LBNF/DUNE

An Experimental Program in Neutrino Oscillations, Nucleon Decay and Particle Astrophysics

Jim Strait, Fermilab

on behalf of the DUNE Collaboration and LBNF Project Team

Brookhaven Forum 2015

7-9 October 2015

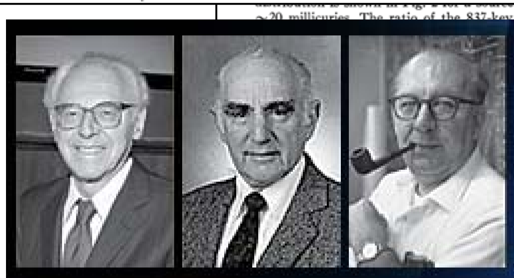
Brookhaven is a special place for neutrinos

1957 Experiment at Brookhaven determines that neutrinos are left-handed

Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR
Brookhaven National Laboratory, Upton, New York
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{\boldsymbol{p}}_\nu = -1$ (negative helicity).



and absorption lines. If the recoil and temperature effects are neglected, a lower limit on the mean life can be set as 1.7×10^{-14} sec. An upper limit is certainly the slowing-down time in the solid, approximately 2×10^{-13} sec,[7] since a stationary nucleus with a level of this mean life will give a cross section less than 1/100 that observed. Conversely, therefore, the gamma ray is emitted in general before the recoil slows down so that the Doppler broadening due to the neutrino emission must be taken into account, and the resonance scatter-

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Our method may be illustrated by the following simple example: take a nucleus A (spin $I=0$) which decays by allowed orbital electron capture, to an excited state of a nucleus $B(I=1)$, from which a γ ray is emitted to the ground state of $B(I=0)$. The conditions necessary for resonant scattering are best fulfilled for those γ rays which are emitted opposite to the neutrino, which have an energy comparable to that of the neutrino, and which are emitted before the recoil energy is lost. Since the orbital electrons captured by a nucleus are almost entirely s electrons (K, L_I, $\cdots$ electrons of spin $S=\frac{1}{2}$), the substates of the daughter nucleus

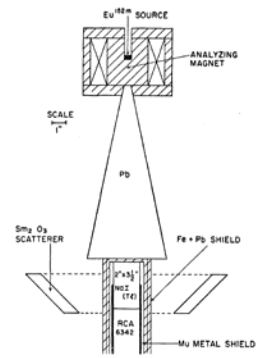


FIG. 1. Experimental arrangement for analyzing circular polarization of resonant scattered γ-rays. Weight of Sm_2O_3 scatterer: 1850 grams.

B, formed when a neutrino is emitted in the Z direction, are $m=-1, 0$ if the neutrino has positive helicity, and $m=+1, 0$ if the neutrino has negative helicity. In either case, the helicity of the γ ray emitted in the $(-Z)$ direction is the same as that of the neutrino. Thus, a measurement of the circular polarization of the γ rays which are resonant-scattered by the nucleus B, yields directly the helicity of the neutrino, if one assumes only the well-established conservation laws of momentum and angular momentum.

To carry out this measurement we have used a nucleus which appears to have the properties postulated in the example given: ${}_{63}Eu^{152m}$(9.3 hr). It probably has spin 0 and odd parity.[1] It decays to an excited state of ${}_{62}Sm^{152}(1-)$ with emission of neutrinos which have an energy of 840 kev in the most prominent case of K-electron capture. This is followed by an $E1$ γ-ray transition of 960 kev to the ground state (0+). The excited state has a mean life of $(3\pm1)\times10^{-14}$ sec, as determined by Grodzins.[1] Thus, even in a solid source most of the γ-ray emission takes place before the momentum of the recoil nucleus has changed appreciably.

The experimental arrangement used is shown in Fig. 1. The Eu^{152m} source is inserted inside an electromagnet which is alternately (every three minutes) magnetized in the up or down direction. The γ rays which pass through the magnet are resonant-scattered from a Sm_2O_3 scatterer (26.8% Sm^{152}), and detected in a 2-in.$\times 3\frac{1}{2}$-in. cylindrical NaI(Tl) scintillation counter. The photomultiplier (RCA 6342) is magnetically shielded by an iron cylinder and a mu-metal shield. The effectiveness of this magnetic shield was demonstrated by check experiments with a Cs^{137} γ-ray source in a manner similar to that described previously.[2] No significant effect of magnetic field reversal on the photomultiplier output was noticed when two narrow acceptance channels were set on the steeply sloping low- and high-energy wings of the 661-kev photopeak, respectively.

The source was produced by bombarding ~10 mg of Eu_2O_3 in the Brookhaven reactor. In typical runs the intensity varied from 50–100 mC. Nine runs varying in length from 3 to 9 hours were carried out. The scattered radiation is shown in Fig. 2. It contains both γ rays emitted from the 960-kev state (960 and 840 kev). Counts were accumulated simultaneously in 3 channels A, B, and C as shown in Fig. 2. A cycle of field reversals was used such that the decay corrections were negligible. No effects of field reversal or decay were noticed in channel C. Channel A exhibited a possible small magnetic field effect which was less than one-tenth of that observed in channel B. In channel B, which bracketed the photopeaks, a total of $\sim3\times10^6$ counts were accumulated. In 6 runs carried out in the arrangement shown in Fig. 1, an effect $\delta=(N_- - N_+)/\frac{1}{2}(N_- + N_+) = +0.017\pm0.003$ was found in channel B after the nonresonant background had been subtracted. Here N_+ is defined as the counting rate with the magnetic field pointing up, and N_- as the counting rate with the field pointing down.

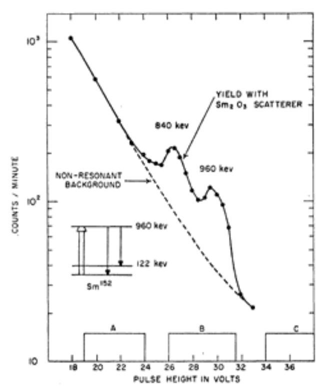
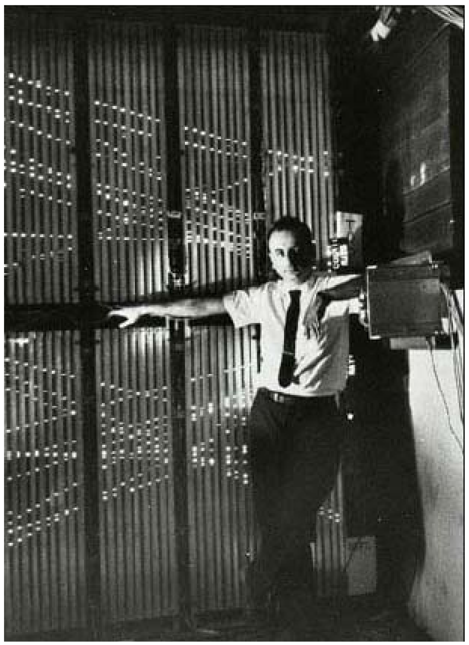


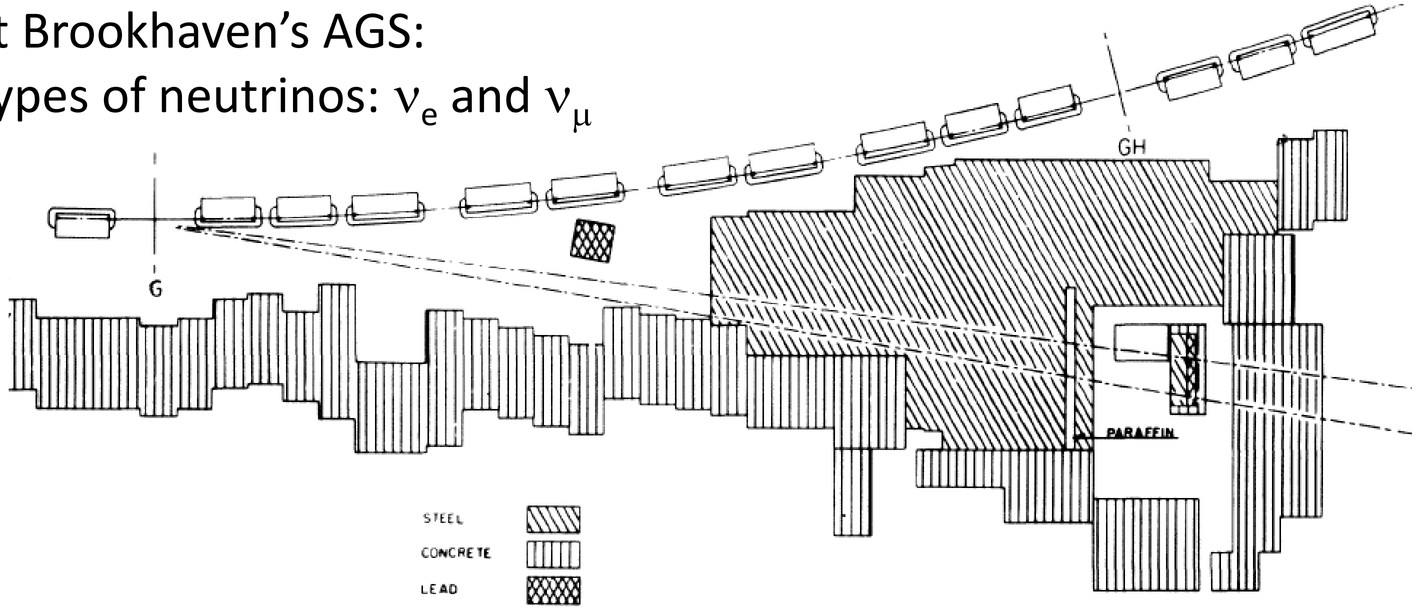
FIG. 2. Resonant-scattered γ rays of Eu^{152m}. Upper curve is taken with arrangement shown in Fig. 1 with unmagnetized iron. Lower curve shows nonresonant background (including natural background).

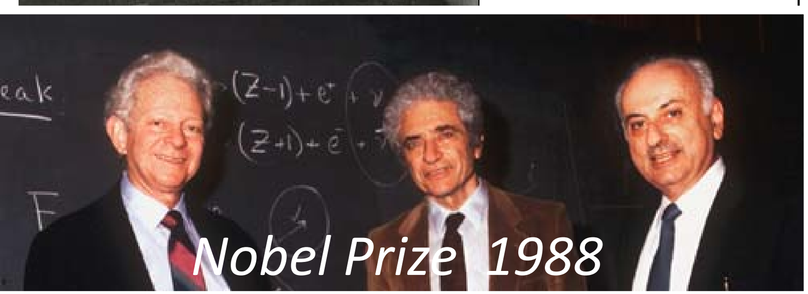
Brookhaven is a special place for neutrinos

1962 Experiment at Brookhaven's AGS:

$\Rightarrow$ There are two types of neutrinos: ν_e and ν_μ







OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

In the course of an experiment at the Brookhaven AGS, we have observed the interaction of high-energy neutrinos with matter. These neutrinos were produced primarily as the result of the decay of the pion:

$$\pi^{\pm} \rightarrow \mu^{\pm} + (\nu/\bar{\nu}). \qquad (1)$$

It is the purpose of this Letter to report some of the results of this experiment including (1) demonstration that the neutrinos we have used produce μ mesons but do not produce electrons, and hence are very likely different from the neutrinos involved in β decay and (2) approximate cross sections.

Behavior of cross section as a function of energy. The Fermi theory of weak interactions which works well at low energies implies a cross section for weak interactions which increases as phase space. Calculation indicates that weak interacting cross sections should be in the neigh-

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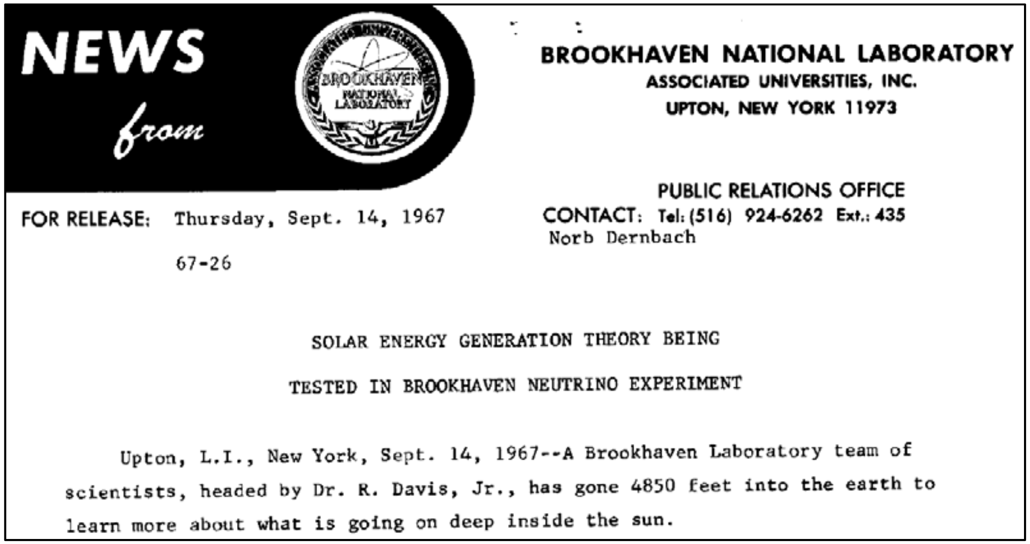
Ray Davis' Solar Neutrino Experiment:



NEWS from

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ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

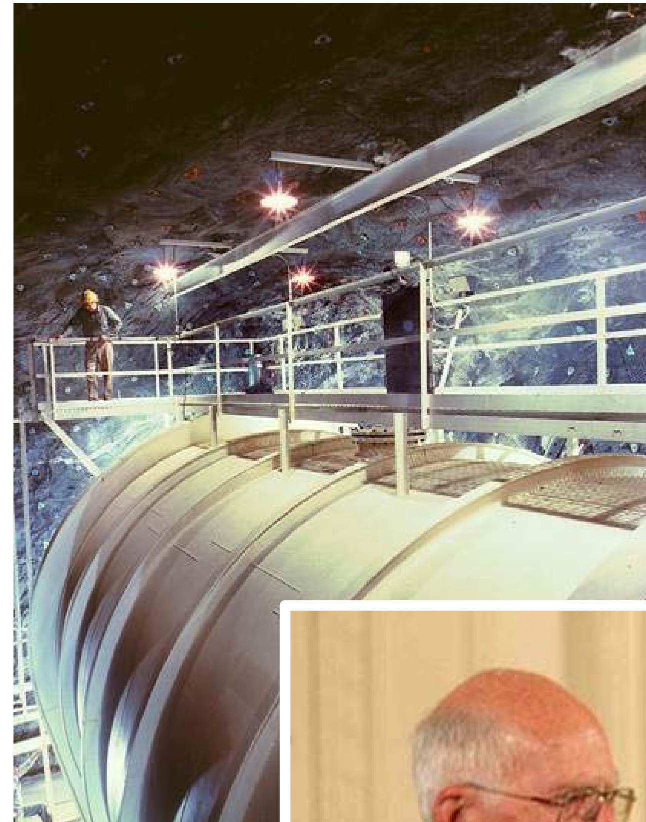
PUBLIC RELATIONS OFFICE
CONTACT: Tel: (516) 924-6262 Ext.: 435
Norb Dernbach

FOR RELEASE: Thursday, Sept. 14, 1967

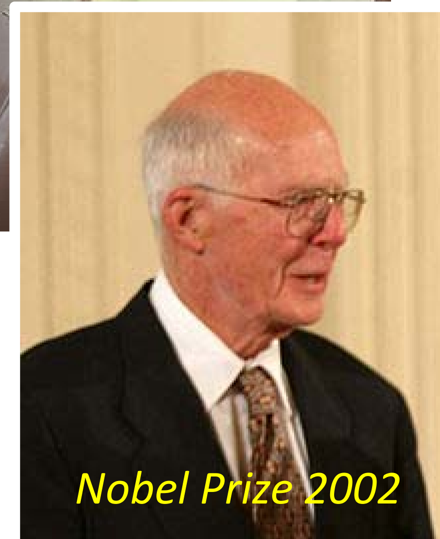
67-26

SOLAR ENERGY GENERATION THEORY BEING
TESTED IN BROOKHAVEN NEUTRINO EXPERIMENT

Upton, L.I., New York, Sept. 14, 1967--A Brookhaven Laboratory team of scientists, headed by Dr. R. Davis, Jr., has gone 4850 feet into the earth to learn more about what is going on deep inside the sun.



- Detect neutrinos via $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$ in 600 t of dry cleaning fluid 4850 feet underground in the Homestake Gold Mine
- Big surprise ... only ~1/3 the expected rate detected
  - *Do we not understand how the sun shines?*
  - *Is there something "wrong" with neutrinos?*



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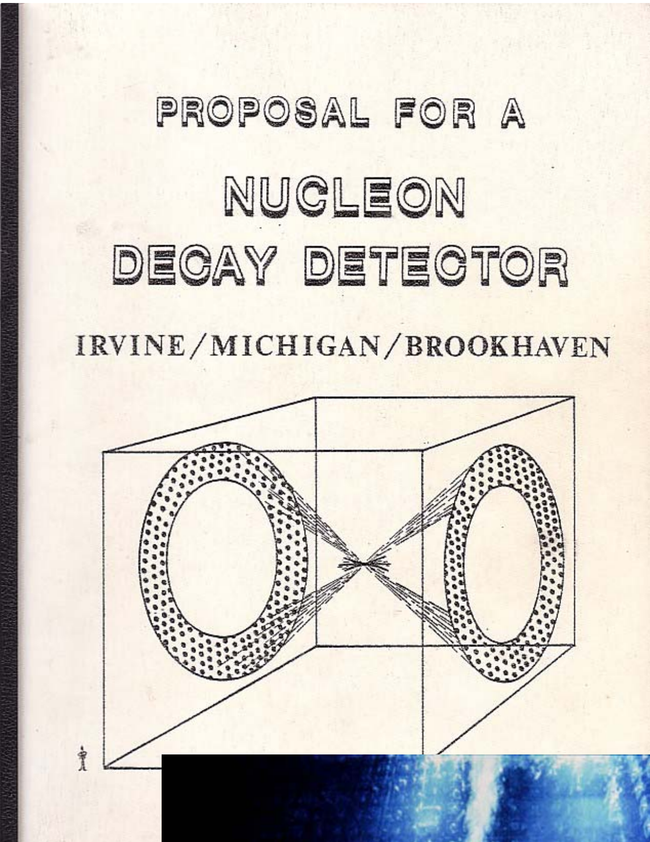

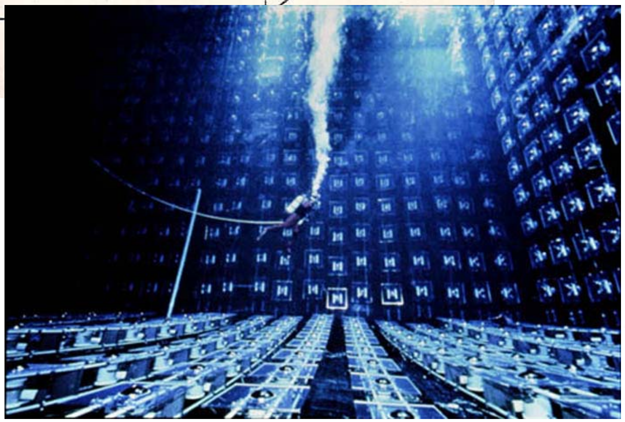

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud

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(Received 13 March 1987)

A burst of eight neutrino events preceding the optical detection of the supernova in the Large Magellanic Cloud has been observed in a large underground water Cherenkov detector. The events span an interval of 6 s and have visible energies in the range 20–40 MeV.

PACS numbers: 97.60.Bw, 14.60.Gh, 95.85.Sz

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Pioneers of what is now LBNF/DUNE

2001

arXiv:hep-ph/0108181v1 22 Aug 2001

Extra Long Baseline Neutrino Oscillations and CP Violation

William J. Marciano
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Abstract

The potential for studying CP violation in neutrino oscillations using conventional ν_μ and $\bar{\nu}_\mu$ beams is examined. For $\Delta m^2_{21} << \Delta m^2_{31}$ and fixed neutrino energy, E_ν, the CP violating asymmetry $A \equiv P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)/P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in vacuum is shown to be measurable with roughly equal maximal statistical precision at distances $L_n \simeq (2n+1)\left(\frac{2\pi E_\nu}{\Delta m^2_{31}}\right), n = 0, 1, 2\ldots$ (up to some n in the leading Δm^2_{21} approximation). For extra long baselines, $n \geq 1$, the falloff in detected oscillation events, $N = N_{\nu_e} + N_{\bar{\nu}_e}$, by $\sim 1/(2n+1)^2$ is compensated by a factor $\sim (2n+1)$ increase in the asymmetry such that the statistical figure of merit F.O.M. $\equiv (\delta A/A)^{-2} = A^2 N/1 - A^2$ is approximately independent of n. However, for the larger $n \geq 1$ asymmetries, some backgrounds as well as systematic uncertainties from flux normalization, detector acceptance etc. which scale with distance as $1/(2n+1)^2$ are shown to be relatively suppressed in $\delta A/A$ by $\sim 1/(2n+1)$. Also, low energy $E_\nu \simeq \mathcal{O}(1\text{GeV})$ extra long baseline experiments with $L_n \simeq 1200$–2900 km (corresponding to $\Delta m^2_{31} \simeq 3 \times 10^{-3}$ eV^2 and $n = 1$–3) are better matched to the remote locations of some proposed very large proton decay detectors which would be essential for neutrino CP violation studies. Effects of matter and realistic neutrino beam energy spread on extra long baseline CP violation experiments are briefly discussed.

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Extra Long Baseline Neutrino Oscillations and CP Violation

William J. Marciano
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arXiv:hep-ph/0108181v1 22 Aug 2001

2002

Neutrino Oscillation Experiments for Precise Measurements of Oscillation Parameters and Search for $\nu_\mu \rightarrow \nu_e$ Appearance and CP Violation.

LETTER OF INTENT to Brookhaven National Laboratory.

