The Deep Underground Neutrino Experiment

*Current **status** and **physics potential***

Maria Brigida Brunetti on behalf of the DUNE Collaboration

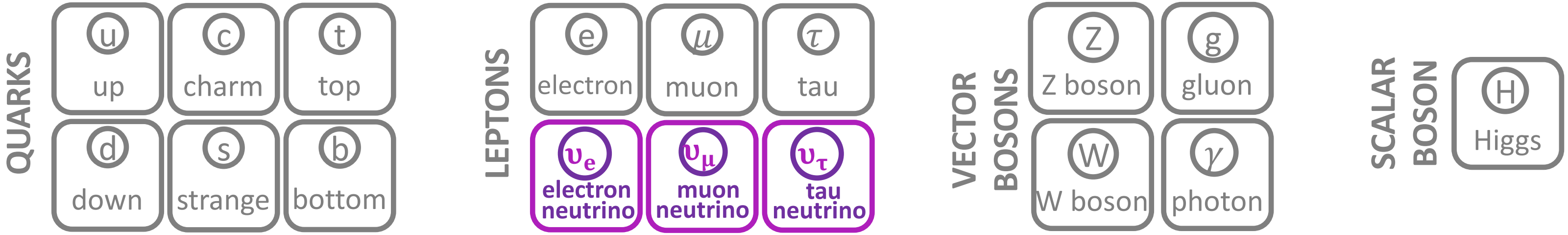
30 March 2023 / International Conference on the Physics of the two Infinities / Kyoto

DUNE

WARWICK
THE UNIVERSITY OF WARWICK

Neutrinos: what we know

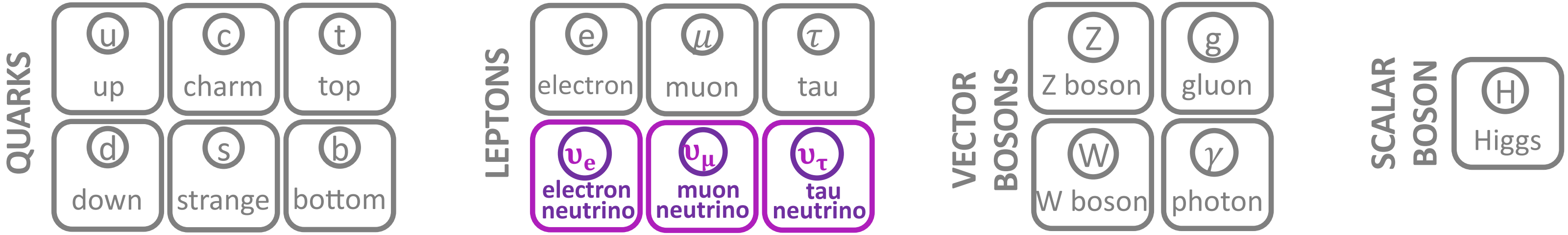
- Three flavours weakly interacting neutral leptons (+ their antiparticles)



- They are massless in the Standard Model

Neutrinos: what we know

- Three flavours weakly interacting neutral leptons (+ their antiparticles)



- They are massless in the Standard Model

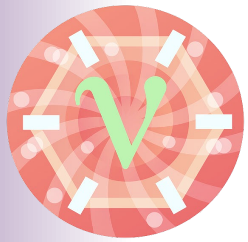
They come from different sources and their energies span 16 orders of magnitude

arxiv:1207.4952

Human-made:

Accelerators

Reactors



From space:

Supernovae

Cosmic sources

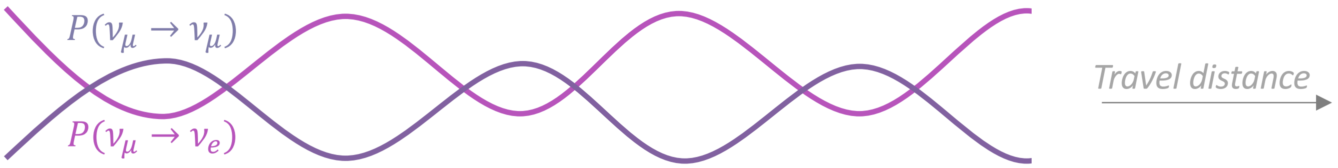
The Sun

The Atmosphere

Artworks by Sandbox Studio, Chicago with Ana Kova

Neutrinos: what we know (2)

- We know they have mass because they *oscillate*



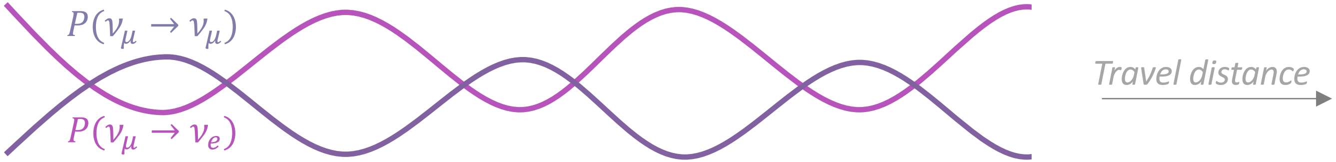
Neutrino Oscillations

- First predicted in 1957 (Pontecorvo)
- Solar neutrino problem (Davis/Bahcall) in 1968
- First evidence of neutrino oscillation (Super-Kamiokande) in 1998

$\nu, \bar{\nu}$ oscillation in solar, atmospheric, reactor, accelerator neutrinos

Neutrinos: what we know (2)

- We know they have mass because they *oscillate*



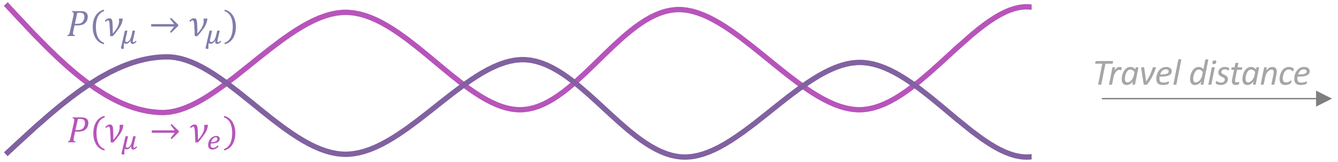
- Oscillations due to *mixing* (as quark sector):
  - Interact as flavour states
  - Propagate as mass states
  - Mass states $\neq$ flavour states

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

flavour PMNS matrix **mass**

Neutrinos: what we know (2)

- We know they have mass because they *oscillate*



Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ One complex CP-violating phase δ_{CP}

$$\begin{pmatrix} \cos\theta_{12}\cos\theta_{13} & \sin\theta_{12}\cos\theta_{13} & \sin\theta_{13}e^{-i\delta_{CP}} \\ -\sin\theta_{12}\cos\theta_{23} - \cos\theta_{12}\sin\theta_{13}\sin\theta_{23}e^{i\delta_{CP}} & \cos\theta_{12}\cos\theta_{23} - \sin\theta_{12}\sin\theta_{13}\sin\theta_{23}e^{i\delta_{CP}} & \cos\theta_{13}\sin\theta_{23} \\ \sin\theta_{12}\sin\theta_{23} - \cos\theta_{12}\sin\theta_{13}\cos\theta_{23}e^{i\delta_{CP}} & -\cos\theta_{12}\sin\theta_{23} - \sin\theta_{12}\sin\theta_{13}\cos\theta_{23}e^{i\delta_{CP}} & \cos\theta_{13}\cos\theta_{23} \end{pmatrix}$$

PMNS matrix

Neutrinos: what we know (3)

Interplay between neutrino energy and travel distance →
different experiments sensitivity to oscillation and mixing parameters

2-flavour appearance probability

PHYSICS

$$P_{\nu_\alpha \to \nu_\beta}(\mathrm{L,E}) = \sin^2 2\theta \sin^2\left(1.27\,\frac{\Delta m^2(\mathrm{eV}^2)\mathrm{L(km)}}{\mathrm{E(GeV)}}\right)$$

EXPERIMENT

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

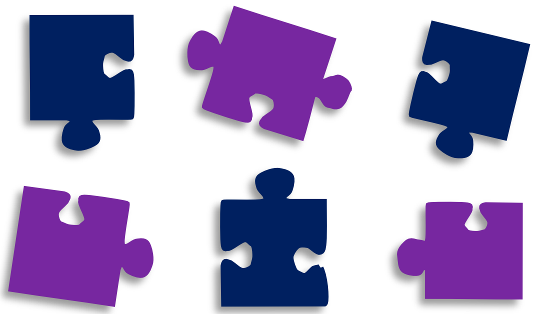
Experiments contributing to present determination oscillation parameters - RPP2020

Neutrinos: what we don’t know

Precise determination of mass differences and mixing parameters

What are their masses?

