Tomorrow we'll start at 9:30am

FRIDAY, 8 JULY

9:30 AM → 10:30 AM	**Introduction to liquid scintillator and tour of LS lab** **Speakers**: Minfang Yeh (BNL) , Richard Rosero	1h	Bldg 555 (Chemistry)	
11:00 AM → 12:00 PM	**Tour of Water-based Liquid Scintillator lab** **Speaker**: Xin Xiang	1h	Bldg 535 (Instrumentation Divi...	

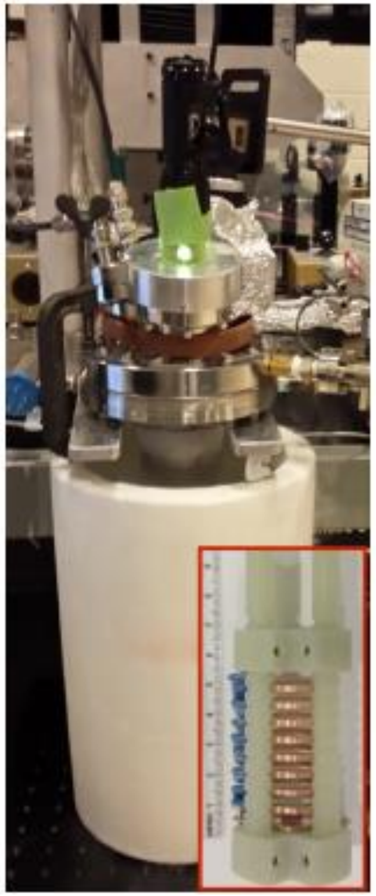
Sterile Neutrino and the Short Baseline Neutrino (SBN) Program

Chao Zhang

Electronic Detector Group, Physics Department

7/7/2022

LAr R&D Facility @BNL

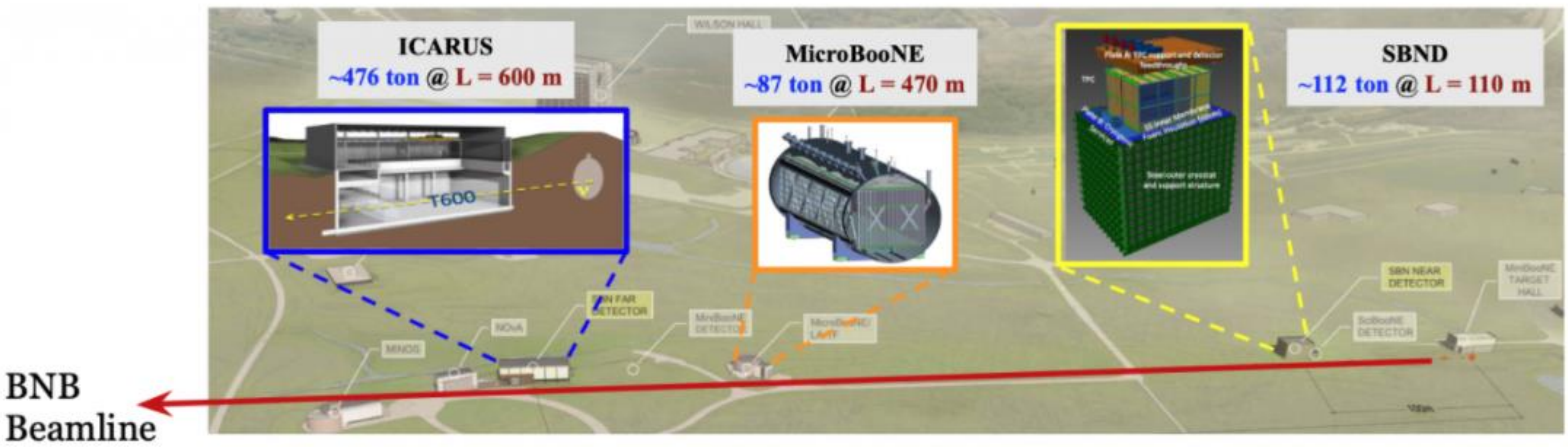


2 L Test Stand

20 L Test Stand

260 L R&D Facility

Short Baseline Neutrino Program



Multiple LArTPC experiments at different distances to search for eV-mass-scale sterile neutrinos

MicroBooNE: took data in 2015 – 2021
ICARUS: started physics data taking this year
SBND: install detector now; expect to take data next year

Outline

- ❑ Neutrino
- ❑ Neutrino oscillations
- ❑ Sterile neutrino
- ❑ the Short Baseline Neutrino (SBN) Program @Fermi Lab
  - MicroBooNE
  - SBND
  - ICARUS
- ❑ Tomorrow: LArTPC data analysis
  - From raw data to event reconstruction
  - Deep Neural Network in LArTPC analysis

"Never underestimate the joy people derive from hearing something they already know."

- Enrico Fermi

A Particle Physicist

Outline

The little neutral one

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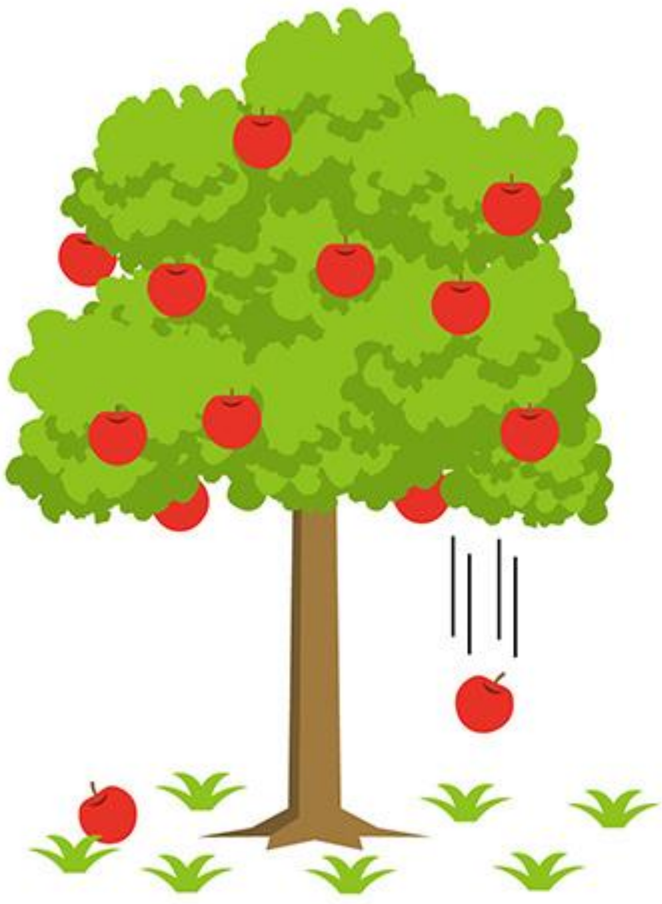
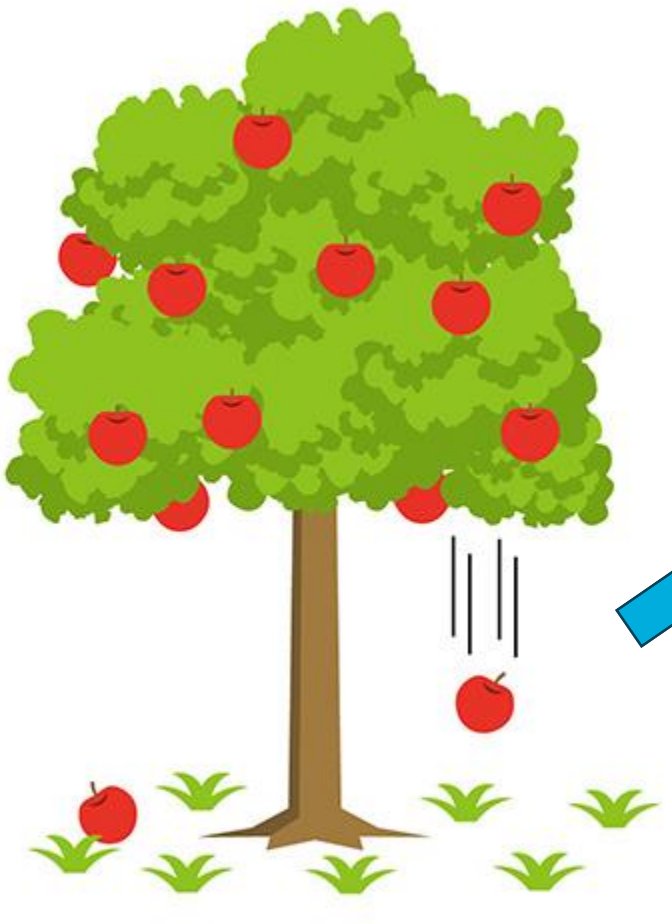
Physics of Everyday Life



Gravity

Physics of Everyday Life



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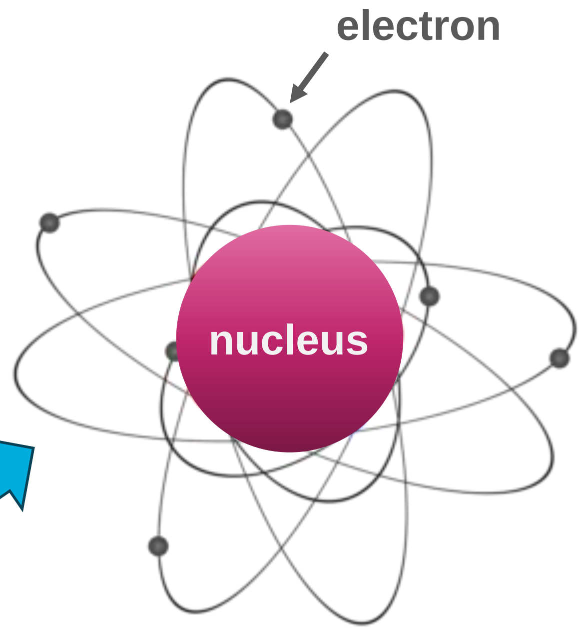
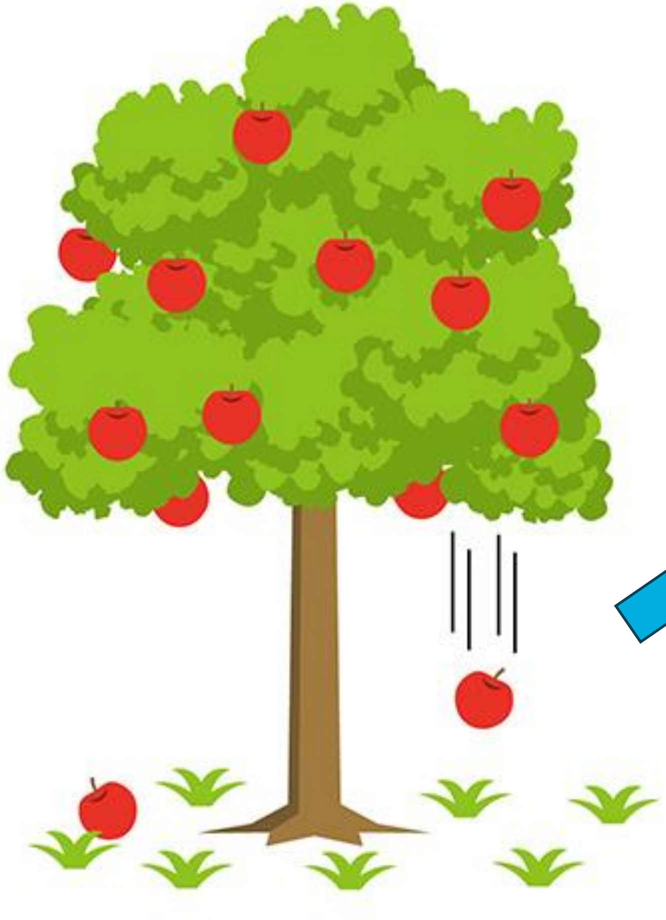


Electromagnetic force

Physics of Everyday Life



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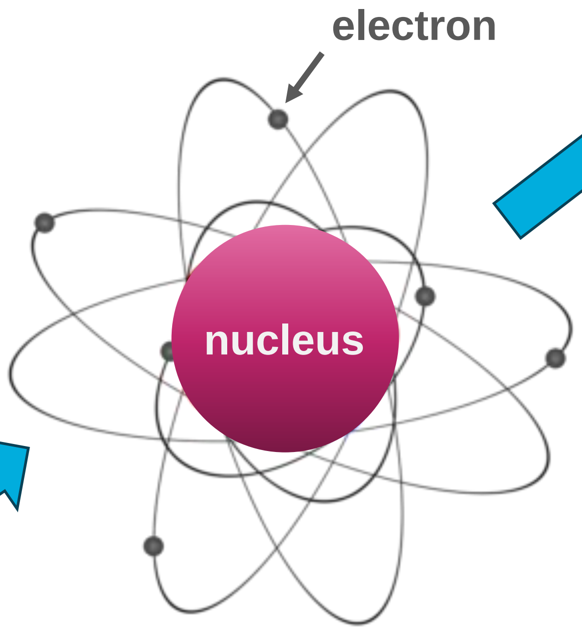
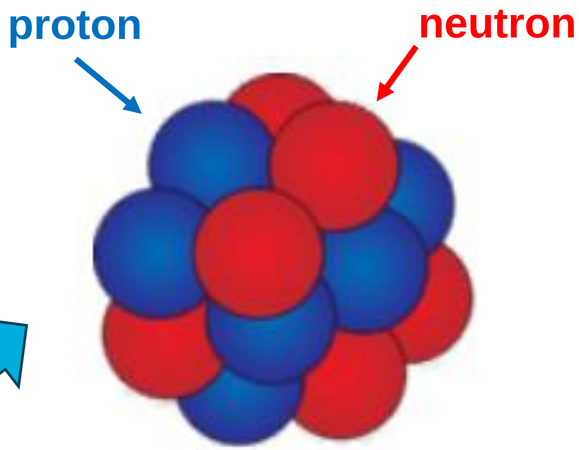
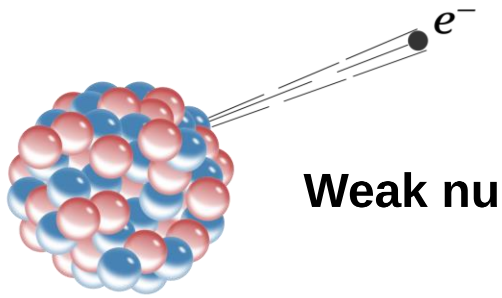


Electromagnetic force



Strong nuclear force

Beta Decay and the Energy Crisis



Weak nuclear force

number of protons and neutrons

$$^{210}_{83}\mathrm{Bi} \rightarrow \, ^{210}_{84}\mathrm{Po} + e^-$$

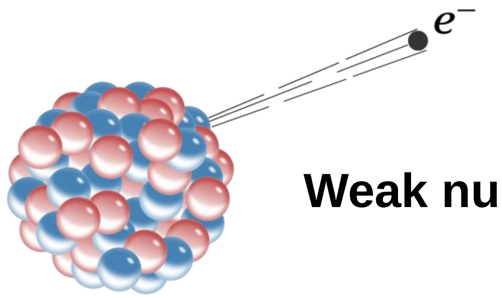
number of protons

$$n \rightarrow p^+ + e^-$$

1899 – 1927

Rutherford, Meitner, Hahn, Chadwick, Ellis, Mott, *et. al*

Beta Decay and the Energy Crisis



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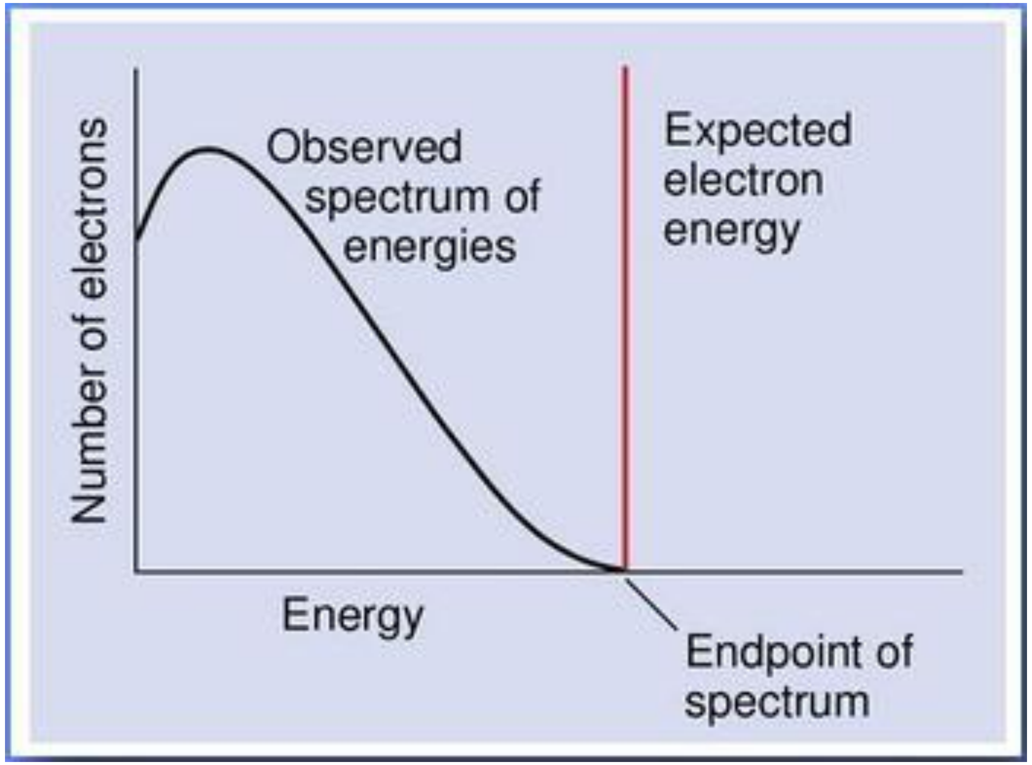
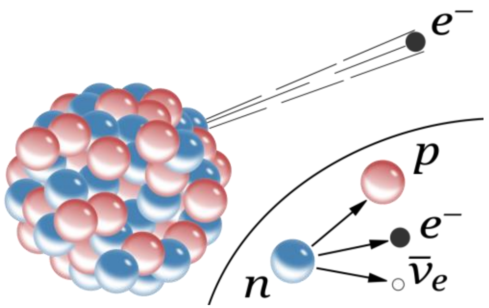


1899 – 1927
Rutherford, Meitner, Hahn, Chadwick, Ellis, Mott, *et. al*

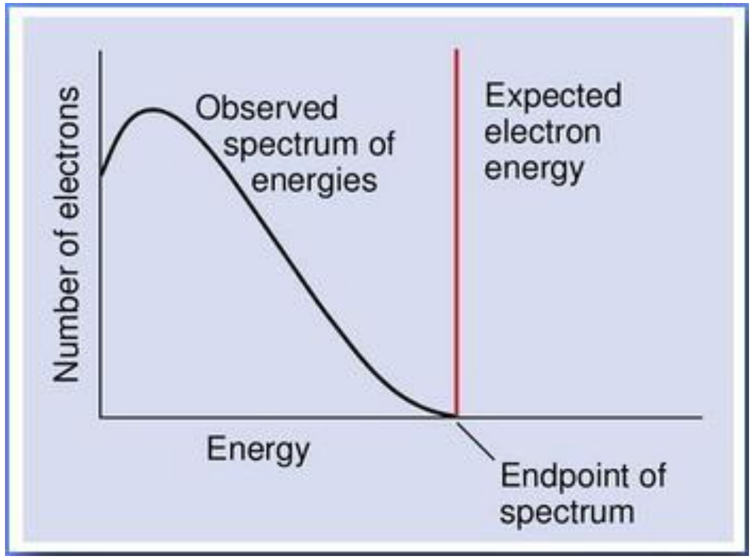
Neutrino: Proposed as a hypothetical particle



$$^{210}_{83}\mathrm{Bi} \rightarrow {}^{210}_{84}\mathrm{Po} + e^- + \bar{\nu}_e$$

