DEEP UNDERGROUND NEUTRINO EXPERIMENT

Status of the DUNE Project

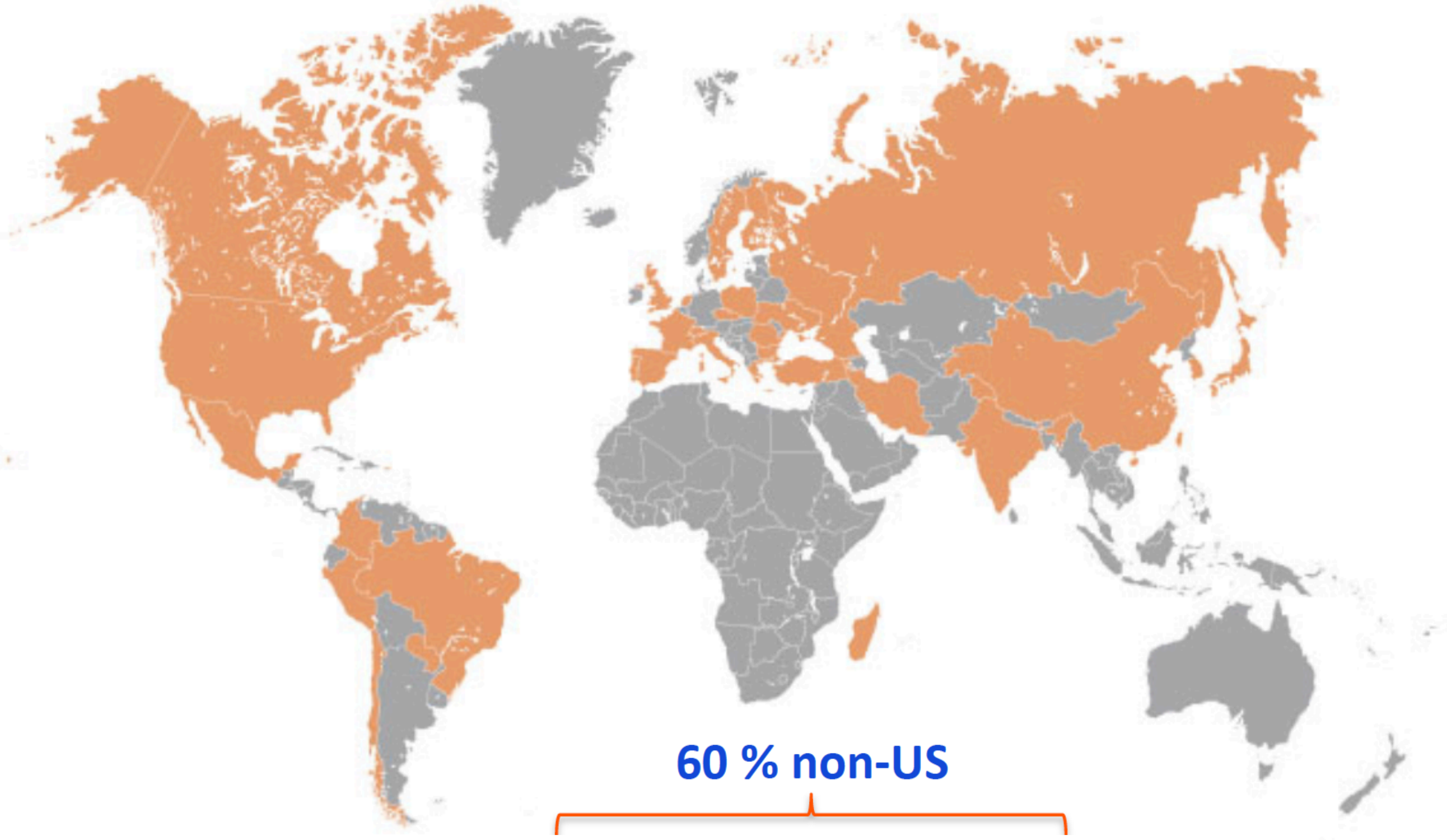
Alexandre Sousa
University of Cincinnati
(on behalf of the DUNE Collaboration)
November 2, 2018

NNN18
Vancouver, BC, Canada

The DUNE Project

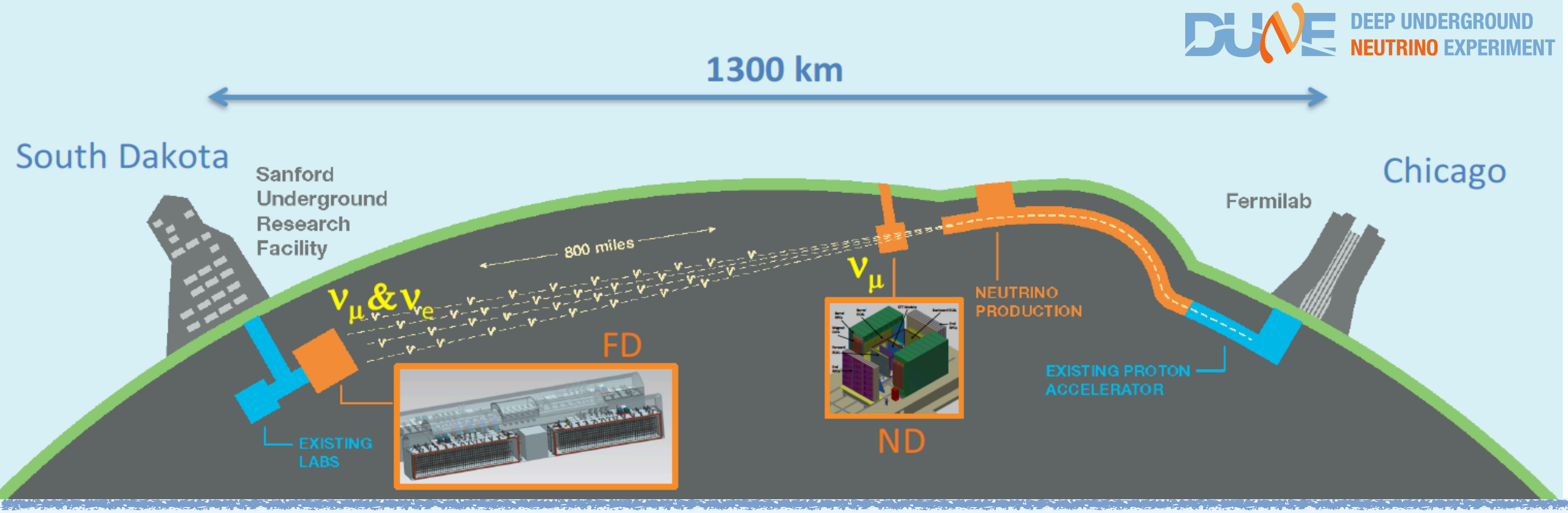
- Measure ν_e and $\bar{\nu}_e$ appearance, and ν_μ and $\bar{\nu}_\mu$ disappearance, over a long baseline using a high-intensity neutrino beam, and high-resolution massive detectors
- Rich Physics program with primary goals:
  - Probe leptonic CP violation and determine neutrino mass ordering
  - High-precision measurements of neutrino mixing parameters
  - Detect supernova neutrinos
  - Search for BSM Physics
- **Large International Collaboration**
- **Construction of Far site underway since July 2017!**
- **protoDUNE Test Beam effort taking data!**

The DUNE Collaboration



60 % non-US

1275 collaborators from 179 institutions in 32 nations

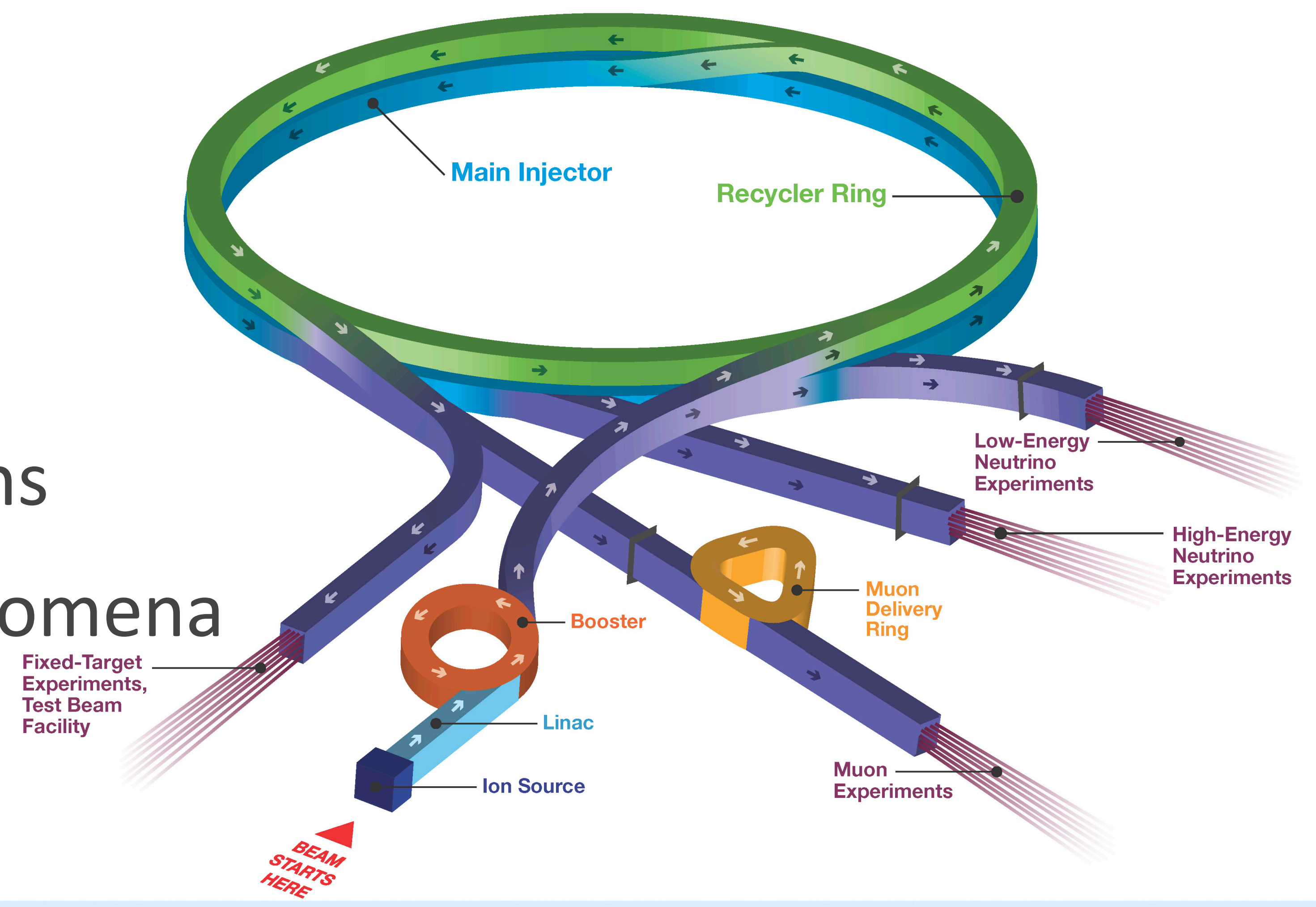


Armenia (3), Brazil (29), Bulgaria (1), Canada (1), CERN (32), Chile (3), China (5), Colombia (13), Czech Republic (11), Spain (34), Finland (4), France (23), Greece (4), India (45), Iran (2), Italy (63), Japan (7), Madagascar (8), Mexico (8), The Netherlands (4), Paraguay (4), Peru (8), Poland (6), Portugal (7), Romania (7), Russia (10), South Korea (4), Sweden (1), Switzerland (35), Turkey (2), UK (136), Ukraine (4), USA (621)

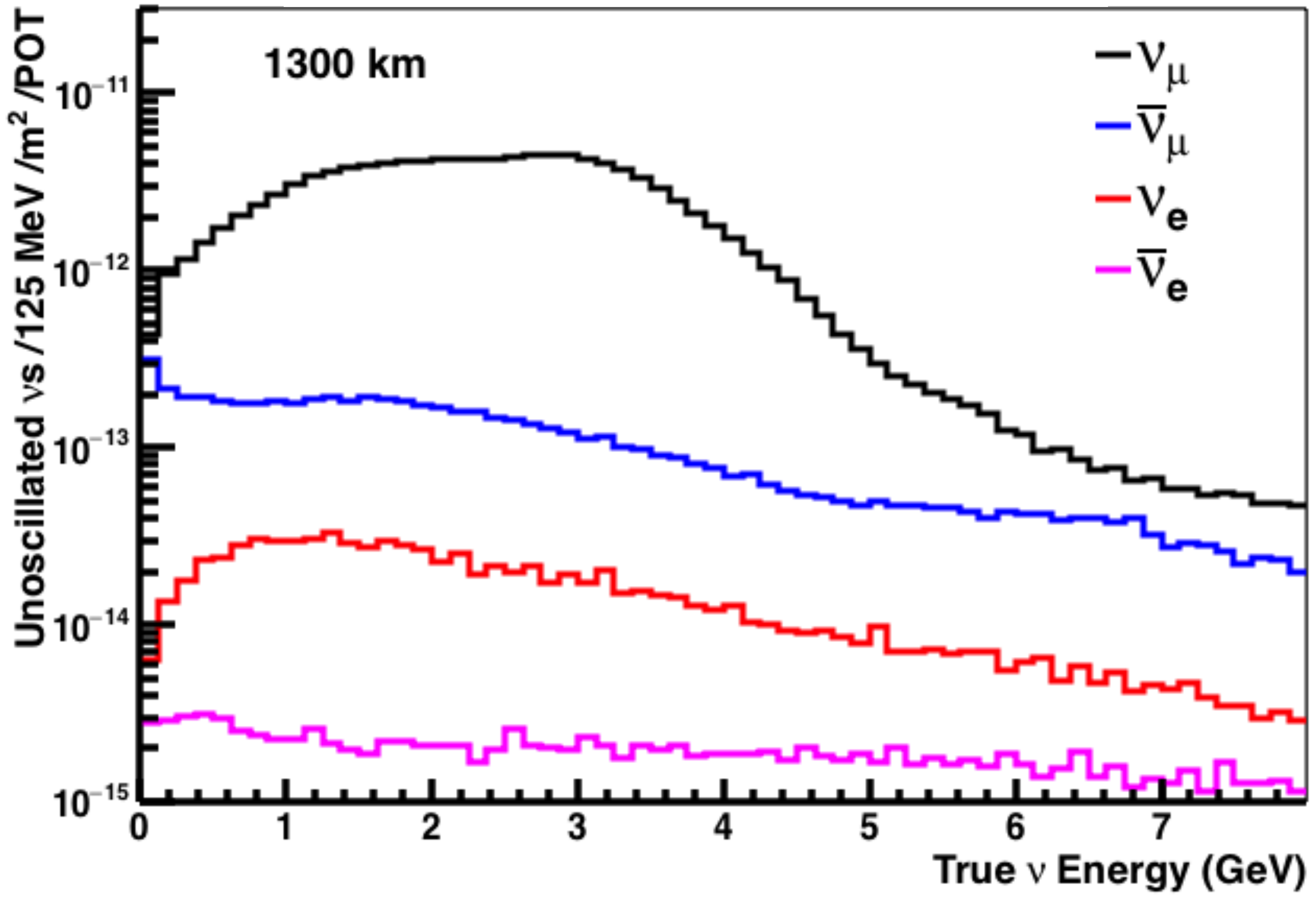
The LBNF Beamline

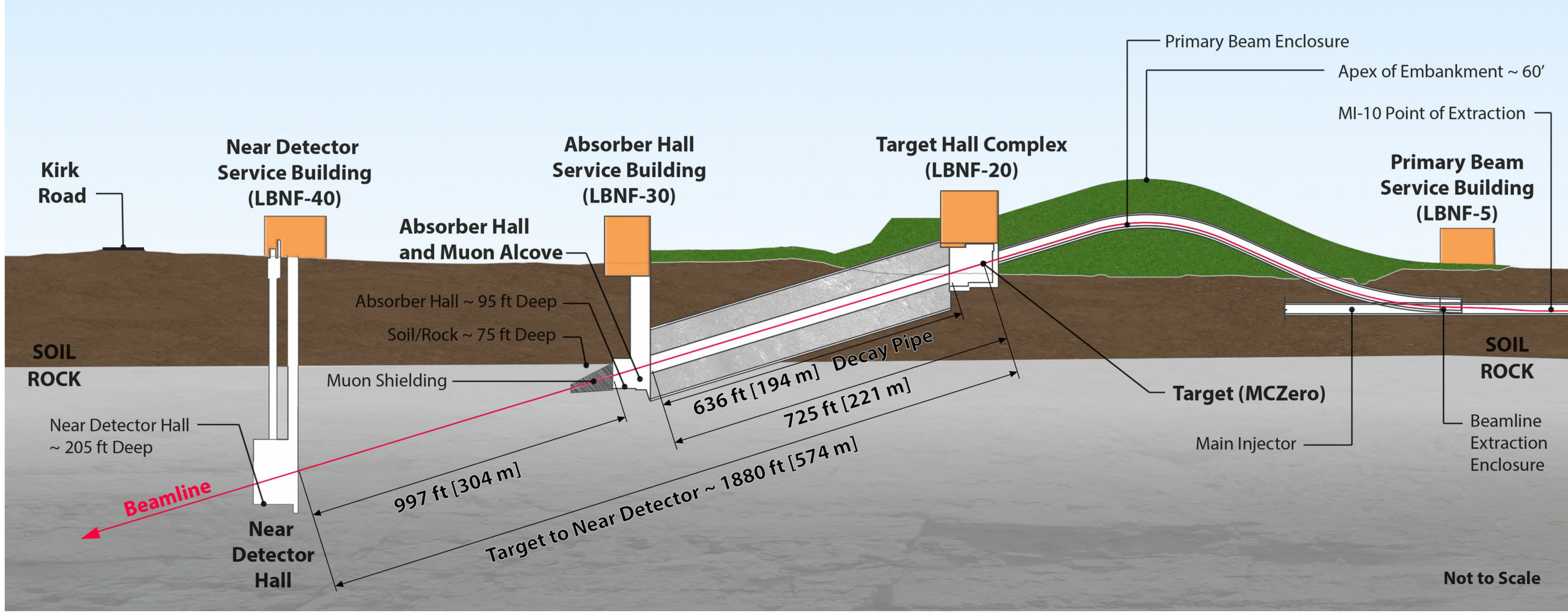
- The LBNF (**L**ong-**B**aseline **N**eutrino **F**acility) neutrino beam will be produced using 60-120 GeV protons from Fermilab's Main Injector
- Initial nominal power of 1.2 MW (10^{14} protons-on-target/sec.), upgradeable to 2.4 MW
- Horn-focused neutrino beamline optimized for CP violation sensitivity using genetic algorithm
  - Engineering design of 3-horn focusing system in progress
- Can run in Neutrino (FHC) and Antineutrino (RHC) modes by switching polarity of magnetic horns
- Wideband beam enables use of second osc. maximum and enhances probing of new BSM phenomena

Fermilab Accelerator Complex



Neutrino Mode - Flux at 1300 km

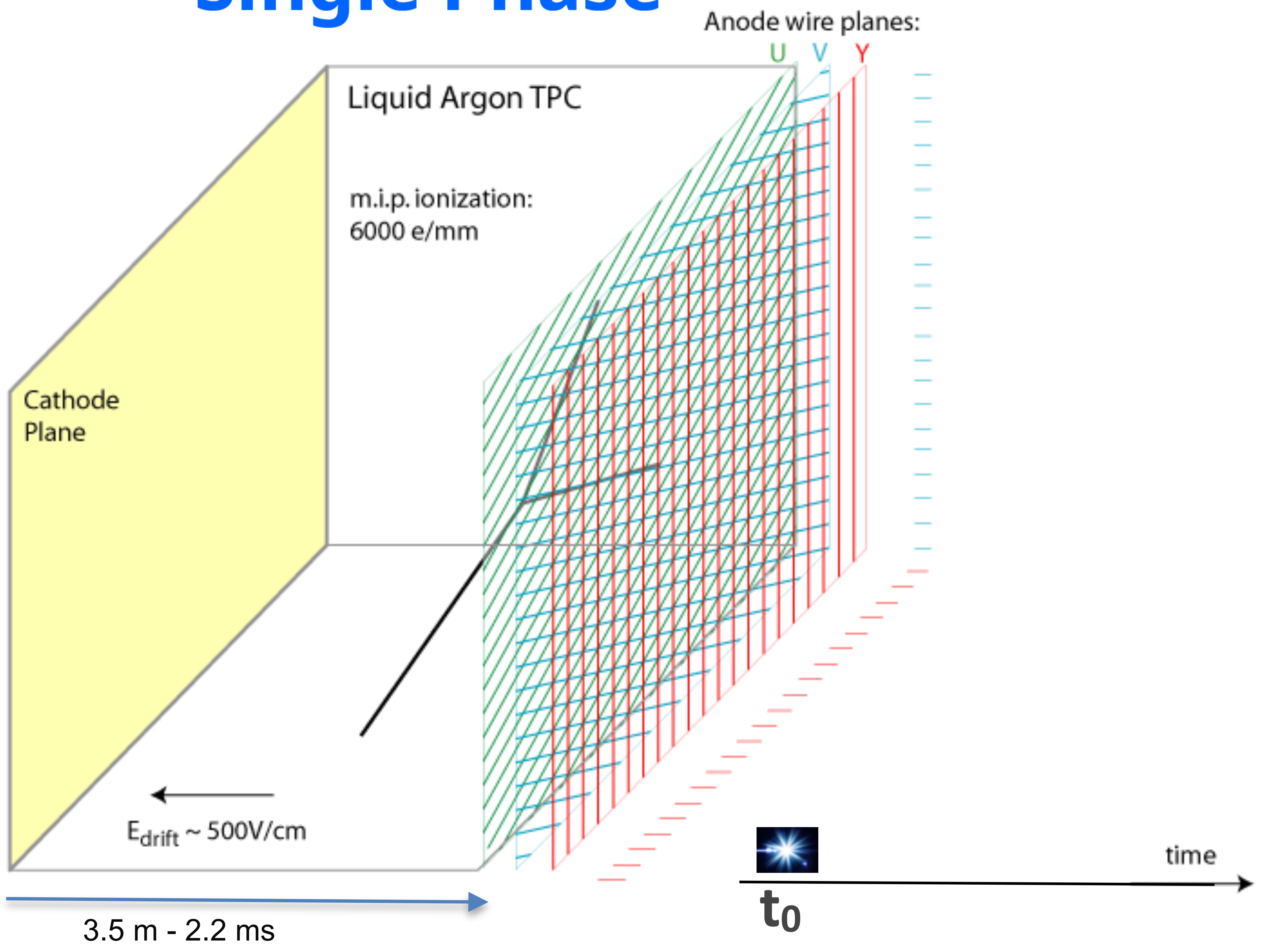




Detector Technology

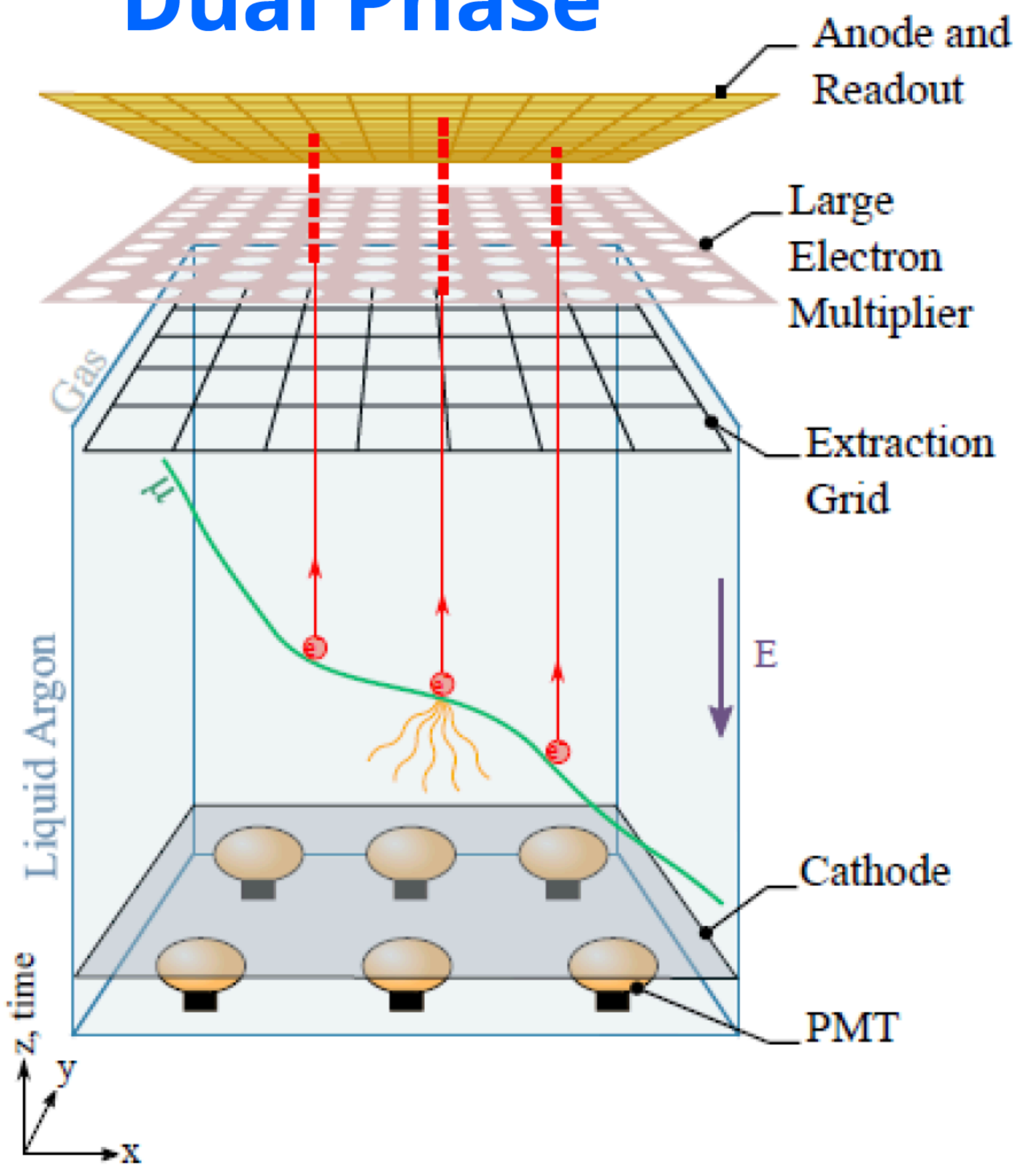
- Liquid Argon Time Projection Chambers (LArTPC), single and dual phase designs
  - Critical to have ultra-high LAr purity, and a uniform and stable electric field

Single Phase



- Energy release from charged particles in LAr:
  - free electron charge (TPC)
  - scintillation light (PD)
- Photon detection for triggering and t_0 determination

Dual Phase



Animated GIF:
https://www.phy.bnl.gov/wire-cell/home/img/signal.gif

Hanna Rogers' "DUNE Signal Processing" talk - Friday Det. Parallel

Babak Abi's "DUNE Electronics, DAQ" talk - Friday Det. Parallel

Zelimir Djurcic's "DUNE Light Detection" talk - Friday Det. Parallel

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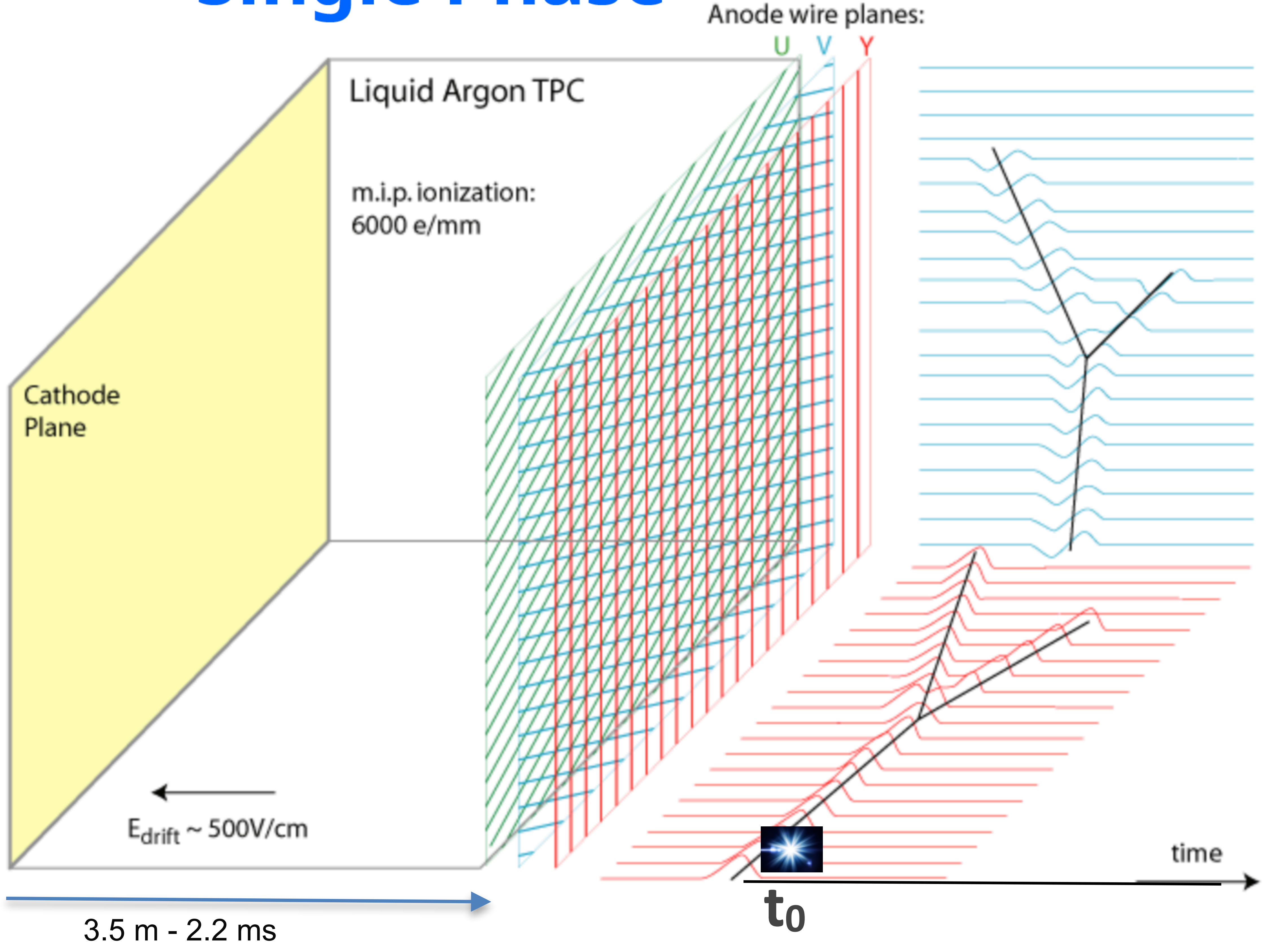

