Probing the Nature of Neutrinos with the Deep Underground Neutrino Experiment

Gianfranco Ingratta (York University)
On behalf of the DUNE Collaboration

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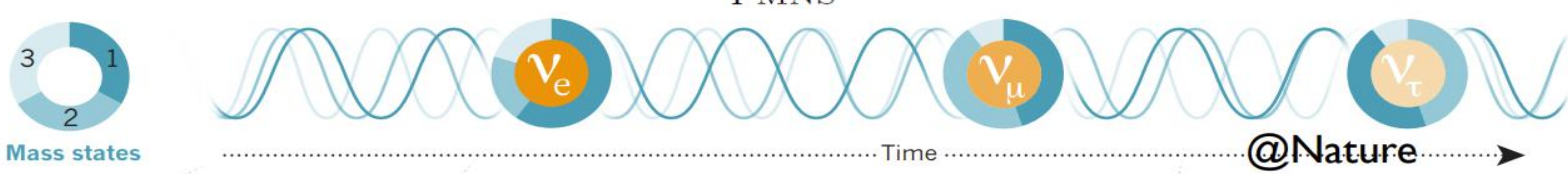
Neutrinos *oscillate*

- Ray Davis, 1960s: the **solar neutrino problem** – detected number of ν_e from the Sun is 2/3 smaller than expected
- Late 1990s/early 2000s: SNO (Ontario) and SuperKamiokande (Japan) solved the mystery: **neutrinos oscillate!**
- Oscillation is a quantum effect: neutrinos are created in one **flavour eigenstate** ν_e , ν_μ, ν_τ , but evolve in time as superpositions of three **mass eigenstates** ν_1 , ν_2, ν_3 having *slightly* different masses
- The probability of detecting one neutrino flavour is function of time (or distance) and energy (i.e **L/E**) and on the **oscillation parameters (3** mixing **angles**, **2** mass **differences** and **1 phase)**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrino Oscillations: open questions

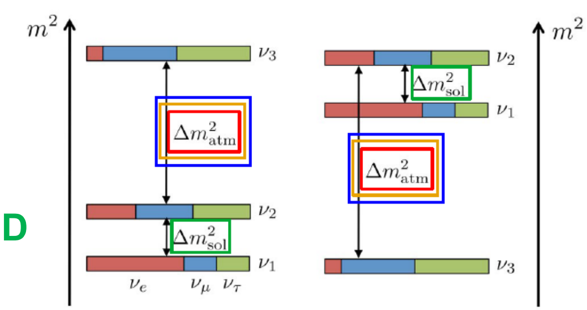
- Assuming three flavor neutrinos, oscillations depend on **3** mixing **angles**, **2** mass **splitting** and **1 phase**
- Open questions:
  - **Is the 3-flavor neutrino picture correct?** Is PMNS unitary?
  - **Is ν_3 the heaviest** (normal ordering) **or the lightest** (inverted ordering)? What is the sign of Δm^2_{31}?
  - **Do ν and $\overline{\nu}$ oscillate differently?** What is the value of δ_{CP}?
  - **Does ν_3 contain more ν_τ or ν_μ?** What Is the θ_{23} octant?

$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\rm CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Super-K **T2K, NOvA** **Daya Bay, Reno** **SNO, KamLAND**

Current best measurements (solid) and complementary measurements (dashed)

The mass ordering problem

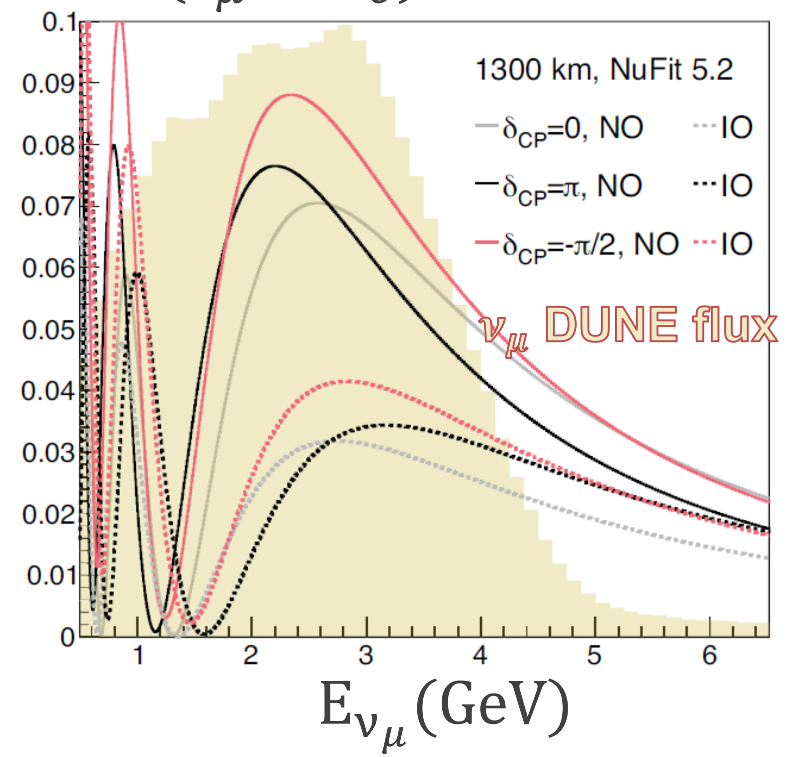


Why DUNE

- Mixing angles are sufficiently large to design an experiment capable of measuring many oscillation parameters $(\Delta m^2_{31}, \theta_{13}, \theta_{23}, \delta_{CP})$.

- An experiment that measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ over a distance of 1300 km with a $\nu_\mu(\bar{\nu}_\mu)$ beam peaked at ~2.5 GeV can determine the values of δ_{CP} and Δm^2_{31} without degeneracy.

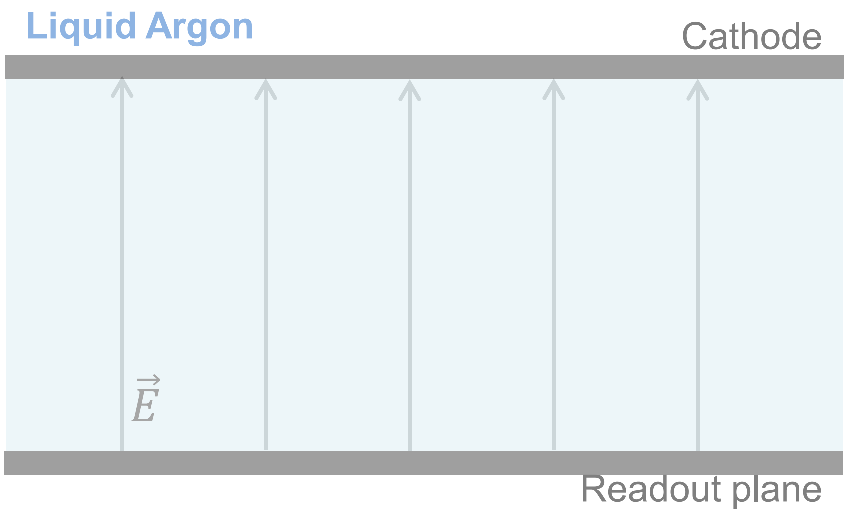
$P(\nu_\mu \to \nu_e)$ at 1300 km



Adapted from Harris, Ilic, Konaka, Canadian Journal of Physics (2025)

How can we see neutrinos?

- Liquid Argon Time Projection Chambers (**LArTPC**s) technology!
- Neutrinos (rarely) collide on an Argon nuclei, producing charged particles
- Charged particles excite and ionize the liquid Argon producing
  - **Scintillation light**: prompt signal, tells the interaction **time**
  - **Ionization**: electrons slowly drift towards readout plane (μs to ms) where they are collected → infers about the position and **energy** of the neutrino



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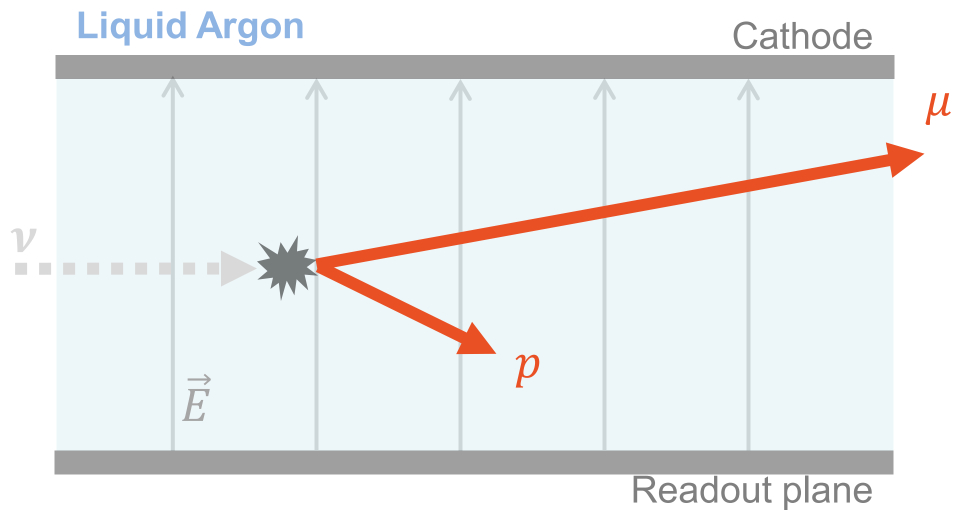

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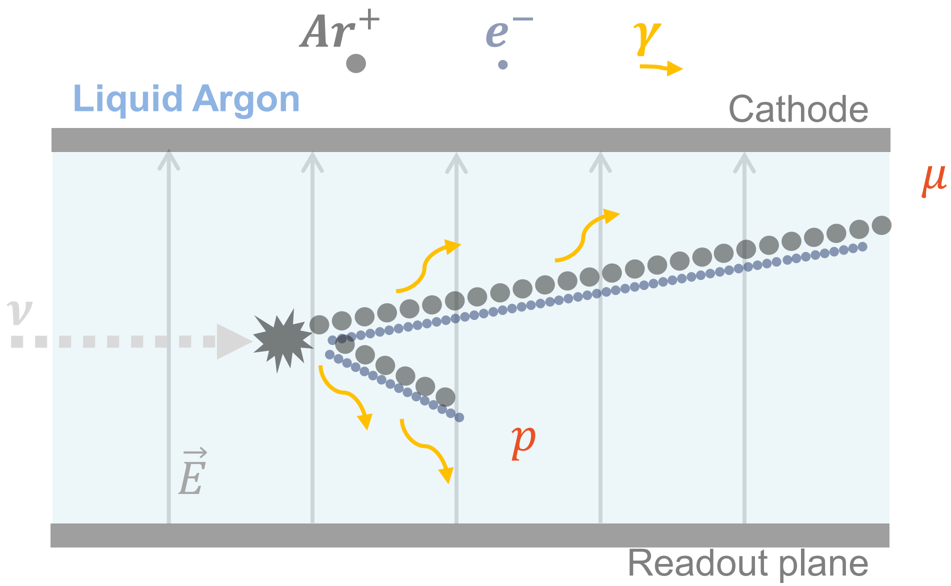

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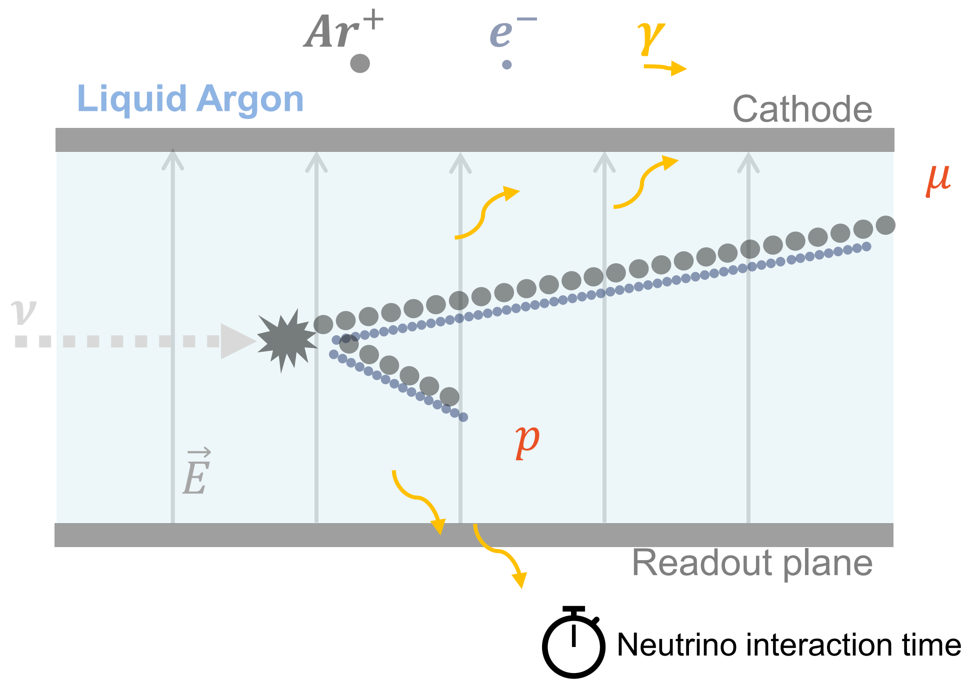