Wolfgang Pauli

1930: Pauli's letter to physicists at a workshop in Tubingen



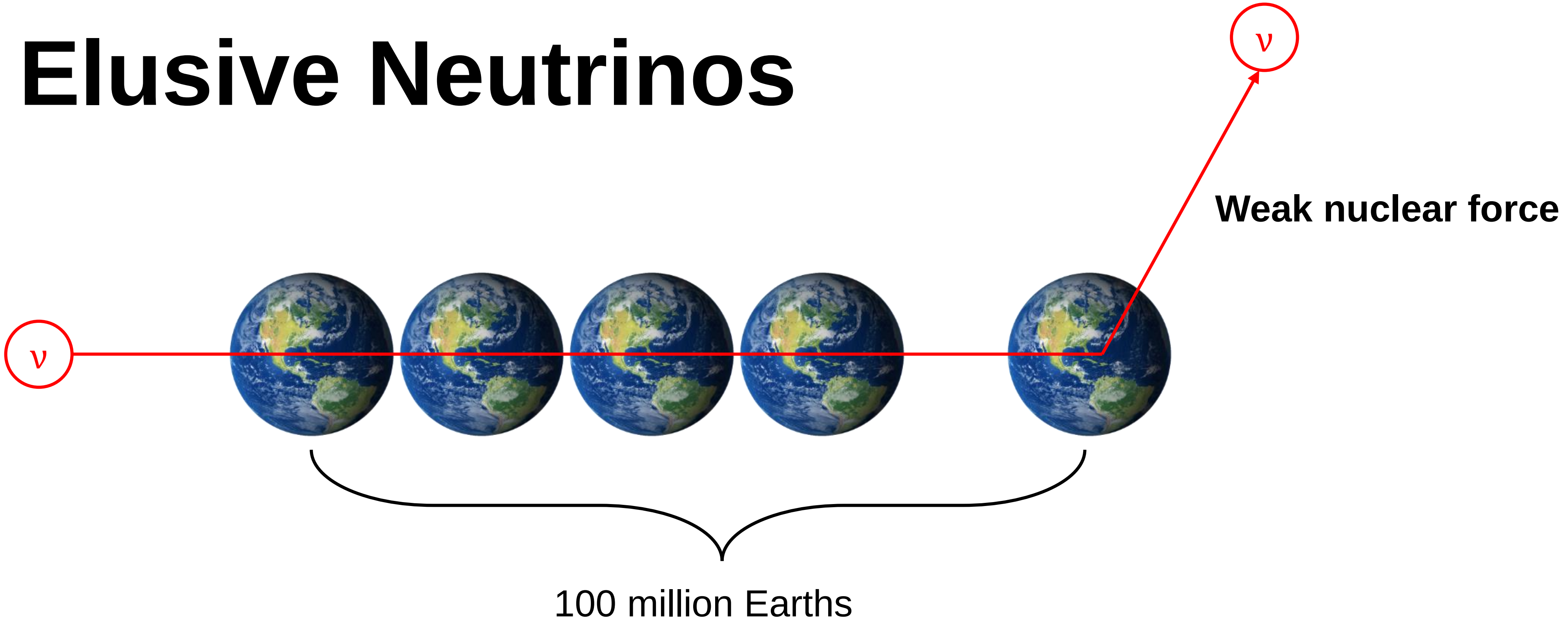
Dear Radioactive Ladies and Gentlemen,

.........., I have hit upon a desparate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant..........
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant

. W. Pauli

"I have done a terrible thing. I have postulated a particle that cannot be detected."

The Elusive Neutrinos



Neutrino detection requires:

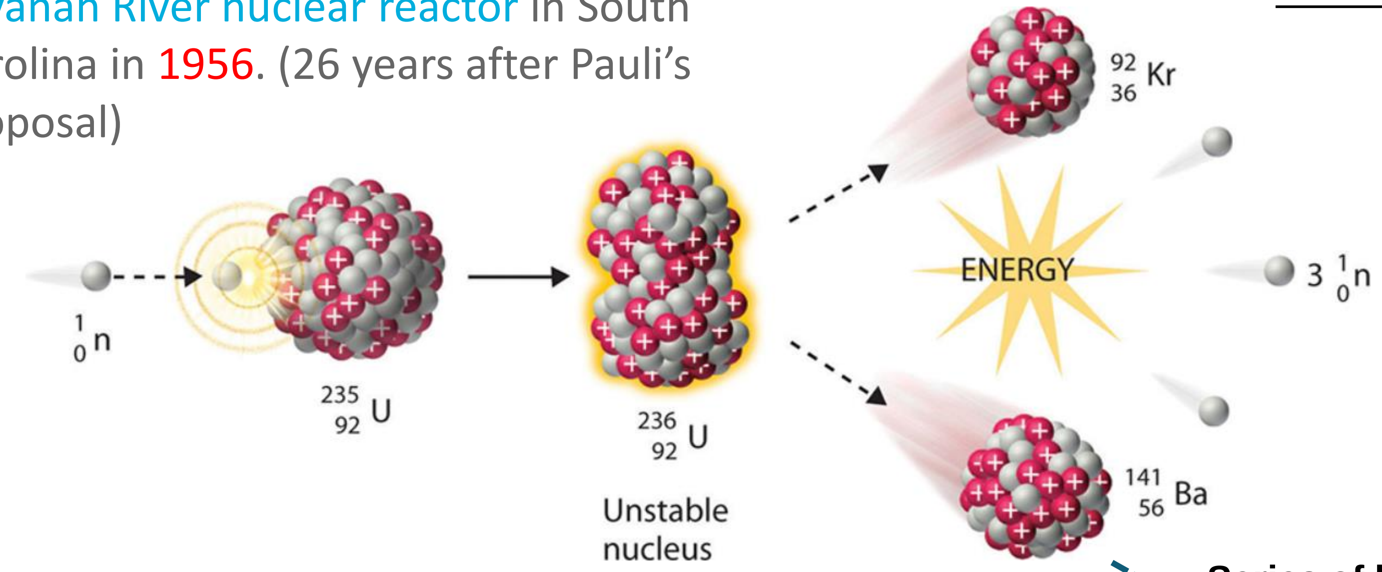
- ❑ An intensive neutrino source: a billion trillion ($\sim 10^{21}$) ν per second
- ❑ A huge neutrino detector: tons to kilotons of target material
- ❑ A distinctive method to tell “neutrino interactions” from other backgrounds

Neutrinos: First Detection

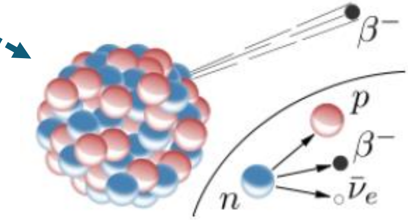
Fission fractions in a typical power reactor	
^{235}U	55%
^{239}Pu	30%
^{238}U	10%
^{241}Pu	5%

Frederick Reines and Clyde Cowan first detected (anti)neutrinos using the Savanah River nuclear reactor in South Carolina in 1956. (26 years after Pauli's proposal)

Nuclear fission



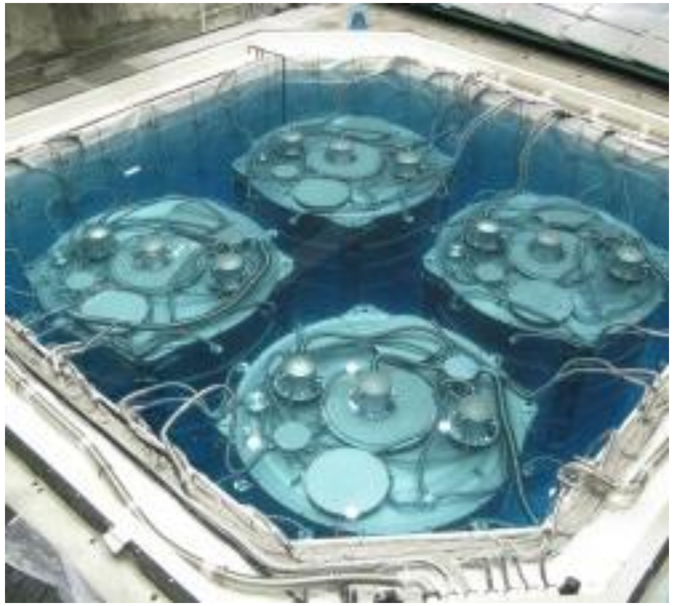
Series of beta decays

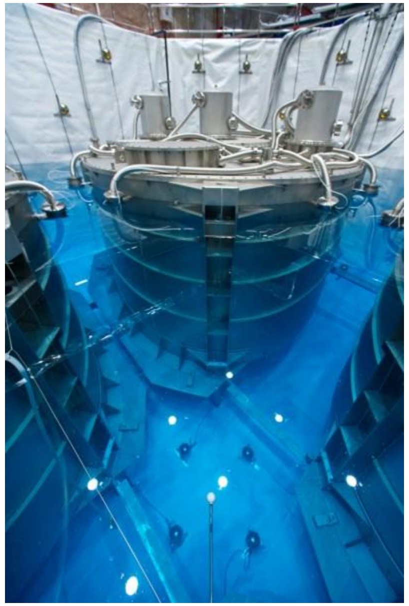


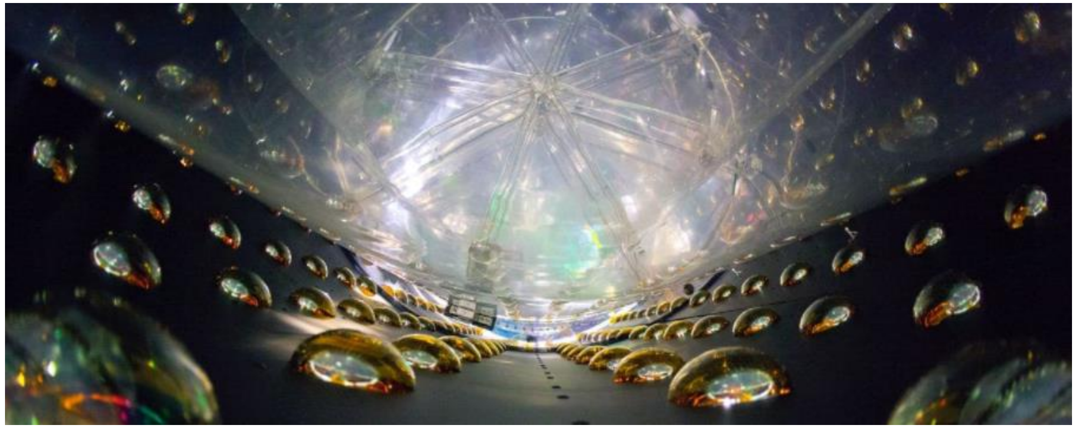
Nuclear reactors

- ❑Pure electron antineutrinos
- ❑Intensive: 2 x 10^{20} ν / sec / gigawatt
- ❑Free (to physicists)

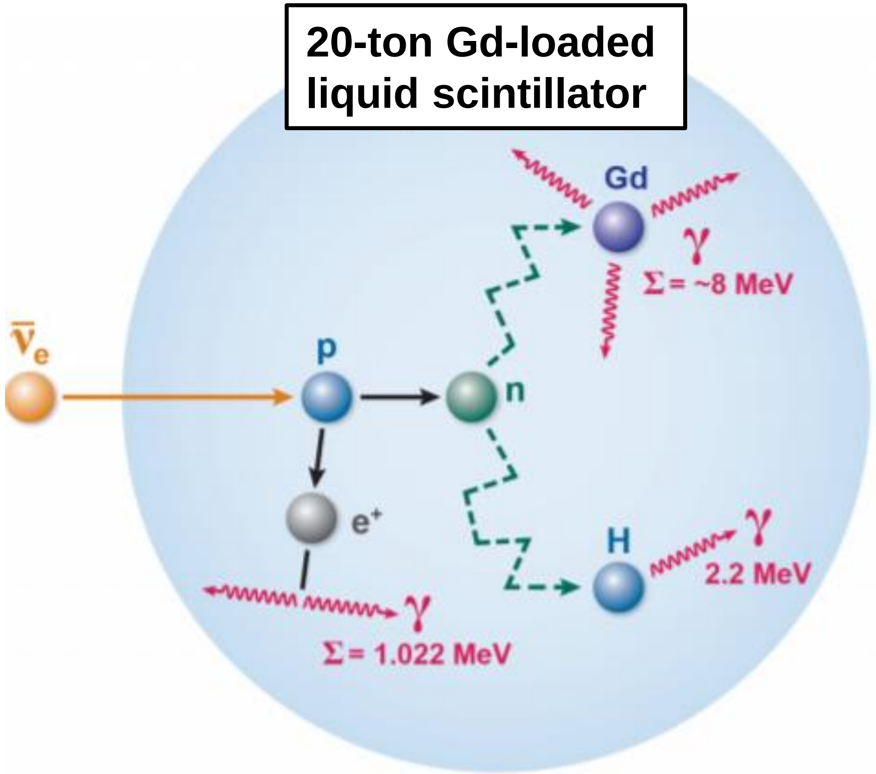
Detecting Reactor Neutrinos with Liquid Scintillator Detectors (Chemistry lab tour)







$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Daya Bay Reactor Neutrino Experiment

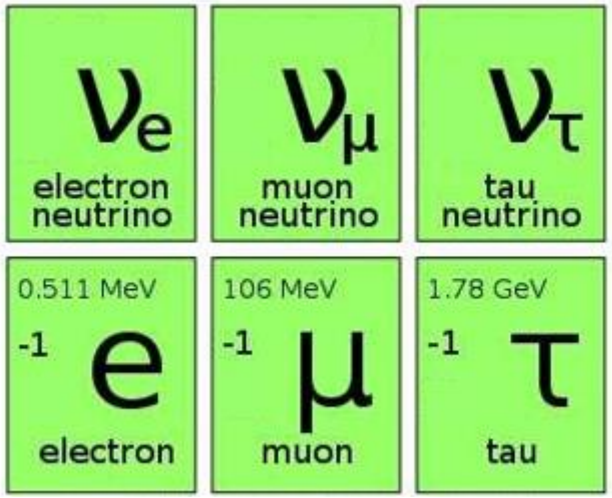
Neutrino “Flavors”

Leptons

I

Neutrino “Flavors”

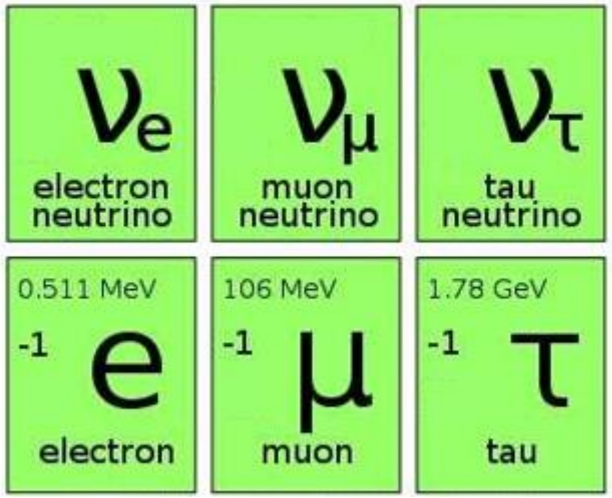
Leptons



I II III

Neutrino “Flavors”

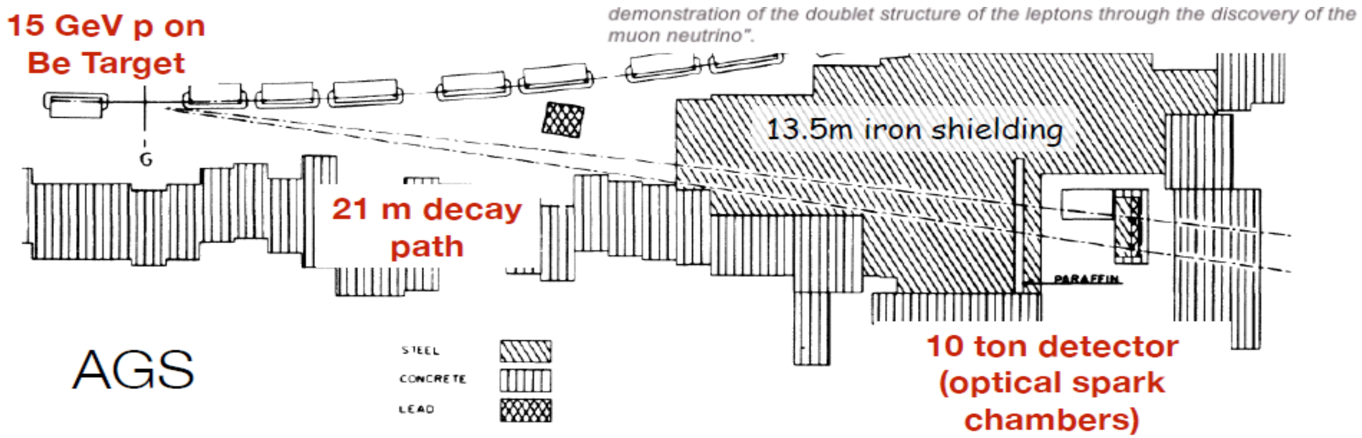
Leptons



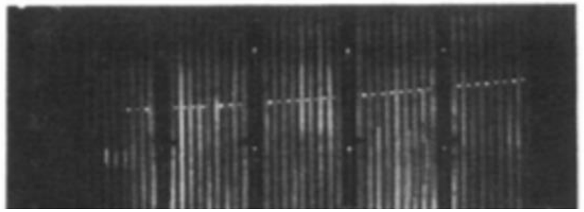
I II III

Discovery of muon neutrino in 1962 at AGS

World’s first accelerator neutrino experiment



$$\nu_\mu + n \rightarrow p + \mu^-$$



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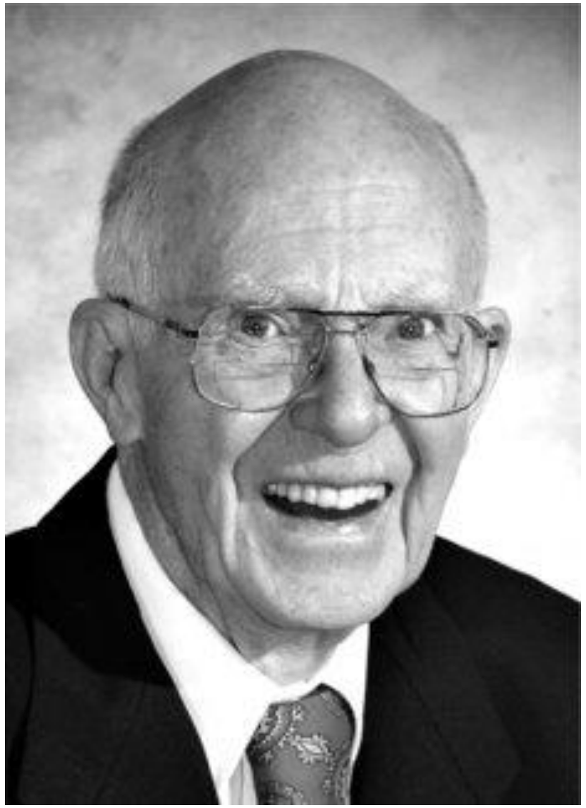
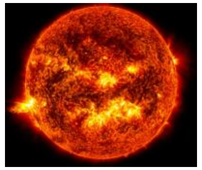


“Neutrinos tell us what happened in the center of the Sun eight minutes ago.”

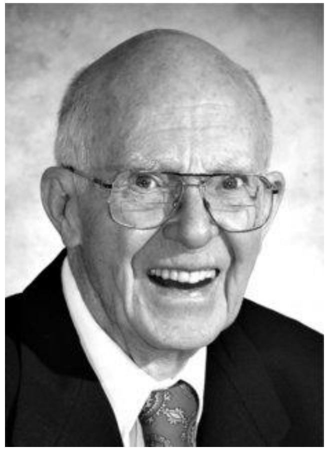
- Raymond Davis, Jr.

