Deep Underground Neutrino Experiment: DUNE

Andrea Zani, *INFN Milano*

for the DUNE Collaboration

Weak Interactions and Neutrinos – WIN 2021

7-12 June 2021

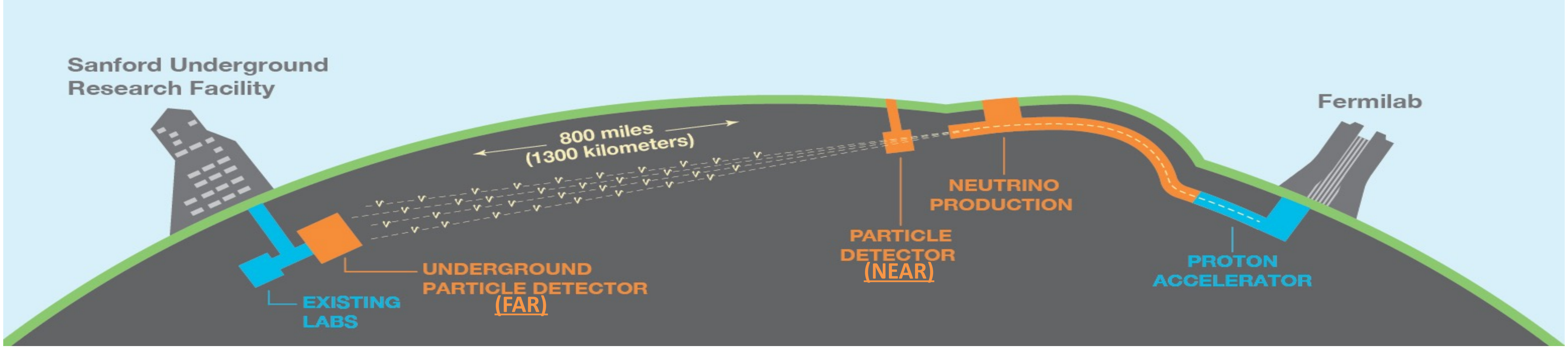
INFN MILANO

DUNE

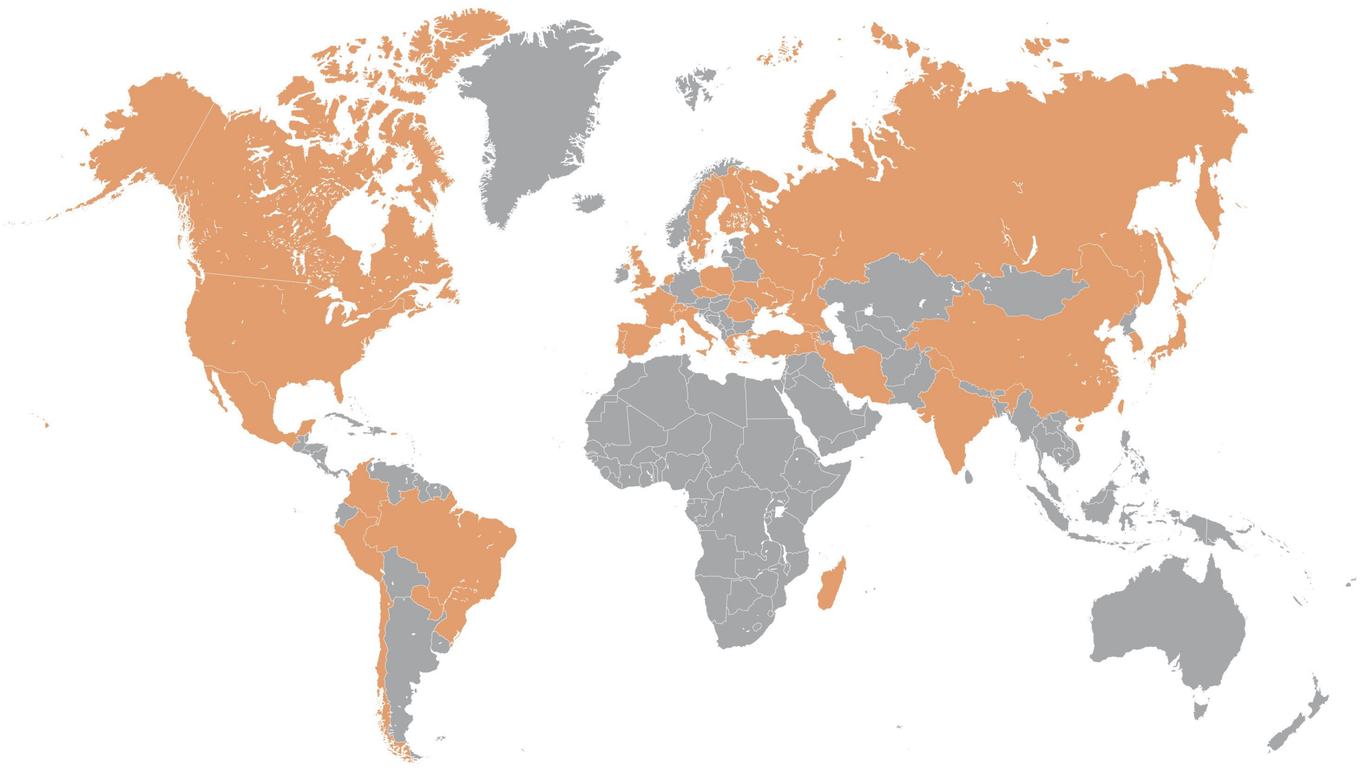
Deep Underground Neutrino Experiment

- Long-baseline (LB - 1300 km) experiment:
  - Neutrino and antineutrino beams
- ~ 70 kton volume far detector, 1.5 km underground, divided in 4 modules
- Multi-technology Near Detector, focused on beam characterization and physics
- > 20 years foreseen life span

- **Primary physics goals**:
  - 3-neutrino oscillations parameters: $\nu_\mu/\overline{\nu_\mu}$ disappearance, $\nu_e/\overline{\nu_e}$ appearance
  - δ_{CP} ; mass hierarchy
- **SuperNova** burst neutrinos
- **Beyond-Standard-Model physics**: baryon number violation, sterile neutrinos, non-standard interactions, etc.



The DUNE Collaboration



- World-spanning community
- Draws on years-long experience of LAr-TPC based neutrino experiments
  - > 1300 collaborators
  - > 200 institutions & CERN
  - 33 countries

DUNE at WIν 2021

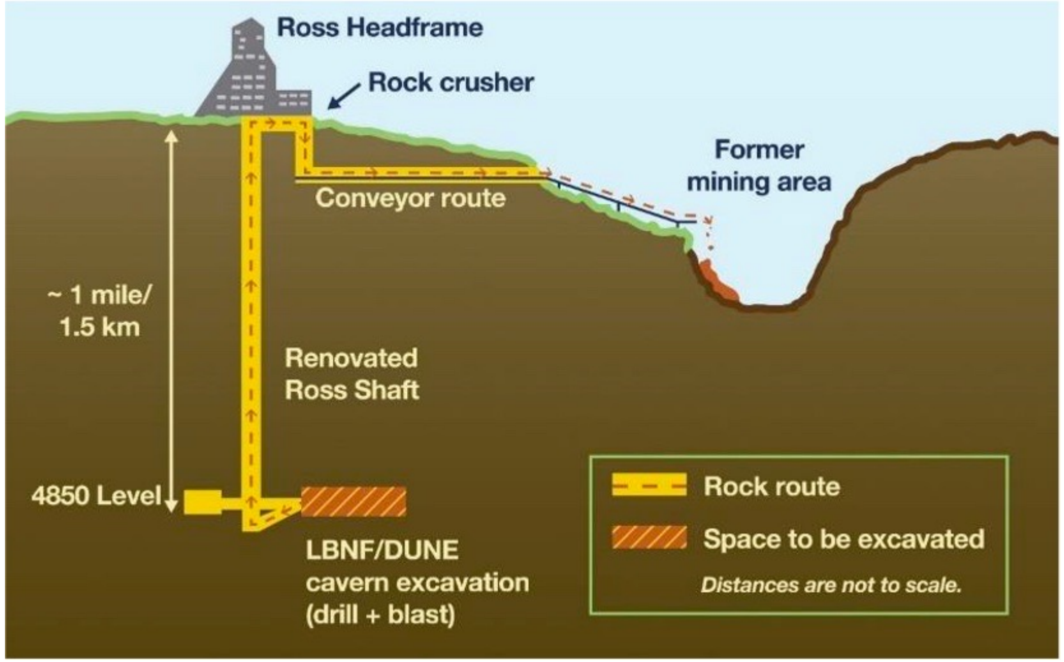
- DUNE- & ProtoDUNE-related posters @ WIN 2021 (not exhaustive list)
  - *"3-Dimensional reconstruction in DUNE"* — Etienne Chardonnet
  - *"Deep Learning Based Event Reconstruction at DUNE"* — Jianming Bian
  - *"A Vertical Drift LArTPC for the DUNE experiment"* — Sabrina Sacerdoti
  - *"Effects of the LBNF Neutrino Beam Focusing Uncertainties on DUNE Neutrino Fluxes with a Focus on the Decay Pipe"* — Pierce Weatherly
  - *"The System for on-Axis Neutrino Detection of the DUNE Near Detector complex"* — Valerio Pia
  - *"Characterization of the DUNE photodetectors and study of the event burst phenomenon"* — Marco Guarise
  - *"Measurements and enhancement of the X-Arapuca light detection efficiency"* — Henrique Souza
  - *"Towards an Inelastic Cross Section Measurement of 6 GeV Kaons on Argon at ProtoDUNE Single-Phase"* — Richard Diurba
  - *"Electron Diffusion in the ProtoDUNE-SP LArTPC"* — Elise Hinkle
  - *"Identification and Reconstruction of Michel Electrons in ProtoDUNE-SP"* — Aleena Rafique

Content

- Introduction to DUNE and its physics goals
  - The LBNF infrastructure
  - The Near Detector Site
  - The Far Detector Site and technologies
- The Physics Potential of DUNE
  - Precision neutrino physics measurements
  - Beyond the Standard Model (BSM) searches
- The DUNE prototypes at CERN
  - The “cauldron” where large-scale R&D takes place
  - Validation and characterization of DUNE modular design on full scale prototypes

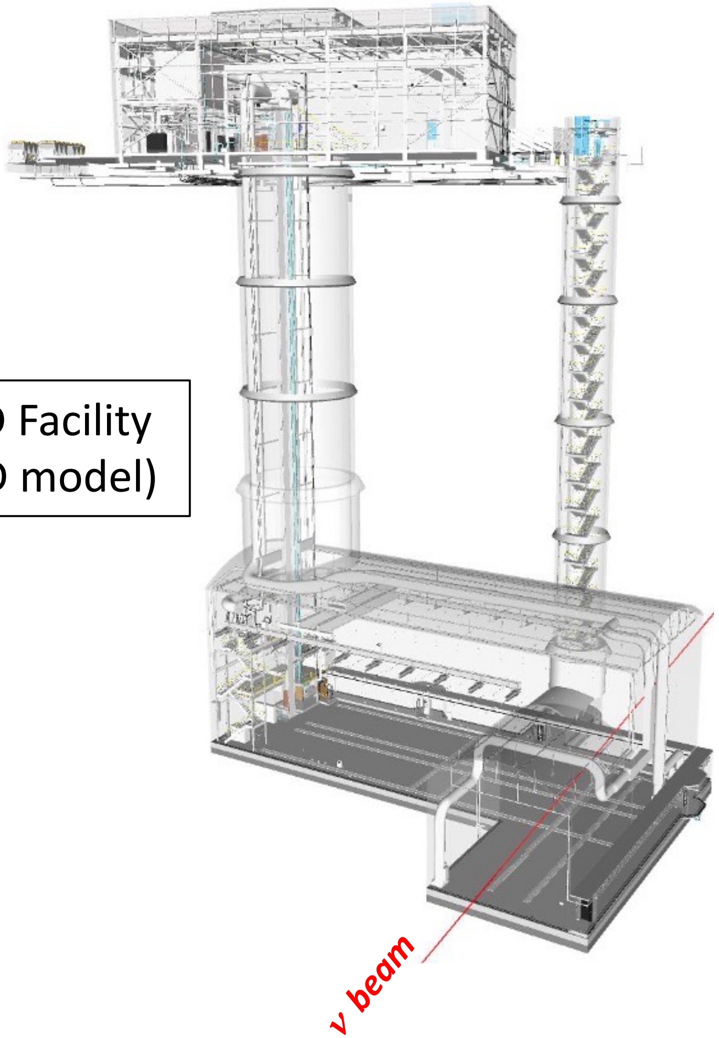
Long Baseline Neutrino Facilities

- **Infrastructures**
  - Excavation works at SURF for Far Detector (FD) caverns
  - Design work for Near Detector (ND) site, due to submission for approval within few months



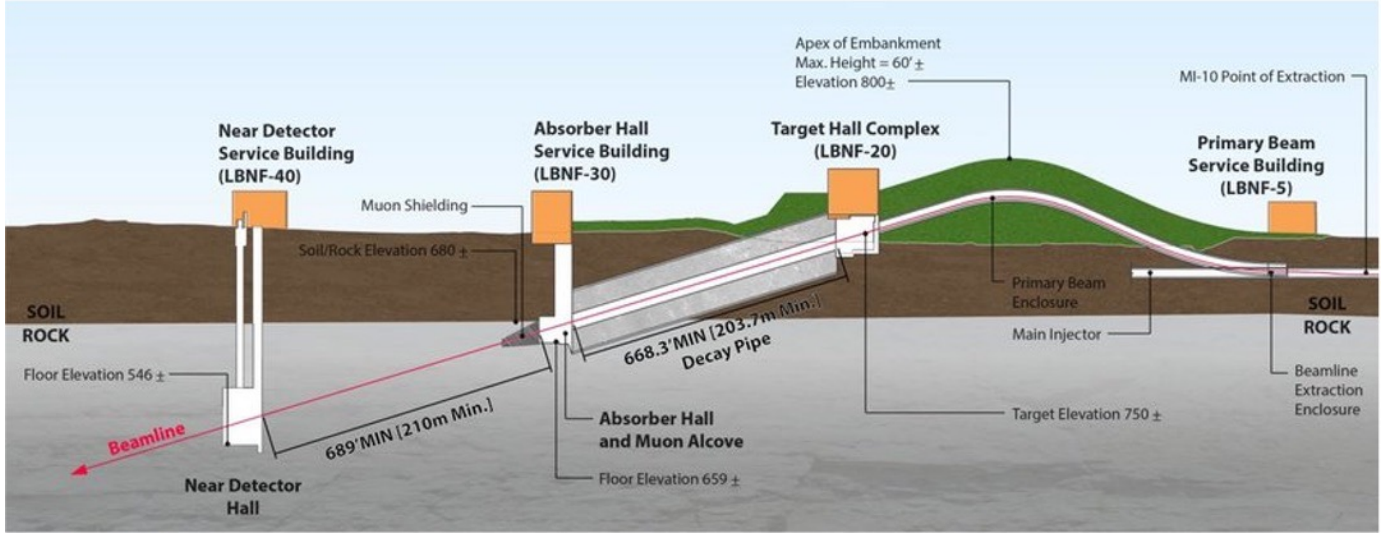
FD excavation sketch

ND Facility (3D model)