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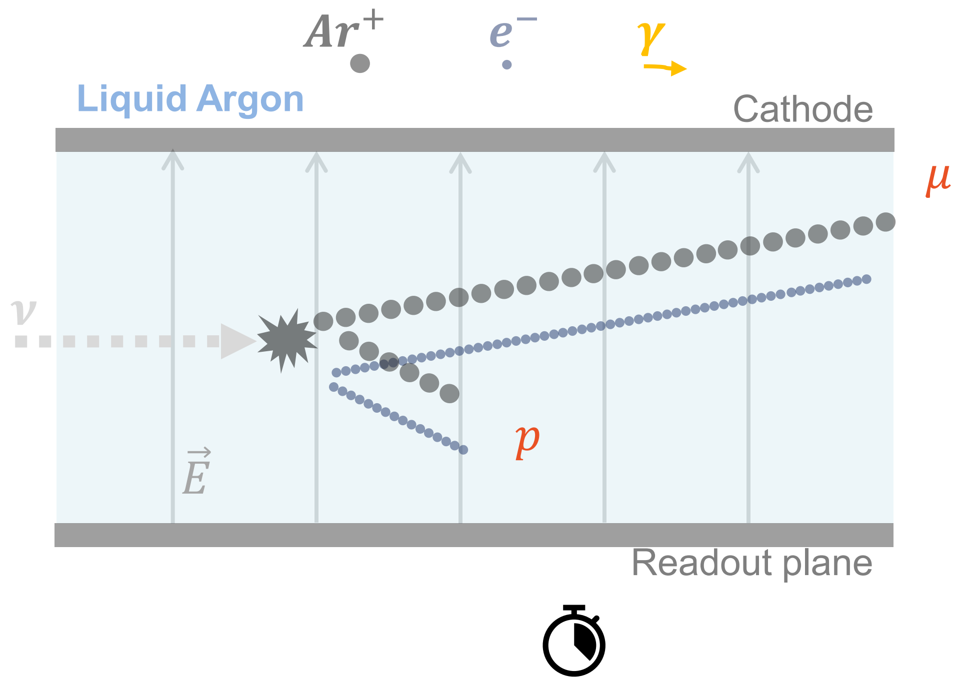

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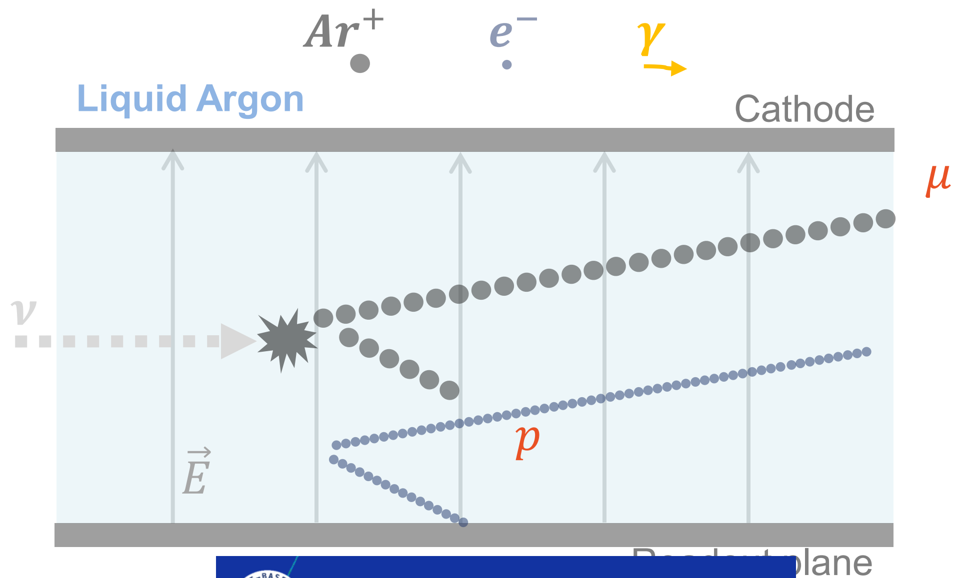

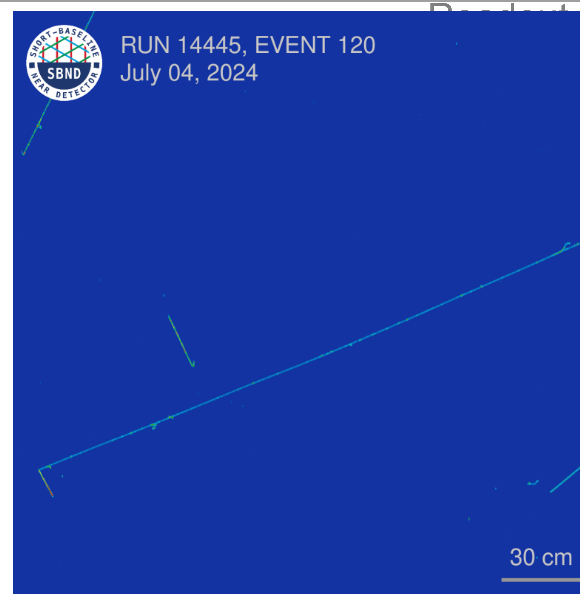

How do we probe oscillations?

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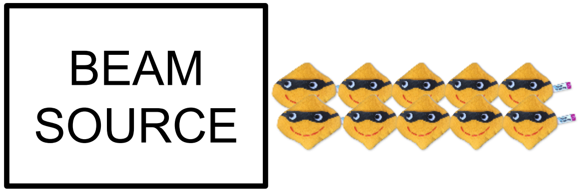
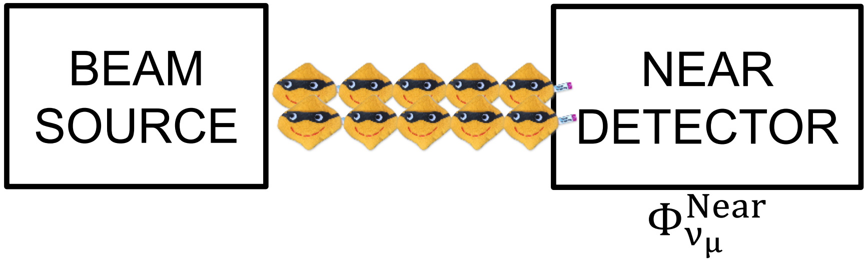


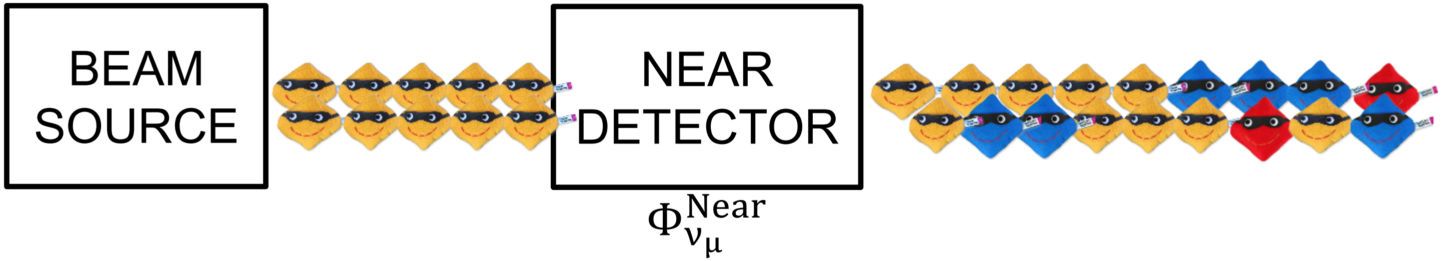
1. Create a pure neutrino beam of ν_μ

How do we probe oscillations?



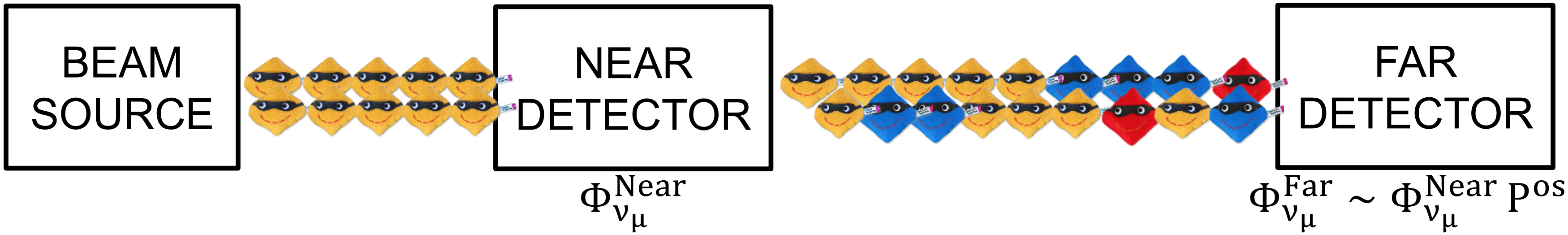
1. Create a pure neutrino beam of ν_μ
2. Measure the flux near to the source (near detector) Φ_{ν}^{Near}

How do we probe oscillations?



1. Create a pure neutrino beam of ν_μ
2. Measure the flux near to the source (near detector) $\Phi_{\nu}^{\mathrm{Near}}$
3. Let neutrinos propagate and oscillate

How do we probe oscillations?



1. Create a pure neutrino beam of ν_μ
2. Measure the flux near to the source (near detector) $\Phi_{\nu}^{\mathrm{Near}}$
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4. Measure the flux after oscillations, far from the source (far detector)

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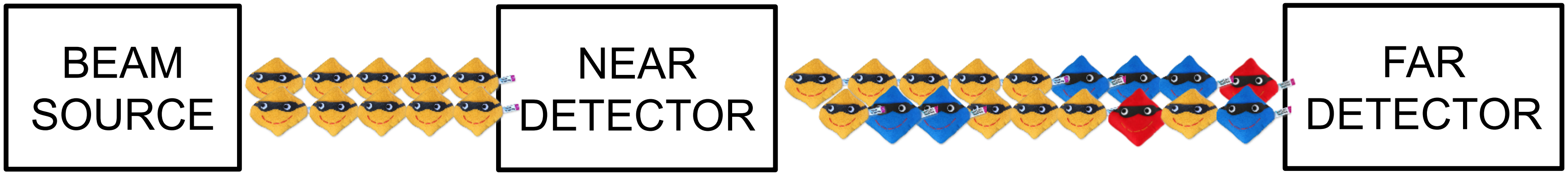

$\Phi_{\nu_\mu}^{\mathrm{Near}}$ $\Phi_{\nu_\mu}^{\mathrm{Far}} \sim \Phi_{\nu_\mu}^{\mathrm{Near}} \mathrm{P}^{\mathrm{osc}}$

1. Create a pure neutrino beam of ν_μ
2. Measure the flux near to the source (near detector) Φ_ν^{Near}
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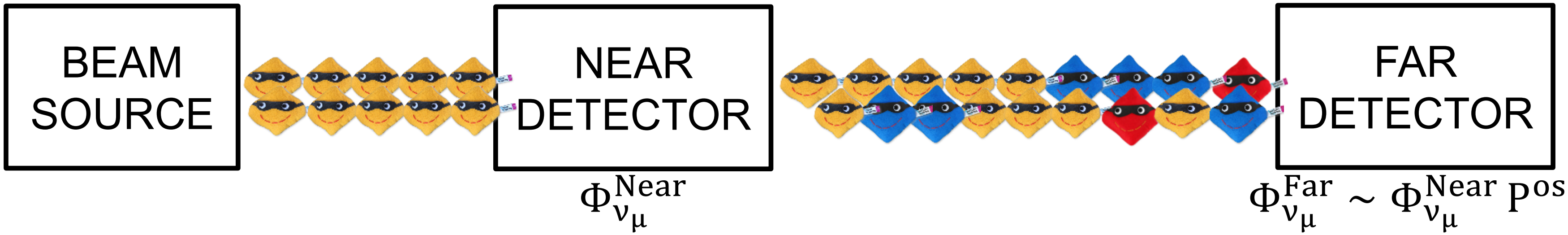
4. Measure the flux after oscillations, far from the source (far detector)
5. Compare near and far flux $\Phi_\nu^{\mathrm{Far}}/\Phi_\nu^{\mathrm{Near}}$ and make oscillation measurements

How do we probe oscillations?



1. Create a pure neutrino beam of ν_μ
2. Measure the flux near to the source (near detector) $\Phi^{\mathrm{Near}}_{\nu}$
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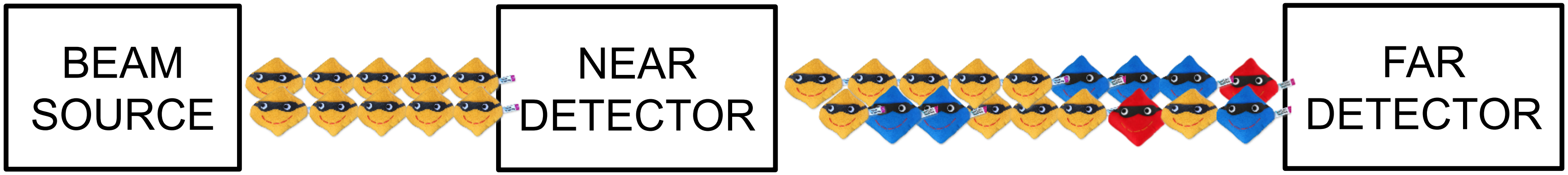
4. Measure the flux after oscillations, far from the source (far detector)
5. Compare near and far flux $\Phi^{\mathrm{Far}}_{\nu}/\Phi^{\mathrm{Near}}_{\nu}$ and make oscillation measurements
6. Collect nobel prize

How do we probe oscillations?



