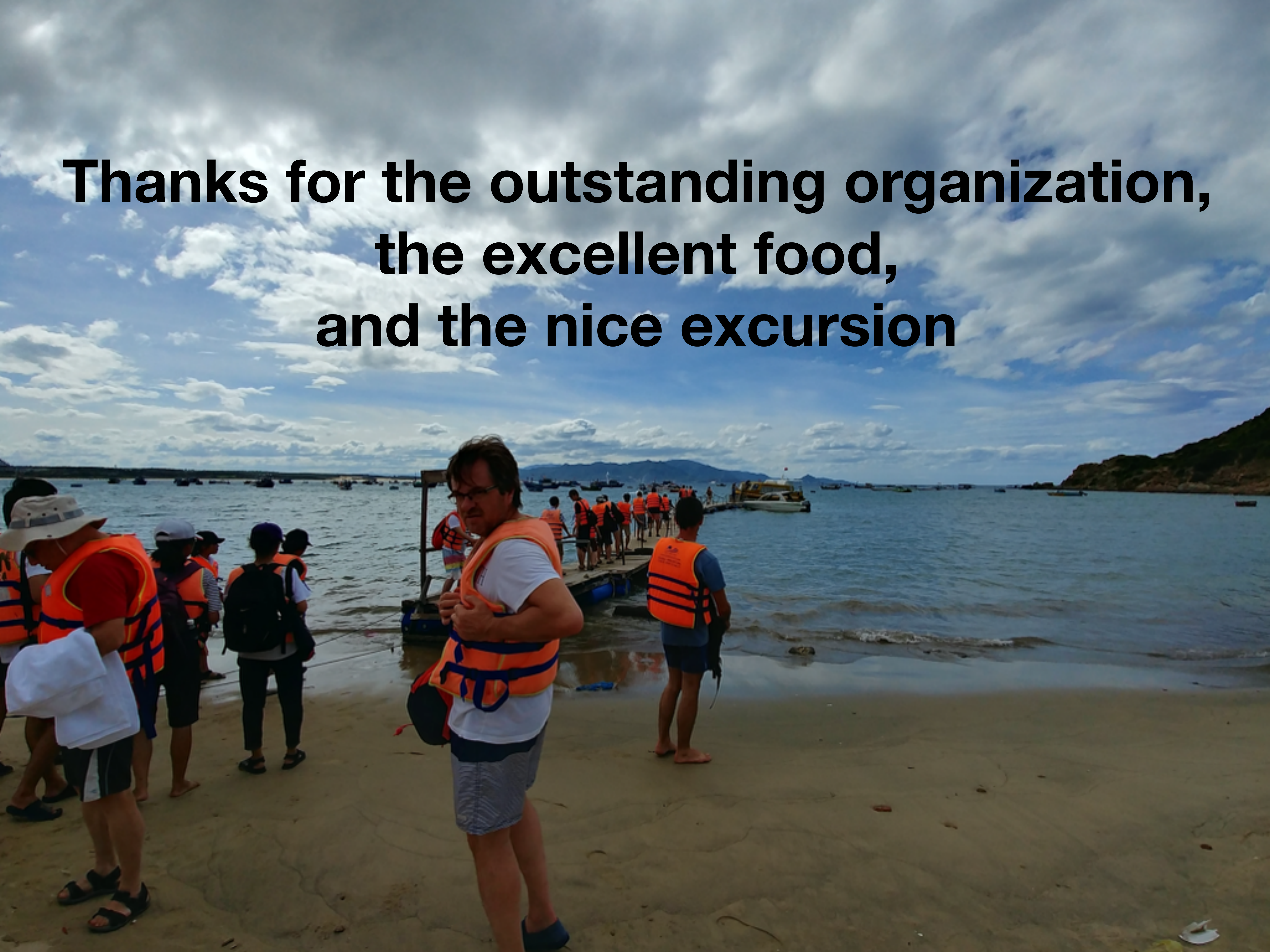

Thanks for the outstanding organization,
the excellent food,
and the nice excursion

International Symposium on Neutrino Frontiers'18
ICISE, Quy Nhon, VN, 19/07/2018

# Status of DUNE

*Anselmo Cervera Villanueva*
**IFIC-Valencia**

**On behalf of the DUNE Collaboration**

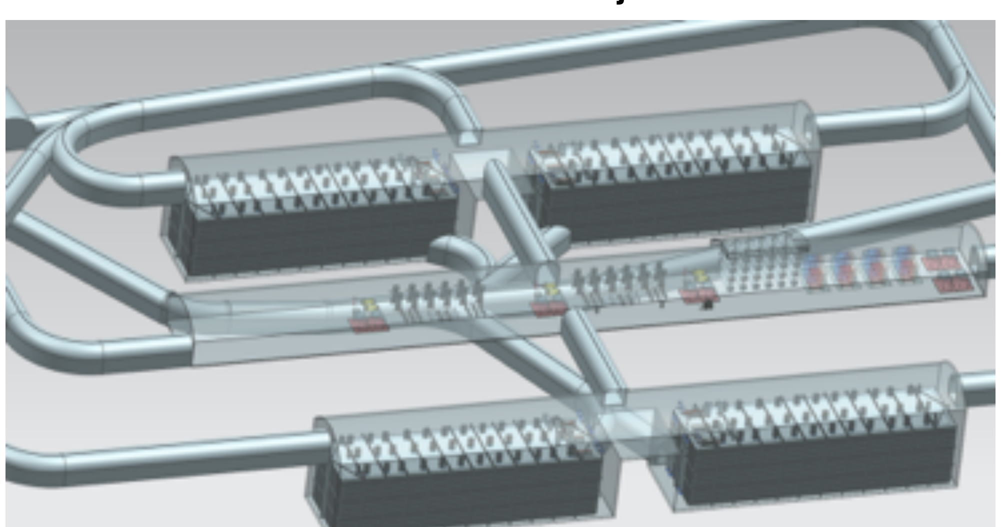
# **D**eep **U**nderground **N**eutrino **E**xperiment

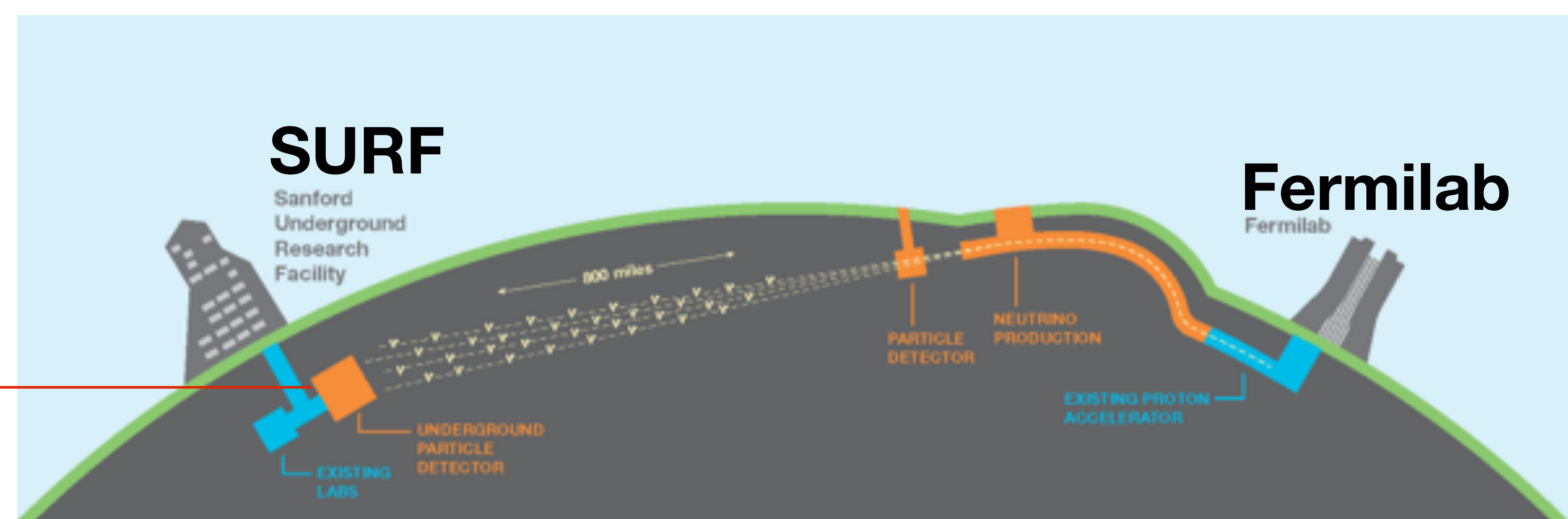
- Next generation neutrino oscillations experiment
  - Measure $\delta_{CP}$ and **mass hierarchy** in a single experiment
- Enabled for other physics w and w/o beam:
  - Beyond Standard Model (BSM) Physics, Nucleon Decay, SuperNova Bursts (SNB), etc

**40 Kton far detector using Liquid Argon TPC technology**

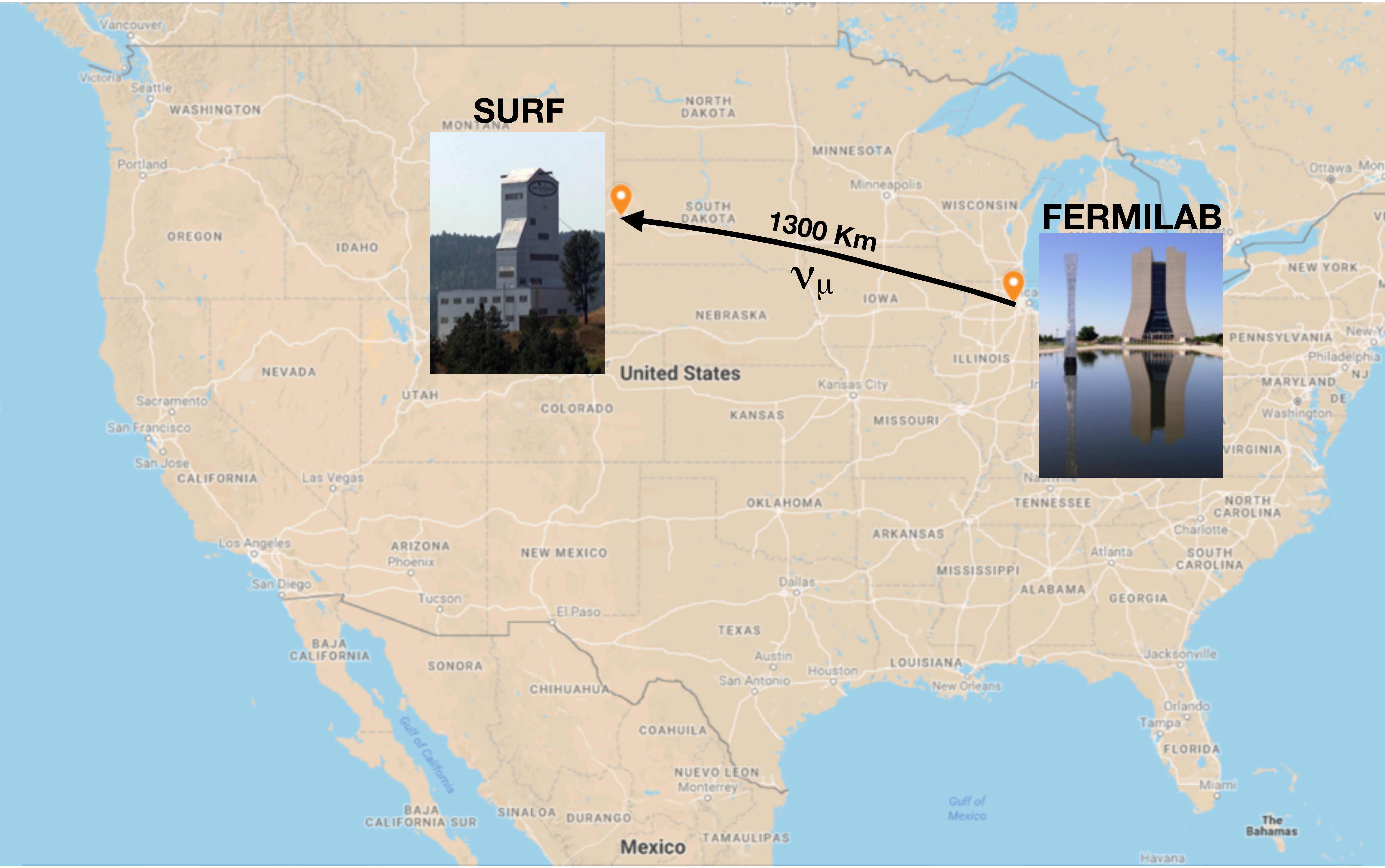
**High power *wide band* muon neutrino beam from Fermilab to SURF, in South-Dakota, 1300 km away**

Time Projection Chamber





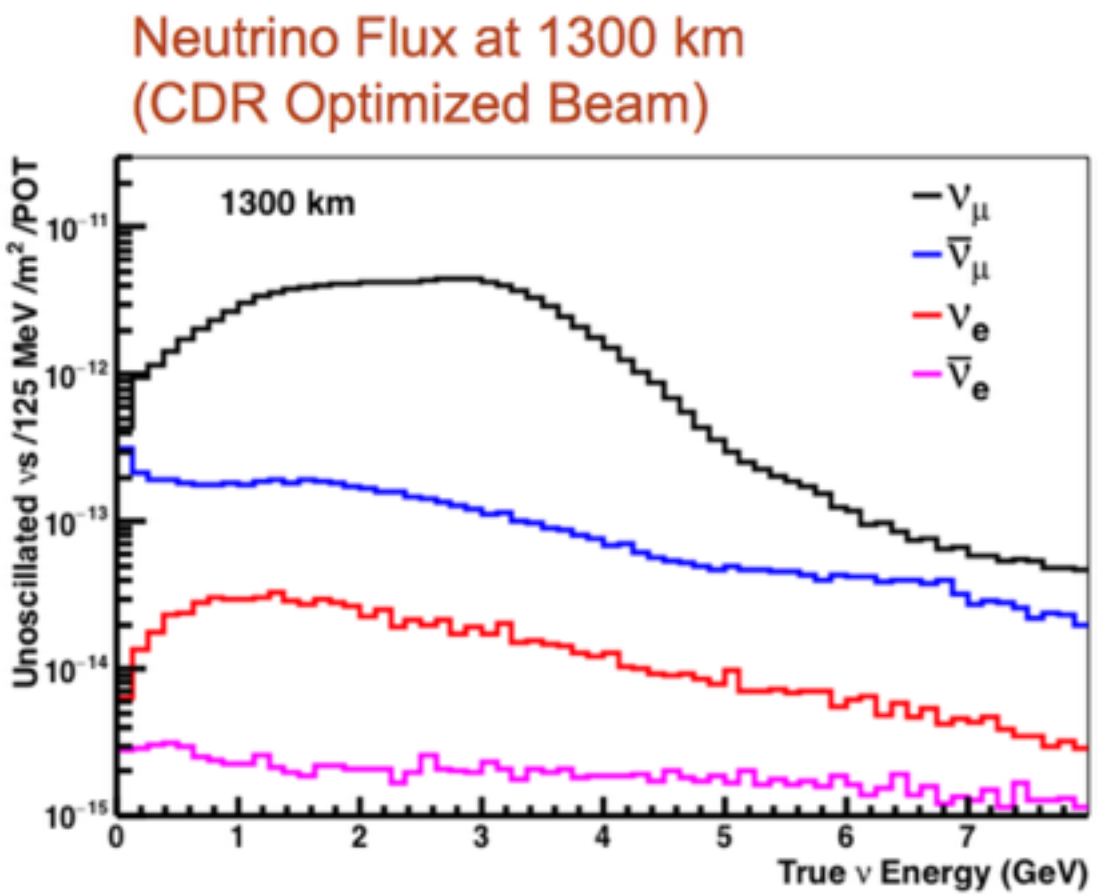
# 1300 Km baseline



# > 1100 collaborators from 32 countries

May 2018 collaboration meeting

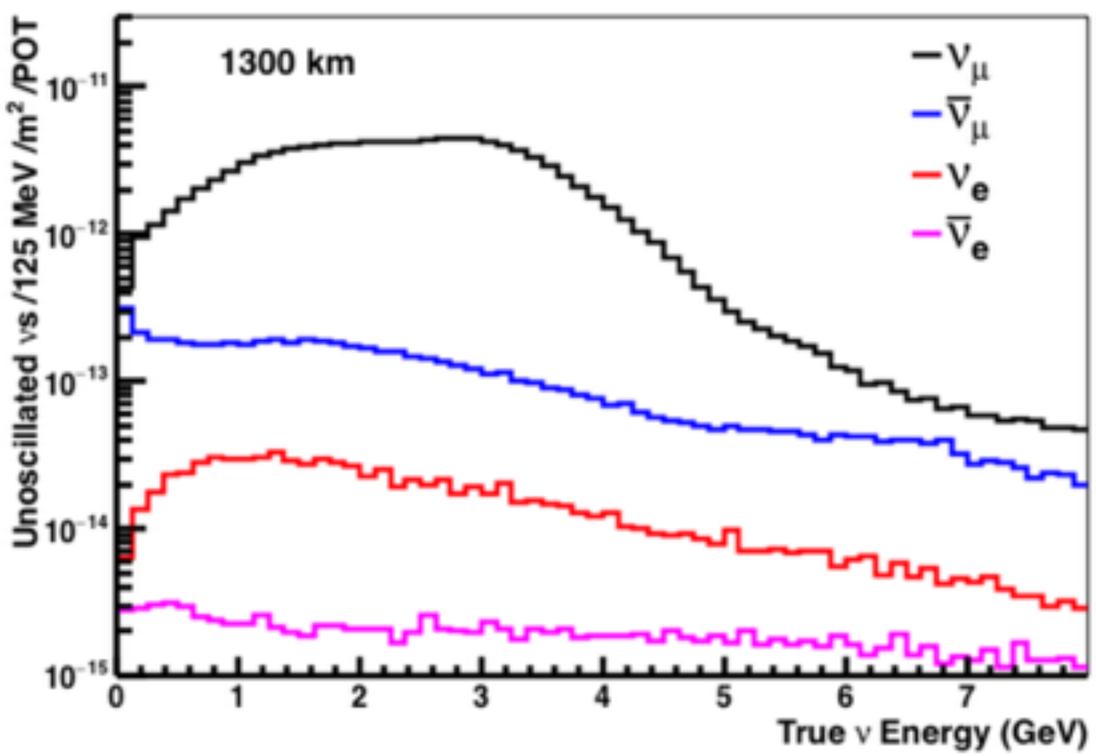
# Observed events



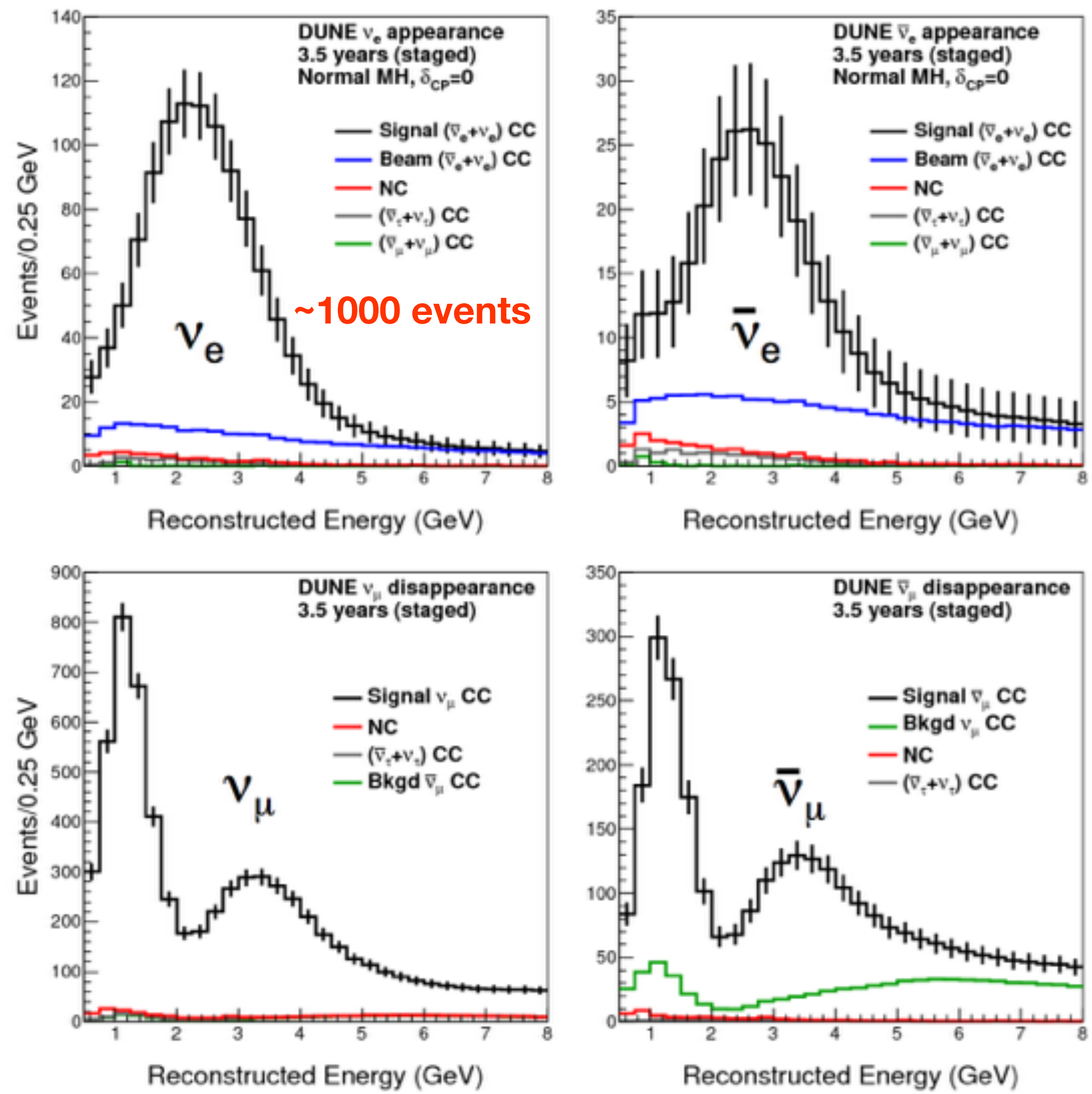

Wide band beam,
contrary to T2K and NOvA

# Observed events

Neutrino Flux at 1300 km
(CDR Optimized Beam)




DUNE Conceptual Design Report (CDR)
arXiv:1512.06148




Wide band beam,
contrary to T2K and NOvA

# DUNE staging assumptions

- Staging scenario assumes equal $\nu$ and $\bar{\nu}$ running time.

| Year | Number of FD modules | Total FD target mass (kt) | LBNF beam power (MW) | Exposure at year end (kt MW yr) |
|---|---|---|---|---|
| 1 | 2 | 20 | 1.2 | 21 |
| 2 | 3 | 30 | 1.2 | 54 |
| 4 | 4 | 40 | 1.2 | 128 |
| 7 | 4 | 40 | 1.2 | 300 |
| 10 | 4 | 40 | 2.4 | 556 |

# DUNE CDR Systematics

Conceptual Design Report

- Sensitivities in DUNE CDR are based on **GLoBES** calculations in which the effect of systematic uncertainty is approximated using signal and background normalization uncertainties.

Spectral uncertainty not included in this treatment.

