

DUNE

**DEEP UNDERGROUND
NEUTRINO EXPERIMENT**

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IFIC Experimental Seminar • Paterna, 13 February 2023

The Five Ws and One H of DUNE

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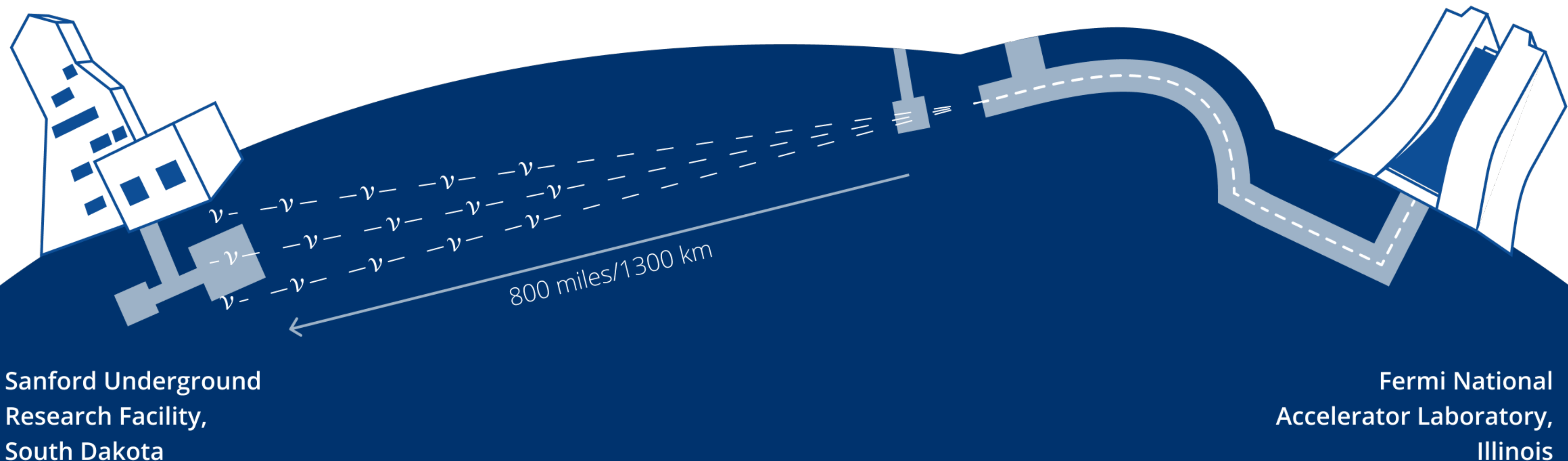
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**5W1H: What, when,
where and who**



The **Deep Underground Neutrino Experiment (DUNE)** is an upcoming long-baseline neutrino oscillation experiment under construction in the United States. It will consist of three new systems:

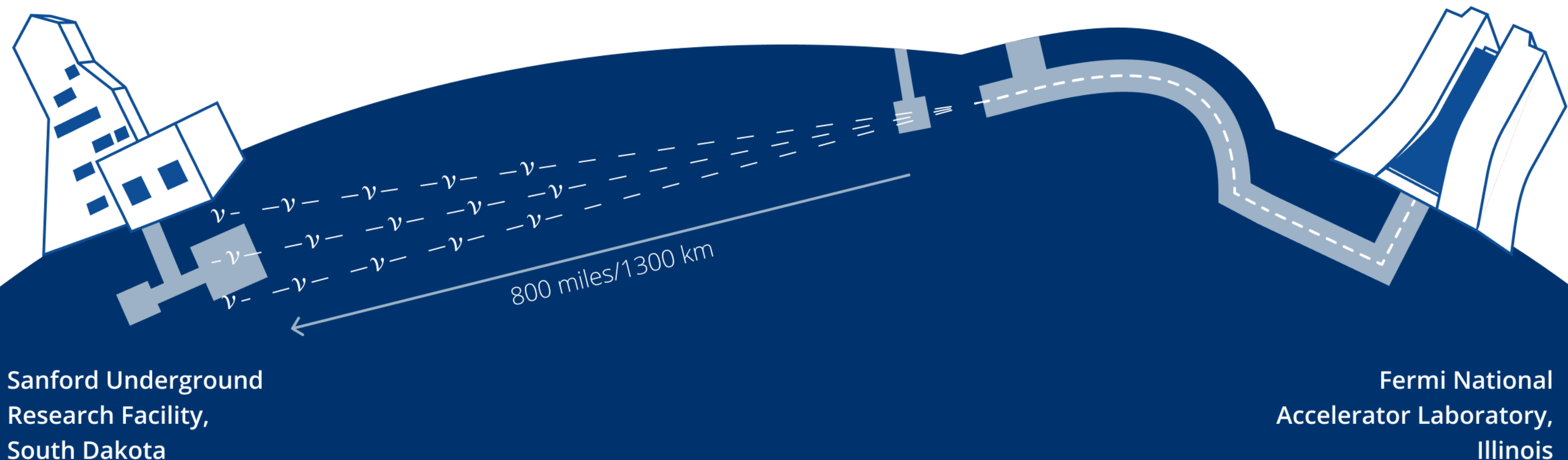
- a new MW-scale neutrino beamline (LBNF);
- a high-resolution, high-rate near detector (ND);
- a far detector (FD) comprising four 17-kiloton liquid argon TPC modules.





The **science program** of DUNE covers three major areas:

- Long-baseline neutrino oscillations.
- Neutrino astrophysics.
- Searches for phenomena beyond the Standard Model (BSM).



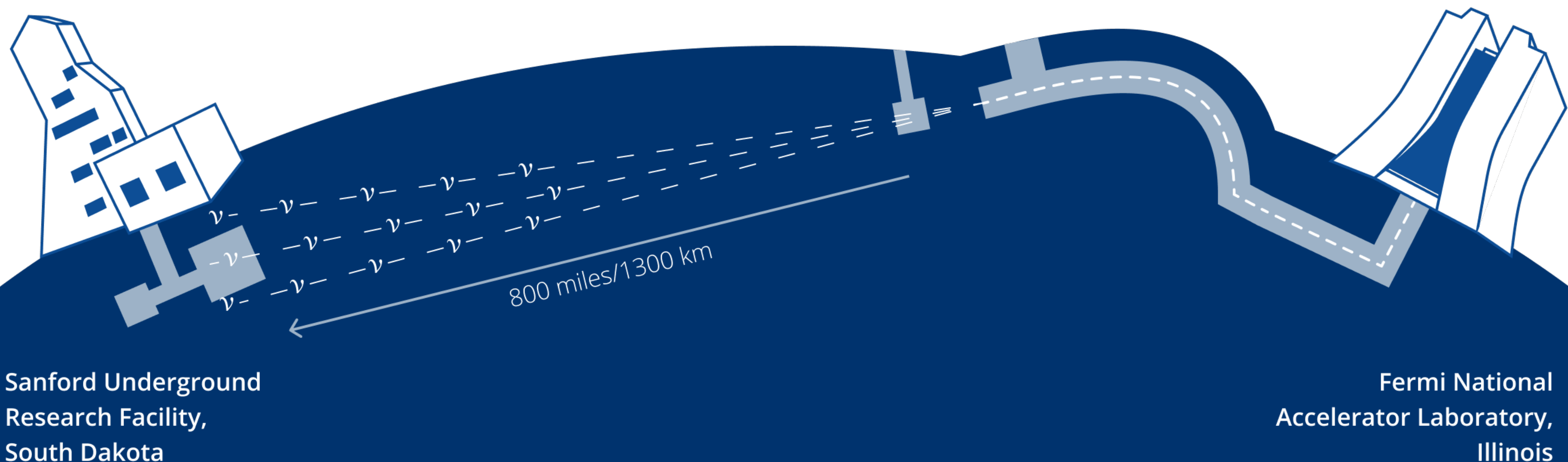
Sanford Underground
Research Facility,
South Dakota

Fermi National
Accelerator Laboratory,
Illinois



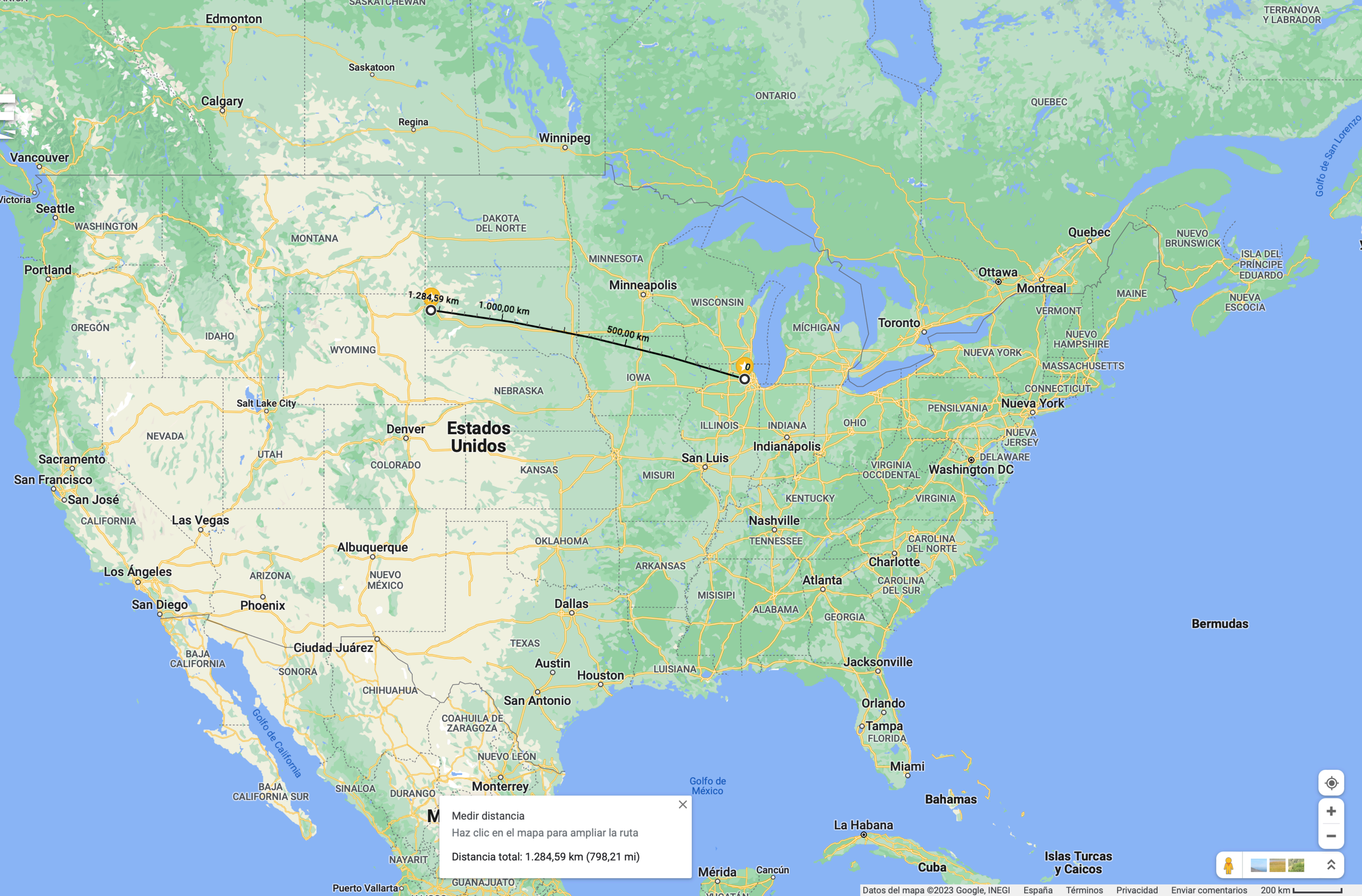
The experiment will be built in two phases:

- Phase I ready by ~2032.
 - Up to 1.2 MW beam power; 2 FD modules; basic ND (NDLAr).
- Phase II ready before 2040.
 - 2.4 MW beam power; 4 FD modules; more capable ND (NDLAr+NDGAr).



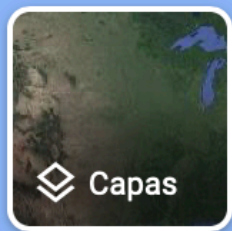
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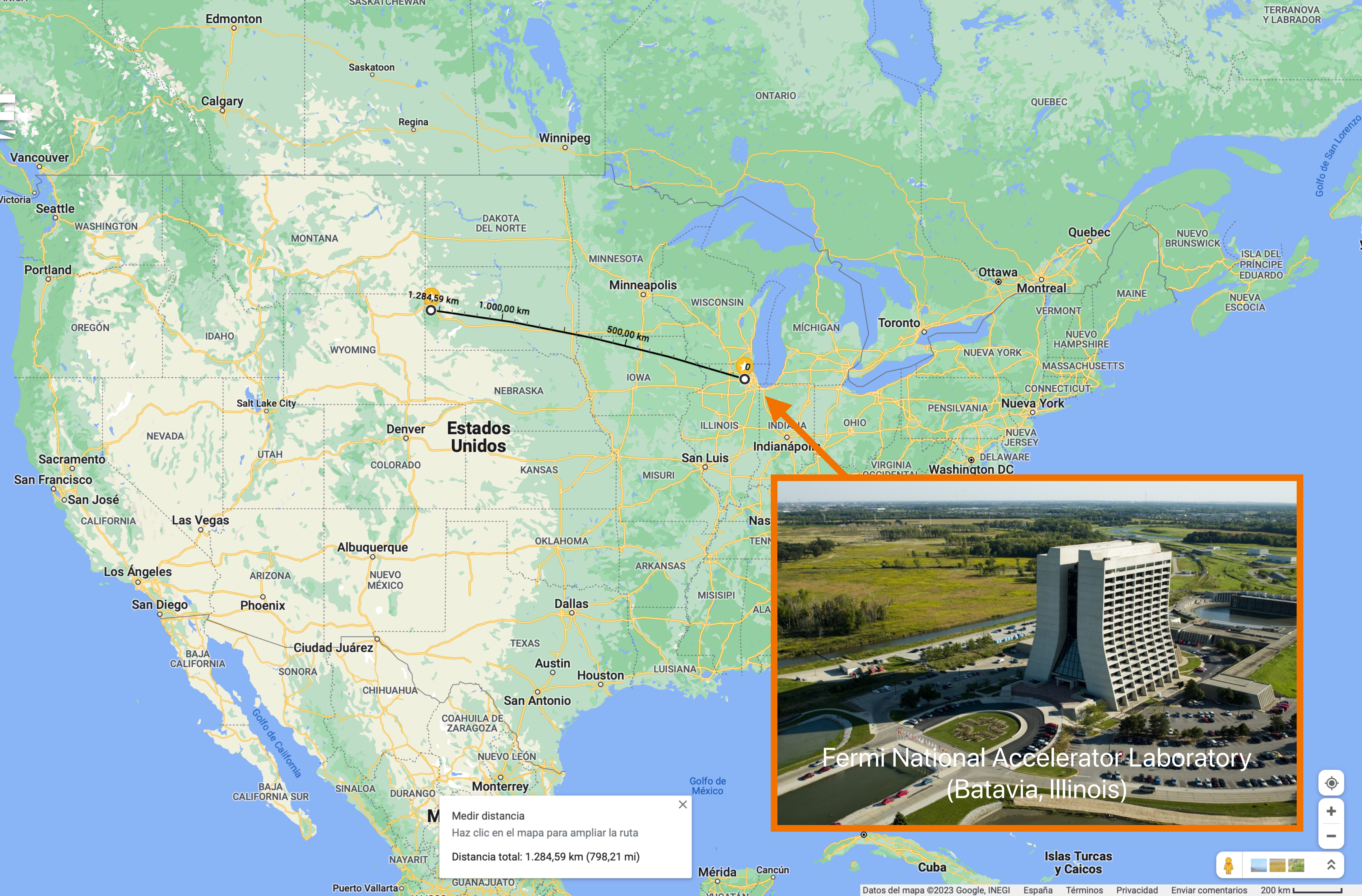
Fermi National
Accelerator Laboratory,
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Estados Unidos

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Haz clic en el mapa para ampliar la ruta
Distancia total: 1.284,59 km (798,21 mi)

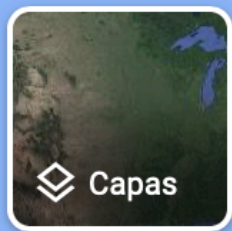


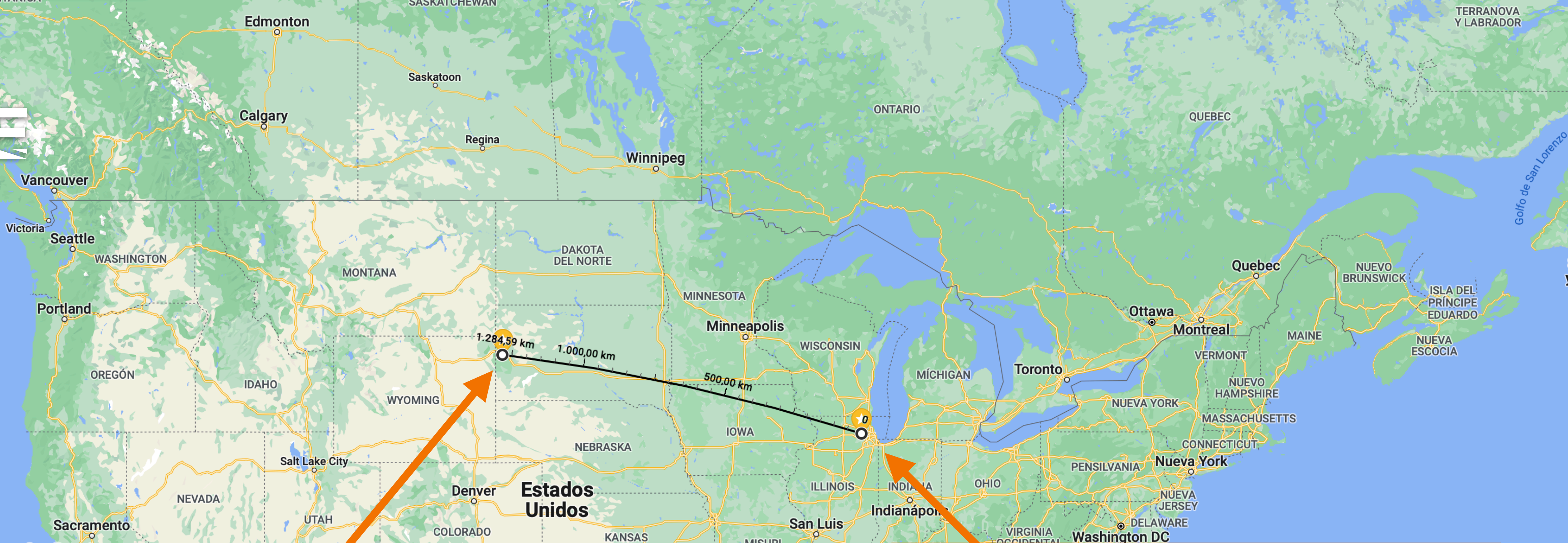


Estados Unidos



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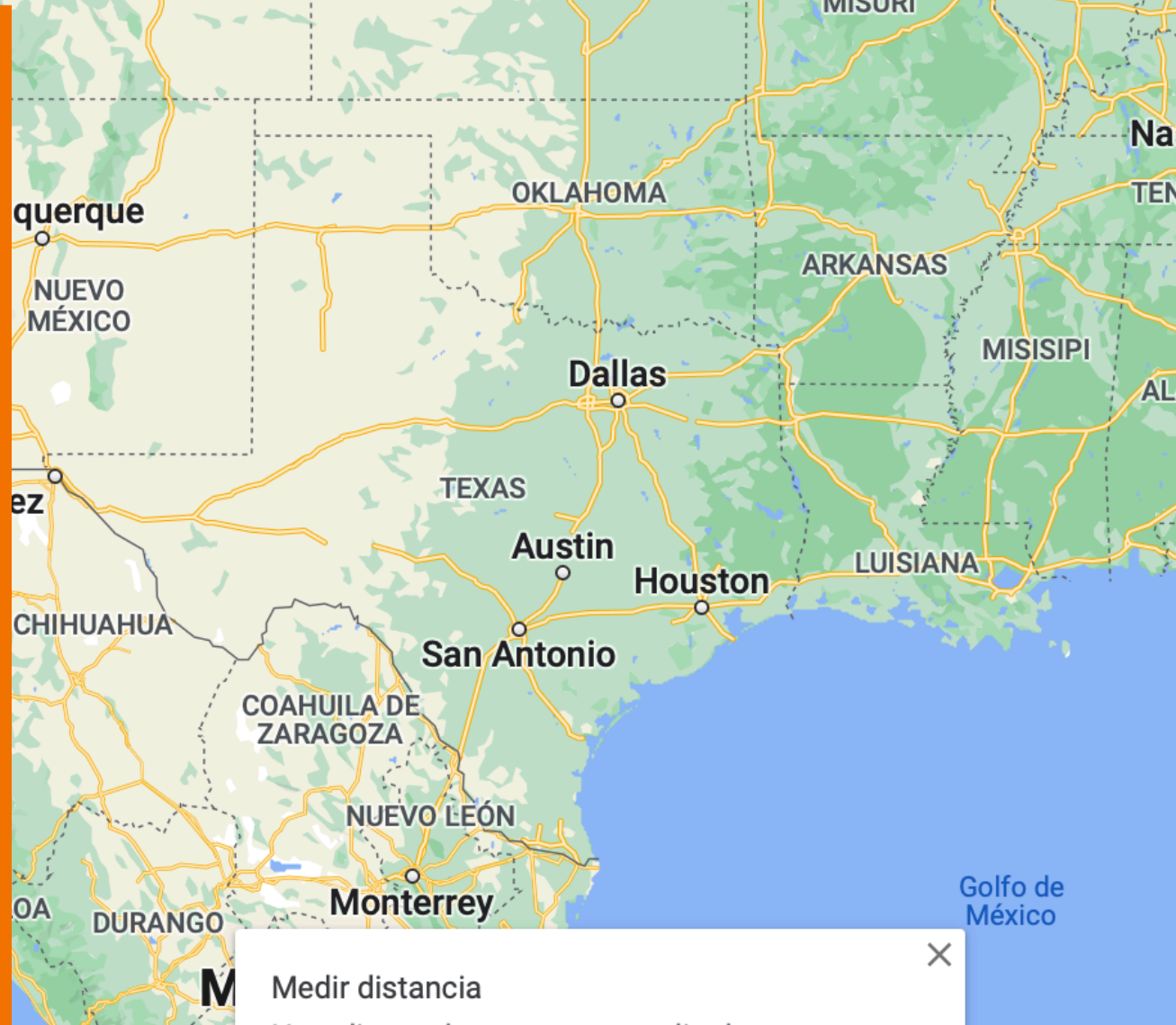




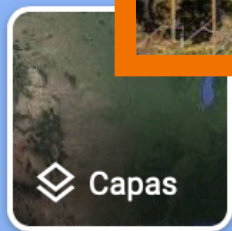
Sanford Underground Research Facility
(Lead, South Dakota)



Fermi National Accelerator Laboratory
(Batavia, Illinois)



Medir distancia
Haz clic en el mapa para ampliar la ruta
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DUNE is an international effort that comprises more than 1,000 collaborators from over 200 institutions in over 30 countries (plus CERN).

Six institutions in Spain: CIEMAT, U. Granada, IFIC, IFT, IGFAE, U. Vigo.

5W1H: Why

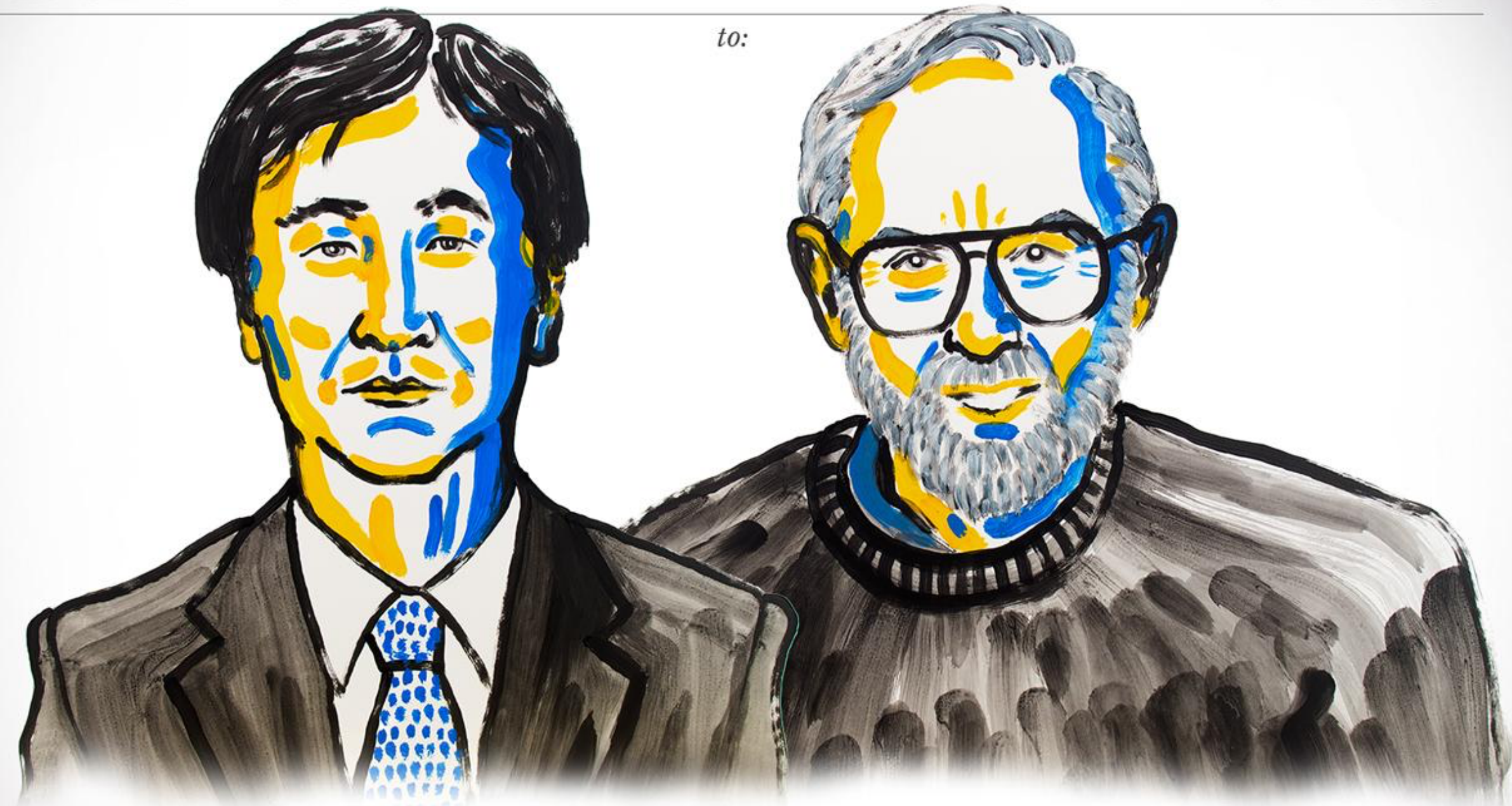
"For the greatest benefit to mankind"
Alfred Nobel



The Royal Swedish Academy of Sciences has decided to award the


2015 NOBEL PRIZE IN PHYSICS

to:



**Takaaki Kajita and
Arthur B. McDonald**

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

 **Nobelprize.org**
The Official Web Site of the Nobel Prize

Illustrations: Niklas Elmehed. Nobel Prize Meddai: © @ The Nobel Foundation. Photo: Lovisa Engblom.