What is their mass ordering?



Are they their own antiparticle?

Are there *sterile* neutrinos?

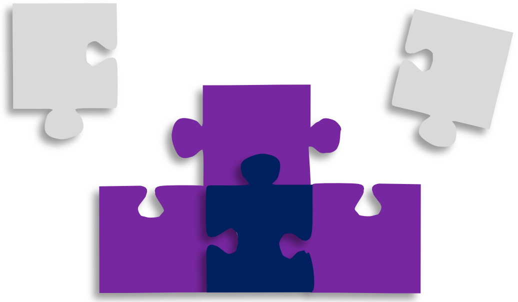
Can they explain matter/antimatter asymmetry?

Neutrino Oscillation Experiments

Precise determination of mass differences and mixing parameters

What are their masses?

Are they their own antiparticle?



What is their mass ordering?

Are there *sterile* neutrinos?

Can they explain matter/antimatter asymmetry?

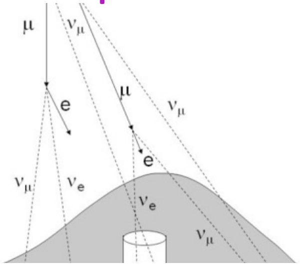
Accelerator Neutrino Oscillation Experiments

- Can design a multi-purpose neutrino experiment by combining
  1. An intense neutrino beam
  2. A baseline tuned for sensitivity to mixing/oscillation parameters
  3. Large scale, cutting edge detector technology

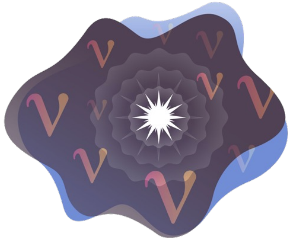
- Sensitivity to neutrinos from additional sources, e.g.:

Accelerators

The atmosphere



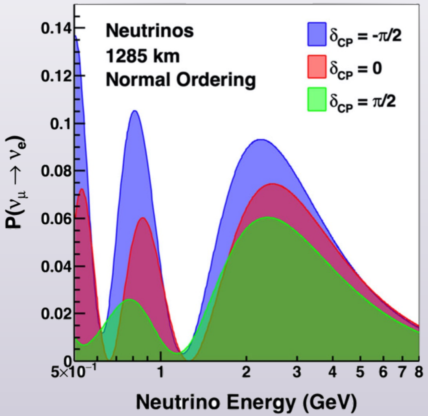
Outer space

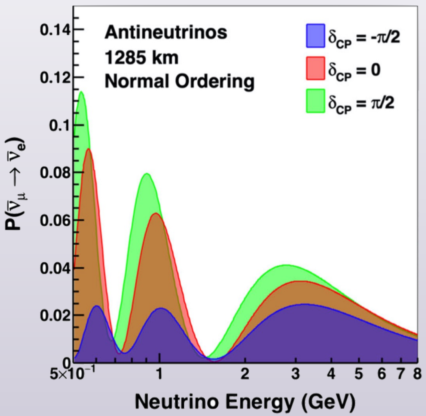


Artworks by Sandbox Studio, Chicago with Ana Kova

DUNE’s approach

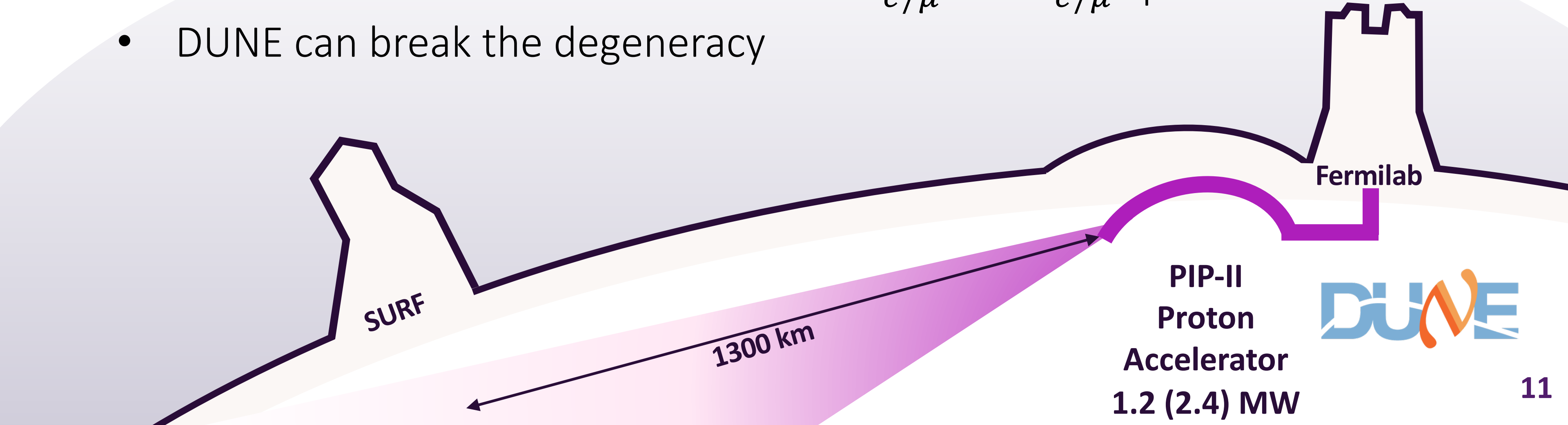
- δCP and matter effects impact ν and $\bar{\nu}$ oscillation probabilities differently
- A long baseline and a high intensity wide band neutrino beam maximise sensitivity to CP violation and mass ordering
  - δCP and matter both affect observed $\nu_{e/\mu}$ and $\bar{\nu}_{e/\mu}$ spectra
  - DUNE can break the degeneracy





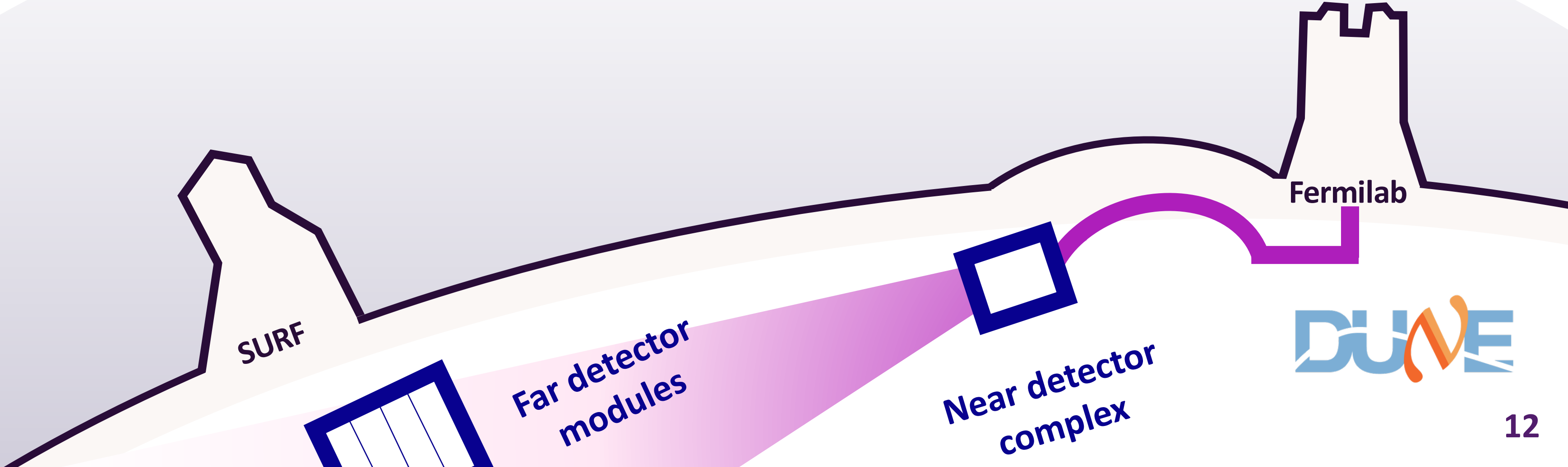
DUNE's approach (2)