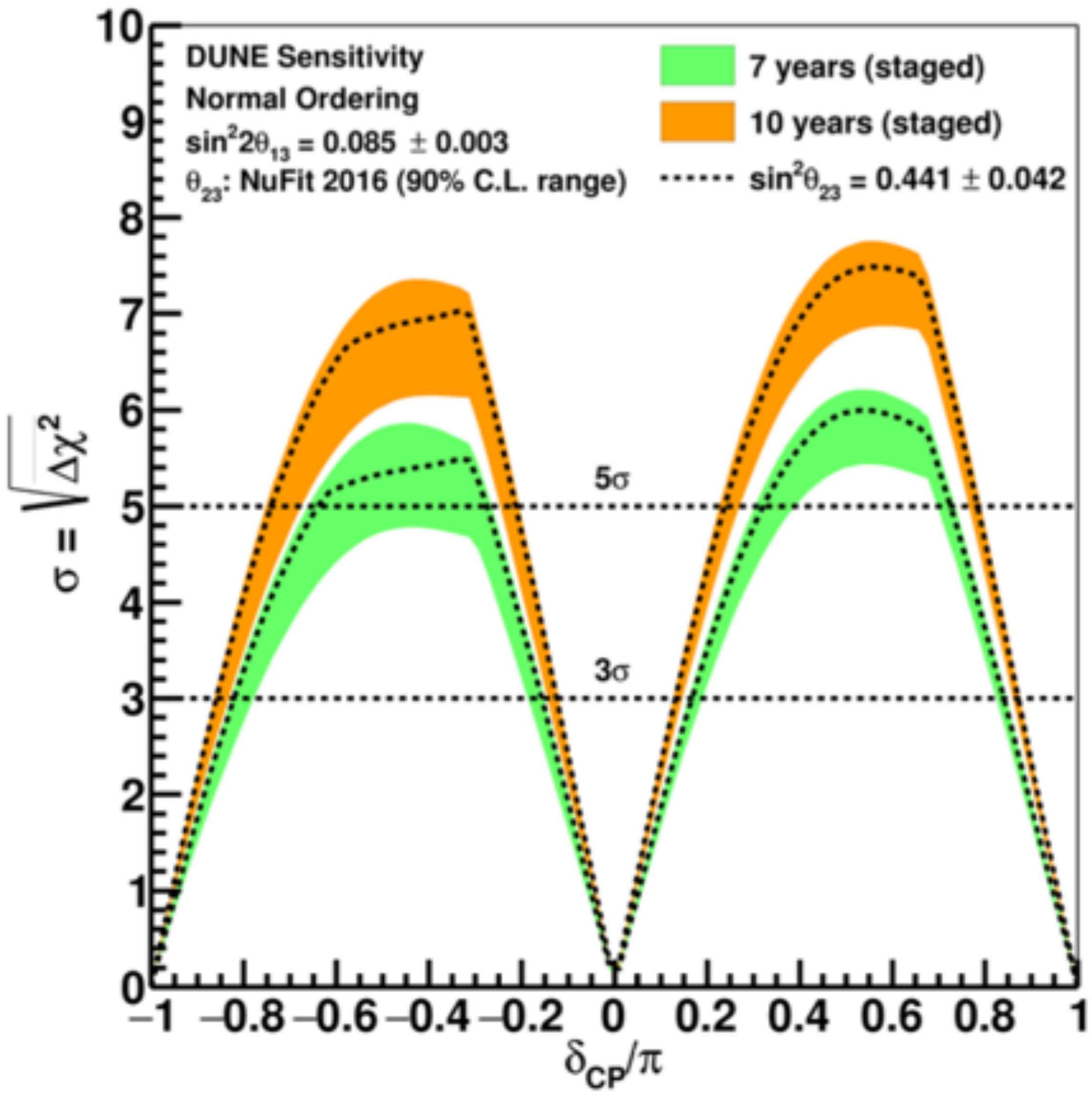
- Signal normalization uncertainties are treated as uncorrelated among the modes ($\nu_e$, $\overline{\nu}_e$, $\nu_\mu$, $\overline{\nu}_\mu$) and represent the residual uncertainty expected after constraints from the near detector and the four-sample fit are applied.
  - $\nu_\mu = \overline{\nu}_\mu = 5\%$ Flux uncertainty after ND constraint
  - $\nu_e = \overline{\nu}_e = 2\%$ Residual uncertainty after $\nu_\mu$ and $\nu/\overline{\nu}$ constraint

# CDR sensitivities (2016)

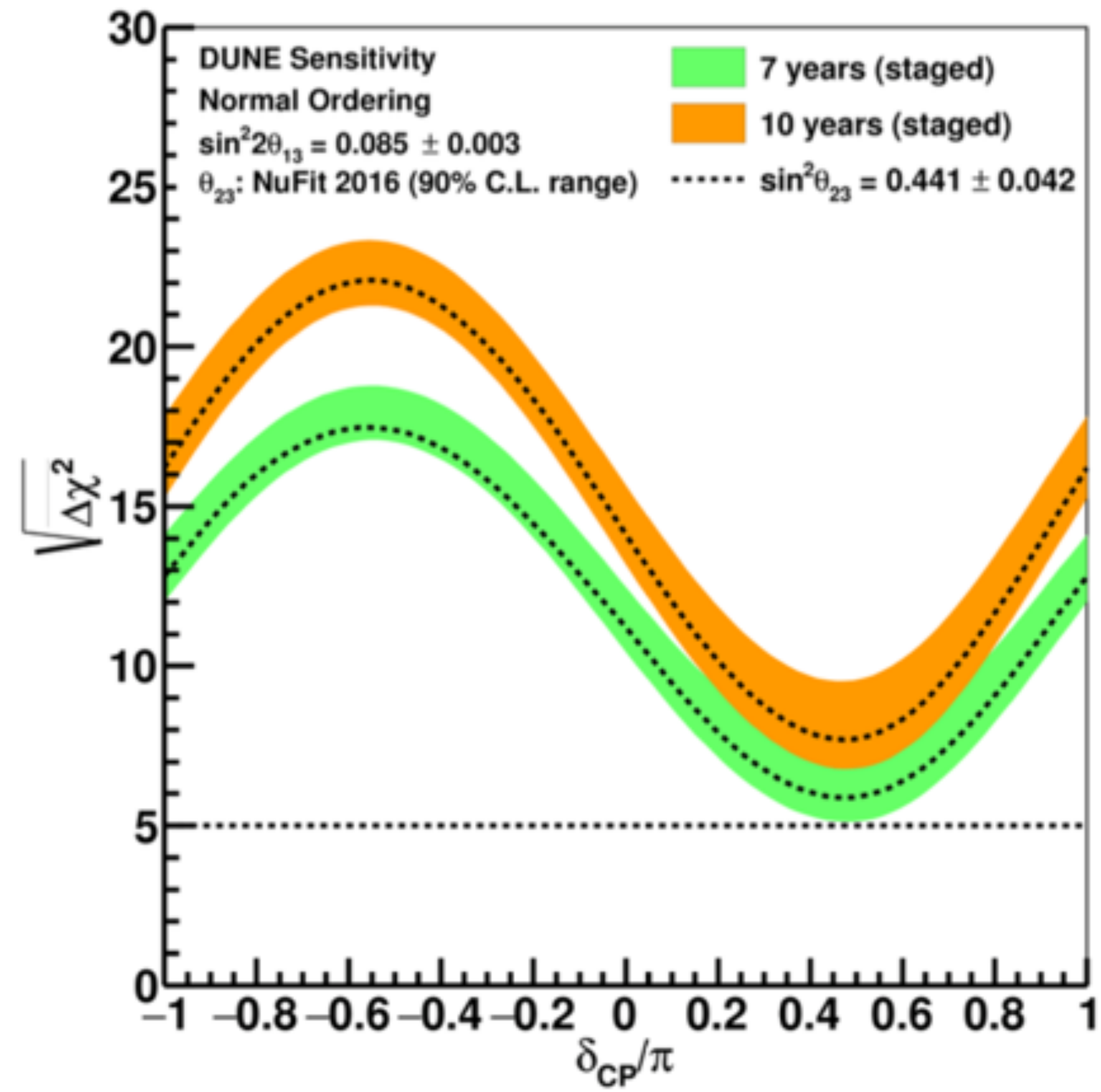
Conceptual Design Report

- Fast MC and pseudo-reconstruction with tuned efficiencies

**CP VIOLATION**




**Mass hierarchy**




width of band indicates variation in posible central values of values of $\theta_{23}$

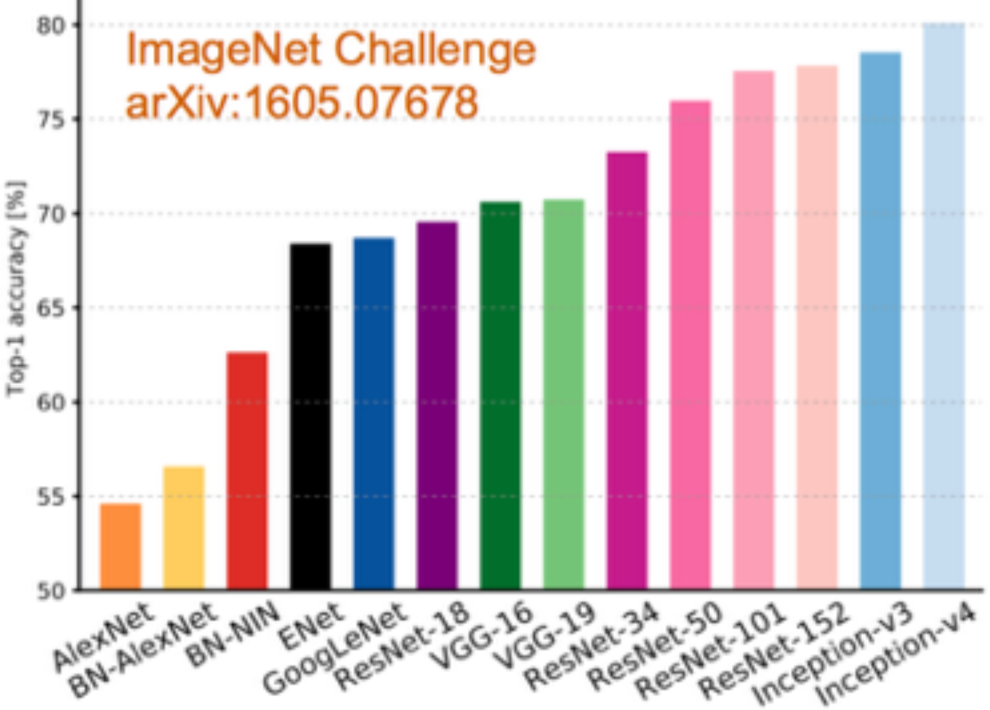
# New MC Analysis (2018)

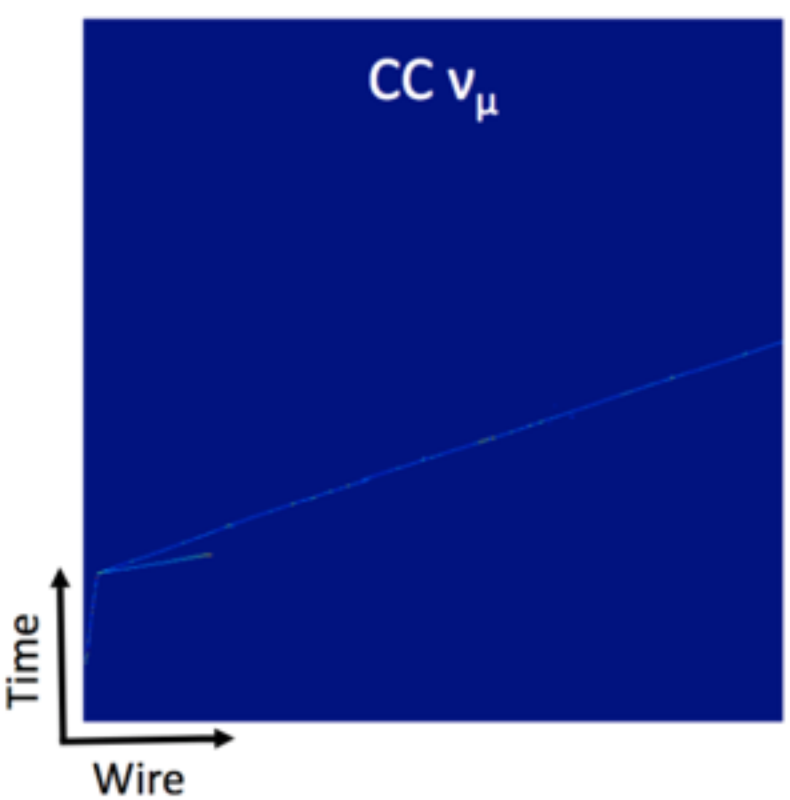
- GEANT4 beam simulation of updated beam design
- Full LArSoft Monte Carlo simulation
  - Shared framework among many LArTPC experiments
  - GENIE event generator
  - GEANT4 particle propagation
  - Detector readout simulation including realistic waveforms and white noise
- Automated signal processing and hit finding
- Automated energy reconstruction
  - Muon momentum from range (contained) or multiple Coulomb scattering (exiting)
  - Electron and hadron energy from calorimetry

# Use CVN techniques

Convolutional Visual Networks

Use ResNet architecture

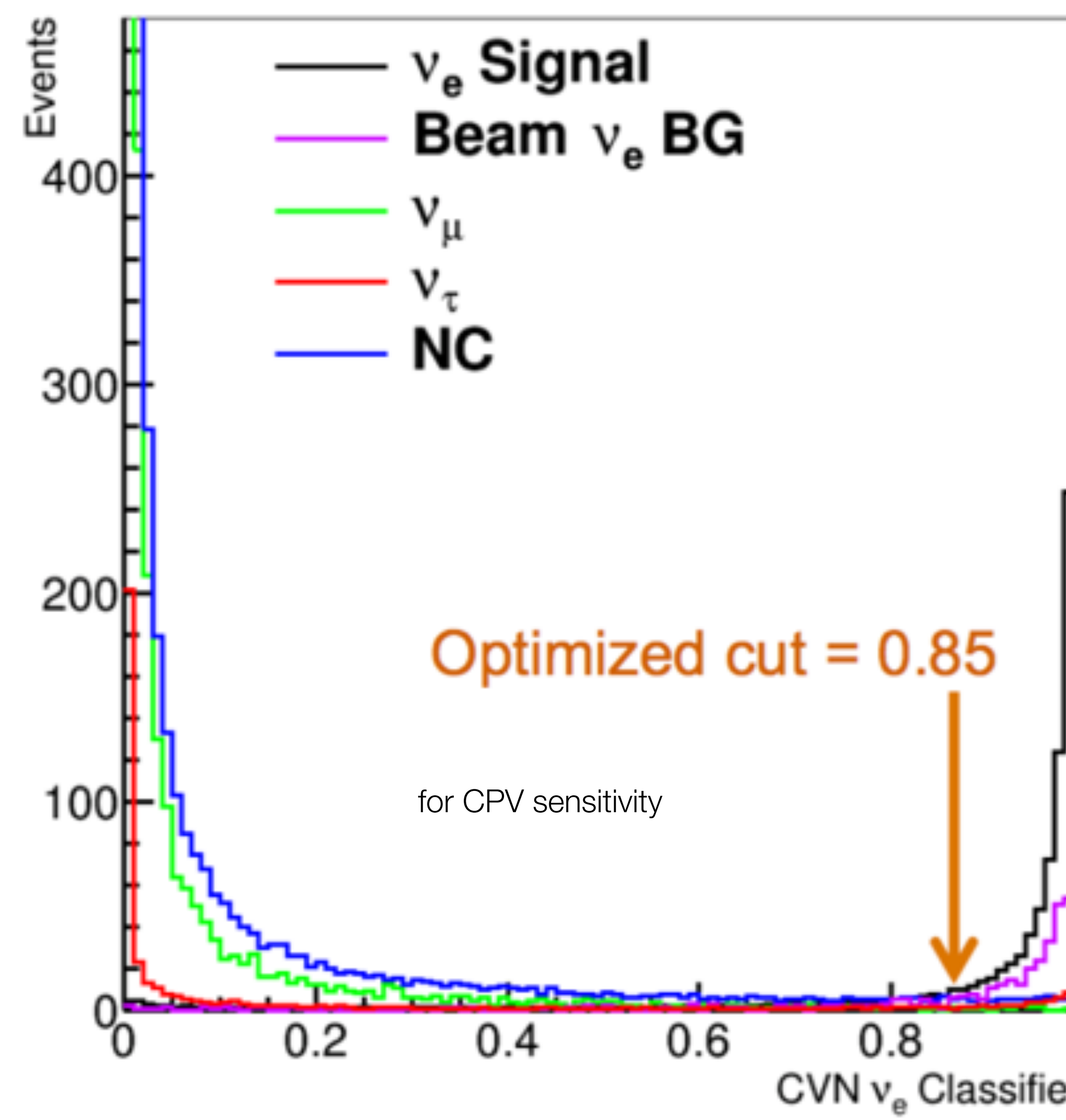



DUNE MC images classified into categories: $\nu_e$CC, $\nu_\mu$CC, $\nu_\tau$CC, NC

Training performed on sets of 500 x 500 DUNE MC images

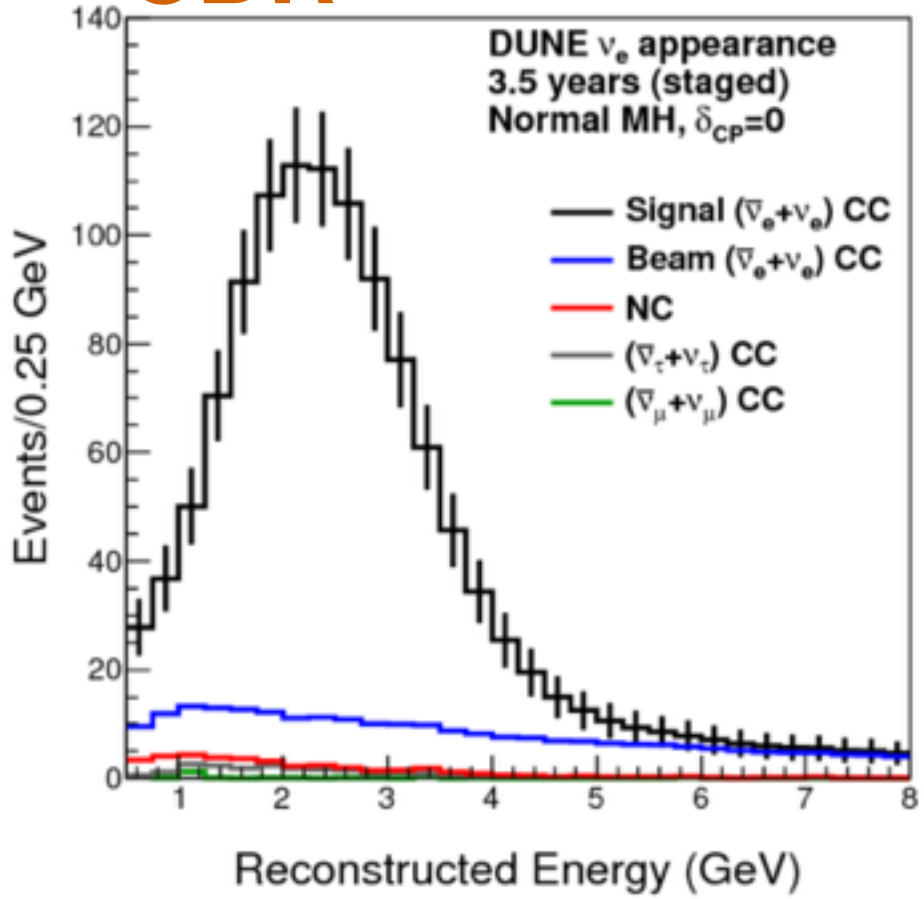
Event selection performed by applying cuts on $\nu_e$CC-like and $\nu_\mu$CC-like CVN classifiers



# Improved sensitivities

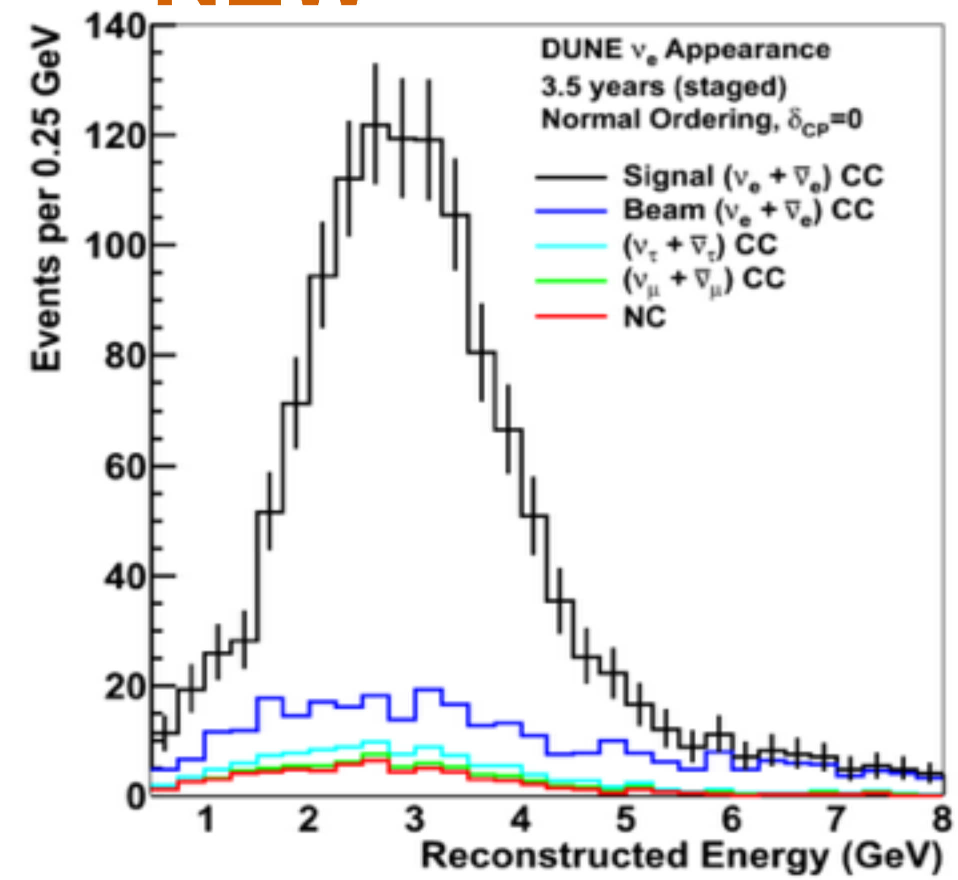
$\nu_e$ in CDR
with assumed efficiency

**CDR**




CVN selected $\nu_e$
with full reconstruction chain

**NEW**

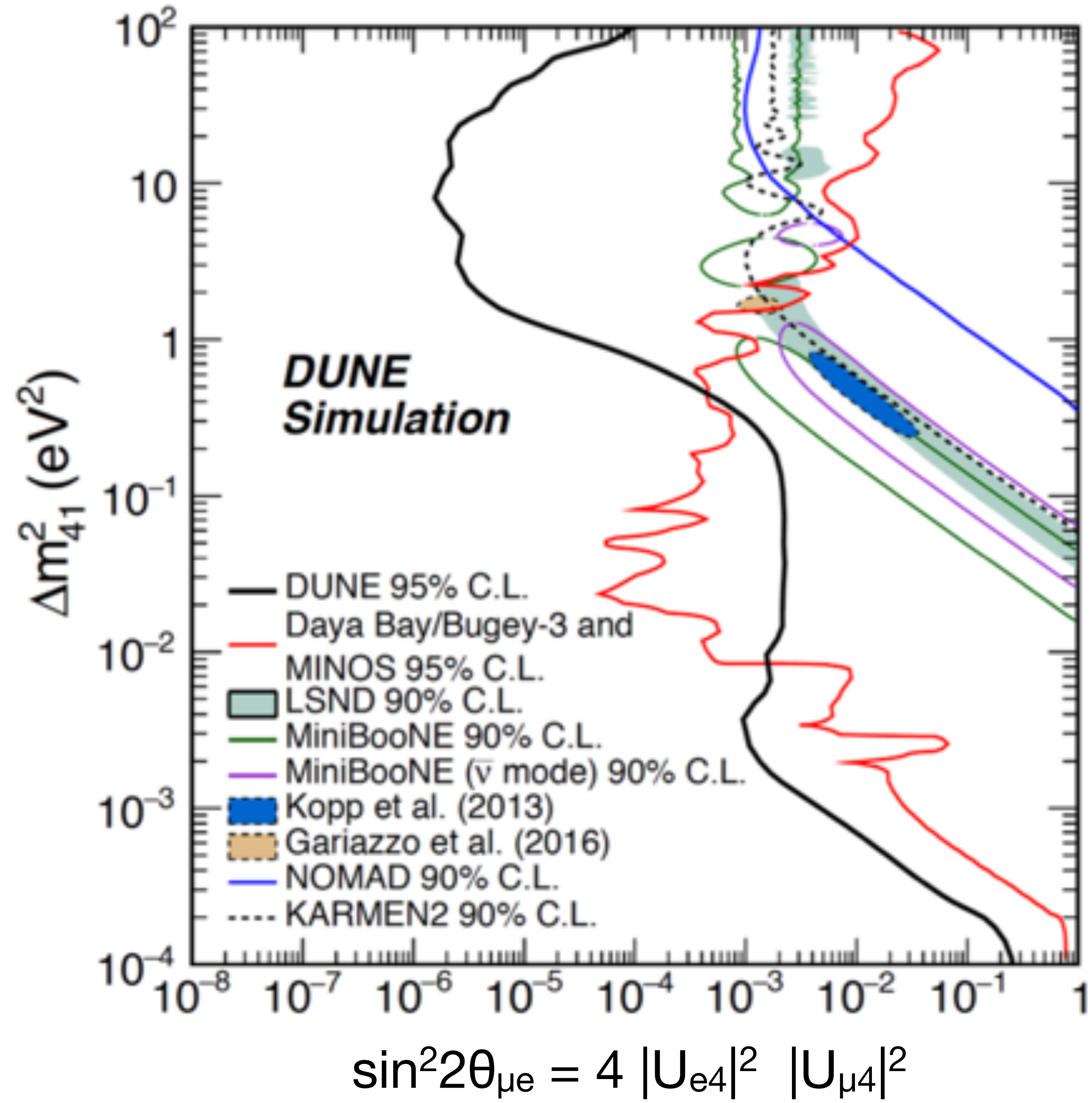



- Sensitivity from MC-based analysis with full reconstruction chain exceeds sensitivity in Conceptual Design Report (CDR)
- Sensitivity plots will be updated soon

# Beyond Standard Model (BSM)

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

**Sterile Neutrino Sensitivity**
**($\nu_e$CC appearance at Near detector)**



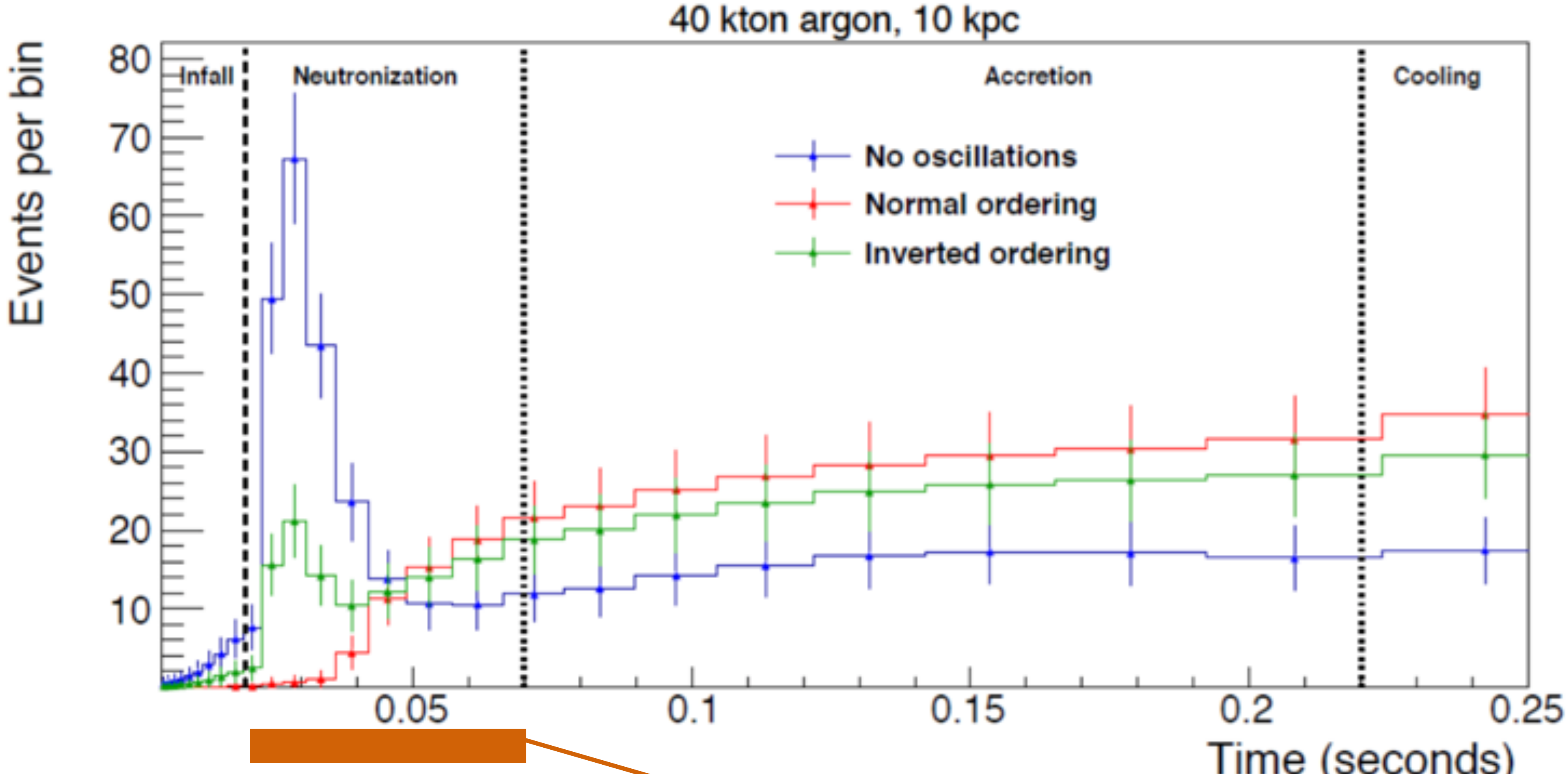
# SuperNova neutrinos

**Expect 2-3 core-collapse supernovae in the Milky Way per century ≈ 3500 neutrinos in 40kt DUNE for SN at 10 Kpc.**

**In LArTPC, SNB signal dominated by electron neutrinos**

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

**LAr uniquely sensitive to neutronization process at ~30ms**



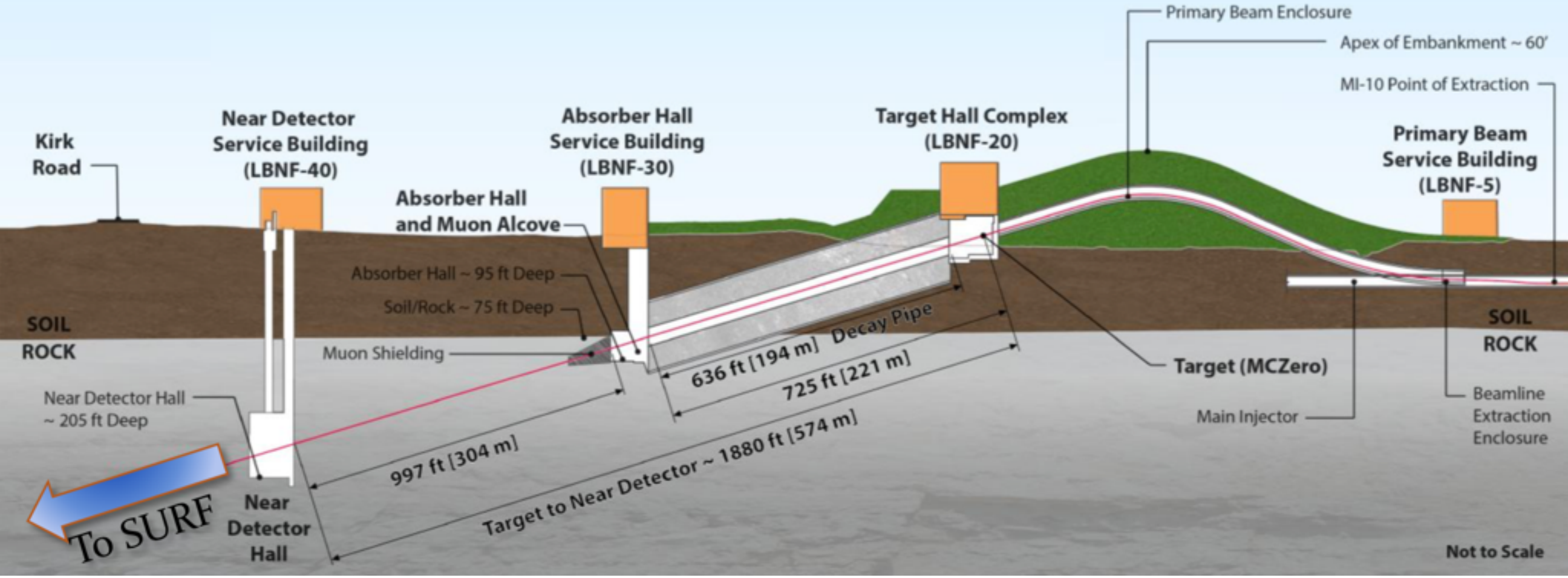

Observation of **early time** development yields sensitivity to neutrino mass ordering and details of SNB model.

