Neutrino Oscillations and DUNE

Mateus F. Carneiro

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Outline

1. Neutrinos
    a. Questions
    b. Historical introduction
    c. Neutrino Oscillation

2. DUNE
    a. DUNE Collaboration
    b. DUNE Detector design
    c. DUNE Physics

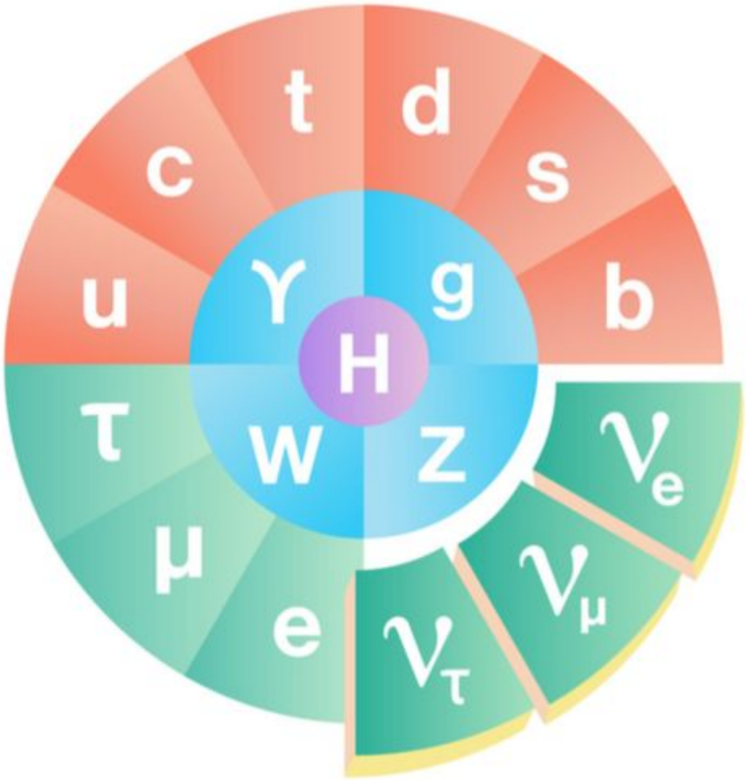
3. Recap + Q&A

Neutrinos!

- What is a Neutrino?

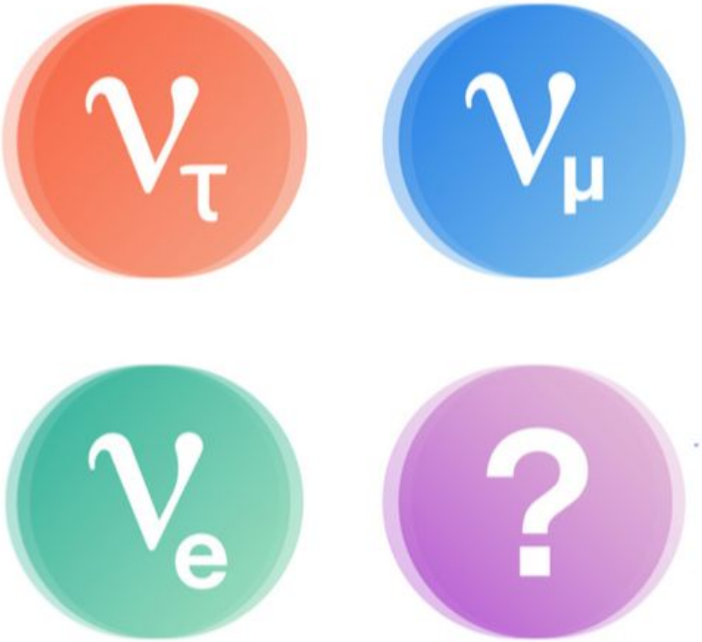
Neutrinos!

- What is a Neutrino?



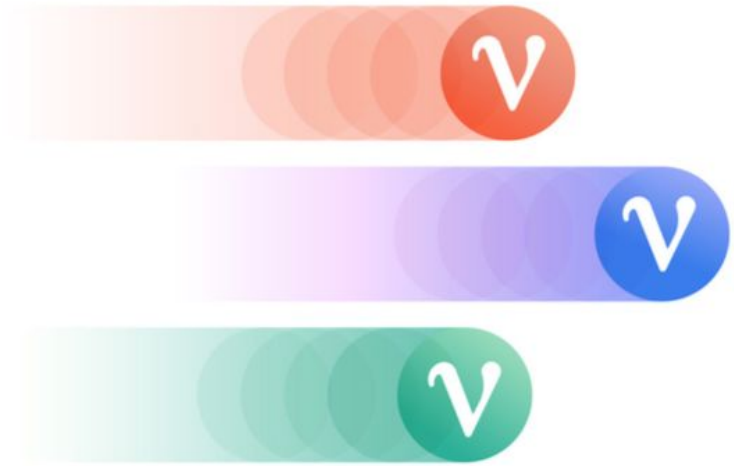
Neutrinos!

- What is a Neutrino?
- Neutrinos have flavors?



Neutrinos!

- What is a Neutrino?
- Neutrinos have flavors?
- Neutrinos have mass?



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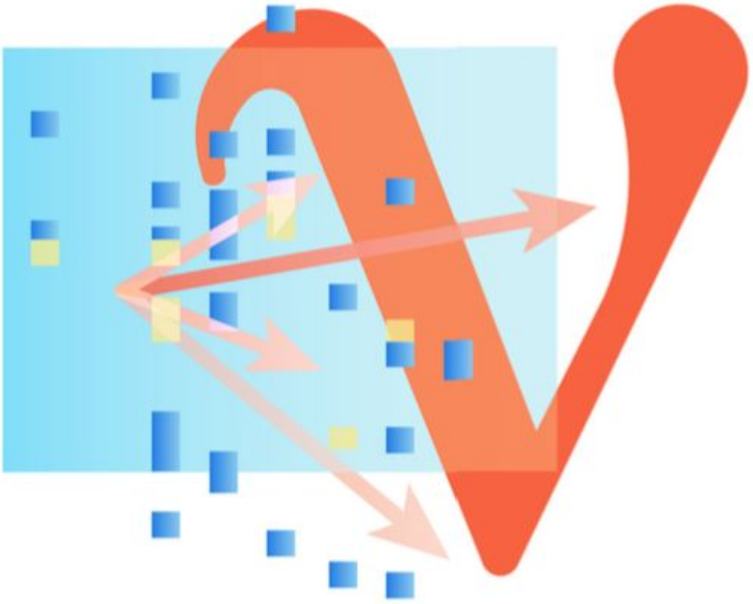

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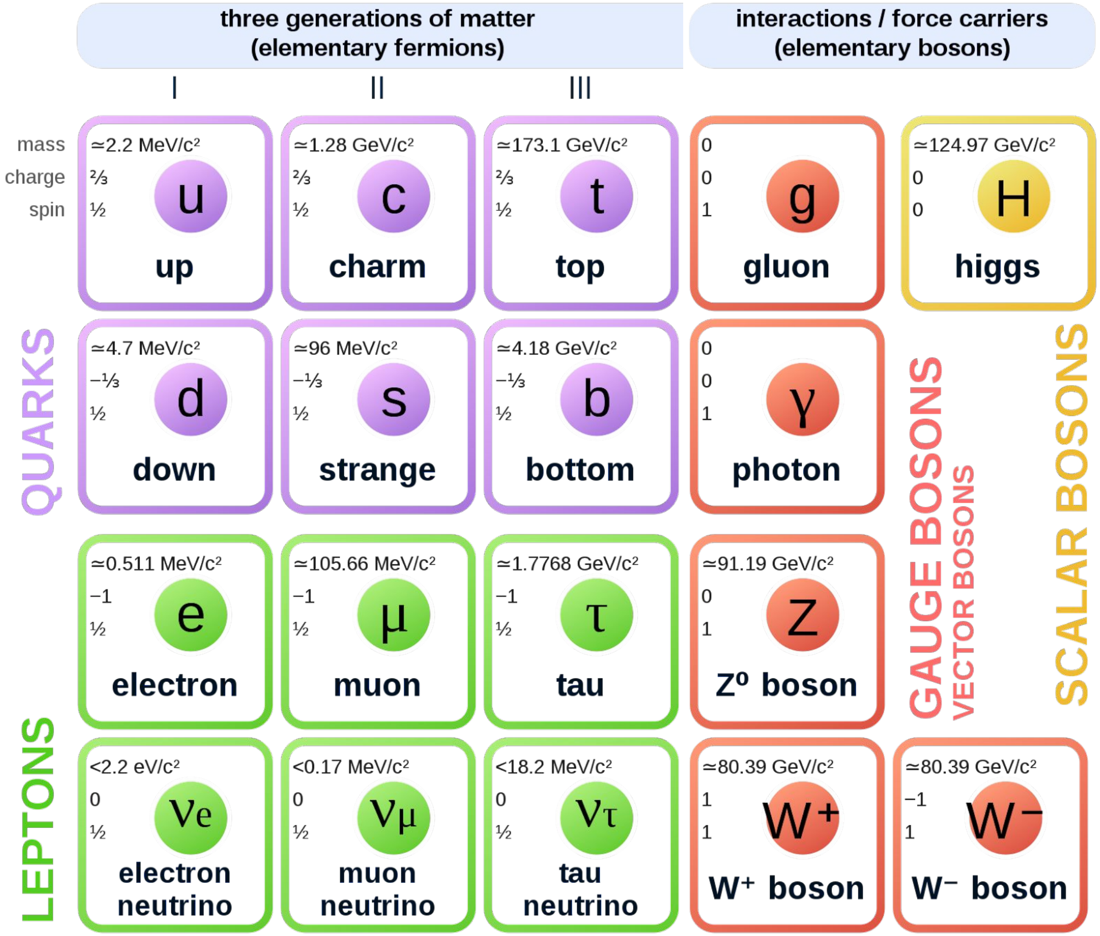
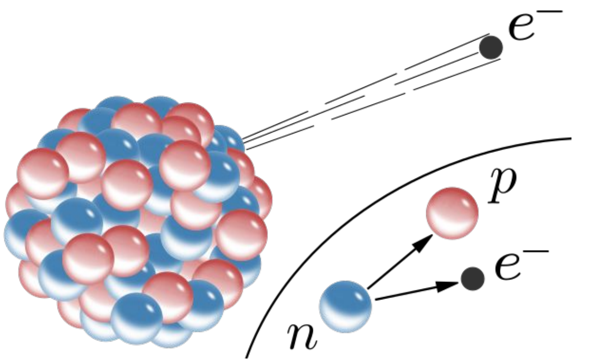


Understanding the Beta Decay



The **beta decay** is a **radioactive decay** in which a **proton in a nucleus is converted into a neutron** (or vice-versa).

In the process the nucleus **emits a beta particle** (either an electron or a positron)

If the decay happens with the atom nucleus at rest, what's the energy of the electron?

number of protons and neutrons

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

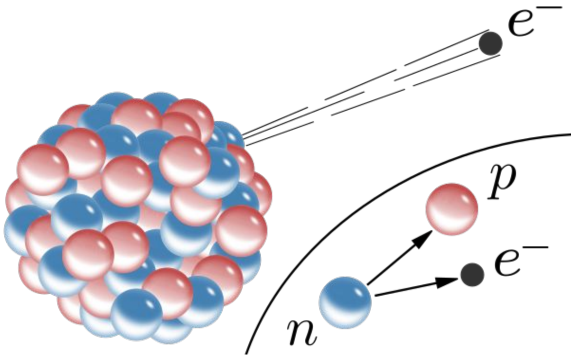
number of protons

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

1899 – 1927

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

Understanding the Beta Decay



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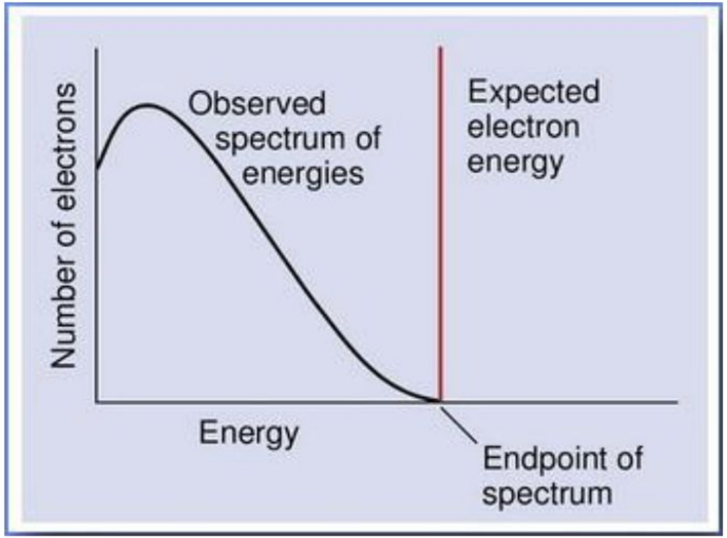
Considering **energy conservation**, we expect always the same energy for the electron, but a spectrum was observed…



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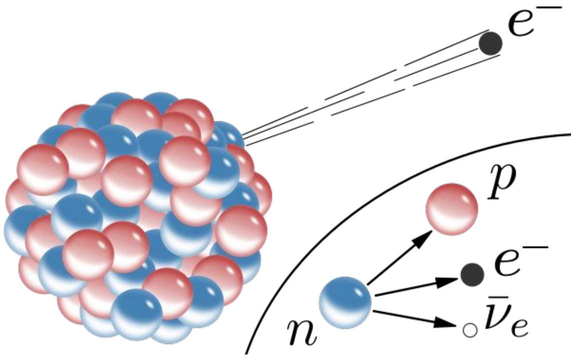
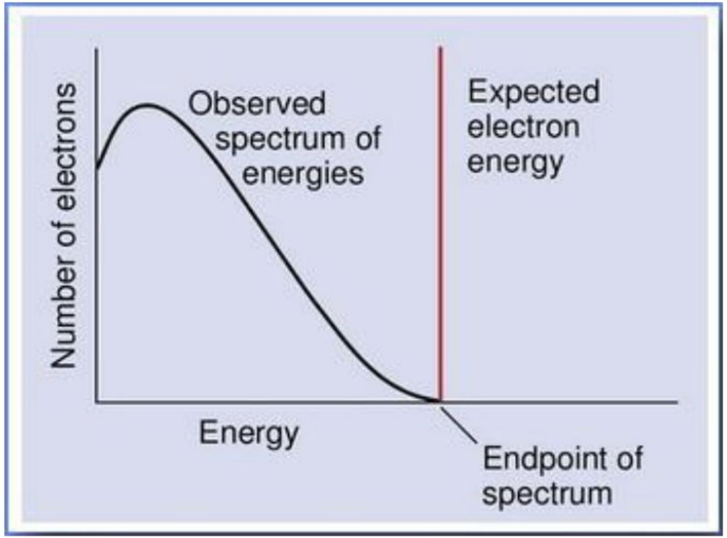


Wolfgam Pauli postulated that an **undetectable particle** was also being emitted in the decay, **sharing the energy available** with the electron and explaining the energy spectrum observed.



