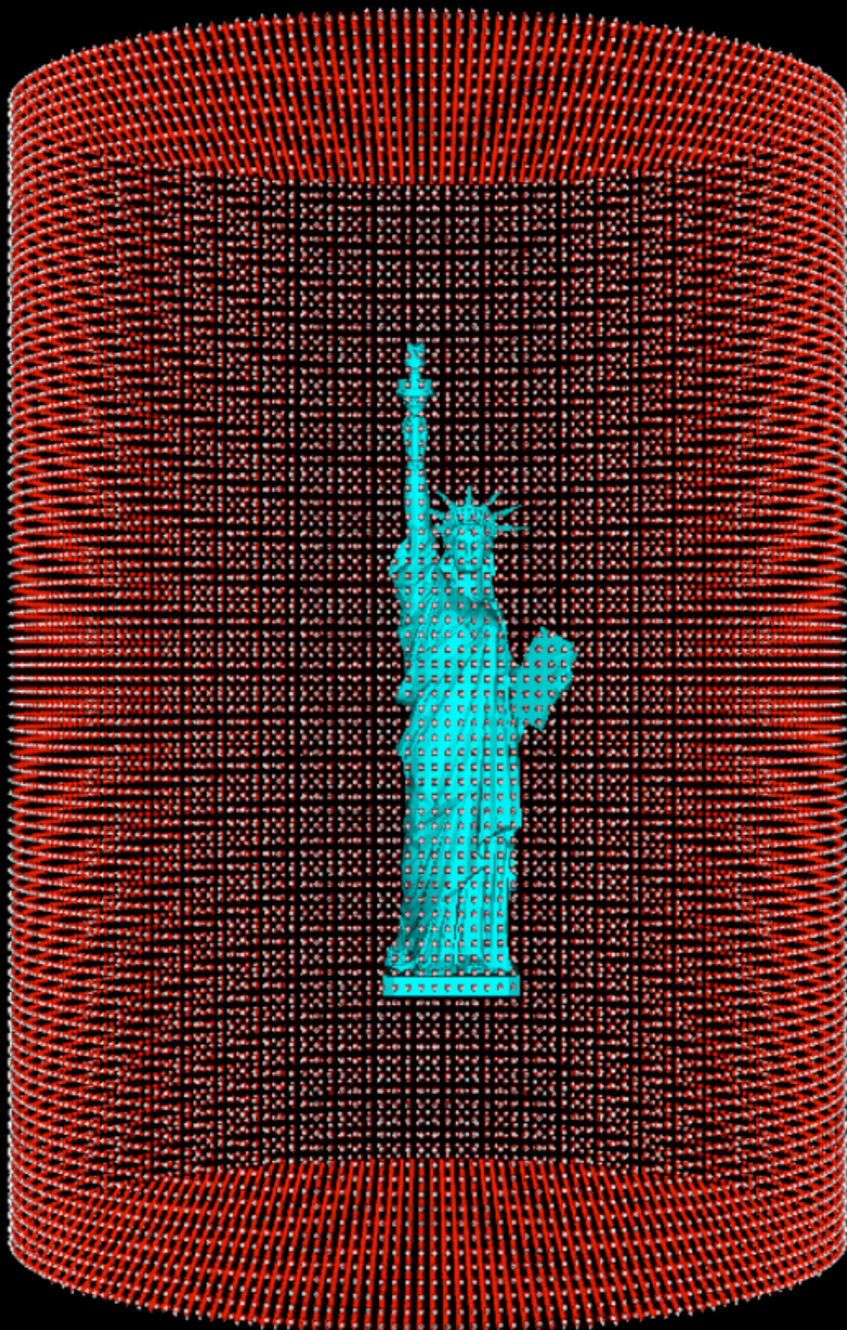

Design of a Water Cherenkov Detector for LBNE

Status Report

R.Svoboda, Fundamental Physics at the Intensity Frontier

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Minnesota: M. Marshak, W. Miller
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NGA: S. Malys, S. Usman
New Mexico: B. Becker, J. Mathews
Notre Dame: J. Losecco
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Pennsylvania: J. Klein, K. Lande, T. Latorre, 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
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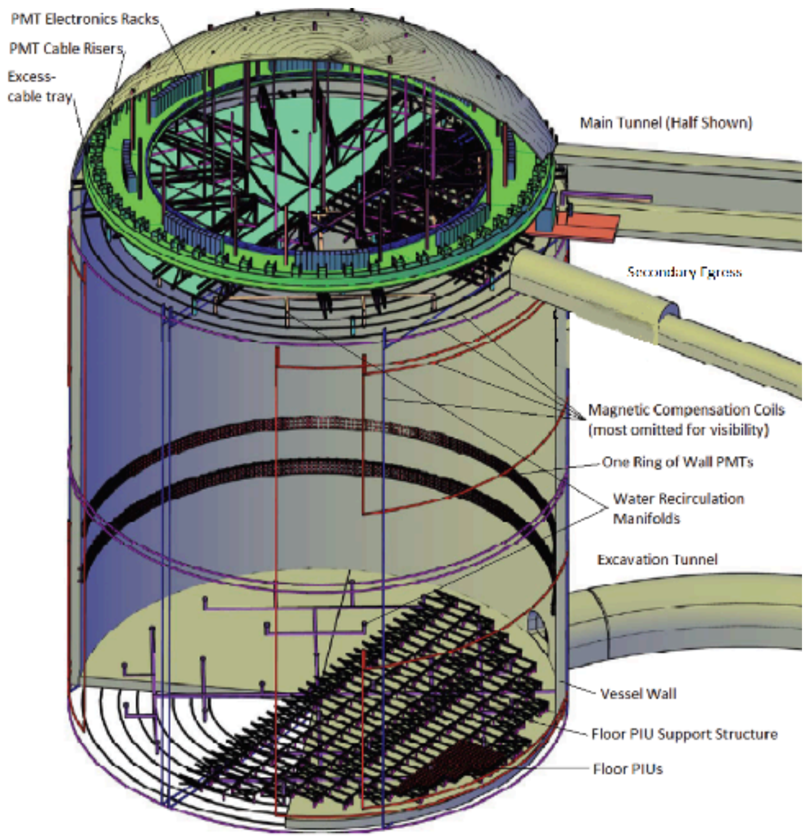
Yale: E. Church, B. Fleming, R. Guenette, K. Partyka, J. Spitz, A. Szelc

2 August 2011

60 Institutions, ~300 scientists and engineers

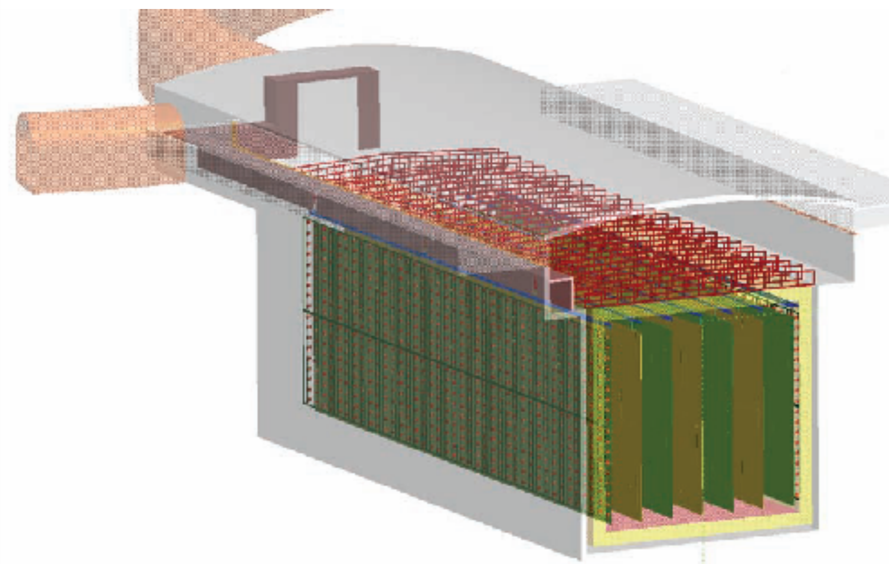
Two Far Detector Options

200 kT water Cherenkov



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

34 kT liquid argon



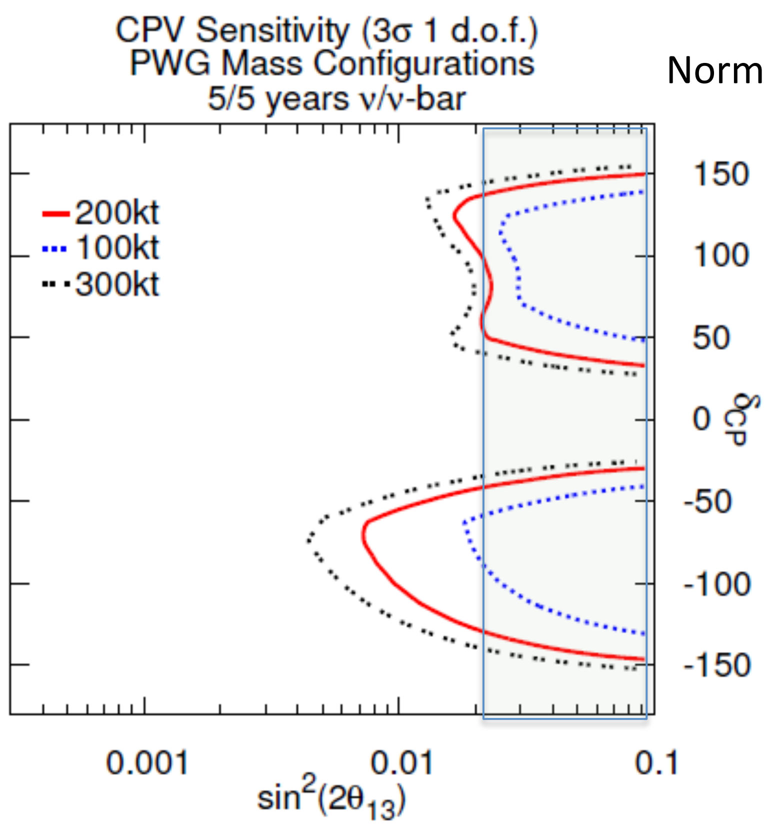
Two 17 kT fiducial LAr detectors
Located at **800 or 4850 foot level**. (one detector shown here)

(See B.Fleming talk, this session)

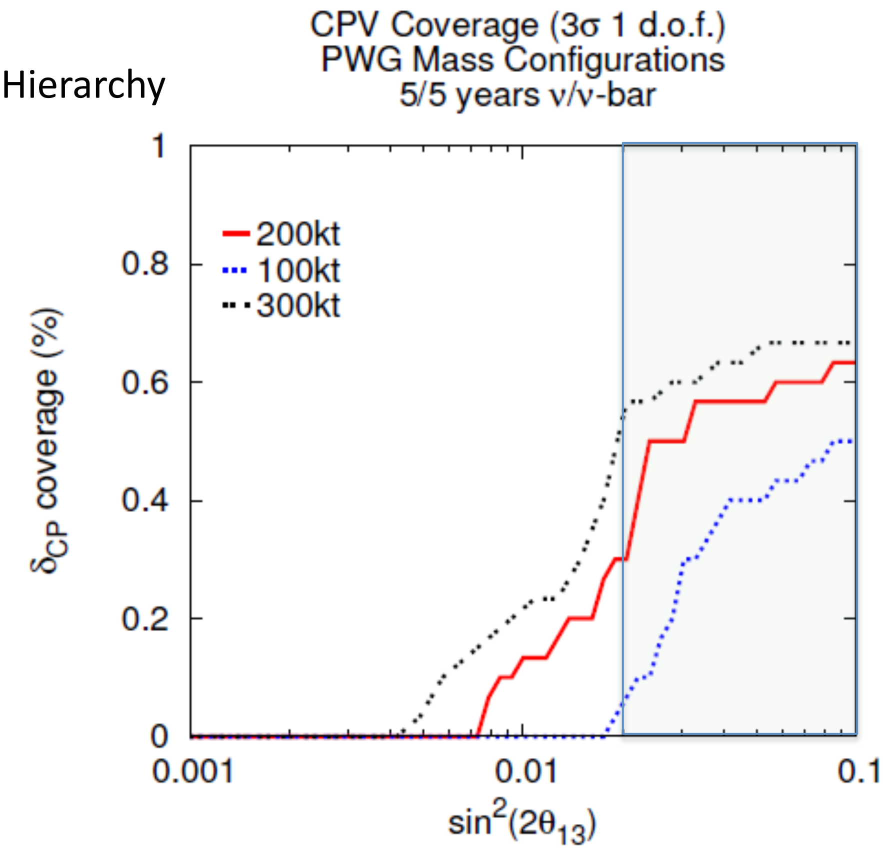
Science Goals

- Resolve the neutrino mass hierarchy problem
- Determine if neutrinos violate CP symmetry
- Obtain time-resolved spectra of the neutrino emission from a galactic supernova
- Search for proton decay
- Precision measurement of neutrino oscillation parameters and model.
- Measure neutrinos from SN at cosmological distances
- **Why 200kT? Why water?**

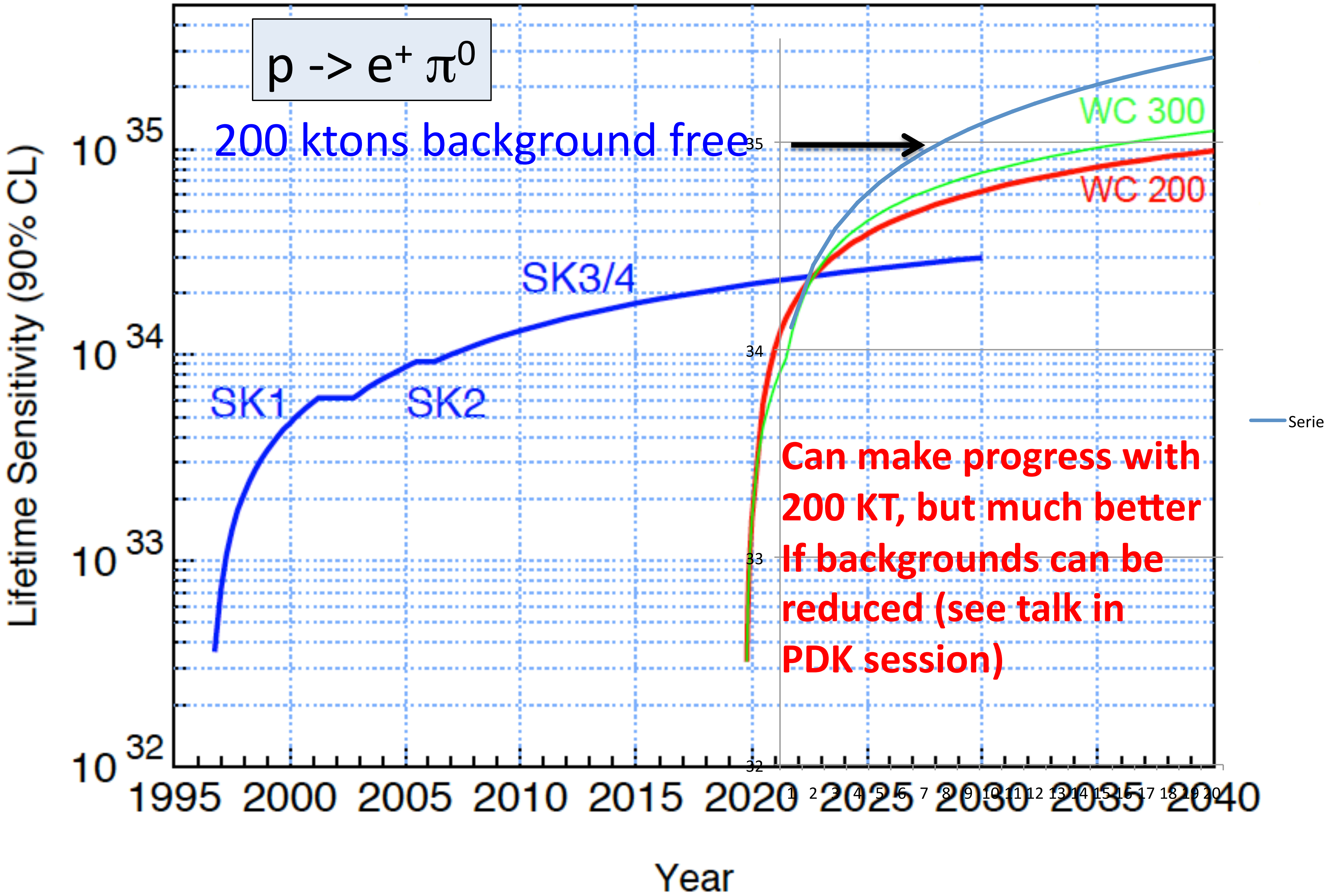
On-Axis means 200 kT sufficient for CPV



Normal Hierarchy



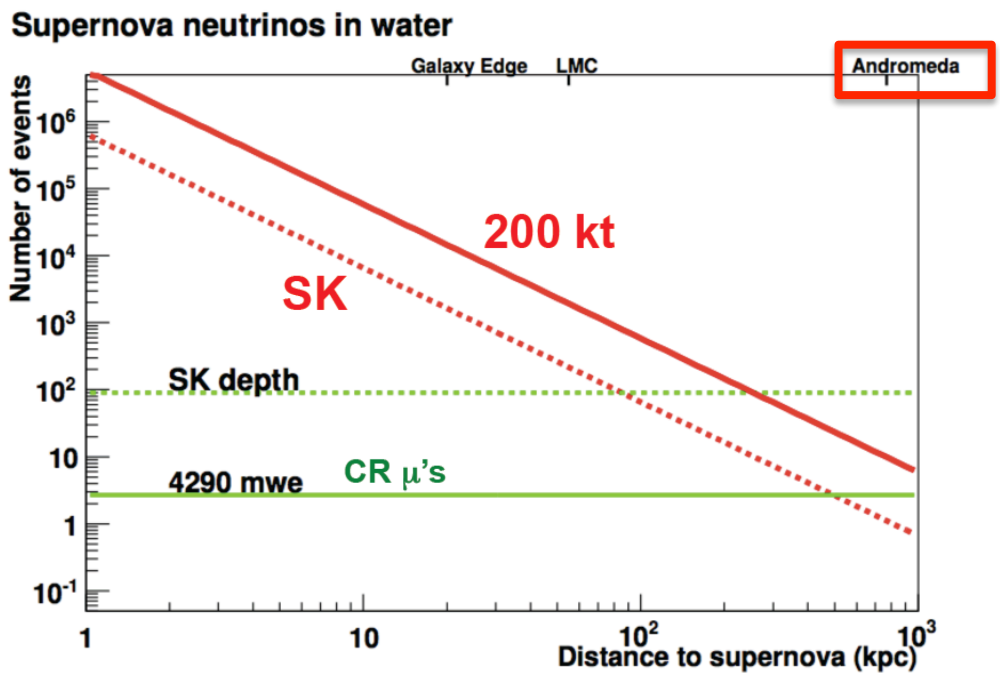
- Adding mass an effective way to improve sensitivity – but diminishing returns at large $\sin^2 2\theta_{13}$
- More mass helps **all** physics


p -> e+ π0
200 ktons background free
WC 300
WC 200
SK3/4
SK1
SK2
Can make progress with
200 KT, but much better
If backgrounds can be
reduced (see talk in
PDK session)
Lifetime Sensitivity (90% CL)
Year
10 35
10 34
10 33
10 32
1995 2000 2005 2010 2015 2020 2025 2030 2035 2040
Serie

