DUNE Physics and Detectors

Stefan Söldner-Rembold

Neutrino Colloquium, Prague

2 November 2017

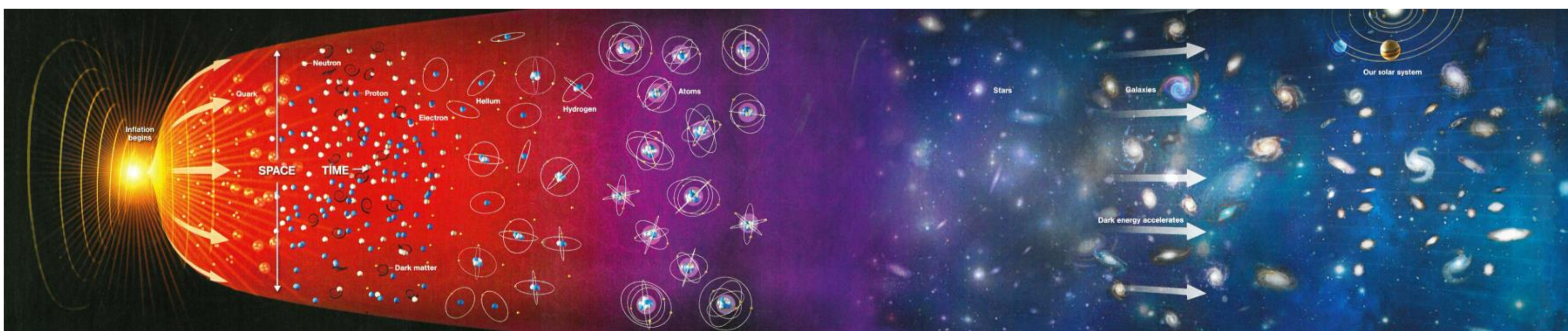
Testing the standard "three-flavour" paradigm

complex phase

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

CP Violation in the lepton sector might provide support for *Leptogenesis* as mechanism to generate the Universe's matter-antimatter asymmetry.

CP Violation: $\delta \neq \{0, \pi\}$ $\quad s_{ij} = \sin\theta_{ij}\ ;\ c_{ij} = \cos\theta_{ij}$



Testing the standard "three-flavour" paradigm

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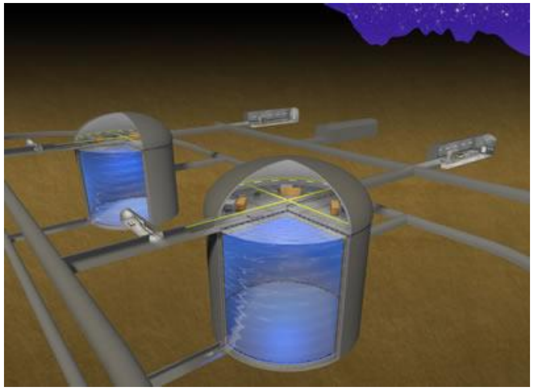
<u>Caveat:</u>

No direct evidence for *Leptogenesis*, since a model is needed to connect the low-scale CPV observed here to high-scale CPV for heavy neutrinos that lead to *Leptogenesis*.

Optimizing L/E for neutrino oscillations

see D. Wark



Water Cherenkov

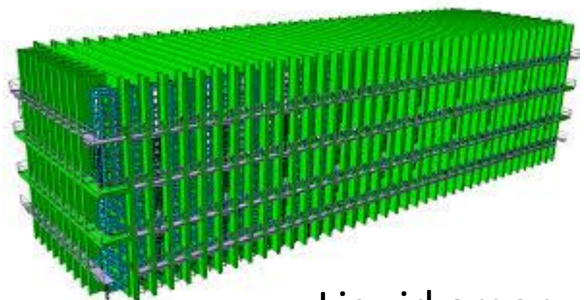
L ≈ 200 km

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

- no matter effects; first oscillation maximum.
- use narrow width beam (off axis).

L > 1000 km

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



Liquid argon

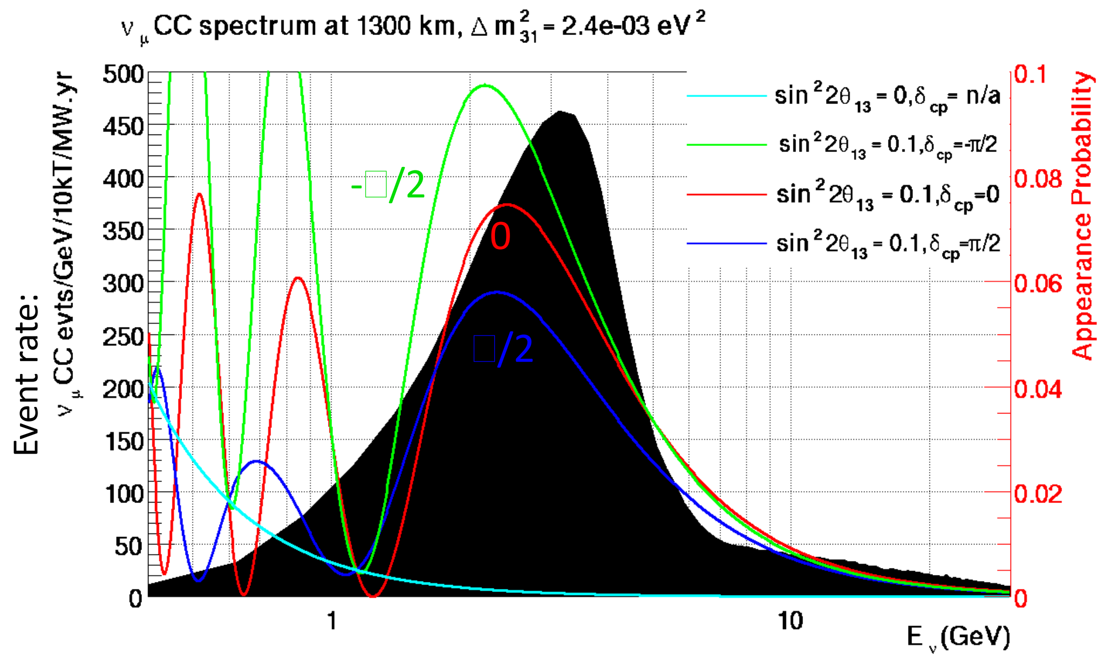
- matter effects; first and second oscillation maximum.
- use broad-band beam (on axis).
- unfold CP and MO effects through energy dependence.

ν_e appearance gives access to δ

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

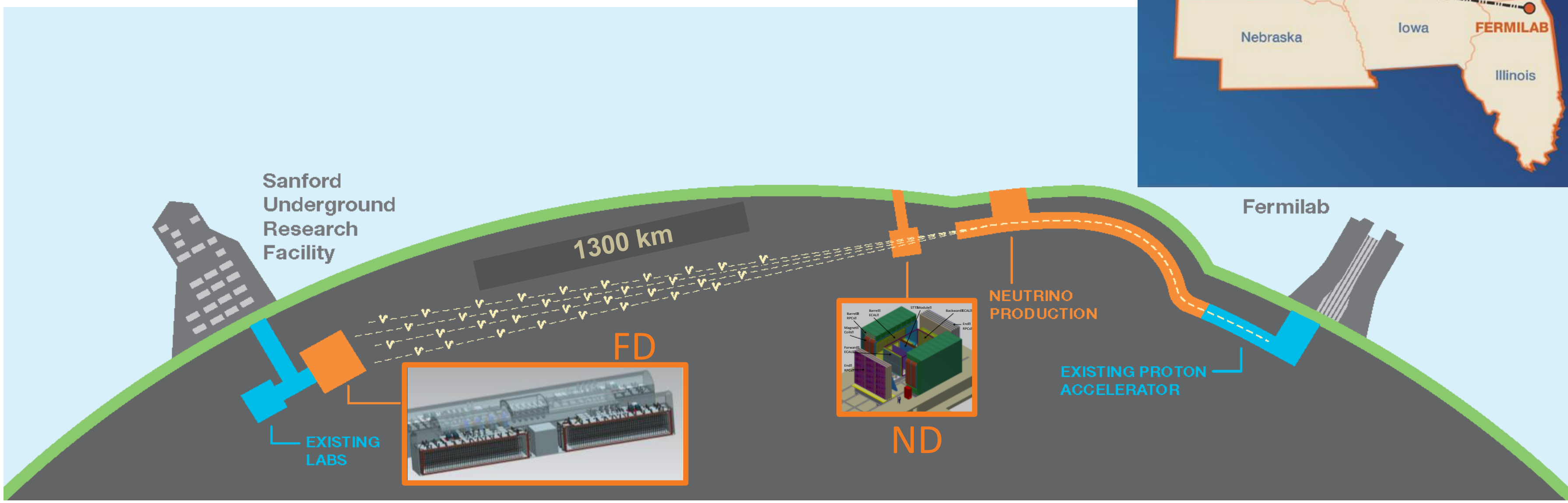
$$a = G_F N_e/\sqrt{2}$$

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



- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects – measurements of all four possible in a single experiment
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample

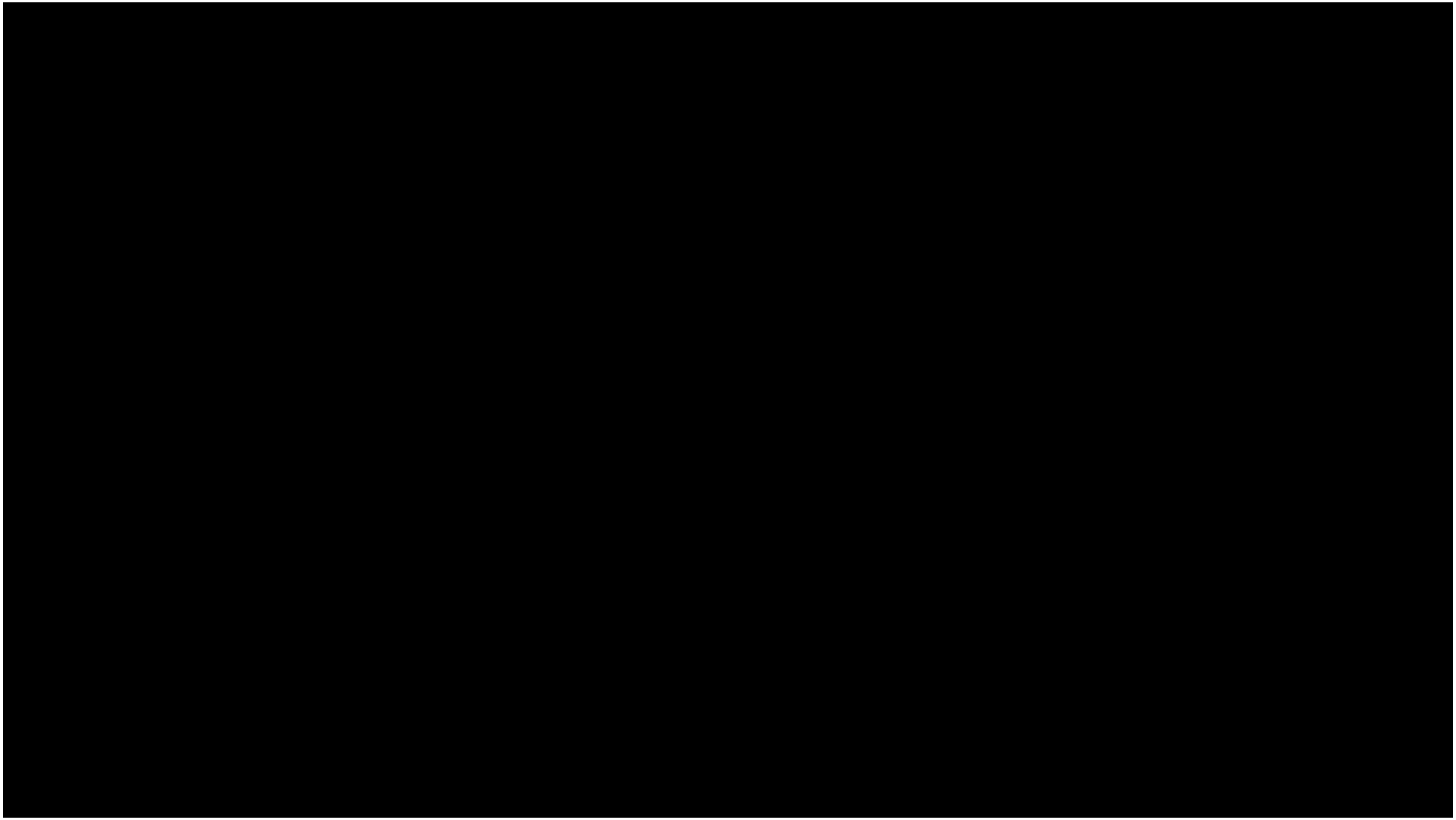
DUNE



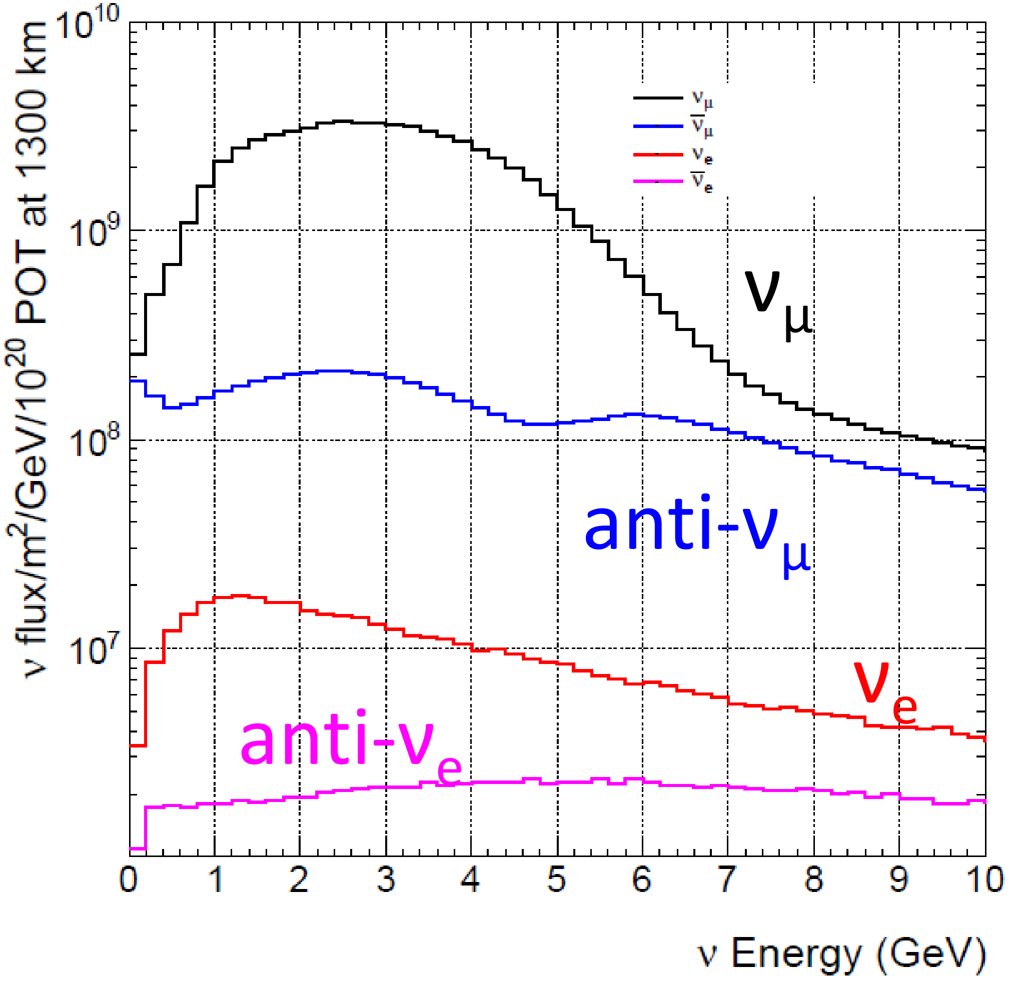
- Approximately 40 kt fiducial mass liquid argon Far Detector.
- Located 1300 km baseline at SURF's 1478 m level (2,300 mwe).
- Compare $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations.

Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report, Volume 4 The DUNE Detectors at LBNF, arXiv:1601.02984.

LBNF/DUNE – Fermilab in



DUNE Far Detector neutrino flux



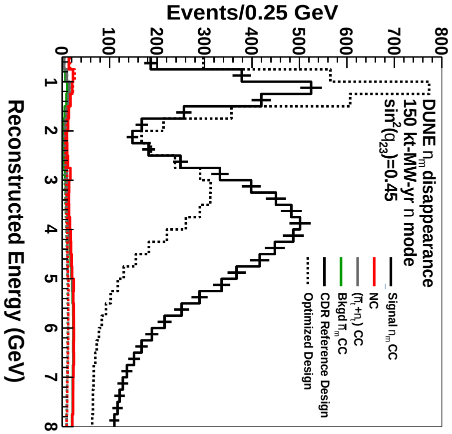
Beam (LBNF):

- 60-120 GeV proton beam energy
- 1.2 MW from Day 1
- upgradeable to 2.4 MW
- assume running of 3.5 years each in neutrino and anti-neutrino mode.

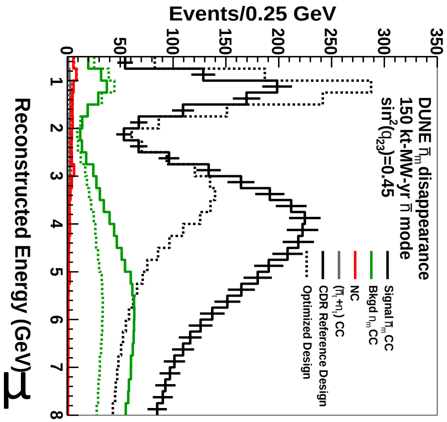
DUNE oscillation strategy

- Wide-band beams allows us to measure ν_e appearance and ν_μ disappearance over range of energies
- Mass ordering and CP violation effects can be separated

