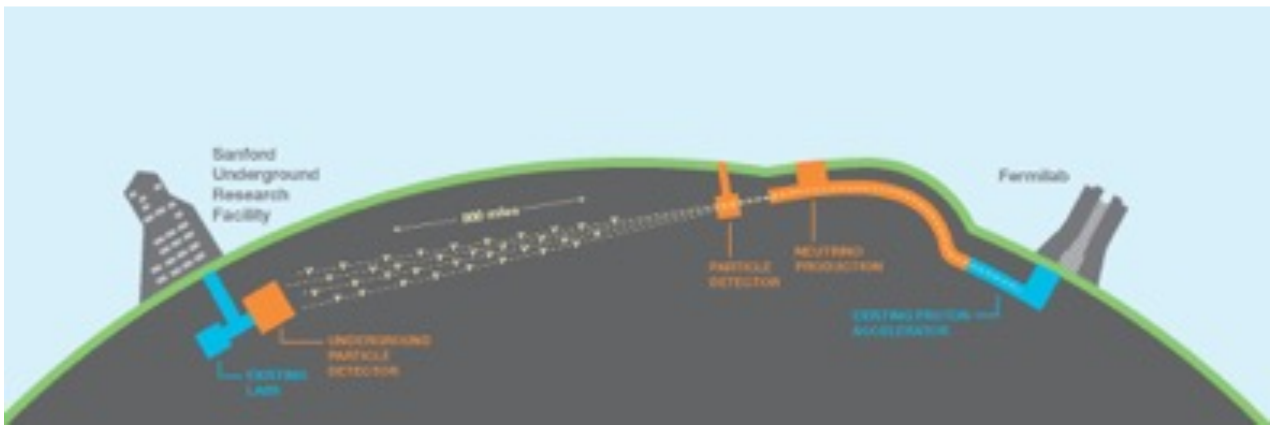
Next Generation neutrino Experiments at Accelerators: the DUNE Experiment at FNAL



Sergio Bertolucci

University of Bologna and INFN

Looking for “unknown unknowns”

Needs a synergic use of:

- High-Energy colliders
- neutrino experiments (solar, atmospheric, cosmogenic, short/long baseline, reactors, $0\nu\beta\beta$ decays, masses)
- cosmic surveys (CMB, Supernovae, BAO, Dark E)
- gravitational waves
- dark matter direct and indirect detection
- precision measurements of rare decays and phenomena
- dedicated searches (WIMPS, axions, dark-sector particles)
- …..

From the P5 Report (USA)

Recommendation 12 : In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

The minimum requirements to proceed are the identified capability to reach an exposure of at least **120 kt*MW*yr by the 2035 timeframe**, the far detector situated **underground** with cavern space for expansion **to at least 40 kt LAr fiducial** volume, and **1.2 MW beam power upgradable to multi megawatt** power. The experiment should have the demonstrated capability to search for **supernova (SN) bursts** and for **proton decay**, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.

From the European Strategy Document

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector.

CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments.

Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

From Japan HEP Community

The committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

……….

Should the neutrino mixing angle $\boldsymbol{\theta}_{13}$ be confirmed as large, **Japan should aim to realize a large-scale neutrino detector through international cooperation**, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.
This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

Standard Three Neutrino Paradigm

Unitary PNMS matrix described by 3 Euler angles (θ_{12},θ_{13},θ_{23}) and 1 complex phase (δ). $\delta \neq \{0, \pi\}$ → **CP Violation**

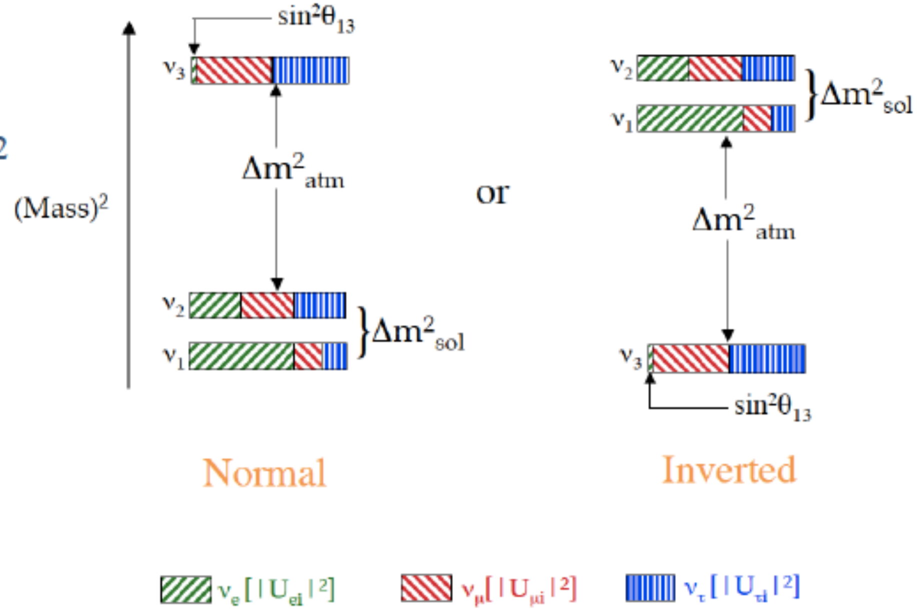
$\theta_{23} \sim 45^\circ$ $\theta_{13} \sim 9^\circ$ $\theta_{12} \sim 30^\circ$

$$U_{\rm PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \; ; \; c_{ij} = \cos\theta_{ij}$$

$\Delta m^2_{atm} \sim 2.5\times10^{-3}$ eV^2

$\Delta m^2_{sol} \sim 7.5\times10^{-5}$ eV^2

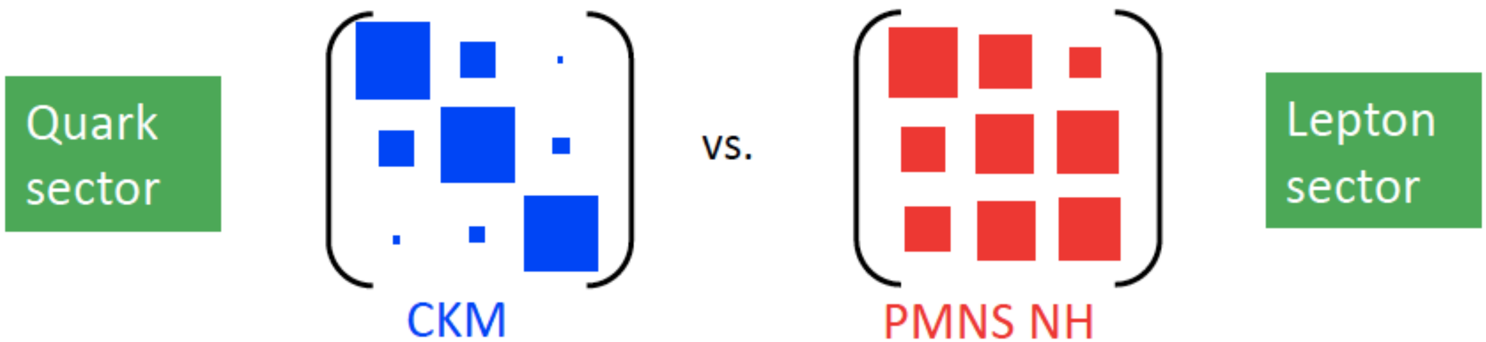


Key Questions in Neutrino Physics

- Do neutrinos violate CP symmetry?

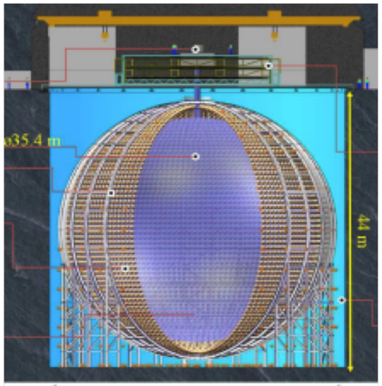
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

- What is the mass ordering?
- Why are the quark and neutrino mixing matrices so different?

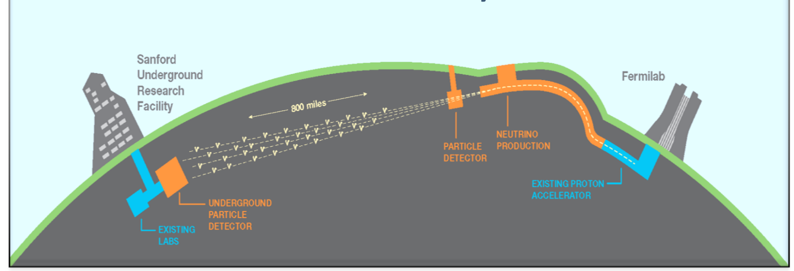


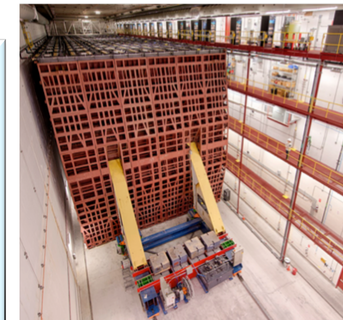
- Are there additional neutrino states?
- Are neutrinos their own antiparticles?
- What is the neutrino mass?

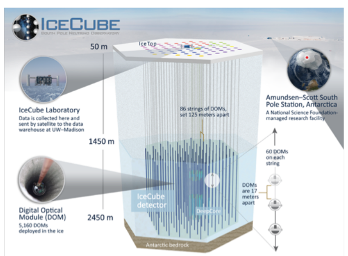
An Exciting Global Initiative to Understand the Most Abundant Known Matter Particle in the Universe

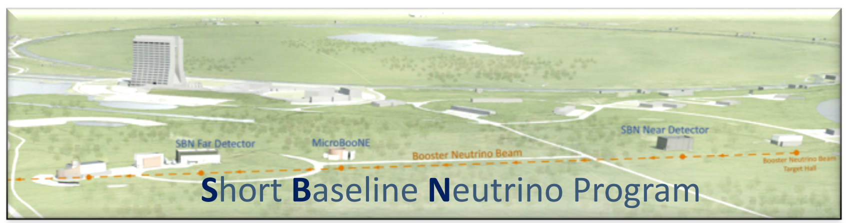


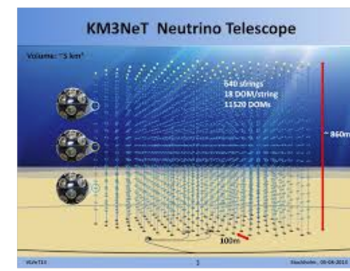
Deep **U**nderground **N**eutrino **E**xperiment
at the
Long **B**aseline **N**eutrino **F**acility

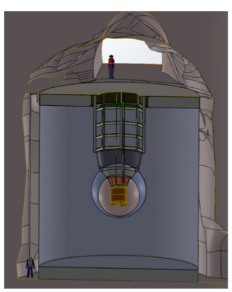


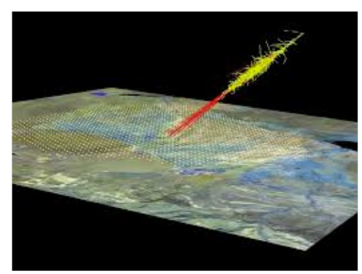


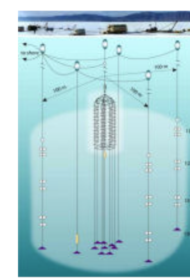












How to search for CP violation

- Compare oscillation oscillation rates for νs and $\bar{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

(in vacuum)

- As in quark sector, CP violating effects $\propto J \equiv c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta$, and require no degenerate masses

- We know mixing angles and mass differences, so we can measure $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$ and determine δ, but there is a complication…

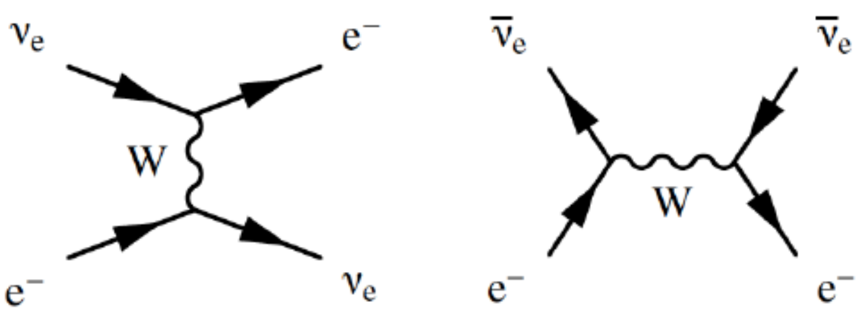
Matter Effects

- In real experiments, even in the absence of CPV,

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq 0$$

Neutrinos travel through material that is not CP symmetric, i.e., matter not antimatter

- In vacuum, the mass eigenstates ν_1, ν_2, ν_3 correspond to the eigenstates of the Hamiltonian:
  - they propagate independently (with appropriate phases)
- In matter, there is an effective potential due to the forward weak scattering processes. **Effect depends on Mass Hierarchy**



$$V = \pm\sqrt{2}G_F n_e$$

Different sign for ν_e vs $\bar{\nu}_e$

Possible Experimental Strategies

EITHER:

- Keep L small (~200 km): so that matter effects are insignificant
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu < 1\,\mathrm{GeV}$$

  - Want high flux at oscillation maximum

➡ **Off-axis beam:** narrow range of neutrino energies

OR:

- Make L large (>1000 km): measure the matter effects (i.e., MH)
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \Rightarrow E_\nu > 2\,\mathrm{GeV}$$

  - **Unfold CPV from Matter Effects through E dependence**

➡ **On-axis beam:** wide range of neutrino energies

Possible Experimental Strategies

EITHER:

- Keep L small (~200 km): so that matter eff… are insignificant
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

  - Want hi… …ation maximum

➡ **Off-… …eam:** narrow range of neutrino energies

Hyper-Kamiokande

OR:

- Make L large (>1000 km): measure the …atter effects (i.e., MH)
  - First oscillation maximum:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

  - **Unfold CPV from Ma… …ts through E dependence**

➡ **On-axis beam:** w…de range of neutrino energies

DUNE

It's not only statistics....

