Physics with Liquid Argon Detectors – from MicroBooNE to DUNE

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Colloquium, DESY Hamburg/Zeuthen

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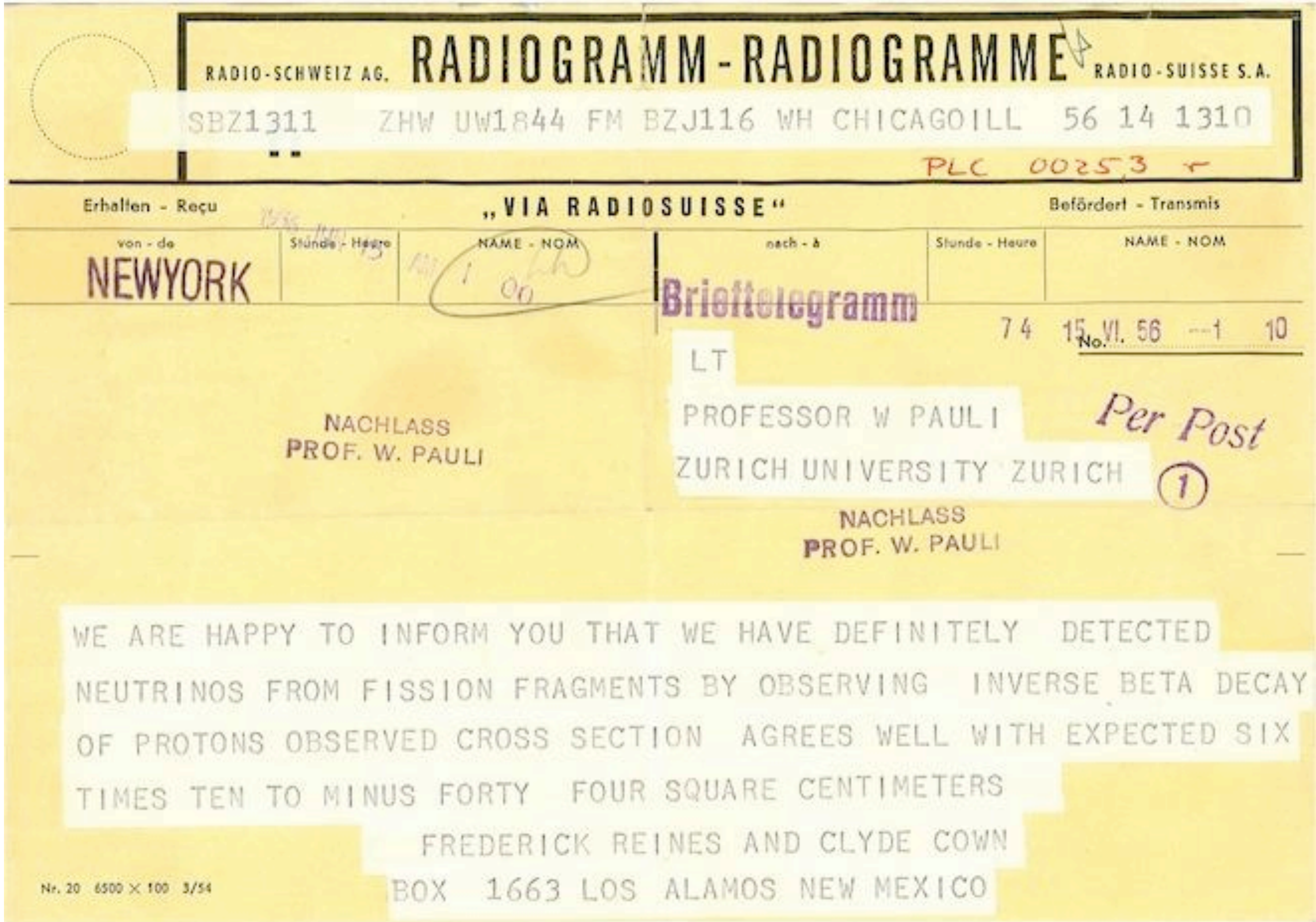
June 15, 1956



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

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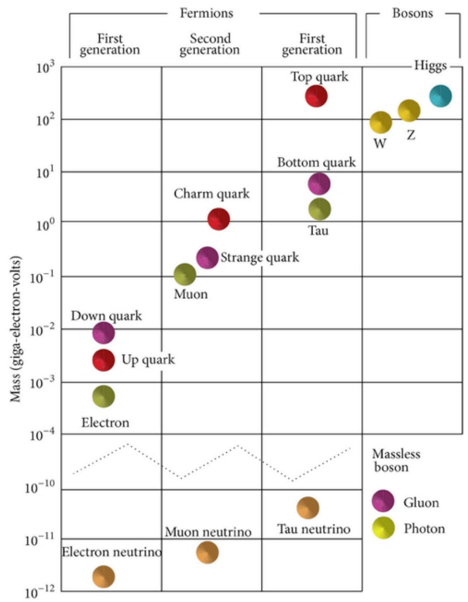
Neutrinos as messengers of physics at large scales

Anomalously small neutrino masses might be linked to physics at high scales through see-saw mechanism:

$$\mathcal{L} \sim -\tfrac{1}{2}\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

$$m_\nu \approx \frac{m_D^2}{M} \qquad M \sim 10^{12} - 10^{16}\,\mathrm{GeV}$$

- Add right-handed neutrinos (ν_R) and Majorana mass term M to SM Lagrangian.



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.
- Probes both supernova properties and neutrino physics.

Neutrinos as messengers of physics at large scales

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

"Three flavour paradigm"

complex phase

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

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

CP Violation: $\delta \neq \{0, \pi\}$

Caveat:

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.

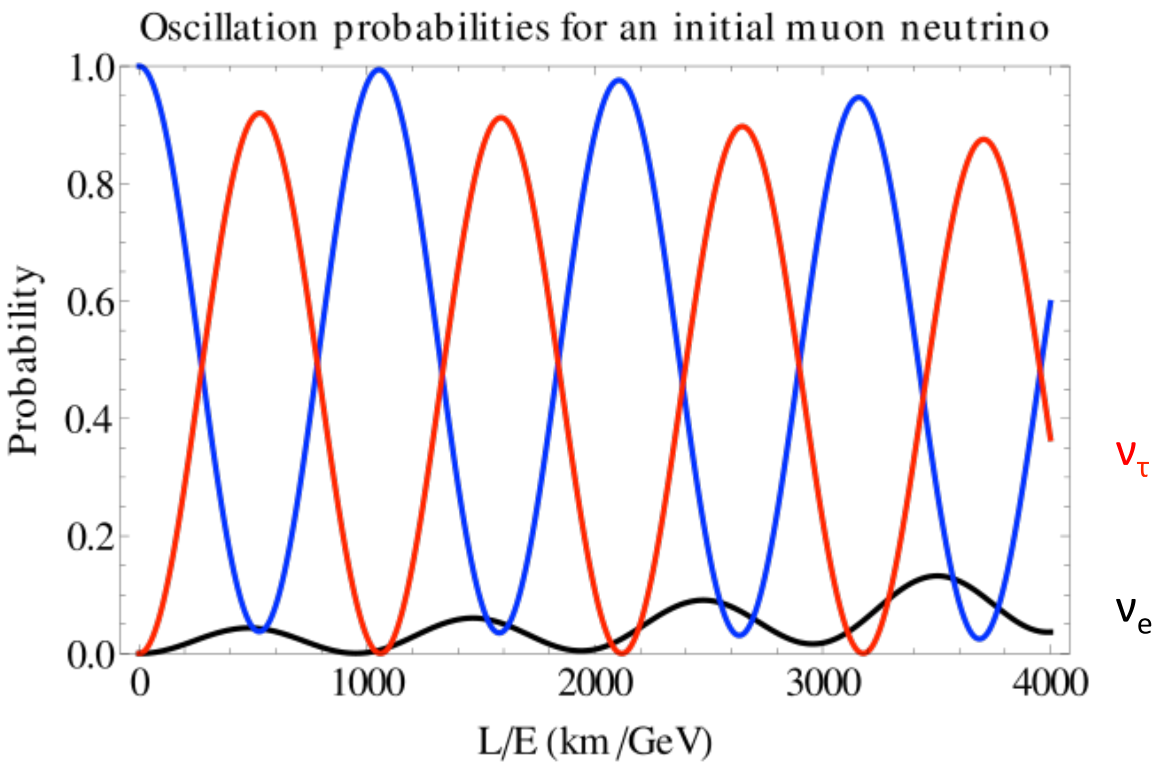
Neutrino oscillations

Amplitude Frequency

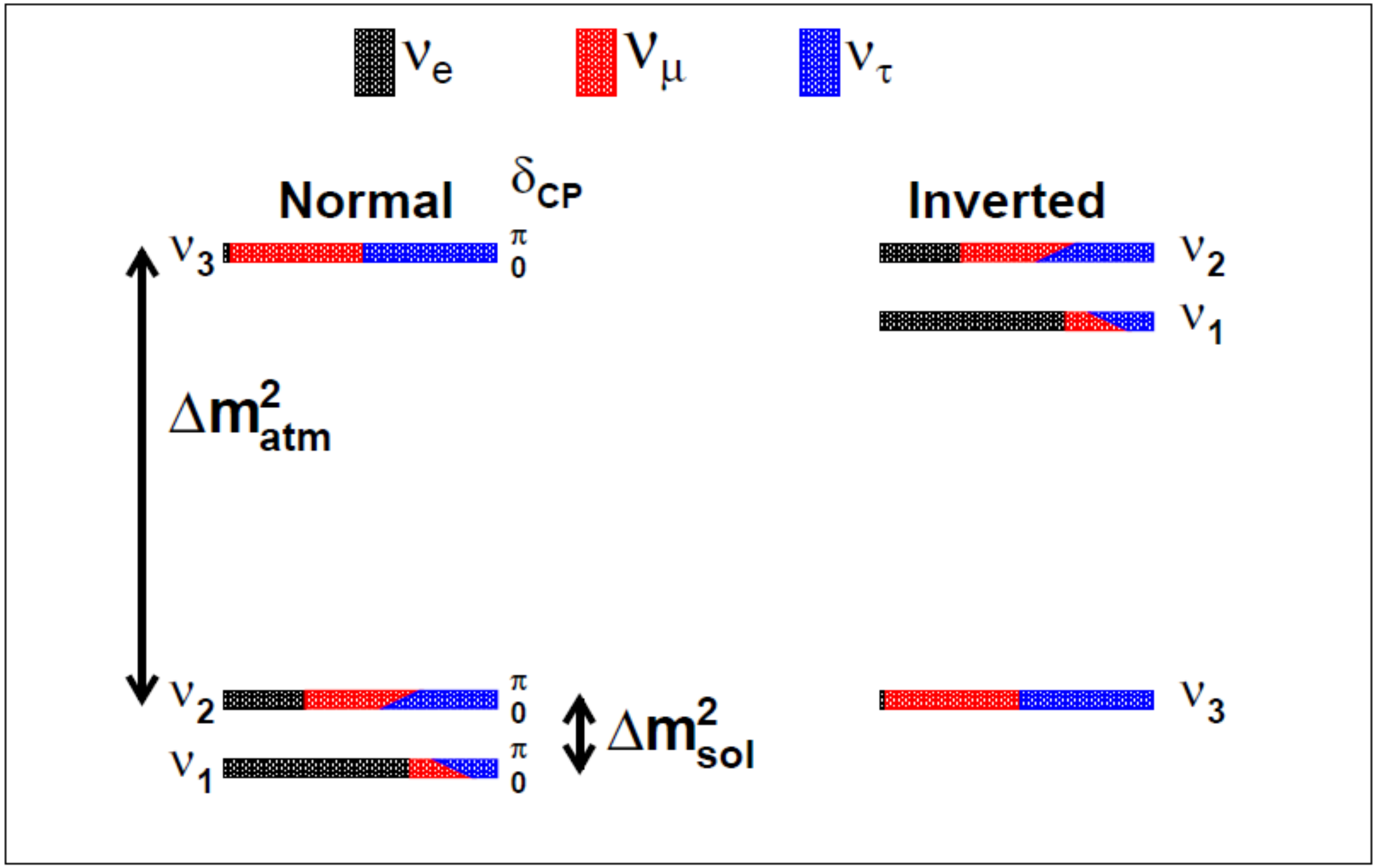
Two flavours

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

Three flavours
with two frequencies
corresponding to
two Δm^2



Mass ordering (MO)



Matter effects (MSW effect)

- Matter is made of electrons, not muons or taus.
- Coherent forward scattering on electrons modifies the oscillation probabilities:

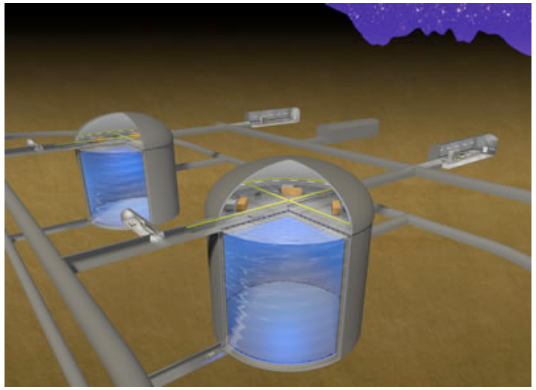
- Matter effects will lead to additional differences between neutrinos and anti-neutrinos even if CP is conserved.
- Their size will depend on the electron density N_e and G_F.
- Depend on neutrino mass ordering (i.e., sign of Δm^2_{23}).

Optimizing L/E

L ≈ 200 km

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

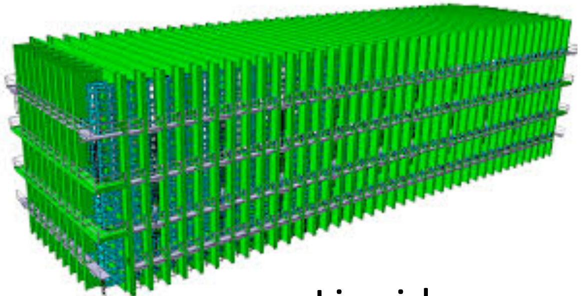
- no matter effects; first oscillation maximum.
- use narrow width beam (off axis).



Water Cherenkov

L > 1000 km

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



Liquid argon

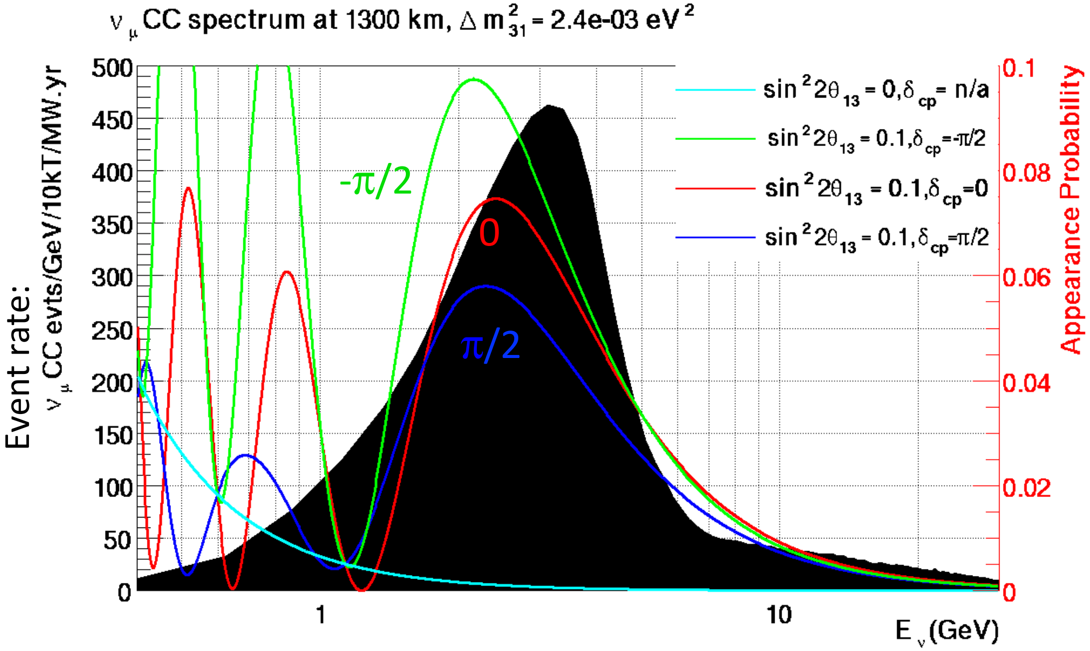
- matter effects; first and second oscillation maximum.
- use broad-band beam (on axis).
- unfold CP and MO effects through energy dependence.

ν_e appearance

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

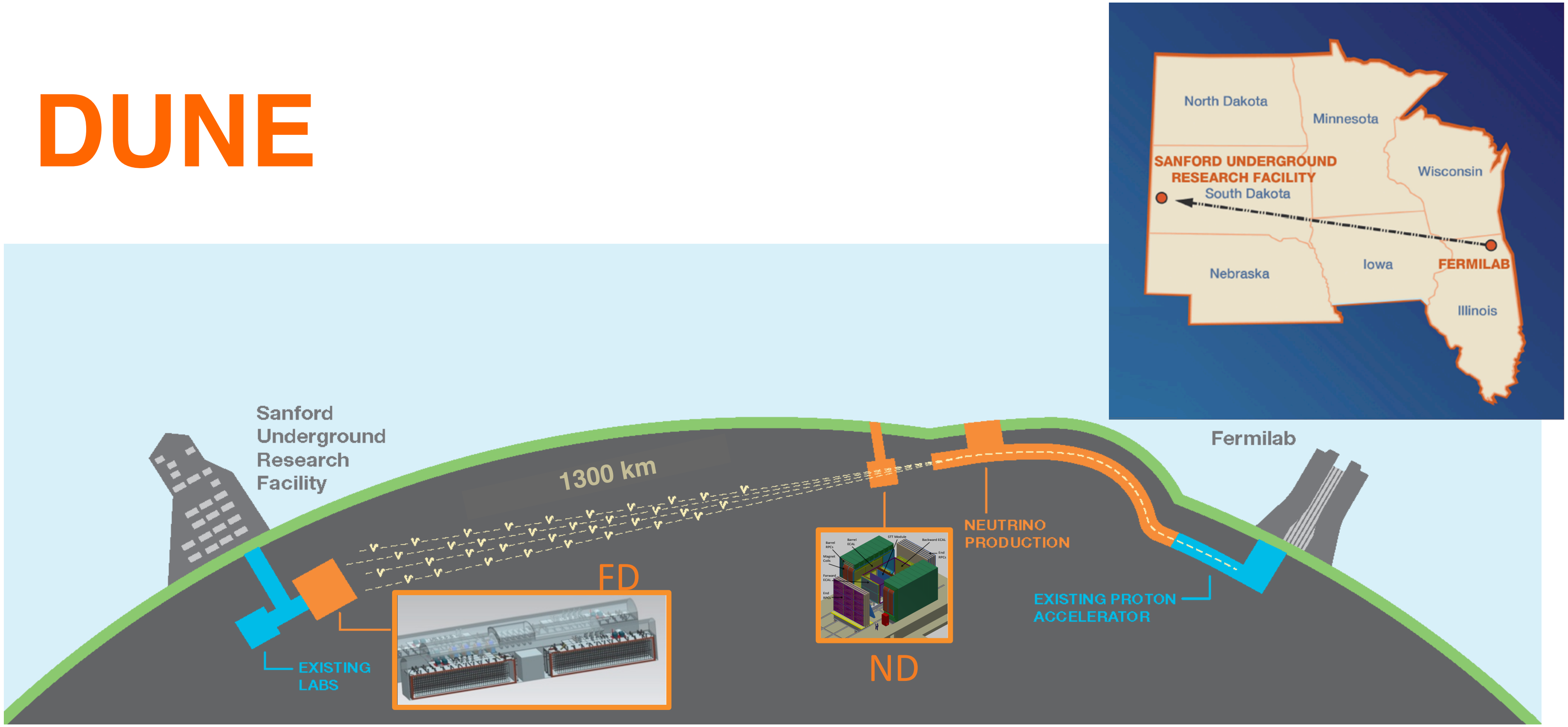
$$a = G_F N_e / \sqrt{2}$$

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



- 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

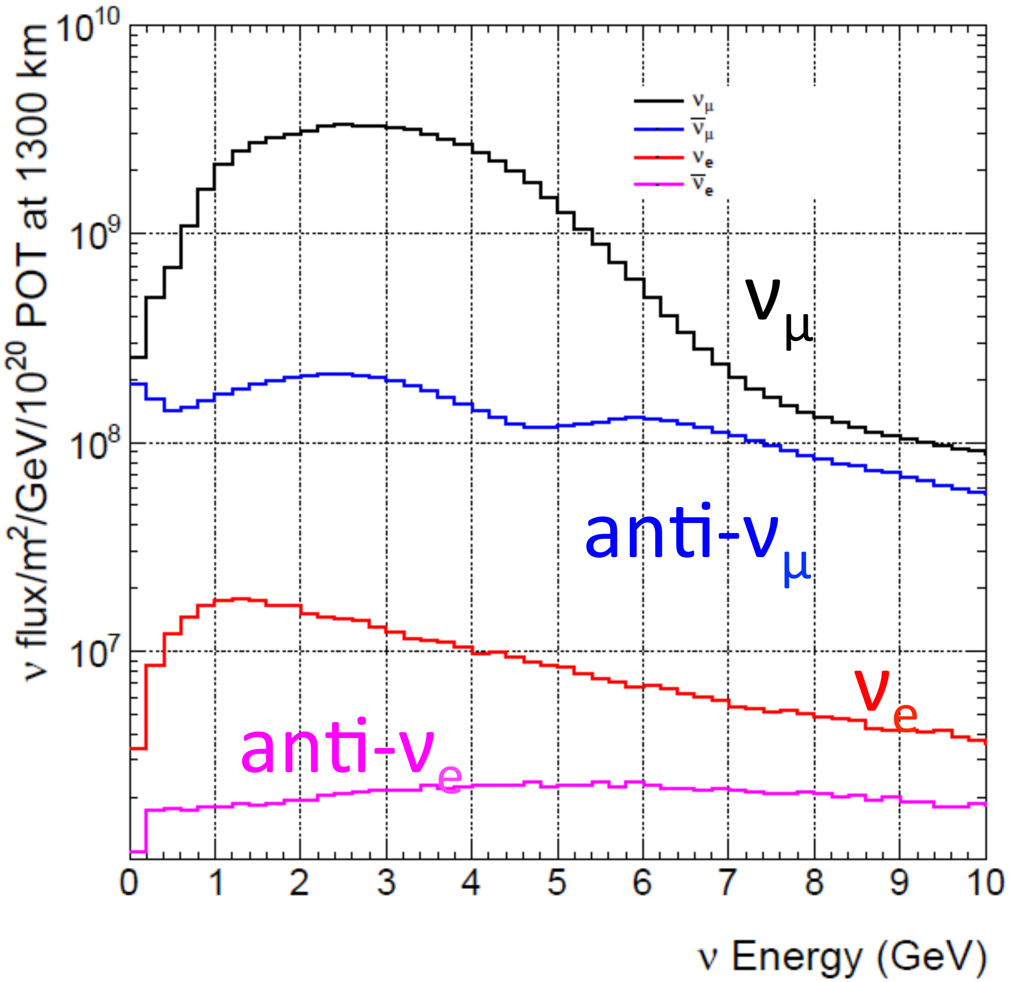
DUNE



- 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 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ 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.

