The Short-Baseline Near Detector Experiment

Daisy Kalra, Columbia University

Fermilab 2024 Summer Students School (The Italian Summer Student Program)

SHORT-BASELINE NEAR DETECTOR SBND

NSF

NEVIS LABORATORIES COLUMBIA UNIVERSITY

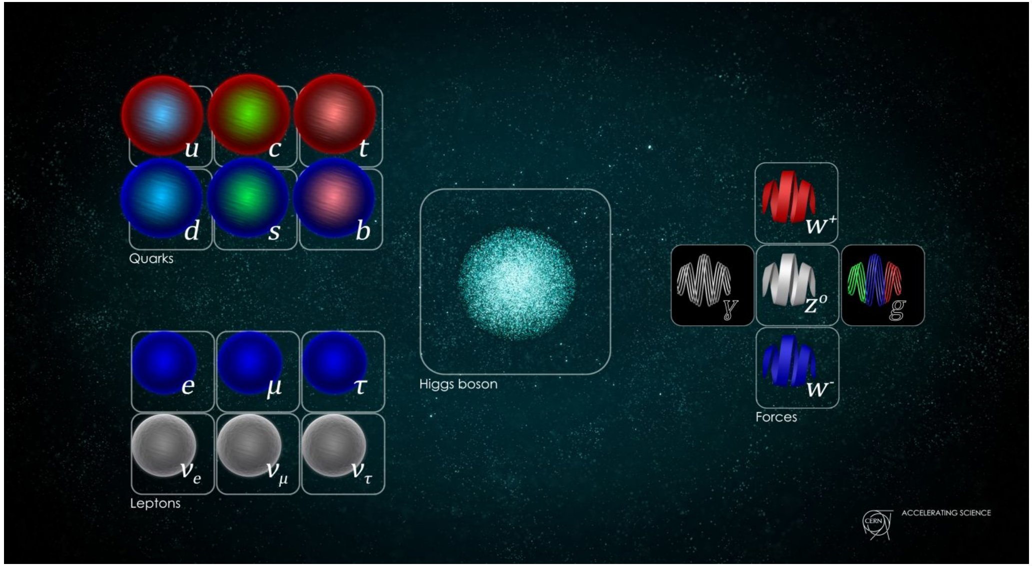
Outline

- ❖ Neutrinos in the Standard Model
- ❖ Neutrino Oscillations
- ❖ Open Questions in field of Neutrino Physics
- ❖ The Short-Baseline Neutrino Program
- ❖ The Short-Baseline Near Detector (SBND) Experiment

Neutrinos in the Standard Model

Only matter particles in the Standard Model (SM) **that don't carry electric charge and only participate in weak interactions.**

Neutrinos are massless within the context of the SM.

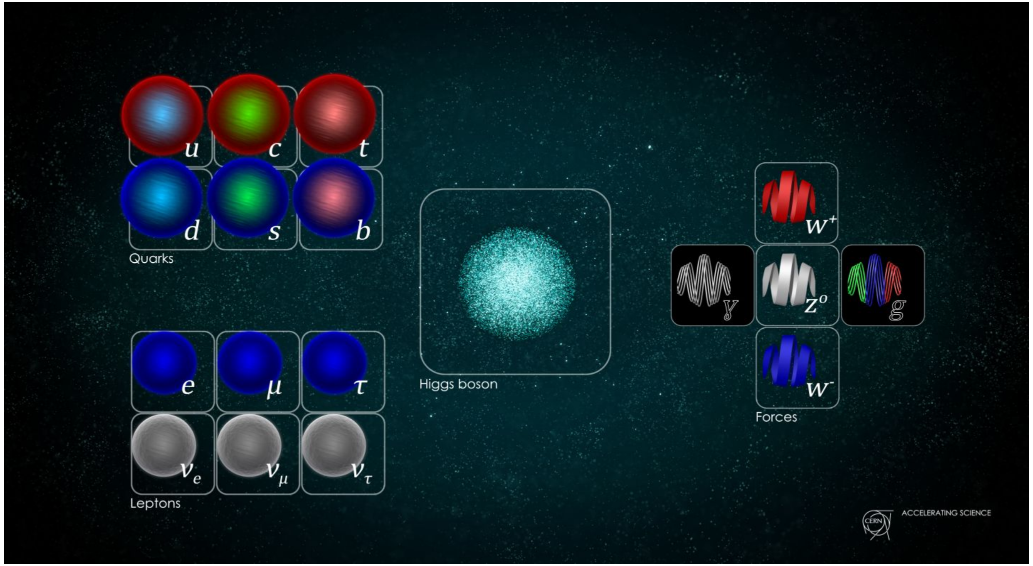


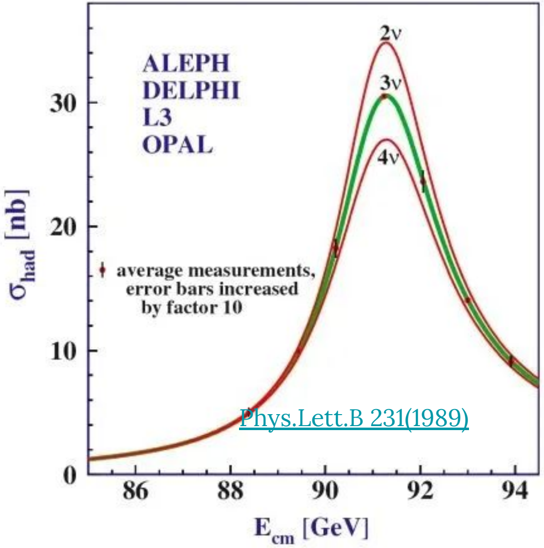
Neutrinos in the Standard Model

Only matter particles in the Standard Model (SM) **that don't carry electric charge and only participate in weak interactions.**

Neutrinos are massless within the context of the SM.

Three flavors of neutrinos:
electron, muon and tau (anti) neutrinos





Phys.Lett.B 231(1989)

Neutrino Generation

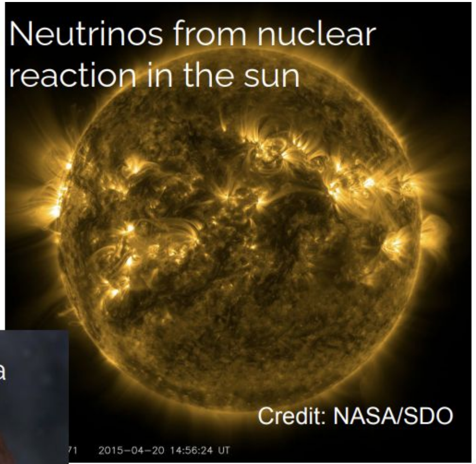
Nuclear interaction

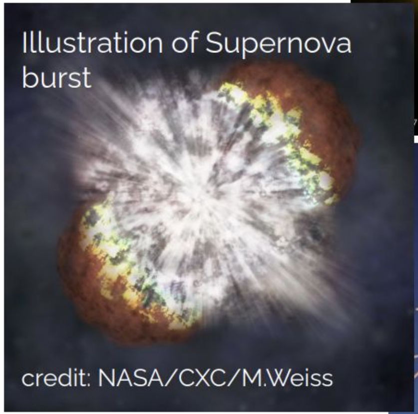
- ❖ Beta-decay $n \rightarrow p + e^- + \bar{\nu}_e$
- ❖ Electron capture (supernova burst)
  $p + e^- \rightarrow n + \nu_e$
- ❖ Nuclear fusion (in Sun)
  $p + p \rightarrow d + n + e^+ + \nu_e$

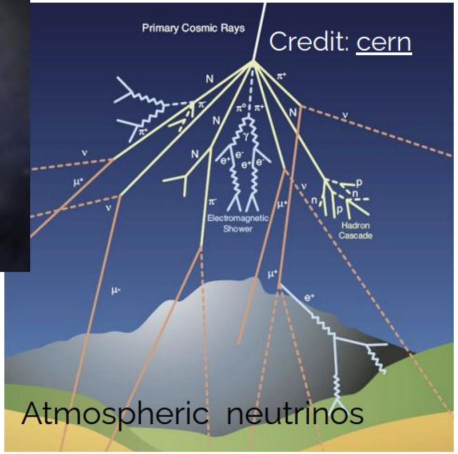
Meson Decay

- ❖ Atmospheric neutrinos
- ❖ Accelerator neutrinos

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

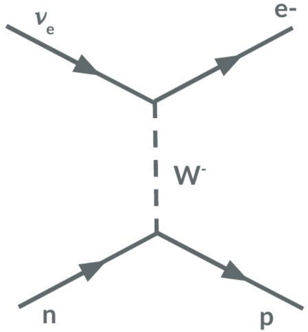


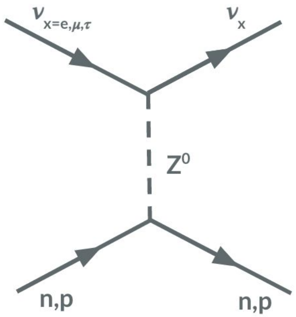


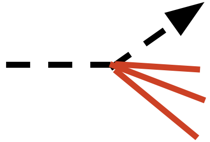


Neutrino Interaction

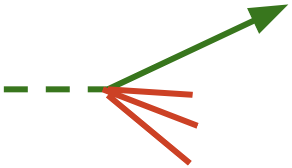
Neutrinos experience only weak interactions



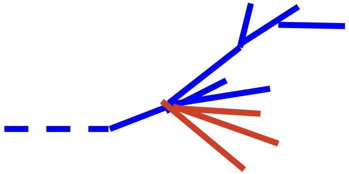




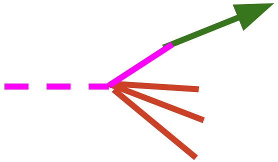
ν NC
hadrons → short event



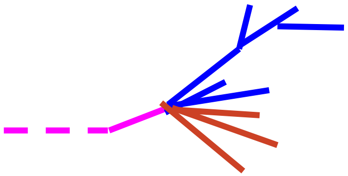
ν_μ CC → penetrating muon → long event



ν_e CC → showering electron → short event



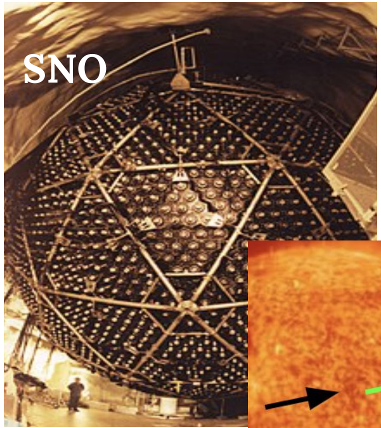
ν_τ CC 18% BF to a penetrating muon
muon → long event

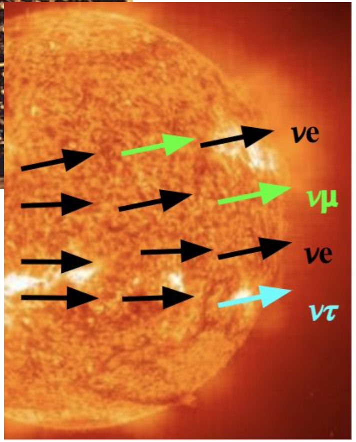


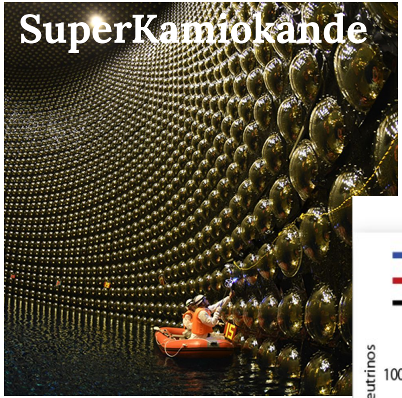
ν_τ CC 18% BF to an showering electron
electron → short event

