Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

BNL Neutrino Research

Chao Zhang
Electronic Detector Group (EDG)

7/10/2023

Electronic Detector Group (EDG)

- ❑ Neutrinos
  - DUNE, MicroBooNE, ICARUS, SBND
  - Daya Bay, PROSPECT
- ❑ Heavy Flavor
  - Belle II
- ❑ Muon Physics
  - g-2
- ❑ Kaon Physics (historical)
  - E949, E787
- ❑ Detector R&D
- ❑ Software & Computing

Current Experiments

https://www.phy.bnl.gov/edg/

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History of BNL Neutrino Research

1956: Theory of Parity Violation in Weak Interactions
T.D. Lee, C.N. Yang

1957: Discovery of Neutrino Helicity
Goldhaber, Grodzins, Sunyar

1962: Discovery of Muon Neutrinos
Lederman, Schwartz, Steinberger

1967: First Measurement of Solar Neutrinos
R. Davis

1990s – 2020s: Neutrino Oscillation Era

- IMB / Super-Kamiokande
- SNO
- MINOS
- Daya Bay / PROSPECT
- LBNE / DUNE
- MicroBooNE / SBND / ICARUS

1957

1988

2002

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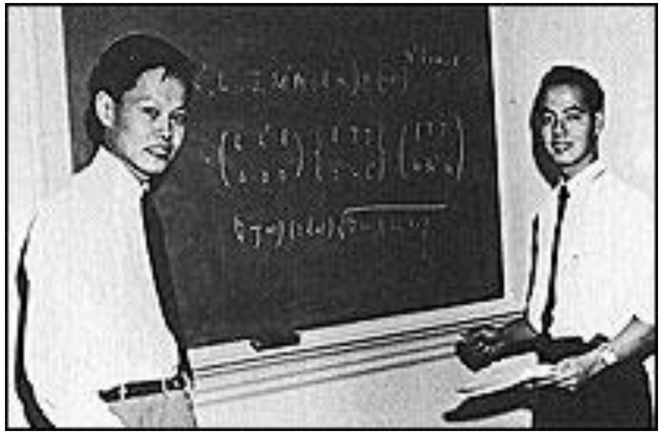
Theory of Parity Violation in Weak Interactions



Phys. Rev. ***104****, 254 (1956)*

Question of Parity Conservation in Weak Interactions*

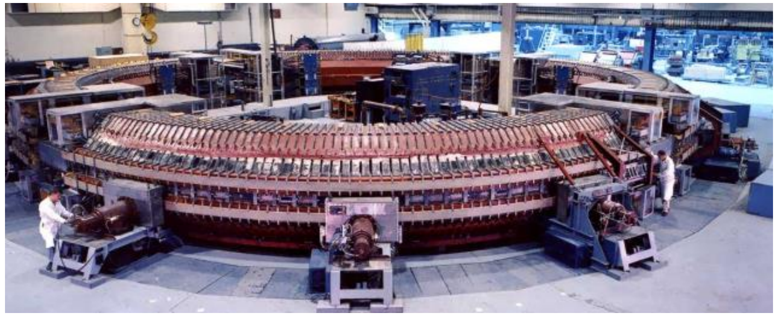
T. D. Lee, *Columbia University, New York, New York*

AND

C. N. Yang,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.



BNL Cosmotron (1952-1966)

First accelerator in the world to send particles to energies in the GeV region

$\theta - \tau$ puzzle:

- ❑ Same mass, lifetime, spin, etc.
- ❑ Different parity

$$\tau^+ \to \pi^+ + \pi^0$$
$$\theta^+ \to \pi^+ + \pi^+ + \pi^-$$

$$K^+ \to \pi^+\pi^0 \text{ or } \pi^+\pi^+\pi^-$$
$$(\tau = 1.2\times10^{-8}\text{s})$$

Neutrino Helicity

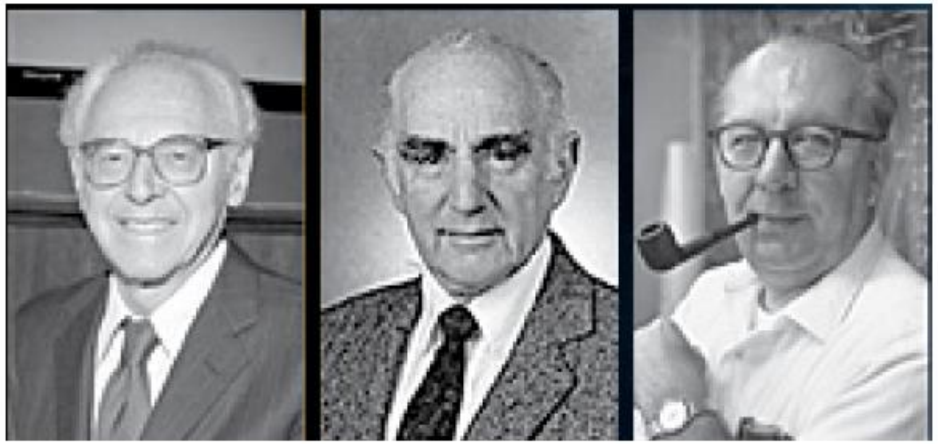
Helicity of Neutrinos*

M. GOLDHABER, L. GRODZINS, AND A. W. SUNYAR

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

Phys. Rev. ***109****, 1015 (1957)*



Maurice Goldhaber Lee Grodzins Andrew Sunyar

Goldhaber: group leader at BNL

Grodzins: Goldhaber's postdoc

Sunyar: Goldhaber's student

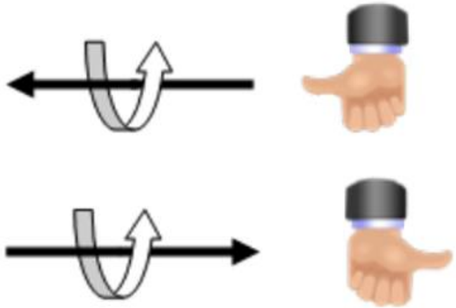
The Goldhaber group were world's experts in nuclear spectroscopy

- Probably the only team then who know the spin level scheme of ^{152}Eu – ^{152}Sm

Goldhaber: "I knew about Europium".

Are neutrinos right-handed or left handed?

$\boldsymbol{\sigma} \cdot \hat{\boldsymbol{p}}$

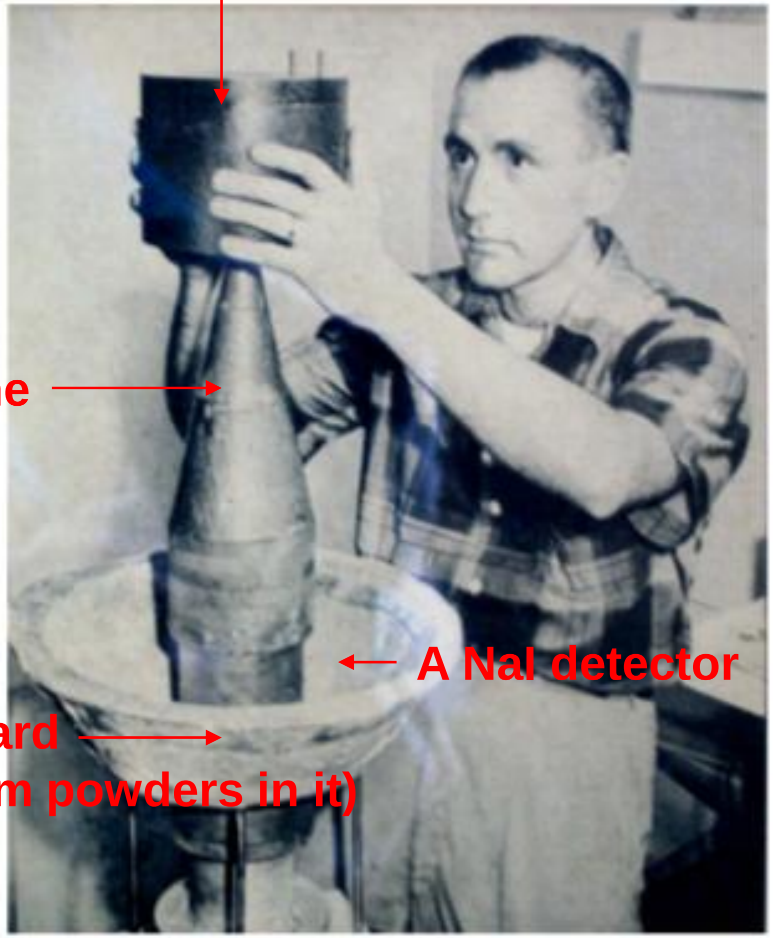


The GGS Experiment

A table-top experiment that cost a few thousand dollars

- ❑A ^{152m}Eu source prepared in a reactor
- ❑An electromagnet for photon polarization
- ❑A Pb cone to block direct gamma ray
- ❑A cardboard to contain $^{152}Sm_2O_3$ powders
- ❑A NaI detector to detect de-excitation gamma ray from $^{152}Sm^*$

Key idea: transfer the neutrino helicity to the photon helicity so that it can be measured



Photograph of Lee Grodzins with the helicity-of-neutrino experimental set-up.

How does it work?

$$^{152m}\mathbf{Eu} + \mathbf{e}^{-} \rightarrow {}^{152}\mathbf{Sm}^{*} + \boldsymbol{\nu}_{\mathbf{e}}$$

0 1/2 1 1/2

neutrino helicity = recoil $^{152}Sm^{*}$ helicity

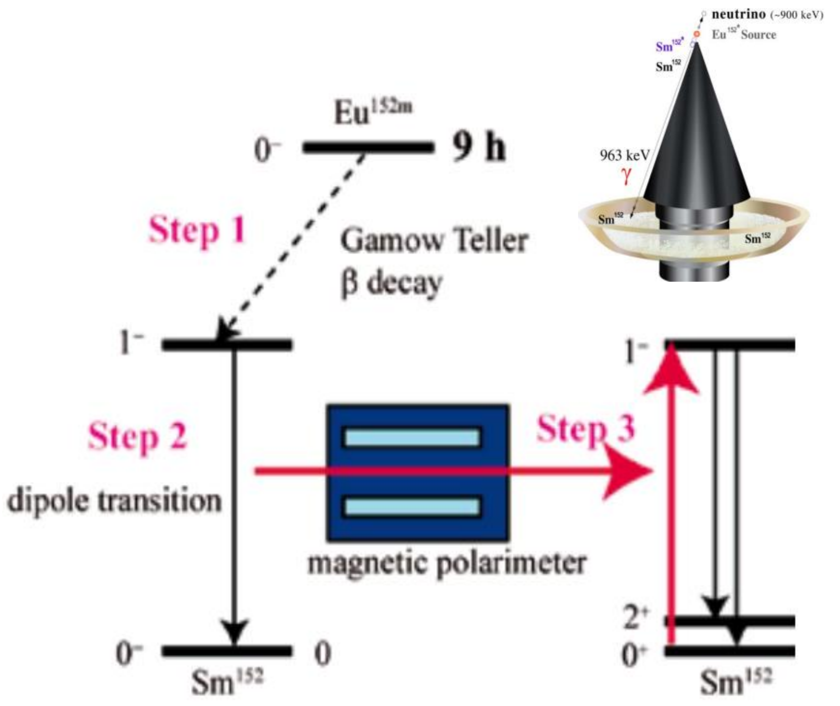
$$^{152}\mathbf{Sm}^{*} \rightarrow {}^{152}\mathbf{Sm} \quad + \boldsymbol{\gamma}\,(\mathbf{963})$$

1 0 1

recoil $^{152}Sm^{*}$ helicity = γ (963) helicity if the γ is emitted in the direction of the recoil

$$\boldsymbol{\gamma}(\mathbf{963}) + {}^{152}\mathbf{Sm} \quad \rightarrow {}^{152}\mathbf{Sm}^{*}$$

Can only happen if the γ (963) is emitted in the direction of the recoil (resonant fluorescence)



Measure neutrino helicity = Measure γ (963) helicity

- Direction: detect the de-excitation of $^{152}Sm^{*}$
- Spin: electromagnet polarization

Neutrino helicity = -1 +- 0.2

Neutrinos are left-handed

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Maurice Goldhabor (1911-2011)

Joined BNL in 1950, become BNL director from 1961-1973

- vital to the growth and development of many areas of research at BNL.