DUNE Far Detector neutrino flux



Beam (LBNF):

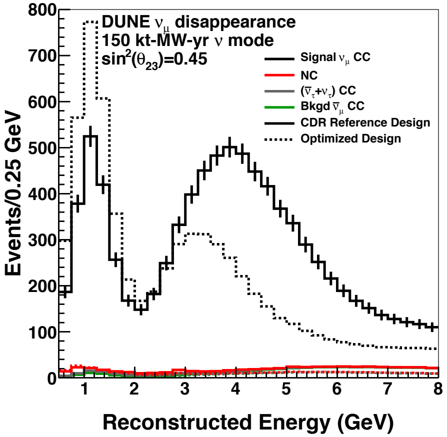
- 1.2 MW from Day 1
- upgradeable to 2.4 MW
- assume running of 3.5 years each in neutrino and anti-neutrino mode.

DUNE oscillation strategy

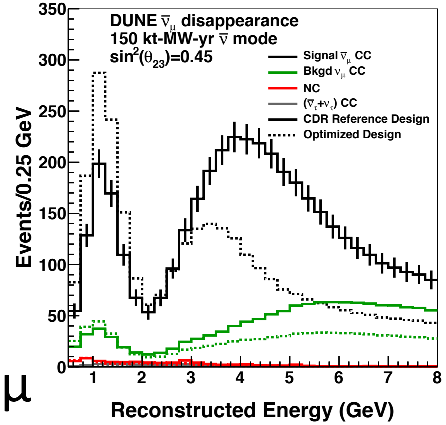
- Wide-band beams allows us to measure ν_e appearance and ν_μ disappearance over range of energies
- Mass ordering and CP violation effects can be separated

muon-neutrino disappearance

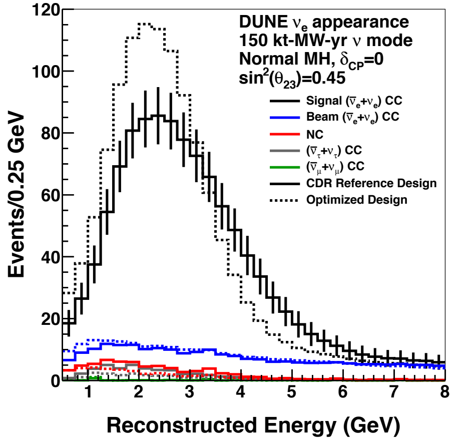
electron-neutrino appearance



ν_μ

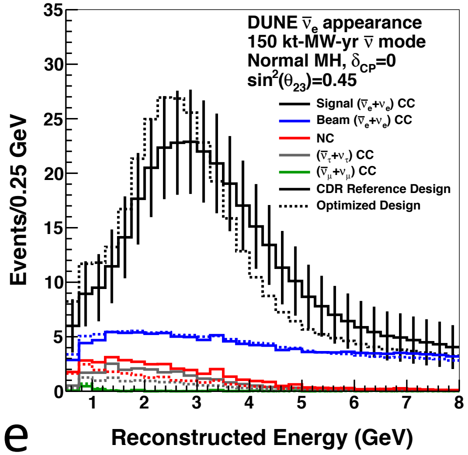


anti-ν_μ



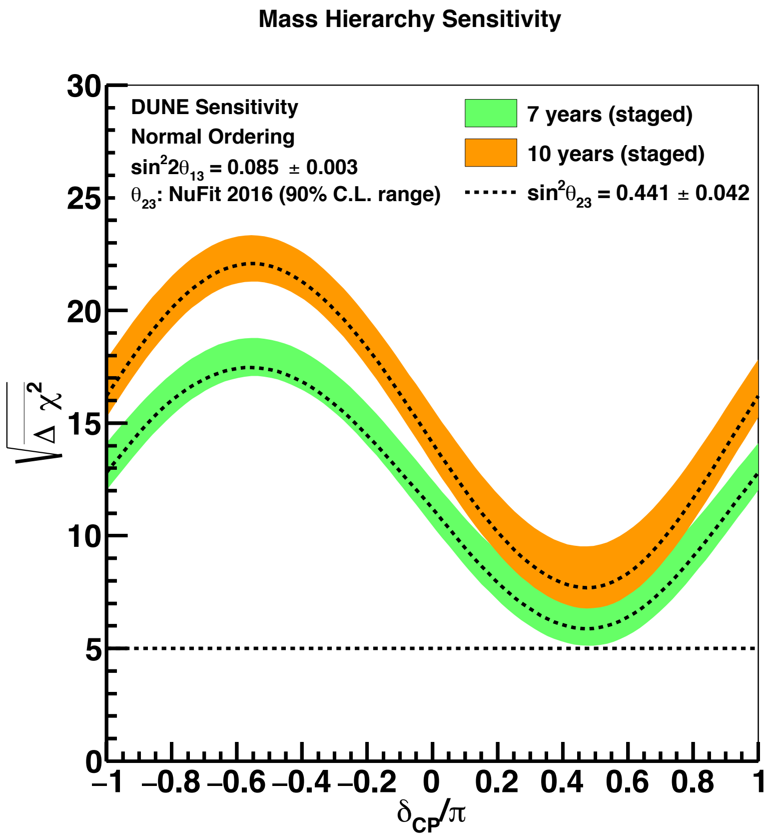
ν_e

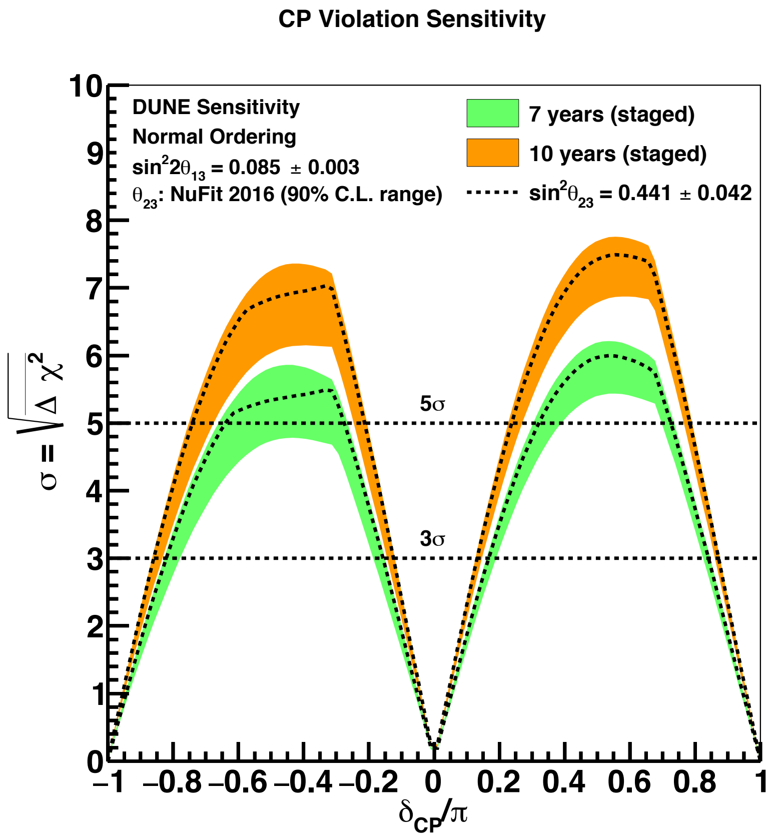
7 years of data



anti-ν_e

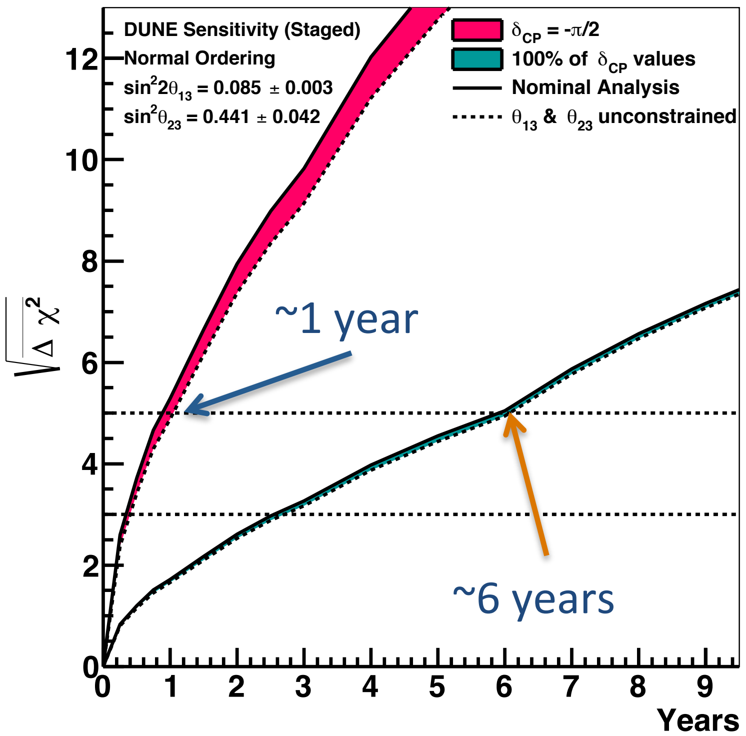
Mass ordering and CPV



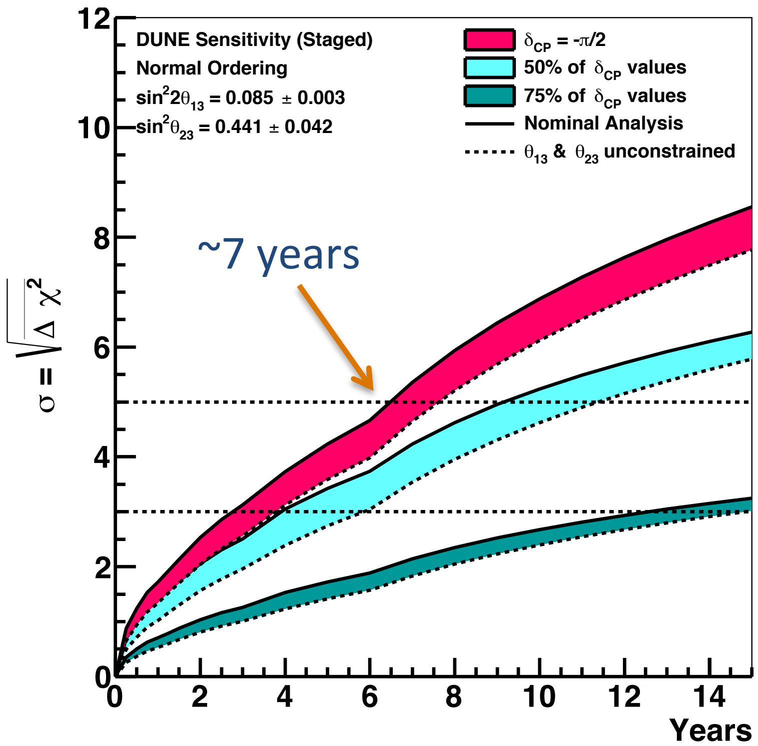


Sensitivity over time

Mass Hierarchy Sensitivity

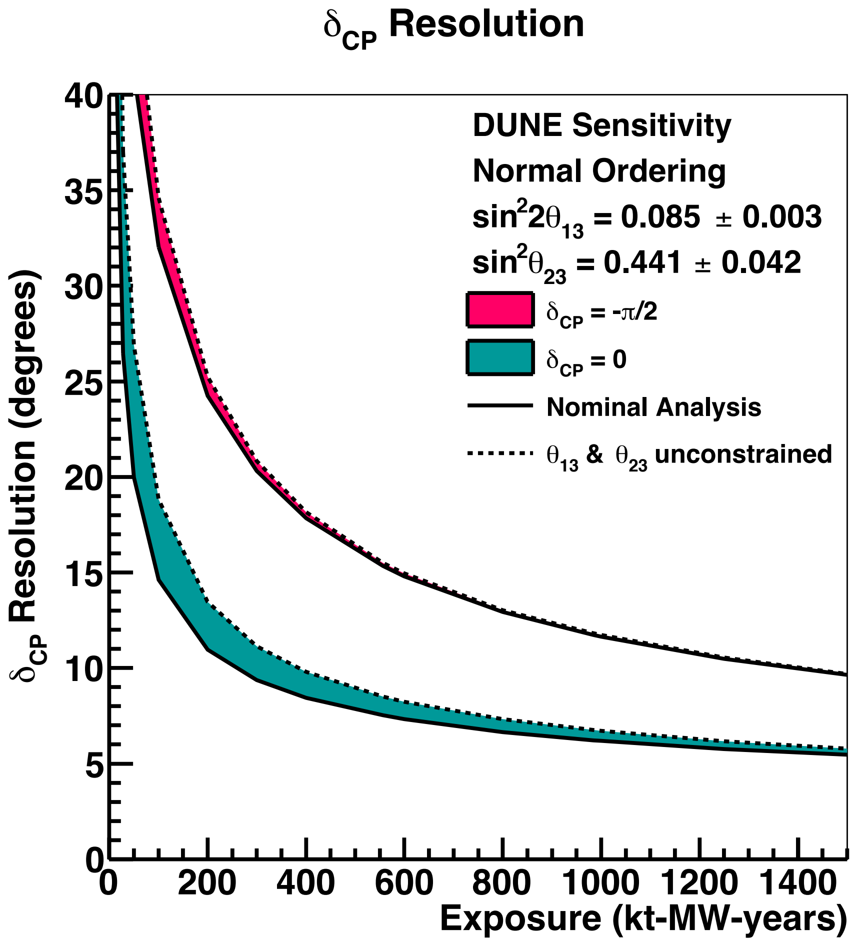


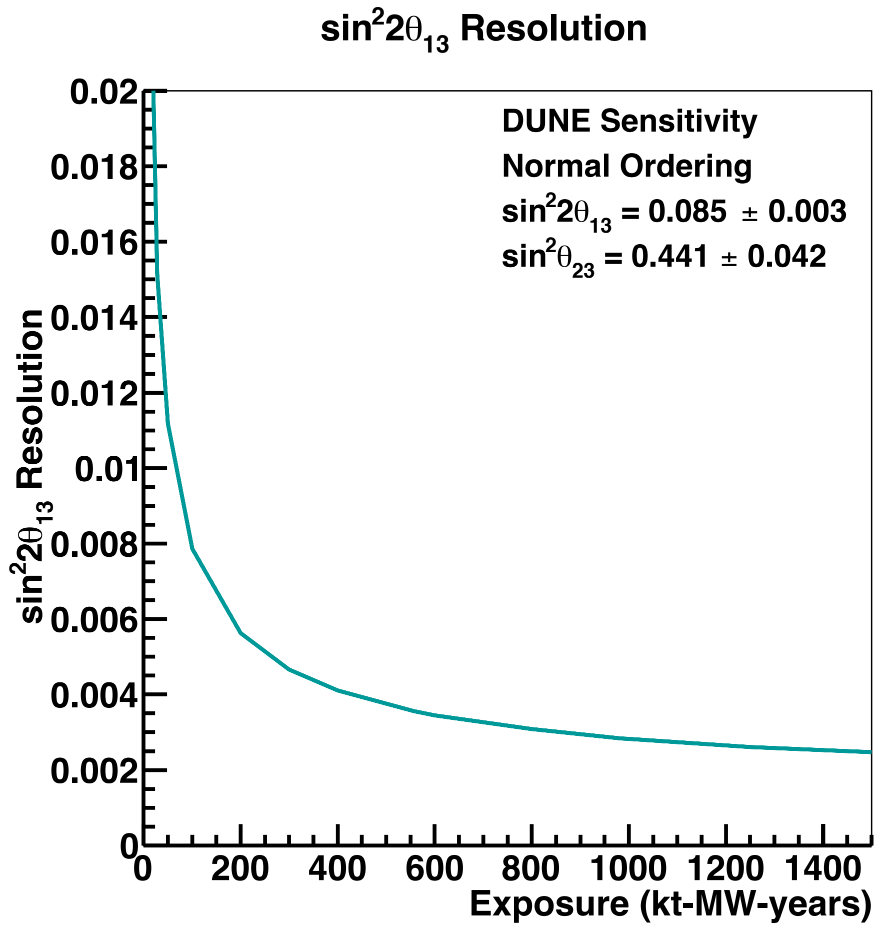
CP Violation Sensitivity



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

Beyond discovery: precision measurements





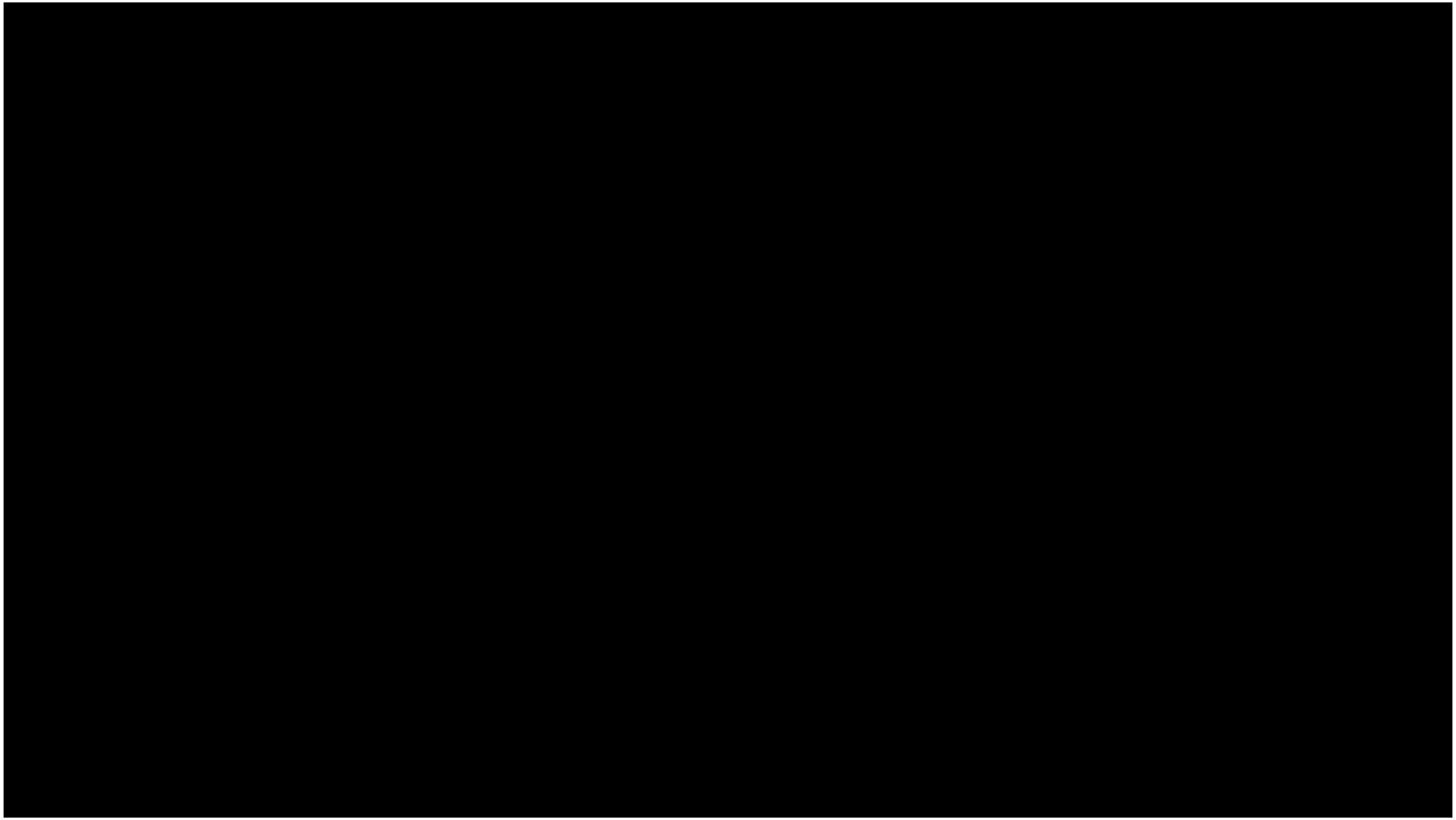
Comparable precision to quark sector

DUNE Collaboration

>900 collaborators from 30 countries

CERN Collaboration Meeting, January 2017

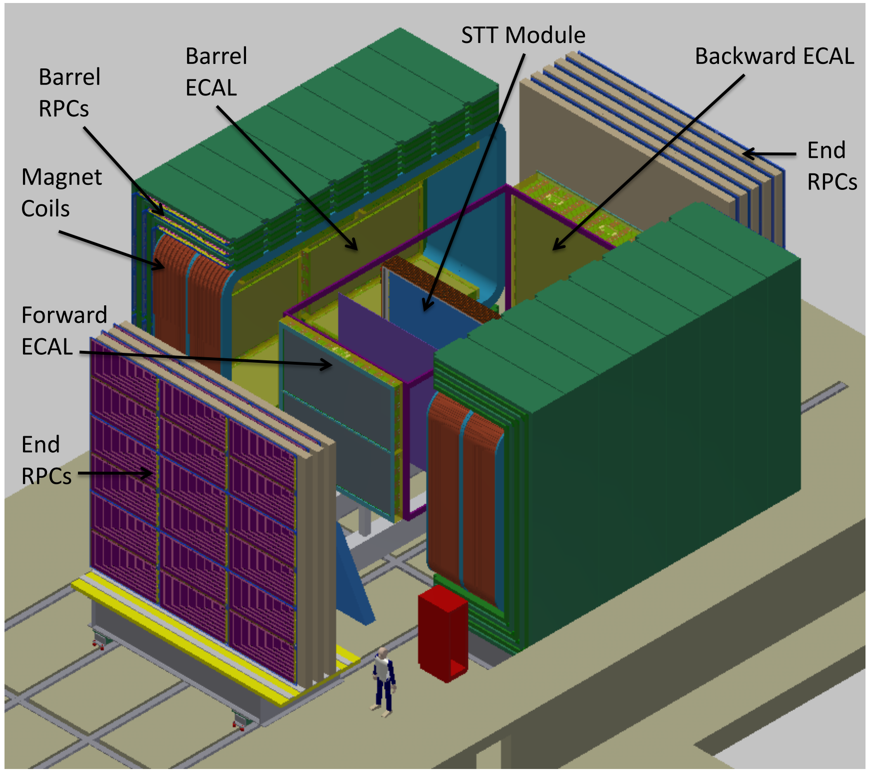
LBNF/DUNE – Fermilab in 2025



DUNE Near Detector

Baseline design is a NOMAD-inspired Fine Grained Tracker (FGT)