# Fermilab

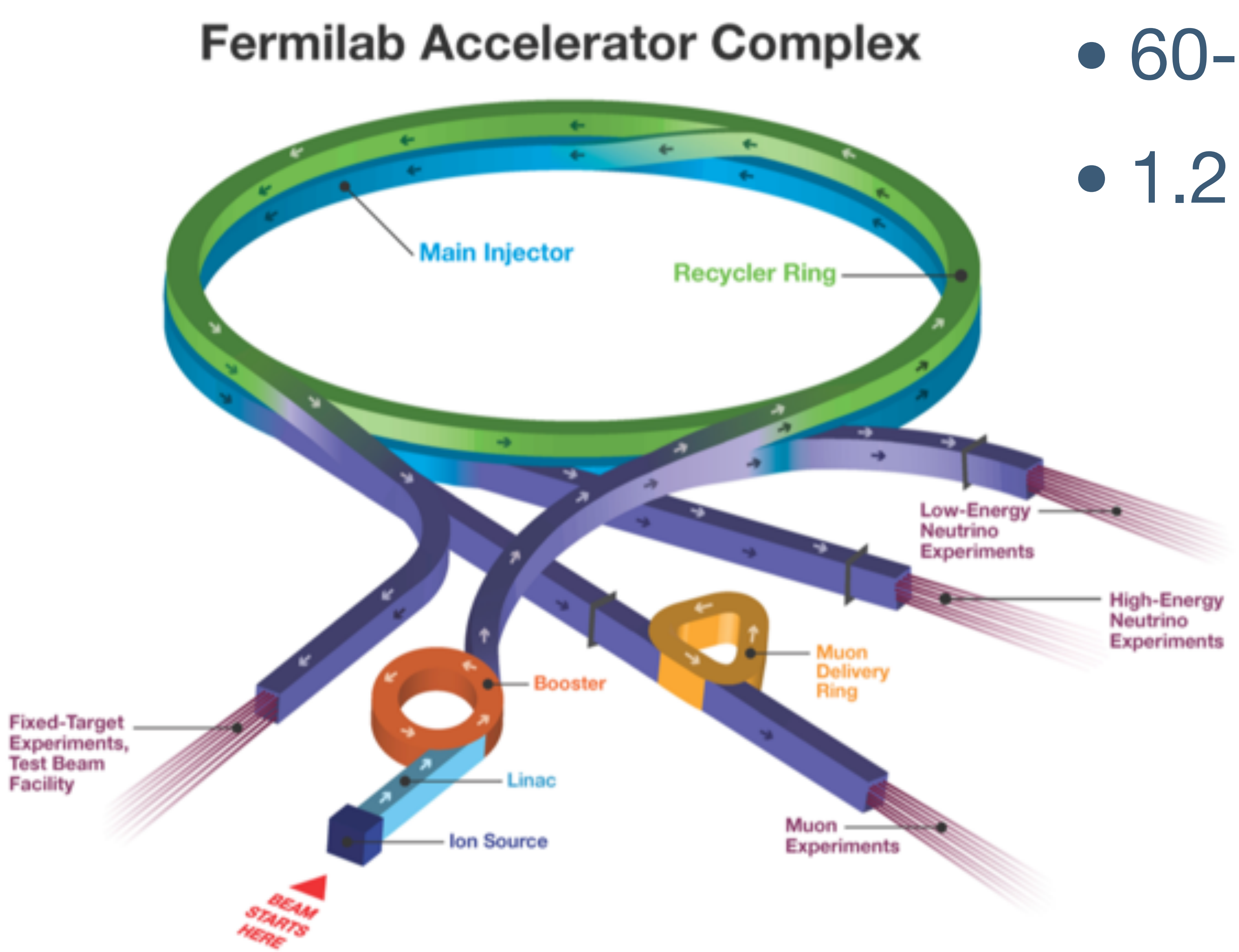

LBNF= Long Baseline Neutrino Facility

**Near Detectors**

**LBNF Neutrino beam-line**

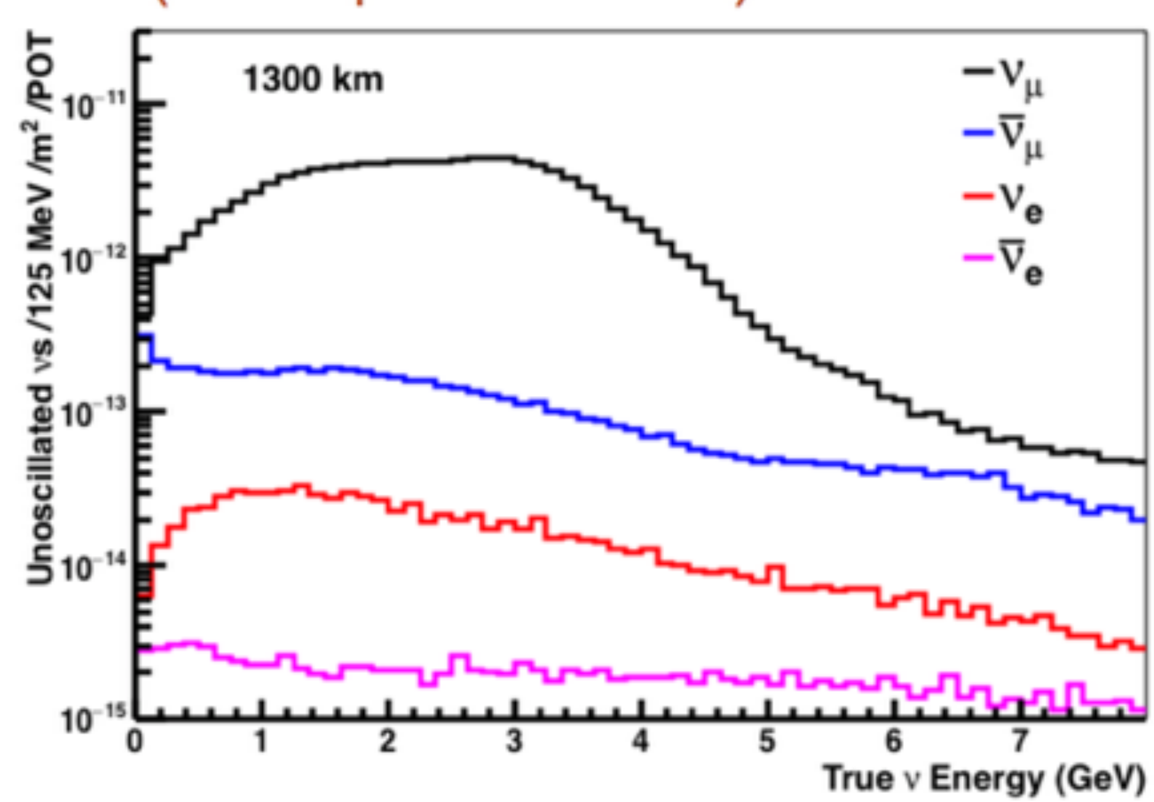


# The LBNF beam




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

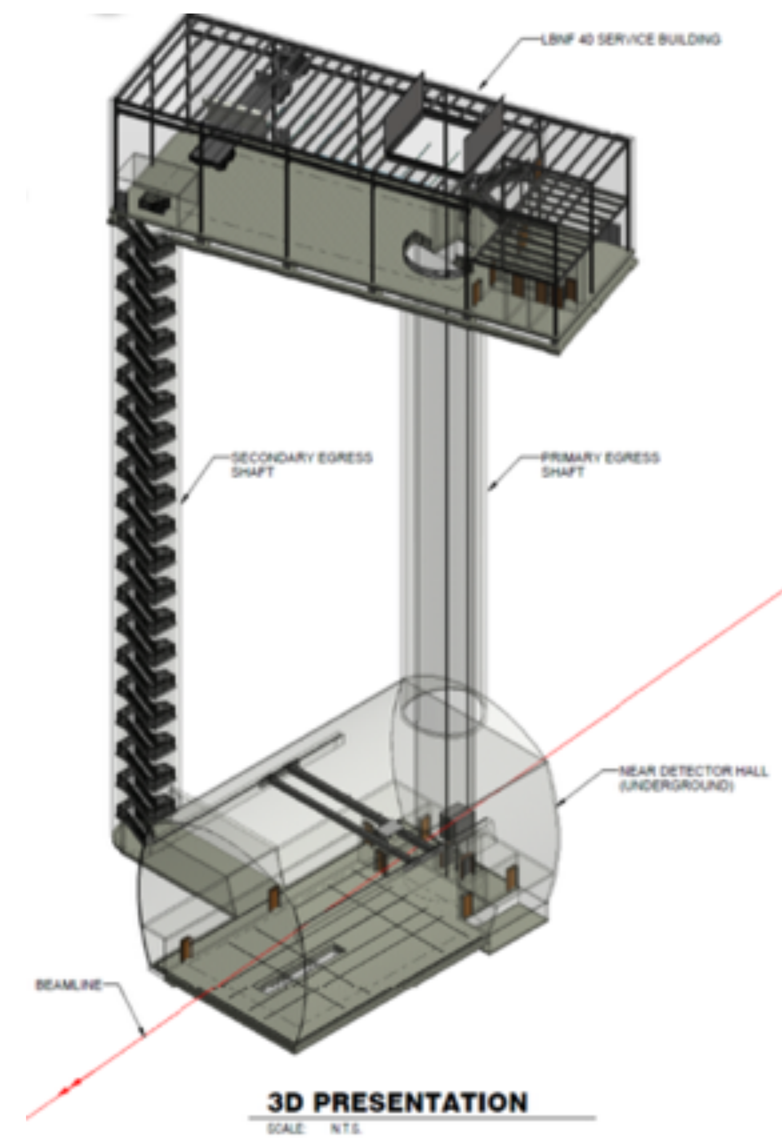
Neutrino Flux at 1300 km (CDR Optimized Beam)




Reference design similar to NuMI, optimized to improve sensitivity to oscillation measurements

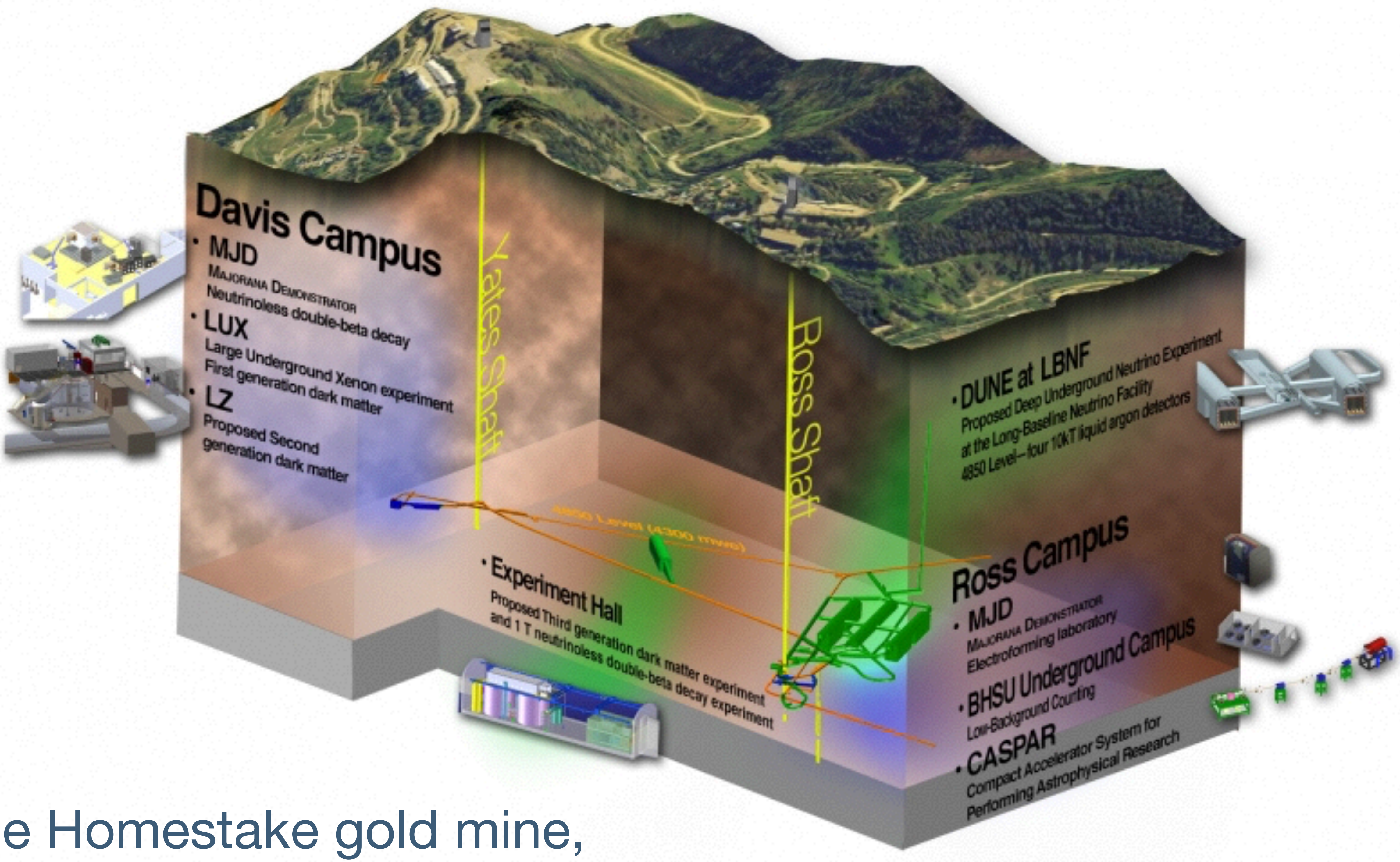
# Near detector

- Constraint systematic uncertainties for LBL oscillation analysis
- ND Conceptual Design Report (CDR) planned for 2019
- Design concept is an integrated system composed of multiple detectors
    - Highly segmented LArTPC
    - Magnetized multi-purpose tracker
    - Electromagnetic calorimeter
    - Muon chambers
- Conceptual design will preserve option to move ND for off-axis measurements



# SURF

Sanford Underground Research Facility (Lead, SD)

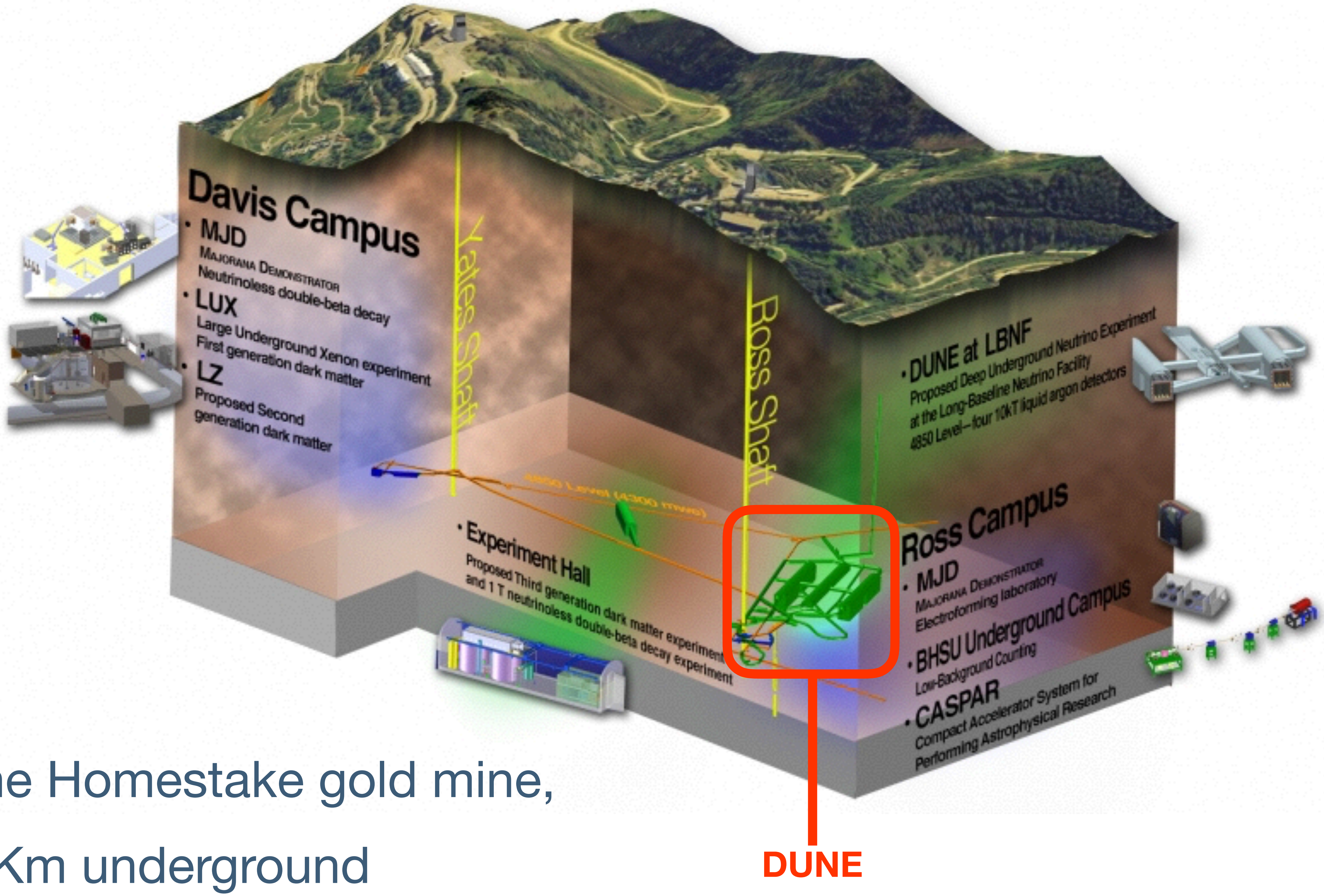



In the Homestake gold mine,

1.5 Km underground

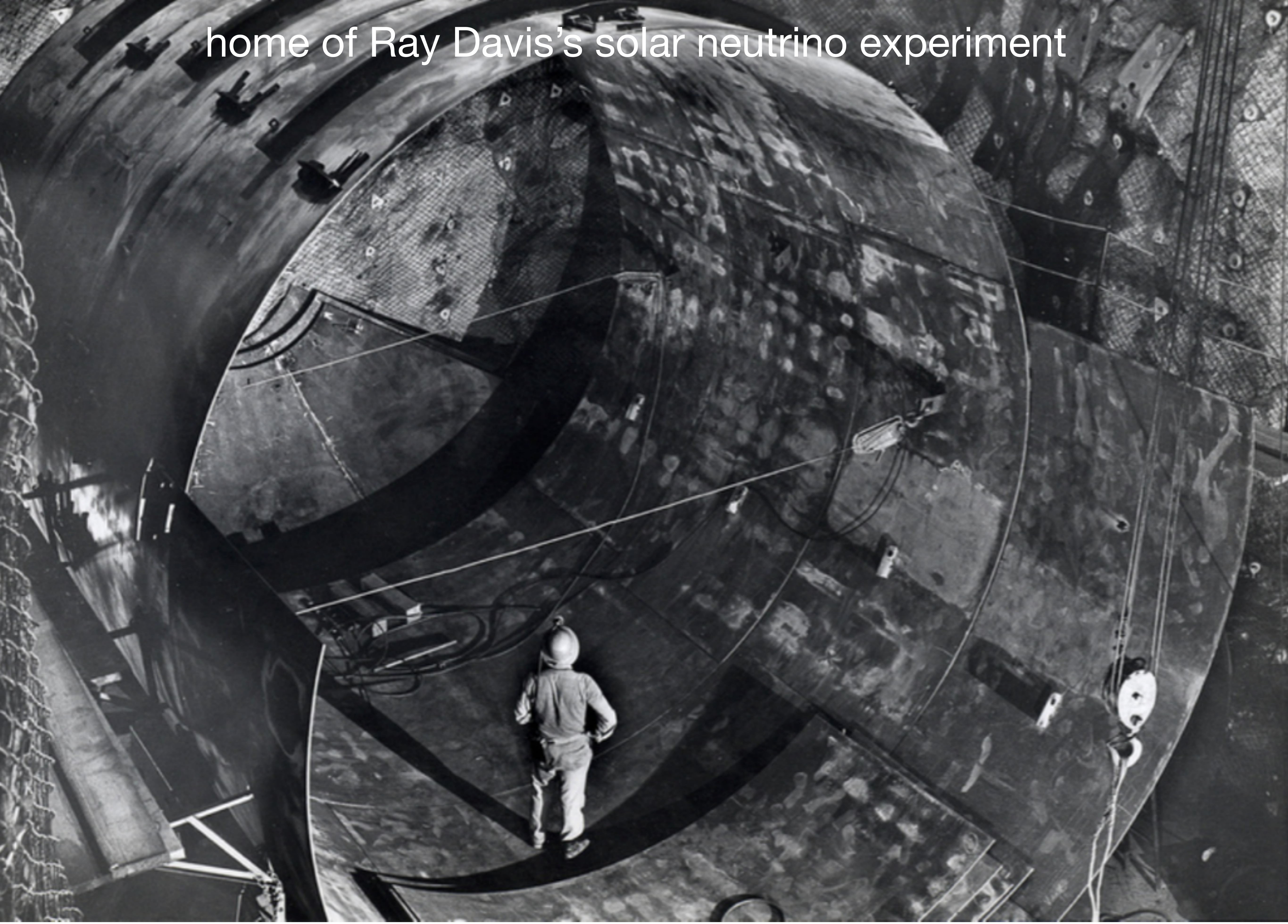
# SURF

Sanford Underground Research Facility (Lead, SD)




