Large Underground Detectors at DUSEL

Milind Diwan
Brookhaven National Laboratory

9/20/2007

B-L Workshop at LBL

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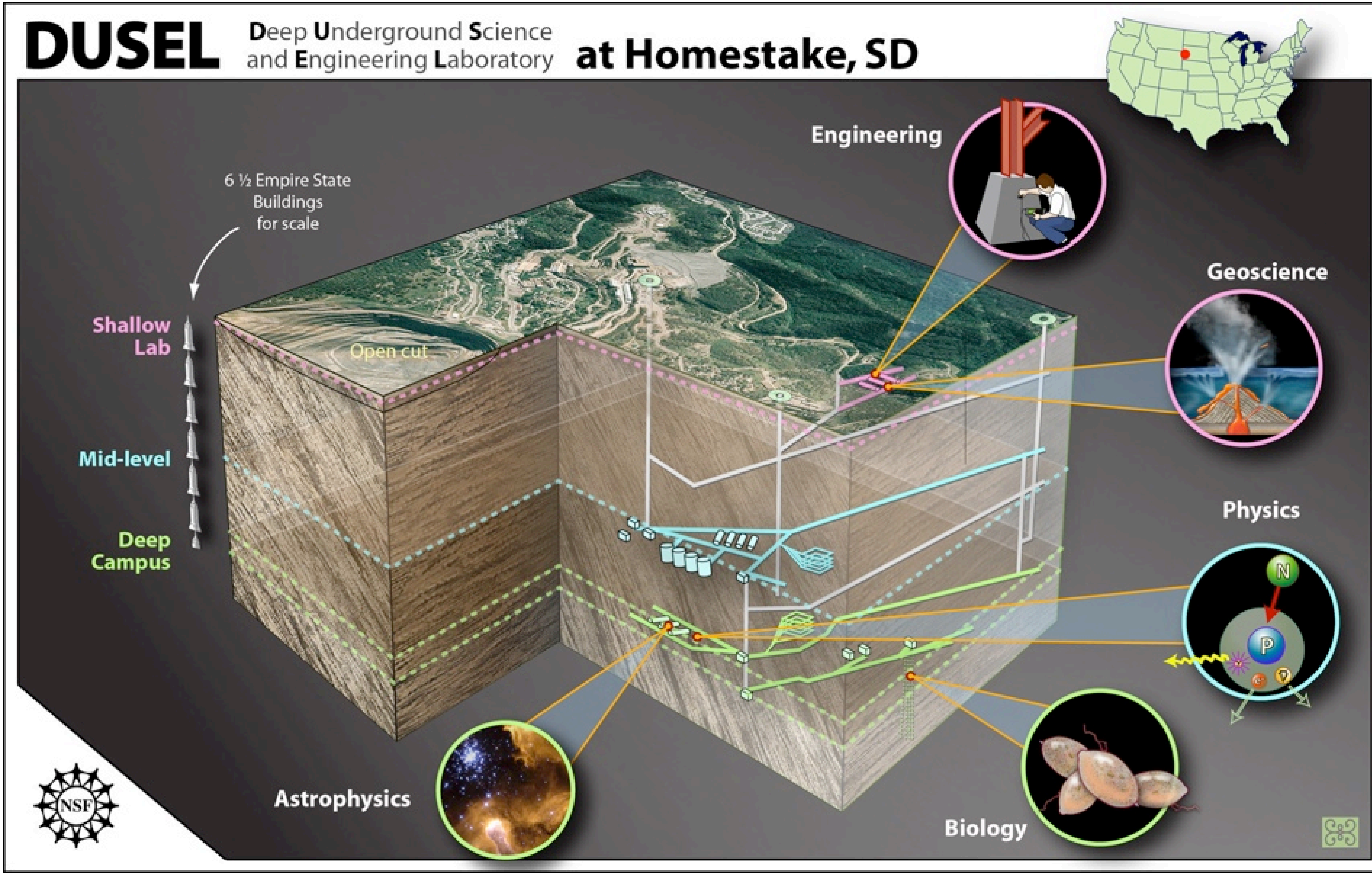
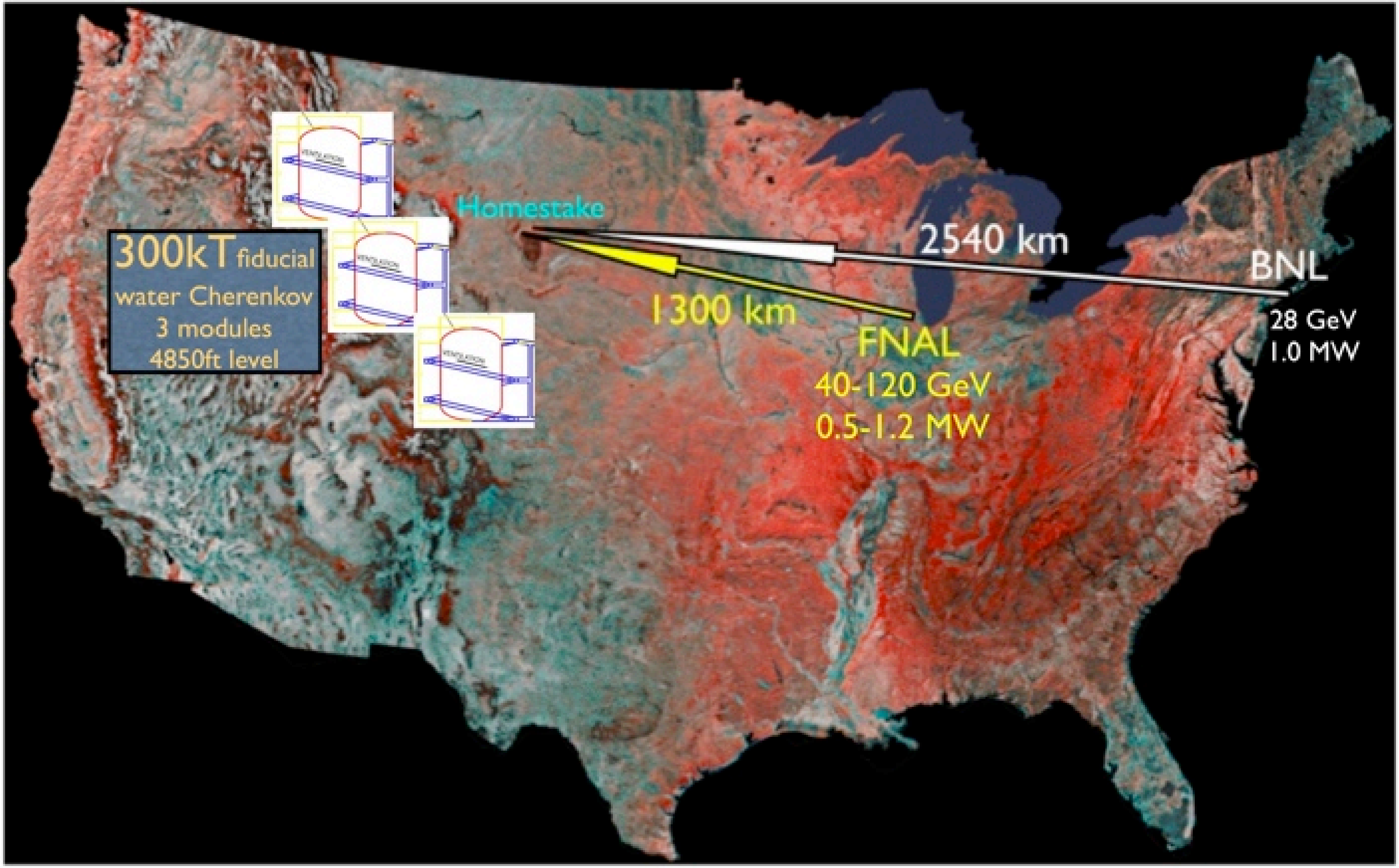


NSF site decision on advice from a 22 member unanimous panel.


Homestake
300kT fiducial
water Cherenkov
3 modules
4850ft level
2540 km
BNL
28 GeV
1.0 MW
1300 km
FNAL
40-120 GeV
0.5-1.2 MW

Science to be addressed with very large detectors

- Nucleon Decay
- Neutrino Astrophysics
- Neutrino Oscillations.
  - ★ What is the size of last mixing angle, θ_{13} ?
  - ★ What is the ordering of Neutrino masses?
  - ★ Do Neutrinos violate the CP symmetry?