D. Beavis, M. Diwan, R. Fernow, J. Gallardo, S. Kahn, H. Kirk, W. Marciano, W. Morse, Z. Parsa, R. Palmer, T. Roser, N. Samios, Y. Semertzidis, N. Simos, B. Viren, W. Weng
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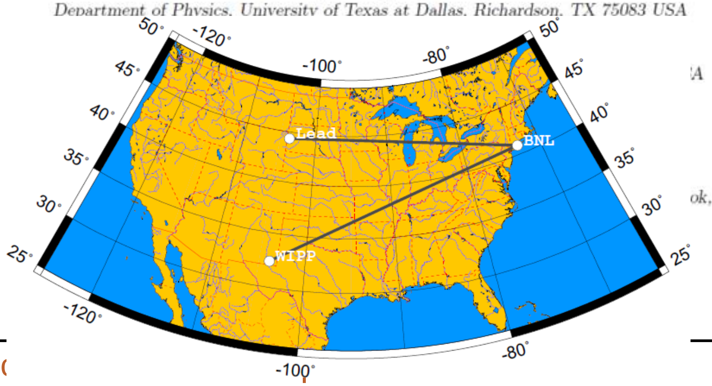
arXiv:hep-ex/0205040v1 14 May 2002



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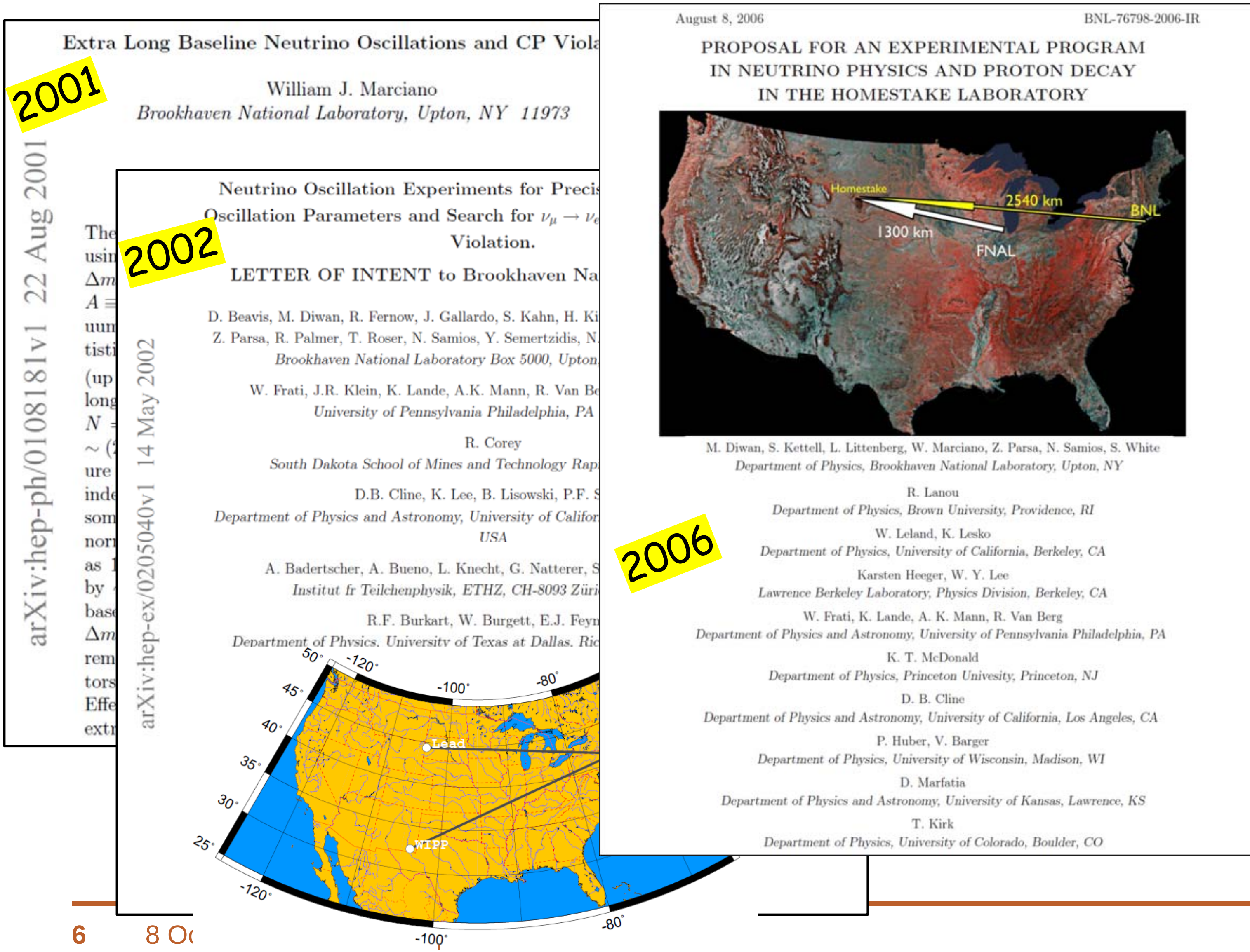

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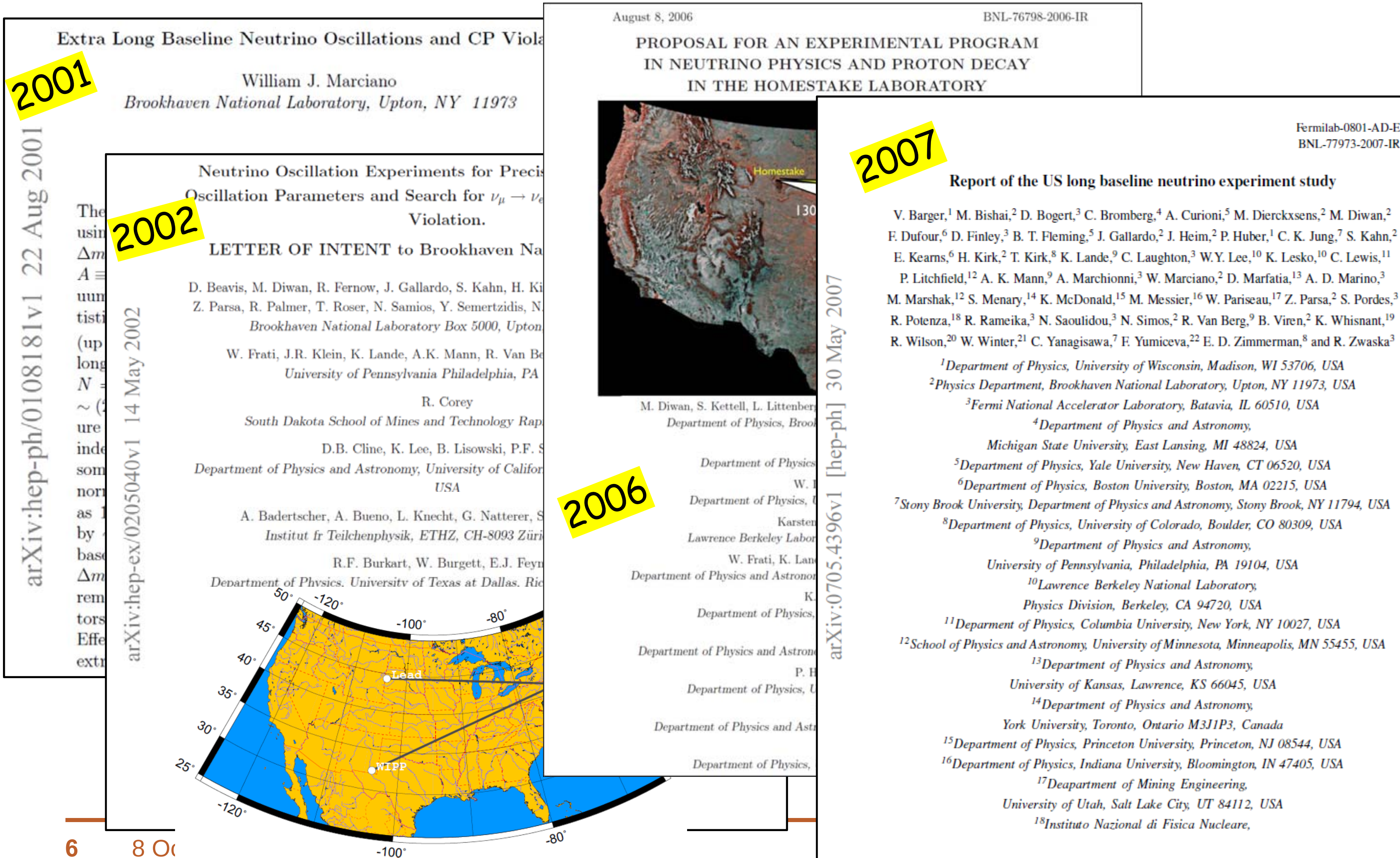

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… and last and surely least…

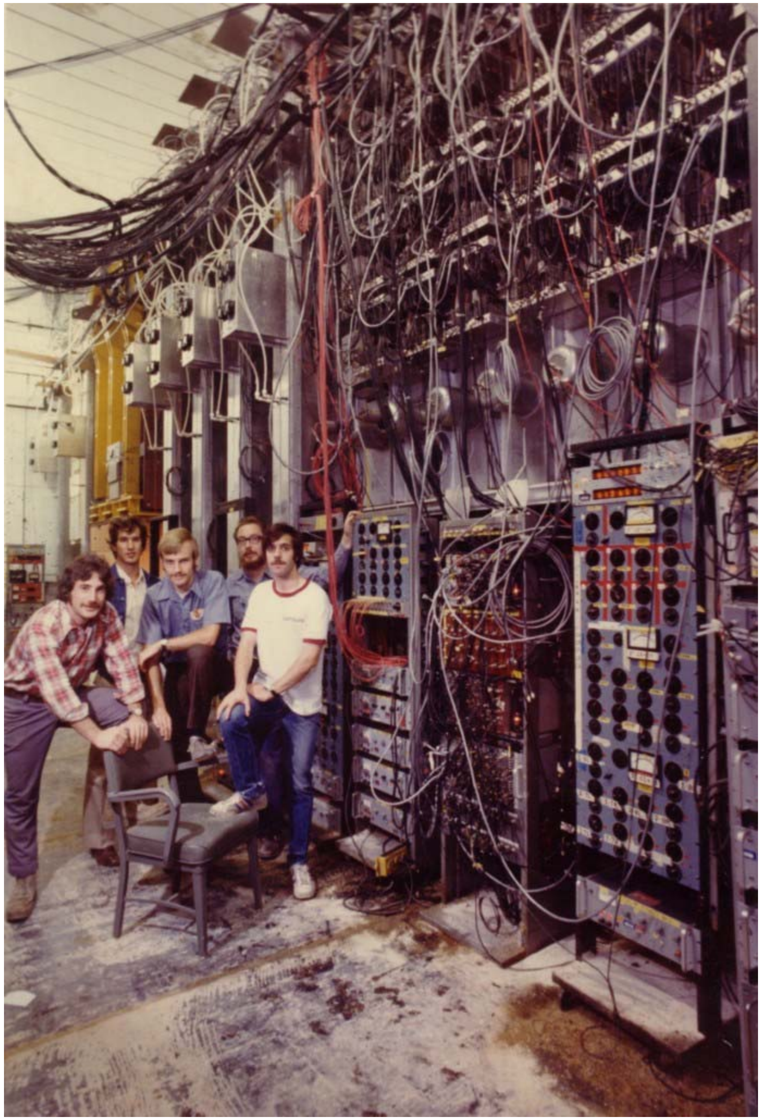
Brookhaven is a special place for neutrinos

… and last and surely least…

The home of my thesis experiment!

BNL E613: 1973 – 1978

First observations and measurements of $\nu\, p \rightarrow \nu\, p$ and $\bar{\nu}\, p \rightarrow \bar{\nu}\, p$



Why are Neutrinos Important?

Neutrinos play an important role in natural processes that are crucial to why we exist.

- The reactions in the core of the sun.
- The explosions of supernova stars in which the heavy elements are created and expelled into space to form planets and provide the building blocks for life.
- Small differences between neutrinos and their anti-particle counterparts *could* help explain why more matter than anti-matter was produced in the Big Bang.

Because neutrinos hardly interact, they can tell us what happens in places we cannot "see" otherwise:

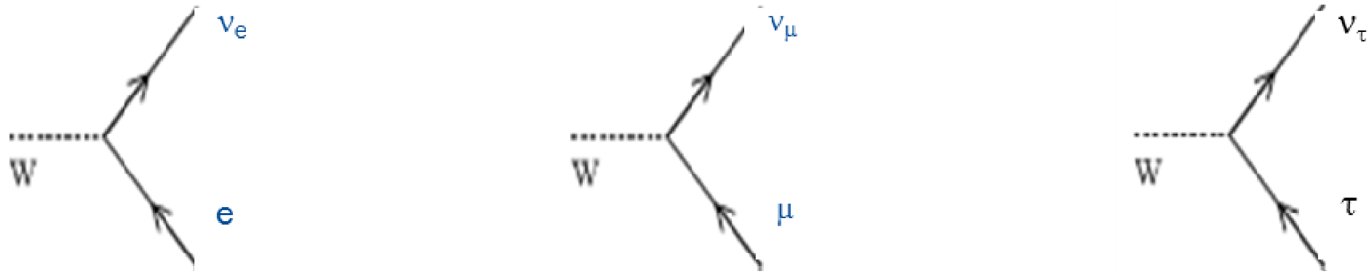
- In the core of the sun
- In the center of a supernova at the moment it explodes

Neutrinos are Unusual Particles

- Only neutral fundamental matter particles (fermions)
  => perhaps they are their own anti-particle? (Majorana particles)
- Dramatically lighter than other fermions
  => Is there a different mechanism for generating their mass?
- Neutrino flavors seem to be strongly mixed
  => Why so different from the quarks?
- Do neutrinos violate matter – antimatter symmetry (CP violation)?
  => Could they be the key to understanding why the universe is made of matter and no antimatter (baryon asymmetry of the universe)?

Neutrino Flavor Mixing

- Neutrino production and detection determined by flavor eigenstates ν_e, ν_μ, ν_τ of the weak interaction



  but propagation through space (and matter) is determined by mass eigenstates ν_1, ν_2, ν_3 of the Hamiltonian (with masses m_1, m_2, m_3), these can be related by

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Different masses will lead to interference between the propagating waves that affects the flavor probability at detection as a function of distance - "flavor mixing" or "neutrino oscillations"

Neutrino Mixing Matrix

Pontecorvo-Maki-Nakagawa-Sakata

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

3 x 3 unitary rotation matrix – 3 angles, 1 CP-phase (+2 Majorana phases)

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$s_{ij} = \sin\theta_{ij}$
$c_{ij} = \cos\theta_{ij}$

atmospheric and accelerator | reactor and accelerator | solar and reactor

Phase δ for neutrinos is unknown – related to CP-violation

Neutrino vs. Quark Mixing

Neutrinos

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

- Strikingly different!
- Is this telling us something fundamental?
  - A different mechanism for mass generation?

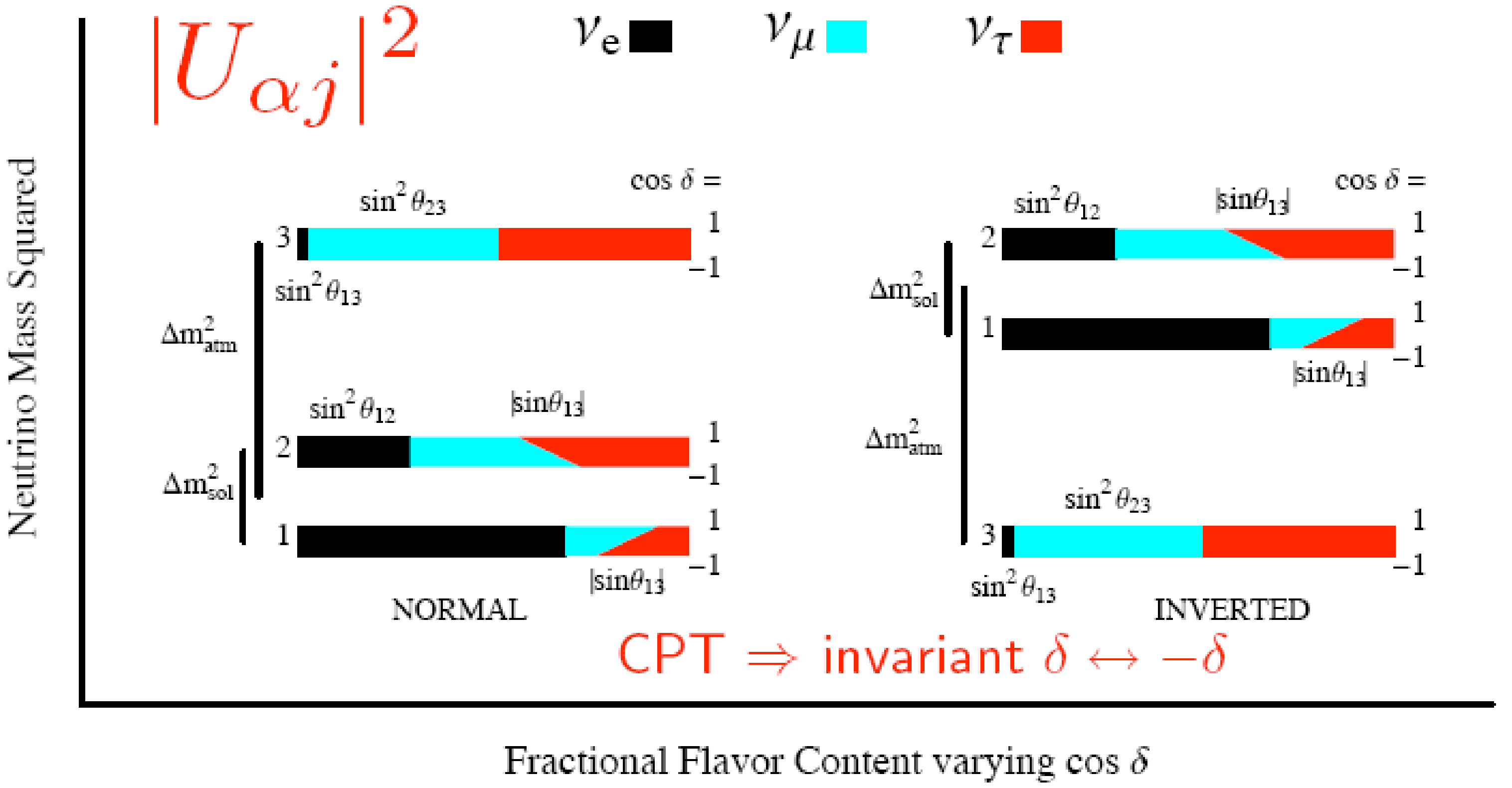
Neutrino Oscillations

- In a simplified 2-neutrino model, the probability of a neutrino produced as one flavor to be detected with a different flavor is:

$$P_{\alpha \to \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- θ is the mixing angle
- $\Delta m^2 = m_2^2 - m_1^2$
- L = distance traveled
- E = neutrino energy

Neutrino Mass Ordering



Δm^2_{21} = +7.6 x 10^{-5} eV^2

$|\Delta m^2_{32}|$ = 2.4 x 10^{-3} eV^2

$\Delta m^2_{21} / |\Delta m^2_{32}| = 0.03$

Is third neutrino heavier or lighter than the other two? (MH question)

What is the overall mass scale?

ν_e Appearance in a ν_μ Beam

Approximation to 3-flavor vacuum mixing with $|\Delta m_{21}^2| << |\Delta m_{31}^2|$

$$P(\nu_\mu \rightarrow \nu_e) \simeq s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E}$$

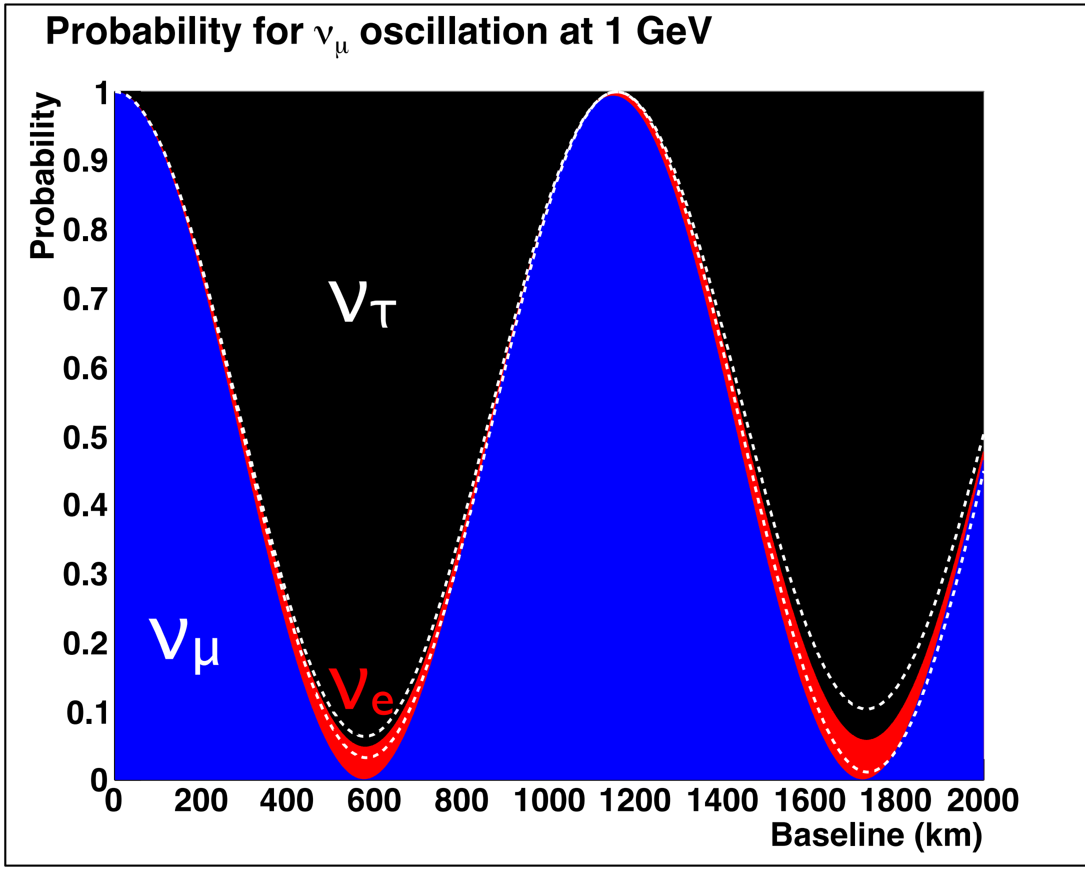
L – distance from source to detection

E – neutrino energy

- Effectively 2-flavor mixing since $\Delta m_{21}^2 \cong 0.03\, |\Delta m_{31}^2|$
- Wavelength in L/E ~ 1.2 km/GeV
  => maximum probability at 600 km for a 1 GeV neutrino
- Amplitude proportional to $\sin^2 2\theta_{13}$

ν_e Appearance in a ν_μ Beam

Approximation to 3-flavor vacuum mixing with $|\Delta m_{21}^2| << |\Delta m_{31}^2|$



$_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$

tance from source to detection

utrino energy

$m_{21}^2 \cong 0.03\ |\Delta m_{31}^2|$

m for a 1 GeV neutrino

13

- ***Quantum interferometry on a continental scale***

ν_e Appearance in a ν_μ Beam

Full equation for 3-flavor mixing

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \quad = \quad & s_{23}^2 \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} + c_{13}^2 c_{23}^2 \sin^2 2\theta_{12} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
& + 8 c_{13}^2 s_{13} c_{12} s_{12} s_{23} c_{23} \sin \frac{\Delta m_{21}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \cos \left(\frac{\Delta m_{32}^2 L}{4E} + \delta \right) \\
& - 2 s_{12}^2 s_{23}^2 \sin^2 2\theta_{13} \sin \frac{\Delta m_{21}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \cos \frac{\Delta m_{32}^2 L}{4E} \\
& + 4 c_{13}^2 s_{12}^3 s_{13} s_{23} \left(s_{23} s_{13} s_{12} - 2 c_{12} c_{23} \cos \delta \right) \sin^2 \frac{\Delta m_{21}^2 L}{4E}
\end{aligned}
$$

J. Boehm, thesis 2009

- Now includes dependence on phase δ manifest in interference terms between the two oscillation scales
- Changing $\nu \to \bar{\nu}$, $\delta \to -\delta$
  => matter/antimatter asymmetry if $\delta \neq 0$ or 180°
- Could this difference help explain why the Big Bang produced more matter than antimatter? ... So that we can exist to ask this question?

Matter Effect

- Additional ν_e interaction → mixing angles and mass differences modified by terms proportional to electron density
- Sign of effect depends on mass ordering => method to determine the Mass Hierarchy
- A complication in determining true matter-antimatter difference

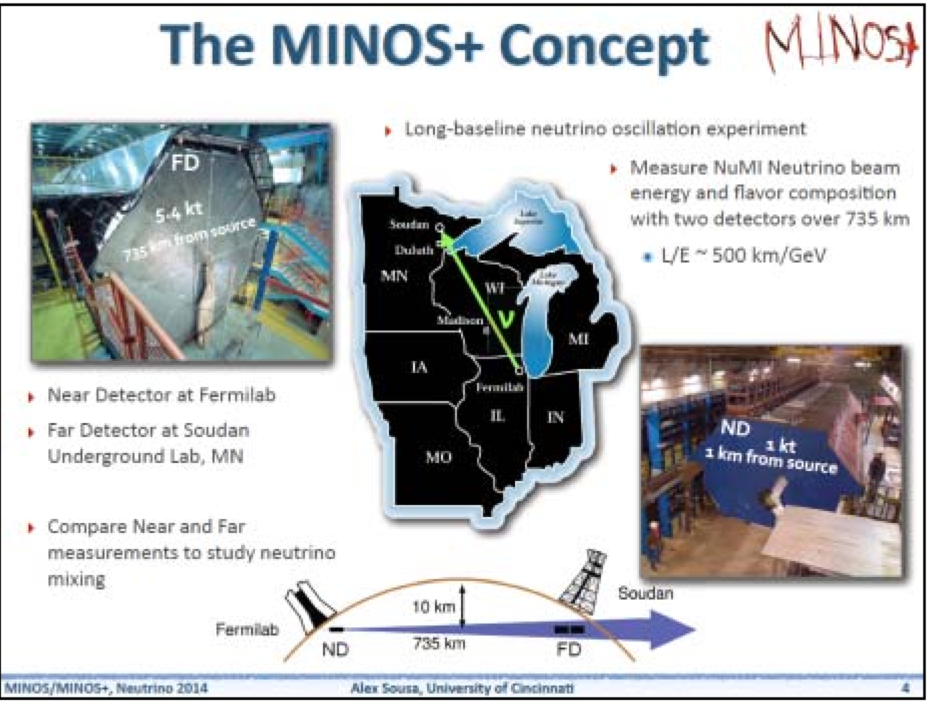
$$
\begin{aligned}
P_{\mu e} \;=\;& s_{23}^2 \frac{\sin^2 2\theta_{13}}{C_{13}^2} \sin^2 C_{13}\Delta - 2\alpha s_{12}^2 s_{23}^2 \frac{\sin^2 2\theta_{13}}{C_{13}^2} \sin C_{13}\Delta \\
& \times \left[\Delta \frac{\cos C_{13}\Delta}{C_{13}} (1 - A\cos 2\theta_{13}) - A \frac{\sin C_{13}\Delta}{C_{13}} \frac{\cos 2\theta_{13} - A}{C_{13}}\right] \\
& + \alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin C_{13}\Delta}{A C_{13}^2} \Big\{ \cos\delta \left[C_{13} \sin(1+A)\Delta \right. \\
& \left. - (1 - A\cos 2\theta_{13}) \sin C_{13}\Delta\right] - C_{13} \sin\delta \left[\cos C_{13}\Delta - \cos(1+A)\Delta\right] \Big\} \\
& + c_{23}^2 \frac{\sin^2 2\theta_{12}}{C_{12}^2} \sin^2 \alpha C_{12}\Delta \\
& - s_{13} \frac{\sin 2\theta_{12}}{C_{12}} \sin 2\theta_{23} \frac{(1-\alpha)\sin \alpha C_{12}\Delta}{1 + A - \alpha + A\alpha c_{12}^2} \Big\{ \sin\delta \left[\cos \alpha C_{12}\Delta - \cos(A + \alpha - 2)\Delta\right] \\
& + \cos\delta \left[\sin(A + \alpha - 2)\Delta - \sin \alpha C_{12}\Delta \left(\frac{\cos 2\theta_{12} - \frac{A}{\alpha}}{C_{12}} - \frac{\alpha A C_{12}}{2(1-\alpha)} \frac{\sin^2 2\theta_{12}}{C_{12}^2} \right)\right] \Big\} \\
& - 2\alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta) \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \qquad \text{(2.6(}
\end{aligned}
$$

Is the Three-Neutrino Model Complete?

- Hints of deviations implying a fourth "sterile" neutrino
  - Reactor anomaly => ~7% deficit at short distances
  - Short-baseline anomaly, a.k.a. "LSND anomaly" => small $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance rate at small L/E
- These effects can be tested by
  - Direct searches for sterile neutrino signatures
  - Over-constraining to PMNS matrix to test it unitarity

- Many neutrino experiments are under way or planned to understand the nature of neutrinos.