muon-neutrino disappearance

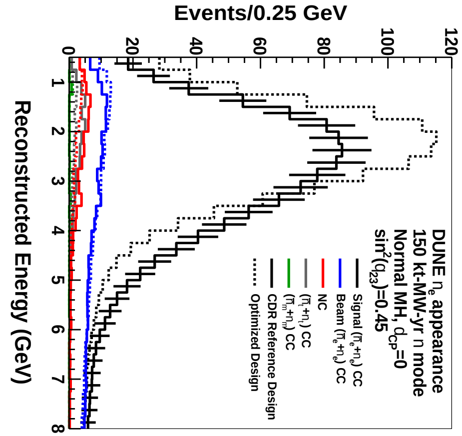


ν_μ



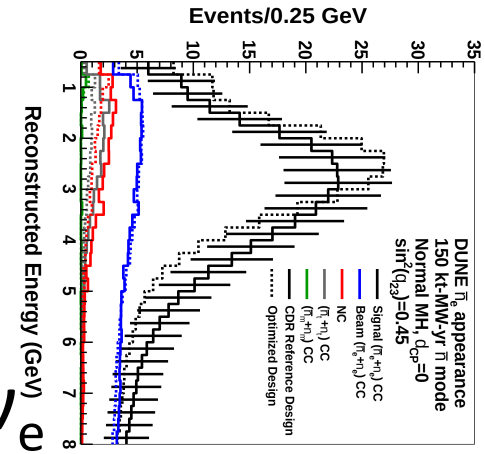
anti-ν_μ

electron-neutrino appearance



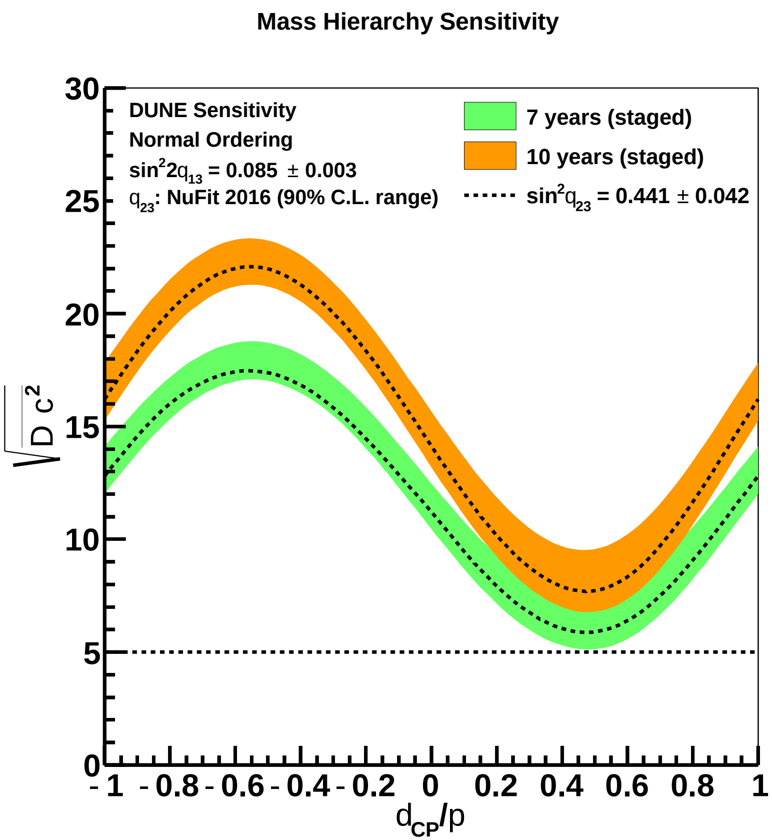
ν_e

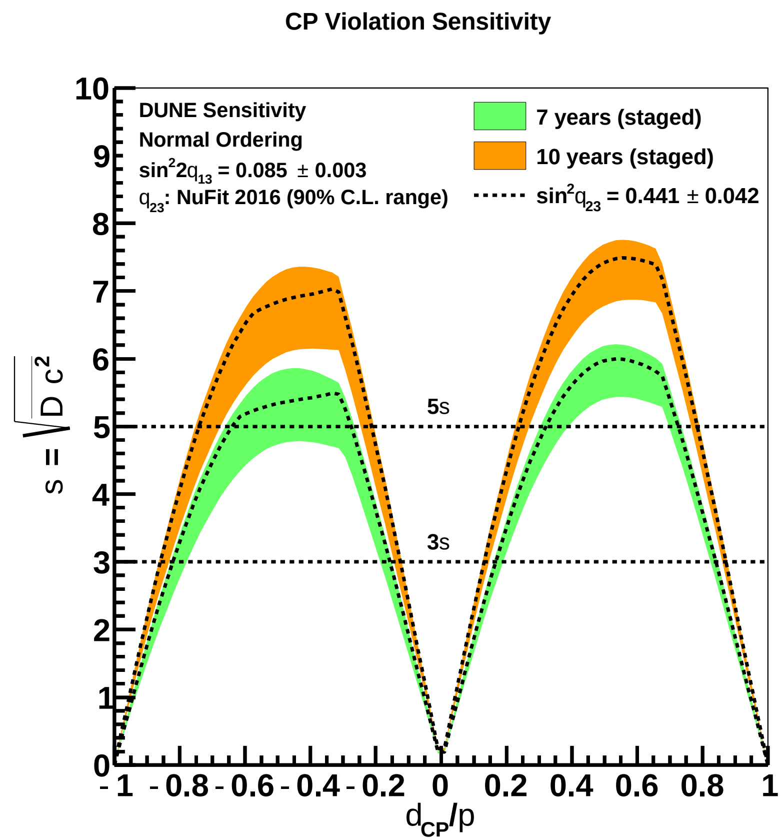
7 years of data



anti-ν_e

Mass ordering and CPV

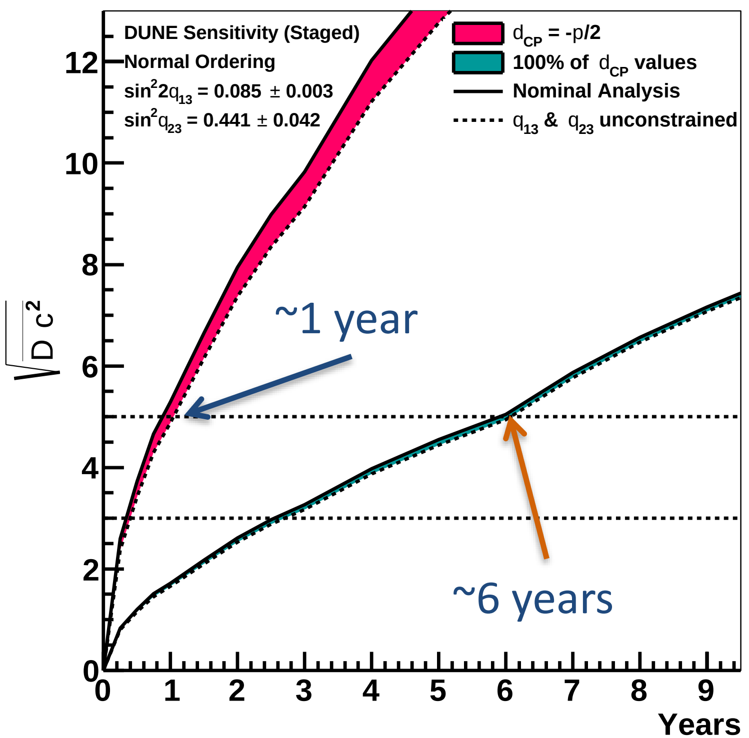




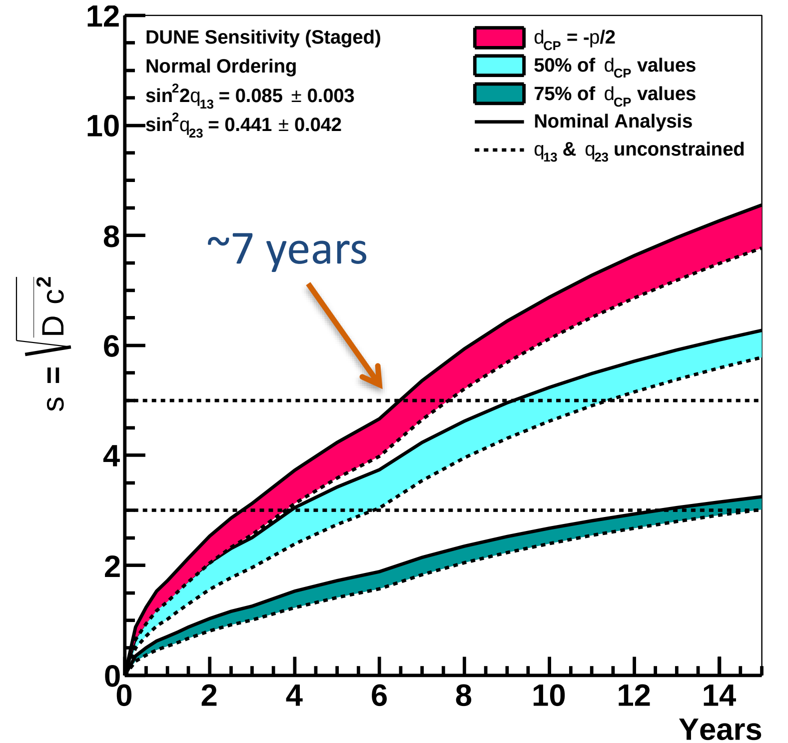
Width of the band represents the range of sensitivities for the 90% C.L. range in ϑ_{23} value

Sensitivity over time

Mass Hierarchy Sensitivity

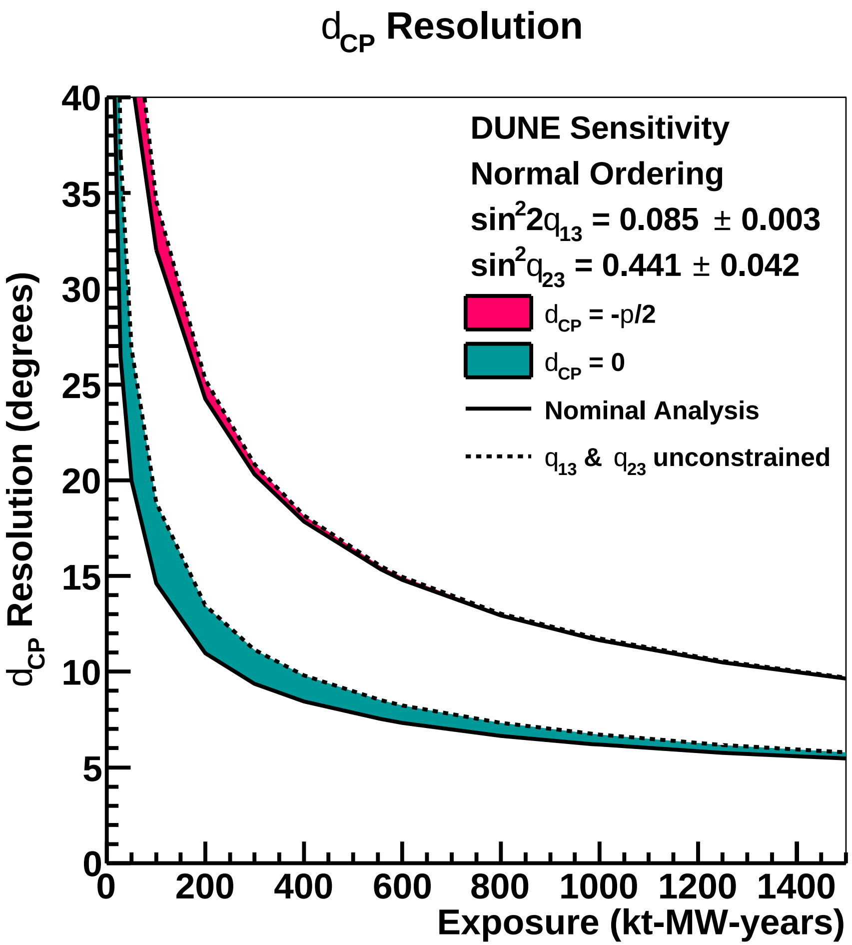


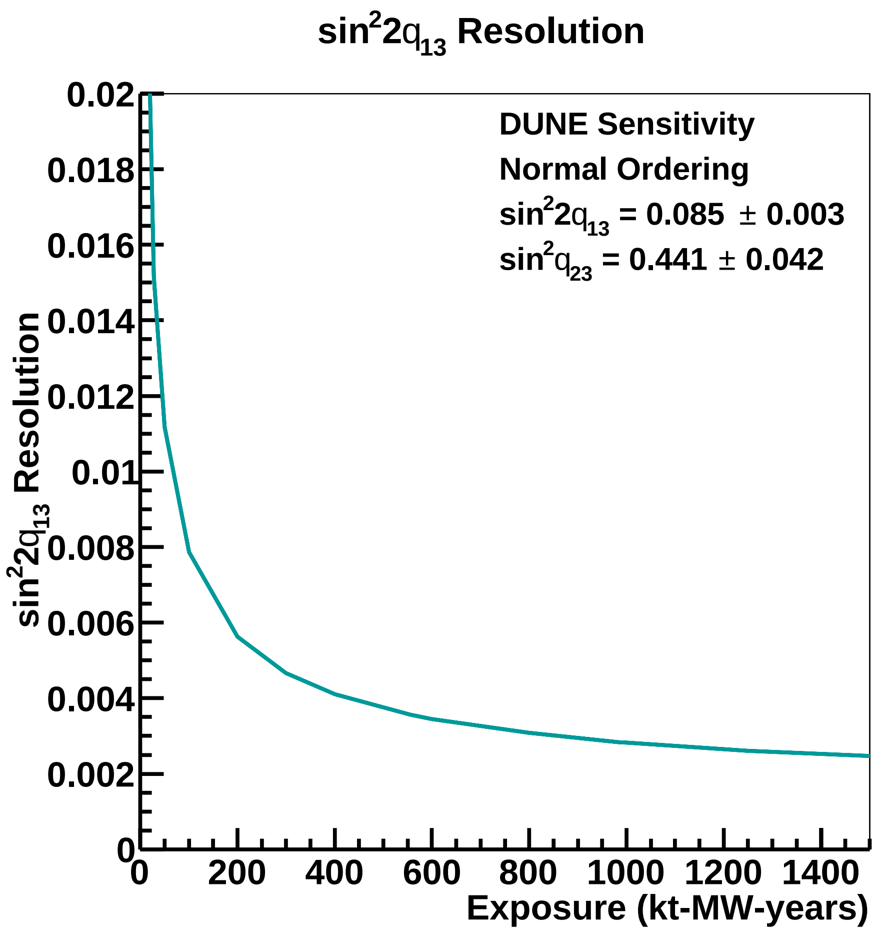
CP Violation Sensitivity



Staged approach: interesting measurements will be made throughout the DUNE physics programme!

Beyond discovery: precision measurements





Comparable precision to quark sector

DUNE Collaboration

1000 collaborators from 30 countries

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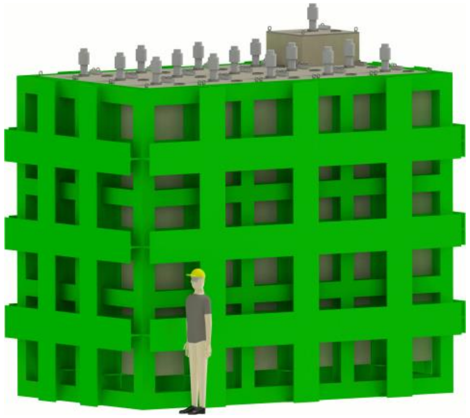
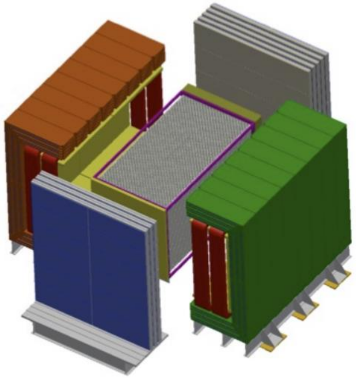
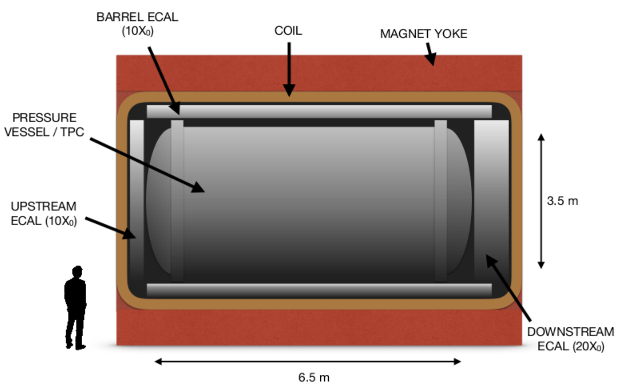
DUNE Near Detector options



- **Liquid Argon TPC**
  - Modular liquid argon design (ArgonCube) to provide identical near/far target
  - Short drifts and pixel readout to deal with high occupancy environment
- **Straw Tube Tracker**
  - NOMAD-inspired type fine grain tracker
  - Magnetized detector for sign discrimination



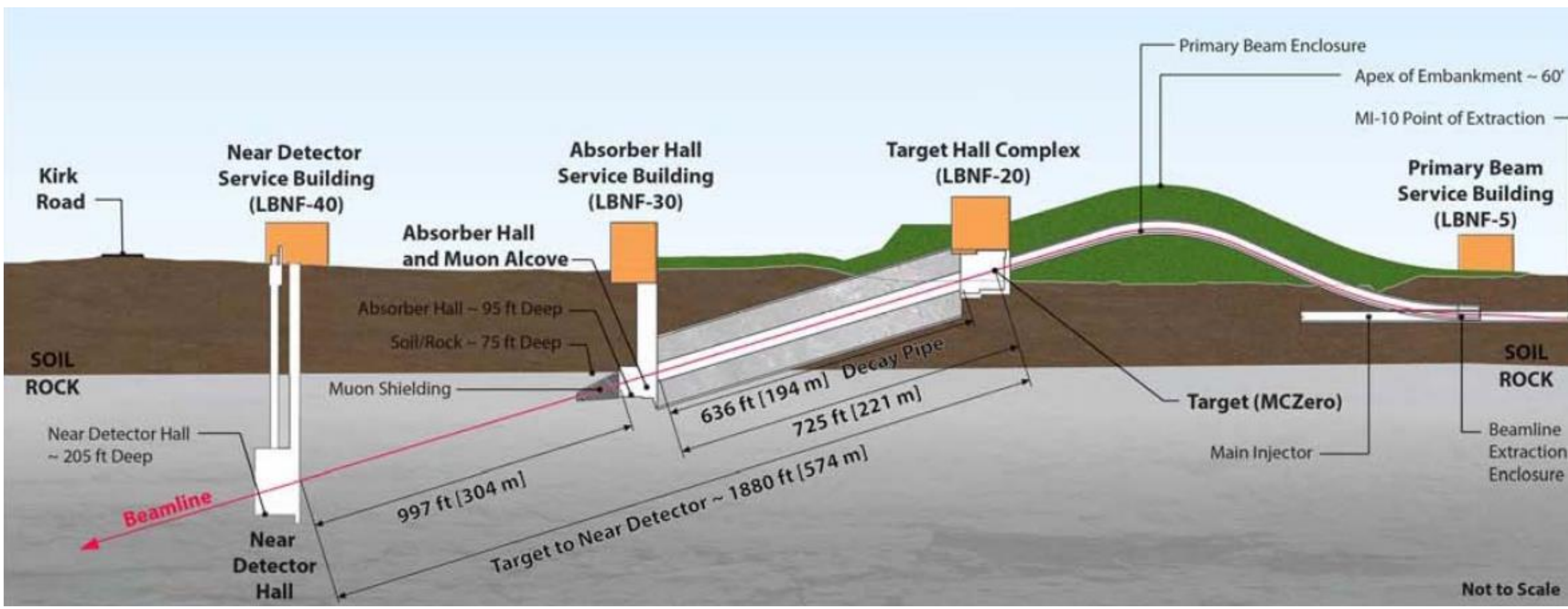
- **High Pressure Gas Argon TPC**
  - High pressure TPC keeps neutrino yield high while providing excellent 3d vertex information
  - Argon nuclear target allows for straightforward near/far extrapolation



- **Other technologies**
  - Scintillating Plastic Tracker
  - “DUNE-PRISM”

DUNE Near Detector

- A hybrid detector is definite possibility.
- Series of workshops to select options and prepare for CDR (2018), TDR (2020).
- Near Detector will be placed at about 575m downstream of beam.