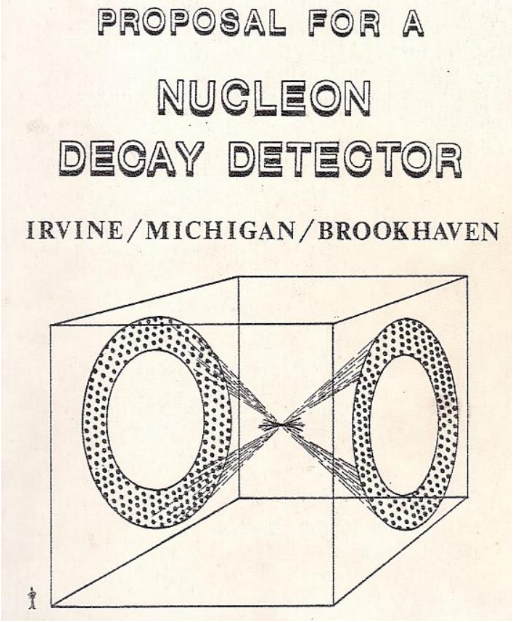
His attitude toward doing experiments:
" … Say what you know and say what you believe, but don't put the belief as a fact …… It's hard to go out of one's way and make a tremendous effort to test something which everybody believes, but when it's easy, at least, do it."

One example: proton decay
"No one has a theory right now which says the proton must be stable, so it's only a belief."

Maurice Goldhabor (1911-2011)

The IMB Experiment
(Irvine–Michigan–Brookhaven)

1979



Actually, the “Brookhaven” has only one person: Maurice Goldhabor.

Therefore, when talked about IMB, he often liked to point to himself and joked “I AM B”.

Discovery of Muon Neutrinos

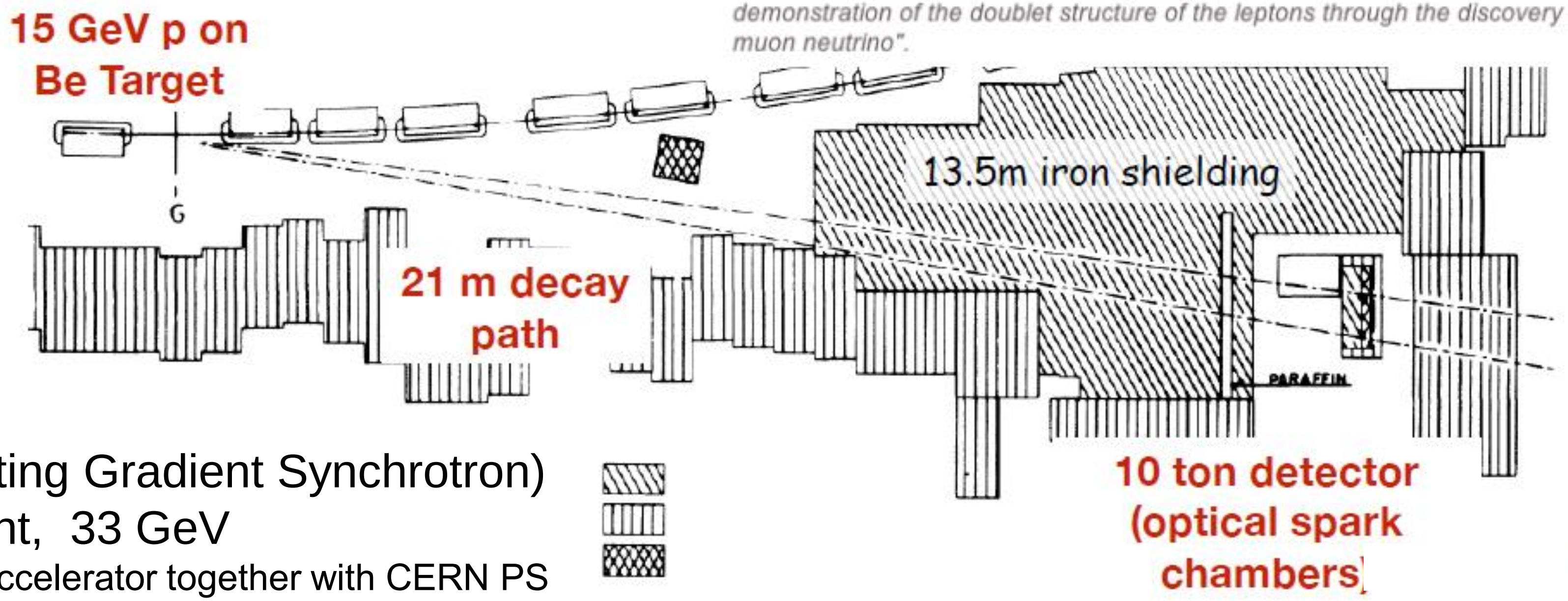
1956: Electron (anti-)neutrinos directly observed at the Savannah River reactor (Cowan, Reines)

Q: Are there (muon) neutrinos that are associated with muons?

1962: The two-nu experiment at BNL
(World's first accelerator neutrino experiment)

Leon M. Lederman Melvin Schwartz Jack Steinberger

The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino".*



AGS (Alternating Gradient Synchrotron)
1960 – present, 33 GeV
World's leading accelerator together with CERN PS

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National Labo

Results

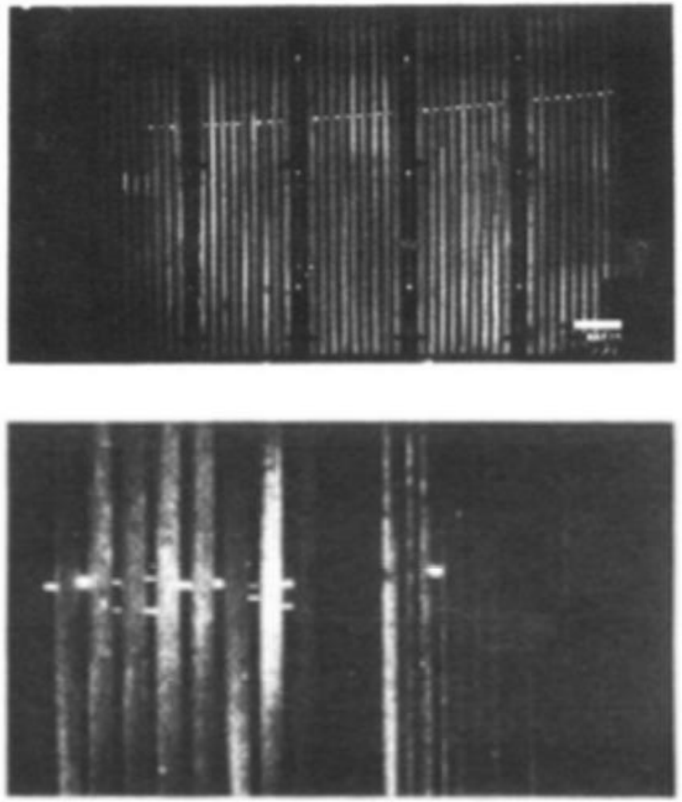
34 single muon events

- 5 are consistent with cosmic ray background

6 “shower” events

- Consistent with neutrons, misidentified muons and beam electron neutrino background

Conclusion: There are two kinds of neutrinos.



- Today we would say that this is a very short baseline $\nu_\mu \rightarrow \nu_e$ oscillation experiment:
  - Average E ~ 1 GeV; Average L ~ 24 m
  - Excluded $\sin^2 2\theta > 0.4$ at 90% C.L. for $\Delta m^2 > 15\ eV^2$

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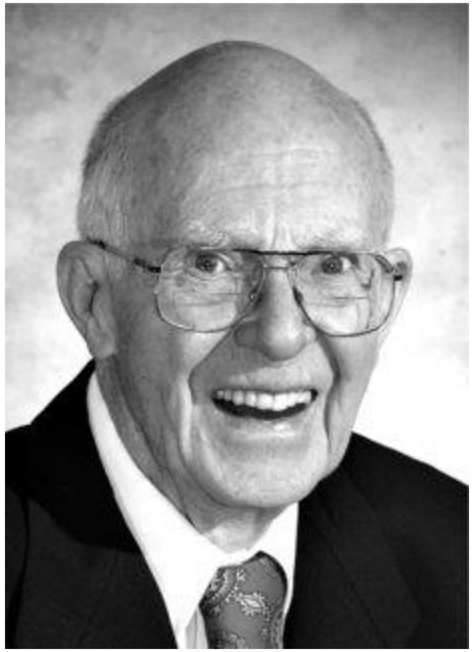
Raymond Davis Jr. (1914 – 2006)

Joined BNL (Chemistry Department) in 1948

On arriving at Brookhaven, he reported to the chairman of the Chemistry Department, Richard Dodson, and ask him what he was expected to do

> "To my surprise and delight, I was advised to go to the library, do some reading and choose a project of my own, whatever appealed to me. Thus began a long career of doing just what I wanted to do and getting paid for it. "



Davis read this article and decided to do an experiment in neutrino physics

REVIEWS OF MODERN PHYSICS VOLUME 20, NUMBER 1 JANUARY, 1948

The Energy and Momentum Relations in the Beta-Decay, and the Search for the Neutrino