FNAL/BNL study

- Launched April 2006 in anticipation of physics urgency as well as DUSEL.
- Chairs: Hugh Montgomery, Sally Dawson
- Advisory committee: F. Cervelli(INFN), M. Diwan(BNL), M. Goodman(ANL), B. Fleming(Yale), K. Heeger(LBL), T. Kajita (Tokyo), J. Klein(Texas), S. Parke(FNAL), R. Rameika(FNAL)
- Several small workshops were held last year.
- Many reports on physics sensitivity, backgrounds, and beam alternatives.
- Work of approximately 20-30 individuals at various levels.
- >10 documents. ~2-3 publications could result

http://nwg.phy.bnl.gov/fnal-bnl/

U.S. Long Baseline Neutrino Experiment Study

Compare the neutrino oscillation physics potential of:

1. A broad-band proposal using a either an upgraded beam of around 1 MW from the current Fermilab accelerator complex or a future Fermilab Proton Driver neutrino beam aimed at a DUSEL-based detector. Compare these results with those previously obtained for a high intensity beam from BNL to DUSEL.

2. Off-Axis next generation options using a 1-2 MW neutrino beam from Fermilab and a liquid argon detector at either DUSEL or as a second detector for the Nova experiment.

Considerations of each should include:

i) As a function of θ_{13}, the ability to establish a finite θ_{13}, determine the mass hierarchy, and search for CP violation and, for each measurement, the limiting systematic uncertainties.

ii) The precision with which each of the oscillation parameters can be measured and the ability to therefore discriminate between neutrino mass models.

iii) Experiment Design Concepts including:

Optimum proton beam energy
Optimum geometries
Detector Technology
Cost Guesstimate

April 5, 2006

Milestone: Presentation to the FNAL PAC, March 29. 2007

http://nwg.phy.bnl.gov/fnal-bnl

Final report released May 2007 V. Barger et al., arXiv:0705.4396

Fermilab-0801-AD-E
BNL-77973-2007-IR

Report of the US long baseline neutrino experiment study

V. Barger,[1] M. Bishai,[2] D. Bogert,[3] C. Bromberg,[4] A. Curioni,[5] M. Dierckxsens,[2] M. Diwan,[2] F. Dufour,[6] D. Finley,[3] B. T. Fleming,[5] J. Gallardo,[2] D. Gerstle,[5] J. Heim,[2] P. Huber,[1] H. Jostlein,[3] C. K. Jung,[7] S. Kahn,[2] E. Kearns,[6] H. Kirk,[2] T. Kirk,[8] K. Lande,[9] C. Laughton,[3] W. Y. Lee,[10] K. Lesko,[10] C. Lewis,[11] P. Litchfield,[12] A. K. Mann,[9] A. Marchionni,[3] W. Marciano,[2] D. Marfatia,[13] A. D. Marino,[3] M. Marshak,[12] S. Menary,[14] K. McDonald,[15] M. Messier,[16] W. Pariseau,[17] Z. Parsa,[2] S. Pordes,[3] R. Potenza,[18] R. Rameika,[3] N. Saoulidou,[3] N. Simos,[2] R. Van Berg,[9] B. Viren,[2] W.T. Weng,[2] K. Whisnant,[19] R. Wilson,[20] W. Winter,[21] C. Yanagisawa,[7] F. Yumiceva,[22] E. D. Zimmerman,[8] and R. Zwaska[3]

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NUSAG Charge

March 3, 2007

Address APS Study's recommendation for a next generation neutrino beam and detector configurations

U.S. Department of Energy
and the
National Science Foundation

March 3, 2006

Professor Eugene Beier
Co-Chair, NuSAG
University of Pennsylvania
209 South 33rd Street
Philadelphia, PA 19104

Professor Peter Meyers
Co-Chair, NuSAG
Princeton University
306 Jadwin Hall
Princeton, NJ 08544

Dear Professors Beier and Meyers:

We would like to thank you and the Neutrino Scientific Assessment Group (NuSAG) for your timely and thoughtful responses to the initial questions that were posed to you, concerning neutrinoless double beta decay, reactor experiments and accelerator-based experiments to determine fundamental neutrino properties. They have already been very useful and will help us put together a strong US program in neutrino physics.

We would now like your group to address the APS Study's recommendation for a next-generation neutrino beam and detector configurations. Assuming a megawatt class proton accelerator as a neutrino source, please answer the following questions for accelerator-detector configurations including those needed for a multi-phase off-axis program and a very-long-baseline broad-band program. This assessment will be used as one of the key elements to guide the direction and timeline of such a possible next generation neutrino beam facility.

In your assessment, NuSAG should look at the scientific potential of the facility, the timeliness of its scientific output, and its place in the broad international context. Specifically:

- **Scientific potential:** What are the important physics questions that can be addressed at the envisioned neutrino beam facility?
- **Associated detector options:** What are the associated detector options which might be needed to fully realize the envisioned physics potentials? What are the rough cost ranges for these detector options?
- **Optimal timeline:** What would be the optimal construction and operation timeline for each accelerator-detector configuration, taking the international context into account?
- **Other scientific considerations:** What other s[illegible] considerations, such as results from [illegible] experiments, will be important in order to [illegible] determine the design [illegible] What would be additional important physics questions that can be addressed [illegible] the same detector(s)?

The DOE a[illegible] the NSF would like a preliminary draft of your report by Decem[illegible] with a [illegible] version [illegible] 2007.

Final report is based on ours. Released July 27.

- What are the physics questions to be addressed?
- What are the detector options needed to realize the physics? Rough Costs?
- What is the optimal construction and operation timeline?
- What would be additional important physics questions that can be addressed by the same detector?

NuSAG requested input from US LBν Study to address APS recommendation

Two approaches

No new beam, but restricted physics because of surface det.

- Off axis: Use existing NUMI beam. NOvA will be built ~10mrad offaxis for the first maximum. NOvA2(100kTLAR) will be built at either 10 mrad or 40 mrad for second maximum. Detectors will be on the surface. Combine the results to extract th13, mass hierarchy, and CPV.

New beam, but detector capable of Nucleon Decay

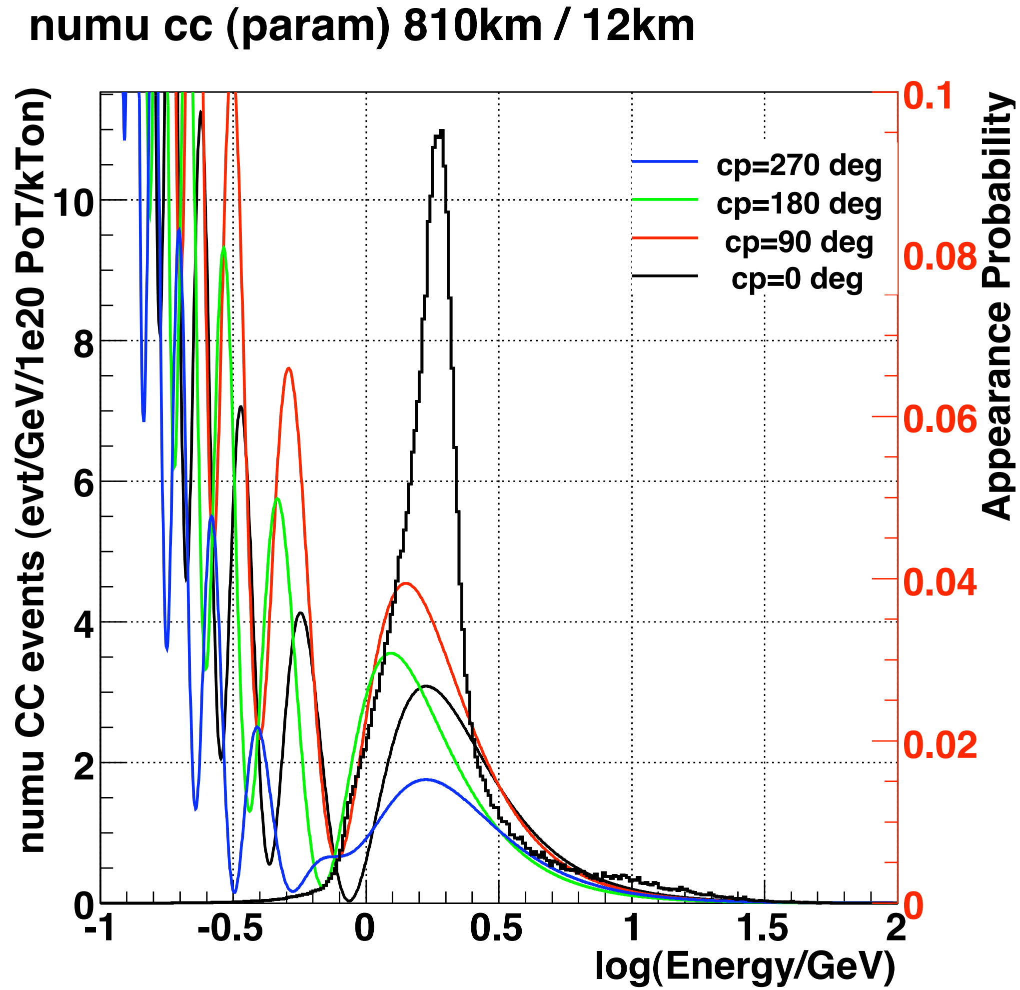
- Wide band Low Energy: Couple the long baseline program to a new deep underground laboratory (DUSEL). Site a large detector (~300kT if water Cherenkov or 100kT LAR) at approximately 5000 mwe. Build a new wide beam with a spectrum shaped to be optimum (0.5-6 GeV). Use detector resolution to extract multiple nodes.