- Central straw-tube tracking system
- Lead-scintillator sampling ECAL
- RPC-based muon tracking systems



DUNE Near Detector

- Other options (e.g., HP-TPC, LAr-TPC, hybrid) being studied.
- In 2017, Collaboration will come together to decide on concept (not independent of funding).
- Once agreed, the Near Detector Expression of Interest process begins.
- CDR (2018), TDR (2020)

The Near Detector will provide:

Constraints on cross sections and the neutrino flux

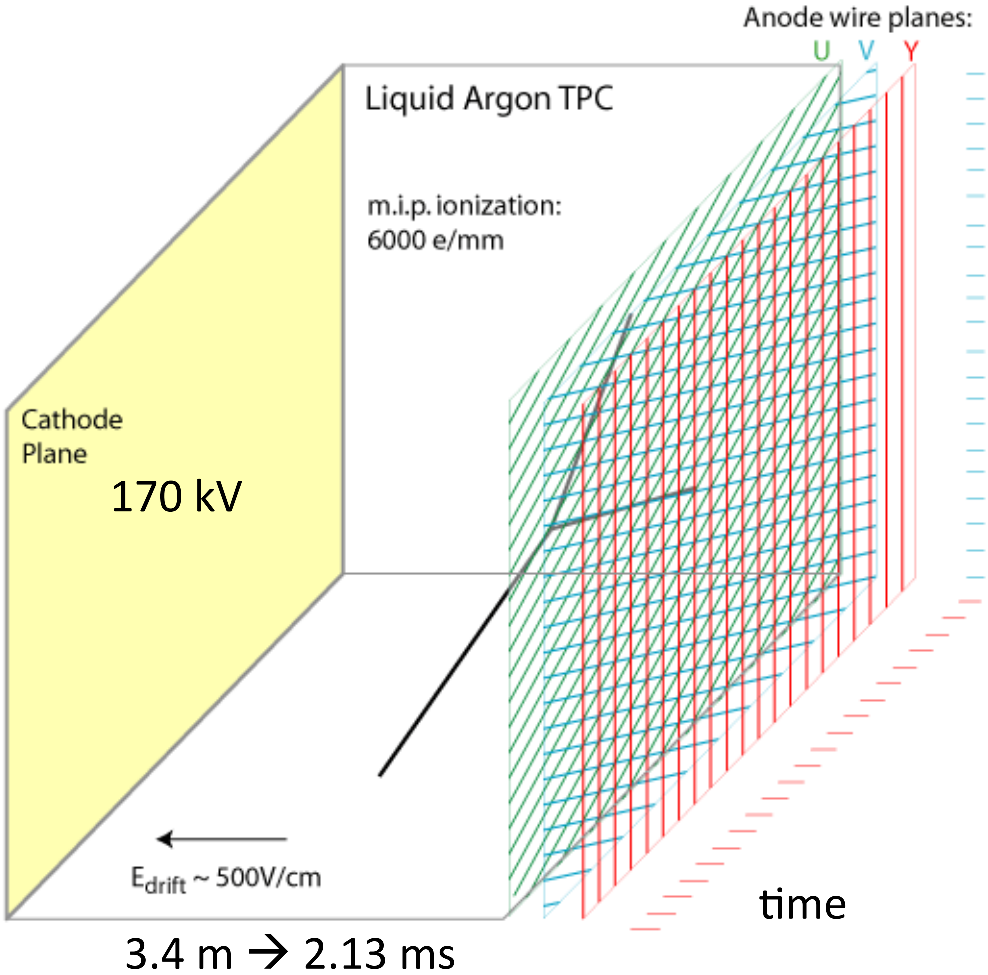
A rich self-contained non-oscillation neutrino physics programme.

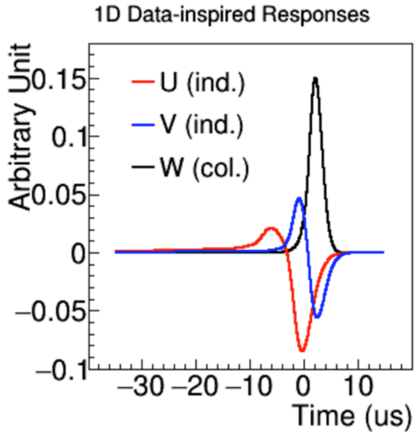
Will result in unprecedented samples of ν interactions

>100 million interactions over a wide range of energies:

strong constraints on systematics

Time Projection Chamber

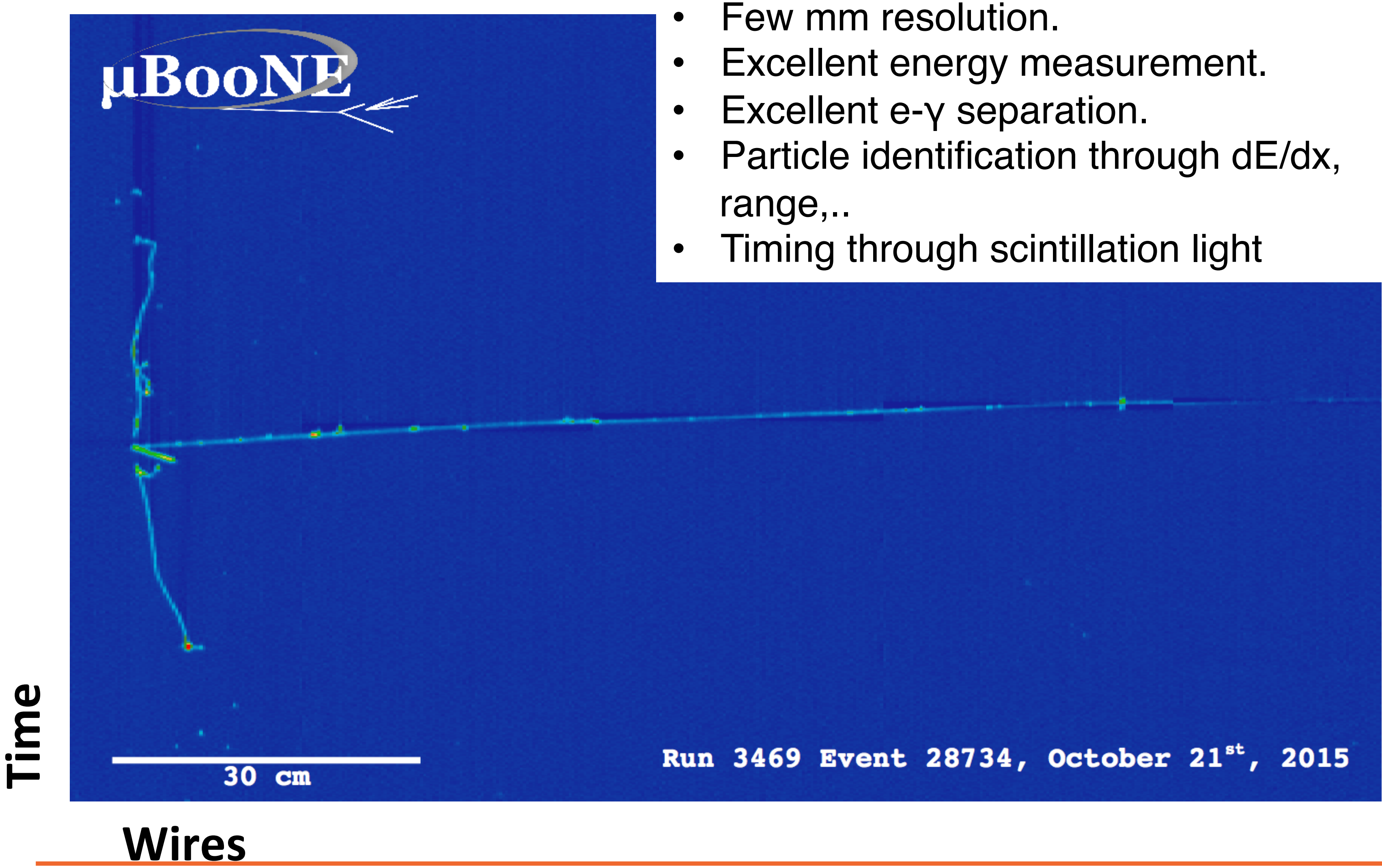




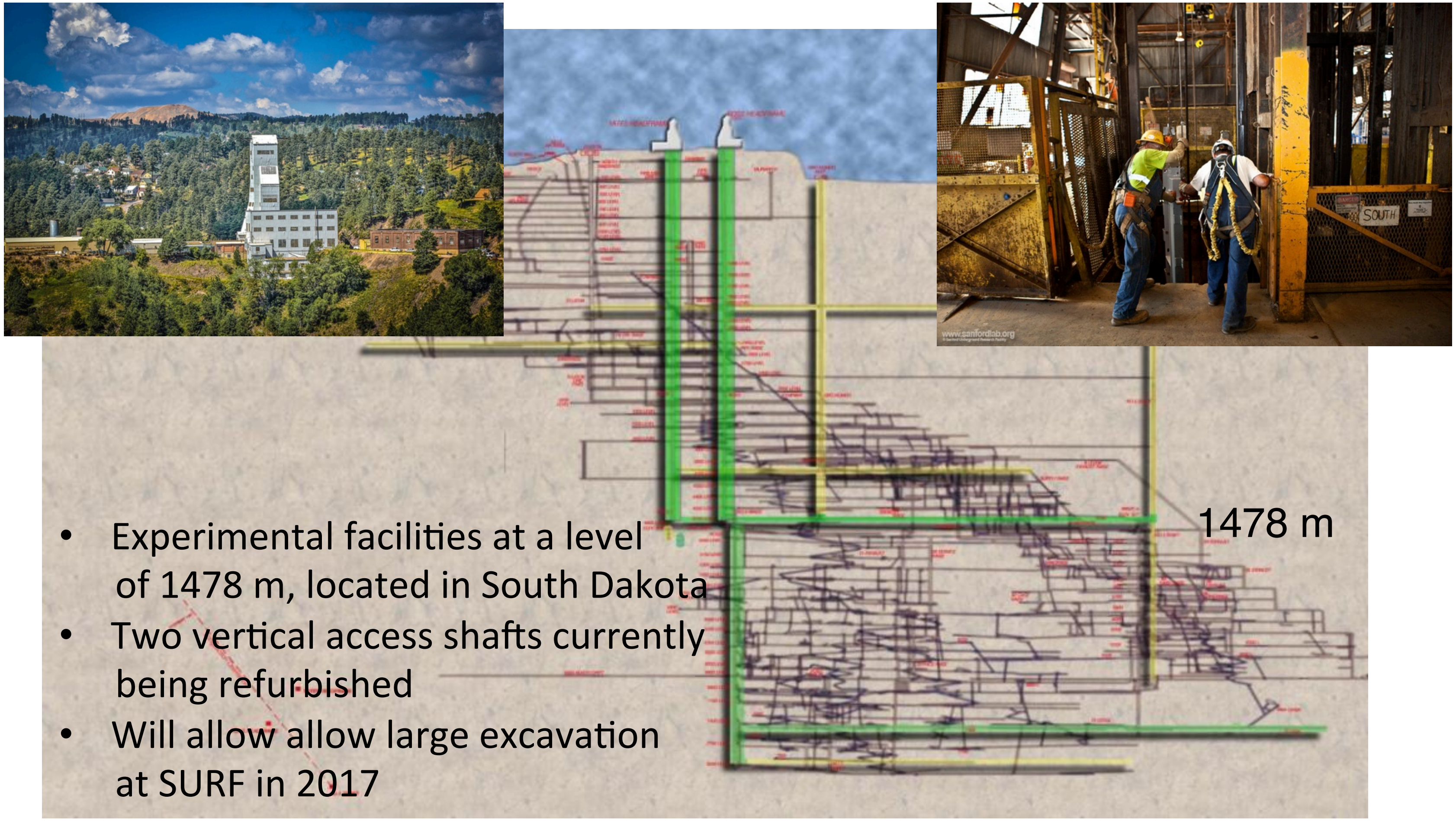
time

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)

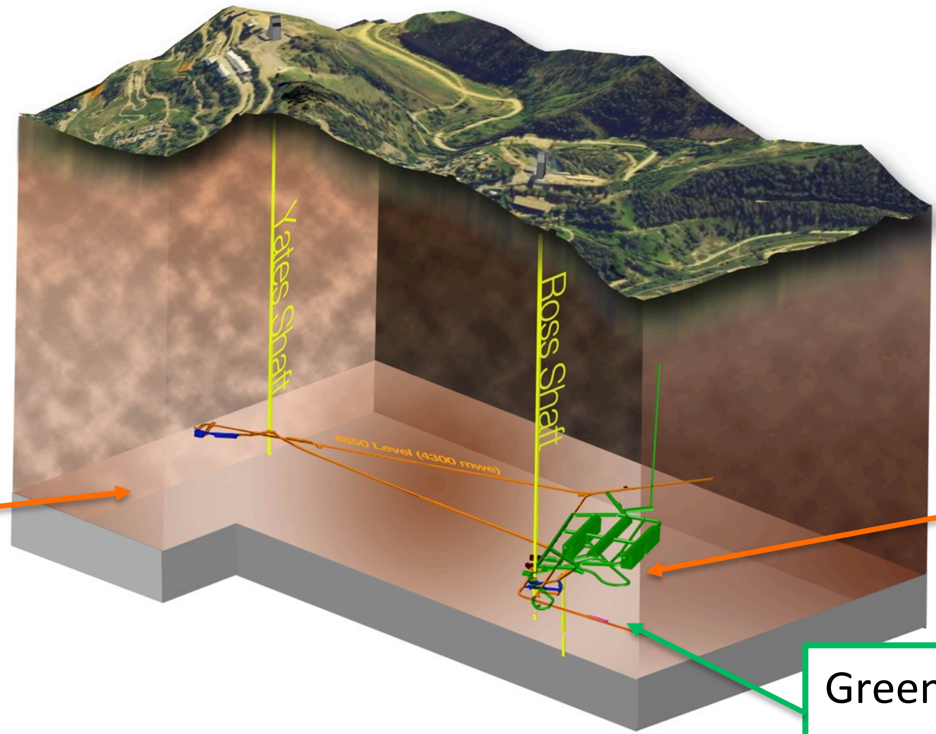


- Experimental facilities at a level of 1478 m, located in South Dakota
- Two vertical access shafts currently being refurbished
- Will allow allow large excavation at SURF in 2017

Underground Laboratory SURF

DUNE Far Detector site

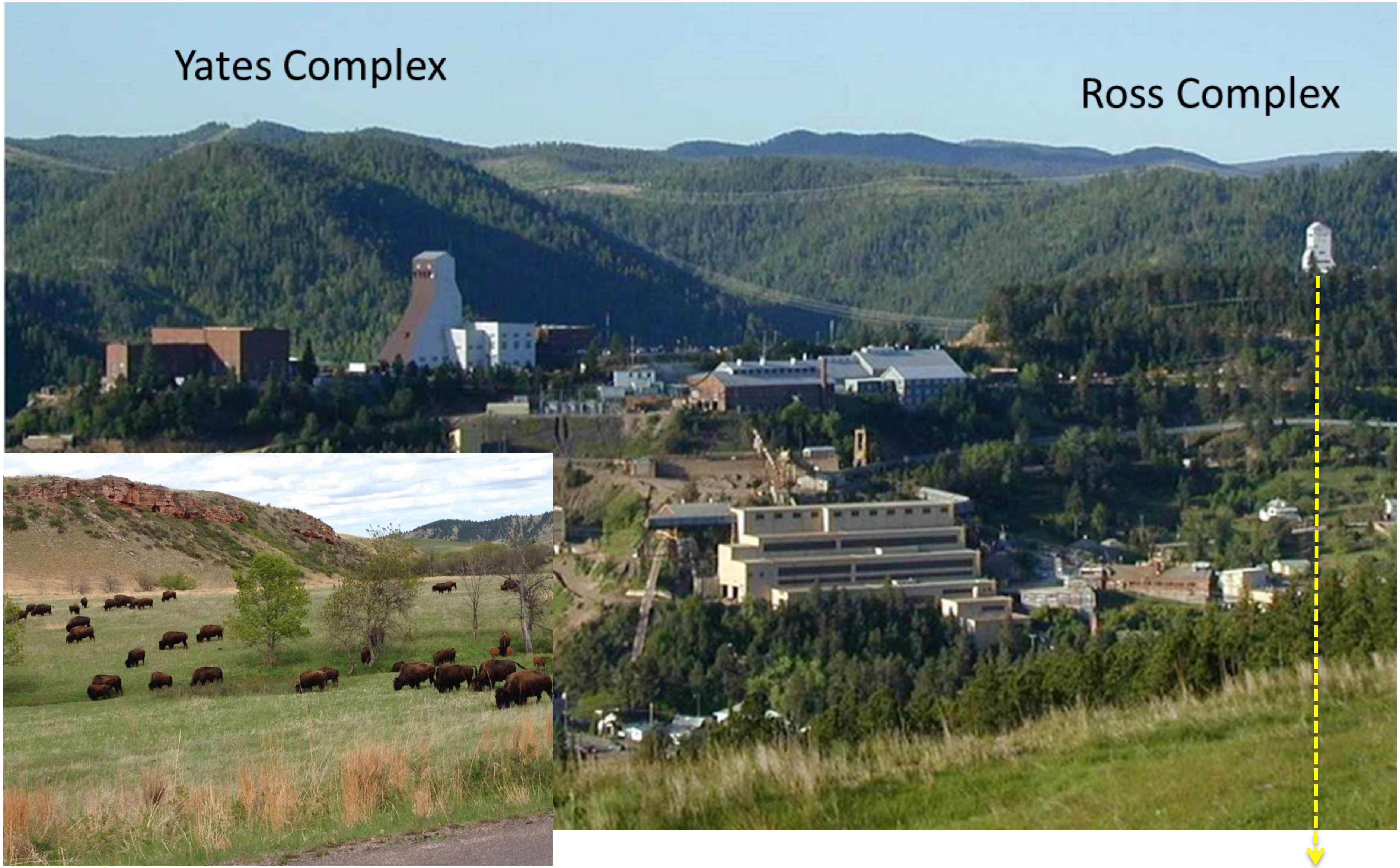
- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)



