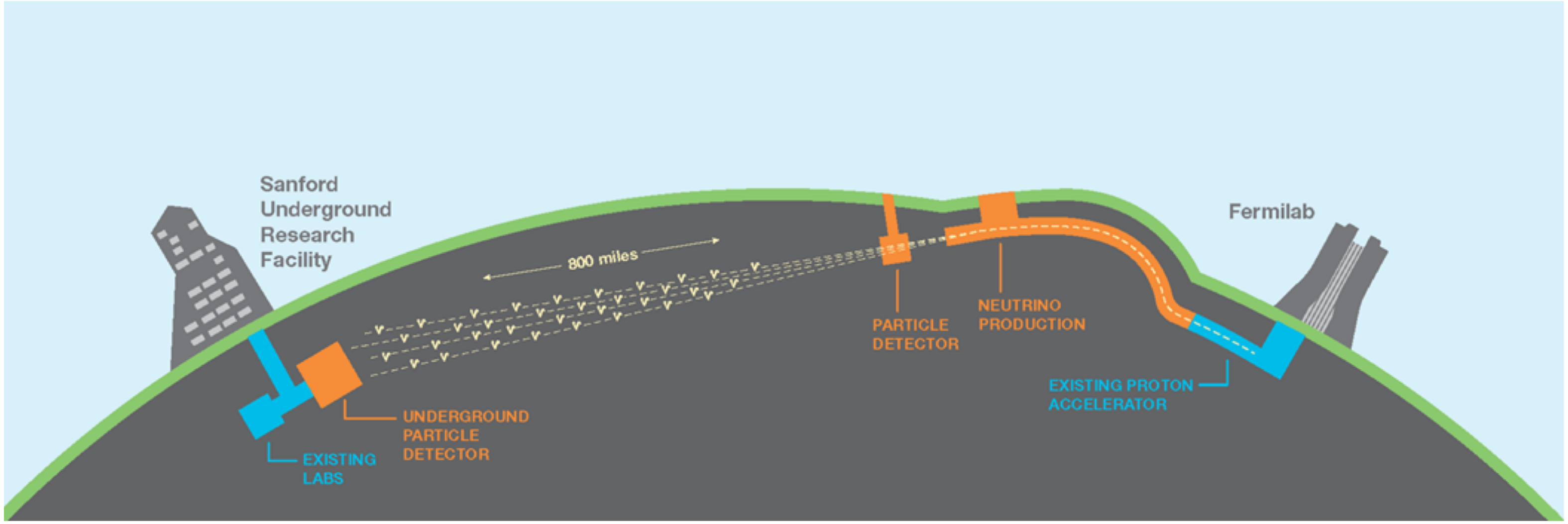
DUNE
Precision Neutrino Physics of the Future



Alfons Weber

for the DUNE Collaboration

LP2019 Toronto

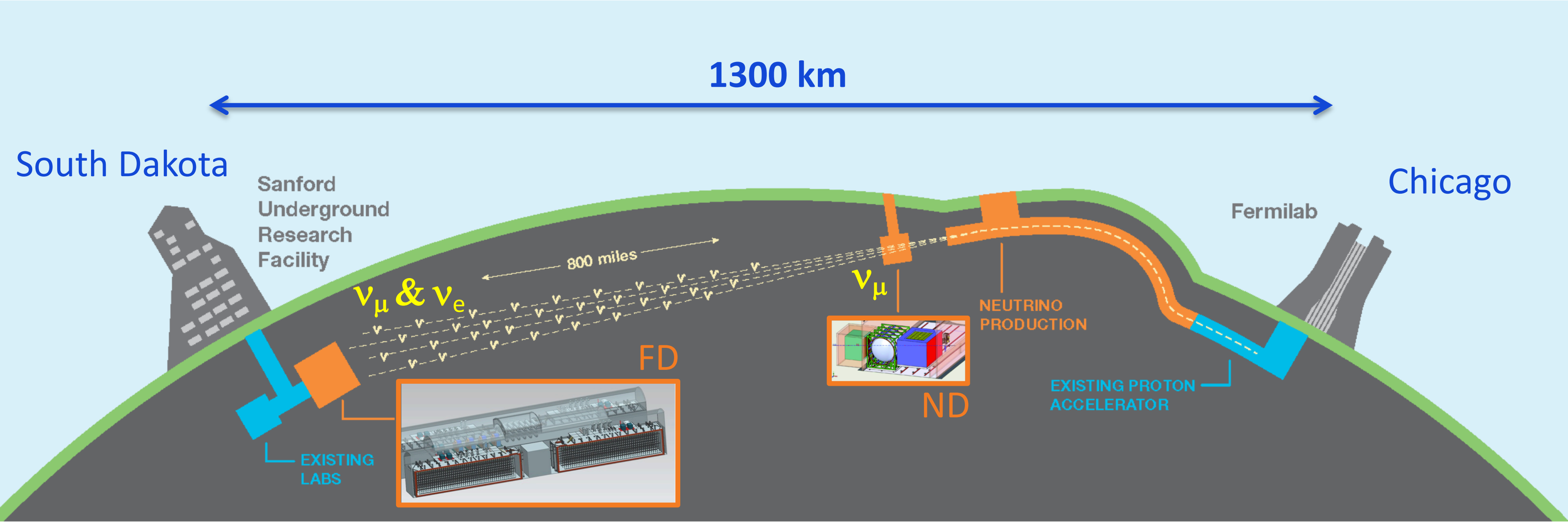
UNIVERSITY OF OXFORD

Science & Technology Facilities Council

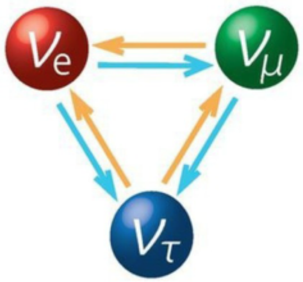
DUNE

General Setup

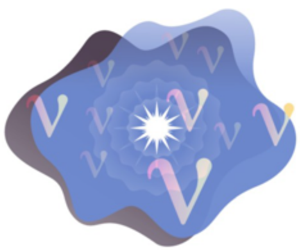
- LBNF/DUNE will consist of
  - An **intense ν-beam** fired from Fermilab
  - A **Near Detector** at Fermilab
  - A massive **40kt** deep **underground LAr detector** in South Dakota



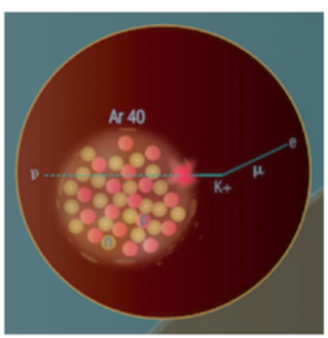
Physics Program



- **Neutrino Oscillations**
  - Search for leptonic CP violation
  - Determine neutrino mass ordering
  - Precision PMNS measurements

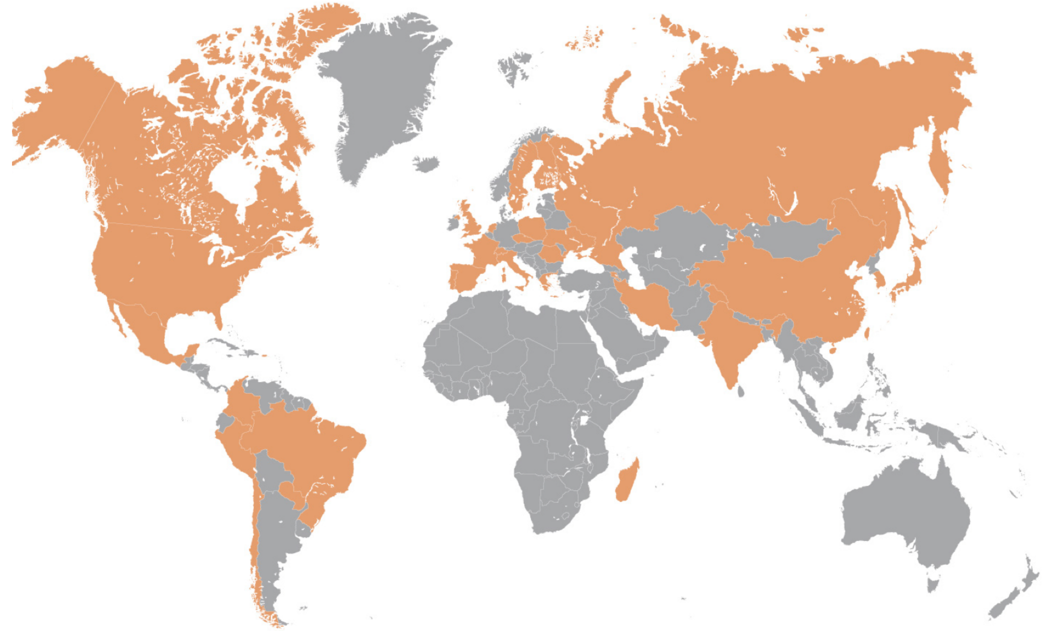


- **Supernova Physics**
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
  - Unique sensitivity to electron neutrinos



- **Baryon number violation**
  - Predicted by many BSM theories
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, $\bar{p} \rightarrow K + \nu$)
  - $\Delta(B-L) \neq 0$ channels accessible (*e.g.*, $n \rightarrow \bar{n}$)

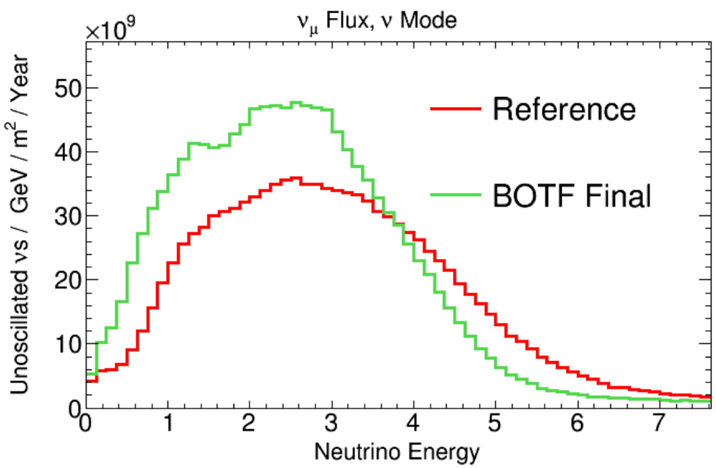
DEEP UNDERGROUND NEUTRINO EXPERIMENT



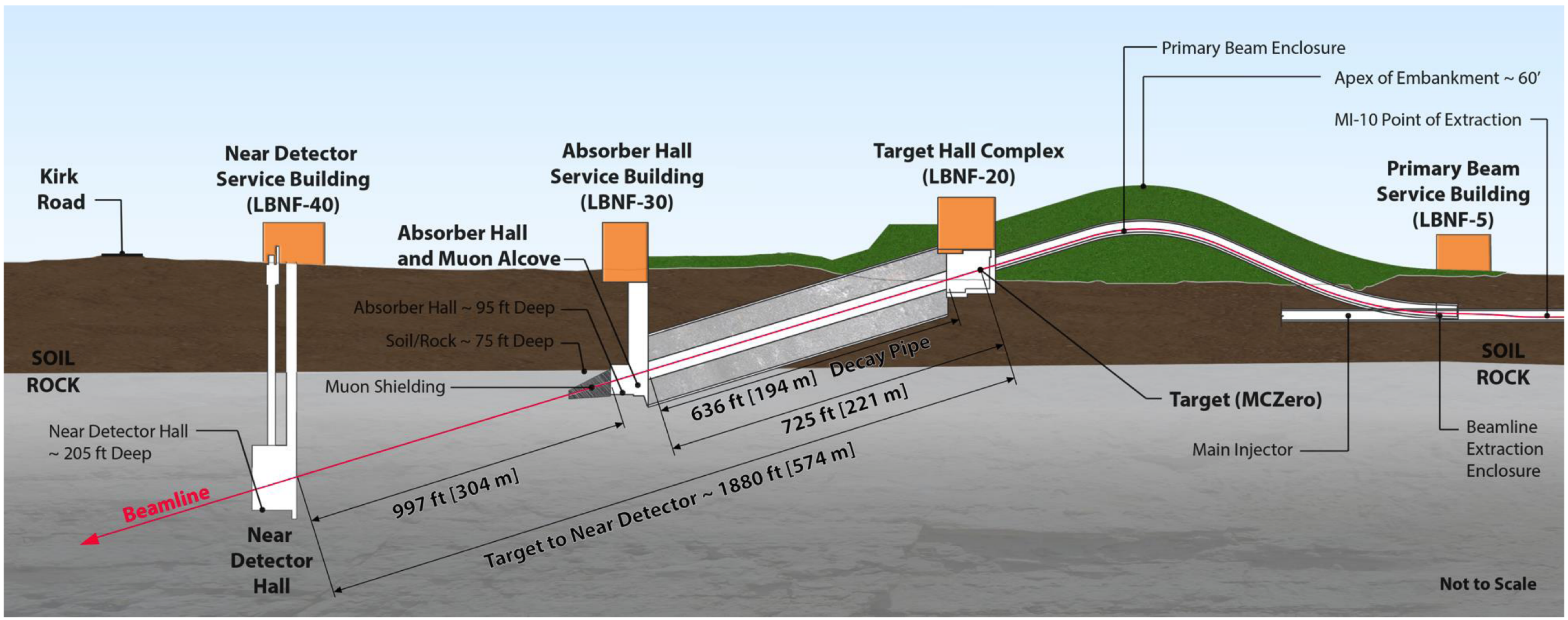
An international science collaboration

1106 collaborators from **184 institutions** in **31 countries**

Beam



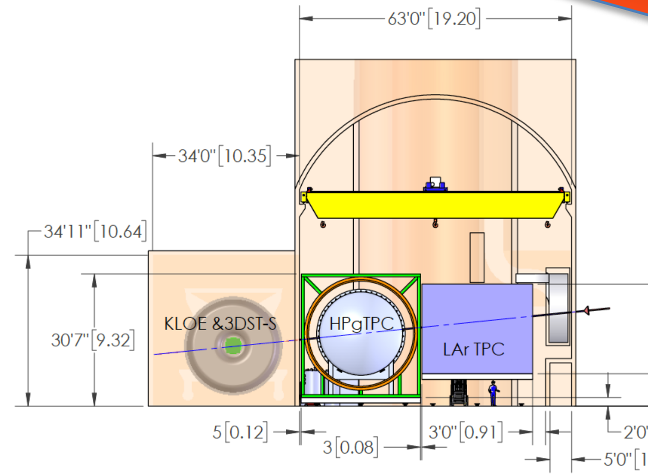
- Proton beam energy 60-120 GeV
- Power
  1.2 MW ➔ 2.4 MW
- Neutrinos and anti-neutrinos

