Future Long-Baseline Neutrino Oscillations: View from North America

Robert J. Wilson
Colorado State University

26th International Conference on
Neutrino Physics and Astrophysics
Boston, USA
June 4th, 2014

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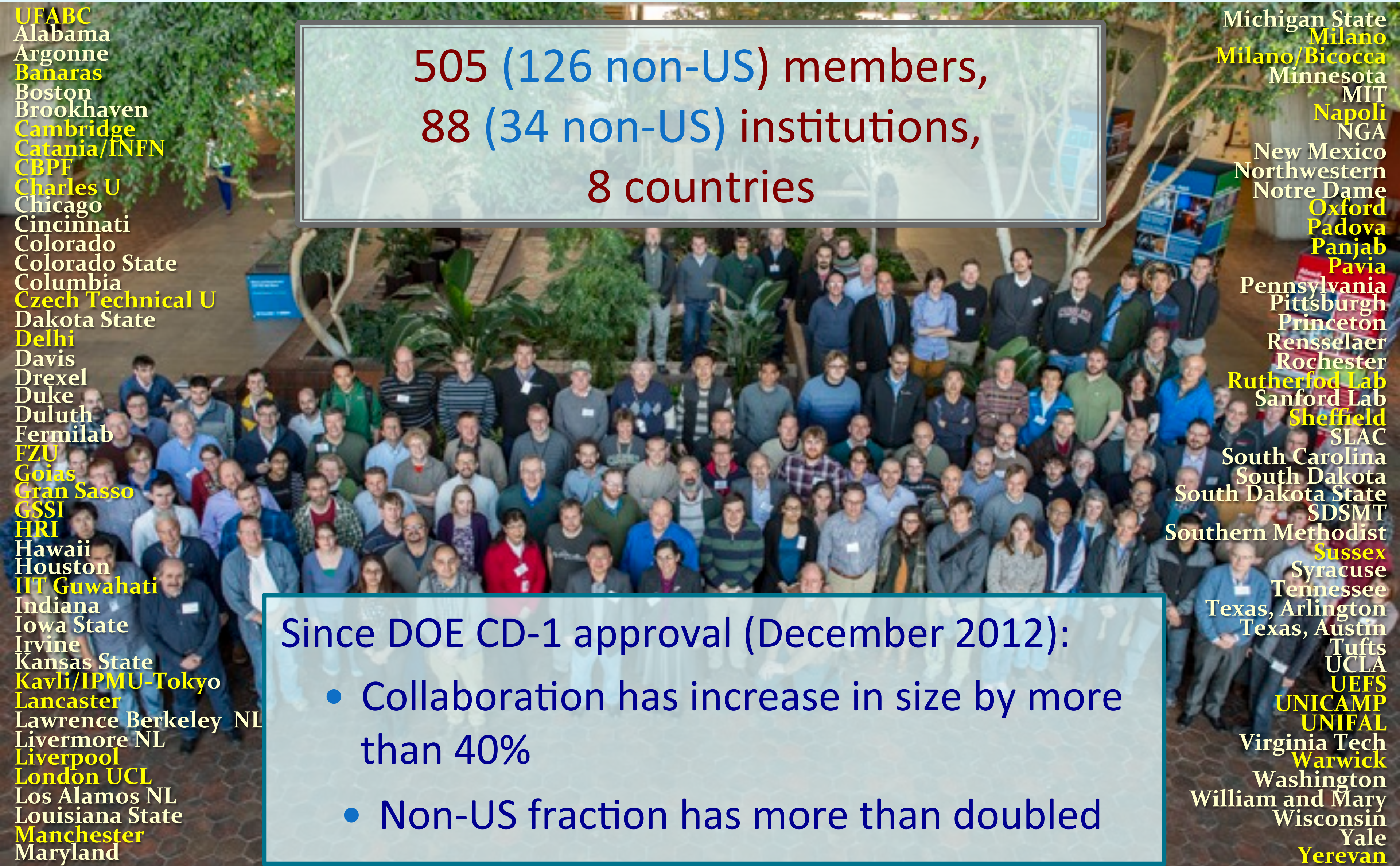
Overview

- Long-Baseline Neutrino Experiment Collaboration
- Science Motivation
  - Long-Baseline Science
  - Underground Science
- LBNE Project
- DOE Prioritization Panel (P5) Report
- Summary and Conclusions

LBNE Collaboration



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

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

Since DOE CD-1 approval (December 2012):

- Collaboration has increase in size by more than 40%
- Non-US fraction has more than doubled

Scientific Motivation

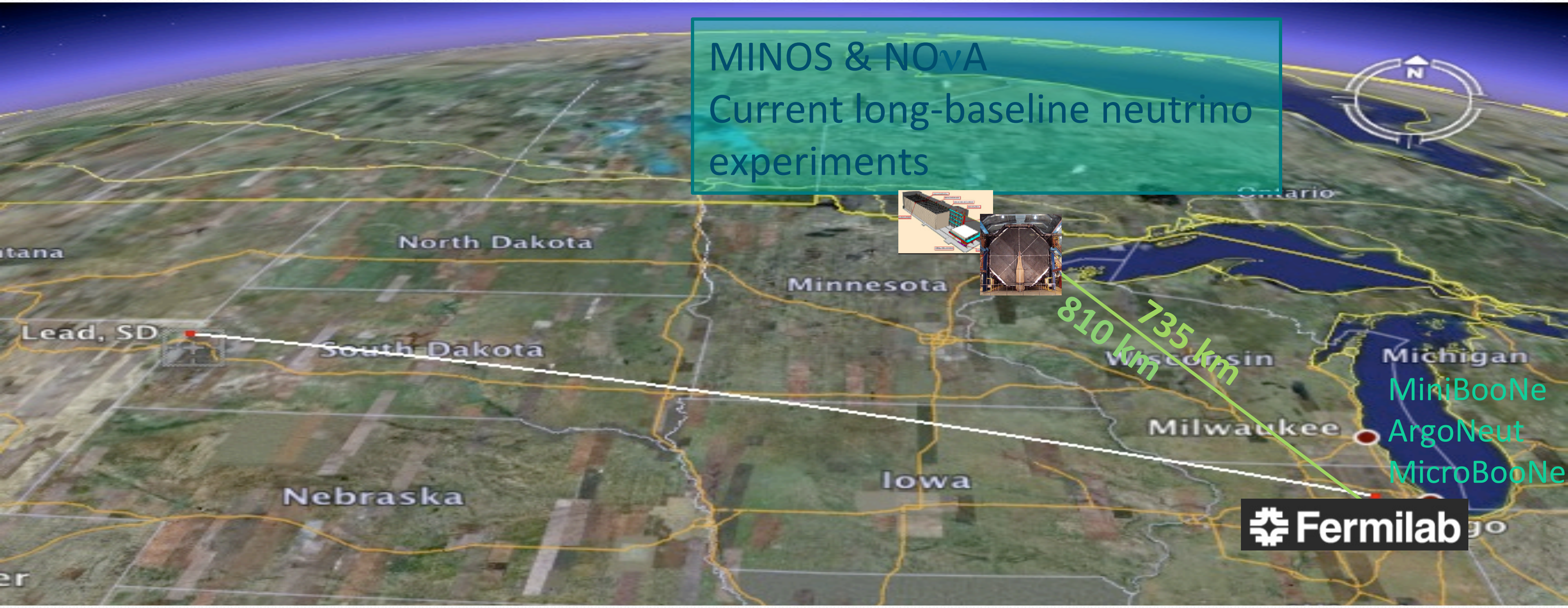
- CP Violation in neutrino sector
  - Violation of a fundamental symmetry of nature; viability of leptogenesis models->matter/antimatter
- Neutrino Mass Hierarchy
  - GUTs, Dirac vs. Majorana nature and feasibility of $0\nu\beta\beta$ decay
- Testing the Three-Flavor Paradigm
  - Precision measurements of known fundamental mixing parameters for neutrinos and anti-neutrinos
  - New physics -> non-standard interactions, sterile neutrinos… (beam + atmospheric ν sources)
  - Precision neutrino interactions studies (near detector)

Scientific Motivation

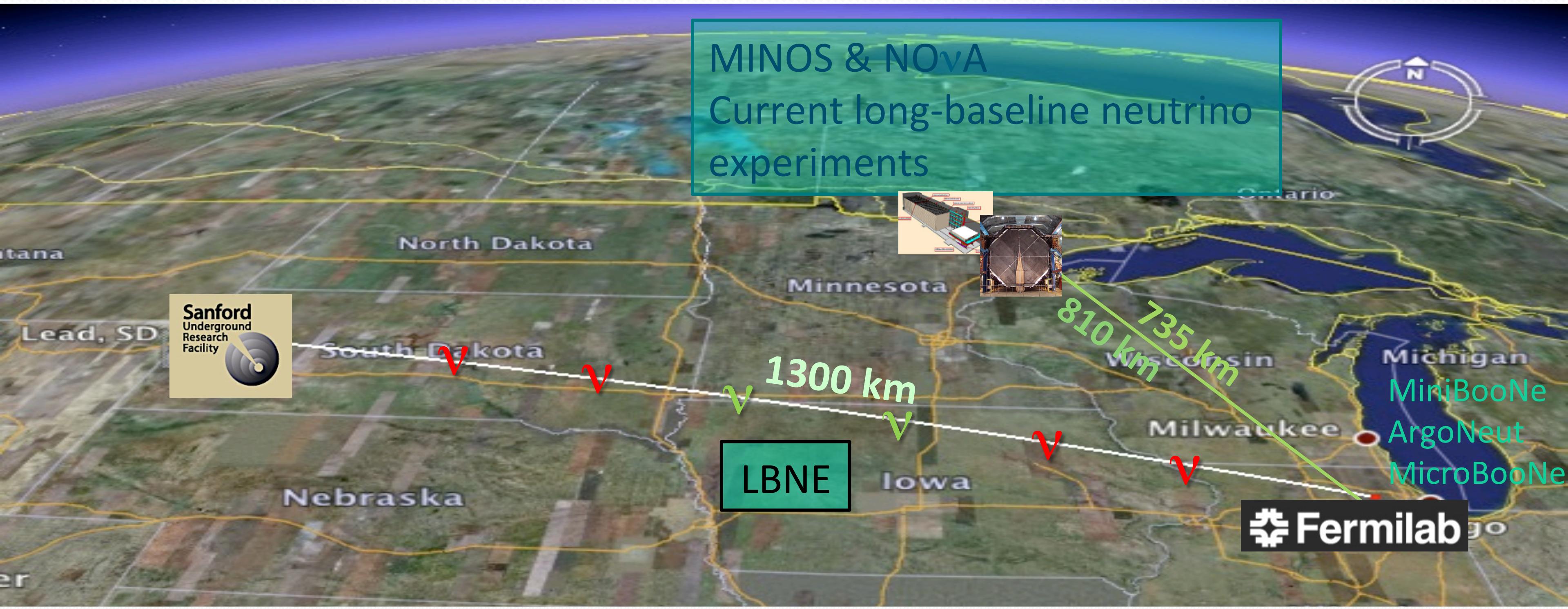
Fundamental physics enabled by massive detectors underground

