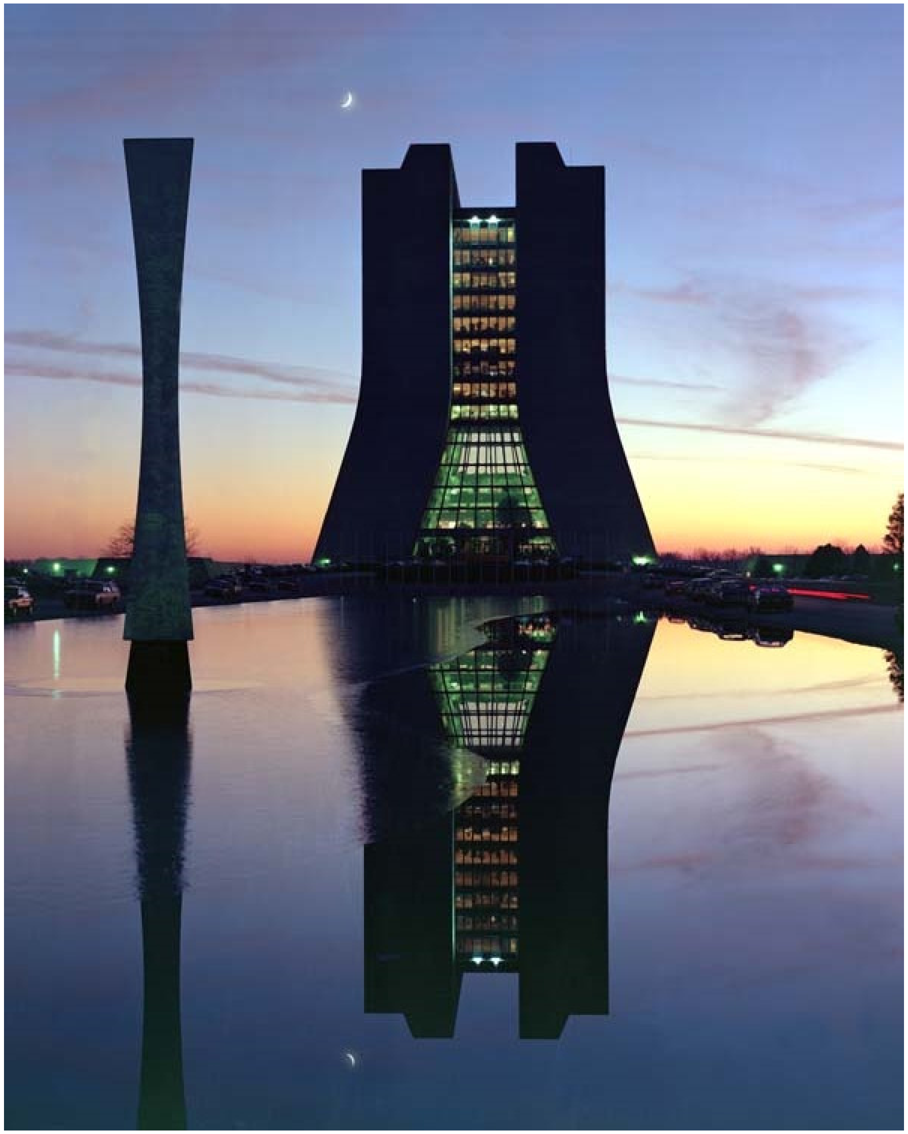
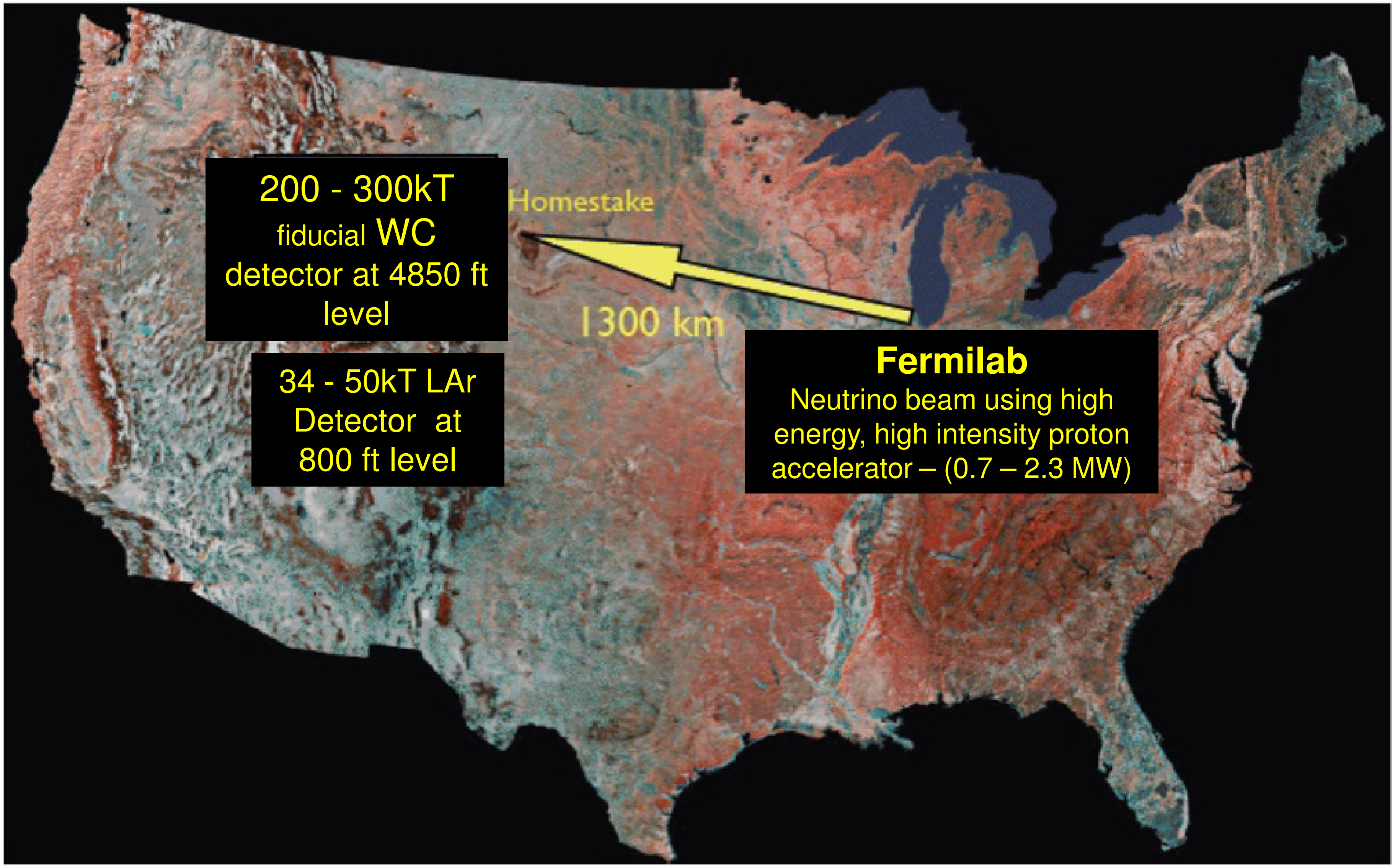


LBNE : Physics Reach & Status

Brajesh Choudhary
University of Delhi, Delhi
On behalf of LBNE Collaboration

12th International Workshop on Neutrino Factories, Superbeams and Beta Beams
20-25 October, 2010,
TIFR-Mumbai, India

LONG BASELINE NEUTRINO EXPERIMENT



200 - 300kT fiducial WC detector at 4850 ft level

34 - 50kT LAr Detector at 800 ft level

Fermilab
Neutrino beam using high energy, high intensity proton accelerator – (0.7 – 2.3 MW)

LBNE COLLABORATION

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Duluth: R. Gran, A. Habig

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Livermore: A. Bernstein, R. Bionta, S. Dazeley, S. Ouedraogo

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NGA: S. Malys, S. Usman

New Mexico: B. Becker, J. Mathews

Notre Dame: J. Losecco

Oxford: G. Barr, J. DeJong, A. Weber

Pennsylvania: J. Klein, K. Lande, A. Mann, M. Newcomer, R. vanBerg

Pittsburgh: D. Naples, V. Paolone

Princeton: Q. He, K. McDonald

Rensselaer: D. Kaminski, J. Napolitano, S. Salon, P. Stoler

Rochester: R. Bradford, K. McFarland

SDMST: X. Bai, R. Corey

SMU: T. Liu, J. Ye

South Carolina: H. Duyang, S. Mishra, R. Petti, C. Rosenfeld

South Dakota State: B. Bleakley, K. McTaggert

Texas: S. Kopp, K. Lang, R. Mehdiyev

Tufts: H. Gallagher, T. Kafka, W. Mann, J. Schnepps

UCLA: K. Arisaka, D. Cline, K. Lee, Y. Meng, F. Sergiampietri, H. Wang

Virginia Tech: E. Guarnaccia, J. Link, D. Mohapatra, R. Raghavan

Washington: S. Enomoto, J. Kaspar, N. Tolich, H.K. Tseung

Wisconsin: B. Balantekin, F. Feyzi, K. Heeger, A. Karle, R. Maruyama, D. Webber, C. Wendt

Yale: E. Church, B. Fleming, R. Guenette, M. Soderberg, J. Spitz

54 Institutions, 257 Members

LBNE COLLABORATION

14.SEPTEMBER.2010 - FERMILAB

PLAN OF THE TALK

1. Neutrino Oscillation Formalism
2. What we know, what we don’t know, and what we will like to know
3. LBNE Beam (Fermilab to DUSEL)
4. LBNE Detectors (ND at Fermilab, FD at DUSEL)
5. Physics with LBNE
    a) Long Baseline Physics Reach
        i. Precise measurement of θ_{13}
        ii. Determination of Mass Hierarchy
        iii. CP Violation in Neutrinos
        iv. Precise measurement of Δm^2_{31} and θ_{23}
    b) Proton Decay
    c) Supernova Neutrino Bursts
    d) Diffuse Supernova Neutrinos
    e) Atmospheric Neutrinos
    f) High Energy Neutrinos
    g) Solar Neutrinos
6. Summary and Conclusions

Not covered in this talk.

NEUTRINO MIXING & PMNS MATRIX

FLAVOR Eigenstates

MASS Eigenstates

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

Atmospheric

Cross Mixing

Solar

Majorana

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$\nu_\mu \leftrightarrow \nu_\tau$

$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

$\nu_e \leftrightarrow \nu_\mu, \nu_\tau$

ν_μ Long Baseline

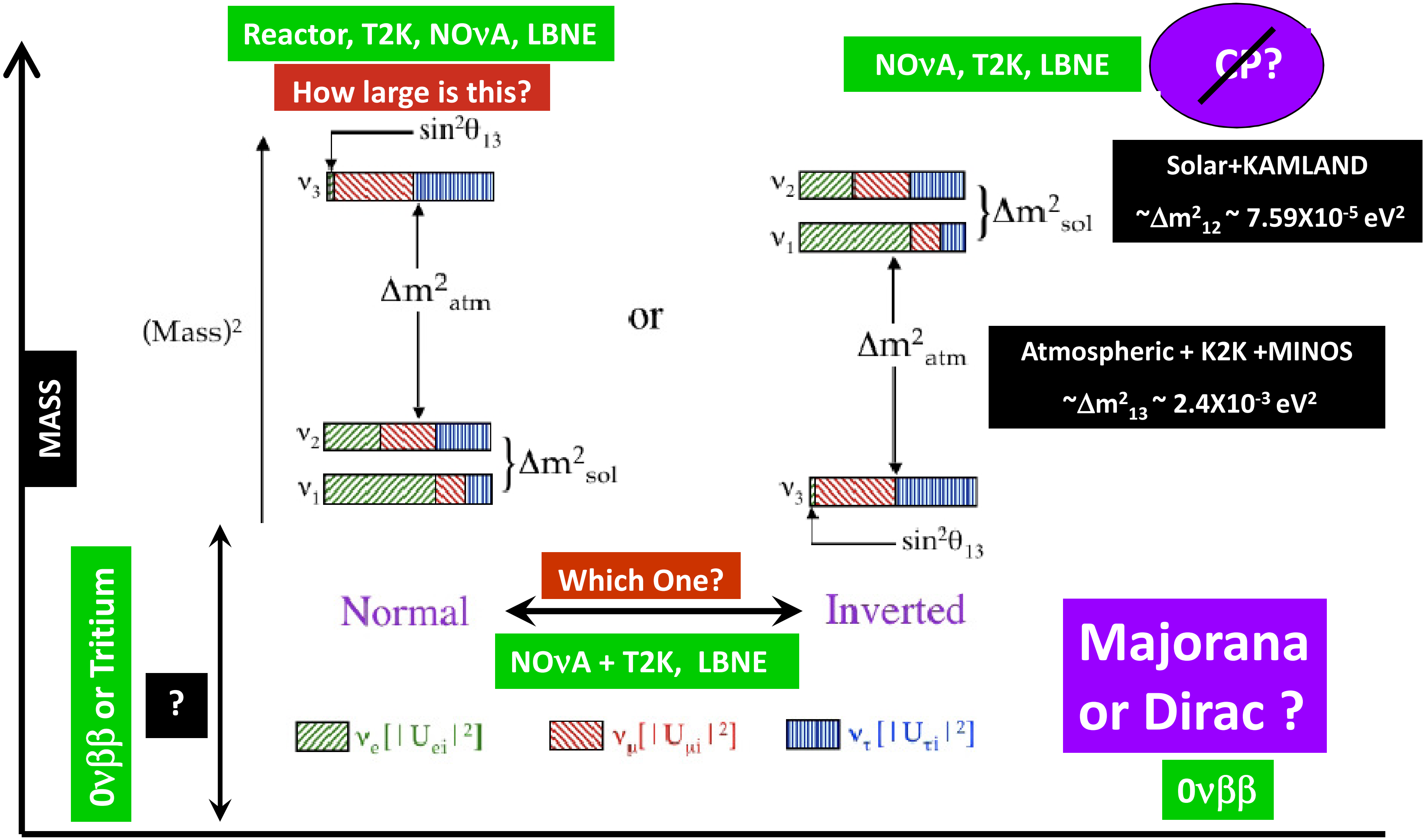
Reactor Short Baseline
ν_μ Long Baseline

Solar
Reactor Long Baseline

Long Baseline Accelerator Experiments

ν oscillations can be described by 2 Δm^2, 3 angles, and one complex CP phase

WHAT WE KNOW, WHAT WE DON'T KNOW, & WHAT WE WOULD LIKE TO KNOW



Reactor, T2K, NOνA, LBNE

How large is this?