- δCP and matter effects impact ν and $\bar{\nu}$ oscillation probabilities differently
- A long baseline and a high intensity wide band neutrino beam maximise sensitivity to CP violation and mass ordering
  - δCP and matter both affect observed $\nu_{e/\mu}$ and $\bar{\nu}_{e/\mu}$ spectra
  - DUNE can break the degeneracy



DUNE's approach (3)

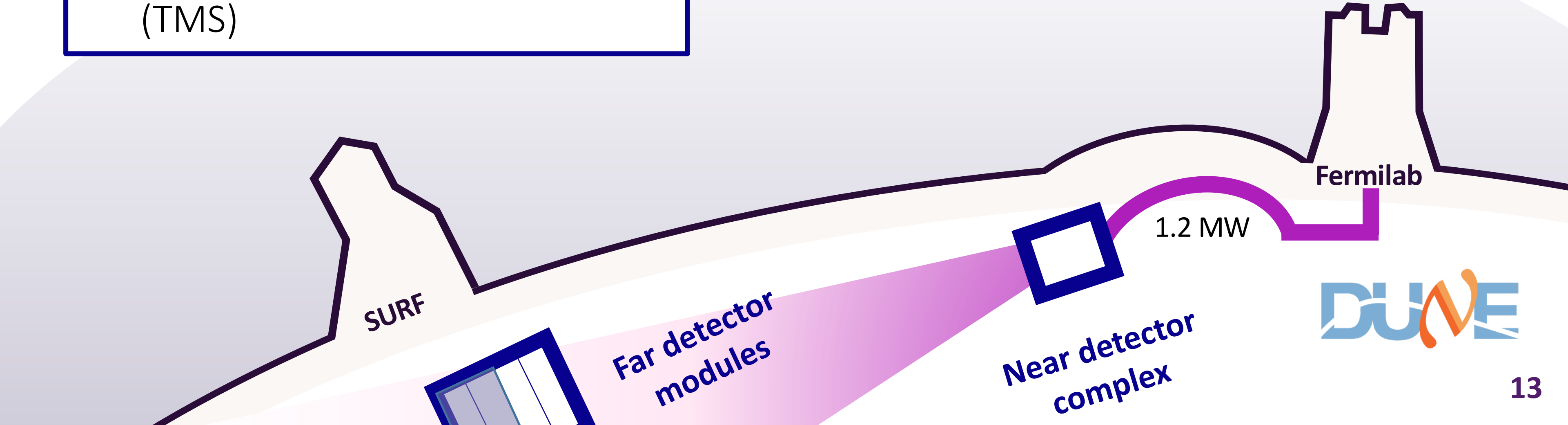
- Characterise $\nu_\mu/\overline{\nu_\mu}$ source, measure flux with sophisticated *near detector*
- Look for $\nu_\mu/\overline{\nu_\mu}$ disappearance and $\nu_e/\overline{\nu_e}$ appearance at a *far detector*
  Four Large (17 kton) detectors
- 1.5 km underground site to suppress cosmic ray muon background



A phased approach

PHASE I

- Two Far Detector modules
- 1.2 MW proton beam
- Three near detectors including temporary muon spectrometer (TMS)



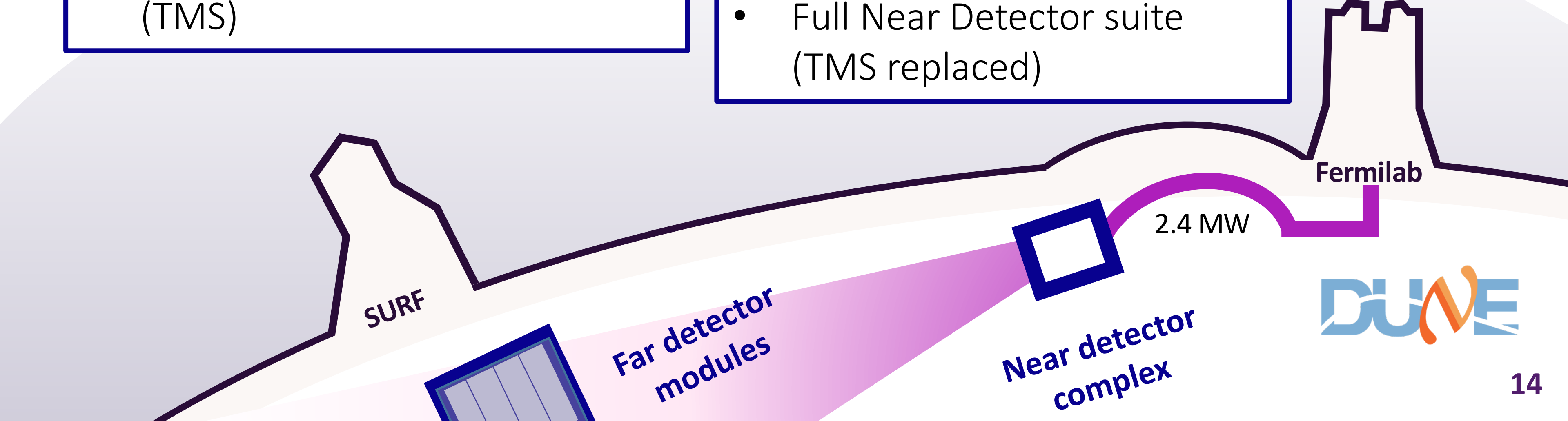
A phased approach

PHASE I

- Two Far Detector modules
- 1.2 MW proton beam
- Three near detectors including temporary muon spectrometer (TMS)

PHASE II

- Four Far Detector modules
- 2.4 MW proton beam upgrade (**most intense neutrino beam in the world**)
- Full Near Detector suite (TMS replaced)

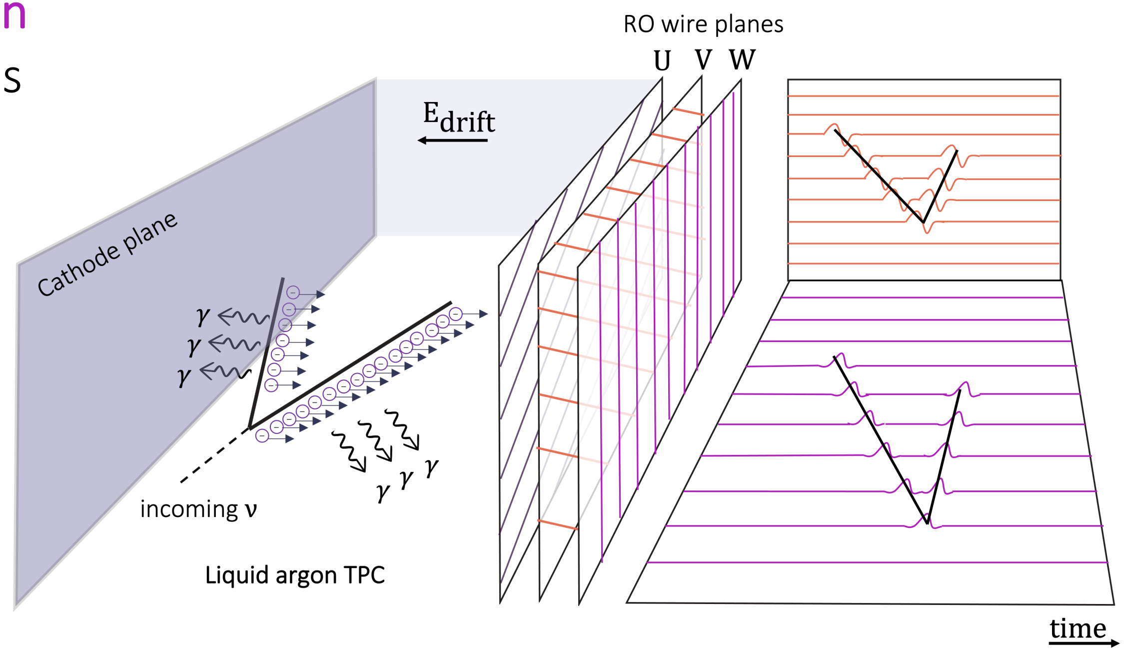


Liquid Argon Time Projection Chamber (LArTPC)