Current Long-Baseline, Accelerator-Based Experiments



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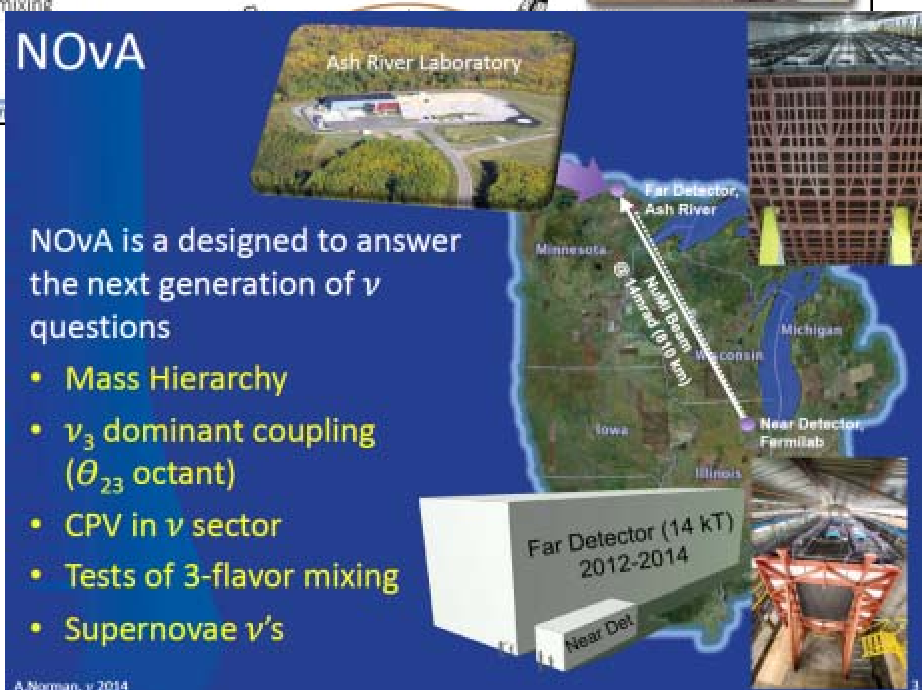

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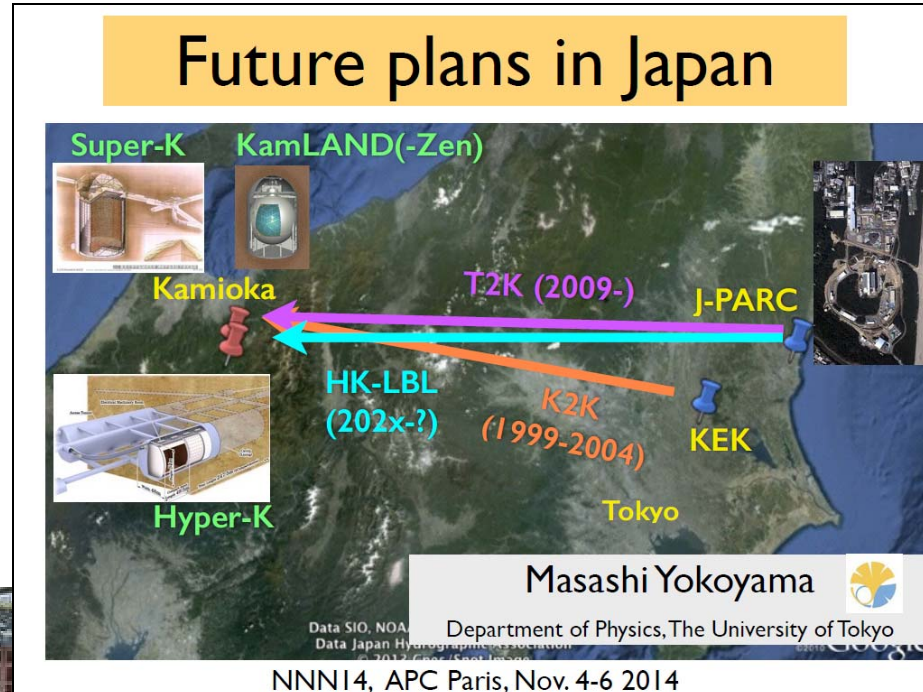

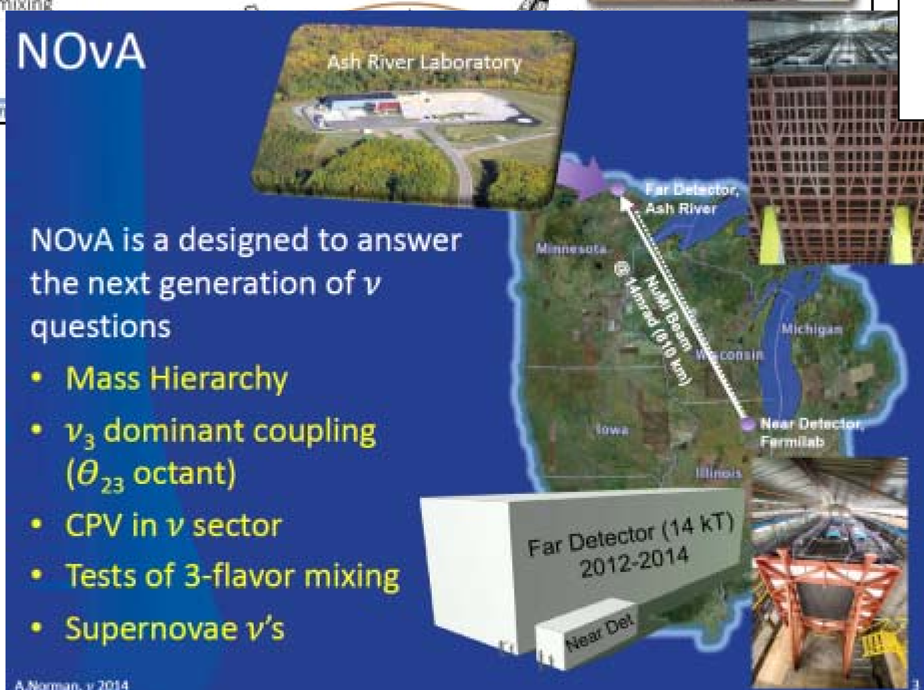

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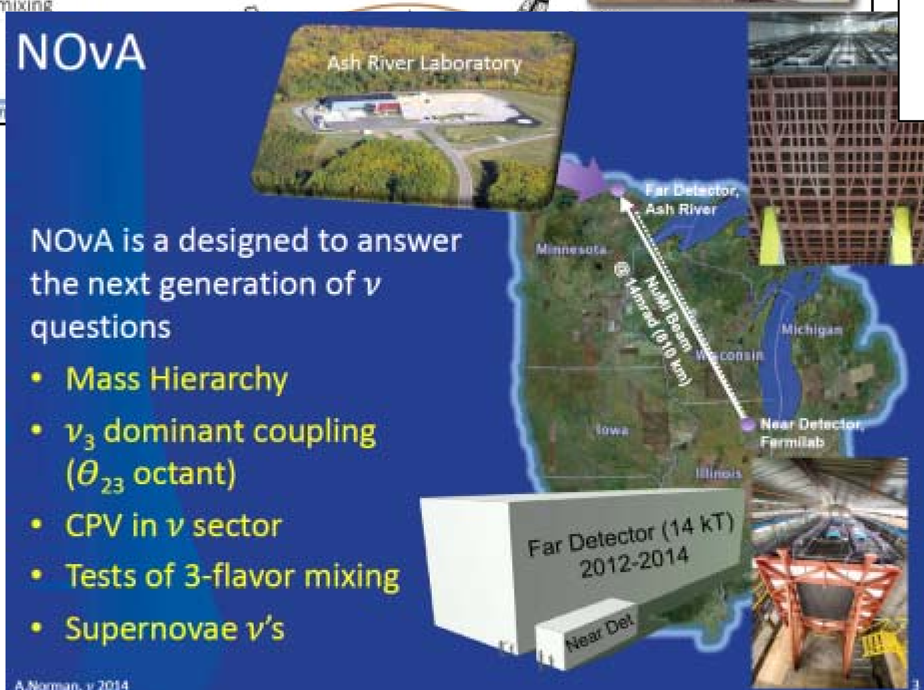
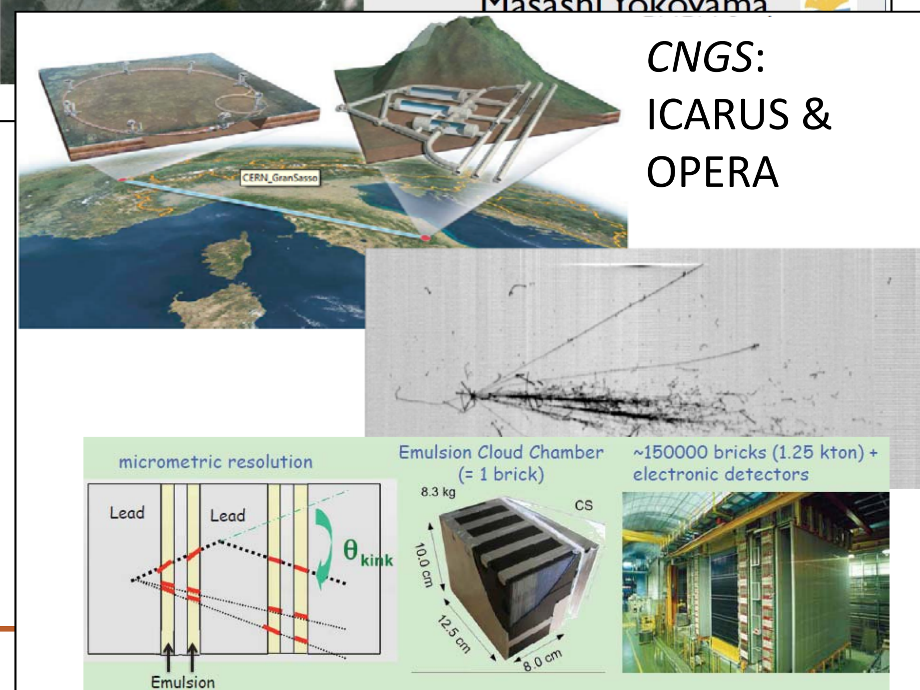
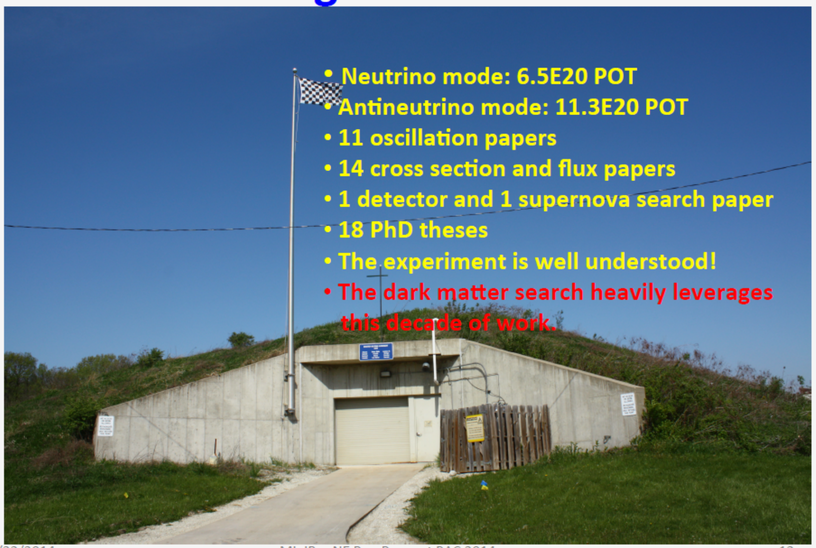




Short-Baseline, Accelerator-Based Experiments

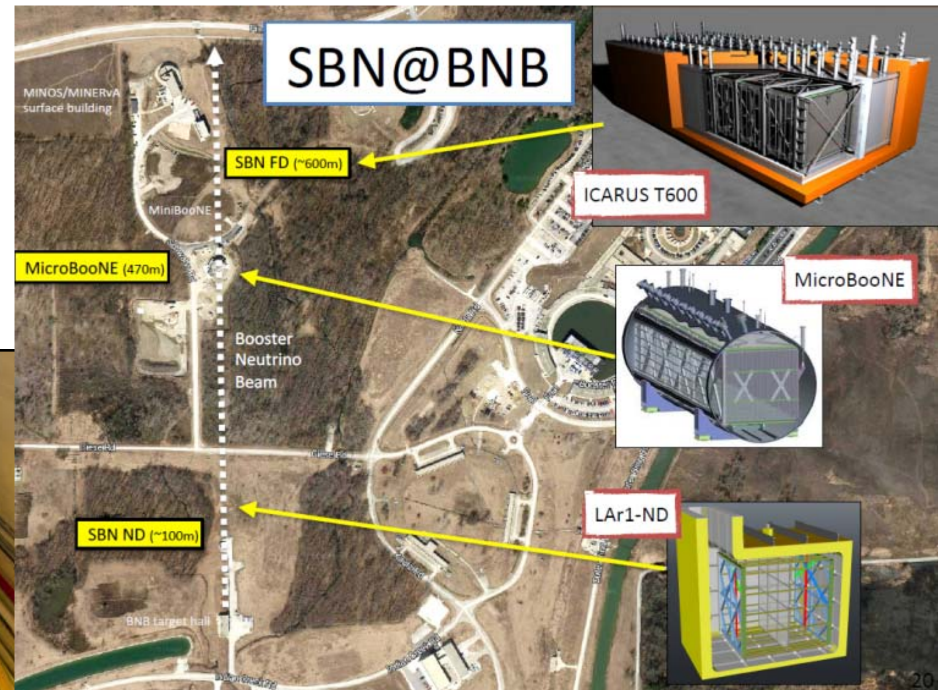
Ten Years of Successful MiniBooNE Running and Results!



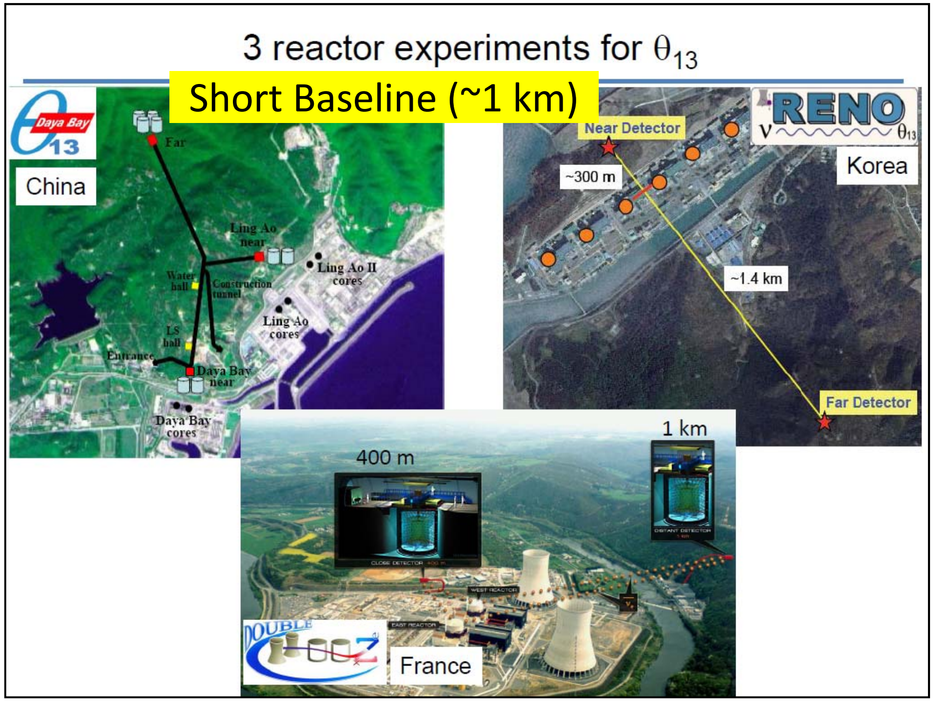
01/22/2014 MiniBooNE Run Request PAC 2014 12

Short-Baseline, Accelerator-Based Experiments

Short-Baseline, Accelerator-Based Experiments



Reactor-Based Experiments



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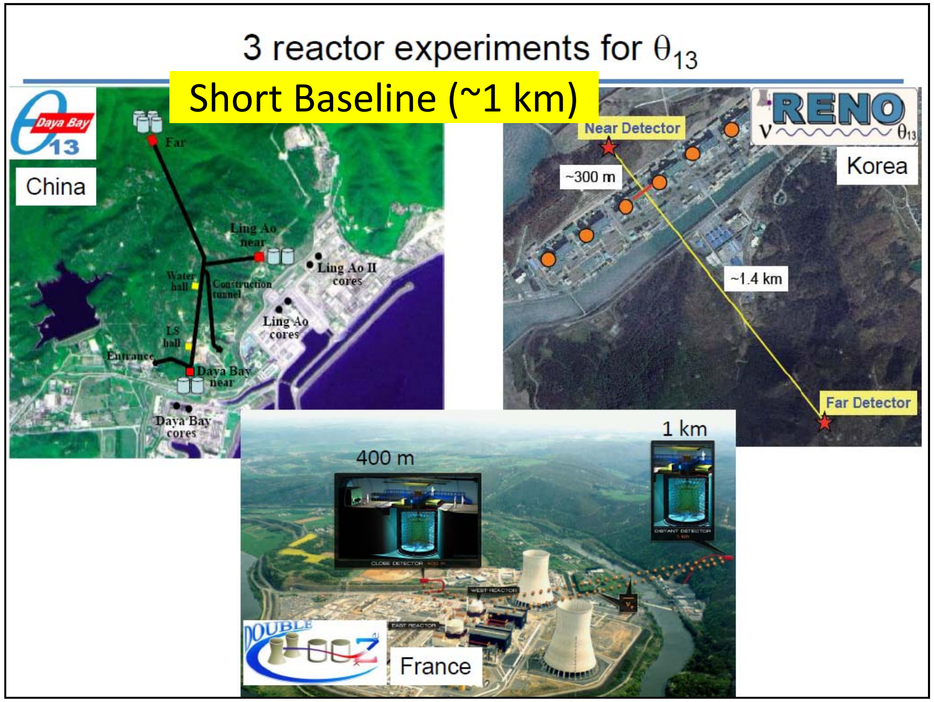

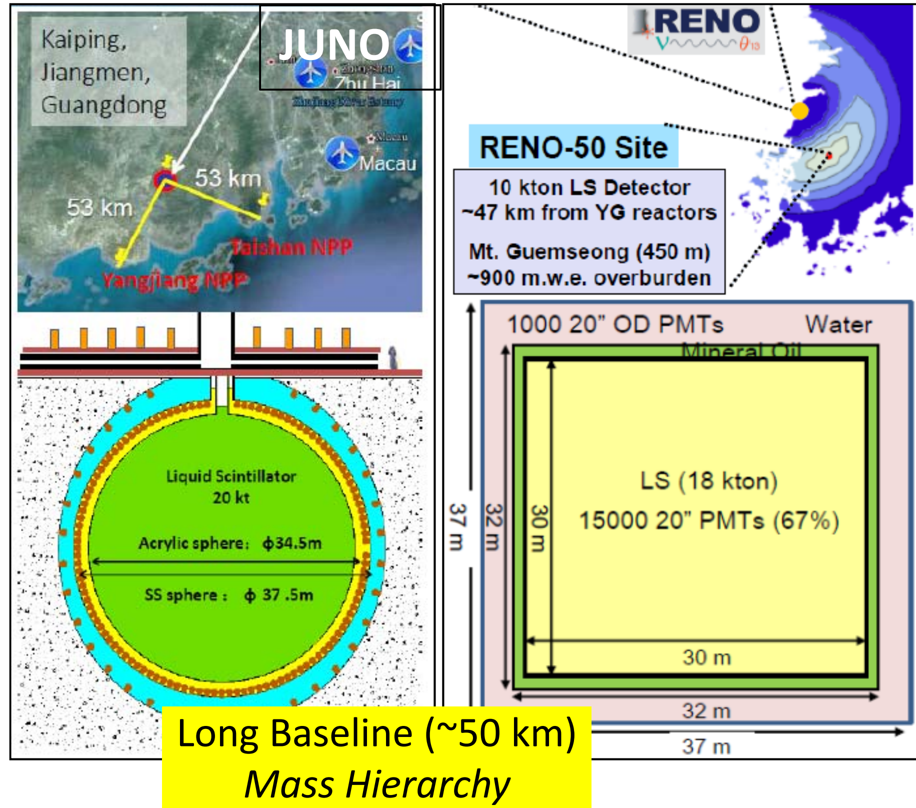

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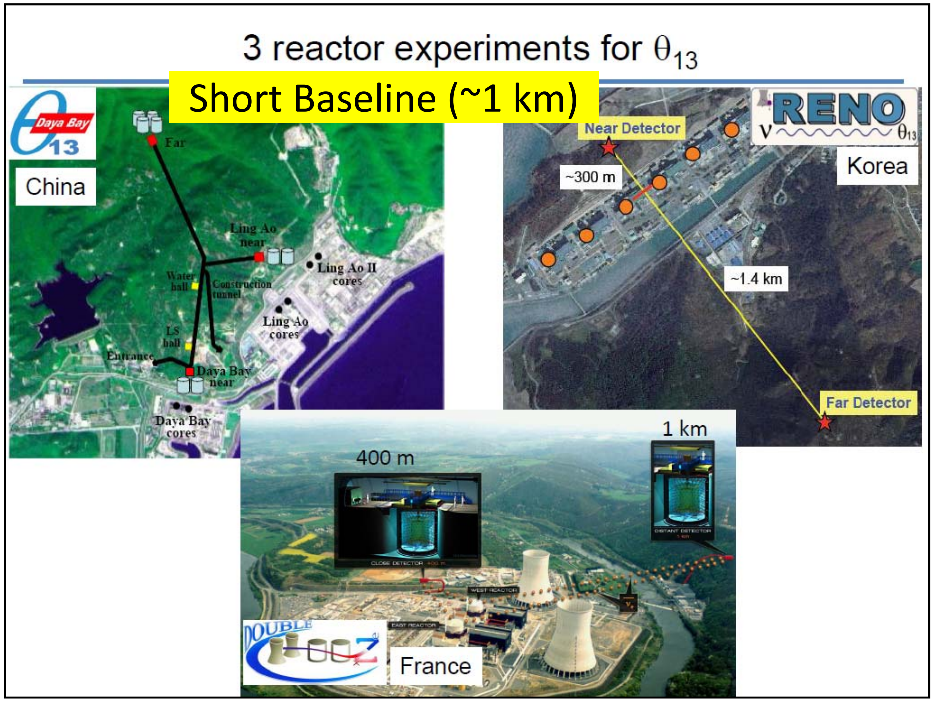
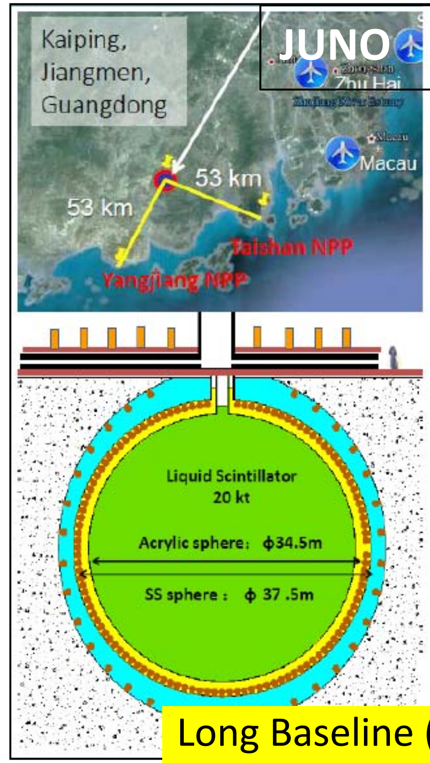
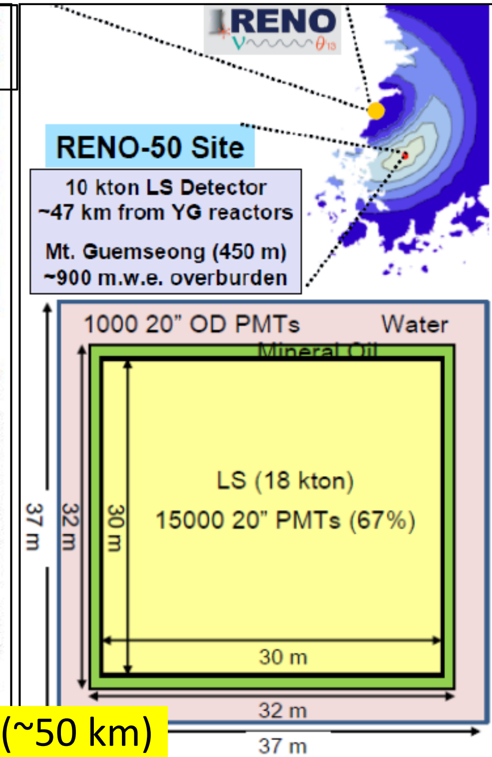
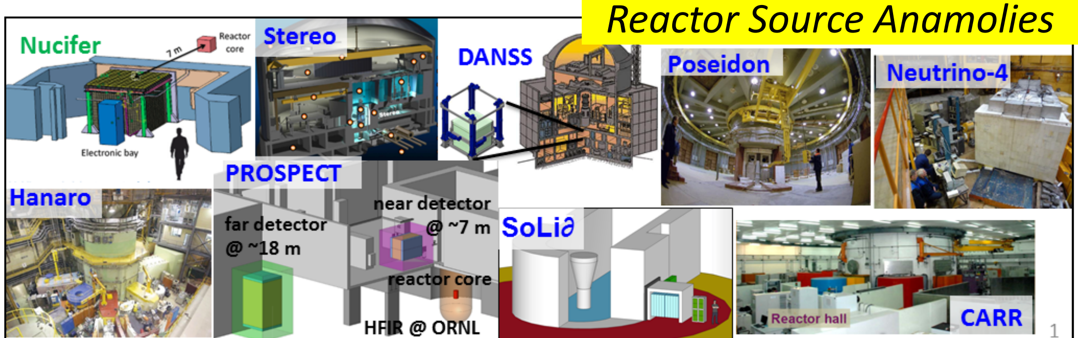




