DUNE:
the Far Detector

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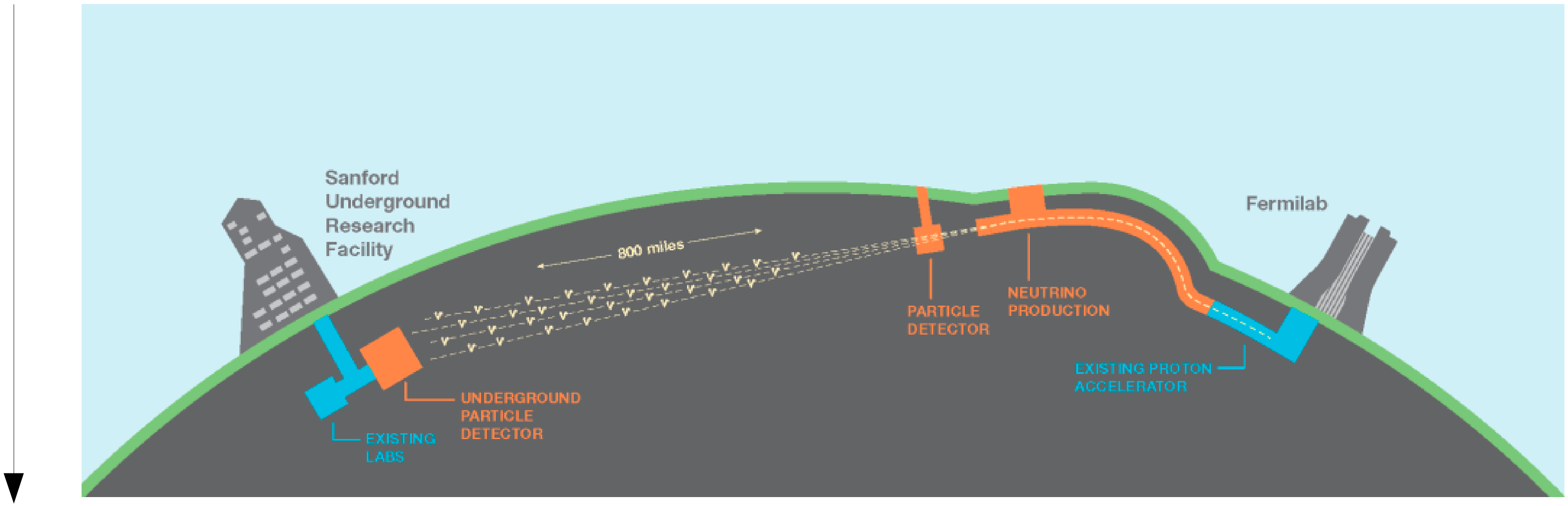
TAUP 2017
Sudbury – Canada
July/26/2017

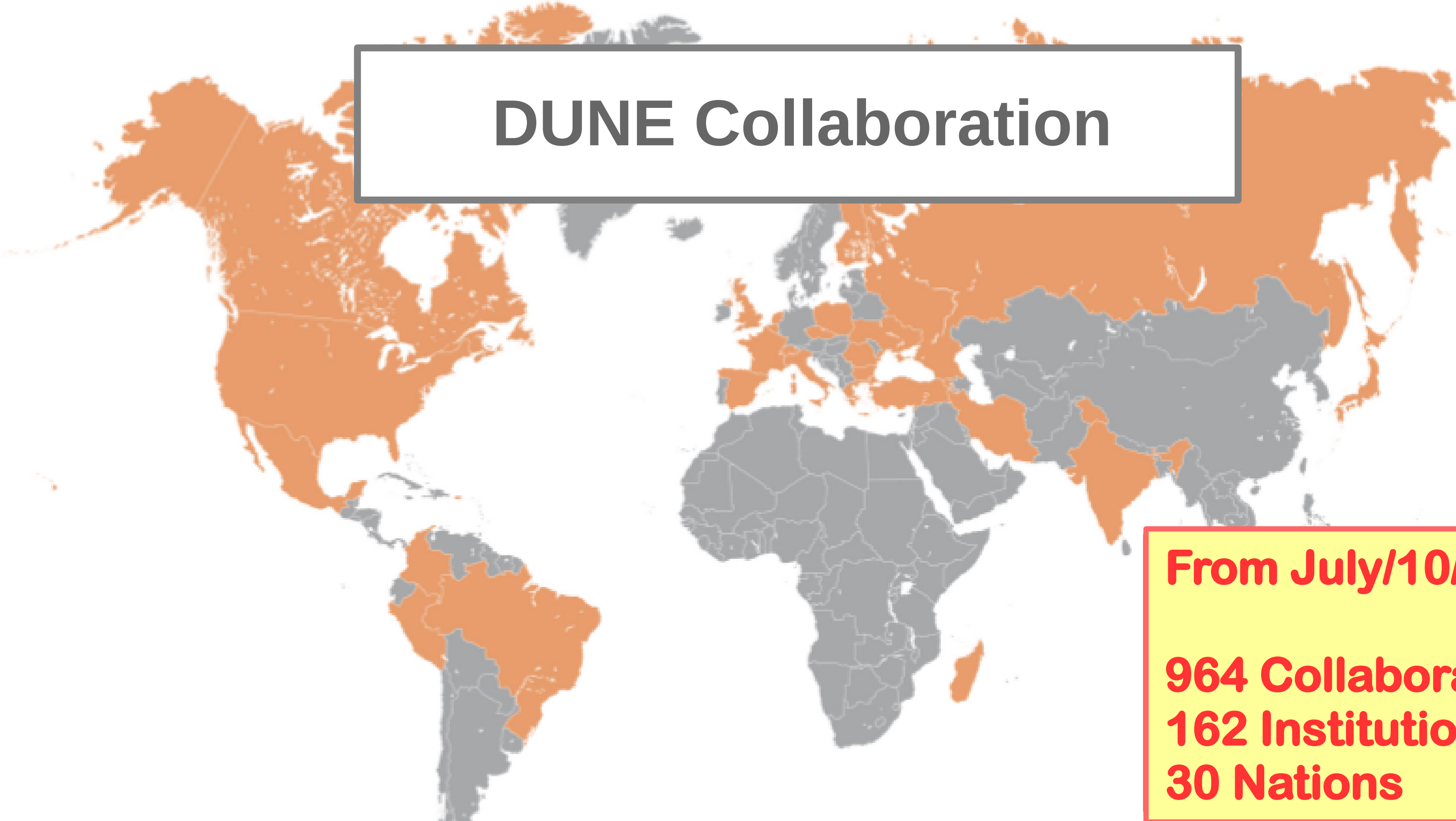
DUNE mission and concept

- What is the origin of the matter-antimatter asymmetry in the universe?
- What are the fundamental underlying symmetries of the universe?
- Is there a Grand Unified Theory of the Universe?
- How do supernovae explode? New physics from a neutrino burst?



- ✓ New neutrino beam facility at Fermilab
- ✓ A highly capable Near Detector at Fermilab to measure the unoscillated neutrino spectrum and flux constraints
- ✓ A large LArTPC deep underground at SURF (Lead (SD) 1300 km baseline) to measure oscillations and non-beam physics
- ✓ Exposure of ~10 years to ν / $\bar{\nu}$ modes (50% / 50%)

DUNE Collaboration



From July/10/2017:

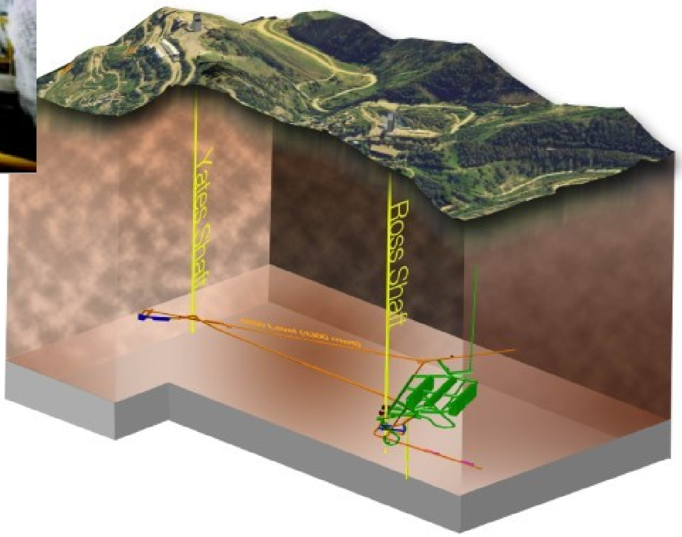
964 Collaborators
162 Institutions
30 Nations

Sanford Underground Research Facility - SURF

The US is keeping open the use of Homestake (SD) for ν, DM & 0νββ

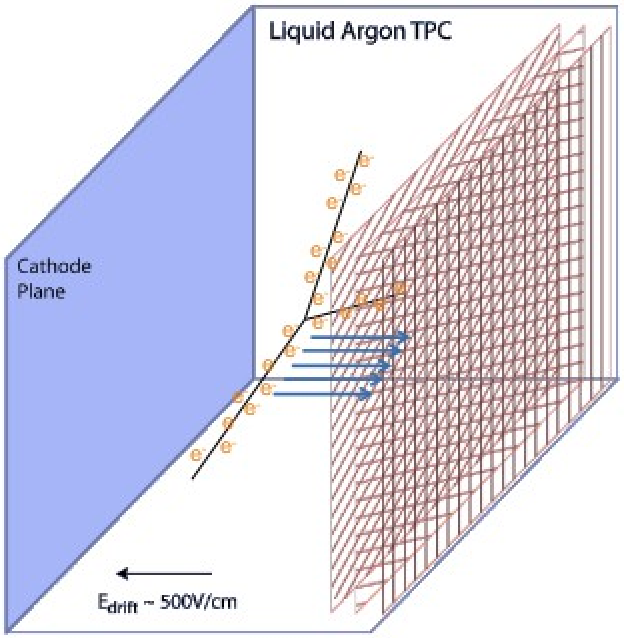
- External Buildings and shaft access
- Halls @ 1480 m deep
- Majoron (0νββ) and LUX (DM) experiments