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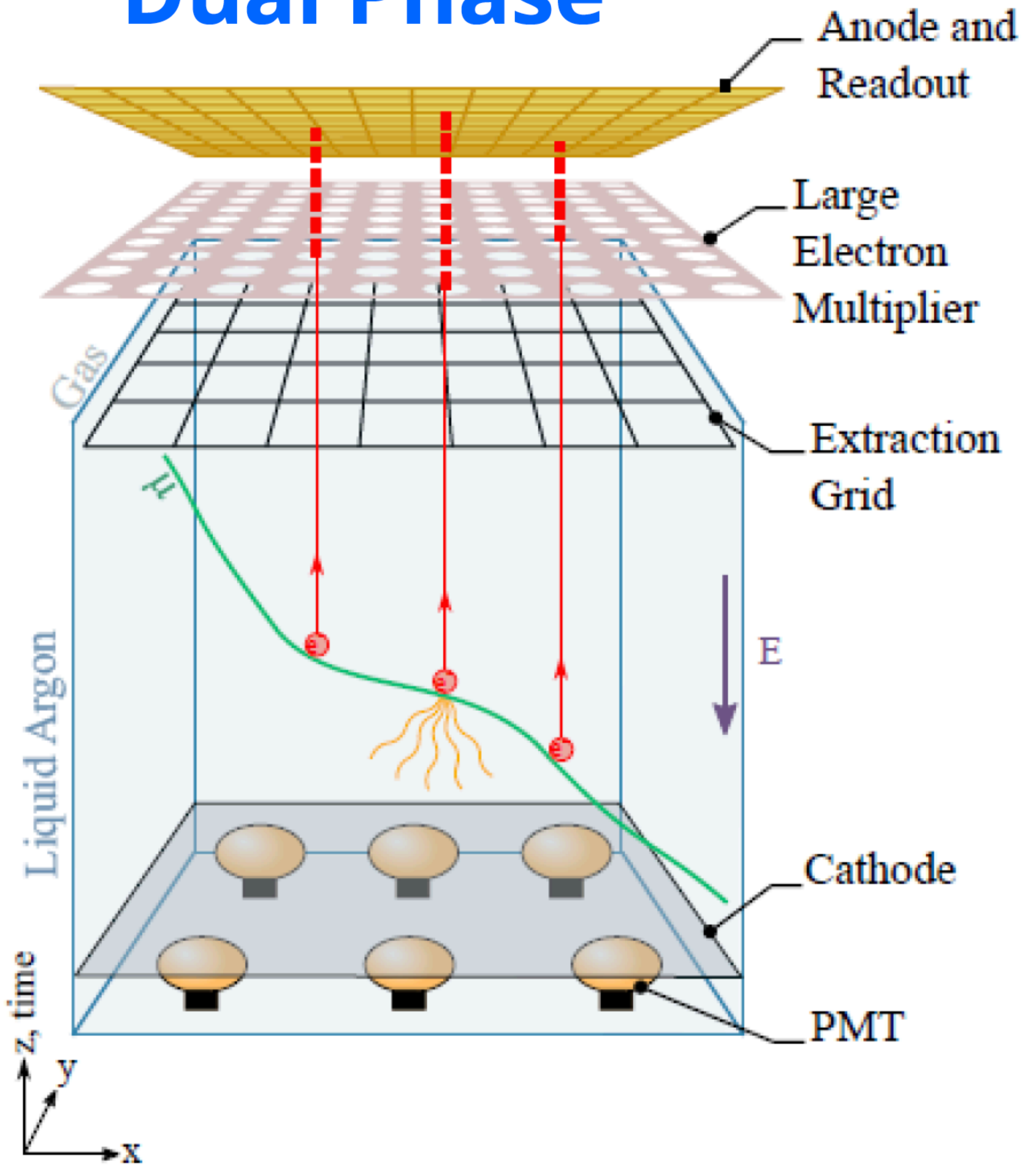

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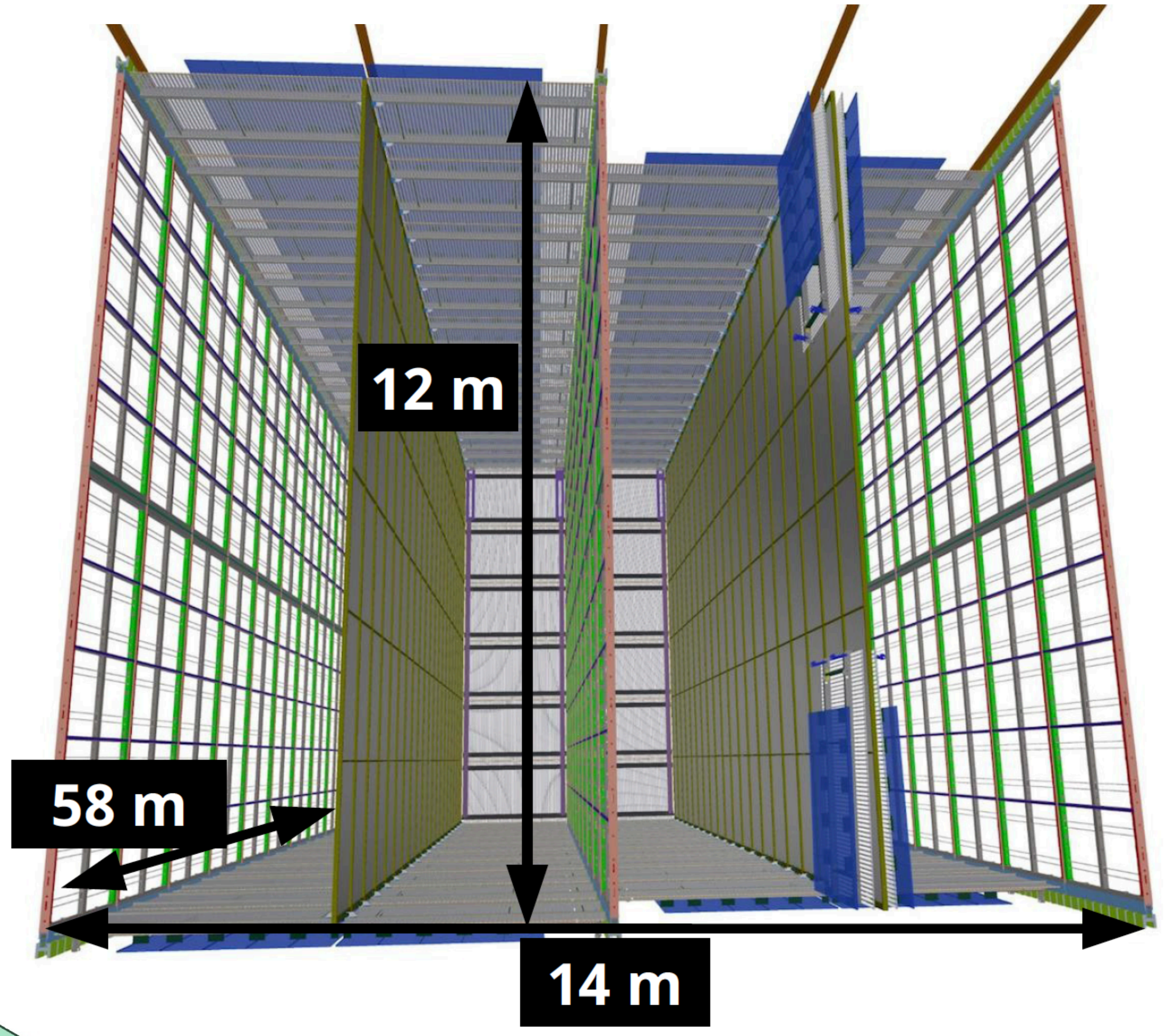
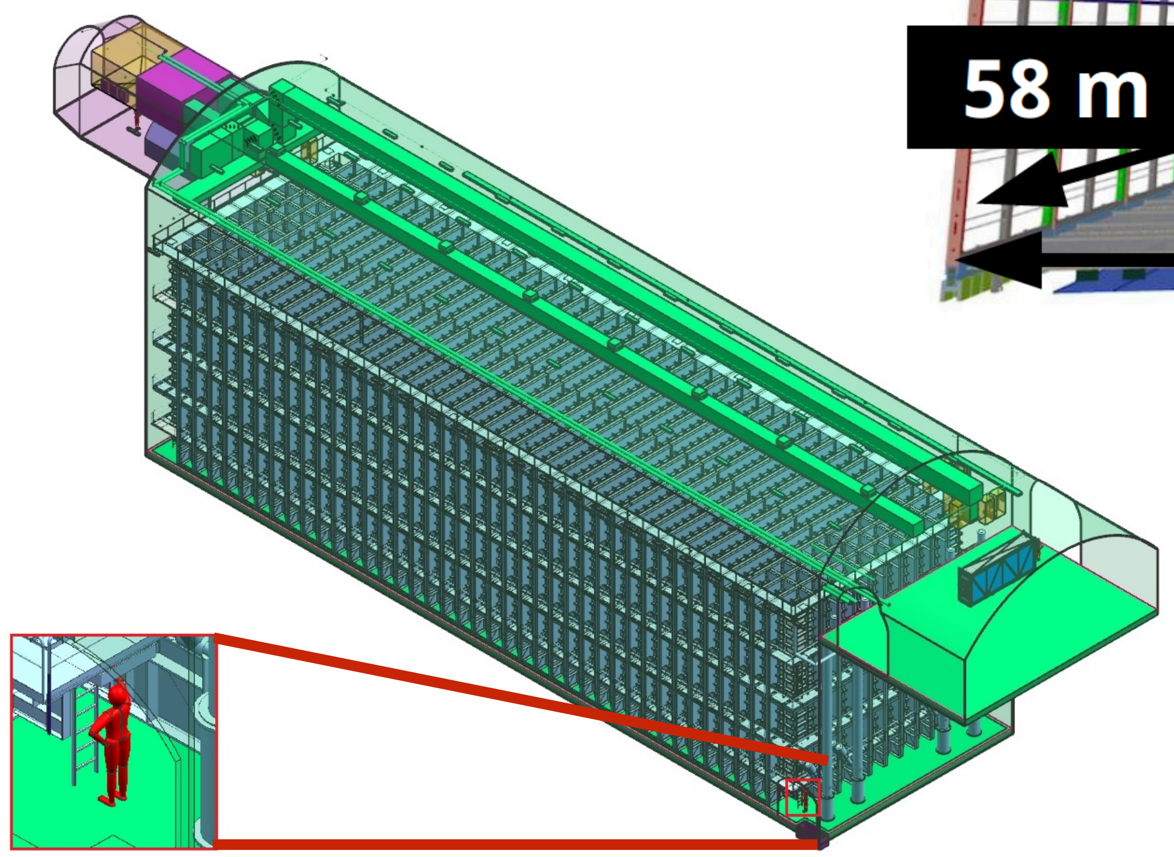
Far Detector

- Located 4850 ft (1500 m) underground at SURF, enables low-energy and atmospheric neutrino physics
- Four 10 kton (fiducial) LArTPC modules, with single and dual phase detector designs
- Integrated photon detection systems

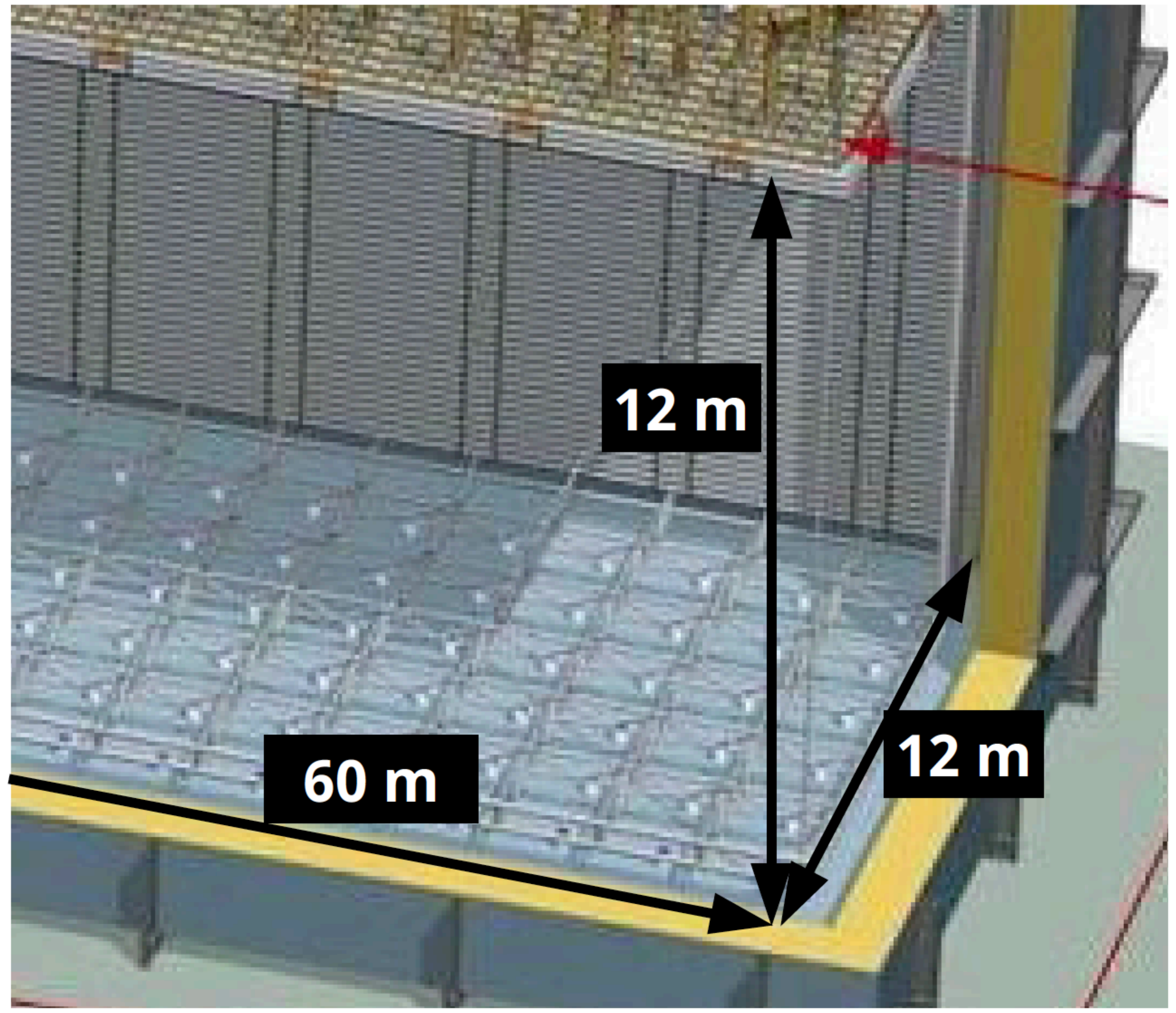
Single Phase

Active height	12 m
Active length	58 m
Maximum drift	3.5 m
Wire spacing	5 mm
Wire channels	384,000
Phot. det. ch.	6000





Dual Phase



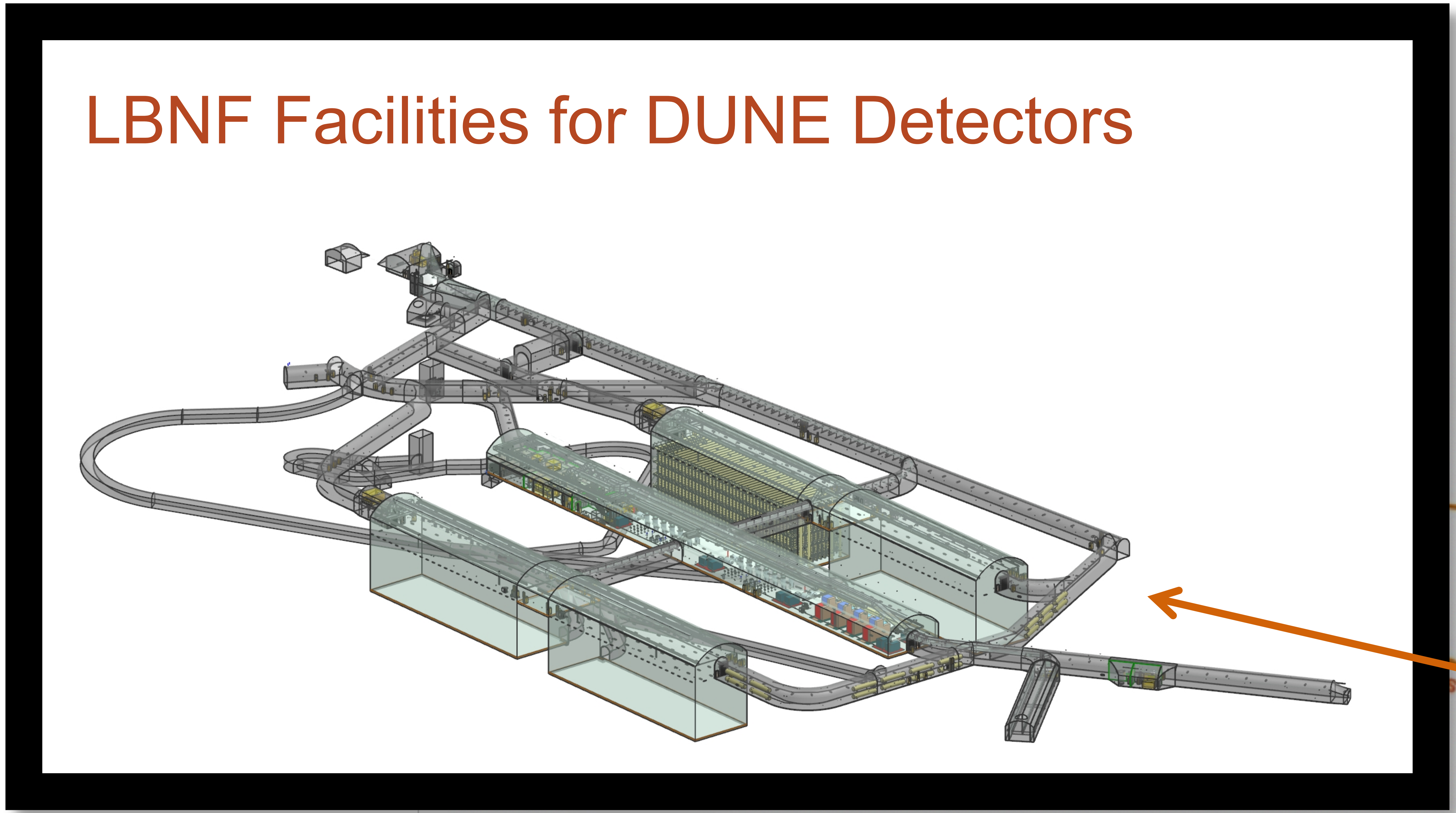
Active width	12 m
Active length	60 m
Maximum drift	12 m
CRP pixel size	3 mm
CRP channels	153,600
PMT channels	720

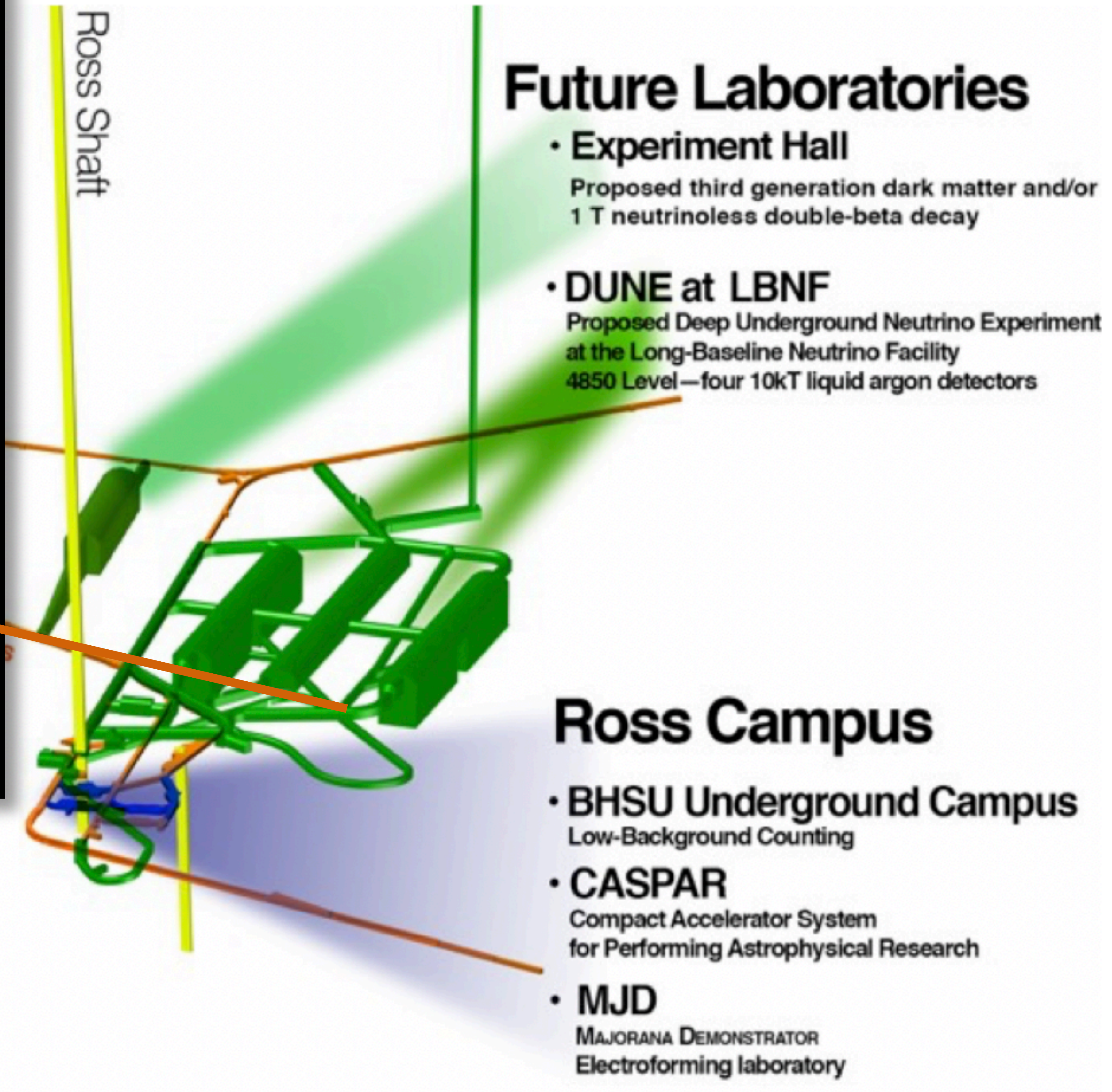
Design drift field: 500 V/cm

Electron drift speed at 500 V/cm: 1.6 mm/μs

Far Detector Location - SURF

- **S**anford **U**nderground **R**esearch **F**acility (Lead, SD)





Far Detector Location - SURF

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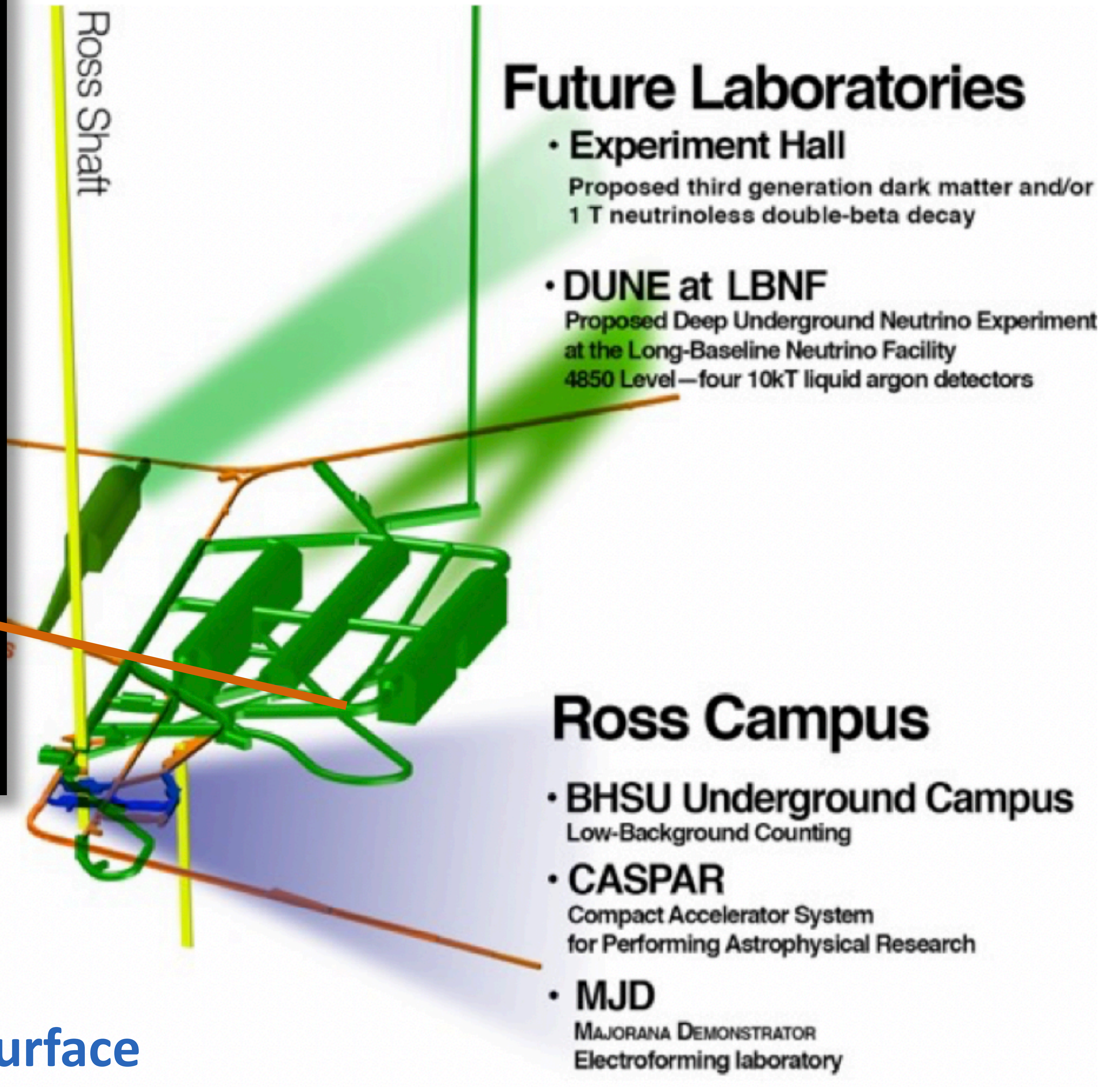
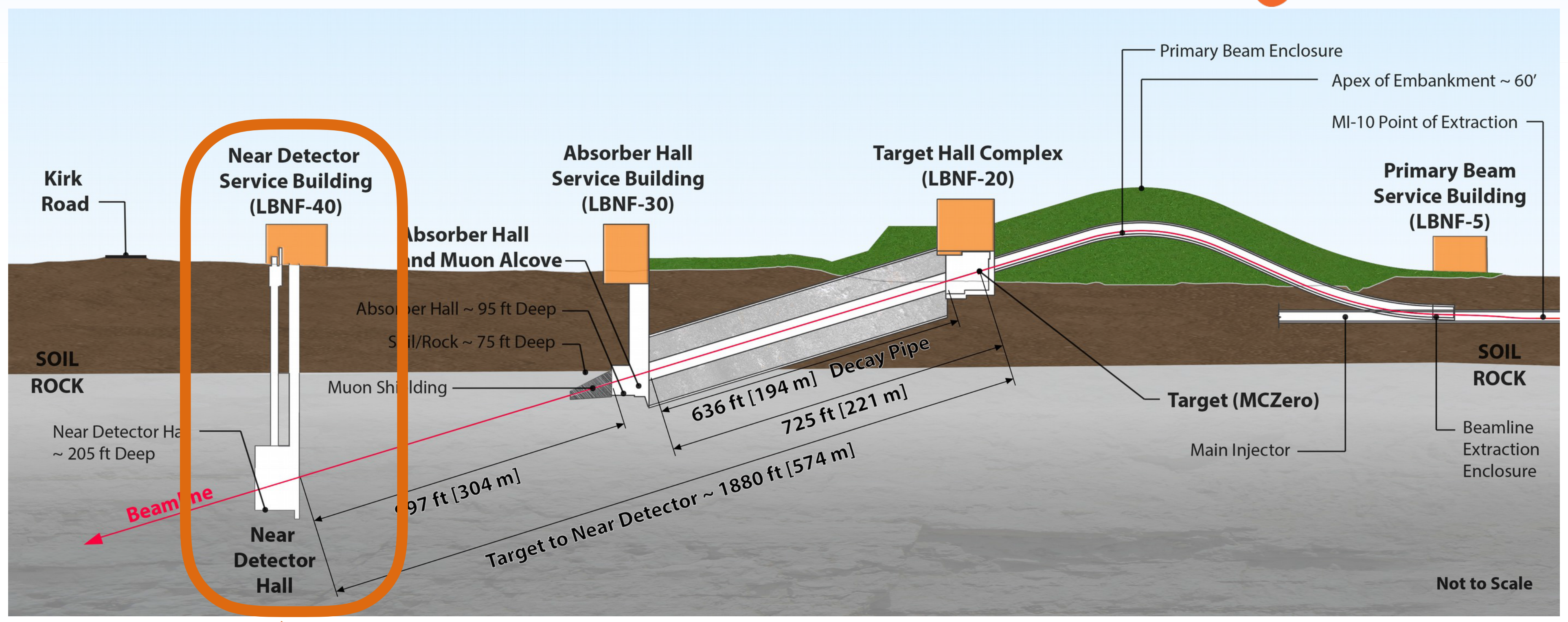
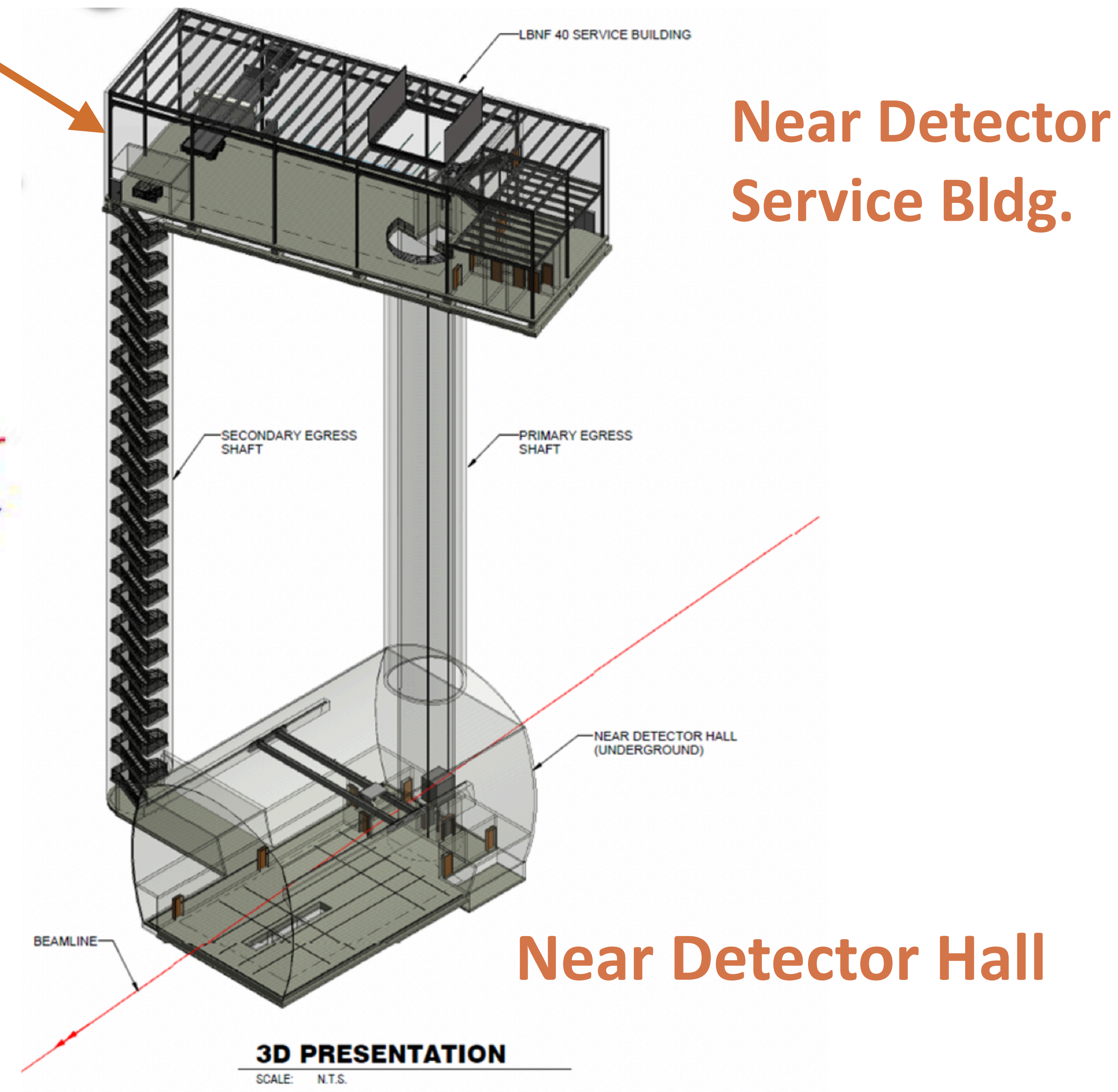