H. R. CRANE

Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan

Brookhaven National Laboratory

The radiochemical reaction

$$^{37}_{17}Cl + \nu_e \rightarrow ^{37}_{18}Ar + e^-$$

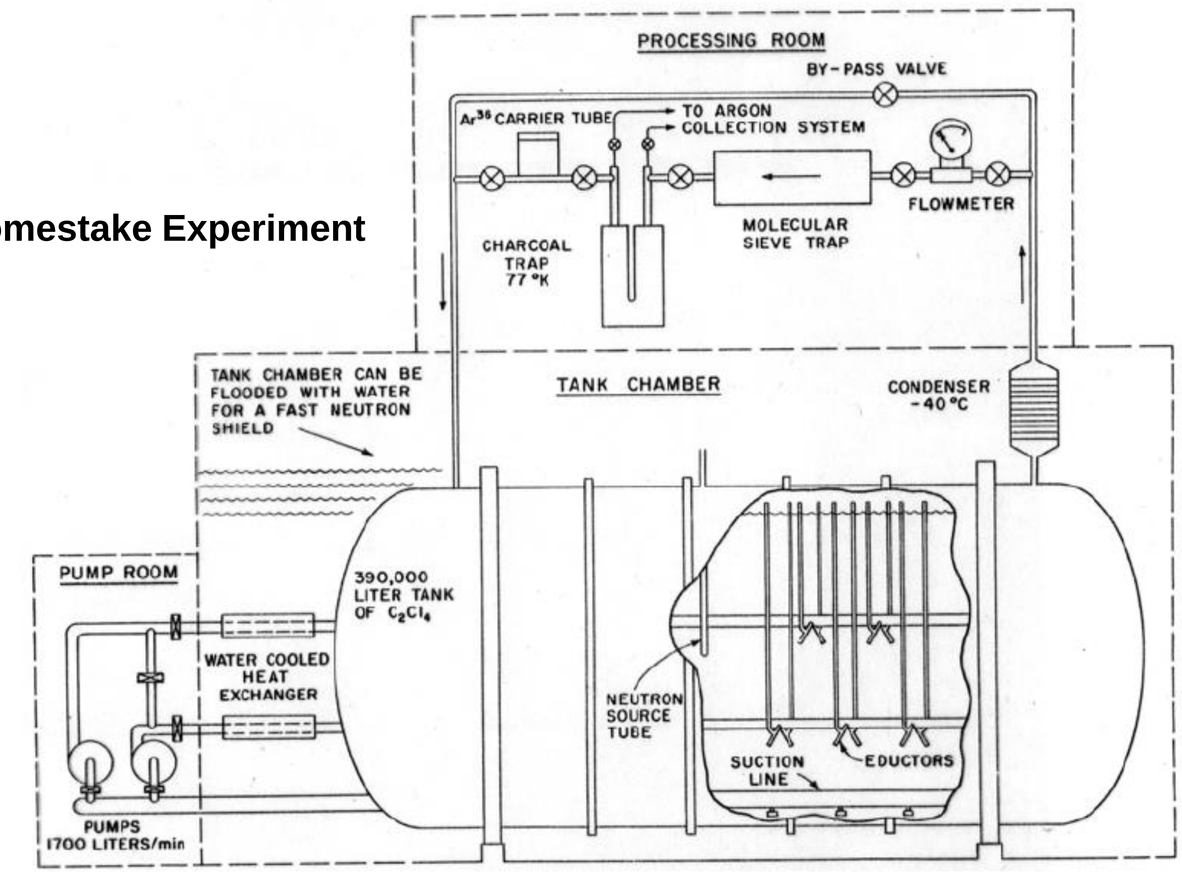
Threshold: 814 keV

proposed by Bruno Pontecorvo in 1946

- 1955: First paper with a 1000 gal. tank of CCl_4 at 19 ft below the sandy soil at BNL
  - First demonstration of extraction and counting of a few ^{37}Ar atoms
  - No positive signal: crude upper limit to the solar neutrino flux of about 40,000 SNU. (1 SNU = 10^{-36} neutrino capture per second per target)

A reviewer of Davis's paper made the following critical but amusing comment: "Any experiment such as this, which does not have the requisite sensitivity, really has no bearing on the question of the existence of neutrinos. To illustrate my point, one would not write a scientific paper describing an experiment in which an experimenter stood on a mountain and reached for the moon, and concluded that the moon was more than eight feet from the top of the mountain."

The Homestake Experiment



100,000 gallons of C_2Cl_4 in a tank at 4850 feet underground at South Dakoda

Atoms of ^{37}Ar extracted by Helium purge every few months (35 days half-life) and their decays are counted in a counting station

- < 1 ^{37}Ar atom produced per day by neutrino capture

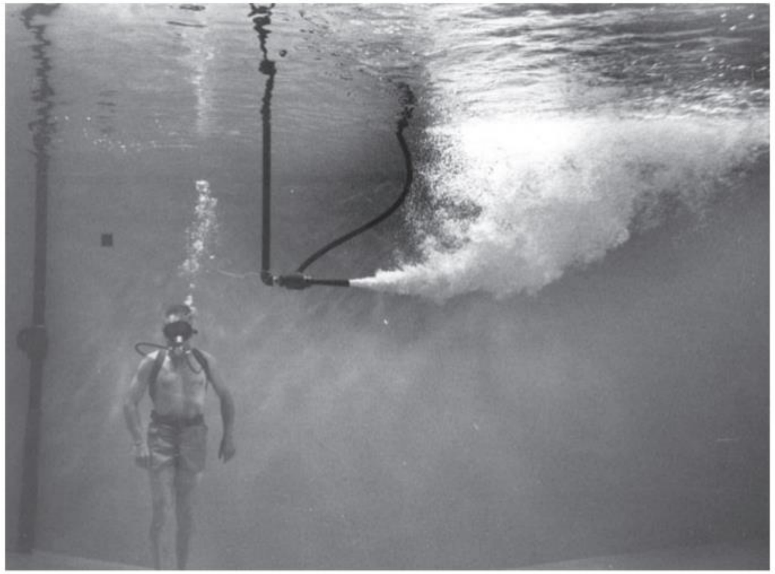
Challenges

1968: Results from the first two runs show no positive signal → upper limit of 3 SNU

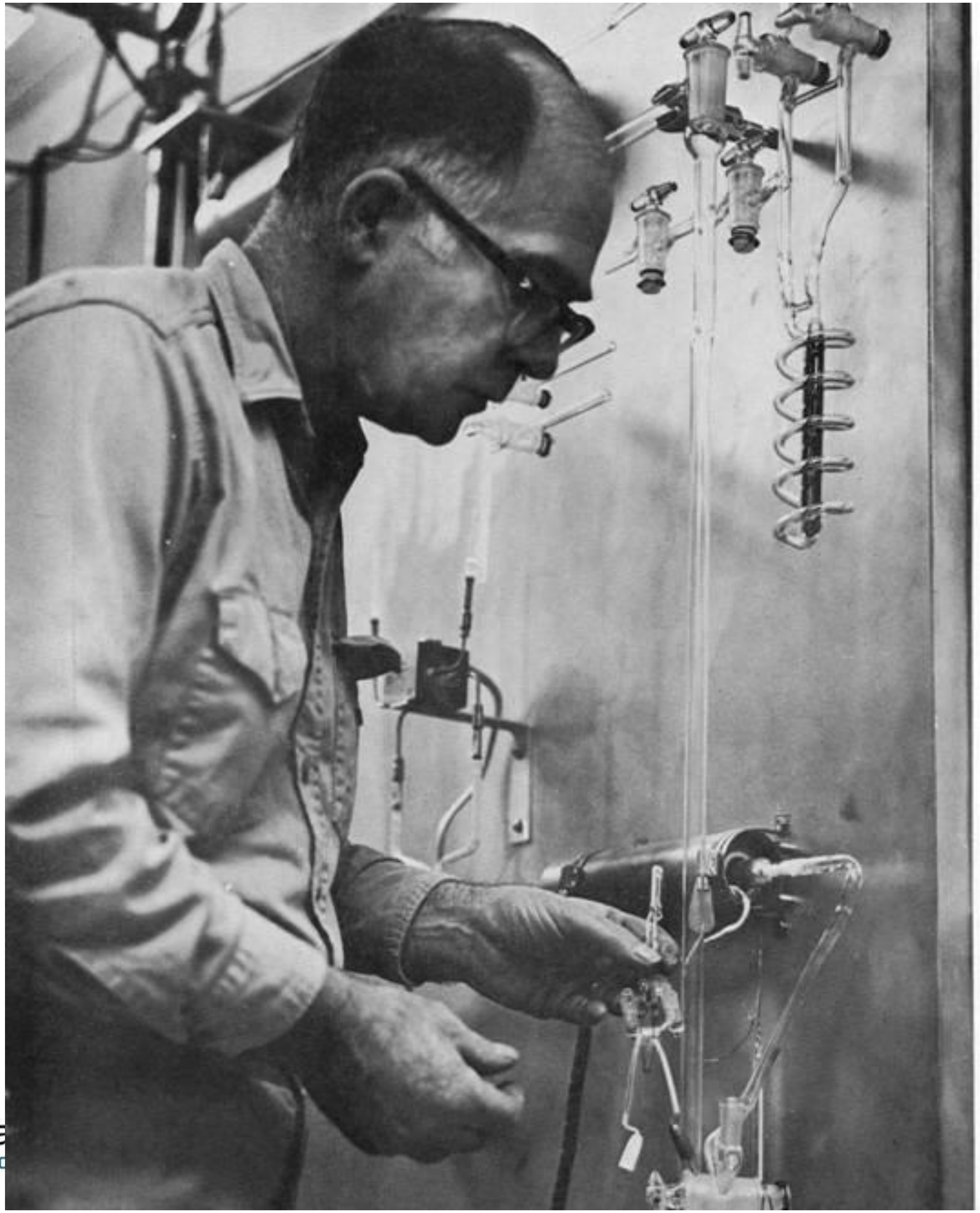
- while theory predicted 7-8 SNU!

Three main challenges:

- Show Argon extraction efficiency is high
  - Known amount of ^{36}Ar and ^{38}Ar carrier gas was injected. Extraction efficiency shown to be always >95%.
- Show cosmic ray rate is as expected
  - Campaign of placing smaller C_2Cl_4 detectors at various depth of the mine.
- Further reduce ^{37}Ar counter background (~10 counts per month)
  - Improvement on electronics

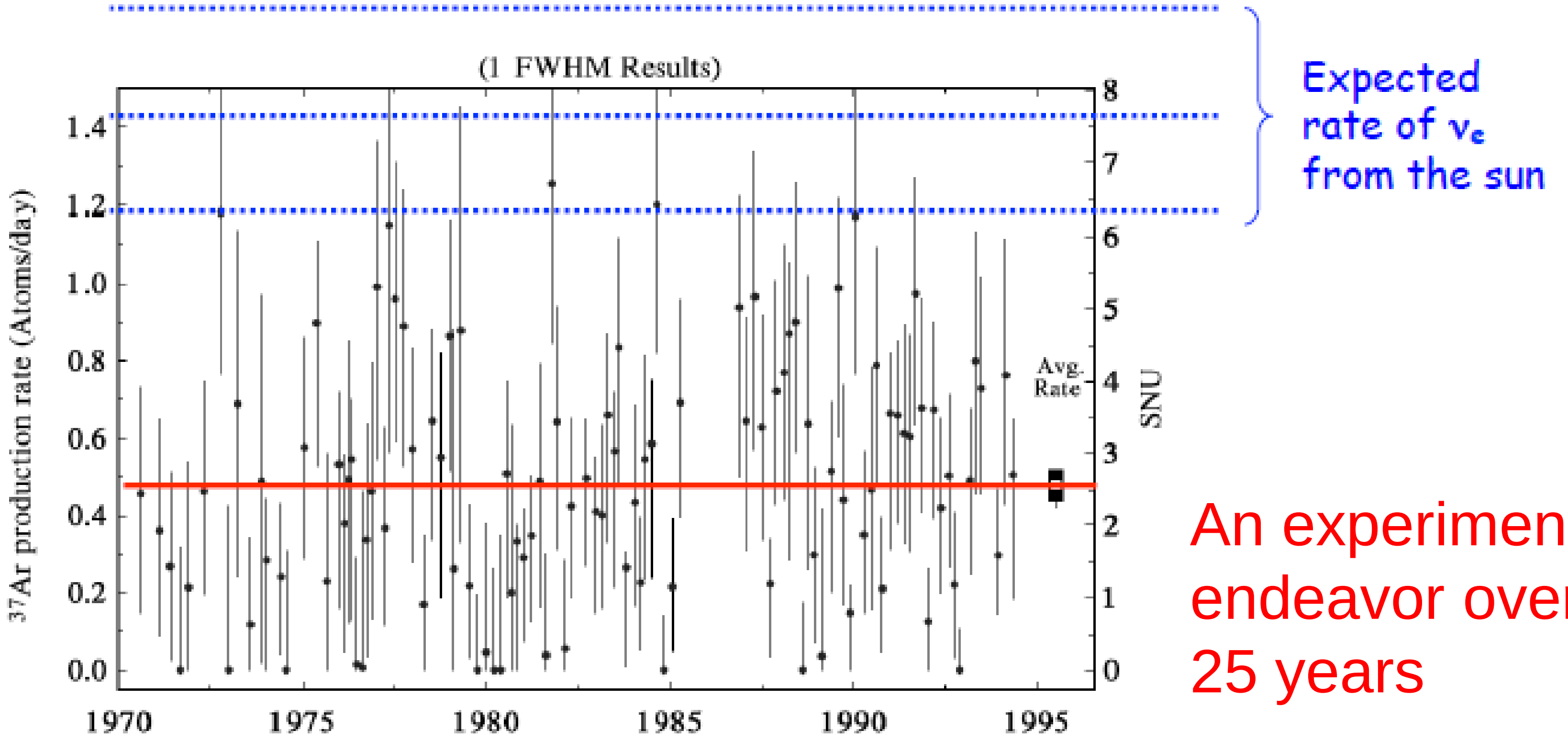


Photography of R. Davis testing the eductors for the Homestake detector's argon-extraction system in BNL's swimming pool.