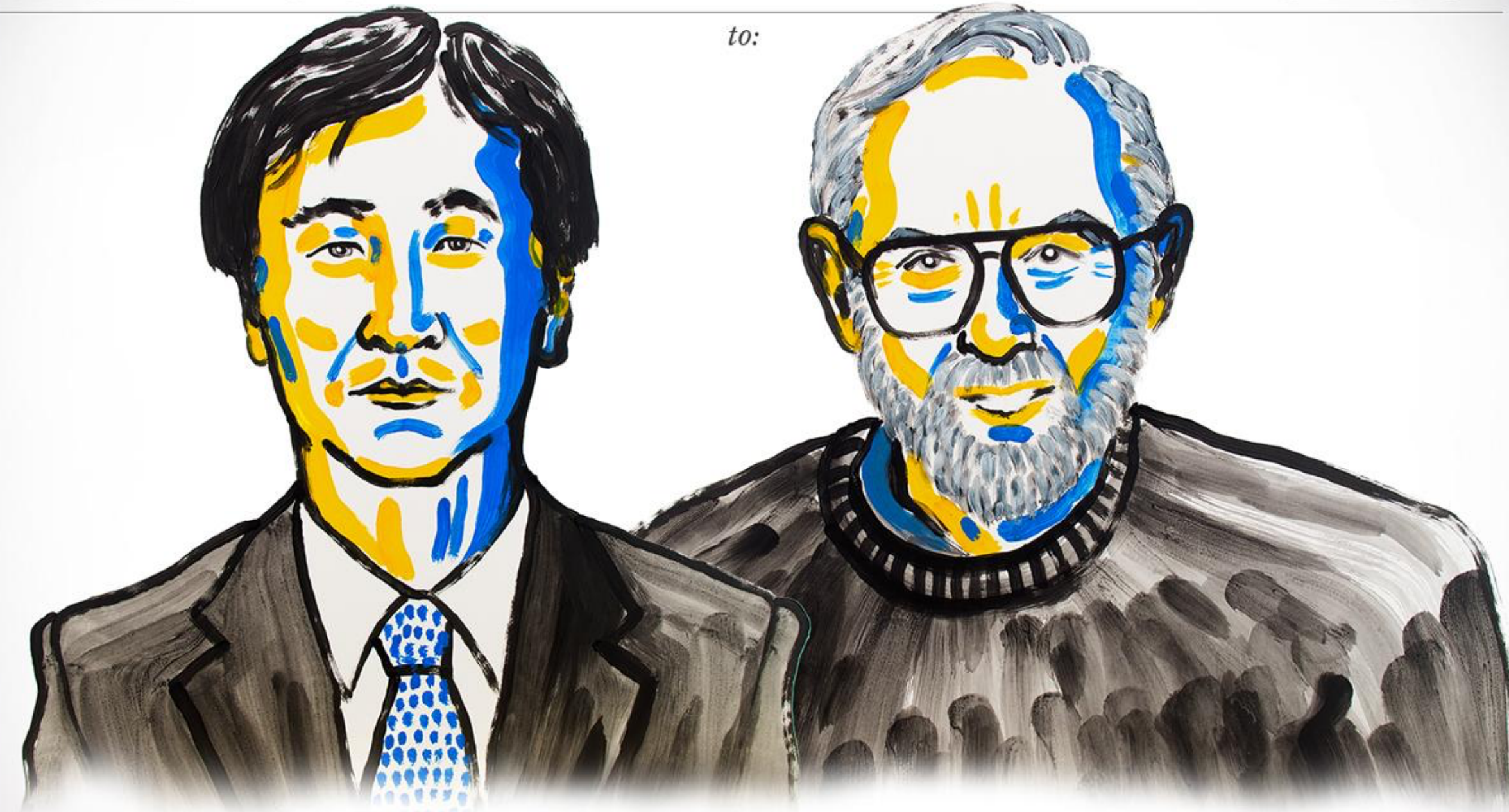
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Illustrations: Niklas Elmehed. Nobel Prize Meddai: © @ The Nobel Foundation. Photo: Lovisa Engblom.

Motivations

Neutrinos are the most abundant matter particles in the universe but the least understood.

In the Standard Model, neutrinos are massless particles. Neutrino masses are thus the first direct evidence of new physics.

Understanding the origin and nature of neutrino masses may pave the way to a more complete theory beyond the Standard Model.

The known unknowns

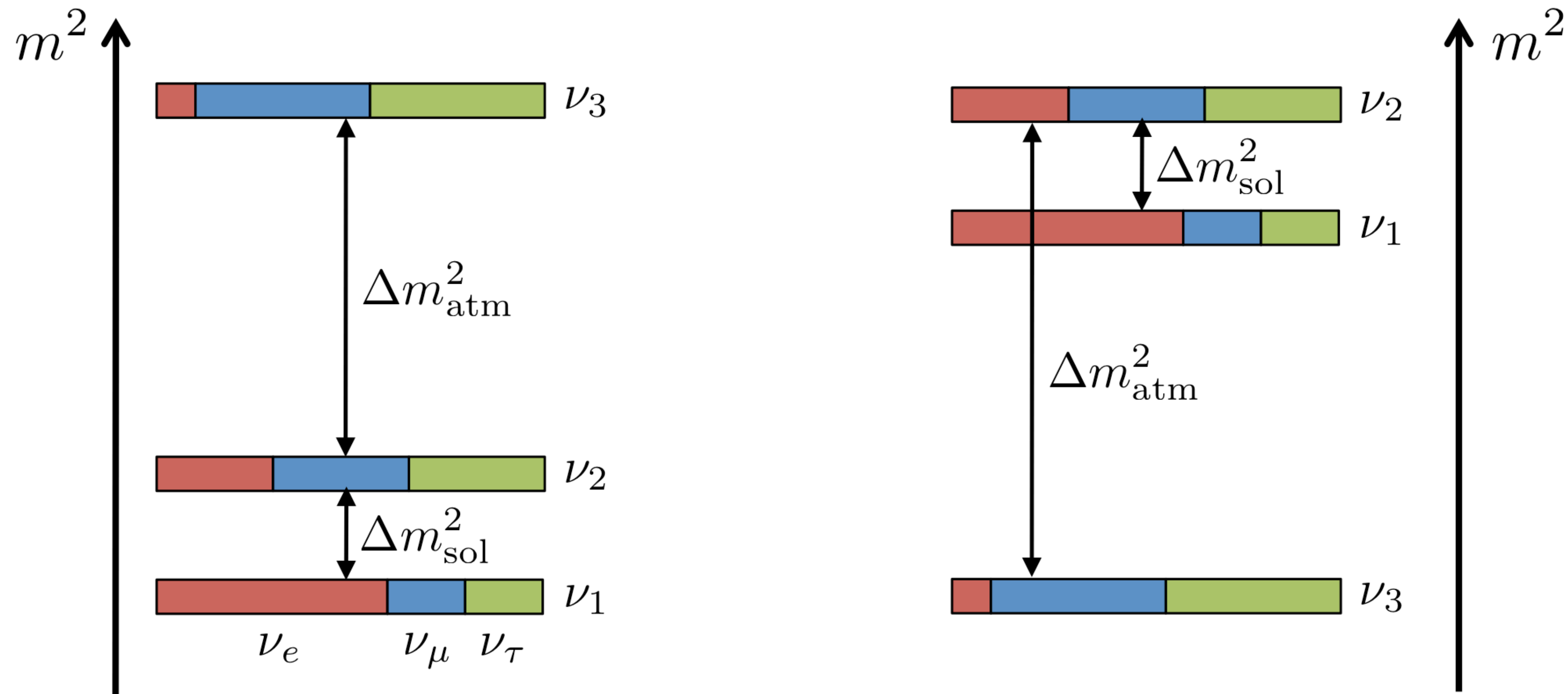
We know neutrinos oscillate... but what is the origin of neutrino mixing? Is there an underlying flavour symmetry?

We know neutrinos have mass... but what is the origin of neutrino mass? Why are the neutrinos so light?

We know there are at least three neutrino states... but are there exactly three? Is the ν SM complete? Is the PMNS matrix unitary?

We know there is a baryon asymmetry... but is leptogenesis a viable explanation?

Neutrino mixing



Oscillation experiments established that neutrinos are massive particles and that the neutrino states participating in the weak interaction (flavour eigenstates) are different from the states controlling free-particle evolution (mass eigenstates).

Neutrino mixing circa 2022

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

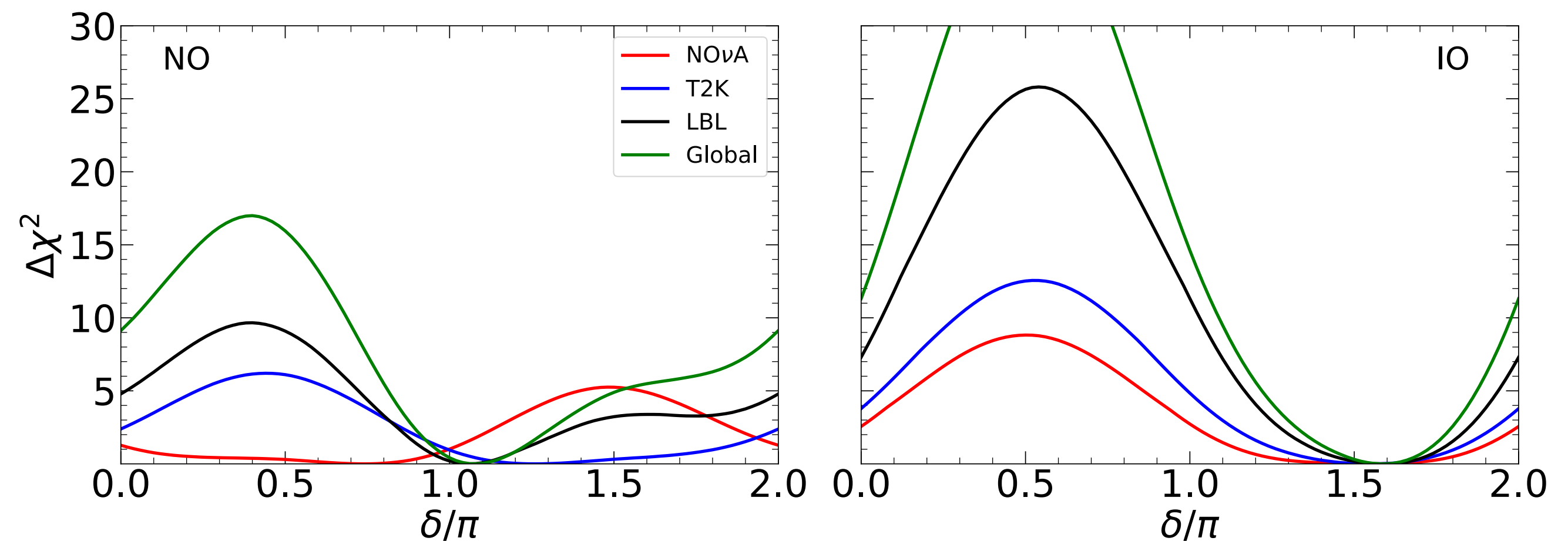
parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m_{21}^2: [10^{-5} \text{ eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.11–7.93	6.94–8.14
$ \Delta m_{31}^2 : [10^{-3} \text{ eV}^2] \text{ (NO)}$	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$ \Delta m_{31}^2 : [10^{-3} \text{ eV}^2] \text{ (IO)}$	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2 \theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\sin^2 \theta_{23}/10^{-1} \text{ (NO)}$	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\sin^2 \theta_{23}/10^{-1} \text{ (IO)}$	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\sin^2 \theta_{13}/10^{-2} \text{ (NO)}$	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\sin^2 \theta_{13}/10^{-2} \text{ (IO)}$	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\delta_{\text{CP}}/\pi \text{ (NO)}$	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta_{\text{CP}}/\pi \text{ (IO)}$	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96

arXiv:2006.11237

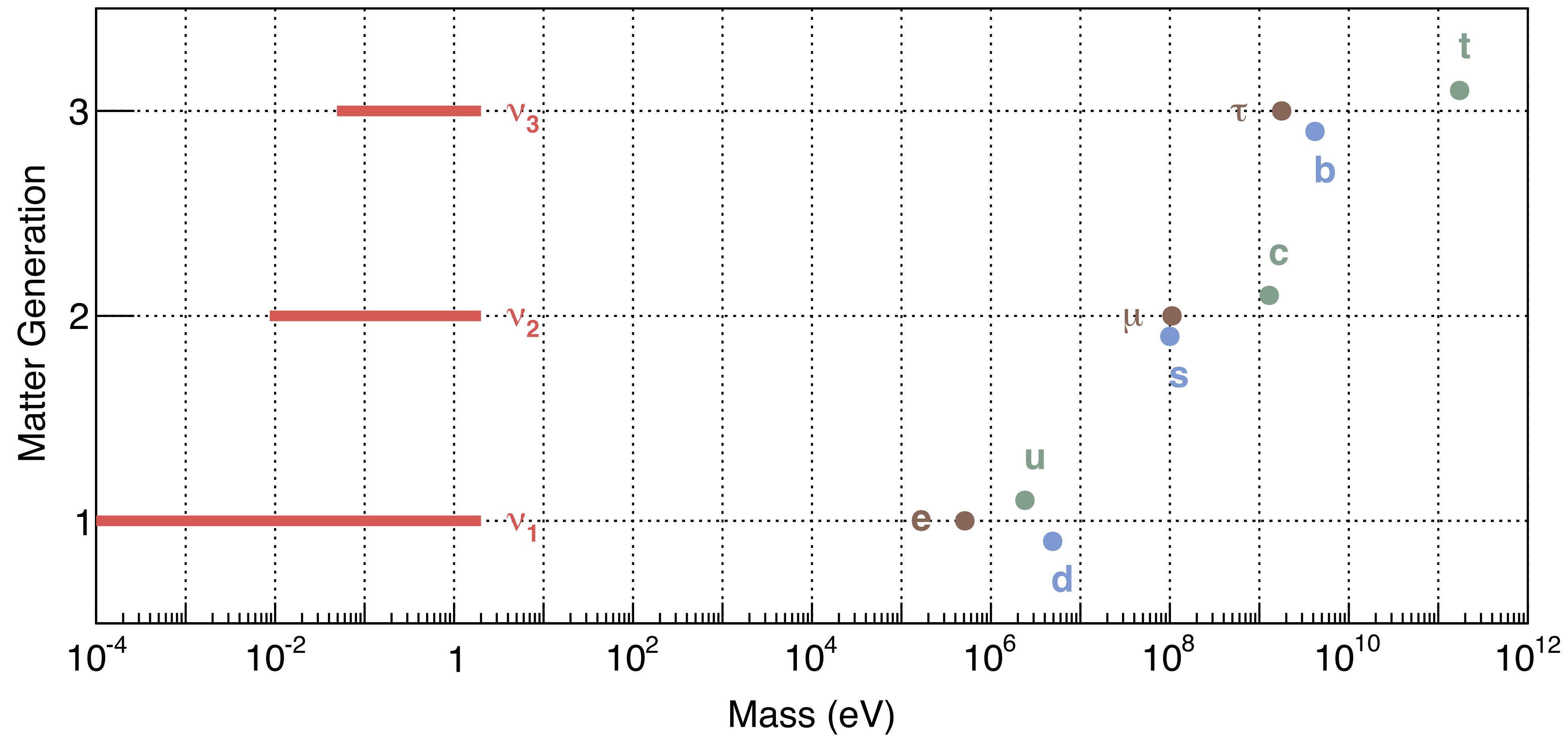
CP violation

A new source of CP violation is required to explain the **matter-antimatter asymmetry** observed in our universe.

Leptogenesis is a popular solution for the problem, but we need to find first any leptonic CPV.



Lepton mass spectrum



(A parenthesis)

Neutrino oscillation experiments cannot address on their own every outstanding issue in neutrino physics.

For example, **double beta decay experiments** are needed to answer whether neutrinos are **Majorana particles** (i.e. whether neutrinos and antineutrinos are the same particle). IFIC is involved in one of such experiments:

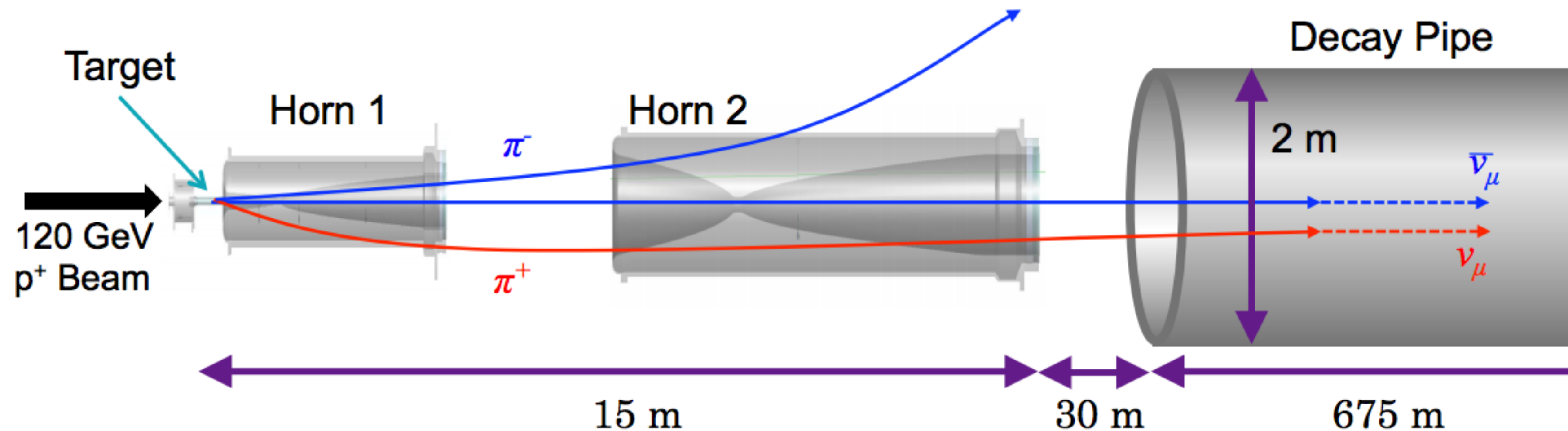


5W1H: How

Oscillation experiments 101



Oscillation experiments 101



Oscillation experiments 101



$$N_{\text{ND}}(E_{\nu}) = \varepsilon \Phi_{\text{ND}}(E_{\nu}) \sigma(E_{\nu})$$

$$N_{\text{FD}}(E_{\nu}) = \varepsilon P_{\text{osc}}(E_{\nu}) \Phi_{\text{FD}}(E_{\nu}) \sigma(E_{\nu})$$

$$P_{\text{osc}}(E_{\nu}) = \frac{\Phi_{\text{ND}}(E_{\nu}) N_{\text{FD}}(E_{\nu})}{\Phi_{\text{FD}}(E_{\nu}) N_{\text{ND}}(E_{\nu})}$$

In a real experiment, perfect cancellations never occur (e.g. ND and FD may have different acceptances or even different target materials), complicating notably the above picture.

Oscillation experiments 101



Muon-neutrino **disappearance** (to leading order):

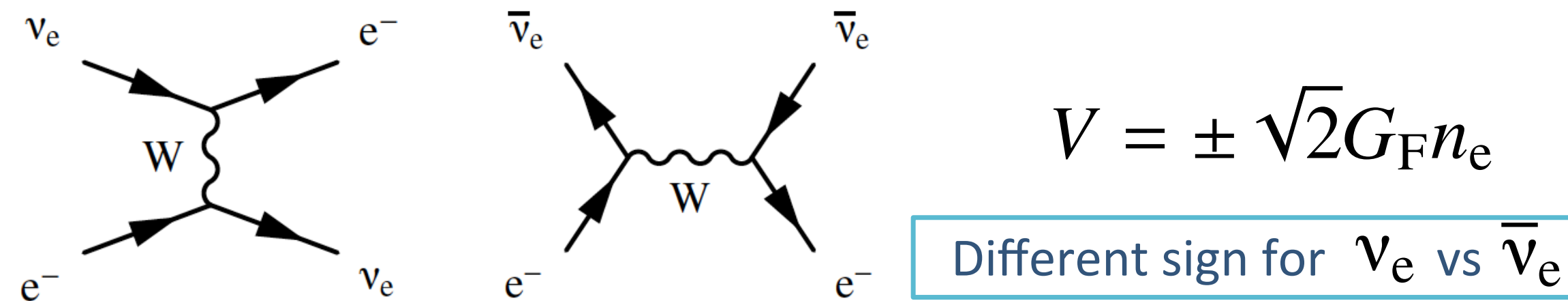
$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2(\Delta m_{32}^2 L/4E)$$

Electron-neutrino **appearance** (plus potentially large CPV and matter effects):

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta m_{32}^2 L/4E)$$

Measuring CP violation

In principle, it is straightforward: just measure the difference in oscillation rates between neutrinos and antineutrinos. However, matter effects complicate the picture: even in the absence of CPV, neutrinos and antineutrinos have different rates.



$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) =$$

ME $\frac{16A}{\Delta m_{31}^2} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$

ME $-\frac{2AL}{E} \sin \left(\frac{\Delta m_{31}^2 L}{4E} \right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$

CPV $-\frac{8 \Delta m_{21}^2 L}{2E} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) \sin \delta \cdot s_{13} c_{13}^2 c_{23} s_{23} c_{12} s_{12}$

with $A = 2 \sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \text{eV}^2 \cdot \frac{\rho}{\text{g cm}^{-3}} \cdot \frac{E}{\text{GeV}}$

Measuring CP violation

Either **keep baseline short** (~ 200 km) so that matter effects are insignificant:

- To maximize signal: $(\Delta m^2 L / 4E) \sim \pi/2 \rightarrow E_\nu < 1$ GeV
- Since cross section is proportional to neutrino energy, need a high flux at oscillation maximum \rightarrow use off-axis, narrow-energy beam.

Or **make baseline long** (> 1000 km) and measure matter effects (and mass ordering):

- To maximize signal: $(\Delta m^2 L / 4E) \sim \pi/2 \rightarrow E_\nu > 2$ GeV
- Unfold CPV from matter effects using energy dependence \rightarrow use on-axis, wide-band neutrino beam.