DUNE Near Detector

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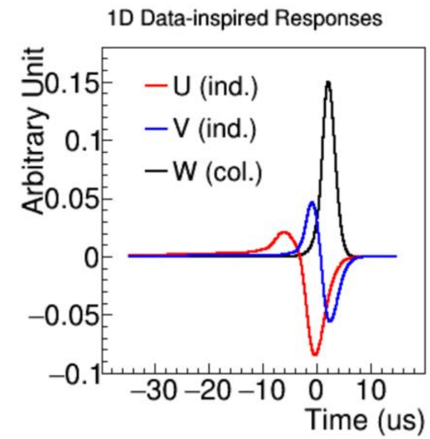
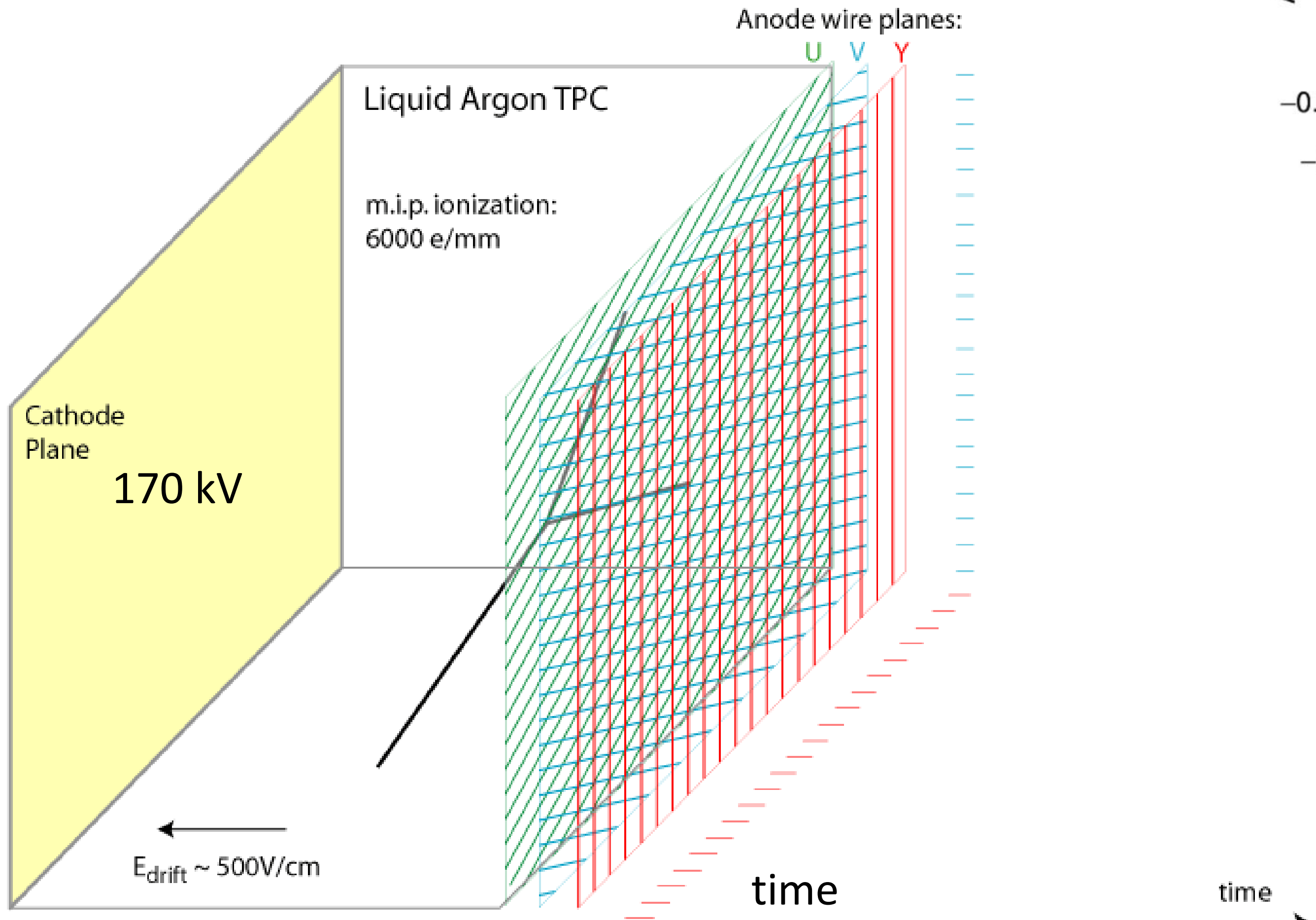
- Near Detector will be placed at about 575m downstream of beam.

The Near Detector will provide:

- constraints on cross sections and neutrino flux.
- a rich non-oscillation neutrino physics programme.
- >100 million interactions over a wide range of energies.
- strong constraints on systematics: the difference between 3% and 1% systematic can have as much as a 30% increase in the amount of required beam time for 5σ discovery of δ_{CP}

Time Projection Chamber (SP)

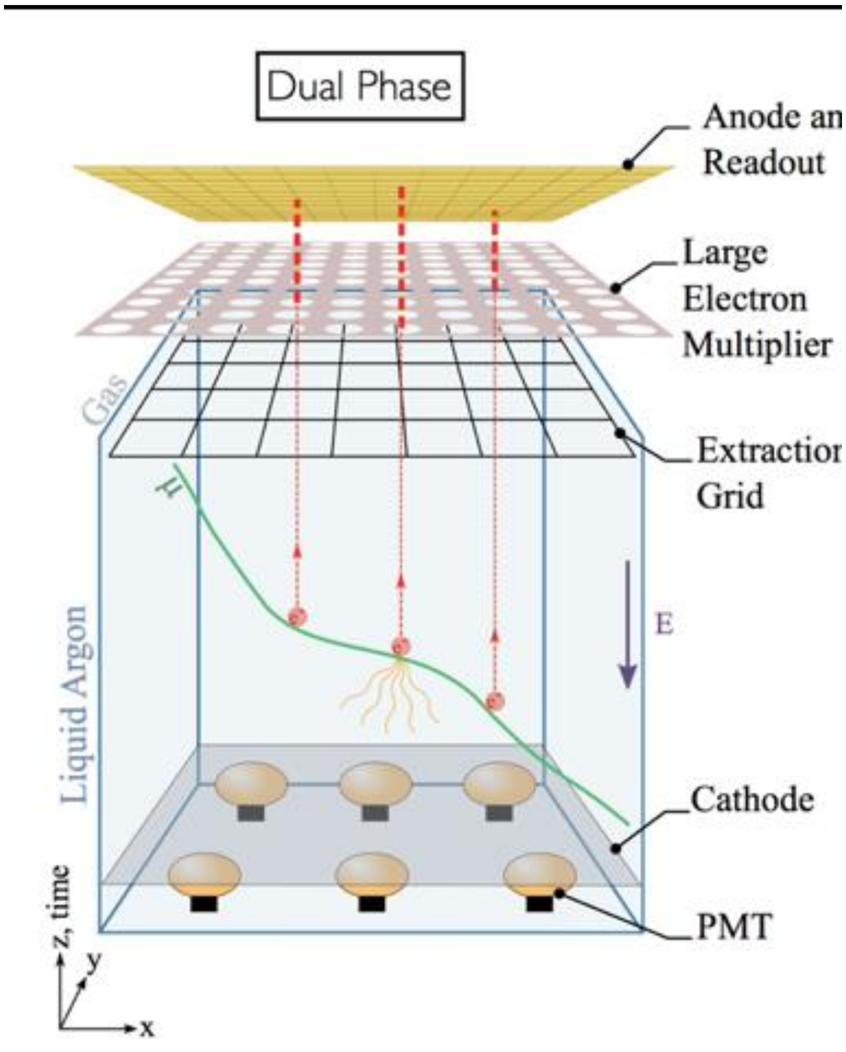




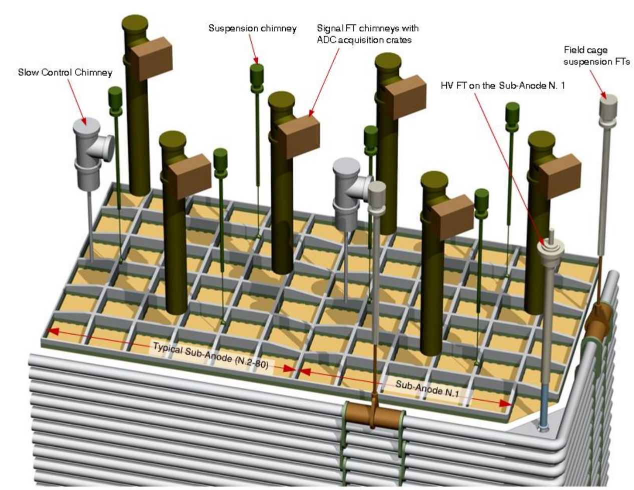
3.4 m → 2.13 ms

Stefan Söldner-Rembold

Time Projection Chamber (DP)

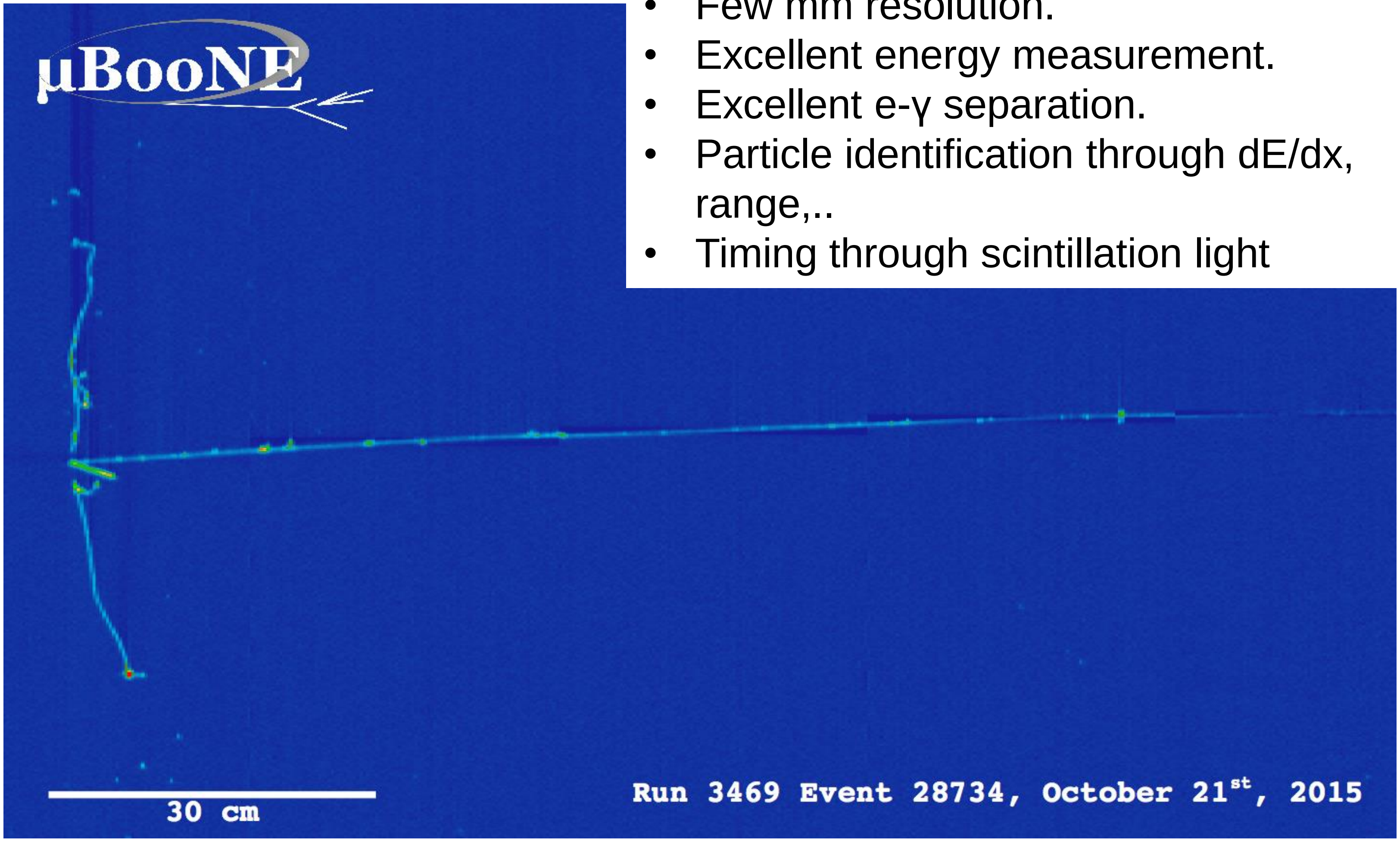


- Larger drift distance (12 m)– higher fields (300 kV)
- Potentially better signal to noise
- Readout/HV access through chimneys on top.

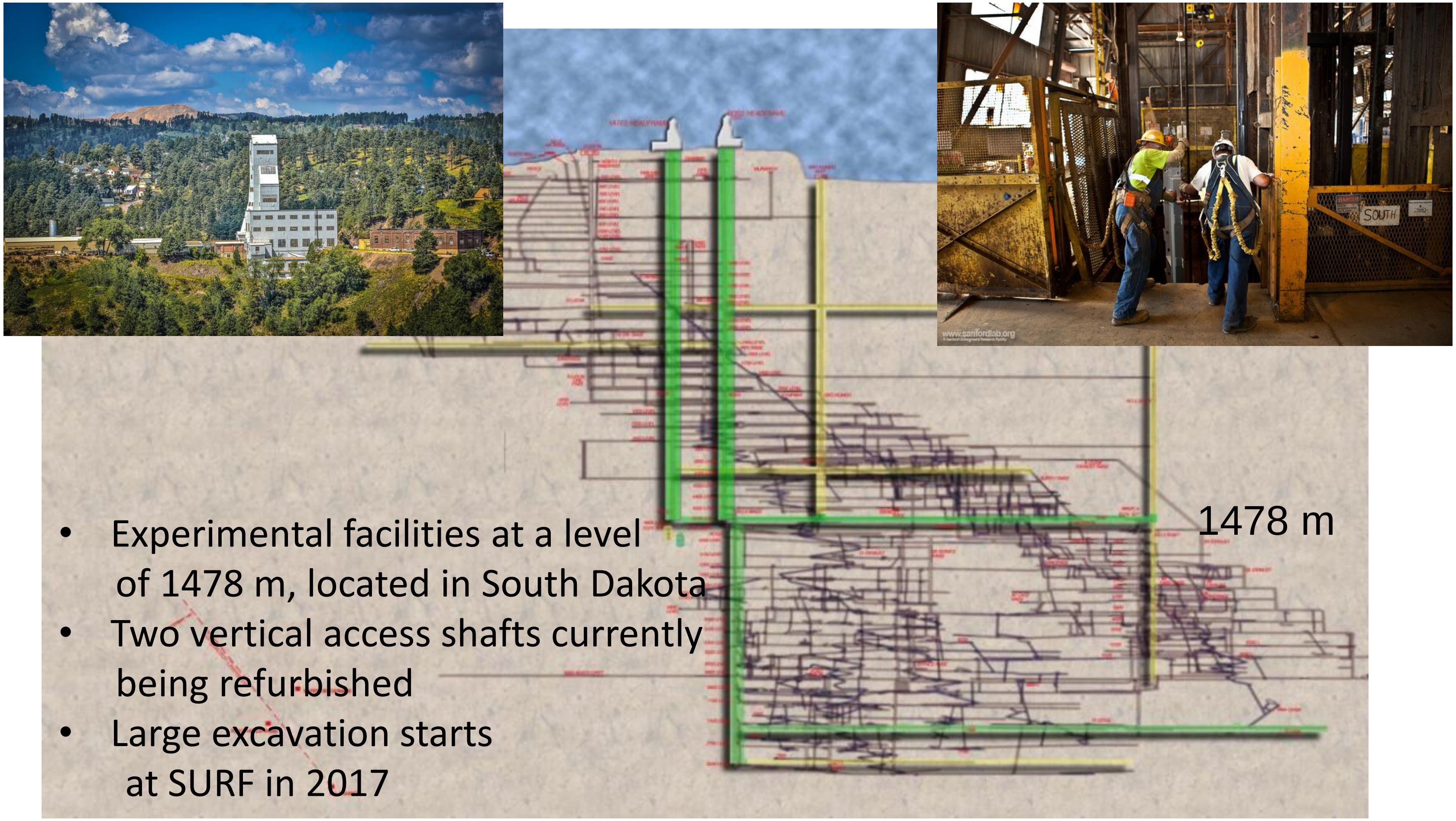


A liquid-argon “bubble chamber”

- Few mm resolution.
- Excellent energy measurement.
- Excellent e-γ separation.
- Particle identification through dE/dx, range,..
- Timing through scintillation light



Sanford Underground Research Facility (SURF)

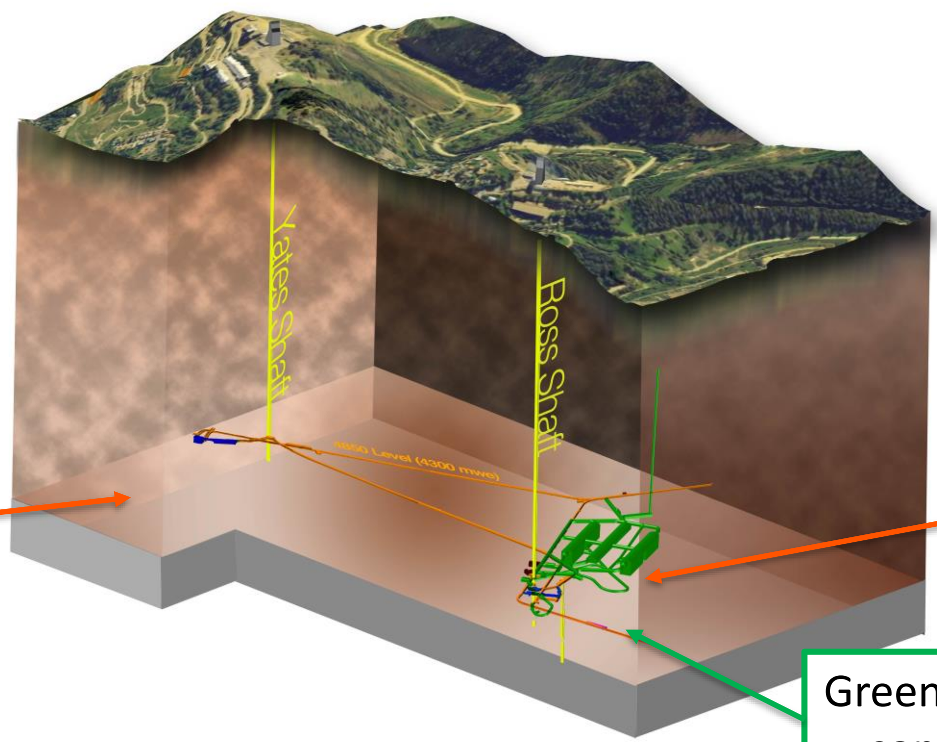


- Experimental facilities at a level of 1478 m, located in South Dakota
- Two vertical access shafts currently being refurbished
- Large excavation starts at SURF in 2017

Underground Laboratory SURF

DUNE Far Detector site

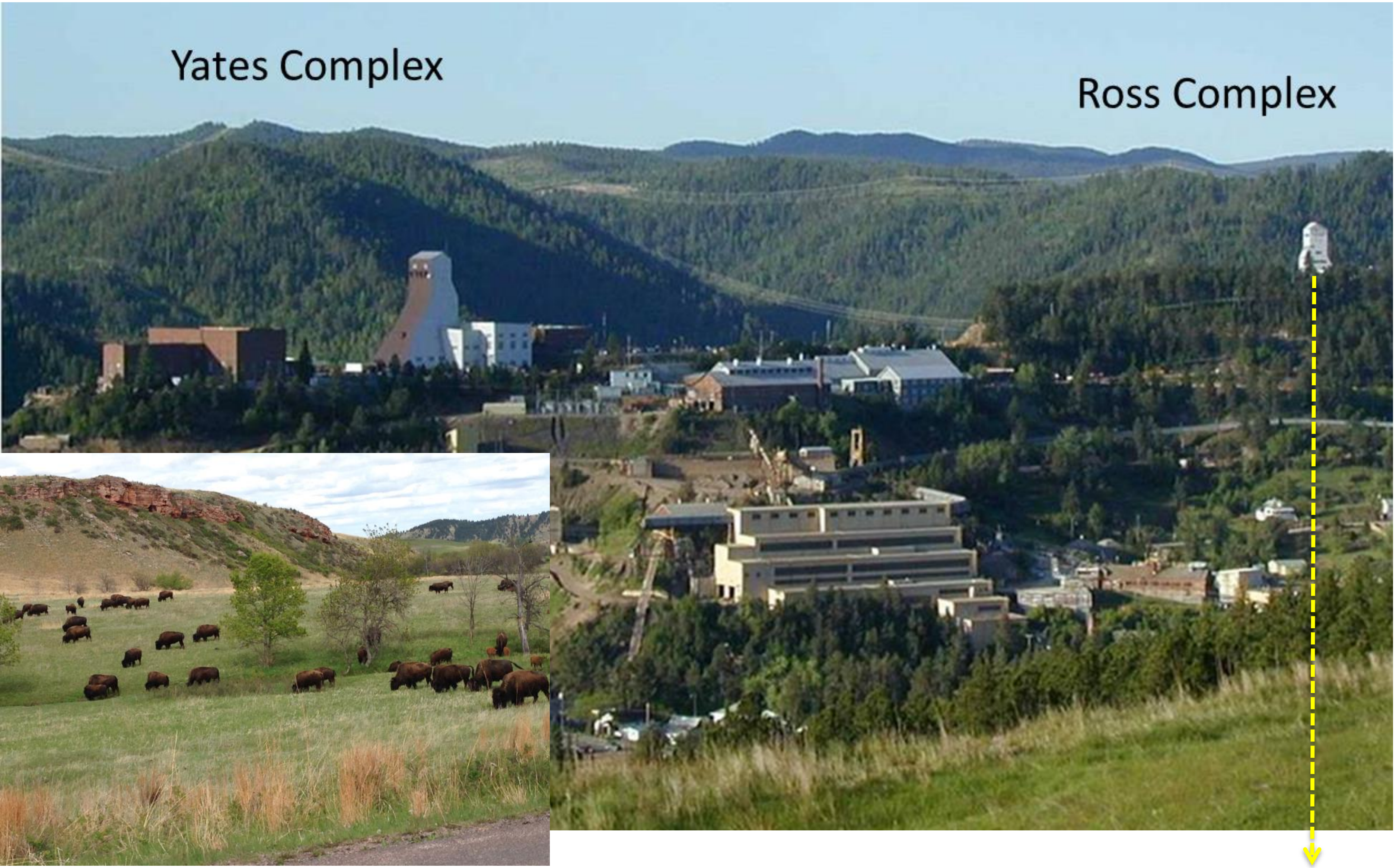
- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)



