What we know about neutrinos

- There are 3 neutrino flavours in the Standard Model: electron, muon and tau
- Neutrinos interact only via the weak force (W and Z bosons)
- Neutrinos oscillate = they change flavour over time
Neutrino oscillations

Simplified 2 neutrino model.

\[
(v_e) = (\cos \theta \sin \theta \ - \sin \theta \cos \theta) (v_1)
\]

Time evolution ⇒ periodic ‘appearance’ and ‘disappearance’ of a weak/flavour state.

Probability for the neutrino to oscillate from flavour $\alpha$ to $\beta$ is:

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \frac{(m_1^2 - m_2^2) L}{4E}
\]

$L$ : distance travelled

$E$ : neutrino energy
What we don't know yet
What we don't know about neutrinos

- Why so light?
- Which mechanism give neutrinos their masses?

Animal characters credit Mozilla foundation
Mass hierarchy

Is the $\nu_1$ mass eigenstate with most $\nu_e$ the lightest one? Or is $\nu_3$ the lightest?

![Diagram of normal and inverted mass hierarchies with masses $\nu_1$, $\nu_2$, $\nu_3$, $\nu_e$, $\nu_\mu$, $\nu_\tau$, $\Delta m^2_{\text{atm}}$, $\Delta m^2_{\text{sol}}$.](image)

Does $\nu_3$ have more $\nu_\mu$ or $\nu_\tau$?
CP violation

Are neutrinos oscillating the same way as antineutrinos?

If not:
⇒ CP violated in the leptonic sector
Potential groundbreaking discovery!

How to know?
By measuring the phase $\delta_{CP}$
if you like maths/matrices, see backup slides 30 - 31

DUNE will compare probabilities: $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$
DUNE
Deep Underground Neutrino Experiment
DUNE, a long baseline oscillation experiment

Key feature: DUNE will measure neutrinos’ properties before and after oscillations

Counting neutrinos & comparing near vs far detectors

Probability of detecting electron, muon and tau neutrinos
Producing the most intense neutrino beam in the world
DUNE's neutrino beam

DUNE powered by Fermilab’s accelerator complex [GIF]: Long Baseline Neutrino Facility (LBNF)

**Step 1: Get some protons** (Fermilab’s main injector)
Accelerate them to 60 - 120 GeV. Power: of 1.2 Megawatt (upgrade later to 2.4 MW)

**Step 2: Aim**
Neutrinos are neutral: no steering!
Beamline draped along 18m hill
Protons angled at -5.8° → South Dakota

**Step 3: SMASH!**
Protons hit a target:
1.5-meter-long rod of graphite
will get to 500 °C in few ms
Cooled by gaseous helium at 720 km/h

**Step 4: focus the debris**
Pions & kaons focused by horns = giant magnets
Horns receive 300,000 amp electromagnetic pulse/s!
LBNF’s striplines supplying the current to the horns

Reidar Hahn, Fermilab
DUNE's Near Detector complex

Monitor the beam + measure the neutrino flux before oscillations ⇒ will reduce uncertainties
Main challenges: 50 interactions within microseconds! ⇒ need new detector design

The Near Detector has also its own physics program:
- neutrino-nucleus scattering measurements
- search for non-standard neutrinos
1285 km later...
DUNE's Far Detector

4 modules of 17 kt of liquid argon

Largest cryogenic instrument ever (89 kT)

Modules installed in stages & different detection technologies.

First module: single phase Liquid Argon Time Projection Chamber → LArTPC
DUNE's Far Detector module

The bigger the detector, the better

How are neutrinos detected?
How a Time Projection Chamber works

[Link]
How a Time Projection Chamber works

Liquid Argon TPC

$E_{\text{drift}} \sim 500\text{V/cm}$

m.i.p. ionization:
$6000\ \text{e/mm}$
How does a real neutrino event look like?
Meanwhile at CERN...
ProtoDUNE: prototyping effort

CERN neutrino platform: 2 prototypes 1/20\textsuperscript{th} the size of DUNE | 770 t total LAr mass
ProtoDUNE event display

A 6 GeV/c electron candidate:

LArTPC technology:
excellent energy & spatial resolution, high background rejection, low energy threshold
Event reconstruction and classification

Pattern recognition  
↓
3D neutrino event

Machine learning  
convolution neural network (CNN)  
↓
Classification

“Neutrino interaction classification with a convolutional neural network in the DUNE far detector”
arXiv:2006.15052
DUNE’s Far Detector will be sensitive to core-collapse supernova in Milky Way neighborhood

- Estimated to occur every 30-200 years
- Challenges on readout systems & computing: more than 100 TB within 100 seconds
- Unique information:
  - 99% of energy is carried away by neutrinos
  - cosmology: core-collapse mechanism, black hole formation…
  - particle physics: flavour transformations in core, mass hierarchy, extra dimensions…

Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment
Timeline

2021
R&D

2029
DUNE construction

2036
DUNE operations
Continued physics exploitation beyond operations

Opportunities for students

Detector development: instrumentation, data acquisition, prototype characterization, etc…

Data analysis: programming, data analysis techniques, machine learning, stats, visualization…

Extra: international collaboration, scientific writing, oral communication, travels, fun :-)

DUNE is gearing toward big discoveries in particle physics. A once-in-a-lifetime chance to join!