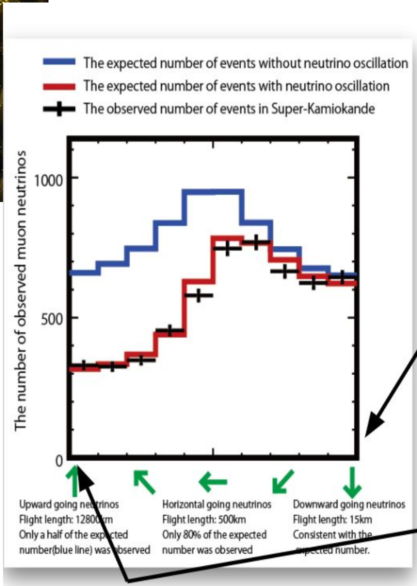
Neutrino Oscillations

The discovery of neutrino oscillations, as shown by SNO (solar neutrino oscillations) and SuperKamiokande (atmospheric neutrino oscillations), altered the SM picture of massless neutrinos

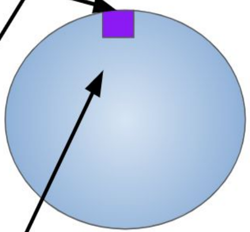








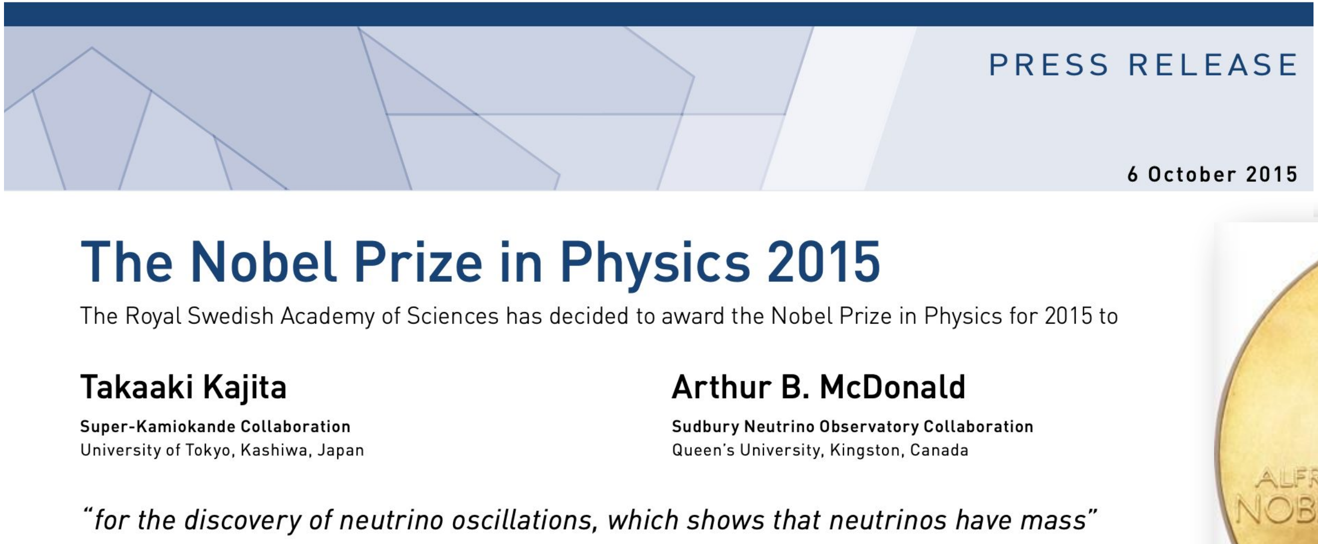
Neutrinos coming from above the Earth's surface **(downward going neutrinos)** have no time to oscillate



Upward going neutrinos travel more distance → **lot of time to oscillate**

Neutrino Oscillations

The discovery of neutrino oscillations, as shown by SNO (solar neutrino oscillations) and SuperKamiokande (atmospheric neutrino oscillations), altered the SM picture of massless neutrinos


PRESS RELEASE

6 October 2015

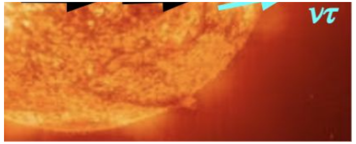
The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

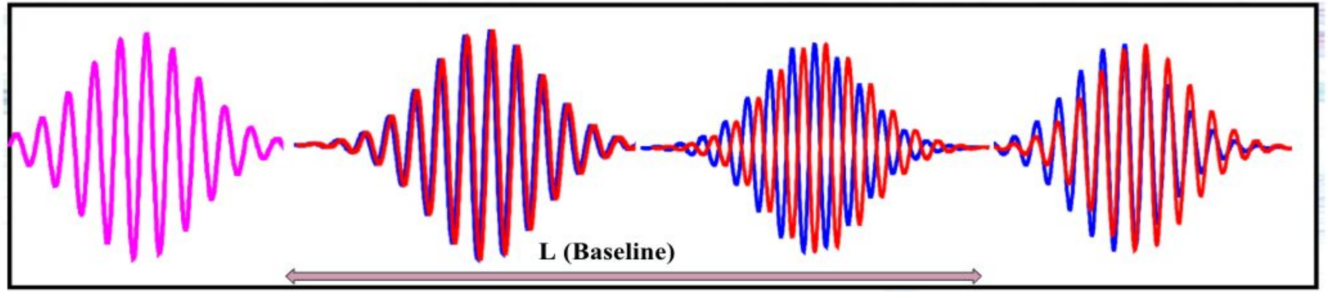
Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"



Neutrino Oscillations



Start with a particular flavor e.g. ν_μ

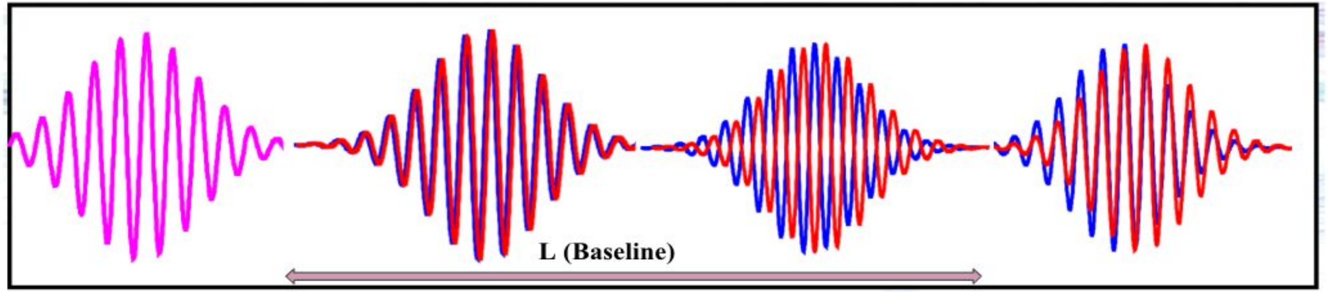
As neutrinos travel, they propagate as a mixture of mass eigenstates and go in and out of phase while traveling
"FLAVOR CHANGE CAN HAPPEN FOR MASSIVE PARTICLES"

End up having two flavors e.g.
ν_μ (Disappearance) and
ν_e (Appearance)

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

Flavor eigenstates | **Mixing matrix - PMNS matrix** | **Mass eigenstates**

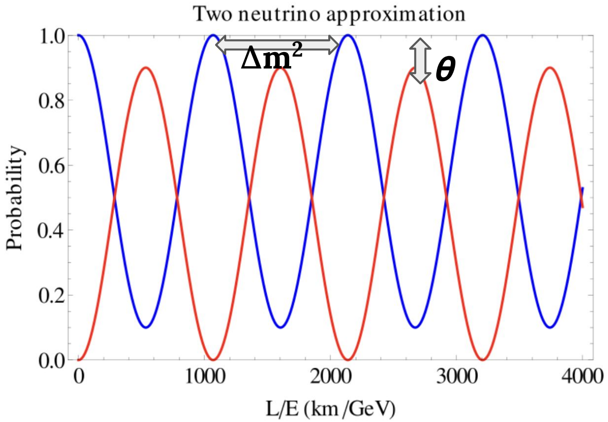
Neutrino Oscillations



Start with a particular flavor e.g. ν_μ

As neutrinos travel, they propagate as a mixture of mass eigenstates and go in and out of phase while traveling
"FLAVOR CHANGE CAN HAPPEN FOR MASSIVE PARTICLES"

End up having two flavors e.g.
ν_μ (Disappearance) and
ν_e (Appearance)



Two neutrino approximation

Appearance probability:

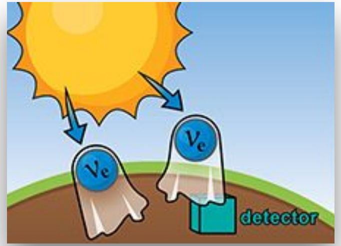
$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

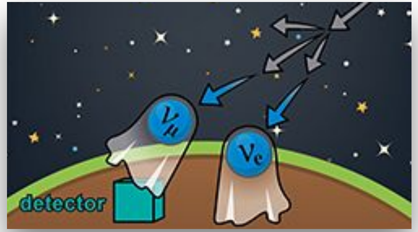
Disappearance probability:

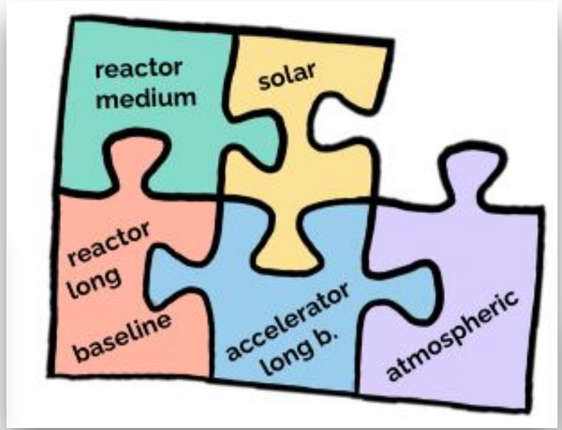
$$1 - \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

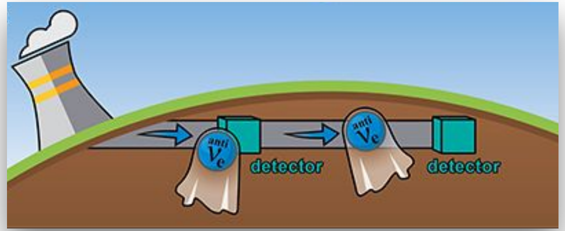
A well understood, three neutrino picture

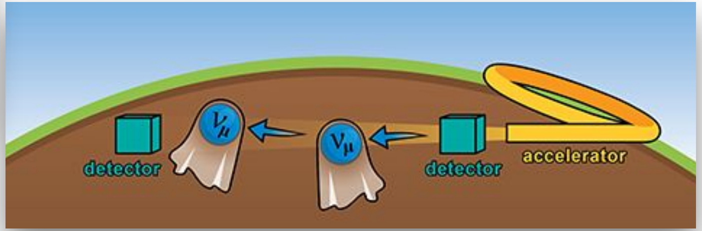
A broad experimental program to study neutrino oscillations [PDG2023].