Davis Campus:
- LUX
- Majorana
- …
- **LZ**

Ross Campus:
- CASPAR
- …
- **DUNE**

Green = new excavation commenced in 2017


Yates Complex
Ross Complex



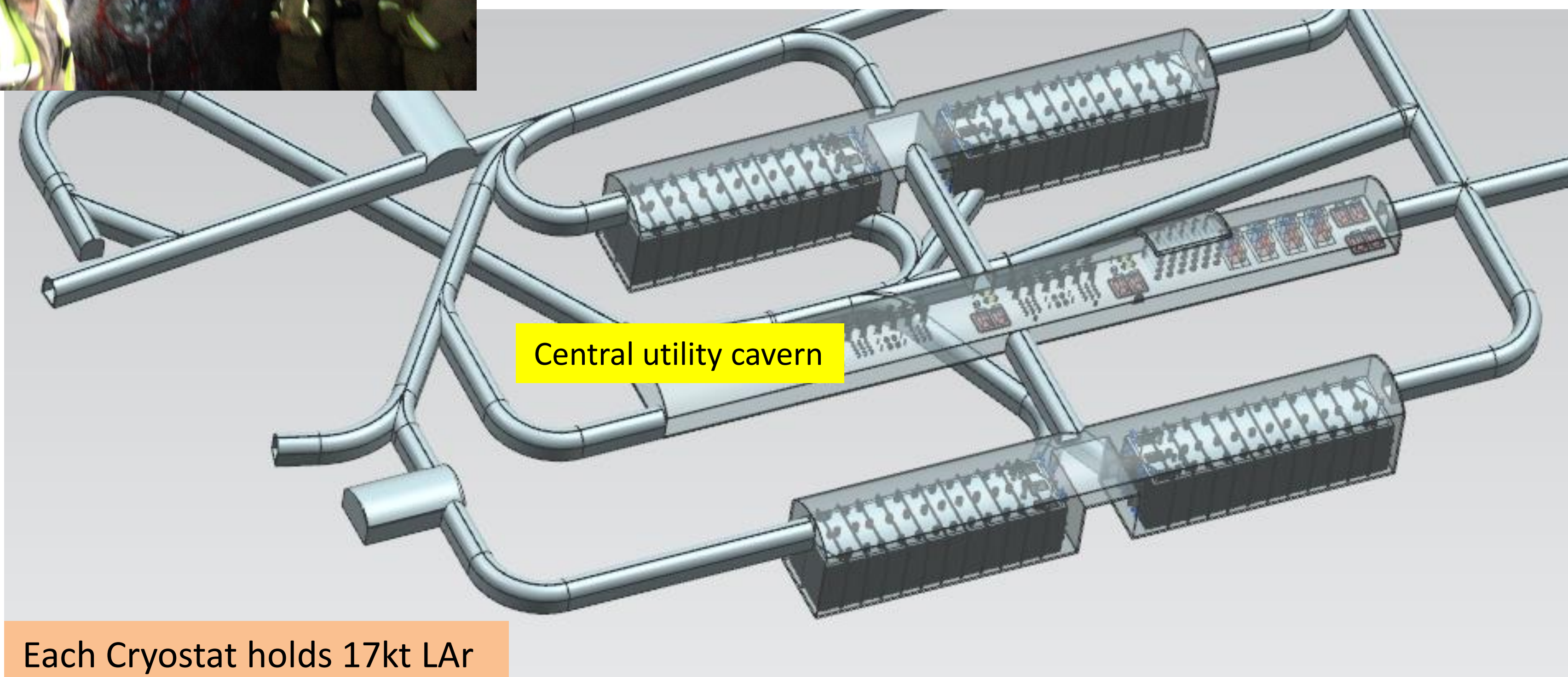

Far Detector lay-out

Four caverns hosting four independent 10-kt (fiducial mass) Far Detector modules:

Allows for staged construction of the Far Detector

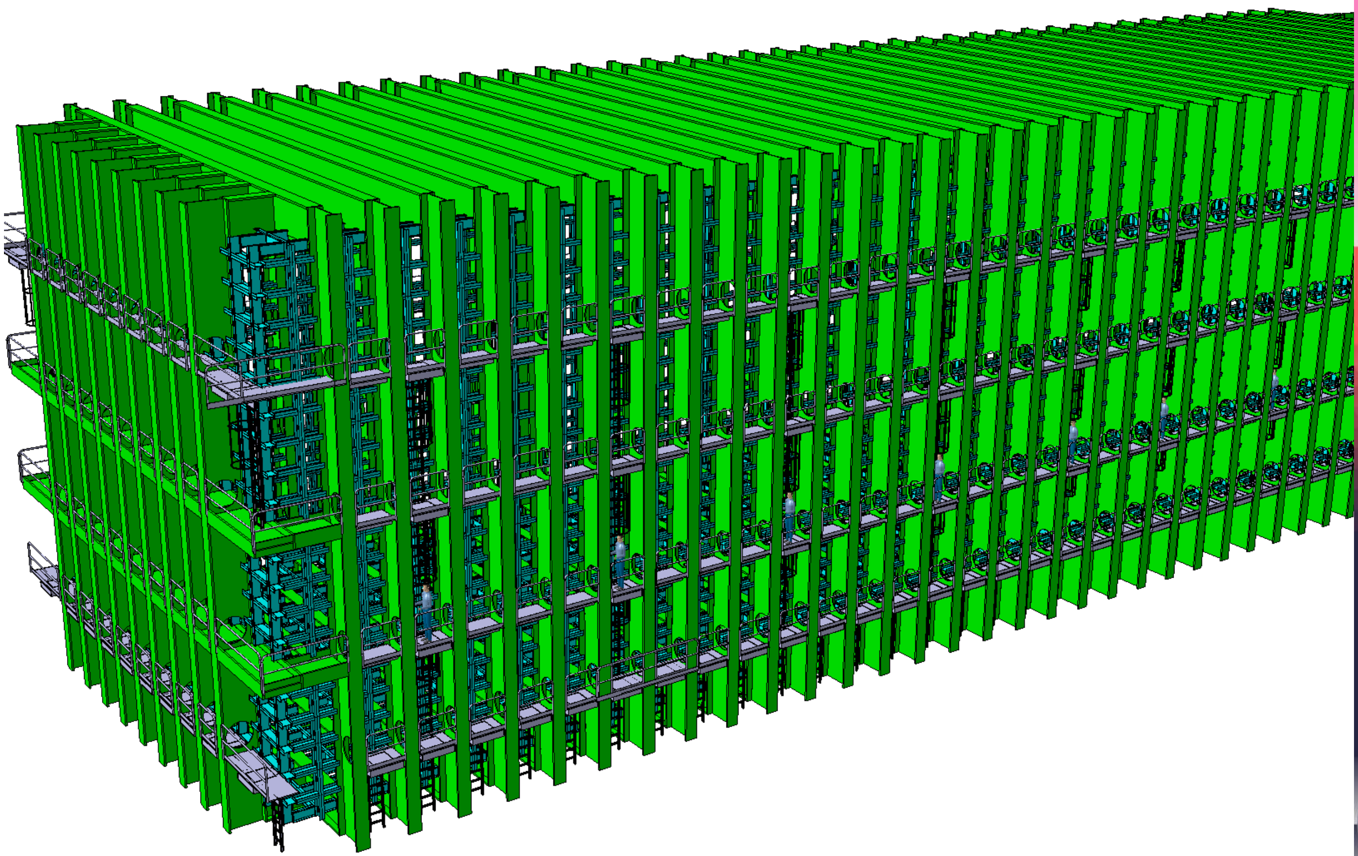
Gives flexibility for evolution of LArTPC technology design

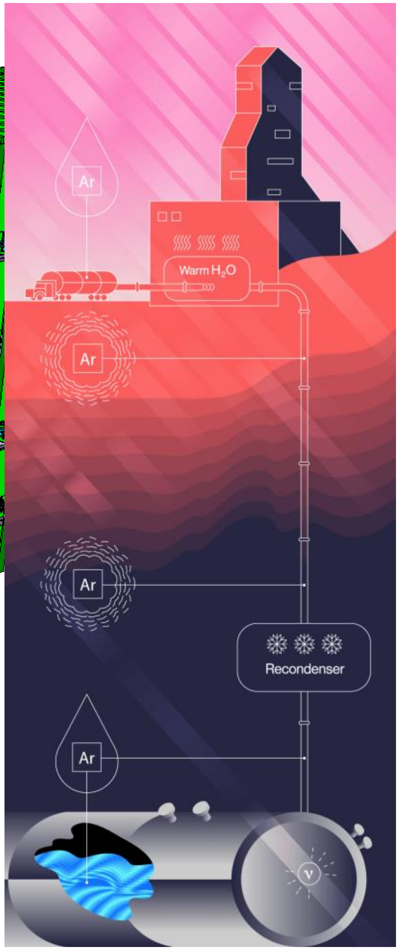
- Four identical cryostats: 15.1 (W) x 14.0 (H) x 62 (L) m^3
- Four 10-kt modules will be similar but not identical



Each Cryostat holds 17kt LAr

Free-standing steel cryostat

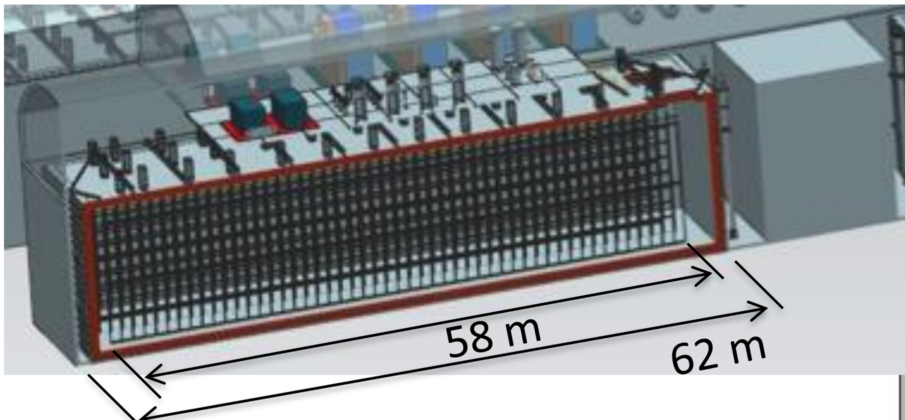


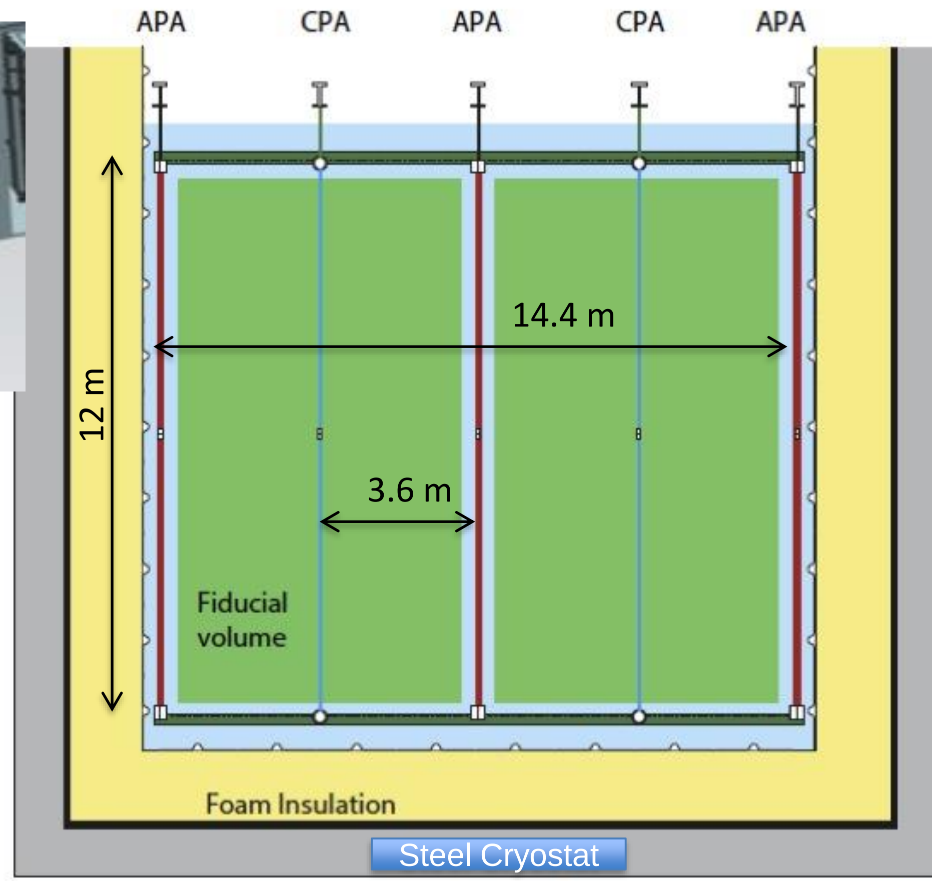


External Dimensions: 19.1m x 18.0m x 66.0m

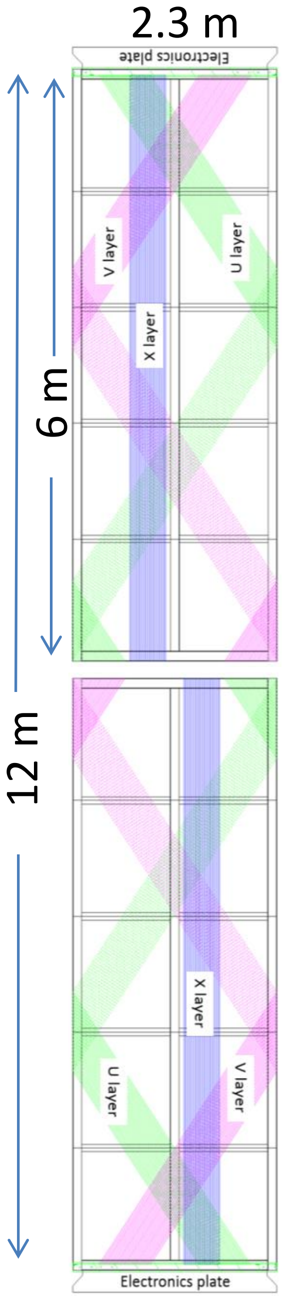
2000 trucks with 20 ton of LAr

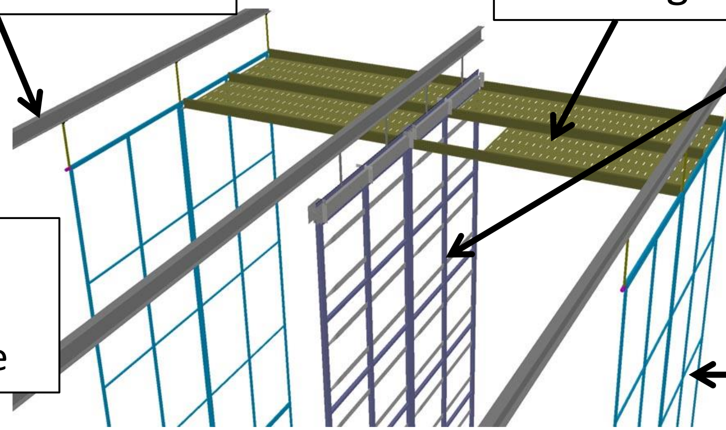
First Detector: single-phase



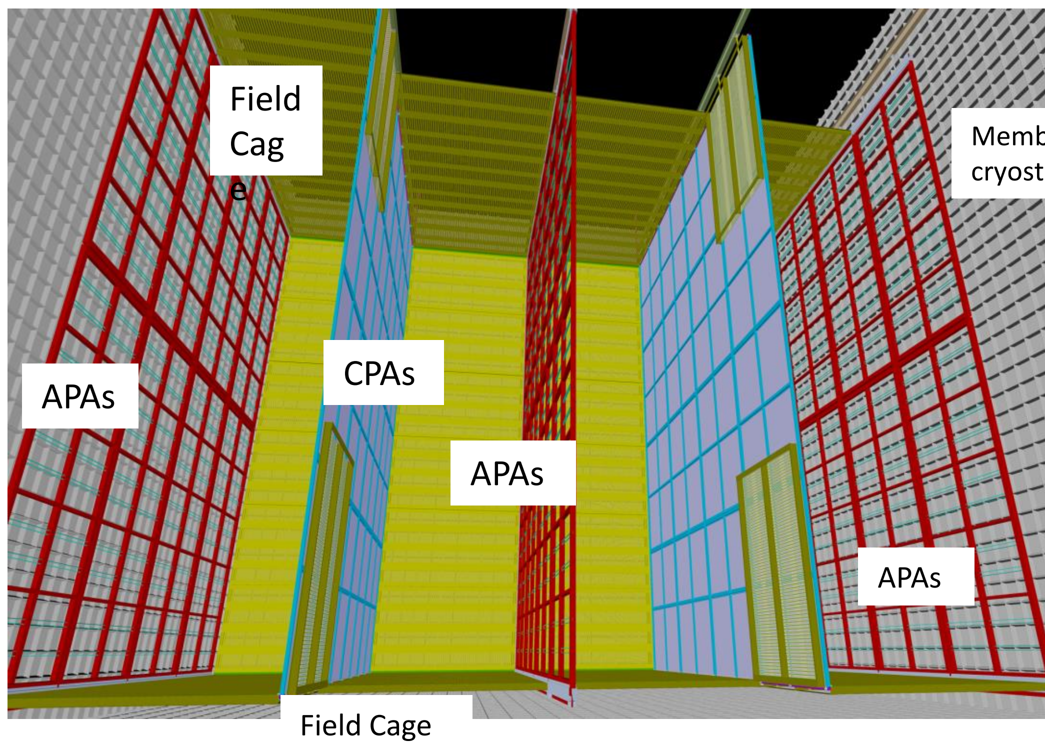


- 3 Anode Plane Assemblies (APA) wide (wire planes)
  - Cold electronics 384,000 channels
- Cathode planes (CPA) at 180 kV
  - 3.6 m max drift length



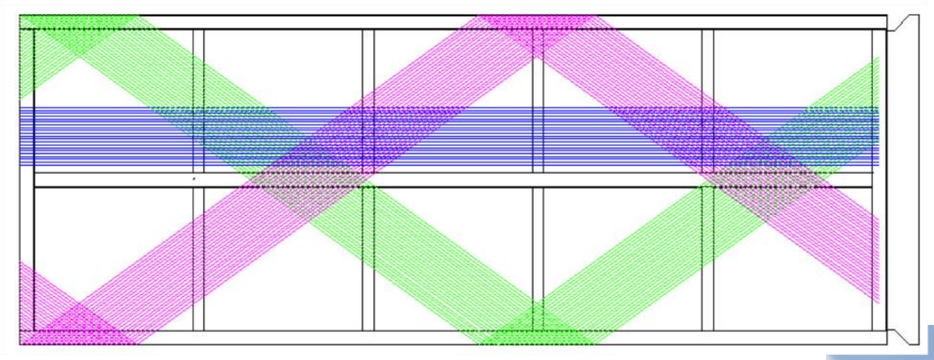


- wrapped wires
- 2 induction & 1 collection plane



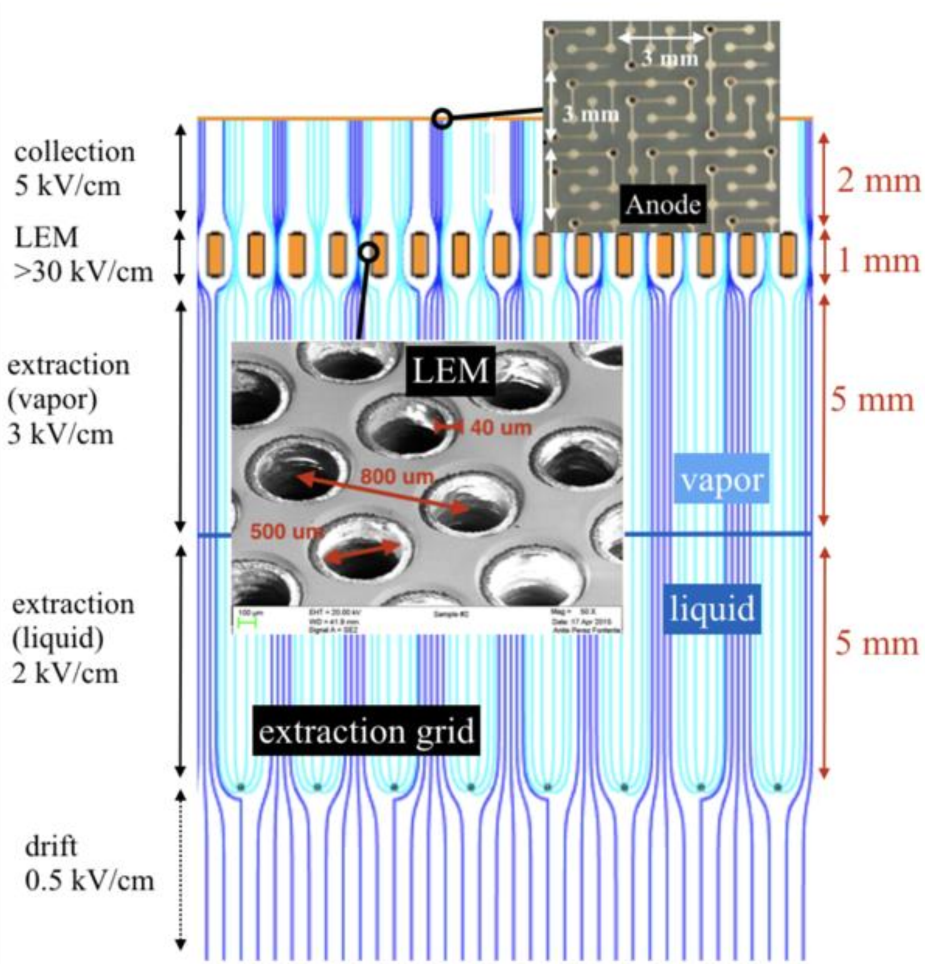
APA Construction Sites

- 150 APAs and 200 CPAs per module.
- Large production site being set up at Daresbury Laboratory (UK) between Manchester and Liverpool.
- At least 2 Production Sites in US.