In the experiment we measure:

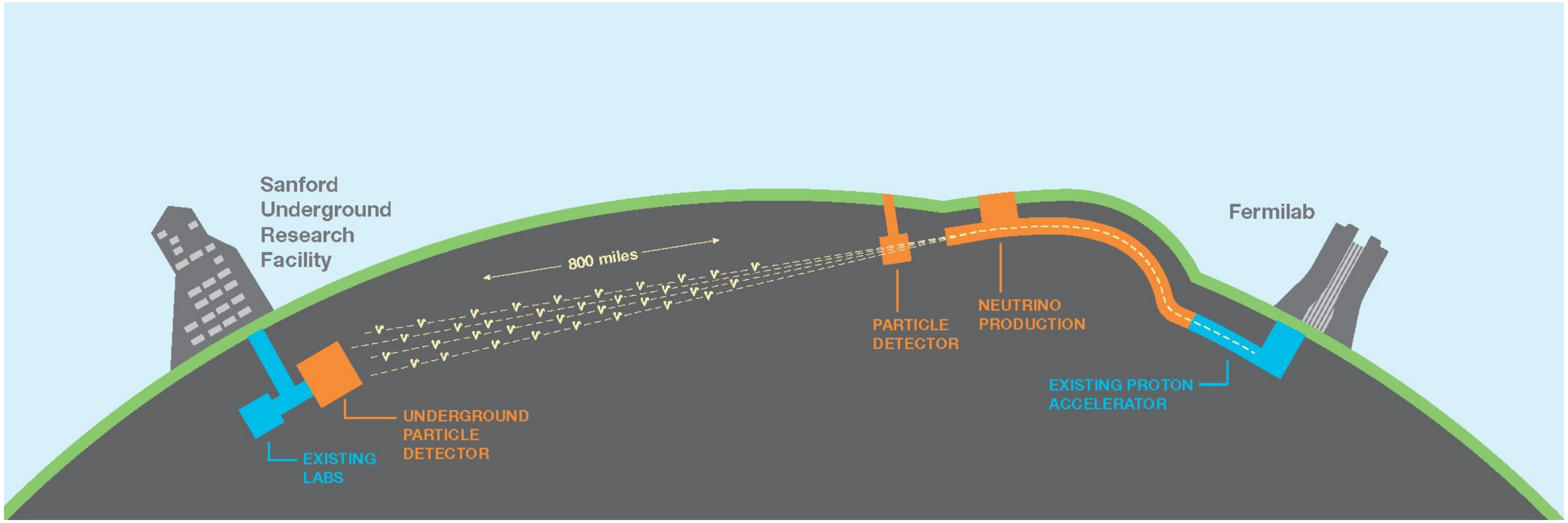
$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * D^{far}_{\nu_e}(E_\nu, E_{rec})\ dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * D^{near}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu}$$

In order to get the physical quantities, we have to control flux, energy distribution/geometry of the beam, efficiencies, acceptances, etc..

Need one (or more) sophisticated Near Detector to control beam and systematics

Long-Baseline Neutrino Facility

The biggest international project hosted in the US



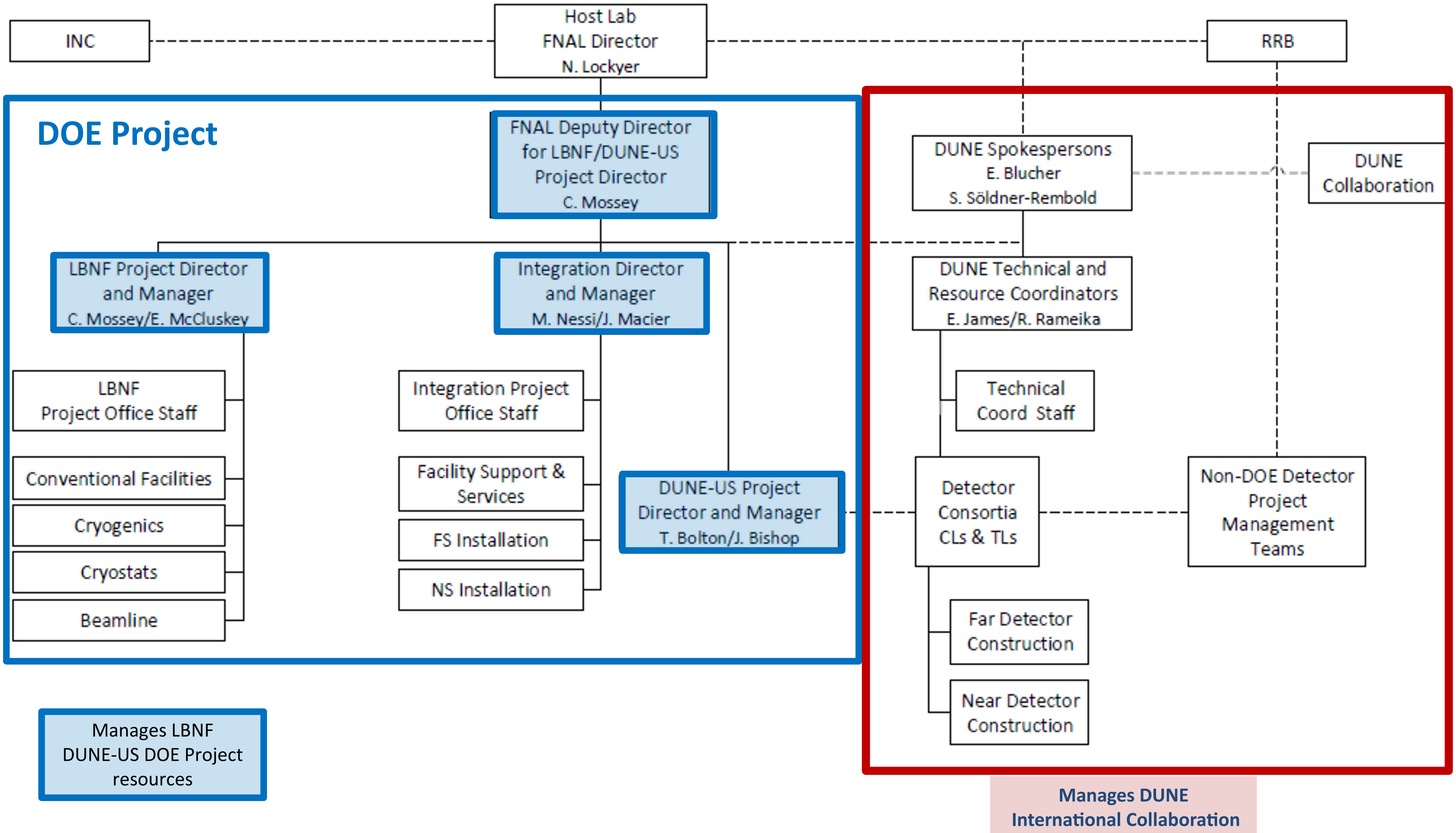
DUNE Far Detector

DUNE Near Detector
Neutrino Beam Source

DUNE Collaboration

- 1180 collaborators from 198 Institutions in 33 Countries
- 628 faculty/scientists, 199 postdocs, 119 engineers, 234 PhD students

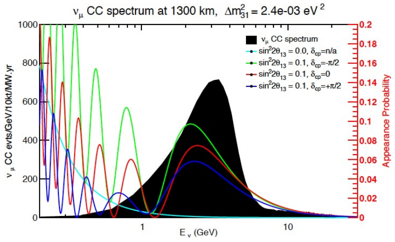
LBNF/DUNE Project Management



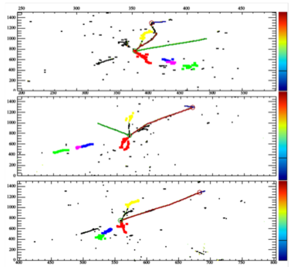
Far Detector Technical Design Report (Feb. 2020)

https://arxiv.org/abs/2002.02967
https://arxiv.org/abs/2002.03005
https://arxiv.org/abs/2002.03008
https://arxiv.org/abs/2002.03010

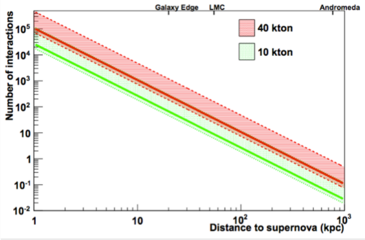
DUNE Primary Science Goals



- Testing the Neutrino Three-Flavor Paradigm
- CP Phase/CP Violation
- Mass Ordering

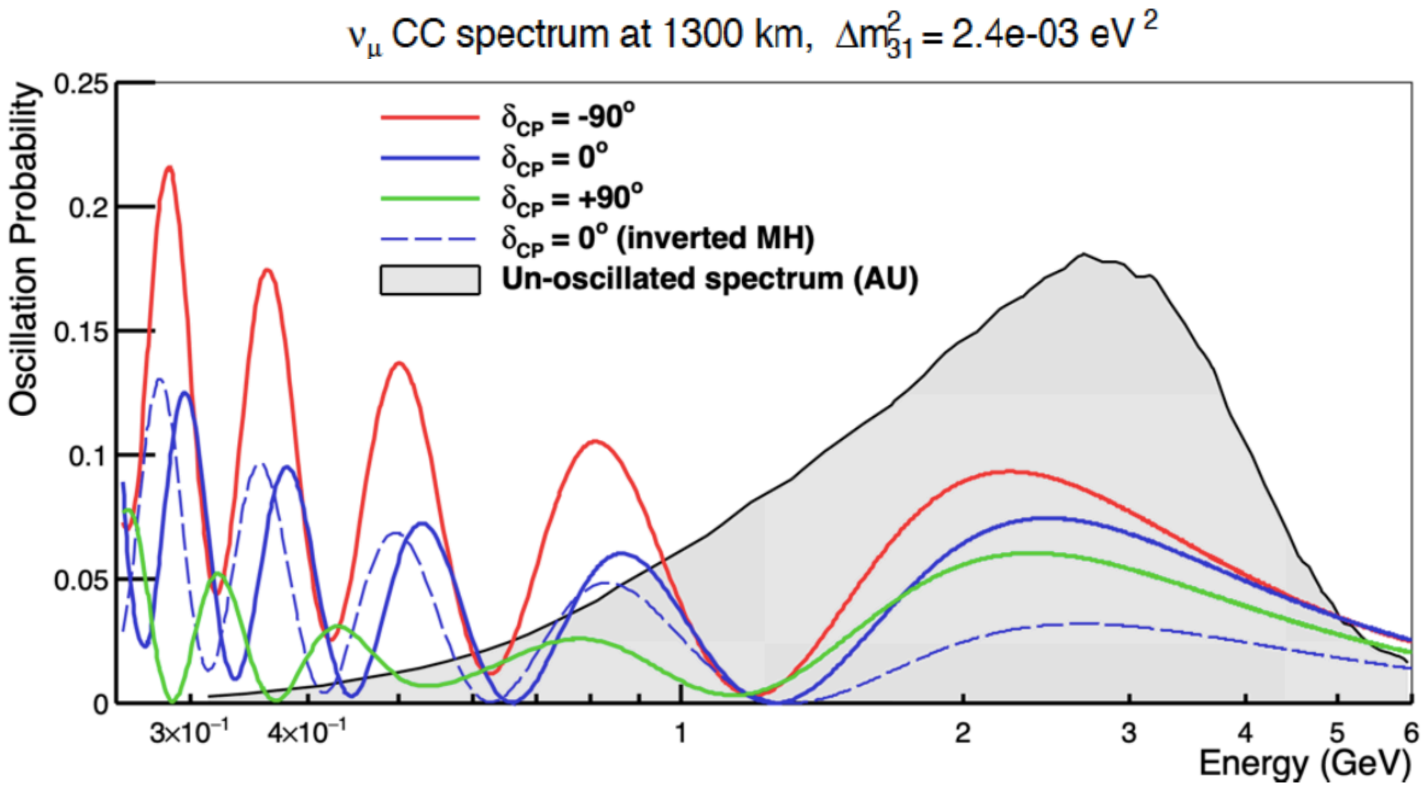


- Baryon Number Violation and Grand Unification
- Nucleon Decay
- Neutron/Anti-Neutron Oscillation



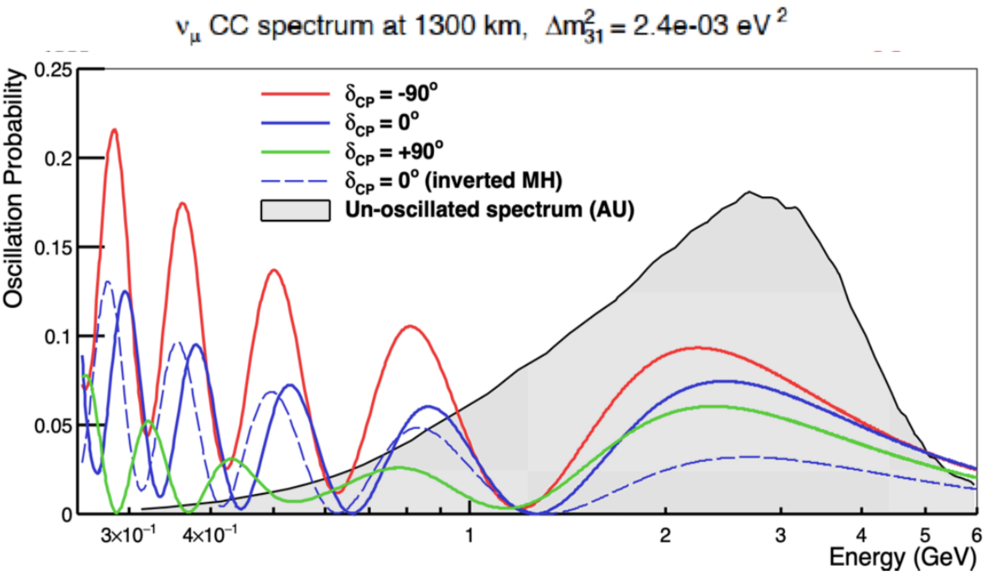
- Neutrino Astrophysics
- Supernova Burst Neutrinos

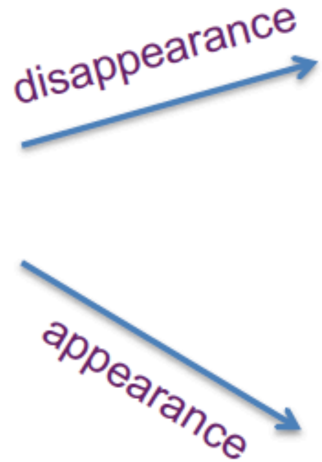
Testing the Neutrino Three-Flavor Paradigm