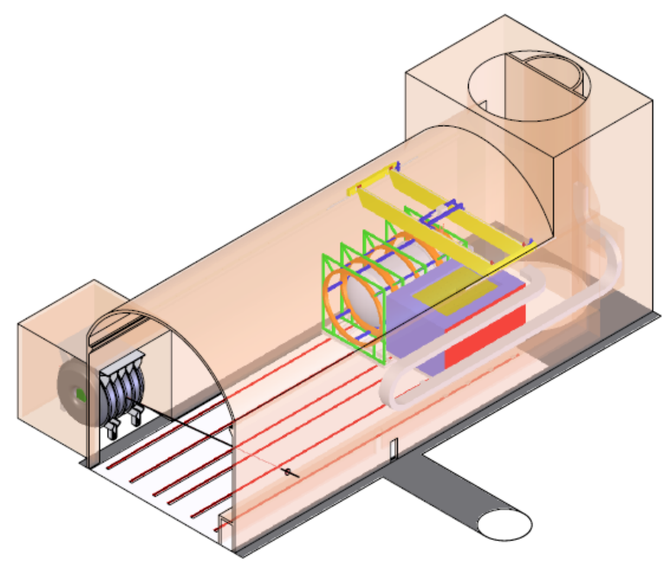


Near Detector Complex

Capabilities of the DUNE Near Detector Complex
K. McFarland (6-Aug, 16:45)

- Four main components, working together:
    1. Liquid argon detector (ArgonCube)
    2. Downstream tracker with gaseous argon target (MPD)
    3. LAr and GAr systems can move to off-axis fluxes (DUNE PRISM)
    4. On-axis flux monitor with neutron detection capability (3DST-S)
- High statistics constrains
    - Cross section & Flux

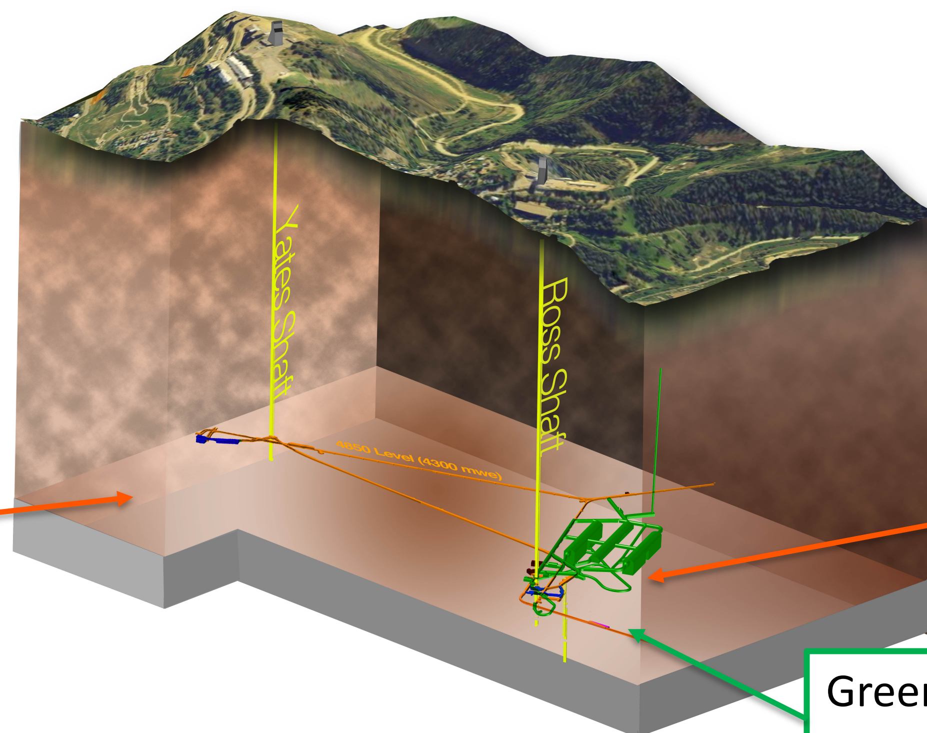




Underground Laboratory SURF

DUNE Far Detector site

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

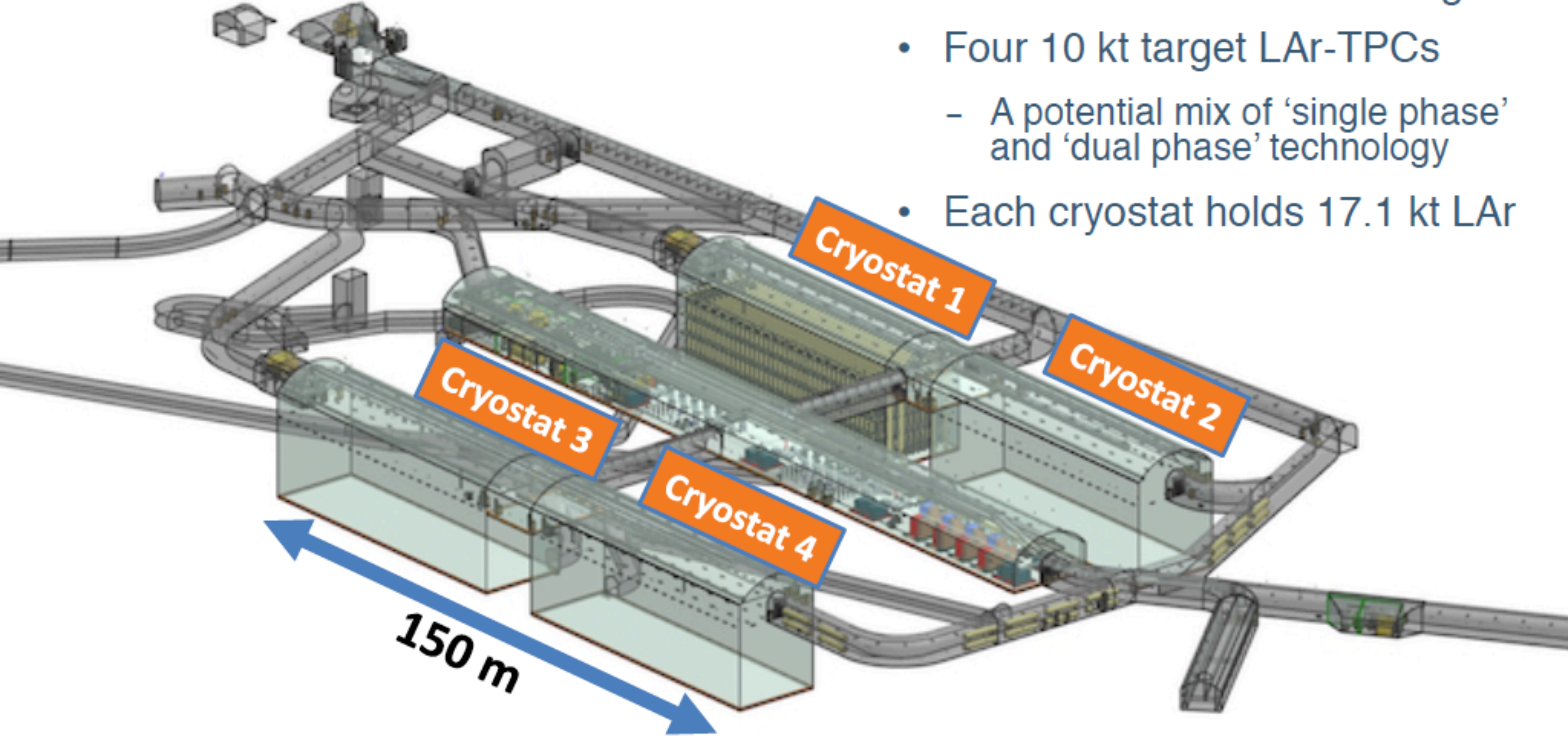


Davis Campus:
- LUX
- Majorana
- …
- **LZ**

Ross Campus:
- CASPAR
- …
- **DUNE**

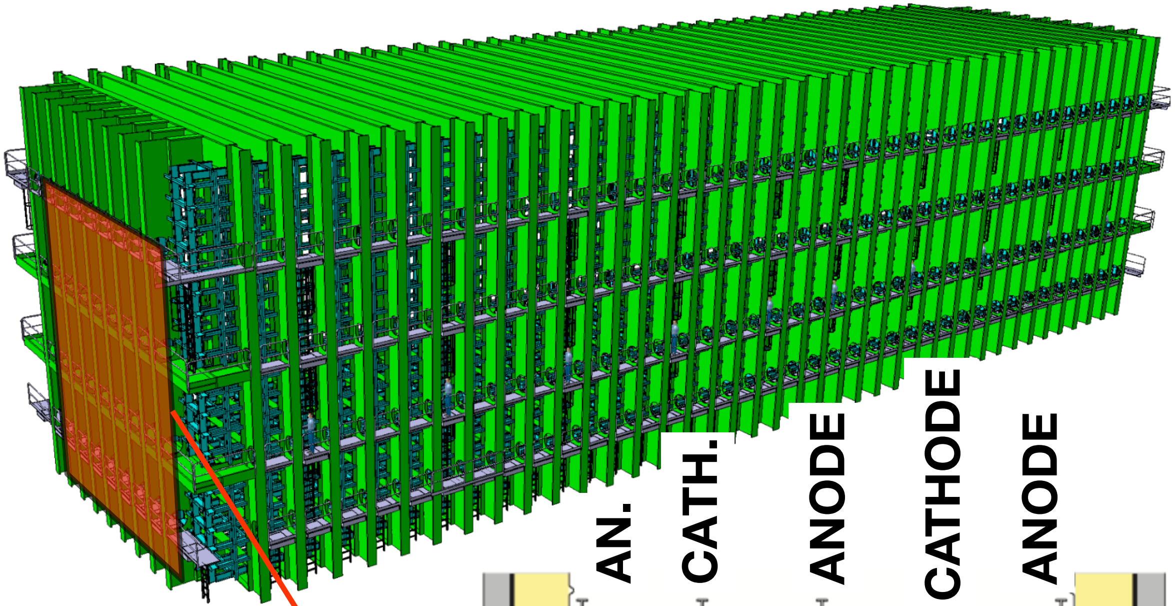
Green = new excavation commenced in 2017