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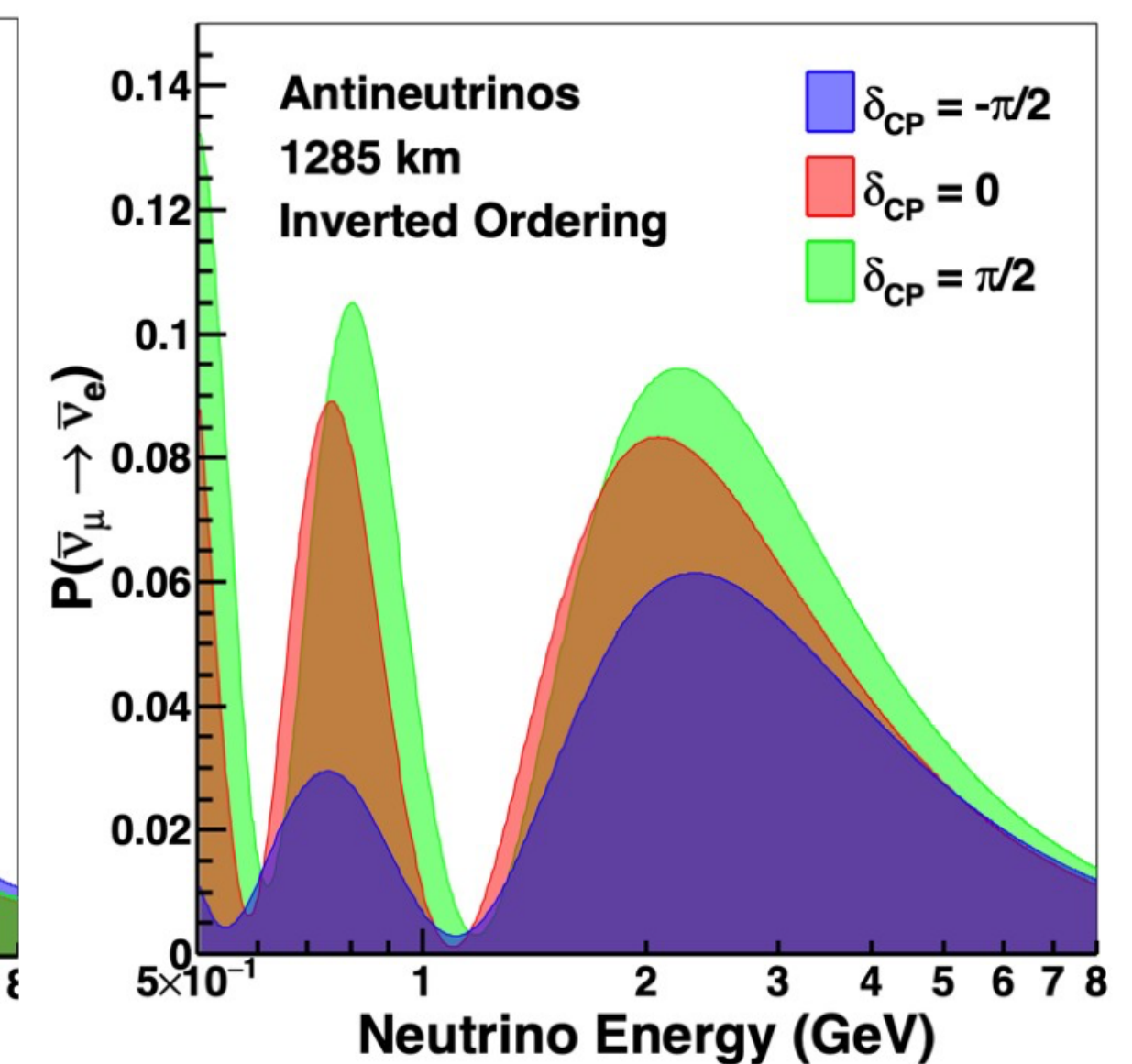
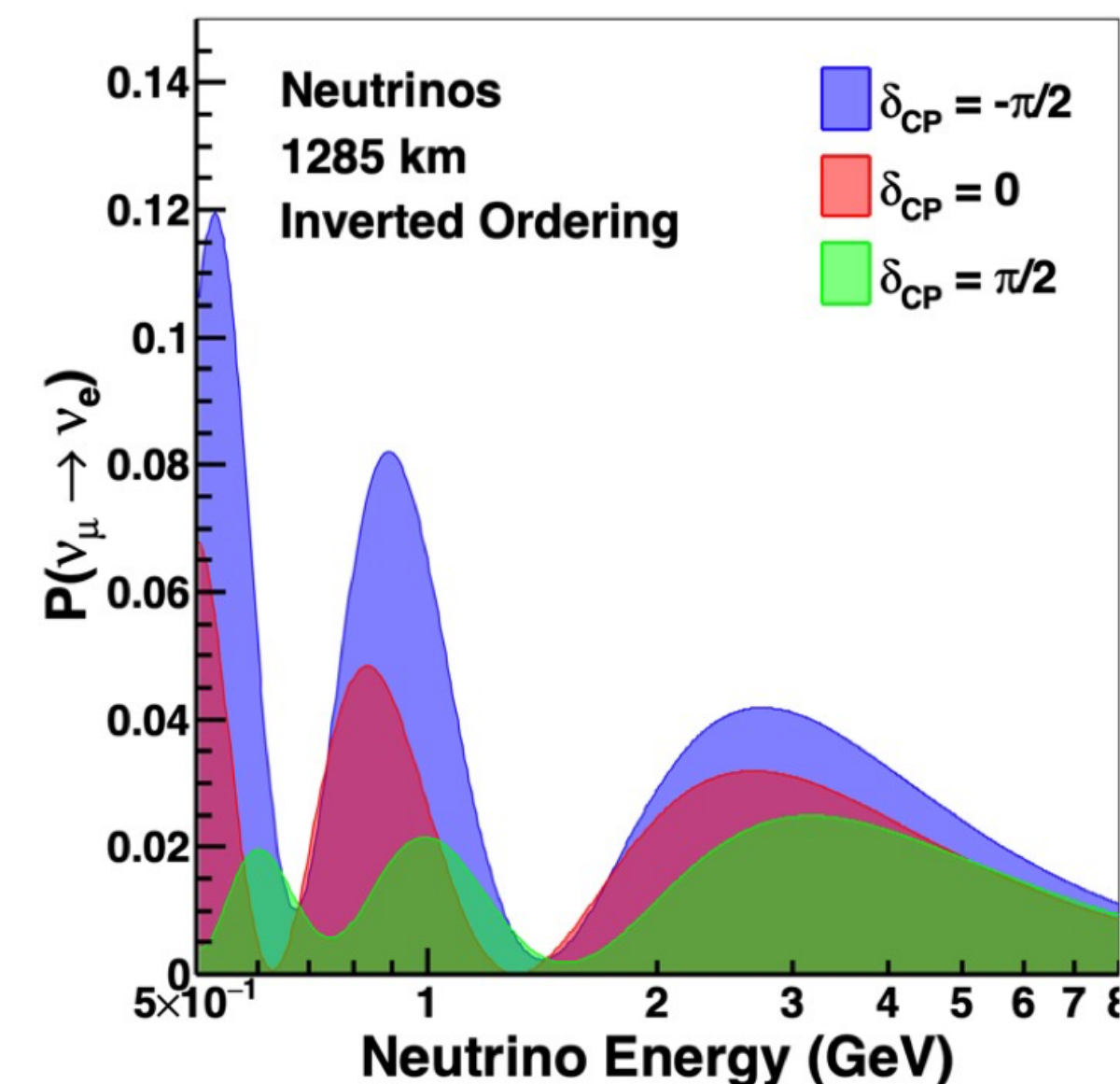
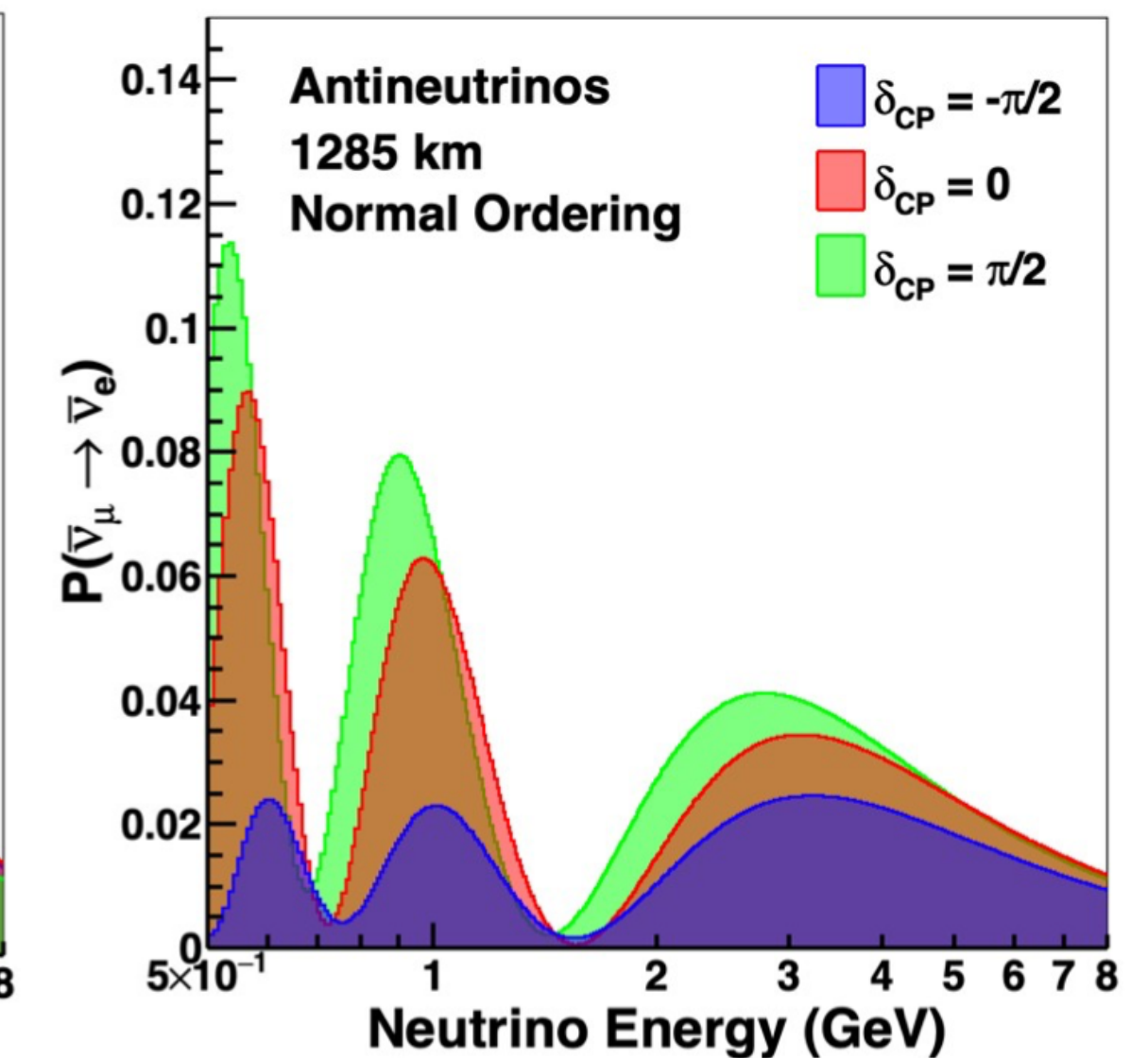
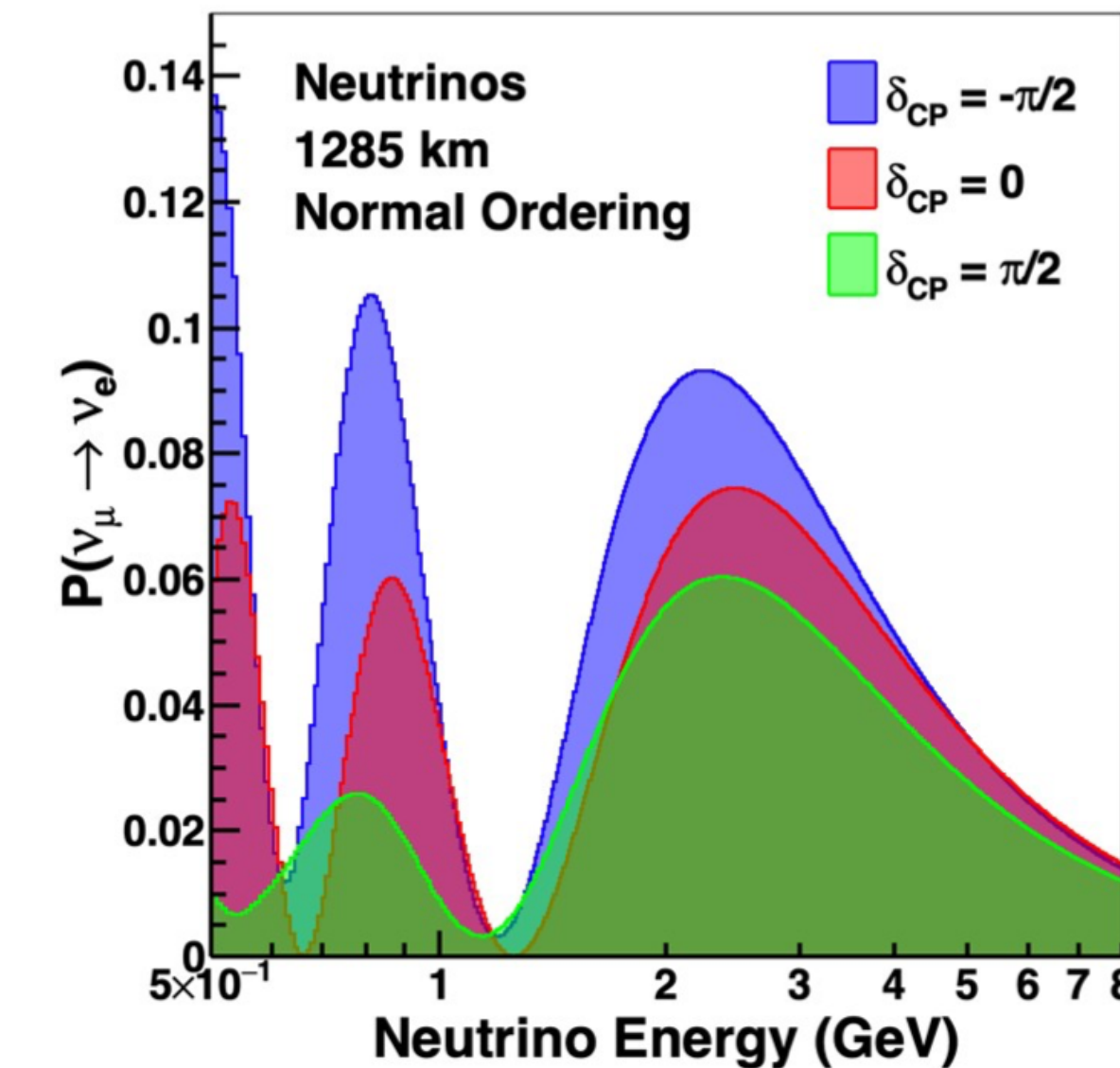
- To maximize signal: $(\Delta m^2 L / 4E) \sim \pi/2 \rightarrow E \gtrsim 2$ GeV
- Unfold CPV from matter effects using energy dependence \rightarrow use on-axis, wide-band neutrino beam.

DUNE measurement strategy

Precise measurement of all parameters that govern long-baseline oscillations $\nu_\mu \rightarrow \nu_{\mu,e}$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_{\mu,e}$, including the still-unmeasured **CP-violation phase**.

Effect of mass ordering, CP violation, θ_{23} octant have different shape as a function of L/E . Measuring oscillations over a wide energy range helps resolve degeneracies.

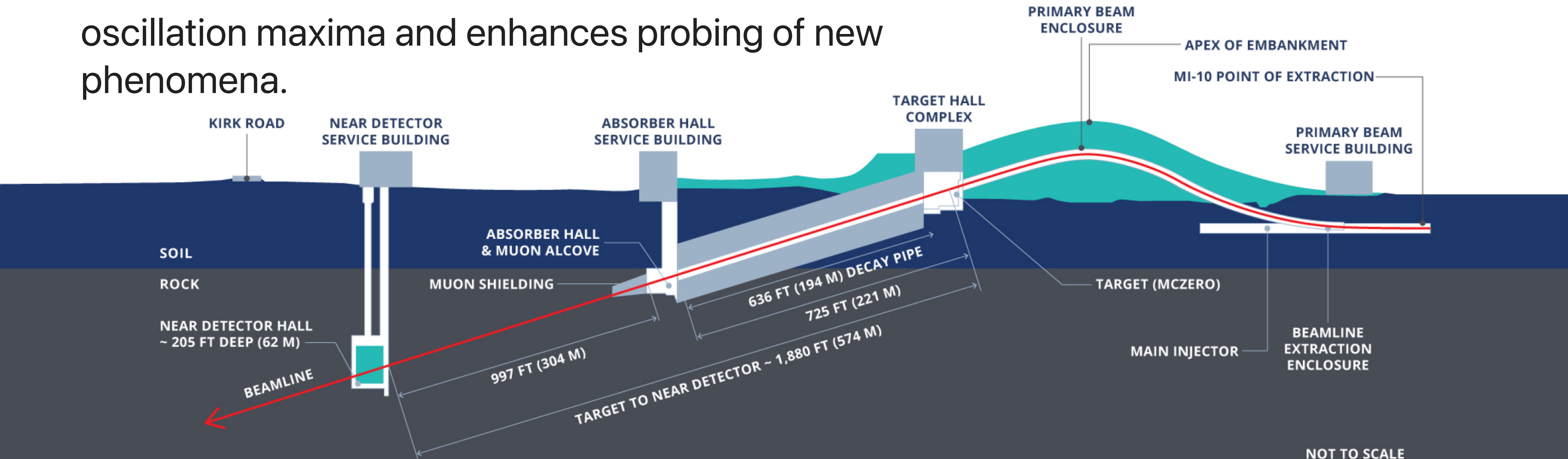
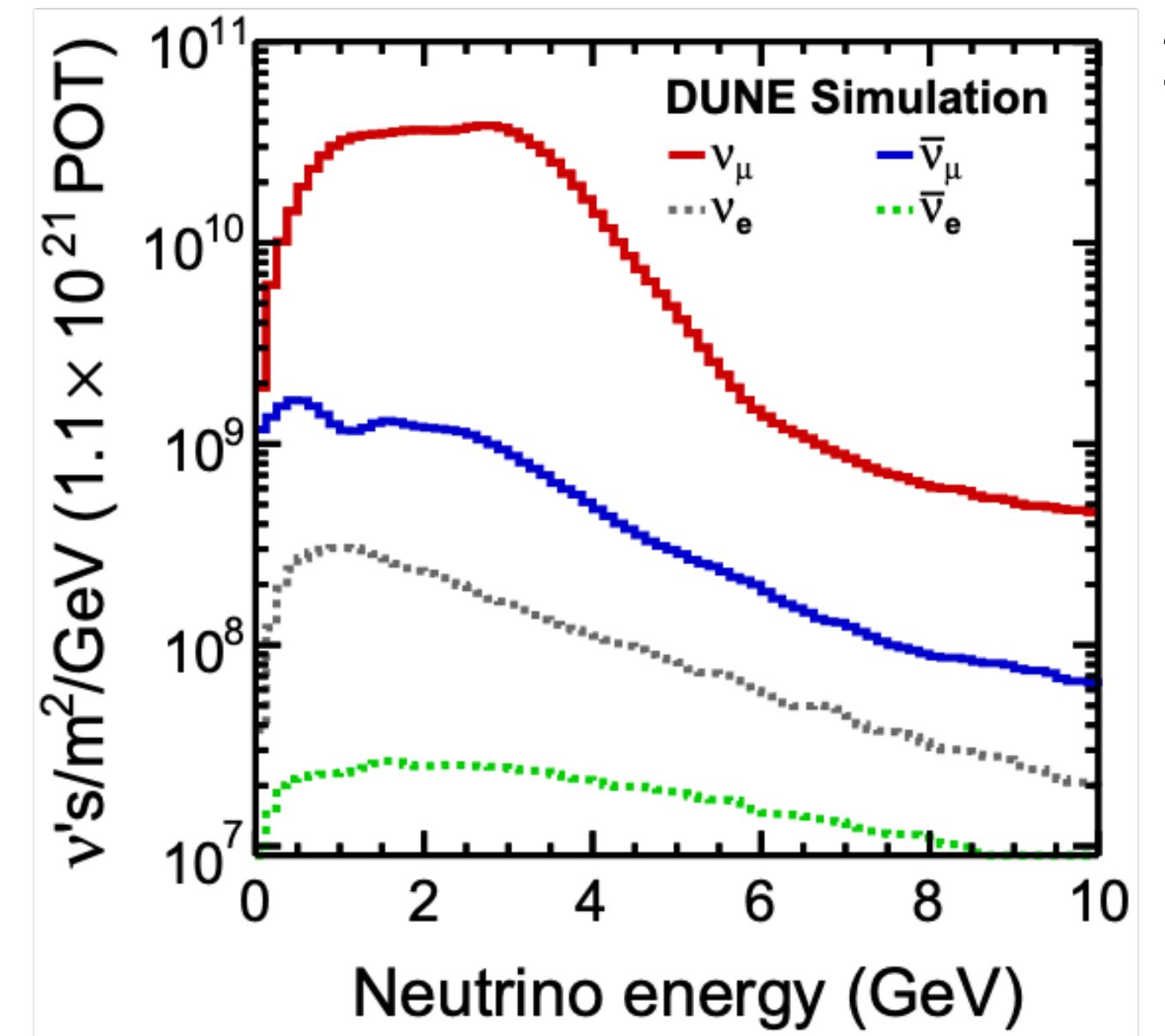
This is unique to DUNE, and complementary to other experiments with narrow flux spectra.



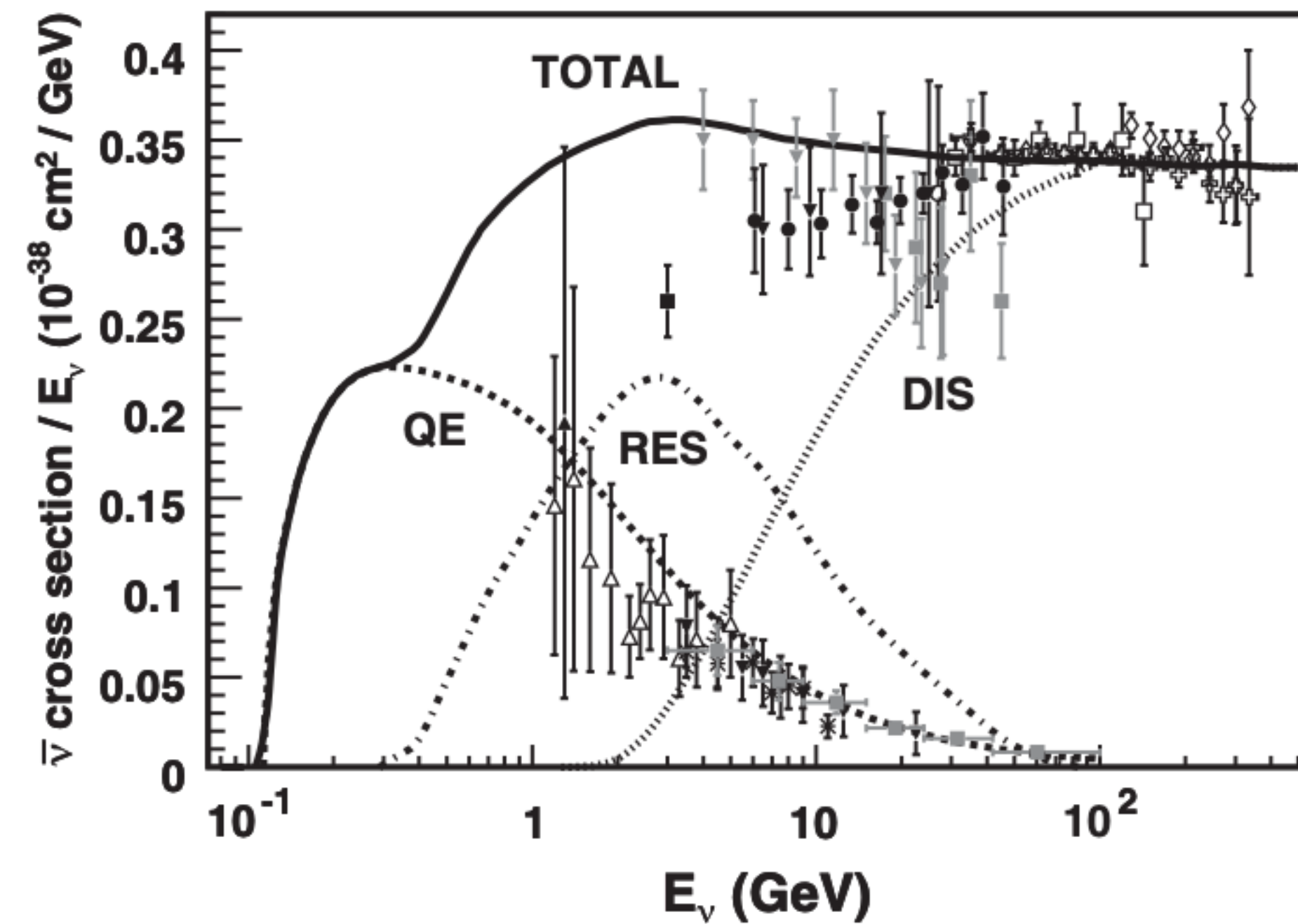
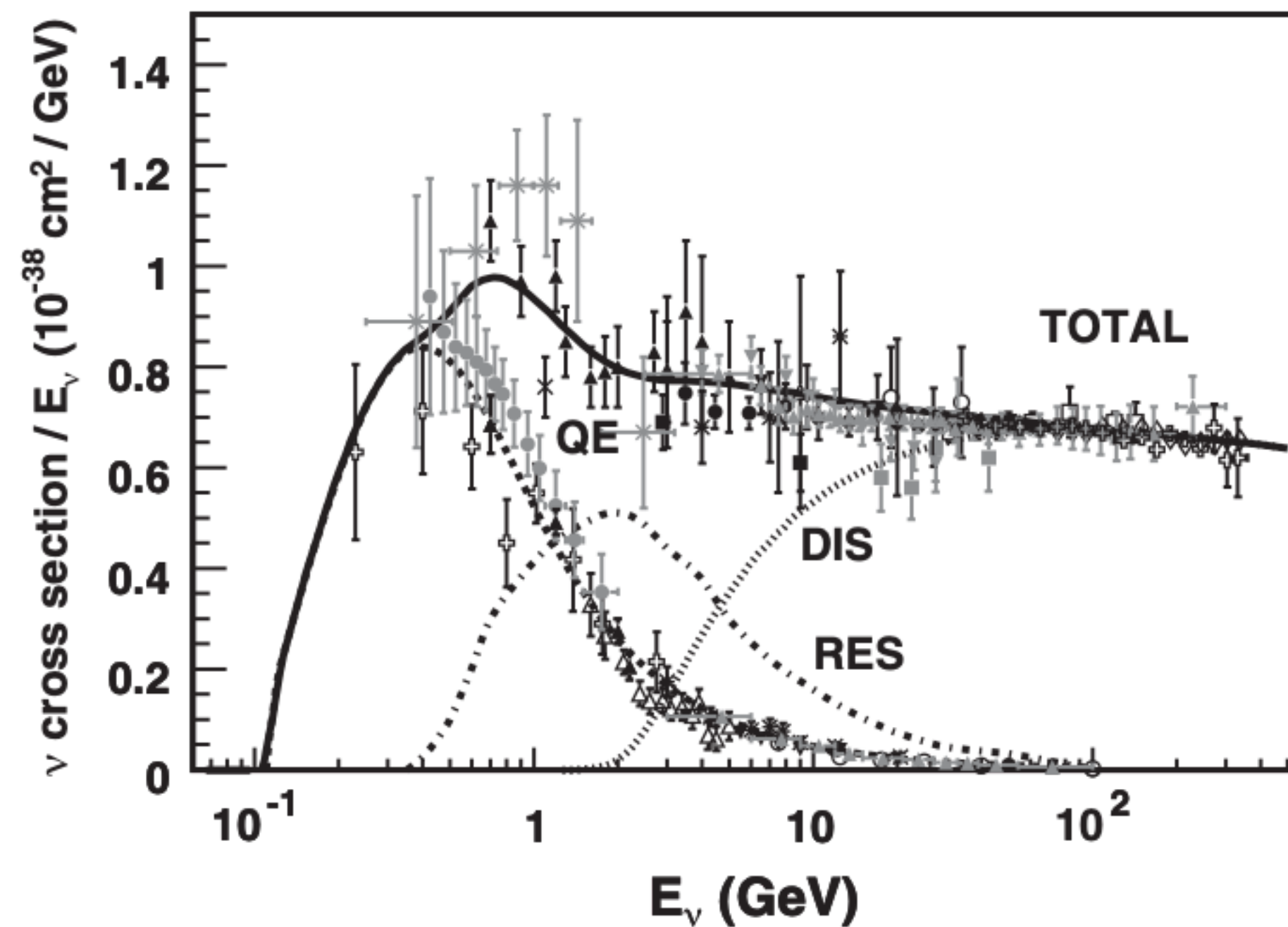
LBNF neutrino beam

It will use protons (60–120 GeV) from Fermilab's Main Injector with an initial power of 1.2 MW ($\sim 10^{21}$ POT/yr), upgradeable later to 2.4 MW.

The wide-band beam enables the use of the 1st and 2nd oscillation maxima and enhances probing of new phenomena.



Neutrino cross sections

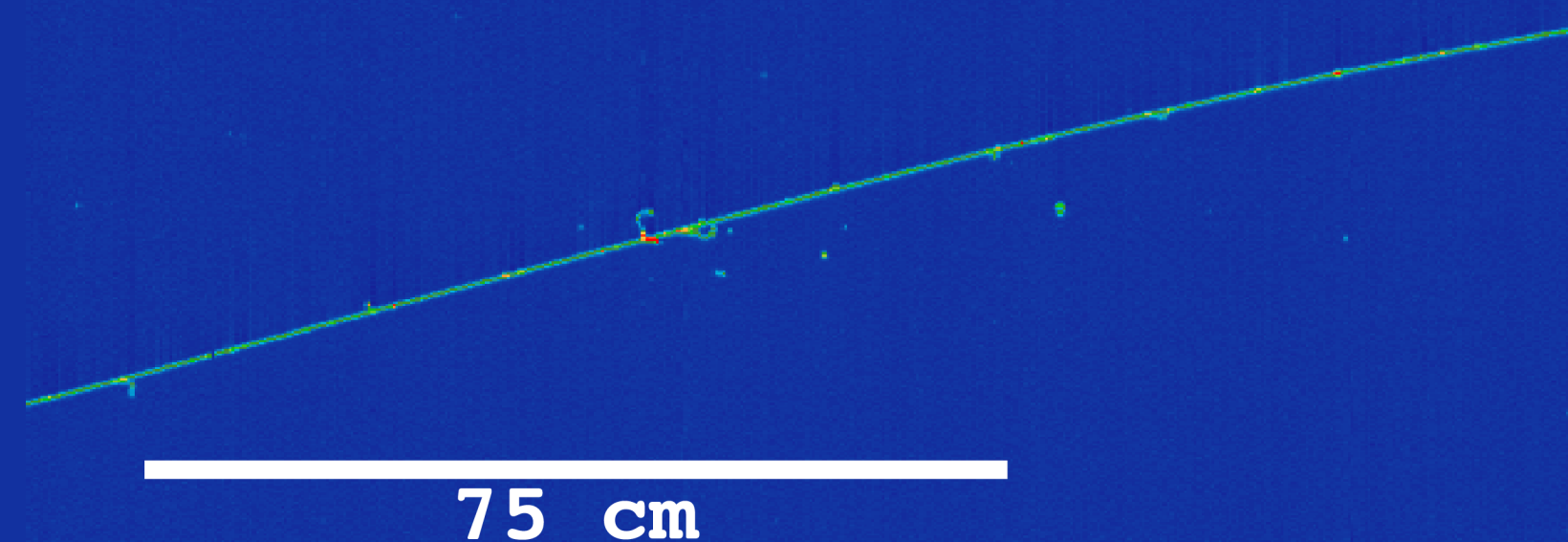


The wide energy range covered by DUNE includes contributions from several underlying processes, resulting in a variety of final states.

Liquid argon time projection chambers

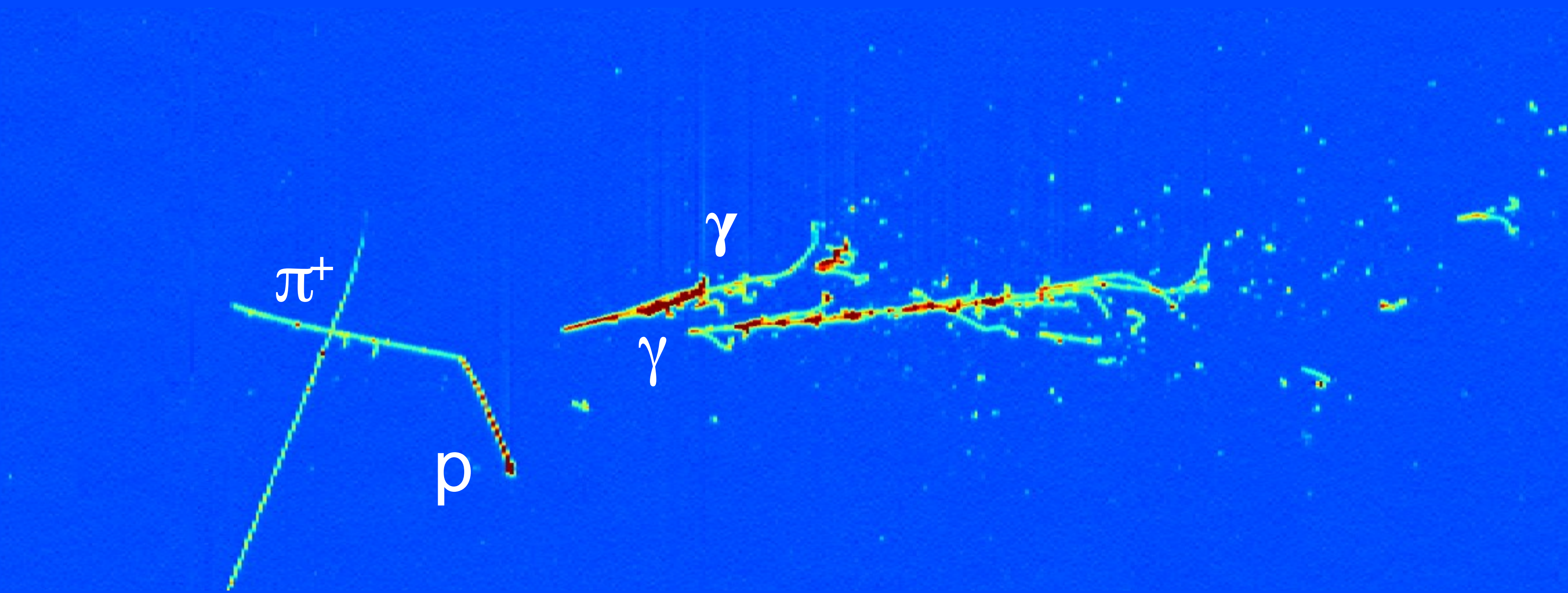
μ BooNE

Fine-grained, 3D images of neutrino interactions.
Low detection thresholds. Close to full acceptance. Particle
identification based on dE/dx and range.