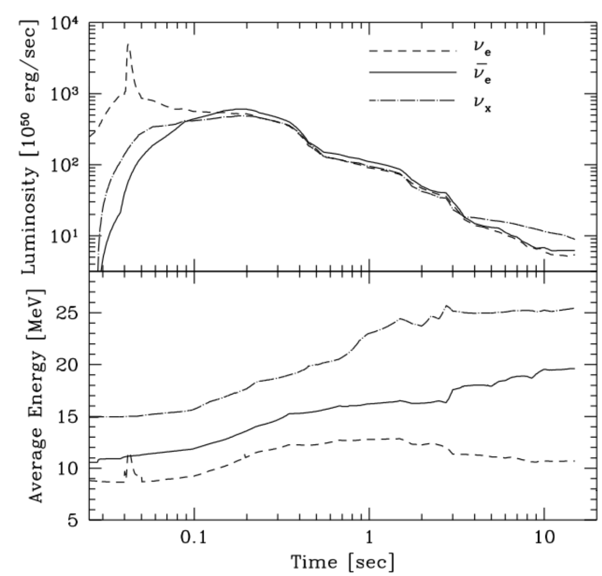
200 kT is sufficient to have huge statistics for a galactic SN: time resolved spectroscopy

Channel	No of events (observed), GKVM	No. of events (observed), Livermore
IBD	30442	50272
ES	774	1198
Nue-O16	748	170
Nuebar-O16	969	1379
NC- O16	0.5	2
Total	**32932**	**53021**

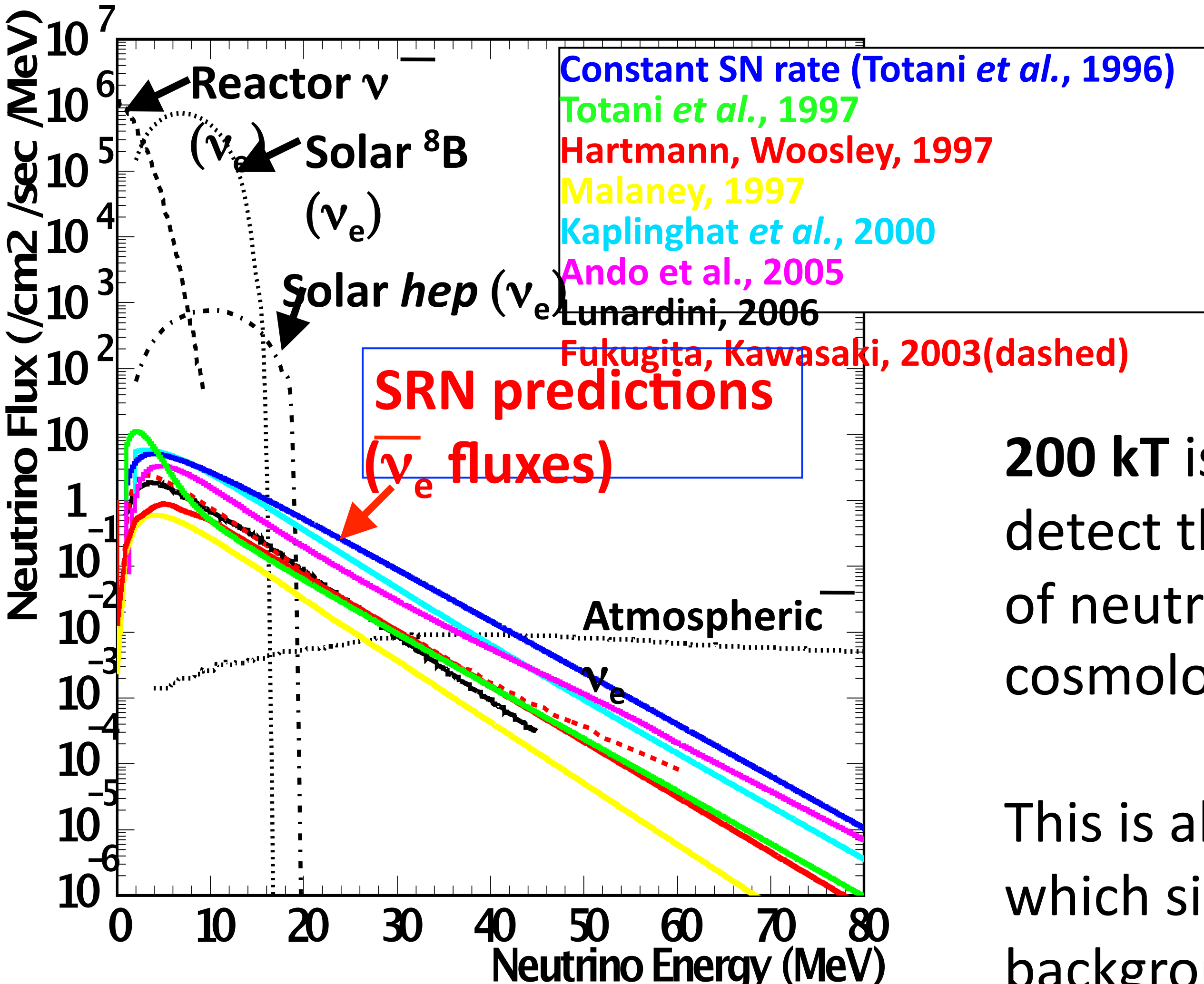
Events in ~30 seconds vs distance: scales as $1/D^2$



It is also enough to see a supernova in the **Andromeda Galaxy** – ten times farther away than the 1987A SN.



Time evolution depends on neutron state E.O.S., flavor mixing, and **ν–ν interactions. What will we see?**



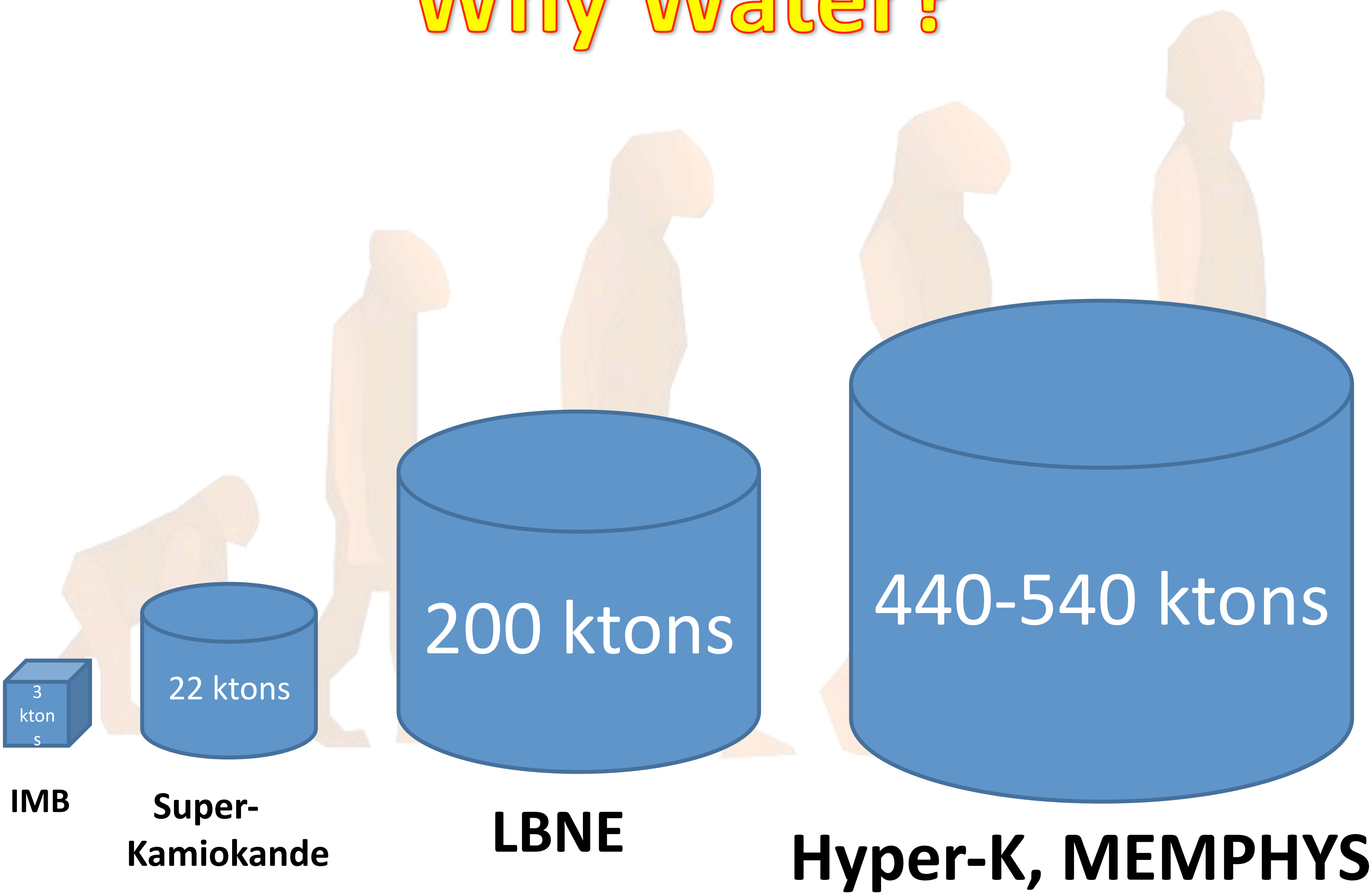
Reference Configuration Number	Expected Annual SRN Signal (events/year)	Expected Annual Background (events/year)	Years of LBNE Data Needed for a 3.0-σ Signal Assuming Maximum SRN Flux	Years of LBNE Data Needed for a 3.0-σ Signal Assuming Minimum SRN Flux
Baseline	2 – 27	187	2.9	526
+ PMTs	3 – 35	214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

Table 10–1: Summary of sensitivities to detecting the supernova relic neutrino flux for different possible LBNE water Cherenkov detector configurations.

200 kT is large enough to detect the background flux of neutrinos from SN at cosmological distances.

This is also due to DEEP DEPTH, which significantly reduces backgrounds from spallation (CR flux through 200 KT at 4850 is x10 lower of that through SK)

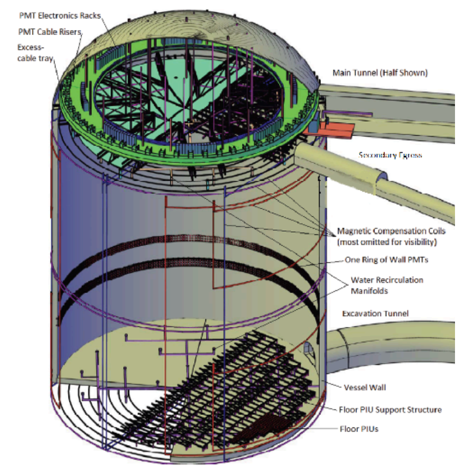
Why Water?

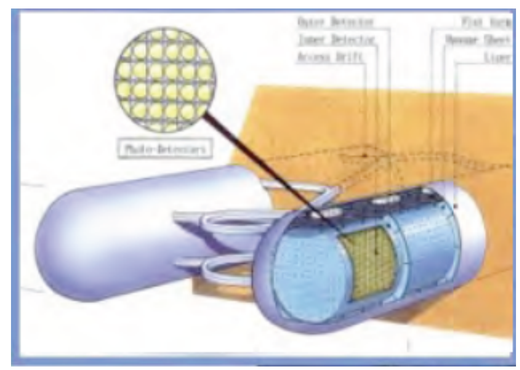

3
kton
s
22 ktons
200 ktons
440-540 ktons
IMB
Super-
Kamiokande
LBNE
Hyper-K, MEMPHYS

Why Take This Approach?

- **Large Size**: due to low cost/kT. Rare events, high statistics.
- **Low Threshold**: 5-7 MeV with high efficiency. Light nuclei for spallation backgrounds.
- **Excellent e/μ** >99% ν_μ rejection in T2K ν_e data
- **Free protons**: proton decay, inverse beta decay, no *hep* "wall"
- **Excellent timing:** 1 ns or better
- **Upgradability:** 100 ps light collectors, gadolinium loading, WLS addition, water-soluble scintillator,…

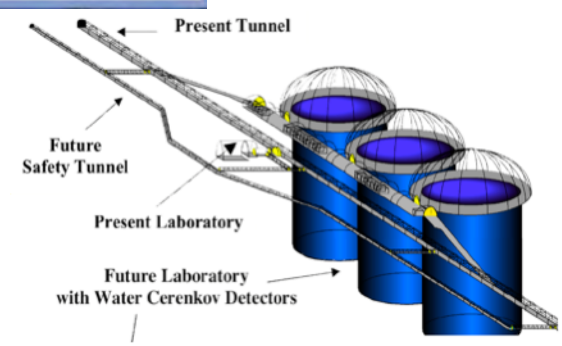
LBNE





HYPER-K

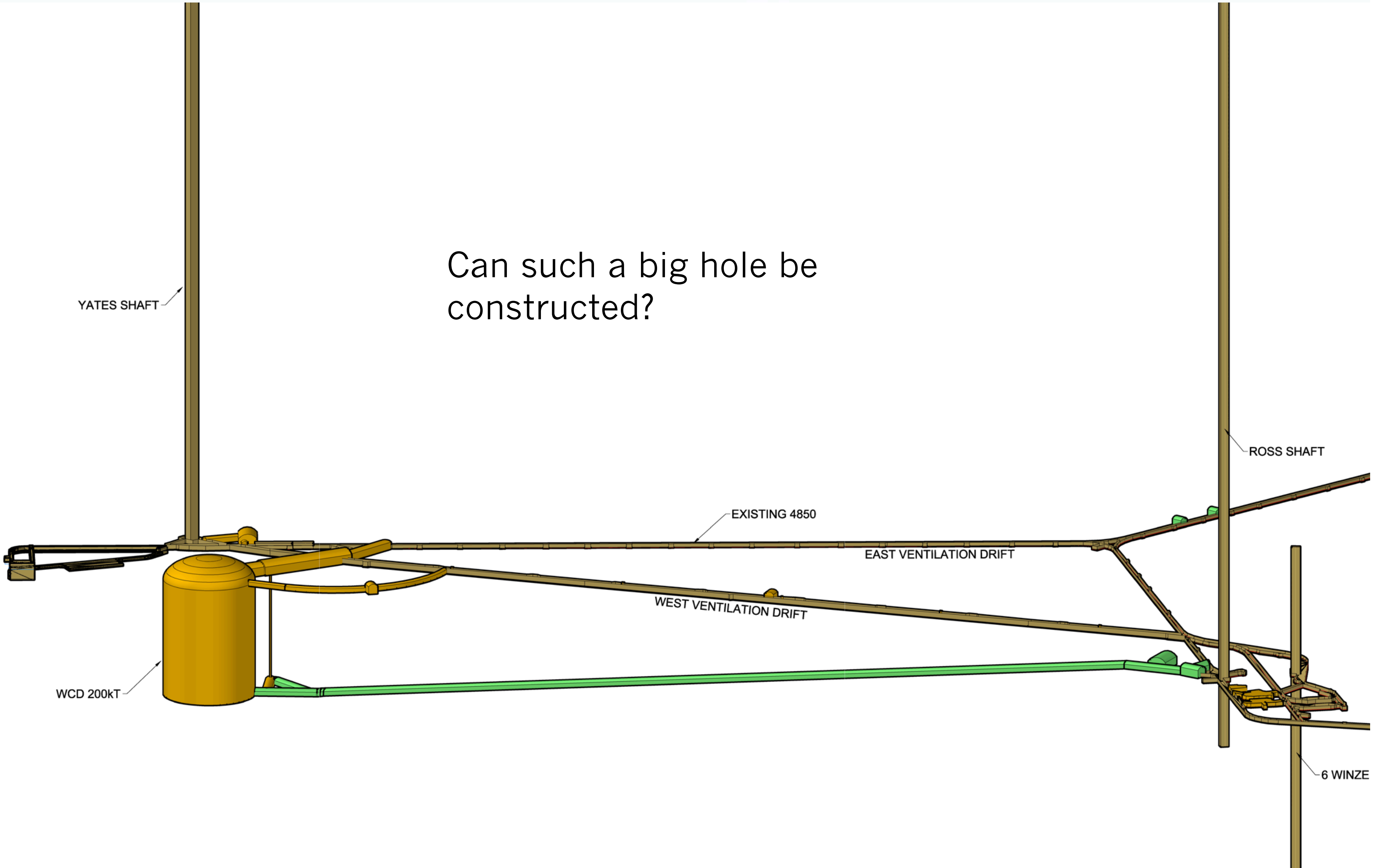
MEMPHYS



Detector Site

Conventional Facilities Overview – 4850ft level

Can such a big hole be constructed?



2 Executive summary

1. A combination of favorable rock mass strength and structural conditions and an in situ stress field that is reasonably benign means that a stable 65 m diameter 102 m high vertical cylindrical cavern can be constructed at the selected location on the 4850 level of the Homestake mine.

