DUNE: Overview

Sungbin Oh, on behalf of the DUNE collaboration
Fermi National Accelerator Laboratory

57th Fermilab Users Meeting
10 July, 2024

U.S. DEPARTMENT OF ENERGY | Office of Science
Fermilab
DUNE

The Universe and the DUNE Science

- Understanding the universe?

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution

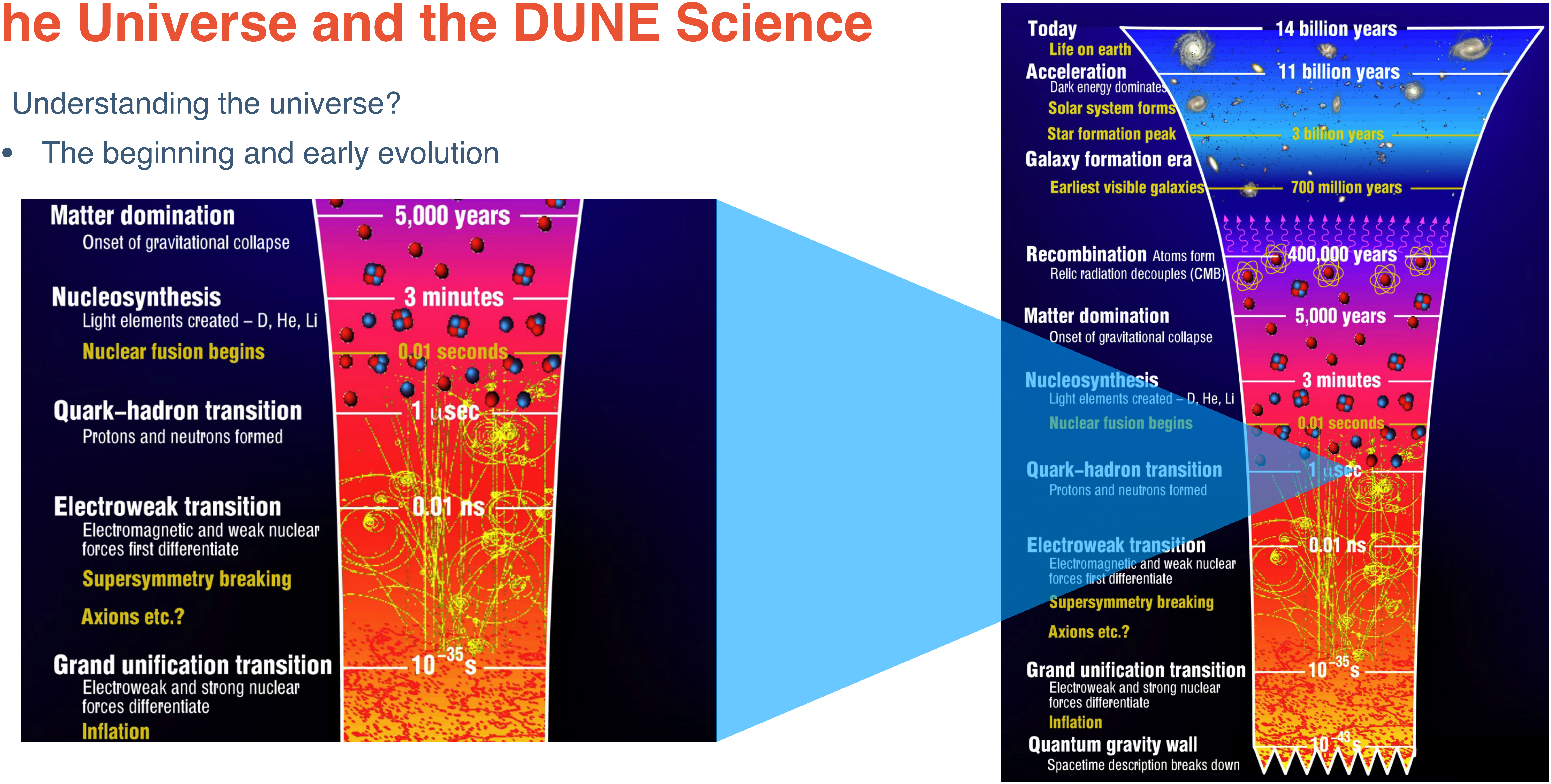
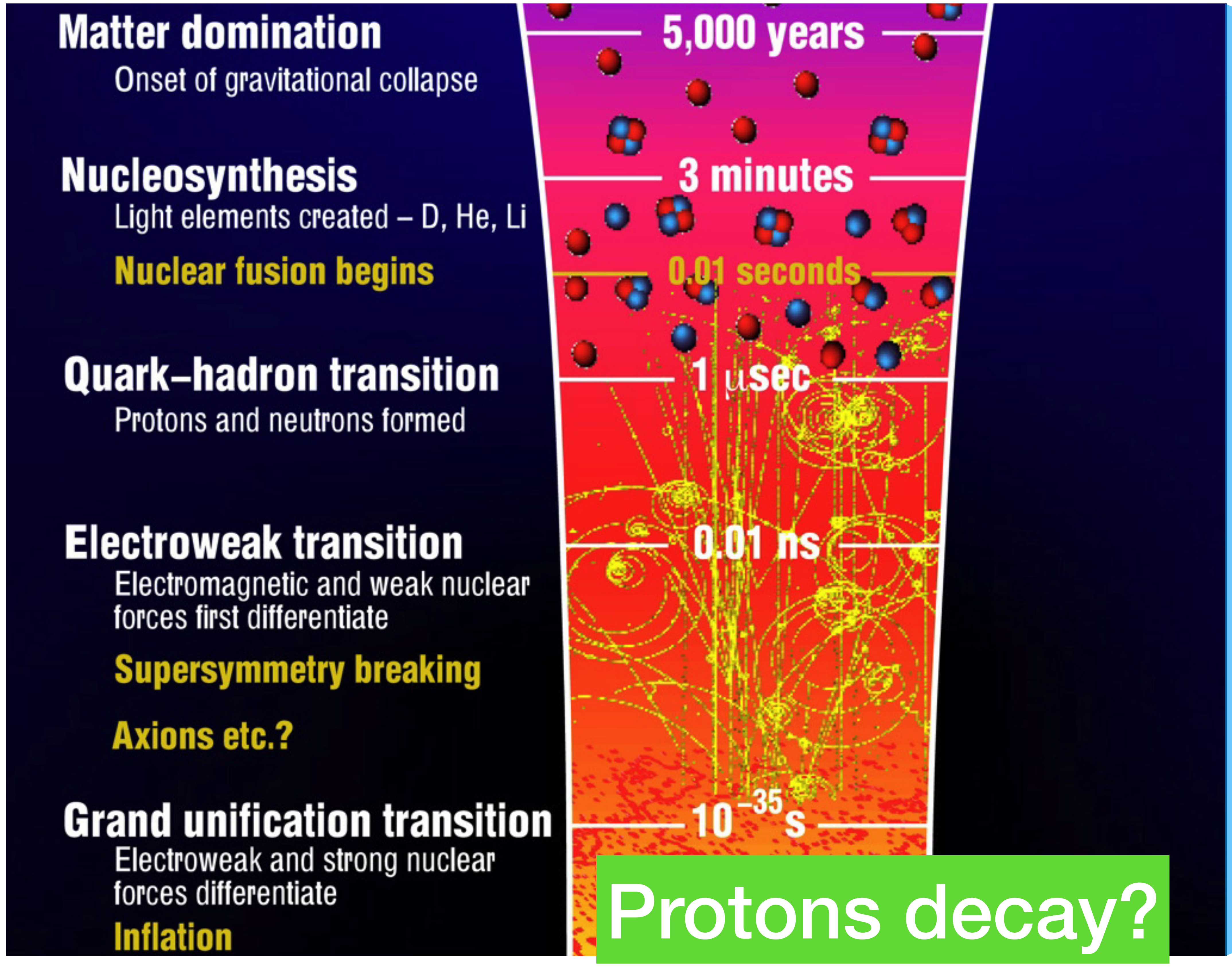


Image by The Stephen Hawking Centre for Theoretical Cosmology

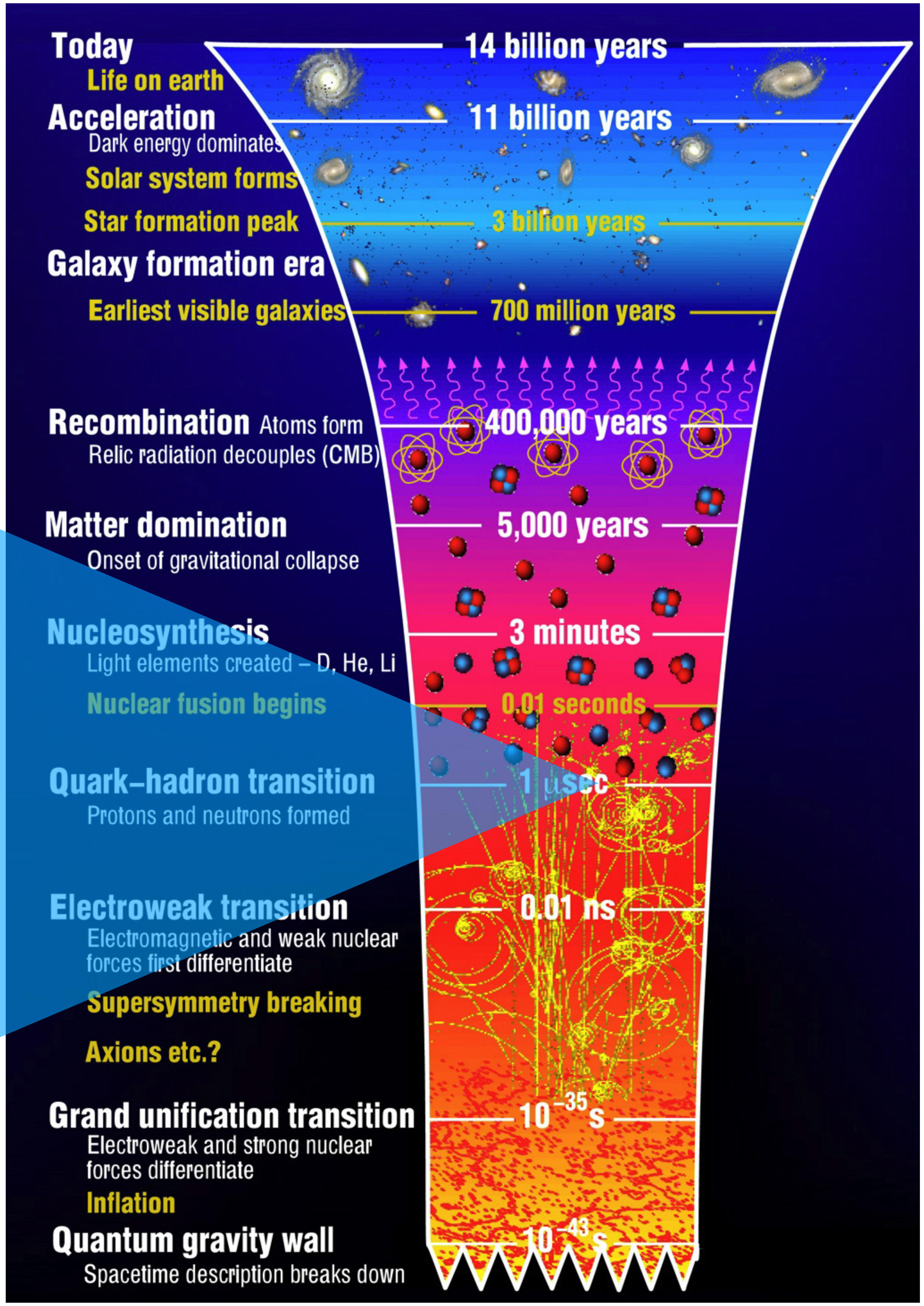
The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution



Protons decay?

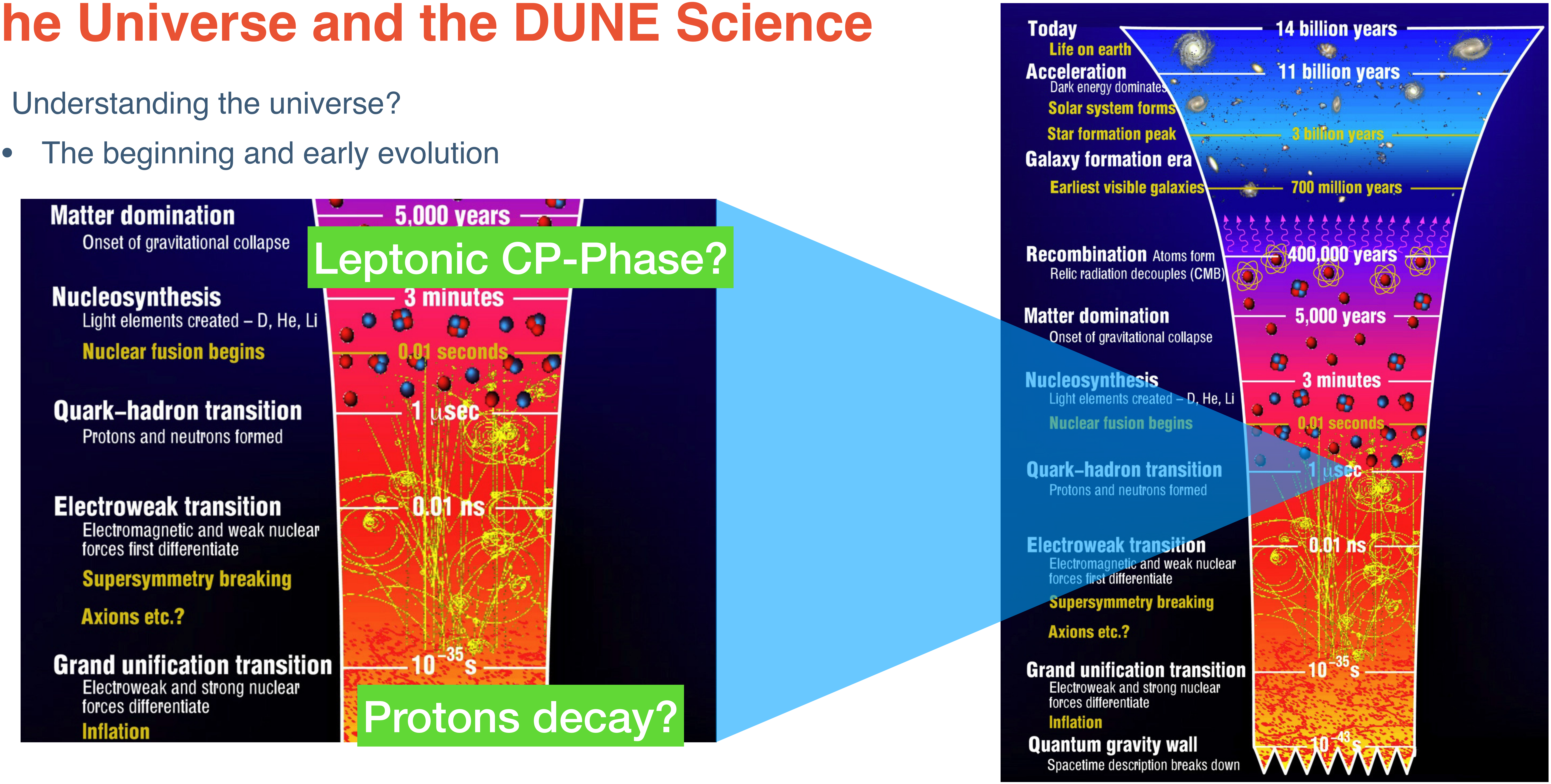
Image by The Stephen Hawking Centre for Theoretical Cosmology



The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution

Image by The Stephen Hawking Centre for Theoretical Cosmology



Leptonic CP-Phase?

Protons decay?

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution

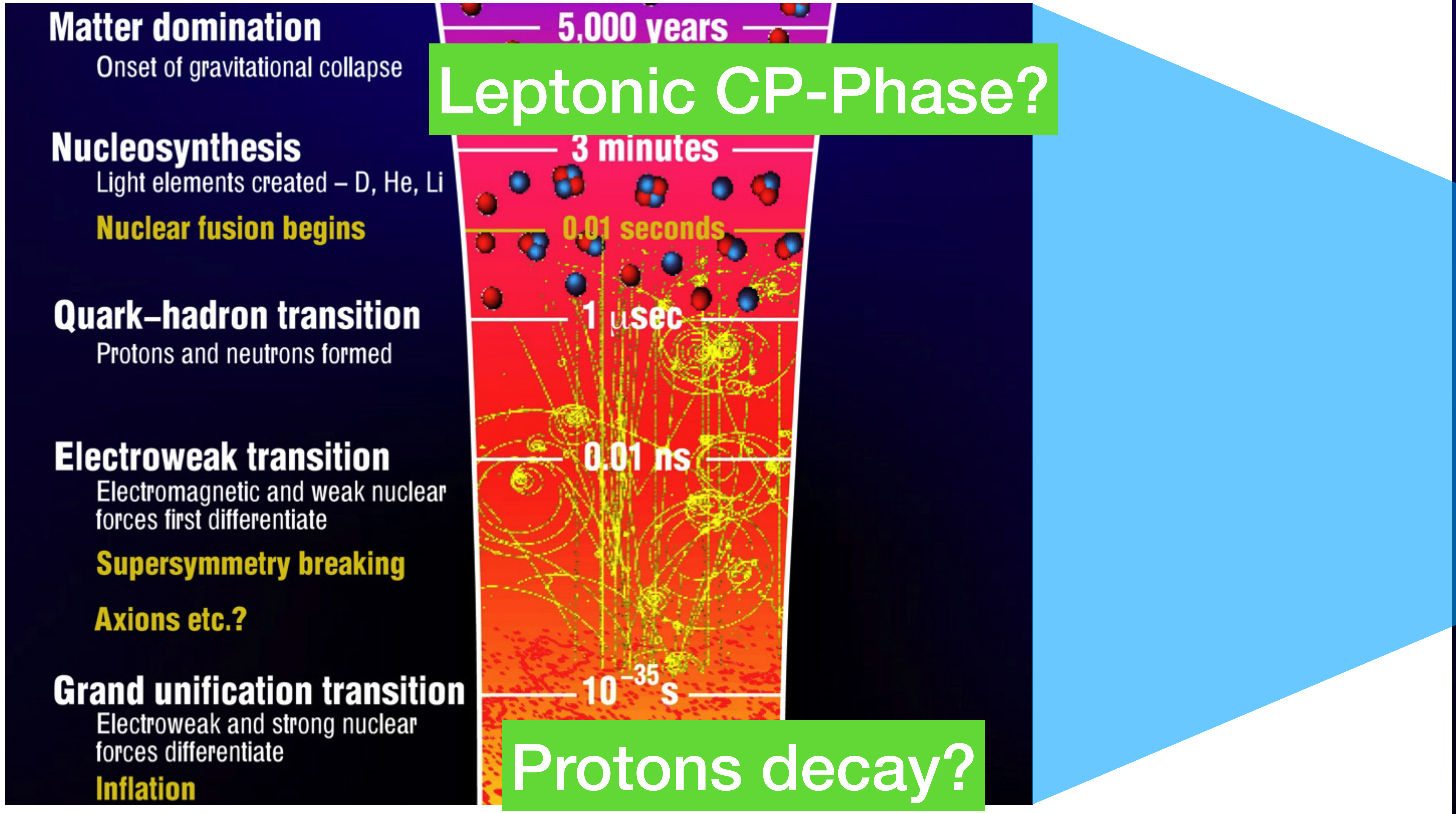
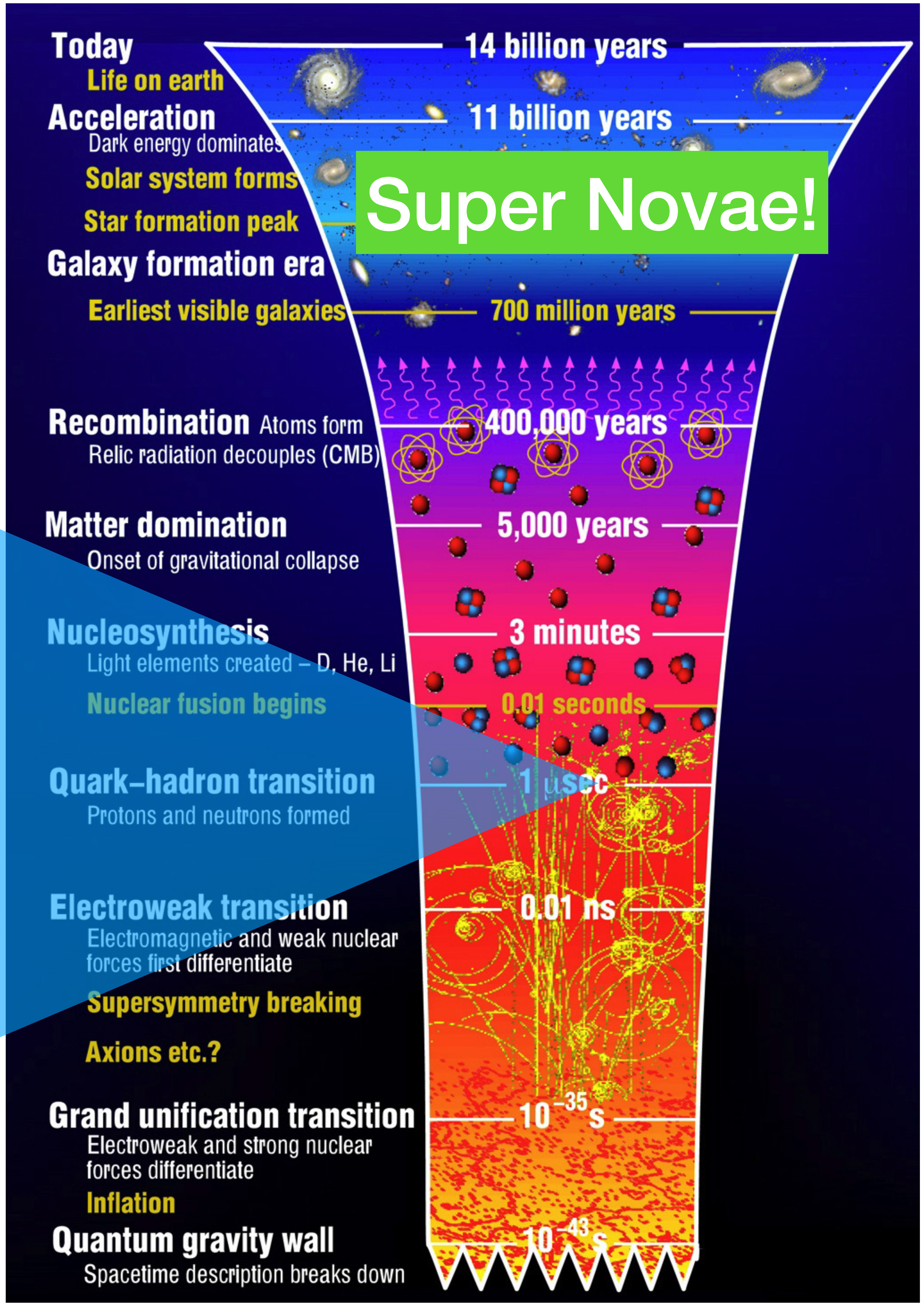
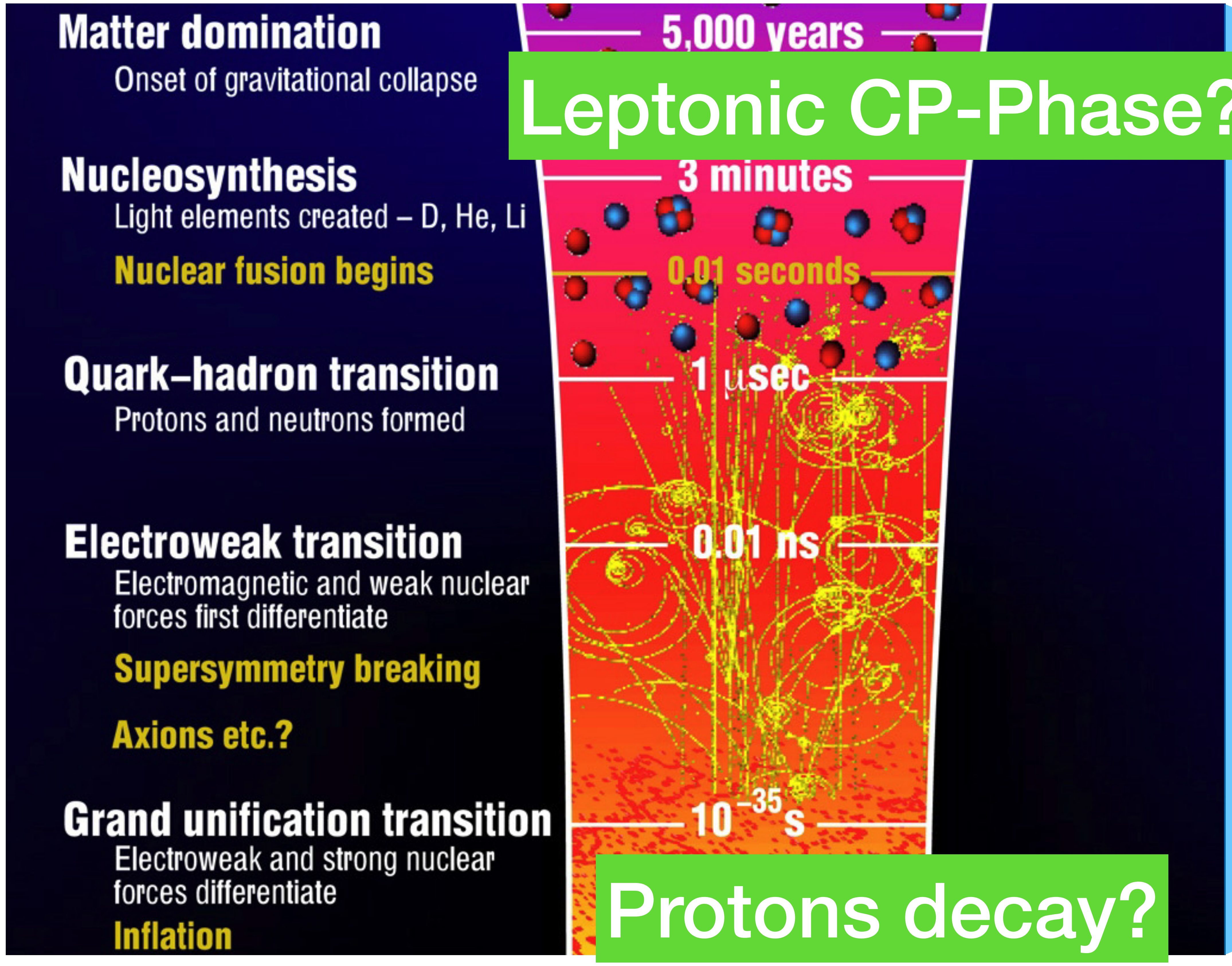


Image by The Stephen Hawking Centre for Theoretical Cosmology



The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution



Leptonic CP-Phase?

Protons decay?

Image by The Stephen Hawking Centre for Theoretical Cosmology

Super Novae!

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution
  - Current state : ingredients and their properties/interactions

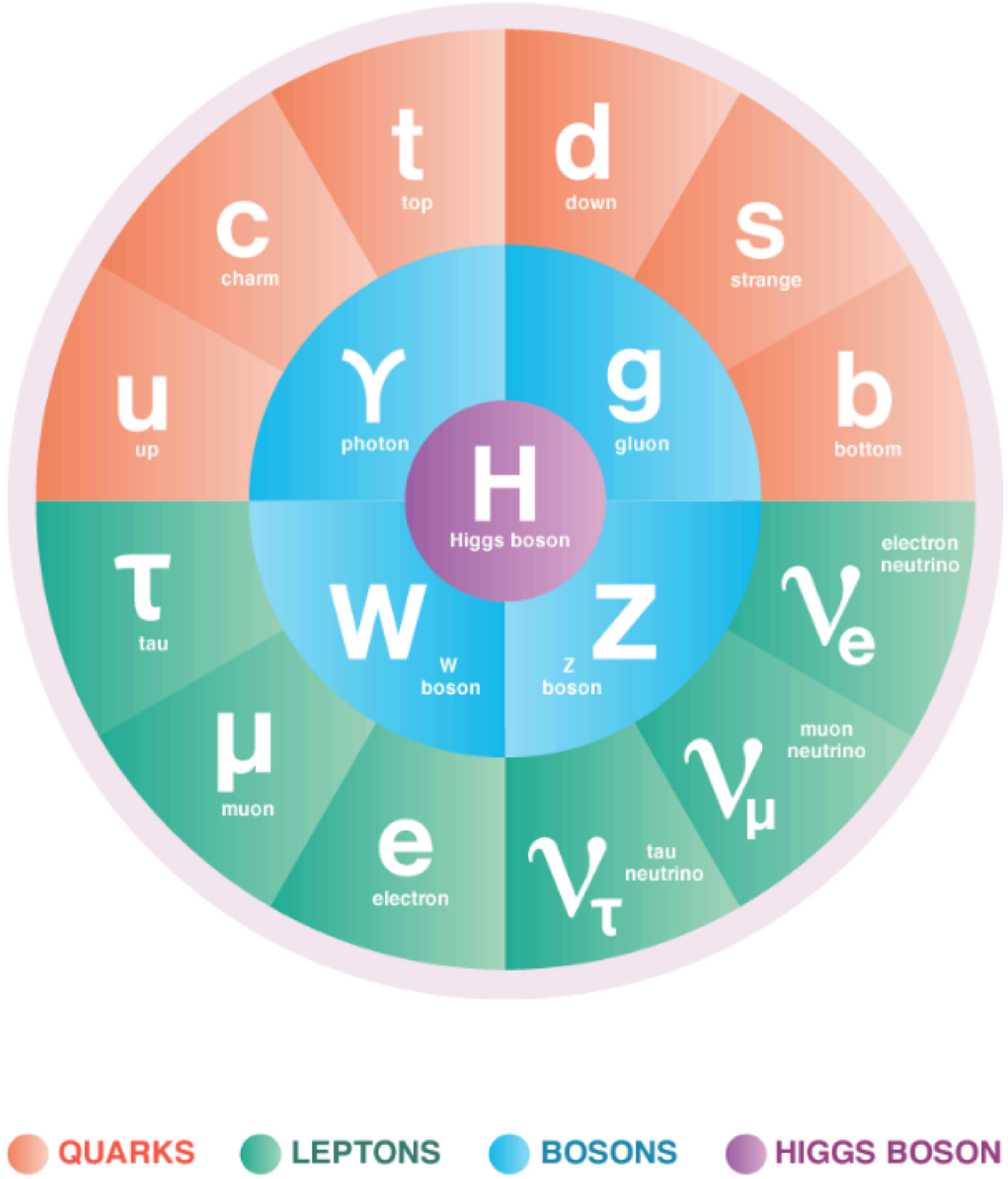
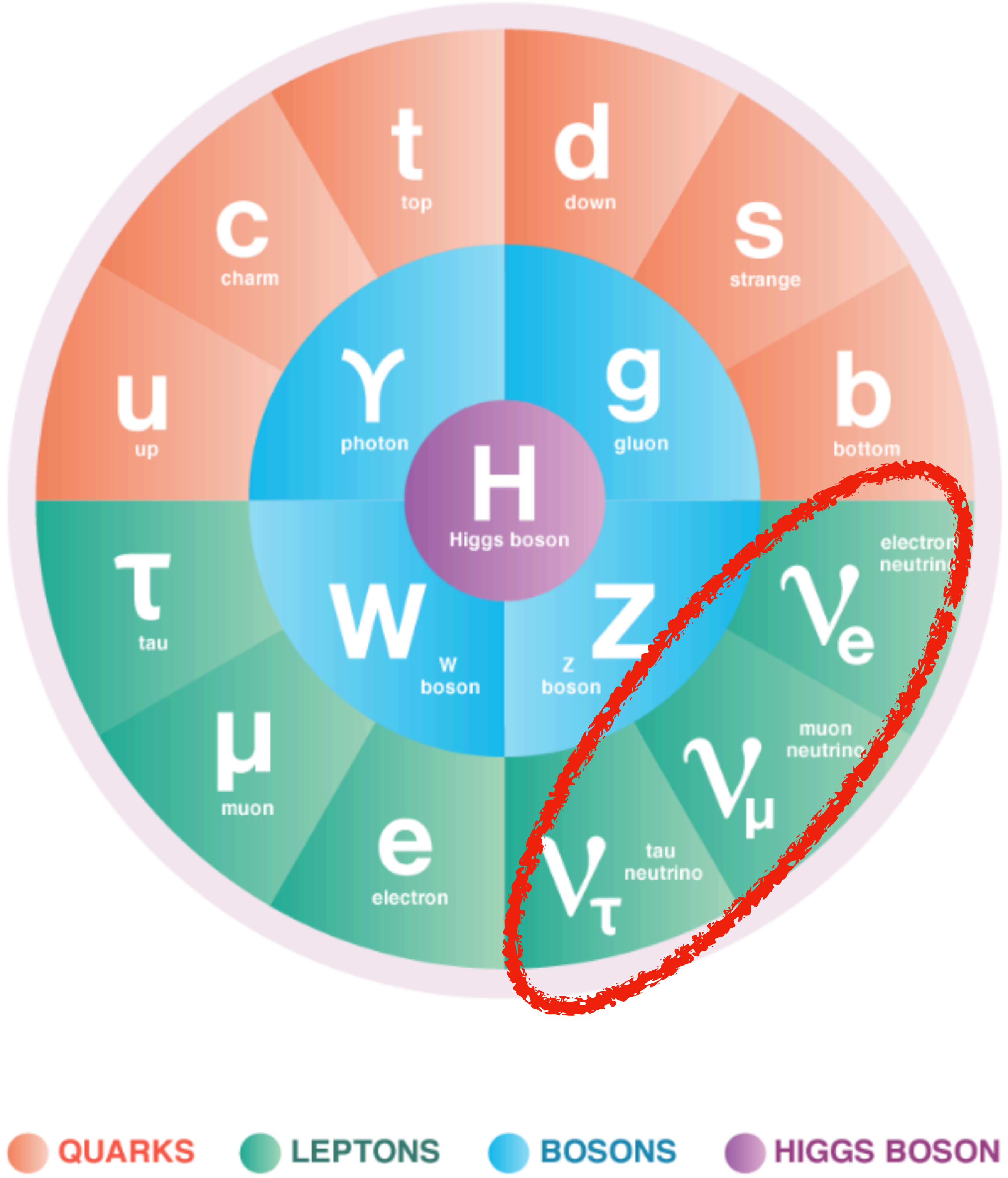


Image by Symmetry Magazine

+ beyond?

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution
  - Current state : ingredients and their properties/interactions



+ beyond?

Image by Symmetry Magazine

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution
  - Current state : ingredients and their properties/interactions

Neutrinos oscillate

Known	Known - Better precision with DUNE	Unknown - DUNE's goal	Unknown - Future Experiments

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution
  - Current state : ingredients and their properties/interactions

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\text{PMNS}\\ \text{matrix}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Flavor
(Interaction)

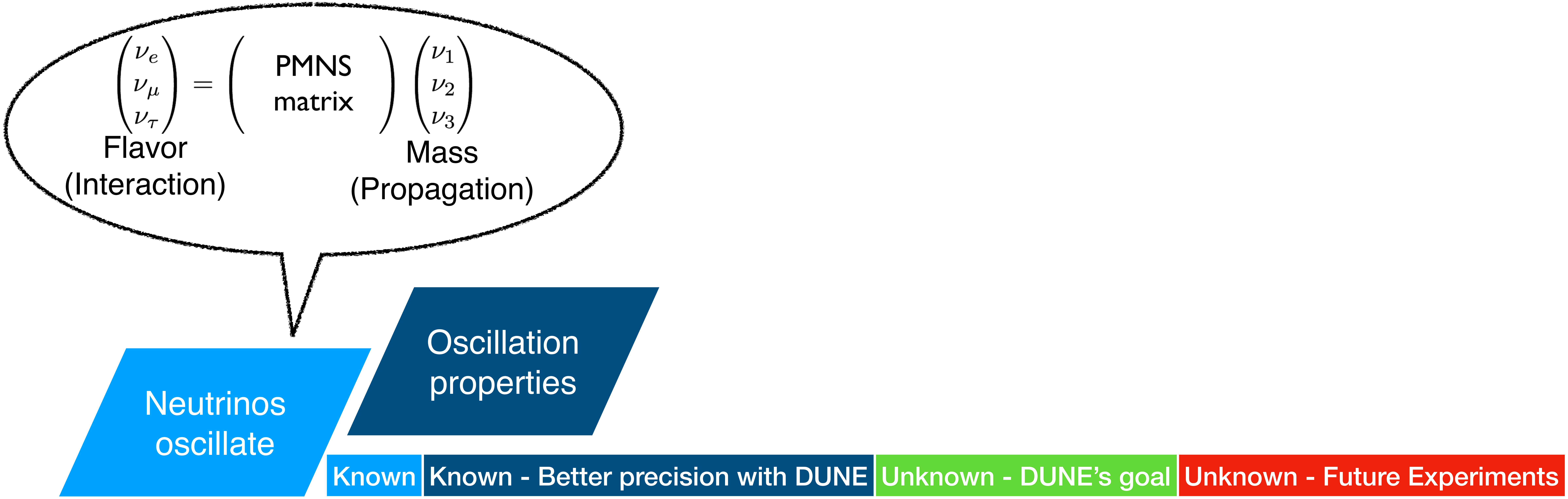
Mass
(Propagation)

Neutrinos oscillate

Known | Known - Better precision with DUNE | Unknown - DUNE's goal | Unknown - Future Experiments

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution
  - Current state : ingredients and their properties/interactions



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Flavor (Interaction)

Mass (Propagation)

Neutrinos oscillate

Oscillation properties

Known

Known - Better precision with DUNE

Unknown - DUNE’s goal

Unknown - Future Experiments

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution
  - Current state : ingredients and their properties/interactions

$$\begin{pmatrix}\text{PMNS}\\ \text{matrix}\end{pmatrix} = \begin{bmatrix}U_{e1}&U_{e2}&U_{e3}\\ U_{\mu1}&U_{\mu2}&U_{\mu3}\\ U_{\tau1}&U_{\tau2}&U_{\tau3}\end{bmatrix} = \begin{bmatrix}1&0&0\\ 0&c_{23}&s_{23}\\ 0&-s_{23}&c_{23}\end{bmatrix}\begin{bmatrix}c_{13}&0&s_{13}e^{-i\delta}\\ 0&1&0\\ -s_{13}e^{i\delta}&0&c_{13}\end{bmatrix}\begin{bmatrix}c_{12}&s_{12}&0\\ -s_{12}&c_{12}&0\\ 0&0&1\end{bmatrix}\begin{bmatrix}e^{i\alpha_1/2}&0&0\\ 0&e^{i\alpha_2/2}&0\\ 0&0&1\end{bmatrix}, \quad \begin{matrix}c_{ij}=\cos\theta_{ij}\\ s_{ij}=\sin\theta_{ij}\end{matrix}$$

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right),$$

L : traveled distance

E : energy

$\Delta m_{ij}^2 = m_i^2 - m_j^2$

Oscillation properties

Neutrinos oscillate

Known | Known - Better precision with DUNE | Unknown - DUNE's goal | Unknown - Future Experiments

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution
  - Current state : ingredients and their properties/interactions

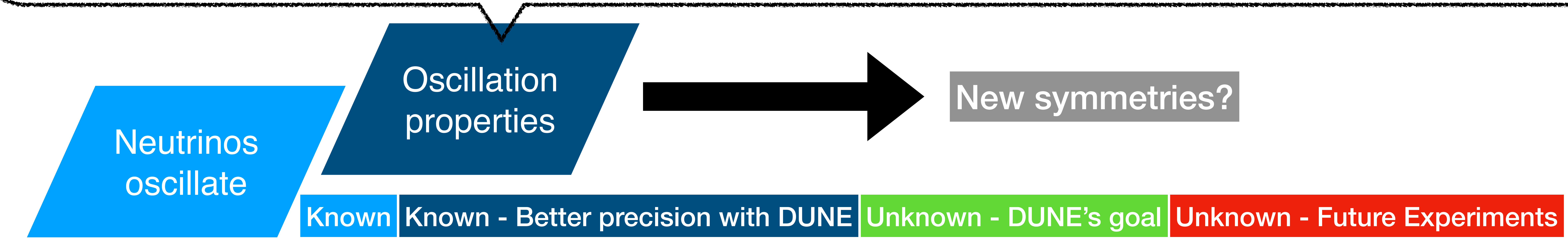
$$\begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \begin{matrix} c_{ij} = \cos\theta_{ij} \\ s_{ij} = \sin\theta_{ij} \end{matrix}$$

$$P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta)\sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right),$$

L : traveled distance

E : energy

$\Delta m_{ij}^2 = m_i^2 - m_j^2$



Neutrinos oscillate

Oscillation properties

New symmetries?

Known | Known - Better precision with DUNE | Unknown - DUNE’s goal | Unknown - Future Experiments

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution
  - Current state : ingredients and their properties/interactions

$$A_{\mathrm{CP}}^{(\alpha\beta)} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = 4 \sum_{j>k} \mathcal{I}_m \left\{ U^*_{\alpha j}\, U_{\beta j}\, U_{\alpha k}\, U^*_{\beta k} \right\} \sin\left(\frac{\Delta m^2_{jk} L}{2E} \right)$$

Neutrinos oscillate

Oscillation properties

Mass ordering & CP phase

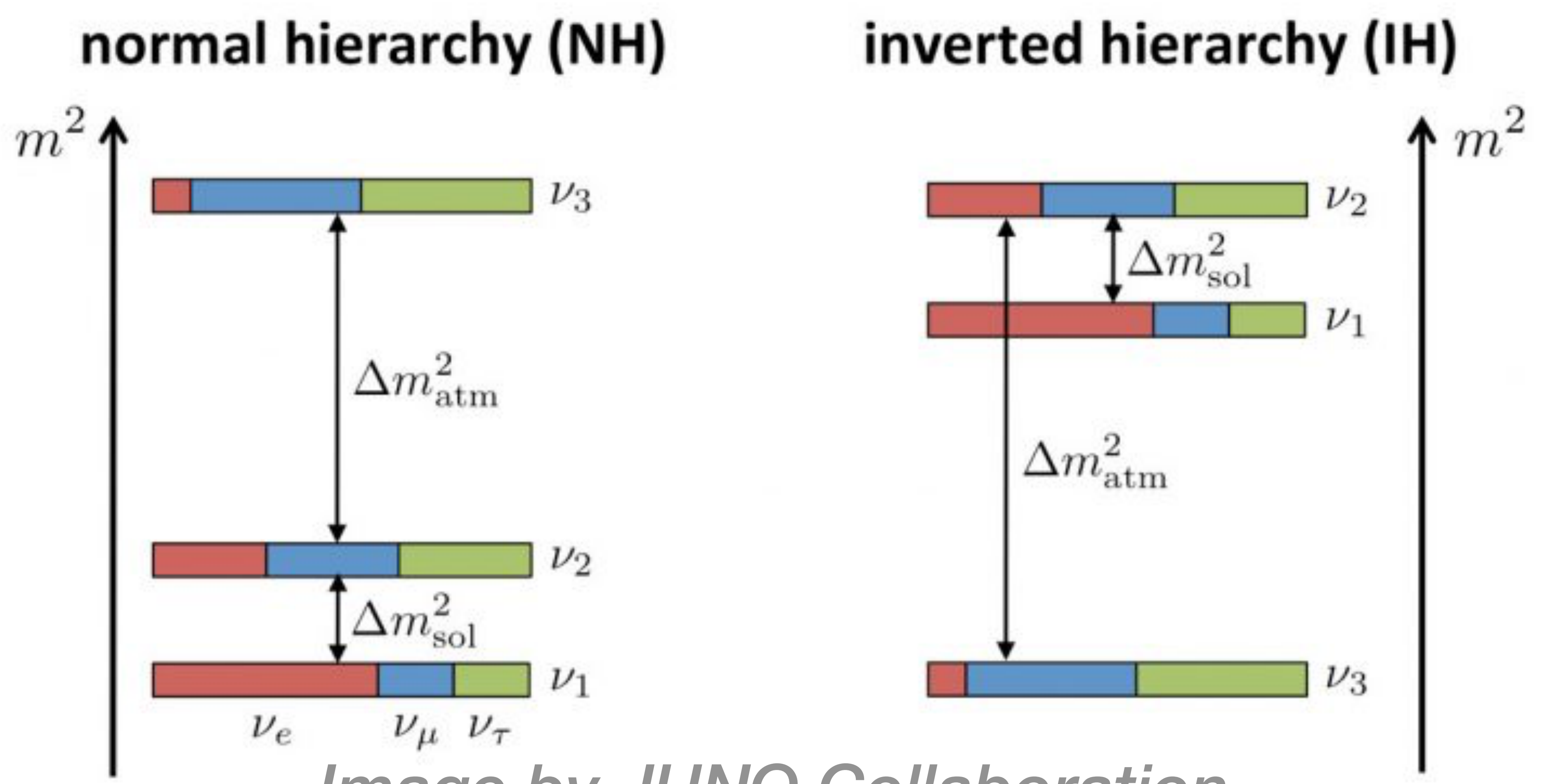
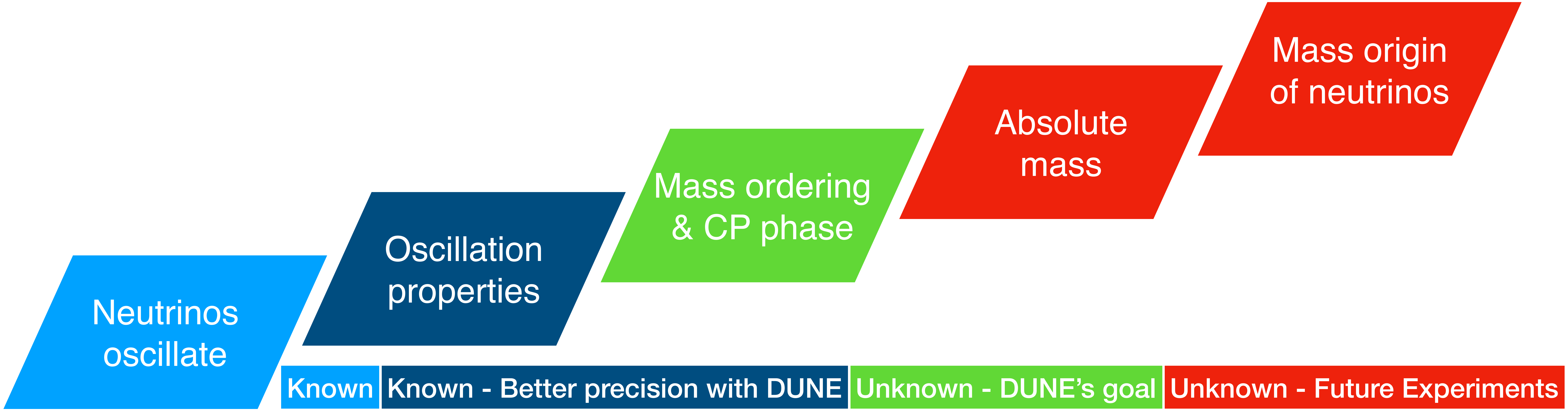


Image by JUNO Collaboration

Known
Known - Better precision with DUNE
Unknown - DUNE's goal
Unknown - Future Experiments

The Universe and the DUNE Science

- Understanding the universe?
  - The beginning and early evolution
  - Current state : ingredients and their properties/interactions



Neutrinos oscillate

Oscillation properties

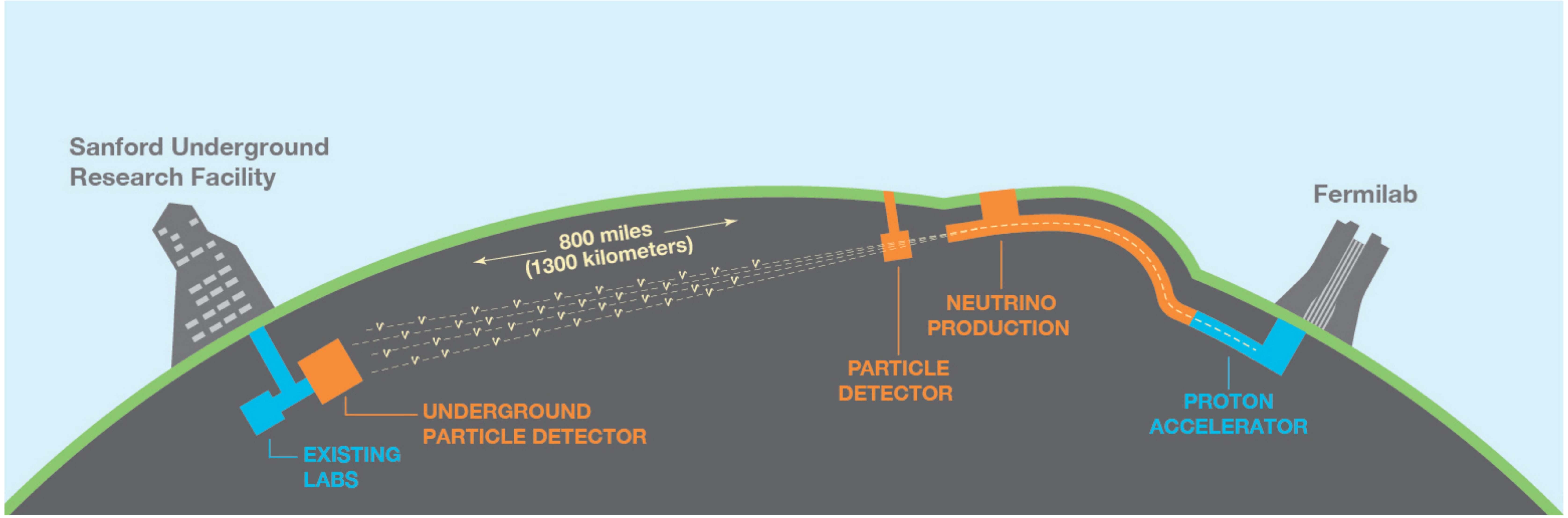
Mass ordering & CP phase

Absolute mass

Mass origin of neutrinos

Known | Known - Better precision with DUNE | Unknown - DUNE’s goal | Unknown - Future Experiments

