

Long-baseline Neutrino Experiment or Facility in US

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Brookhaven National Laboratory

6/23/2014

International Meeting for Large Neutrino Infrastructures

Also present at this meeting: Bob Wilson (Colorado, Co-spokesman) Jim Strait (Fermilab, Project Director), Maury Goodman (Argonne, Deputy Spokesperson), Mark Thomson (Cambridge, Exec committee member), Brajesh Choudhary (India), Francesco Pietropaolo (Italy). Alfonse Weber (UK), Christos Touramanis (UK)

LBNE Configuration.



Far site is at the former Homestake mine (site of Davis experiment)

LBNE Collaboration

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

Since DOE Critical Decision-1 (CD-1) approval
(December 2012):
Collaboration has increase by more than 40%
Non-US fraction has more than doubled
Working towards a full international collaboration

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

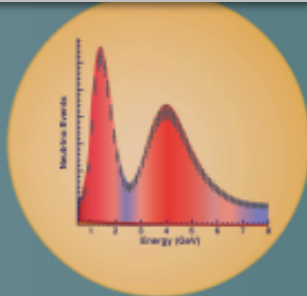
Michigan State
Milano
Milano/Bicocca
Minnesota
MIT
Napoli
NGA
New Mexico
Northwestern
Notre Dame
Oxford
Padova
Panjab
Pavia
Pennsylvania
Pittsburgh
Princeton
Rensselaer
Rochester
Rutherford Lab
Sanford Lab
Sheffield
SLAC
South Carolina
South Dakota
South Dakota State
SDSMT
Southern Methodist
Sussex
Syracuse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

LBNE Science Book

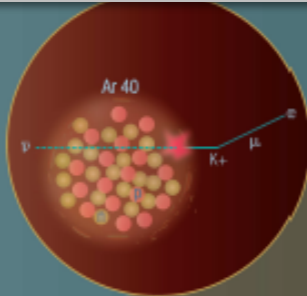
<http://lbne.fnal.gov/>

arXiv:1307.7335v3 [hep-ex] 22 Apr 2014

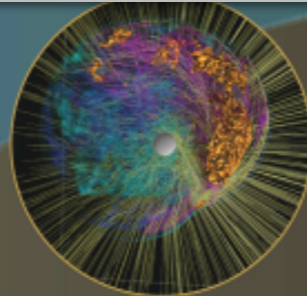
LBNE science and configuration has been through multiple internal, external, and national scientific reviews since 2003 with extensive documentation of choices made at each step.



Through precise studies of neutrino flavor oscillations enabled by an intense, optimized beam and advanced detectors, LBNE aims to shed light on the mystery of the matter-antimatter asymmetry in the Universe.



With the world's largest cryogenic particle detector deep underground, LBNE will probe the stability of matter and its relation to the Grand Unification of forces.



LBNE's observation of thousands of neutrinos from a core-collapse supernova in the Milky Way would allow us to peer inside a newly-formed neutron star and potentially witness the birth of a black hole.



Office of Science










The Long-Baseline Neutrino Experiment

Exploring Fundamental Symmetries of the Universe

LBNE Science Book was started for Community Study (snowmass) 2013. It will be updated regularly.

The recent P5 report has endorsed the science goals and configuration from this document.

Long-Baseline in the US

- 1998-99: New initiatives towards next generation underground detectors and beams  NNN workshops, Nufact, and other workshops.
- 2001-2003: Realization of conventional approach towards neutrino CP violation with small dependence on θ_{13} and baseline.  2003 US-HEP Facilities list: super neutrino beam. Evaluation at BNL or FNAL.
- 2004-2006: NSF Development of a plan for US underground laboratories and infrastructure.  Scientific and engineering evaluation of 8 sites and establishment of Sanford facility with site donation from mining company.
- 2006-2008: US long-baseline study and evaluation by NUSAG, P5, and various PACs.  Recommendation to proceed with a goal for a large underground detector and a super neutrino beam at FNAL.
- 2008-2011: Establishment of a collaboration and thorough engineering evaluation of beam and feasibility for Water and LAr detectors.  Decision to proceed with liquid argon with full support from Fermilab, and the Department of Energy.
- 2012-2013: Detection of θ_{13} , re-evaluation of the experimental configuration and strategy.  Consensus to proceed with the FNAL to Sanford lab. configuration in phases. First phase ~\$900M.
- 2013-2014: US community endorsement of the full scope configuration of LBNE.  **Could start construction in 2018**

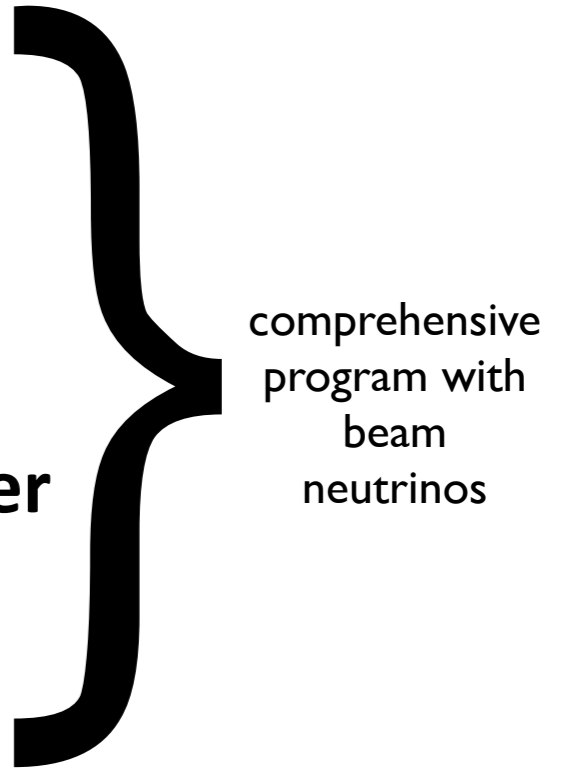
We expect the project to continue to change as new partners bring in important ideas.

Consistent focus on both science and frugality

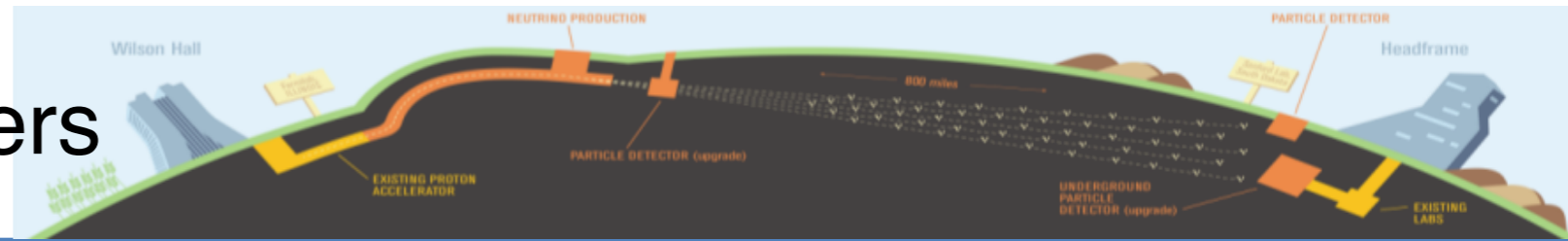
Experimental Strategy

- A comprehensive experiment with sensitivity to CP asymmetry, mass ordering and spectral shape.
- Our experimental focus is on $\nu_\mu \rightarrow \nu_e$ and $\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e$ with superb particle identification and energy resolution, as this channel is most suitable for current neutrino beam and detector technologies.
- The measured neutrino mixing parameters in the 3-flavor framework suggest that the CP asymmetry will be $<30\%$ (first max) and higher at lower energies and therefore >1000 events are needed.
- World-wide studies have concluded that beams with 1-2 MW of power at high energies and unprecedented large far detector fiducial mass is needed regardless of baseline to achieve above statistics.
- A baseline of >1000 km and a broad-band beam are needed to satisfy these conditions.
- Detector must have sufficient overburden to allow sensitivity to nucleon decay and supernova.

Scientific Priorities

- **LBNE design follows these priorities**
 - ➡ **CP violation in the neutrino sector**
 - ➡ **CP phase measurement regardless of its value.**
 - ➡ **Neutrino mass hierarchy determination.**
 - ➡ **Determination of θ_{23} octant and precision parameter measurements.**
 - ➡ **Precision tests of 3-flavor neutrino model.**
 - ➡ **Atmospheric neutrino measurements (confirmation of mass ordering with independent data)**
 - ➡ **Nucleon decay**
 - ➡ **Supernova burst neutrinos**
 - ➡ **As a very capable near detector will be needed, it is recognized that it could have a synergistic scientific program of precision neutrino and weak interaction physics.**
- 
- comprehensive
program with
beam
neutrinos

Experimental Parameters



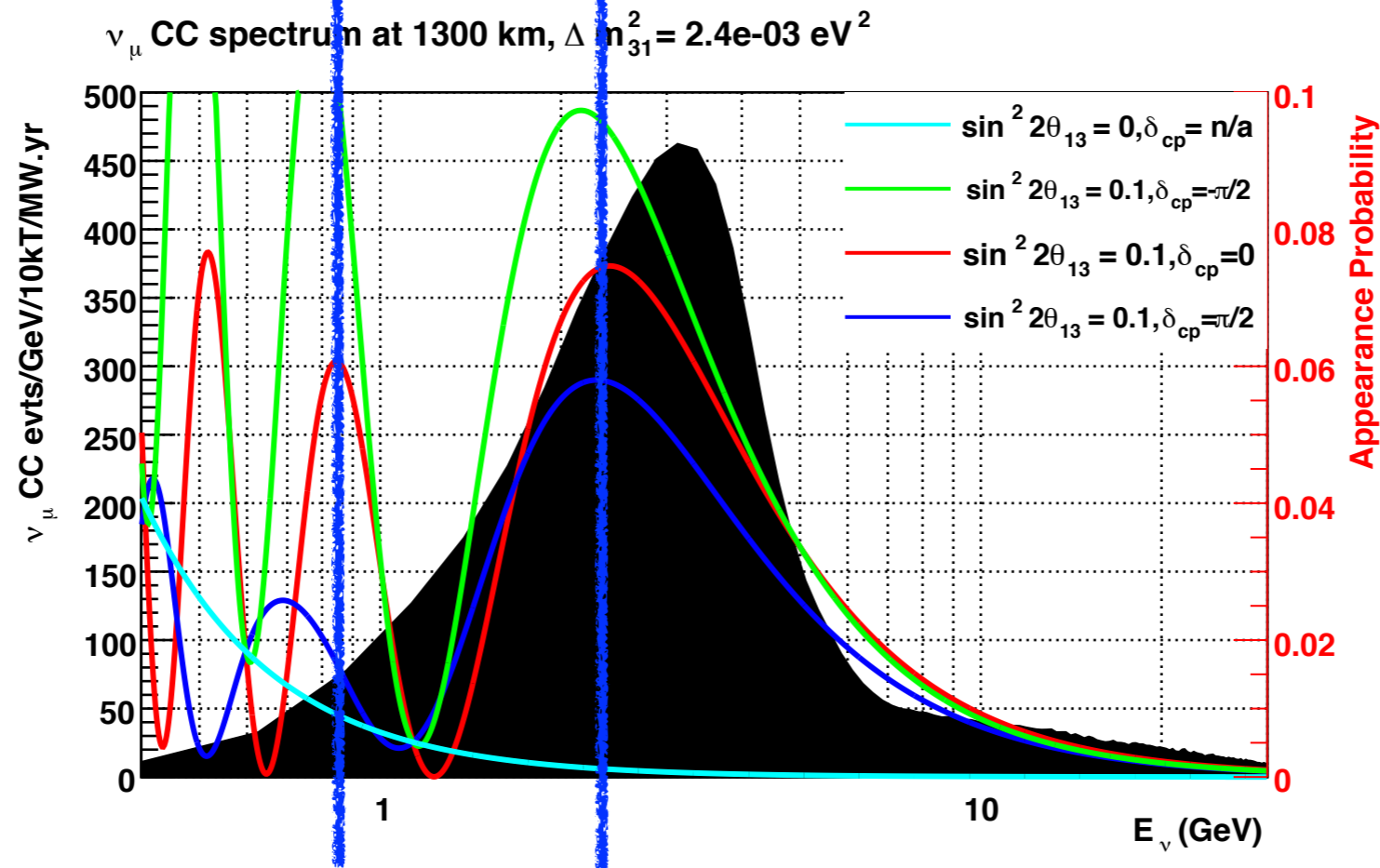
- Wide band neutrino beam from FNAL
 - **protons: 60-120 GeV, 1.2 MW; upgradable to 2.3 MW**
 - 10 μ S pulses every 1.0 to 1.33 sec depending on P energy&power.
 - Neutrinos: sign selected, horn focused, 0.5 - 5 GeV
 - **1300 km** thru the Earth to Sanford Underground Research Facility.
- Liquid argon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