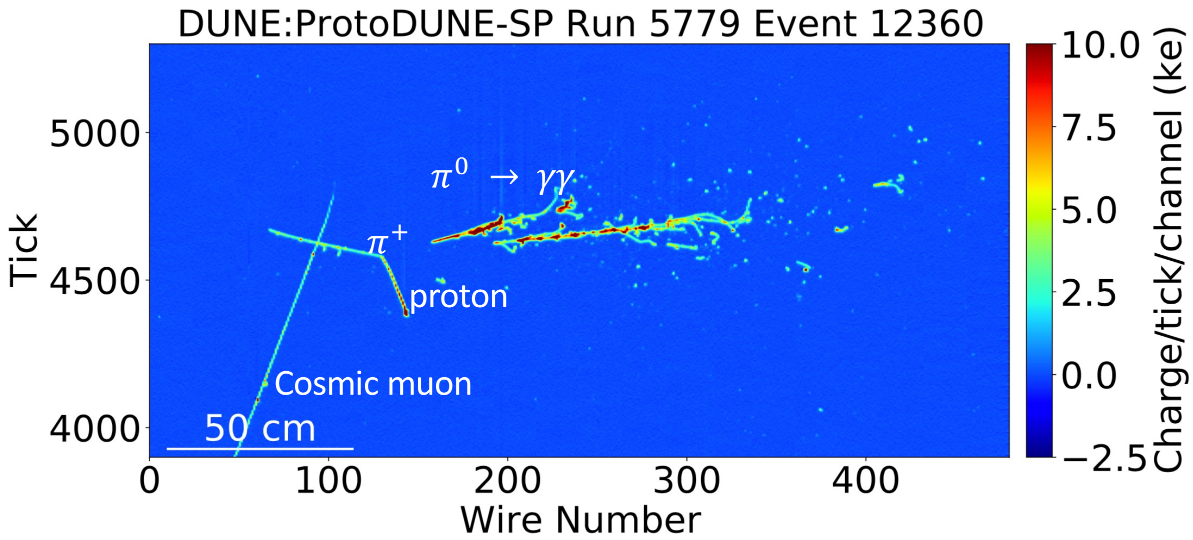
- Use scintillation and ionization to find 3D position of particles and interactions

- Drift charge recorded by several readout (RO) wire planes, with different orientations, forming images

- Light collected by photon detection system



LArTPC images



3 GeV π^+ from ProtoDUNE-SP H4 beamline – charge exchange

- LArTPC technology combines tracking and calorimetry
- Exquisite 3D imaging capabilities over large volume detectors

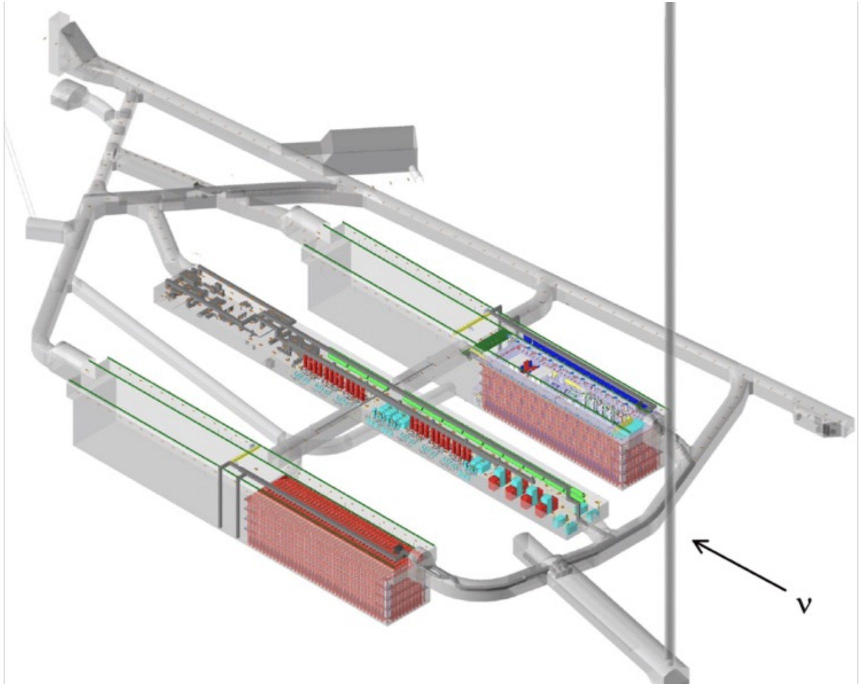
  → excellent particle ID and energy reco capabilities

Spatial resolution ~ mm
Time resolution 14 ns

The DUNE Far Detector

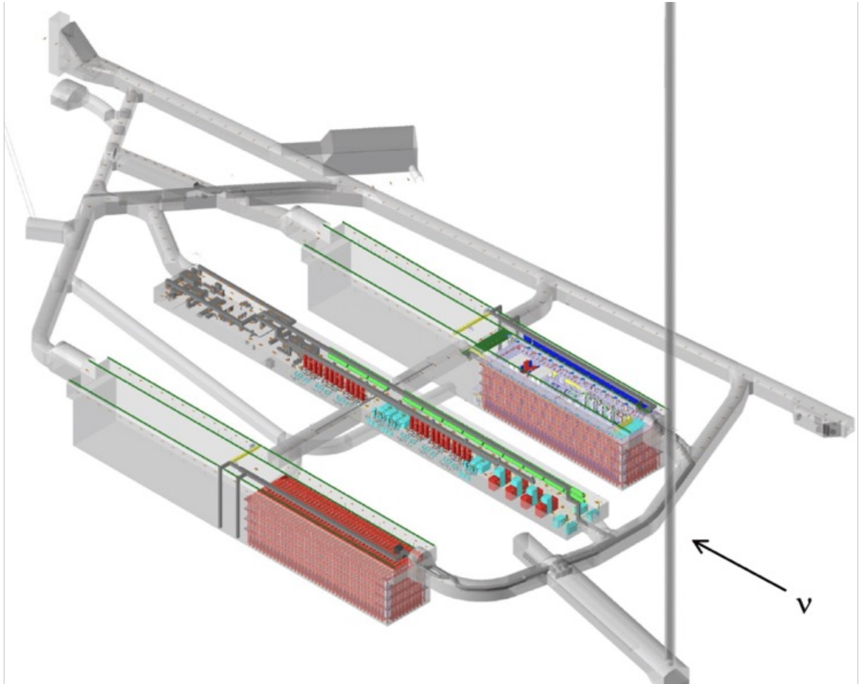
- Four 17 kton modules
  - Modules 1, 2 and 3 liquid argon TPCs
  - Module 4: “Module of Opportunity” → Expand physics scope

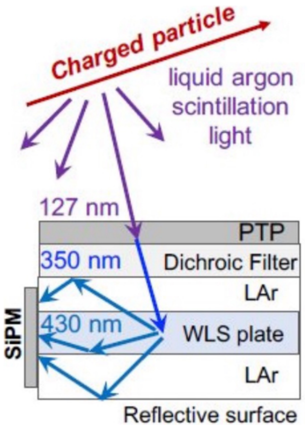
Several technologies under consideration

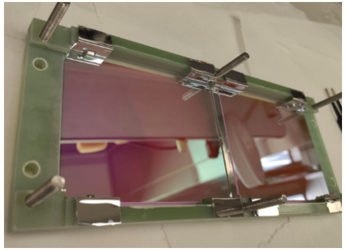


The DUNE Far Detector

- Four 17 kton modules
  - Modules 1, 2 and 3 liquid argon TPCs
  - Module 4: "Module of Opportunity"