Run 3493 Event 41075, October 23rd, 2015

Liquid argon time projection chambers



[ProtoDUNE-SP Run 5779 Event 12360]

The DUNE technology

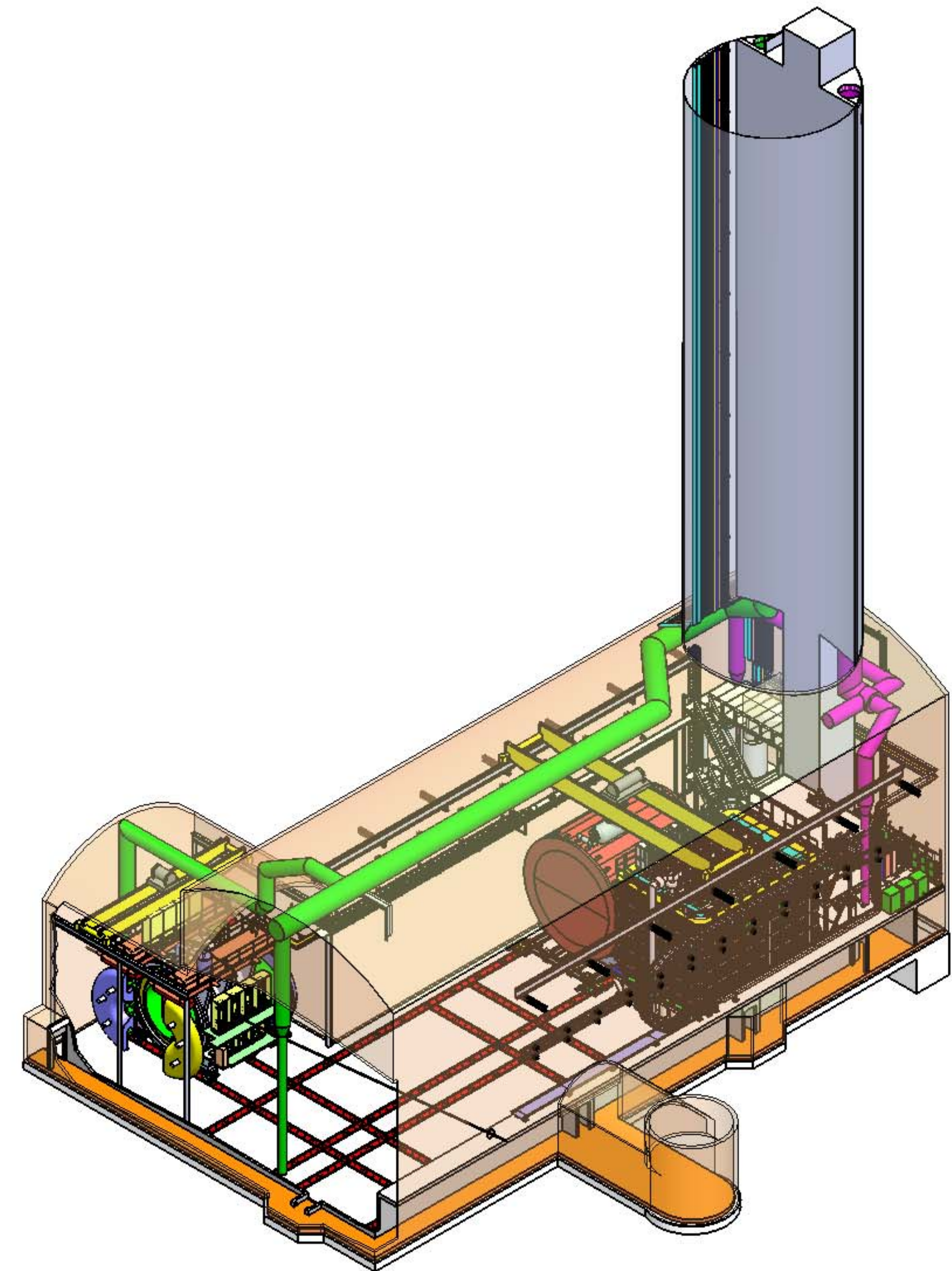
The near detector

Large uncertainties on flux, cross sections and detector response will be constrained to the few percent level by the ND.

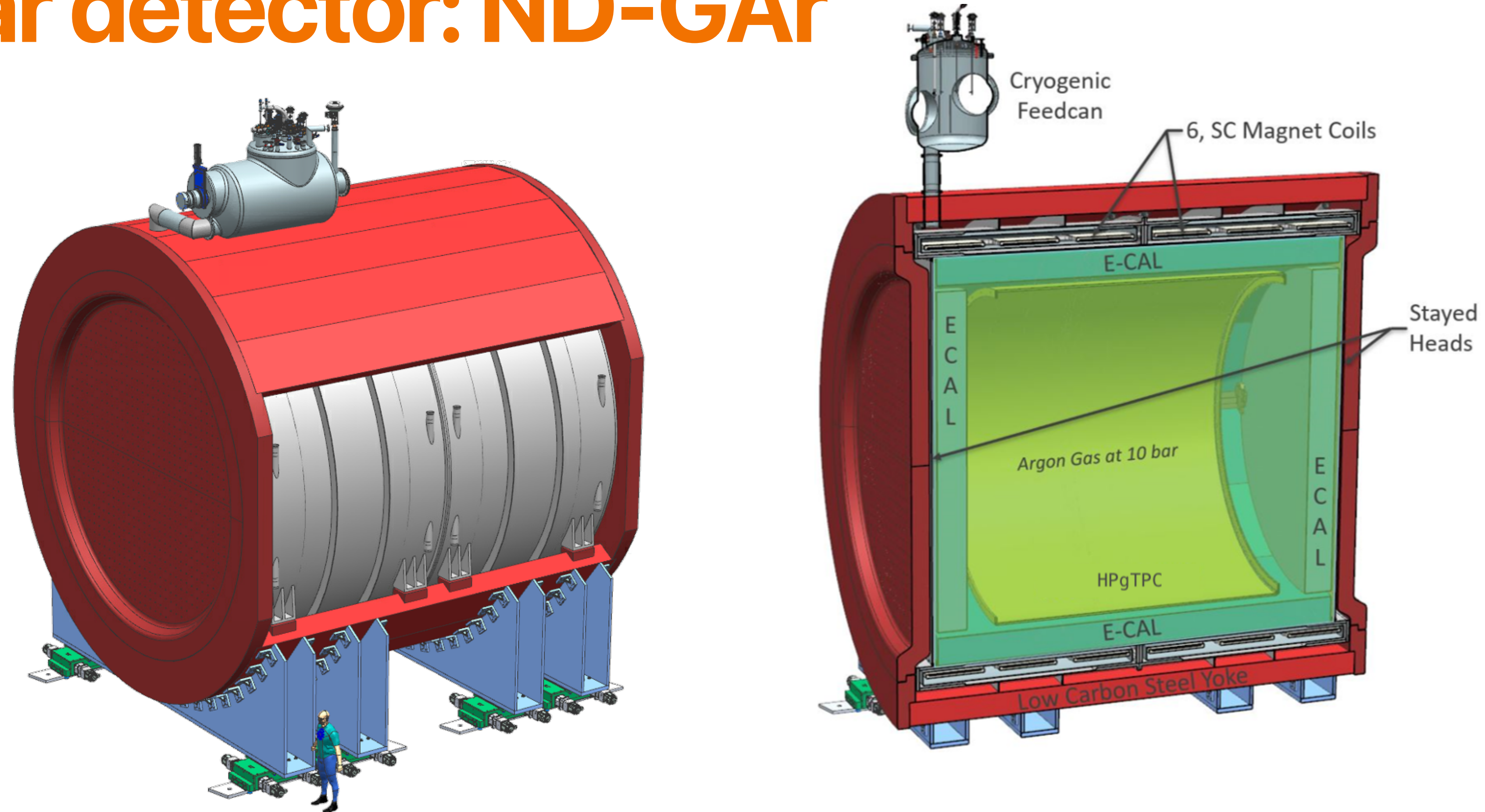
The conceptual design includes three different components:

- NDLAr: 150 t LArTPC with pixelated readout.
- TMS: magnetised muon spectrometer.
- SAND: magnetised tracker and ECAL used as beam monitor.

The design includes the possibility of taking data at off-axis positions with the Ar TPCs, exposing them to neutrino fluxes with different spectra.

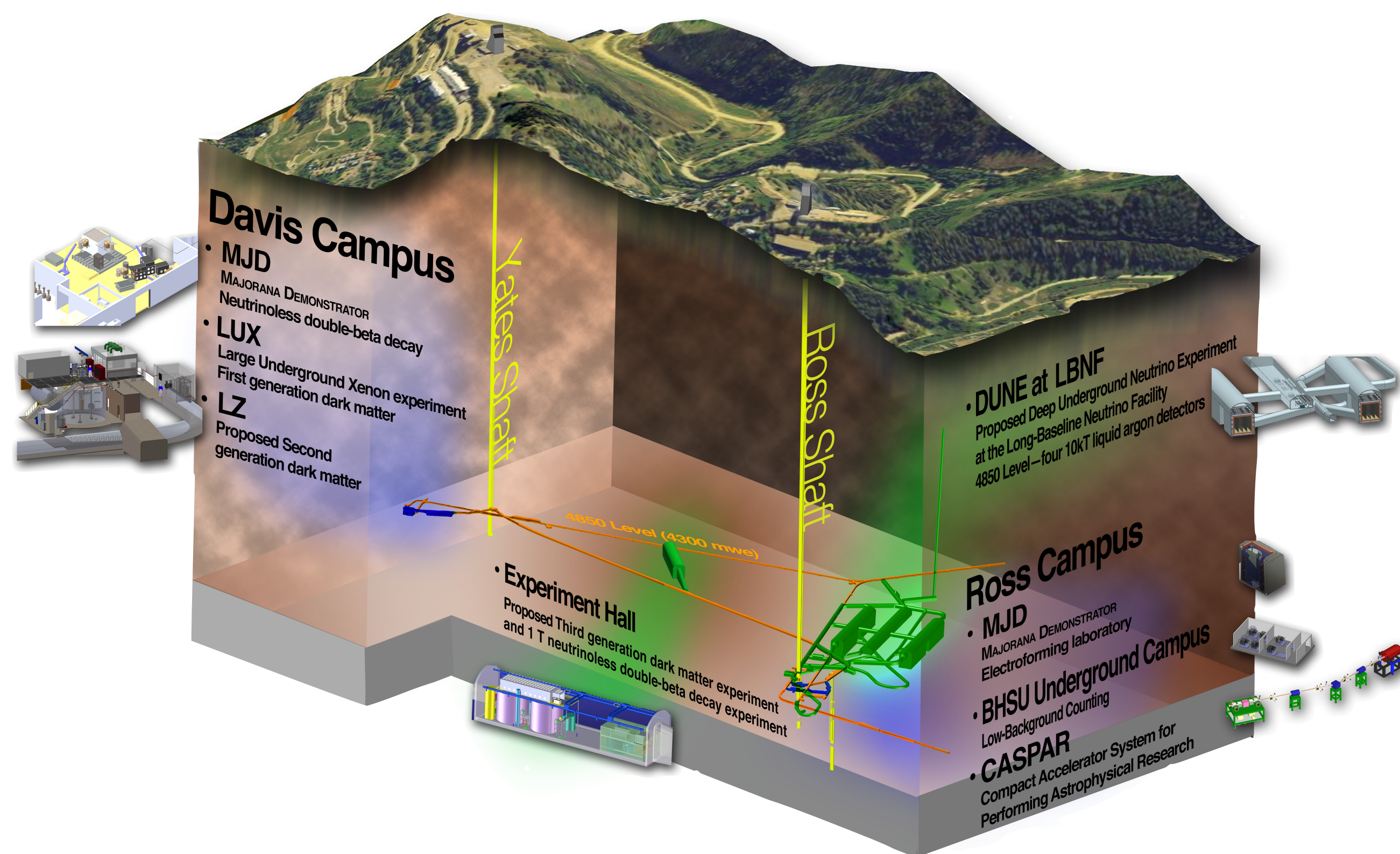


The near detector: ND-GAr

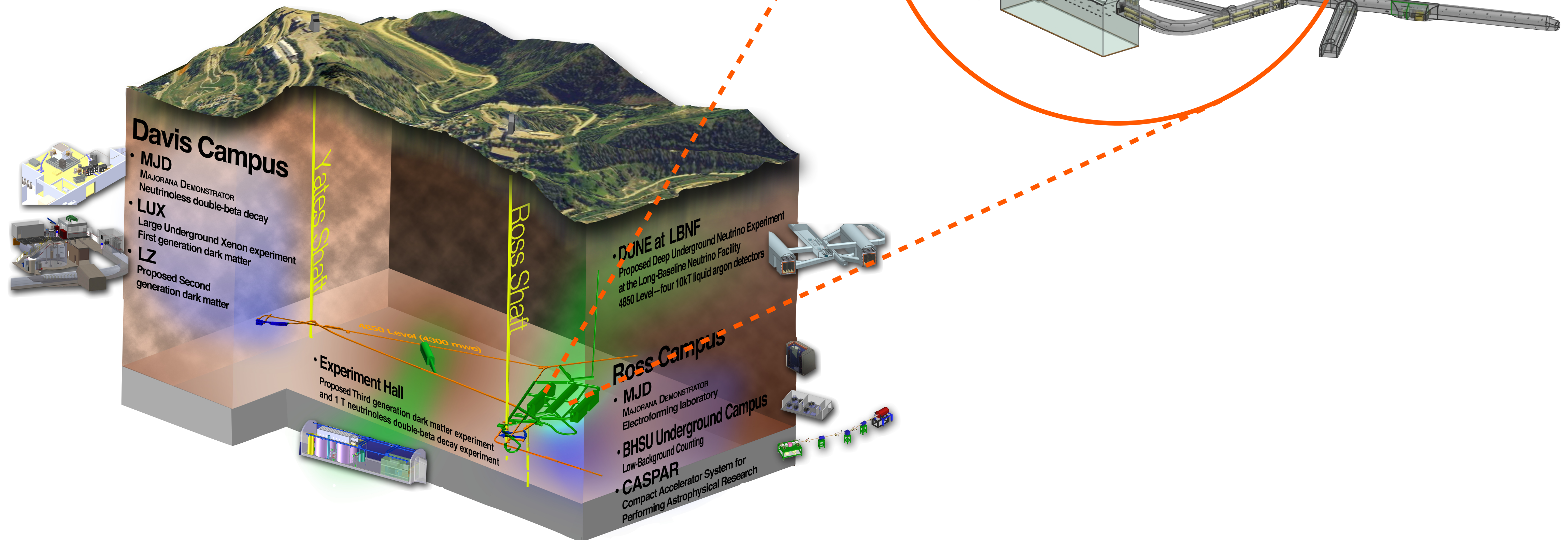


In Phase II, TMS will be replaced by a magnetised 1-tonne argon gas TPC (NDGAr). IFIC (together with IGFAE and Vigo) participates in the R&D effort for this detector.

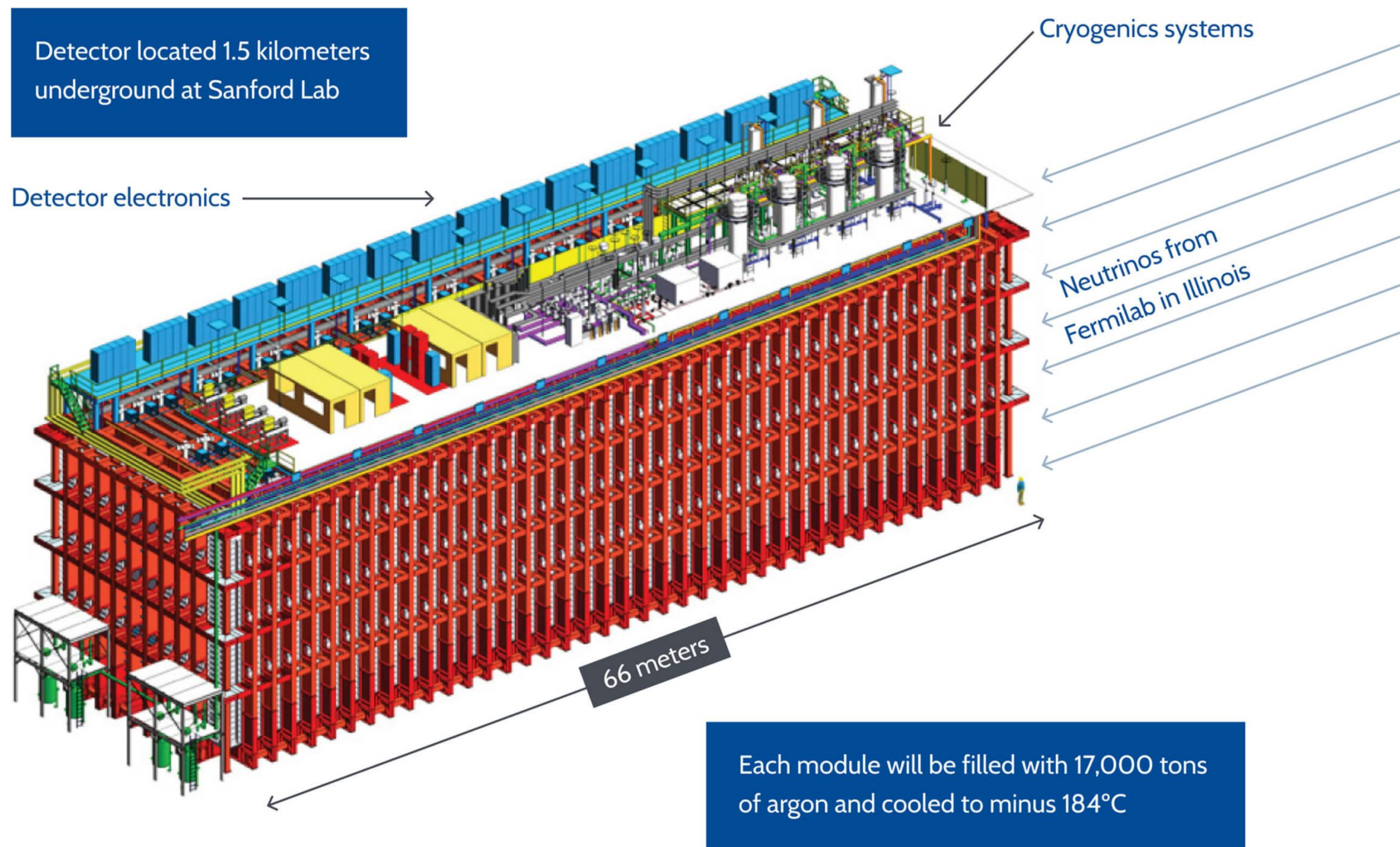
The DUNE far detector



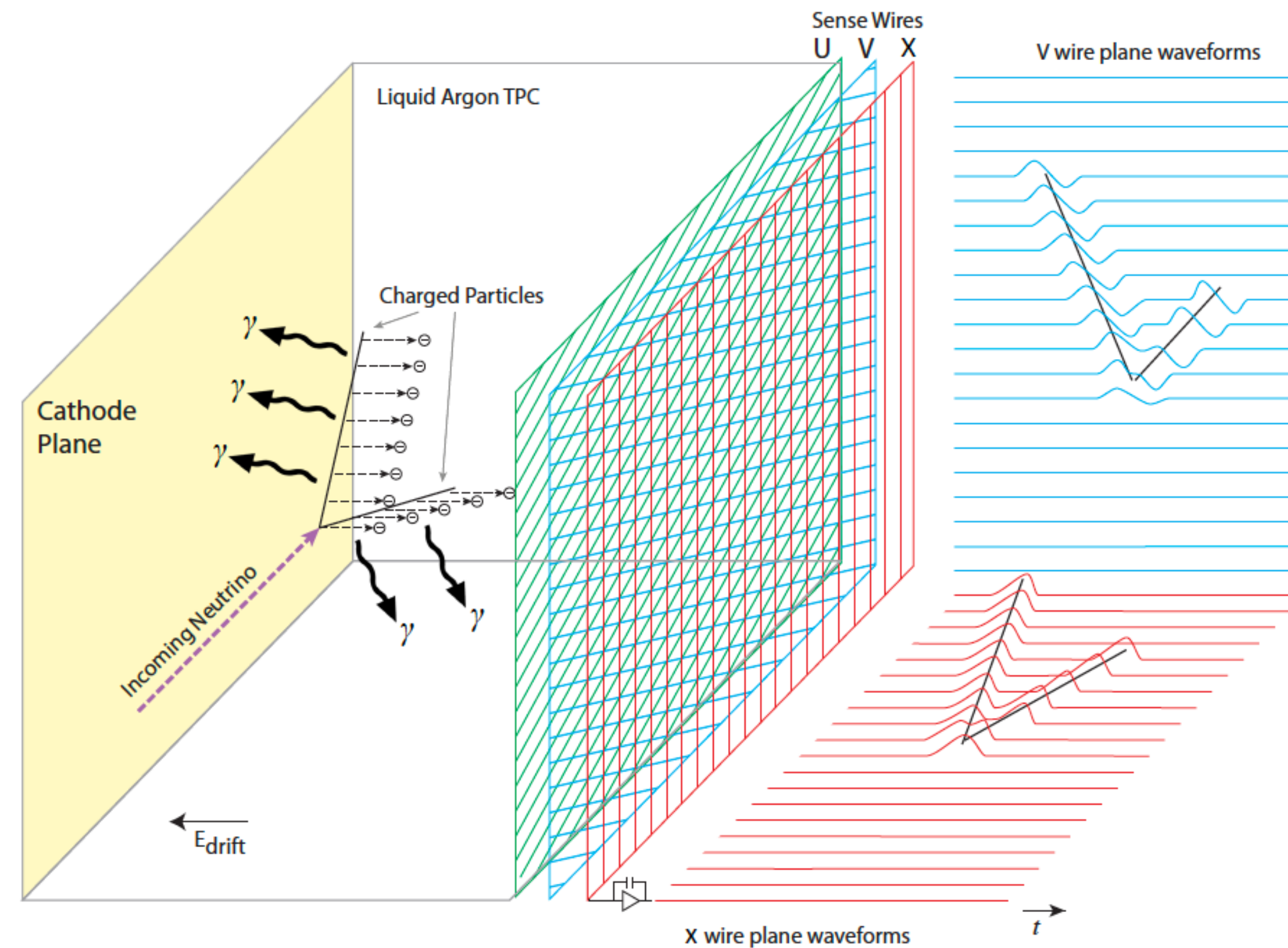
The DUNE far detector



The DUNE far detector

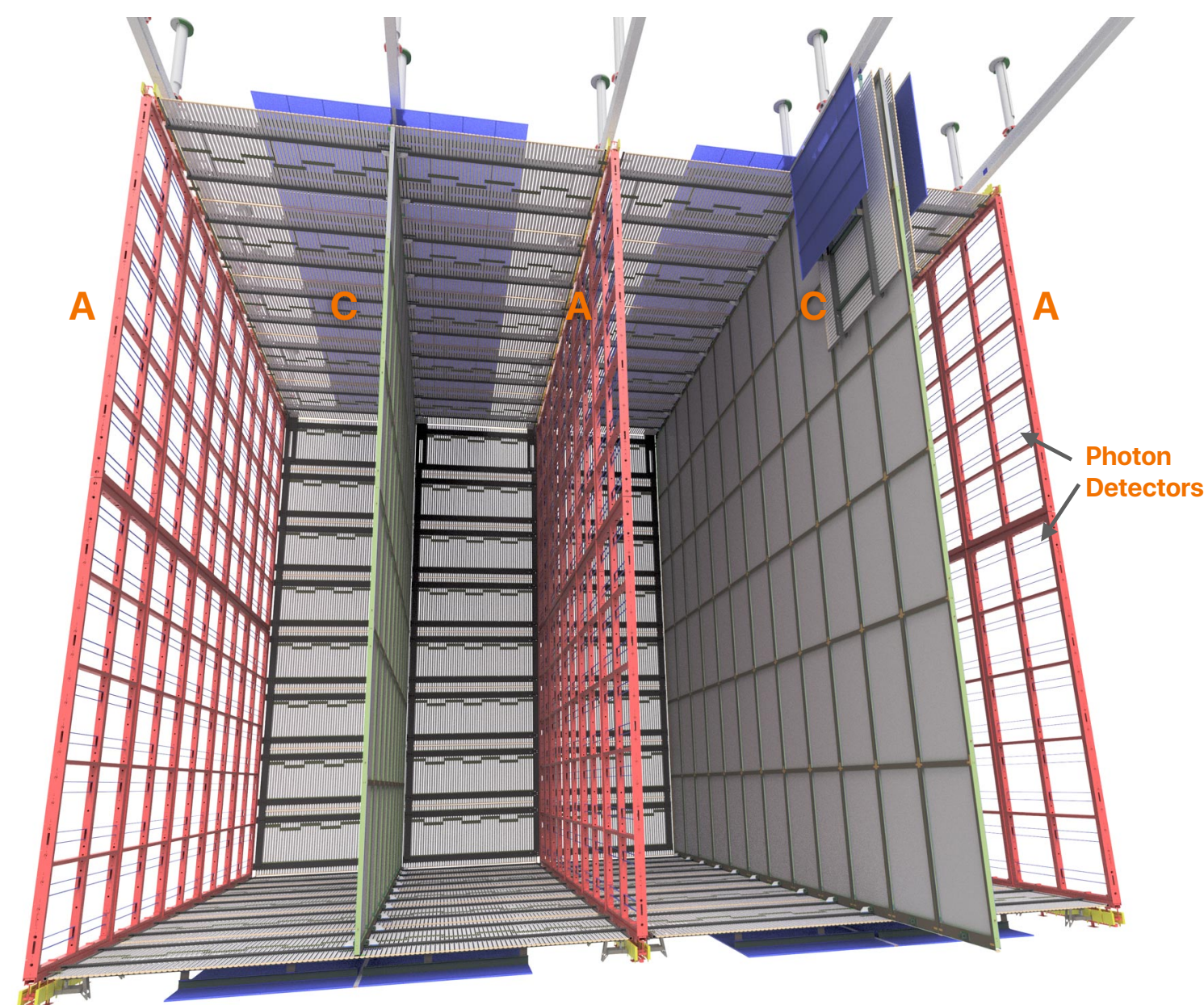


The DUNE far detector

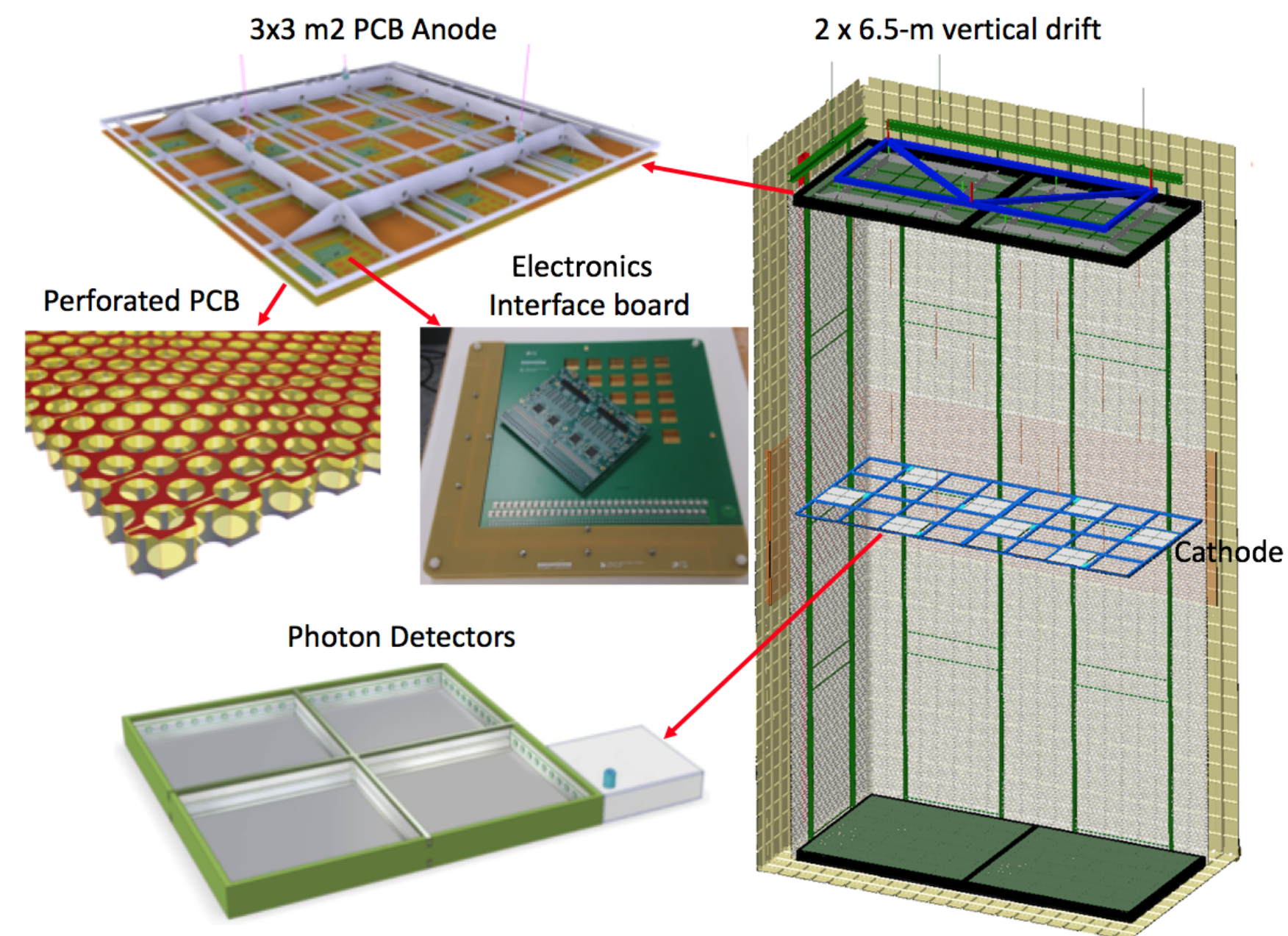


Photon detectors (not shown) collect the scintillation light produced in the interaction to signal the start time of the interaction. Ionization electrons produced by interacting particles drift in an electric field towards the readout plane (in this case, consisting of three planes of sense wires).