In the Homestake gold mine,

1.5 Km underground

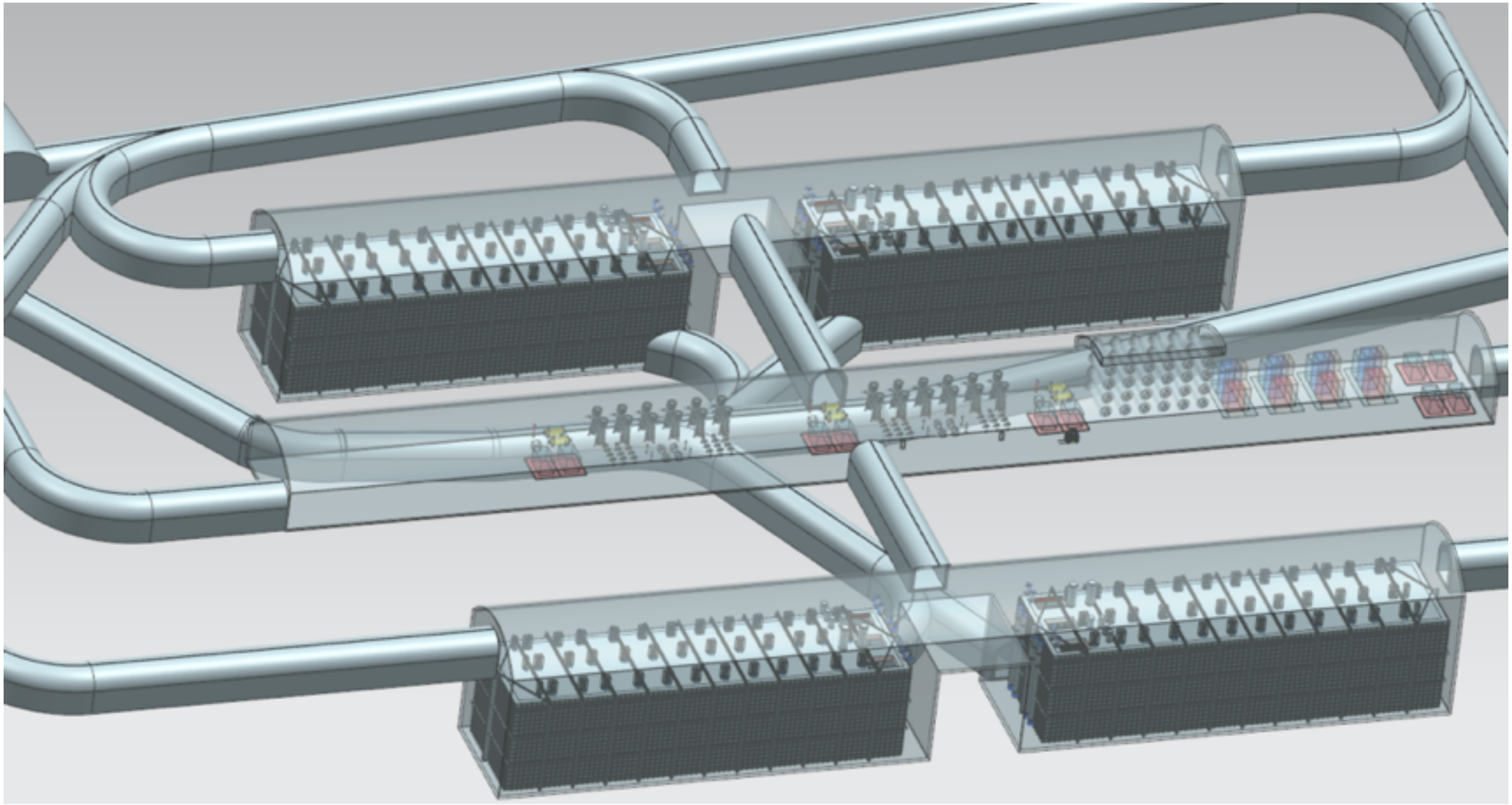

home of Ray Davis's solar neutrino experiment

# SURF groundbreaking

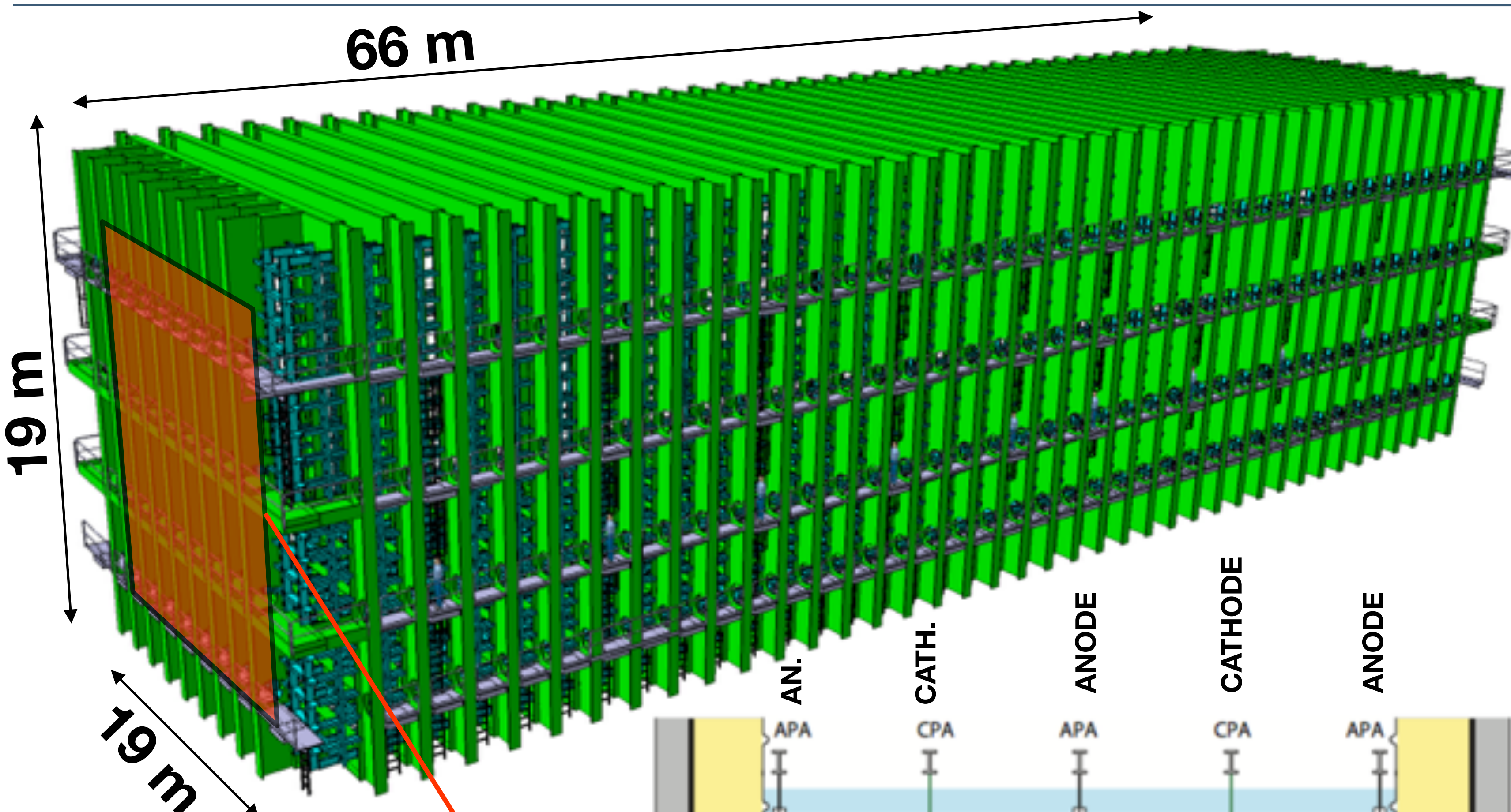
Groundbreaking ceremony at 4850 ft level – July 21st 2017

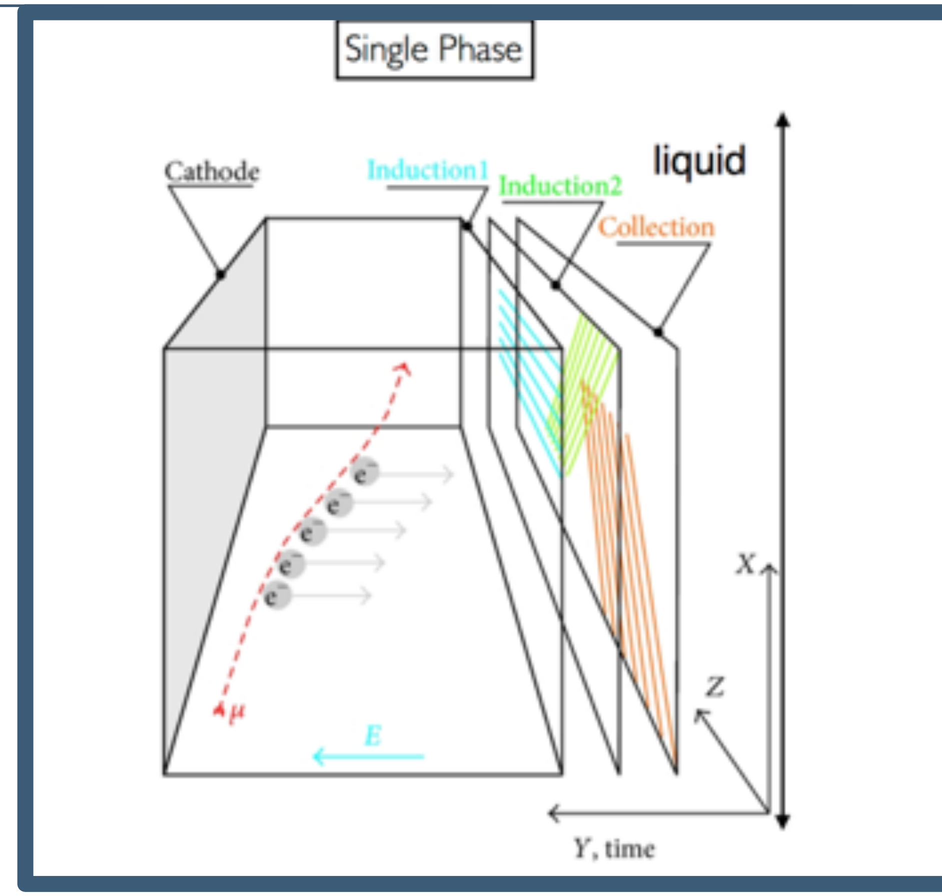
# Far detectors

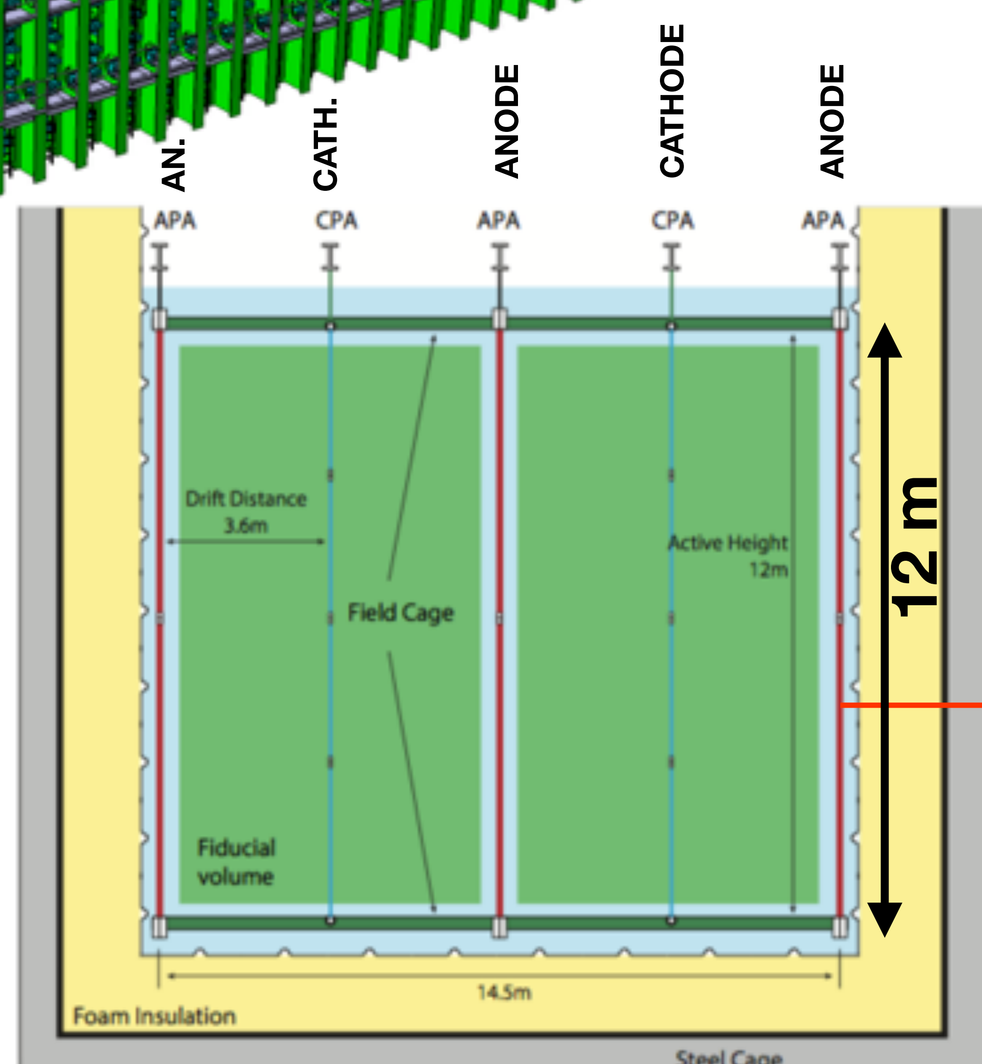
- Four 10 Kton fiducial mass Liquid Argon TPCs



# Far detectors: 1st module



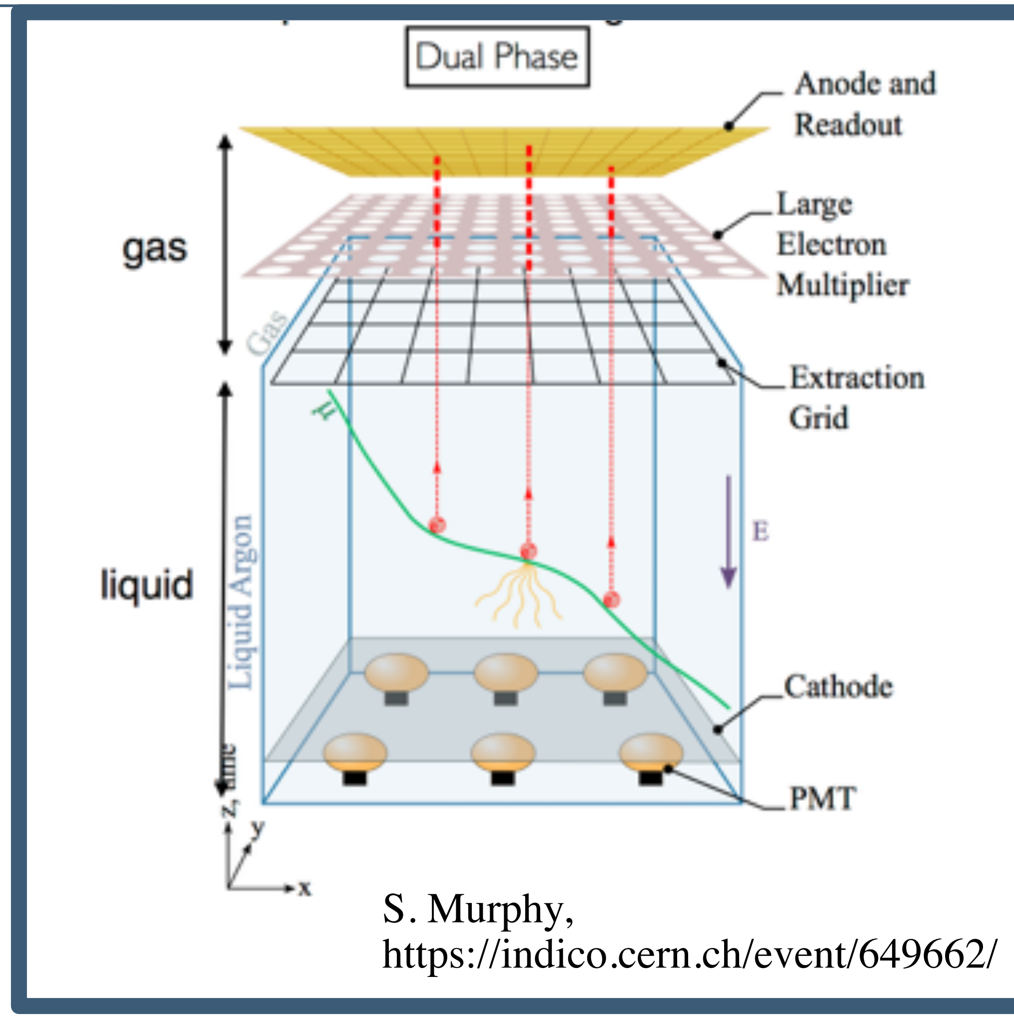



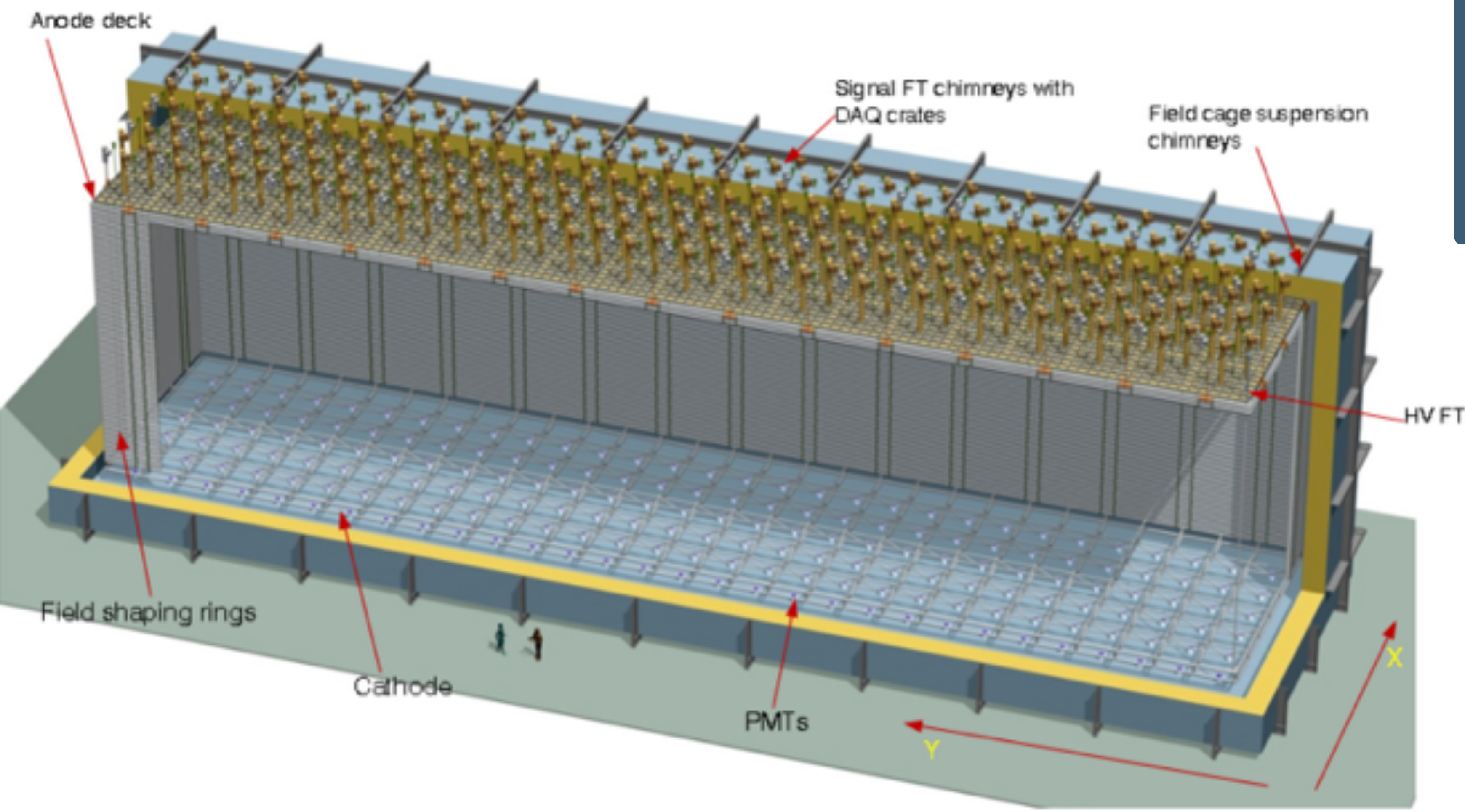


- Single-Phase

# Far detectors: 2nd module

- Dual-Phase, with signal amplification in the gas phase



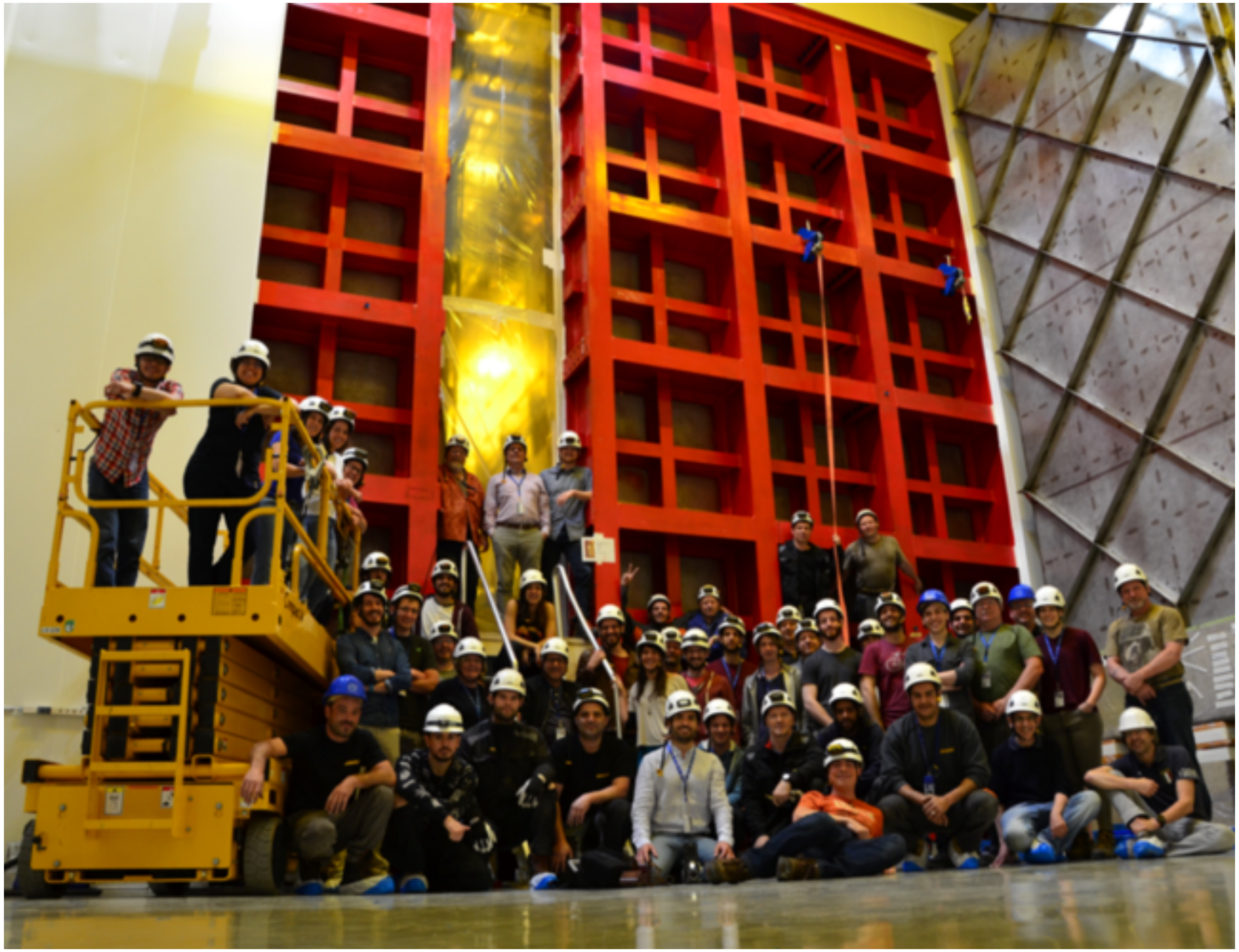



# Icarus x 20


1/2 Icarus
LArTF
BARNHART
www.barnhartcrane.com
#IcarusTrip
I'm ICARUS a neutrino hunter Follow my journey
IcarusTrip.fnal.gov
OVERSIZE LOAD

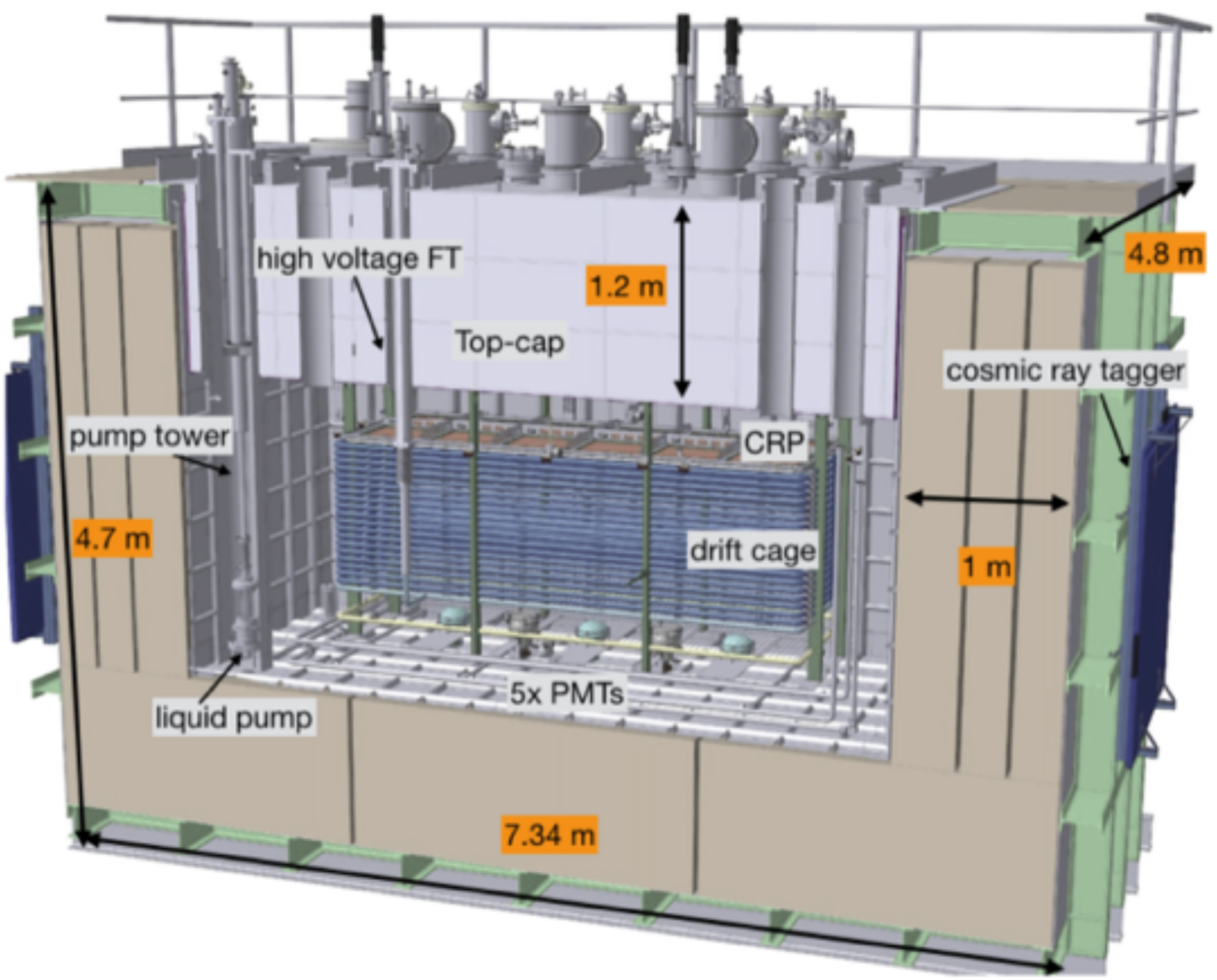
# Detector prototyping

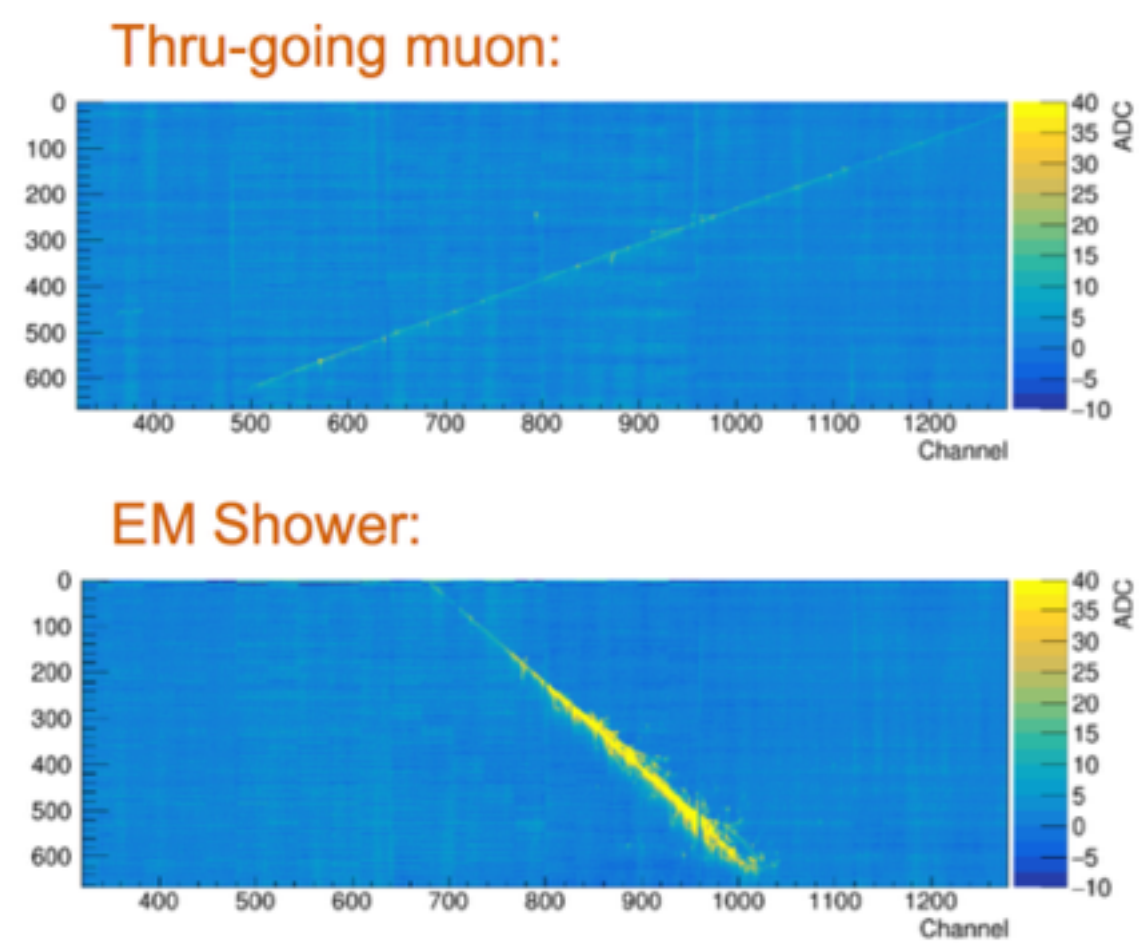
- The **single** and **dual** phase technologies are being prototyped at CERN