- Nucleon Decay
  - Is normal matter stable?
  - Grand Unification Theory
- Astrophysics
  - Supernova ν burst – evolution of a stellar collapse

Long-Baseline Measurements



Long-Baseline Measurements



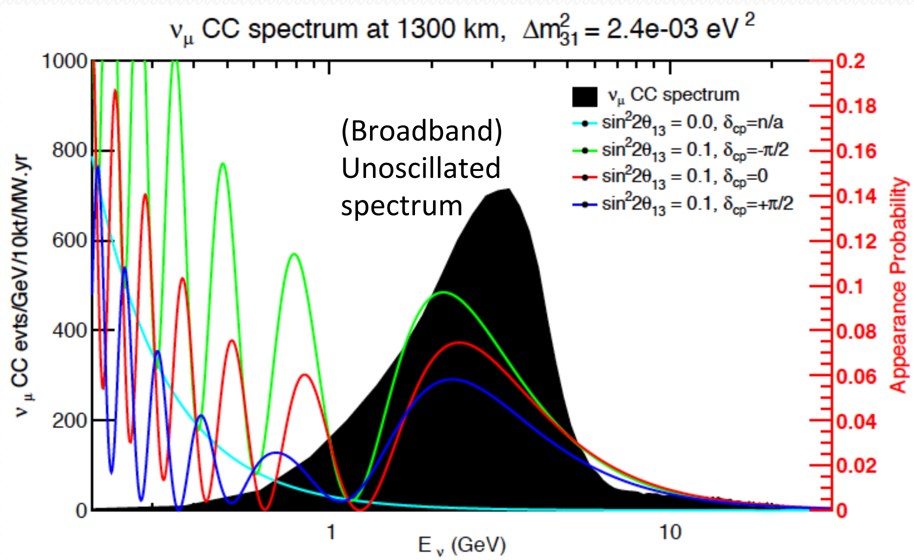
Comprehensive CP Violation, Mass Hierarchy, Non-Standard Interactions
Need Longer Baseline
and High Intensity Broadband Neutrino/Anti-Neutrino Beam

Oscillations…what we know

- Magnitudes of Δm_{31}^2, Δm_{21}^2, θ_{12} are well-measured (few %)
- θ_{23} is large, possibly maximal – measurement <15%
- **θ_{13} is now well-measured and large enough so event rates are sufficient for CP and MH measurements**
    - Less than two years ago we were still afraid it was zero!
- Matter induced asymmetry should be large (~40% for LBNE) and separable from CP asymmetry at appropriately chosen neutrino energy and baseline

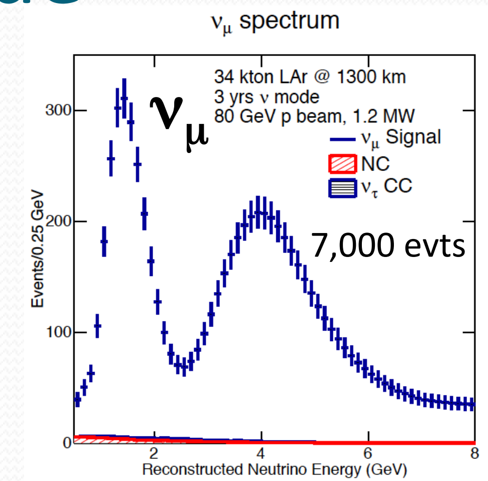
- **We can accurately predict the events rates for unknown CP phase angles and mass hierarchy in the three-flavor model**

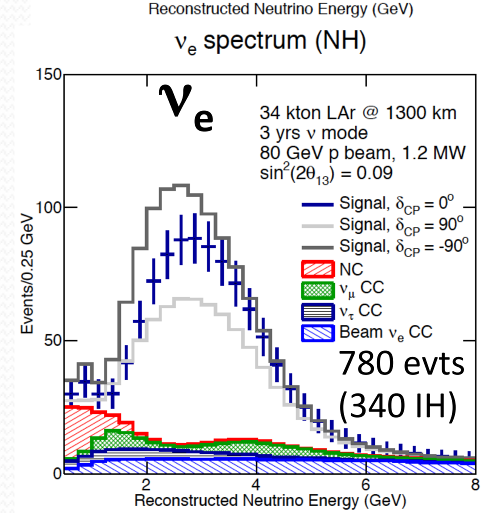
Essential Experimental Technique



disappearance

appearance



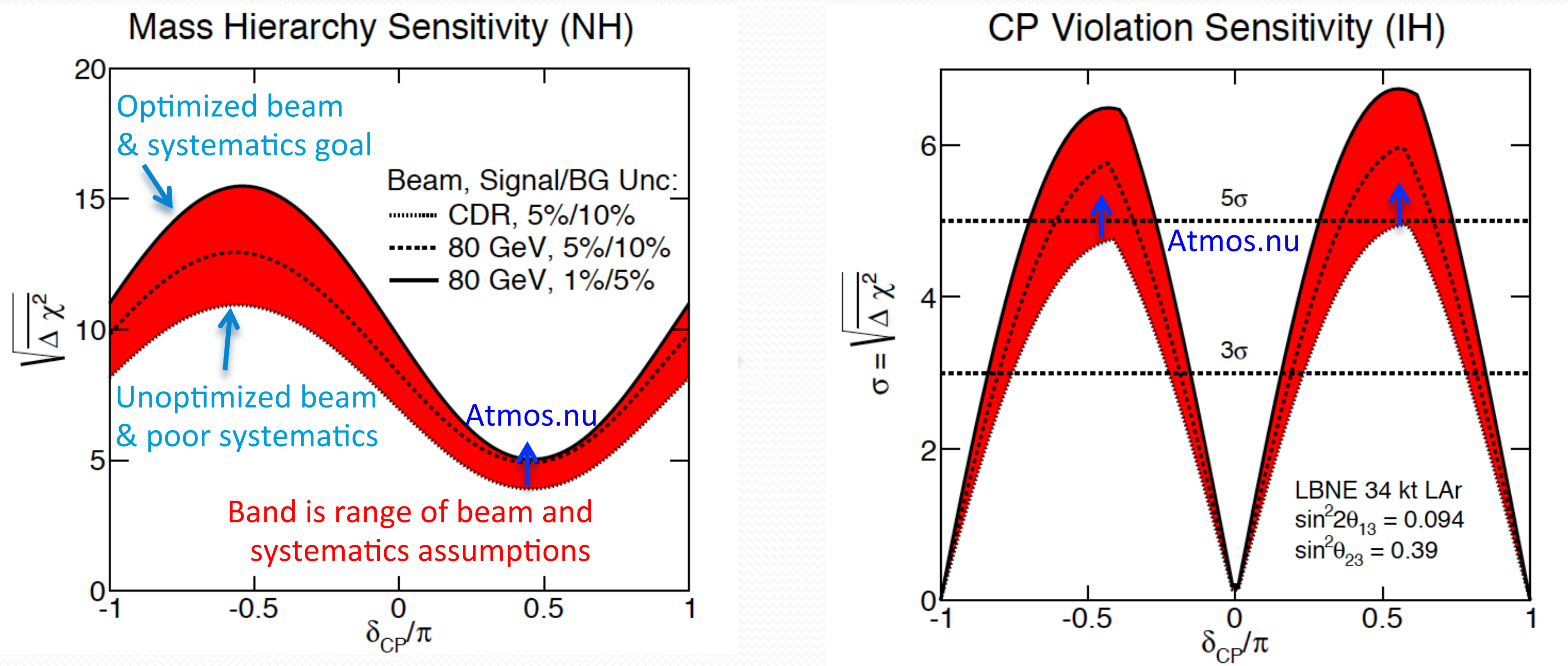


- Produce a pure ν_μ muon-neutrino beam with energy spectrum matched to oscillation pattern at the chosen distance
- Measure spectrum of ν_μ and ν_e at a distant detector
- **LBNE is a near optimal choice of beam and distance for sensitivity to CP violation, CP phase, neutrino mass hierarchy and other oscillation parameters *in same experiment***