The DUNE far detector



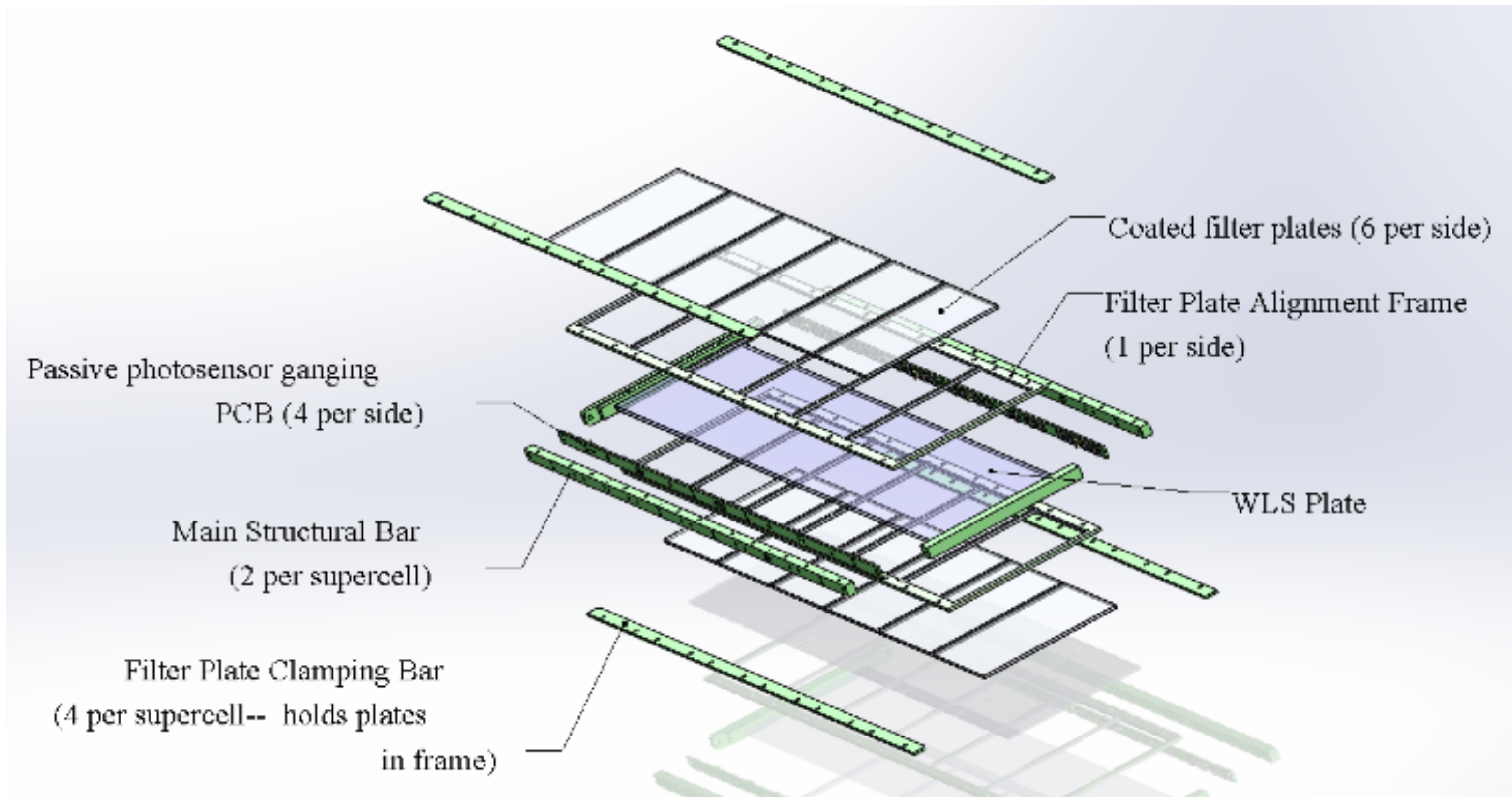
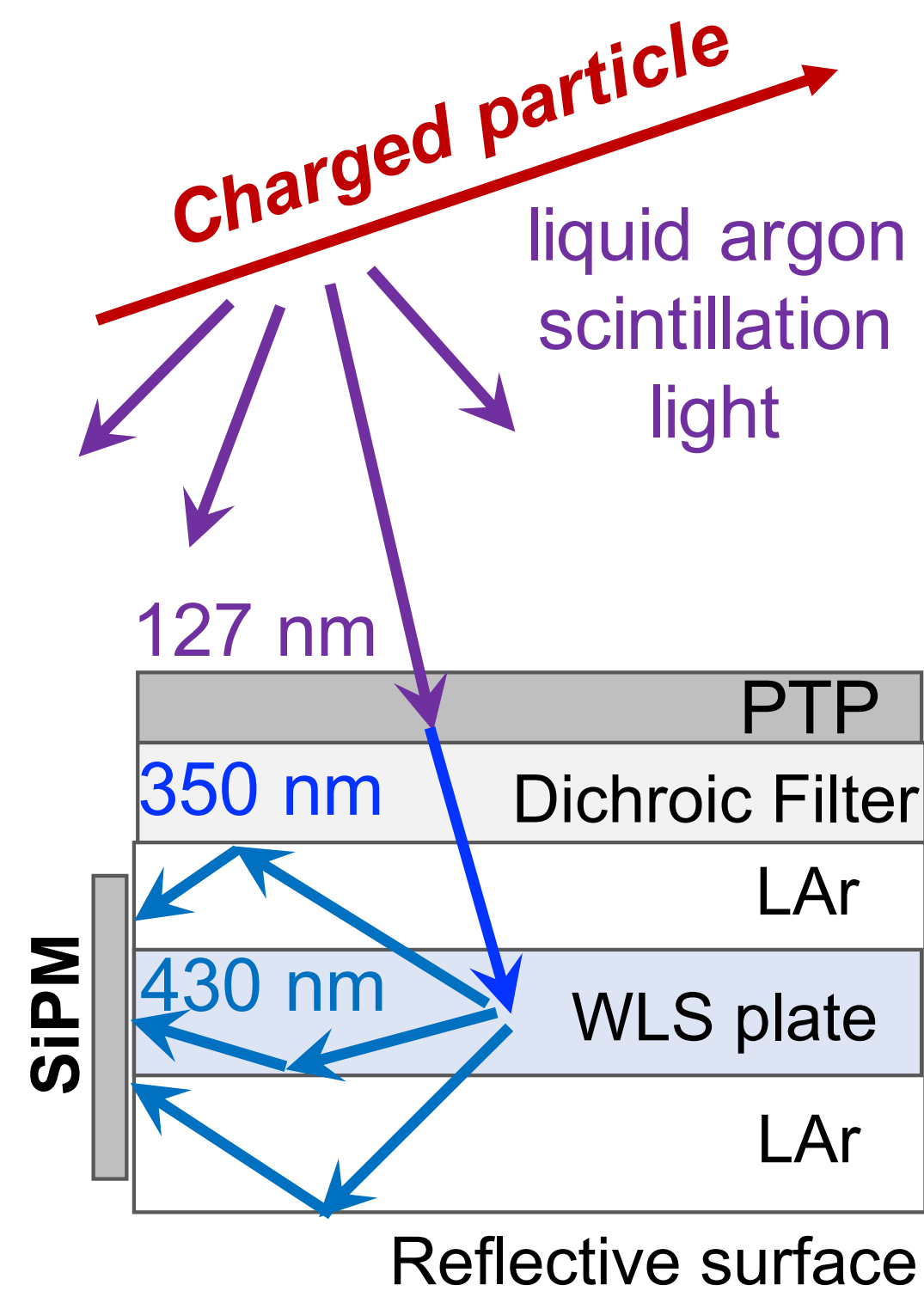
FD-1: Horizontal drift



FD-2: Vertical drift

The four DUNE modules are not a clone of a single system because they reap the advances of the R&D that is ongoing (as soon as it is mature for a large-scale implementation).

FD photon detection system (PDS)

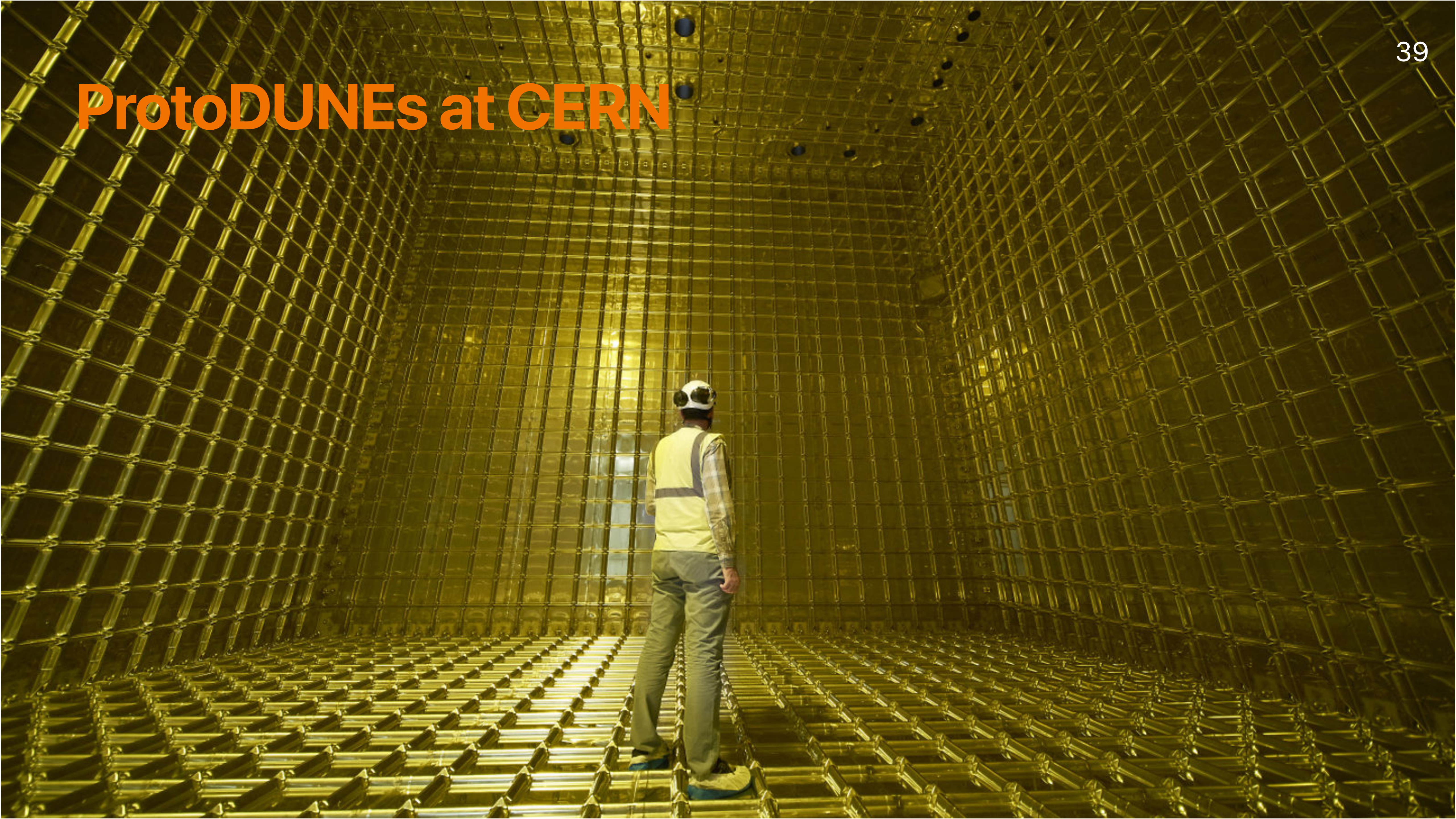


The PDS —based on the X-ARAPUCA concept— is the main area of involvement of IFIC (and the other Spanish groups) in the construction of the DUNE FD.

ProtoDUNE_s at CERN

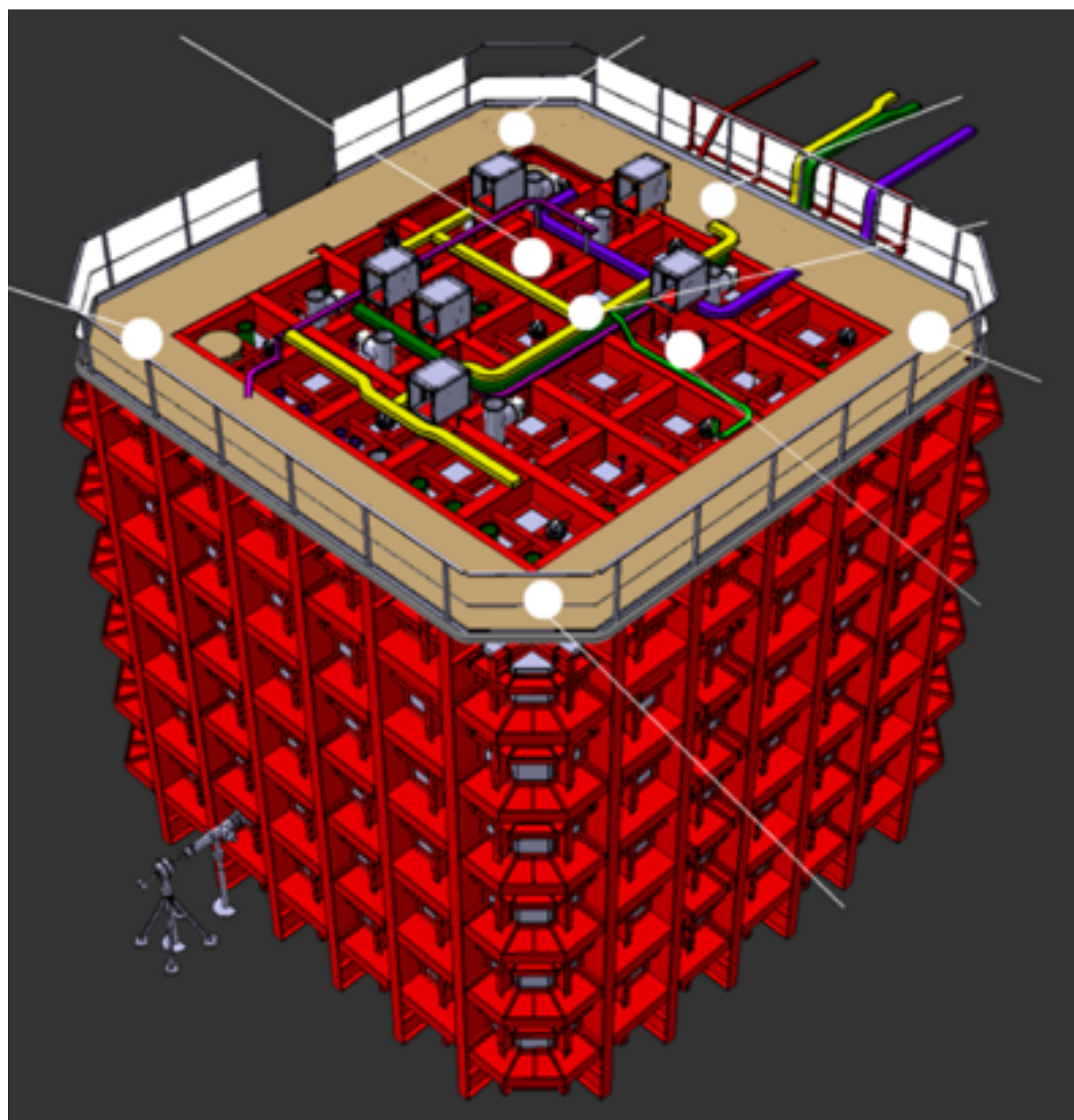


ProtoDUNE_s at CERN

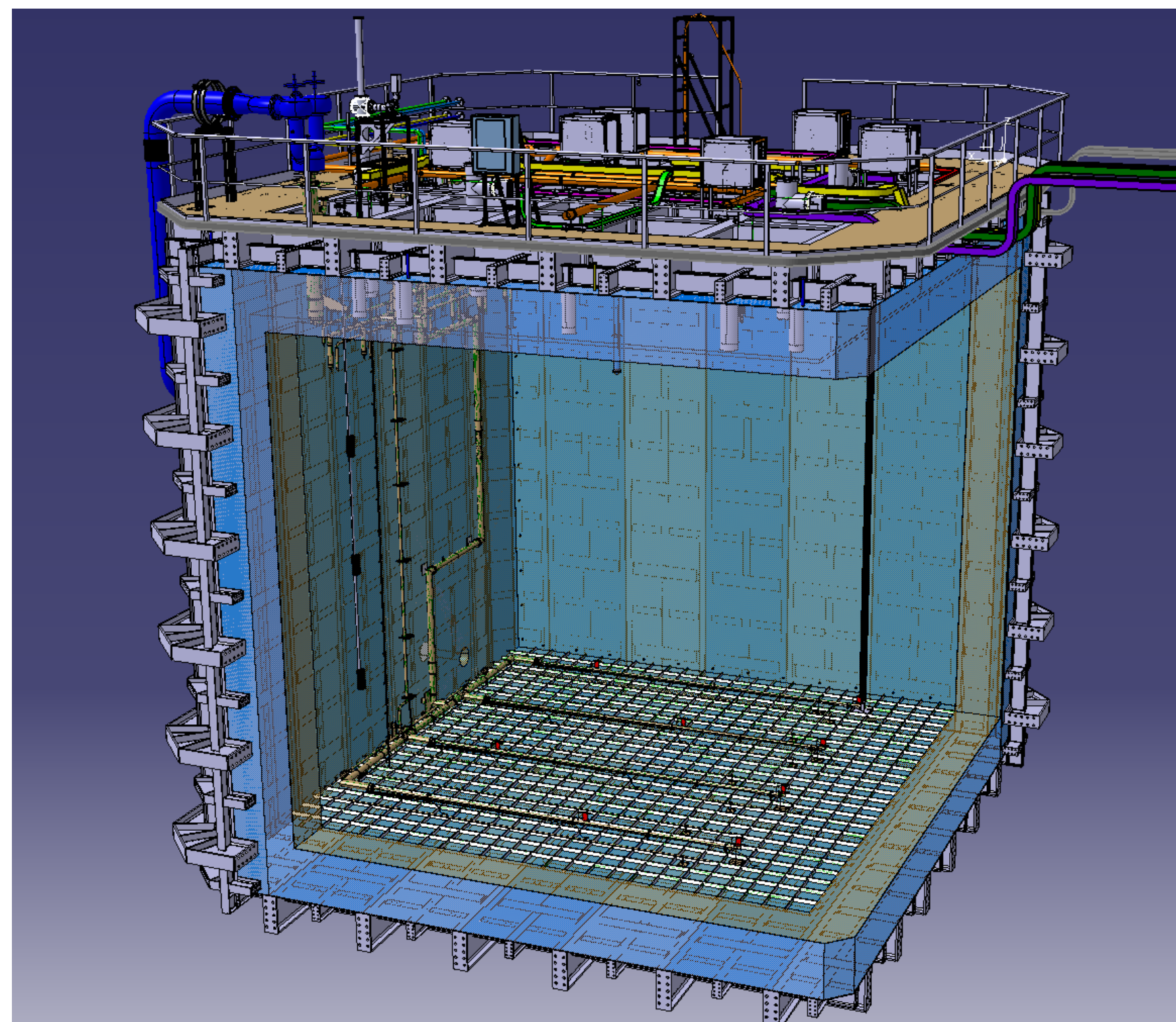
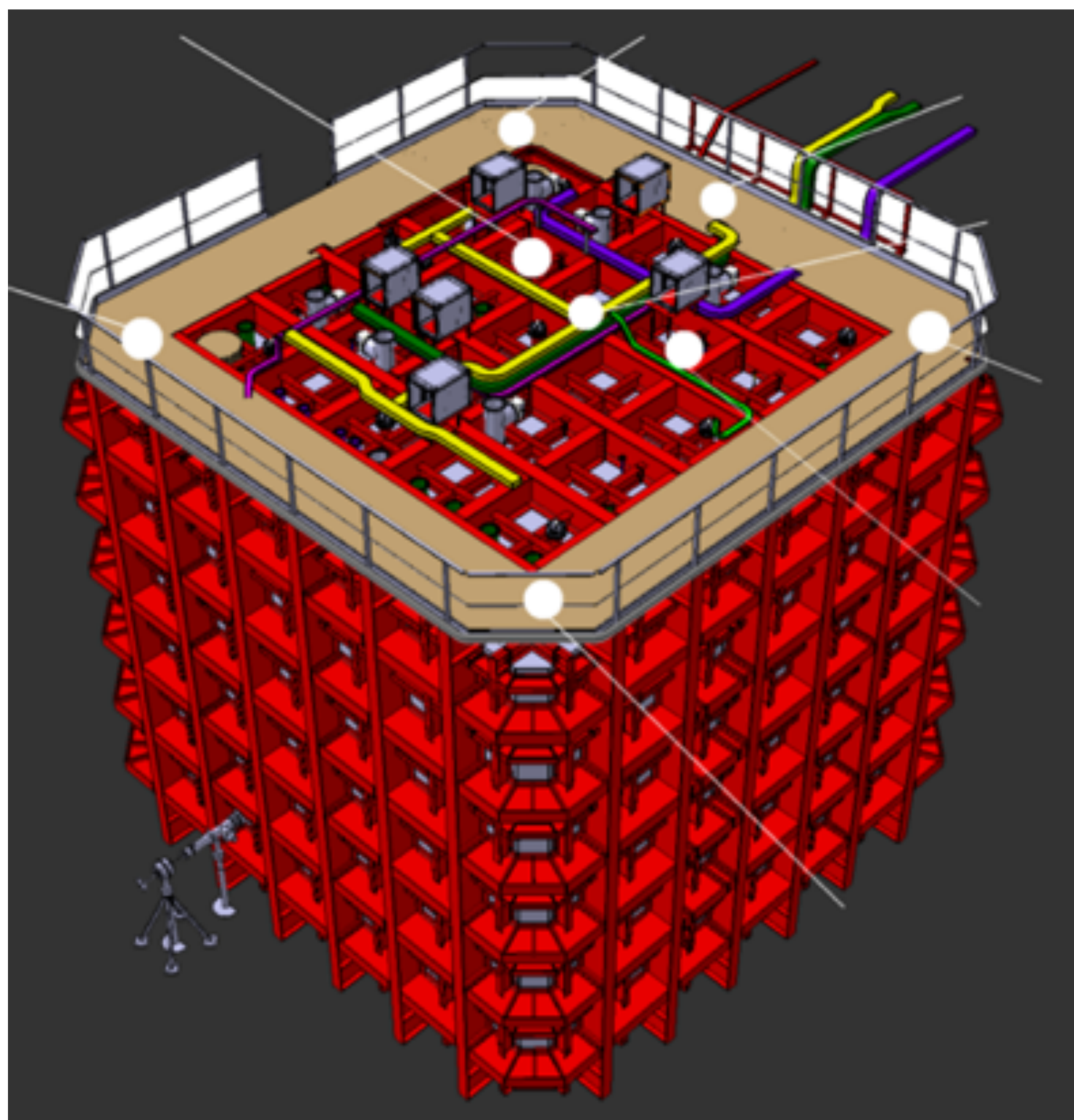