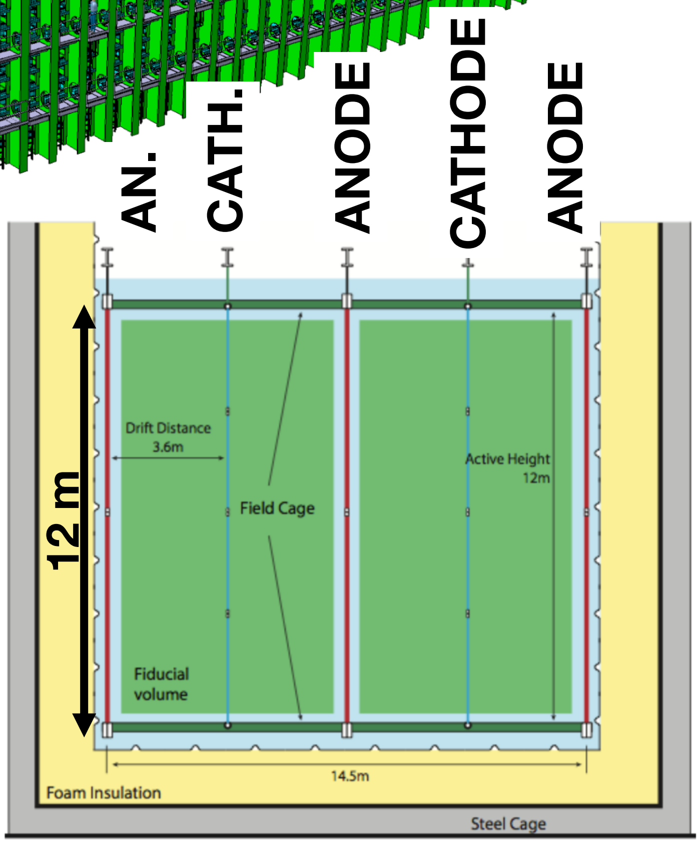
DUNE Far Detector



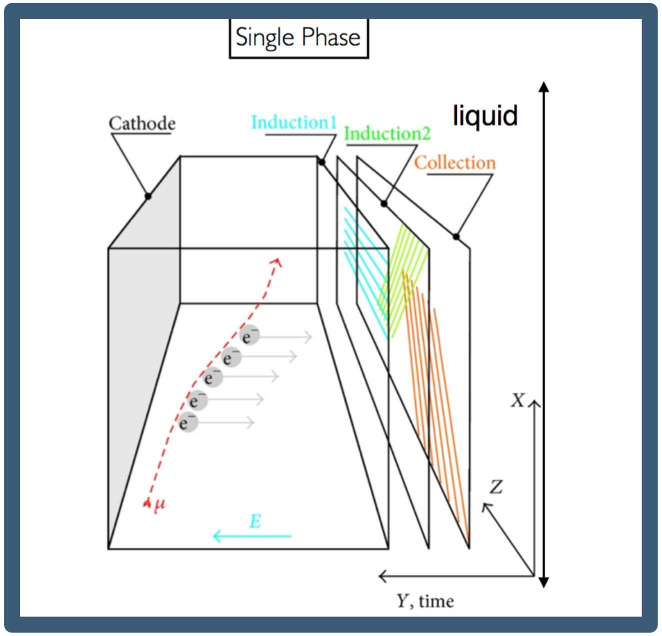
- 1478 m underground
- 1300 km from the beam target
- Four 10 kt target LAr-TPCs
  - A potential mix of 'single phase' and 'dual phase' technology
- Each cryostat holds 17.1 kt LAr

Far detectors: 1st module

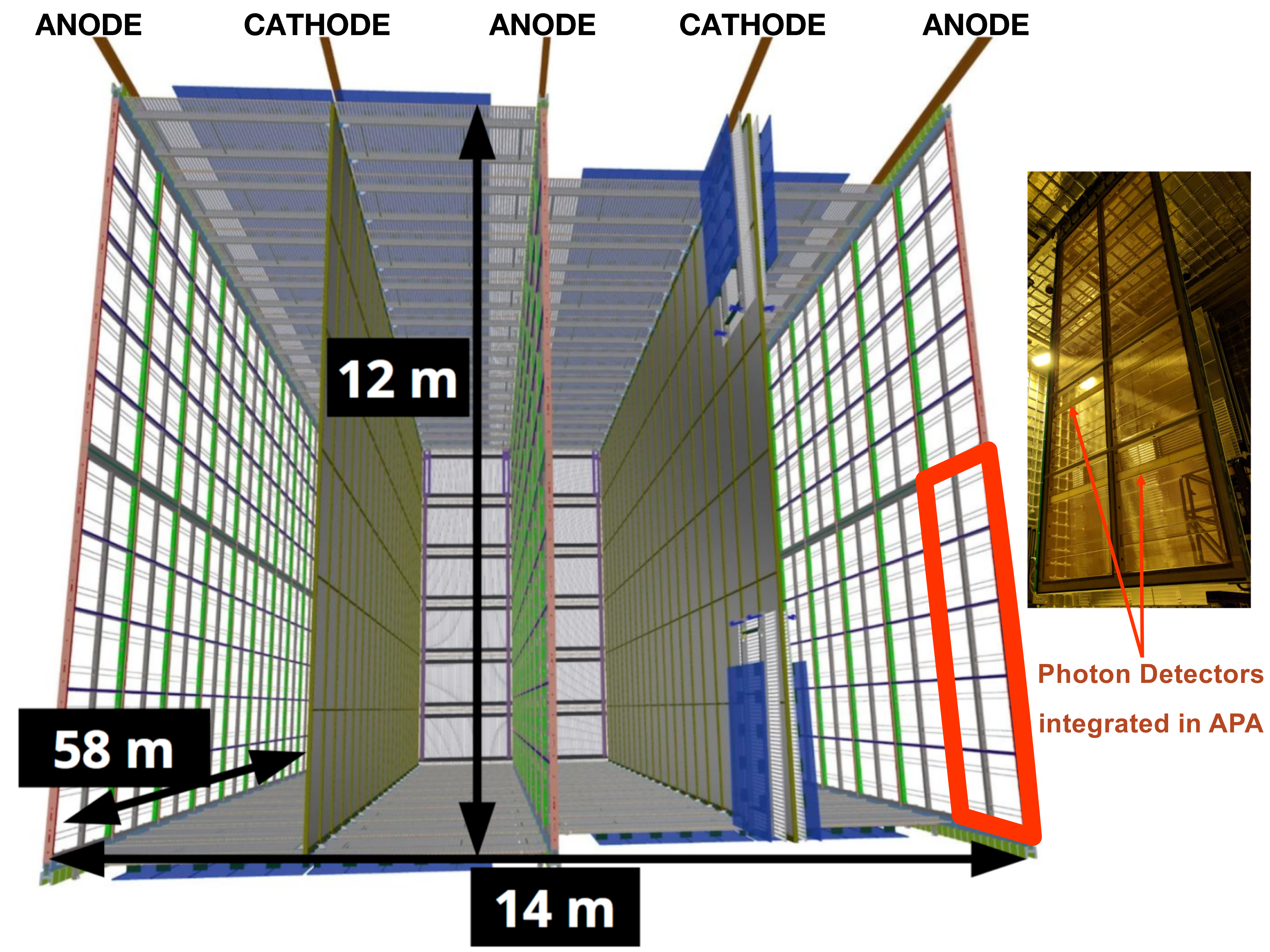




Single-Phase



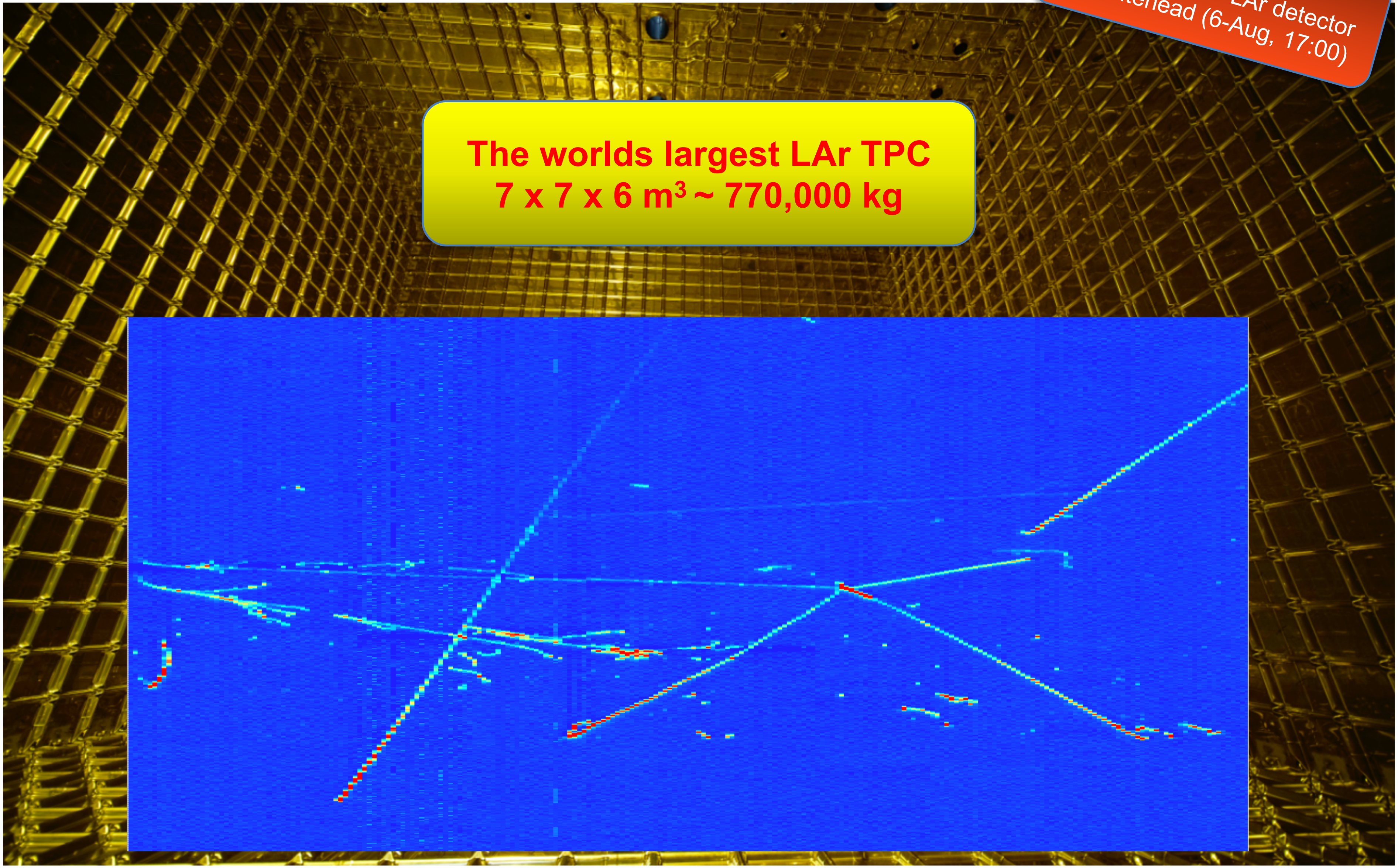
E-field = 500 V/cm


ANODE
CATHODE
ANODE
CATHODE
ANODE
12 m
58 m
14 m
Photon Detectors
integrated in APA

ProtoDUNE

Performance of the ProtoDUNE-SP LAr detector
L. Whitehead (6-Aug, 17:00)

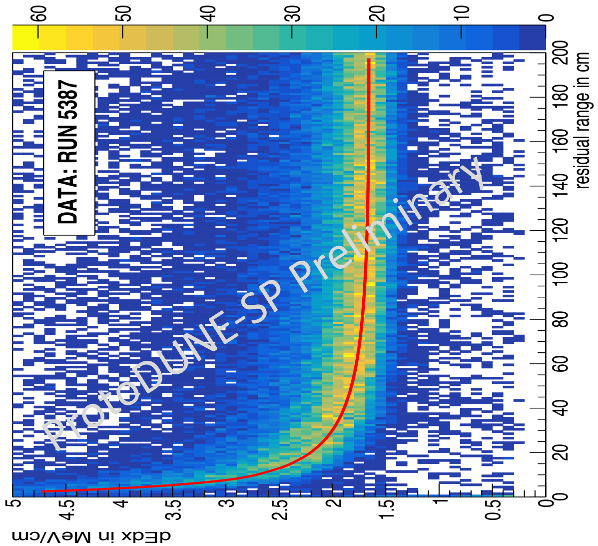
The worlds largest LAr TPC
7 x 7 x 6 m^3 ~ 770,000 kg