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

Neutrino Asymmetries

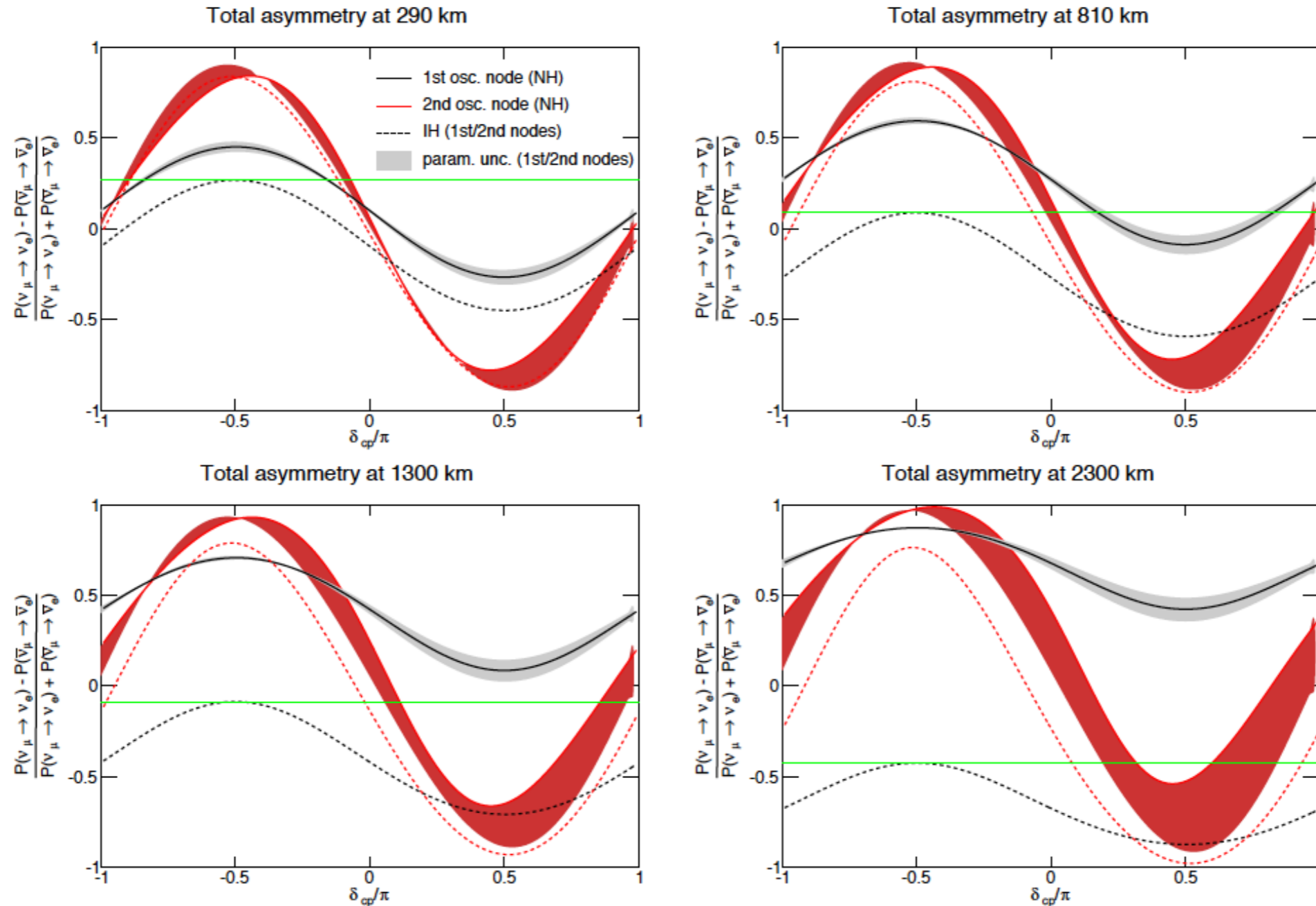
Larger CP effects: 2nd

1st: larger matter effects



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

Baseline optimization



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

Event rate and spectra expectation.

Assumptions:

34 kt LArTPC

1.2 MW operation at 80 GeV.

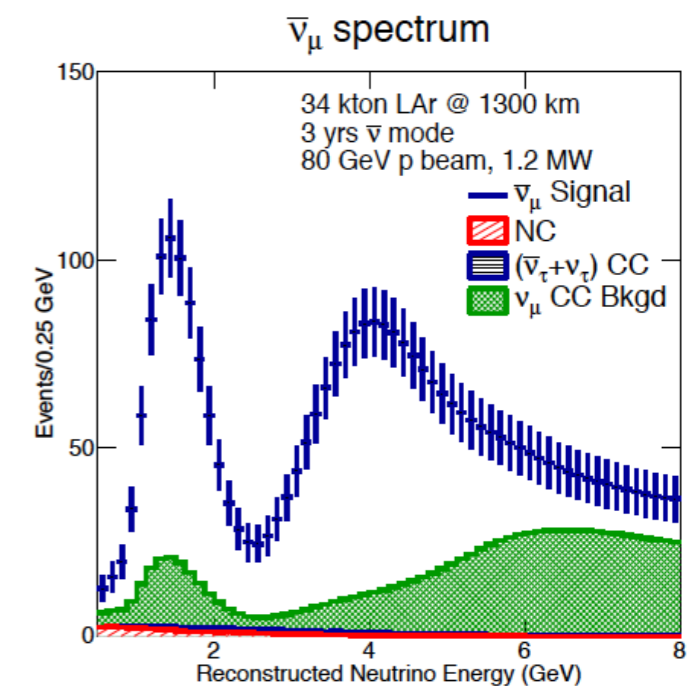
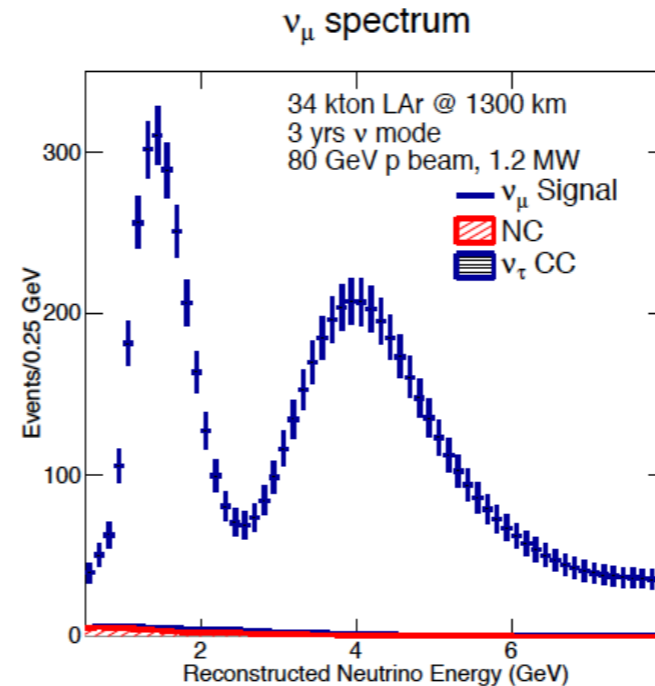
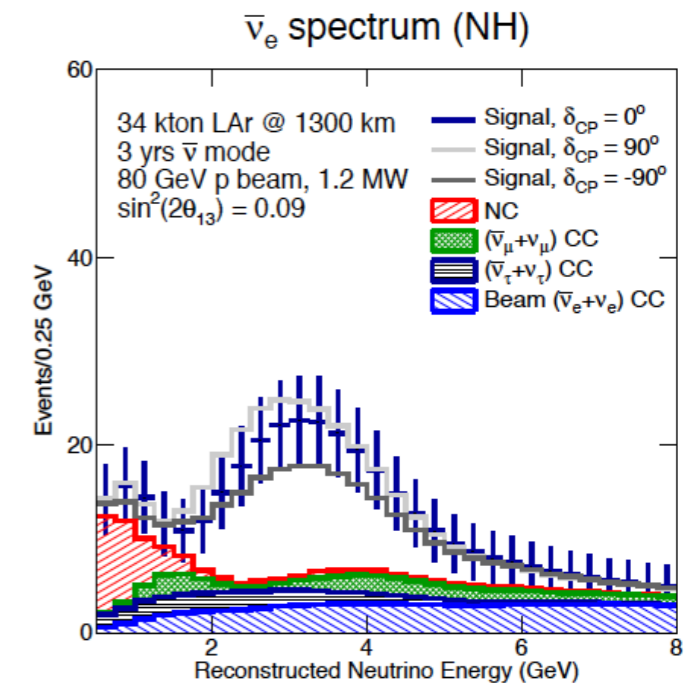
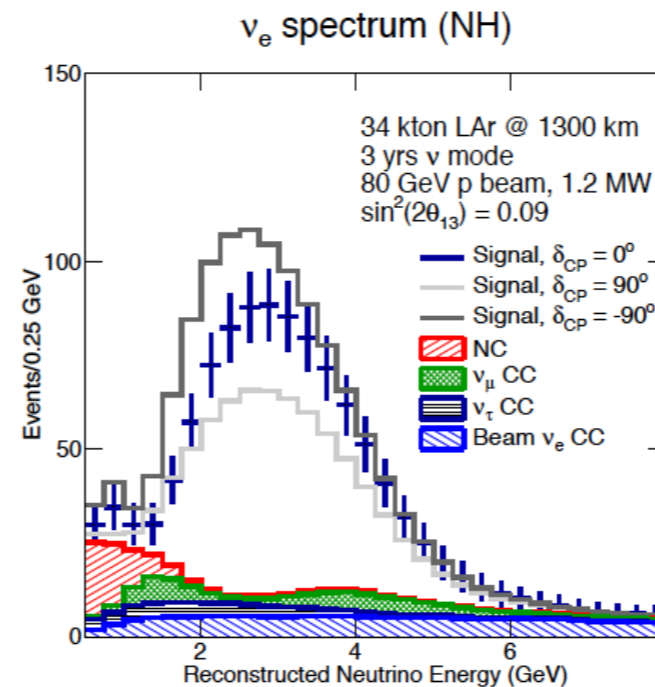
~3 yrs for each polarity.

Normal Hierarchy

$\delta_{CP} = 0$

Rest of the parameters are at best fit from 2012

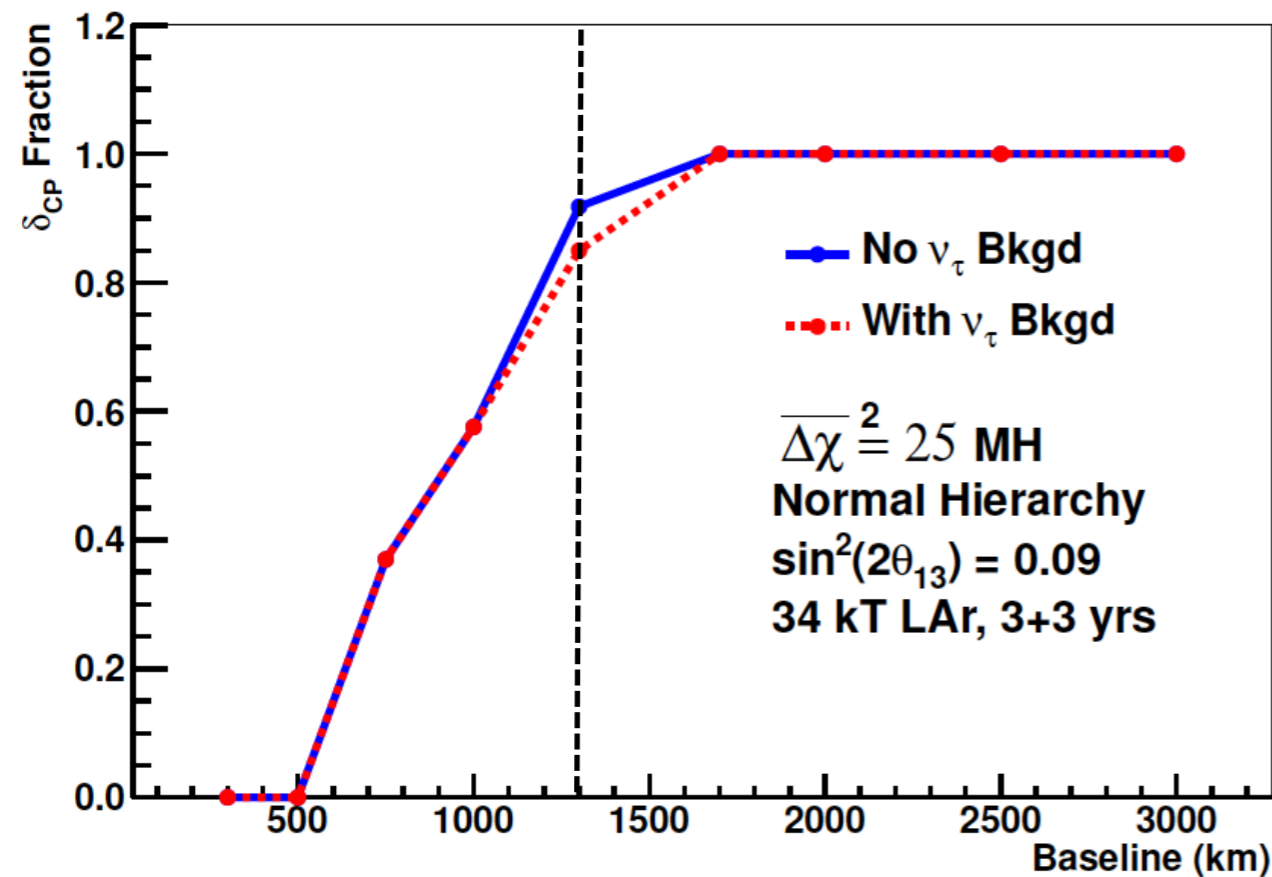
80 GeV Beam	ν mode	$\bar{\nu}$ mode
Signal: $\nu_e + \bar{\nu}_e$	777	189
BG: NC	67	39
BG: $\nu_\mu + \bar{\nu}_\mu$ CC	84	39
BG: Beam $\nu_e + \bar{\nu}_e$	147	81
BG: $\nu_\tau + \bar{\nu}_\tau$ CC	49	32