- Layout of underground experimental hall



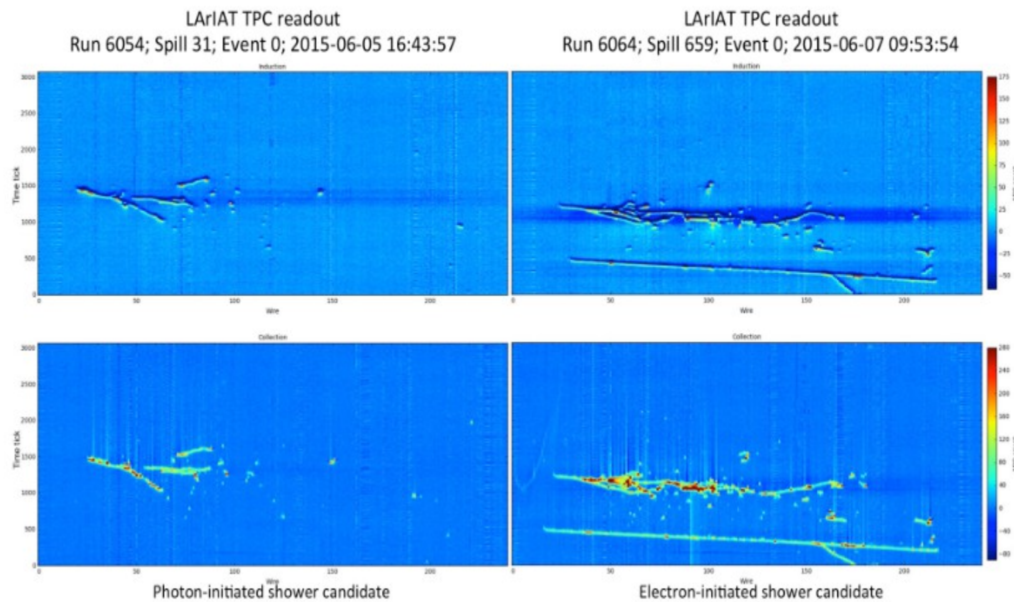
More details on Jaret Heise's next talk

LArTPC: the Far Detector technology



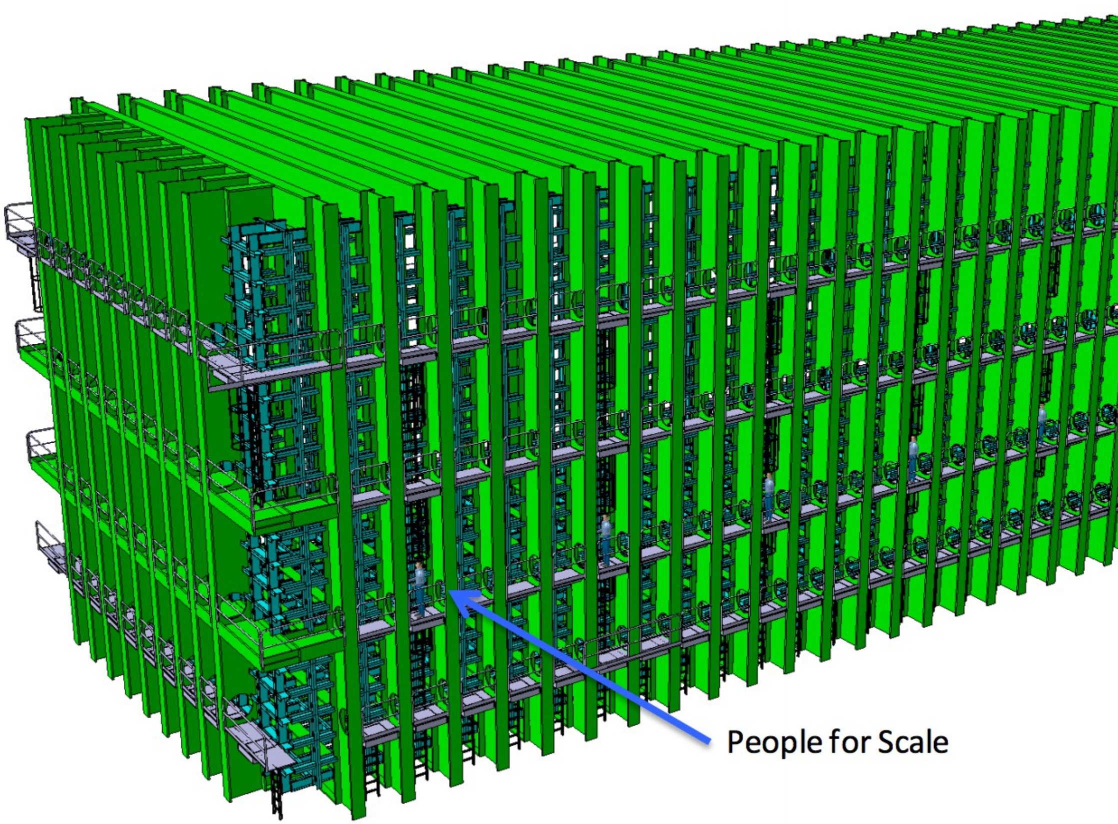
- Ionization charge drifts to finely segmented collection planes.
- Scintillator light detected for drift time.

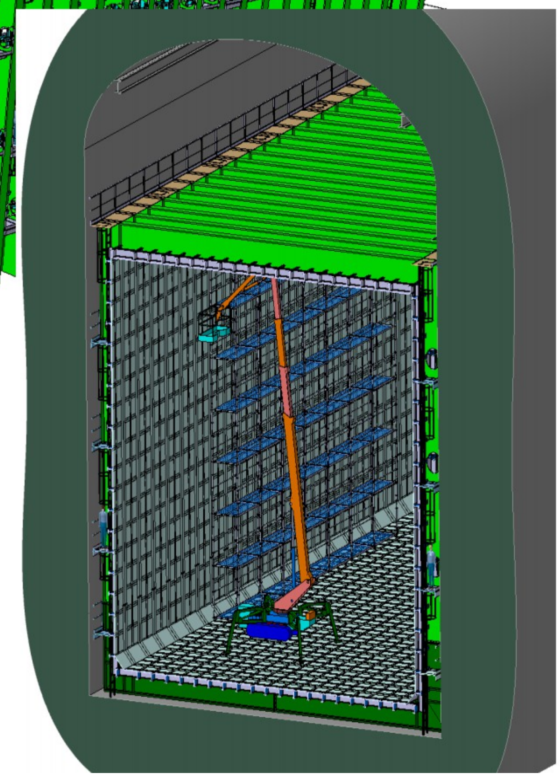
- High resolution data.
- High event selection efficiency and excellent background rejection.



Far Detector: LArTPC

Free-Standing Steel Cryostat





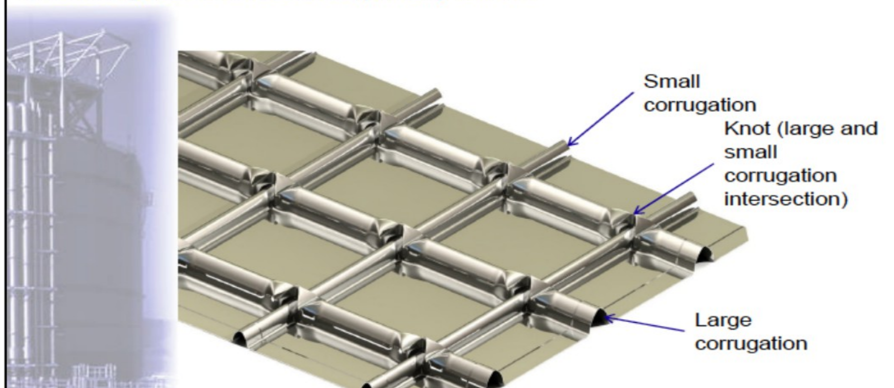
<u>External (Internal) Dimensions</u>

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

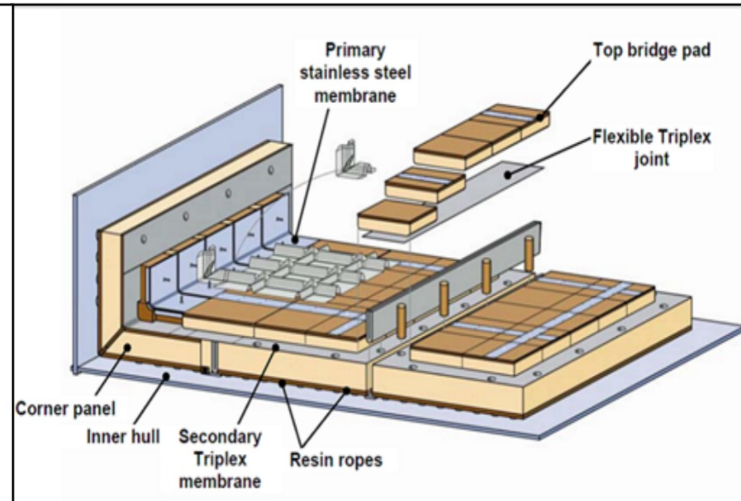
Far Detector: LArTPC

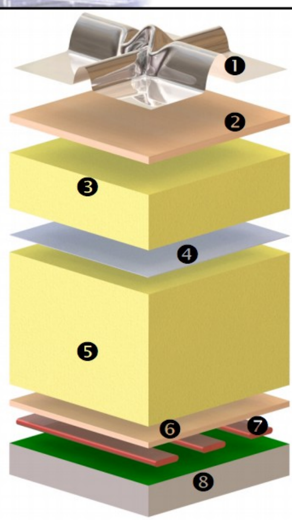
Design Scope – Membrane Cryostat

The corrugated stainless steel primary barrier:



- Thickness:1.2 mm
- Material: Stainless steel 304L

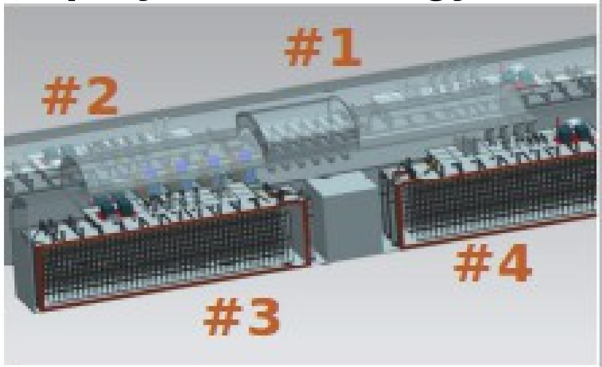


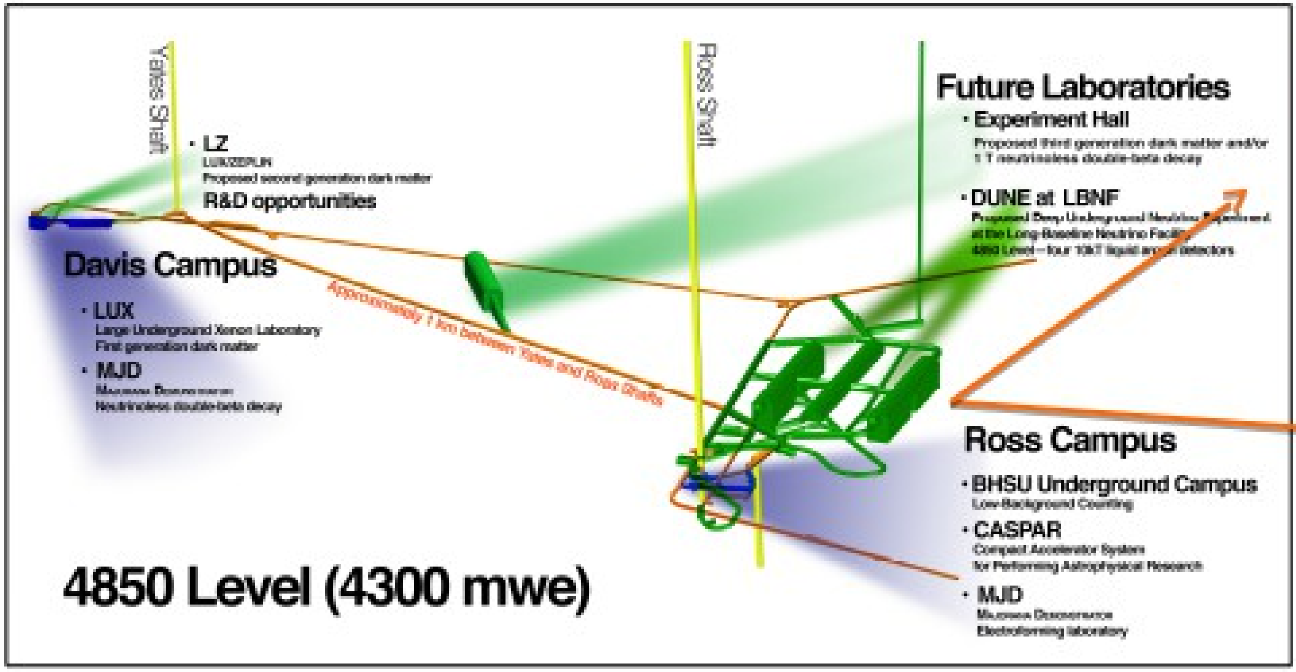


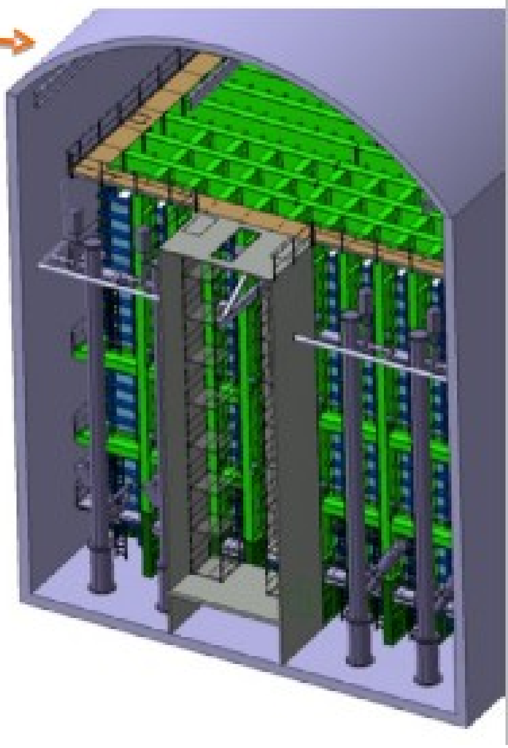
1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Steel structure with moisture barrier