NOνA, T2K, LBNE

~~CP?~~

Solar+KAMLAND

$\sim\Delta m^2_{12} \sim 7.59\text{X}10^{-5}$ eV^2

Atmospheric + K2K +MINOS

$\sim\Delta m^2_{13} \sim 2.4\text{X}10^{-3}$ eV^2

Which One?

NOνA + T2K, LBNE

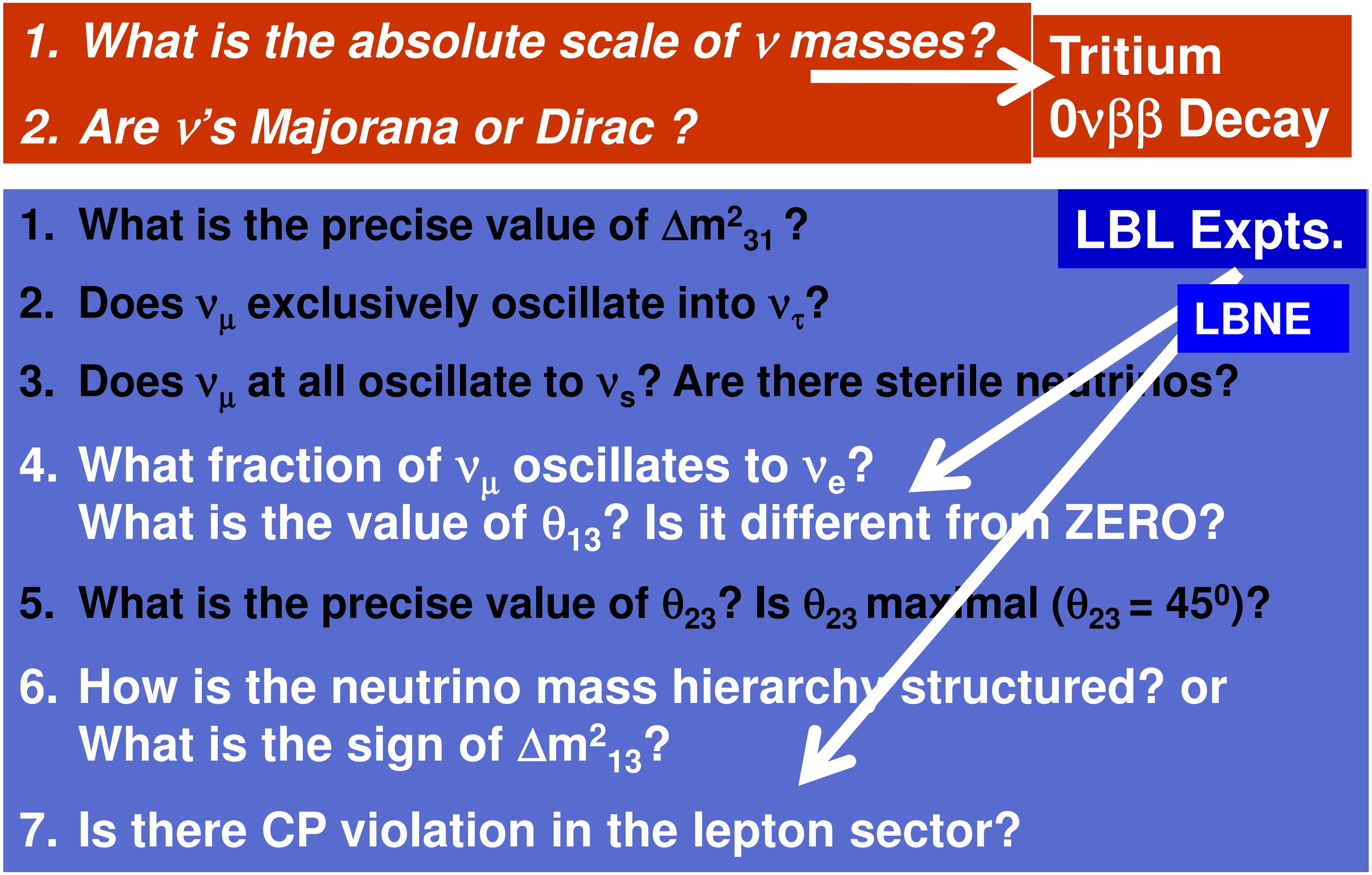
0νββ or Tritium

?

Majorana or Dirac ?

0νββ

NEUTRINO OSCILLATIONS – OPEN QUESTIONS



1. *What is the absolute scale of ν masses?*
2. *Are ν's Majorana or Dirac ?*

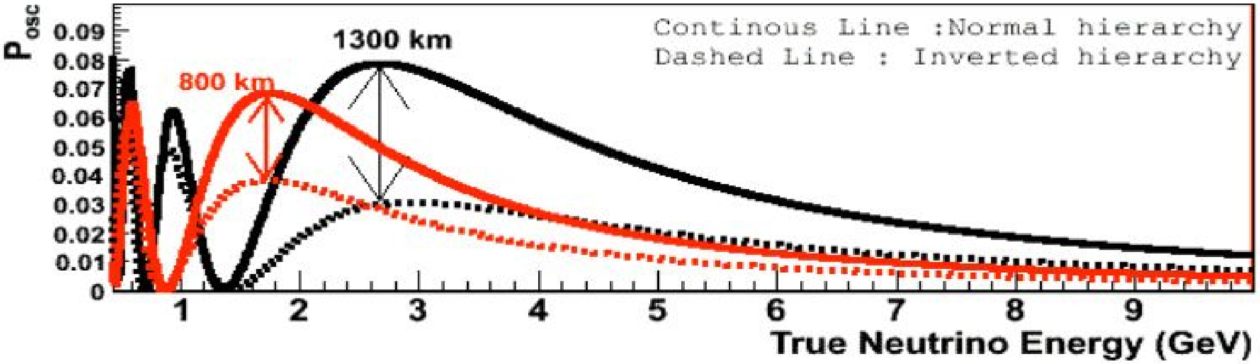
Tritium
$0\nu\beta\beta$ Decay

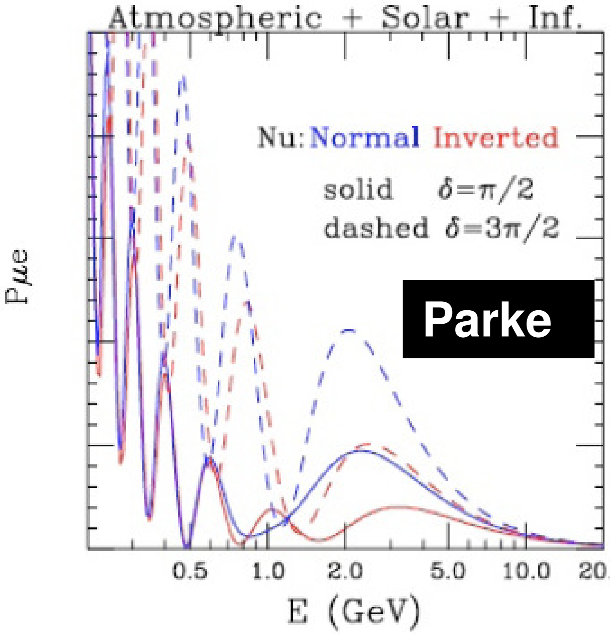
LBL Expts.

LBNE

1. **What is the precise value of Δm^2_{31} ?**
2. **Does ν_μ exclusively oscillate into ν_τ?**
3. **Does ν_μ at all oscillate to ν_s? Are there sterile neutrinos?**
4. **What fraction of ν_μ oscillates to ν_e?**
   What is the value of θ_{13}? Is it different from ZERO?
5. **What is the precise value of θ_{23}? Is θ_{23} maximal ($\theta_{23} = 45^0$)?**
6. **How is the neutrino mass hierarchy structured? or**
   What is the sign of Δm^2_{13}?
7. **Is there CP violation in the lepton sector?**

LONG BASELINE WINS THE GAME

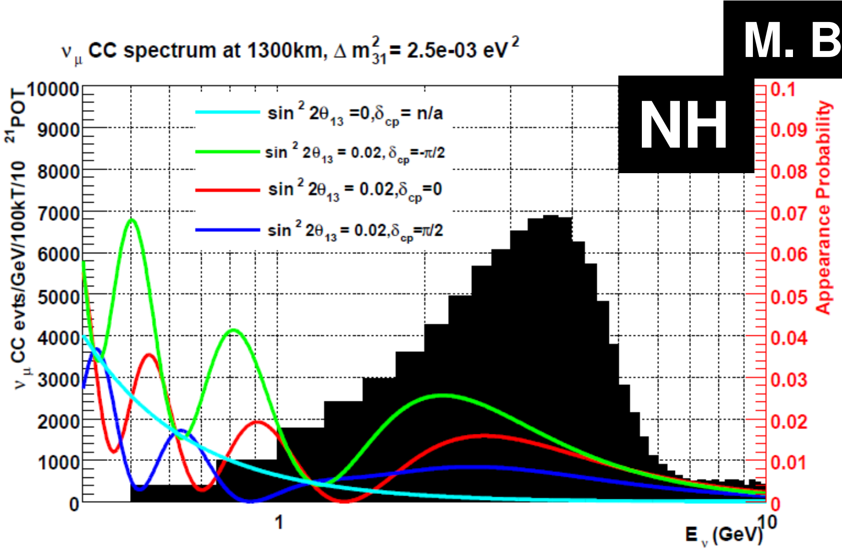


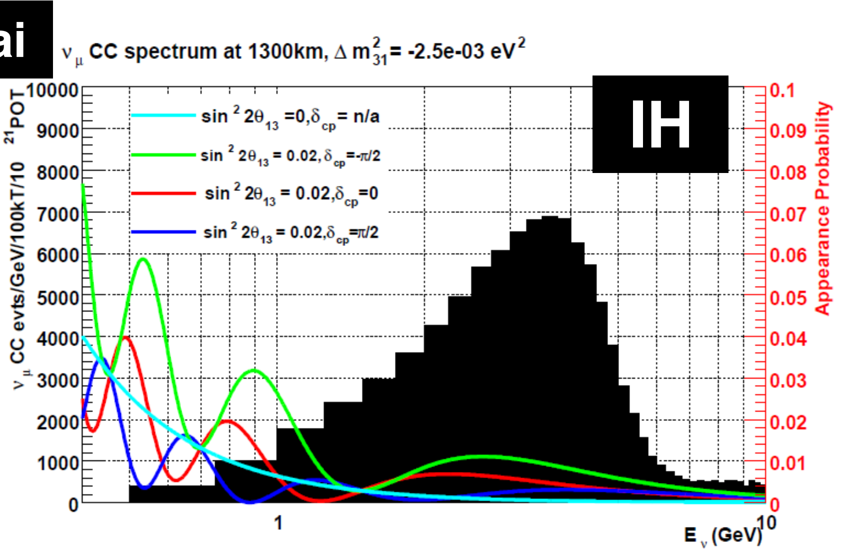


1. **Fermilab – Homestake (South Dakota) = 1290 Km**
2. **Wide Band Low Energy Beam – Information from 1st and 2nd maxima at achievable neutrino energy**
3. **Larger separation between normal and inverted hierarchy**
4. **All neutrino parameters measured in the same detector complex**