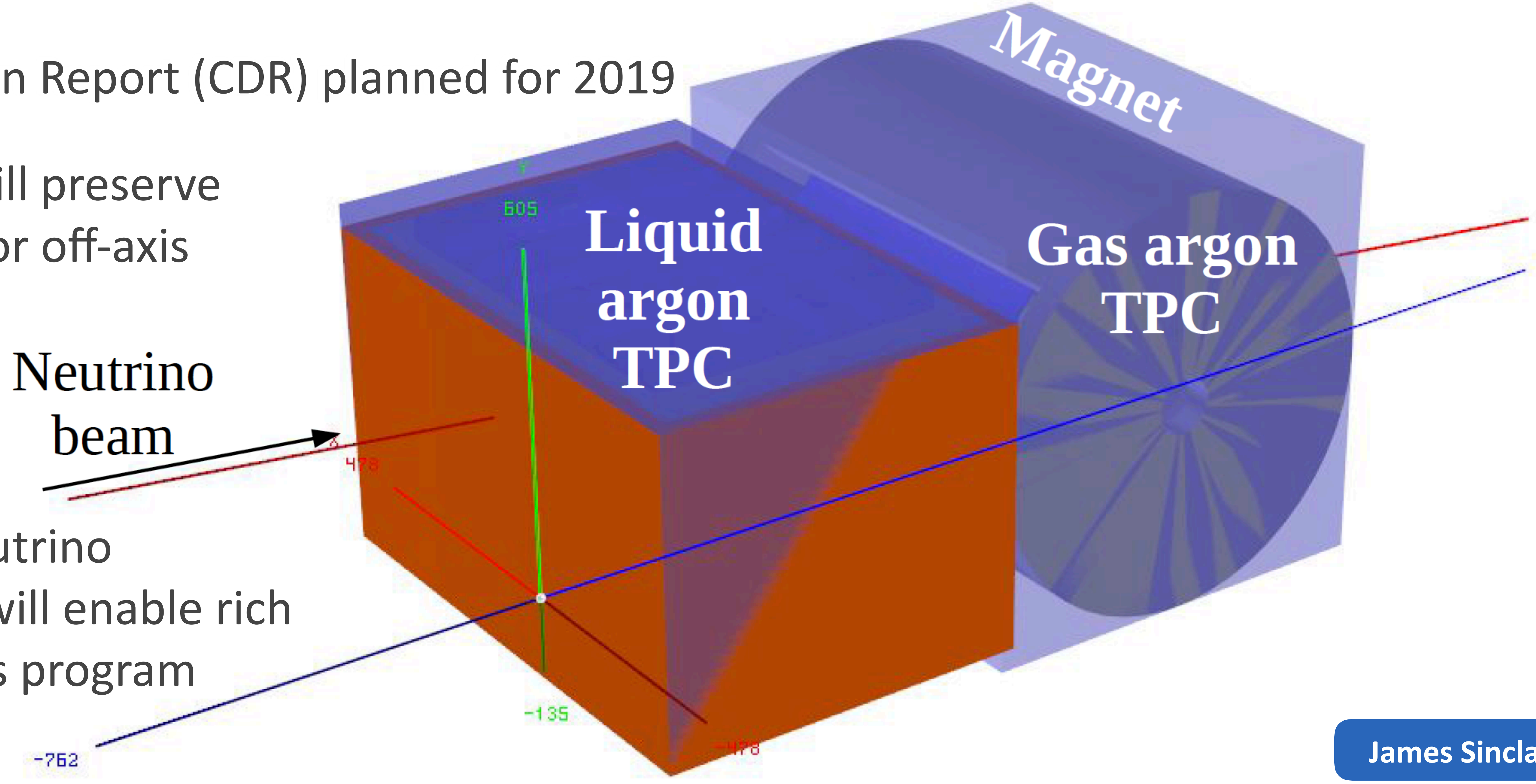
- Far site pre-excavation preparations underway since July 2017!
- Cavern excavation will require transporting 875,000 tons of rock to surface

Near Detector

- Highly-capable ND, located 574 m downstream of production target, will constrain systematic uncertainties for long-baseline oscillation analyses
  - flux, cross-section, and detector uncertainties
- Integrated system composed of multiple detectors
  - Finely-segmented, pixel readout LArTPC
  - Magnetized multi-purpose tracker
  - Electromagnetic calorimeter
  - Muon chambers
- ND Conceptual Design Report (CDR) planned for 2019
- Conceptual design will preserve option to move ND for off-axis measurements
- $\mathcal{O}$(10 million/year) neutrino interactions in argon will enable rich non-oscillation physics program







James Sinclair's "LArTPC R&D for DUNE ND" talk - Friday Det. Parallel

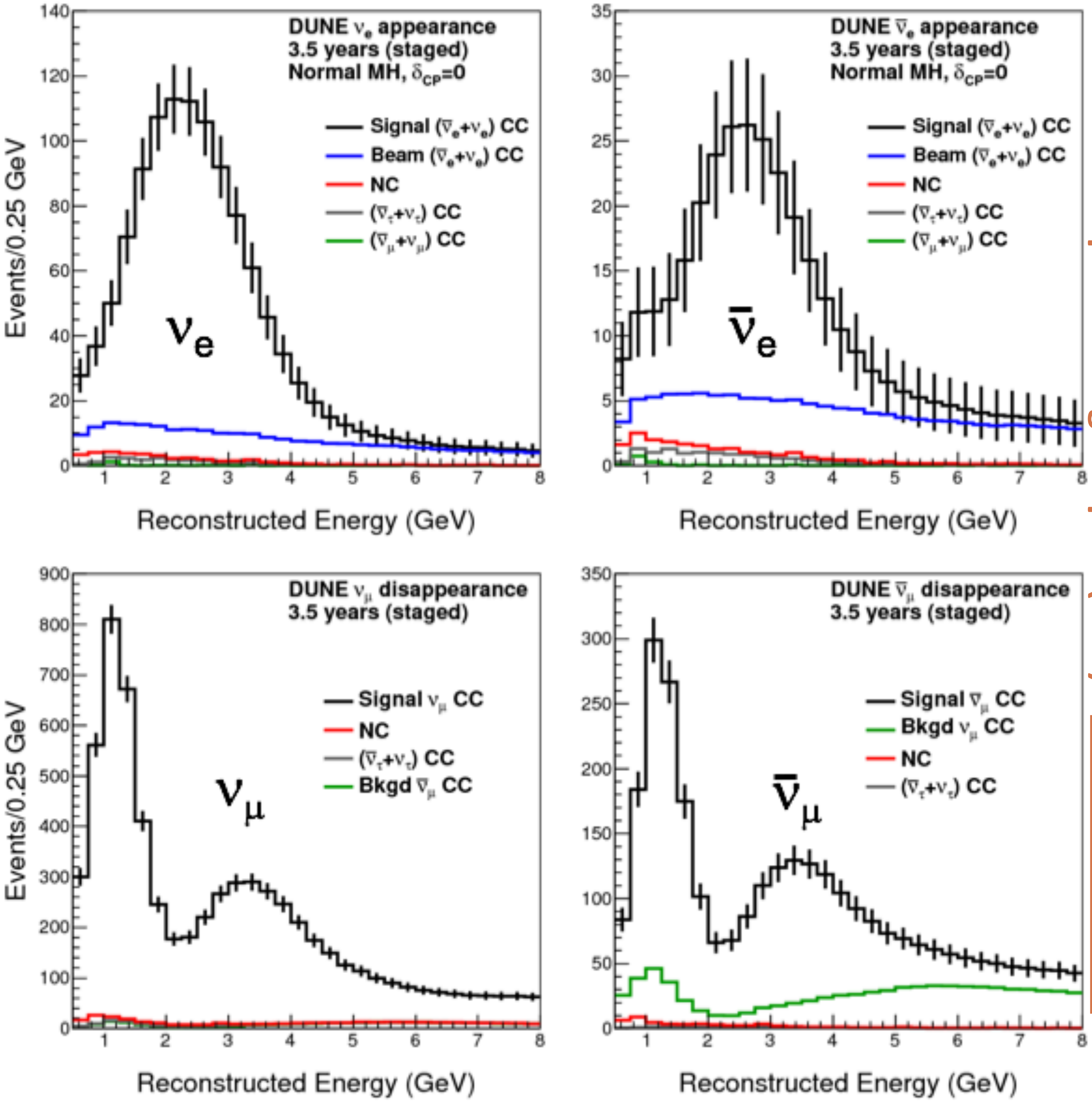
Chris Marshall's "DUNE Near Detectors" talk - Saturday Plenary

Dan Dwyer's "Pixelated Charge Readout for DUNE ND" talk - Friday Det. Parallel

DUNE Oscillation Sensitivities

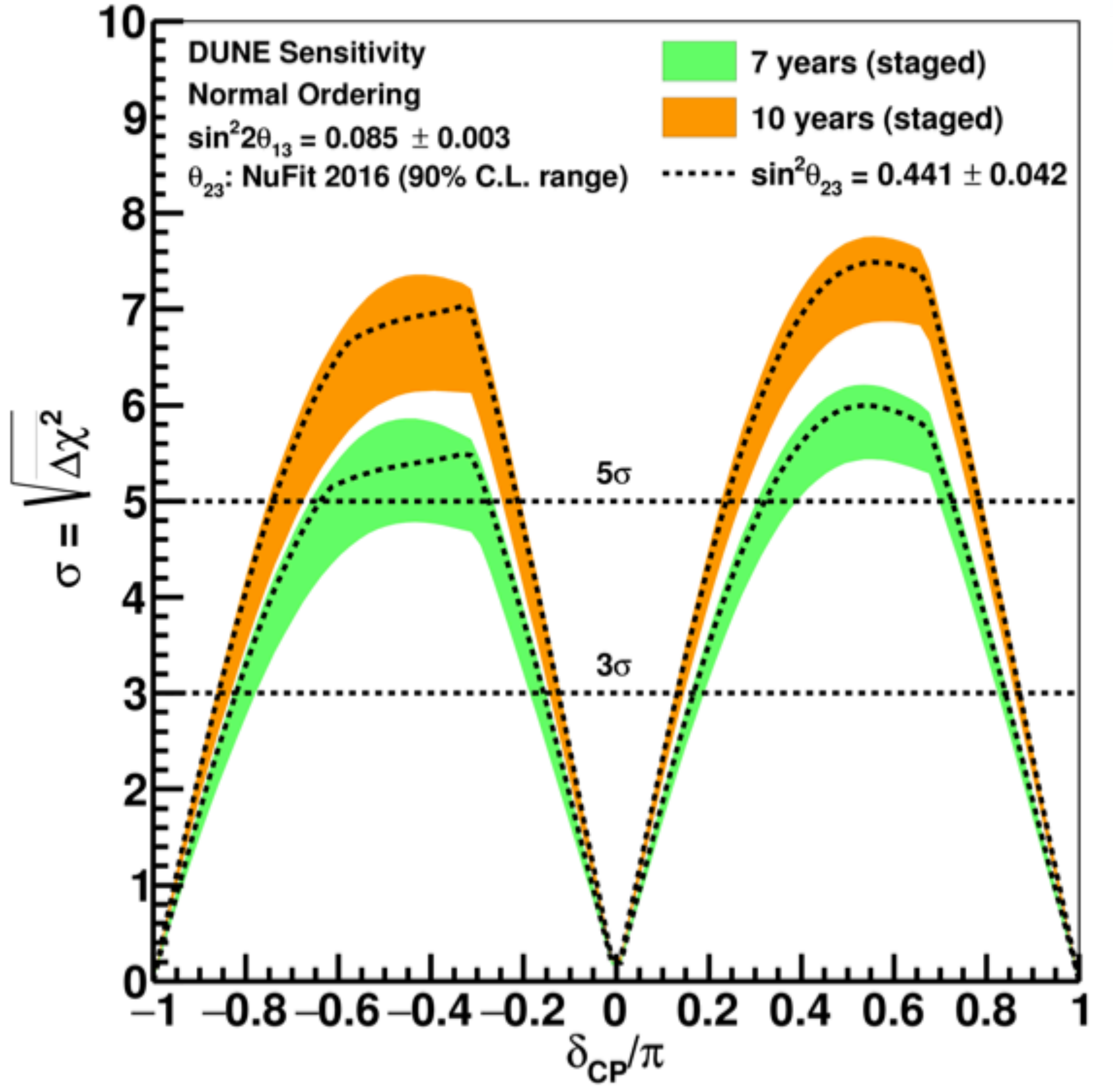
- Reconstructed spectra based on GEANT4 beam simulation, GENIE event generator, and Fast MC using detector response parameterized at the single-particle level
  - Efficiency tuned using hand scan results
- Expect 1000 ν_e appearance events in ~7 years of equal running in neutrino and antineutrino mode
- Simultaneous fit to four spectra to extract oscillation parameters, systematics enter as normalization parameters
- GLoBES configurations in arXiv:1606.09550
- Assume DUNE FD staging strategy

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 Conceptual Design Report (CDR) - arXiv:1512.06148

CP Violation Sensitivity



- Sensitivities for 7 and 10 year exposures (staged)
- Width of bands shows variation in central values of θ_{23}

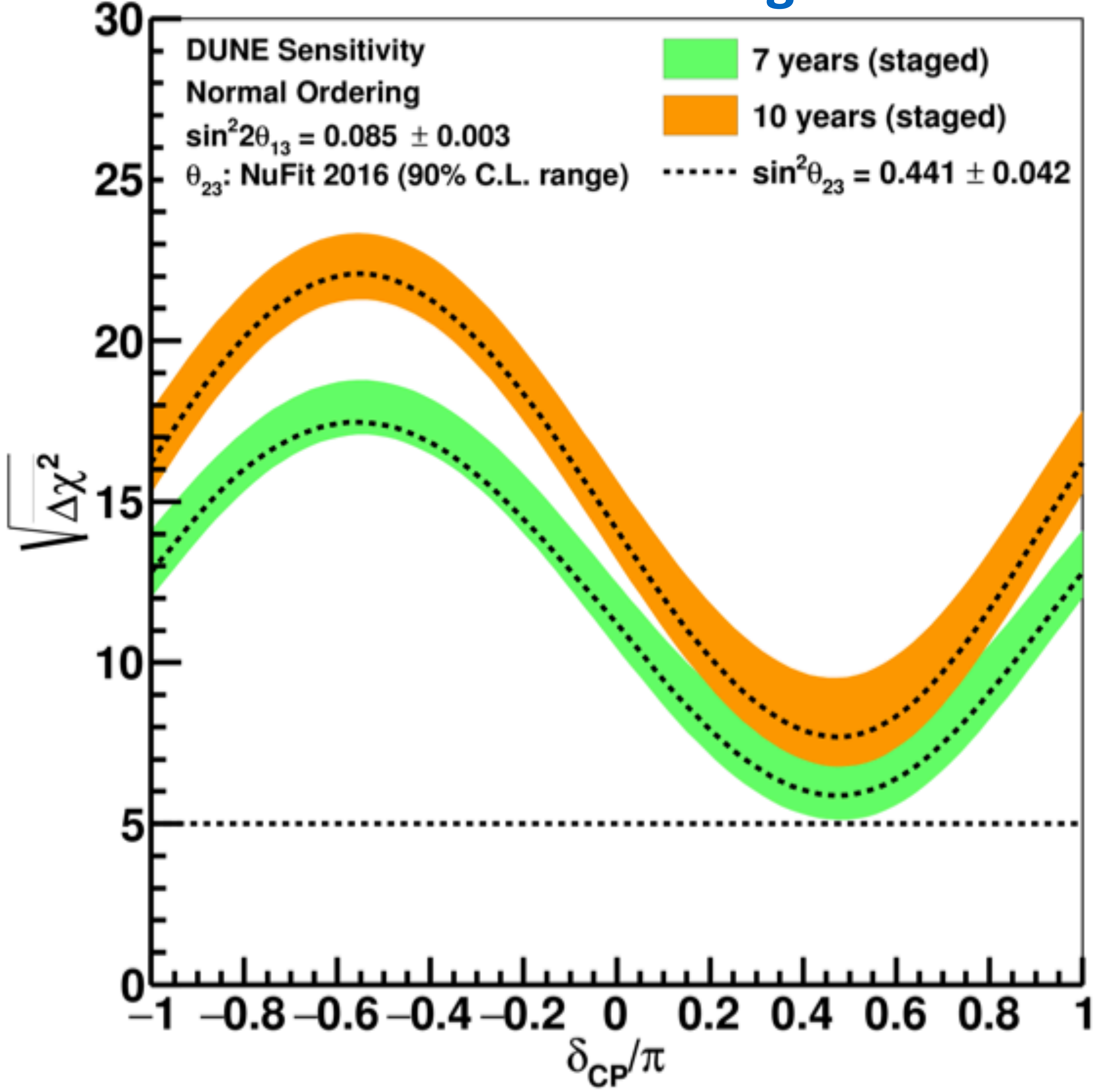
DUNE CDR

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

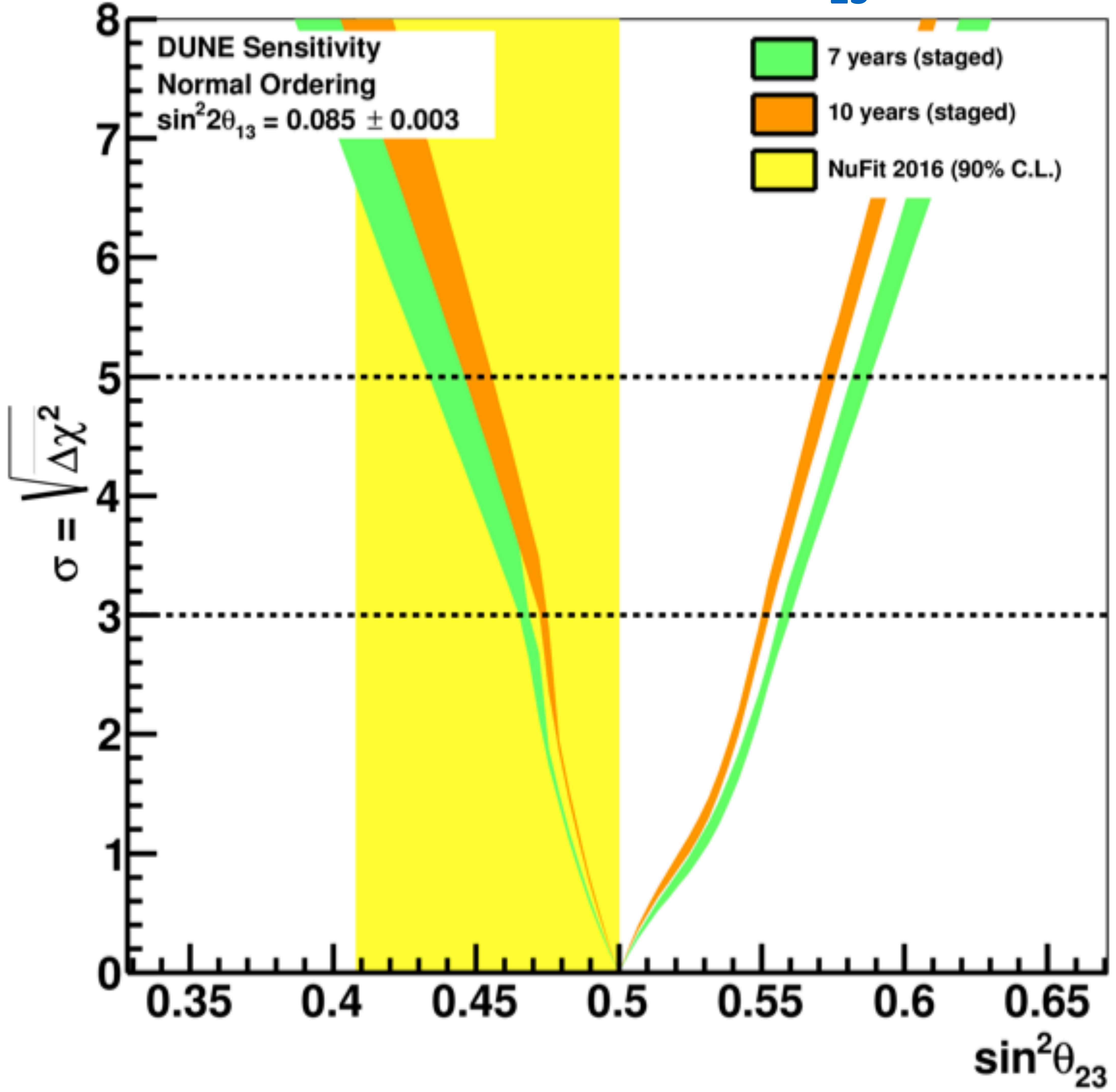
- 5σ discovery of CP violation in 7 years of running if δ_{CP} near $-\pi/2$
- 3σ over 65% of δ_{CP} range

Mass Ordering and Octant of θ_{23}

Mass Ordering



Octant of θ_{23}

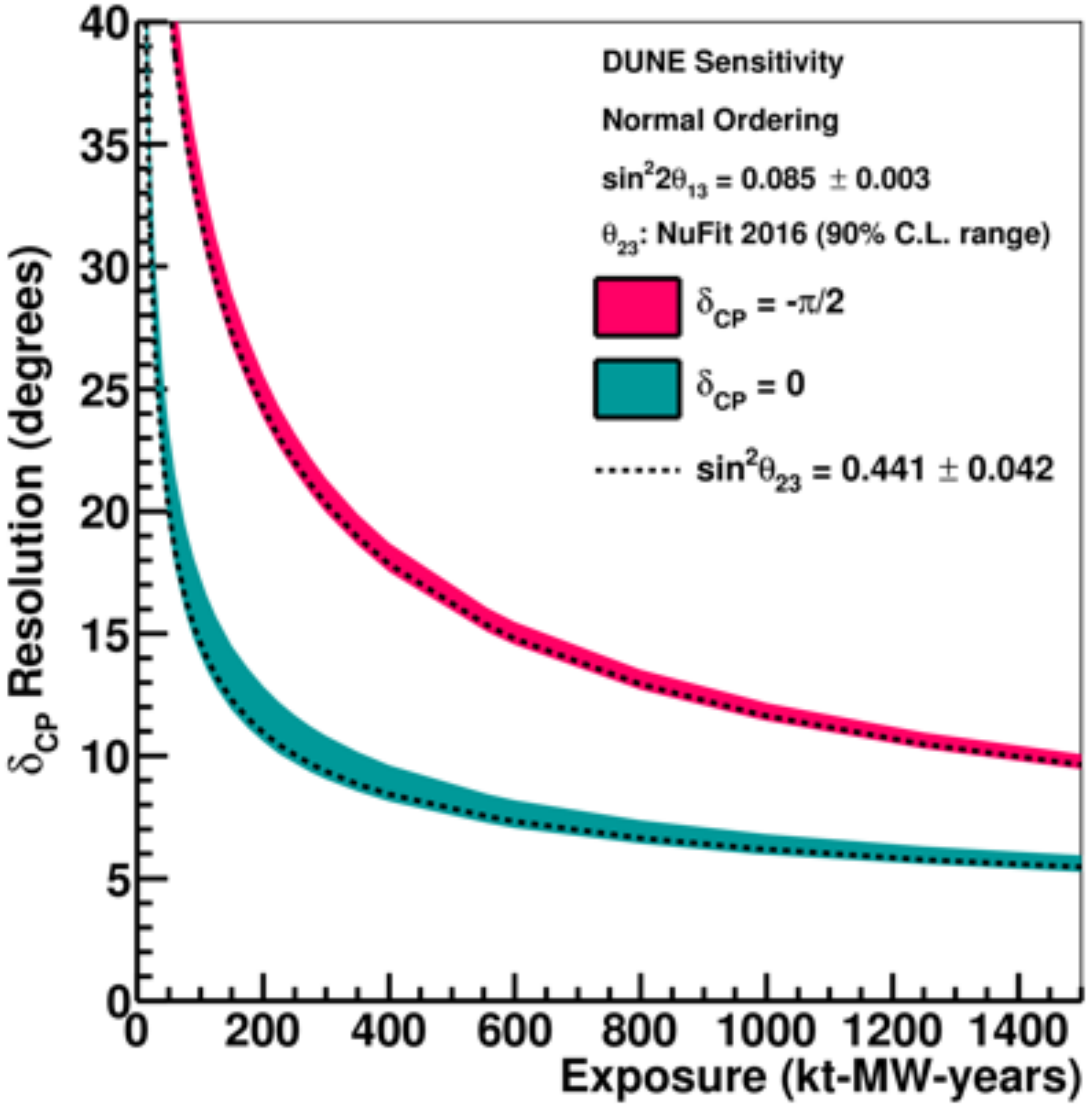


- Width of bands shows variation in central values of θ_{23}
- Neutrino mass ordering determined at > 5σ for all parameter values

- Width of bands shows variation in values of δ_{CP}

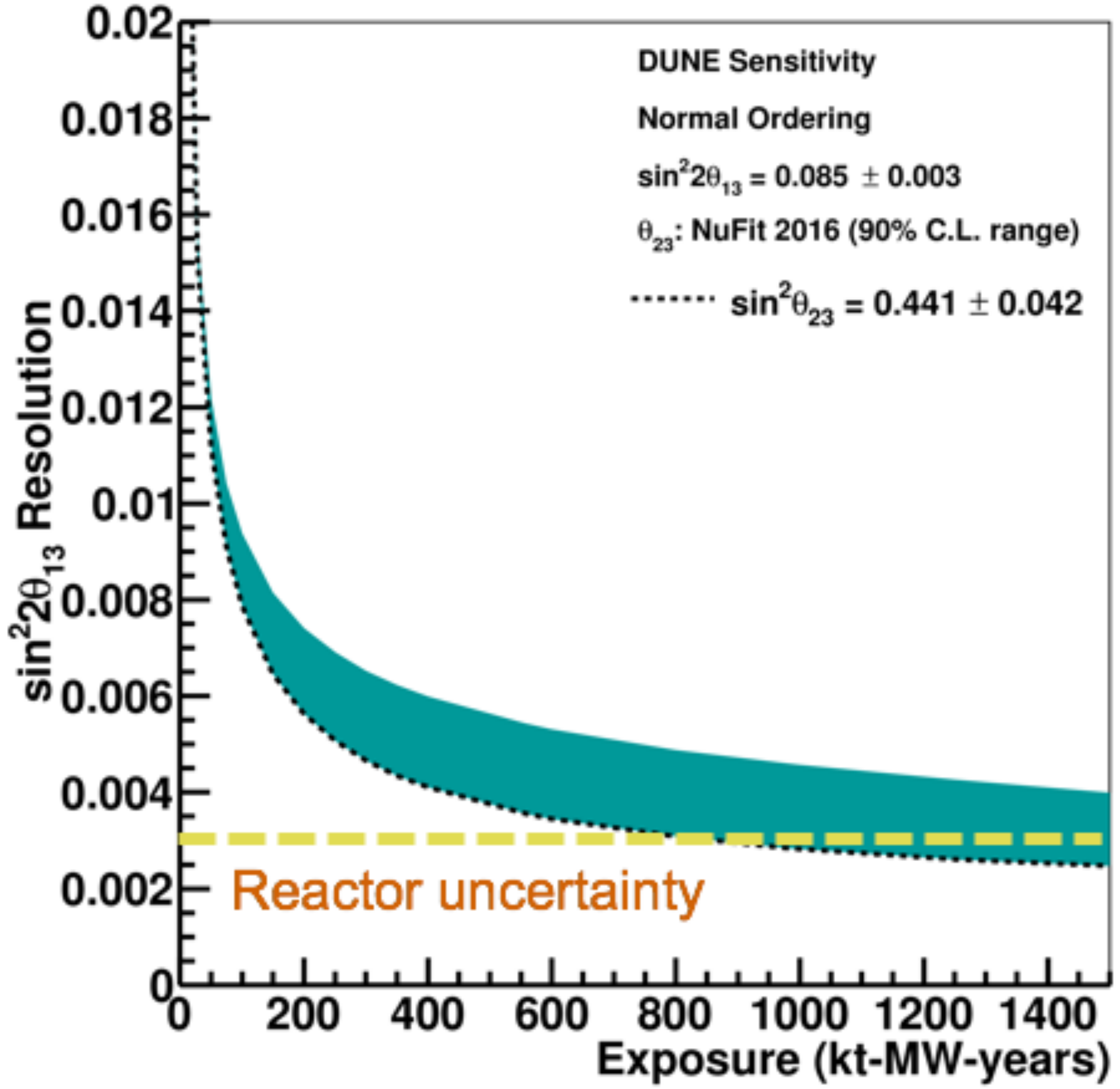
Evolution of Osc. Parameter Sensitivities