DUNE Far Detector at SURF

10 kton each in staged deployment strategy

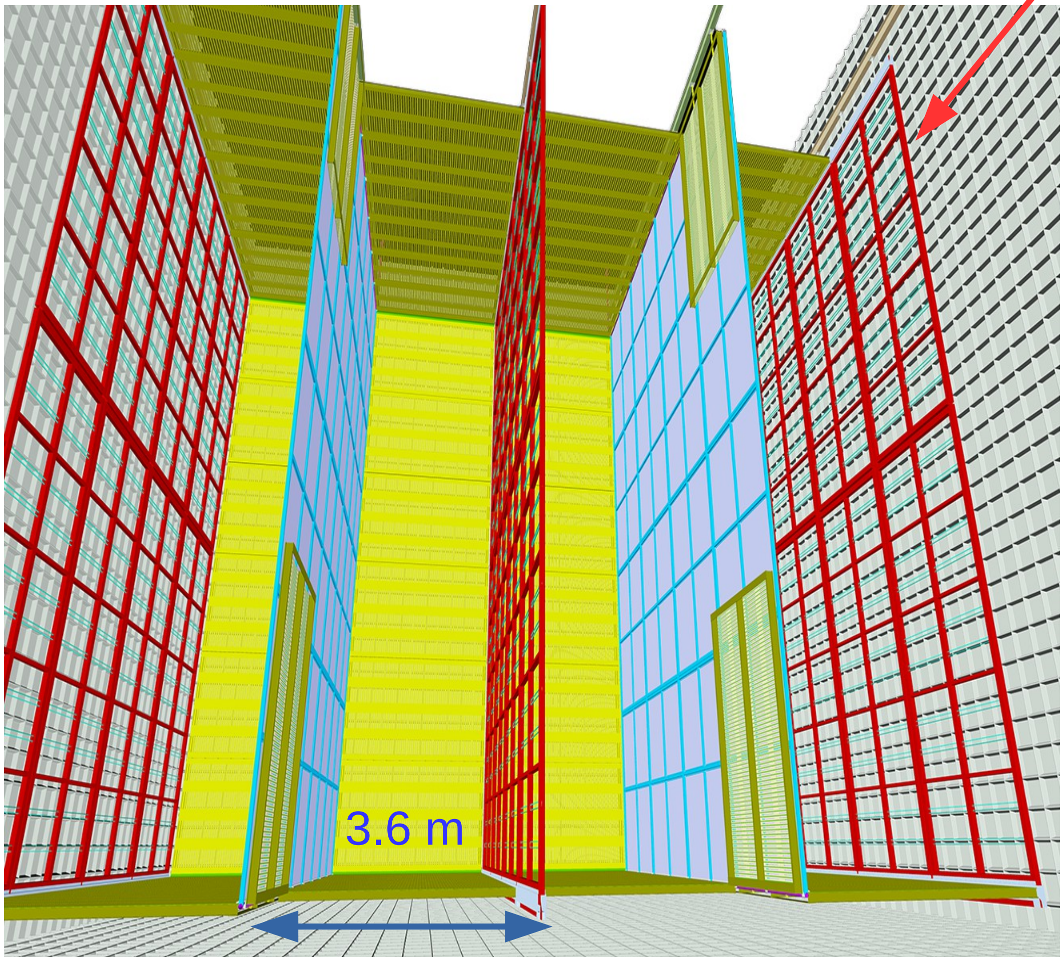






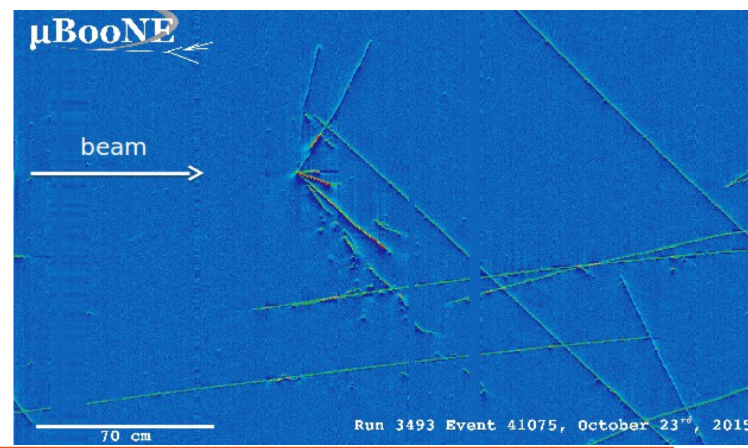
- The first module will be a single phase TPC (live in 2024). Its design is mature and the basis for the engineering prototype at CERN
- Subsequent modules can incorporate design changes that are demonstrated by ongoing R&D efforts, including a dual phase TPC option

Far Detector: LArTPC



- Anode Plane Assemblies (APAs) with three instrumented wire planes on each side (one collection and two induction) to readout ionization charge
- Drift field of 500 V/cm (cathode planes: 180 kV)
- Four drift regions 3.6 m each
- Photon Detection System (slide 17) integrated into APAs to measure (early) scintillation light for non-beam event timing

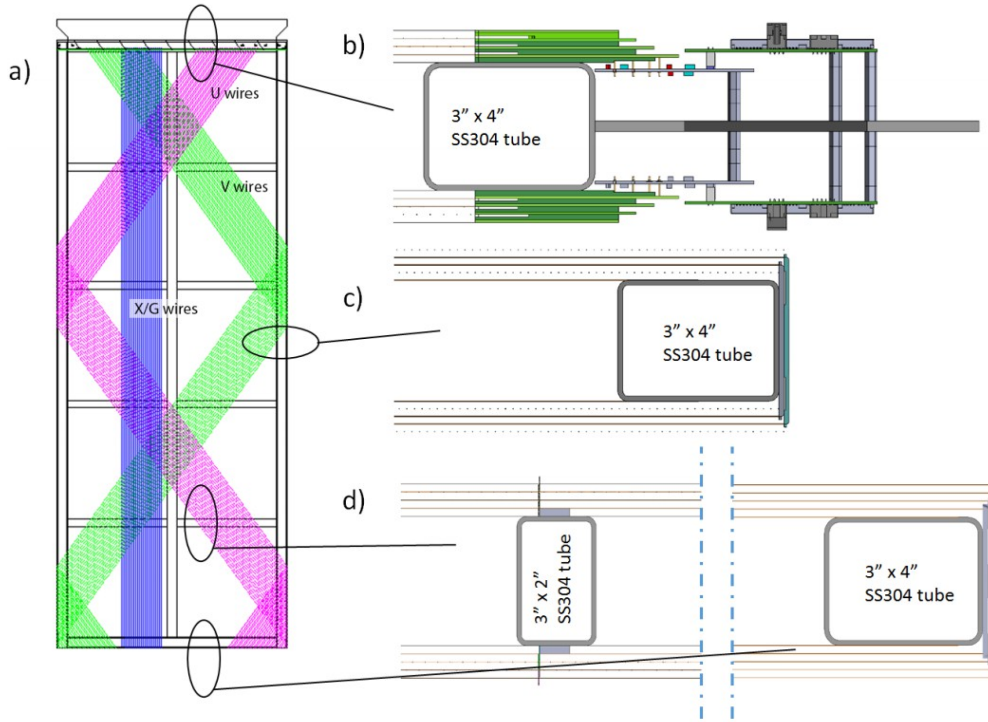
mm spatial resolution →



Far Detector: LArTPC - APAs

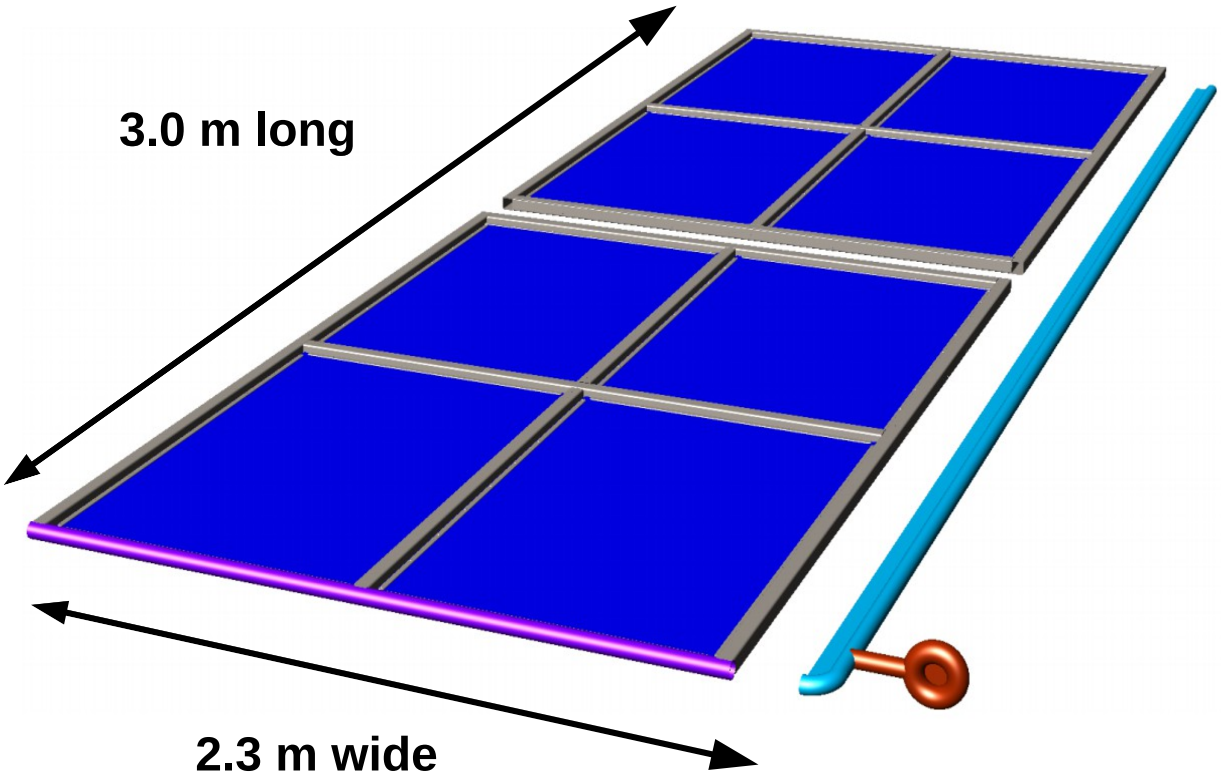
Parameters of the four planes of wires on an APA