LBNE BEAM DESIGN

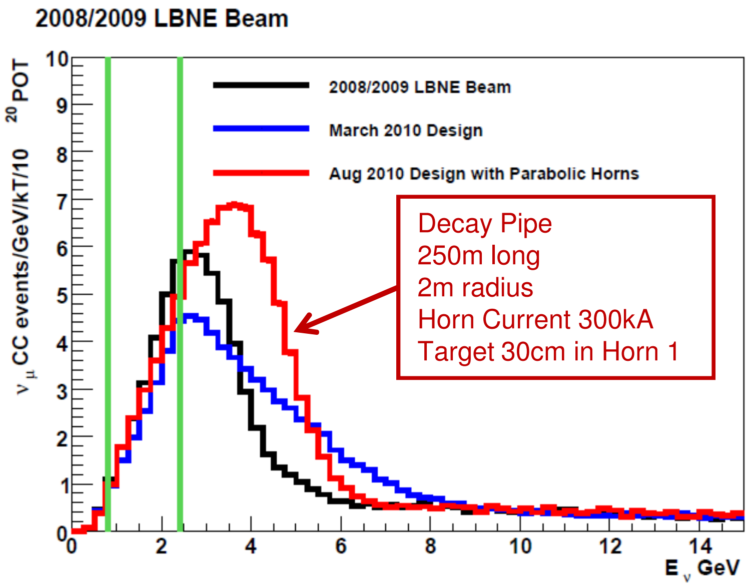
M. Bishai





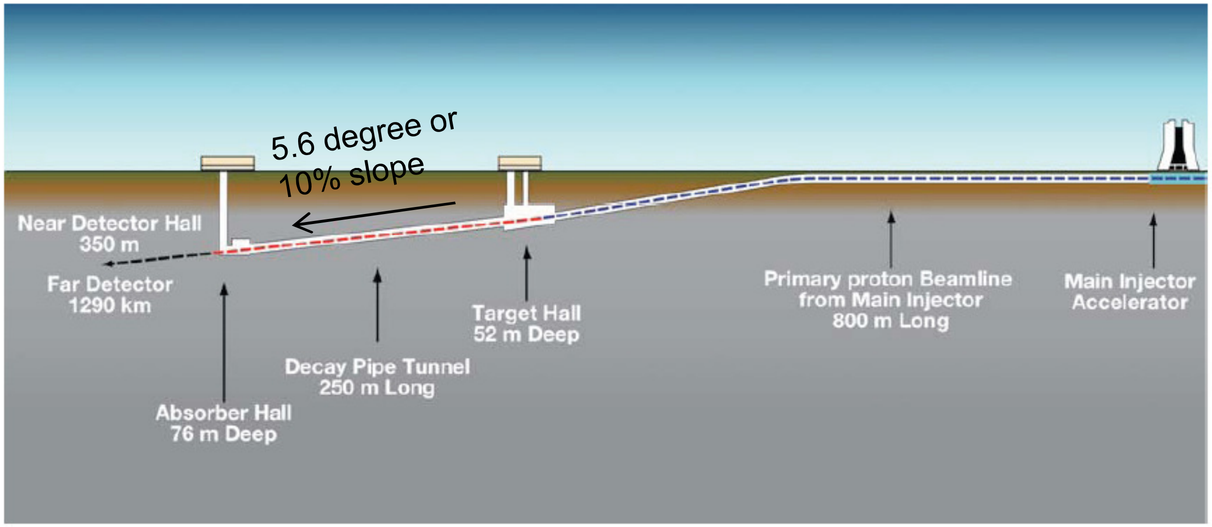
Requirements:

1. Wide band beam from 0.5GeV to few GeV to cover 1st (2.4GeV) and 2nd (0.8GeV) oscillation maxima
2. Minimize flux above 5GeV to reduce NC background from feed down
3. Minimize beam ν_e by design
4. Target, shielding & material need to handle 700 kW
5. Civil construction and some technical component to be rated for 2.3MW



Decay Pipe
250m long
2m radius
Horn Current 300kA
Target 30cm in Horn 1

LBNE BEAM DESIGN

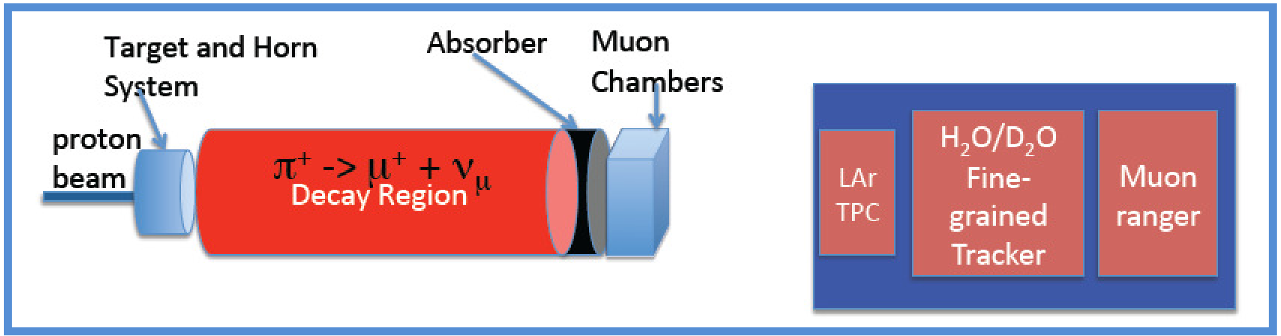


Parameter	Value
Protons per cycle	4.9×10^{13}
Cycle time (120 GeV)	1.33 sec
Duration (10μs)	1.0×10^{-5} sec
Energy	60 to 120 GeV
Power at 120 GeV	708 kW
Operational Efficiency*	63%
Protons at target per year	7.3×10^{20}
Beam size at Focus *x,y*	1.5 mm
Beam Divergence *x,y*	0.017 mrad

Element	Parameter	Range	Reference design value
Target	material	graphite, Be	graphite
	diameter	0.5 to 1.6 cm	1.53 cm
	length	~2 interaction lengths	96.6cm
Focusing Horn 1	length	250 to 350 cm	300 cm
	current	180 to 300 kA	300 kA
Focusing Horn 2	length	300 to 400 cm	353 cm
	current	180 to 300 kA	300 kA
	distance from start of Horn 1	600 to 800 cm	660 cm
Decay Pipe	length	200 to 350 m	250 m
	radius	1.5 to 2 m	2 m
	atmosphere	Air, He, Vacuum	air STP
Near Detector Cavern	distance from target	Maximum, fits within site bdyboundary	700 m

LBNE DETECTORS – NEAR DETECTORS

1. Near Detectors (ND) will be on the Fermilab site.
2. The ND enclosure will be ~420m downstream of the absorber hall
3. The enclosure will be ~110m below the earth's surface.
4. A complex of small detectors with different technologies and capabilities offers the best opportunity to fully characterize the beam to the precision needed for normalization of the far detector observations.
5. The options for ND complex include (from Sanjib Mishra):
   - ✓ Reference Design - A 70T LAr, MicroBooNE-like (B = 0) detector, followed by HiResMν (with H_2O target) + Muon Chambers (MINOS like)
   - ✓ Option 2 - A 20T Magnetized LAr detector followed by MINERνA like detector (with H_2O target) + Muon Chambers (MINOS like)

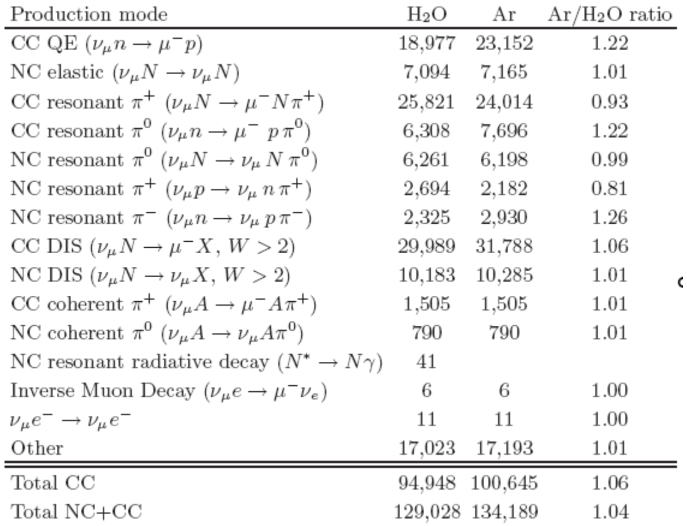


Design of LBNE ND – talk by Sanjib Mishra - 22.10.2010 WG1/WG2 Joint Session – 11:30AM

LBNE NEAR DETECTOR REQUIREMENTS

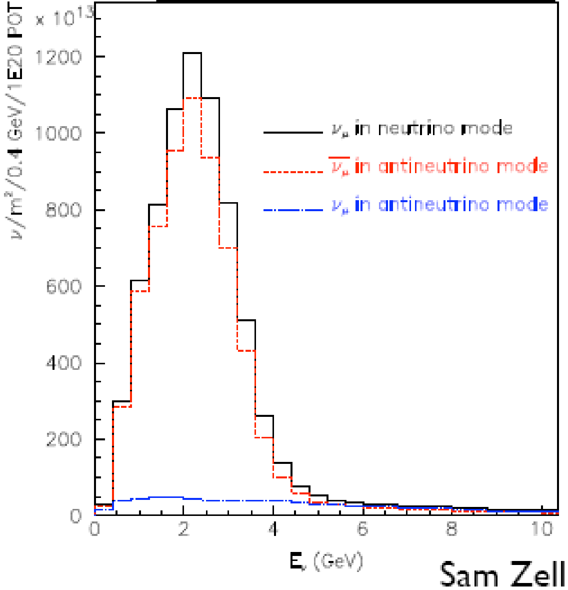
- ✓ Define the measurement required at the near site to meet the goals of LBL neutrino analyses
- ✓ How well we must measure the predicted neutrino fluxes?
  - ✓ *Intrinsic ν_e contamination in the beam*
- ✓ How well we must predict signal and background rates and topologies
  - ✓ *What measurement must be made to accomplish these predictions?*
  - ✓ *Charged current background and signal – extracting the neutrino flux at far site – un-oscillated ν_μ spectrum*
  - ✓ *Neutral current background - ν_μ NC π^0 and NC γ*
- ✓ Both for ν and $\bar{\nu}$ beam
- ✓ Same nuclear target as far detector

Events per ton per 10^{20} POT



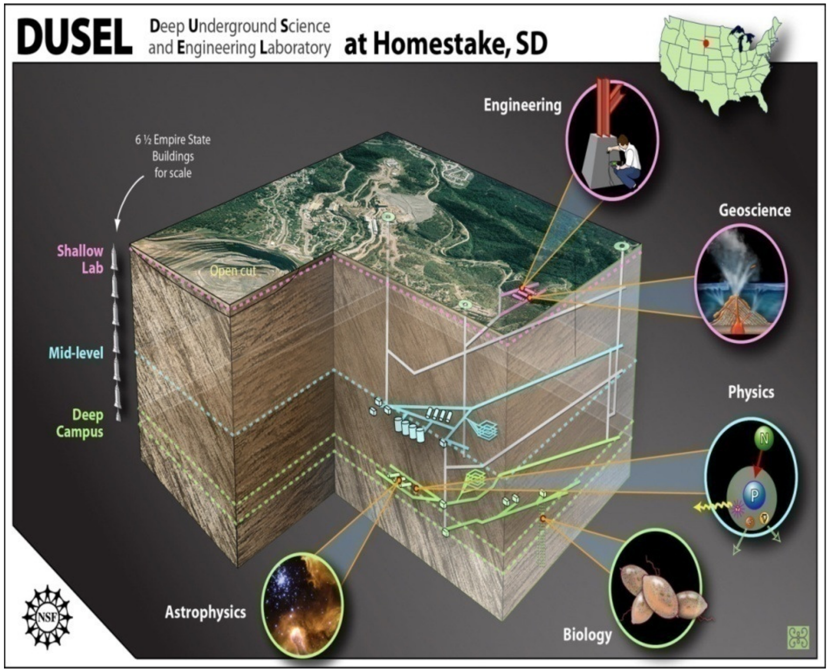
Production mode	H_2O	Ar	Ar/H_2O ratio
CC QE ($\nu_\mu n \rightarrow \mu^- p$)	18,977	23,152	1.22
NC elastic ($\nu_\mu N \rightarrow \nu_\mu N$)	7,094	7,165	1.01
CC resonant π^+ ($\nu_\mu N \rightarrow \mu^- N \pi^+$)	25,821	24,014	0.93
CC resonant π^0 ($\nu_\mu n \rightarrow \mu^- \, p \, \pi^0$)	6,308	7,696	1.22
NC resonant π^0 ($\nu_\mu N \rightarrow \nu_\mu \, N \, \pi^0$)	6,261	6,198	0.99
NC resonant π^+ ($\nu_\mu p \rightarrow \nu_\mu \, n \, \pi^+$)	2,694	2,182	0.81
NC resonant π^- ($\nu_\mu n \rightarrow \nu_\mu \, p \, \pi^-$)	2,325	2,930	1.26
CC DIS ($\nu_\mu N \rightarrow \mu^- X$, $W > 2$)	29,989	31,788	1.06
NC DIS ($\nu_\mu N \rightarrow \nu_\mu X$, $W > 2$)	10,183	10,285	1.01
CC coherent π^+ ($\nu_\mu A \rightarrow \mu^- A \pi^+$)	1,505	1,505	1.01
NC coherent π^0 ($\nu_\mu A \rightarrow \nu_\mu A \pi^0$)	790	790	1.01
NC resonant radiative decay ($N^* \rightarrow N\gamma$)	41		
Inverse Muon Decay ($\nu_\mu e \rightarrow \mu^- \nu_e$)	6	6	1.00
$\nu_\mu e^- \rightarrow \nu_\mu e^-$	11	11	1.00
Other	17,023	17,193	1.01
Total CC	94,948	100,645	1.06
Total NC+CC	129,028	134,189	1.04