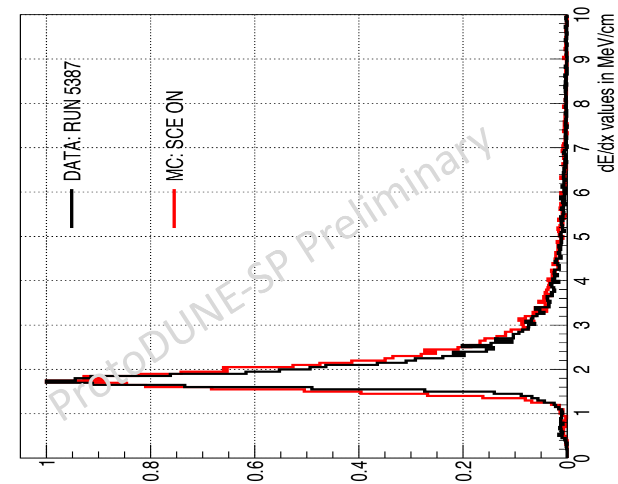


ProtoDUNE Performance

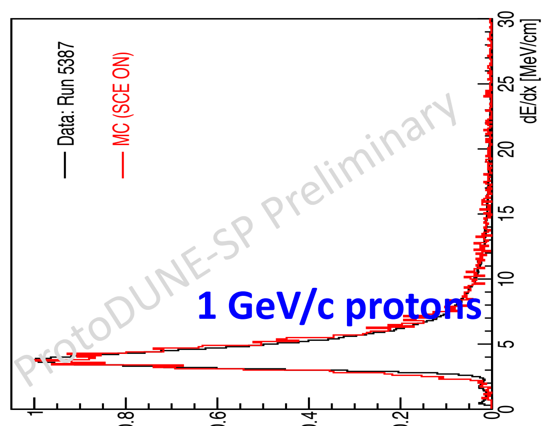
dE/dx

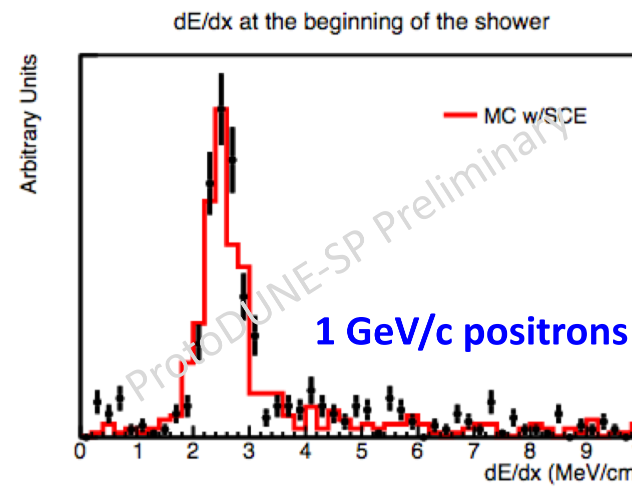
Calibrated with muons →





Applied to other particles →

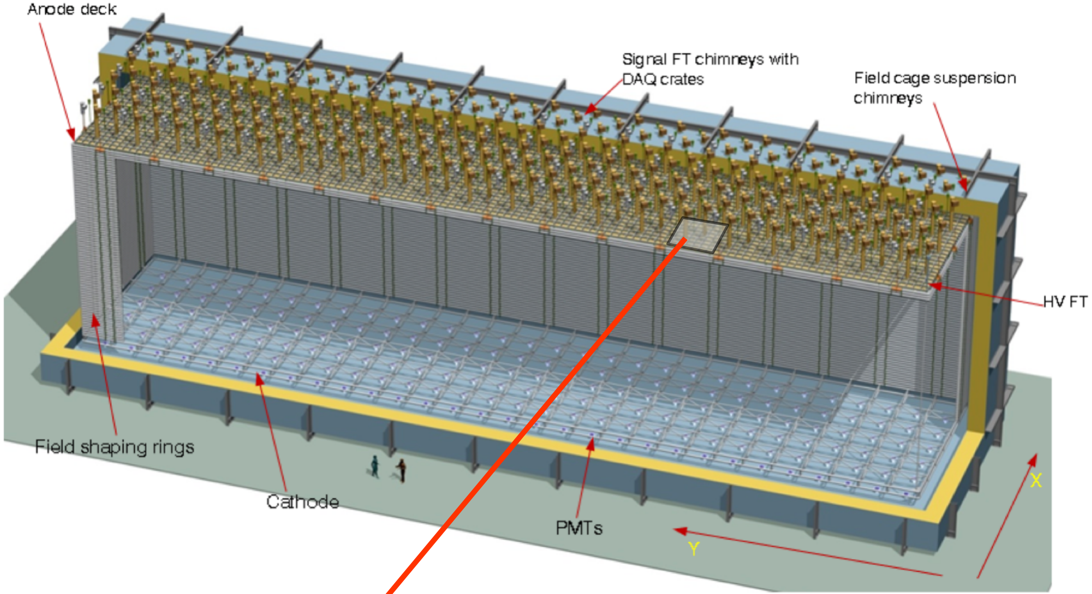




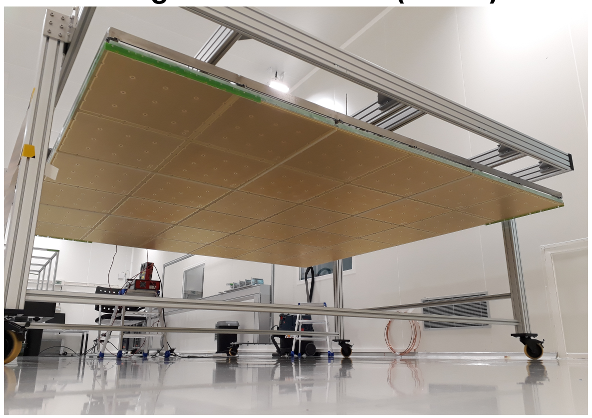
Very good agreement between data and simulation!

Additional calibration work and
particle-Ar cross section measurements are underway

Far detectors: 2nd module

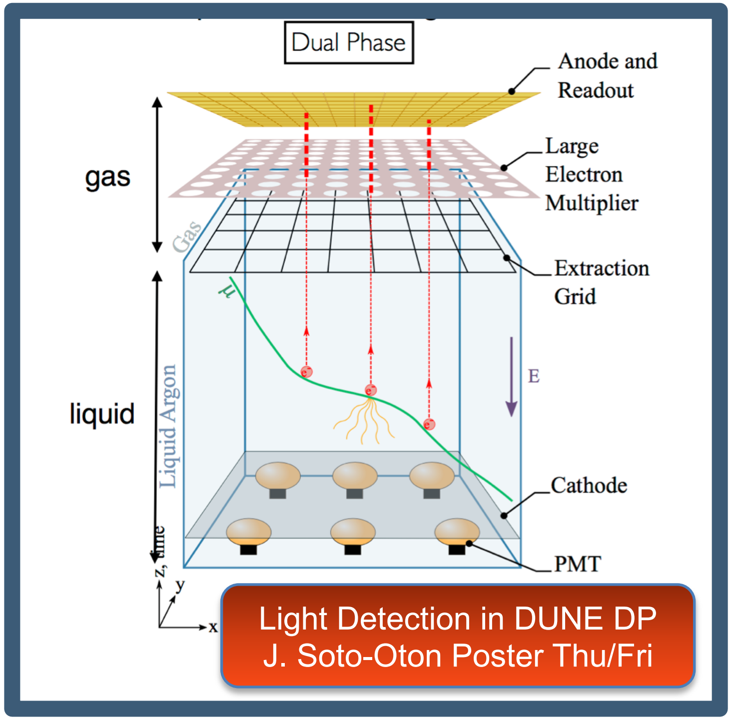


Charge Readout Plane (Anode)



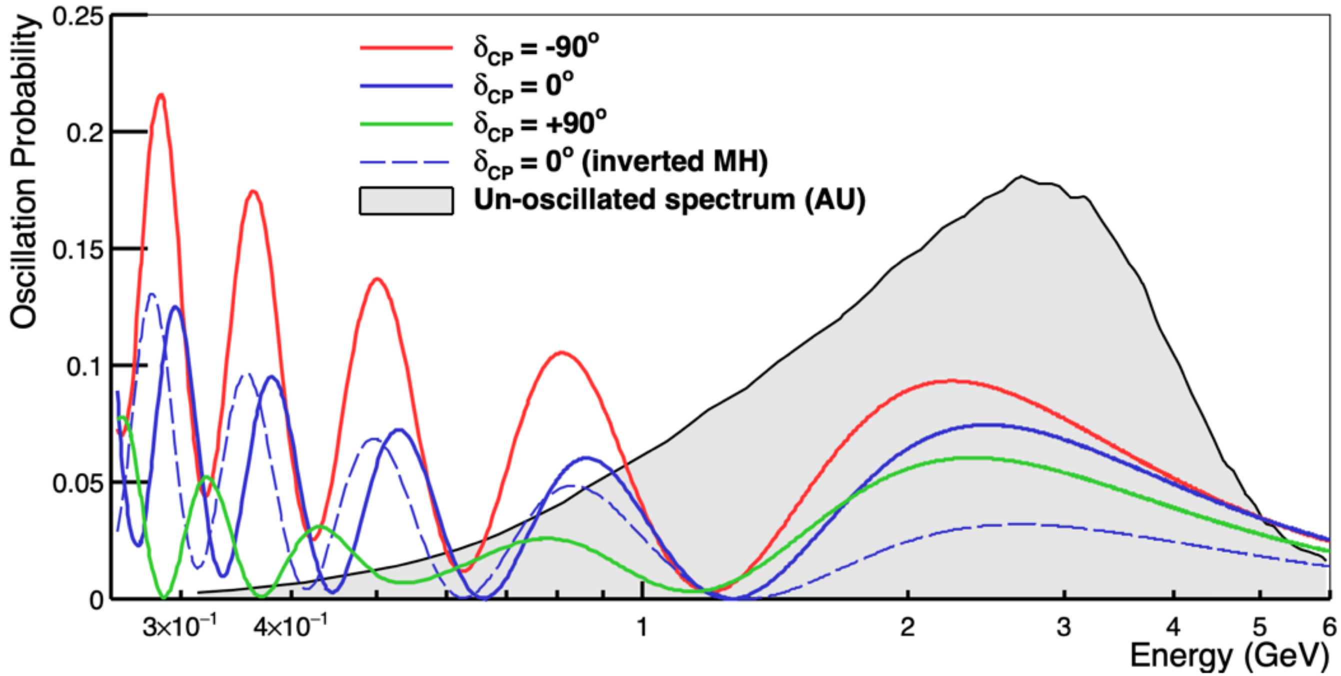
Dual-Phase

signal amplification in the gas phase



Photon detectors below cathode

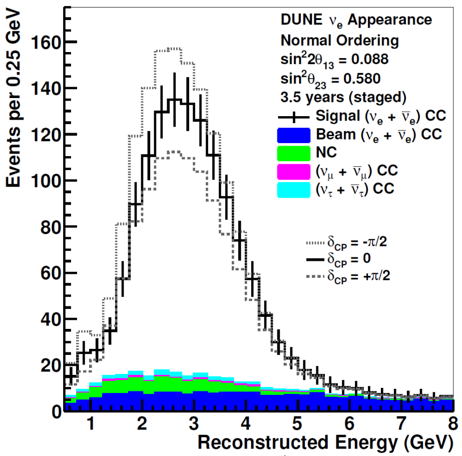
Experimental Technique

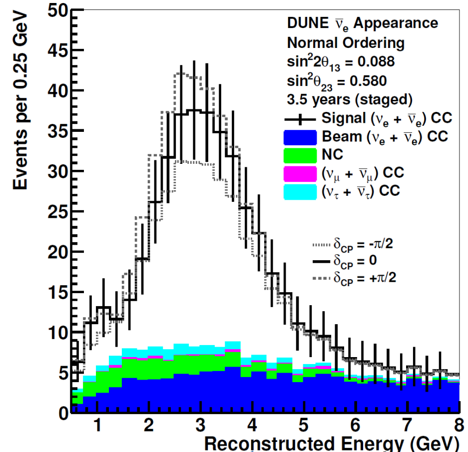


- Produce wide-band pure ν_μ beam
  - Cover 1st and 2nd oscillation maximum
- Constrain models and systematics with near detector
- Measure spectrum of ν_μ and ν_e at a far detector
  - Combined analysis

Measurement Strategy

DUNE simulation

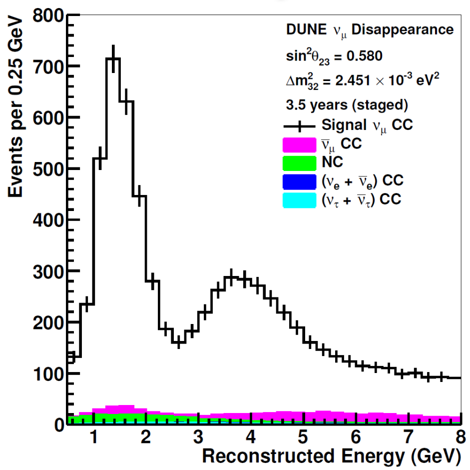


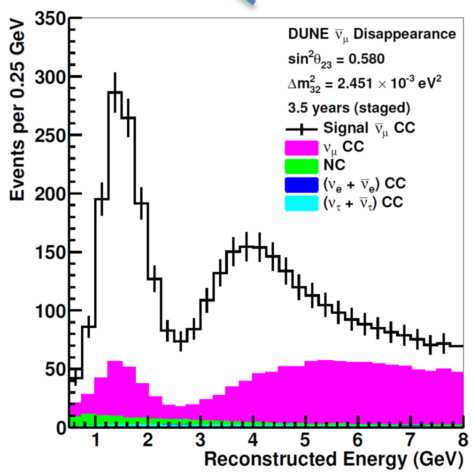


~1,000 ν_e / $\bar{\nu}_ģ$
appearance events
in 7 years!