Label	Function	Orientation (from vertical)	Pitch (mm)	Number	Bias Voltage (volt)
G	Shield/grid plane	0°	4.79	960	−655
U	1^{st} induction plane	+35.7°	4.67	800	−365
V	2^{nd} induction plane	−35.7°	4.67	800	0
X	Collection plane	0°	4.79	960	+860



Far Detector: LArTPC – CPAs

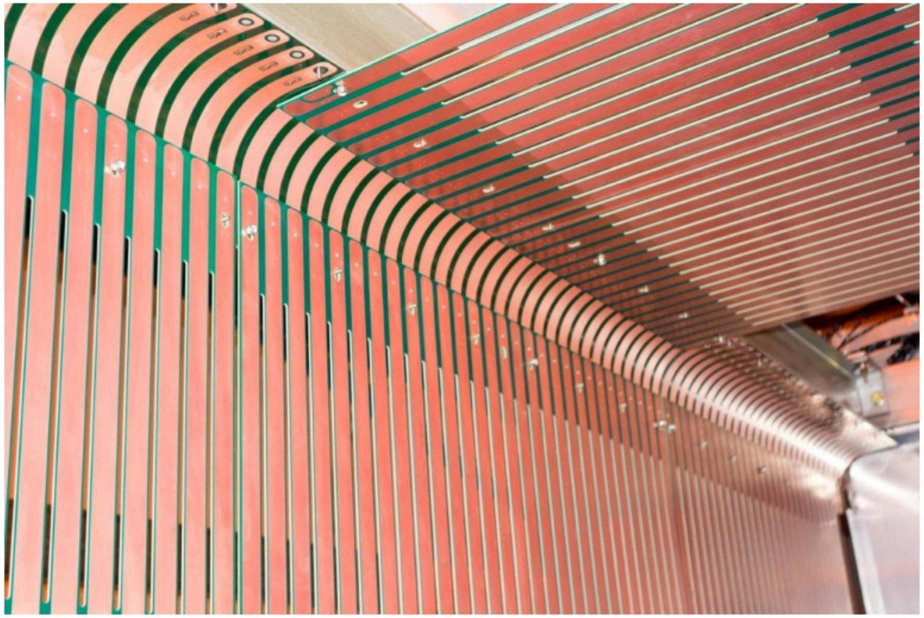
CPA: provides HV
Stainless steel tiles and frame

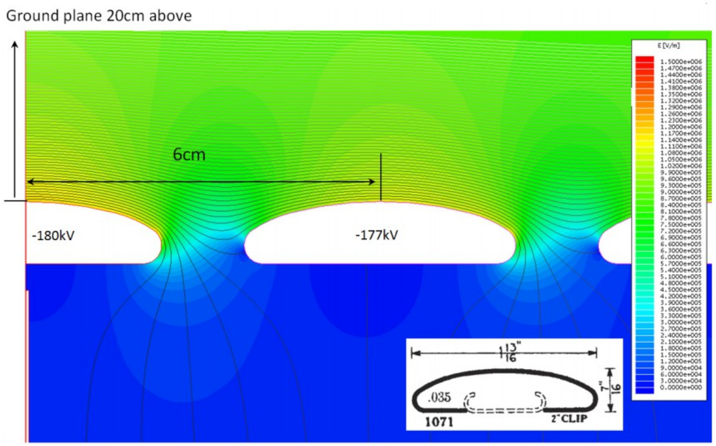


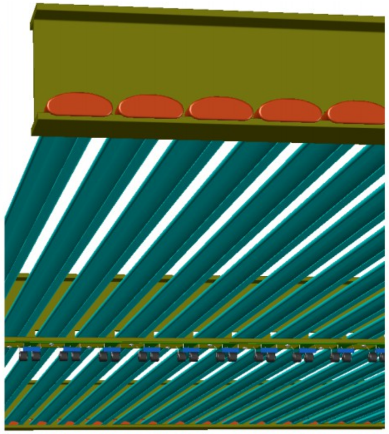
Far Detector: LArTPC – Field Cage

Field Cage: field shaping PCB structure

(picture from the corner of the 35 ton prototype)

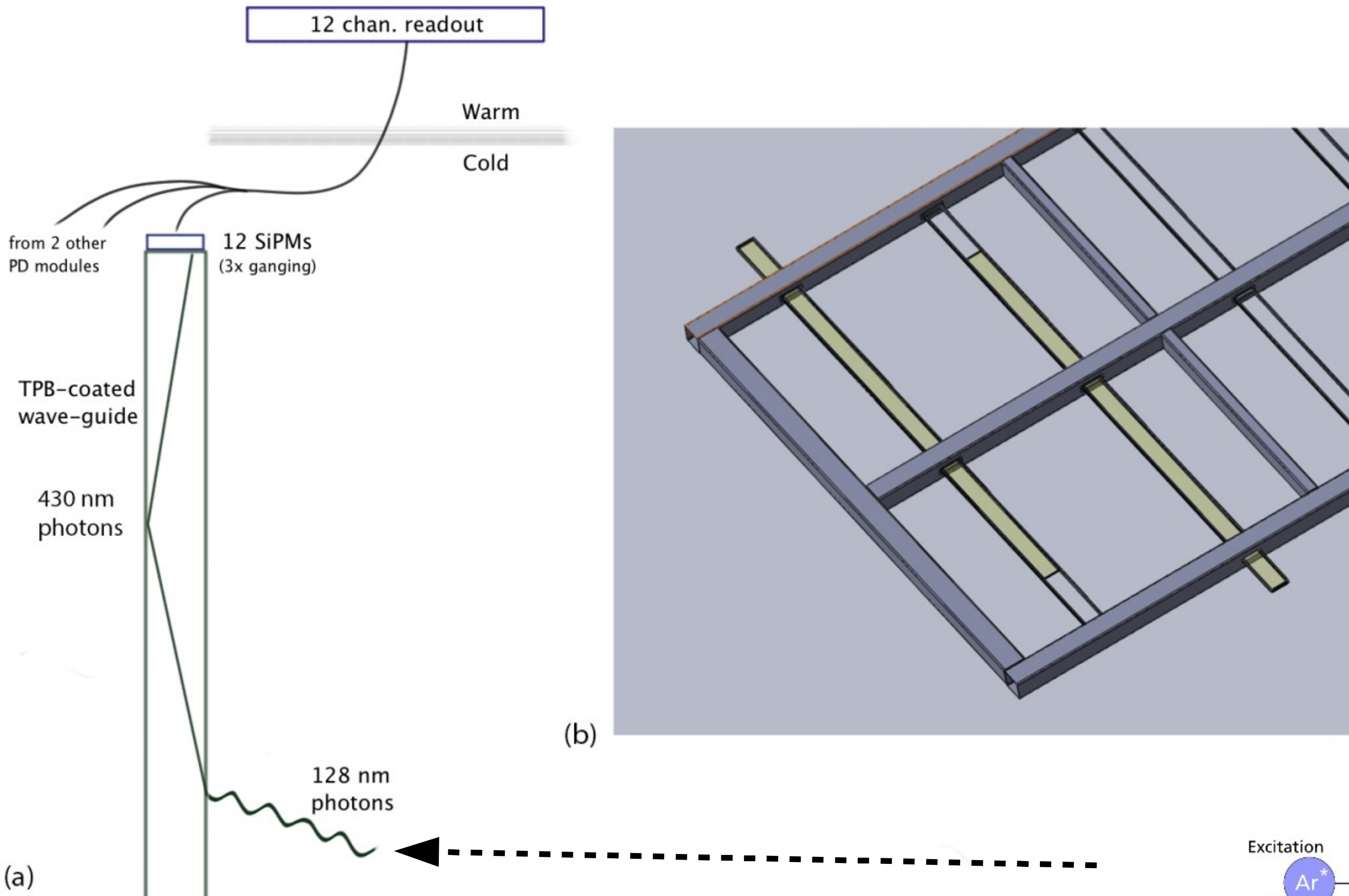






Electric Field simulations showing a very good uniformity in a safe distance from the FC elements

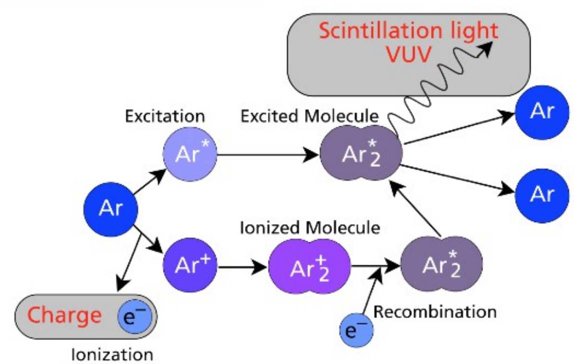
Far Detector: Photon Detection System



Scintillation components: fast (6ns), slow (1,6 µs)

e^- drift velocity: ~ ms

LIGHT provides T_0 !!!

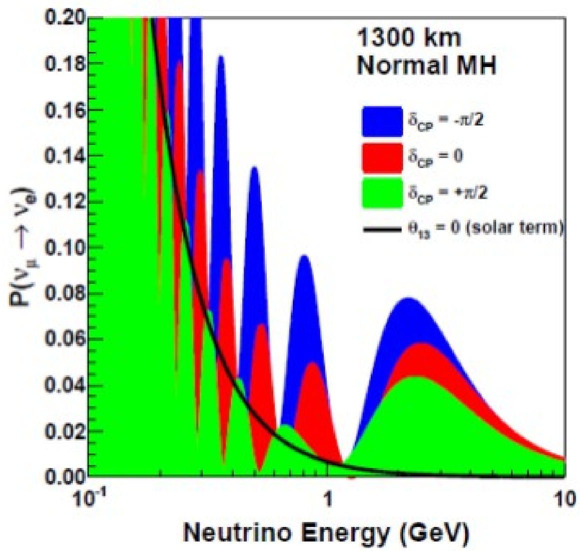


Far Detector TPC performance

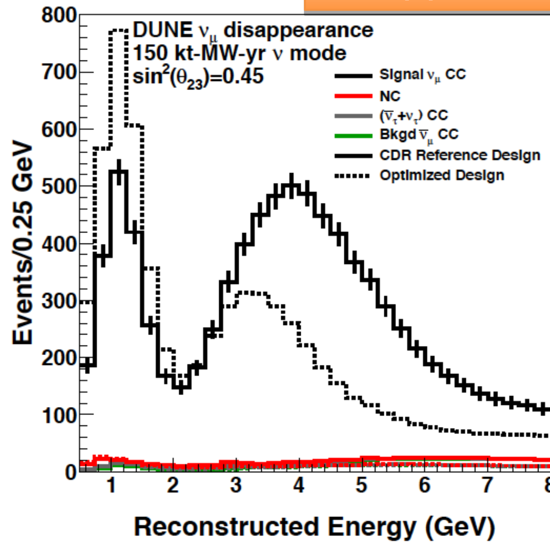
arXiv:1601.02984

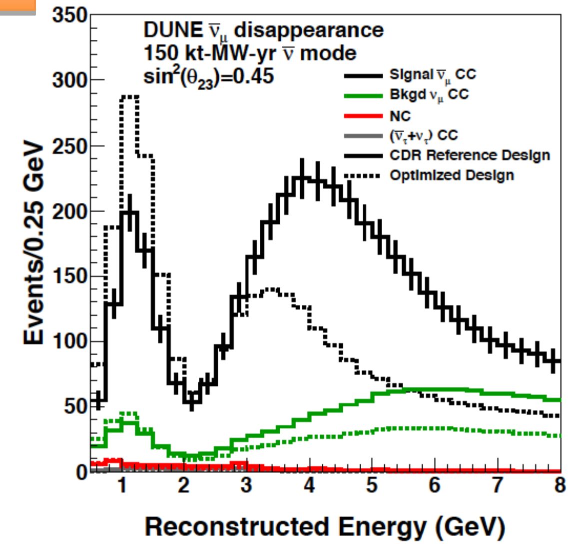
Parameter	Requirement	Achieved Elsewhere	Expected Performance
Signal/Noise Ratio[1]	$9:1$	$10:1$ [11, 12][2]	$9:1$
Electron Lifetime	3 ms	>15 ms [12]	>3 ms
Uncertainty on Charge Loss due to Lifetime	$<5\%$	$<1\%$ [12]	$<1\%$
Dynamic Range of Hit Charge Measurement	15 MIP		15 MIP
Vertex Position Resolution[3]	(2.5,2.5,2.5) cm		(1.1,1.4,1.7) cm [13, 14]
$e-\gamma$ separation ϵ_e	>0.9		0.9
$e-\gamma$ separation γ rejection	>0.9		0.99
Multiple Scattering Resolution on muon momentum[4]	$\sim 18\%$	$\sim 18\%$ [15, 16]	$\sim 18\%$
Electron Energy Scale Uncertainty	$\sim 5\%$	$\sim 2.2\%$[17]	From LArIAT and CERN Prototype
Electron Energy Resolution	$0.15/\sqrt{E(\mathrm{MeV})} \oplus 1\%$	$0.33/\sqrt{E(\mathrm{MeV})}$ [17] $+1\%$	From LArIAT and CERN Prototype
Energy Resolution for Stopping Hadrons	$<10\%$		From LArIAT and CERN Prototype
Stub-Finding Efficiency[5]	$>90\%$		$>90\%$