The DUNE Experiment



- Three central components
  - (1) **High intensity neutrino source** - MWs class proton Accelerator at Fermilab
  - (2) **Far detector** situated 1.5 km underground at the Sanford Underground Research Facility (SURF)
  - (3) **Near detector** just downstream of the neutrino source

- Long-Baseline Neutrino Facility (**LBNF**) project
  - Provides the beamline and the civil construction for the DUNE experiment

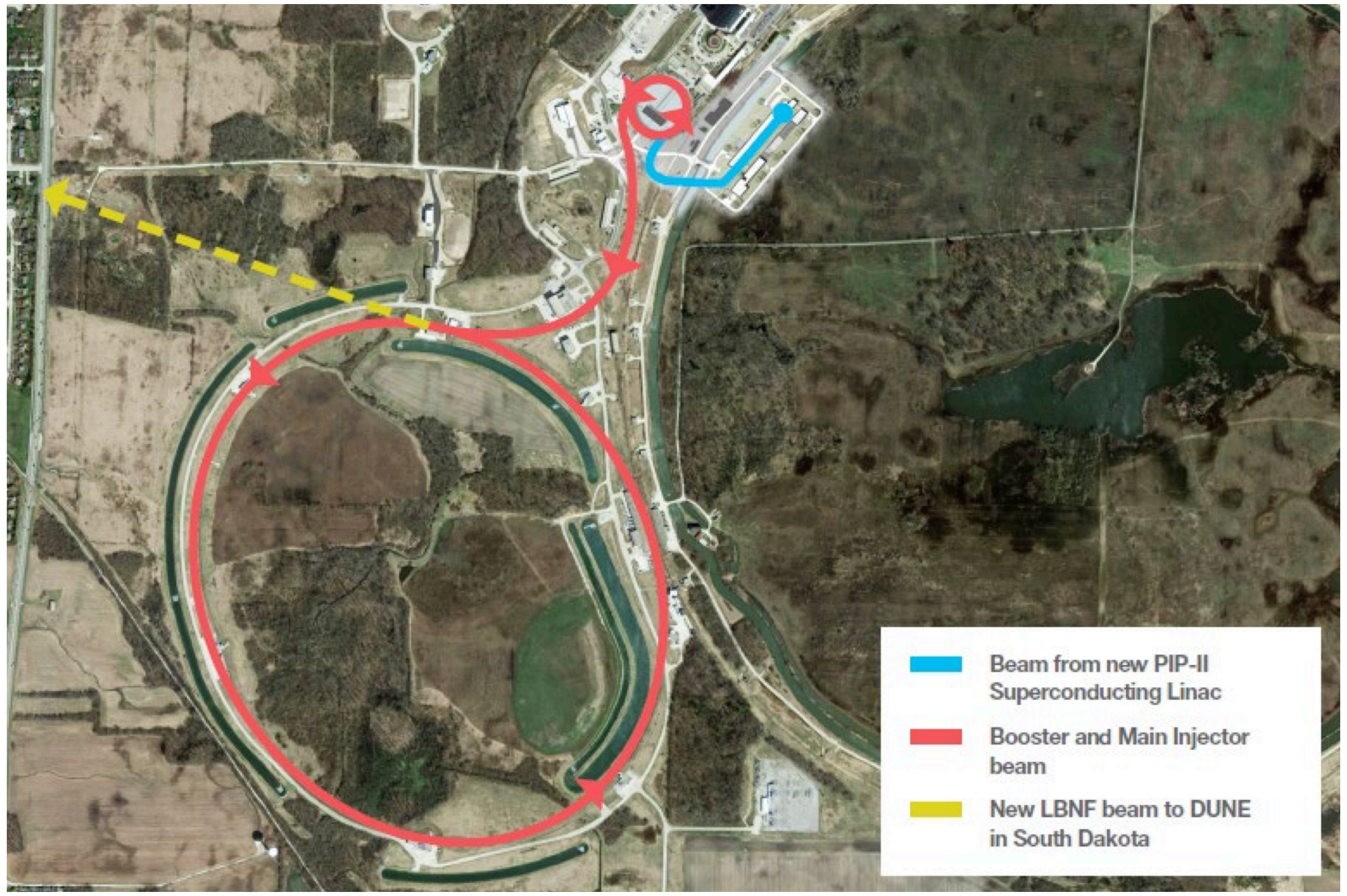
The DUNE Collaboration

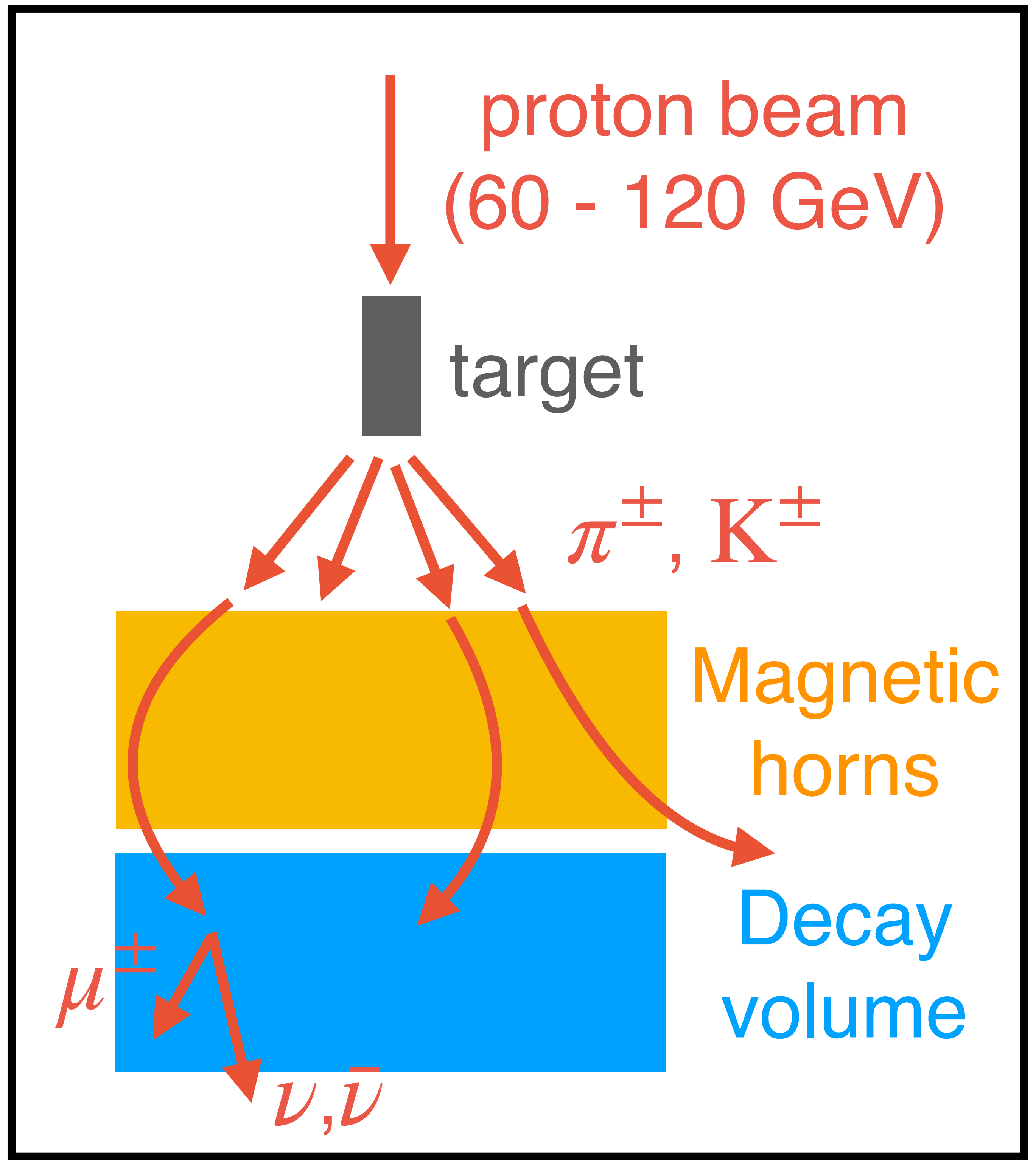
DUNE Collaboration Meeting, May 2024, Fermilab

- ~ 1400 scientists and engineers
- International collaboration
  - Total 207 institutions at Africa, Asia, Europe, North and South America as of 5th July 2024

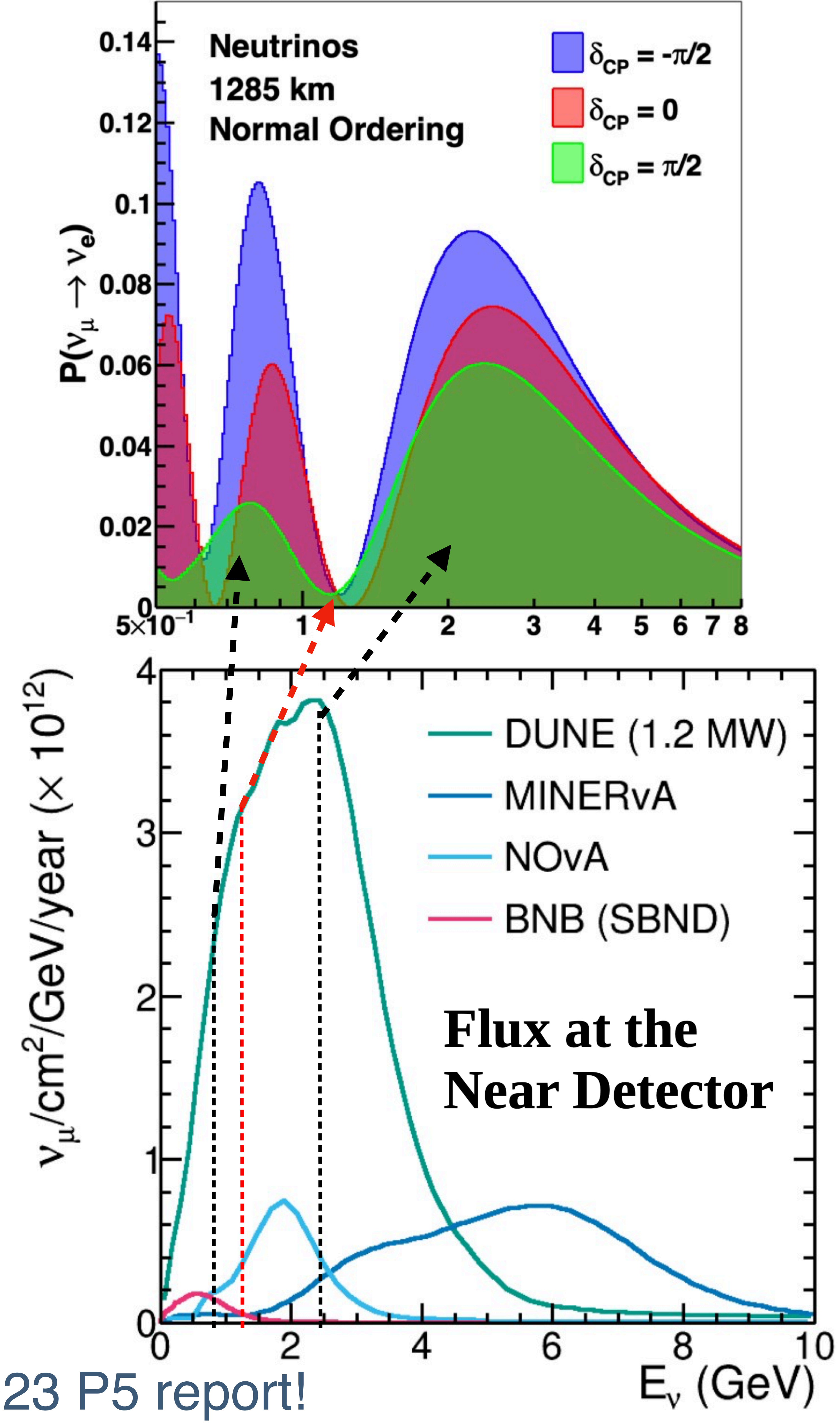
(1) High intensity neutrino source

- Beam protons on target (POT)!





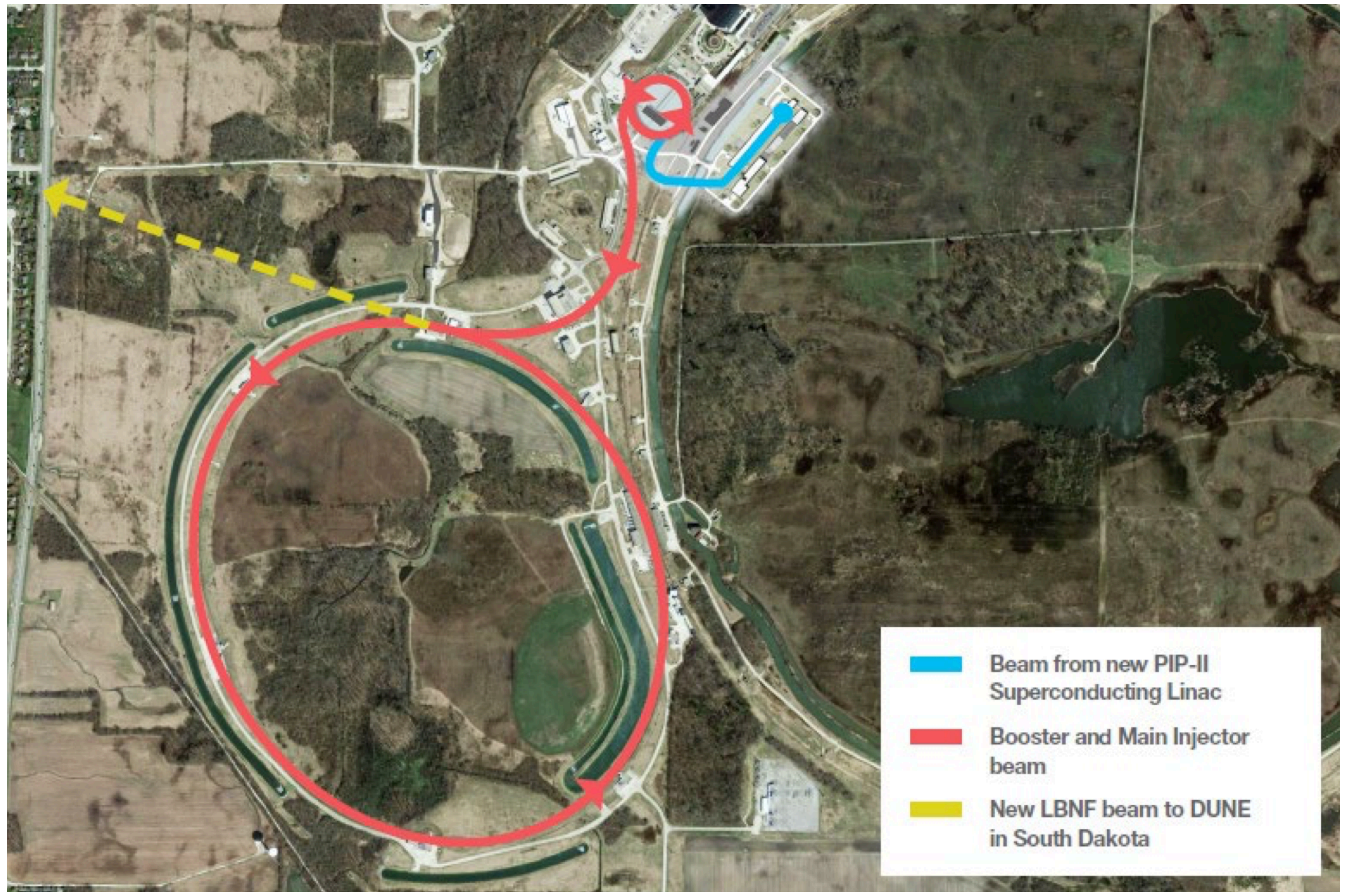
Eur.Phys.J.C 80 (2020) 10, 978

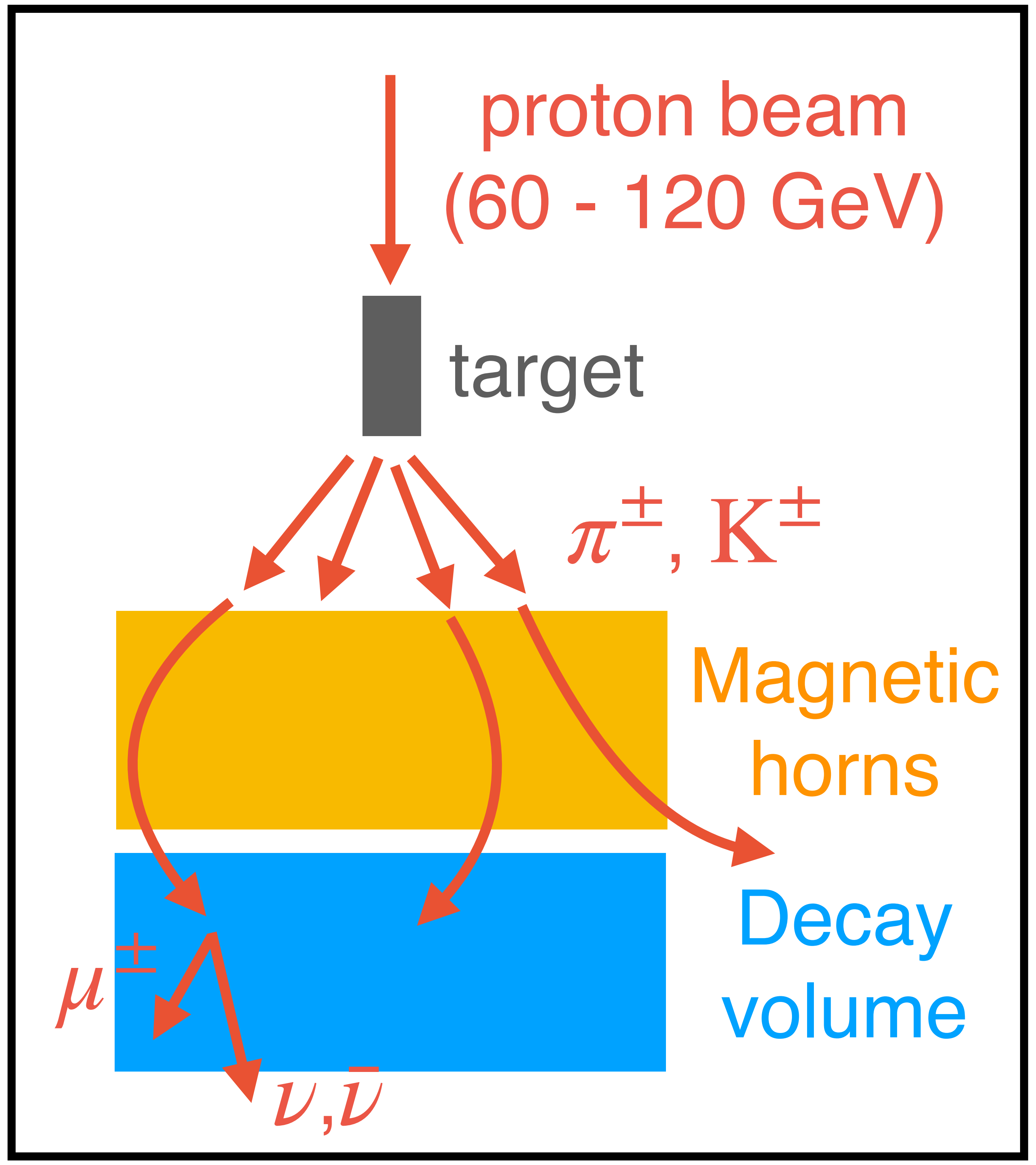


- Very high flux with wide energy spectrum
- Proton Improvement Plan-II (PIP-II) is ongoing - 1.2 MW
- The further improvement plan for beyond 2 MW is also recommended by 2023 P5 report!

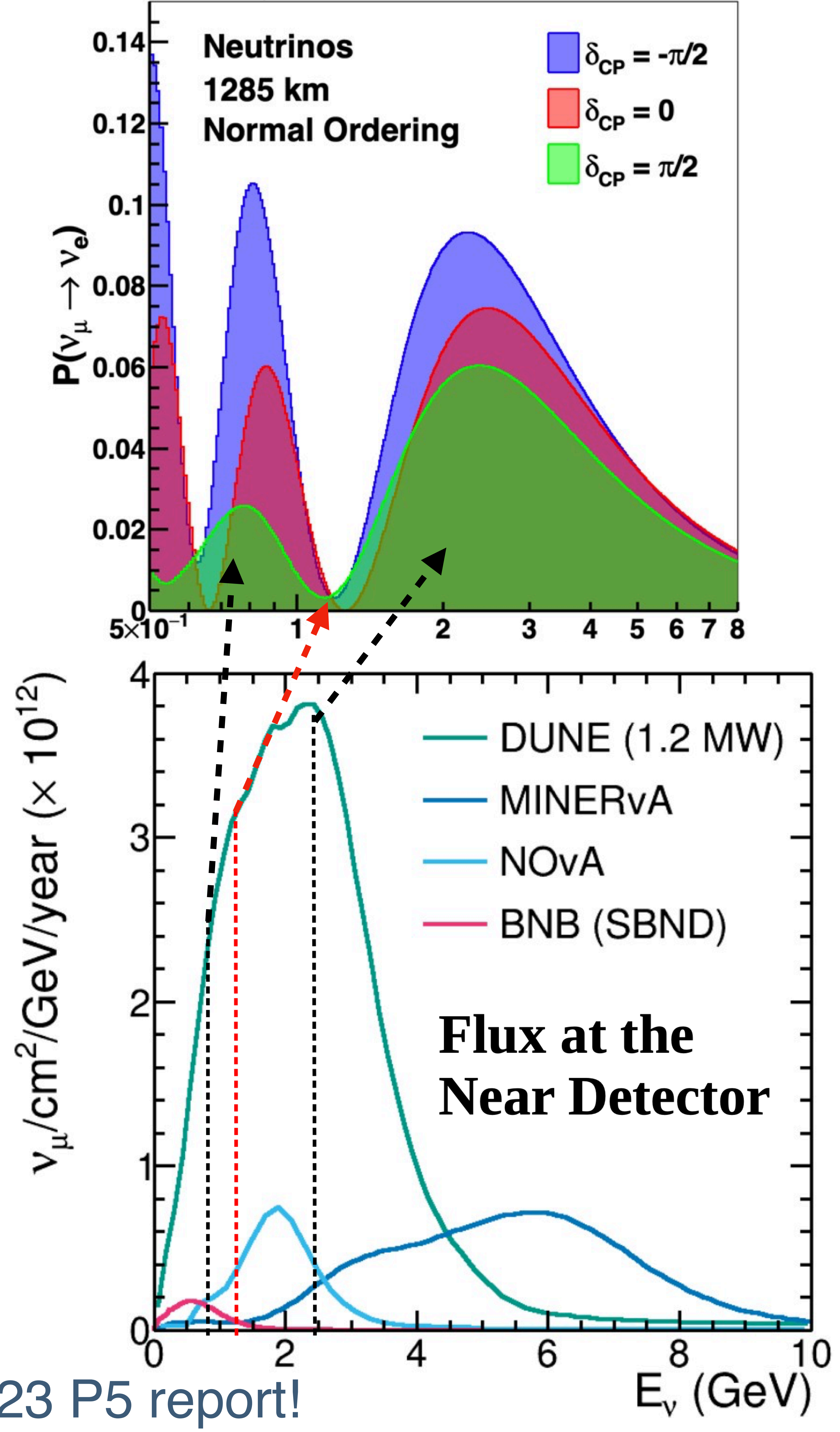
(1) High intensity neutrino source

- Beam protons on target (POT)!





Eur.Phys.J.C 80 (2020) 10, 978

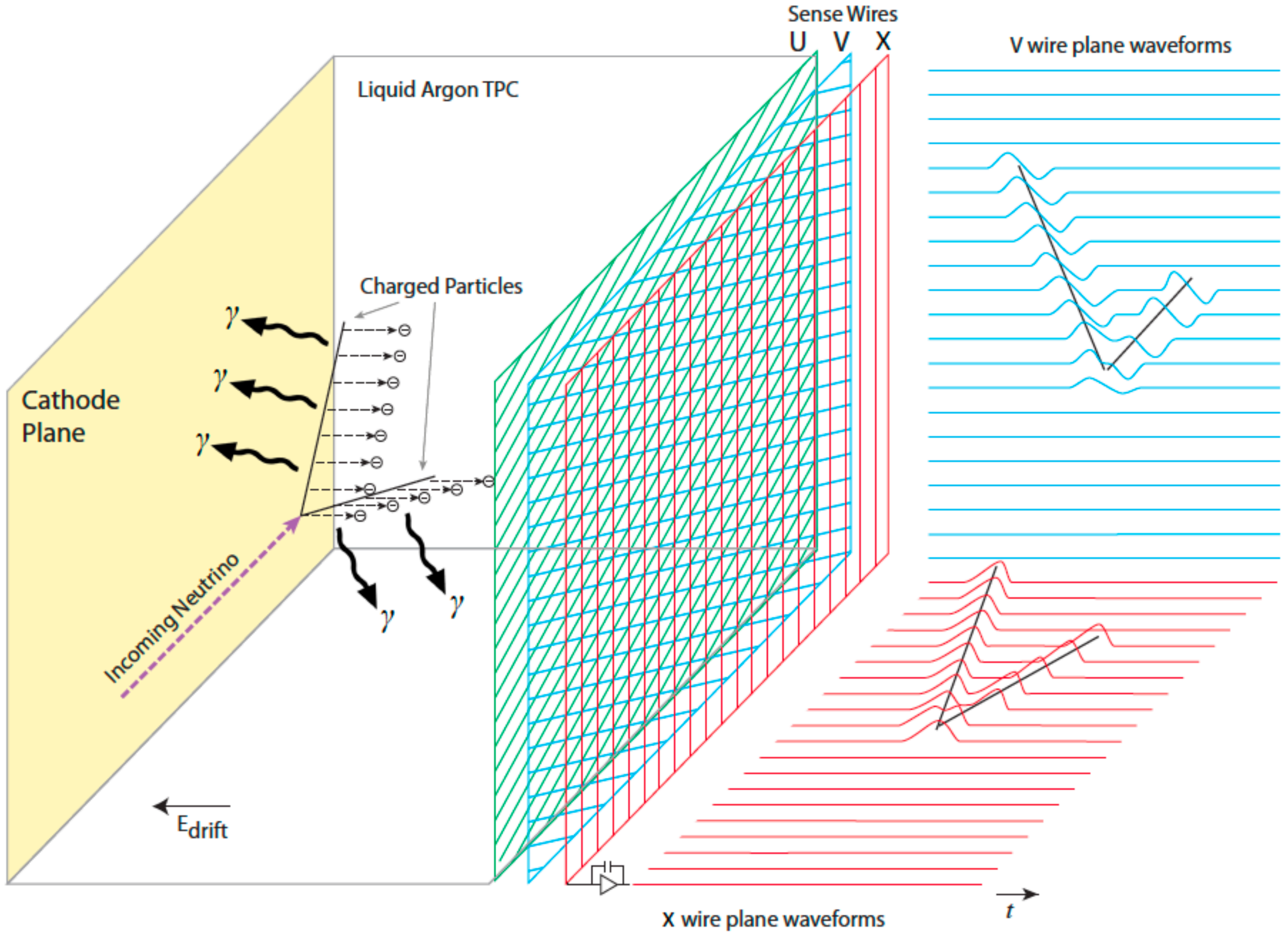


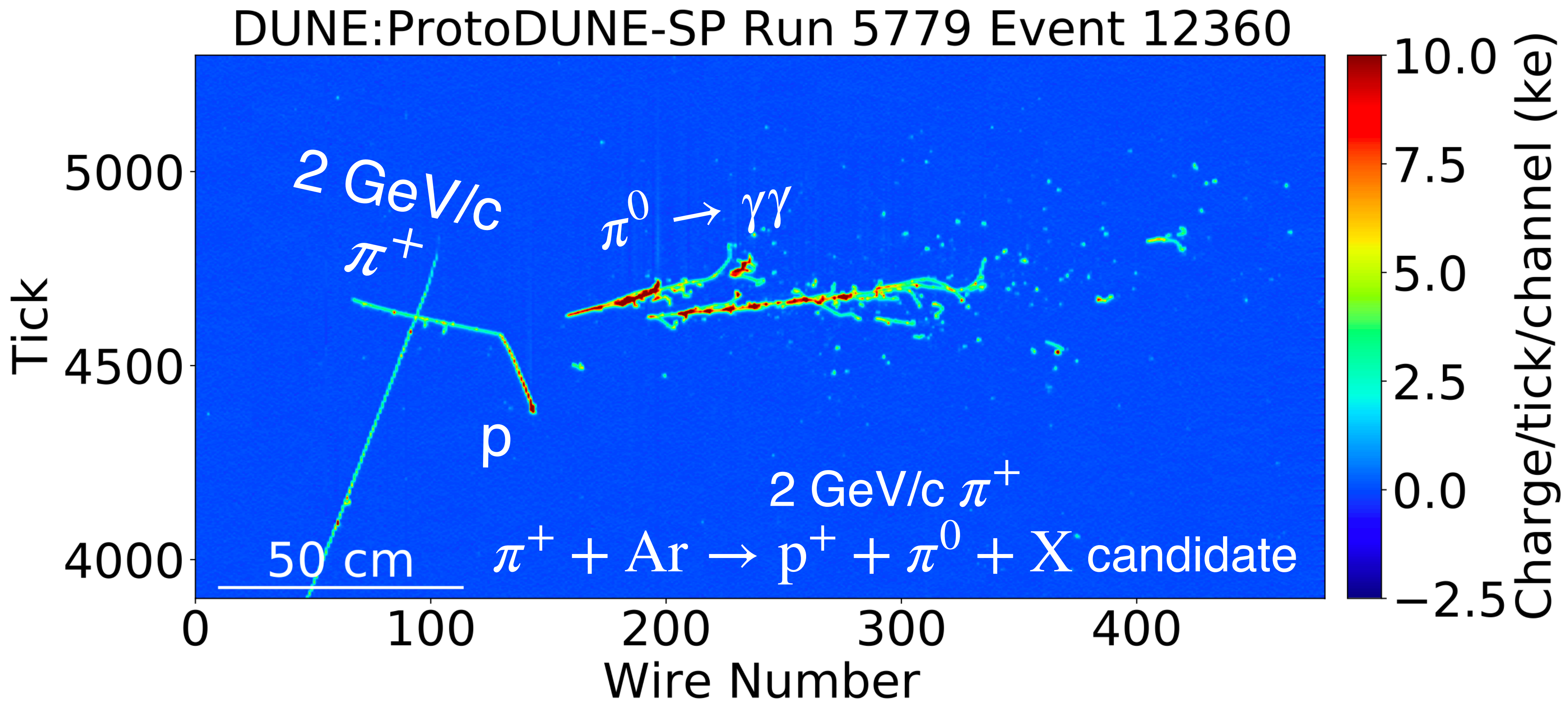
- Very high flux with wide energy spectrum
- Proton Improvement Plan-II (PIP-II) is ongoing - 1.2 MW
- The further improvement plan for beyond 2 MW is also recommended by 2023 P5 report!

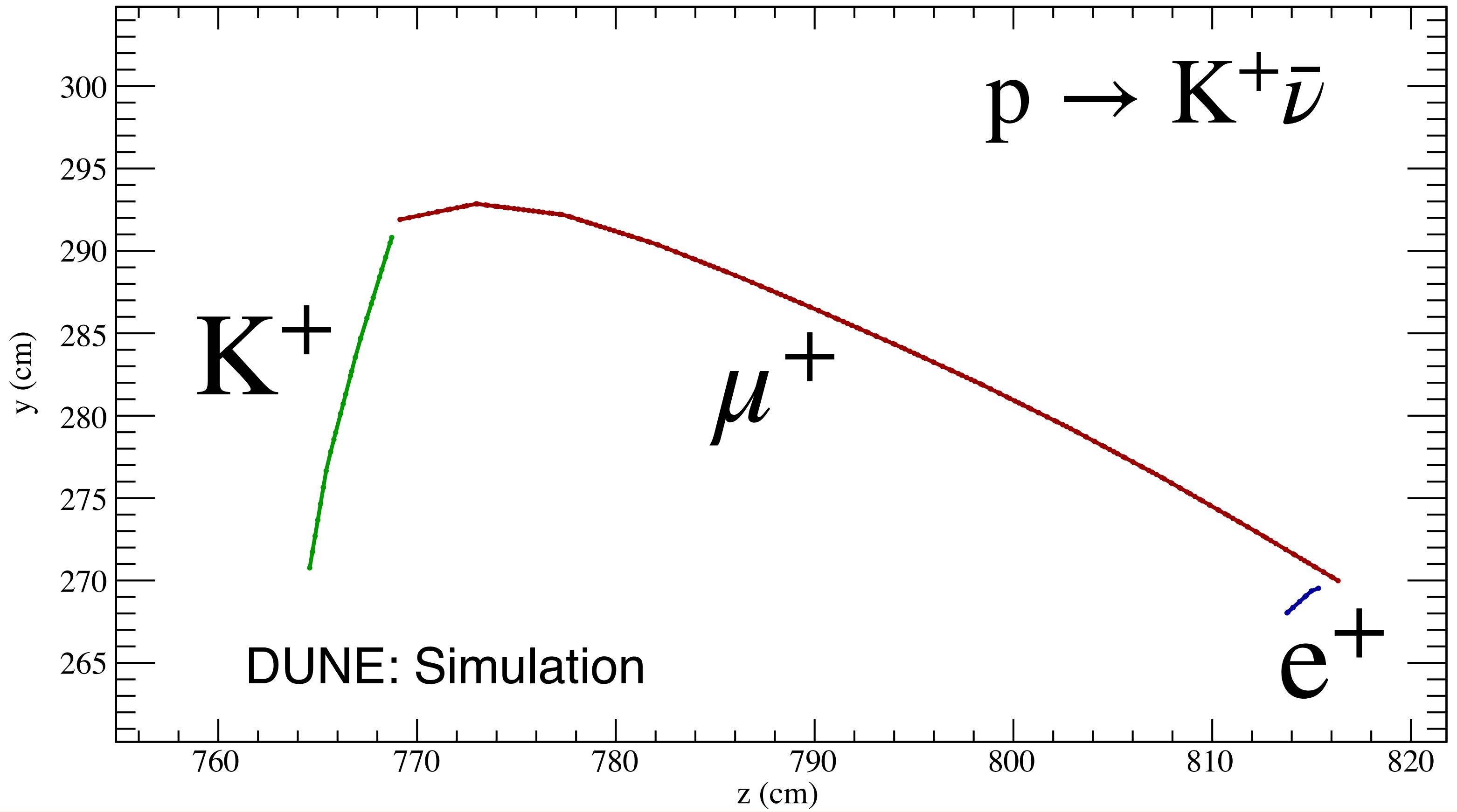
"PIP-II Overview & Update"
Jul 11, 1:30 PM, Pantaleo Raimondi

(2) Far Detector (FD)

- Liquid argon time projection chambers (LArTPCs)
  - Excellent interaction imaging performance in position and energy resolution

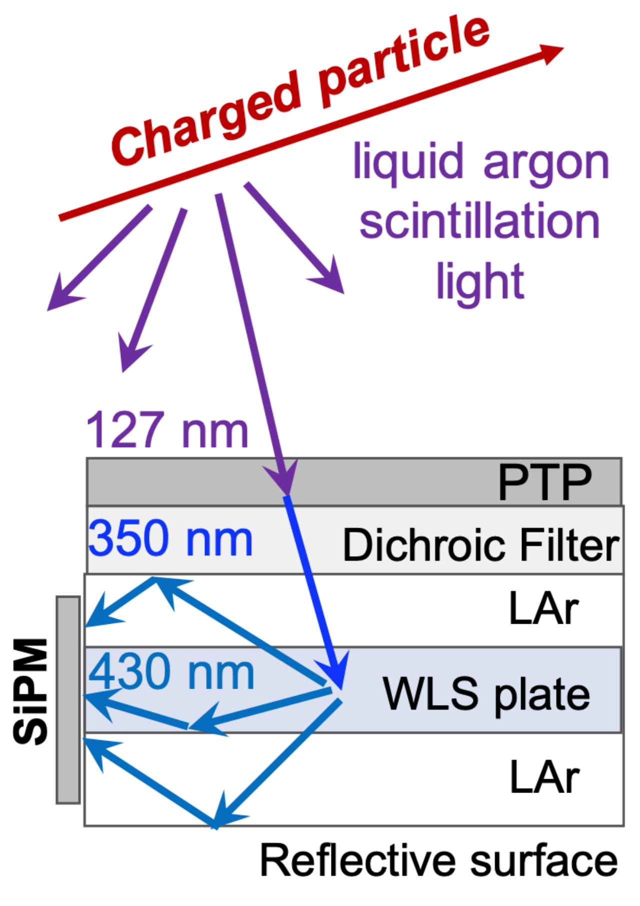






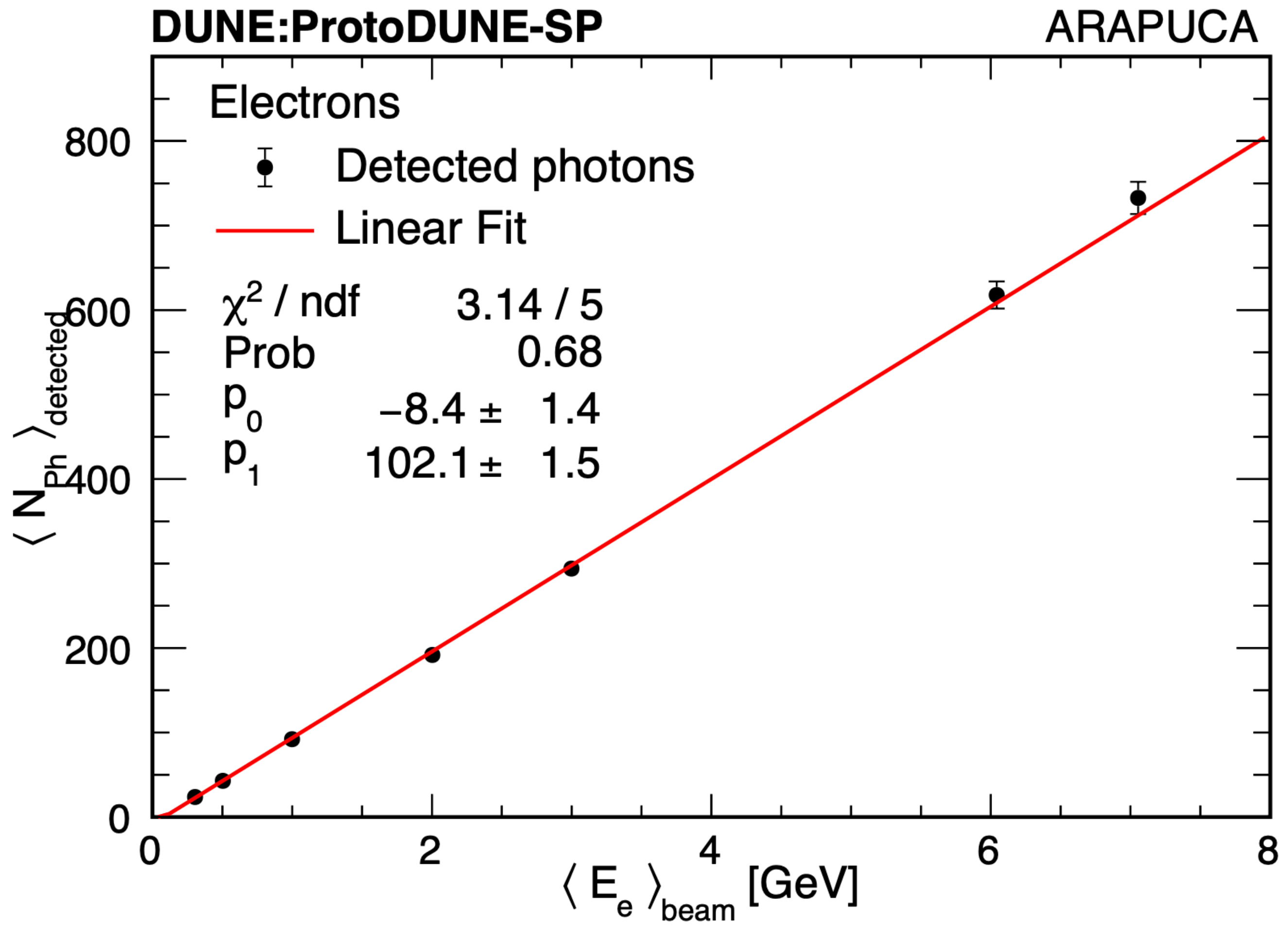
(2) Far Detector (FD)

- Position in electron-drifting direction is determined by reference time of each event (t_0)
  - The neutrino beam timing
  - Photon detection system (PDS) - using a light trap technology, X-ARAPUCA
- PDS
  - Essential for nucleon decay searches and solar neutrino studies
  - Provide complimentary calorimetric information
  - $1\ \mu s$ timing resolution → 1 mm position resolution for 10 MeV supernova burst neutrinos
    - Goal is better than 100 ns



Not to scale.

JINST 15 (2020) 08, T08010

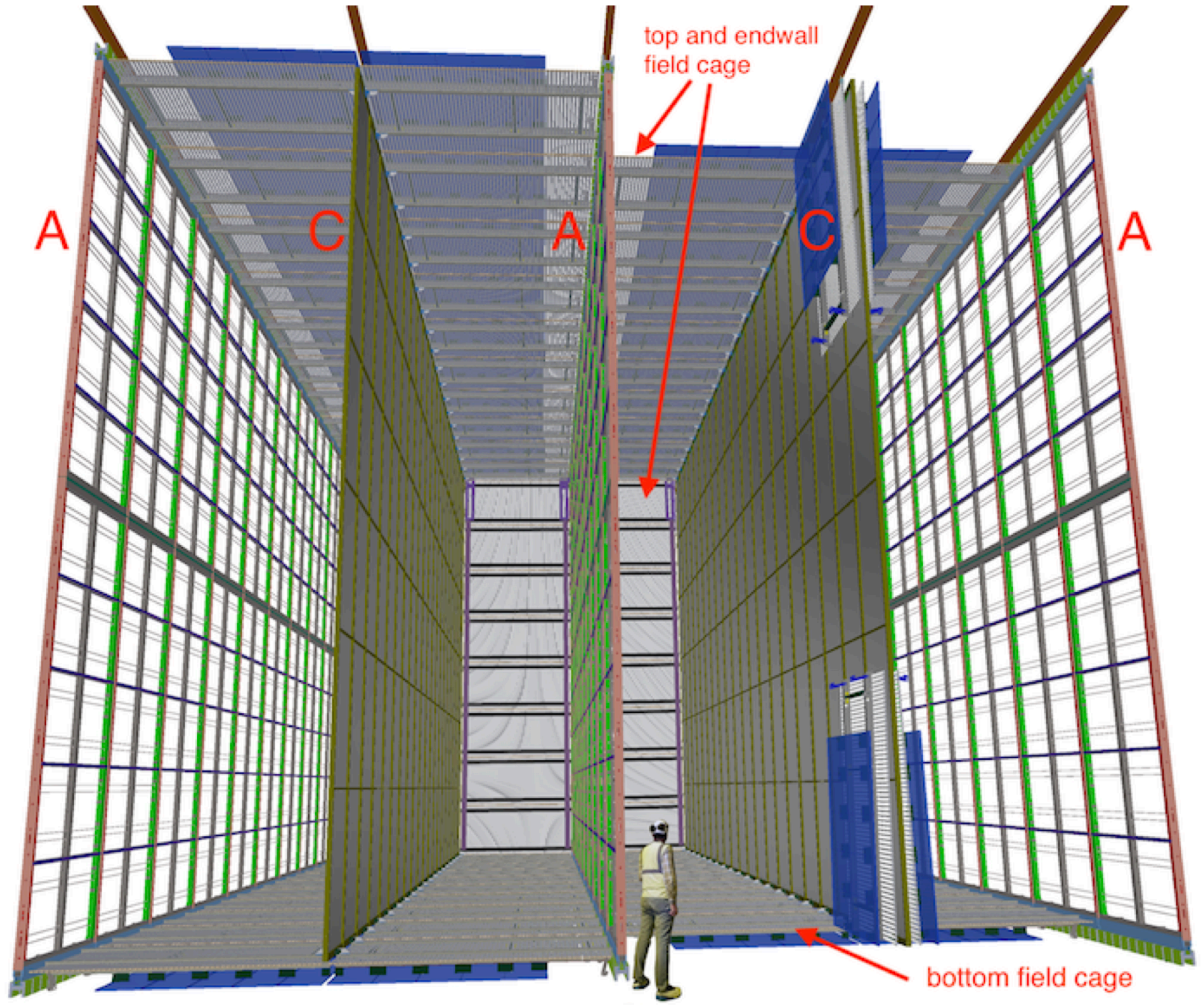


JINST 15 (2020) 12, P12004

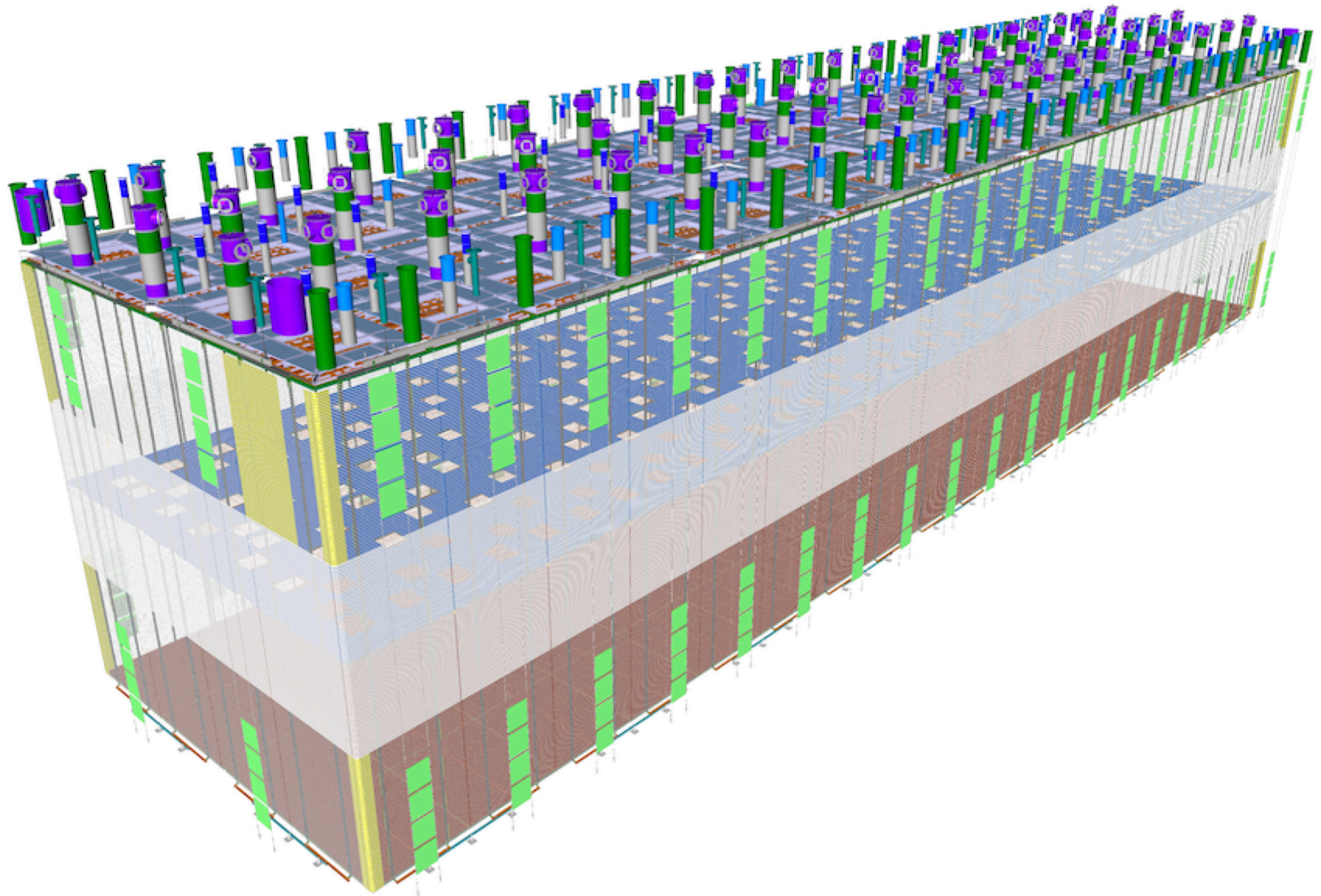
(2) Far Detector (FD)

- Four 17-kt LArTPC detector modules
- Situated 1.5 km underground
- Design is fixed for DUNE Phase I FDs
  - Horizontal drift (HD) *JINST 15 T08010 (2020)*
  - Vertical drift (VD) *arXiv:2312.03130*

A (anode)
C (cathode)