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

Understanding the Beta Decay

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

Wolfgang Pauli

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

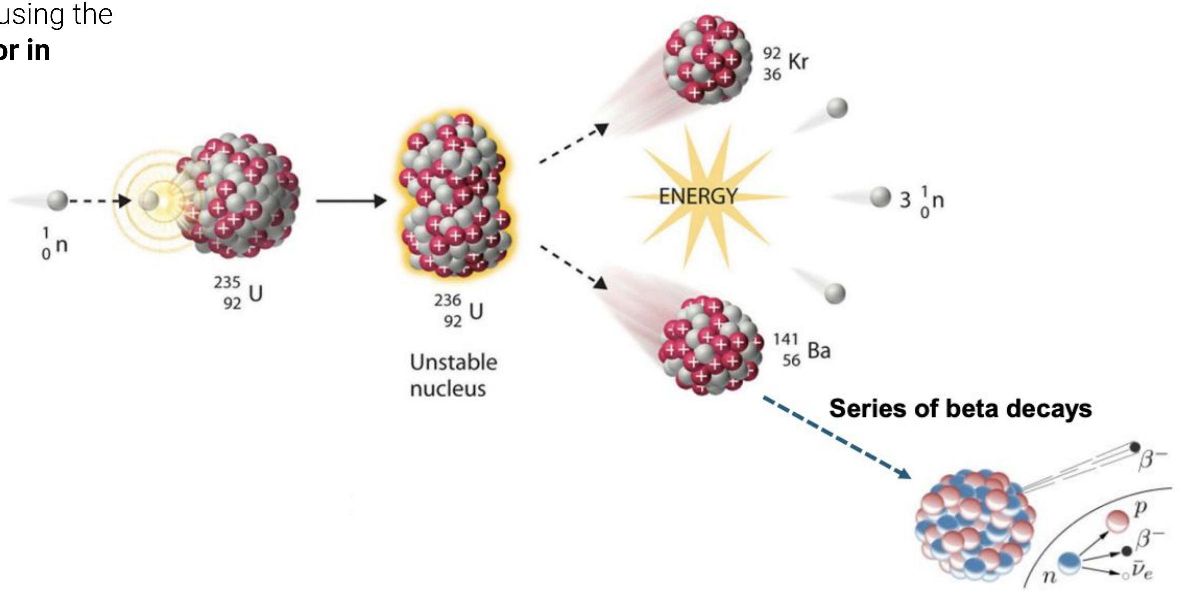
"I have done a terrible thing. I have postulated a particle that cannot be detected."

First Detection

Frederick Reines and **Clyde Cowan** first detected (anti)neutrinos using the **Savanah River nuclear reactor in South Carolina** in 1956

Nuclear fission

[Science 124, 3212:103]



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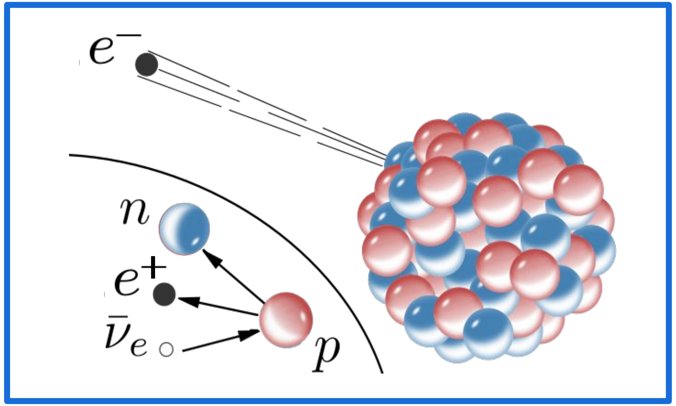

Inverse Beta Decay

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

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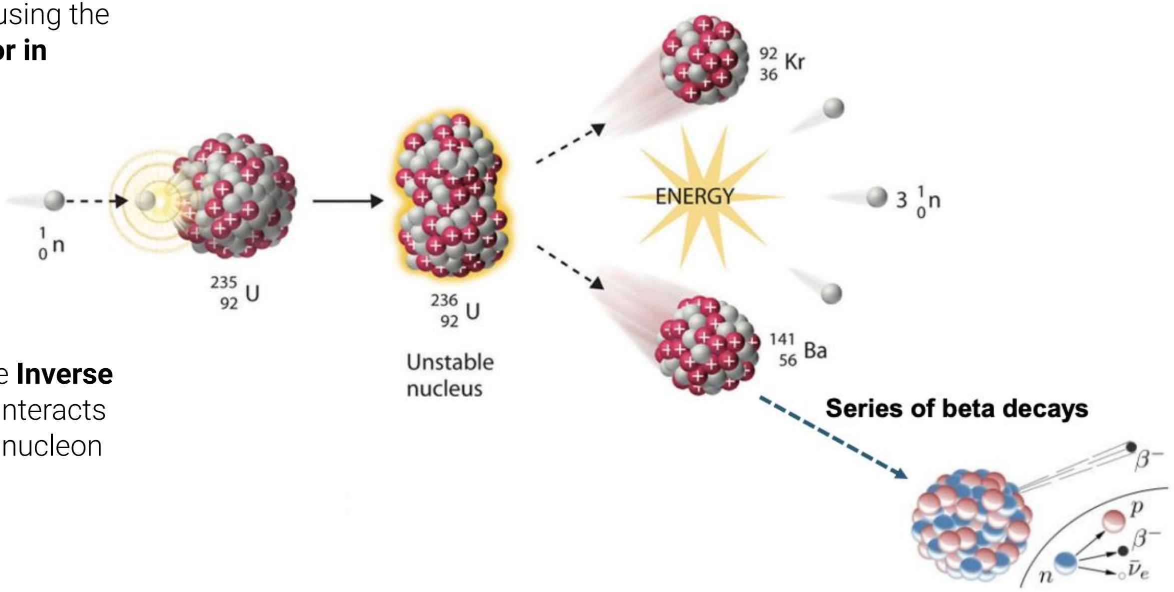

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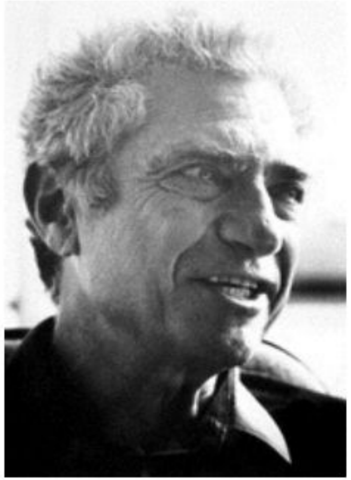
Detection was made using the **Inverse Beta decay** where a neutrino interacts with a proton, turning it into a nucleon and emitting a positron

Nobel Prize in Physics 1995

More Flavors



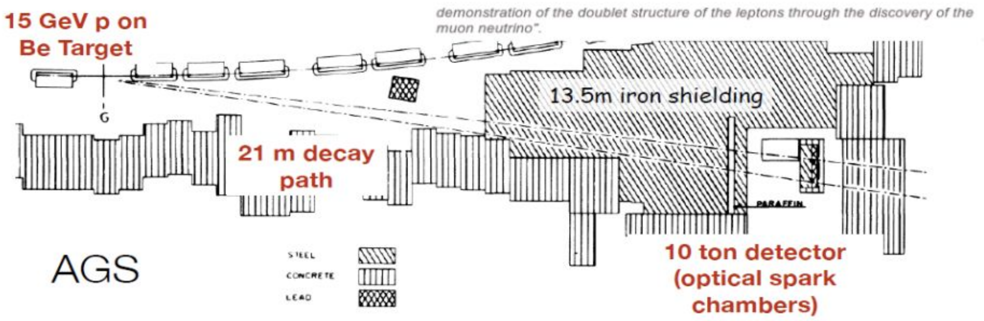


Muon neutrinos were discovered in 1962 by **L. Lederman, M. Schwartz and J. Steinberger**.

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

Nobel Prize in Physics 1988

World's first accelerator neutrino experiment



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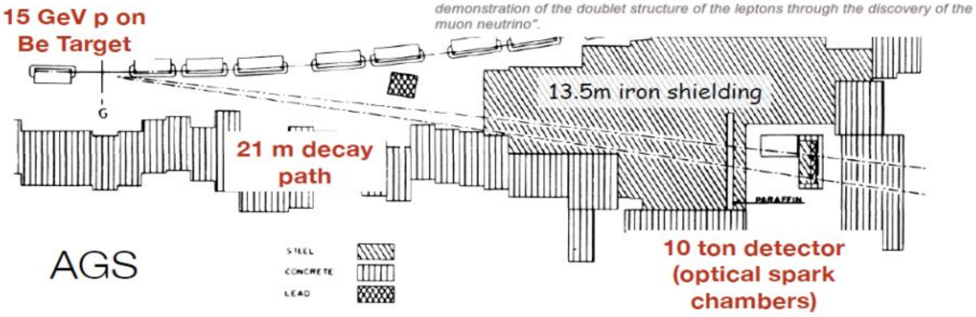


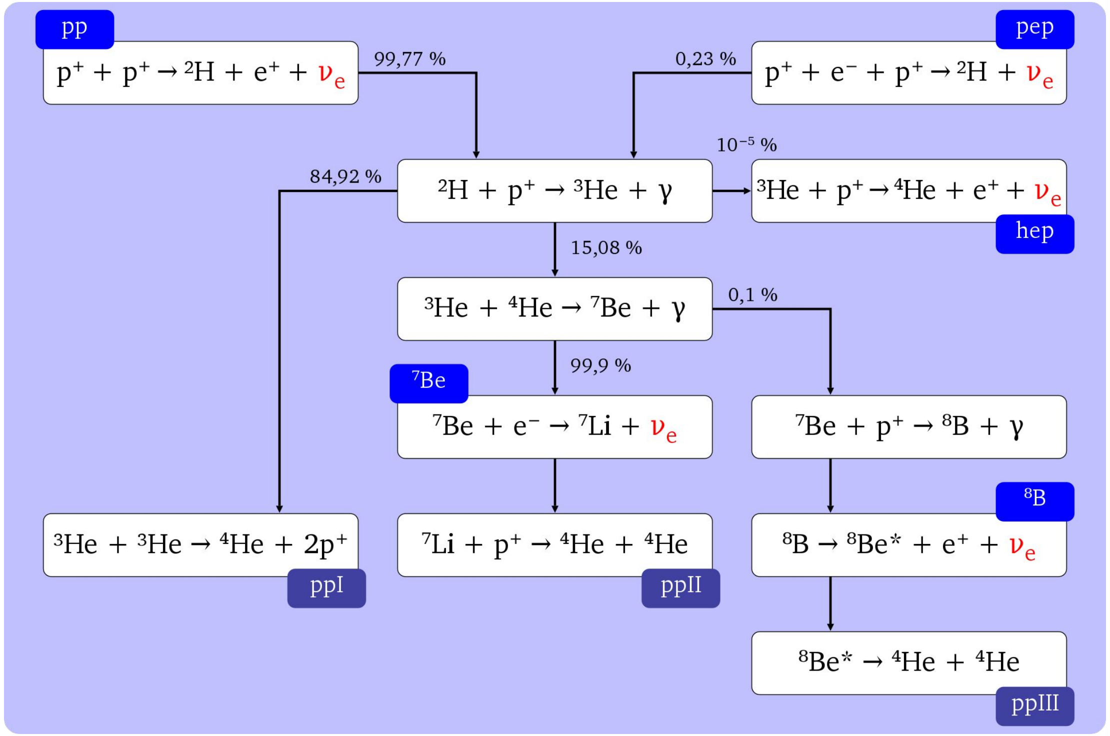
Tau neutrinos were discovered by the **DONUT experiment** at Fermilab in 2000

The Solar Neutrino Problem

About **100 billion solar neutrinos** pass through your thumbnail every second, can we detect some?