DR. RAY DAVIS is holding a small proportional counter which he is preparing to fill with radioactive argon-37 recovered from the storage vessel. This extremely sensitive counter will register the radioactive decay of argon-37 if it is produced in the vessel by a neutrino "capture."

Results: The Solar Neutrino Problem



An experimental endeavor over 25 years

Measurement: 2.56 +- 0.23 SNU

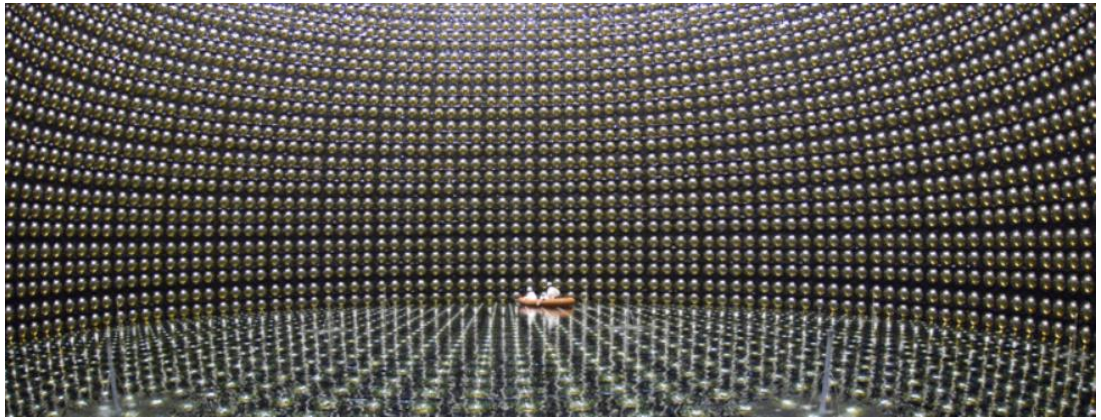
Standard Solar Model prediction: 7.6 +- 1.3 SNU

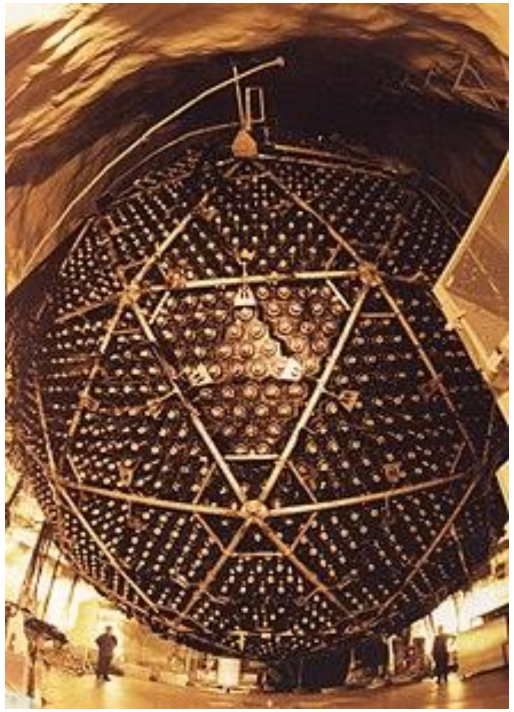
Two thirds of the solar neutrinos were missing

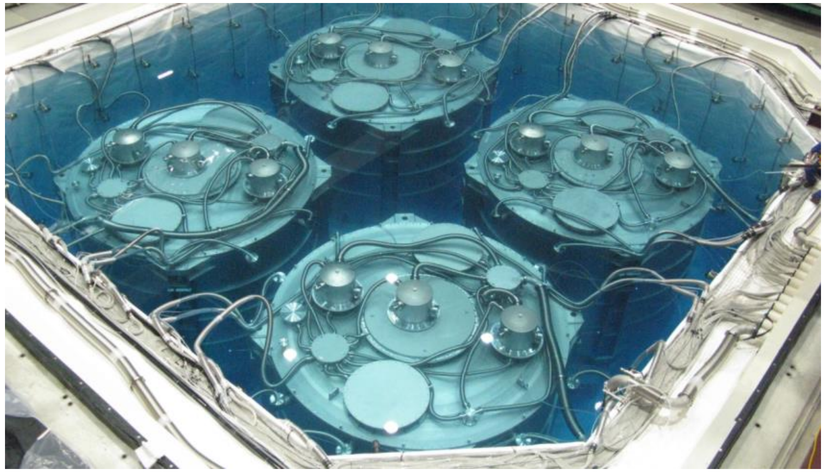
Proposals of possible solutions

turbulent diffusion of ^3He (Schatzman 1969); neutrino oscillations (Gribov and Pontecorvo 1969; Wolfenstein 1978); an overabundance of ^3He in the present Sun (Kocharov and Starbunov 1970); the effect of a magnetic field (Abraham and Iben 1971; Bahcall and Ulrich 1971; Bartenwerfer 1973; and Parker 1974); a secular instability such that the presently observed solar luminosity does not equal the current energy-generation rate (Fowler 1968, 1972; Sheldon 1969); quark catalysis (Libby and Thomas 1969; Salpeter 1970); a very low heavy element abundance in the solar interior (Bahcall and Ulrich 1971); an appreciable magnetic moment for the neutrino (Cisneros 1971); an instability of the Sun that makes now a special time (Fowler 1972; Dilke and Gough 1972); neutrino decay (Bahcall, Cabibbo and Yahil 1972); a low-energy resonance in the ^3He-^3He reaction (Fowler 1972; Fetisov and Kopysov 1972); rapid rotation of the solar interior (Demarque, Mengel, and Sweigert 1973; Roxburgh 1974; and Rood and Ulrich 1974); rotation plus magnetic fields (Snell, Wheeler, and Wilson 1976); a burned-out Sun with a helium core (Prentice 1973); a half-solar mass core of large heavy element abundance that survived the big bang and subsequently accreted another half solar mass at the time of the formation of the solar system (Hoyle 1975); a departure from the Maxwellian distribution (Clayton et al. 1975); a fractionation of the primordial hydrogen and helium (Wheeler and Cameron 1975); accretion onto a black hole in the center of the Sun (Clayton, Newman, and Talbot 1975); and multiplicative mass creation (Maeder 1977).

This led to another 30 years of neutrino oscillation experimental research at BNL until today







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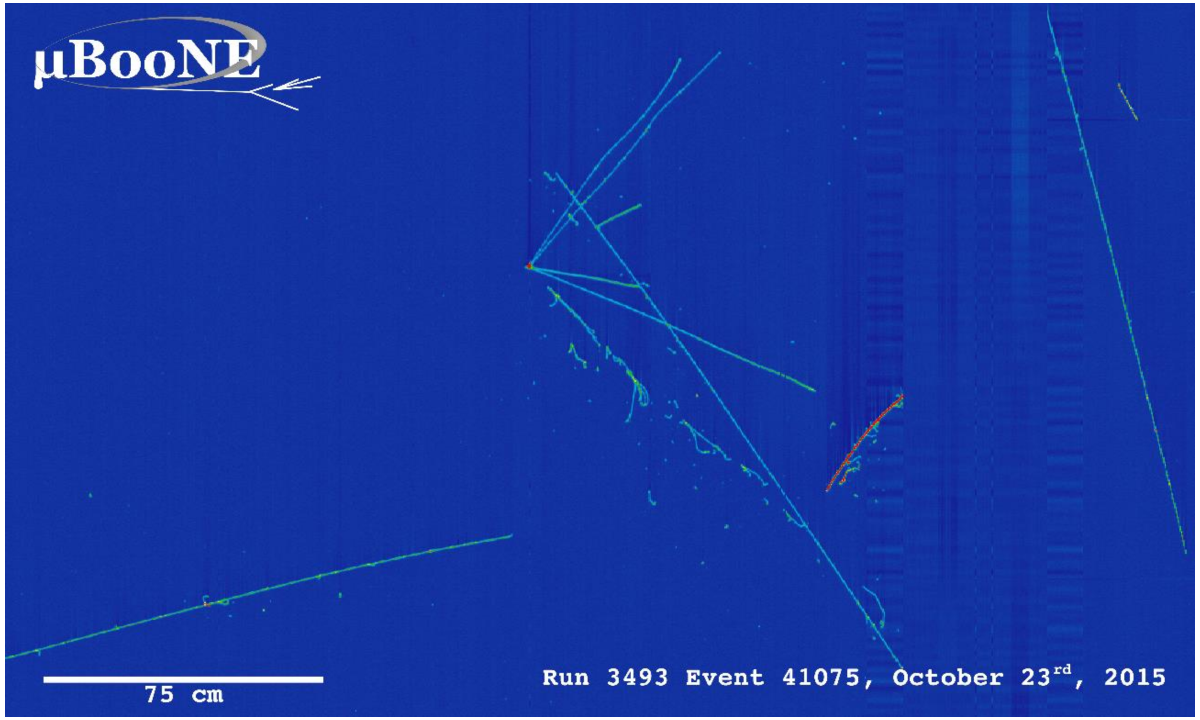
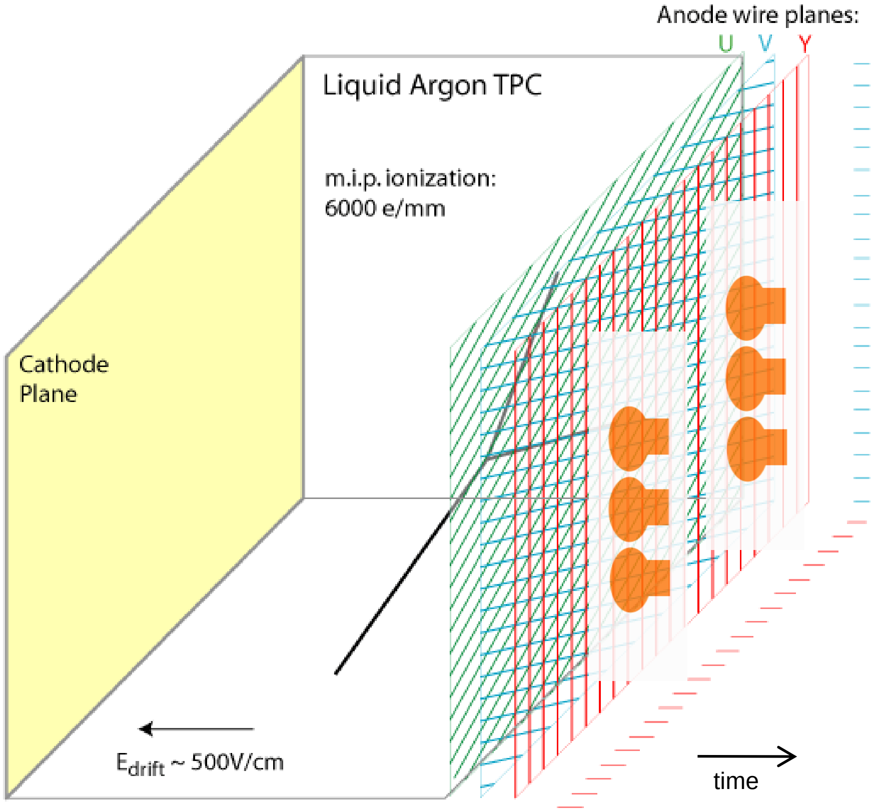
Liquid Argon Time Projection Chamber (LArTPC)

