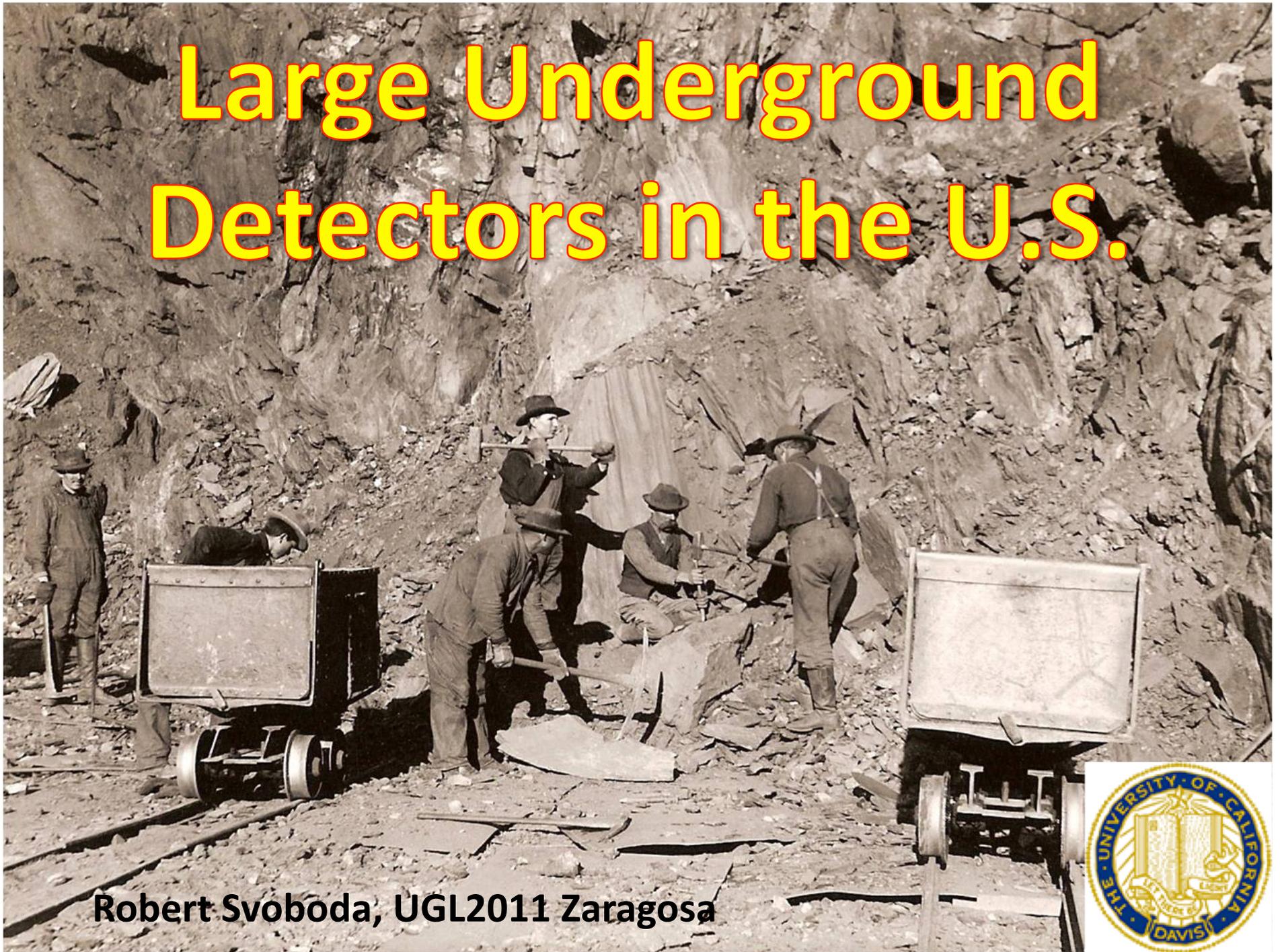
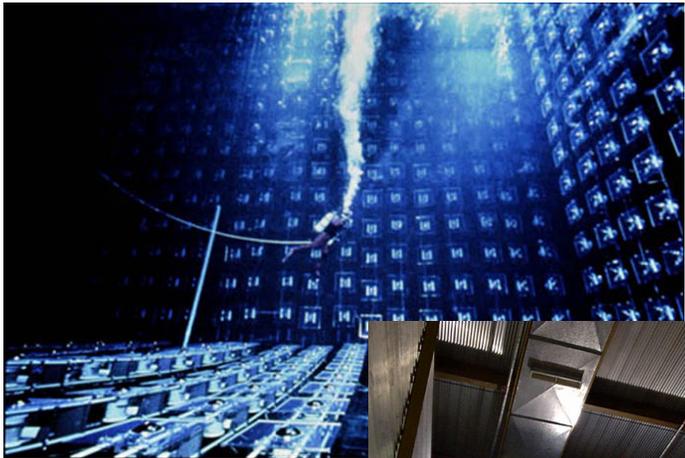


# Large Underground Detectors in the U.S.



Robert Svoboda, UGL2011 Zaragosa

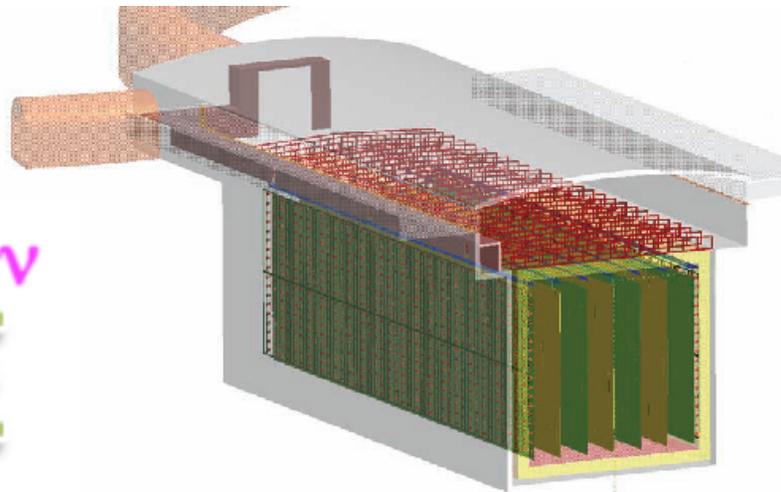
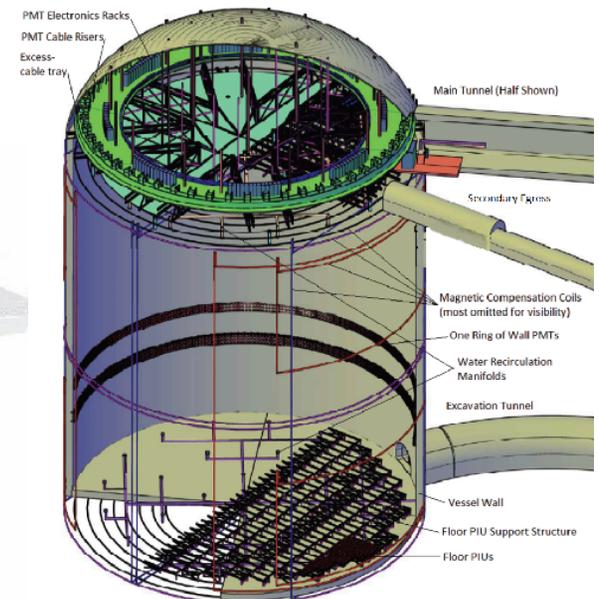




IMB 3.3 ktons, 1982-1992

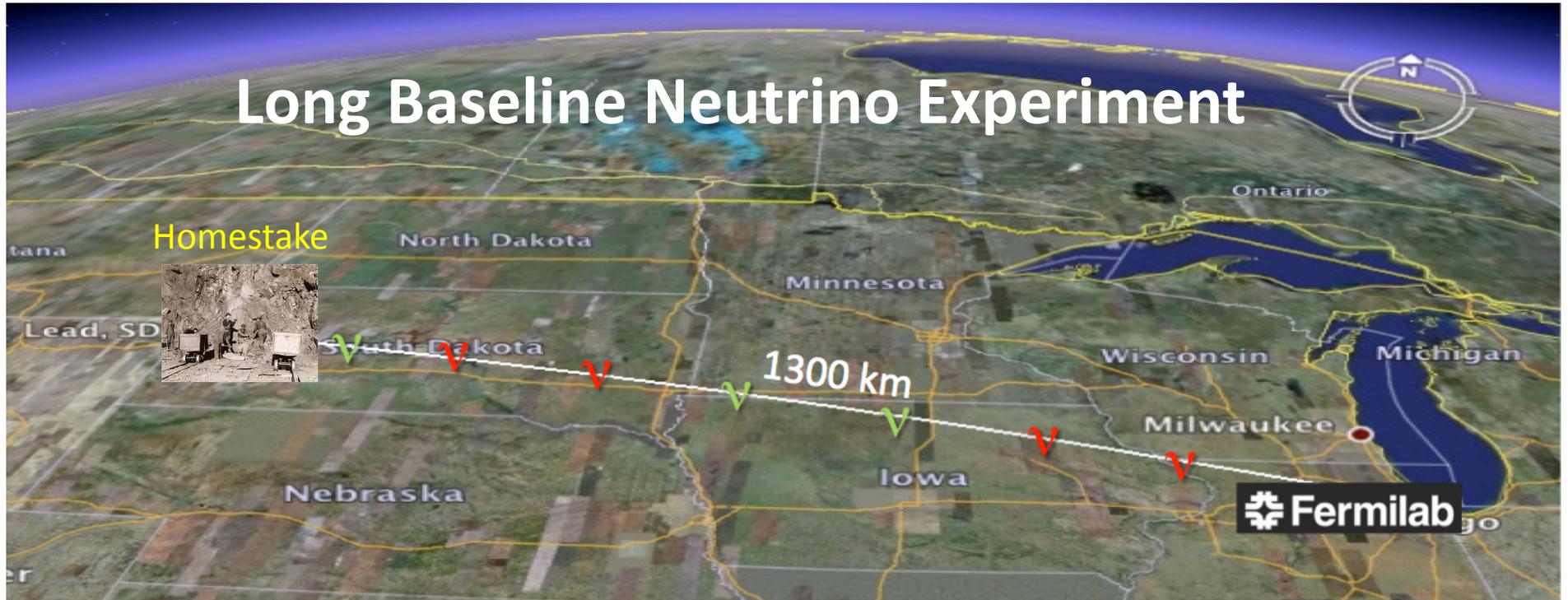


Soudan 1 kton, 1989-2001



LBNE<sup>v</sup>

# Long Baseline Neutrino Experiment



Beam: 700 kW, 60-120 GeV, 5 years  $\nu$  + 5 years  $\bar{\nu}$

on-axis, wide band, upgradable to 2.3 MW

Baseline: 1300 km FNAL to Homestake

Far Site: Underground location to facilitate broad program

Near Site: on current Fermilab property

Configurations: several options under study for beam,  
near, and far detectors



# Long-Baseline Neutrino Experiment Collaboration

**Alabama:** J. Goon, I Stancu

**Argonne:** M. D'Agostino, G. Drake, Z. Djurcic, M. Goodman, X. Huang, V. Guarino, J. Paley, R. Talaga, M. Wetstein

**Boston:** E. Hazen, E. Kearns, S. Linden, J. Stone

**Brookhaven:** M. Bishai, R. Brown, H. Chen, M. Diwan, J. Dolph, G. Geronimo, R. Gill, R. Hackenberg, R. Hahn, S. Hans, D. Jaffe, S. Junnarkar, J.S. Kettell, F. Lanni, L. Littenberg, J. Ling, D. Makowiecki, W. Marciano, W. Morse, Z. Parsa, C. Pearson, V. Radeka, S. Rescia, T. Russo, N. Samios, R. Sharma, N. Simos, J. Sondericker, J. Stewart, H. Tanaka, C. Thorn, B. Viren, Z. Wang, S. White, L. Whitehead, M. Yeh, B. Yu

**Caltech:** R. McKeown, X. Qian, C. Zhang

**Cambridge:** A. Blake, M. Thomson

**Catania/INFN:** V. Bellini, G. Garilli, R. Potenza, M. Trovato

**Chicago:** E. Blucher

**Colorado:** S. Coleman, R. Johnson, A. Marino, M. Tzanov, E. Zimmerman

**Colorado State:** M. Bass, B. Berger, J. Brack, N. Buchanan, J. Harton, V. Kravtsov, W. Toki, D. Warner, R. Wilson

**Columbia:** R. Carr, L. Camillieri, C.Y. Chi, G. Karagiorgi, C. Mariani, M. Shaevitz, W. Sippach, W. Willis

**Crookston:** D. Demuth

**Dakota State:** B. Szczerbinska

**Davis:** M. Bergevin, R. Breedon, J. Felde, P. Gupta, M. Tripanthi, R. Svoboda

**Drexel:** C. Lane, J. Maricic, R. Milincic, K. Zbiri

**Duke:** T. Akiri, J. Fowler, K. Scholberg, C. Walter, R. Wendell

**Duluth:** R. Gran, A. Habig

**Fermilab:** D. Allspach, M. Andrews, B. Baller, E. Berman, D. Boehnlein, M. Campbell, A. Chen, S. Childress, B. DeMaat, A. Drozhdin, T. Dykhuis, C. Escobar, A. Hahn, S. Hays, A. Heavey, J. Howell, P. Huhr, J. Hylan, C. James, M. Johnson, J. Johnstone, T. Junk, B. Kayser, G. Koizumi, T. Lackowski, P. Lucas, B. Lundberg, T. Lundin, P. Mantsch, E. McCluskey, N. Mokhov, C. Moore, J. Morfin, B. Norris, V. Papadimitriou, R. Plunkett, C. Polly, S. Pordes, O. Prokofiev, J. Raaf, G. Rameika, B. Rebel, D. Reitzner, K. Riesselmann, R. Rucinski, R. Schmidt, D. Schmitz, P. Shanahan, M. Stancari, J. Strait, S. Striganov, K. Vaziri, G. Velev, G. Zeller, R. Zwaska

**Hawaii:** S. Dye, J. Kumar, J. Learned, S. Matsuno, S. Pakvasa, M. Rosen, G. Varner

**Indian Universities:** V. Singh (BHU); B. Choudhary, S. Mandal (DU); B. Bhuyan [IIT(G)]; V. Bhatnagar, A. Kumar, S. Sahijpal(PU)

**Indiana:** W. Fox, C. Johnson, M. Messier, S. Mufson, J. Musser, R. Tayloe, J. Urheim

**Iowa State:** M. Sanchez

**IPMU/Tokyo:** M. Vagins

**Irvine:** G. Carminati, W. Kropp, M. Smy, H. Sobel

**Kansas State:** T. Bolton, G. Horton-Smith

**LBL:** R. Kadel, B. Fujikawa, D. Taylor

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

**London-UCL:** J. Thomas

**Los Alamos:** S. Elliott, A. Friedland, V. Gehman, G. Garvey, T. Haines, D. Lee, W. Louis, C. Mauger, G. Mills, A. Norrick, Z. Pavlovic, G. Sinnis, W. Sondheim, R. Van de Water, H. White

**Louisiana State:** W. Coleman, T. Kutter, W. Metcalf, M. Tzanov

**Maryland:** E. Blaufuss, R. Hellauer, T. Straszheim, G. Sullivan

**Michigan State:** E. Arrieta-Diaz, C. Bromberg, D. Edmunds, J. Huston, B. Page

**Minnesota:** M. Marshak, W. Miller

**MIT:** W. Barletta, J. Conrad, T. Katori, R. Lanza, L. Winslow

**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, S. Seibert, 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. McTaggart

**Syracuse:** M. Artuso, S. Blusk, T. Skwarnicki, M. Soderberg, S. Stone

**Texas:** S. Kopp, K. Lang, R. Mehdiev

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

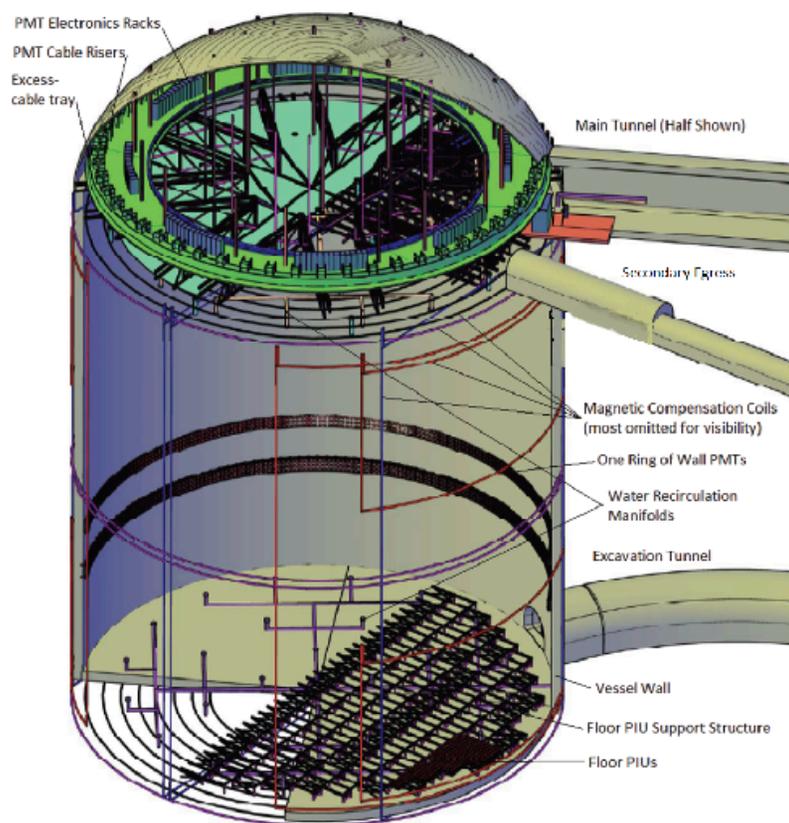
**Wisconsin:** B. Balantekin, F. Feyzi, K. Heeger, A. Karle, R. Maruyama, D. Webber, C. Wendt

**Yale:** E. Church, B. Fleming, R. Guenette, K. Partyka, J. Spitz, A. Szelc

~300 physicists and engineers, 55 institutions

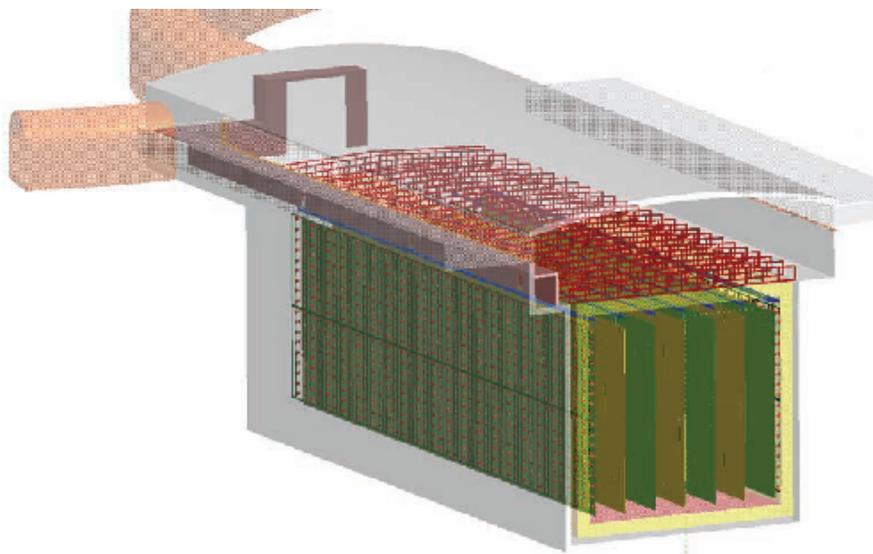
# Two Far Detector Options

## 200 kT water Cherenkov



One 200 kT fiducial WC detector  
Located at the **4850 foot level**

## 34 kT liquid argon



Two 17 kT fiducial LAr detectors  
To be located at a new drive-in  
site at **800 foot level**. (one detector  
shown here)

# Current News

- This talk will present present state of design of the experiment. Nothing is yet completely fixed, but options have been narrowed down and work is ongoing to evaluate cost and schedule.
- NSF had been planning to pay ~10% of LBNE construction costs and operate DUSEL. Now the U.S. Dept of Energy (DOE) is planning to bear the full construction cost and be responsible for facility operations since NSF said they do not want to run a lab.
- A decision was made by DOE to, at least initially, continue planning for **only** the Homestake site. A formal review was held at SLAC in March under a "blue ribbon" panel commissioned by the Director of the Office of Science (all science, not just HEP). Report on his desk now.