1σ resolution of δ_{CP} as a function of exposure



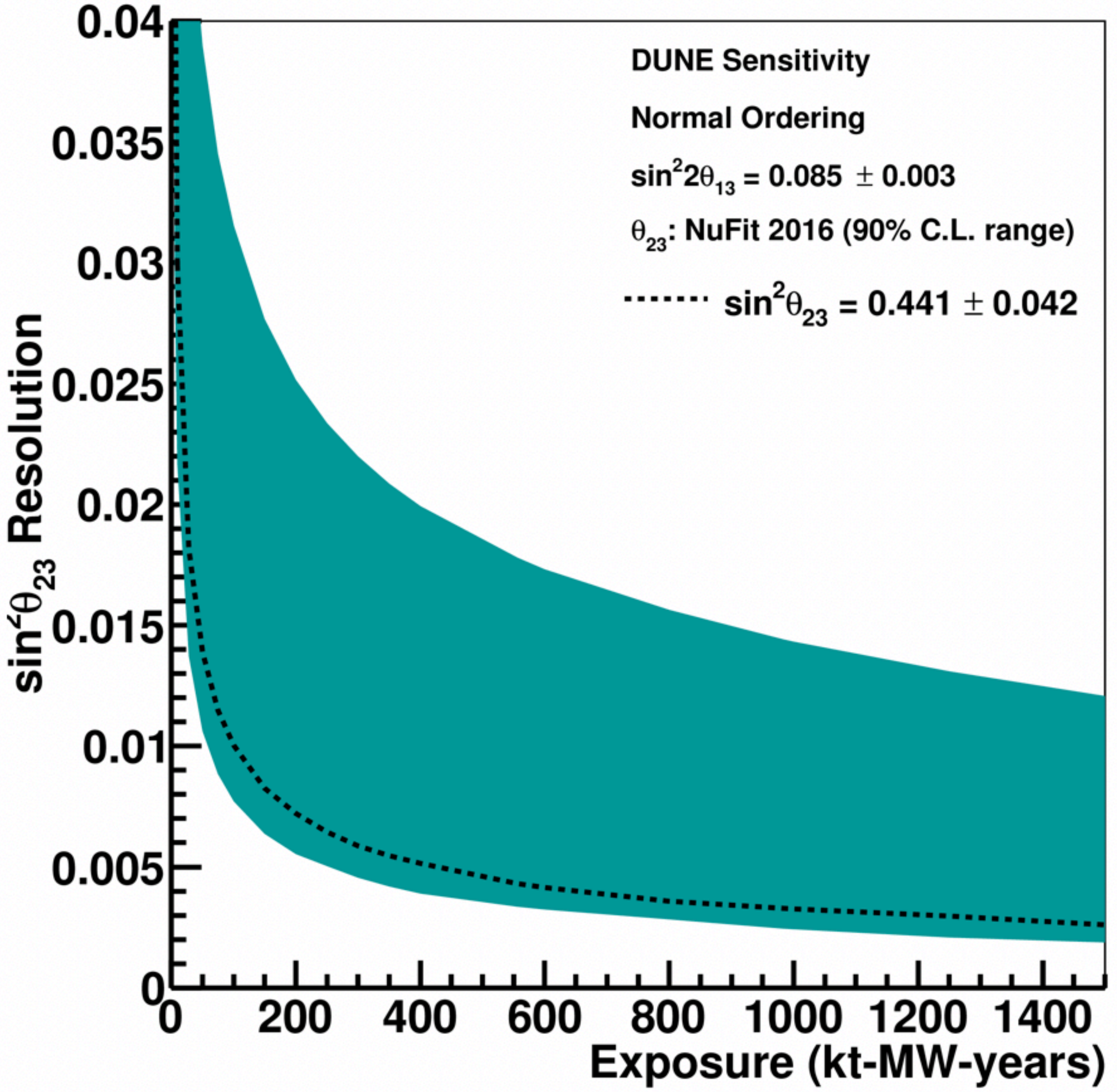
- Reach ~7° (16°) res. in 10yrs for δ_{CP}=0° (-90°)

1σ resolution of $\sin^2 2\theta_{13}$ as a function of exposure



- Reach reactor uncertainty level in ~13 years

1σ resolution of $\sin^2\theta_{23}$ as a function of exposure



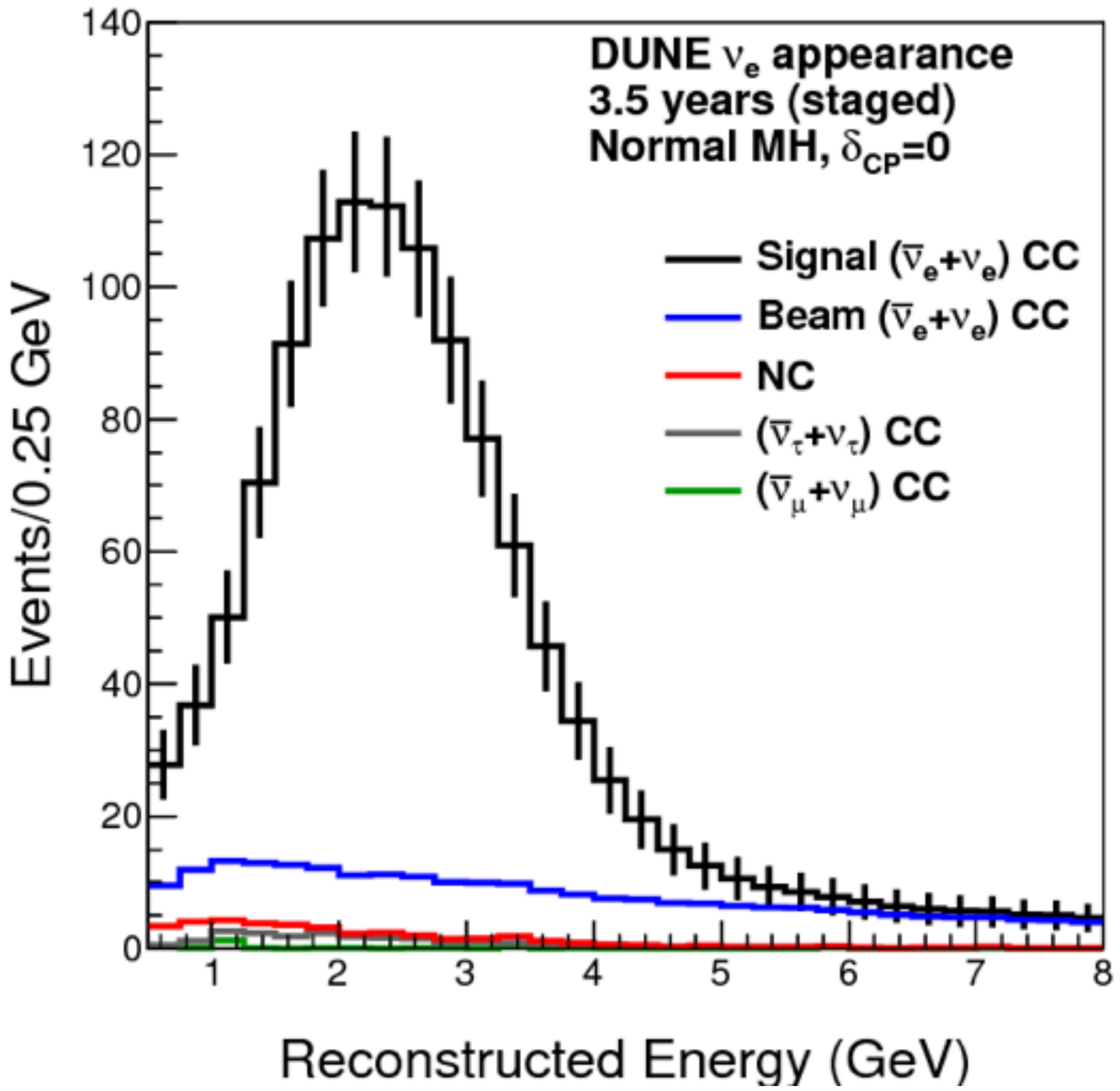
- Can make better than 1% measurement of atmospheric mixing parameters

DUNE capable of high-precision measurements of all non-solar oscillation parameters within a single experiment

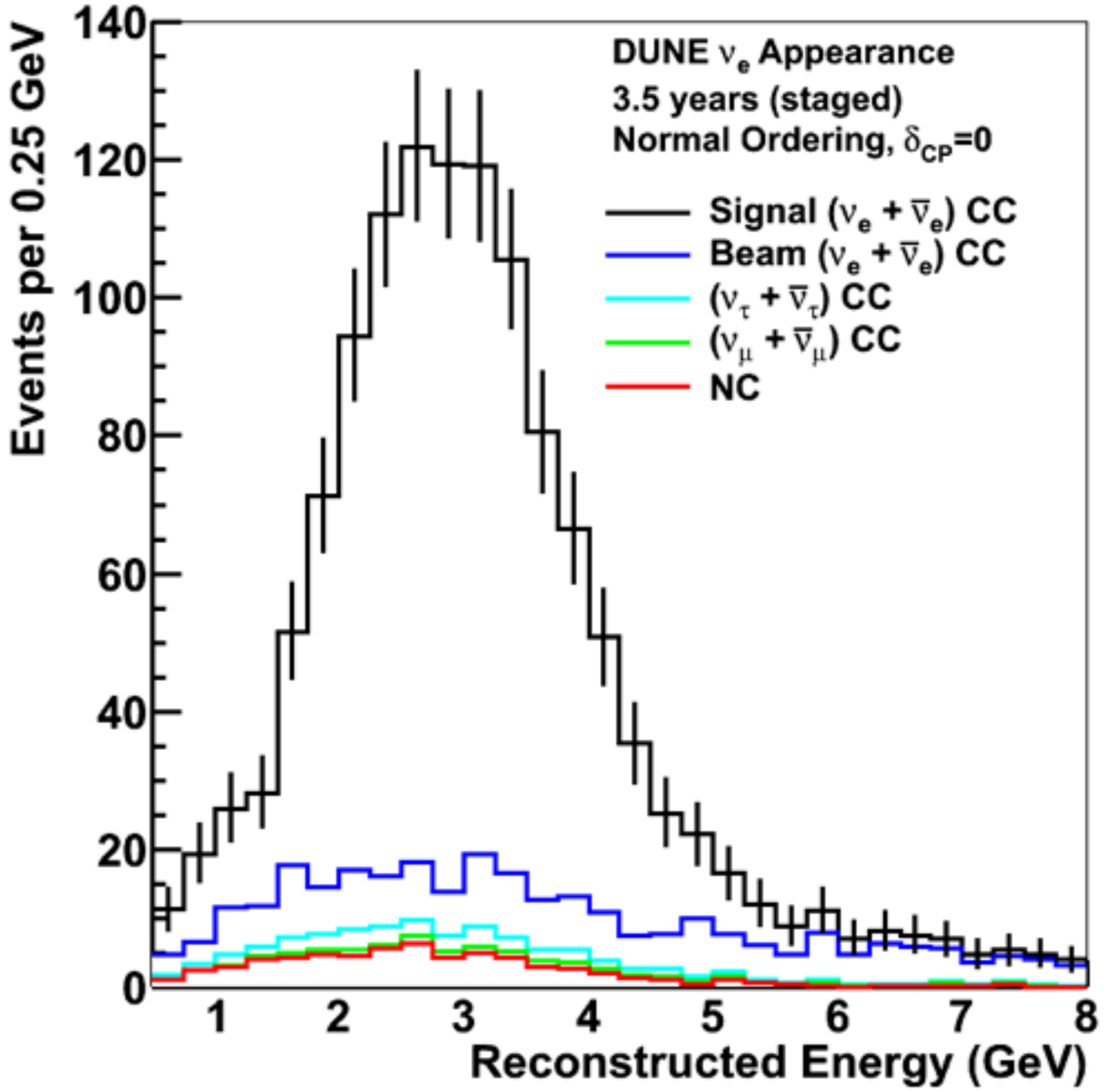
New Monte Carlo Analysis

- Full GEANT4 beam simulation of updated beam design
- Full LArSoft Monte Carlo simulation, using GENIE, Geant 4 for particle propagation, and readout simulation including realistic waveforms and noise
- Automated signal processing and hit finding, and automated energy reconstruction
- Event selection using convolutional visual network (CVN) algorithm adapted from NOvA
- Oscillation analysis using CAFAna fitting framework also used by NOvA

CDR



New!



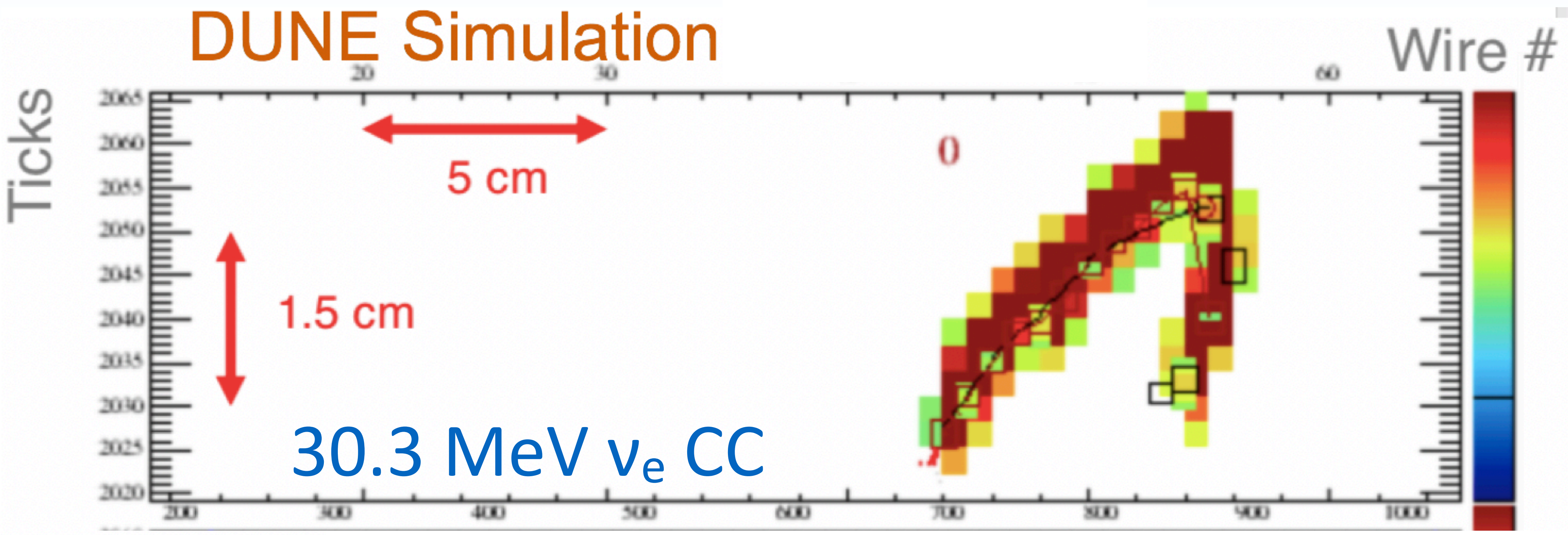
Sensitivity from full end-to-end simulation chain with automated reconstruction and CVN PID very similar to CDR's

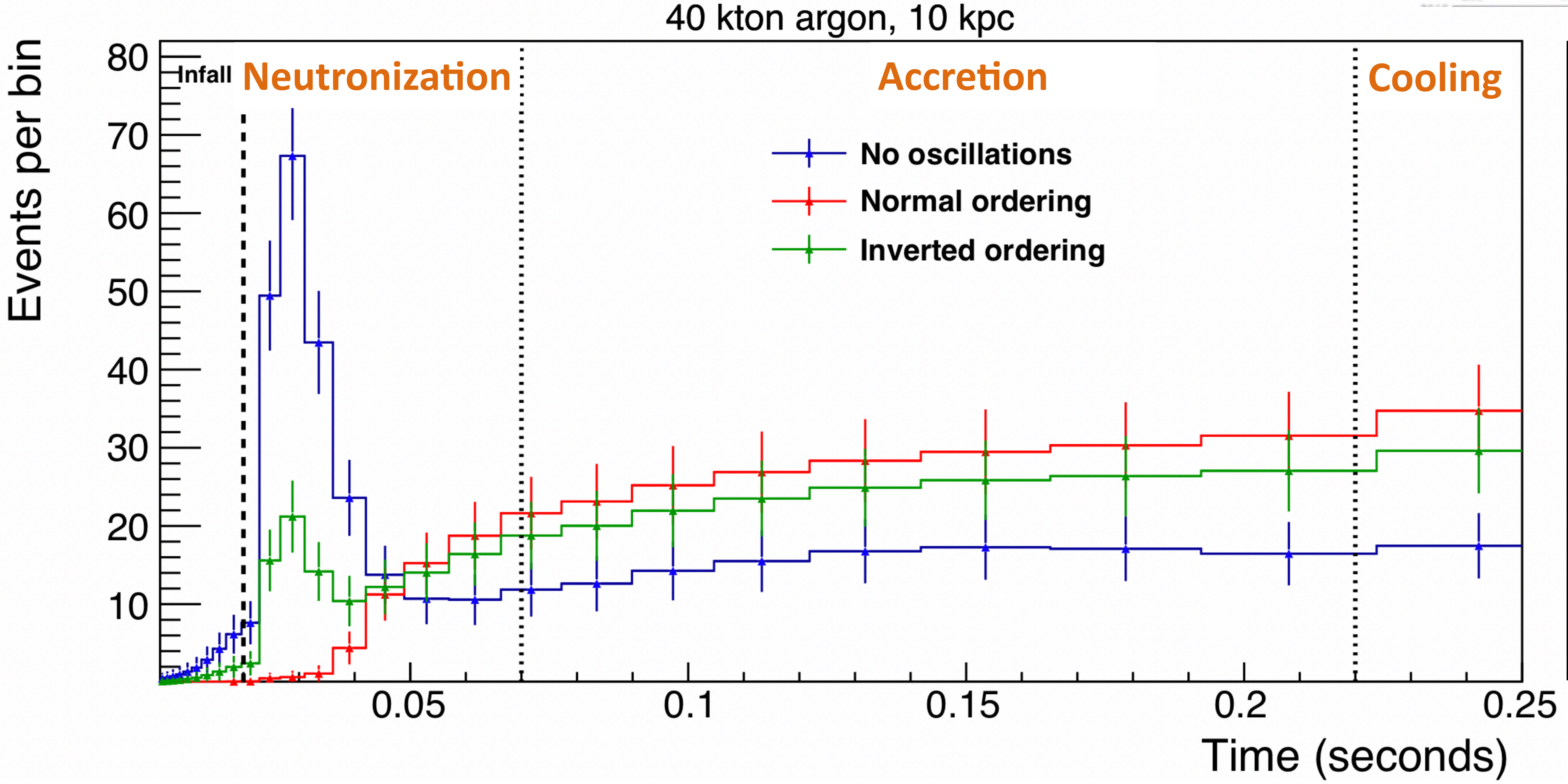
Chris Backhouse's "DUNE Analysis Methods" talk - Friday Syst. Paralel

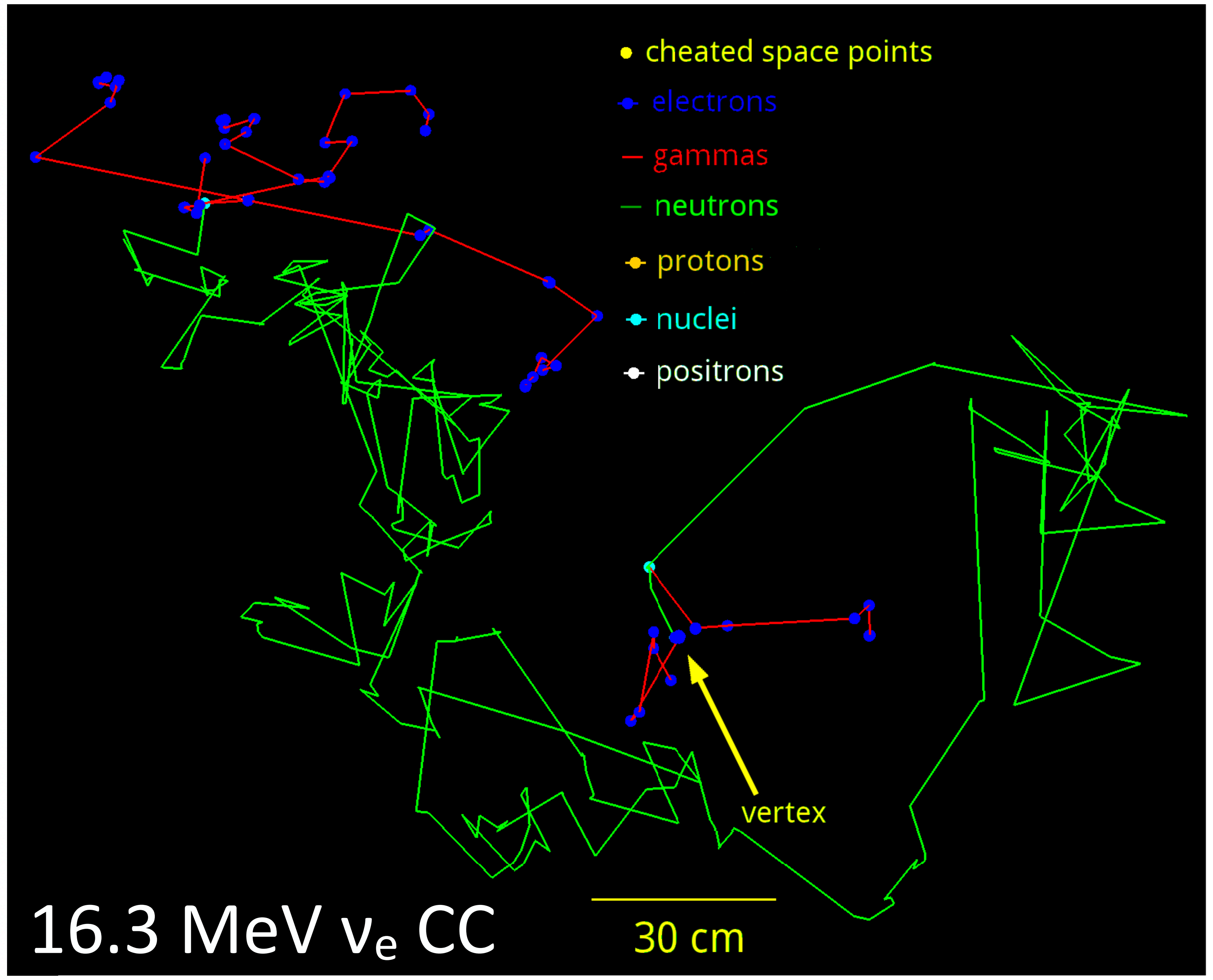
- Full update of sensitivity plots with detailed systematics in the TDR in 2019

Supernova Burst Neutrinos

- In a LArTPC, SNB signal primarily from ν_e: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$
- Sensitivity to mass ordering during early time neutronization phase
- Work underway to improve event reconstruction and tagging of 5-100 MeV events, and on DAQ/triggering



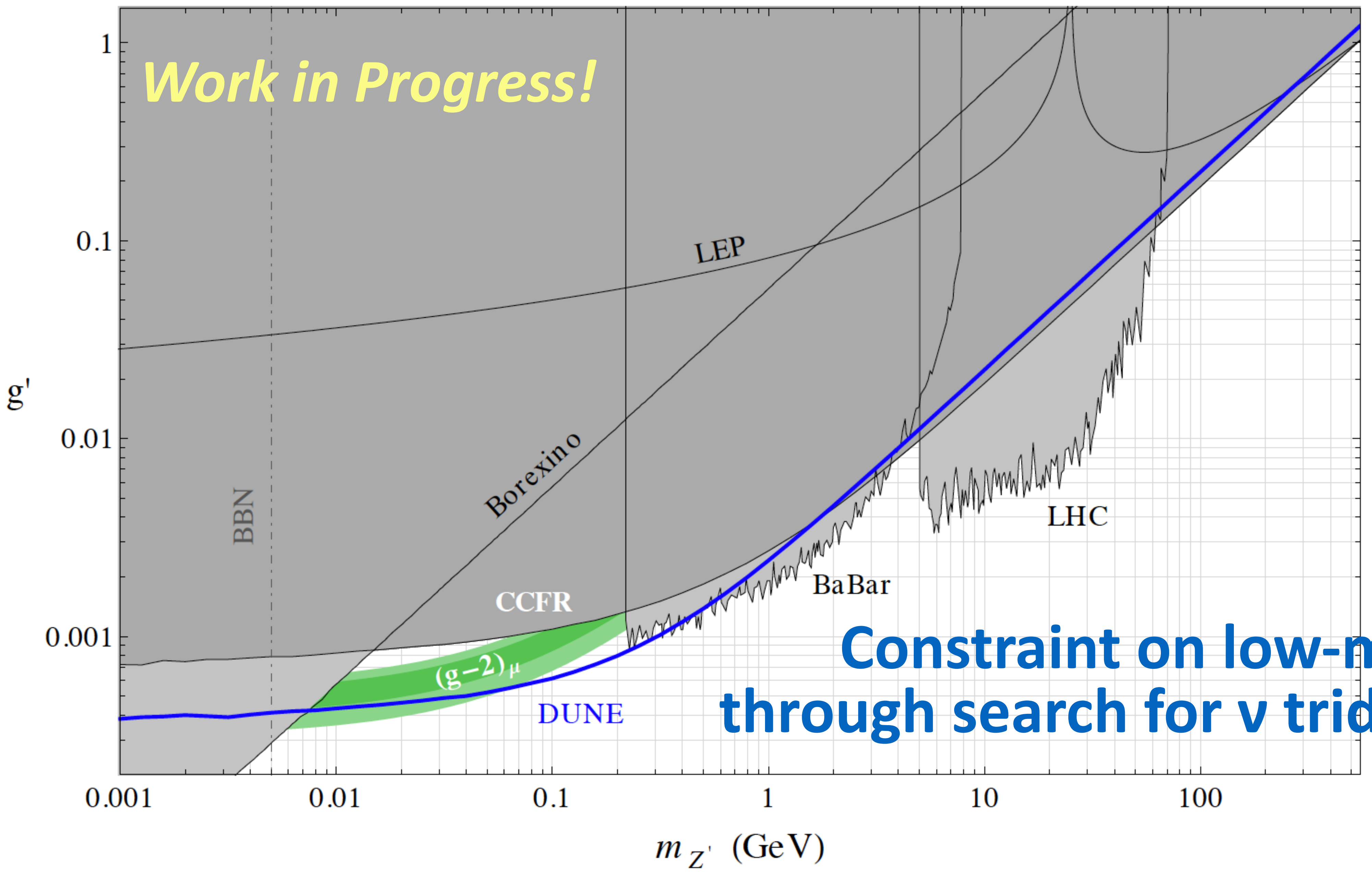




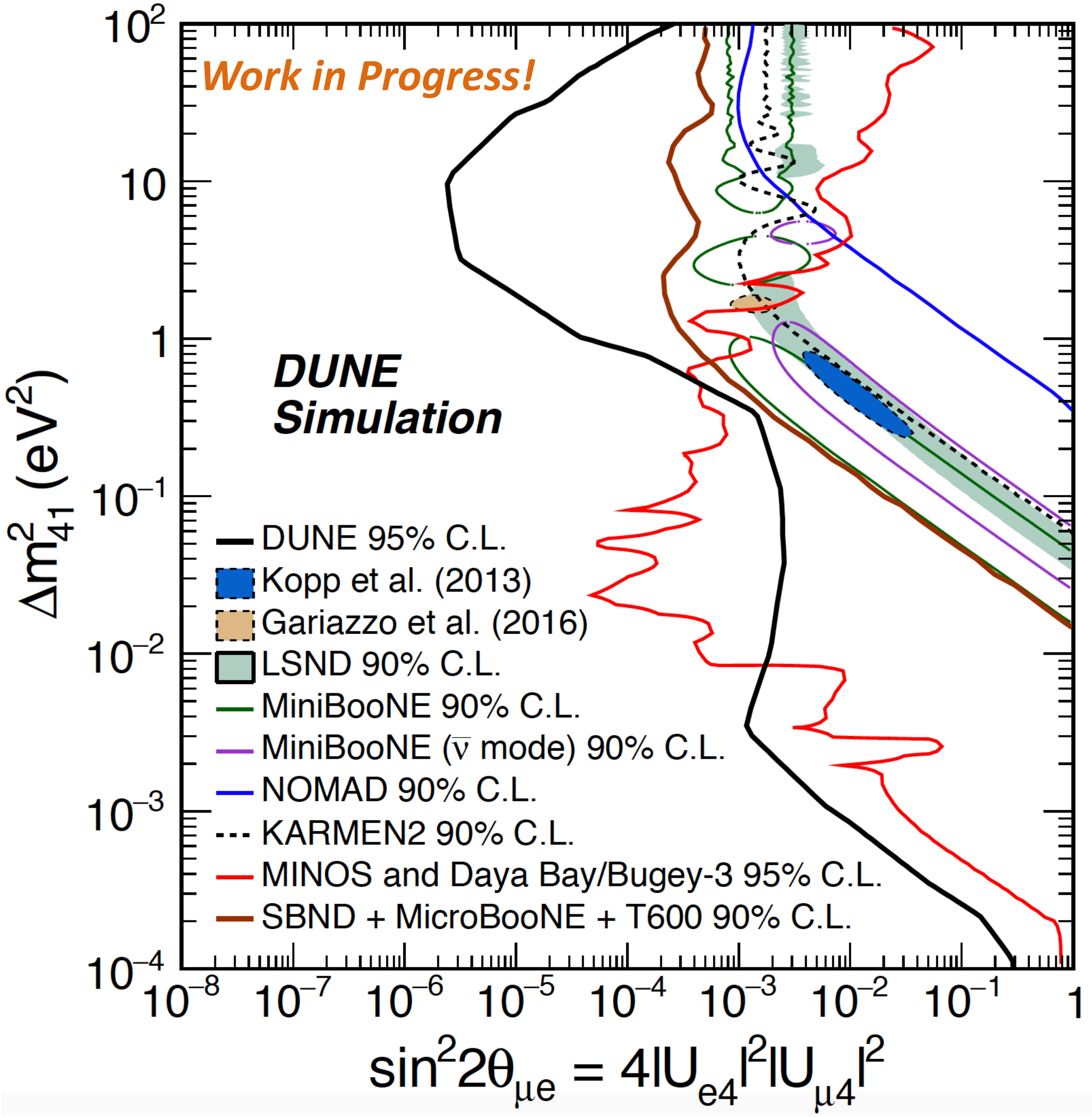
MARLEY event generator: marleygen.org

BSM Physics Searches

- DUNE sensitive to many BSM Physics probes, for instance:
  - Low-mass dark matter and boosted dark matter
  - Sterile neutrinos
  - Non-standard interactions, non-unitary mixing, CPT violation
  - Neutrino trident searches
  - Neutrinos from dark matter annihilation in sun
- Active area of research within phenomenology community as well as within the DUNE collaboration