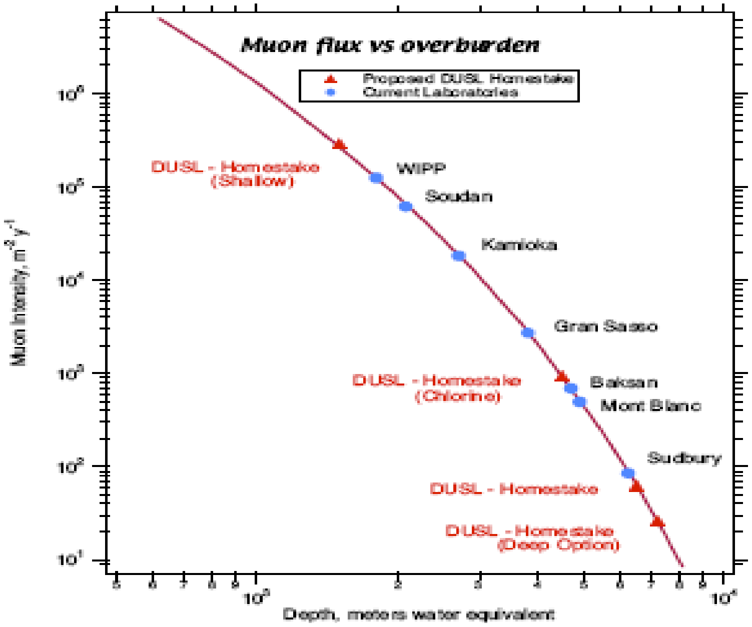
Flux of neutrinos at ND
91% ν_μ, 8% $\bar{\nu}\mu$, <1% ν_e

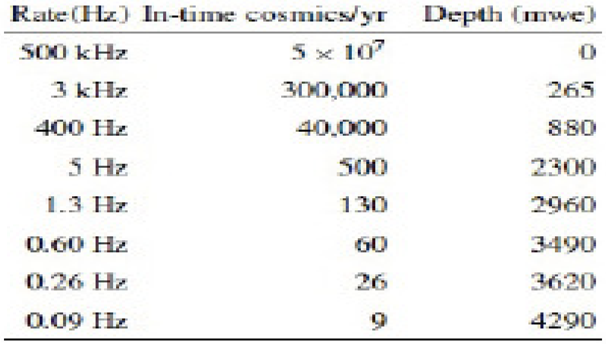


Sam Zelle

LBNE FAR DETECTOR - DEEP UNDERGROUND HELPS







Rate(Hz)	In-time cosmics/yr	Depth (mwe)
500 kHz	5×10^7	0
3 kHz	300,000	265
400 Hz	40,000	880
5 Hz	500	2300
1.3 Hz	130	2960
0.60 Hz	60	3490
0.26 Hz	26	3620
0.09 Hz	9	4290

- Cosmic ray rate at 4850ft ~0.1Hz –
- Helps in Proton Decay, relic neutrinos

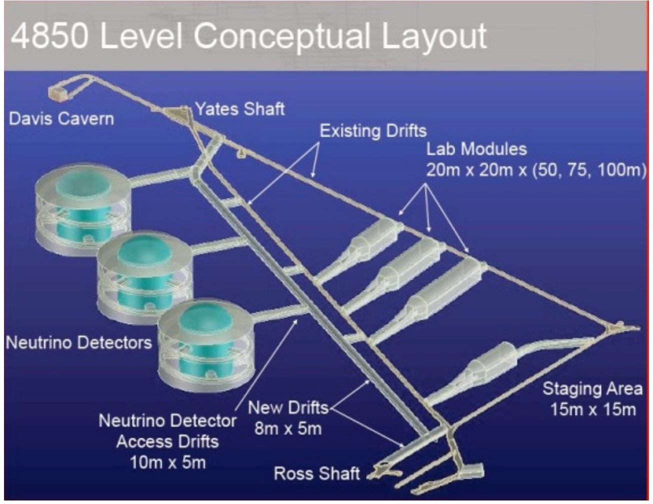
LBNE DETECTORS – WATER CHERENKOV

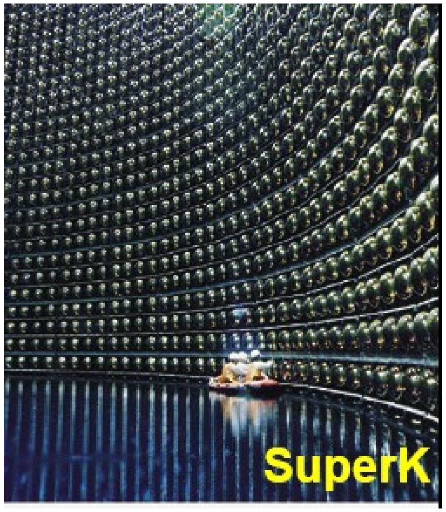
Advantages:

- Tried and tested technology and proven Physics reach – SK/T2K – 50K Detector
- Low cost sensitive medium – photosensor “off the shelf”
- Good tracking especially at 1 GeV or less
- Good PID at low energy
- Energy resolution for e and μ ~3% (SK)
- Excellent sensitivity to $p \rightarrow \pi^0 e^+$
- Situated at 4850ft
- Cosmic ray rate at 4850ft ~ 0.1 Hz
- Low ν_e signal efficiency (~15-20%)
- Low efficiency for $p \rightarrow K^+ \nu$bar
- Could aim to go to 300kTon
- Could be supplemented with Gadolinium for low energy ν physics

Challenges:

- ✓ Large number of phototubes needed (~100K for 40% coverage – each module). Reduction by a factor of 2 works well for higher energy applications (LBL and Proton Decay). Optimization needed for low energy ν physics.
- ✓ Very large underground cavities needed.



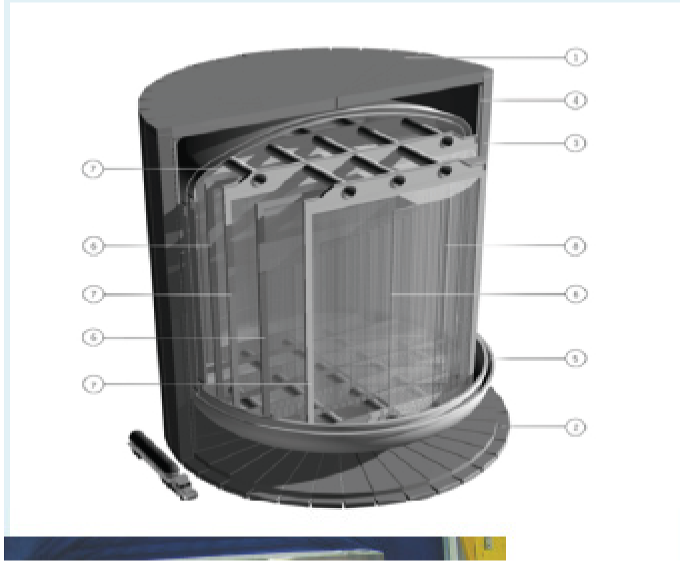


For more on performance and challenges of a large WC Detector – talk by Lisa Whitehead - 22.10.2010 WG1/WG2 Joint Session – 12:36PM

LBNE DETECTORS – LIQUID ARGON

Advantages:

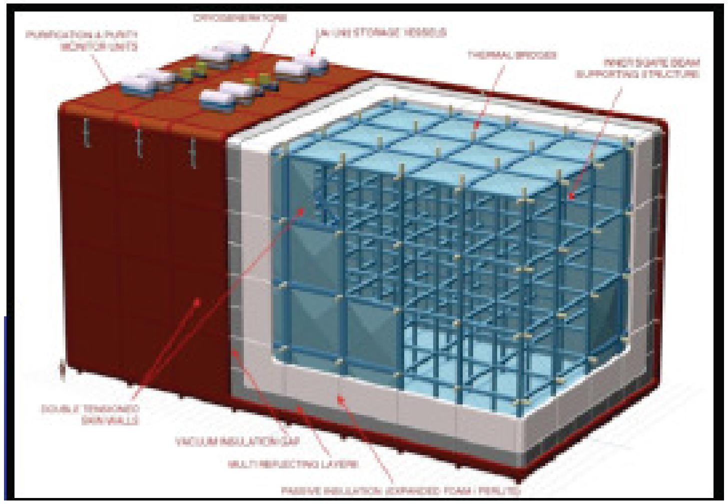
- Bubble chamber like imaging; detailed event topology with few mm position resolution
- Very good energy resolution and track reconstruction for every particle, even at higher energies
- Very high efficiency and almost background free for many processes
- PID with dE/dx, separation of tracks possible
- Very good sensitivity for p → $K^+\bar{\nu}$
- Possibly situated at 300 ft or 800 ft



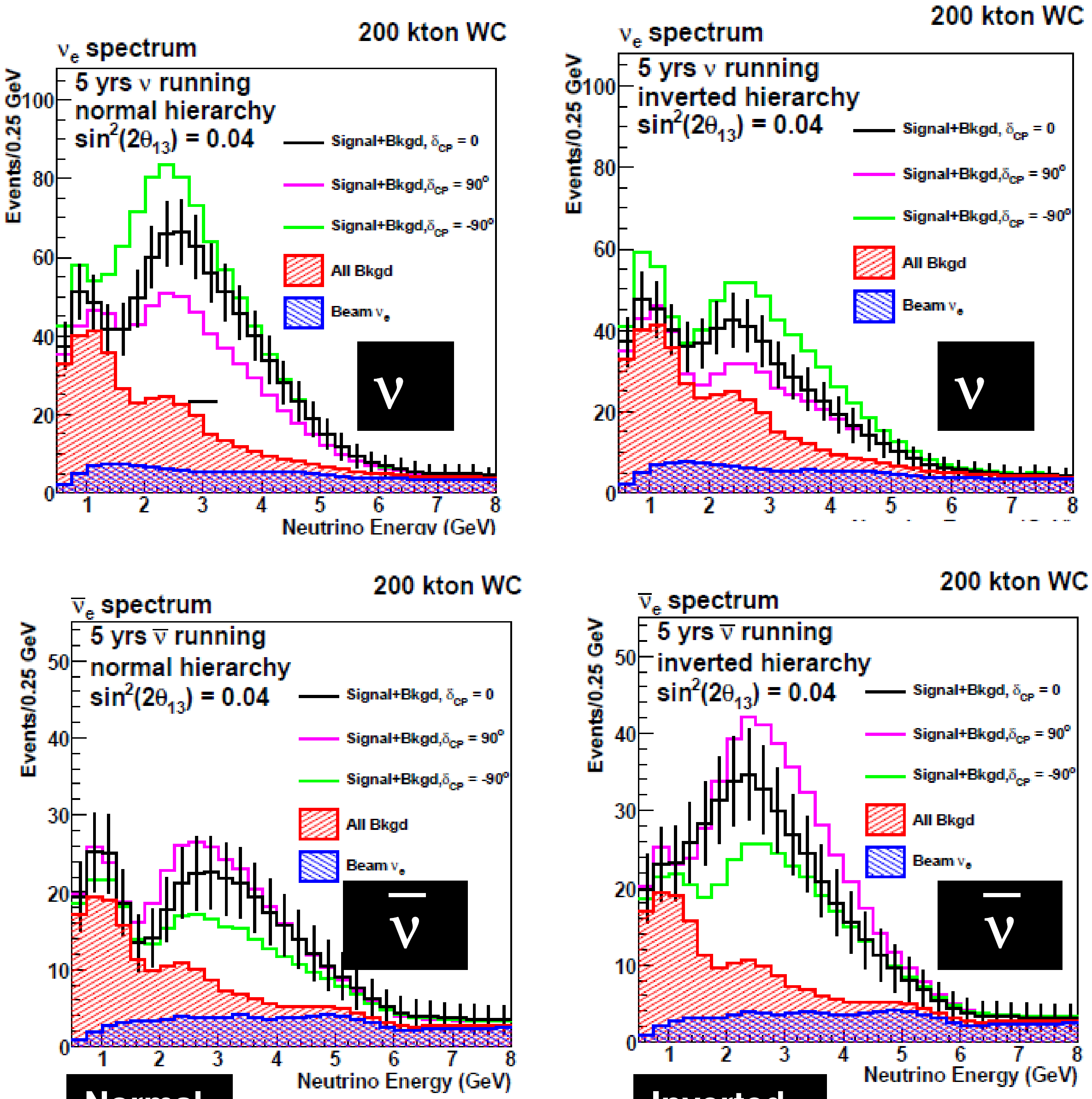
Challenges:

- ✓ Complicated detector technology
- ✓ Huge number of channels (depending on position resolution)

- ✓ Technology not yet proven for 50KTon
- ✓ Safety issues and technical risk for underground environment
- ✓ Uncertain cost