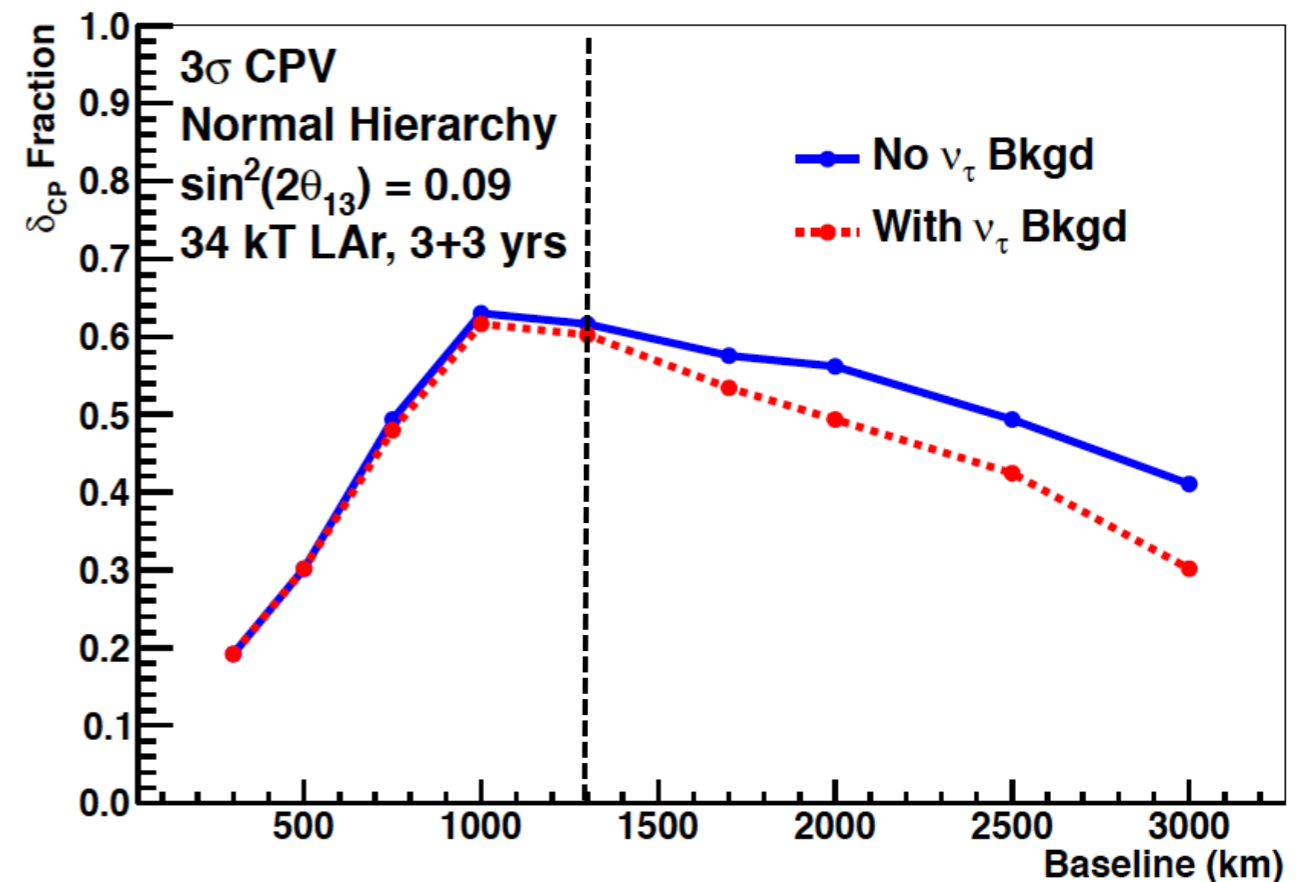
- At 1300 km full oscillation structure is visible in the energy spectrum.
A combined spectral fit provides unambiguous parameter sensitivity in a single experiment.

Baseline Optimization

Mass Hierarchy

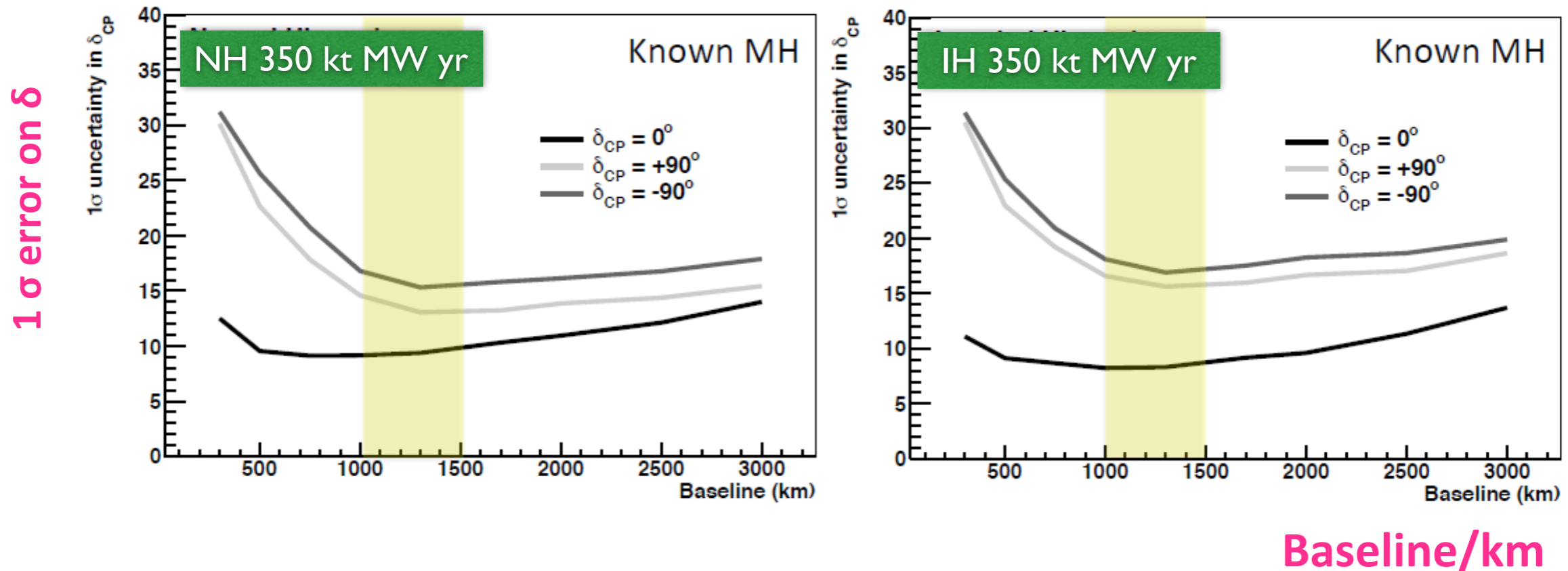


CP Violation



- Based on simulations for Fermilab NuMI 120-GeV, 1.2 MW proton beam
 - Target-1st horn distance tuned to cover 1st oscillation node + part of 2nd
 - Decay pipe length tuned (280-580 m)
 - For short baselines (<1000 km) use off-axis beam simulation to produce most flux
- Baselines 1000-1300 km near optimal**

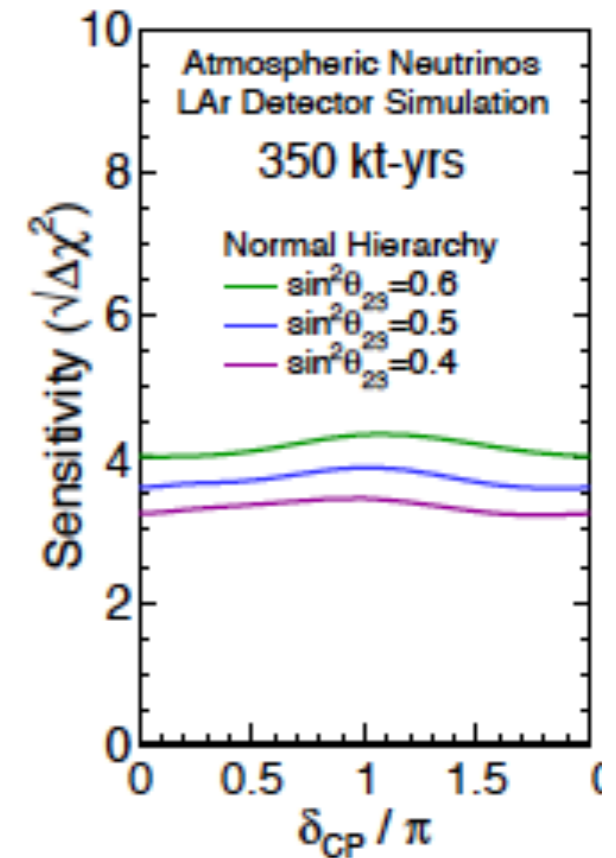
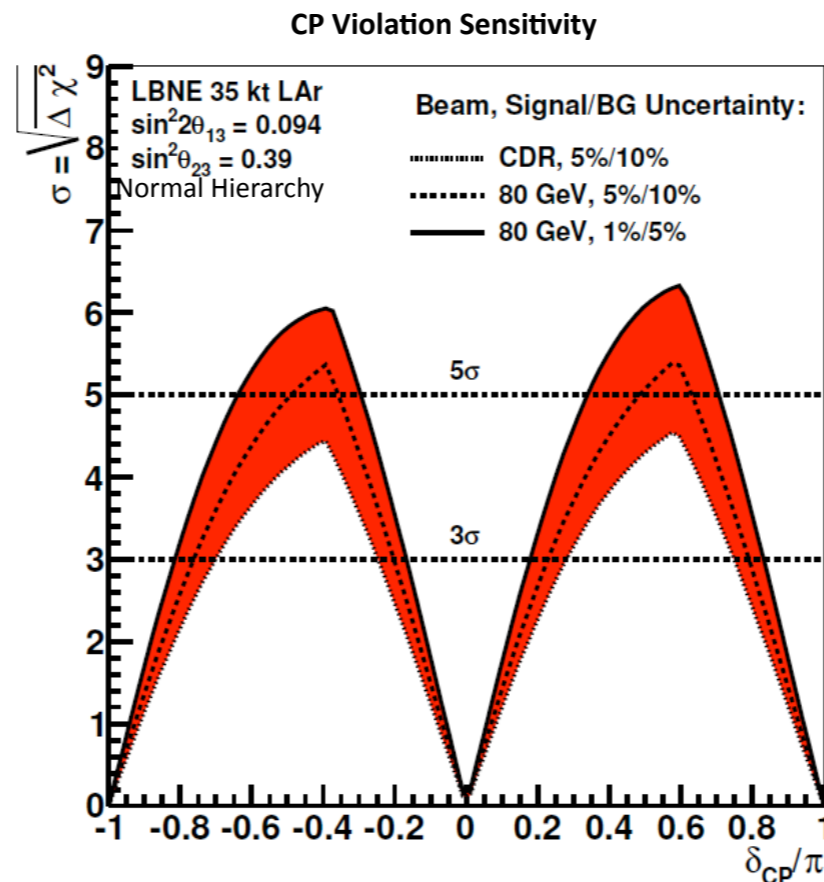
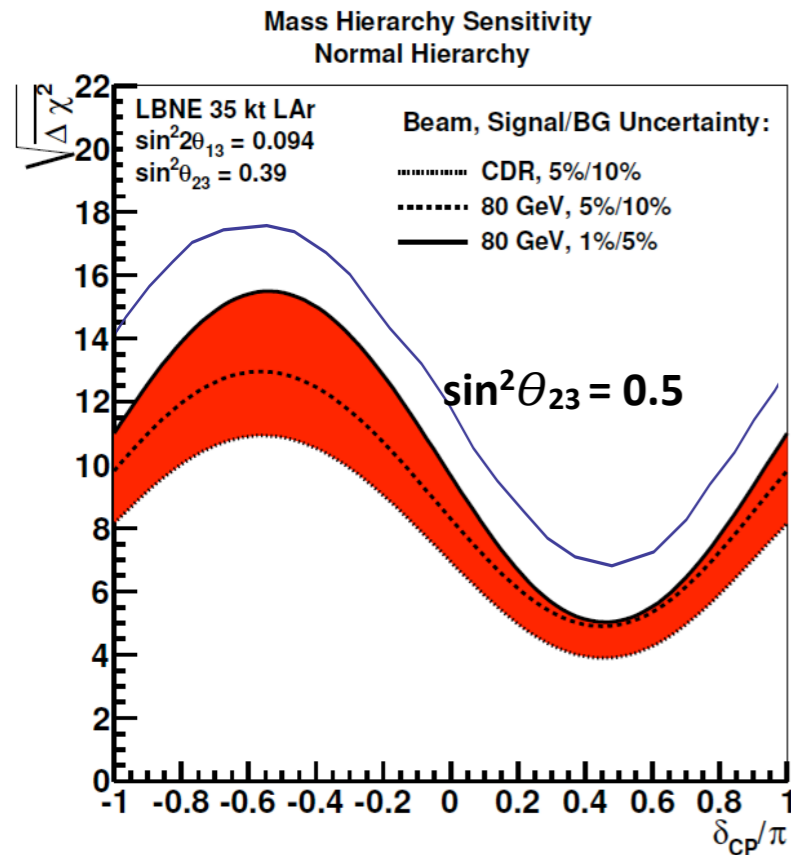
Baseline Optimization



- The phase resolutions calculated as a function of exposure as well as baseline length. An optimum is obtained for phase resolution when there is sufficient shape information and statistics.