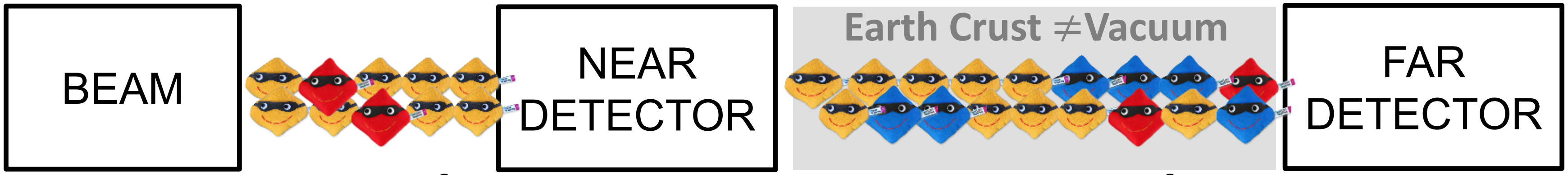
$\Phi_{\nu_\mu}^{\mathrm{Near}}$ $\quad$ $\Phi_{\nu_\mu}^{\mathrm{Far}} \sim \Phi_{\nu_\mu}^{\mathrm{Near}} P^{\mathrm{osc}}$

1. Create a pure neutrino beam of ν_μ
2. Measure the flux near to the source (near detector) Φ_ν^{Near}
3. Let neutrinos propagate …
4. Measure the flux after o… …rce (far detector)
5. Compare near and far flux $\Phi_\nu^{\mathrm{Far}}/\Phi_\nu^{\mathrm{Near}}$ and m… …scillation measurements
6. Collect nobel prize

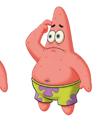
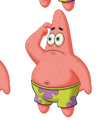
HOW ABOUT UNCERTAINTIES?

More details here

… a more realistic picture



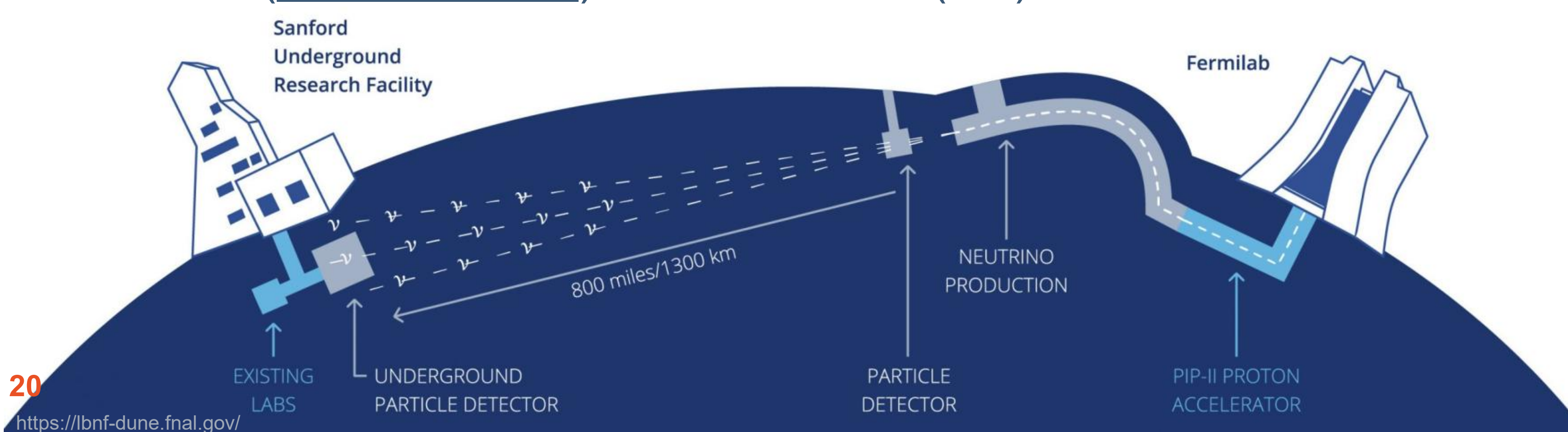
$$\int \Phi_\nu^{\text{Near}} \sigma_\nu R_{\text{detector}}^{\text{Near}} \, dE \qquad \int \Phi_\nu^{\text{Far}} \sigma_\nu R_{\text{detector}}^{\text{Far}} P^{\text{osc}} dE$$

1. Create a ~~pure~~ neutrino beam of ν_μ, contaminated by $\bar{\nu}_\mu, \bar{\nu}_e, \nu_e$ 
2. Measure the ~~flux~~ rate near to the source (near detector)   
3. Let neutrinos propagate and oscillate (…account for matter effect)
4. Measure the ~~flux~~ rate after oscillations, far from the source (far detector) 
5. Compare near and far flux $\Phi_\nu^{\text{Far}}/\Phi_\nu^{\text{Near}}$ and make oscillation measurements… after having accumulated data for years

~~6. Collect nobel prize~~ maybe?

Deep Underground Neutrino Experiment in a nutshell

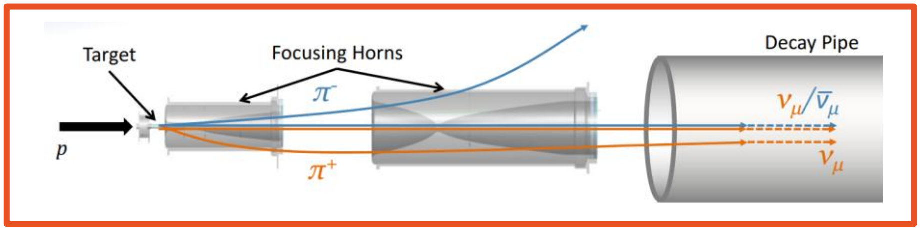
- Pillars of DUNE's design: a **large mass**, **high exposure**, **high precision**, deep **underground** accelerator experiment capable of measuring neutrino and antineutrinos over a **wide range of energy covering two oscillations maxima**
- 1500 collaborators over 35 countries (including 🇨🇦)
- Sited in two facilities:
  - **FNAL** (near Chicago)**:** neutrino **beam source** and **Near Detector** (ND)
  - **SURF** (South Dakota)**: Far Detector** (FD)



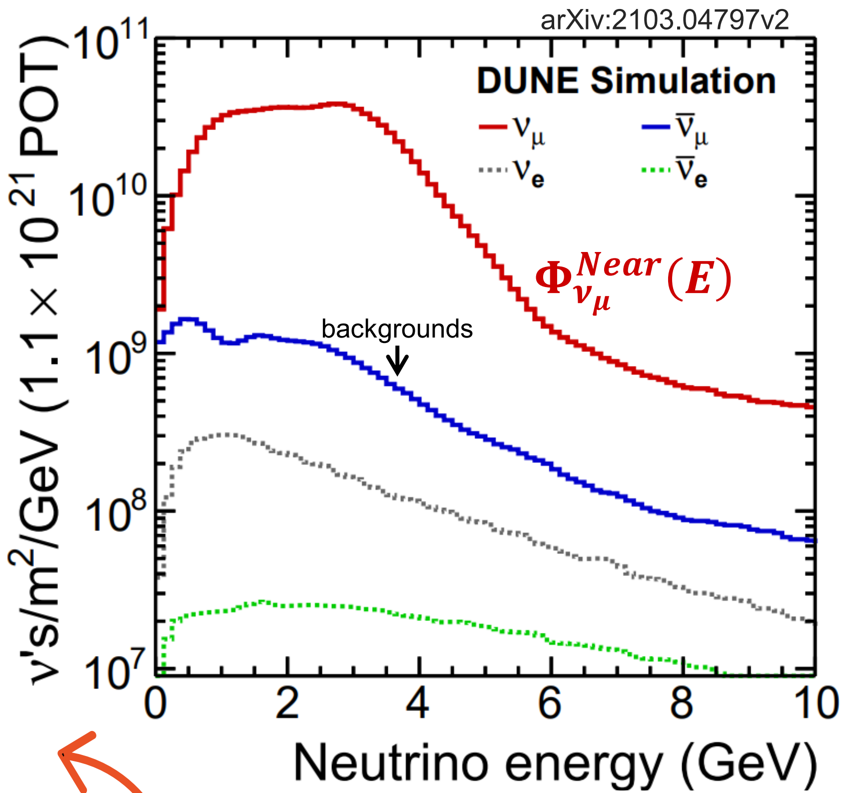
https://lbnf-dune.fnal.gov/

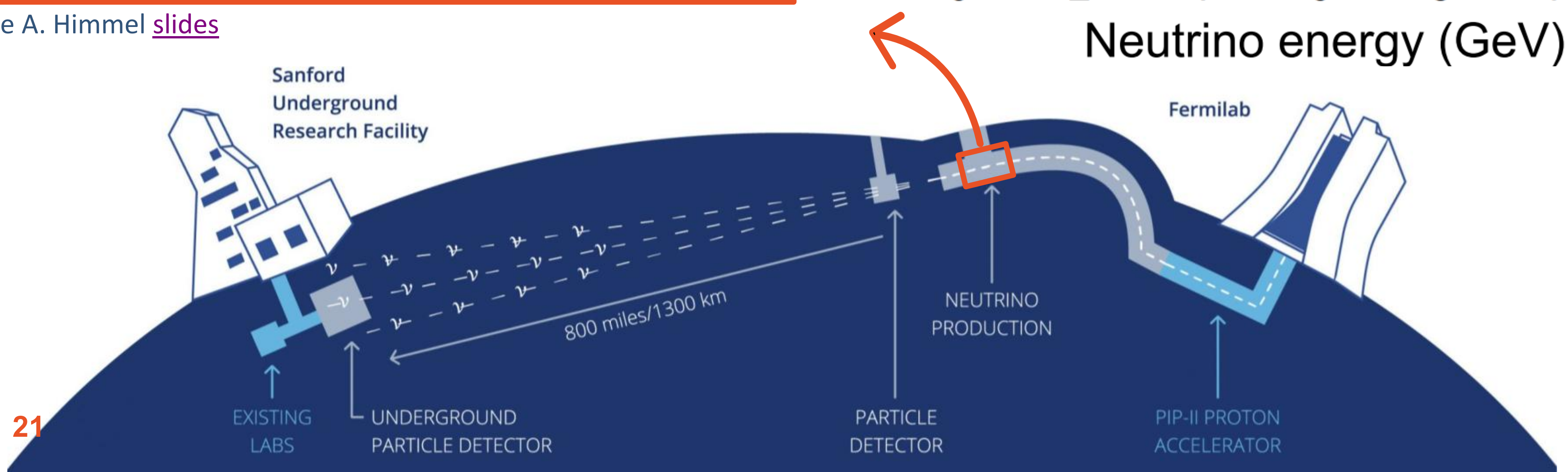
Neutrino beam source

- Powerful neutrino beam of **1.2 MW** (DUNE phase I) upgradable to **>2 MW** (DUNE phase II)
- Unique **broad band** beam covering **2 oscillation maxima**
- Note: High-energy tail above $\boldsymbol{\nu_\tau}$ **CC threshold**



See A. Himmel slides





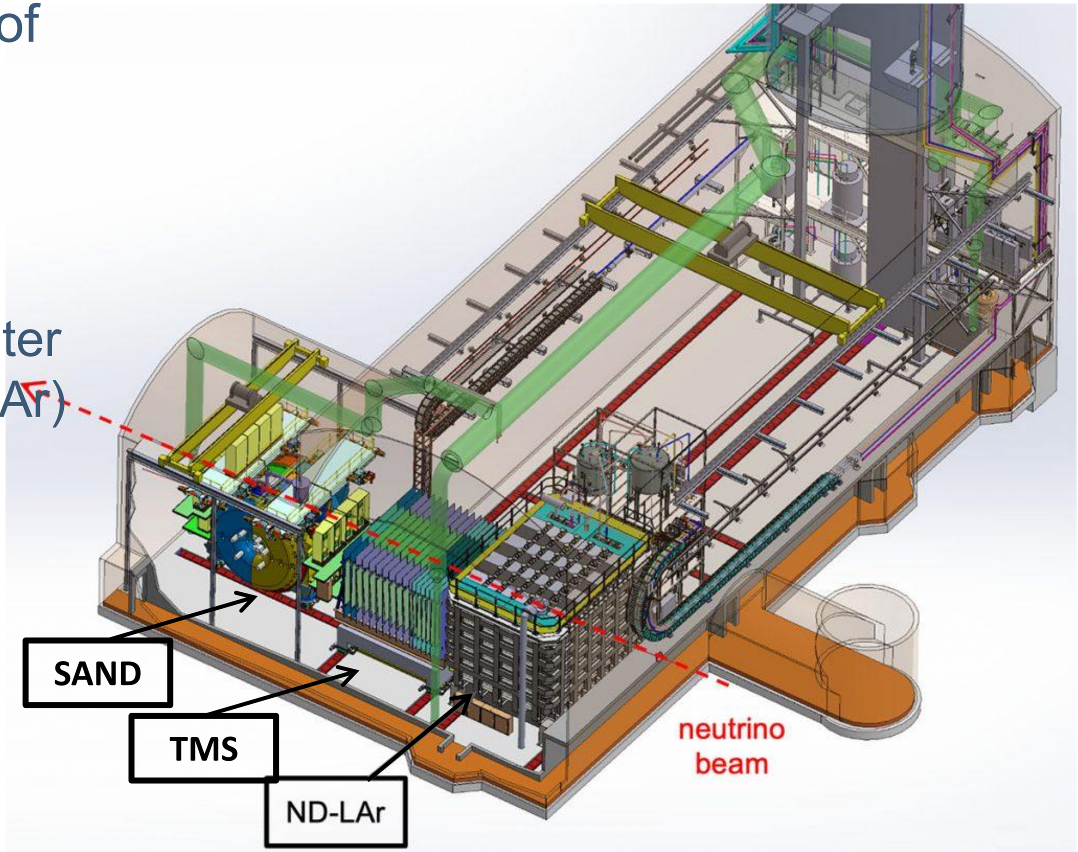
Near Detector complex design

- Characterize the flux close to the source, **constrains** systematic uncertainties (xsec, flux, …) and **predicts** the far detector flux