$\nu_\mu \rightarrow \nu_e$ APPEARANCE SPECTRA – WC DETECTOR



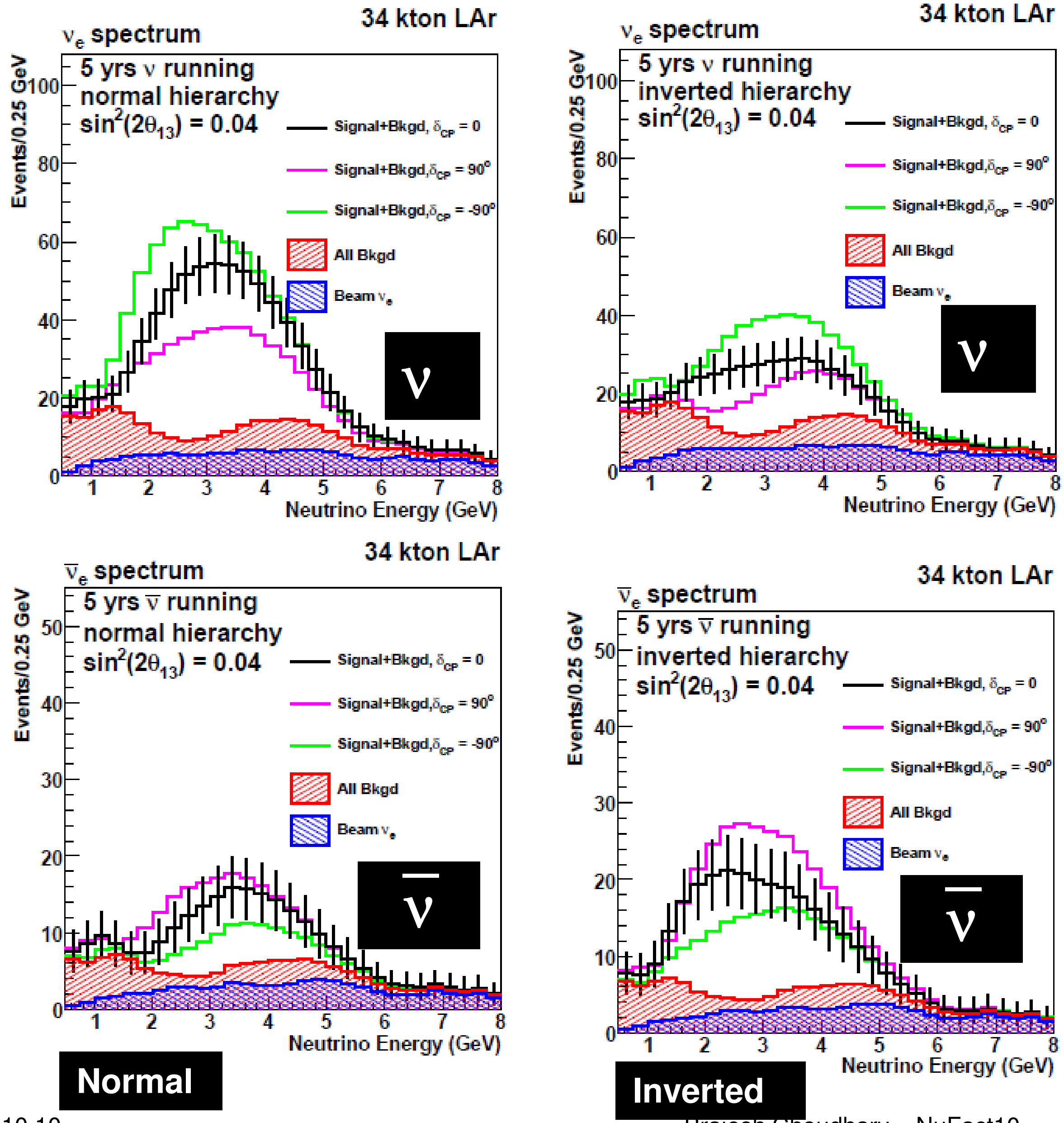
Normal

Inverted

- ✓ 120 GeV protons on target
- ✓ 700 kW power
- ✓ 200 kTon WC detecor
- ✓ 5 yr ν exposure
  +
  5yr $\bar{\nu}$ exposure
- ✓ 2×10^7 sec/yr
- ✓ δ_{CP} = 0, +90 & -90
- ✓ Background all beam

From L. Whitehead

$\nu_\mu \to \nu_e$ APPEARANCE SPECTRA – LAr DETECTOR



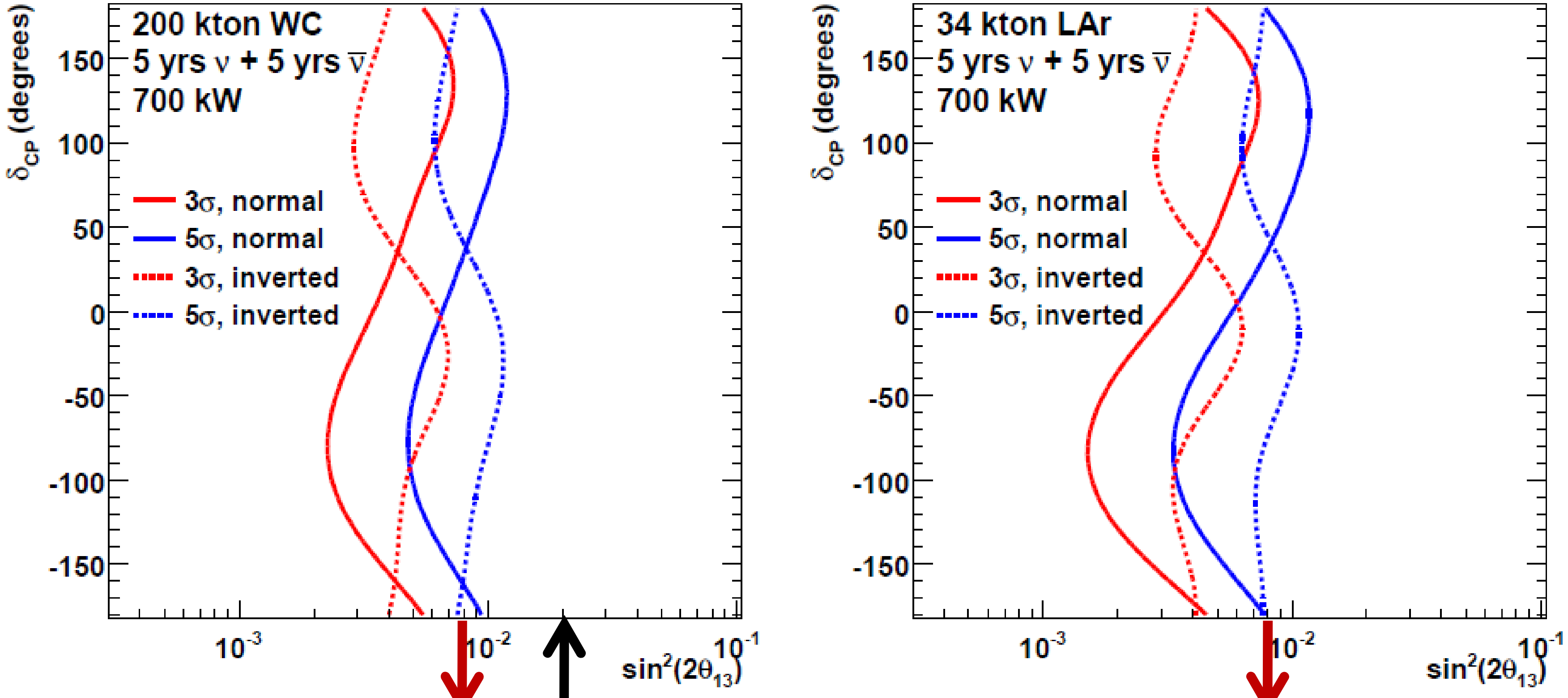
- ✓ 120 GeV protons on target
- ✓ 700 kW power
- ✓ 34 kTon LAr detecor
- ✓ 5 yr ν exposure

  \+

  5yr $\bar{\nu}$ exposure
- ✓ $2\text{x}10^7$ sec/yr
- ✓ δ_{CP} = 0, +90 & -90
- ✓ Backgropund all beam

From L. Whitehead

θ_{13} SENSITIVITY



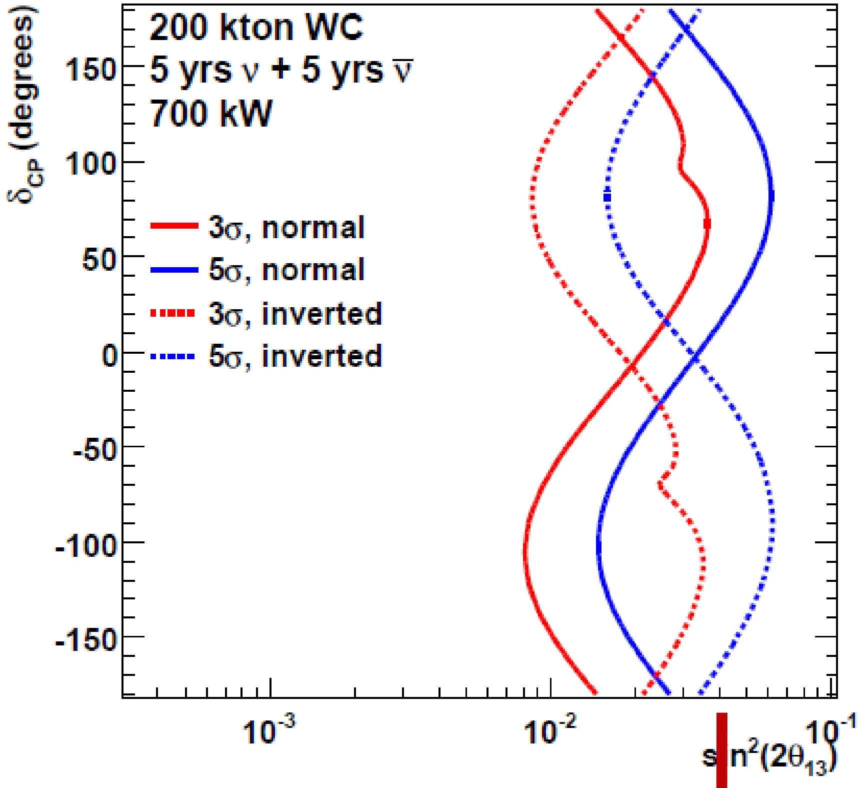
0.008

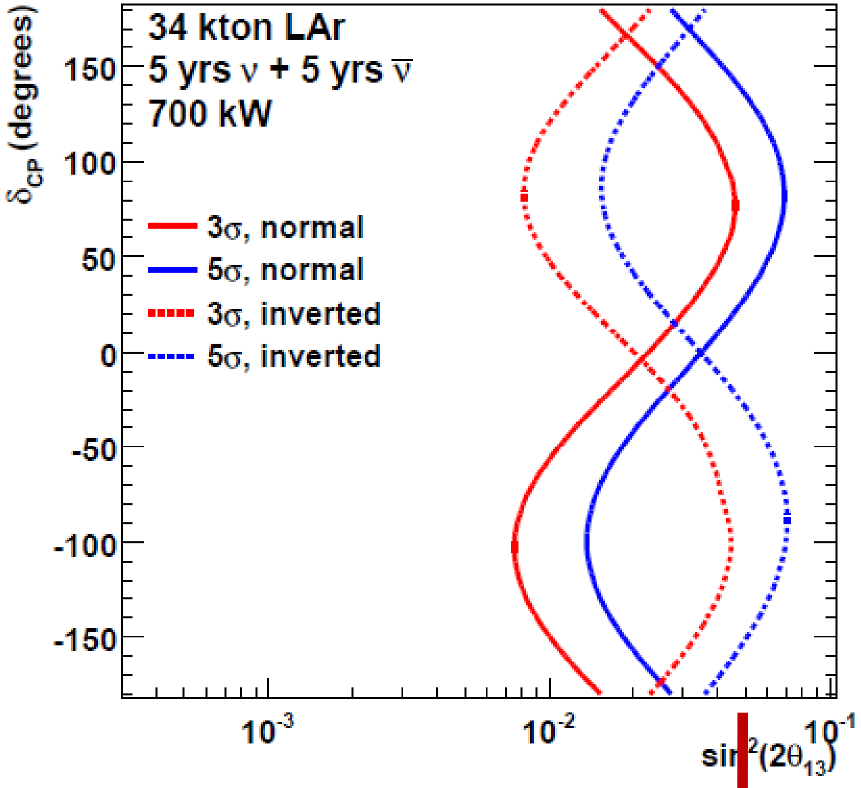
0.008

3σ all δCP

- ✓Double CHOOZ , Daya Bay, Reno
- ✓NOνA or T2K (50% δ_{CP})