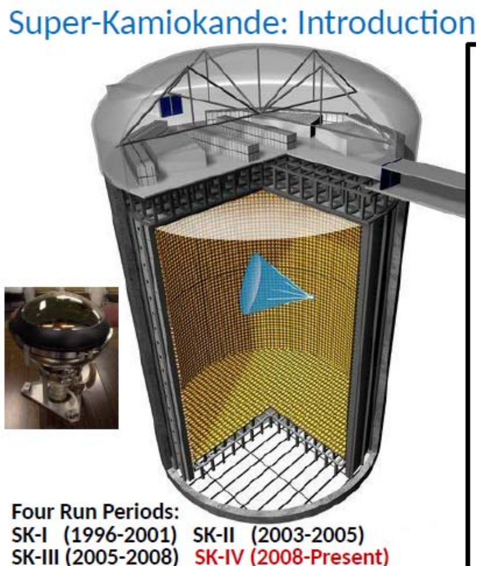


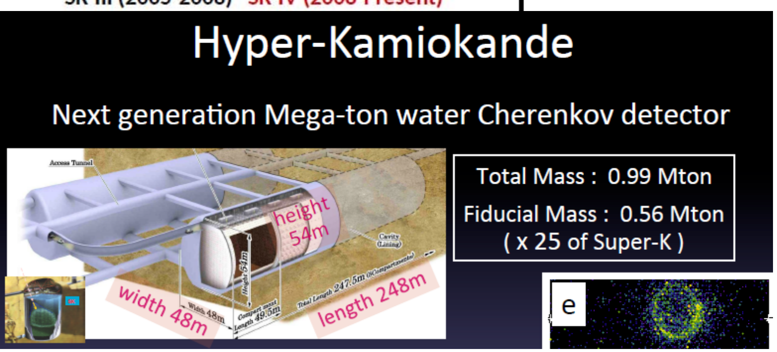
Long Baseline (~50 km)
Mass Hierarchy

Very Short Baseline (~10 m)
Reactor Source Anamolies



Atmospheric and Ultra-High Energy Neutrino Experiments





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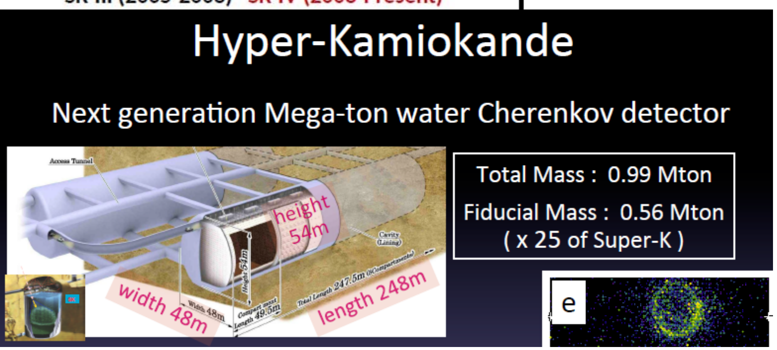

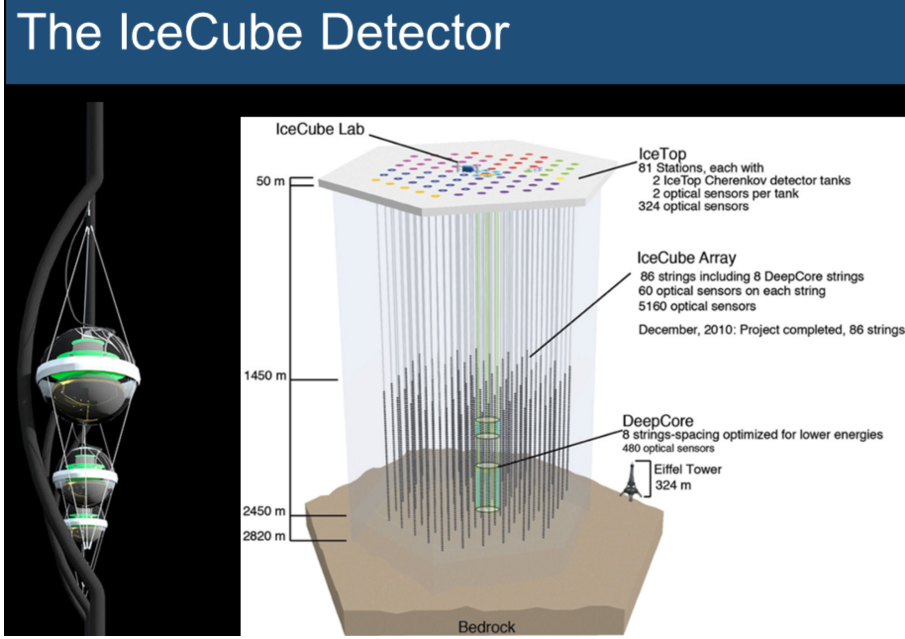

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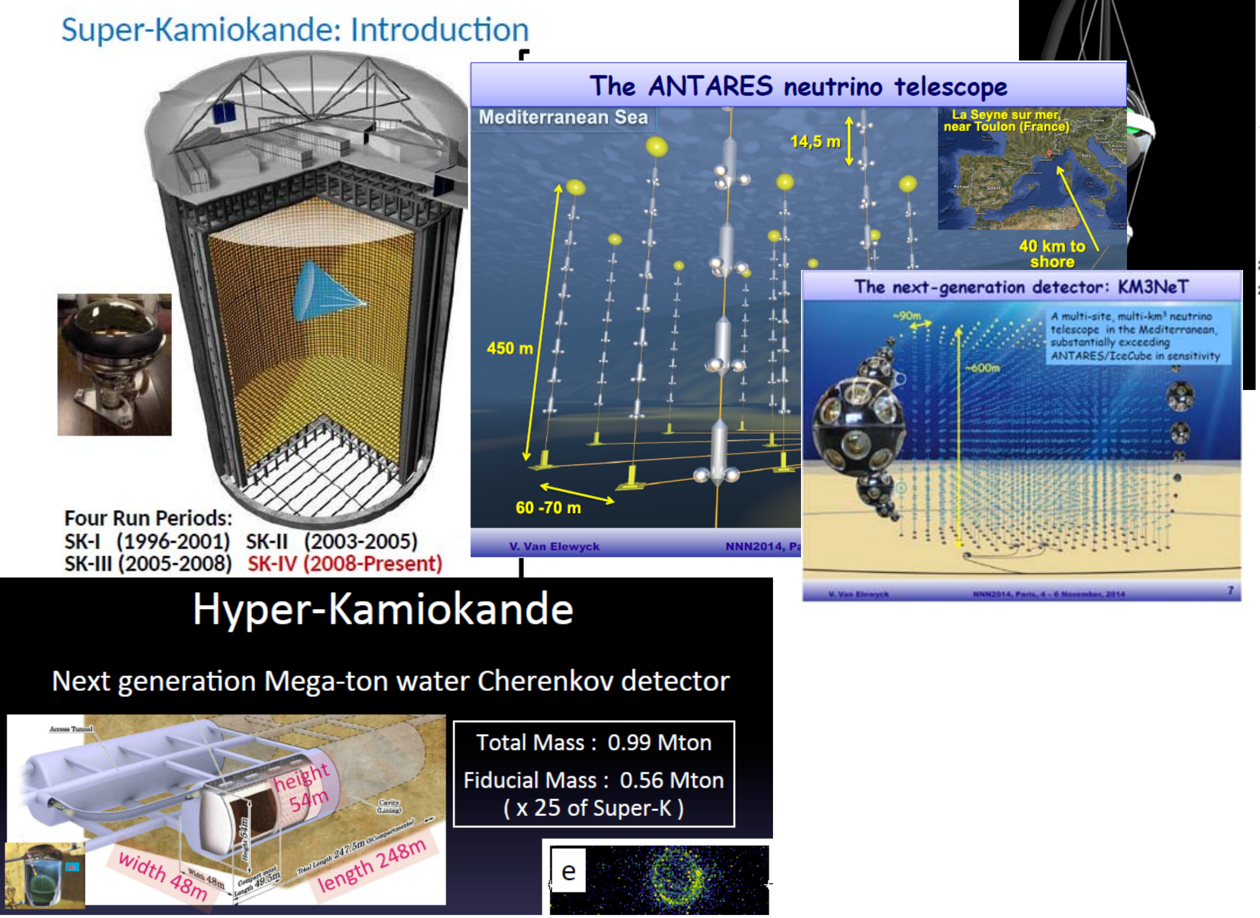

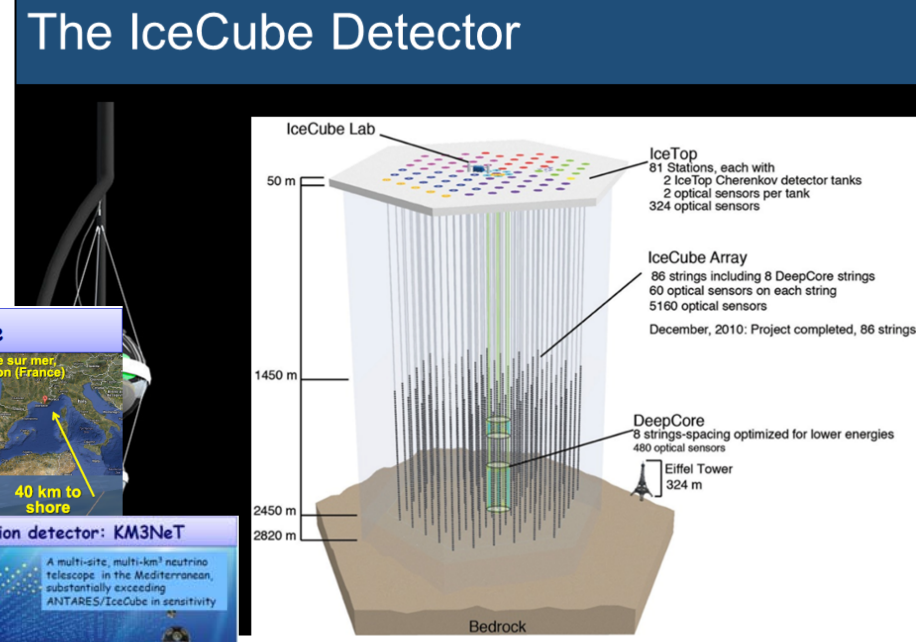

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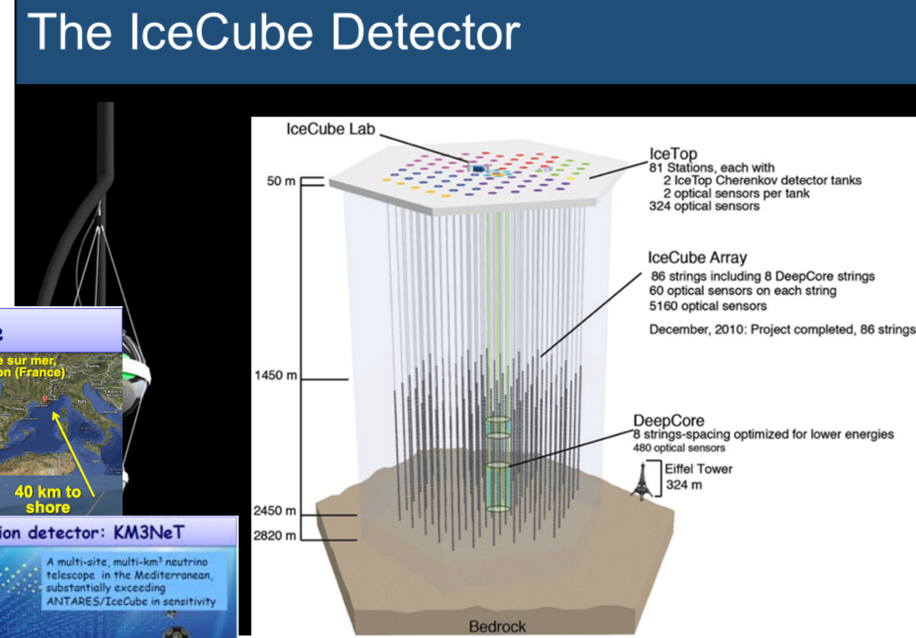

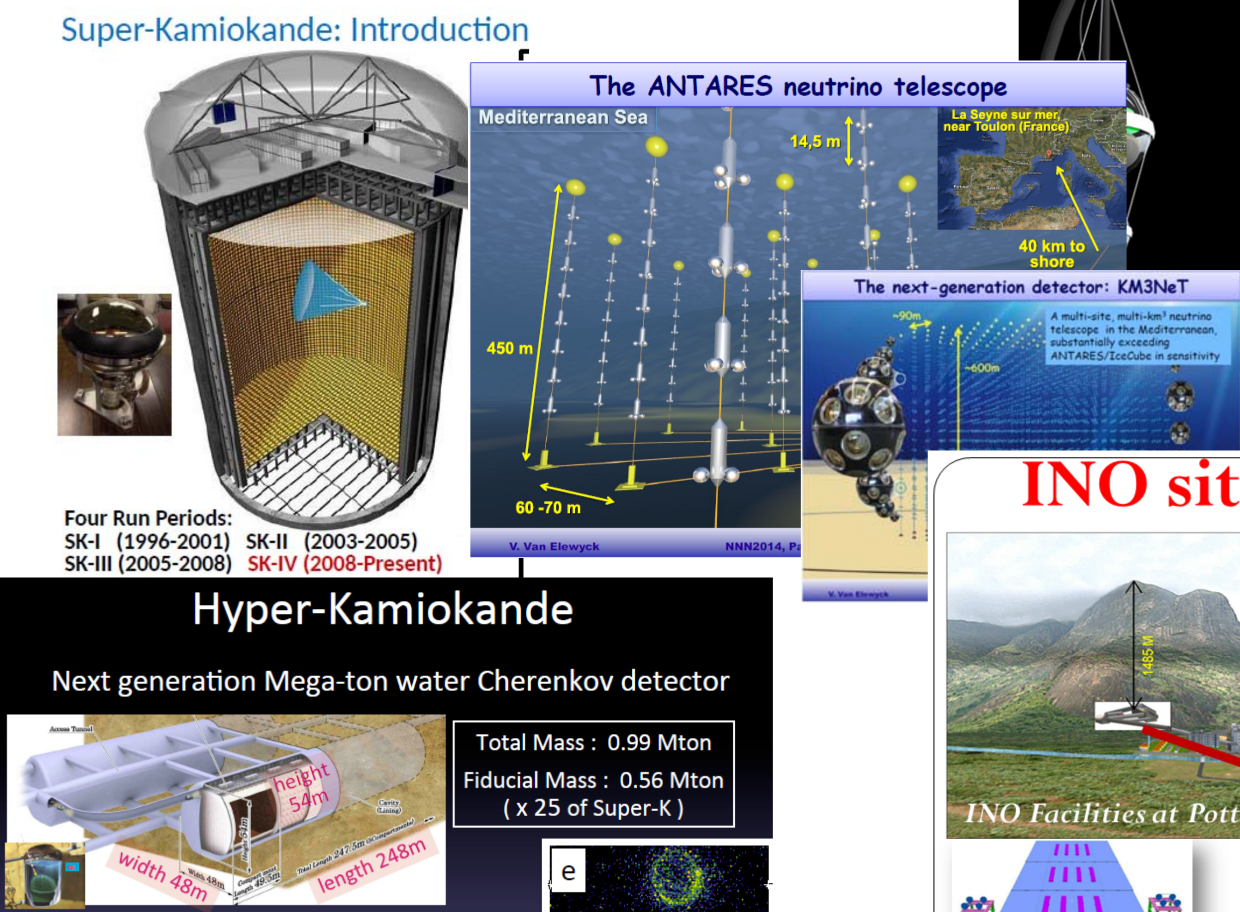

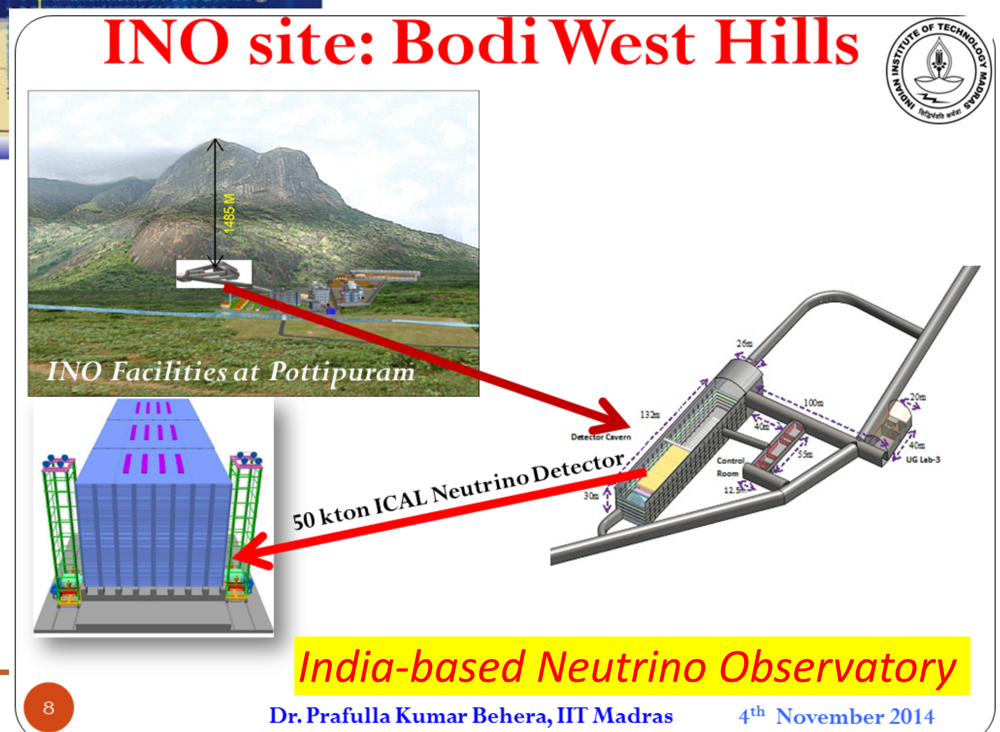

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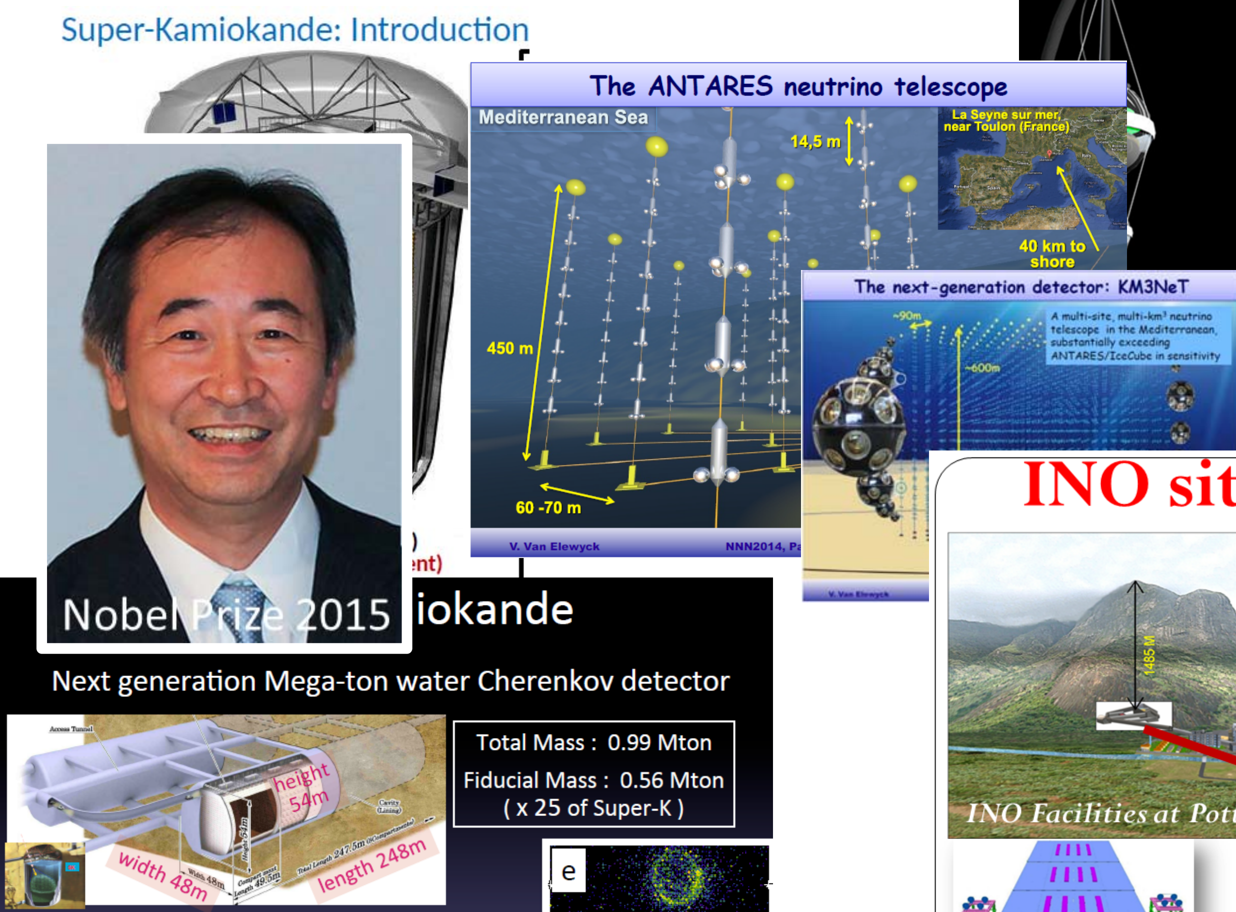
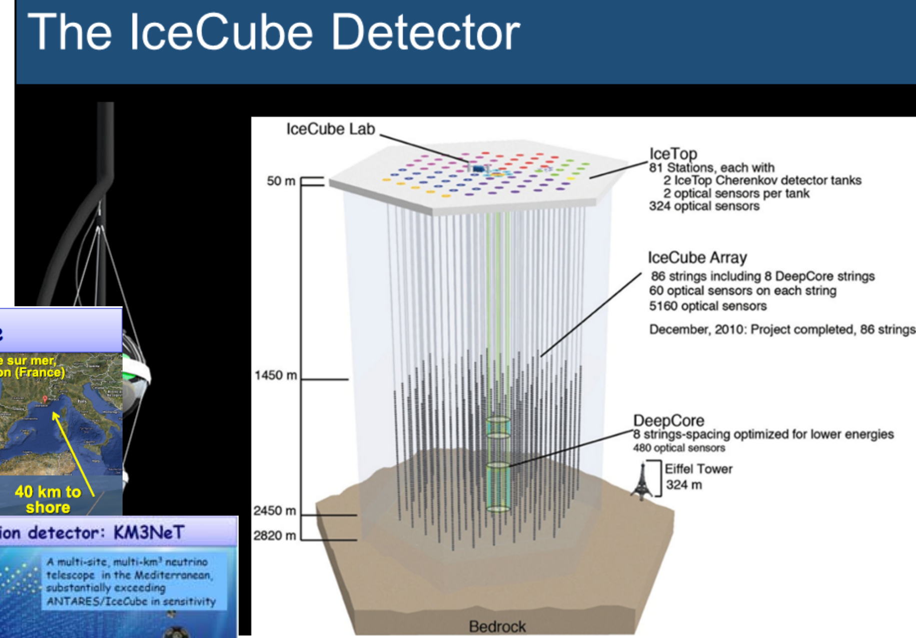
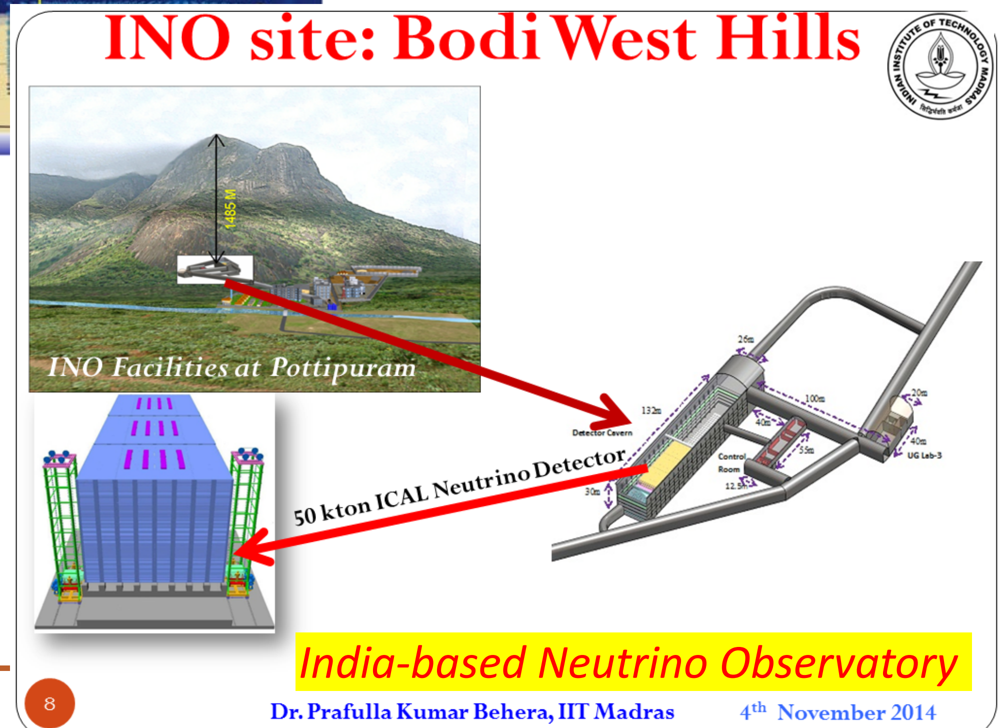
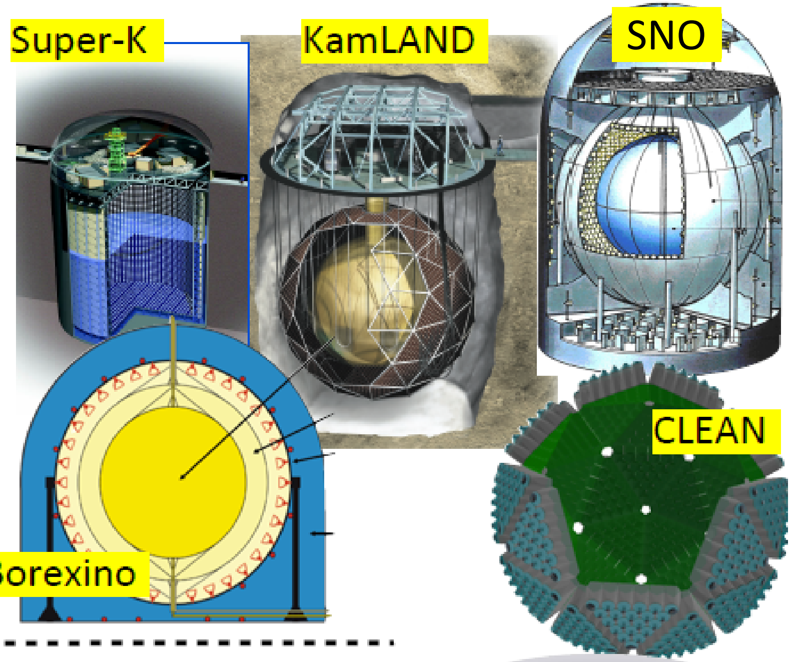