Sensitivity

median sensitivity to reject IH

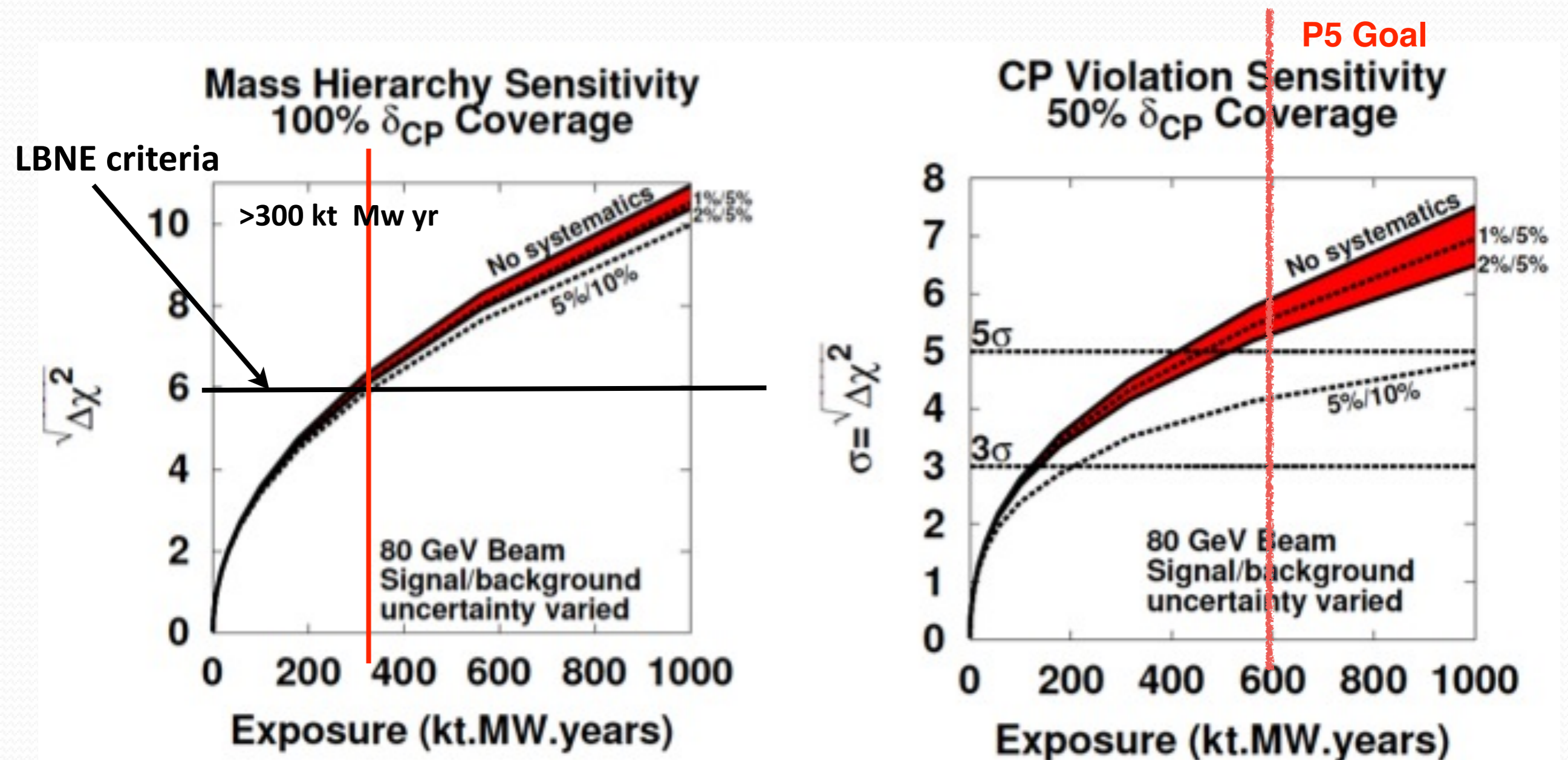


Exposure 245 kt.MW.yr
1.2 MW x 35 kt x(3 ν +3 $\bar{\nu}$) yr

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

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

Impact of Normalization Uncertainties

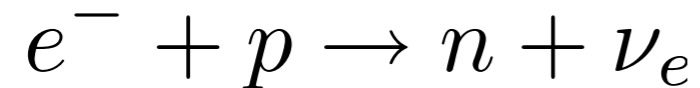


- <3% errors appear realistic with recent progress.
- The systematic precision is required to be better than the expected statistics at each stage of the experiment. High precision is needed after 200kt*MW*yr.
- MH relatively insensitive to systematics; but further study needed.
- MINOS appearance result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

Detector Mass/Beam Power Scenario

- Plausible timeline for a phased international program
 - **2025-2030**
Detector mass: 15 kt (fid.)
Proton beam power: 1.2 MW
 - Exposure: 90 kt.MW.yr
- **2030-2035**
Add 20 kt = 35 kt
Proton beam power: 2.3 MW
- **Total Exposure: 490 kt.MW.yr**
- P5 report recommends the following feasible goal.
- Minimum requirements: 120 kt*MW*yr by 2035 \Rightarrow 10-12 kt undergrounds w/ 1.2 MW beam
 - The report recommends to plan for a cavern to accommodate 40 kt fiducial mass and set as a goal 600 kt*MW*yr exposure

Supernova burst

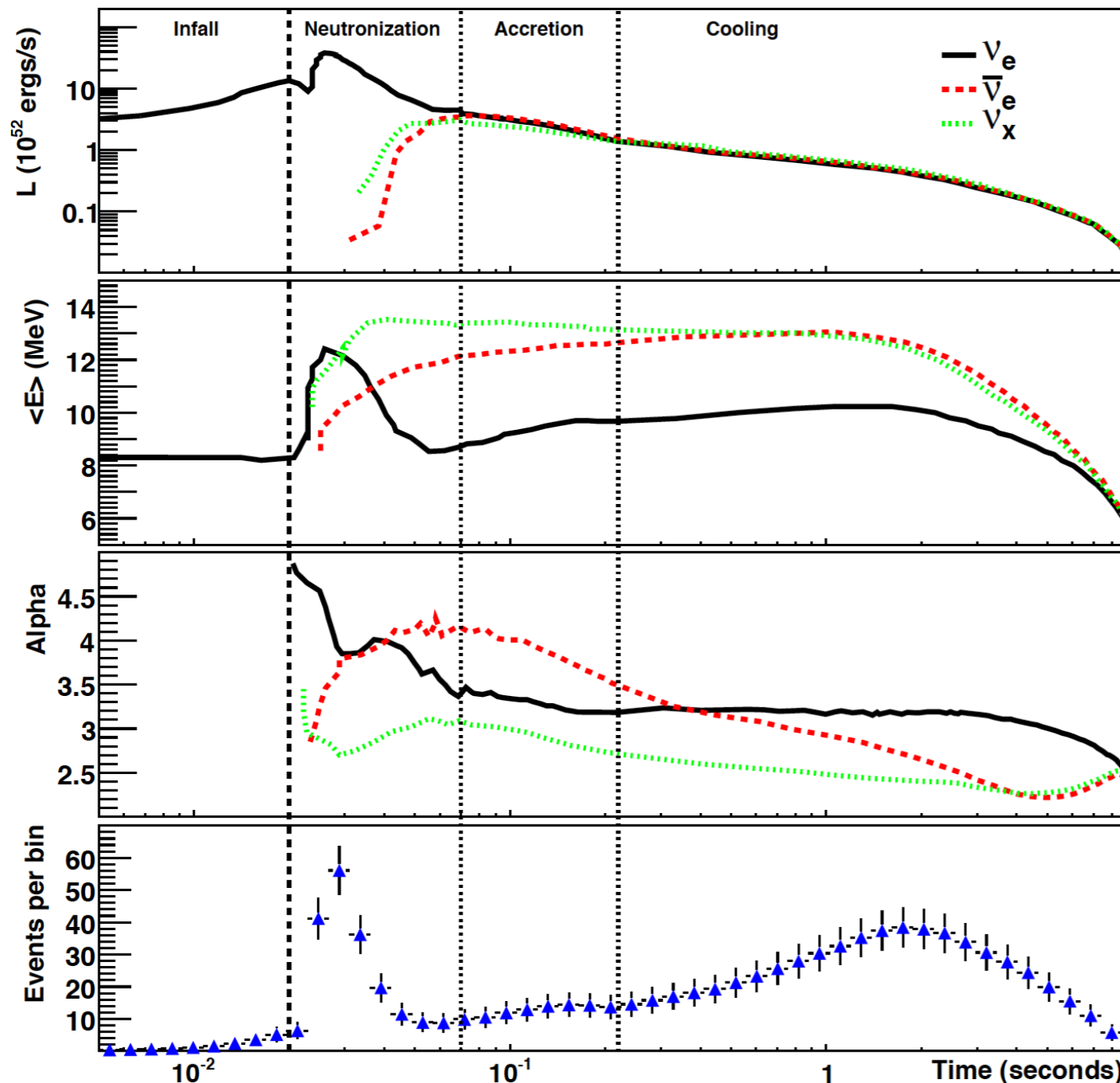


LAr mainly sensitive to electron neutrinos.
(water is sensitive to anti-electron-neutrinos)

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

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

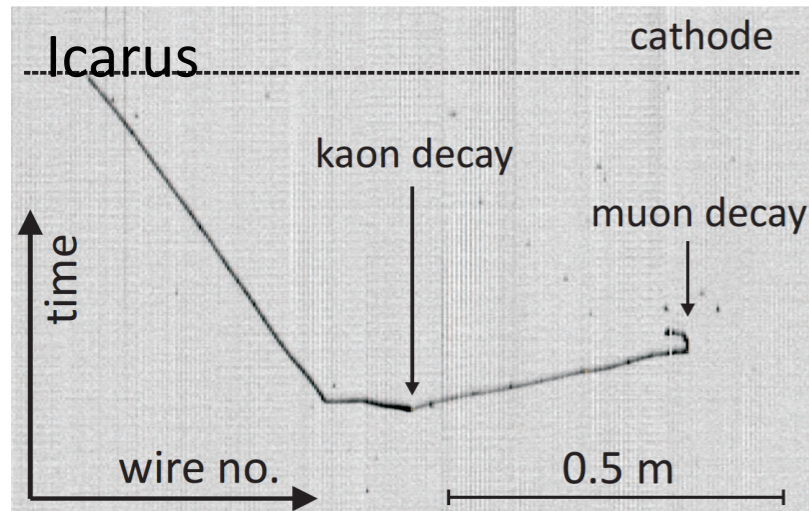
Precision astrophysics and cosmology needs precise laboratory data on neutrinos so that correlations can be resolved.