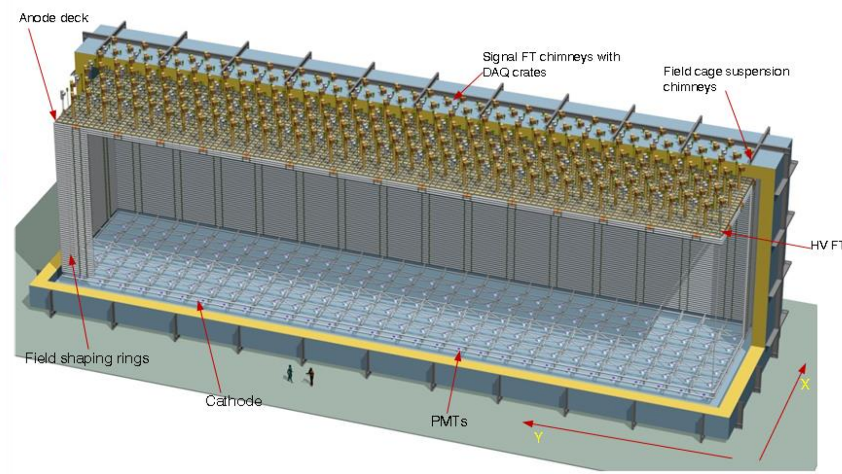
Delivery of first protoDUNE

Second Detector: Dual-phase

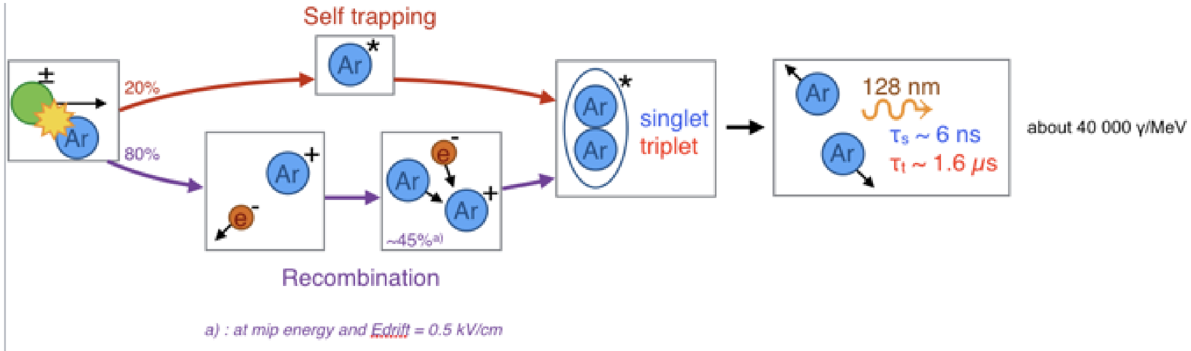


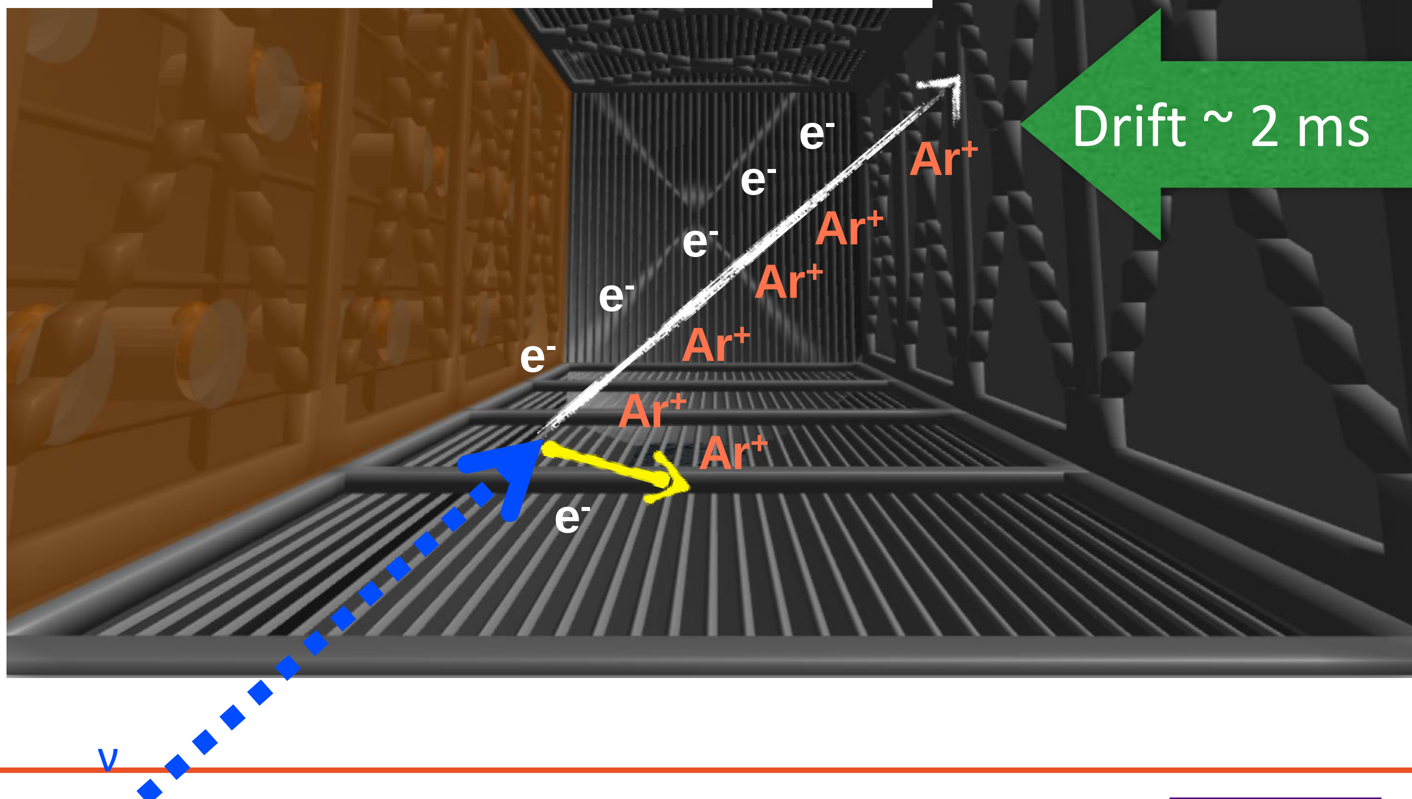
Current staging plan

- First 10 kt module will be SP
- Second 10 kt module will be DP

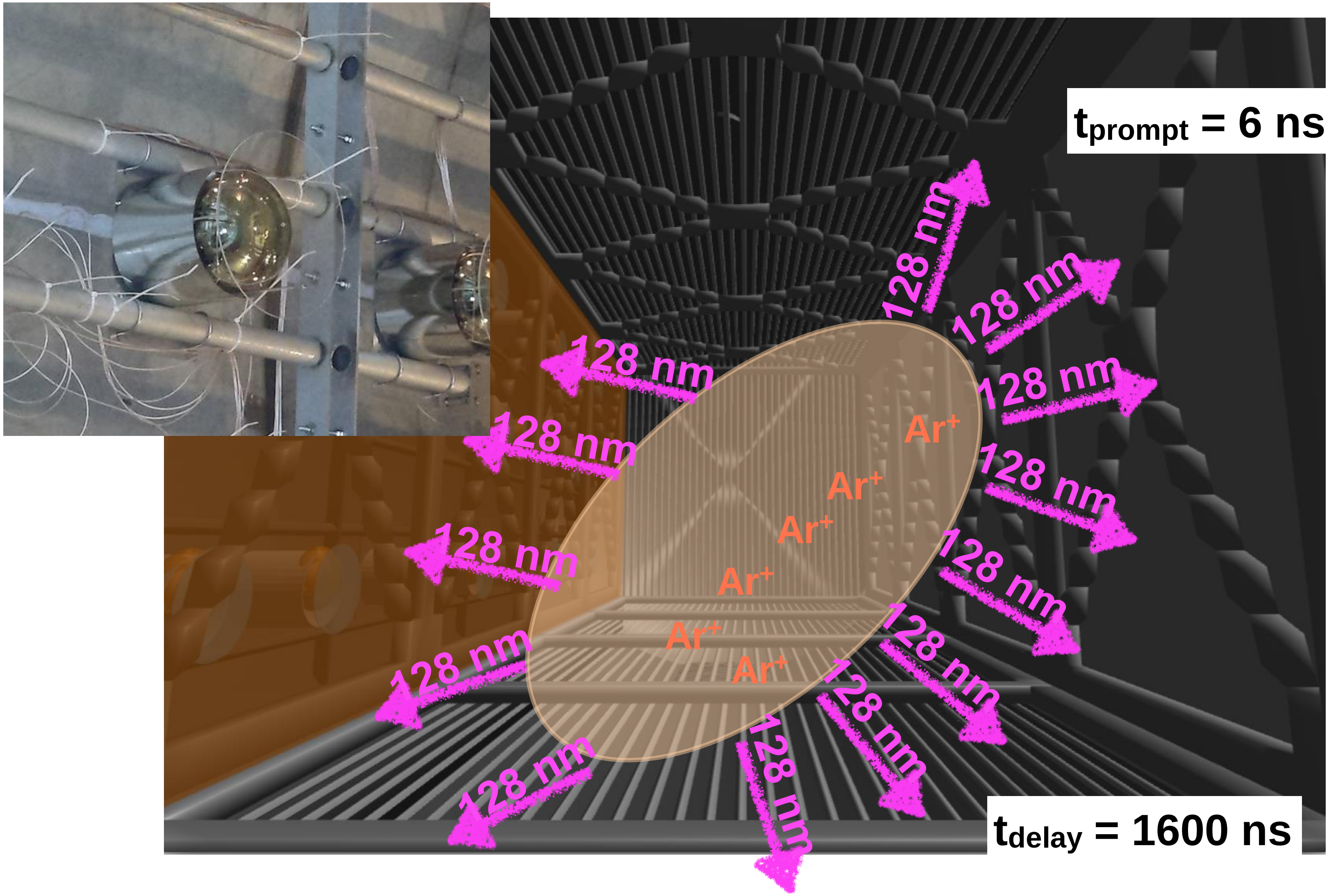


Photon detection



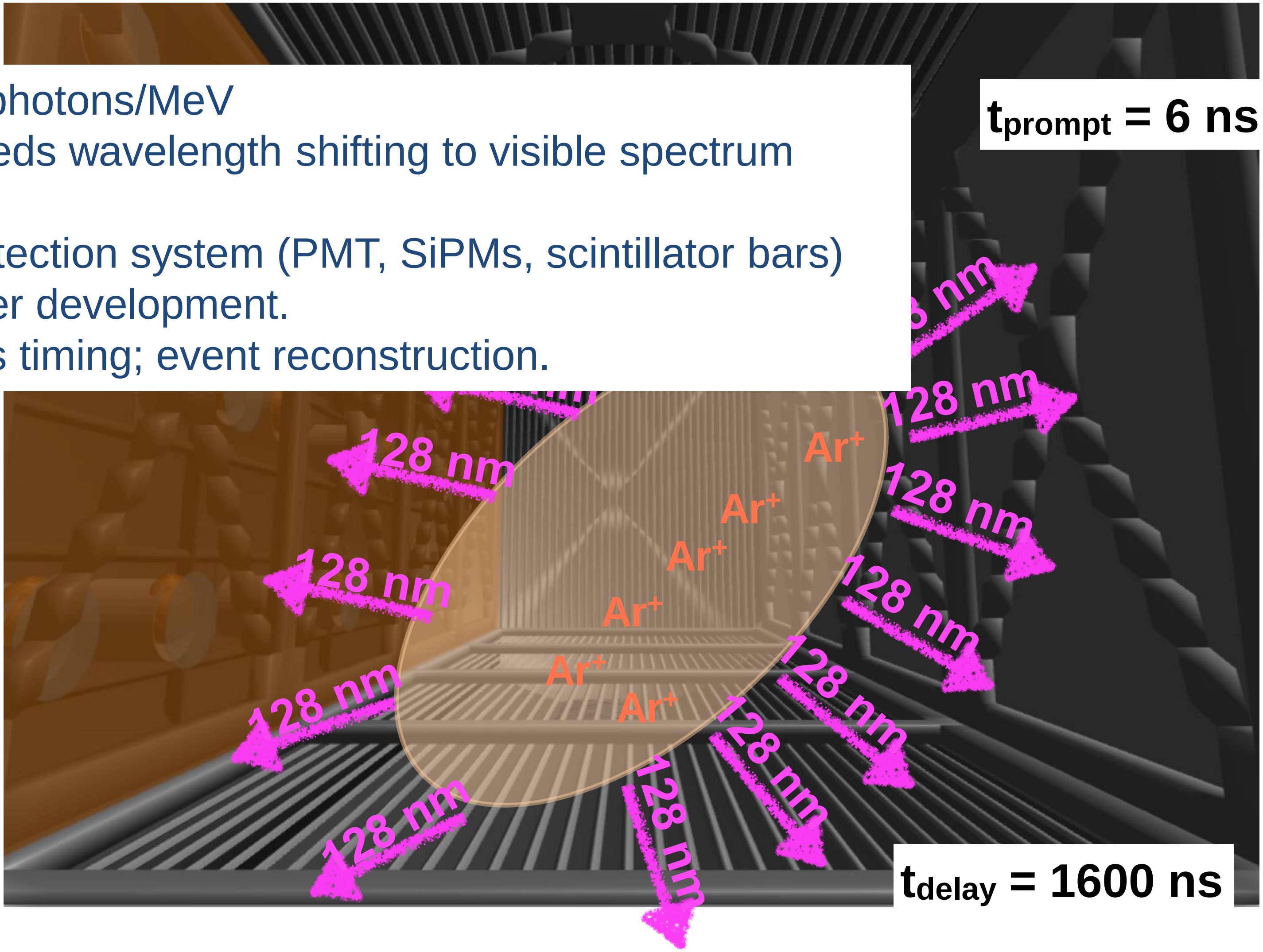


Photon detection



Photon detection

- 20,000 photons/MeV
- VUV needs wavelength shifting to visible spectrum (TBP).
- Light detection system (PMT, SiPMs, scintillator bars) still under development.
- Provides timing; event reconstruction.



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DUNE

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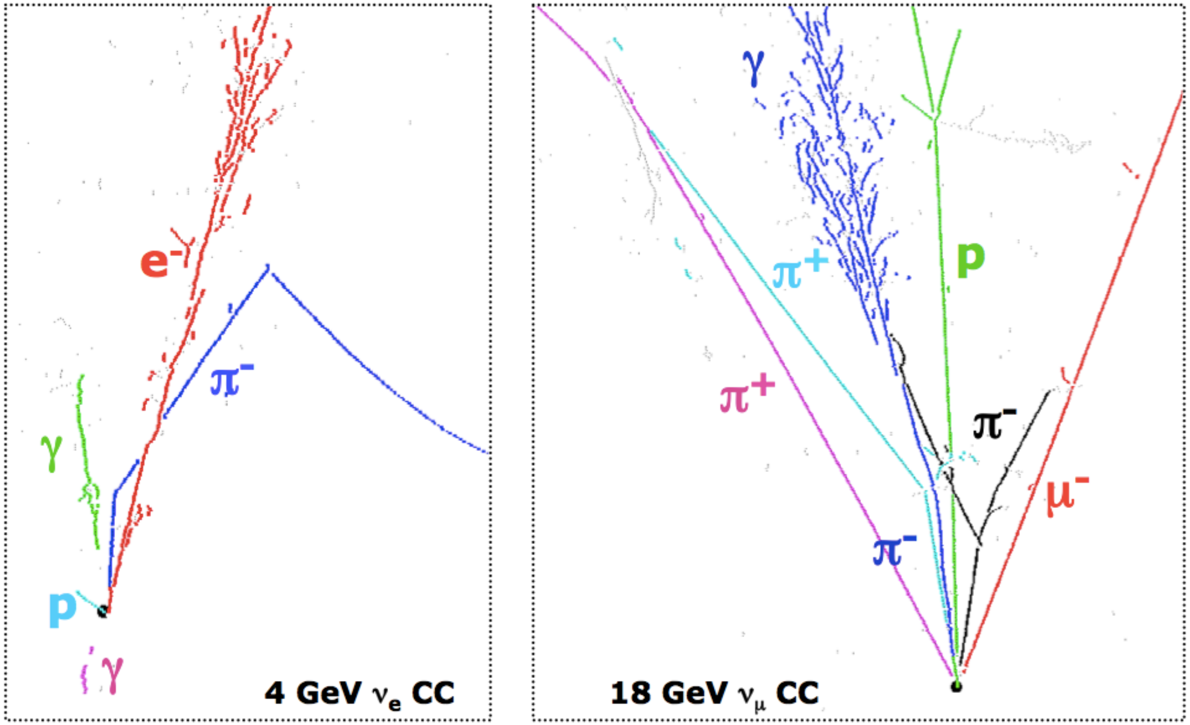
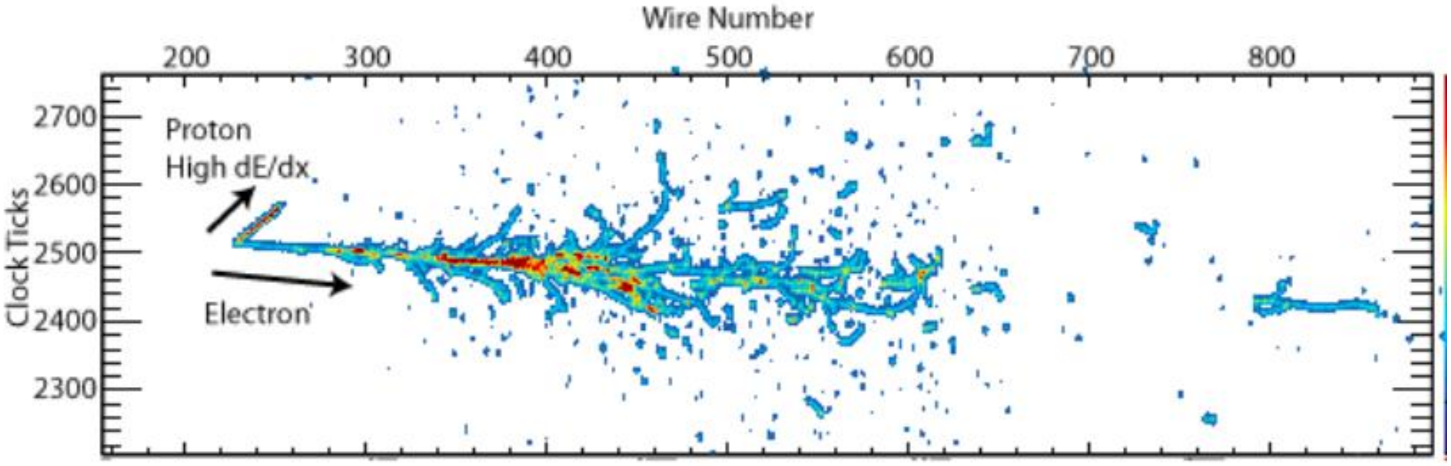
Other challenges: event reconstruction



- Need to reconstruct tracks and showers, measure their energy and perform particle identification.
- Complex event topologies require sophisticated algorithms (e.g., CNNs).