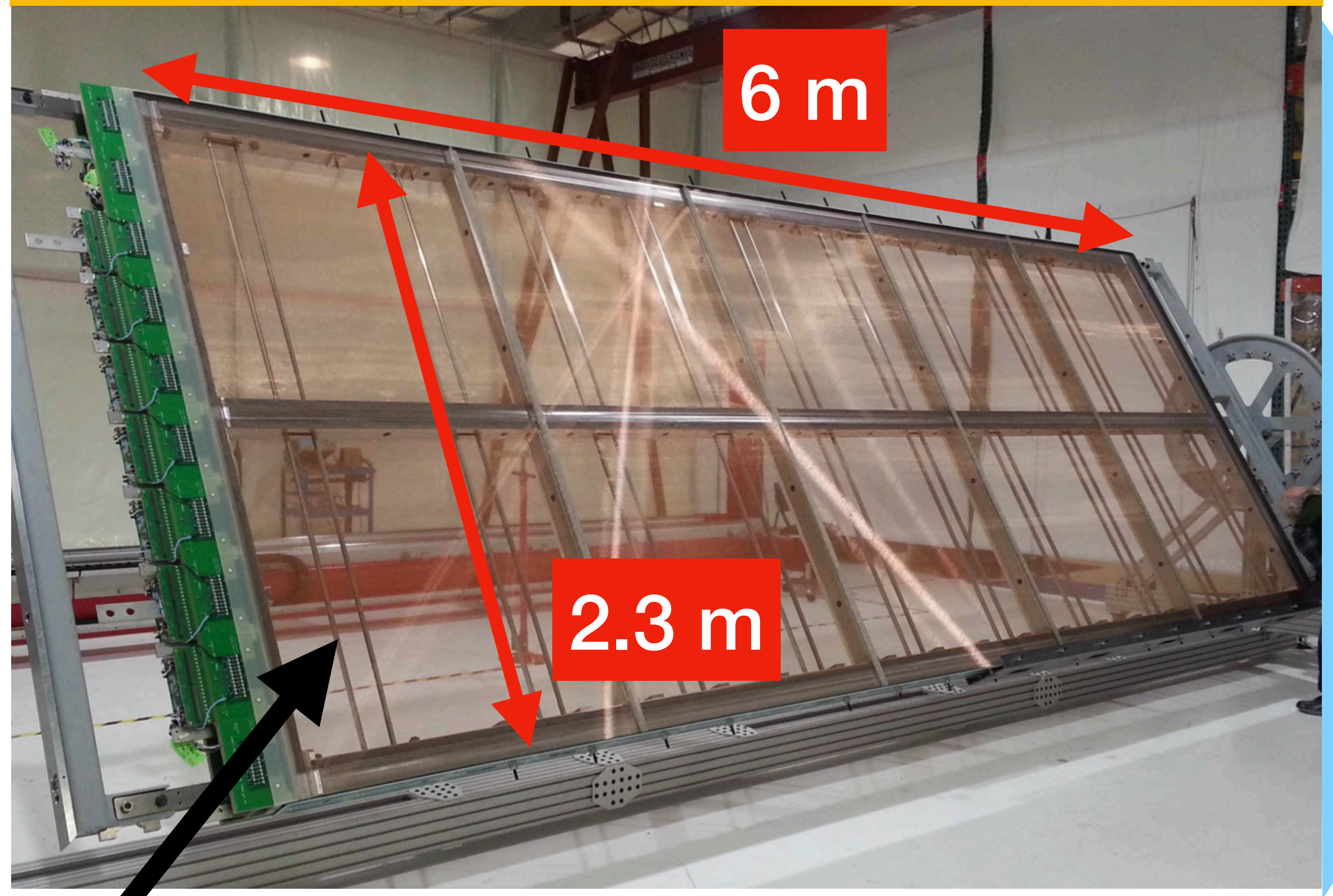
HD : 4 drift volumes, wire readout



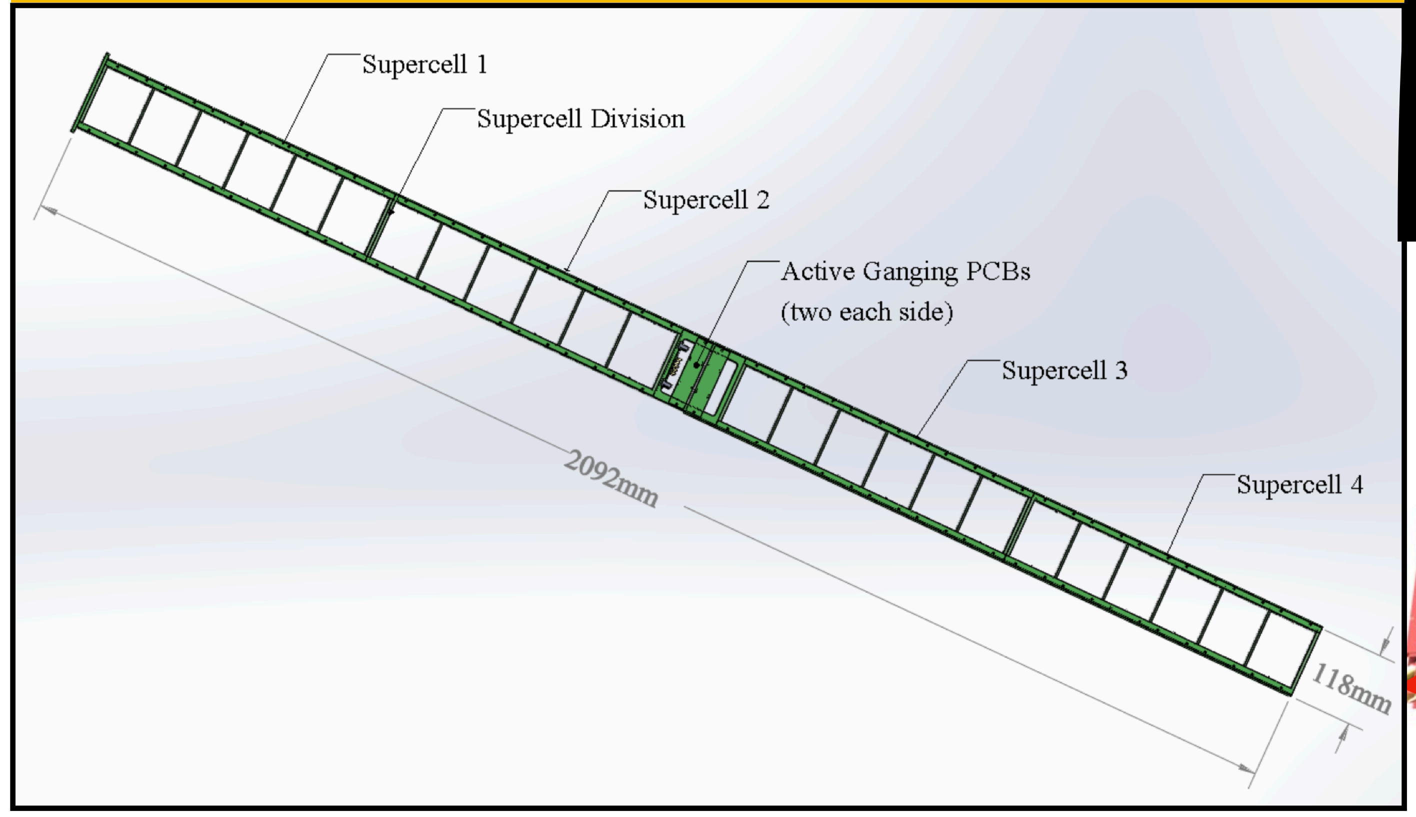
VD : 2 drift volumes, perforated readout strips

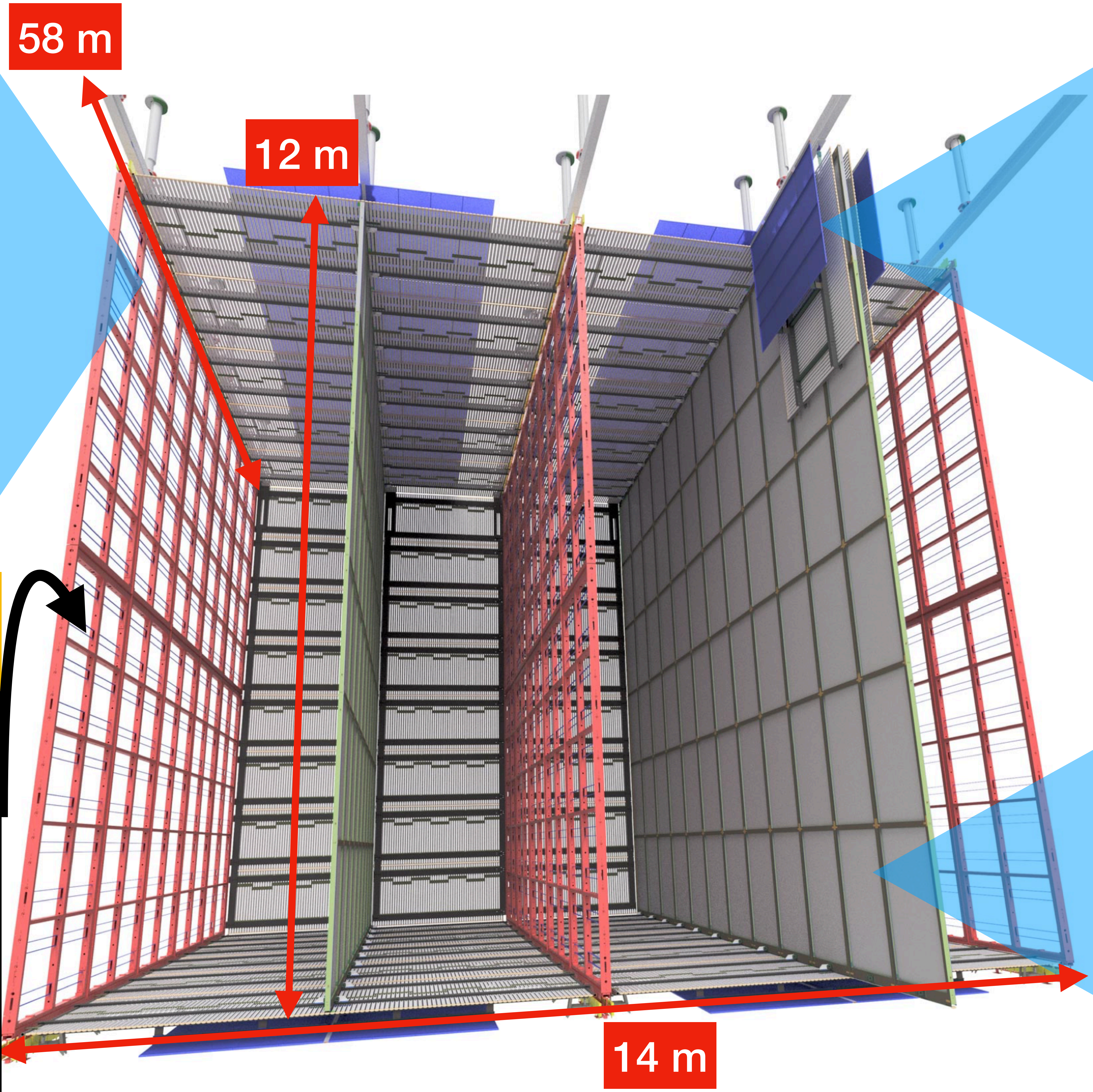
(2) Far Detector (FD) - Horizontal Drift (HD)

Anode plane assembly (APA)

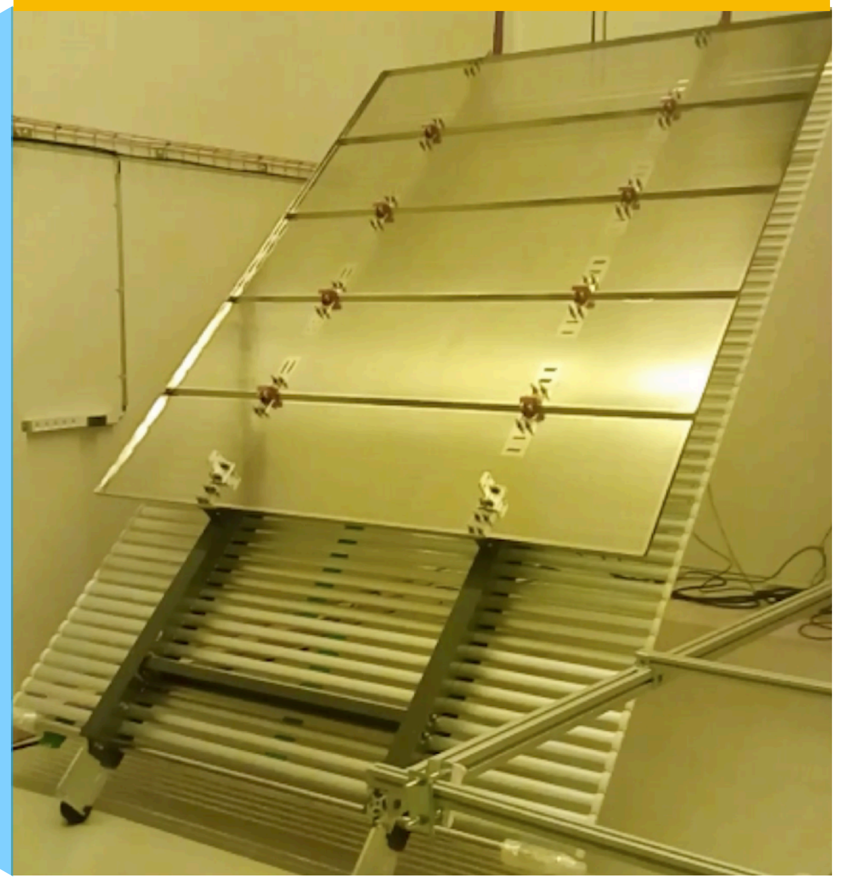


Photon detection system (PDS) Module

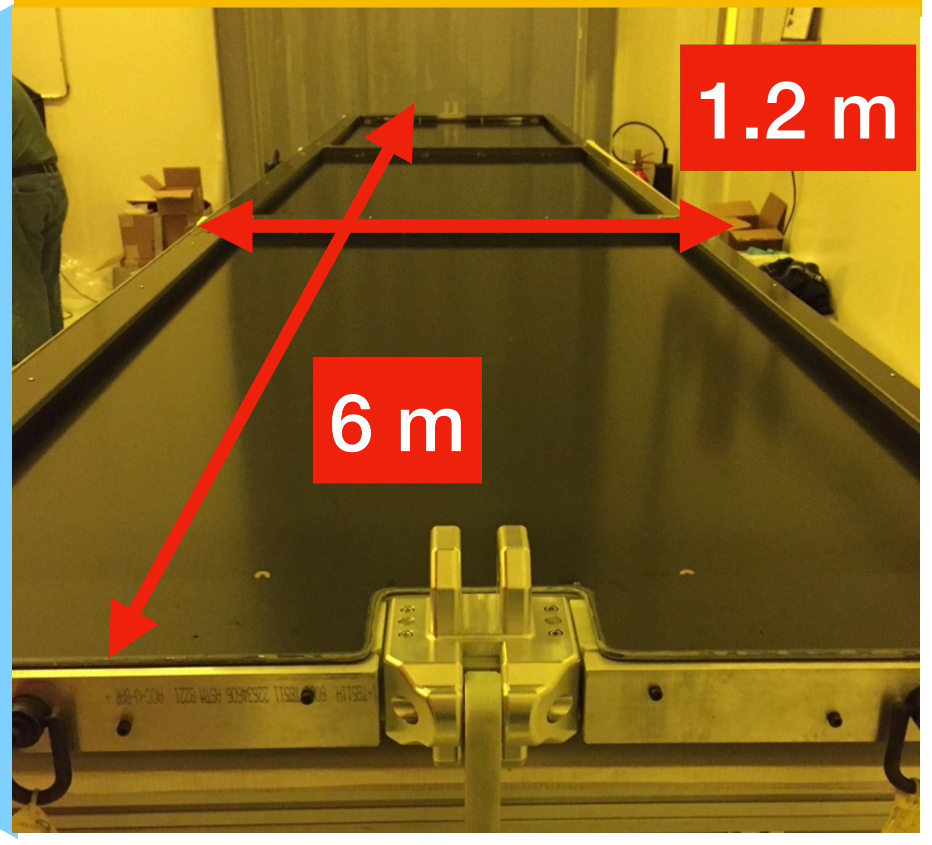




Multiple versions of field cage modules

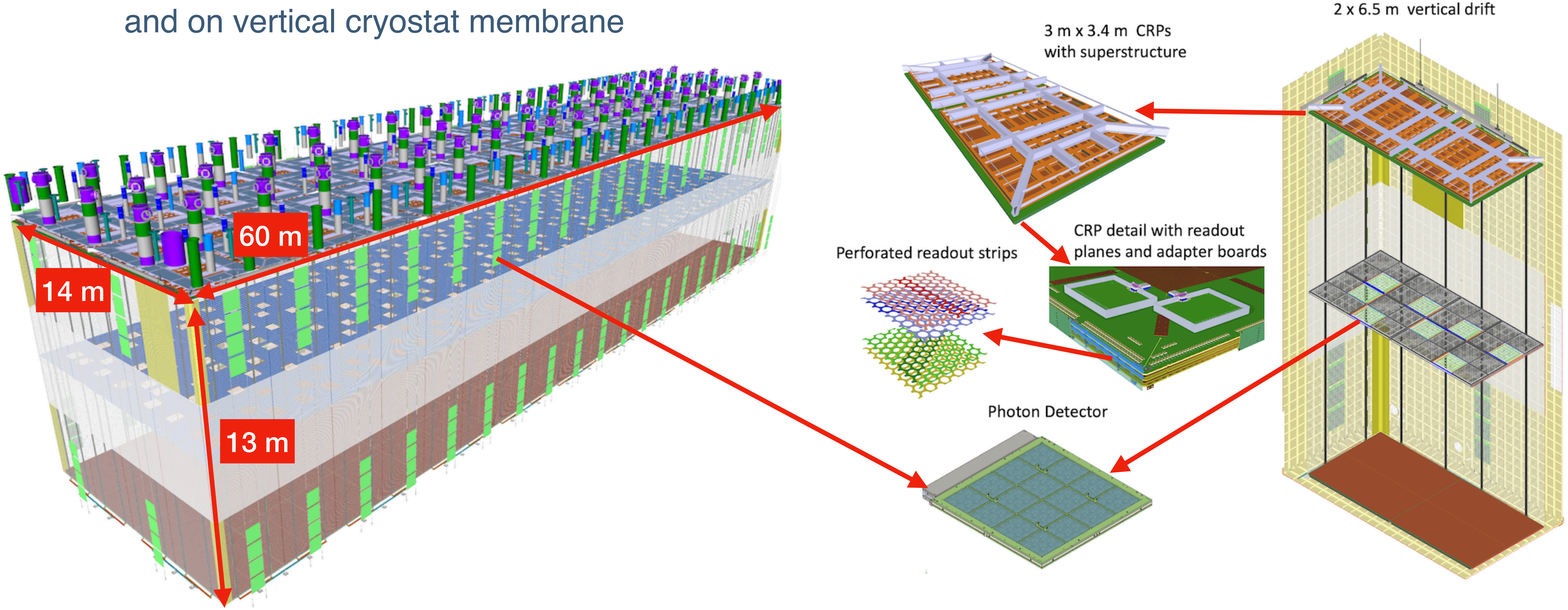


Side-by-side resistive plates (FR-4)



(2) Far Detector (FD) - Vertical Drift (VD)

- Charge readout plane (CRT)
- Photon detectors (X-ARAPUCAs) on cathode plane and on vertical cryostat membrane

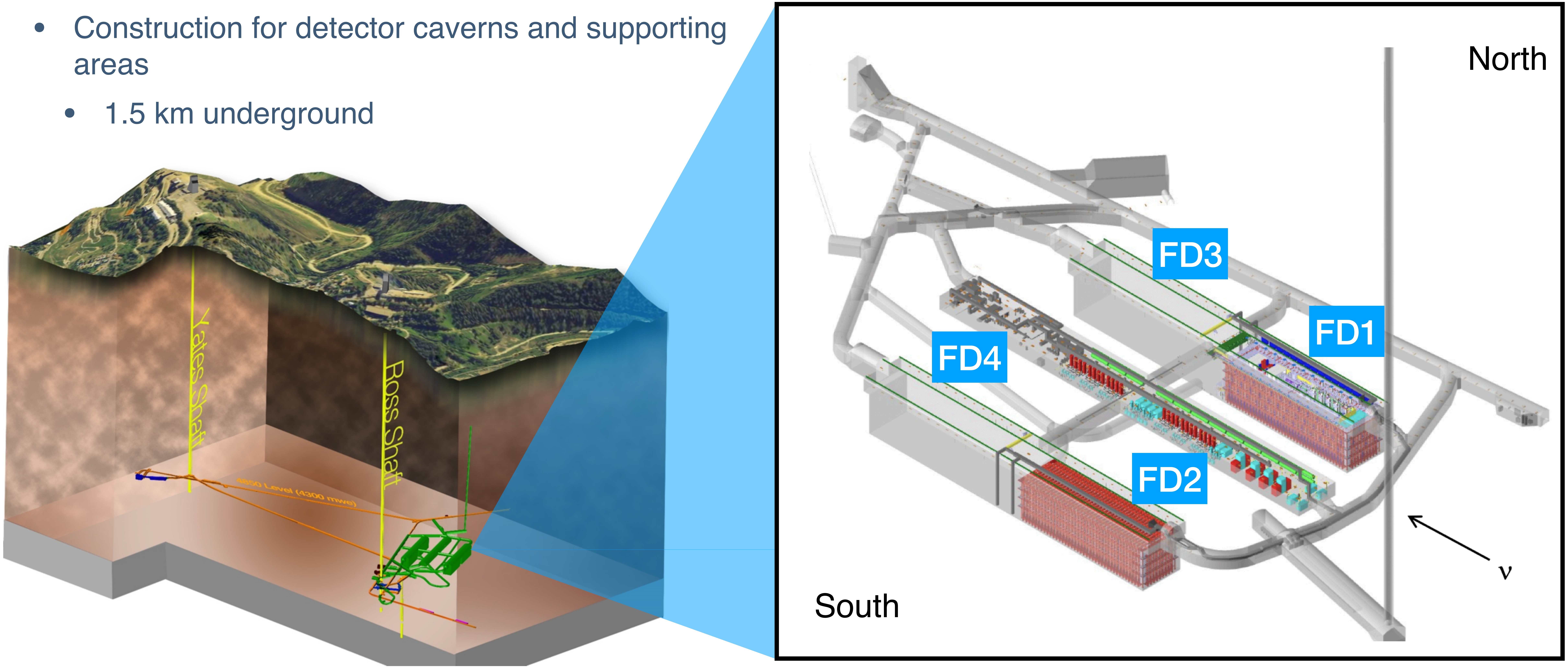


(2) Far Detector (FD) - Site

- Sanford Underground Research Facility (SURF), SD
- It was the Homestake gold mine
    - Hometown of neutrino oscillation - Solar neutrino problem by Davis, The Nobel prize in physics 2002
- Hosting underground experiments, i.e. LUX-ZEPLIN, MAJORANA demonstrator
- ~ 1300 km from Fermilab

(2) Far Detector (FD) - Site

- Construction for detector caverns and supporting areas
  - 1.5 km underground



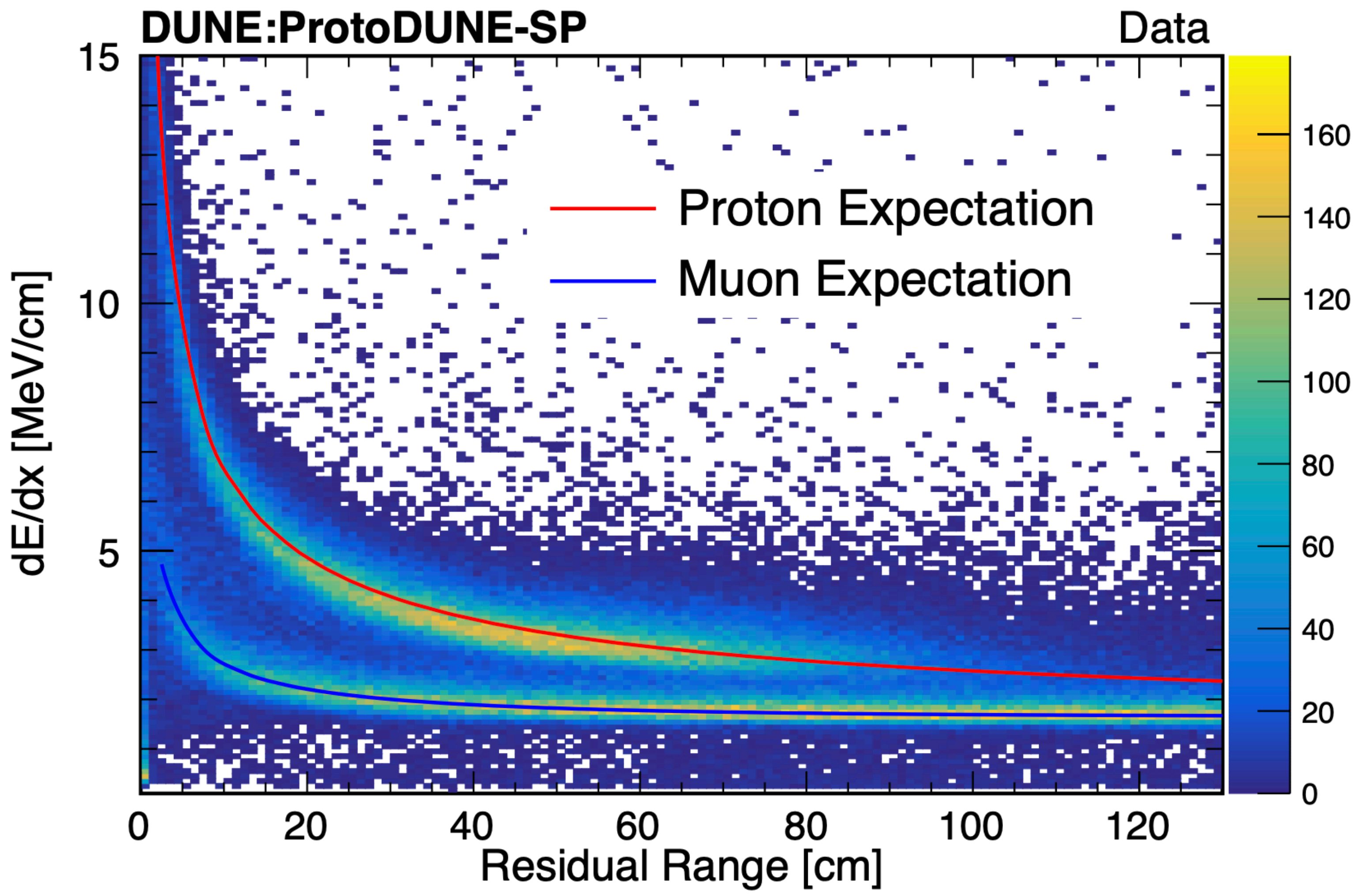
(2) Far Detector (FD) - Site

- Underground excavation is completed in February 2024!

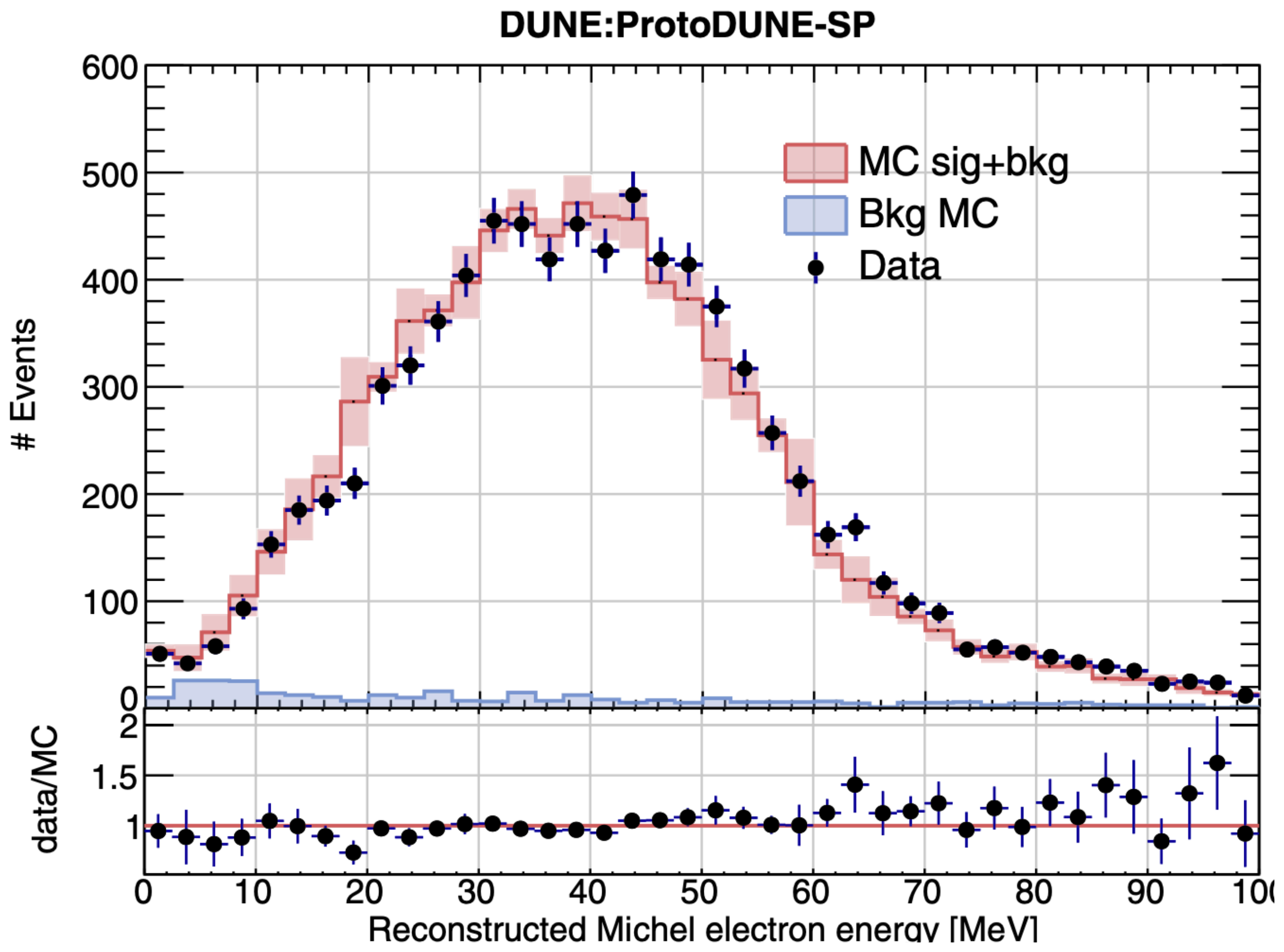
- Focus is moving to construction for buildings and infrastructure
- Cryostat installation begins in 2025

(2) Far Detector (FD) - Prototyping

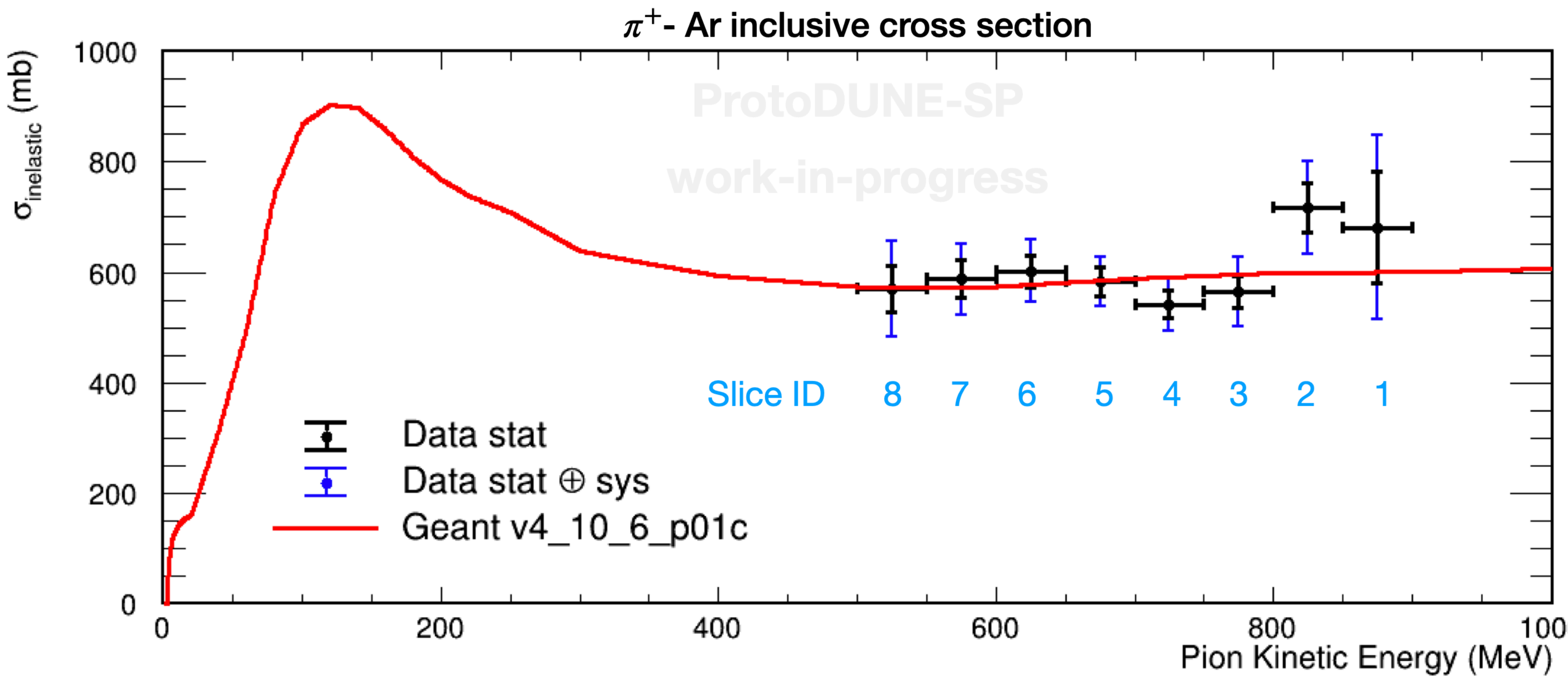
- First horizontal drift prototype at CERN Neutrino Platform was successful (0.77-kt LAr, 2018 - 2020)
  - Meets or surpasses the specifications set for the FD-HD
  - Good dE/dx reconstruction performance for both Bragg peak and MIP region
  - Low energy electron study using Michele electrons : $\sigma(\mathrm{E})/\mathrm{E} \sim$ 25% at 50 MeV
  - Hadron-argon cross section measurements
    - Data with a tagged and momentum analyzed incident beam



JINST 15 (2020) 12, P12004

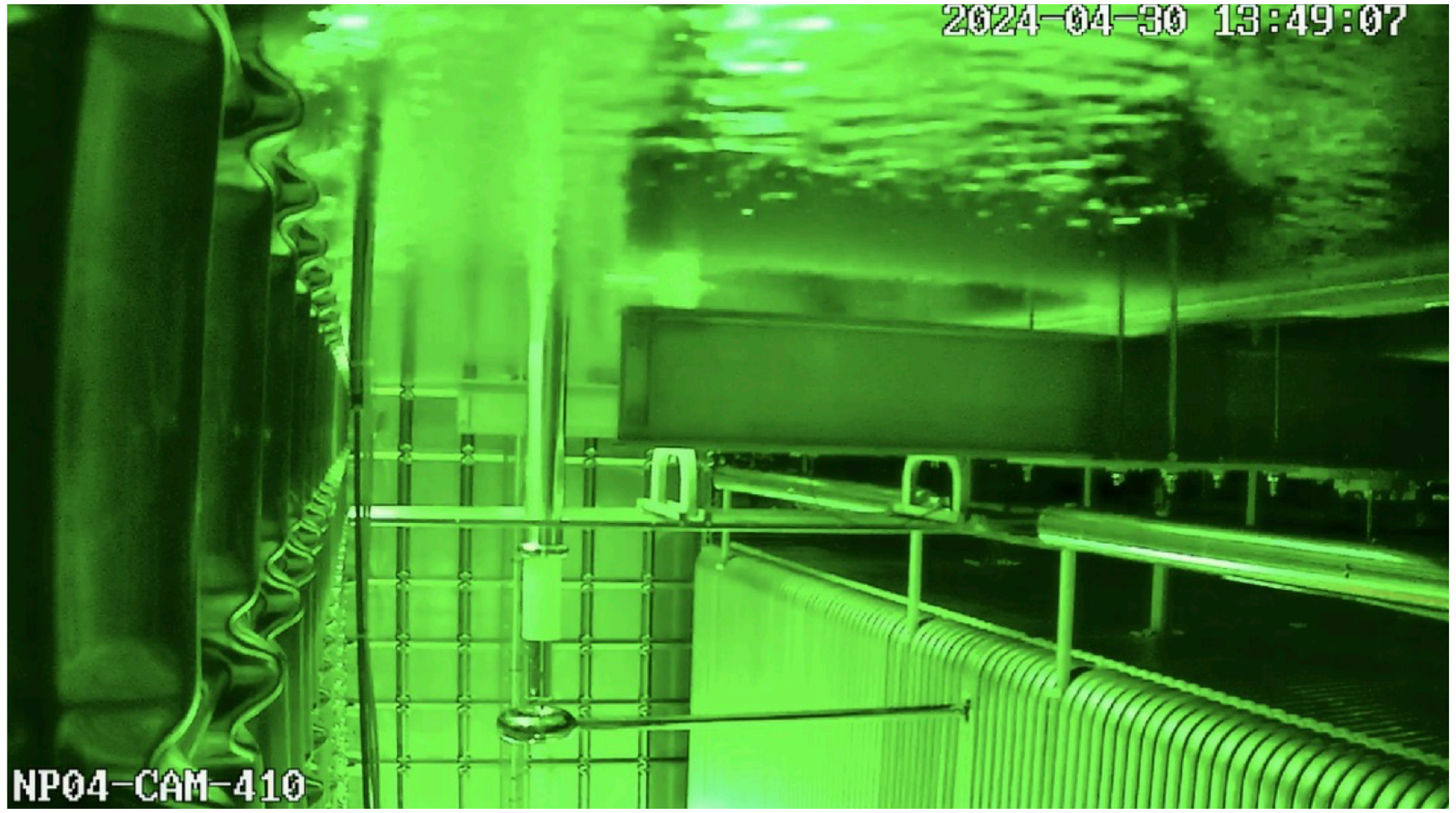


Phys.Rev.D 107 (2023) 9, 092012

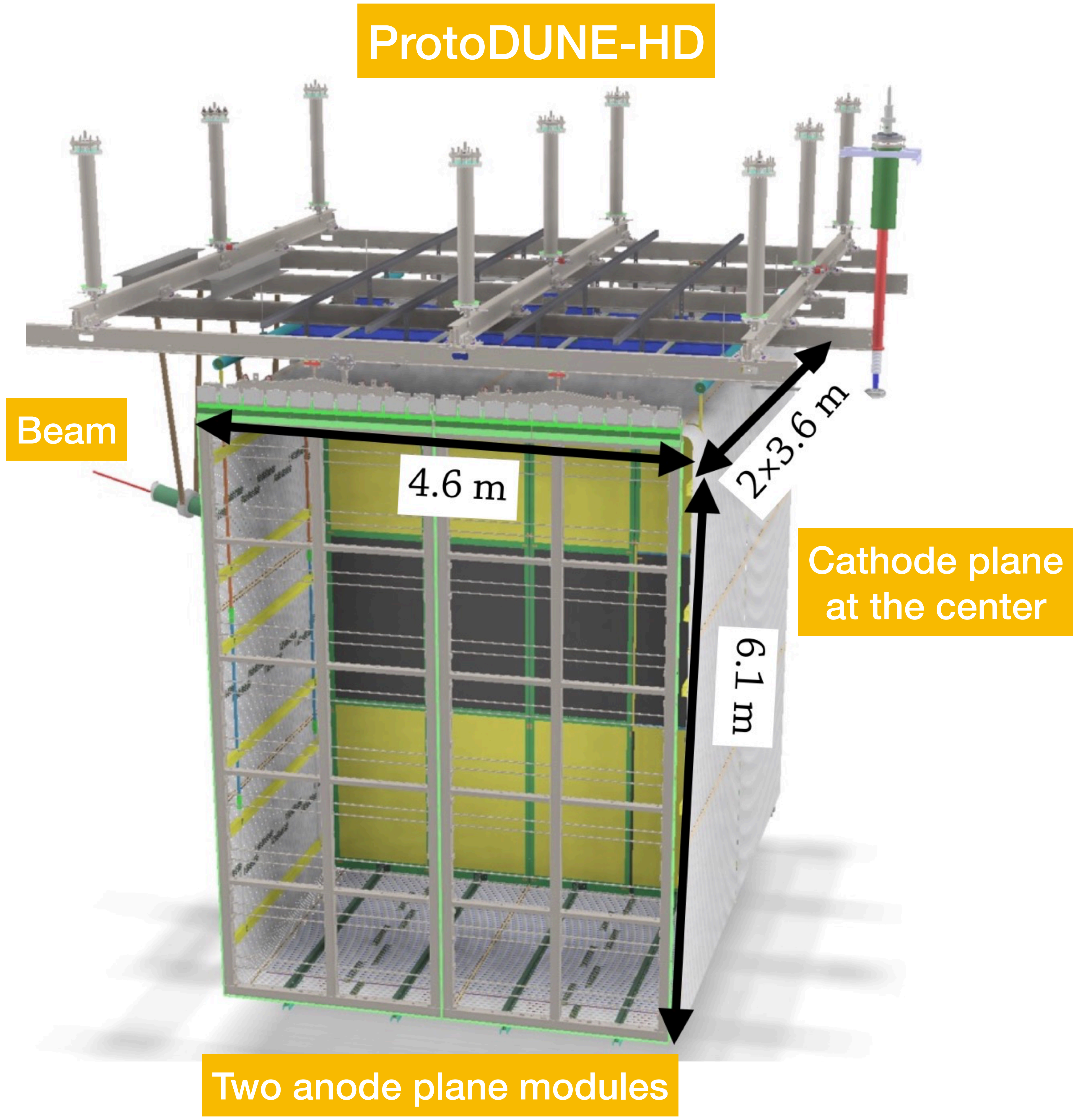


(2) Far Detector (FD) - Prototyping

- Second run is ongoing this year
- ProtoDUNE-HD
  - Argon filling completed in 30th April
  - First week of beam : 19th-26th June, > 3M events



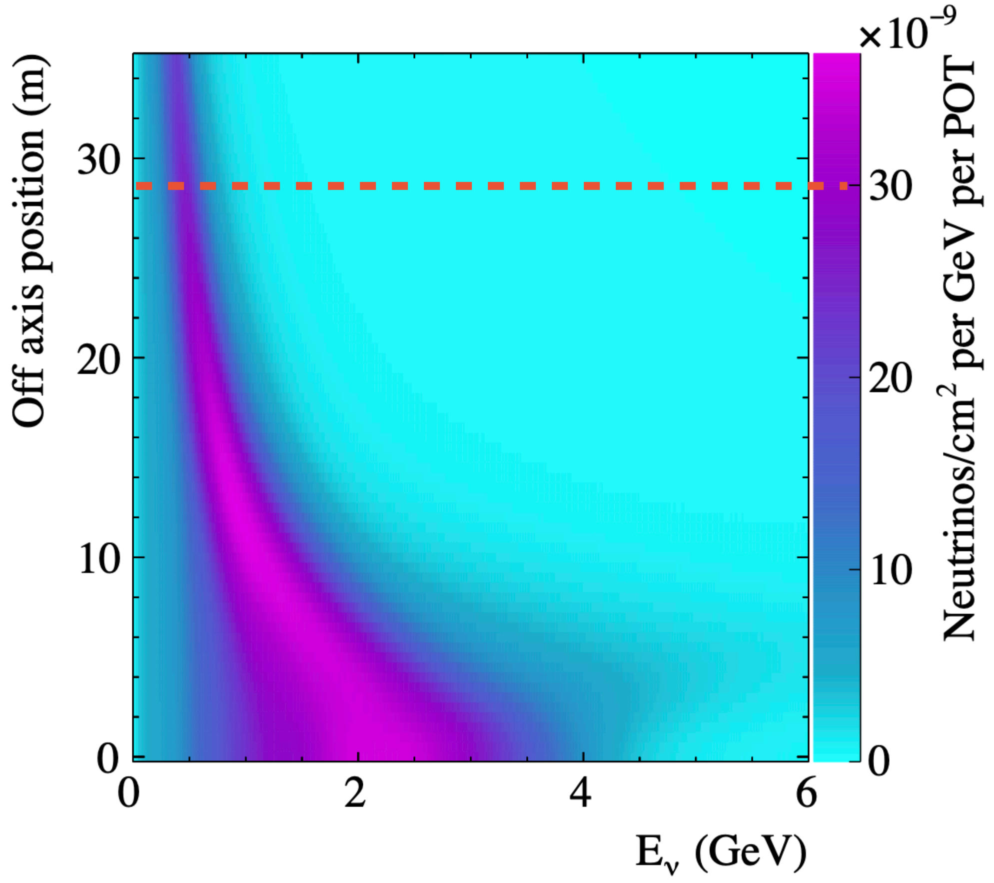
- ProtoDUNE-VD
  - LAr will be transferred in October to start run in early 2025

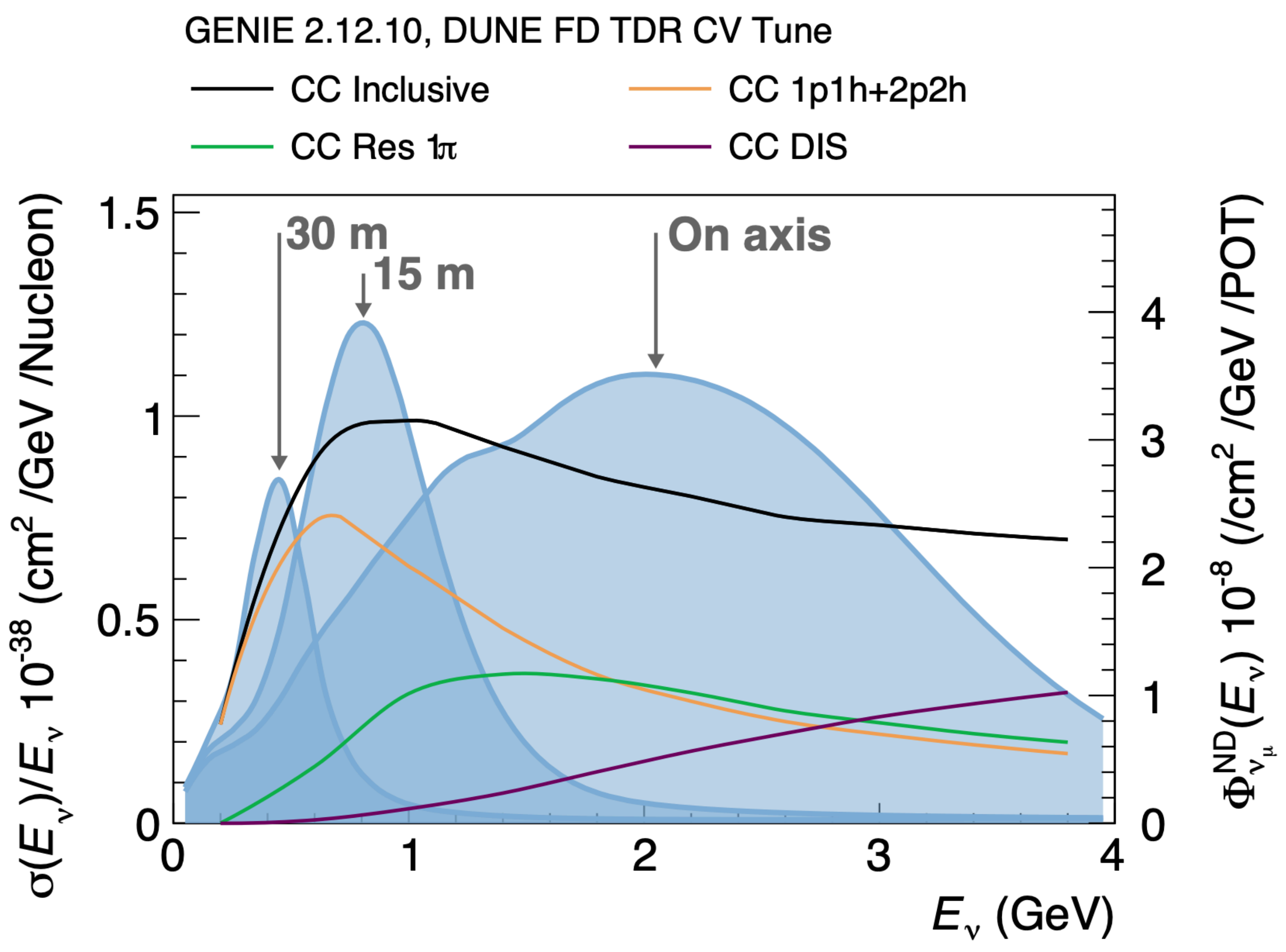


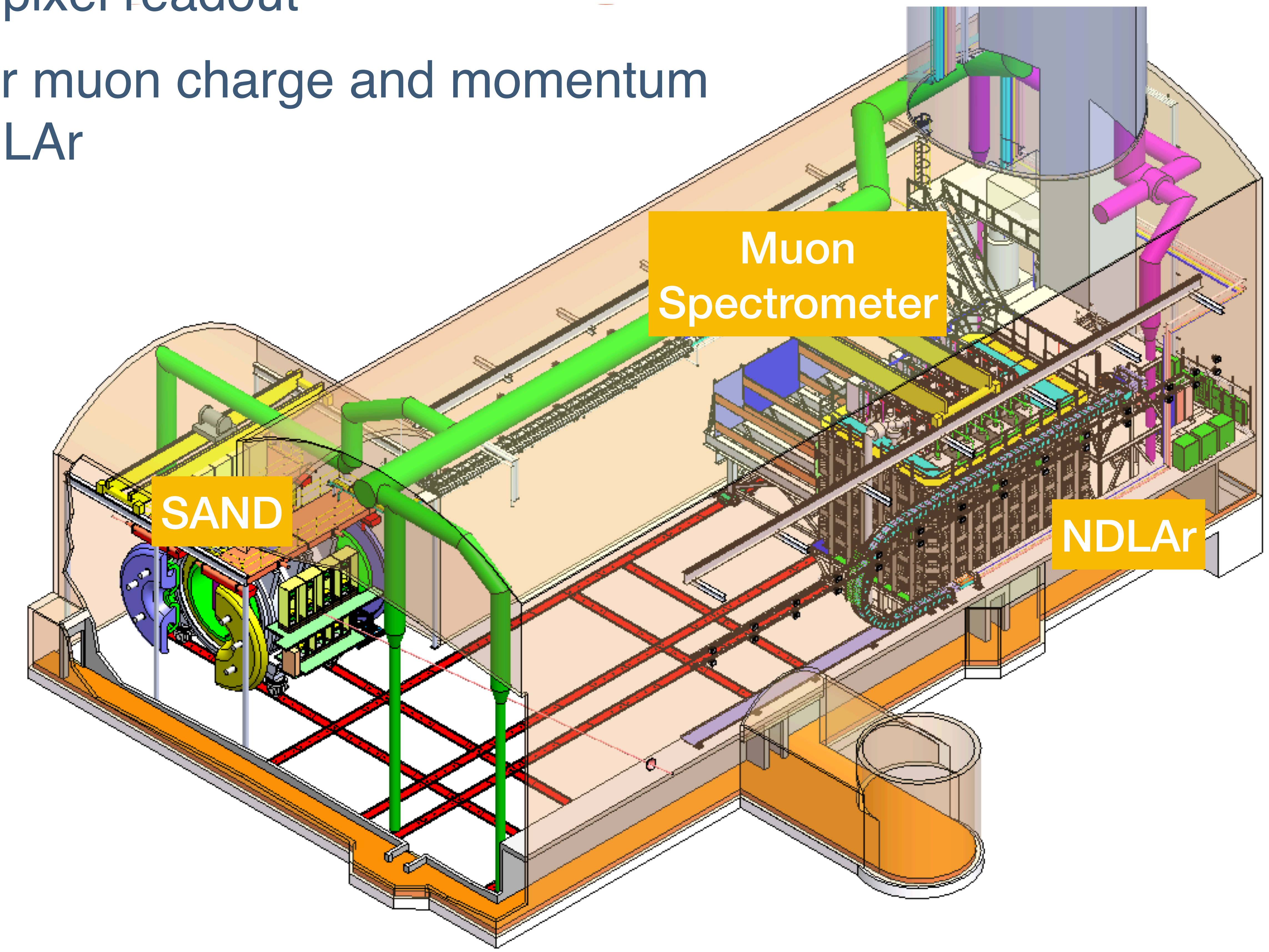
(3) Near Detector (ND)