A Brookhaven Chemist

The Solar Neutrino Problem

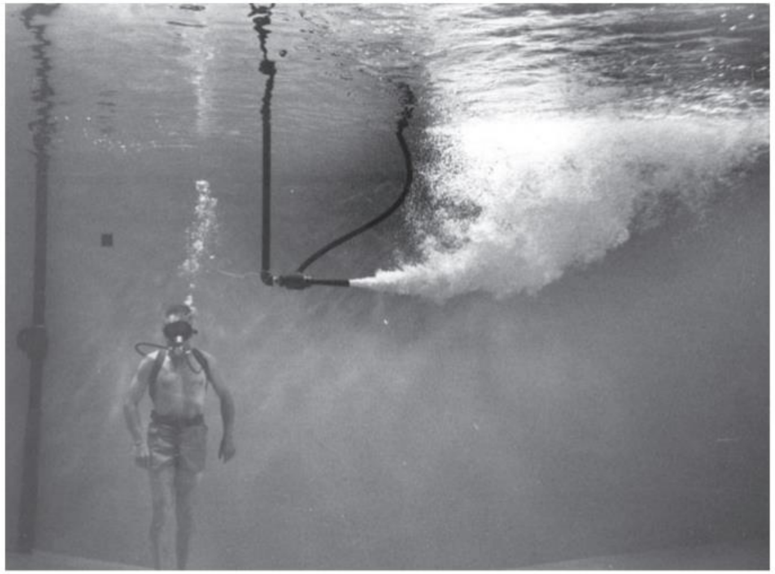


$$\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^-$$



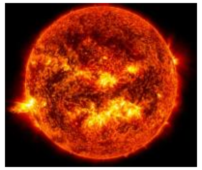
Raymond Davis Jr.

- 100,000 gallons of cleaning fluid (Perchloroethylene, C_2Cl_4)
- 4850 feet underground in the Homestake mine, South Dakota
- Atoms of ^{37}Ar extracted by helium purge every few months and counted
  - < one ^{37}Ar atom produced per day by neutrino capture



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

The Solar Neutrino Problem



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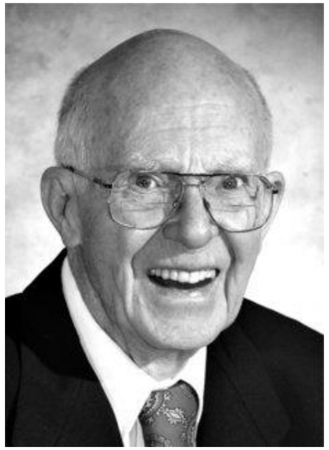
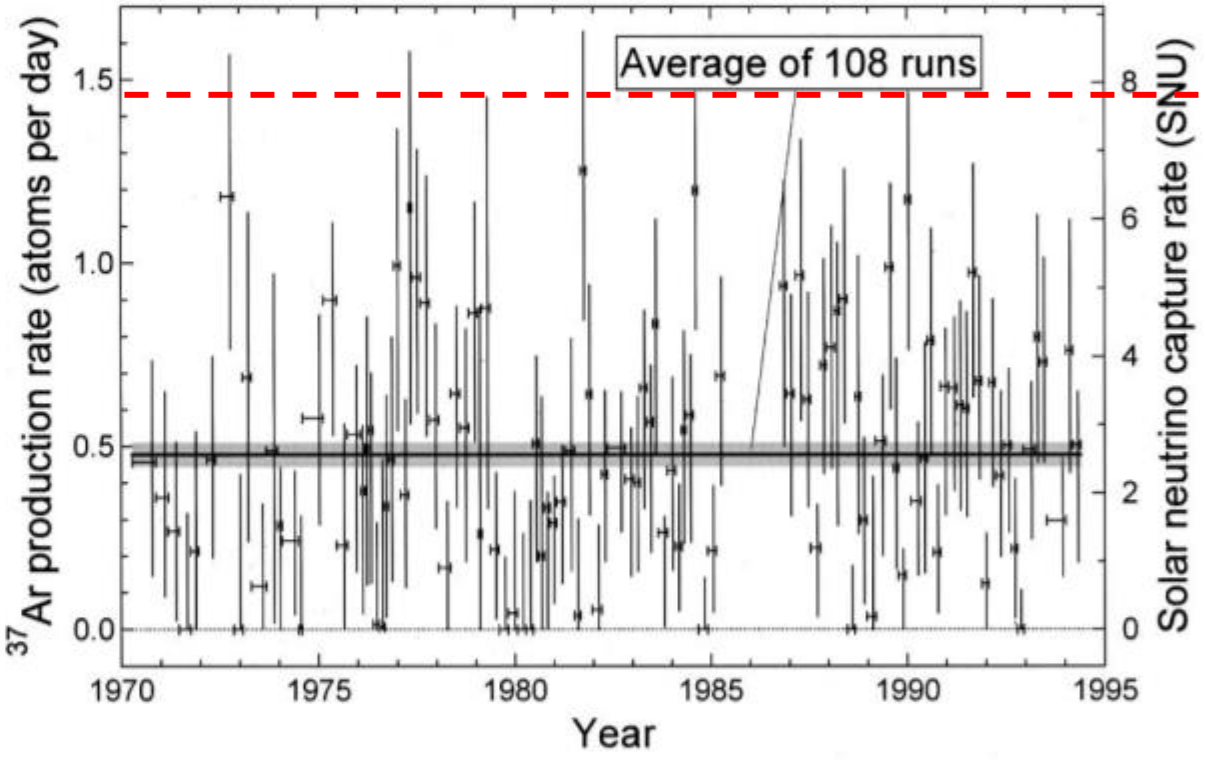


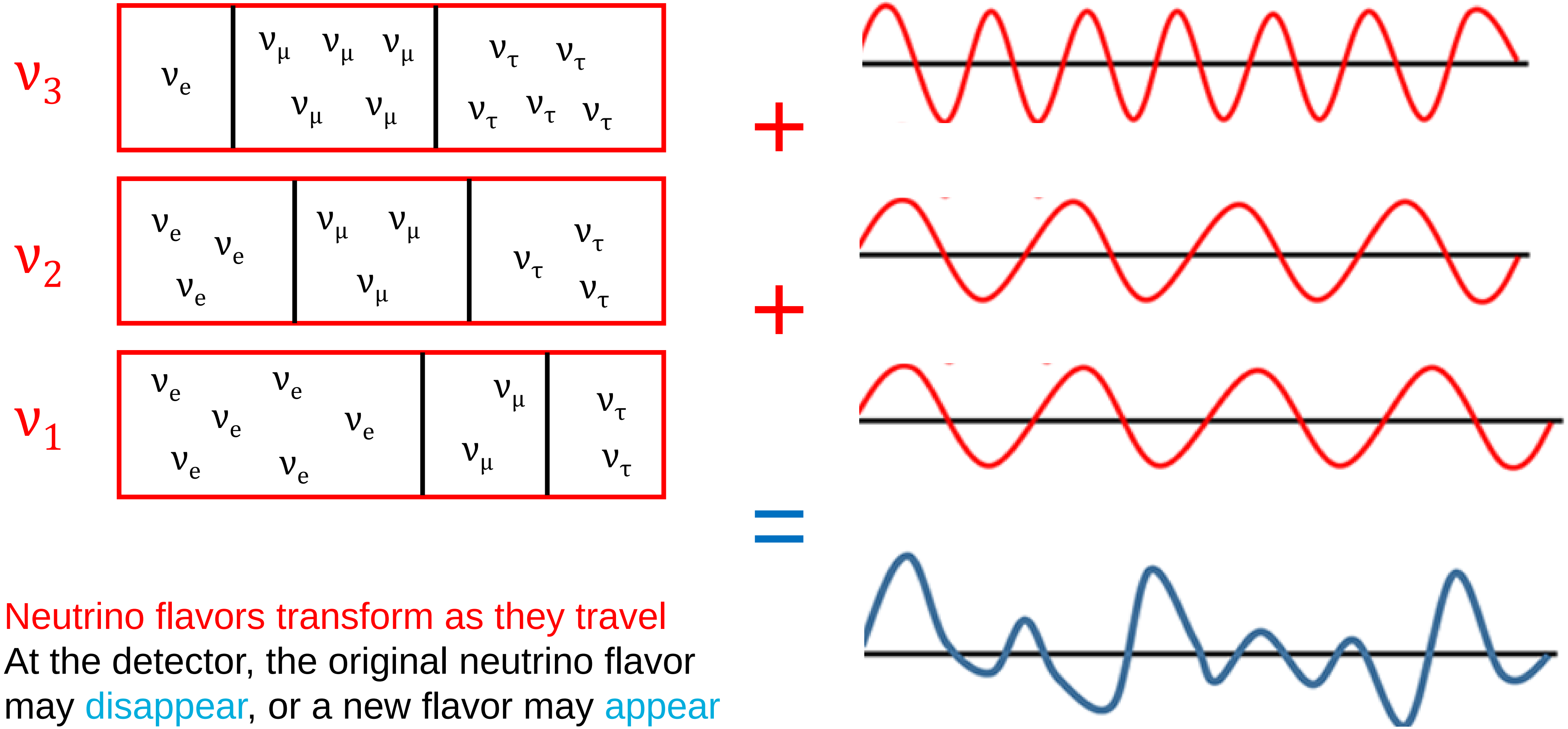
Raymond Davis Jr.



- ❑ An experimental endeavor over 25 years
- ❑ Solar neutrino was detected for the first time (Nobel prize 2002)
- ❑ But 2/3 of them seemed to be missing (first hint of neutrino oscillations)

Neutrino “Flavor” vs “Mass” States

Neutrino Mixing



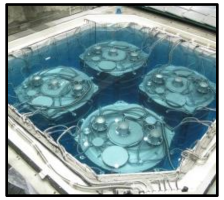
- ❑ Neutrino flavors transform as they travel
- ❑ At the detector, the original neutrino flavor may disappear, or a new flavor may appear

Neutrino Oscillations

$\bar{\nu}_e$ $\bar{\nu}_e$
$\bar{\nu}_e$ $\bar{\nu}_e$ $\bar{\nu}_e$

$\bar{\nu}_\mu$ $\bar{\nu}_\tau$
$\bar{\nu}_e$ $\bar{\nu}_e$ $\bar{\nu}_e$

detector



Probability of one flavor transforming to another

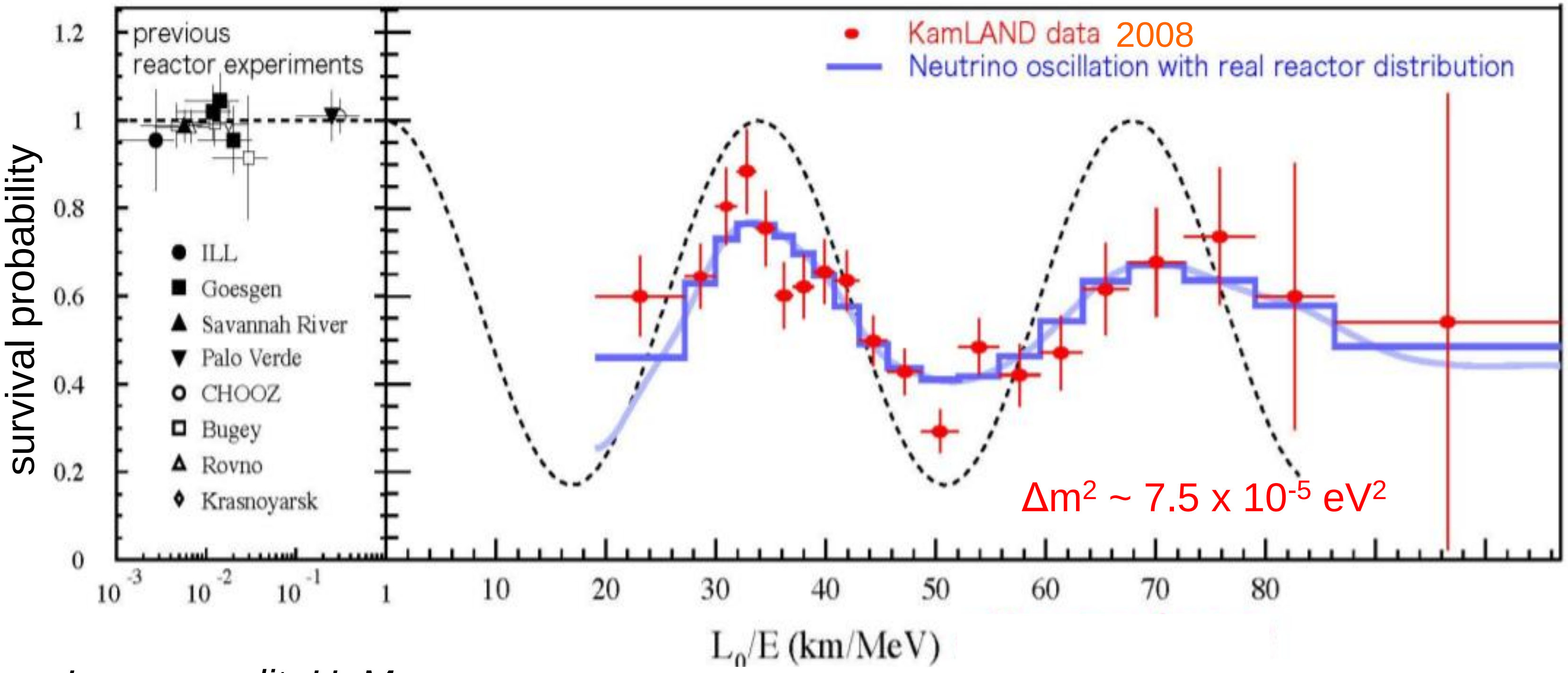
$$= \boxed{\sin^2 2\theta \cdot \sin^2(1.27|\Delta m^2| \cdot \frac{L\,(distance)}{E(energy)})}$$

amplitude
(mixing angle)

frequency
(mass^2 difference)

- ❑ Neutrino flavor states must “mix” with mass states
- ❑ Neutrinos must have mass

survival probability $= 1 - \sin^2 2\theta \cdot \sin^2(1.27|\Delta m^2| \cdot \frac{L}{E})$



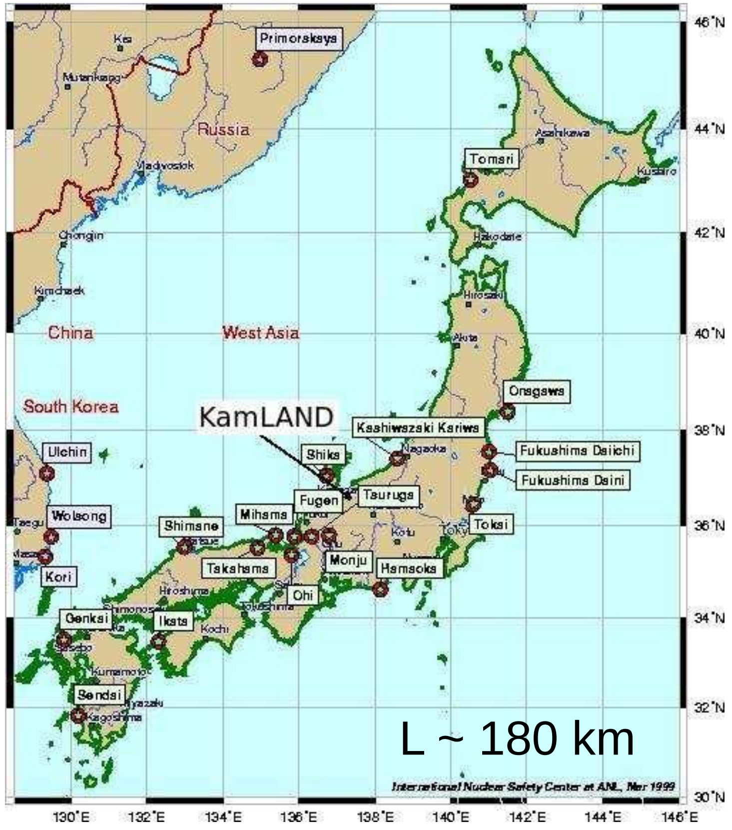
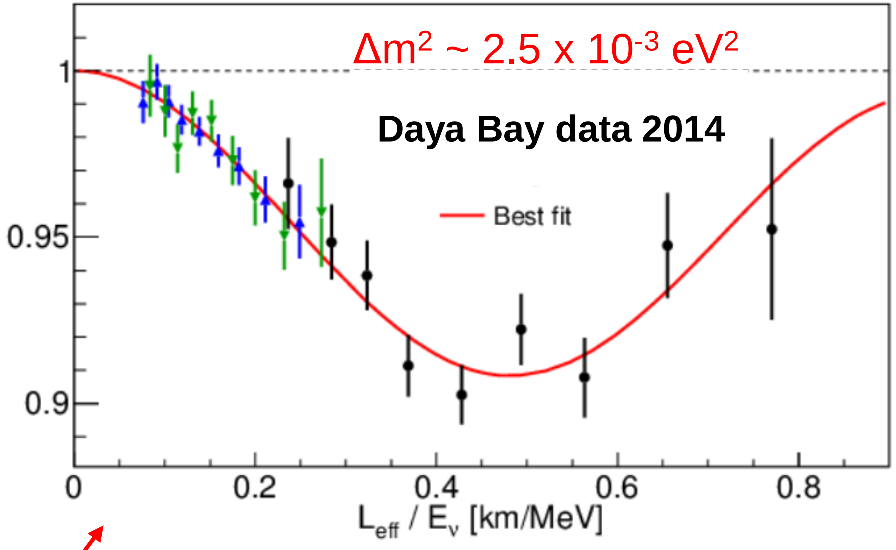
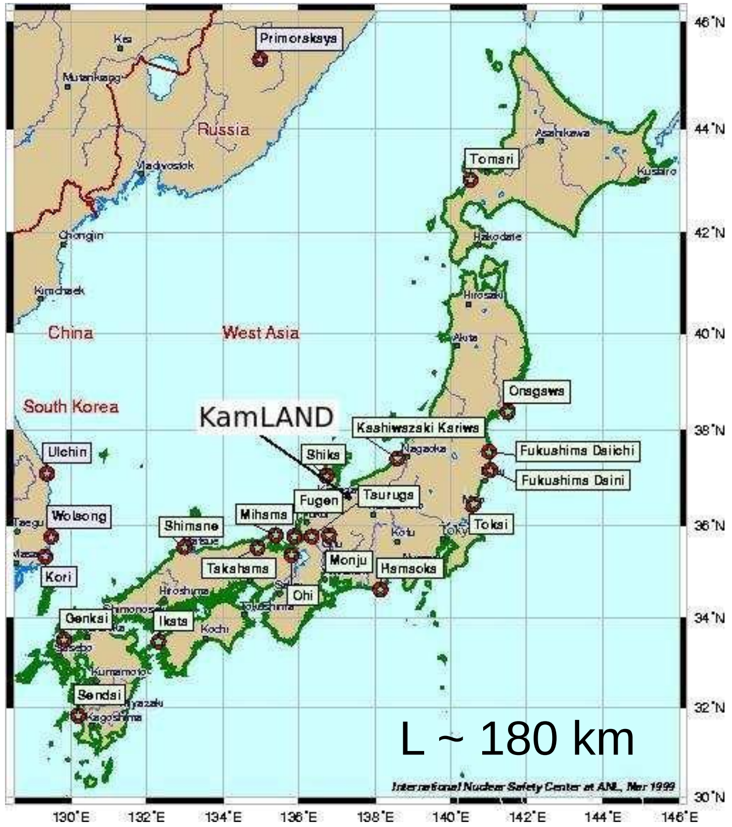
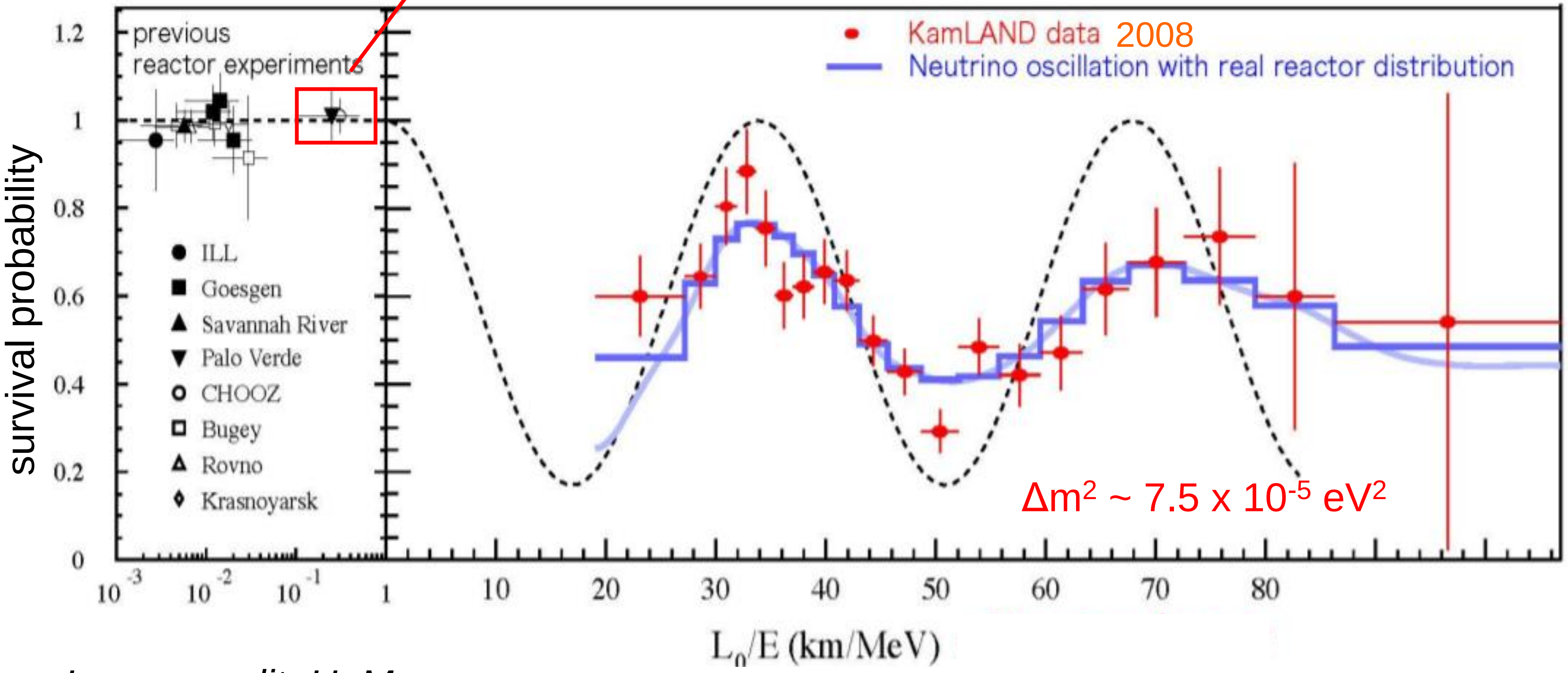