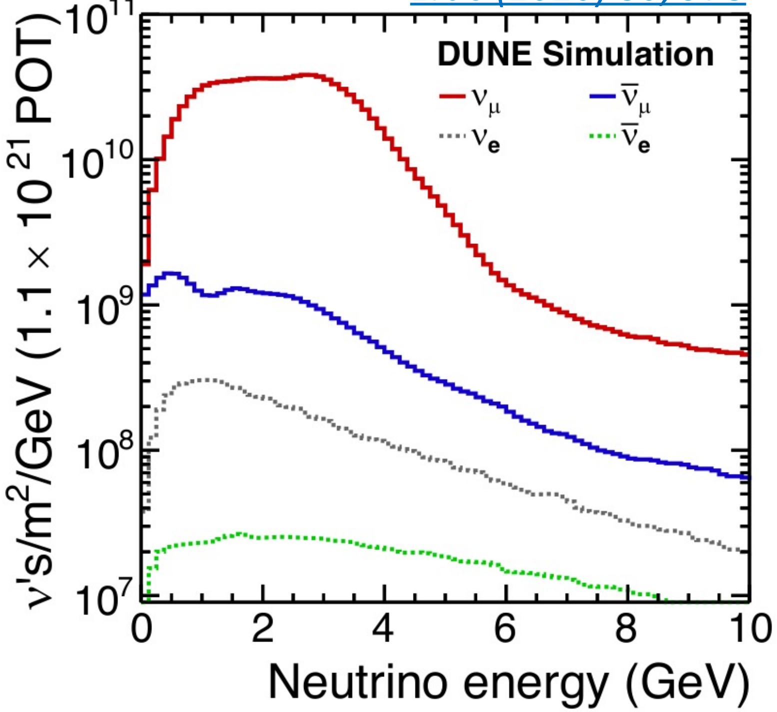


Long Baseline Neutrino Facilities

- **Beam line** design under way
  - 60-120 GeV proton beam
  - 5.8 degree vertical bend, to reach SURF
  - 1.2 MW by late 2020's, upgradable to 2.4 MW
  - Assumed minimum uptime of 55%



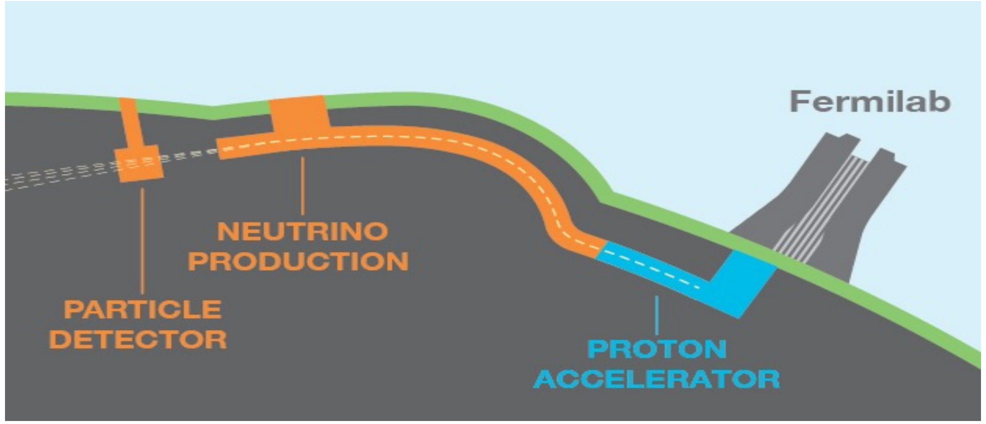
EPJC (2020) 80, 978

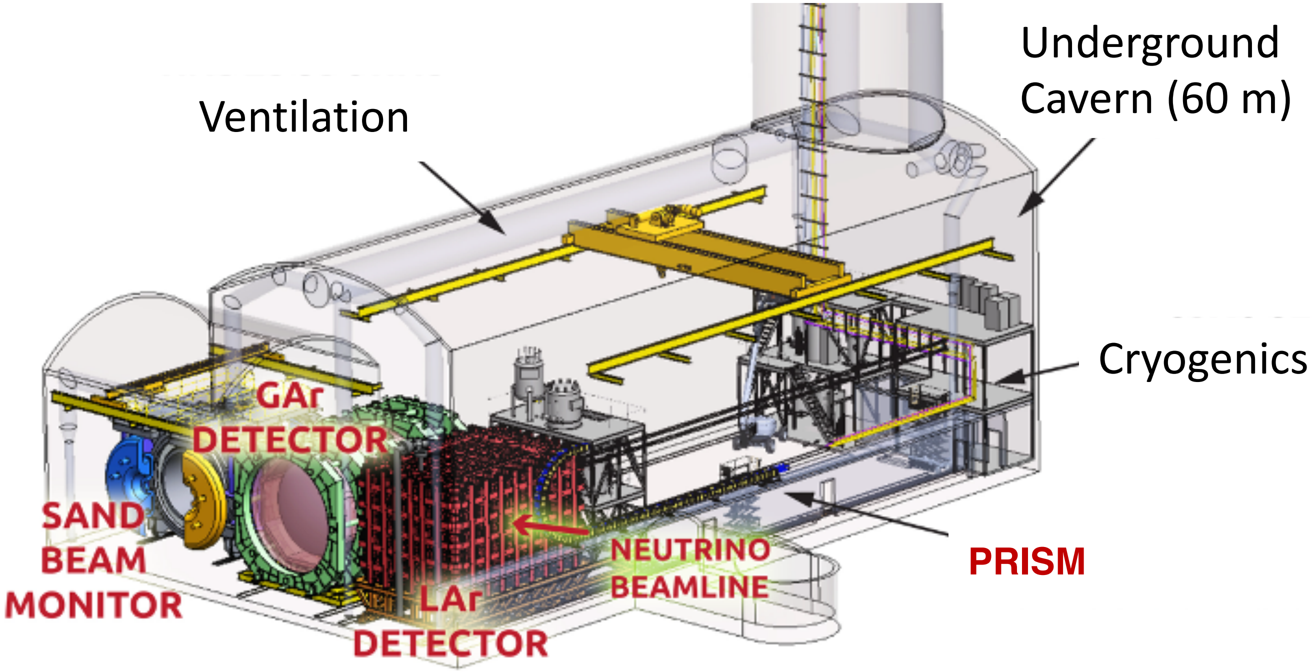


(1.1-1.9) x 10^{21} POT*/y @ 1.2 MW
10 μs pulse duration
*Protons On Target

The Near Detector Station

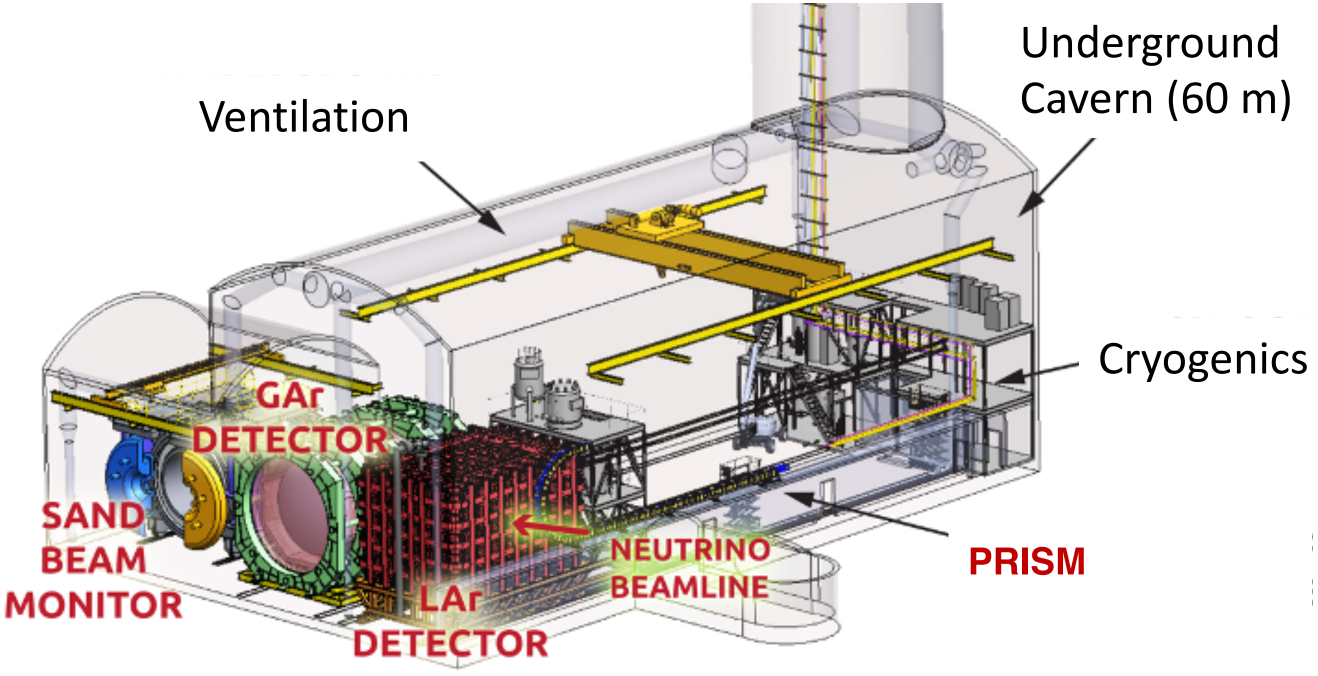
- **DUNE ND complex**
  - Located 574 m from proton beam target
  - Precise characterization of neutrino beam
  - Limitation of cross-section uncertainties for LB neutrino oscillation measurements





The Near Detector Station

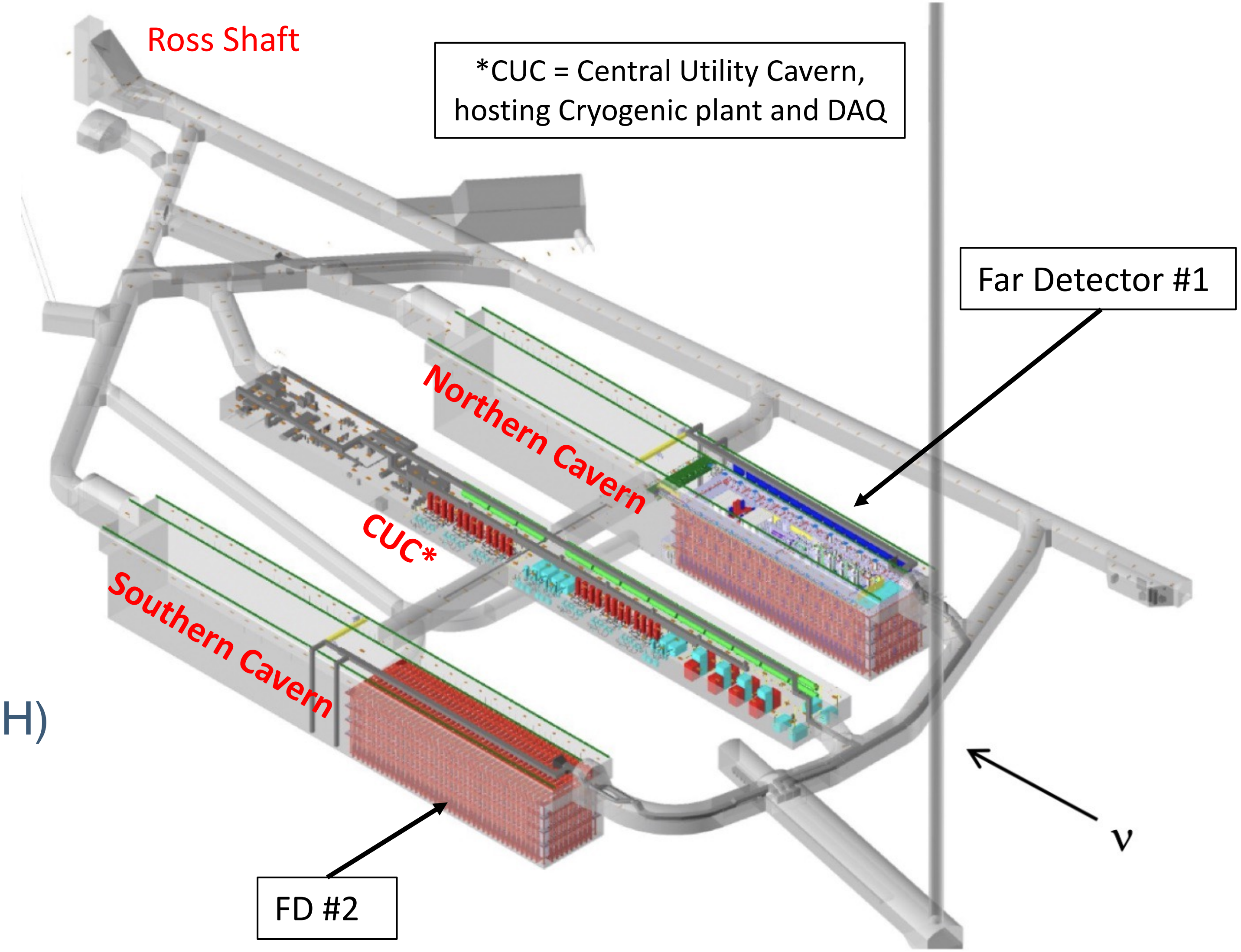
- Multiple complementary systems:
  - **ND-LAr** primary target, modular, pixelated charge read-out LAr-TPC (300 ton)
    - Module 0 successfully tested at Univ. Bern
  - **ND-GAr**: high-pressure GAr-TPC, surrounded by ECAL and magnet
    - intercepts muons escaping LAr-TPC
    - Muon spectrometer; nuclear interaction model constraints
    - Will come at a later stage. A Temporary Muon Spectrometer (**TMS**) will be installed at Day 1
  - **SAND**: inner tracker surrounded by 100 ton ECal and SC magnet (0.6 T)
    - On-axis beam monitor (spectrum/stability)