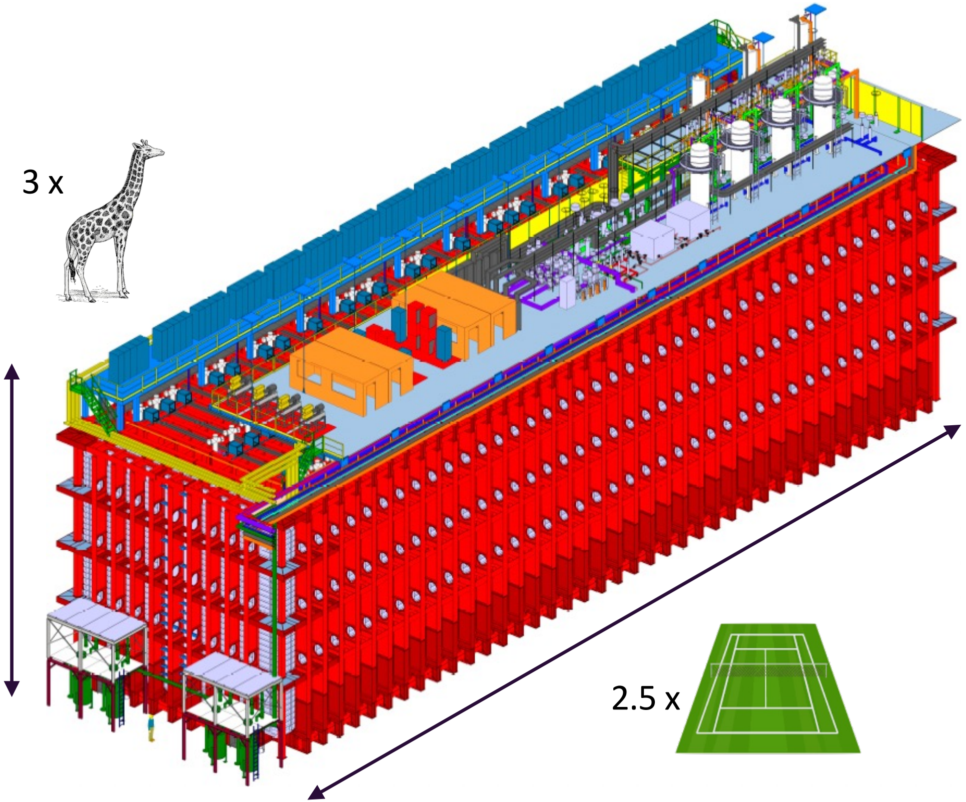




Many technology upgrades since first LArTPCs
e.g. DUNE photon detection system based on **X-ARAPUCA** light trap

C. Brizzolari et al 2021 JINST 16 P09027

The Horizontal Drift Far Detector



- Technology validated across multiple neutrino experiments
- TPC size 12.0 m×14.0 m×58.2 m
- Drift length 3.5 m, field 500 V/cm
- Modular wire-based charge readout
- 4 drift volumes defined by 5 arrays of anode and cathode planes

Photon detection system

→ shift light to visible spectrum

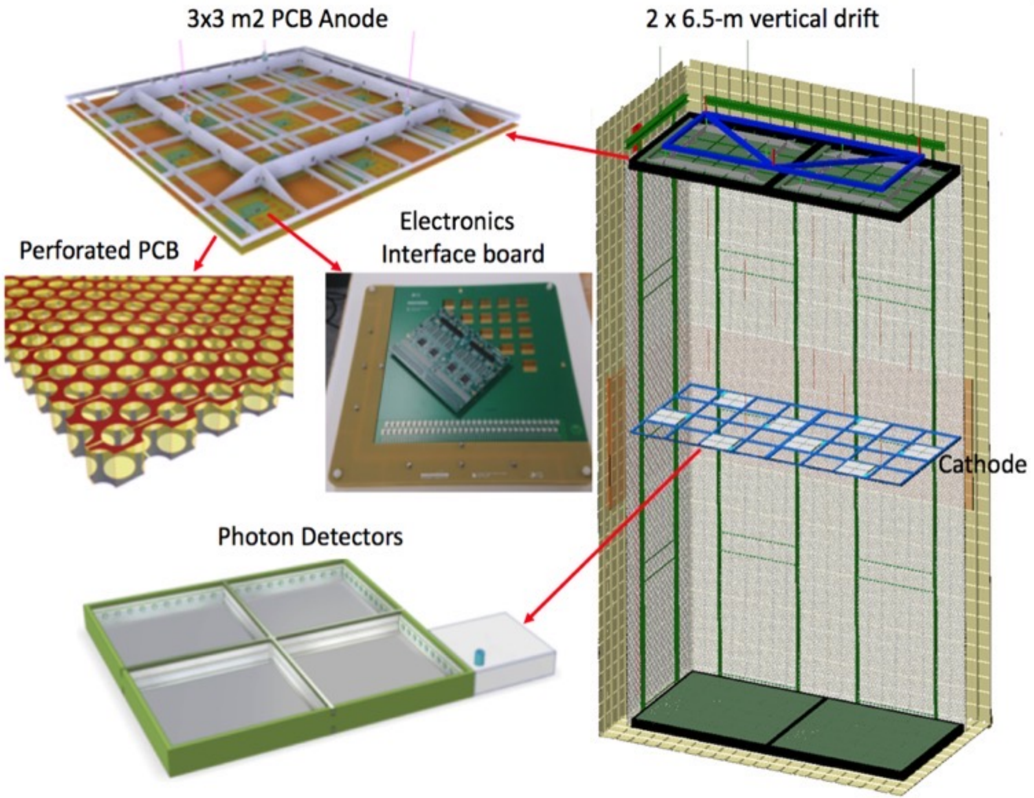
→ Trap photons and transport to silicon photomultipliers

The Vertical Drift Far Detector

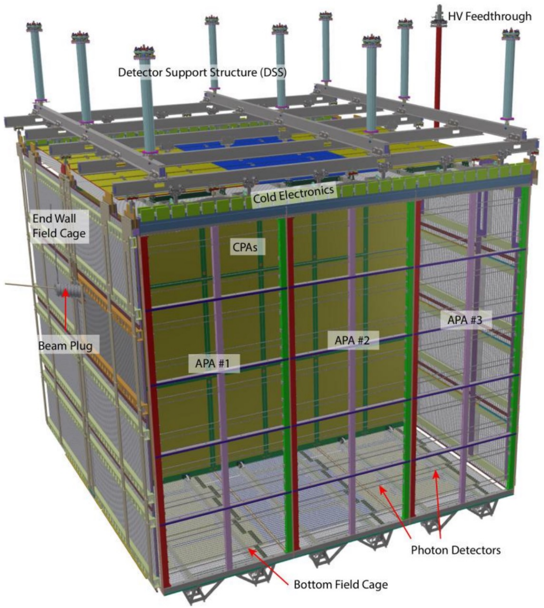
- Two drift volumes
- longer drift (6-7 m)
- Simpler to construct – more efficient use of LAr volume
- PCB-based charge readout

Photon detectors

→ Integrated on cathode plane and on the field cage walls



DUNE Far Detector prototypes at CERN



ProtoDUNE Single Phase

arxiv:2007.06722

- 1/30th of a FD module fiducial volume
- Real-size readout elements, scalable to FD

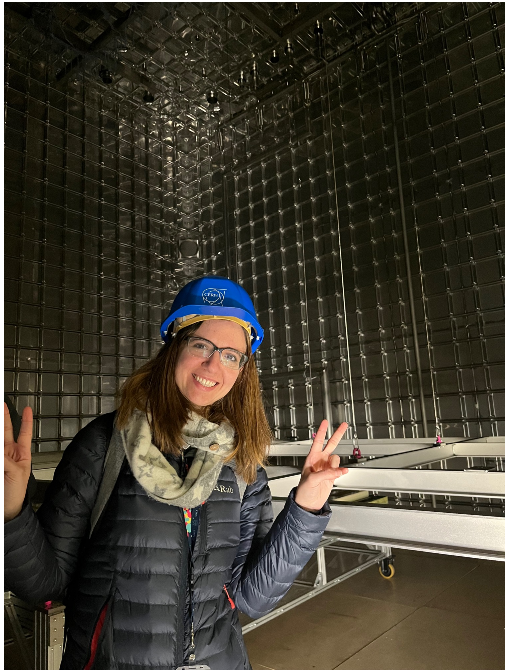
→ Validate technology in charged particle beam 0.3-7 GeV and cosmic rays

