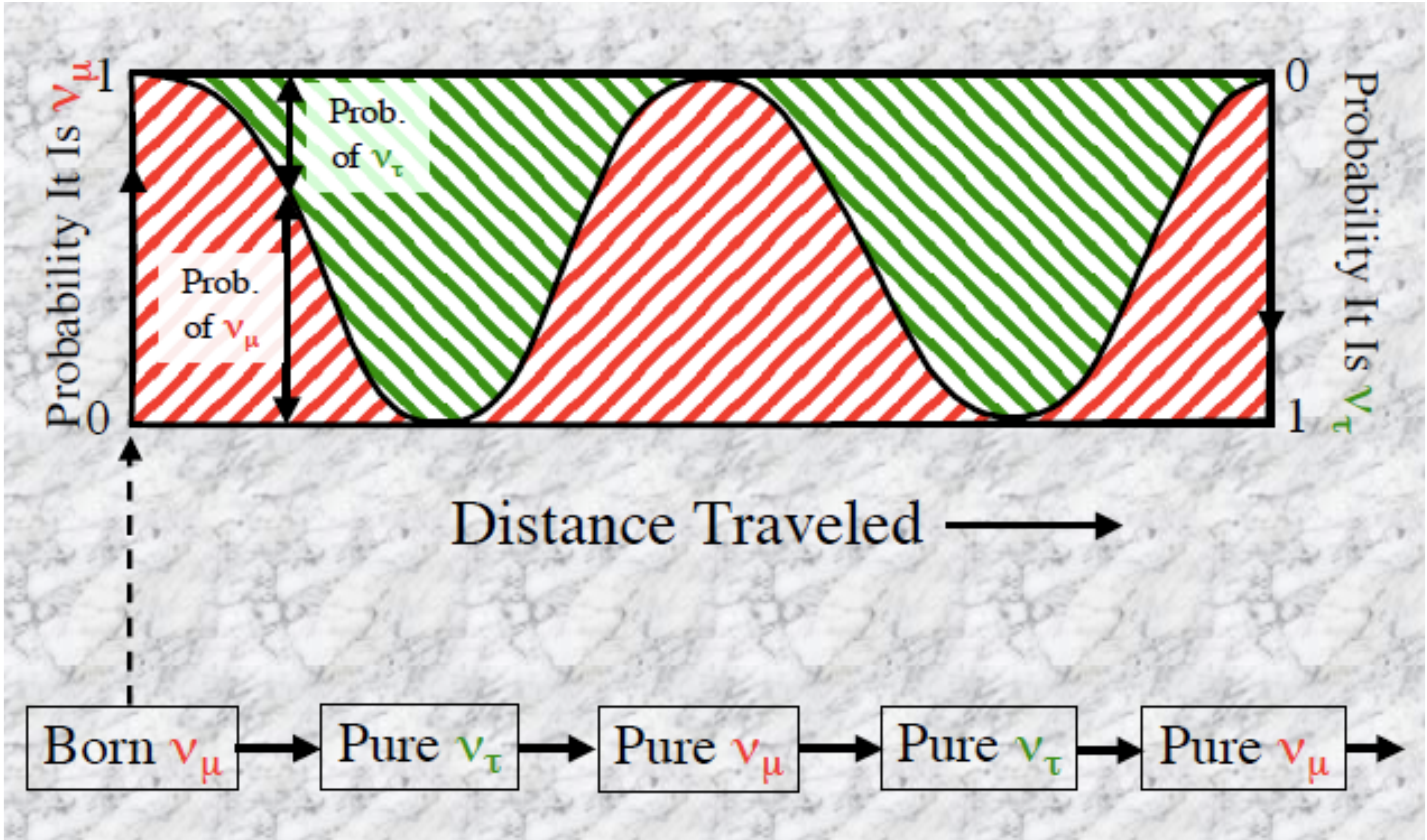
Sufficient to understand most of the physics:

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1 GeV$, $L = 494 km$.

Picture with $\theta = 45$ deg



Everything we know about neutrino properties comes from this astonishing effect.

As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li}|\nu_i\rangle$

For 3 Active neutrinos.

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

✔ Atmospheric, Accel. | ? CP Violating Phase | ✔ Reactor, Accel. | ✔ Solar,Reactor | ? Majorana CP Phases

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

✔ Range defined for Δm_{12}, Δm_{23}

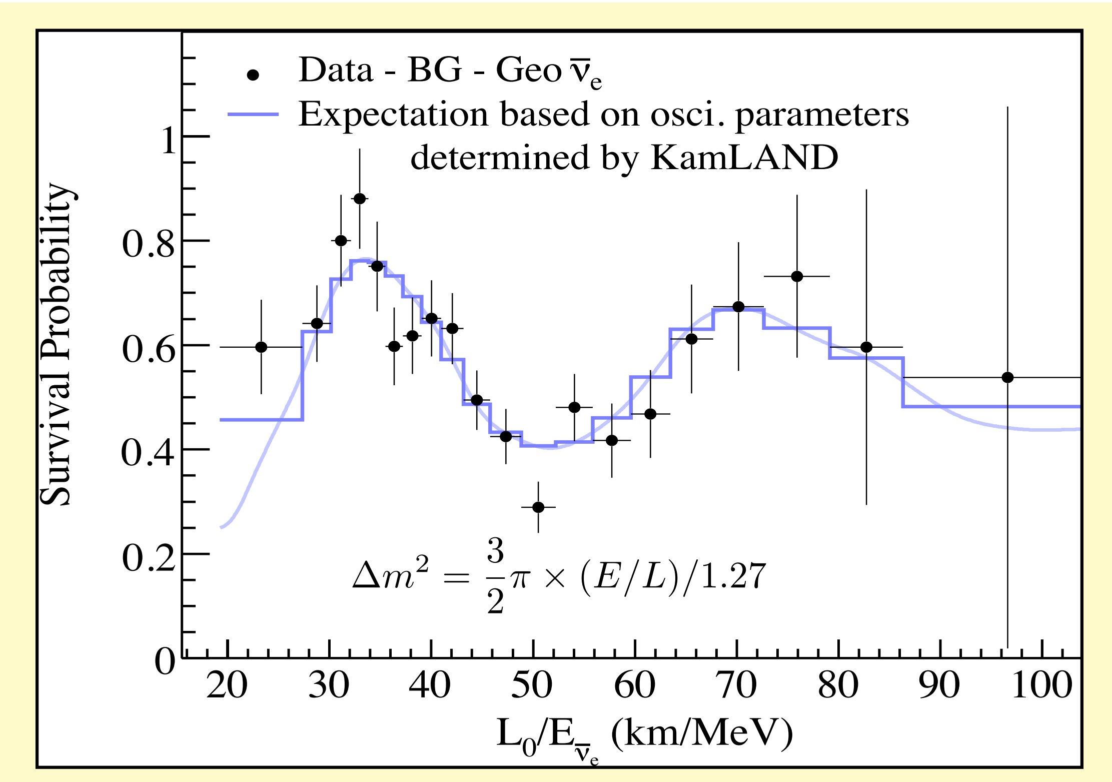
For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

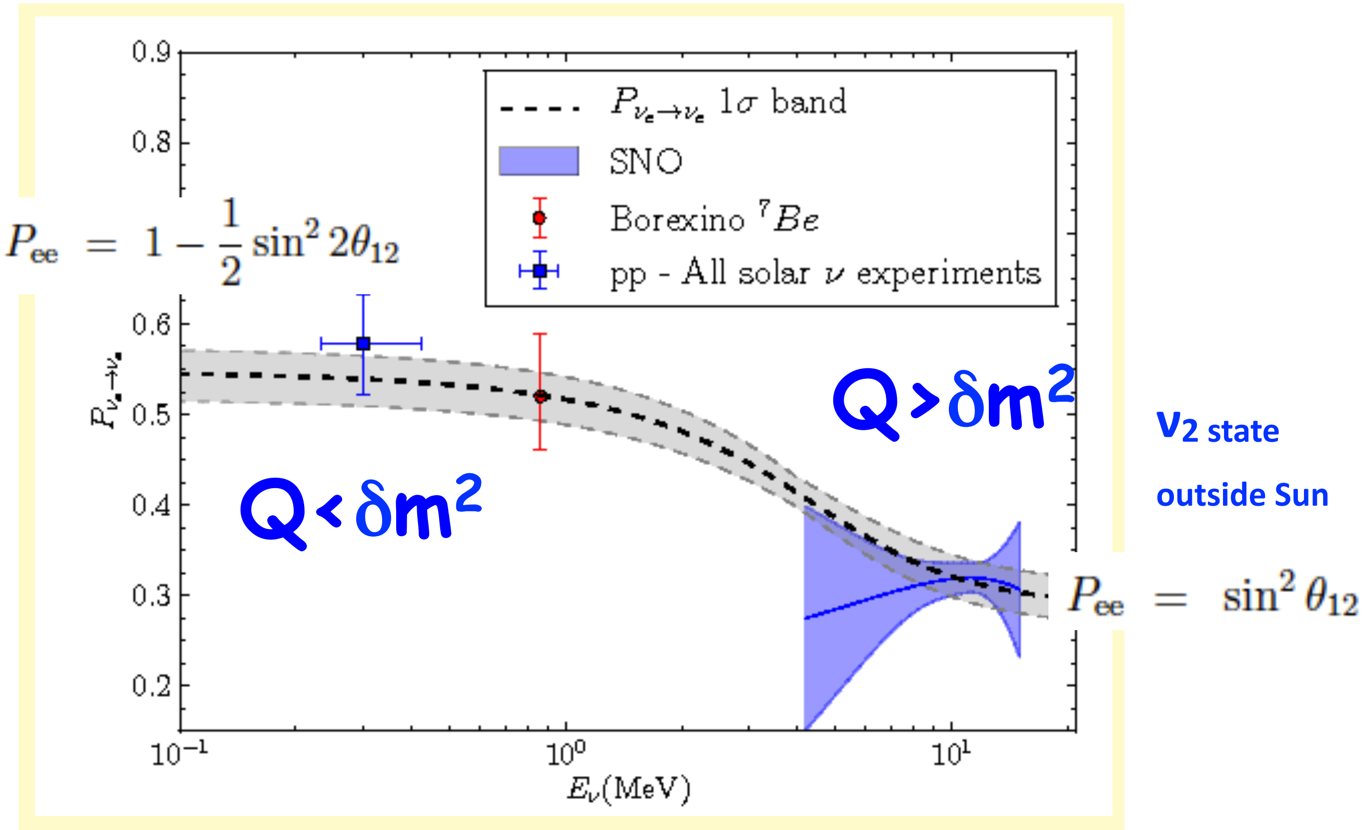
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

CP Violating Phases: implication for Antimatter/Matter asymmetry via Leptogenesis?

The ν_e state

- $\nu_e \sim 0.82\ \nu_1 + 0.55\ \nu_2 + e^{-i\delta}\ 0.16\ \nu_3$





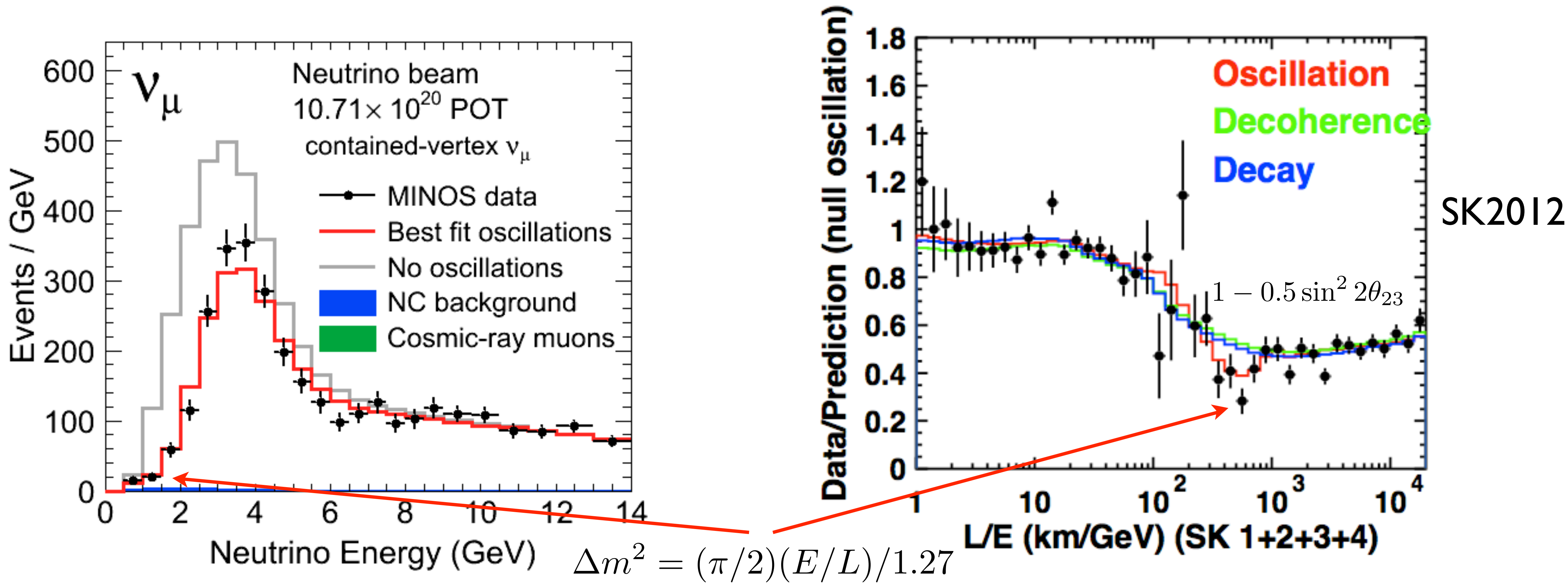
Kamland Reactor data determines the first two elements of this mixing with a well-defined frequency or mass splitting. Data from the Sun (SNO, Borexino, Gallium) is needed to determine which one is heavier !

$\delta m^2 = m^2_2 - m^2_1 \sim 7.5 \times 10^{-5} eV^2$ $\theta_{12} \approx 35^o$

The ν_μ state

- $\nu_\mu \sim -(p)0.4\ \nu_1 + (p')0.5\ \nu_2 - 0.7\ \nu_3$

Important confirmation of tau neutrino mixing from OPERA



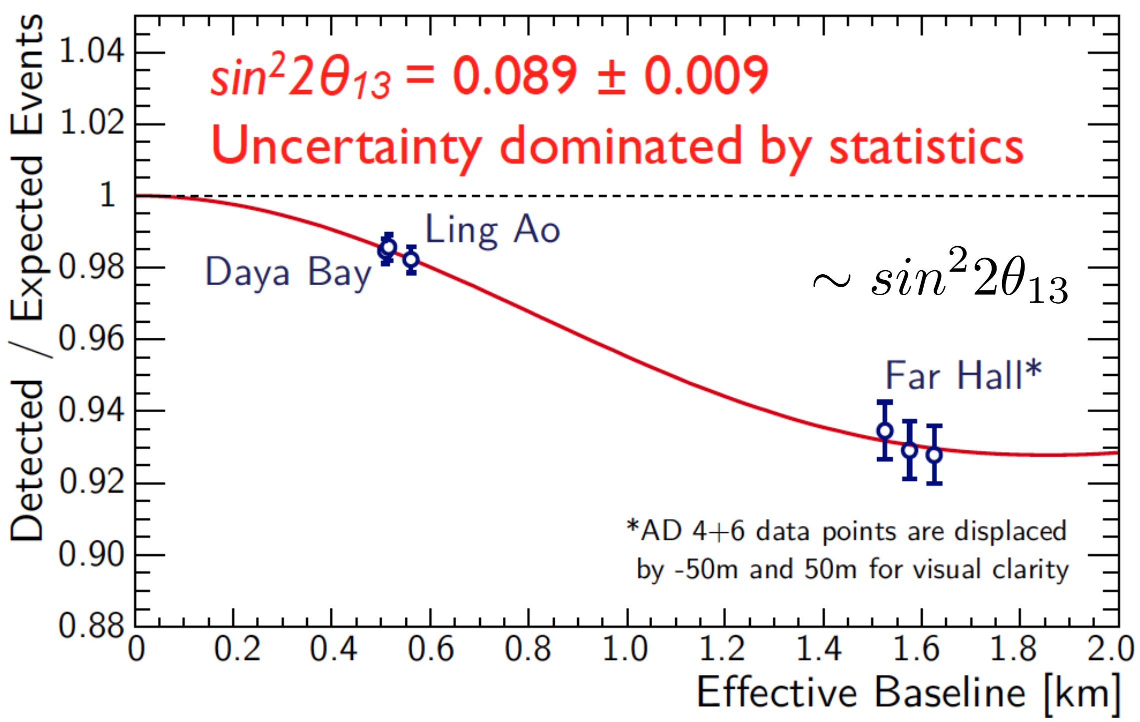
Accelerator MINOS data provides precise difference of mass for the third element, and atmospheric SuperK data shows the mixing to be maximal, but we do not know which is heavier.

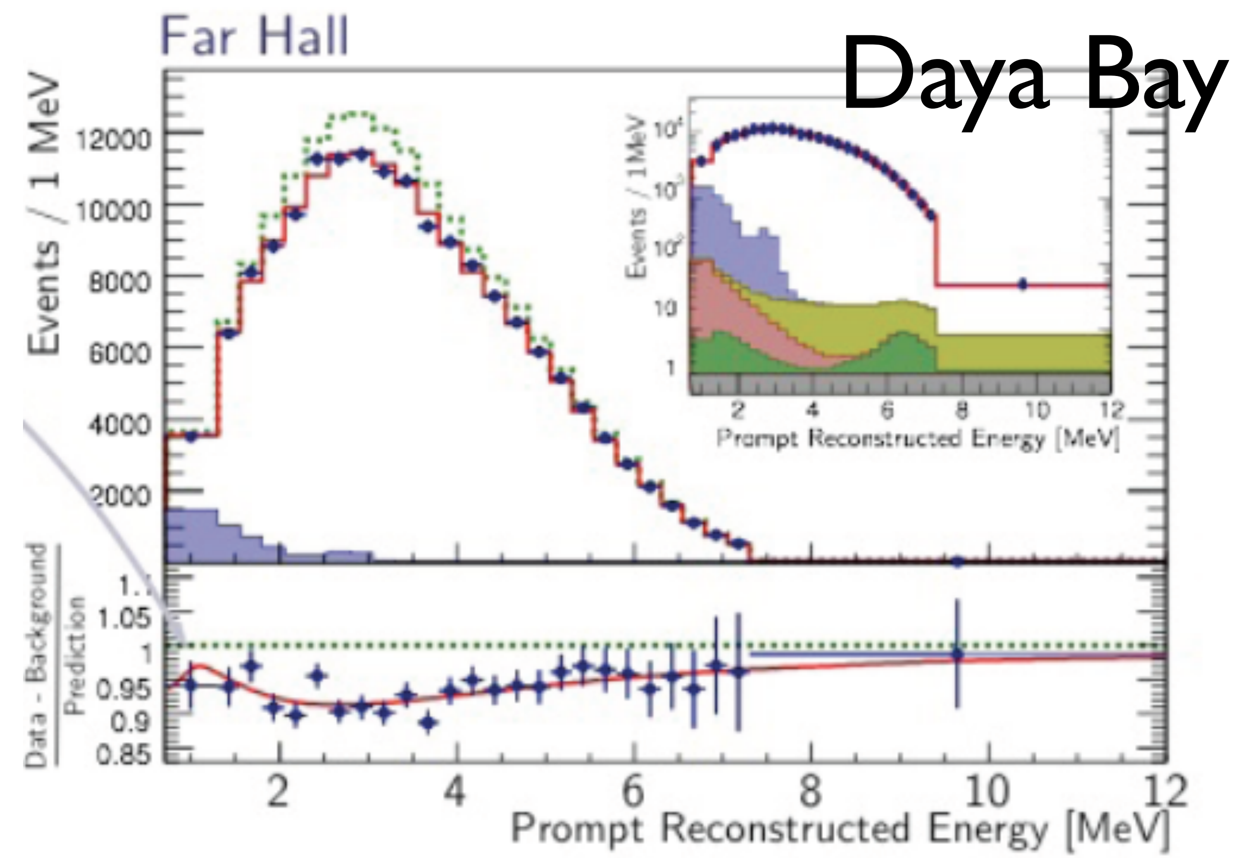
$\Delta m^2 = |m_3^2 - m_{1,2}^2| \sim 2.4 \times 10^{-3}\ eV^2$ $\theta_{23} \approx 45^o$

p, p' represent phases. Cannot determine sign of mass diff.

The ν_e state again !

- $\nu_e \sim 0.82\, \nu_1 + 0.55\, \nu_2 + e^{-i\delta}\, 0.16\, \nu_3$





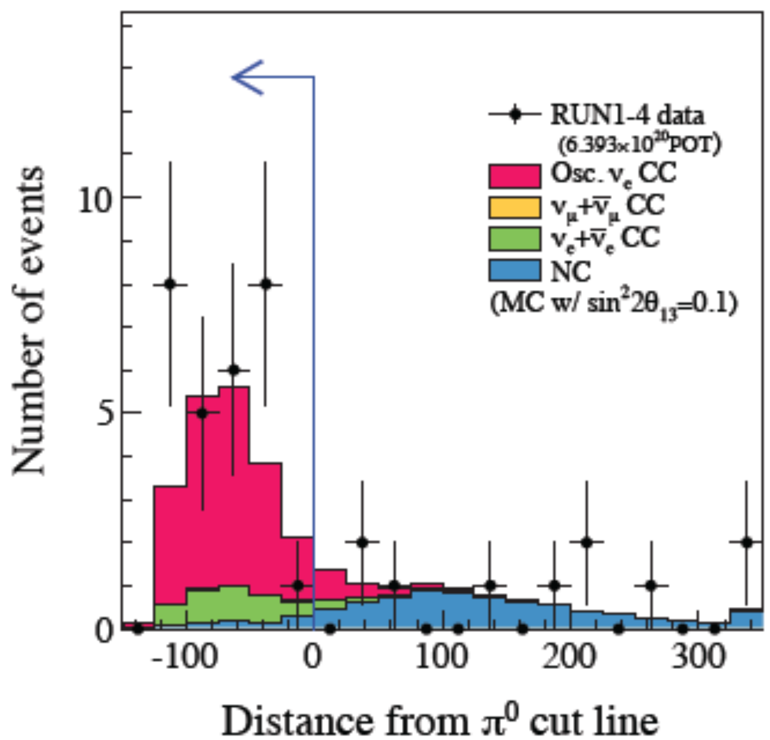
Daya Bay/DC/Reno Reactor data determines that the last element (with an unknown phase) is indeed non-zero and that the mass difference is the SAME as the one measured in the case of the ν_μ.