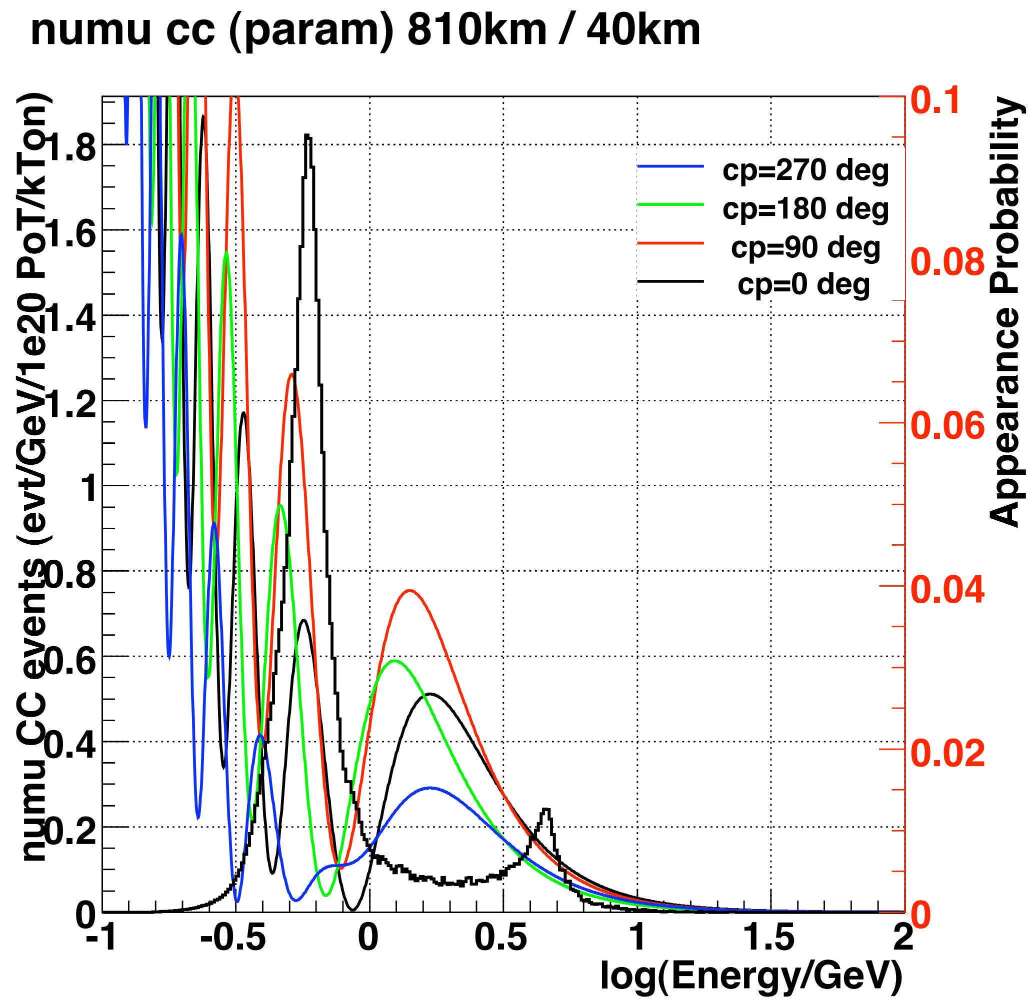
- Concerns: event rate, NC background, resolution, parameter sensitivity, total cost and timeliness.

Proton Intensity

	Now	Proton Plan	NOvA *	SNuMI	Project X	
Batch Intensity (8 GeV)	4.4×10^{12}	4.3×10^{12}	4.1×10^{12}	4.5×10^{12}	5.6×10^{13}	protons/pulse
Rep Rate	7	9	12	13.5	5	Hz
Protons/hour	1.1×10^{17}	1.4×10^{17}	1.8×10^{17}	2.2×10^{17}	1.0×10^{18}	
Main Injector batches	7	11	12	18	3	
MI batches to pbar target	2	2	0	0	0	
MI Cycle Time	2.4	2.2	1.33	1.33	1.4	sec
MI Beam Power (120 GeV)	176	338	710	1169	2314	kW
8 GeV Beam Power (available)	18	17	16 *	0	206	kW
Injection energy into 1st synchrotron	400	400	400	400	8000	MeV

off-axis spectra with LE tune





sin^22t13 =0.04

- 12 km (nova-I) CCrate: ~16.2 per (kT*10^20 POT)
- 40 km (nova-II)CCrate: ~1.0 per (kT*10^20 POT)

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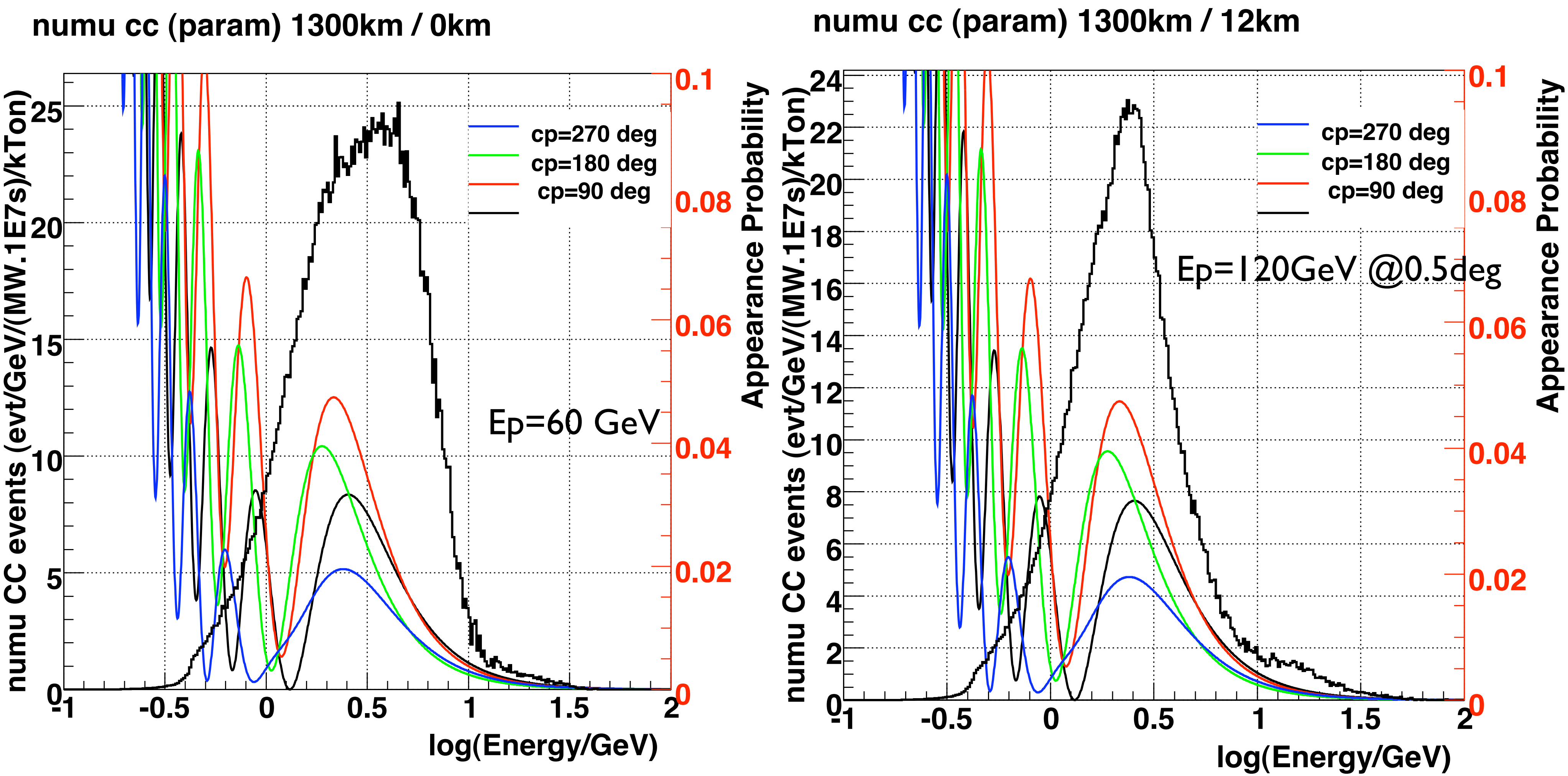
Spectra FNAL to DUSEL (WBLE:wide band low energy)



- 60 GeV at 0deg: CCrate: 14 per (kT*10^20 POT)
- 120 GeV at 0.5deg:CCrate: 17 per(kT*10^20POT)

Work of M. Bishai and B.Viren using NuMI simulation tools

Key Event Rate in 100kT*MW*10^7

$$\nu_\mu \longrightarrow \nu_e$$

$\Delta m^2_{21,31} = 8.6 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ $\sin^2 2\theta_{12,23} = 0.86, 1.0$ $\sin^2 2\theta_{13} = 0.02$

$$\delta_{CP}$$

	$sgn(\Delta m^2_{31})$	0 deg	+90 deg	180 deg	-90 deg
NuMI-15mrad (810km)	+	76	36	69	108
NuMI-15mrad (810km)	-	46	21	52	77
WBLE (1300km)	+	87	48	95	134
WBLE (1300km)	-	39	19	51	72

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Key Experimental Factor

- Need ~100kT of fiducial mass with good efficiency.
- At this mass scale cosmic ray rate becomes the driving issue for detector placement and design.