PRISM: ND-LAr and TMS/ND-GAr can move up to 30 m Off-Axis for beam characterization and lower-energy ν detection

Far Detector Site - SURF

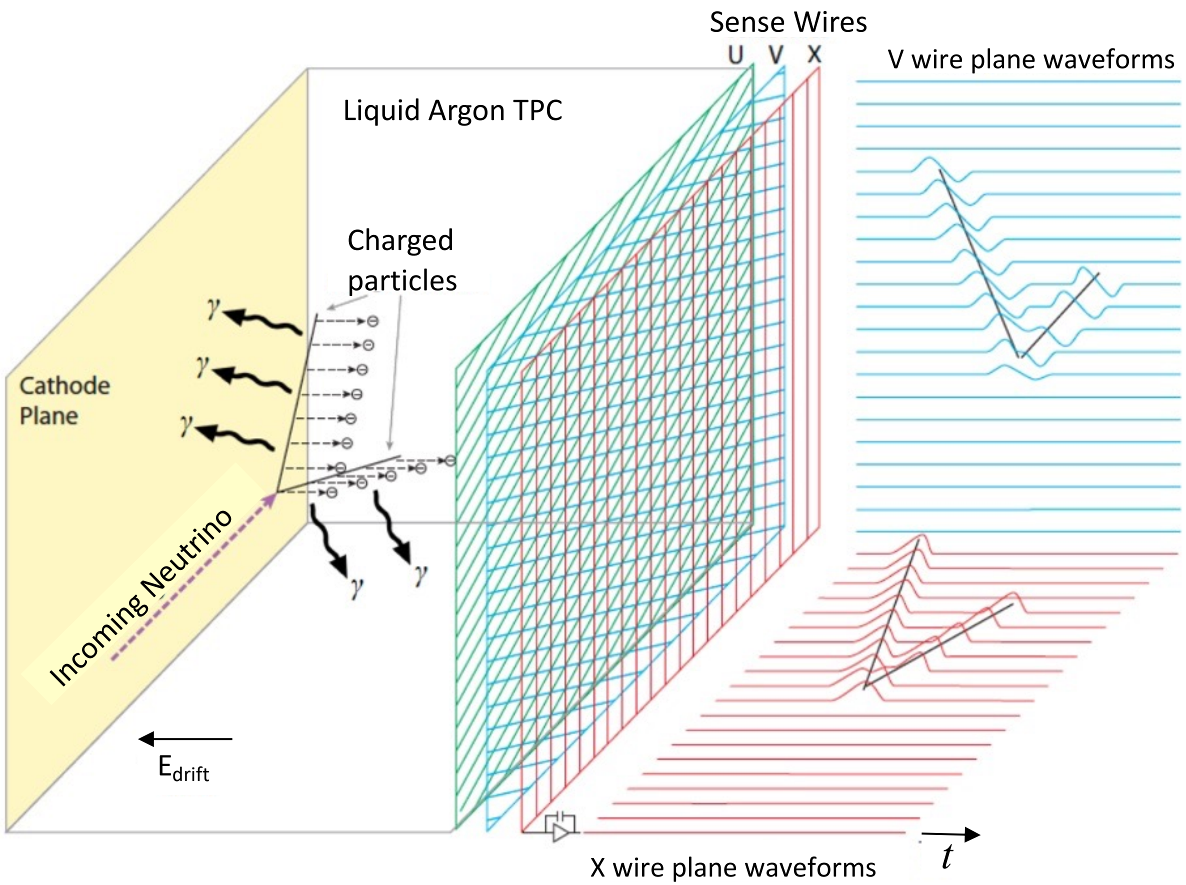
- 4 Detector modules, ~17 kton total volume each
  - Construction in stages
- **FD #1, #2** will be **single-phase (SP) LAr-TPCs,** with Horizontal Drift (HD) and Vertical Drift (VD), respectively
- FD #1 construction starts in mid 2020's
- Maximal cryostat external dimensions: ~ 66 x 19 x 18 m (LxWxH)



LAr-TPC technology

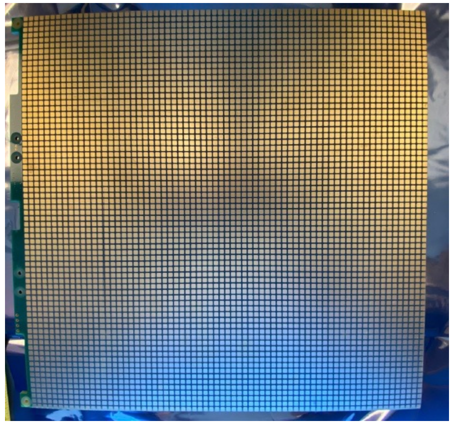
- Charge/light production and collection with wire read-out (HD technology)

- Mature, reliable technology (ICARUS, MicroBooNE)
- Fully compatible with very-long expected life span of the detectors



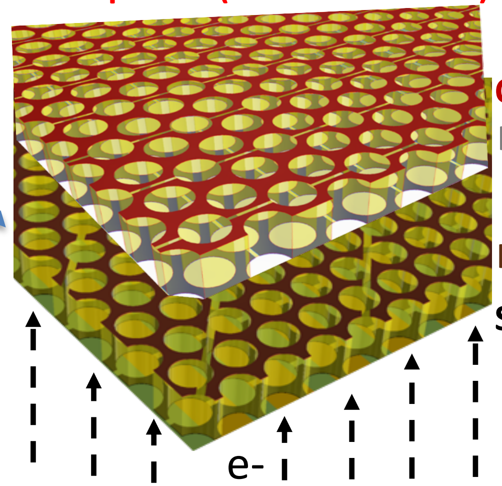
Other read-out solutions:

- Pixels (ND LAr-TPC)
- Perforated PCBs (Vertical Drift)

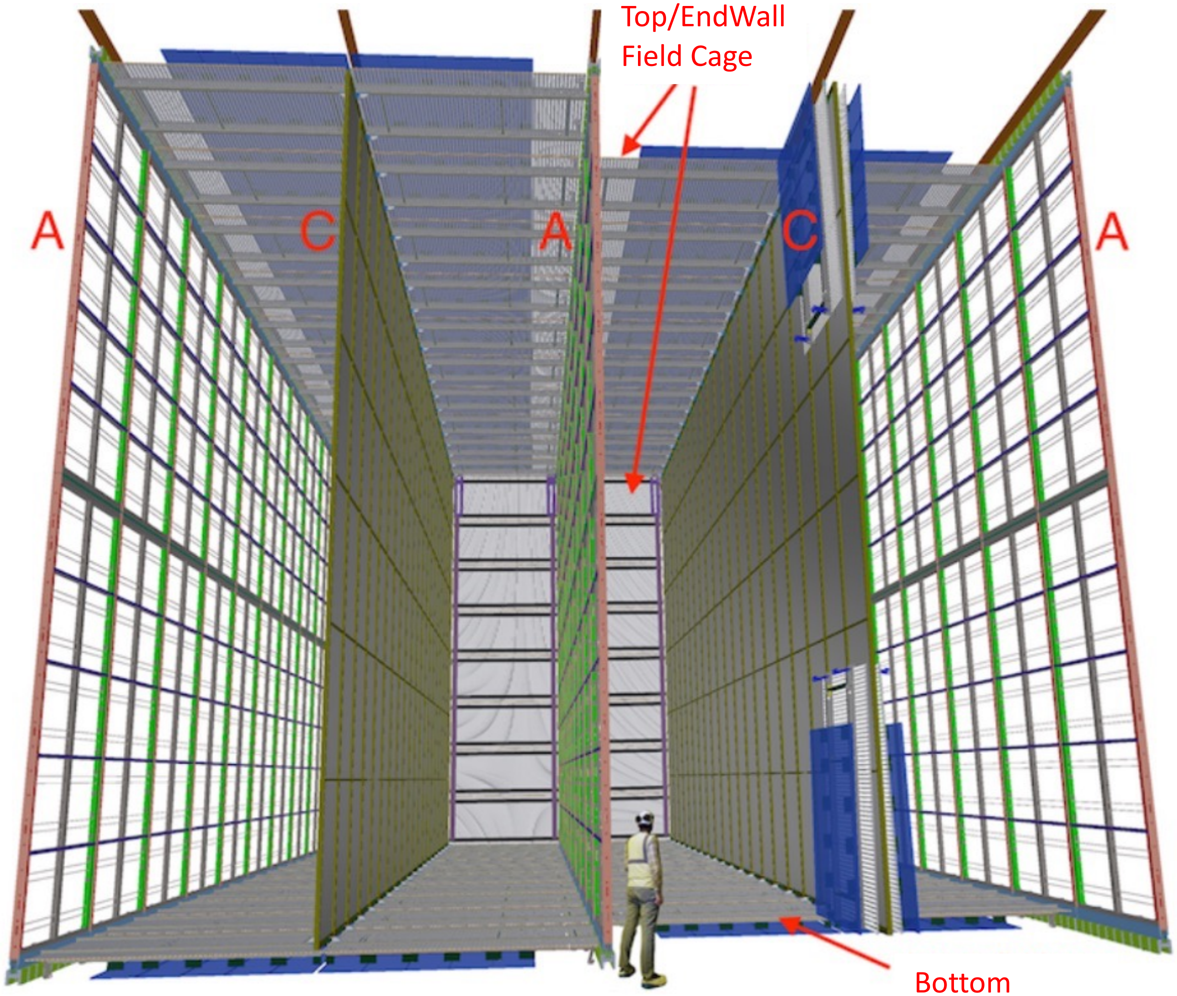


LArPix anode
32 x 32 cm
4.9k pixels

Three planes (3D corner detail)

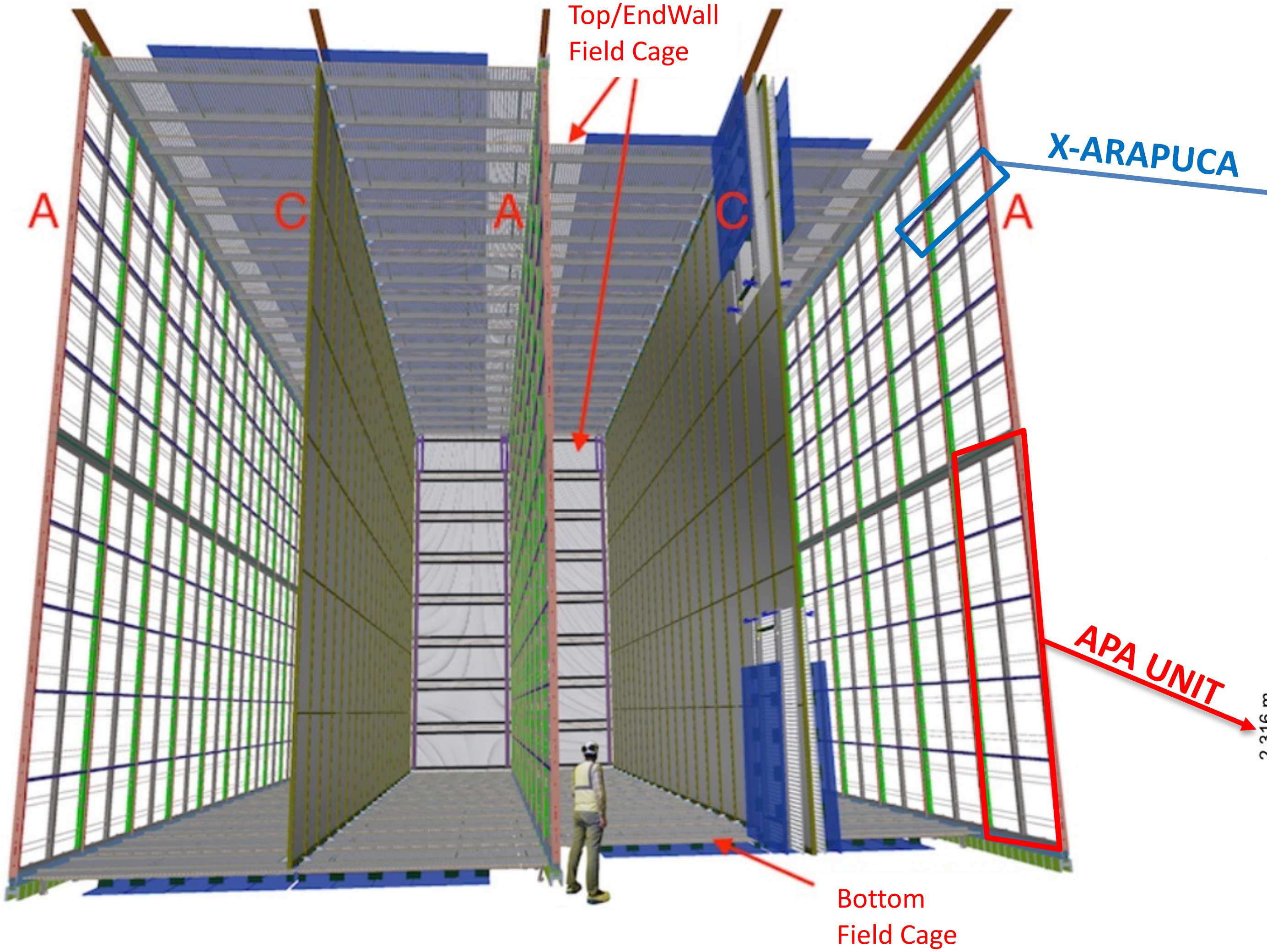


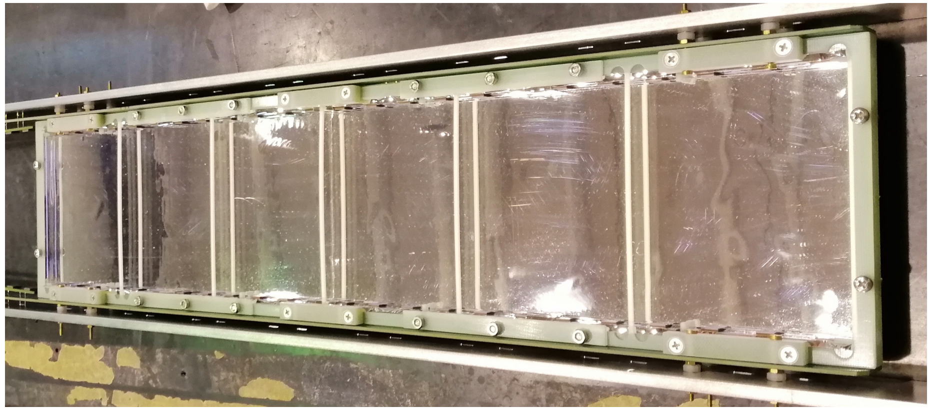
Far Detector #1 (Horizontal Drift)