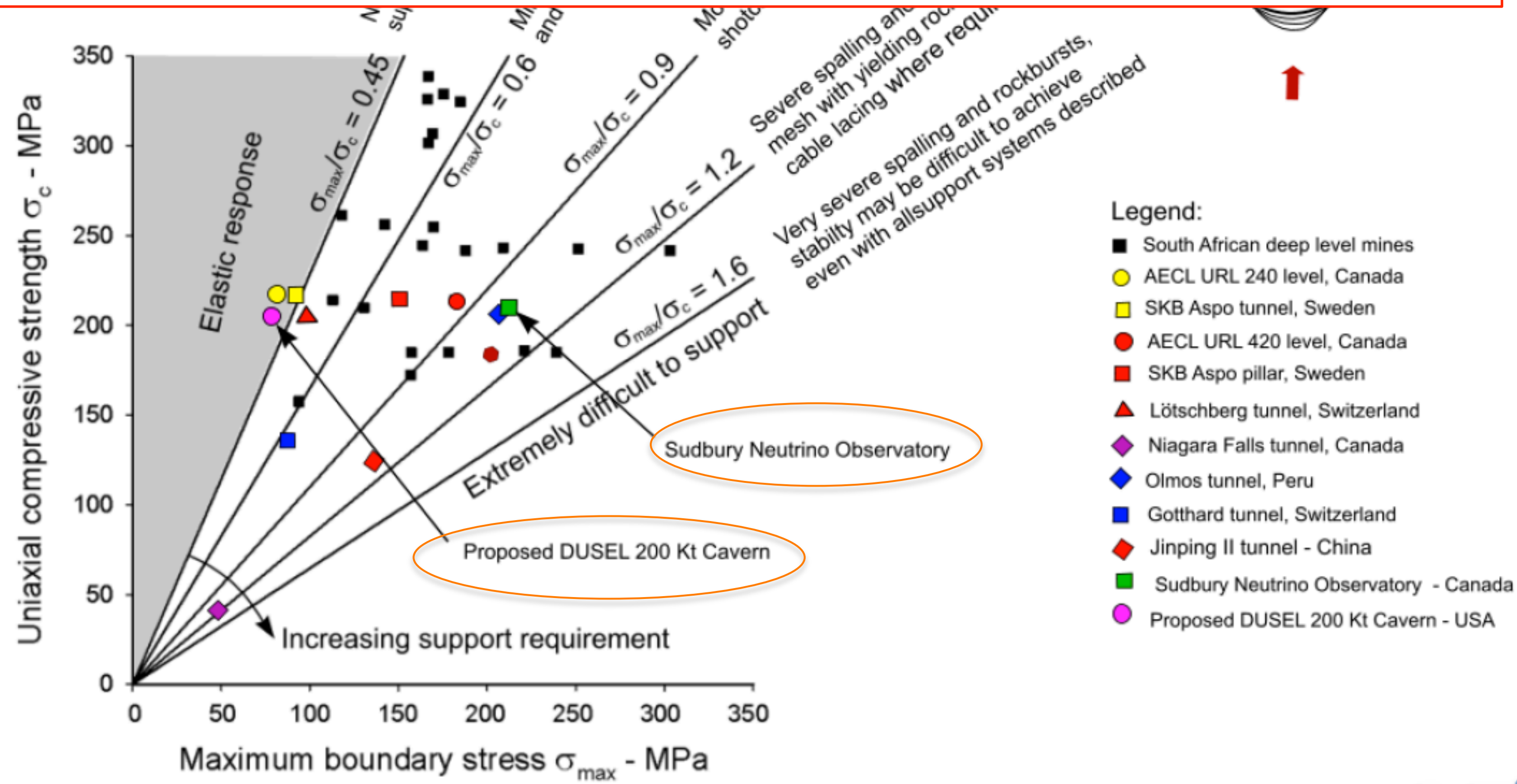


Figure 5: Spalling and difficulty of support in rock surrounding highly stressed excavations

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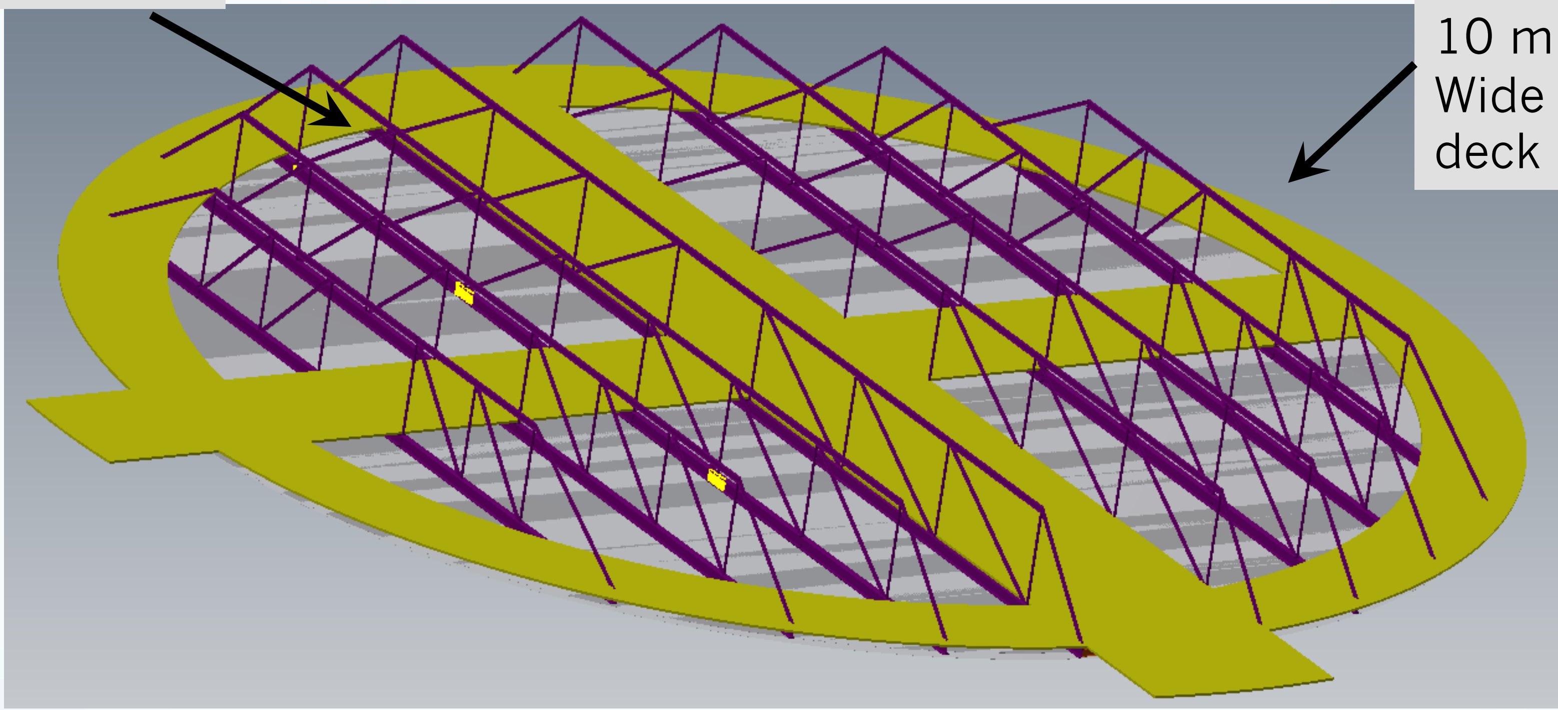
Trusses supported from dome

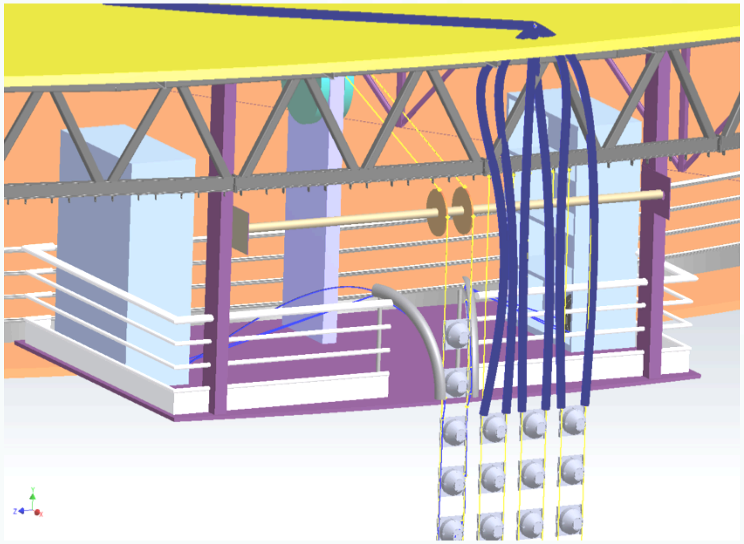
Deck Design



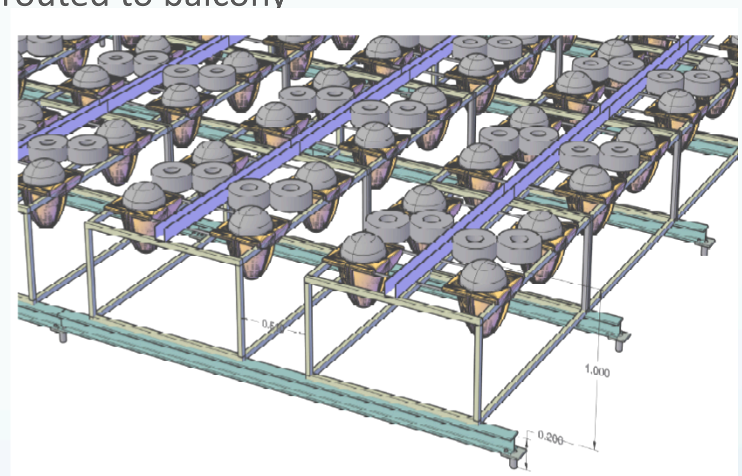
10 m
Wide work deck

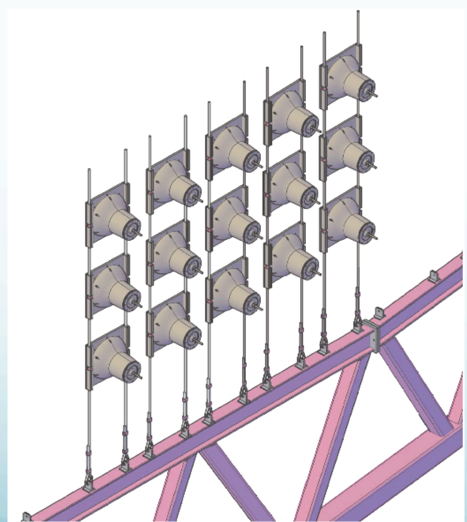
Investigating low mass tensile architecture design

PMT Deployment



- Wall PMTs deployed from deck and supported on steel cables
- No attachment to wall
- Buoyant force resisted by ring truss on floor
- Signal cables supported by steel cables and routed to balcony





- Floor PMTs supported on frames on floor
- Access isles between tight but possible
- Cables routed to perimeter and up to balcony
- Deck PMTs supported similarly but inverted

Photodetectors

PMT Coverage (How Many?)

- Used the R11781 12" Hamamatsu PMT for present design
  - Final PMT decision will be result of a detailed procurement process.
- If selected the HQE version would be used.
- Peak QE for 10" tubes is 35% higher then NQE tubes.
- Assumed a 30% increase in peak QE for the 12" to be conservative.
- HQE tubes are blue enhanced so this corresponds to about a 60% increase in light yield in air. Verified by lab tests.
- The 200kt detector was modeled in MC
  - The PMT and water characteristics included
  - Model was verified with cross check to Super-K
- 38k tubes had equal light yield to Super-K II
- Assume a 40% increase in light yield is possible with use of Winston cones or scintillator plates.
- Present design is based on 29,000 12" PMTs with light collectors.

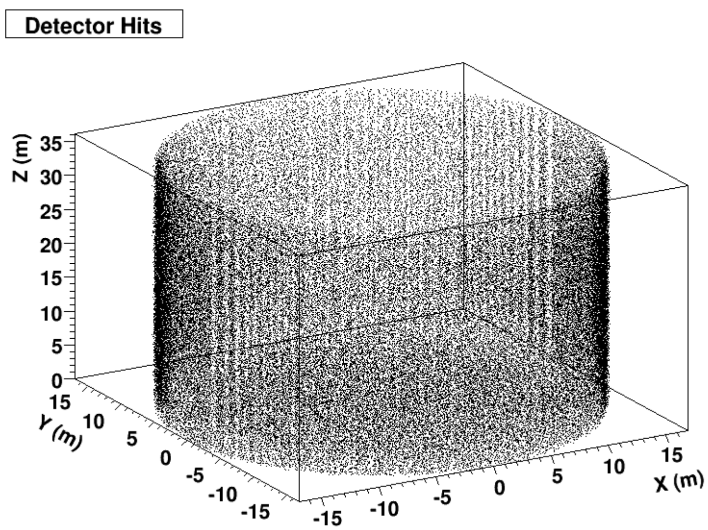
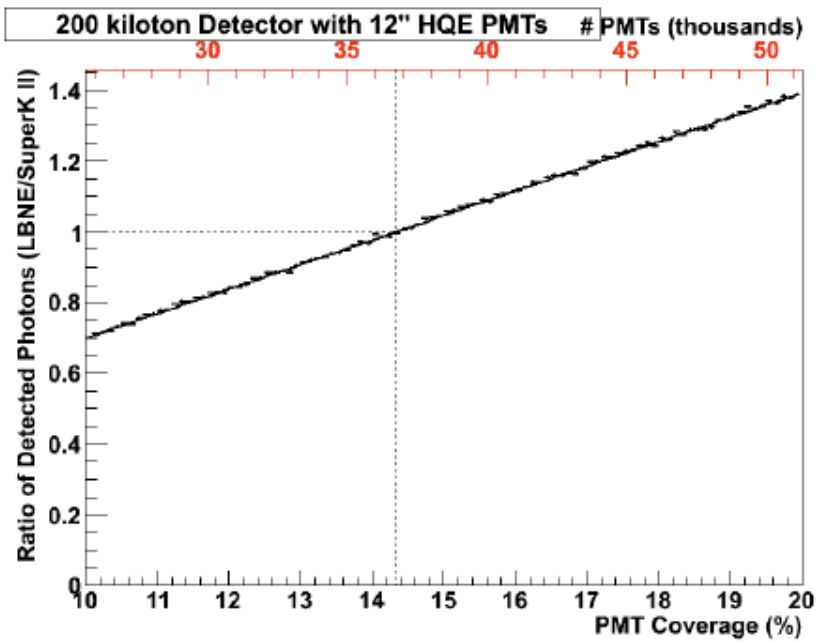


Figure 5: Target Hits for the Simulated SuperK II Detector



PMT Coverage

- Projected physics sensitivities based on measured Super-K II performance
- Super-K performance was fairly constant when coverage changed from 11,146 20” PMTs to 5,182 PMTs
- MC studies are underway and initial results are as expected
- WCD coverage adjusted to give same light yield as Super-K II
- Note: pixelization is better than SK-II (1.3 pixel/m^2 for LBNE versus 1.0 for SK-II). LBNE-specific software still being developed.

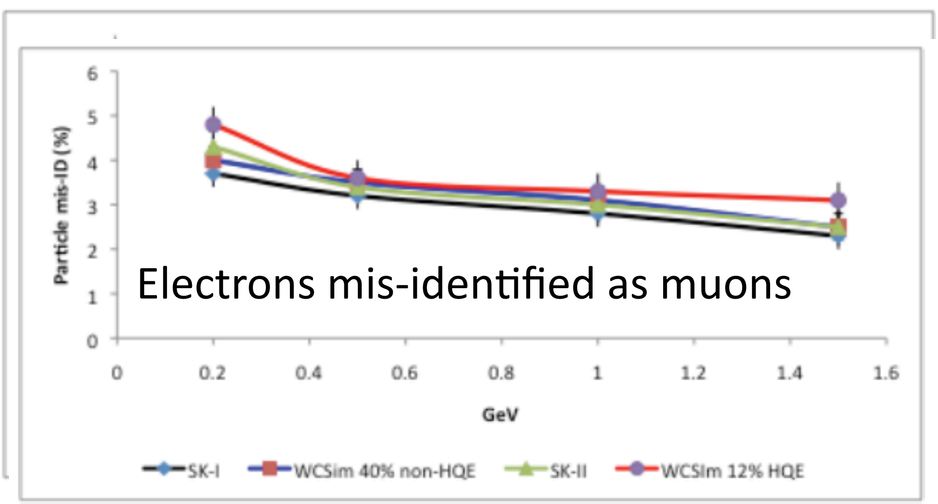


Figure 11 Percentage of single track electrons mis-identified as muons as a function of energy. Note: this does not use a muon decay tag as the official SK software does.

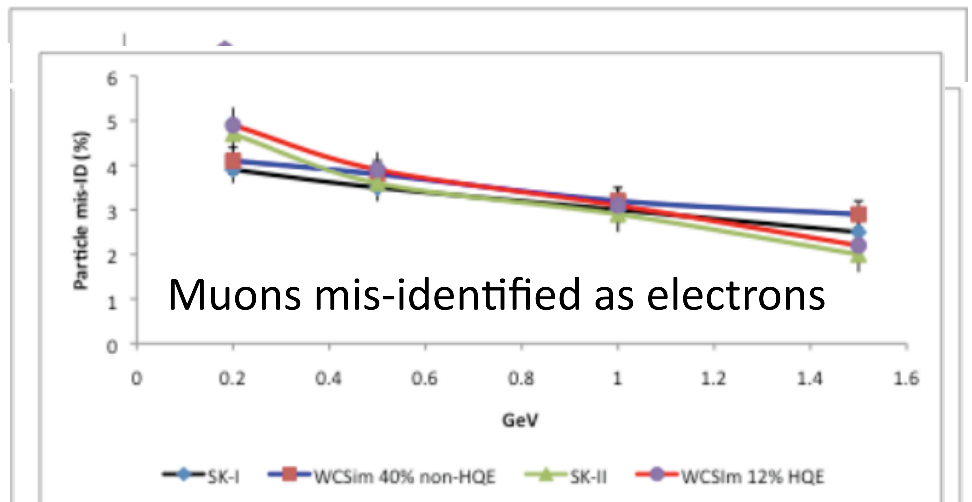


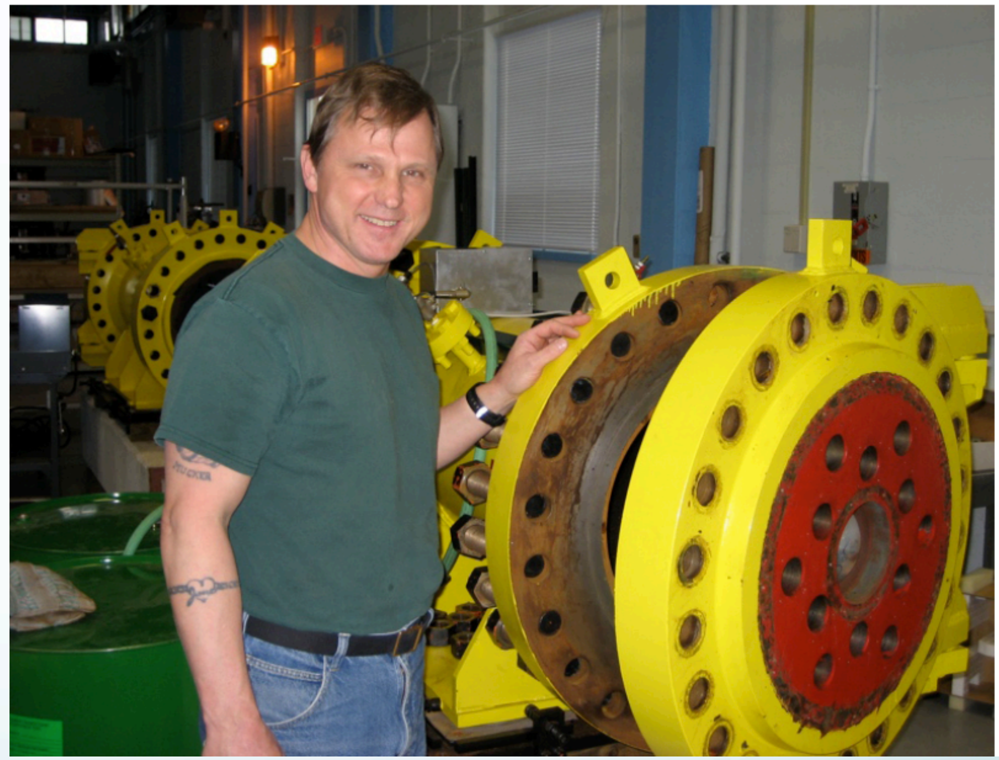
Figure 12 Percentage of single track muons mis-identified as electrons as a function of energy. Note: this does not use a muon decay tag as the official SK software does.