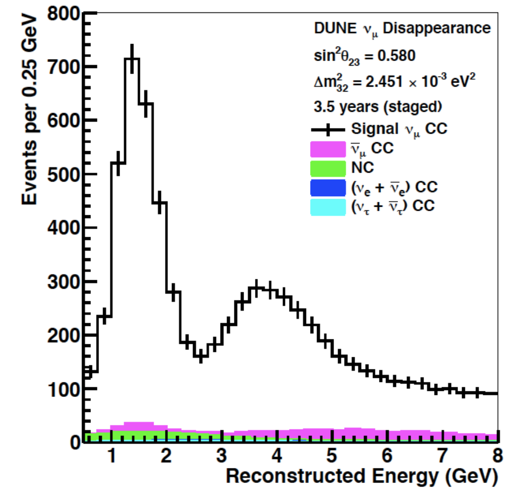


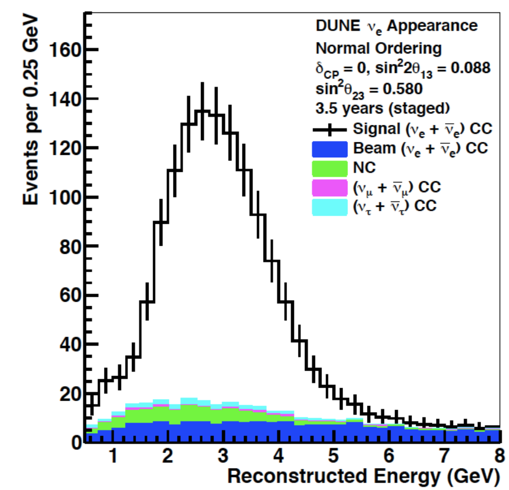
- Oscillation probability depends on the ratio of distance travelled (L) and neutrino energy (E): L/E
- Lines shows ν_e appearance probability for a pure ν_μ beam for L = 1300 km for three values of CP violating phase δ_{CP}
- Filled in curve shows ν_μ energy spectrum at L if there were no oscillations

Experimental Method





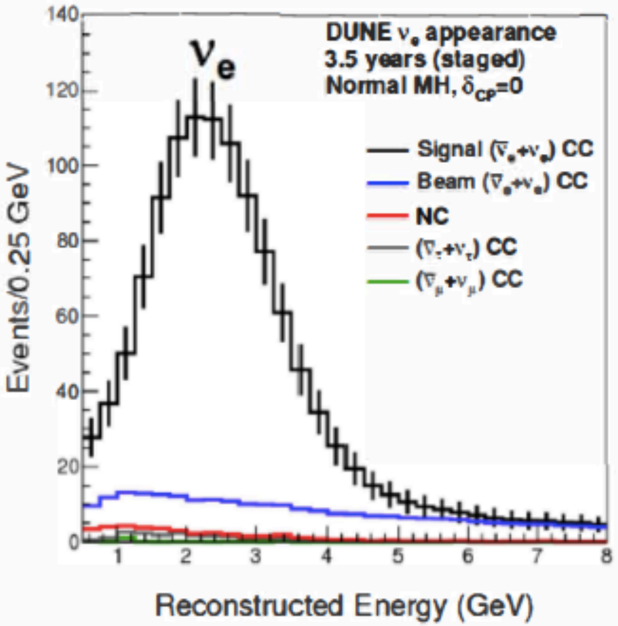




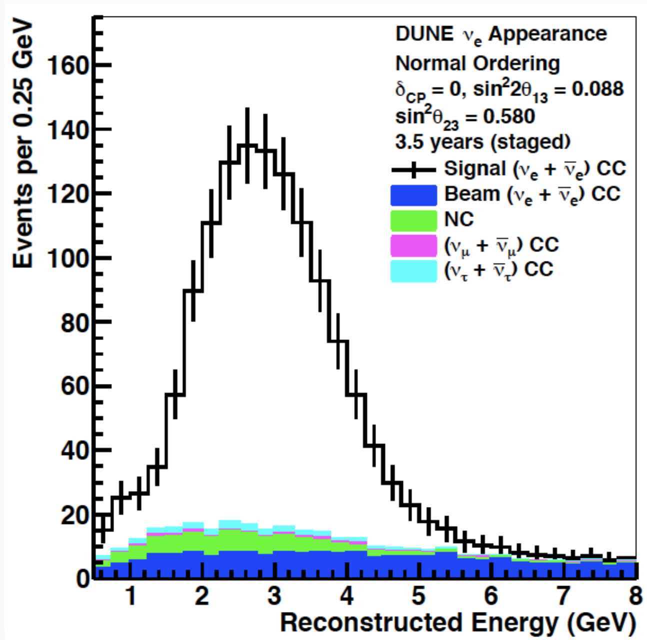
- Produce a pure on-axis ν_μ beam with spectrum matched to oscillation pattern at the chosen distance
- Measure spectrum of ν_μ and ν_e at a distant detector
- Do the same with anti-neutrinos
- **Fit all four spectra simultaneously**
- DUNE optimized the choice of beam and distance to have sensitivity to CP violation, CP phase, neutrino mass ordering, and other oscillation parameters ***in the same experiment***

Improving Our Tools

Conceptual Design Report (2016):
Parametrized detector response and estimated efficiency

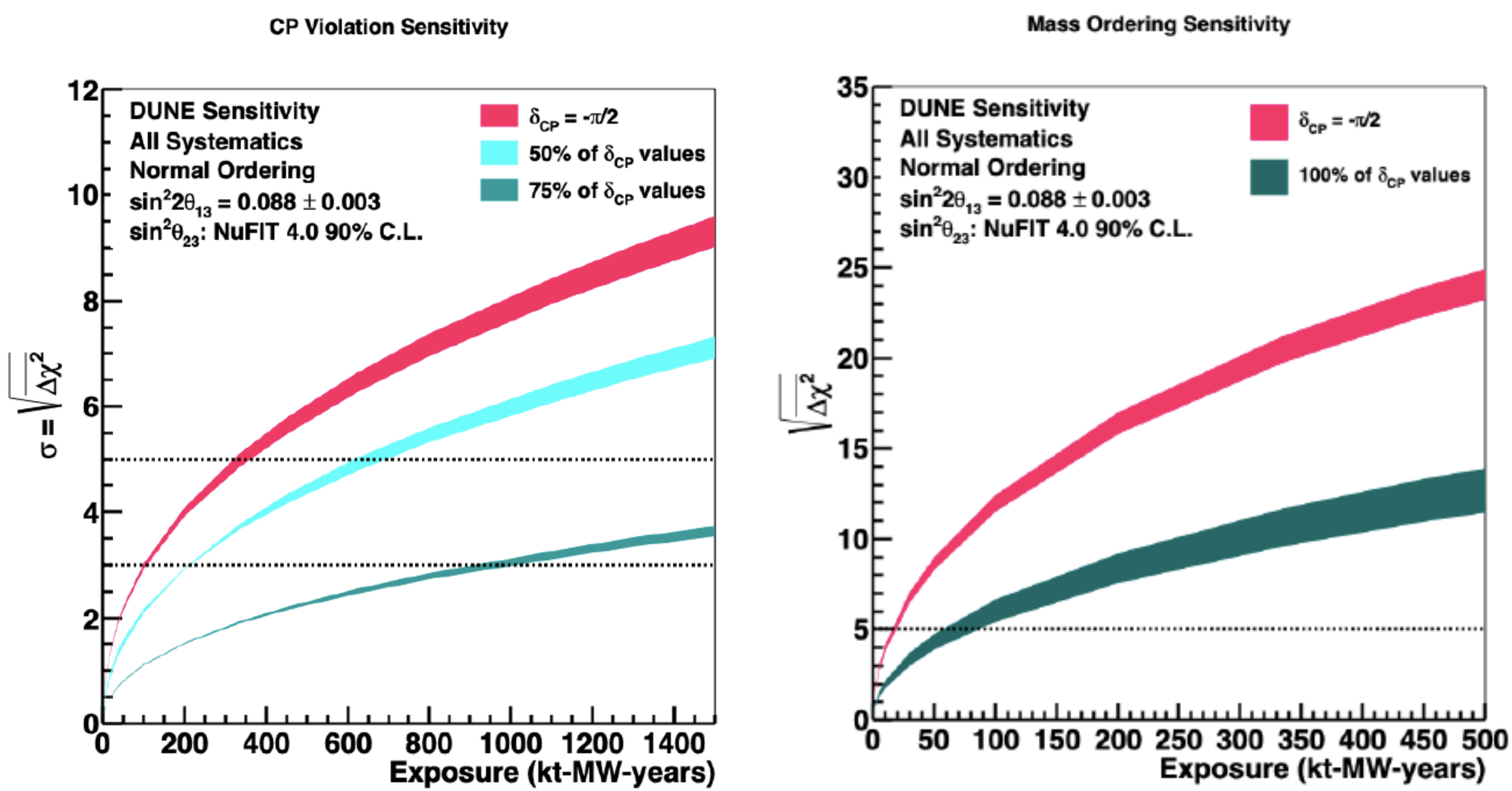


Technical Design Report(2020):
Full simulation reconstruction+ chain and CVN event selection



- Sensitivity from MC-based analysis with full reconstruction chain similar/better than in Conceptual Design Report (CDR)
- Sensitivity plots have been updated for the TDR

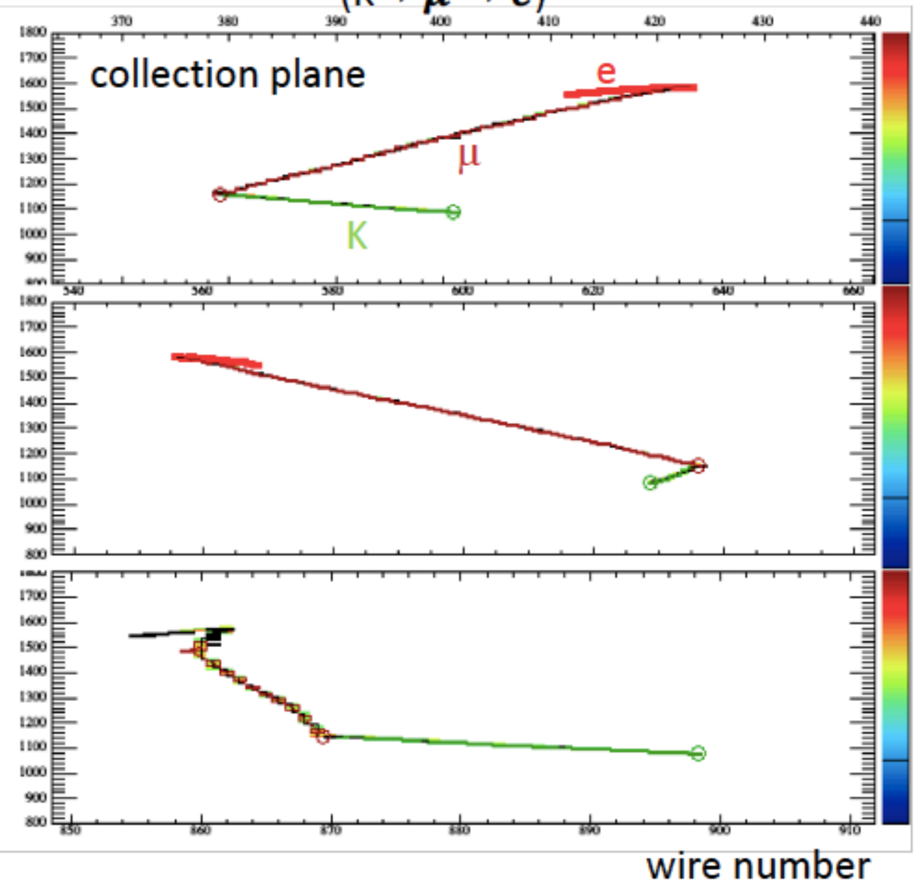
CP Violation and MH Sensitivity



Baryon Number Violation

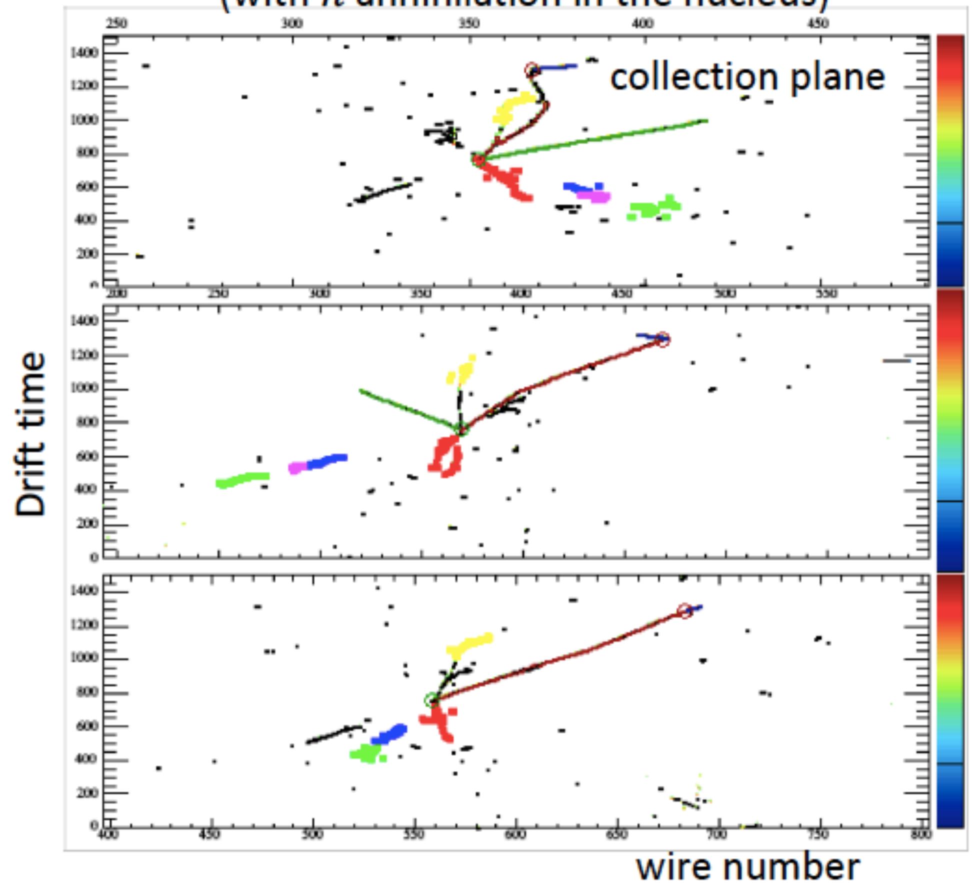
$p \to \bar{\nu} K$

(K→ $\mu \to e$)