Other challenges: data acquisition



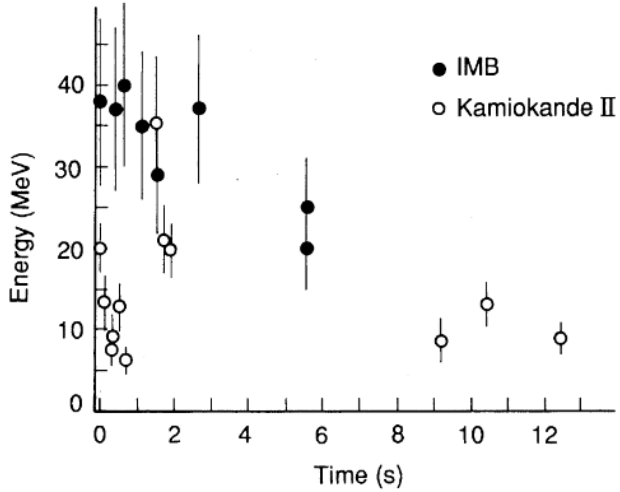
Detector always live

- Pre-trigger TPC data rate of about 1 TB/s.
- Low underground event rate (one beam spill per second, one cosmic ray per minute) allows online data processing.
- Supernova trigger: 10 TB over 10 s.

Non-beam physics in DUNE – supernova neutrinos

Astrophysical neutrinos, e.g. from a galactic supernova, probe physics at astrophysical scales:

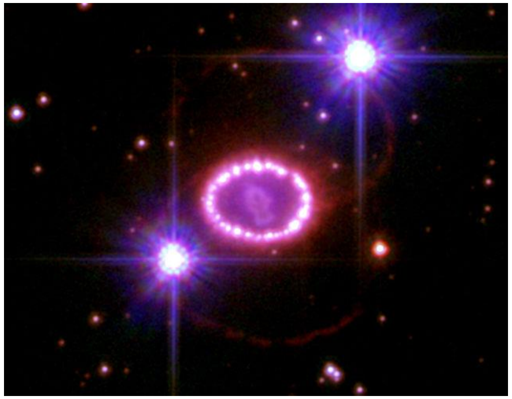
- 99% of the binding energy of a core-collapse supernova emitted through neutrinos (0.01% as light).
- Probes both supernova properties and neutrino physics.



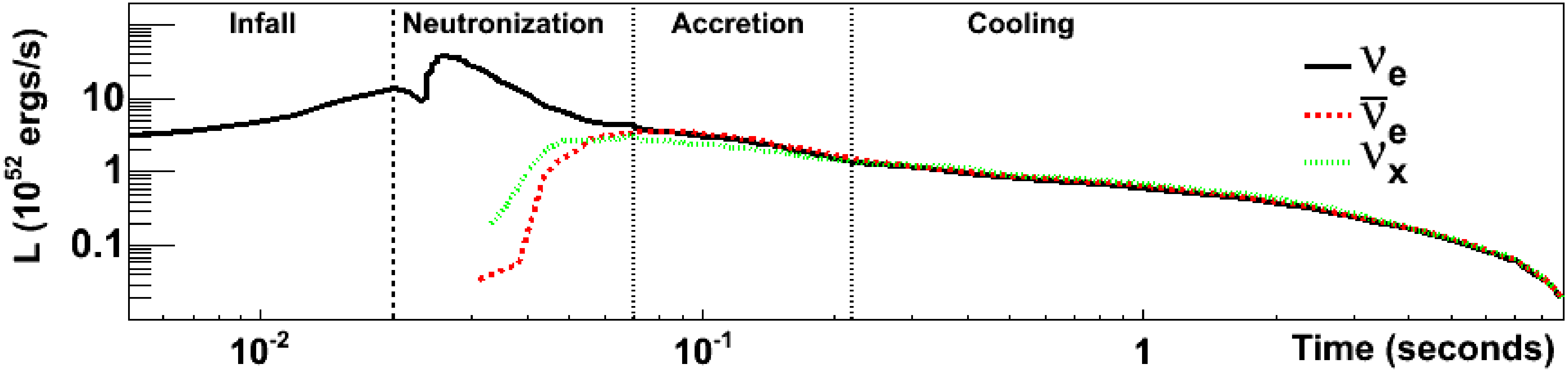
SN1987A, about 24 neutrinos observed, 3 hours before photons.

Core-collapse supernova

- Neutrino emission lasts ≈10 sec
- 1-3 SNs/century in our Galaxy (≈10 kpc)



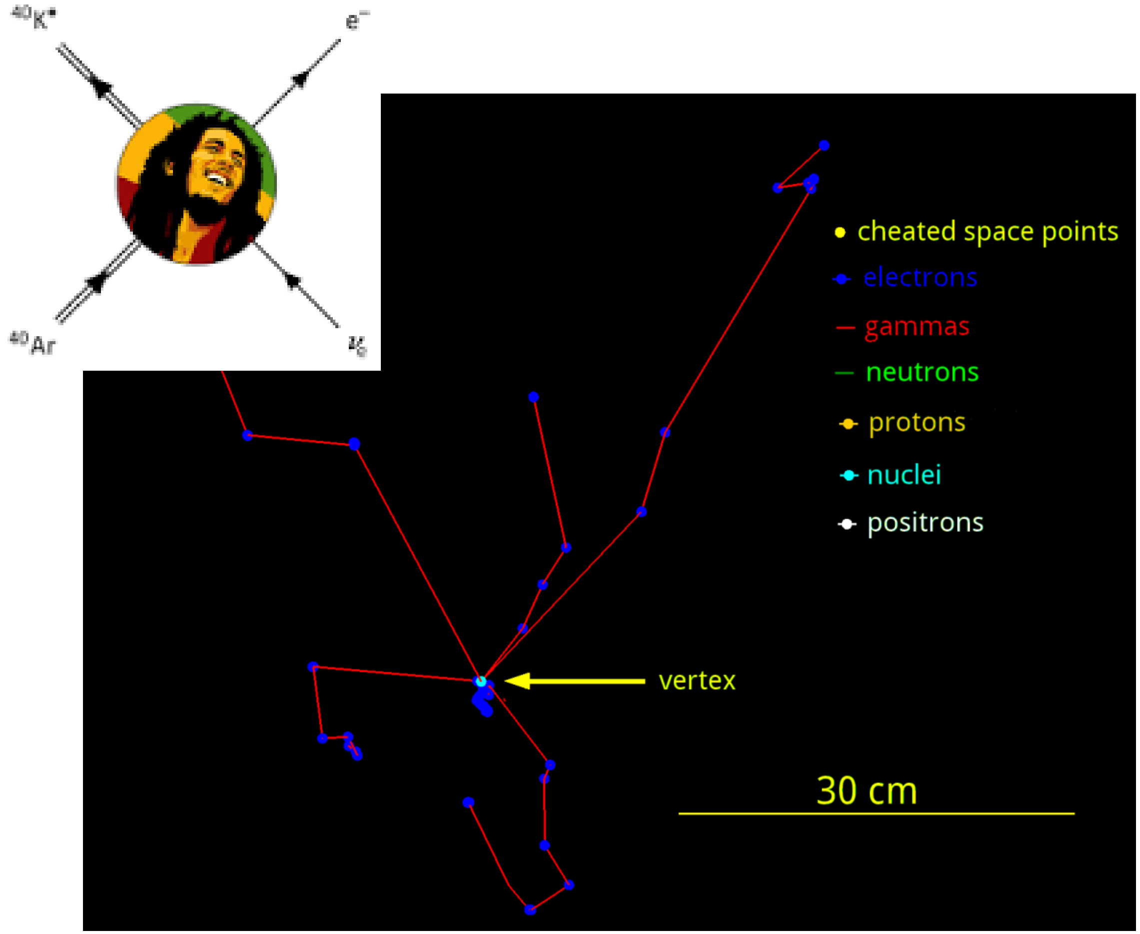
SN1987A: detected ≈ 20 neutrino events in total (essentially anti-ν_e)



Supernova neutrino signal in LAr

Main detection process:

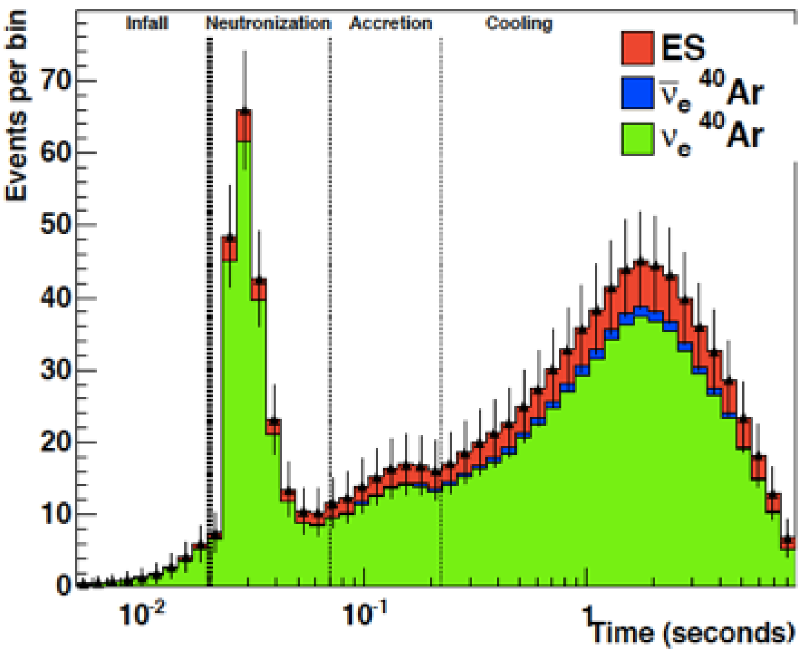
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



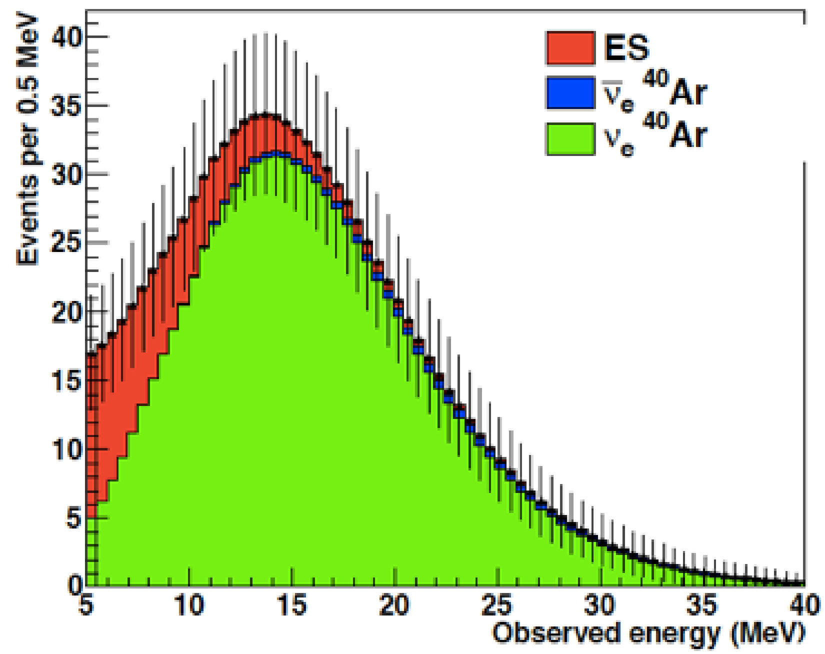
- Reconstruct photons from nuclear de-excitations.
- Need to understand underlying nuclear physics.
- Possible low-energy background from ^{39}Ar.

SN neutrino spectra in DUNE

- SN at 10 kpc in DUNE (40 kt)
- Strong dependence on MH
- Required energy resolution < 10%
- Energy threshold ~ 5 MeV



Time-dependent signal

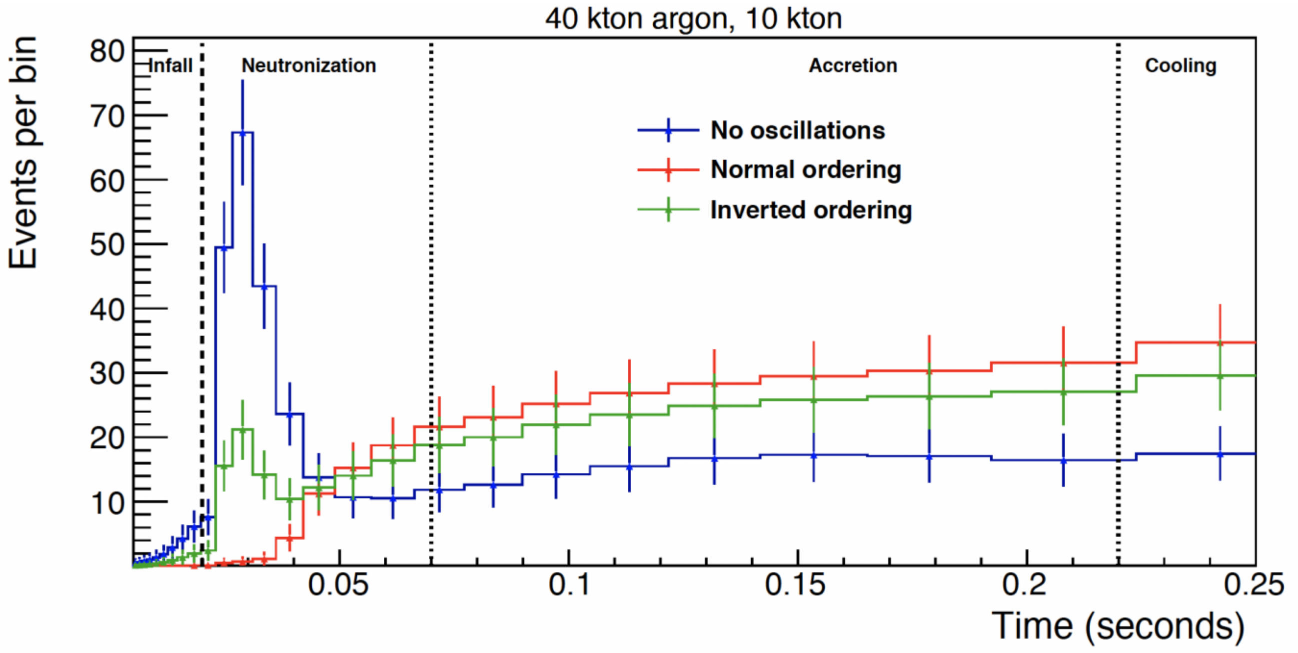


Time-integrated energy spectrum

Garching model, ICARUS energy resolution, 5 MeV threshold

SN neutrino spectra in DUNE

- SN at 10 kpc in DUNE (40 kt)
- Strong dependence on MH
- Required energy resolution < 10%
- Energy threshold ~ 5 MeV



Time-dependent signal

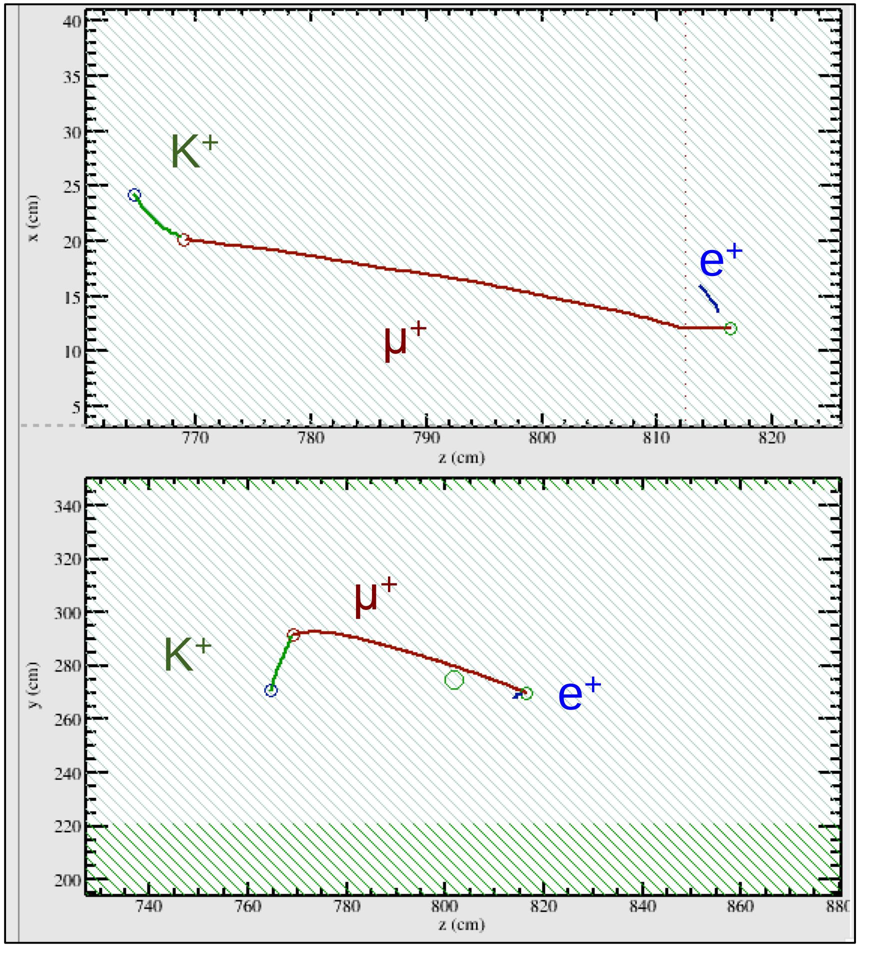
Garching model, ICARUS energy resolution, 5 MeV threshold