PMT Selection

- A request for information was sent to PMT vendors with the LBNE specifications.
  - Hamamatsu and ADIT/ETL expressed interest and are developing PMTs
- Candidate PMTs are:
  - 10" Hamamatsu HQE
  - 12" Hamamatsu HQE PMT (First tubes delivered)
  - 11" ADIT/ETL PMT (Under Development delivery in Spring)
- First 12" Hamamatsu High QE PMTs under test
- First 11" ADIT/ETL mechanical samples available
  - Working in conjunction with Schott Glass

Process of working with vendors toward the final selection is underway

Static Pressure Testing

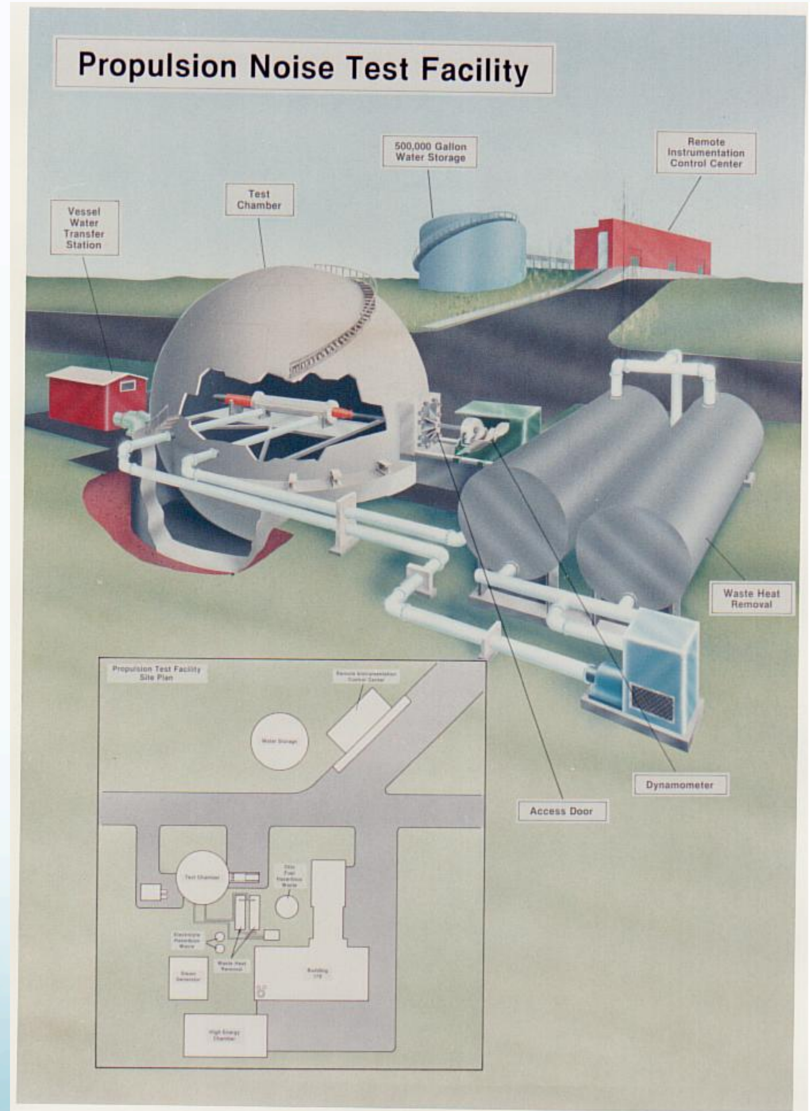


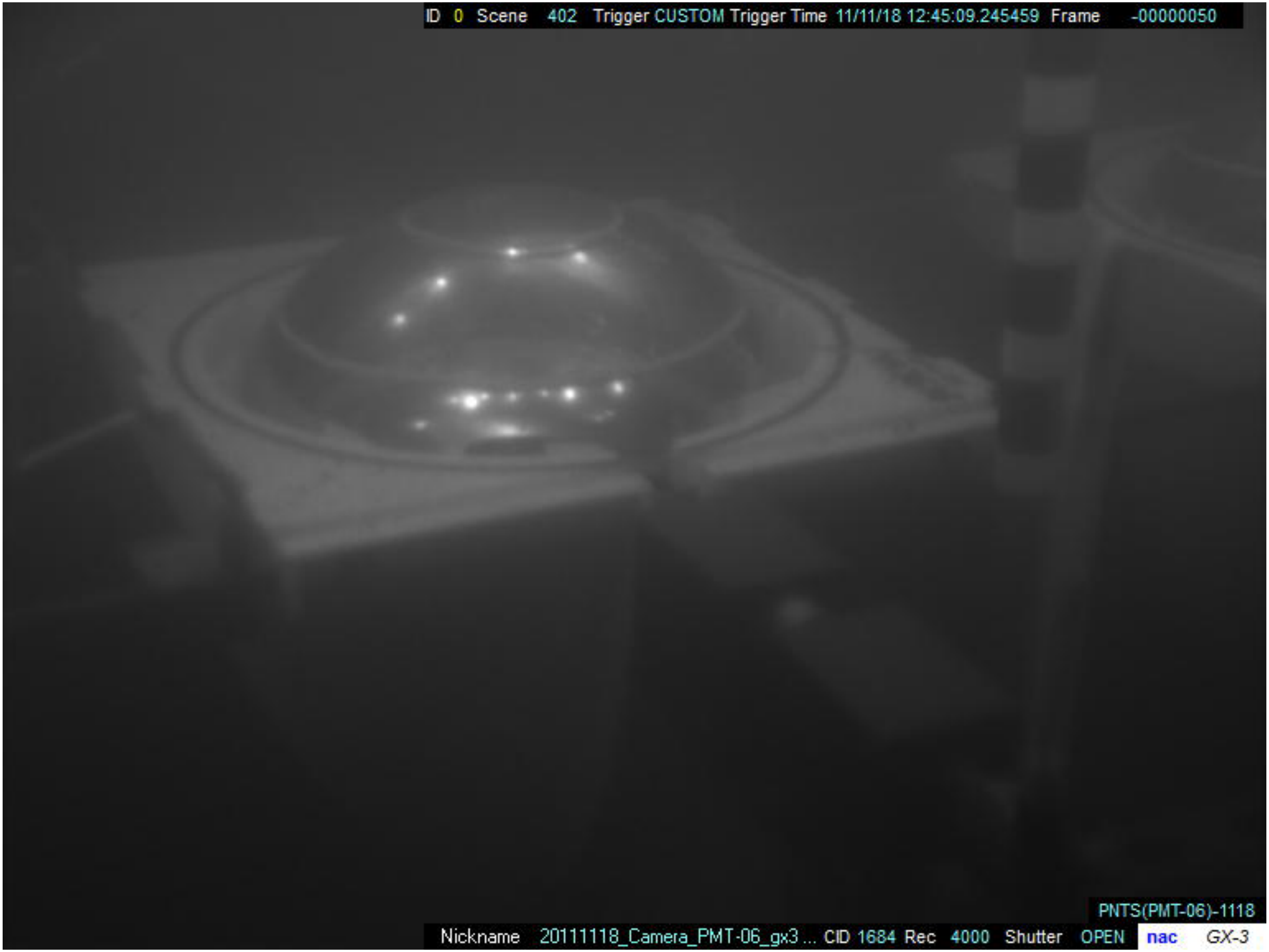
First Hamamatsu 12” PMT tested at 300 PSI without implosion!
Three times the maximum pressure in the WCD

NUWC Testing

Test Facility

- Propulsion Noise Test facility
- 50 ft diameter
- Rated for 100 psig at centerline
- ½ million gallons water
- ~10ms data without reflections

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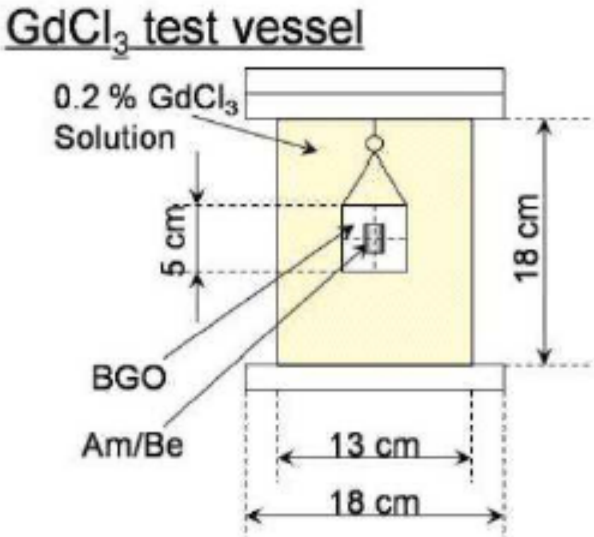
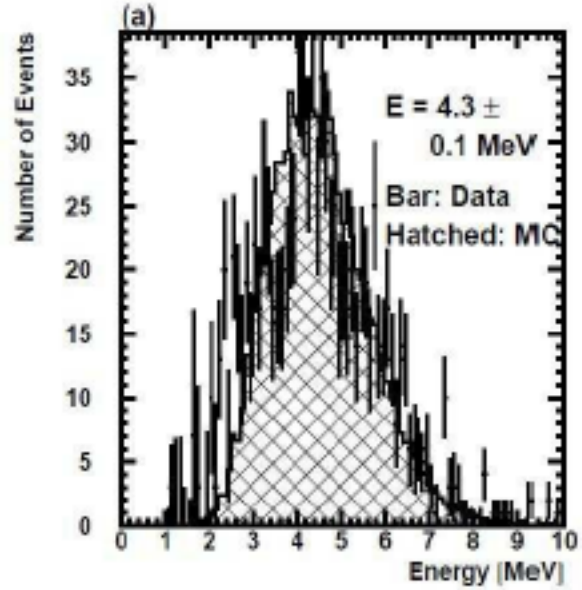
PNTS(PMT-06)-1118
Nickname 20111118_Camera_PMT-06_gx3 ... CID 1684 Rec 4000 Shutter OPEN nac GX-3

Upgrades

Addition of Gadolinium





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.

Cosmological and galactic SN, DAEDALUS, proton decay, solar neutrinos, possible beam event tagging?

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

Calculated: **2.1 +/- 0.9 ev/Mton/yr**

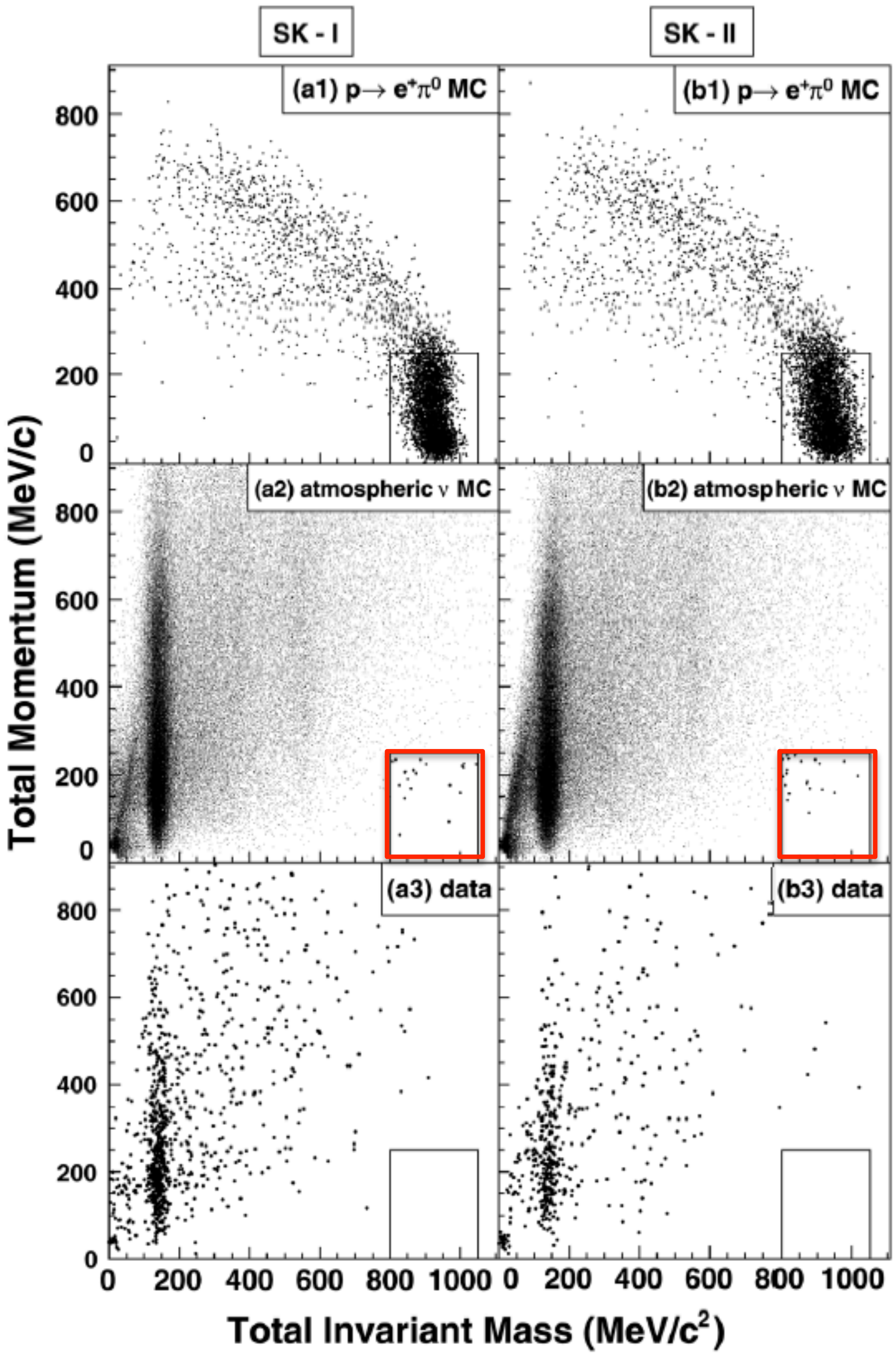
Measured*
in LE beam: **1.63 (+0.42/-0.33 stat) (+0.45/-0.51 syst.) ev/Mton/yr**

- Super-Kamiokande currently has **NO** candidates at 0.141 Mton-yr
- A 0.2 Mton detector would have ~3 background events after 10 years. 9 events for 0.56 Mton. Background limitations will enter.
- **Can this be improved?**

Efficiency dominated by nuclear effects. Background dominated by resolution.

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

*PRL 102:141801 (2009)



- background is from atmospheric neutrino interactions
- Estimate that this is dominated by CC (81%), with 51% of these 1+ pion production (PRL 102, 2009)
- How many background events will have one or more neutrons, either from initial interaction, FSI in nucleus, or nuclear de-excitation?
- **Discussions ongoing about a low-energy neutrino beam experiment.**

Will Proton Decay Result in Neutrons?

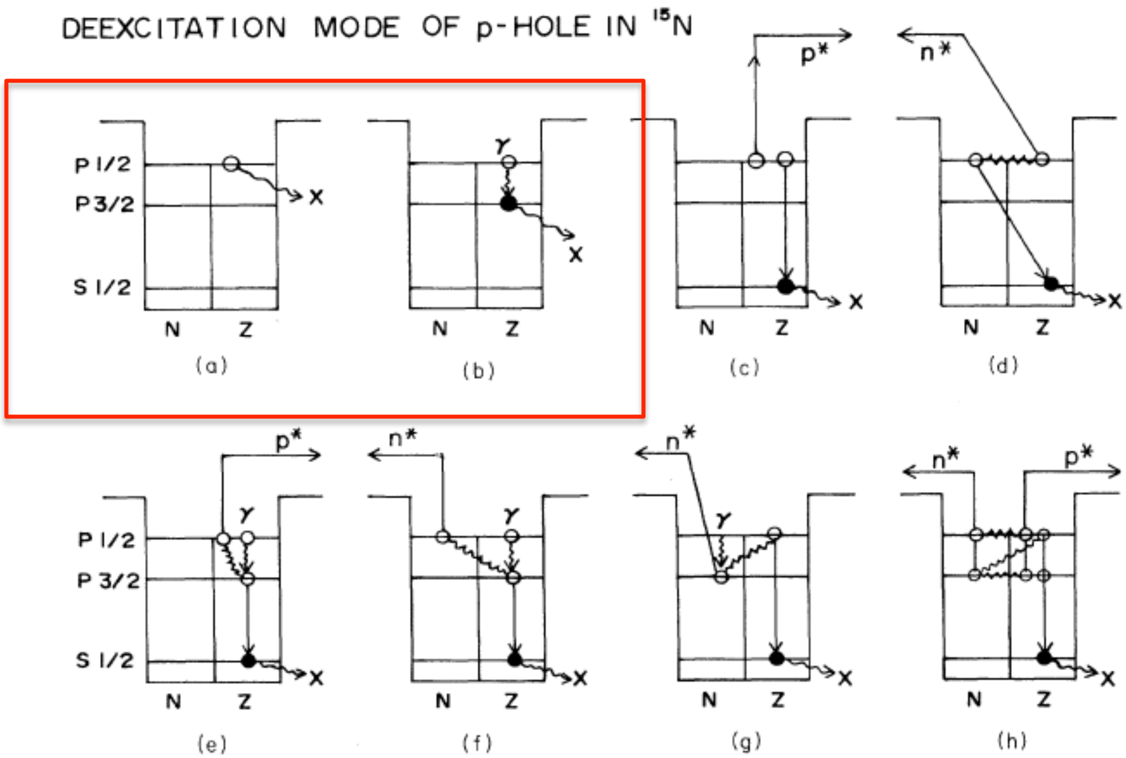


FIG. 1. Deexcitation scheme of a proton hole produced by proton decay ($p \rightarrow x$) in ^{16}O. N and Z stand for neutron and proton shells, respectively. p^* and n^* are protons and neutrons emitted into the continuum region.