Constraint on low-mass Z' through search for ν tridents in ND

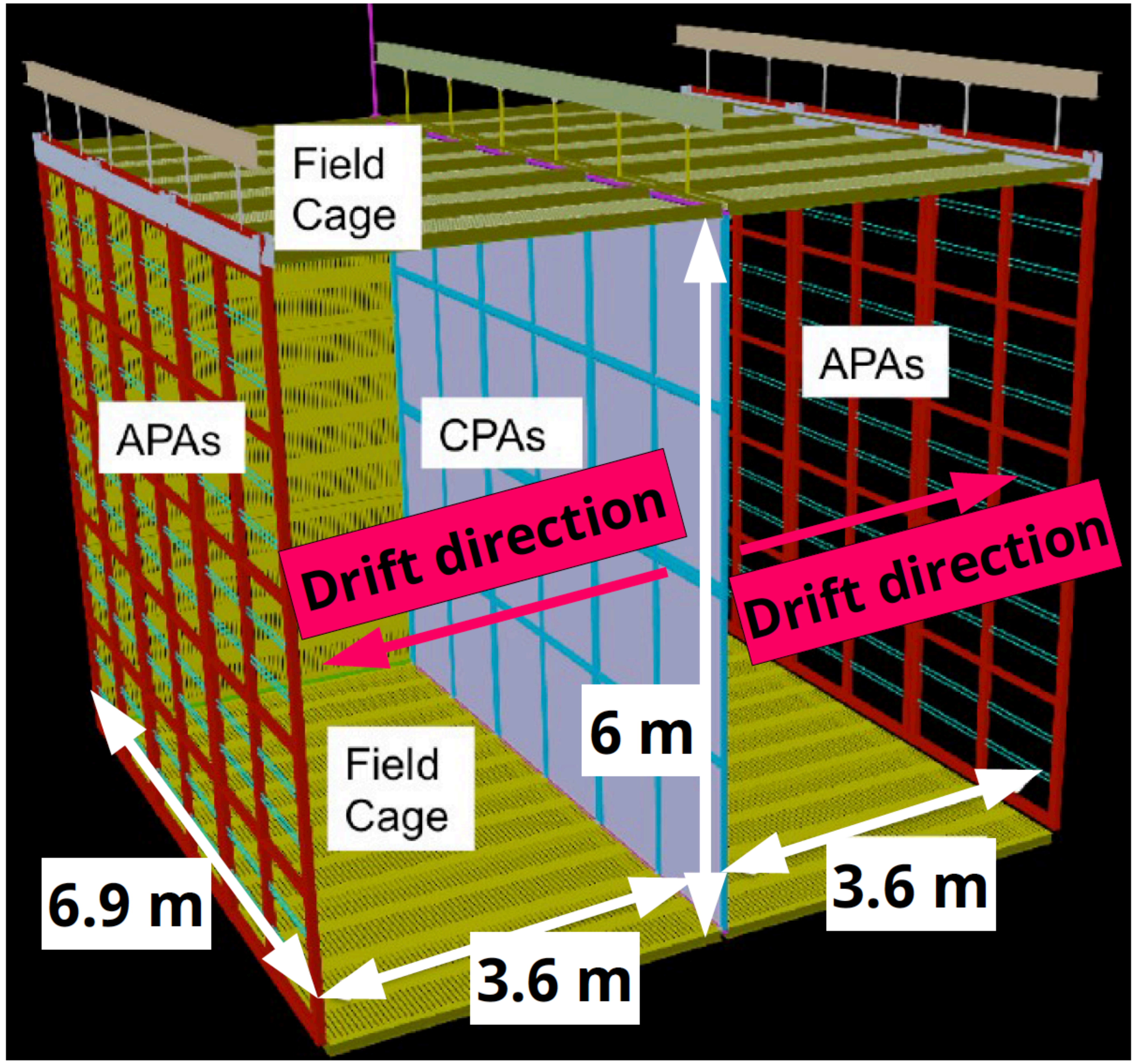


Sterile Neutrino Sensitivity (Nonstandard ν_e CC Appearance)

protoDUNEs

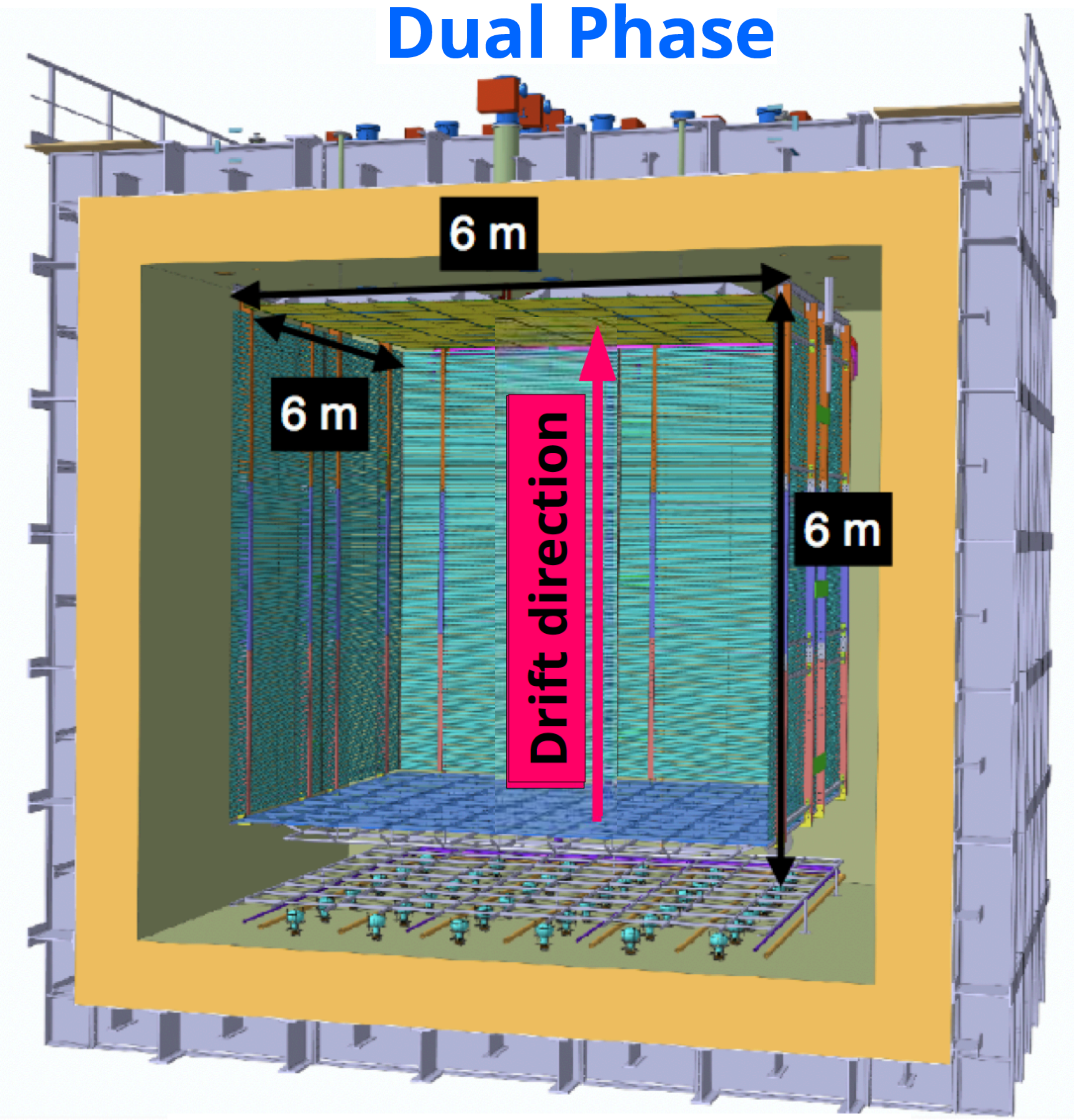
- Single-phase and dual-phase prototypes to be exposed to a test beam at CERN
  - protoDUNE-SP has 770 ton total, 420 ton active Ar mass (larger than ICARUS T600)

Single Phase



Active volume 6.9 x 7.2 x 6.0 m^3

Dual Phase



Active volume 6.0 x 6.0 x 6.0 m^3

CERN Neutrino Platform - ENH1

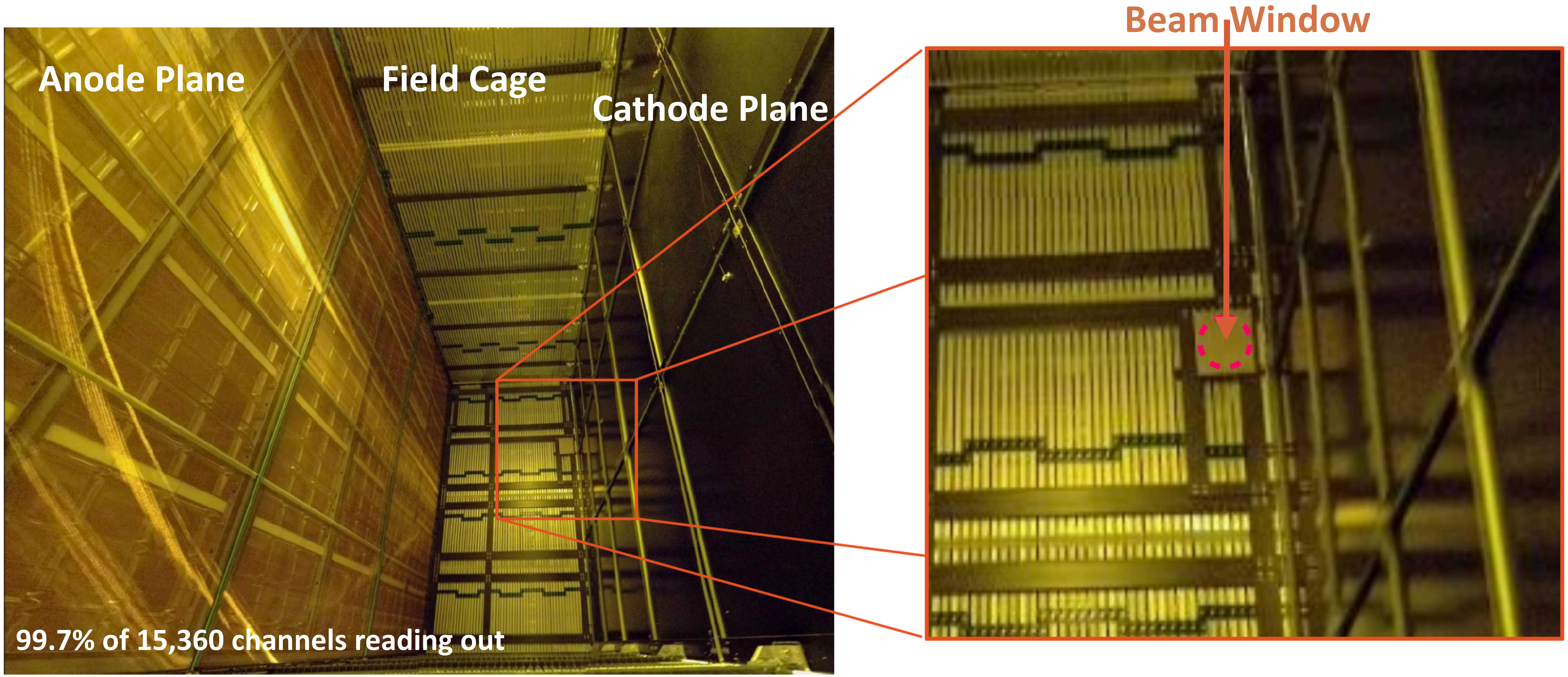
Dual-Phase Cryostat

Single-Phase Clean Room and Cold Box

Single-Phase Cryostat

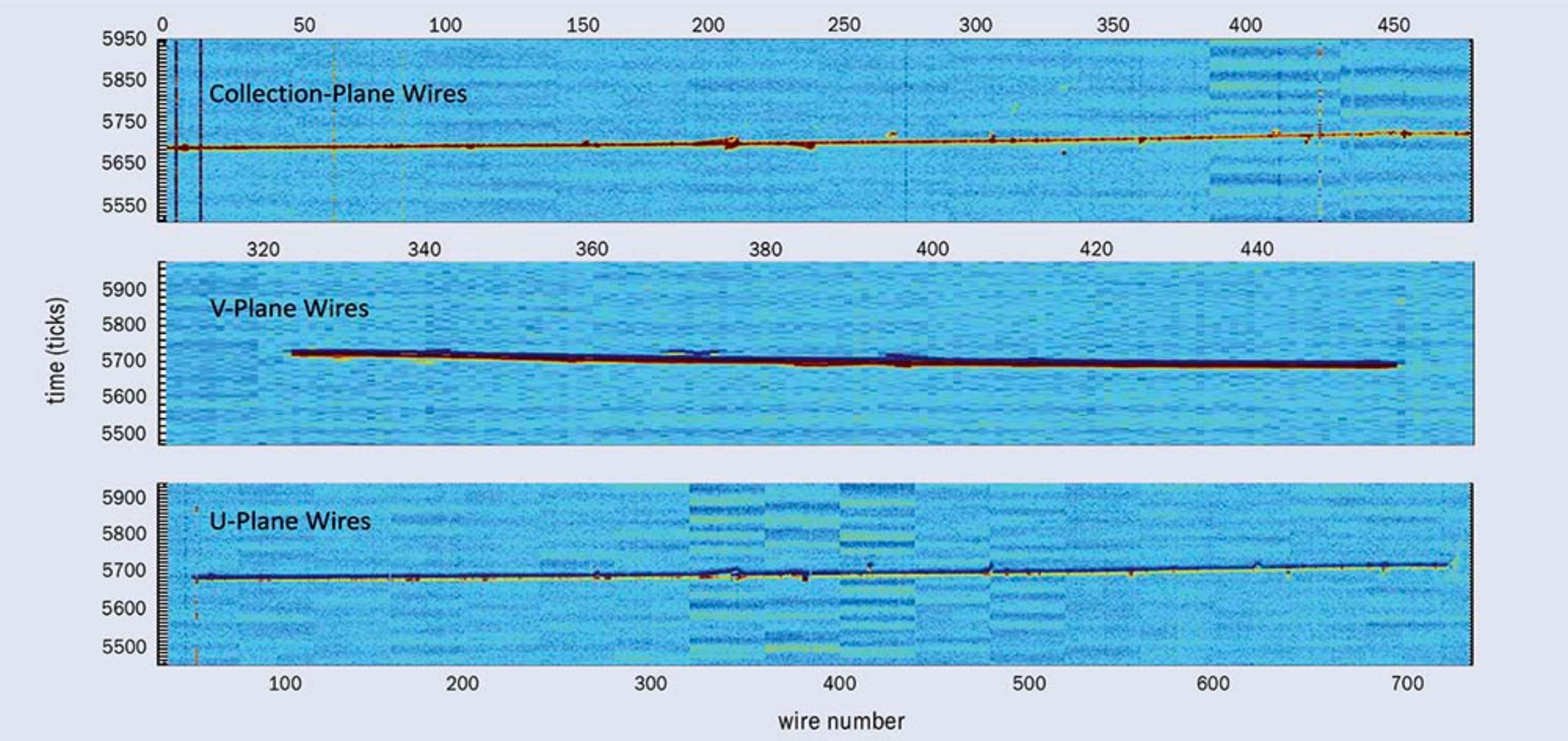
protoDUNE-SP Complete!

- 30 months from starting of Experimental Hall outfitting in March 2016 to operations in September 2018!
- Tertiary beamline provides low energy particles in the momentum range of 0.4 to 7 GeV/c
- Beamline instrumented for momentum selection, particle ID
- Calibrate and verify detector response to particles of known type and momentum
- Prototypes share same basic mechanical design, readout, electronics and DAQ as those planned for DUNE



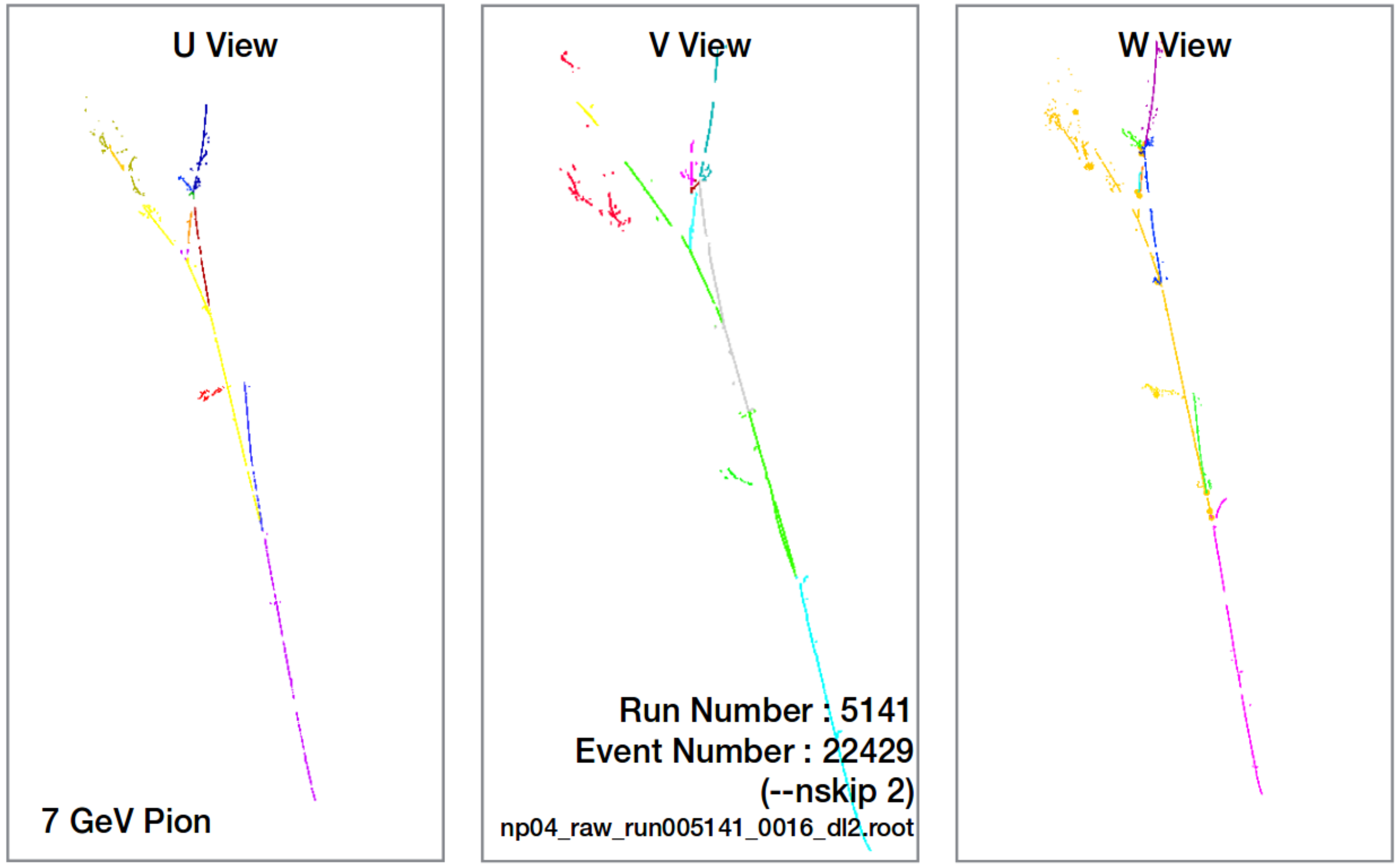
protoDUNE-SP Cosmic Data

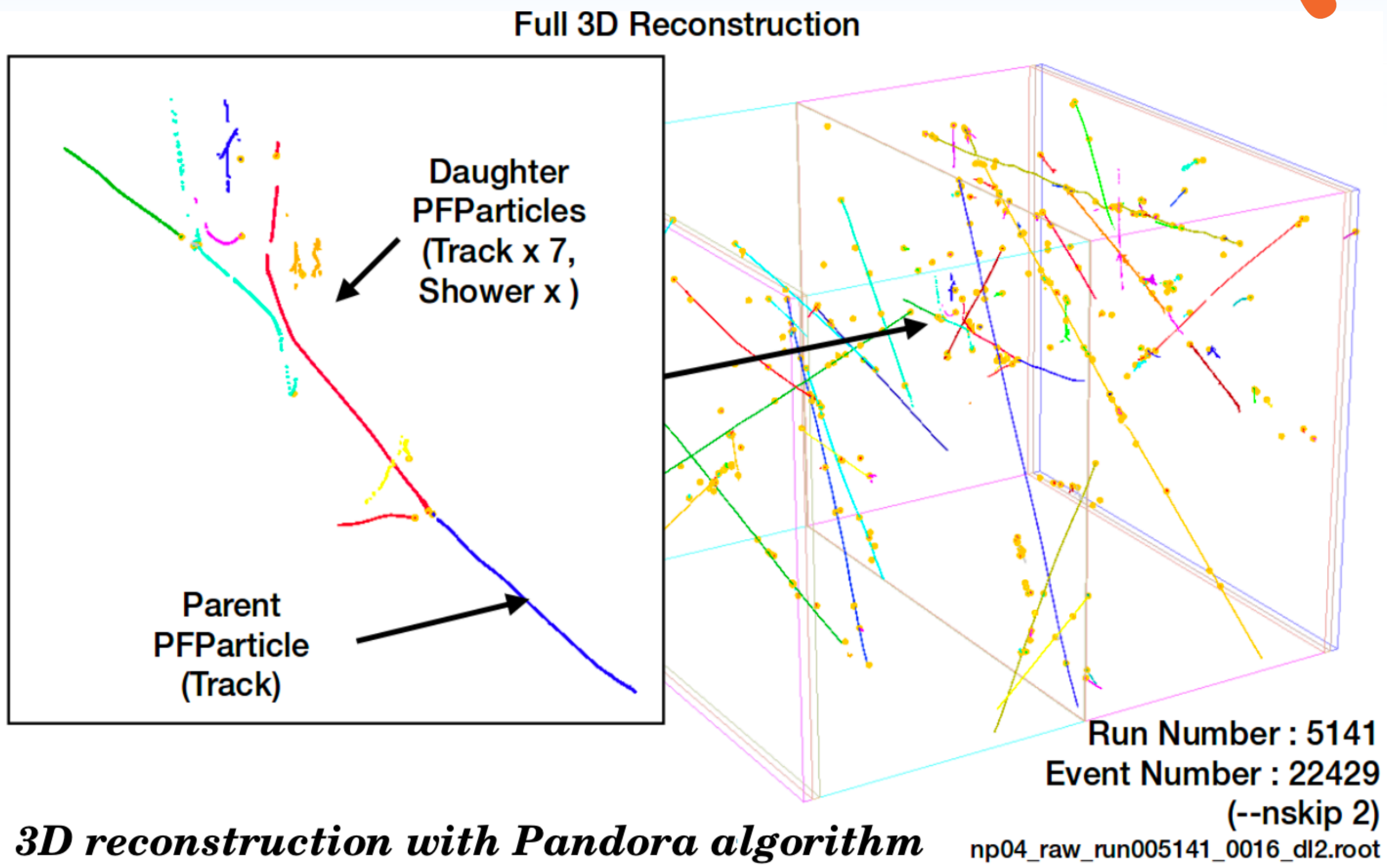
- 3.8 m long cosmic muon recorded in September 2018



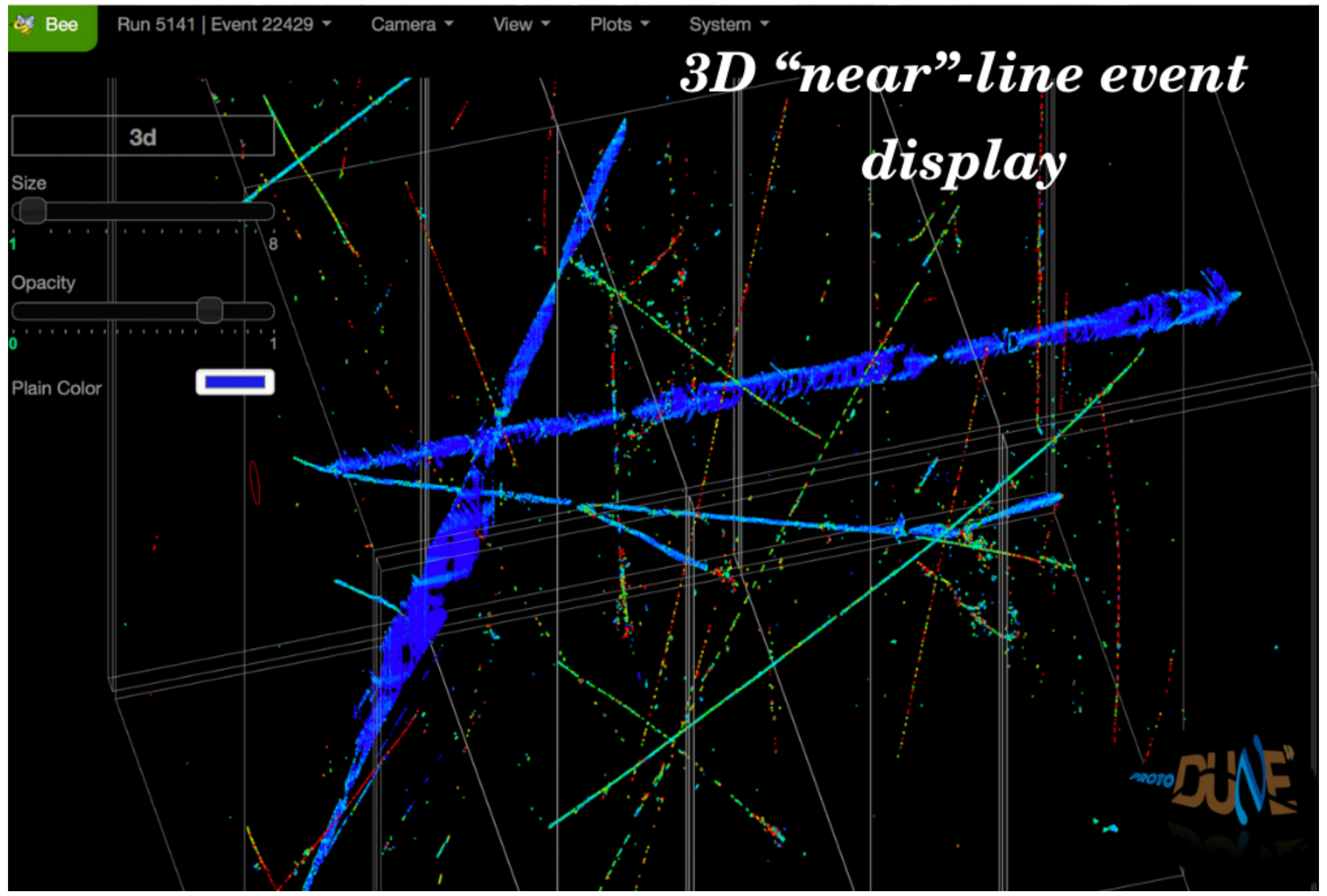
protoDUNE-SP Beam Data

- 7 GeV Pion from test beam reconstructed with Pandora algorithm both in 2D and 3D
- Algorithm correctly identified particle as a beam event and distinguished parent from daughter particles