"Things are more like they are now than they ever were before"

D.Eisenhower



# Physics Research Goals of LBNE

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The primary science objectives of the LBNE Project are:

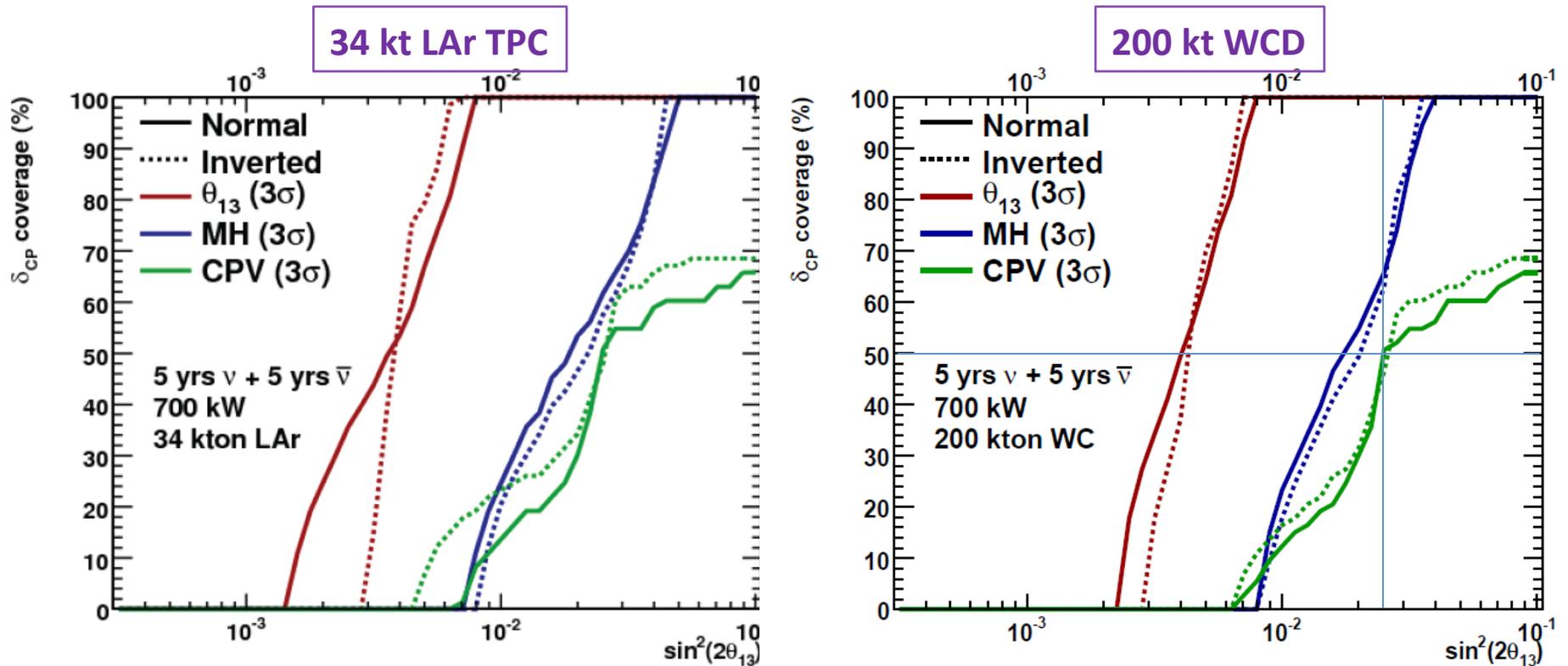
1. A search for, and precision measurements of, the parameters that govern  $\nu_\mu \rightarrow \nu_e$  oscillations. This includes measurement of the third mixing angle  $\theta_{13}$ , for whose value only an upper bound is currently known, and if  $\theta_{13}$  is large enough, measurement of the CP-violating phase  $\delta$  and determining of the mass ordering (sign of  $\Delta m^2_{32}$ ).
2. Precision measurements of  $\theta_{23}$  and  $|\Delta m^2_{32}|$  in the  $\nu_\mu$  disappearance channel.
3. Search for proton decay, yielding a significant improvement in current limits on the partial lifetime of the proton ( $\tau/\text{BR}$ ) in one or more important candidate decay modes, e.g.  $p \rightarrow e + \pi^0$  or  $p \rightarrow K^+ \nu$ .
4. Detection and measurement of the neutrino flux from a core collapse supernova within our galaxy, should one occur during the lifetime of LBNE.

Though outside of the primary objectives, the far detector placed at the proposed depth could enable studies of atmospheric  $\nu$  physics, and with additional upgrades, studies of day/night  $^8\text{B}$  solar  $\nu$  physics and relic supernova neutrinos.

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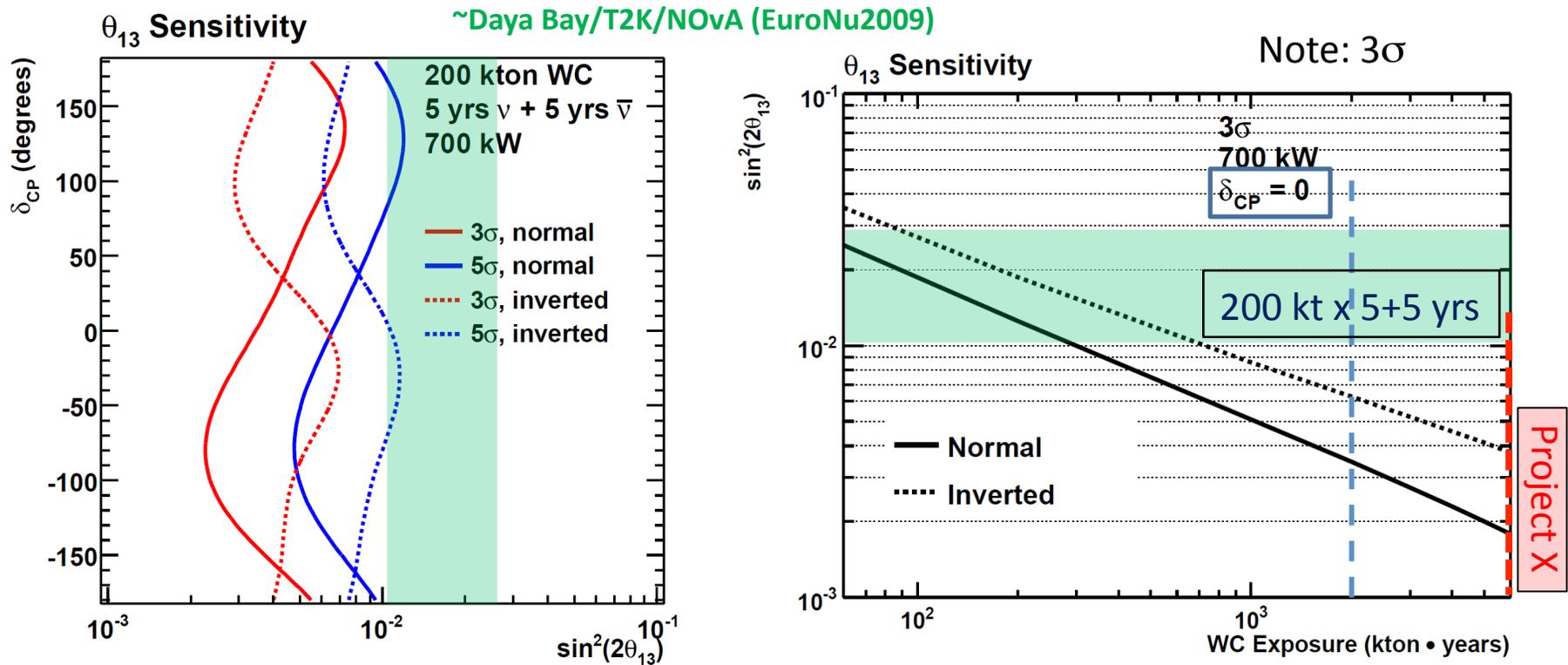
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# Physics with the Neutrino Beam



- For beam physics: **200 kt WCD**  $\approx$  **34 kt LAr**  $\approx$  **100 kt WCD + 17 kt LAr**
  - Ongoing work to tune efficiency and signal/background may affect this equivalence
  - Will alternate WCD/LAr plots in this talk
  - 5+5 years turns out to be near optimal in shallow minimum
- Quantitative & qualitative performance differences for some non-beam physics

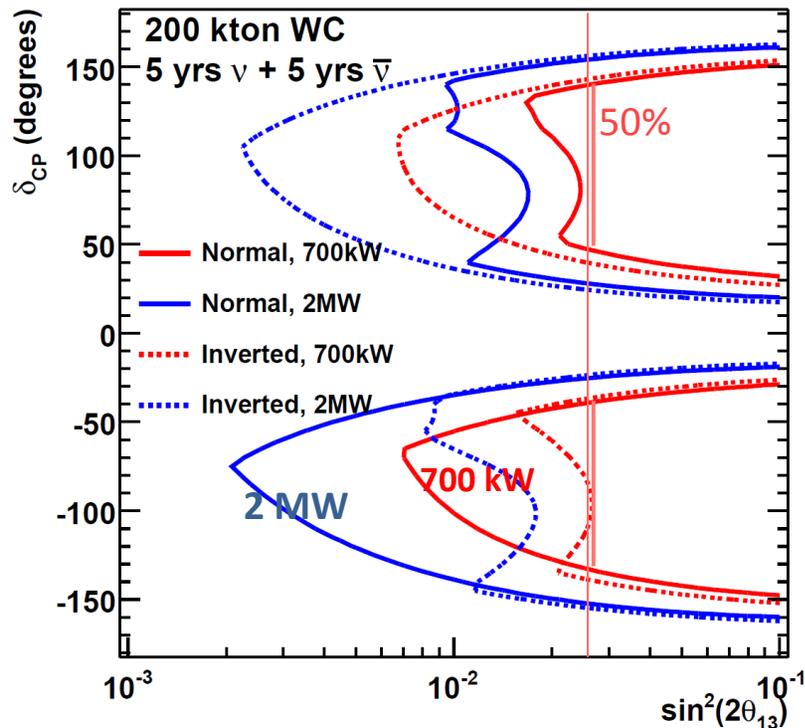
# $\sin^2 2\theta_{13} \neq 0$ Sensitivity: statistically limited



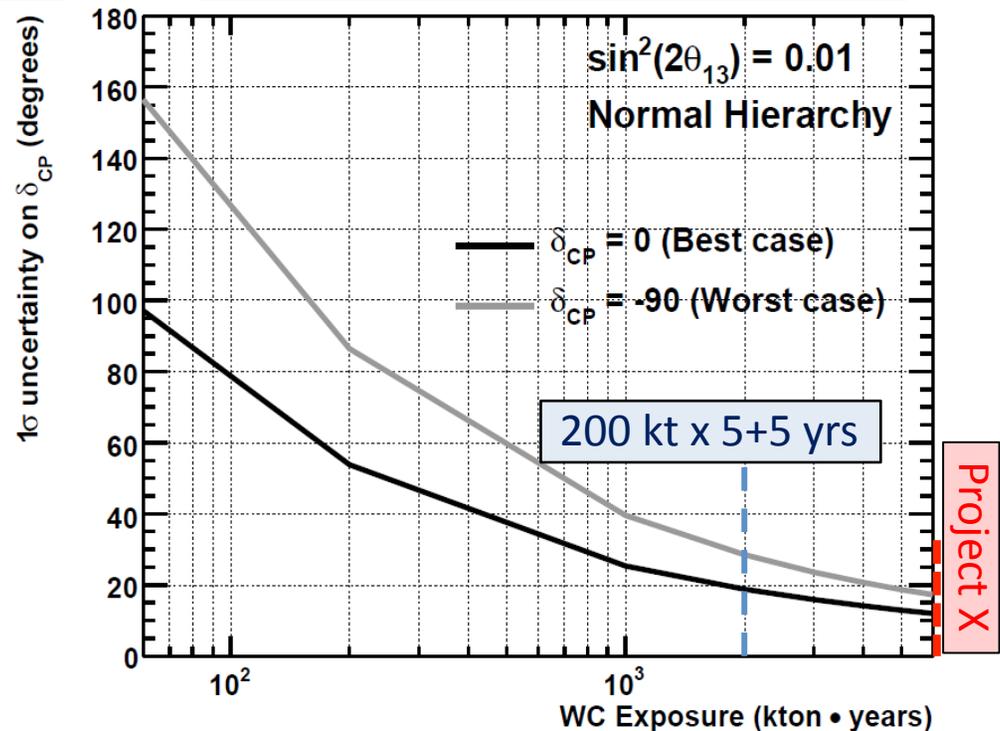
- $\sin^2 2\theta_{13}$  3- $\sigma$  sensitivity: 0.002--0.008 (~0.001--0.004 with 2 MW beam)
- While not designed as a primarily  $\theta_{13}$  experiment, sensitivity is still very good, especially with Project X

# CP Sensitivity: Project X

$3\sigma$  exclusion of CP conserving  $\delta_{CP}=0^\circ$  or  $180^\circ$

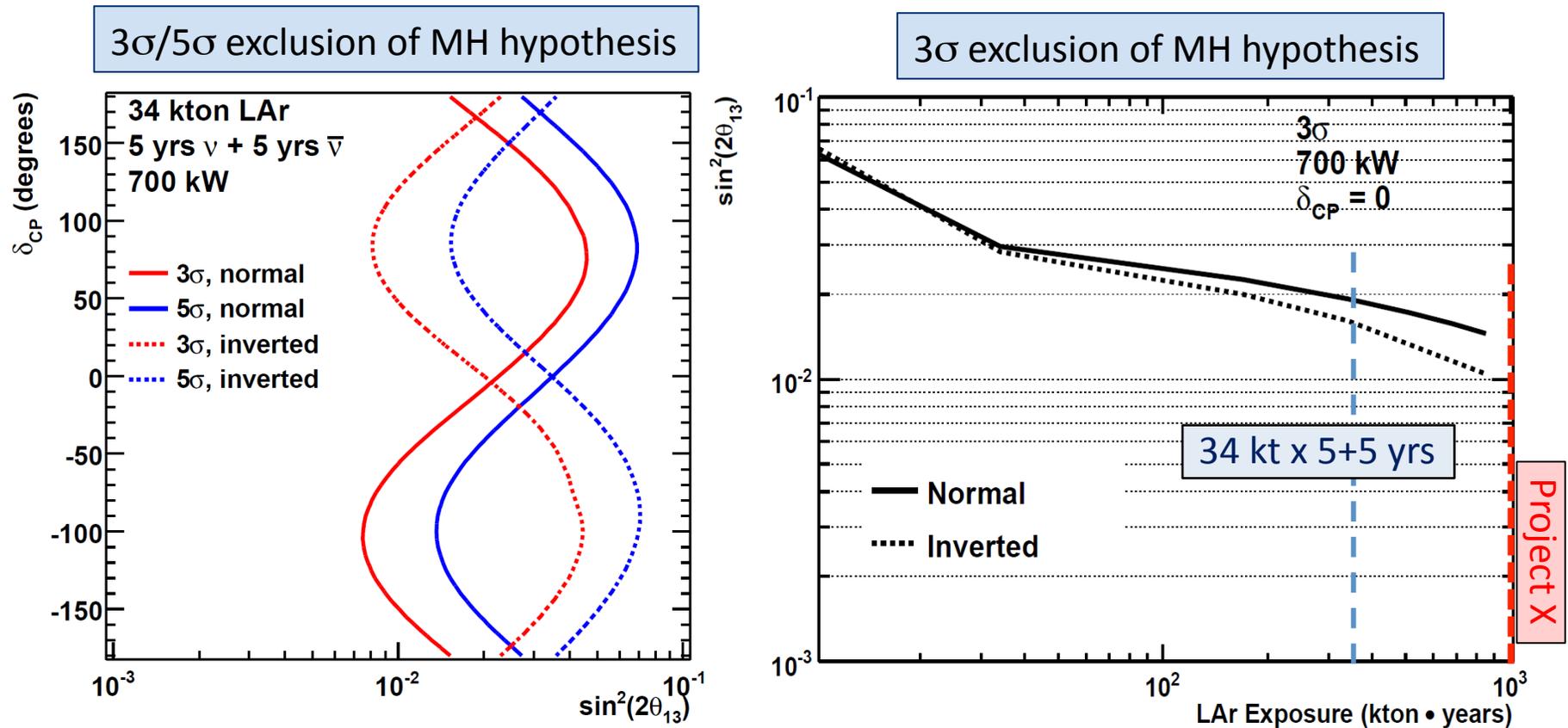


$1\sigma$  resolution on  $\delta_{CP}$  measurement



- Cover 50%  $\delta_{CP}$  phase space down to  $\sin^2 2\theta_{13} = 0.03$ ; resolution on  $\delta_{CP} = \pm 19^\circ$
- Optimal  $\nu/\bar{\nu}$  running - shallow minimum around 50:50
- 2 MW beam = rapid feedback on parameter values— guide future running

# MH Sensitivity

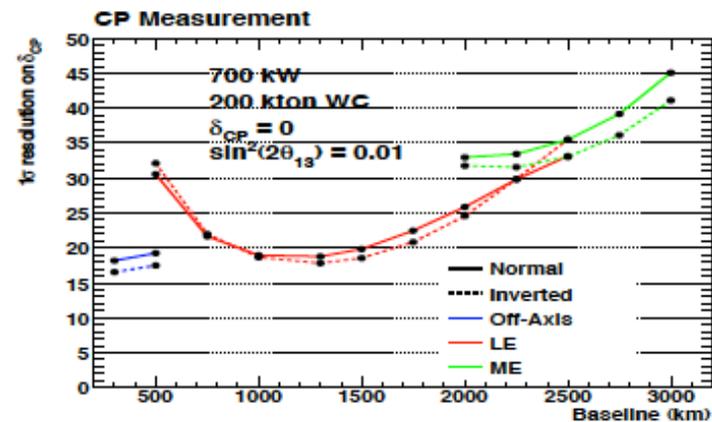
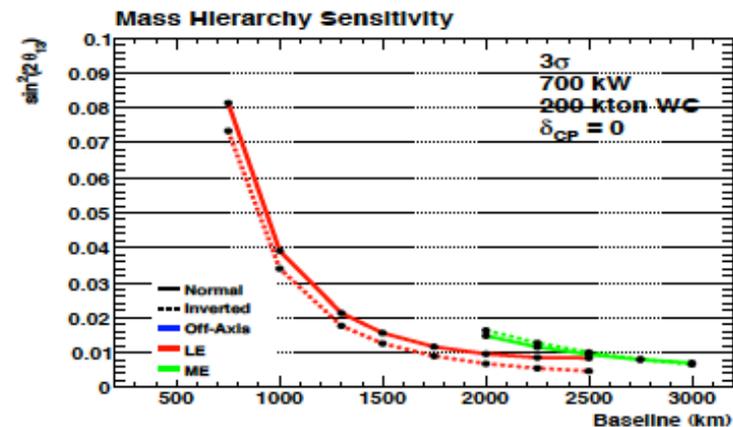
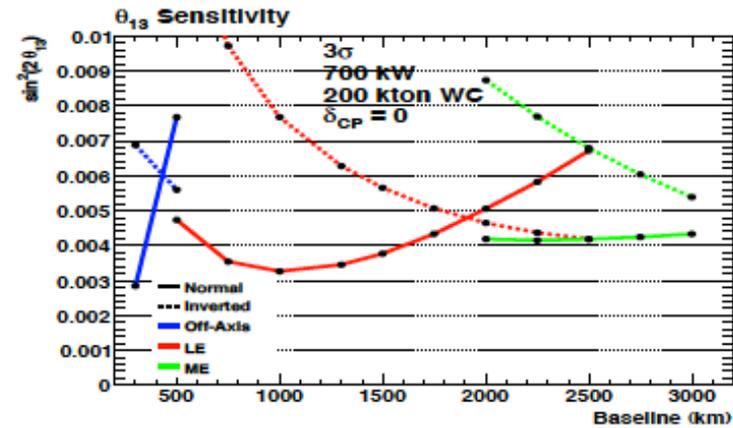


- 340 kt-y LAr exposure can resolve MH at 3σ for all  $\delta_{CP}$  down to  $\sin^2 2\theta_{13} = 0.04$
- Shorter baselines (NOvA, T2K) challenged by inherent degeneracies between CP-violating asymmetries and matter effects.

# Homestake is at a good distance

## A 1300 km baseline:

- Large matter effects
- Higher energy at oscillation peak with enhanced cross section compare to MINOS
- Interplay between  $\theta_{13}$ , mass hierarchy, and CPV is complex
- Lower flux due to  $1/r^2$  is important
- **FNAL-Homestake distance makes three important measurements possible with a single experimental configuration.**
- **Possibility of a large  $\theta_{13}$ ?**



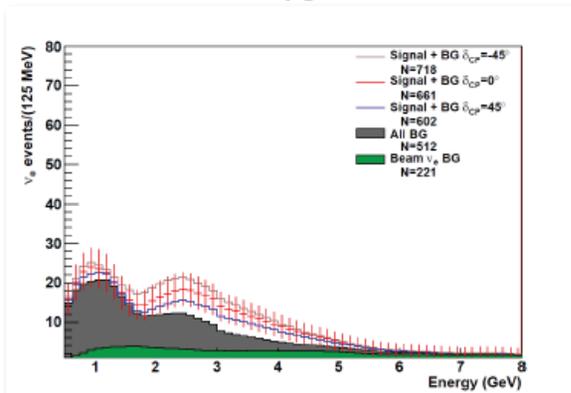
(Beam returned at each distance)



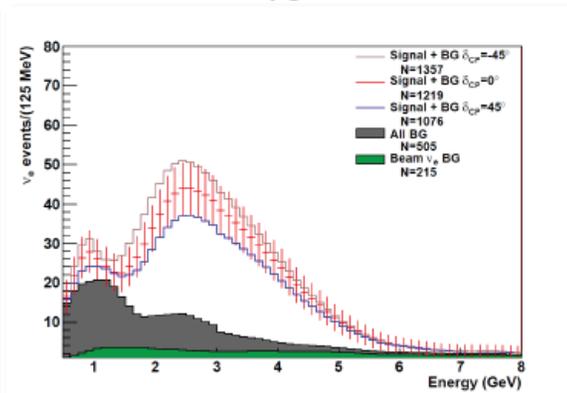
# Larger $\theta_{13}$ Means Larger Signals

3

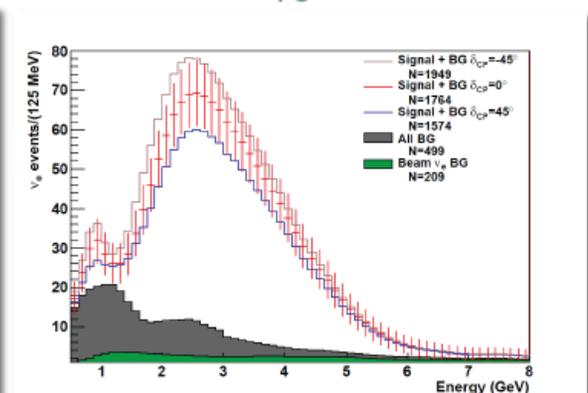
$\sin^2 2\theta_{13} = 0.01$



$\sin^2 2\theta_{13} = 0.06$



$\sin^2 2\theta_{13} = 0.11$



(M. Bass, B. Wilson)

#  $\nu_e$  signal events for 200 kton WC, 5 yrs  $\nu$ , 700 kW, 1300km, NH,  $\delta=0$   
(expect smaller rates for IH, also for anti- $\nu$  running)