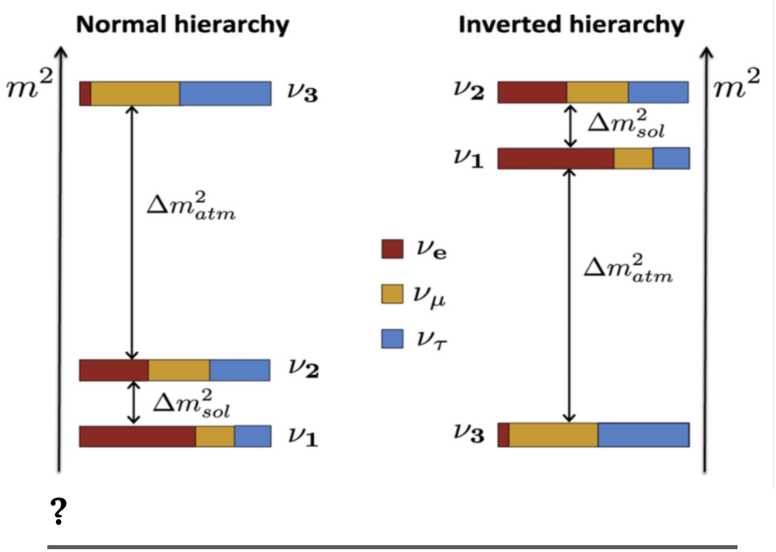






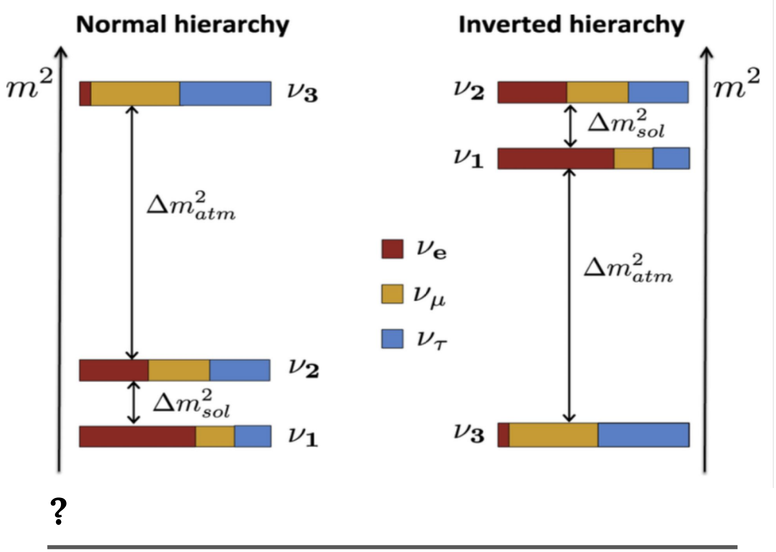
Open Questions

- ➔ What is the absolute mass of neutrinos? Mass hierarchy?
- ➔ Are neutrinos responsible for matter-antimatter asymmetry in the Universe?
- ➔ Are neutrinos dirac or majorana?
- ➔ Are there additional neutrino states beyond three?



Open Questions

- ➔ What is the absolute mass of neutrinos? Mass hierarchy?
- ➔ Are neutrinos responsible for matter-antimatter asymmetry in the Universe?
- ➔ Are neutrinos dirac or majorana?
- ➔ Are there additional neutrino states beyond three?



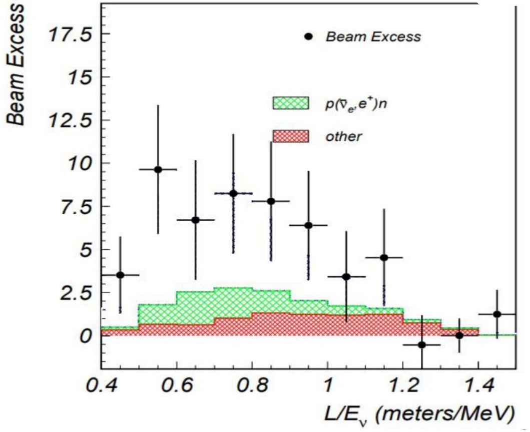
Are there additional neutrino states beyond three?

Short-baseline experiments

LSND (liquid scintillator detector)
Using antineutrinos from pion decay-at-rest, observed **3.8σ excess in $\bar{\nu}_e$** .

MiniBooNE (mineral oil cherenkov detector)
Using neutrinos and antineutrinos from pion decay-in-flight beam, same L/E as LSND, observed **4.8σ excess in $\bar{\nu}_e$ and ν_e.**

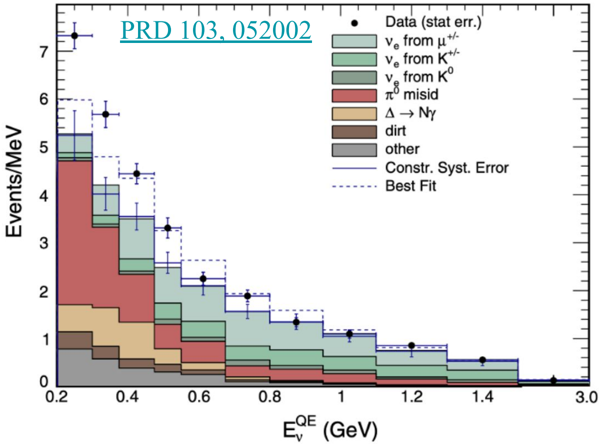
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



PRD 64, 112007

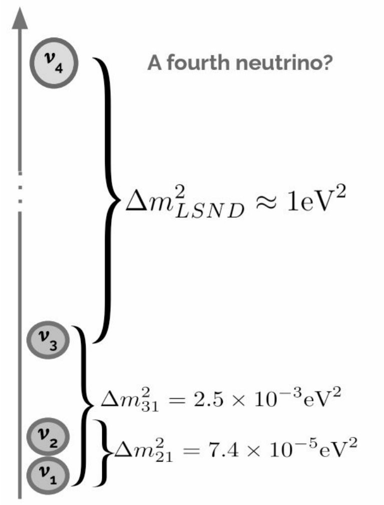
$\nu_\mu \rightarrow \nu_e$

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



Are there additional neutrino states beyond three?

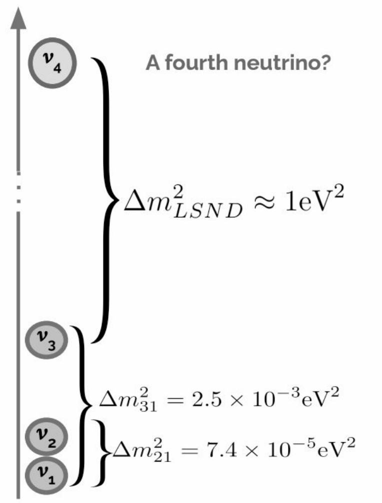
Short-baseline neutrino anomalies



- ❖ **These anomalies indicate a higher oscillation frequency than two others independently measured**!
  can not be accommodated within the standard three-neutrino picture
  → beyond the Standard Model
- ❖ Minimal model (3+1) requires an additional heavier neutrino mass eigenstate (m_4) : **sterile neutrino**

Are there additional neutrino states beyond three?

Short-baseline neutrino anomalies

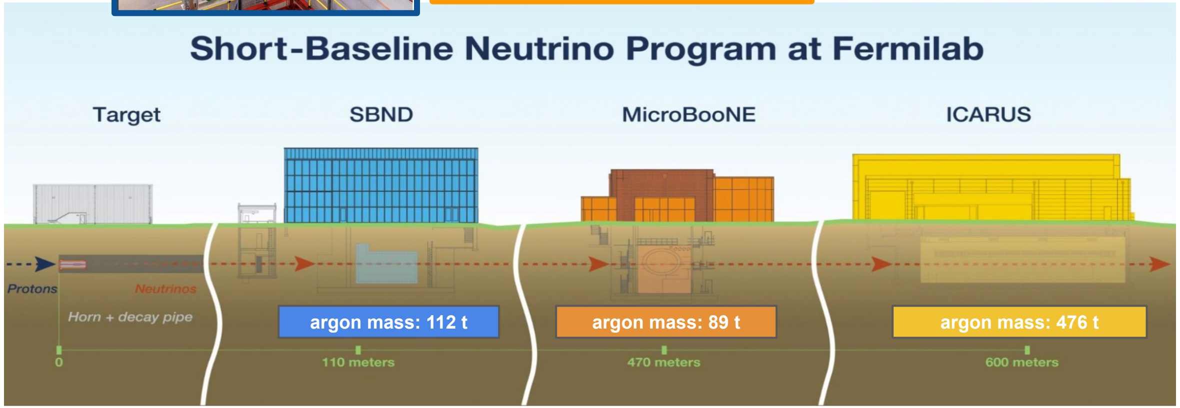


- ❖ **These anomalies indicate a higher oscillation frequency than two others independently measured**!
  can not be accommodated within the standard three-neutrino picture
  → beyond the Standard Model
- ❖ Minimal model (3+1) requires an additional heavier neutrino mass eigenstate (m_4) : **sterile neutrino**

Primary goal of the Short-Baseline Neutrino Program at Fermilab

The Fermilab Short-Baseline Neutrino (SBN) Program

- ❖ The Fermilab SBN program comprises three liquid argon time projection chamber (LArTPC) detectors



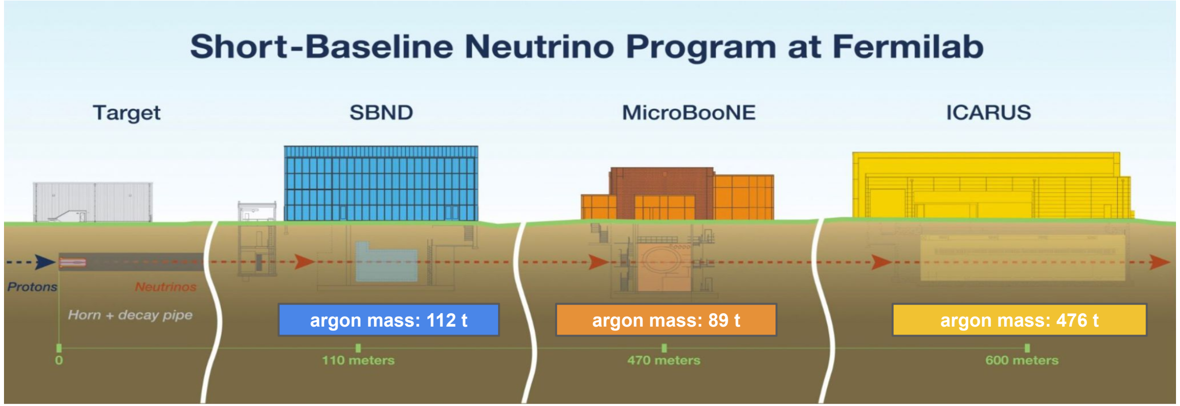
Collecting beam data since July 2024

Data collection period- 2015-2021

Collecting data since Oct. 2021

The Fermilab Short-Baseline Neutrino (SBN) Program

❖ The Fermilab SBN program comprises three liquid argon time projection chamber (LArTPC) detectors with three primary physics goals:
(1) Definitive search for light sterile neutrino oscillations
Motivated from short-baseline neutrino anomalies seen by the **LSND** and **MiniBooNE** experiments



Collecting beam data since July 2024.