0556-2813/93/48(3)/1442(3)/$06.00 48 1442

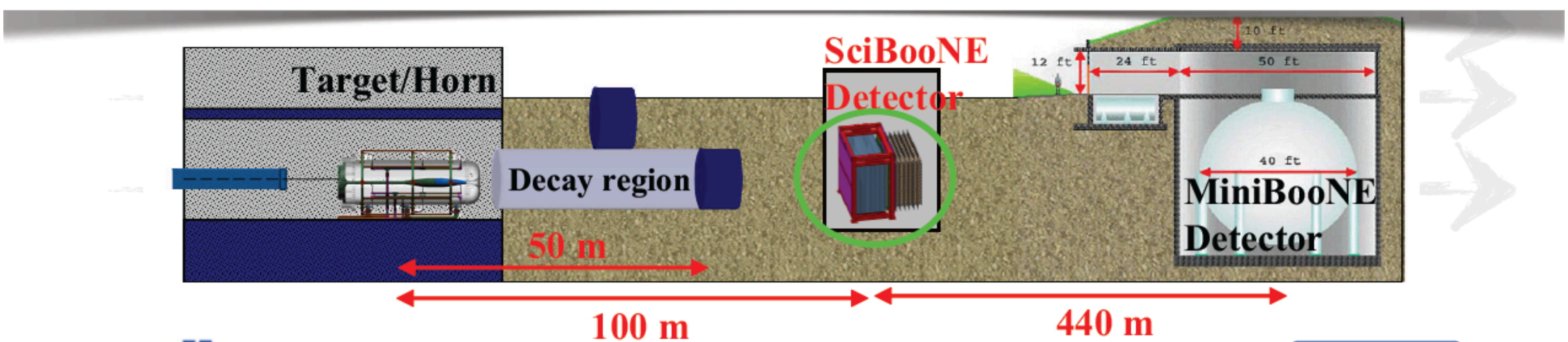
Neutrons from Proton Decay in Water

- 2/10 of protons are free protons. No neutrons.
- 2/10 of protons are in $P_{1/2}$ shell. If they decay nucleus is already in the ground state. No neutrons
- 4/10 of protons are in $P_{3/2}$ shell. If they decay then a $P_{1/2}$ proton will drop down, giving a 6 MeV gamma. No neutrons. (Ejiri gives 94% B.R. for this)
- **~80% of proton decays should give neutrons only indirectly from FSI.** (such FSI usually makes them undetectable anyway) This is fairly model independent. Ejiri's more detailed estimate gives 81%
- Similar numbers for neutron decay.

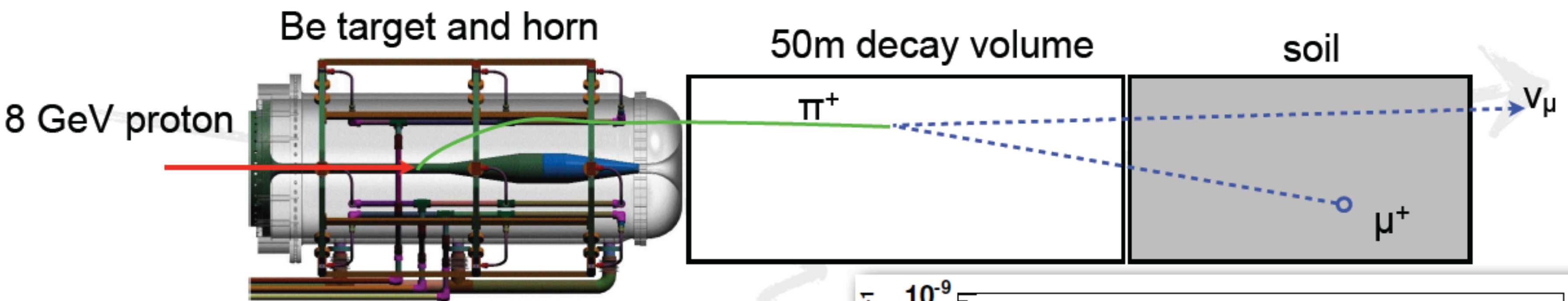
…But Do Atmospheric Neutrino Interactions Have Neutrons?

- Direct neutron production via CC-QE
- FSI scattering in nucleus (p,n), (π,n)
- Nuclear de-excitation with neutron emission
- Secondary production in water. E.g. π^- capture and (p,n) interactions
- Difficult calculation, but estimates are that there should be 1-3 neutrons on average per event. What is the actual number? Can we measure it for relevant neutrino energies?

SciBooNE Overview

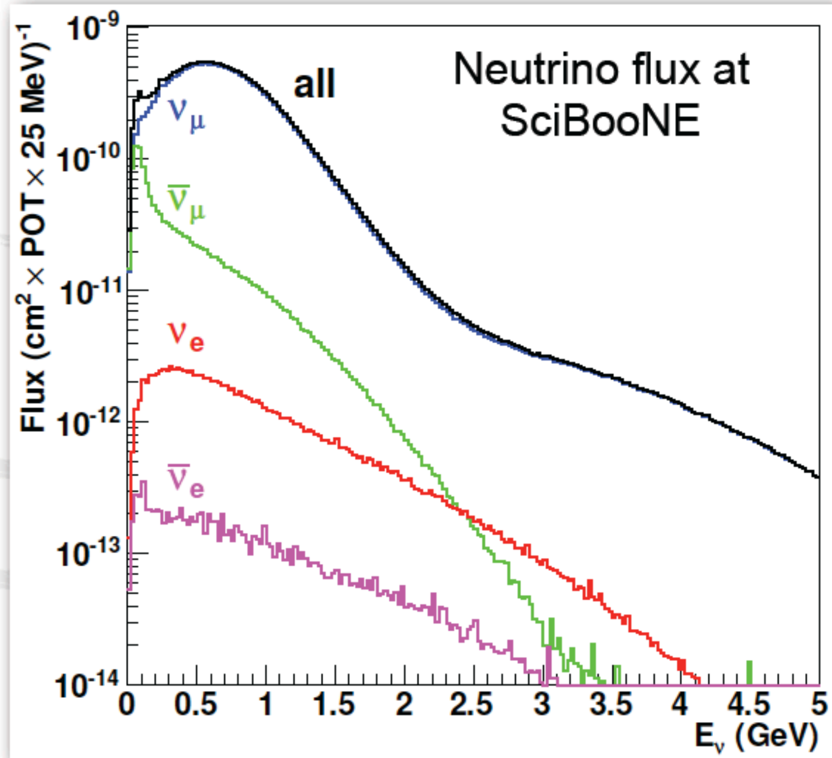


Booster Neutrino Beam



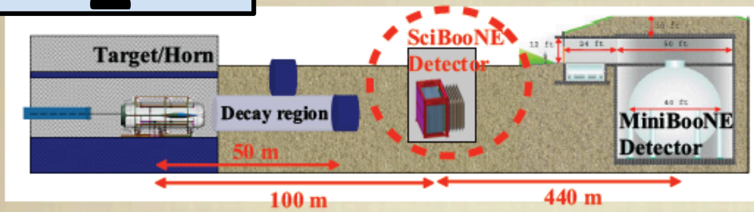
- Intense ν_μ beam with mean energy ~0.8 GeV
  - 93% pure ν_μ beam.
- $\bar{\nu}_\mu$ beam is produced by inverting horn polarity.
- Uncertainties reduced with CERN HARP data

Phys.Rev.D79 072002 (2009)



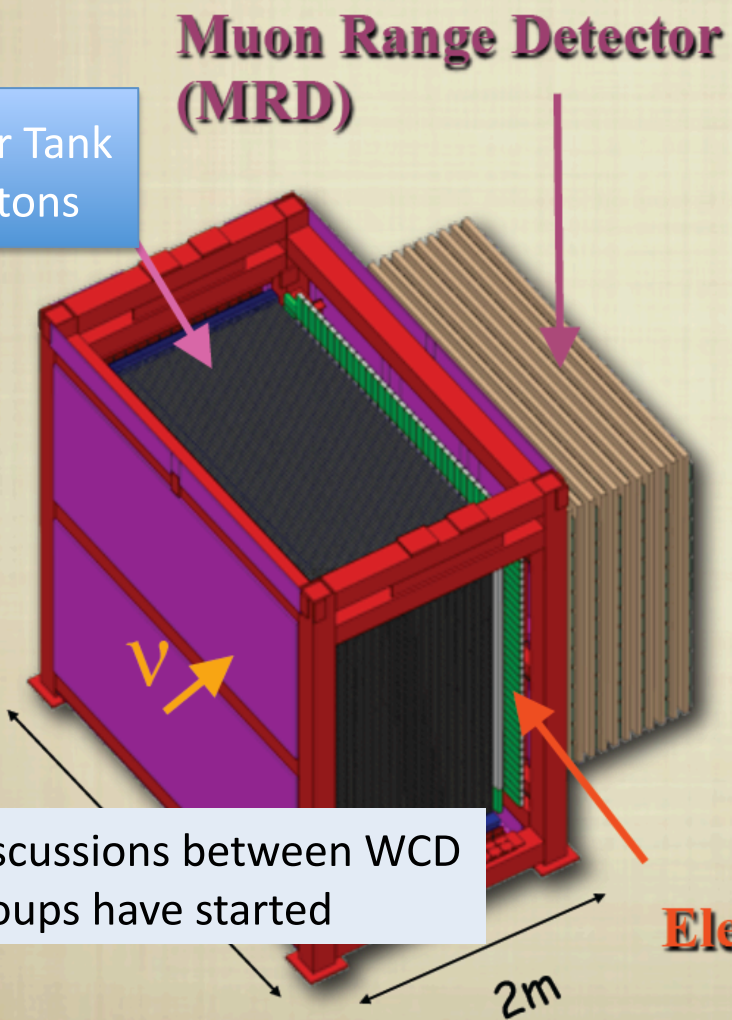
H_2O BooNE detector

SciBooNE



- Located 100 m downstream of the target.
- SciBar:
  - Full active scintillator tracker (~14000 strips)
  - Neutrino target (~10 ton)
  - Main component : CH
- Muon Range Detector (MRD)
  - A sandwich type detector of steel + plastic scintillator.
  - Can stop muons up to ~1.2GeV
  - Reconstruct muon momentum from its path-length

Water Tank
~ 5 tons



Discussions between WCD groups have started

The LAPPD Project

Large Area Picosecond Photodetector Collaboration

John Anderson, Karen Byrum, Gary Drake, Henry Frisch, Edward May, Alexander Paramonov, Mayly Sanchez, Robert Stanek, Robert G. Wagner, Hendrik Weerts, Matthew Wetstein, Zikri Zusof

High Energy Physics Division, Argonne National Laboratory, Argonne, IL

Bernhard Adams, Klaus Attenkofer, Mattieu Chollet

Advanced Photon Source Division, Argonne National Laboratory, Argonne, IL

Zeke Insepov

Mathematics and Computer Sciences Division, Argonne National Laboratory, Argonne, IL

Mane Anil, Jeffrey Elam, Joseph Libera, Qing Peng

Energy Systems Division, Argonne National Laboratory, Argonne, IL

Michael Pellin, Thomas Prolier, Igor Veryovkin, Hau Wang, Alexander Zinovev

Materials Science Division, Argonne National Laboratory, Argonne, IL

Dean Walters

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David Beaulieu, Neal Sullivan, Ken Stenton

Arradiance Inc., Sudbury, MA

Sam Asare, Michael Baumer, Mircea Bogdan, Henry Frisch, Jean-Francois Genat, Herve Grabas, Mary Heintz, Sam Meehan, Richard Northrop, Eric Oberla, Fukun Tang, Matthew Wetstein, Dai Zhongtian

Enrico Fermi Institute, University of Chicago, Chicago, IL

Erik Ramberg, Anatoly Ronzhin, Greg Sellberg

Fermi National Accelerator Laboratory, Batavia, IL

James Kennedy, Kurtis Nishimura, Marc Rosen, Larry Ruckman, Gary Varner

University of Hawaii, Honolulu, HI

Robert Abrams, valentin Ivanov, Thomas Roberts

Muons, Inc., Batavia, IL

Jerry Va'vra

SLAC National Accelerator Laboratory, Menlo Park, CA

Oswald Siegmund, Anton Tremsin

Space Sciences Laboratory, University of California, Berkeley, CA

Dimitri Routkevitch

Synkera Technologies Inc., Longmont, CO

David Forbush, Tianchi Zhao

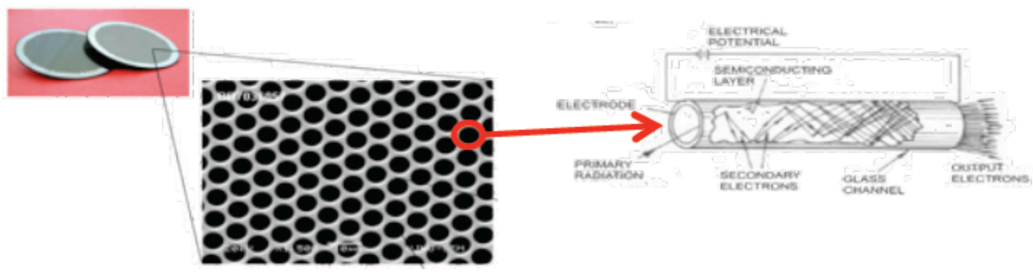
Department of Physics, University of Washington, Seattle, WA

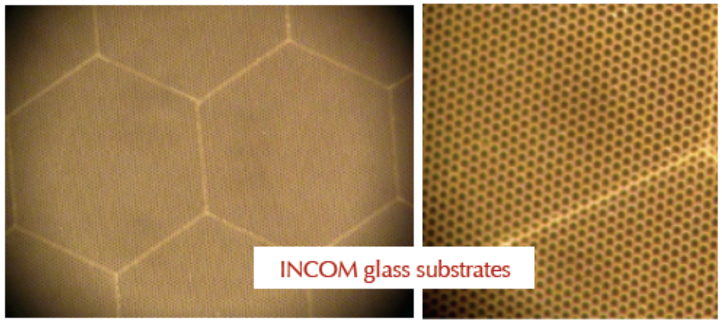
- A 3-year DOE project to develop Large Area Fast Photodetectors based on microchannel plate (MCP) technology started at ANL August '09.

- The goals are:
  - To develop cheap, scalable, flat panel photodetectors with precision time resolution, capable of picosecond-level time of flight (TOF) measurements.
  - To get a commercializable prototype on the 3 year time scale.

Project in its 2nd year

Microchannel Plate Fabrication



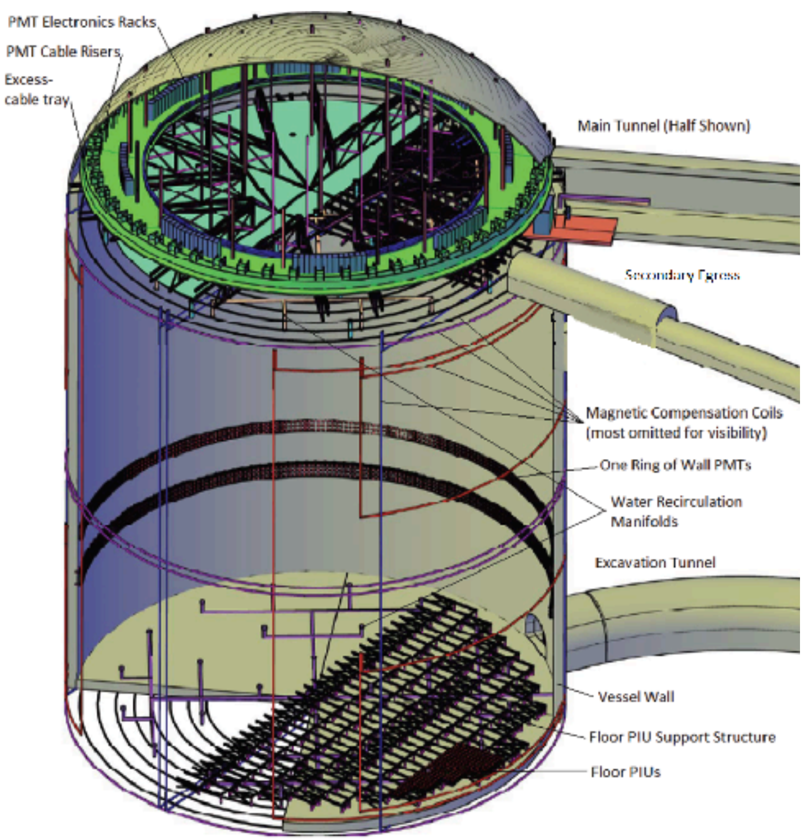


- Conventional MCP Fabrication:
  - Pore structure formed by drawing and slicing lead-glass fiber bundles. The glass also serves as the resistive material.
  - Chemical etching and heating in hydrogen to improve secondary emissive properties.
  - Expensive, requires long conditioning, and uses the same material for resistive and secondary emissive properties.

- Proposed approach by LAPPD:
  - Separate out the three functions: resistive, emissive and conductive coatings.
  - Handpick materials to optimize performance.
  - Use Atomic Layer Deposition (ALD), a cheap industrial batch method.

J. Elam, A. Mane, Q. Peng, (ANL:ESD/HEP),
N. Sullivan (Arradiance), A. Tremsin (Arradiance, SSL)

Achievement: Successful MCP fabrication by ALD on both 33 mm and 8″ substrates: able to control resistance and secondary electron yield.



Conclusions

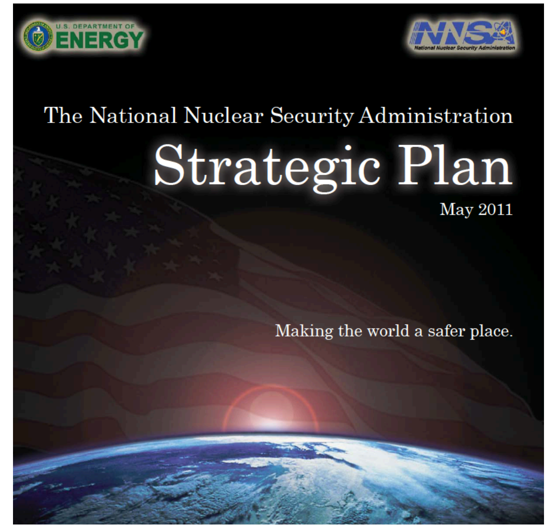
- possible large θ_{13} has added momentum to LBNE
- ambitious program to be ready for CD-1 **next year**
- water Cherenkov is a viable far detector option
- interest in broadening the science program through NSF proposals. This is still being worked out but one or more Fall 2012 proposals are likely.