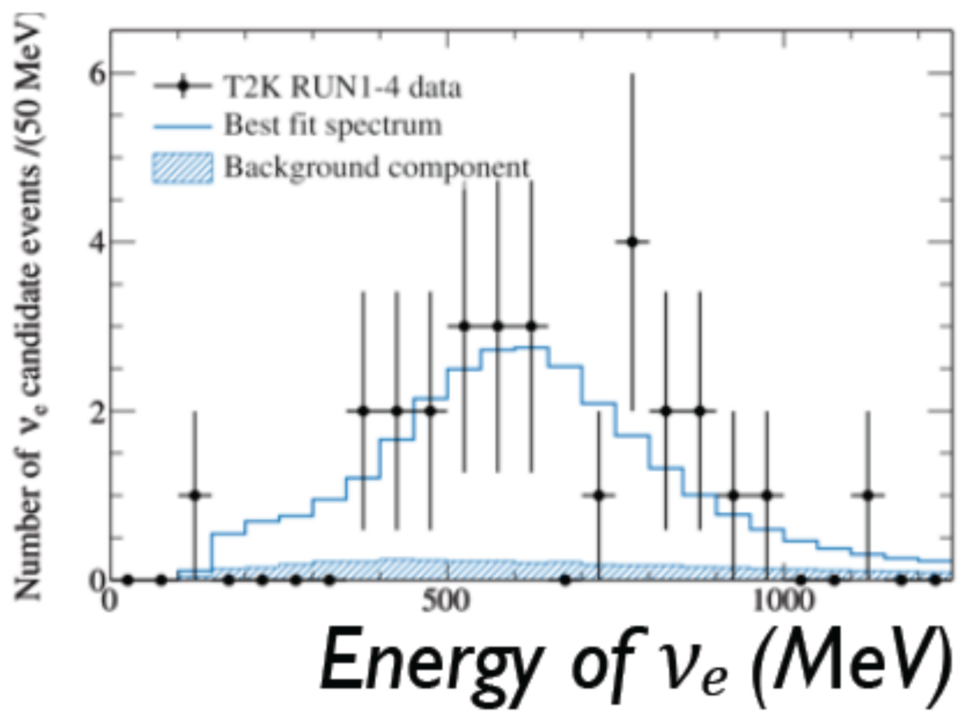
$$\Delta m^2 = |m_3^2 - m_{1,2}^2| \sim 2.4 \times 10^{-3}\ eV^2 \quad \sim \pi/2(3.5MeV/1800m)/1.27$$

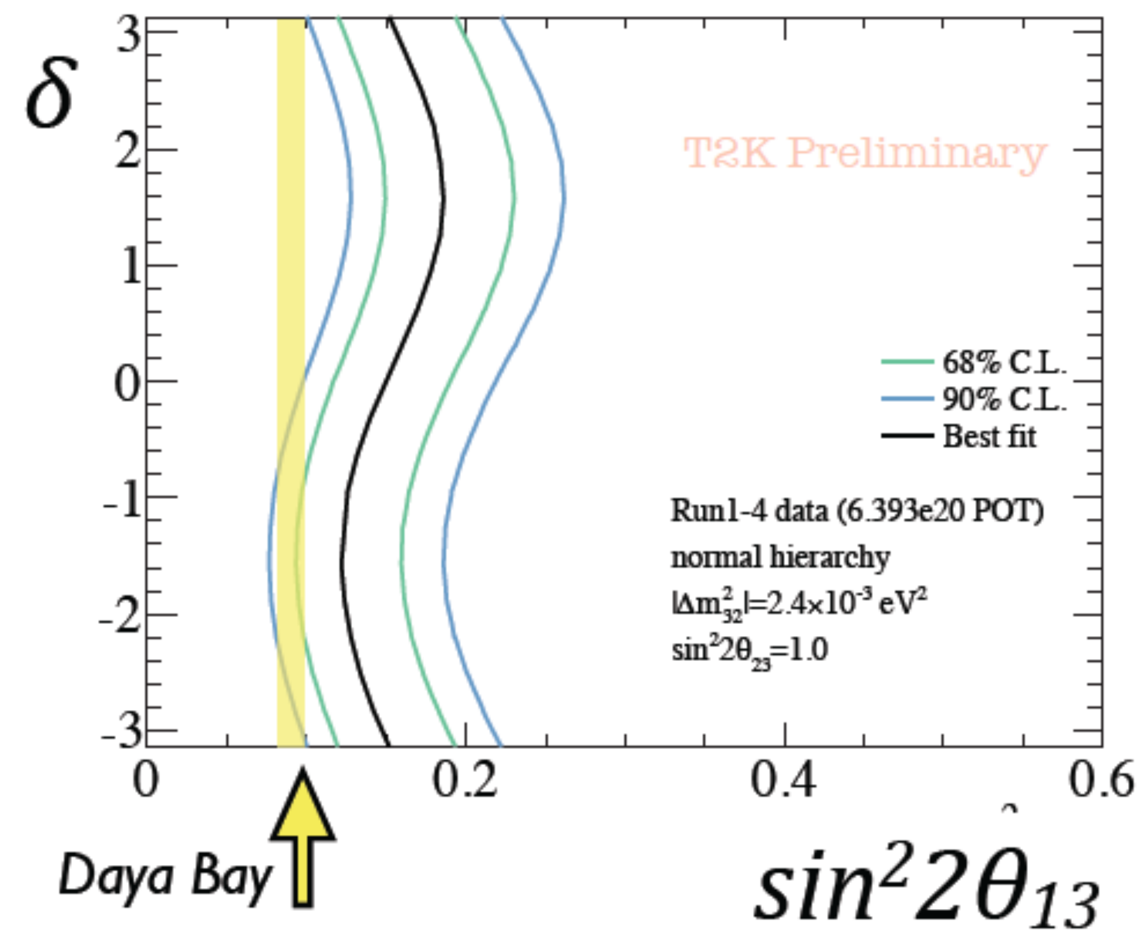
$$\delta m^2 = m_2^2 - m_1^2 \sim 7.5 \times 10^{-5} eV^2$$

T2K: $\nu_\mu \rightarrow \nu_e$ Appearance

M. Wilking, EPS 2013, Stokholm
Phys. Rev. D 88, 032002 (2013)







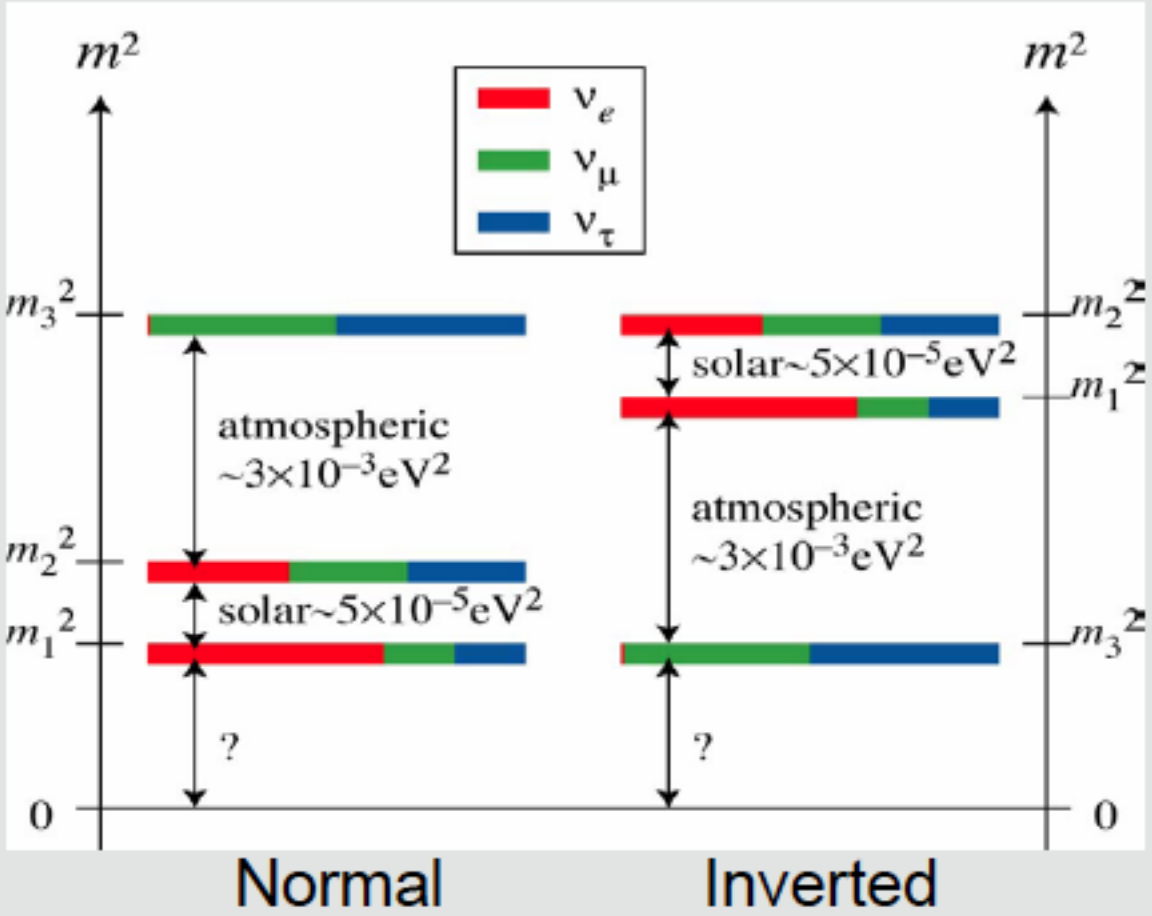
Hints of $\delta \neq 0$?

SUMMARY OF RESULTS FOR THREE ACTIVE ν TYPES

Δm~0.05 eV

Parameter	best-fit (±1σ)
$\Delta m^2_{\odot}$ [10^{-5} eV ^{2}]	$7.58^{+0.22}_{-0.26}$
$\lvert\Delta m^2_A\rvert$ [10^{-3} eV ^{2}]	$2.35^{+0.12}_{-0.09}$
$\sin^2\theta_{12}$	$0.306\ (0.312)^{+0.018}_{-0.015}$
$\sin^2\theta_{23}$	$0.42^{+0.08}_{-0.03}$
$\sin^2\theta_{13}$ [140]	$0.021\ (0.025)^{+0.007}_{-0.008}$
$\sin^2\theta_{13}$ [142]	0.0251 ± 0.0034

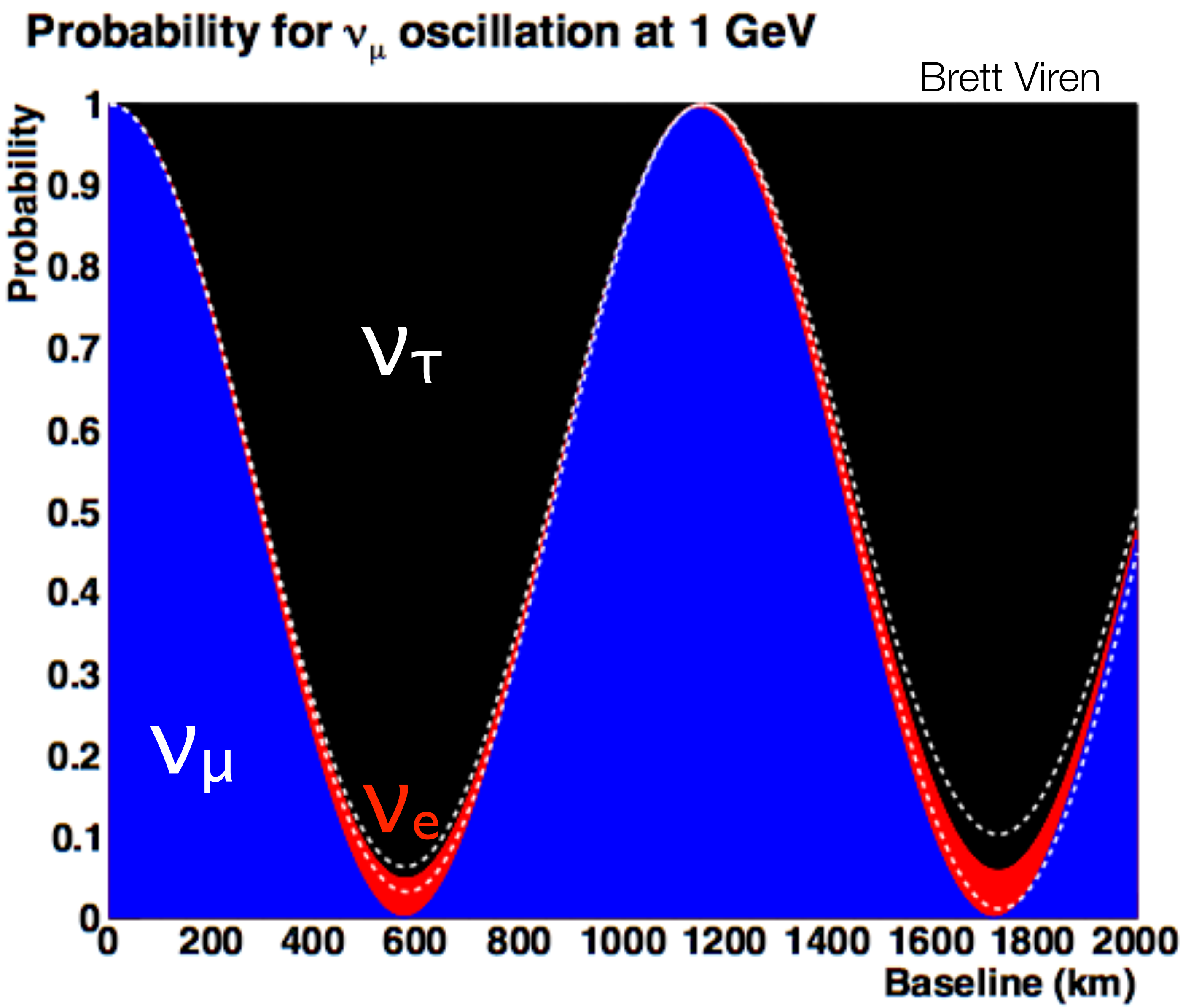
Mass Hierarchies



No strong theoretical motivation for choosing between these hierarchies

Hierarchy, CP phase, and precise values of mixings could be very important to gain understanding of underlying symmetries. See talk by Smirnov from recent meeting.

The full picture of the oscillation effect starting with pure muon type neutrino.



Dashed white lines correspond to CP violation or the unknown phase.

Notice that for sizable effects one needs long distances and large energies.

- **There are precise predictions:**
  - **Large Matter Effects (not yet seen in a laboratory experiment)**
  - **Potentially large CP violation (not yet seen)**
  - **We should measure this picture with a detailed spectrum. We need to measure electron and muon type of neutrinos at high energies.**

Implications of the large θ_{13}

- It should be possible to see effects of matter enhancement with atmospheric neutrinos and determine the mass hierarchy => large underground detectors with statistics and energy resolution.

- It should be possible to see oscillatory signal in reactor neutrinos and determine the mass hierarchy => JUNO (China), RENO50 (Korea), etc. over 50 km with massive (>20 kt) det.

- Current generation of accelerator experiments will see events accumulate slowly ~10-20/yr for NOVA and T2K

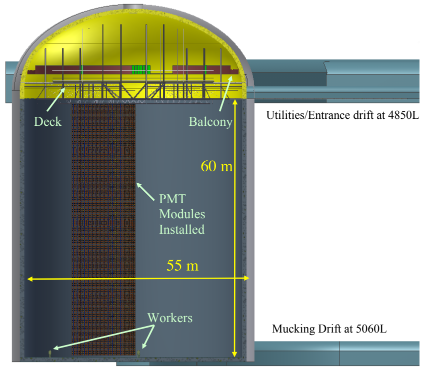
- A new accelerator based program to get enough statistics to perform a comprehensive experiment with $\nu_\mu \to \nu_e$

US discussion over future program

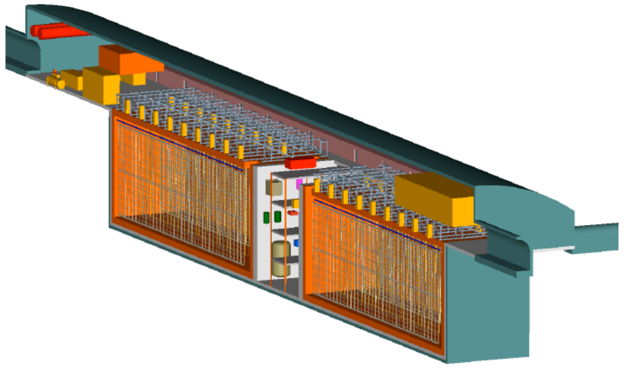
- The success of Super-Kamiokande was the catalyst for new discussion on a very larger underground detector and its scientific potential. Started in 1999.

- If coupled to an accelerator muon neutrino beam, such a detector and beam project would be highly motivated. But the scale has to be huge.

- Physics motivation is CP violation in neutrinos, proton decay, and neutrino astrophysics.
- Accidentally: the size of detector needed for both CP violation and next steps in proton decay are roughly the same. The detector requirements are also the same !
- CP violation requires evidence of 3-generation mixing ($\Theta_{13} \neq 0$)
- The needed detector X beam power are approximately independent of Θ_{13}, and therefore planning can be done without detailed knowledge.



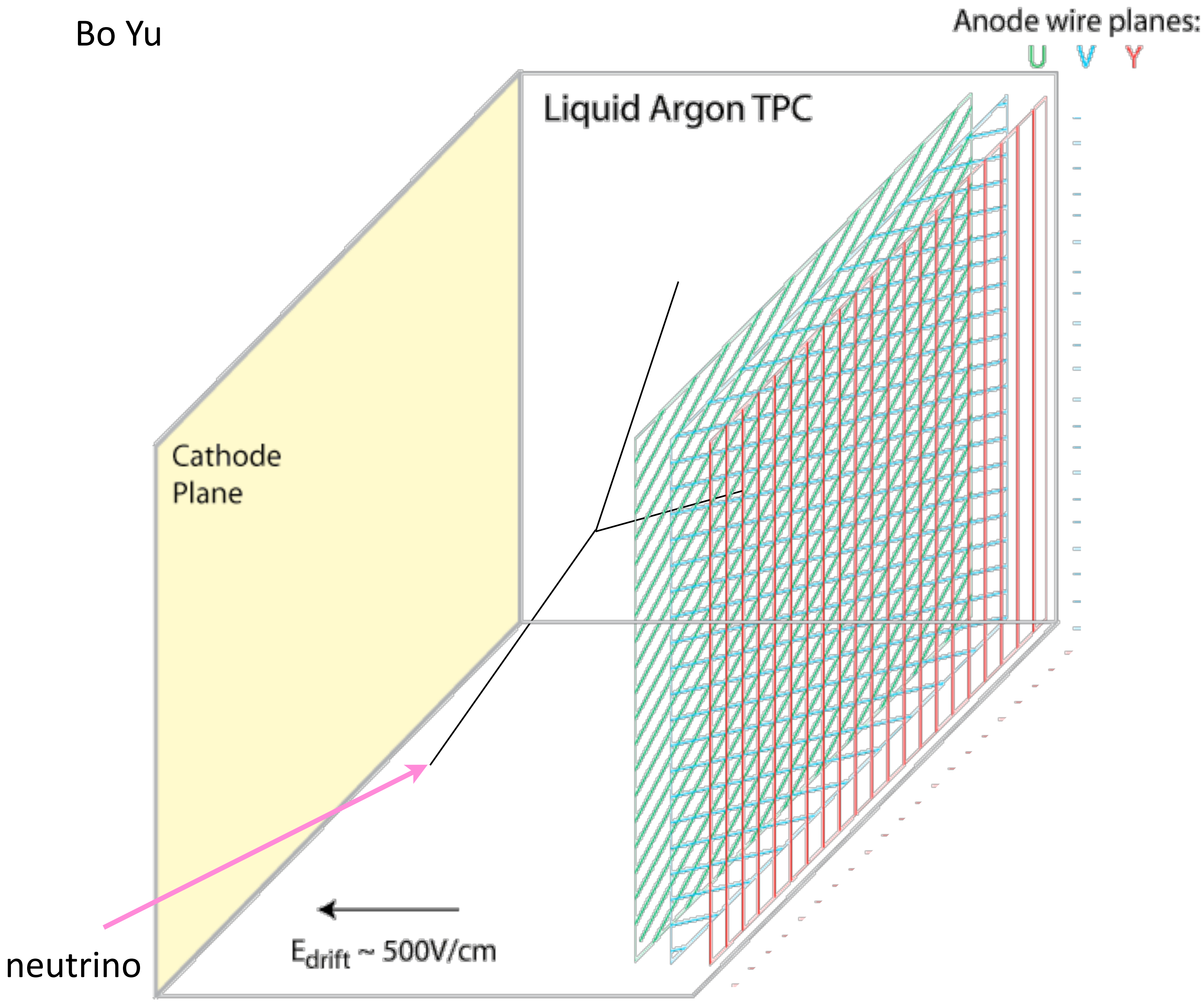
Detector Technology



- In 2001 it was determined that a detector with minimal mass of ~100,000 tons was needed. The only choice 10 yrs ago was a water Cherenkov detector.
- A water Cherenkov detector has low efficiency and high backgrounds for high energy neutrino events that are well measured and so it needed to be even larger: 300-500 kt.
- The alternative technology of a liquid argon time projection chamber (LArTPC) has very high efficiency and extremely good background rejection, but needed technological development to prove at large scale.
- The ICARUS T600 program finally showed that such a detector was indeed possible and could operate stably over a long period of time. Largely on the basis of ICARUS success, the US decided to select a 35000 ton LArTPC.

How Does a LArTPC Work?

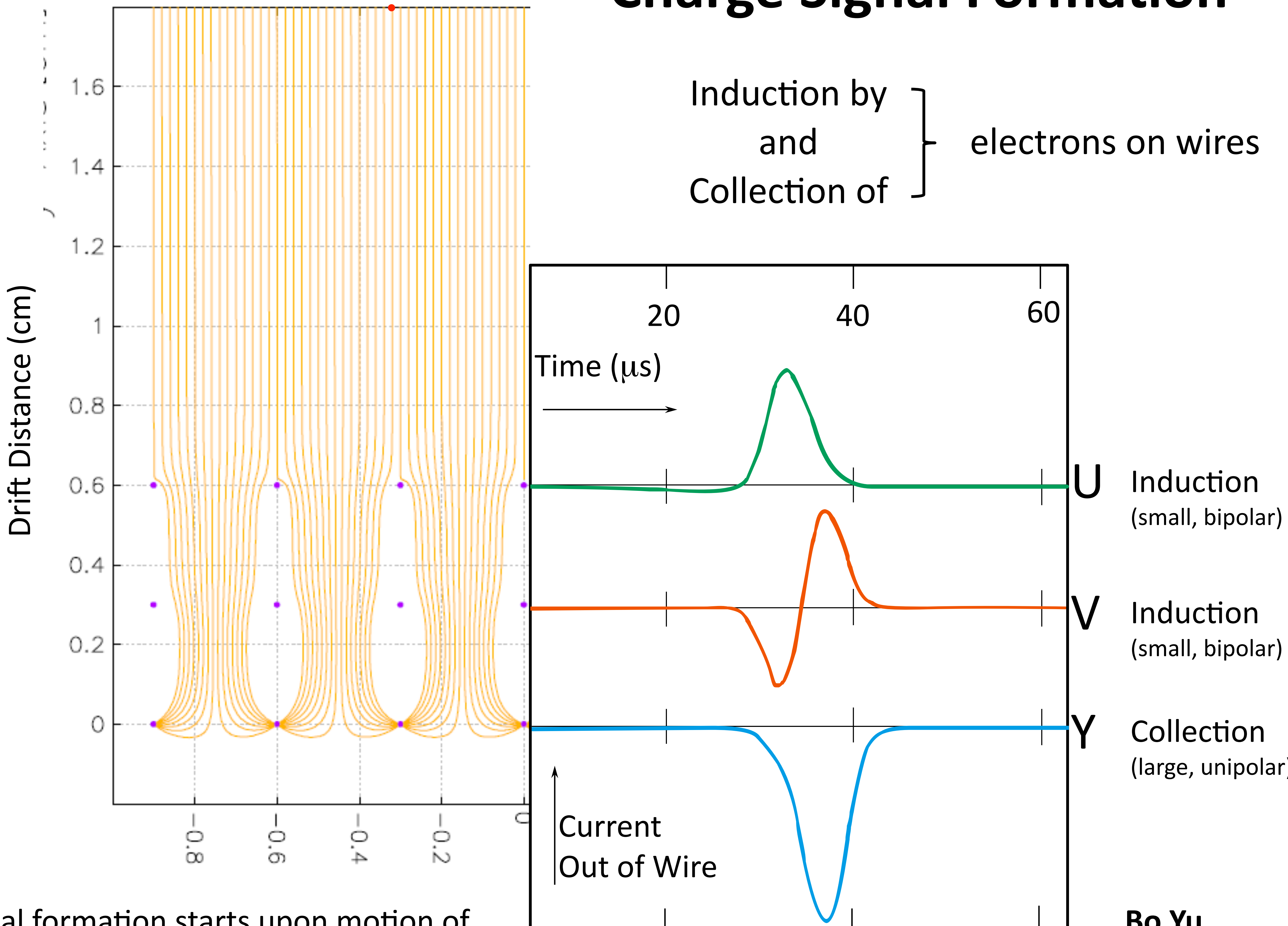
Bo Yu



LAr also scintillates. We intend to detect the light also.