ν's oscillations



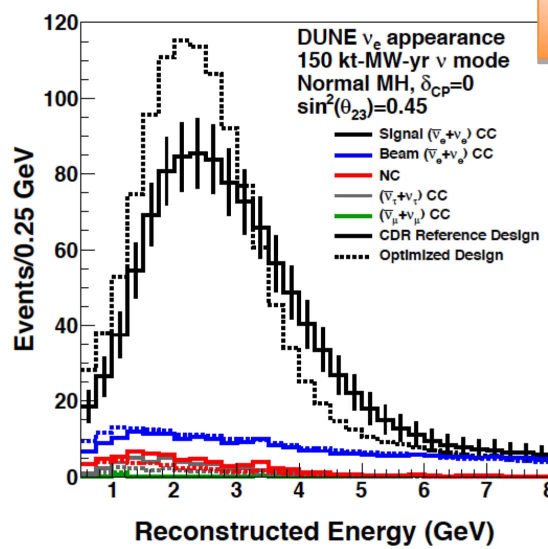
disappearance

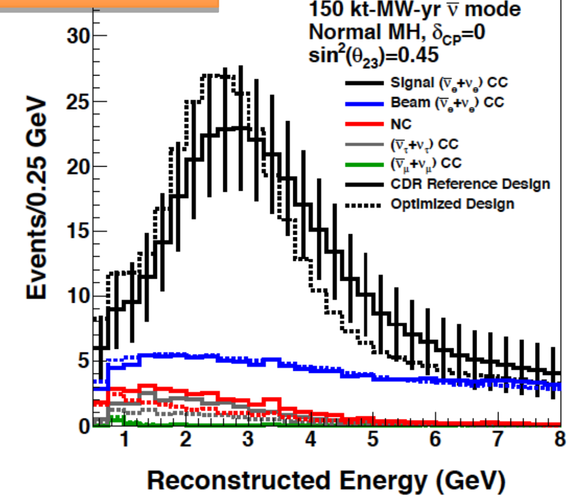




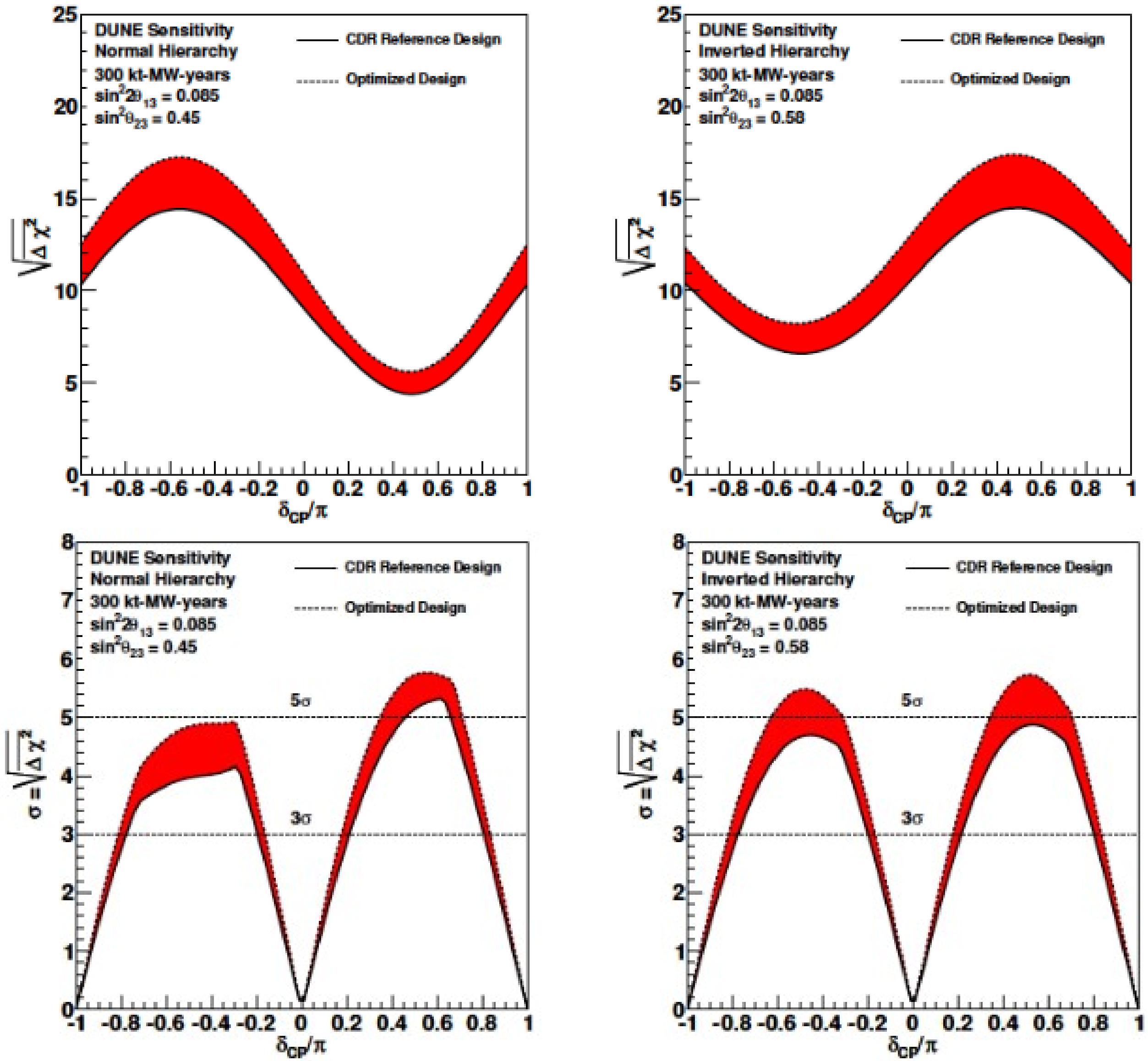
- Simultaneous fit to extract MH and δ_{CP}
  (ν_μ, anti-ν_μ, ν_e, anti-ν_e)
- Plots below assume normal MH and δ_{CP}=0
- Exposure: y 300 kTon*MW*years

appearance





Sensitivities: Mass Hierarchy and δ_{CP}

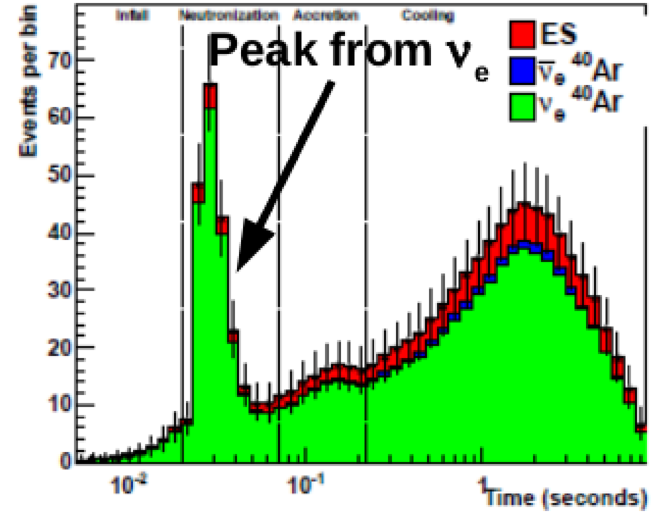


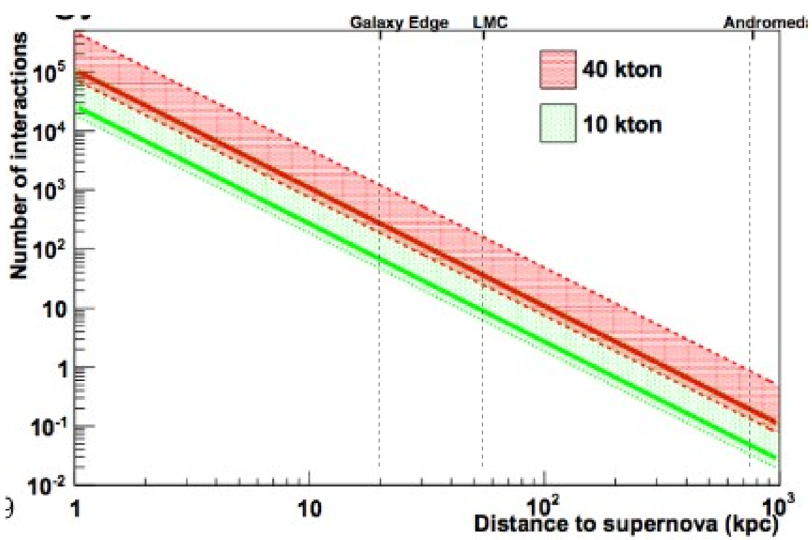
More details on Lisa Whitehead's talk

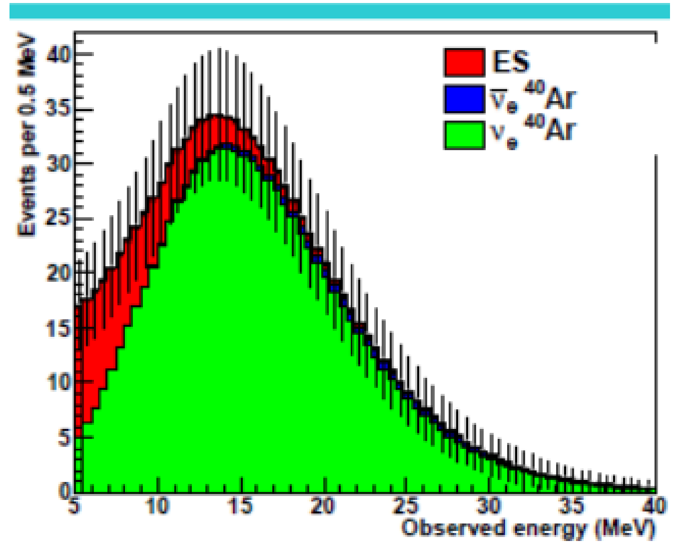
Supernova Detection

More details on Amanda Weinstein's talk

- Requires an efficient non-beam trigger
- Other experiments rely on ν_e capture via inverse β-decay
- DUNE will be able to observe the ν_e flux through capture on Ar40
  – Unique sensitivity to the electron flavor component of the flux
  – Provides information on time, energy and flavor structure
  – Rates depend on core collapse model, ν oscillation models, and distance.
  – Expect >3000 events from a supernova at 10 kpc