3D reconstruction with Pandora algorithm

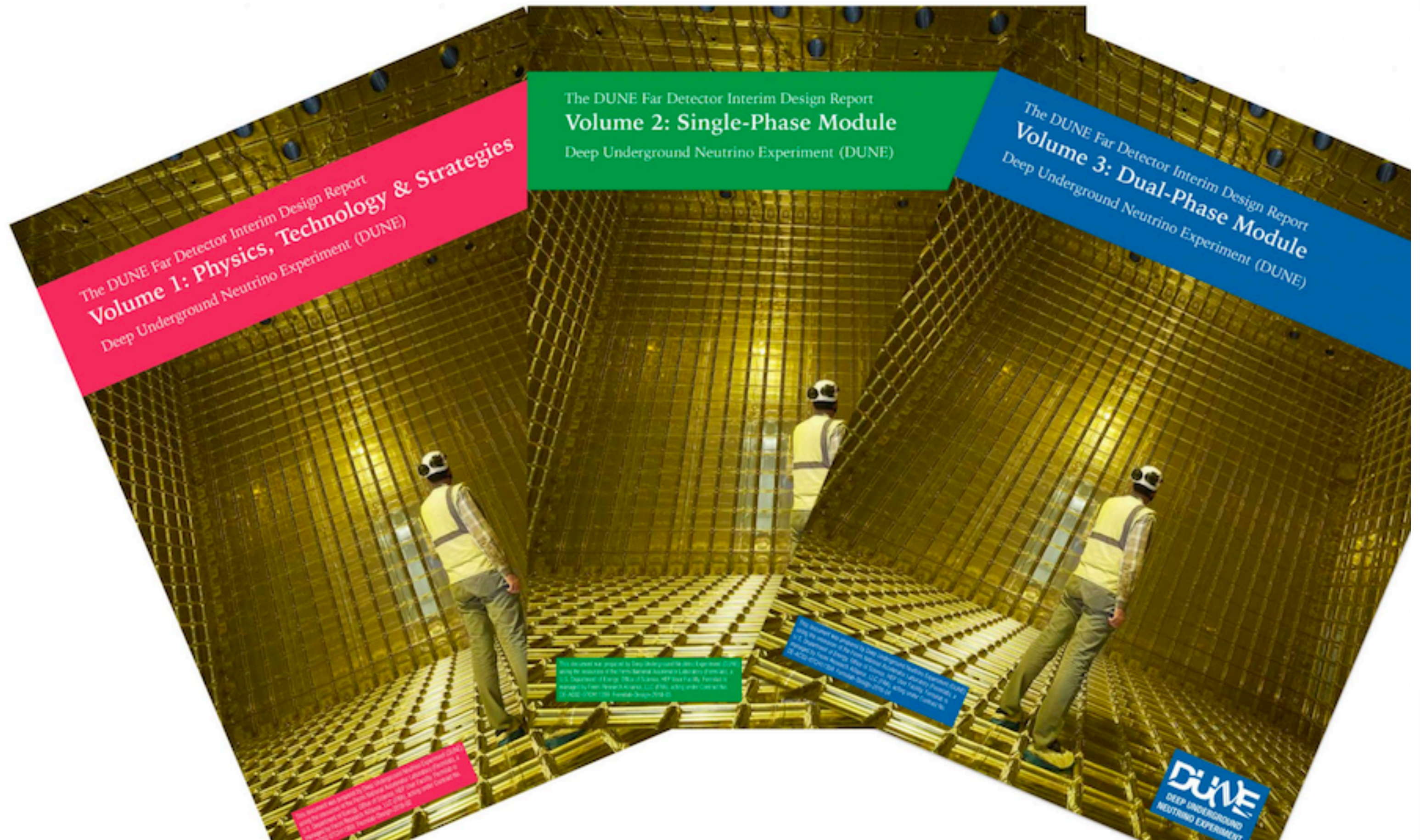


Francesca Stocker's "protoDUNE SP R&D" talk - Friday Det. Paralel

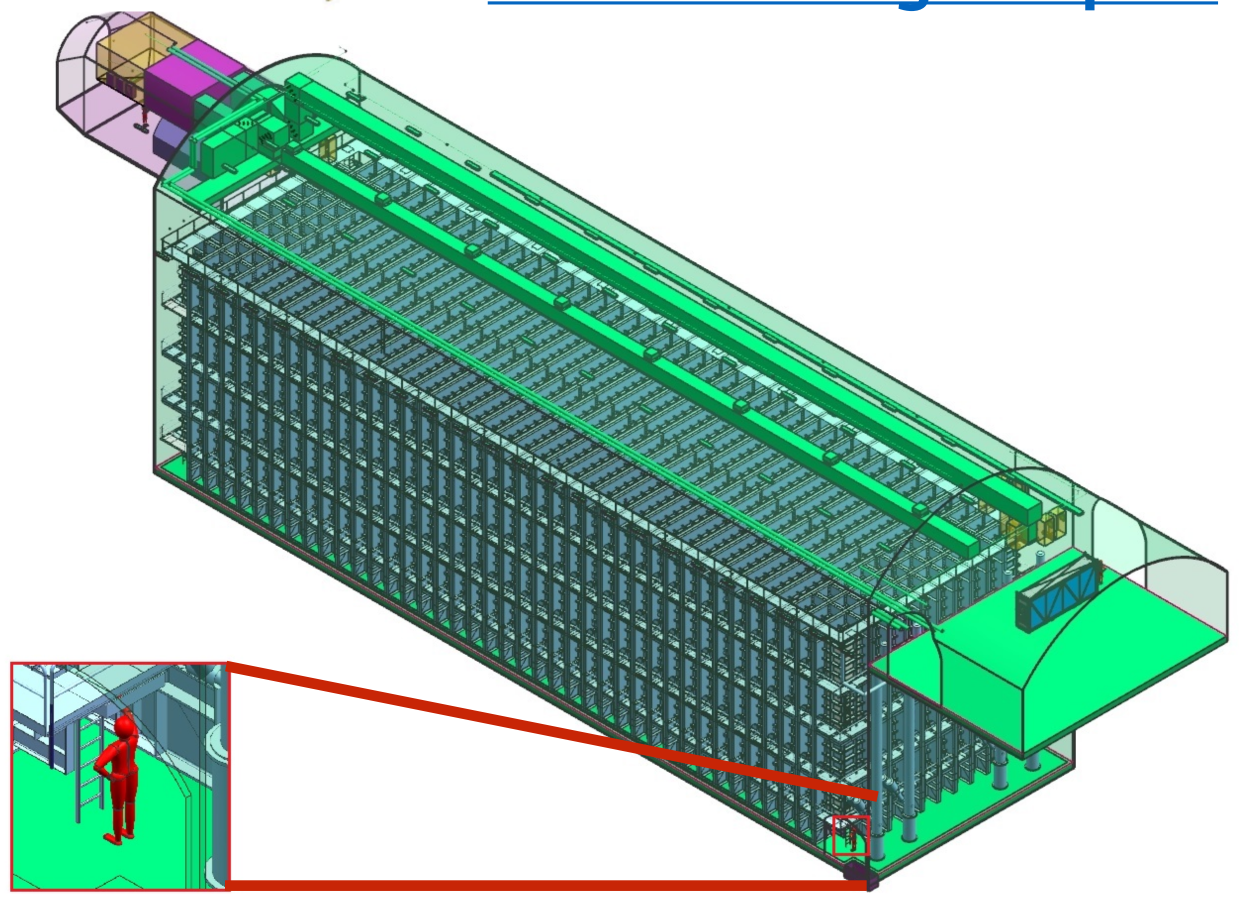
protoDUNE Future Plans

- September - November 2018 (CERN Long-Shutdown): SP Detector operations, Test-Beam run + Cosmics
- Winter 2019 - Dual-Phase installation complete
- 2019: Endurance run with Cosmics [long-term stability]
- 2020: Continuing operations with Cosmics, if required
- 2021: Keep open the option of recording Test Beam data after CERN Long-Shutdown

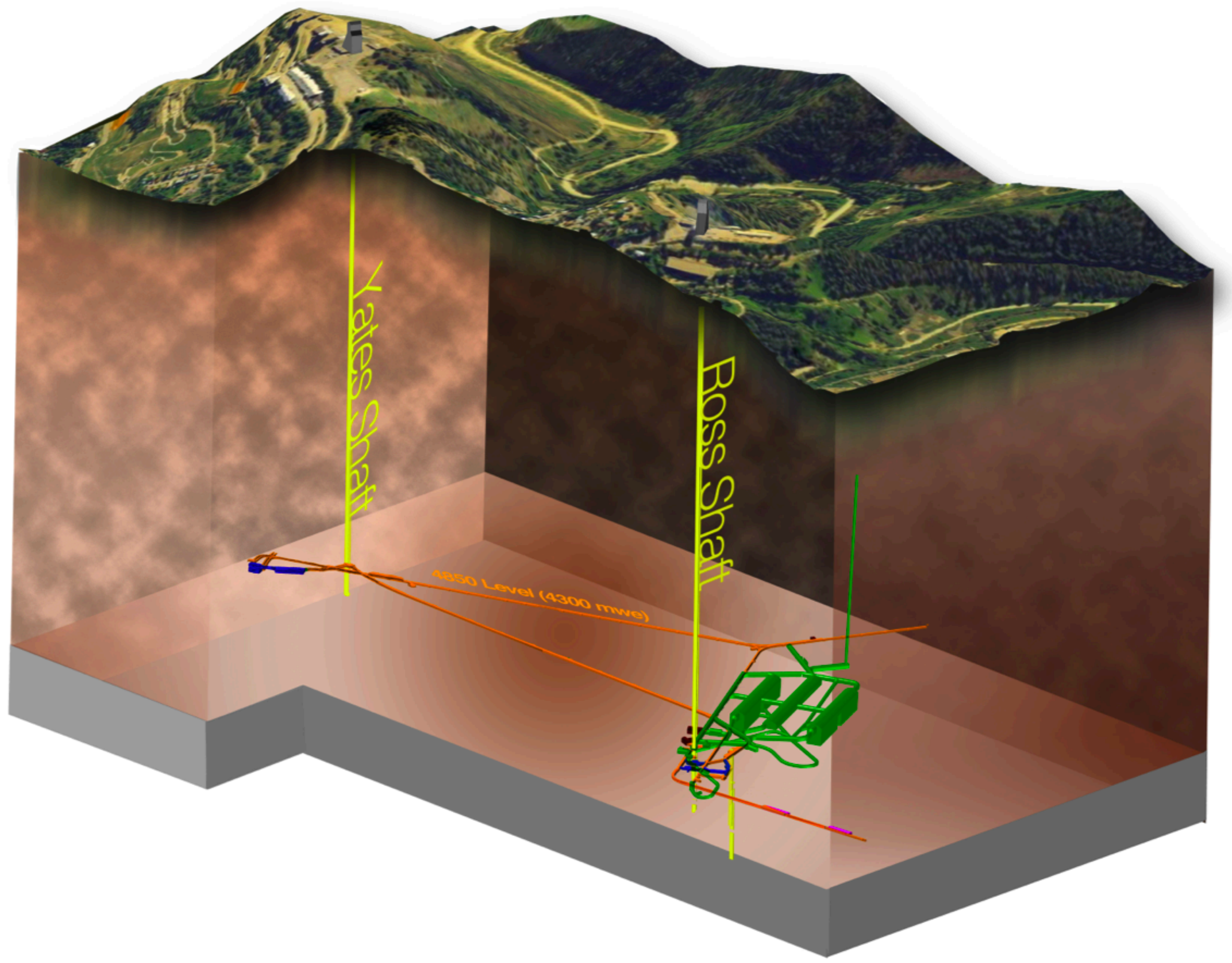
DUNE Project Timeline



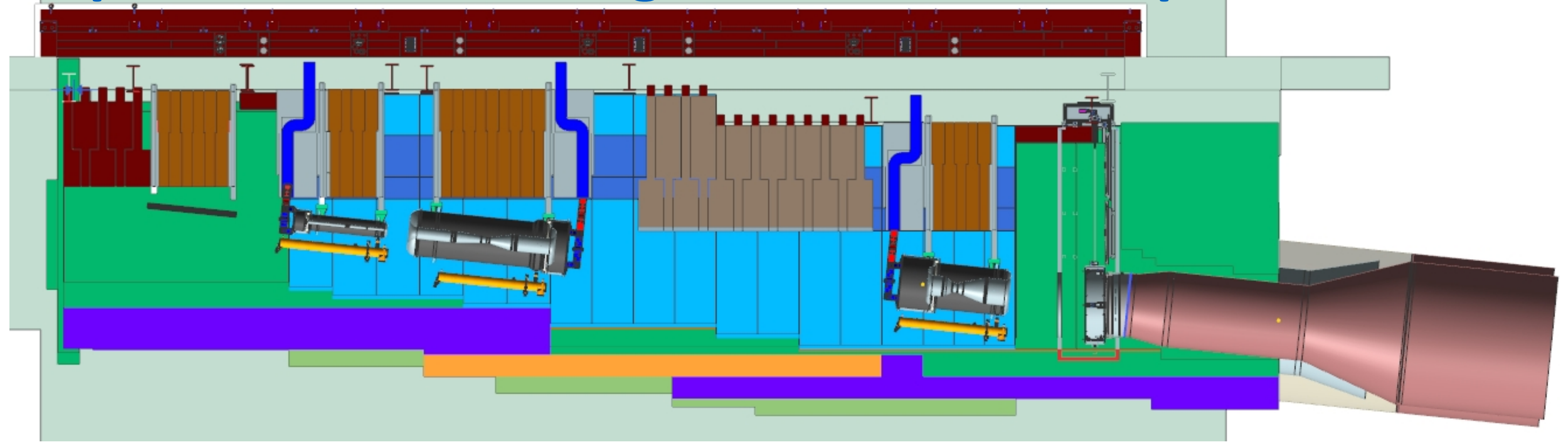
Interim Design Report



- 2018: protoDUNEs at CERN
- 2019: Technical Design Report
- 2019: Far Site Primary Excavation Begins
- 2022: First Module Installation Begins
- 2026: Neutrino Beam Available



Optimized Beam Target + Horns Concept

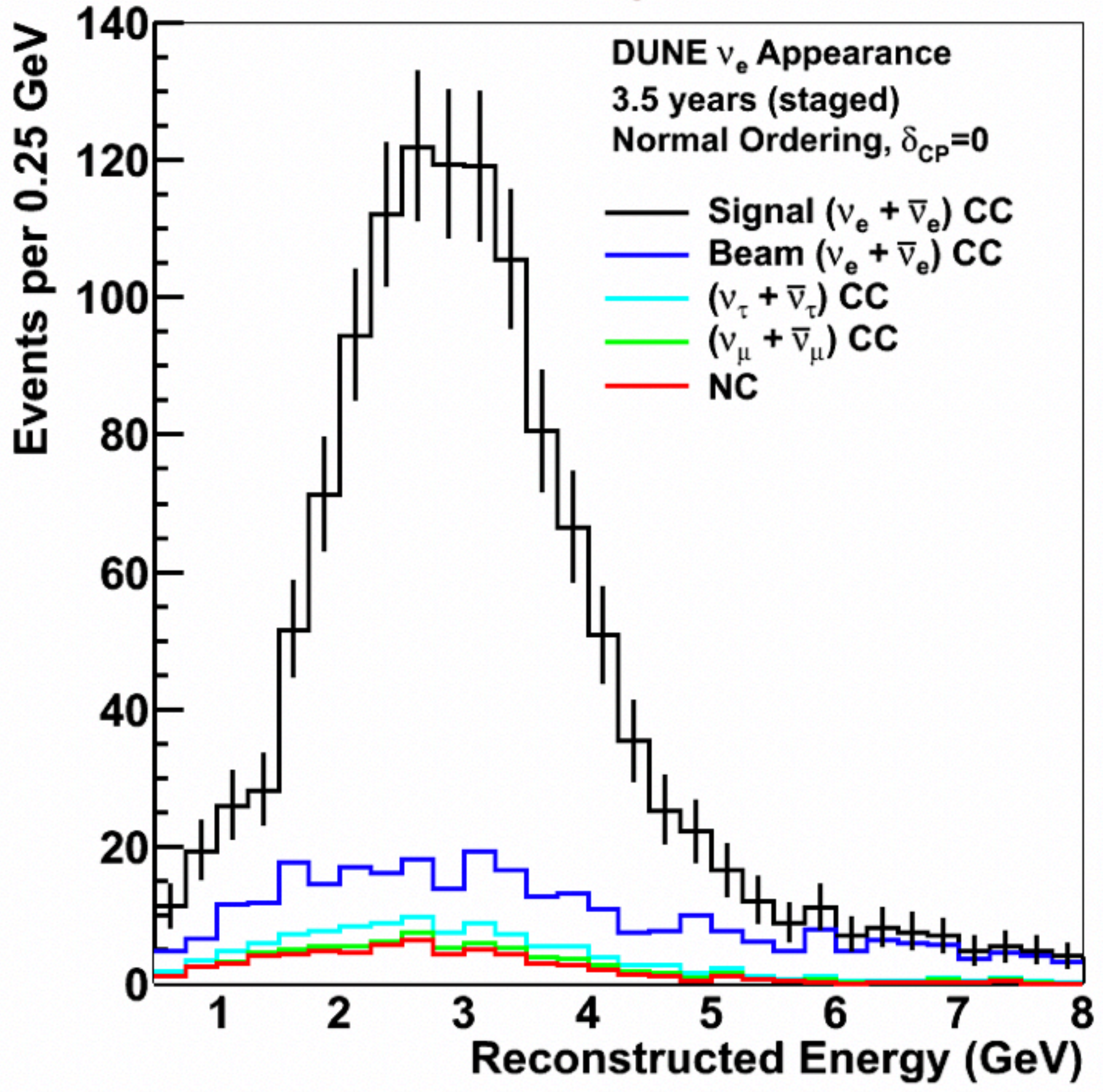


- Will take atmospheric neutrino data as soon as first module is completed in 2024

Summary and Outlook

- LBNF/DUNE has become a global international neutrino collaboration
- Rapid progress being made on facility construction, detector design, and physics analysis
- DUNE has a broad and rich physics program including CP violation probes, mass ordering determination, precision neutrino oscillation measurements, Supernova neutrinos, atmospheric neutrinos, and many BSM Physics searches
- New full-simulation sensitivity analysis producing results similar to CDR
- protoDUNE SP at CERN taking beam and cosmics data
  - Essential step towards first 10 kton modules at SURF
- Look for DUNE Technical Design Report and protoDUNE SP and DP results in 2019!
- Anticipate first DUNE Far Detector data in 2024!

New Analysis



DEEP UNDERGROUND
NEUTRINO EXPERIMENT

The DUNE Collaboration @ Fermilab, September 2018

Thank You!

Supplements

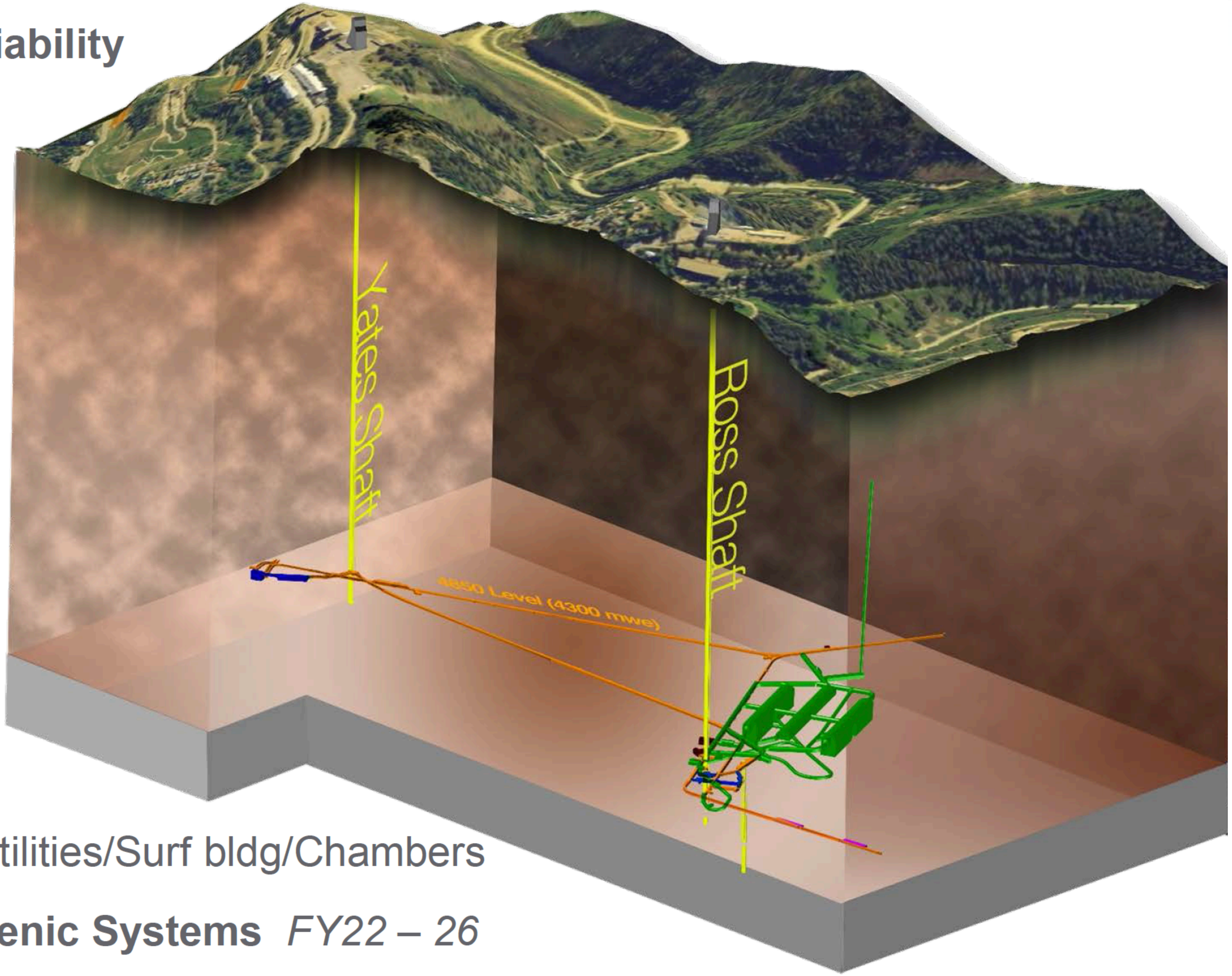
Far Site - Phases of Work

1. **Sanford Lab Reliability Projects**
   FY16 – 19
   - Ross shaft rehab
   - Hoist motor rebuilds, more…

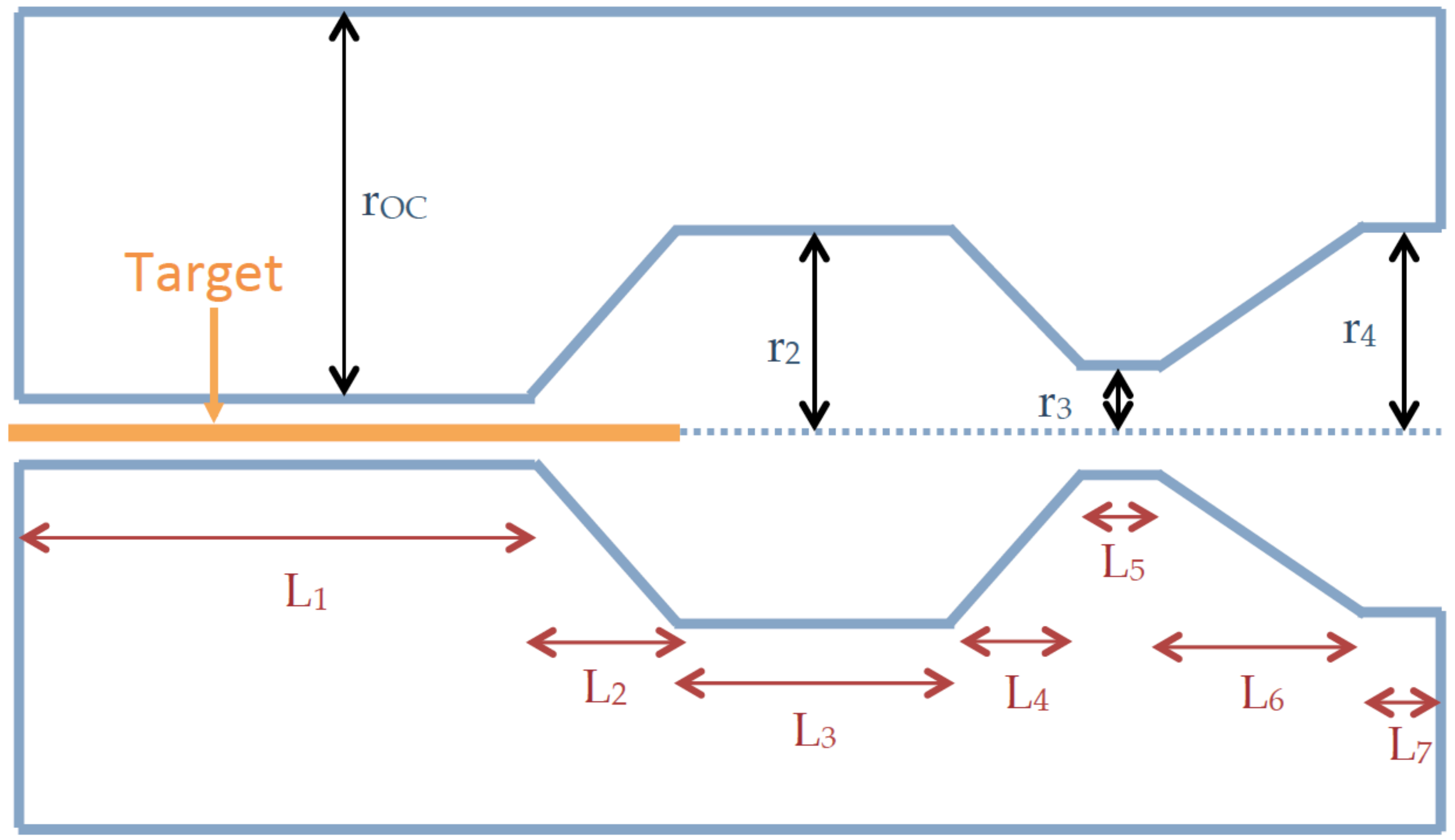
2. **Pre-Exec Const**
   FY17 - 20
   - Rock disposal systems
   - Ross headframe upgrade, more…

3. **Exec & Surface Construction**
   FY21 – 24
   - Brow/CUC/Drifts/Utilities/Surf bldg/Chambers

4. **Cryostats/Cryogenic Systems** *FY22 – 26*



Beam Optimization



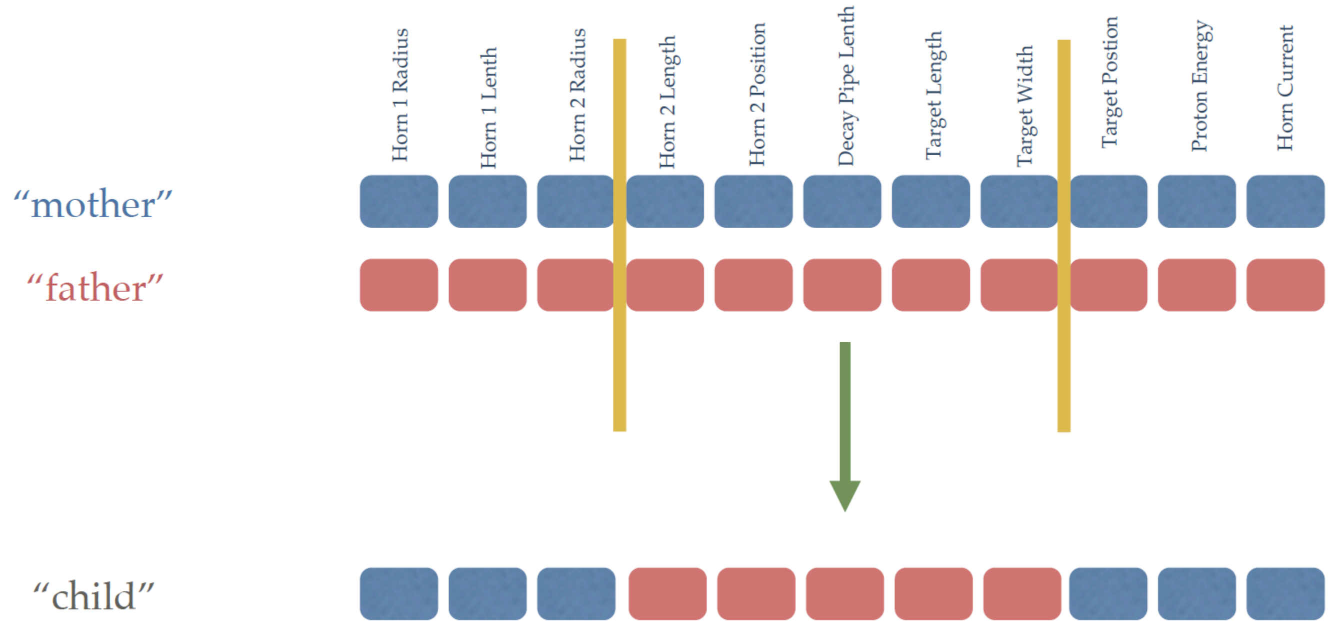
Parameters Varied:

- Horn 1 shape parameters (see figure)
- Width/length of carbon fin-style target
- Horn current
- Horn 2 radial and longitudinal scales
- Horn separation
- Proton beam momentum & radius

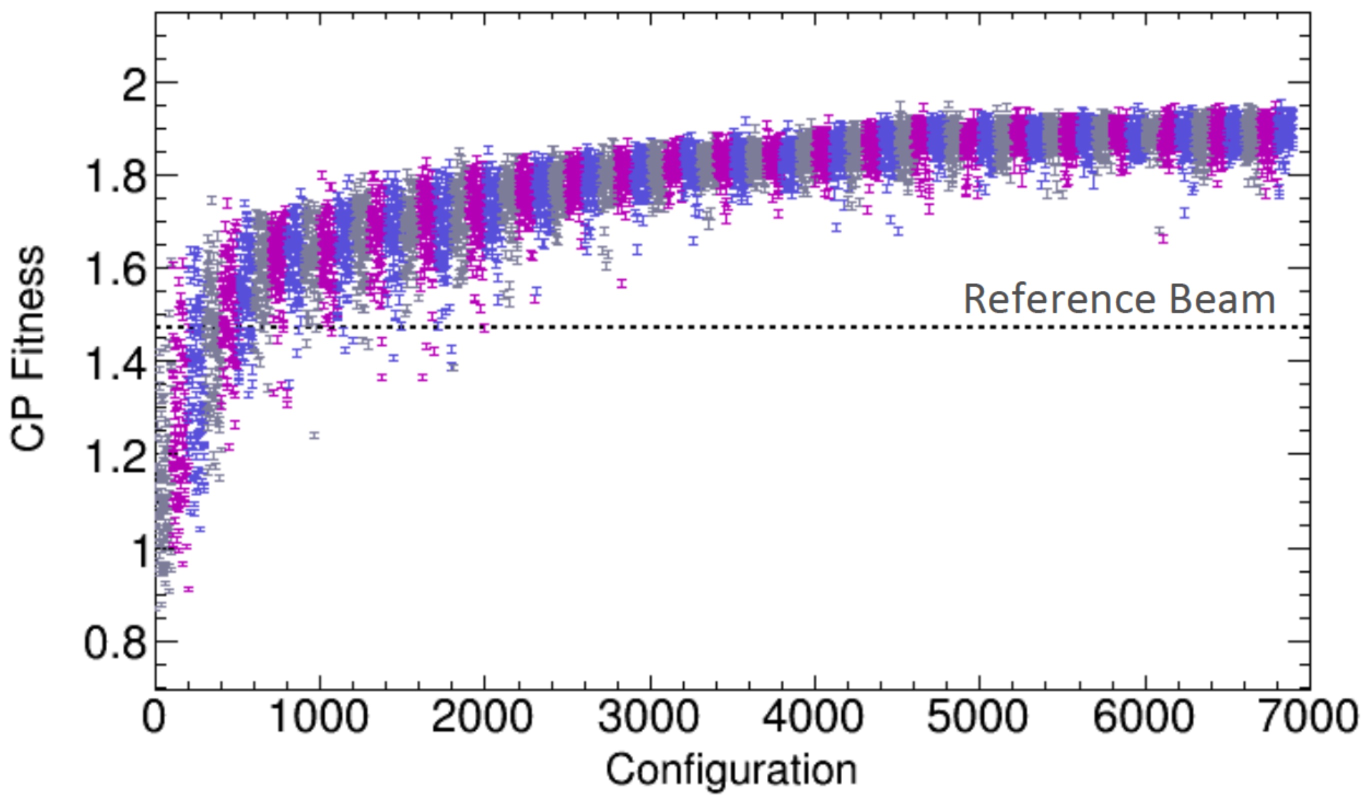
Genetic Algorithms

M.~Calviani, S.~Di Luise, V.~Galymov and P.~Velten, ``Optimization of neutrino fluxes for future long baseline neutrino oscillation experiments, arXiv:1411.2418

- Since we wanted to build the beam sometime in our lifetimes, we developed a genetic algorithm
  - A beam configuration is viewed as an organism; you start with a sample of randomly chosen organisms
  - Configurations are judged based on "fitness" (CP sensitivity) and best configurations are mated together to form new (and better) designs

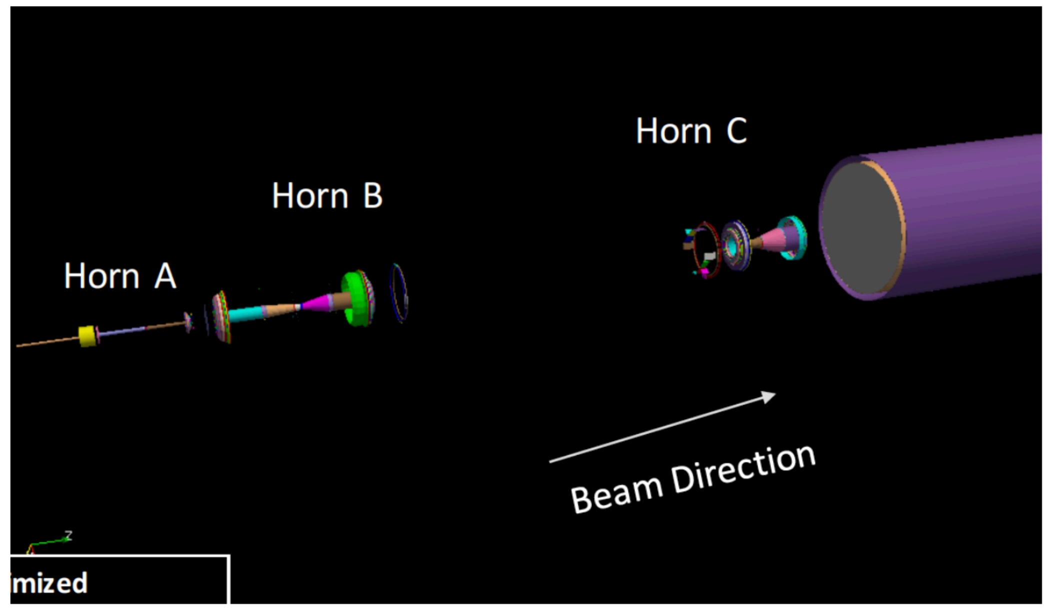


- Eventually, the algorithm converges on an optimal beam design
  - Each generation runs in parallel on the Fermigrid and takes ~ 2 hours; convergence takes a few weeks



We know that this algorithm produces good beam designs.