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

Ross Campus:
- CASPAR
- …
- **DUNE**

Green = new excavation commences in 2017



Yates Complex
Ross Complex

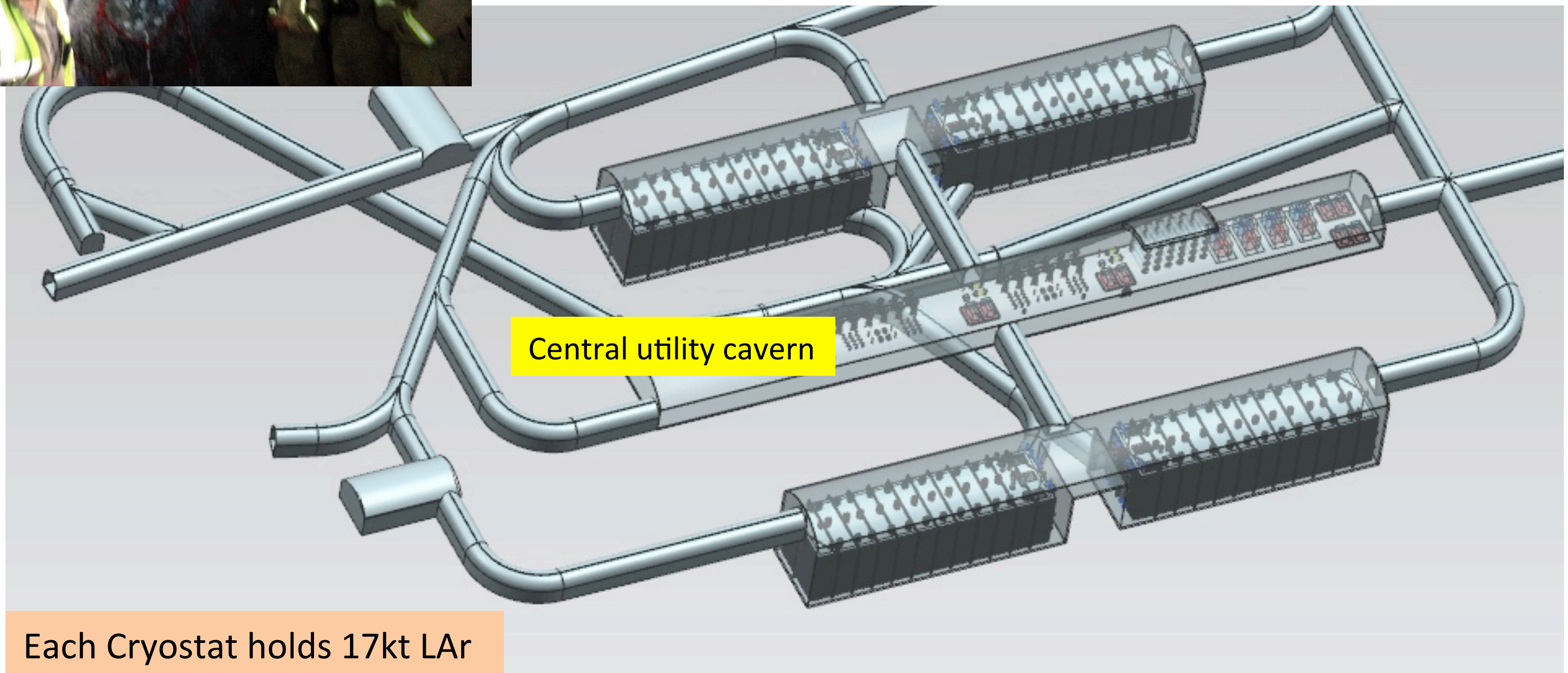
Far Detector lay-out

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

Allows for staged construction of the Far Detector

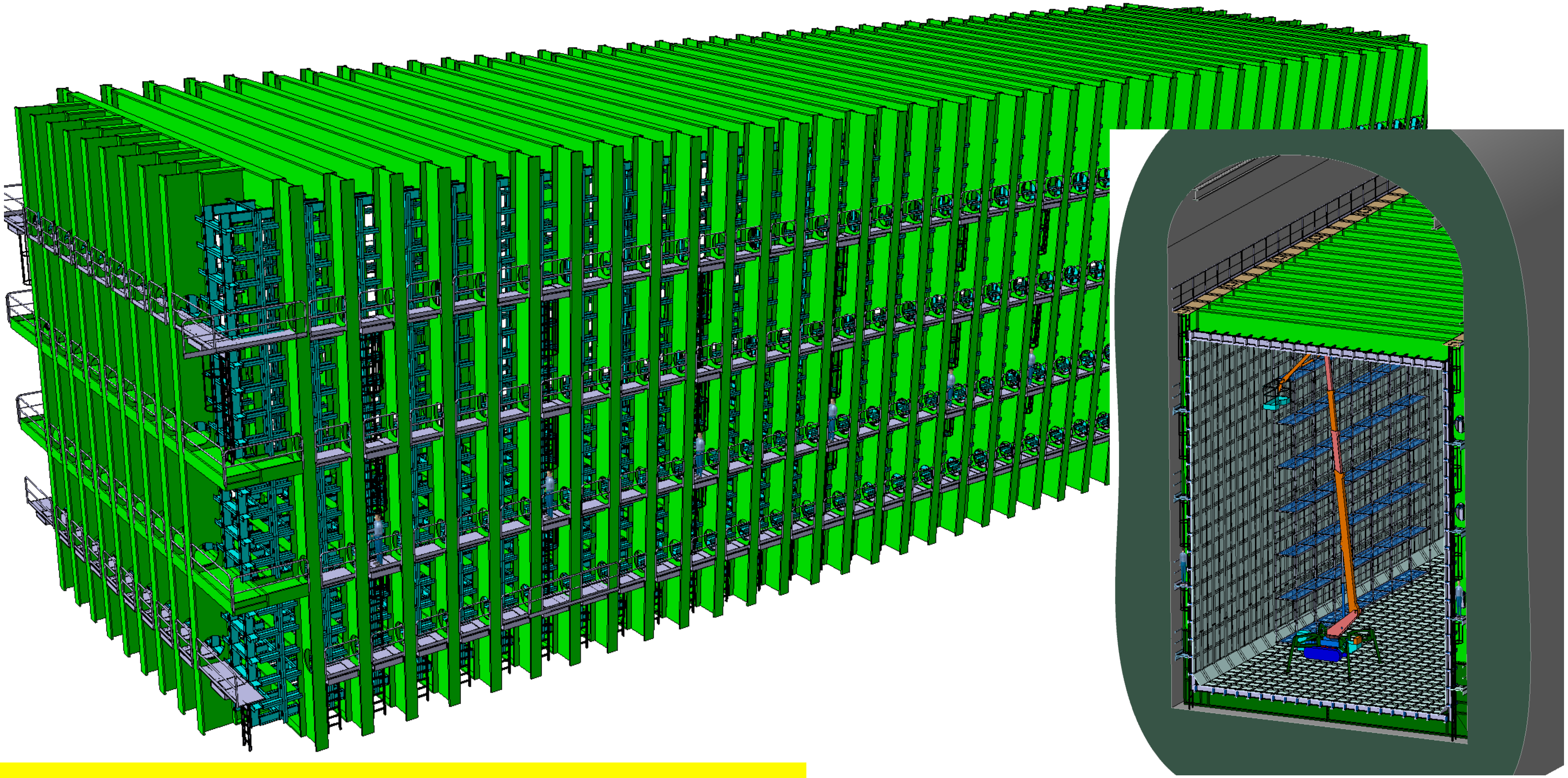
Gives flexibility for evolution of LArTPC technology design

- 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



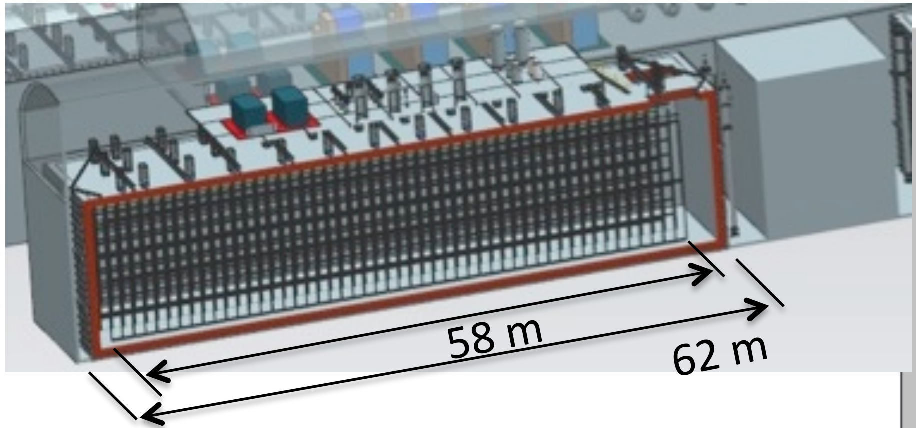
Each Cryostat holds 17kt LAr

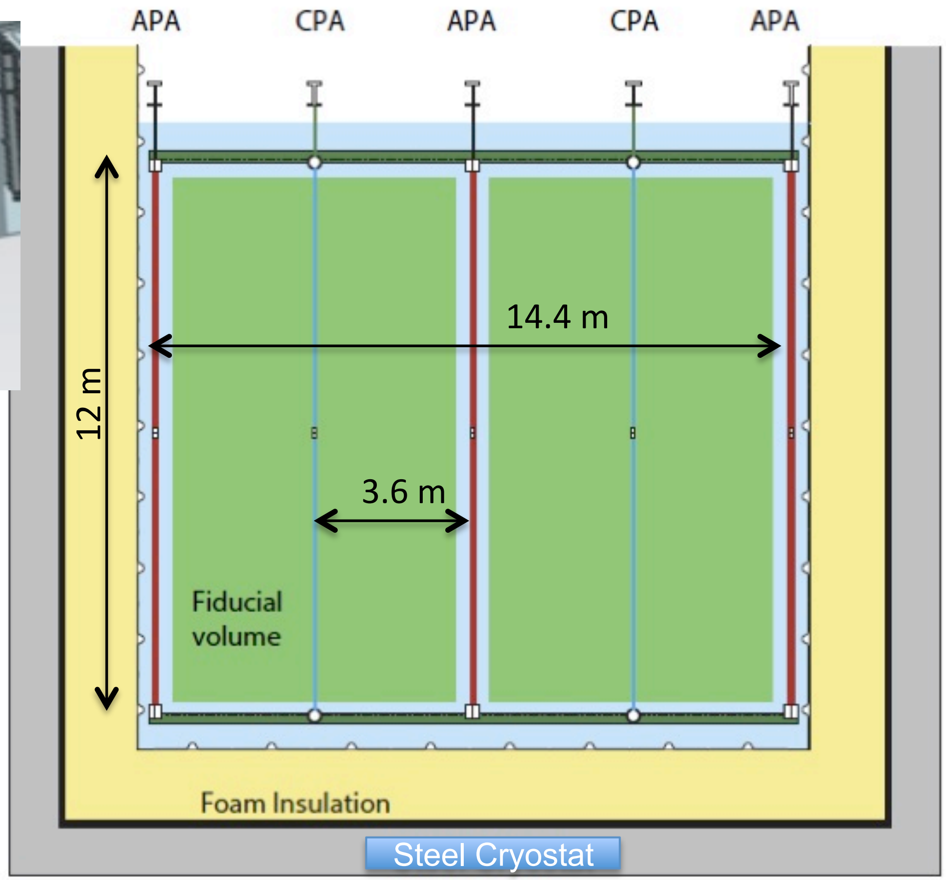
Free-standing steel cryostat



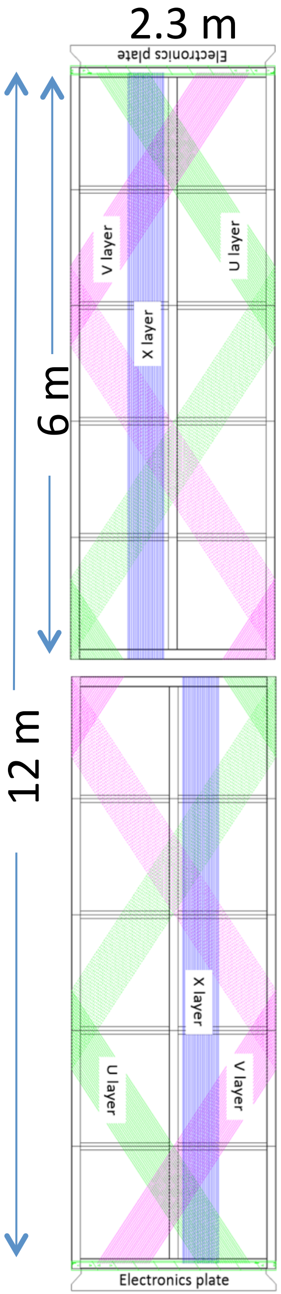
<u>External Dimensions: </u>19.1m x 18.0m x 66.0m

First Detector: single-phase

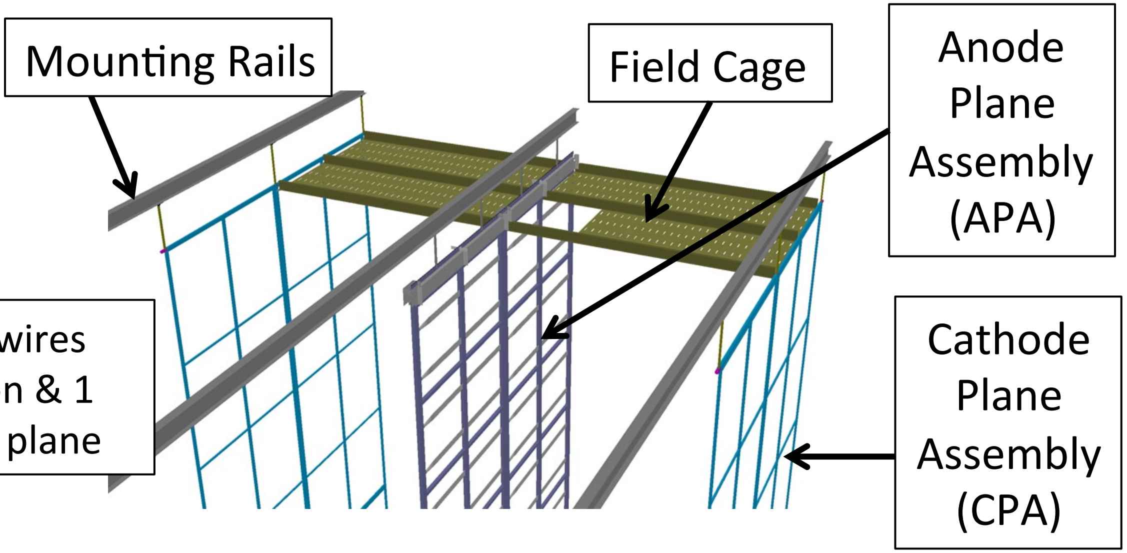


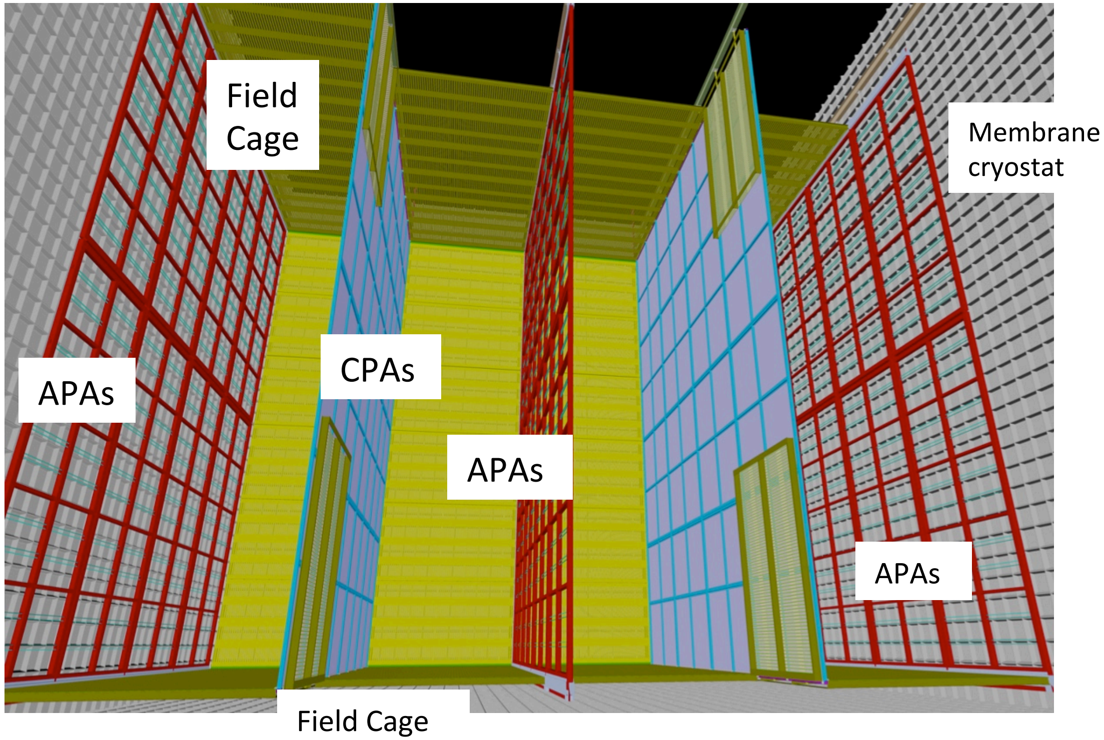


- 3 Anode Plane Assemblies (APA) wide (wire planes)
  - Cold electronics 384,000 channels
- Cathode planes (CPA) at 180kV
  - 3.6 m max drift length



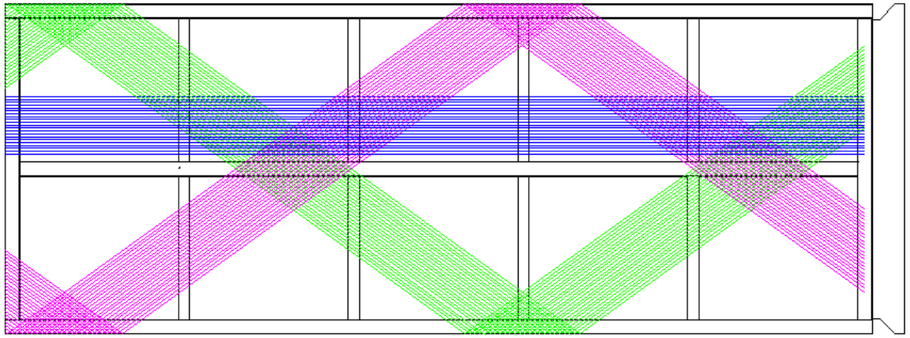
- wrapped wires
- 2 induction & 1 collection plane

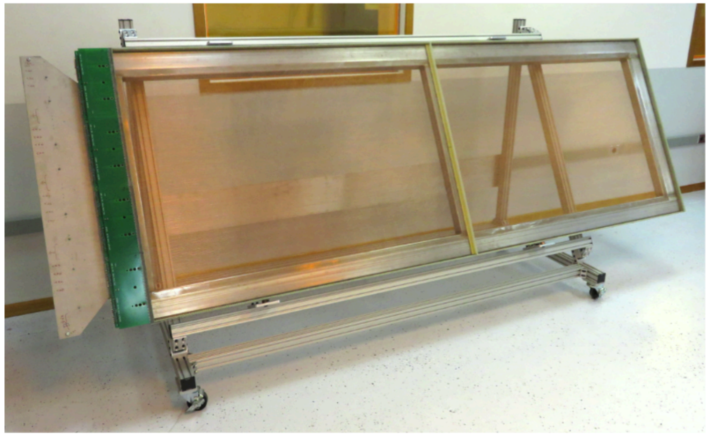




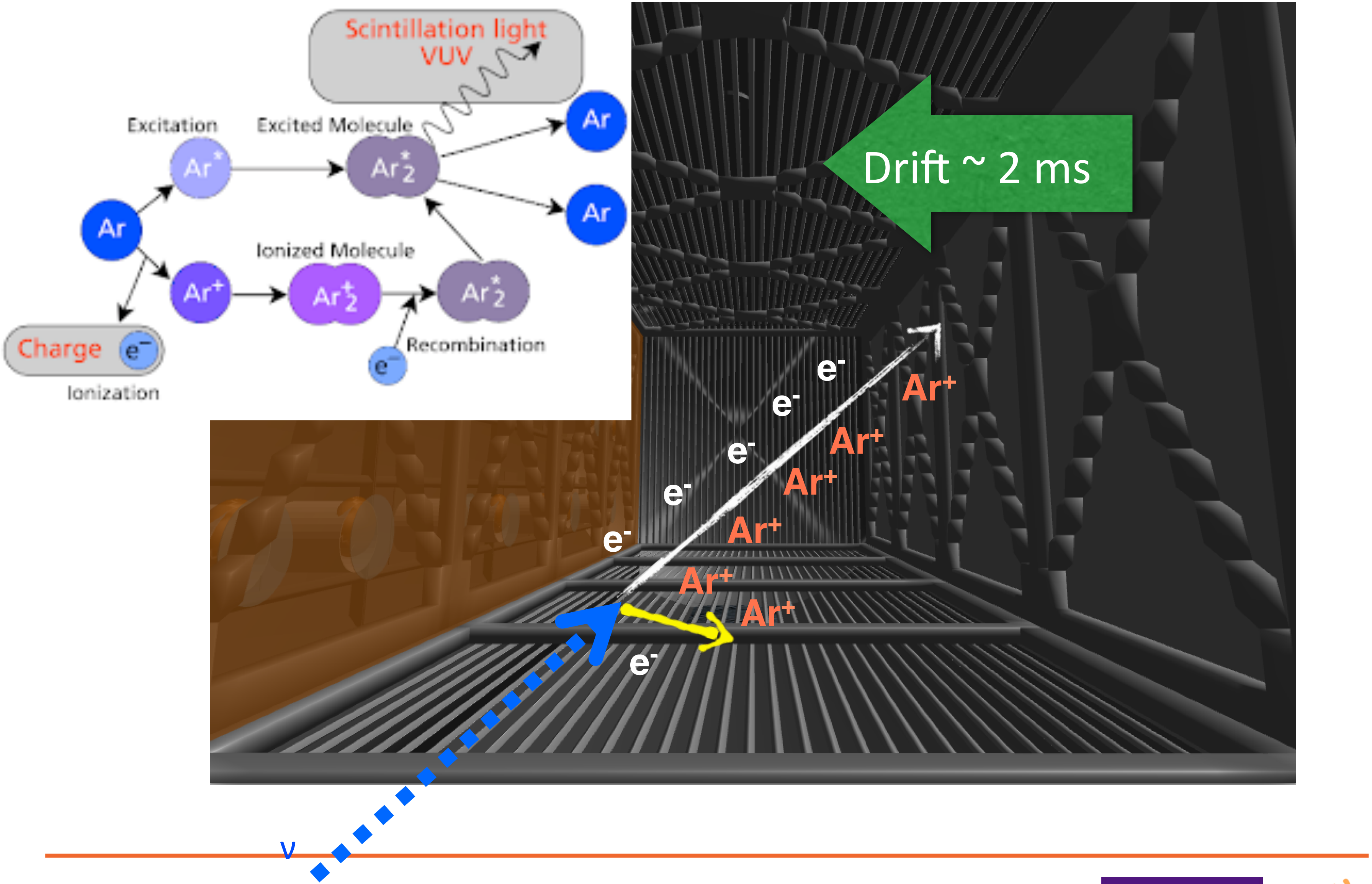
APA Construction Sites

- We require 150 APAs and 200 CPAs per module.
- Large production site being set up at Daresbury Laboratory between Manchester and Liverpool.
- Will need 3-4 construction sites for DUNE.