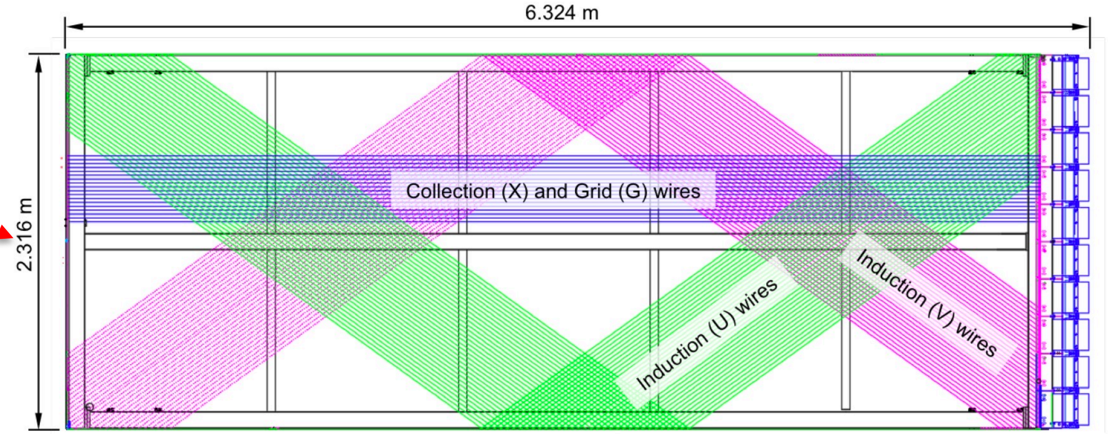
- Structure wholly suspended on roof
- Alternating Anode and Cathode Plane Assemblies (APA – CPA)
  - 4 drift volumes, 3.6 m drift / Electric field = 500 V/cm (HV = -180 kV)
  - High-resistivity CPA for fast discharge prevention
- Anode: 150 APAs, each with 4 wire planes (Grid, 2 x Induction, Collection)
  - Wrapped induction wires
- Photon Detectors: X-ARAPUCA light traps
  - 10 modules / APA
  - Timing
  - Cosmic / SN / BSM event triggering

Far Detector #1 (Horizontal Drift)





1 SuperCell = ¼ PDS module -- SiPM readout
High-reflectivity inner surfaces
Wavelength-shifting + dichroic filter for light trapping

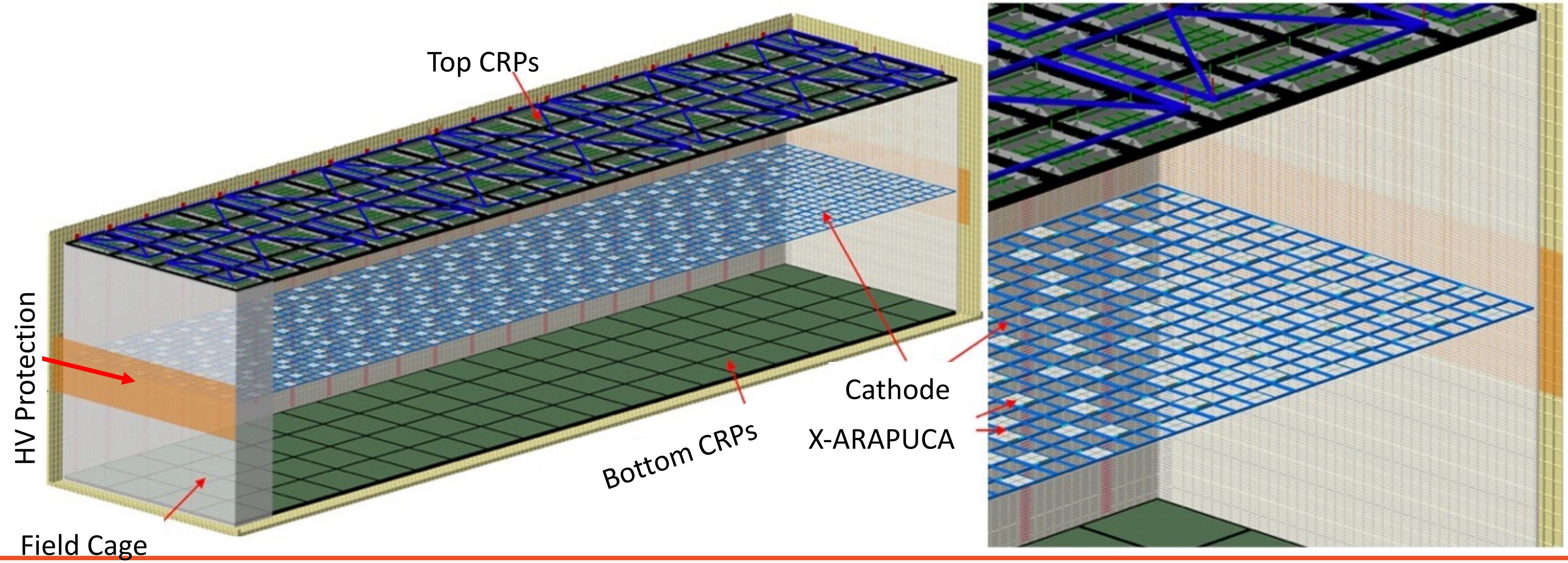


2560 wires/unit -- Inter-plane distance = 4.75 mm

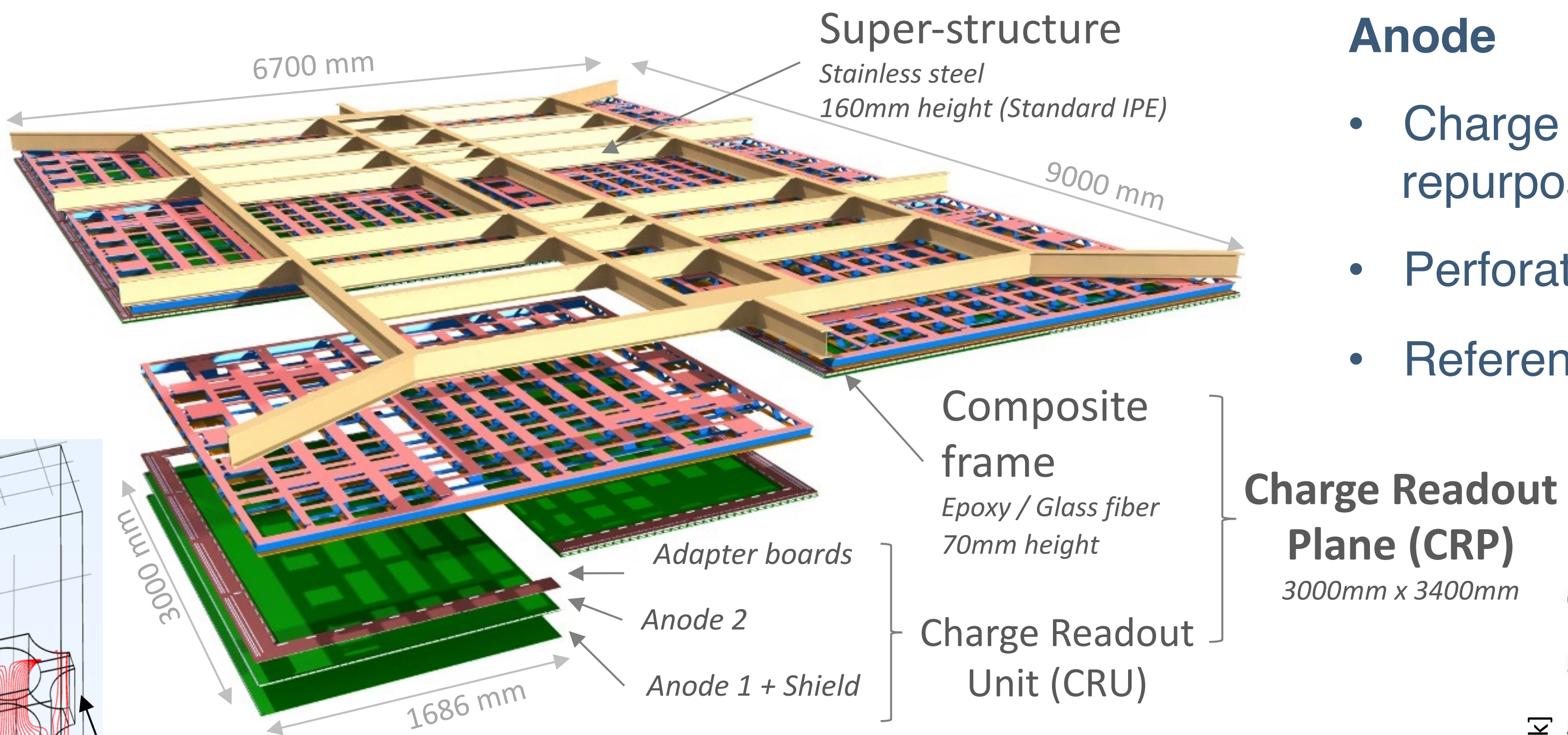
Far Detector #2 (Vertical Drift)

- Single-phase, read-out on cryostat top and bottom
- 2 x 6 m drift ⇔ 300 kV HV on (central) cathode
- Technological challenges on many detector aspects (HV, LAr Purity, Photon Detection,…)
- Strong R&D program at FNAL, CERN

- Dedicated CERN set-up for small-scale tests: 50 liters LAr-TPC
- Large-scale tests of anode and cathode+PD modules in dedicated “cold-box” at CERN by late 2021

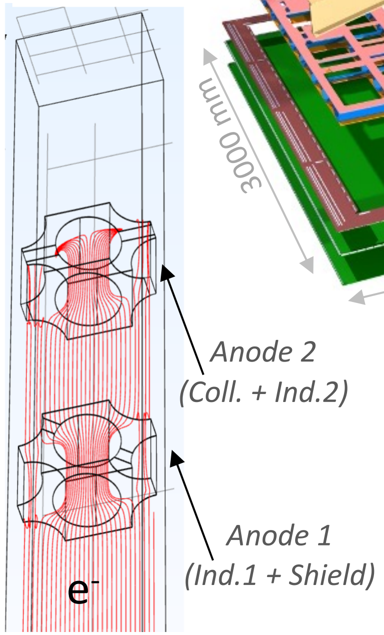


Far Detector #2 (Vertical Drift)



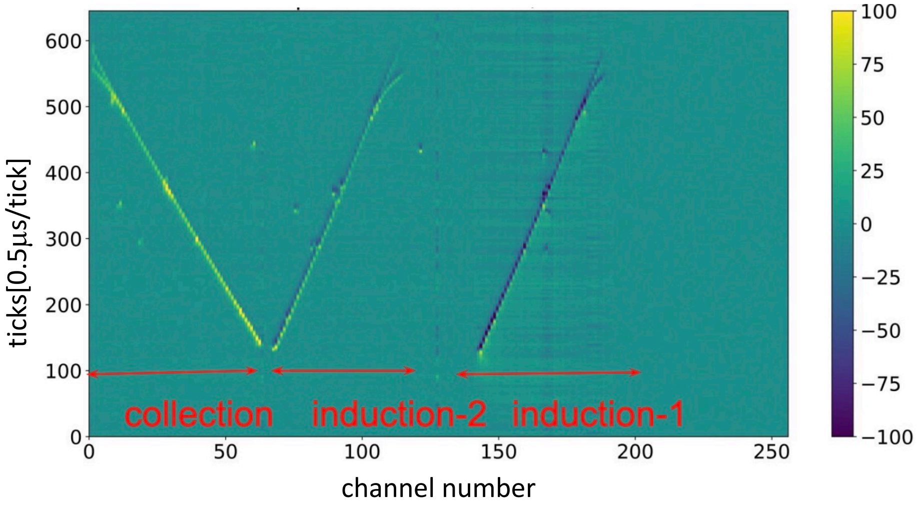
Anode

- Charge Readout Planes from Dual Phase repurposed for VD
- Perforated PCB anode, fully immersed in LAr
- Reference: 3-view design plus shield (2 anodes)