149

714

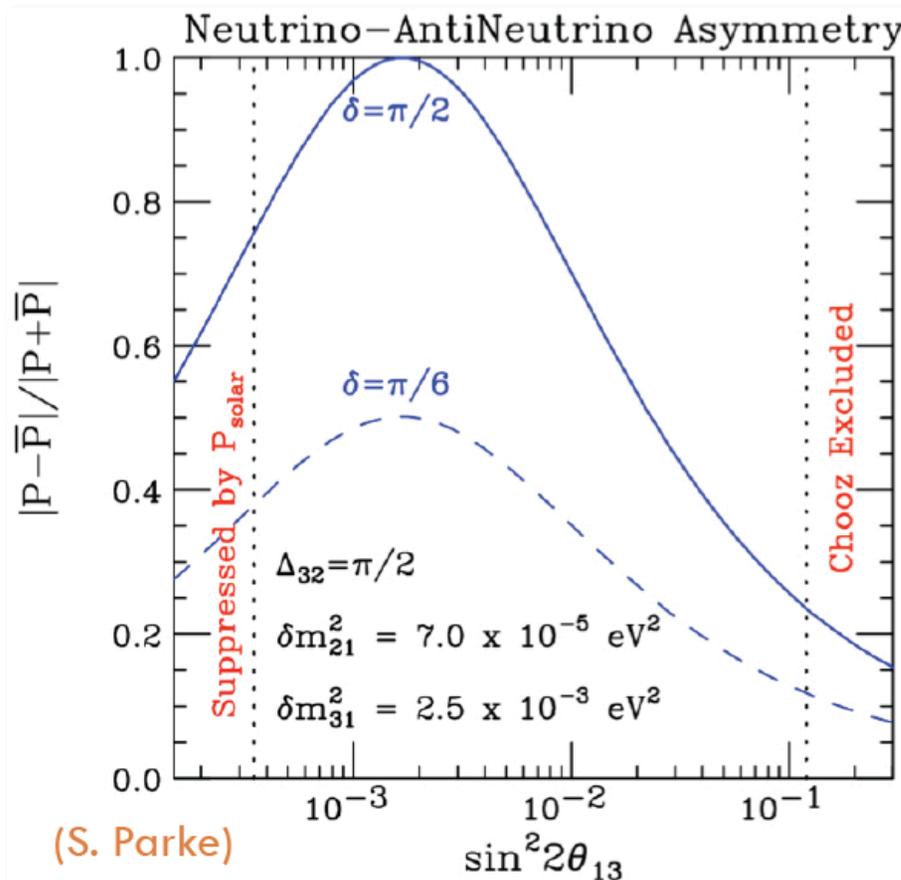
1,265

(almost x10 increase in # signal events in going from  $\sin^2 2\theta_{13} = 0.01$  to 0.1)



# $\nu/\bar{\nu}$ Asymmetry in Vacuum

9



- the asymmetry

$$\frac{P(\nu_{\mu} \rightarrow \nu_e) - P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e)}{P(\nu_{\mu} \rightarrow \nu_e) + P(\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e)}$$

is proportional to  $\sim 1/\sin\theta_{13}$

- the asymmetry gets smaller as  $\theta_{13}$  increases

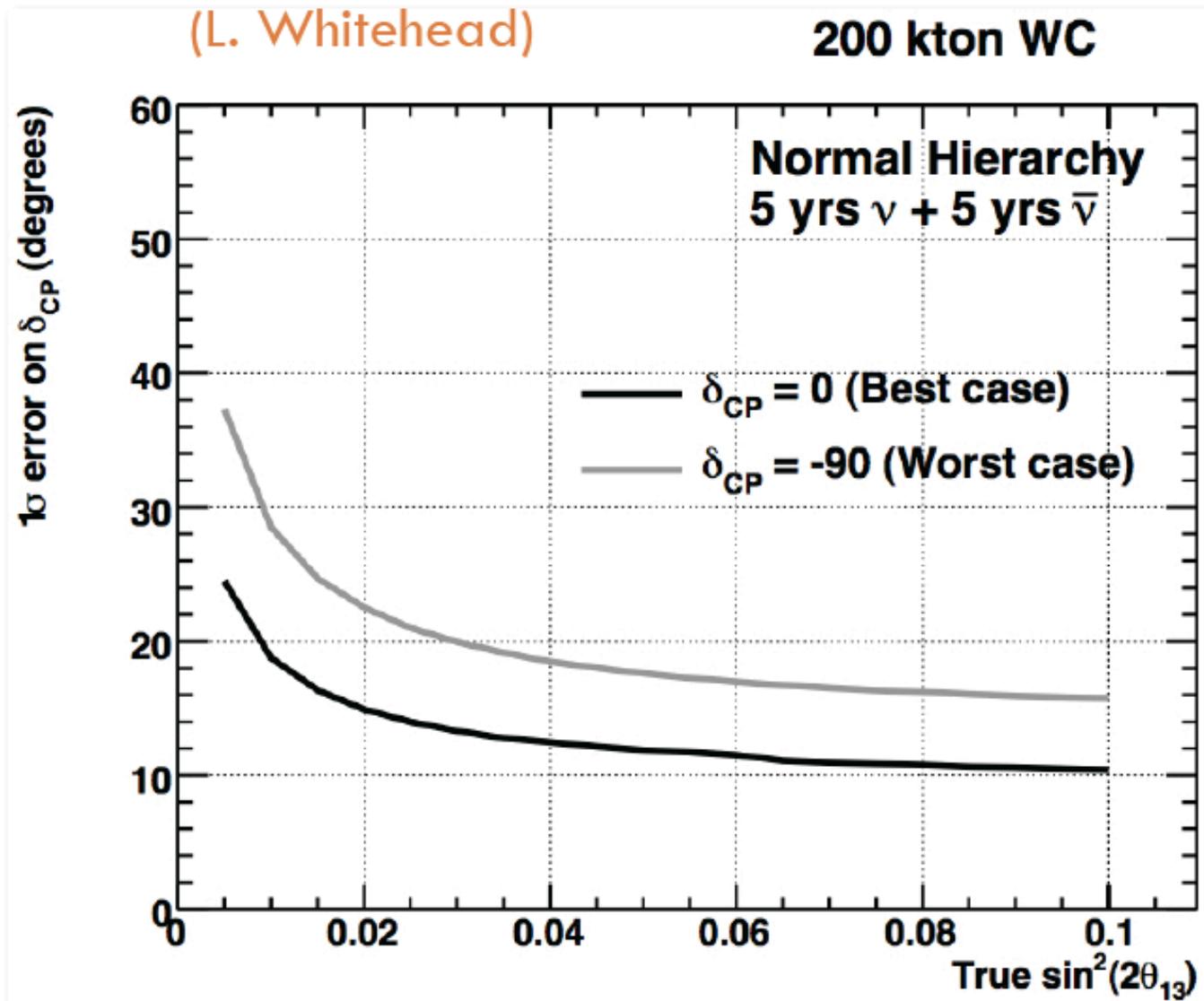
$$\left. \begin{array}{l} \sim 75\% \text{ for } \sin^2 2\theta_{13} = 0.01 \\ \sim 25\% \text{ for } \sin^2 2\theta_{13} = 0.10 \end{array} \right\} \delta_{\text{CP}} = \pi/2$$

factor  $\sim 3$  reduction in CP asymmetry (independent of baseline)

- signal rate increases w/  $\theta_{13}$  ( $\sim \times 10$  increase from 0.01 to 0.1; so  $\sim \times 3$  improvement in stat sig of signal)

(ignoring matter effects & backgrounds for now)

# $\delta_{CP}$ resolution not strongly dependent on $\theta_{13}$



While resolution of mass hierarchy improves, CP violation search only requires  $\sin^2 2\theta_{13} > 0.01$

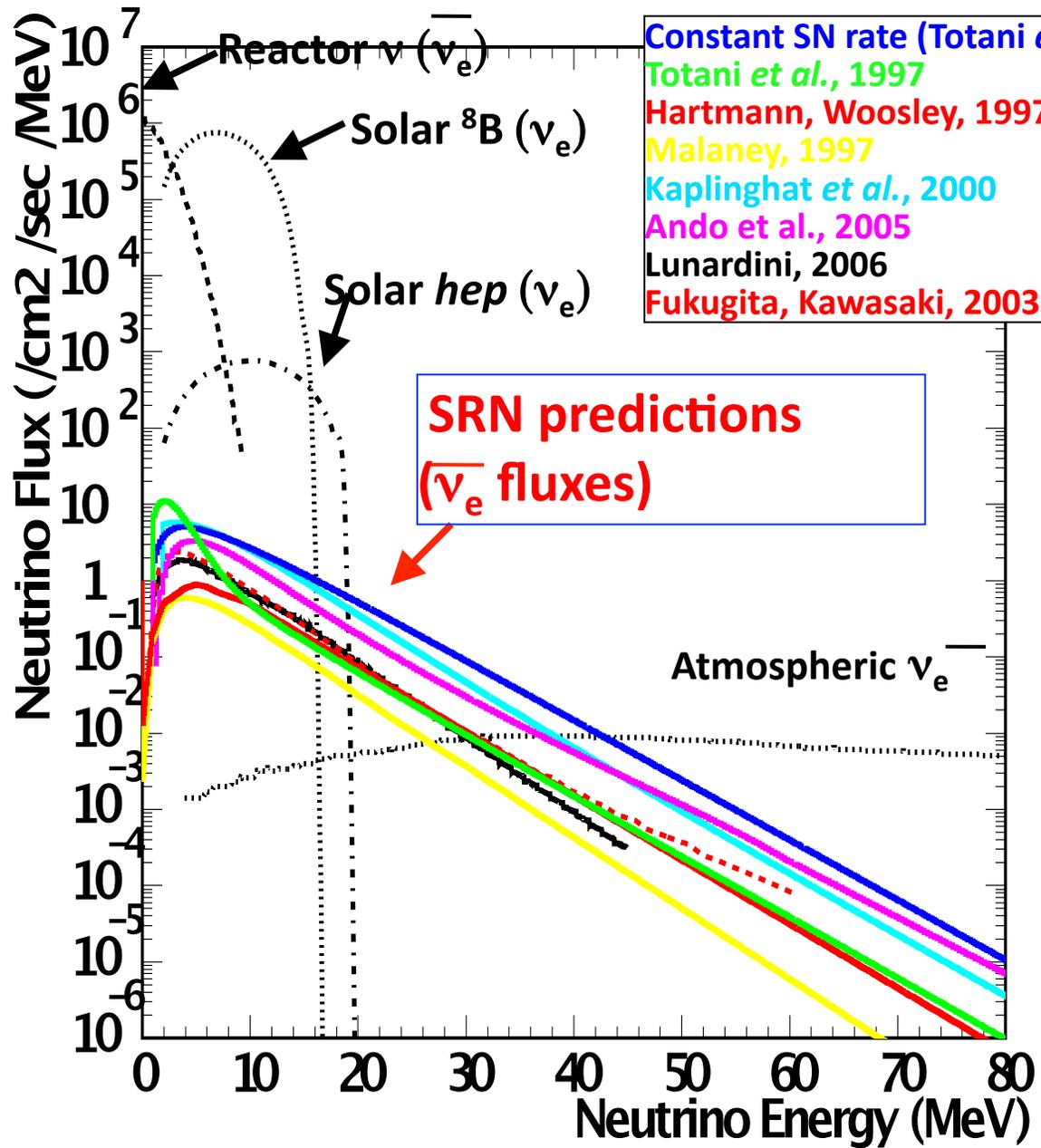
# Other Physics: Supernova Neutrinos

- When a star's core collapses ~99% of the gravitational binding energy of the proto-neutron star goes into  $\nu$ 's
- SN at galactic core (10 kpc)  
⇒ tens of thousands of interactions  
in tens of seconds
- **Large detectors can discriminate between core collapse models**



Sanduleak -69° 202 → SN 1987A

"You don't have to be lucky, you just have to be patient."



### Detection of Relic SN

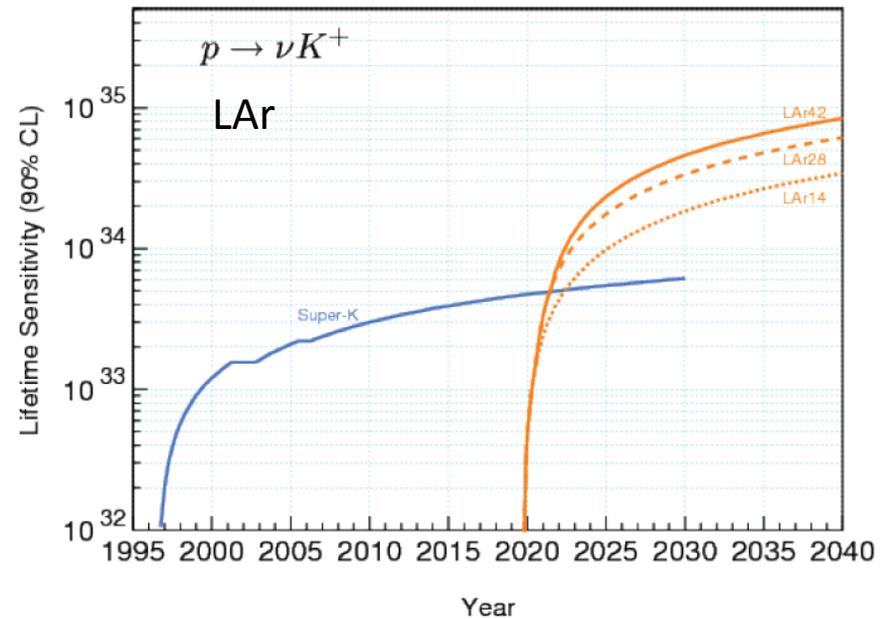
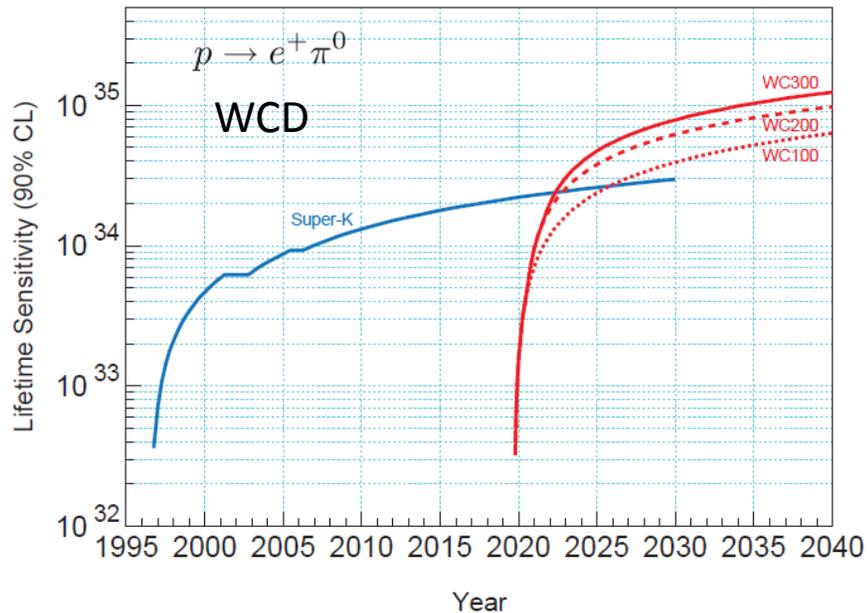
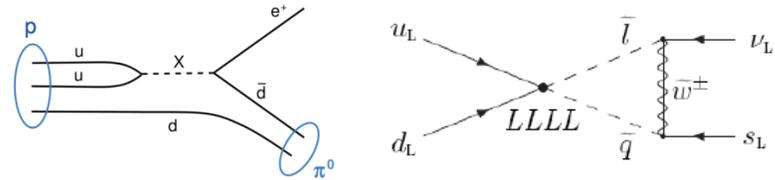
Differences due to core collapse models and assumed SN rate and luminosity

Large WC detector or LS detectors are best.

HEP solar neutrinos limits LAr sensitivity ( $\nu_e$ ) – plus need for large size.

Conclusion: LAr detector too small to justify added costs of deep site for this physics

# Proton Decay



- $e^+\pi^0$ : WC200 reach  $\sim 10^{35}$  in 20 years -- 7.5x SK current; 5x SK ultimate
- $\bar{\nu}K^+$ : LAr34 reach  $\sim 7 \times 10^{34}$  in 20 years -- 23x SK current; 10x SK ultimate
- Detector mass is the main issue, backgrounds also come into play

# The Far Site



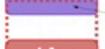
# Underground Lab Basic Layout

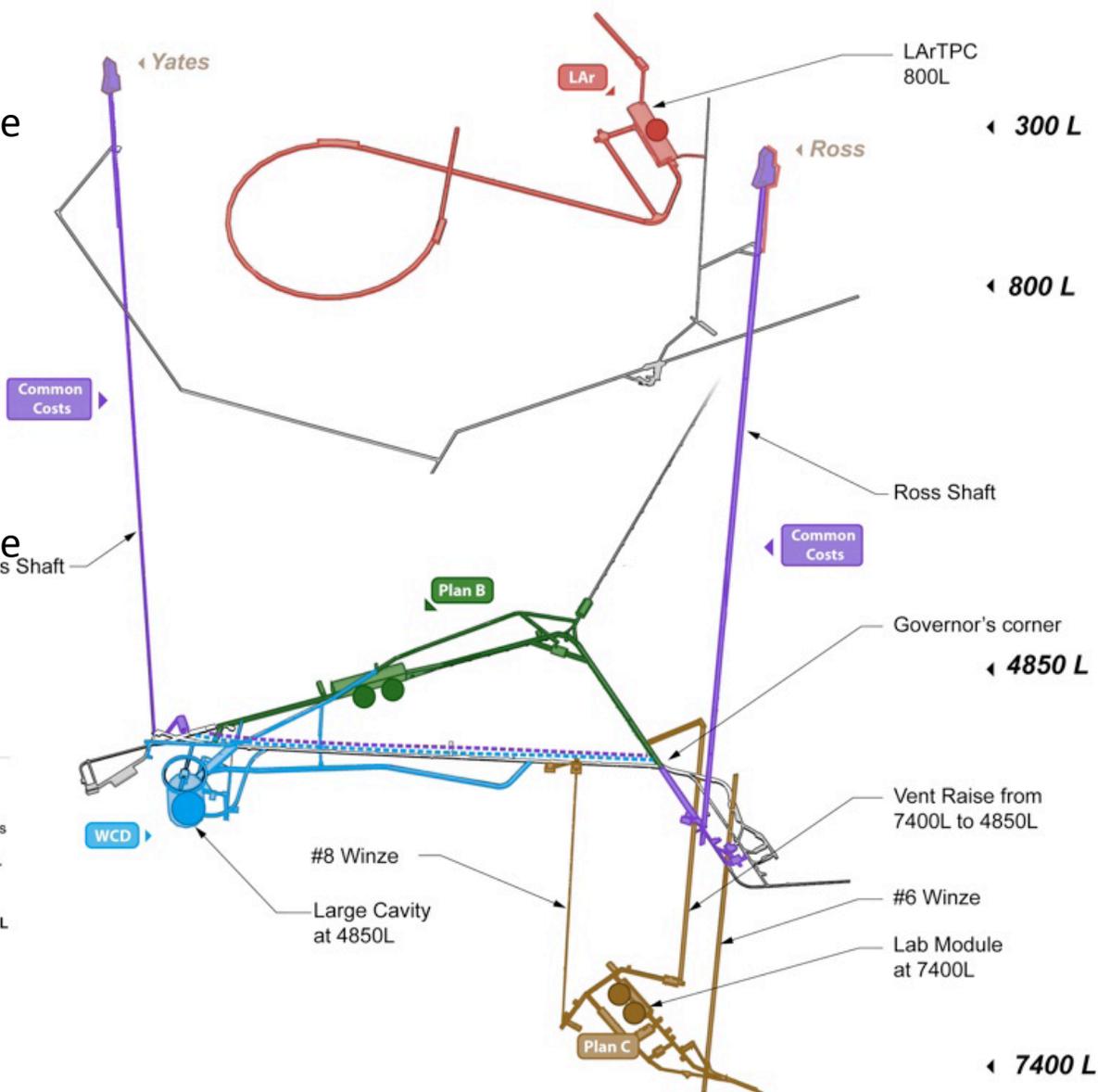
4850 campus at 4200 mwe  
 Davis Lab (existing)  
 Large Cavity Site  
 General lab module

800 campus at 700 mwe  
 LAr detector lab

7400 campus at 6400 mwe  
 Deep Lab module

## LEGEND

	Surface and Infrastructure
	Liquid Argon Development at 800L
	Water Cherenkov Detector @ 4850L
	Lab Module @ 4850L
	Lab Module @ 7400L



# Depth Requirements for Proton Decay: Liquid Argon

- A unique feature of LAr detectors are their ability to reconstruct the  $K^+$  decay from the SUSY-motivated decay mode  $p \rightarrow \nu K^+$ . This would allow sensitivity to this mode five times that of Super-Kamiokande over a 10 year run.
- The most significant background expected is from CR muons that make a  $K^0_L$  that enters the detector from the outside and then charge exchanges into a  $K^+$ .