Mass Hierarchy and CP Violation Sensitivity

Exposure 245 kt.MW.yr

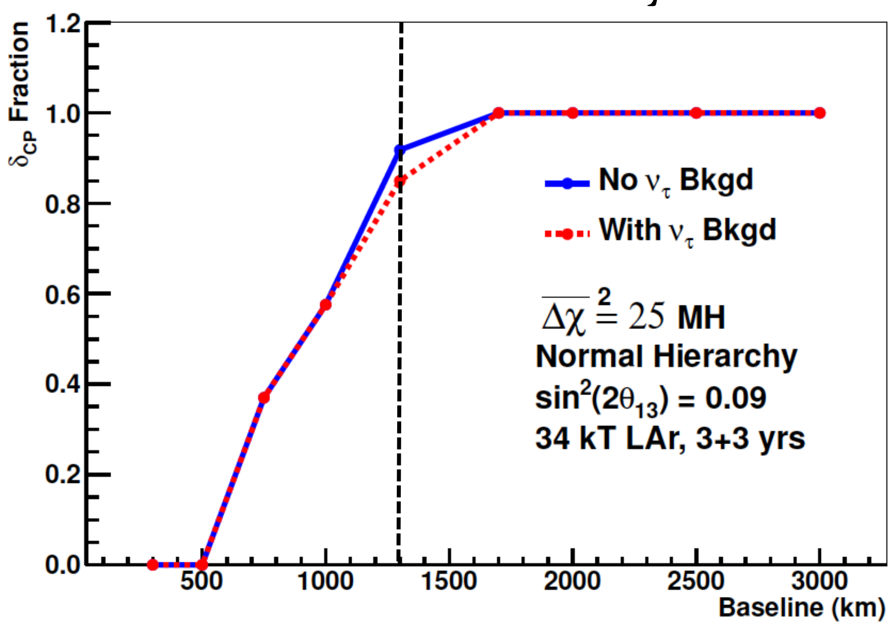
34 kt x 1.2 MW x ($3\nu+3\bar{\nu}$) yr



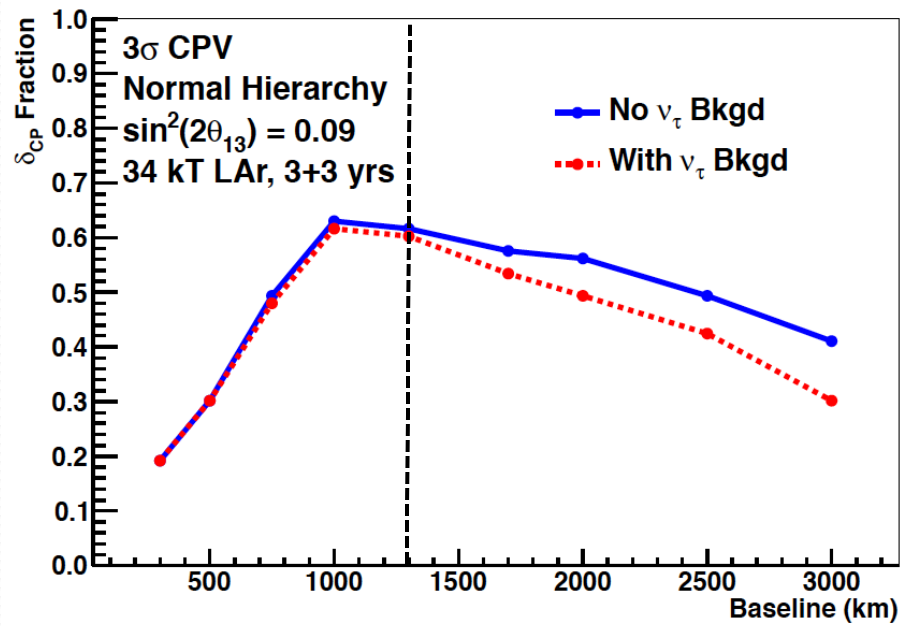
- Mass hierarchy is very well determined over most of δ_{CP} range
- CPV > 3σ over most of range and > 5σ for maximal CPV
- Atmospheric neutrinos in LBNE provide
  - an independent~$\Delta\chi^2$=4 cross-check on MH
  - ~1σ increased CPV sensitivity if combined with beam

Baseline Optimization

Mass Hierarchy



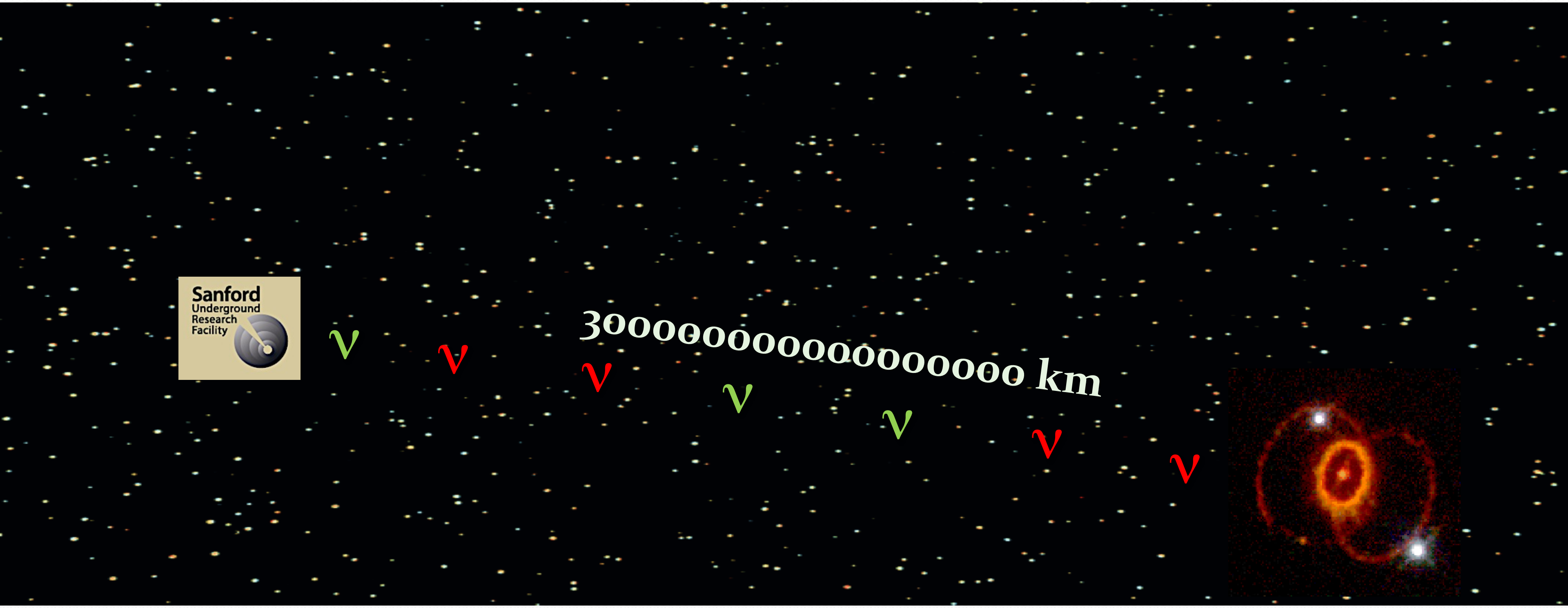
CP Violation



- **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**
- For very long baselines event rate suppression in one of beam polarities makes observation of explicit CP-violation asymmetry difficult

Deep Underground Science

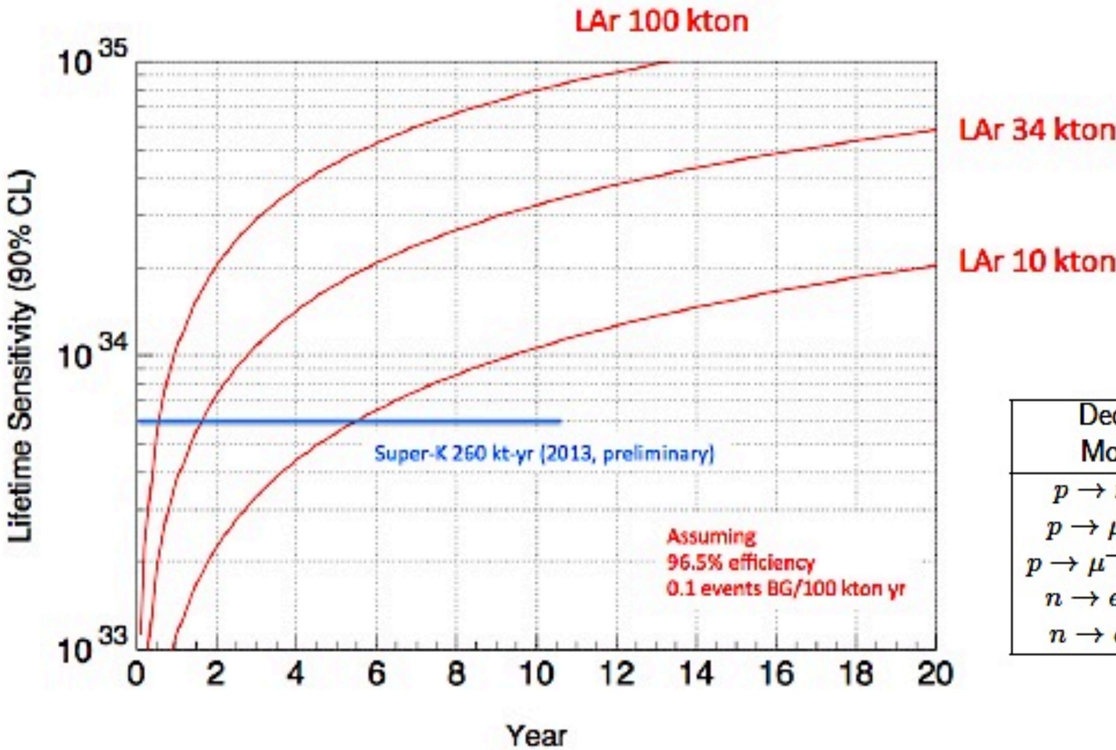
Supernova Burst Neutrinos

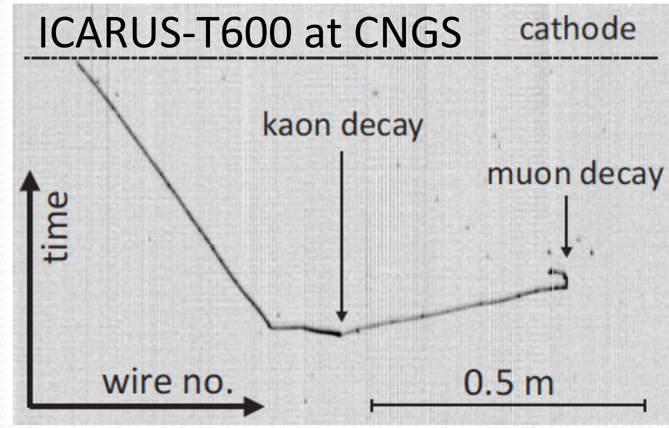


- When a star's core collapses ~99% of the gravitational binding energy of the proto-neutron star goes into ν's
- SN at galactic core (10 kpc) ⇒ several thousand interactions in 35 kt LArTPC in tens of seconds – reconstructed w/ sub-millisec precision
- **Talks by C. Lunardini and K. Scholberg; poster #99 F. Rossi Torres**

Proton Decay

- Missing link to Grand Unified Theories
- Determines the ultimate fate of the universe!