ProtoDUNE_s at CERN

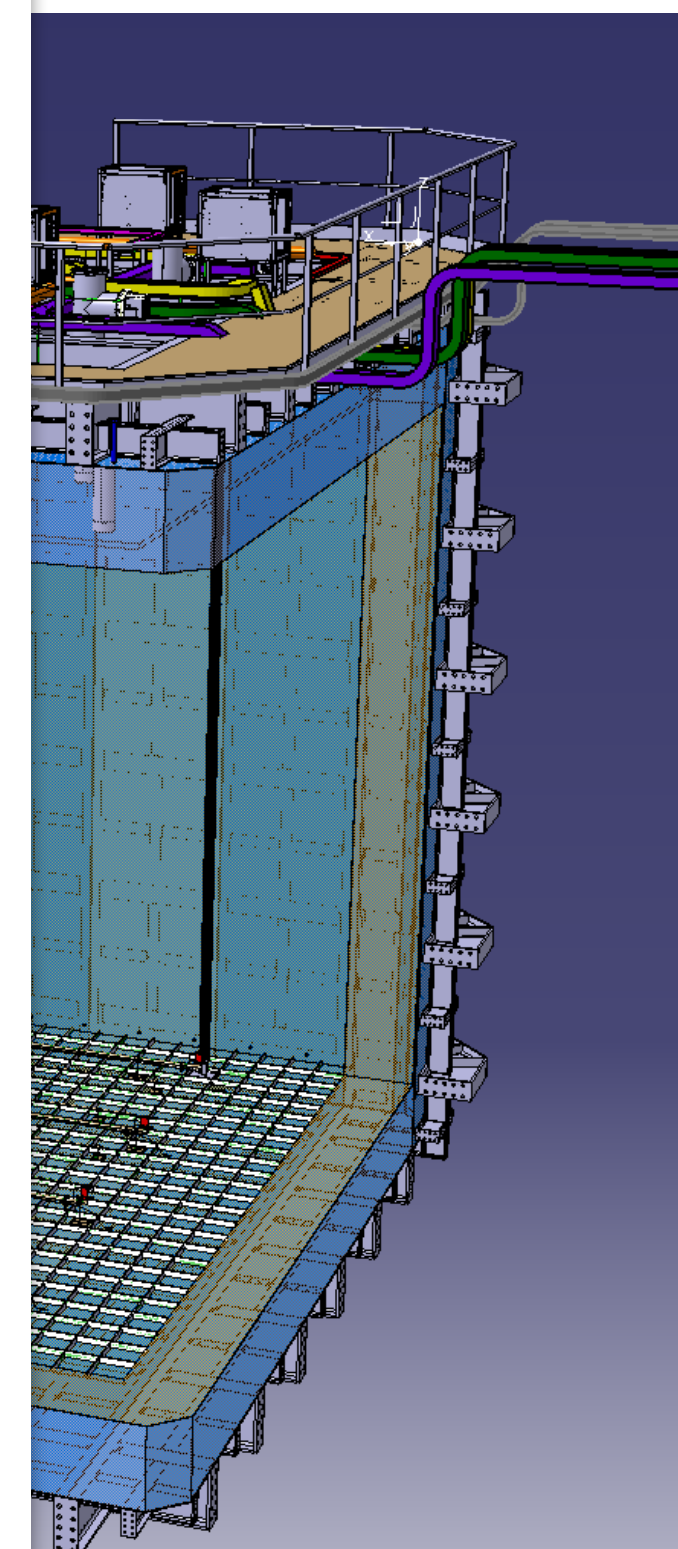
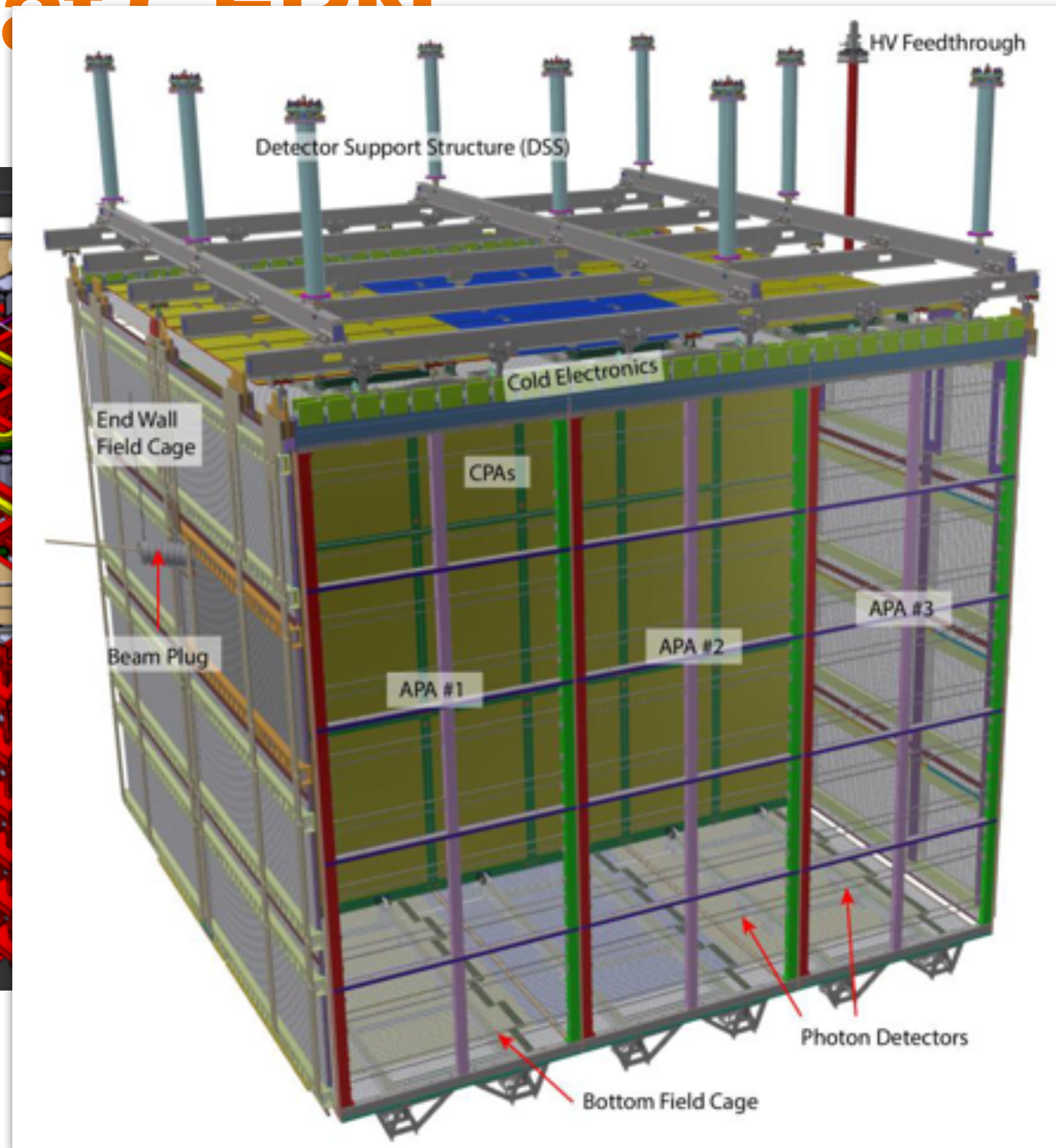
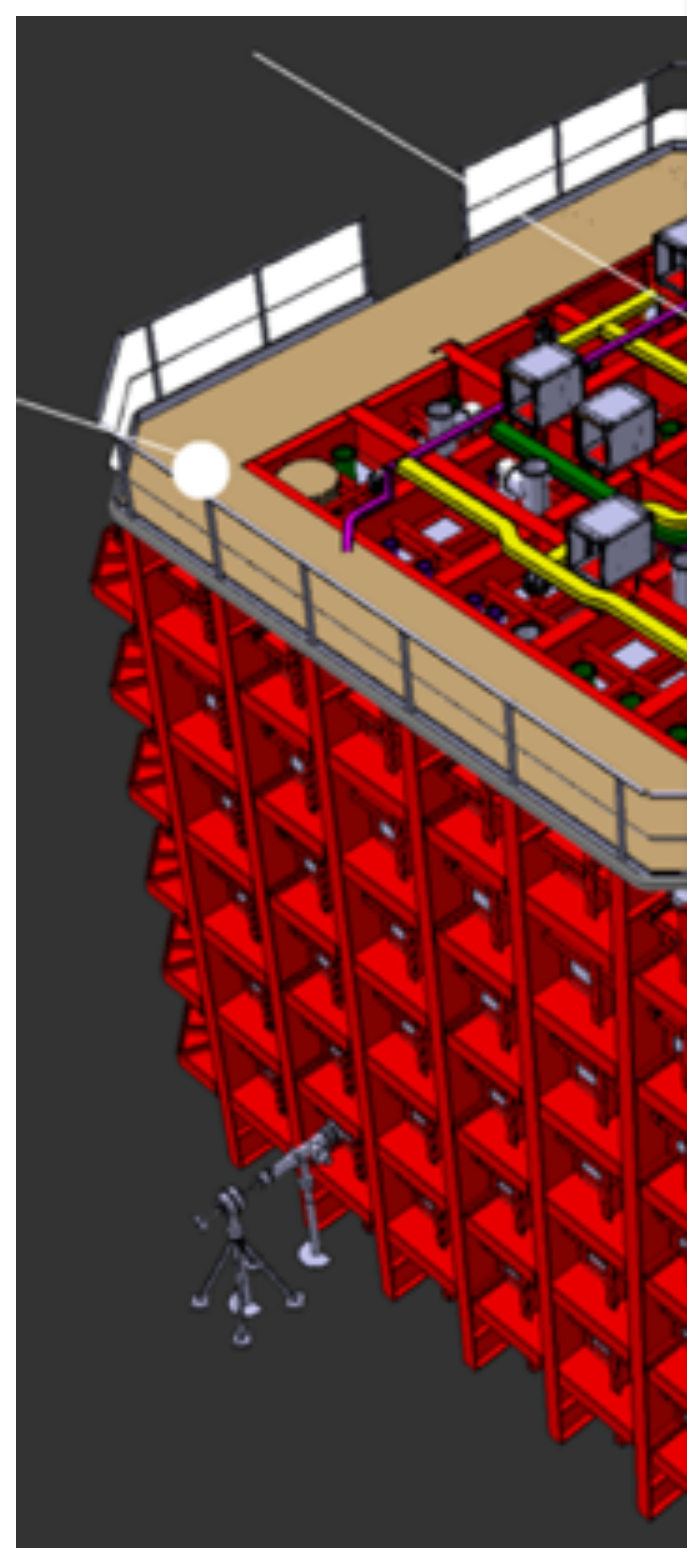
ProtoDUNE_s at CERN



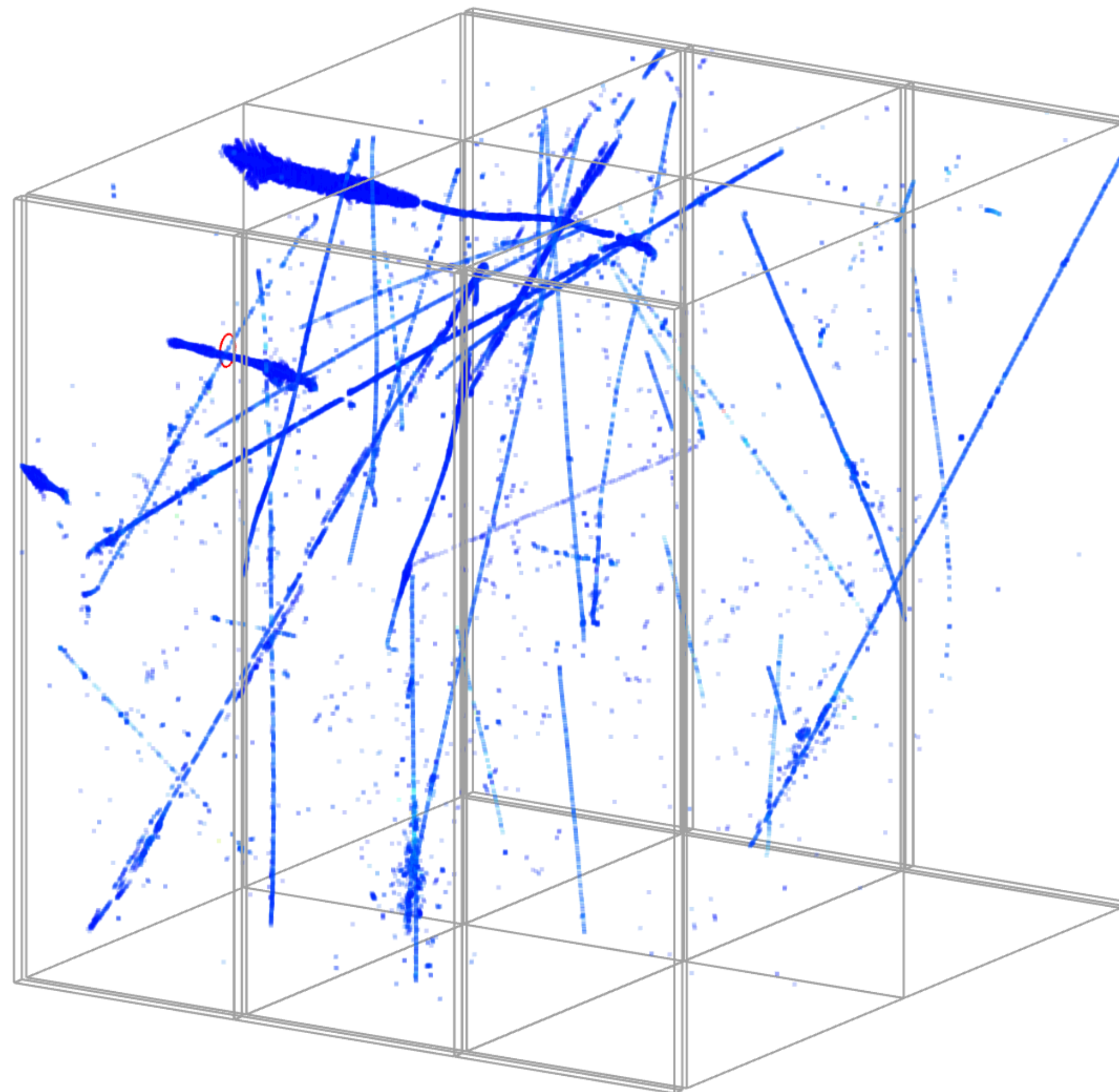
ProtoDUNE_s at CERN



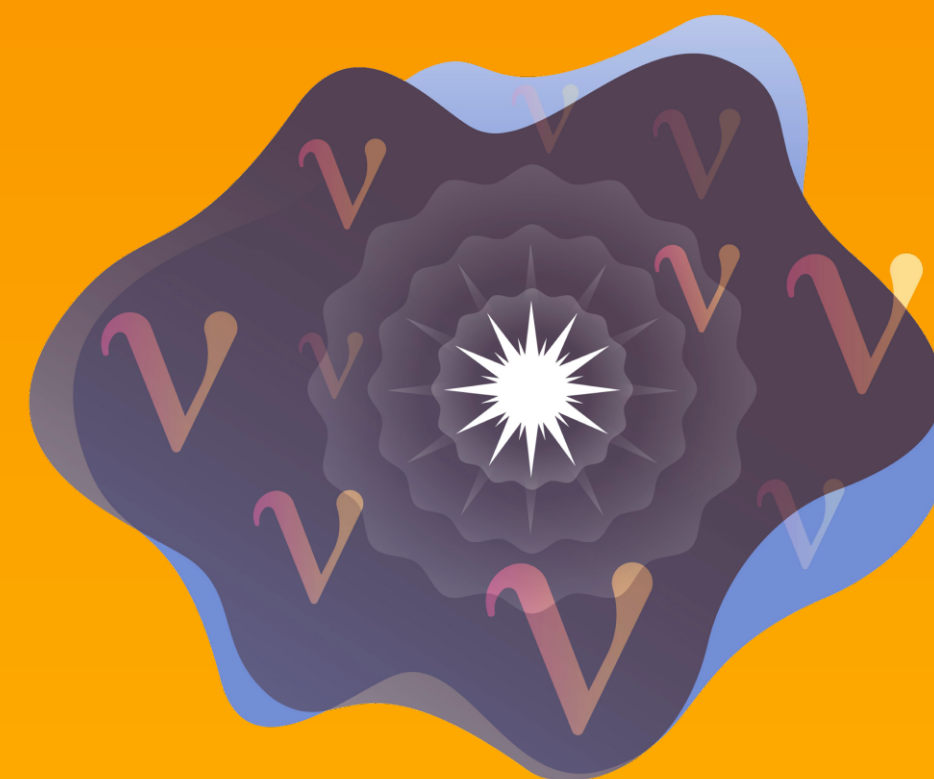
ProtoDUNE at CEDR



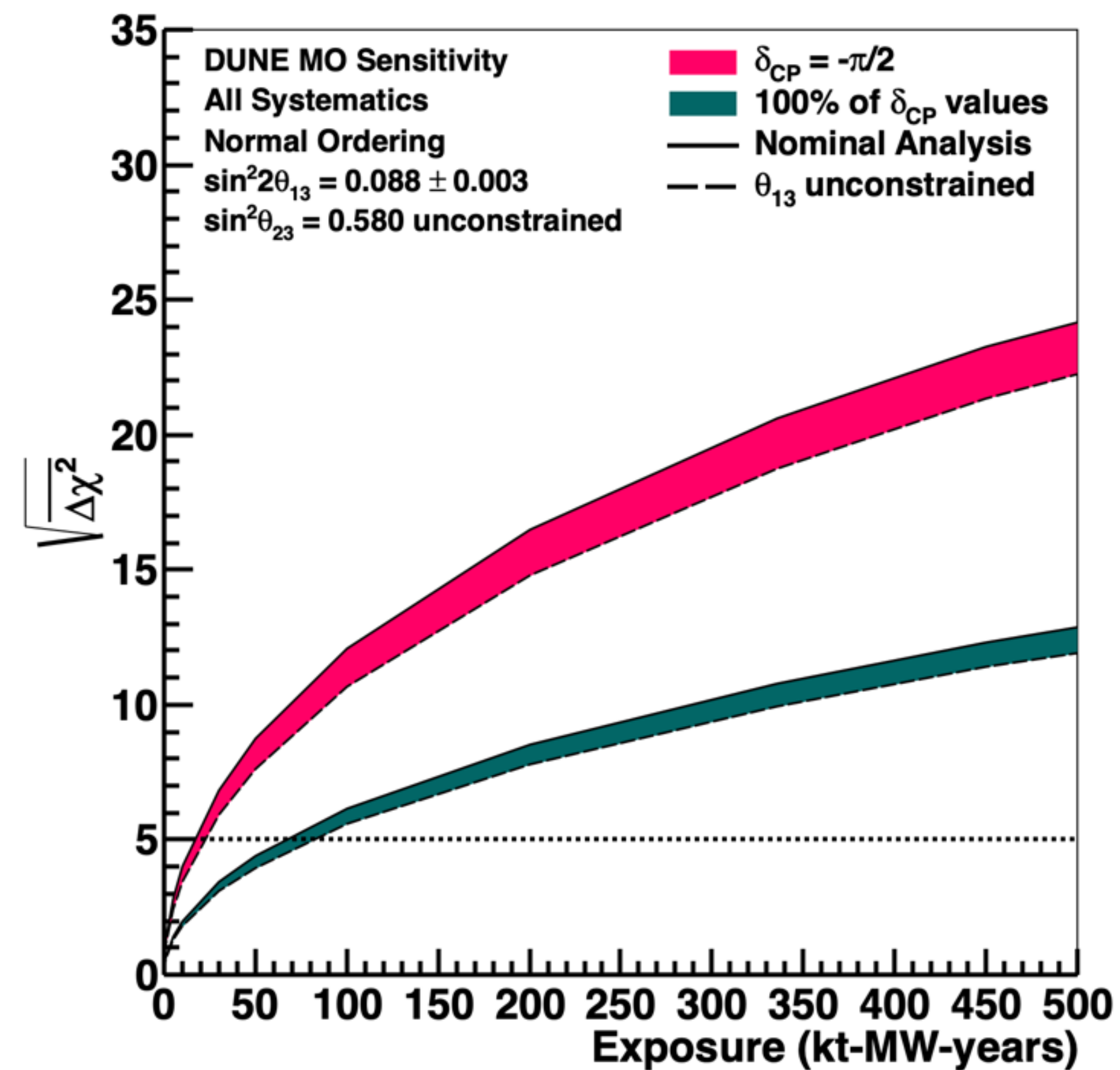
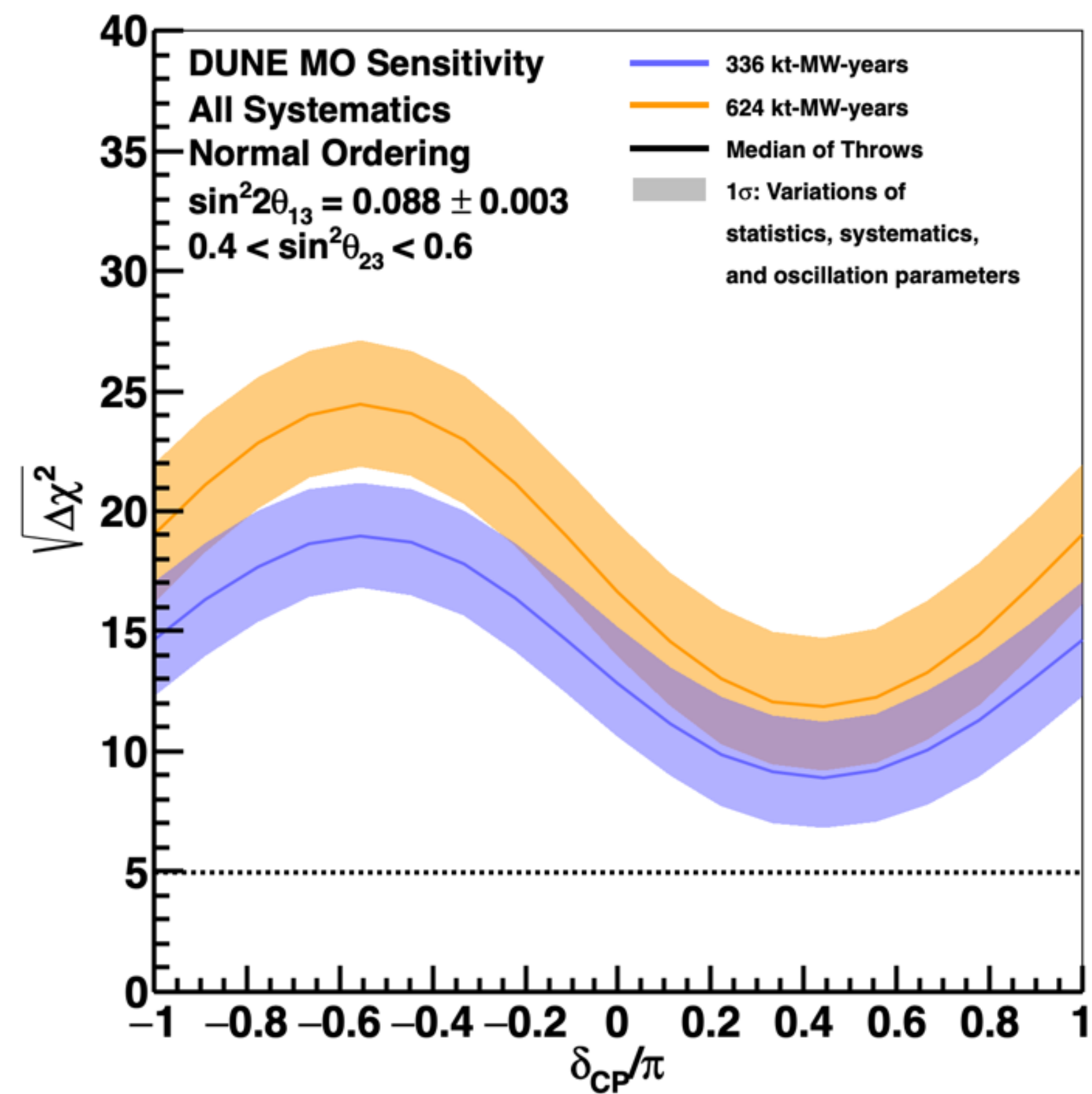
ProtoDUNE's at CERN



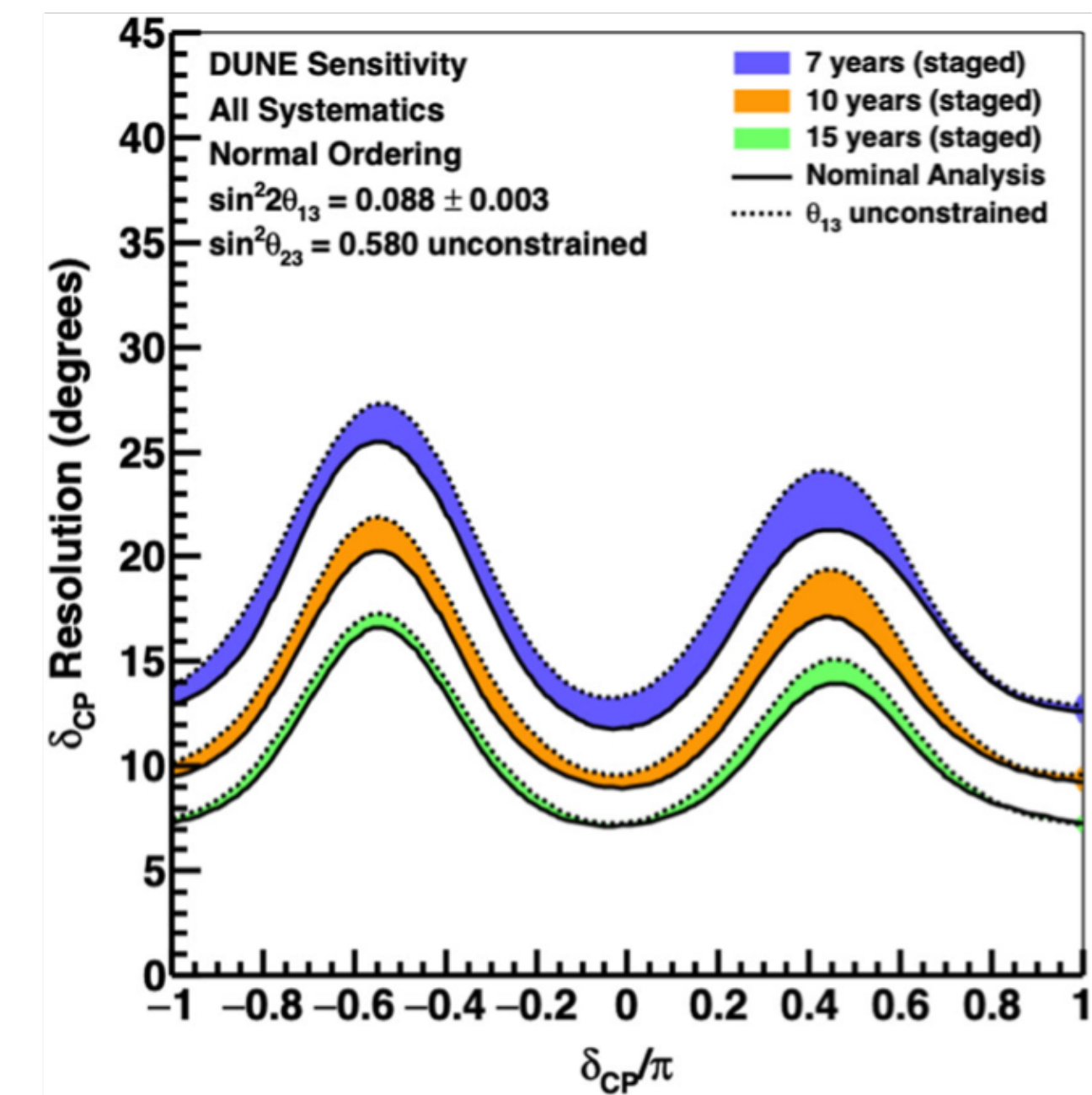
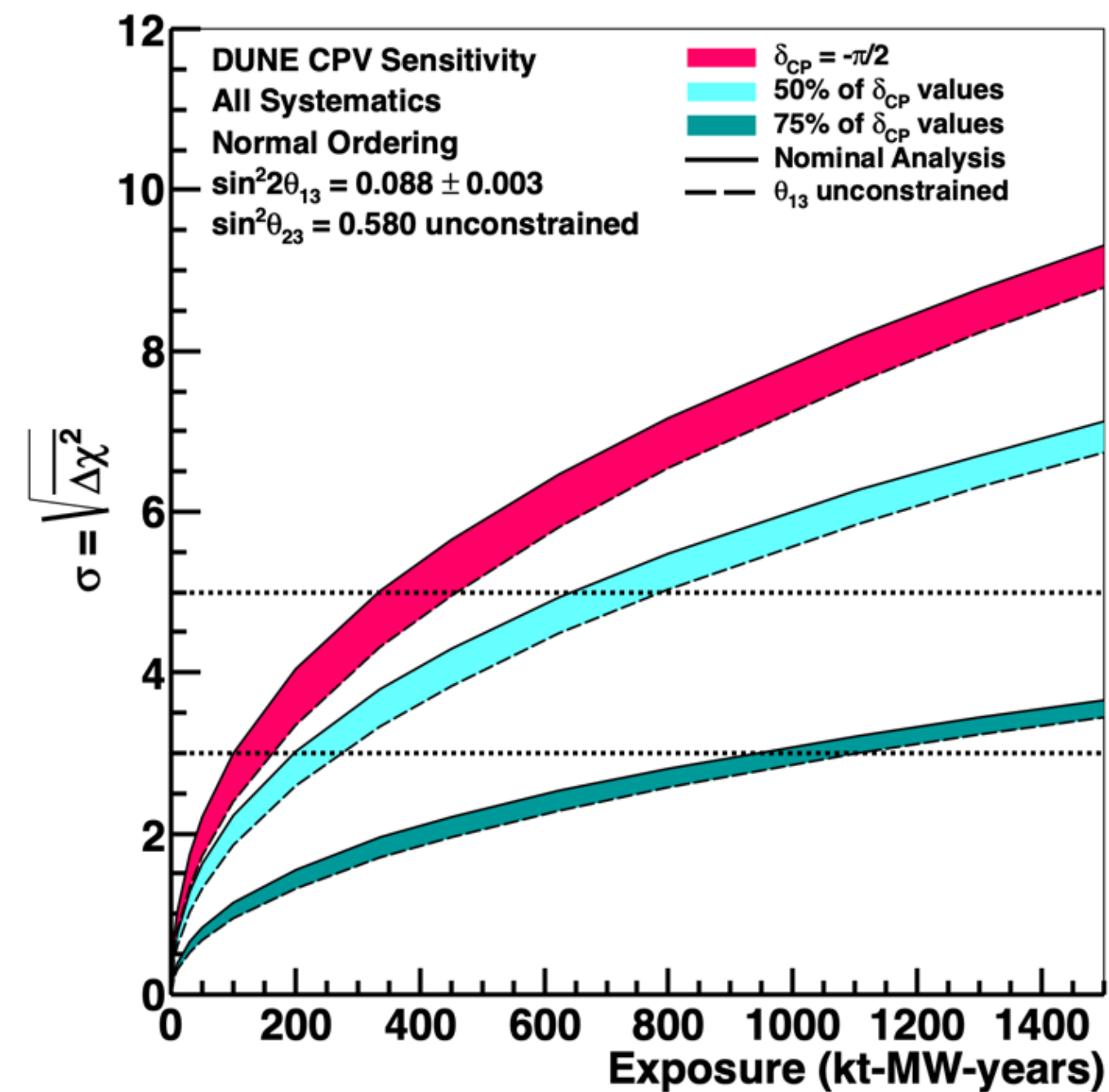
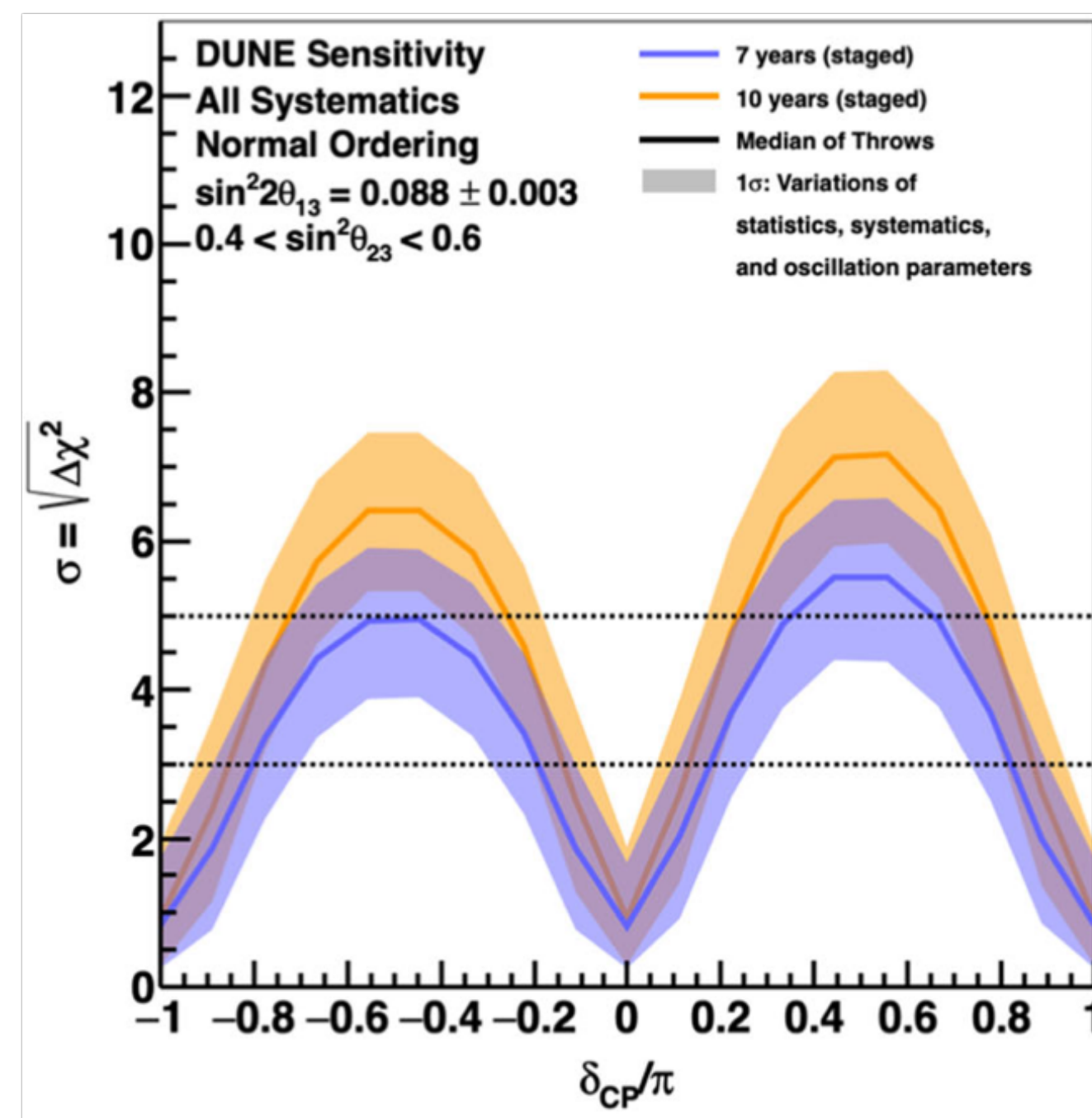
Physics opportunities at DUNE