$\sin^2 2\theta_{13} = 0.02$

signal~50 evts/yr

Cosmic rate in 50m h/dia detector in $10\mu s$ for 10^7 pulses

Intime cosmics/yr	Depth (mwe)	
5×10^7	0	
4230	1050	
462	2000	
77	3000	
15	4400	DUSEL depth

If detector is placed on the surface it must have cosmic rejection for muons $\sim 10^8$ and for gammas $\sim 10^4$ beyond accelerator timing.

=> fully active fine grained detector.

NUSAG Detector findings

D1 The off-axis beam approaches considered in the US are based on a detector technology that is to be deployed on or near the earth's surface. An ability to acquire data at a high rate, an ability to process the large volume of data originating from cosmic rays, and an ability to reject background to neutrino oscillation induced by cosmic rays or their secondary products must be demonstrated for this detector technology to be feasible for an experiment sited near the earth's surface. Water Cherenkov detectors do not satisfy this criterion; it remains to be demonstrated that liquid argon time projection chambers do.

D2 The wide-band beam approach could be implemented with the established water Cherenkov detector technology or with a liquid argon detector, if that technology proves successful. Water Cherenkov detectors must be deployed underground for the cosmic ray event rate to be manageable. If liquid argon is deployed underground, there are additional cost and safety issues that are presently not addressed.

Water Cherenkov

One of the achievements of the joint study group.

WC-1 Water Cherenkov detectors are an established technology for neutrino oscillation and nucleon decay physics. Adequate rejection of background π^0 events in neutrino oscillation experiments has been demonstrated in detailed simulations using the full reconstruction made available by the Super-Kamiokande experiment.

WC-2 The water Cherenkov detector wide-band beam neutrino oscillation experiment could be ready to proceed at the time $\sin^2 2\theta_{13}$ is determined. The cost of this option is driven by the cost of photo-multiplier tubes, and the schedule is driven by the time to manufacture the photo-multiplier tubes.

WC-3 The water Cherenkov detector technology has been demonstrated to be a suitable technology for a general purpose search for nucleon decay.

WC-4 Water Cherenkov detectors are not suitable for deployment at or near the earth's surface due to the large rate of cosmic ray events.

LAR commentary

LAr-1 The principal advantage of a liquid argon detector for neutrino oscillation physics is excellent spatial resolution that results in good rejection of neutral current induced π^0 background. This property results in an estimated factor of four to five greater detection efficiency per unit mass relative to the water Cherenkov approach. The liquid argon detector is highly suited to the study of the decay mode $p \rightarrow K^+\overline{\nu}$ favored in supersymmetric models of nucleon decay.

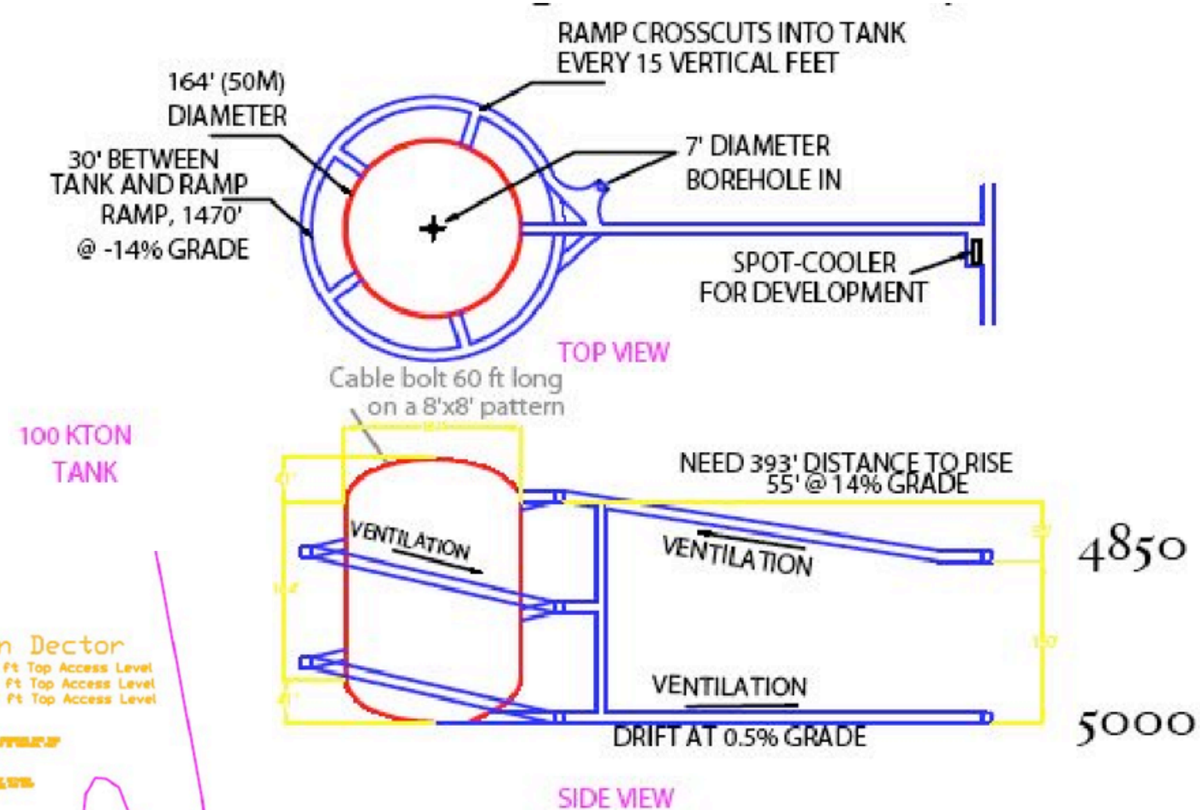
LAr-2 Initiation of construction of liquid argon detectors of 50-100 kton fiducial mass on the time scale of a decision to proceed with a long baseline neutrino oscillation program requires the success of an aggressive R&D program.

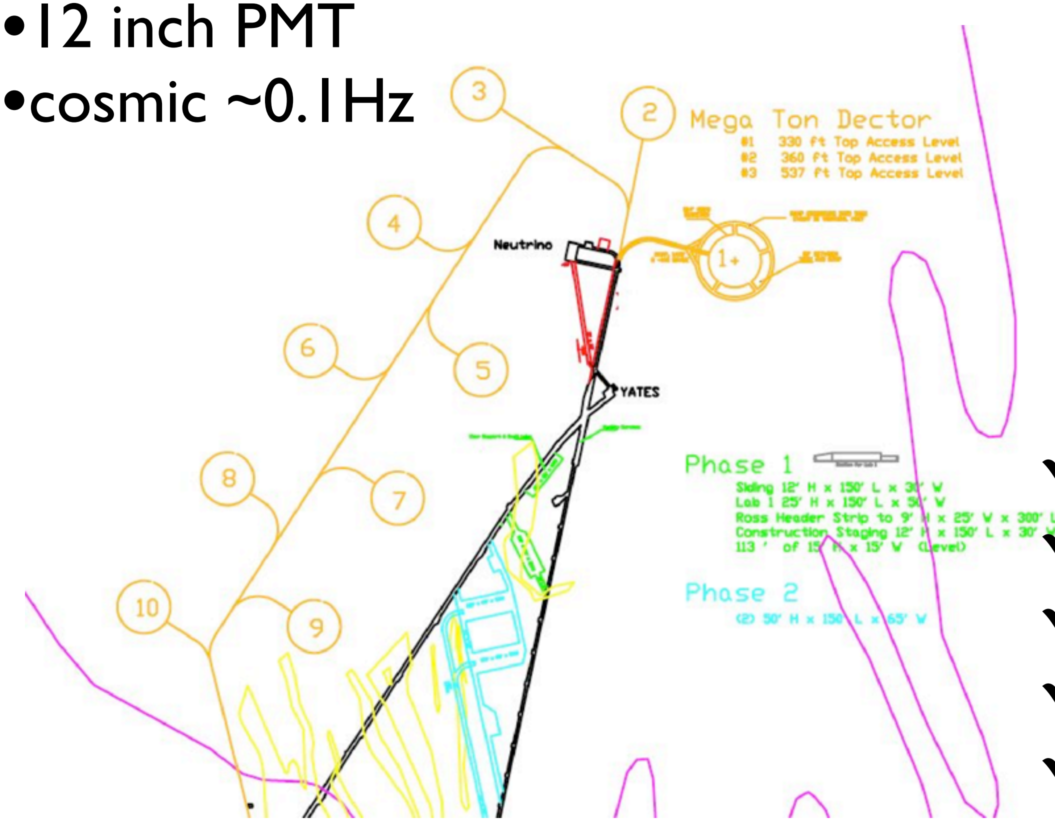
LAr-3 Liquid argon detectors are an attractive option for the wide-band beam approach if all R&D is successfully completed and the cost per unit effective mass is competitive.