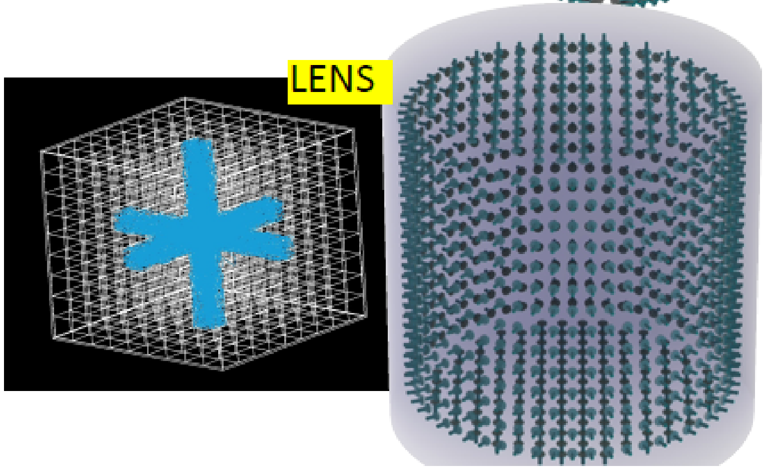


Solar Neutrino Experiments



- Elastic Scattering detection
  - Large-scale water Cherenkov
  - Large-scale liquid scintillator
  - Inorganic scintillator

- Charged Current detection
  - Segmented detector
  - Large-scale water-based LS



Solar Neutrino Experiments

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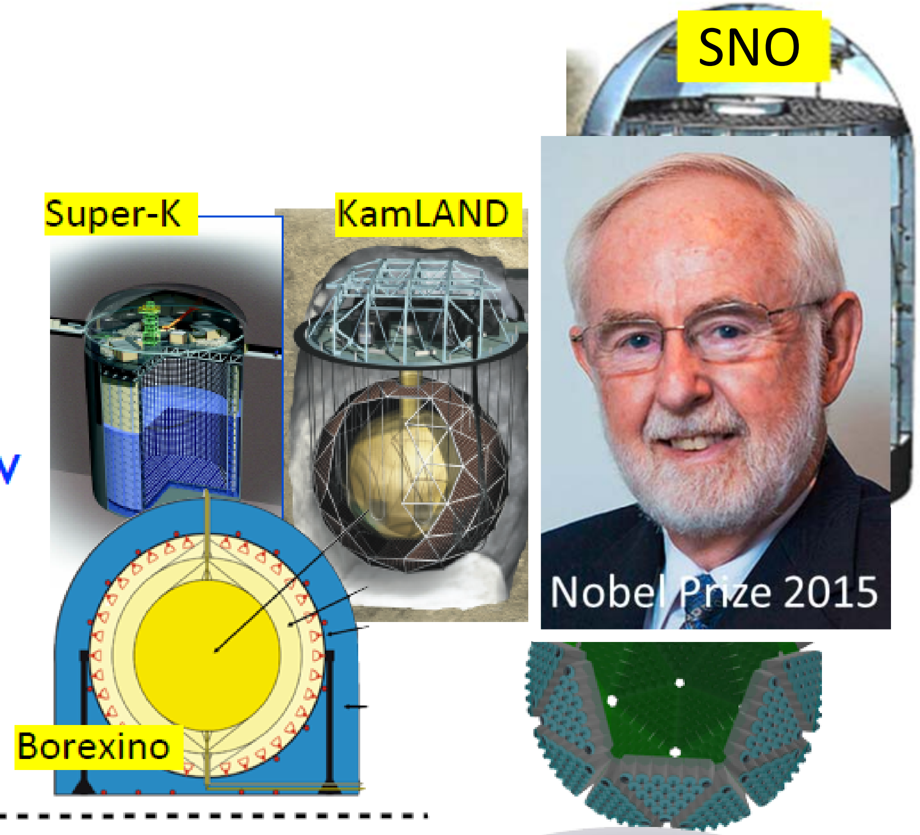

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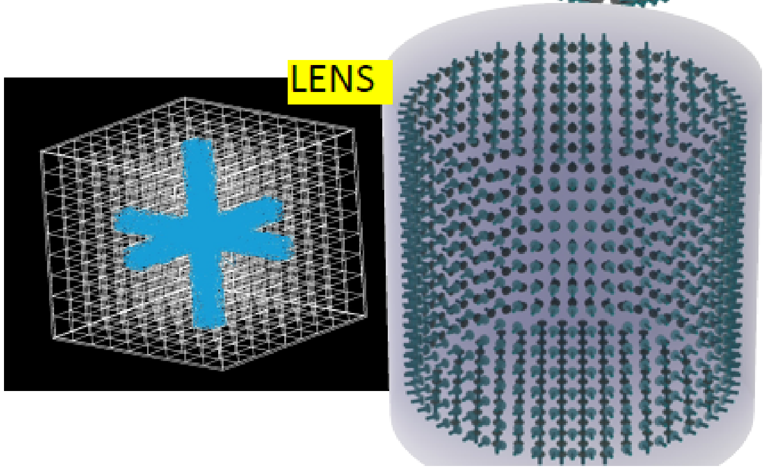
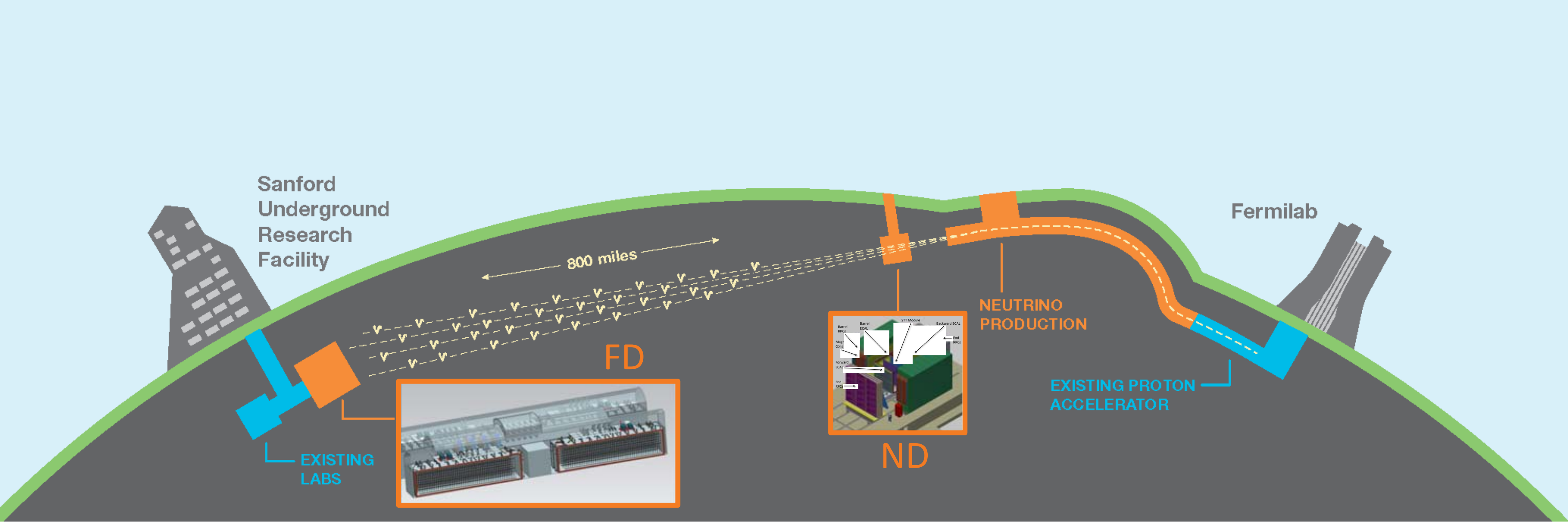


The Next-Generation Long-Baseline Experiment: LBNF / DUNE



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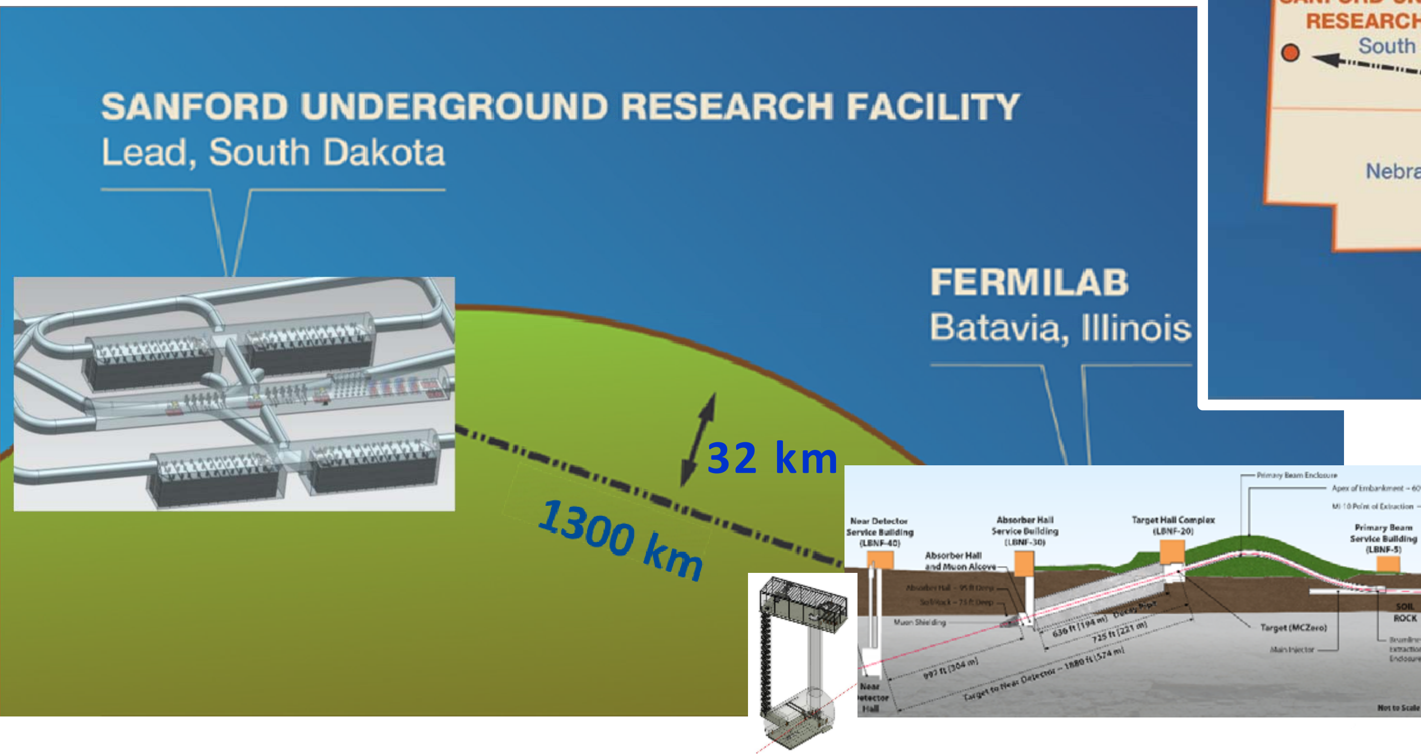

- Comprehensive experimental program to determine CP violation, Mass Hierarchy, and make precision measurements of oscillation parameters
- Astrophysical neutrinos and proton decay with a massive underground Liquid Argon TPC Far Detector
- Precision neutrino scattering measurements with Near Detector

DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astroparticle physics:

1) Neutrino Oscillation Physics

- CPV in the leptonic sector
  - "Our best bet for explaining why there is matter in the universe"
- Mass Hierarchy
- Precision Oscillation Physics & testing the 3-flavor paradigm

2) Nucleon Decay

- Predicted in beyond the Standard Model theories [but not yet seen]
  - e.g. the SUSY-favored mode, $p \rightarrow K^{+}\overline{\nu}$

3) Supernova burst physics & astrophysics

- Galactic core collapse supernova, sensitivity to ν_e
  - Time information on neutron star or even black-hole formation

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  - Galactic core collapse supernova, sensitivity to ν_e
    - Time information on neutron star or even black-hole formation

Any would be a <u>major</u> discovery

DUNE Ancillary Science Program

Enabled by the intense LBNF beam and the DUNE near and far detectors

- **Other LBL oscillation physics with BSM sensitivity**
  - Neutrino non-standard interactions (NSIs)
  - Sterile Neutrinos at the near and far sites
  - Measurements of tau neutrino appearance
- **Oscillation physics with atmospheric neutrinos**
- **Neutrino Physics in the near detector**
  - Neutrino cross section measurements
  - Studies of nuclear effects, FSI etc.
  - Measurements of the structure of nucleons
  - Neutrino-based measurements of $\sin^2\theta_W$
- **Search for signatures of Dark Matter**

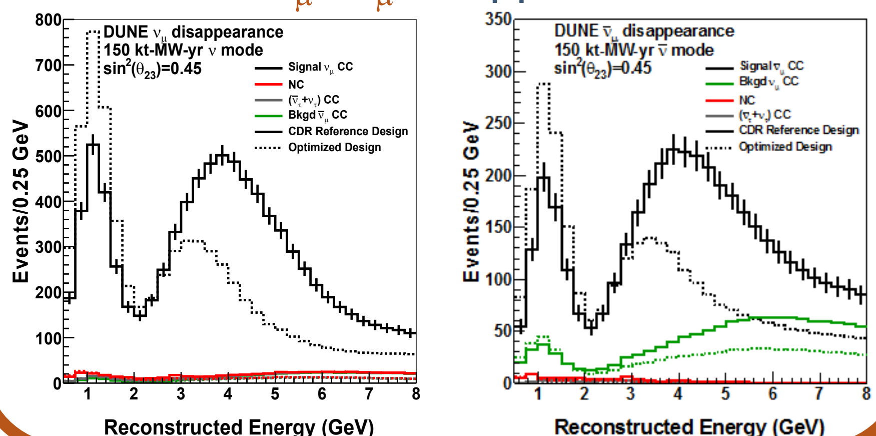
Neutrino Oscillation Strategy

Measure neutrino spectra at 1300 km in a wide-band beam

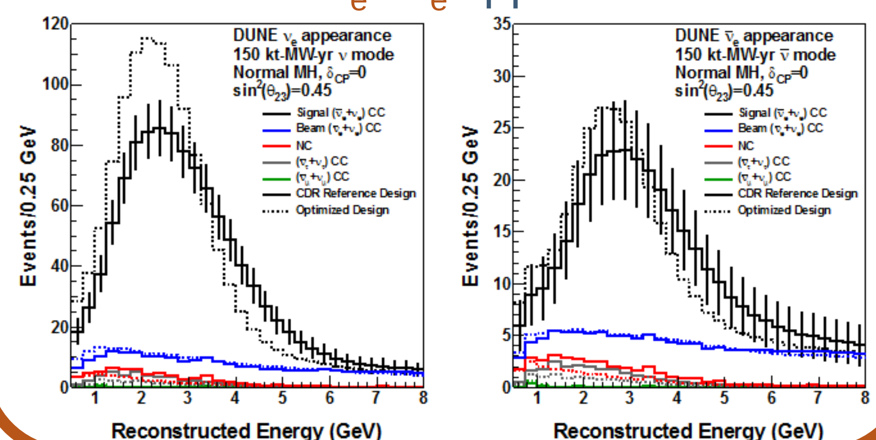
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects are separable

E ~ few GeV

ν_μ / $\bar{\nu}_\mu$ disappearance



ν_e / $\bar{\nu}_e$ appearance

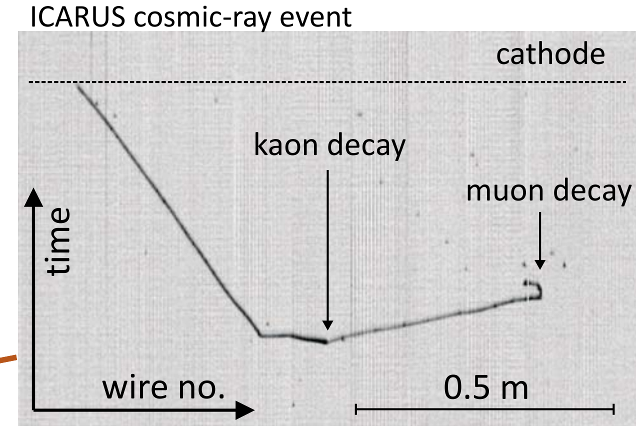


Nucleon Decay & Supernova νs

Nucleon decay $p \rightarrow K^{+}\overline{\nu}$

- **Image particles from nucleon decay**
  - target sensitivity to kaons (from d*E*/d*x*) from SUSY-inspired GUT p-decay modes

E ~ O(200 MeV)

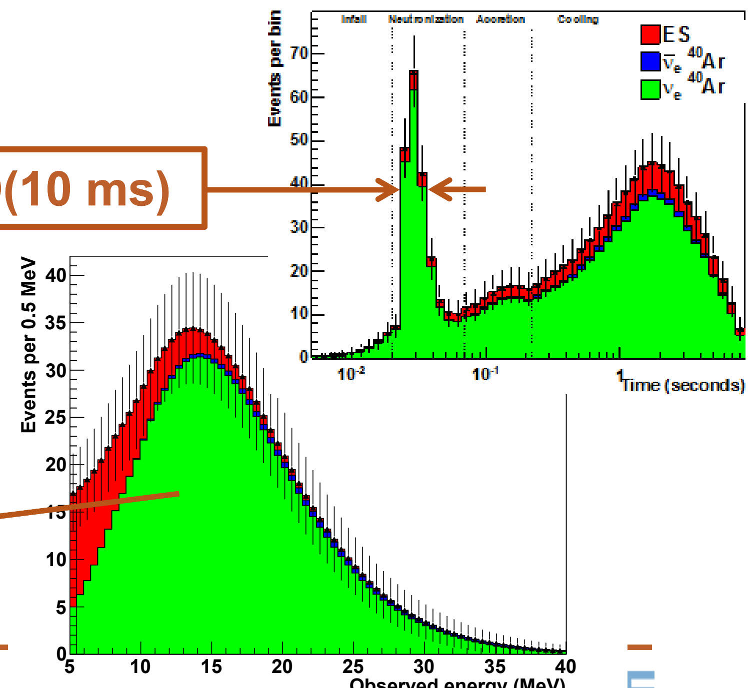


Supernova burst neutrinos

- **Astrophysics *and* neutrino physics**
  - To date only observed $\overline{\nu}_e$ from single SN
  - In argon, the largest sensitivity is to ν_e
    - CC interaction: $\nu_e + {}^{40}Ar \rightarrow e^{-} + {}^{40}K^{*}$

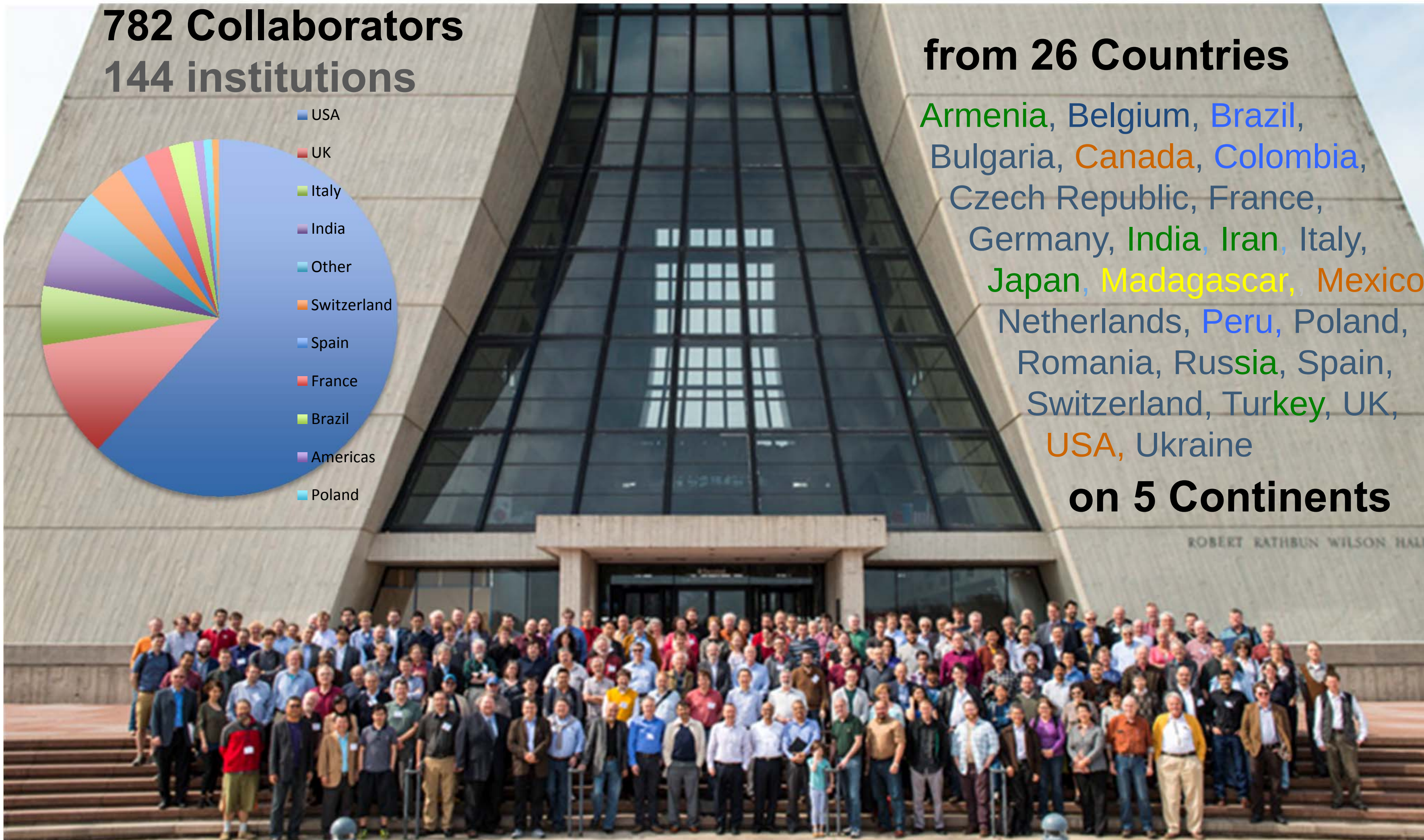
δt ~ O(10 ms)

E ~ O(10 MeV)



The DUNE Collaboration

Formed this year from the previous LBNE and LBNO collaborations plus many new institutions