(normal ordering)

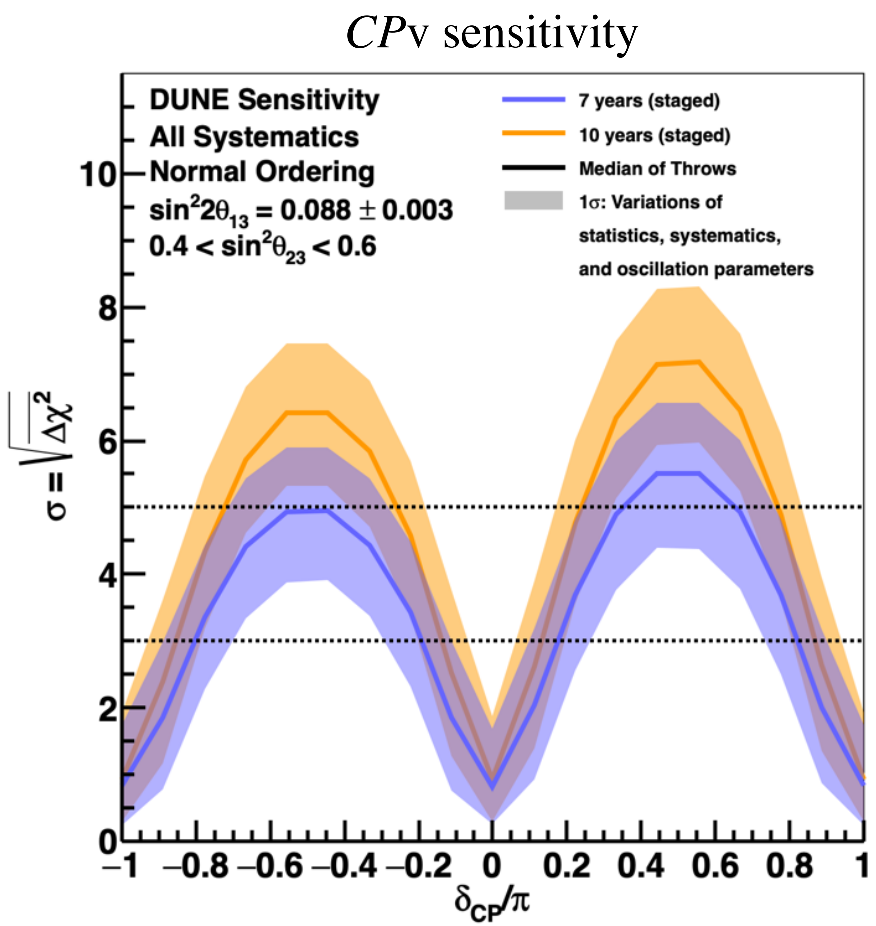
ND Constrains → Global Fit → **Oscillation Parameter**

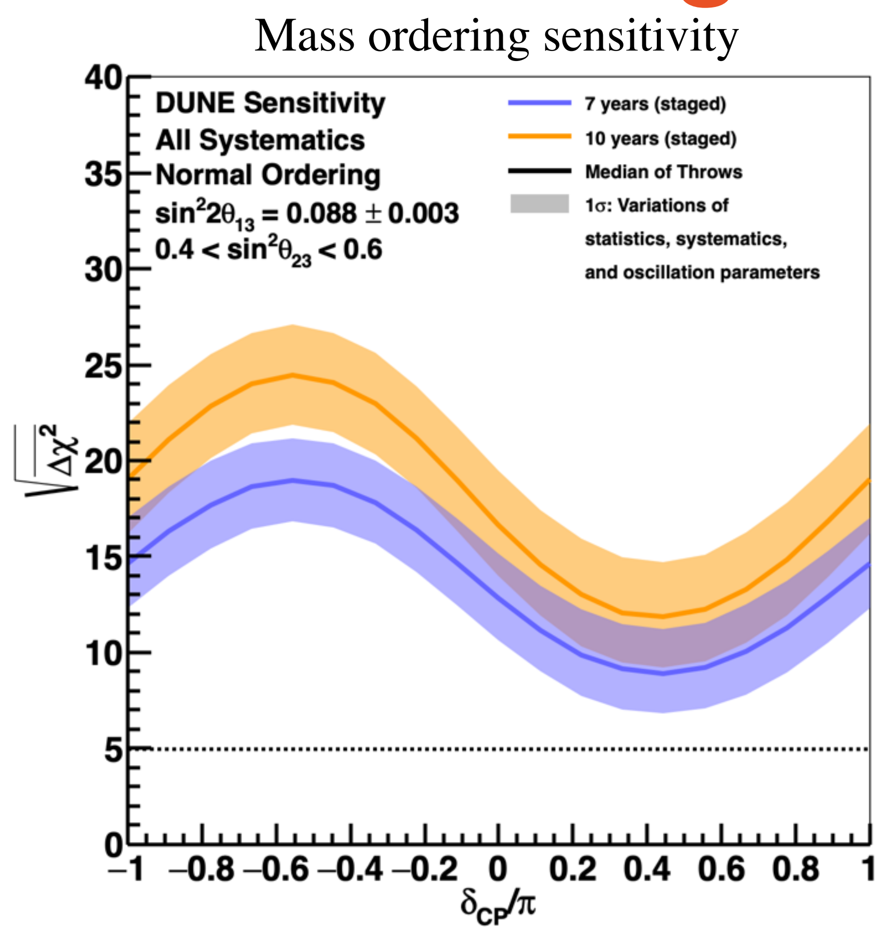




~10,000 ν_μ / $\bar{\nu}_{\square}$ events

CP Violation and Mass Ordering

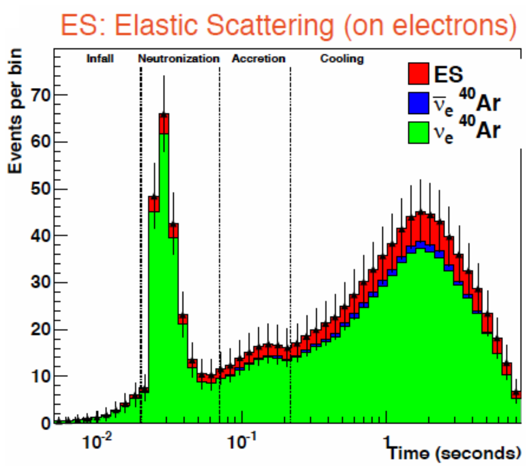




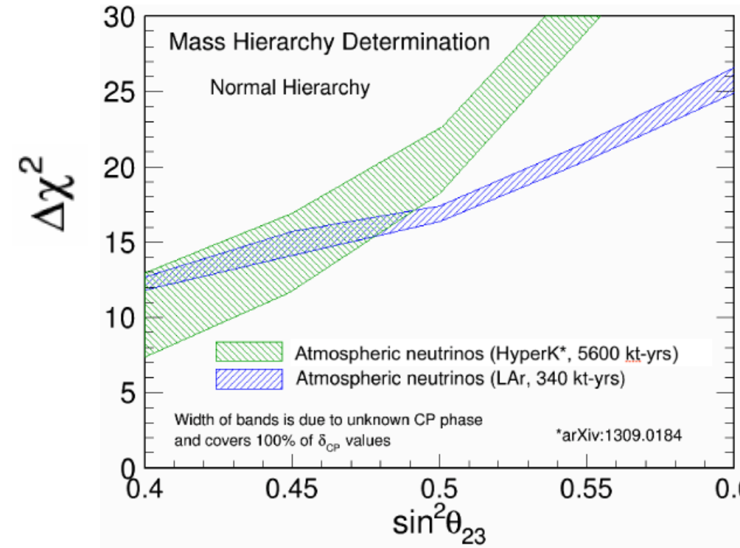
- Updated Sensitivity with realistic systematics and reconstruction
  - Move quickly to potential ***CP* violation discovery**
  - Rapid, definitive **mass ordering determination** (>5σ)

Other Physics

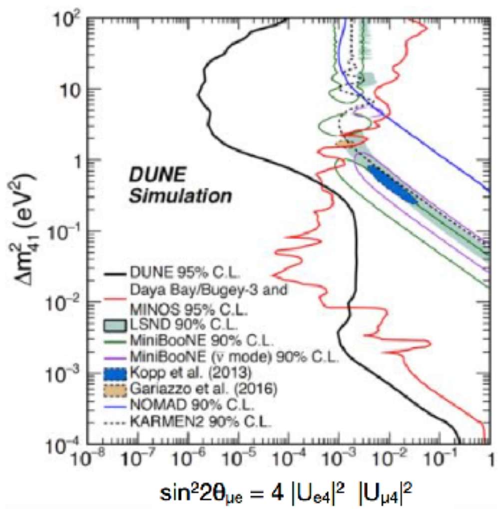
supernova



atmospheric neutrinos



sterile neutrinos



- Dark matter
- Large extra dimensions
- Dark photons
- NS interactions

Summary and Conclusion

- DUNE has an ambitious physics program
  - Precision oscillation parameter measurements
  - CPV, mass ordering
  - Nucleon decay, SN
- Truly international project with strong support
  - US & internationally
- Technology is well understood
  - Prototyping and verifications are well underway
- DUNE is the neutrino physics of the future

Computing in DUNE
H.M. Schellman, 8-Aug 10:30

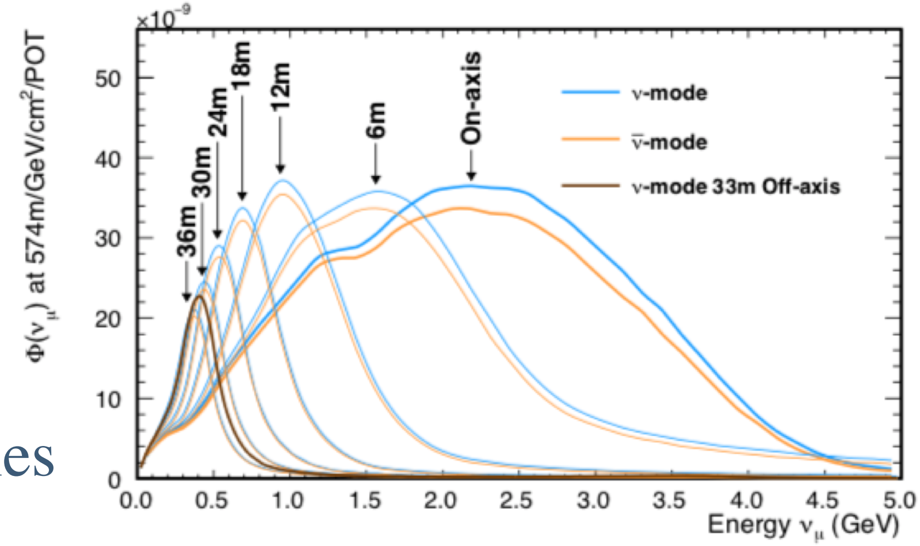
Backup

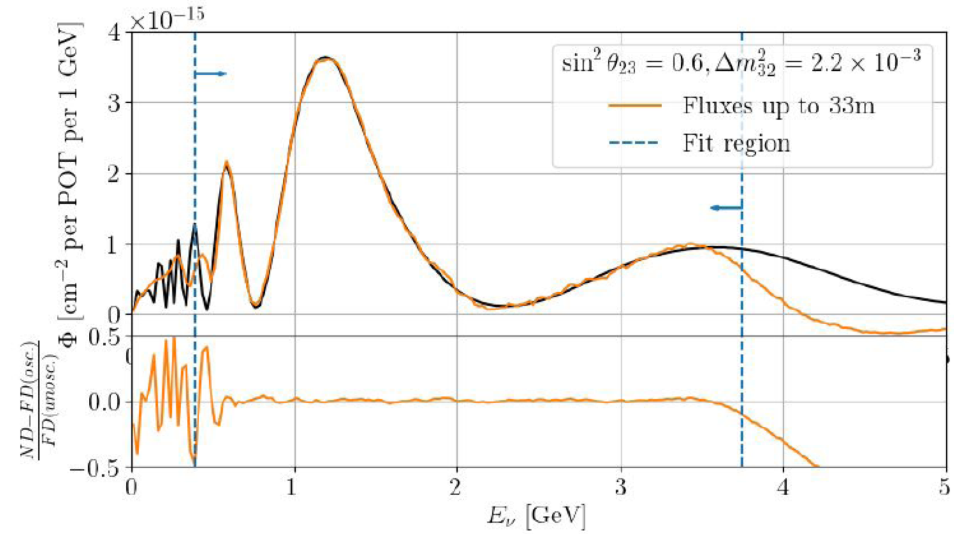
Why Liquid Argon ?