$n - \bar{n}$ **oscillation**

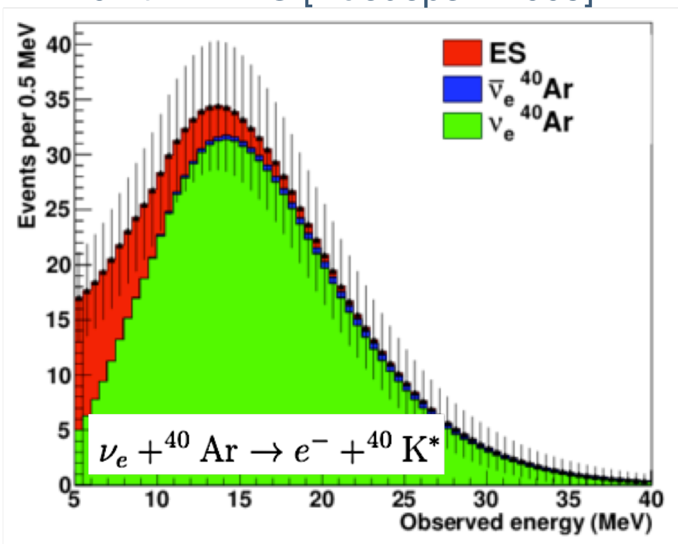
(with $\bar{n}$ annihilation in the nucleus)



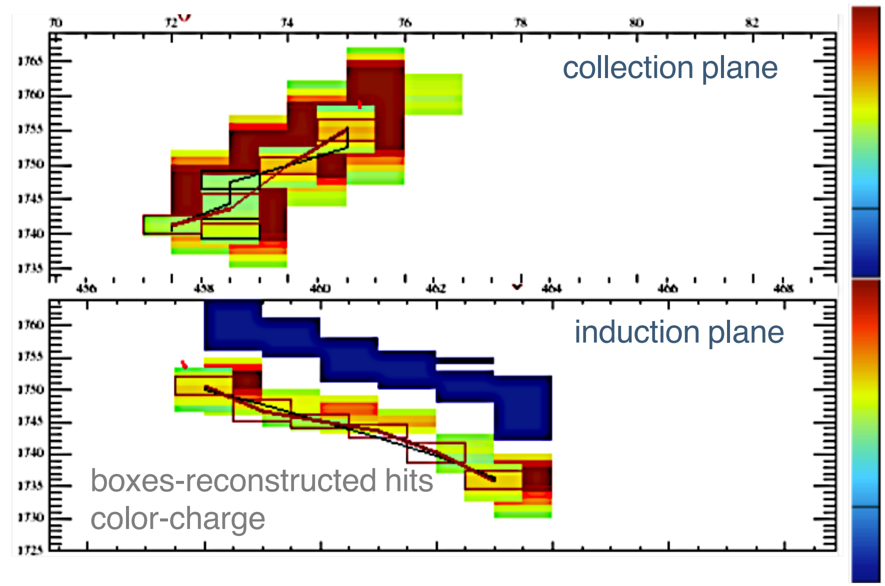
- Full simulation and reconstruction

Supernova Burst/Low Energy Neutrinos

Electron-capture SN at 10 kpc in
40-kt LArTPC [Huedepohl 2009]



10.25 MeV electron



- Sensitive to ν_e; complementary to water Cherenkov detectors
- Tracks only a few centimeters long but event-by-event energy reconstruction is possible in LAr
- Pointing may be possible using elastic scattering (ES) from electrons
- Triggering understood for SNB (100 sec readout buffer) but a challenge for solar neutrinos

INFN and DUNE

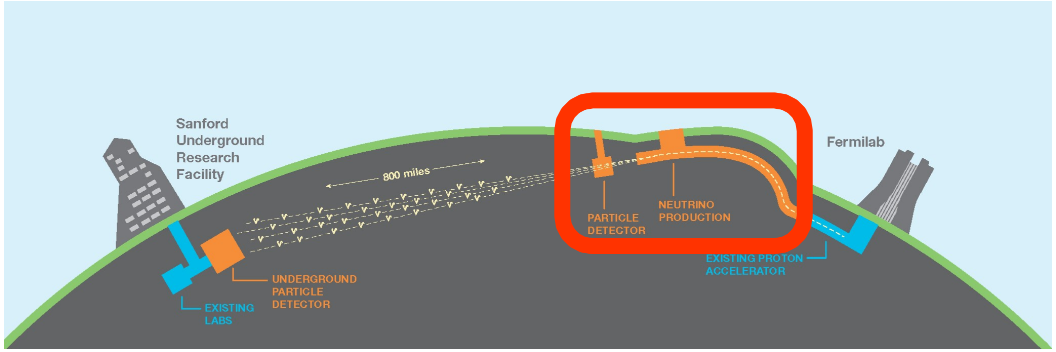
- Following the decision of the DUNE Collaboration of the two detectors configuration, **INFN is willing to provide all the needed resources** to dismount, refurbish, deliver, reassemble and commission a fully functional magnet + e.m. calorimeter+ LAr active target (~1.5 t)

- INFN is contributing to the Photon Detection System of the far detector

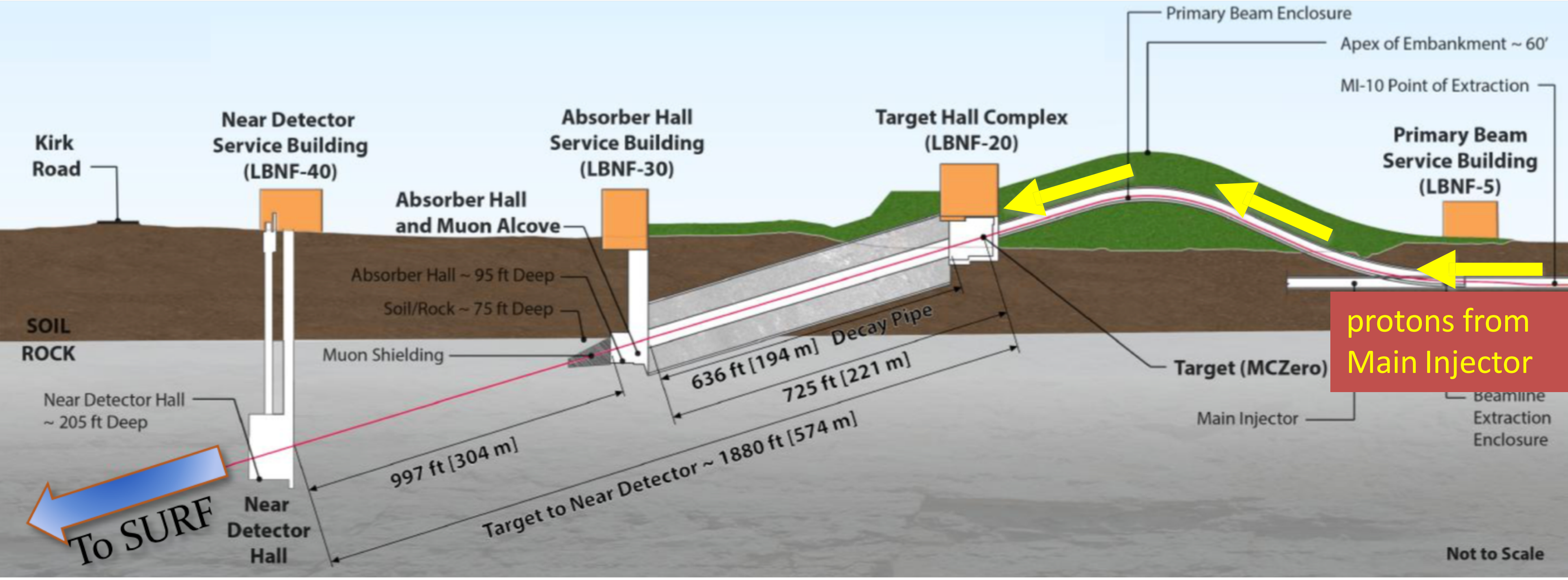
- INFN has also started to contribute to the design of the magnet for the new detector, and it is considering to contribute to its construction.

- INFN is contributing to PIP-II, the new high-power beam of FNAL

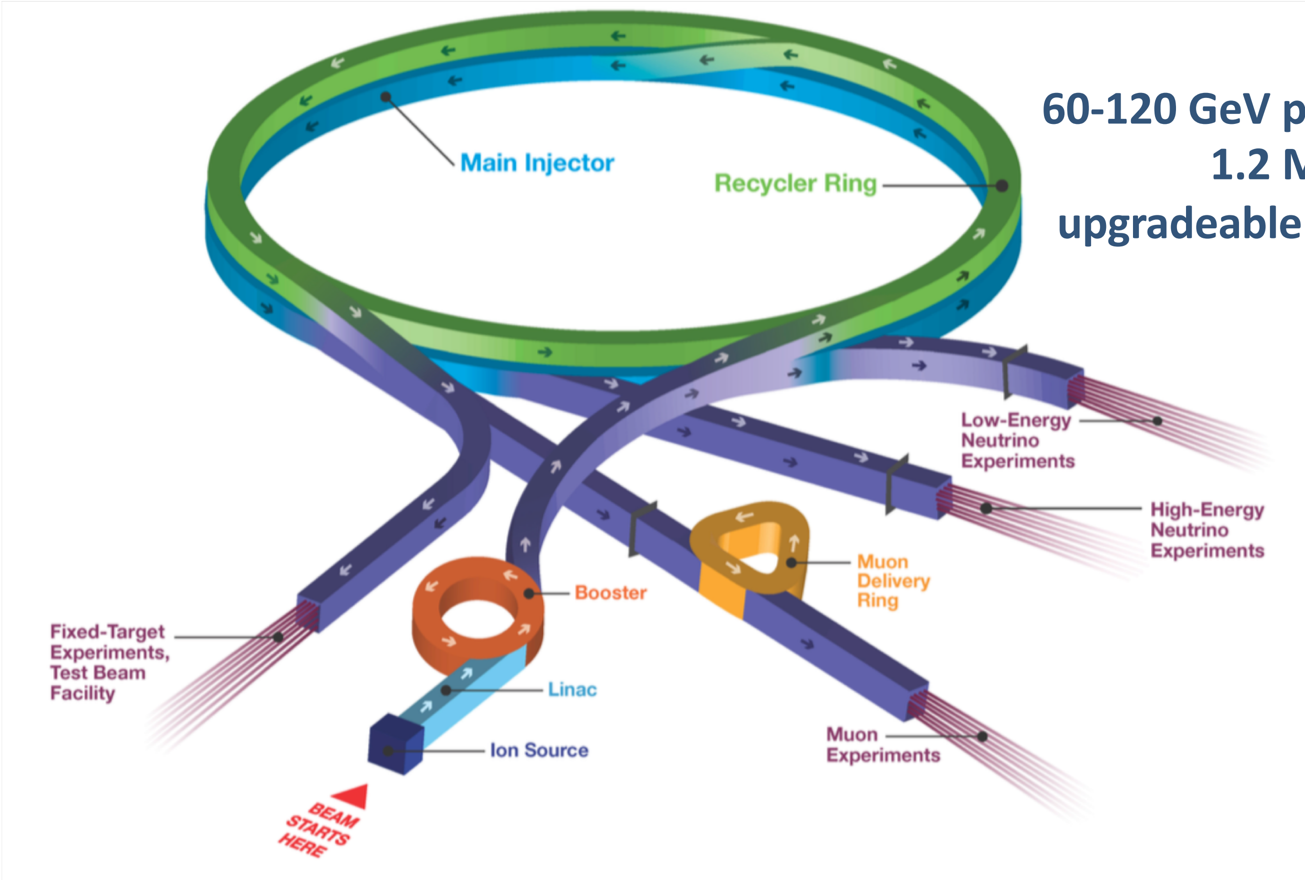
Long-Baseline Neutrino Facility (LBNF)



Near Detectors | **LBNF Neutrino beam-line**



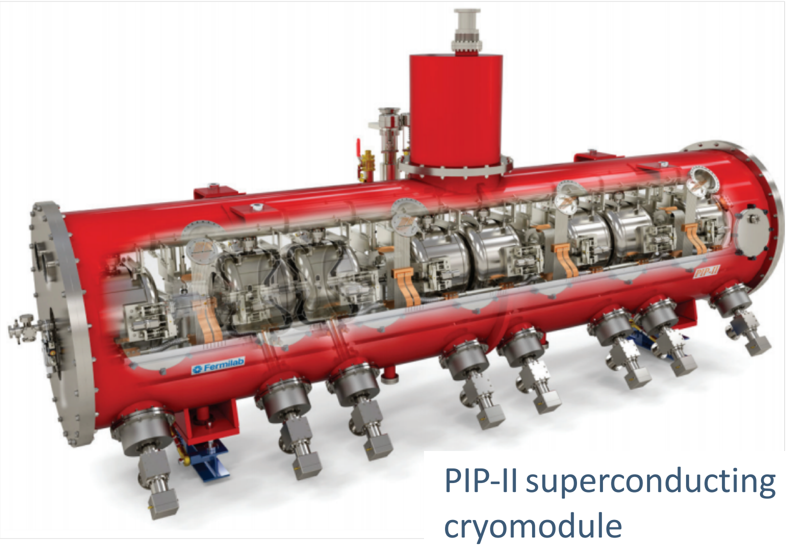
Fermilab Accelerator Complex



60-120 GeV proton beam
1.2 MW
upgradeable to 2.4 MW

- Reference design similar to existing NuMI (used for the NOvA experiment), optimized to improve sensitivity to oscillation measurements

Proton Improvement Plan



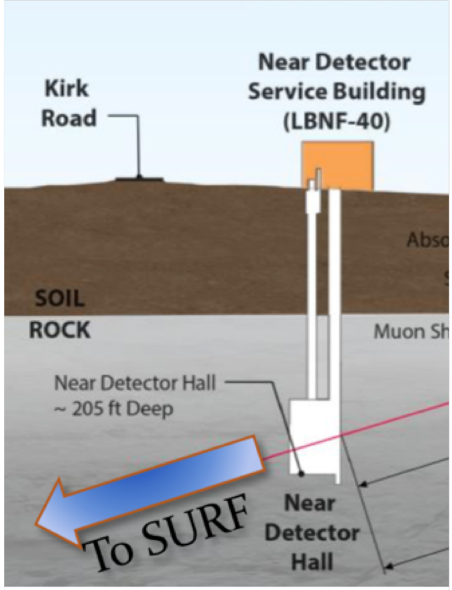
PIP-II superconducting cryomodule

- Megawatt proton beams
- 700-foot-long 800 MeV superconducting linear accelerator
- PIP-II Groundbreaking November 2019!