$$\text{rate} = \int \Phi_\nu^{\text{Near}} \; \sigma_\nu \; R \; dE$$

flux — xsec — detector effects

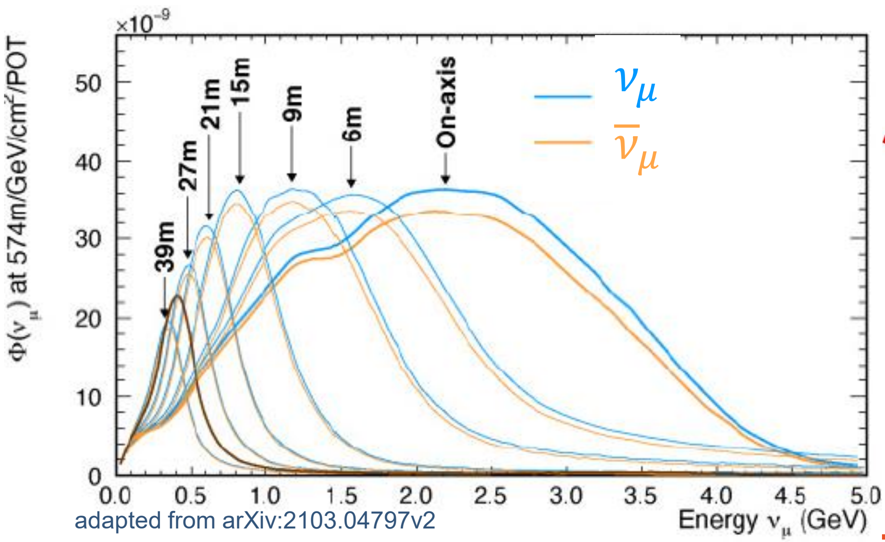
- Located 574 m downstream of neutrino beam source and includes three components:
  - **ND-LAr**: 67 t LArTPC
  - **TMS**: The Muon Spectrometer (many muons escape ND-LAr)
  - **SAND**: **S**ystem for on **A**xis **N**eutrino **D**etection, a multipurpose magnetized detector



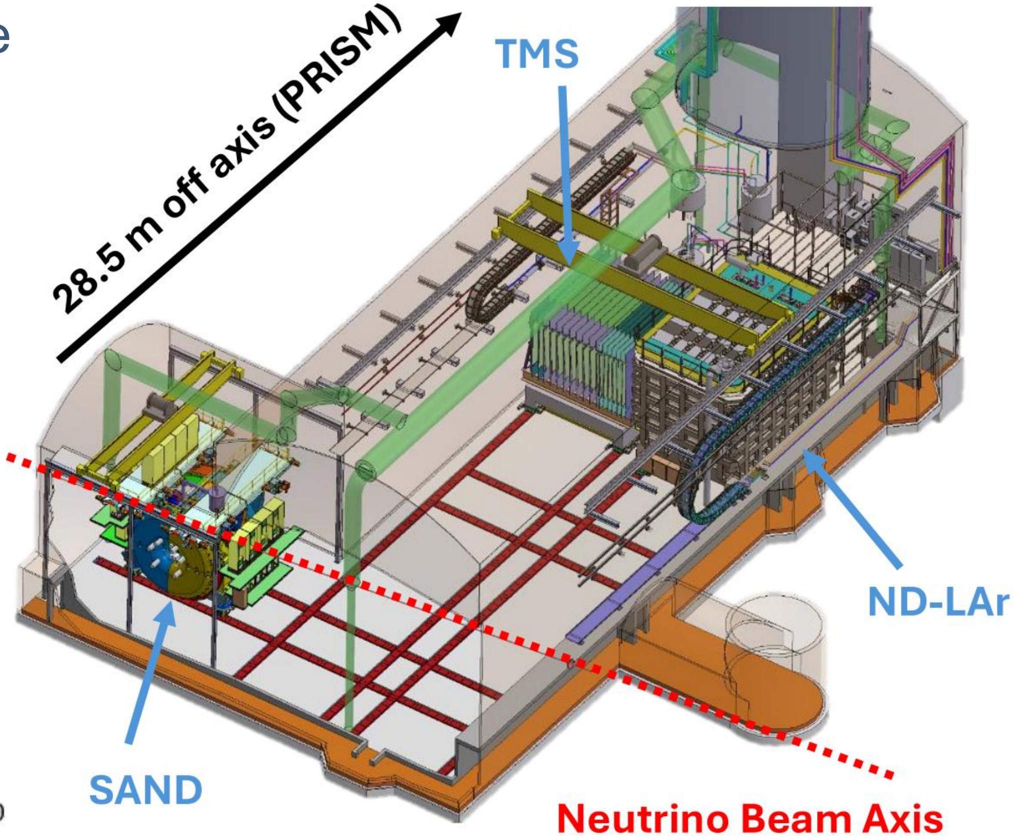
Constraining uncertainties

- NDLAr and TMS will jointly move off-axis to constrain systematic uncertainties
- The flux $\Phi_{\nu}^{\mathrm{Near}}$ varies with the distance from the beam axis due to pion decay kinematics, whereas the cross section σ_{ν} and the detector response R remain the same

$$\mathrm{rate} = \int \underbrace{\Phi_{\nu}^{\mathrm{Near}}}_{\text{flux}} \; \underbrace{\sigma_{\nu}}_{\text{xsec}} \; \underbrace{\mathrm{R}}_{\text{detector effects}} \, dE$$

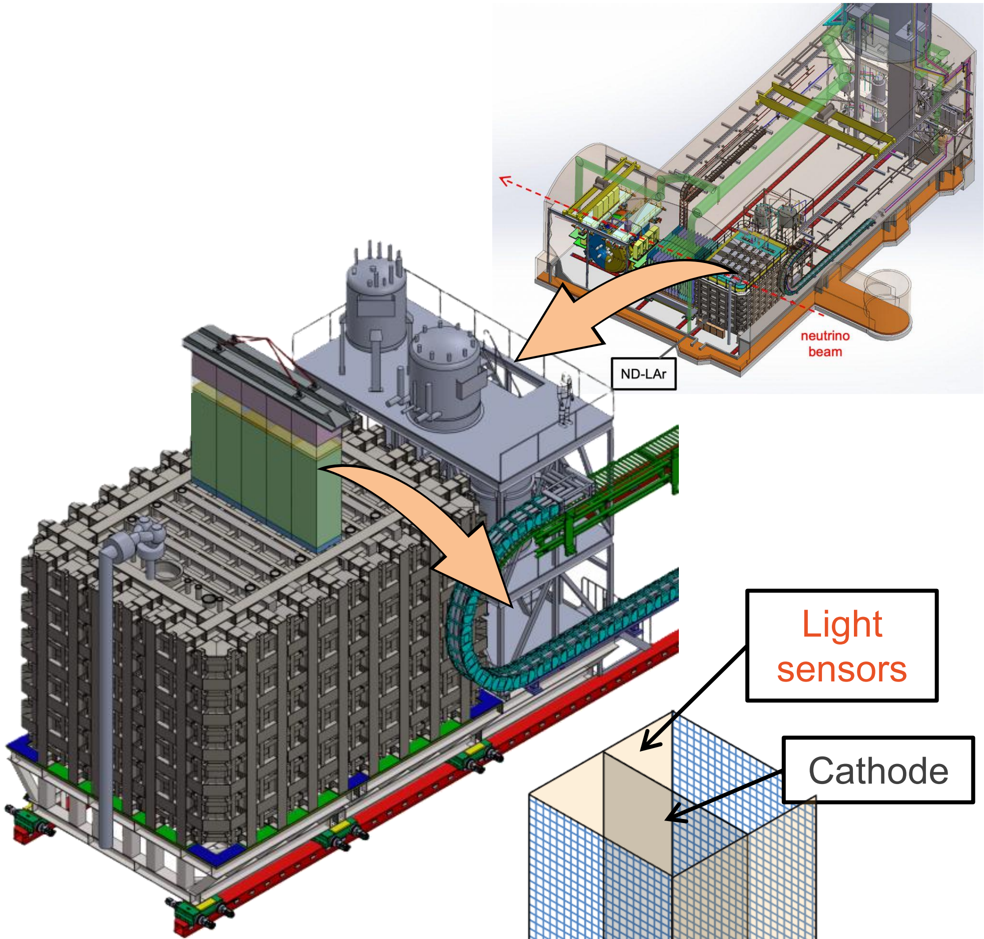


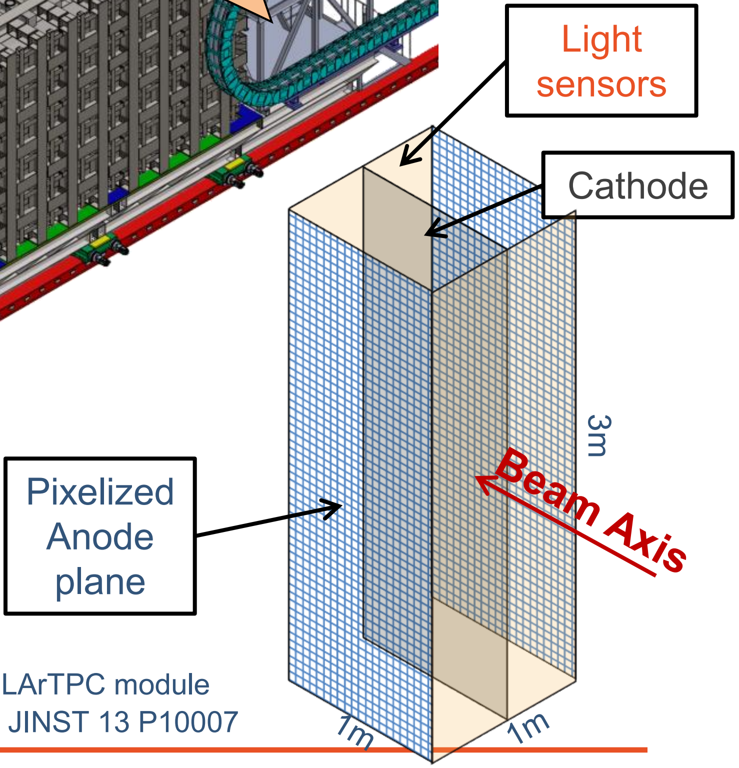
adapted from arXiv:2103.04797v2



LArTPC design

- The biggest challenge is to handle the event pileup: **O(100) neutrino interactions** (fiducial + surroundings) in a **10 μs** window (**spill**),
- **Traditional** TPCs are **slow** (up to milliseconds electron drift time) and have **wire-based readout** with too many hits on a single wire
- NDLAr will be **modular** with 35 separated 1×1×3 m^3 TPC (300 μs max drift time) with **pixelized** readout