- **Dense**:
  40% denser than water
- **Cheap**:
  abundant (1% of atmos.)
- **Ionizes easily**:
  55,000 electrons/cm
- **Excellent scintillation**:
  20,000 photons/MeV
  (@ 500 V/cm)

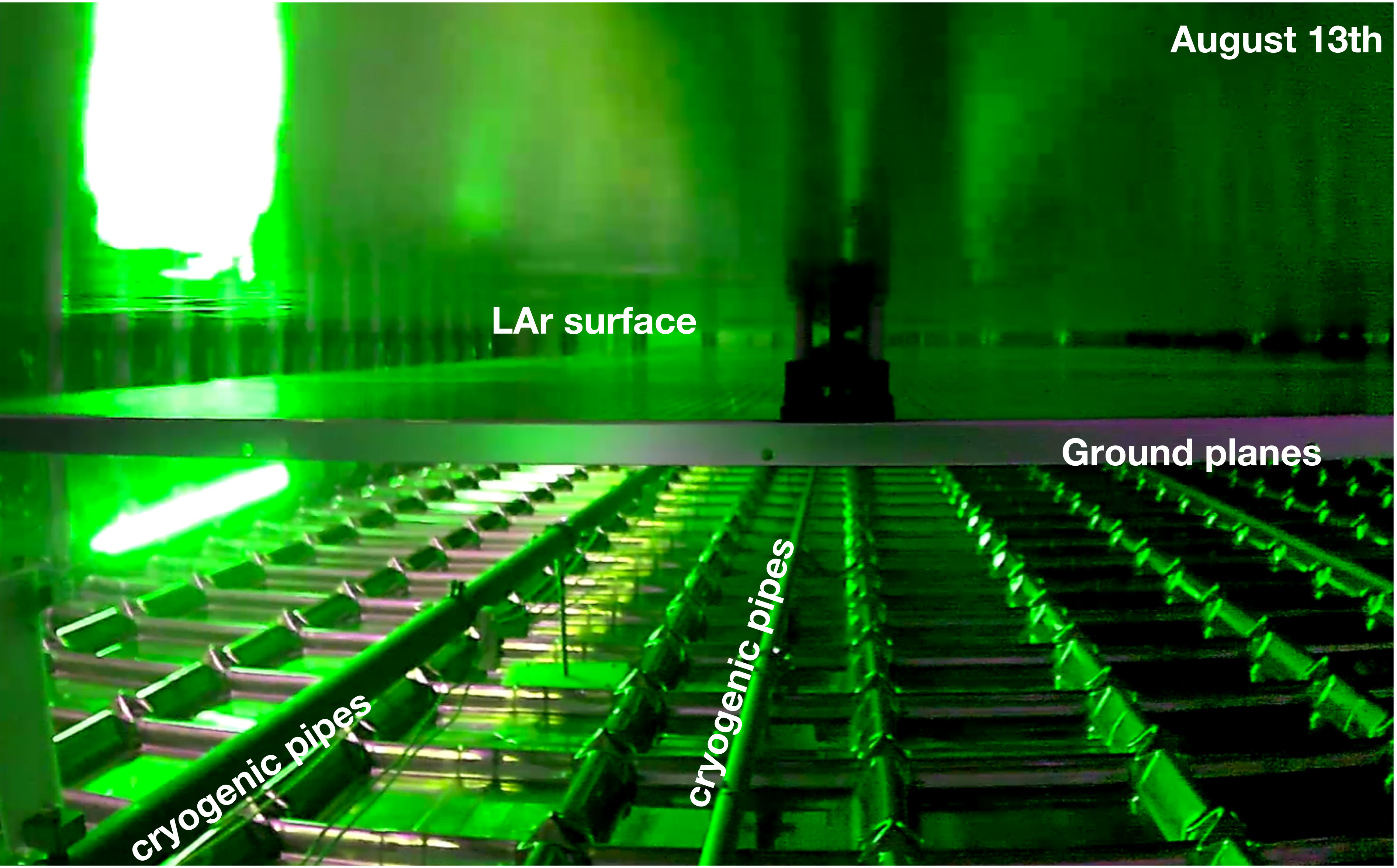
DUNE-PRISM

- **Vary the incident neutrino spectrum** by moving off-axis
- Break cross section model degeneracies
- Linearly combine off-axis samples to craft **"arbitrary" neutrino spectra**
  - *- narrow Gaussian spectra*
  - *- FD-like oscillated spectra*
- Unprecedented **reduction** in cross section **modeling uncertainties**

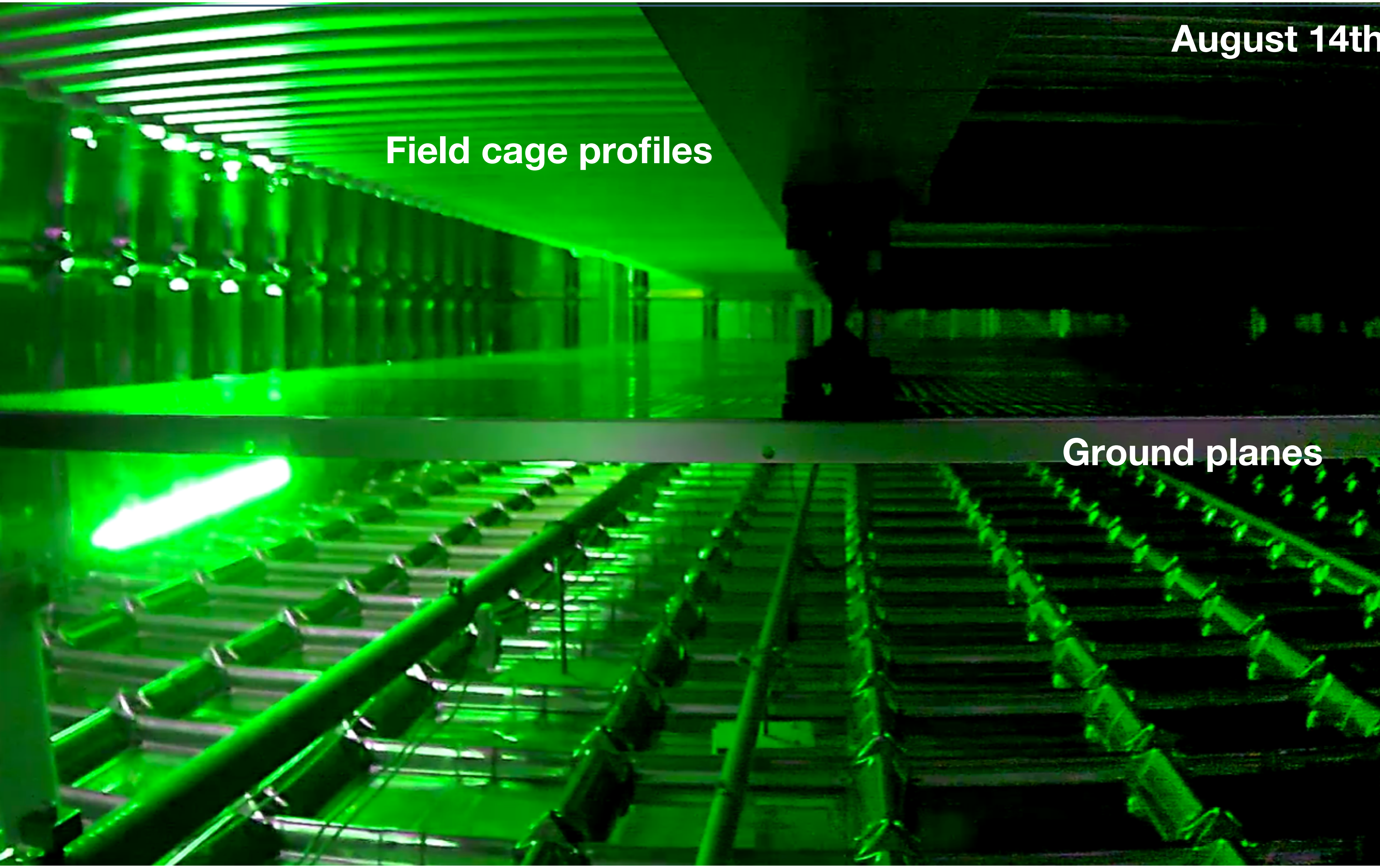




Filling ProtoDUNE (I)



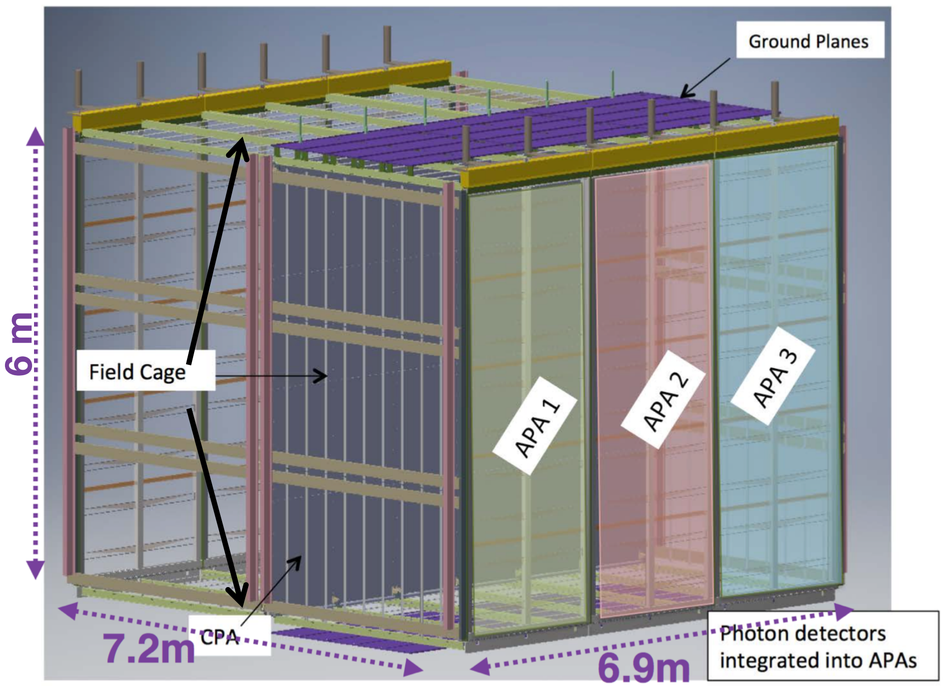
Filling ProtoDUNE (II)