Detector at Homestake

Modular Detector

- ~50m dia/h
- 100kT fiducial
- 4850 mwe
- 25% PMT cov.
- 12 inch PMT
- cosmic ~0.1Hz





- ✓Initial detector 3 modules
- ✓Space can be planned for 10
- ✓ Cost estimate $115M/module
- ✓6 yrs construction to first 100kT
- ✓8 yrs to full 300 kT.

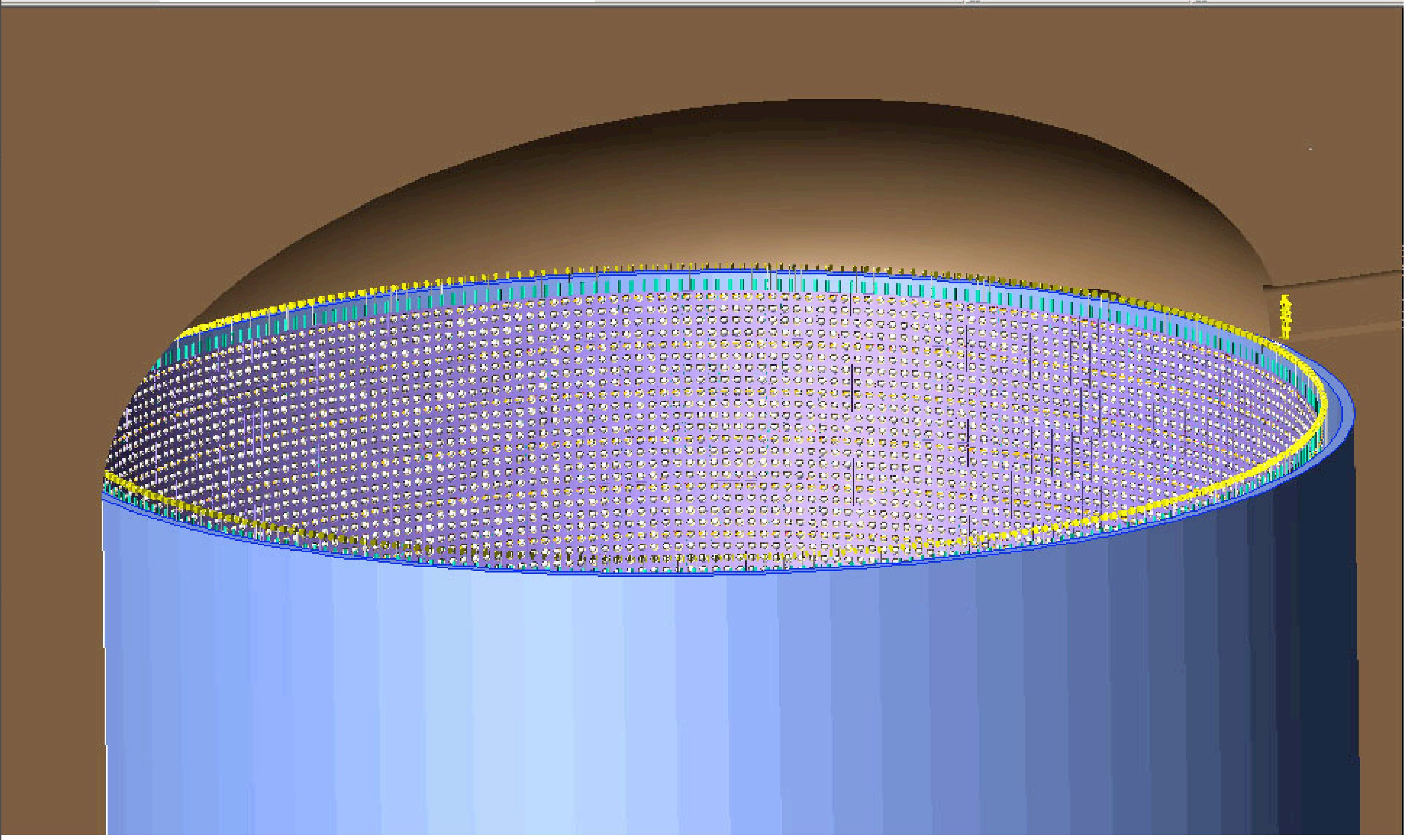
Fiducial vol depends on rock stability studies and PMT pressure rating.

Summary cost ($FY07) for 300kT at Homestake

Cavity construction (30% contingency)	$78.9M
PMT+electronics	$171.3M
Installation+testing	$35.7M
R&D,Water, DAQ, etc.	$8.2M
Contingency(non-civil)	$50.8M
Total	$344.9M

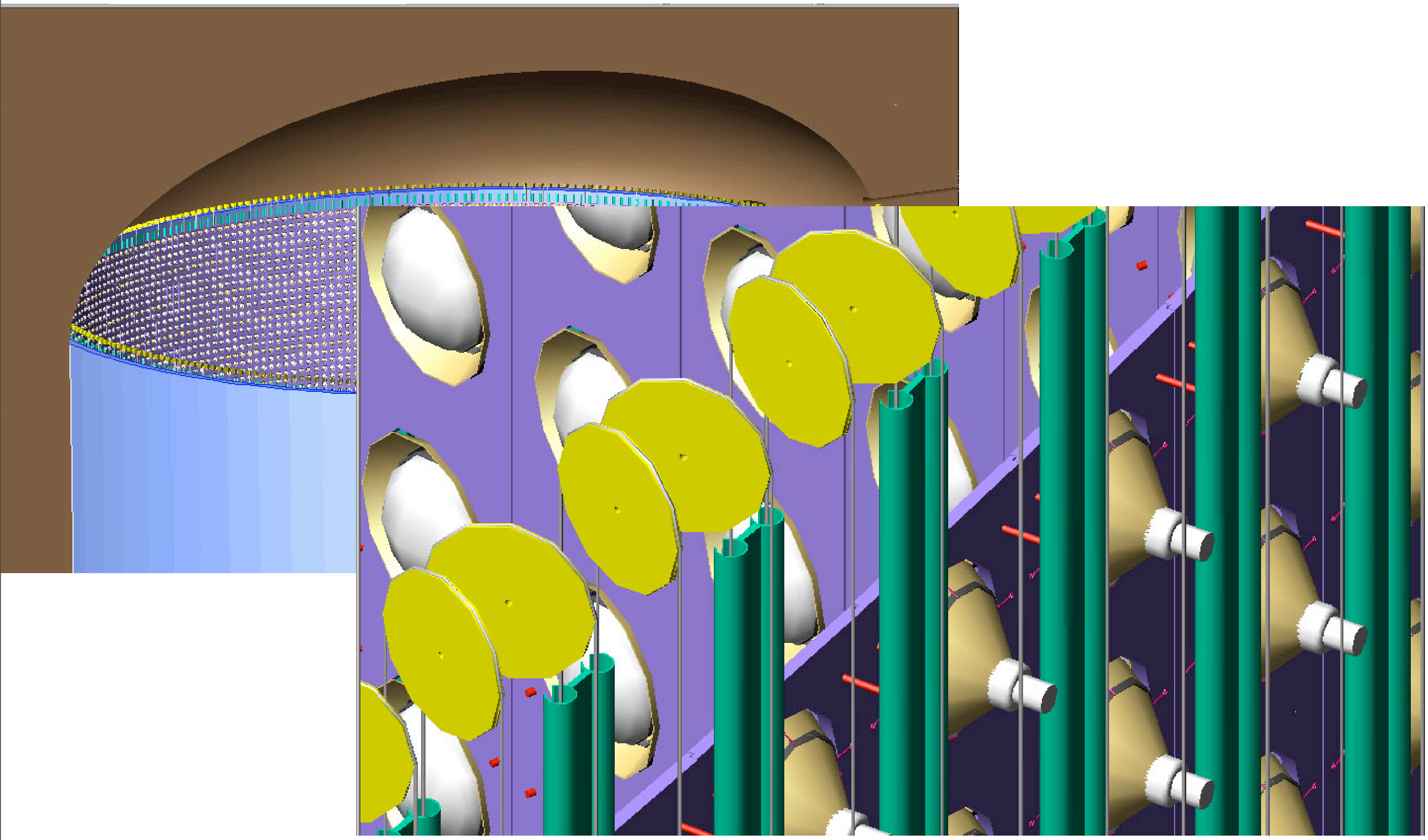
- Cost for 3 modules of ~100kT fiducial mass. 6 yrs to first 100kT, 8 yrs for full 300kT.
- Civil cost recently reviewed by RESPEC (consultants) and found to be consistent with other projects. (In addition, construction could be faster).
- Consultations with C. Laughton and Homestake on overhead factors (not included in civil).