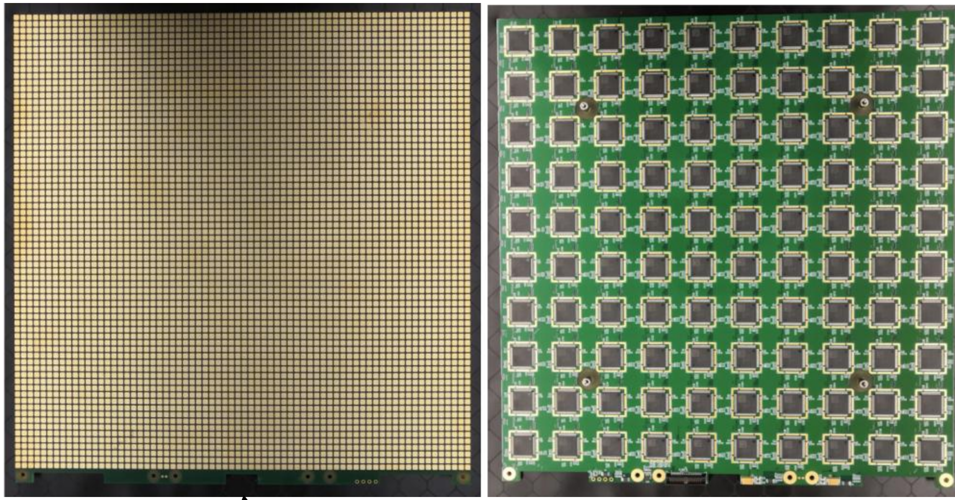




Cartoon of a single LArTPC module
LArPix Design Paper: JINST 13 P10007

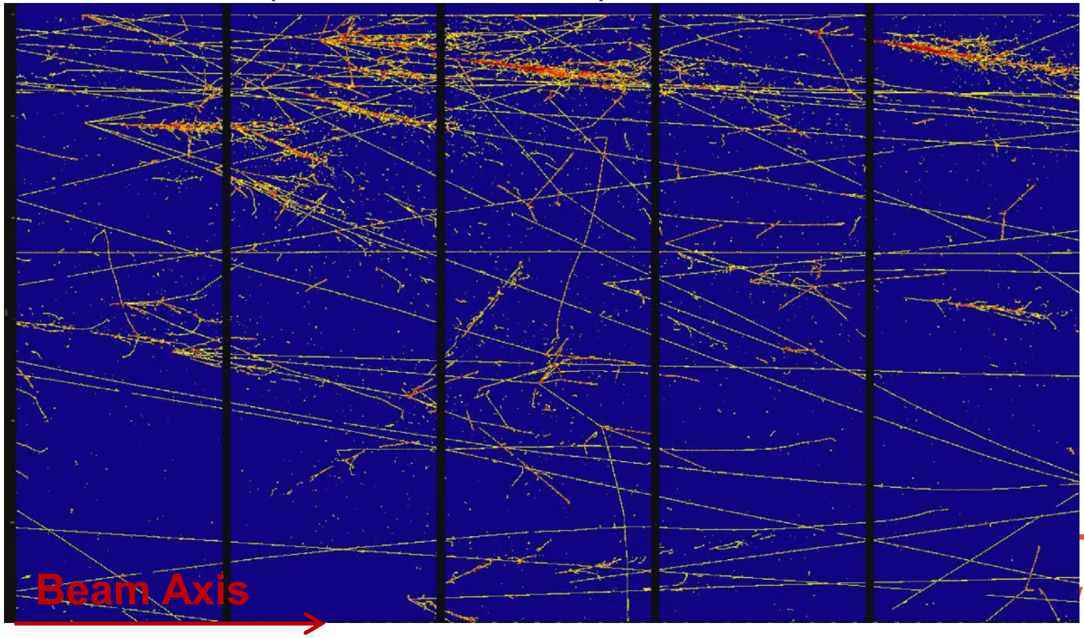
LArTPC design

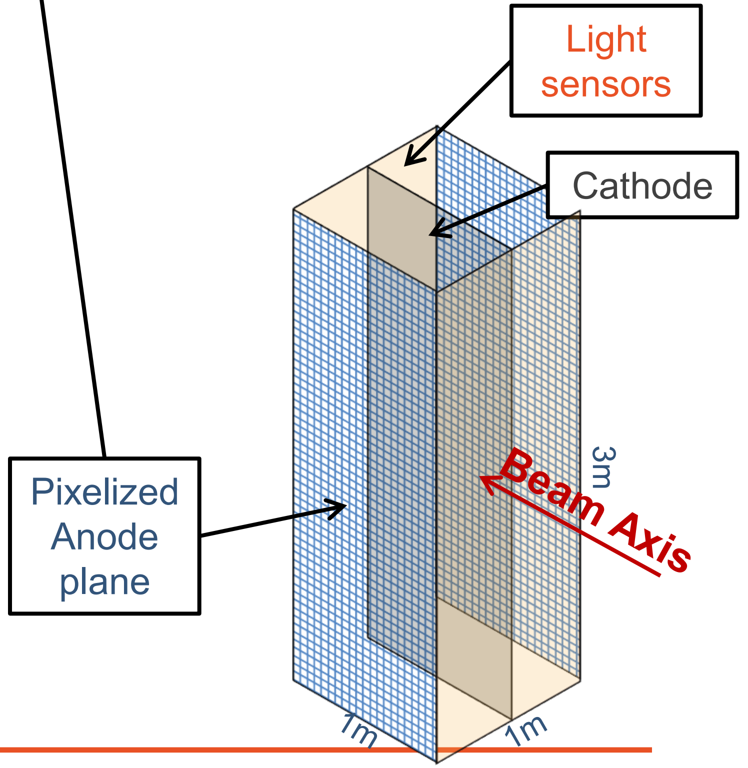
arXiv:2403.03212v1



- Right pic: Front and back of a TPC anode tile.The front contains 4,900 charge-sensitive pixels with 4.43 mm pitch that face the cathode, and the back contains a 10 ×10 array of LArPix ASICs

- Bottom pic: Simulation of tracks produced in one spill inside NDLAr. Black bands are gaps between modules (K. Wood slides)





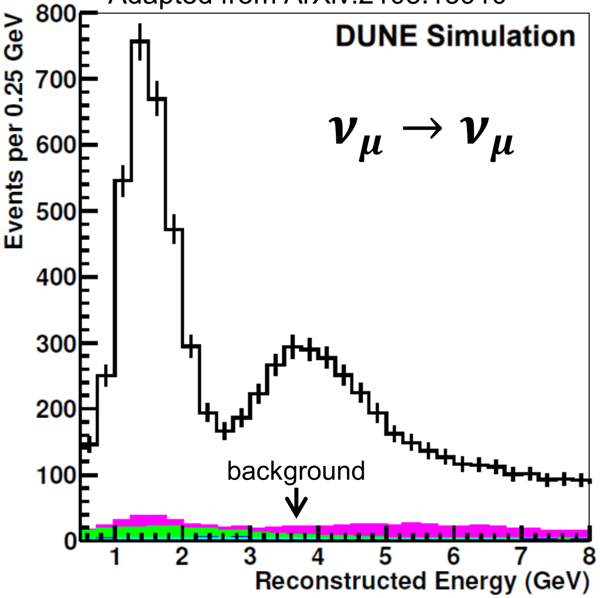
Far Detector

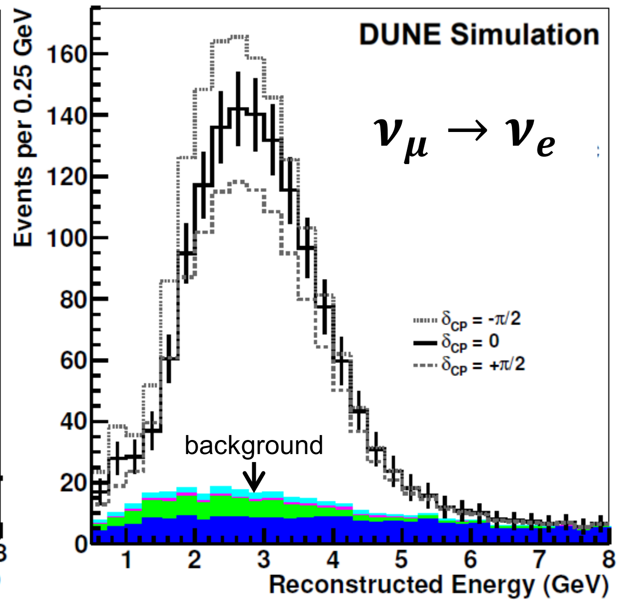
Oscillation probability

$$\text{rate} = \int \Phi^{Far}_{\nu_\mu/\nu_e} \; \sigma_\nu \; R \; \boxed{P^{osc}} \, dE$$

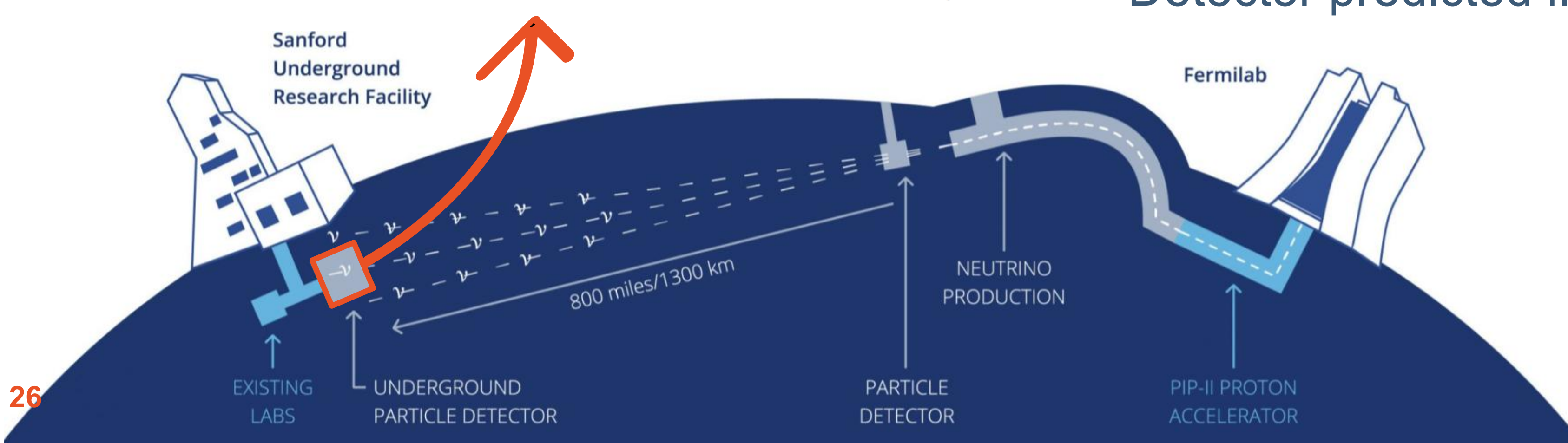
flux — xsec — detector effects

Adapted from ArXiv:2103.13910



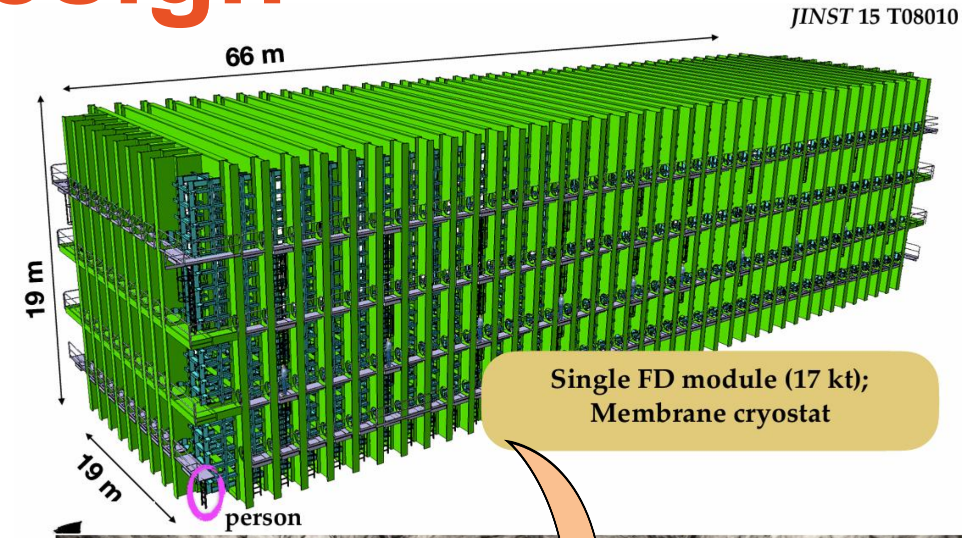


- The Far Detector (FD) measures the $\nu_\mu(\overline{\nu}_\mu)$ disappearance and the $\nu_e(\overline{\nu}_e)$ appearance over a **wide range of energy** using **multi-kiloton LArTPCs**
- Repeat the measurement with **antineutrino beam**!
- Compare with Near Detector predicted flux



Far Detector design

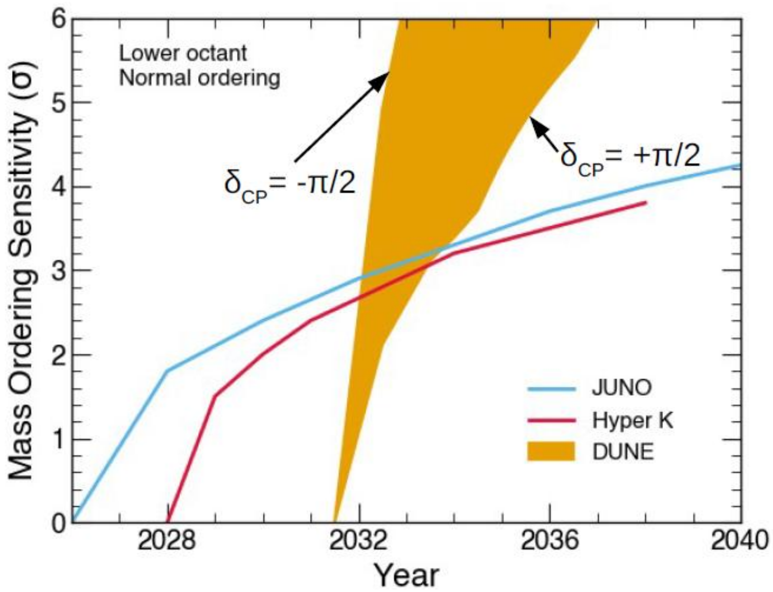
- The largest LArTPC ever to be built
- DUNE will start with **2 FD modules** (DUNE Phase I), each **17 kt** total mass 1 mile underground with different configuration:
  - **Horizontal** drift (3.5 m), **wire readout** (5 mm wire spacing) providing high granularity
  - **Vertical** drift (6.5 m)
- The final FD design foresees **four** modules (DUNE Phase II)