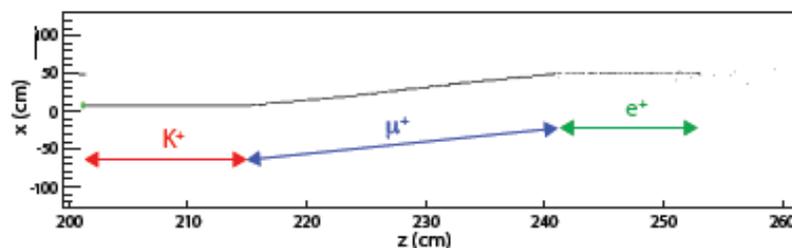
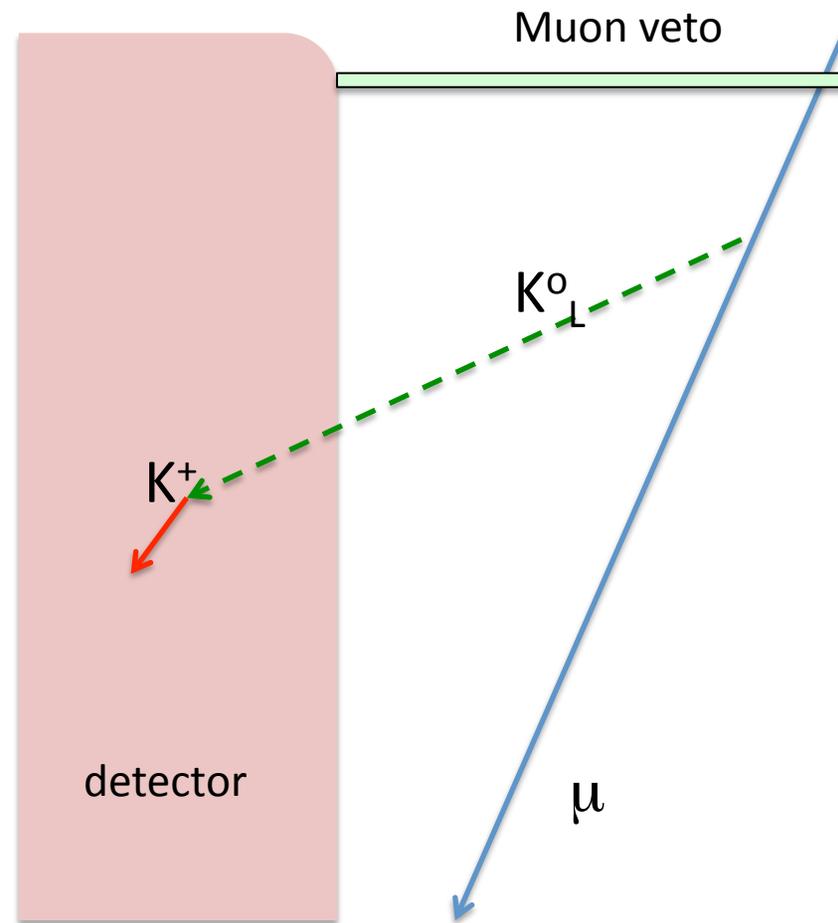


Figure 4-4: LArSoft simulation of an example  $K^+ \rightarrow \mu^+ \rightarrow e^+$  decay chain.

# Requirement for Muon veto

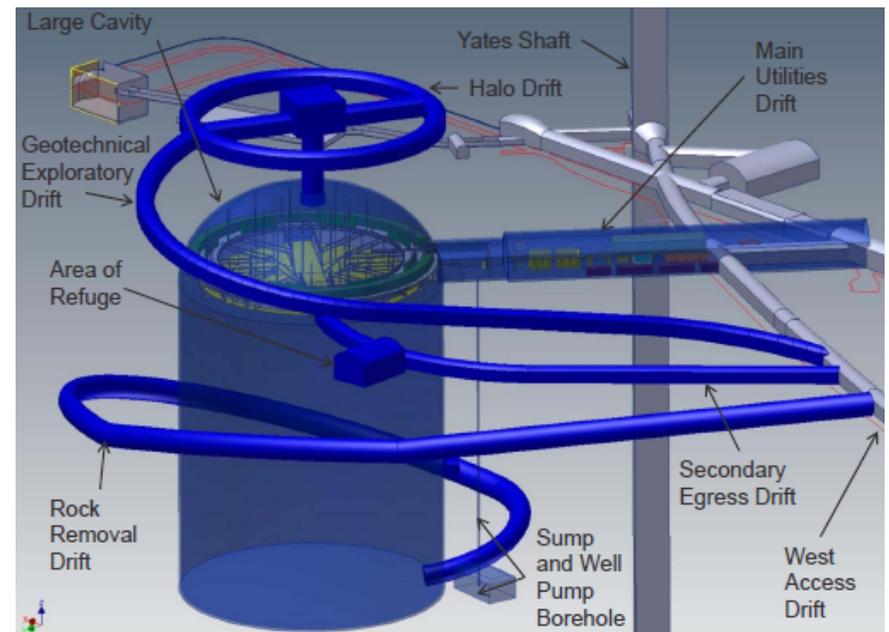
- Without a muon veto, a fiducial volume cut of 5-7 meters from the wall is predicted to be necessary
- With an effective veto this can be significantly reduced.
- At 800 feet, a muon veto is planned that would retain roughly 80% of the FV.
- Conclusion: with a sufficiently well-designed muon veto, 800 feet should be sufficient. This is currently the driving factor in the depth requirement.



# WCD Conventional Facilities (CF) at Homestake

WCD CF based on requirements of experiment

- 150kt-200kt cavern at 4850 level
- Space on surface for water fill system, underground for water recirculation system
- Experimental utilities: power, water for tank, drainage of leak & native water from the tank, drainage for tank maintenance

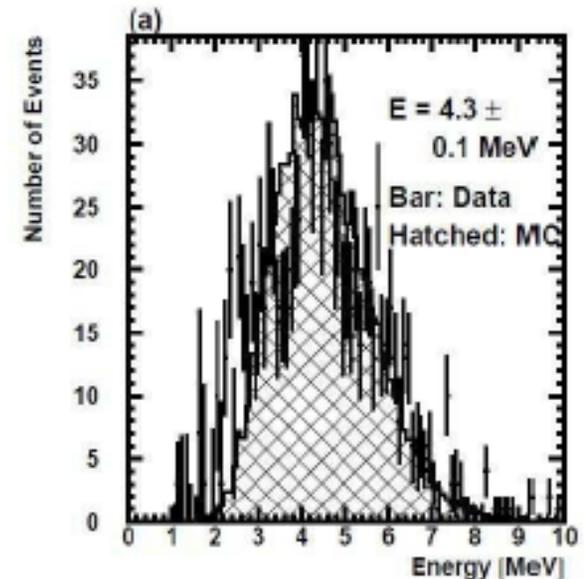
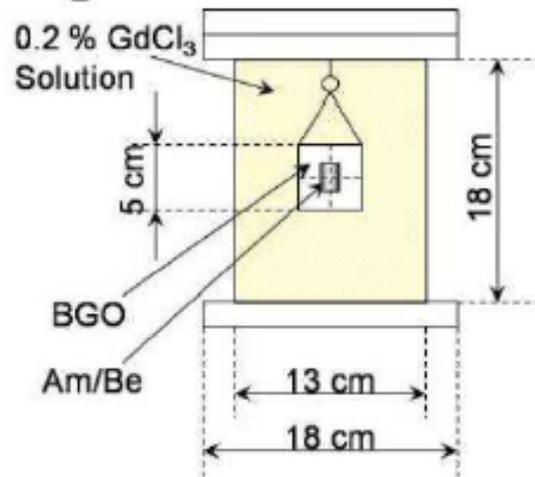


**Why at 4850?**

**Potential for broad program and future upgrades**

# Addition of Gadolinium

GdCl<sub>3</sub> test vessel



Tests with Super-Kamiokande have shown that neutron tagging via gadolinium in the water is feasible. LBNE Case Study document details the increased light collection needed for LBNE. Roughly a factor of two is desirable to achieve good efficiency.

**Depth requirement for Water Cherenkov driven by desire for a program in low energy neutrino physics in addition to beam:**

Cosmological SN, DEADALUS, solar neutrinos, geoneutrinos, high mass  $p \rightarrow \nu K^+$  search

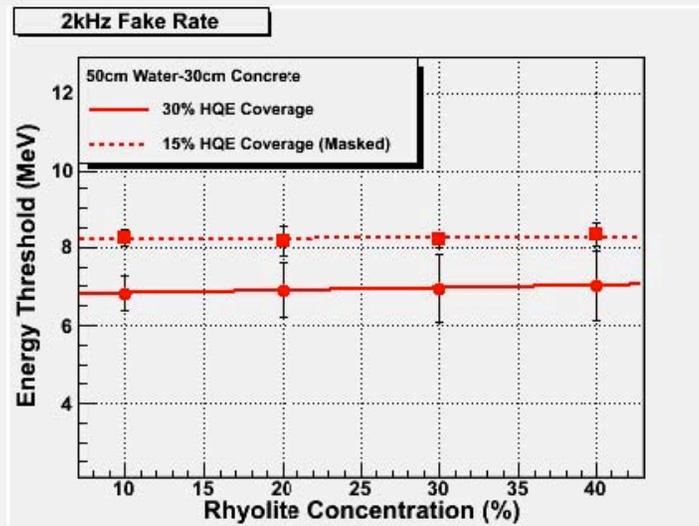
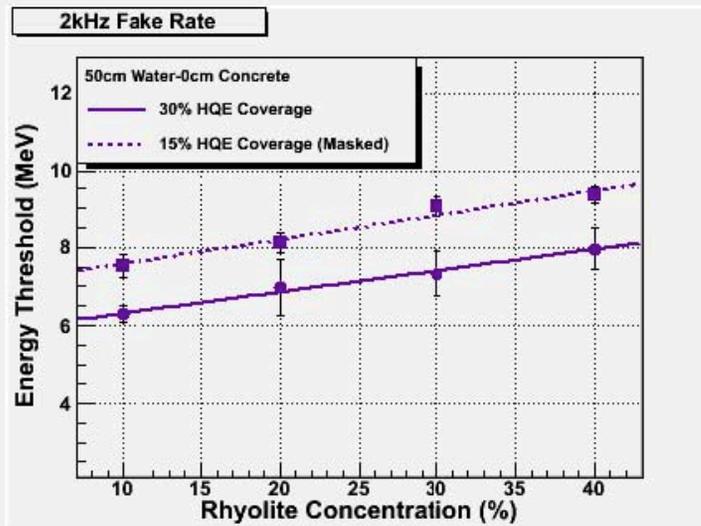
# Low Energy Physics: Radiopurity at Homestake very good

For the WC detector option, extensive hit-level studies have been done of the effects of radiopurity on detector energy threshold performance.

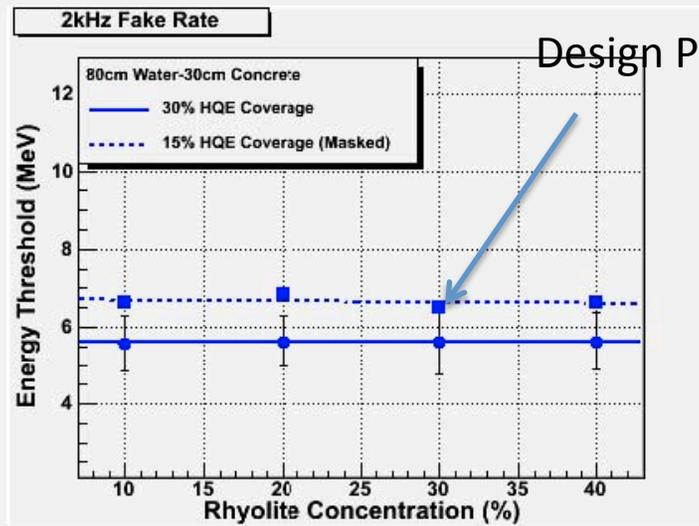
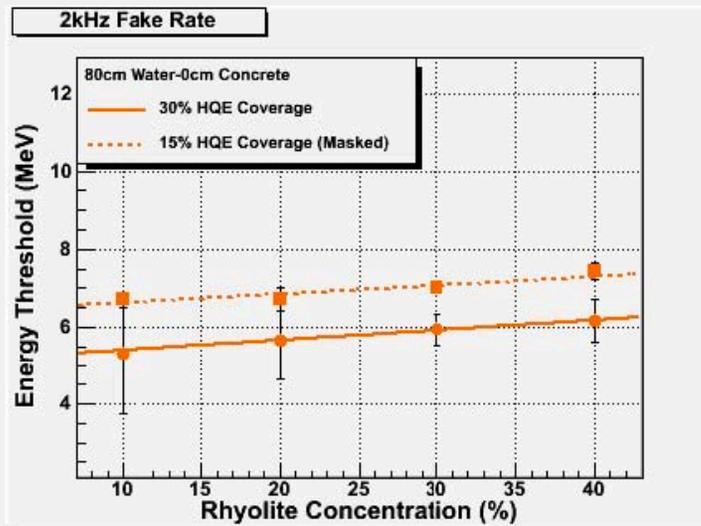
	Concentrations		
Material	U	Th	K
Amphibolite	0.16 ppm	0.20 ppm	0.154%
Rhyolite	8.67 ppm	12.2 ppm	2.82%
60% - 40% Mix	3.564 ppm	5 ppm	1.22%
Concrete	2.02 ppm	1.87 ppm	0.23%
PMT Glass	67 ppb	25 ppb	16 ppm

Table 1: Concentrations of radioactive elements in materials<sup>[2][3]</sup>

**Threshold independent of rock with 80 cm buffer.** Nominal threshold with design coverage is  $\sim 6.7$  MeV. No concrete liner BETTER since Homestake rock has quite good radiopurity compared to typical concrete.



With  
concrete  
liner



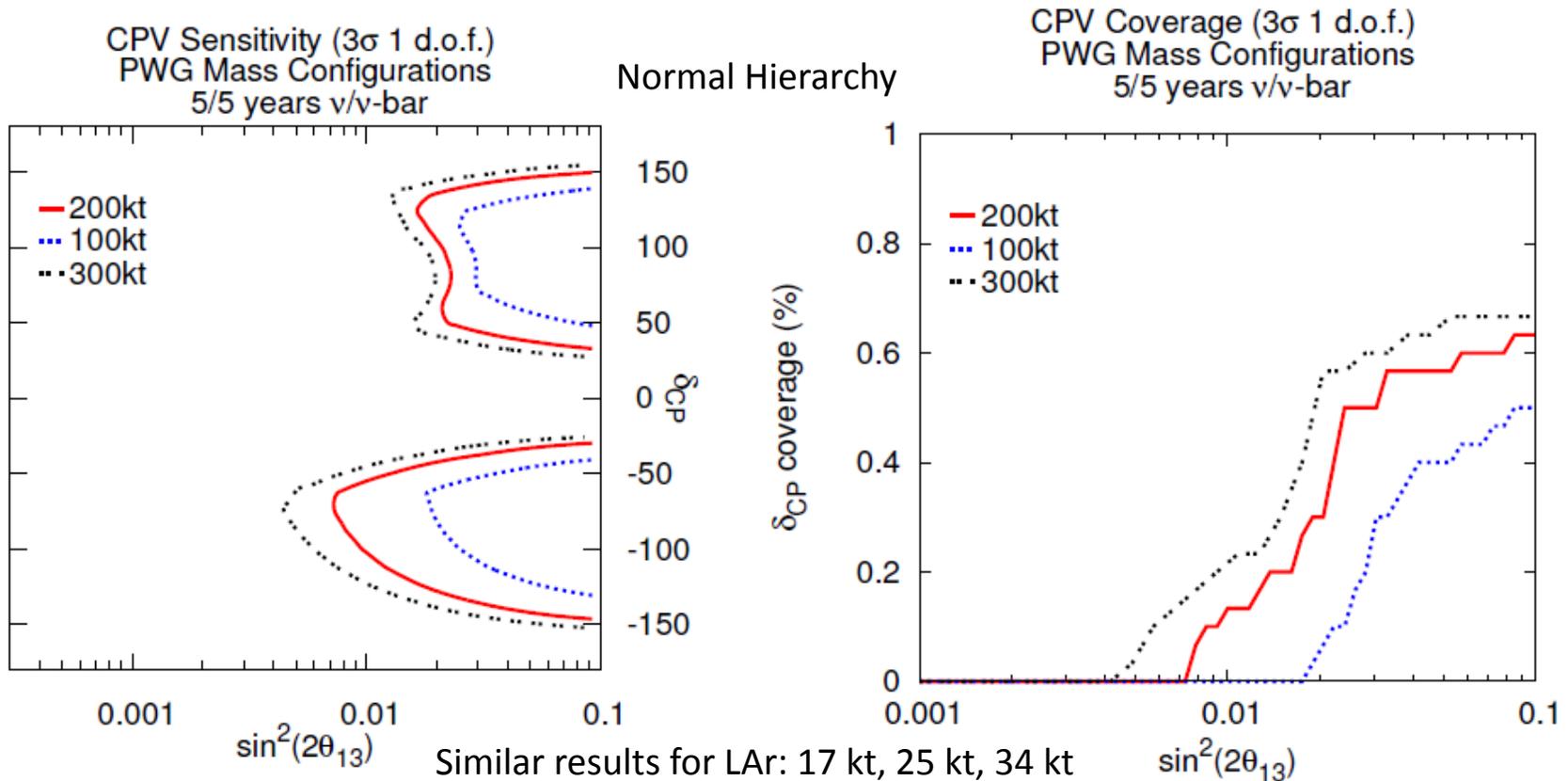
Design PMT coverage

Without  
concrete  
liner

# The Far Detectors

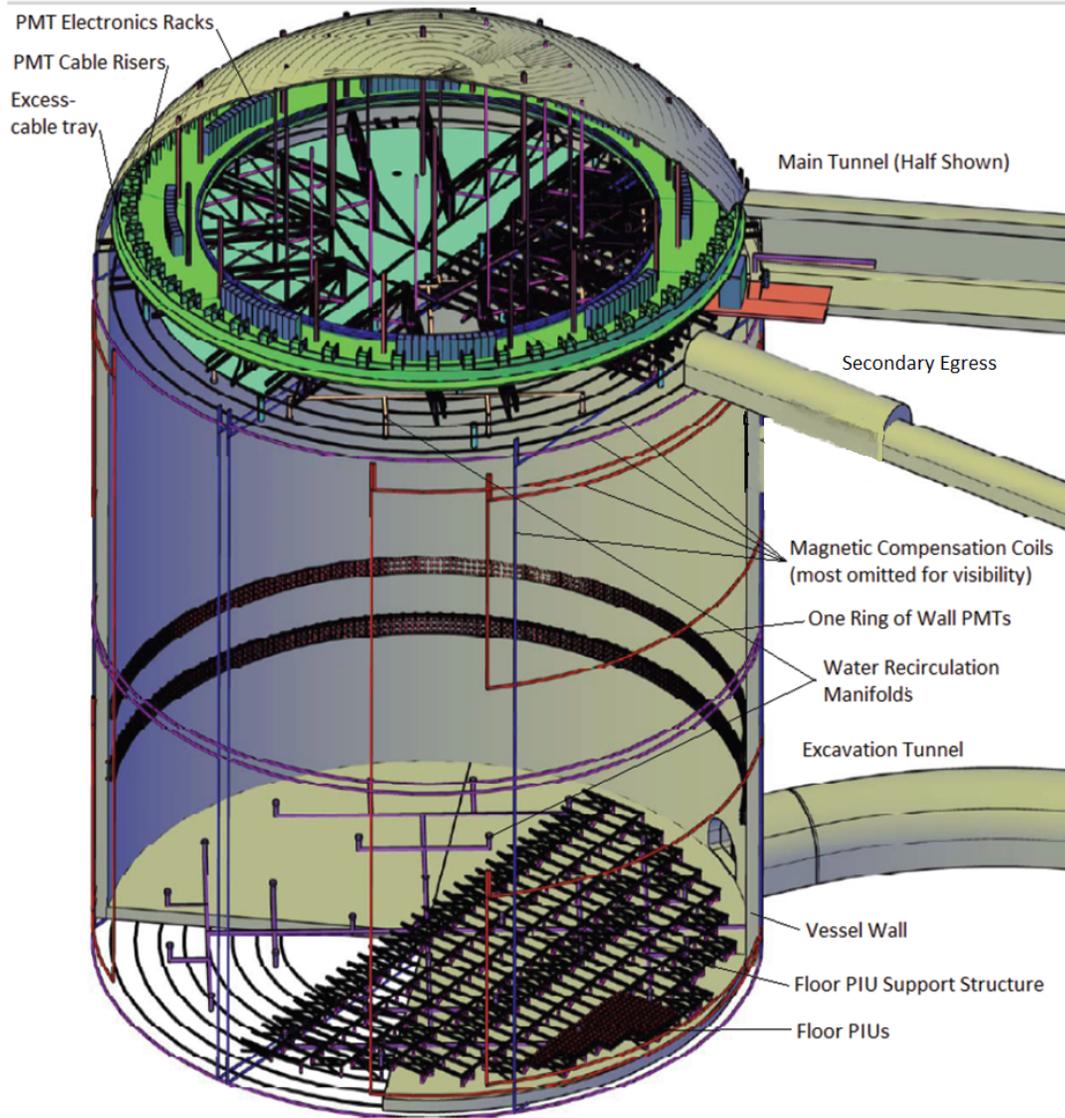


# CP Sensitivity – Target Mass



- Adding mass an effective way to improve sensitivity – adding later is difficult
- More mass helps all non-beam physics