~mm scale position resolution in 3D

From Bo Yu (BNL)





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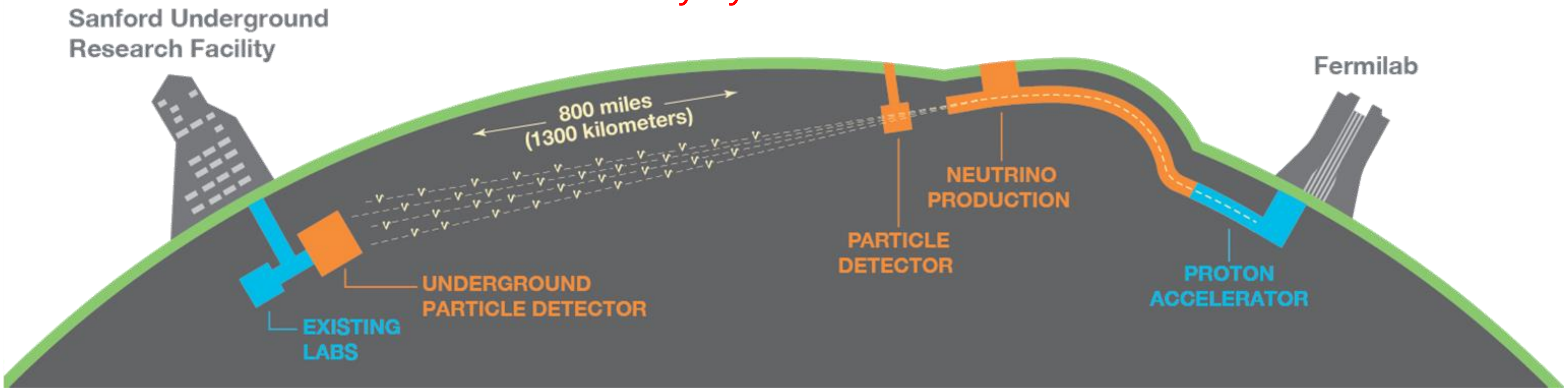
drift speed 1.6 m/milisec @ 500 V/cm E-filed
wire pitch 3 mm

Deep Underground Neutrino Experiment

Talk today by Mateus Carneiro



DUNE will be the flagship neutrino experiment in the U.S. for the next 20 years

- 40 kt LArTPC as the far detector
- Expect first data taking in late 2020s

- ❑ CP violation in neutrino sector
- ❑ Neutrino mass ordering
- ❑ Precision neutrino oscillation parameters
- ❑ Phenomenon from sterile neutrinos
- ❑ Supernova neutrinos
- ❑ Nucleon decay
- ❑ …

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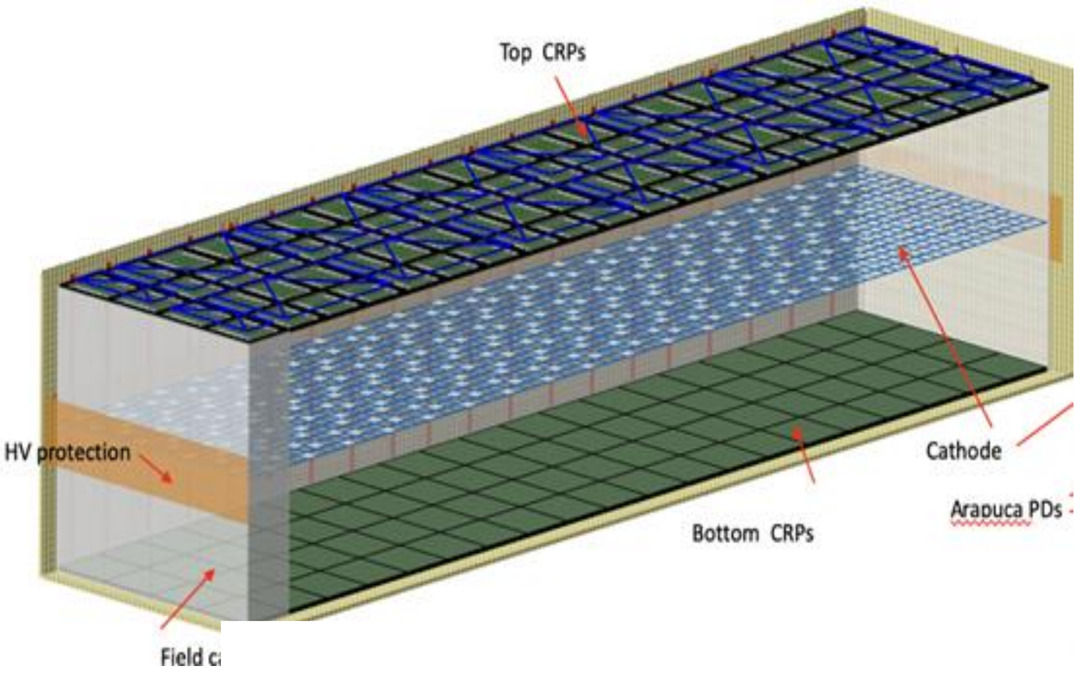
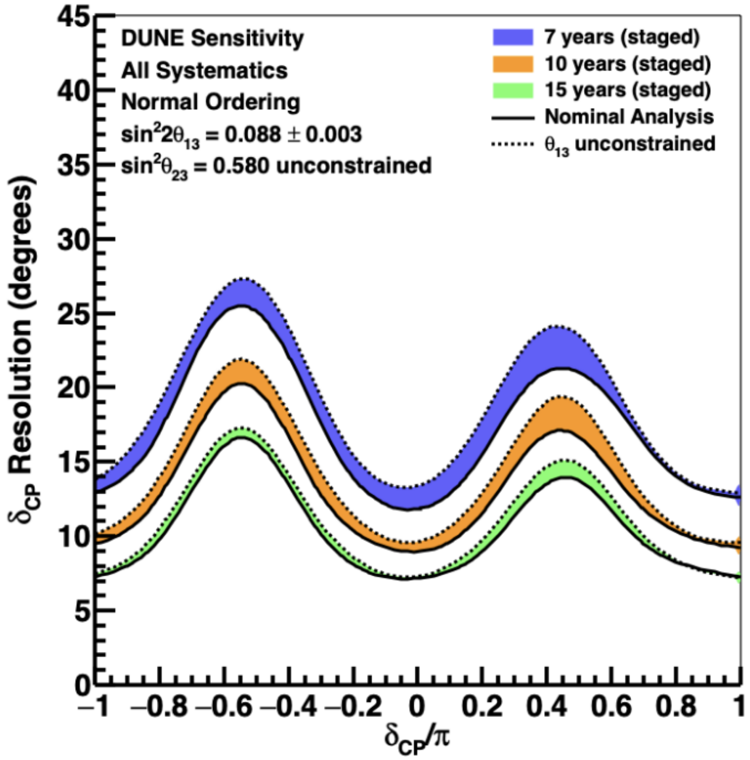
BNL in DUNE

- Far Detector 2 (Vertical Drift)
  - Leading overall international Vertical Drift project
  - Leading US Vertical Drift project
  - Leading development of anode readout (CRP), HV, cold electro
  - Leading US contributions to HV, CRP and installation;
  - major contributions to cold electronics
- Far Detector 1 (Horizontal Drift)
  - Major effort in cold electronics (key technology for both FD1 and FD2)
  - Lead HV
  - Leading Installation planning
- LBNF/DUNE Project Leadership Roles
  - Mary Bishai: co-spokesperson
  - Steve Kettell: FD2 Technical Coordinator
  - Jim Stewart: FD Installation Manager
- DUNE Physics Studies
  - Elizabeth Worcester: physics coordinator
  - LArTPC reconstruction, software tools, etc.





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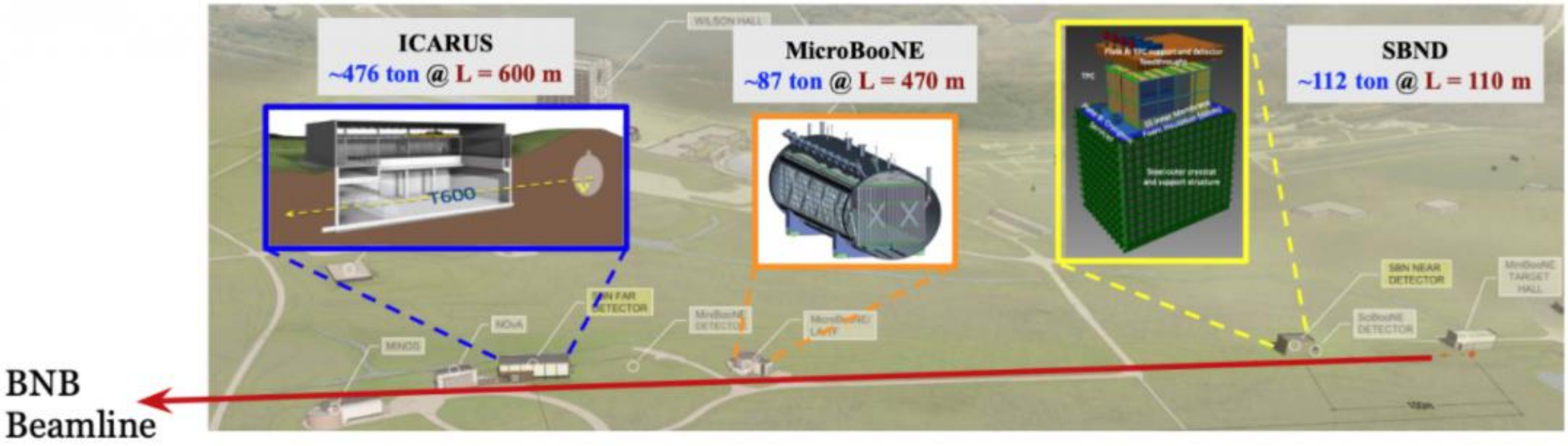
Short Baseline Neutrino Program

Talk today by Jay Jo



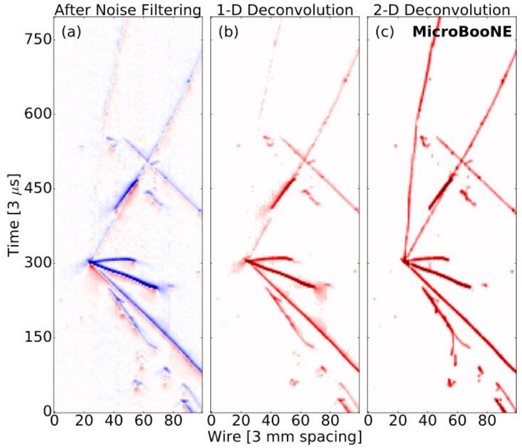
Multiple LArTPC experiments at different distances to search for different oscillation patterns from eV-scale sterile neutrinos

MicroBooNE: 2015 – 2022
ICARUS: started data taking last year
SBND: expect to take data end of this year