- The ND hall will be located 574 m downstream from the target
- Movable LArTPC system
  - ND-LAr : 7×5 array of $1 \times 1 \times 3\ \mathrm{m}^3$ LArTPCs with pixel readout
  - Muon spectrometer : magnetized steel range stack for muon charge and momentum measurements from ν_μCC interactions inside the ND-LAr
  - Move up to 28.5 m off-axis
- SAND : on-axis magnetized neutrino detector

Instruments 5 (2021) 4, 31

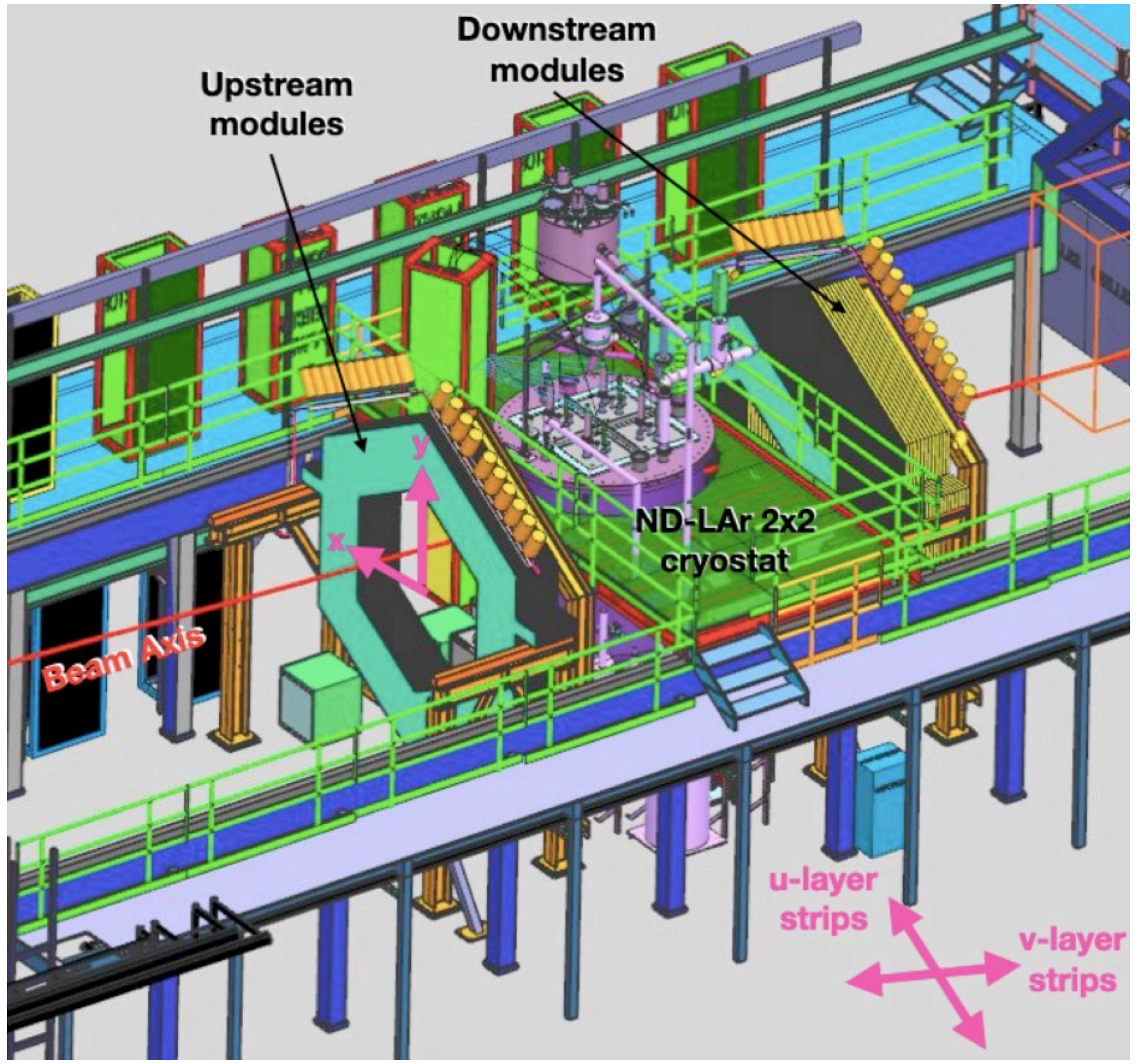


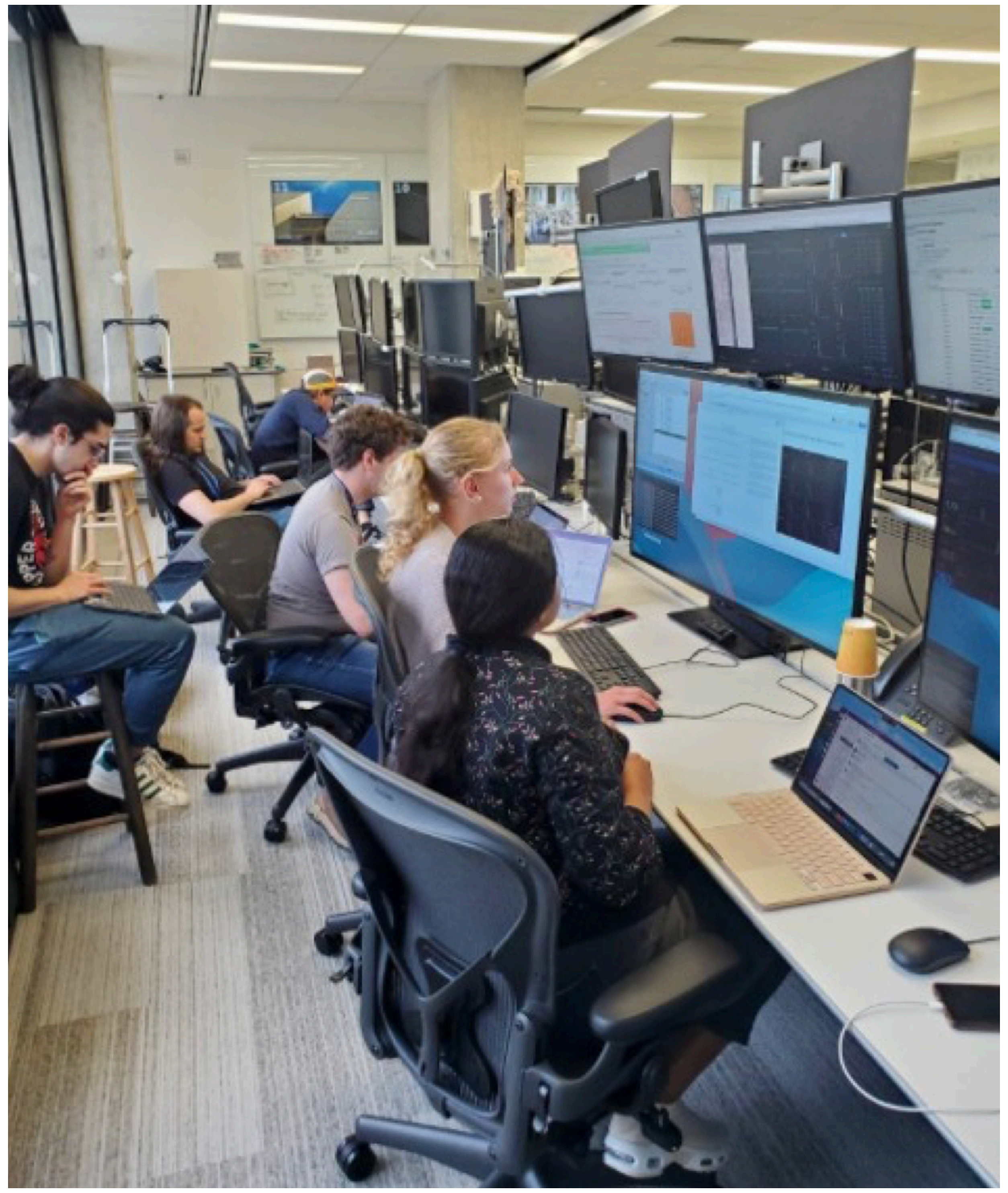




(3) Near Detector (ND) - Prototyping

- The 2x2 demonstrator: demonstration of ND-LAr design with 4 modules at ~ 60% scale
  - Together with reconfigured Minerνa modules
- Detector installation, LAr fill, and commissioning complete
- Currently operating with high LAr purity and 500 V/cm nominal electric field





DUNE Phase-I in 2023 P5 Report

- Introduced only DUNE Phase-I status/plan so far

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

a. HL-LHC;

b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos. Knowledge of this fundamental property is a crucial input to cosmology and nuclear science (elucidate the mysteries of neutrinos, section 3.1).

c. …

DUNE Phase-II Upgrade

- (1) High intensity neutrino source
  - Beam intensity upgrade to beyond 2 MW from PIP-II’s 1.2 MW
  - ACE-MIRT : 2 MW without new accelerator construction
  - ACE-BR : 2.4 MW with booster replacement

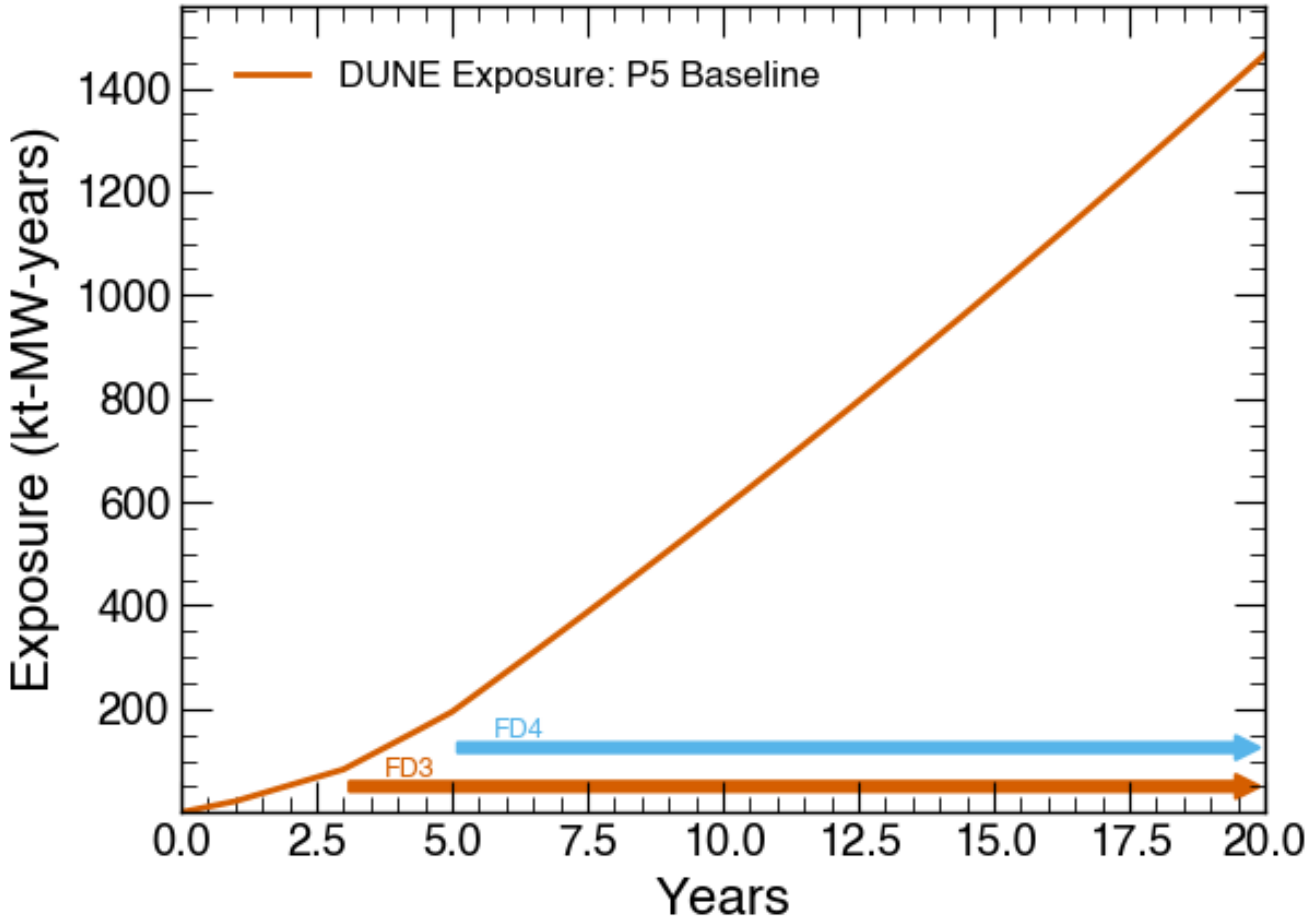
- (2) Far detector
  - Two more 17kt LArTPCs - baseline design is VD

- (3) Near detector
  - More capable near detector (MCND) : high pressure gas argon TPC (ND-GAr) with ECAL under B-field
  - Low energy threshold with better energy resolution and PID performance

- Most of these plans were re-envisioned in 2023 P5 report
  - FD4 : “yes” in more favorable budget scenario, and “R&D only” in other cases
  - ACE-MIRT : “R&D only” for less favorable budget scenario
  - ACE-BR : “Conditionally yes after review” in more favorable budget scenario, and “R&D only” in other cases

DUNE Physics Sensitivity

- Beam exposure scenario is based on the P5 baseline



DUNE Physics Sensitivity - Mass Ordering

- Energy spectrum of electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$) events constrains the mass ordering

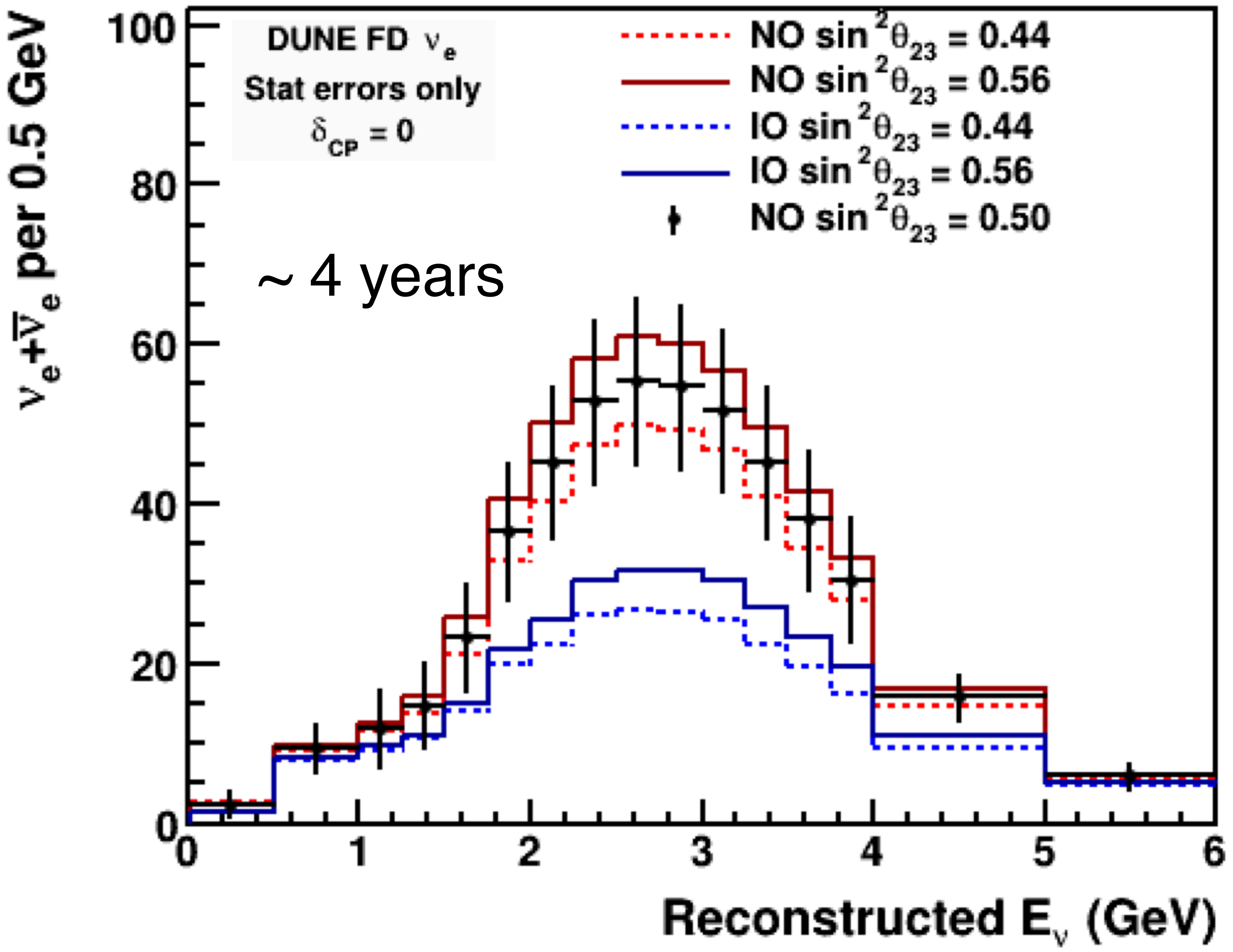
$$P_{\nu_\mu\to\nu_e,(\bar{\nu}_\mu\to\bar{\nu}_e)} \approx 4\,\sin^2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\,\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2} + 8\,\alpha\,J_{\mathrm{CP}}^{\mathrm{max}}\cos(\Delta\pm\delta_{\mathrm{CP}})\,\frac{\sin\Delta A}{A}\,\frac{\sin\Delta(1-A)}{1-A}$$

$$J_{\mathrm{CP}}^{\mathrm{max}} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}\,,$$

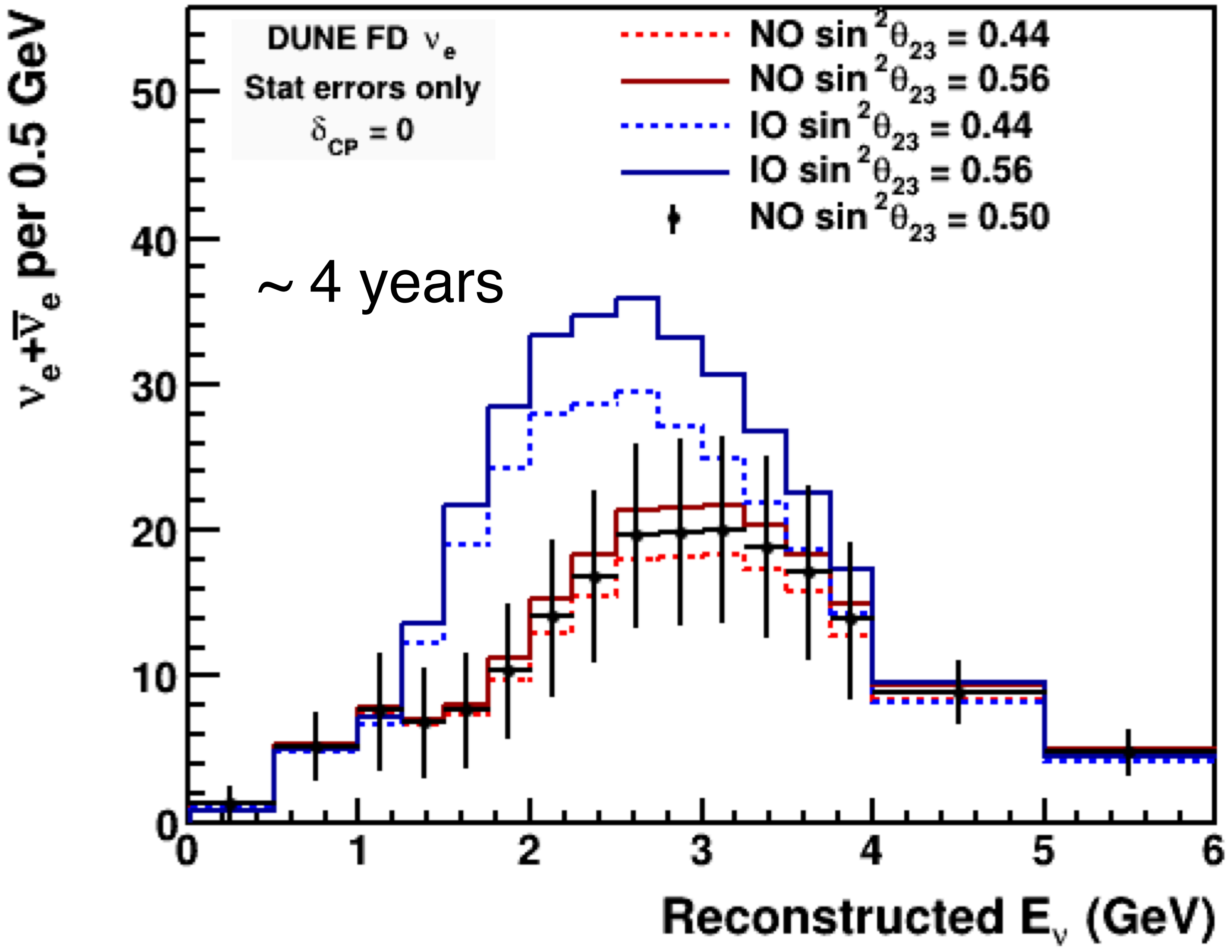
$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$$

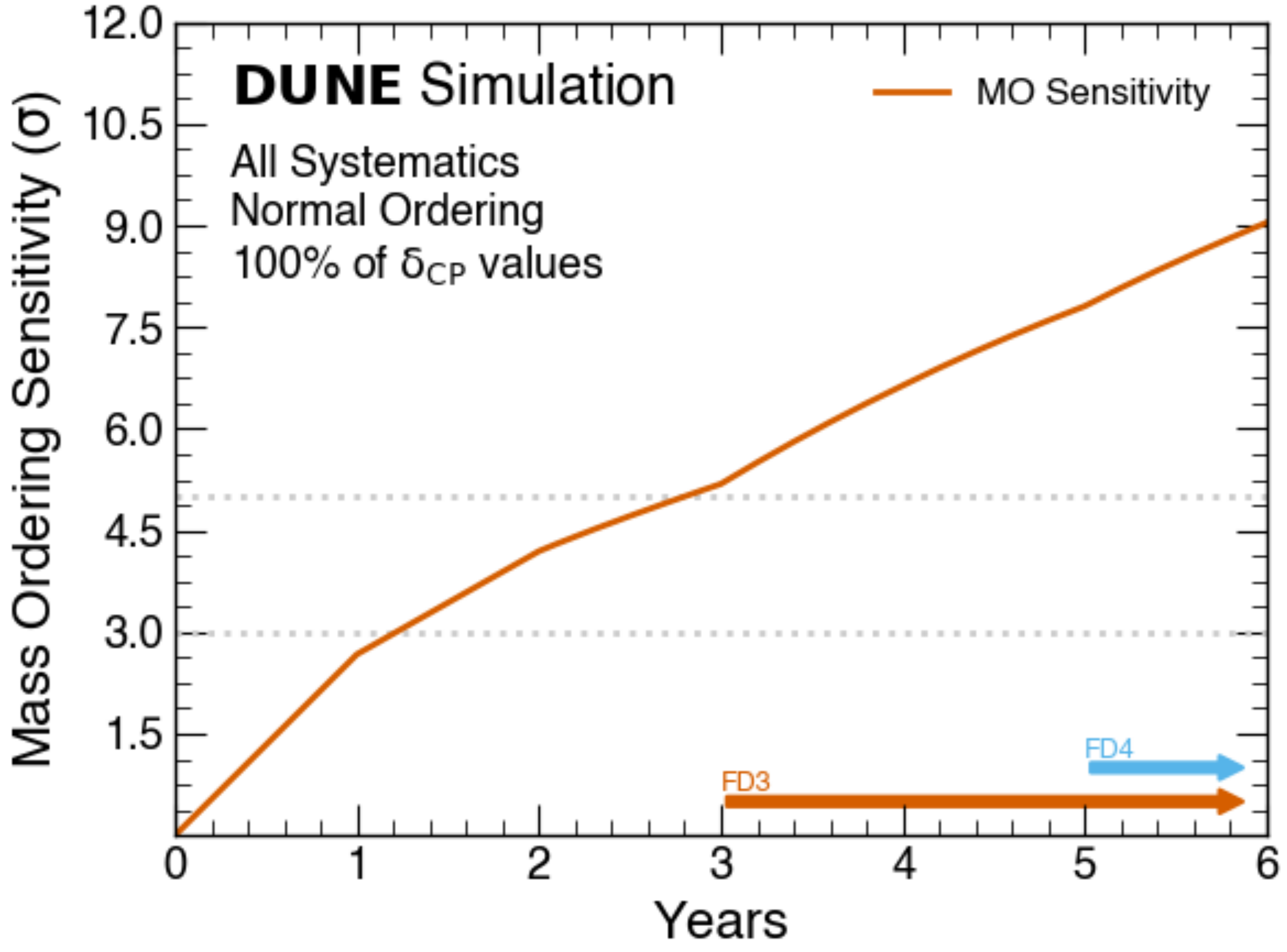
$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu}\,,\qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}\,,$$

Beam ν mode



Beam $\bar{\nu}$ mode





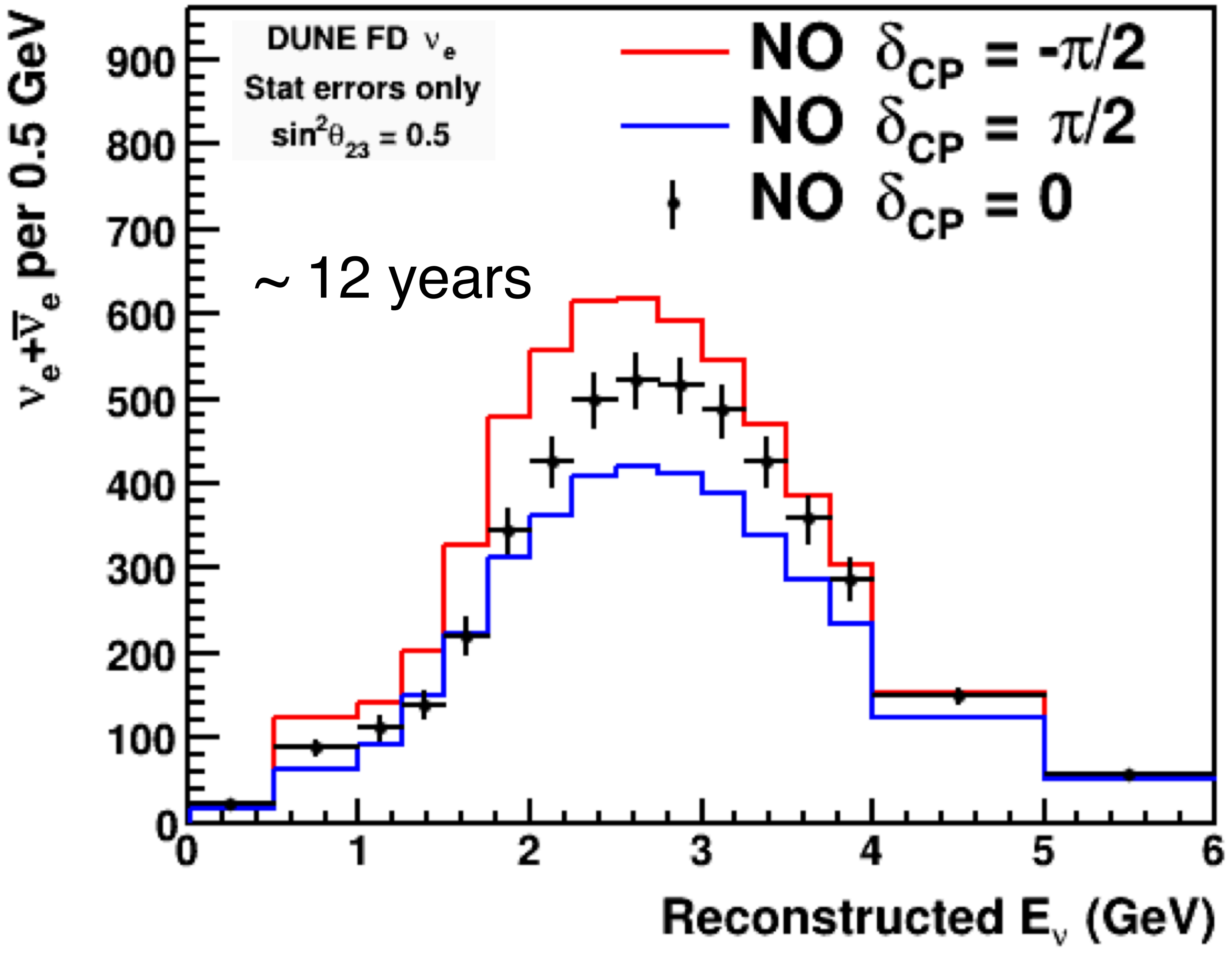
DUNE Physics Sensitivity - δ_{CP}

- Energy spectrum of electron neutrino appearance ($\nu_\mu \rightarrow \nu_e$) events constrains the mass ordering

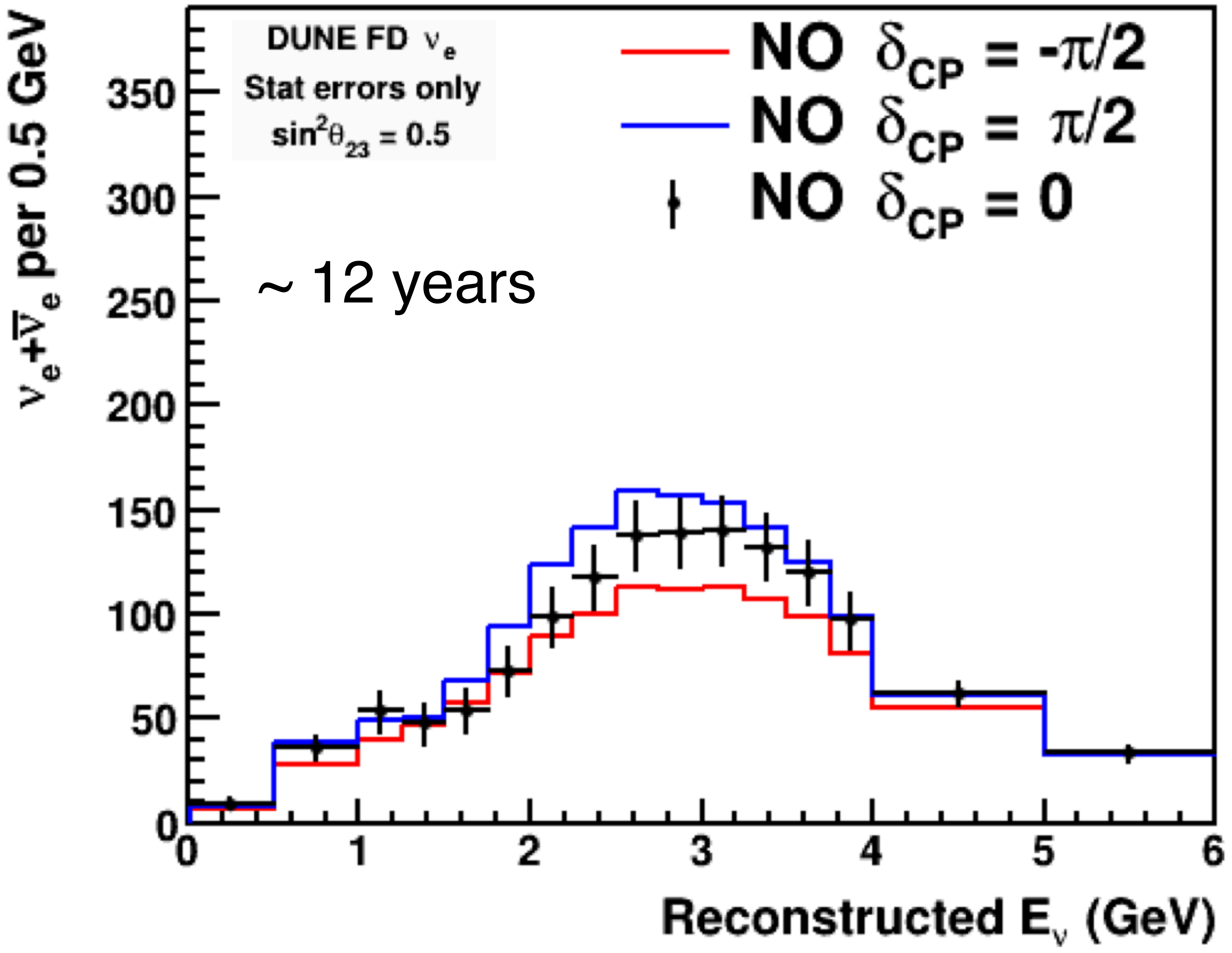
$$P_{\nu_\mu\to\nu_e,(\bar\nu_\mu\to\bar\nu_e)} \approx 4\,\sin^2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\,\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2} + 8\,\alpha\,J_{\mathrm{CP}}^{\max}\cos(\Delta\pm\delta_{\mathrm{CP}})\,\frac{\sin\Delta A}{A}\,\frac{\sin\Delta(1-A)}{1-A}$$

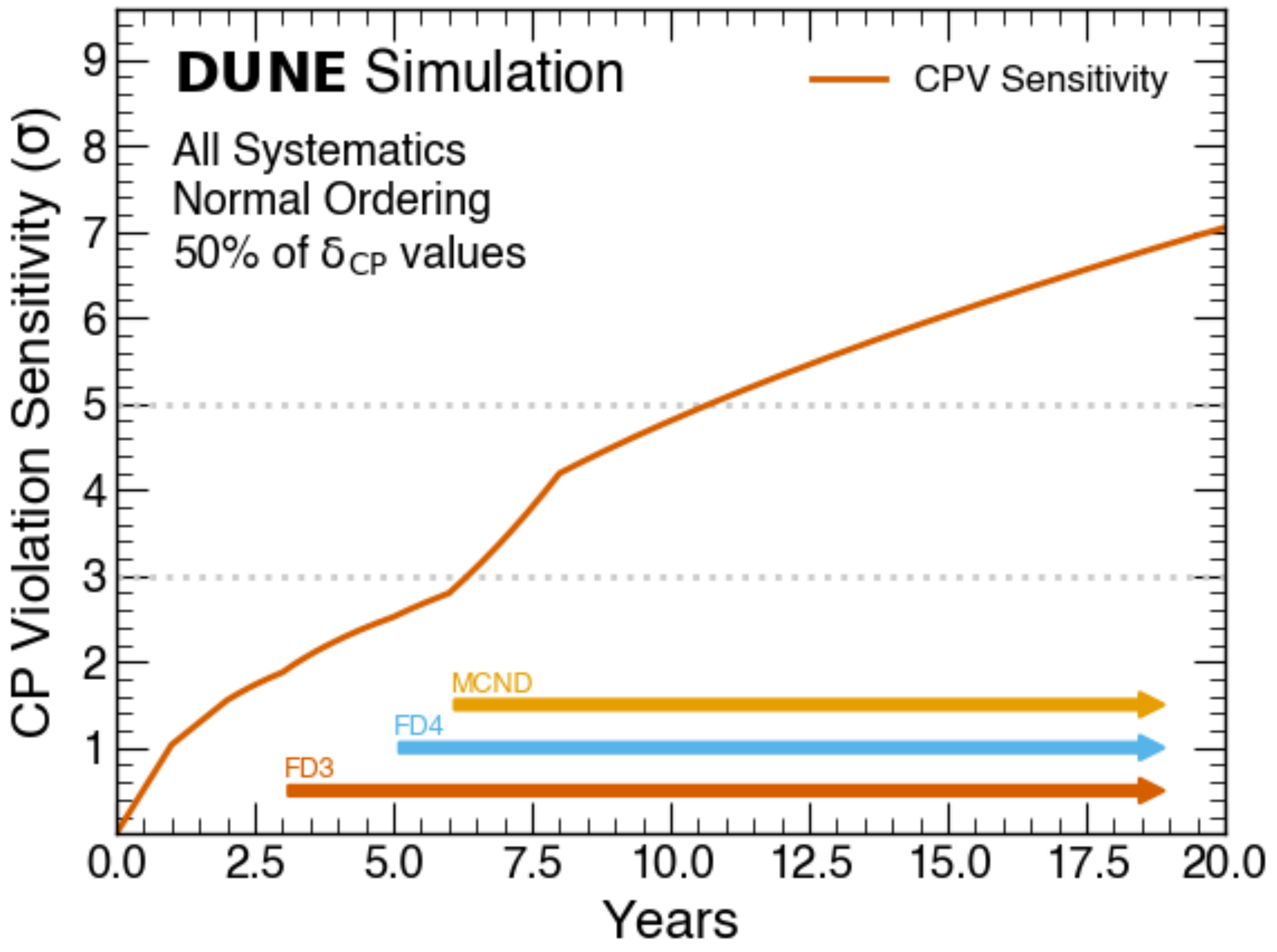
$$J_{\mathrm{CP}}^{\max} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}\,,$$
$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$$
$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu}\,, \quad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}\,,$$

Beam ν mode



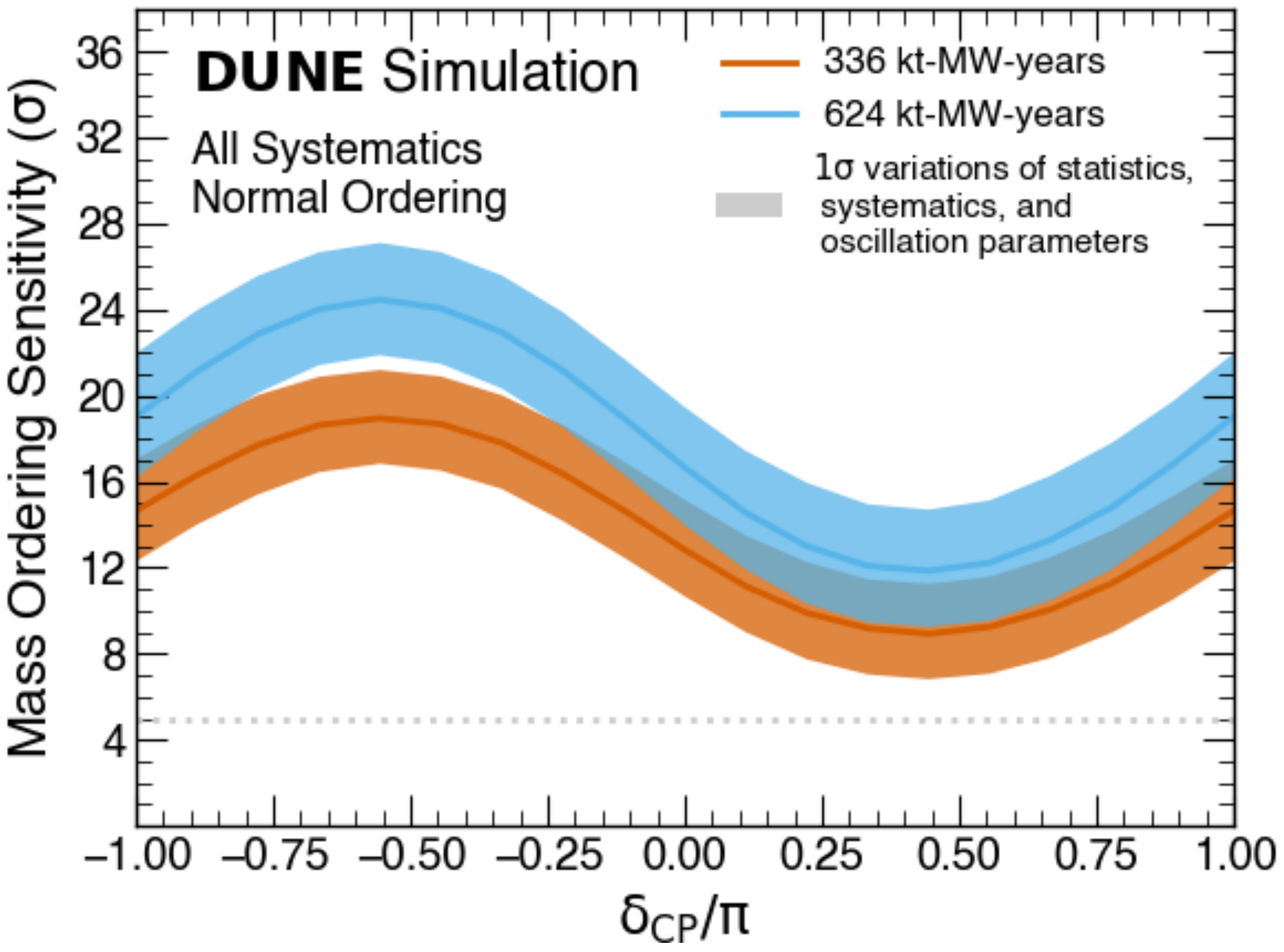
Beam $\bar\nu$ mode

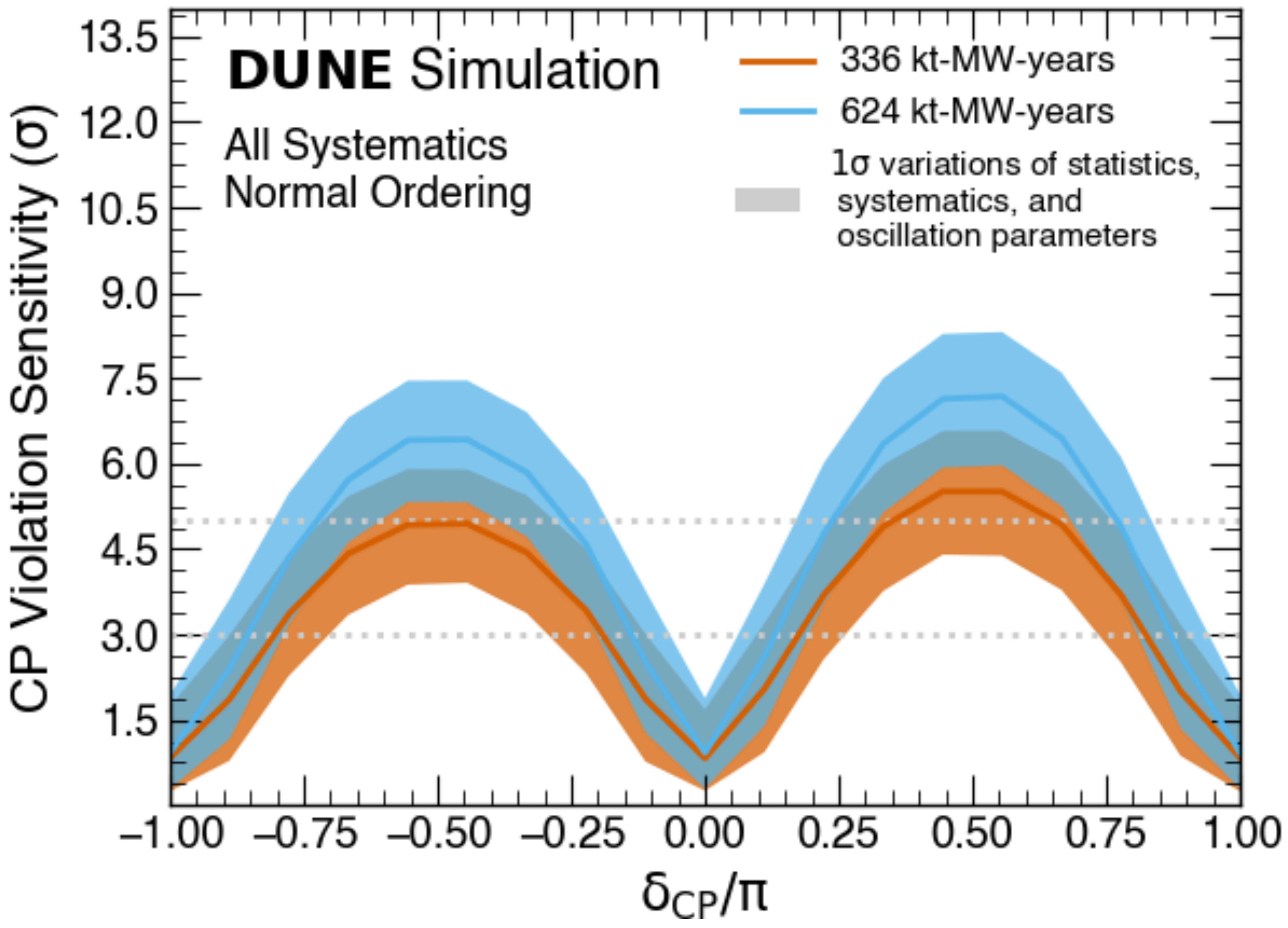




DUNE Physics Sensitivity - Mass Ordering & δ_{CP}

- 336-kt-MW-years ~ 6.5 years
- 624 kt-MW-years ~ 10.5 years

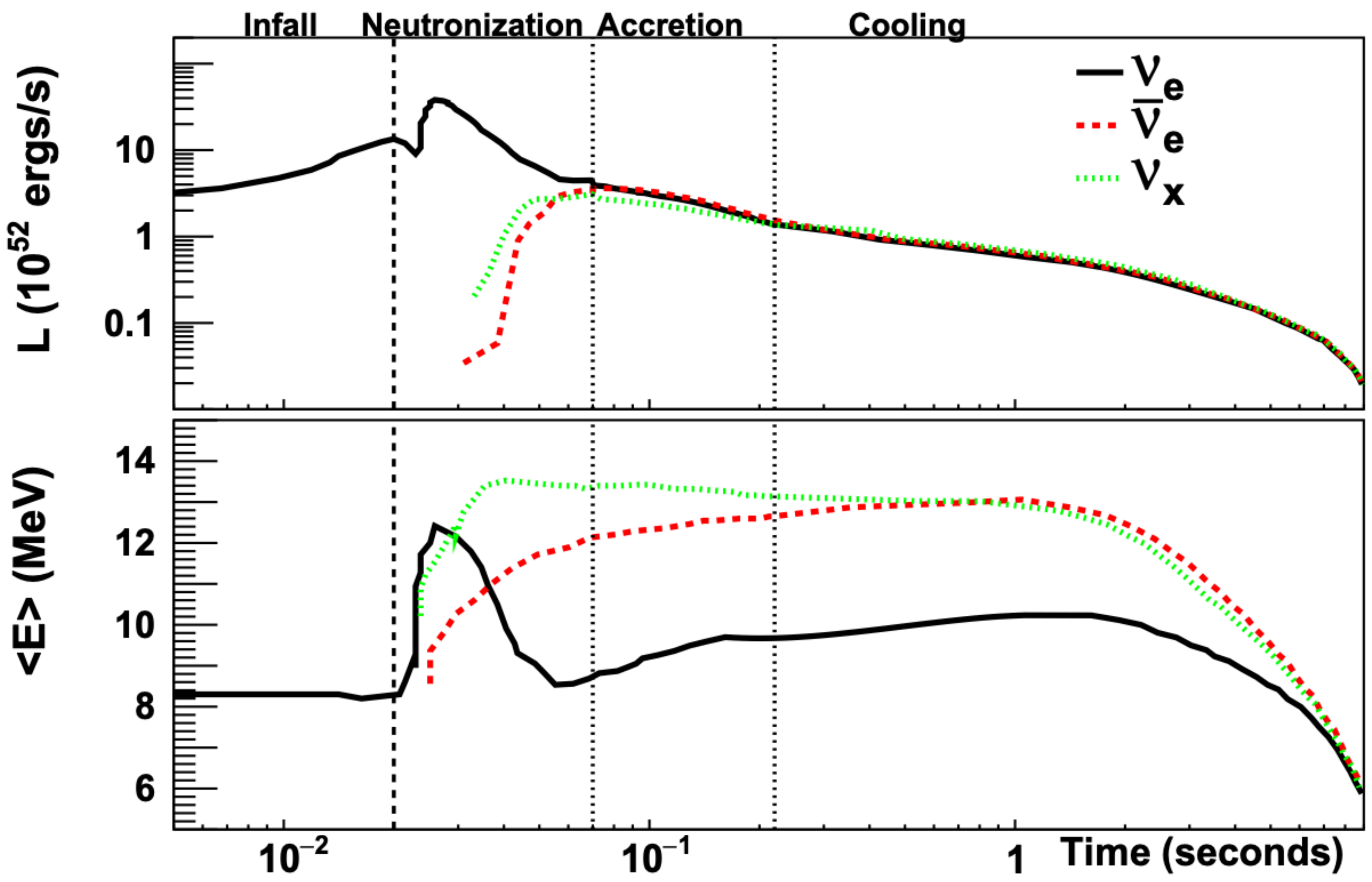




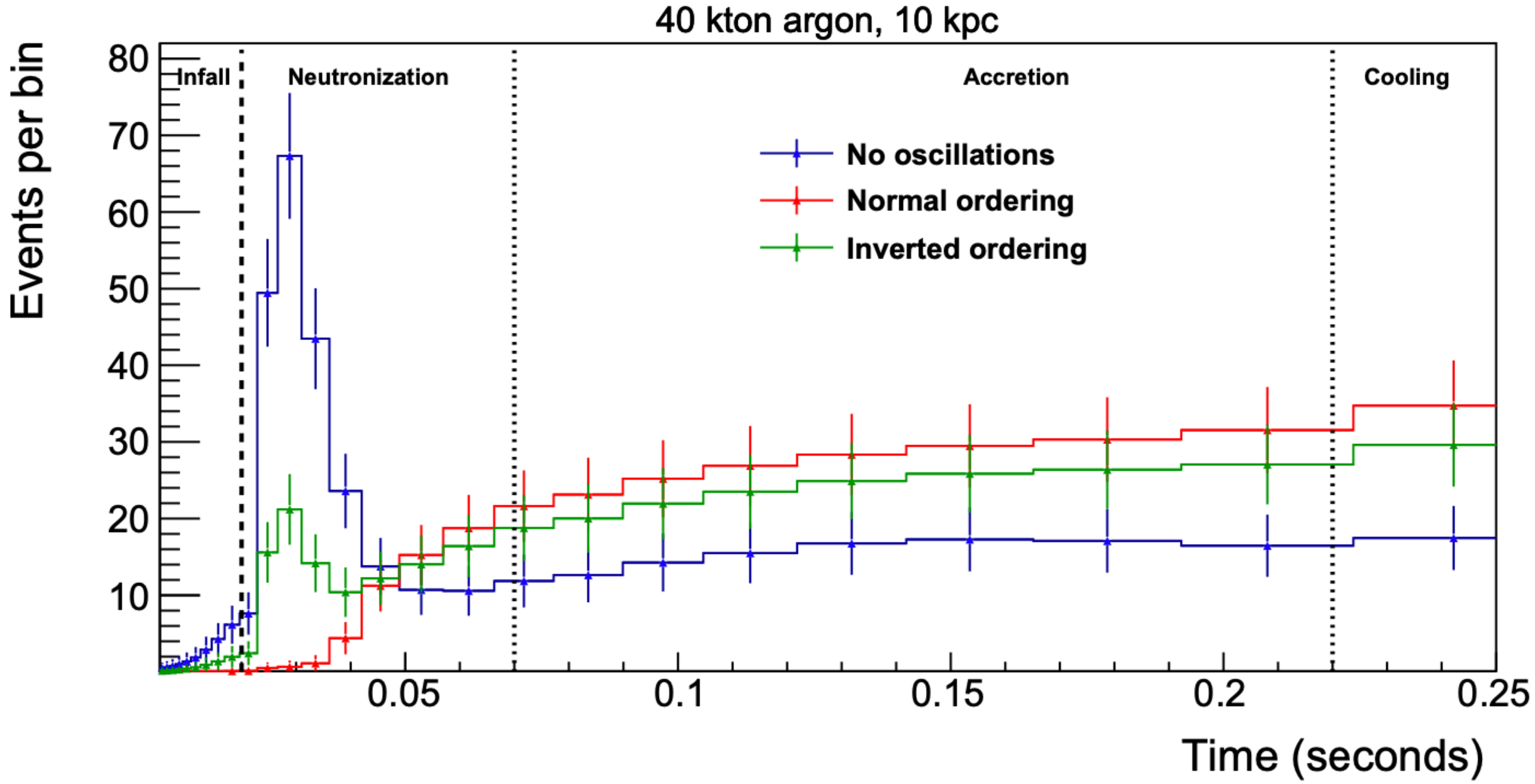
DUNE Physics Sensitivity - Core-collapse Supernova