Installation



Conceptual design for installation

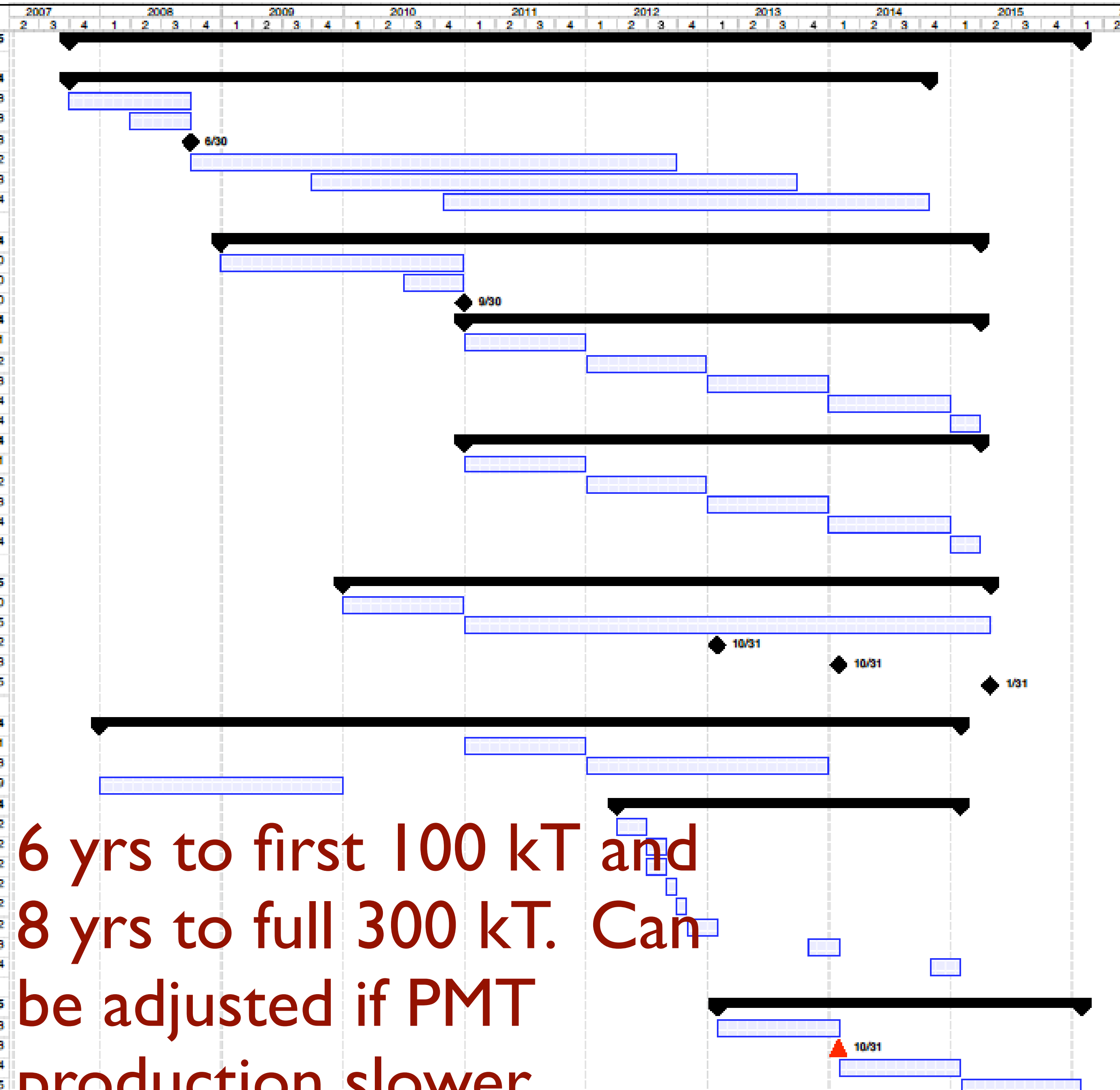
Installation



Conceptual design for installation

Long Baseline Neutrinos + PDK
Schedule No. 2

ID	Task Name	Start	Finish
1	**Long Baseline Neutrinos + PDK**	7/2/07	10/30/15
2			
3	**Chamber Construction**	7/2/07	7/30/14
4	Chamber R&D	7/2/07	6/30/08
5	Contract Process	1/1/08	6/30/08
6	Chamber Construction Contract Award	6/30/08	6/30/08
7	Module 1	7/1/08	6/29/12
8	Module 2	7/1/09	6/28/13
9	Module 3	8/2/10	7/30/14
10			
11	**PMs**	10/1/08	12/31/14
12	PM R&D	10/1/08	9/30/10
13	Contract Process	4/1/10	9/30/10
14	PMs Contract Award	9/30/10	9/30/10
15	**Vendor 1**	10/1/10	12/31/14
16	Qty 10,000 PMs	10/1/10	9/30/11
17	Qty 20,000 PMs	10/3/11	9/28/12
18	Qyt 20,000 PMs	10/1/12	9/30/13
19	Qty 20,000 PMs	10/1/13	9/30/14
20	Qty 5,000 PMs	10/1/14	12/31/14
21	**Vendor 2**	10/1/10	12/31/14
22	Qty 10,000 PMs	10/1/10	9/30/11
23	Qty 20,000 PMs	10/3/11	9/28/12
24	Qyt 20,000 PMs	10/1/12	9/30/13
25	Qty 20,000 PMs	10/1/13	9/30/14
26	Qty 5,000 PMs	10/1/14	12/31/14
27			
28	**Testing**	10/1/09	1/31/15
29	Test Facility	10/1/09	9/30/10
30	Testing of PMs	10/1/10	1/30/15
31	1st Module PMs ready for Installation	10/31/12	10/31/12
32	2nd Module PMs ready for Installation	10/31/13	10/31/13
33	Final Module PMs ready for Installation	1/31/15	1/31/15
34			
35	**Other Equipment**	10/1/07	10/31/14
36	Calibration Equipment R&D	10/1/10	9/30/11
37	Calibration Equipment	10/3/11	9/30/13
38	Development Labor	10/1/07	9/29/09
39	**Water Purification**	1/2/12	10/31/14
40	Purchase Order	1/2/12	3/30/12
41	Vendor	4/2/12	5/31/12
42	Shop Conversion	4/2/12	5/31/12
43	Install Water Systems (3 systems)	6/1/12	6/29/12
44	Test Water (to see if suitable)	7/2/12	7/31/12
45	Fill up 1st Chamber	8/1/12	10/31/12
46	Fill up 2nd Chamber	8/1/13	10/31/13
47	Fill up 3rd Chamber	8/1/14	10/31/14
48			
49	**Installation**	11/1/12	10/30/15
50	Module 1	11/1/12	10/31/13
51	Physics Turn-On	10/31/13	10/31/13
52	Module 2	11/1/13	10/31/14
53	Module 3	11/3/14	10/30/15



6 yrs to first 100 kT and 8 yrs to full 300 kT. Can be adjusted if PMT production slower.