Two Technologies

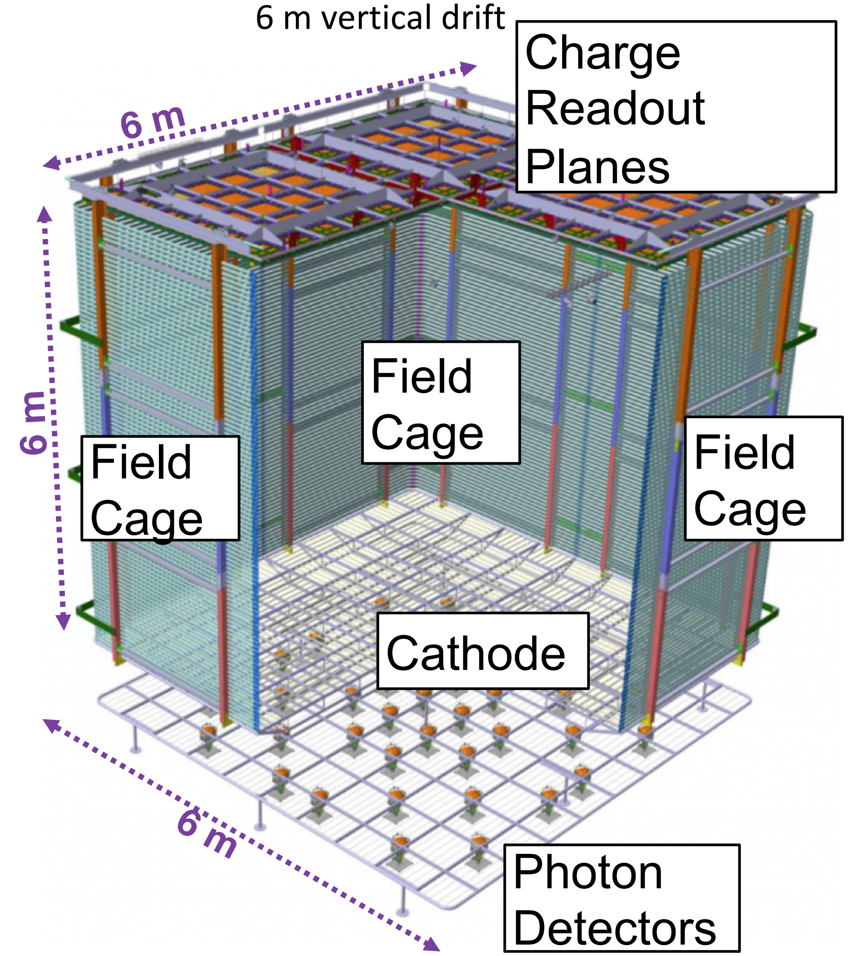
Single-Phase

3.6 m horizontal drift



Dual-Phase

6 m vertical drift



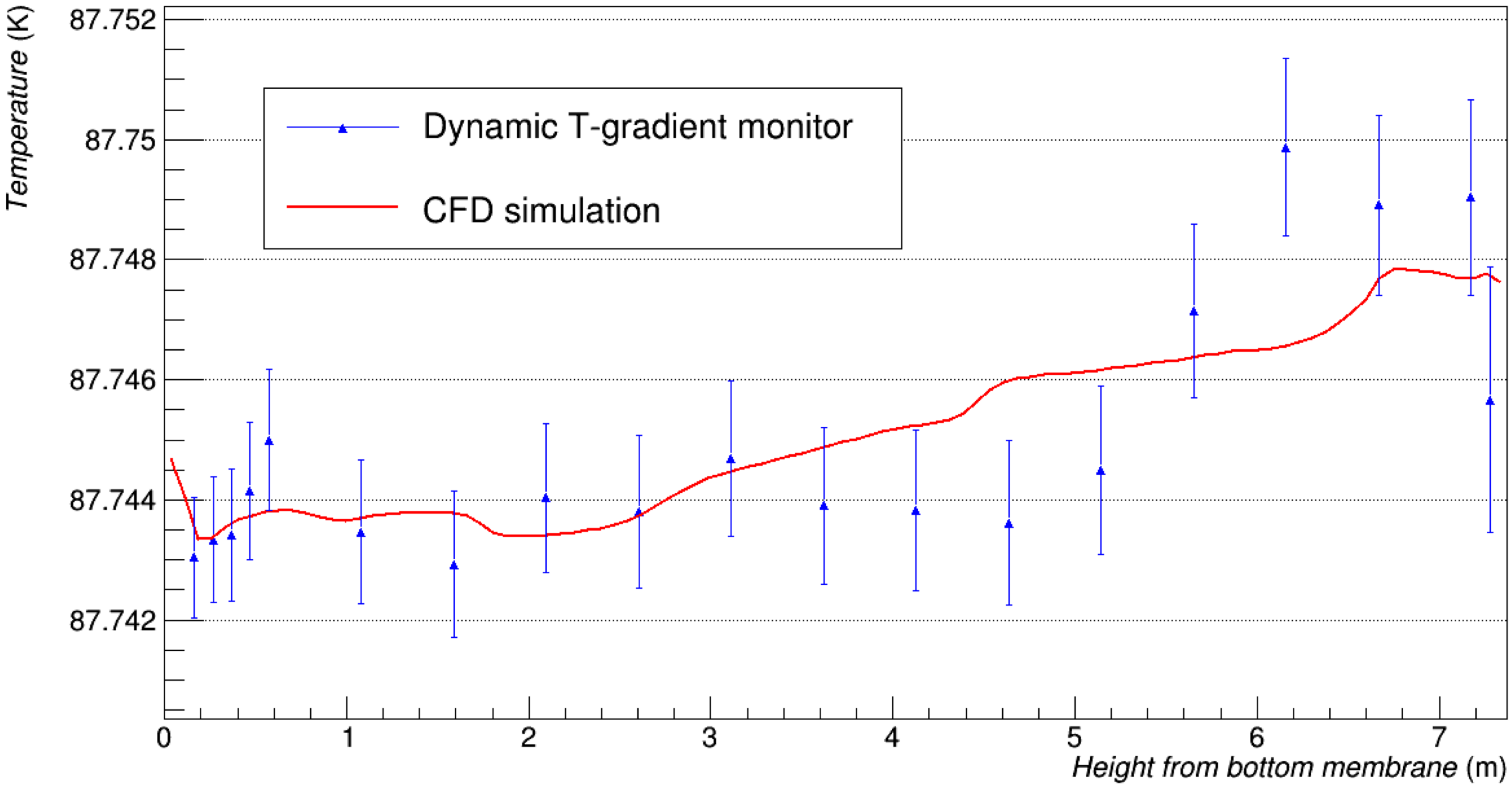
ProtoDUNE status

- **ProtoDUNE-SP** detector was completed at the end of June, filling of the cryostat completed on September 13th, TPC activated and on data taking since September 21st
- **ProtoDUNE-SP** took beam data until November 11th, followed by an endurance run with cosmics to assess the stability and performances of the detector
- ***ProtoDUNE-DP*** being filled now
- Once filled, ***ProtoDUNE-DP*** will go for an extended cosmic run to assess the stability and performances of the detector

ProtoDUNEs have submitted a proposal to the SPSC for taking data with beam after Long Shutdown 2

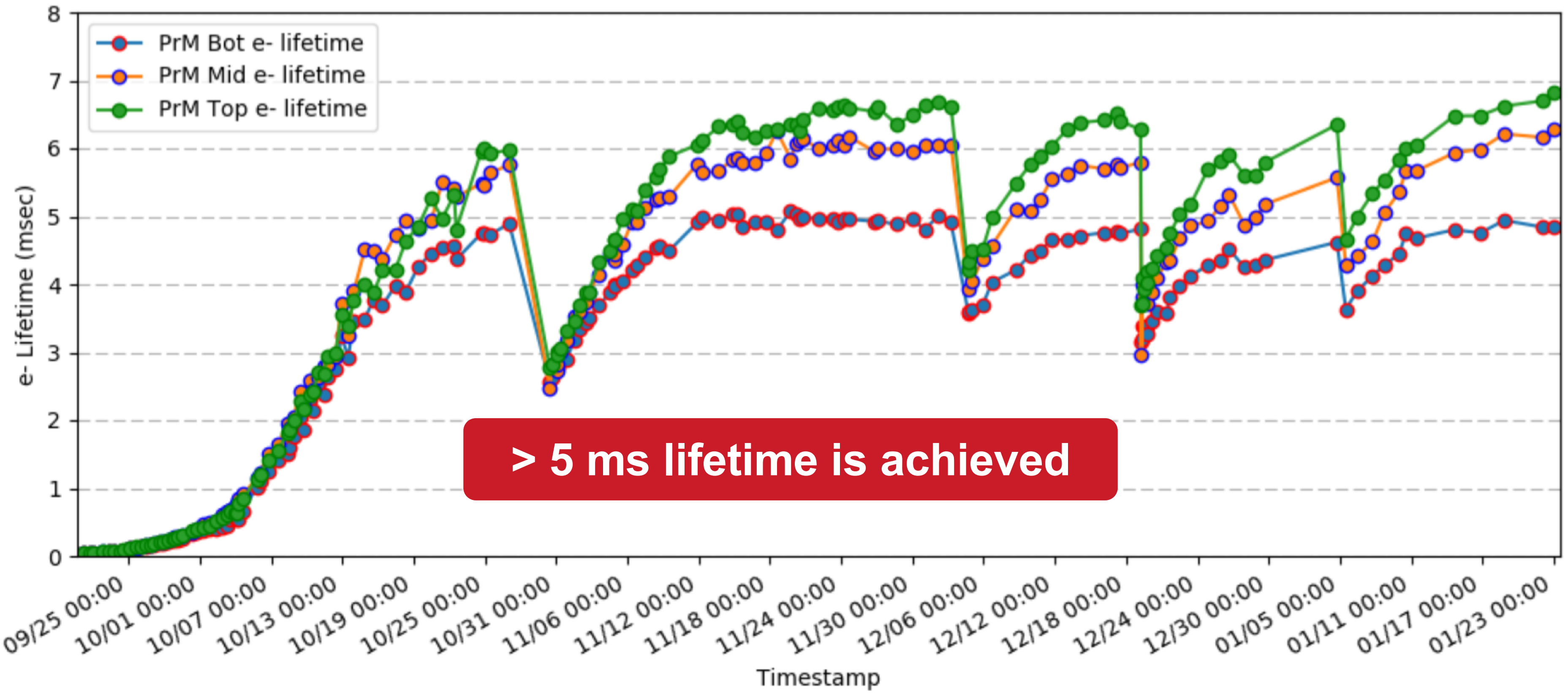
Liquid Argon Temperature

Temperature varies < 0.01 K across the cryostat



Liquid Argon Purity

The purity is measured as the electron lifetime



> 5 ms lifetime is achieved

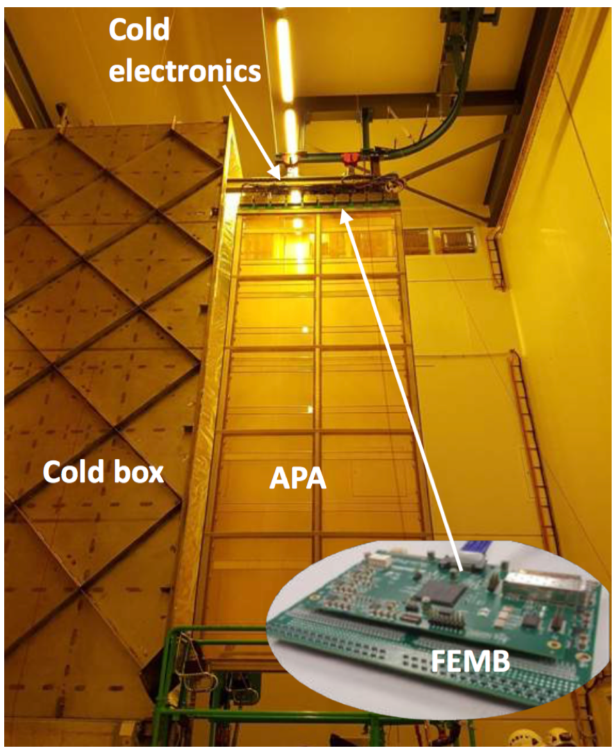
Electrons need 3 ms to cross the drift volume

APAs and Cold Electronics

Exceptionally low noise operation and scalable cryostat design

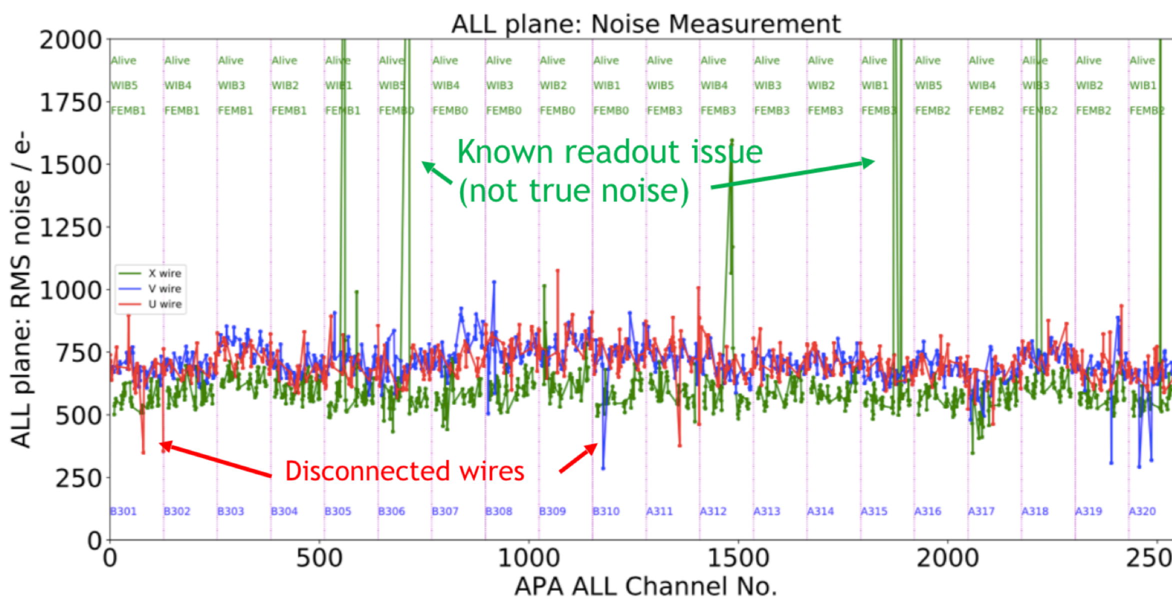
~ 15000 wires, only 4 channels dead (0.03%)