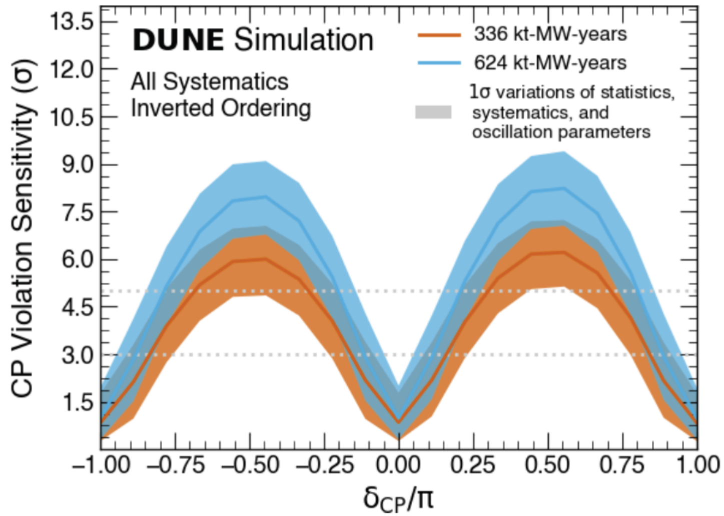


DUNE Far Detector cavern, Lead (South Dakota), that will host two of the four modules

DUNE sensitivity

- DUNE can determine the mass ordering to 5σ within 5 years **for any value of δ_{CP}**
- In the long term, DUNE can
  - establish CP violation over 75% of δ_{CP} values at >3σ
  - Measure δ_{CP} with 10 degrees precision
- DUNE will also **reach current sensitivity** on mixing angles being very well measured by **reactors** (θ_{13})

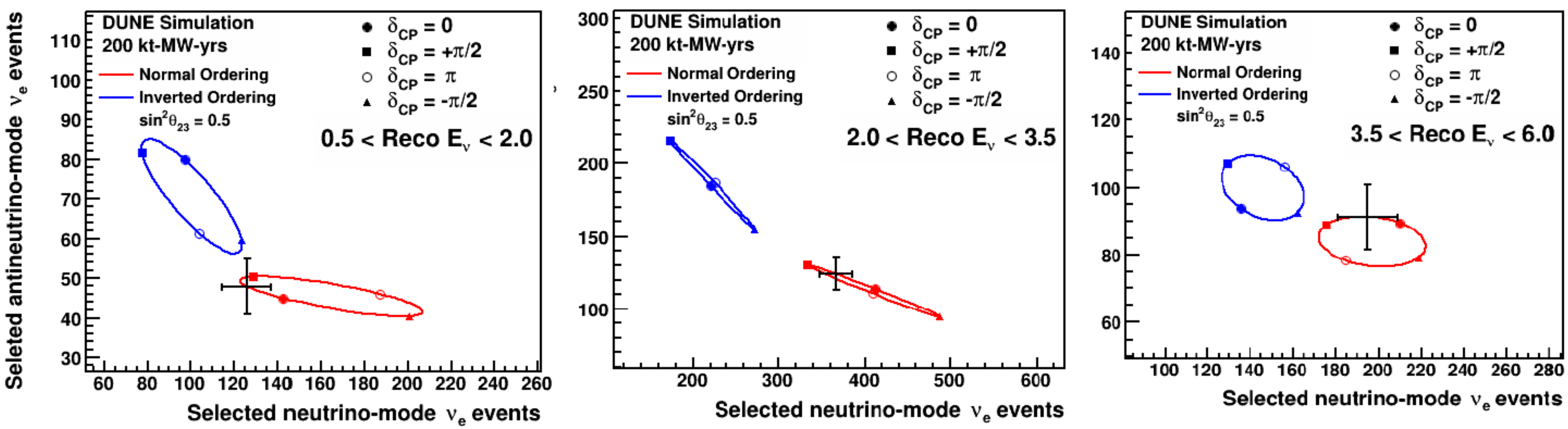




Plots from C. Marshall, Fermilab Colloquium (Indico here)

Testing the three-ν paradigm

- Bi-events plot: count ν_e and $\overline{\nu}_e$ in appearance at the far detector and compare against predicted counts for a given set of oscillation parameters
  - Because of the **long baseline**, the matter effect is **not degenerate with** the (possible) **CP** violation effect
  - Broad band beam: bi-events plot as function of L/E
- Test the consistency of data with the 3-flavor oscillation hypothesis across different energy bins



Supernova physics at DUNE FD

- DUNE FD is sensitive to ν_e from supernova burst (**neutronization phase**) through the dominant CC interaction:

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

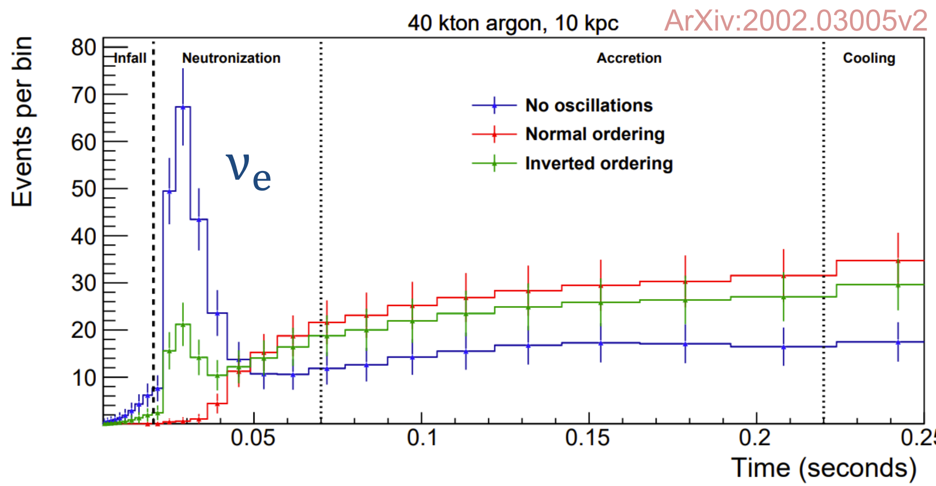
- About 5° pointing resolution on supernova location using

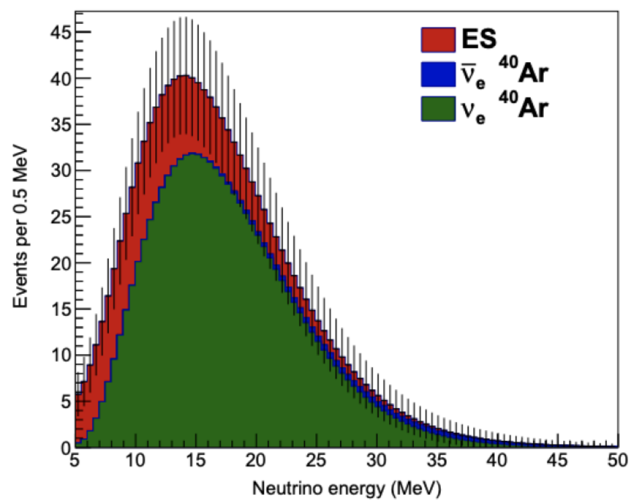
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- **Complementary** measurements to others experiments

Exp.	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

1. SK Coll Astropart.Phys. 81 (2016)
2. Lu, Li & Zhou Phys.Rev.D 94 (2016)





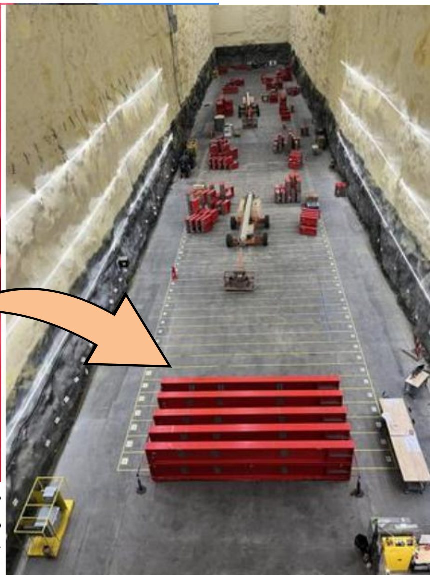
Expected ν_e rate for 10 kpc distant supernova assuming “Garching model”

DUNE under construction

Lead, South Dakota. DUNE Far Detector cavern : 1 mile underground, the cavern is 475’ long, 90’ high, and 60’ wide The first detector will fill half of this cavern, and includes >6,000,000 lbs of steel

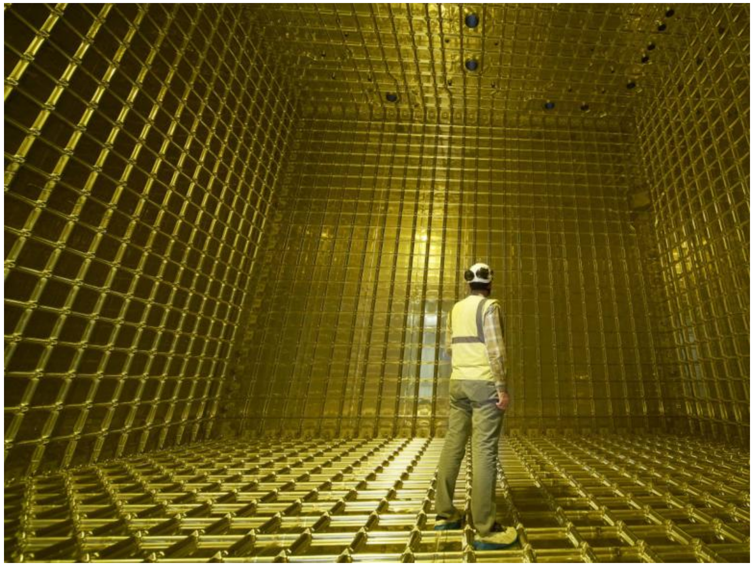
DUNE under construction

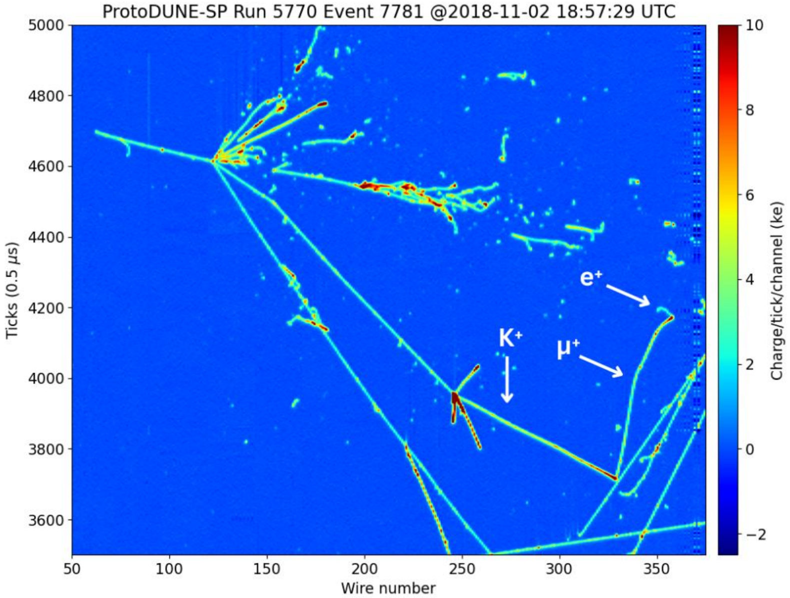
- DUNE Phase I:
  - Far Detectors 1 and 2 installation expected to be complete and starting to operate ~**2029**
  - Cryostats constructed at CERN, shipped to South Dakota → installation starting soon!
  - Physics in early **2030s**
- DUNE Phase II:
  - Far Detector Modules 3 and 4 within ~**5 years** from Phase I
  - Beam power upgrade



FD prototypes - ProtoDUNE

- DUNE is already doing science with its prototypes!
- ProtoDUNE program includes two 770 t (horizontal and vertical drift design) prototypes operating at **CERN** (Geneva)
  - Both designs are successfully operating under test beam → 13 papers! (Ar-π interactions, Xe doping in Ar, etc.)
- University of Toronto 🇨🇦 involved in data acquisition and physics study (ν_τ appearance, low energy etc.)