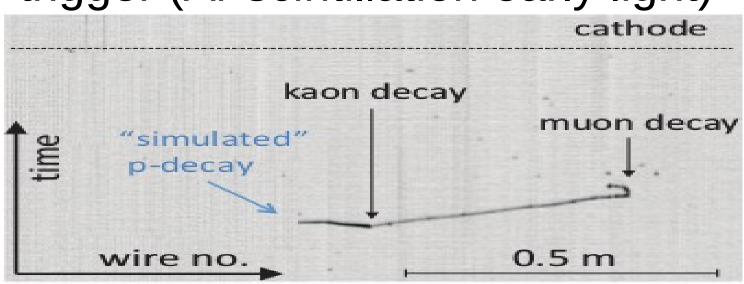
Baryon Number Violation: p-decay

Superior detection efficiency for K production modes

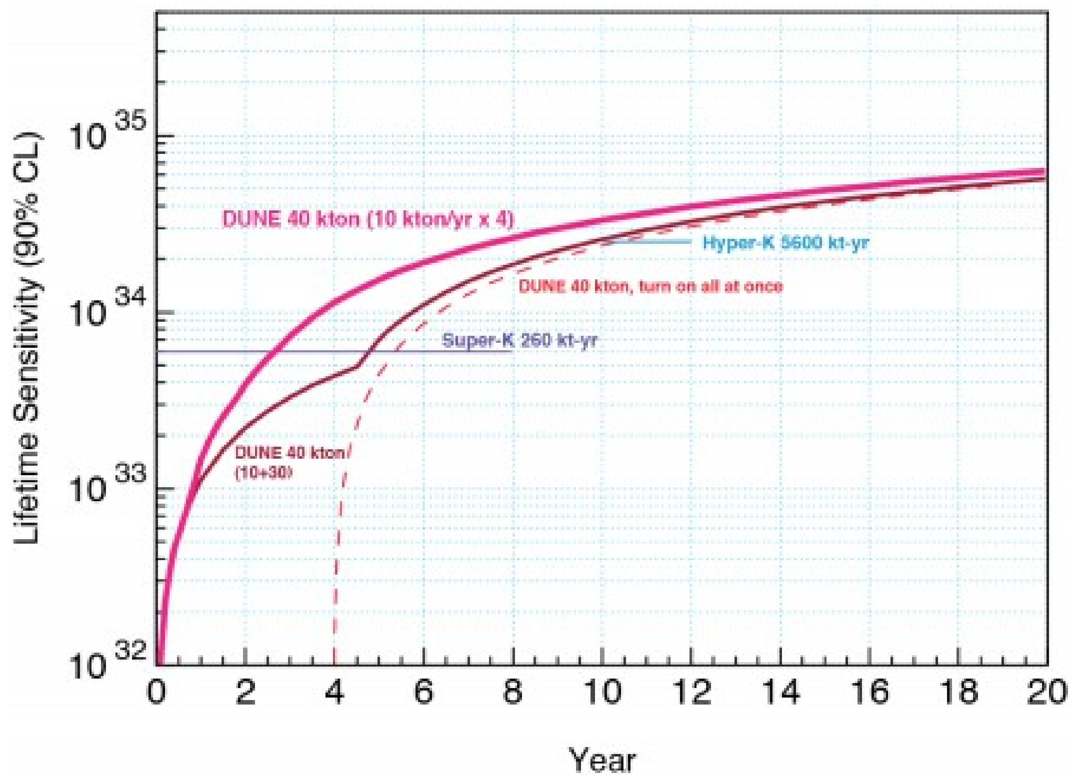
- K PID through dE/dx
- High spatial resolution and low energy thresholds
  → rejection atmospheric backgrounds

- High Efficiency (>90%), high purity selections for
  p → $K^+ + \nu$ and p → $K^0 + \mu^+$

- Requires efficient non-beam trigger (Ar scintillation early light)



Decay Mode	Water Cherenkov Efficiency	Water Cherenkov Background	Liquid Argon TPC Efficiency	Liquid Argon TPC Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8



Timeline

- A 35t LarTPC prototype 2015.
- Full-scale prototype at CERN 2018.
- First 10kt LArTPC module (single phase) underground 2021.
- Choose technology for the 2nd, 3rd, 4th 10kt module.
- Collect FD data by 2024.
- Beam on by 2026.
- Finish a fine-grained tracker ND by 2026.
- Finish all construction by 2028.
- Reach an exposure of 120 kt.MW.years by 2035.

Conclusions

- DUNE will have: MW neutrino beam, highly-capable fine-grained near detector, 40kt LArTPC deep underground at SURF (see Jaret Heise's talk).
- Clear plan has been made. Strong collaboration formed.
- Aim to solve neutrino mass hierarchy and CP-violating phase via oscillation measurement (see Lisa Whitehead's talk).
- Rich non-oscillation physics topics: proton decay, supernova, ν interactions, and more (see Amanda Weinstein's talk).
- Many opportunities both for new collaborators and students.

Future is promising !!

The End

Special credits for DUNE colleagues (comments and slides inspiration):

Jim Strait, Maury Goodman, Dan Cherdack, Mary Bishai, Michele Stancari, Hongyue Duyang, Bob Wilson, Gabriel Santucci, Thomas Kutter

Main Content:
Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) : Volumes 2 and 4
e-Print: arXiv:1601.02984 , arXiv:1512.06148

BACKUP

DUNE + LBNF

Detectors and science collaboration will be managed separately from the neutrino facility and infrastructure.

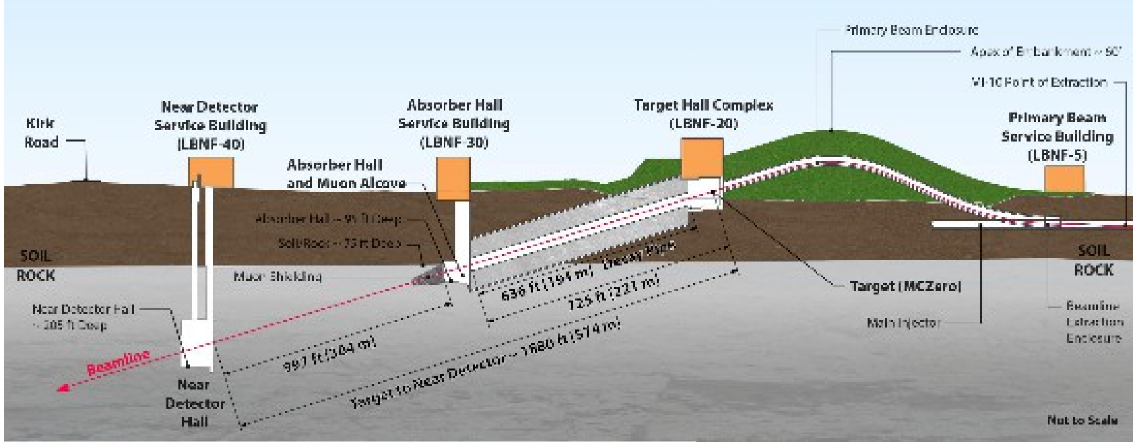
- LBNF(Long-Baseline Neutrino Facility):
  - Neutrino beamline.
  - Near detector conventional facilities.
  - Far detector hall; conventional facilities.

LBNF

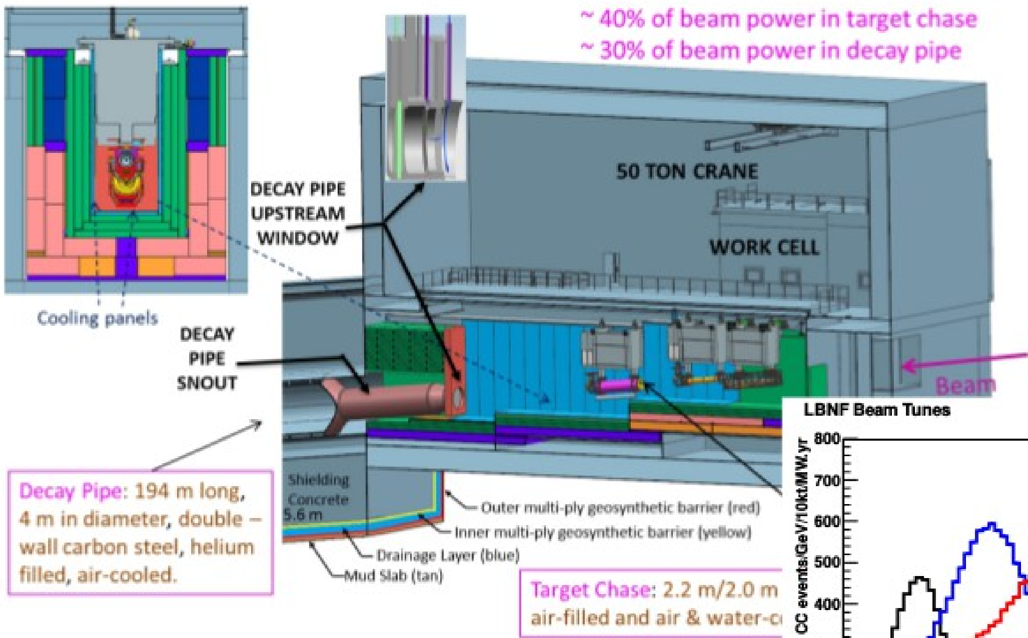
- DUNE(Deep Underground Neutrino Experiment):
  - Far and near detectors
  - Scientific research program

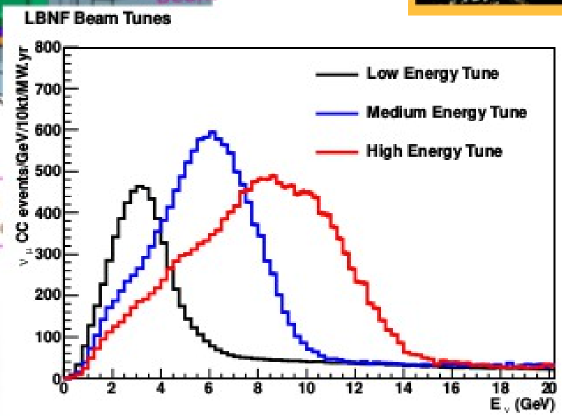
DUNE

Beam: LBNF

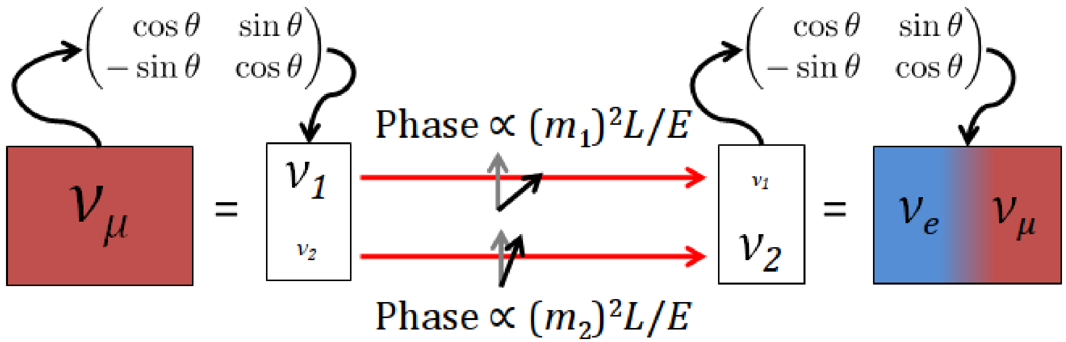


Advanced conceptual design *tunable wide-band* NuMI-style focusing:





ν's oscillations



Flavor

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass

$c_{13}=\cos\theta_{13}$; $s_{13}=\sin\theta_{13}$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