Image credit: H. Murayama







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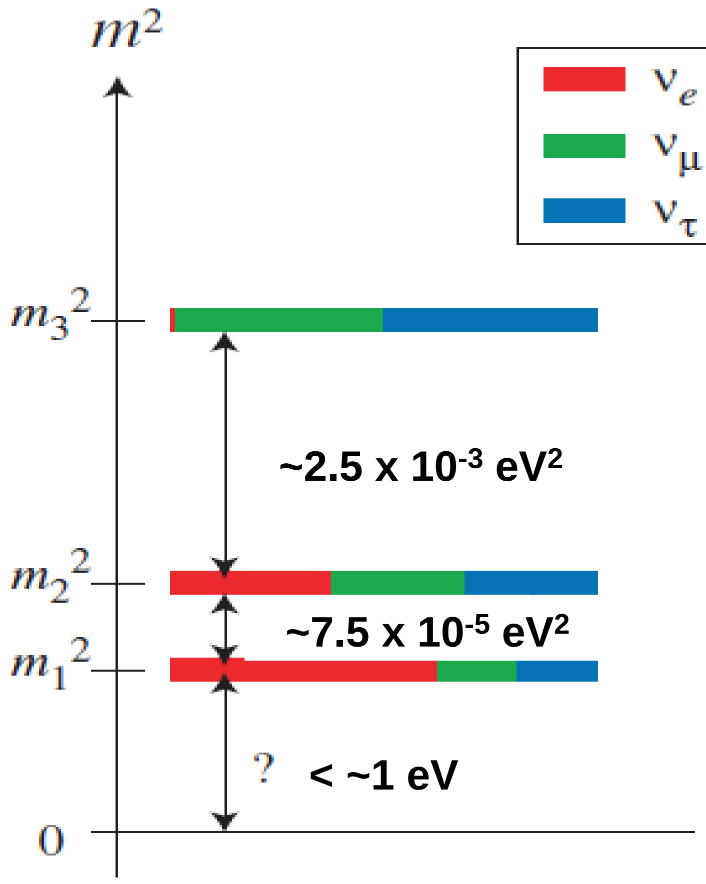
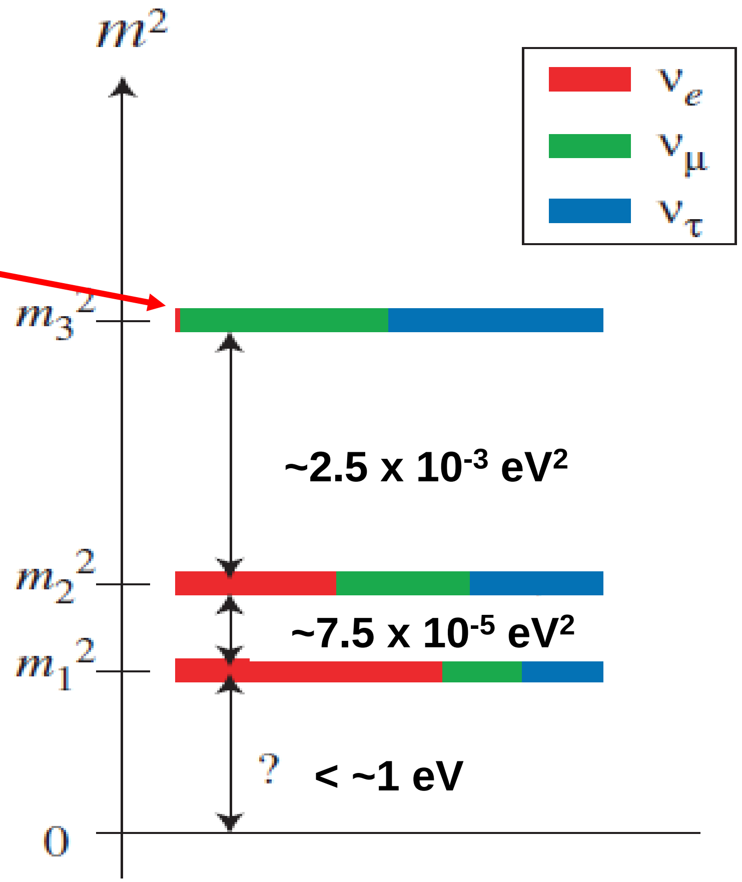
The Three-neutrino Mixing Scheme



The Three-neutrino Mixing Scheme

ν_e mixing in ν_3 : ~2%
(Daya Bay)



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ν_e mixing in ν_3 : ~2%
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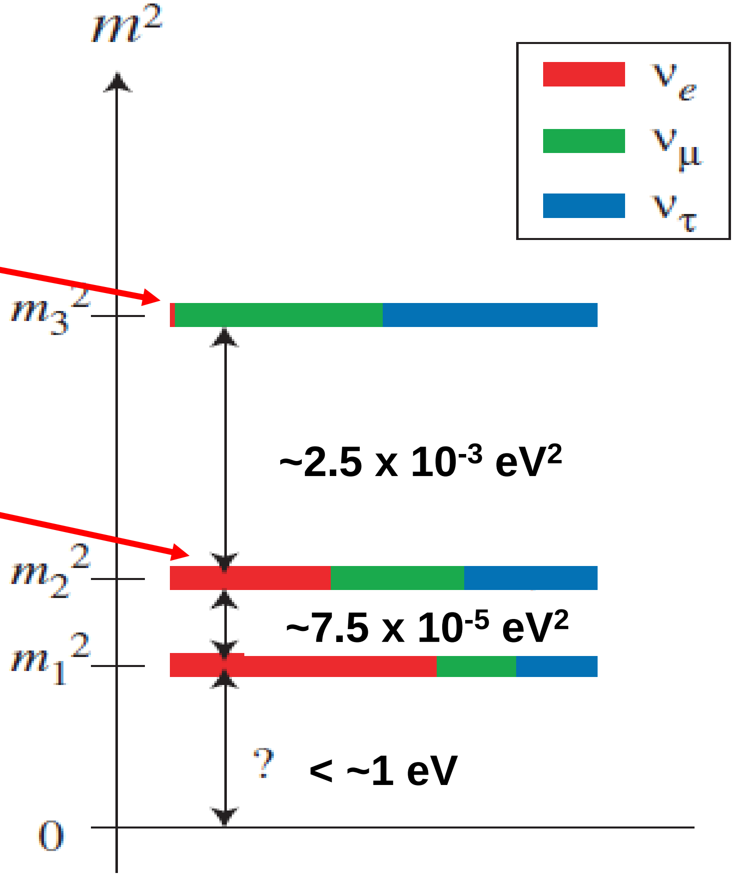
ν_e mixing in ν_2 : ~1/3
(Solar ν, KamLAND)



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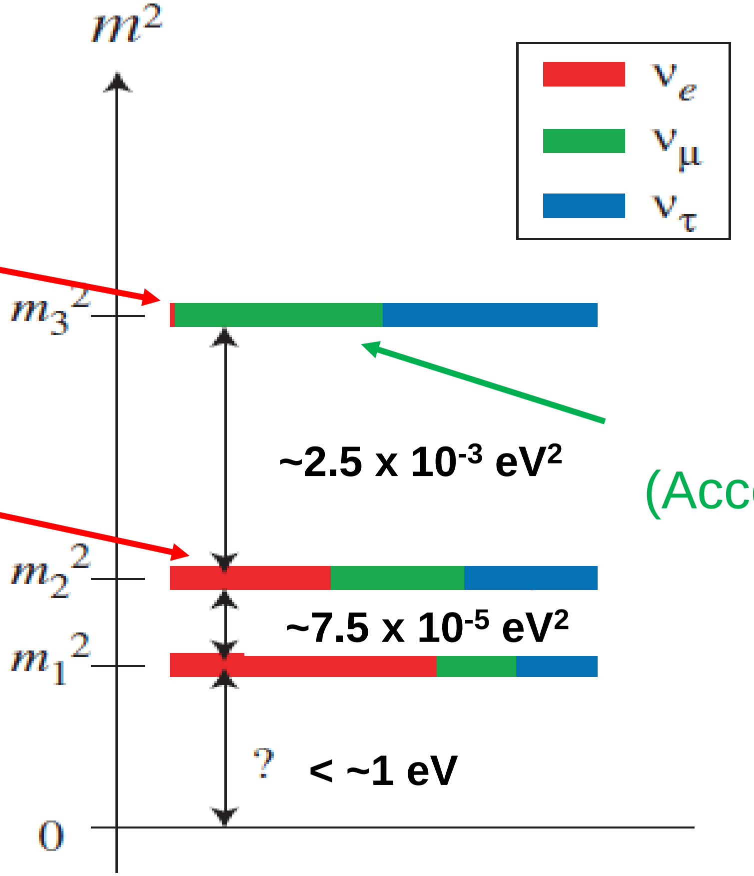

ν_μ mixing in ν_3 : ~1/2
(Accelerator ν, Atmospheric ν)

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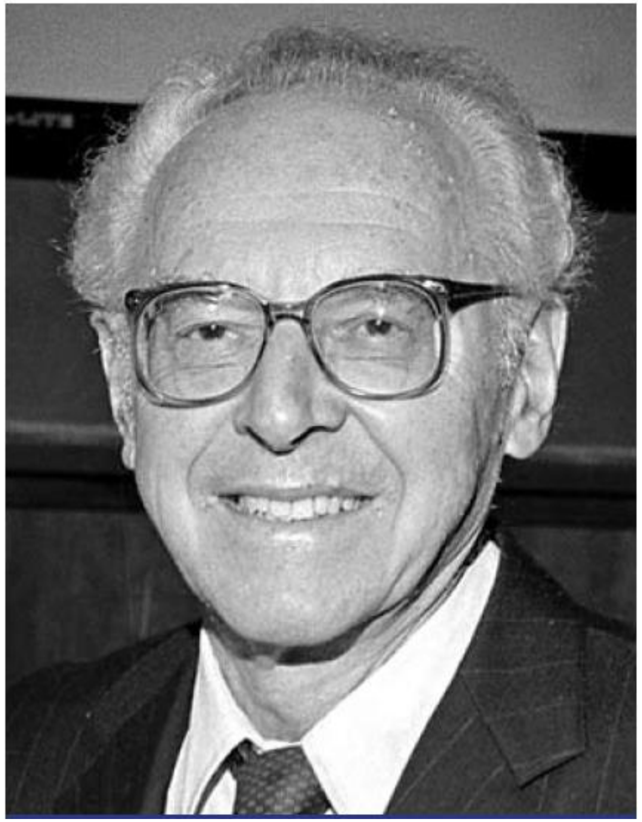


“I knew about Europium.”

- Maurice Goldhaber

Director of BNL (1961-1973)

Discovery of Neutrino Helicity

Brookhaven National Laboratory

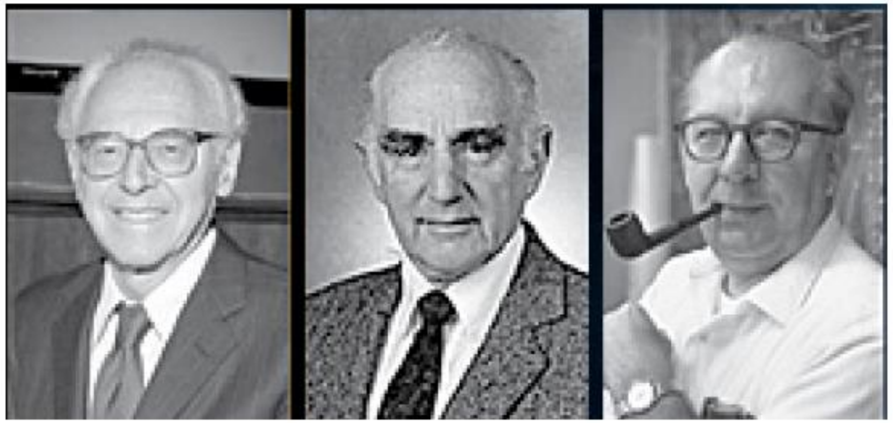
Helicity of Neutrinos*

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

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

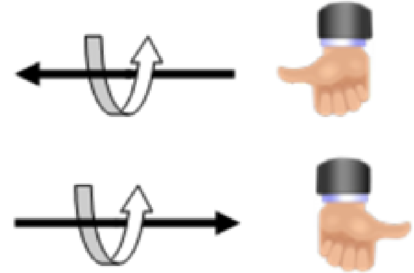
Phys. Rev. ***109****, 1015 (1957)*



Maurice Goldhaber   Lee Grodzins   Andrew Sunyar

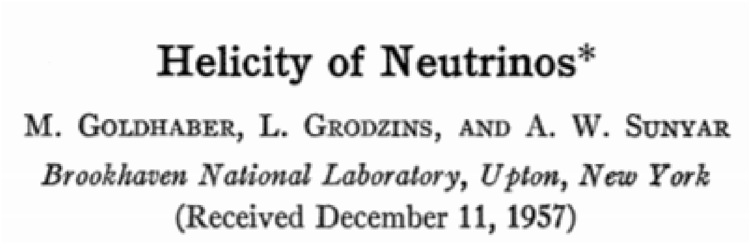
Are neutrinos right-handed or left-handed?

$\sigma \cdot \hat{p}$



L. Grodzins working on the *helicity-of-neutrino* setup built from an electromagnet (with a ^{152}Eu source), a lead cone, and a cardboard (with ^{152}Sm powders)

Discovery of Neutrino Helicity



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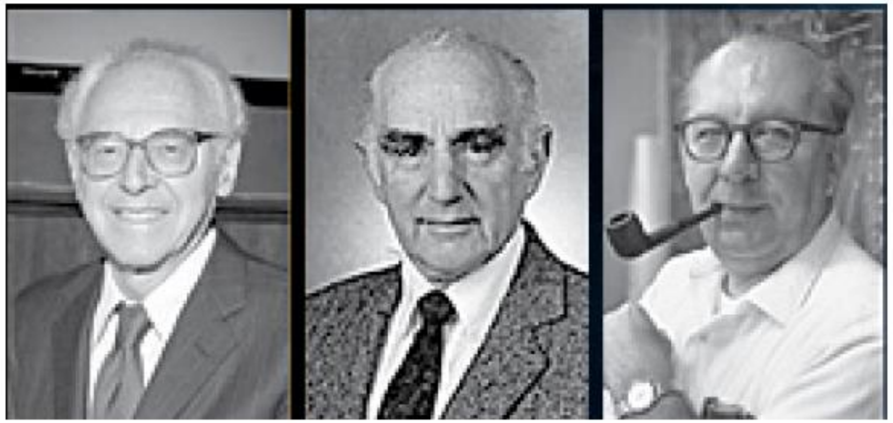

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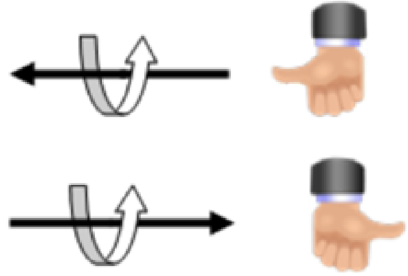

Neutrinos are only left-handed

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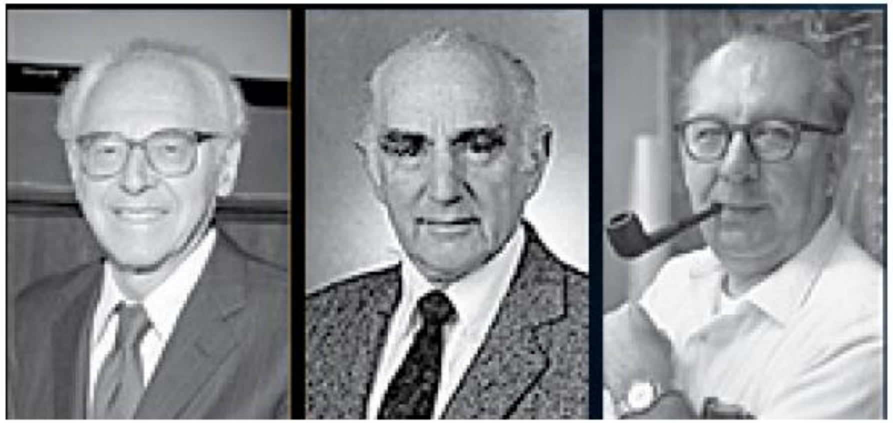

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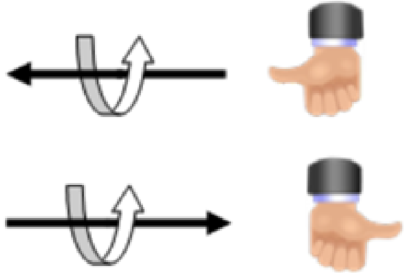
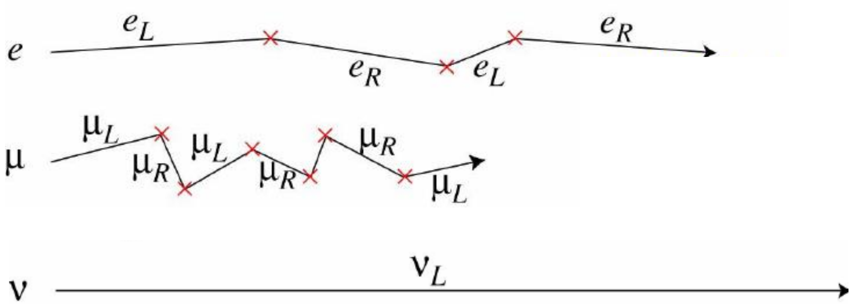
Are neutrinos right-handed or left-handed?

$\sigma \cdot \hat{p}$



Neutrinos are only left-handed



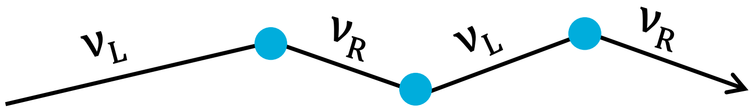
neutrinos are massless

Sterile Neutrino: Proposed as a hypothetical particle

Neutrino Oscillations

⇓

Neutrinos have mass

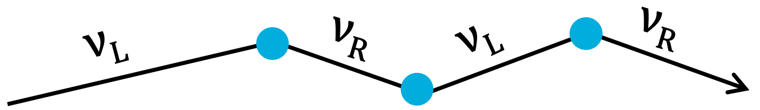


Left-handed neutrinos	Right-handed neutrinos
ν_e ν_μ ν_τ	ν_s
active neutrinos	sterile neutrinos
experience weak nuclear force	don’t experience any known forces (except gravity)

Sterile Neutrino: Proposed as a hypothetical particle

Neutrino Oscillations

Neutrinos have mass



Left-handed neutrinos

$\nu_e \; \nu_\mu \; \nu_\tau$

active neutrinos

experience weak nuclear force

Right-handed neutrinos

ν_s

sterile neutrinos

don’t experience any known forces (except gravity)

“I have done a terrible thing. I have postulated a particle that cannot be detected.”