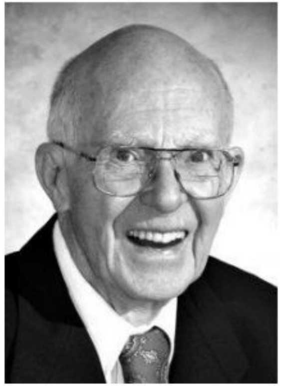
R. Davis used the Homestake experiment to detect solar neutrinos, based on an experimental technique by **Pontecorvo**

Nobel Prize in Physics 2002



The Solar Neutrino Problem

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



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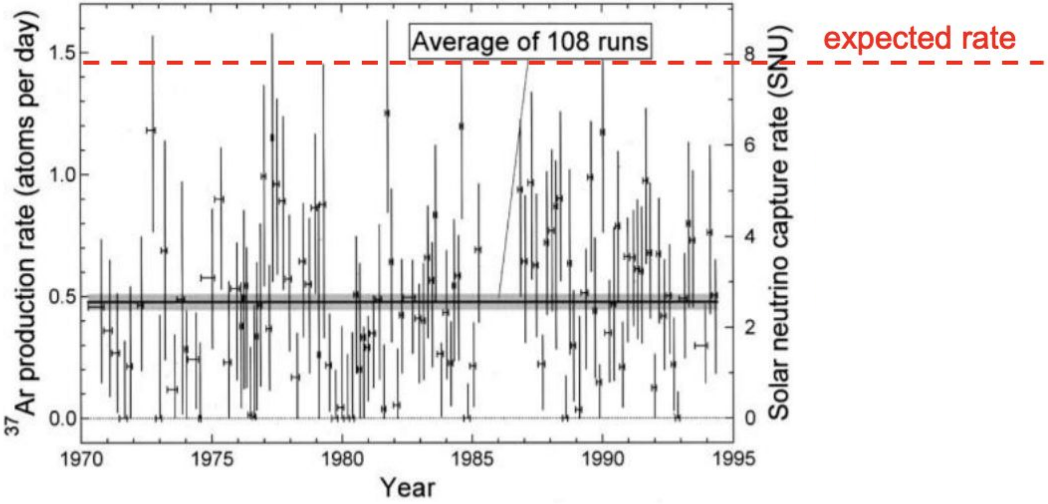
But **2/3 of them seemed to be missing**

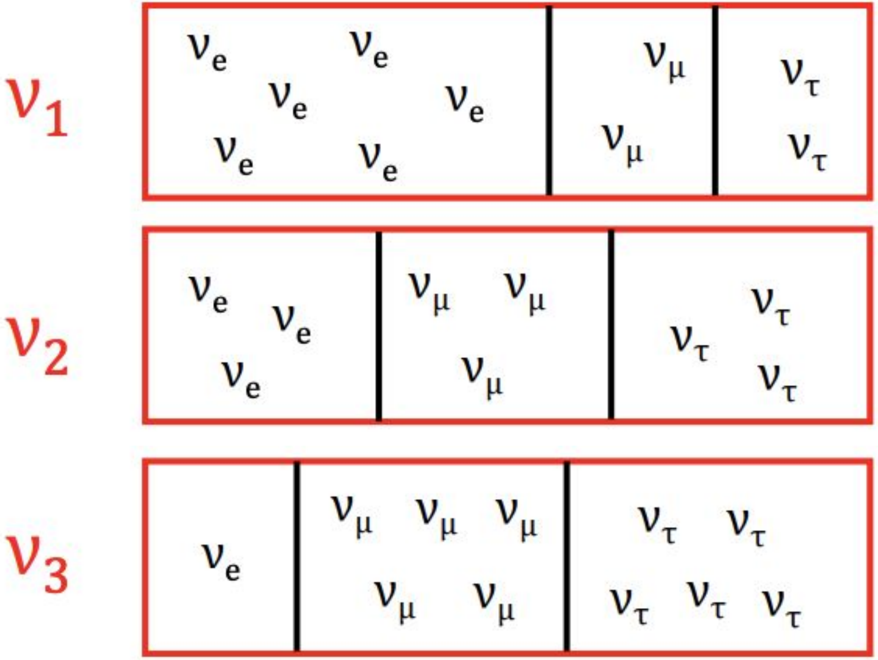


Modeling Neutrino Oscillations

Flavor mixing: mismatch between weak/flavor eigenstates and mass eigenstates of fermions due to coexistence of 2 types of interactions:

Weak eigenstates: members of weak isospin doublets transforming into each other through the interaction with the W boson;

Mass eigenstates: states of definite masses that are created by the interaction with the Higgs boson (Yukawa interactions).



Modeling Neutrino Oscillations

flavor (α = e, μ, τ) ⇔ linear combinations ⇔ mass (i = 1, 2, 3)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle \quad \Longleftrightarrow \quad |\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \underbrace{\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}}_{\text{Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix}} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

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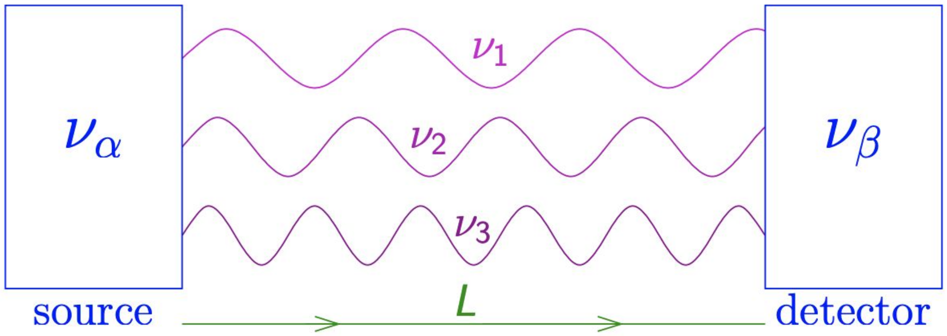
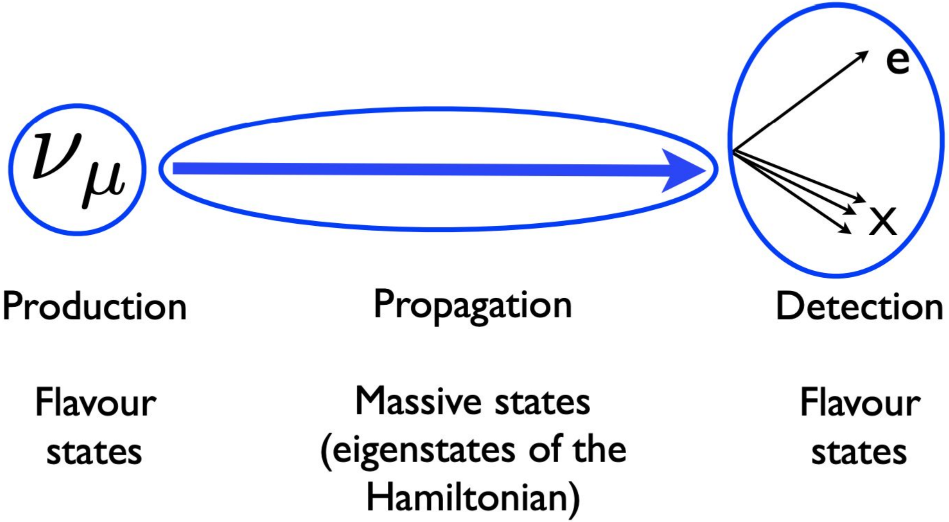


We can only detect the flavour eigenstates

Because of relativity, the mass eigenstates will experience time/distance differently

Their propagation phase will be different, changing the mixing

This difference in mixing is detected as a different flavor



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The **PMNS matrix** defines the different combinations relating **mass** and **flavour eigenstates**

We can choose well our problems to divide it in 3 different matrices based on the **Mixing angles** between mass eigenstates

Mixing angles = $(\theta_{12}, \theta_{23}, \theta_{13})$, δ_{CP} is the CP-violation phase

$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\substack{\text{I} \\ \text{atmospheric}}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\substack{\text{II} \\ \text{reactor}}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\substack{\text{III} \\ \text{solar}}}$$

where: $c_{\alpha\beta} = \cos\theta_{\alpha\beta}$; $s_{\alpha\beta} = \sin\theta_{\alpha\beta}$

Nonzero δ_{CP} ⟹ neutrinos and antineutrinos oscillate different

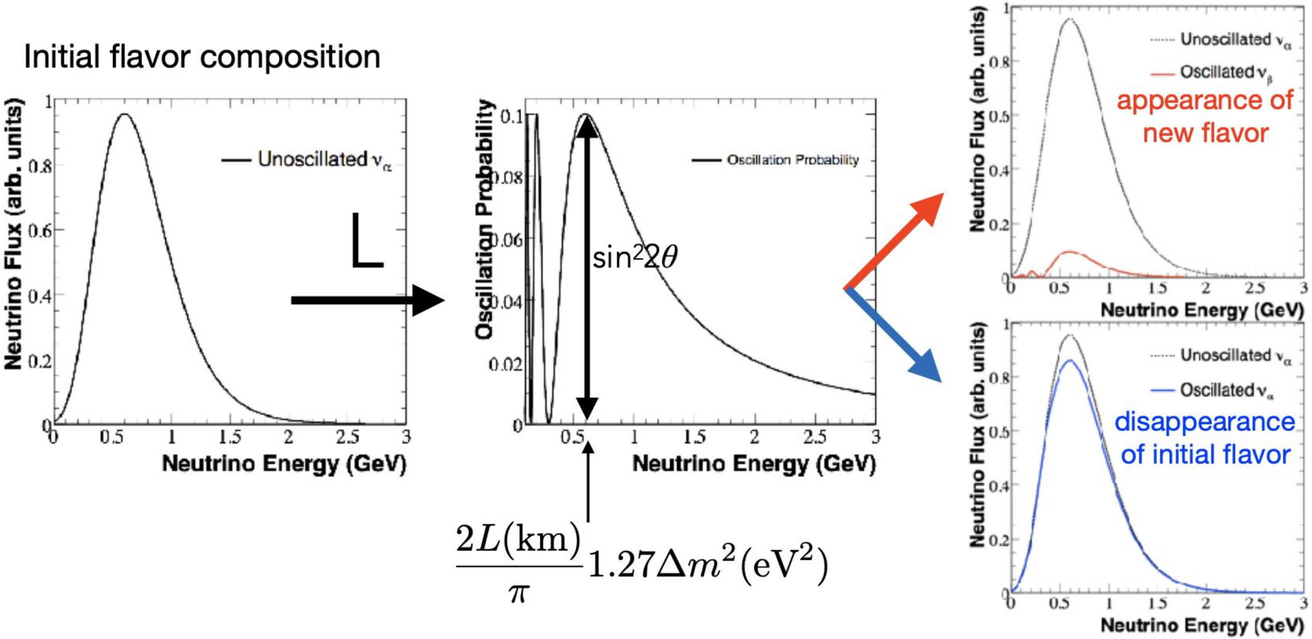
Two Flavor approximation

Considering only 2 flavours we can rewrite the mixing matrix as:

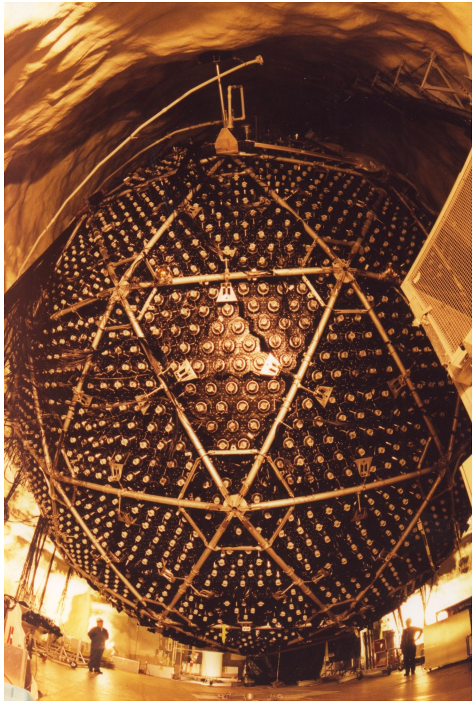
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

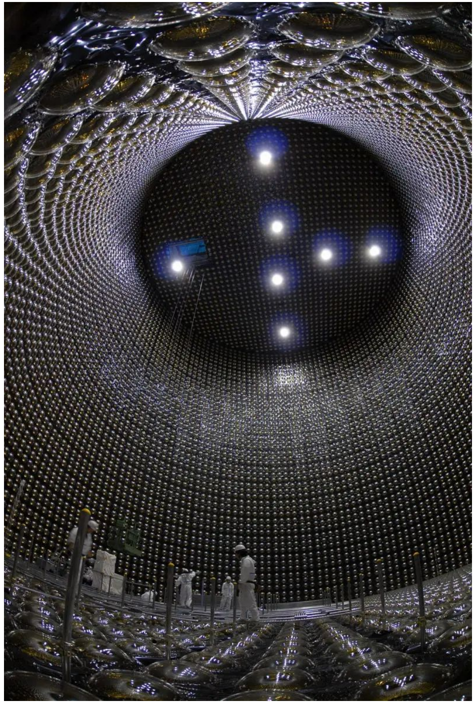
and we can derive transition probabilities:

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Do neutrinos really oscillate?

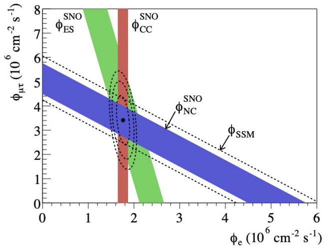


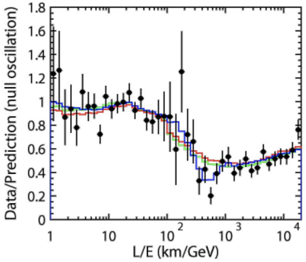


Yes! **SNO fixed the "solar problem"** by looking at channels sensitive to all neutrino flavours from the Sun, and **Super Kamiokande** showed **strong dependence for oscillation on the path length** from production to detection

The 2015 Nobel Prize for Physics has been awarded to **Arthur B McDonald (director of SNOlab)** and **Takaaki Kajita (SuperKamiokande):** *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

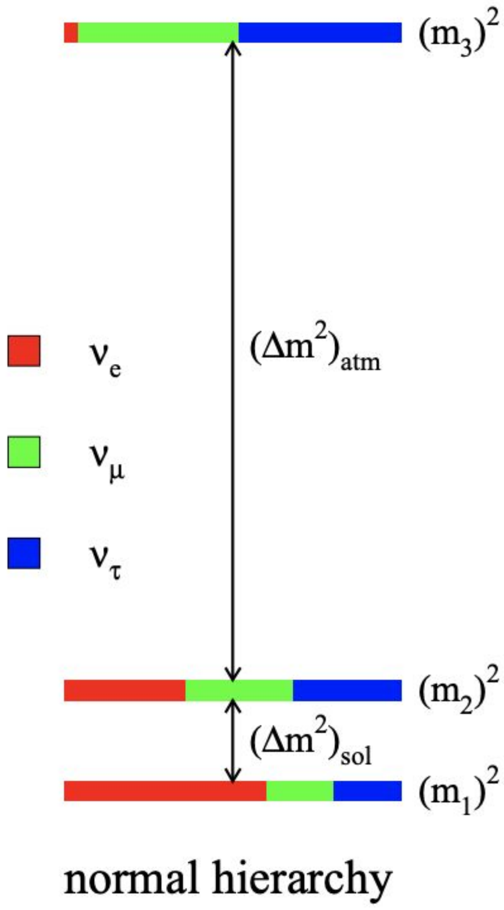
This is considered the start of "modern neutrino physics"!