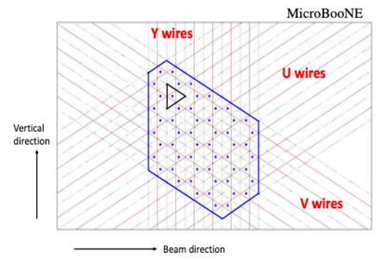
Wire-Cell Event Reconstruction

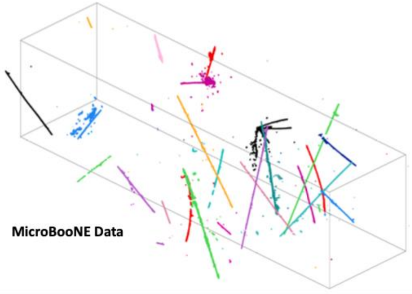
Talks on Thursday by Haiwang Yu and Nitish Nayak

TPC simulation	3D imaging	3D trajectory & dQ/dx fitting	multi-track fitting
noise filtering	clustering	cosmic muon tagger	DL-3D vertexing
signal processing	charge-light matching		particle identification

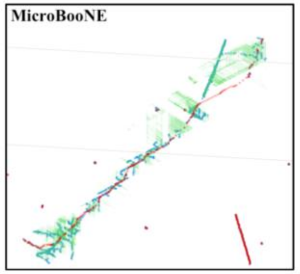


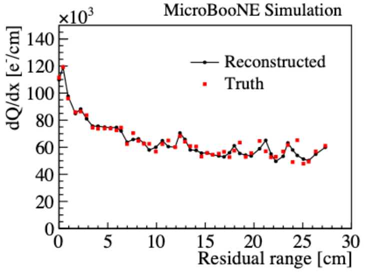
JINST 12 P08003 (2017)
JINST 13 P07006 (2018)
JINST 13 P07007 (2018)
JINST 16 P01036 (2020)



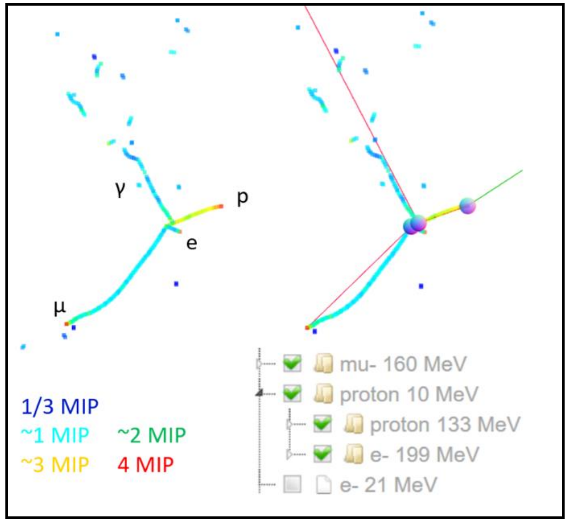


JINST 13 P05032 (2018)
JINST 16 P06043 (2021)





Phys. Rev. Applied 15 064071 (2021)



JINST 17 P01037 (2022)

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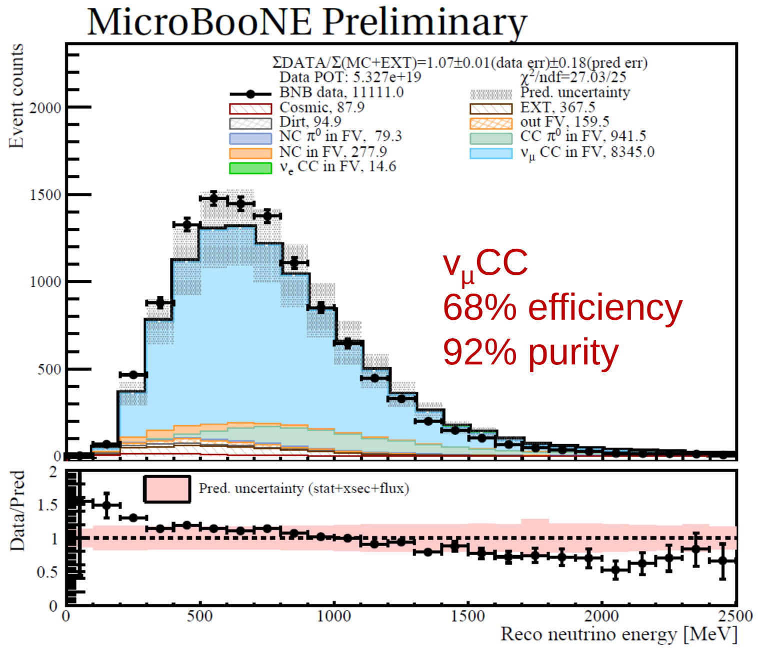
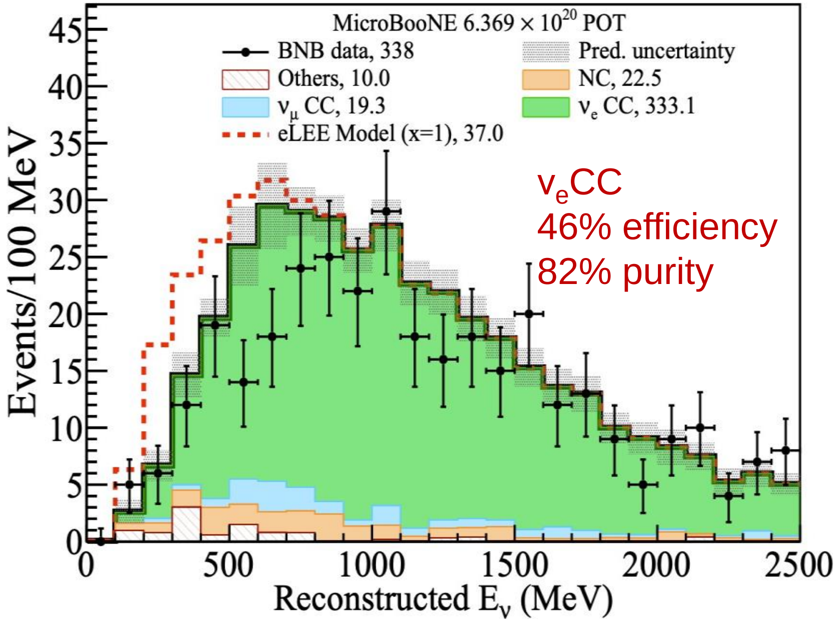
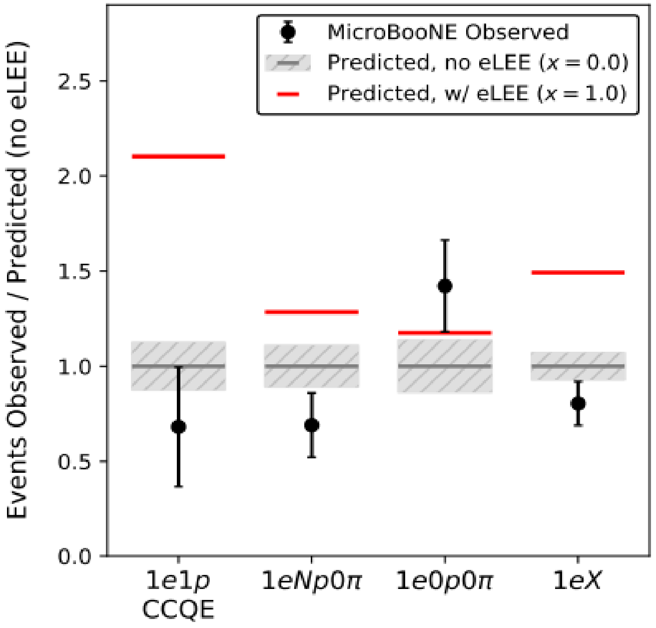
Wire-Cell in MicroBooNE

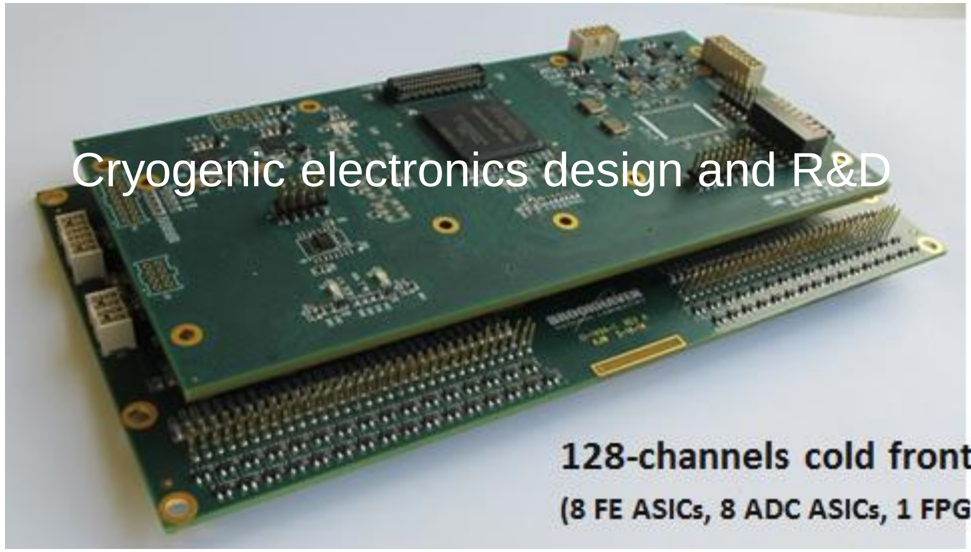
- High-performance inclusive charged-current ν_μ and ν_e event selection is achieved for **the first time** in a LArTPC
- Low Energy Excess analysis (best sensitivity among 4 analyses)
- Sterile Neutrino Oscillation analysis
- Inclusive and exclusive cross section measurements
- Wire-Cell Team: BNL, Yale, U. Michigan, UCSB, U. Chicago, LSU