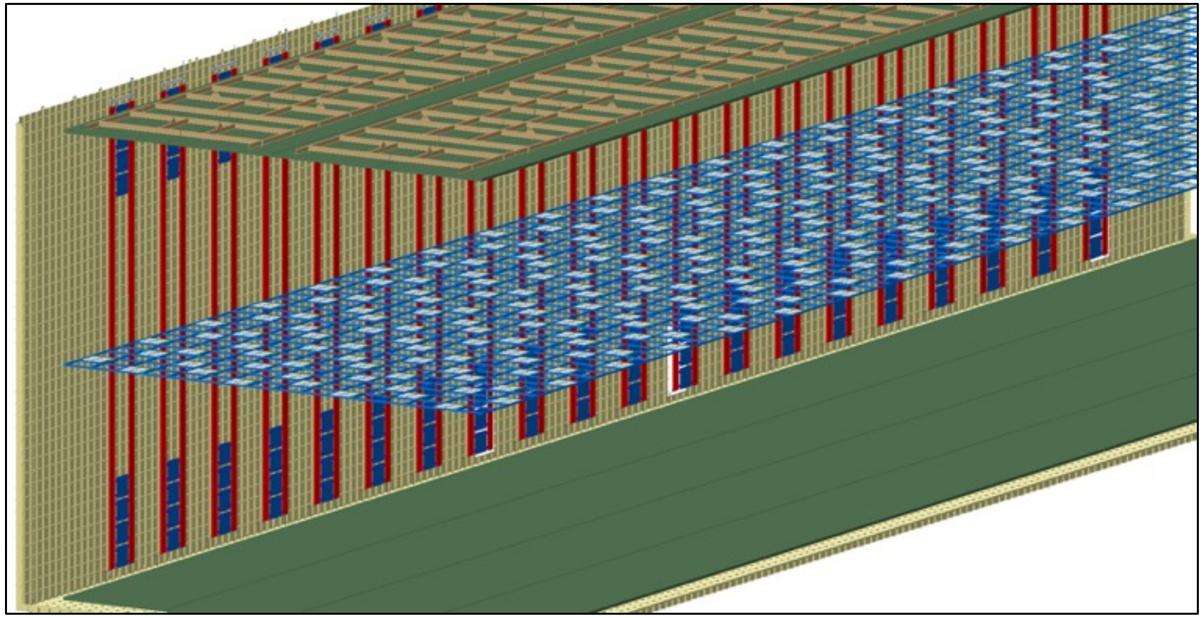


50L test set-up

- 3-view anode: two 35 x 35 cm PCBs, overseeing a 50 cm drift volume.
- Very promising first data (cosmic μ's)



Far Detector #2 (Vertical Drift)



- 320 X-ARAPUCA 60 x 60 cm^2 on cathode, analog readout
- 320 X-ARAPUCA 60 x 60 cm^2 on cryostat membrane, ~3 m from cathode
  - Enhanced field cage transparency -> 70%

Photon Detection

- Based on X-ARAPUCA – “4π” reference design
- SiPM and electronics partially on Cathode: @ 300 kV
- Aggressive R&D program concerning Power-over-Fiber and Signal-over-Fiber technology
- Enhanced scintillation yield by doping with Xenon (tested in ProtoDUNE SP)
- High trigger efficiency down to 10 MeV

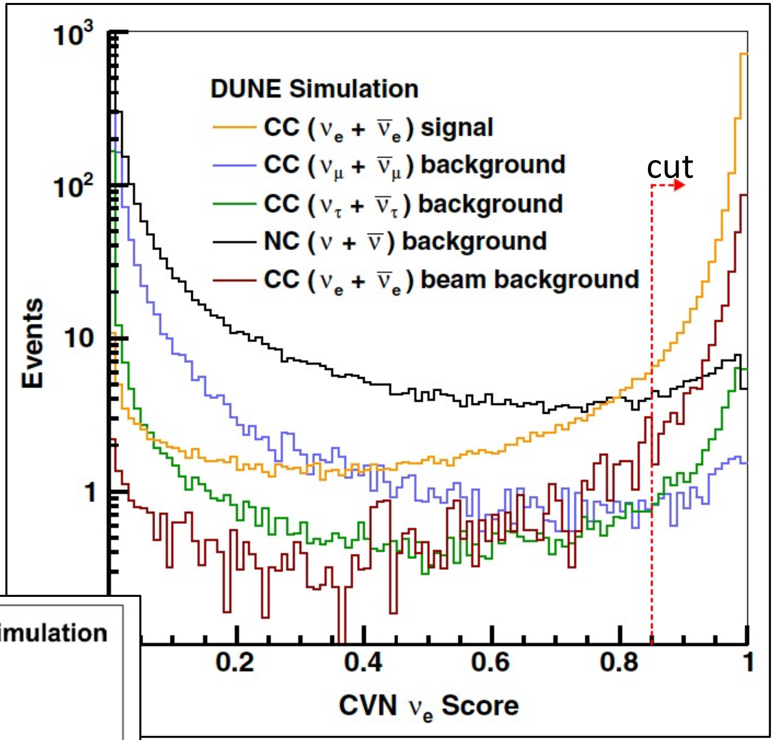
Back-up solution foresees fully instrumented membrane, with no detectors on cathode

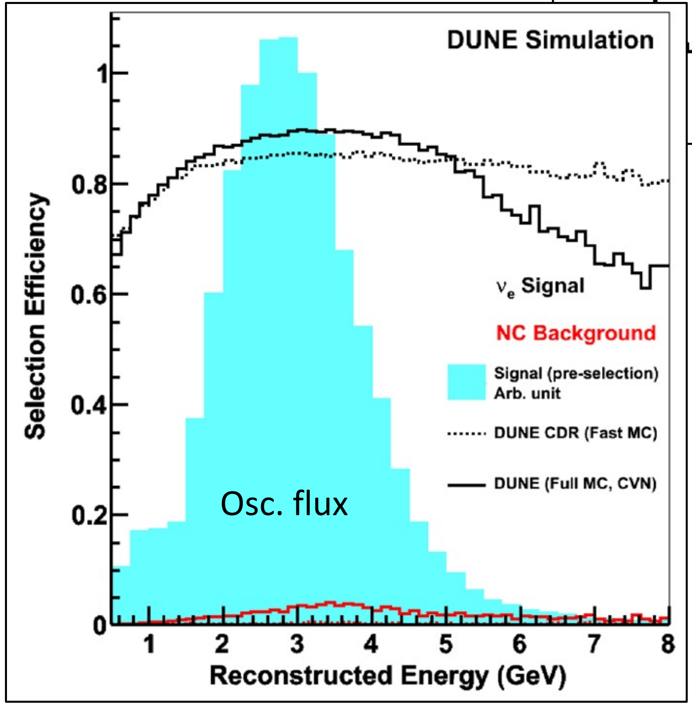
- No losses in physics requirements w.r.t. reference

Neutrino Reco/Identification

- Algorithms trained on Convolutional Neural Networks (CNN)
- Hit identification on 2D views and identification of distinct tracks/showers (clustering) with *Pandora*
  - 3D events produced from matching of 2D hits
- Neutrino event reconstruction from 2D images is the perfect input for machine learning / image analysis techniques
  - CNNs trained on, and aiming to classify, images (TPC views) -> Convoluted Visual Network (CVN)
    - 80-90% recognition efficiency for both ν_μ and ν_e
    - low mis-identification rates

ν-beam mode
3.5 y sim. exposure





- ν_e CNN score (top)
- Resulting ν_e selection efficiency with top cut (left)

PRD 102 (2020), 9, 092003

INFN MILANO DUNE

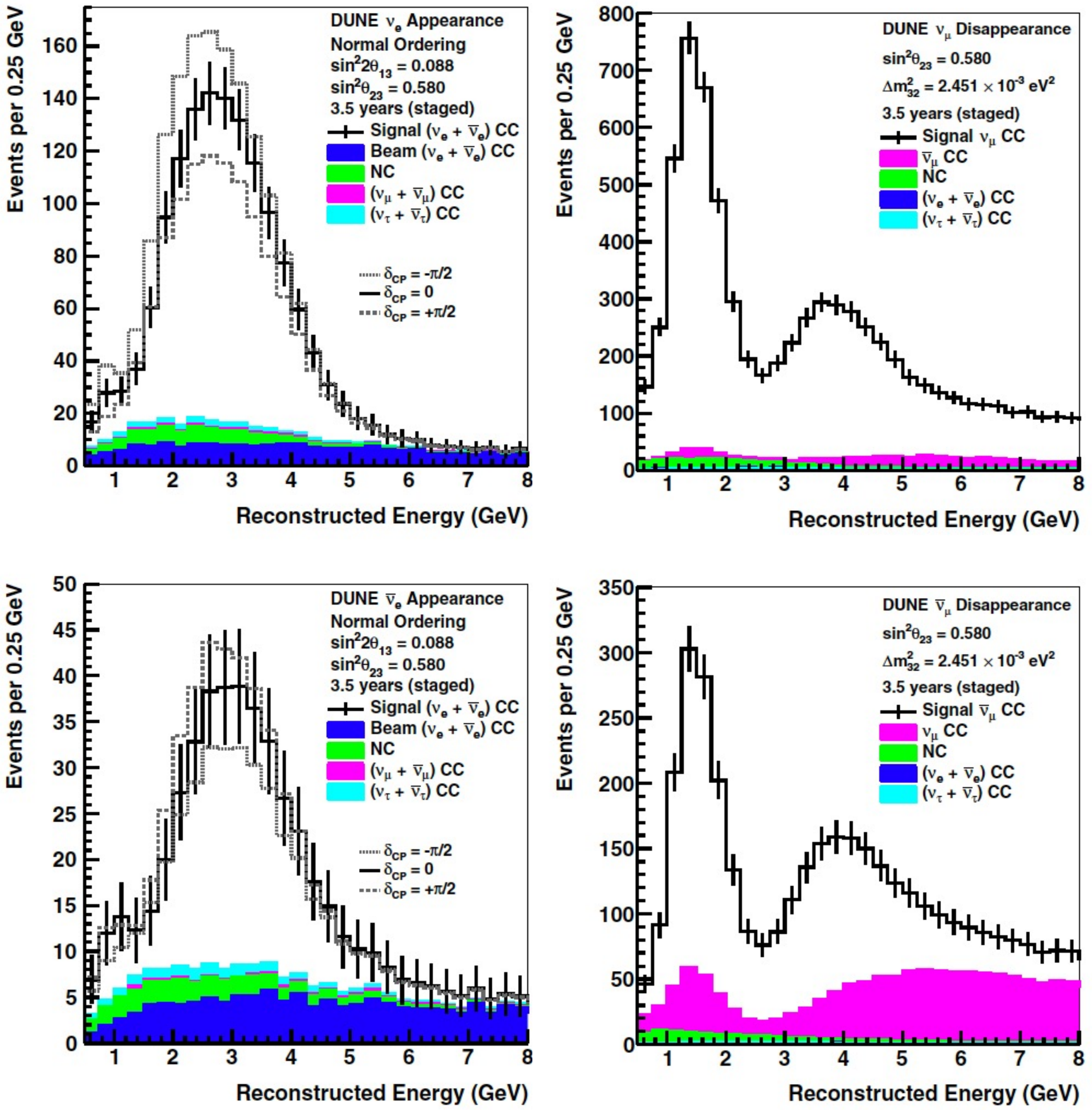
Neutrino Oscillations

- Projected results for $\nu_\mu/\overline{\nu_\mu}$ disappearance and $\nu_e/\overline{\nu_e}$ appearance, assuming:
  - normal ordering
  - 7 staged years (3.5 y ν-beam mode + 3.5 y $\bar{\nu}$-beam mode)

- Measurement and simultaneous fit of oscillation parameters over the four components of FD data

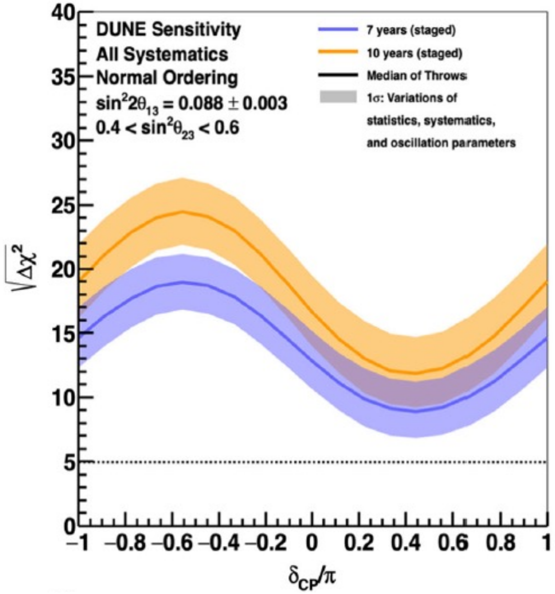
- Sensitivity assessment includes full FD systematics treatment (flux, cross-section, and detector) and ND constraints