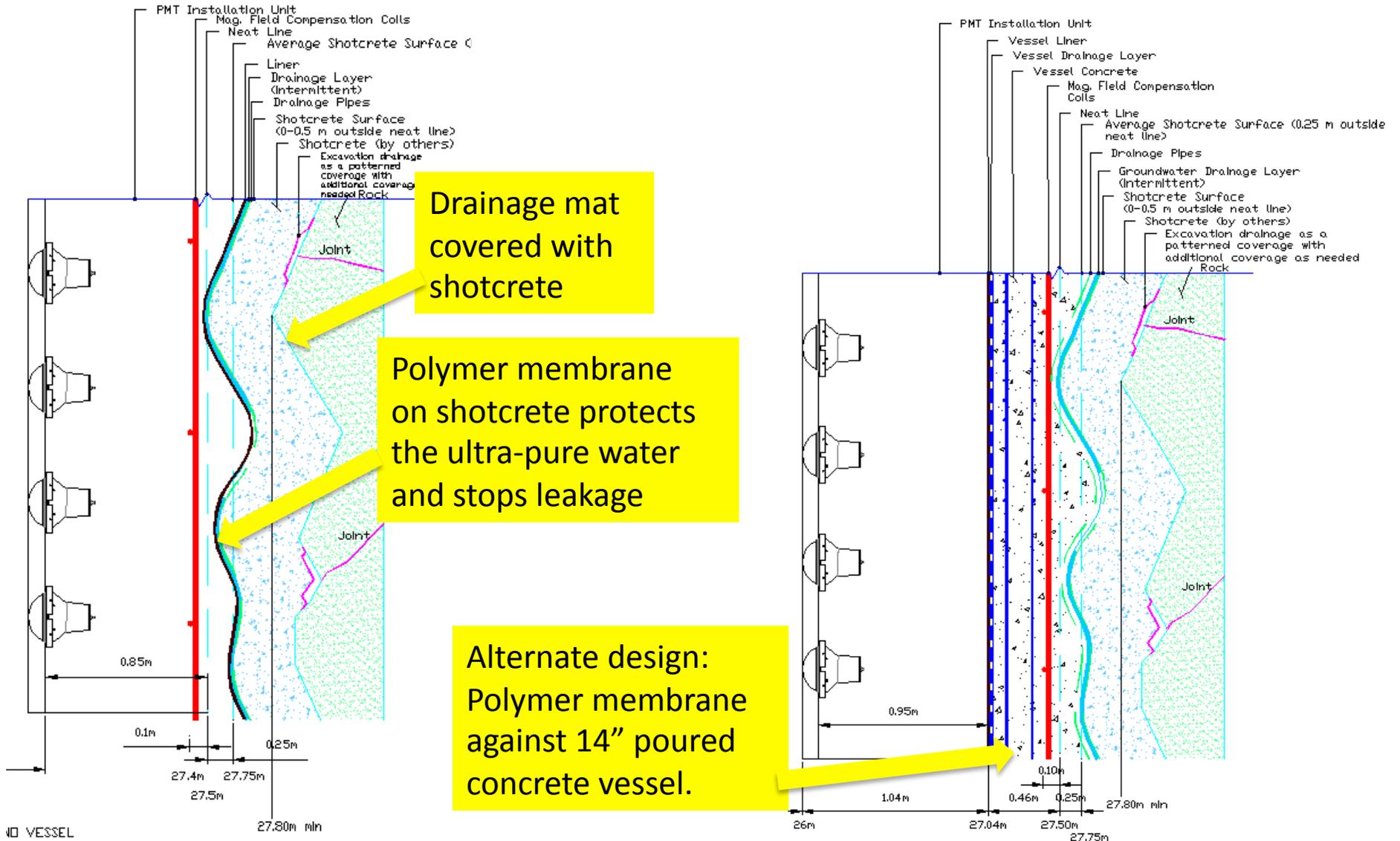
# Water Cherenkov Detector Overview



## Main Detector Components

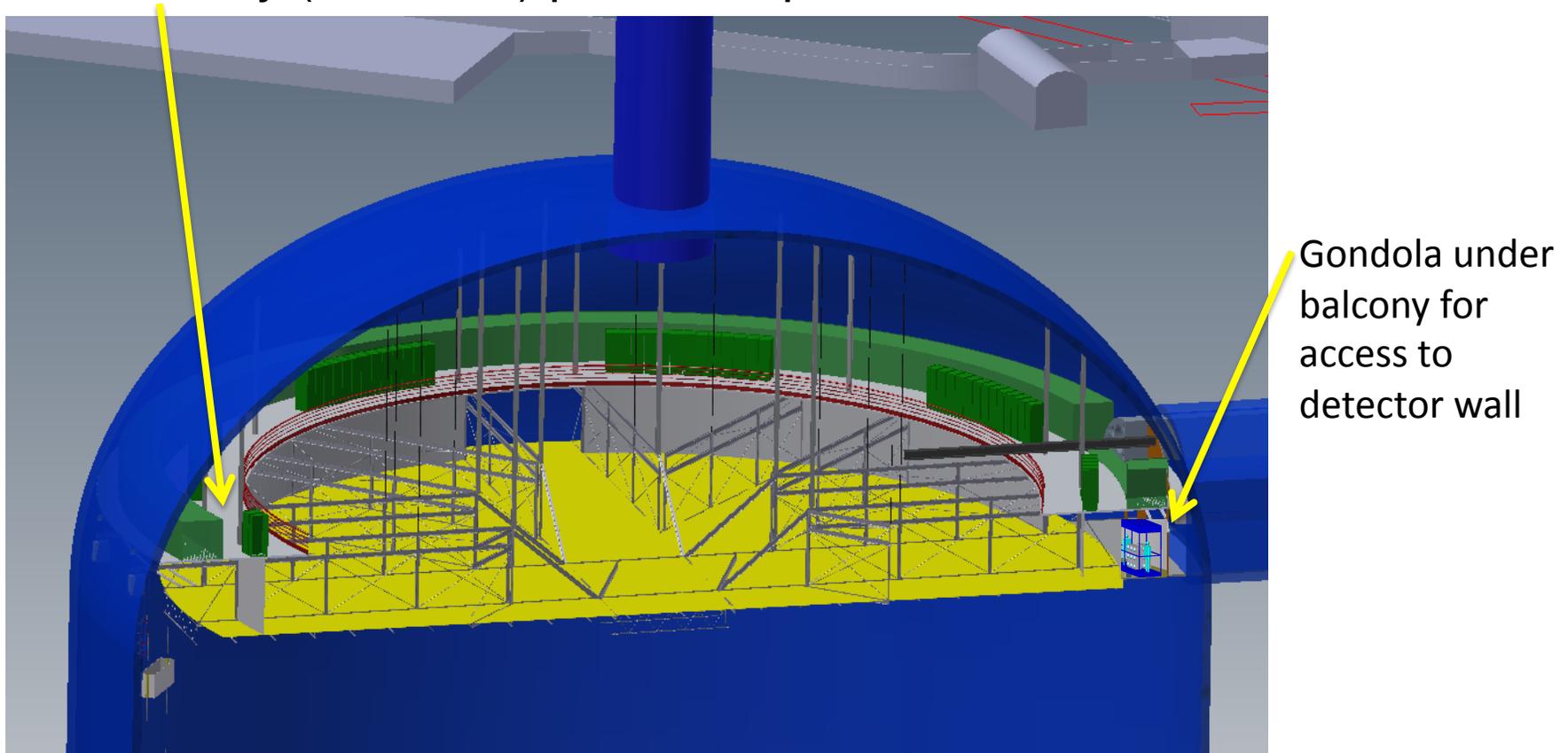
- Large Cavern
- Water Vessel
- Ultra-pure water system
- PMTs with Electronics
- 2 sizes under consideration:  
150 kt or 200 kt fiducial mass  
(7-9 x SuperK)
- **PMT + light collectors give  
photon detection  
efficiency equivalent to  
SuperK II**

# Water Containment

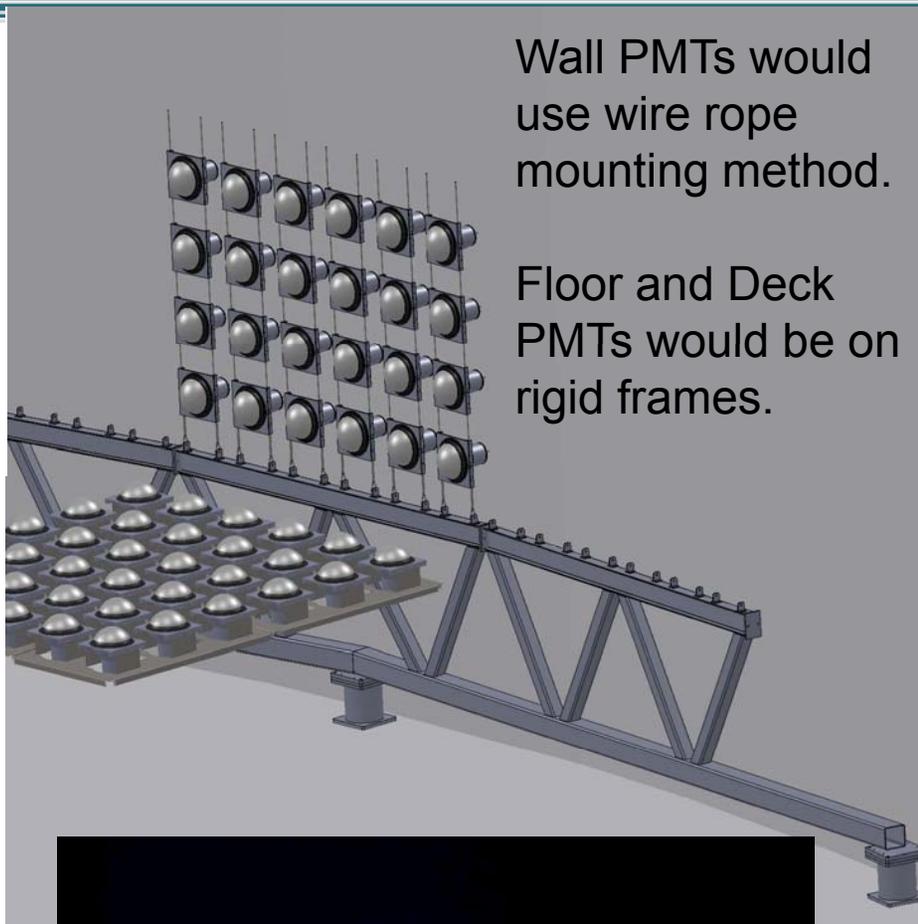


# Water Cherenkov Detector Deck

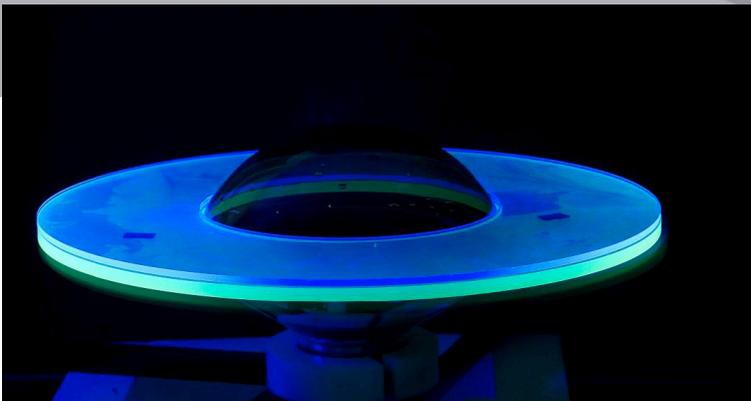
- Spans the 65m diameter cavern, suspended from the dome.
- Provides a light-tight, air-tight barrier for the detector.
- Balcony (8 m wide) provides space to mount electronics.



# Phototube System

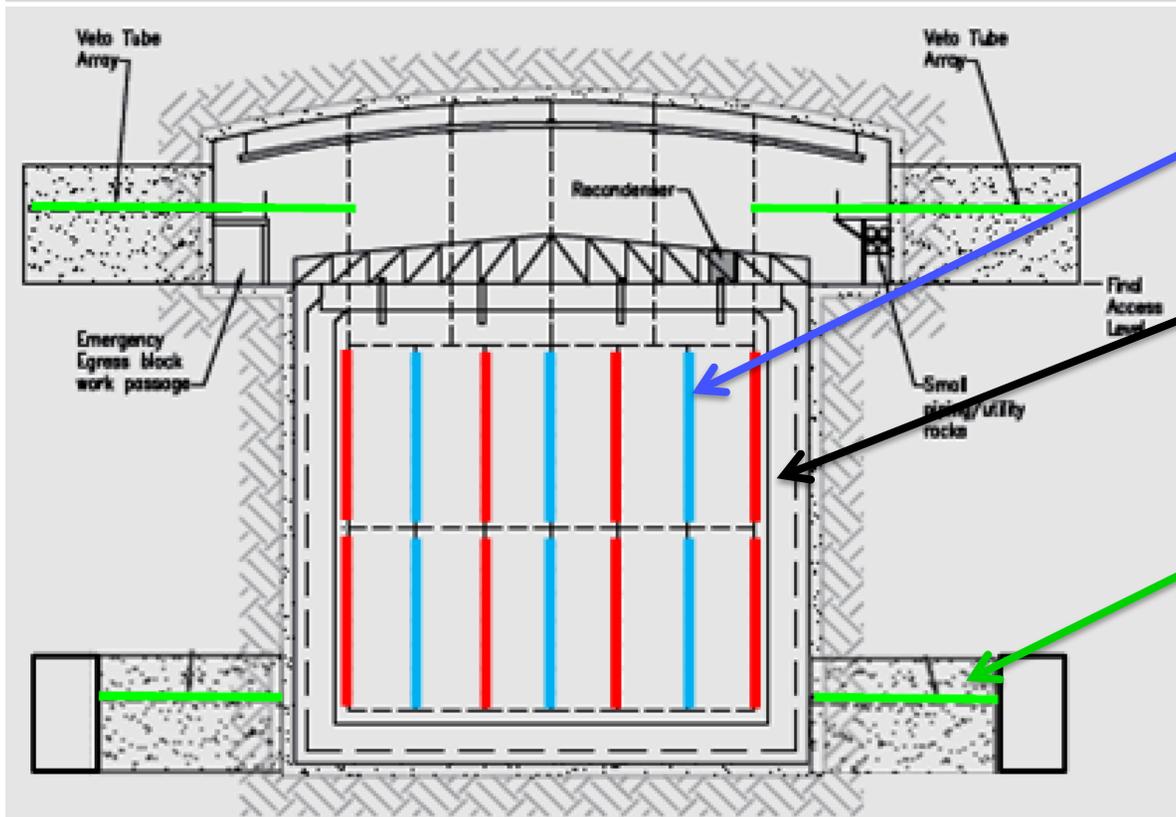


- 23,000 (29,000) 12" HQE PMTs in 150 kt (200 kt) detector
  - Will be catalogue item this year
  - Competing 11" tube also available this year
- Light collectors will be used
  - Winston cones or scintillator plates
  - 40% increase in light assumed
  - Both can achieve >50%
- HQE PMTs + light collectors give photon detection efficiency equivalent to SuperK II.



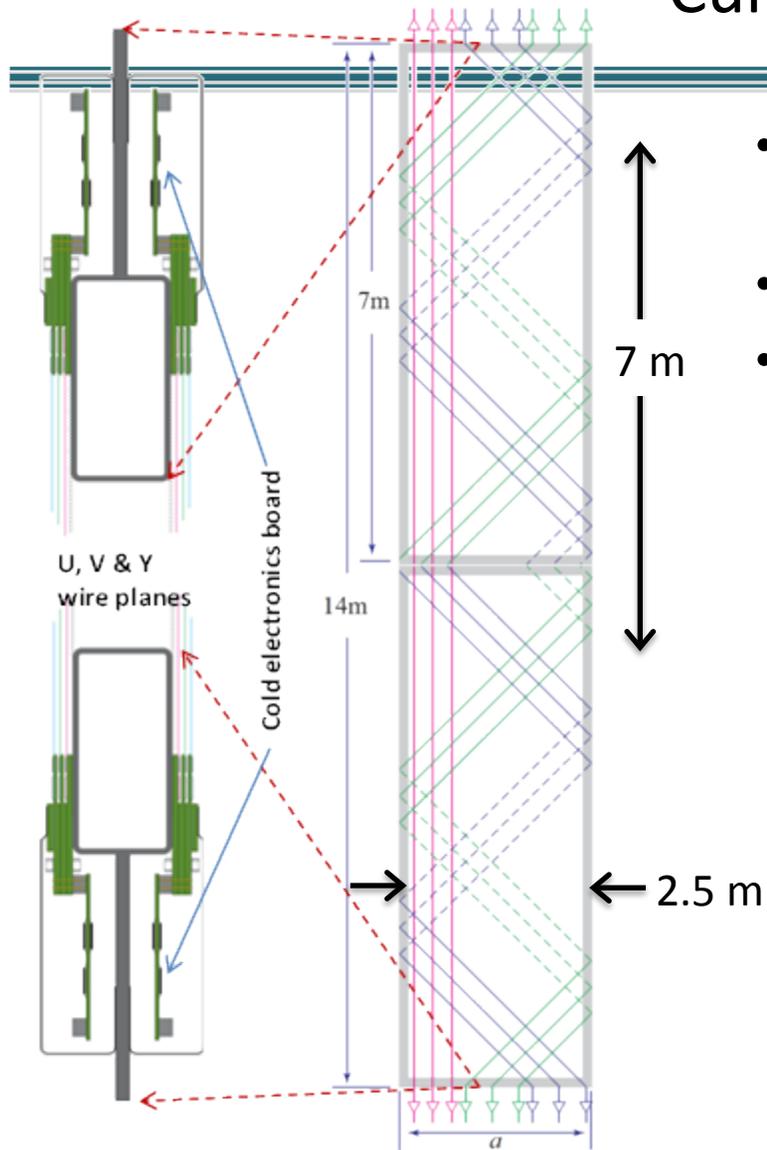
"flying saucer" - one design being considered

# Liquid Argon TPC Overview

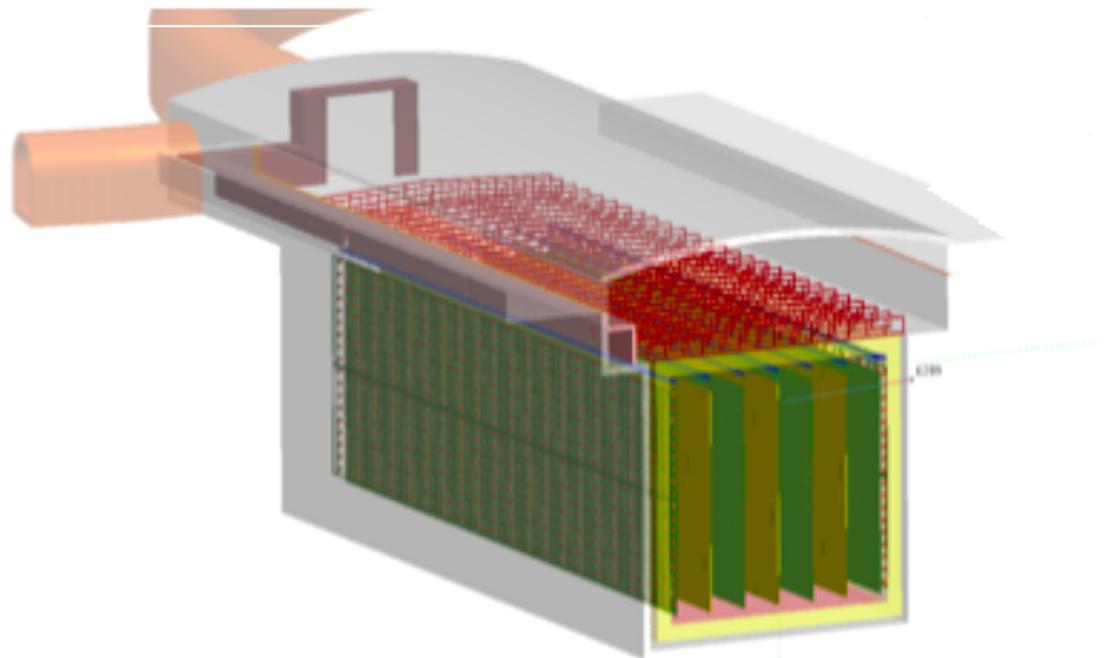


- Alternating Cathode and Anode Plane Assemblies (CPA, APA).
- Foam-insulated cryostat inside concrete containment vessel (membrane cryostat)
- Veto system to tag cosmic rays passing through the adjacent rock.
- Photon detectors provide  $t=0$  for non-beam physics.
- Two detectors, 12-17 kt each, in a common cavern at the 800 level.

# Current TPC Design



- Modular APA design: 3 views on a 2.5 m x 7 m frame, mounted 2 high in cryostat
- 3 or 5 mm wire pitch
- 3.75 m or 2.5 m drift cell

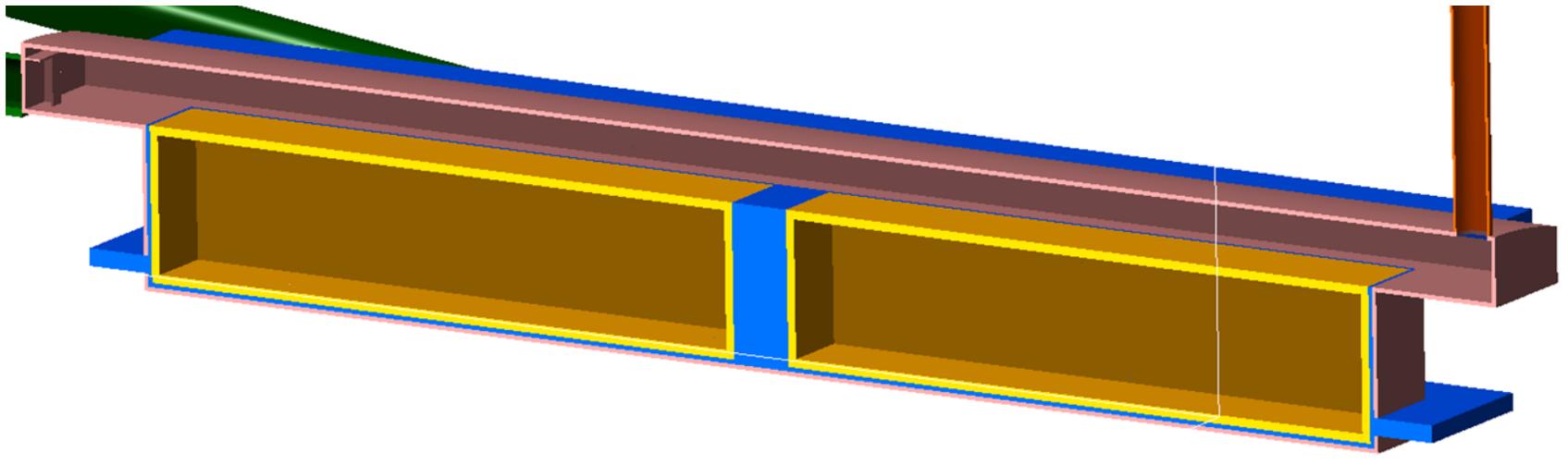


## LAr Detector Size

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- Active volume of each detector:
  - 20-22.5 m wide (depending on drift length)
  - 14 m high
  - 33-55 m long (depending on fiducial mass)
- Two detectors end-to-end in common cavern



# LAr Prototyping Program

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LBNE LAr development builds on world-wide R&D program

LBNE-specific prototyping program includes:

- 3 x 3 m<sup>2</sup> membrane cryostat wall panel – testing in progress
- 3 x 3 x 3 m<sup>3</sup> membrane cryostat prototype
  - Understand cryostat technology
  - Verify purity in this cryostat
  - Preliminary design complete; operational in 2012
- kton-scale full engineering prototype
  - Full engineering prototype of complete detector system
  - Leverage DZero infrastructure to minimize construction cost and time, and operating cost.
  - Early planning stage; schedule depends on funding, but could be operational in 2014.
- DOE panel estimate – ~five years of R&D required.
- It would make sense to have a common international program on this.