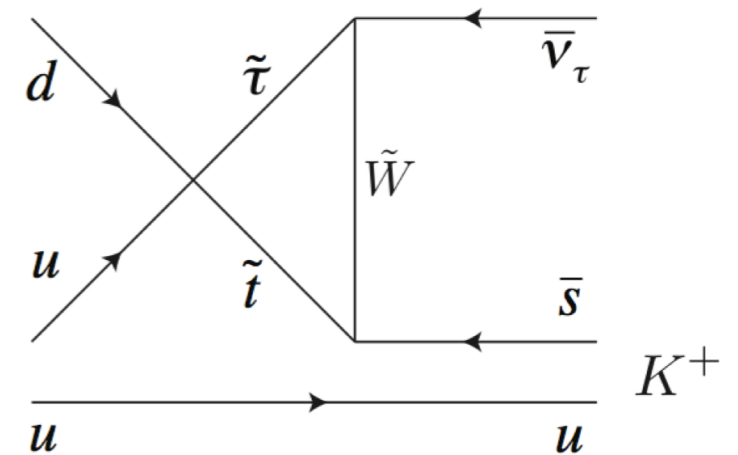
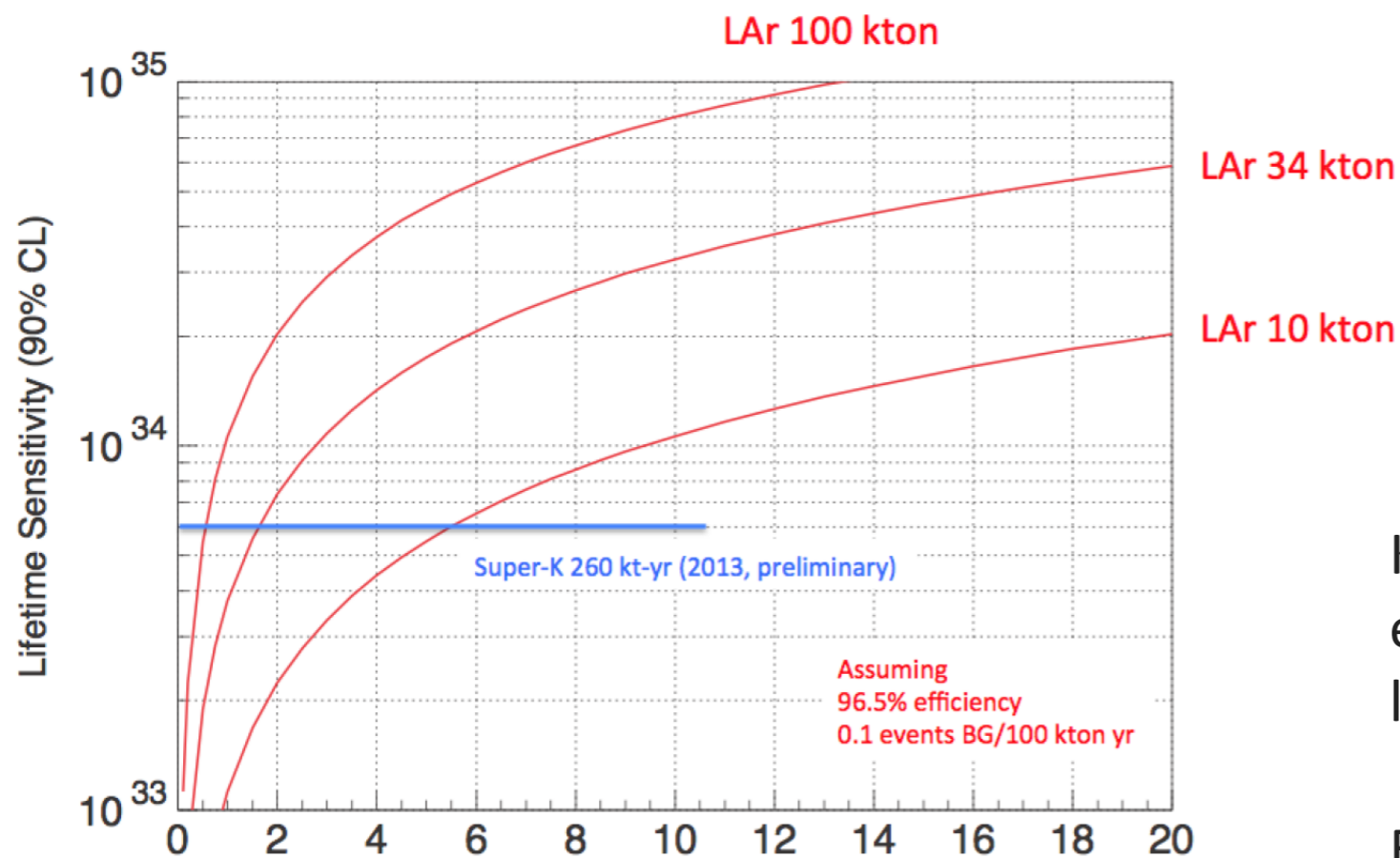
Estimated rate: ~ 3000 evts @ 10 kpc for 34 kt LAr TPC

Will we all decay ?

Nucleon decays



Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow K^+ \bar{\nu}$	19%	4	97%	1
$p \rightarrow K^0 \mu^+$	10%	8	47%	< 2
$p \rightarrow K^+ \mu^- \pi^+$			97%	1
$n \rightarrow K^+ e^-$	10%	3	96%	< 2
$n \rightarrow e^+ \pi^-$	19%	2	44%	0.8

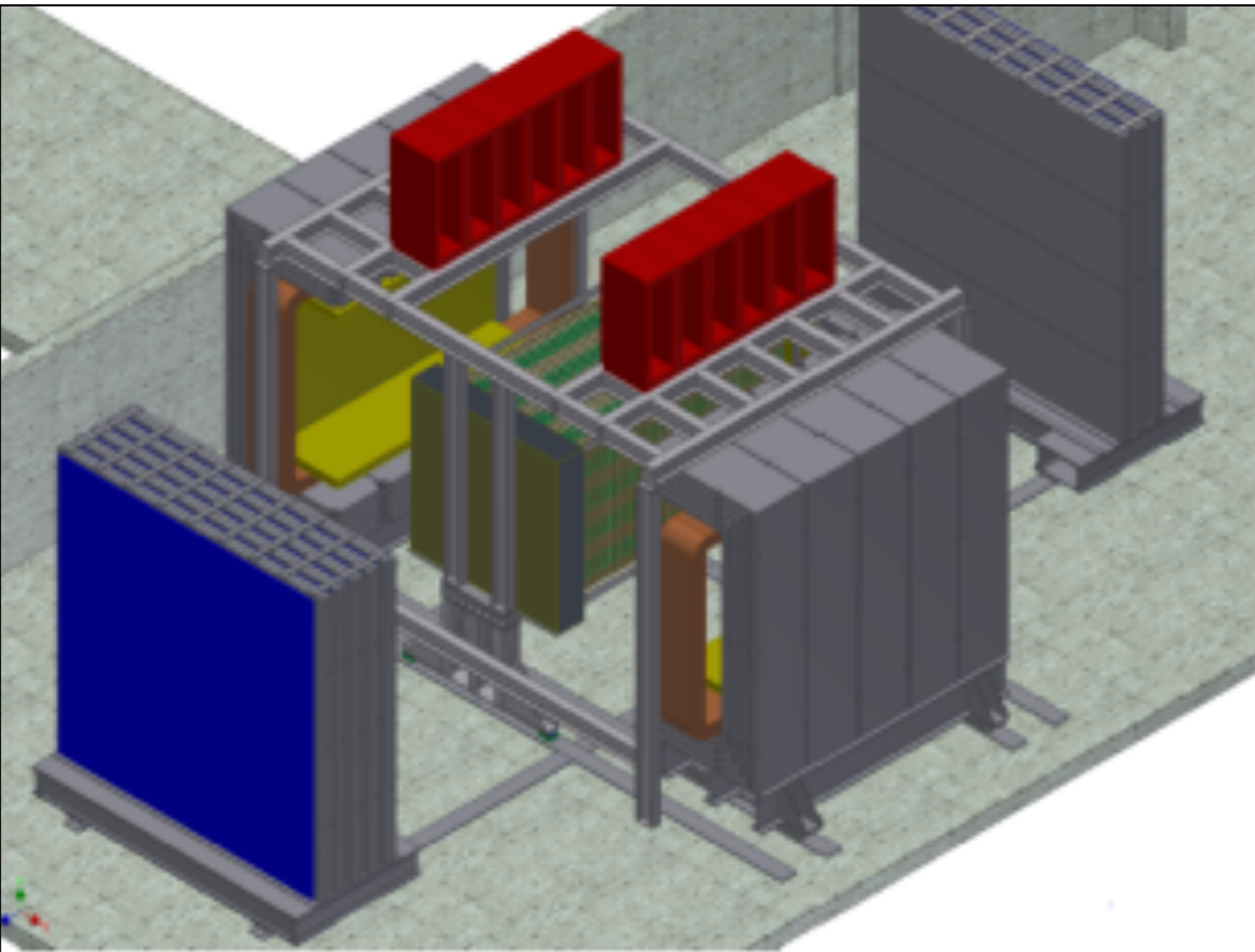


Kaon modes in LAr with high efficiency and low background, leading to high s/b.

Example: SUSY models

Examination in 2008 concluded that 4850 ft depth is sufficient

LBNE Near Detector

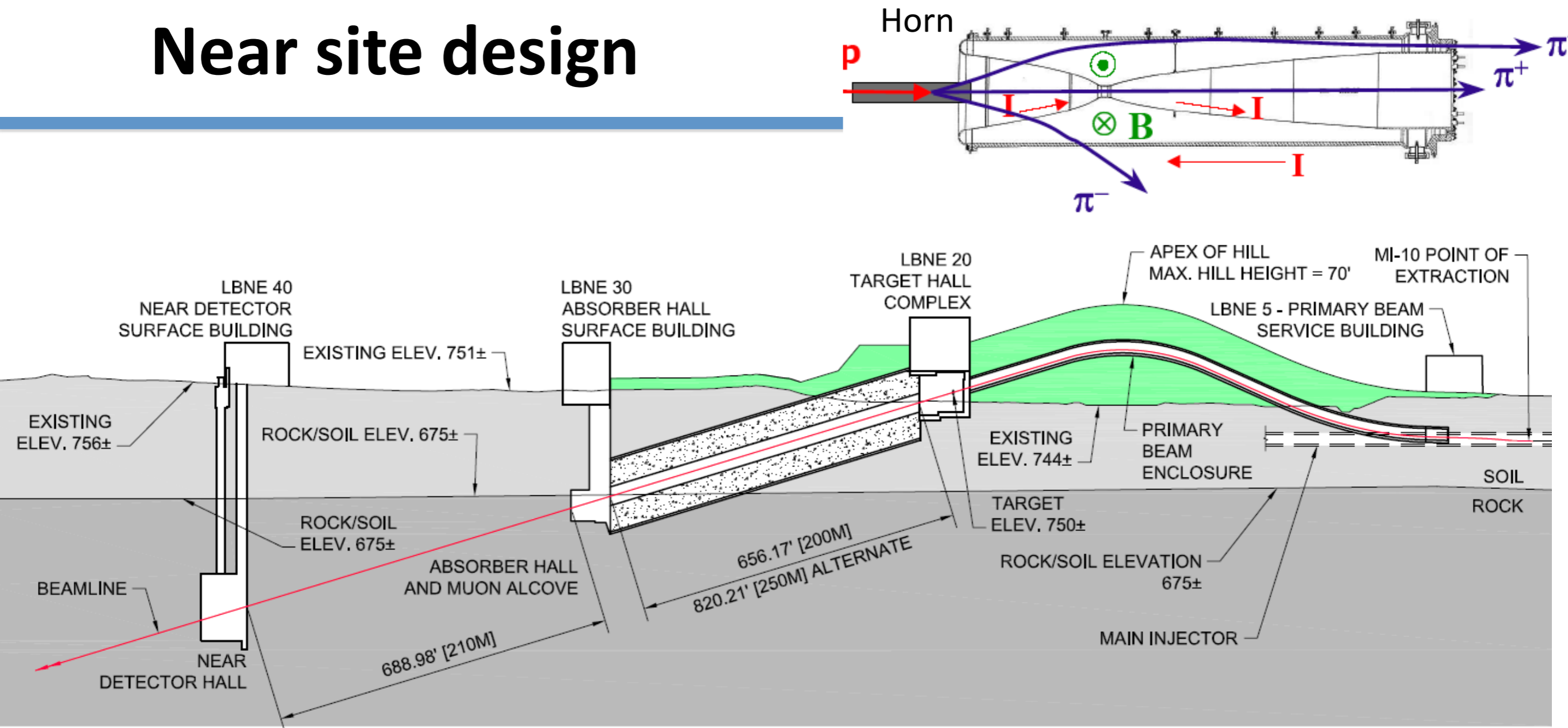


- **Fine-Grained Tracker – 460 m from target**
 - **Low-mass straw-tube tracker with pressurized gaseous argon target**
 - **Relative/absolute flux measurements**
 - **High precision neutrino interaction studies**
 $\approx 10^7$ interactions/year!
 - **Additional target materials possible**