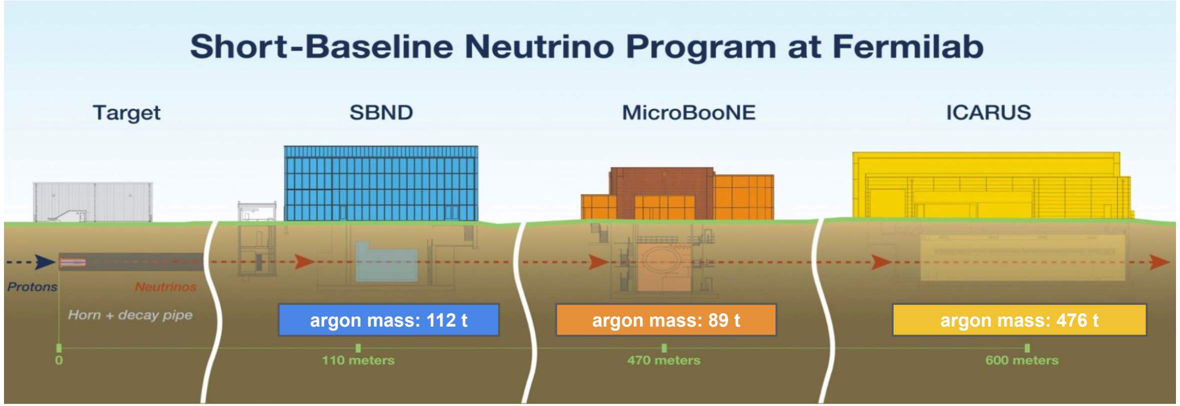
Data collection period- 2015-2021

Collecting data since Oct. 2021

The Fermilab Short-Baseline Neutrino (SBN) Program

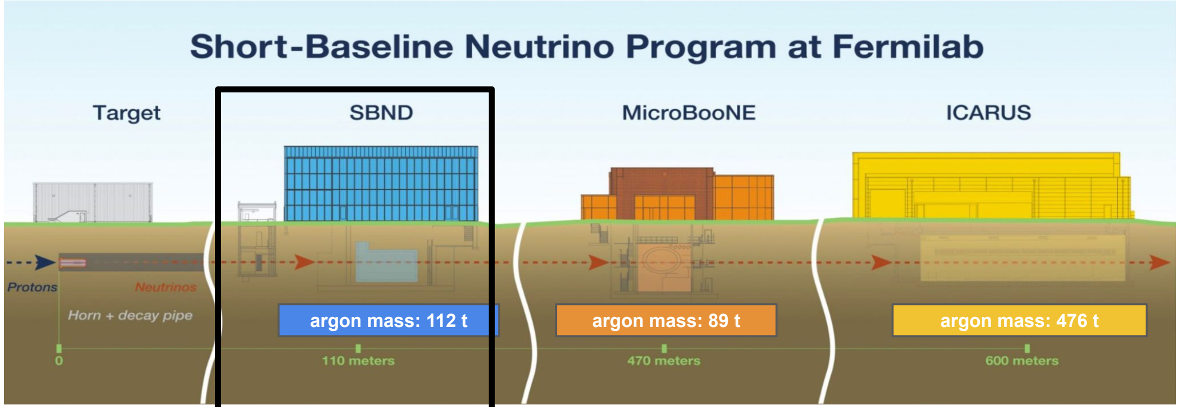
- The Fermilab SBN program comprises three liquid argon time projection chamber (LArTPC) detectors with three primary physics goals:
  (1) Definitive search for light sterile neutrino oscillations
  Motivated from short-baseline neutrino anomalies seen by the **LSND** and **MiniBooNE** experiments
  (2) High-precision neutrino-argon cross section measurements
  (3) Search for beyond-the-Standard-Model (BSM) physics processes.

- The detector trio share the same primary neutrino beam, nuclear target and detector technology to reduce systematic uncertainties to the level of a few %.



Collecting beam data since July 2024. | **Data collection period- 2015-2021** | **Collecting data since Oct. 2021**

The Short-Baseline Near Detector (SBND)

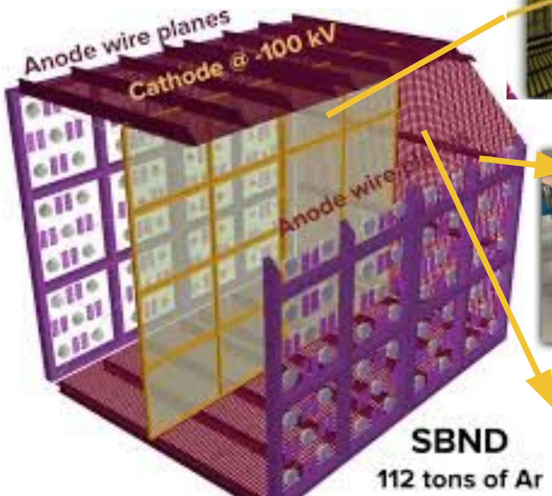


Collecting beam data since July 2024.

Data collection period- 2015-2021

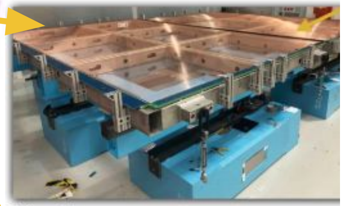
Collecting data since Oct.2021

The Short-Baseline Near Detector (SBND)



4x4x5m^3

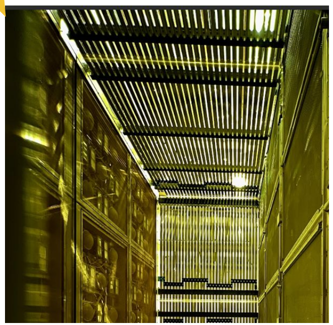
Cathode plane at -100kV in the center, divides the detector into two drift volumes (2m drift region)



Anode plane on either side, each with three wire planes with 3mm wire spacing

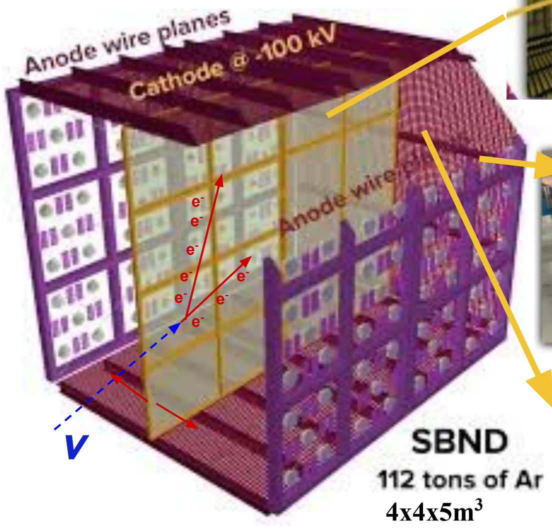
Total of 11,260 wires

JINST 15 P06033



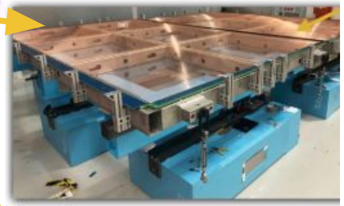
Field cage to ensure a uniform electric field of 500V/cm

The Short-Baseline Near Detector (SBND)



4x4x5m^3

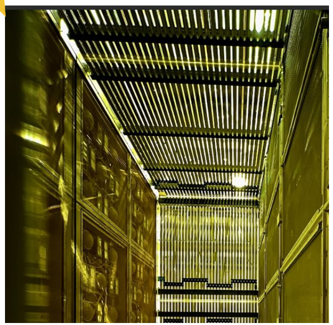
Cathode plane at -100kV in the center, divides the detector into two drift volumes (2m drift region)



Anode plane on either side, each with three wire planes with 3mm wire spacing

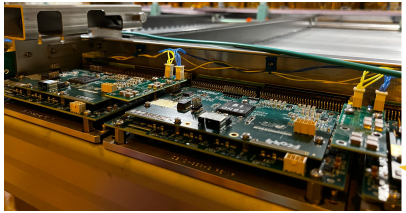
Total of 11,260 wires

JINST 15 P06033

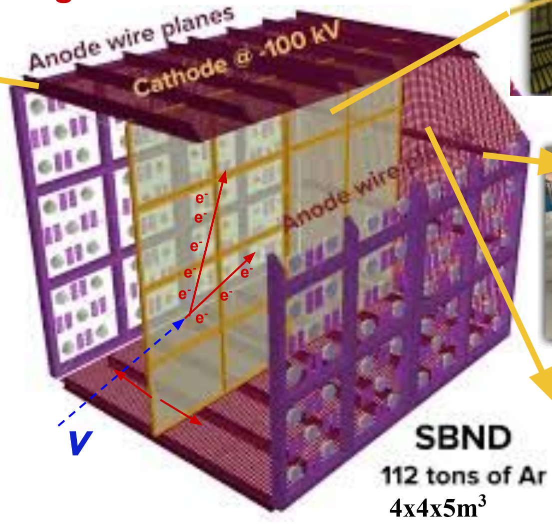


Field cage to ensure a uniform electric field of 500V/cm

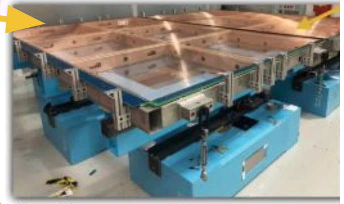
The Short-Baseline Near Detector (SBND)



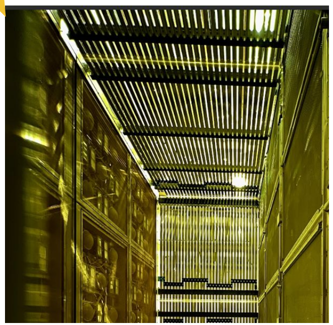
Cold electronics (in LAr)
Amplify and digitize **anode wire ionisation signals**.



Cathode plane at -100kV in the center, divides the detector into two drift volumes (2m drift region)

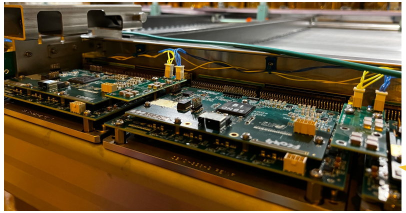


Anode plane on either side, each with three wire planes with 3mm wire spacing
Total of 11,260 wires
JINST 15 P06033



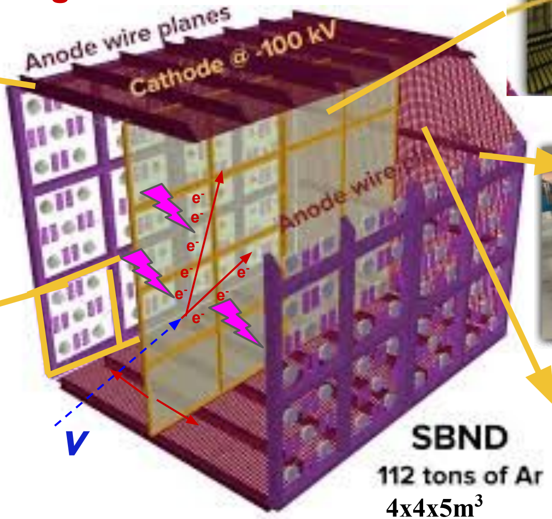
Field cage to ensure a uniform electric field of 500V/cm

The Short-Baseline Near Detector (SBND)



Cold electronics (in LAr)
Amplify and digitize **anode wire ionisation signals.**

Cathode plane at -100kV in the center, divides the detector into two drift volumes (2m drift region)



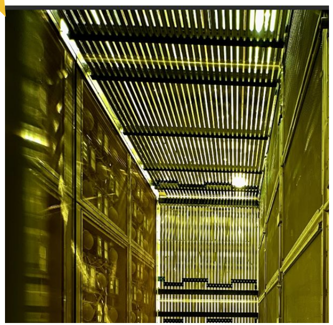
4x4x5m^3

Anode plane on either side, each with three wire planes with 3mm wire spacing
Total of 11,260 wires
JINST 15 P06033

Photon Detection System to record the prompt **scintillation light**

120 PMTs
(80% TPB-coated, 20% uncoated)
192 X-ARAPUCAs

arXiv: 2406.07514(SBND Collaboration)

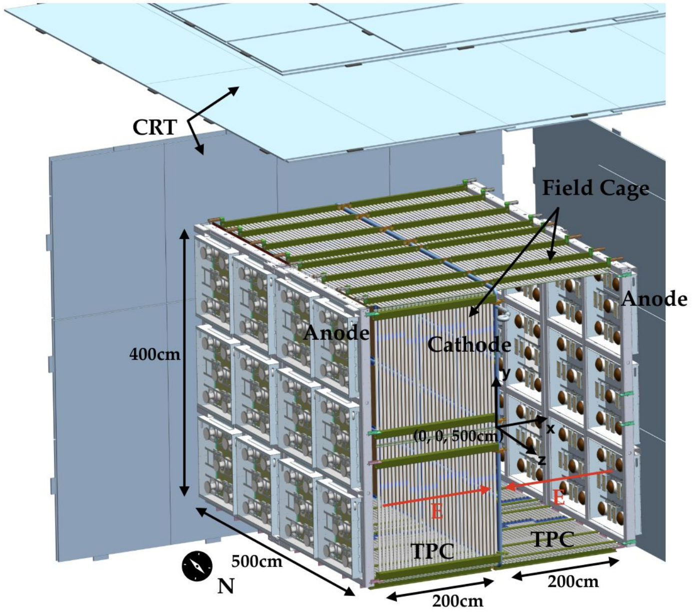


Field cage to ensure a uniform electric field of 500V/cm

New technology to be demonstrated within SBND:
R&D for the next-generation DUNE experiment.