Organizing the neutrinos

From different experiments we have some of the parameters of neutrino oscillation measured



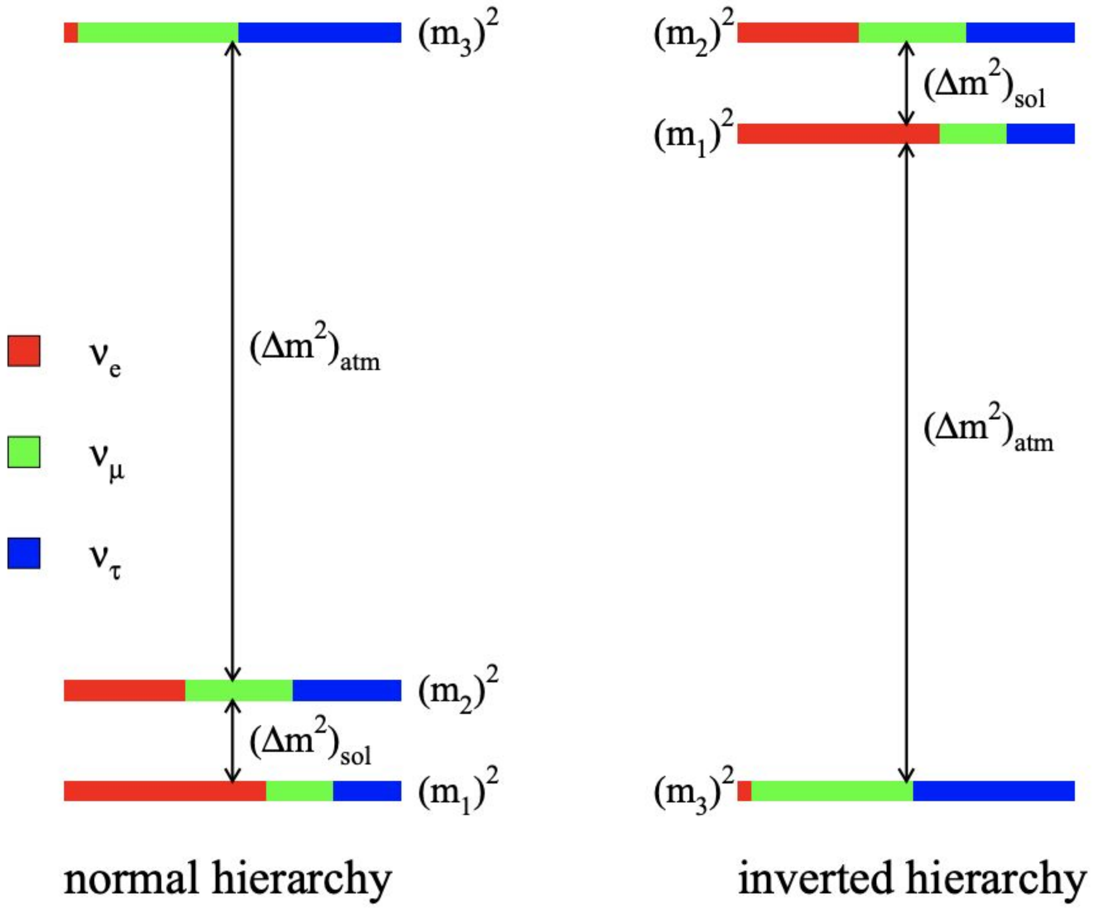
$$\Delta m^2_{\rm sol} \equiv \Delta m^2_{21} \simeq 7.5 \times 10^{-5}\ {\rm eV}^2$$
$$\Delta m^2_{\rm atm} \equiv |\Delta m^2_{32}| \simeq 2.5 \times 10^{-3}\ {\rm eV}^2$$

$$\sin^2\theta_{21} \simeq 0.31$$
$$\sin^2\theta_{23} \simeq 0.45\text{–}0.55$$
$$\sin^2\theta_{13} \simeq 0.02$$

Organizing the neutrinos

From different experiments we have some of the parameters of neutrino oscillation measured

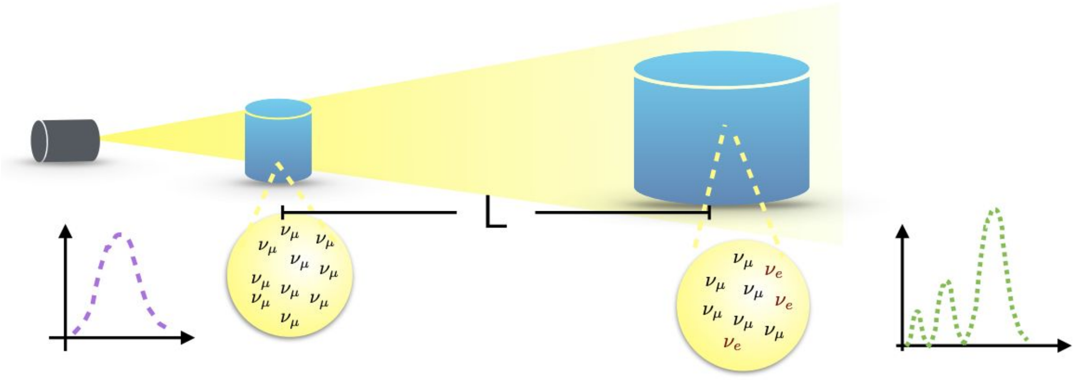
We still have parameters to measure, including the absolute **mass of the neutrino**, and the **mass ordering**



How do we measure* oscillation parameters?

***using accelerator neutrinos**

1. Measure the rate of neutrino events in the **Near Detector**
2. use geometry differences (and oscillation hypothesis) to **predict the Far Detector flux**
3. Measure the rate of neutrino events in the **Far Detector**
4. compare simulation and data and **test your hypothesis**



$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

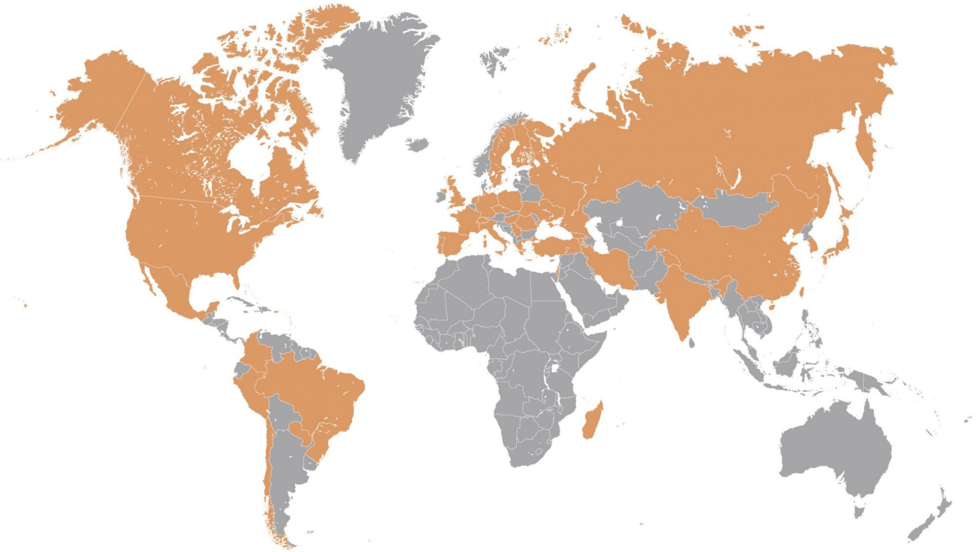
$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Oscillation probability

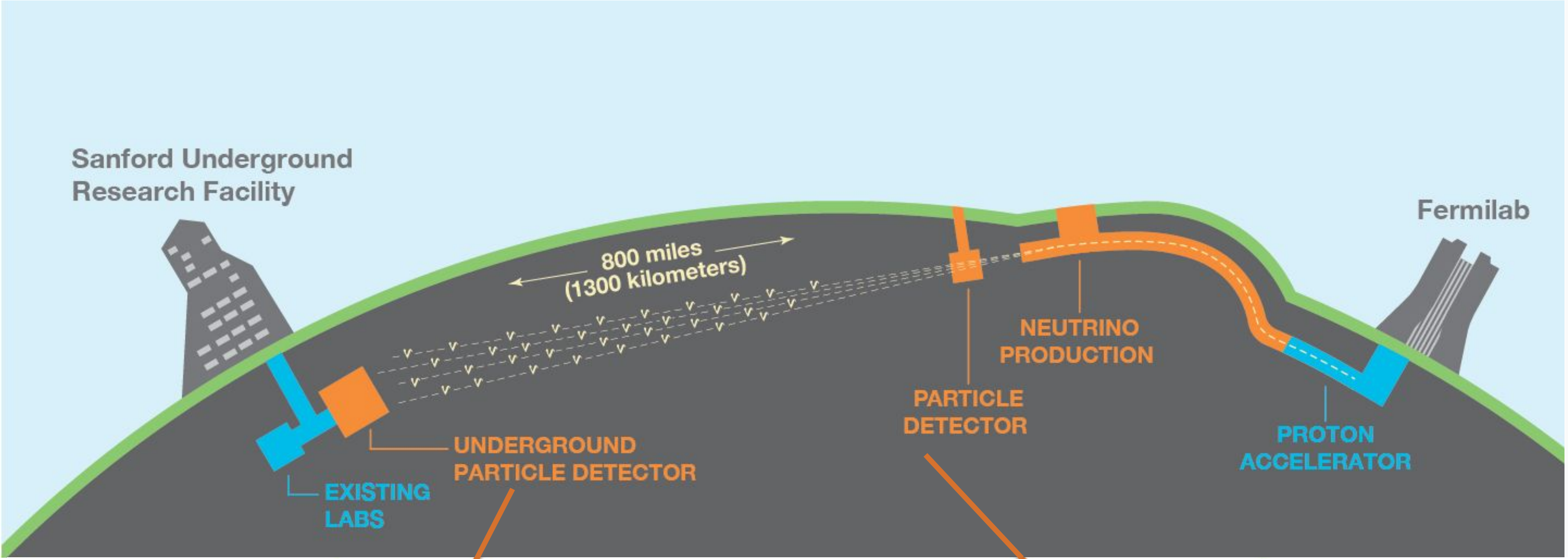
$$P(\nu_\mu \to \nu_x) \sim \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{true}}\right)$$

DEEP UNDERGROUND NEUTRINO EXPERIMENT



The DUNE Science Collaboration is currently made up of over **1400 collaborators from over 200 institutions in over 30 countries**

DUNE Experimental Design



Far Site

- *1300km from the proton source*
- *very large LAr TPCs (each 17 ktons)*
- *underground in South Dakota*

Near Site

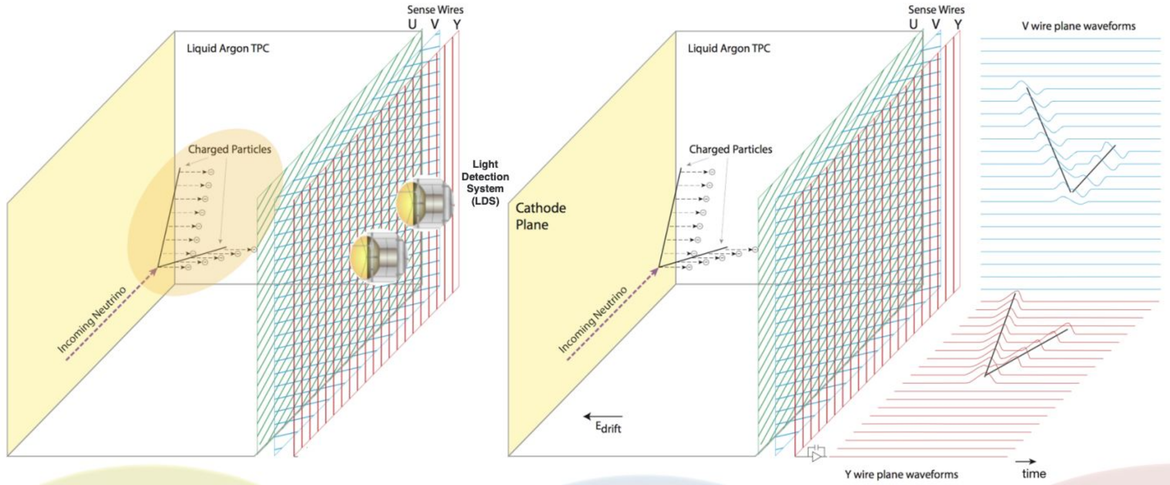
- *550m from proton source*
- *on-site at Fermilab*
- *both stationary & moveable detectors*

Liquid Argon Time Projection Chamber (LArTPC)

3D reconstruction with mm resolution

Excellent particle identification with dE/dx information

Low energy thresholds, subMeV to GeV



Charged particles in LAr produce free ionization electrons and scintillation light

Ionization charge drifts in a uniform electric field towards the readout wire-planes