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

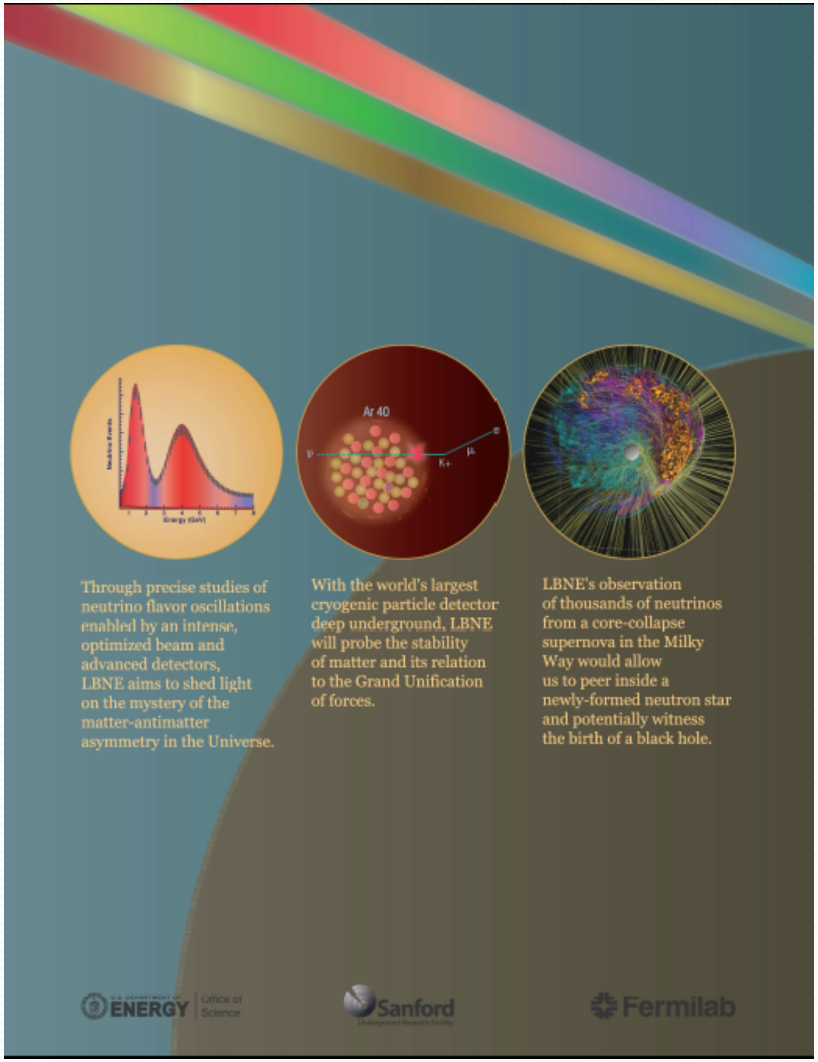
events per Mt.yr

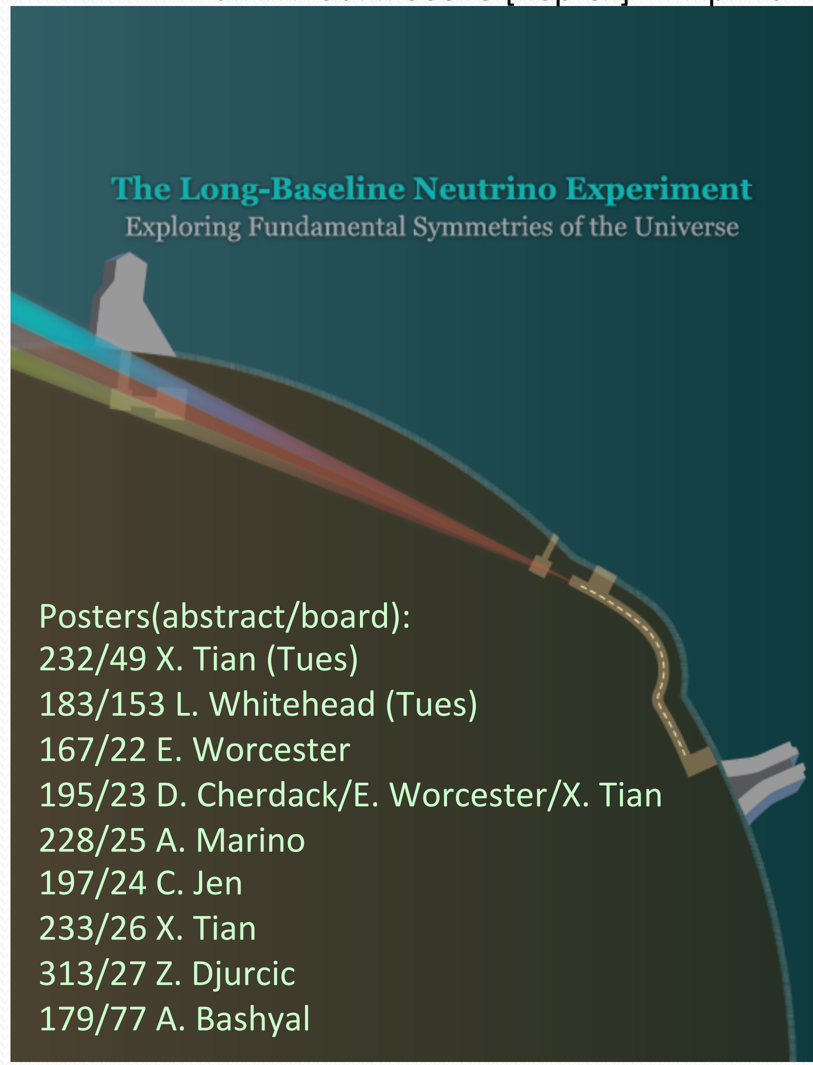
- LAr TPC high efficiency/low background for kaon modes
    - Discovery from a single well-reconstructed event with sufficiently low bgkd
- Especially interesting if SUSY discovered at LHC

LBNE Science Book

http://lbne.fnal.gov/

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





Importance of LBNE Science

Planning the Future of U.S. Particle Physics

Report of the 2013 Community Summer Study

The Long-Baseline Neutrino Experiment (LBNE) will measure the mass hierarchy and is uniquely positioned to determine whether leptons violate CP. Future multi-megawatt beams aimed at LBNE, such as those from Project X at Fermilab, would enable studies of CP violation in neutrino oscillations with conclusive accuracy. An underground LBNE detector would also permit the study of atmospheric neutrinos, proton decay, and precision measurement of any galactic supernova explosion. This represents a vibrant global program with the U.S. as host.

Report of the 2013 "Snowmass" Summer Study

f. Rapid progress in neutrino oscillation physics, with significant European involvement, has establishe a strong scientific case for a long-baseline neutrir programme exploring CP violation and the mas hierarchy in the neutrino sector. *CERN shoul develop a neutrino programme to pave the way fo a substantial European role in future long-baselin experiments. Europe should explore the possibilit of major participation in leading long-baseline neutrino projects in the US and Japan.*

The European Strategy for Particle Physics, Update 2013

The Science Drivers:

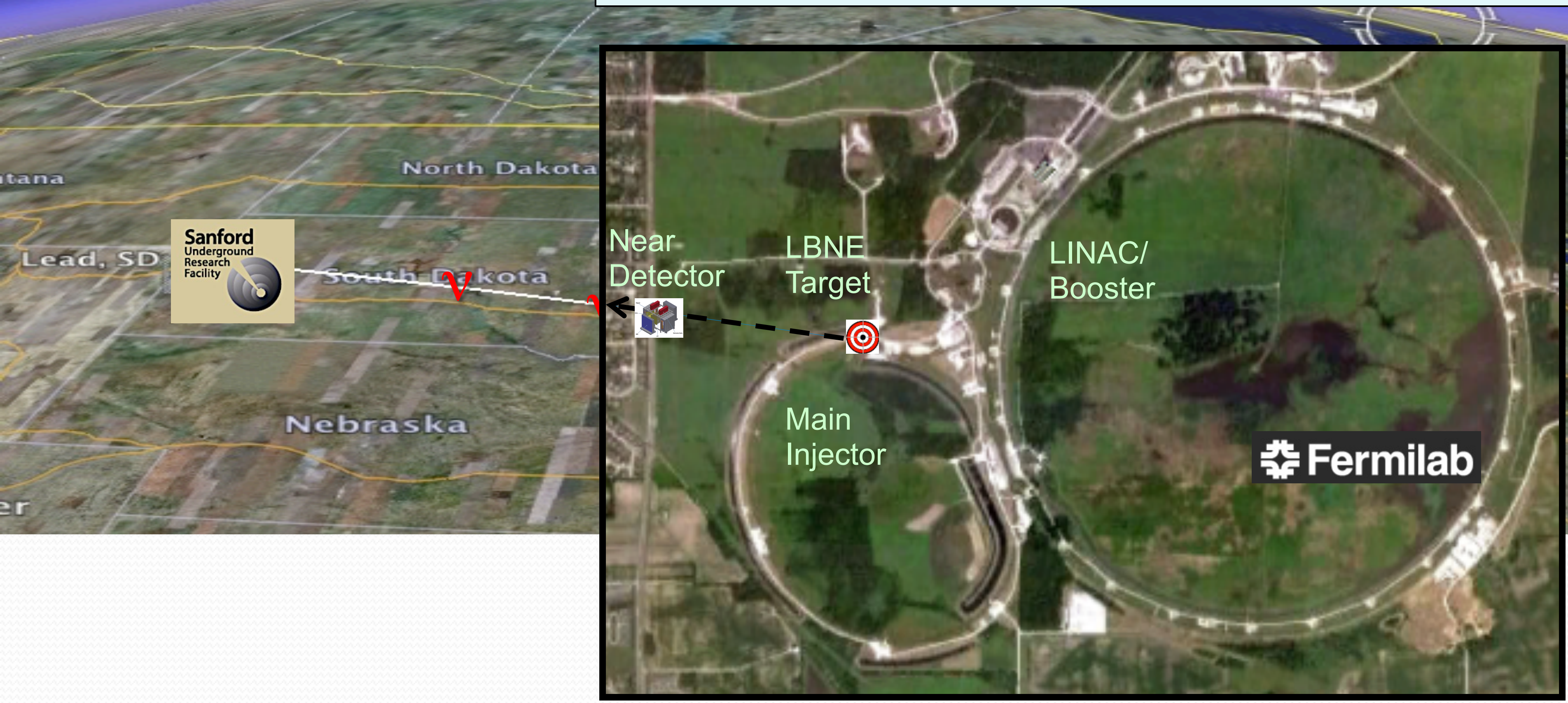
- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