Charge Signal Formation

Induction by
and
Collection of
} electrons on wires

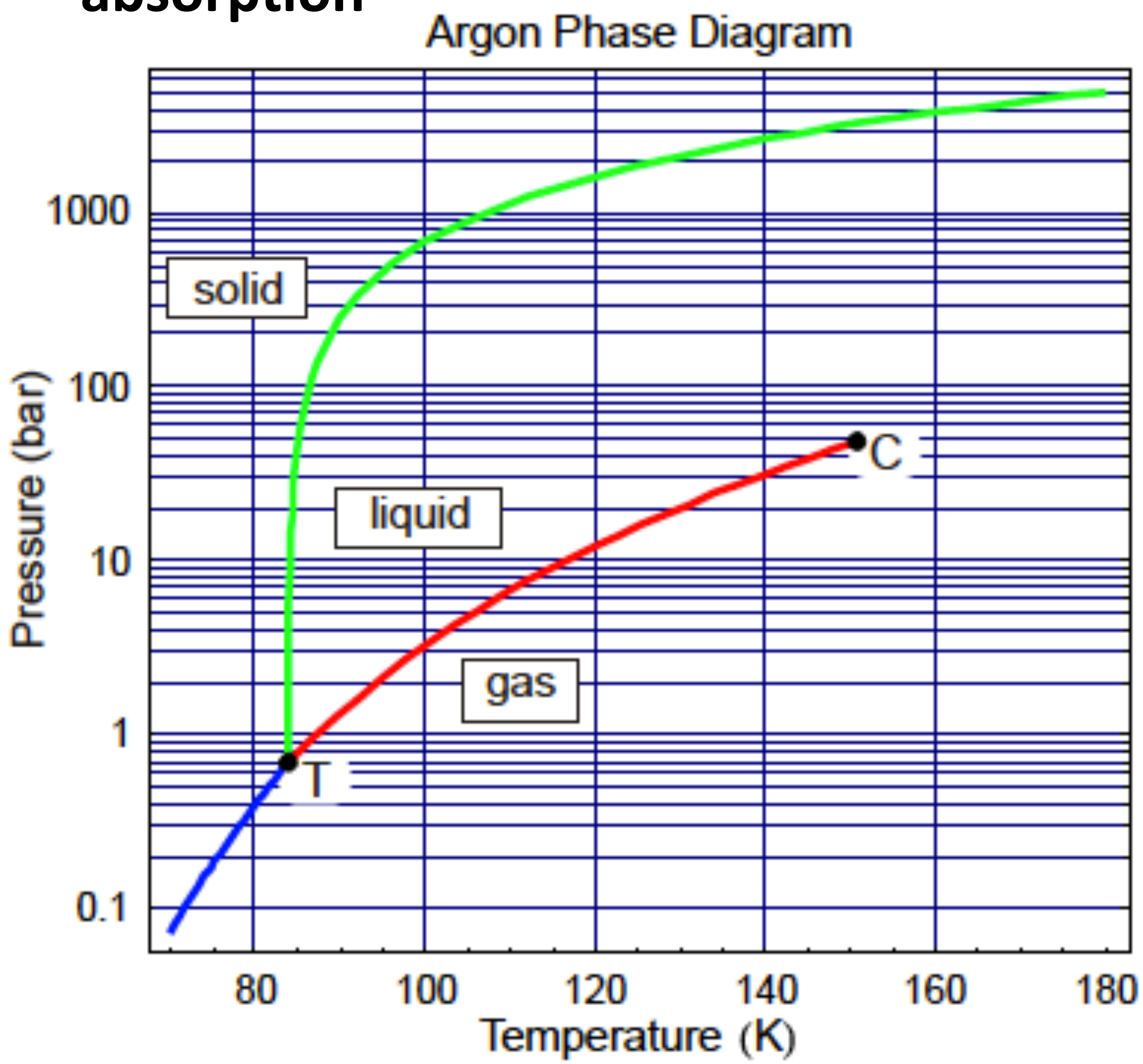


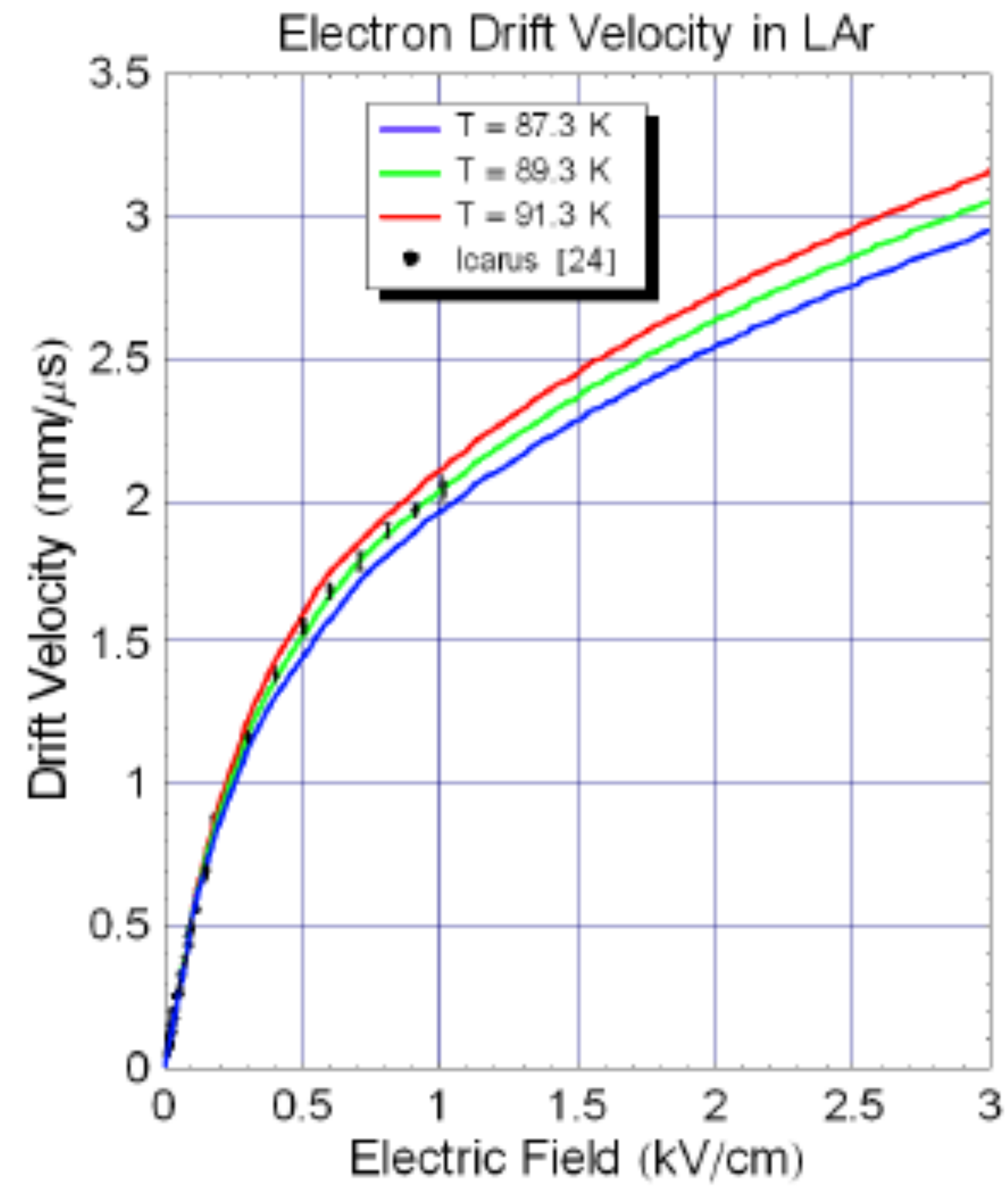
Signal formation starts upon motion of the charge.

Bo Yu (BNL)

Key Technical Issues for a Liquid Argon Detector

liquid argon must be extremely pure: ~1 part in 10^{10} to allow long drift without absorption

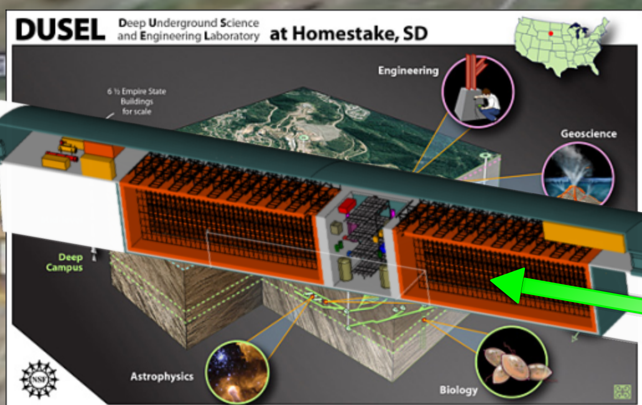




It is cold ! And this makes it inaccessible and difficult to work with.

It is slow ! Electrons drift slowly. Drives many issues of design.

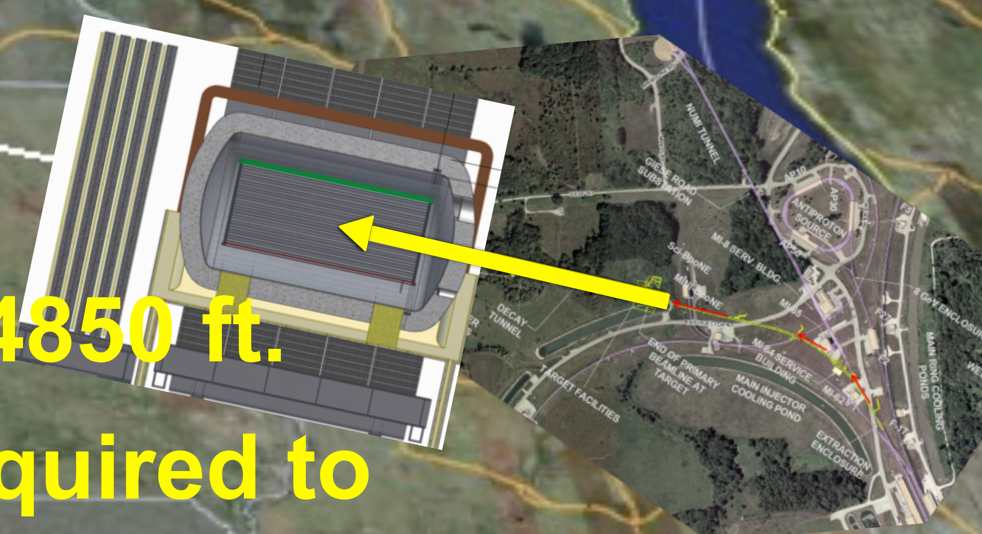
Long Baseline Neutrino Experiment
LBNE



New Neutrino Beam at Fermilab…

Precision Near Detector on the Fermilab site

1300 km



Directed towards a distant detector

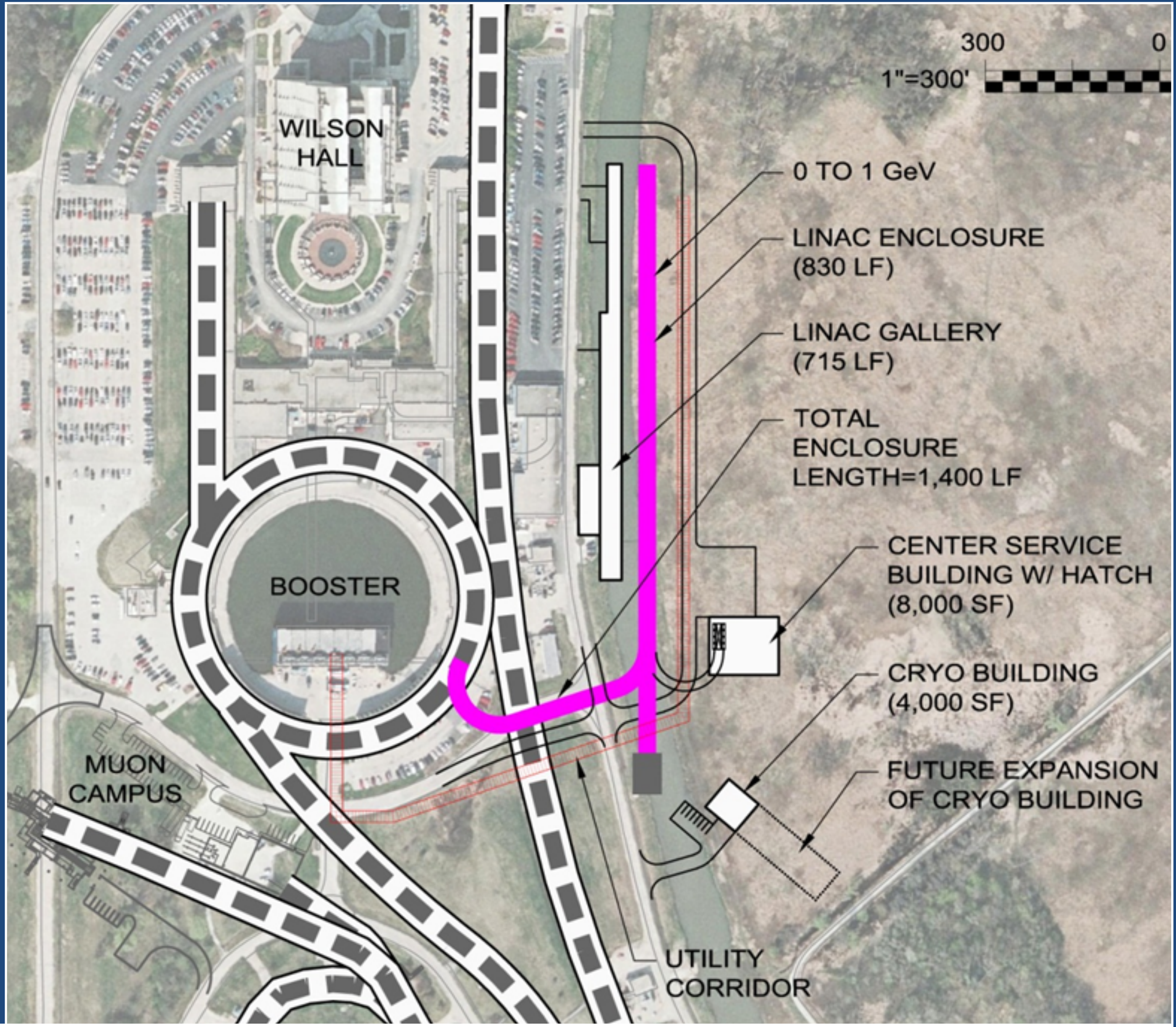
34 kton Liquid Argon TPC Far Detector 4850 ft.

And all the Conventional Facilities required to support the beam and detectors

Conceptual design for all aspects of LBNE exists and has been costed to be ~1.5B, but US DOE has asked us to break this up. First chunk will be $867M from the US.

Proton-Improvement-Plan Phase II (PIP-II)

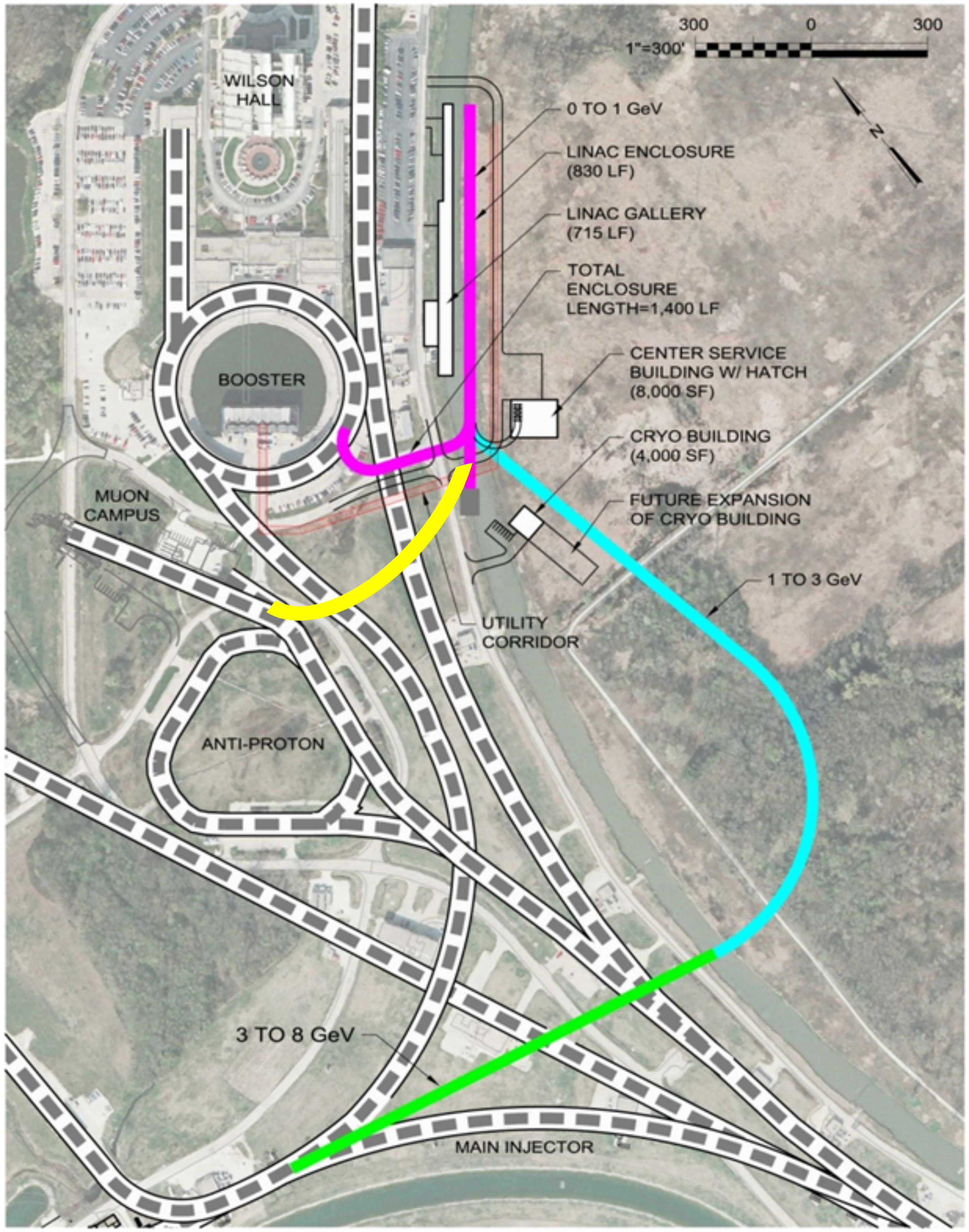
- Replace existing 400 MeV linac with a new 800 MeV superconducting Linac
- 1.2 MW beam power to LBNE at start-up of experiment.
- Plan is based on well-developed superconducting RF technology with international partnerships.
- Strong support from DOE and in the recent Prioritization Panel report.
- Flexible design - future upgrades could provide > 2MW to LBNE.



Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

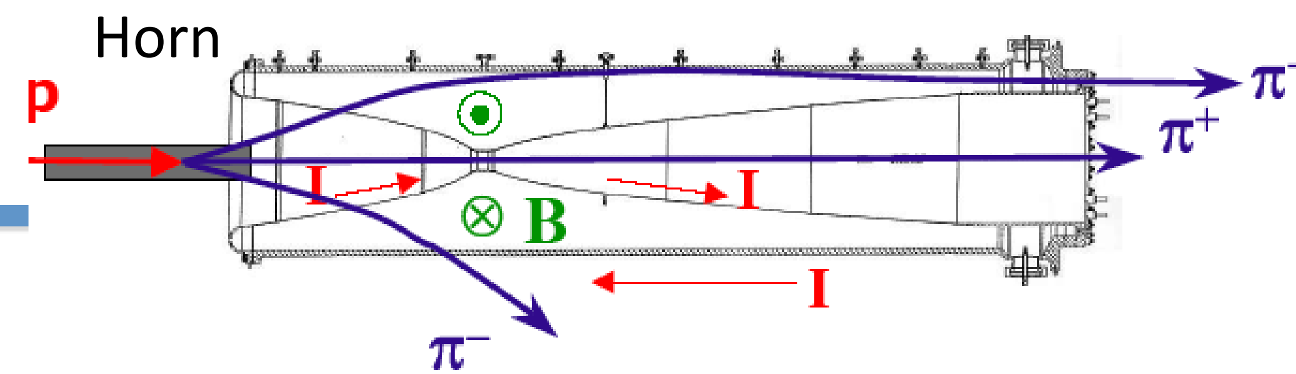
Flexible Platform for the Future

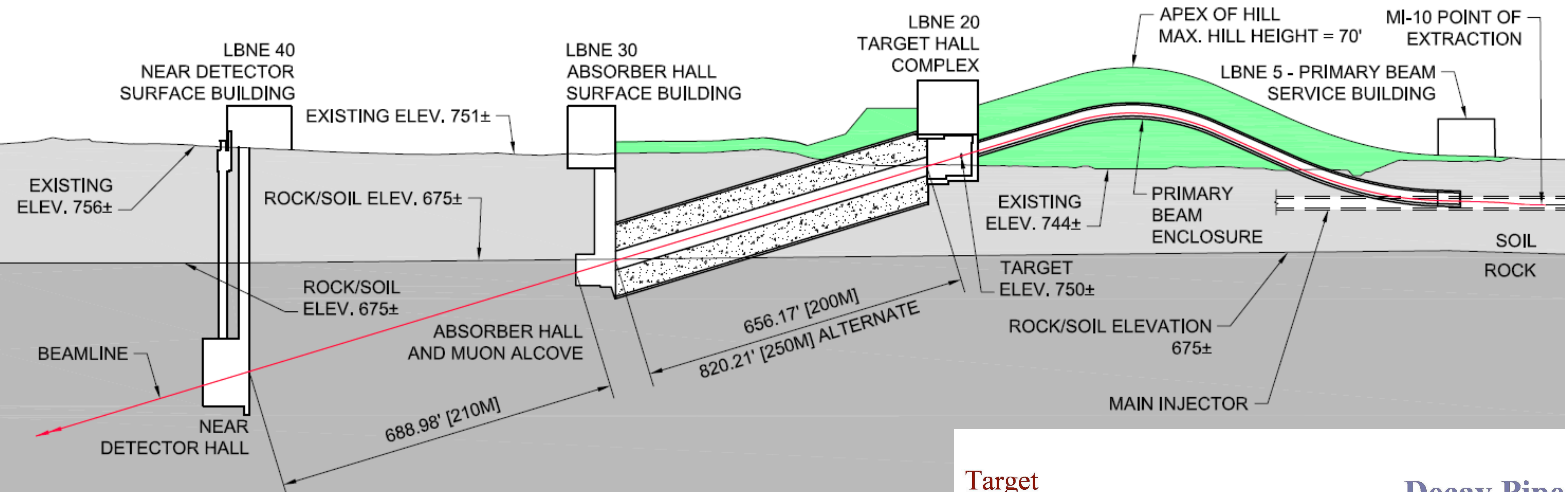
- PIP-II Inherent Capability
  - ~200 kW @ 800 MeV
- Future upgrade would provide > 2 MW to LBNE
- Flexibility for future experiments
  - Muons, Kaons at 100's kW



Fermilab

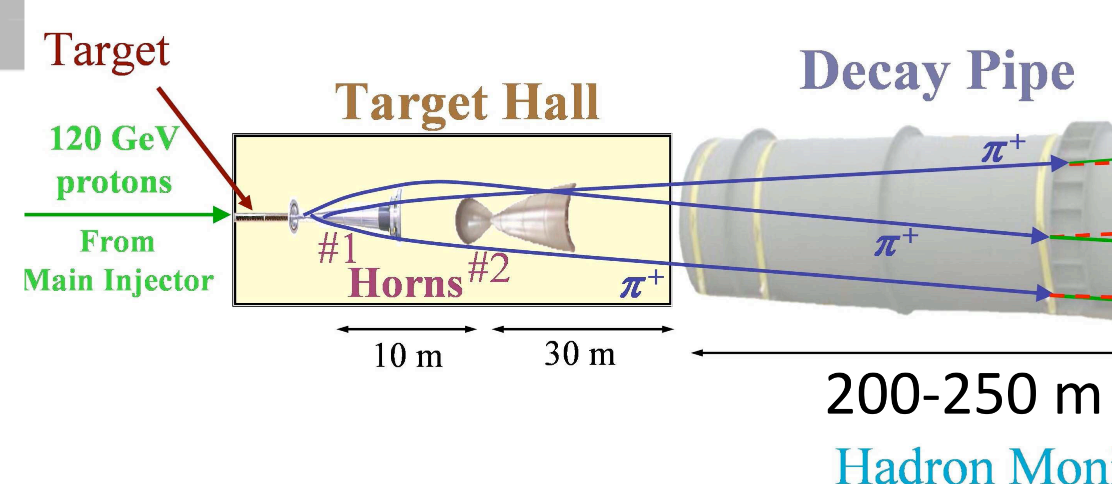
LBNE Neutrino Beamline





Proton beam

- $60 \leq E_{beam} \leq 120$ GeV
- Beam power 700 kW, upgradeable to 2.3 MW
- Innovative design for safety and upgradeability.
- Many options still under development (decay pipe, horns, targets,etc)



Far Detector at Sanford Underground Research Facility in the Black Hills of South Dakota

SURF site is open for science with all legal issues in order

Donated to Science

South Dakota Science and Technology Authority

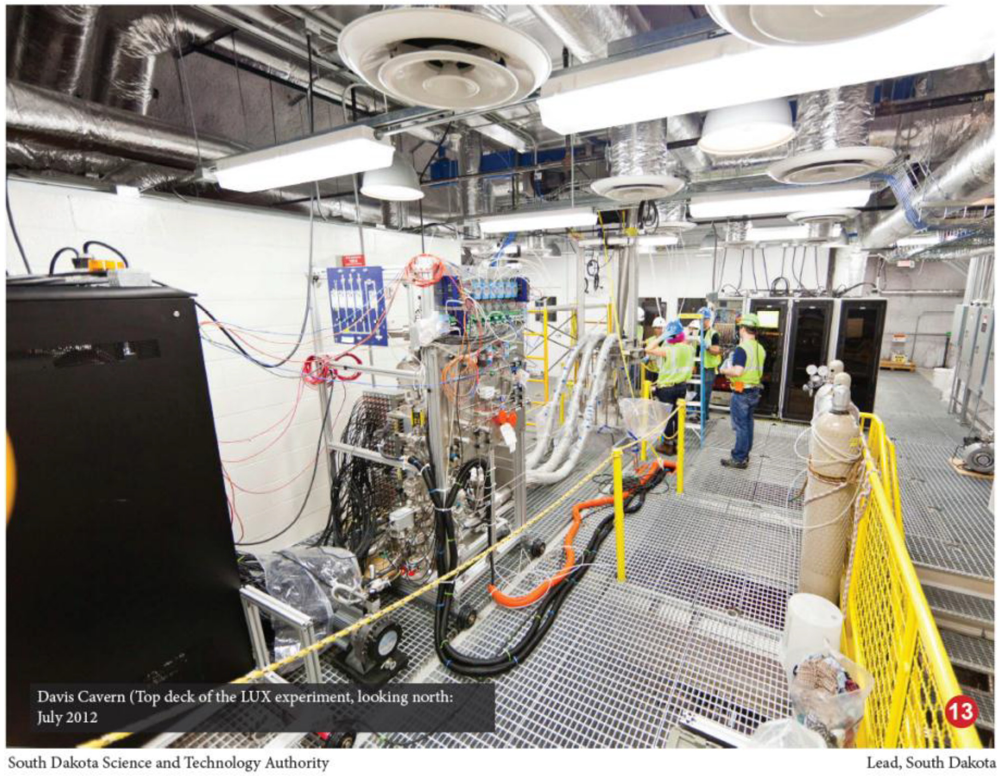
Lead, South Dakota

The shafts go down to 4850 ft and are being upgraded. We have benefited greatly from early interactions with LNGS.