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

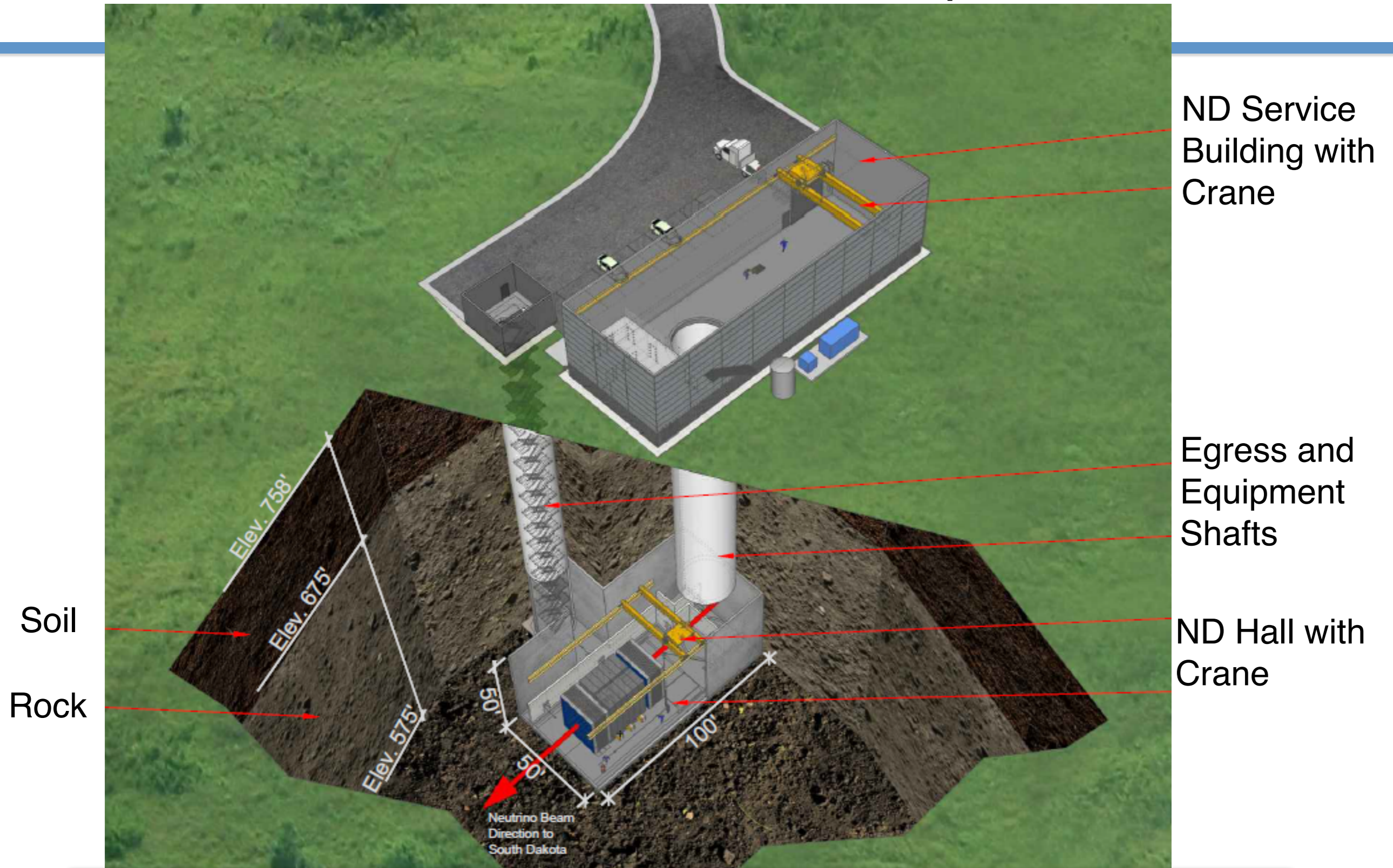
The physics strategy and design of the ND is critical for LBNE. Simulations, reconstruction and R&D work is in initial phase with input from Indian colleagues. Open working meeting at FNAL on July 28-29.

Near site design



- Innovative design for safety and upgradeability.
- The geotechnical work has started and hill could be ready to be built in 2016.

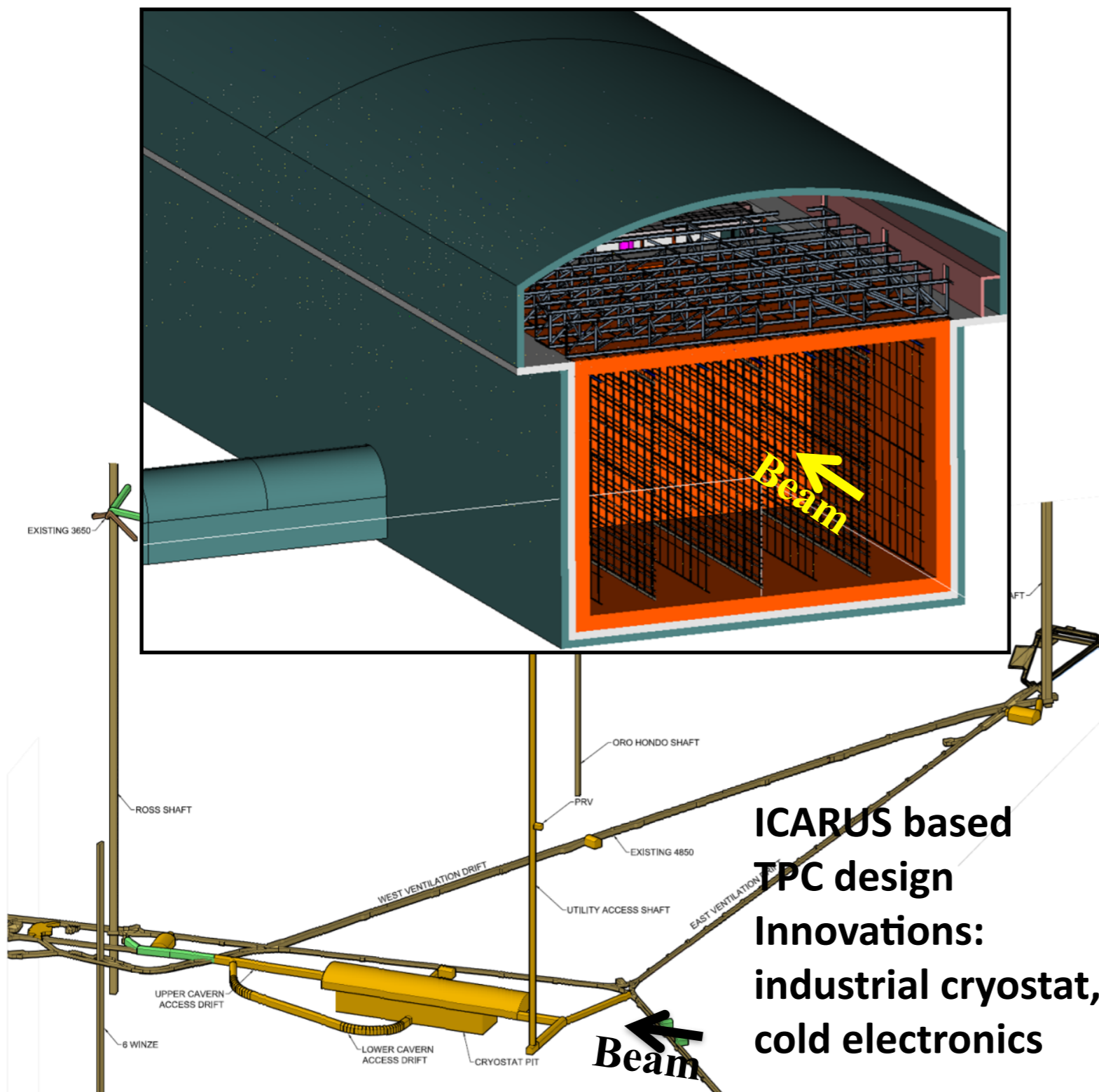
Near Neutrino Detector Update



Near conceptual design used for civil planning onsite

Far Detector LArTPC Design at 4850 ft depth

Conceptual design allows progress on civil construction, but not fixed



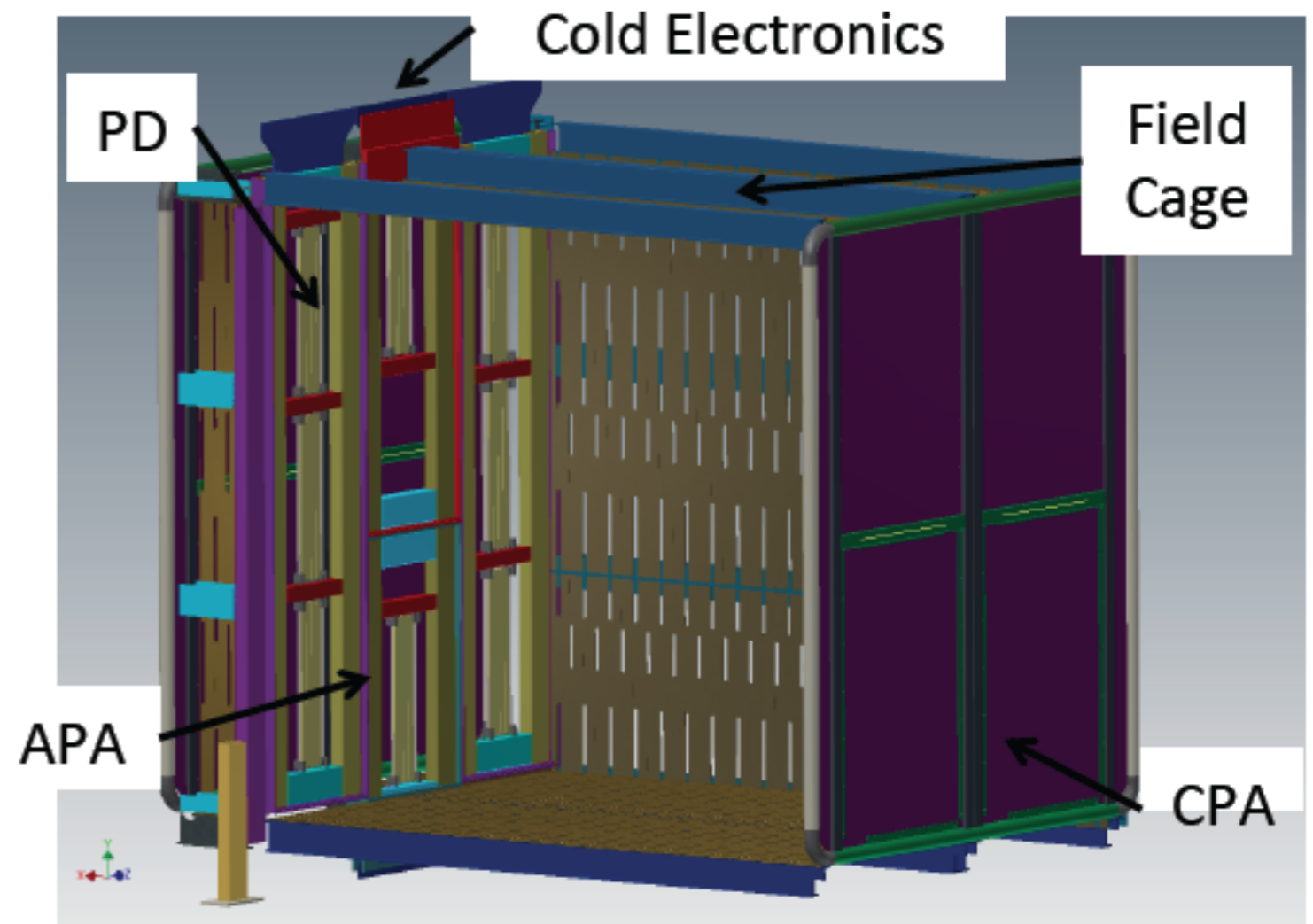
- Two detectors in a common cavern at 4850 ft. depth
- Active volume of each detector:
 $22.4 \times 14 \times 45.6 \text{ m}^3$
- 34 kt fiducial mass
- TPC design:
 - 3.7 m drift length 500v/cm
 - 5 mm wire spacing
 - three stereo views
 - 2X108 anode chambers
 - 2 X 275k channels
 - S/N ~ 10

**ICARUS based
TPC design
Innovations:
industrial cryostat,
cold electronics**

Far Detector Prototyping

35t scale prototype

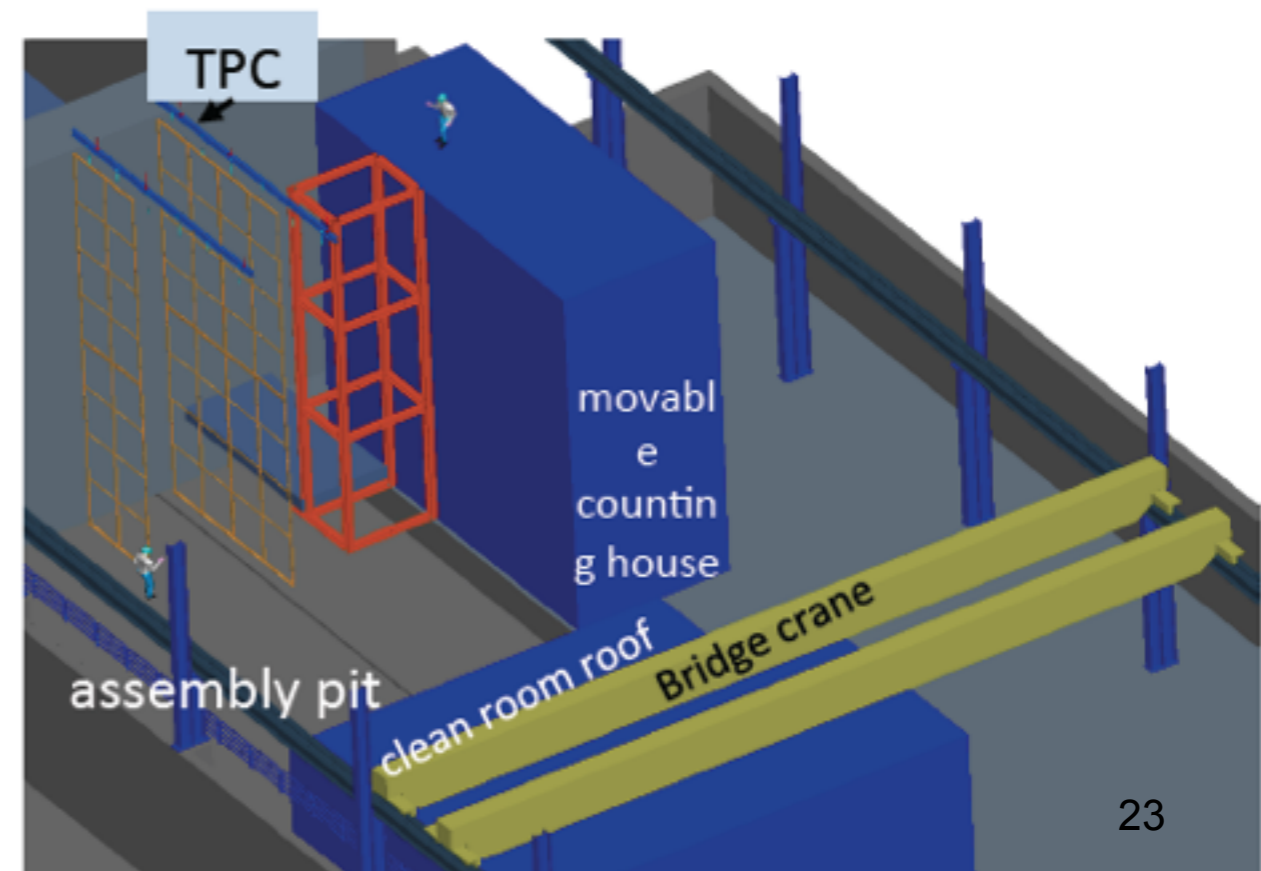
- Test membrane technology
- Cryo-system design
- Cryogenic commissioning now!
- Install prototype TPC next summer.
- Take cosmic data in ~1 year.