P5 Report, May 2014

LBNE

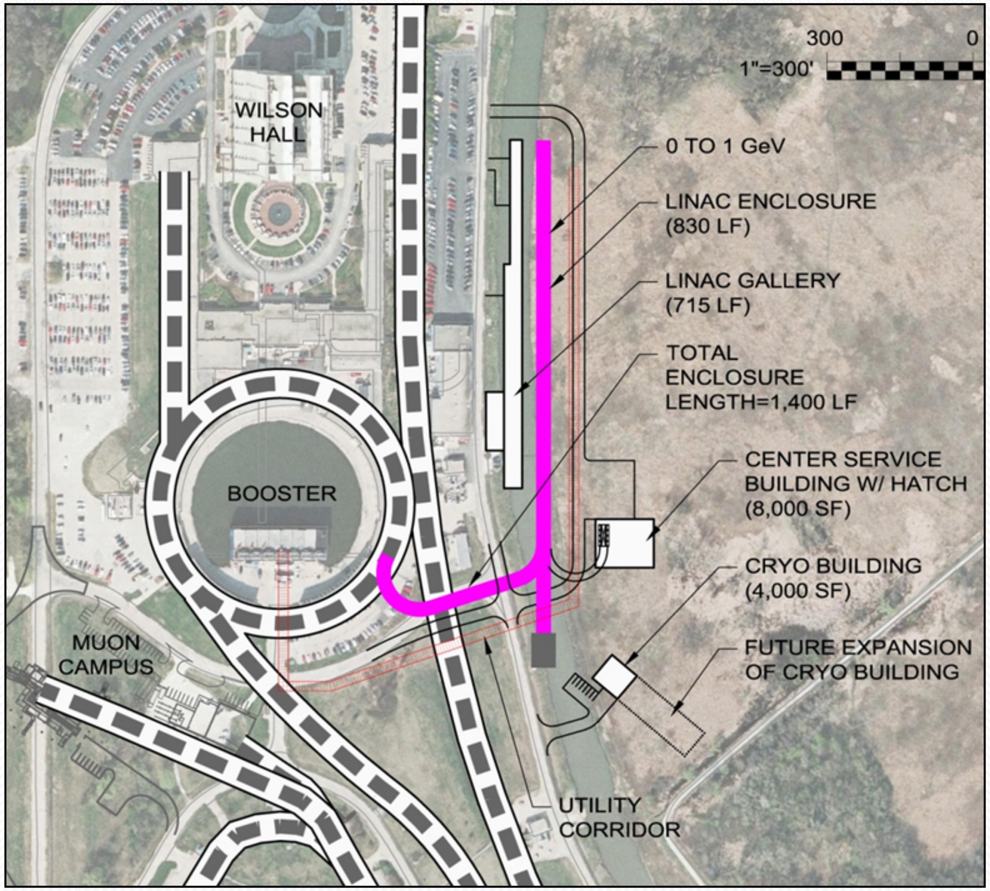

North Dakota
Minnesota
Ontario
Lead, SD
Sanford Underground Research Facility
South Dakota
1300 km
Wisconsin
Michigan
Milwaukee
Nebraska
Iowa
Fermilab

~~700~~ 1200 kW proton beam (upgradeable to > 2 MW) used to generate neutrinos or anti-neutrinos

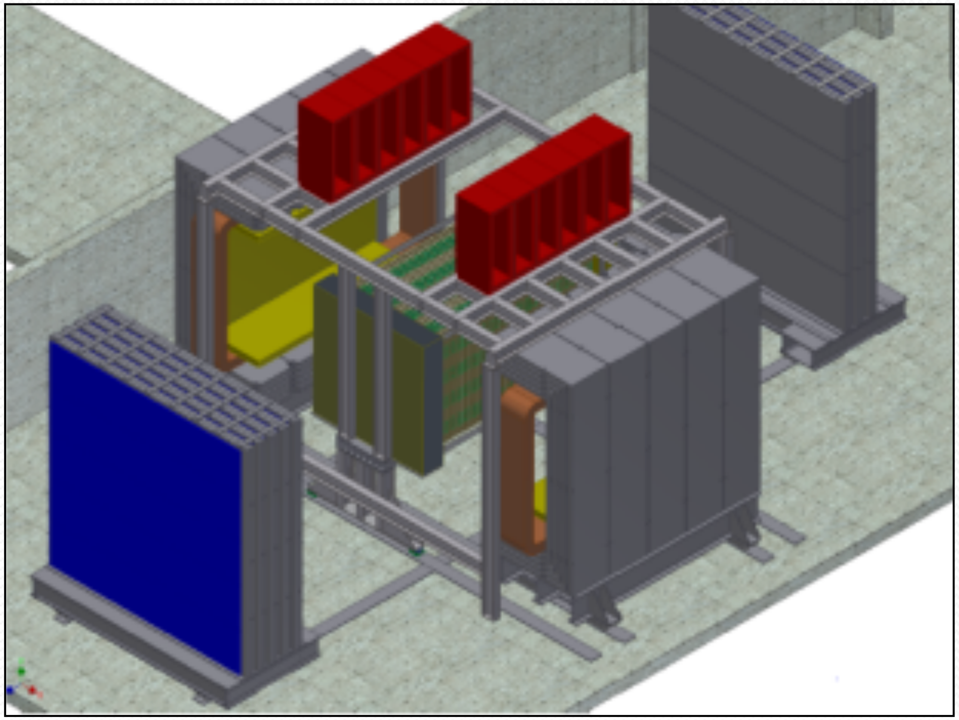


Proton-Improvement-Plan Phase II (PIP-II)

- Replace existing 400 MeV linac with a new 800 MeV superconducting linac
- 1.2 MW beam power to LBNE at t=0
- Plan is based on well-developed SRF technology
- Strong support from DOE and in the recent Prioritization Panel report
- Flexible design - future upgrades could provide > 2MW to LBNE and x10 Mu2e sensitivity



Highly-Capable Near Detector System



- 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 ~10^7 interactions/year!
  - Additional target materials possible
  - Proposal pending in India

Poster #49 X. Tian

- Muon monitor system

LBNE Far Site

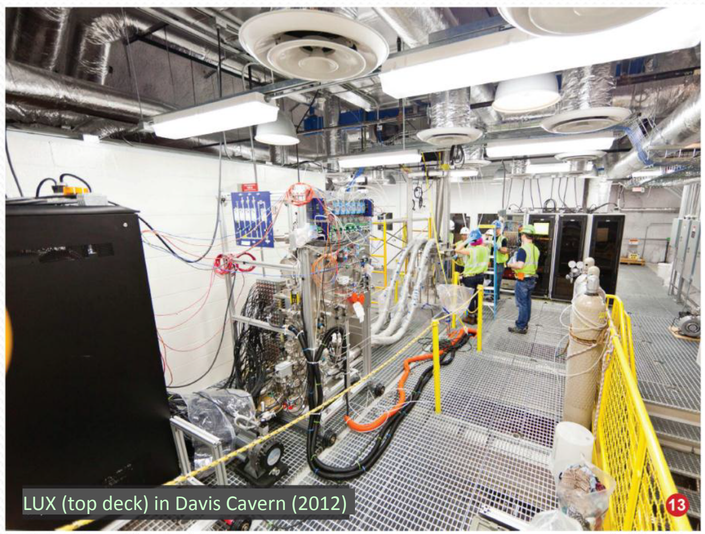
Sanford Underground Research Facility at Homestake Mine
Facilities at 4300 mwe depth