# Detector Mass Requirements

- The 200 kT mass selected for a WC detector is driven by the statistics necessary to address the physics goals in a ten year run, for  $\sin^2 2\theta_{13}$  in the range of current experimental sensitivity.
- If  $\sin^2 2\theta_{13}$  is outside this range, LBNE has enough sensitivity to make the most sensitive search for this parameter.
- The smaller 34 kT mass for LAr is based on the ability to use non-QECC events to look for  $\nu_{\mu} \rightarrow \nu_e$  oscillations due to event ID and NC rejection.
- Why the difference for WC and LAr?

	WC ( $\nu$ mode)	WC ( $\bar{\nu}$ mode)
<u>Normal mass hierarchy:</u>		
Oscillated $\nu_e + \bar{\nu}_e$	484	180
Beam $\nu_e + \bar{\nu}_e$	218	115
NC	276	118
Mis-identified $\nu_\mu$ CC	15	7
<u>Inverted mass hierarchy:</u>		
Oscillated $\nu_e + \bar{\nu}_e$	212	261
Beam $\nu_e + \bar{\nu}_e$	221	114
NC	276	118
Mis-identified $\nu_\mu$ CC	15	7

Table 6–1: Number of  $\nu_e$  and  $\bar{\nu}_e$  events expected in a 200 kton WC detector in 5 years each of neutrino and antineutrino running in a 700 kW beam. Rates have been integrated over the region from 0.5 – 12 GeV. In correspondence with Figure 6–1, this assumes  $\sin^2 2\theta_{13} = 0.04$  and  $\delta_{CP} = 0$ .

	LAr ( $\nu$ mode)	LAr ( $\bar{\nu}$ mode)
<u>Normal mass hierarchy:</u>		
oscillated $\nu_e + \bar{\nu}_e$	497	112
beam $\nu_e + \bar{\nu}_e$	326	168
NC	81	34
mis-identified CC	162	52
<u>Inverted mass hierarchy:</u>		
oscillated $\nu_e + \bar{\nu}_e$	212	261
beam $\nu_e + \bar{\nu}_e$	329	167
NC	81	34
mis-identified CC	162	52

Table 5–1: Number of  $\nu_e$  and  $\bar{\nu}_e$  events expected in a 34-kt LAr detector at 1300 km in 5 years each of neutrino and antineutrino running in a 700 kW beam [3]. Rates have been integrated over the region from 0.5 – 60 GeV. Like Figure 5–4, this assumes  $\sin^2 2\theta_{13} = 0.04$  and  $\delta_{CP} = 0$ .

Event rates for  $\nu_e$  and  $\bar{\nu}_e$  events in LAr (bottom) and WC (top).

Note the difference in the background components for the two detector types.

A measurement with two different detector types would be complimentary – the systematic uncertainties in the background are quite different.

# The Beam



# Beam Reference Design

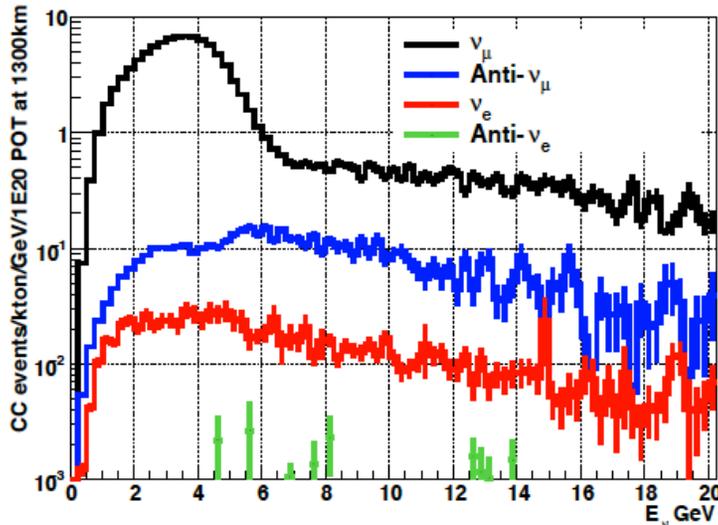
The LBNE design selected for physics studies maximizes the  $\nu_e$  appearance signal at 1300km.

**Target:** Carbon target,  $r=0.6\text{cm}$ ,  $l=80\text{cm}$ ,  $\rho = 2.1 \text{ g/cm}^3$ . Located -30cm from Horn1.

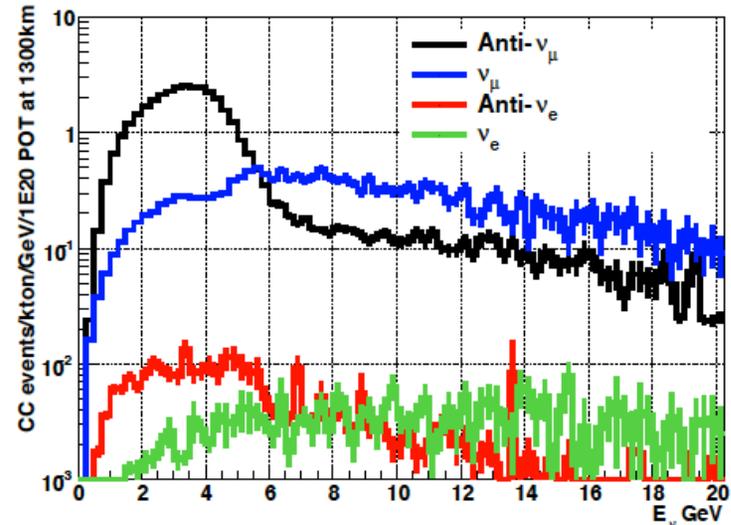
**Horns:** 2 Al NuMI Horns, 6m apart, 250 kA.

**Decay Pipe:**  $r=2\text{m}$ ,  $l=280\text{m}$ , He filled/evacuated.

Aug 2010 Neutrino Beam



Aug 2010 Anti-Neutrino Beam

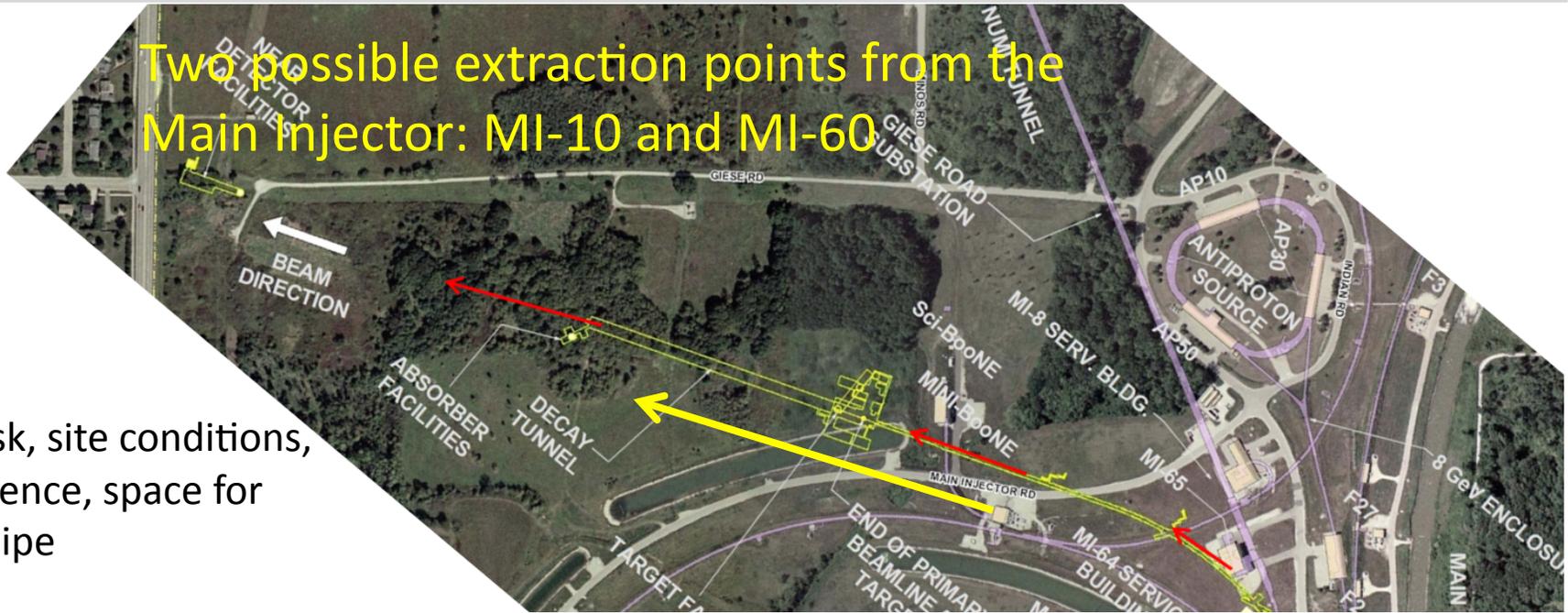


Oscillation CC rates/(100 kT.MW.yr):

$$\nu \text{ beam, } \Delta m_{31}^2 = +2.5 \times 10^{-3} \text{ eV}^2, \delta_{\text{CP}} = 0, \sin^2 2\theta_{13} = 0.04$$

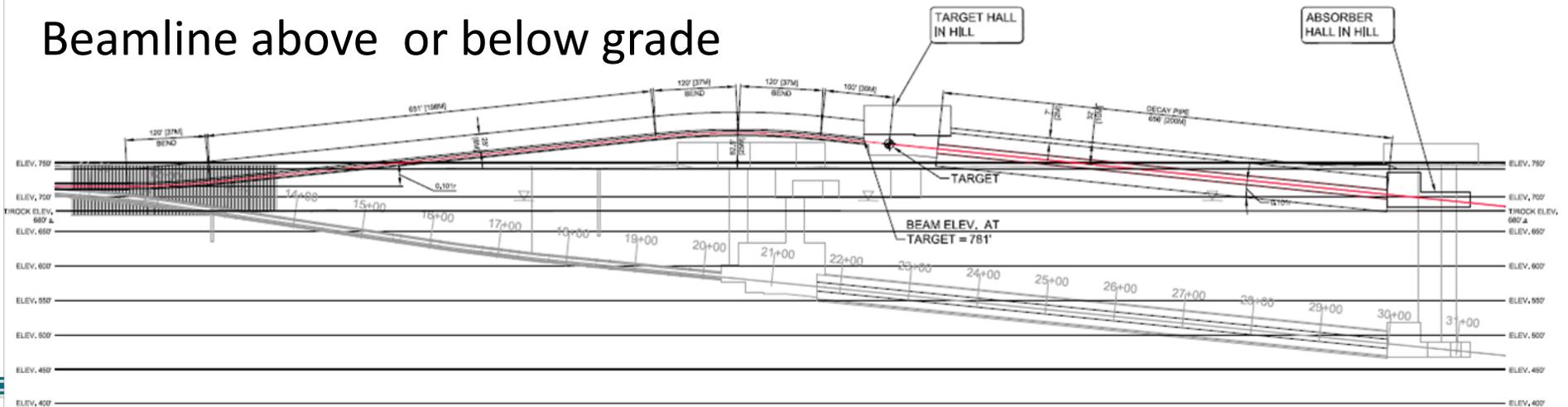
Beam Tune	$\nu_\mu$	$\nu_\mu$ osc	$\nu_e$ beam	$\nu_\mu \rightarrow \nu_e$	$\nu_\mu \rightarrow \nu_\tau$
Low-Energy (LE)	29K	11K	260	560	140

# OVERVIEW: Four options for the neutrino beam



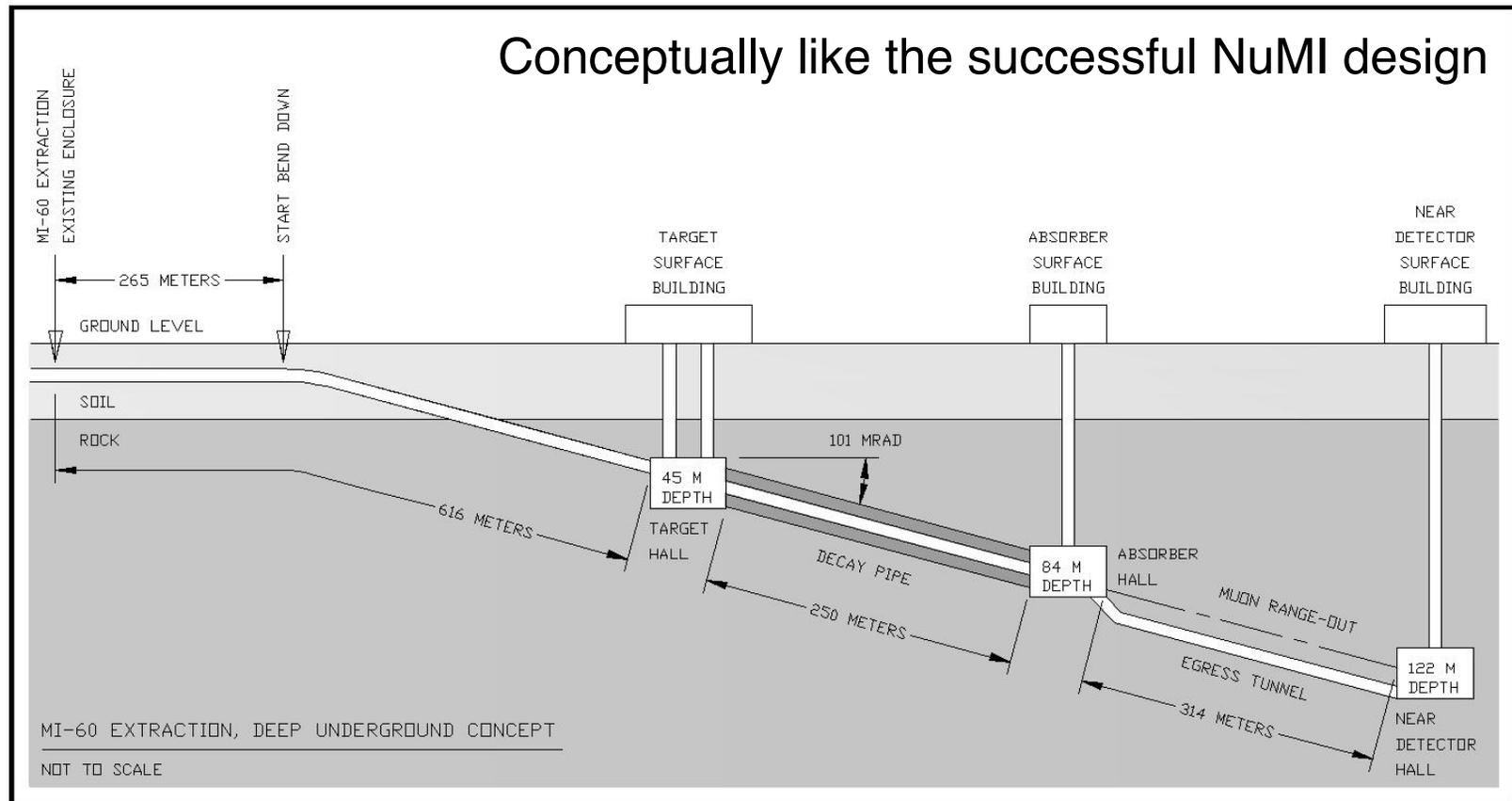
Cost, risk, site conditions, interference, space for decay pipe

## Beamline above or below grade





# Most Conservative: MI-60, deep



- Longer primary proton beamline
  - Significant excavation deep underground
- => Substantially higher cost

# Where to now?





- The "blue ribbon" panel has completed its report – it is quite favorable, and we are promised a clear decision by DOE as to what extent they will use the Homestake site – not only for LBNE but for all the "underground" science experiments. This decision needs to be made in time for FY13 budget request, **by end of this summer**.
- A decision on which technology to pursue (water or liquid argon) will be made as soon as possible – delayed due to NSF and DUSEL uncertainty. **Collaboration would like to pursue both** – but probably too expensive without **significant** international participation.
- Next Science Collaboration meeting July 13-15 at Fermilab. "Observers" welcome, as are new collaborators!

# Backup Slides

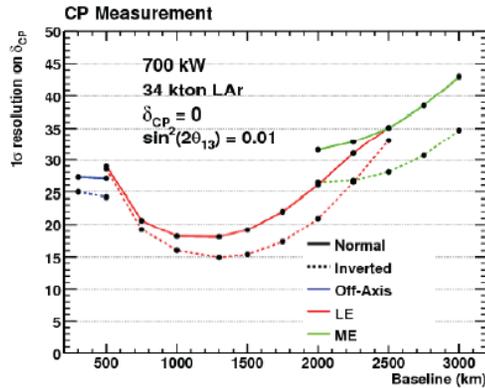


Figure 6-2: Sensitivity of LBNE to neutrino the CP-violating phase  $\delta$  with the LAr40 Far Detector, as a function of baseline for on-axis “low” (red) and “medium” energy (green) beam configurations, as well as for an off-axis beam (blue).

Baseline and beam options for LAr show that 1300 km is still a near optimal distance.

Note: possible shorter baseline experiments may not be able to determine mass ordering, especially off-axis.

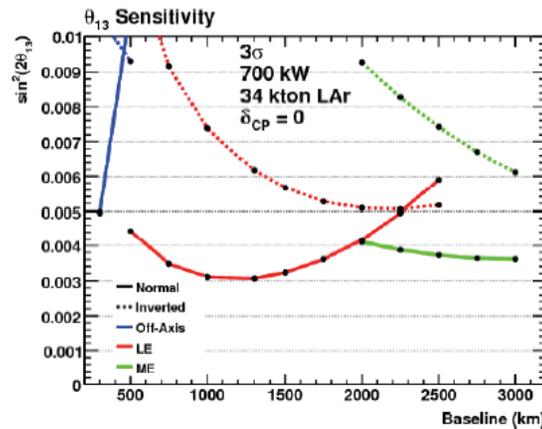
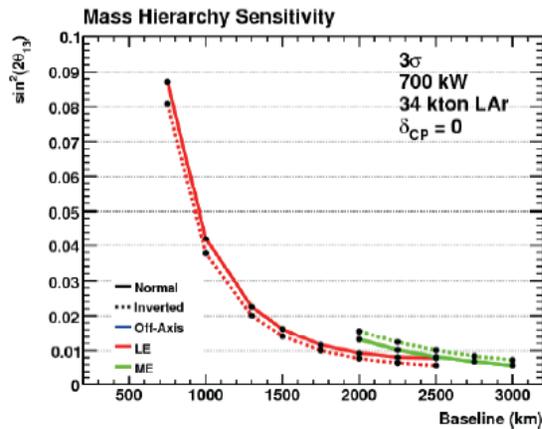
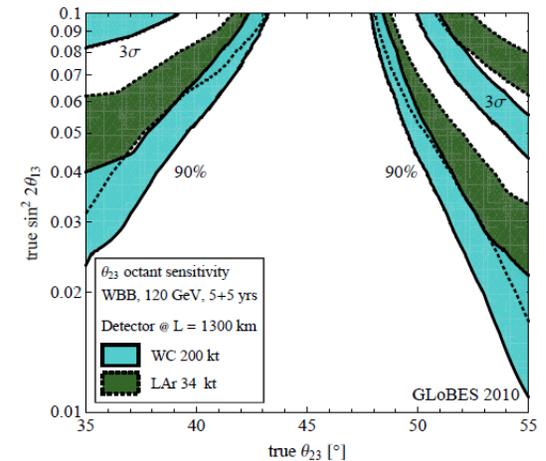
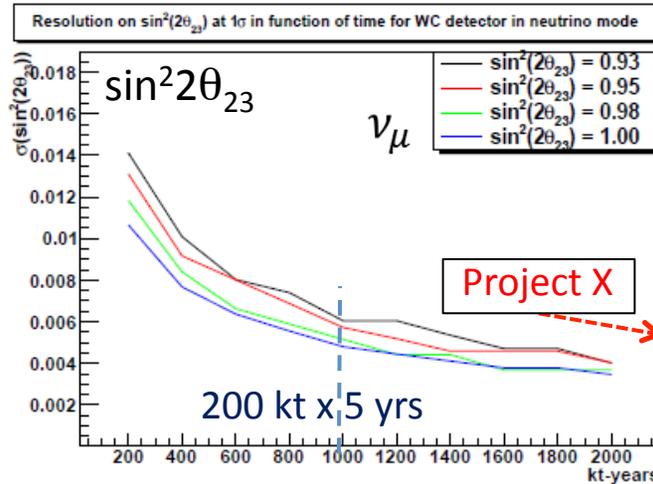
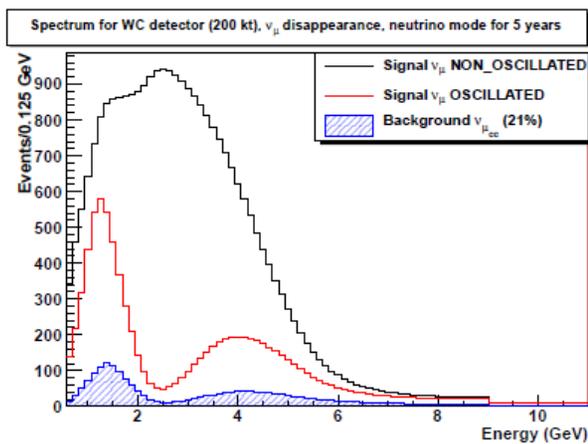


Figure 6-1: Sensitivity of LBNE to neutrino mass hierarchy (left) and  $\theta_{13}$  (right) with the LAr40 Far Detector, as a function of baseline for on-axis “low” (red) and “medium” energy (green) beam configurations, as well as for an off-axis beam (blue).