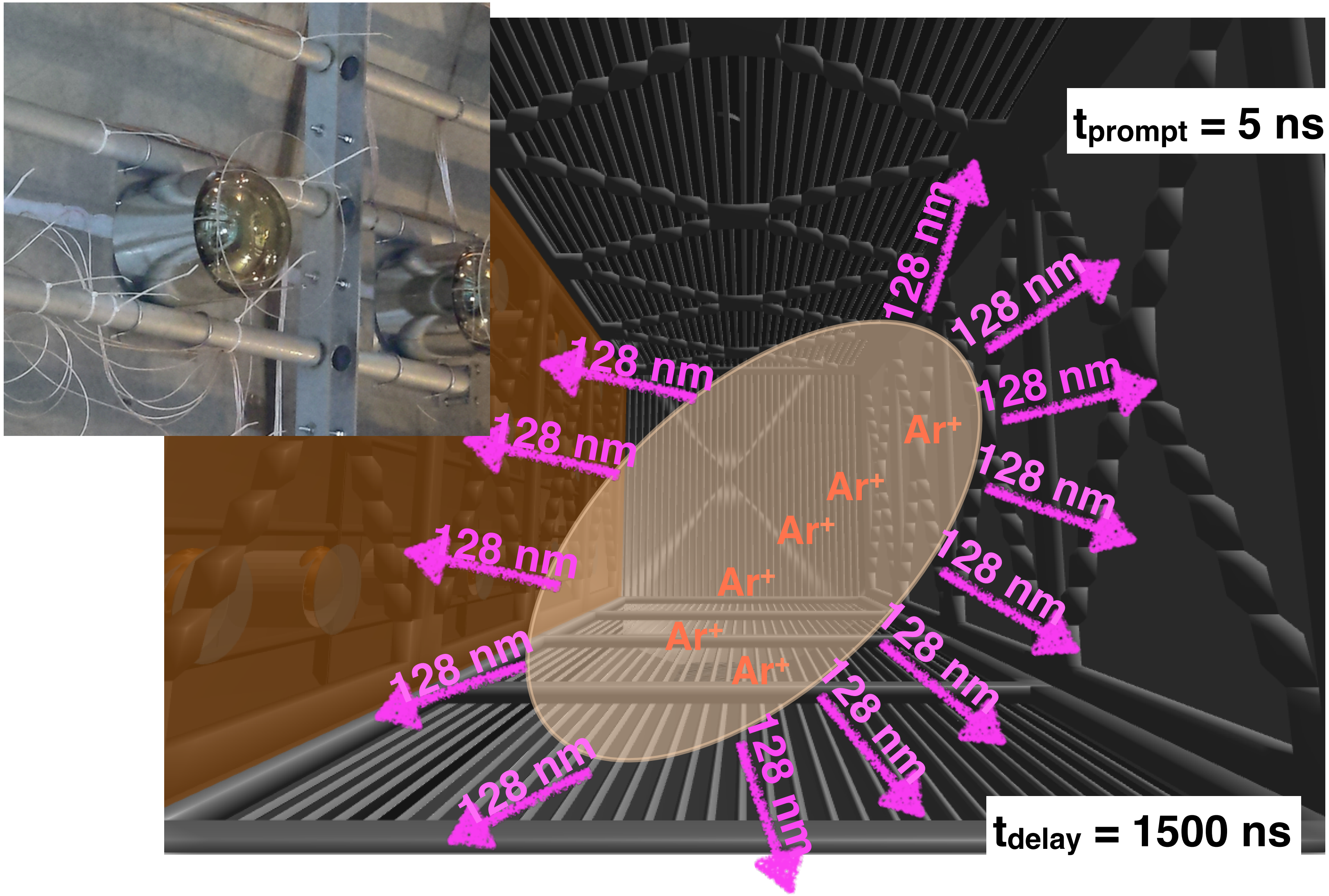




Photon detection

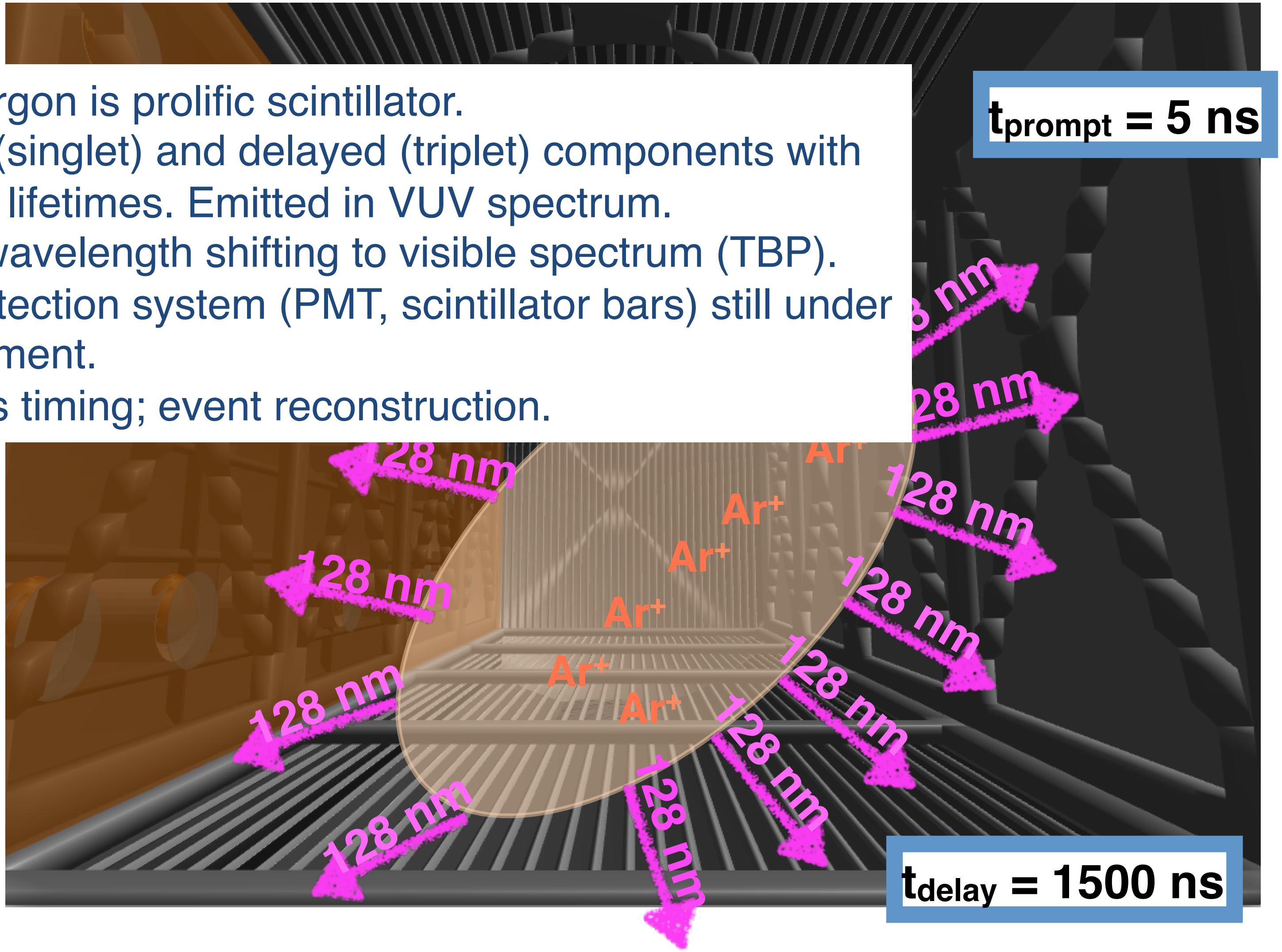


Photon detection



Photon detection

- Liquid argon is prolific scintillator.
- Prompt (singlet) and delayed (triplet) components with different lifetimes. Emitted in VUV spectrum.
- Needs wavelength shifting to visible spectrum (TBP).
- Light detection system (PMT, scintillator bars) still under development.
- Provides timing; event reconstruction.



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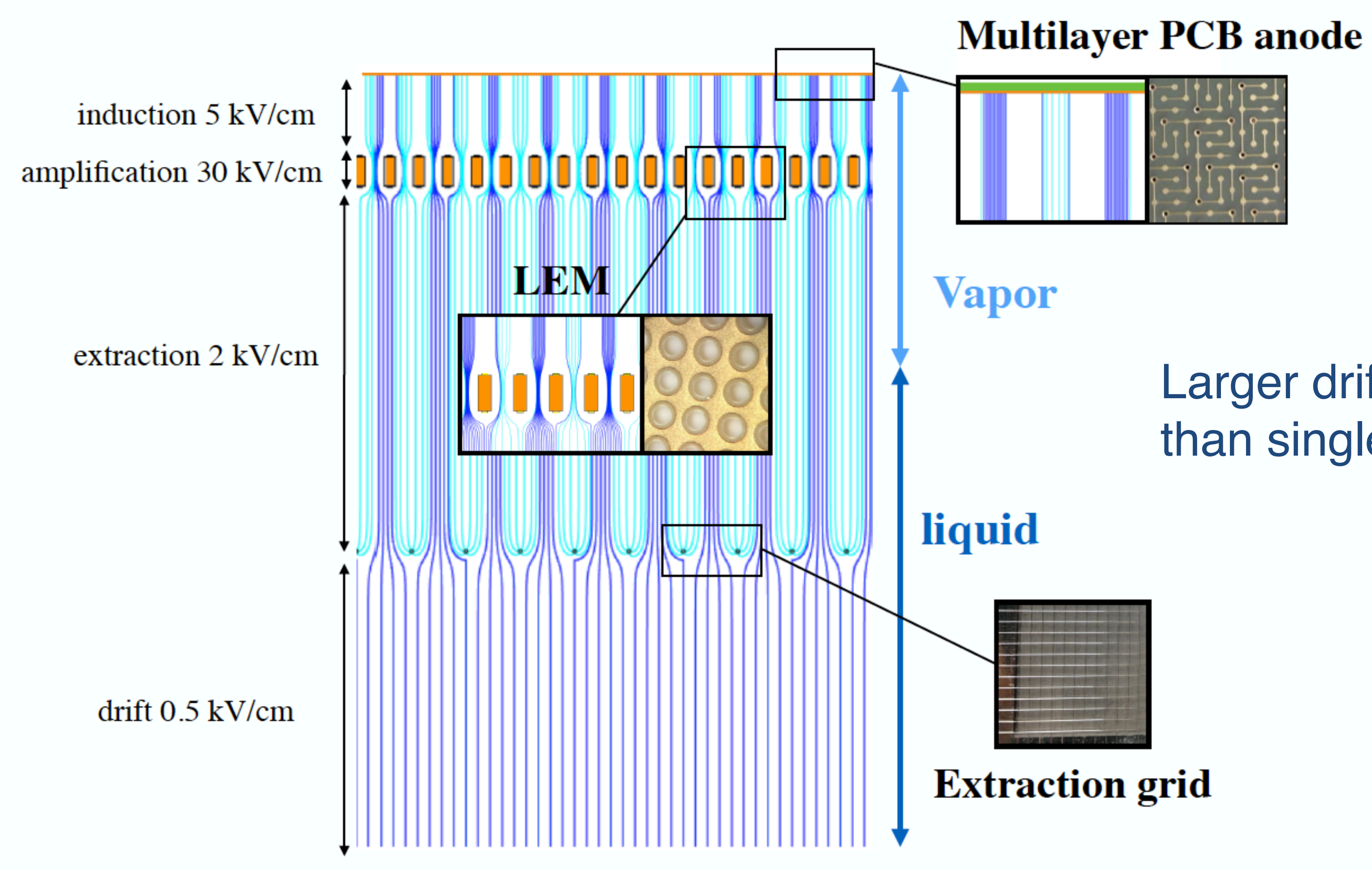
Alternative Design: Dual-phase

Could form basis of second or subsequent 10-kt FD modules

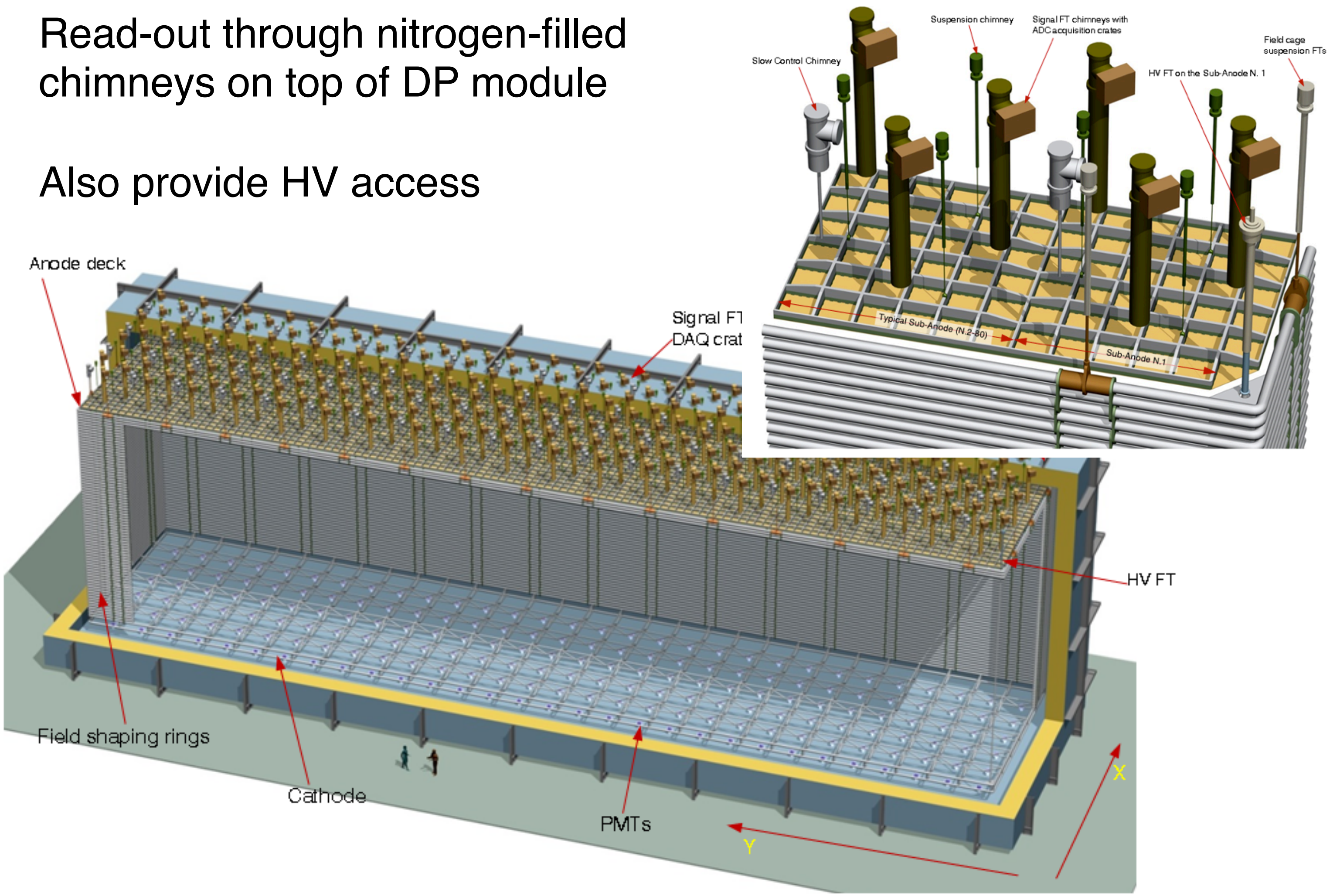


Larger drift distances than single-phase

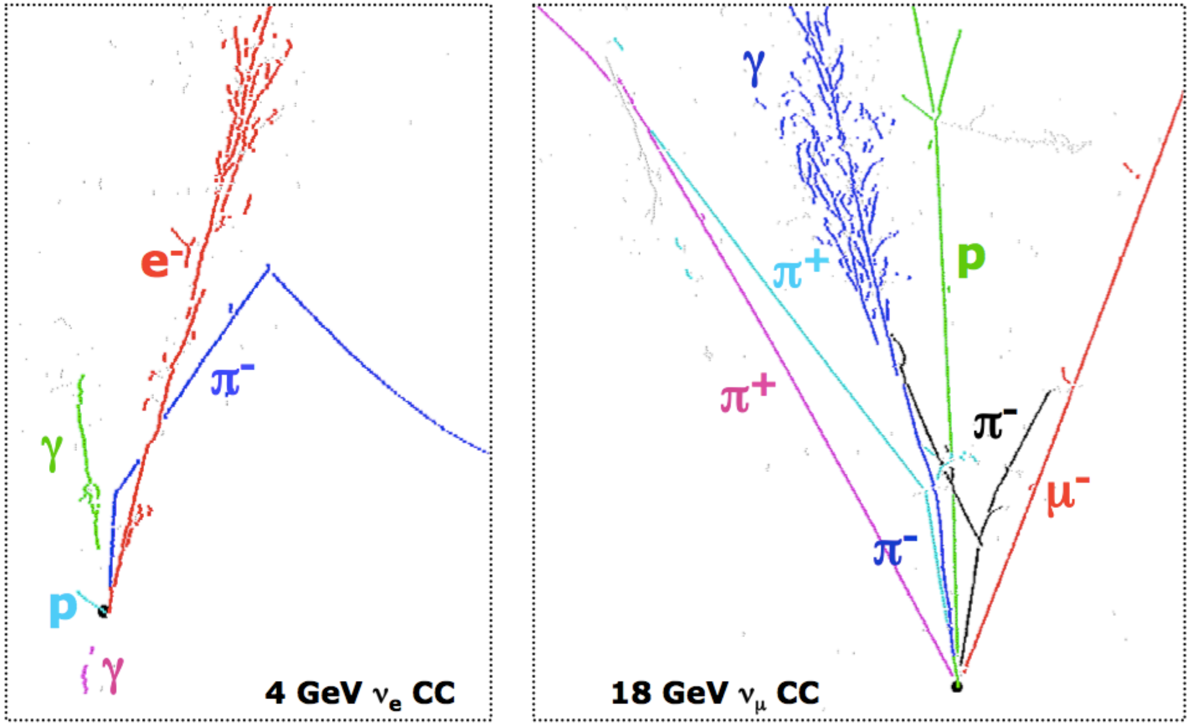
Alternative Design: Dual-phase

Read-out through nitrogen-filled chimneys on top of DP module

Also provide HV access

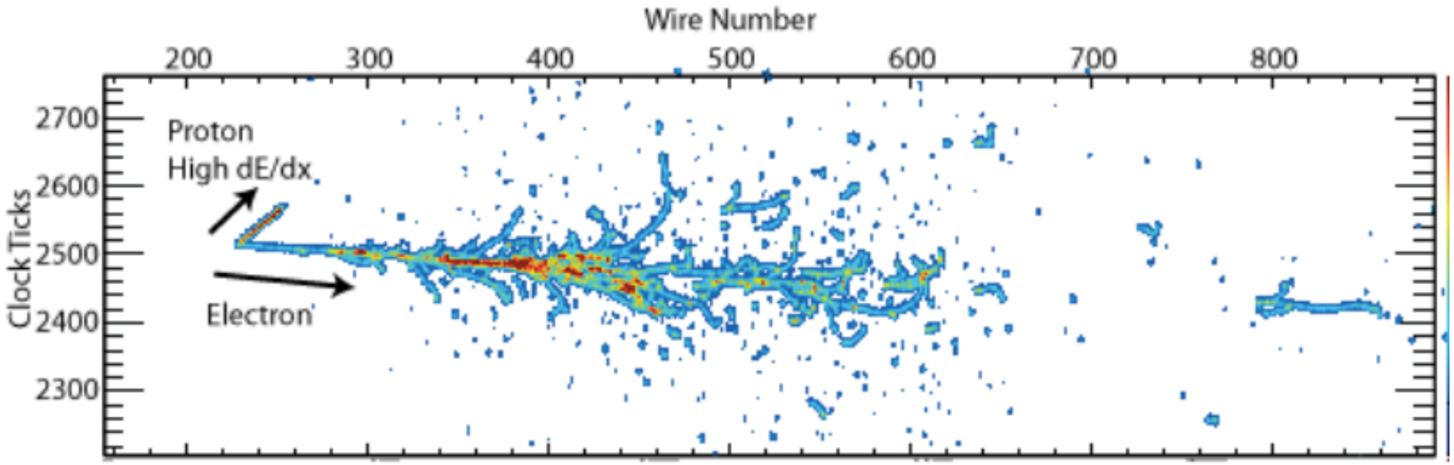


Other challenges: event reconstruction



- Need to reconstruct tracks and showers, measure their energy and perform particle identification.
- Complex event topologies require sophisticated algorithms
- Automatisation a major challenge.