ν's oscillations

What we do know:

$$\left[|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2\right]$$

$$\Delta m^2_{\rm sol} \equiv \Delta m^2_{21} \simeq 7.5 \times 10^{-5}\ {\rm eV}^2$$

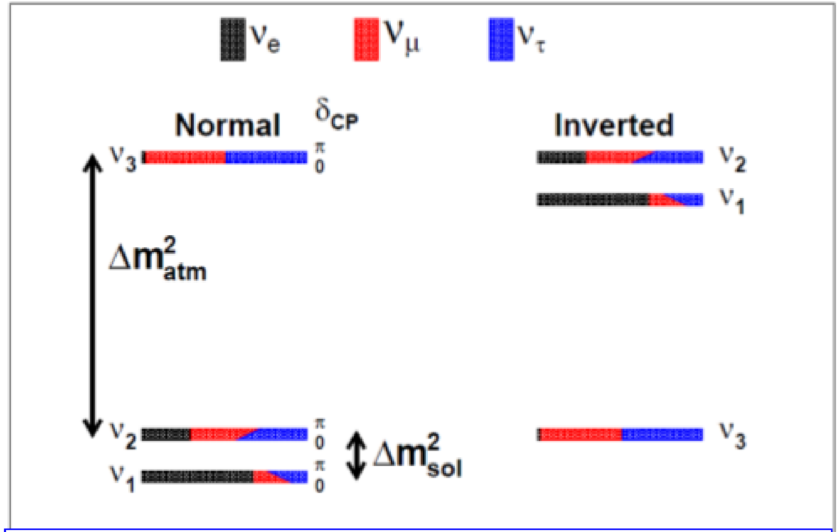
$$\Delta m^2_{\rm atm} \equiv |\Delta m^2_{32}| \simeq 2.5 \times 10^{-3}\ {\rm eV}^2$$

$$\sin^2\theta_{21} \simeq 0.31$$

$$\sin^2\theta_{23} \simeq 0.45\text{–}0.55$$

$$\sin^2\theta_{13} \simeq 0.02$$

Neutrino Mass Hierarchy



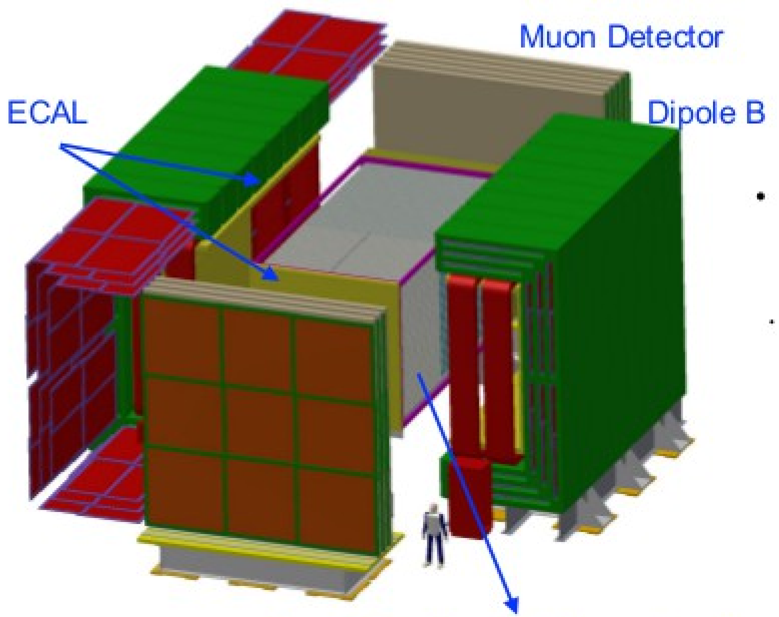
X. Qian & P. Vogel, arXiv:1505.01891

What needs to be determined:

mass hierarchy (sign of $\Delta m_{32}{}^2$), θ_{23} octant (dominant flavor in ν_3), CP violation in the lepton sector

Near Detector

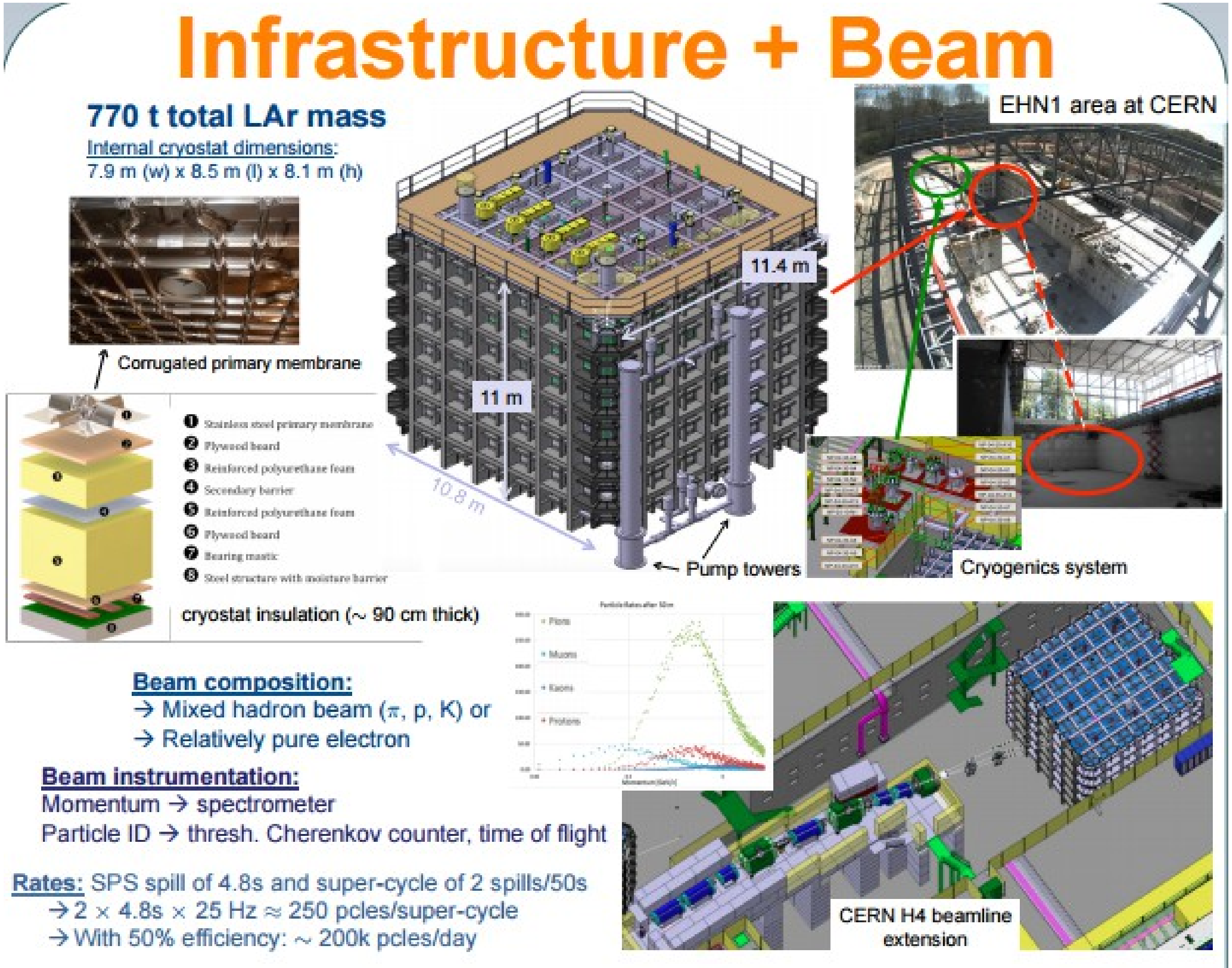
- ND goals:
  - Constrain systematics to the ν_e appearance measurement.
  - Precision physics measurements on its own.
- Alternative designs:
  - LArTPC
  - High-Pressure Argon Gas TPC
  - Hybrid detector.

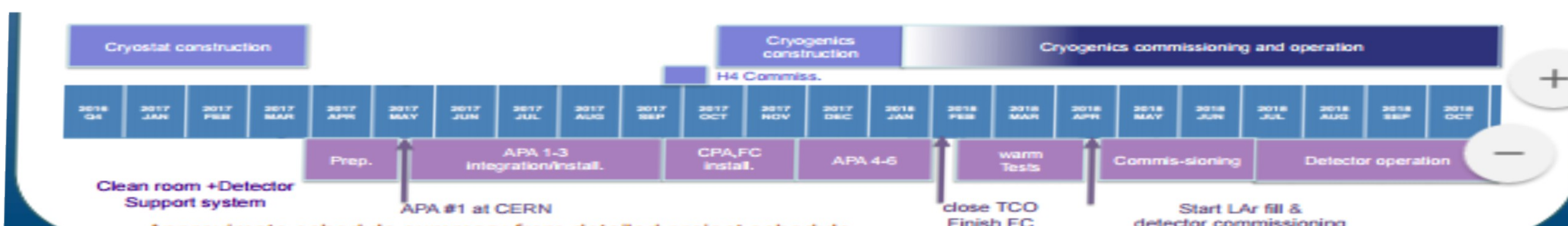


The reference design:
High Resolution Fine-Grained Tracker.

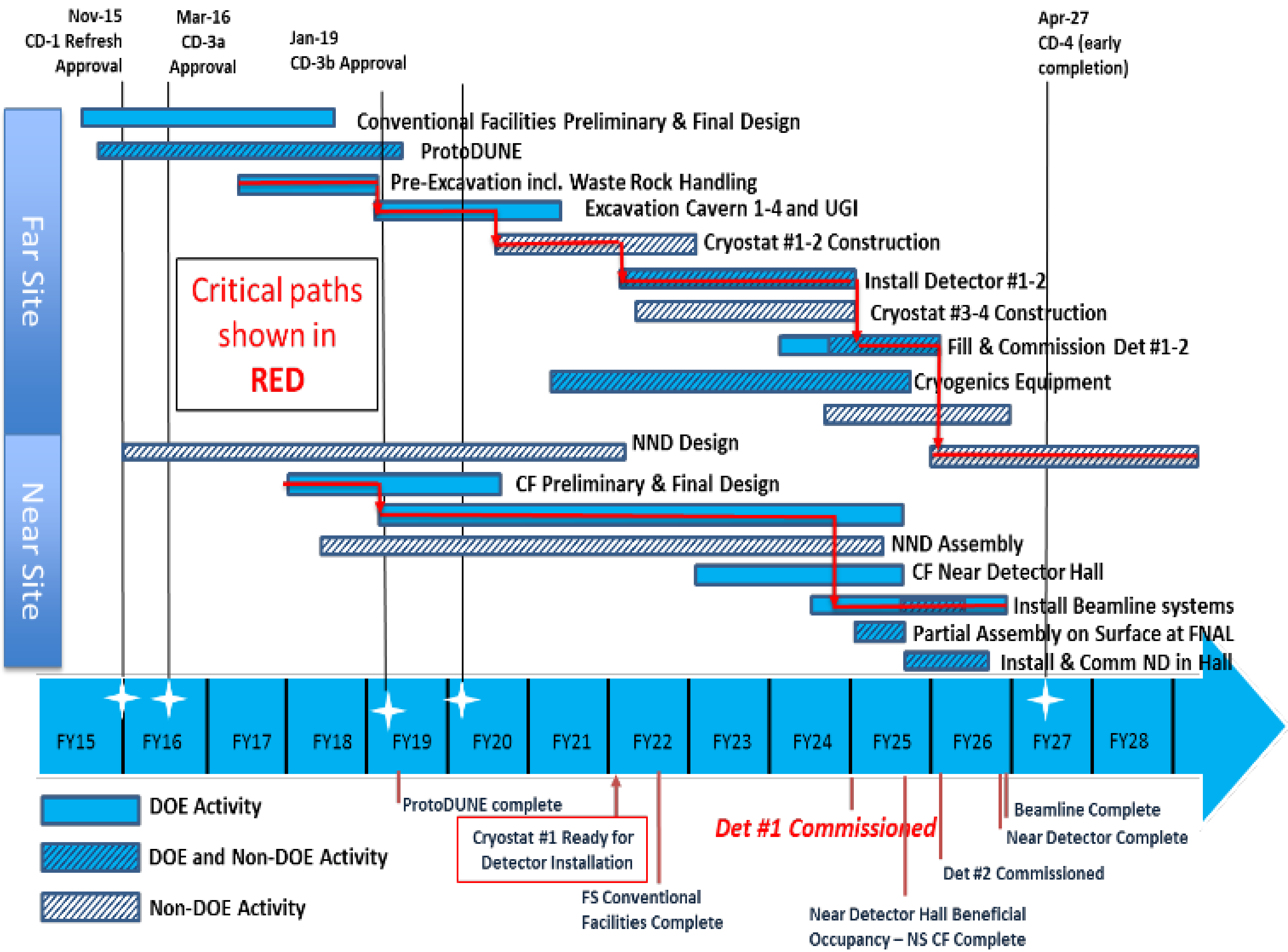
- ~3.5m×3.5m×6.5mSTT ($\rho \simeq 0.1$ g/cm^3).
- 4π ECAL in a dipole magnetic field (B = 0.4 T).
- 4π MuID (RPC) in dipole and up/downstream.
- Pressurized ^{40}Ar target ≃ ×10 FD statistics