# 3x1x1 prototype (WA105)

- Successful demonstration of Dual-Phase technology
- Operated at CERN between June and November 2017



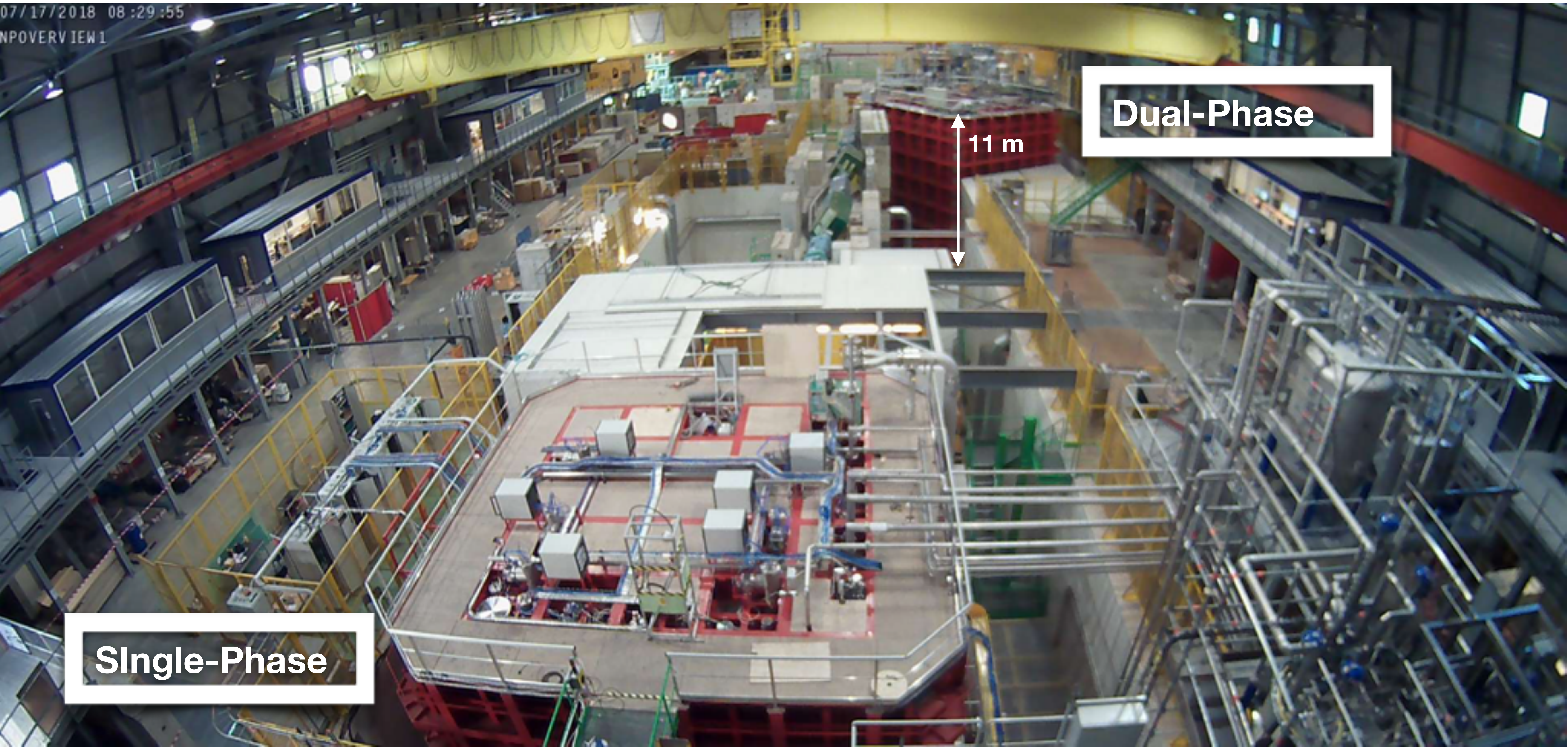



# ProtoDUNEs at CERN

## March 2016

# October 2016

# Today

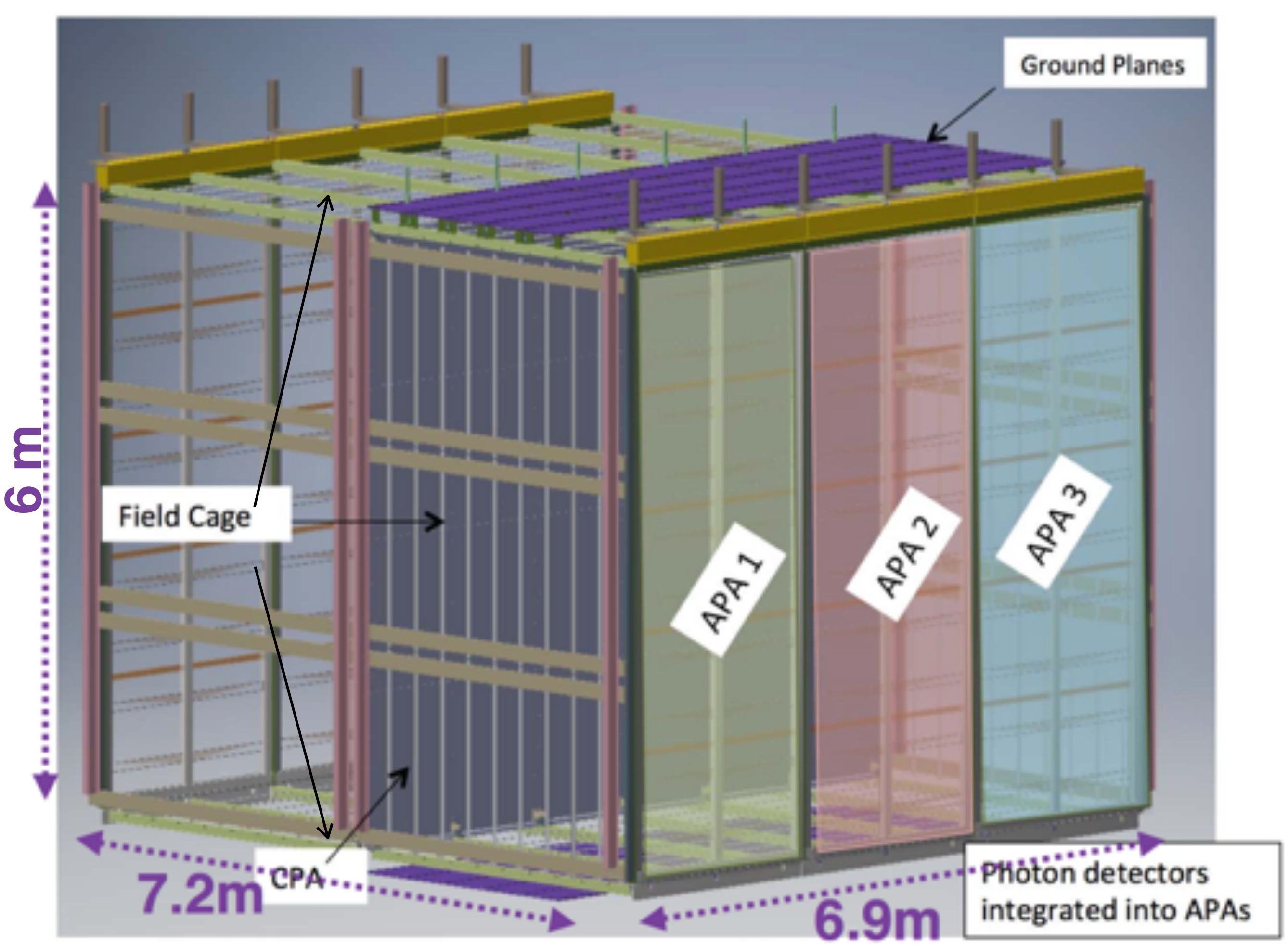


# ProtoDUNEs goals

- Prototyping production and (underground) installation procedures
- Validating the design from basic detector performance
- Accumulating large test-beam data for detector response understanding, calibration, dE/dx, PID etc.
- Demonstrating long-term operational stability