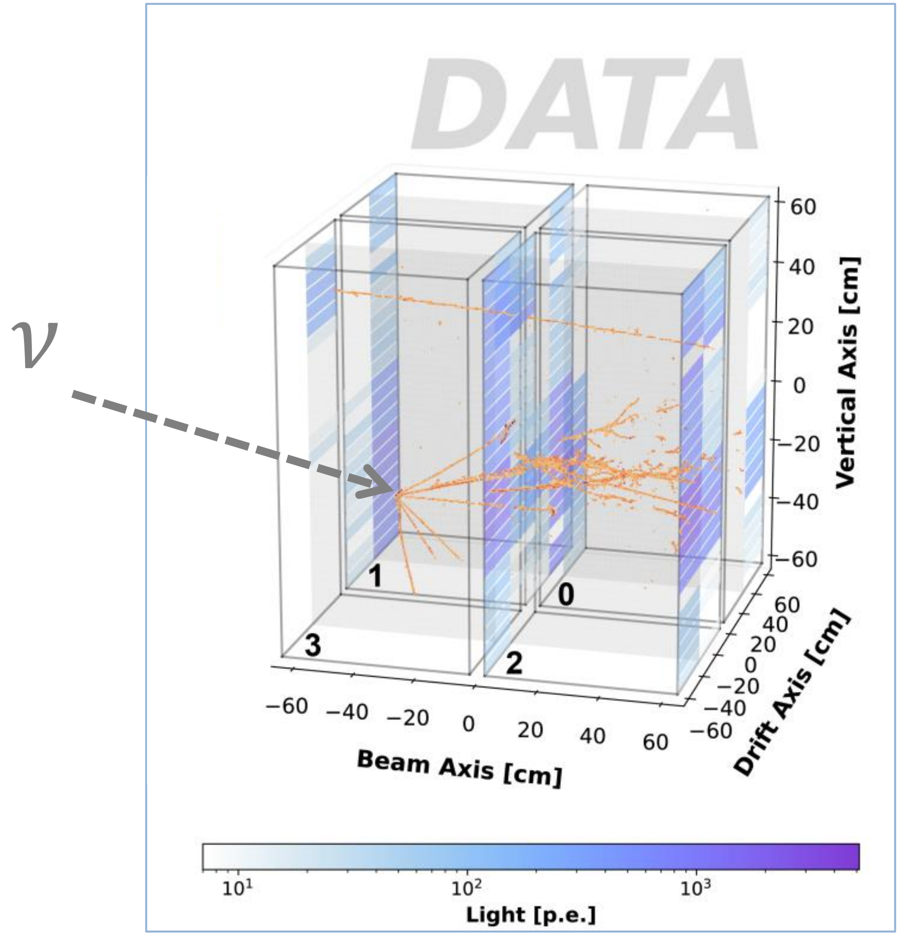
DUNE ND-LAr prototypes I

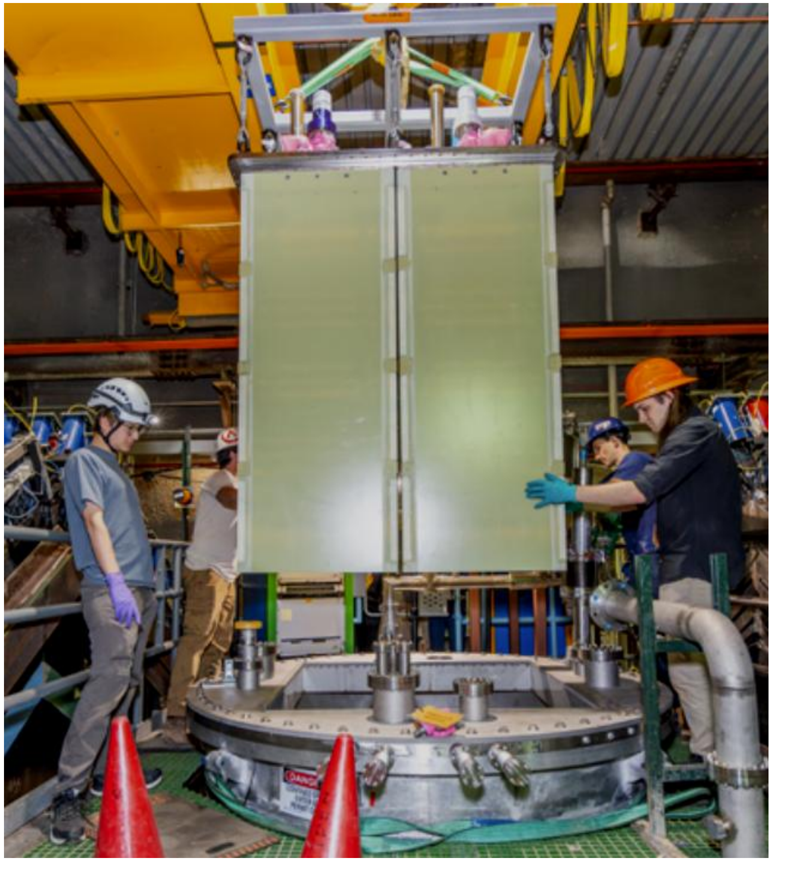
- **2x2 Demonstrator:** an array of four LArTPC modules (1,2x0,6x0.6 m^3) operating at Fermilab under neutrino beam (NuMI)
- In 2024 collected 30.000 neutrino events and over 100M cosmic ray events
- Upcoming neutrino beam run II this fall!
- YorkU 🇨🇦 directly involved in simulations, calibration, reconstruction and analysis
  - **Digital Research Alliance** resources support DUNE oscillation sensitivity analyses

Digital Research Alliance of Canada | Alliance de recherche numérique du Canada

YORK UNIVERSITÉ UNIVERSITY DUNE

DUNE ND-LAr prototypes I

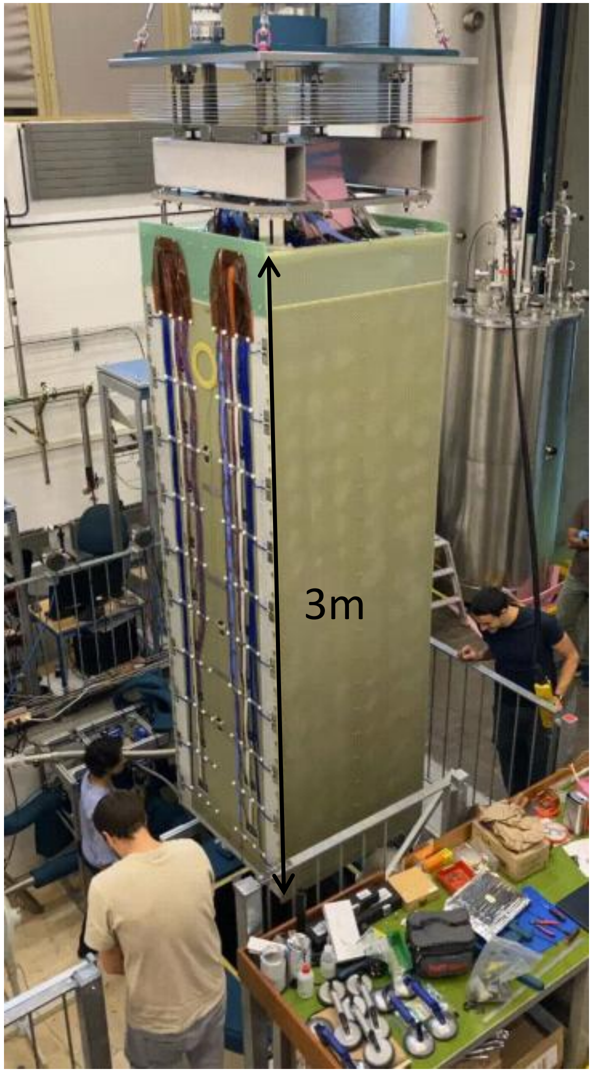




arXiv:2509.07012v1

DUNE ND-LAr prototypes II

- **F**ull **S**cale **D**emonstrator (FSD): a single ~2 t full scale TPC module operating at Bern
- Run successfully in summer 2024, collecting over 70M cosmic–ray events and data from F-18 radioactive source



More on prototypes: R. Diurba @ [NuFACT 2025]

Conclusions

Despite the enormous progress made since their discovery, many questions around neutrino remains unanswered:

- Are there neutrinos that we haven't discovered yet?
- What is the mass of neutrinos?
- Is the universe matter/antimatter asymmetry due to neutrino CP violation?

We want to answer these questions… are you joining us?

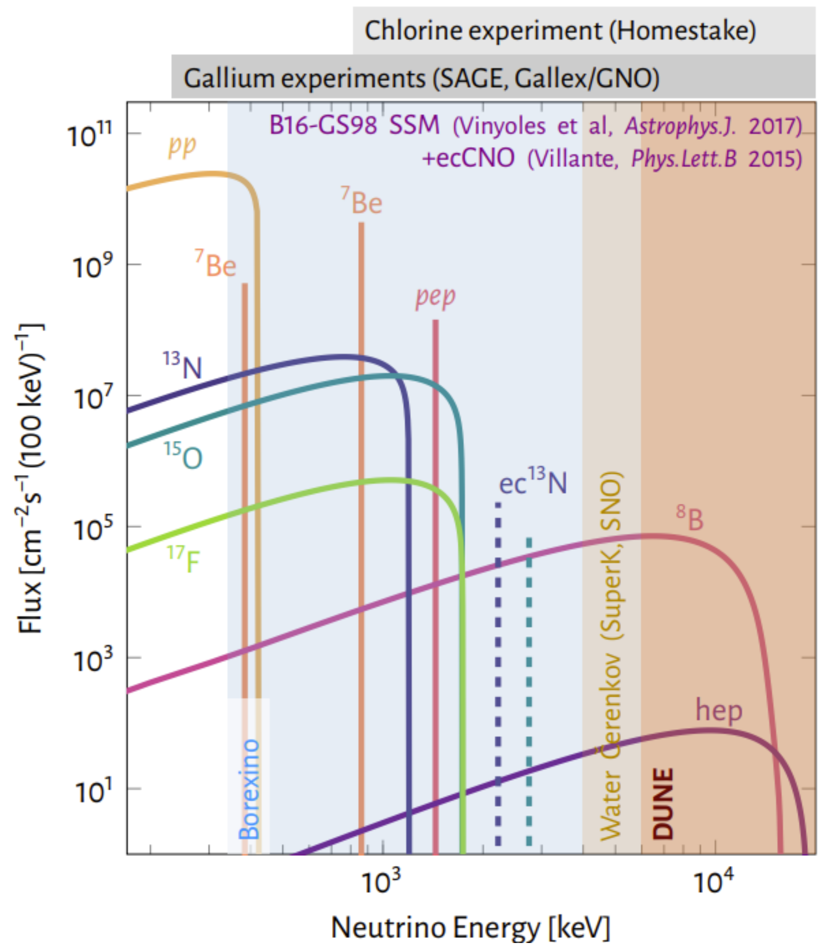
This document was prepared by DUNE using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Forward Discovery Group, LLC, acting under Contract No. 89243024CSC000002.

Backup


A Cryostat Beam Signing Event
to mark the start of installation phase
DUNE Collaboration Meeting, SURF, Lead, SD
May 22, 2026
25
6/17/2026

Solar neutrinos in DUNE FD

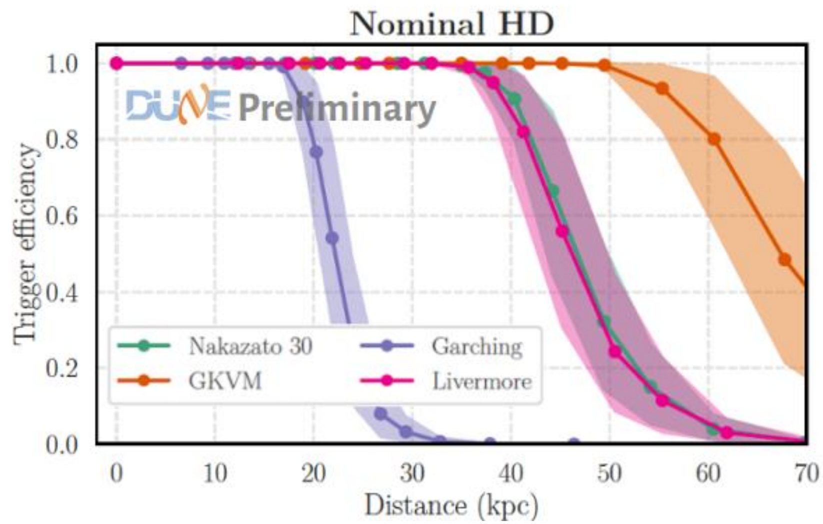
- DUNE FD will have sensitivity to *hep* neutrinos flux with energy above ~ 10 MeV
- Control of background is crucial:
  - Most challenging backgrounds are **fast neutrons** from cavern and **gammas** from neutron activation in rock, that extend well beyond 5 MeV
- Passive shielding would help to reduce the background (studies ongoing)



Supernova trigger efficiency

DUNE Coll, Eur.Phys.J.C 81 (2021) 5, 423

- The general strategy will be to record data from all channels over a **30-100 second** period around every trigger
- A real-time algorithm should provide **trigger primitives** by searching for photomultiplier hits and **optical clusters**, where the latter combines several hits together based on their time/spatial information
- 1/month false trigger rate
- During the first 50 ms of a 10-kpc-distant supernova, the mean interval between successive neutrino interactions is 0.5−1.7 ms depending on the model. The TPC alone provides a time resolution of 0.6 ms



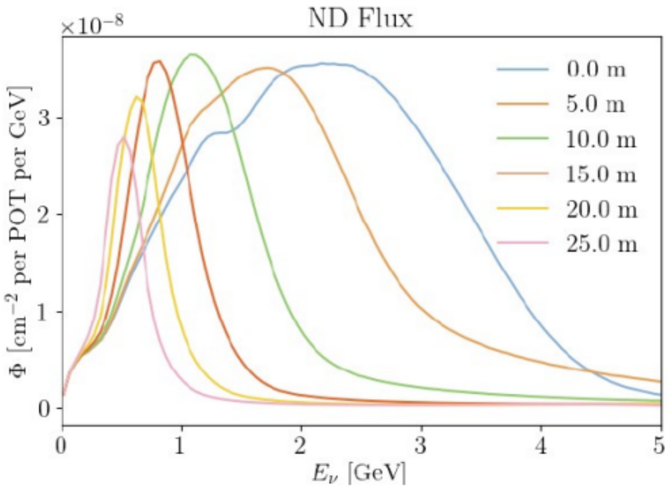
Trigger system:

- Trigger can use both TPC and PDS information, exploiting signal coincidences over the SNB timescale
- Aims at 95% efficiency @ 20 kpc
- 1/month false trigger rate

Preliminary results for PDS-only trigger:

- Trigger primitives made of PDS hits + clusters based on space-time information
- >90% efficiency on a SNB at $\lesssim$ 20 kpc (Milky Way edge)

PRISM: how and why it works (4)



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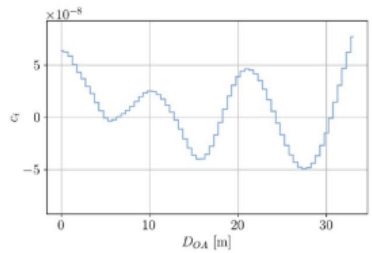