Other challenges: data acquisition

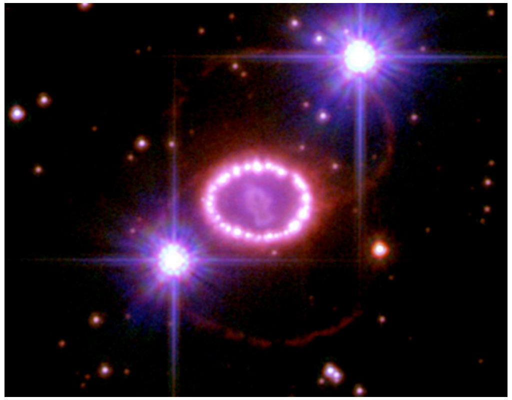


Detector always live

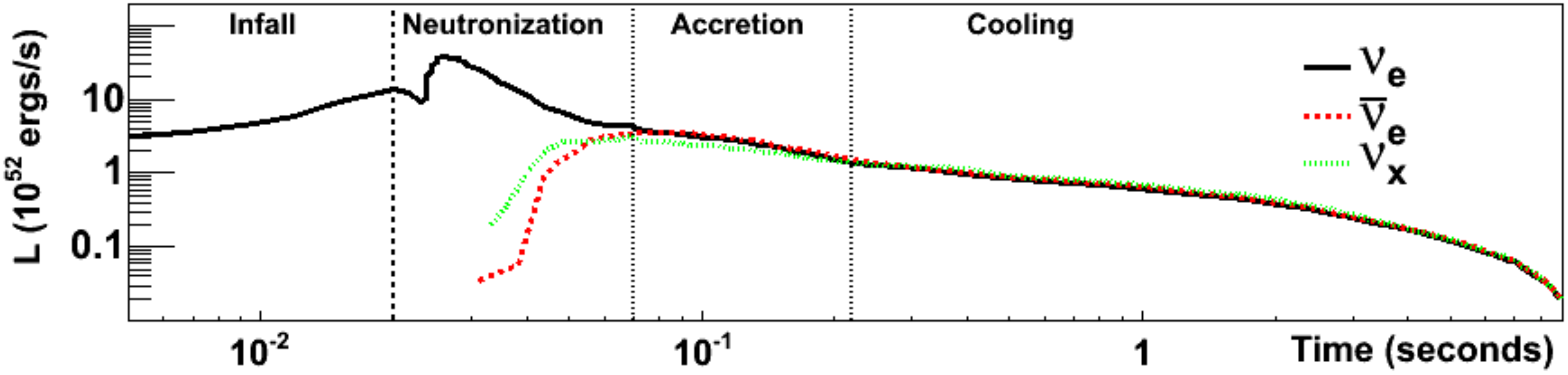
- Pre-trigger TPC data rate of about 1 TB/s.
- Low underground event rate (one beam spill per second, one cosmic ray per minute) allows online data processing.
- Supernova trigger: 10 TB over 10 s.

Core-collapse supernova

- Gravitational binding energy released:
  - 99% neutrinos ($N \approx 10^{58}$)
  - 1% kinetic energy of exploding matter
  - 0.01% light
- Neutrino emission lasts ≈10 sec
- 1-3 SNs/century in our Galaxy (≈10 kpc)



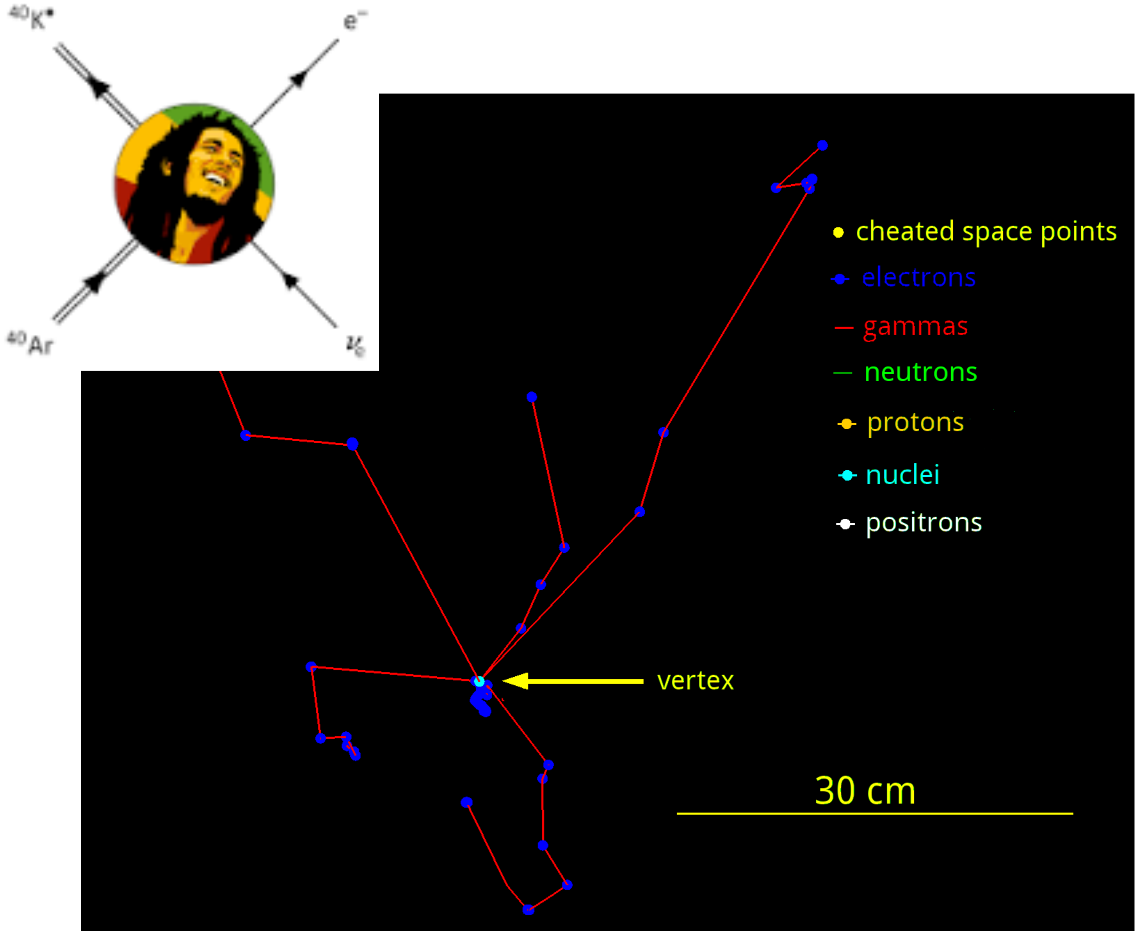
SN1987A: detected ≈ 20 neutrino events in total (essentially anti-ν_e)



Supernova neutrino signal in LAr

Main detection process:

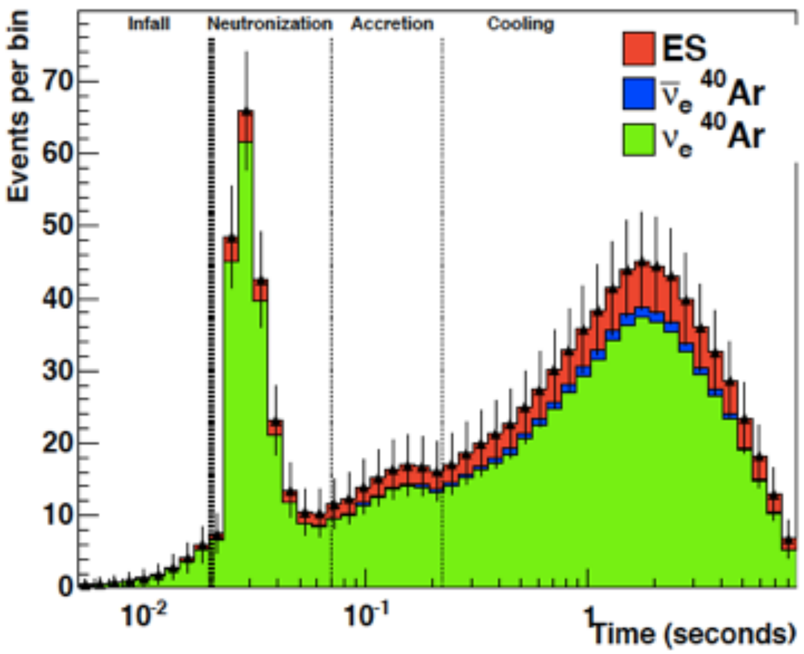
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



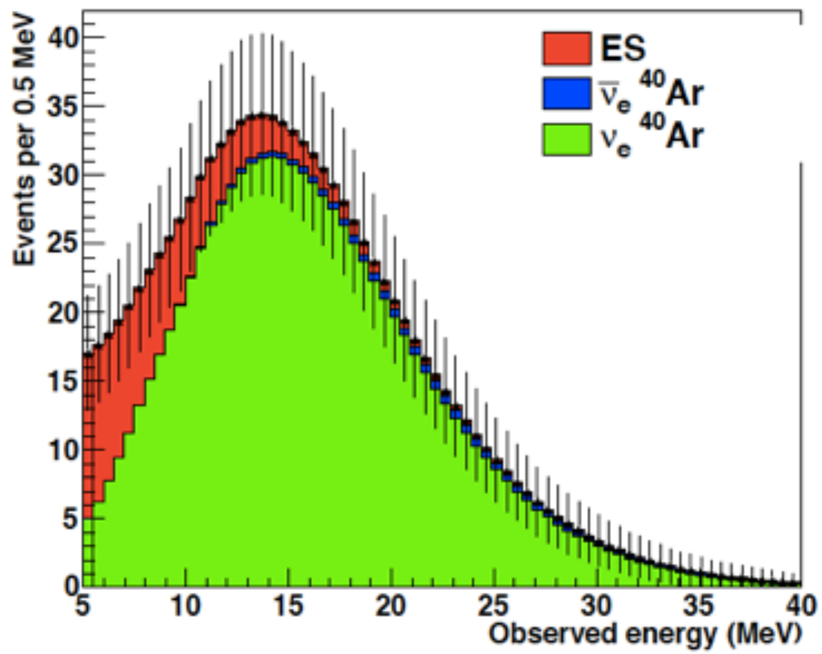
- Reconstruct photons from nuclear de-excitations.
- Need to understand underlying nuclear physics.
- Possible low-energy background from ^{39}Ar.

SN neutrino spectra in DUNE

- SN at 10 kpc in DUNE
  in 40 kt LAr dector
- Required energy resolution < 10%
- Energy threshold ~ 5 MeV



Time-dependent signal

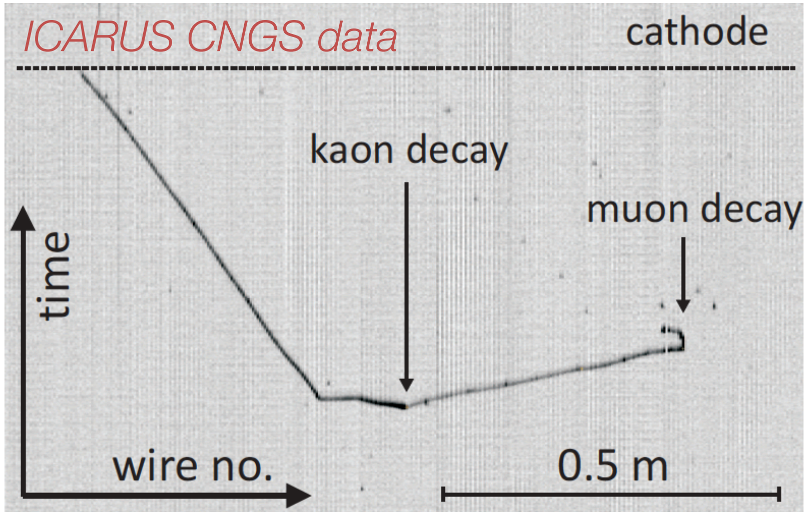


Time-integrated energy spectrum

Garching model, ICARUS energy resolution, 5 MeV threshold

Nucleon decay channels

- Many possible decay modes
- The strength of LAr: kaon modes, e.g. p ➔ν K⁺ (SUSY motivated)
- Kaons clearly identified by dE/dx and decay chain.

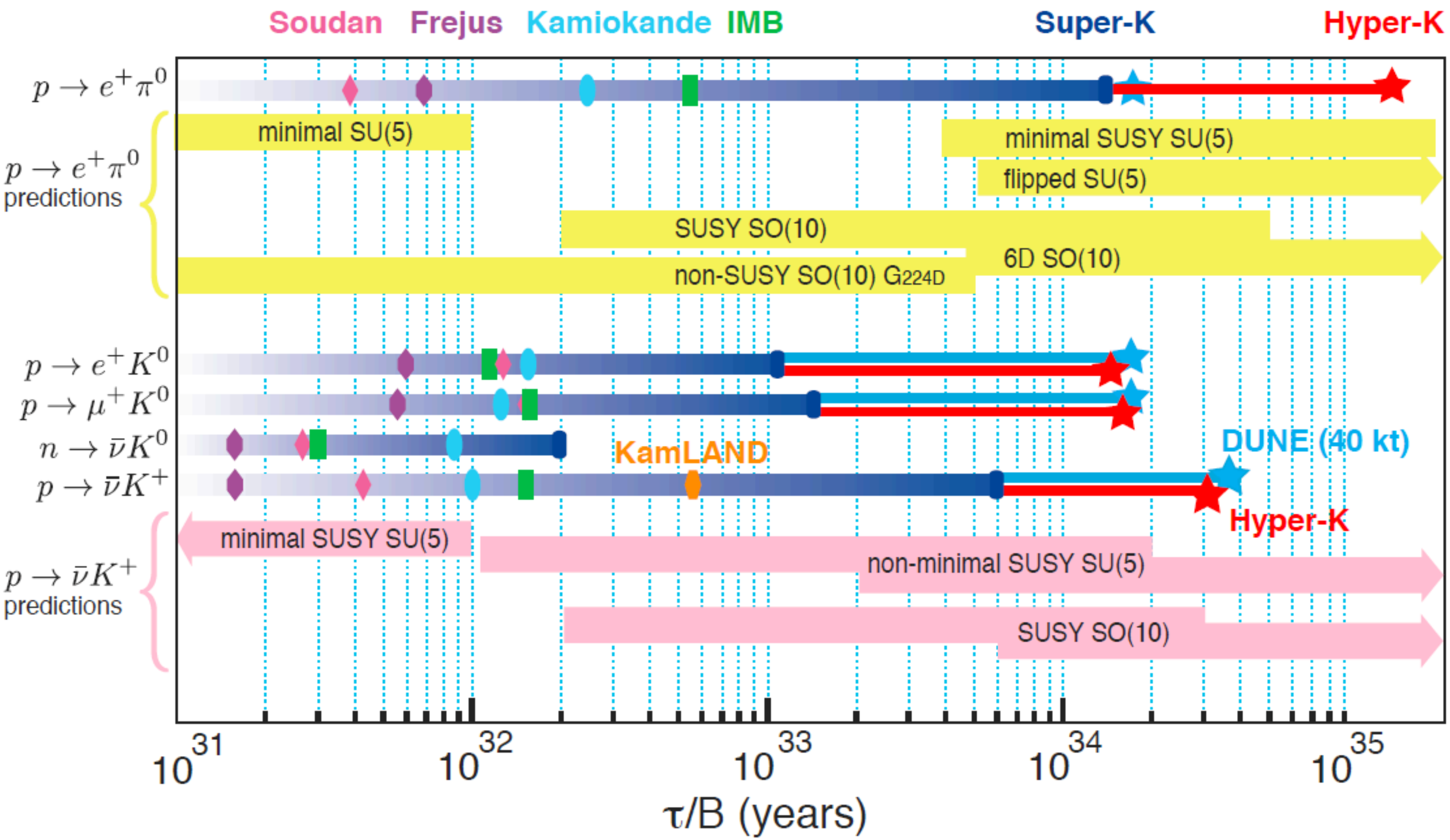


Efficiency and background rate per Mton per year JHEP 0704 (2007) 041

Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	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

Background -free channels

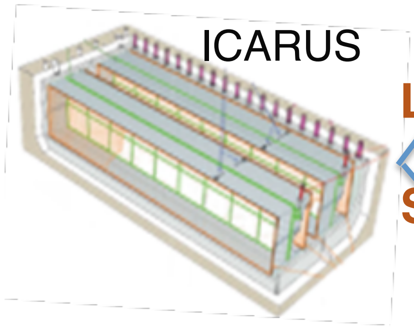
Proton Decay Searches



Far Detector Development Path

Single-Phase

ICARUS



ArgoNeuT
LArIAT

LBL

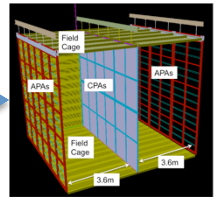
SBL

35-t prototype

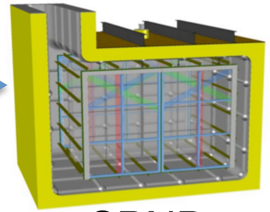
2015

MicroBooNE

protoDUNE @ CERN

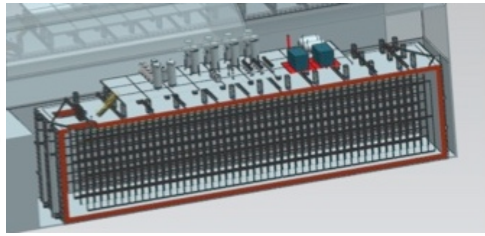


2018



SBND

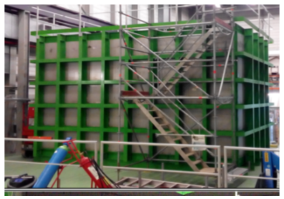
DUNE Reference Design



TDR 2019

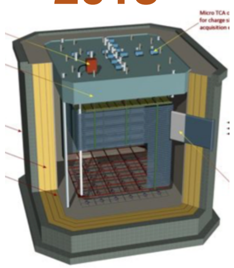
Dual-Phase

2016



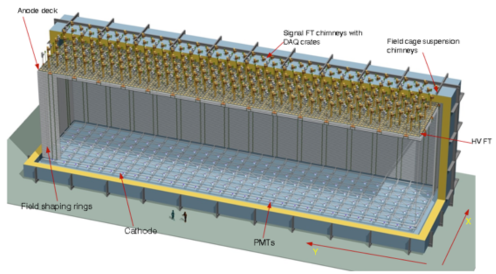
WA105: 1x1x3 m^3

2018



WA105
(6x6x6 m^3)

DUNE Alternative Design

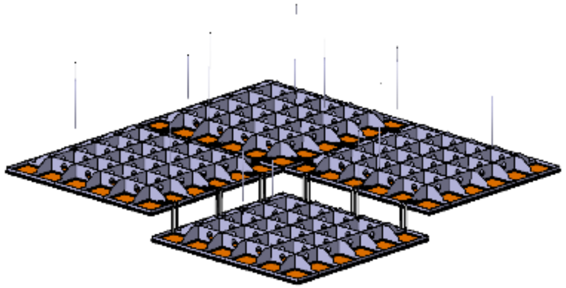


ProtoDUNE: Dual-phase demonstrator

Validate construction techniques and operational performance of full-scale module

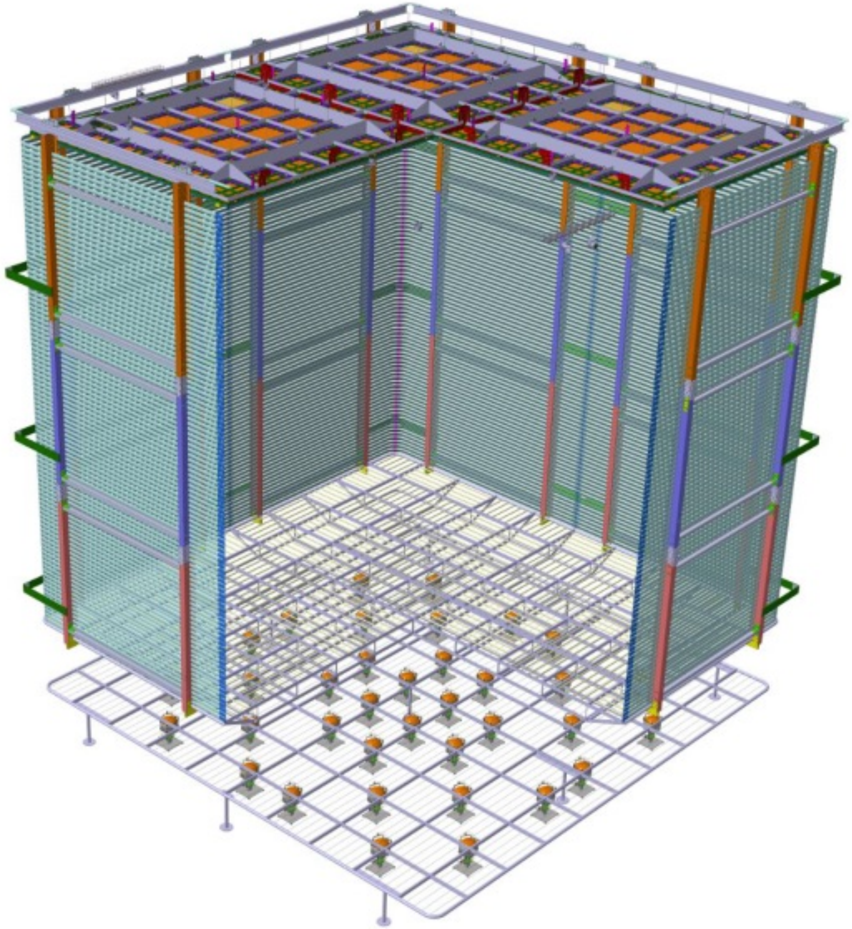
Calibrate detector with charged-particle beam