Sanford Underground Research Facility

Majorana (0νββ)

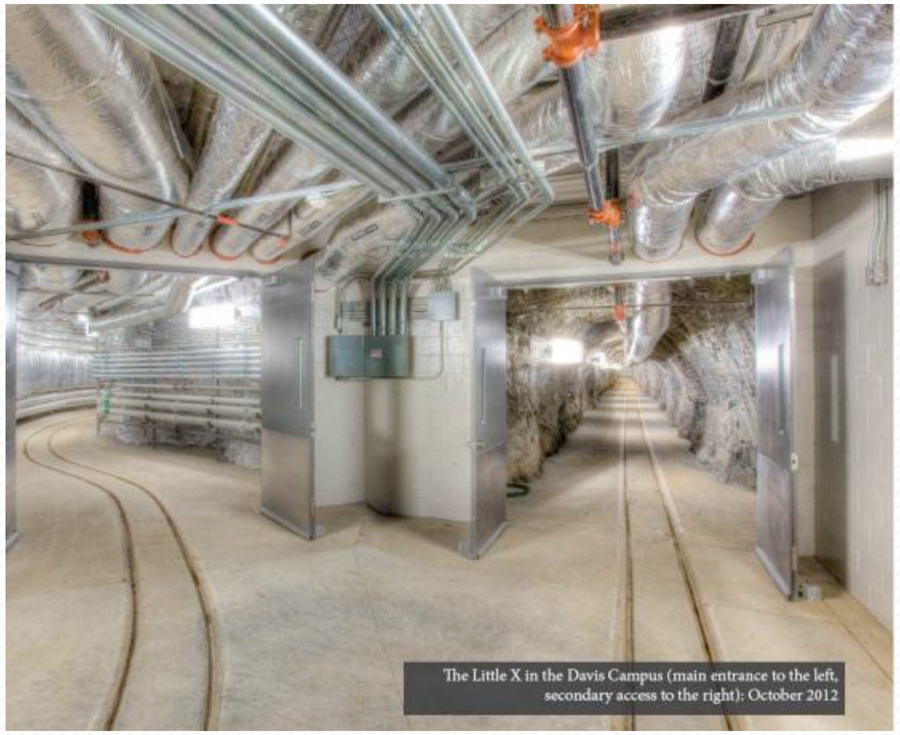
- Experimental Facility at 4300 MWE
- Two vertical access shafts for safety.
- Shaft refurbishment has been on-going and has reached 1700’ level
- Total investment in underground infrastructure is >$100M.
- Facility donated to the State for science in perpetuity.



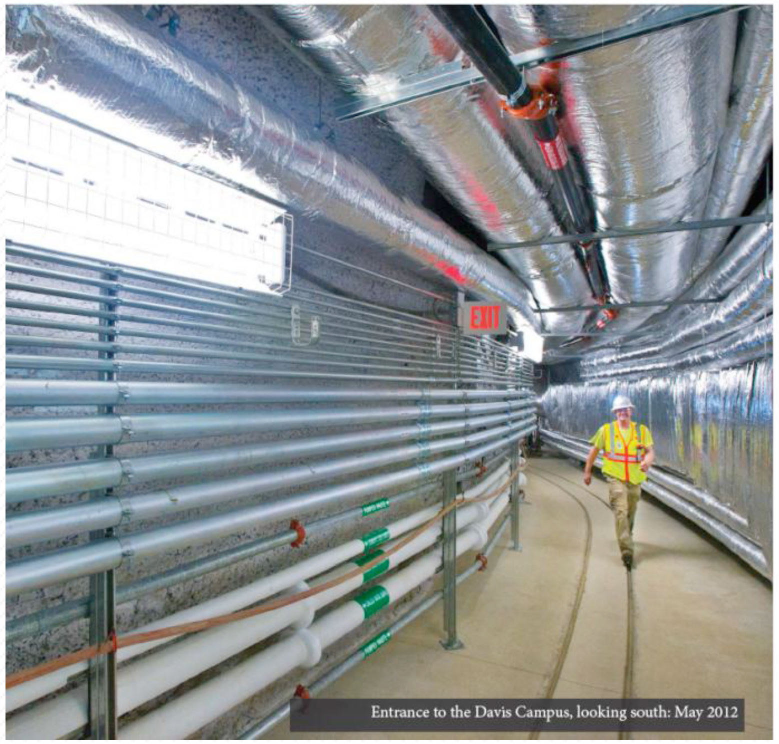
LUX (dark matter)

SURF Today

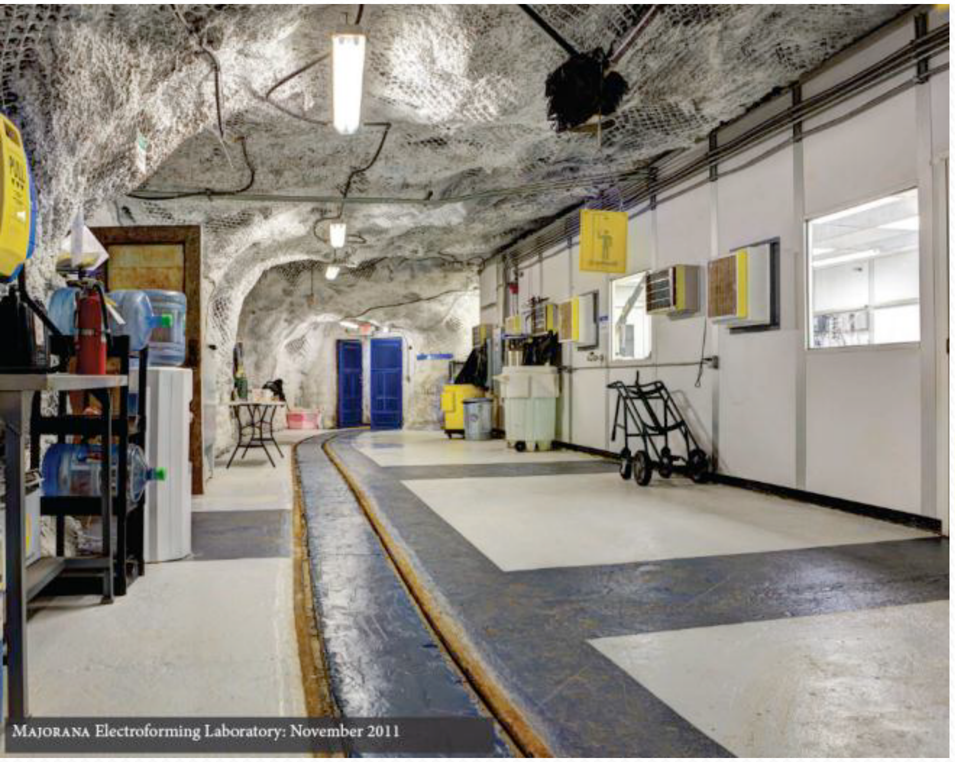
Majorana detector assembly room: December 2012



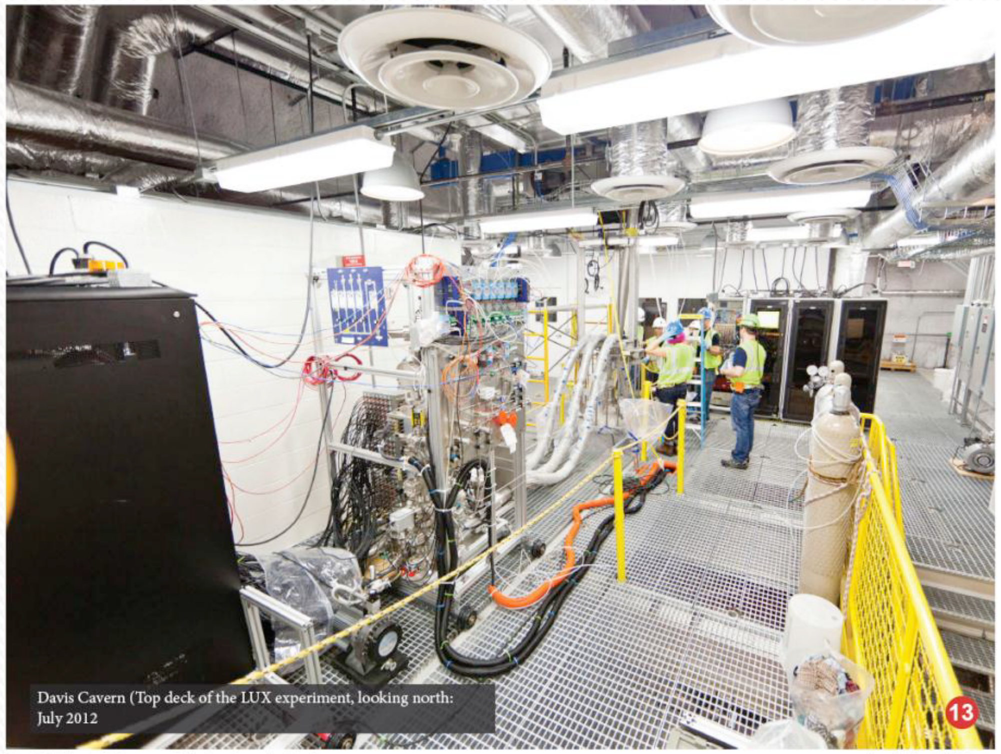
The Little X in the Davis Campus (main entrance to the left, secondary access to the right): October 2012



Entrance to the Davis Campus, looking south: May 2012



Majorana Electroforming Laboratory: November 2011



Davis Cavern (Top deck of the LUX experiment, looking north: July 2012

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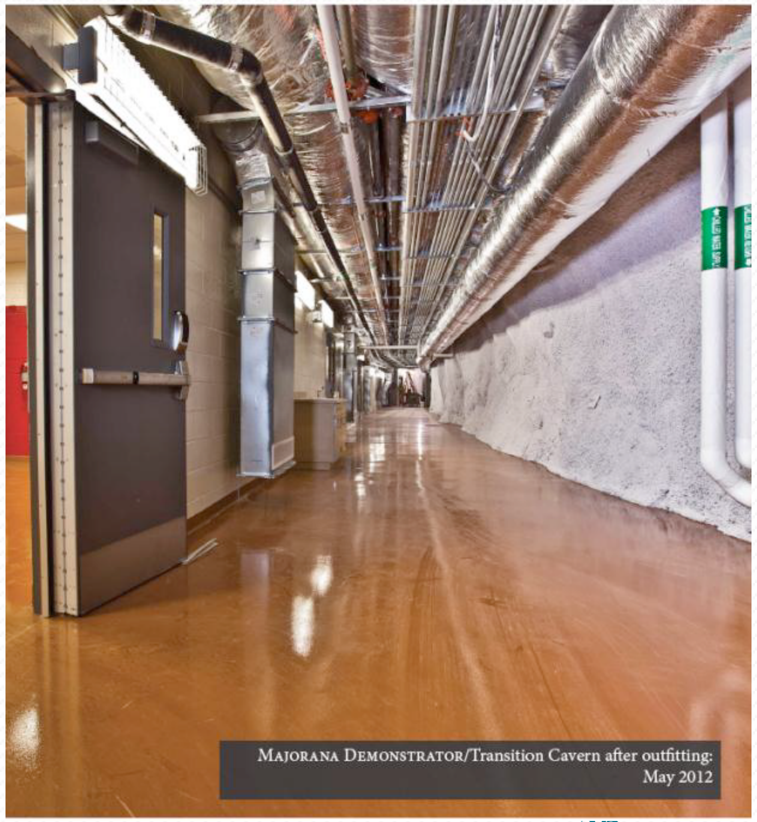
South Dakota Science and Technology Authority

Lead, South Dakota

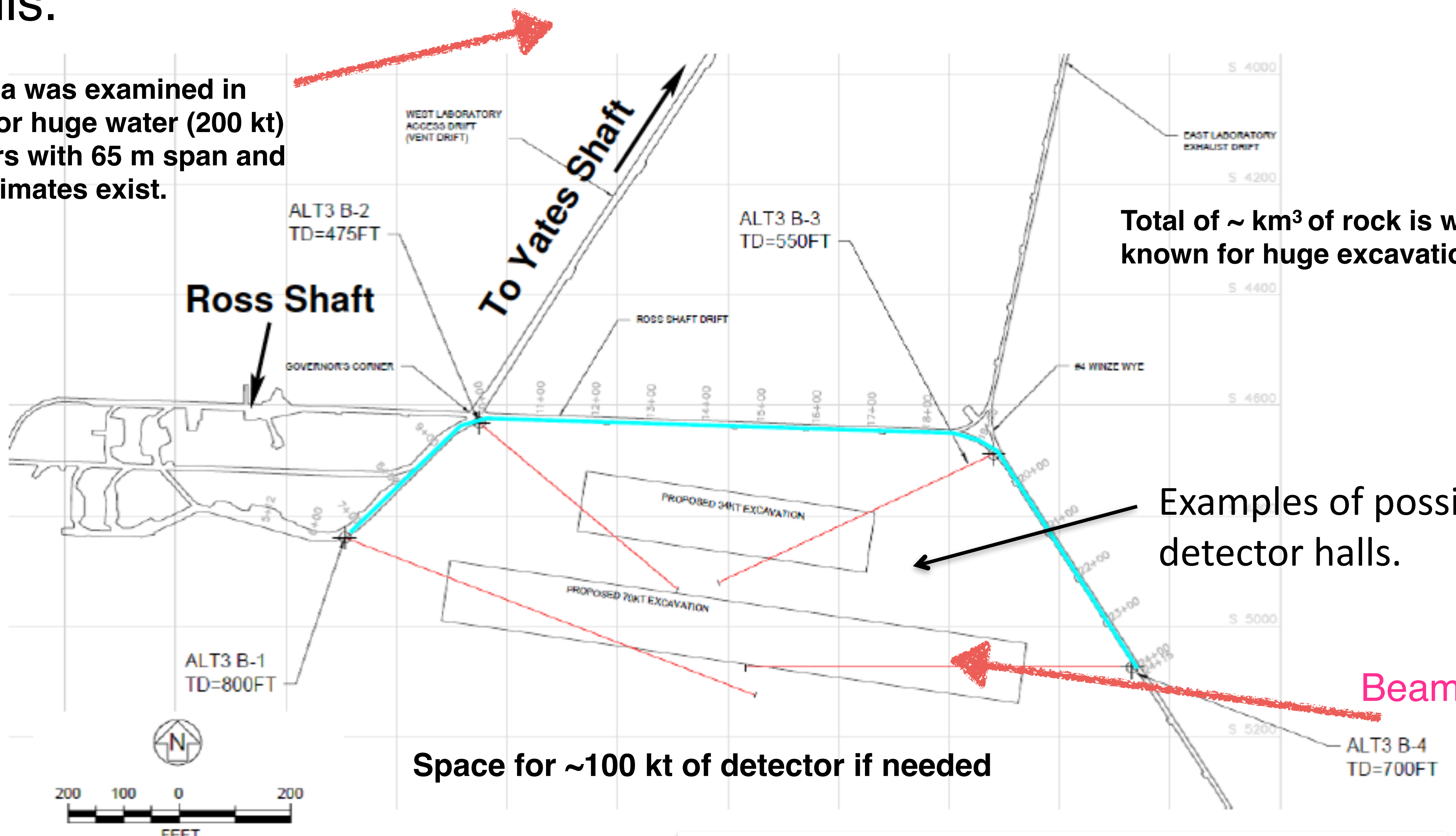


Majorana Demonstrator/Transition Cavern after outfitting: May 2012

CF Far Site Geotech Program

- General area where detector(s) could be placed is being explored.
- This drilling program was recently completed. The rock is known to be quite capable of handling large excavations, but report will contain details.

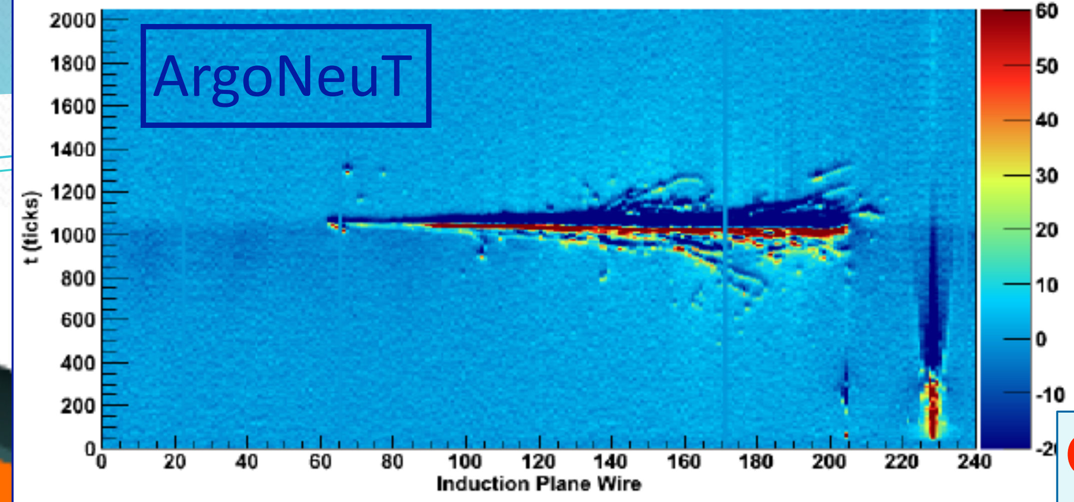
This area was examined in earlier for huge water (200 kt) detectors with 65 m span and cost estimates exist.



Total of ~ km^3 of rock is well known for huge excavations.

Examples of possible detector halls.

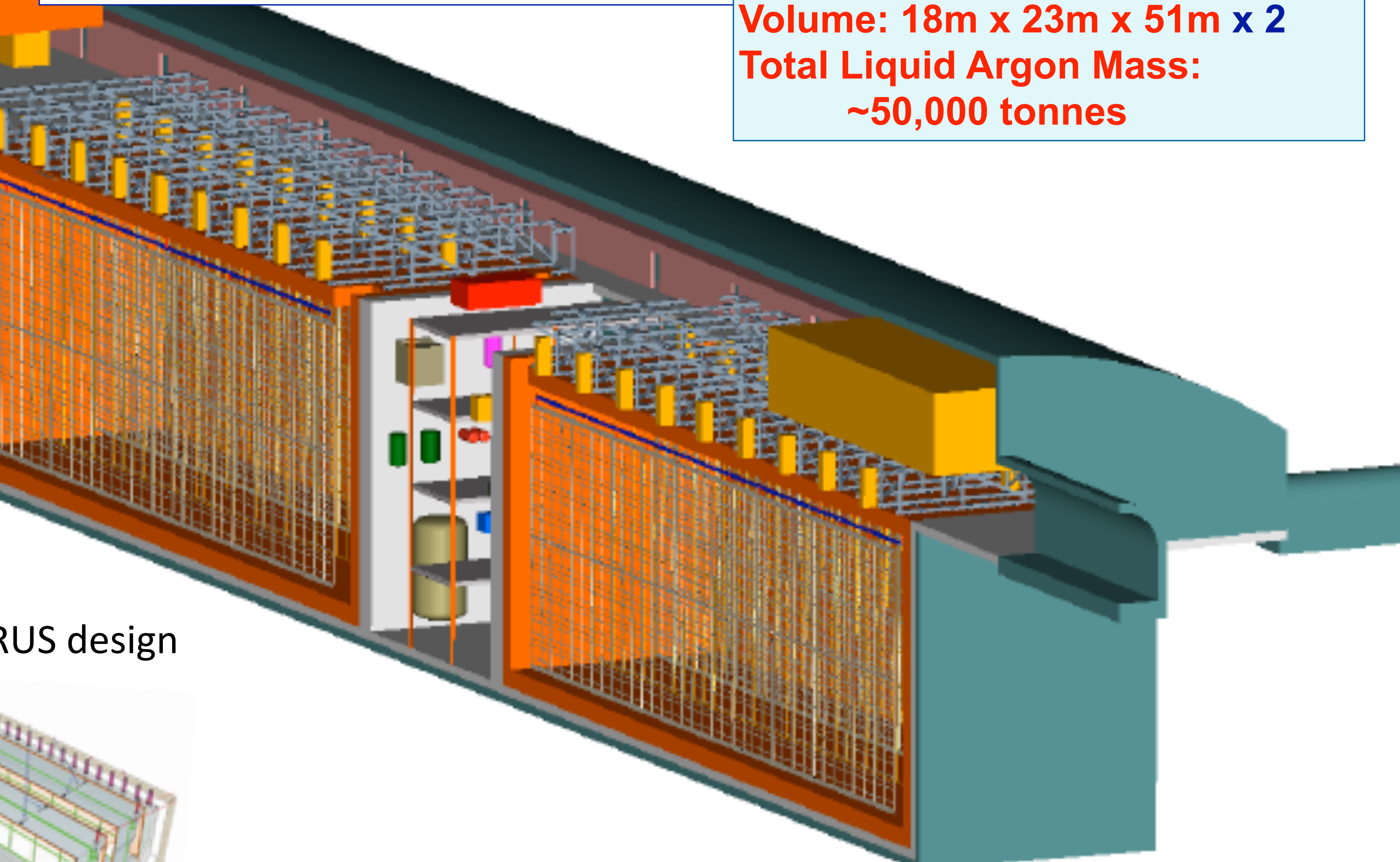
Space for ~100 kt of detector if needed

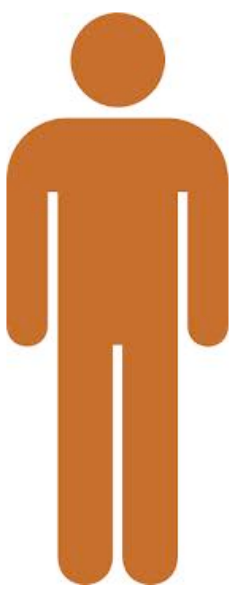


mm-scale resolution!