Sensitivity to mass ordering



Sensitivity to CPV



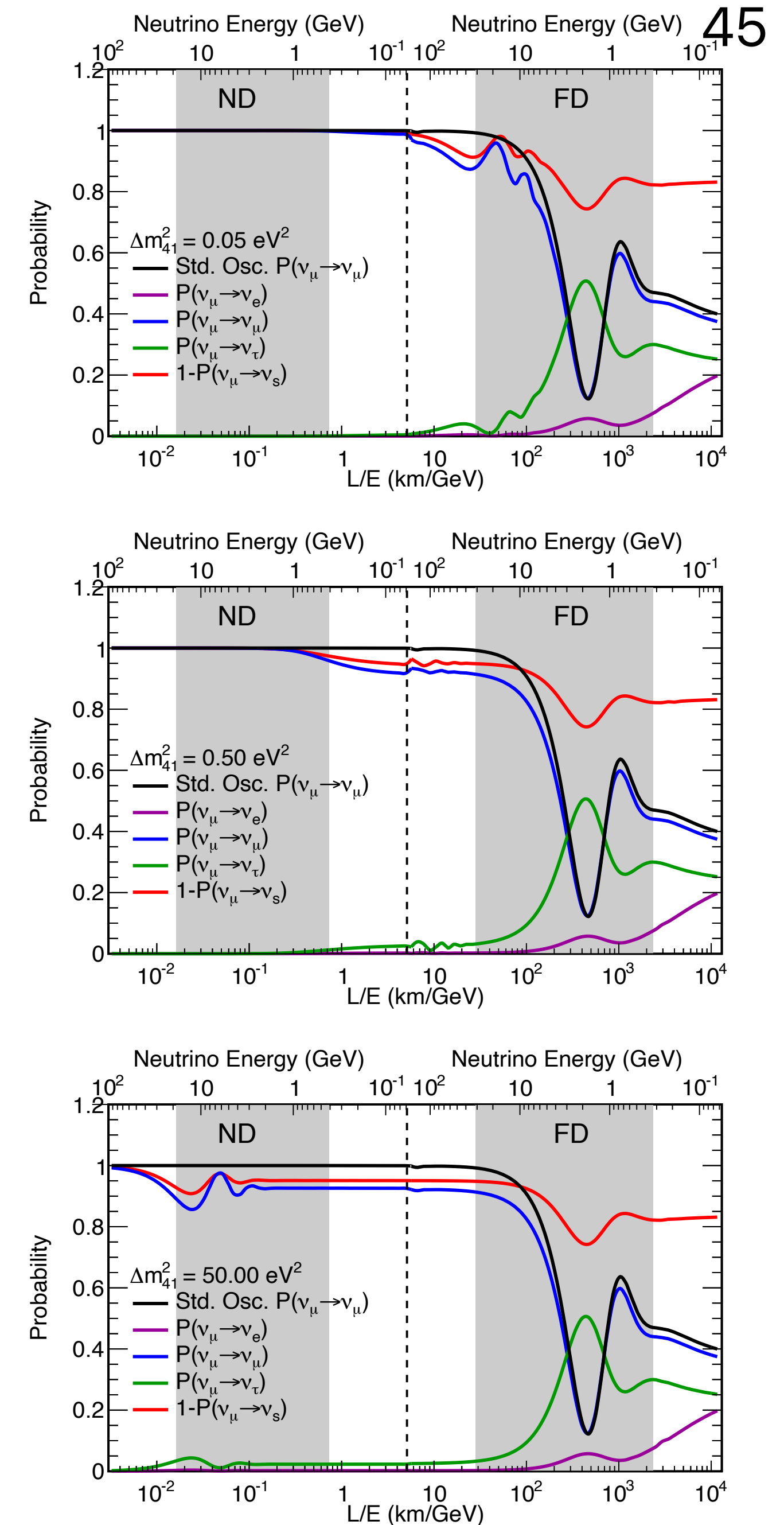
Discovery sensitivity to CP violation over a broad range of possible values; 6° – 16° resolution to δ_{CP} without dependence on other experiments.

Sterile neutrino mixing

Sterile (right-handed) neutrinos are a prediction of many BSM models explaining the origin of neutrino masses.

Oscillations between active and new light sterile neutrino states would distort the standard oscillation probabilities (see plots).

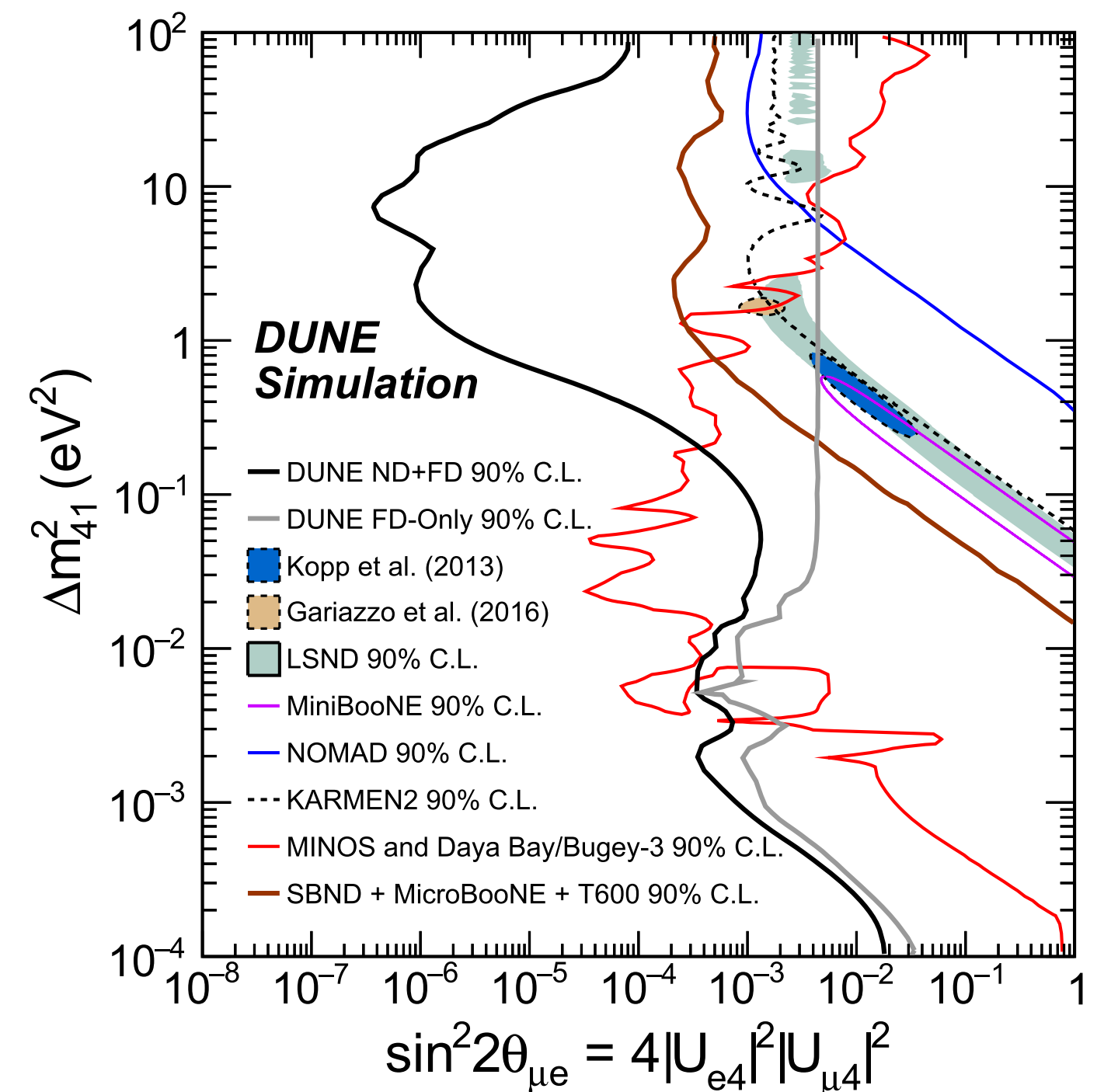
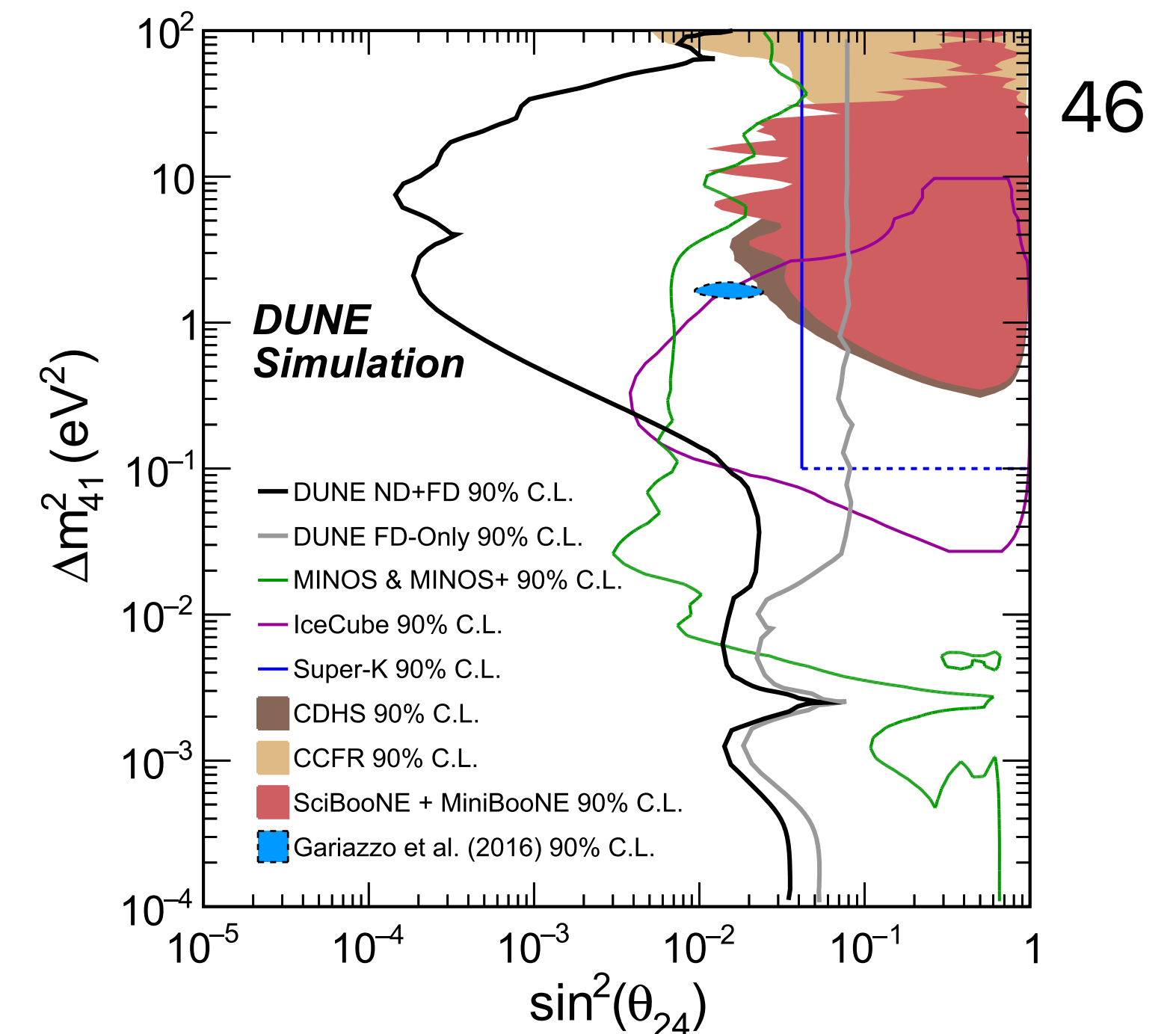
DUNE will be sensitive to this effect through the combined analysis of the ν_μ and ν_e spectra from both the near and far detectors. The wide span of neutrino energies from LBNF beam enables probes over large regions of parameter space.



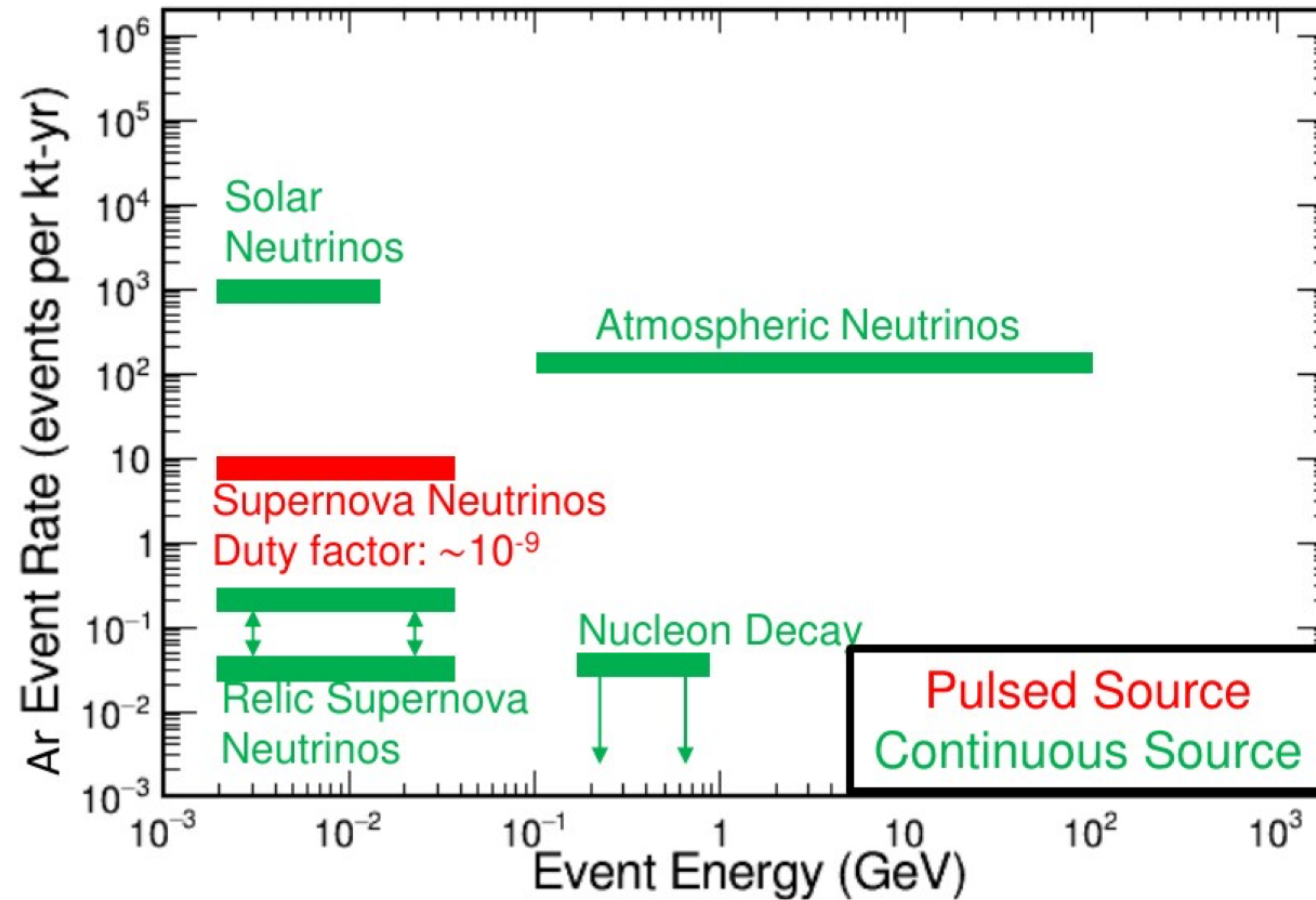
Sterile neutrino mixing

Assuming 300 kton MW yr exposure (staged 7 year running) for 3+1 model with oscillations in ND and FD:

- On its own, DUNE can potentially probe the sterile mixing parameter space at same level or better than present and future experiments.
- Sensitivities include normalization-only systematics, so the two DUNE lines represent best (black) and worst (grey) scenarios.



Astroparticle events in DUNE

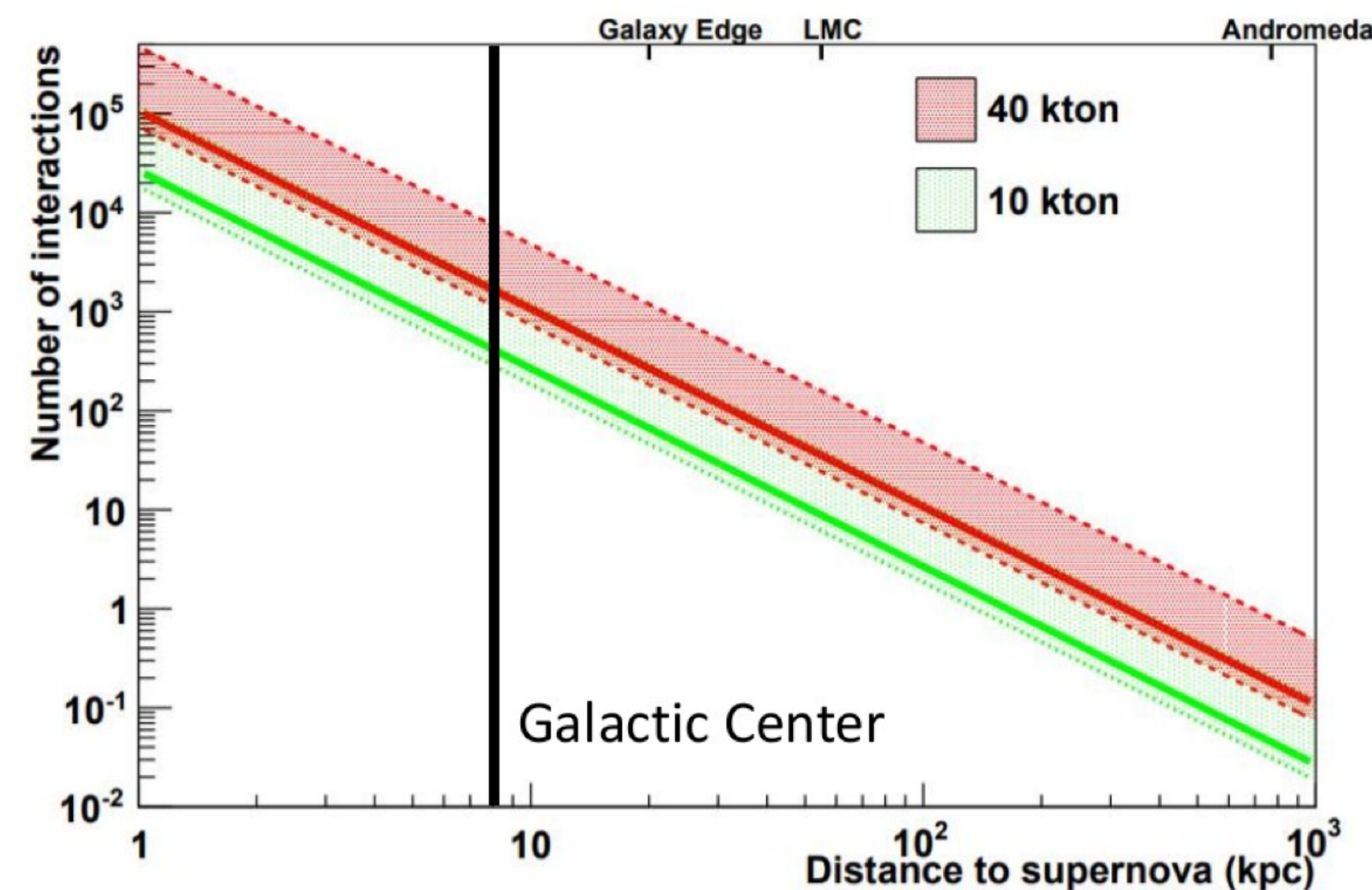
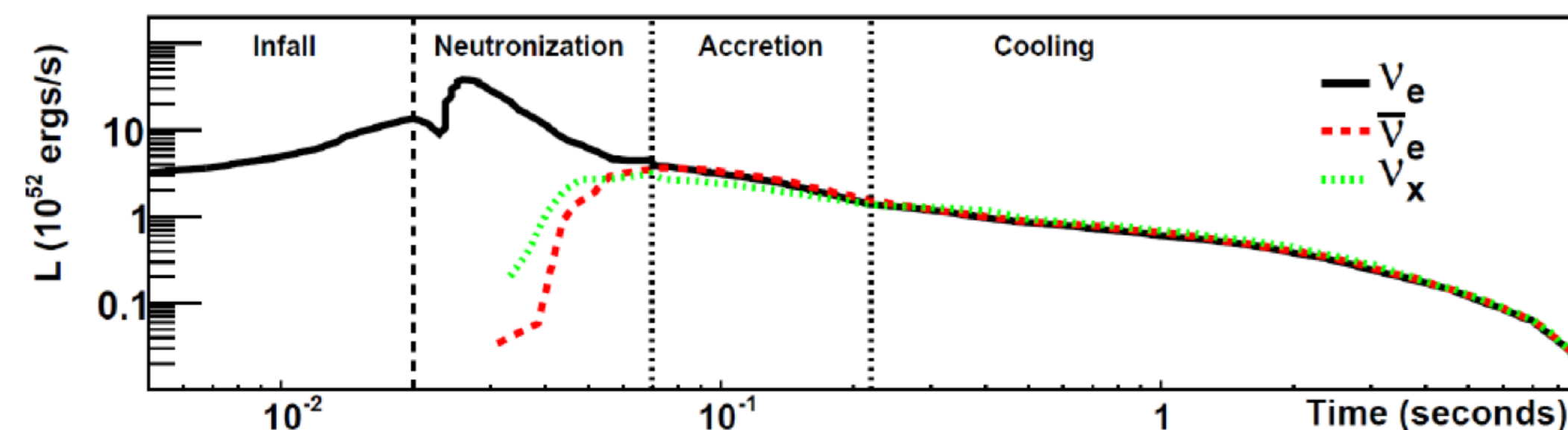


Supernova neutrinos

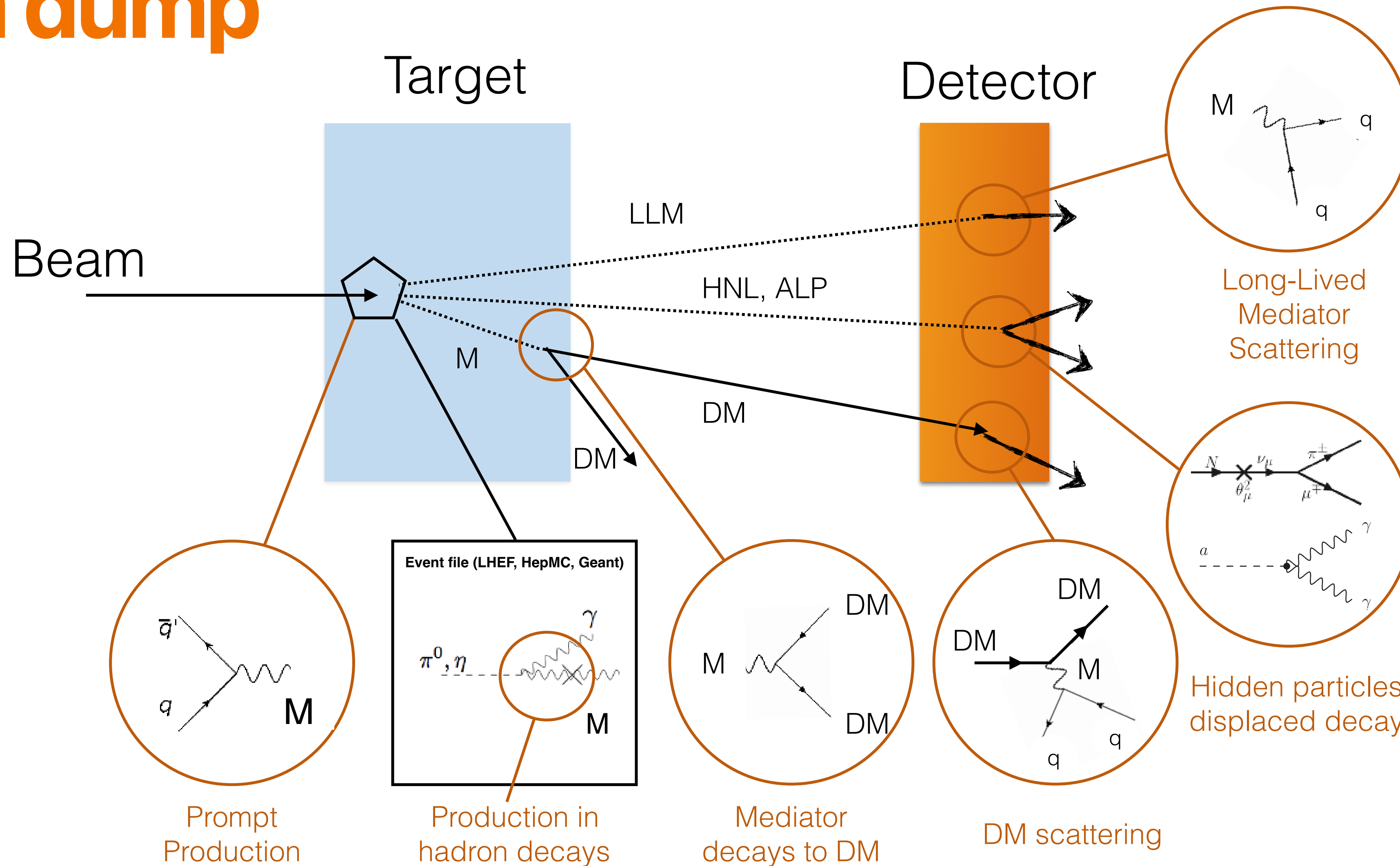
DUNE has unique sensitivity to supernova electron neutrinos (dominant emission during neutronization burst), complementary with other sensitive large detectors.