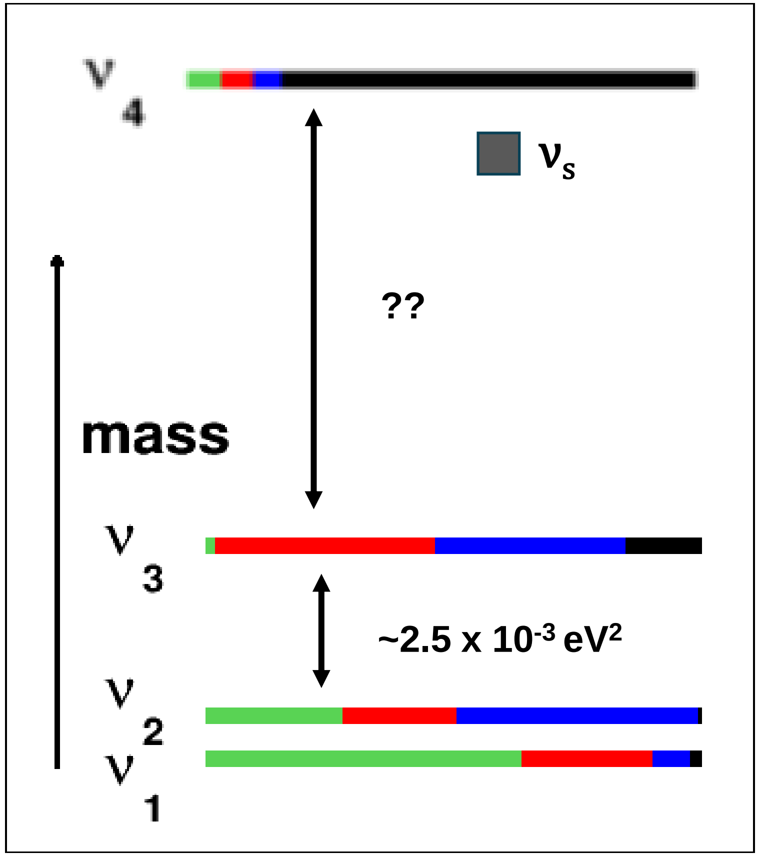
How to Detect Sterile Neutrinos?

A sterile neutrino may mix with active neutrinos through a new "mass state"

A sterile neutrino can cause a new oscillation pattern at a different mass scale

- KamLAND: 180 km, $\Delta m^2 \sim 7.5 \times 10^{-5}$ eV^2
- Daya Bay : 1.5 km, $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2
- New experiment: ?? km, $\Delta m^2 \sim$?? eV^2

3+1 mixing model



Mass Scale of Sterile Neutrinos

- Mass scale of sterile neutrinos can be anywhere
  - heavy sterile neutrinos (~10^{15} GeV) may explain the lightness of active neutrinos

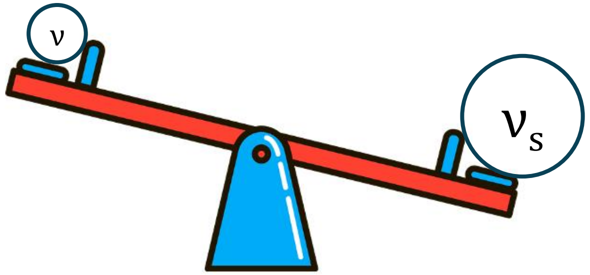
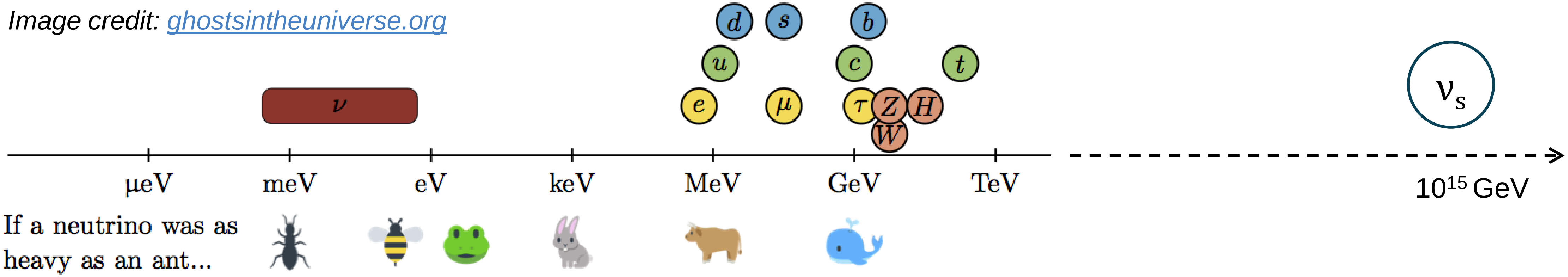
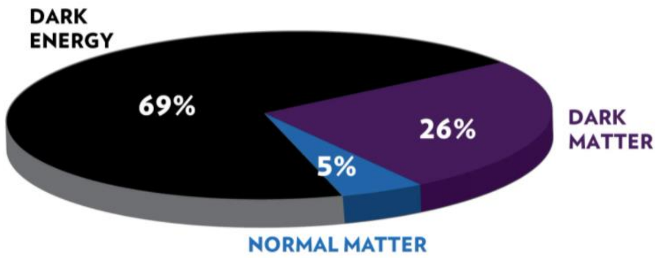


Image credit: ghostsintheuniverse.org



  - keV-scale sterile neutrinos are possible dark matter candidate
  - eV-scale sterile neutrinos are approachable by neutrino oscillation experiments



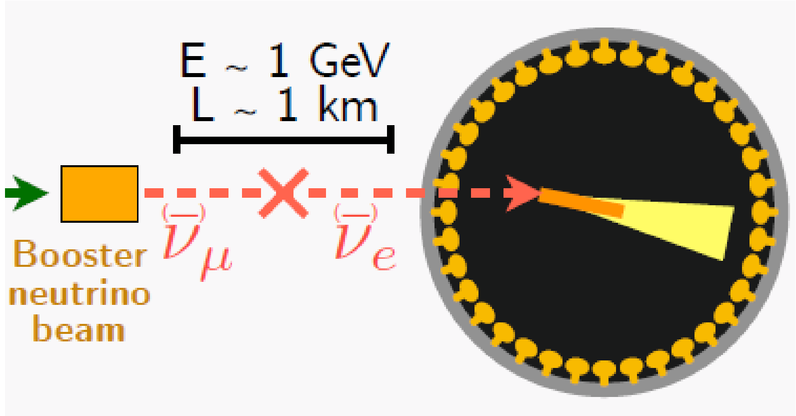
Hints of "eV-mass-scale" Sterile Neutrinos

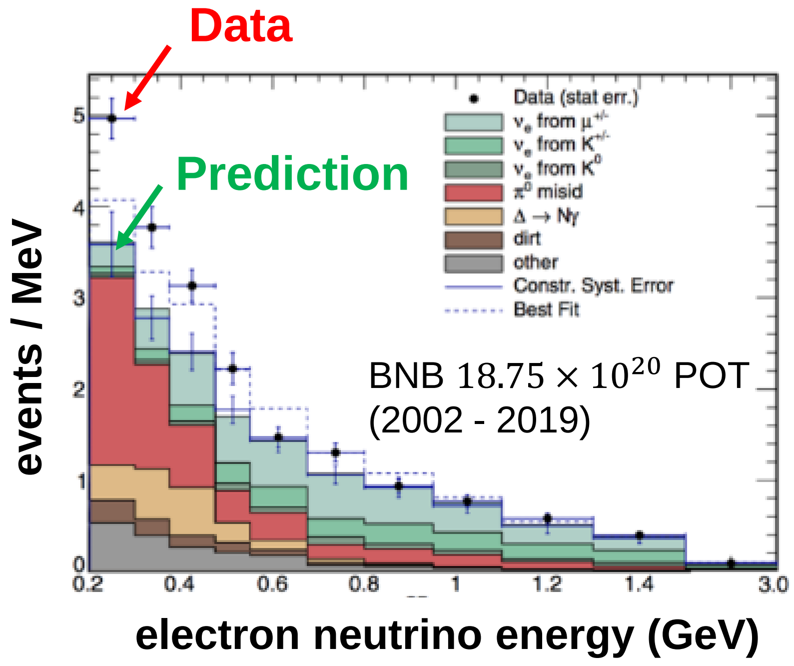
	Source	Search method	Distance / Energy (L/E)
Reactor Antineutrino Anomaly	$\bar{\nu}_e$	$\bar{\nu}_e$ disappearance	m / MeV
Neutrino-4 Anomaly	$\bar{\nu}_e$	$\bar{\nu}_e$ disappearance	m / MeV
Gallium/BEST Anomaly	ν_e	ν_e disappearance	m / MeV
LSND Anomaly	$\bar{\nu}_\mu$	$\bar{\nu}_e$ appearance	30 m / 30 MeV
MiniBooNE Anomaly	ν_μ / $\bar{\nu}_\mu$	ν_e / $\bar{\nu}_e$ appearance	500 m / 500 MeV

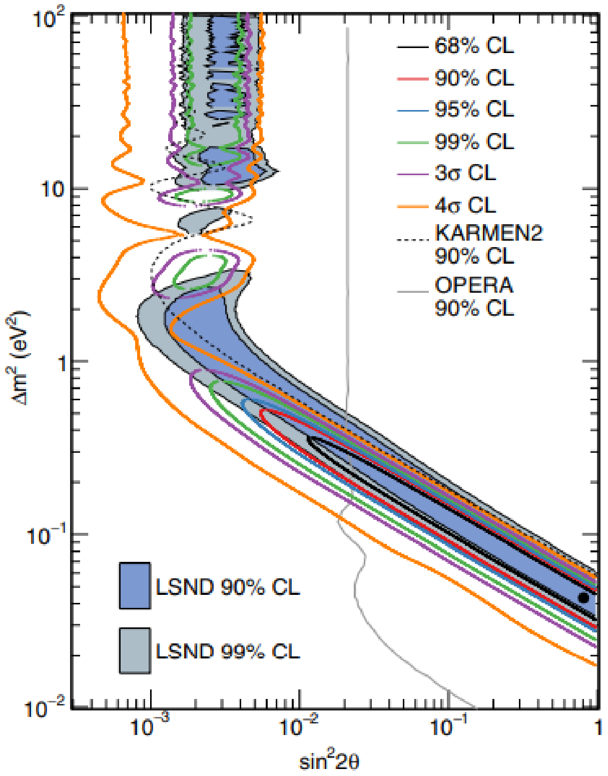
Target of the SBN program

The MiniBooNE Anomaly

Phys. Rev. D103, 052002

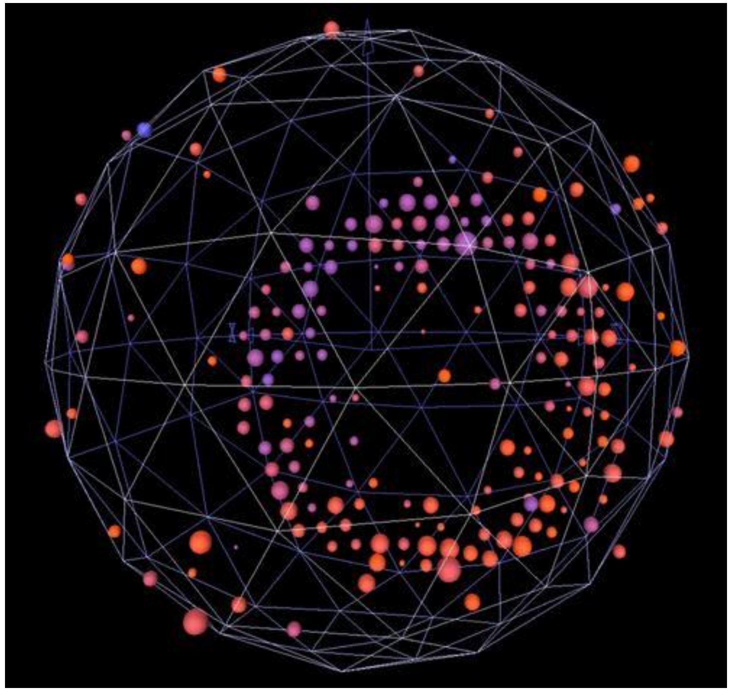




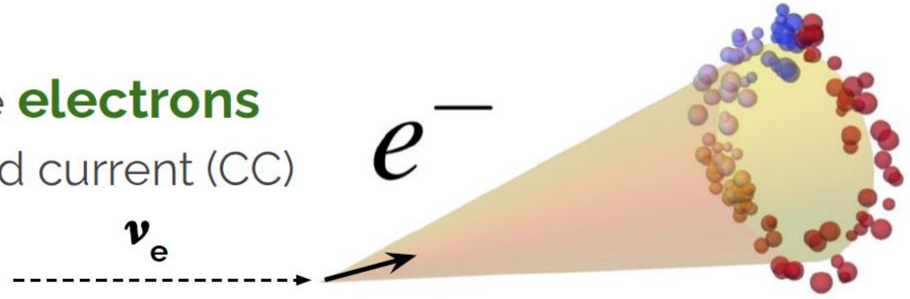


- ❑ MiniBooNE have observed low-energy excess (LEE) of electron-neutrino-like events since 2007
  - Most recent results have a 4.8σ (systematics limited) significance
- ❑ If LEE is interpreted as ν_e appearance in the primarily ν_μ beam, would suggest a 4th (sterile) eV-scale neutrino

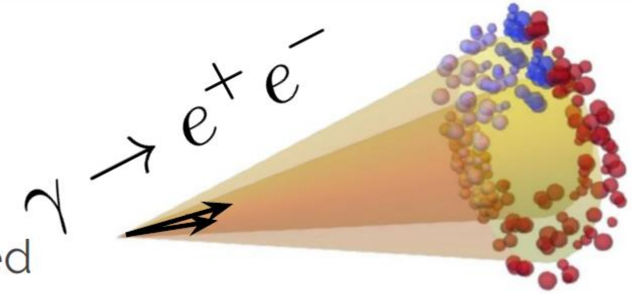
MiniBooNE: A Cherenkov Detector



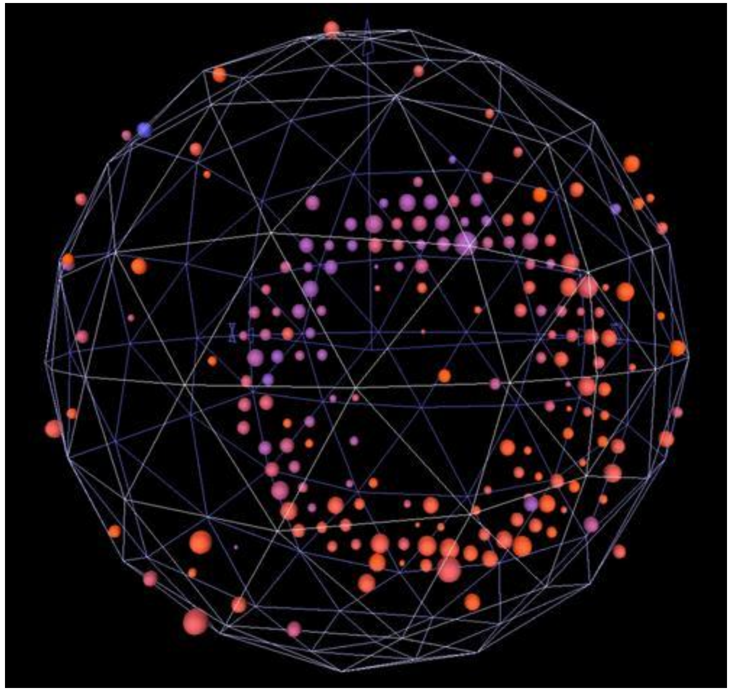
It detected ν_e by the **electrons** produced in charged current (CC) interactions.



However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring



MiniBooNE: A Cherenkov Detector



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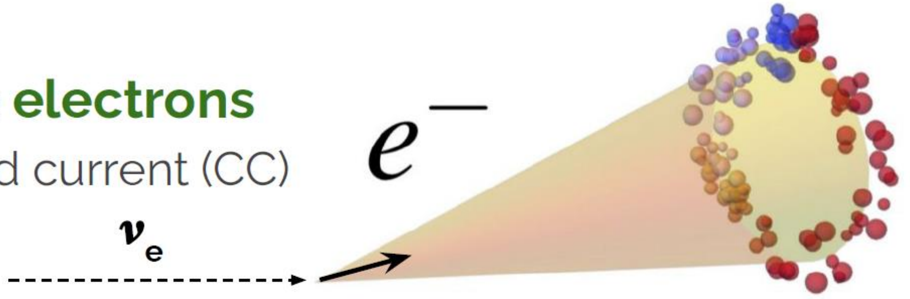
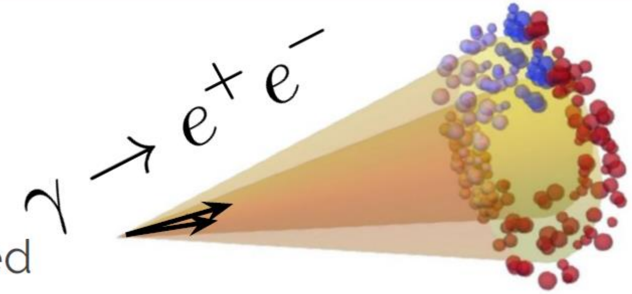


However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring

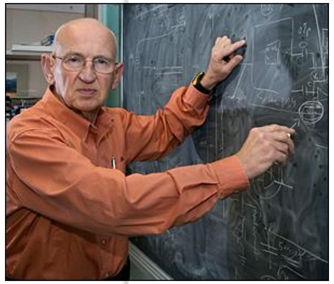


The MicroBooNE experiment was proposed to understand the nature of MiniBooNE LEE (e or γ?) with the Liquid Argon Time Projection Chamber (LArTPC) technology

Liquid Argon Time Projection Chamber (LArTPC)

LAr as total absorption calorimeter

- ❑ Dense, abundant and cheap
- ❑ Ionization and scintillation signals
- ❑ Pioneering paper lays out electrode geometry and signal processing in a liquid argon ionization chamber



NUCLEAR INSTRUMENTS AND METHODS 120 (1974) 221–236; © NORTH-HOLLAND PUBLISHING CO.