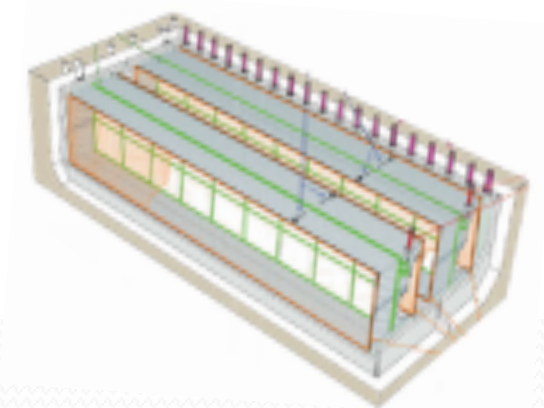
LBNE Liquid Argon TPC

GOAL: 34 kt fiducial mass
Volume: 18m x 23m x 51m x 2
Total Liquid Argon Mass:
~50,000 tonnes



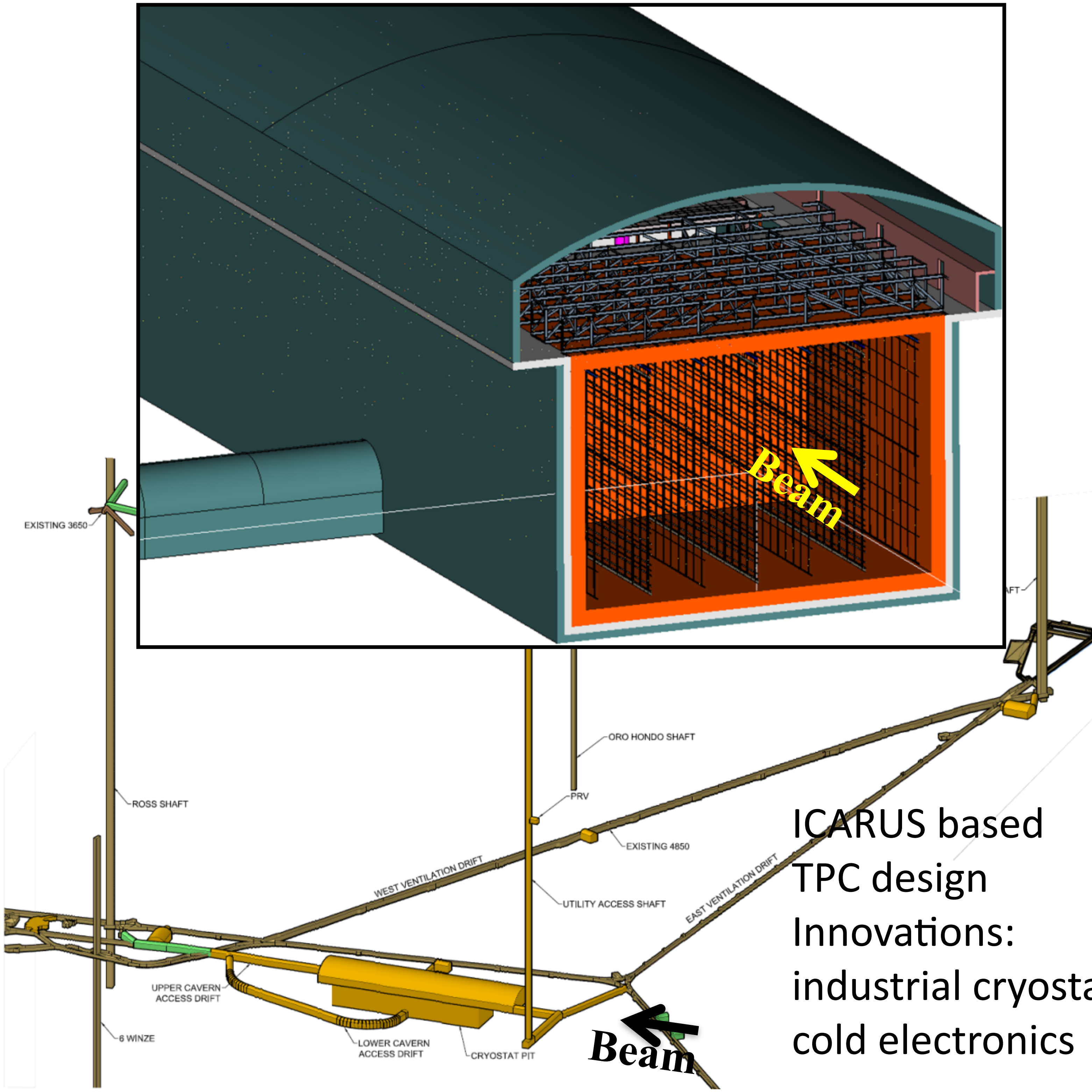


Based on the ICARUS design



Have also developed a 10 kt fid. design to meet current US funding approval

Far Detector Design at depth: LAr TPC Detector at 4850 ft



ICARUS based TPC design Innovations: industrial cryostat, cold electronics

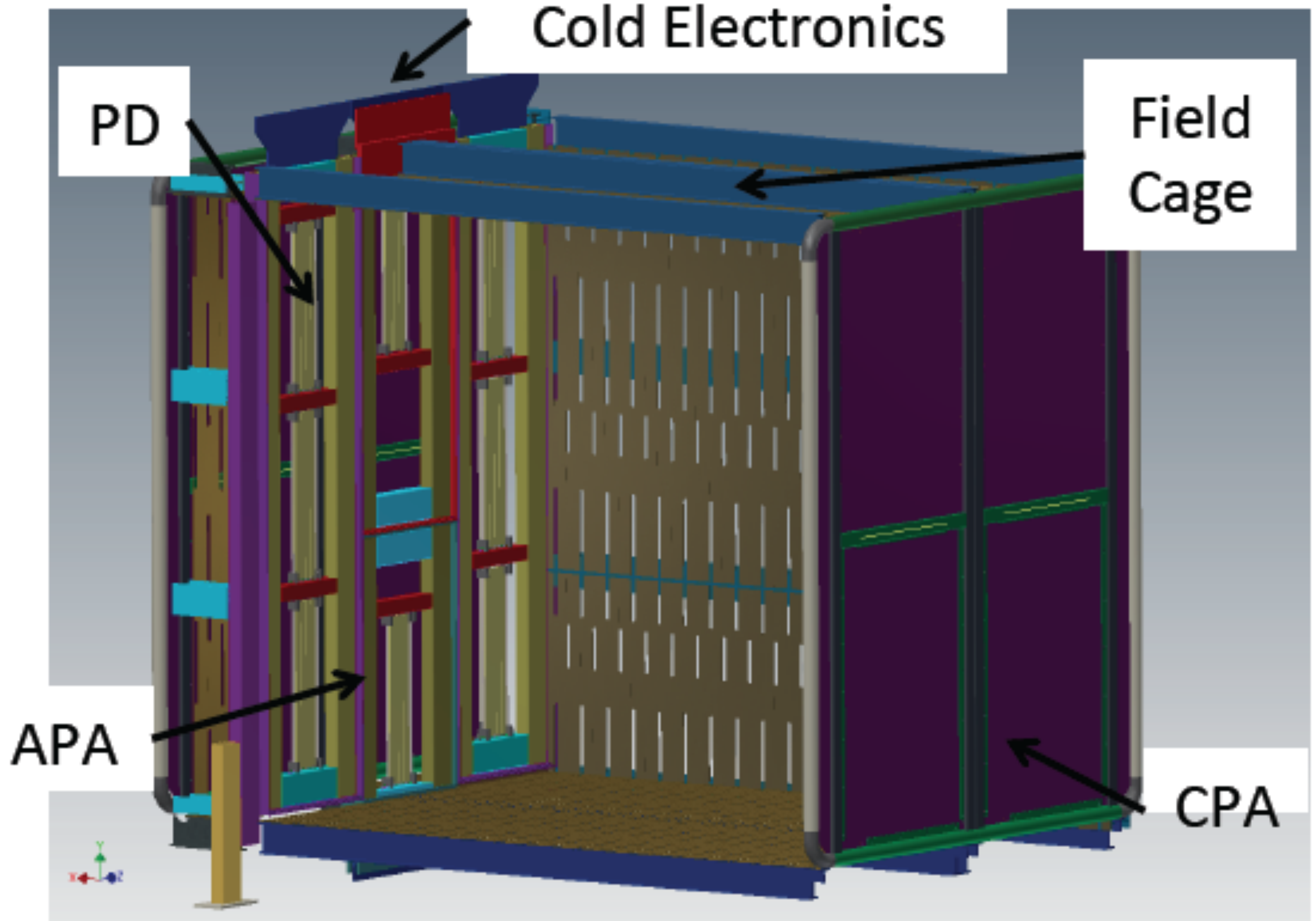
- Two detectors in a common cavern at 4850 ft. depth
- Active volume of each detector: 22.4 x 14 x 45.6 m^3
- 34 kt fiducial mass
- TPC design:
  - 3.7 m drift length
  - 5 mm wire spacing
  - three stereo views
  - 2X108 anode chambers
  - 2 X 275k channels
  - S/N ~ 10

Challenges for scale up are under control : Purity, installation, safety

Far Detector Prototyping

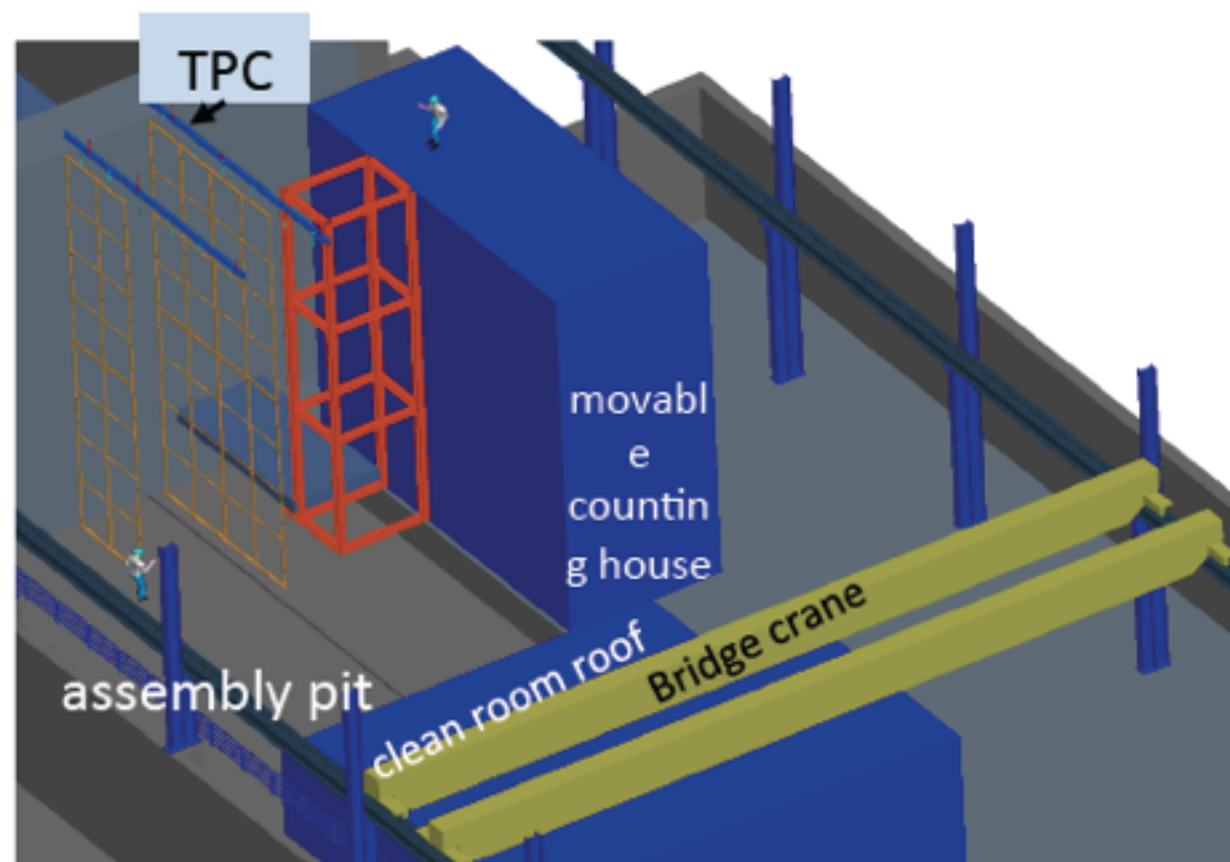
35t scale prototype

- Test membrane technology
- Cryo-system design
- Cryogenic commissioning now!
- Istaall prottoype TPC next summer.
- Take cosmic data in ~1 year.



Full scale warm prototype

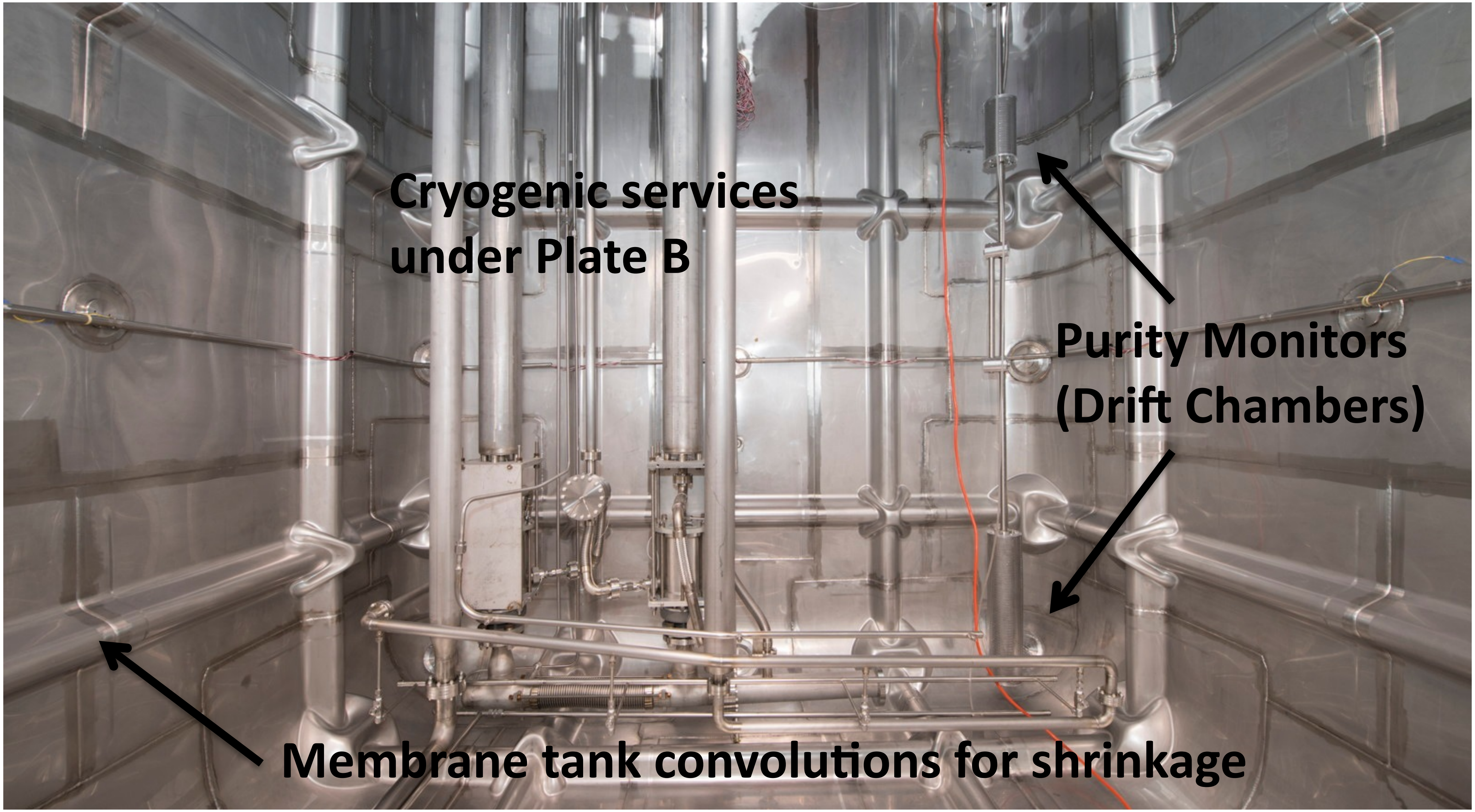
- Start construction in 1 year
- Full scale TPC module constructed.
- Installed at FNAL



LBNE 35 Ton Liquid Argon Tank

- LBNE 35 Ton is a prototype membrane tank at Fermilab for liquid argon built by the Japanese company IHI using LNG industry technology
- Liquid volume of 27.7 m^3 which is equivalent to 38.7 tonnes of liquid argon
- Connected to the existing LAPD cryogenic purification system
- Commissioning started in November 2013

View Inside of 35 Ton Tank

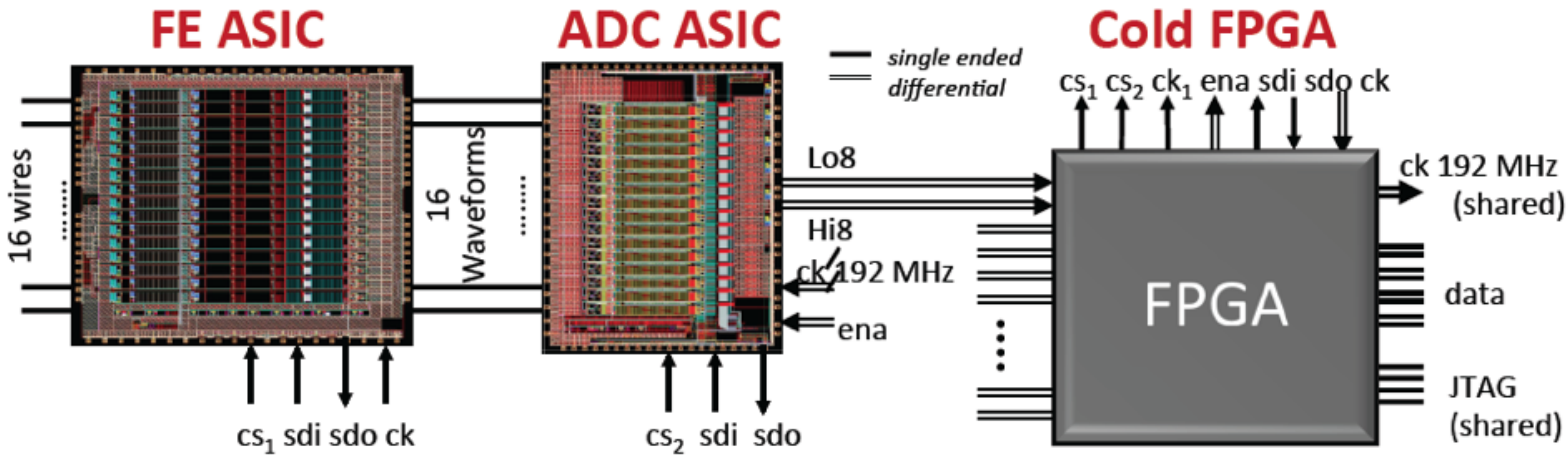


View On Top of 35 Ton Tank

Far Detector Status

Cryogenics:	Cryostat design starts in 1 year and is 80% complete in 2yrs. Cryo-plant is being designed. Model exists and working on part lists and specifications.
TPC:	Design/Construction of full scale TPC module will start in 1 year.
DAQ:	Fully functional DAQ will be operational for the 35t test this year.
Photon System:	Baseline PD hardware tested last month at FNAL. Alternate photon detection devices will be tested in the 35t setup. Will select baseline device in 1-2yrs.
Installation:	Detailed installation planning will start in FY15. Now focused on 35t and grounding-shielding.
Cold Electronics	Pre-amp chip is final and used in MicroBooNE. ADC is at revision 4 and will be used in the 35t test. Cold digital control ASIC developemt has started. Configuraiton will be selected after 35t test.

Cold CMOS Electronics



- low-noise analog amplification
- programmable gain, shaping, coupling

Production ready

- ADC 12-bit 2MS/s
- small buffer
- 2 x **8:1 multiplexing**

Prototype V4 in 1 mo

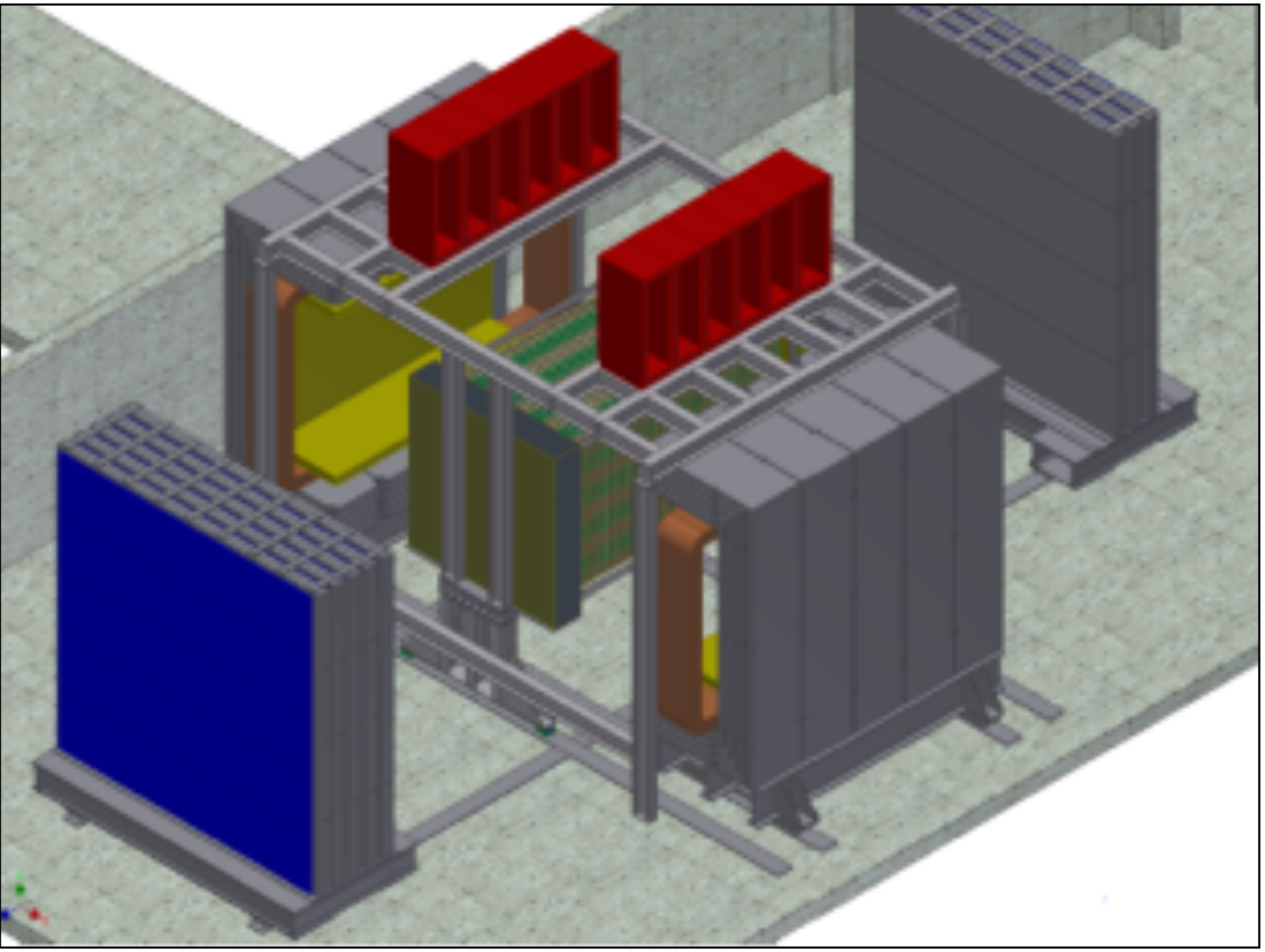
- **Digital Control Development**
- **Result for 35t defines baseline configuraiton**

Many issues here
Architecture
Low level testing
Power management
Decision tree
Risk analysis
(30year lifetime)
Interfaces and
redesign of ADC.

Cold Digital Control Development

Decide Cold commercial FPGA or Custom ASIC in FY15
Functionality defied in 35t test
Prototyping design rules for cold digital process now.