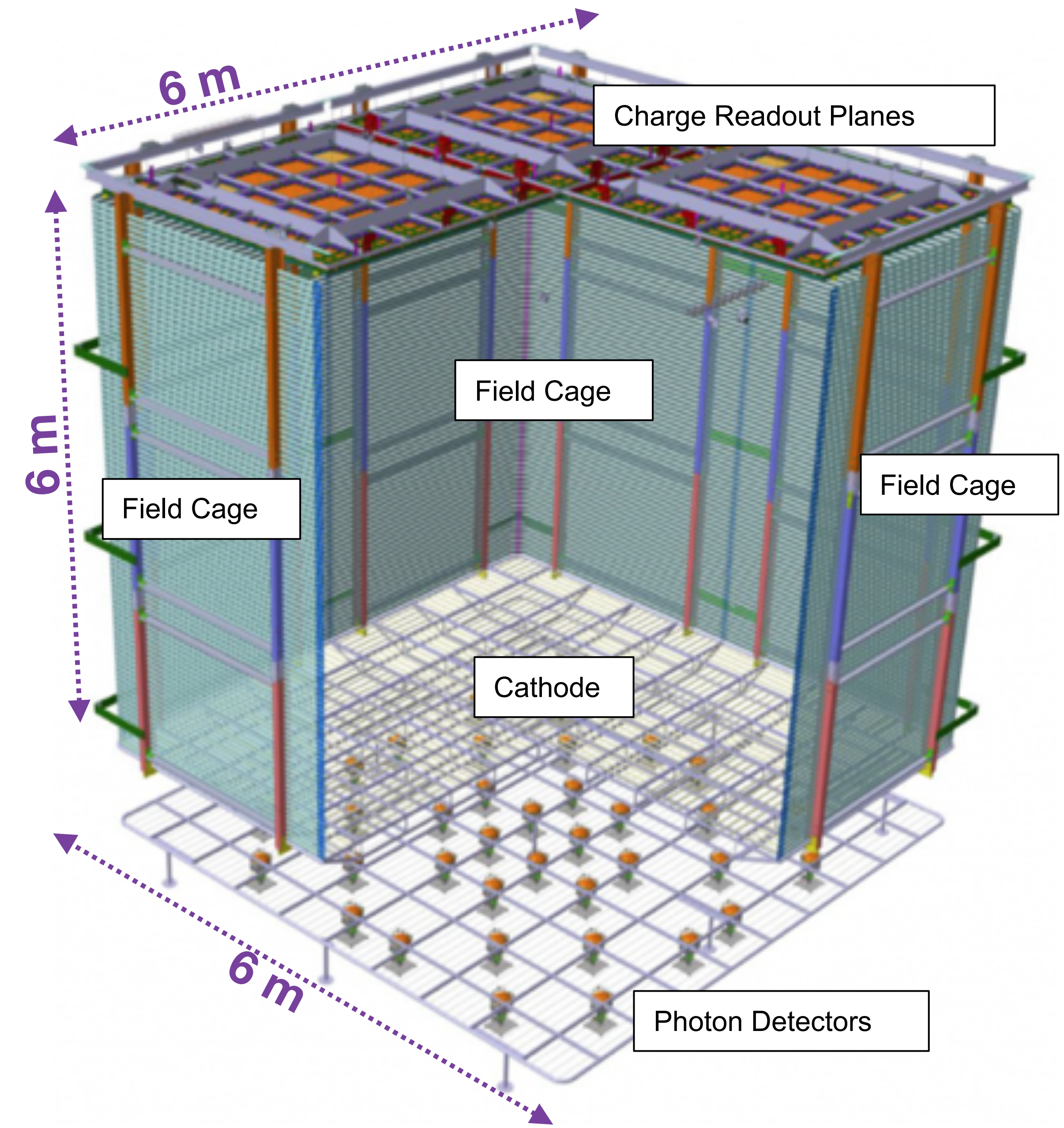
## Single-Phase

3.6 m horizontal drift

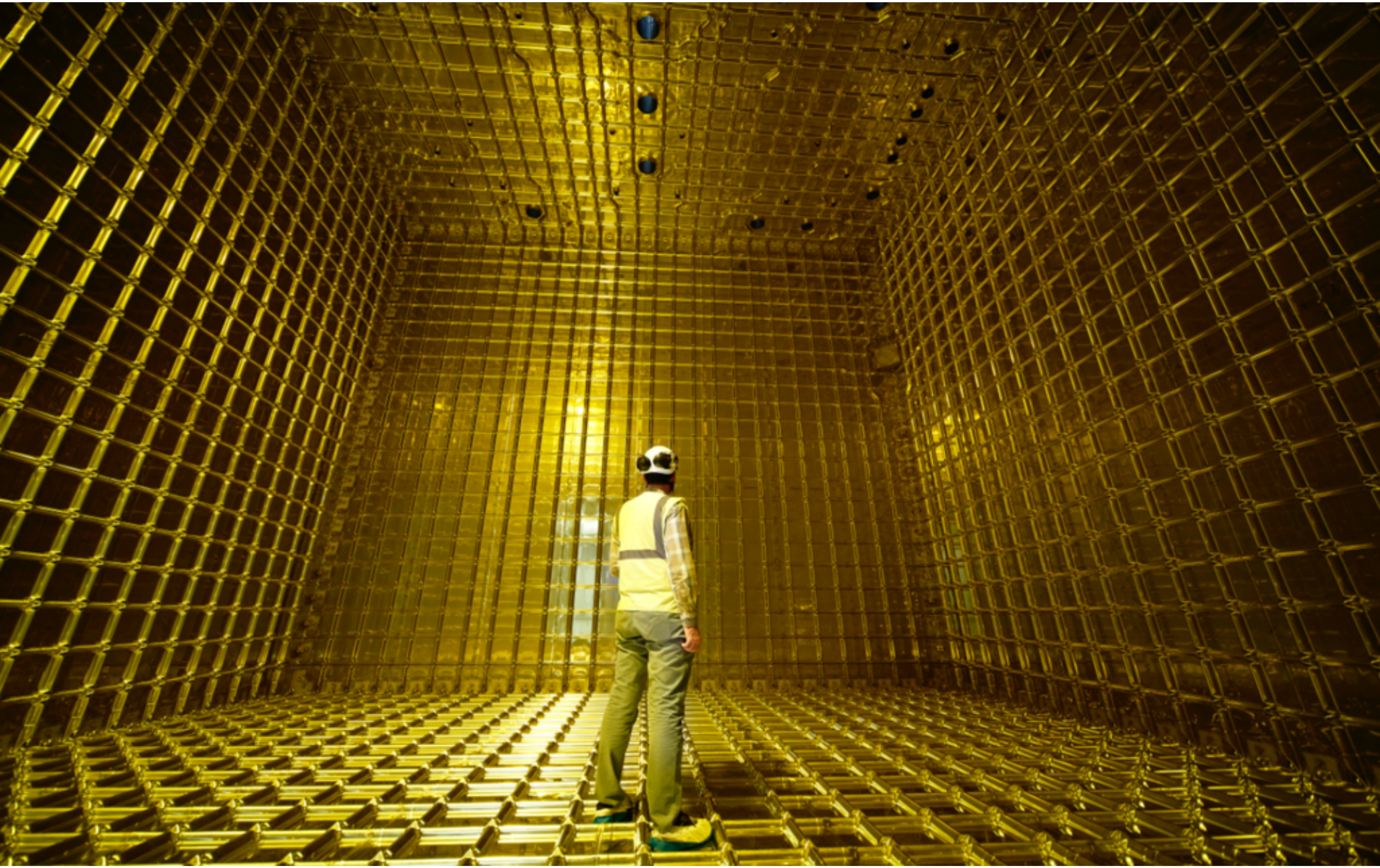



## Dual-Phase

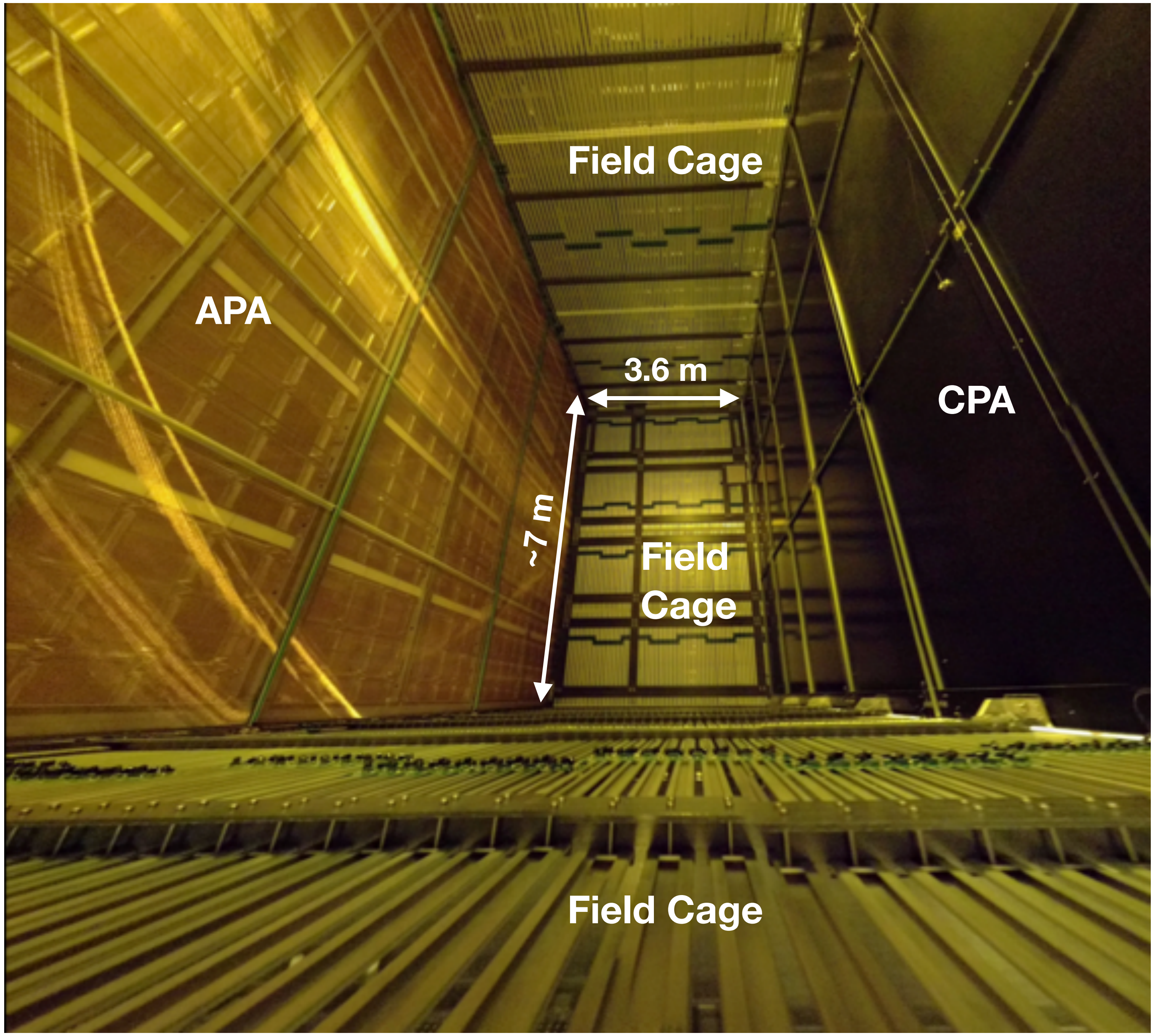
6 m vertical drift



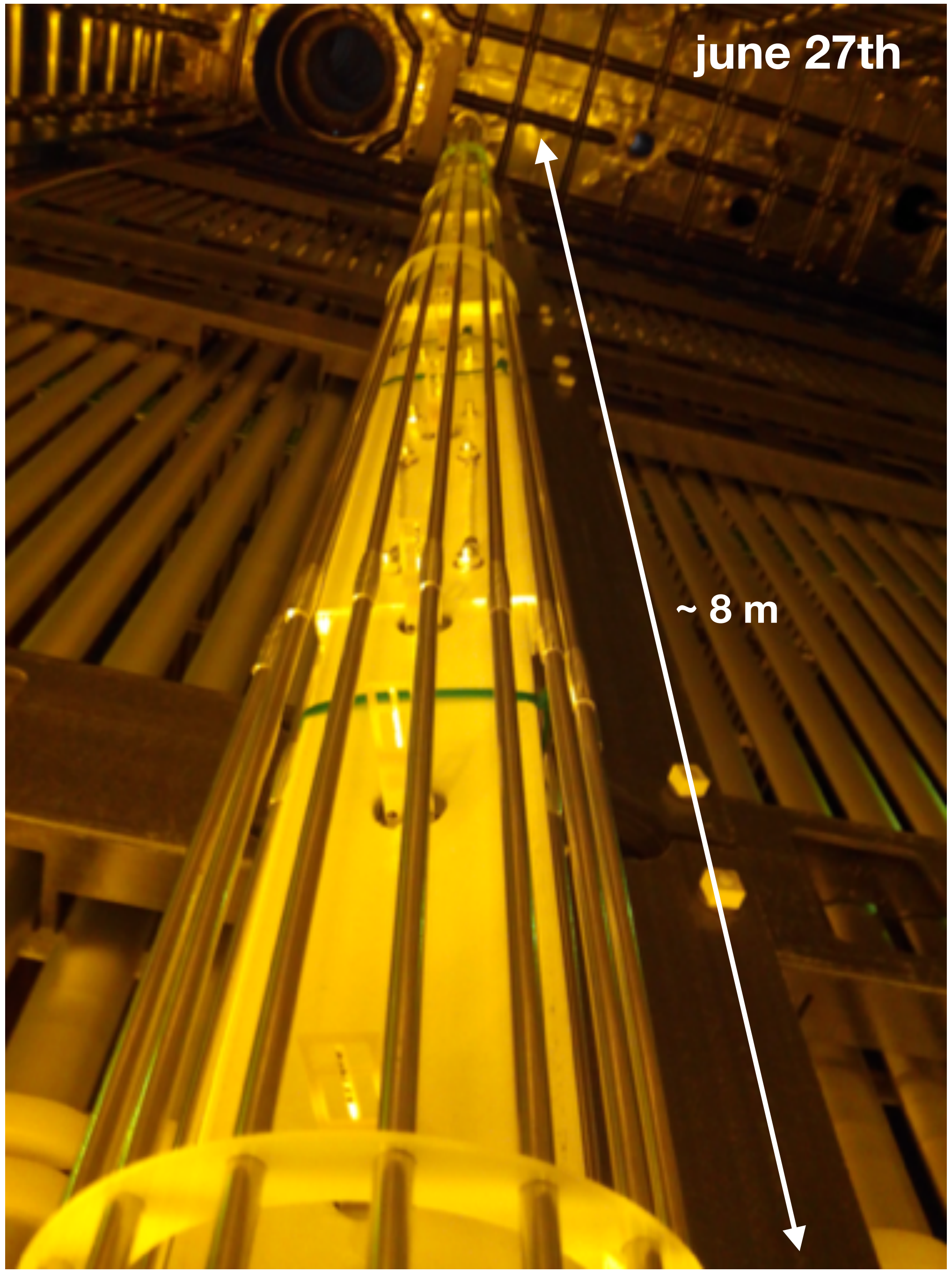
# Empty cryostat



## One fully instrumented drift volume



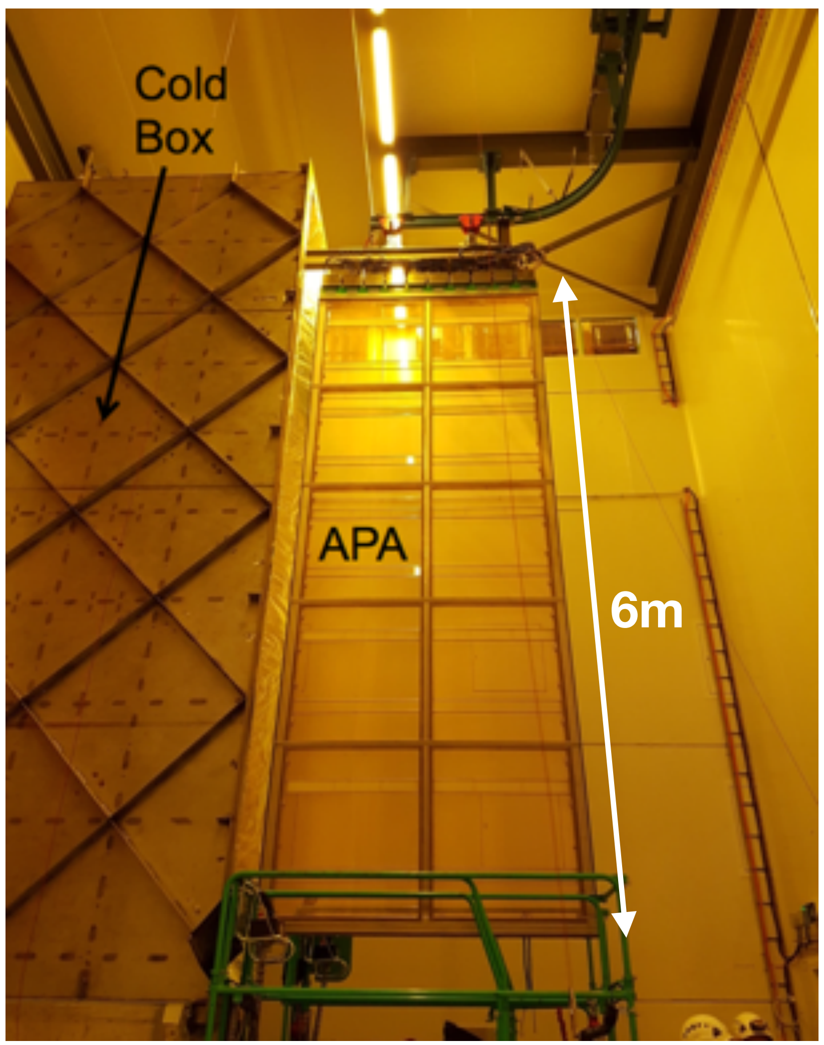

## T-Gradient monitor



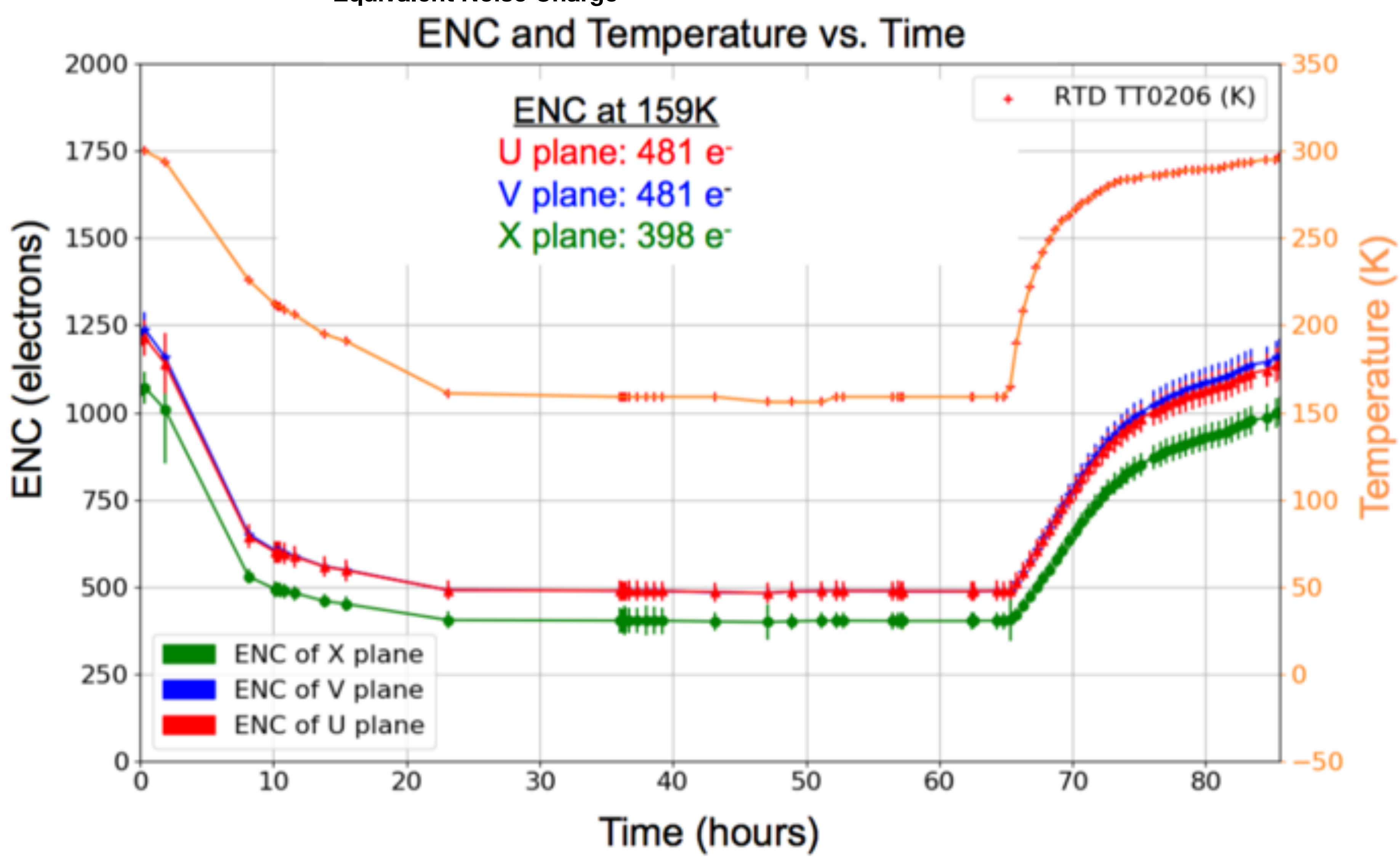
# ProtoDUNE cold box results

- Promising results of APA wire noise in cold box

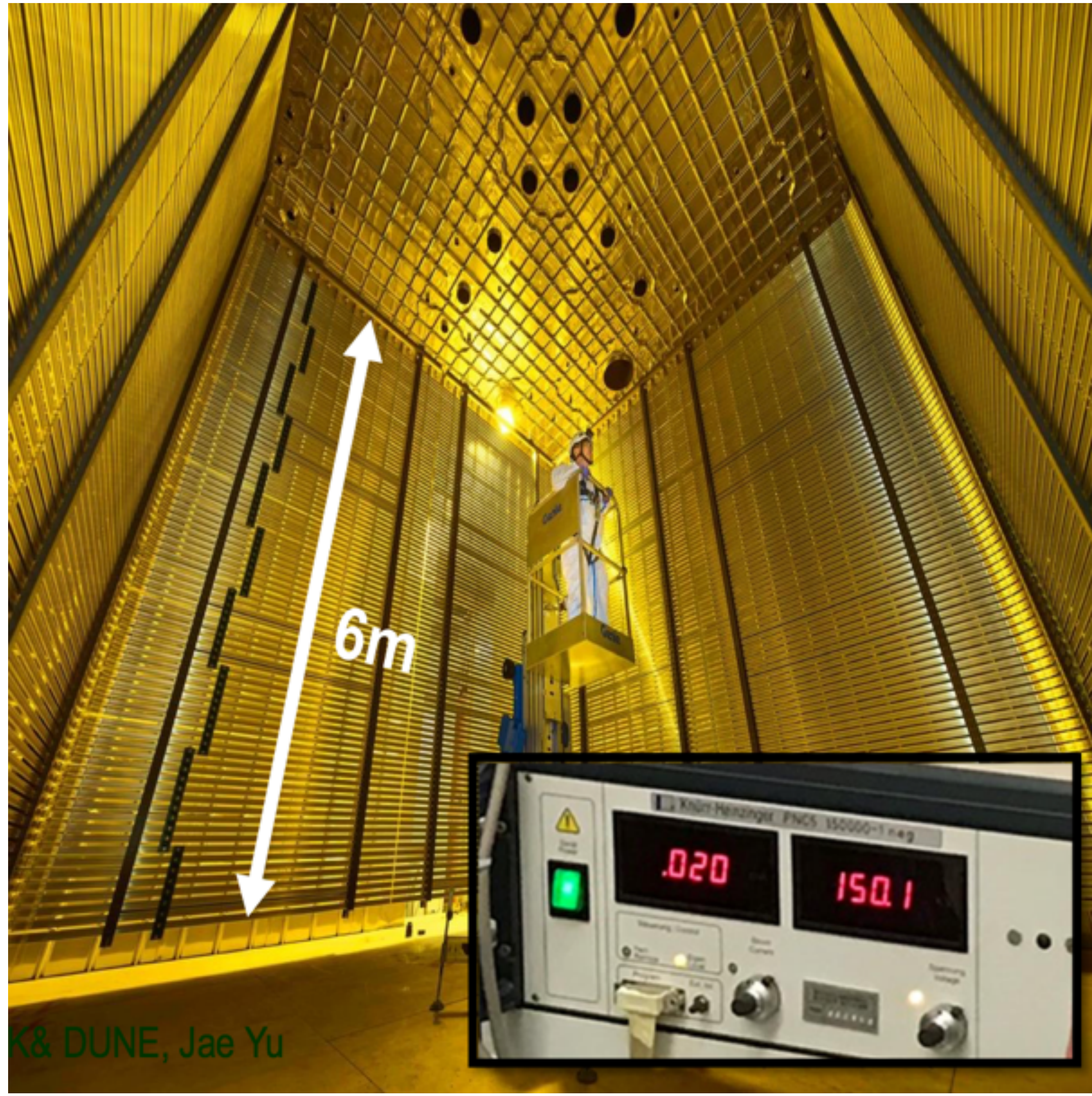
Anode Plane Assembly




Equivalent Noise Charge

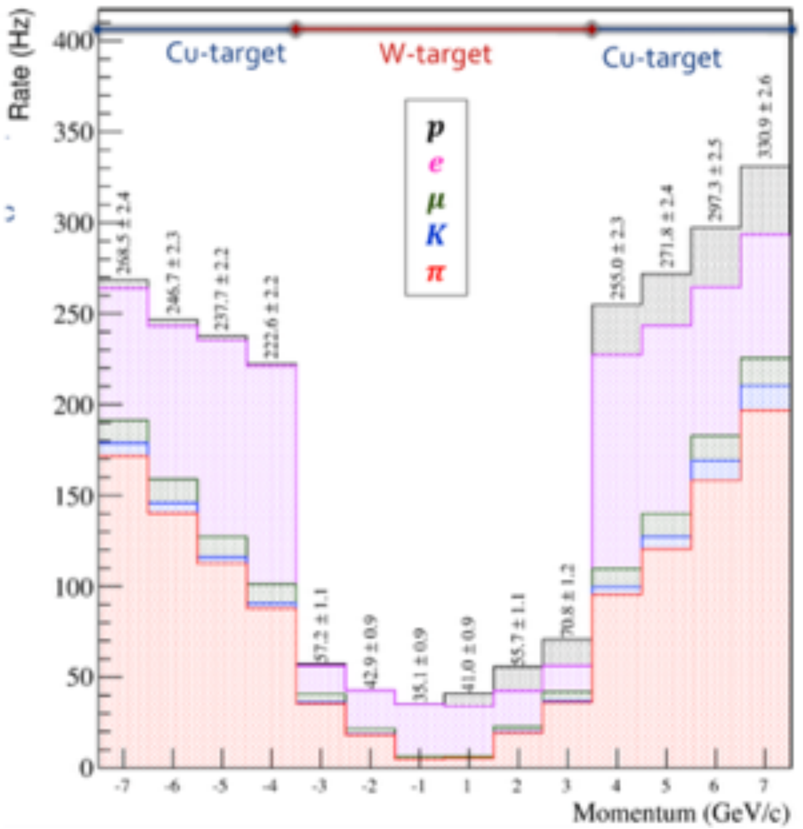


- DP Field Cage complete in April 2018
- Successful HV tests at 150 KV



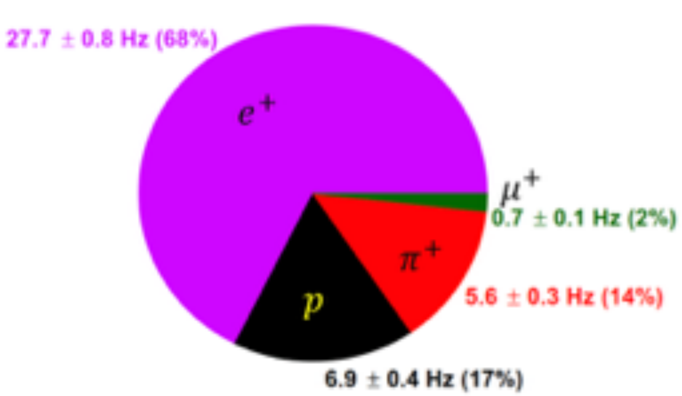
# The test beam

## Particle rates

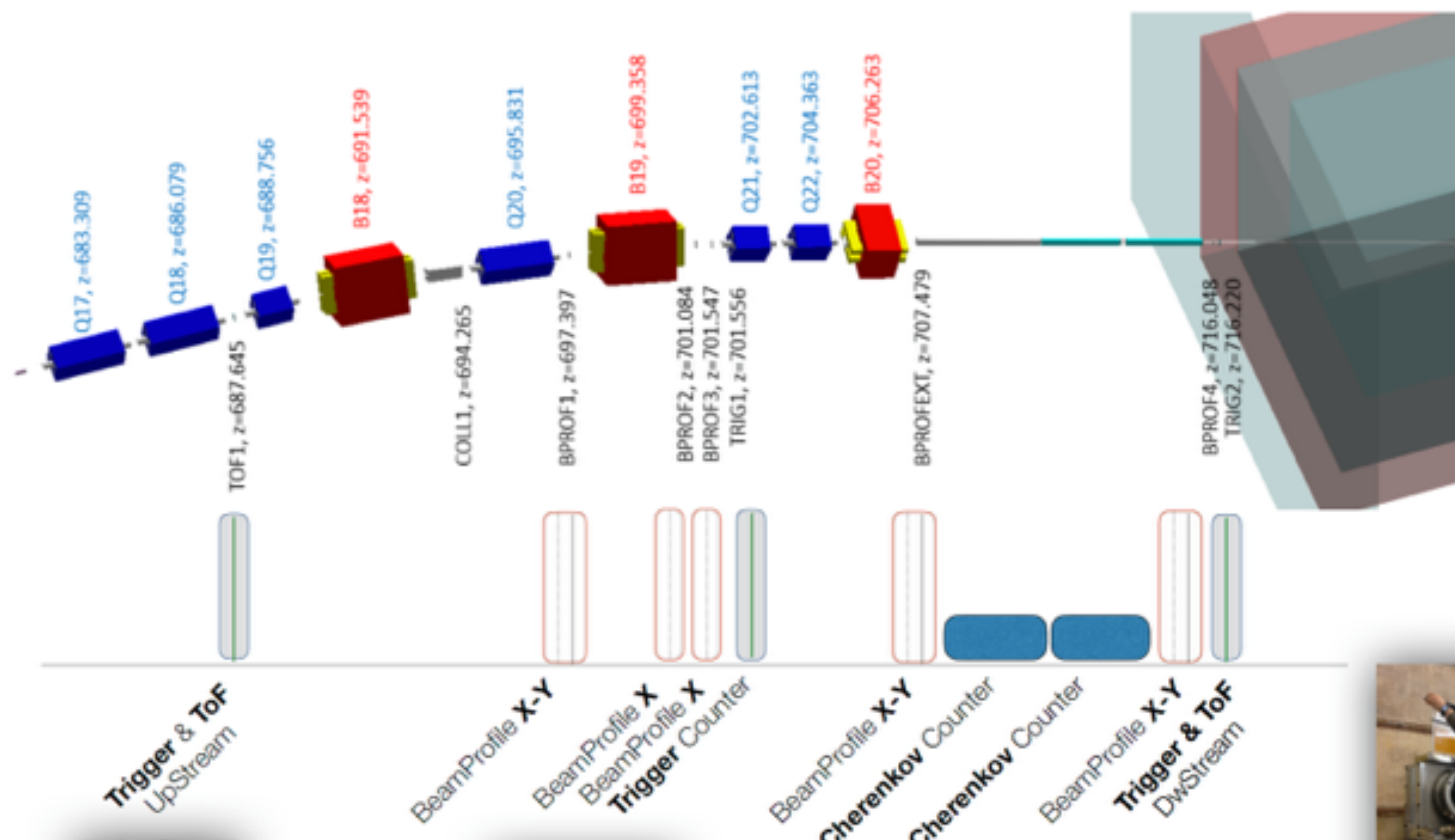


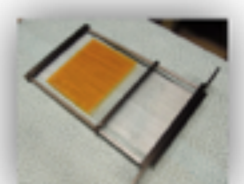

**Rates at 1 GeV/c**

Rate with Collimator




## Fully calibrated test-beam



NP04/H4 Beam Line & Beamline Detectors

**Blue: quadrupoles.**
**Red: bending magnets**

**Boxes: Beam detector supports**
Beam Profile X,Y = Scint. Fibre Tracker
Trigger & Time-of-Flight detector = 
= Scint. Fibre paddle

Cherenkov counters

# Timeline

**2018**

ProtoDUNEs at CERN

# Timeline

**2018**

ProtoDUNEs at CERN

**June-2018**

ProtoDUNE-SP installation completed

**Aug-2018**

ProtoDUNE-SP LAr filling

**Sep-Nov 2018**

ProtoDUNE-SP test beam

**Fall 2018**

ProtoDUNE-DP installation completed

# Timeline

**2018**
ProtoDUNEs at CERN

- **June-2018** — ProtoDUNE-SP installation completed
- **Aug-2018** — ProtoDUNE-SP LAr filling
- **Sep-Nov 2018** — ProtoDUNE-SP test beam
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**2019**
Technical Design Report

**2019**
Far Site Primary Excavation Begins

**2022**
First Module Installation Begins

**2026**
Neutrino Beam Available

# Timeline

**2018**
ProtoDUNEs at CERN

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ProtoDUNE-SP installation completed

**Aug-2018**
ProtoDUNE-SP LAr filling

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ProtoDUNE-SP test beam

**Fall 2018**
ProtoDUNE-DP installation completed

**2019**
Technical Design Report

**2019**
Far Site Primary Excavation Begins

**2022**
First Module Installation Begins

**2026**
Neutrino Beam Available

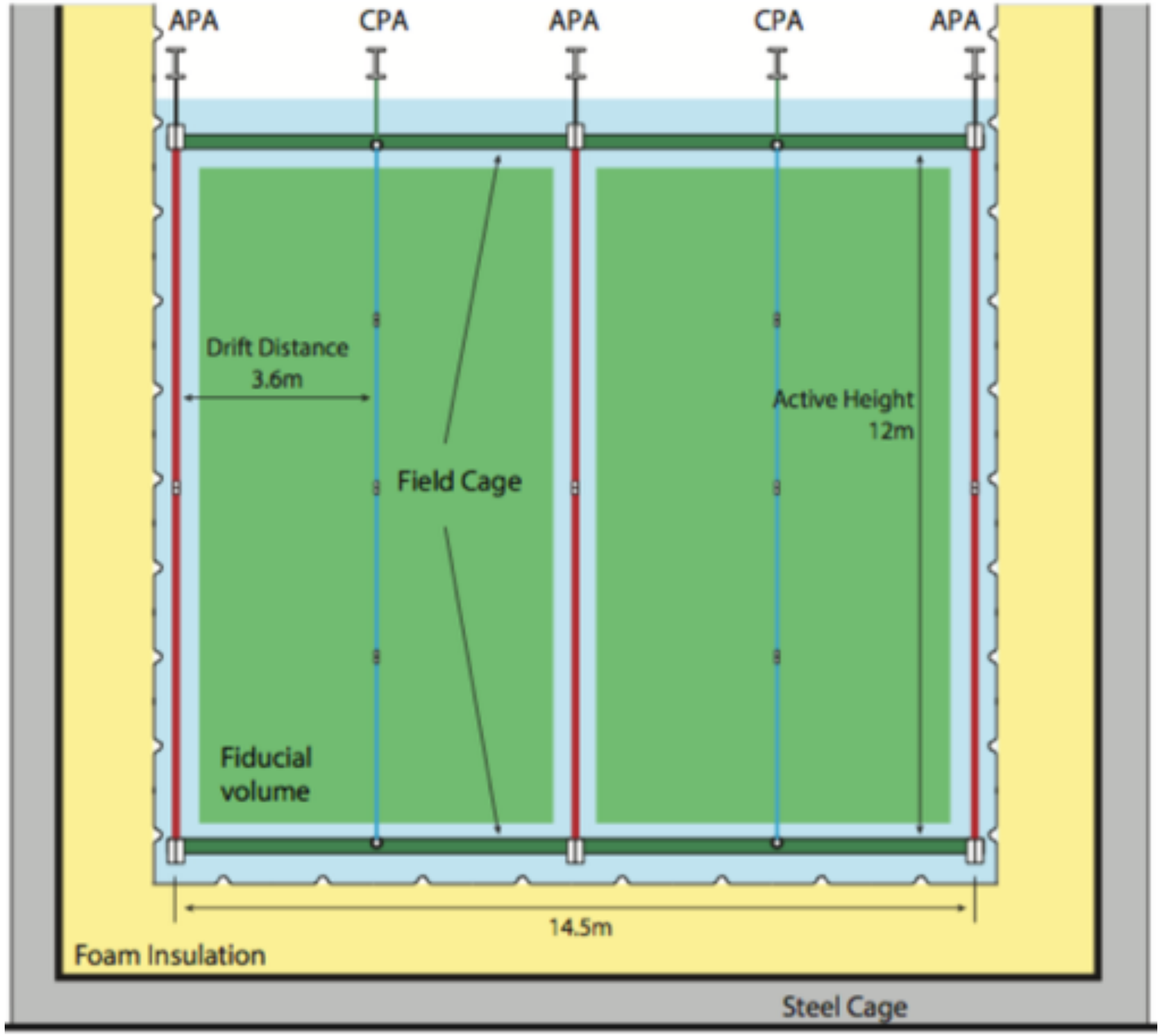
**Physics data as soon 1st module complete**
Atmospherics, SBN and solar neutrinos
Baryon number violation
Detector calibration

# Outlook

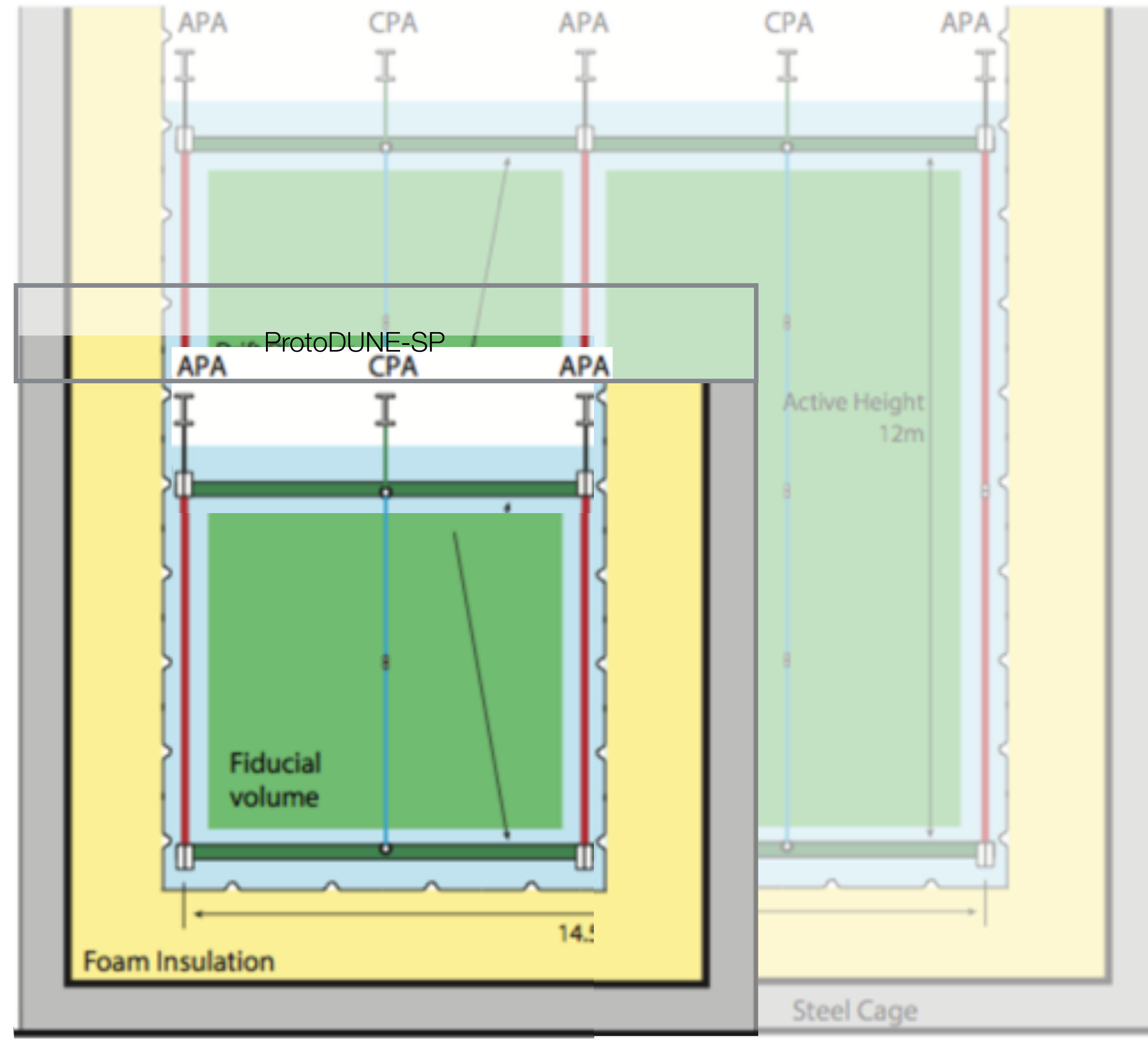
- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis
- New MC-based oscillation sensitivity analysis exceeds CDR-level sensitivity to CP violation
- First look at ProtoDUNE pre-commissioning data is very promising
- Look for DUNE Technical Design Report and ProtoDUNE SP and DP results in 2019
- Expect first DUNE FD data in ~2024...