- DUNE will observe ~ thousands of neutrino interactions from next Galactic core-collapse supernova
- Unique chance to understand
  - Neutrino properties such as the mass ordering
  - Supernova neutrino burst spectrum modeling

Eur. Phys. J. C (2021) 81: 423



Supernova @ 10 kpc



DUNE Physics Sensitivity - Core-collapse Supernova

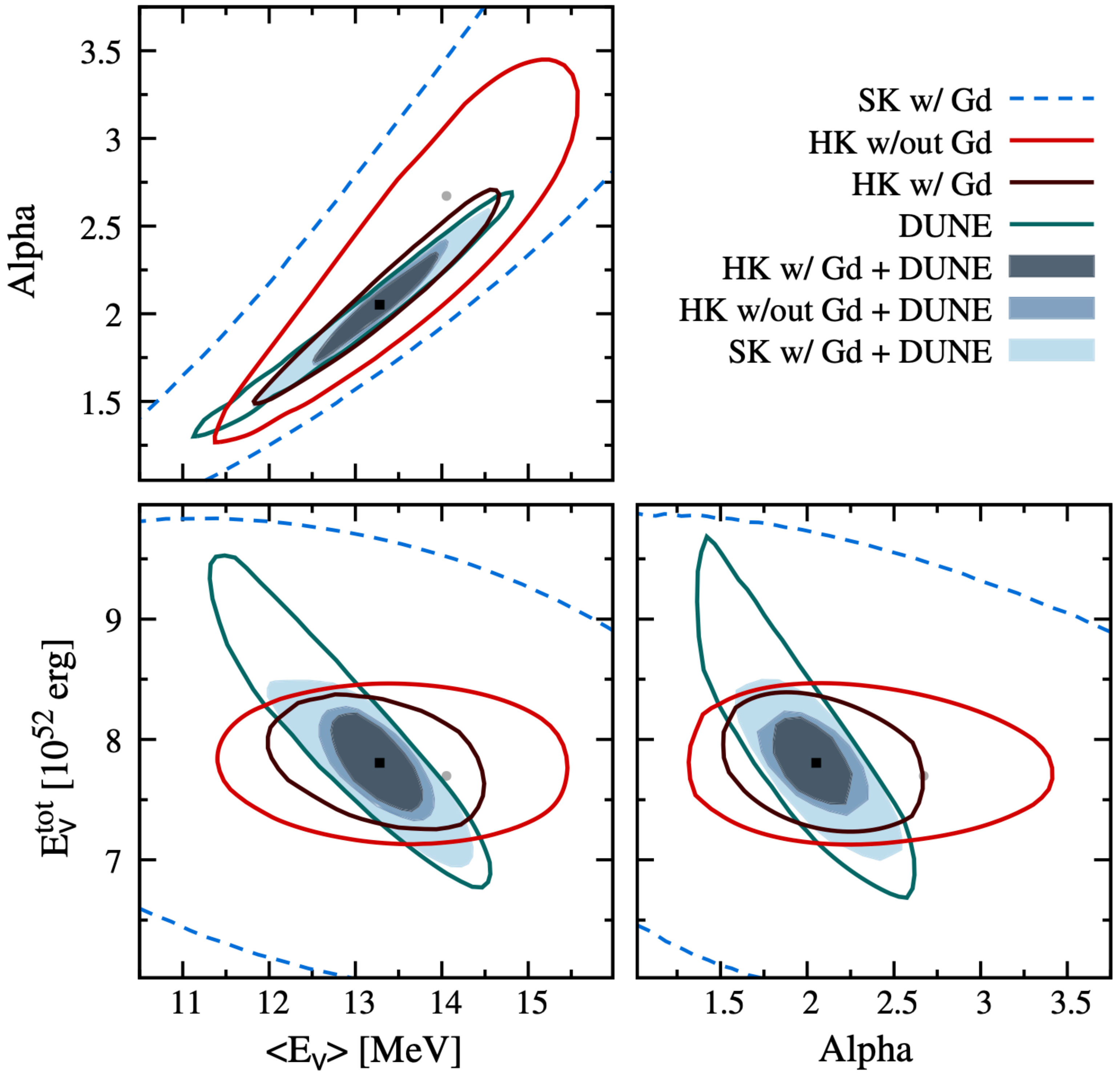
- DUNE will observe ~ thousands of neutrino interactions from next Galactic core-collapse supernova
- Unique chance to understand
  - Neutrino properties such as the mass ordering
  - Supernova neutrino burst spectrum modeling

Supernova neutrino burst flux parameterization with α and $<\mathrm{E}_\nu>$

$$\boxed{\frac{dN_\nu}{dE_\nu}(E_\nu) = A\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right],}$$

$$\boxed{A = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu\rangle\Gamma(\alpha+1)}}$$

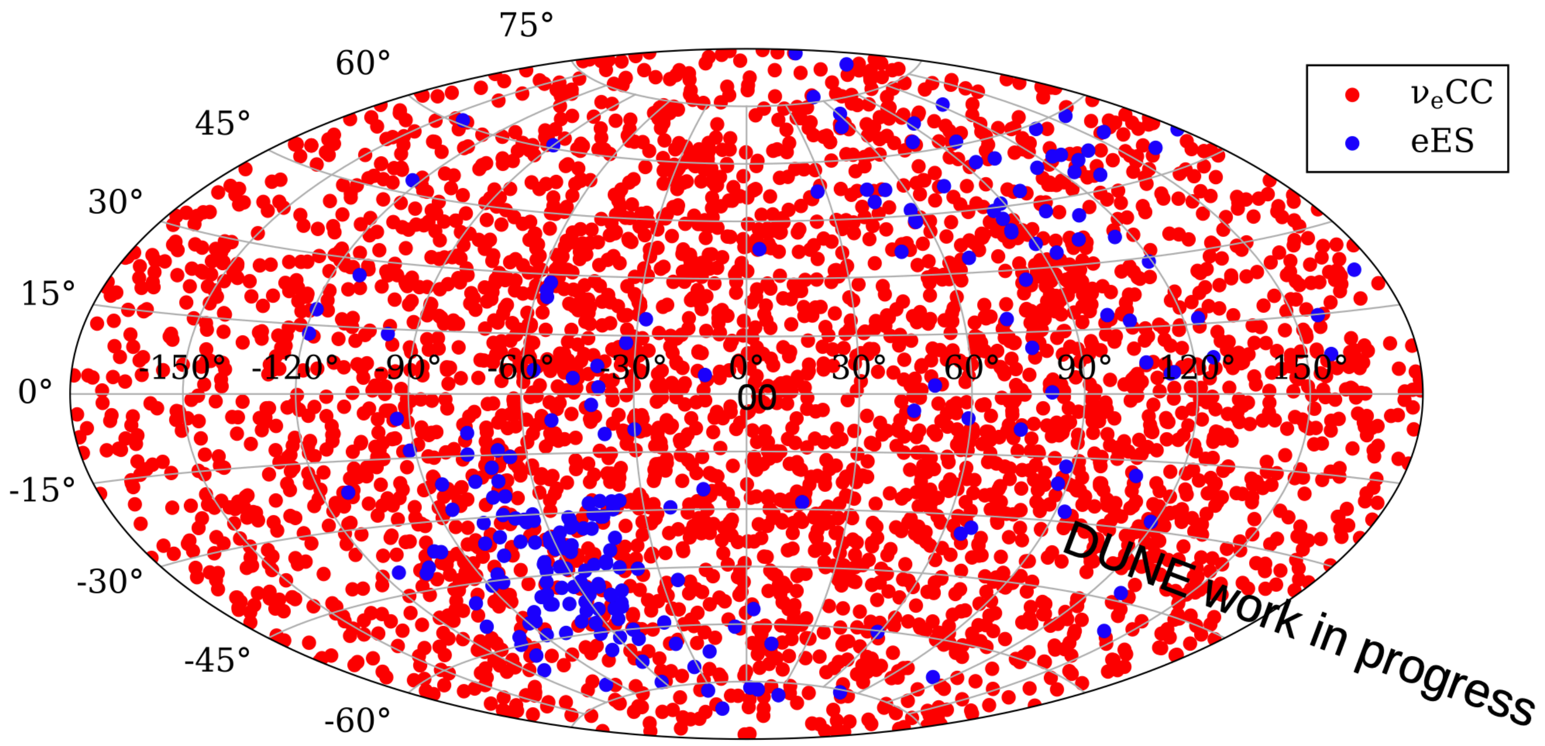
Astrophys.J. 590 (2003) 971-991

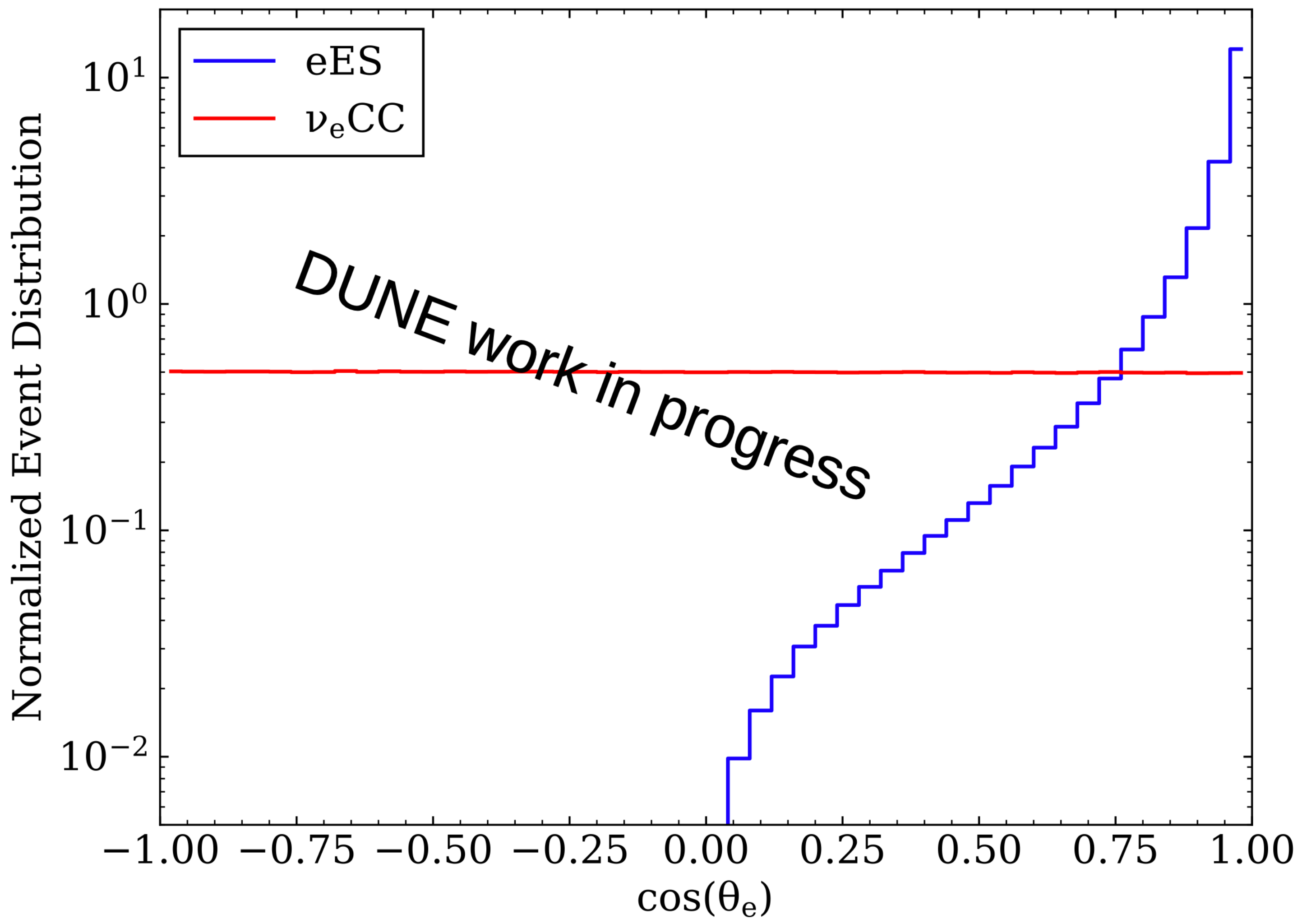


Phys. Rev. D 97, 023019

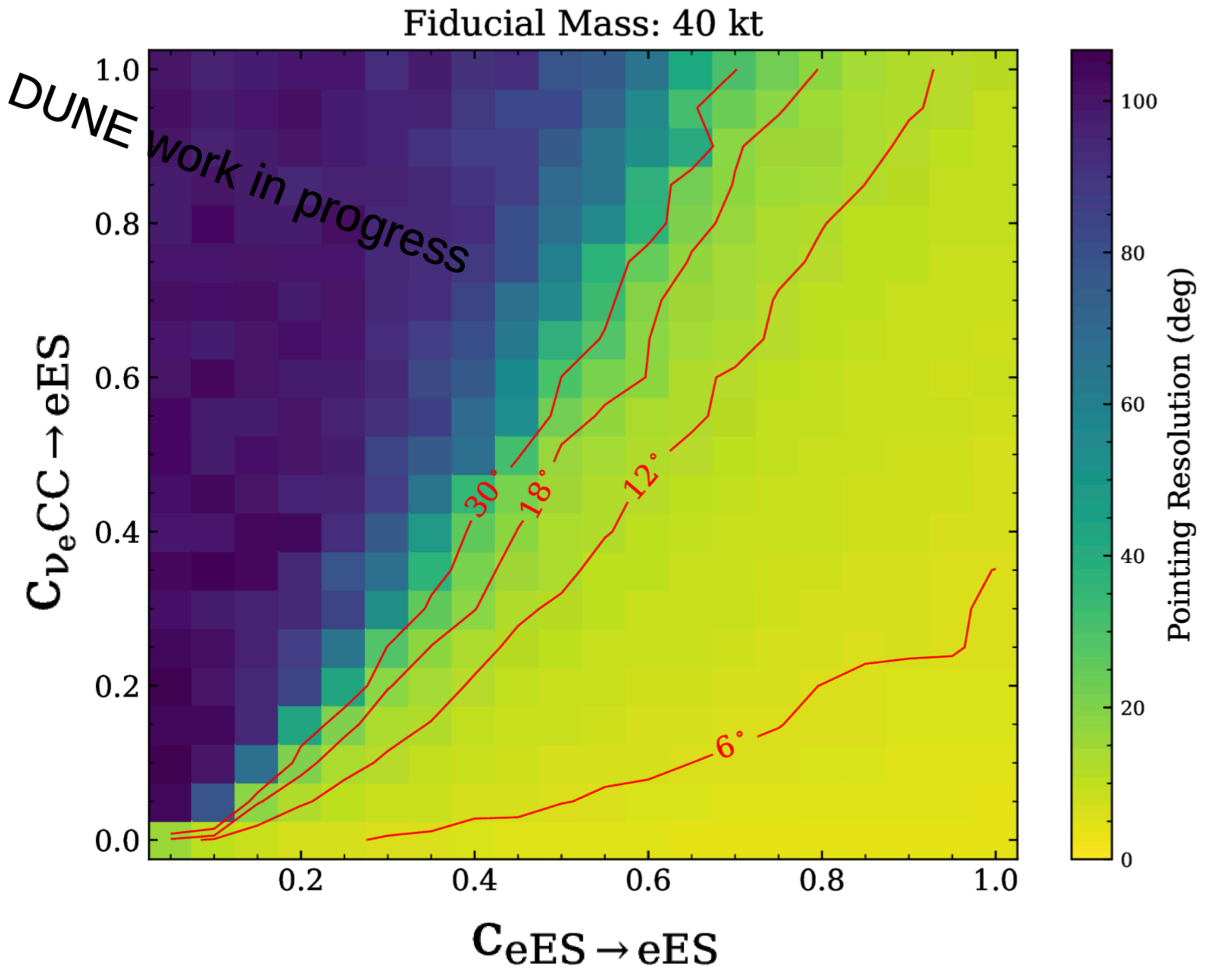
DUNE Physics Sensitivity - Core-collapse Supernova Pointing

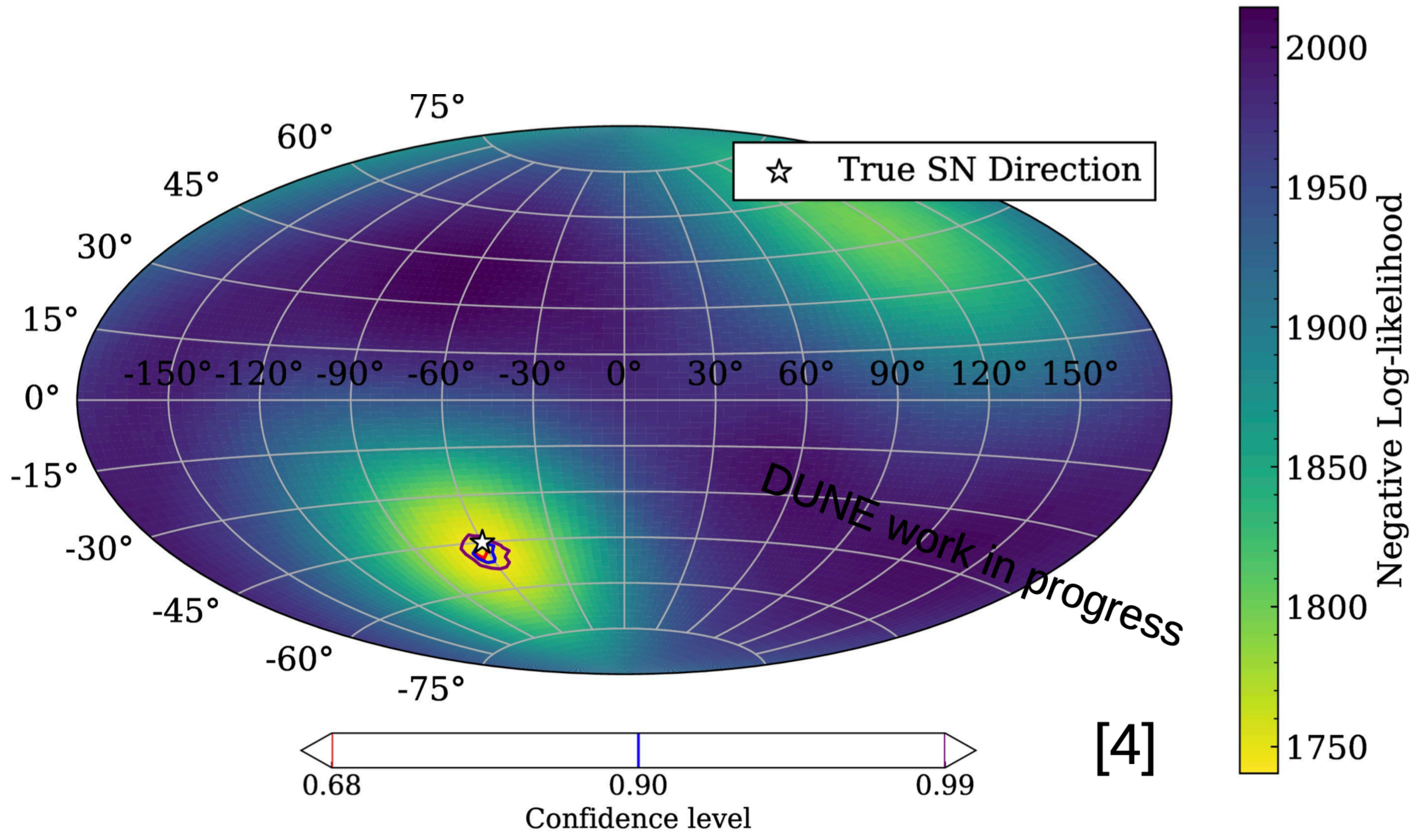
- DUNE can detect ν_e from supernova neutrino bursts
- Dominant channels
  - ν_eCC ($\nu_e + \mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}*$) : ~ 3k events for supernova at 10 kpc
  - eES ($\nu_e + e^- \rightarrow \nu_e + e^-$) : ~ 0.3k events for supernova at 10 kpc
- ~ 5° pointing resolution with $\mathrm{P}(\nu_e\mathrm{CC} \rightarrow \mathrm{eES})$ = 4% at 10 kpc
- Paper is imminent





Angle between ν_e and e^-



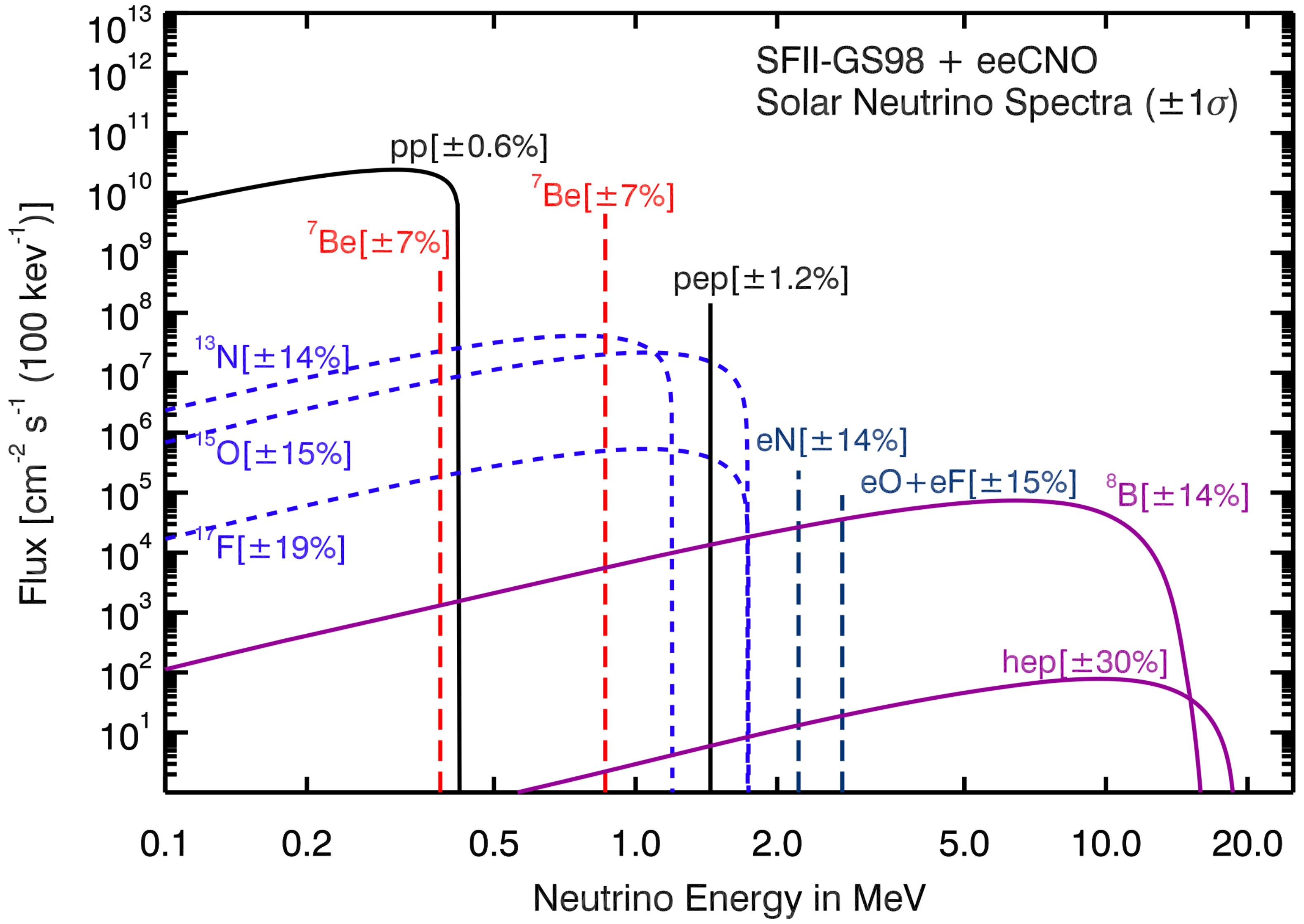


[4]

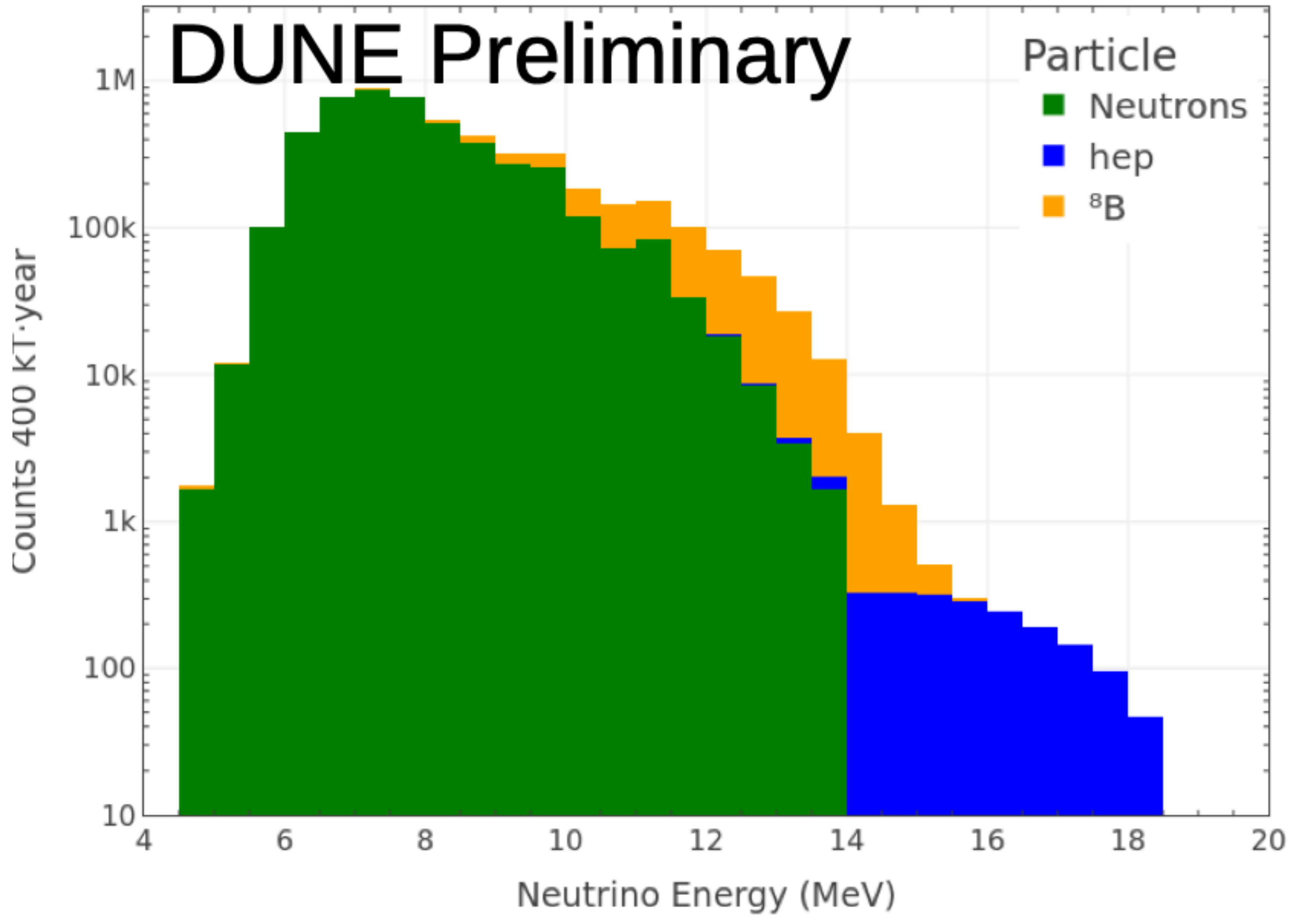
Example pointing

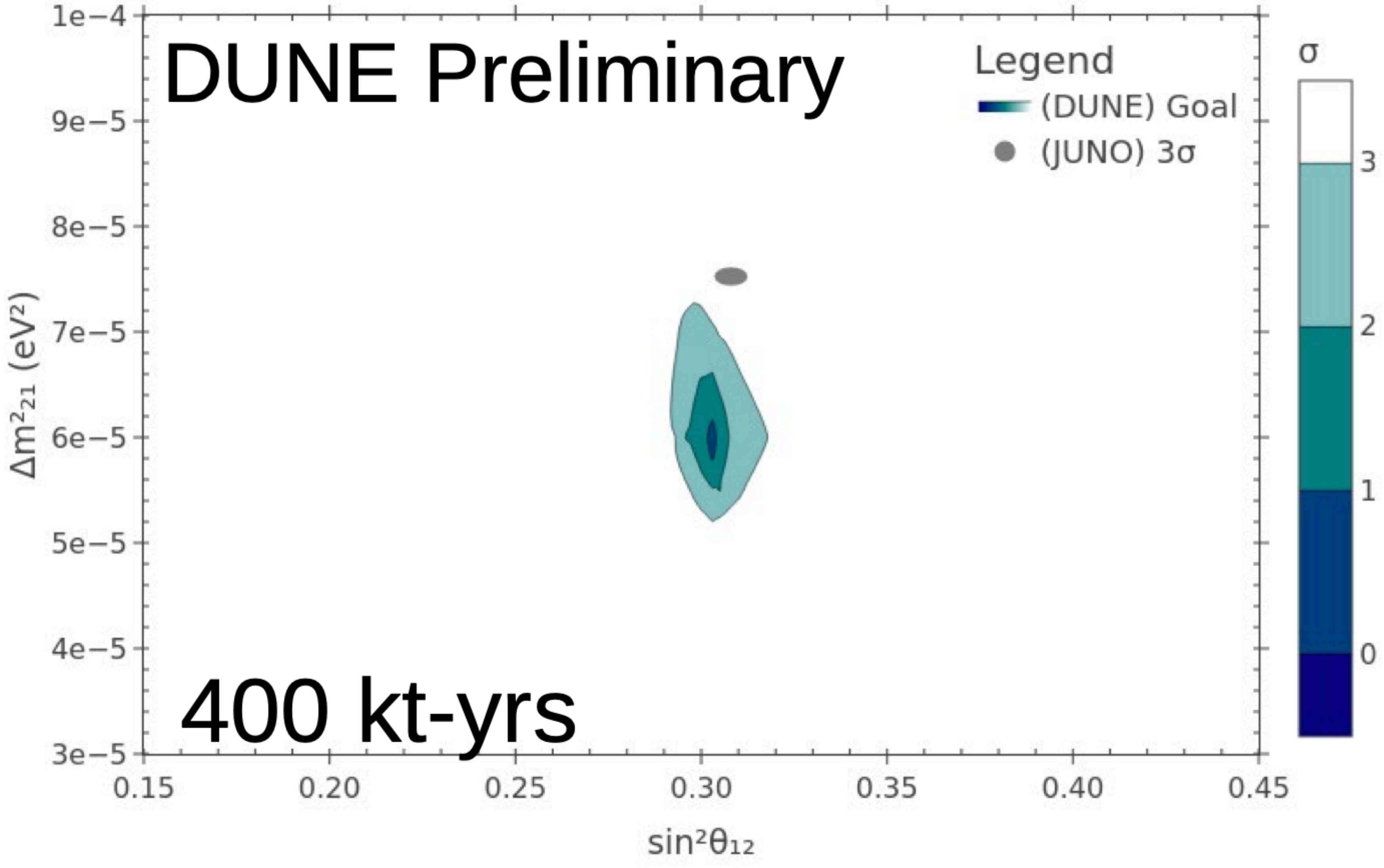
DUNE Physics Sensitivity - Solar Neutrinos

- DUNE has excellent sensitivity for solar neutrinos with energy above 10 MeV
- Understanding better the pp chain of the Sun
    - Discovering sensitivity for $^{3}\mathrm{He} + \mathrm{p} \rightarrow {}^{4}\mathrm{He} + \mathrm{e}^{+} + \nu_{\mathrm{e}}$ (hep)
- Improvement upon existing solar oscillation measurements
    - Using day-night asymmetry from the Earth matter effect
    - Current analysis assumes dedicated trigger and flash matching



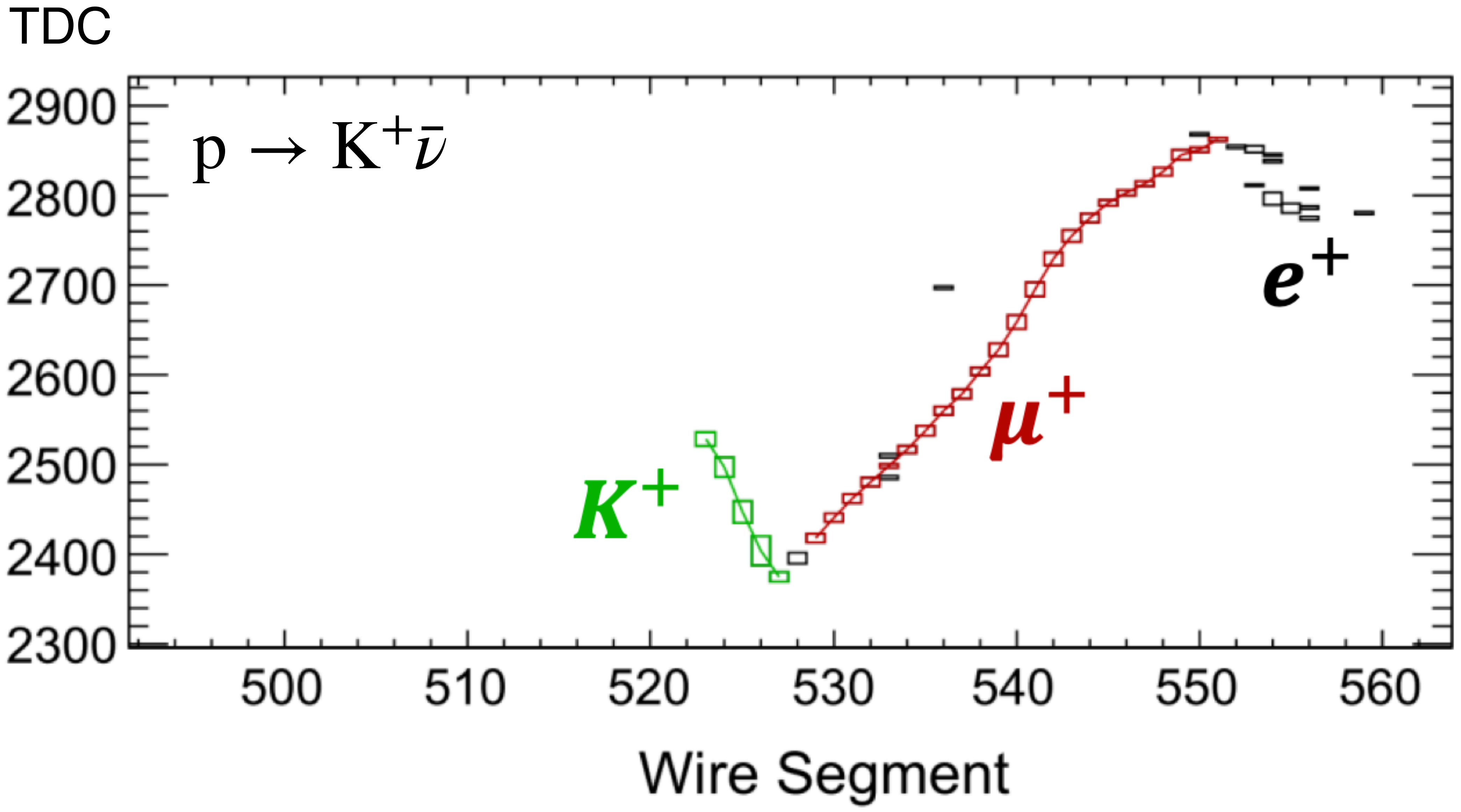
Eur.Phys.J.A 52 (2016) 4, 78





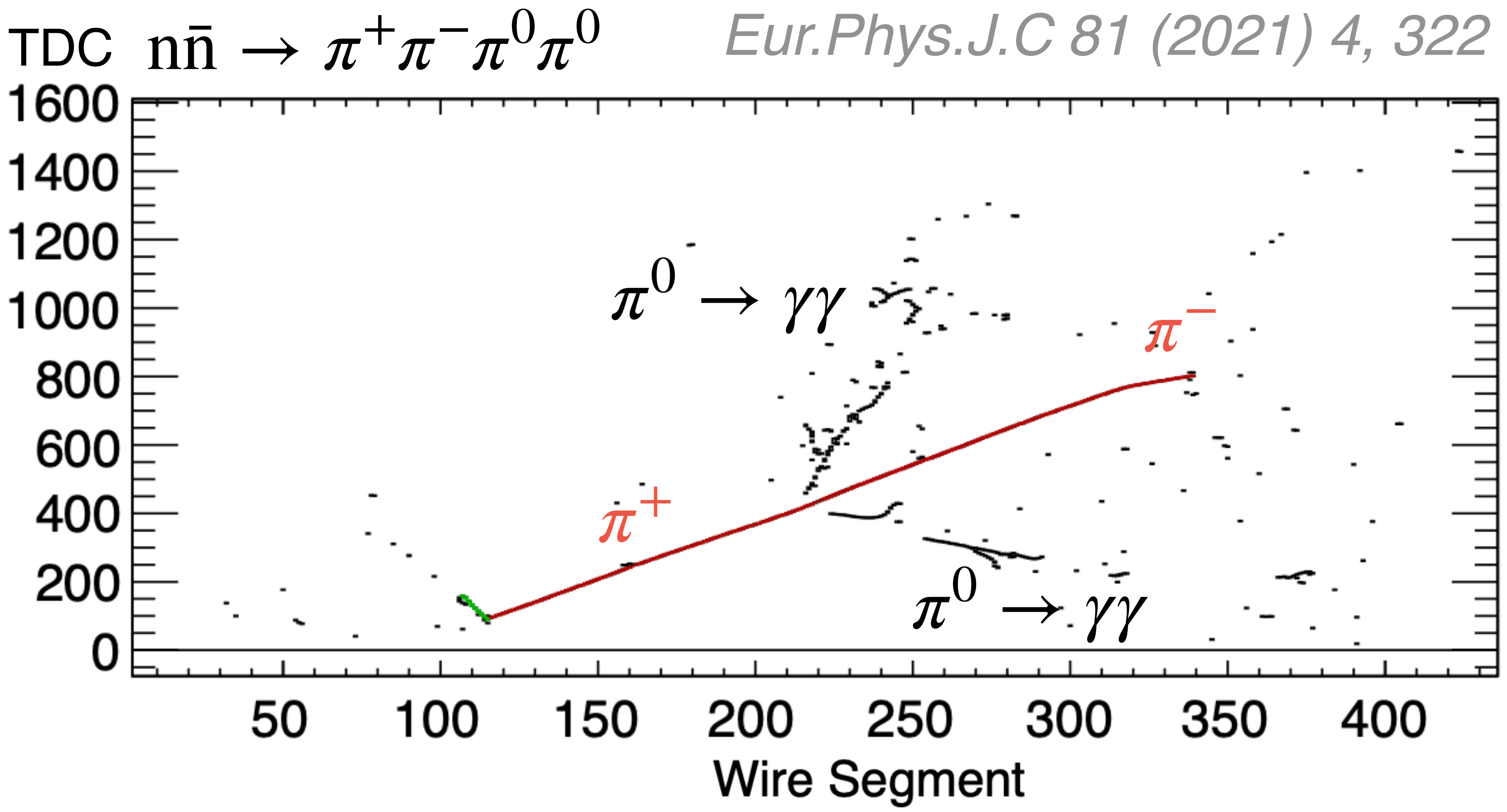
DUNE Physics Sensitivity - Baryon Number Violations

- Search for baryon number violation is important
  - Matter dominance of the universe - baryogenesis
  - Many Grand Unified Theories (GUTs) predict proton decays
  - Baryon number conservation is an accidental symmetry in the SM
- DUNE can record all particles from $\mathrm{p} \rightarrow \mathrm{K}^+\bar{\nu}$ decay
- Many pions signature of $\mathrm{n} \rightarrow \bar{\mathrm{n}}$ transition also can be detected



For $^{40}\mathrm{Ar}$

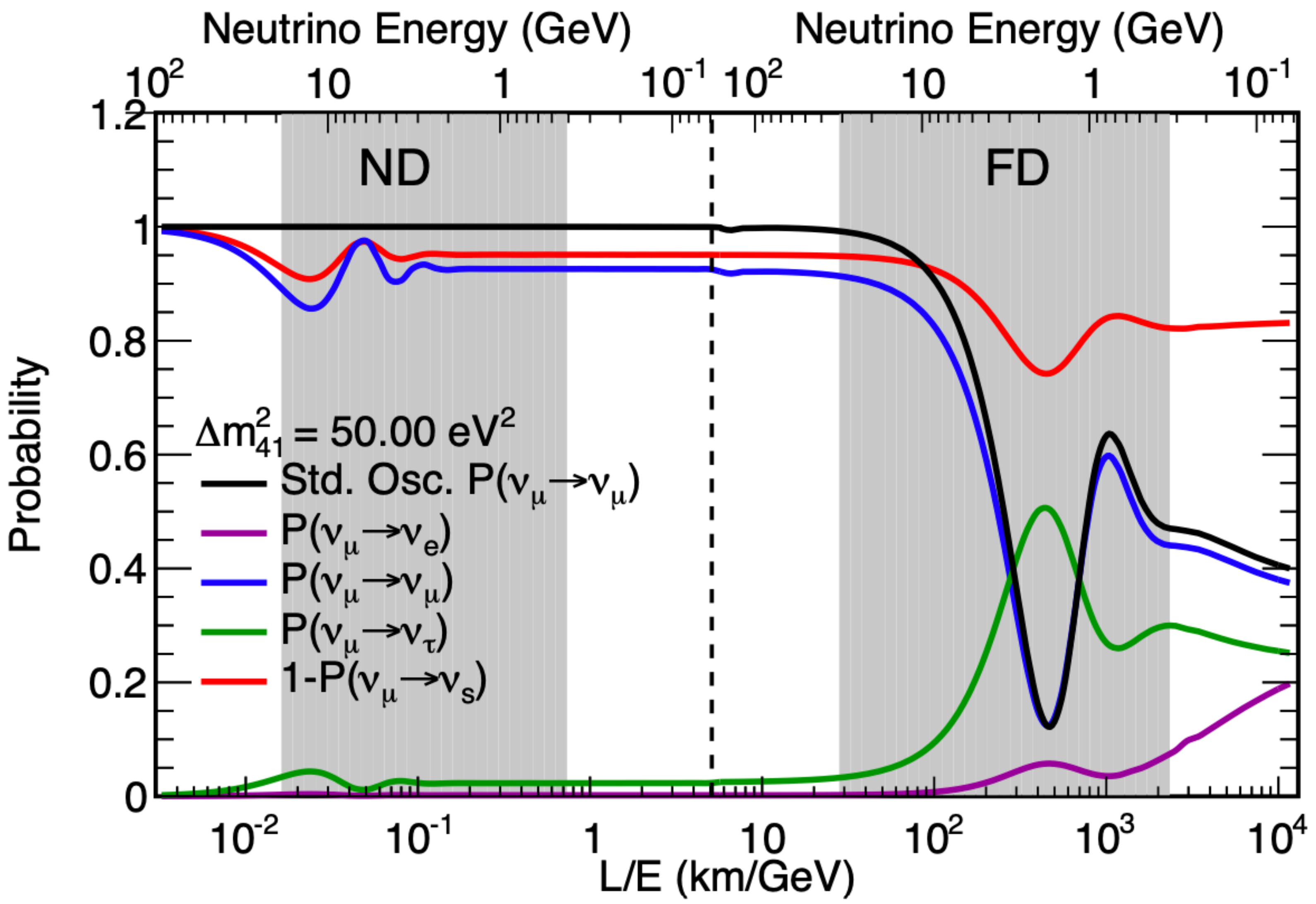
Channel	Branching ratio
$\bar{n} + p$:	
$\pi^+\pi^0$	1.2%
$\pi^+2\pi^0$	9.5%
$\pi^+3\pi^0$	11.9%
$2\pi^+\pi^-\pi^0$	26.2%
$2\pi^+\pi^-2\pi^0$	42.8%
$2\pi^+\pi^-2\omega$	0.003%
$3\pi^+2\pi^-\pi^0$	8.4%
$\bar{n} + n$:	
$\pi^+\pi^-$	2.0%
$2\pi^0$	1.5%
$\pi^+\pi^-\pi^0$	6.5%
$\pi^+\pi^-2\pi^0$	11.0%
$\pi^+\pi^-3\pi^0$	28.0%
$2\pi^+2\pi^-$	7.1%
$2\pi^+2\pi^-\pi^0$	24.0%
$\pi^+\pi^-\omega$	10.0%
$2\pi^+2\pi^-2\pi^0$	10.0%



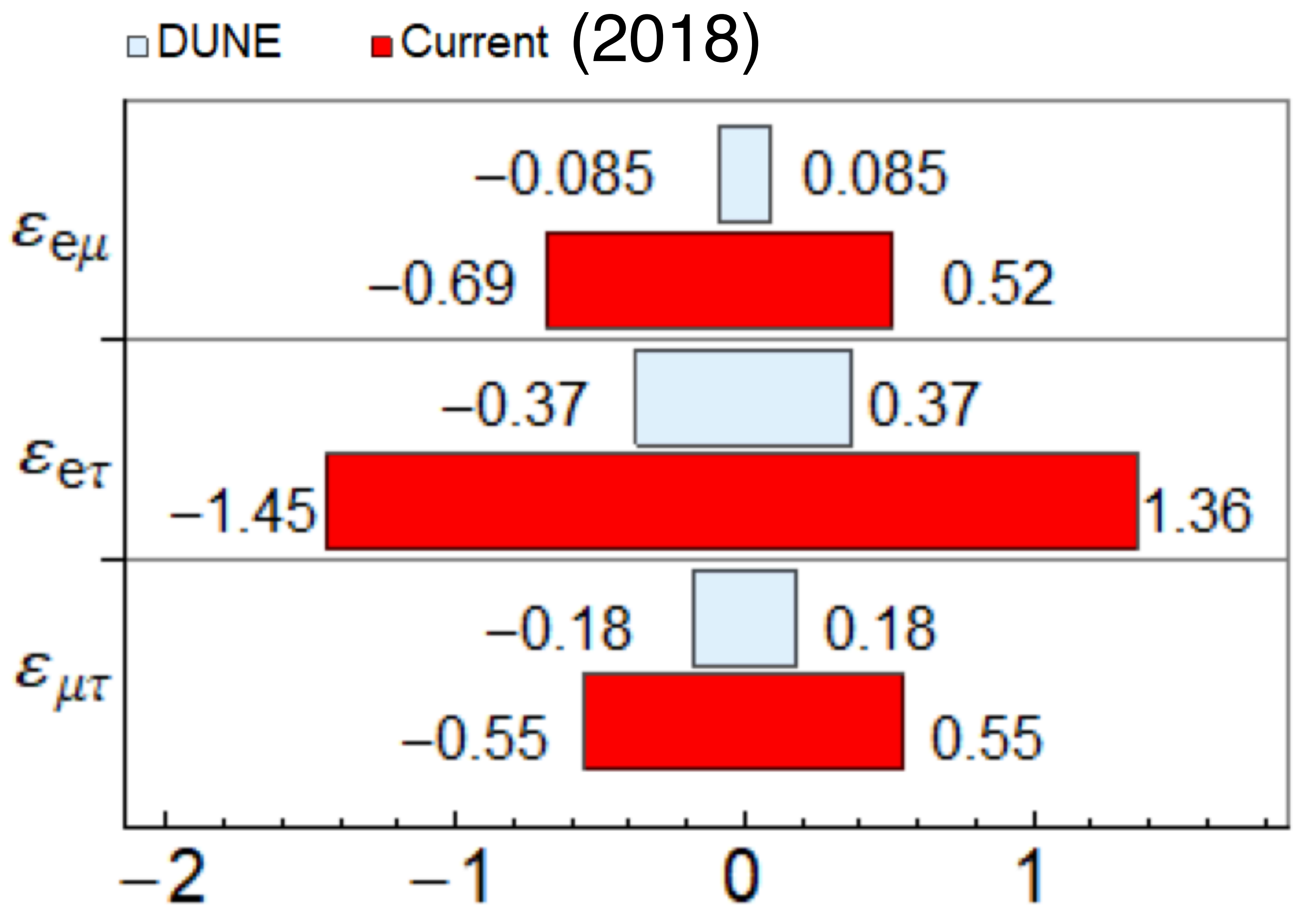
Eur.Phys.J.C 81 (2021) 4, 322

DUNE Physics Sensitivity - Various BSM Searches

- Wide neutrino energy spectrum, ND, and FD
  - Broad L/E → sensitivity for oscillations beyond the 3-flavors
- Long baseline - 1300 km
  - Neutral current non-standard neutrino interactions (NC-NSI)'s contribution on top of the matter effect
- High intensity proton beam on target - excellent sensitivity to exotic particles
- And more and more…

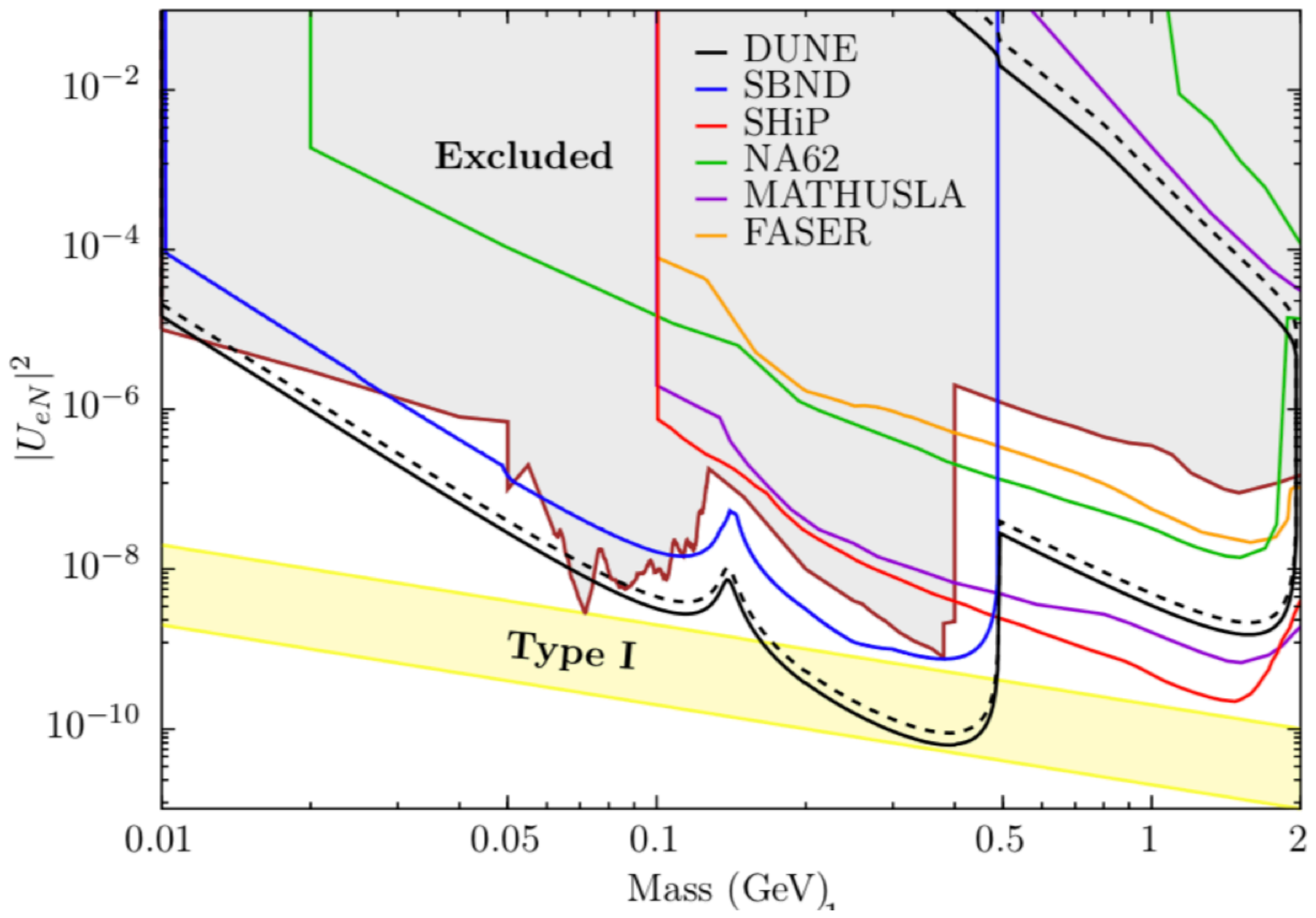


Sterile Neutrino



NC-NSI

Eur.Phys.J.C 81 (2021) 4, 322



Heavy Neutral Lepton

Summary

- The DUNE science program can improve our understanding of the universe
    - Early evolution : baryon number violation, leptonic CP phase, and core-collapse supernova
    - Neutrino properties : more precise PMNS parameters, mass ordering, and leptonic CP phase

- DUNE is having great progress in all three central components
    - Neutrino beam facility upgrade
    - Far detector construction and prototyping
    - Near detector design and prototyping

- In the light of the P5 report
    - Completing DUNE phase-I is highest priority
    - Phase-II is re-envisioned : ACE-MIRT, FD3, and MCND in next decade, and R&D for FD4 and ACE-BR

- DUNE's physics sensitivity promises to deliver multiple discoveries!