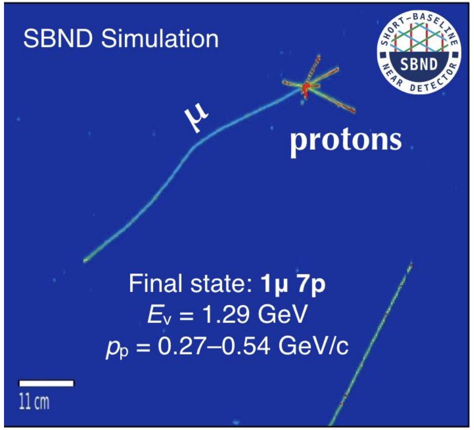
Cosmic Ray Tagger (CRT) for SBND

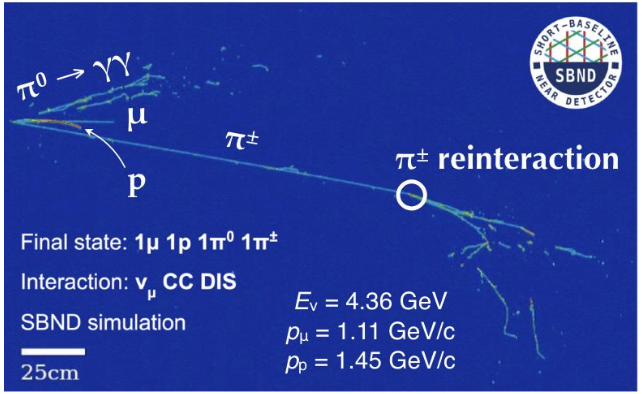
- ❖ SBND is not deep underground, but operated on-surface, therefore subject to a lot of random cosmogenic activity (background to many neutrino analyses).
- ❖ The SBND cryostat is surrounded by the CRT system (scintillator strips) → 4π coverage to tag cosmic activity.
- ❖ The CRT system helps remove cosmic ray tracks more efficiently using trajectory and timing of these particles as they traverse the detector walls.

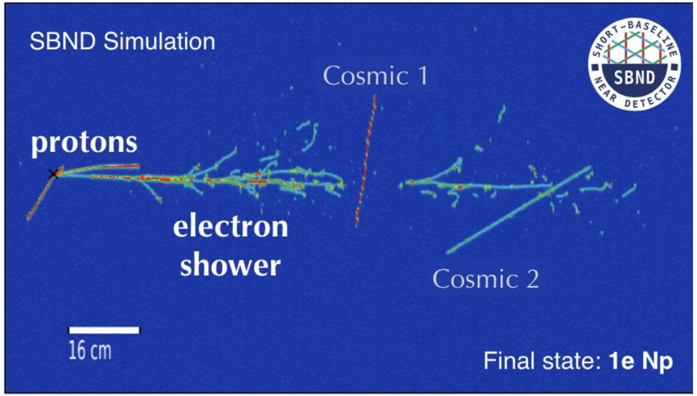


LArTPC Detector Capabilities

- 3D reconstruction with excellent, mm-scale resolution.
- Excellent particle identification.
- Disentangling complex final states.
- Low energy thresholds (demonstrated by previous LArTPC experiments)



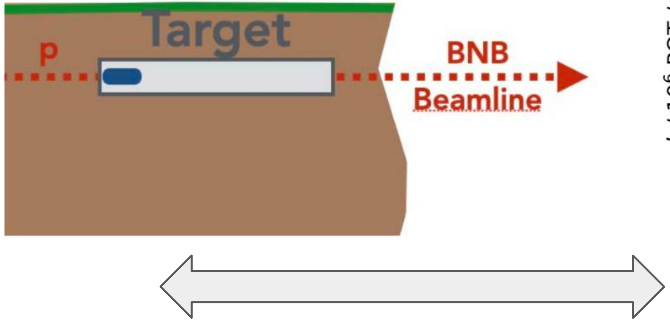




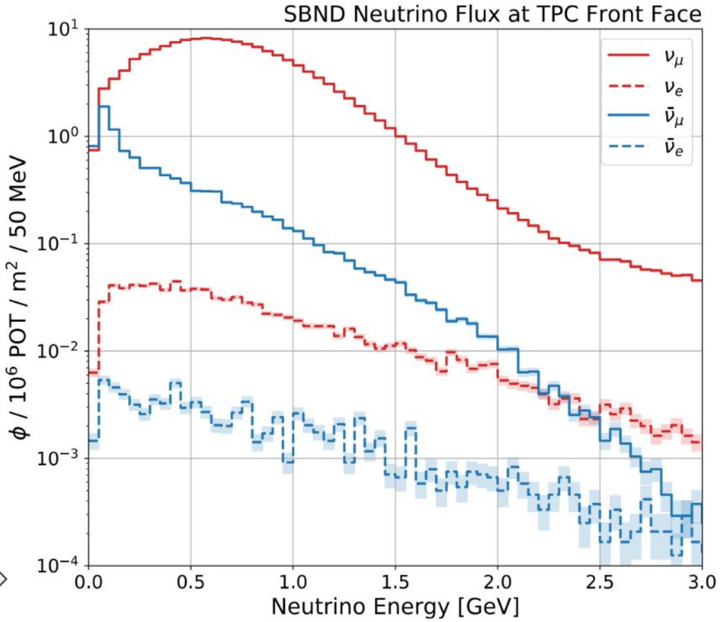
Neutrino Flux at SBND

Booster Neutrino Beamline (BNB) in Neutrino Running Mode

High-intensity neutrino beam from 8 GeV proton beam on Be target



SBND is 110 m away from neutrino production



Neutrino flux at the SBND front face

Mean muon-neutrino energy: ~0.8 GeV

Beam composition:

ν_μ (93.6%)

$\bar{\nu}_\mu$ (5.9%)

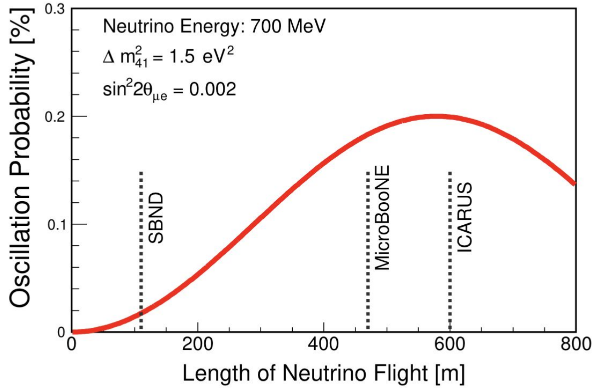
$\nu_e+\bar{\nu}_e$ (0.5%)

SBND Physics

SBND Physics: (1) eV-Scale Sterile Neutrinos

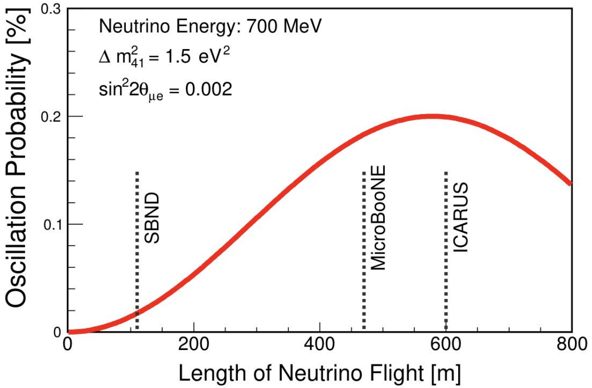
arXiv:1903.04608

❖ SBND, together with MicroBooNE and ICARUS, aims to **definitively test the light sterile neutrino oscillation interpretation of the short-baseline neutrino anomalies.**

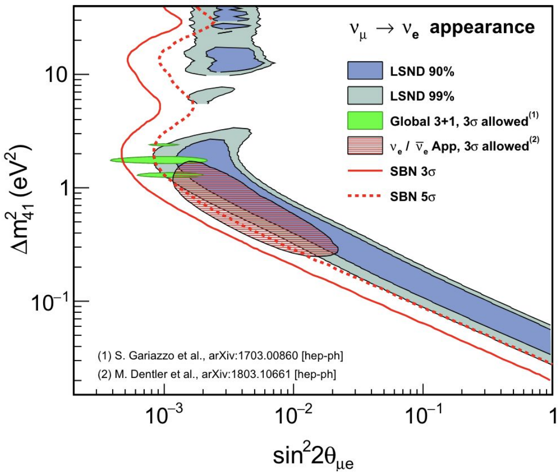


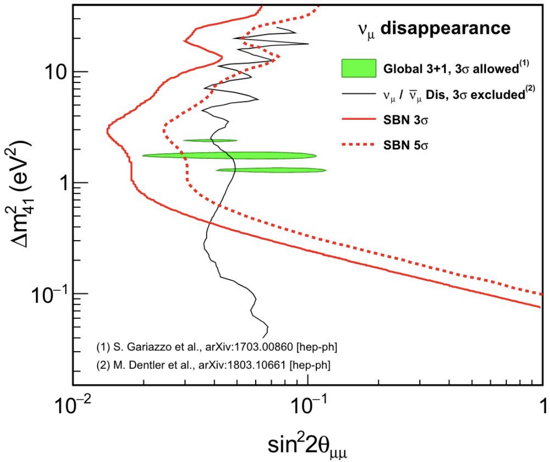
SBND Physics: (1) eV-Scale Sterile Neutrinos

arXiv:1903.04608



- SBND, together with MicroBooNE and ICARUS, aims to **definitively test the light sterile neutrino oscillation interpretation of the short-baseline neutrino anomalies.**
- **SBND will measure intrinsic ν_e and ν_μ components of BNB flux with high statistics before any *significant* oscillation happens, providing a powerful constraint on flux and cross-section.**
- ICARUS and MicroBooNE can search for deviations from the extrapolated predictions w.r.t SBND measurement.
- SBN will be providing world leading sensitivity to **ν_e appearance** and **ν_e and ν_μ disappearance at short-baselines.**



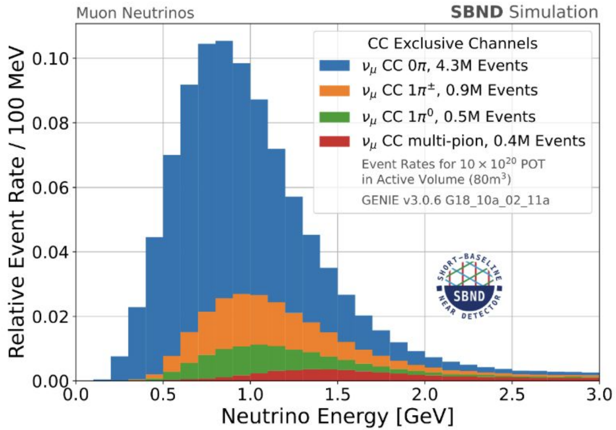


SBND Physics: (2) Cross Sections

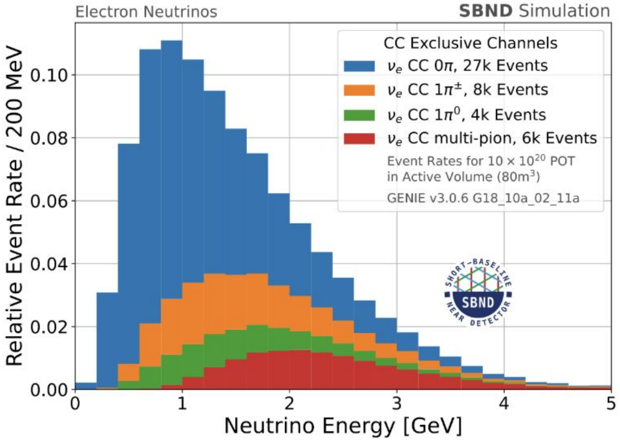
- Due to its close proximity to the target, **SBND will record the world's largest neutrino-argon interaction dataset** to study **neutrino-argon interactions in the GeV energy range.**

- **High statistics in SBND (~7000 neutrinos per day)** will allow a broad set of neutrino interaction measurements enabling **multi-dimensional differential measurements** and **searches for rare channels** (stat. limited in other existing experiments) e.g. hyperon production, ***ν***-e scattering on Ar, neutral current single-photon production, etc.