LBNE Near Detector

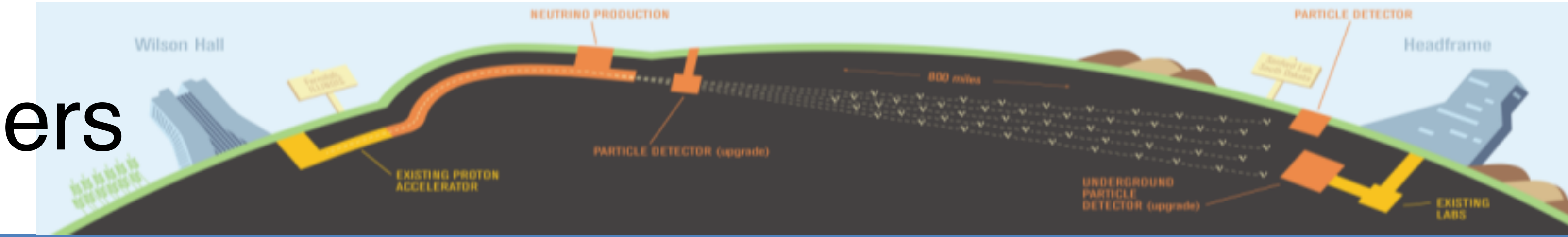


- **Fine-Grained Tracker – 460 m from target**
  - **Low-mass straw-tube tracker with pressurized gaseous argon target**
  - **Relative/absolute flux measurements**
  - **High precision neutrino interaction studies $\approx 10^7$ interactions/year!**
  - **Additional target materials possible**

A liquid argon TPC or pressurized gas TPC are possible choices also.

The physics strategy and design of the ND is critical for LBNE. Simulations, reconstruction and R&D work is in initial phase with input from Indian colleagues. Open working meeting at FNAL on July 28-29.

Experimental Parameters

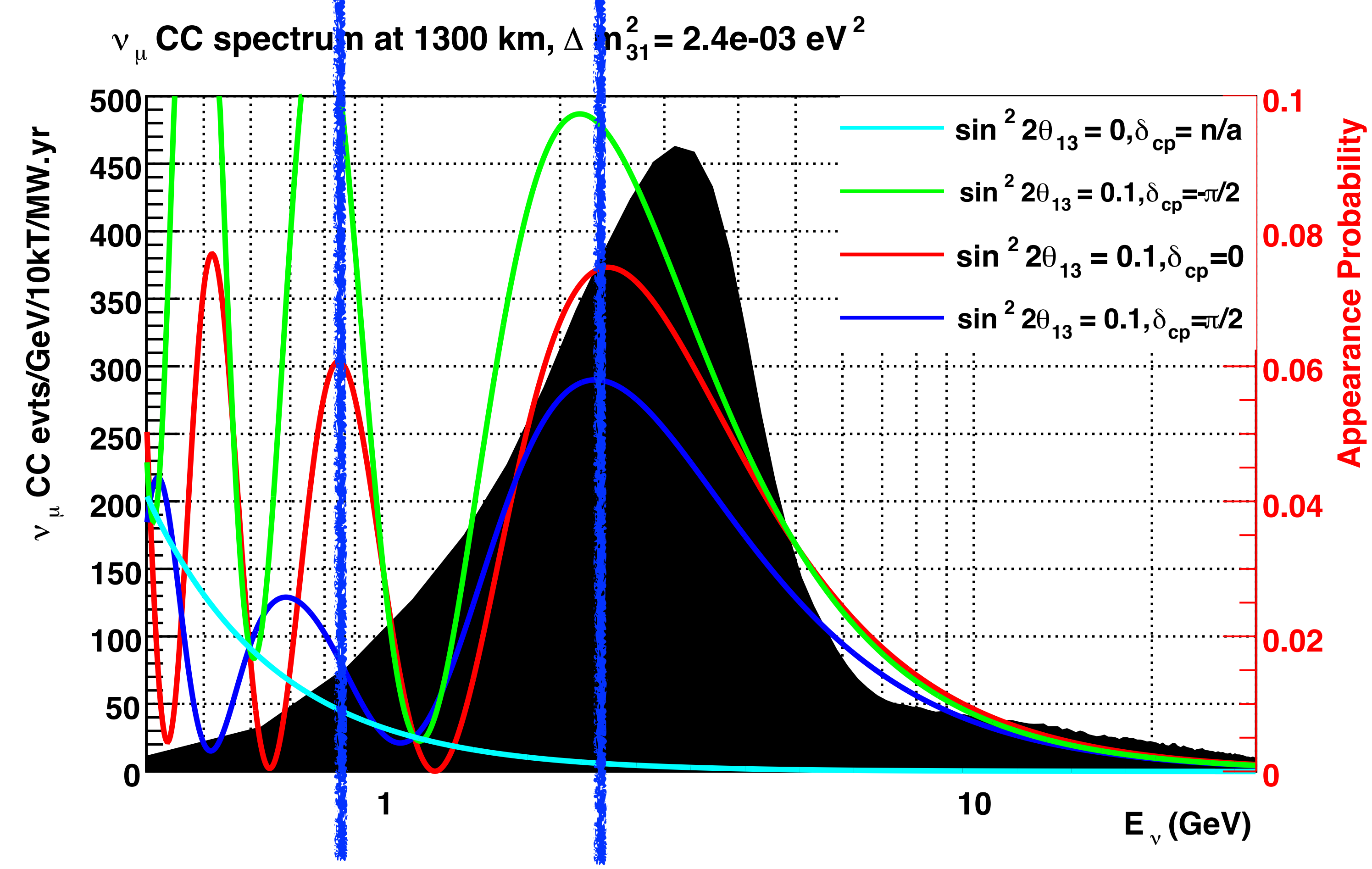


- Wide band neutrino beam from FNAL
  - protons: 60-120 GeV, 1.2 MW; upgradable to 2.3 MW
  - 10 μS pulses every 1.0 to 1.33 sec depending on P energy&power.
  - Neutrinos: sign selected, horn focused, 0.5 - 5 GeV
  - 1300 km thru the Earth to Sanford Underground Research Facility.
- Liquid argon TPC parameters
  - 34 kt fiducial (50kt tot) at 4850 ft level. cosmics ~0.1Hz, beam ~ 9k CC/yr
  - drift ~3.5 m, field: 500 V/cm, 2 mods = (14m(H)X 22m(W)X45m(L))
  - readout: x,u,v, pitch: 5 mm, wrapped wires, 2X108 APAs, 2X(275k ch)
  - Max Yield: ~9000 e/mm/MIP, 10000 ph/mm/MIP
- near detector parameters
  - distance ~450 m, ~3M events/ton/MW/yr
  - Magnetized Fine Grained Tracker (8 ton) with ECAL, and muon id.
  - Supplemented by a small LARTPC (few tons) or gas TPC.

Scale of project is dictated by physics. Beam and ND and FD detectors require high technology. Project can be done in phases with international partners.

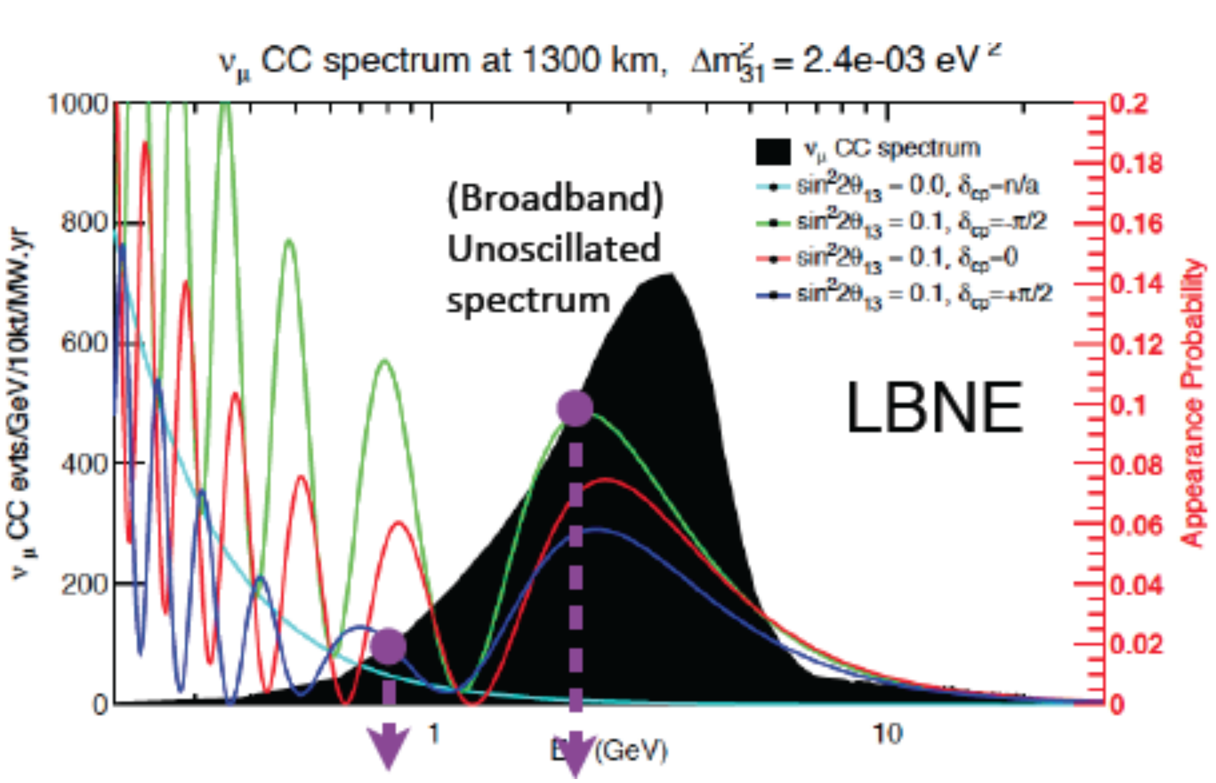
Neutrino Asymmetries

Larger CP effects: 2nd　　　　1st: larger matter effects

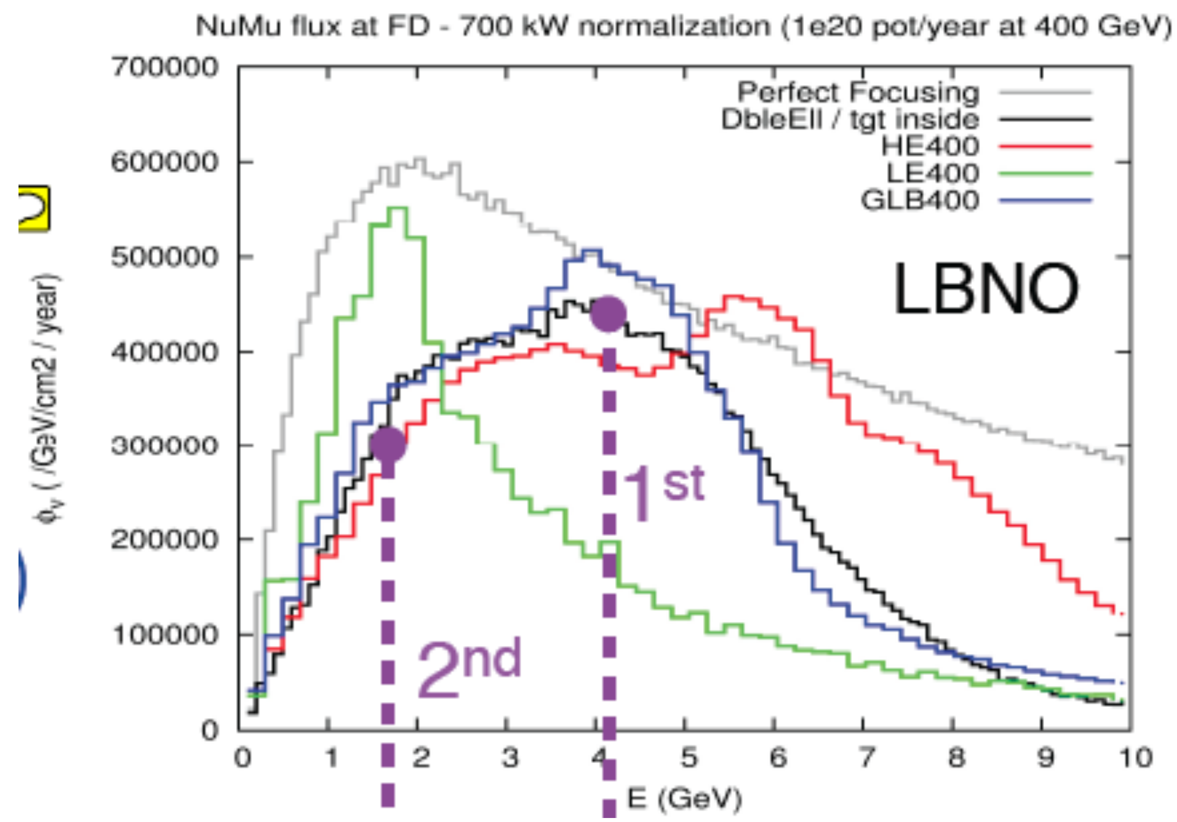


- At 1300 km the events from 1st and 2nd maximum (and in-between) measure the asymmetries from both matter effects and CP.
- With sufficient statistics all ambiguities can be resolved. We need ~1000-2000 events with good energy resolution and particle ID.
- The requirement for statistics and low systematics is difficult and is required of any reasonable design.
- Event rate at 2nd is limited by pion decay kinematics and X-section indep. baseline

Comparison to SPS based beam



This is EVENT RATE



This is FLUX

LBNO Rate (4.5 GeV)/Rate(1.5 GeV) = 42/27 * 3 ~ 4.7

LBNE Rate(2.5 GeV)/Rate(0.8 GeV) = 440/90 = 4.9

The LBNE beam is reusing the NuMI technology without optimization to save costs.

After including cross section the ratio of first to second max event rates should be roughly independent of baseline because of kinematics and cross section.

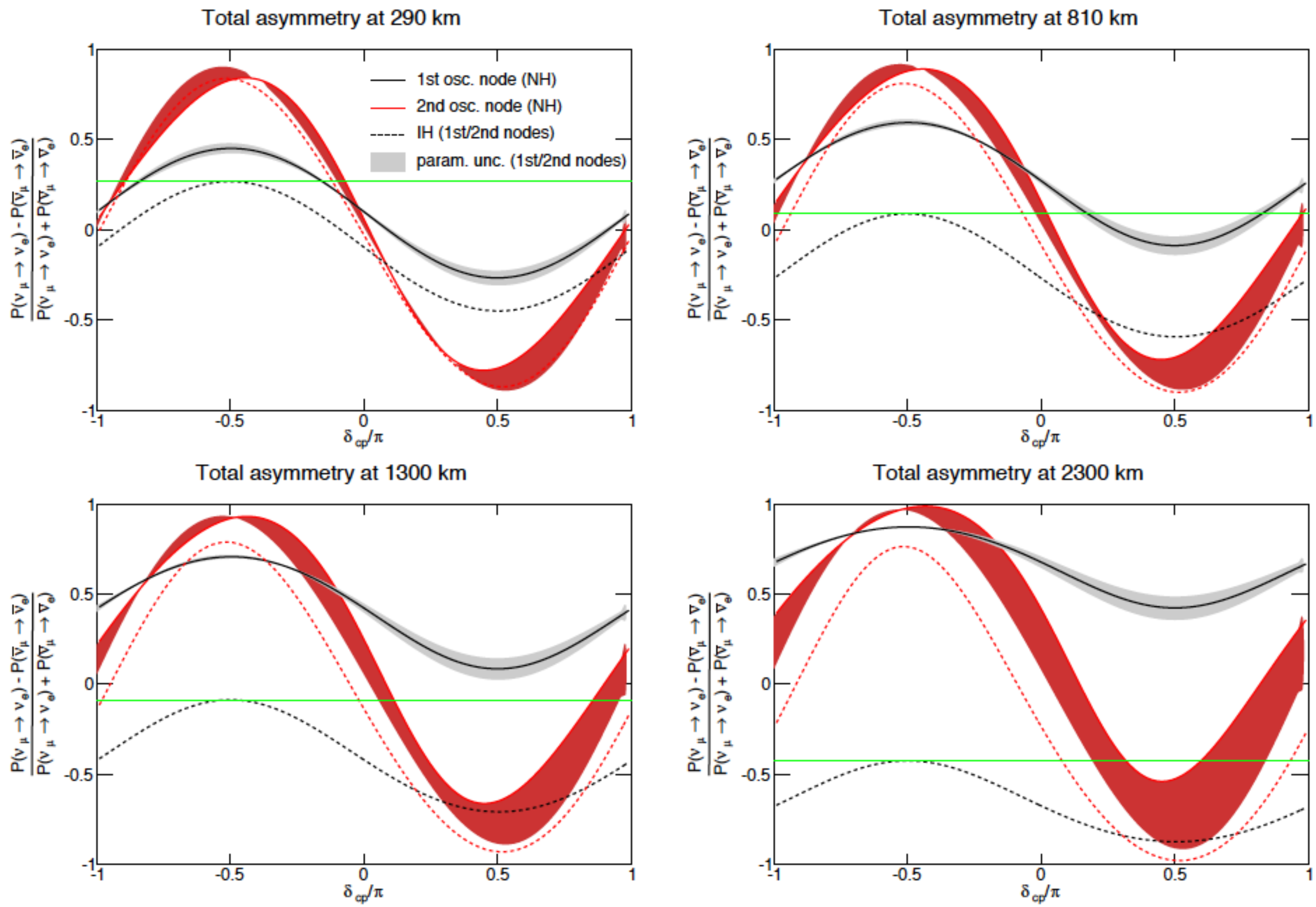
Considered design changes that increase the physics potential

Ratio of $\nu_\mu \rightarrow \nu_e$ CC appearance rates at the far detector

Change	0.5-2.0 GeV	2.0-5.0 GeV
DK pipe Air → He *	1.07	1.11
DK pipe length 200 m → 250 m (4m D)	1.04	1.12
DK pipe diameter 4 m → 6 m (200m L)	1.06	1.02
Horn current 200 kA → 230 kA	1.00	1.12
Proton beam 120 → 80 GeV, 700 kW	1.14	1.05
Target graphite fins → Be fins	1.03	1.02
Total	1.39	1.52

* Simplifies the handling of systematics as well

Baseline optimization

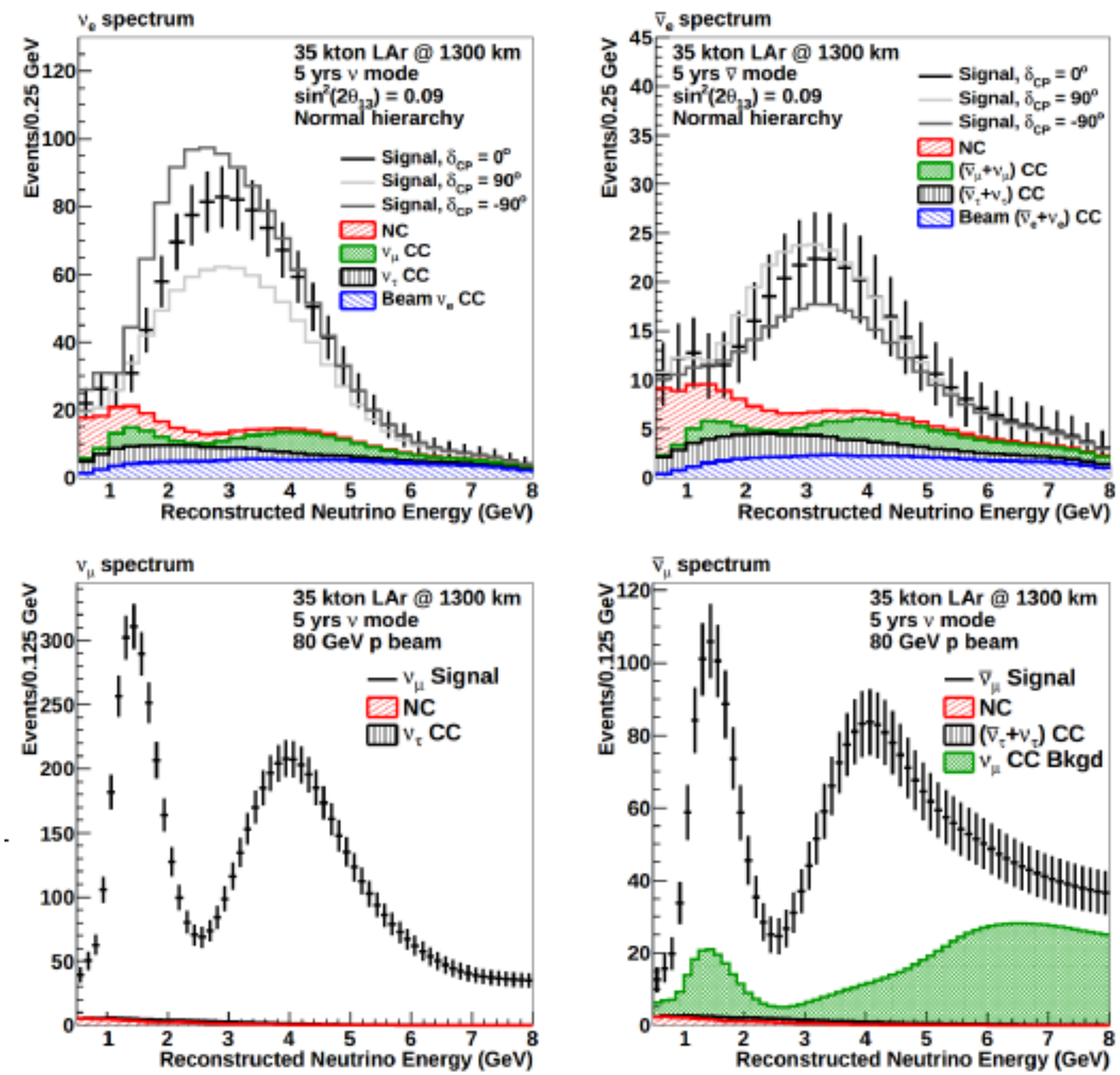


- >1000 km is needed to break the degeneracy between CP and matter effects. Statistics at both nodes improve sensitivity.
- At >2000 km suppression of events in one polarity is very high: nu/anu asymmetry measurement a challenge.

Event rate and spectra expectation.