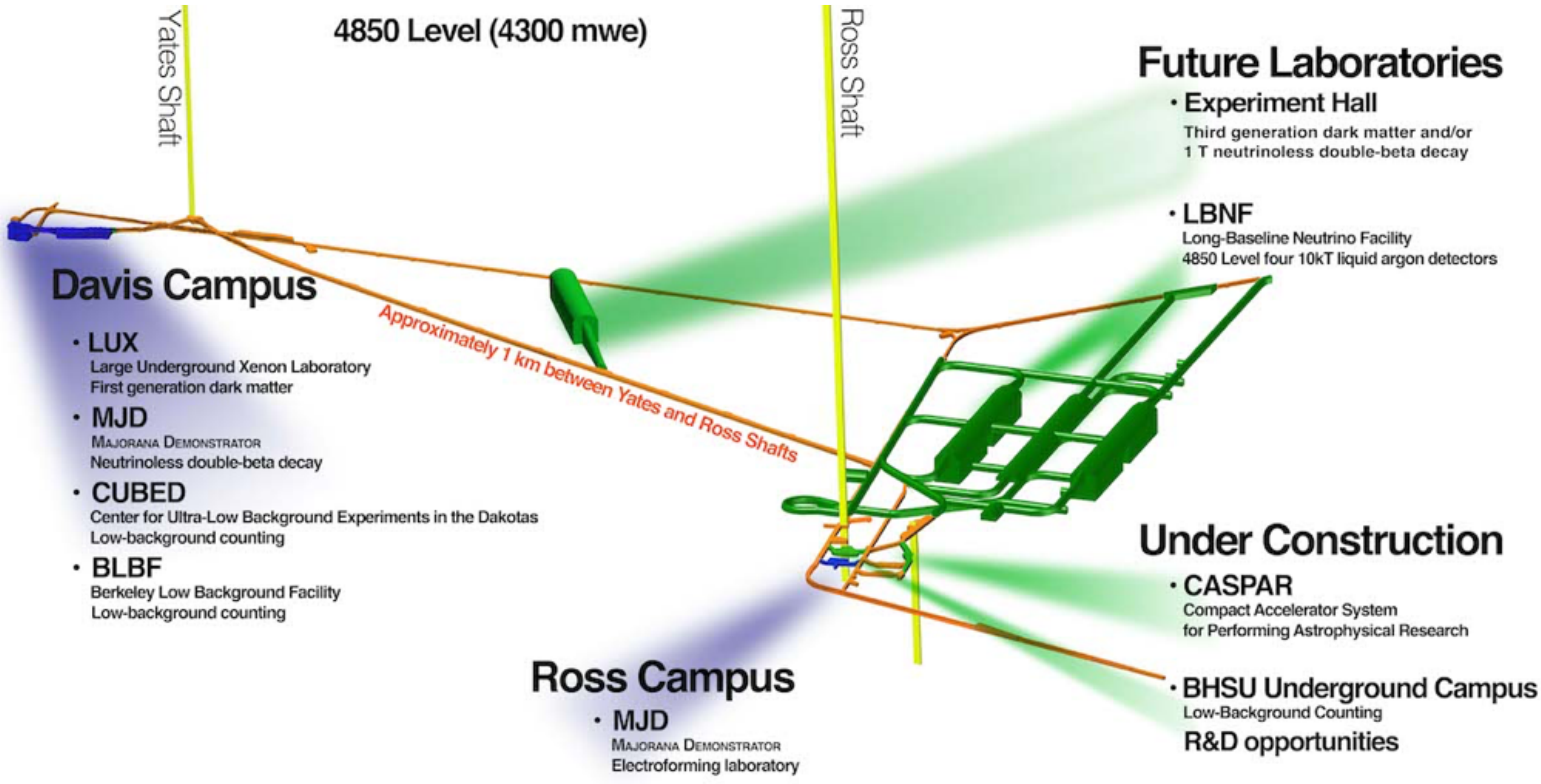
# BACKUP SLIDES

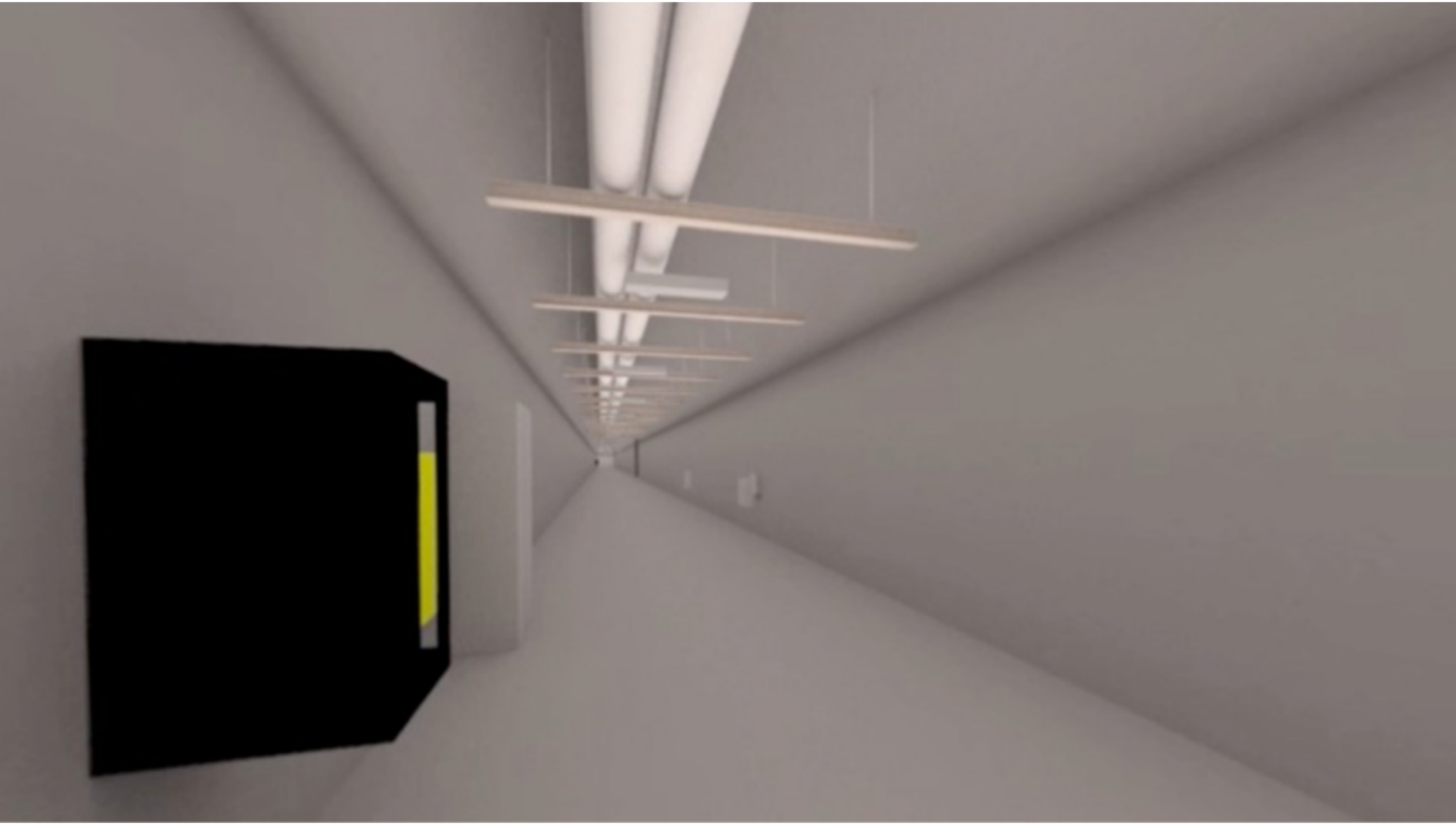
# ProtoDUNE en el CERN



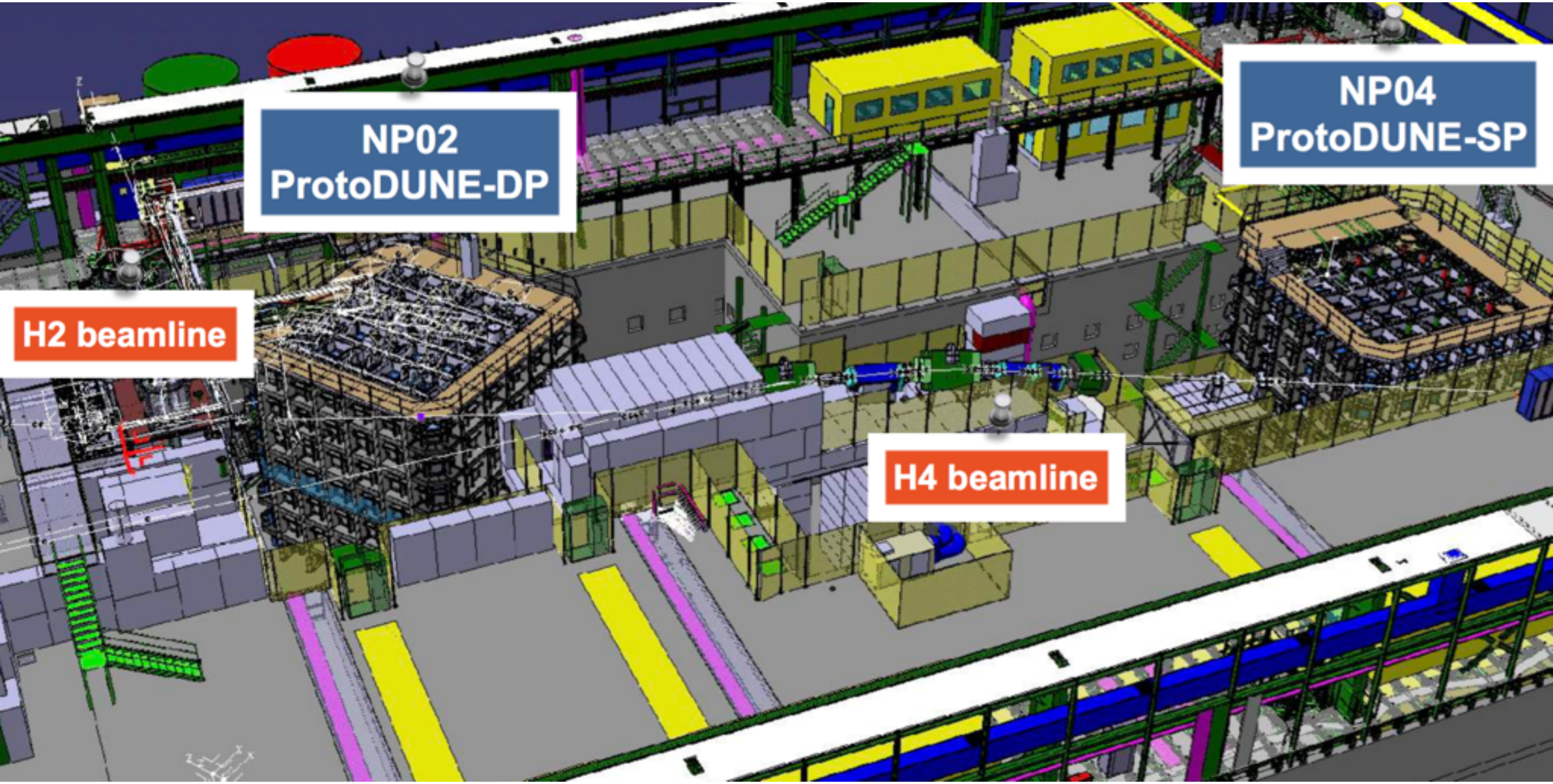
# ProtoDUNE en el CERN

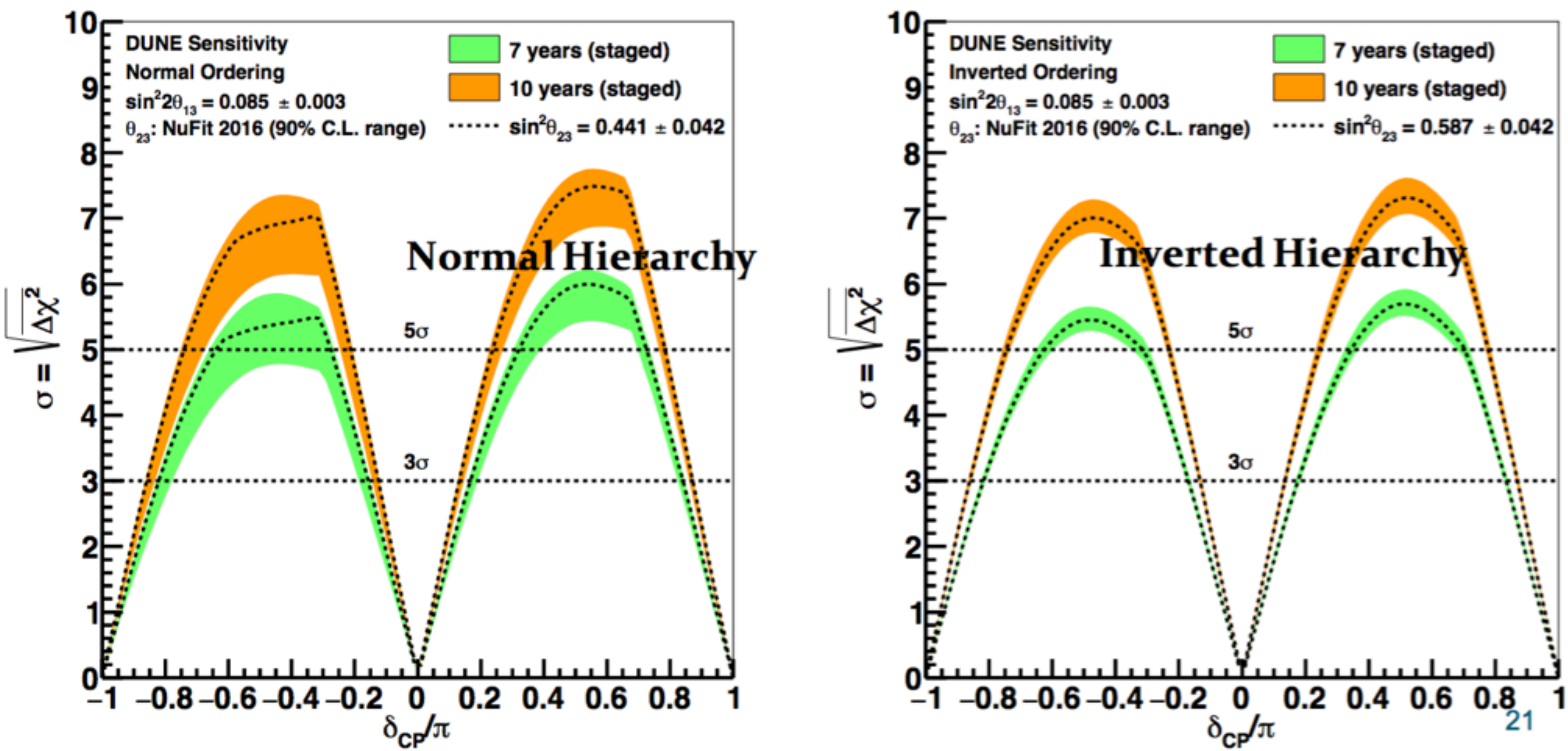



4850 Level (4300 mwe)
Yates Shaft
Ross Shaft
Future Laboratories
• Experiment Hall
Third generation dark matter and/or
1 T neutrinoless double-beta decay
• LBNF
Long-Baseline Neutrino Facility
4850 Level four 10kT liquid argon detectors
Davis Campus
• LUX
Large Underground Xenon Laboratory
First generation dark matter
• MJD
Majorana Demonstrator
Neutrinoless double-beta decay
• CUBED
Center for Ultra-Low Background Experiments in the Dakotas
Low-background counting
• BLBF
Berkeley Low Background Facility
Low-background counting
Approximately 1 km between Yates and Ross Shafts
Under Construction
• CASPAR
Compact Accelerator System
for Performing Astrophysical Research
• BHSU Underground Campus
Low-Background Counting
R&D opportunities
Ross Campus
• MJD
Majorana Demonstrator
Electroforming laboratory

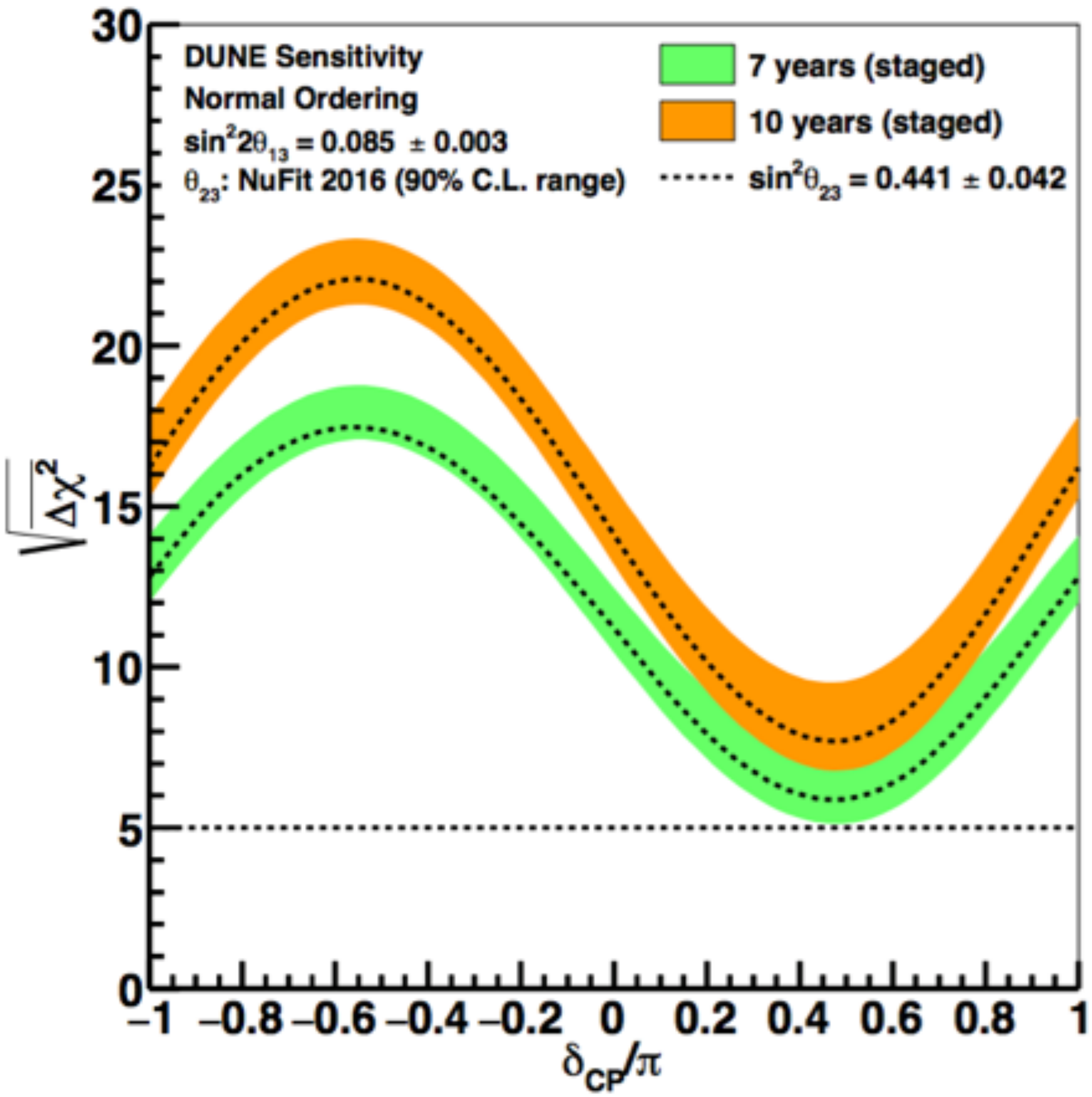


# Another view

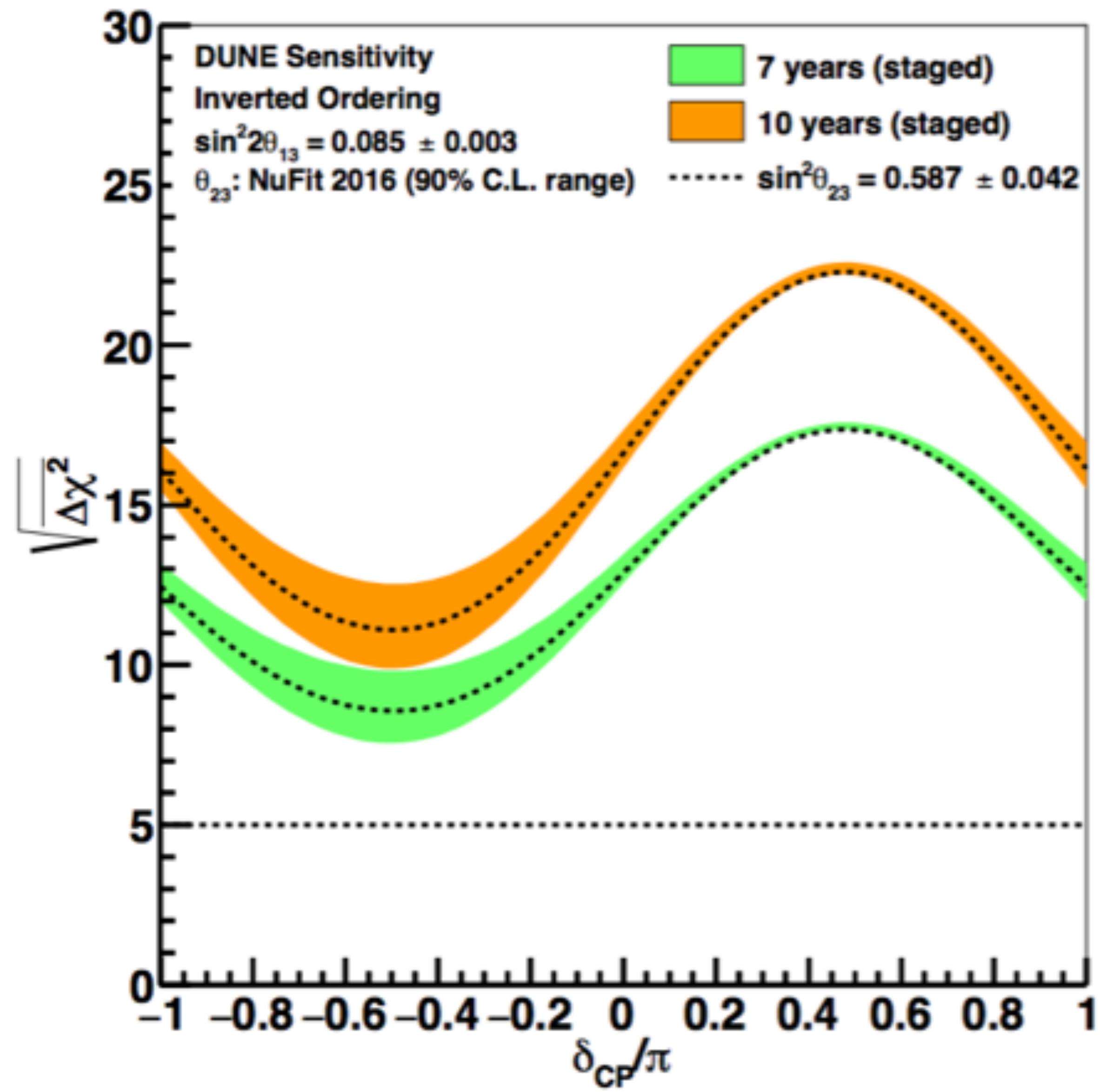



DUNE Sensitivity
Normal Ordering
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$
$\theta_{23}$: NuFit 2016 (90% C.L. range)
7 years (staged)
10 years (staged)
$\sin^2\theta_{23} = 0.441 \pm 0.042$
Normal Hierarchy
5σ
3σ
$\sigma = \sqrt{\Delta\chi^2}$
$\delta_{CP}/\pi$
DUNE Sensitivity
Inverted Ordering
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$
$\theta_{23}$: NuFit 2016 (90% C.L. range)
7 years (staged)
10 years (staged)
$\sin^2\theta_{23} = 0.587 \pm 0.042$
Inverted Hierarchy
5σ
3σ
$\sigma = \sqrt{\Delta\chi^2}$
$\delta_{CP}/\pi$
21

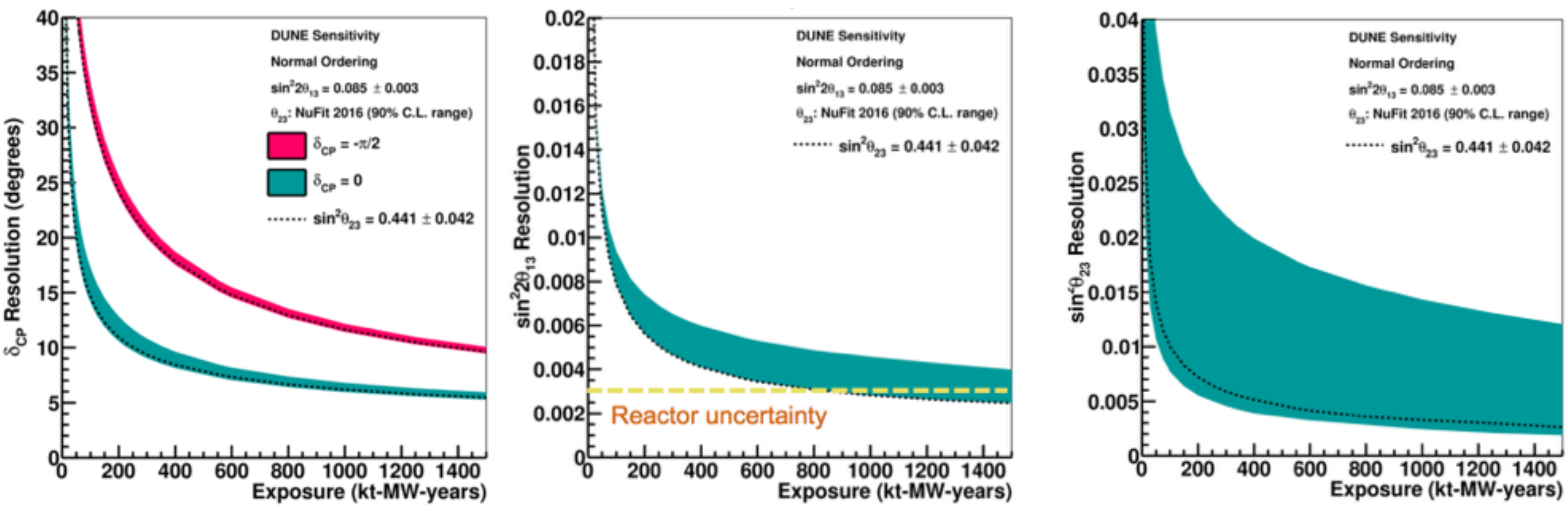
## Normal ordering




## Inverted ordering



# Resolution



DUNE Sensitivity
Normal Ordering
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$
$\theta_{23}$: NuFit 2016 (90% C.L. range)
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\sin^2\theta_{23} = 0.441 \pm 0.042$
$\delta_{CP}$ Resolution (degrees)
$\sin^2 2\theta_{13}$ Resolution
$\sin^2\theta_{23}$ Resolution
Reactor uncertainty
Exposure (kt-MW-years)