Thank you!

DUNE Collaboration Meeting, May, 2024, Fermilab

Back Up

P5

Chapter 2. The Recommended Particle Physics Program - Overview

…

DUNE will comprehensively explore the quantum realm of neutrinos, potentially un- earthing new physics beyond current theoretical frameworks. Early implementation of the accelerator upgrade ACE-MIRT advances the DUNE program significantly, hastening the definite discovery of the neutrino mass ordering. This upgrade in conjunction with the deployment of the third far detector and a more capable near detector are indispensable components of the re-envisioned next phase of DUNE. R&D for an advanced fourth detector enables the expansion of the physics program of LBNF. These substantial initiatives find synergy with smaller-scale experiments to elucidate the mysteries of neutrinos.

…

2.2 Recommendations

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

a. HL-LHC;

b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos. Knowledge of this fundamental property is a crucial input to cosmology and nuclear science (elu- cidate the mysteries of neutrinos, section 3.1).

c. …

2.2 Recommendations

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

a. CMB-S4;

b. A re-envisioned second phase of DUNE with an early implementation of an enhanced 2.1 MW beam—ACE-MIRT—a third far detector, and an upgraded near-detector complex as the definitive long-baseline neutrino oscillation experiment of its kind (section 3.1).

c. …

2.2 Recommendations

Recommendation 4: Invest in a comprehensive initiative to develop the resourc- es—theoretical, computational, and technological—essential to realizing our 20-year strategic vision. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a 10 TeV pCM collider.

a.

b.

c.

d.

e. Conduct R&D efforts to define and enable new projects in the next decade, including detectors for an e+e– Higgs factory and 10 TeV pCM collider, Spec-S5, DUNE FD4, Mu2e-II, Advanced Muon Facility, and line intensity mapping (sections 3.1, 3.2, 4.2, 5.1, 5.2, and 6.3).

2.6 Adapting to Alternative Budget Scenarios

2.6.1 – Less Favorable Budget Scenario

Recommendation 1 as our highest priority. The agencies should launch the same major initiatives as outlined in Recommendation 2, some of them with significantly reduced scope:

a. CMB-S4;

b. DUNE Third Far Detector (FD3), but defer ACE-MIRT and the More Capable Near Detector (MCND). Infrastructure required to accommodate international contributions remains a priority.

…

2.6.2 – More Favorable Budget Scenario

c. Medium Projects

i. ;

ii. Initiate construction of an advanced fourth far detector (FD4) for DUNE that will expand its neutrino oscillation physics and broaden its science program.

…

Chapter 2 Summary Plot

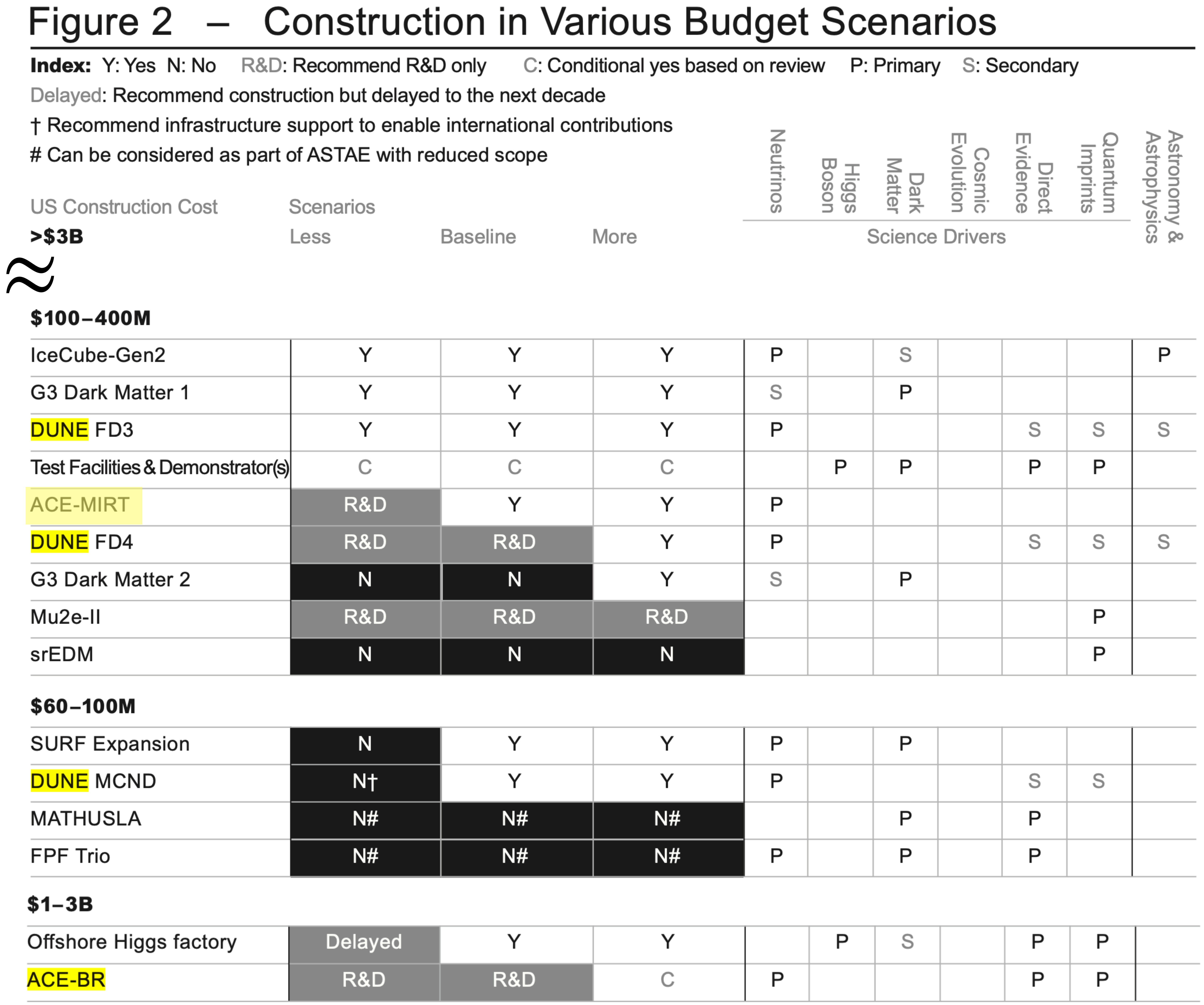


Figure 2 – Construction in Various Budget Scenarios

Index: Y: Yes N: No R&D: Recommend R&D only C: Conditional yes based on review P: Primary S: Secondary

Delayed: Recommend construction but delayed to the next decade

† Recommend infrastructure support to enable international contributions

Can be considered as part of ASTAE with reduced scope

US Construction Cost	Scenarios			Science Drivers						
	Less	Baseline	More	Neutrinos	Higgs Boson	Dark Matter	Cosmic Evolution	Direct Evidence	Quantum Imprints	Astronomy & Astrophysics
>$3B										
≈										
$100–400M										
IceCube-Gen2	Y	Y	Y	P		S				P
G3 Dark Matter 1	Y	Y	Y	S		P				
DUNE FD3	Y	Y	Y	P				S	S	S
Test Facilities & Demonstrator(s)	C	C	C		P	P		P	P	
ACE-MIRT	R&D	Y	Y	P						
DUNE FD4	R&D	R&D	Y	P				S	S	S
G3 Dark Matter 2	N	N	Y	S		P				
Mu2e-II	R&D	R&D	R&D						P	
srEDM	N	N	N						P	
$60–100M										
SURF Expansion	N	Y	Y	P		P				
DUNE MCND	N†	Y	Y	P				S	S	
MATHUSLA	N#	N#	N#			P		P		
FPF Trio	N#	N#	N#	P		P		P		
$1–3B										
Offshore Higgs factory	Delayed	Y	Y		P	S		P	P	
ACE-BR	R&D	R&D	C	P				P	P	

Chapter 3 - Decipher the Quantum Realm

3.1 Elucidate the Mysteries of Neutrinos

Recommendation 1 as our highest priority. The agencies should launch the same major initiatives as outlined in Recommendation 2, some of them with significantly reduced scope:

a. CMB-S4;

b. DUNE Third Far Detector (FD3), but defer ACE-MIRT and the More Capable Near Detector (MCND). Infrastructure required to accommodate international contributions remains a priority.

…

2.6.2 – More Favorable Budget Scenario

c. Medium Projects

  i. ;

  ii. Initiate construction of an advanced fourth far detector (FD4) for DUNE that will expand its neutrino oscillation physics and broaden its science program.

  …

Neutrino Oscillations

Three neutrino oscillation and CP asymmetry

$$|\,\nu_j(t)\,\rangle = e^{-i\left(E_j t - \vec{p}_j\cdot\vec{x}\right)}\,|\,\nu_j(0)\,\rangle$$

Ultrarelativistic limit

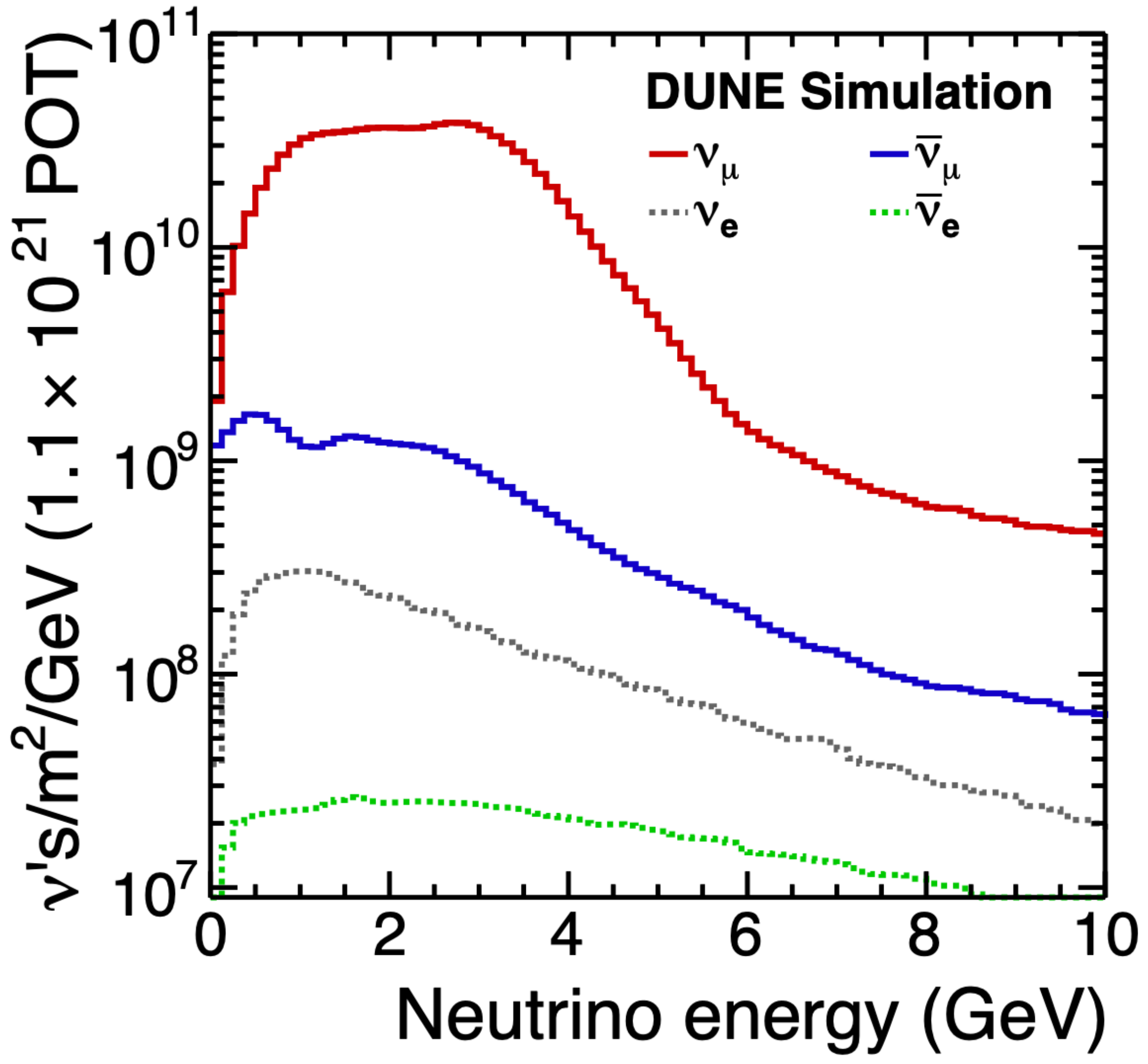
$$|\,\nu_j(L)\,\rangle = e^{-i\left(\frac{m_j^2\,L}{2\,E}\right)}\,|\,\nu_j(0)\,\rangle$$

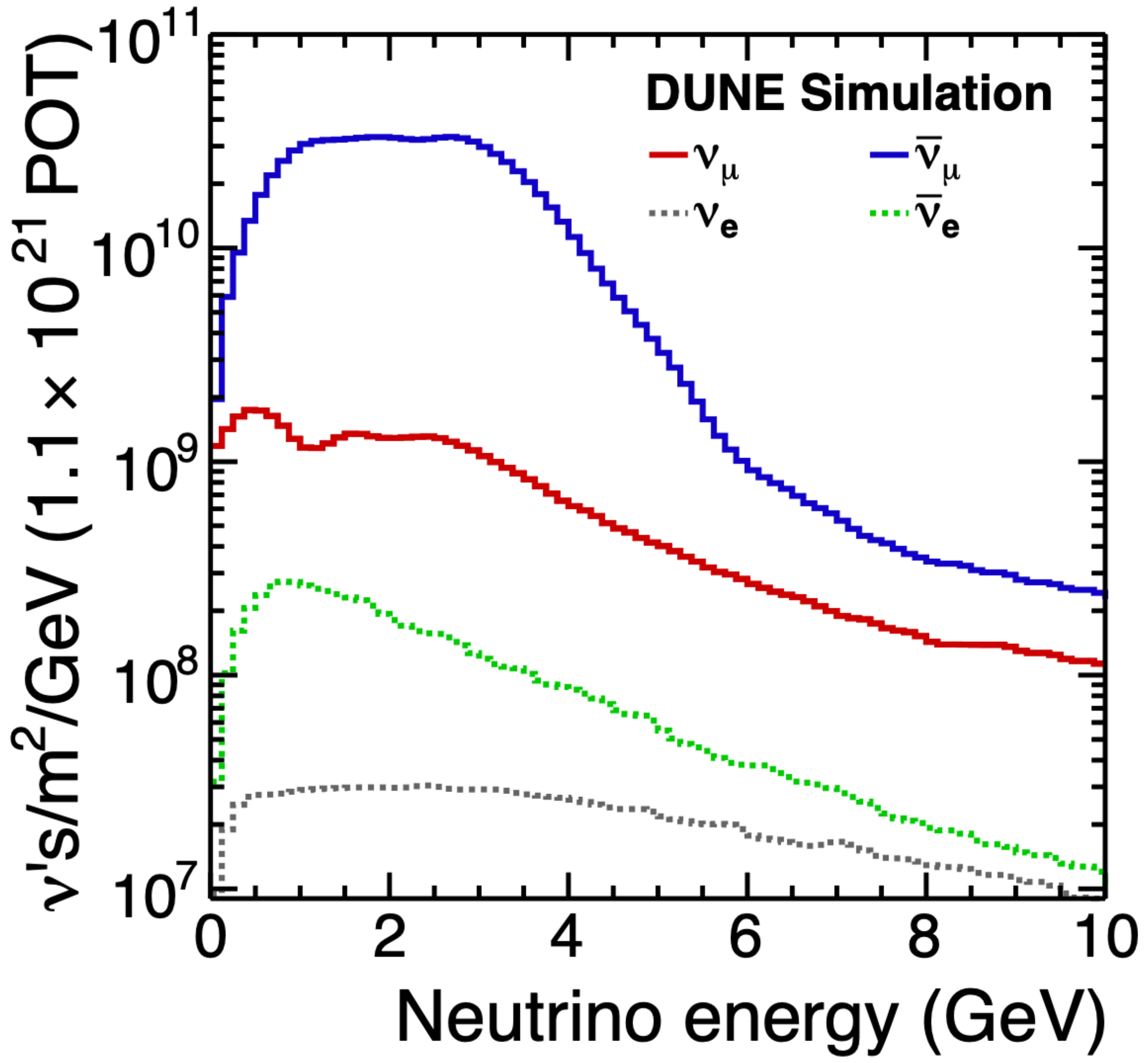
$$\begin{aligned} P_{\alpha\to\beta} = \delta_{\alpha\beta} &- 4\sum_{j>k} \mathcal{R}_e\left\{ U^*_{\alpha j}\,U_{\beta j}\,U_{\alpha k}\,U^*_{\beta k} \right\} \sin^2\left(\frac{\Delta m^2_{jk}L}{4E}\right) \\ &+ 2\sum_{j>k} \mathcal{I}_m\left\{ U^*_{\alpha j}\,U_{\beta j}\,U_{\alpha k}\,U^*_{\beta k} \right\} \sin\left(\frac{\Delta m^2_{jk}L}{2E}\right), \end{aligned}$$

$$A^{(\alpha\beta)}_{\text{CP}} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = 4\sum_{j>k} \mathcal{I}_m\left\{ U^*_{\alpha j}\,U_{\beta j}\,U_{\alpha k}\,U^*_{\beta k} \right\} \sin\left(\frac{\Delta m^2_{jk}L}{2E}\right)$$

Neutrino Beam

Flux


DUNE Simulation
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
ν's/m^2/GeV (1.1 × 10^{21} POT)
10^{11}
10^{10}
10^9
10^8
10^7
0
2
4
6
8
10
Neutrino energy (GeV)


DUNE Simulation
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
ν's/m^2/GeV (1.1 × 10^{21} POT)
10^{11}
10^{10}
10^9
10^8
10^7
0
2
4
6
8
10
Neutrino energy (GeV)

ACE , + MIRT, +BR

Accelerator Complex Evolution (ACE) plan

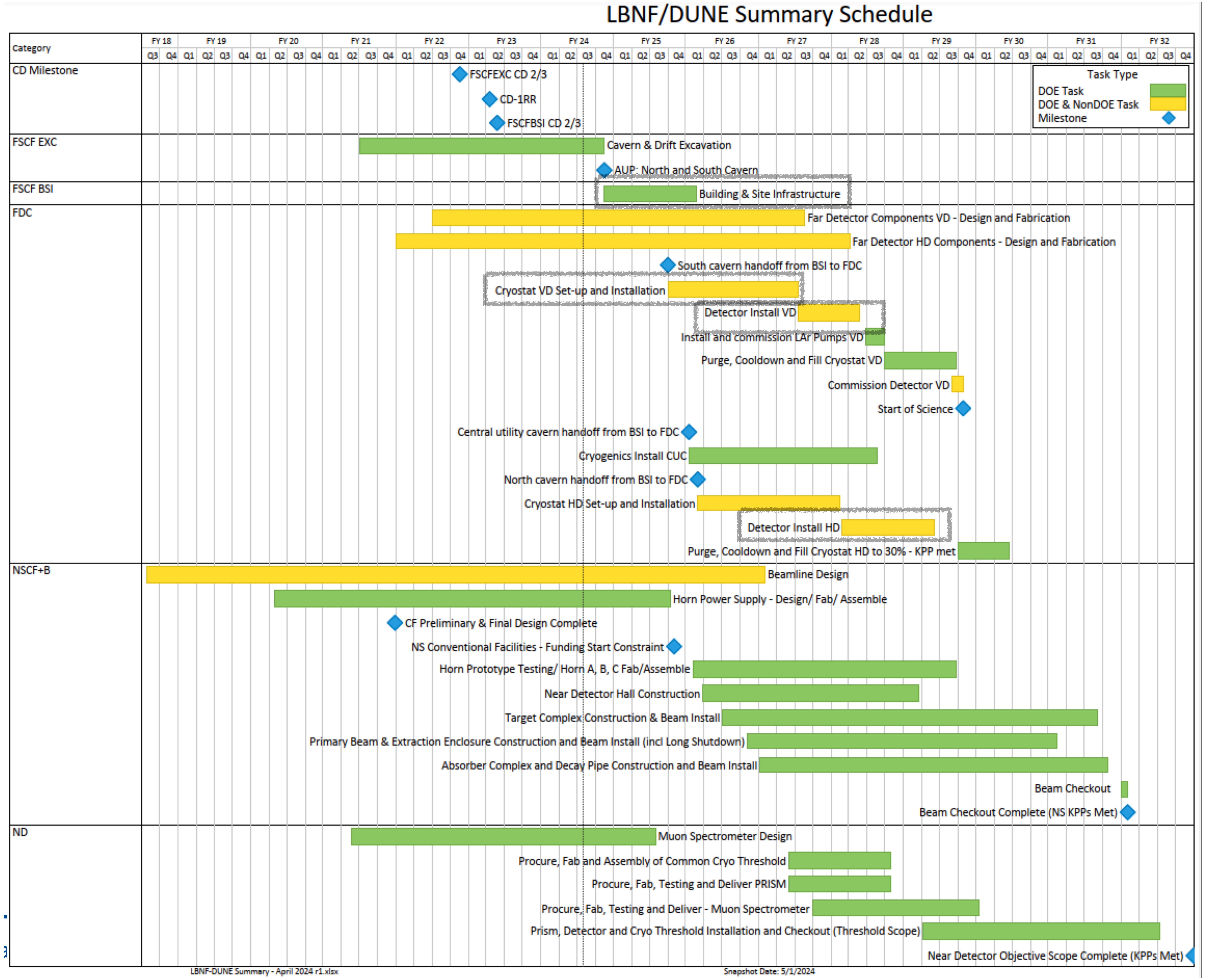
Main Injector Ramp and Targets (MIRT)

- Reach 2 MW without new accelerator construction
- Main driving factor of higher intensity : faster main injector ramp rate
  - $\sim \times 2$ frequency of spills

Booster Replacement (BR)

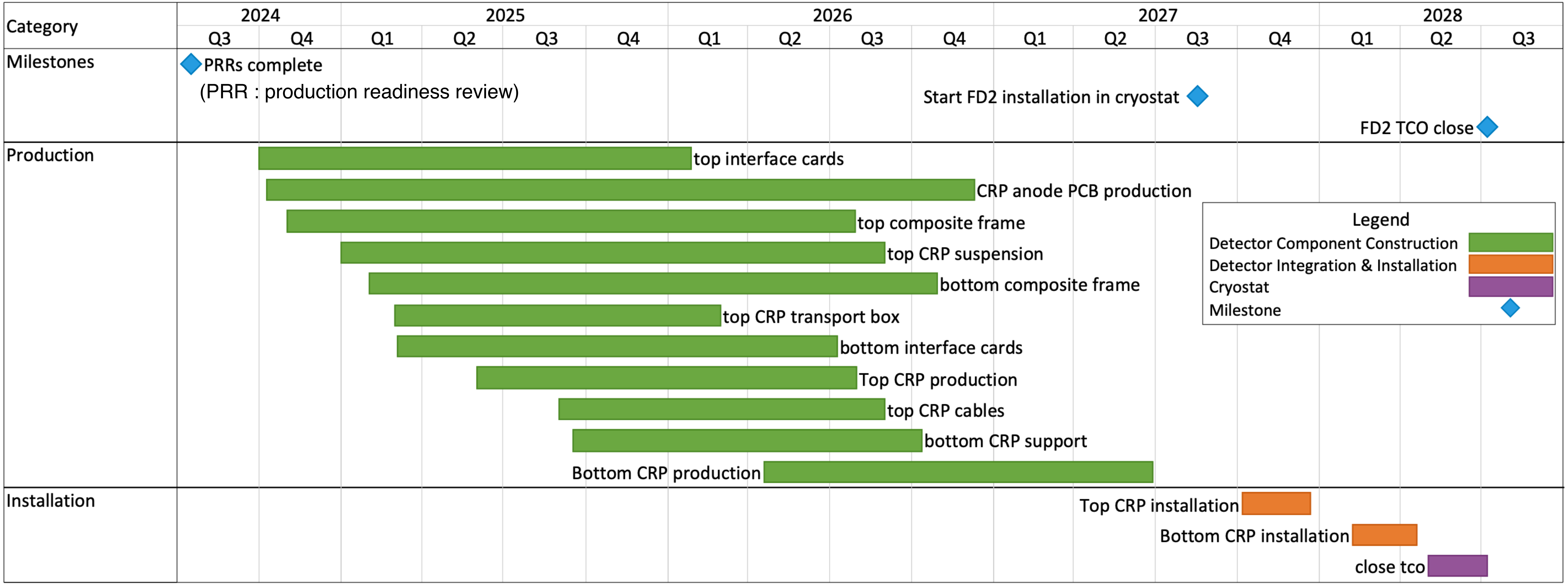
Far Detector

FD Site Plan

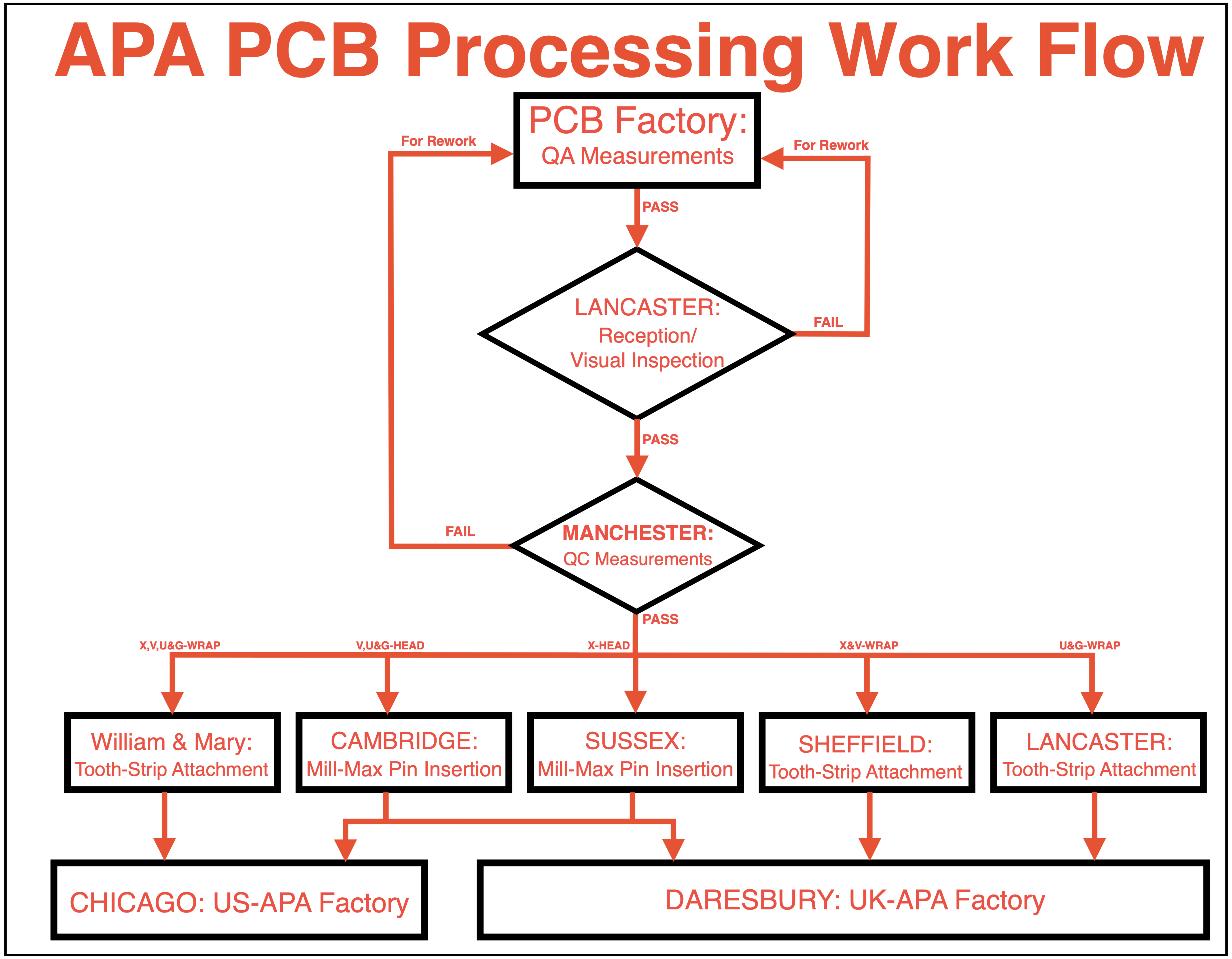

LBNF/DUNE Summary Schedule
Category
FY 18
FY 19
FY 20
FY 21
FY 22
FY 23
FY 24
FY 25
FY 26
FY 27
FY 28
FY 29
FY 30
FY 31
FY 32
Q1
Q2
Q3
Q4
Task Type
DOE Task
DOE & NonDOE Task
Milestone
CD Milestone
FSCFEXC CD 2/3
CD-1RR
FSCFBSI CD 2/3
FSCF EXC
Cavern & Drift Excavation
AUP: North and South Cavern
FSCF BSI
Building & Site Infrastructure
FDC
Far Detector Components VD - Design and Fabrication
Far Detector HD Components - Design and Fabrication
South cavern handoff from BSI to FDC
Cryostat VD Set-up and Installation
Detector Install VD
Install and commission LAr Pumps VD
Purge, Cooldown and Fill Cryostat VD
Commission Detector VD
Start of Science
Central utility cavern handoff from BSI to FDC
Cryogenics Install CUC
North cavern handoff from BSI to FDC
Cryostat HD Set-up and Installation
Detector Install HD
Purge, Cooldown and Fill Cryostat HD to 30% - KPP met
NSCF+B
Beamline Design
Horn Power Supply - Design/ Fab/ Assemble
CF Preliminary & Final Design Complete
NS Conventional Facilities - Funding Start Constraint
Horn Prototype Testing/ Horn A, B, C Fab/Assemble
Near Detector Hall Construction
Target Complex Construction & Beam Install
Primary Beam & Extraction Enclosure Construction and Beam Install (incl Long Shutdown)
Absorber Complex and Decay Pipe Construction and Beam Install
Beam Checkout
Beam Checkout Complete (NS KPPs Met)
ND
Muon Spectrometer Design
Procure, Fab and Assembly of Common Cryo Threshold
Procure, Fab, Testing and Deliver PRISM
Procure, Fab, Testing and Deliver - Muon Spectrometer
Prism, Detector and Cryo Threshold Installation and Checkout (Threshold Scope)
Near Detector Objective Scope Complete (KPPs Met)
LBNF-DUNE Summary - April 2024 r1.xlsx
Snapshot Date: 5/1/2024

VD Production Plan

arXiv:2312.03130



APA Production Chain



APA PCB Processing Work Flow

PCB Factory: QA Measurements

PASS

LANCASTER: Reception/ Visual Inspection

FAIL – For Rework

PASS

MANCHESTER: QC Measurements

FAIL – For Rework

PASS

X,V,U&G-WRAP → William & Mary: Tooth-Strip Attachment → CHICAGO: US-APA Factory

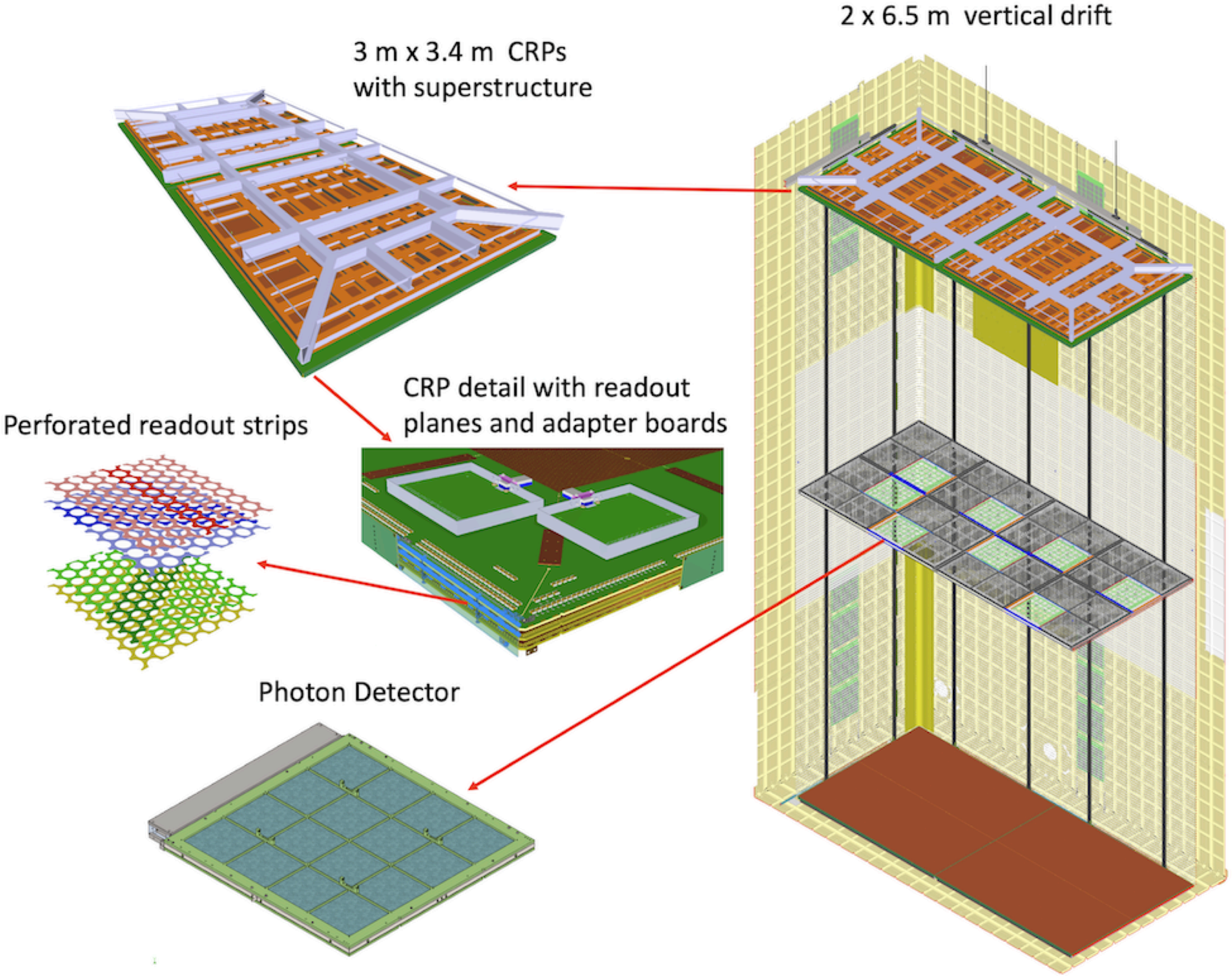
V,U&G-HEAD → CAMBRIDGE: Mill-Max Pin Insertion → CHICAGO: US-APA Factory; DARESBURY: UK-APA Factory

X-HEAD → SUSSEX: Mill-Max Pin Insertion → CHICAGO: US-APA Factory; DARESBURY: UK-APA Factory

X&V-WRAP → SHEFFIELD: Tooth-Strip Attachment → DARESBURY: UK-APA Factory

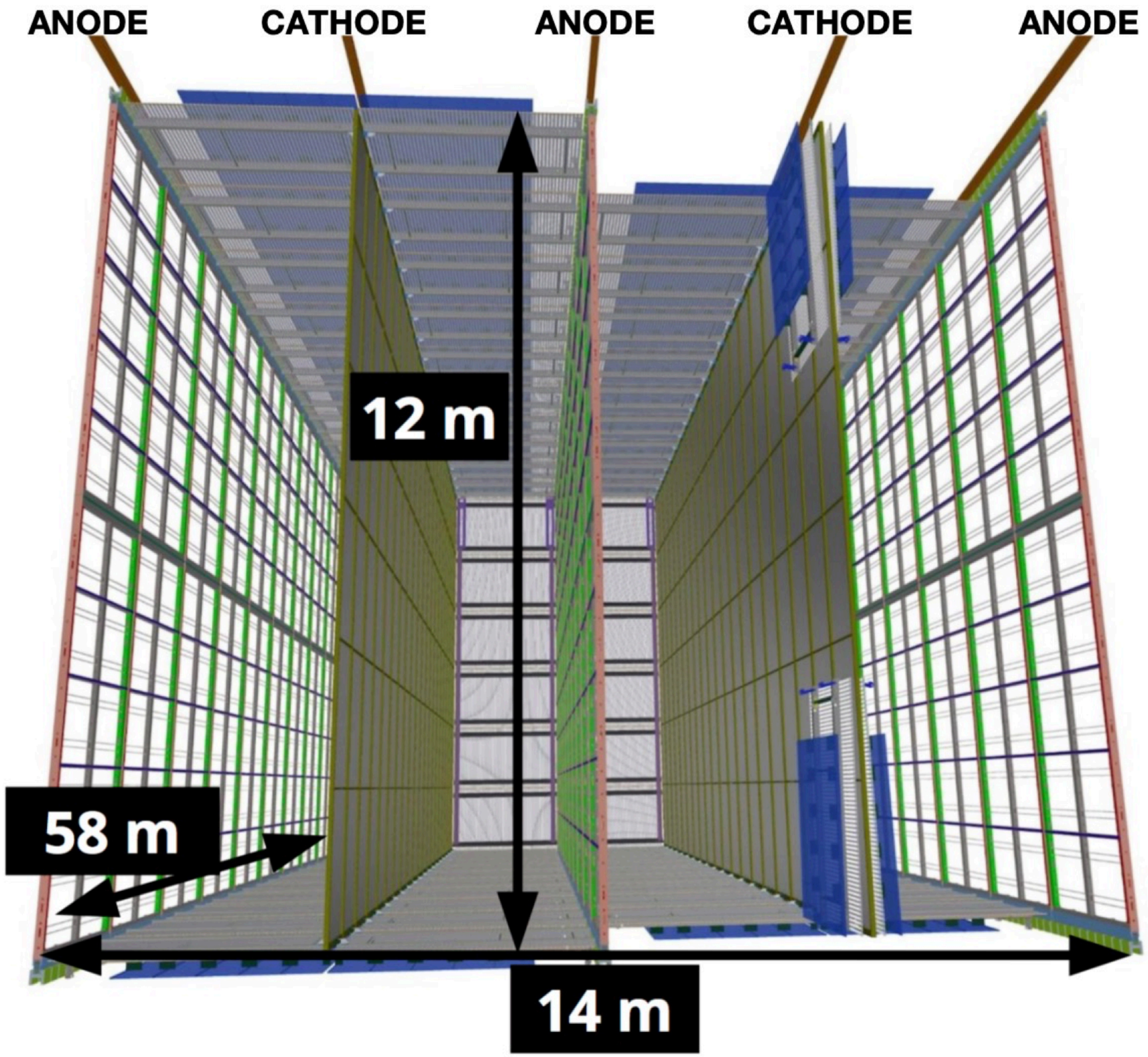
U&G-WRAP → LANCASTER: Tooth-Strip Attachment → DARESBURY: UK-APA Factory