Backup Slides

When loaded with Gd plus commercial WLS or water-soluble scintillator, 200 kT detector is large enough to allow remote detection of nuclear reactors. An AIEA-sponsored study has recommended this capability be developed by member states.

IAEA
International Atomic Energy Agency
Atoms for Peace

Remote monitoring also part of DOE Strategic Plan.



Select Initiatives

Strengthen Nuclear Safeguards:

- By 2013, deploy new non-destructive assay technologies to directly quantify plutonium in spent fuel.
- By 2016, demonstrate remote monitoring capabilities for reactor operations.

Counterterrorism and Nuclear Threat Response:

- By 2012, hold joint nuclear facility or transportation security exercises with two established foreign partners.
- By 2012, establish new partnerships with two additional foreign partners.
- By 2012, complete nuclear materials and energetic materials characterization and prioritization, initiate development of new nuclear counterterrorism render safe tools, and conduct the 100th counterterrorism tabletop exercise.

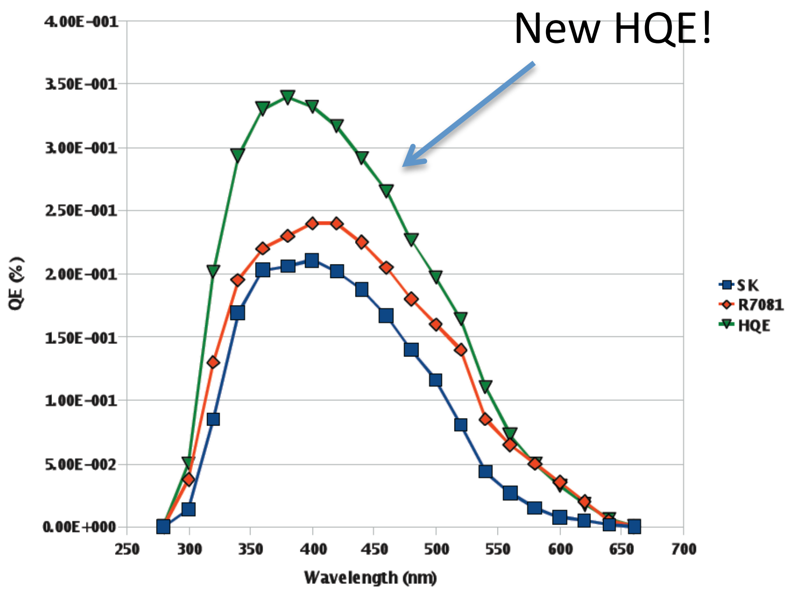
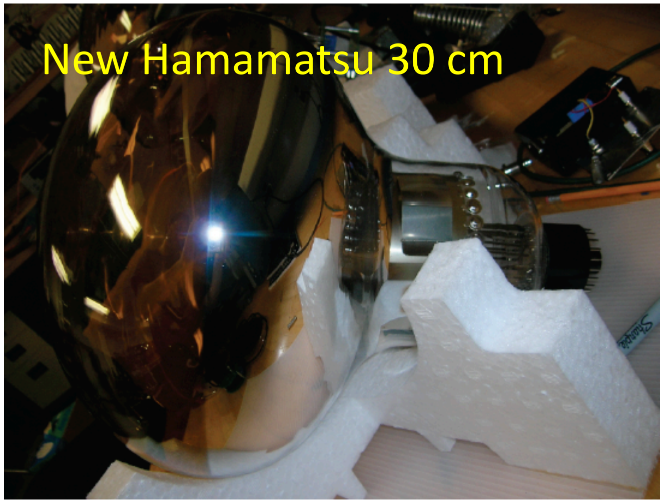
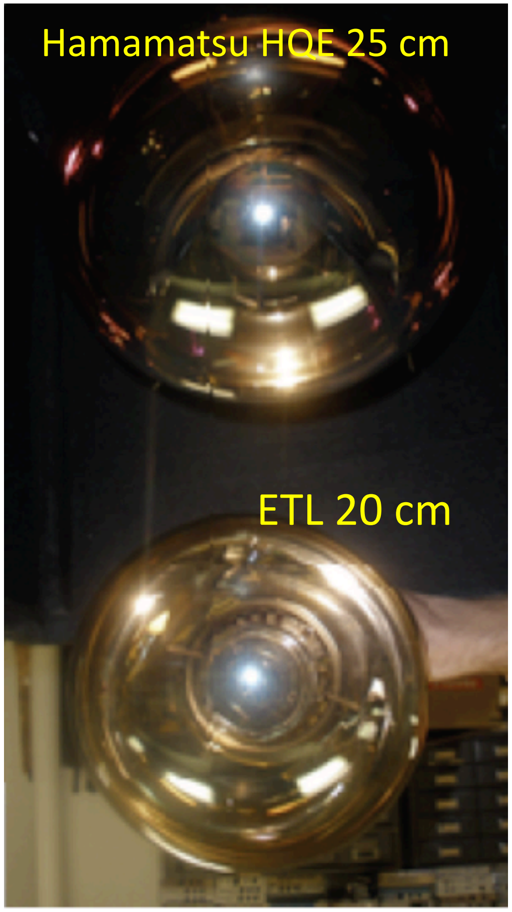


Figure 2 Quantum efficiency curves used in WCSim. Shown are the curves for the 20" SK R3600 (blue), 10" Double Chooz and ICECUBE R7081 (red), and 10"

The development of new HQE PMT has impacted the number of needed for a given coverage

Predicted from Hamamatsu curves: factor of 1.6 ! **This has Been confirmed in head-to-head tests.**



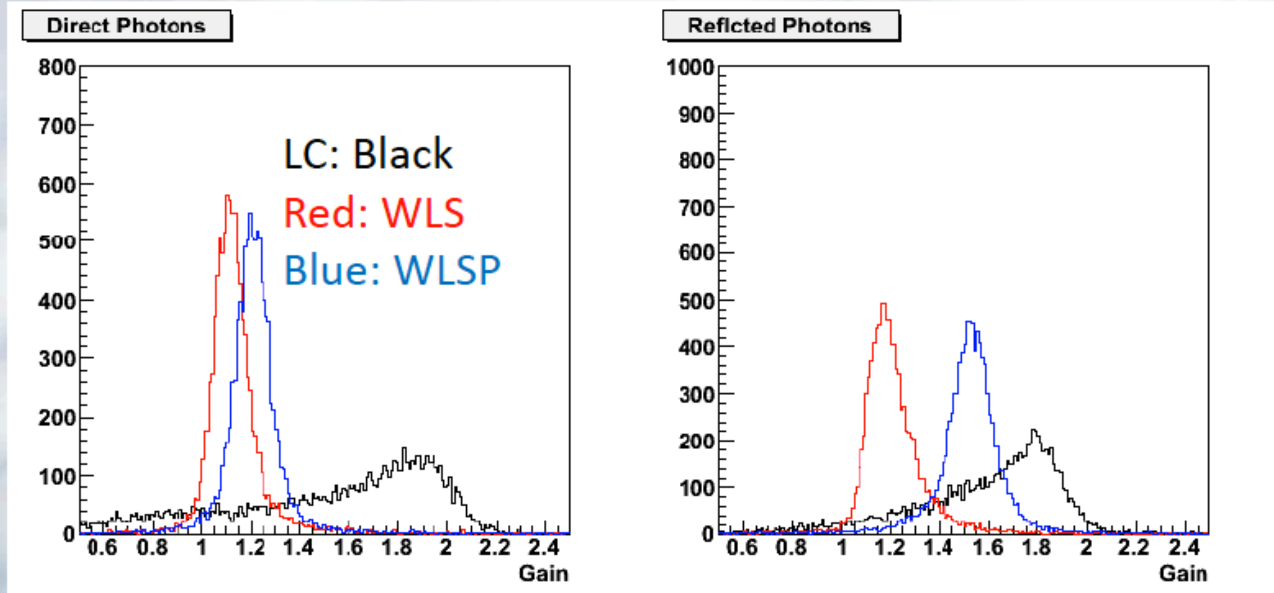


Direct Light vs. Reflected Light (Electrons)

Ratio of collected NPE with LCs to that noLC

Direct light

Indirect light = Total Light – Direct Light



	Light Collector	WLS Film	WLS Plate
Direct Light Increment	1.53	1.14	1.21
Indirect Light Increment	1.59	1.21	1.52

Reflect Light vs. Direct Light ~ 1.1 : 1

Note: for WLSP, offset 10 mm→ 35 mm, 21% gain → ~33% gain (WLSP talk by Norm).

LC gives higher gain, but larger spread. WLSP gives more reflected lights. Both technologies give > 30% gain in direct light in simulation.

Alternate Cavern Shape Study Conclusions

Table 2.1: Case scenarios and cavern geometries

Case	Fiducial Volume (kt)	Shape*	Excavation Volume (yd3)	Length (ft)	Width or Diameter** (ft)	Wall Height*** (ft)	Dome Height (ft)
1	100	LC	238,239	-	180.4	210.0	62.3
2	150	LC	348,401	-	215.9	210.0	70.5
3	300	LC	689,673	-	285.4	225.4	98.4
4	300	LC	593,913	-	215.9	391.1	70.5
5	150	MB	349,887	378.9	105.0	210.0	35.0
6	300	MB	669,281	547.9	134.5	210.0	44.8

* LC denotes cavity with the cylindrical base, MB stands for mailbox shaped cavity
** Denotes cavity diameter for LC analyses and cavity width for MB analyses
*** Measured from cavern bottom to spring-line (base of the dome)

⇦ 100kt Design (Case 1)
⇦ Increase Ø for 150kt (Case 2)
⇦ Large diameter (Case 3)
⇦ 150kt diameter+deep (Case 4)
⇦ Mailbox (discouraged) (Case 5)

- 150 kt cavern is economically constructible.
- Diameters larger than around 216ft are discouraged.
- A 300kt 216ft diameter excavation is not recommended.
- 200kt may be the optimal size.

	Heat Load (kW)					Total		
T = 13 C	From Rock	From Deck, No Insul	From Deck, Insulated	From PMT's	From Mag Coils	w/out Insulation	w/ Insulation	% Drop
100 kTon No Vessel	30.6	35.9	7.5	5.1	25.8	97.3	68.9	29.2
150 kTon Opt	35.0	47.6	9.9	6.8	40.7	130.1	92.4	29.0
150 kTon Wide	34.9	50.1	10.4	6.9	40.7	132.5	92.8	30.0
150 kTon Tall	36.2	35.9	7.5	6.8	40.7	119.6	91.2	23.8
200 kTon	38.9	50.1	10.4	8.6	46.6	144.2	104.5	27.5
T = 4 C	From Rock	From Deck, No Ins	From Deck, Ins	From PMT's	From Mag Coils	w/out Insulation	w/ Insulation	% Drop
100 kTon No Vessel	48.7	82.0	17.1	5.1	25.8	161.6	96.7	40.2
150 kTon Opt	55.9	108.8	22.7	6.8	40.7	212.2	126.1	40.6
150 kTon Wide	55.9	114.6	23.9	6.9	40.7	218.1	127.4	41.6
150 kTon Tall	57.0	82.0	17.1	6.8	40.7	186.5	121.6	34.8
200 kTon	61.9	114.6	23.9	8.6	46.6	231.8	141.1	39.1

2 0 8 6 4 2 0 8 6 4

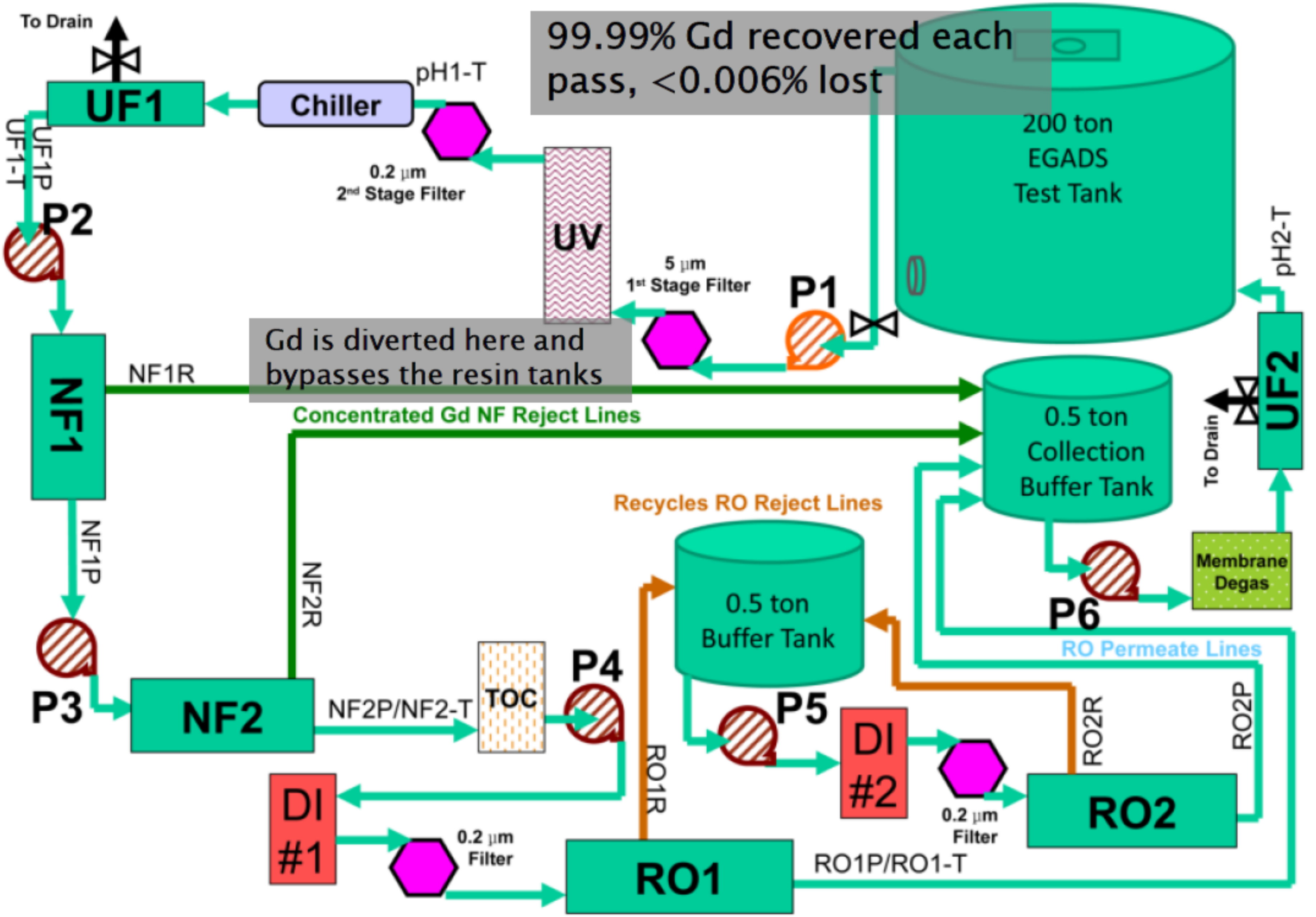
Requirements for operation with Gd

- Physics requirements
  - High efficiency for neutron capture
  - Light attenuation mean free path 80-100m
- Implementation
  - Use Gd in a compound that won't degrade detector materials, so far: $Gd_2(SO_4)_3$
  - Gd clean and injection system on the surface
  - Gd recovery system at L4850/part of recirculation system
  - Gd removal from leakwater system at L4850
  - Gd detector volume return to surface for drain
  - Gd removal from detector volume on the surface

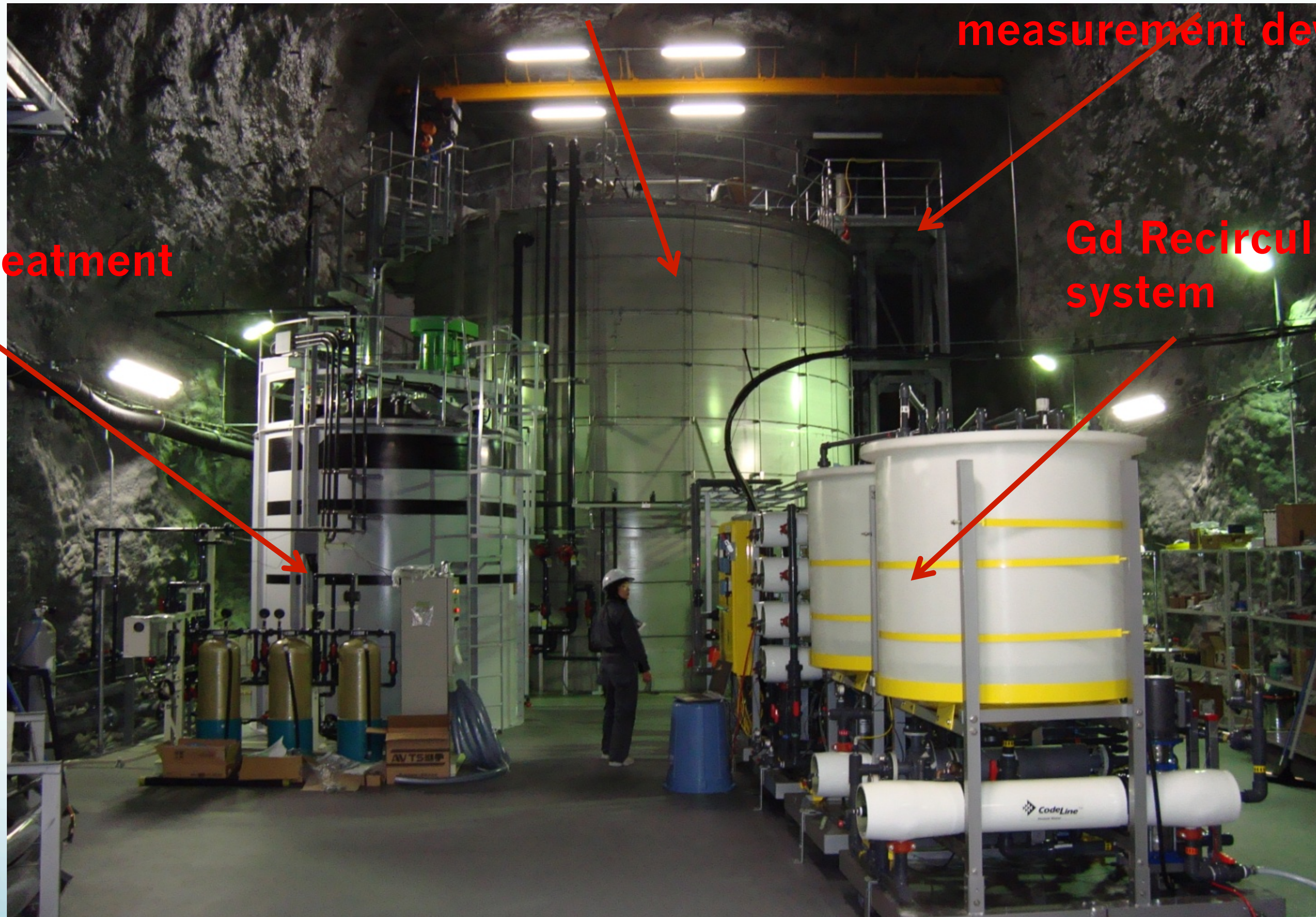
Ongoing experiments

- UC Irvine-
  - Design and small scale testing of techniques for:
    - Gd cleaning
    - Selective filtration
    - Gd removal
    - Materials testing
    - High precision light attenuation measurement
- EGADS
  - Large scale testing of all techniques in Japan
  - Temperature rise test