EPJC (2020) 80, 978

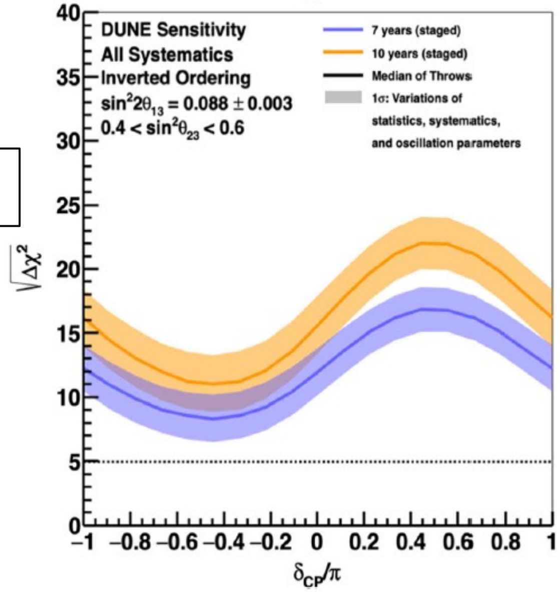


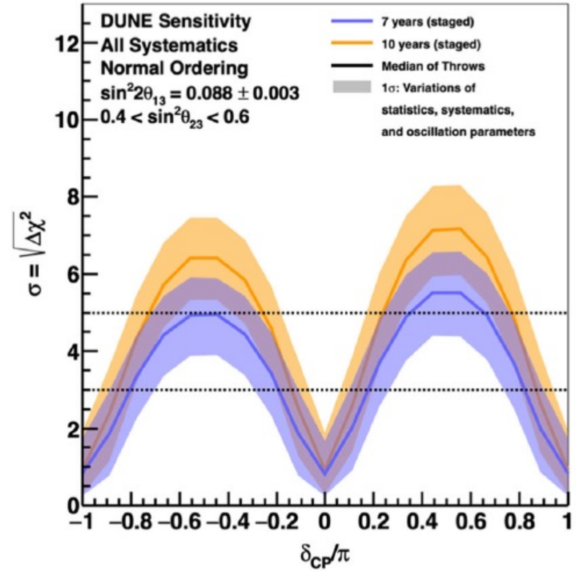
DUNE sensitivity

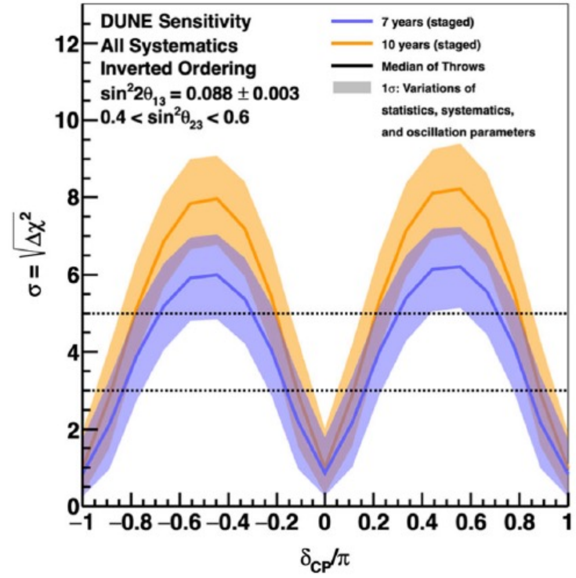
- Assumed staged running as in Technical Design Report (summing ν-beam mode and $\bar{\nu}$-beam mode)
- Potential of CP-violation (δ_{CP}) discovery in 7-10 years (left)
- 2-3 years to unambiguously determine mass hierarchy (NO vs IO, below)



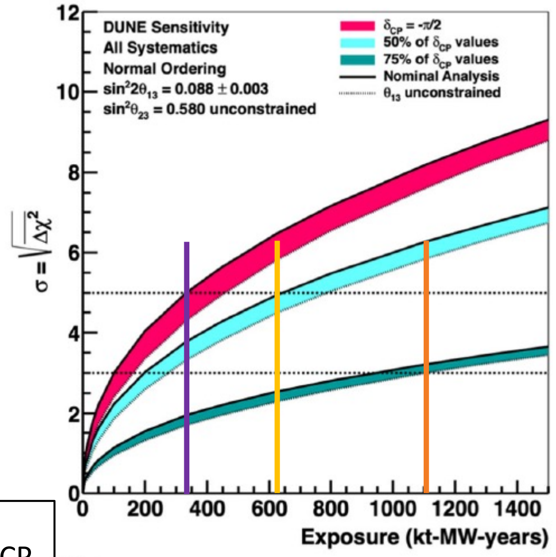
MO



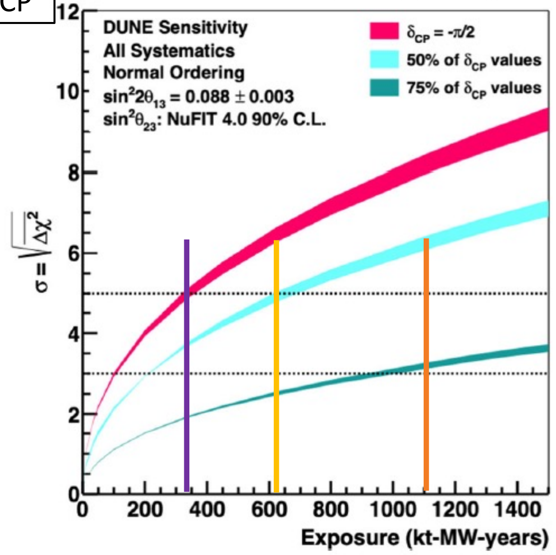




[EPJC (2020) 80, 978]



δ_{CP}



= 7 years (staged)
= 10 years (staged)
= 15 years (staged)

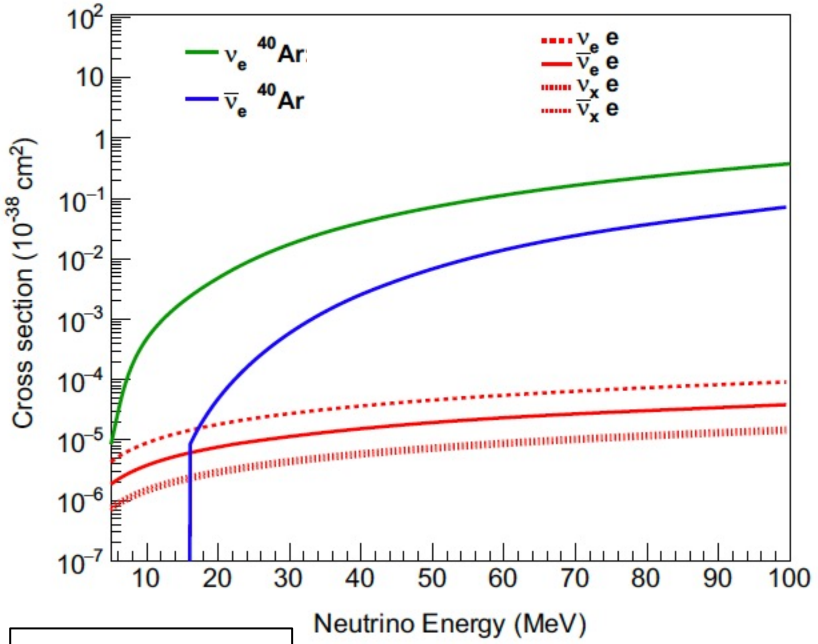
Cosmic Neutrinos

- The DUNE FD will be sensitive to cosmic neutrinos from MeV to tens of GeV in energy
  - Stellar core-collapse supernova (SN) neutrinos
  - Solar neutrinos?
- For a **galactic SN**, DUNE expects to observe up to thousands of ν interactions over the duration of the burst
- High reconstruction efficiency for SN neutrino energy range, 15-20% expected energy resolution with both TPC and PDS

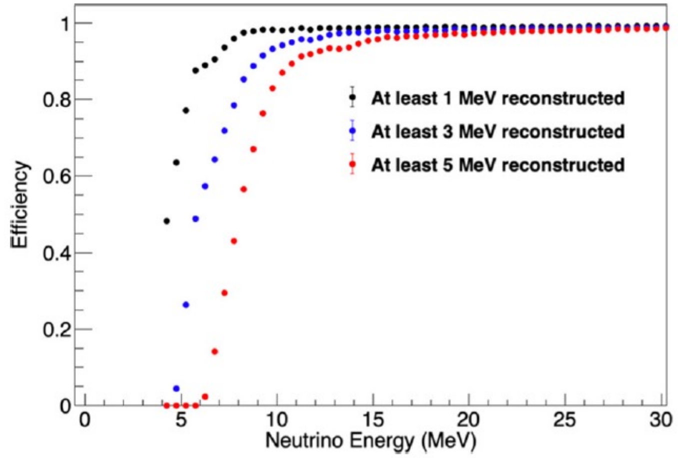
EPJC (2021) 81, 423

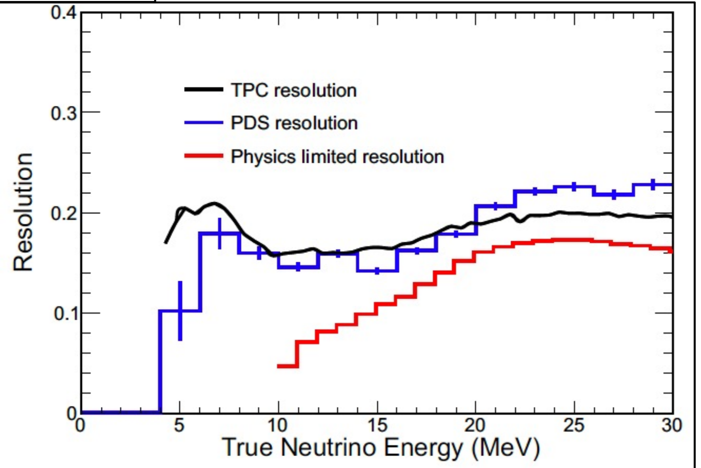
$\nu_e + {}^{40}Ar \dashrightarrow e^- + {}^{40}K^*$ *(dominant)*

$\bar{\nu}_e + {}^{40}Ar \dashrightarrow e^+ + {}^{40}Cl^*$



SN sensitivity

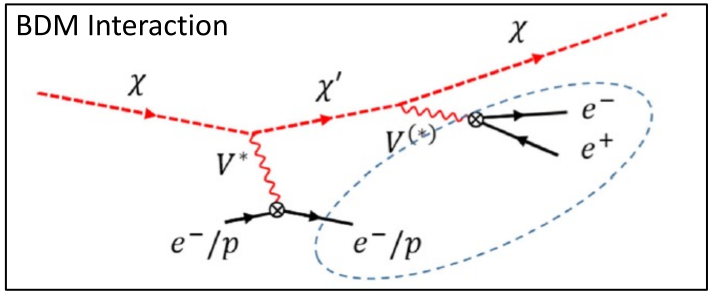


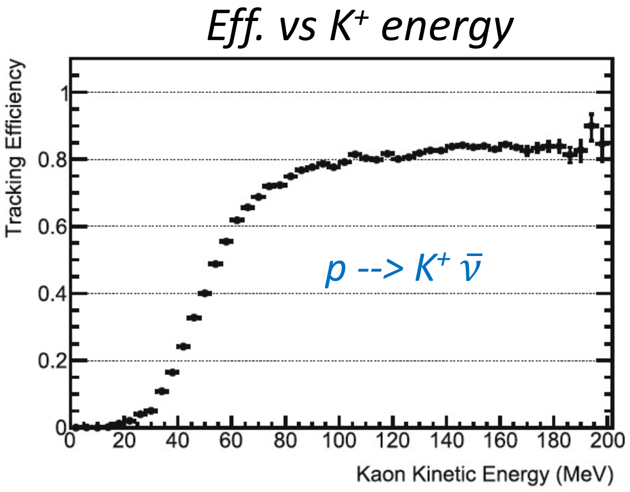


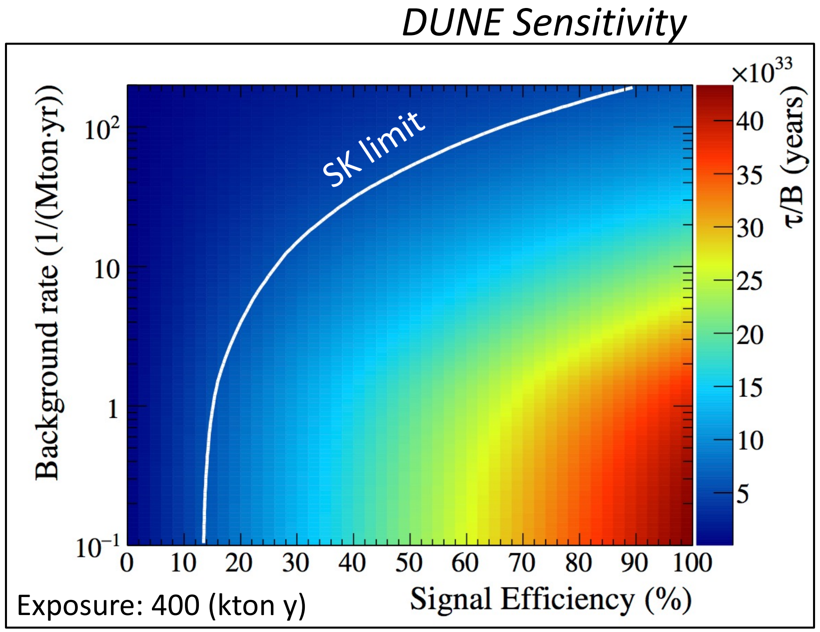
- **Solar neutrino** detection candidates:
  - from ^{8}B, hep (10 < endpoint < 20 MeV)
  - Background limited (detector materials)
  - Feasibility studies underway

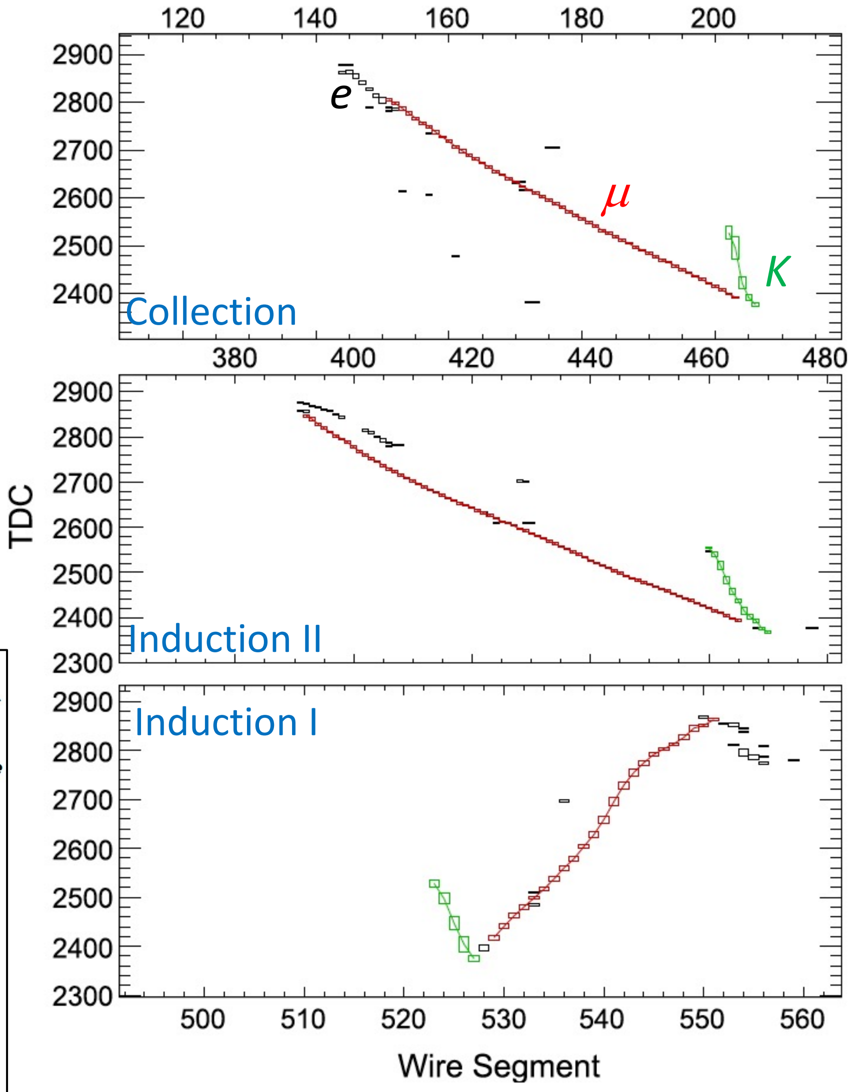
BSM Physics

- DUNE can probe several sources of new physics
  - Sterile ν-mixing
  - Non-standard ν interactions
  - Barion number violation
  - **Nucleon decay**
  - Low-mass Dark Matter (@ ND)
  - **(in-)elastic Boosted Dark Matter - BDM (@ FD)**
  - … [EPJC (2021) 81, 322]