The DUNE Near Detector

- Constrain systematic uncertainties for LBL oscillation analysis
  - Also enables high precision neutrino interaction physics

- Integrated system composed of multiple detectors
  - Highly segmented Liquid Argon Time Projection Chamber (~75 t fid.) (ArCube)
  - Magnetized multi-purpose tracker w/ High Pressure Ar-CH_4 TPC (~1 t fid.) surrounded by electromagnetic calorimeter and muon tagger (MPD)
  - Magnetized on axis detector for monitoring and redundancy (SAND)

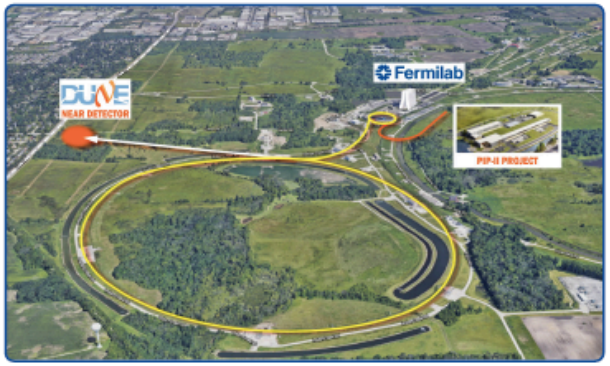


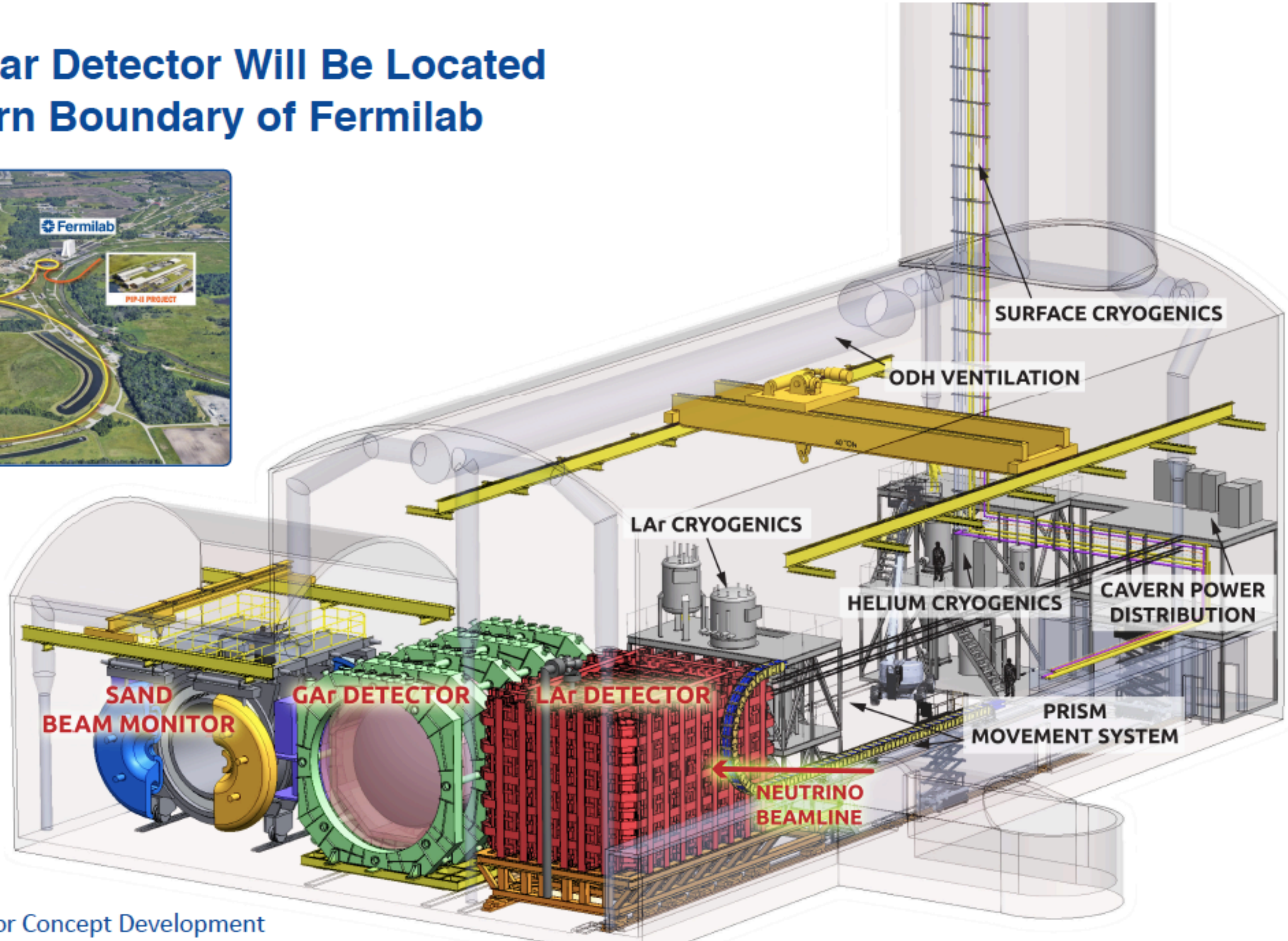
- Capability for the ArCube +MPD to move off axis

- ND Conceptual Design Report (CDR) end 2020

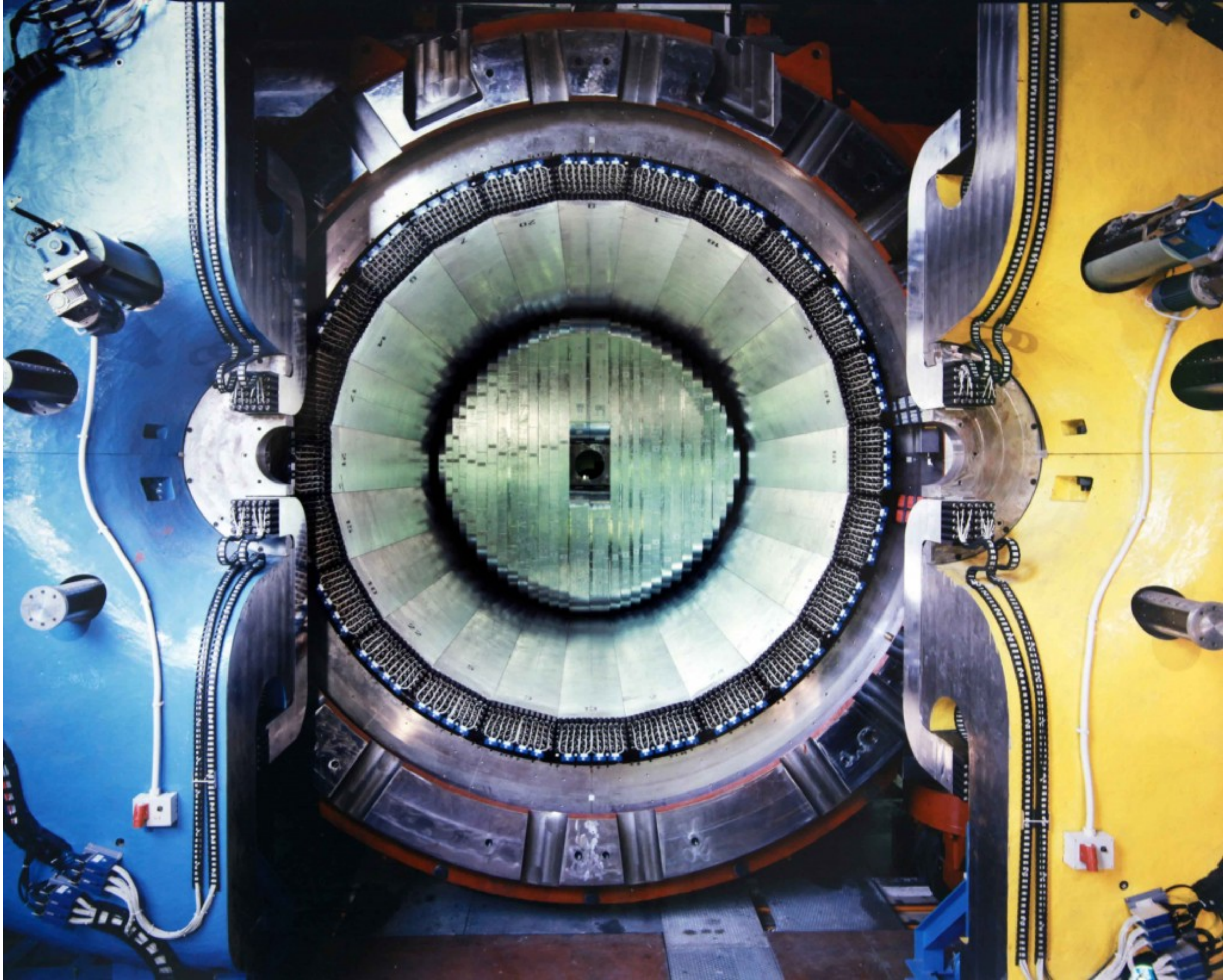
SAND within the ND complex

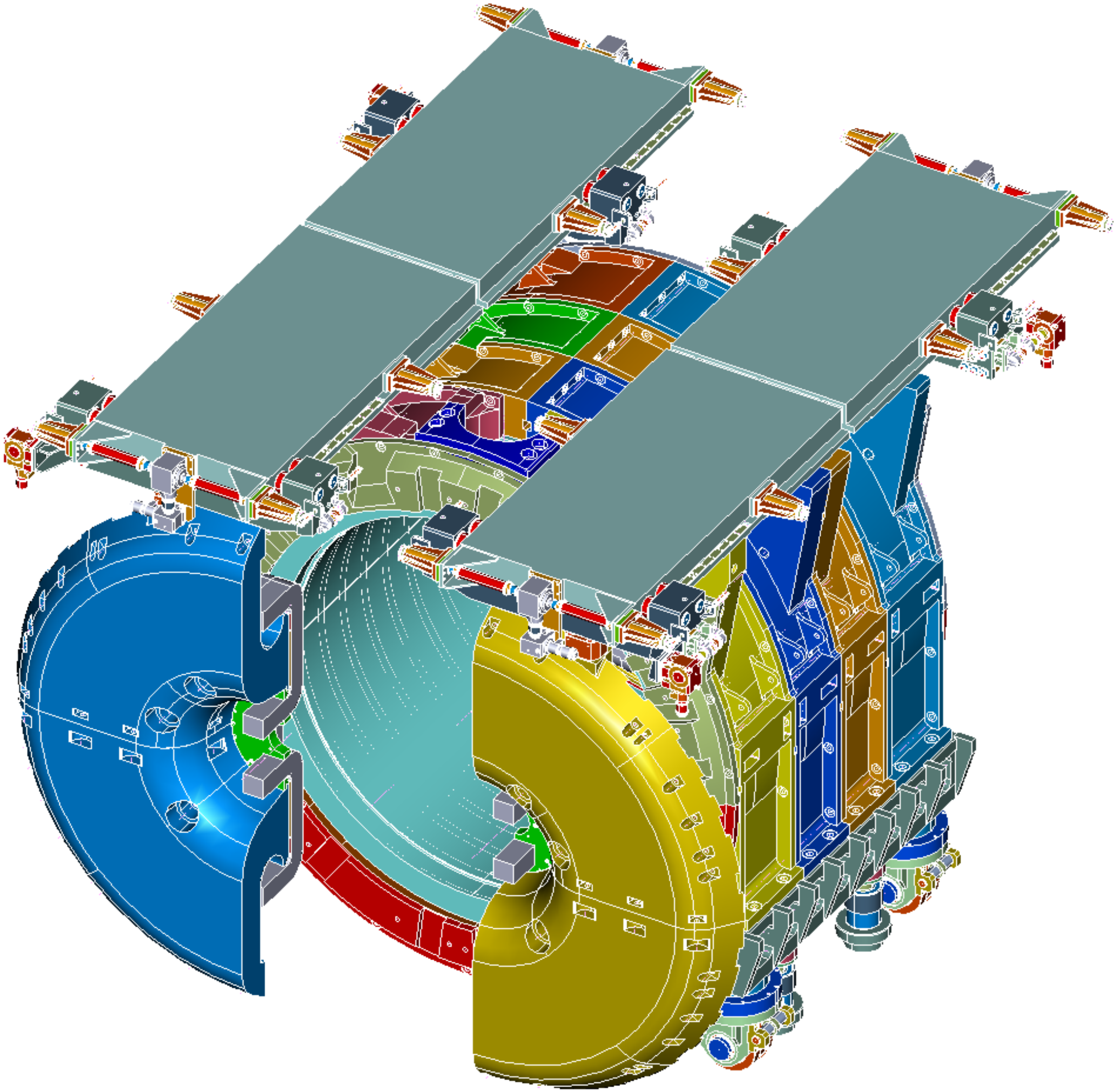
The DUNE Near Detector Will Be Located At The Western Boundary of Fermilab