# DUNE/LBNF Staging Assumption

Year 1 (2026): 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints

Year 2 (2027): 30-kt FD

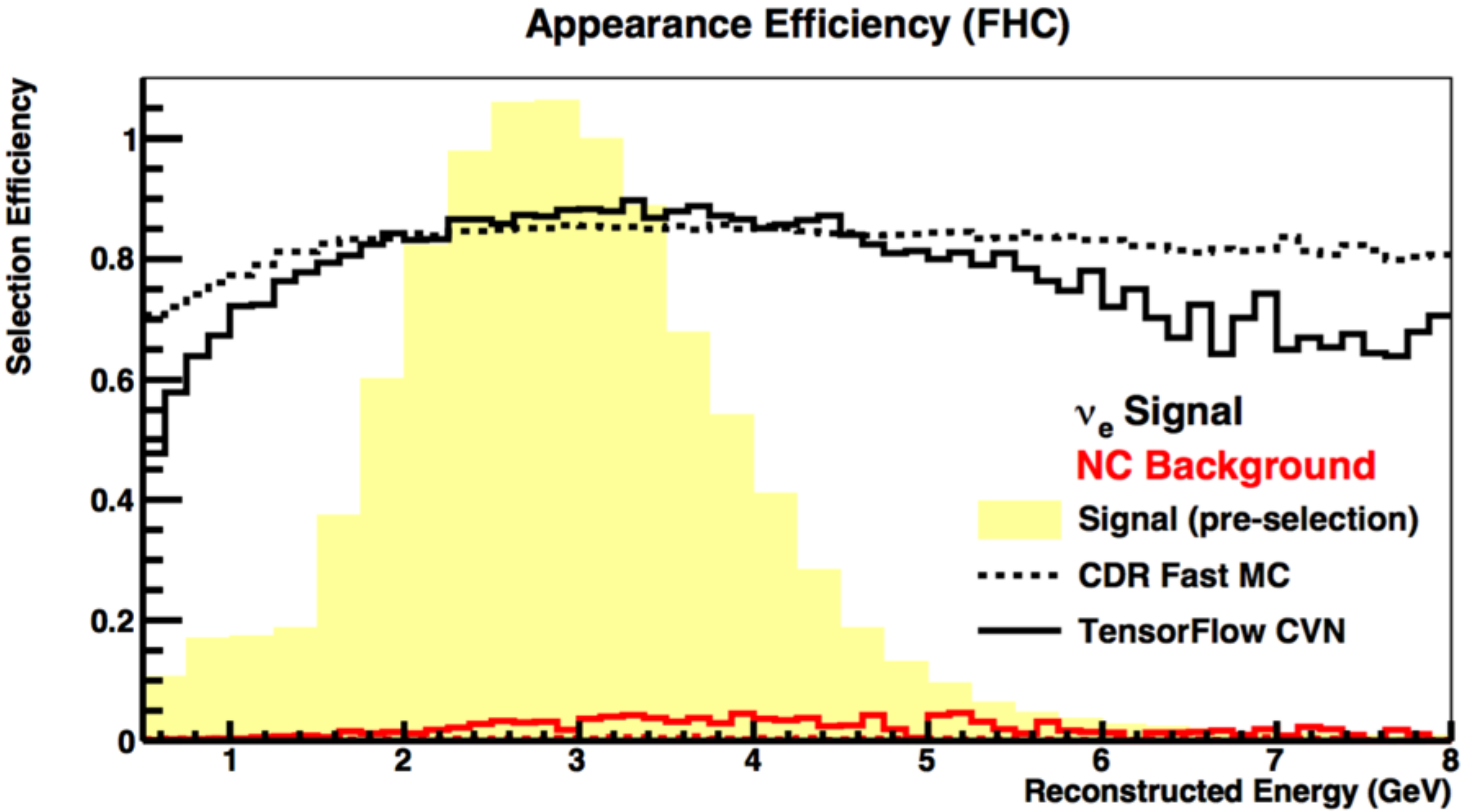
Year 4 (2029): 40-kt FD and improved ND constraints

Year 7 (2032): upgrade to 2.14 MW (80-GeV) beam

| Exposure Years | Number of FD modules | Total FD target mass (kt) | LBNF beam power (MW) | Exposure (kt MW yr) |
|---|---|---|---|---|
| 1 | 2 | 20 | 1.07 | 21 |
| 2 | 3 | 30 | 1.07 | 54 |
| 4 | 4 | 40 | 1.07 | 128 |
| 7 | 4 | 40 | 2.14 | 300 |
| 10 | 4 | 40 | 2.14 | 556 |

Staging scenario assumes equal $\nu$ and $\bar{\nu}$ running time

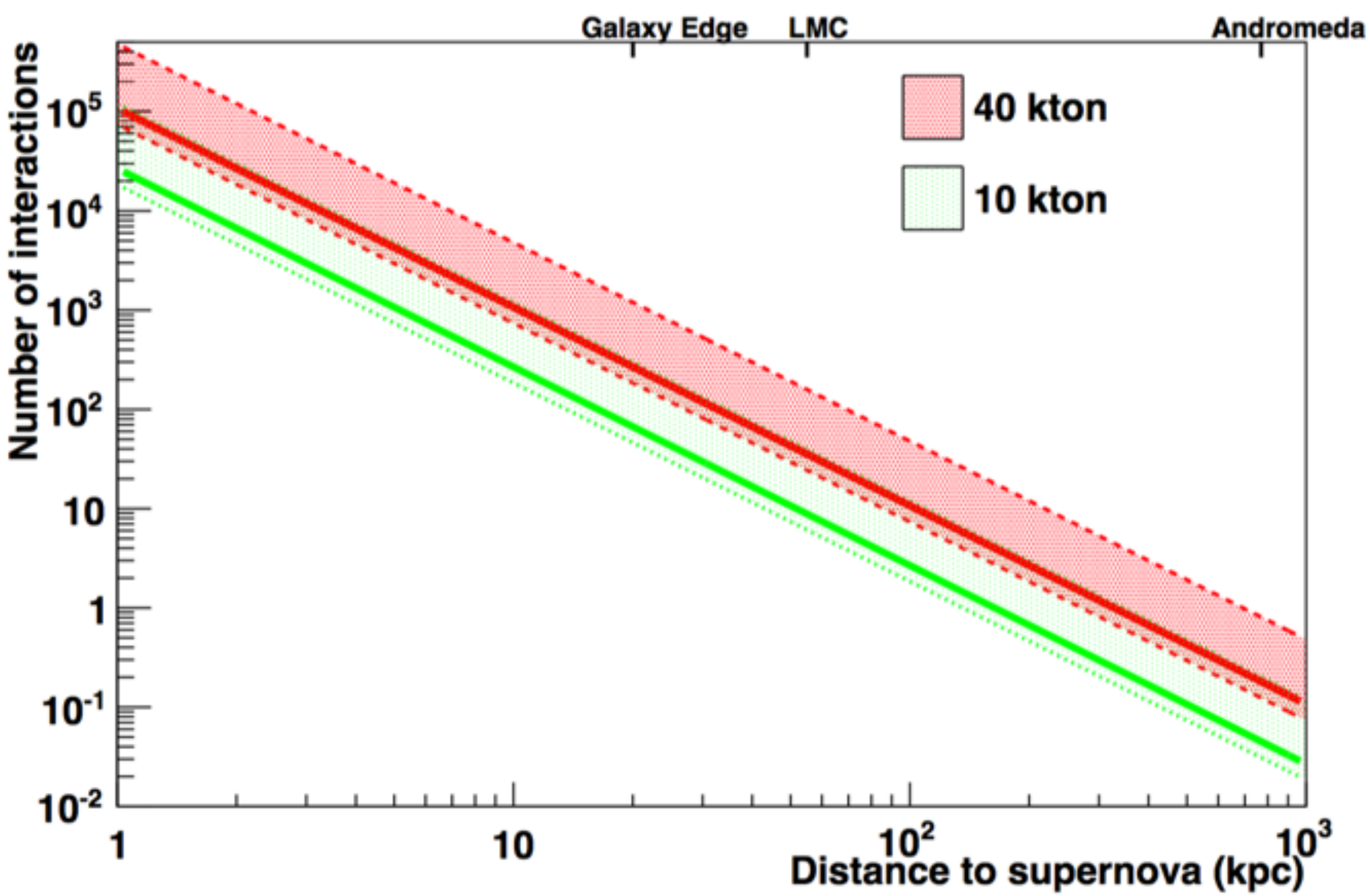
# Selection efficiency




CVN $\nu_e$ event selection efficiency similar to that from CDR Fast MC

# Supernova event rates

- Expected total ν signal from SNOwGLoBES). Solid lines are from Huedepohl (2010), for both 10 kt and the full 40 kt DUNE: systematic bands are from the Garching parameterization (2014) of <E>=12 MeV and <E>=2 (top) and <E>=8 MeV and <E>=6 (bottom).



# SNB event rates

Table 5.1: Event rates for different supernova models in 40 kt of liquid argon for a core collapse at 10 kpc, for $\nu_e$ and $\bar{\nu}_e$ charged-current channels and elastic scattering (ES) on electrons. Event rates will simply scale by active detector mass and inverse square of supernova distance. The "Livermore" model assumes no oscillations; "GKVM" assumes collective oscillation effects. Oscillations (both standard and "collective") will potentially have a large, model-dependent effect.

| **Channel** | Events "Livermore" model | Events "GKVM" model |
|---|---|---|
| $\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$ | 2720 | 3350 |
| $\bar{\nu}_e + ^{40}\mathrm{Ar} \rightarrow e^+ + ^{40}\mathrm{Cl}^*$ | 230 | 160 |
| $\nu_x + e^- \rightarrow \nu_x + e^-$ | 350 | 260 |
| Total | 3300 | 3770 |

- **Engineering Run:**
  - Beam-line detectors activation and DAQ sync,
  - Beam Trigger activation/test/debug,
  - Secondary (Pion) Beam Intensity Tuning (measure/mitigation Muon Halo in LArTPC) ⇨ StartUp Physics Run

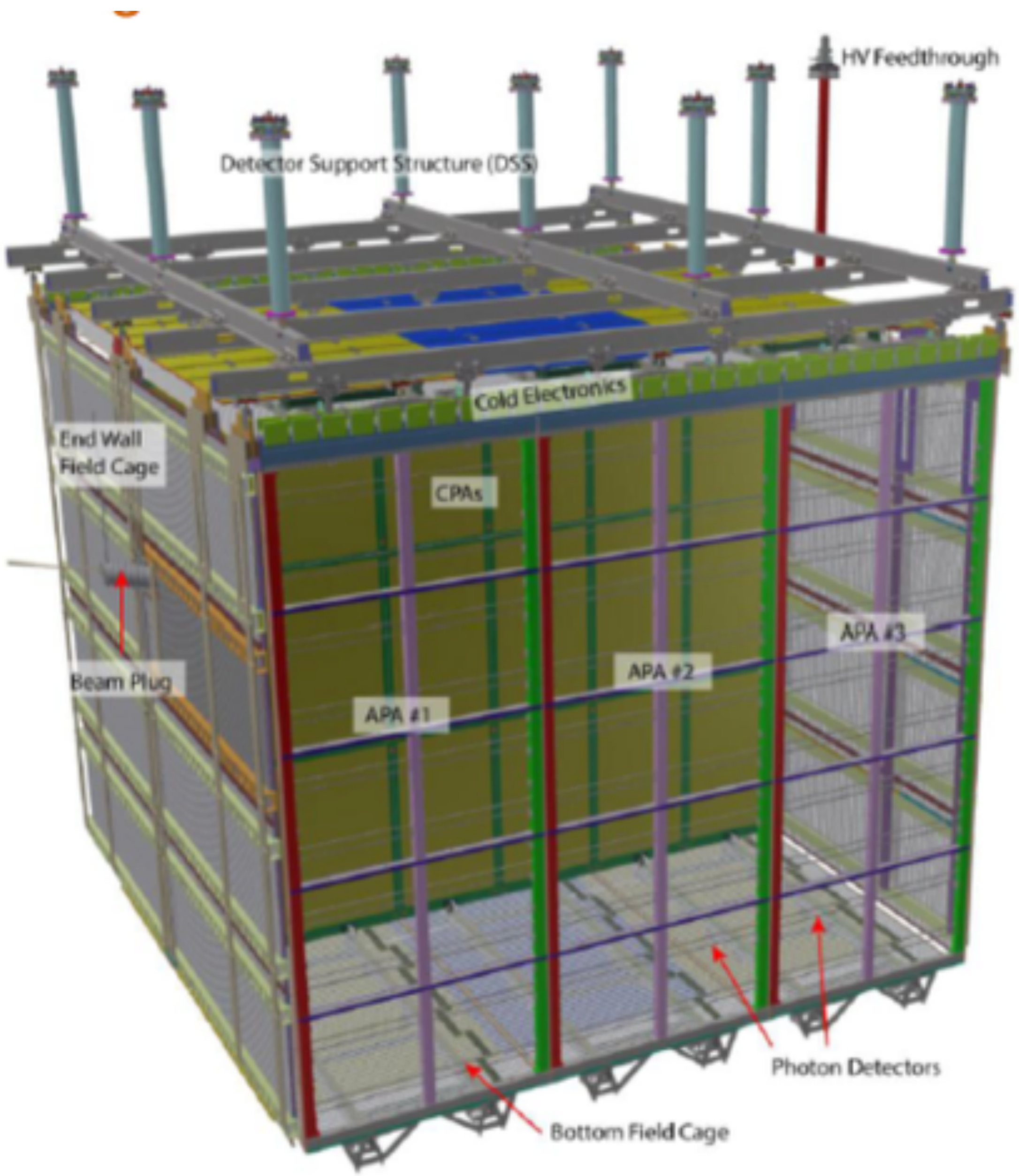
| Beam Setting (Mom, Sign) | Beam Rate | | Beam Time |
|---|---|---|---|
| 2 GeV/c – Negative | 27 Hz | 50% π-, 50% e- | **1 week** |

- **Physics Run** **[expected 3000 spill/day]:**
  - ➡Hadron Beam - Goals:
    ≥ 500 k Pion evt per momentum setting
    ≥ 100 k Proton evt per momentum setting
  - ➡Electron Beam - Goal:
    ≥ 75 k Electron evt per energy setting

| | Hadron Beam | *Cu Target* | |
|---|---|---|---|
| **Beam Setting (Mom, Sign)** | **Accumul. Stat. (goal)** | **Trig. Rate/Beam Rate** | **Beam Time** |
| **2 GeV/c - Positive** | 750 k [500 k π] | 25 Hz / 38 Hz | **1 week** |
| **3 GeV/c - Positive** | 750 k [500 k π] | 25 Hz / 56 Hz | |
| **no beam** | - | - | 1 week |
| **1 GeV/c - Positive** | 1 M [500 k π] | 25 Hz / 27 Hz | **2 week** |
| **no beam** | - | - | 1 week |
| **4 GeV/c - Positive** | 600 k [500 k π] | 25 Hz / 196 Hz | **2 week** |
| **5 GeV/c - Positive** | 600 k [500 k π] | 25 Hz / 200 Hz | |
| **6 GeV/c - Positive** | 600 k [500 k π] | 25 Hz / 226 Hz | |
| **7 GeV/c - Positive** | 600 k [500 k π] | 25 Hz / 252 Hz | |
| **no beam** | - | - | 1 week |
| | **Electron Beam** | ***Pb Target*** | |
| **Energy Ramp: 0.5, 0.6, 0.7, 0.8, 0.9, 1., 2., 3., 4., 5., 6., 7. GeV** | 75 k per En. setting<br>900 k Tot. | 25 Hz / 60 Hz | **1.5 week** |

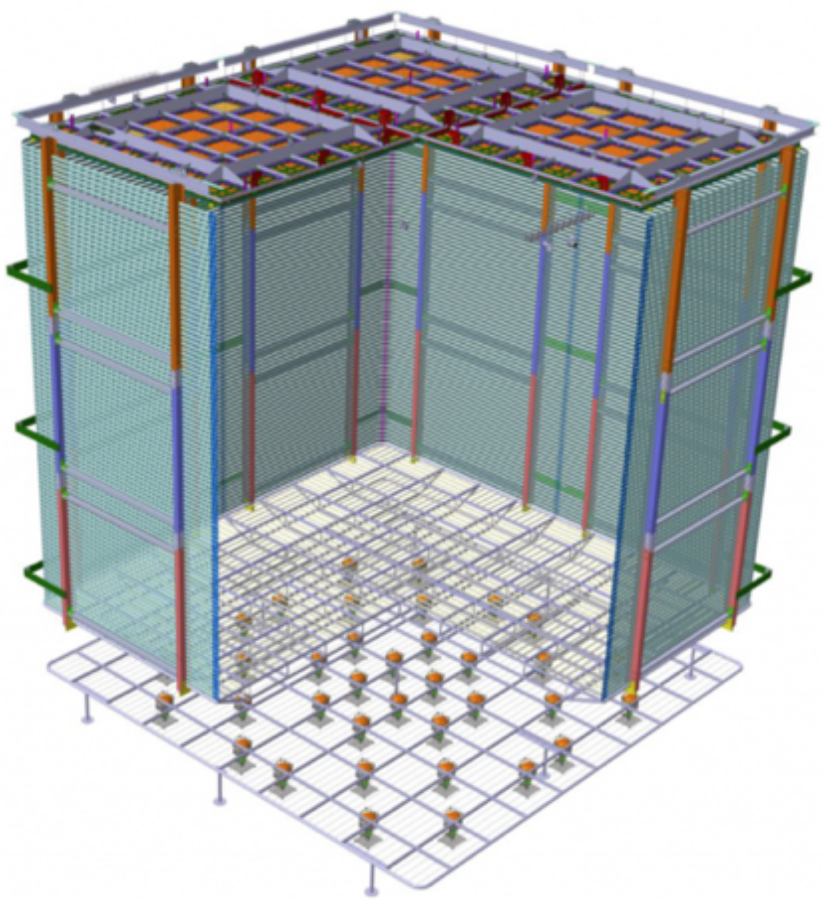
## Single-Phase

horizontal drift



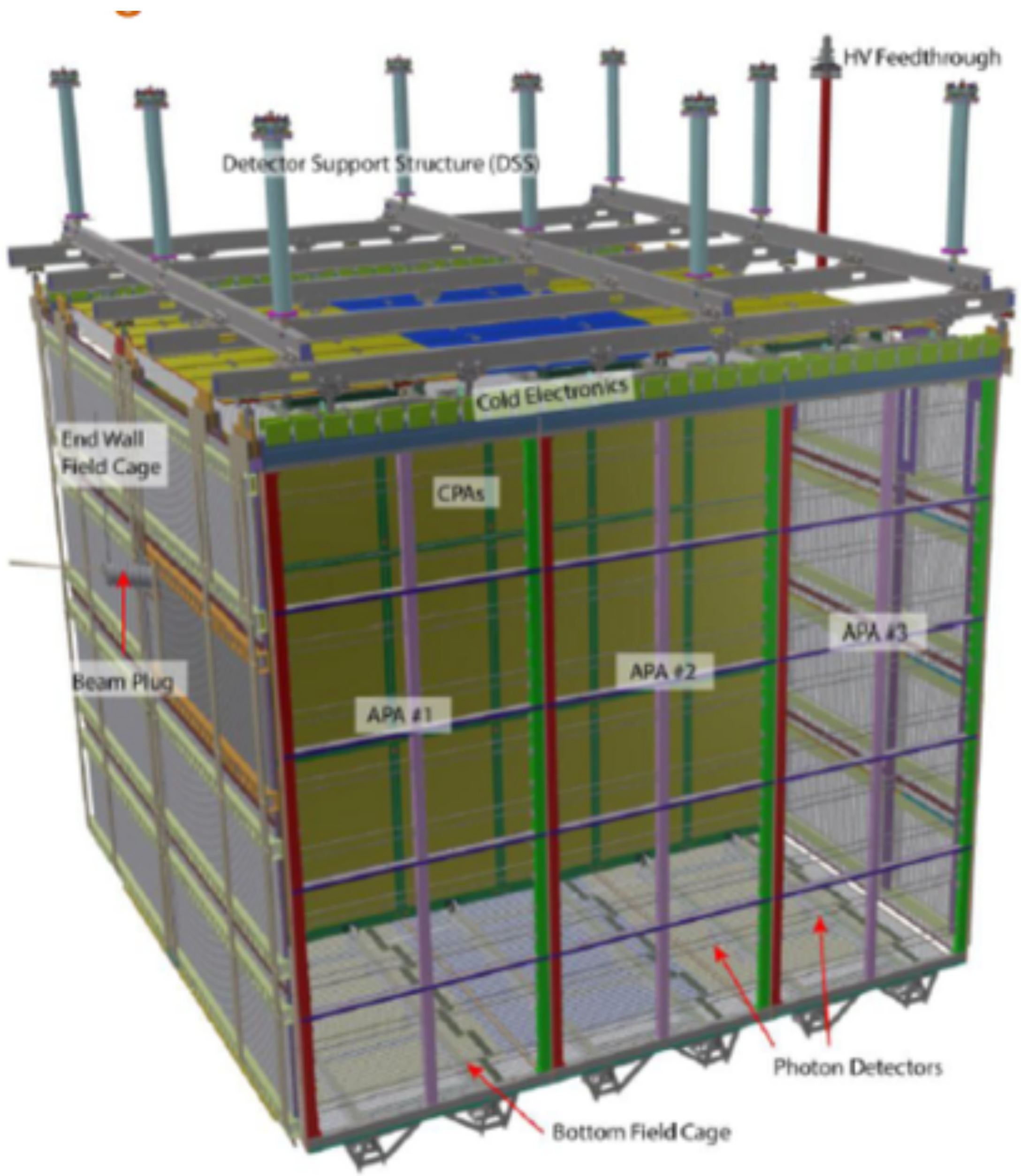

## Dual-Phase

vertical drift



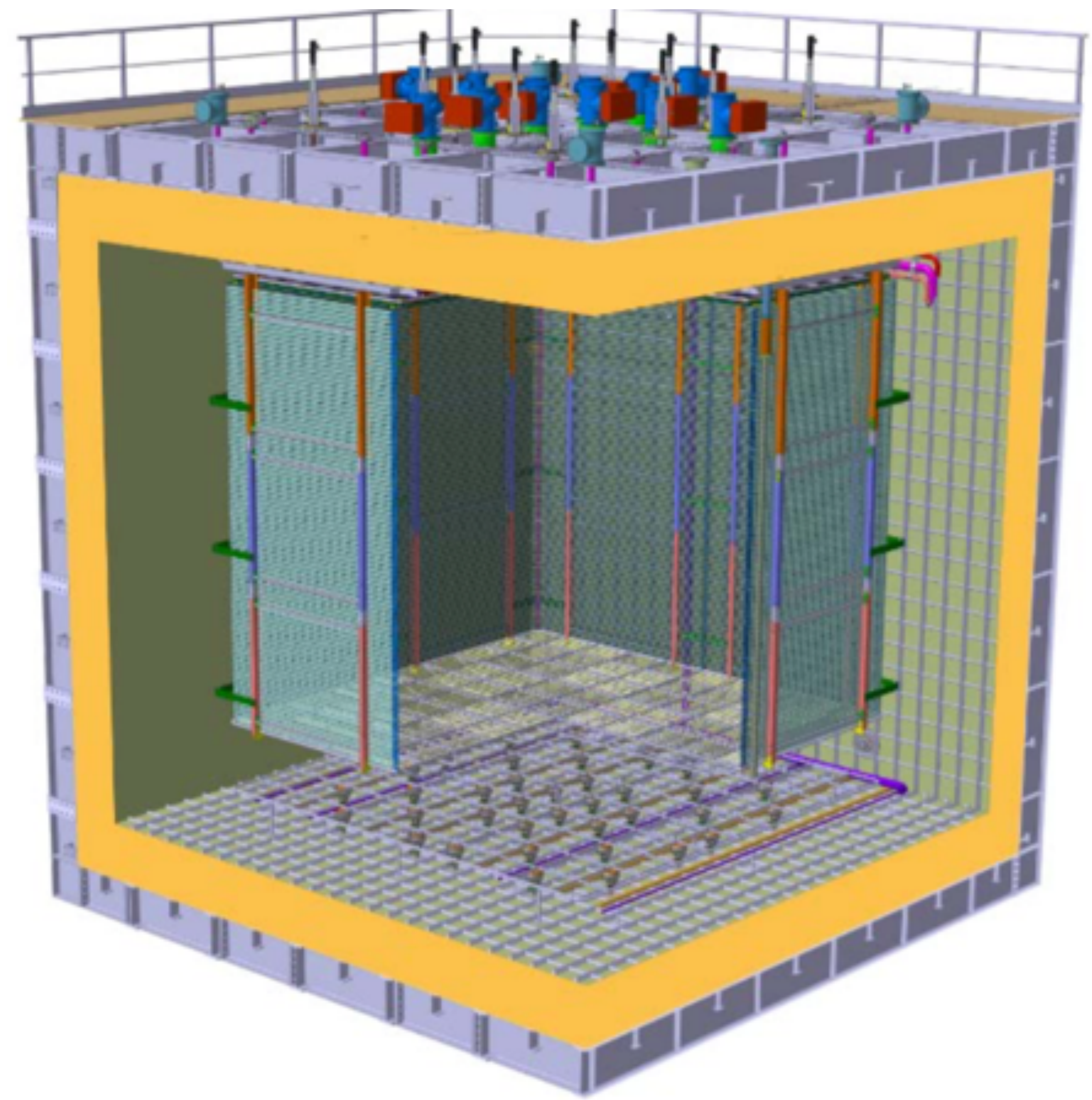
## Single-Phase

horizontal drift




## Dual-Phase

vertical drift



**Total Uncertainties Assigned to the Normalization Parameters**

Based on the preceding considerations, the DUNE signal normalization uncertainty is taken to be $5\% \oplus 2\%$ in both neutrino and antineutrino mode, where 5% is the normalization uncertainty on the FD $\nu_\mu$ sample and 2% is the effective uncorrelated uncertainty on the FD $\nu_e$ sample after fits to both near and far detector data and all external constraints. These signal normalization parameters are treated as 100% uncorrelated between neutrinos and antineutrinos. The normalization uncertainties on background to these samples and their respective correlations are given in Table 3.9. These assumptions for the non-oscillation systematic uncertainties are used to calculate the sensitivities presented in Section 3.2. The goal for the *total* uncertainty on the $\nu_e$ sample in DUNE is less than 4%, so the $5\% \oplus 2\%$ signal normalization uncertainty used for sensitivity calculations is appropriately conservative. Additionally, cancellation of the correlated portion of the uncertainty is expected in the four-sample fit, so the residual uncorrelated normalization uncertainty on the $\nu_e$ sample is expected to be reduced to the 1–2% level, such that the 2% residual normalization uncertainty used in the sensitivity calculations is also well-justified. Variations on these assumptions are explored in Section 3.6.3.

Table 3.9: Normalization uncertainties and correlations for background to the $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, and $\bar{\nu}_\mu$ data samples

| **Background** | Normalization Uncertainty | Correlations |
|---|---|---|
| For $\nu_e/\bar{\nu}_e$ appearance: | | |
| Beam $\nu_e$ | 5% | Uncorrelated in $\nu_e$ and $\bar{\nu}_e$ samples |
| NC | 5% | Correlated in $\nu_e$ and $\bar{\nu}_e$ samples |
| $\nu_\mu$ CC | 5% | Correlated to NC |
| $\nu_\tau$ CC | 20% | Correlated in $\nu_e$ and $\bar{\nu}_e$ samples |
| For $\nu_\mu/\bar{\nu}_\mu$ disappearance: | | |
| NC | 5% | Uncorrelated to $\nu_e/\bar{\nu}_e$ NC background |
| $\nu_\tau$ | 20% | Correlated to $\nu_e/\bar{\nu}_e$ $\nu_\tau$ background |

# Systematics

| Source of Uncertainty | MINOS $\nu_e$ | T2K $\nu_e$ | DUNE $\nu_e$ | Comments |
|---|---|---|---|---|
| Beam Flux after N/F extrapolation | 0.3% | 3.2% | 2% | See "Flux Uncertainties" in Section 3.6.2 |
| Interaction Model | 2.7% | 5.3% | $\sim 2\%$ | See "Interaction Model Uncertainties" in Section 3.6.2 |
| Energy scale ($\nu_\mu$) | 3.5% | included above | (2%) | Included in 5% $\nu_\mu$ sample normalization uncertainty in DUNE 3-flavor fit. |
| Energy scale ($\nu_e$) | 2.7% | 2.5% includes all FD effects | 2% | See "$\nu_e$ Energy-Scale Uncertainties" in Section3.6.2 |
| Fiducial volume | 2.4% | 1% | 1% | Larger detectors = smaller uncertainty. |
| Total | 5.7% | 6.8% | 3.6 % | |
| Used in DUNE Sensitivity Calculations | | | $5\% \oplus 2\%$ $\nu_\mu$ $\nu_e$ | Residual $\nu_e$ uncertainty: 2% |