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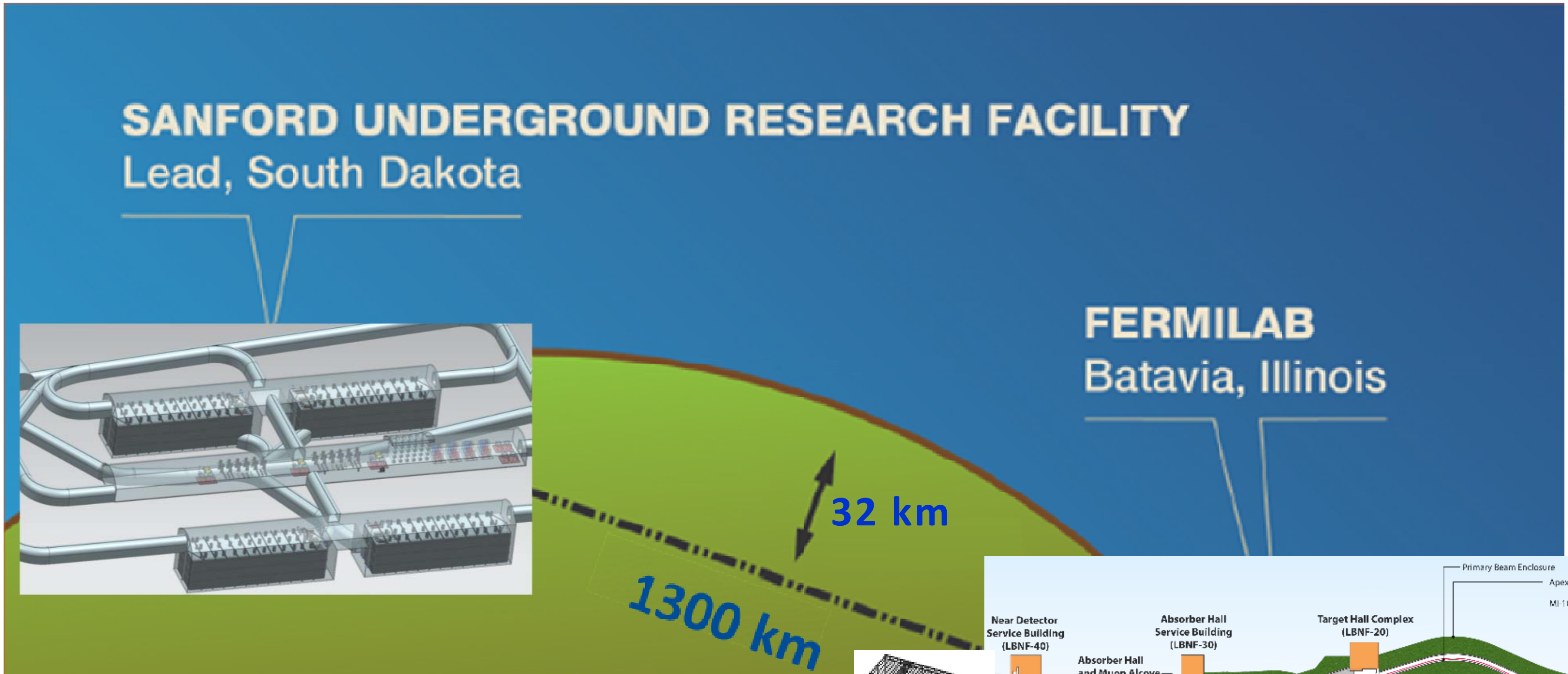
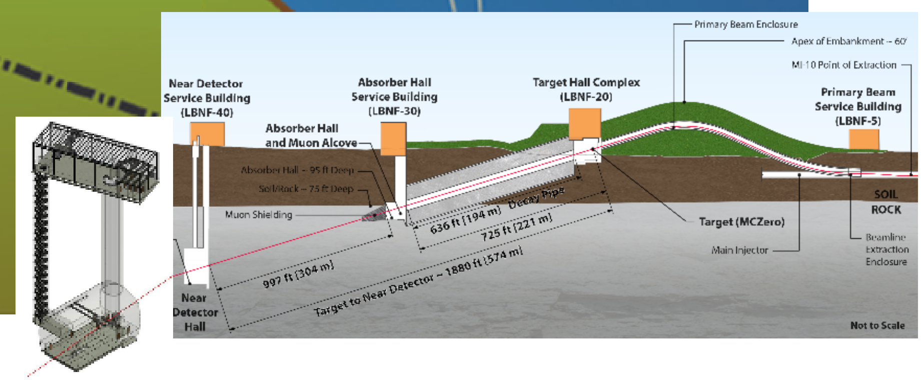
LBNF/DUNE Overview



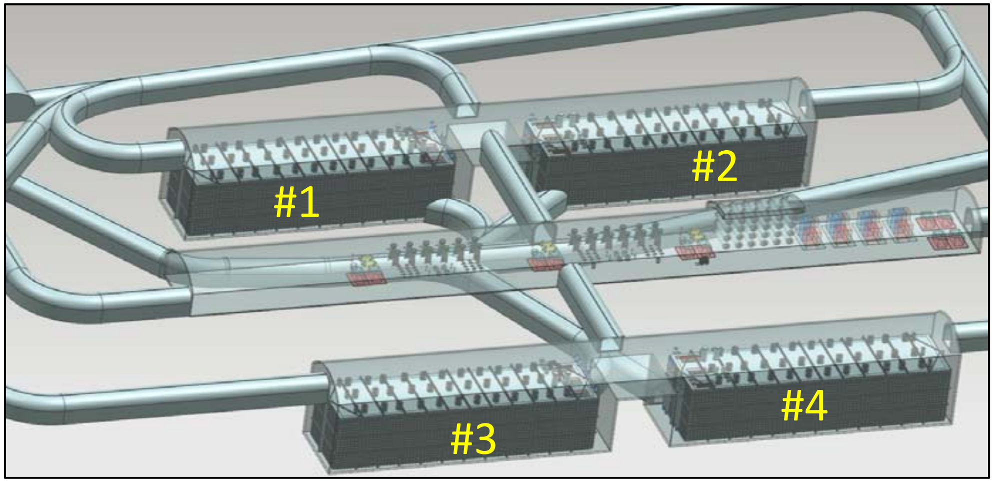


- 40 kt fiducial mass LAr TPC far detector, 1480 m underground
- High-power, broad-band $\nu_\mu/\bar{\nu}_\mu$ beam
- Precision near detector

Staged Approach to 40 kt

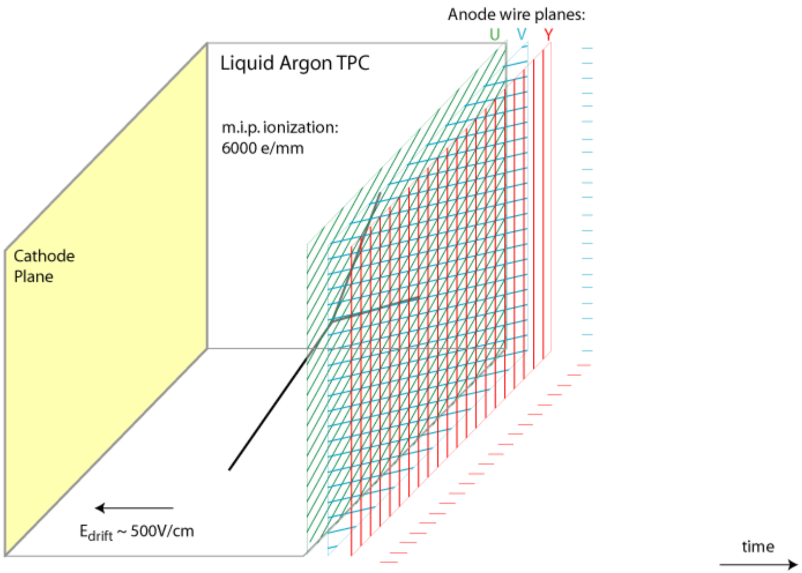
Four-Cavern Layout at the Sanford Underground Research Facility (SURF) at the 4850 foot Level (4300 m.w.e.)

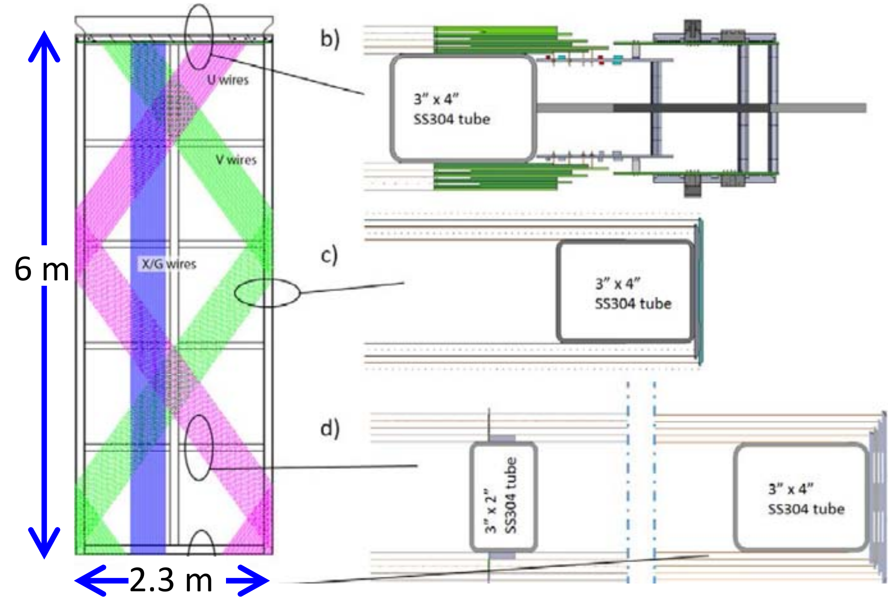
- **four caverns hosting four independent 10-kt (fiducial mass) Far Detector modules**
  - Allows for staged construction of the Far Detector
  - Gives flexibility for evolution of LArTPC technology design
    - Assume four identical cryostats: 15.1 (W) x 14.0 (H) x 62 (L) m^3
    - Assume the four 10-kt modules will be similar but **not identical**



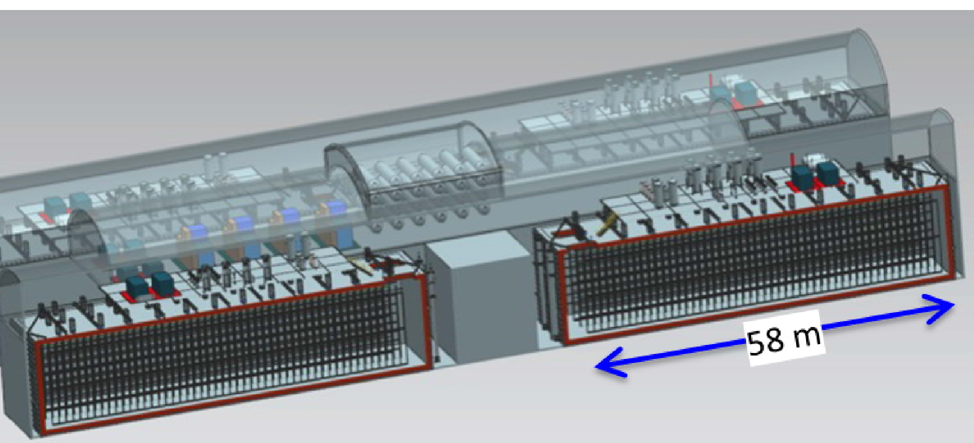
Reference Design: Single-Phase LAr TPC

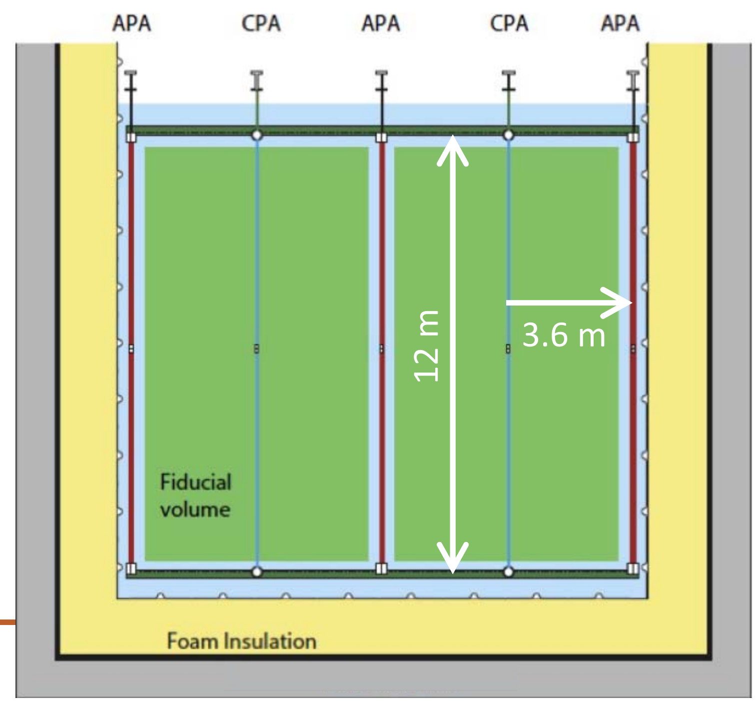
Based on the successful design pioneered by the ICARUS Collaboration





Anode Plane Assembly (APA)





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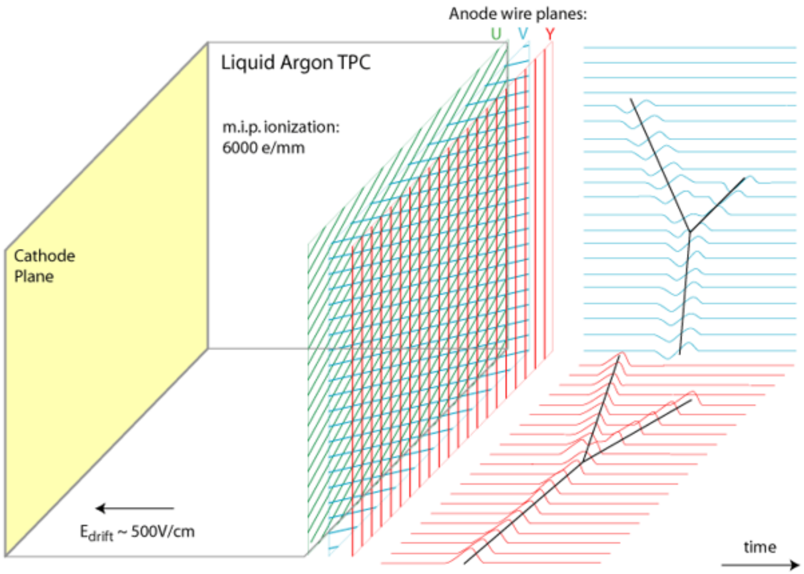

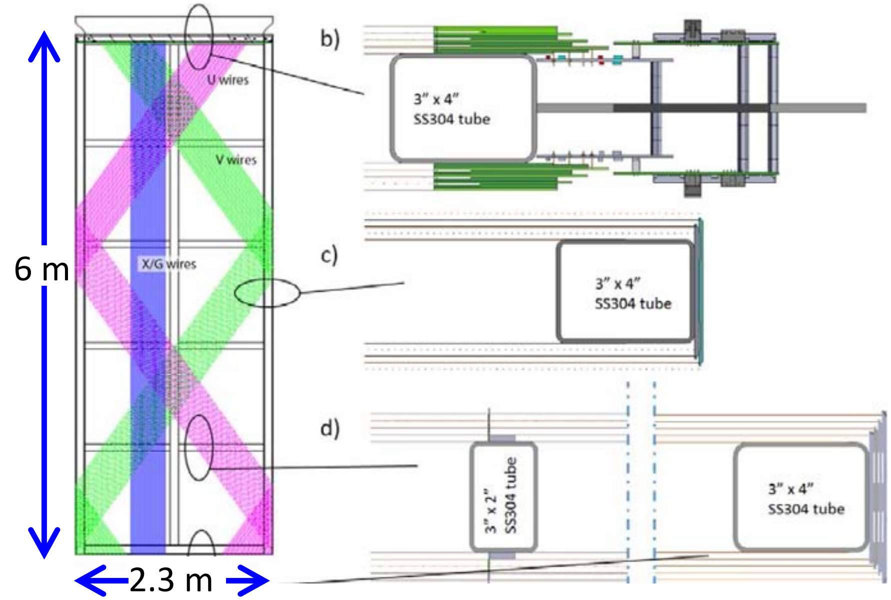

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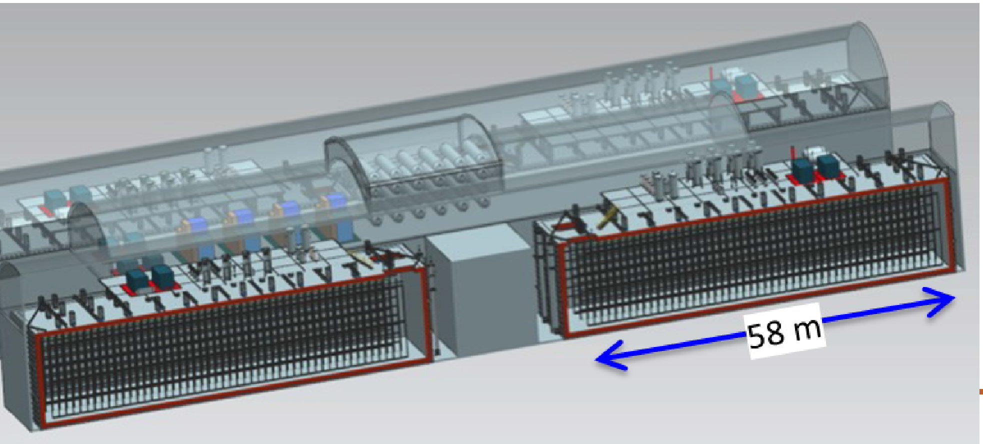
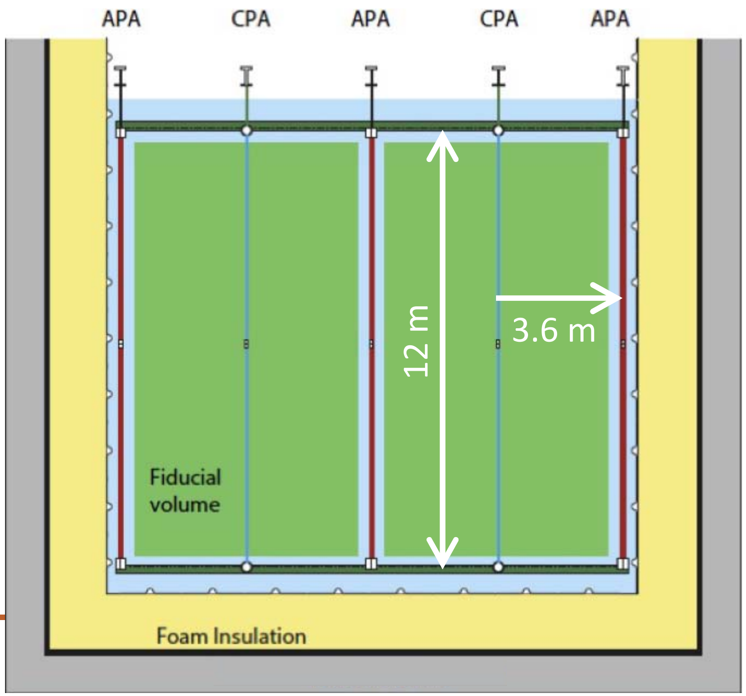
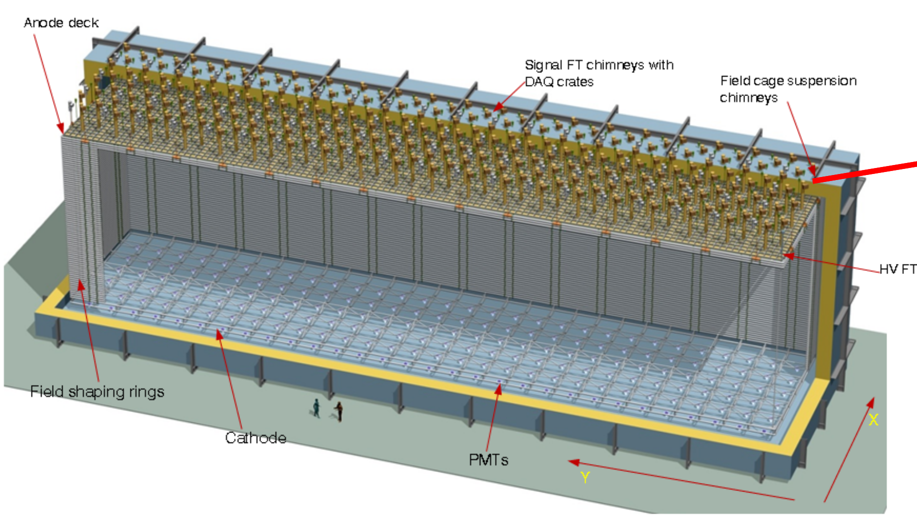


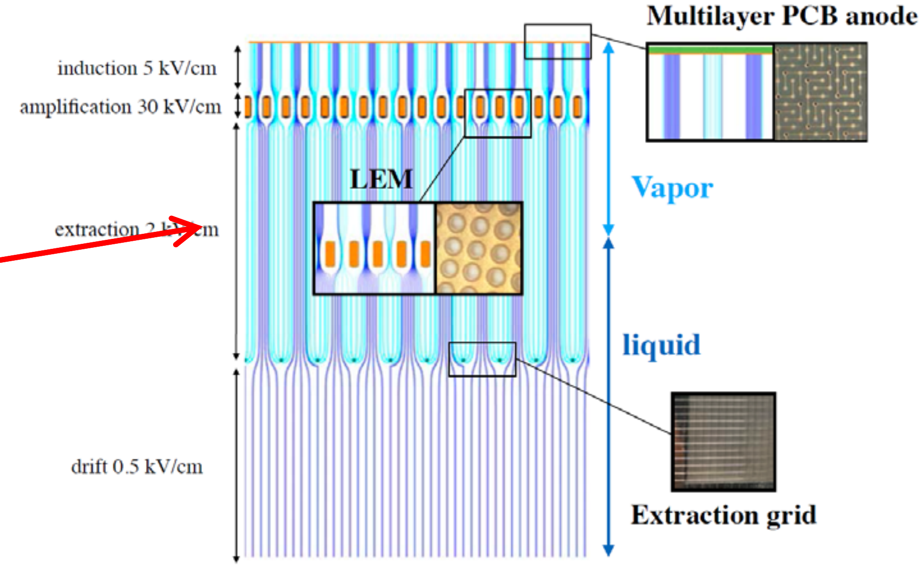


Alternative Design: Dual-phase LAr TPC

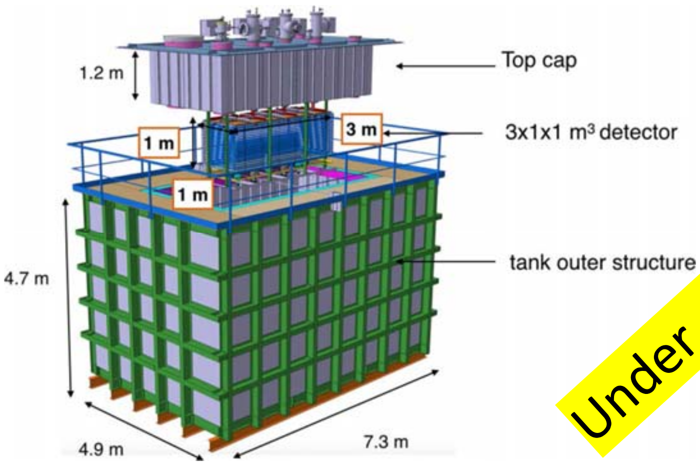
DUNE collaboration recognizes the potential of the dual-phase technology

- Strongly supports the WA105 development program at the CERN neutrino platform
- If demonstrated, could form basis of second or subsequent 10-kt far detector modules



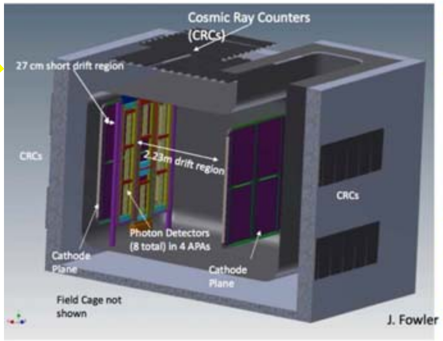


Far Detector Prototypes



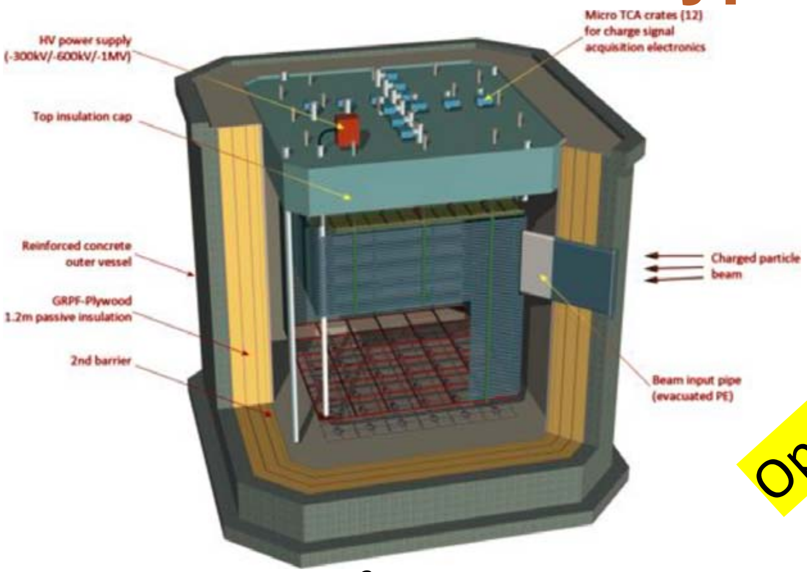
$1 \times 1 \times 3$ m^3 dual-phase prototype at CERN