LIQUID-ARGON IONIZATION CHAMBERS AS TOTAL-ABSORPTION DETECTORS*

W. J. WILLIS†

Department of Physics, Yale University, New Haven, Connecticut 06520, U.S.A.

and

V. RADEKA

Instrumentation Division, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

Received 14 May 1974

1974

TPC as 4π charged particle detector

- ❑ 3D reconstruction with a fully active volume

The Time-Projection Chamber
- A new 4π detector for charged particles

David R. Nygren

Lawrence Berkeley Laboratory
Berkeley, California 97420

1974

LAr+TPC to obtain fine-grained 3D tracking with local dE/dx information and fully active target medium

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

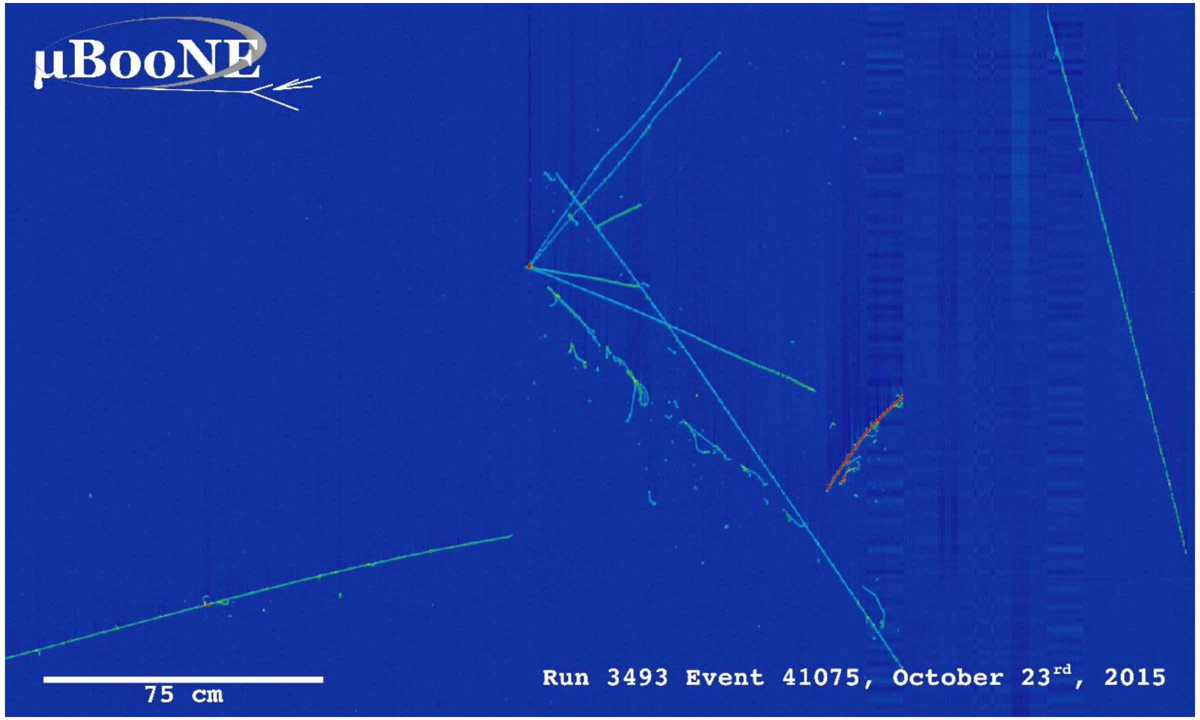
C. Rubbia

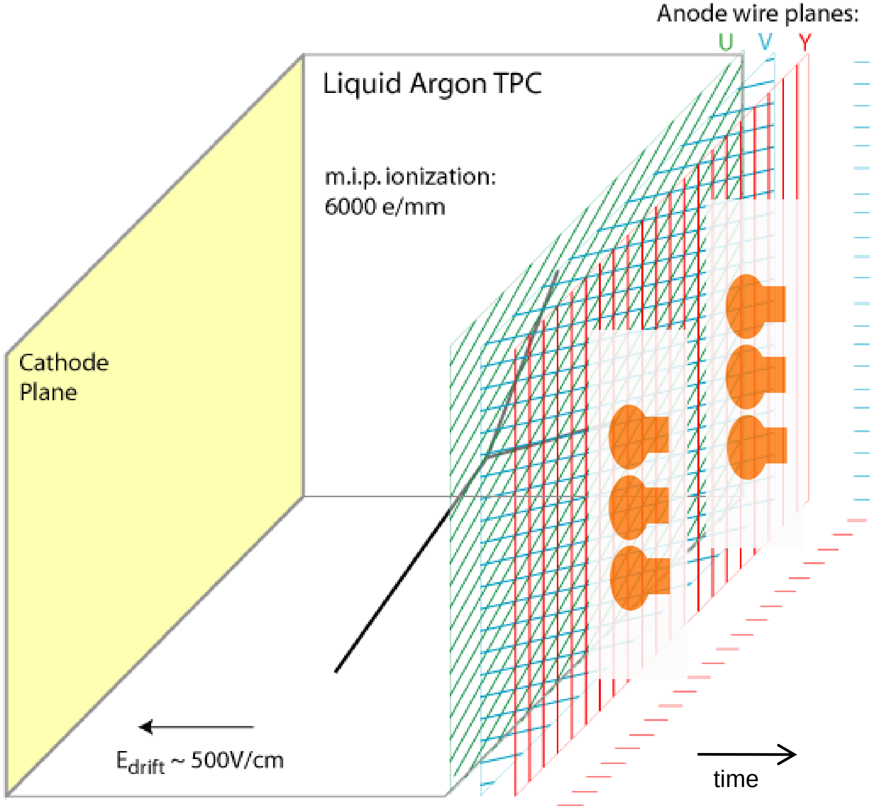
1977

Liquid Argon Time Projection Chamber (LArTPC)

- ~mm scale position resolution in 3D

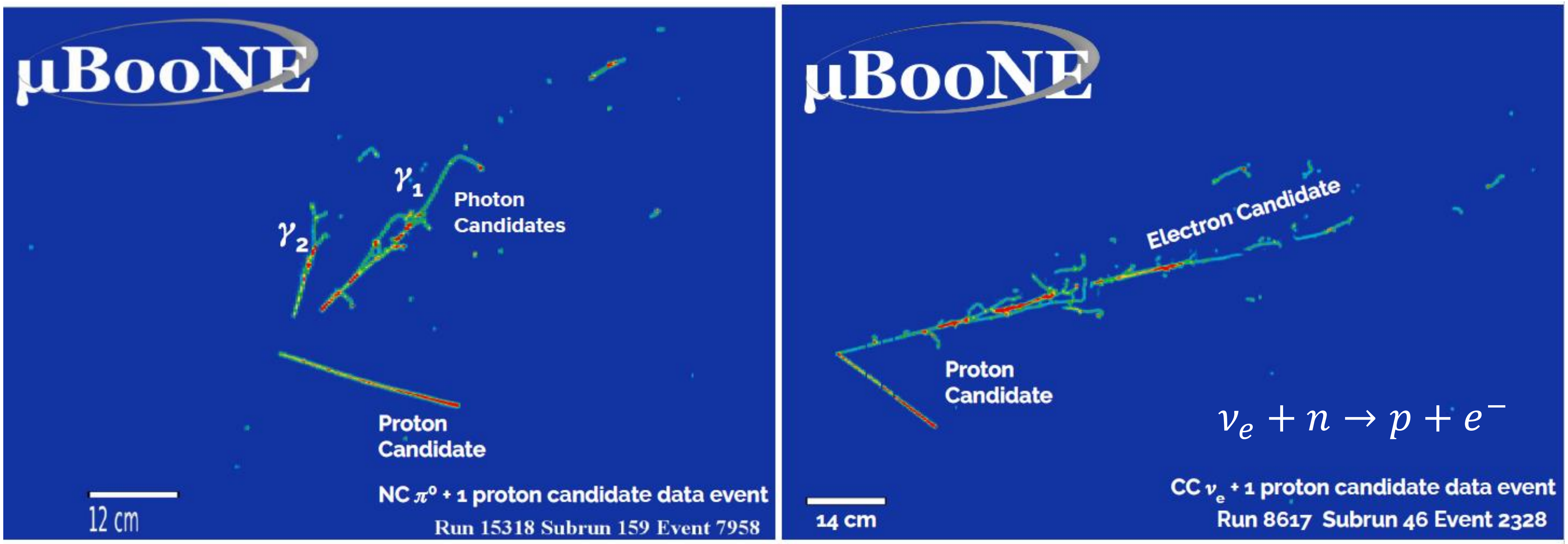
From Bo Yu (BNL)



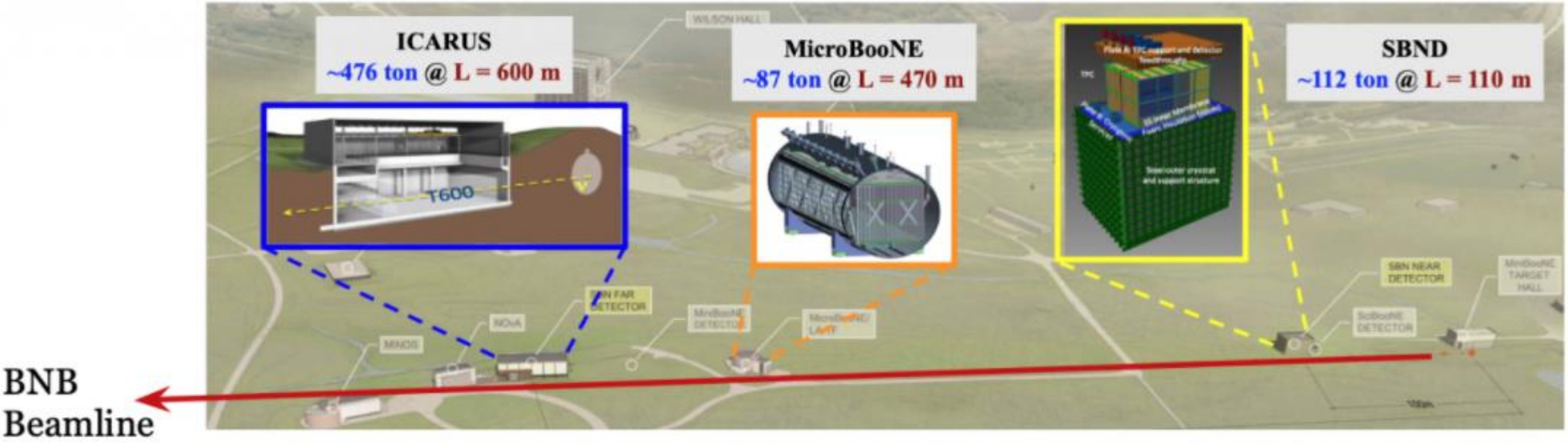


drift speed 1.6 m / milisec
wire pitch 3 mm

Particle Identification in LArTPC

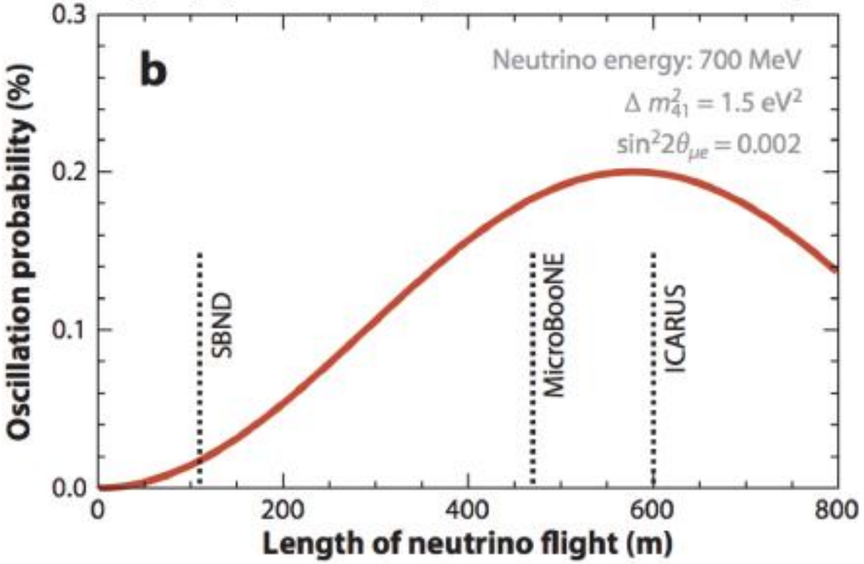


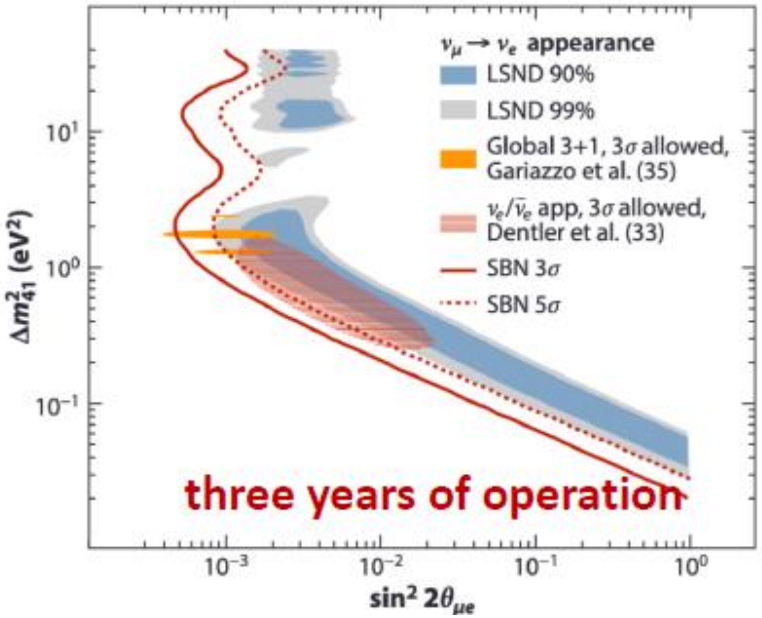
- ❑ Separate EM showers (e/γ) from tracks (proton, muon): topology
- ❑ Separation e from γ: gap identification + dE/dx
  - advantage over Cherenkov detector



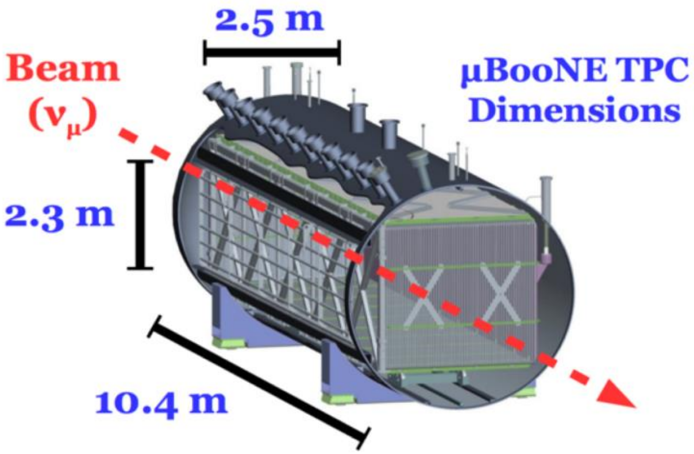
Annu. Rev. Nucl. Part. Sci. 2019. 69: 363-87

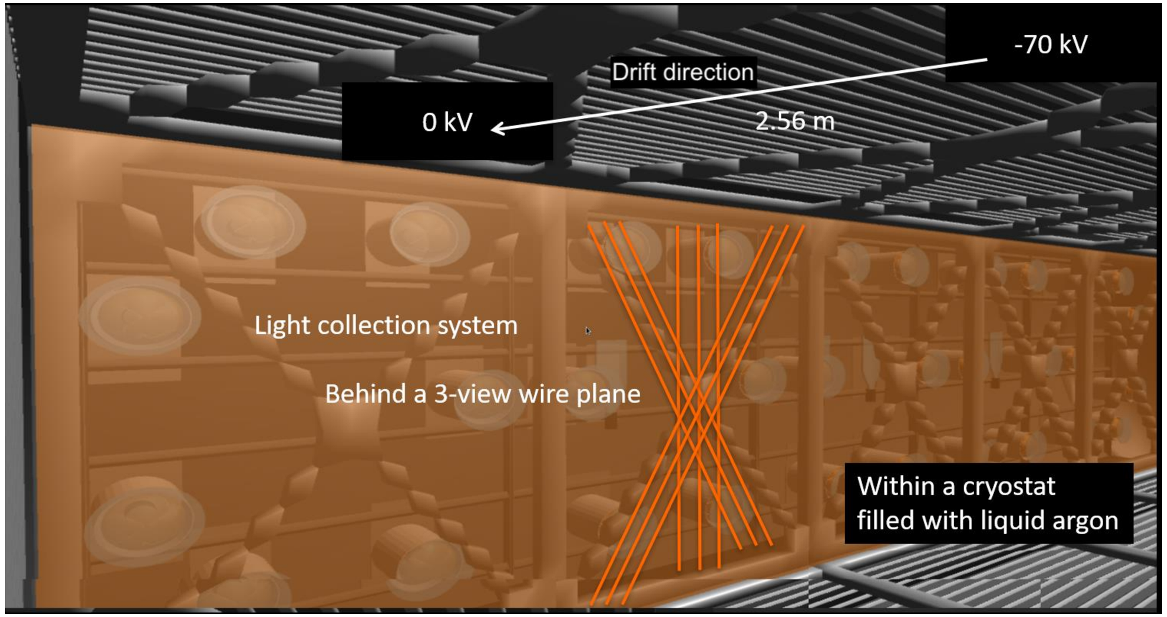
ν_e appearance (+ sterile neutrino)

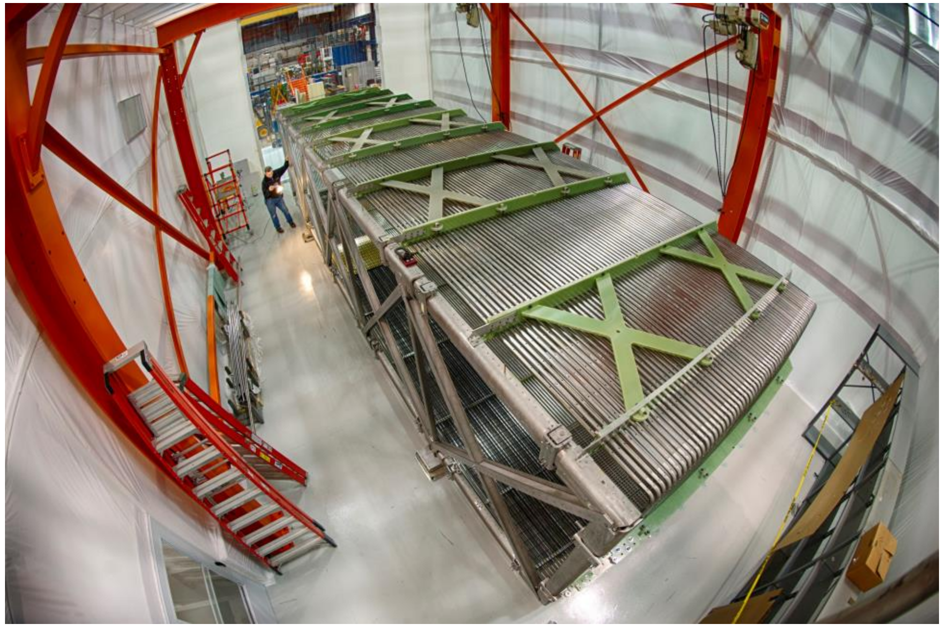




MicroBooNE

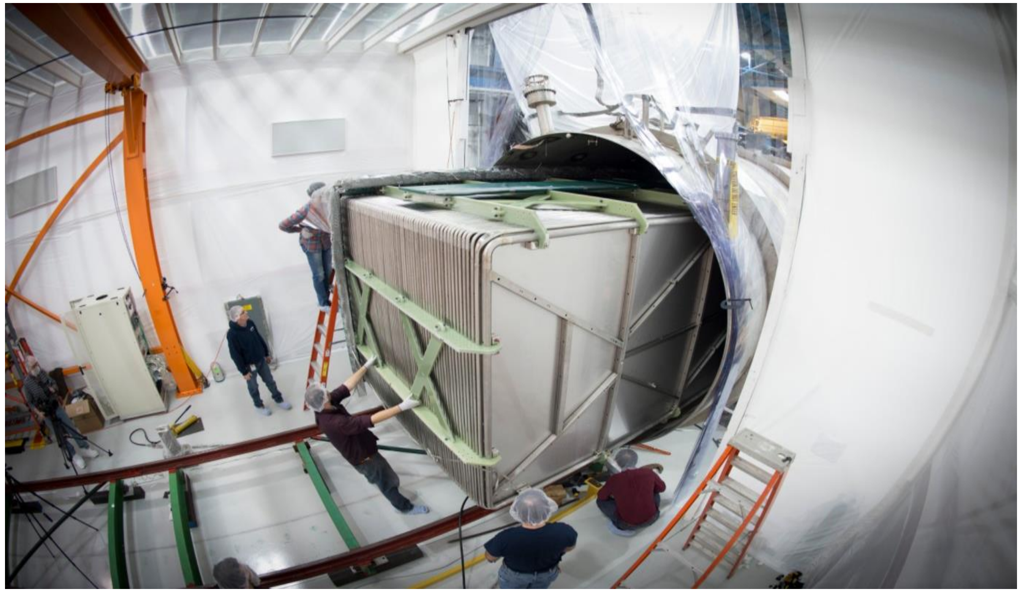

Beam
(ν_μ)
2.5 m
μBooNE TPC
Dimensions
2.3 m
10.4 m


-70 kV
Drift direction
0 kV
2.56 m
Light collection system
Behind a 3-view wire plane
Within a cryostat
filled with liquid argon