Digitized signals from the wires are collected [*time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge*]

m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

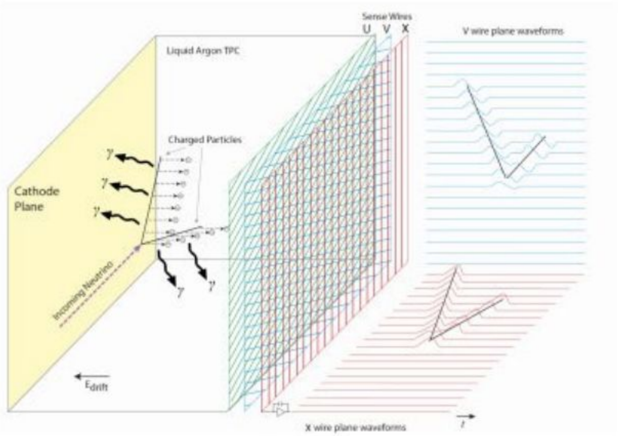
Electron drift time ~ ms

VUV photons propagate and are shifted into VIS photons

Scintillation light fast signals from LDSs give event timing

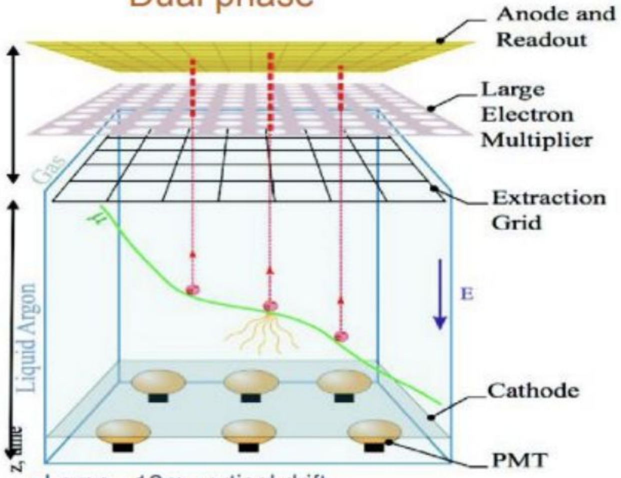
DUNE - Far Detector Technologies

Single phase

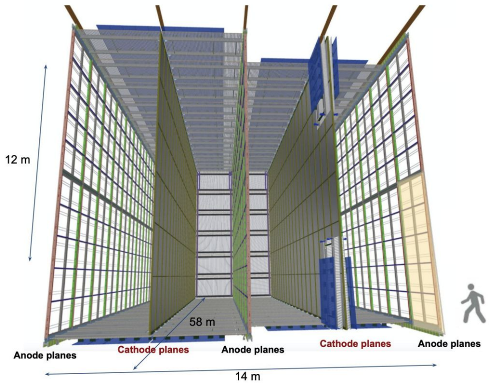


- Horizontal drift, 3.6 m drift distance
- Anode wires immersed in LAr
- Vertical Anode and Cathode Planes Assembles (APA, CPA)
- 1 collection + induction planes, rotated at ~37 degrees + 5 mm wire pitch
- Photon detectors: light guides + SiPMs in APAs → fast triggering light + calibration

Dual phase



- Large ~12m vertical drift
- Ionisation extracted and further amplified in Gas
- LEM electron amplifier
- 1 collection + induction planes, rotated at calibration
- Possible better resolution but more detector off challenges
- Bottom PMTs for prompt light collection



DUNE - Far Detector

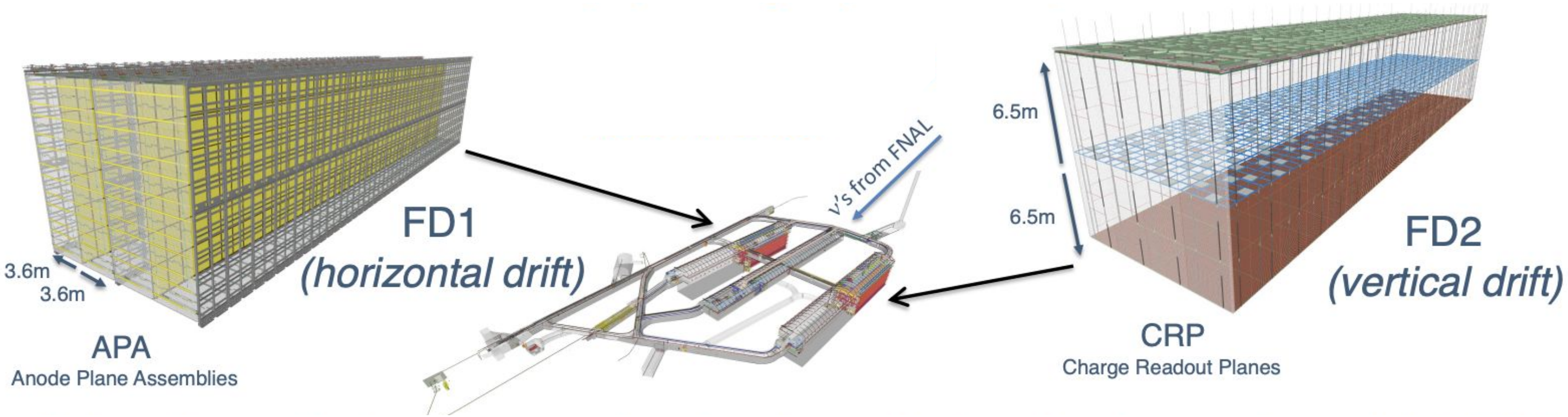
DUNE installation and operation is split in 2 phases

Phase 1 will include caverns for 4 detector modules in South Dakota and 2 far detector modules, each 17 kton of LAr, the largest LAr TPCs ever constructed

Far Detector 1: horizontal drift
Far Detector 2: vertical drift

Order of magnitude more mass than has been deployed up to now from all LAr TPCs

Cryostat installation starts in 2024!

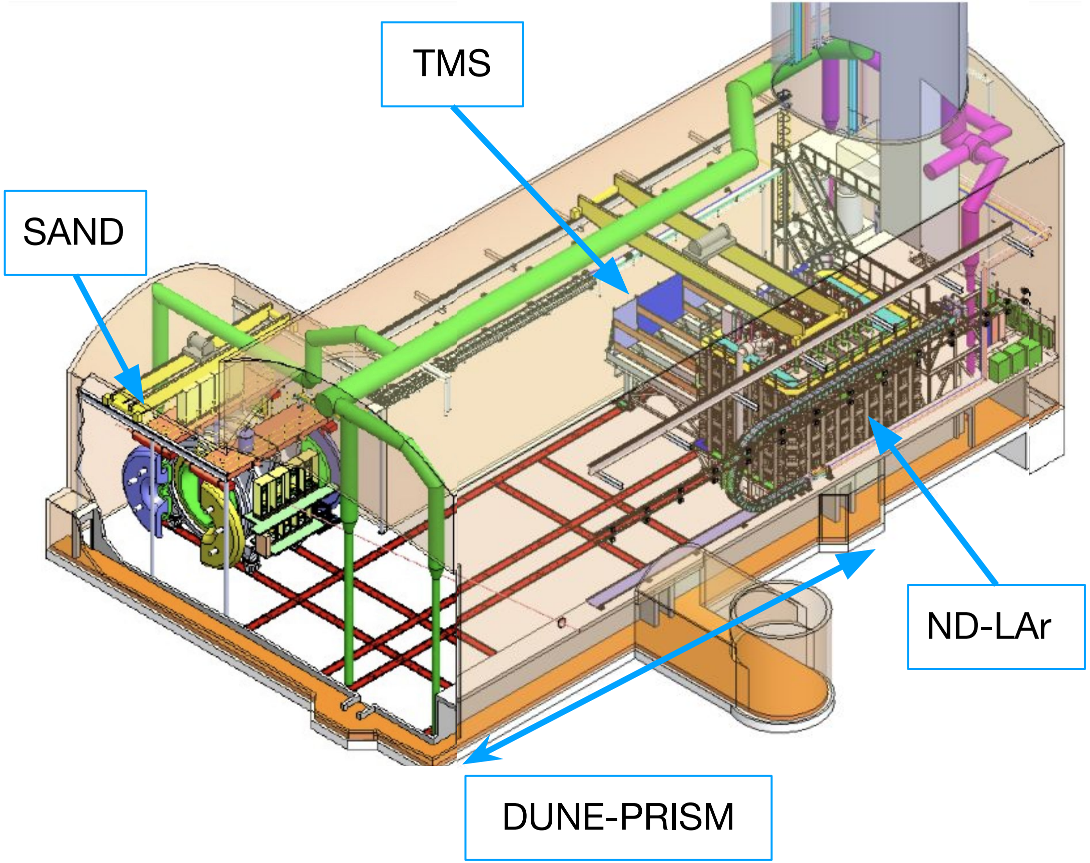


DUNE - Near Detector

Primary purpose is to constrain systematic uncertainty for oscillation analysis, constrain flux, measure cross section, etc

Phase 1 Detector
- Moveable **DUNE-PRISM**: Move up to 28.5 m off-axis:
  - **ND-LAr**: 7 x 5 array of modular 1x1x3 m3 LArTPCs with pixel readout with low-mass window
  - **TMS**: Magnetized steel range stack for measuring muon momentum/sign from CC interactions in ND-LAr

- **SAND**: On-axis magnetized beam spectrum monitor with STT, GRAIN, ECAL



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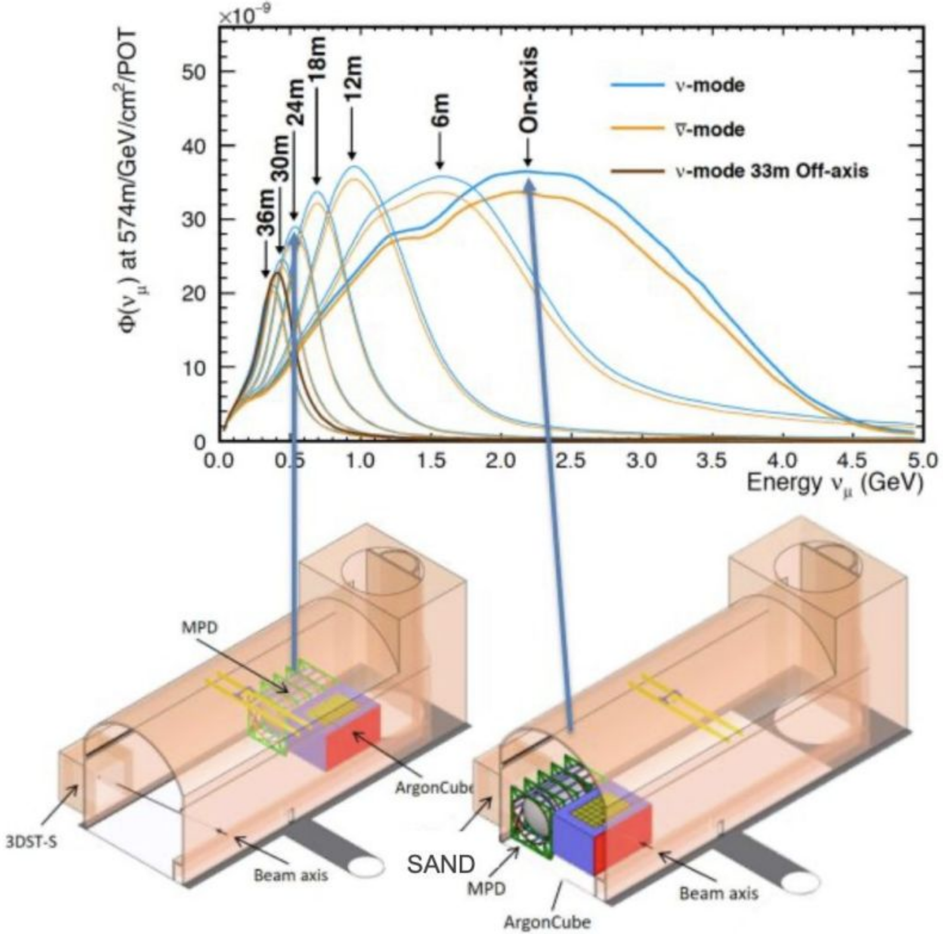
  TMS: Magnetized steel range stack for measuring muon momentum/sign from CC interactions in ND-LAr

- **SAND**: On-axis magnetized beam spectrum monitor with STT, GRAIN, ECAL



DUNE - Physics Program

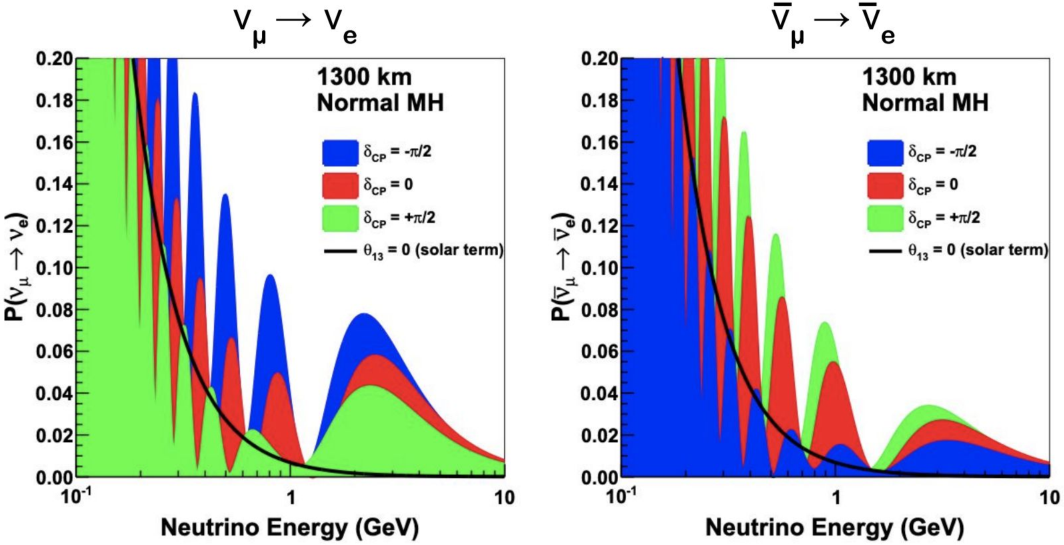
Mixing angles = $(\theta_{12}, \theta_{23}, \theta_{13})$, δ_{CP} is the CP-violation phase

$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\mathrm{I}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\mathrm{II}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathrm{III}}$$

atmospheric reactor solar

Reactor Neutrinos:

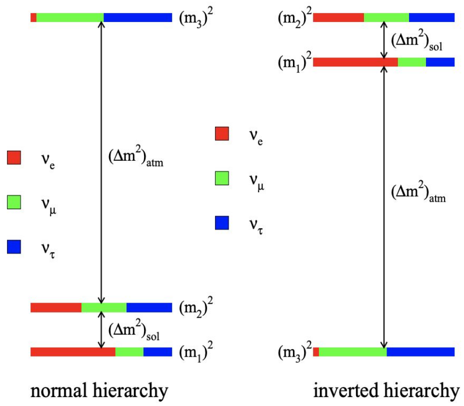
- Measure CP Violation
-

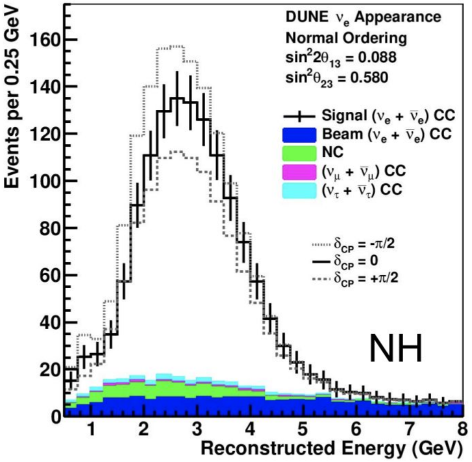


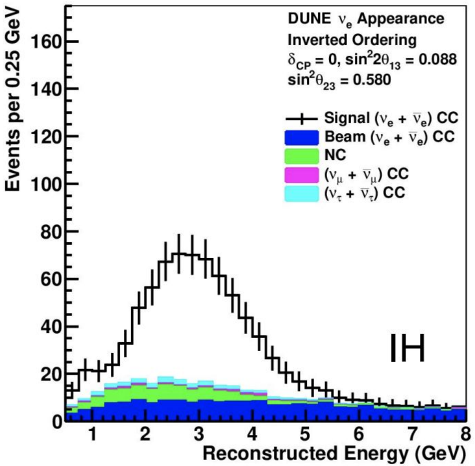
DUNE - Physics Program

Reactor Neutrinos:

- Measure CP Violation
- Measure Mass Ordering
-







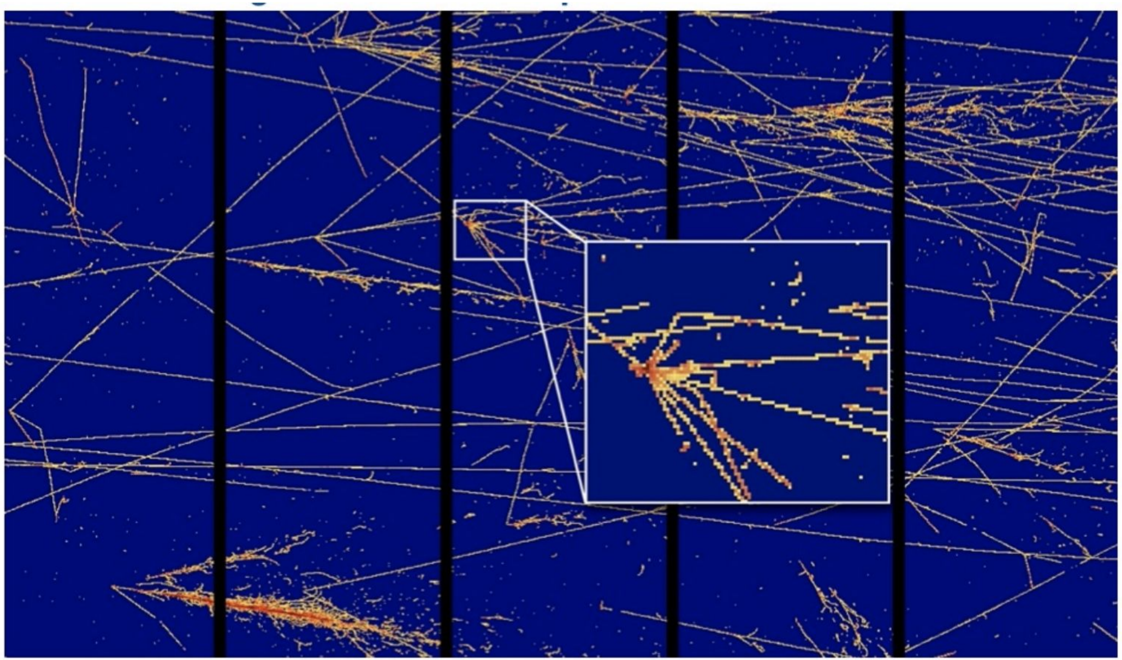
DUNE -
Physics Program

Reactor Neutrinos:
- Measure CP Violation
- Measure Mass Ordering
- Do we only have 3 flavors?

Solar Neutrinos:
- measure all of the n mixing parameters in a single experiment

Supernovae Neutrinos:
- Unique sensitivity to electron neutrinos

Atmospheric Neutrinos
- While not as sensitive, are also a tool for studying n oscillations to compare with bea

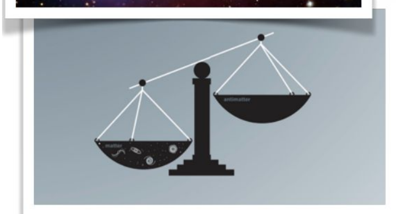


Questions & Discussion!

Backup Slides

Mateus F. Carneiro

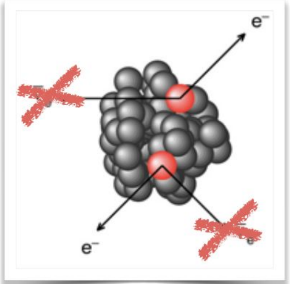
Neutrino Physics outstanding questions (guided by neutrino experiments)

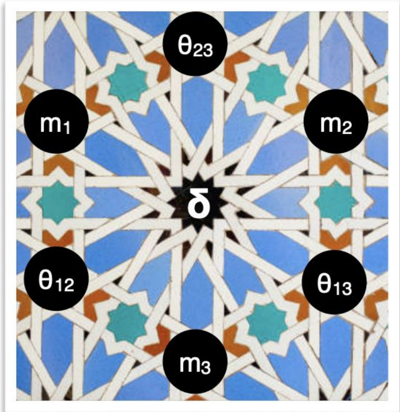


The mechanism of neutrino masses
The nature of neutrinos
The unification of all forces
The matter-antimatter asymmetry
Neutrinos as a portal to new physics
CP violation in the leptonic sector
The absolute masses of neutrinos
Neutrino mixings: patterns and symmetries
Existence of extra neutrino species
The nature of dark matter
CP violation in strong interactions
The existence of dark sectors

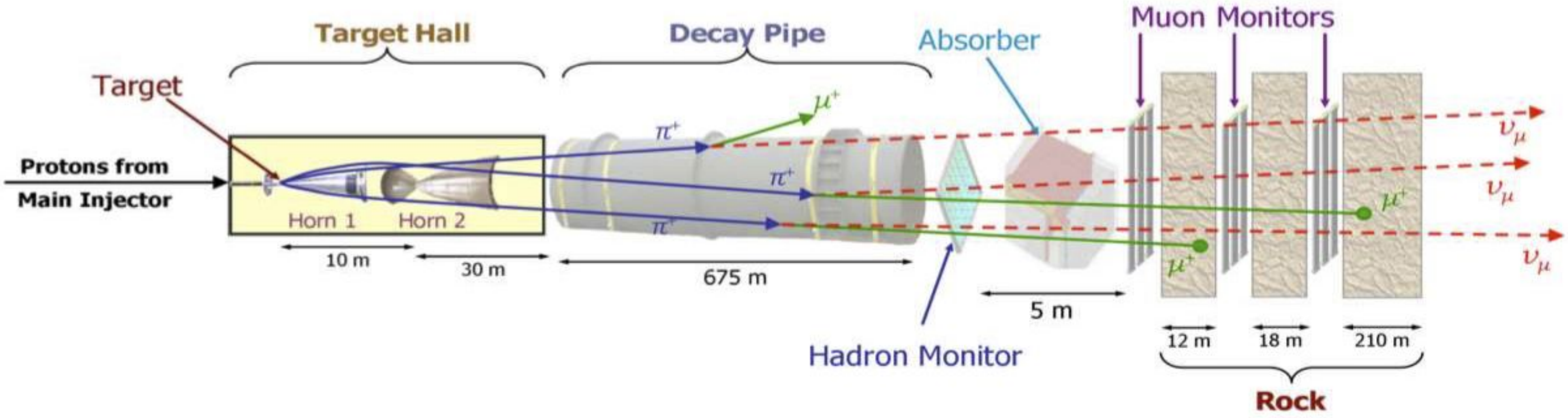
…

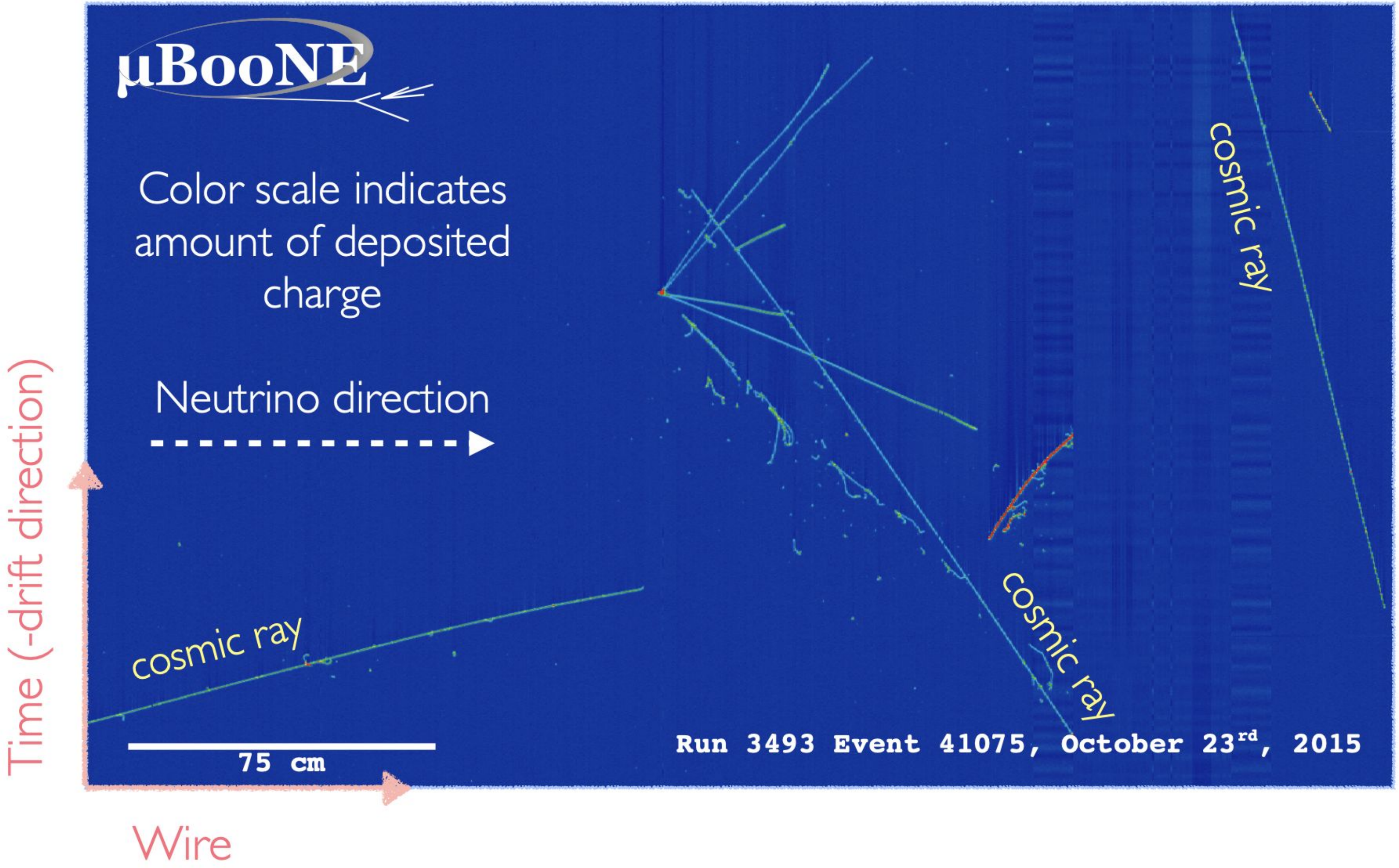
Where does the standard model break?





Producing Neutrinos



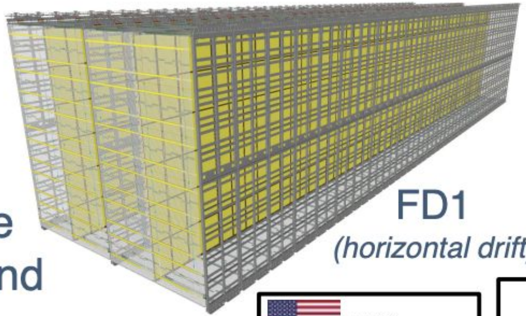

μBooNE
Color scale indicates amount of deposited charge
Neutrino direction
cosmic ray
cosmic ray
cosmic ray
75 cm
Run 3493 Event 41075, October 23rd, 2015
Time (-drift direction)
Wire

Far Detector Partners (Phase I)

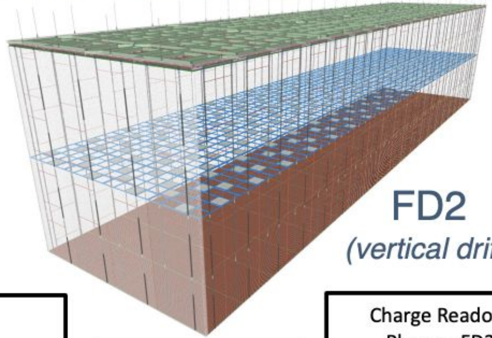
(Mary Bishai's talk)

- Multiple international partners have invested significant resources in the DUNE FDs

- ~50/50 share U.S./non-U.S (M&S)
- our partners are preparing to send detectors and components
- we are on schedule and getting ready to build these detectors!