Successful operation between 2018 and 2020

➢ Met or exceeded DUNE requirements

Upgraded ProtoDUNE-HD test new techniques and components, and take more beam data at low momentum

DUNE Far Detector prototypes at CERN (2)



ProtoDUNE Vertical Drift, and me

- A dual phase liquid-gas argon design was tested at CERN between 2019 and 2020

- Validated large-scale use of PCBs and proved longer vertical drift possible

→ **Valuable insight led to new vertical drift concept**

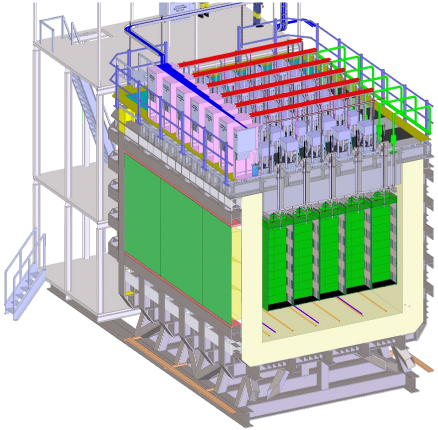
Upgraded ProtoDUNE-HD and ProtoDUNE-VD to start operation at CERN Neutrino Platform in 2023

The DUNE Near Detector (Phase I)

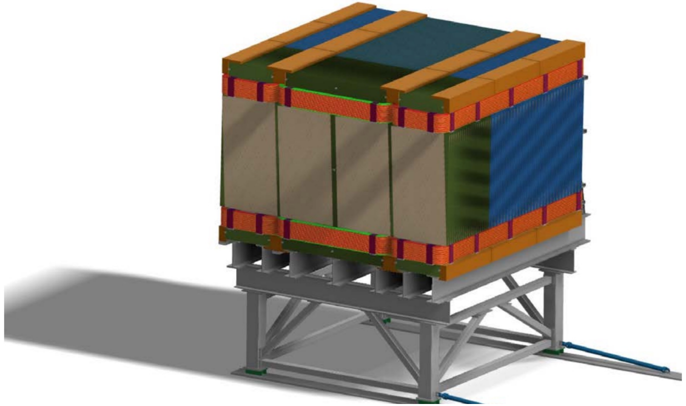
Observed ν_e energy spectrum at the FD:

$$N(\nu_e) = \text{Flux} \times \text{Cross section} \times \text{Detector response} \times \text{Oscillation probability}$$

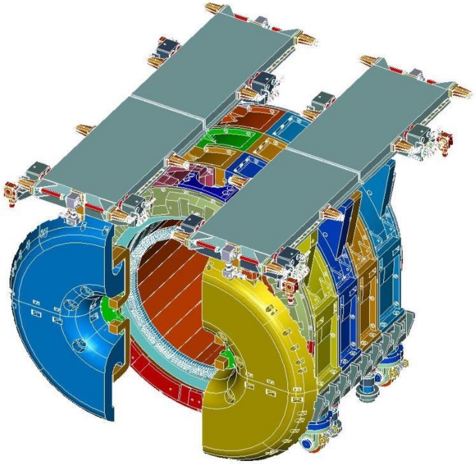
- Sophisticated ND to understand neutrino source, characterise unoscillated beam



ND-LAr (to match FD)



Temporary muon spectrometer



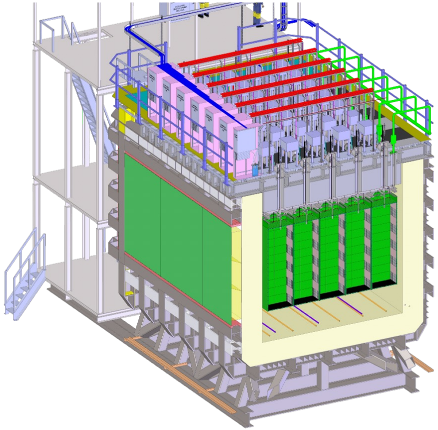
SAND (Beam monitor)

The DUNE Near Detector (Phase II)

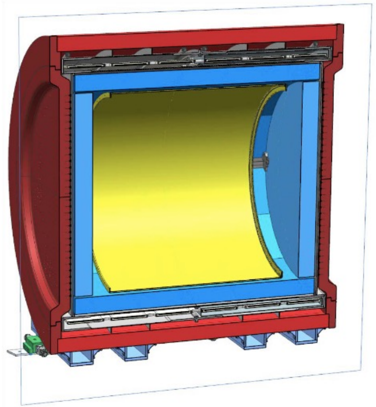
Observed ν_e energy spectrum at the FD:

$$N(\nu_e) = \text{Flux} \times \text{Cross section} \times \text{Detector response} \times \text{Oscillation probability}$$

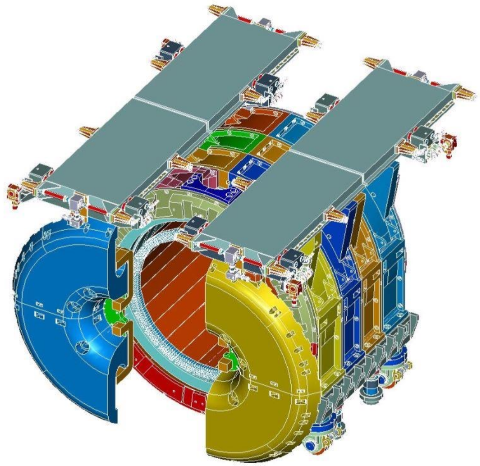
- Sophisticated ND to understand neutrino source, characterise unoscillated beam



ND-LAr (to match FD)



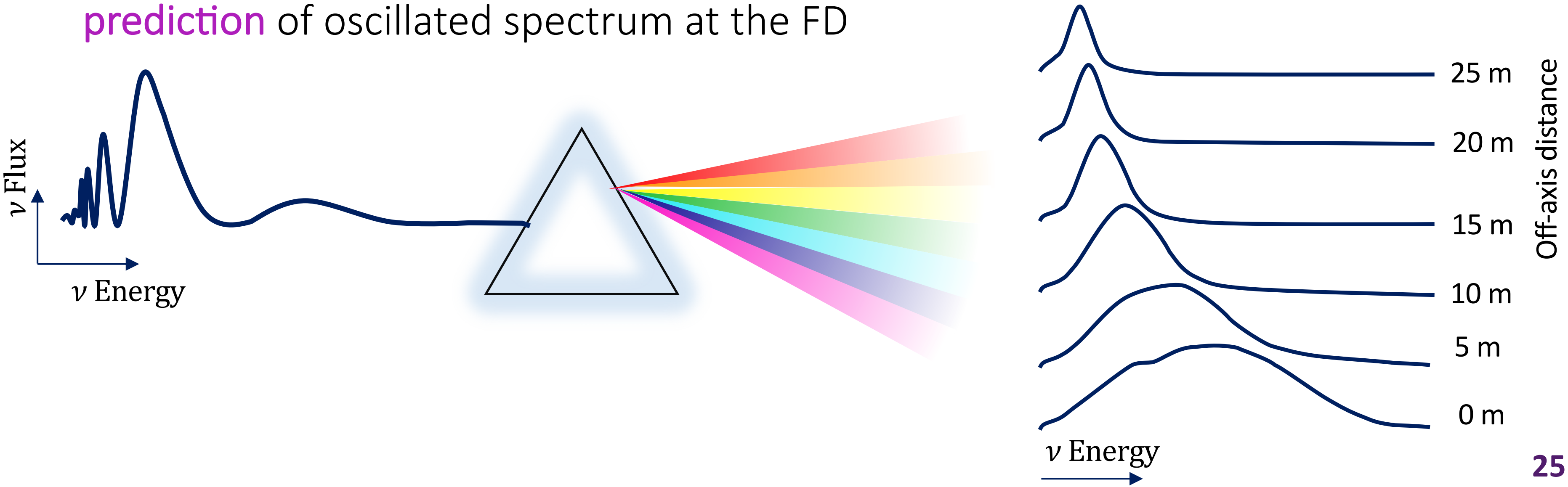
ND-GAr (contain muons, widen physics scope)