MASS HIERARCHY



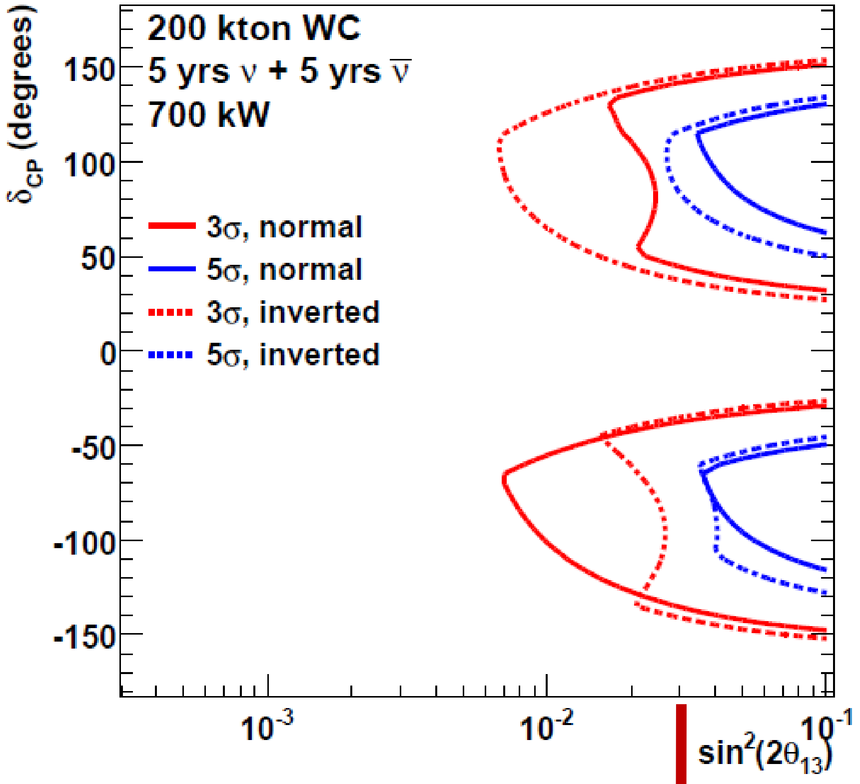


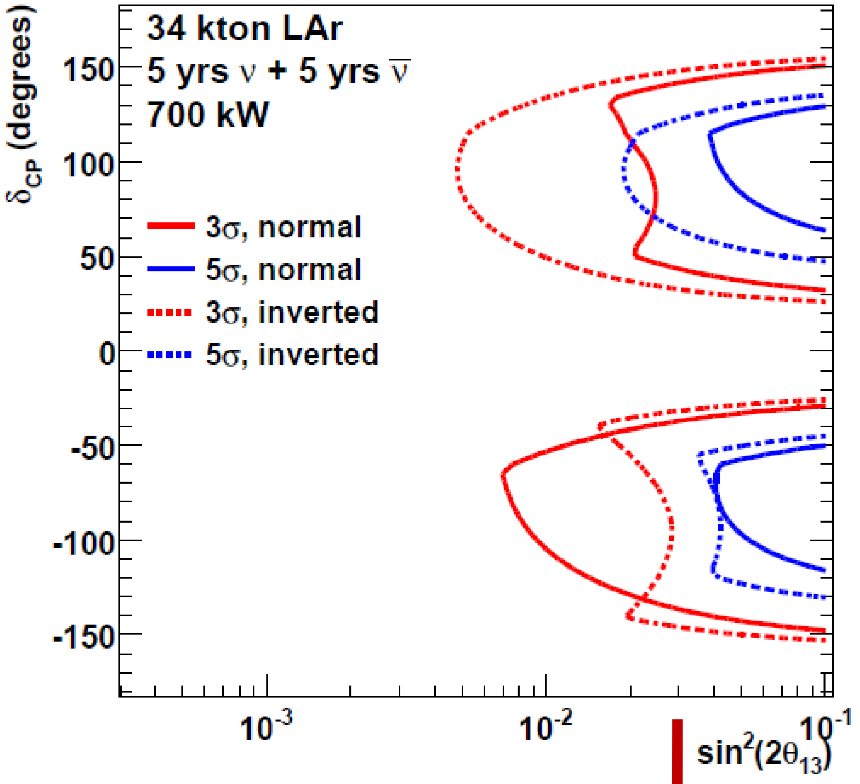
3σ all δCP

0.04

0.05

CP VIOLATION



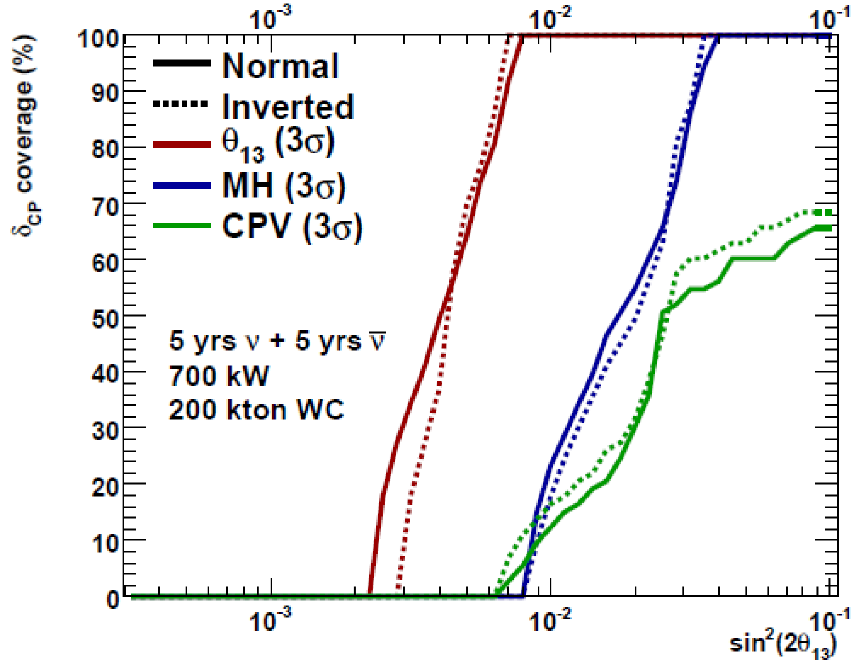


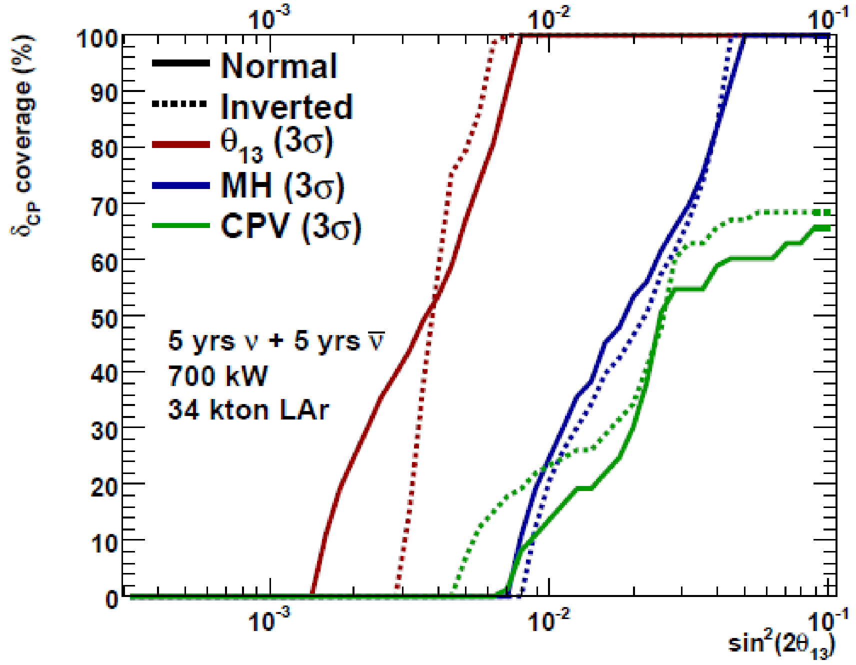
3σ 50% δCP

0.03

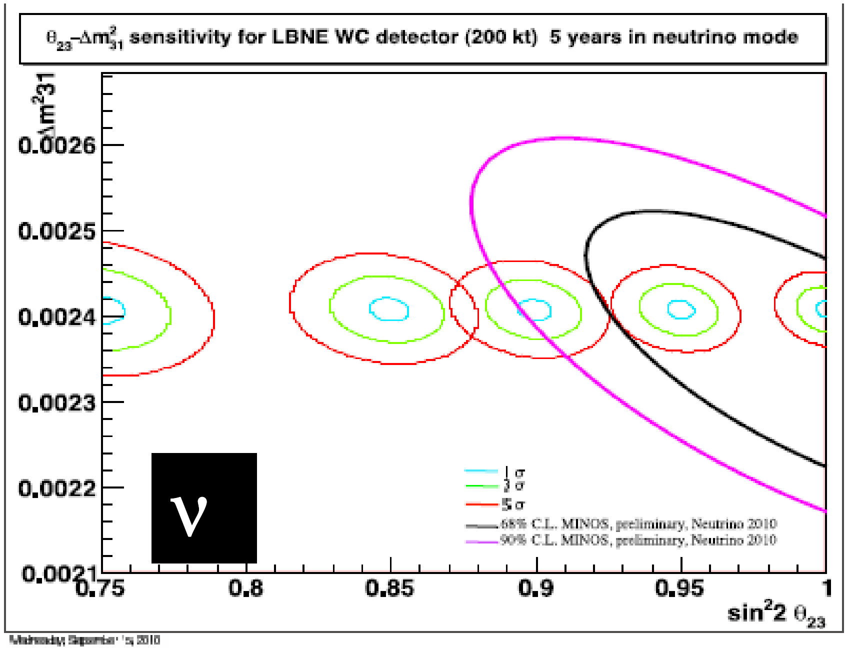
0.03

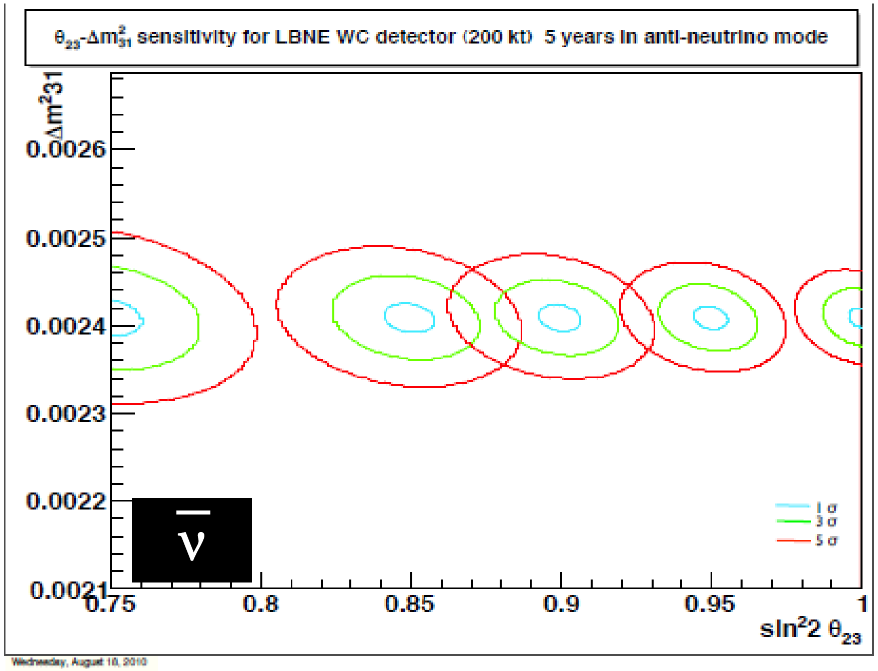
3σ REACH IN θ_{13}, CPV & HIERARCHY





SIMULTANEOUS MEASUREMENT OF Δm^2_{23} & $\mathrm{Sin}^2 2\theta_{23}$





- ✓ 120 GeV protons on target
- ✓ 700 kW power
- ✓ 200 kTon WC
- ✓ 5 yr ν exposure
- ✓ 2×10^7 sec/yr

- ✓ 34 kTon LAr Detector has almost similar sensitivity

<1% measurement of Δm^2_{31} & $\mathrm{Sin}^2 2\theta_{23}$ possible (at 1σ) with either a 200kTon WC or 34 kTon LAr detector. With anti-ν similar measurement possible at similar exposure.