DUNE-ND I&I Team
Supported Early Detector Concept Development

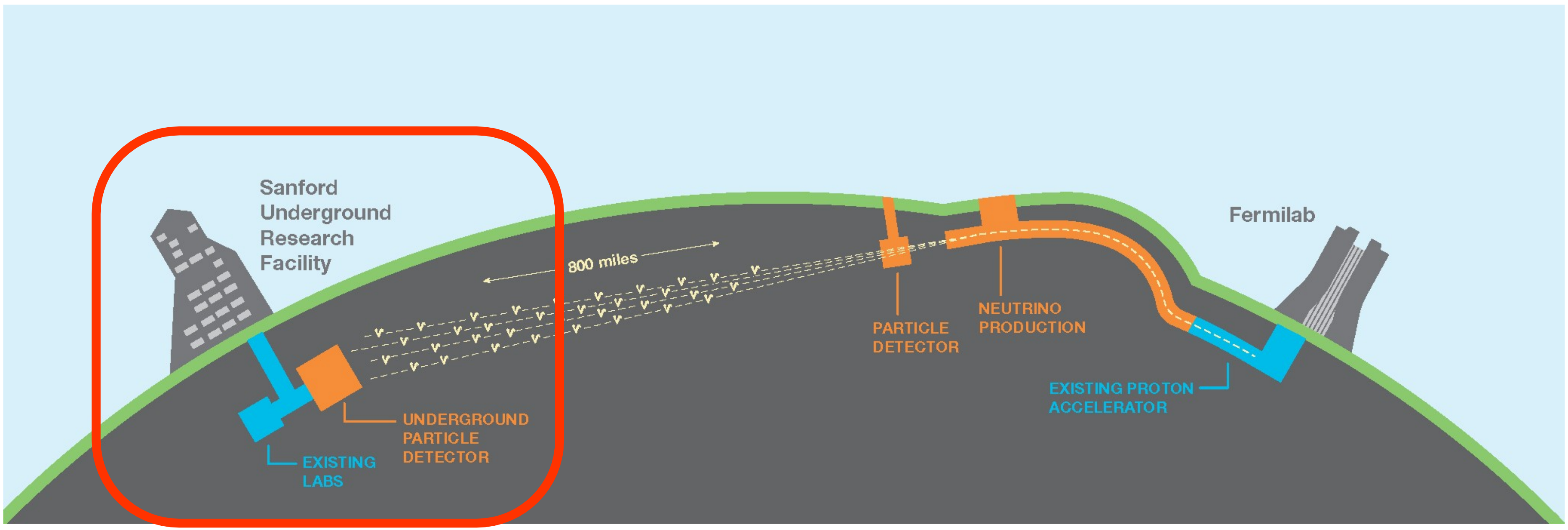


Sanford Underground Research Facility (SURF)

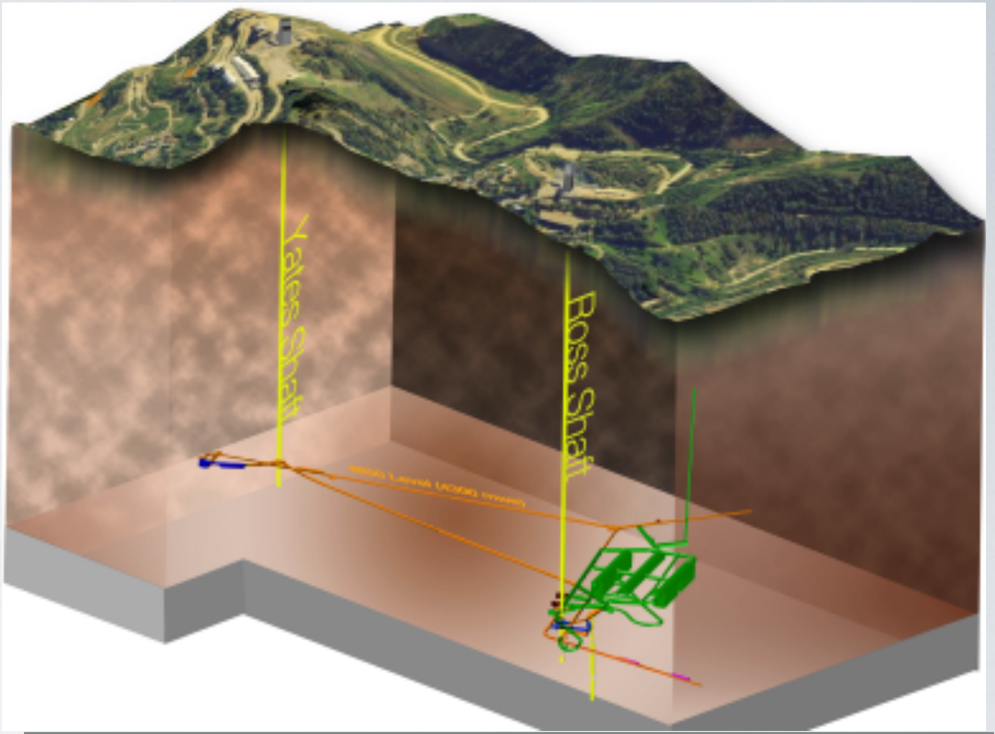
https://sanfordlab.org/

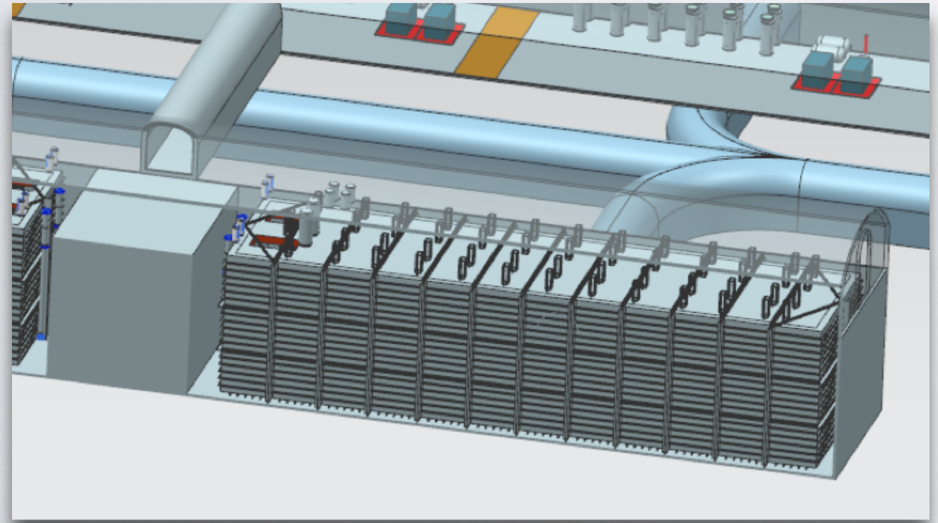
Far Site: 1300 km from Fermilab

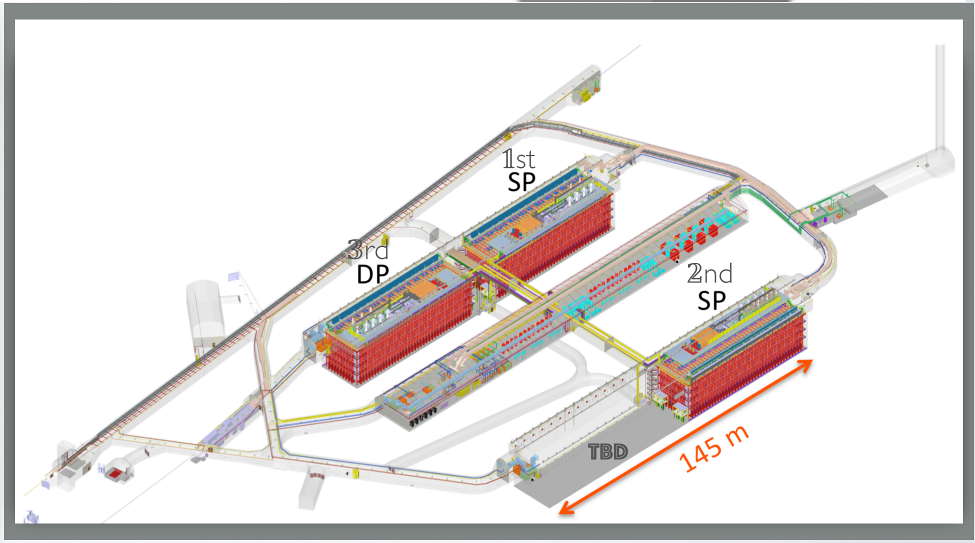


"Far Site": SURF 4850 Level

- Major underground excavation removing ~800,000 tons of rock
- Two large caverns housing **four** cryostats and a central utility space
- **~ 70000 tons of LAr to fill the cryostats:** ***the target for neutrino interactions***



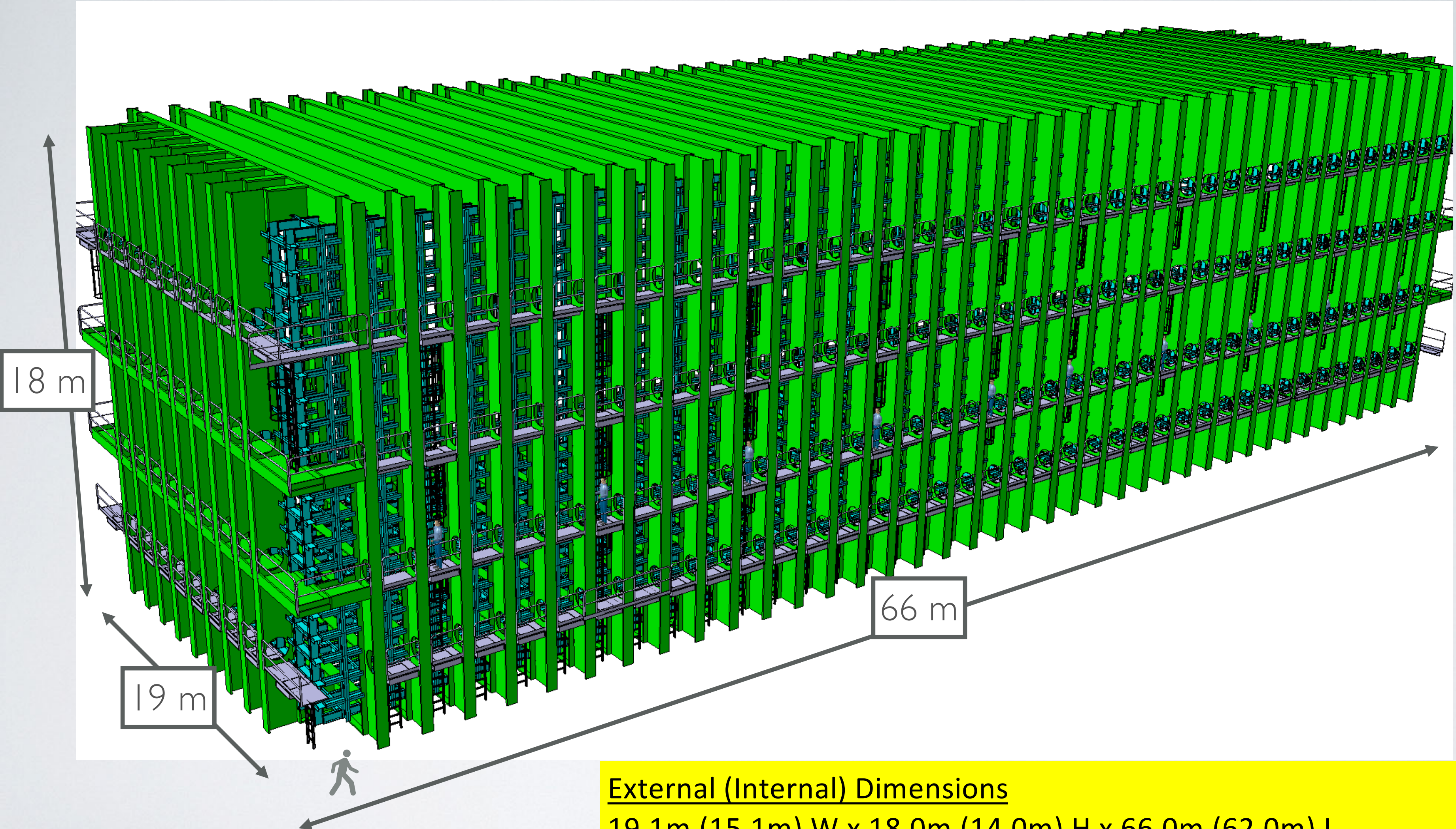




The first FD Module:

17 kt LAr cryostat

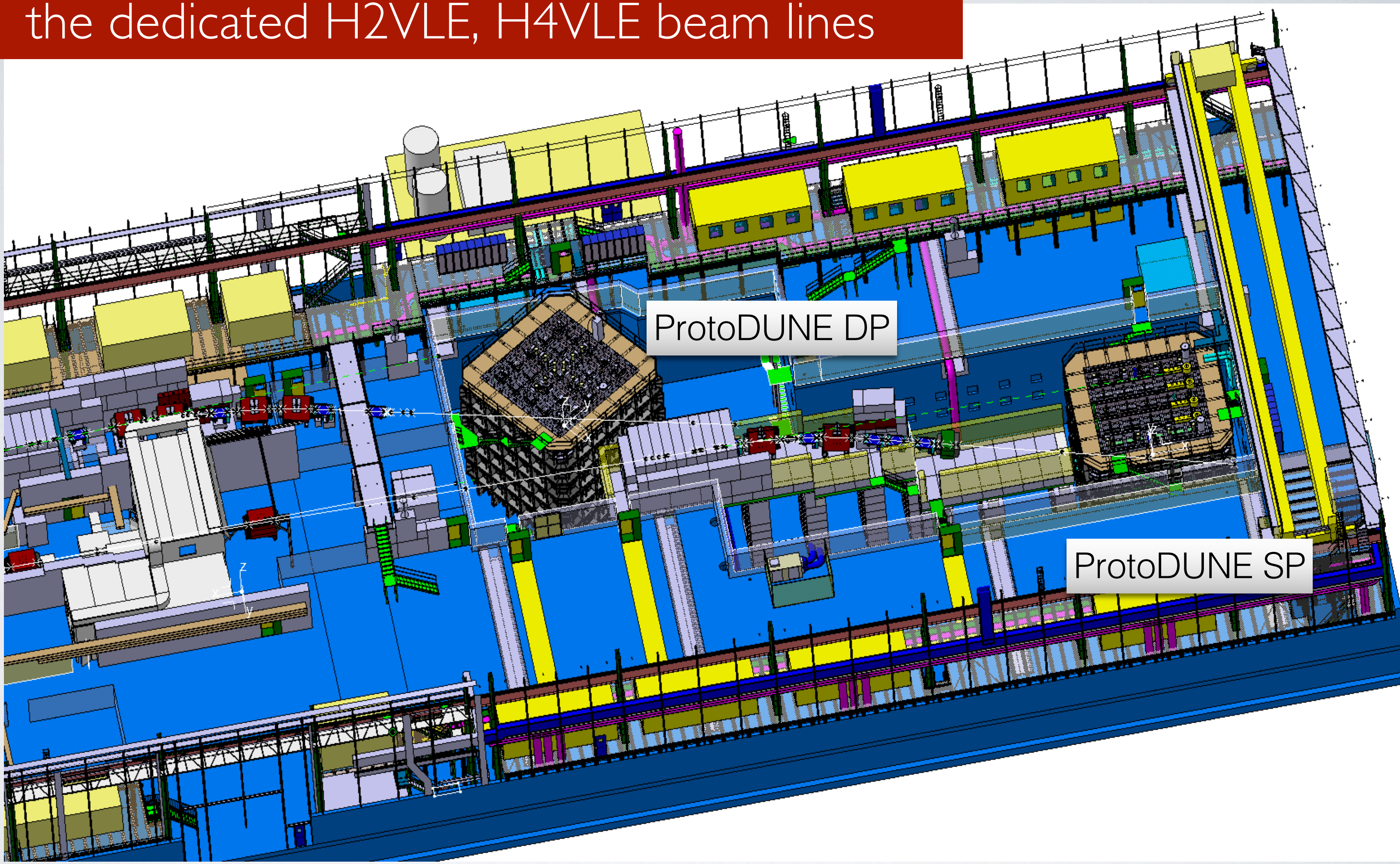
DEEP UNDERGROUND NEUTRINO EXPERIMENT



<u>External (Internal) Dimensions</u>

19.1m (15.1m) W x 18.0m (14.0m) H x 66.0m (62.0m) L

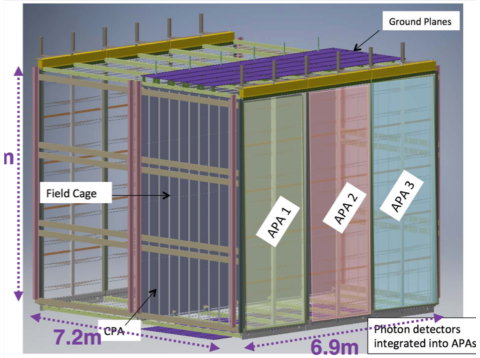
The Neutrino Platform and the dedicated H2VLE, H4VLE beam lines