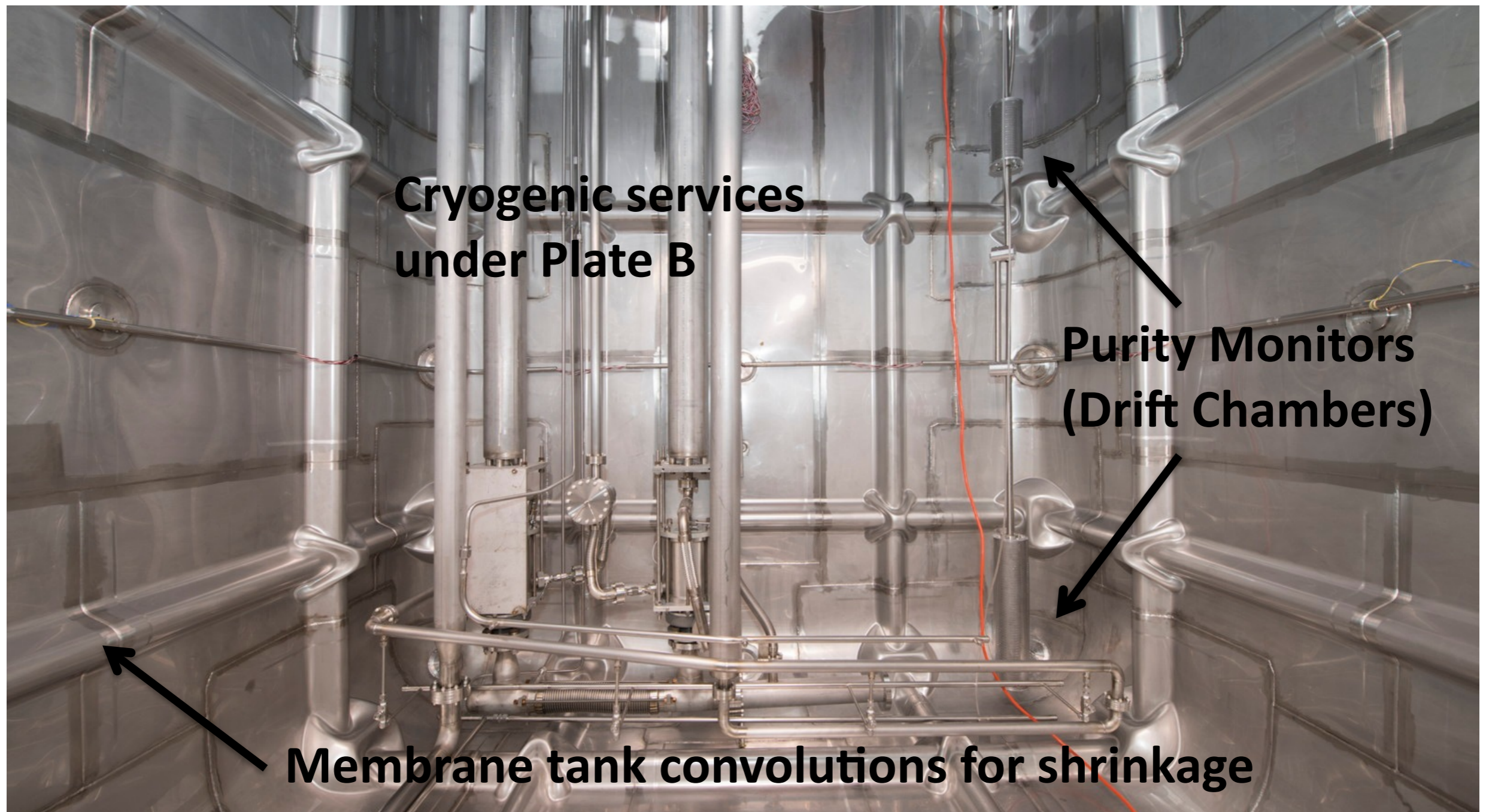
Full scale warm prototype

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

Short baseline will be coordinated to serve as R&D platform



View Inside of 35 Ton Tank



View On Top of 35 Ton Tank

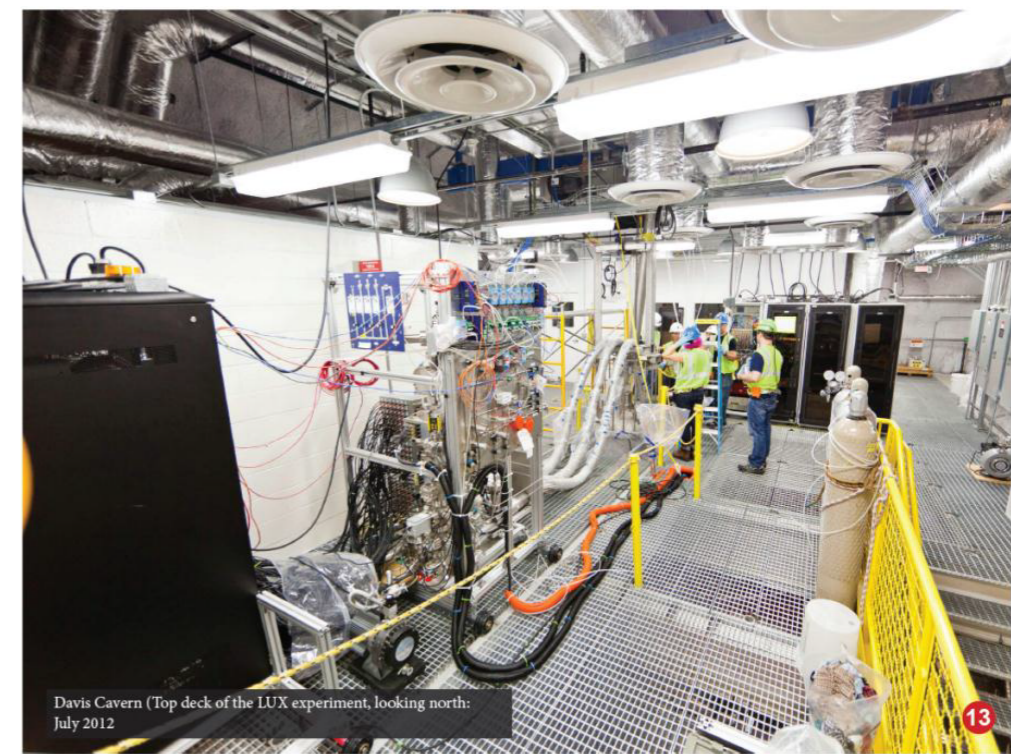


Sanford Underground Research Facility

Majorana ($0\nu\beta\beta$)



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

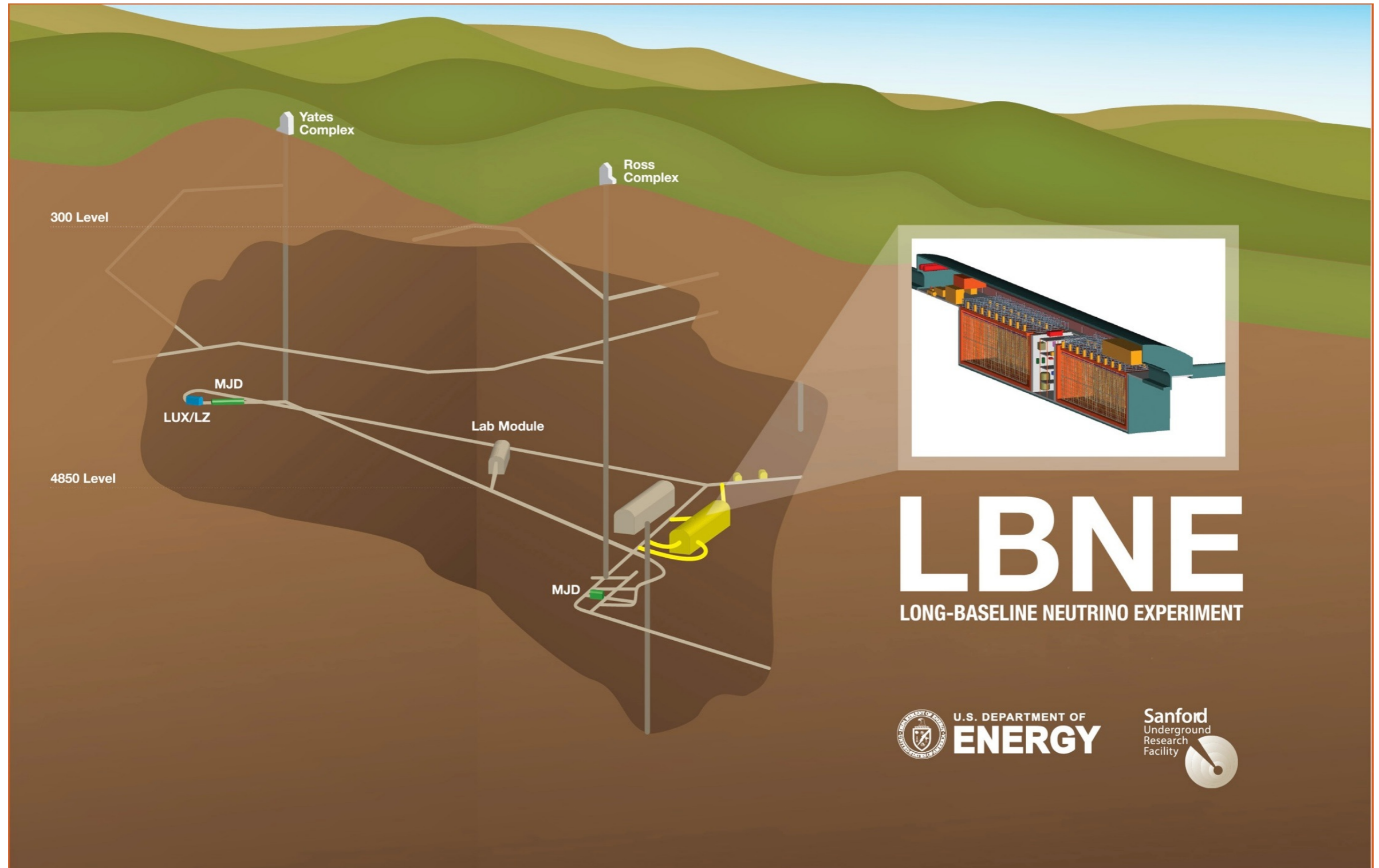


South Dakota Science and Technology Authority

LUX (dark matter)