R. Guenette

PROTON DECAY

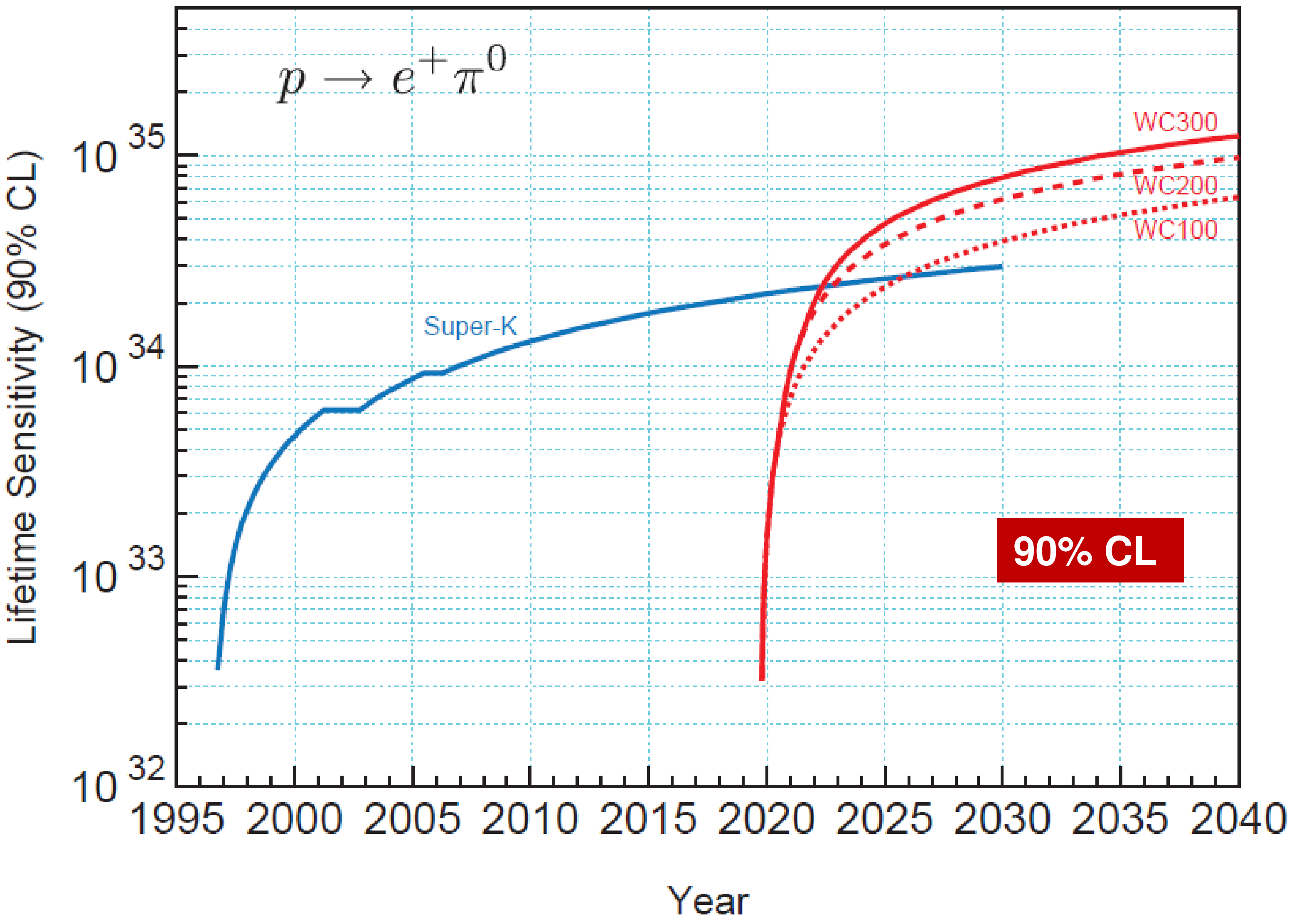
- ✓ Tests the fundamental law of Baryon conservation
- ✓ Is predicted by wide range of GUTs
- ✓ GUT are often able to accommodate massive neutrinos – as discovered in last decade.
- ✓ The unification scale is suggested experimentally and theoretically – by the apparent convergence of the running coupling constant of the SM in excess of 10^{15} GeV.
- ✓ The Unification scale is not accessible by any accelerator experiment and thus need to be probed by virtual processes such as proton decay.
- ✓ The dominant proton decay mode to identify the likely GUT scenario – gauge mediated or due to SUSY.
- ✓ Baryon number non-conservation has also cosmological consequences, such as inflation and baryon asymmetry of the Universe.

Two decay modes are favored:

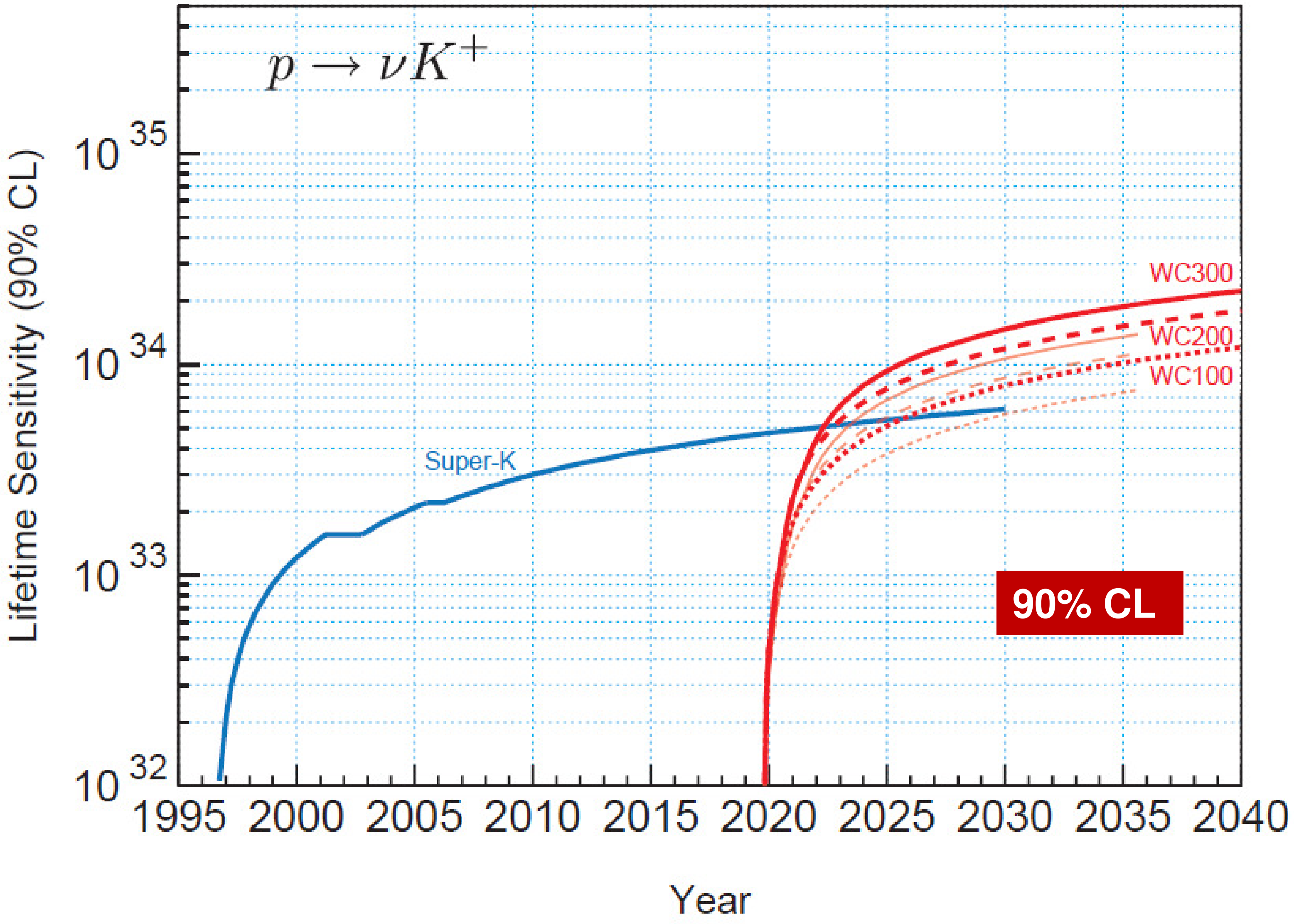
$p \rightarrow \pi^0 + e^+$ (gauge mediated – favored for WC detector)

$p \rightarrow K^+ + \bar{\nu}$ (SUSY mediated – better for LAr detector)

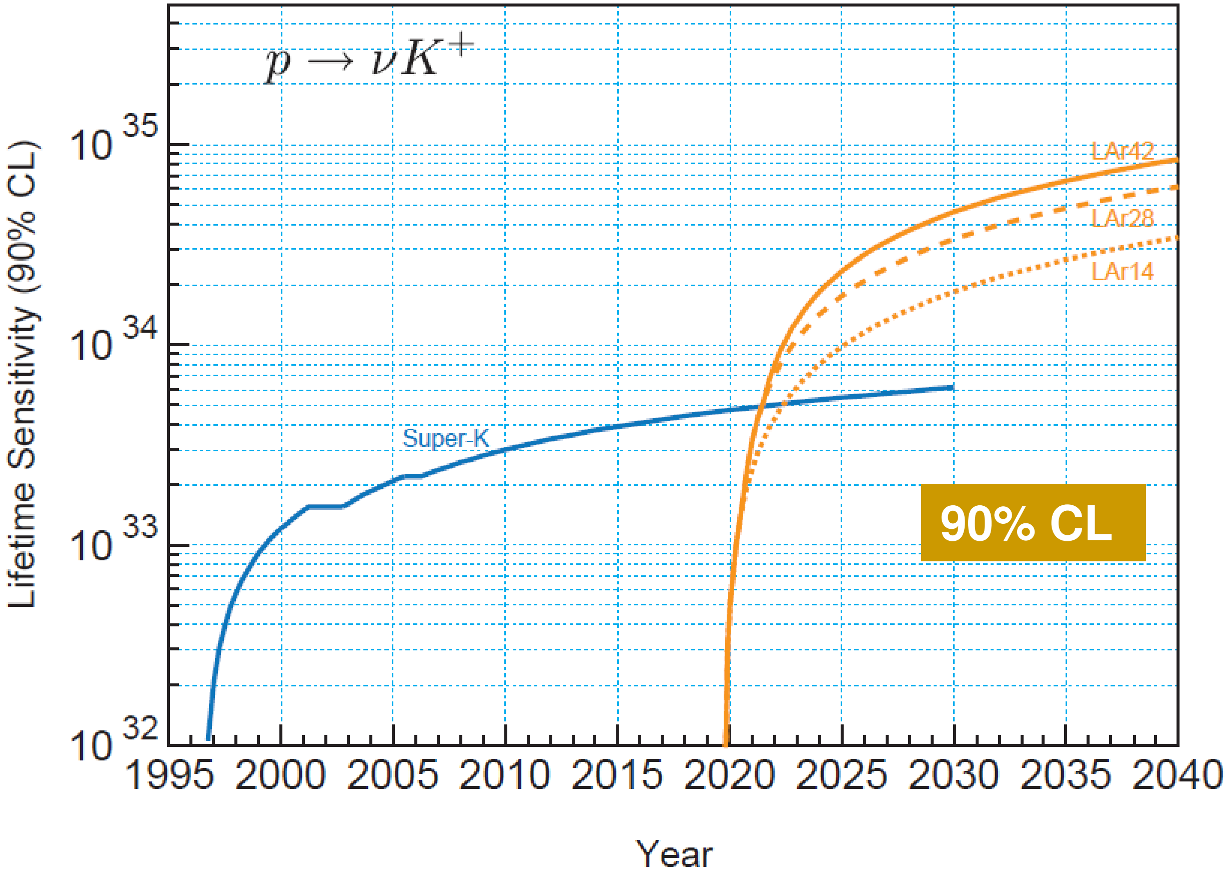
PROTON DECAY WITH LBNE



PROTON DECAY WITH LBNE



PROTON DECAY WITH LBNE



1. **Super-K with 20+ years of data before LBNE turns-on**
2. **Liquid Argon detector significantly better for Kaon mode because 340 MeV/c K^+ will be below Cherenkov threshold in WC and hence invisible. However in LAr a K^+ will be directly observable by dE/dx and subsequent decay of $K^+ \rightarrow \mu^+\nu_\mu$**

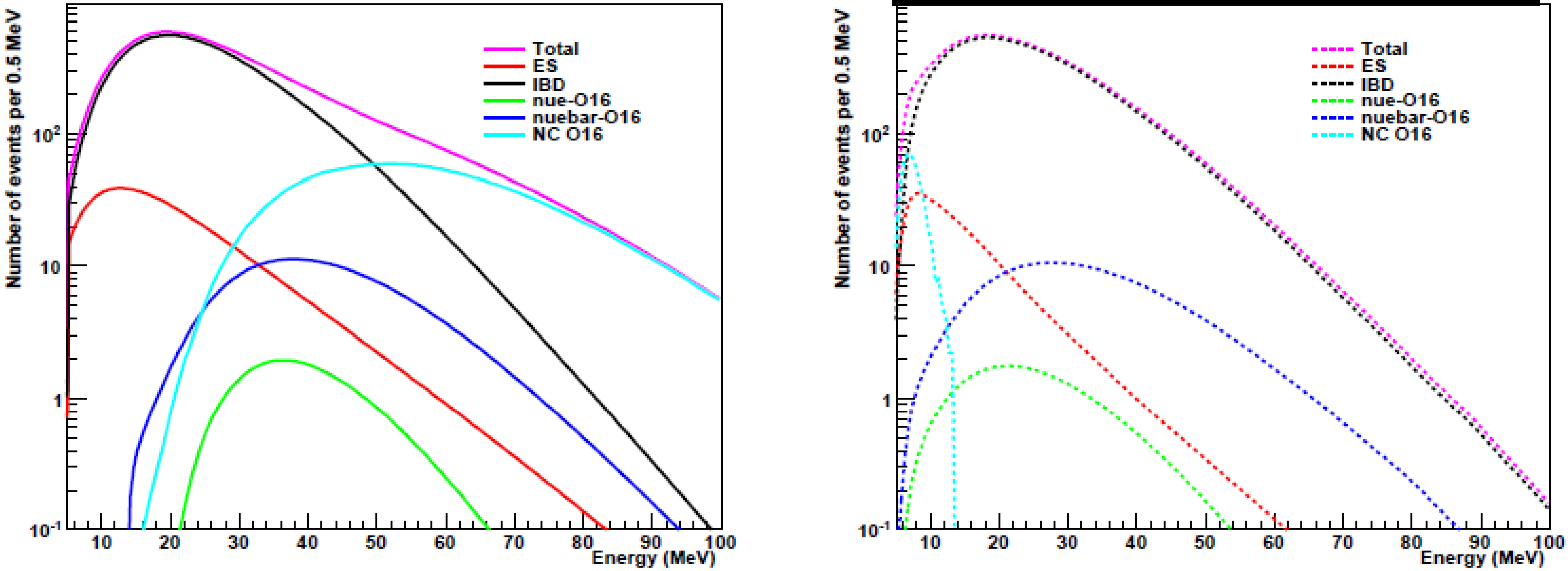
SUPERNOVA BURST

- When a star's core collapses, ~99% of the gravitational binding energy of the proto-neutron star goes into ν's of all flavors with ~MeV energy
- Timescale for neutrino escape ~ few 10's of seconds
- Core-collapse expected - 2-3 per century in the Milky way.
- Number of event expected – several thousands to 10's of thousands depending on the distance of the Supernova burst
- Very precise knowledge of cross-section for IBD – $\nu_e + p \to e^+ + n$ for WC
- With Gadolinium – double coincidence – almost zero background
- Positron spectrum mirrors neutrino spectrum
- A 40% probability to observe core collapse in a 20 year run