MAJORANA detector assembly room


DAVIS Cavern entrances

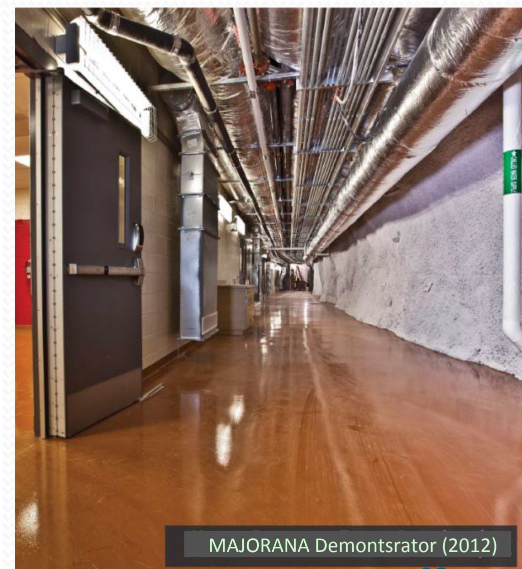
Davis Cavern entrance


MAJORANA Electroforming Laboratory

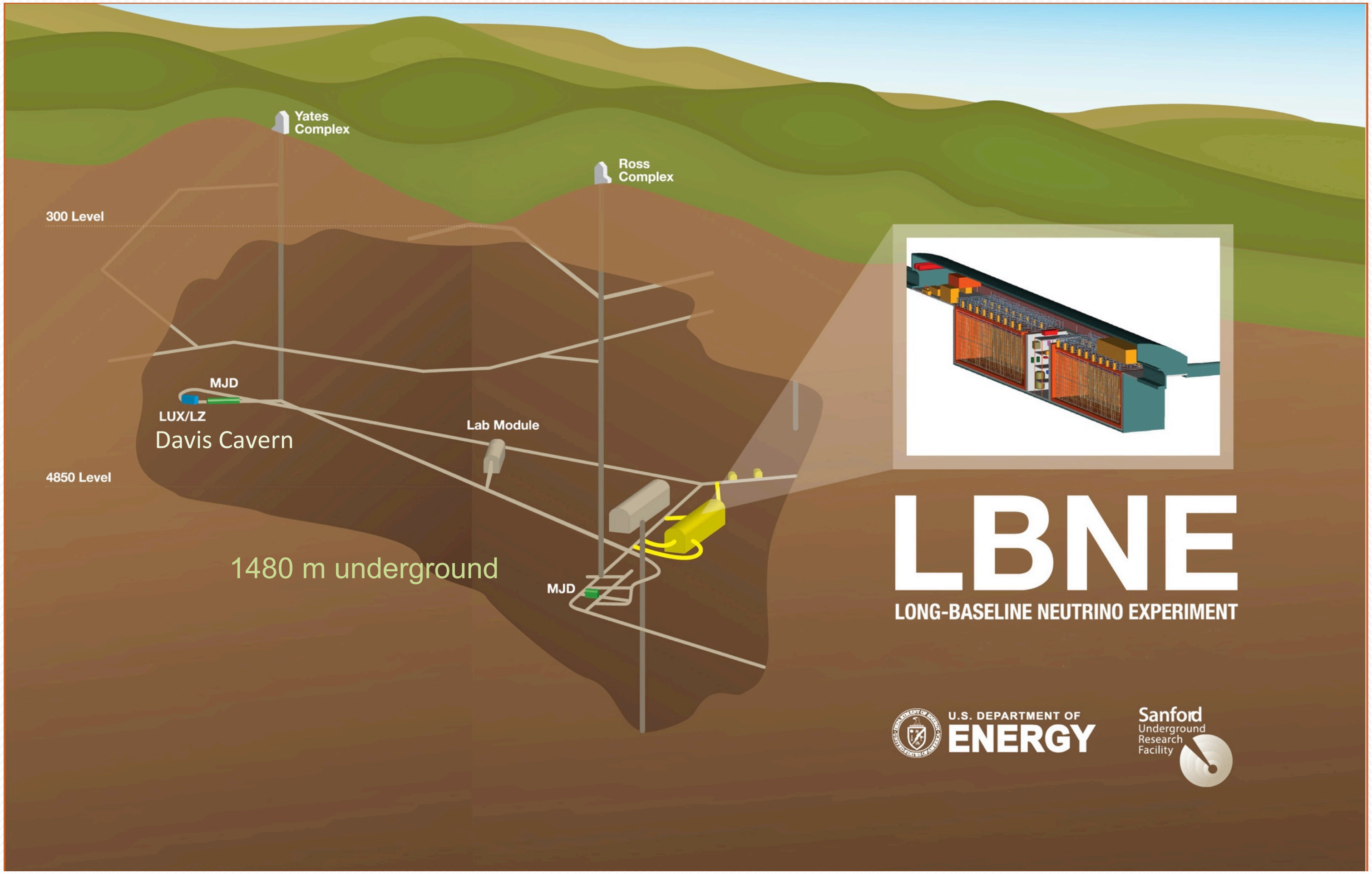

LUX (top deck) in Davis Cavern (2012)

South Dakota Science and Technology Authority

Lead, South Dakota

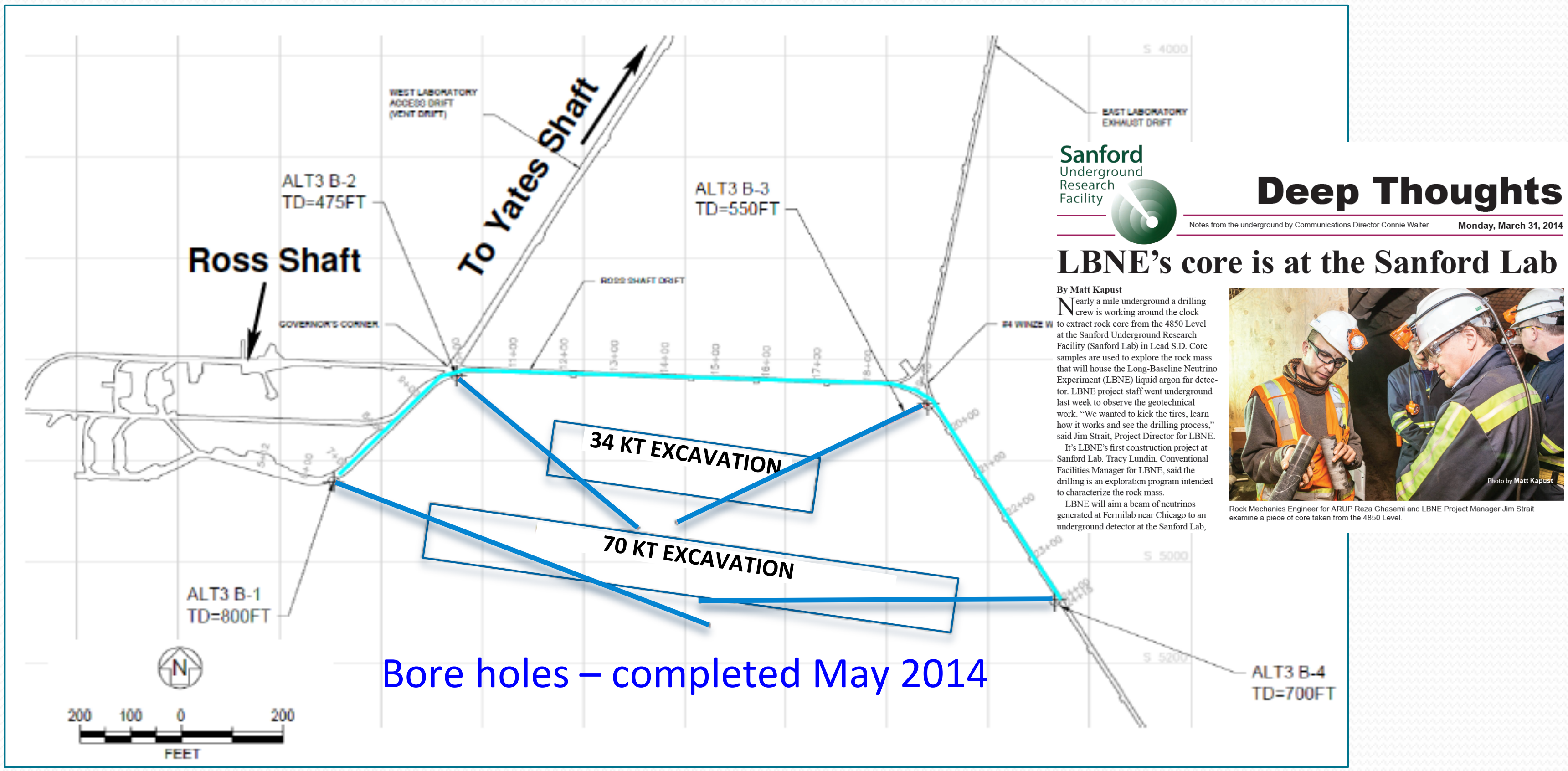

MAJORANA Demontsrator (2012)

LBNE Far Detector



Geotechnical Investigations

- We have launched geotechnical investigation of the LBNE detector site at the 4850L
- Four bore holes completed – rock quality very good on preliminary inspection. Full analysis by August providing information to begin excavation design



Sanford Underground Research Facility

Deep Thoughts

Notes from the underground by Communications Director Connie Walter — Monday, March 31, 2014

LBNE's core is at the Sanford Lab

By Matt Kapust

Nearly a mile underground a drilling crew is working around the clock to extract rock core from the 4850 Level at the Sanford Underground Research Facility (Sanford Lab) in Lead S.D. Core samples are used to explore the rock mass that will house the Long-Baseline Neutrino Experiment (LBNE) liquid argon far detector. LBNE project staff went underground last week to observe the geotechnical work. "We wanted to kick the tires, learn how it works and see the drilling process," said Jim Strait, Project Director for LBNE.

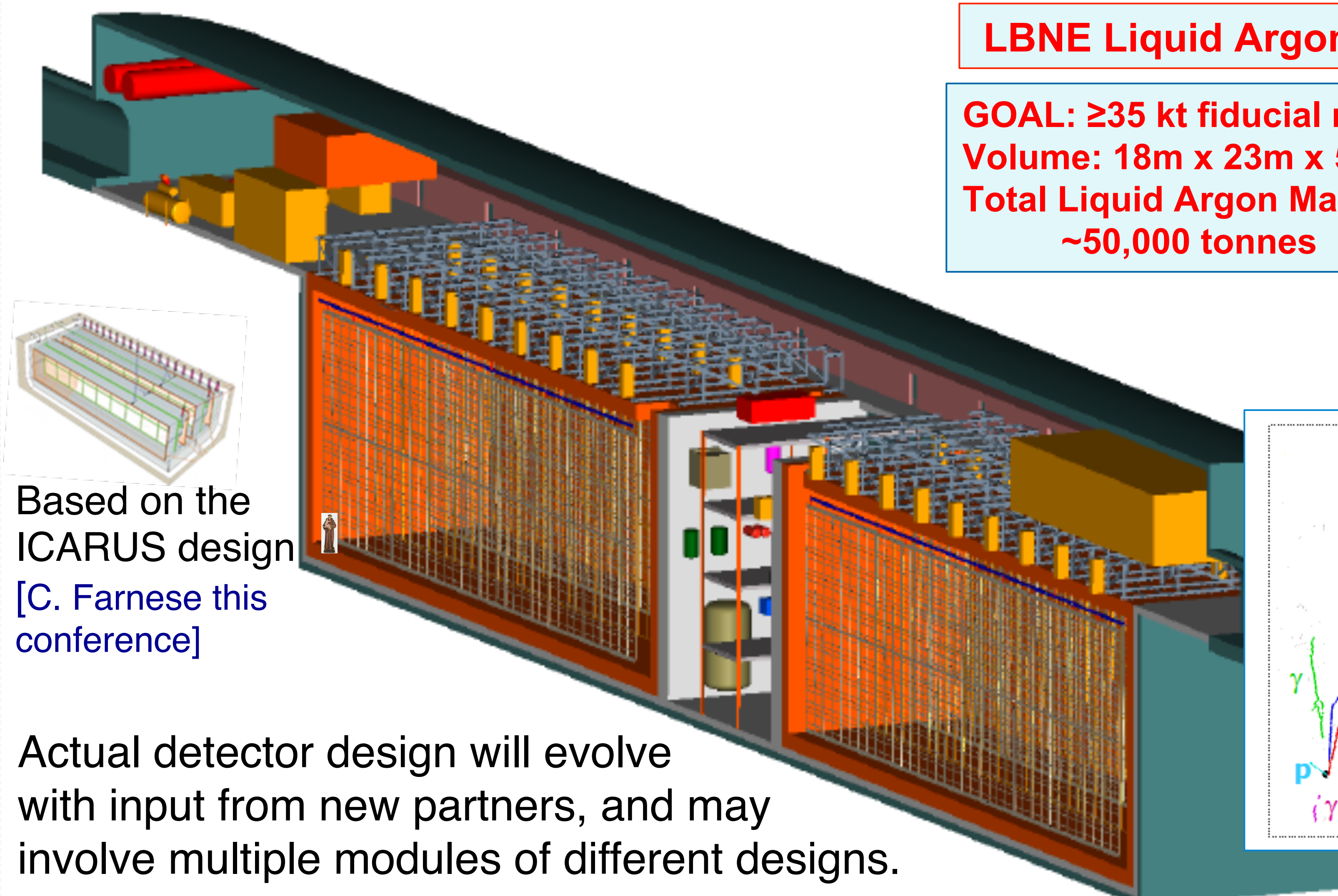
It's LBNE's first construction project at Sanford Lab. Tracy Lundin, Conventional Facilities Manager for LBNE, said the drilling is an exploration program intended to characterize the rock mass.