SAND (Beam monitor)

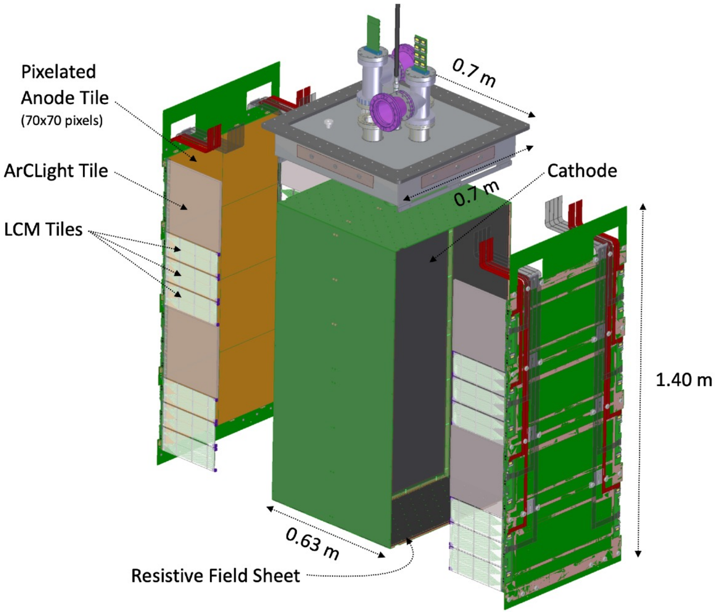
The PRISM concept

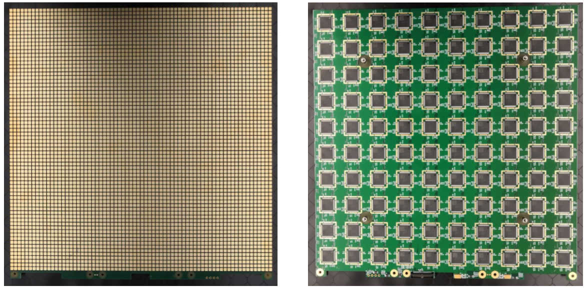
- Want to extrapolate oscillated FD flux from flux measured at ND
- As the ND moves off axis, the energy spectrum shifts downwards
- Off-axis measurements reduce cross-section and ν energy uncertainties
- Different off-axis spectra can be combined into model-independent data-driven prediction of oscillated spectrum at the FD



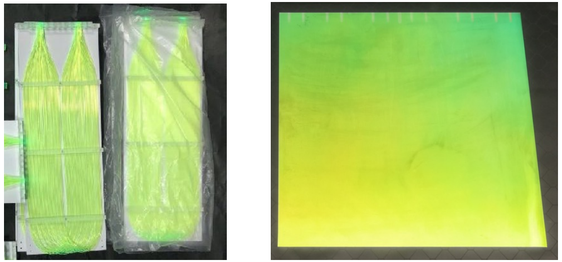
ProtoDUNE-ND (ArgonCube 2x2)

- A modularized LArTPC demonstrator in the Fermilab NuMI Beam
- Smaller but complete version of ND-LAr module ($0.7\times0.7\times1.4\ \mathrm{m}^3$)





LArPix
Pixelated charge readout



Two ARAPUCA-based photon detection systems being tested
LCM (left)
ArCLight (right)

DUNE physics programme

- Mass ordering, θ_{23} octant
- High precision δCP
- High precision measurements of $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, Δm^2_{32}
- Study ν_τ sector
- Sensitivity to low energy neutrinos → supernova, solar neutrinos
- Low background → sensitivity to BSM physics E.g. baryon number violation
- Atmospheric neutrino oscillation
- Neutrino physics and more (e.g. dark matter searches) in the ND

Complementarity with Hyper-Kamiokande – different beam, baseline, technology
→ Different interactions, parameter space and systematics

Neutrinos from Core Collapse Supernova

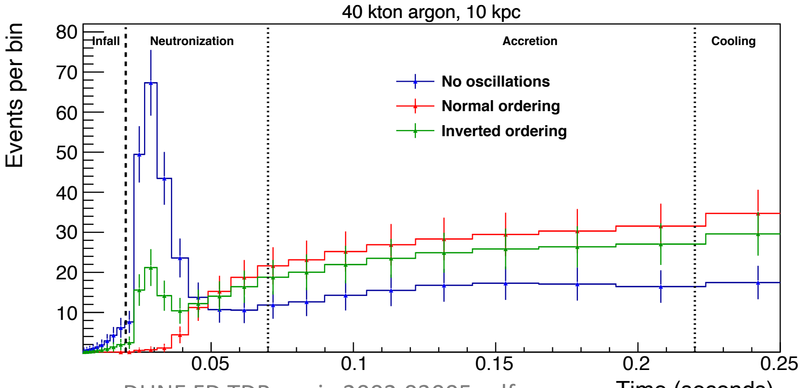
- Over 99% of all gravitational binding energy of collapsed core emitted as neutrinos
- Flavour content and spectra change throughout the phases of the core collapse

➢ Use neutrinos to study collapse mechanism, time evolution, black hole formation

➢ First particles to reach Earth: pointing information in multi-messenger astronomy

1-3 Galactic Core Collapse SN/100 years

SN1987A – ESO Schmidt Telescope



DUNE FD TDR: arxiv:2002.03005.pdf

DUNE has unique sensitivity to electron-flavour neutrinos

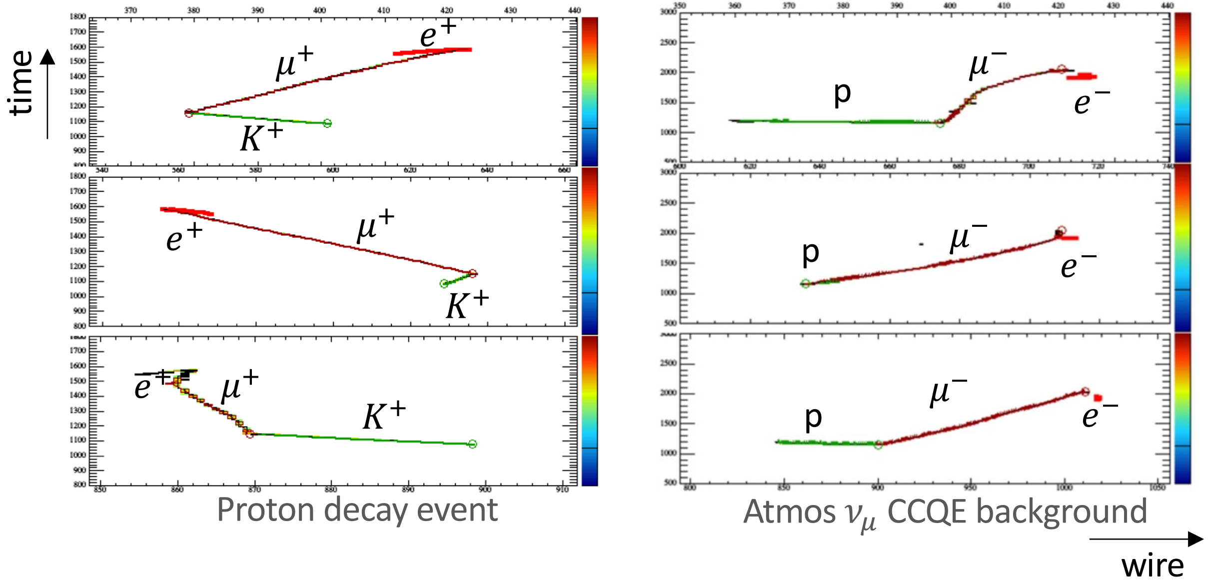
Physics Beyond the Standard Model

- Baryon number violation, dark matter searches, sterile neutrinos, etc.