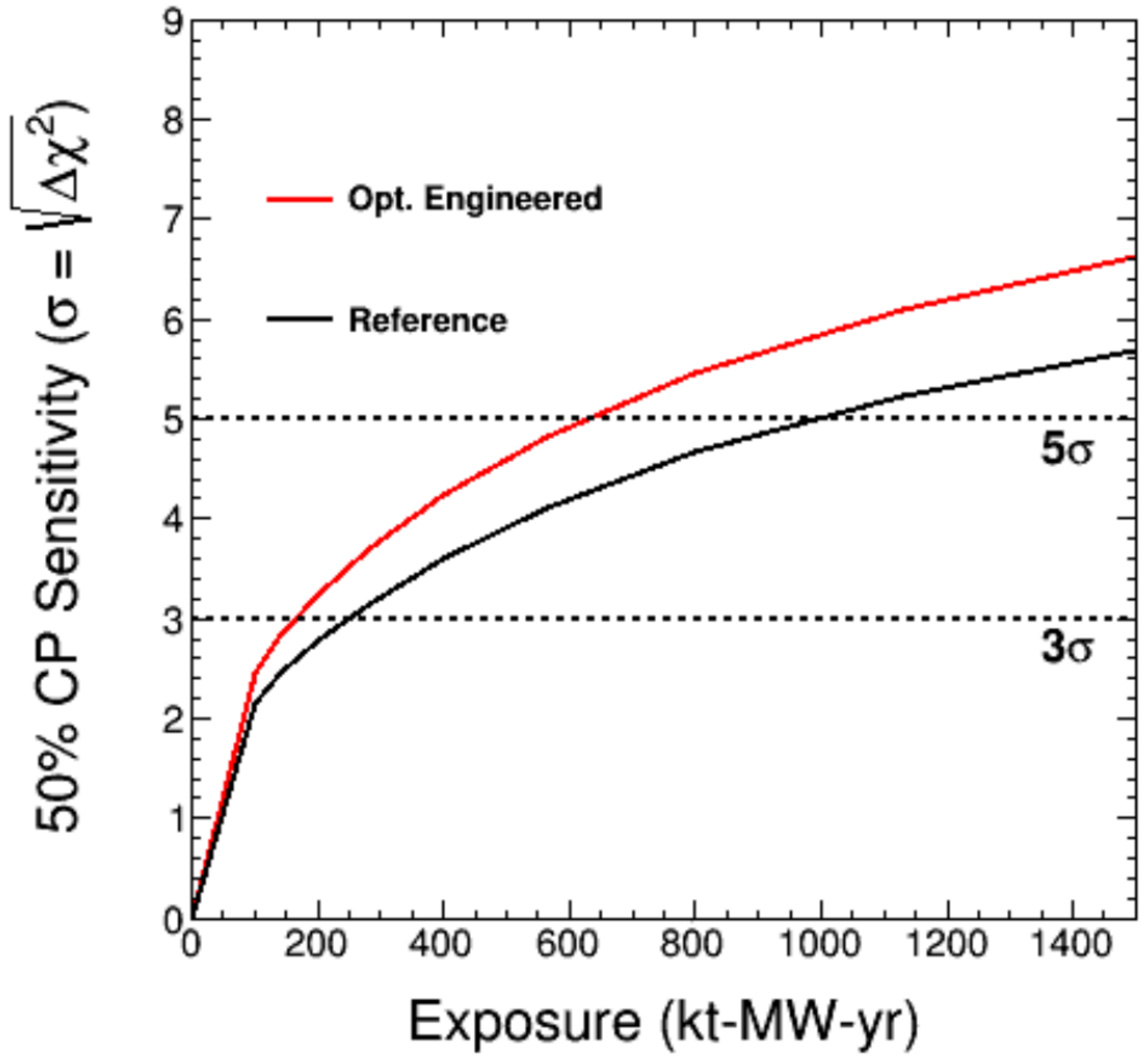
We can never know that it gave us the best possible design



Optimized Design

Three horns, not similar to NuMI, run at 300 kA

2.2 m long carbon target



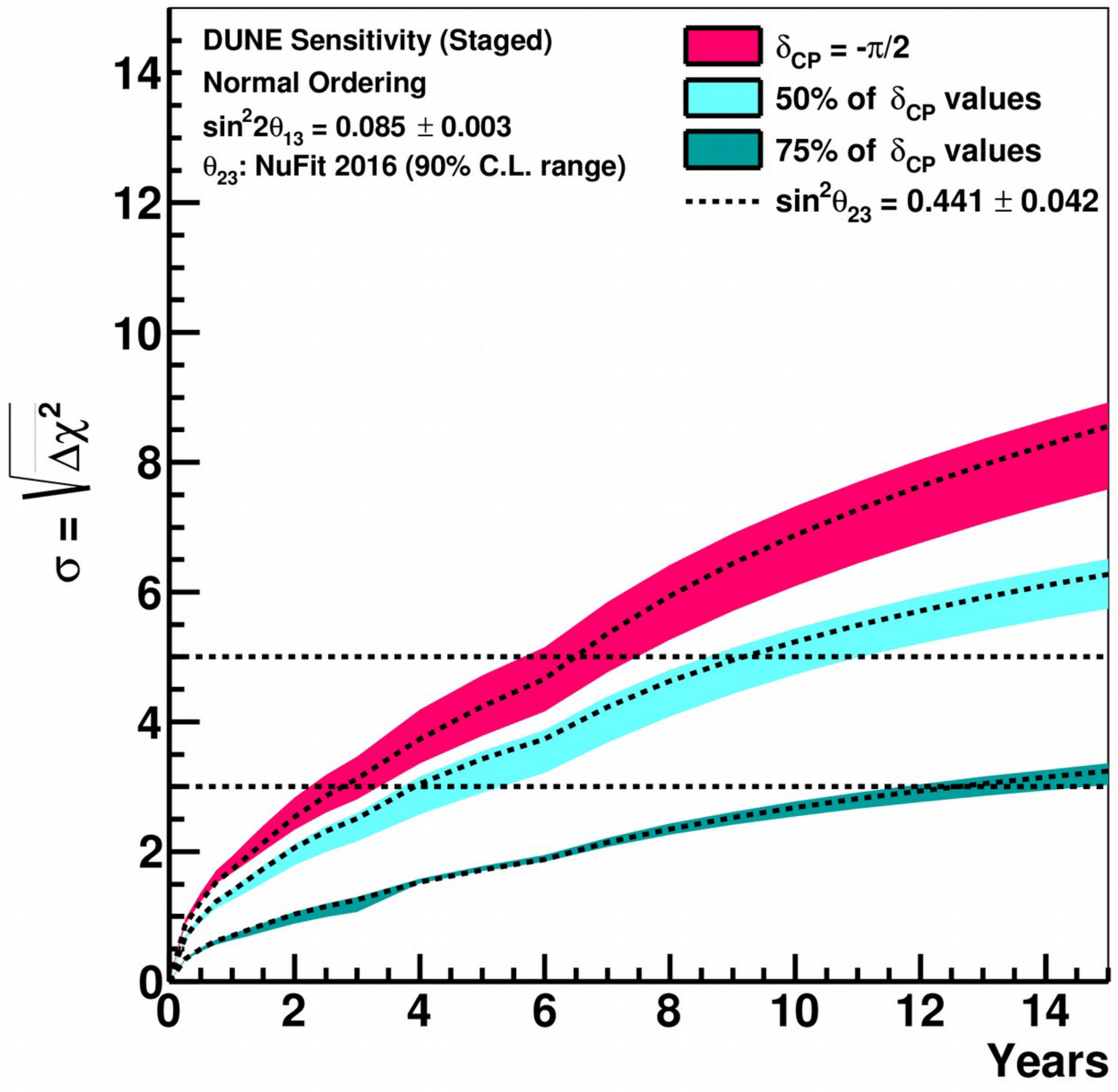
Heidi Schellman, ICHEP 2018

DUNE FD Staging Strategy

- Sensitivities assume DUNE FD staging strategy in table below

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

Significance of δ_{CP} measurement as a function of exposure



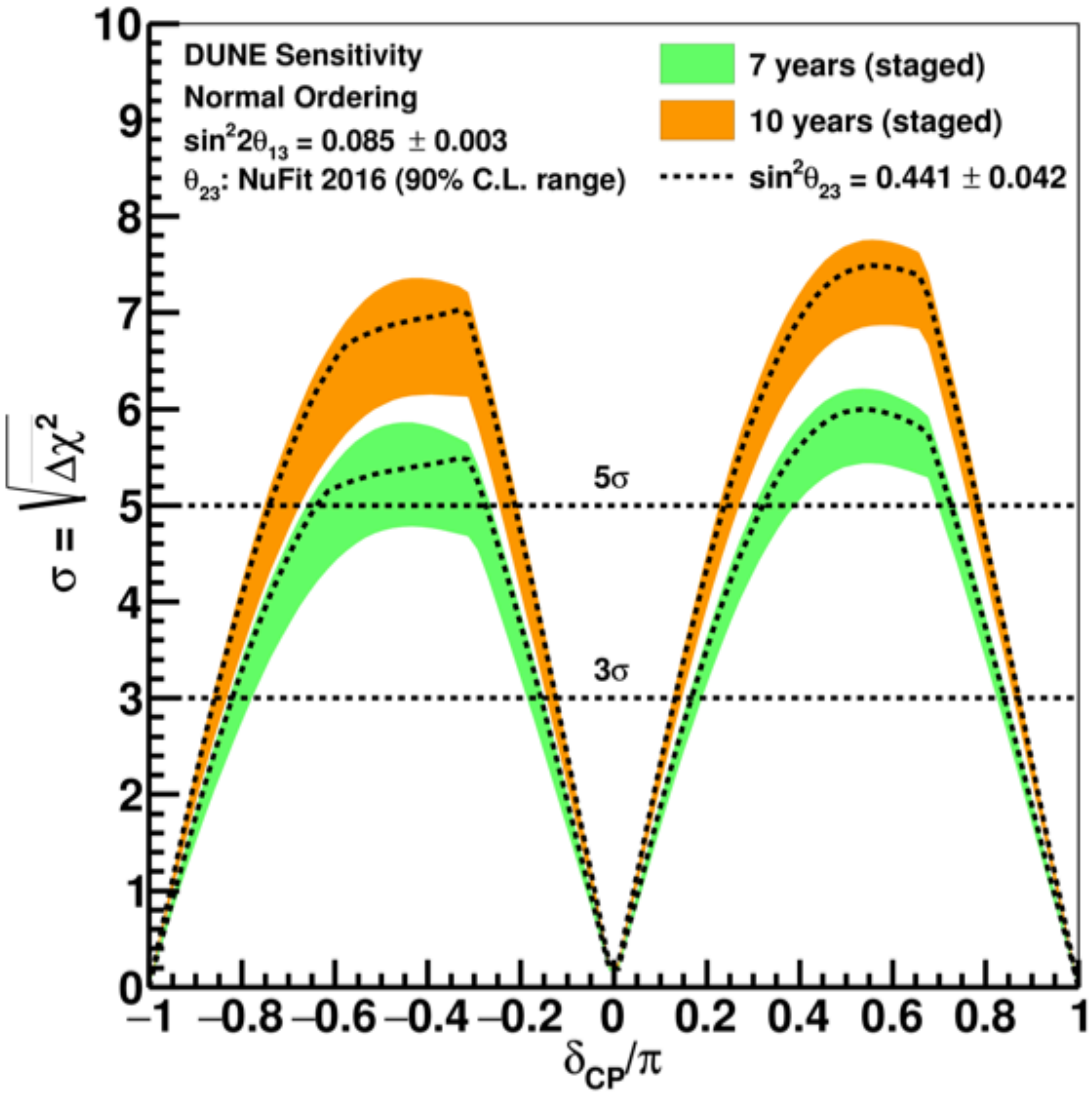
DUNE CDR Systematics

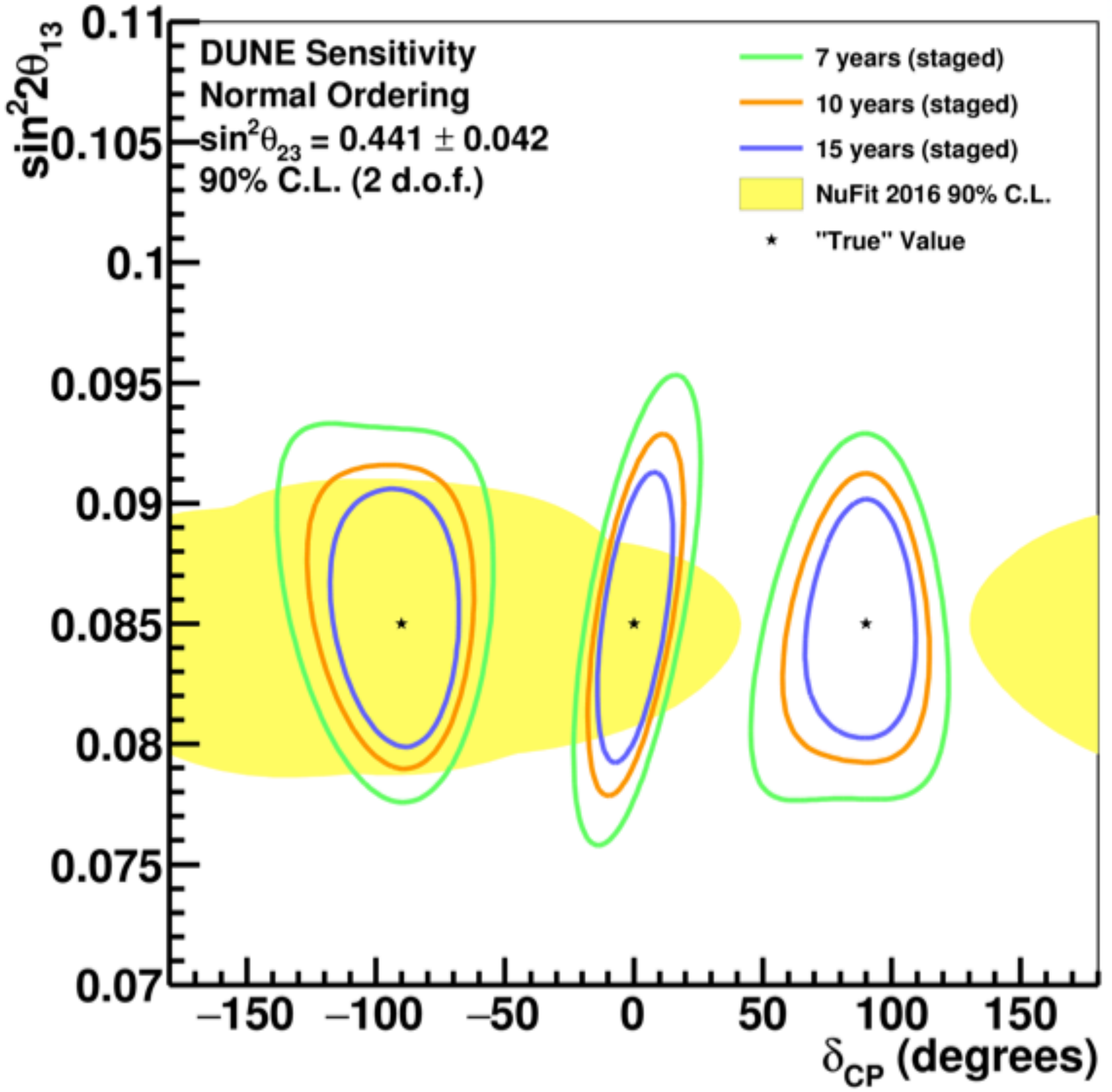
- Sensitivities in DUNE CDR are based on GLoBES calculations in which the effect of systematic uncertainty is approximated using signal and background normalization uncertainties
  - Spectral uncertainty not included in this treatment
- Signal normalization uncertainties are treated as uncorrelated among the modes (ν_e, $\bar{\nu}_e$, ν_μ, $\bar{\nu}_\mu$) and represent the residual uncertainty expected after constraints from the near detector and the four-sample fit are applied
  - $\nu_\mu = \bar{\nu}_\mu = 5\%$ → Flux uncertainty after ND constraint
  - $\nu_e = \bar{\nu}_e = 2\%$ → Residual uncertainty after ν_μ and $\nu/\bar{\nu}$ constraint
- Oscillation parameter central values and uncertainties are taken from NuFit 2016 (arXiv:1611.01514). Parameters are allowed to vary constrained by 1/6 of the ±3σ range in the global fit

Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e
Beam Flux after N/F extrapolation	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	$\sim 2\%$
Energy scale (ν_μ)	3.5%	included above	(2%)
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial volume	2.4%	1%	1%
Total	5.7%	6.8%	3.6 %
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$

CDR - Table 3.8

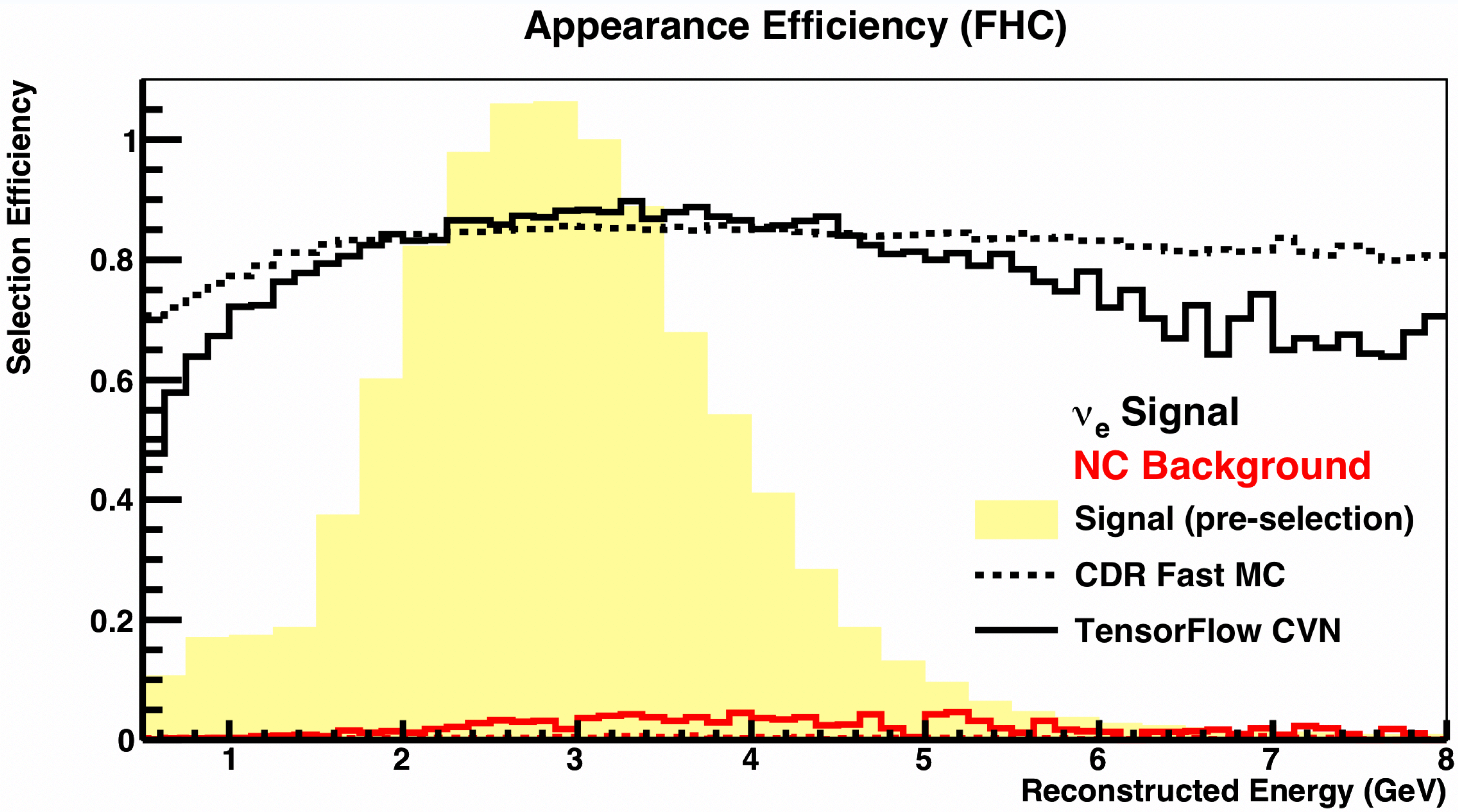
CP Violation Sensitivity





- Sensitivities for 7 and 10 year exposures (staged)
- Width of bands shows variation in central values of θ_{23}
- Sensitivities to simultaneous measurement of neutrino mixing angles and δ_{CP} for 7, 10, and 15-year exposures

New Monte Carlo Analysis

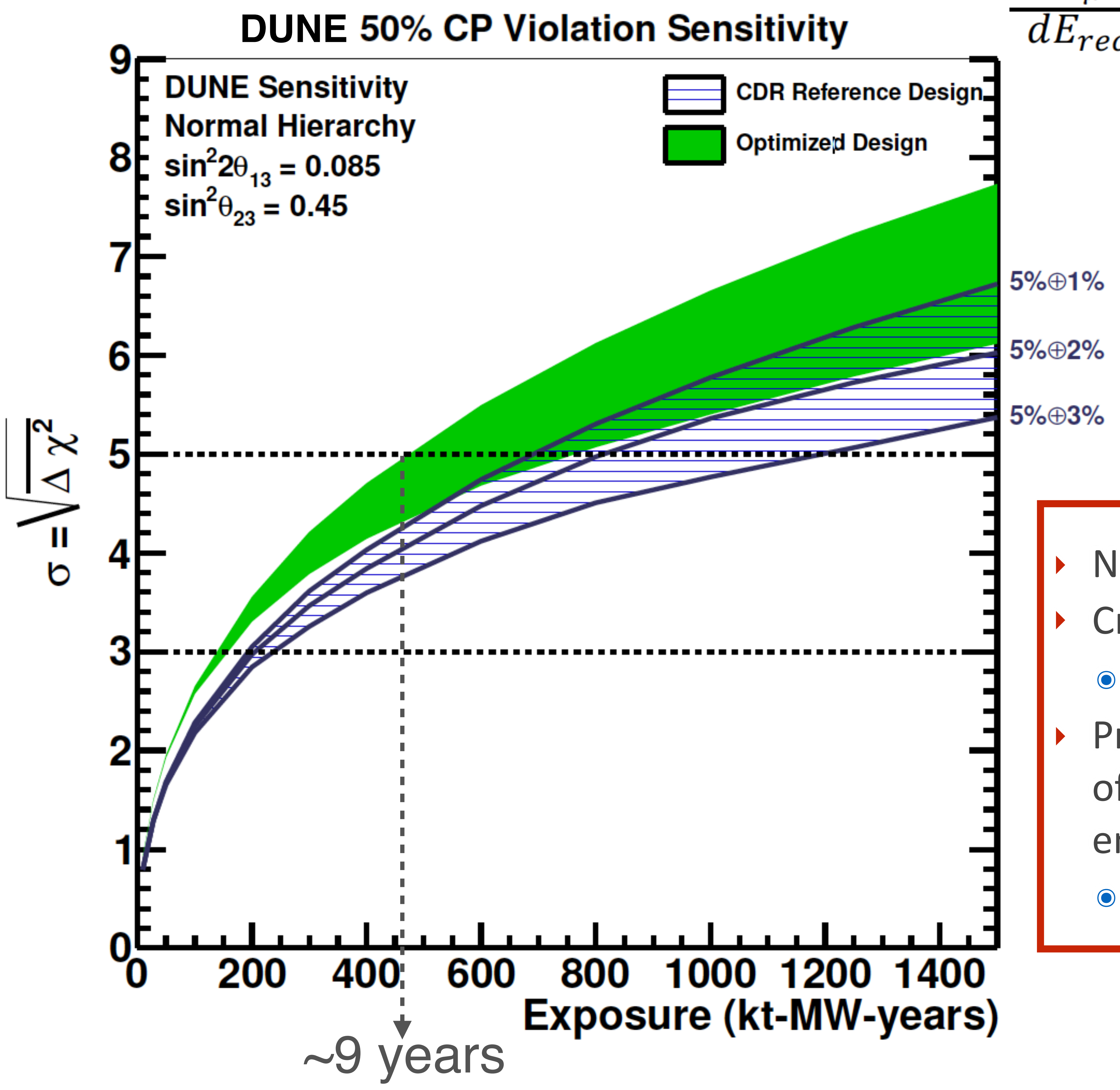


- CVN ν_e event selection efficiency similar to that from CDR Fast MC

Effect of Systematic Uncertainties

$\nu_\mu \rightarrow \nu_e$ osc. signal

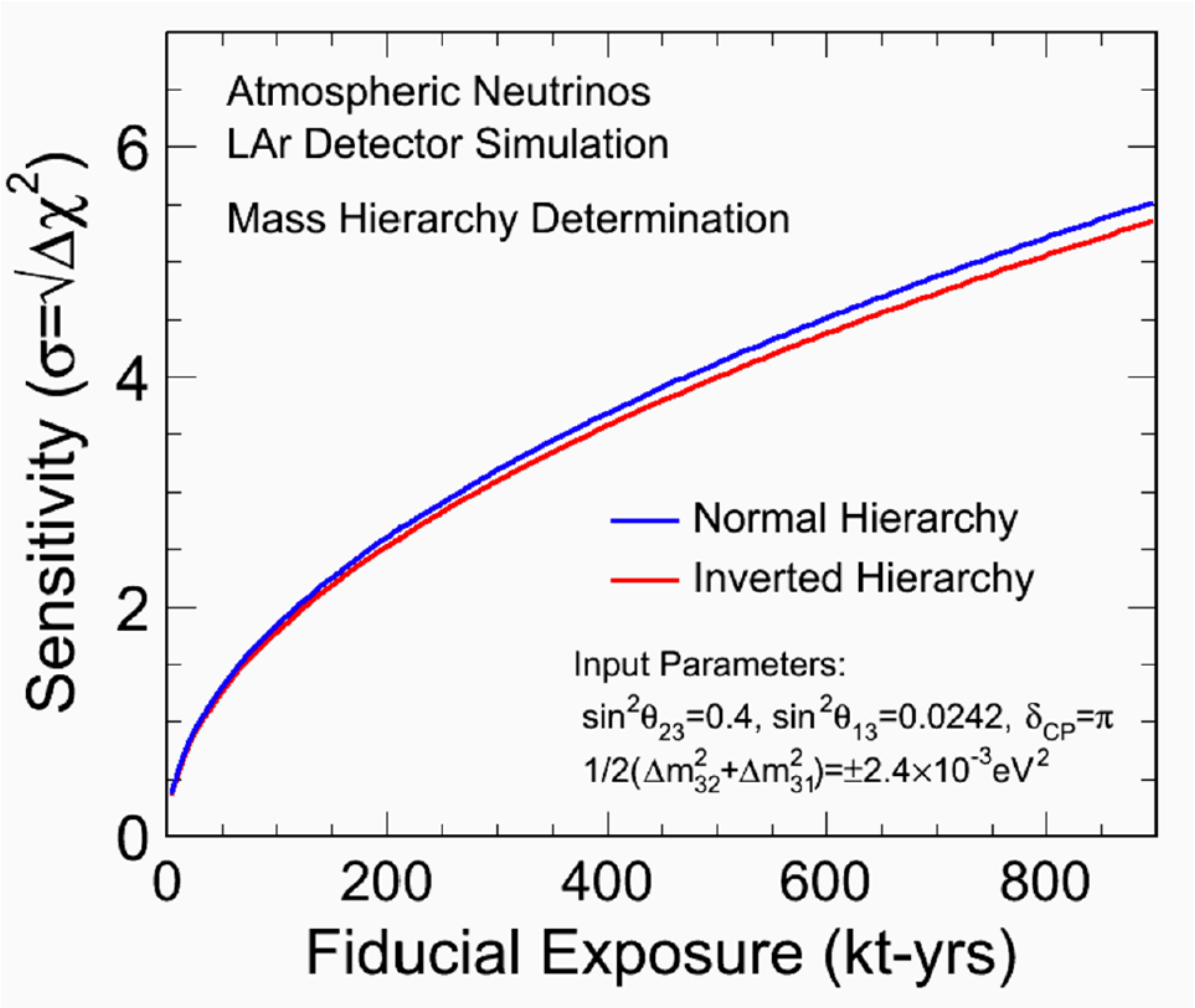
$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu\rightarrow\nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}(E_\nu) * D^{far}_{\nu_e}(E_\nu, E_{rec})\ dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}(E_\nu) * D^{near}_{\nu_\mu}(E_\nu, E_{rec})\ dE_\nu}$$



- Reduction of systematic uncertainties required for a short(er) timescale to reach future physics milestones
  - Note: As of 2017, NOvA and T2K reported 11% syst. errors on their sample bgs and 6-7% in signal

- Near Detector is essential
- Cross sections of ν_e,$\overline{\nu}_e$ measured in FD not directly cancelled by ND measurements of ν_μ,$\overline{\nu}_\mu$
  - Need better knowledge of ν_e,$\overline{\nu}_e$ cross sections and uncertainties on $\sigma(\nu_e)/\sigma(\nu_\mu)$ and $\sigma(\overline{\nu}_e)/\sigma(\overline{\nu}_\mu)$
- Precise understanding of absolute flux rate and shape necessary to disentangle convolution of hadron production and beam optics, cross sections, and detector effects to determine energy scale
  - Hadron production experiments, test beams, and detector R&D