# $\nu_\mu/\bar{\nu}_\mu$ Disappearance



- $\sin^2 2\theta_{23}$  to  $\sim 0.6\%$  and  $\Delta m_{31}^2$  to  $\sim 0.8\%$  precision in 5-year  $\nu$  run
  - “Competitive” to NOvA full run
- Clear multiple oscillation pattern due to very long baseline
- Resolve  $\theta_{23}$  octant degeneracy for angles  $< 40^\circ$  if  $\sin^2 2\theta_{13} > 0.075$  (WCD slightly better)
  - NOvA cannot due to  $\sin^2 2\theta_{23}$  and  $\delta_{CP}$  correlations (would combine w/ Daya Bay)

# Expected Backgrounds for $p \rightarrow e^+\pi^0$

Calculated:  $2.1 \pm 0.9$  ev/Mton/yr

Measured\*

in LE beam:  $1.63 (+0.42/-0.33 \text{ stat}) (+0.45/-0.51 \text{ syst.})$  ev/Mton/yr

- Super-Kamiokande currently has **NO** candidates at 0.141 Mton-yr
- A 0.2 Mton detector would have  $\sim 4$  background events after 10 years.
- **Can this be improved?**

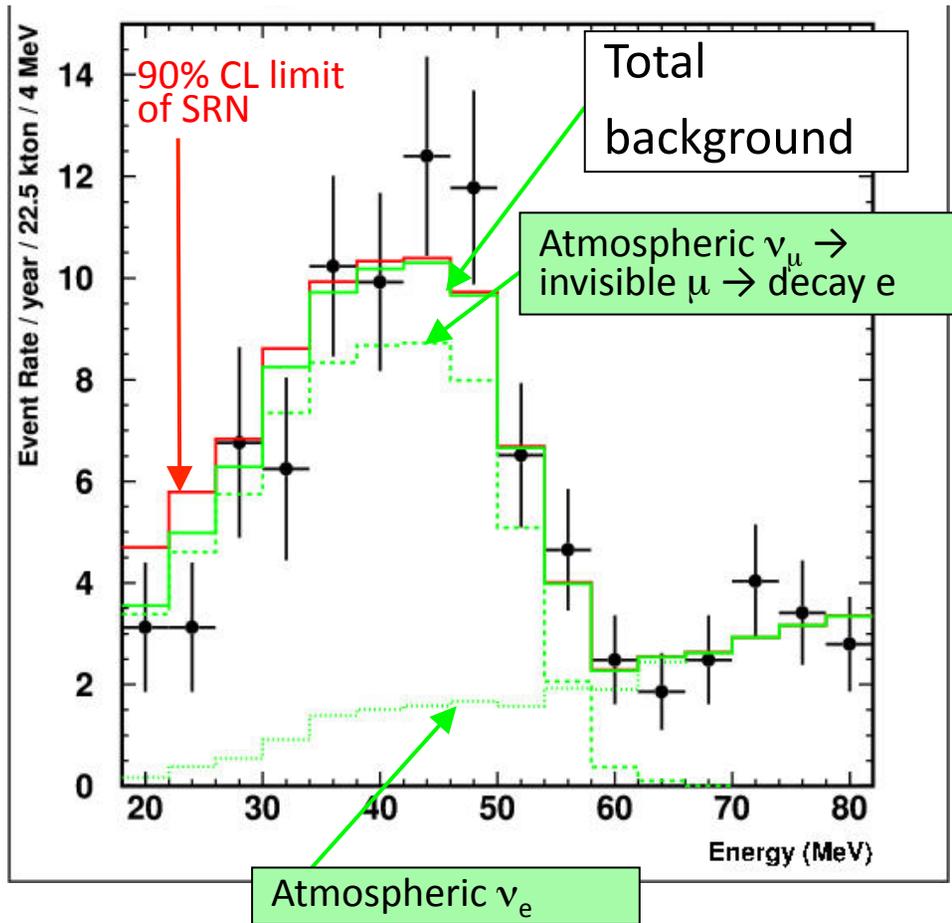
Higher resolution and improved detector capabilities have improved backgrounds in the past.

	$\epsilon \times B_{\text{meson}}$	BKG (/Mtonyr)	BG (/yr)
<i>IMB3</i>	0.48	26	0.087
<i>KAM-I</i>	0.53	<15	<0.015
<i>KAM-II</i>	0.45	<8	<0.008
<i>Super-K</i>	0.44	2.1	0.047

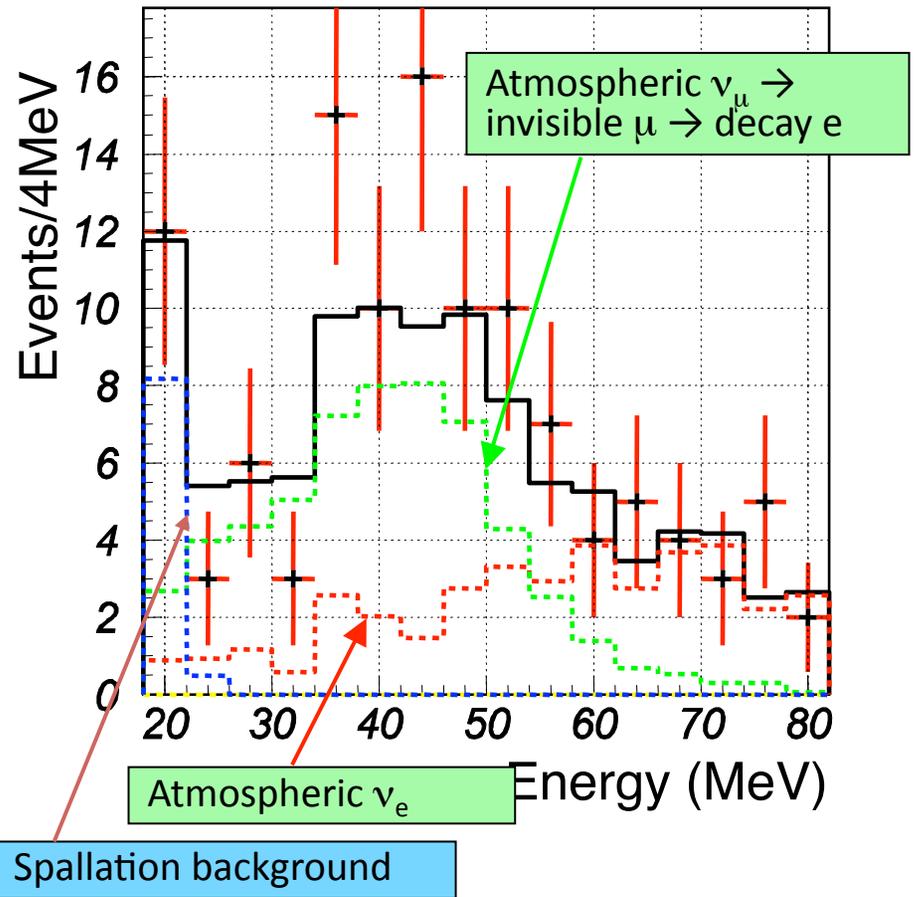
\*PRL 102:141801 (2009)

# SRN results of SK-I and SK-II

SK-I (1496days)



SK-II (791 days)



Observed spectra are consistent with estimated backgrounds.  
Searches are limited by the invisible muon background (SK-I)  
and the spallation background (SK-II)..

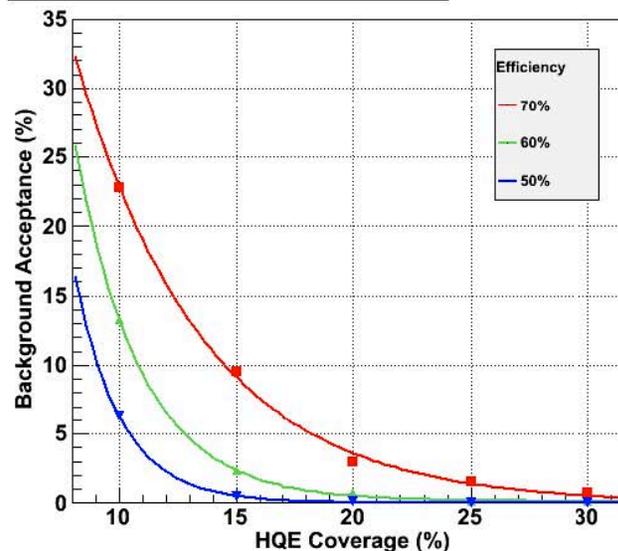
Hit level simulations show that at 12% coverage detection of Gd capture is marginal. Includes effects of gammas from glass, rock, and radon, plus dark noise.

Coverage	background@70% efficiency
12%	15%
24%	1.5%

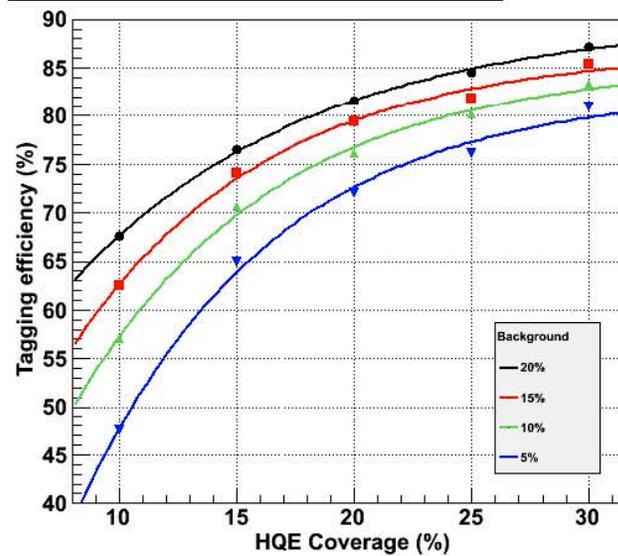
Coverage	efficiency@ 5% mid-ID
12%	55%
24%	77%

Driver is reduction of background from “stealth” muons by tagging actual IBDK events.

Fixed Tagging Efficiency (80cm buffer)



Fixed Background Acceptance (80cm buffer)

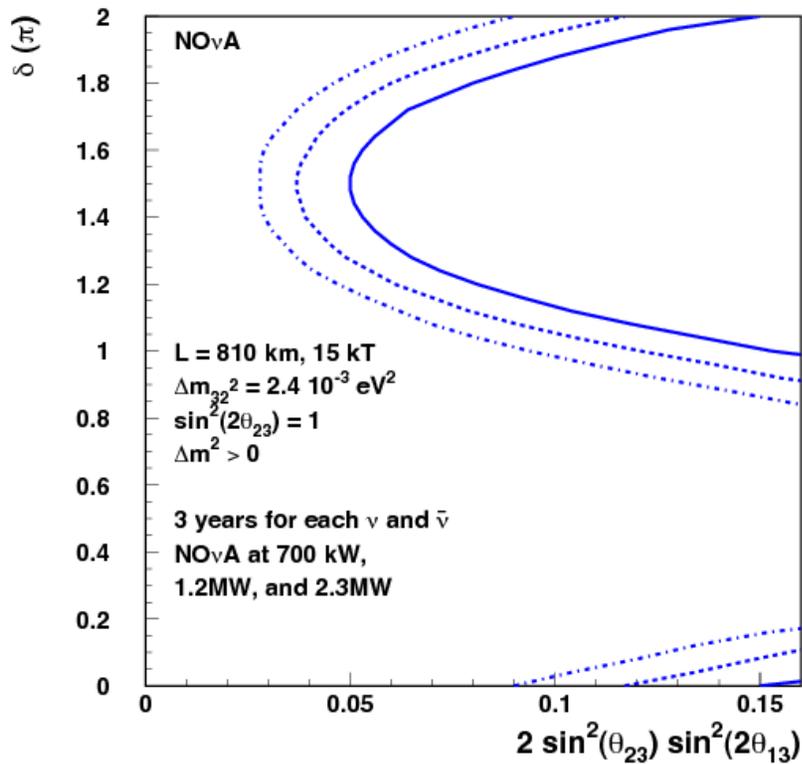


# NO $\nu$ A

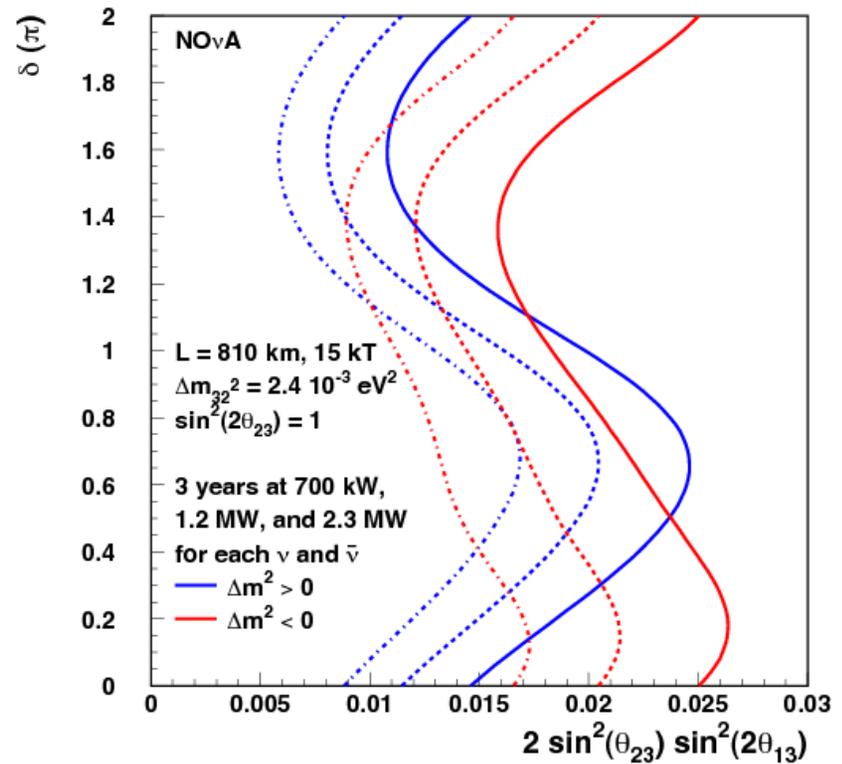
NH

Note: Figure caption says “2-sigma”

95% CL Resolution of the Mass Ordering



3  $\sigma$  Sensitivity to  $\sin^2(2\theta_{13}) \neq 0$



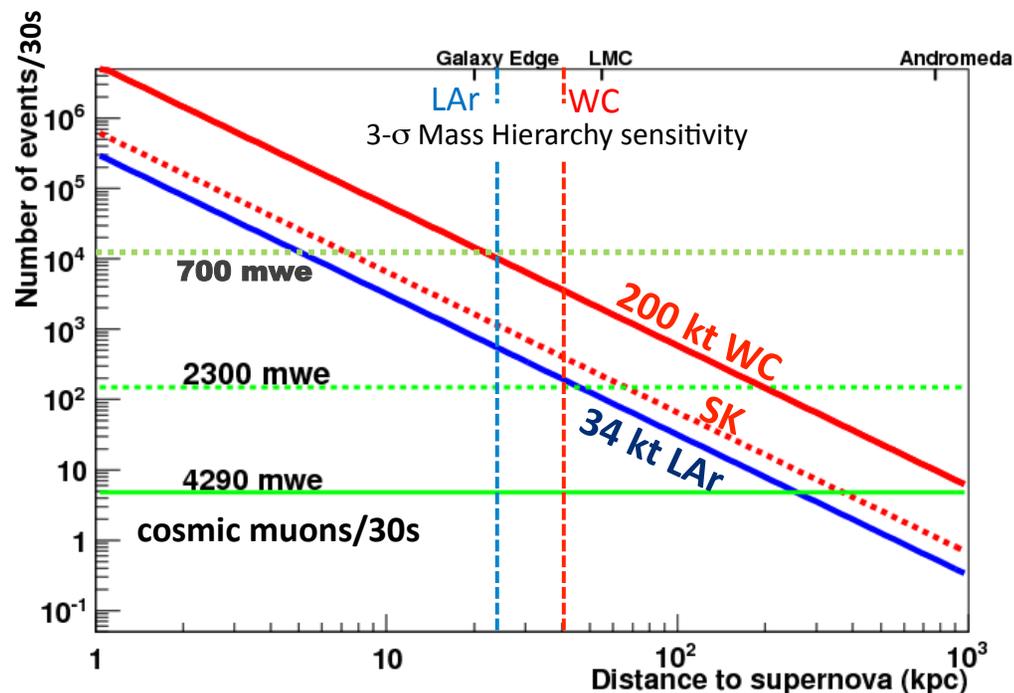
# South Dakota's commitment to science

**S.D. Legislature: \$ 50,303,000**  
**H.U.D. Grant: \$ 10,000,000**  
**Denny Sanford donation: \$ 70,000,000**  
**Total state commitment: \$130,303,000\***

*•Note: Sanford gift includes \$5 million for Sanford Center for Science Education construction and \$15 million endowment for operating it.*



# SN Rates and Reach



Significant difference in model event rate prediction - but still large

Channel	Events, "Livermore" model	Events, "GKVM" model
$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	2308	2848
$\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^+ + {}^{40}\text{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	2798	3160

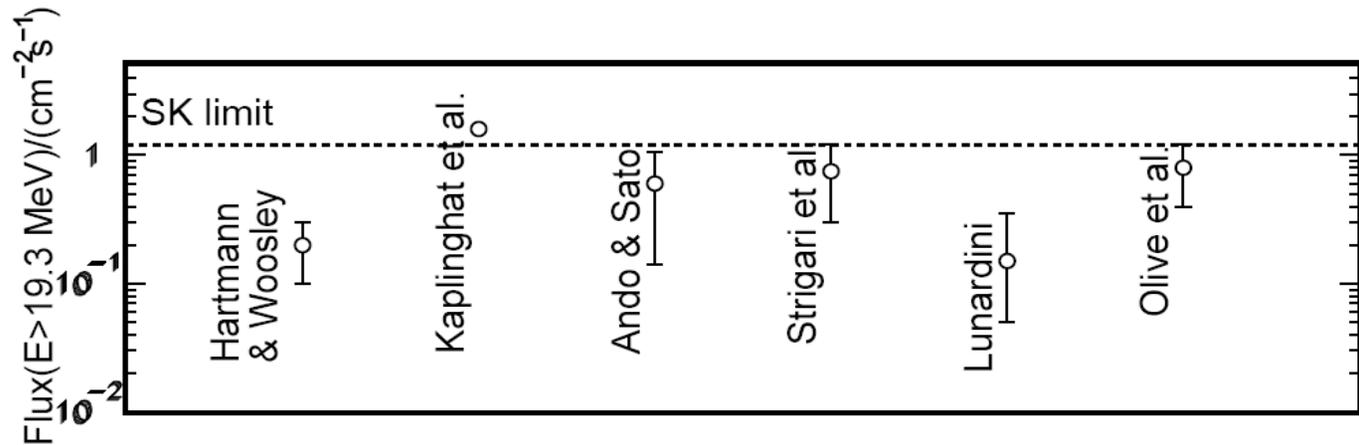
Table 5-6: Event rates for different models in two 17 kt modules of LAr.

Channel	Events, "Livermore" model	Events, "GKVM" model
$\bar{\nu}_e + p \rightarrow e^+ + n$	50272	30442
$\nu_x + e^- \rightarrow \nu_x + e^-$	1198	774
$\nu_e + {}^{16}\text{O} \rightarrow e^- + {}^{16}\text{F}$	170	748
$\bar{\nu}_e + {}^{16}\text{O} \rightarrow e^+ + {}^{16}\text{N}$	1379	968
$\nu_x + {}^{16}\text{O} \rightarrow \nu_x + {}^{16}\text{O}^*$	2	0.5
Total	53021	32932

Table 8-1: Event rates for different models in 200 kton of water.