Lead, South Dakota

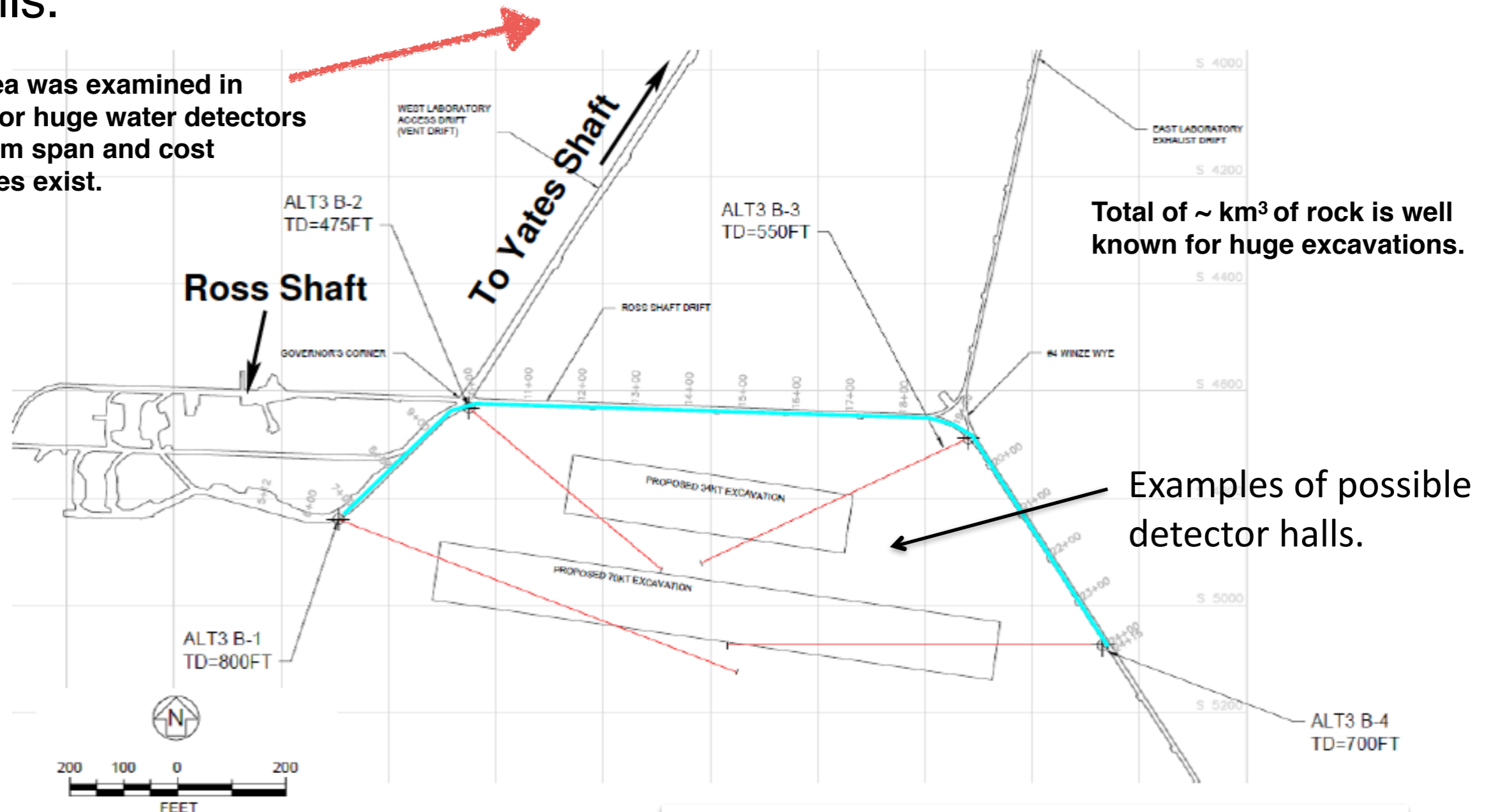
Far Detector in Sanford Underground Facility



CF Far Site Geotech Program

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

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



Financial and International Issues

From the US-P5 committee:

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

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

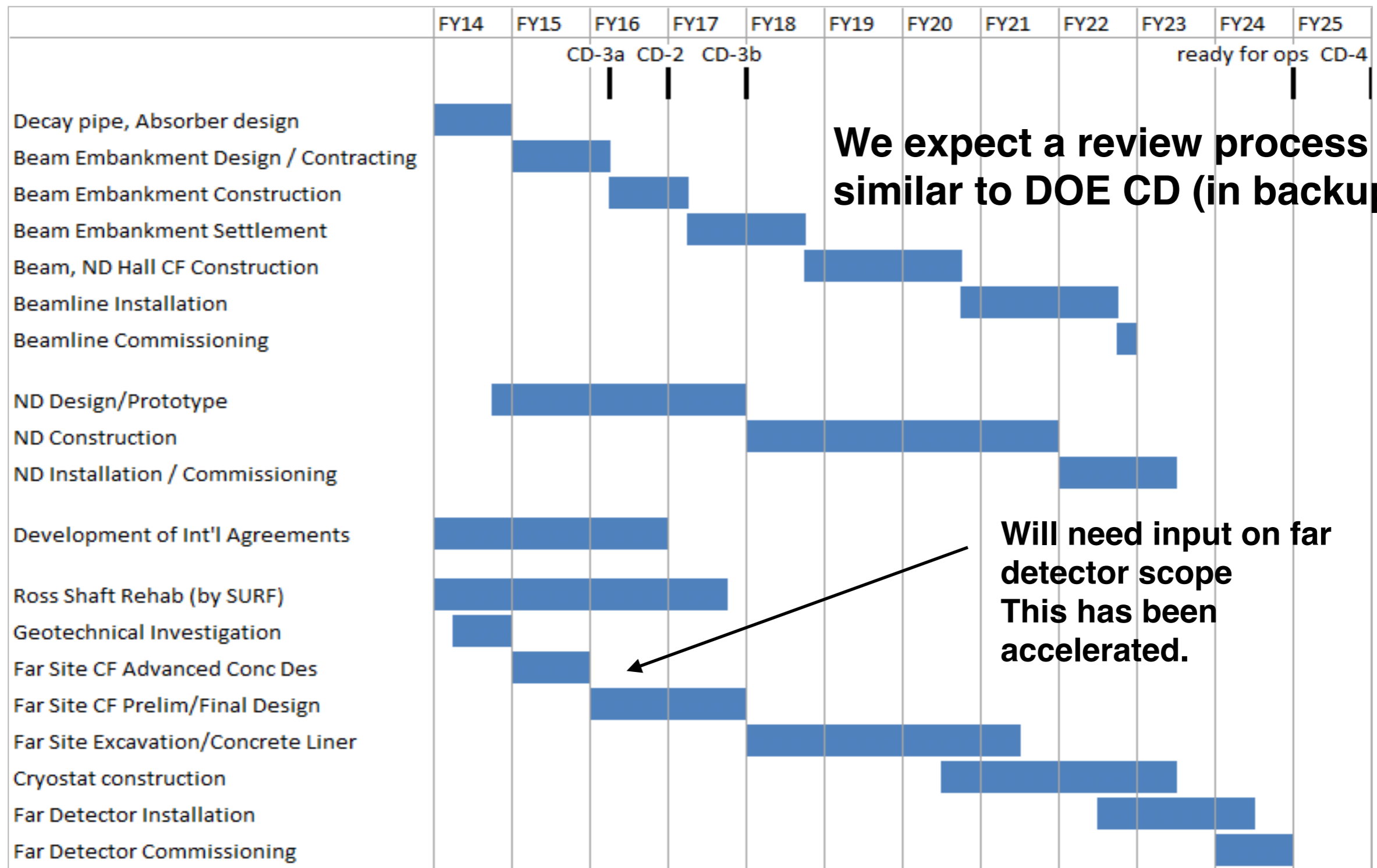
- **Working with US-DOE-OHEP and FNAL director to develop a fully international LBNE/F at all levels. CD1 approval allows flexibility.**
- **The LHC collaborations and others are examples to be studied.**
- **The collaboration based on common scientific goals. No national boundaries are recognized in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

Conceptual design costs.

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

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

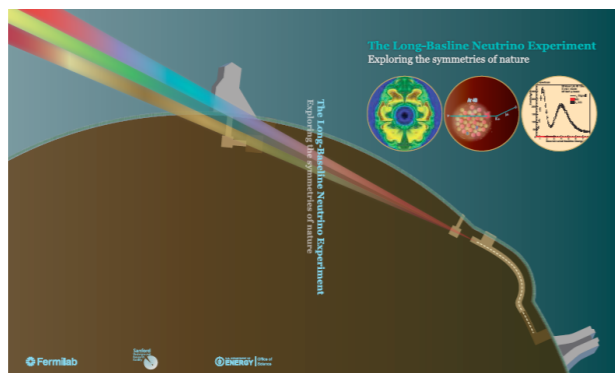
Plausible Technically Limited Schedule for international LBNF. Depends on resources and international project management



The exact timeline will depend on partnerships
host nation funding³ and review process.

Conclusion

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

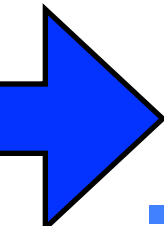


- Snowmass detailed-whitepaper
[arXiv:1307.7335](https://arxiv.org/abs/1307.7335)

Backups

The US DOE Critical Decision Process

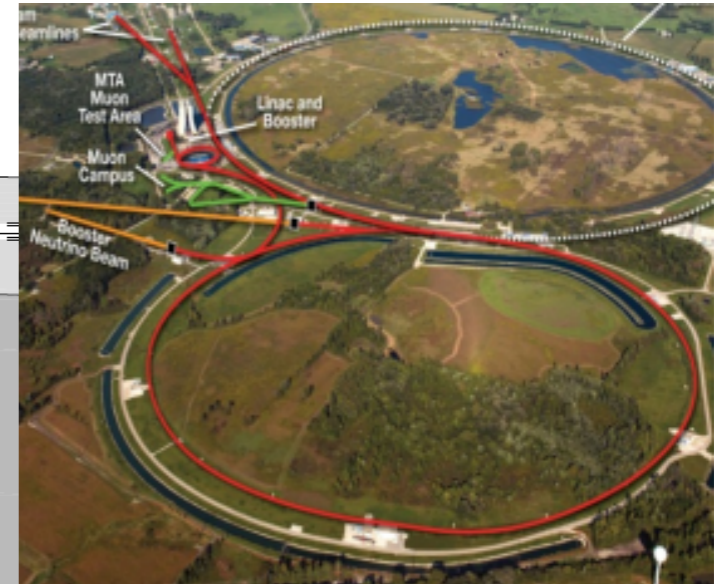
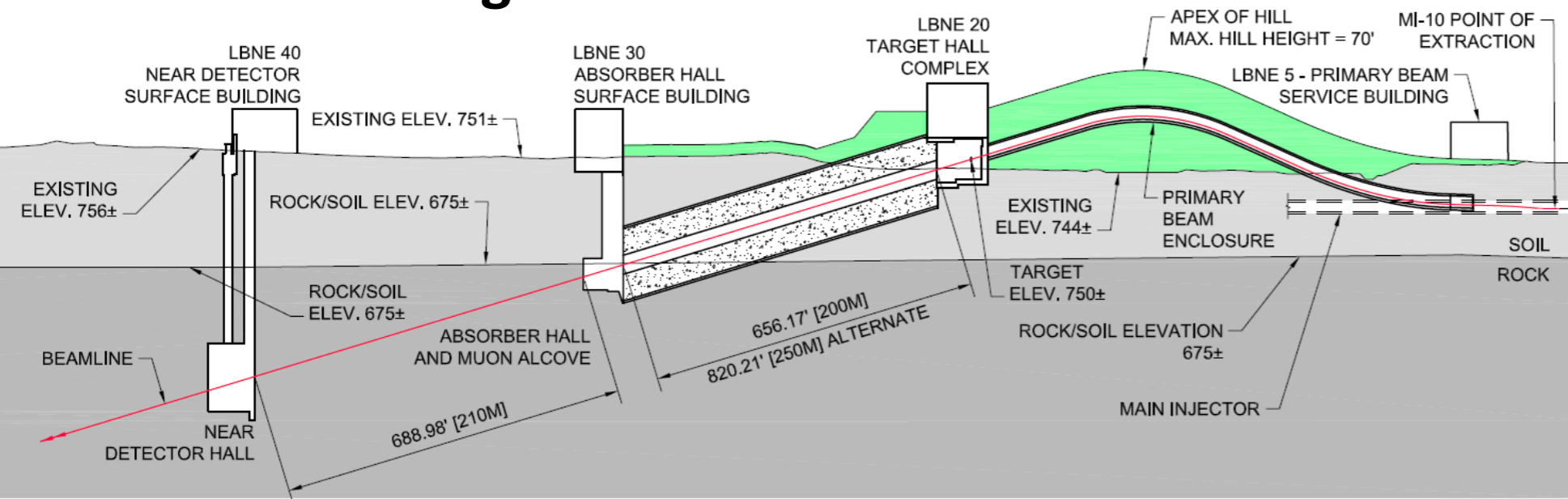
This is flexible and an equivalent process will be developed for an international project.

- 
- CD-0 (“Mission Need”) approves the need for the project. Jan 2010
 - CD-1 (“Alternative Selection and Cost Range”) approves overall design, cost and schedule. Dec 2012
(for phase 1)
 - CD-2 (“Performance Baseline”) approves the precise technical design, cost and schedule.
 - CD-3A (“Approve Long-Lead Item Procurements”) approves early start of selected parts of the project.
 - CD-3 (“Start of Construction”) approves the start of full construction of the rest of the project.
 - CD-4 (“Project Completion”) approves transition to operations.

We are beyond CD1. The future process will depend on creation of an international financial and project management by DOE and partner funding agencies.

Some pictures

LBNE beam design



LUX @ Sanford

Considered design changes that increase the physics potential

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

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

* Simplifies the handling of systematics as well