Selective Water Filtration



Gd Test Set-up in Japan



Cascade Implosion Test at NUWC

- Goals:
  - Assess overall likelihood of cascade implosion
  - Validate the simulation for multi-PMTs implosion test
  - Check the current PA design

- Test Plan:
  - 2-3 cascade PMT implosion tests
  - 5 PMTs per test (Hamamatsu R7081)
  - PA cable mounting scheme
  - ~11 PCB ICP blast sensors
  - ~4 Accelerometers
  - Distance between PMTs ~50cm

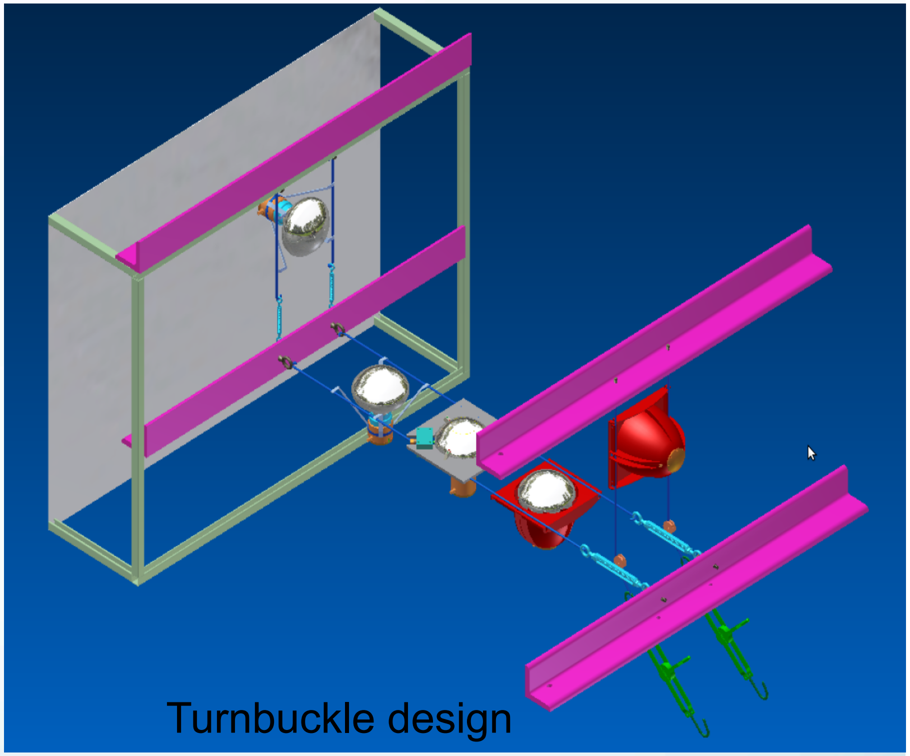
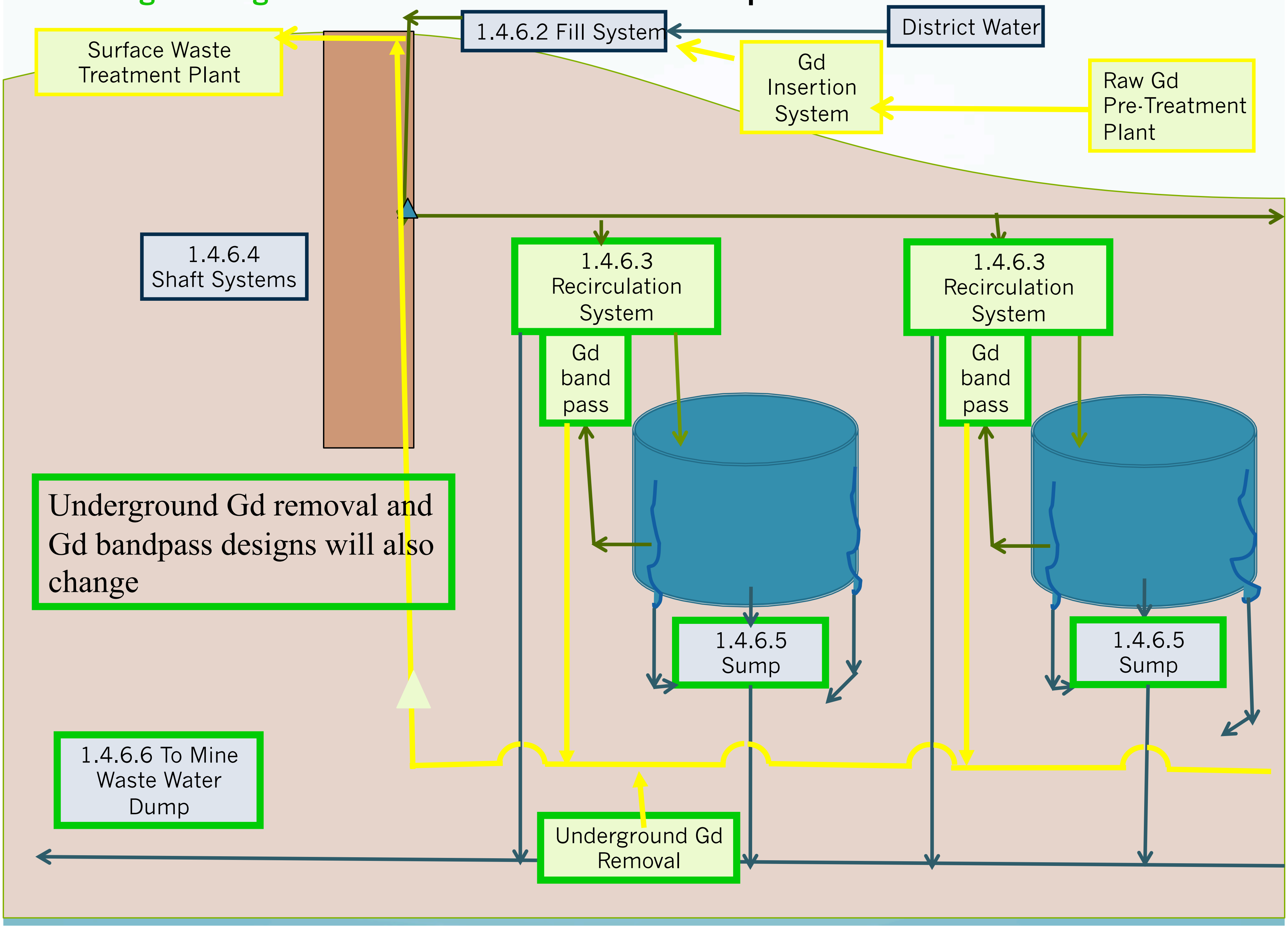


Image from R. Sharma and J. Ling @BNL

Value Engineering cost exercises will effect the Gd Option

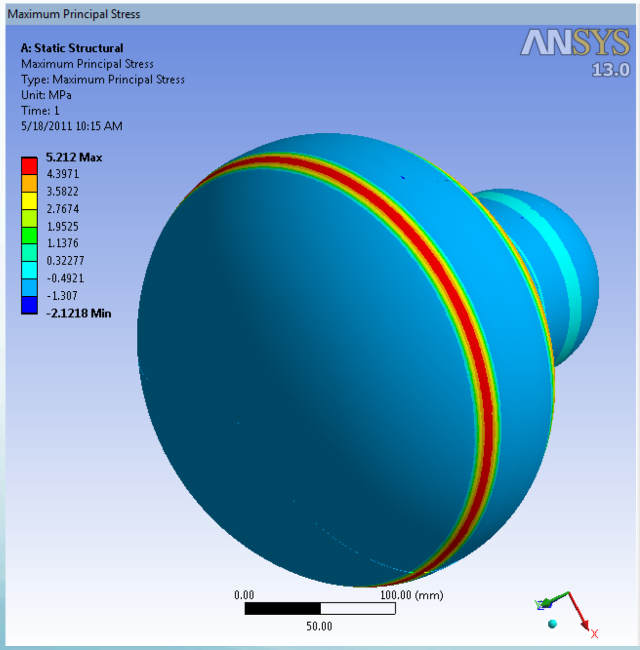


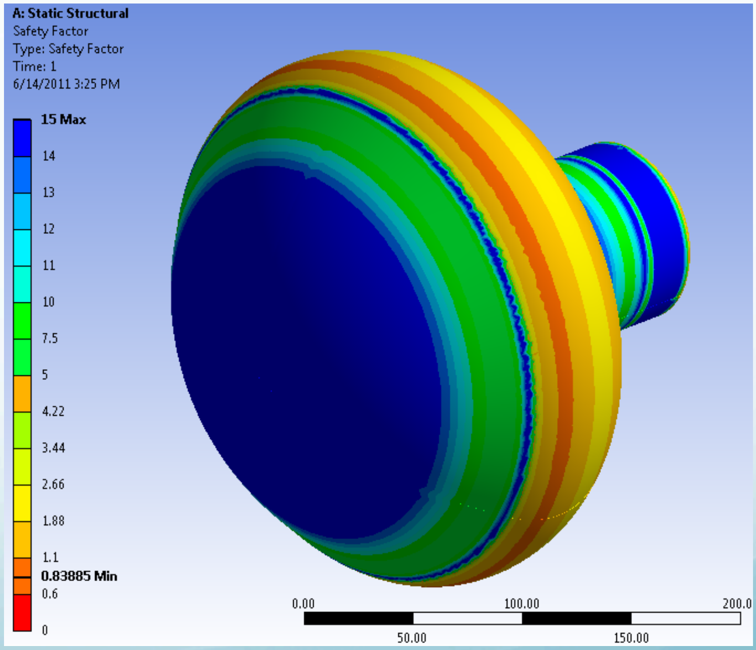
PMT Stress Analysis

Stress analysis of candidate PMTs + potted base assemblies is underway.

Conclusions so far:

- R7081 has weak region above the equator due to an inflection.
- 12” PMTs from Hamamatsu and 11” ADIT/ETL have significantly reduced stresses due to their more spherical shape.
  - Should lead to a higher pressure rating.





Selection of the Far Detector Configuration

- August 2010 report from the Physics Working Group evaluated SIXTEEN detector combinations (300 WC equivalent). Discussed in week-long workshop at the INT with theory community for scientific impact across many fields. Available on INT web site
- LBNE Executive Committee Retreat in September decided to consider only 200 WCE options due to cost, and to look at LAr only at 800 foot option and WC only for 4850 option. It was decided that a final decision should be made "on the timescale of CD-1"

Fall 2010 Report from the LBNE Physics Working Group

A. Beck, O. Benhar, F. Beroz, M. Bishai†, A. Blake, E. Blaufuss†, R. Carr, A. Dighe, M. Diwan, H. Duan, B. Fleming, A. Friedland, H. Gallagher†, G.T. Garvey, D. Gorbunov, R. Guenette, P. Huber, D. Jaffe, W. Johnson, E. Kearns†, S. Kettell, J. Kneller, J. Kopp, J.M. Link, W. Louis, C. Lunardini, W. Melnitchouk, S.R. Mishra, D. Mohapatra, A. Moss, V. Paolone, R. Petti†, J. Raaf, G. Rameika, D. Reitzner, K. Scholberg†, M. Shaevitz, M. Shaposhnikov, M. Smy†, R. Svoboda, R. Tayloe, N. Tolich†, M. Vagins†, B. Viren, D. Webber, L. Whitehead, R.J. Wilson*, G. Zeller†, R. Zwaska

† *Topical Group Convener* * *Physics Working Group Coordinator/Editor*

(Dated: March 13, 2011)

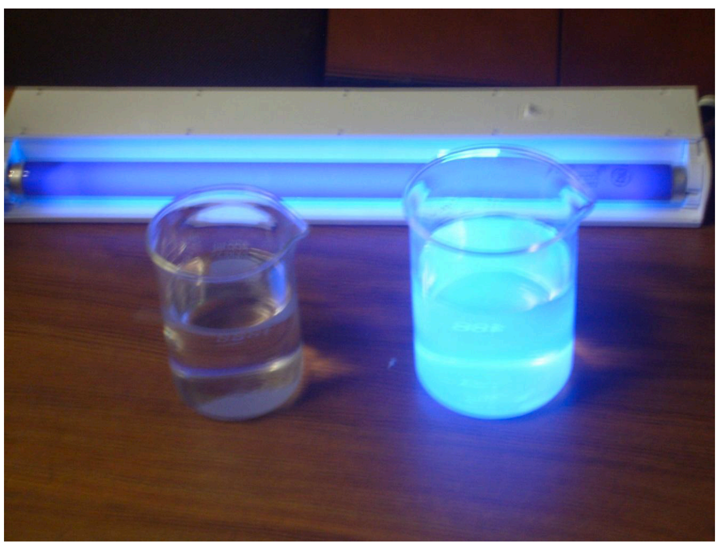
This report has been prepared by the LBNE Science Collaboration Physics Working Group at the request of the collaboration co-spokesmen and the Executive Committee. It is the first of an anticipated series of internal documents intended to assist the collaboration and the LBNE Project with establishing the best possible science case.

The primary purpose of this “Fall 2010” document is to assist in discussions of a collaboration statement on the Far Detector configuration. Nine initial topics were identified as scientific areas that motivate construction of a long-baseline neutrino experiment with a very large far detector. We summarize the scientific justification for each topic and the estimated performance for each of a set of Far Detector reference configurations. We report also on a study of optimized beam parameters and the physics capability of proposed Near Detector configurations.

Other Possible Future Upgrades

Wavelength Shifter

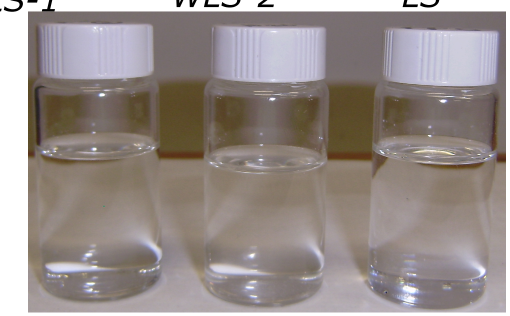
- Factor of two enhancement in light collection by shifting UV to PMT region
- SNO initiated
- LLNL now working on this

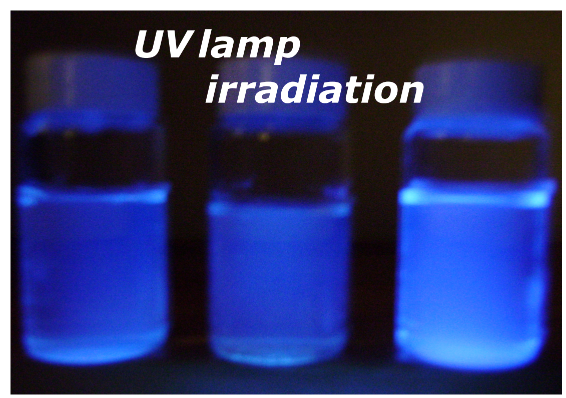


Water Soluble Scintillator

- BNL project to develop actual scintillator that dissolves in water

WLS-1 *WLS-2* *LS*





- At the December 2010 Executive Committee retreat, it was decided that a "mixed" technology solution was preferred "assuming that a funding cap is not considered."
- At the January full LBNE meeting it was decided to prepare three "Case Studies"
- 200 ktons of WC at 4850, 34 ktons of LAr at 800, and "mixed" 150+17/200+34.
- Completed in April, these studies showed that the "mixed" option has the best science potential, but is far more expensive than a single technology option.

#	Detector configuration	LBP	PDK		SNB	SRN	Atm	Sol
			$e\pi$	$K\nu$				
1	Three 100 kt WC, 15%	A1	C2	D4	B3	D4	B1	D3
1a	Three 100 kt WC, 30%	A1	C2	C3	B3	C4	B1	B1
1b	Three 100 kt WC, 30% with Gd	A1	B1	B2	B3	A1	B1	B1
2	Three 17kt LAr, 4850', γ trig	A1	E5	A1	B4	E5	B1	E5
2a	Three 17kt LAr, 300', no γ trig	A1	E5	A2	B4	E5	B1	E5
2b	Three 17kt, LAr, 800', γ trig	A1	E5	A2	B4	E5	B1	E5
3	Two 100 kt WC, 15% + One 17 kt LAr, 300', no γ trig	A1	D4	B4	A2	D4	B3	D3
3a	Two 100 kt WC, 30% + One 17 kt LAr, 300', no γ trig	A1	D3	B4	A1	D4	B3	C2
3b	One 100 kt WC, 15% + One 100 kt WC, 30% & Gd + One 17 kt LAr, 300', no γ trig	A1	C3	B3	A1	B2	B3	C2
4	Two 100 kt WC, 15% + One 17 kt LAr, 800', γ trig	A1	D4	B4	A2	D4	B2	D3
4a	Two 100 kt WC, 30% + One 17 kt LAr, 800', γ trig	A1	D3	B4	A1	D4	B2	C2
4b	One 100 kt WC, 15% + One 100 kt WC, 30% & Gd + One 17 kt LAr, 800', γ trig	A1	C3	B3	A1	B2	B2	C2
5	One 100 kt WC, 30% & Gd + Two 17 kt LAr, 300', no γ trig	A1	D4	A2	B2	B3	B3	C2
6	One 100 kt WC, 30% & Gd + Two 17 kt LAr, 800', γ trig	A1	D4	A2	B2	B3	B2	C2

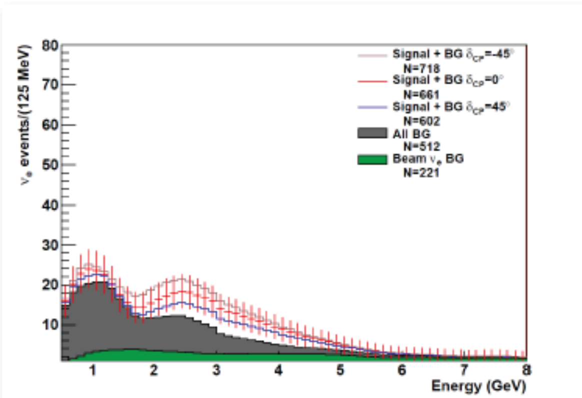
TABLE XXX. Summary of the relative impact of the reference far detector configurations on the measurement sensitivity. Only topics where LBNE will make a competitive measurement are included. The entries consist of two parts: 1) a letter from A-E indicating the impact of the LBNE measurement made possible by a particular configuration as compared to the [expected] state of world knowledge, and 2) the relative ranking of the different configurations for the physics topic of interest. Highlighted boxes indicate the preferred option for that topic.