Assumptions:
35 kt LArTPC
1.2 MW operation at 80 GeV.
~3 yrs for each polarity.
Normal Hierarchy
δ_{CP}= 0
Rest of the parameters are at best fit from 2012

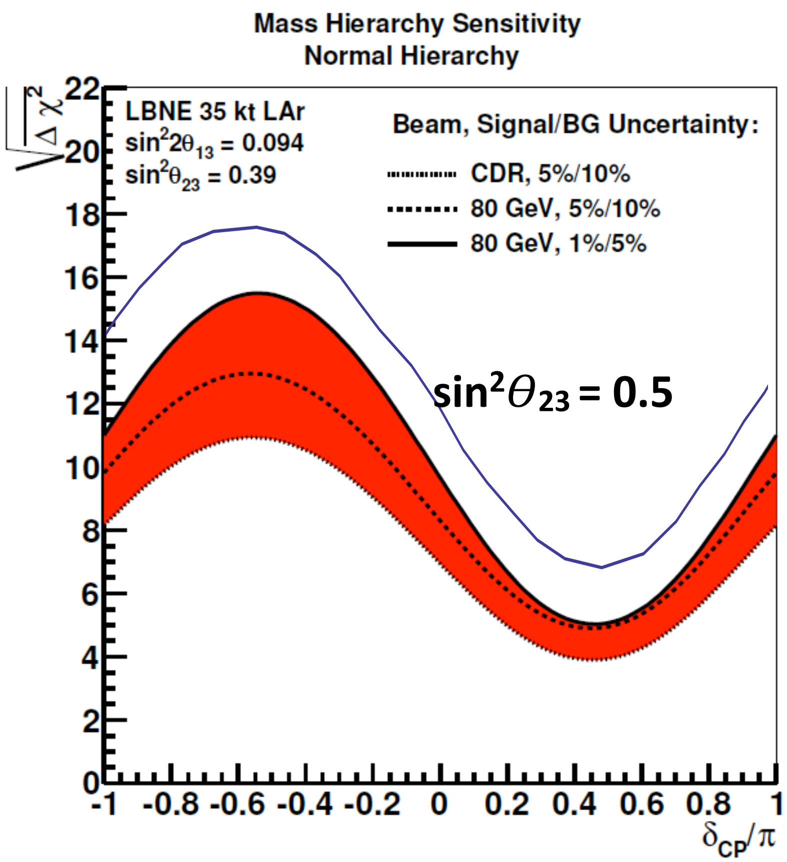
80 GeV Beam	ν mode	$\bar{\nu}$ mode
Signal: $\nu_e + \bar{\nu}_e$	777	189
BG: NC	67	39
BG: $\nu_\mu + \bar{\nu}_\mu$ CC	84	39
BG: Beam $\nu_e + \bar{\nu}_e$	147	81
BG: $\nu_\tau + \bar{\nu}_\tau$ CC	49	32

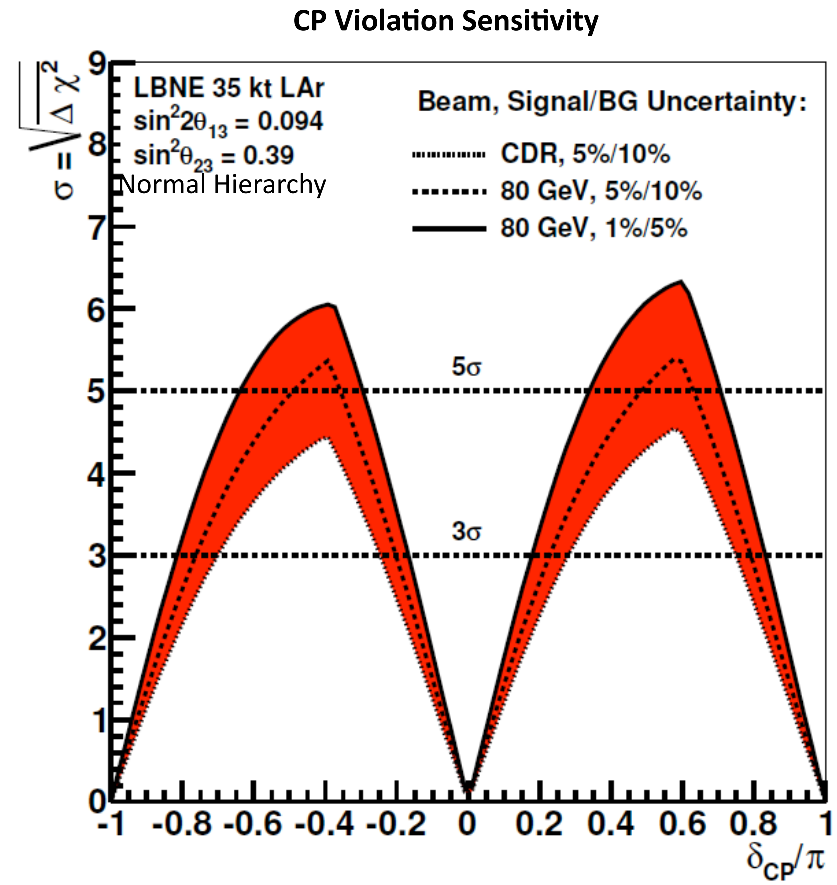


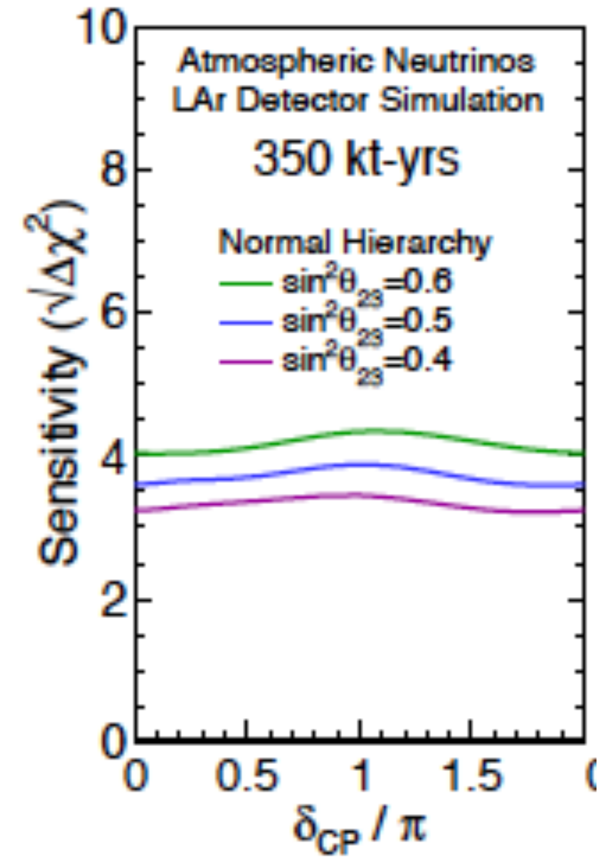
- **At 1300 km full oscillation structure is visible in the energy spectrum. A combined spectral fit provides unambiguous parameter sensitivity in a single experiment. This is a comprehensive experiment.**

Sensitivity

median sensitivity to reject IH







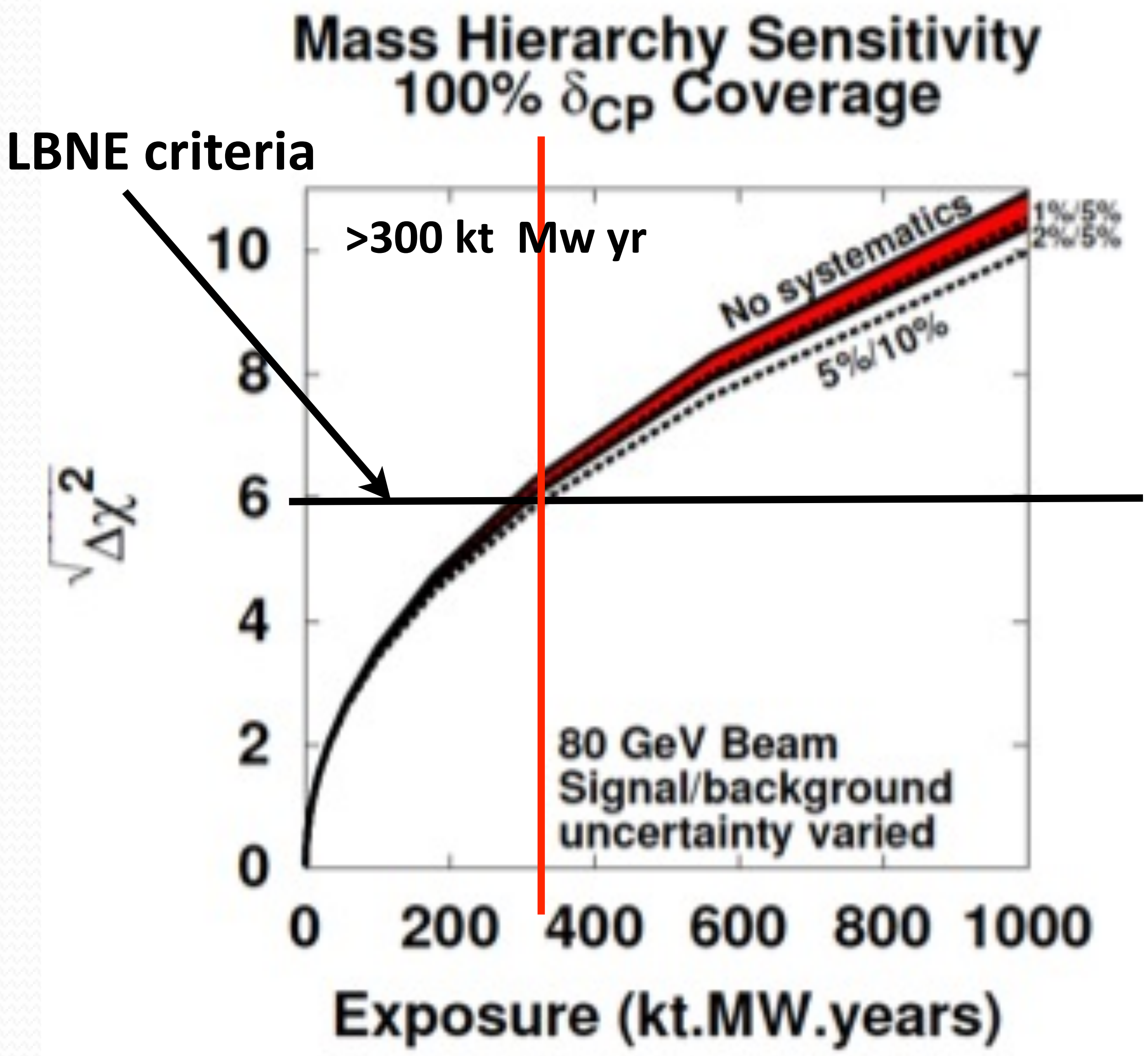
Exposure 245 kt.MW.yr

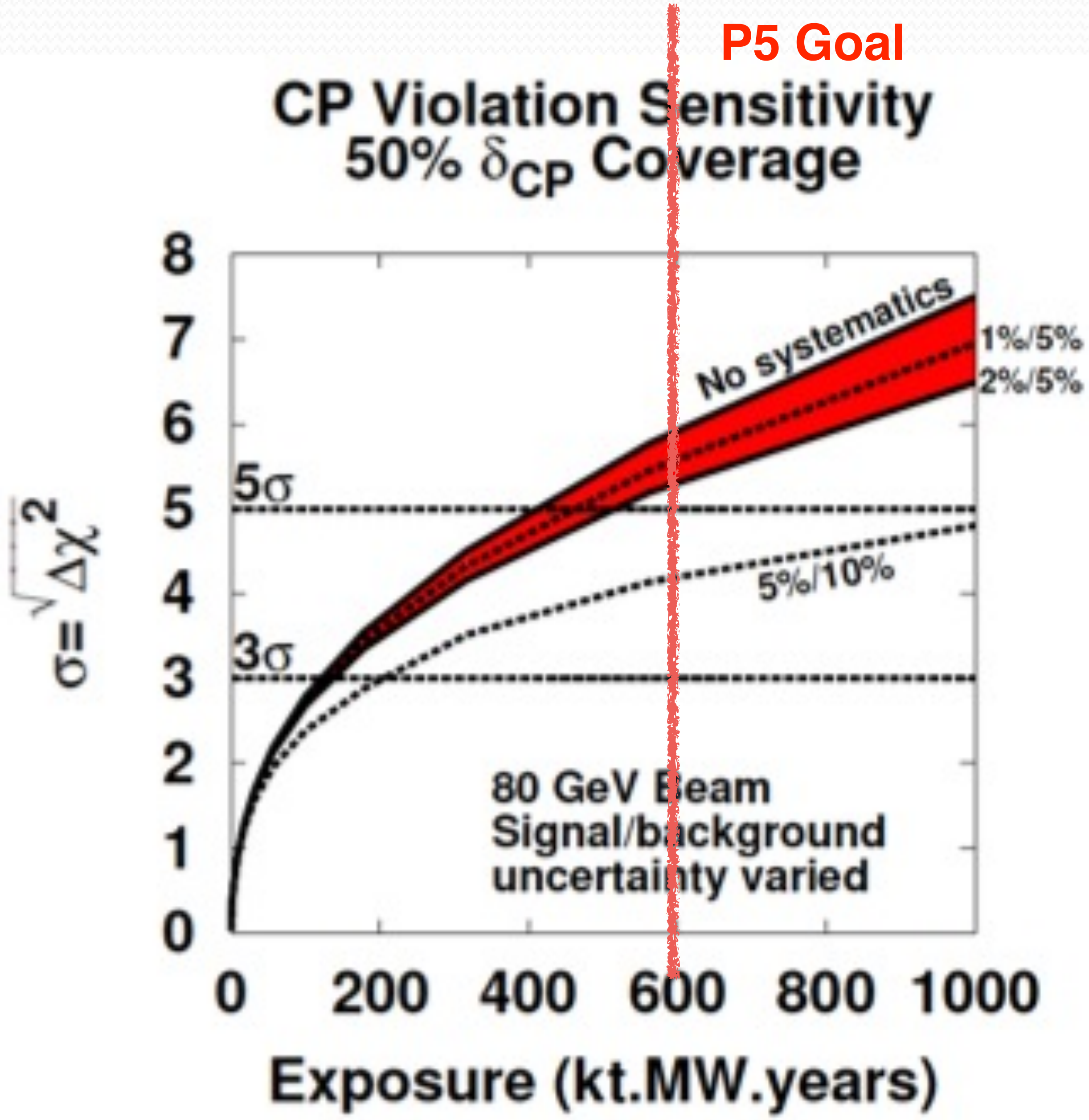
1.2 MW x 35 kt x(3ν+3ν̄) yr

Parameter sensitivity to $\sin^2\theta_{23} = 0.39 \rightarrow 0.5$

- **For NH versus IH hypothesis testing, following PDG two-hypothesis testing formalism, we find that α = β < 0.13% to be a sufficient criteria. These are probabilities of either rejecting the correct hierarchy or accepting the wrong one, respectively, for the worst case assumptions on parameters.**
- **LBNE will produce two independent checks on hierarchy (beam and ATM nus) with median sensitivity > 36 (beam) or >9 (atmospheric).**

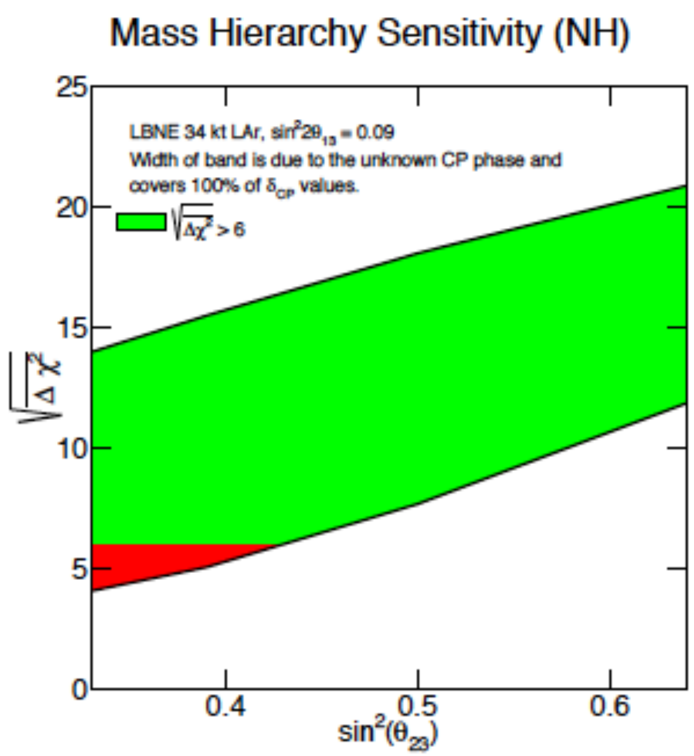
Impact of Normalization Uncertainties

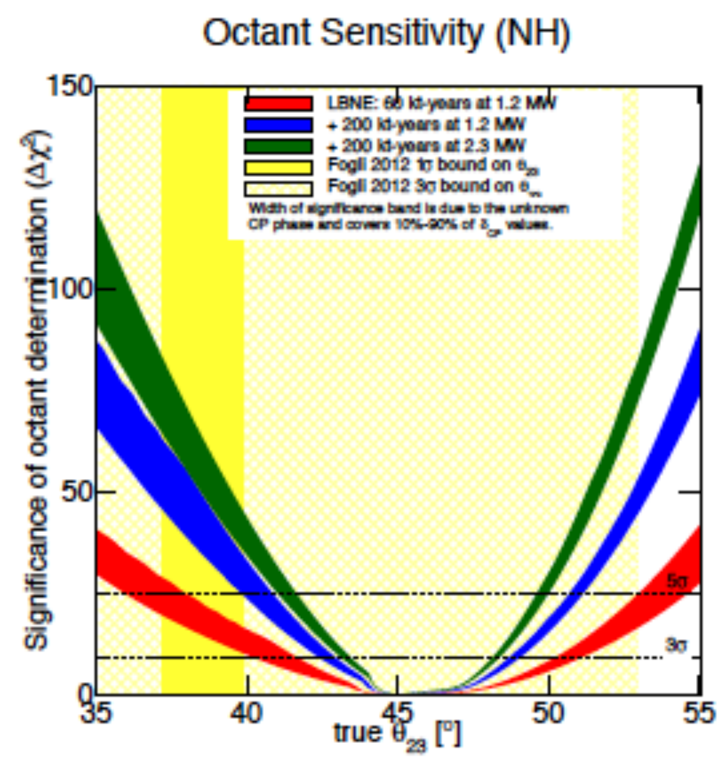


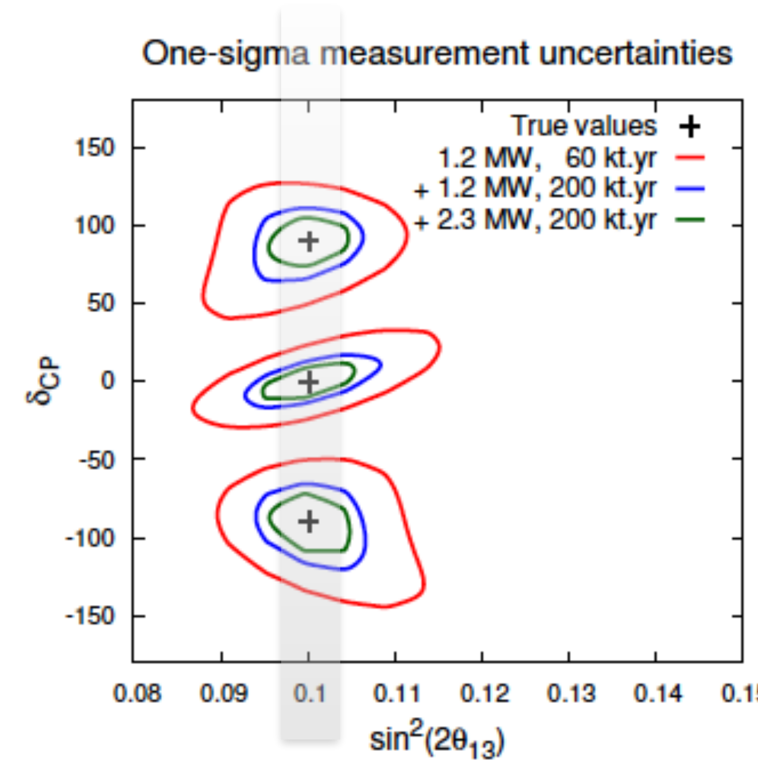


- <3% errors appear realistic with recent progress.
- The systematic precision is required to be better than the expected statistics at each stage of the experiment. High precision is needed after 200kt*MW*yr.
- MH relatively insensitive to systematics; but further study needed.
- MINOS appearance result has achieved better than 5%/5% systematics.

Other measurements for a comprehensive program.

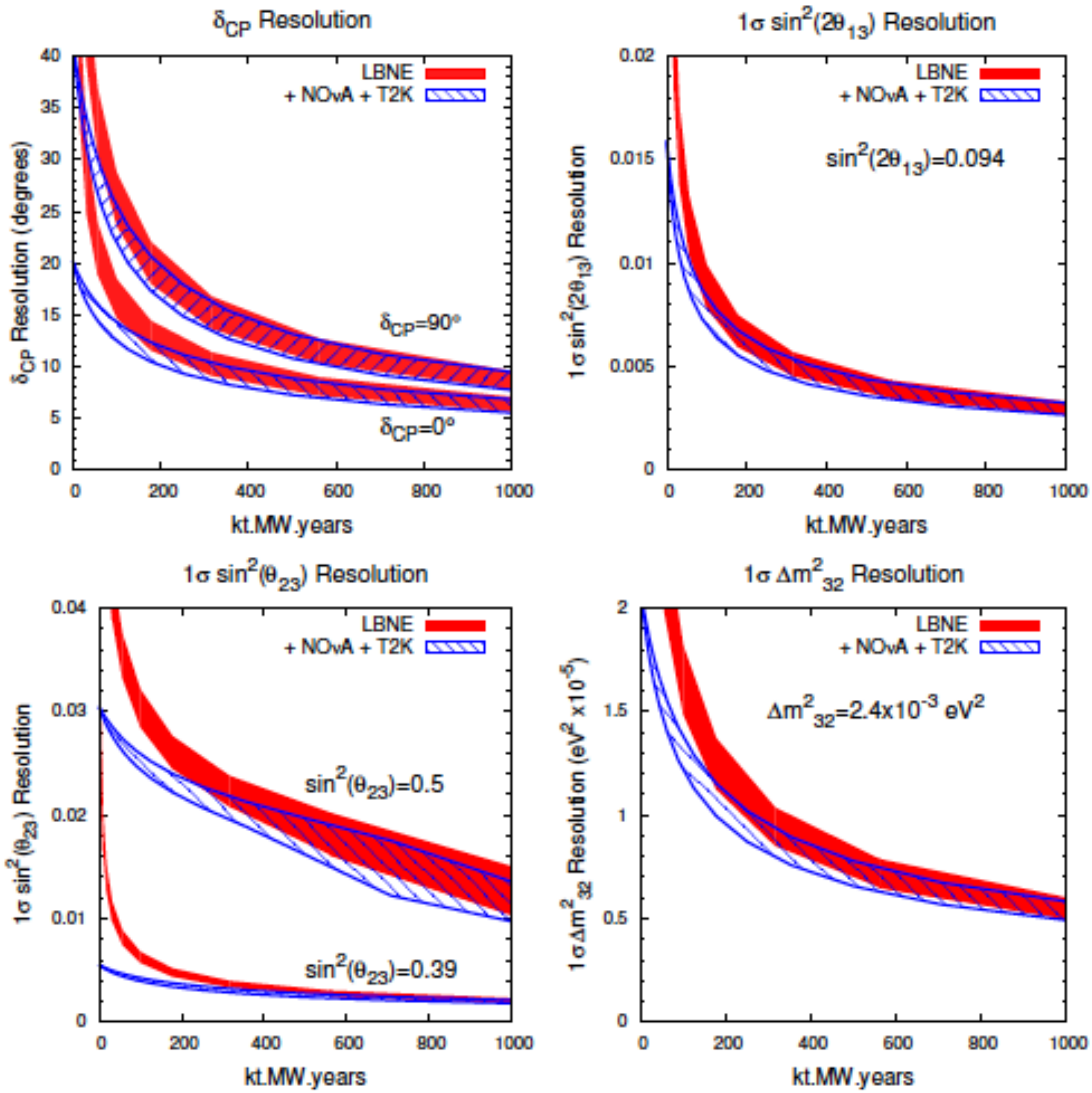






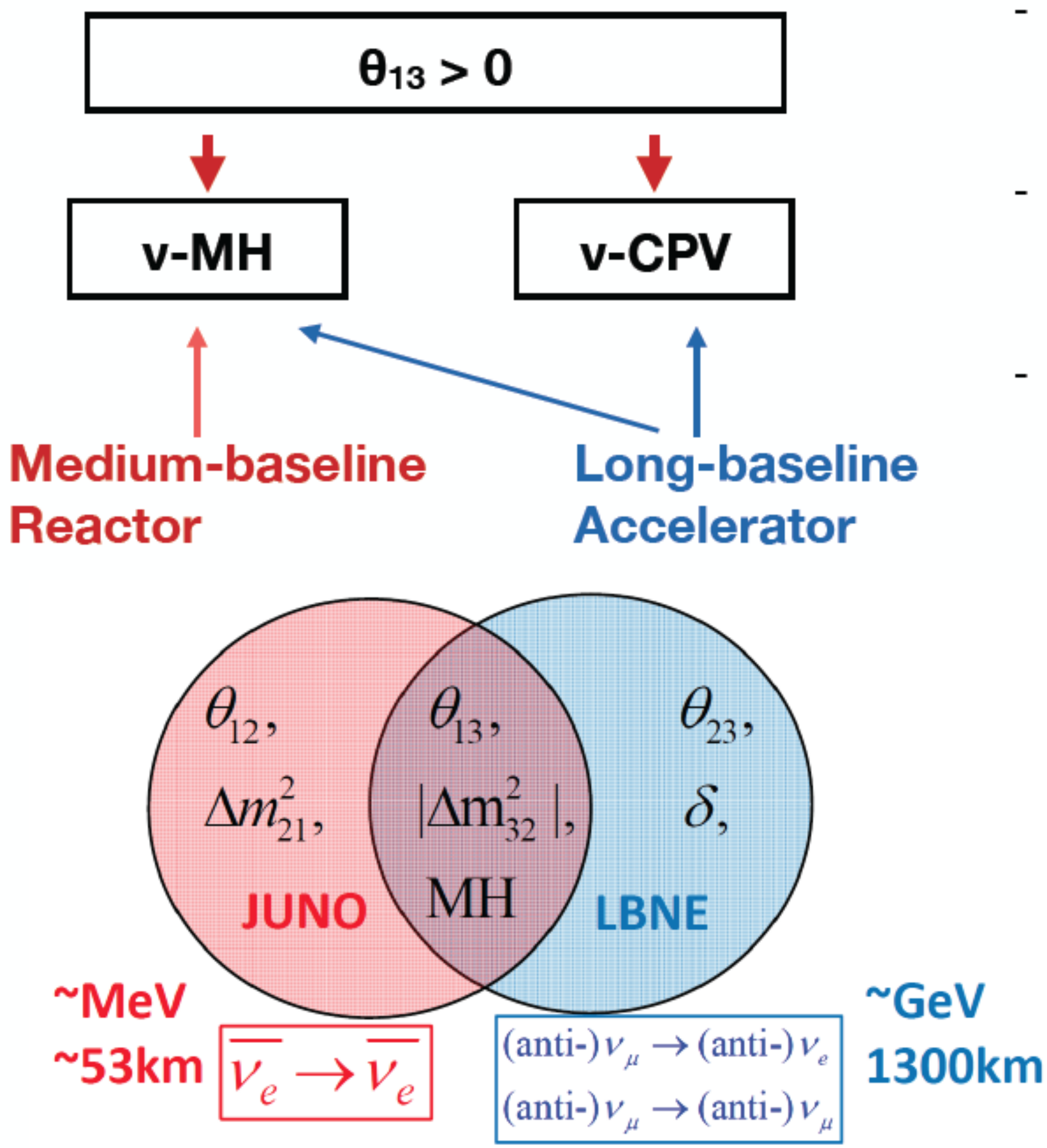
Ultimate reactor sensitivity

Because of the event rate the program will provide redundant and comprehensive parameter sensitivity for testing the 3-nu model.