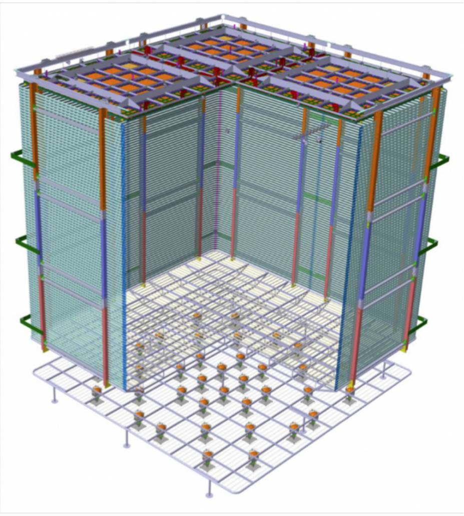
extension of the EHN1 experimental area at CERN's Prévessin site

DUNE Far Detector: Two LAr TPC Approaches

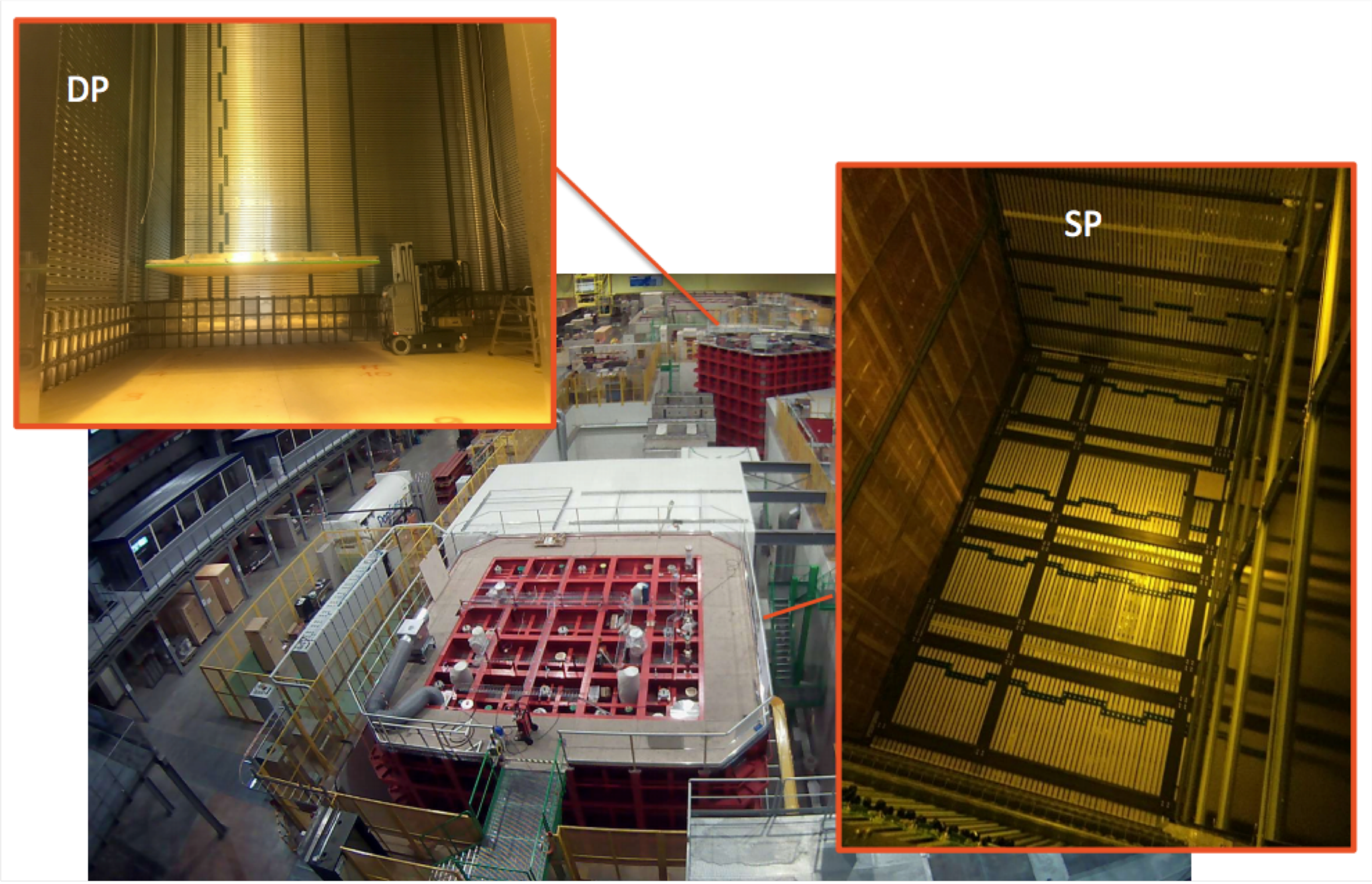
- Single-Phase
- ICARUS concept
- 3.6-m horizontal drift in liquid
- readout in liquid (no avalanche amplification)



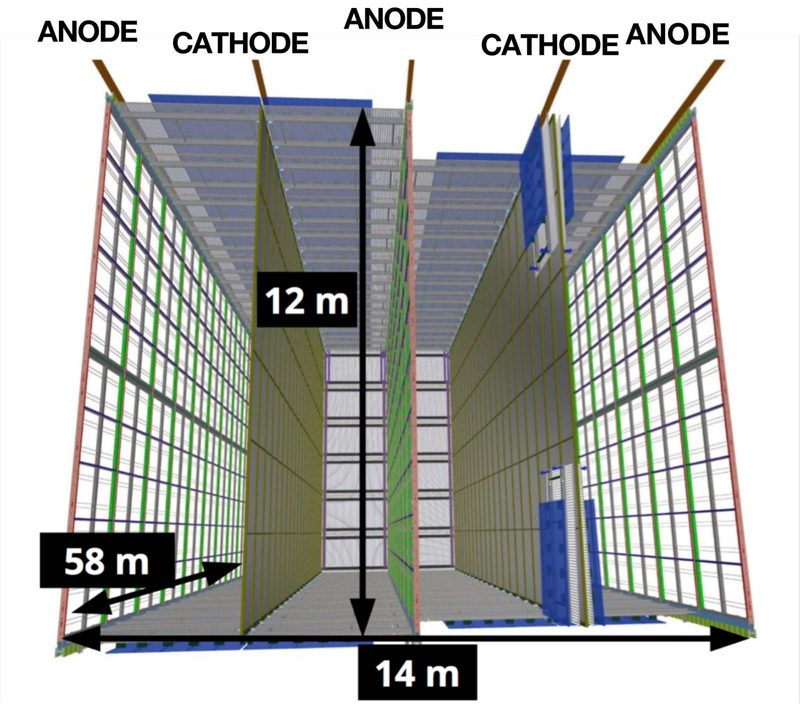
- Dual-Phase
- 12-m vertical drift in liquid
- extraction from liquid to gas (avalanche amplification in gas)



Large-Scale Prototypes: ProtoDUNE



Single Phase TPC Module

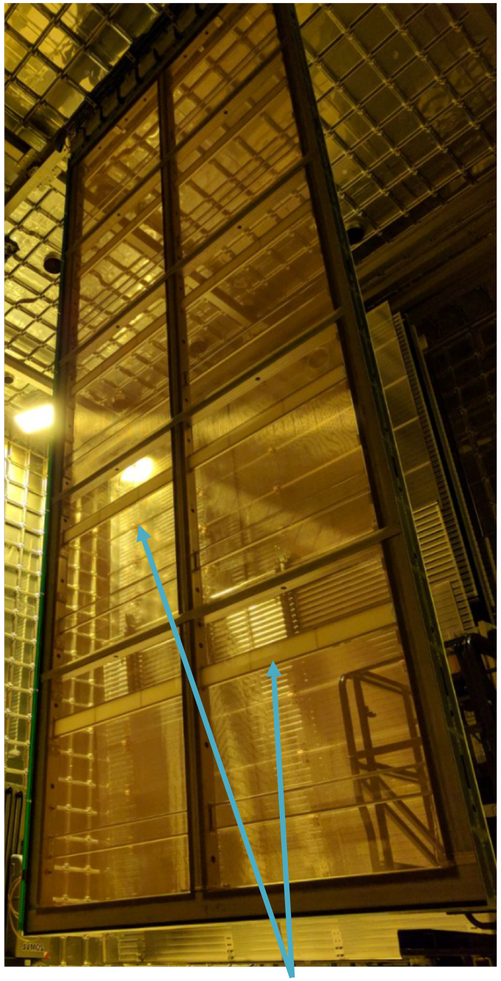


- “Wrapped” anode planes sensitive from both sides (X, U, V, G planes)
- Anode Plane Assembly (APA): 6 m x 2.8 m; 150 APAs per 17 kt module
  - 3520 wires/APA; 2560 readout channels/APA
- 500 V/cm drift field: 180 kV at the cathode

Single Phase Module – Photon Detectors

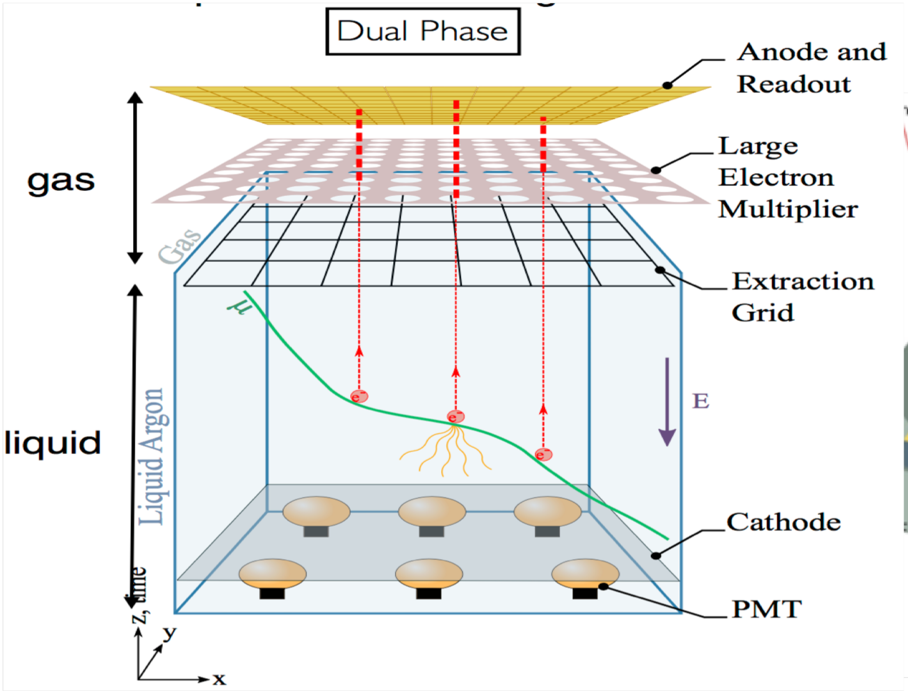
- Event time essential for nucleon decay and SNB neutrino events localization and energy correction
- Complementary trigger to TPC for SNB and extends sensitivity out to nearby dwarf galaxies
- Challenge: Need to be embedded within the ~5cm space between anode planes

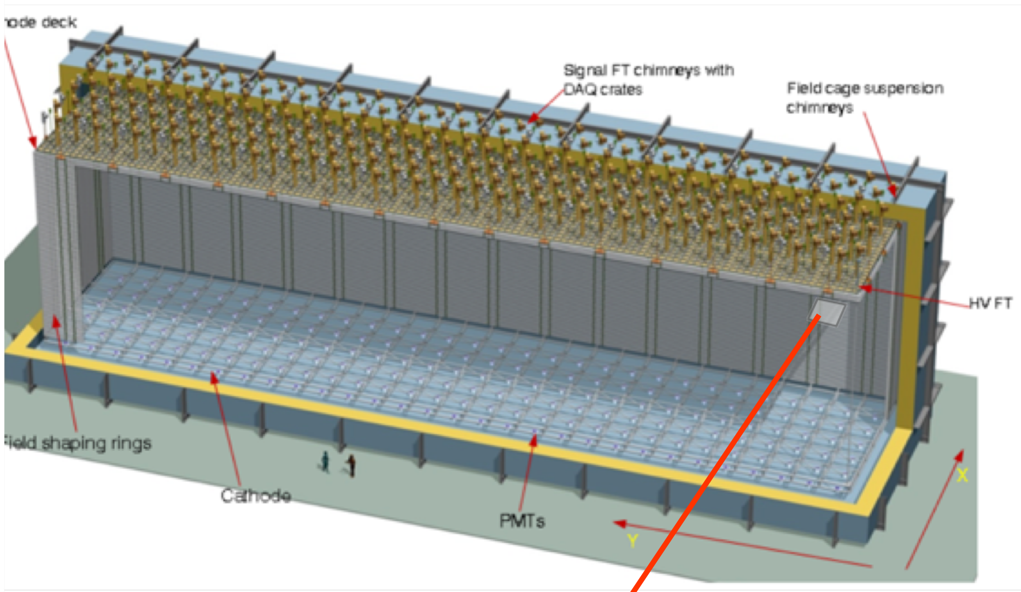
- X-ARAPUCA is a novel photon detector that uses a "light-trapping" concept to enhance collection efficiency
  - 3.5% photon detection efficiency achieved for incident 127 nm scintillation light
- PD system enhances the energy measurement and may provide better resolution than the TPC below 20 MeV