Atmospheric Neutrinos



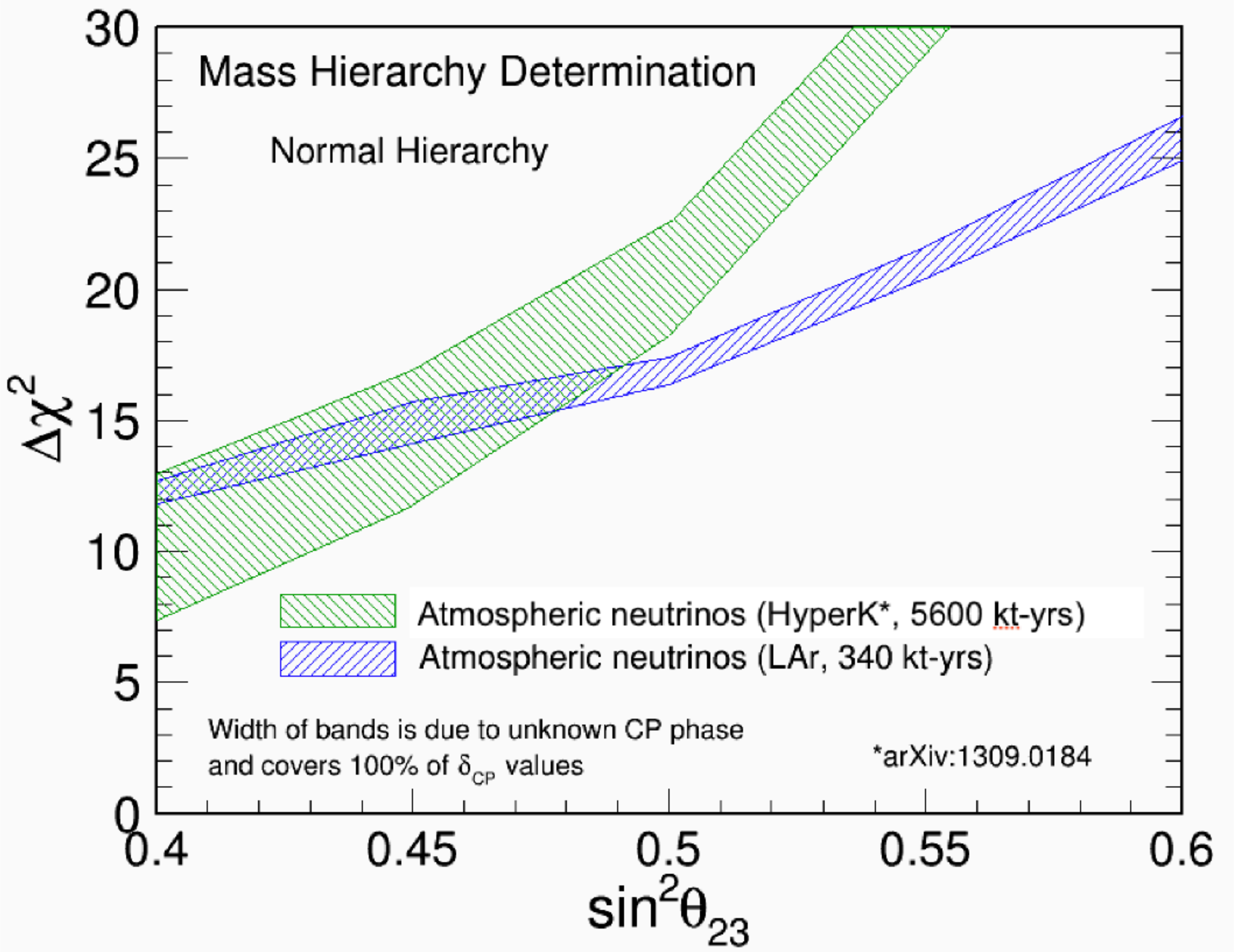


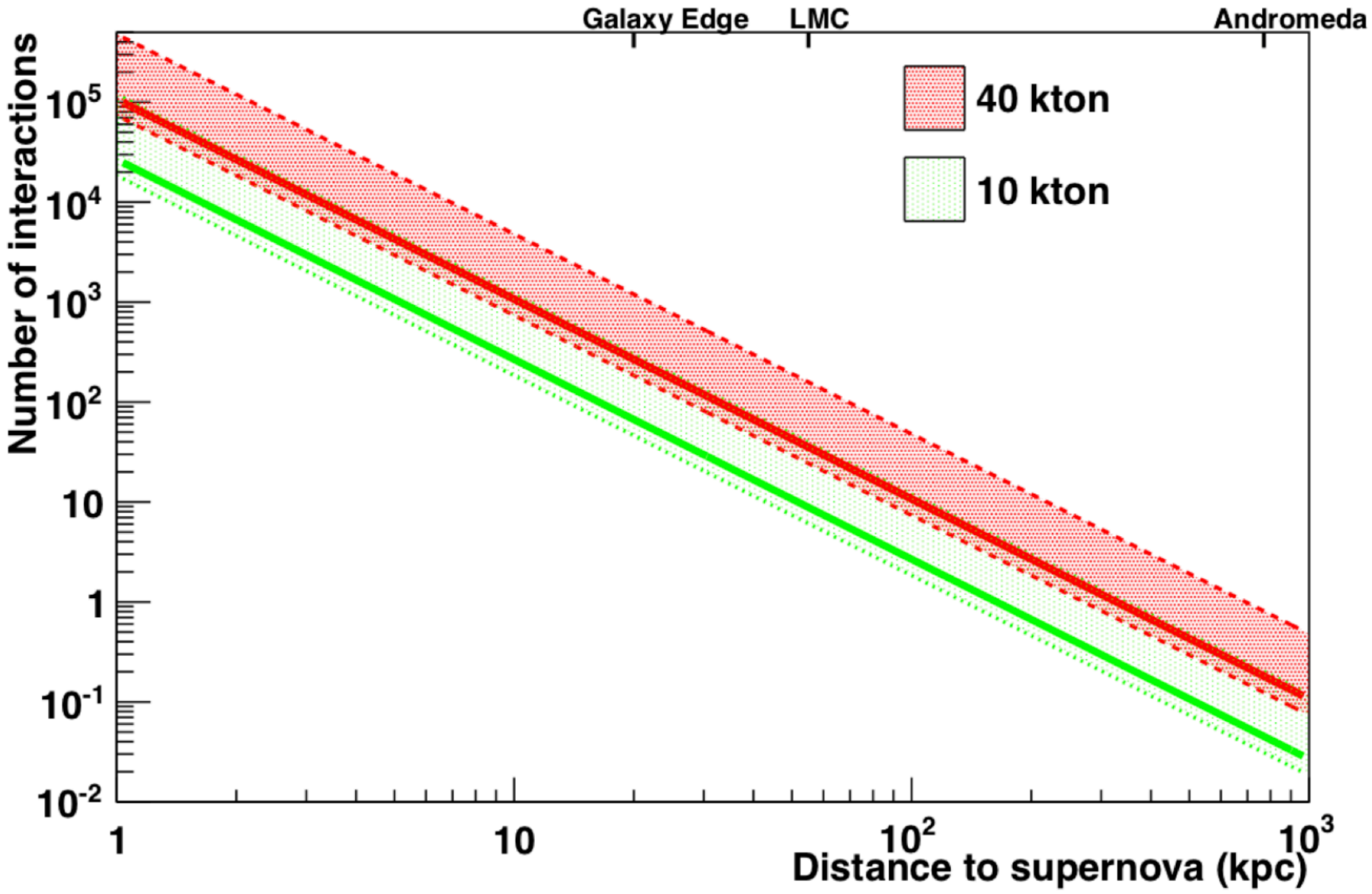
Figure 4.7: Sensitivity to mass hierarchy using atmospheric neutrinos as a function of fiducial exposure in a liquid argon detector (left), and as a function of the true value of θ_{23} (right). For comparison, Hyper-K sensitivities are also shown [104].

Supernova Neutrino Rates

- 10 kton: one DUNE module
- 40 kton: entire DUNE detector
- Error bands: range of flux models
- Places of interest:

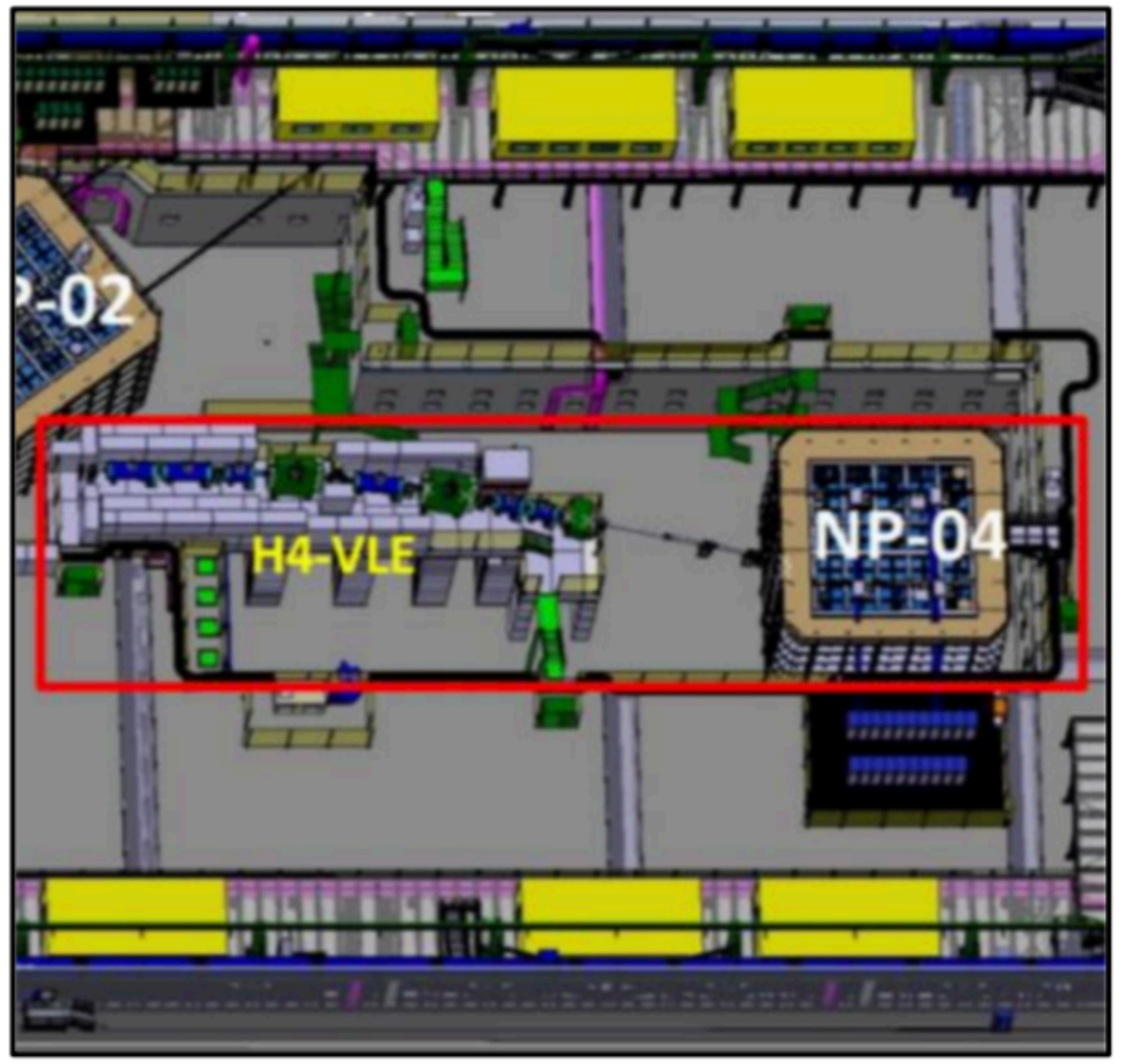
Distance from Earth (kpc)	# CC events	# NC events	# ES events
10	3000	100	310
50 (LMC)	120	4	12
770 (Andromeda)	0.5	0.02	0.05

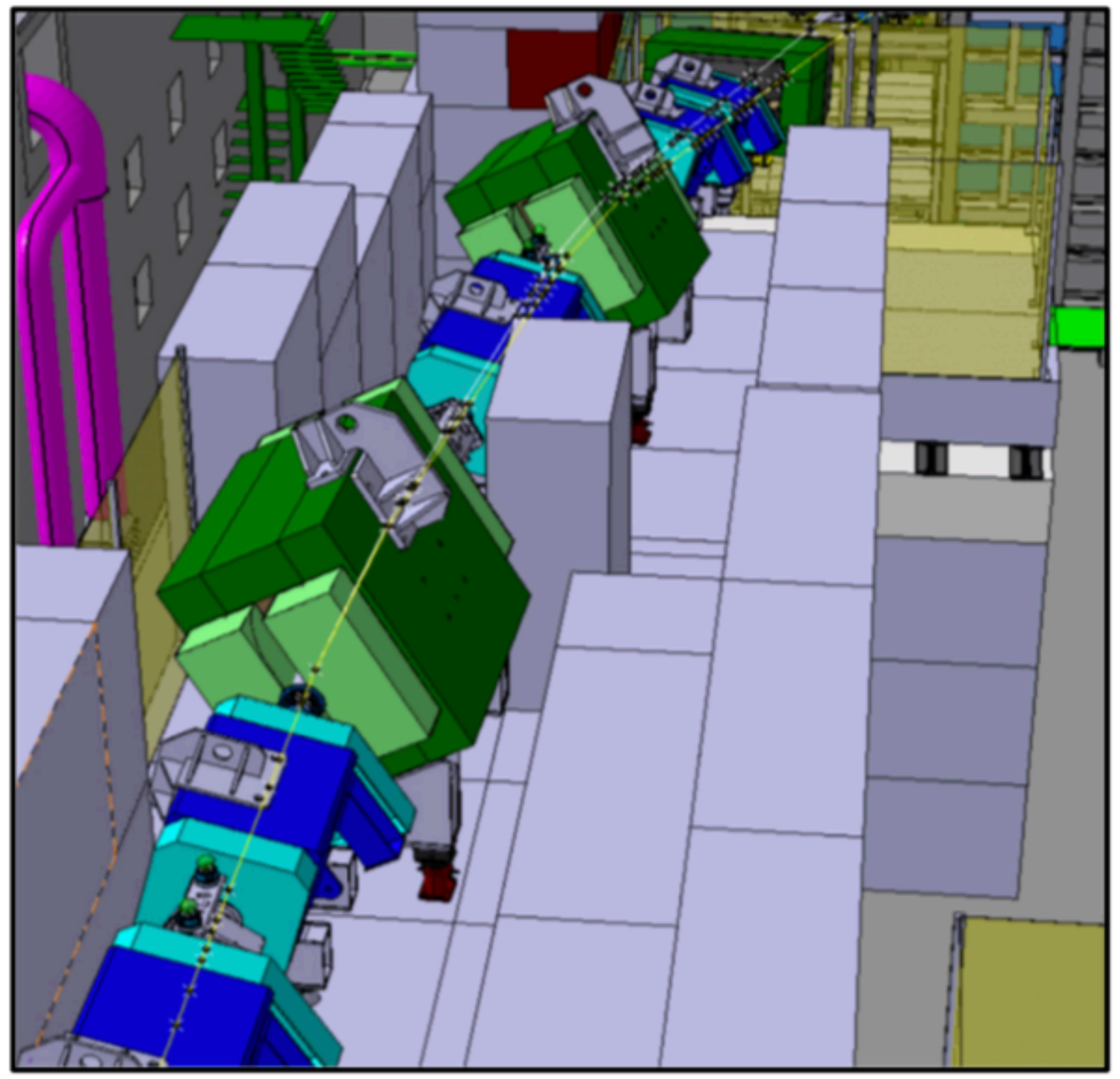
Number of interactions expected to be seen in DUNE detector

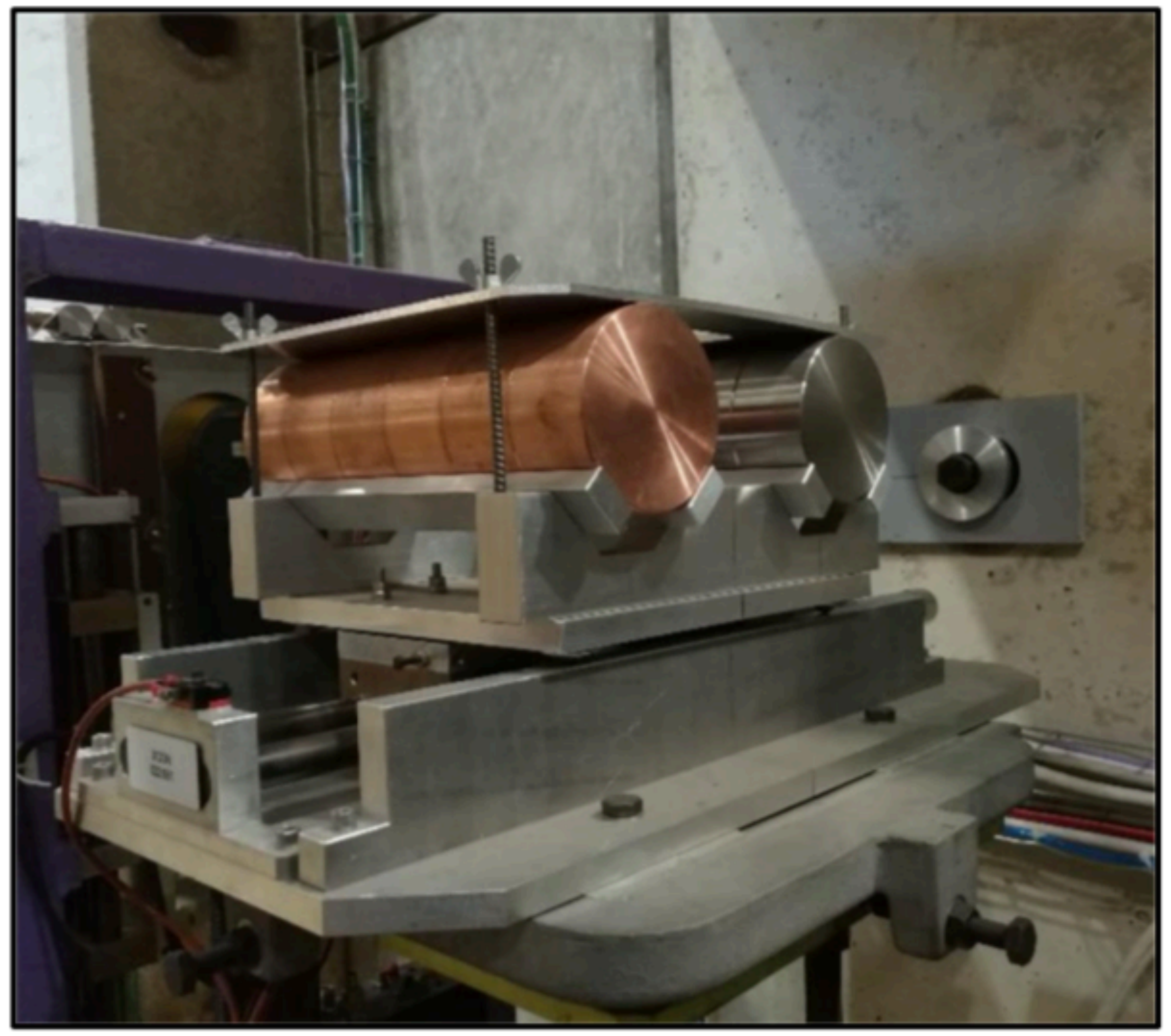


protoDUNE - Beamline Instrumentation

- PHYS. REV. ACCEL. BEAMS **20**, 111001 (2017)
- 2 secondary targets
  - W for lower momenta (0-3 GeV/c)
  - Cu for higher momenta (4-7 GeV/c)
- 3 dipoles for bending and momentum selection
- Quadruples for focusing the beam
- Collimator for increasing the momentum resolution
- 3 scintillators for trigger
  - 2 for TOF
- 8 beam profilers (scintillating fibers)
  - 5 profile the X (drift) coordinate
  - 3 profile the Y (vertical) coordinate
- 2 Cherenkov detectors for particle tagging (along with TOF)







Dual-Phase LArTPC

THE DUAL-PHASE CONCEPT

Lar TPC: Basic technique established → Technical Challenges towards very long drifts and very massive detectors
- **Long drifts requires ultra high purity → charge attenuation along the drift path**
- **No charge amplification in single phase**
  → Compensate the effect with charge multiplication at the anode

Charge Collection on anode readout (2 orthogonal views) **(no induction plane)**

↑

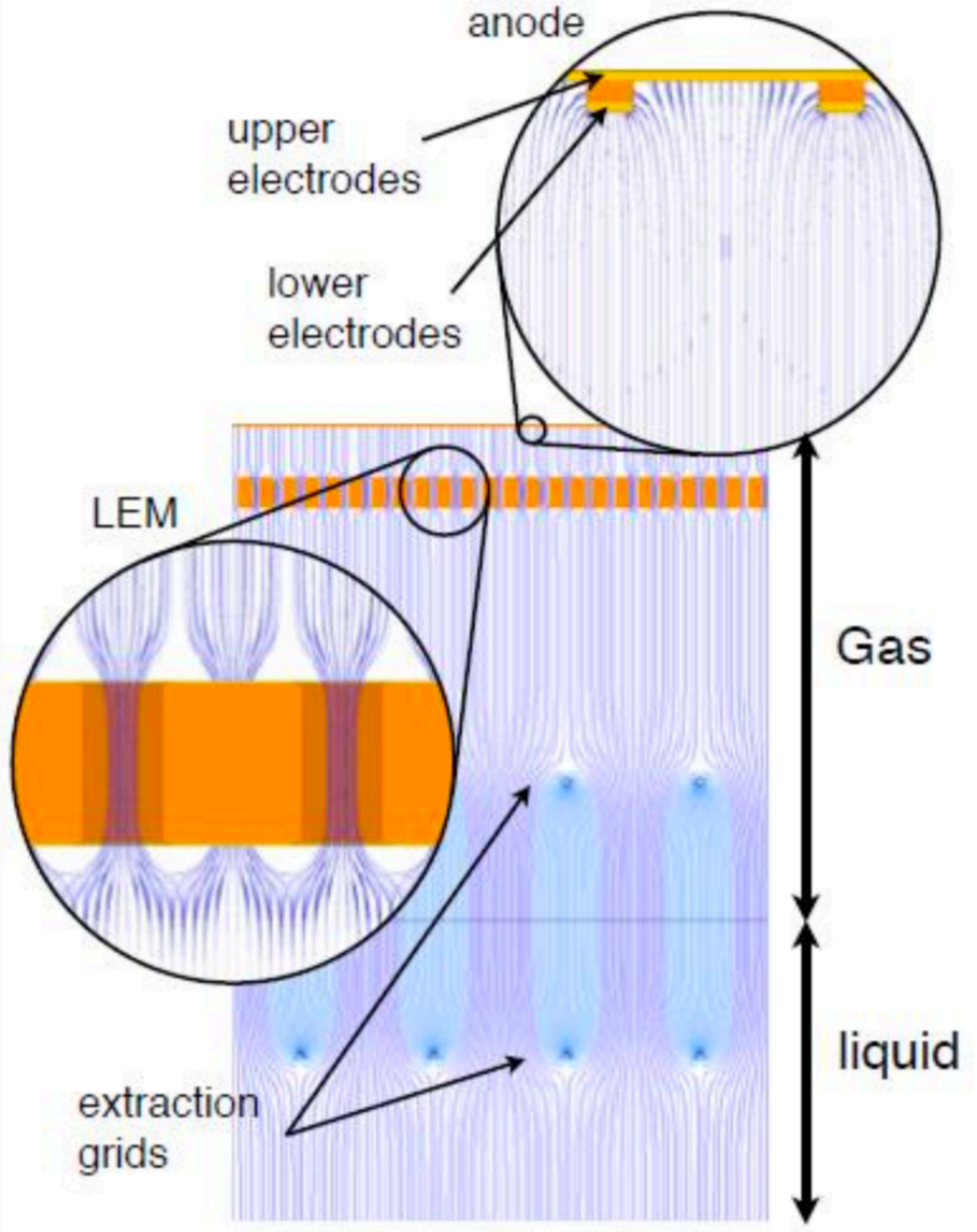
Charge multiplication: LEM – Large Electron Multipliers

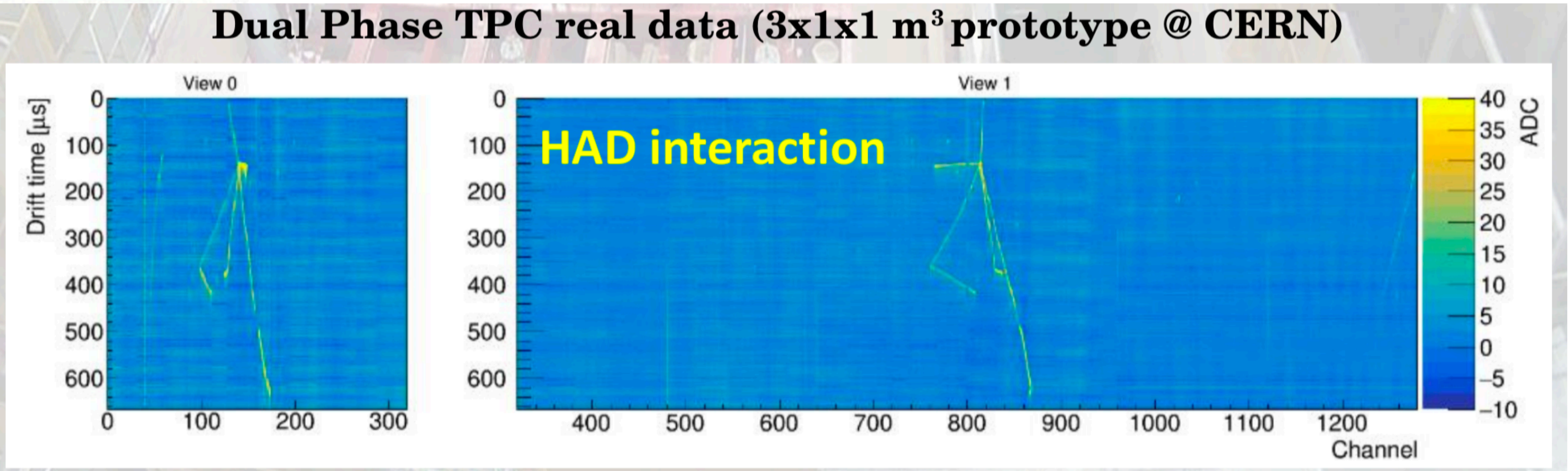
↑

Electrons extraction from liquid to gas phase through a grid

↑

Ionization electrons drift towards the liquid argon surface





Global Three-Flavor Fit Table

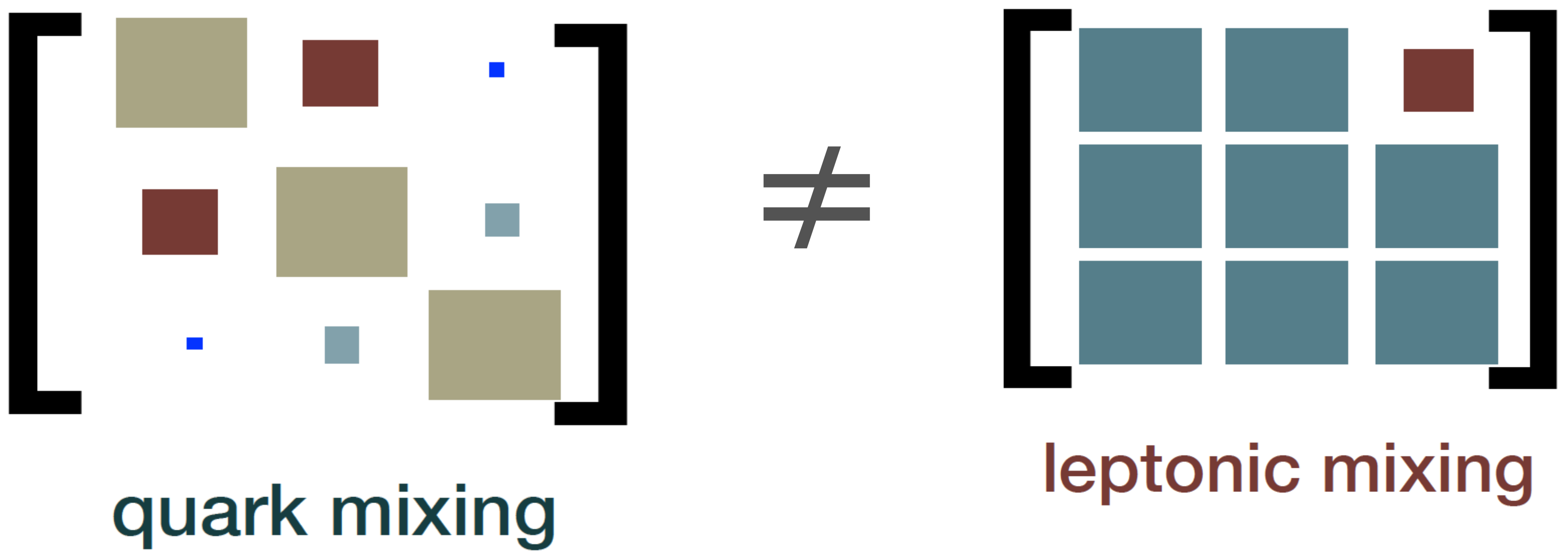
Esteban et al., JHEP 01 (2017) NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix}+2.399 \to +2.593 \\ -2.536 \to -2.395\end{bmatrix}$

- Inverted mass ordering disfavored at 2σ level
- δ_{CP}=1.3π at best fit
- CP-conserving cases (0, π) disfavored at ~2σ level
- Large portion of δ_{CP} parameter space disfavored at >3σ
- Consistent with maximal mixing and maximal disappearance
- θ_{13} is mixing angle measured with highest precision

Mass Ordering, δ_{CP}, and maximality of θ_{23}

- Why do we want to answer these questions?
- sin δ_{CP} determines the size of CP violation in the lepton sector
  - May explain matter-antimatter asymmetry through ***Leptogenesis***
  - Measuring δ_{CP} precisely is needed to understand structure of PMNS matrix and underlying symmetries
- Mass Ordering is a good model discriminator
  - Important to understand if neutrinos are Majorana or Dirac particles
- $\theta_{23}=45°$ could be a hint for a not yet understood symmetry
  - Precision measurements of θ_{23} needed to test PMNS unitarity and for model building



Reference		Hierarchy
Anarchy Model:		
dGM	[18]	Either
$L_e - L_\mu - L_\tau$ Models:		
BM	[35]	Inverted
BCM	[36]	Inverted
GMN1	[37]	Inverted
GL	[38]	Inverted
PR	[39]	Inverted
S_3 and S_4 Models:		
CFM	[40]	Normal
HLM	[41]	Normal
		Normal
KMM	[42]	Inverted
MN	[43]	Normal
MNY	[44]	Normal
MPR	[45]	Normal
RS	[46]	Inverted
		Normal
TY	[47]	Inverted
T	[48]	Normal
A_4 Tetrahedral Models:		
ABGMP	[49]	Normal
AKKL	[50]	Normal
Ma	[51]	Normal
SO(3) Models:		
M	[52]	Normal
Texture Zero Models:		
CPP	[53]	Normal
		Inverted
		Inverted
WY	[54]	Either
		Either
		Either

Albright, Chen, PRD 74, 113006 (2006)