VD Modules



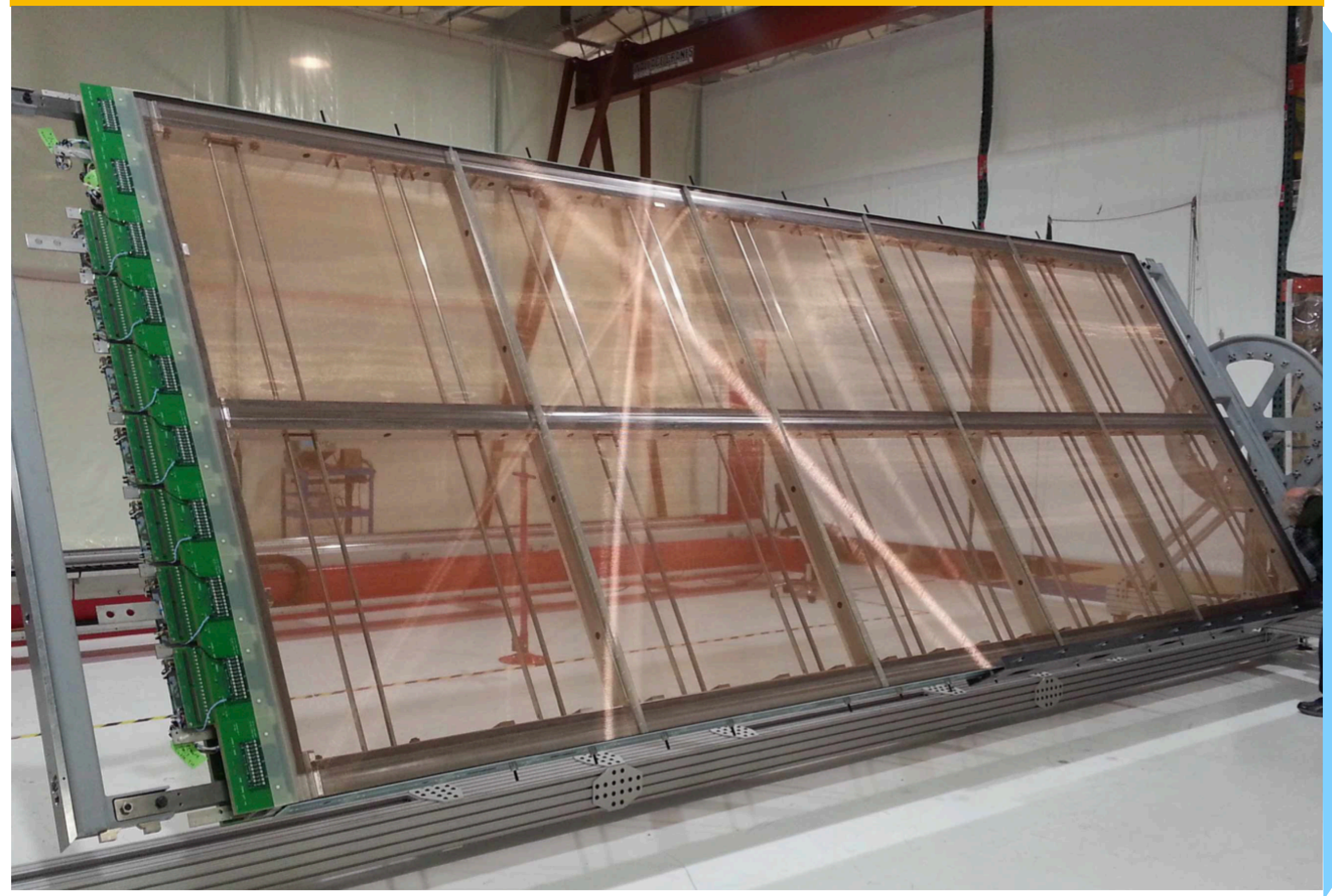
80 CRPs / Anode

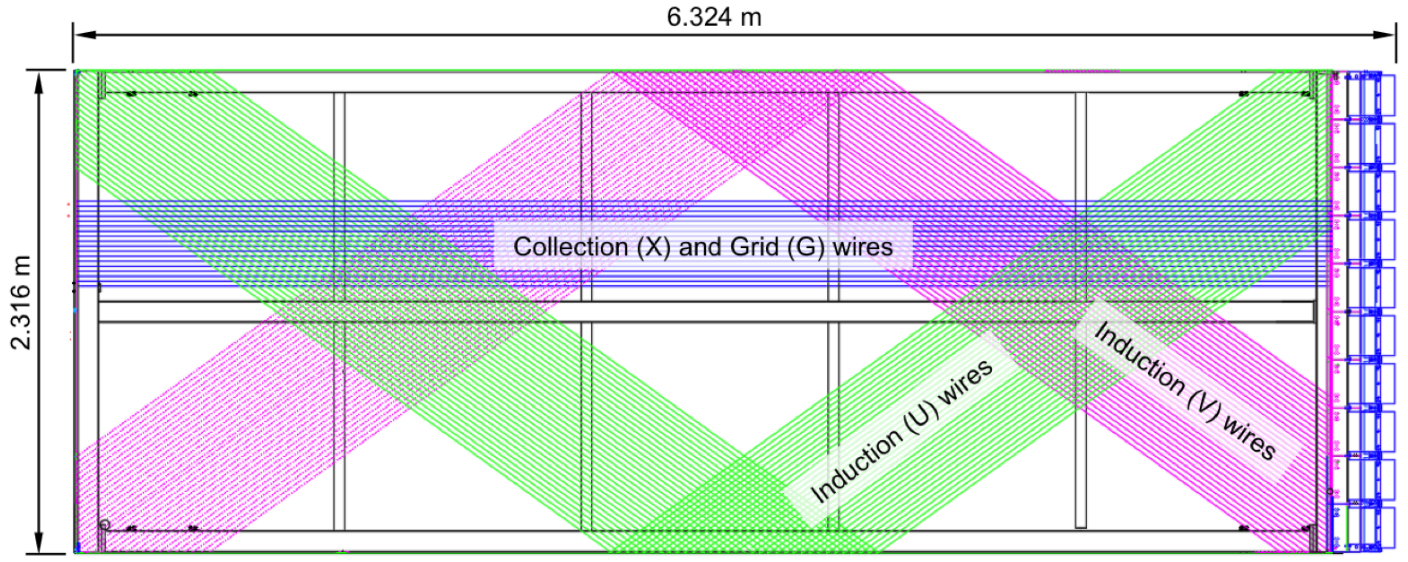
HD Dimension

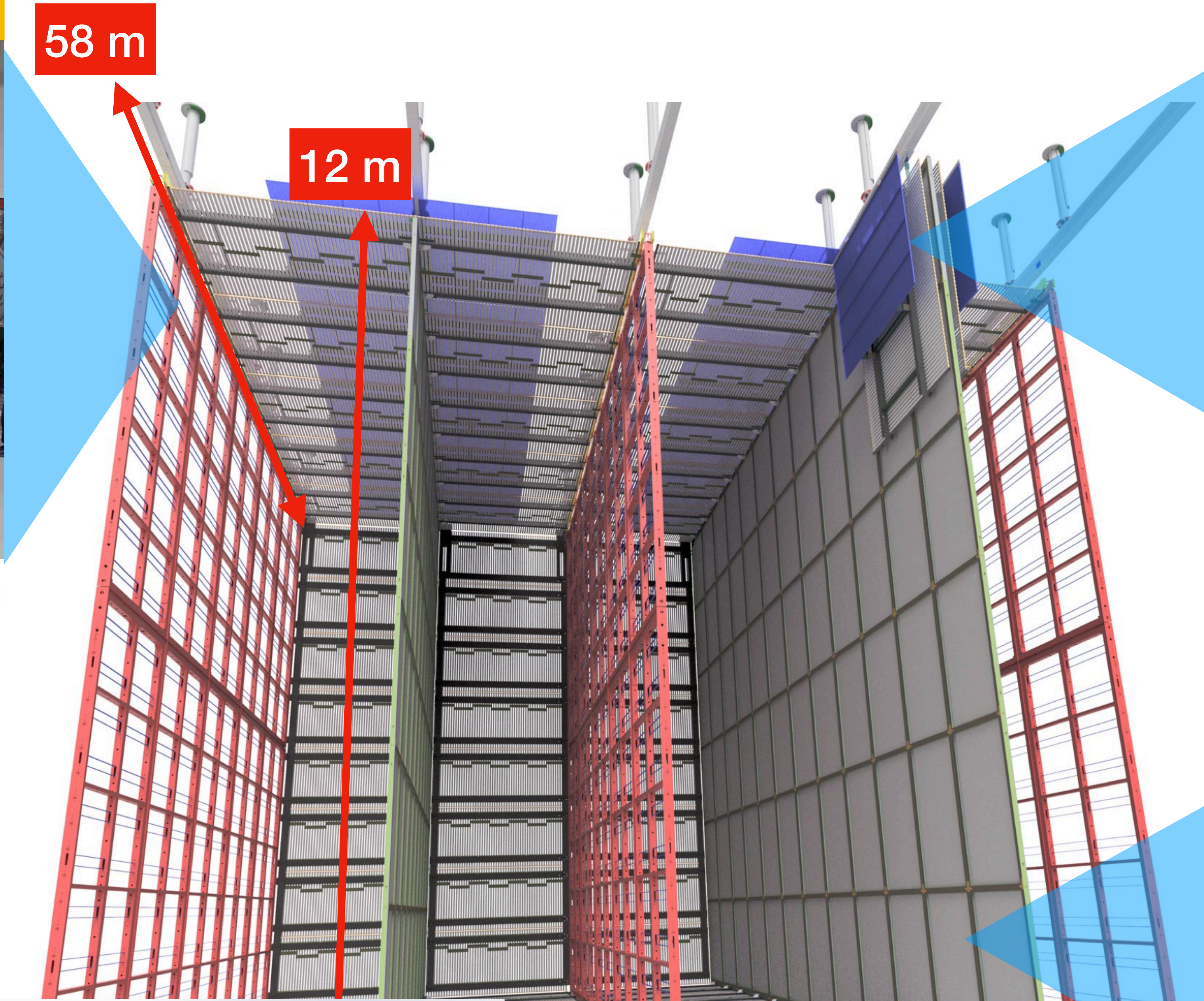


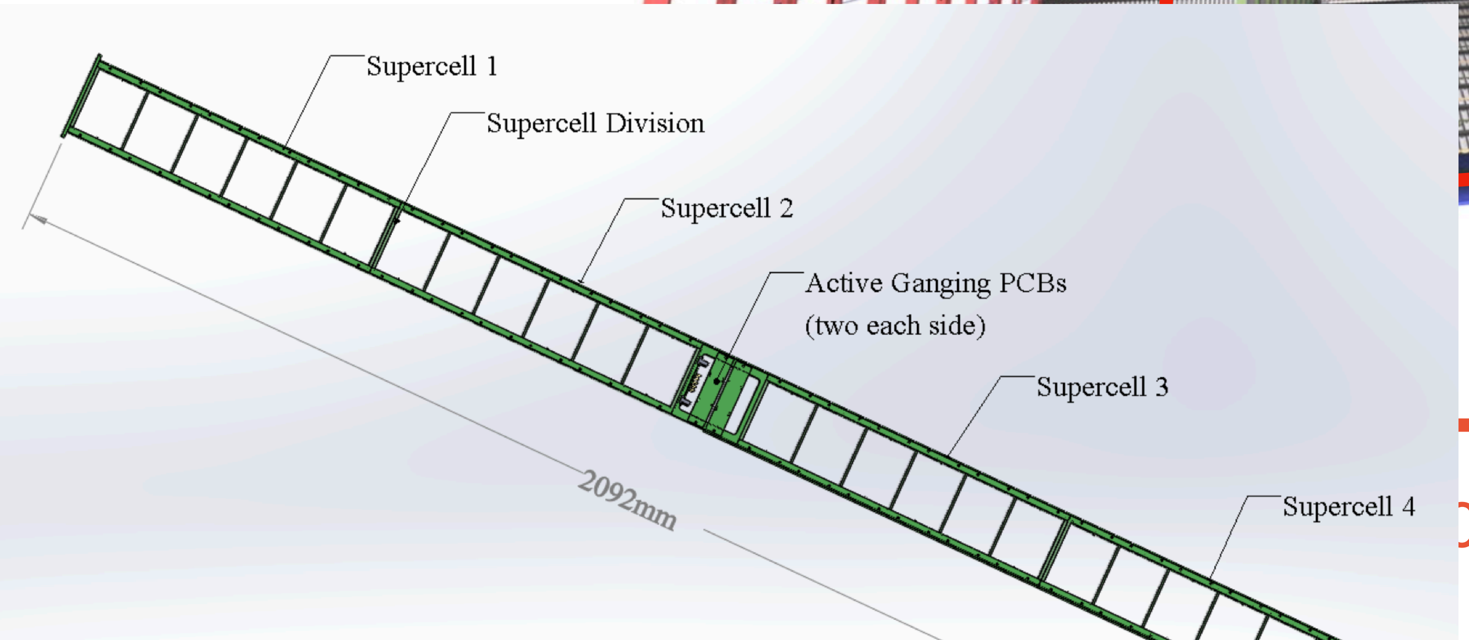
(2) Far Detector (FD) - Horizontal Drift (HD)

Anode plane assembly (APA)

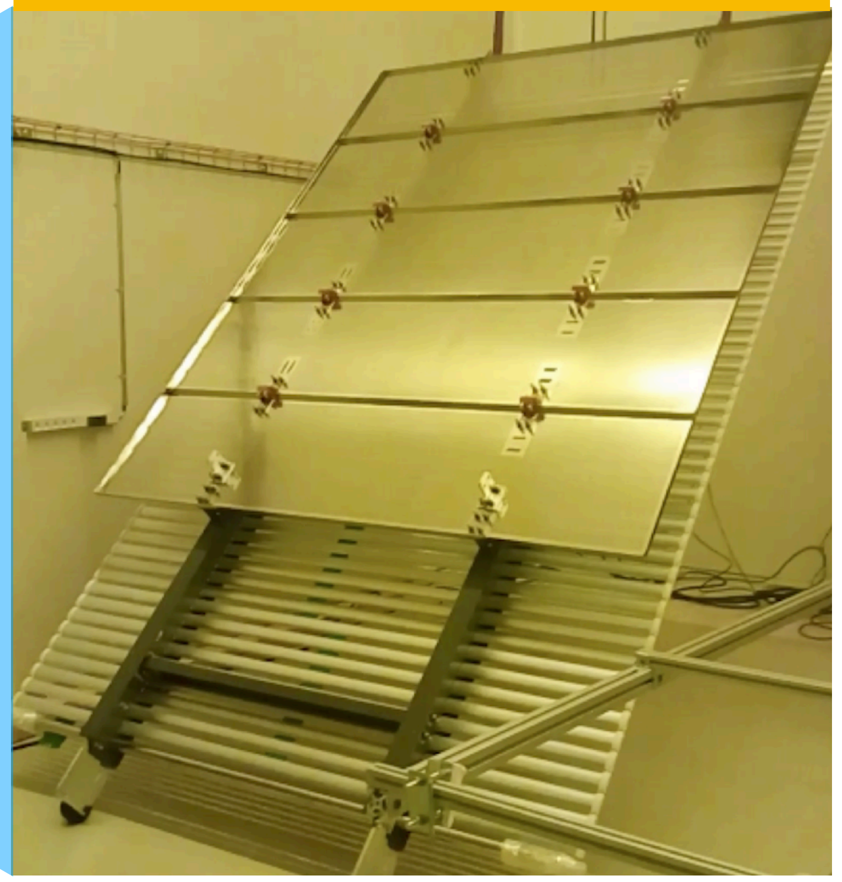




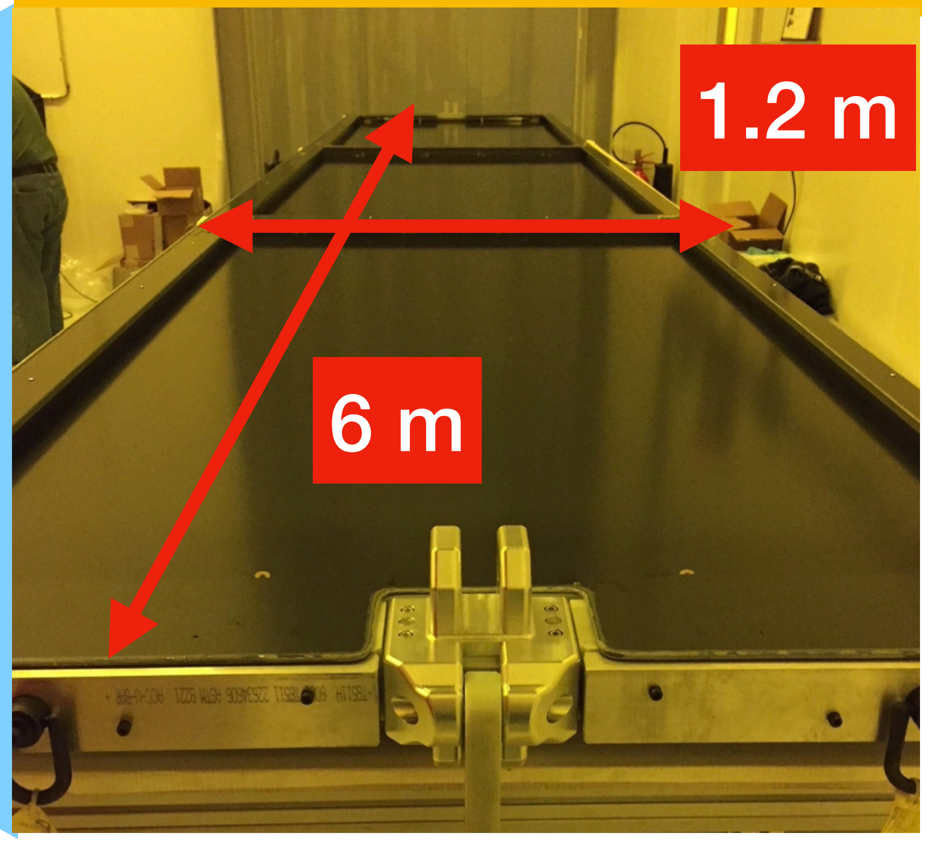




Multiple versions of field cage modules



Side-by-side resistive plates (FR-4)



ProtoDUNE

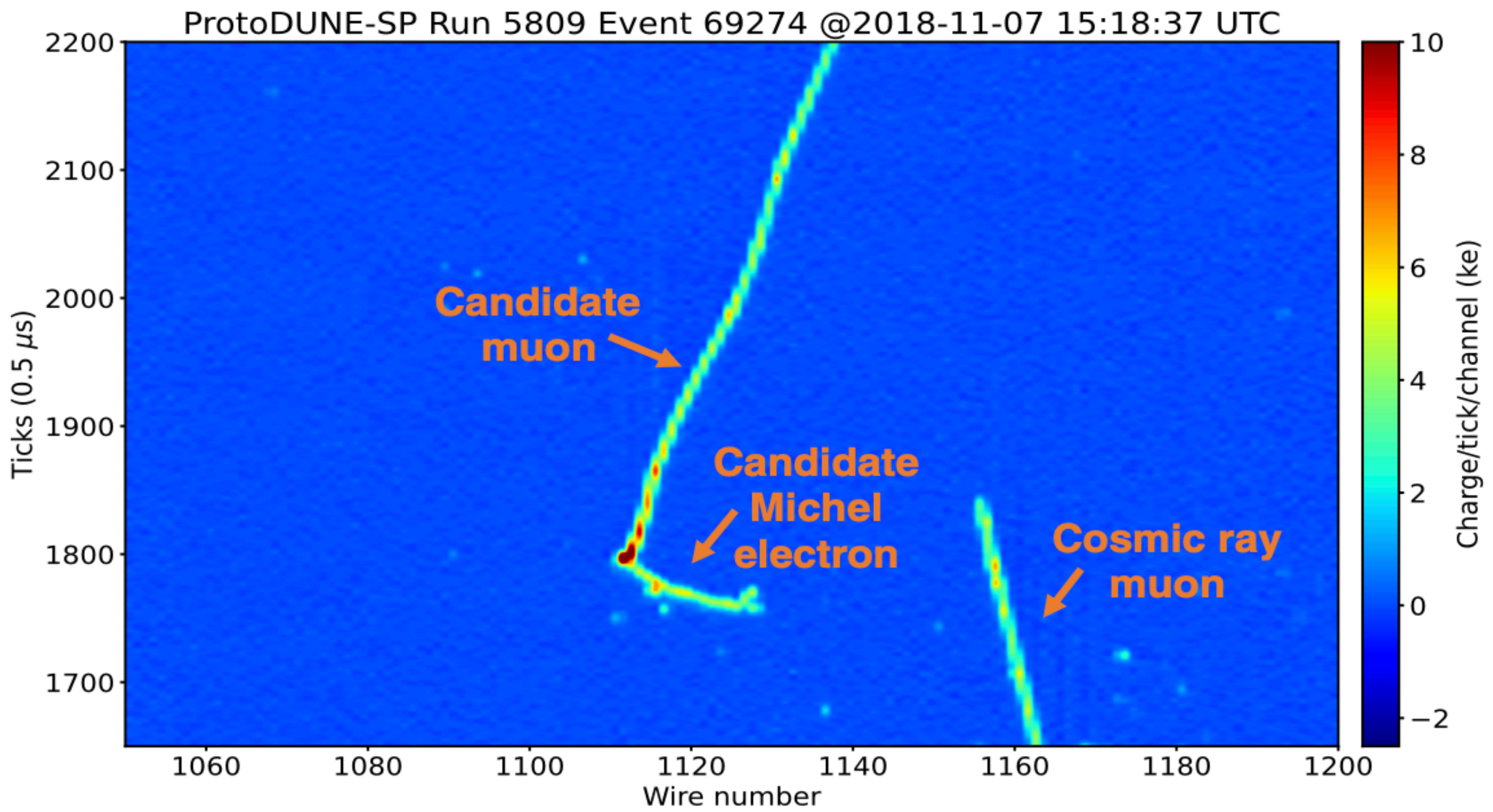
ProtoDUNE-HD Improvements

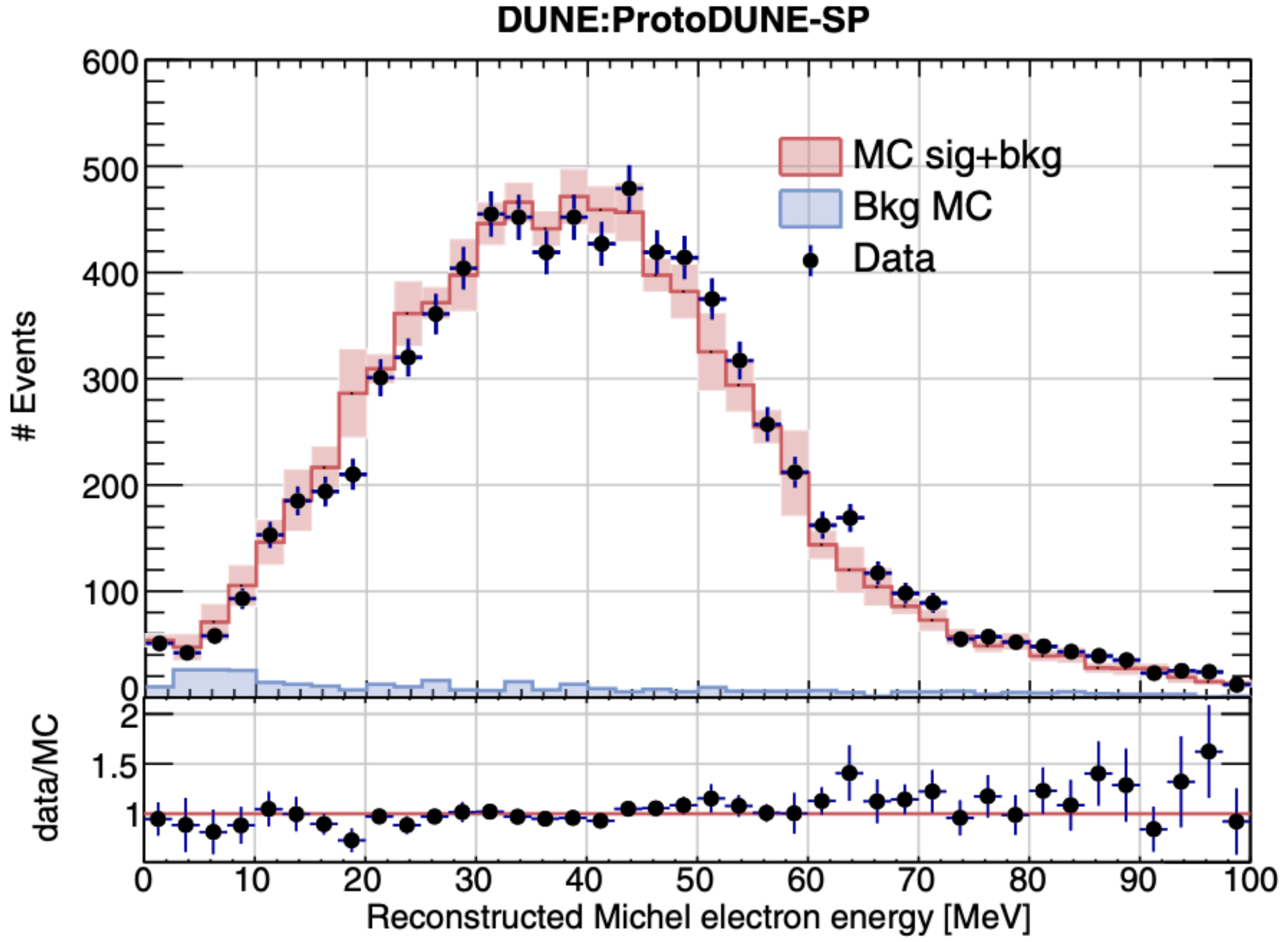
- Updated APA, CPA and cold electronics designs
- 4 APAs to match the field cage-cryostat distance of the FD module (ProtoDUNE-SP had 6 APAs)
- PDS with X-ARAPUCA technology
-

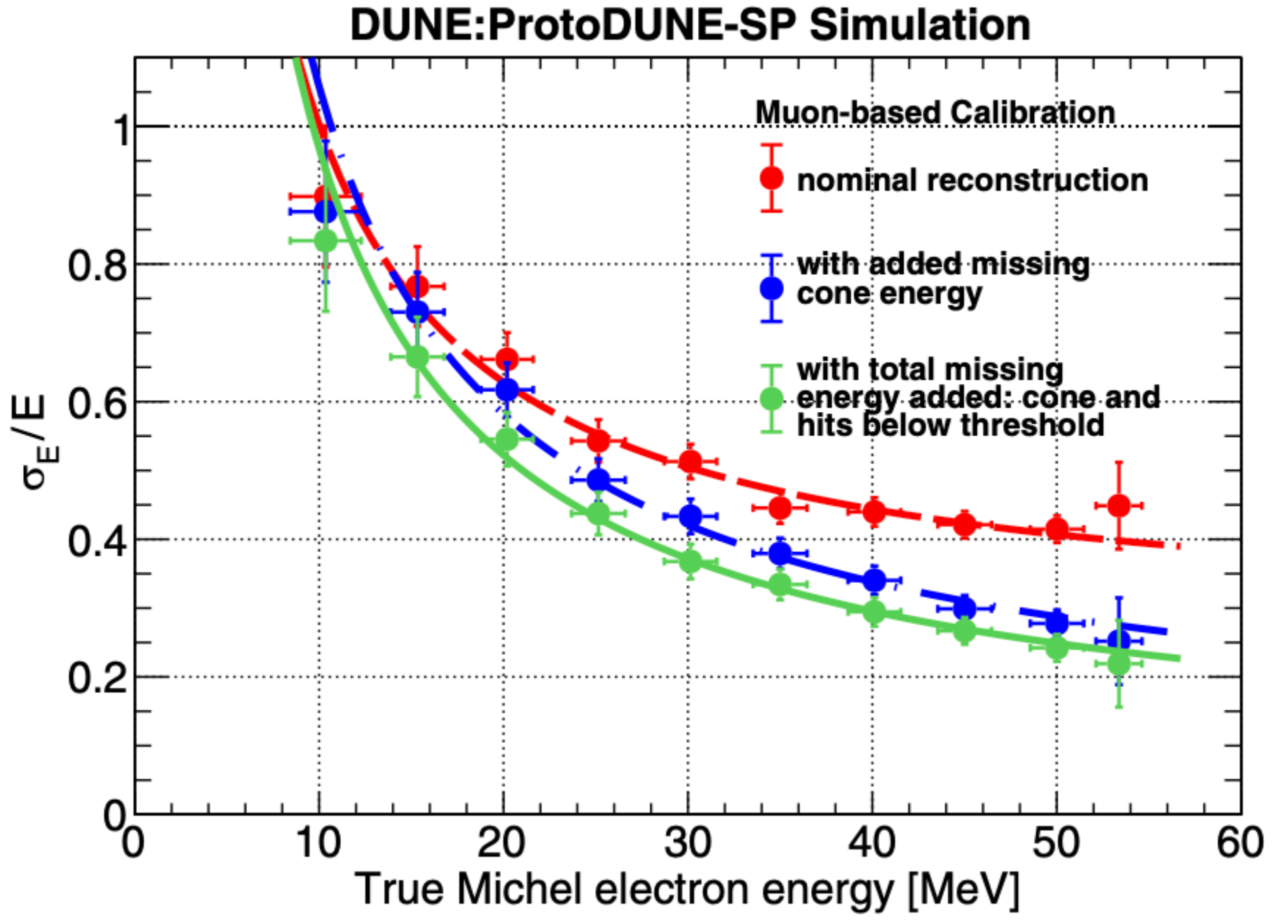
Low Energy Electron ID and Reco.

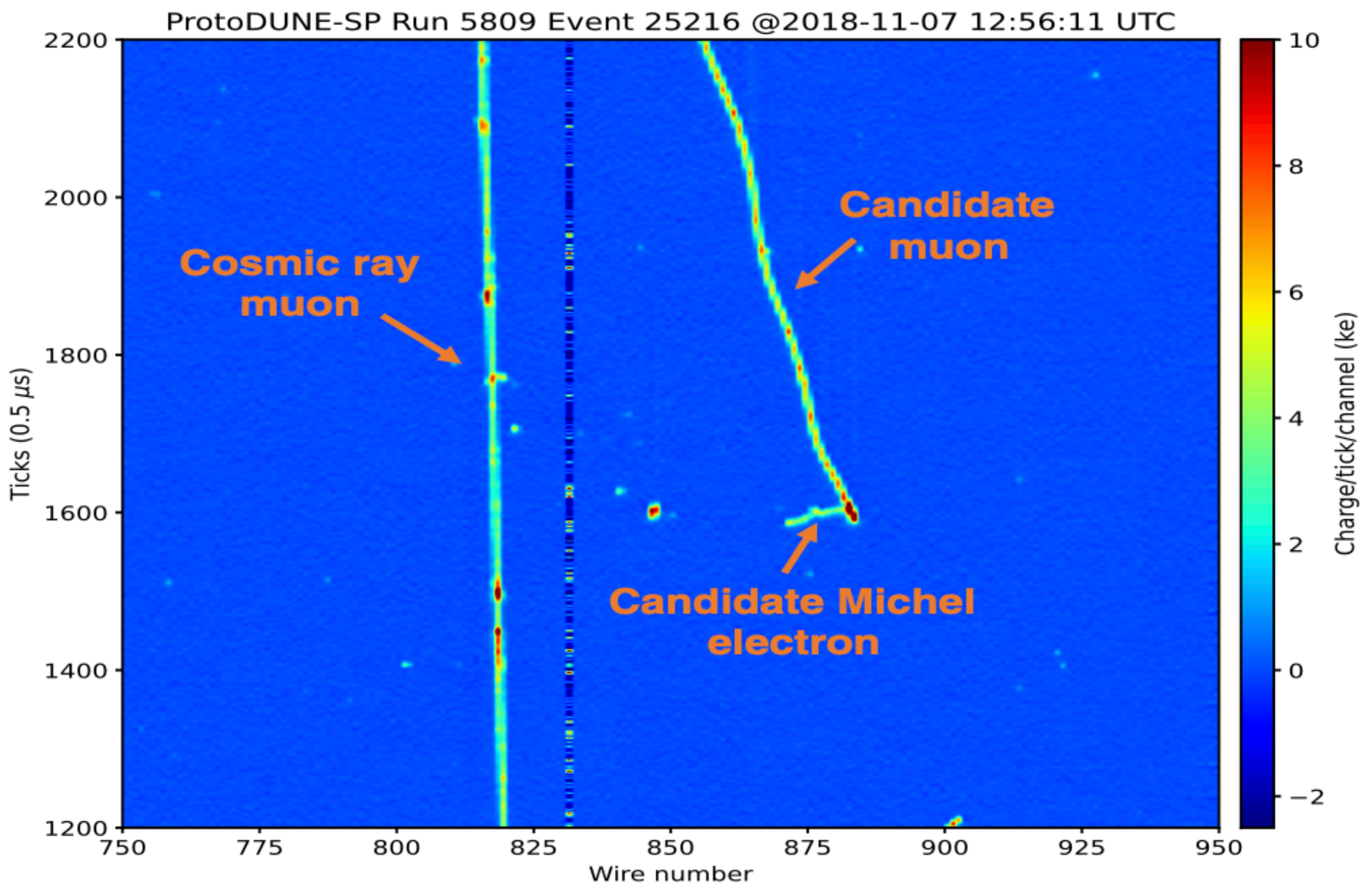
- Study using Michel electrons from muon decays

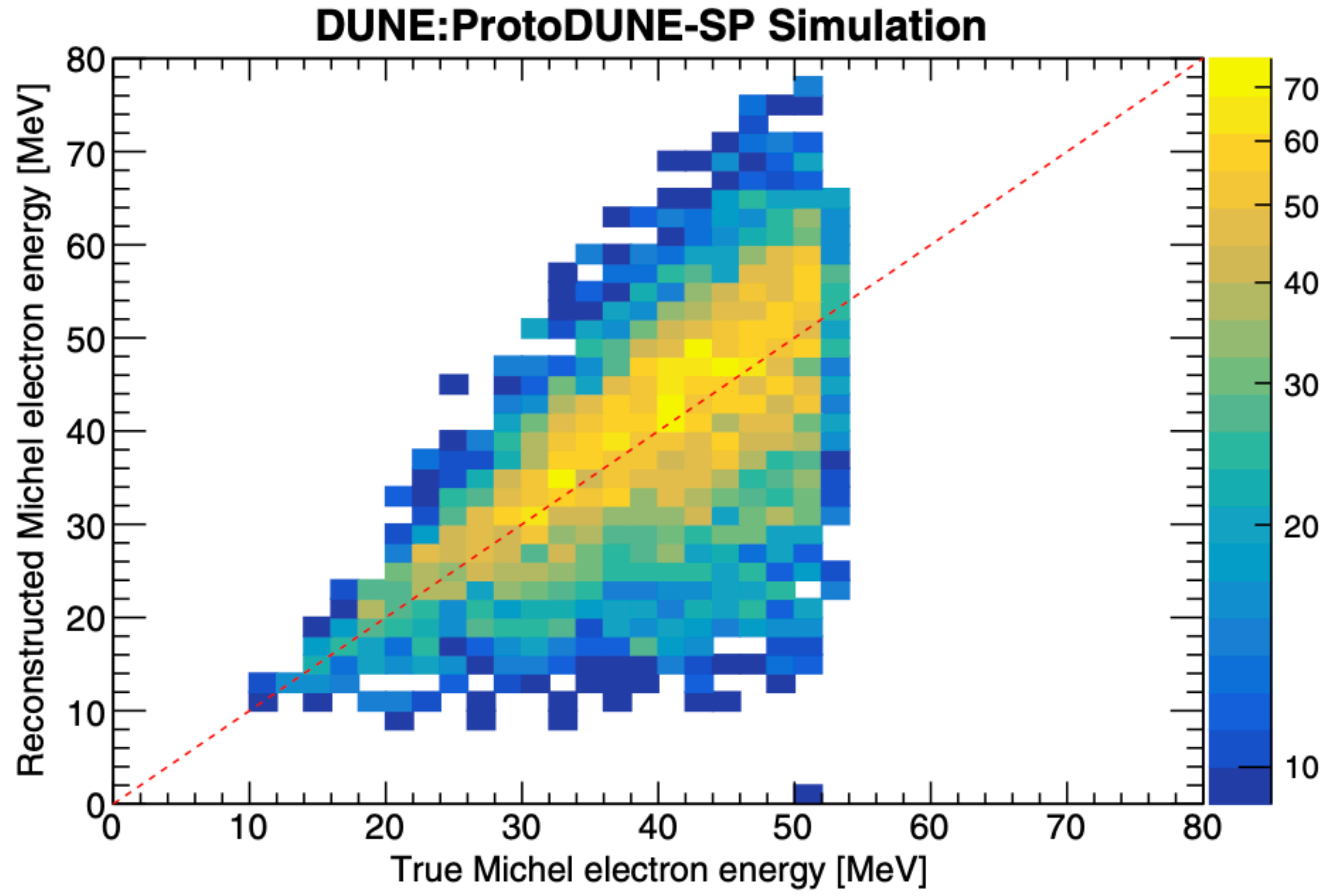
Phys.Rev.D 107 (2023) 9, 092012

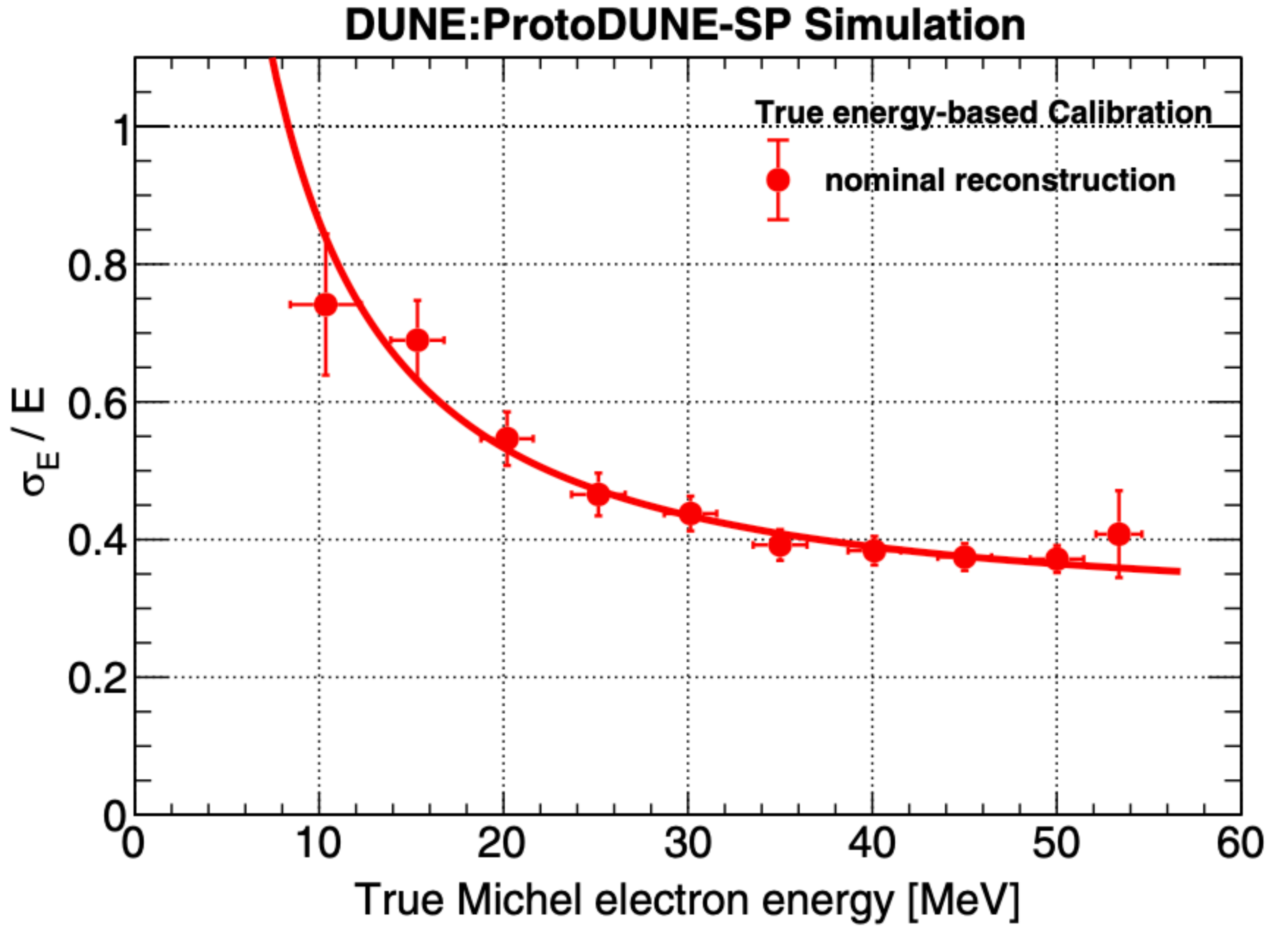












Performance - Summary

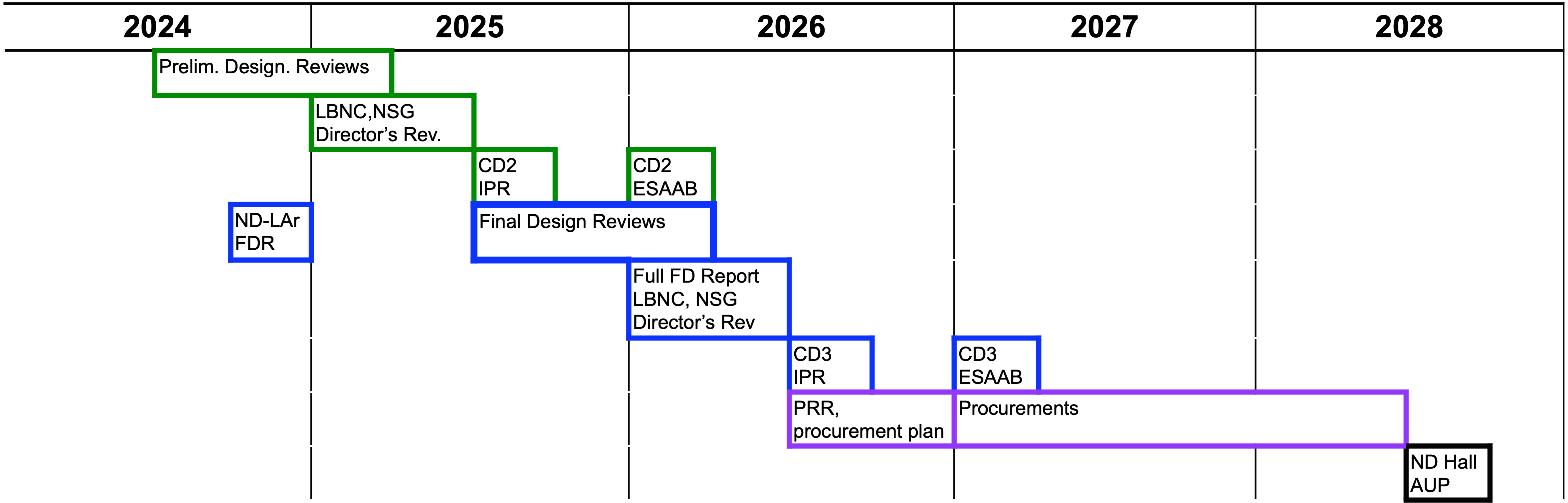
- ProtoDUNE-SP meets or surpasses the specifications set for the DUNE far detector
  - Effectiveness of the single-phase DUNE far detector design
  - Execution of the fabrication, assembly, installation, commissioning, and operations phases

JINST **15 (2020) 12, P12004**

Detector parameter	*ProtoDUNE-SP performance*	*DUNE specification*
Average drift electric field	500 V/cm	250 V/cm (min) 500 V/cm (nominal)
LAr e-lifetime	> 20 ms	> 3 ms
TPC+CE		
Noise	(C) 550 e, (I) 650 e ENC (raw)	< 1000 e ENC
Signal-to-noise ⟨SNR⟩	(C) 48.7, (I) 21.2 (w/CNR)	
CE dead channels	0.2% 😁	< 1%
PDS light yield	1.9 photons/MeV (@ 3.3 m distance)	> 0.5 photons/MeV (@ cathode distance — 3.6 m)
PDS time resolution	14 ns	< 100 ns

Near Detector

ND Plan



2024
2025
2026
2027
2028

Prelim. Design. Reviews

LBNC,NSG
Director’s Rev.

CD2
IPR

CD2
ESAAB

ND-LAr
FDR

Final Design Reviews

Full FD Report
LBNC, NSG
Director’s Rev

CD3
IPR

CD3
ESAAB

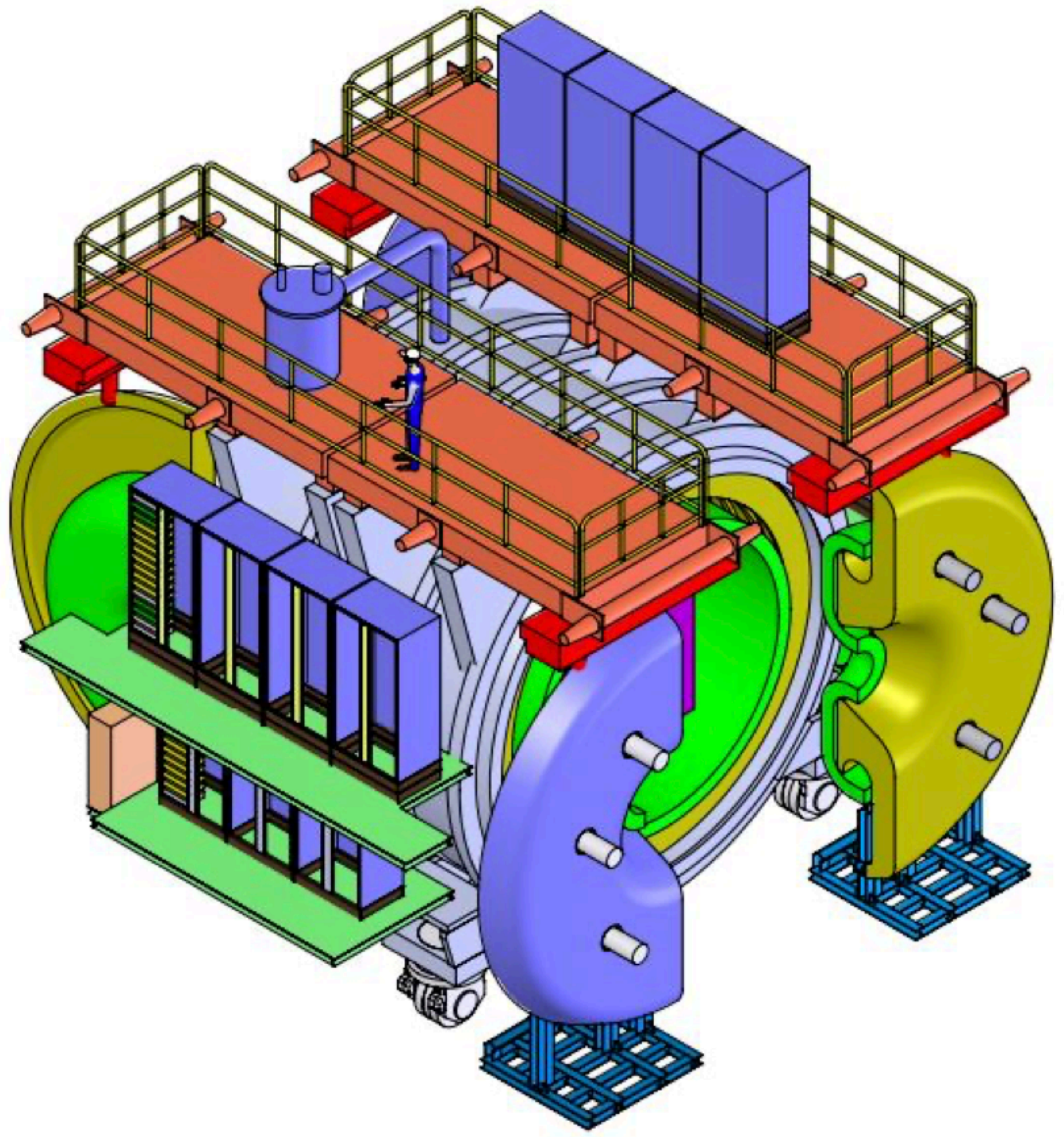
PRR,
procurement plan

Procurements

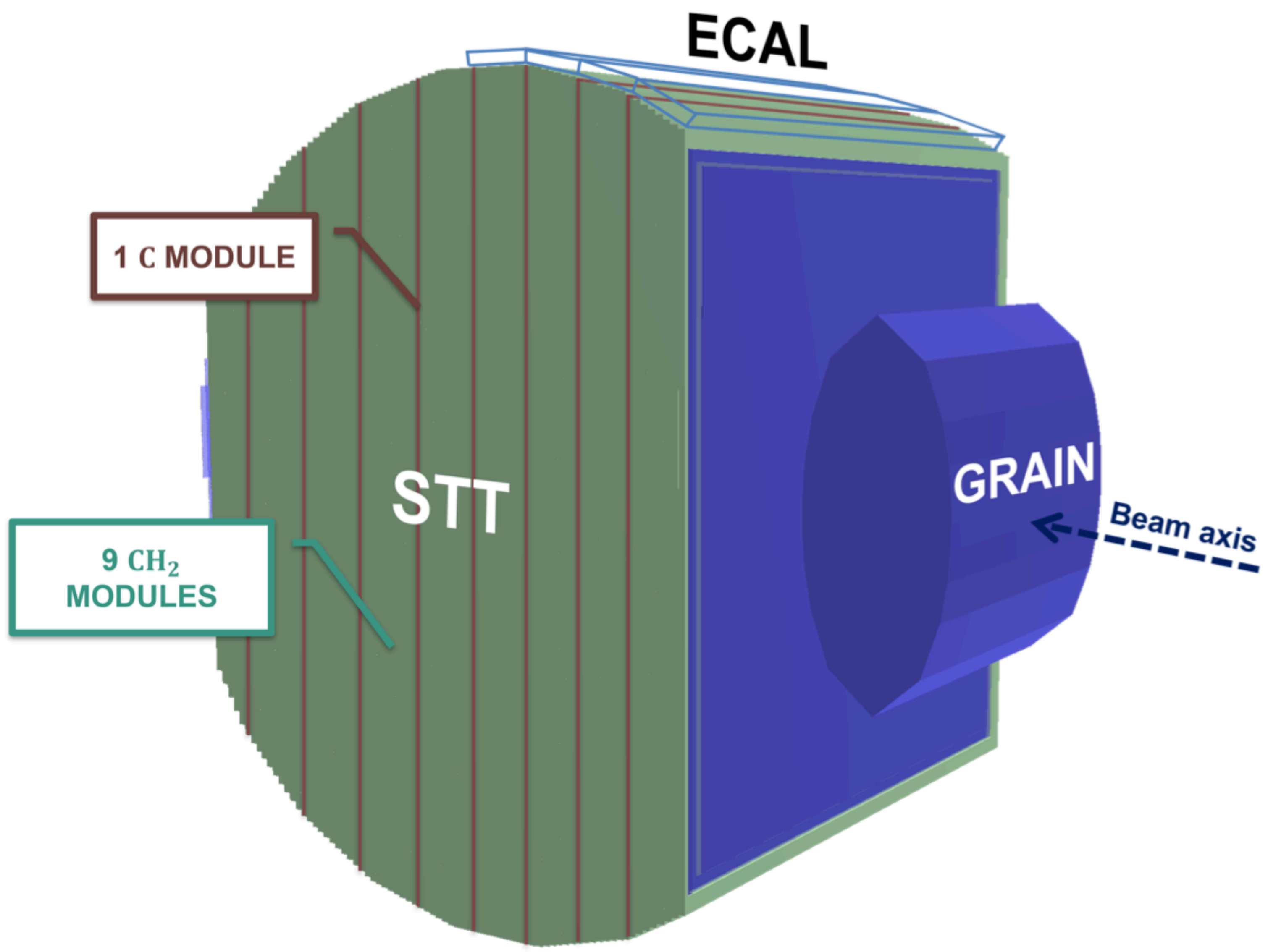
ND Hall
AUP

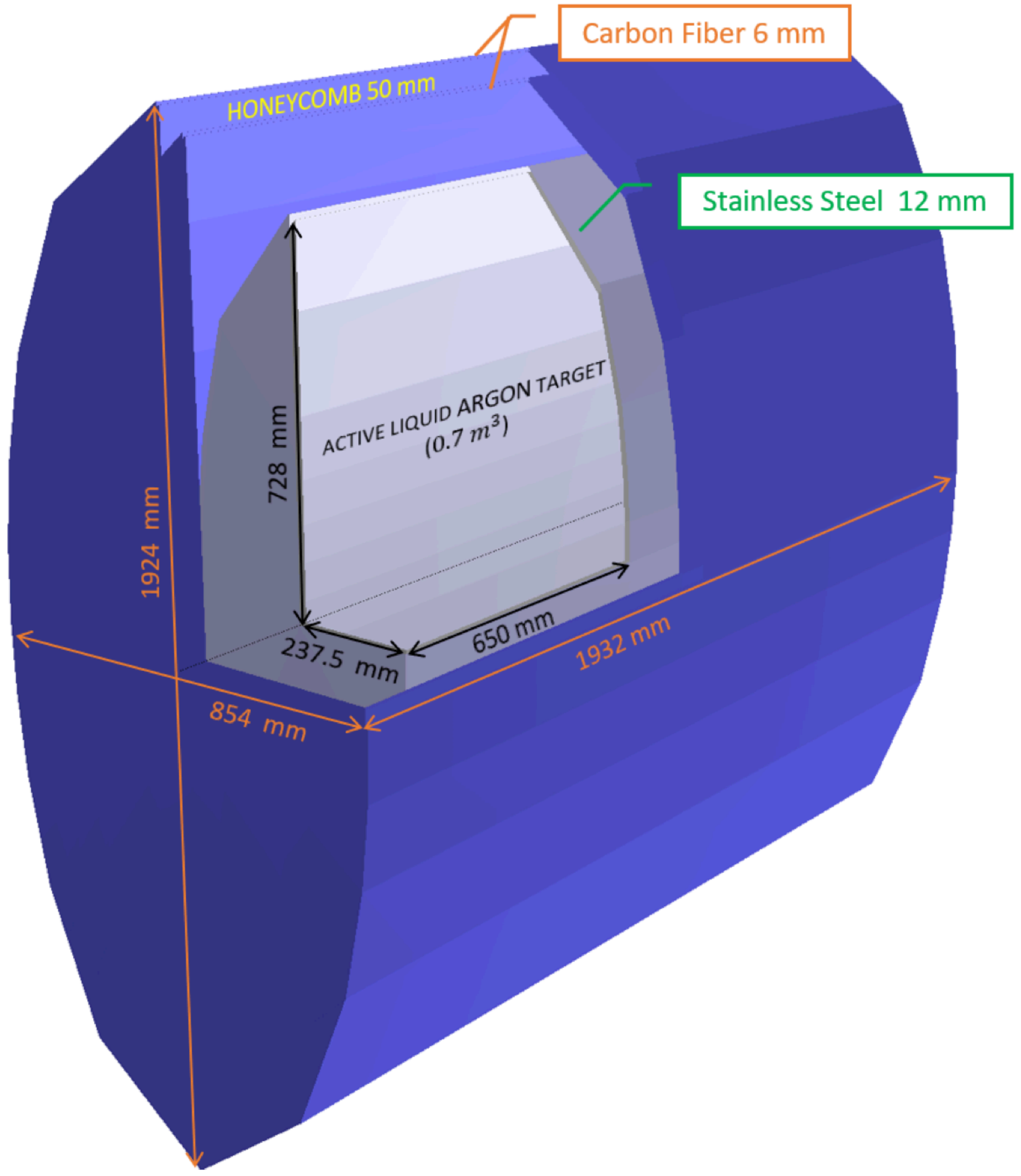
- Thus far:
  - Conceptual Design Report published in Sep 2021, Conceptual Design Review in July 2020
- Next step is to achieve Preliminary Design
  - Includes: preliminary Technical Design Report (PDR) and Preliminary Design Reviews of all subsystems by the LBNF/DUNE Review OFfice
- Goal: ready for installation when the Near Detector Hall is ready (second half of 2028)