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



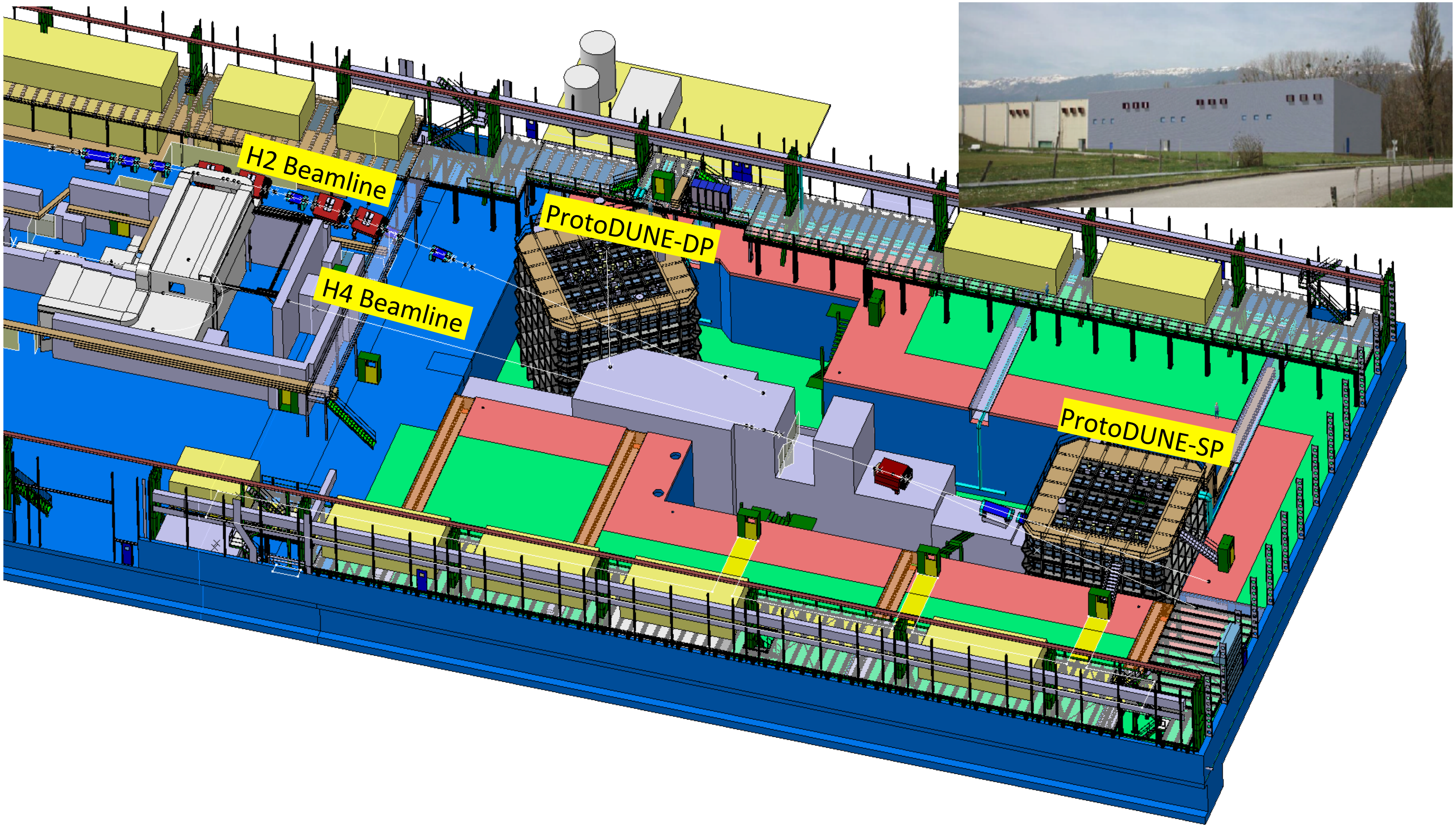
Being constructed at CERN

MANCHESTER 1824 DUNE

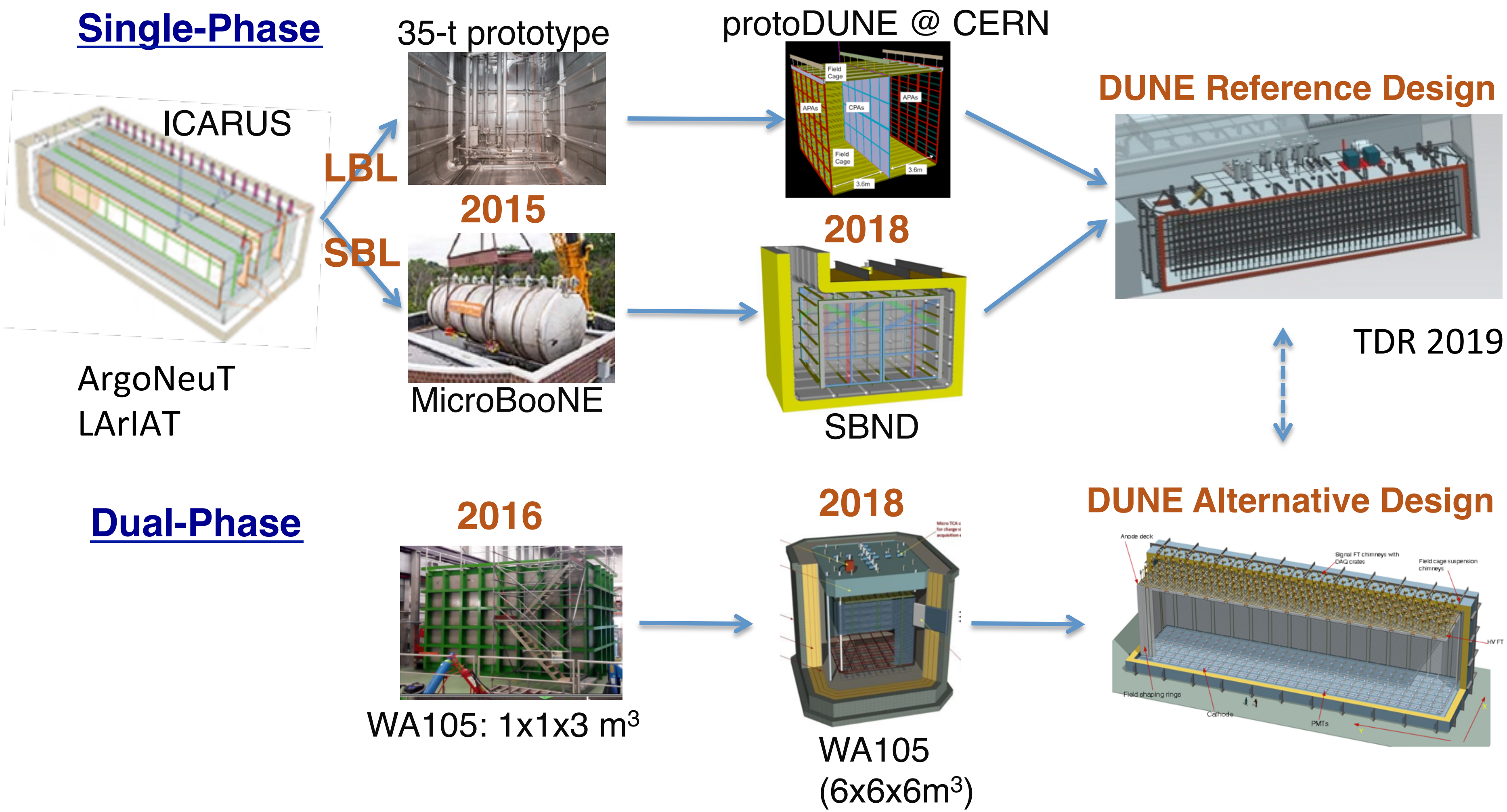
ProtoDUNE: Single-phase demonstrator

- 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
- A:C:A arrangement
- Cathode at -180 kV for 3.5 m drift

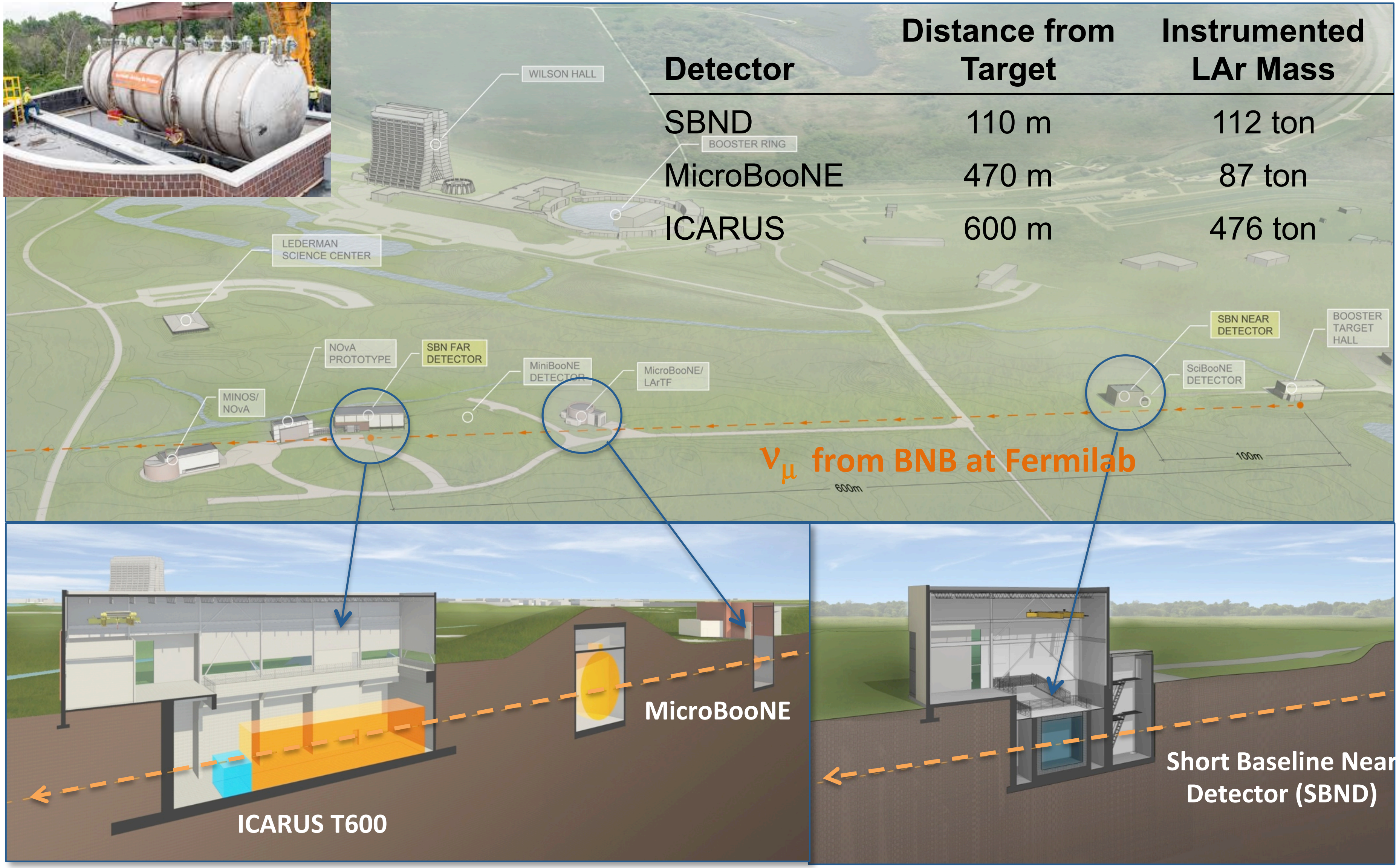
ProtoDUNEs at CERN's North Area



Far Detector Development Path



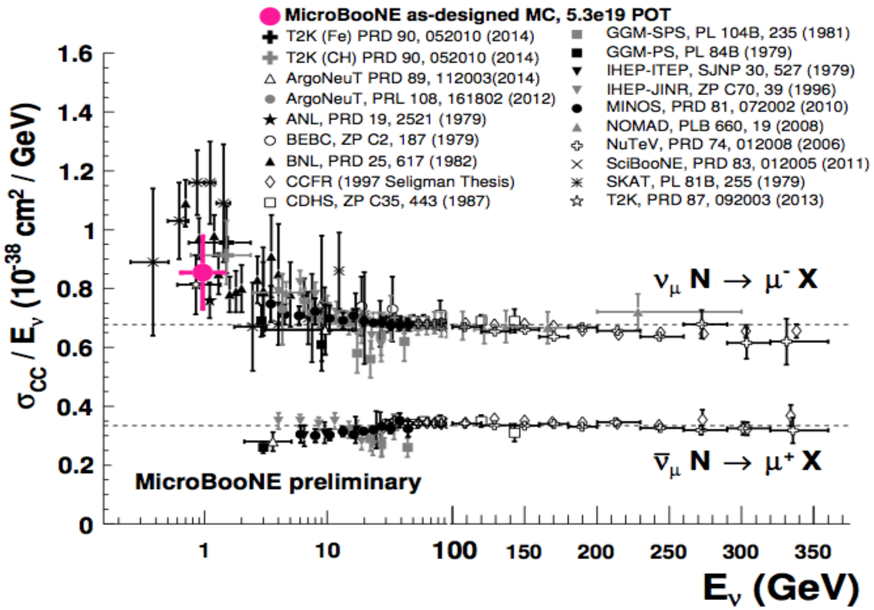
LAr TPC Detectors at Fermilab (short-baseline)



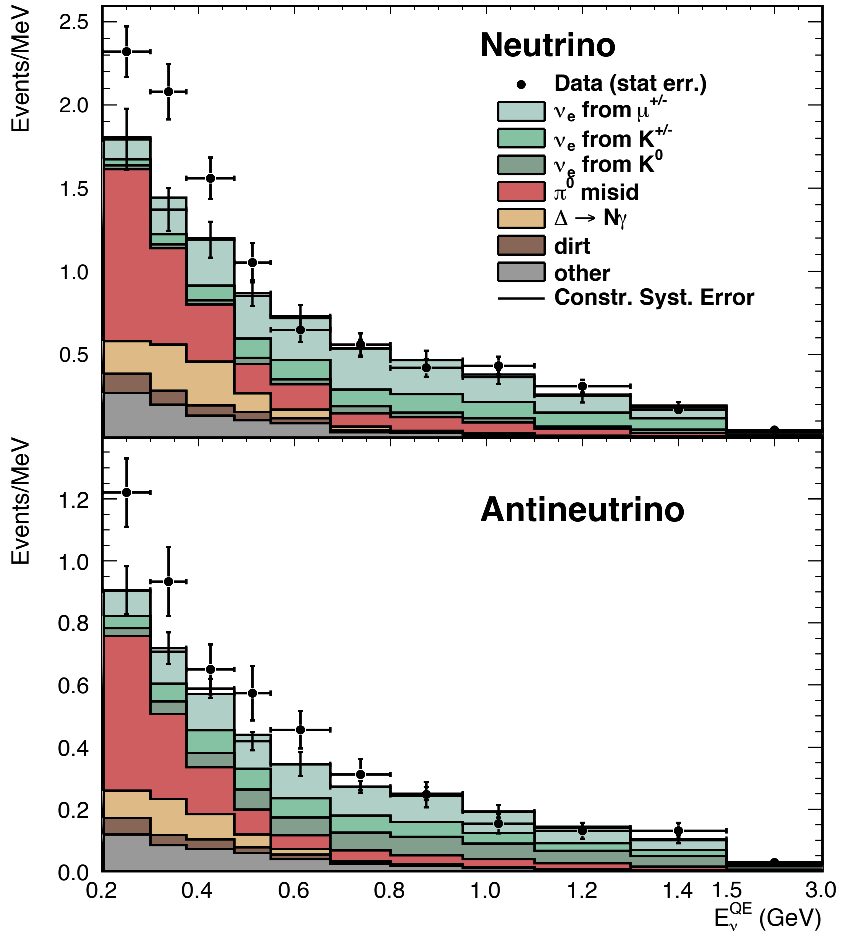
Detector	Distance from Target	Instrumented LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

Short-baseline physics goals

- Explore MiniBooNE anomaly.
- Search for low-mass sterile neutrinos.
- Measure neutrino cross sections on argon in 1 GeV energy range – important for entire LAr programme.



low energy excess



Stefan Söldner-Rembold

Short-baseline physics goals

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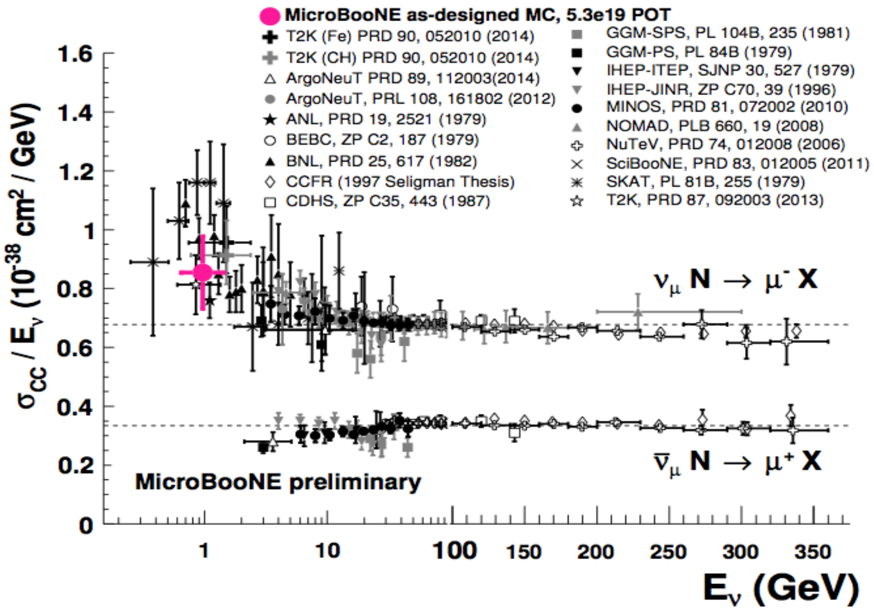
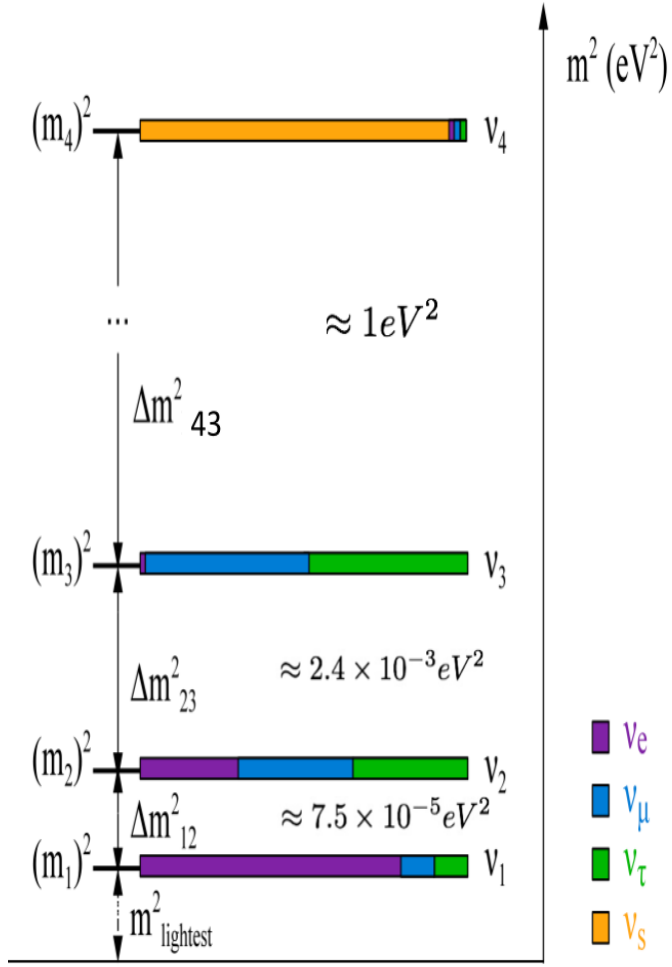
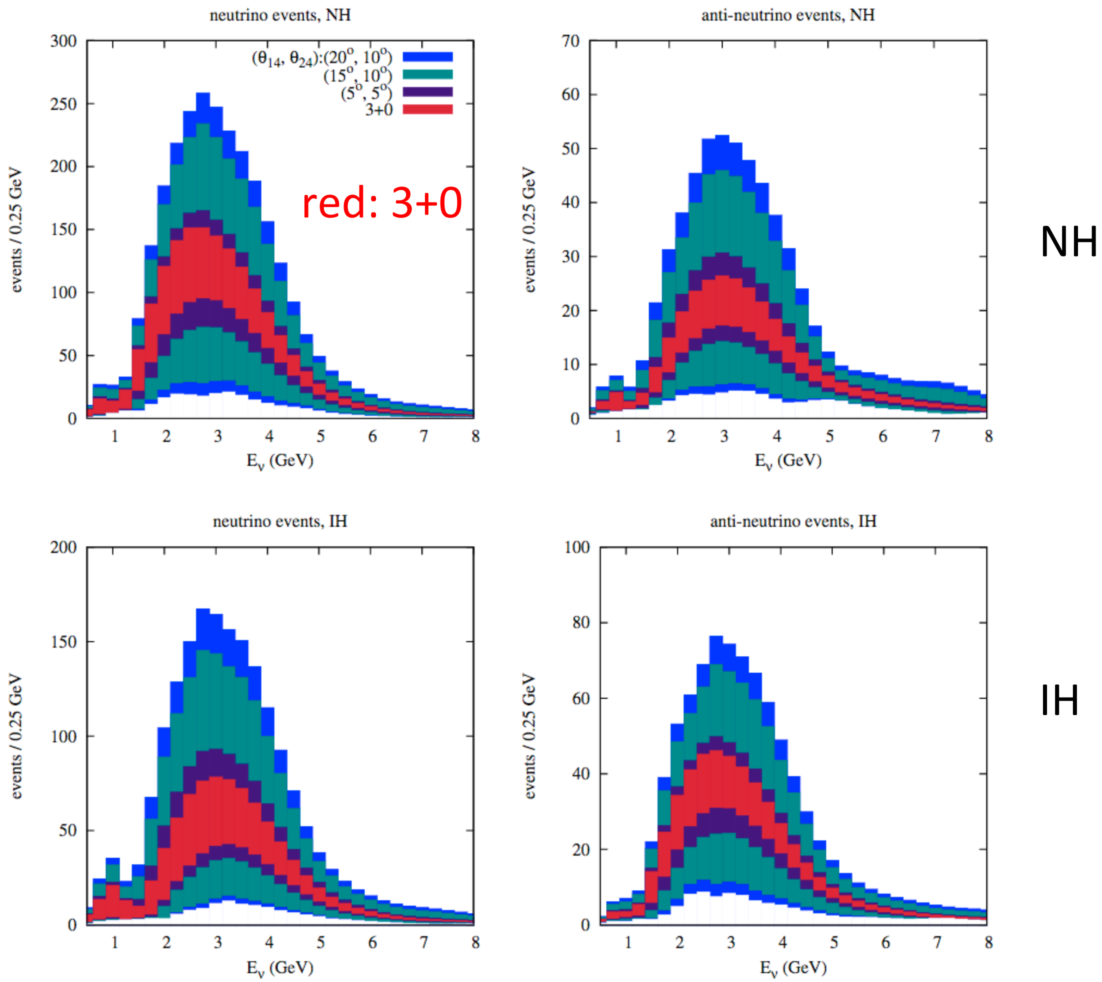




Impact of Sterile Neutrinos on DUNE

- Presence of sterile neutrinos creates degeneracies when interpreting data in terms of CP violation.
- Testing the sterile neutrino sector is an important input for future long-baseline experiments.