FD1
(horizontal drift)



FD2
(vertical drift)

High Voltage
FD1, FD2

Anode Plane Assemblies - FD1

TPC Electronics
FD1, FD2-B

Photon Detection
FD1, FD2

Data Acquisition
FD1, FD2

Charge Readout Planes - FD2

CALCI
FD1, FD2

Electronics
FD2-T

Brookhaven National Laboratory
BERKELEY LAB
Argonne NATIONAL LABORATORY
Fermilab
Los Alamos NATIONAL LABORATORY
+ many Universities

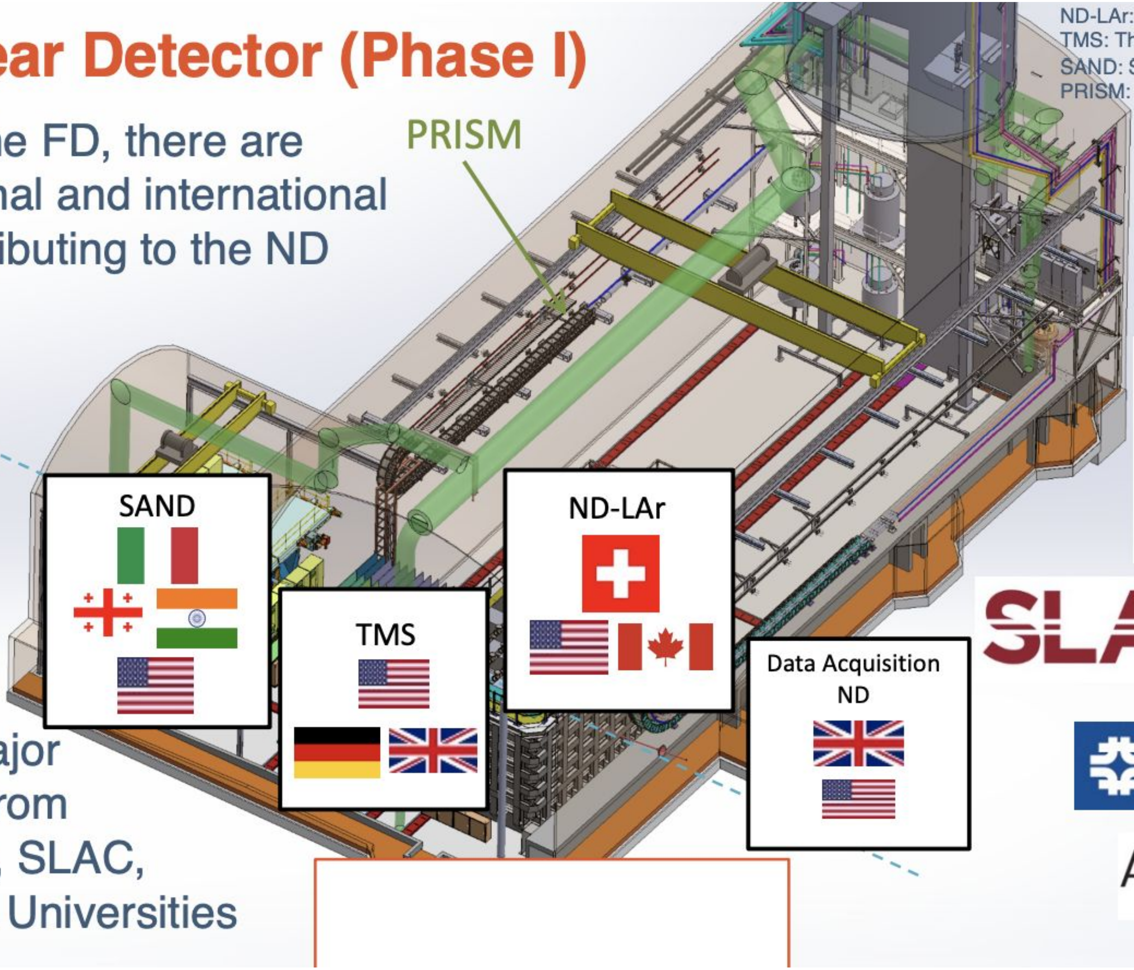
DUNE Near Detector (Phase I)

ND-LAr: liquid argon TPC near detector
TMS: The Muon Spectrometer
SAND: System for On-Axis ν Detection
PRISM: off-axis movement system

- Just as with the FD, there are multiple national and international partners contributing to the ND

- Our partners have been building prototypes & sending detector components

- In the U.S., major contributions from LBNL (pixels!), SLAC, ANL, FNAL, & Universities



BERKELEY LAB

SLAC NATIONAL ACCELERATOR LABORATORY

Fermilab

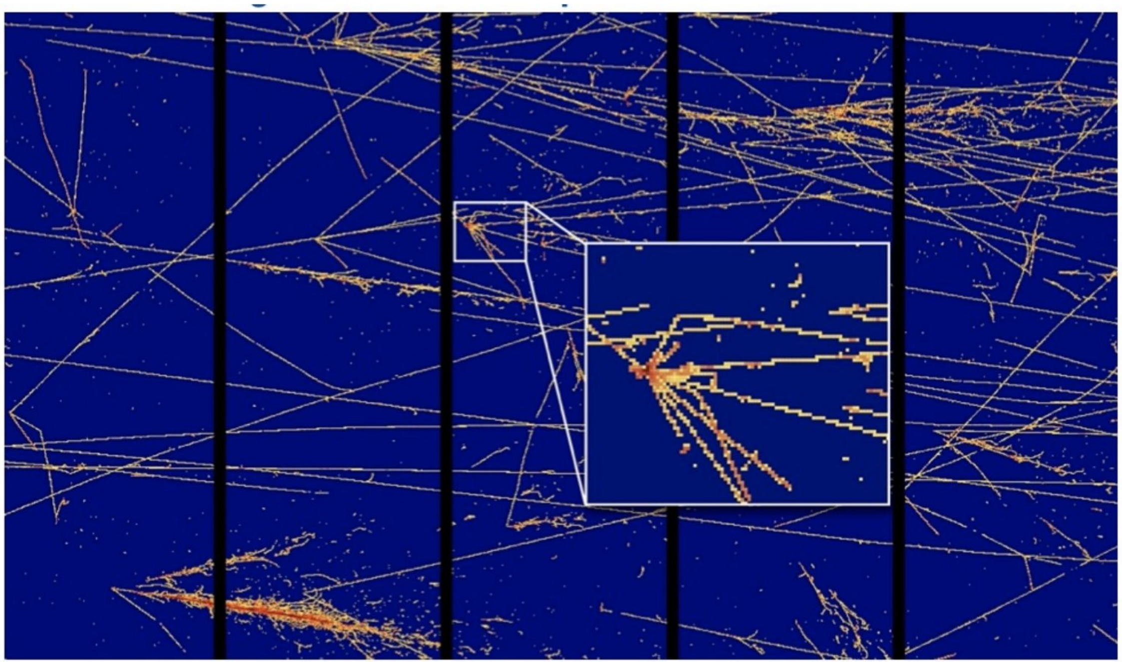
Argonne NATIONAL LABORATORY

DUNE ND - nu interaction physics

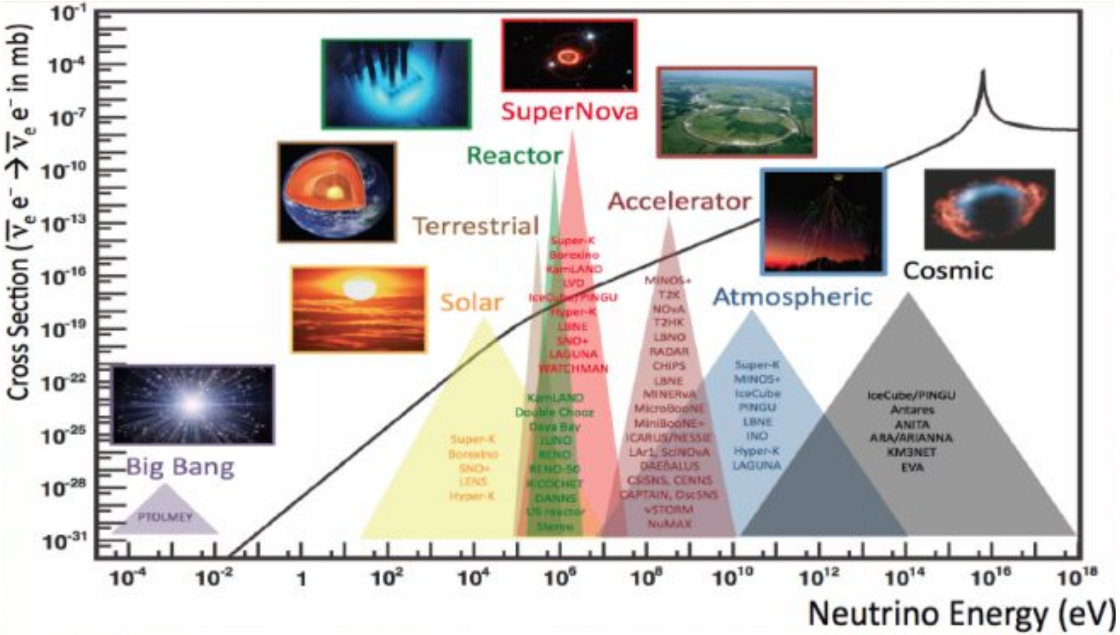
ND must measure the flux, ν-Ar cross sections, and LAr TPC detector response

ND-LAr is as similar as possible to FD; differences (modularity, pixelization) are to cope with high event rate & pile-up

It is critical to measure how neutrinos interact, and what we see in LArTPC



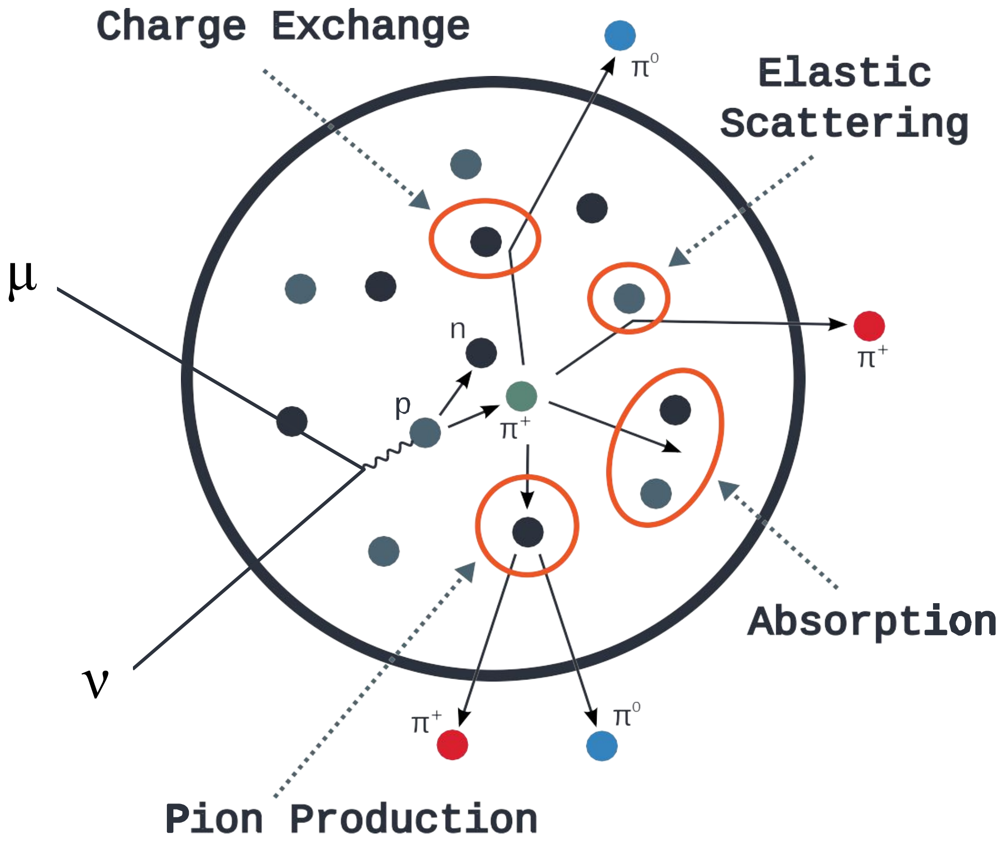
J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012), via Snowmass Neutrino WG Summary



The Nucleus!

Final State Interactions (FSI)

the strong-interaction physics in play alters:
- final state particle compositions and kinematics
- determination of the incident neutrino energy, and
- neutrino versus antineutrino scattering

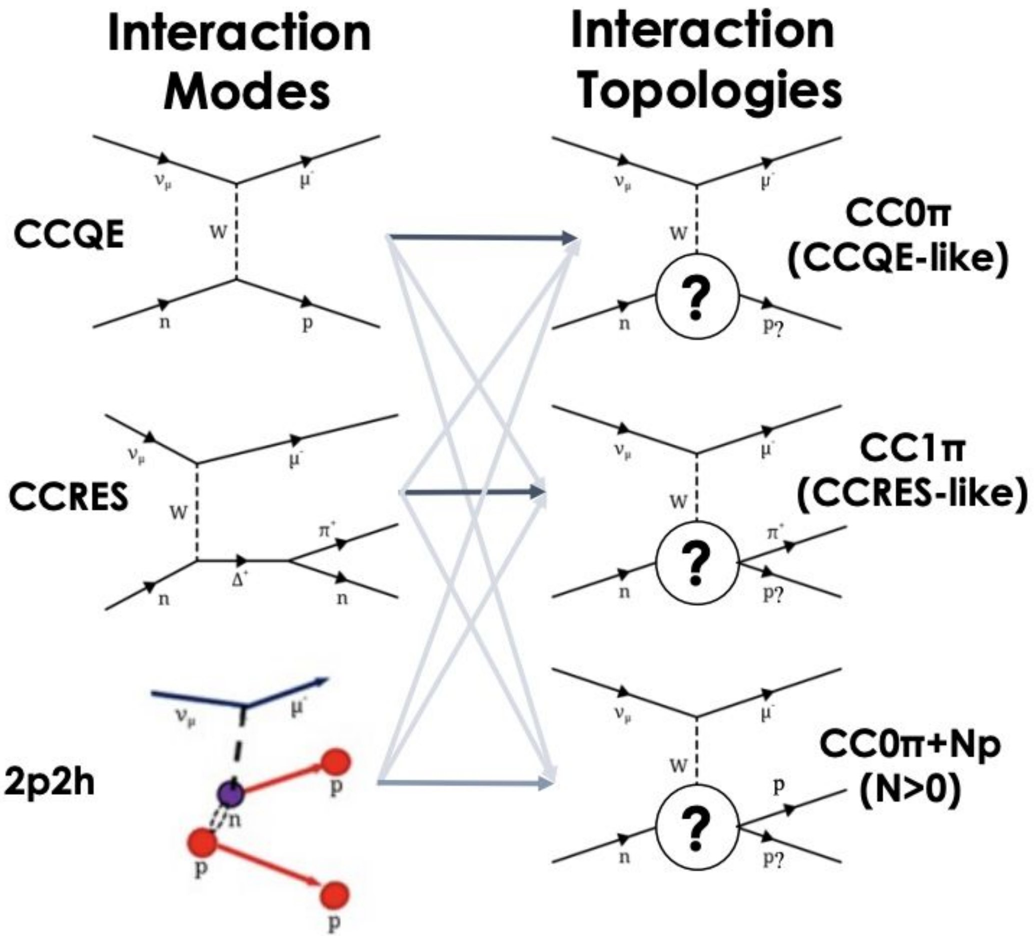


The Nucleus!