SAND



(a) SAND engineering model



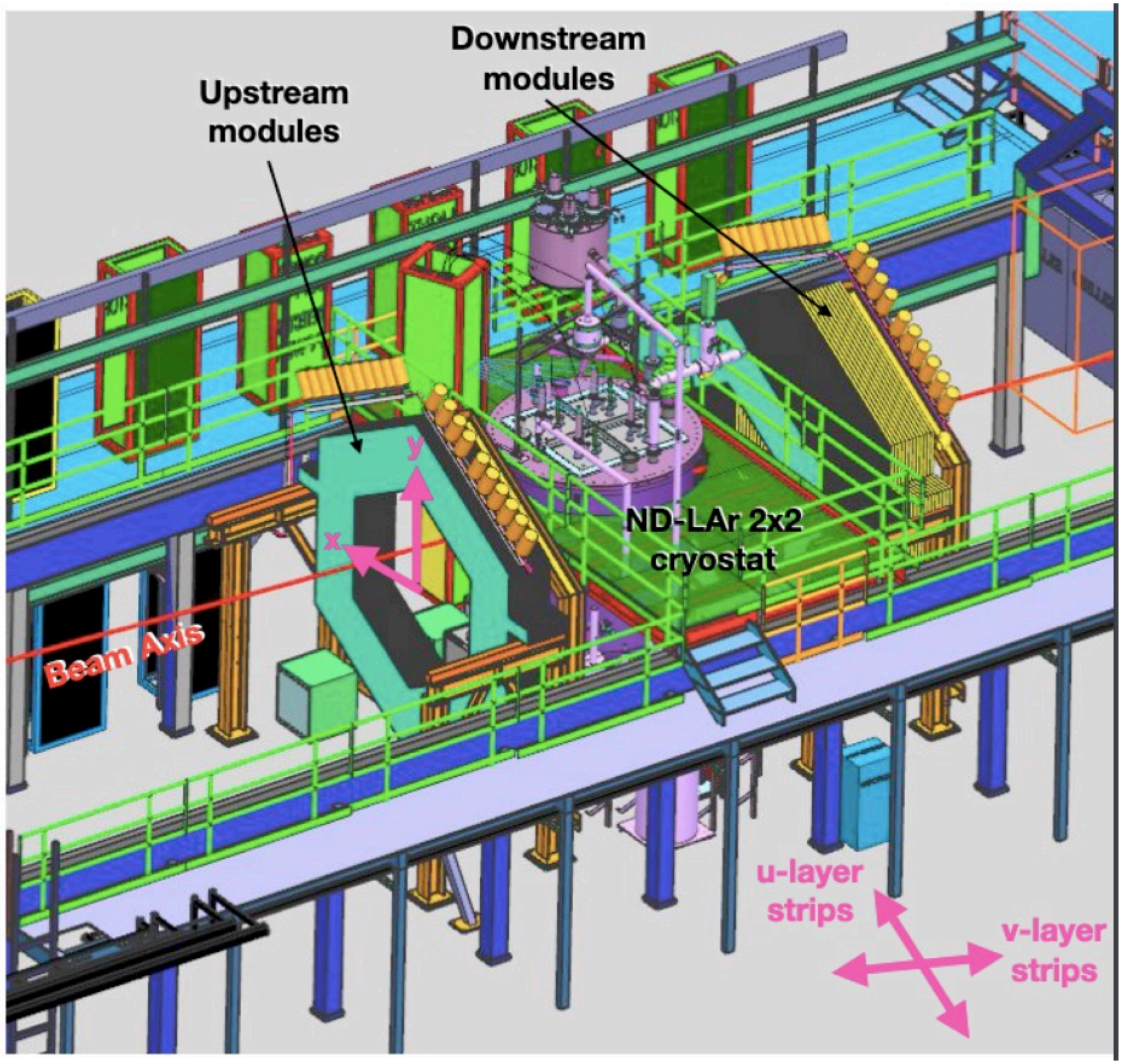


Straw-tubes tracker (STT) as tracker

GRAIN : active LAr target

2x2 Demonstrator

- 4 ND-LAr modules
- Reconfigured MINERvA
  - 44 modules w/total 76 scintillator planes
  - 12 **upstream tracker** modules (each is 2 scintillator planes)
  - 10 **downstream tracker** modules (each is 2 scintillator planes)
  - 10 **downstream ECAL** modules (each is 2 scintillator planes and 2 lead layers
  - 12 **downstream HCAL** modules (each is 1 scintillator plane and 1 steel plate



Jen Raaf's slides

DUNE Sensitivity

DUNE Phase-I in 2023 P5 Report

- Introduced only DUNE Phase-I status/plan so far

Recommendation 1: As the highest priority independent of the budget scenarios, complete construction projects and support operations of ongoing experiments and research to enable maximum science.

a. HL-LHC;

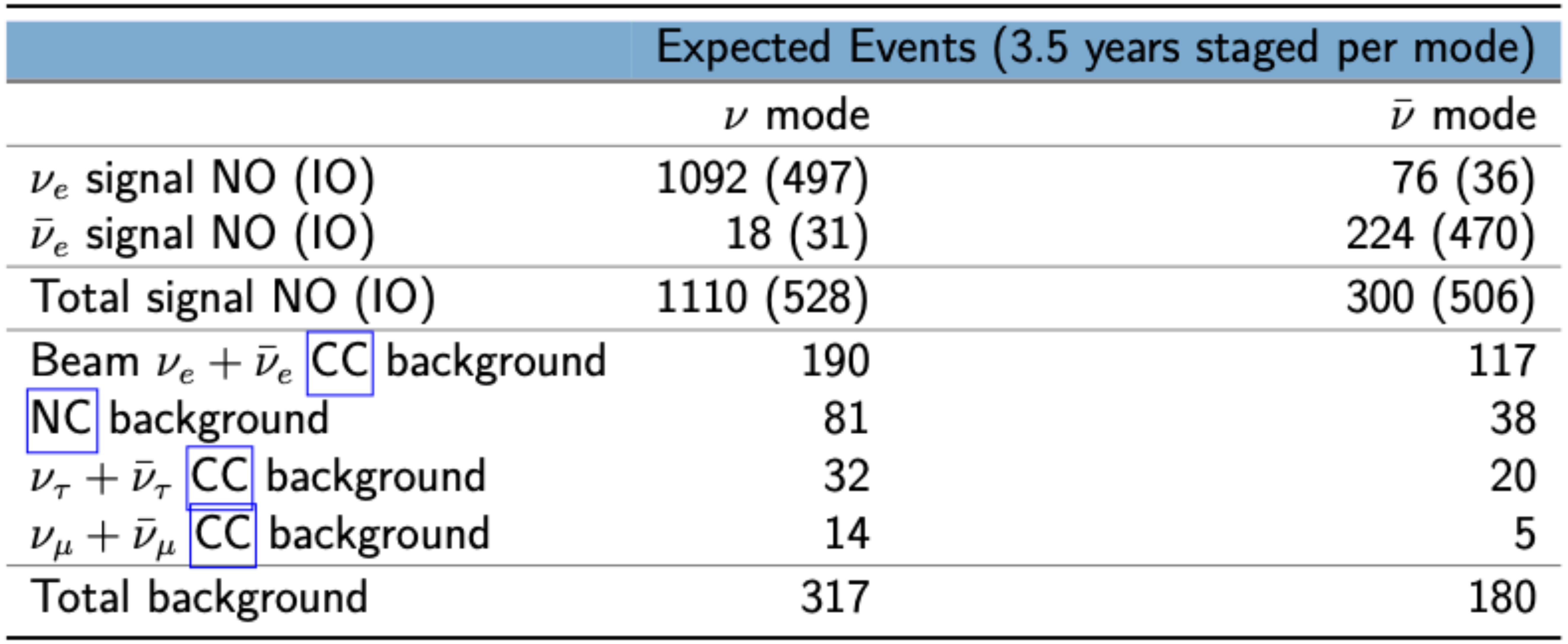
b. The first phase of DUNE and PIP-II to open an era of precision neutrino measurements that include the determination of the mass ordering among neutrinos. Knowledge of this fundamental property is a crucial input to cosmology and nuclear science (elucidate the mysteries of neutrinos, section 3.1).

c. …

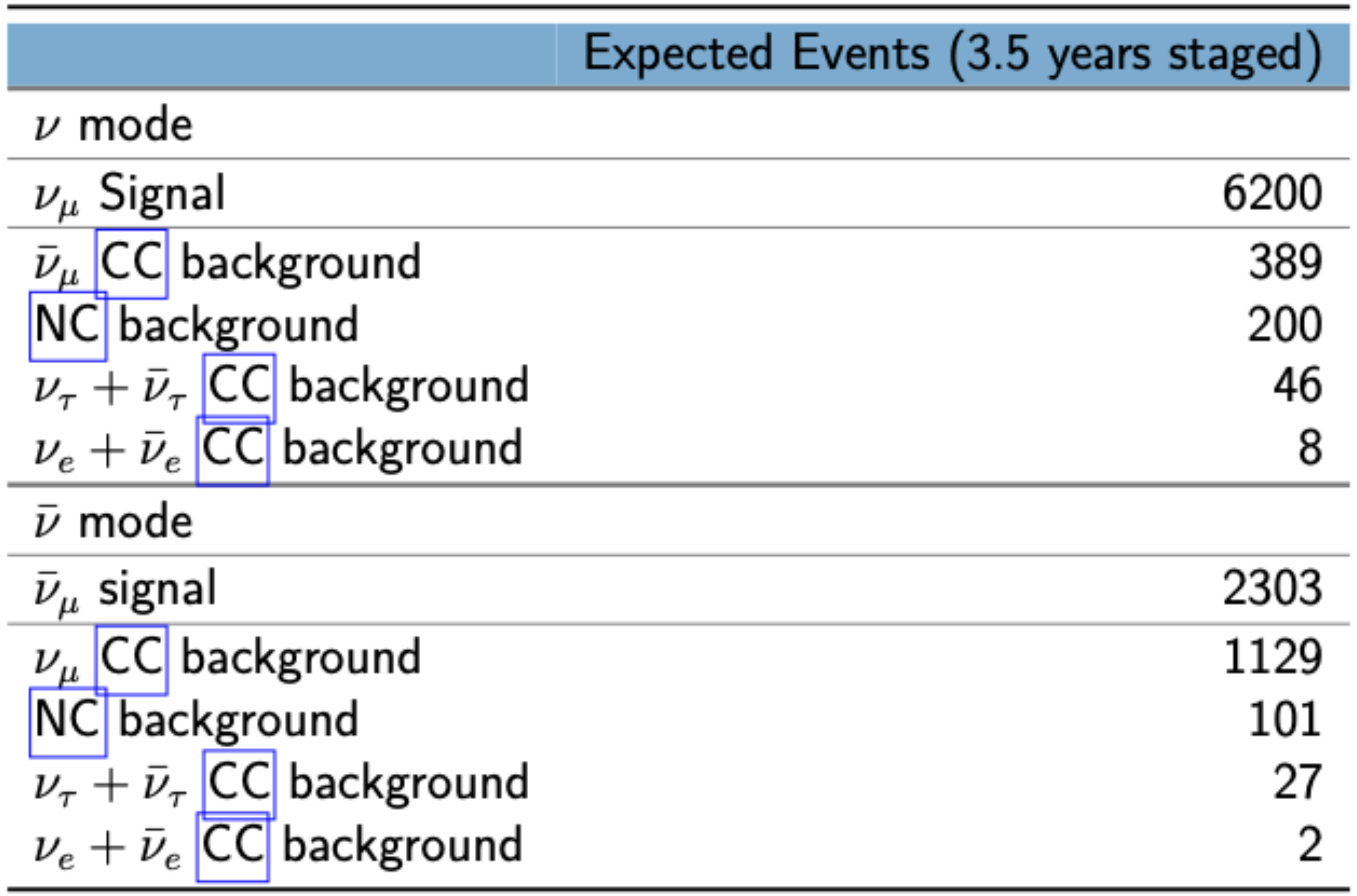
- Complete the first FD module installation and start science in 2029
- Second FD module, ND and neutrino beam will be ready around 2031-32

DUNE Physics Sensitivity -δ_{CP}

- Expected number of events



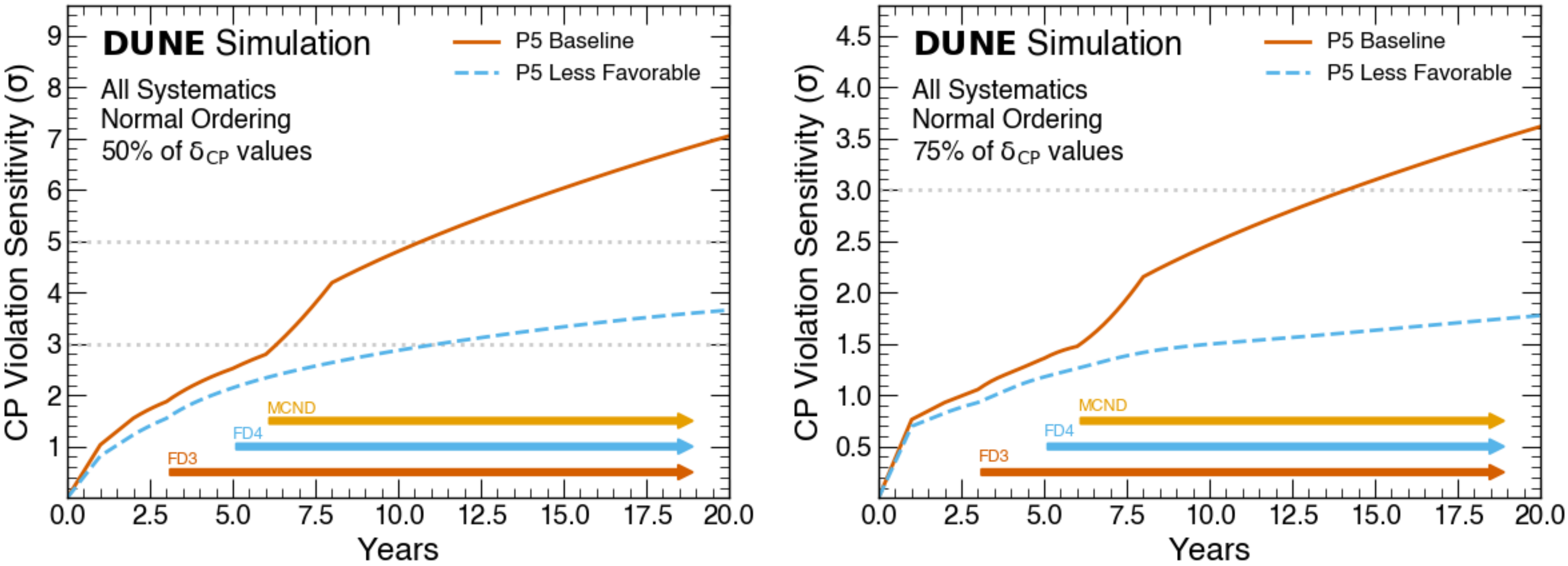
	Expected Events (3.5 years staged per mode)	
	ν mode	$\bar{\nu}$ mode
ν_e signal NO (IO)	1092 (497)	76 (36)
$\bar{\nu}_e$ signal NO (IO)	18 (31)	224 (470)
Total signal NO (IO)	1110 (528)	300 (506)
Beam $\nu_e + \bar{\nu}_e$ CC background	190	117
NC background	81	38
$\nu_\tau + \bar{\nu}_\tau$ CC background	32	20
$\nu_\mu + \bar{\nu}_\mu$ CC background	14	5
Total background	317	180



	Expected Events (3.5 years staged)
ν mode	
ν_μ Signal	6200
$\bar{\nu}_\mu$ CC background	389
NC background	200
$\nu_\tau + \bar{\nu}_\tau$ CC background	46
$\nu_e + \bar{\nu}_e$ CC background	8
$\bar{\nu}$ mode	
$\bar{\nu}_\mu$ signal	2303
ν_μ CC background	1129
NC background	101
$\nu_\tau + \bar{\nu}_\tau$ CC background	27
$\nu_e + \bar{\nu}_e$ CC background	2

DUNE Physics Sensitivity -δ_{CP}

- P5 Less Favorable : no FD4, no ACE-MIRT, and no MCND

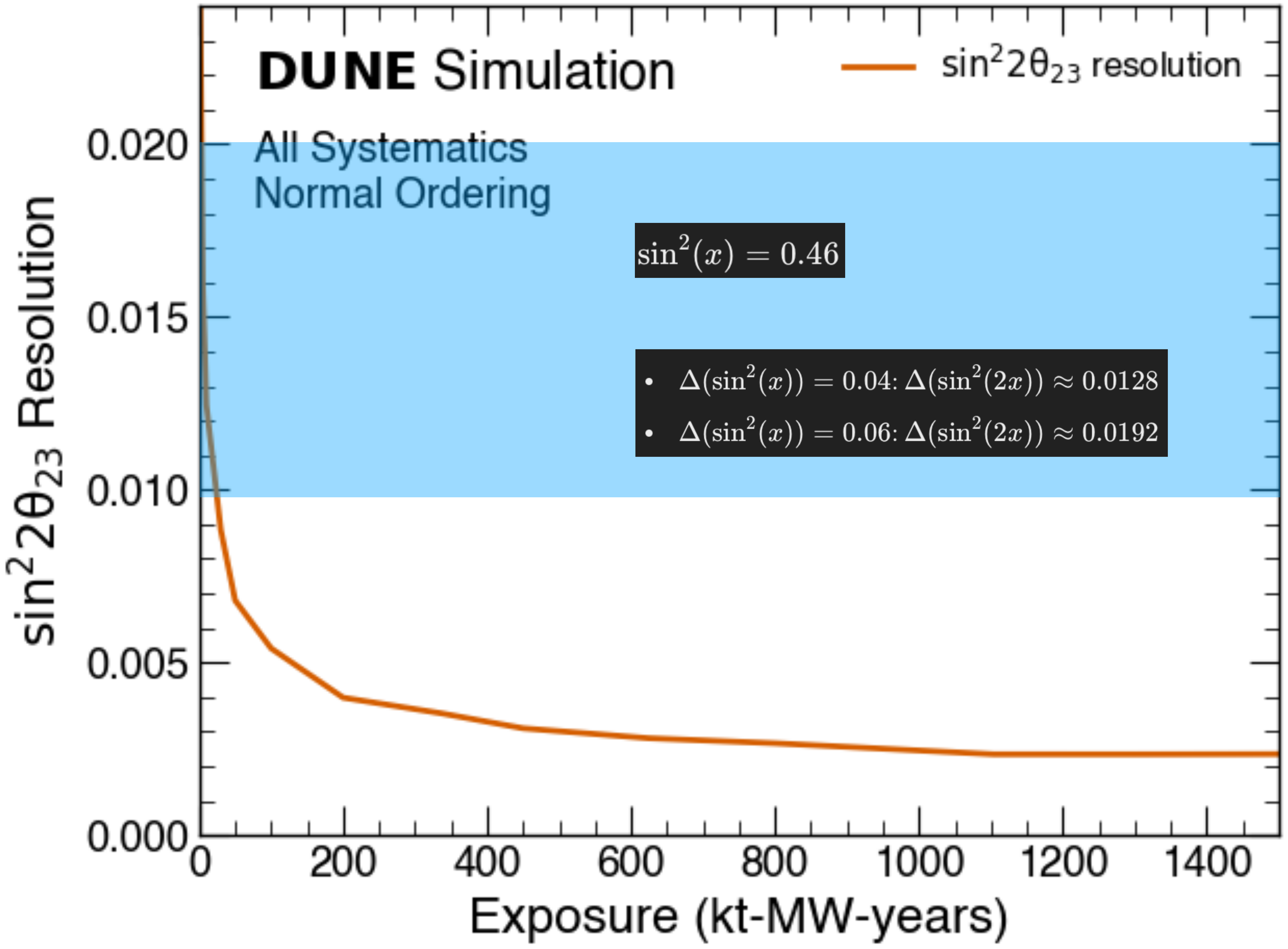


Current Uncertainties for PMNS Parameters

- θ_{23} resolution is dependent on its value

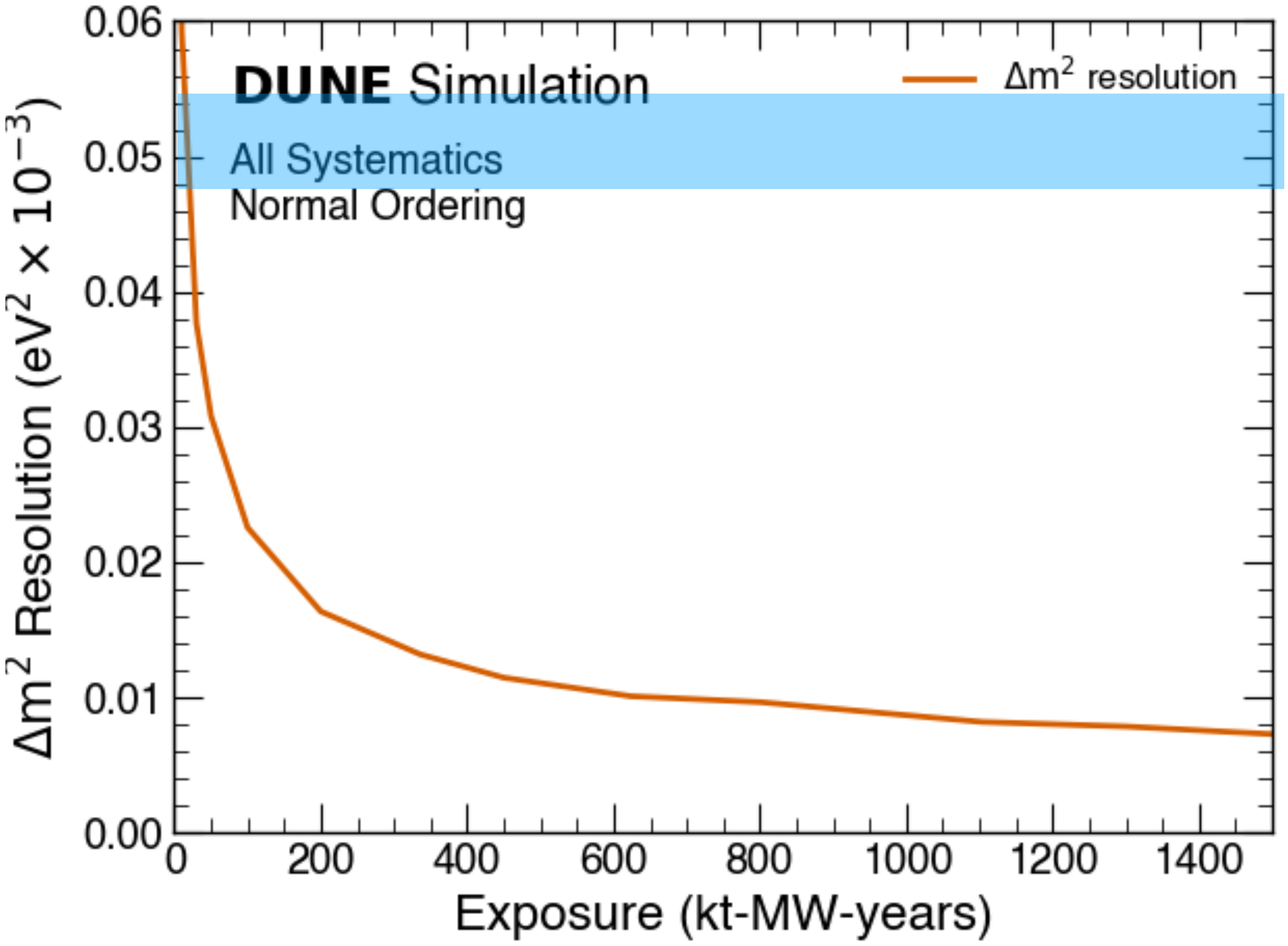
T2K $\Delta m^2_{32} = 2.48^{+0.05}_{-0.06} \times 10^{-3}\ \mathrm{eV}^2$ *Phys.Rev.D 108 (2023) 7, 072011*

Nova $\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2$ *Phys.Rev.D 106 (2022) 3, 032004*



$\sin^2(x) = 0.46$

- $\Delta(\sin^2(x)) = 0.04$: $\Delta(\sin^2(2x)) \approx 0.0128$
- $\Delta(\sin^2(x)) = 0.06$: $\Delta(\sin^2(2x)) \approx 0.0192$



DUNE Physics Sensitivity - θ_{23} Octant

- A combination of both ν_e appearance and ν_μ disappearance measurements can probe both maximal mixing and the θ_{23} octant.
- 10 years : 624 kt MW year
- 15 years : 1104 kt MW year

ambiguous octant

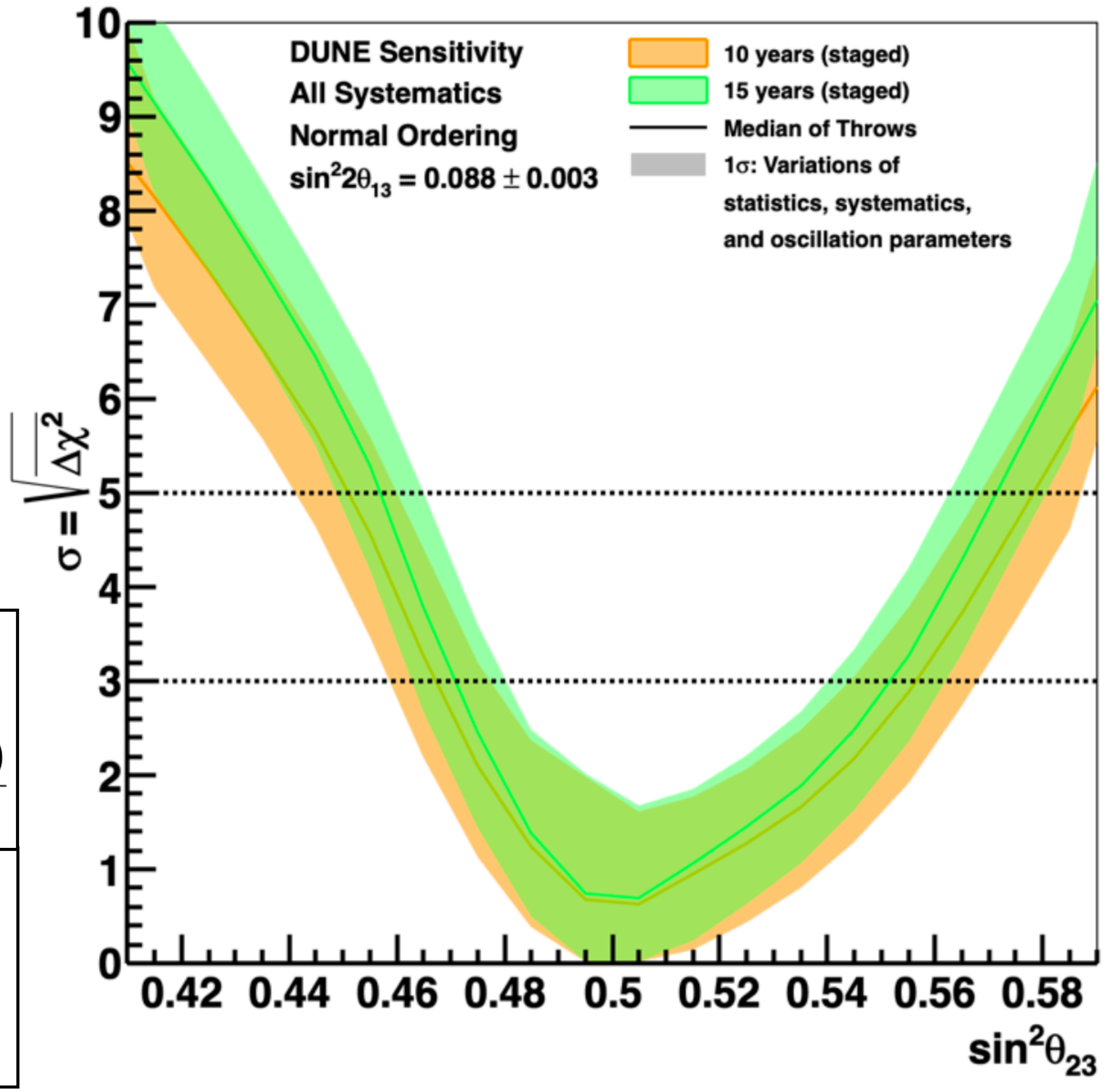
$$P_{\nu_\mu\to\nu_\mu} \approx 1 - \sin^2 2\theta_{\mu\mu}\,\sin^2\frac{\Delta m^2_{\mu\mu}L}{4E_\nu} \approx 1-\cos^2\theta_{13}\,\sin^2(2\theta_{23})\,\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} + \mathcal{O}(\alpha, s^2_{13})\,,$$

with

$$\begin{aligned}\sin^2\theta_{\mu\mu} &= \cos^2\theta_{13}\sin^2\theta_{23}\,,\\ \Delta m^2_{\mu\mu} &= \sin^2\theta_{12}\Delta m^2_{31}+\cos^2\theta_{12}\Delta m^2_{32}\\ &\quad +\cos\delta_{\mathrm{CP}}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}.\end{aligned}$$

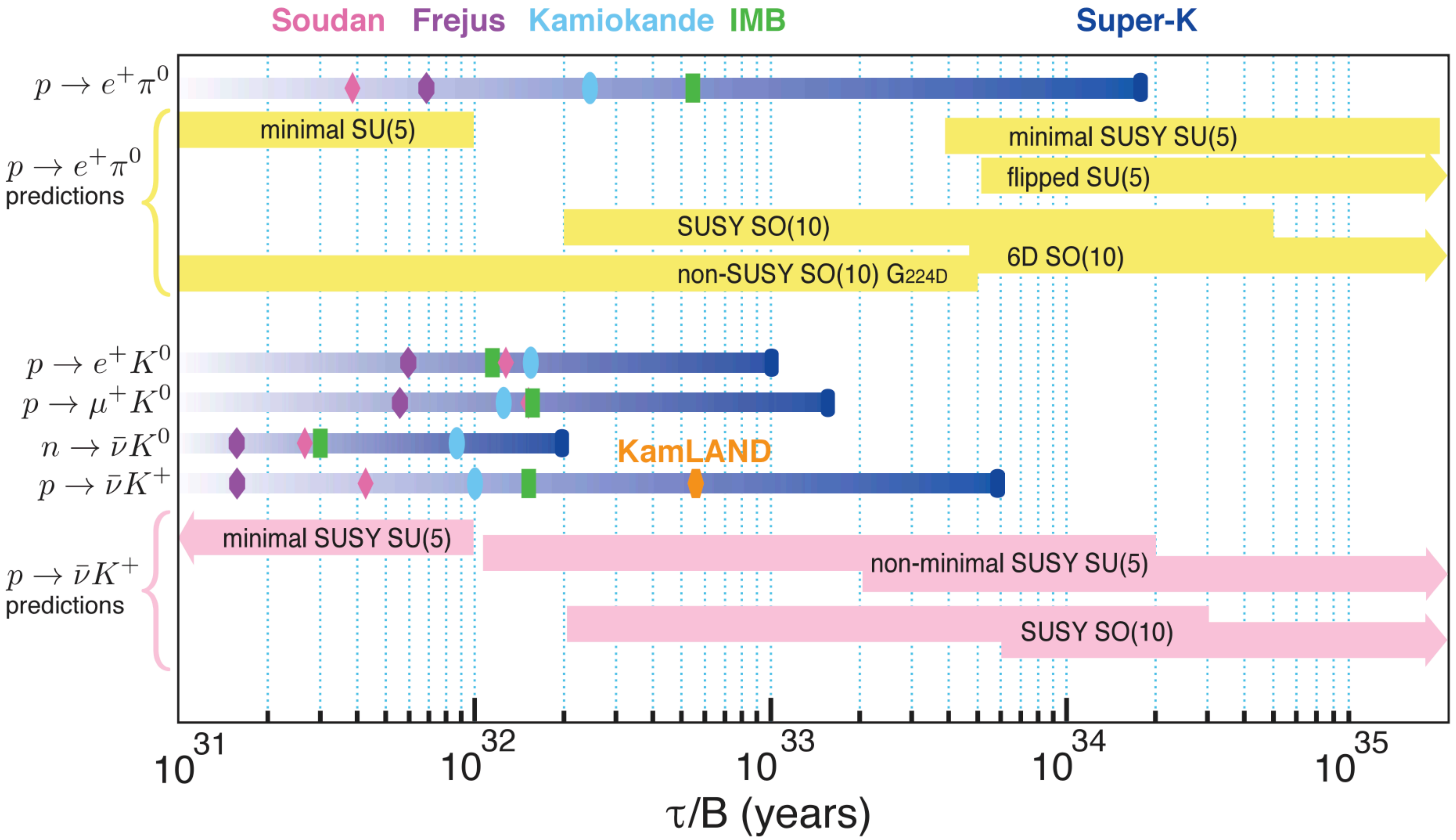
$$\begin{aligned}P_{\nu_\mu\to\nu_e,(\bar\nu_\mu\to\bar\nu_e)} \approx\ & 4\,\sin^2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\,\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2}\\ & + 8\,\alpha\,J^{\max}_{\mathrm{CP}}\cos(\Delta\pm\delta_{\mathrm{CP}})\,\frac{\sin\Delta A}{A}\,\frac{\sin\Delta(1-A)}{1-A}\end{aligned}$$

$$\begin{aligned}J^{\max}_{\mathrm{CP}} &= \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}\,,\\ \alpha &\equiv \Delta m^2_{21}/\Delta m^2_{31}\\ \Delta &\equiv \frac{\Delta m^2_{31}L}{4E_\nu}\,, \quad A\equiv\frac{2E_\nu V}{\Delta m^2_{31}}\,,\end{aligned}$$



DUNE Physics Sensitivity - Proton Decay

- With 30% detection efficiency for $p \rightarrow K^{+}\bar{\nu}$, DUNE Phase-II expected limit is 1.3×10^{34} years
  - Super-K : 5.9×10^{33} years
  - Hyper-K expected limit : 3×10^{34} years



DUNE Physics Sensitivity - Supernova Event

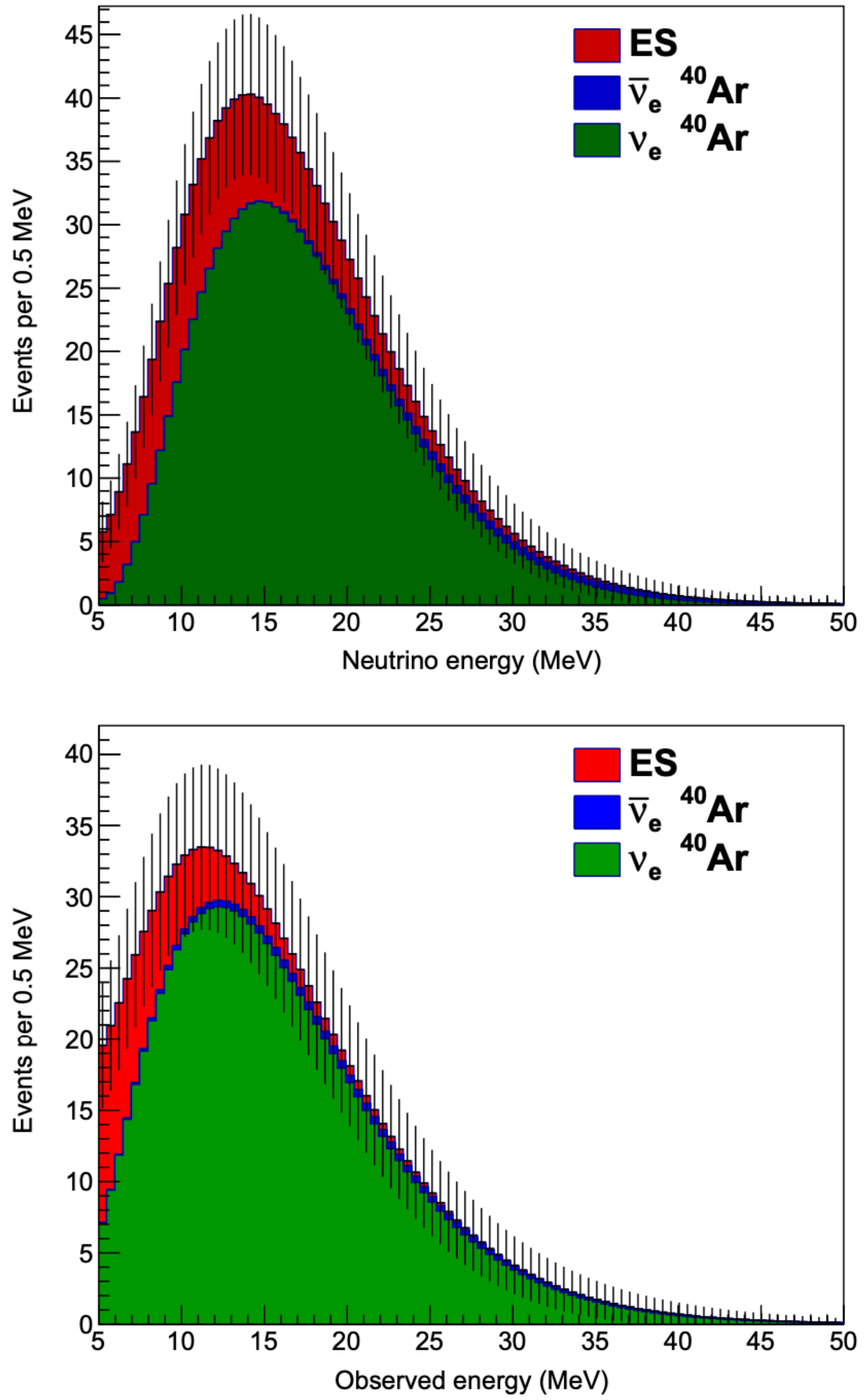
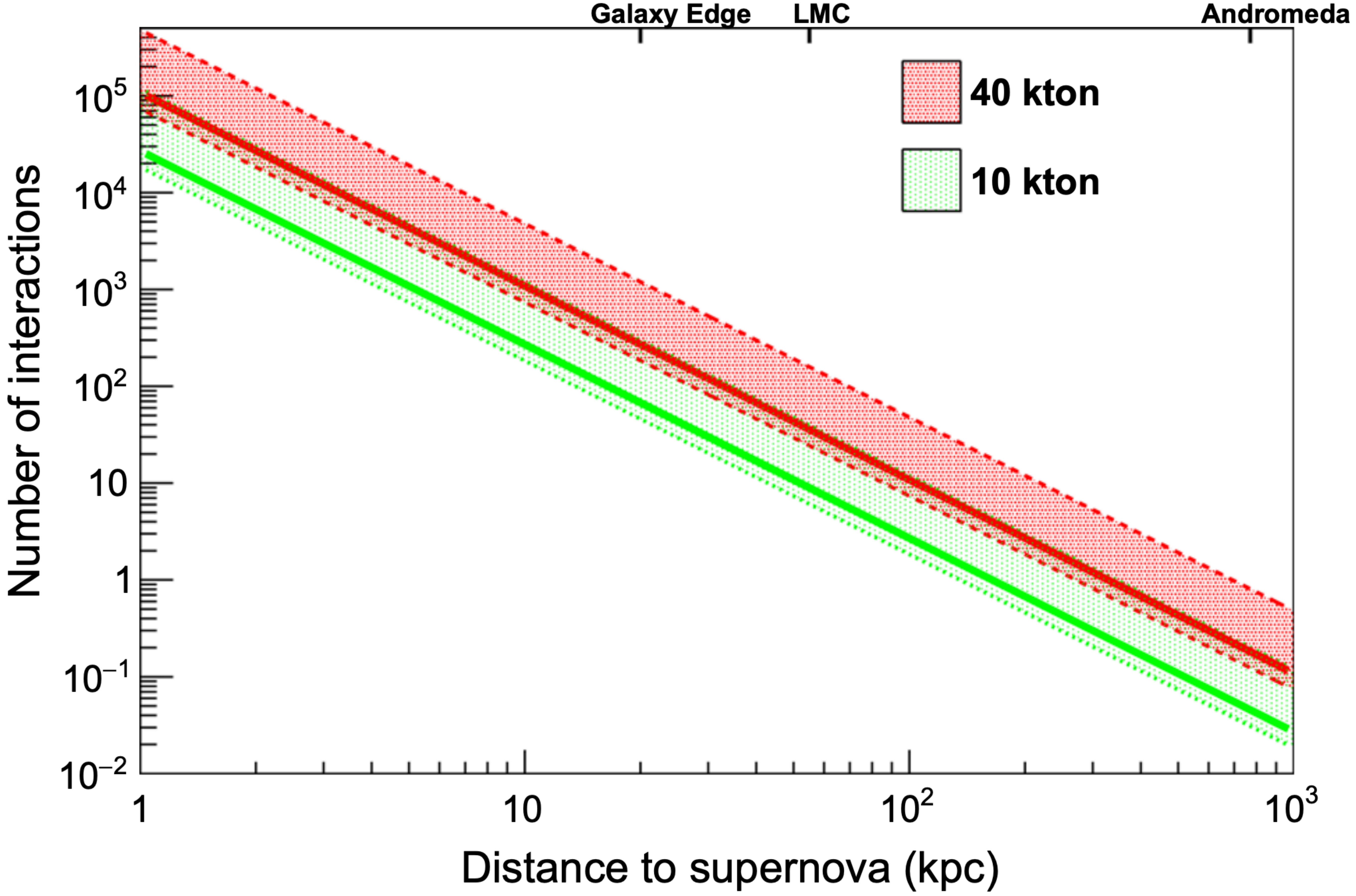
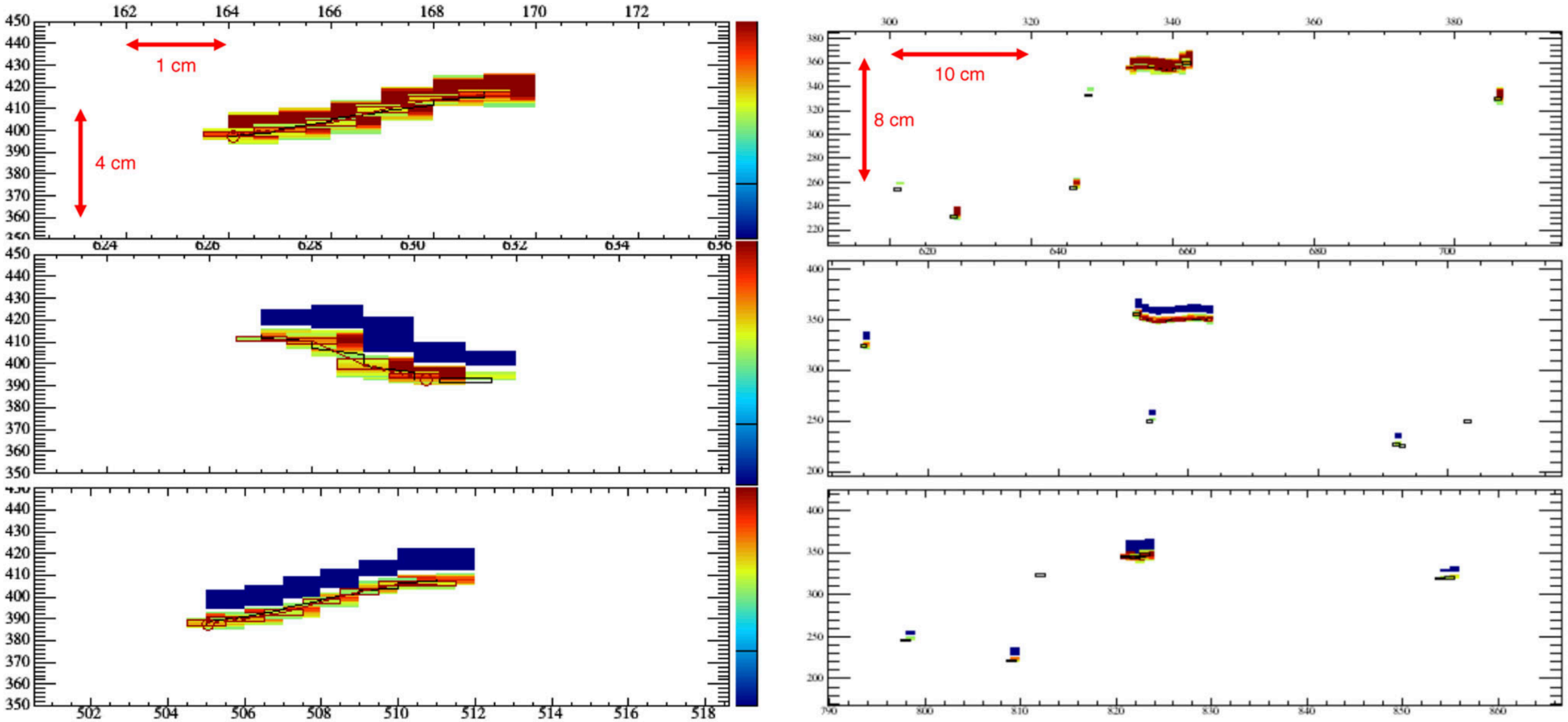


Fig. 10 Top: Spectrum as a function of interacted neutrino energy computed with SNOwGLoBES in 40 kton of liquid argon for the electron-capture supernova [8] ("Garching" model) at 10 kpc, integrated over time, and indicating the contributions from different interaction channels. No oscillations are assumed. Bottom: expected measured spectrum as a function of observed energy, after detector response smearing



DUNE Physics Sensitivity - MeV Neutrino Events

Elastic Scattering of 10.25 MeV



CC of 20.25 MeV

Fig. 4 Left: DUNE event display showing a simulated neutrino-electron ES event (10.25 MeV electron) with track reconstruction. The vertical dimension indicates time and the horizontal dimension indicates wire number. Color represents charge. The top panel shows the collection plane and the bottom panels show induction planes. The boxes represent reconstructed hits. Right: simulated ν_eCC event (20.25 MeV neutrino), showing electron track and blips from Compton-scattered gammas. The events have different spatial scales, as indicated on the figures

DUNE Physics Sensitivity - NC-NSI Propagation H

$$H = U \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2/2E & \\ & & \Delta m_{31}^2/2E \end{pmatrix} U^\dagger + \tilde{V}_{\text{MSW}} \,,$$

with

$$\tilde{V}_{\text{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1 + \epsilon_{ee}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m \\ \epsilon_{e\mu}^{m*} & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\ \epsilon_{e\tau}^{m*} & \epsilon_{\mu\tau}^{m*} & \epsilon_{\tau\tau}^m \end{pmatrix}$$

General Neutrino Physics

Neutrino Sources for PMNS Matrix Elements

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

Solar, Reactor LBL

$$P^{2\nu,\mathrm{sun}}_{ee} \simeq 1 - \frac{1}{2}\sin^2(2\theta_{12}) \qquad \text{for } E_\nu \lesssim \text{few} \times 100 \text{ keV}\,,$$

$$P^{2\nu,\mathrm{sun}}_{ee} \simeq \sin^2(\theta_{12}) \qquad \text{for } E_\nu \gtrsim \text{few} \times 1 \text{ MeV}\,,$$

$$P^{2\nu,\mathrm{kam}}_{ee} = 1 - \sin^2(2\theta_{12})\sin^2\frac{\Delta m^2_{21}L}{4E_\nu}.$$

Reactor MBL

$$P_{\nu_e\to\nu_e} = 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{ee}L}{4E_\nu} + \mathcal{O}(\alpha^2)\,,$$

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}\,.$$

Atmo.

$$\frac{N_e}{N_e^0} - 1 \approx (r\sin^2\theta_{23} - 1)P_{2\nu}(\Delta m^2_{32}, \theta_{13}) + (r\cos^2\theta_{23} - 1)P_{2\nu}(\Delta m^2_{21}, \theta_{12})$$
$$- \sin\theta_{13}\sin 2\theta_{23}\, r\,\Re(A^*_{ee}A_{\mu e})\,.$$

CP-phase

$$\frac{N_\mu}{N_\mu^0} - 1 \approx \sin^2\theta_{23}\left(\frac{1}{r} - \sin^2\theta_{23}\right)P_{2\nu}(\Delta m^2_{32}, \theta_{13}) - \frac{1}{2}\sin^2 2\theta_{23}\,[1 - \Re(A_{33})]$$

Acce. LBL

$$P_{\nu_\mu\to\nu_\mu} \approx 1 - \sin^2 2\theta_{\mu\mu}\sin^2\frac{\Delta m^2_{\mu\mu}L}{4E_\nu} \approx 1 - \cos^2\theta_{13}\sin^2(2\theta_{23})\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} + \mathcal{O}(\alpha, s^2_{13})\,, \qquad (14.76)$$

with

$$\begin{aligned} \sin^2\theta_{\mu\mu} &= \cos^2\theta_{13}\sin^2\theta_{23}\,, \\ \Delta m^2_{\mu\mu} &= \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} \\ &\quad + \cos\delta_{\mathrm{CP}}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}. \end{aligned}$$

$$P_{\nu_\mu\to\nu_e,(\bar{\nu}_\mu\to\bar{\nu}_e)} \approx 4\sin^2\theta_{13}\sin^2\theta_{23}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2}$$
$$+ 8\,\alpha\, J^{\max}_{\mathrm{CP}}\cos(\Delta \pm \delta_{\mathrm{CP}})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{1-A}$$

$$J^{\max}_{\mathrm{CP}} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}\,,$$
$$\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$$
$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu}\,, \quad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}\,,$$