"Instant" determination of mass hierarchy

Nucleon decay

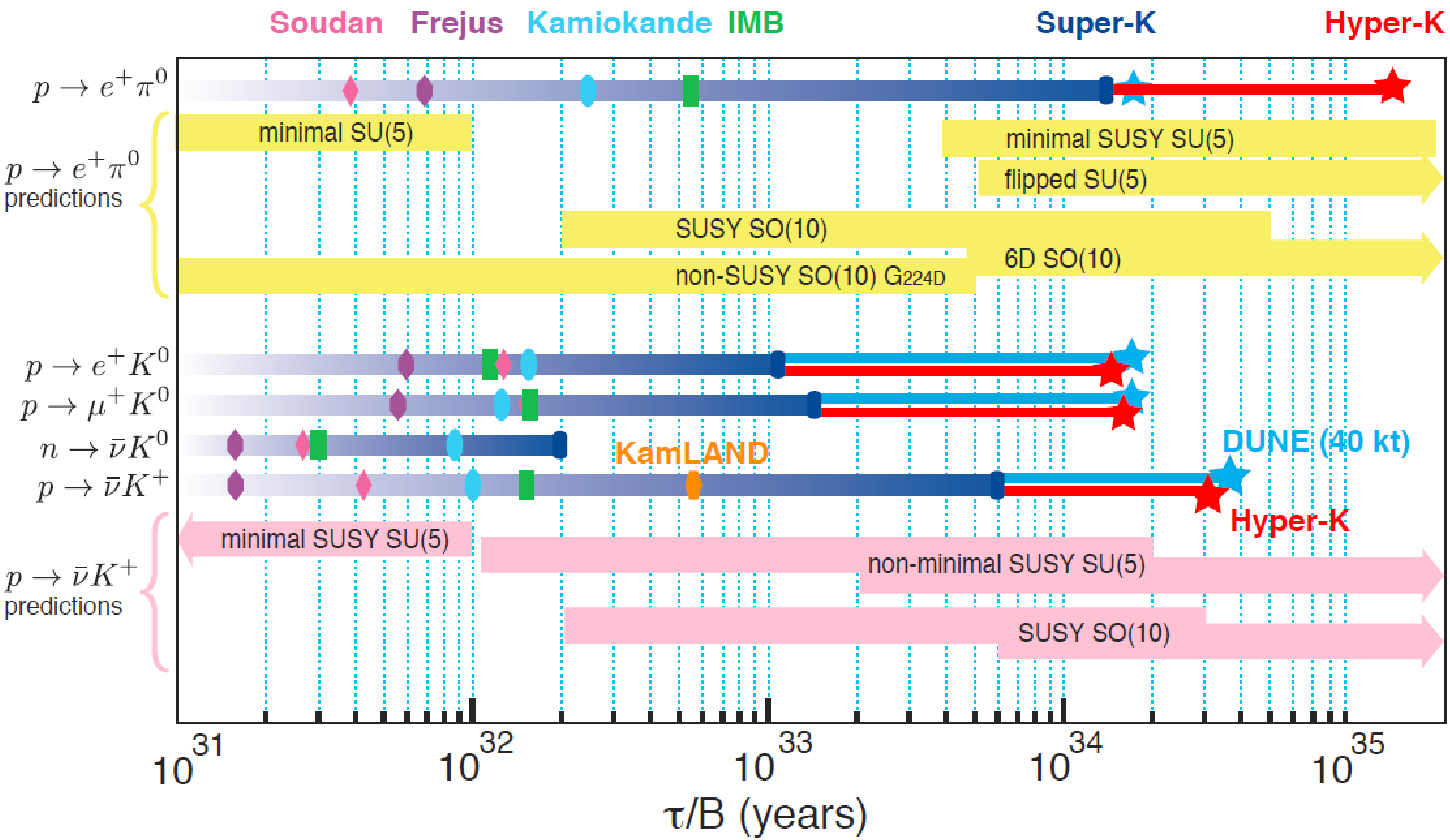
- Test of **fundamental symmetries**
  - Matter-antimatter asymmetry requires baryon number non-conservation (Sakharov Conditions)
- Well-motivated Grand Unification Theory models suggest **proton decay** may exist and be observable
  - GUTs make specific predictions about proton decay modes and branching fractions that can be tested in DUNE
- Many possible decay modes, kaon modes best suited for argon. Almost background free

Simulated p → νK⁺ event:



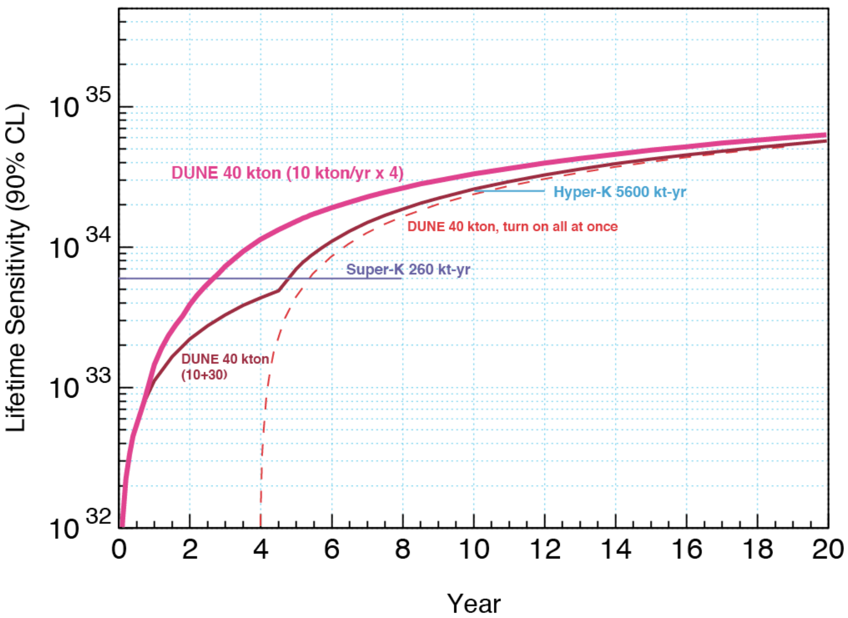
MANCHESTER 1824 DUNE

Proton Decay Searches

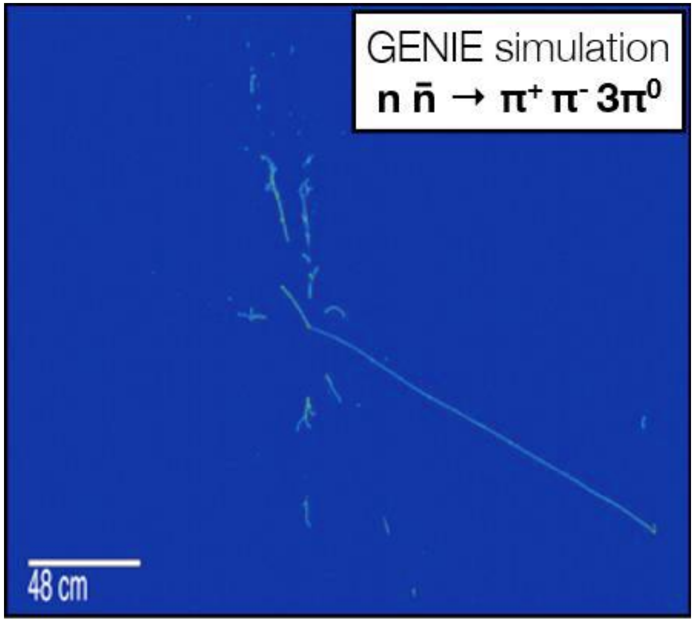


Baryon number violation

Proton decays to Kν



Neutron-antineutron oscillations

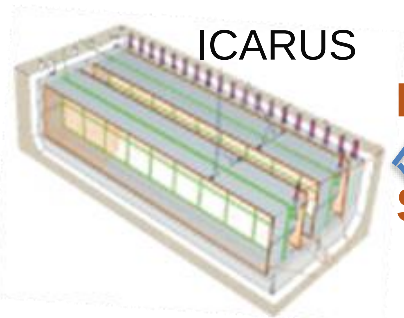


- A low-background mode with high detection efficiency.
- DUNE will do well in decay modes with kaons, modes with neutrinos, and with complicated topologies.

- Current best limit from Super-K
- Signature in LArTPC is spherical cascade of pions.

Far Detector Development Path

Single-Phase



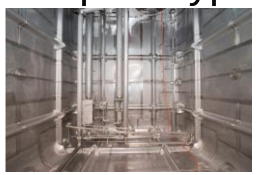
ICARUS

LBL

SBL

ArgoNeuT
LArIAT

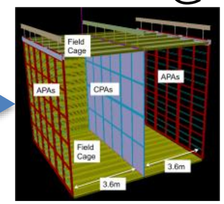
35-t prototype



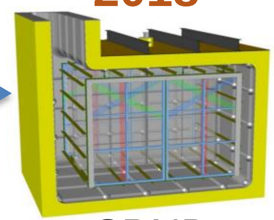
2015

MicroBooNE

protoDUNE @ CERN

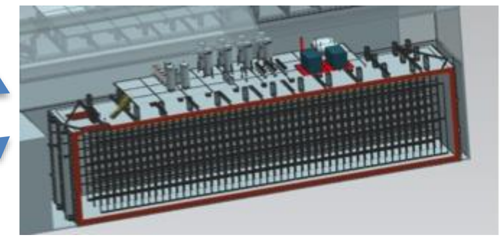


2018



SBND

DUNE Reference Design



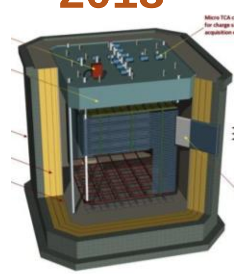
TDR 2019

Dual-Phase

2016

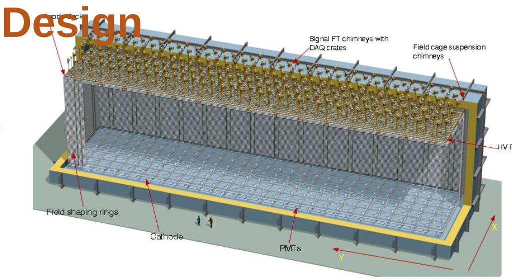
WA105: 1x1x3 m^3

2018

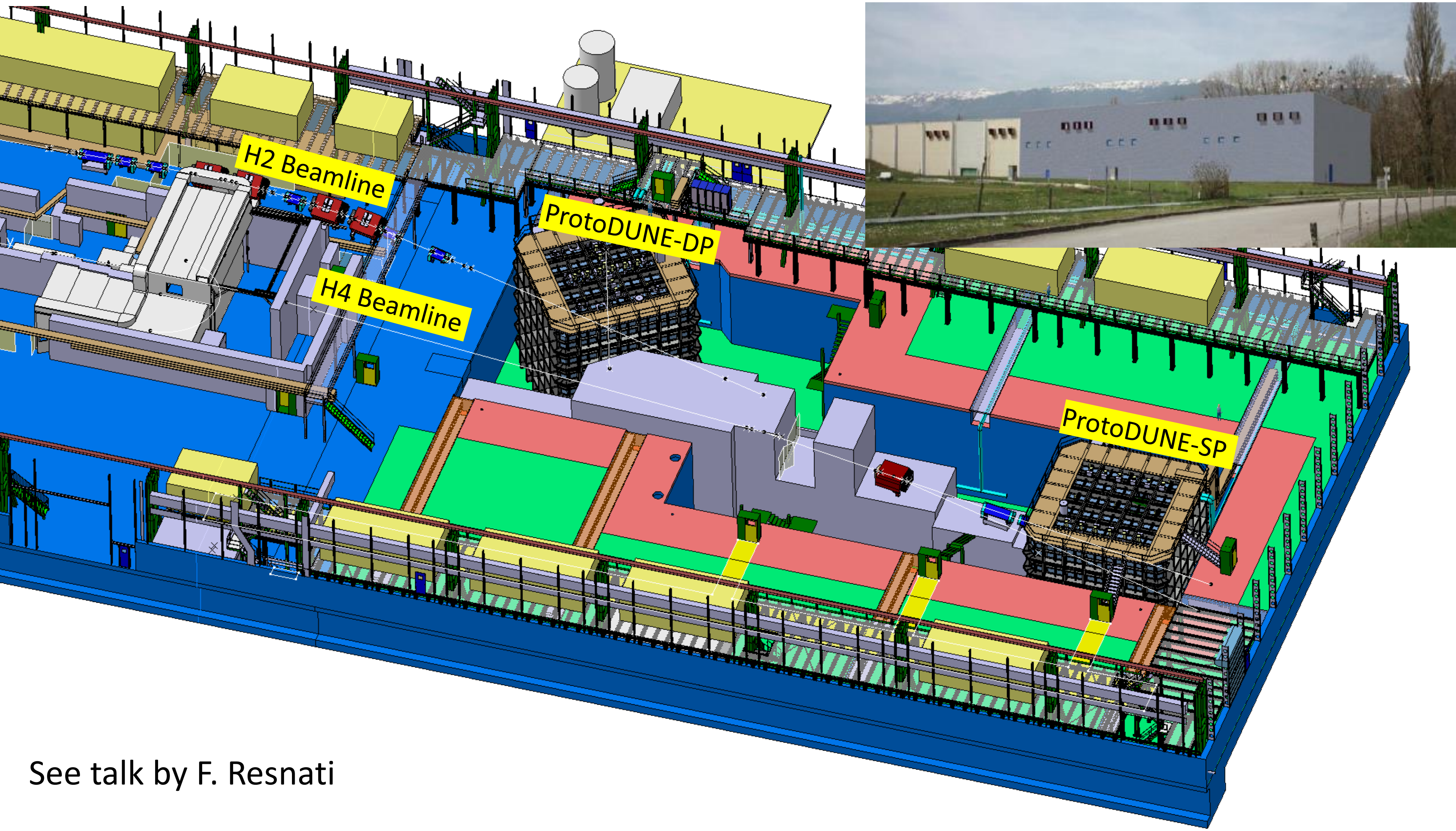


WA105
(6x6x6 m^3)

DUNE Alternative Design

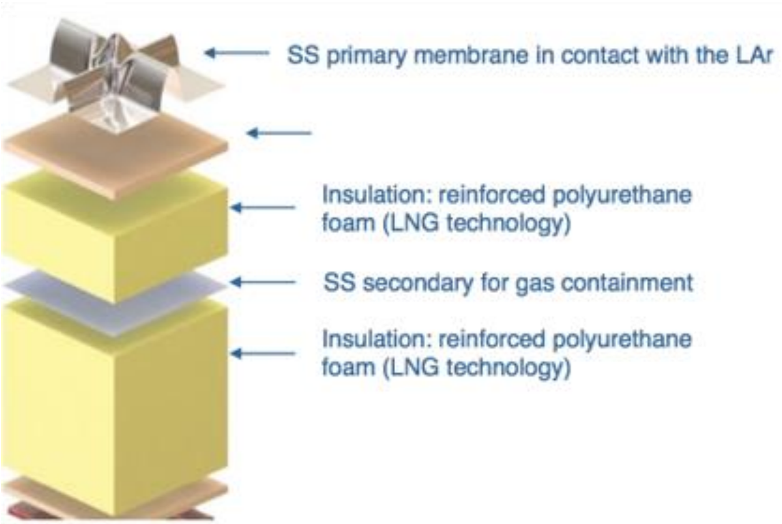


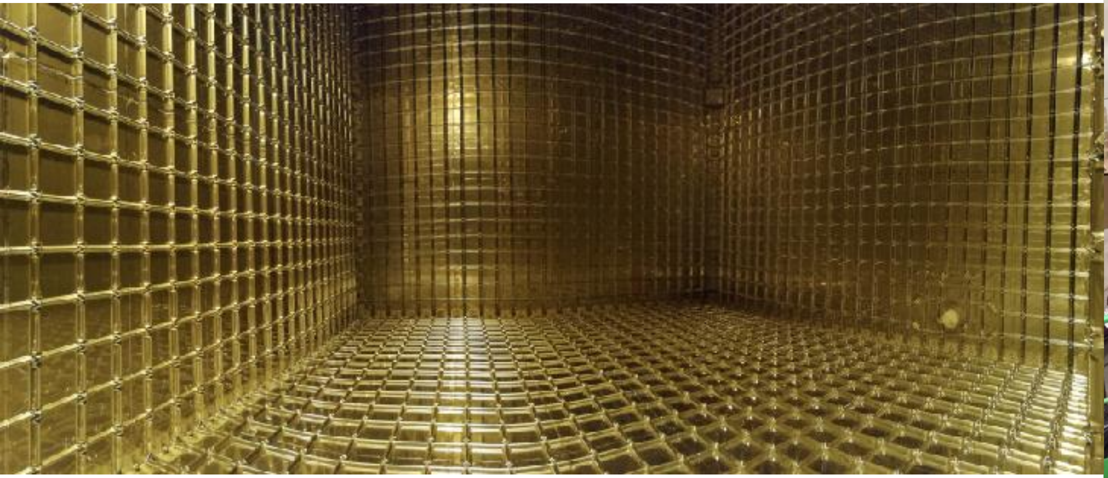
ProtoDUNEs at CERN's North Area



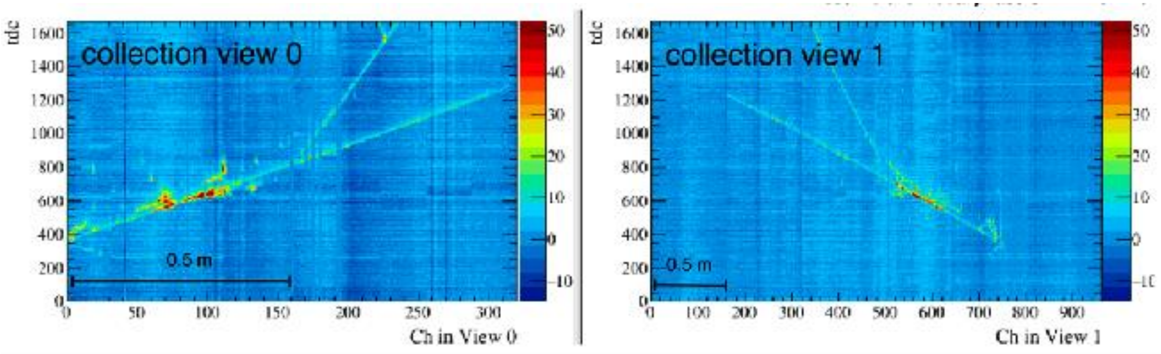
See talk by F. Resnati

ProtoDUNE cryostats





ProtoDUNE: Dual-phase demonstrator

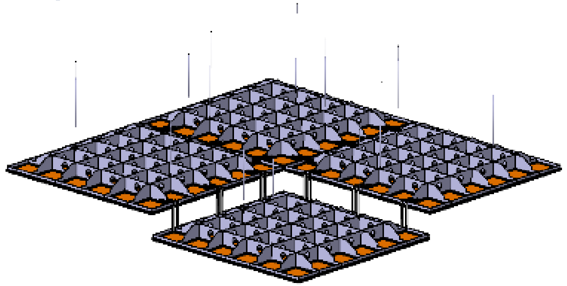


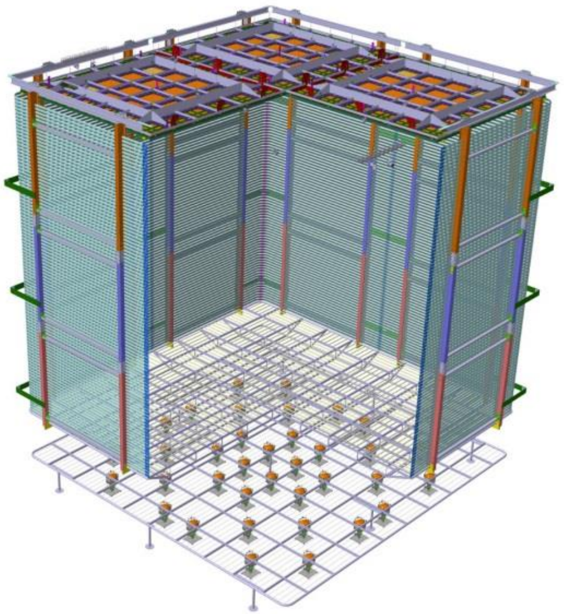
WA105

Validate construction techniques and operational performance of full-scale module

Calibrate detector with charged-particle beam

6 m x 6 m anode plane made of four 3 m x 3 m independent readout units





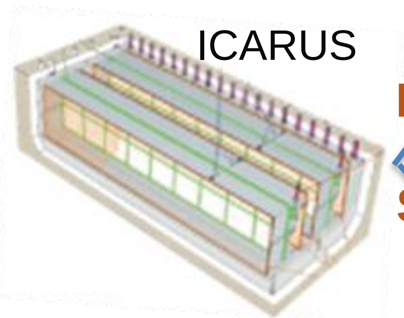
6 m vertical drift => 300 kV cathode voltage

ProtoDUNE: Single-phase demonstrator

- Active volume: 6 x 7 x 7 m^3
- 6 Anode Plane Assemblies
  - 6 m high x 2.3 m wide
- 6 Cathode Plane Assemblies
  - 3 m high x 2.3 m wide
- Cathode at -180 kV for 3.5 m drift
- First US-built APA delivered and tested.
- Will be ready for data taking in LS2.