MicroBooNE Timeline

- ❑ Oct. 2007: MicroBooNE was proposed
- ❑ Jun. 2012: Start TPC construction
- ❑ Dec. 2014: Complete detector installation
- ❑ Jun. 2015: Fill detector with liquid argon
- ❑ Aug. 2015: Turn on detector
- ❑ Oct. 2015: Start neutrino beam data-taking



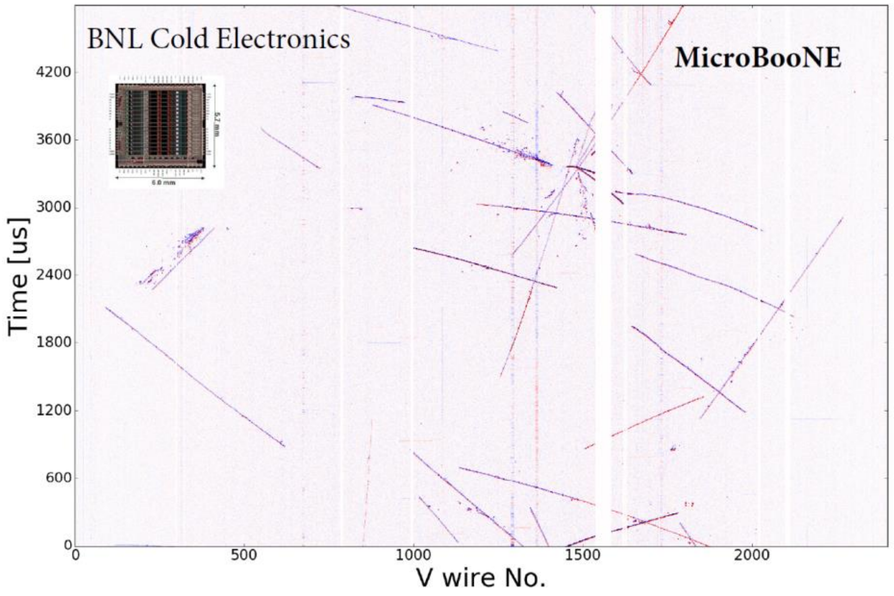
Successful demonstration of:

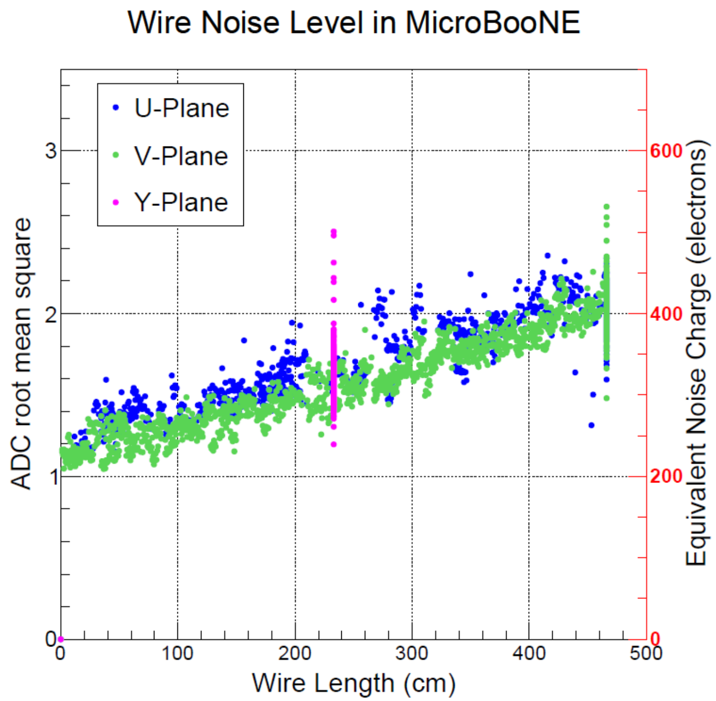
- ❑ Cold, low noise electronics
- ❑ Excellent (near perfect) purity
- ❑ Variety of detector physics
  - ▪ Signal processing, diffusion, space charge, etc.
- ❑ Stable, long-term running
  - • 500k interactions over 5 years

Cold electronics (Lab tour @3pm today)

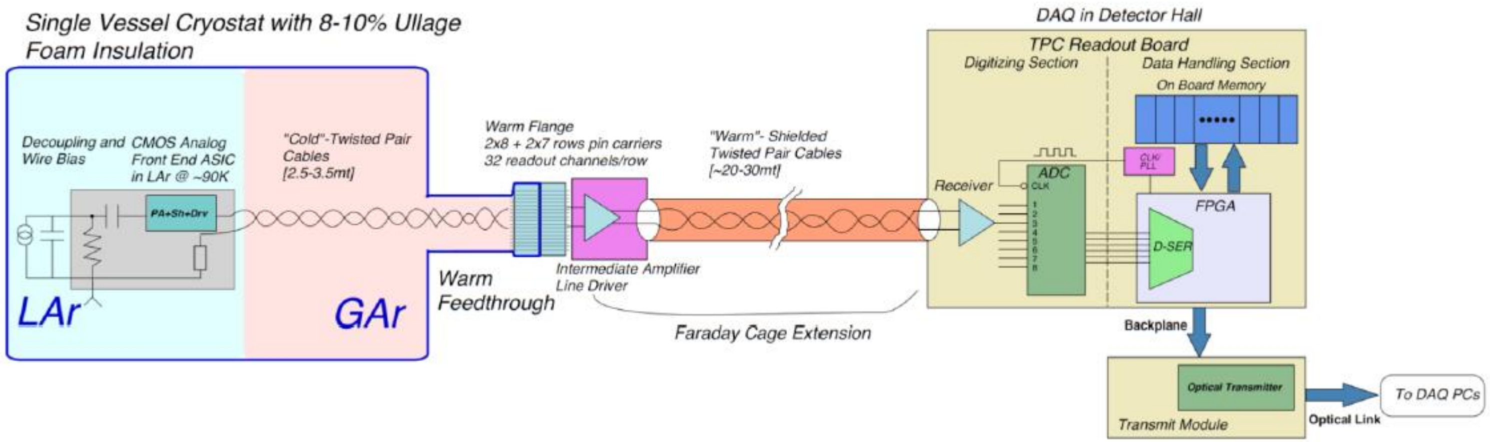
- Placing the preamplifier inside LAr significantly reduced the electronics noise (5-6 times compared to past warm electronics)

  - **~40:1** (20:1) MIP peak-to-noise ratio in the collection (induction) wire plane



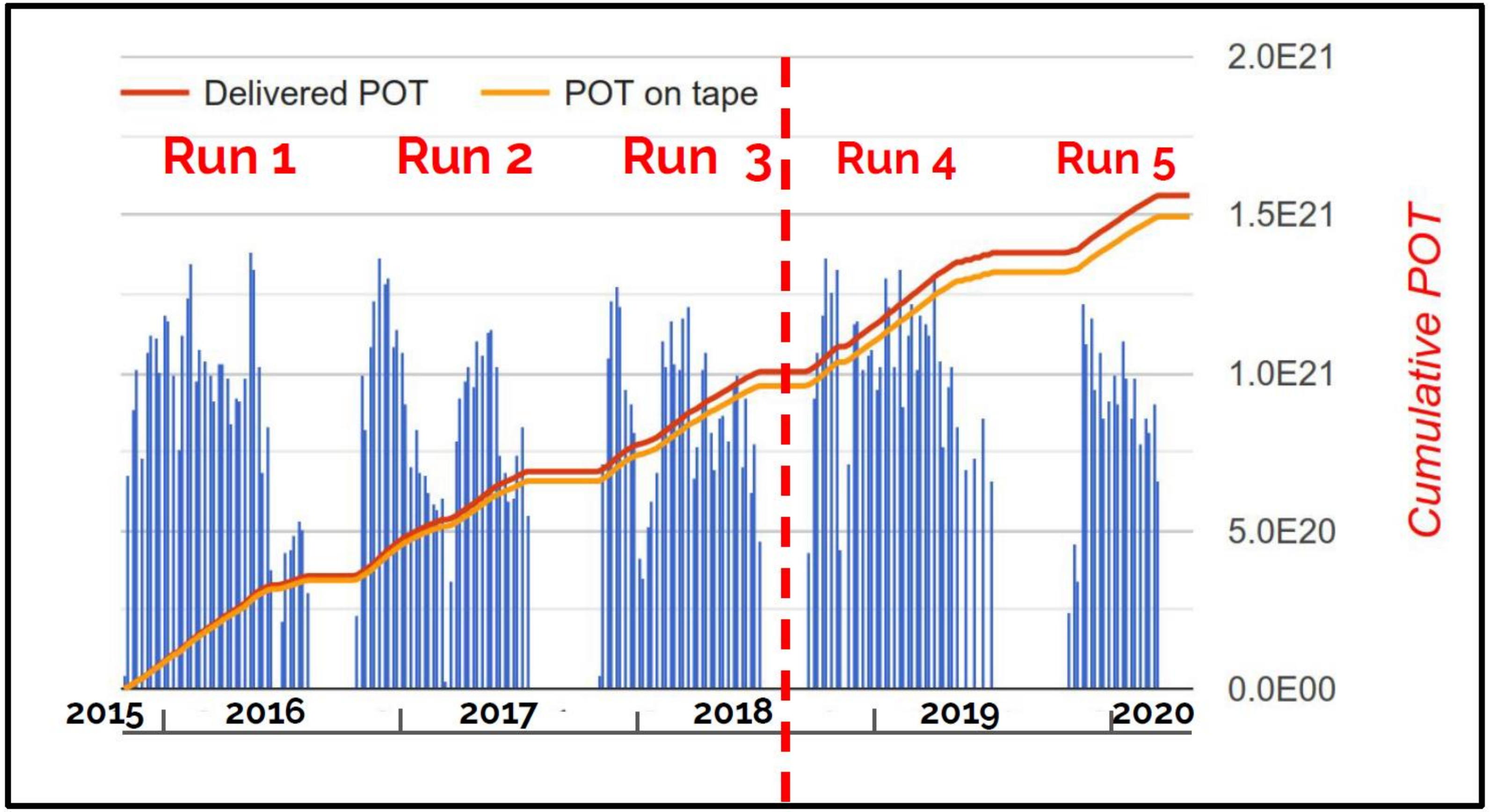


JINST 12, P08003 (2017)



Largest Sample of Neutrino Interactions on Argon in the World

2015-10-15 first beam



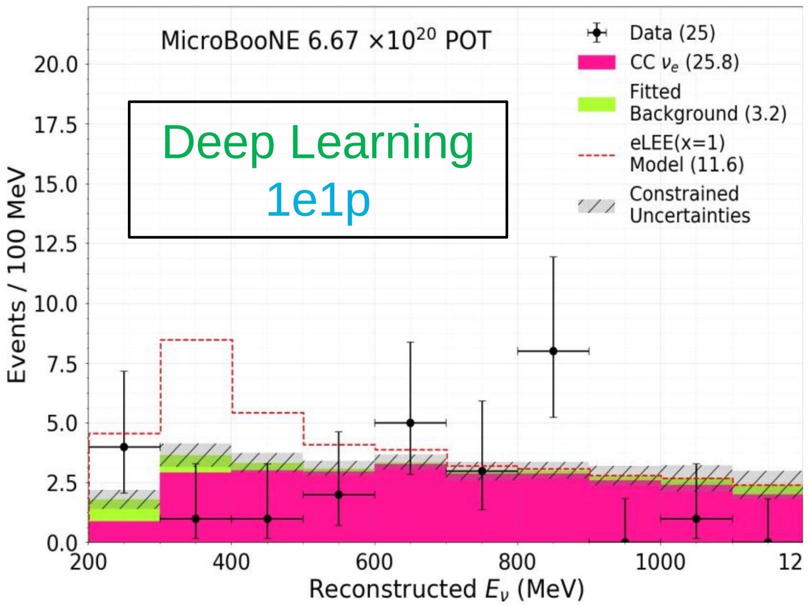
First Results in 2021 from run 1 – 3 (~7e20 protons-on-target)

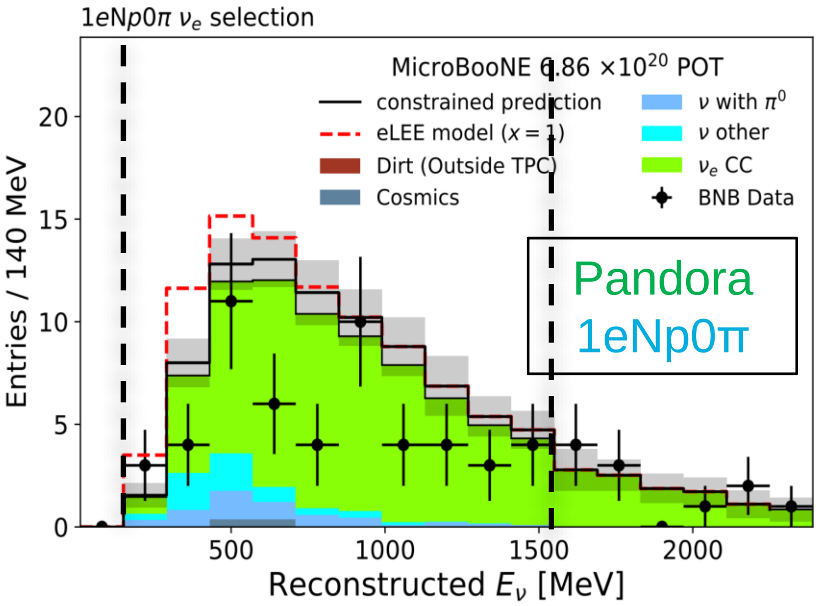
MicroBooNE First Results

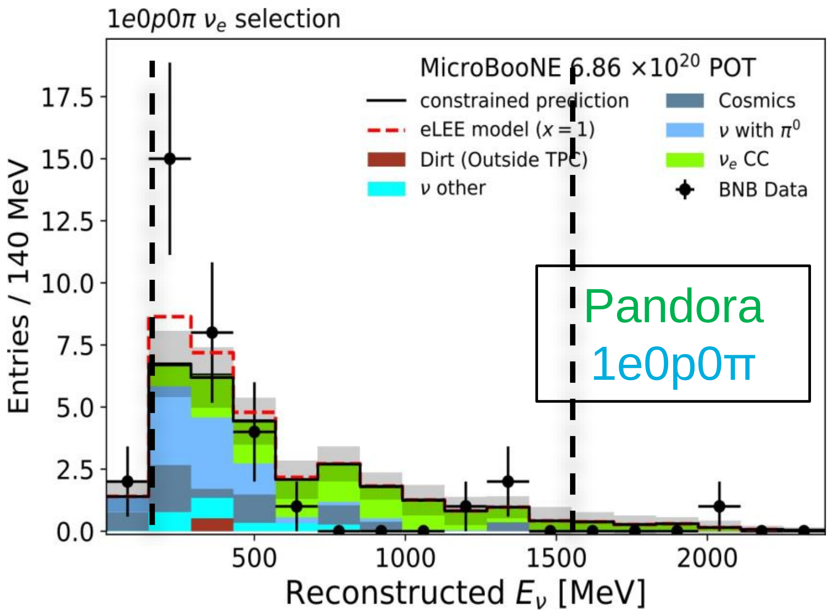
- Restricting to quasi-elastic kinematics (Deep Learning , 1e1p)
- MiniBooNE-like final state (Pandora, 1eNp0π, 1e0p0π)
- Inclusive ν_e final states (Wire-Cell, 1eX)

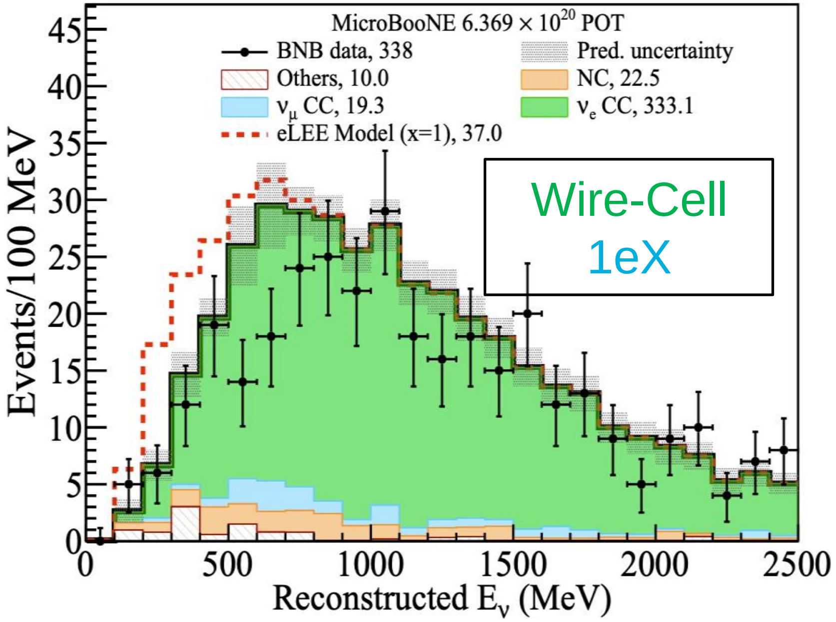
No ν_e excess were observed in all 4 different final state topologies

Phys. Rev. Lett. 128, 241801 (2022)

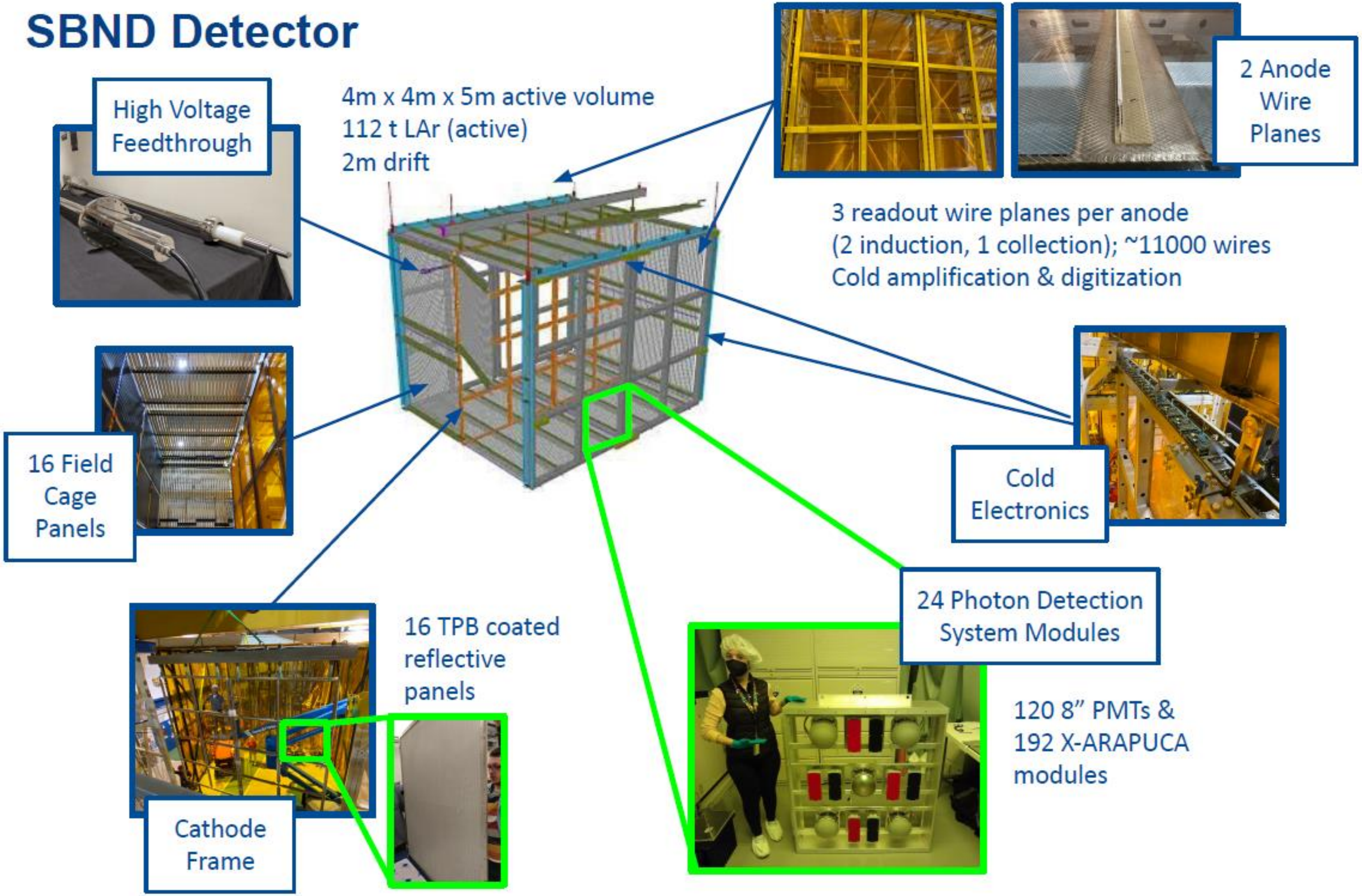








SBND Detector



SBND Construction Status

- SBND is about to complete the construction of the TPC
  - Both wire planes and the cathode were installed into the Assembly Transport Frame in 2021
  - Field Cage modules and Cold Electronics installed in end of 2021 & 2022
  - Photon Detection System will be installed this summer