Under construction now



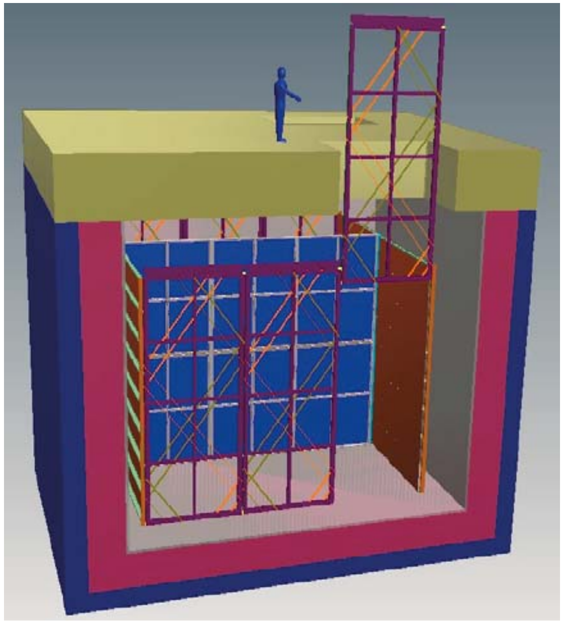
35 t single-phase Prototype at Fermilab

Far Detector Prototypes

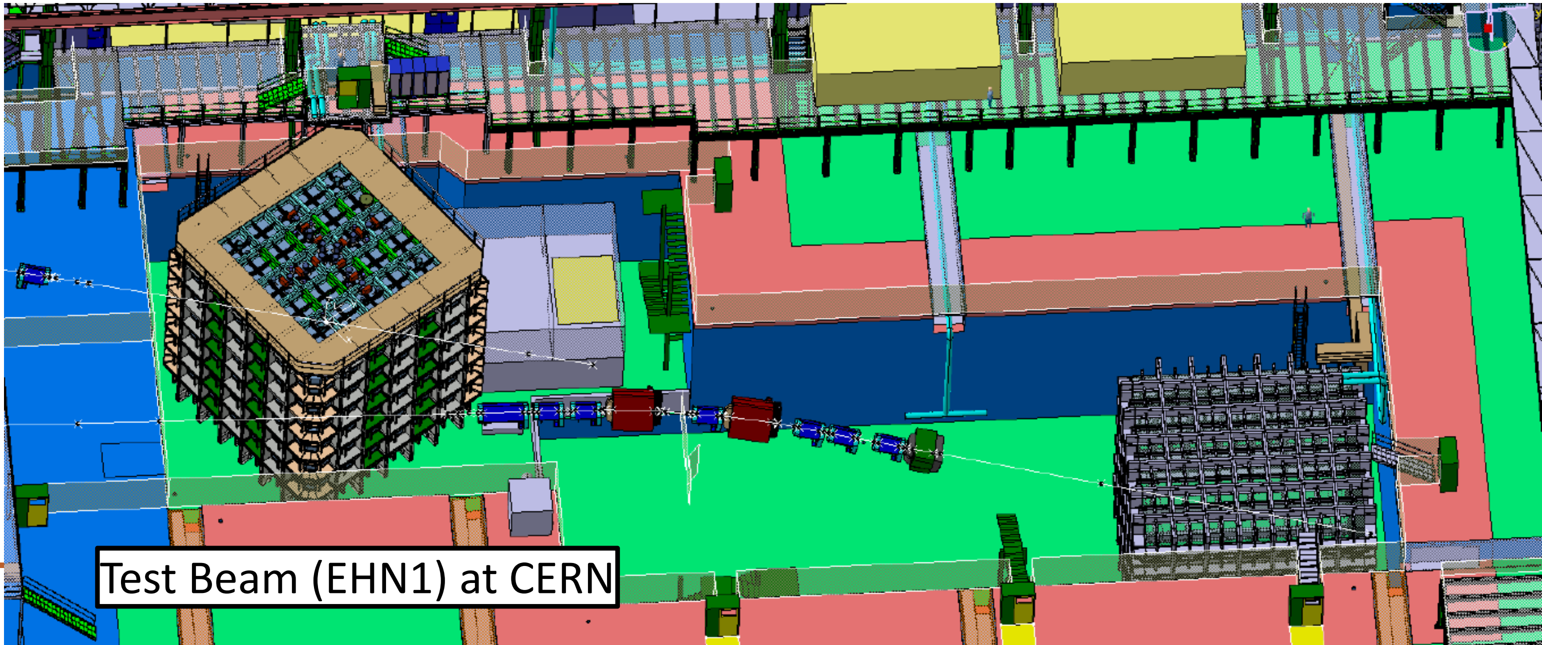


WA105: 6 x 6 x 6 m^3 dual-phase prototype at CERN

Operational by 2018



protoDUNE: single-phase prototype (6 full-scale APAs) at CERN



Test Beam (EHN1) at CERN

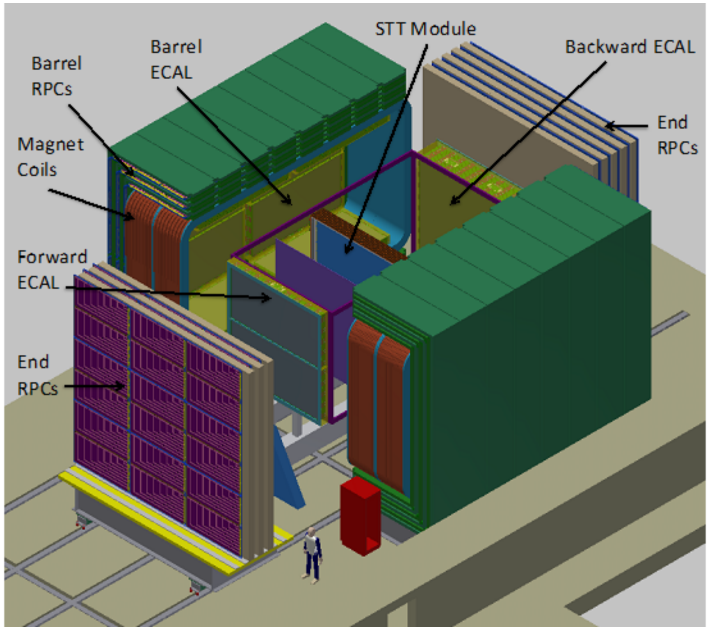
DUNE Near Detector

- **Top-level Requirements**
  - Ability to constrain systematic uncertainties for the DUNE oscillation analysis
  - Drives the design and implies the capability to precisely measure exclusive neutrino interactions
  - ⇨ Naturally results in a self-contained non-oscillation neutrino physics program
    - Exploiting the intense LBNF neutrino beam
- **International context**
  - The proposed contribution of Indian institutions to the design and construction of the DUNE near detector is a central part of the DUNE strategy for the construction of the experiment

Near Detector Reference Design

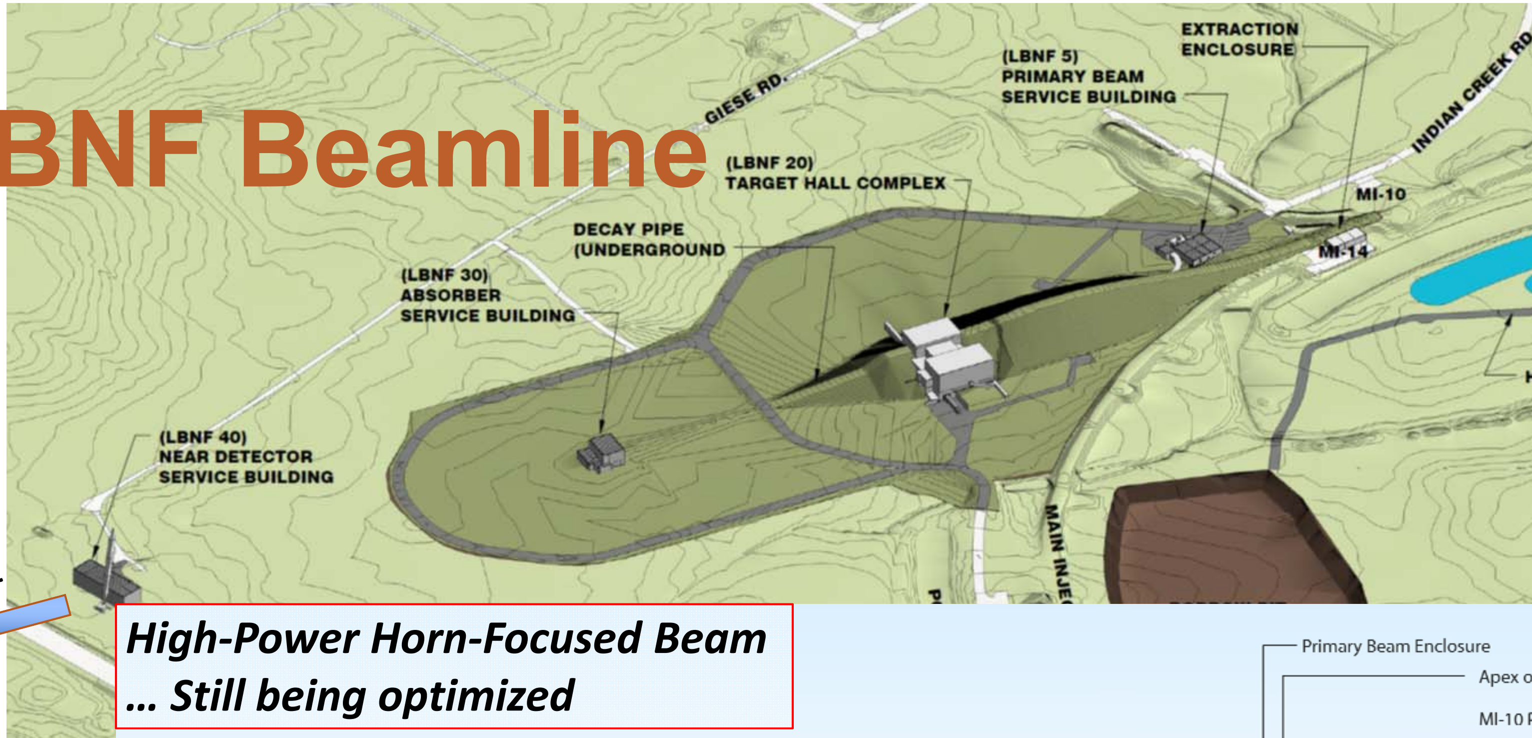
The NOMAD-inspired Fine-Grained Tracker (FGT)

- **It consists of:**
  - Central straw-tube tracking system with embedded nuclear targets
  - Lead-scintillator sampling ECAL (4π)
  - Large-bore warm dipole magnet
  - RPC-based muon tracking systems

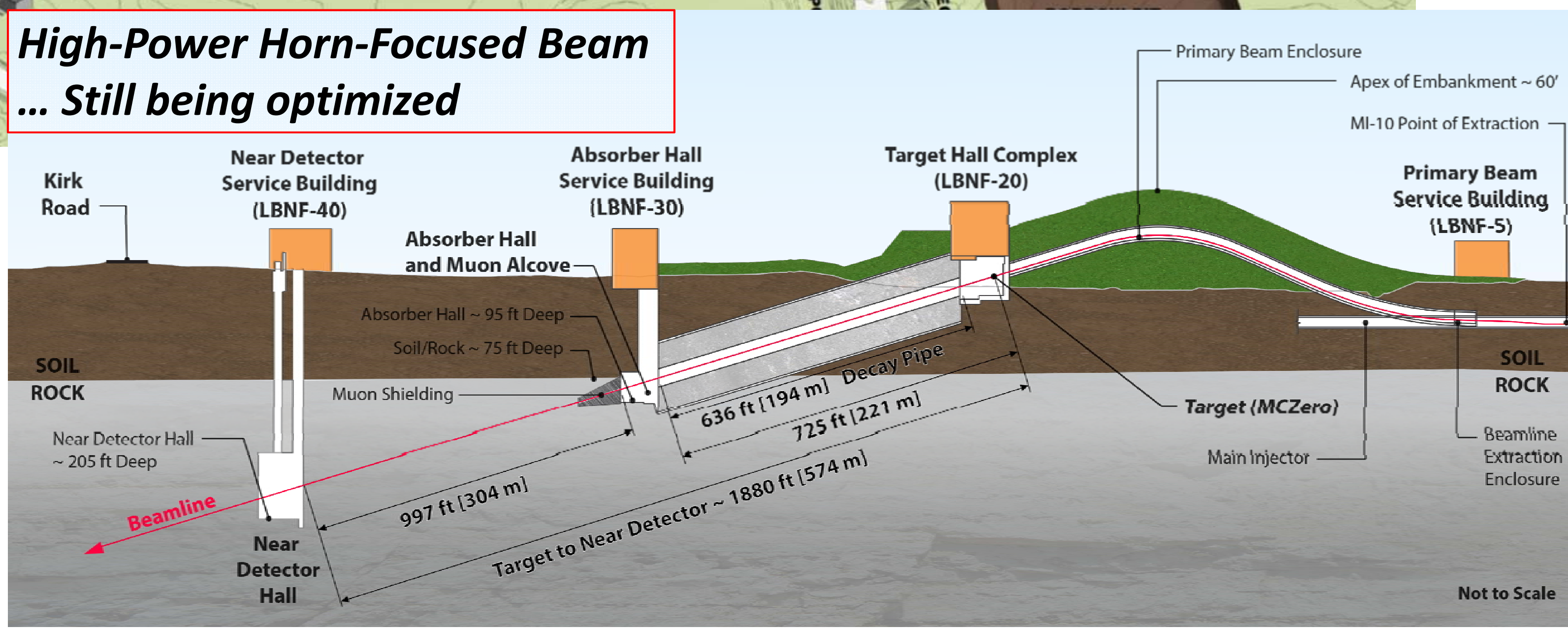


- **It provides:**
  - Constraints on cross sections and the neutrino flux
  - A rich self-contained non-oscillation neutrino physics program
- **DUNE has set up a ND task force**
  - End-to-end physics study of FGT measurements and LBL analysis
  - Quantifying the benefits of augmenting the ref. design with a LArTPC or high-pressure gaseous argon TPC

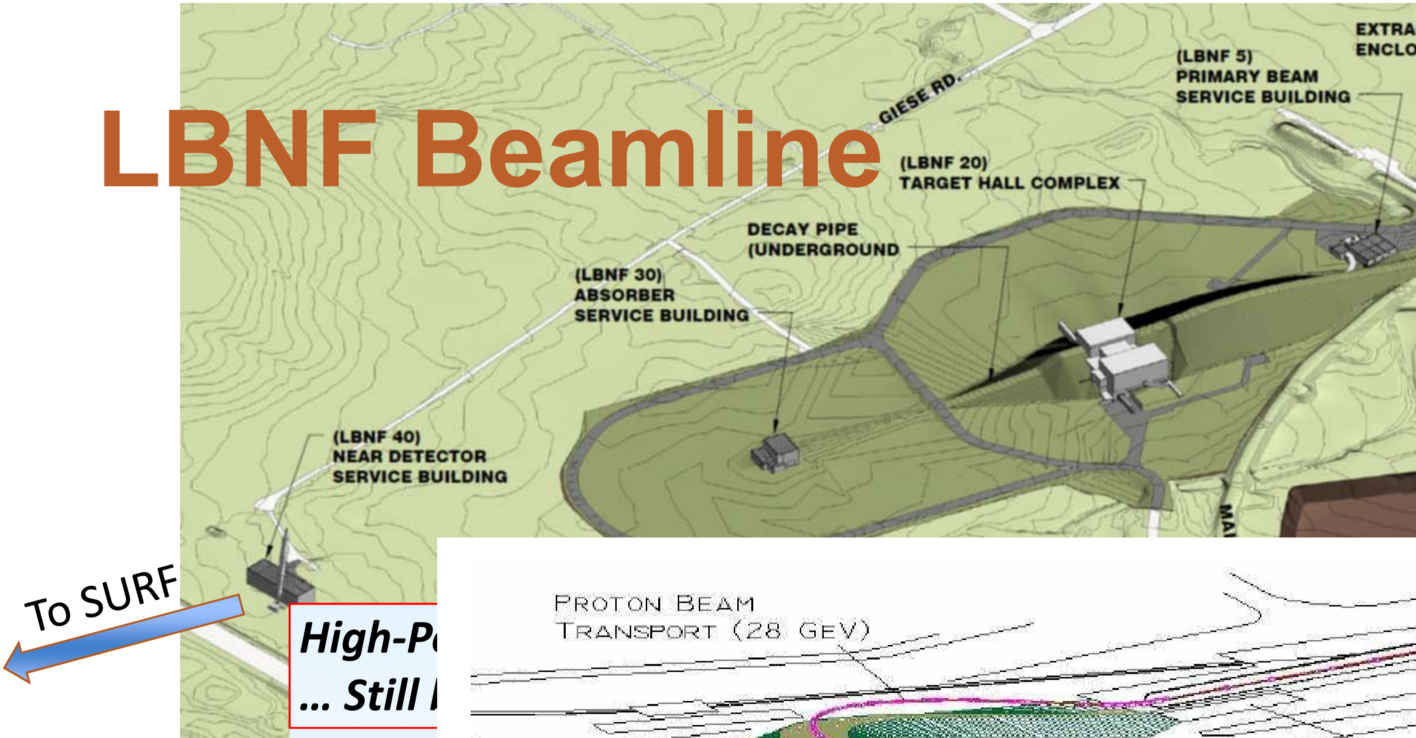
LBNF Beamline

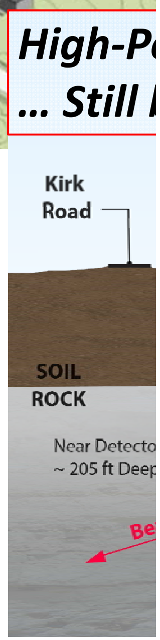


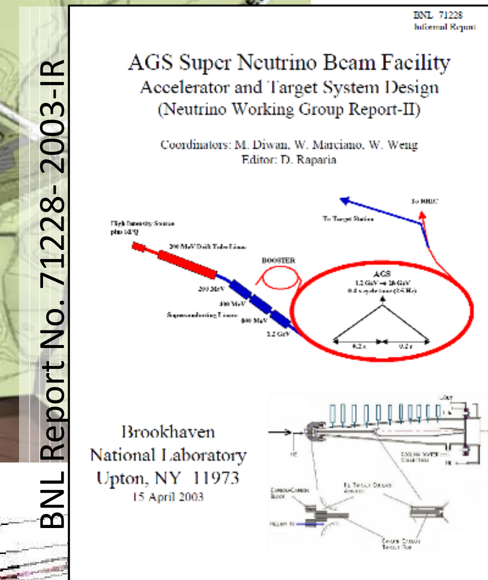
High-Power Horn-Focused Beam
… Still being optimized

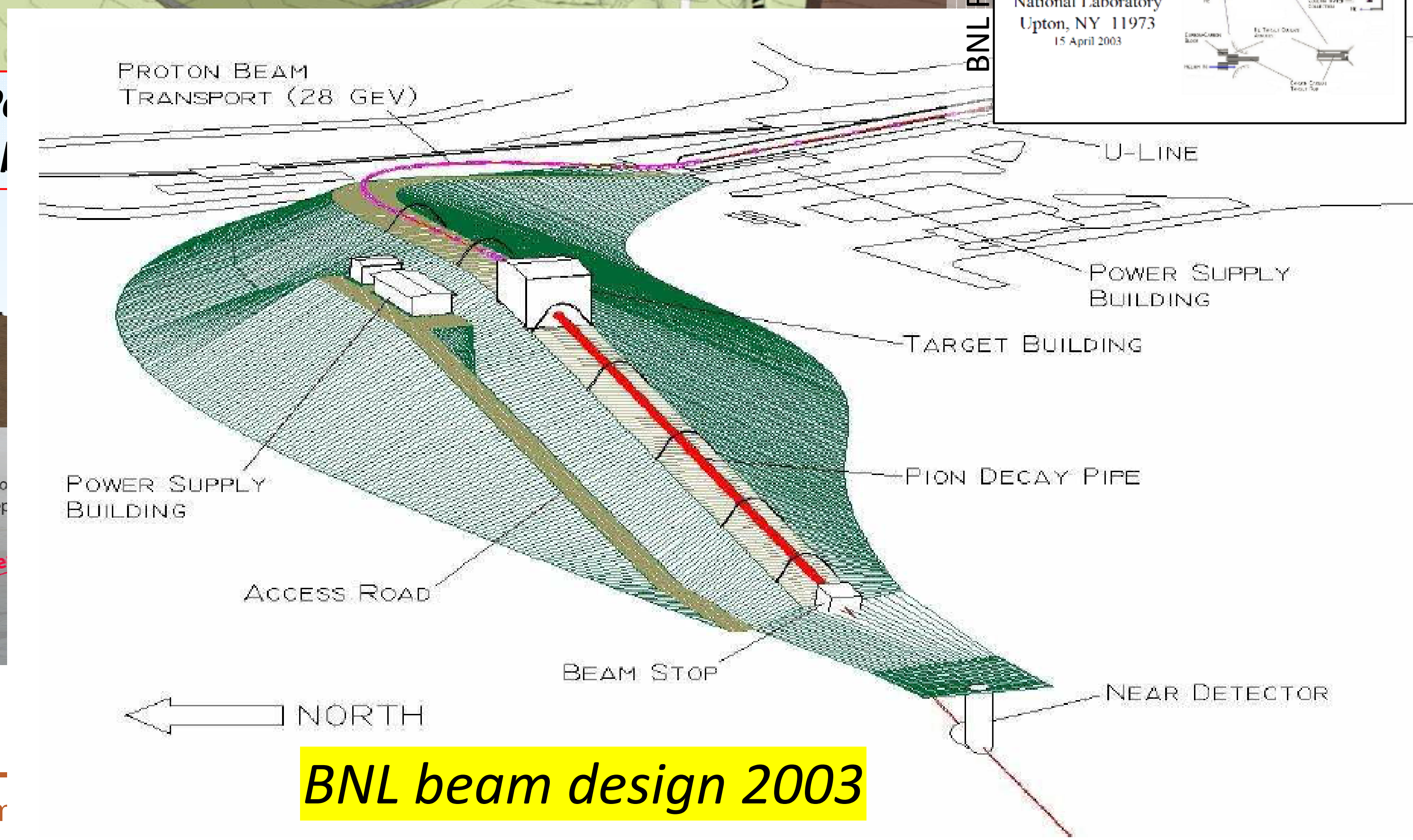


LBNF Beamline



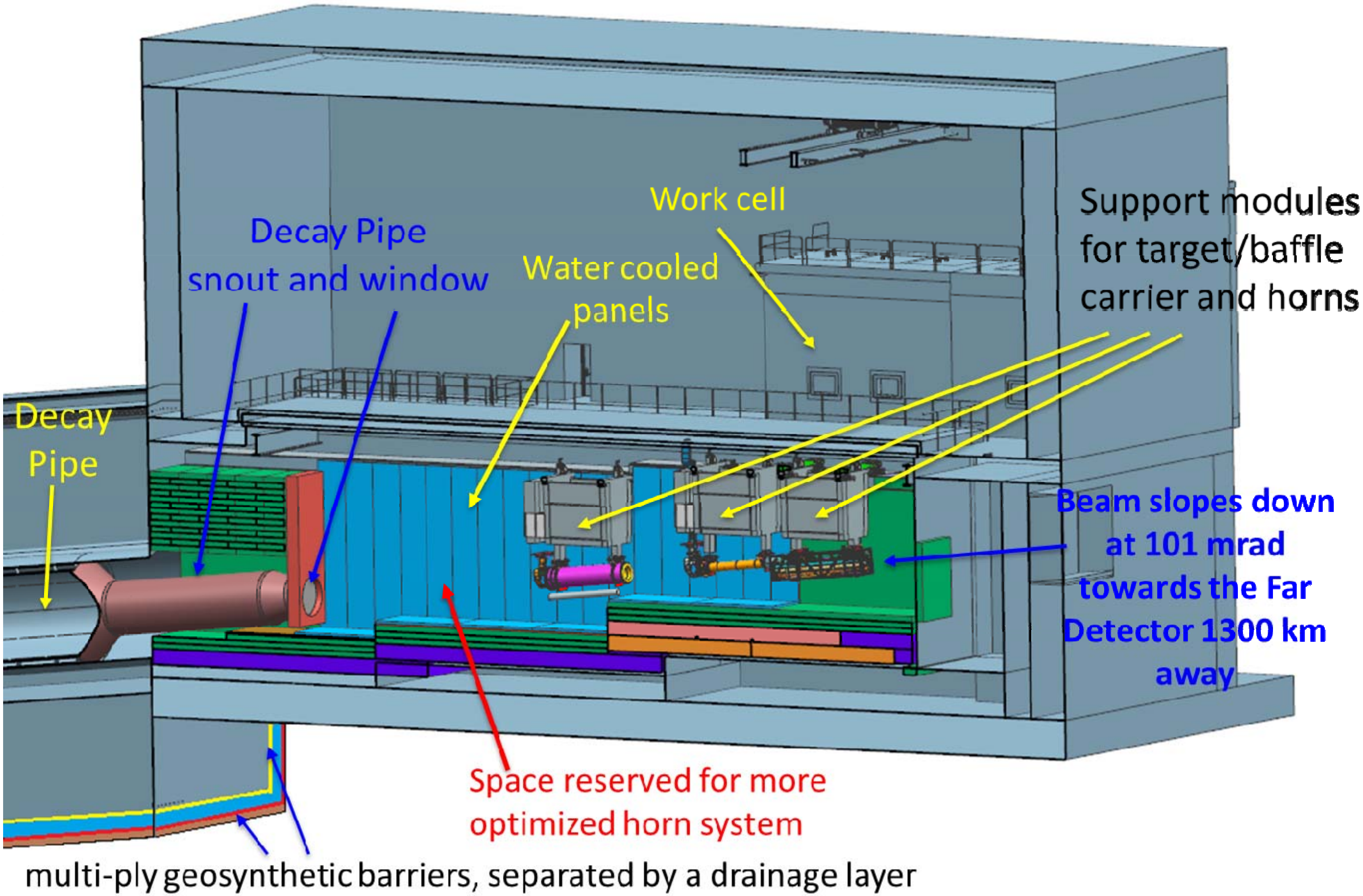






BNL beam design 2003

Neutrino Beam Configuration

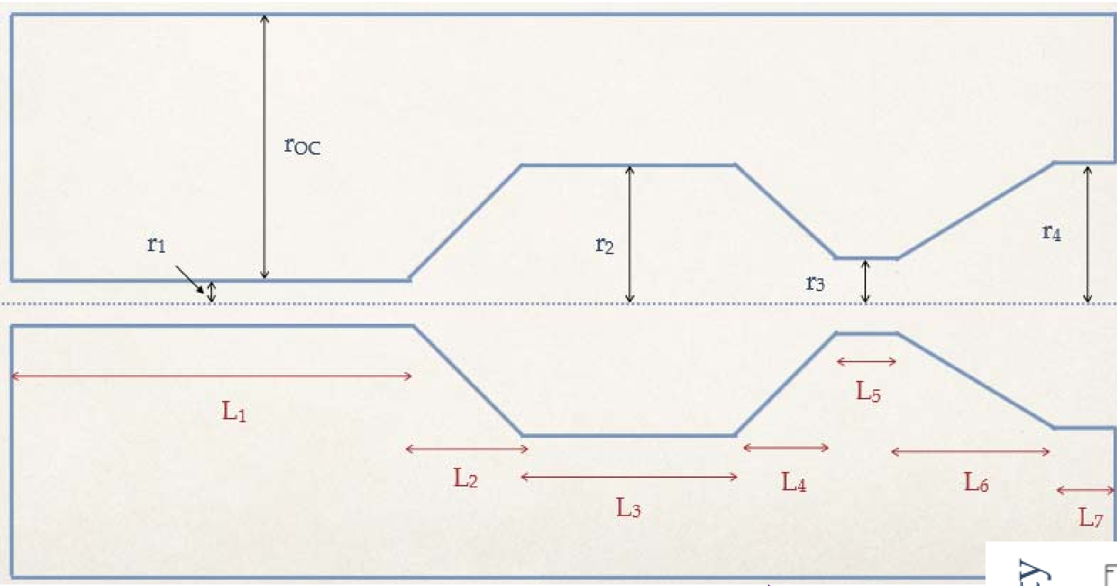


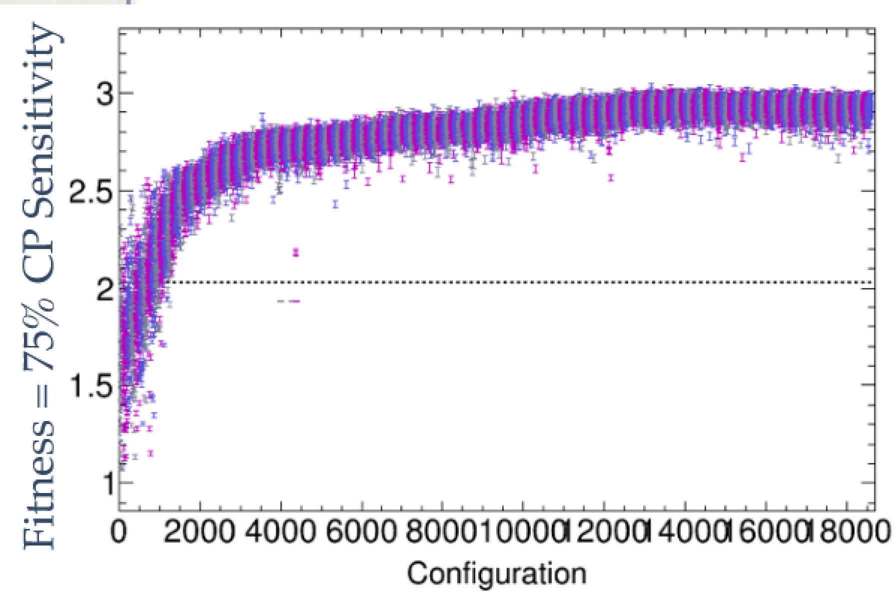
Optimizing the Neutrino Beam

- Proton energy choice in the range 60-120 GeV (some programmatic consequences).
- Horns
  - Shape/size
  - current (power supply up to 300 kA, just completed new conceptual design)
- Target (currently two interaction lengths)
  - Size/shape/position with respect to Horn 1
  - Material(s) (higher longevity can increase up time - ongoing R&D)
- Studied Decay Pipe length and diameter. Current length 194 m (studied 170 m - 250 m). Current diameter 4 m (studied 2-6 m). *Recently fixed at 194 m long x 4 m diameter.*