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



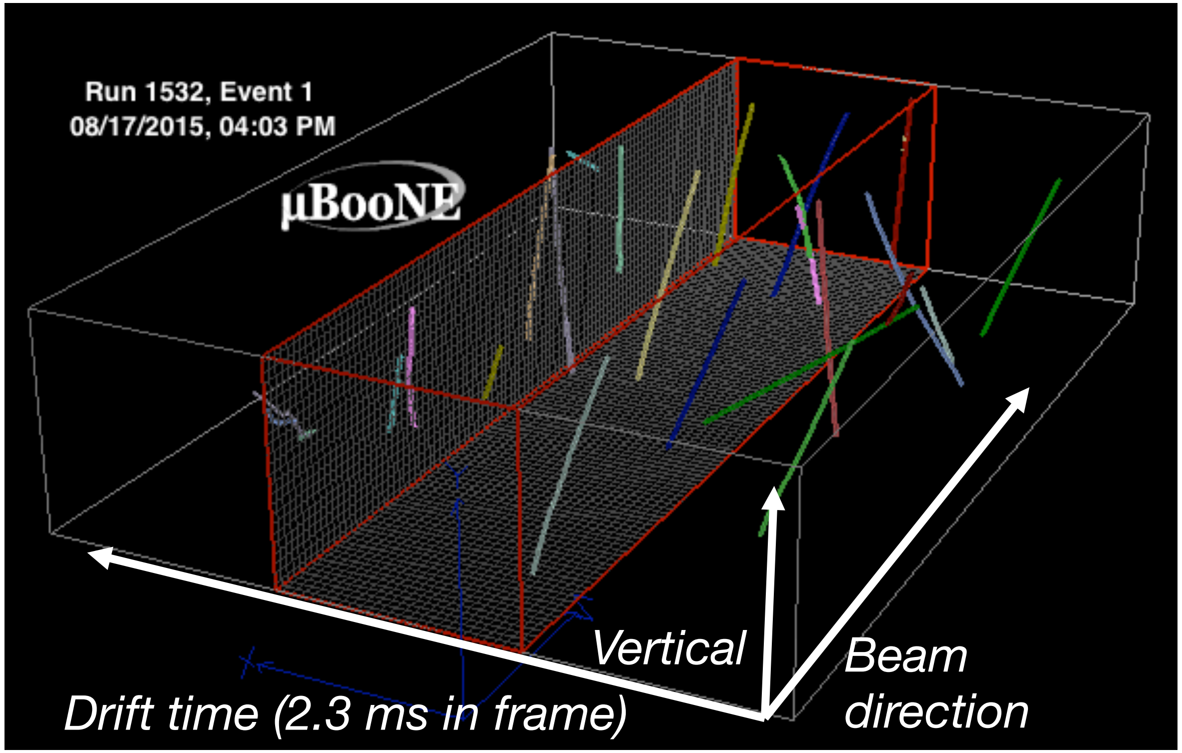
R. Ghandi, B. Kayser, M. Masud, S. Prakash. arXiv:1508.06275

MicroBooNE: Cosmic Rays

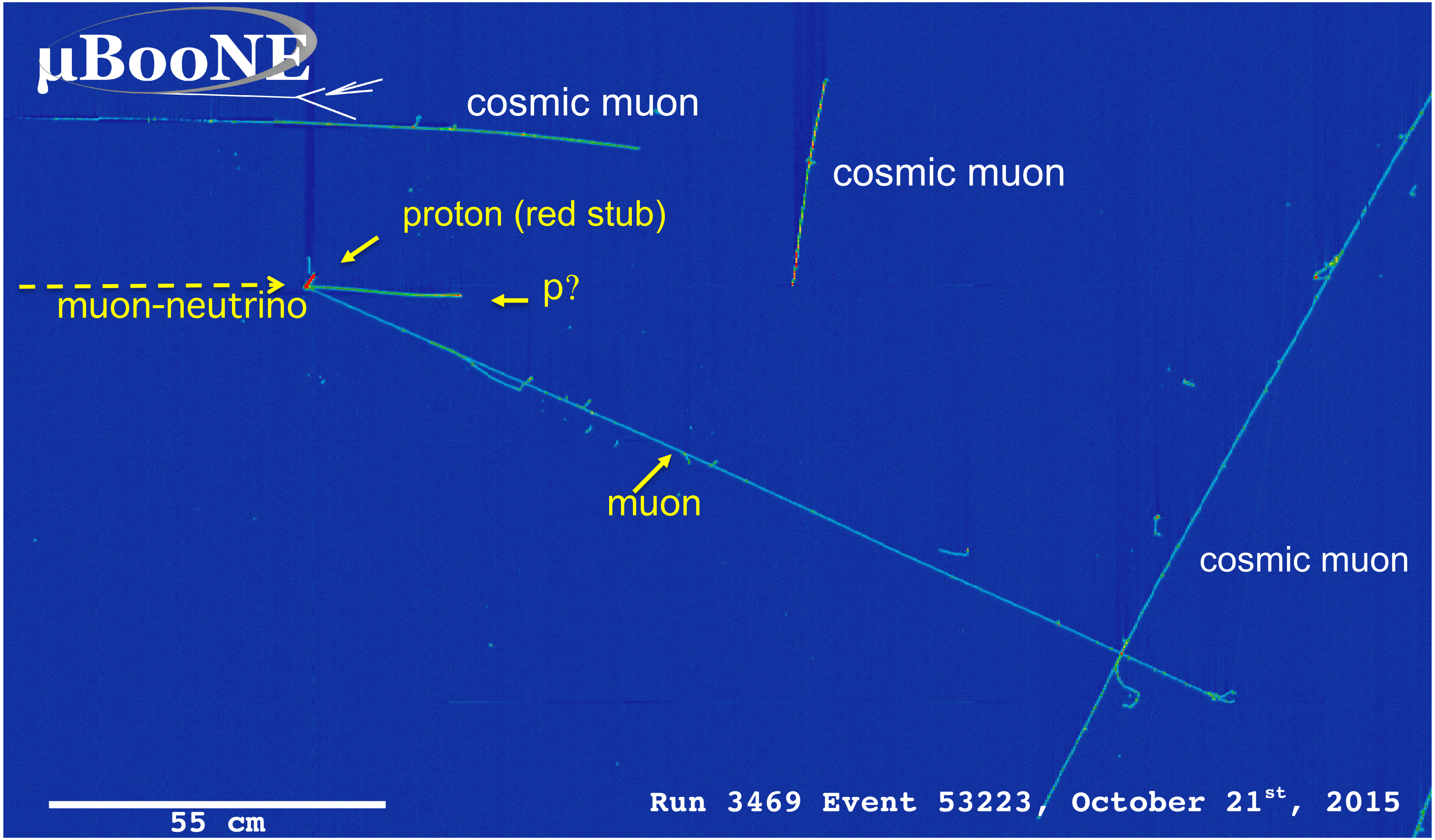
Detector located on surface; more often a cosmic ray triggers readout than a neutrino.

<u>Challenges:</u>

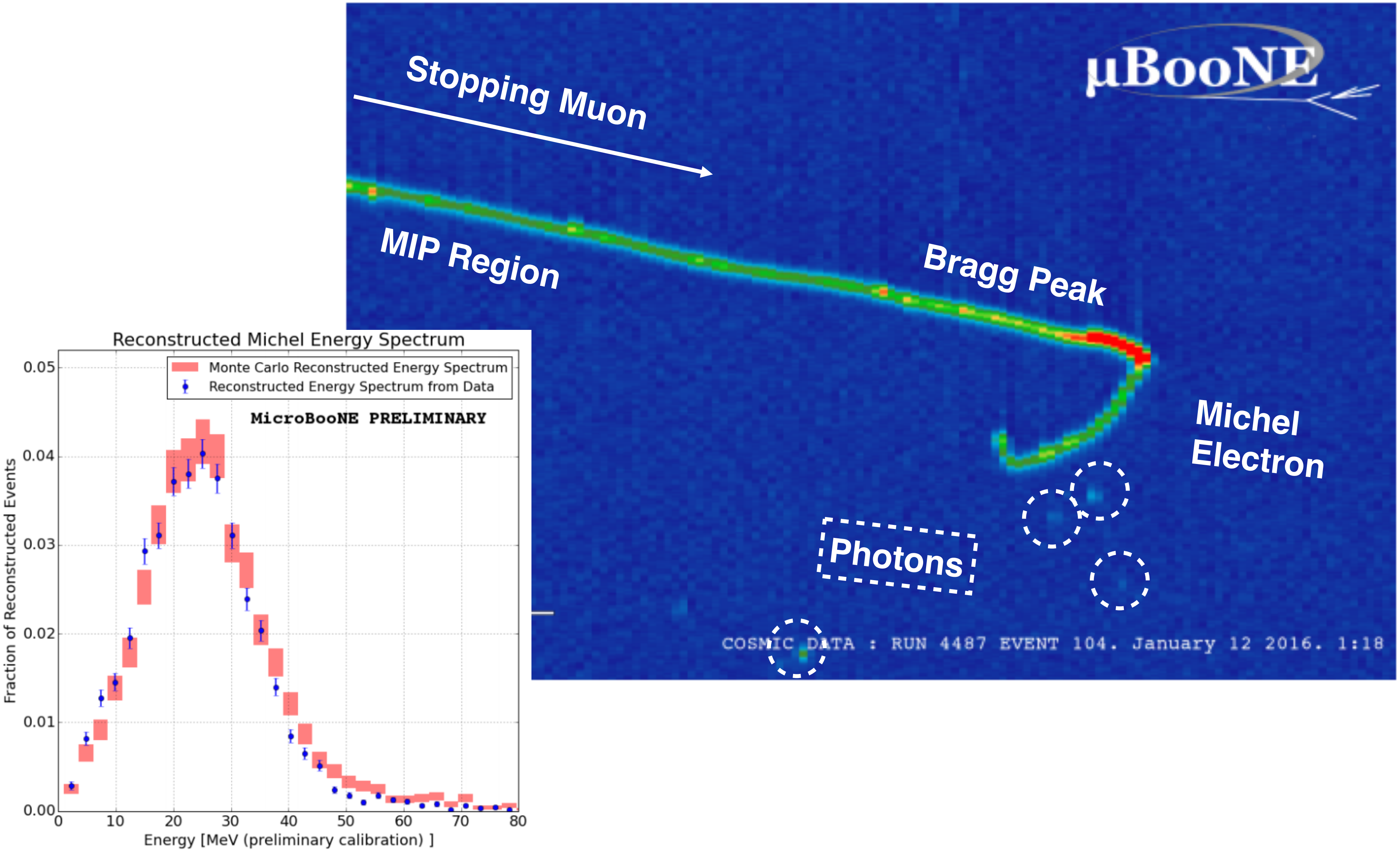
- reject events with only cosmic-rays.
- discriminate between neutrino interactions and cosmic rays.
- space charge effects.



First Neutrino Events in MicroBooNE



Michel electrons



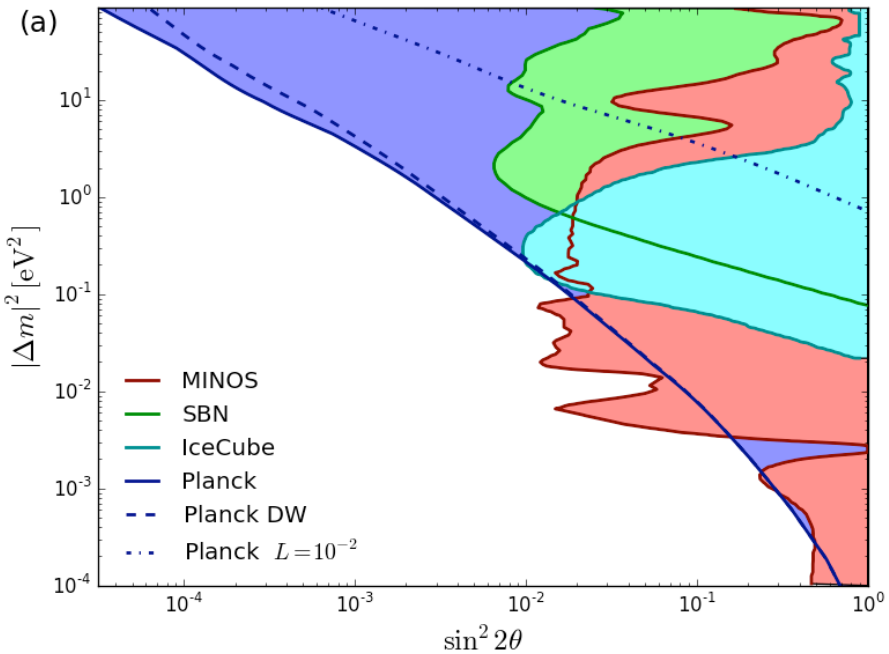
muon-neutrino disappearance

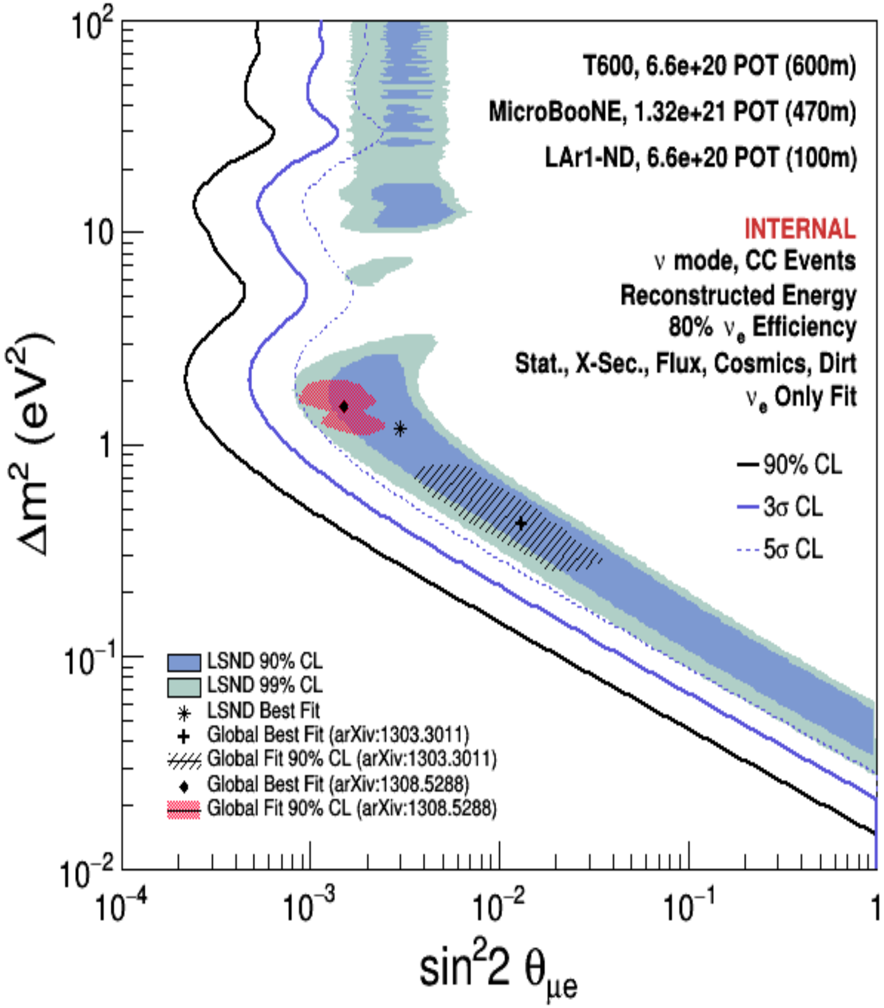
electron-neutrino appearance

Physics Letters B
Volume 764, 10 January 2017, Pages 322–327
Open Access

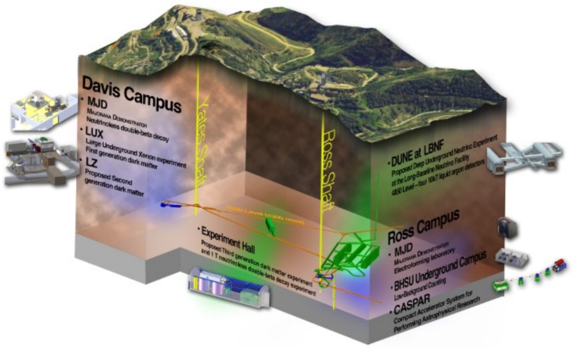
A combined view of sterile-neutrino constraints from CMB and neutrino oscillation measurements

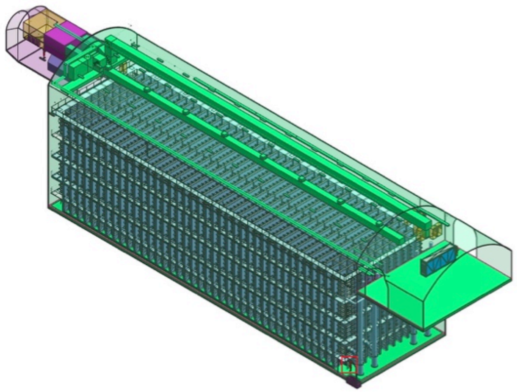
Sarah Bridle, Jack Elvin-Poole, Justin Evans, Susana Fernandez, Pawel Guzowski, Stefan Söldner-Rembold

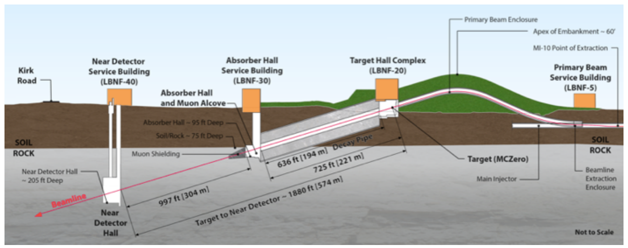




DUNE Timeline







2017: Far Site Construction Begins

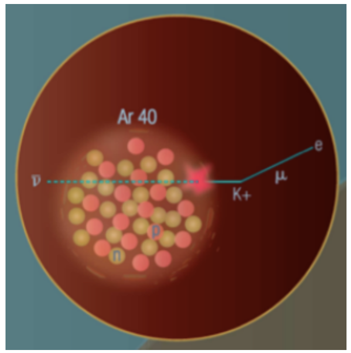
2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

2026: Neutrino Beam Available

The CERN Neutrino Platform



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

Summary

DUNE will

- Probe leptonic CP violation with unprecedented position
- Definitively determine the Mass Ordering to greater than 5 s.d.
- Test the three-flavour paradigm
- Significantly advance the discovery potential for proton decay
- (With some luck) provide a wealth of information on supernova bursts neutrino physics and astrophysics

MicroBooNE/SBND/ICARUS will

- Discover or constrain the existence of low-mass sterile neutrinos
- Measure neutrino cross sections on liquid argon
- Provide a wealth of data/experience with liquid-argon detector