Hundreds to thousands of neutrinos from galactic SNB.

Measurement of the time and energy distribution informs supernova modelling.



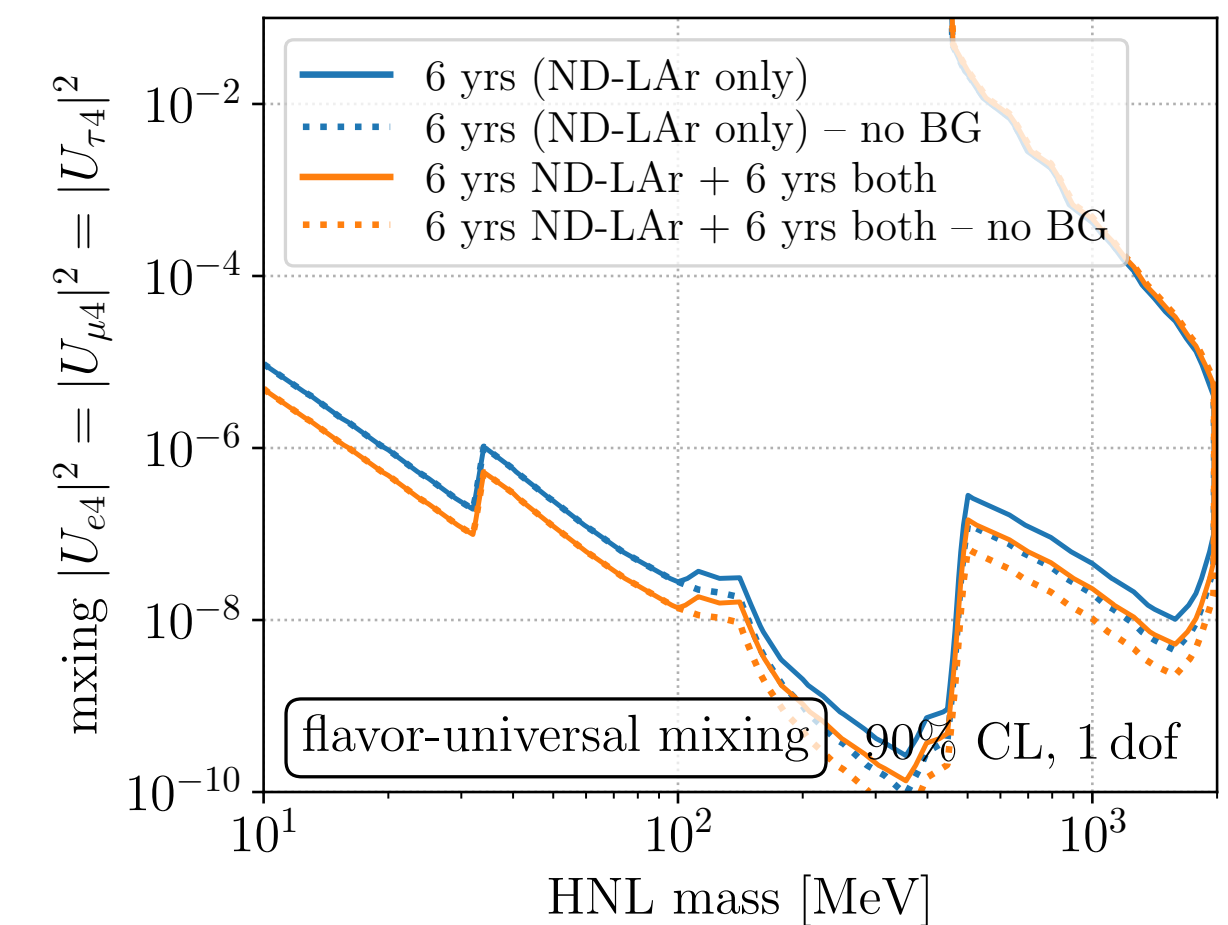
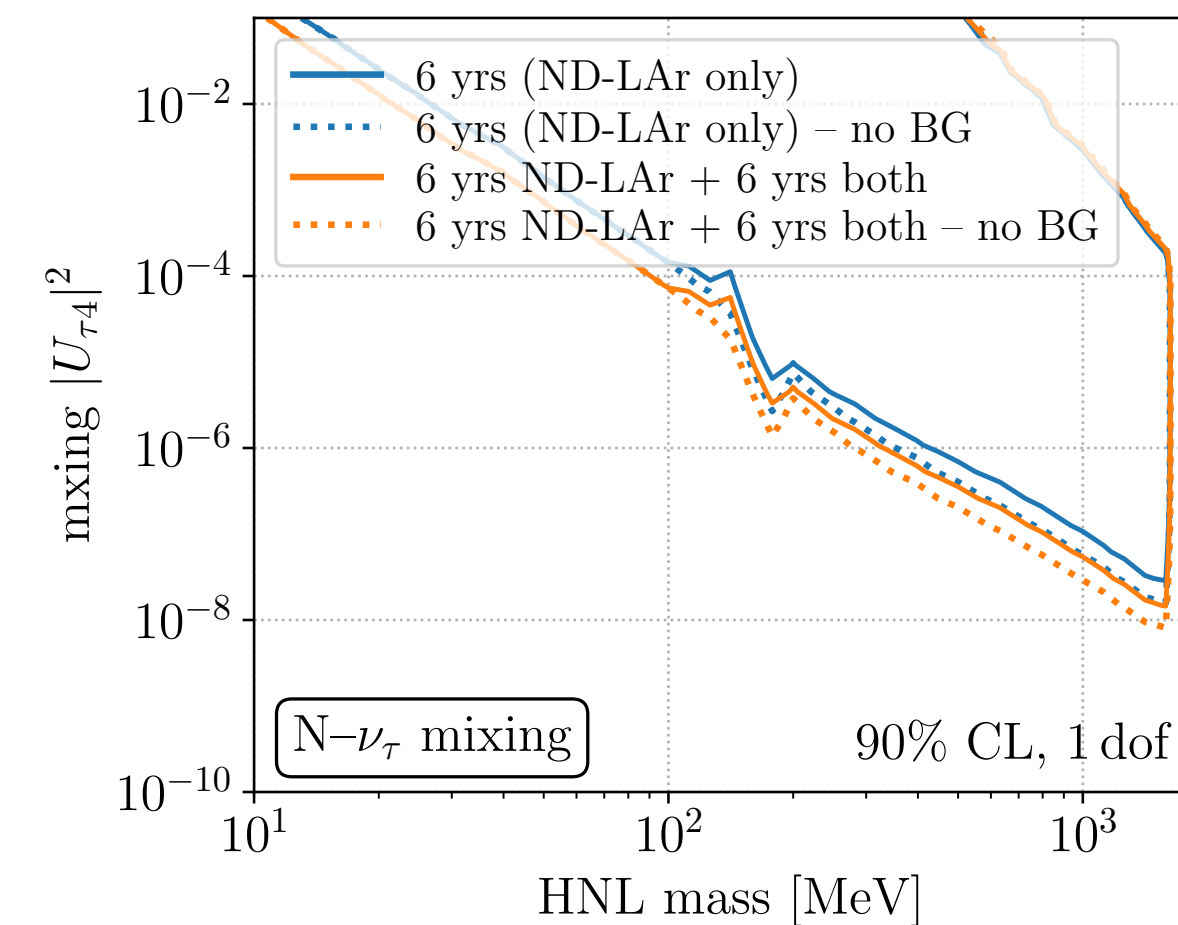
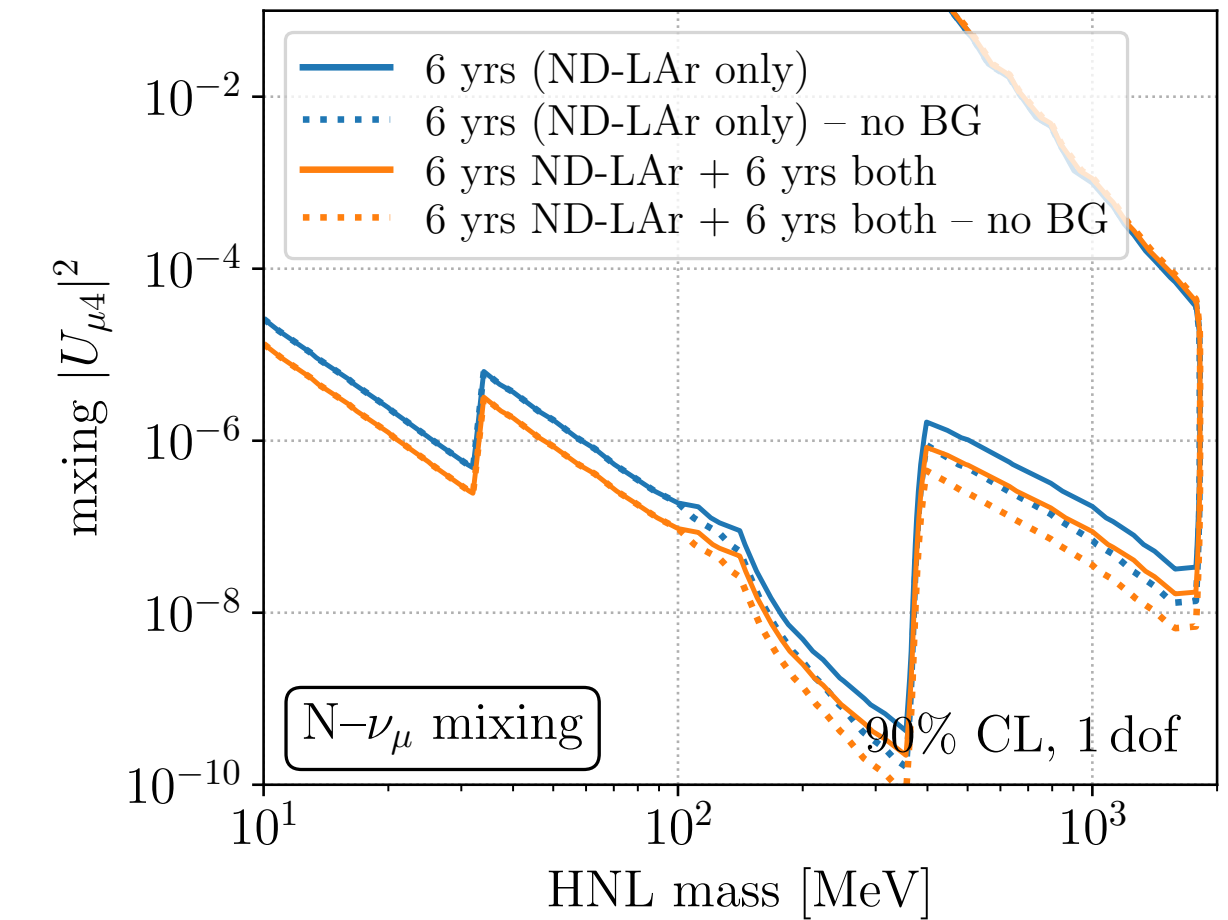
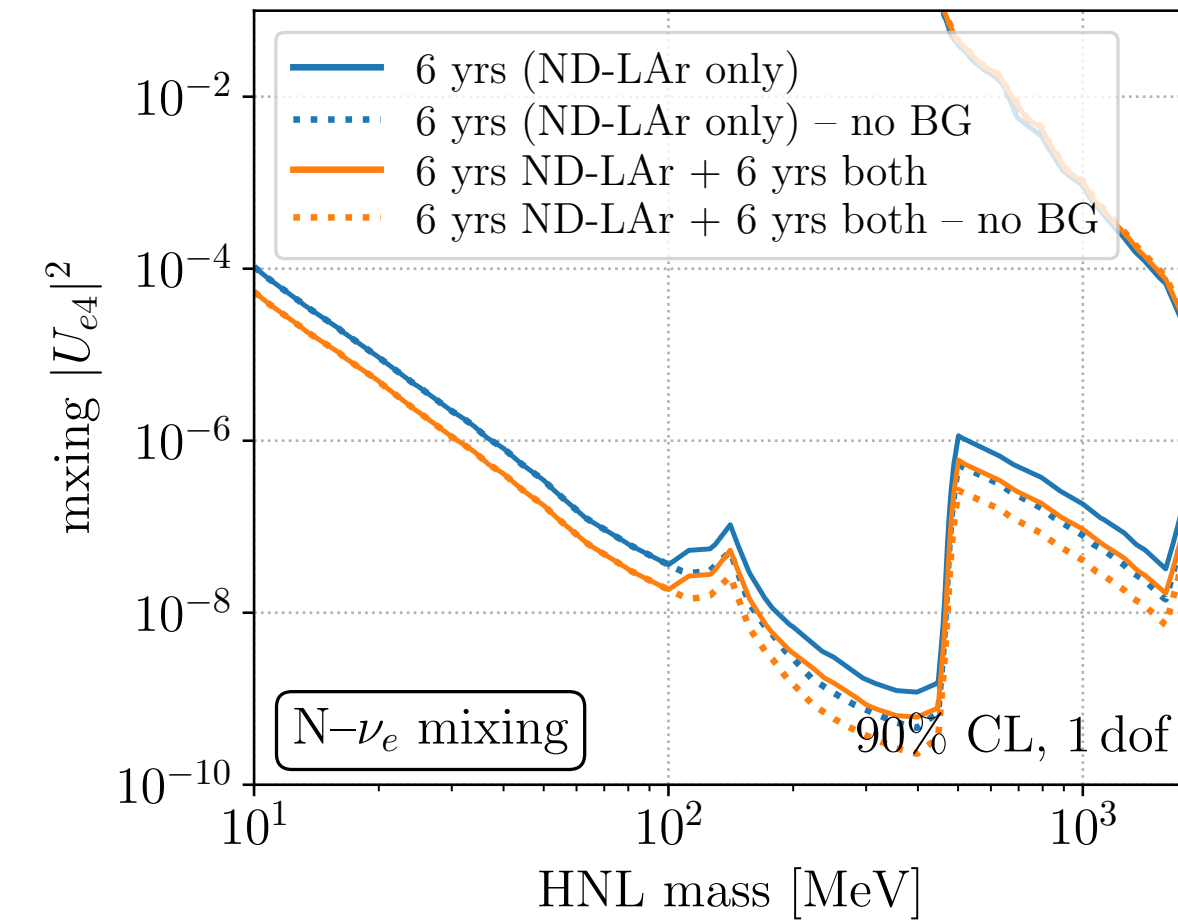
Beam dump



Heavy neutral leptons

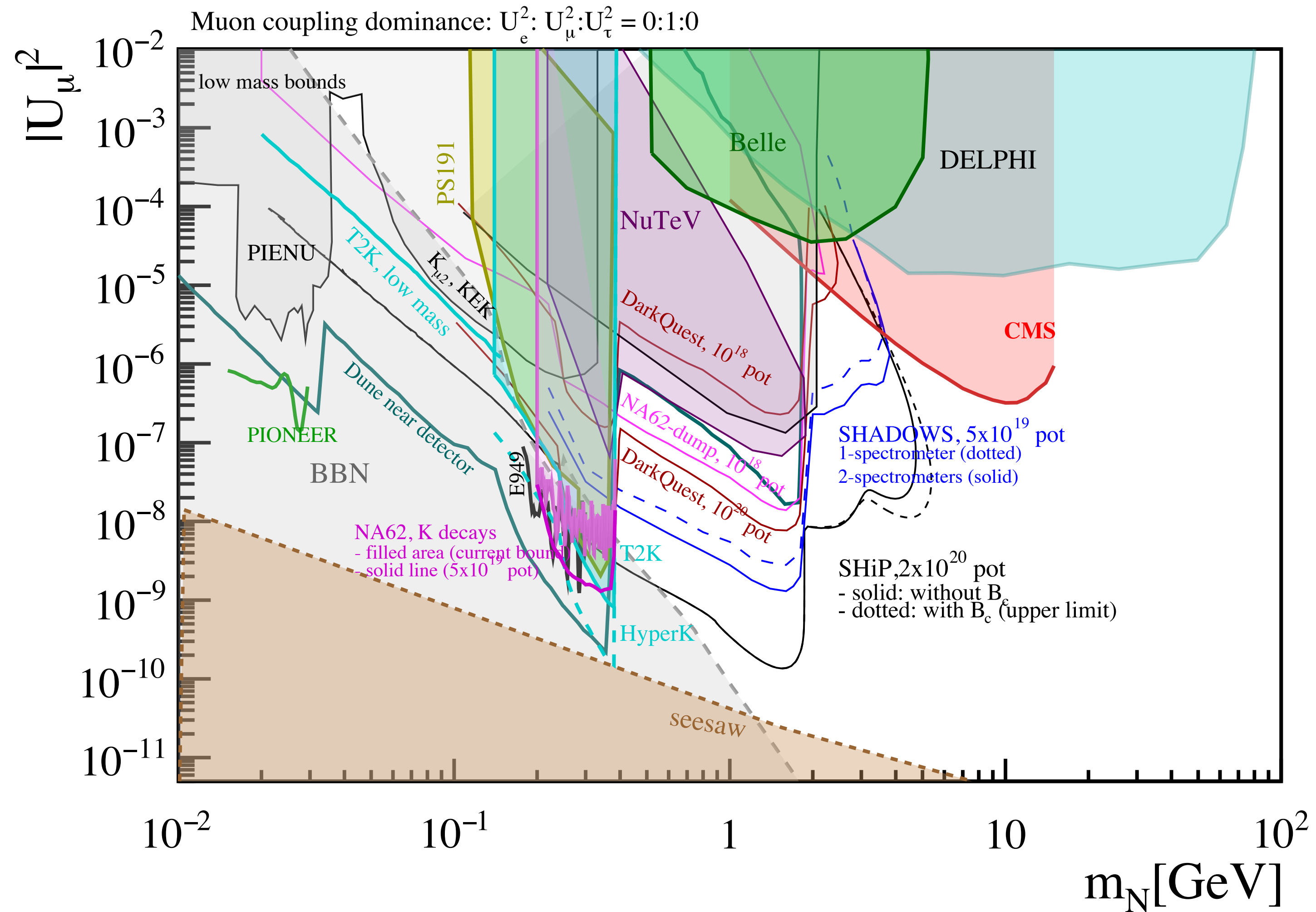
Heavy right-handed singlets predicted in many extensions of the SM may be produced by the LBNF beam.

Depending on their properties, the HNLs could reach the DUNE ND, where they would be detected via their decay products.



Abdullahi et al., arXiv:2203.08039v1

Heavy neutral leptons



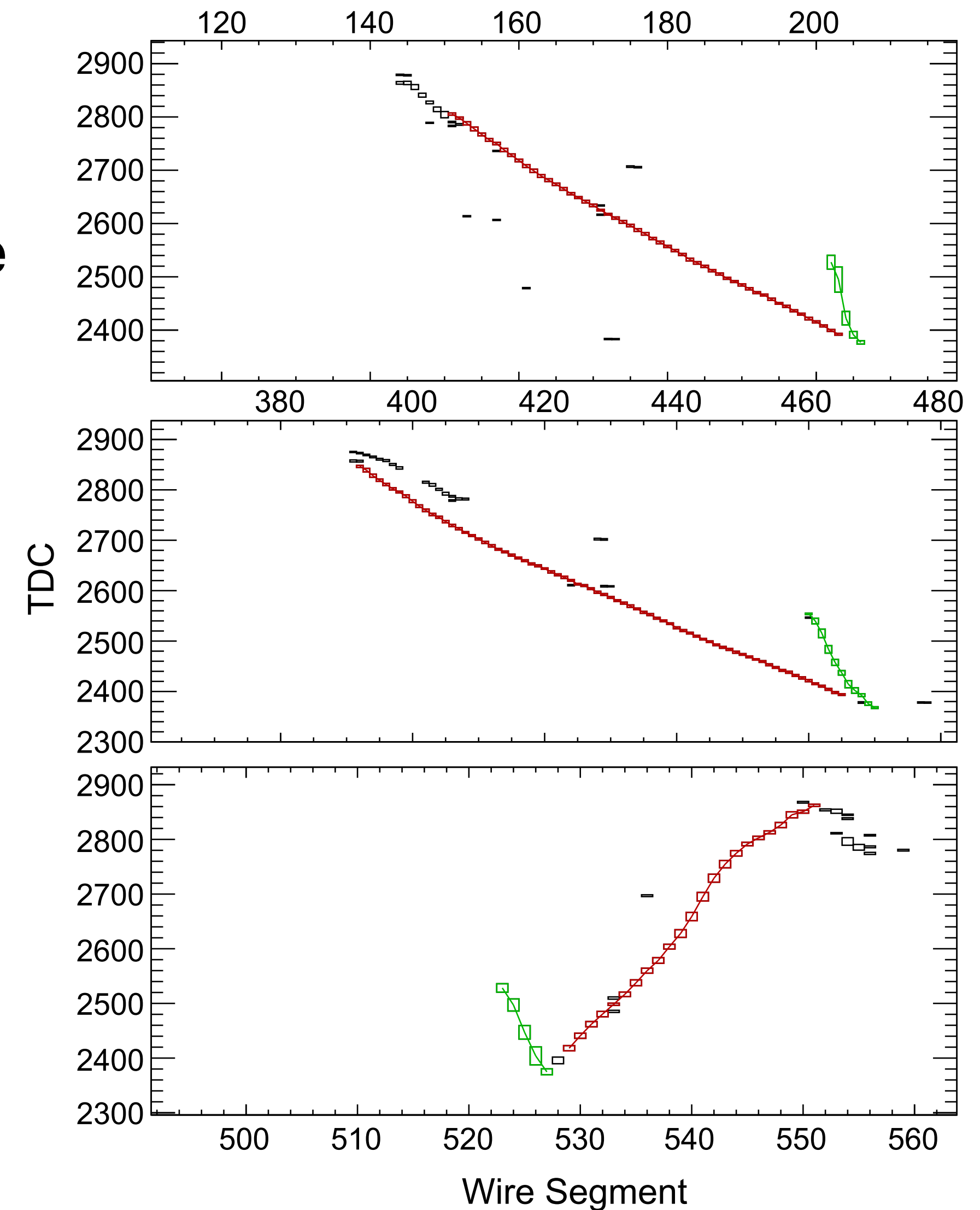
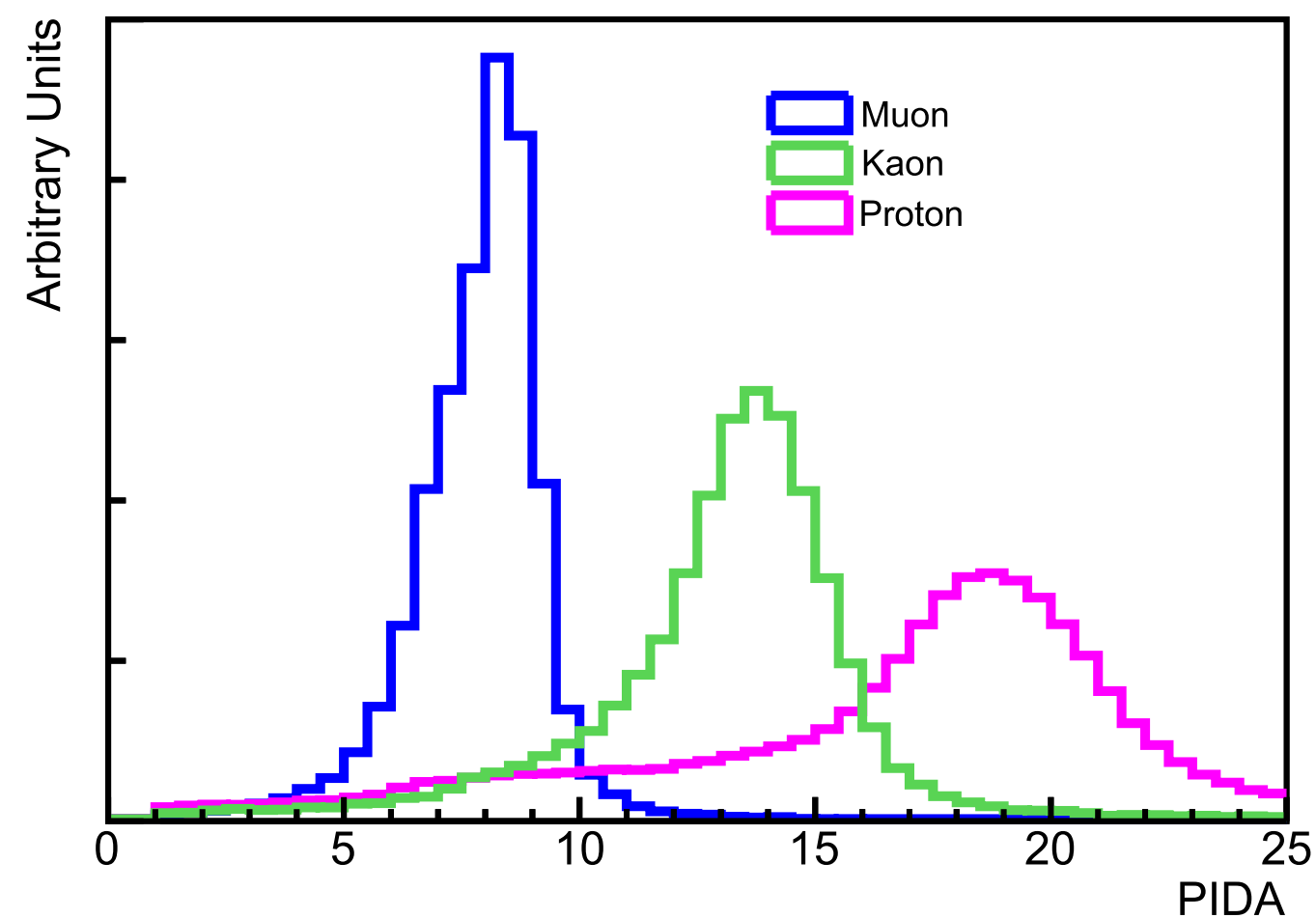
Abdullahi et al., arXiv:2203.08039v1

Proton decay

Grand unified theories extending the SM predict low-energy observables such as nucleon decay, including the decay of the proton into a kaon.

The DUNE FD has the unique ability to track and identify the kaons produced in those decays.

A lower limit on the proton lifetime of 1.3×10^{34} years is expected if no signal is observed in 10 years.



Summary

DUNE is gearing up:

- Successful prototyping effort at CERN underway.
- The construction of the FD-1 and FD-2 has already started and is proceeding fast.

A lot of exciting physics lies ahead:

- DUNE will resolve the **neutrino mass ordering**, and **measure δ_{CP}** with CP violation sensitivity over a broad range of parameter space.
- DUNE will precisely measure long-baseline oscillations to **test the 3-flavour paradigm**.
- DUNE has unique **sensitivity to low-energy neutrinos** from a galactic **supernova** burst.
- DUNE has competitive sensitivity to a wide range of **physics beyond the Standard Model**.