Far Detector Development Path

Single-Phase



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LBL

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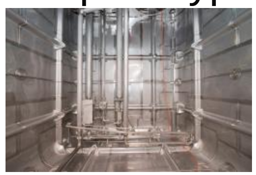

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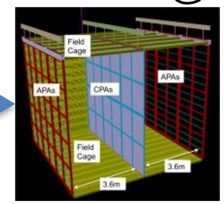
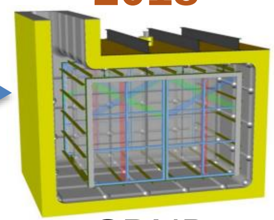


2018



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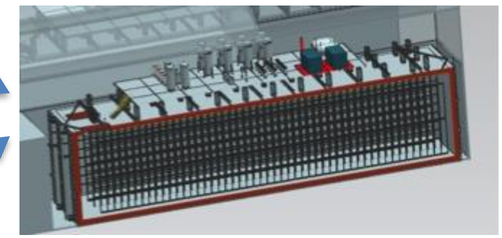

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Dual-Phase

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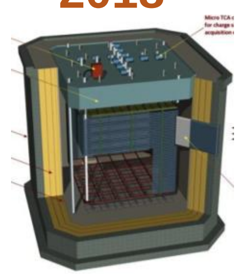
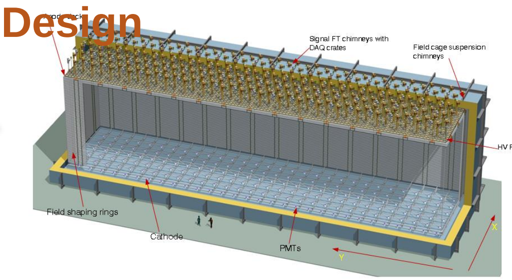


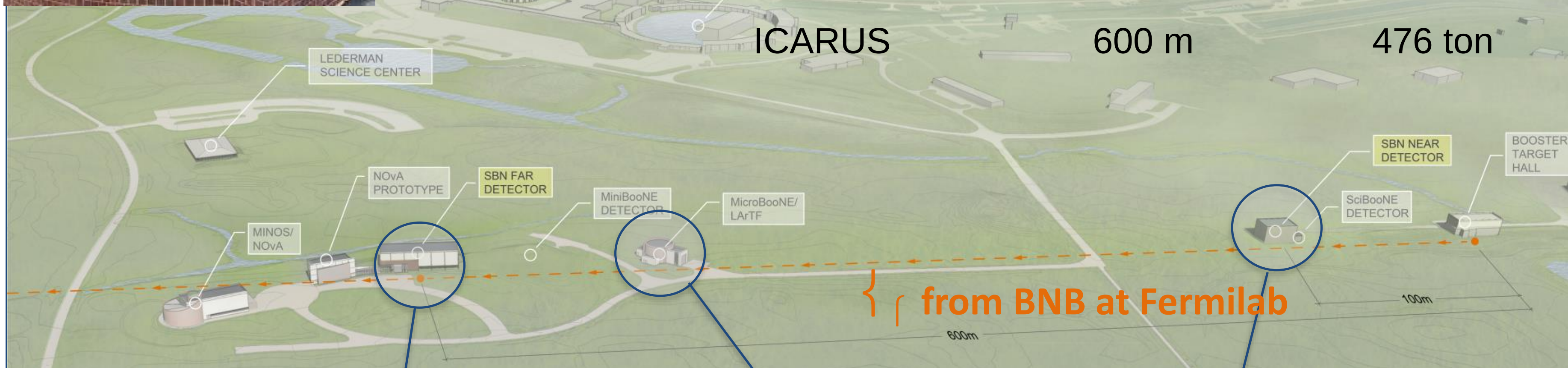
WA105
($6x6x6m^3$)

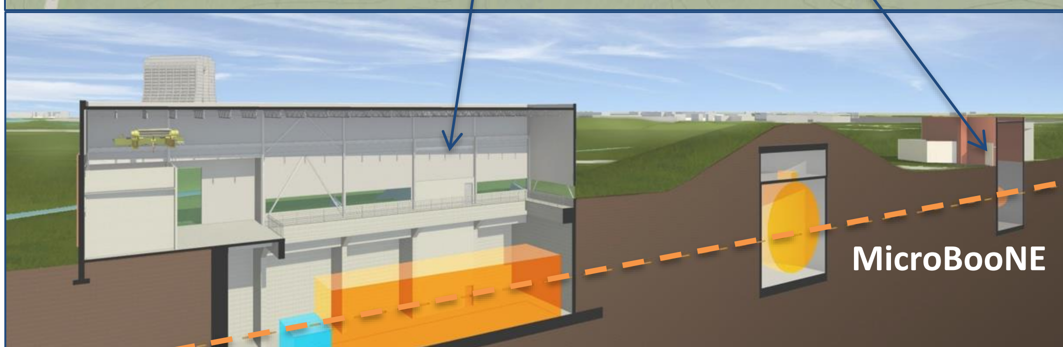
DUNE Alternative Design

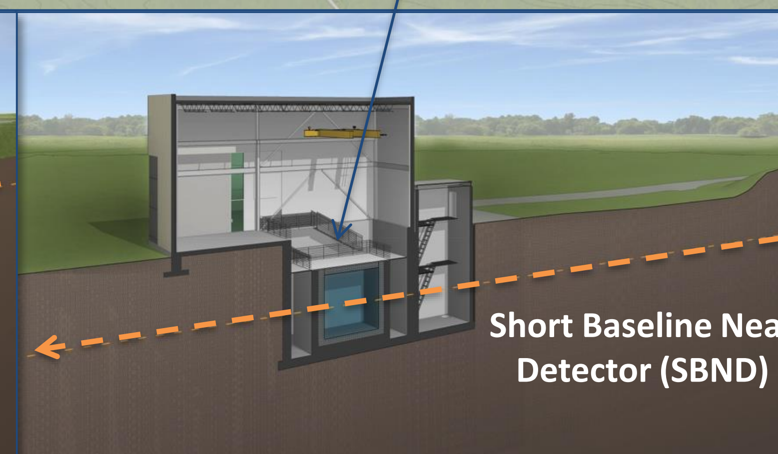


LAr TPC Detectors at Fermilab (short-baseline)

Detector	Distance from Target	Instrumented LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton



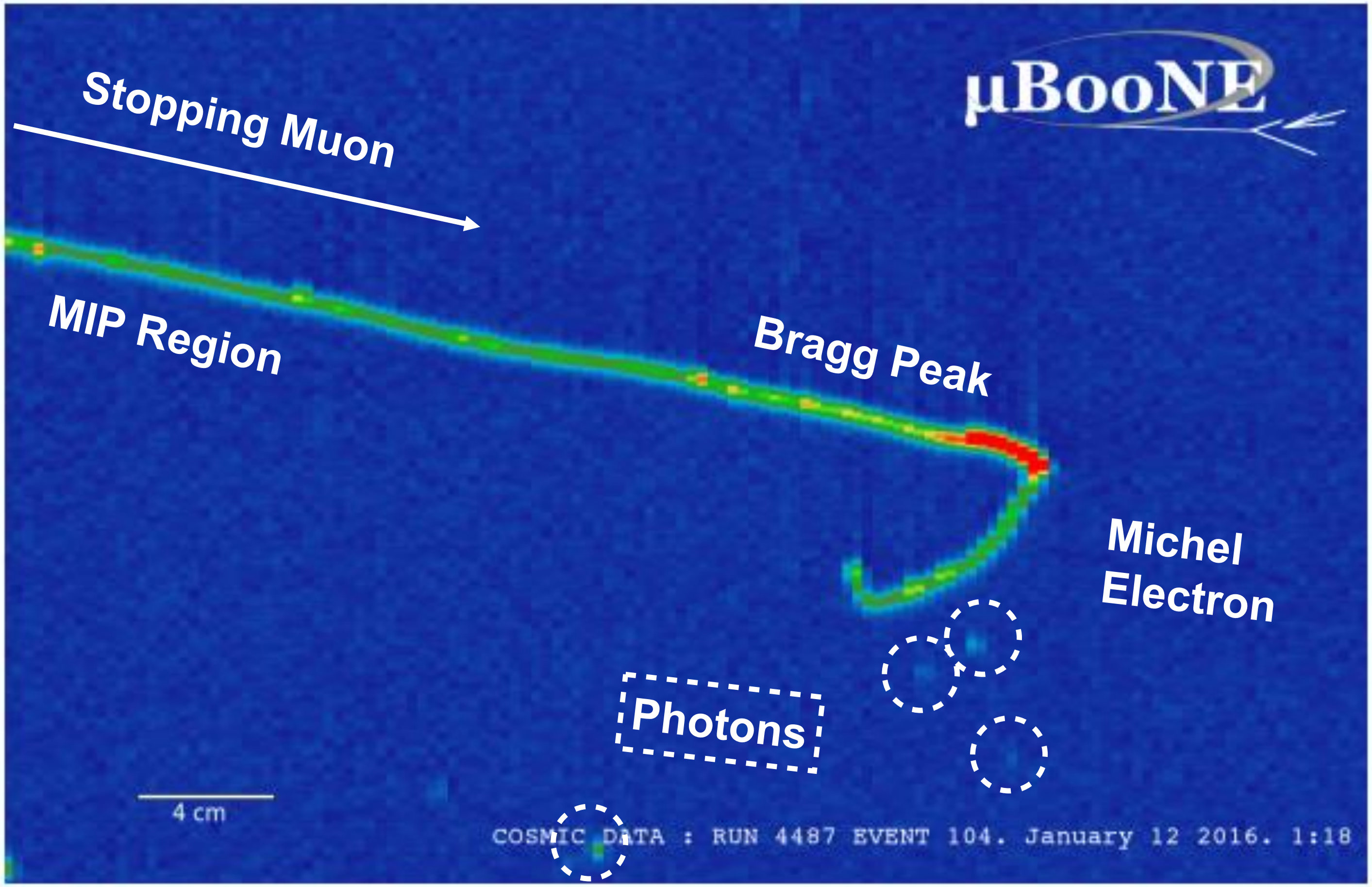


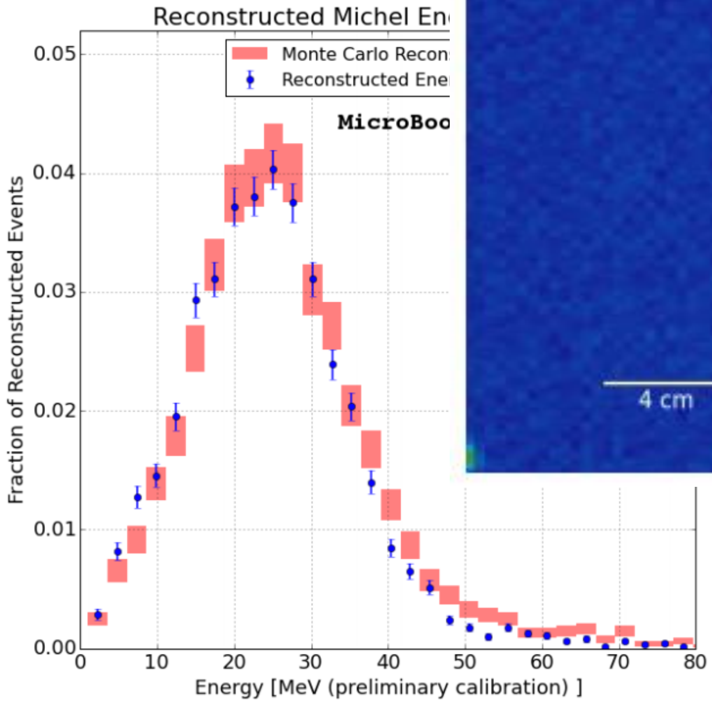


See talk by C. Touramanis

Michel electrons

Textbook plot !





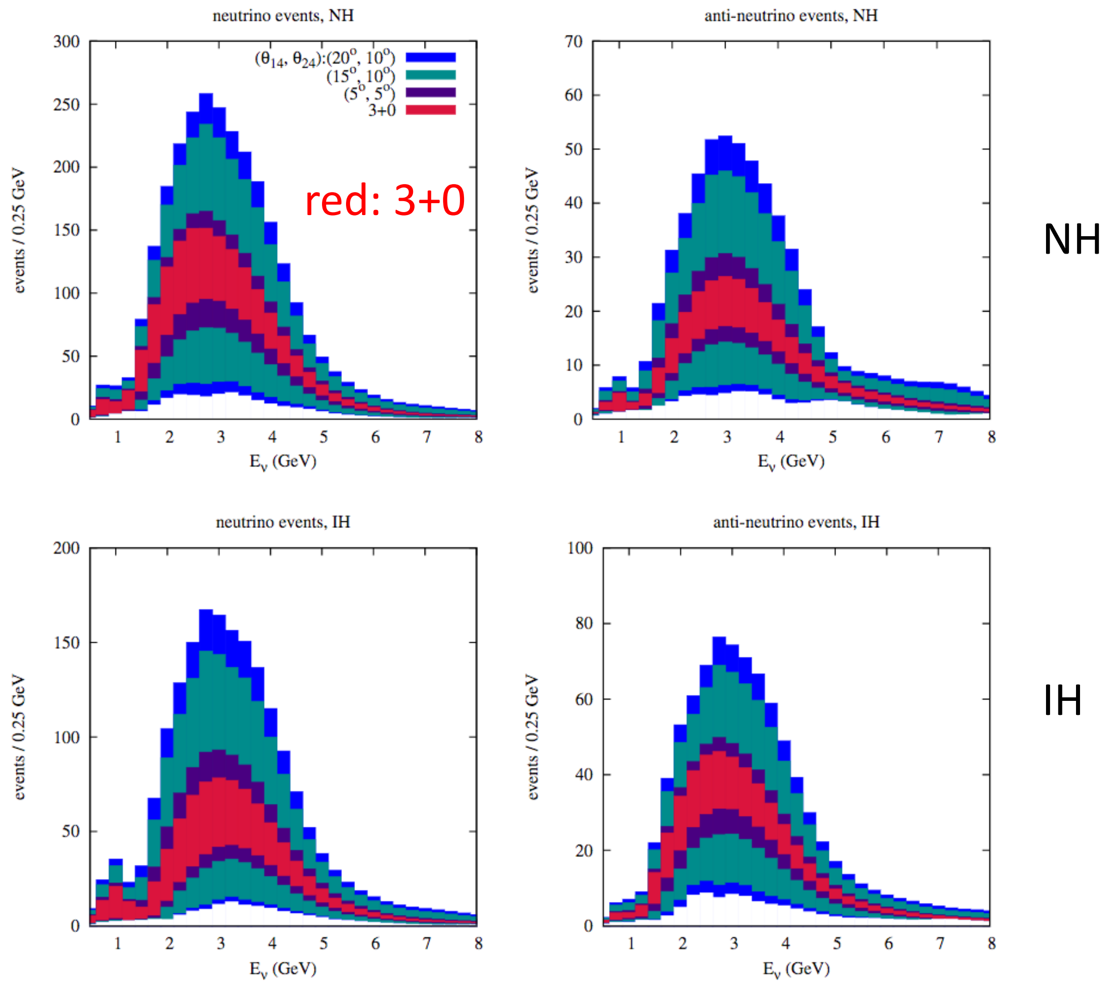
SBN measurements of cross sections on argon will be crucial for DUNE.

Impact of Sterile Neutrinos on DUNE

- Presence of sterile neutrinos creates degeneracies when interpreting data in terms of CP violation.

- Testing the sterile neutrino sector at the SBN is an important input for DUNE.

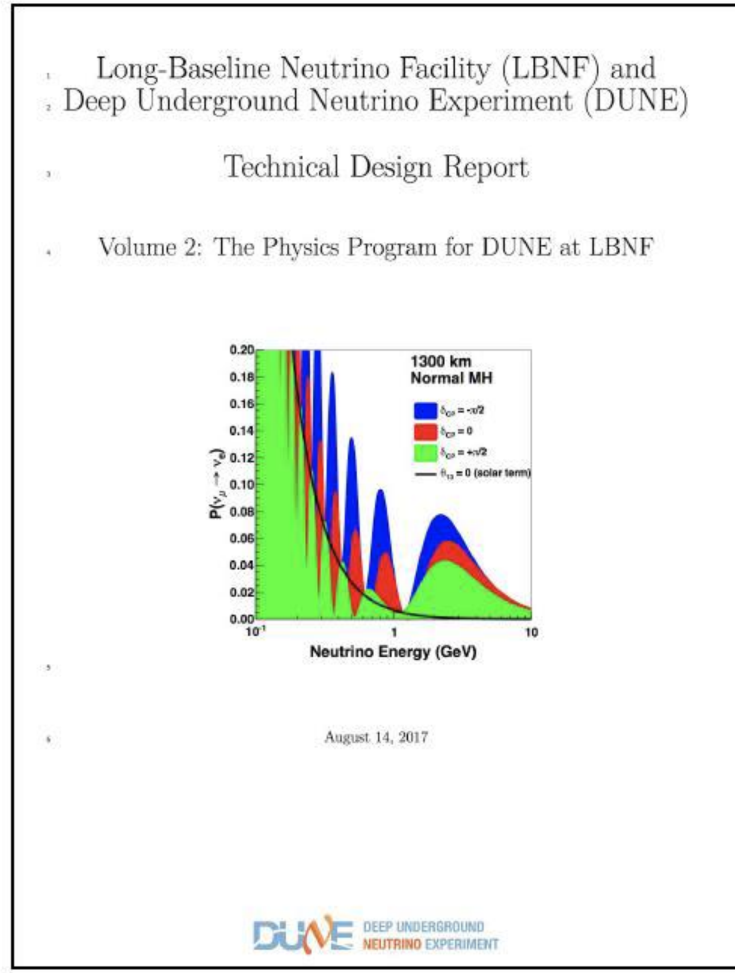
Bands show variation of CP phases
for 3+0 and 3+1 scenarios with 1 eV sterile neutrino.



R. Ghandi, B. Kayser, M. Masud, S. Prakash. arXiv:1508.06275

Technical Design Report (TDR)

- This summer, several international consortia were formed:
  - Single phase: APA, Photon Detection system, TPC Electronics
  - Dual phase: CRP, Photon Detection system, TPC Electronics
  - Joint: HV System, DAQ, Slow Controls & Cryogenic Instrumentation
- Consortia will produce a Technical Proposal (TP) in 2018 and a Technical Design Report in 2019.

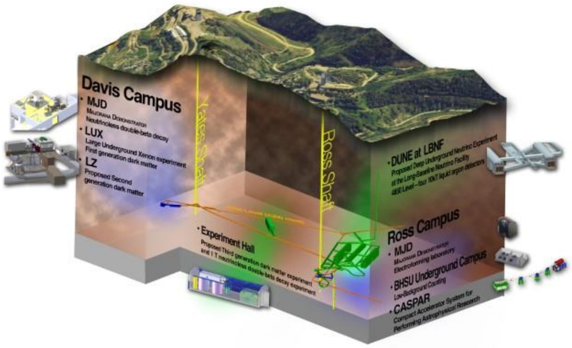

Long-Baseline Neutrino Facility (LBNF) and
Deep Underground Neutrino Experiment (DUNE)

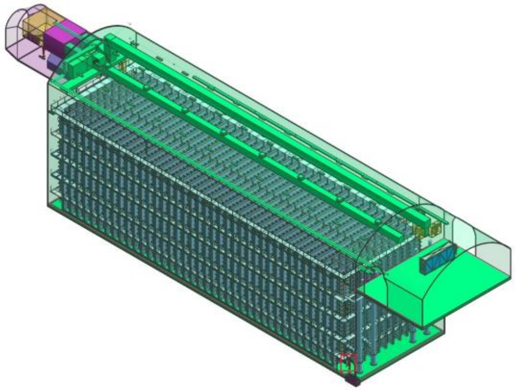
Technical Design Report

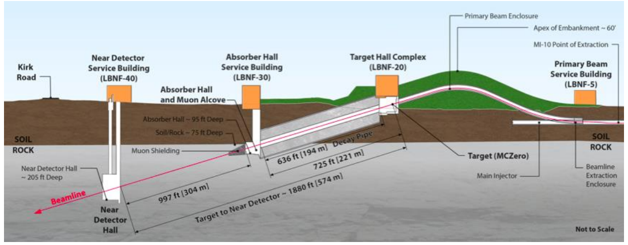
Volume 2: The Physics Program for DUNE at LBNF

August 14, 2017

DUNE Timeline







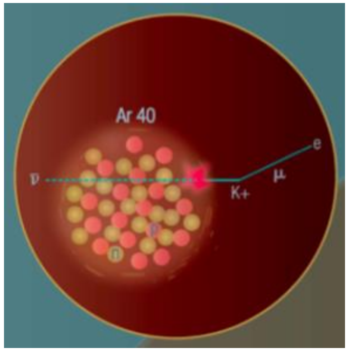
2017: Far Site Construction Begins

2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available



Beam power: 1.07 MW at 80 GeV
Planned upgrade to > 2 MW

Summary

Physics milestone		Exposure kt-MW-year
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	**1 year**	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)		60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	**2 years**	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)		210
MH at 5σ (worst point)	**5 years**	230
10° resolution ($\delta_{CP} = 0$)		290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	**7 years**	320
CPV at 5σ 50% of δ_{CP}		550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)		850
CPV at 3σ 75% of δ_{CP}		850