The Final State

FSI can make different interaction modes give the same final state topology

What is actually seen in the detector **cannot be classified in terms of the Initial Interactions**

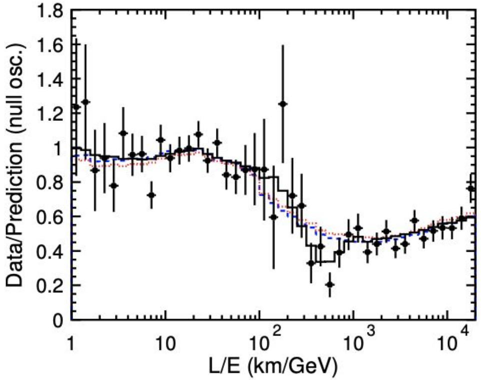


A Brief History of Neutrino Oscillations

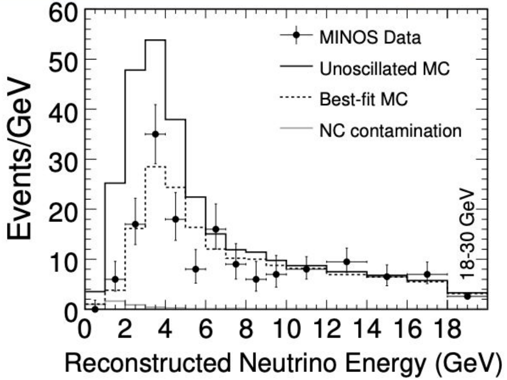
- 1957: Pontecorvo proposed Neutrino Oscillations in analogy with $K^0 \leftrightarrows \bar{K}^0$ oscillations (Gell-Mann and Pais, 1955) $\Longrightarrow$ $\nu \leftrightarrows \bar{\nu}$
- In 1957 only one neutrino type $\nu = \nu_e$ was known! The possible existence of ν_μ was discussed by several authors. Maybe the first have been Sakata and Inoue in 1946 and Konopinski and Mahmoud in 1953. Maybe Pontecorvo did not know. He discussed the possibility to distinguish ν_μ from ν_e in 1959.
- 1962: Maki, Nakagava, Sakata proposed a model with ν_e and ν_μ and Neutrino Mixing:
  "weak neutrinos are not stable due to the occurrence of a virtual transmutation $\nu_e \leftrightarrows \nu_\mu$"
- 1962: Lederman, Schwartz and Steinberger discover ν_μ
- 1967: Pontecorvo: intuitive $\nu_e \leftrightarrows \nu_\mu$ oscillations with maximal mixing. Applications to reactor and solar neutrinos ("prediction" of the solar neutrino problem).
- 1969: Gribov and Pontecorvo: $\nu_e - \nu_\mu$ mixing and oscillations. But no clear derivation of oscillations with a factor of 2 mistake in the phase

- 1975-76: Start of the "Modern Era" of Neutrino Oscillations with a general theory of neutrino mixing and a rigorous derivation of the oscillation probability by Eliezer and Swift, Fritzsch and Minkowski, and Bilenky and Pontecorvo. [Bilenky, Pontecorvo, Phys. Rep. (1978) 225]
- 1978: Wolfenstein discovers the effect on neutrino oscillations of the matter potential ("Matter Effect")
- 1985: Mikheev and Smirnov discover the resonant amplification of solar $\nu_e \to \nu_\mu$ oscillations due to the Matter Effect ("MSW Effect")
- 1998: the Super-Kamiokande experiment observed in a model-independent way the Vacuum Oscillations of atmospheric neutrinos ($\nu_\mu \to \nu_\tau$).
- 2002: the SNO experiment observed in a model-independent way the flavor transitions of solar neutrinos ($\nu_e \to \nu_\mu, \nu_\tau$), mainly due to adiabatic MSW transitions. [see: Smirnov, arXiv:1609.02386]
- 2015: Takaaki Kajita (Super-Kamiokande) and Arthur B. McDonald (SNO) received the Physics Nobel Prize "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

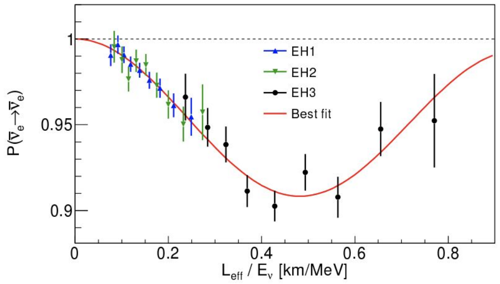
Observations of Neutrino Oscillations



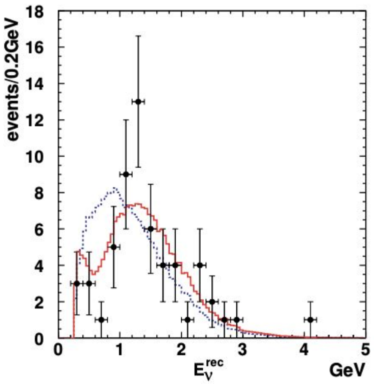
[Super-Kamiokande, PRL 93 (2004) 101801, hep-ex/0404034]



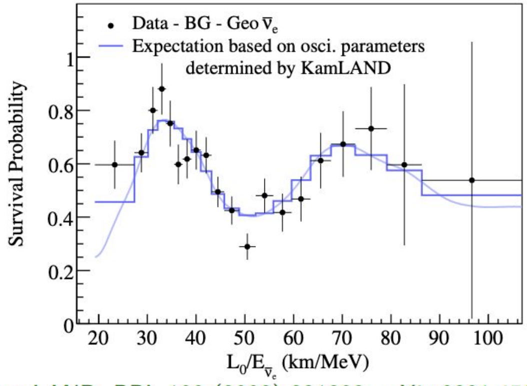
[MINOS, PRD 77 (2008) 072002, arXiv:0711.0769]



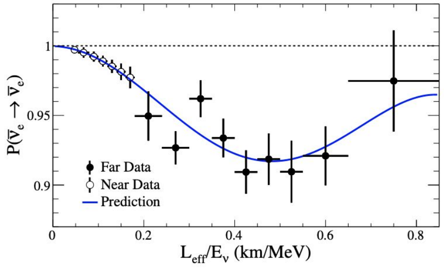
[Daya Bay, PRL, 112 (2014) 061801, arXiv:1310.6732]



[K2K, PRD 74 (2006) 072003, hep-ex/0606032v3]

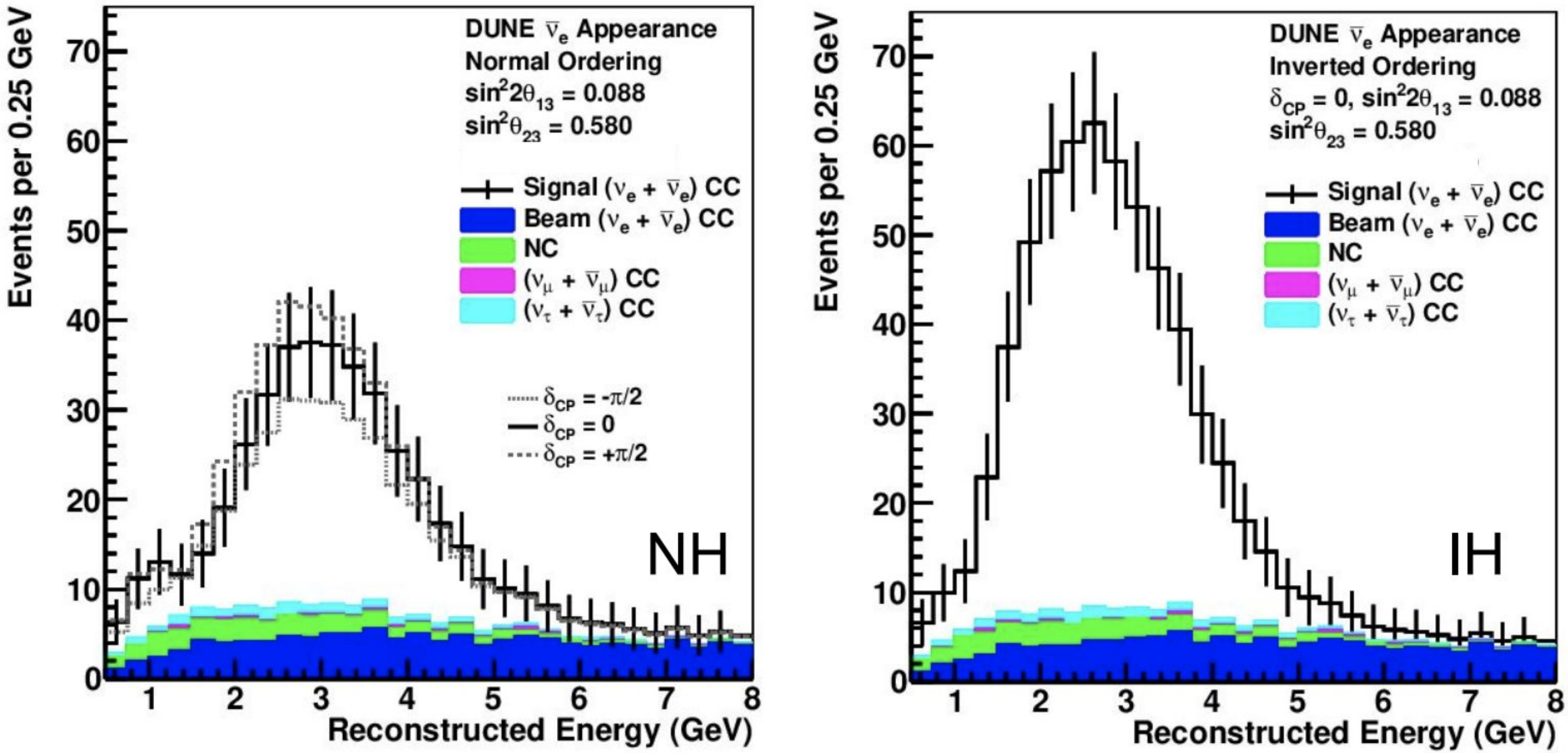


[KamLAND, PRL 100 (2008) 221803, arXiv:0801.4589]



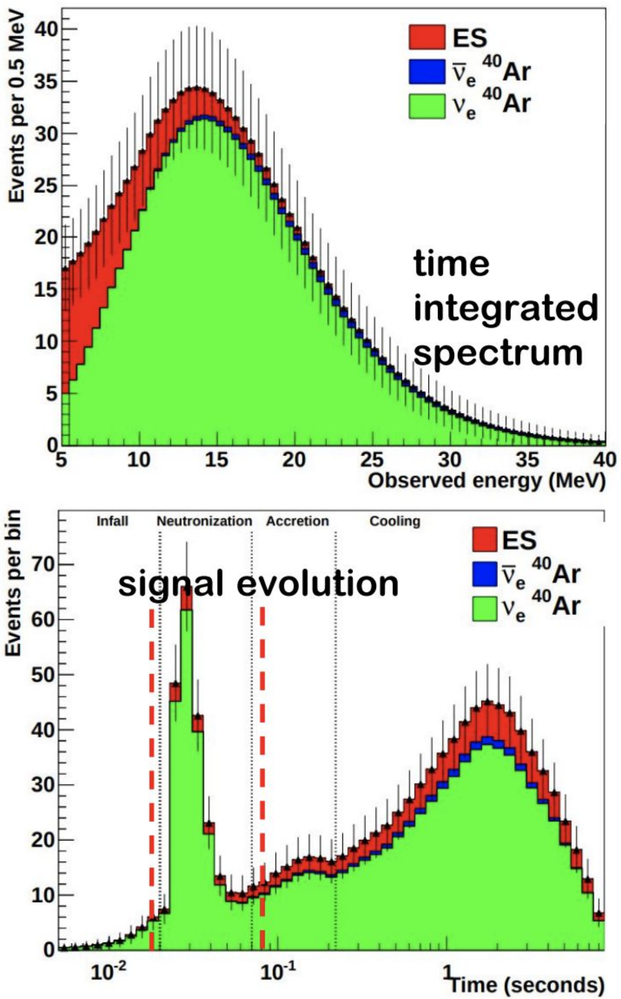
[RENO, arXiv:1511.05849]

Reconstructed $\overline{\nu}_e$ energy (CC-like events)

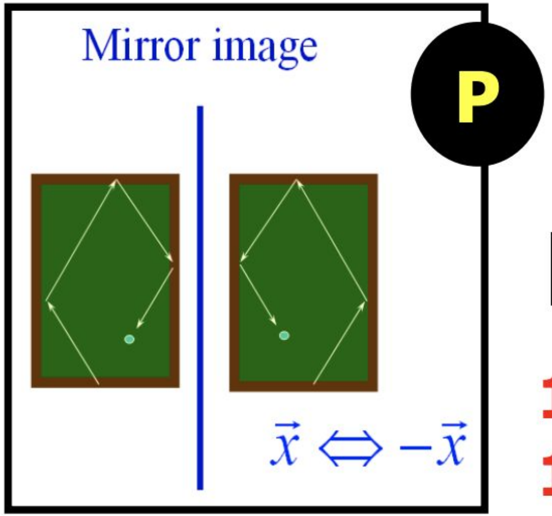


DUNE:
SN ν rates and spectrum

- Other experiments rely on $\bar{\nu}_e$ capture via inverse β-decay
  - complementarity
- DUNE will be able to observe the ν_e flux through capture on Ar40
- Unique sensitivity to the electron flavor component of the flux
- Provides information on time, energy and flavor structure



CP violation: matter and antimatter, or a reaction & its CP-conjugate process, are distinguishable --- coexistence of 2 types of interactions.



C

Charge-conjugation

1957: P violation

1964: CP violation