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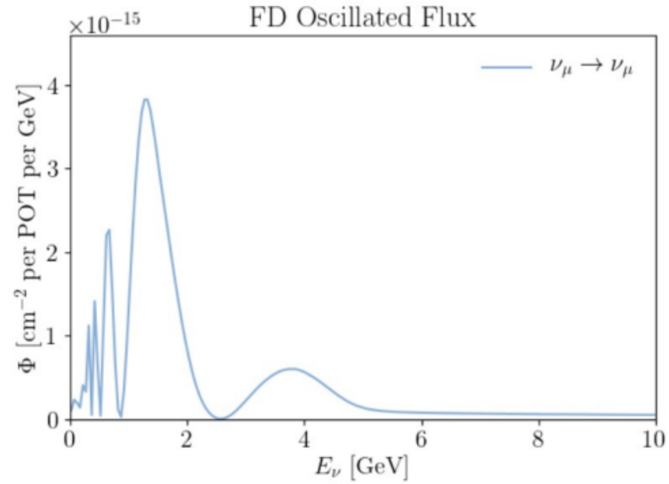
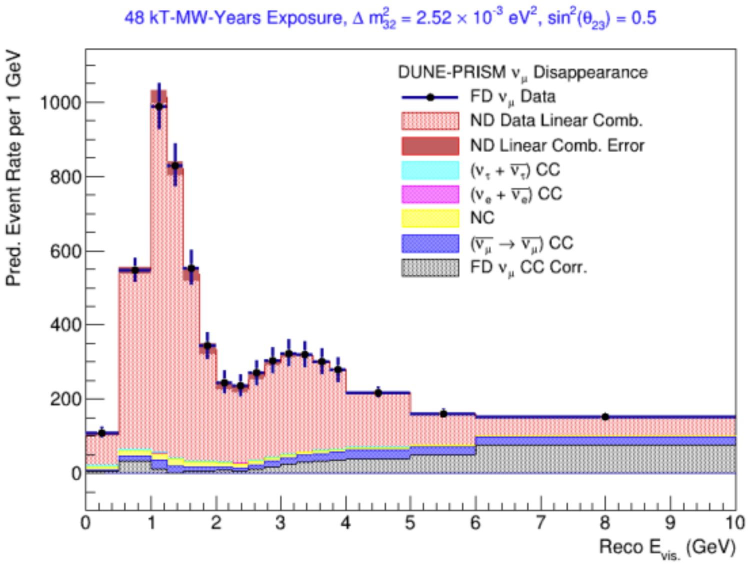
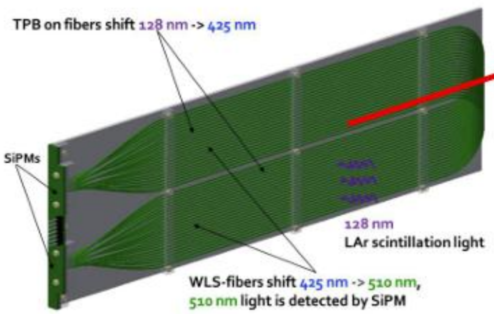


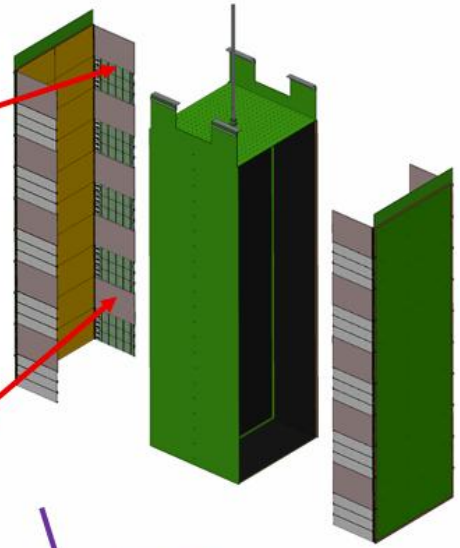


- Direct, data-to-data analysis
- To leading order, no dependence on cross section model
  - Second-order dependence due to backgrounds, acceptance corrections, etc.
  - Improved modeling can still improve sensitivity

Light readout

LCM optical fibre detector





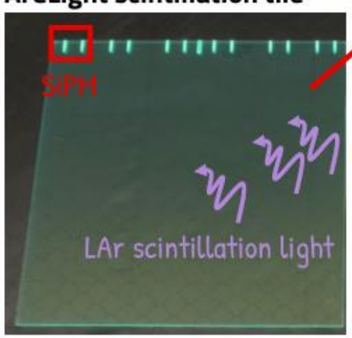
Complementary light readout system alongside the charge readout:

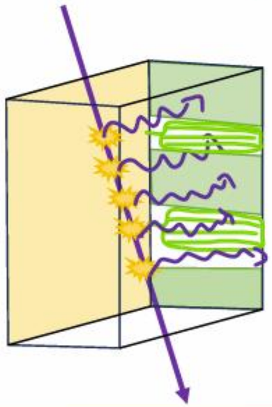
- **LCM** for **detection efficiency**
- **ArCLight** for **position sensitivity**

Optimized for UV Ar scintillation light

Allow to give the t0 of « an event » to get a 3D positioning and help reducing the pile up.

ArCLight scintillation tile





Charged particle excite Ar.
Fast scintillation light signal **O(1 µs)** is recorded by two different light readout system.

Testing DUNE's Near Detector Strategy

9

- Noe Roy's talk @ CAP2025

Why LAr TPCs?

- Scalable: we need a massive detector being the neutrino cross-section extremely small
- Provides both neutrino interaction time and space information
- Liquid Argon
  - High **electron mobility**
  - Possibility of high **purification** (<50 ppt for a 2.5 m drift) → electrons can reach the readout plane before being absorbed
  - **High** electron-ion pairs **yield** → more signal
  - **Transparent** to its own radiation (Nitrogen < 1 ppm) → we can see the light signal
  - reasonably **cheap**

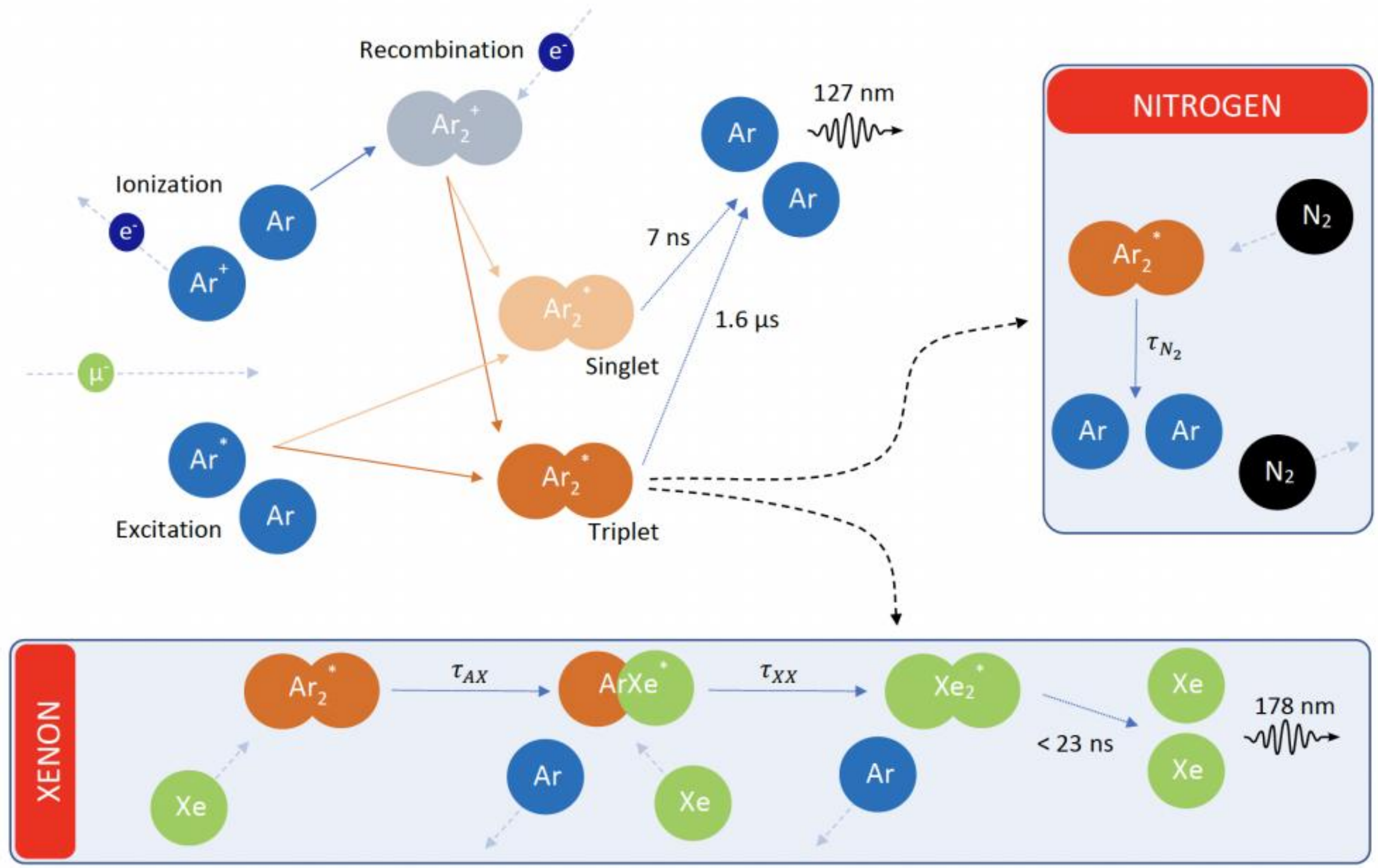
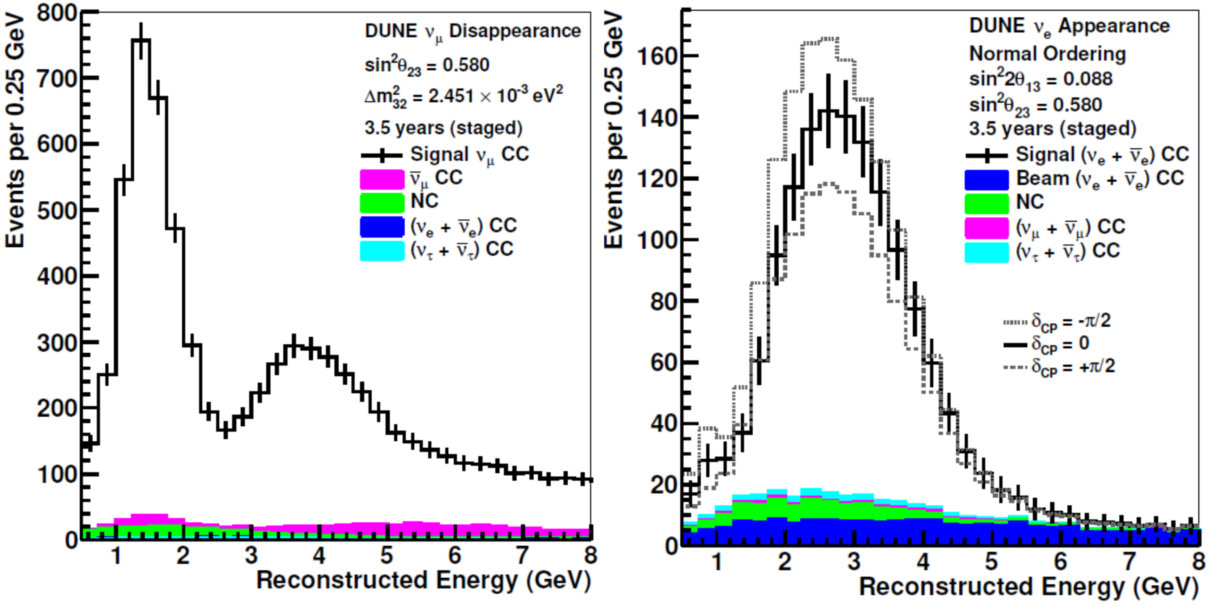


Figure 1. Schematic representation of the production process of scintillation light in pure liquid argon, and the way it is affected by xenon doping and nitrogen quenching. The time constants of the non-radiative energy-transfer processes τ_{AX} and τ_{XX} depend on the xenon concentration in LAr.

- [2024 JINST 19 P08005]()


DUNE ν_μ Disappearance
$\sin^2\theta_{23} = 0.580$
$\Delta m^2_{32} = 2.451 \times 10^{-3}\ eV^2$
3.5 years (staged)
Signal ν_μ CC
$\bar{\nu}_\mu$ CC
NC
$(\nu_e + \bar{\nu}_e)$ CC
$(\nu_\tau + \bar{\nu}_\tau)$ CC
Events per 0.25 GeV
Reconstructed Energy (GeV)
DUNE ν_e Appearance
Normal Ordering
$\sin^2 2\theta_{13} = 0.088$
$\sin^2\theta_{23} = 0.580$
3.5 years (staged)
Signal $(\nu_e + \bar{\nu}_e)$ CC
Beam $(\nu_e + \bar{\nu}_e)$ CC
NC
$(\nu_\mu + \bar{\nu}_\mu)$ CC
$(\nu_\tau + \bar{\nu}_\tau)$ CC
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = +\pi/2$
Events per 0.25 GeV
Reconstructed Energy (GeV)