2M ν_μ CC events in an year



15k ν_e CC events in an year

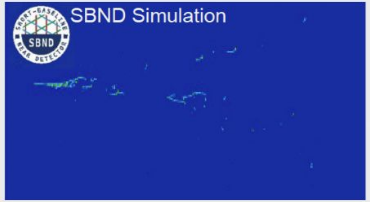


SBND Physics: (3) BSM

❖ Explore new BSM physics processes, including alternative solutions to short-baseline neutrino anomalies and other exotic physics processes.

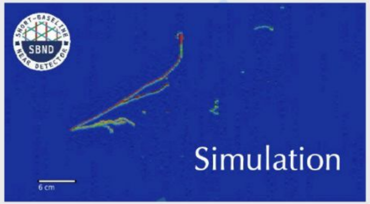
Thanks to high statistics that SBND will collect, high intensity beam, and LArTPC excellent particle identification capabilities.

Light Dark Matter



single e^- scattering or e^+e^- pair with no hadronic activity

Dark Neutrinos

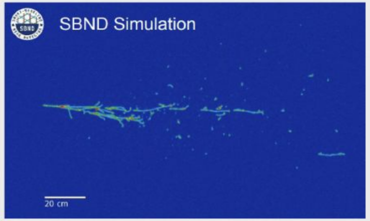


e^+e^- pair with or without hadronic activity

Millicharged Particles

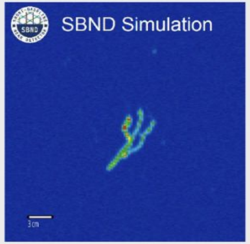
blips or faint tracks

Heavy Neutral Leptons



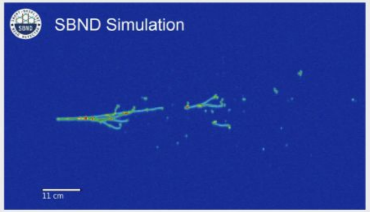
e^+e^-, $\mu^+\mu^-$, or $\mu^\pm\pi^\mp$ pair with no hadronic activity

Higgs Portal Scalar



e^+e^- or $\mu^+\mu^-$ pair with no hadronic activity

Axion-Like Particles

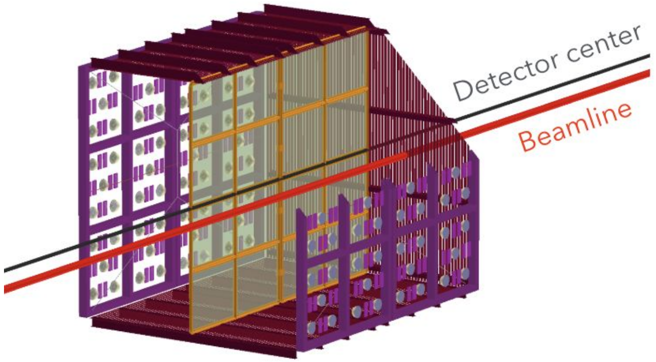


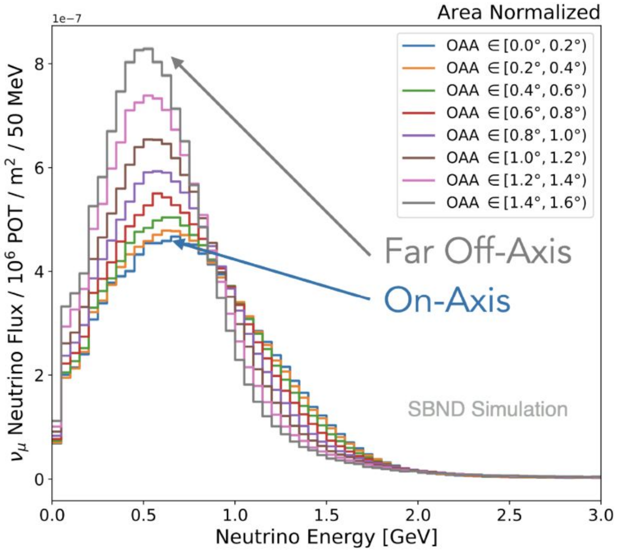
high-energy e^+e^- or $\mu^+\mu^-$ pair

SBND Physics: (4) PRISM

Precision **R**eaction **I**ndependent **S**pectrum **M**easurement

- ❖ SBND is very close (110m) to the neutrino source and is ~75cm off-axis with the neutrino beamline.
- ❖ SBND can sample multiple off-axis fluxes with the same detector (leveraging the PRISM concept)
  - ➢ Access to event samples with different average energies → allows for better understanding of any energy dependent effects (e.g. cross-section, and potentially oscillations) in a single detector.





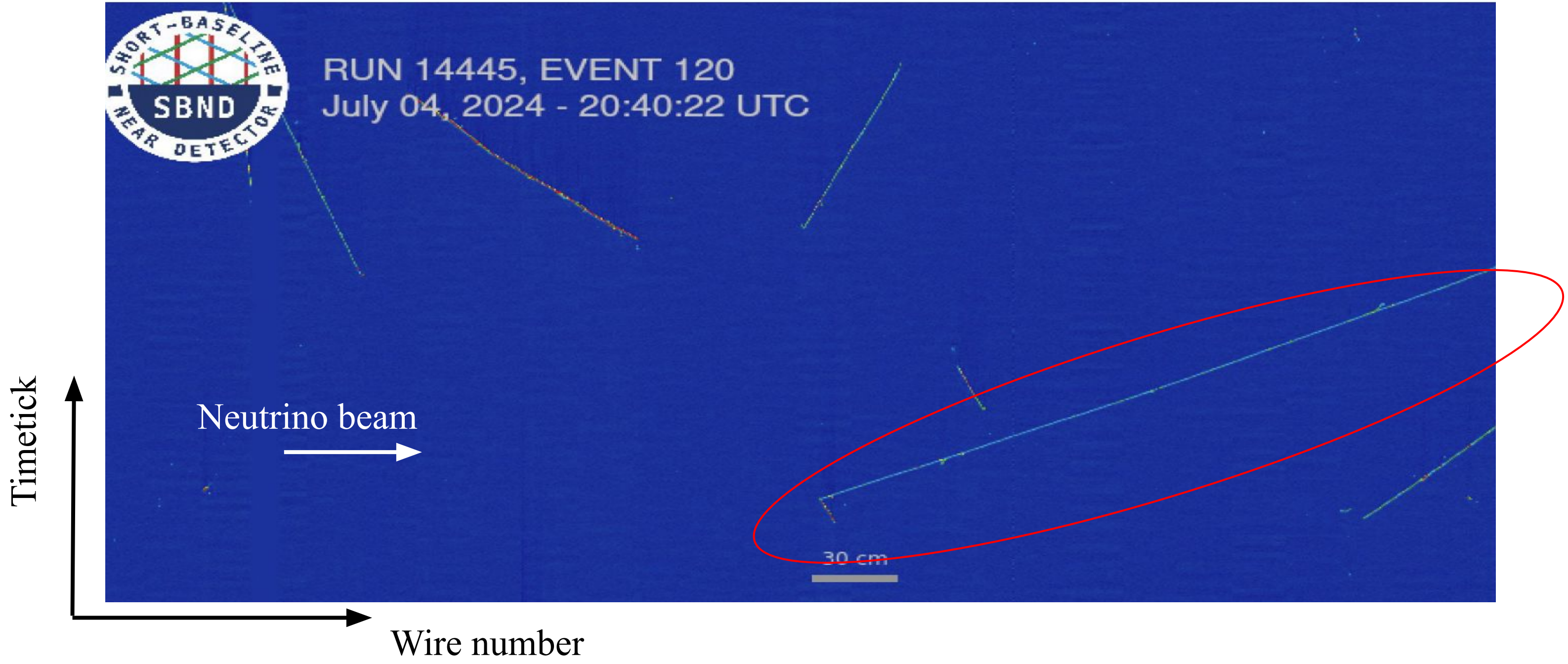
Current Status of SBND

Current Status of SBND

- **SBND started collecting beam data on July 3, 2024!**
  (with cathode HV at the design target of 100kV!)

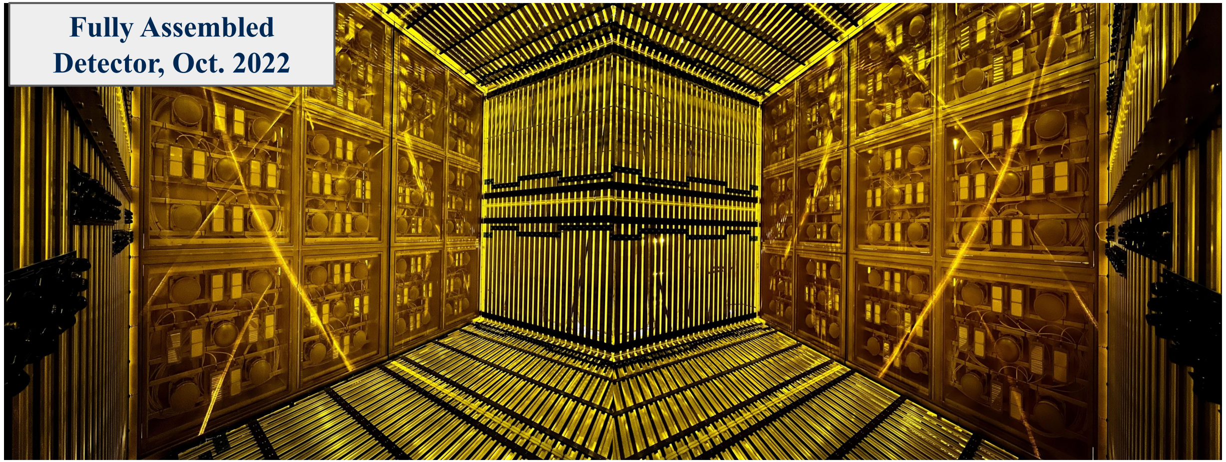
Current Status of SBND

- ❖ **SBND started collecting beam data on July 3, 2024!**
  (with cathode HV at the design target of 100kV!)