Example: proton decay

➢ Underground location
➢ Large fiducial mass
➢ Imaging capabilities

$p \rightarrow K^{+}\overline{\nu}$
(dominant SUSY GUT mode)



Proton decay event

Atmos ν_μ CCQE background

- Identify kaon by dE/dx and decay products
- Main background: atmospheric neutrinos

Status and timeline

North detector cavern
Photo by Matt Kapust, SDSTA – 19 Jan 2023

- FD site excavation over half complete
- Beamline design is almost 2/3 completed and on track
- Facilities final design complete

➢ 2029 Start of Science
(First two Far Detector modules)

Atmospheric nu, astrophysics

➢ 2031 Start of Phase I

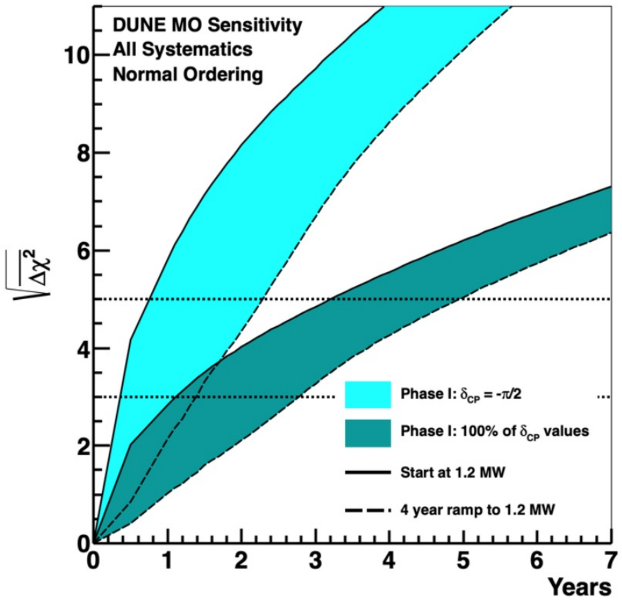
LBL, atmospheric nu, astrophysics

➢ 2037-2038 Start of Phase II

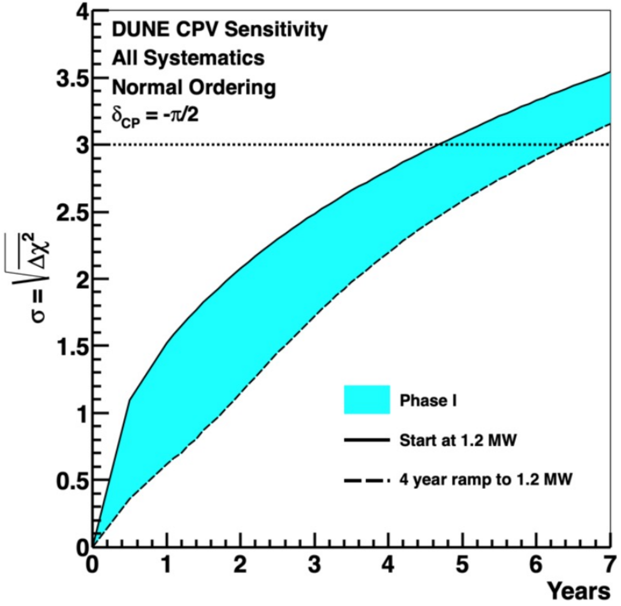
Full physics scope

DUNE Phase I

Mass ordering



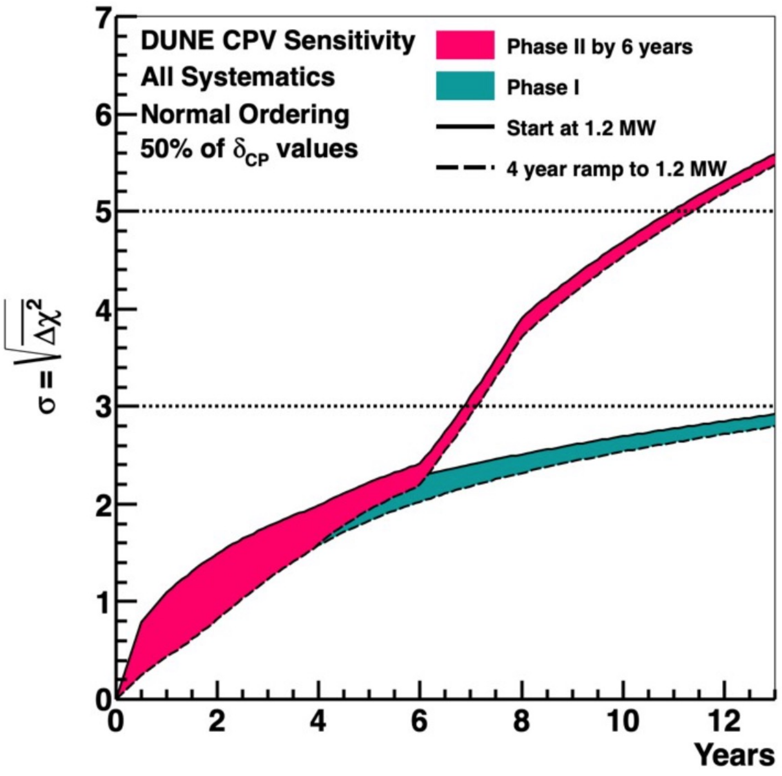
CPV



- Determine mass ordering (3-5 y)
- 3σ CP violation if $\delta\mathrm{CP} = -\pi/2$ (4-6y)
- Precision measurement of oscillation parameters
- Full sensitivity to SN neutrinos

Need phase II to achieve full physics potential

DUNE Phase II



- Most precise measurement of δCP, no matter the true values of unknown parameters (7-16° resolution)
- 5σ CP violation discovery sensitivity over 50% **δCP** values (11y)
- Independent measurement of $sin^2 2\theta_{13}$
- Sensitivity to θ_{23} octant
- Test three-flavour paradigm
- World-leading sensitivity to BSM physics and astrophysics

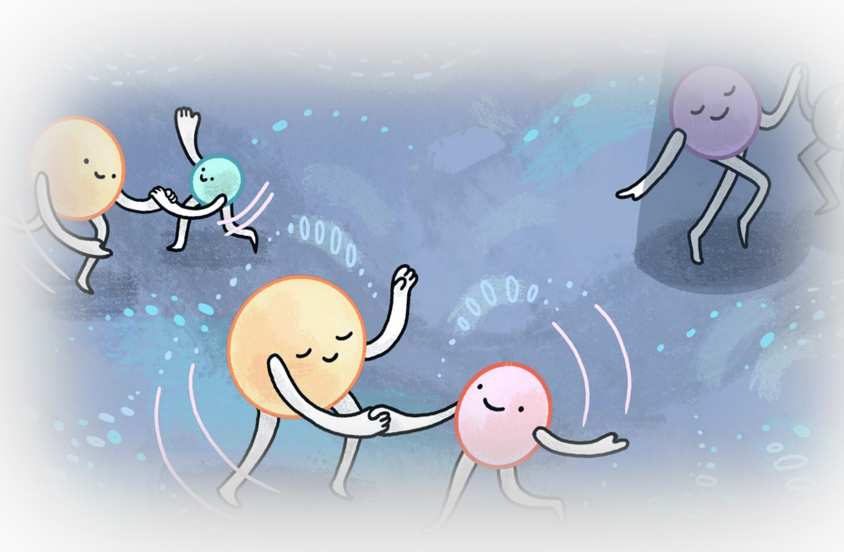
The DUNE Collaboration

- More than 1300 collaborators
- More than 200 institutions
- More than 30 countries (plus CERN)

DUNE CM January 2023

Summary

- DUNE is a next generation neutrino experiment
  - Long baseline, most intense neutrino beam in the world, large-scale state-of-the-art detector technology, complementarity with Hyper-Kamiokande
- Simultaneously measure all parameters governing $\nu_1 - \nu_3$ and $\nu_2 - \nu_3$ mixing in single experiment, without external constraints
- Mass ordering, SN neutrinos and precision measurements in phase I
- Full physics potential in phase II
- Exciting times ahead!



Artworks by Sandbox Studio, Chicago with Ana Kova