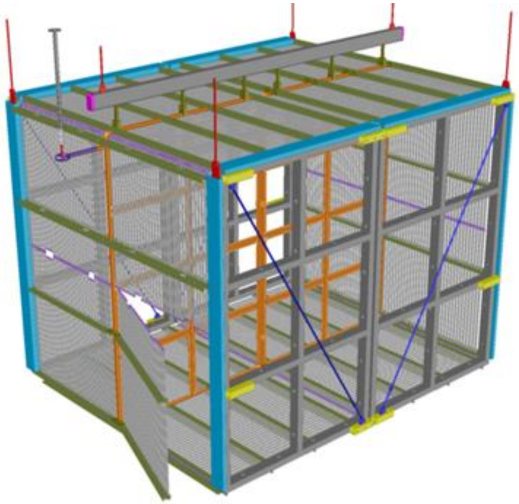


LArTPC R&D at BNL



Tour this afternoon by Shanshan Gao

LArTPC novel designs



Tour on Thursday by Yichen Li

https://lar.bnl.gov/

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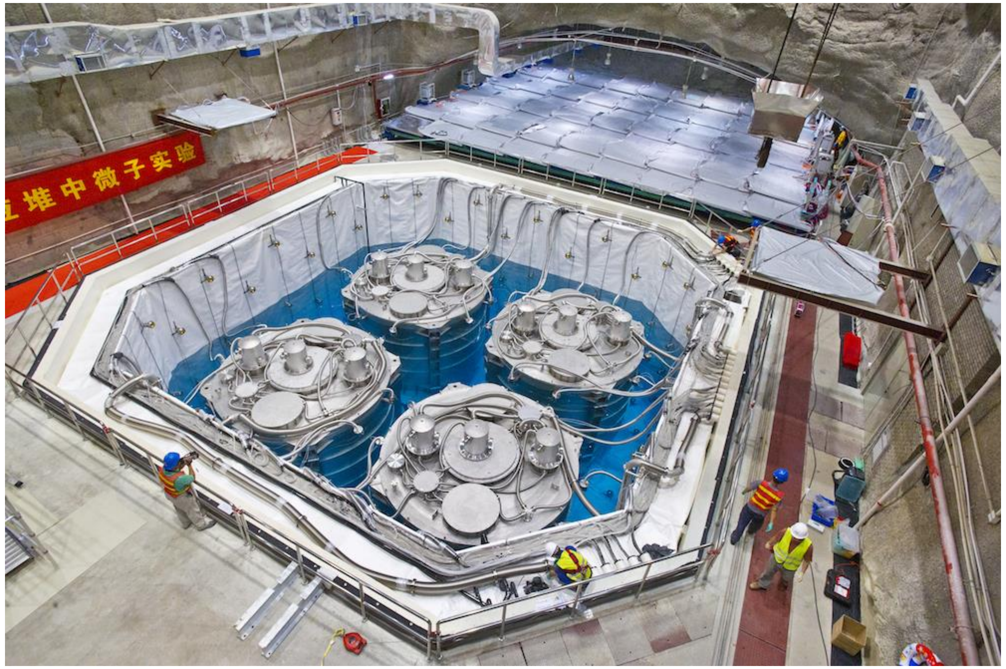
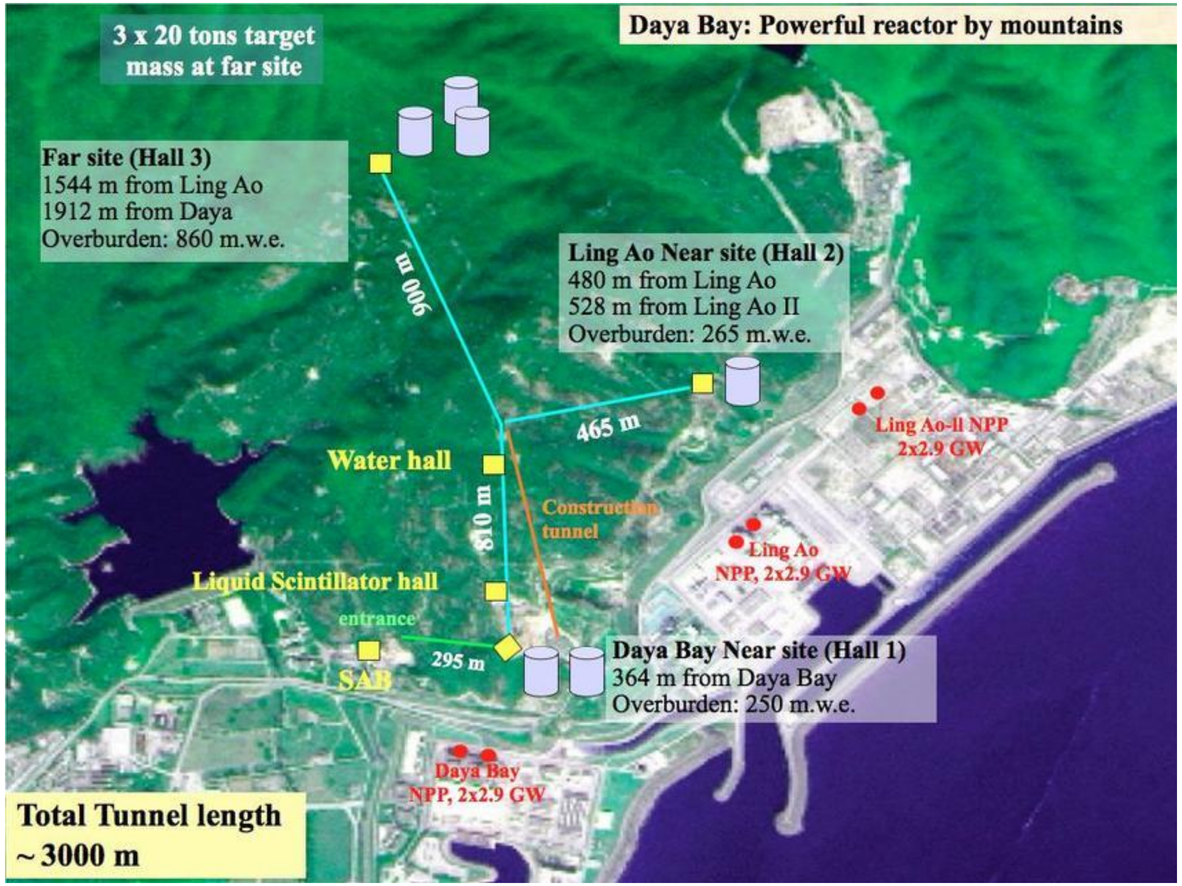
Daya Bay Reactor Neutrino Experiment

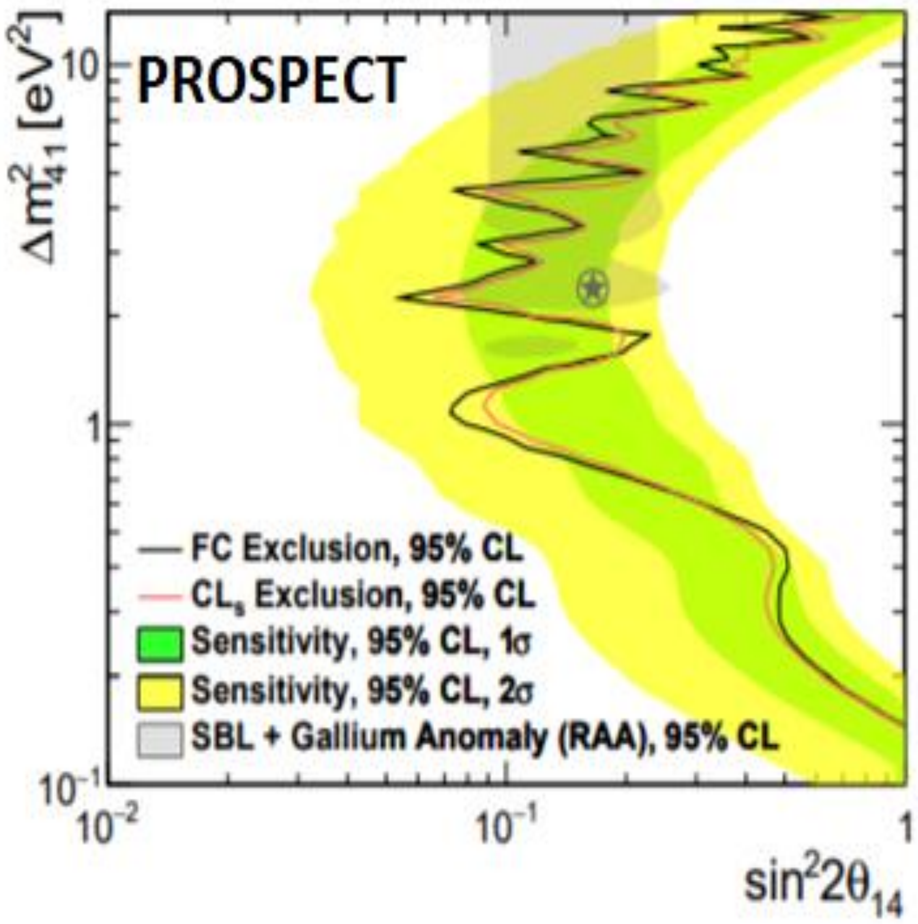


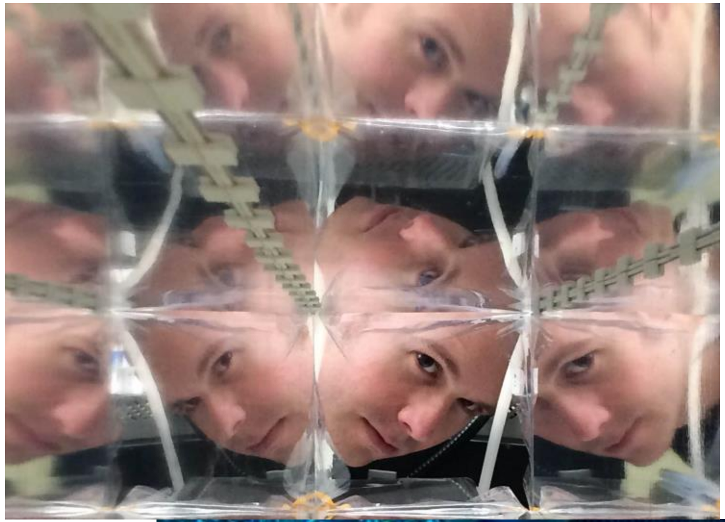
Talk on Tuesday by Chao Zhang

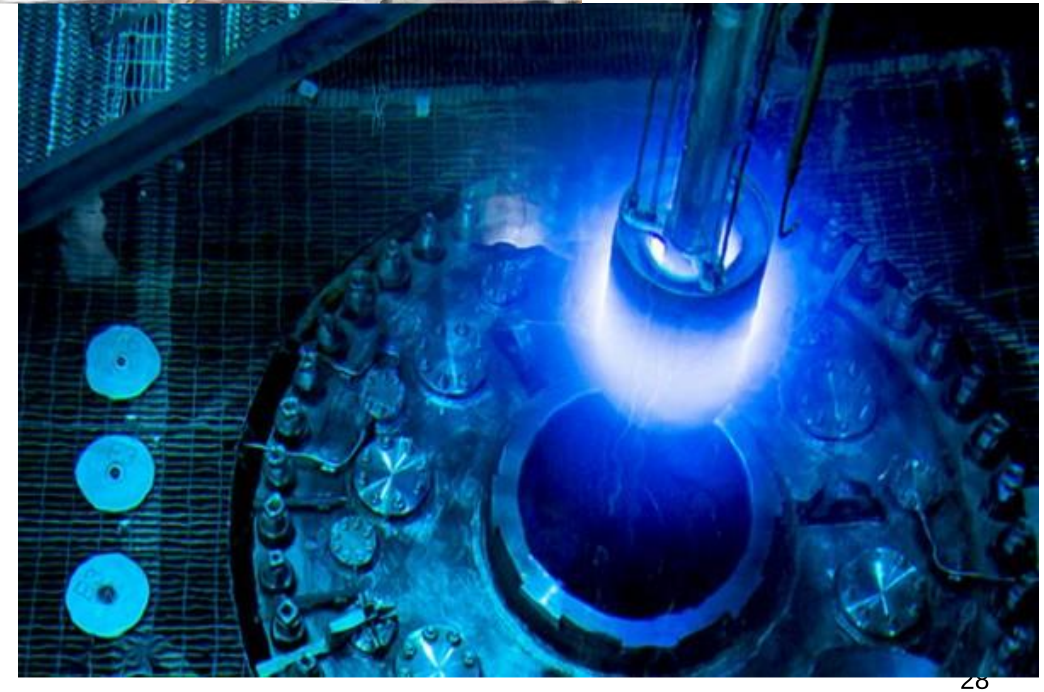


https://www.bnl.gov/science/dayabay.php

PROSPECT Reactor Neutrino Experiment



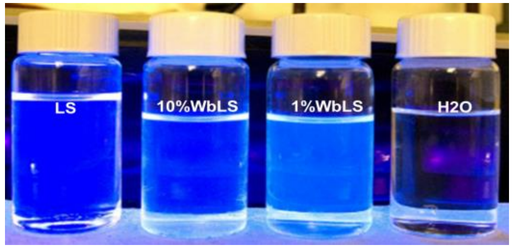




The High Flux Isotope Reactor (HIFR), Oakridge National Lab

(Tours on Tuesday in Chemistry Department and Instrumentation Division)

BNL Liquid Scintillator Development



Advanced development of novel liquid scintillator-based detector for neutrinos and other rare-event physics

- ❑Developer and production lead of Gd-doped LS for DayaBay experiment and LZ dark matter search
- ❑Initiator of Water-based Liquid Scintillator (WbLS): high energy Cherenkov & low-energy scintillation; A rich physics program spanning topics in nuclear, high-energy, and astrophysics, and across a dynamic range from hundreds of keV to many GeV.
- ❑Leverage existing expertise and facilities in photon detection and scintillator detector research with unique scientific leads across CO/IO/PO
  - LS Research Center includes in-house ton-scale LS production facility and multiple instrumentation labs
  - 1T-BNL Testbed: highly instrumented; capable of testing different liquid matrix; commissioned in 2022
  - 30T-BNL demonstrator; scale-up subsystems: WbLS circulation, Gd-plant, organic-nanofiltration, water-purification for WbLS kton-deployment; ~ready in 2023
- Ideal research platform for student researches (host ~3 per year)


Figure of 1-ton WbLS Testbed and ton-scale LS production facility.