ProtoDUNE


Infrastructure + Beam
770 t total LAr mass
Internal cryostat dimensions:
7.9 m (w) x 8.5 m (l) x 8.1 m (h)
Corrugated primary membrane
Stainless steel primary membrane
Plywood board
Reinforced polyurethane foam
Secondary barrier
Reinforced polyurethane foam
Plywood board
Bearing mastic
Steel structure with moisture barrier
cryostat insulation (~ 90 cm thick)
11.4 m
11 m
10.8 m
Pump towers
EHN1 area at CERN
Cryogenics system
Beam composition:
→ Mixed hadron beam (π, p, K) or
→ Relatively pure electron
Beam instrumentation:
Momentum → spectrometer
Particle ID → thresh. Cherenkov counter, time of flight
Rates: SPS spill of 4.8s and super-cycle of 2 spills/50s
→ 2 × 4.8s × 25 Hz ≈ 250 pcles/super-cycle
→ With 50% efficiency: ~ 200k pcles/day
CERN H4 beamline extension


Cryostat construction
Cryogenics construction
Cryogenics commissioning and operation
H4 Commiss.
Prep.
APA 1-3 integration/install.
CPA,FC install.
APA 4-6
warm Tests
Commis-sioning
Detector operation
Clean room +Detector Support system
APA #1 at CERN
close TCO
Start LAr fill &

Timeline



Nov-15
CD-1 Refresh
Approval
Mar-16
CD-3a
Approval
Jan-19
CD-3b Approval
Apr-27
CD-4 (early
completion)
Far Site
Near Site
Conventional Facilities Preliminary & Final Design
ProtoDUNE
Pre-Excavation incl. Waste Rock Handling
Excavation Cavern 1-4 and UGI
Cryostat #1-2 Construction
Install Detector #1-2
Cryostat #3-4 Construction
Fill & Commission Det #1-2
Cryogenics Equipment
Critical paths
shown in
RED
NND Design
CF Preliminary & Final Design
NND Assembly
CF Near Detector Hall
Install Beamline systems
Partial Assembly on Surface at FNAL
Install & Comm ND in Hall
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
FY23
FY24
FY25
FY26
FY27
FY28
DOE Activity
DOE and Non-DOE Activity
Non-DOE Activity
ProtoDUNE complete
Cryostat #1 Ready for
Detector Installation
FS Conventional
Facilities Complete
Det #1 Commissioned
Near Detector Hall Beneficial
Occupancy – NS CF Complete
Det #2 Commissioned
Beamline Complete
Near Detector Complete

PDS design

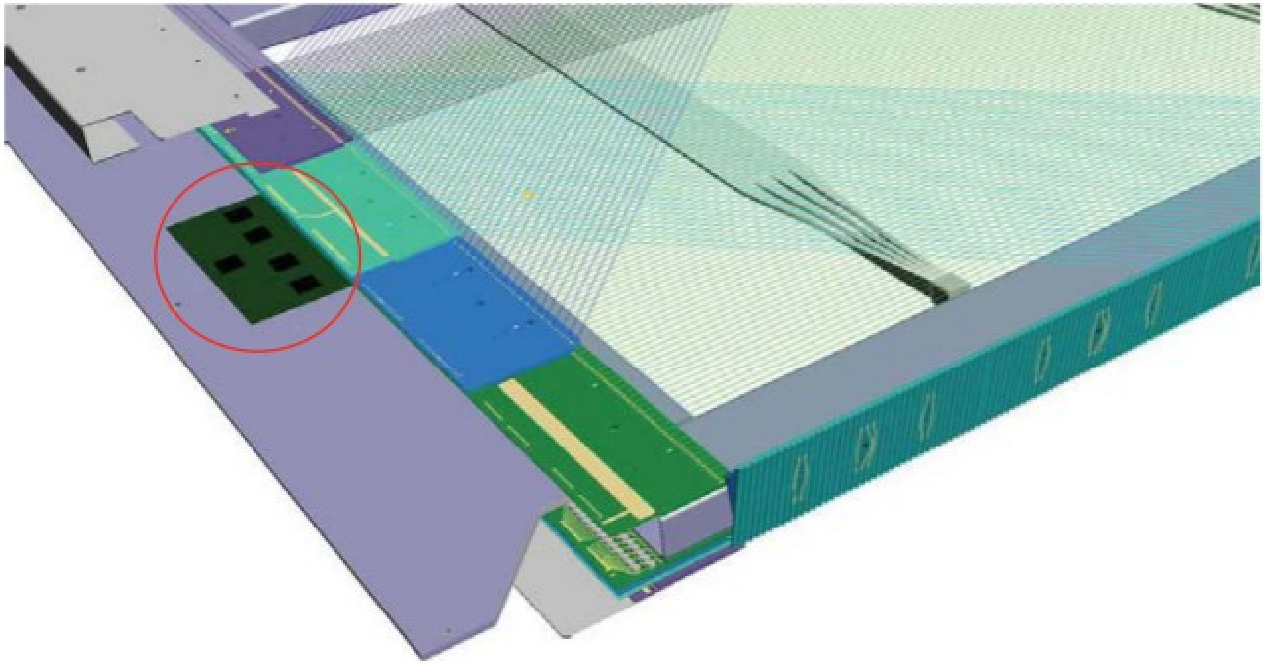


Figure 4.13: The front-end electronics, shown in the red circle, as mounted on an APA. (Note that this figure was not updated to show the current photon detection system scheme.)

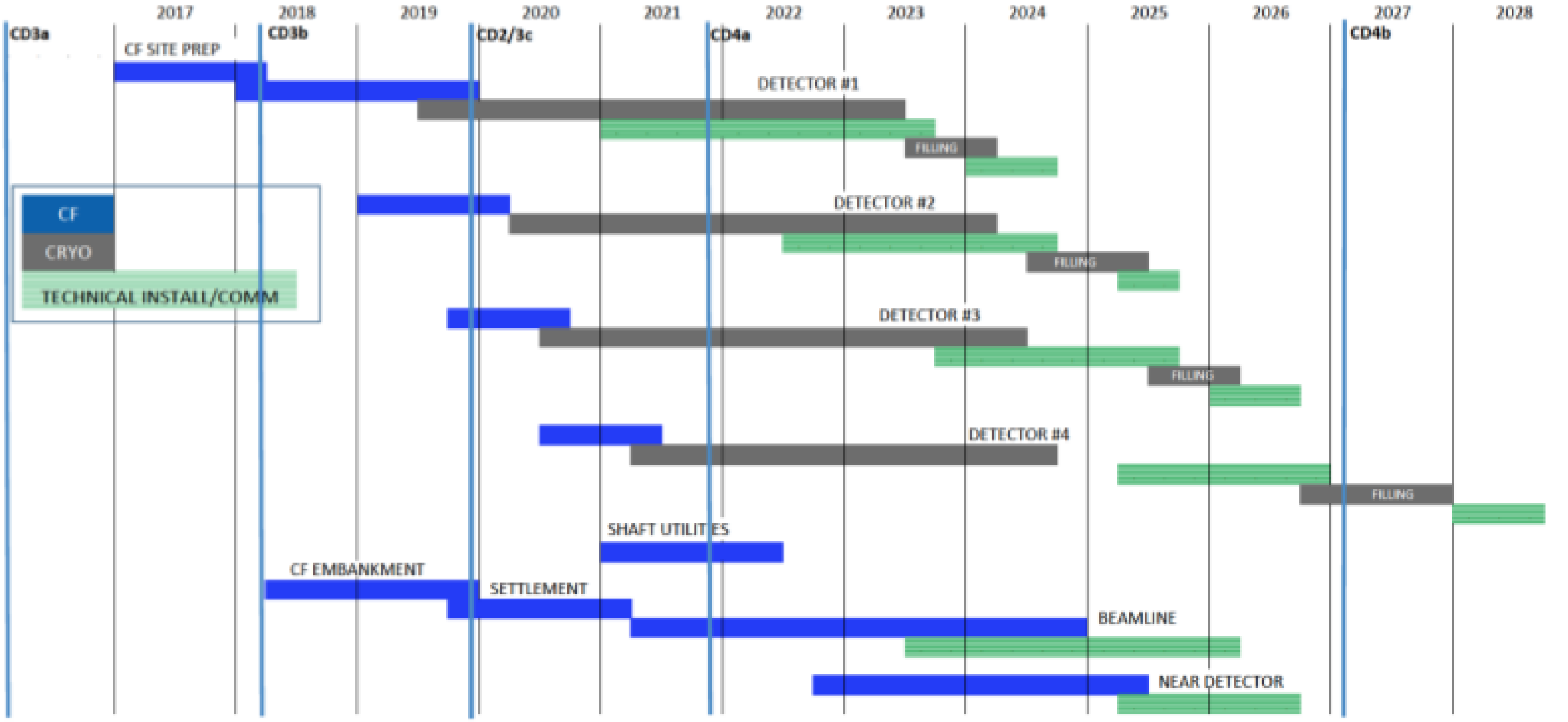
Expected Signals

	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_e Signal NH (IH)	861 (495)	945 (521)
$\bar{\nu}_e$ Signal NH (IH)	13 (26)	10 (22)
Total Signal NH (IH)	874 (521)	955 (543)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	159	204
NC Bkgd	22	17
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	42	19
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	3	3
Total Bkgd	226	243
$\bar{\nu}$ mode (150 kt · MW · year)		
ν_e Signal NH (IH)	61 (37)	47 (28)
$\bar{\nu}_e$ Signal NH (IH)	167 (378)	168 (436)
Total Signal NH (IH)	228 (415)	215 (464)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	89	105
NC Bkgd	12	9
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	23	11
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	2	2
Total Bkgd	126	127

ν

$\bar{\nu}$

Timeline


2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
CD3a
CD3b
CD2/3c
CD4a
CD4b
CF SITE PREP
DETECTOR #1
FILLING
CF
CRYO
TECHNICAL INSTALL/COMM
DETECTOR #2
FILLING
DETECTOR #3
FILLING
DETECTOR #4
FILLING
SHAFT UTILITIES
CF EMBANKMENT
SETTLEMENT
BEAMLINE
NEAR DETECTOR