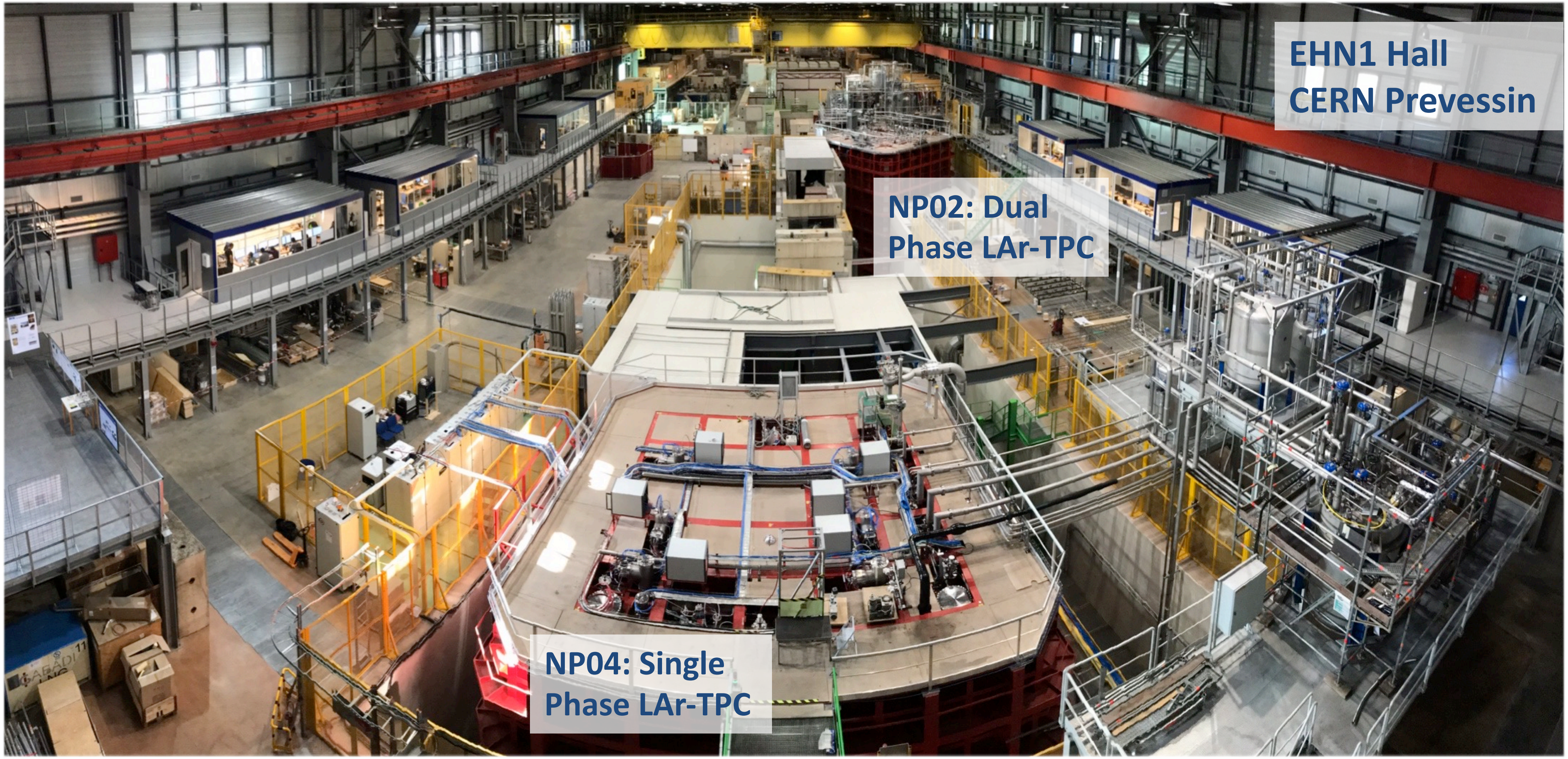






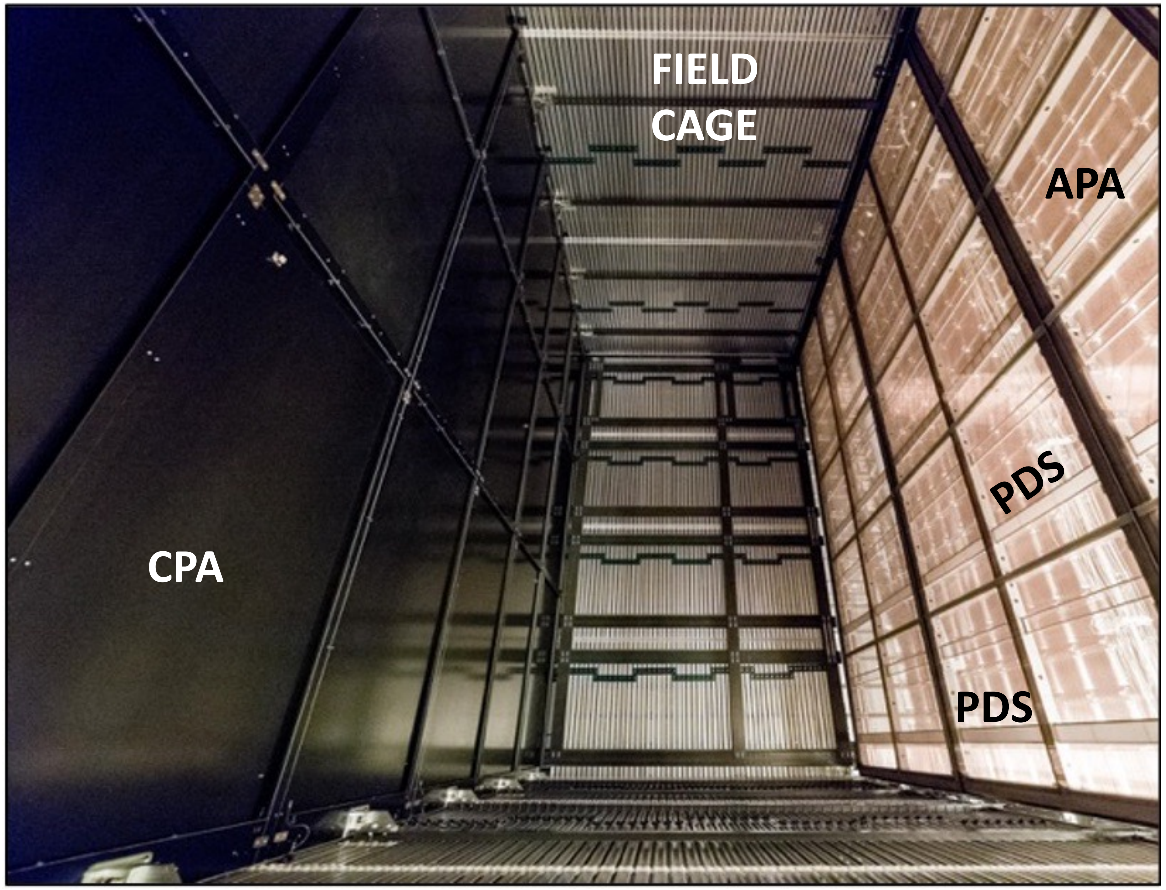
BKG: $\nu_\mu\, n \dashrightarrow \mu^- p$,
if p is mis-identified
as K (atmospheric)

The past and the future – ProtoDUNEs



The past and the future – ProtoDUNEs

- Two ~1 kton prototypes (6 x 6 x 6 m inner dimensions)
- Exposed to Very Low Energy (VLE) charged particle beams at CERN
- Validation of DUNE components design & installation, commissioning and performance study: **FULL-SCALE** prototypes
- **ProtoDUNE-Single Phase (HD)** operated 2018–2020
  - 4-month beam run in late 2018, then cosmics
  - Event reconstruction/identification training
  - R&D site: low-energy calibration (neutron gun), Xenon doping, Higher Voltage tests, …
  - Upcoming Phase-II on beam with HD updated design
- **ProtoDUNE-Dual Phase** operated 2019–2020
  - Development of CRP technology
  - Very High Voltage / large drift studies
  - Evolved into Vertical Drift -> Phase II

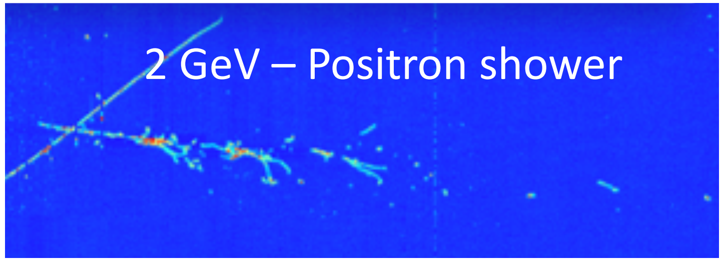


ProtoDUNE SP (HD) drift volume (3.6 m)

ProtoDUNE SP performance - I

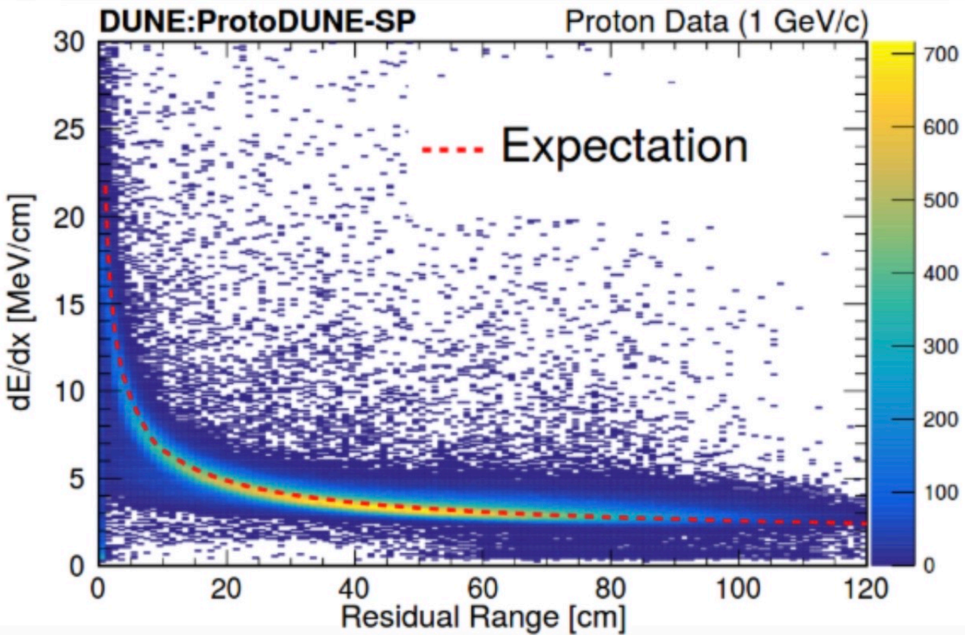
HV / Cryo

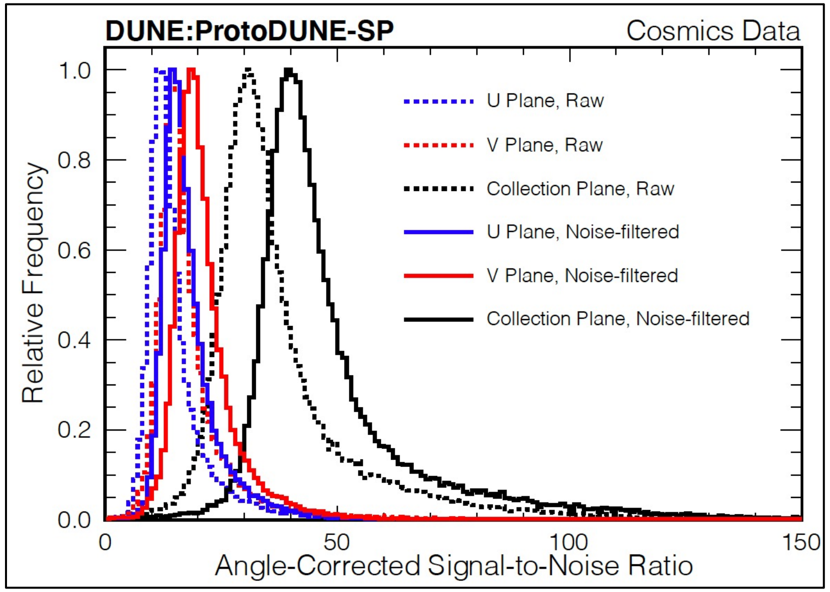
- Very high stability of HV: > 99% up-time
- Purity well above minimal requirements (> 20 ms)