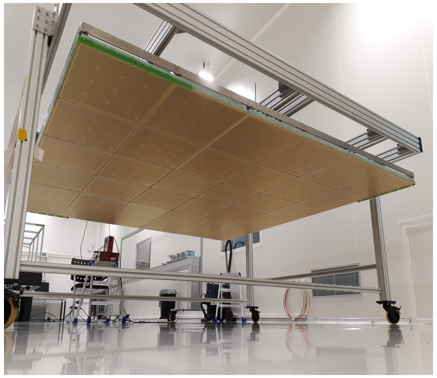
Photon detector embedded in the anode planes

Dual Phase TPC Module



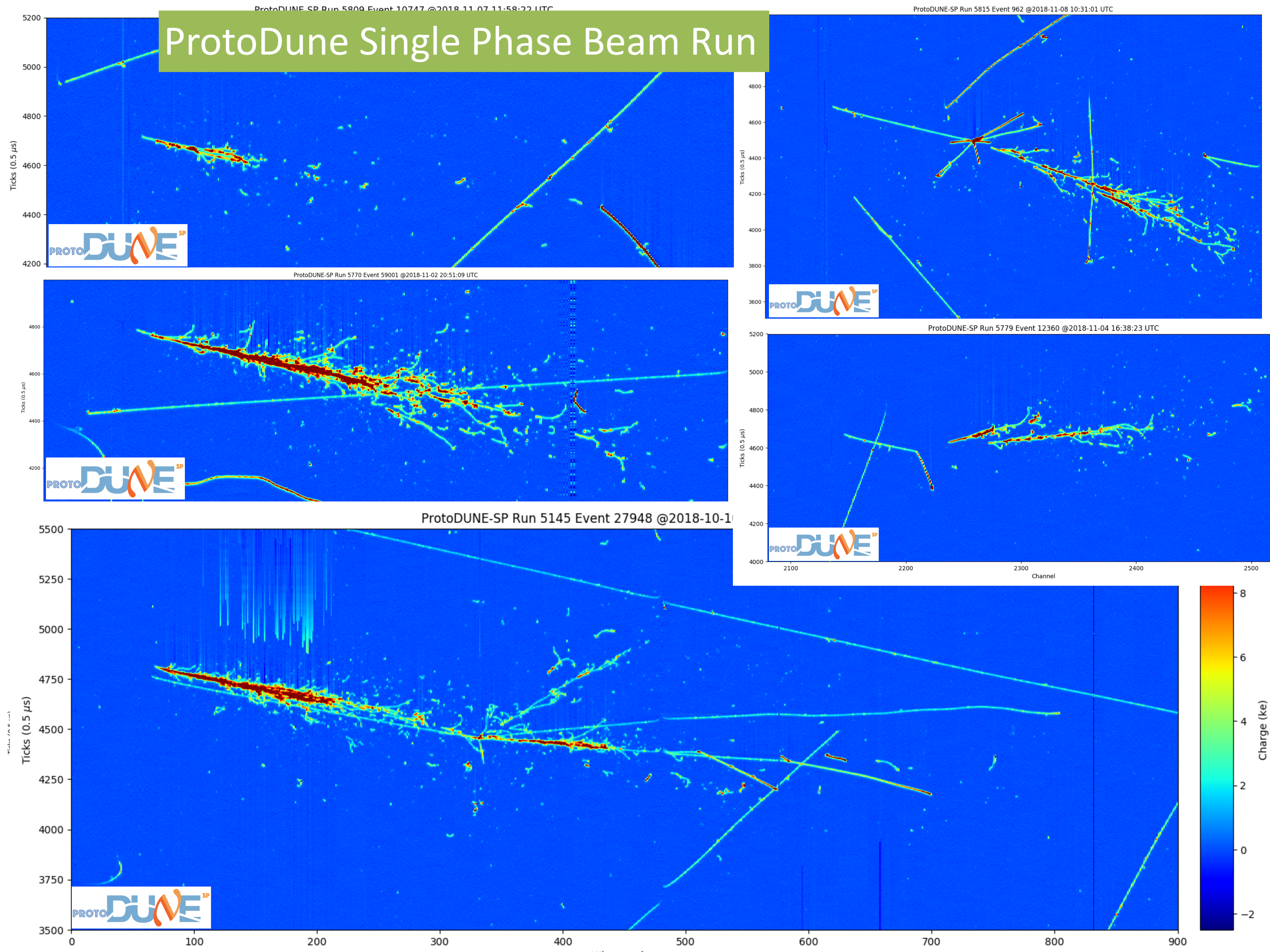


Charge Readout Plane (Anode)



- Single homogeneous LAr drift volume
- Signal amplification in the gas phase leads to improved signal/noise
- Photosensors under semi-transparent cathode grid
- 500 V/cm drift field: 600 kV at the cathode

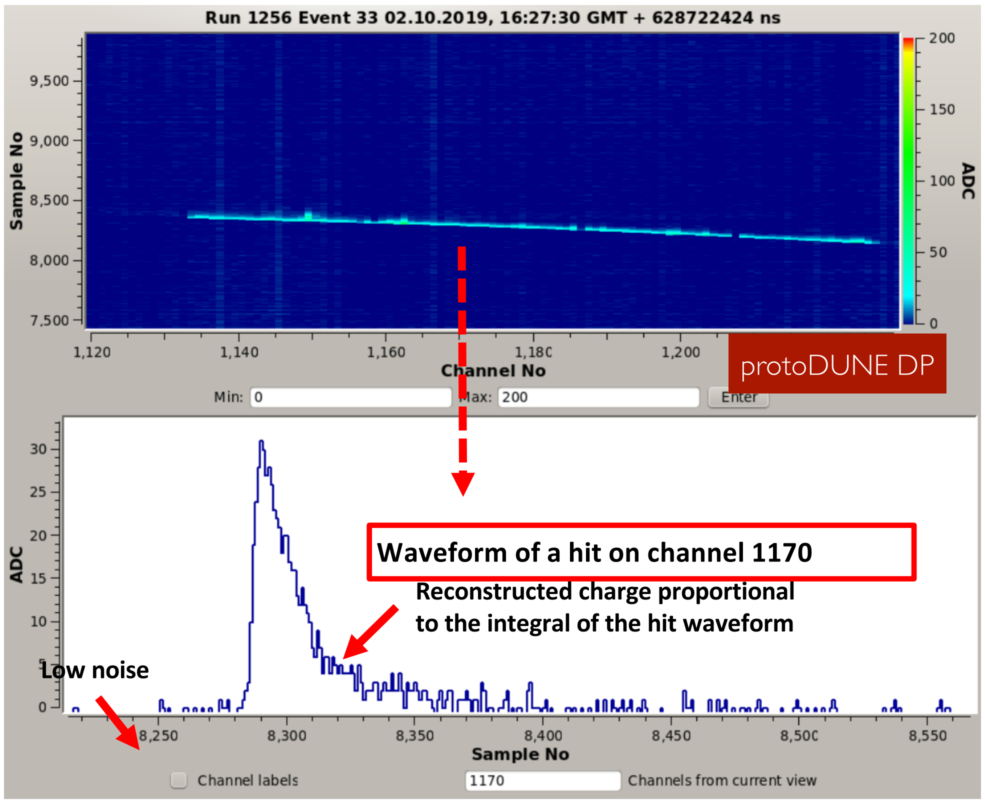
ProtoDune Single Phase Beam Run

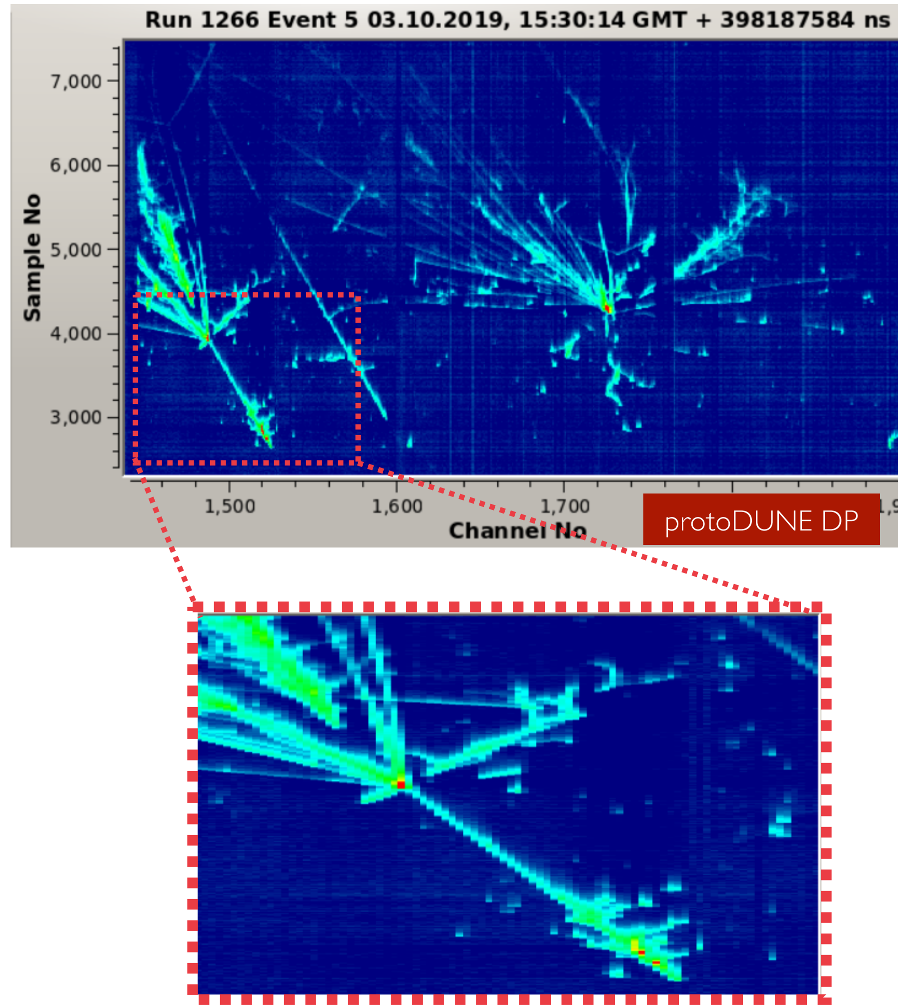


ProtoDune DoublePhase Cosmic Rays Events

Horizontal muon track
- LEM ΔV= 3.1 kV

Multiple hadronic interactions in a shower - LEM ΔV= 3.2 kV





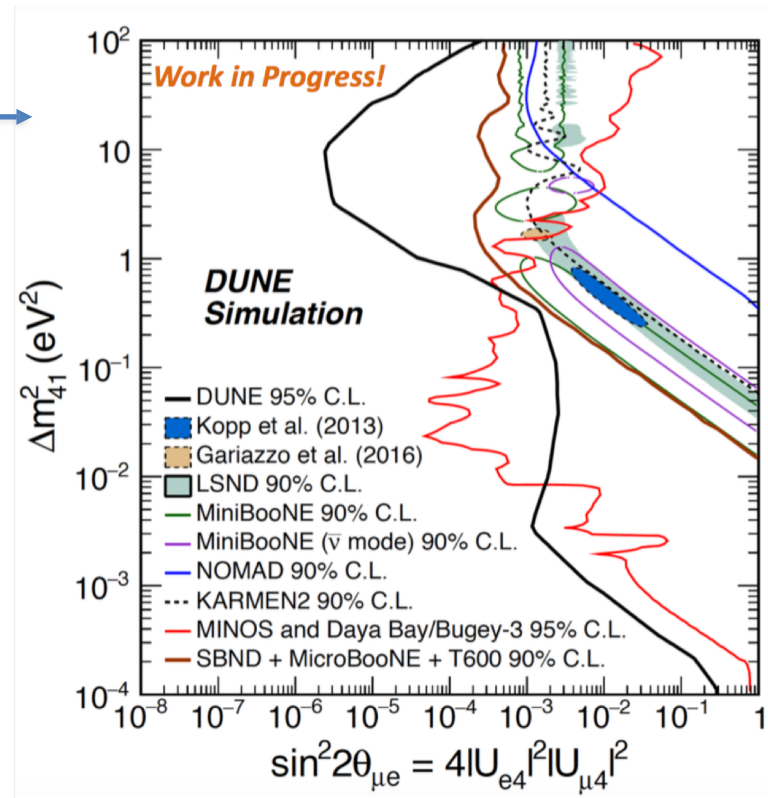
DUNE/LBNF Outlook

- LBNF
  - Far site pre-excavation work underway (rock disposal systems etc.); cavern excavation 2021-24
  - Near site construction starts 2021
  - Neutrino beam construction started
- DUNE
  - Far Detector TDR February 2020; Near Detector CDR fall 2020
  - Module 1 Single Phase installation begins end 2024
  - Followed immediately by a second module
  - Module 4 “module of opportunity” for a different design – a workshop later this year to begin exploration of ideas
- First module live ~2026 – SNB & atmospheric neutrino

Beyond Standard Model

- DUNE sensitive to many BSM particles and processes
- Sterile neutrinos
- Light dark matter
- Boosted dark matter
- Non-standard interactions, non-unitary mixing, CPT violation
- Neutrino trident searches
- Large extra dimensions
- Neutrinos from dark matter annihilation in sun

Sterile Neutrino Sensitivity
(ν_eCC appearance at Near Detector)



To conclude

- Since 1998, neutrinos have given us the most promising hints of BSM physics.
- Their nature and their properties are still a central questions in particle physics.
- A new generation of experiments is underway, with a substantial and strategic Italian involvement in DUNE
- DUNE/LBNF is heralding this effort addressing the challenge in a global context and enabling a long term, first class environment to enhance our understanding of Fundamental Physics.

Thank You

…and thanks to E. Blucher, F. Cavanna, E. Worcester, et al. for the looted material and many useful discussions.