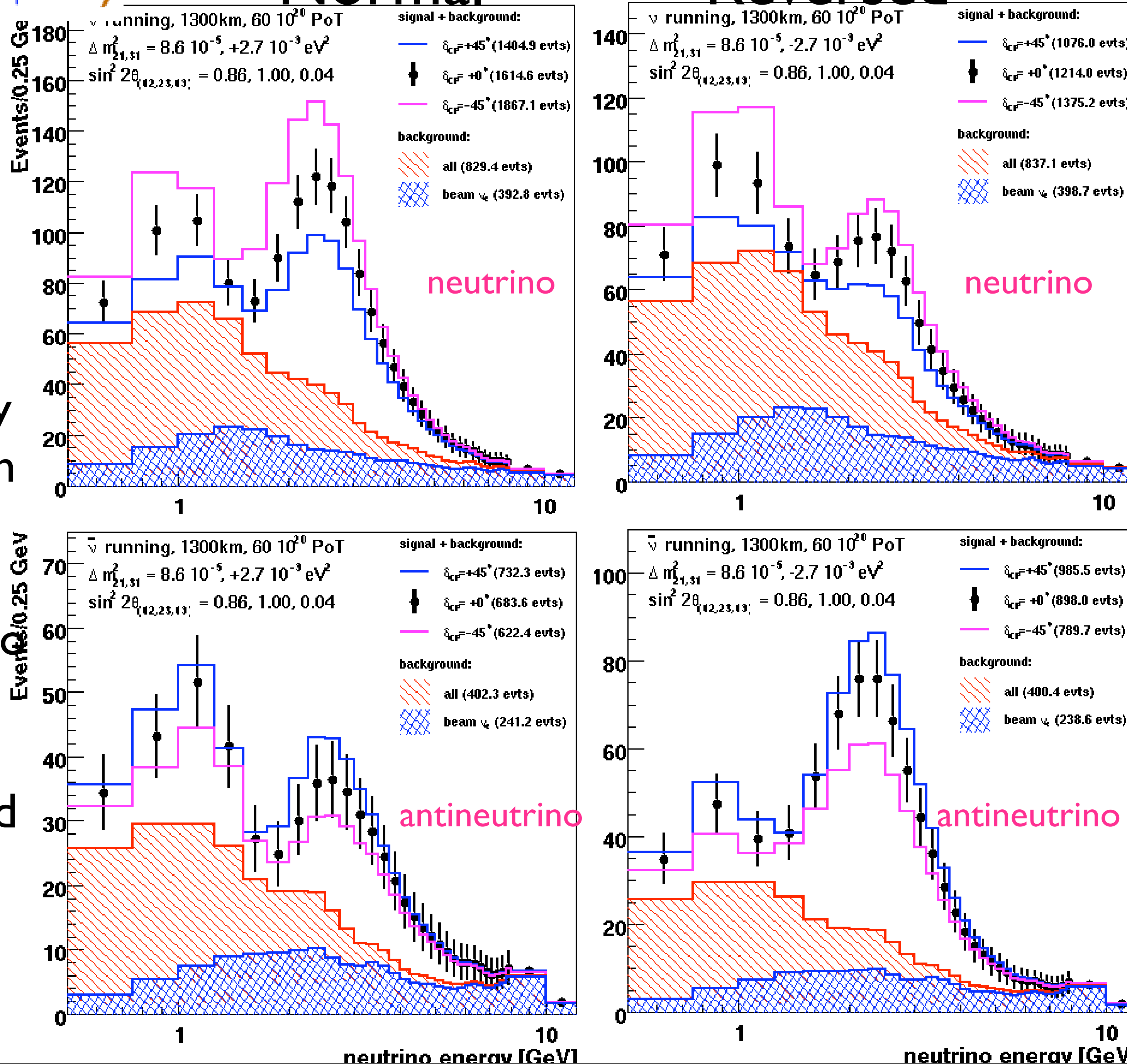
Electron neutrino appearance spectra

$\sin^2 2\theta_{13} = 0.04$, 300kT WCe. , WBLE 120 GeV, 1300km, 60E20 POT.

$(-\delta_{cp} = -45^\circ, -\delta_{cp} = +45^\circ)$

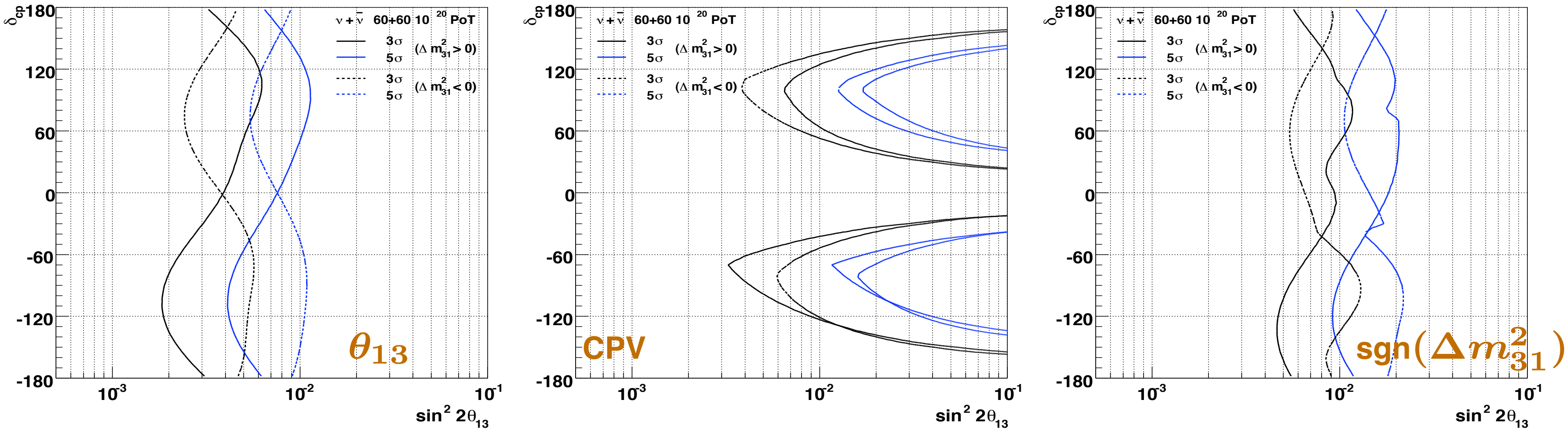
- All background sources are included.
- S/B ~ 2 in peak.
- NC background about same as beam nue backg.
- For normal hierarchy sensitivity will be from neutrino running.
- For reversed hierarchy anti-neutrino running essential.
- Better efficiency at low energies expected with higher PMT counts.

Normal Reversed

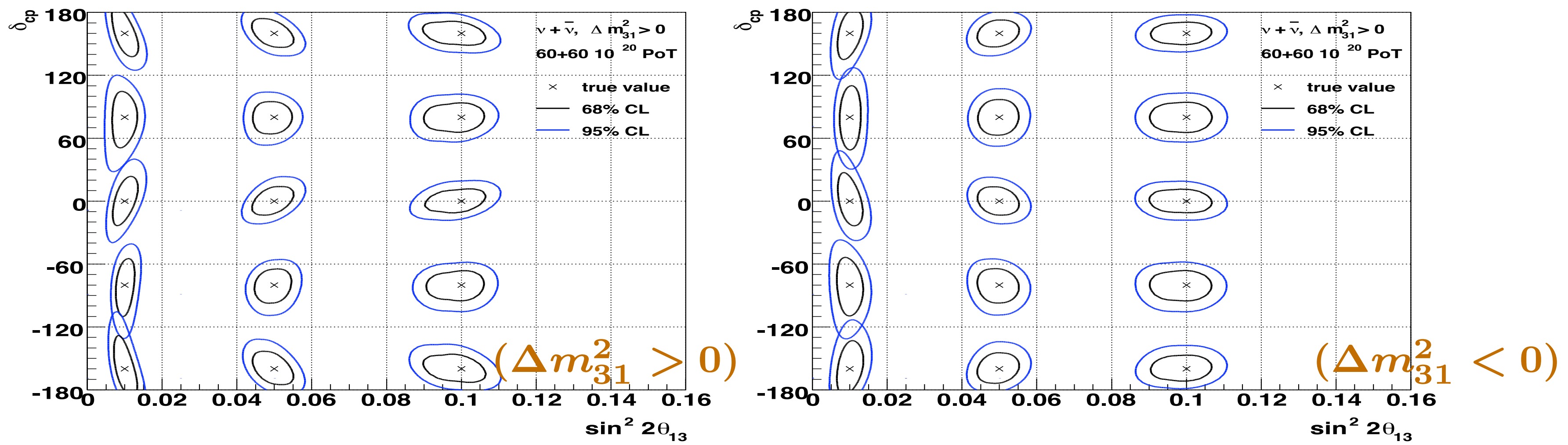


WBLE FNAL to DUSEL (1300km)

Discovery potential (— 5σ — 3σ). WCe. 300 kT, 1.2 (2) MW, 12 (7) yrs:



Measurement (—95% CL —68% CL) :



Summary

- CP violation in neutrinos should guide the Long baseline program in the future. Program is doable with known technology (water Cherenkov detector) and currently planned accelerator intensity upgrades.
- A very large detector ~100 kT efficient mass is needed to carry out the program. Megawatt proton source obviously helps.
- It is desirable that such a detector support a broad program including nucleon decay and neutrino astrophysics. This will require depth.
- A SUSEL based detector and a longer baseline has many advantages in the long run.

How do we get ready to launch this program in 5-6 yrs ?

NuSAG Recommendations

Recommendation 1. The US should prepare to proceed with a long baseline neutrino oscillation program to extend sensitivity to $\sin^2 2\theta_{13}$, to determine the mass ordering of the neutrino spectrum, and to search for CP violation in the neutrino sector. Planning and R&D should be ready for a technology decision and a decision to proceed when the next round of results on $\sin^2 2\theta_{13}$ becomes available, which could be as early as 2012. A review of the international program in neutrino oscillations and the opportunities for international collaboration should be included in the decision to proceed.