Configurations evaluated in the 2010 PWG report. The full document is available on the INT web site.

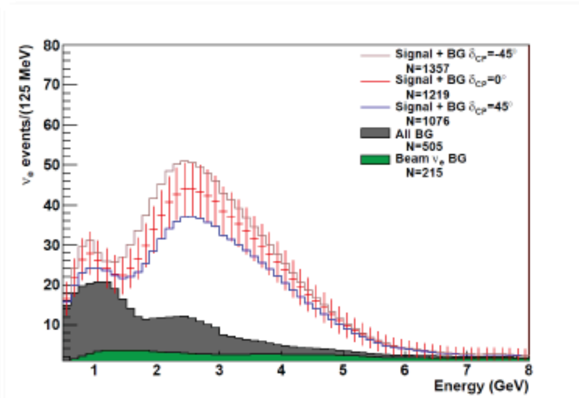
- In it's July 2011 meeting the Executive Committee decided to pursue the "single technology" options, but left open the door for a "mixed" option if there was still sufficient interest in the collaboration. This has not materialized. Thus TWO options survive.
- The EC also gave final approval to the "Principles" and "Procedures" for making the final technology choice by developing the scientific Case Studies, costs, and schedules into a package that could be reviewed internally and externally for validity and completeness. These are public documents that were developed with the concurrence of the Collaboration, DOE OHEP, and FNAL Director.
- It was decided that LAr would also be reconsidered at 4850 due to concerns with the rising costs for the 800 level and the disconnect with the potential broad program at 4850. It was not thought that this would delay the scientific evaluation of the Case Studies, but might delay the final costs until late October.
- The Executive Committee is on track to make a final recommendation by the end of 2011.
- **While we will move expediently, we will not be rushed – but will do what is necessary to ensure a complete, thoughtful, and final recommendation. Risks recognized and evaluated, costs understood, schedules not allowed to lapse unnecessarily or be unrealistically optimistic.**

Larger θ_{13} Means Larger Signals

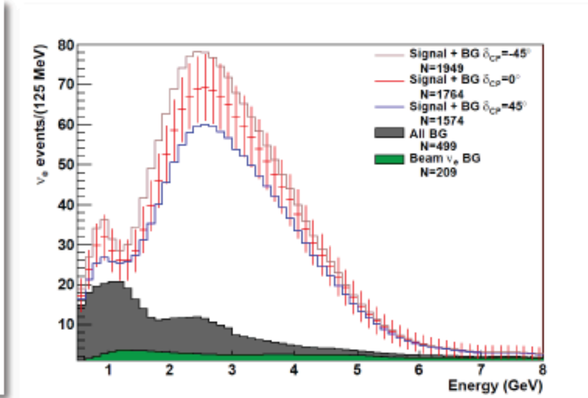
$\sin^2 2\theta_{13}=0.01$



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



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



(M. Bass, B. Wilson)

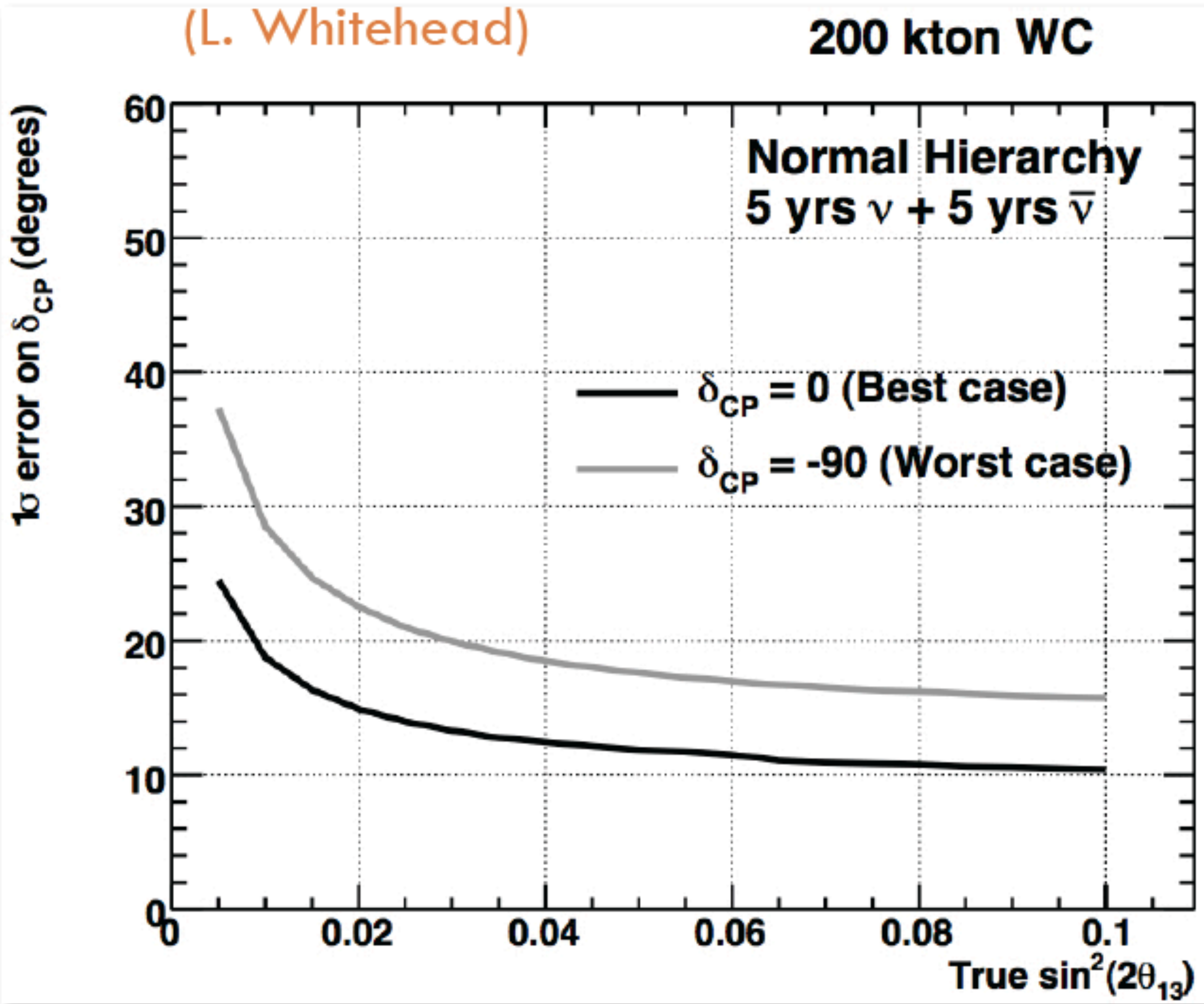
ν_e signal events for 200 kton WC, 5 yrs ν, 700 kW, 1300km, NH, δ=0

(expect smaller rates for IH, also for anti-ν running)

149	714	1,265

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

δ_{CP} resolution not strongly dependent on θ_{13}



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

One needs large detectors for CP violation searches

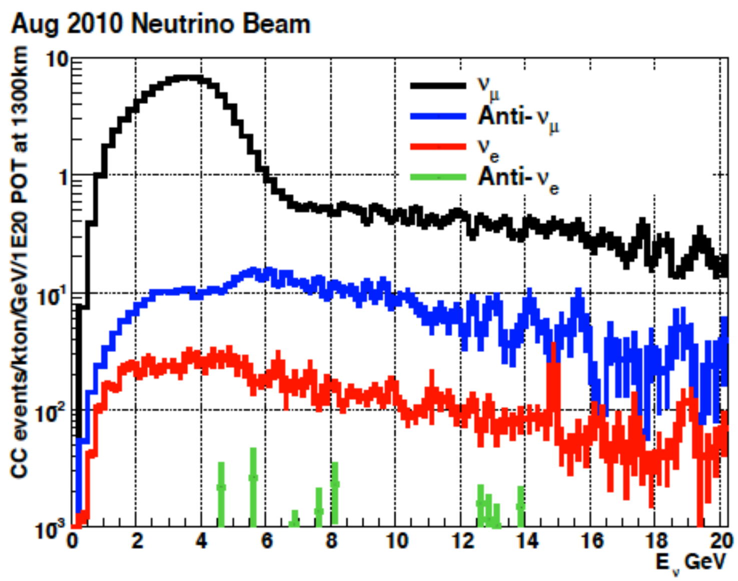
Beam Reference Design

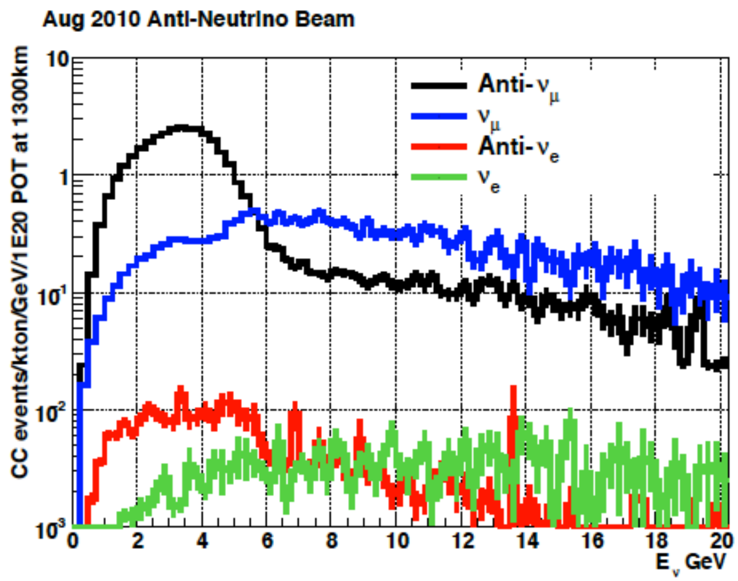
The LBNE design selected for physics studies maximizes the ν_e appearance signal at 1300km.

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

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

Decay Pipe: r=2m, l=280m, He filled/evacuated.



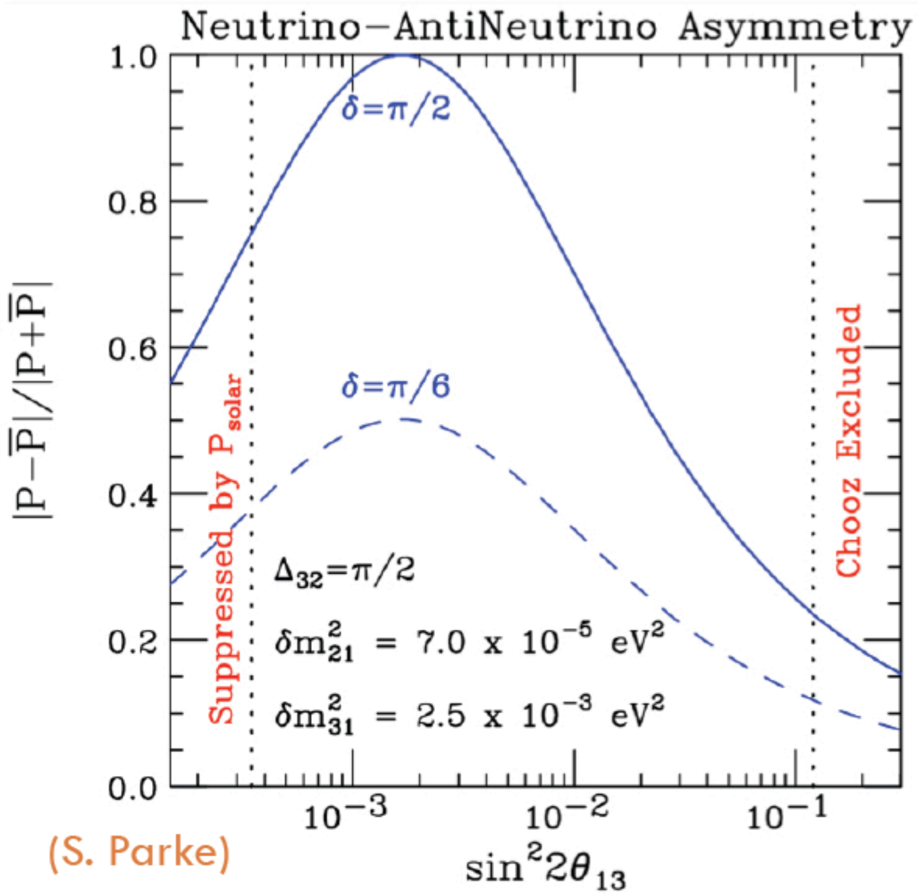


Oscillation CC rates/(100 kT.MW.yr):

ν beam, $\Delta m^2_{31} = +2.5 \times 10^{-3}\mathrm{eV}^2$, $\delta_{cp} = 0$, $\sin^2 2\theta_{13} = 0.04$

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

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



(ignoring matter effects & backgrounds for now)

- 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 θ_{13} increases**

$\sim$75% for $\sin^2 2\theta_{13}=0.01$
$\sim$25% for $\sin^2 2\theta_{13}=0.10$ } $\delta_{CP}=\pi/2$

factor ~3 reduction in CP asymmetry (independent of baseline)

- **signal rate increases w/ θ_{13}**

(~x10 increase from 0.01 to 0.1; so ~x3 improvement in stat sig of signal)

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

Table 6–3: Number of ν_μ and $\overline{\nu_\mu}$ 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 ν_μ ($\overline{\nu_\mu}$) QE events in the case of neutrino (antineutrino) mode running. Wrong-sign backgrounds refer to ν_μ events in the antineutrino mode beam.

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

Table 5–3: Number of ν_μ and $\overline{\nu_\mu}$ 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 ν_μ ($\overline{\nu_\mu}$) CC events in the case of neutrino (antineutrino) mode running. Wrong-sign backgrounds refer to ν_μ 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

	WC (ν mode)	WC ($\bar{\nu}$ mode)
Normal mass hierarchy:		
Oscillated $\nu_e+\overline{\nu_e}$	484	180
Beam $\nu_e+\overline{\nu_e}$	218	115
NC	276	118
Mis-identified ν_μ CC	15	7
Inverted mass hierarchy:		
Oscillated $\nu_e+\overline{\nu_e}$	212	261
Beam $\nu_e+\overline{\nu_e}$	221	114
NC	276	118
Mis-identified ν_μ CC	15	7

Table 6–1: Number of ν_e and $\overline{\nu_e}$ 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 (ν mode)	LAr ($\bar{\nu}$ mode)
Normal mass hierarchy:		
oscillated $\nu_e+\overline{\nu_e}$	497	112
beam $\nu_e+\overline{\nu_e}$	326	168
NC	81	34
mis-identified CC	162	52
Inverted mass hierarchy:		
oscillated $\nu_e+\overline{\nu_e}$	212	261
beam $\nu_e+\overline{\nu_e}$	329	167
NC	81	34
mis-identified CC	162	52

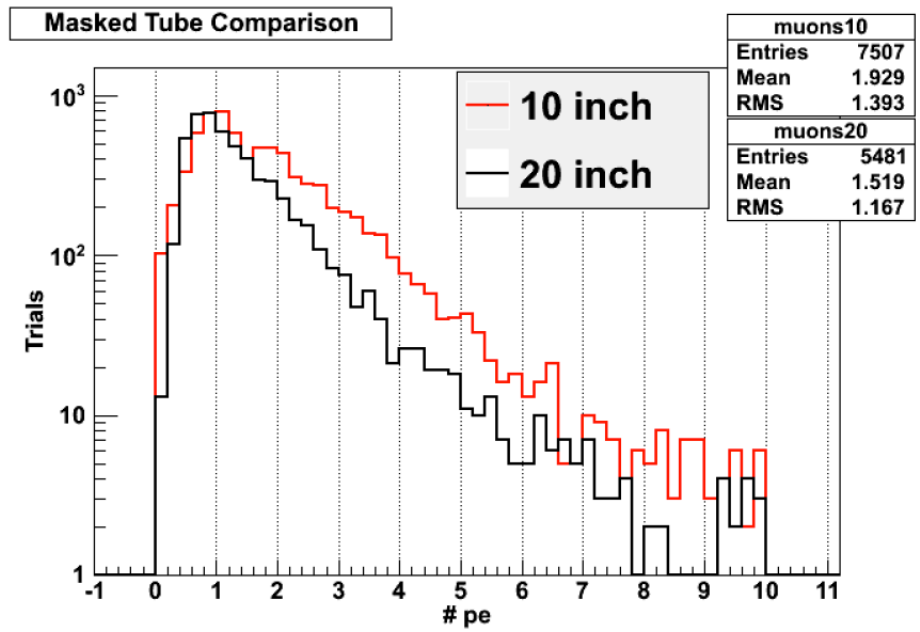
Table 5–1: Number of ν_e and $\overline{\nu_e}$ events expected in a 34-kt LAr detector at 1300 km in 5 years each of neutrino and antineutrino running in a 700 kW beam [3]. Rates have been integrated over the region from $0.5 - 60$ GeV. Like Figure 5–4, this assumes $\sin^2 2\theta_{13} = 0.04$ and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

Event rates for nue and nuebar 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.

HQE gain verified by lab tests



$$\frac{< q_{10} >}{< q_{20} >} = \frac{1.93}{1.52} \Rightarrow \frac{\mu_{10}}{\mu_{20}} = \frac{1.50}{0.90} = \boxed{1.67 \pm 0.1}$$

$$< q > = \frac{G\mu}{1 - e^{-\mu}}$$

Where G is the gain of the PMT which we measure before the test. And <q> is measured in number of photoelectrons.

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Executive Summary

In October 2008, the Division of Technical Support (SGTS) convened a *Workshop on Antineutrino Detection for Safeguards Applications* to target emerging and future antineutrino detection uses in the safeguards regime.

The objective of the meeting was to define applicable inspection needs and to examine the use and effectiveness of antineutrino detection and monitoring in meeting those needs, particularly those covering the implementation of safeguards for reactor facilities. It brought together 12 Agency personnel from the SG Department Support Divisions with 19 external experts from eight Safeguards Member State Support Programmes (MSSP).

The meeting concluded that antineutrino detectors have unique abilities to non-intrusively monitor reactor operational status, power and fissile content in near real-time, from outside containment. Several detectors, built specifically for safeguards applications, have demonstrated robust, long-term measurements of these metrics in actual installations at operating power reactors, and several more demonstrations are planned. It was agreed that the detector design is sufficiently robust and mature as to allow a reusable module to be developed that could be adapted to specific reactors.