- Larger detector mass -> further reach
- Could potentially resolve Mass Hierarchy to 3- $\sigma$  out to Galaxy Edge (both LAr & WC) if "spectral swap" features observed
- In a hybrid WCD+Lar: Good spectral information of  $\nu_e$  from LAr will help resolve flavor content of the primarily  $\nu_e$ -bar in WCD

Published SK limit on diffuse SN flux compared with several models



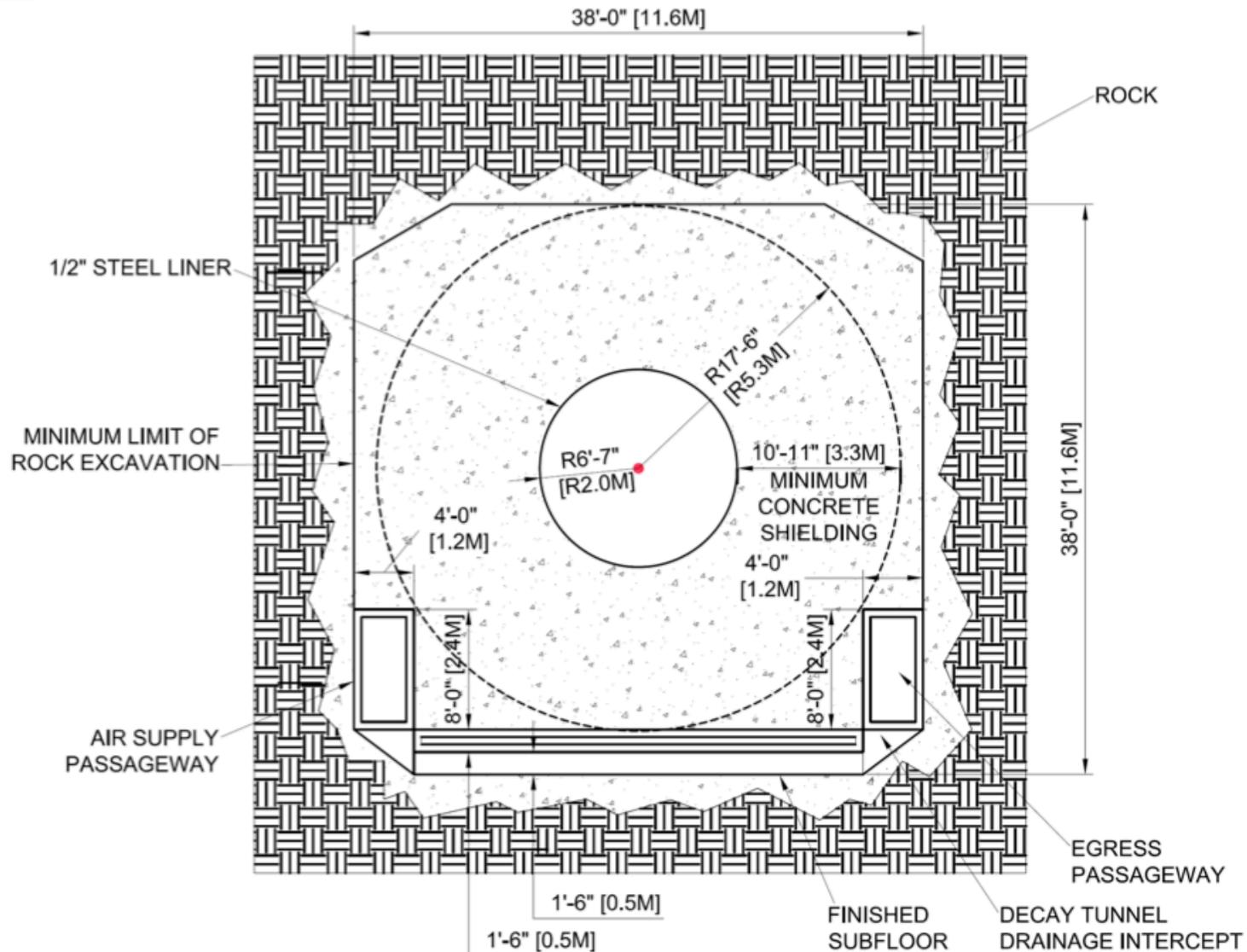
The Homestake muon rate an order of magnitude smaller than Kamioka, so expect 15.5 MeV threshold instead of 19.3 MeV. **This enhances signal by 40% in addition to just detector mass scaling.**

Due to geomagnetic latitude, atmospheric neutrino rate per kton is 50% higher at Homestake as compared to Kamioka. **This enhances background by 50%.**

Reference Configuration Number	Expected Annual SRN Signal (events/year)	Expected Annual Background (events/year)	Years of LBNE Data Needed for a 3.0- $\sigma$ Signal Assuming Maximum SRN Flux	Years of LBNE Data Needed for a 3.0- $\sigma$ Signal Assuming Minimum SRN Flux
Baseline	2 – 27	187	2.9	526
+ PMTs	3 – 35	214	2.0	268
+ PMTs + Gd	9 – 50	43	0.19	1.3

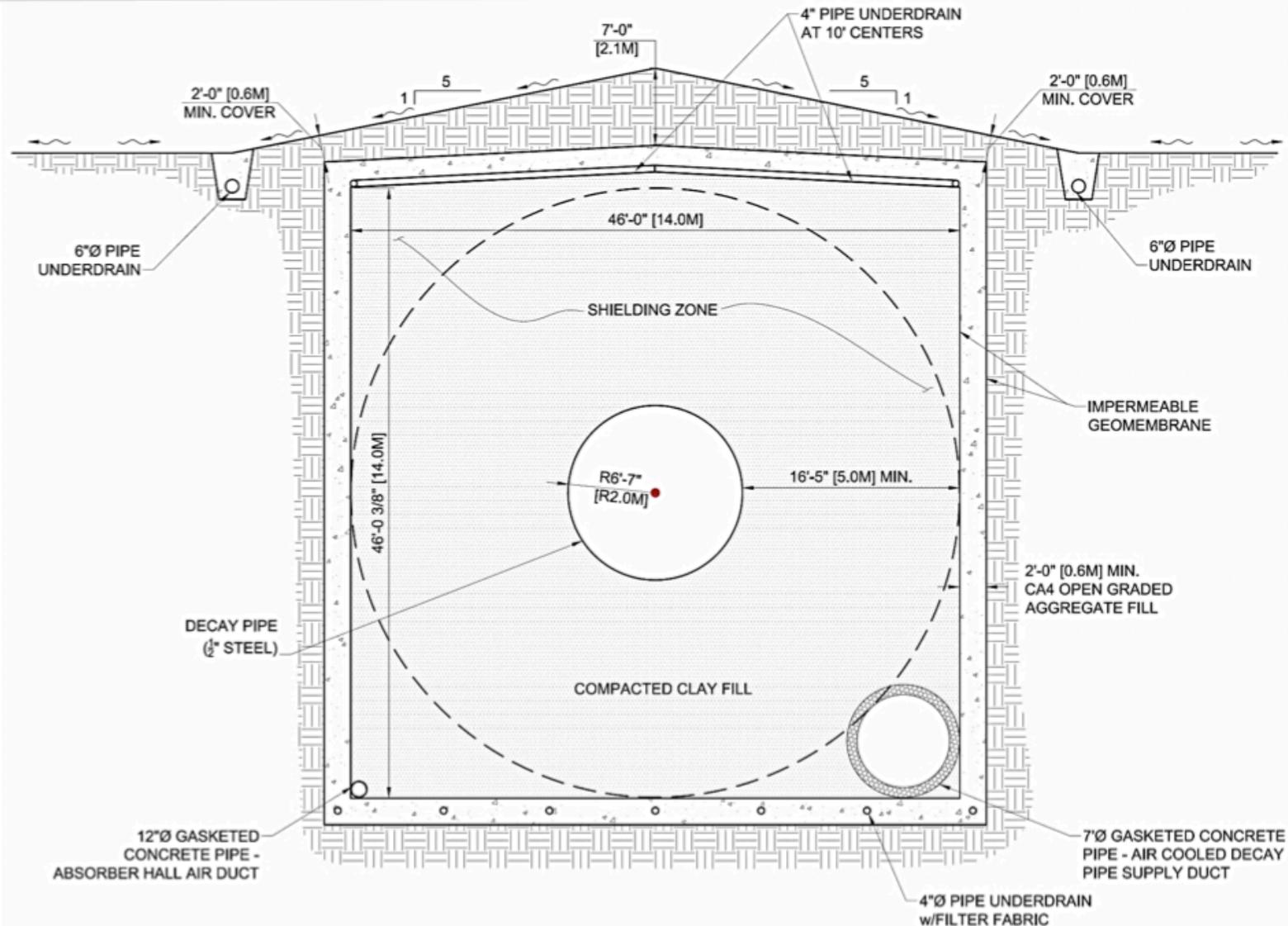
# Design Evolution and Options

## MI-60 Deep – Decay Pipe Section



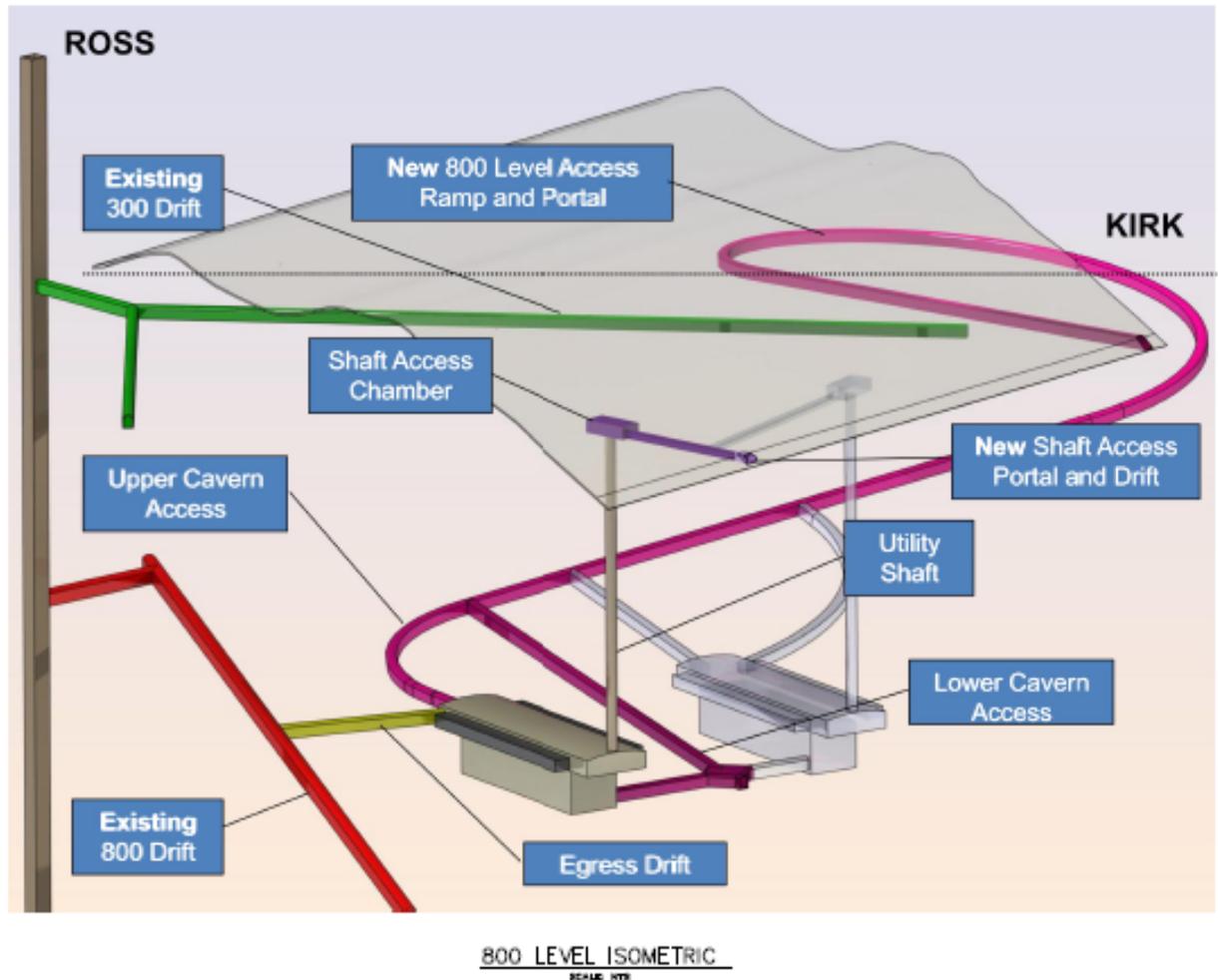
# Design Evolution and Options

## MI-10 Shallow – Decay Pipe Section

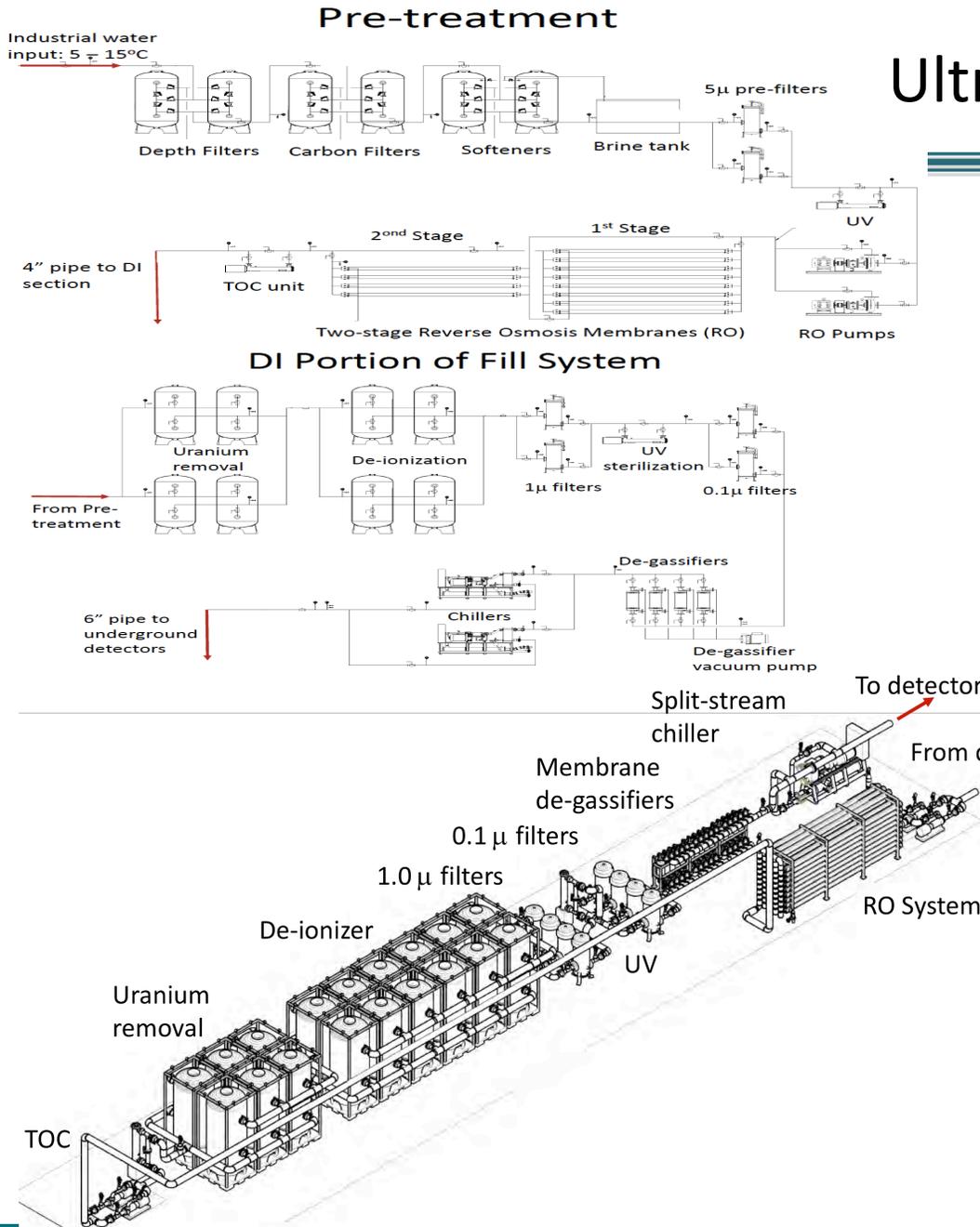


# LAr 800 level lab at Homestake

- 24-34kt cavern at 800 level
- Space on surface for cryogenics system
- Drive-in access for experiment installation
- Experimental utilities: power, ventilation for cryogenic safety
- Why 800 level?
  - SN detection, atmospheric neutrinos detection improved
  - Critical for proton decay



# Ultra-Pure Water System



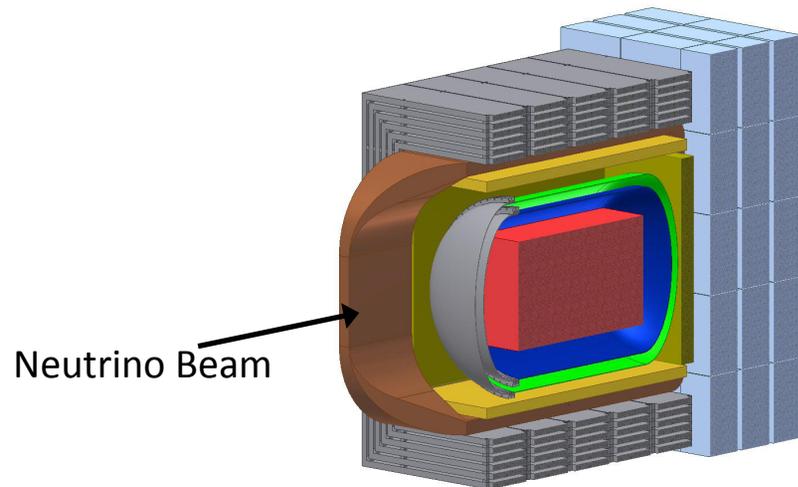
## 125 gal/min fill system

- takes industrial water
- filters and removes minerals
- Removes gasses, U/Th and sterilizes
- 4.5 to 6 months to fill

## 700-1200 gal/min recirculation system

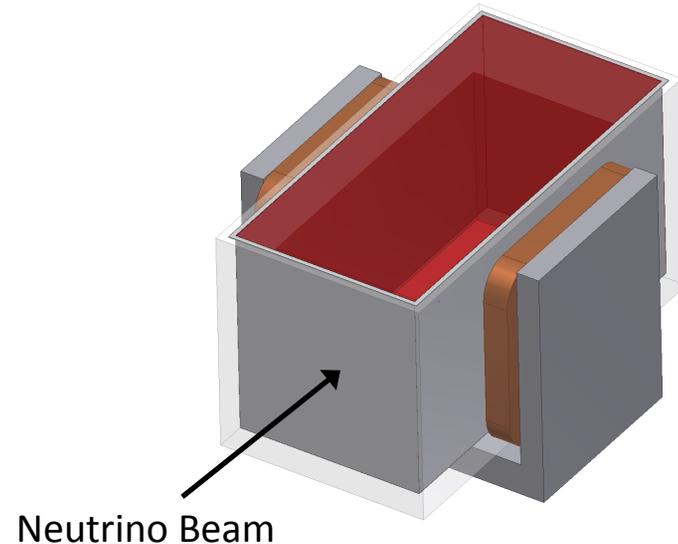
- Filters and sterilizes the water
- Removes U/Th and gasses
- Removes heat
- Cooling to 13-15 degrees

# Near Neutrino Detector Options: LAr Far Detector



## TPC Tracker

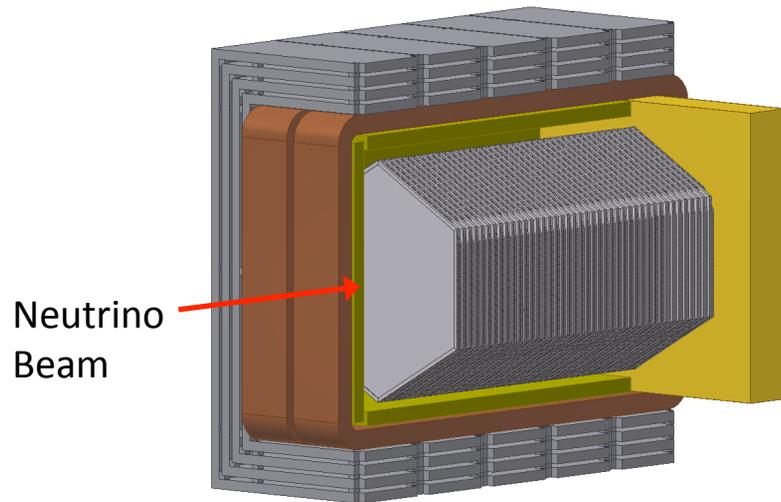
- 0.4 T dipole
- Small TPC (13 tons)
- Instrumented dipole yoke and downstream EM and hadron calorimeters



## LAr Membrane Tracker

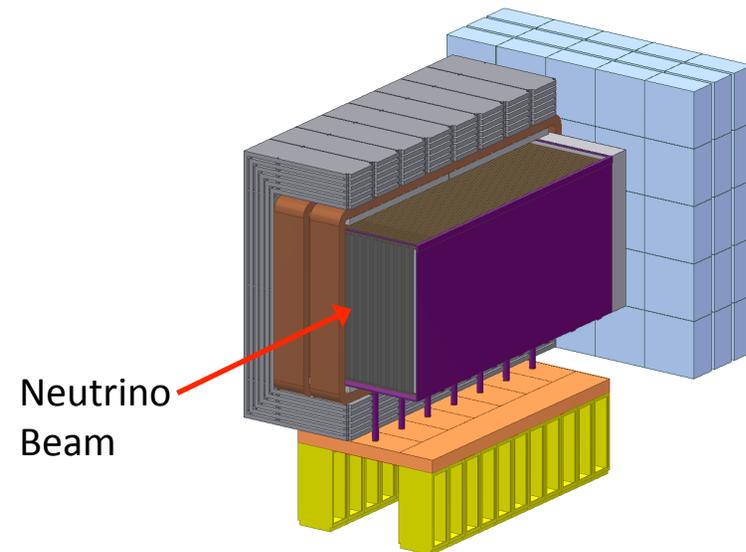
- 0.4 T dipole (central field)
- Larger TPC (350 tons)
- Full containment of hadrons and EM showers
- Mimics far detector.

# Near Neutrino Detector Options: H<sub>2</sub>O Far Detector



## Scintillator Tracker

- 0.4 T dipole
- MINERvA(-like) scintillator strips – totally active.
- Embedded H<sub>2</sub>O and D<sub>2</sub>O targets
- Instrumented dipole yoke and downstream EM calorimeter.



## Straw Tube Tracker

- 0.4 T dipole
- Low-density straw tube tracker (based on NOMAD design)
- Embedded H<sub>2</sub>O and D<sub>2</sub>O targets
- Instrumented dipole yoke and downstream EM calorimeter.

	WC ( $\nu$ mode)	WC ( $\bar{\nu}$ mode)
<u>No oscillations:</u>		
QE signal	27,947	18,220
non-QE background	5,884	3,767
wrong-sign background	–	2,725
<u>With oscillations:</u>		
QE signal	8,955	5,500
non-QE background	1,888	1,133
wrong-sign background	–	1,366

Table 6–3: Number of  $\nu_\mu$  and  $\bar{\nu}_\mu$  events expected in a 200 kton WC detector for 5 years each of neutrino and antineutrino running in a 700 kW beam. Rates have been integrated over the region from 0 – 10 GeV. The signal samples are assumed to be  $\nu_\mu$  ( $\bar{\nu}_\mu$ ) QE events in the case of neutrino (antineutrino) mode running. Wrong-sign backgrounds refer to  $\nu_\mu$  events in the antineutrino mode beam.

	LAr ( $\nu$ mode)	LAr ( $\bar{\nu}$ mode)
<u>No oscillations:</u>		
CC signal	26,040	10,248
NC background	51	23
wrong-sign background	–	3,110
<u>With oscillations:</u>		
CC signal	8,489	3,182
NC background	51	23
wrong-sign background	–	1,791

Table 5–3: Number of  $\nu_\mu$  and  $\bar{\nu}_\mu$  events expected in a 34 kt LAr detector for 5 years each of neutrino and antineutrino running in a 700 kW beam [3]. Rates have been integrated over the region from 0 – 10 GeV. The signal samples are assumed to be  $\nu_\mu$  ( $\bar{\nu}_\mu$ ) CC events in the case of neutrino (antineutrino) mode running. Wrong-sign backgrounds refer to  $\nu_\mu$  events in the antineutrino mode beam.

Event rates for numu and numubar events in LAr (bottom) and WC (top).

These tables indicate why sensitivities are similar in this mode. The wrong-sign background in LAr is compensated by the reduced background from non-QE/NC