Recommendation 2. Research and development towards an intense, conventional neutrino beam suitable for these experiments should be supported. This R&D may be to support intensity upgrades to the existing NuMI beam, as well as development of a new beam directed towards DUSEL, which would likely employ the wide-band beam approach.

Recommendation 3. Research and development required to build a large water Cherenkov detector should be supported, particularly addressing questions of minimum required photocathode coverage, cost, and timescale.

Recommendation 4. A phased R&D program with milestones and using a technology suitable for a 50-100 kton detector is recommended for the liquid argon detector option. Upon completion of the existing R&D project to achieve purity sufficient for long drift times, to design low noise electronics, and to qualify materials, construction of a test module that could be exposed to a neutrino beam is recommended.

Electron neutrino appearance spectra

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Normal — Reversed

- All background sources are included.
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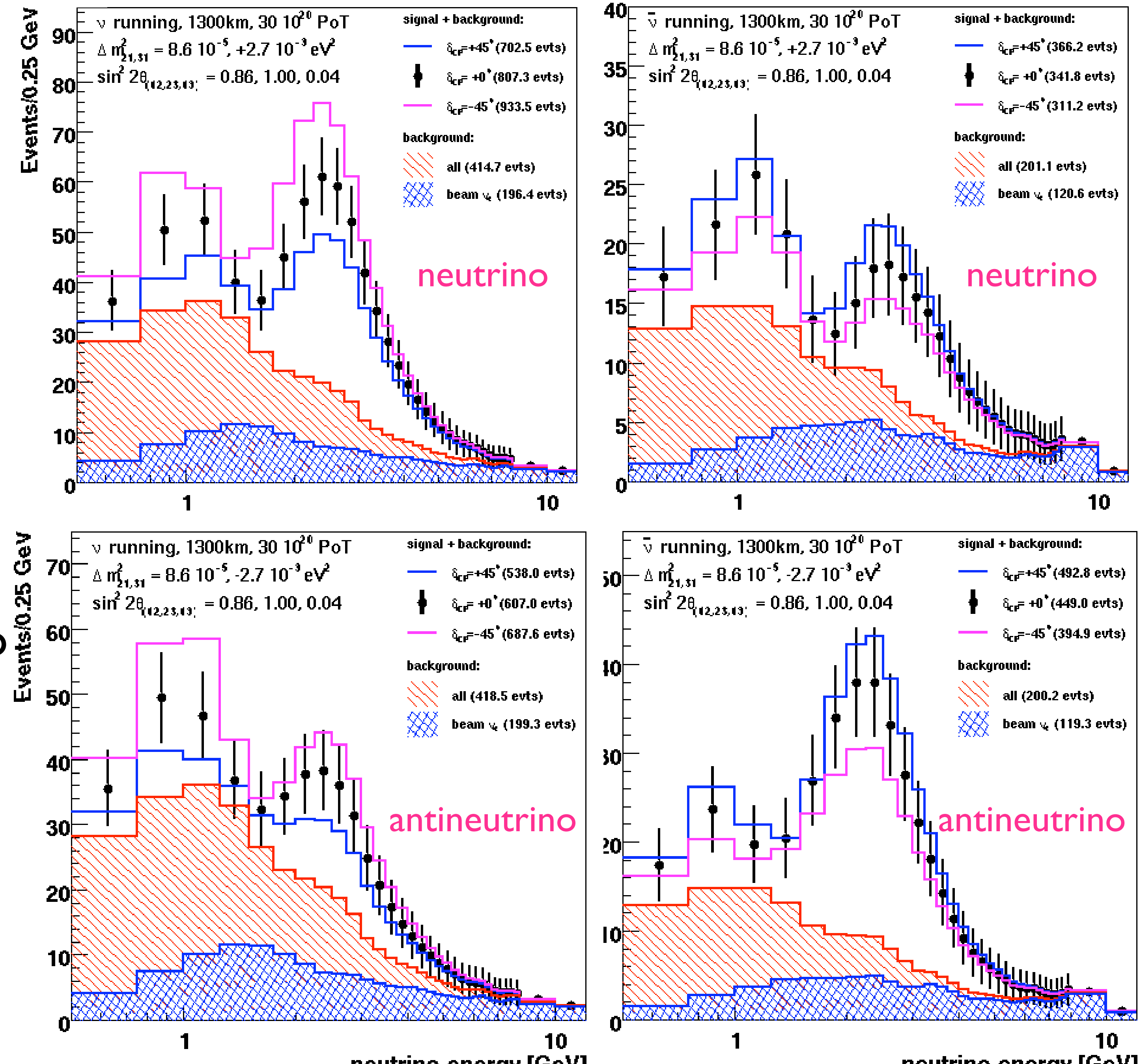
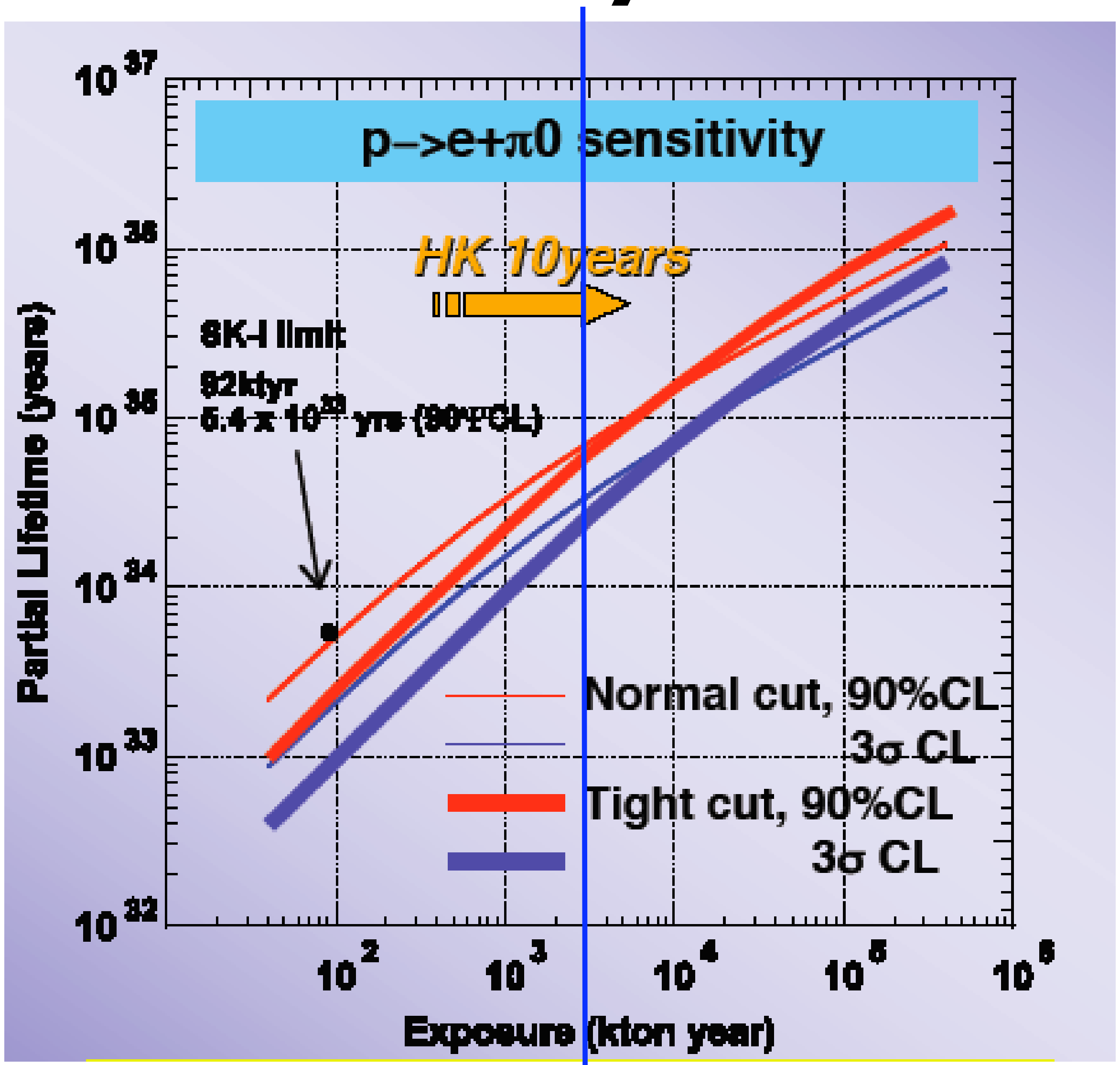


Nucleon decay

- Large body of work by HyperK, and UNO.
- background levels for the positron+Pion mode
  - 3.6/MTon-yr (normal)
  - 0.15/MTon-yr (tight)

(300kT) will hit backg. in ~1yrs. It could be important to perform this first step before building bigger. Sensitivity on K-nu mode is about ~8x10^33 yr



Ref: Shiozawa (NNN05) 300kTX10yrs 7X10^34 yrs