Dec 2019

Empty Assembly Transport Frame

Assembly tent with TPC inside

May 2022

Cathode and Field Cage

Membrane Cryostat installation in progress

- Cryostat steel support structure completed in Nov 2019; Membrane cryostat installation in progress right now
- The detector will be transported to its final position in the BNB beamline end of 2022, and start commissioning in 2023

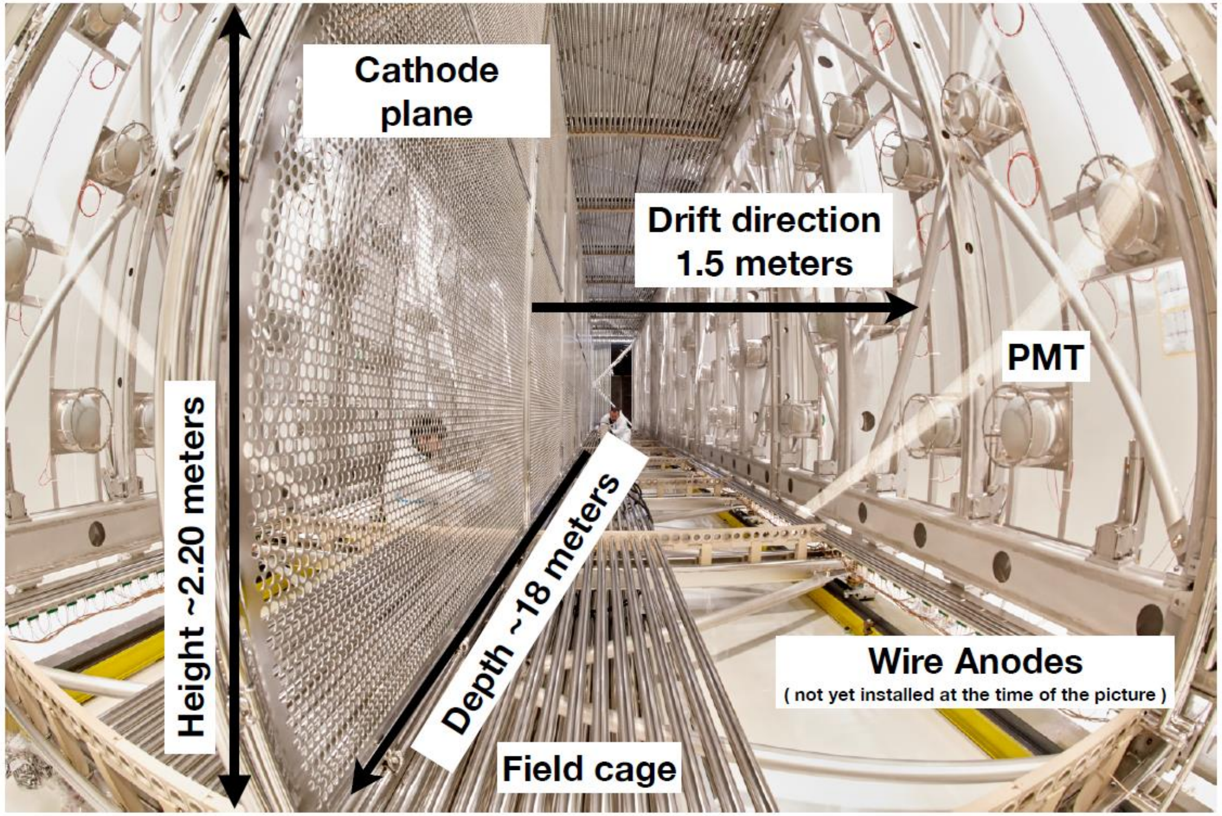
Video: SBND Detector Assembly

SBND Video

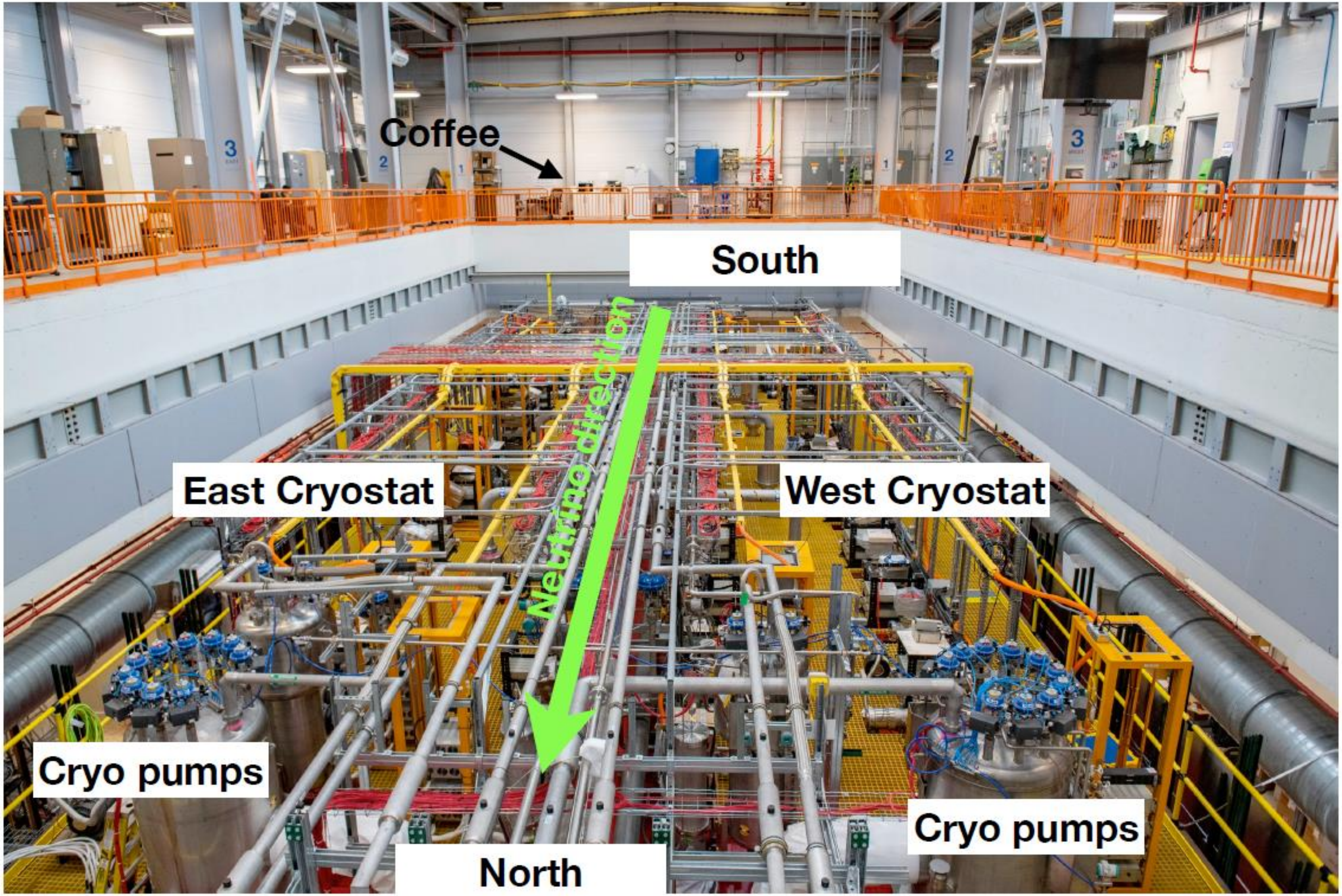
ICARUS

2 LArTPC modules
Total of 760t LAr (467t active)

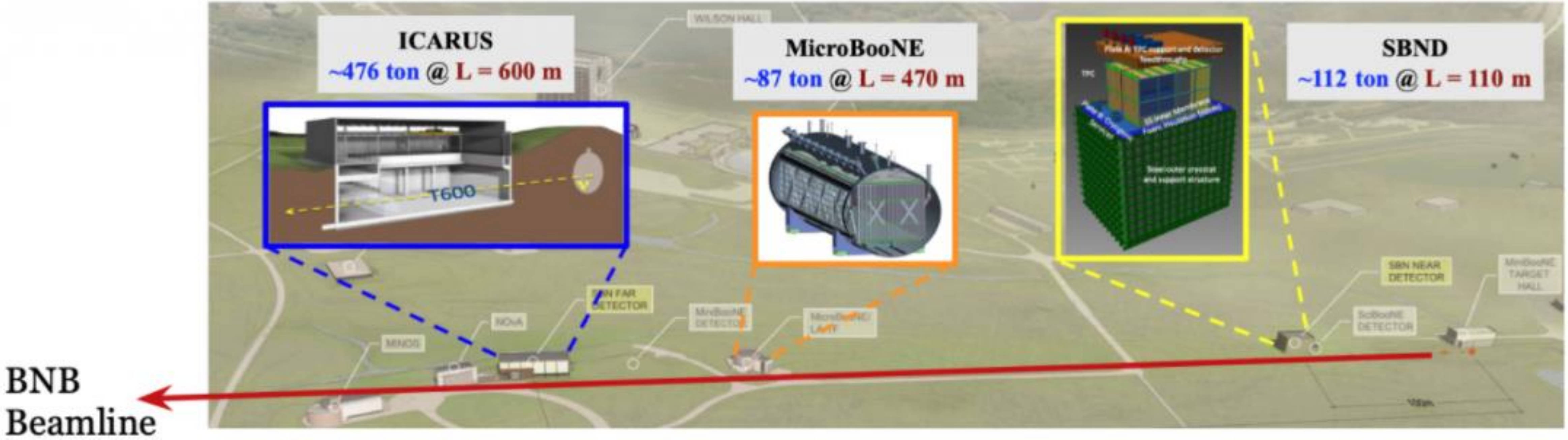
cryostat




ICARUS


Coffee
South
Neutrino direction
East Cryostat
West Cryostat
Cryo pumps
Cryo pumps
North

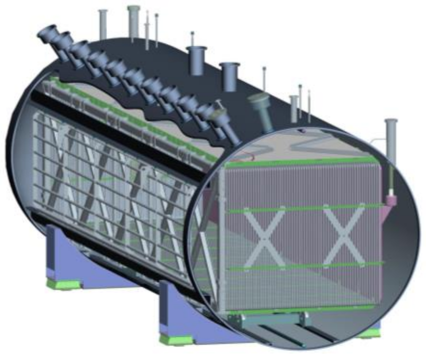
Short Baseline Neutrino Program



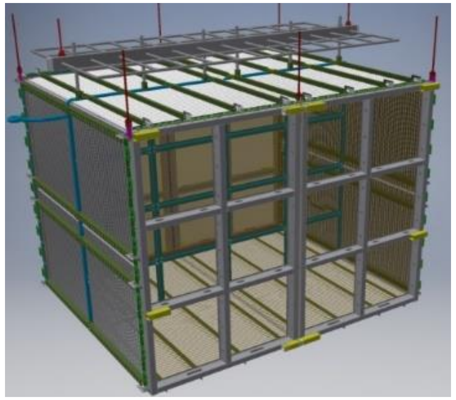
Multiple LArTPC experiments at different distances to search for eV-mass-scale sterile neutrinos

MicroBooNE: took data in 2015 – 2021
ICARUS: started physics data taking this year
SBND: install detector now; expect to take data next year

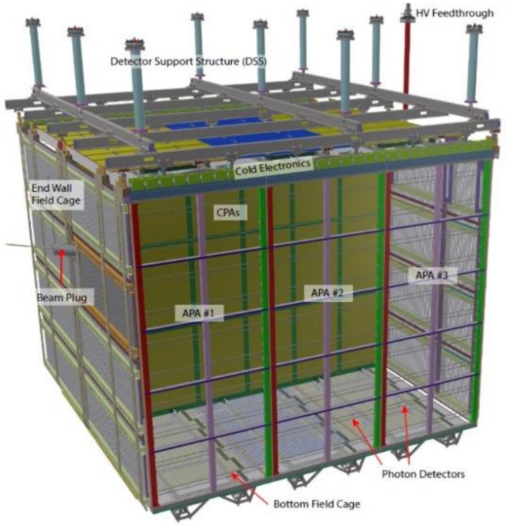
Future: DUNE will be ~x100 Bigger



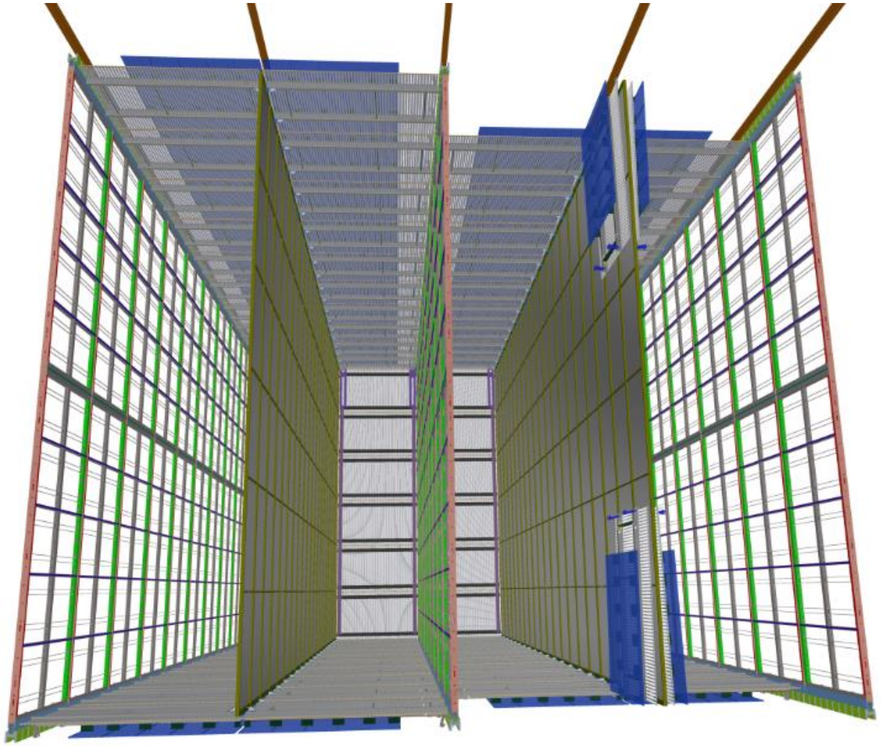
MicroBooNE, 87 ton
2.3m x 2.5m x 10.4m



SBND, 112 ton
4m x 4m x 5m

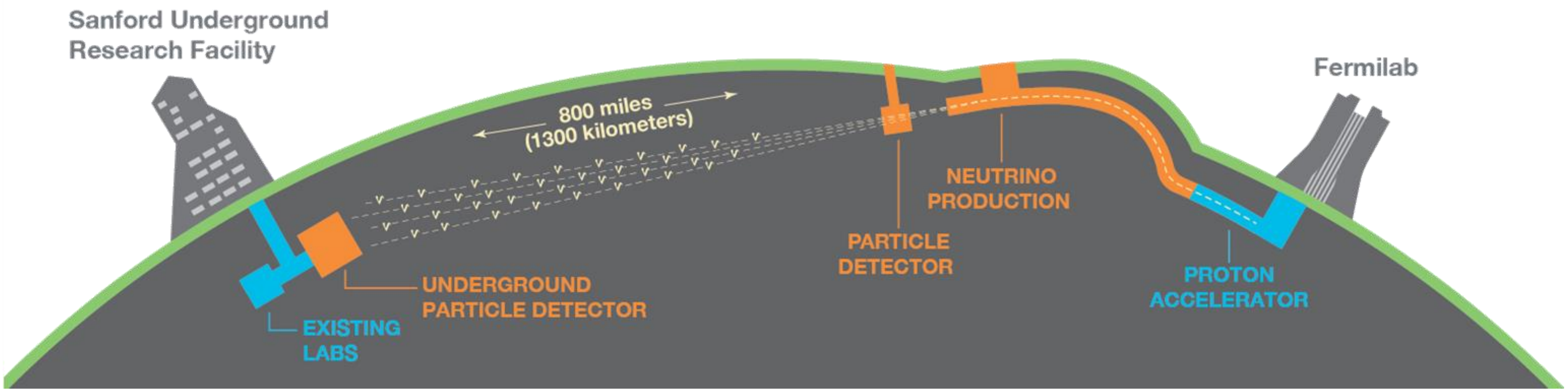


ICARUS, 476 ton
1.5m x 2.2m x 18m x 4



DUNE, 40,000 ton
14m x 12m x 58m x 4

Deep Underground Neutrino Experiment



- 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

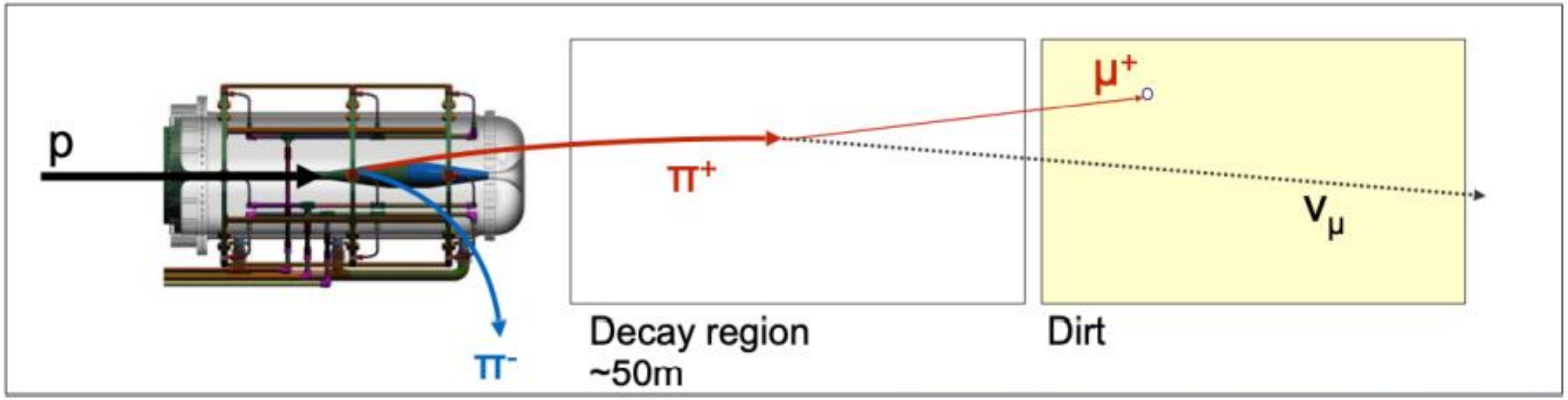
- CP violation in neutrino sector
- Neutrino mass ordering
- Precision neutrino oscillation parameters
- Phenomenon from sterile neutrinos
- Supernova neutrinos
- Nucleon decay
- …

Tomorrow: LArTPC Data Analysis

- What do raw data in LArTPC look like?
- How to turn raw data into 2D images
- How to reconstruct a 3D event from 2D images
- How to learn physics quantities from the 3D event
- How to apply Deep Neutral Network in LArTPC analysis

Backup Slides

Booster Neutrino Beam (BNB)



- 8 GeV protons from Booster
  - Up to 5 Hz and 5 x 10^{12} protons per pulse
- Beryllium target (7 x 10.2cmx1cm Ø slugs)
- Horn pulsed at 170 kA (neutrino and antineutrino modes)
- 50-m long decay region