Optimizing the focusing system for greater physics reach

Genetic algorithm, inspired by work done by LBNO Collaboration
to optimize for CP Violation sensitivity





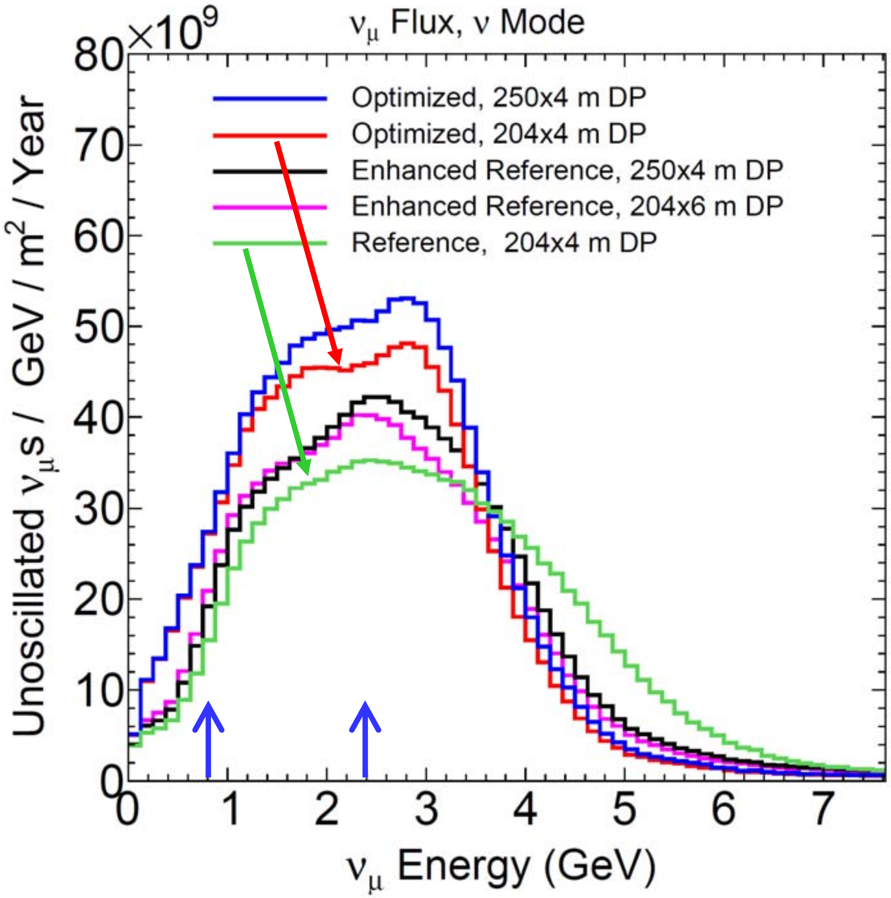
Genetic algorithm and new shape of Horn 1

Horn 2 is NuMI shape in this case but rescaled radially and longitudinally

Target length varied – longer target preferred: $2 \rightarrow 5\ \lambda_I$

Neutrino Flux of best configurations compared with Reference Design

80 GeV protons



Substantial flux increase, especially at the 2nd oscillation maximum which is very important for the CP violation and mass ordering measurements.

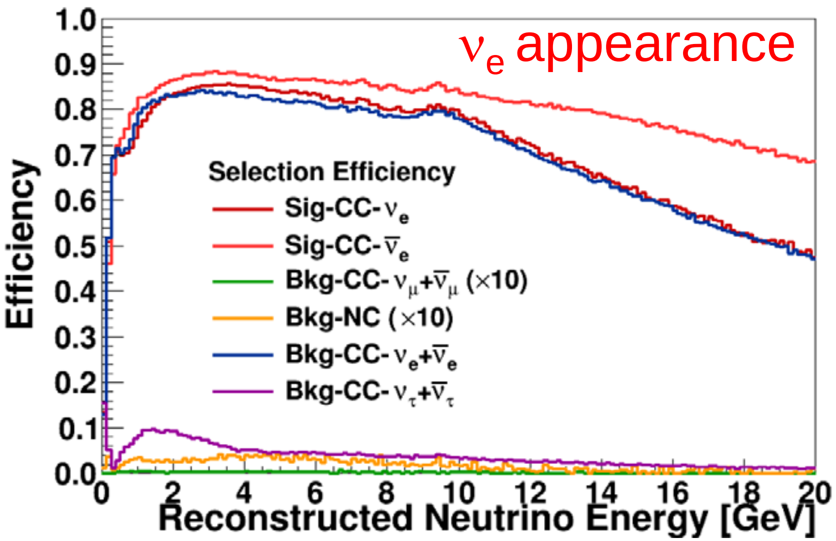
… Optimization is continuing.

2nd *1st osc max*

Evaluating DUNE Sensitivities

Many inputs to calculation (implemented in GLoBeS):

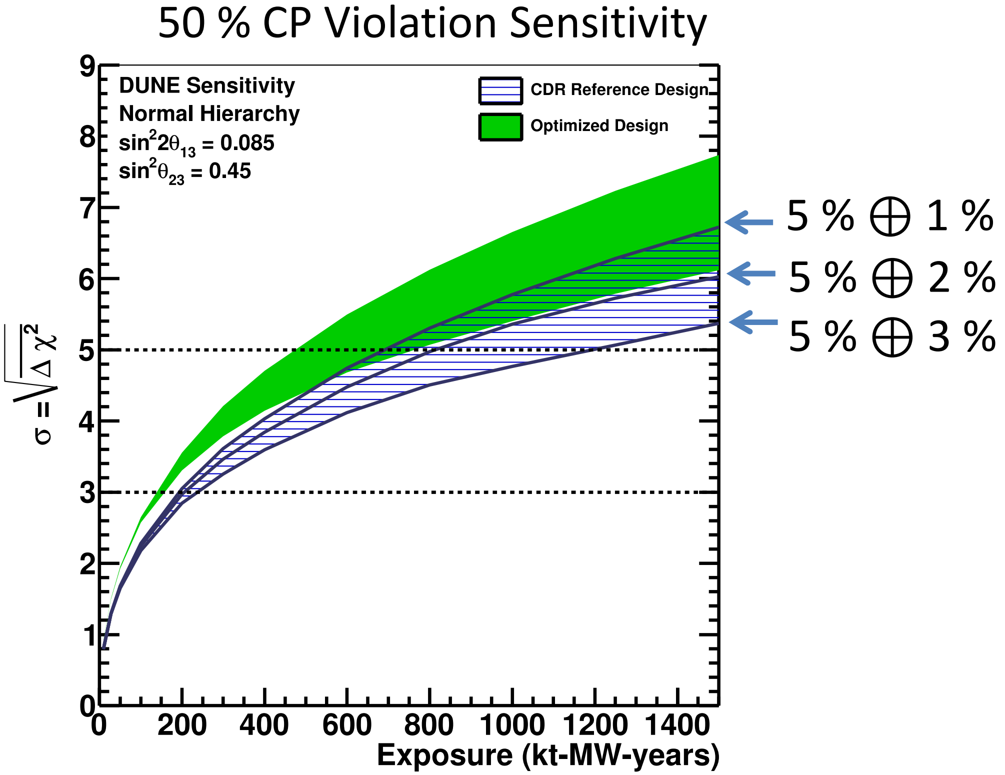
- **Reference Beam Flux**
  - 80 GeV protons
  - 1.07 MW
  - NuMI-style two horn system
- **Optimized Beam Flux**
  - Horn system optimized for lower energies
- **Expected Detector Performance**
  - Based on previous experience (ICARUS, ArgoNEUT, …)
  - **Fast MC** smears response at generated final-state particle level
    - "Reconstructed" neutrino energy
    - kNN-based MV technique used for ν_e "event selection": parameterized efficiencies

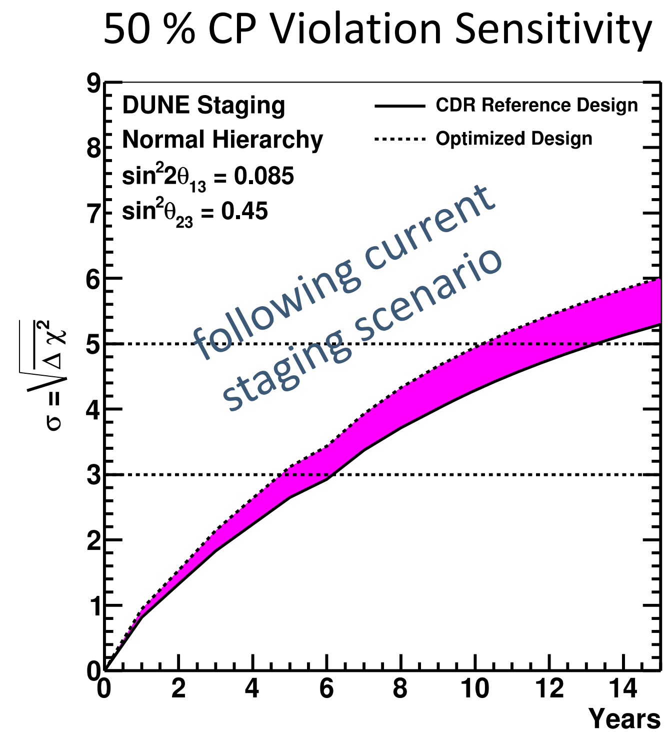


DUNE Sensitivity to CP Violation

Propagate to Oscillation Sensitivities

using assumptions for systematics (from the ND)

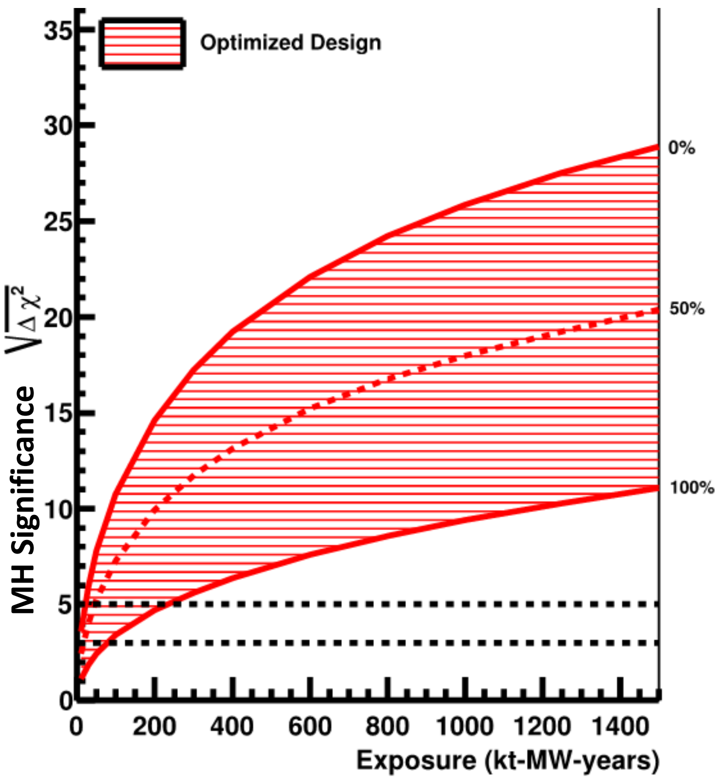




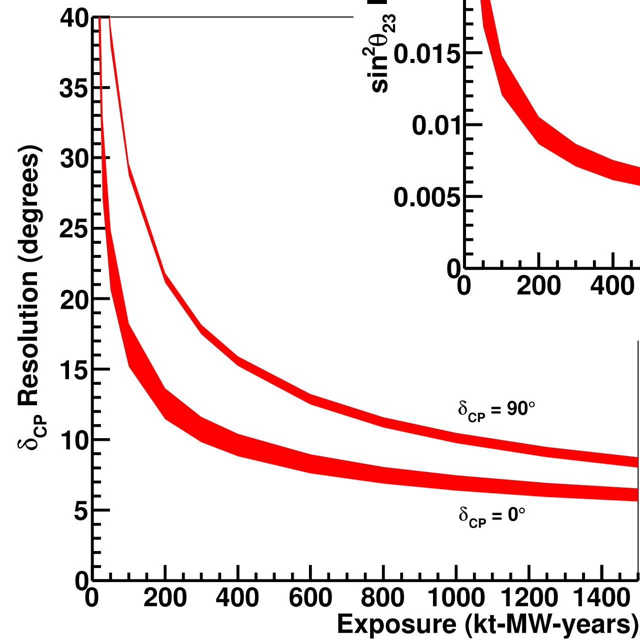
<3 % ν_e systematics important after ~200 kt.MW.yr

MH, δ_{CP} and $\sin^2\theta_{23}$ Sensitivities

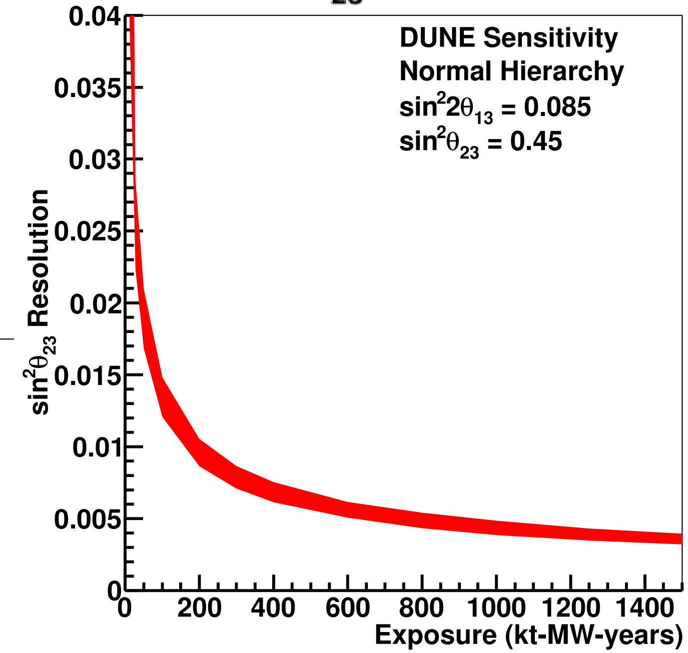
Mass Hierarchy Determination



δ_{CP} Resolution



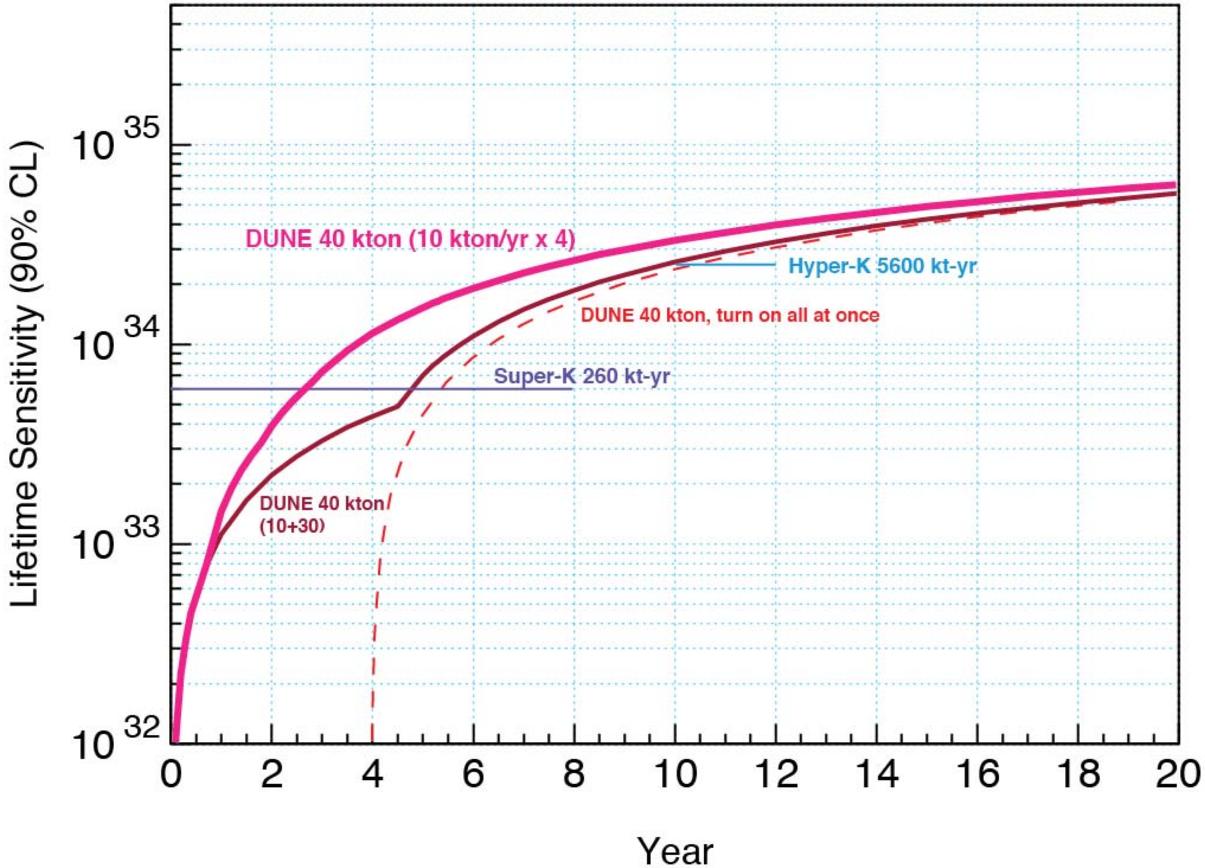
$\sin^2\theta_{23}$ Resolution



Proton Decay Sensitivity

$p \rightarrow K^+ \bar{\nu}$

- DUNE for various staging assumptions



Physics Milestones

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - with **60 – 70 kt.MW.year** reach **3σ** CPV sensitivity
- e.g. in best-case scenario for MH :
  - with **20 – 30 kt.MW.year** reach **5σ** MH sensitivity

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{CP} = 0$)	450	290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

★ **Genuine potential for early physics discovery**

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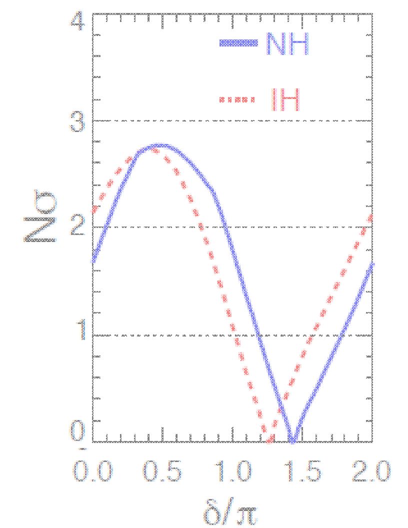
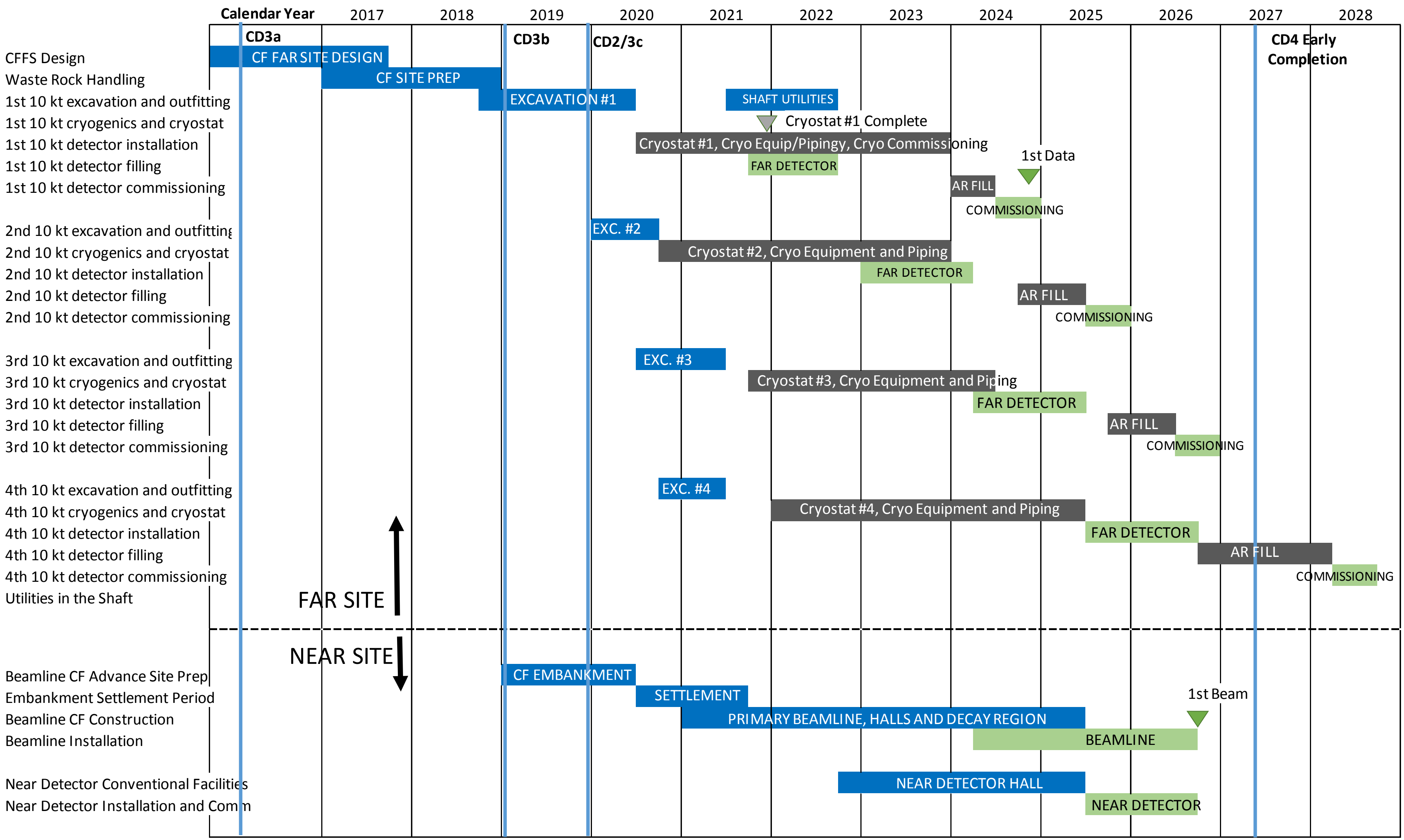
Global Fit
E.Lisi et al.
Moriond 2015



★ **Genuine potential for early physics discovery**

LBNF/DUNE Schedule Summary Overview



Summary

LBNF/DUNE has

- **an advanced design for a world-leading experiment focused on fundamental open questions in particle physics and astroparticle physics**
- **a clear scientific strategy and a project plan to implement it**
- **the capability of making major discoveries in**
  - **Long-baseline oscillation physics**
  - **Nucleon decay**
  - **Neutrino astrophysics**
  - **Neutrino scattering physics**
  - **. . .**