Channel	Events, "Livermore" model
$\bar{\nu}_e + p \to e^+ + n$	27116
$\nu_x + e^- \to \nu_x + e^-$	868
$\nu_e +^{16}\text{O} \to e^- +^{16}\text{F}$	88
$\bar{\nu}_e +^{16}\text{O} \to e^+ +^{16}\text{N}$	700
$\nu_x +^{16}\text{O} \to \nu_x +^{16}\text{O}^*$	513
Total	29284

100kT WC Detector + 30% PMT Coverage

SUPERNOVA BURST


Interaction rate vs. Neutrino Energy

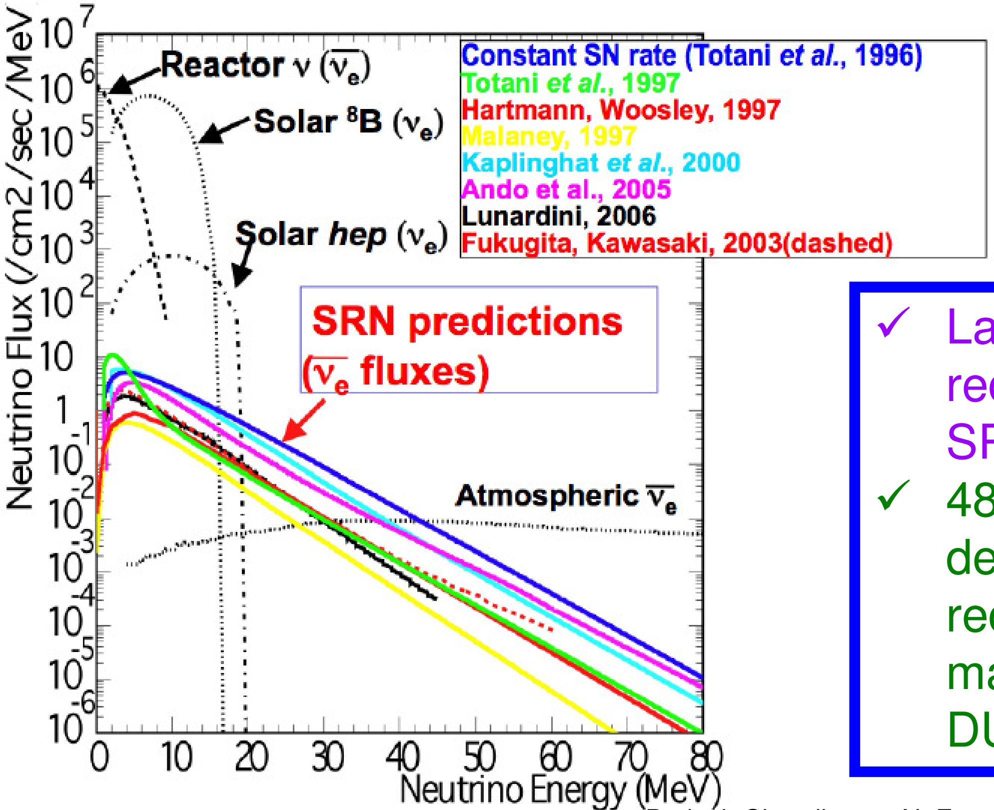
Distribution of observed event energy in the detector

Event rate in Water, for Livermore model and 30% coverage

1. Measure time integrated spectra of neutrinos
2. Measure evolution of the Supernova burst with neutrino spectra
3. Try to understand the stages of Supernova burst through distinct neutrino signals
4. Measure θ_{13} beyond the reach of laboratory experiments
5. Measure neutrino hierarchy, etc.

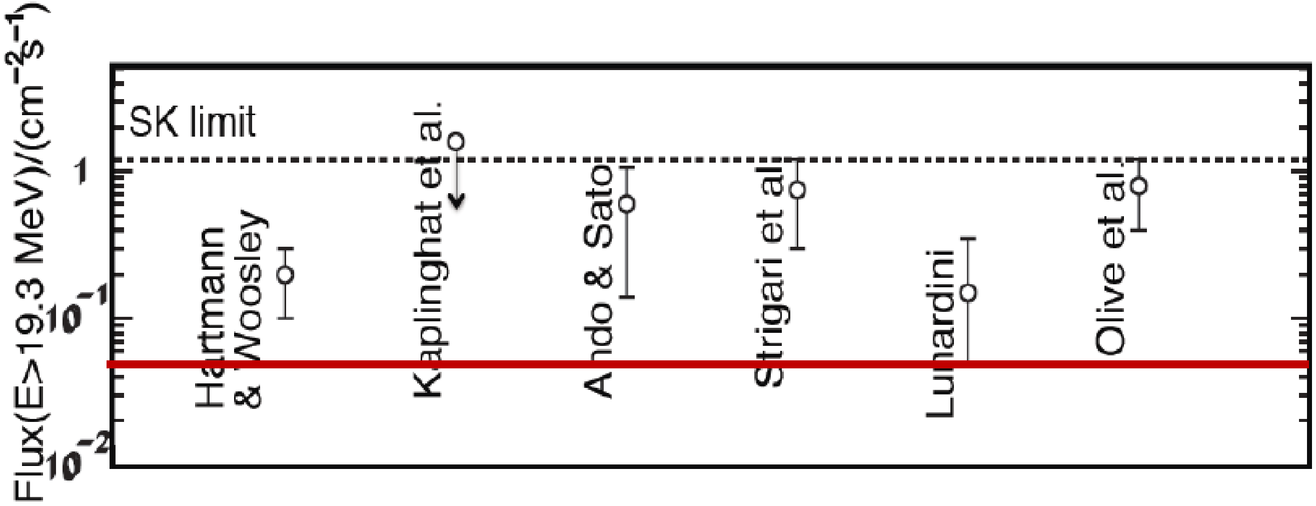
SUPERNOVA RELIC NEUTRINOS

- ✓ Supernova relic neutrinos or the diffuse supernova neutrinos (SRN) has not been discovered so far.
- ✓ They carry unique information about one of the most dramatic processes in the stellar life-cycle, the process responsible for the production and dispersal of all the heavy elements in the universe.
- ✓ Although galactic supernovas are rare – supernovas are not rare themselves



- ✓ Large target mass and background reduction necessary for observing SRN
- ✓ 4850 ft depth at DUSEL, large detector mass (200-300kT) and reduced comic background will make SRN detection possible at DUSEL

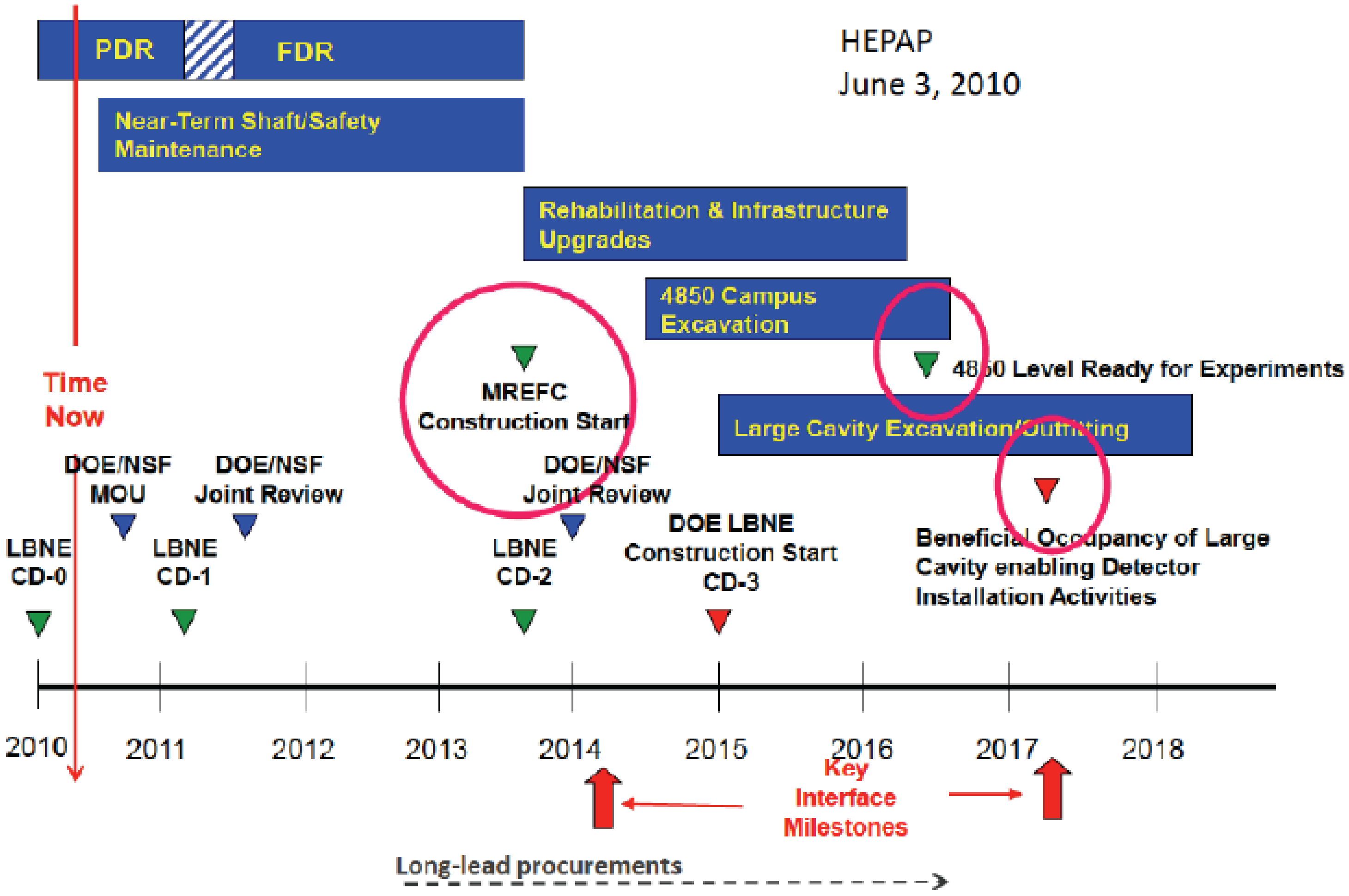
SUPERNOVA RELIC NEUTRINOS



DUSEL – 300kT Gd loaded at 4850ft

Compared to Super-K, at DUSEL cosmic muon rate is an order of magnitude lower. Super-K threshold 19.3 MeV. DUSEL can expect to go to 15.5 MeV. Will enhance signal by 40%. Addition of Gd to help further in sensitivity. Good chances of observing SRNs.

LBNE TIME LINE



HEPAP
June 3, 2010

PDR
FDR

Near-Term Shaft/Safety Maintenance

Rehabilitation & Infrastructure Upgrades

4850 Campus Excavation

4850 Level Ready for Experiments

Large Cavity Excavation/Outfitting

Time Now

MREFC Construction Start

DOE/NSF MOU

DOE/NSF Joint Review

DOE/NSF Joint Review

LBNE CD-0

LBNE CD-1

LBNE CD-2

DOE LBNE Construction Start CD-3

Beneficial Occupancy of Large Cavity enabling Detector Installation Activities

Key Interface Milestones

Long-lead procurements

SUMMARY AND CONCLUSIONS

1. LBNE is the most ambitious long-baseline neutrino project in planning and execution stage.
2. Will have the best reach in determining values of θ_{13}, CPV and mass hierarchy in the neutrino sector.
3. Both WC and LAr detectors - well suited for proton decay – to an order of magnitude beyond the current limit.
4. Well suited for detecting Supernova burst and Supernovae relic neutrinos.
5. Many measurements possible with atmospheric, solar and high energy neutrinos (not discussed in this talk).
6. Detector R&D for WC and LAr in progress. Detector choices may be made sometimes in 2011.
7. Detector construction to begin in 2014-2015.
8. **Physics by the end of the decade.**

LBNE SUMMARY IN PROJECT-X ERA

- ✓ A 2.3 MW wide band beam with 120 GeV protons, aimed at a 300 kTon Water Cherenkov detector 1290 km away, during a period of 6 years – with 3 years each of ν and anti-ν running can achieve sensitivities at 3σ:

	$\text{Sin}^2 2\theta_{13} > 0$	
$\text{Sin}^2 2\theta_{13} \neq 0$	0.004	All δ_{CP}
Sign (Δm^2_{31})	0.014	All δ_{CP}
CP Violation	0.012	50% δ_{CP}

- ✓ If θ_{13} is large enough – measure $\text{Sin}^2 2\theta_{13}$ to ~5% and δ_{CP} to ~15%
- ✓ Similar sensitivities using a 50kTon LAr detector
- ✓ A 60 GeV proton beam with 3/4th power gives similar results

THANK YOU