TPC

- > 99% of TPC channels (wires) alive
- SNR far larger than minimal requirements
- Purity and Space Charge corrections flow into calibration & energy reconstruction studies
- Particle tracking enhanced by external Cosmic Ray Tagger (CRT)



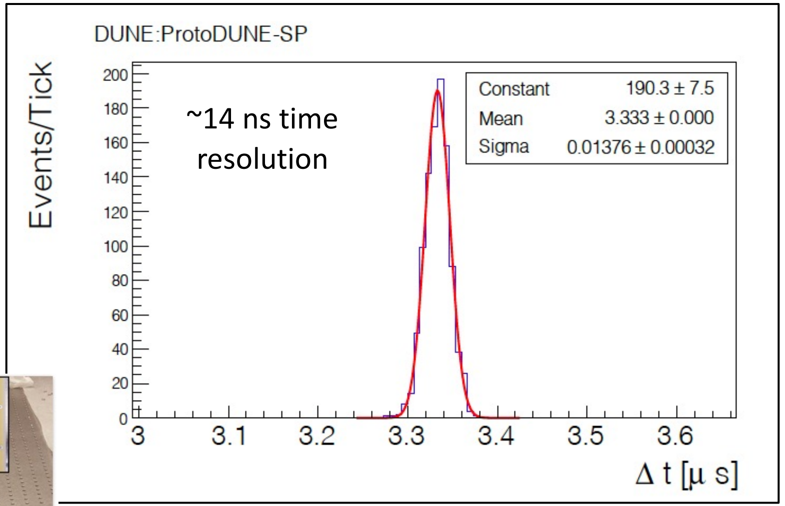


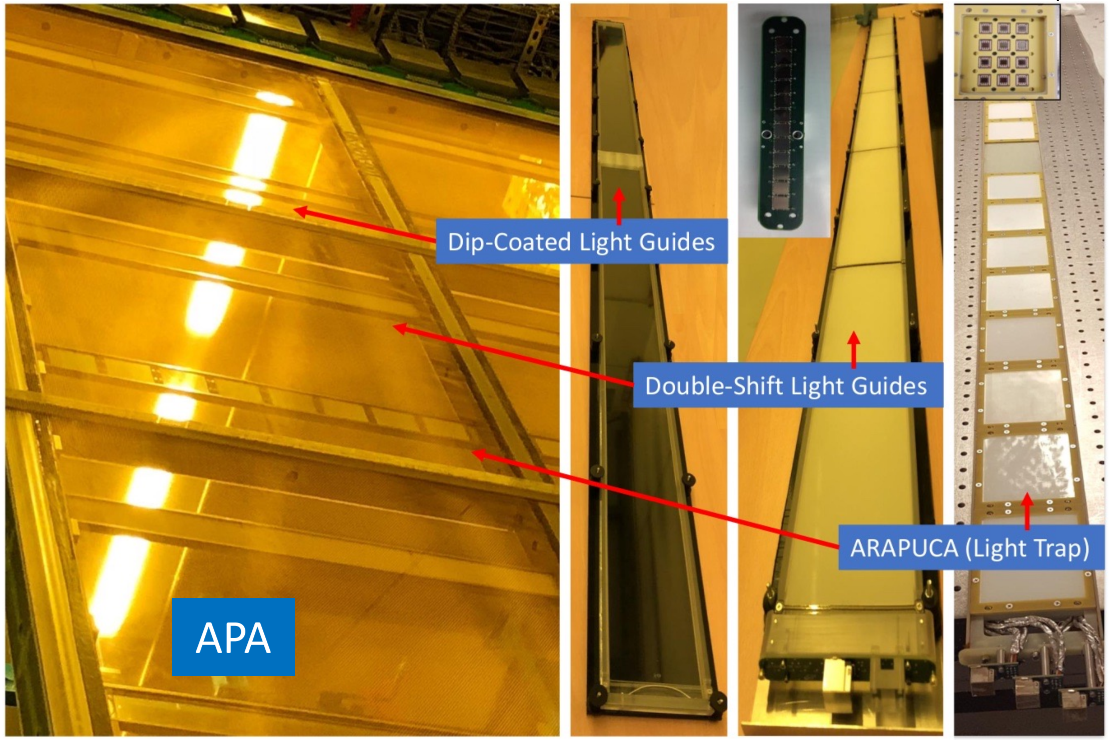
JINST 15 (2020) 12, P12004

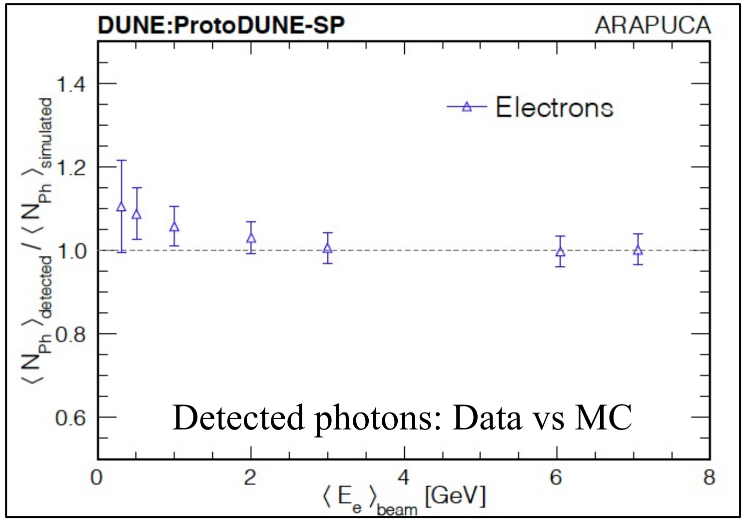
ProtoDUNE SP performance - II

Photon Detection System (PDS)

- 3 technologies based on light-guide modules with WLS (TPB or PTP) read by arrays of SiPM
- Calibration system based on pulsed LED light installed on the cathode
- ARAPUCA technology shows best results with 2% efficiency
- 1.9 phe/MeV light yield

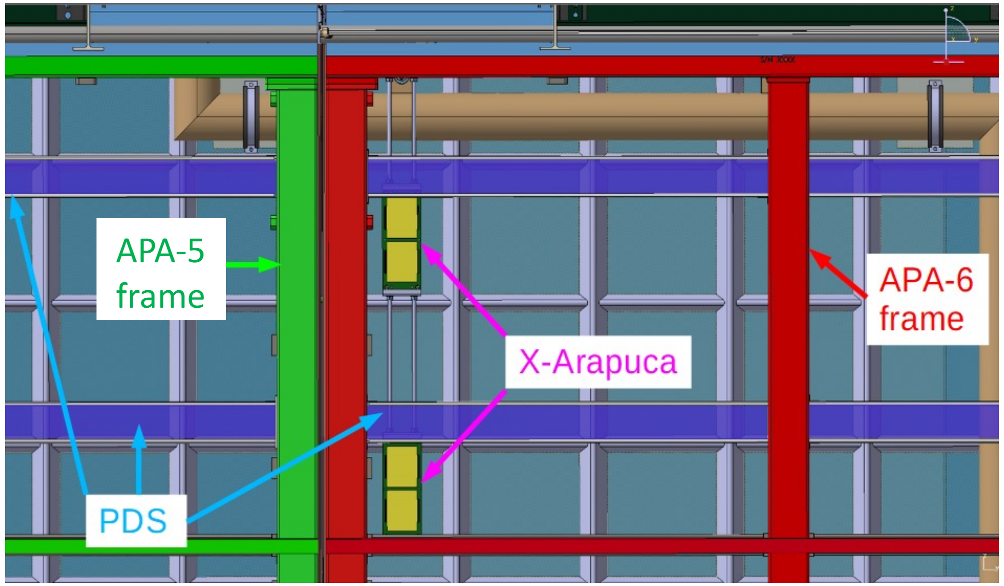






[JINST 15 (2020) 12, P12004]

ProtoDUNE SP R&D – Xenon Doping



Location of custom X-ARAPUCAs behind APAs for Xe-doping run

- ~ 20 ppm of Xenon introduced in LAr (~13.5 kg)
- Demonstrated efficient energy transfer from Ar^*_2 to Xe^*_2
- In ProtoDUNE SP, doping also helped recovering light loss due to N_2 pollution (issue with recirculation pump)

Dedicated paper in preparation

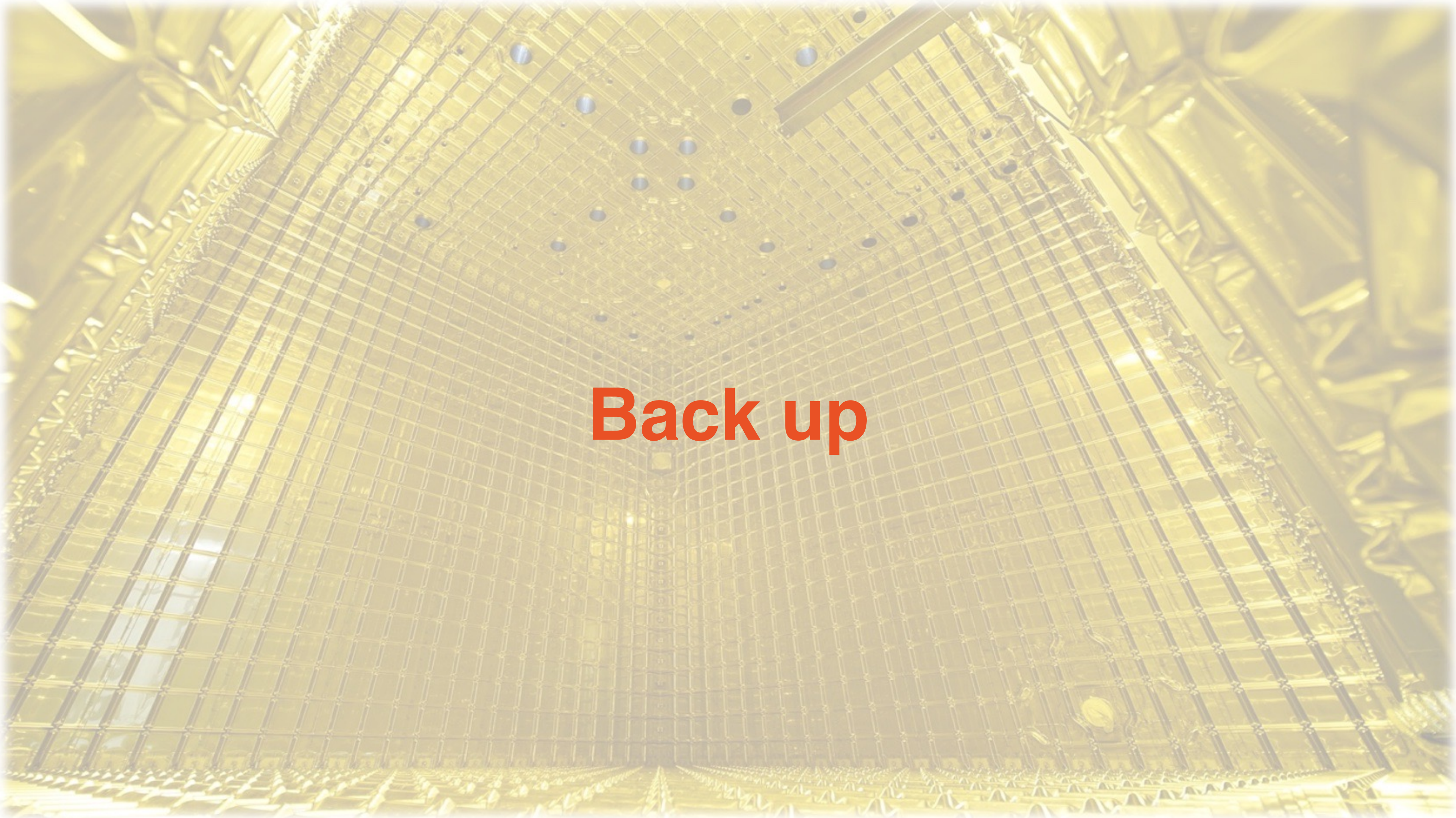
- Xenon doping of LAr considered for DUNE, to enhance PDS response
- scintillation light shifted from 128 nm (Ar) to 178 nm (Xe)
  - Photon detectors have higher detection efficiency
  - Shorter pulses -> faster detector response
  - Larger Rayleigh Scattering length -> more uniform response in space (recovering light far from sensors)
- Dedicated studies in ProtoDUNE, with PDS and custom dedicated X-ARAPUCA detectors
  - First successful doping process of a very-large volume LAr-TPC
  - No effect on TPC response
  - Response independent of Drift Field
  - First test of X-ARAPUCA in a large-scale detector

Conclusions and Outlook

- DUNE: next-gen neutrino experiment, will allow precision neutrino physics measurements:
  - Oscillation parameters, mass hierarchy, CP violation
  - SN burst neutrinos
  - Possibility to probe several BSM channels (sterile ν's, Dark Matter, B violation)
- Beam Line & Near Detector Infrastructure designs under way
- Infrastructure at Far Detector site -> excavation is advancing
- Near Detector technology (multi-station) is defined
  - Design finalization in a few months
- Far detector technology defined for FD #1 (Horizontal Drift)
  - Design validation with "Module 0" in upcoming ProtoDUNE SP Run-II
- Vertical Drift LAr-TPC proposed for FD #2, aggressive R&D program at FNAL and CERN
  - Design validation in ProtoDUNE NP02 with proposed HV test in 2021 and later "Module 0"

Published DUNE TDR Volumes
JINST 15 (2020) T08008/09/10

Thank you!



Back up

Cryostat technology

- **Modular design** for transport into cavern
  - Scalability / Exact prototyping (ProtoDUNEs)
- **Membrane cryostats**
  - ~ elastic, 1.2 mm thick stainless steel (SS) inner skin, accommodates cryogenic shrinking
  - used on LNG transport ships – mature technology; commercial partners
  - No need for vacuum -> argon purge
  - Leak tightness tested intensively on ProtoDUNEs