Learn more at [www.dunescience.org](http://www.dunescience.org) and [atwork.dunescience.org](http://atwork.dunescience.org)
More details
What we know

- There are 2 basis that are ‘rotated’, with superposition of states:

  Flavour eigenstates
  neutrino in detection
  through weak interaction

  \[ \nu_e \quad \nu_\mu \quad \nu_\tau \]

  Mass eigenstates
  neutrino in propagation
  free flight

  \[ \nu_1 \quad \nu_2 \quad \nu_3 \]

- The Pontecorvo–Maki–Nakagawa–Sakata (PMNS) unitary matrix

  \[
  \begin{pmatrix}
  \nu_e \\
  \nu_\mu \\
  \nu_\tau 
  \end{pmatrix}
  =
  \begin{pmatrix}
  \text{PMNS matrix} \\
  \nu_1 \\
  \nu_2 \\
  \nu_3 
  \end{pmatrix}
  \]
What we know

- Parametrization:
  
  $\begin{pmatrix}
  \nu_e \\
  \nu_\mu \\
  \nu_\tau
  \end{pmatrix} = \begin{pmatrix}
  \text{PMNS matrix}
  \end{pmatrix}
  \begin{pmatrix}
  \nu_1 \\
  \nu_2 \\
  \nu_3
  \end{pmatrix}$

  \[
  \begin{pmatrix}
  1 & 0 & 0 \\
  0 & c_{23} & s_{23} \\
  0 & -s_{23} & c_{23}
  \end{pmatrix}
  \begin{pmatrix}
  c_{13} & 0 & s_{13} e^{-i\delta} \\
  0 & 1 & 0 \\
  -s_{13} e^{i\delta} & 0 & c_{13}
  \end{pmatrix}
  \begin{pmatrix}
  c_{12} & s_{12} & 0 \\
  -s_{12} & c_{12} & 0 \\
  0 & 0 & 1
  \end{pmatrix}
  \begin{pmatrix}
  1 & 0 & 0 \\
  0 & e^{i\alpha_1/2} & 0 \\
  0 & 0 & e^{i\alpha_2/2}
  \end{pmatrix}
  \]

  $c_{ij} \equiv \cos \theta_{ij}, \ s_{ij} \equiv \sin \theta_{ij}$

- Only 4 parameters:
  - 3 angles: $\theta_{12}, \theta_{13}, \theta_{23}$
  - 1 phase $\delta_{\text{CP}}$

Number freak?
Check [www.nu-fit.org](http://www.nu-fit.org)
Neutrino oscillation in matter

Oscillation probability of $\nu_\mu \rightarrow \nu_e$ through matter in the standard three-flavor model:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 \theta_{23} \sin^2 2 \theta_{13} \frac{\sin^2 (\Delta_{31} - a L)}{(\Delta_{31} - a L)^2} \Delta_{31}^2$$

$$+ \sin 2 \theta_{23} \sin 2 \theta_{13} \sin 2 \theta_{12} \frac{\sin (\Delta_{31} - a L)}{(\Delta_{31} - a L)} \Delta_{31} \times \frac{\sin (a L)}{(a L)} \Delta_{21} \cos (\Delta_{31} \pm \delta_{CP})$$

$$+ \cos^2 \theta_{23} \sin^2 2 \theta_{12} \frac{\sin^2 (a L)}{(a L)^2} \Delta_{21}^2,$$

Asymmetry:

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \approx \frac{\cos \theta_{23} \sin 2 \theta_{12} \sin \delta_{CP}}{\sin \theta_{23} \sin \theta_{13}} \left( \frac{\Delta m_{21}^2 L}{4 E_{\nu}} \right) + \text{matter effects}$$

In the GeV range of $E_\nu$, the degeneracy between the asymmetries from matter effect and $C_{PV}$ effect is resolved for baselines $> 1200$ km.
Appearance probability in DUNE  $L = 1285$ km

Energy spread

**NEUTRINO FLUXES**

- $\nu_\mu$
- $\bar{\nu}_\mu$
- $\nu_e$
- $\bar{\nu}_e$

**ANTINEUTRINO FLUXES**

- $\nu_\mu$
- $\bar{\nu}_\mu$
- $\nu_e$
- $\bar{\nu}_e$

$\nu/s/m^2/GeV$ vs. Neutrino energy (GeV)
Deep Underground Neutrino Experiment

DUNE is a “long baseline neutrino oscillation experiment.”

Intense beam of neutrino is sent through Earth to a far away detector (called far detector)
DUNE
Near Detector

SAND Multi-Purpose Detector LAr-ND ArgonCube
Event display in protoDUNE

First beam data events: noise levels low → S/N ratio > 10 in all planes, > 40 for collection plane
Stable running since first operations began in 2018
Neutrino oscillations: $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance

![Graph showing Neutrino oscillations](image-url)
Sensitivity plots

What we should expect
Sensitivity vs time

Mass Hierarchy sensitivity

5σ after 2 years of running

CP Violation Sensitivity

5σ sensitivity after 10 years for 50% of $\delta_{CP}$ values
Sensitivity vs time

Mass Hierarchy sensitivity

5σ after 2 years of running

CP Violation Sensitivity

5σ sensitivity after 10 years for 50% of $\delta_{CP}$ values

2 years

10 years
Mass hierarchy sensitivity

DUNE Sensitivity
All Systematics
Normal Ordering
\[ \sin^2 2\theta_{13} = 0.088 \pm 0.003 \]
\[ 0.4 < \sin^2 \theta_{23} < 0.6 \]

\[ \Delta \chi^2 \]

DUNE Sensitivity
All Systematics
Inverted Ordering
\[ \sin^2 2\theta_{13} = 0.088 \pm 0.003 \]
\[ 0.4 < \sin^2 \theta_{23} < 0.6 \]

\[ \Delta \chi^2 \]
CP-violation significance vs true $\delta_{CP}$

Significant CP violation discovery potential over wide range of true $\delta_{CP}$ values in 7-10 years (staged)
Core-collapse supernova in DUNE’s FD