LBNE will aim a beam of neutrinos generated at Fermilab near Chicago to an underground detector at the Sanford Lab,

Photo by Matt Kapust

Rock Mechanics Engineer for ARUP Reza Ghasemi and LBNE Project Manager Jim Strait examine a piece of core taken from the 4850 Level.

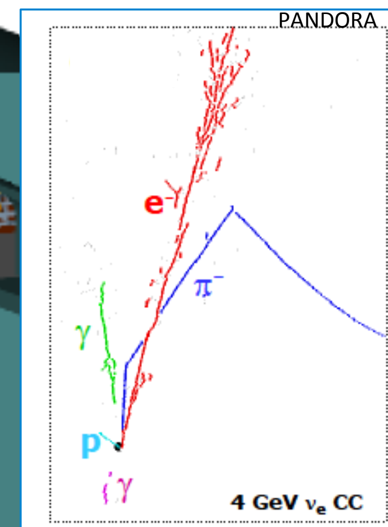
Current Far Detector Design



LBNE Liquid Argon TPC

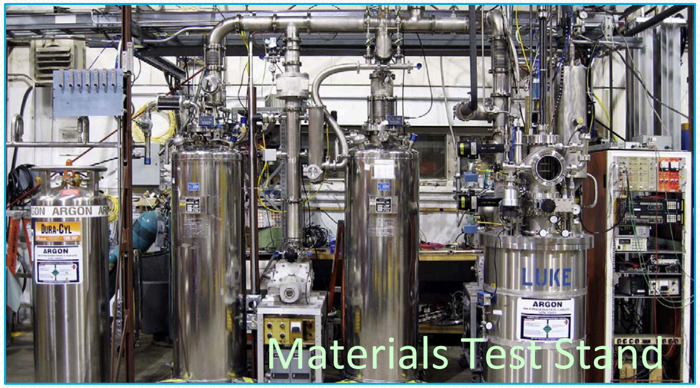
GOAL: ≥35 kt fiducial mass
Volume: 18m x 23m x 51m x 2
Total Liquid Argon Mass: ~50,000 tonnes

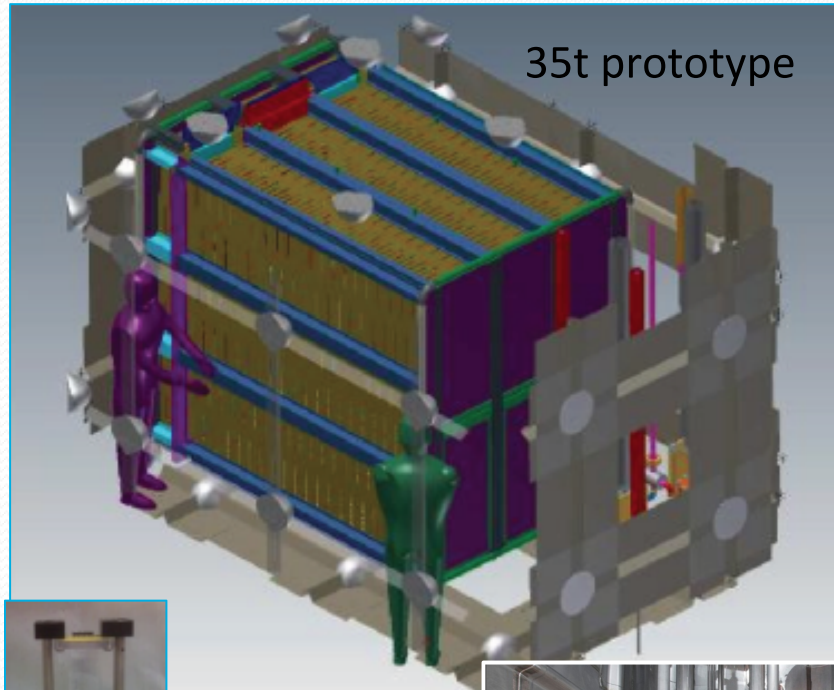
Based on the ICARUS design
[C. Farnese this conference]

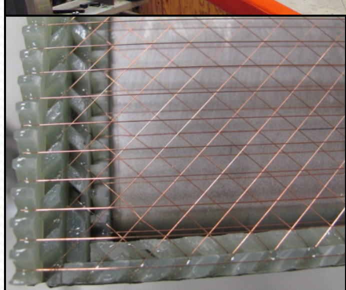


Actual detector design will evolve with input from new partners, and may involve multiple modules of different designs.

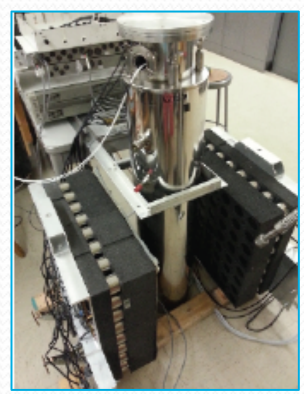
FD Prototyping







TPC Anode Plane

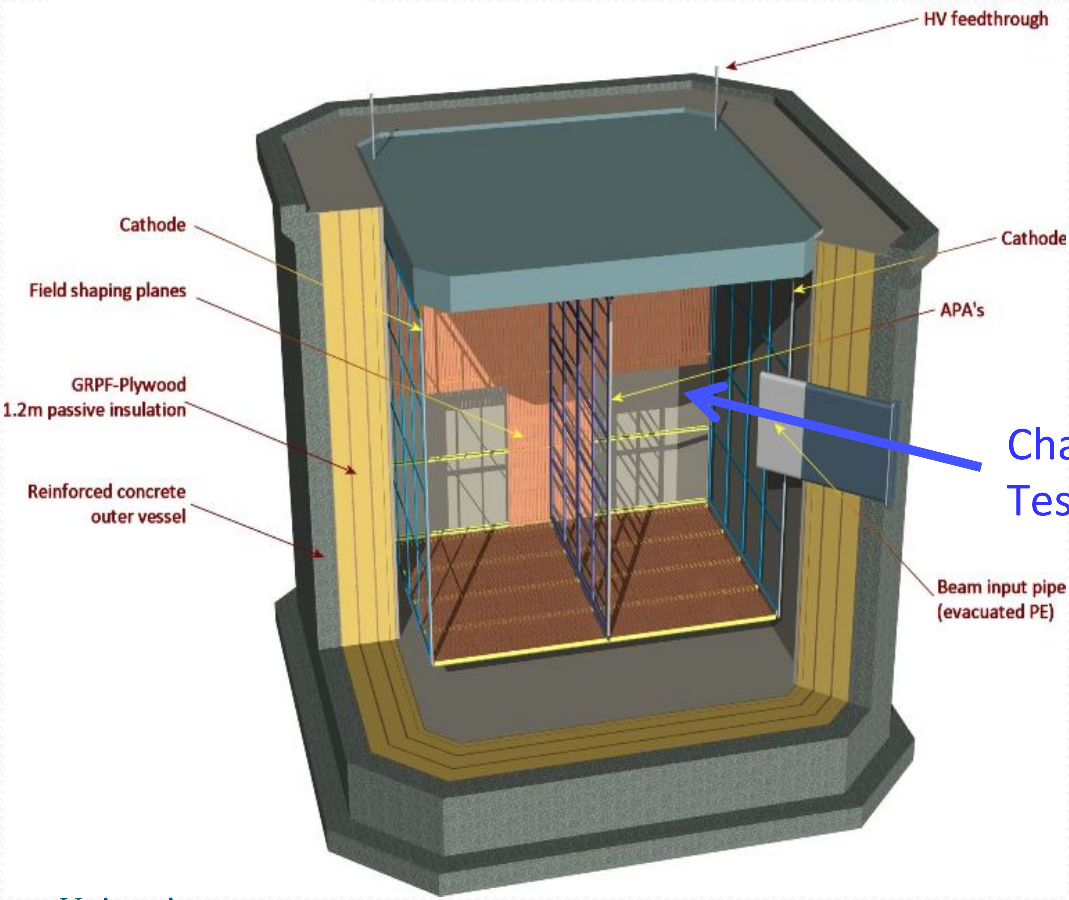


Photon detector R&D

LAr purity demonstrated;
detector testing next fall

Full-Scale Prototype in LBNO-DEMO Cryostat

- Together with CERN and the LBNO Collaboration, we are developing a plan to test full-scale LBNE drift cell(s) in the 8x8x8 m^3 cryostat to be built at CERN as part of WA105.