Parameter resolutions

Precision measurements of U_{PMNS} with laboratory experiments.



And, huge opportunities for underground science! proton decay, supernova… etc

- Why is leptonic mixing angles large compared to quark mixing in CKM?
- Is there any pattern in U_{PMNS} that guide us to the theory of flavor
- Is U_{PMNS} unitary?

The journey of PMNS unitarity test in the precision neutrino physics era just began!

X.Qian, C.Zhang, P.Vogel, M.Diwan arXiv: 1308.5700

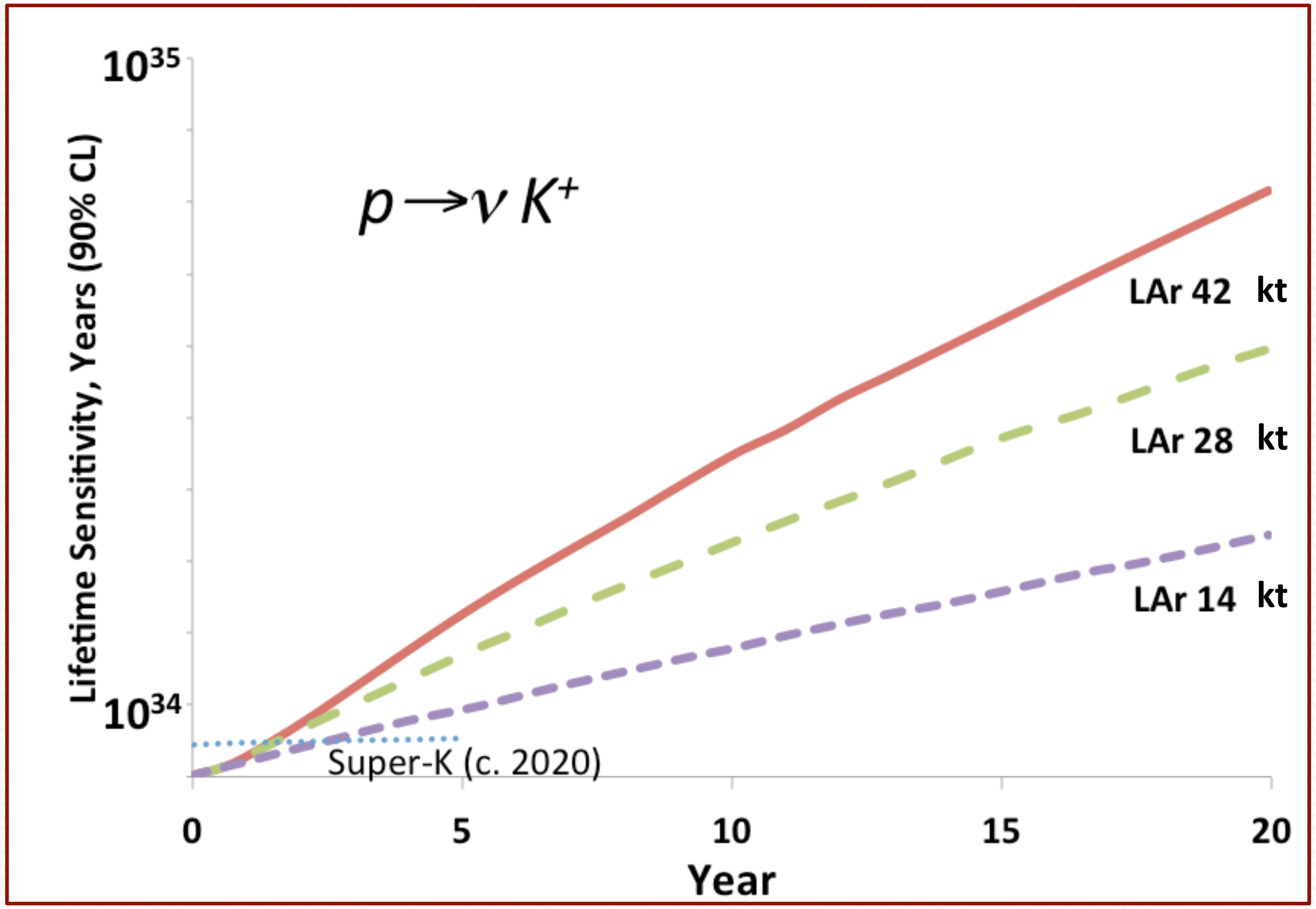
	JUNO	LBNE
$\sin^2 2\theta_{12}$	0.7%	
Δm^2_{21}	0.6%	
$\|\Delta m^2_{32}\|$	0.5%	0.3%
MH	3-4σ*	>5σ
$\sin^2 2\theta_{13}$	14%**	3%
$\sin^2 \theta_{23}$		3%
δ_{CP}		10°

* 4σ requires 1% $|\Delta m^2_{uu}|$ ** Daya Bay reaches 3%

LBNE is a comprehensive experiment. When combined with a reactor effort we characterize the whole matrix redundantly.

Proton Decay

In Liquid argon the Kaon will travel ~13 cm



The key enabling issue is depth. The minimum depth required depends on active vetos if possible.

A depth at 4850 ft level would eliminate any risk.

What new justification can be made for this search, esp. regarding a LAr detector ?

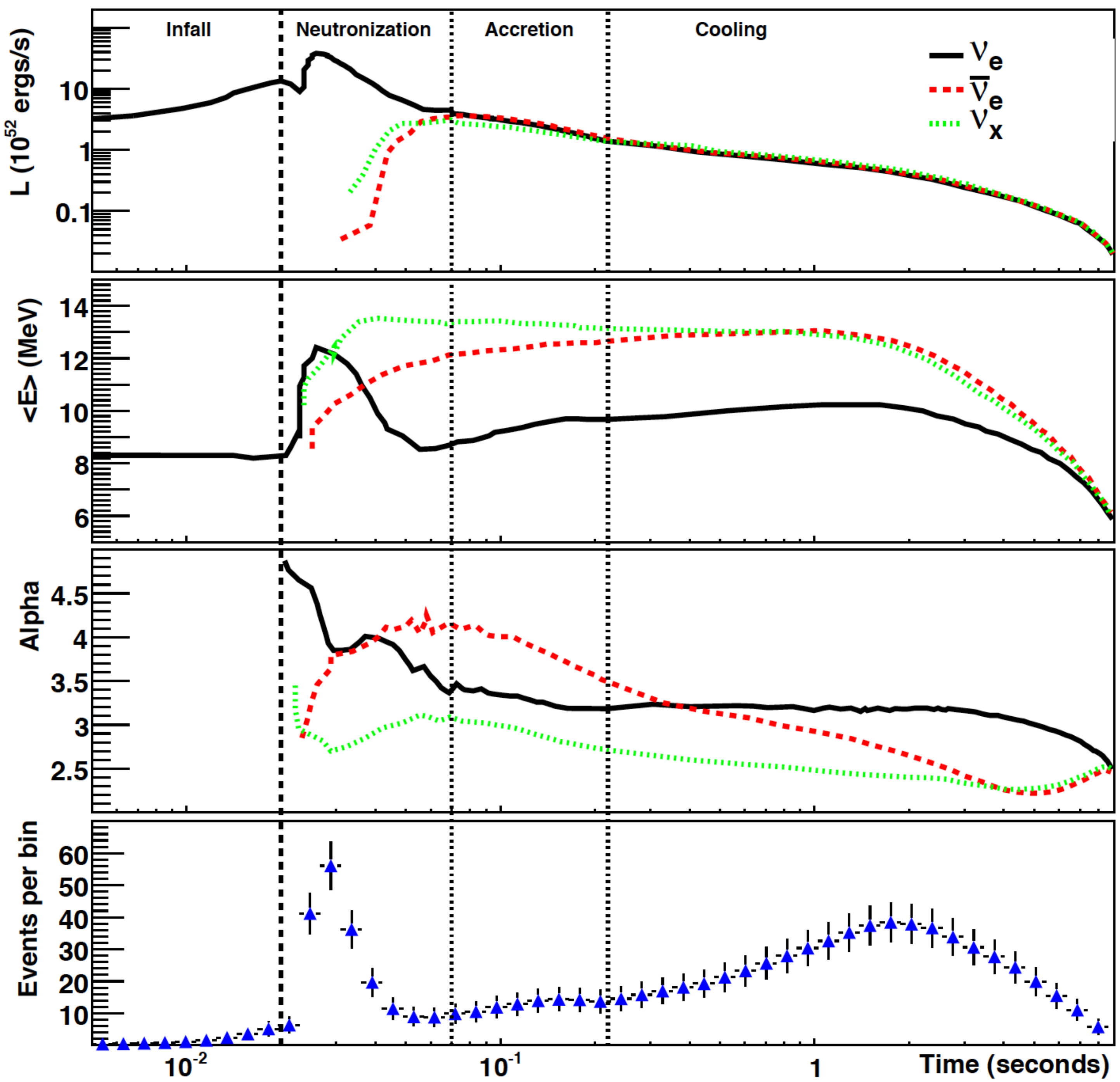
- LAr has high efficiency for SUSY-favored decay modes
- High spatial precision and energy resolution enable reconstruction of many potential decays modes
- Much more work is possible here.

Mode	Efficiency	Background Rate (evts/100 kton-y)
	B-L	
$p \rightarrow e^+\pi^0$	45%	0.1
$p \rightarrow \nu K^+$	97%	0.1
$p \rightarrow \mu^+ K^0$	47%	< 0.2
	B+L	
$p \rightarrow \mu^-\pi^+ K^+$	97%	0.1
$p \rightarrow e^+ K^+$	96%	< 0.2
	$\Delta B = 2$	
$N\bar{N} \rightarrow n(\pi)$	TBD	TBD

Supernova burst

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

LAr mainly sensitive to electron neutrinos.
(water is sensitive to anti-electron-neutrinos)



A large theory effort is underway to understand neutrino related dynamics of the supernova. Both oscillations, mass, and self-interactions have large effects on observables.

e.g. mass hierarchy could have very distinct effects on the spectrum.

Precision astrophysics and cosmology needs precise laboratory data on neutrinos so that correlations can be resolved.

Estimated rate: ~3000 evts @ 10 kpc for 34 kt LAr TPC

Physics Opportunities

Atmospheric neutrinos

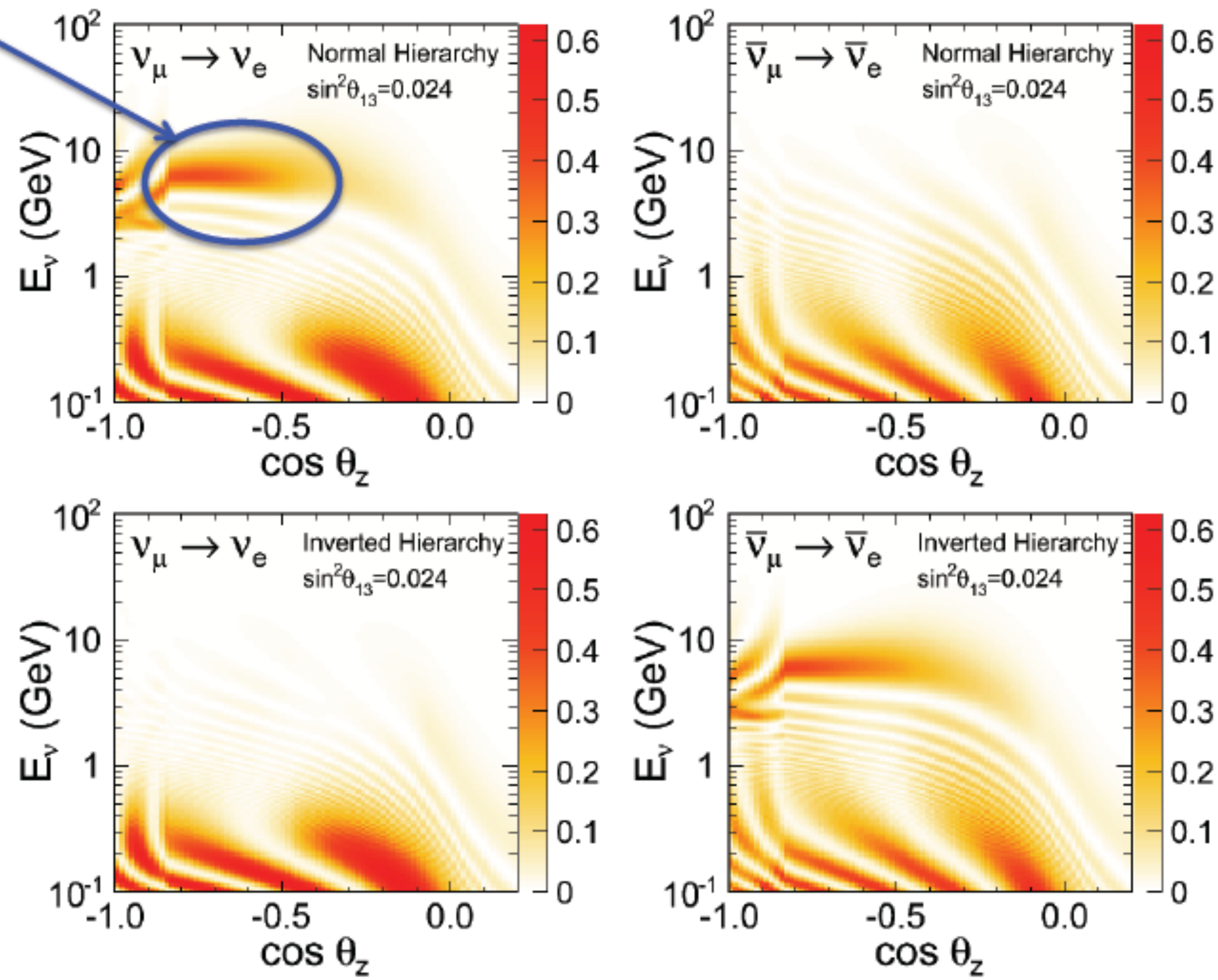
Large θ_{13} means MSW enhancement for 2-10 GeV upgoing neutrinos (NH) or anti-neutrinos (IH).

All flavors present in oscillated flux.

Possibilities for tau appearance.

Ideal detector:

- Excellent flavor ID
- Energy resolution
- Angular resolution
- Nu/nubar separation
- Big!!



~42000 evts/ 350kt*yr

- **The atmospheric data can be used to either enhance parameter sensitivity in combination with beam or use the beam measurements to look for new effects. This is similar to INO, but has less target mass.**

LBNE Collaboration

505 (126 non-US) members,
88 (34 non-US) institutions,
8 countries

UFABC
Alabama
Argonne
Banaras
Boston
Brookhaven
Cambridge
Catania/INFN
CBPF
Charles U
Chicago
Cincinnati
Colorado
Colorado State
Columbia
Czech Technical U
Dakota State
Delhi
Davis
Drexel
Duke
Duluth
Fermilab
FZU
Goias
Gran Sasso
GSSI
HRI
Hawaii
Houston
IIT Guwahati
Indiana
Iowa State
Irvine
Kansas State
Kavli/IPMU-Tokyo
Lancaster
Lawrence Berkeley NL
Livermore NL
Liverpool
London UCL
Los Alamos NL
Louisiana State
Manchester
Maryland

Michigan State
Milano
Milano/Bicocca
Minnesota
MIT
Napoli
NGA
New Mexico
Northwestern
Notre Dame
Oxford
Padova
Panjab
Pavia
Pennsylvania
Pittsburgh
Princeton
Rensselaer
Rochester
Rutherfod Lab
Sanford Lab
Sheffield
SLAC
South Carolina
South Dakota
South Dakota State
SDSMT
Southern Methodist
Sussex
Syracuse
Tennessee
Texas, Arlington
Texas, Austin
Tufts
UCLA
UEFS
UNICAMP
UNIFAL
Virginia Tech
Warwick
Washington
William and Mary
Wisconsin
Yale
Yerevan

Since DOE Critical Decision-1 (CD-1) approval (December 2012):

- Collaboration has increase by more than 40%
- Non-US fraction has more than doubled
- Working towards a full international collaboration

Financial and International Issues

From the US-P5 committee:

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

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.

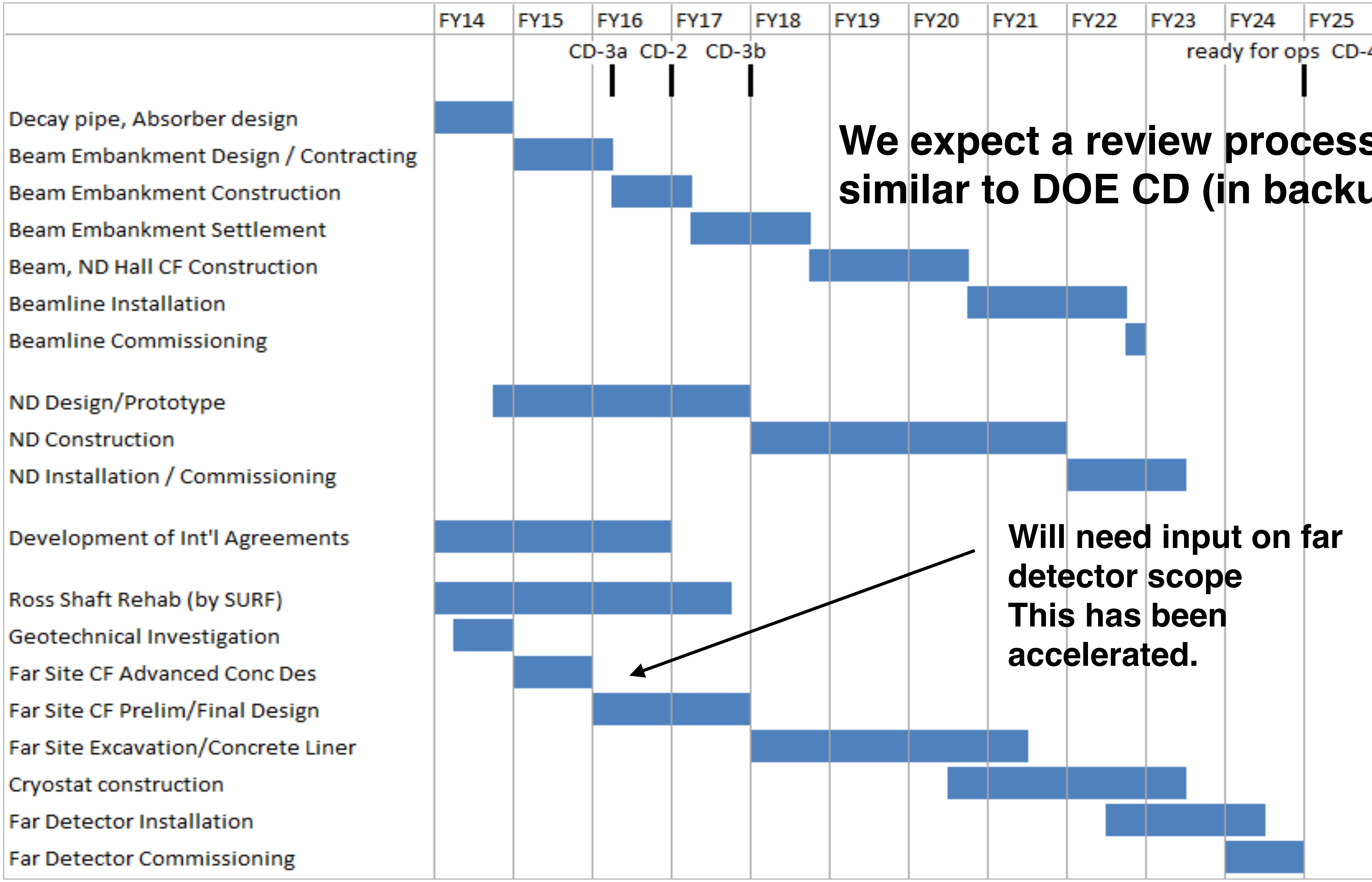
- **Working with US-DOE-OHEP and FNAL director to develop a fully international LBNE/F at all levels. CD1 approval allows flexibility.**
- **The LHC collaborations and others are examples to be studied.**
- **The collaboration based on common scientific goals. No national boundaries are recognized in the scientific governance.**
- **A common process to be developed for financial and project management. Could be based on agreed to requirements and well known methods of change control.**

Conceptual design costs.

WBS	Beam+ ND+10kt LArTPC underground, CF	Beam+ND+34kt LArTPC underground, CF	Contin gency
Total Project cost	1225	1529	41%
Management Top down cntg.	91 62	100 70	29% 0
Beamline	169	169	30%
Near Detector	136	136	29%
Far Detector	278	495	44%
Civil Facilities	489	559	31%

Numbers are $M. Indirect costs, escalation, and contingency is included in the numbers. Estimates are bottoms up and reviewed. It is too early to understand international distribution, but US as host will need to bear majority of the infrastructure costs. $US cost ~$900M.

Plausible Technically Limited Schedule for international LBNF. Depends on resources and international project management



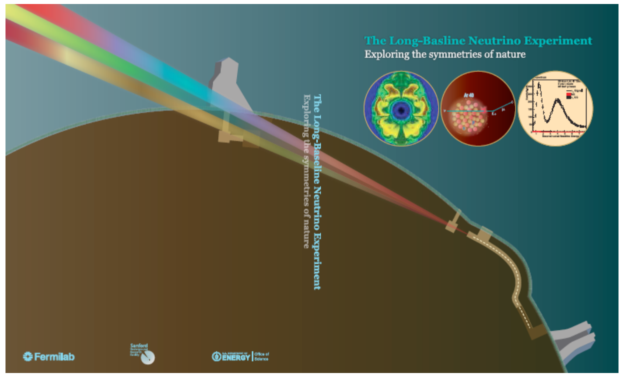
We expect a review process similar to DOE CD (in backup)

Will need input on far detector scope This has been accelerated.

The exact timeline will depend on partnerships host nation funding and review process.

Conclusion

- **Scientific motivation and scale of the next generation long-baseline neutrino oscillation experiment is well-known. LBNE design meets the requirements for a comprehensive experiment aimed towards CP violation in the neutrino sector.**
- **The US has unique assets to host this program given the availability of high intensity accelerator**
  - **700 kW upgrade in commissioning**
  - **1.2 MW by the time of LBNE start**
  - **Further upgrades to >2.3 MW**
- **An operating world-class Sanford Underground Research Facility (Dark Matter and Double Beta Decay experiments have started at 4850L)**
- **Committed to make this a fully international scientific program.**



- Snowmass detailed-whitepaper arXiv:1307.7335