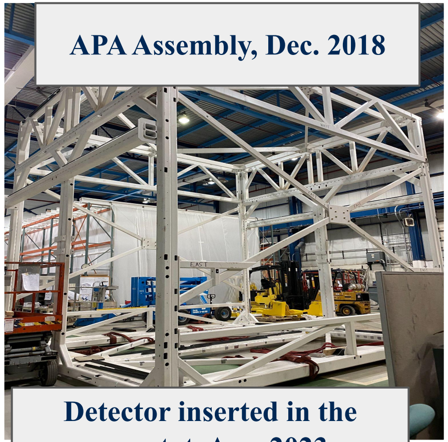


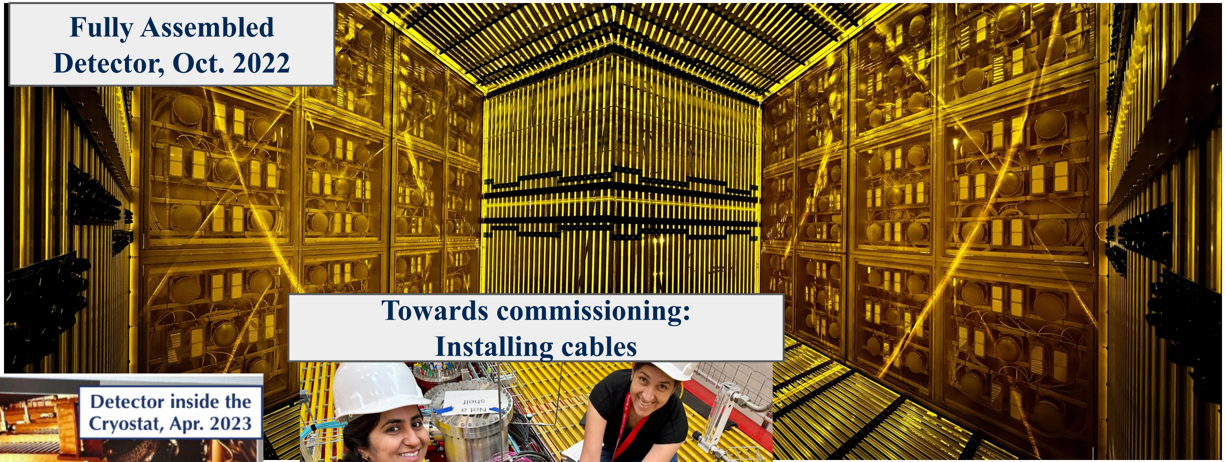
Reaching this milestone has been quite an exciting journey

Journey to Data Taking: Detector Assembly

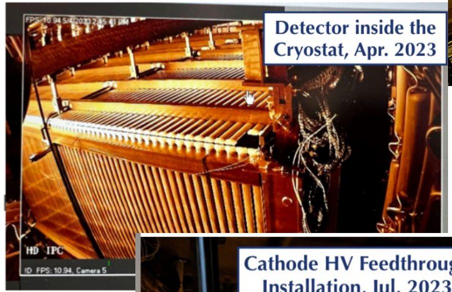


Journey to Data Taking: Detector Assembly to Commissioning


APA Assembly, Dec. 2018


Fully Assembled Detector, Oct. 2022


Detector inserted in the cryostat, Apr. 2023


Detector inside the Cryostat, Apr. 2023


Cathode HV Feedthrough Installation, Jul. 2023

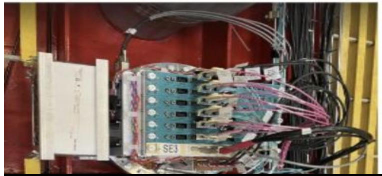

Towards commissioning: Installing cables


Towards commissioning: Purity monitors

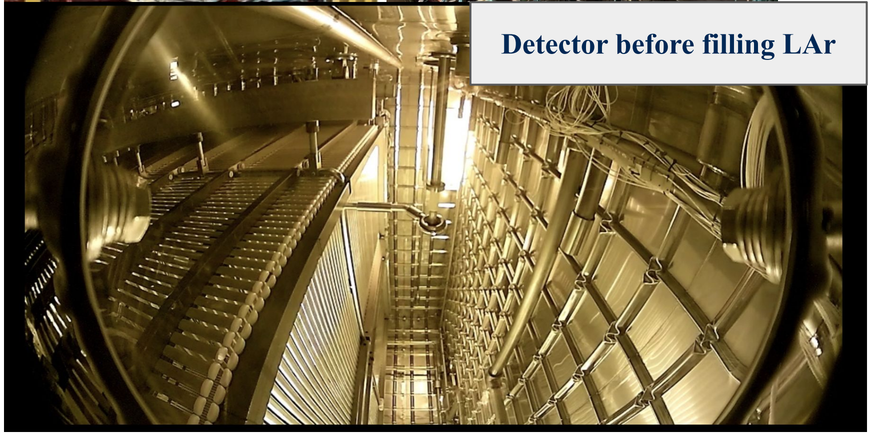
Journey to Data Taking: Detector Assembly to Commissioning


Fully Commissioned Detector, Dec. 2023

Journey to Data Taking: Detector Assembly to Commissioning



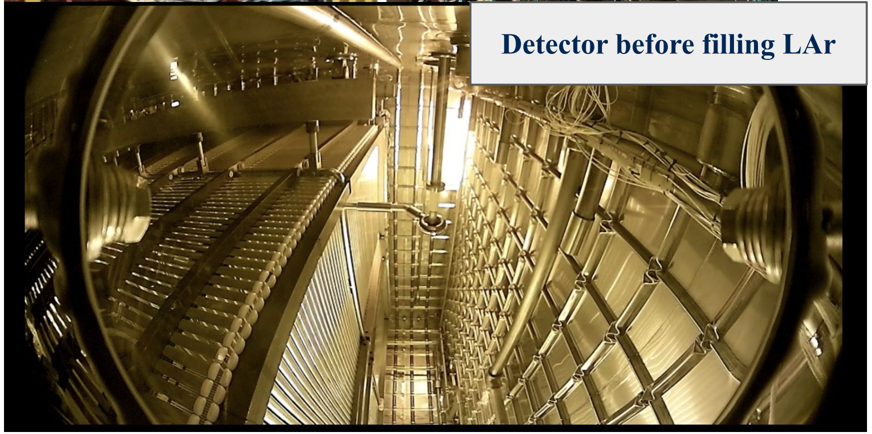
Fully Commissioned Detector, Dec. 2023



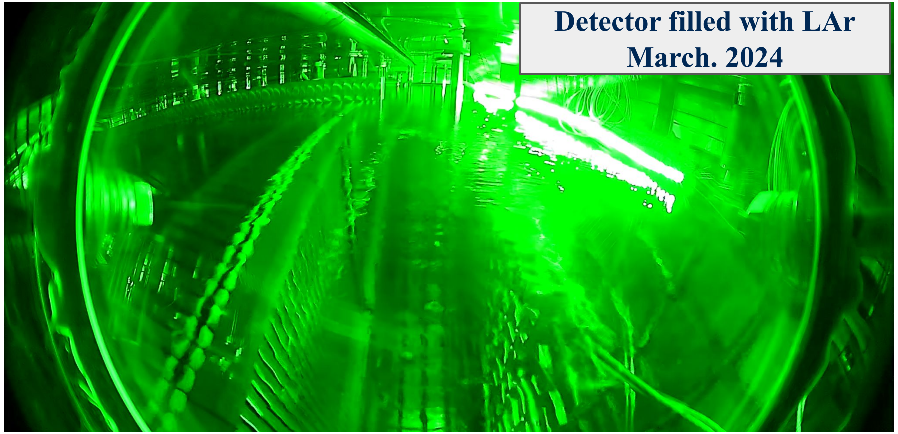
Detector before filling LAr

Journey to Data Taking: Detector Assembly to Commissioning

Fully Commissioned Detector,
Dec. 2023



Detector before filling LAr

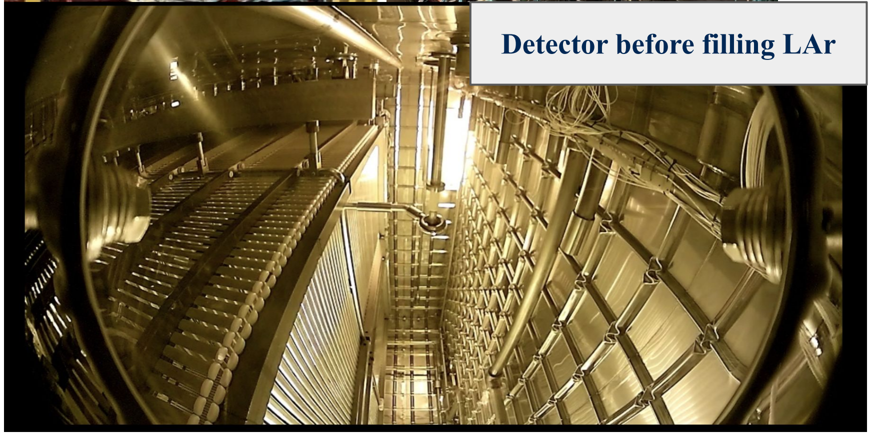


Detector filled with LAr
March. 2024

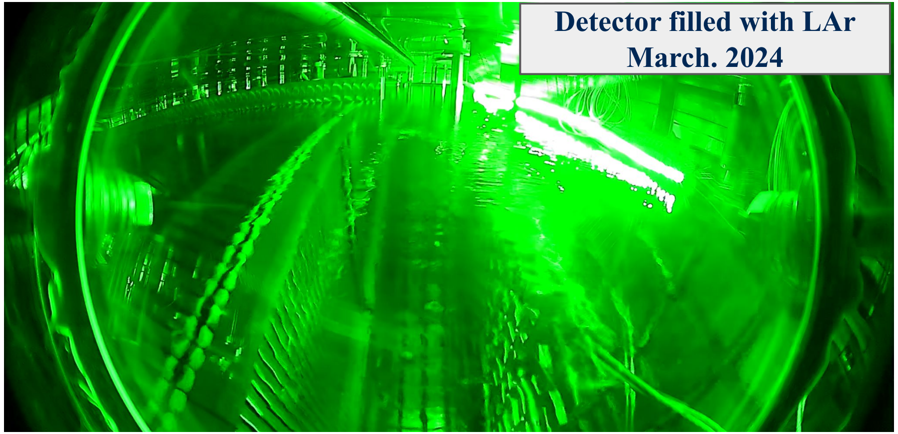
Journey to Data Taking: Detector Assembly to Commissioning

Fully Commissioned Detector, Dec. 2023

All the detector subsystems were powered ON in March 2024!



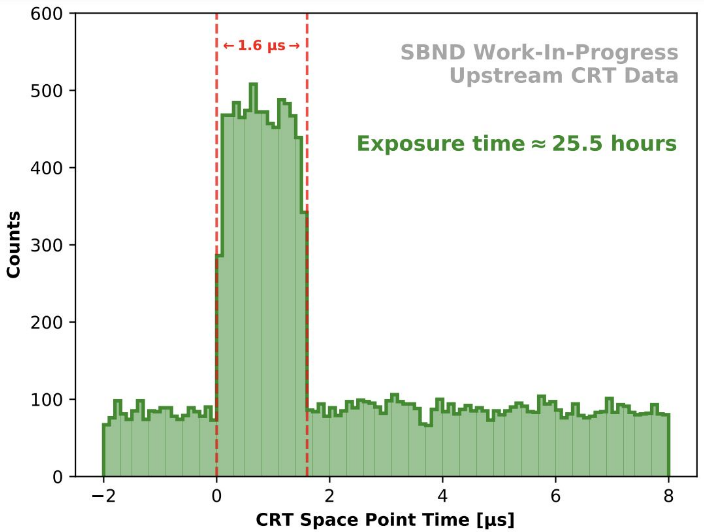
Detector before filling LAr

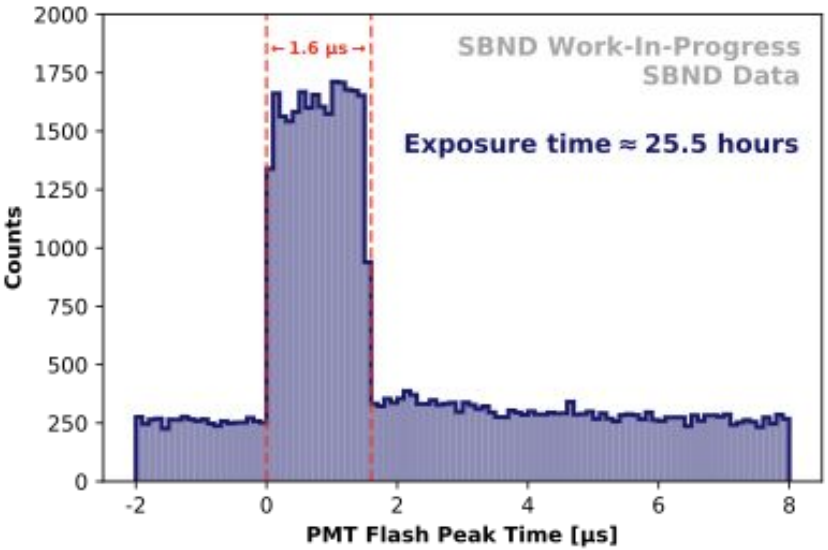


Detector filled with LAr March. 2024

Journey to Data Taking: Successful Commissioning

- **Successful demonstration of SBND commissioning using CRT and PMT data**
  → clear peaks in CRT and PMT data from the neutrino beam
  - **1.6μs wide peak reflecting the duration of the BNB spill**