Figure of the future home of the 30-ton demonstrator at BNL.

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QUESTIONS? DISCUSSION

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History of Neutrinos at BNL

Goldhaber Helicity Experiment 1957: Brookhaven Lab's Maurice Goldhaber performed an experiment that revealed neutrinos to be "left-handed."

Discovery of the Muon Neutrino 1962:, a new type of neutrino, the muon neutrino, was discovered at the Alternating Gradient Synchrotron at Brookhaven. Leon Lederman, Mel Schwartz, and Jack Steinberger received the 1988 Nobel Prize for this work, which established that there was more than one flavor of neutrino.

The Solar Neutrino Problem (Homestake Mine in South Dakota 1962-1980s): Ray Davis was the first to directly detect electron neutrinos produced by the sun. But he only observed about one-third of the expected amount. Ray Davis shared the Nobel Prize in 2002

The Irvine-Michigan-Brookhaven (IMB) detector Brookhaven's Maurice Goldhaber was also a founding member of a pioneering experiment in the Morton salt mine in Ohio in the early 1980s that became famous for observing neutrinos from Supernova 1987A (along with the Kamioka detector in Japan).

GALLEX and SNO: From the 1990s through the mid-2000s, Brookhaven's neutrino group played important roles in the GALLEX (Gallium Experiment) and SNO (Sudbury Neutrino Observatory) experiments in Italy and Canada, respectively. In 2015, Arthur B. McDonald of Canada's Queen's University and SNOLAB, shared the Nobel Prize in Physics with Takaaki Kajita, leader of the Super-Kamiokande experiment in Japan, for their work demonstrating that neutrinos change identities, or oscillate.

Super-Kamiokande: Brookhaven was represented by physicist and former Lab Director Maurice Goldhaber, confirmed that neutrinos do indeed oscillate and have mass.

MINOS 1990's-2015: Brookhaven then became involved in the ongoing MINOS (Main Injector Neutrino Oscillation Search) experiment based at Fermilab, which began taking data in 2005 and has since provided measurements of mixing angles and oscillation frequency that describe how muon and tau neutrino types oscillate between one form and another.

T2K: Physicists in Brookhaven's Superconducting Magnet Division used direct wind machines to make superconducting corrector magnets for the JParc beamline that takes protons to the target for making neutrinos for T2K. The correctors were completed in 2008.

Daya Bay: BNL had a lead role in the Daya Bay Neutrino Project, which took data from 2011-2021.

MicroBooNE Cryogenic Neutrino Detector: Brookhaven scientists and engineers played leading roles in design, construction and analysis of MicroBooNE at Fermilab.

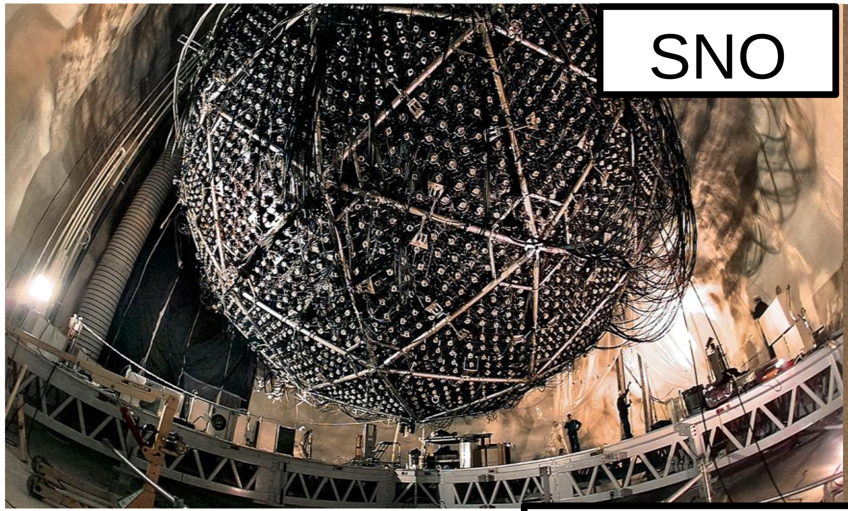
The Precision Reactor Oscillation and Spectrum Experiment (PROSPECT): The study of antineutrinos with PROSPECT allows scientists to search for a previously unobserved particle, the so-called sterile neutrino, while probing the nuclear processes inside a reactor. BNL engineers, physicits and chemists involved in many aspects of PROSPECT

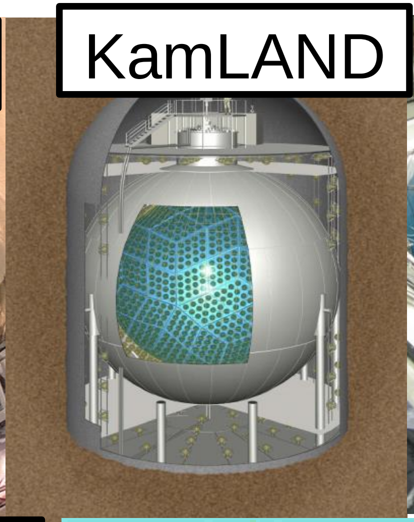
LBNE: BNL conceived an intense wide-band neutrino beam to travel 800 hundred miles through the Earth to a far detector .This program evolved into the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE).

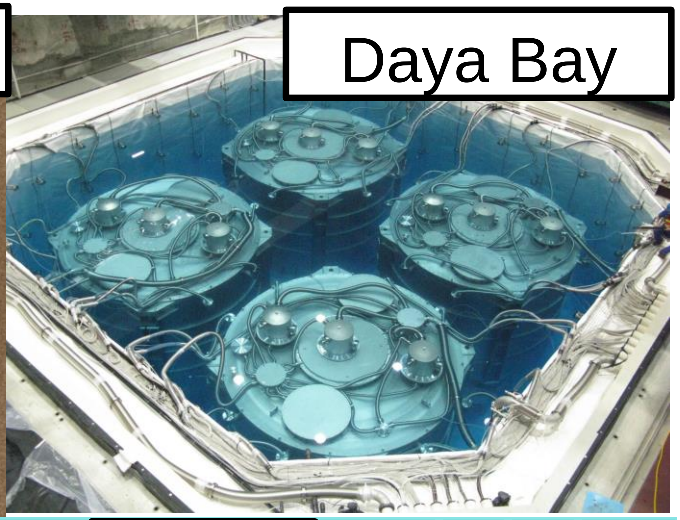
The Deep Underground Neutrino Experiment (DUNE) More than 1100 collaborators. A huge liquid argon Time-Projection-Chambers detector in the Sanford Underground Research Facility (SURF) in Lead, SD. Fermilab's Main Injector Ring will produce an intense collimated beam of neutrinos that will travel 800 miles through the Earth before striking its target at SURF (Homestake Mine in which Ray Davis did his experiment). Brookhaven Lab is one of the principal collaborators in the planning, design, and operation of this experiment. From fundamental neutrino science to beam and detector design, prototyping and construction, Brookhaven Lab has had a foundational role in DUNE.

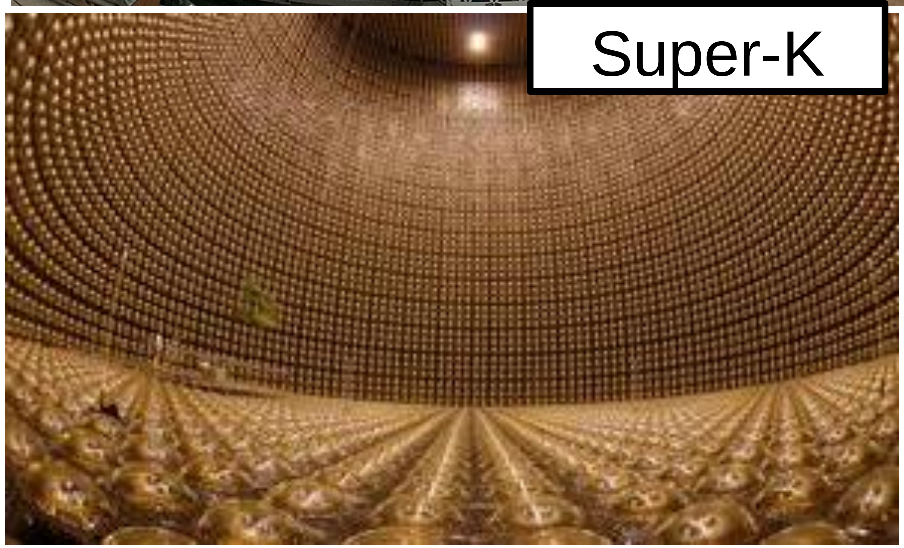
2016 Breakthrough Prize in Fundamental Physic

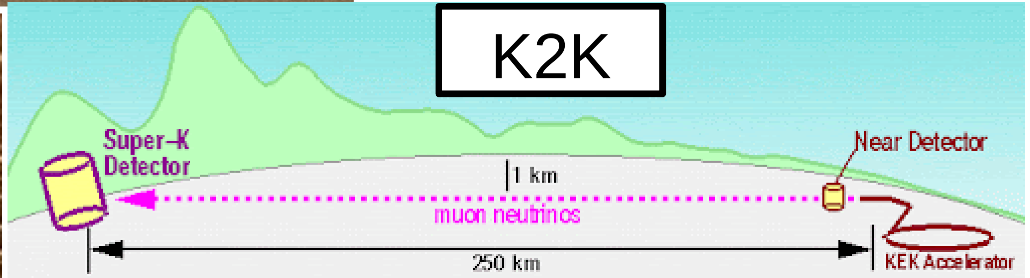
1400 Scientists
6 Experiments
$3M Prize

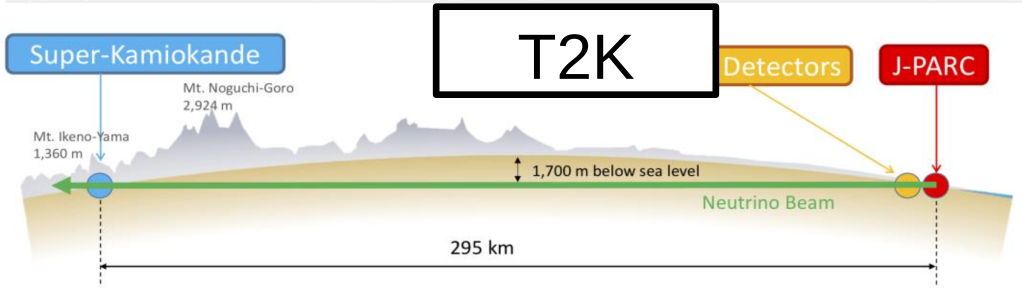












2015 Nobel Prize
Takaaki Kajita &
Art McDonald