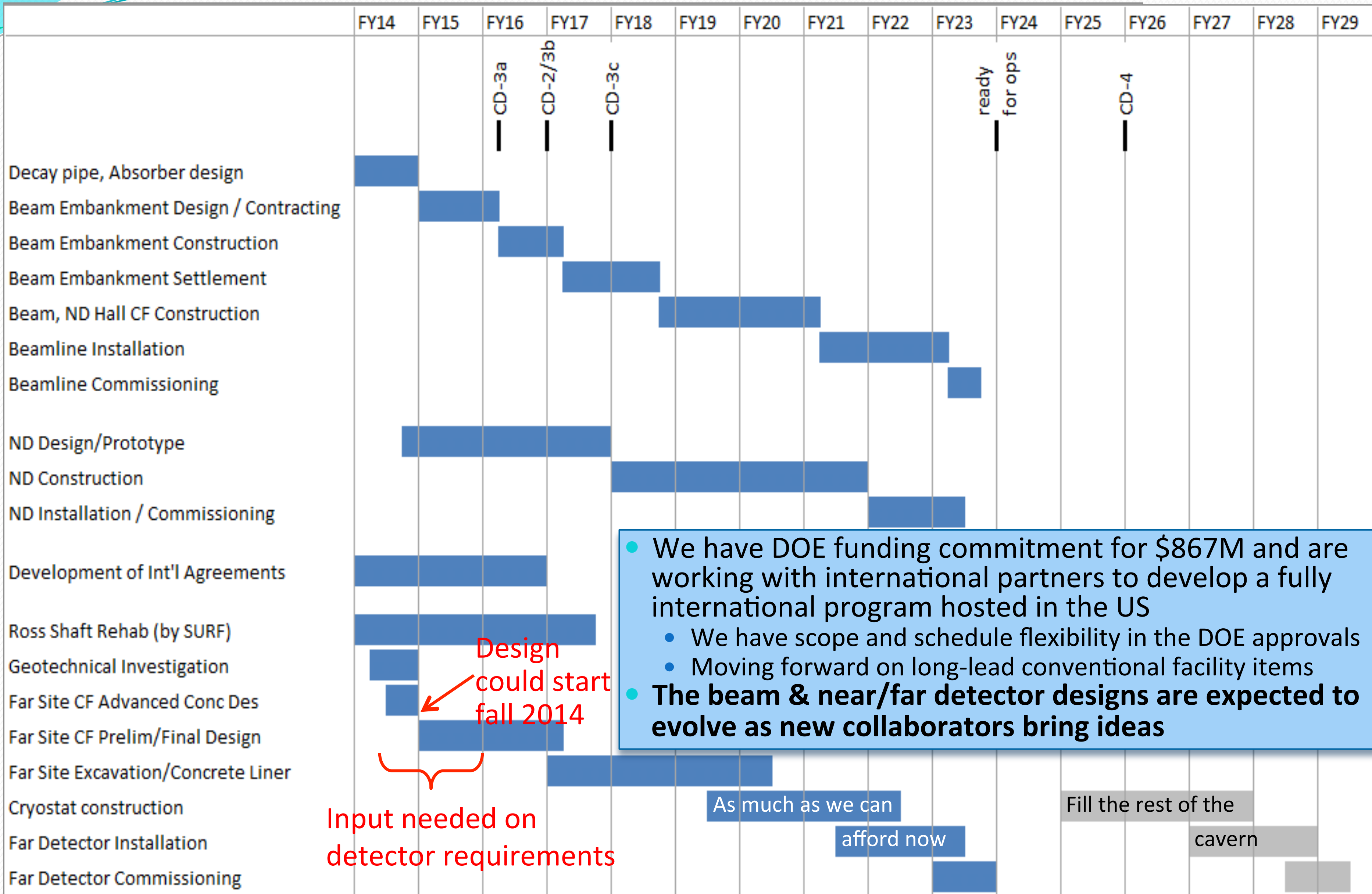


Charged Particle
Test Beam

Related Activities

- LBNE Related R&D/Physics proposals
  - LARIAT – LArTPC in charged particle beam at FNAL
  - CAPTAIN – LArTPC neutron flux at LANL -> FNAL
  - LAr1-ND – LArTPC short-baseline in FNAL Booster Neutrino Beam
  - ICARUS – LArTPC short-baseline in FNAL Booster Neutrino Beam
  - NA61-US – proton target characterization
- Mt-scale Water Cherenkov
  - CHIPS – CHerenkov In mine PitS
    - Water Cherenkov in NuMI beam NOvA -- arXiv:1307.5918
    - Not recommended by P5
    - R&D with 50t prototype to be deployed this summer

Technically Limited Schedule for International LBNE



- We have DOE funding commitment for $867M and are working with international partners to develop a fully international program hosted in the US
  - We have scope and schedule flexibility in the DOE approvals
  - Moving forward on long-lead conventional facility items
- **The beam & near/far detector designs are expected to evolve as new collaborators bring ideas**

Particle Physics Project Prioritization Panel (P5)

- A sub-panel of the High Energy Physics Advisory Panel (HEPAP)
  - HEPAP is official mechanism for community input to the US Department of Energy Office of High Energy Physics
  - P5 charged to advise on project priorities for the next 10 years in a 20 year context

Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context

Report of the Particle Physics Project Prioritization Panel (P5)

HEPAP
22 May 2014

S. Ritz

Slides: *http://science.energy.gov/~/media/hep/hepap/pdf/May%202014/P5MayHEPAP-Ritz.pdf*
P5 Report: *http://science.energy.gov/~/media/hep/hepap/pdf/May%202014/FINAL_DRAFT2_P5Report_WEB_052114.pdf*

Science Drivers

- We distilled the eleven groups of physics questions from Snowmass* into five compelling lines of inquiry that show great promise for discovery over the next 10 to 20 years.
- The Science Drivers:
  - Use the Higgs boson as a new tool for discovery
  - **Pursue the physics associated with neutrino mass**
  - Identify the new physics of dark matter
  - Understand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles
- The Drivers are deliberately not prioritized because they are intertwined, probably more deeply than is currently understood.
- A selected set of different experimental approaches that reinforce each other is required. Projects are prioritized.
- The vision for addressing each of the Drivers using a selected set of experiments – their approximate timescales and how they fit together – is given in the report.

* See Appendix D and http://www.slac.stanford.edu/econf/C1307292/

Project-specific Recommendations

#12-15:

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.

Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

Project-specific Recommendations

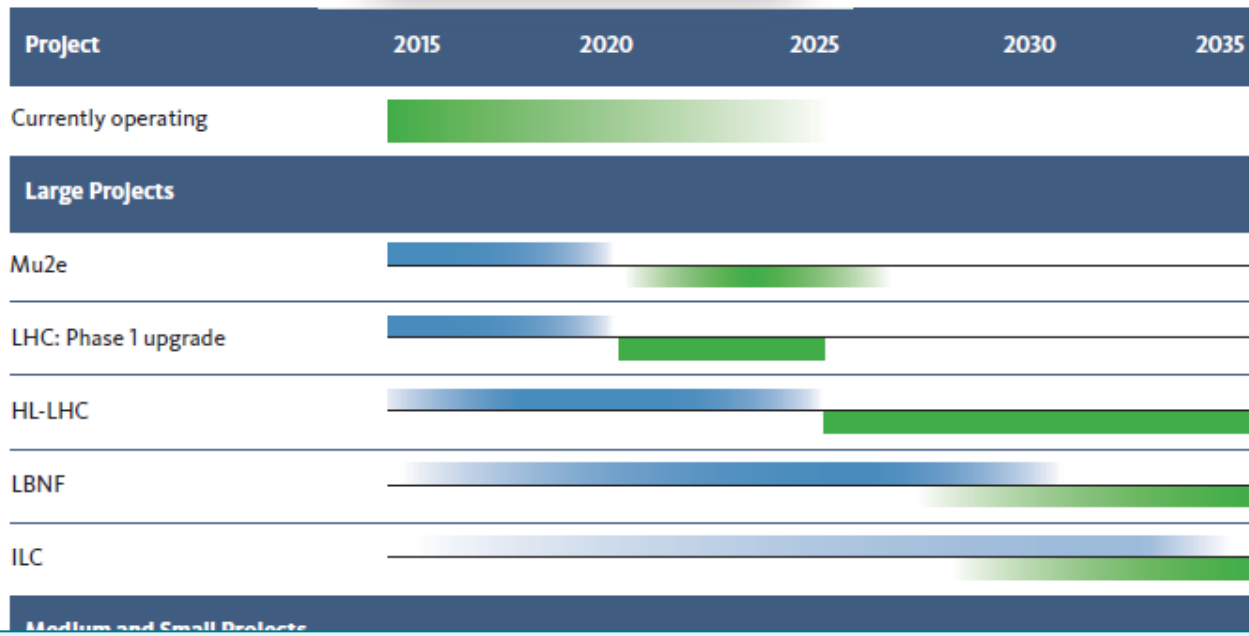
#12-15:

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.

- **LBNE leadership is working with DOE OHEP and Fermilab Director to develop a fully international collaboration at all levels**
  - There will be a series of meetings in the coming months with all "stakeholders" – 1st is "International Meeting on Large Neutrino Infrastructure," Paris 23-24 June
- **Minimum requirements: 120 kt*MW*yr by 2035 ⇒ 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

Figure 1
Construction and Physics Timeline



- **Timeline indicates how P5 priorities could fit within the budget scenarios in the panel charge**
- **Actual timeline will depend on many factors**
  - Enacted budgets, other factors and constraints within DOE, ***interests and resources of international partners***
- **P5 report was eagerly awaited by the international community, which can now organize to produce an optimized and sustainable global program for High Energy Physics**

(Large [>$200M] in the upper section, Medium and Small [<$200M] in the lower section), shown for Scenario B. The LHC: Phase 1 upgrade is a Medium project, but shown next to the HL-LHC for context. The figure does not show the suite of small experiments that will be built and produce new results regularly.

Summary and Conclusions

- LBNE will perform far-reaching measurements of CP violation, mass hierarchy, non-standard interactions, proton decay and supernova burst neutrinos from intra-galactic distances
- Building on substantial investments already made, an international partnership will deliver:
  - A high-power neutrino beam
  - A high-resolution near detector system
  - A far detector of ≥10 kt fiducial mass in a cavern that can accommodate a ≥ 35 kt detector
- A series of meetings with government agencies, (inter)national laboratories, and researchers is being organized to fully internationalize the design, funding, construction and operation of the facility
- **We hope many (more) of you will be part of this exciting program!**