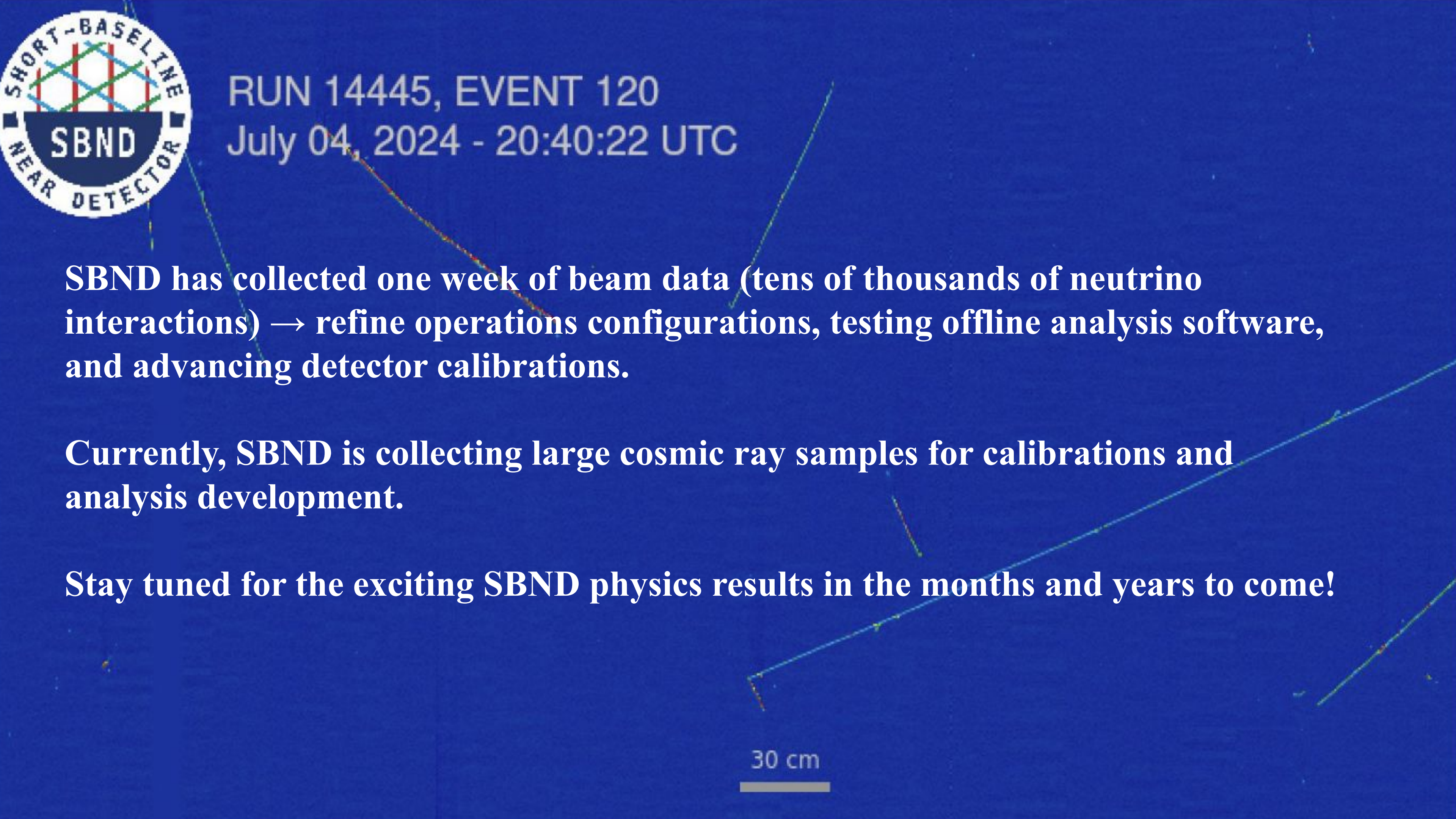


Journey to Data Taking: Fully Operational

- **Ramped up cathode HV to the design target 100kV on July 3, 2024!**
  The cathode HV was gradually increased in steps, with stability monitored over several hours.

- SBND has collected beam data from July 3 to July 12 (beam summer shutdown)

ROC-West, Wilson Hall. July 3rd, 2024



SBND has collected one week of beam data (tens of thousands of neutrino interactions) → refine operations configurations, testing offline analysis software, and advancing detector calibrations.

Currently, SBND is collecting large cosmic ray samples for calibrations and analysis development.

Stay tuned for the exciting SBND physics results in the months and years to come!

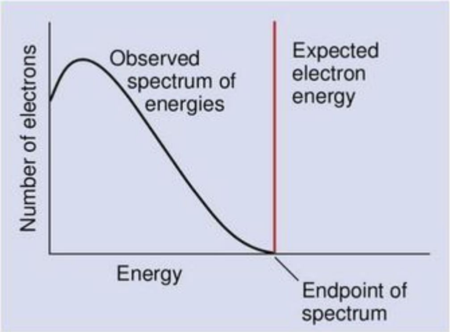
Thank you!

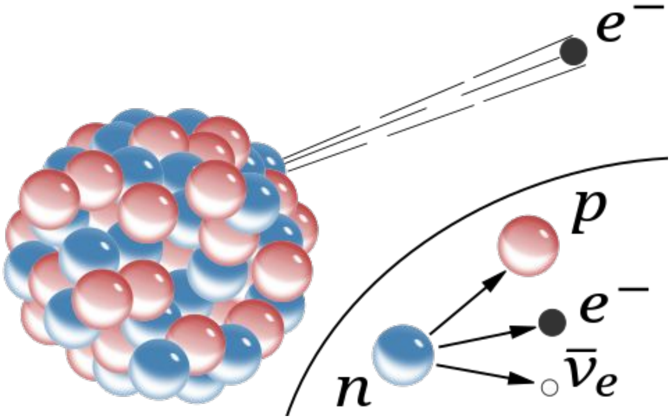
Back-up

Brief history of neutrinos

1930

Neutrinos were proposed by W. Pauli to explain continuum beta decay spectrum.



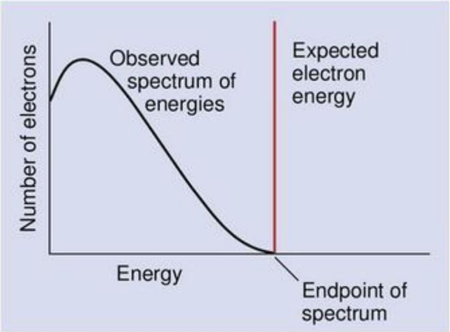


Named as neutrino by E. Fermi.

Brief history of neutrinos

1930

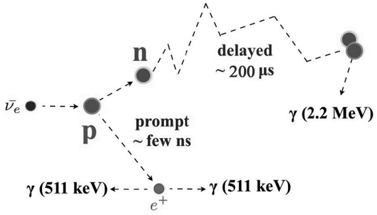
Neutrinos were proposed by W. Pauli to explain continuum beta decay spectrum.



Named as neutrino by E. Fermi.

1956

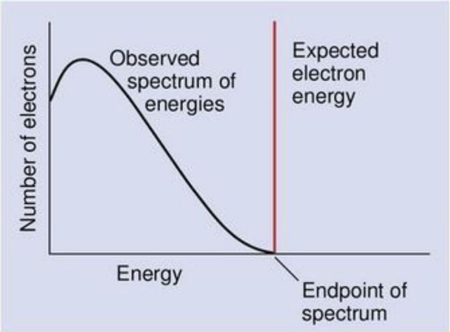
First detection of ν_e by F. Reines & C. Cowans.
Instrumentation: Liquid scintillator detector
Physics: Inverse beta decay & timing.



Brief history of neutrinos

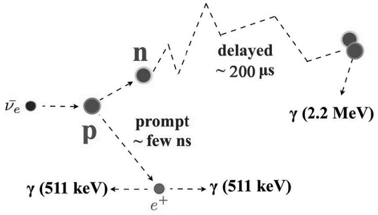
1930 | **1956** | **1962**

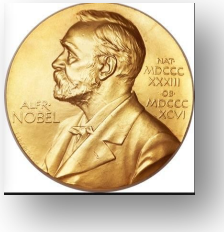
Neutrinos were proposed by W. Pauli to explain continuum beta decay spectrum.



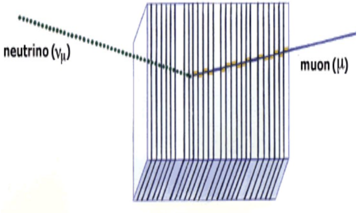
Named as neutrino by E. Fermi.

First detection of ν_e by F. Reines & C. Cowans.
Instrumentation: Liquid scintillator detector
Physics: Inverse beta decay & timing.

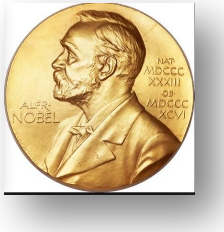




ν_μ was detected by L. Lederman, M. Schwartz, and J. Steinberger.
Instrumentation: Spark chamber detector
Physics: Ionisation & timing.



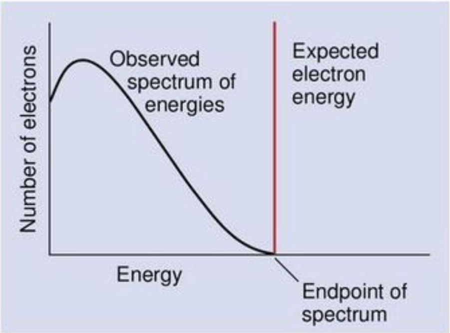
A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.



Brief history of neutrinos

1930

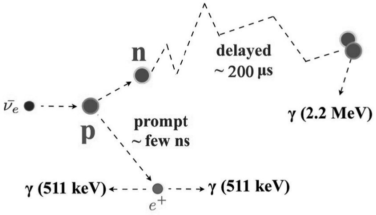
Neutrinos were proposed by W. Pauli to explain continuum beta decay spectrum.



Named as neutrino by E. Fermi.

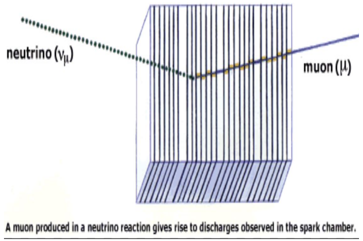
1956

First detection of $\boldsymbol{\nu}_e$ by F. Reines & C. Cowans.
Instrumentation: Liquid scintillator detector
Physics: Inverse beta decay & timing.



1962

$\boldsymbol{\nu}_\mu$ was detected by L. Lederman, M. Schwartz, and J. Steinberger.
Instrumentation: Spark chamber detector
Physics: Ionisation & timing.



2001

$\boldsymbol{\nu}_\tau$ was by DONUT experiment.
Instrumentation: Emulsion detector
Physics: Ionisation.