Electronics on top of APAs submerged in LAr at 87 K

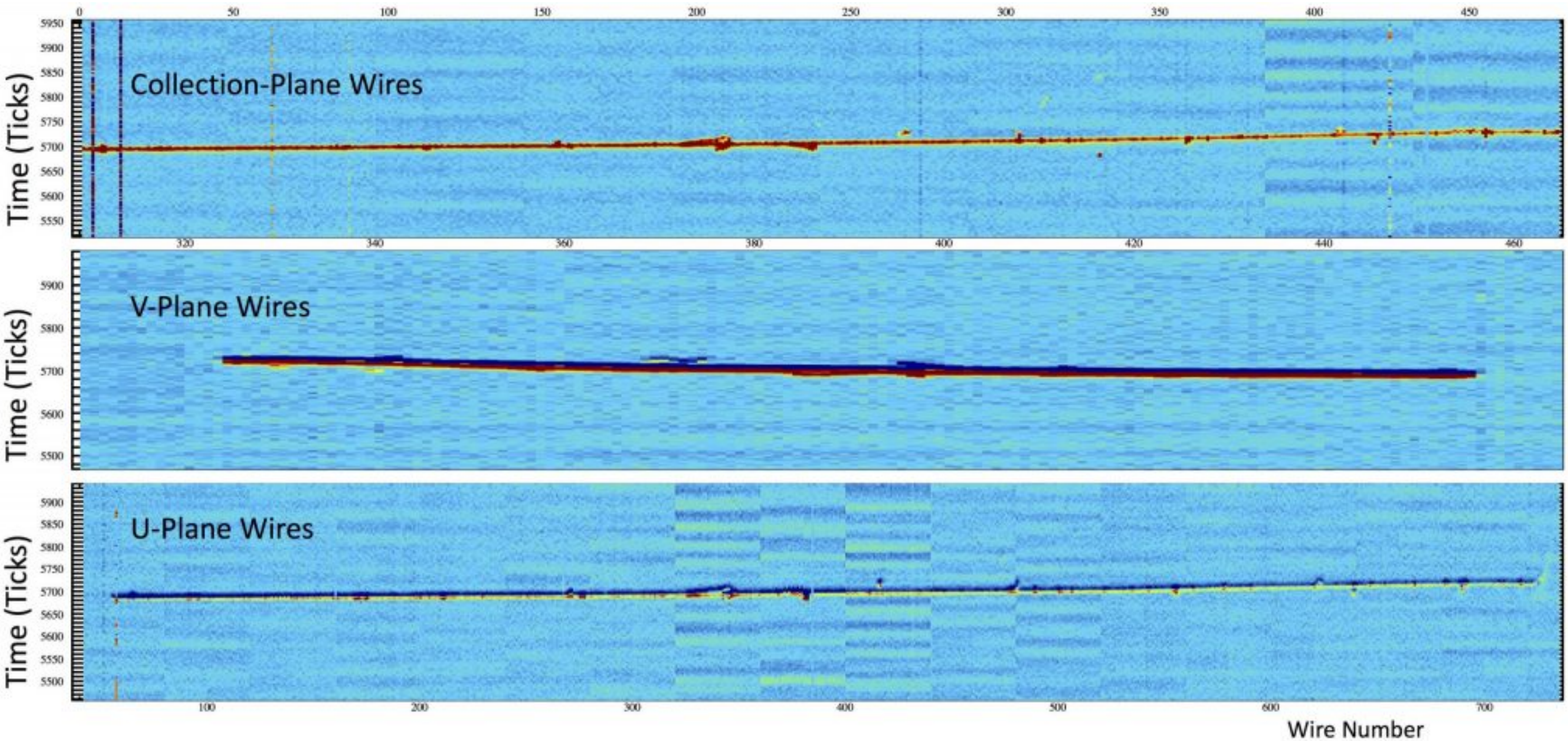


ENC < 750 e^- ⟶ S/N ~ 20

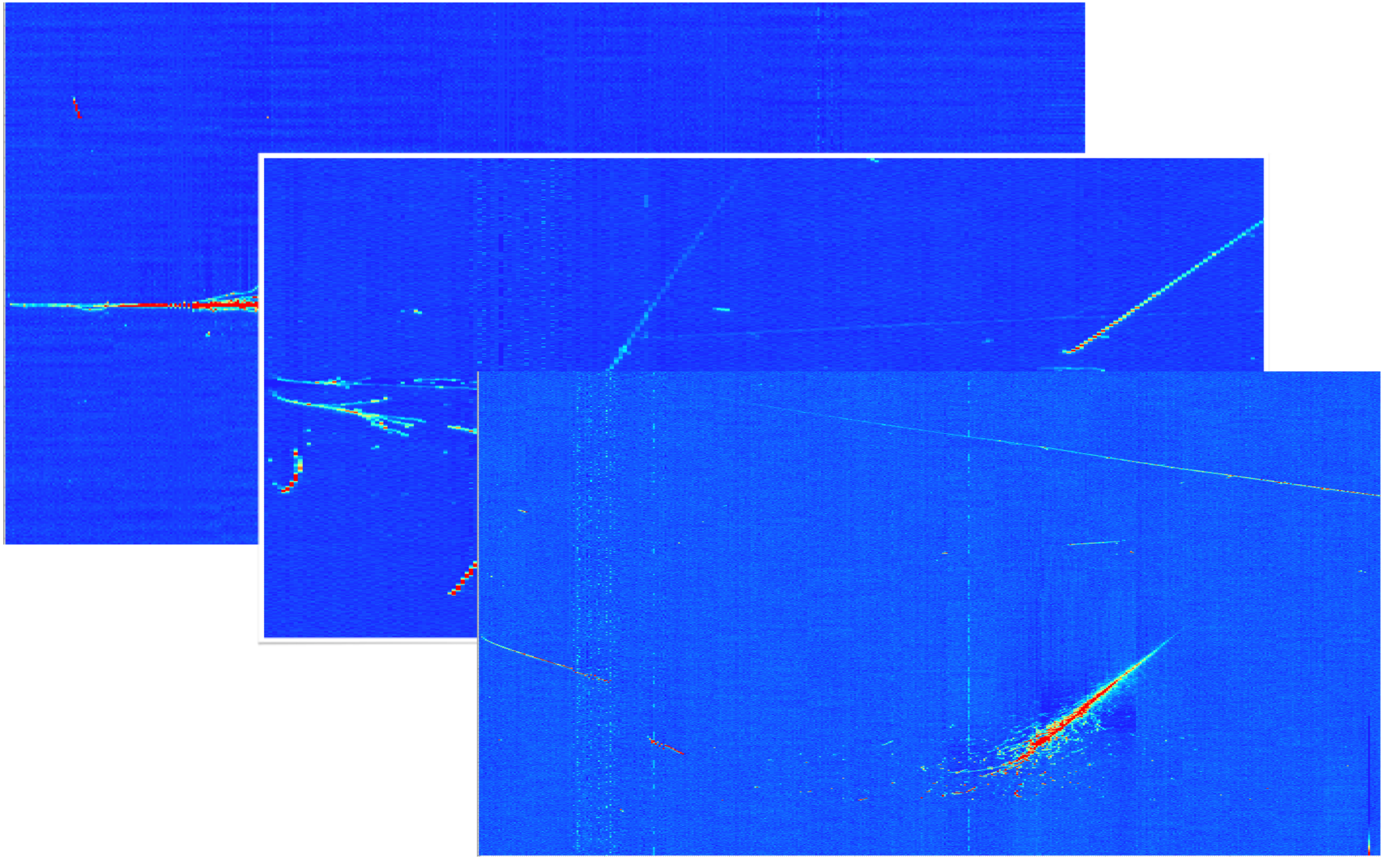
meets DUNE requirements (S/N>10)



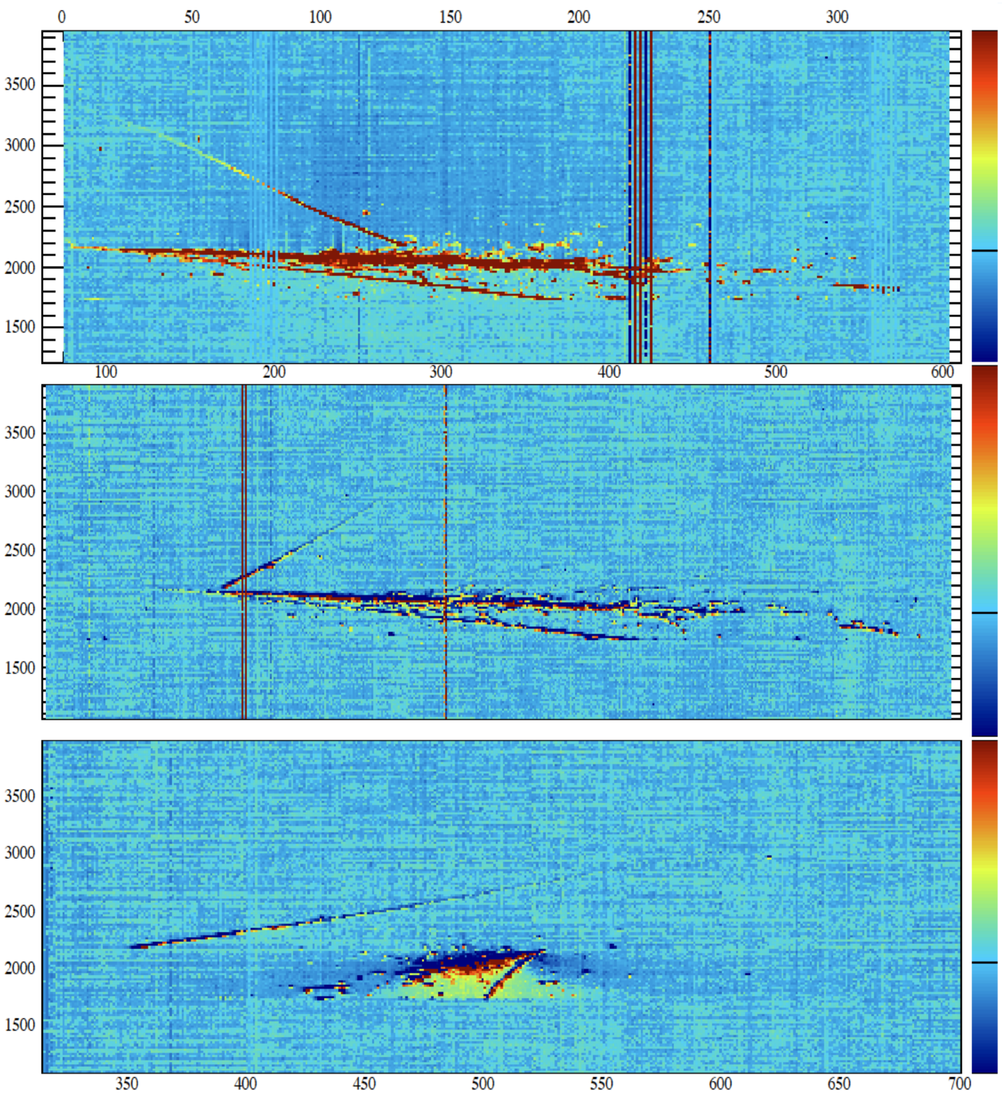
The First Event

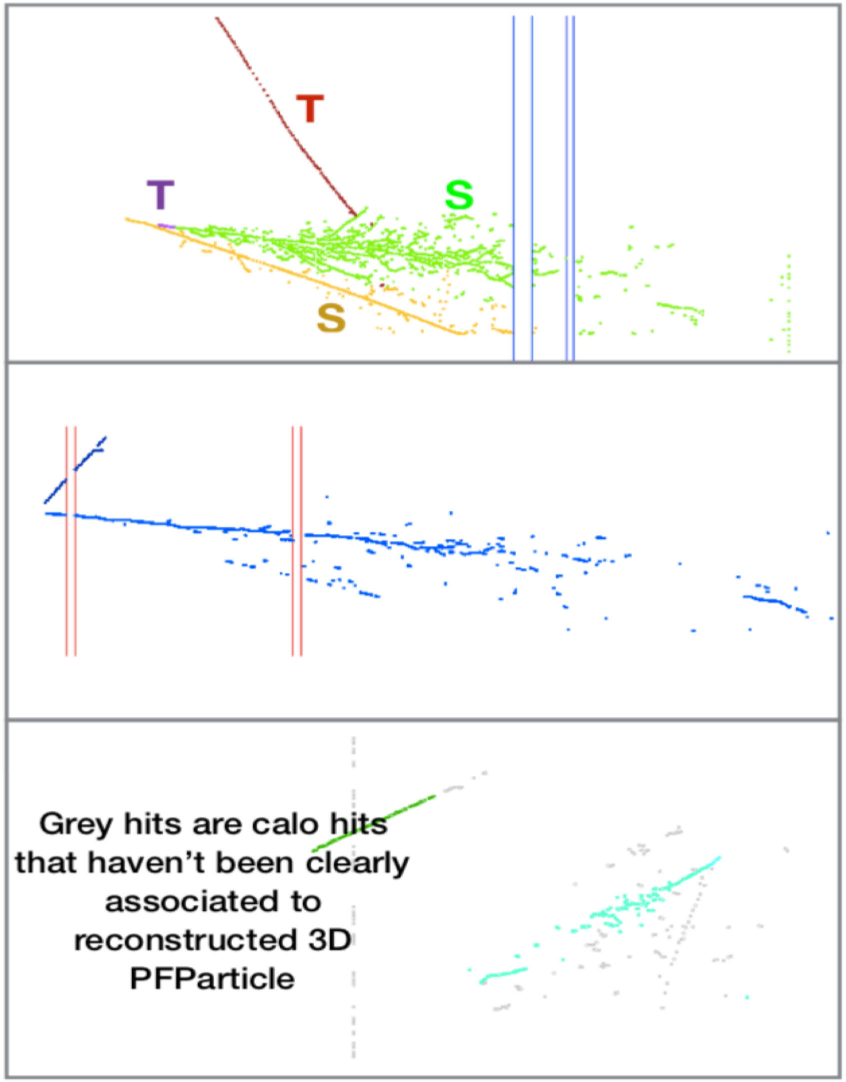


Real Events

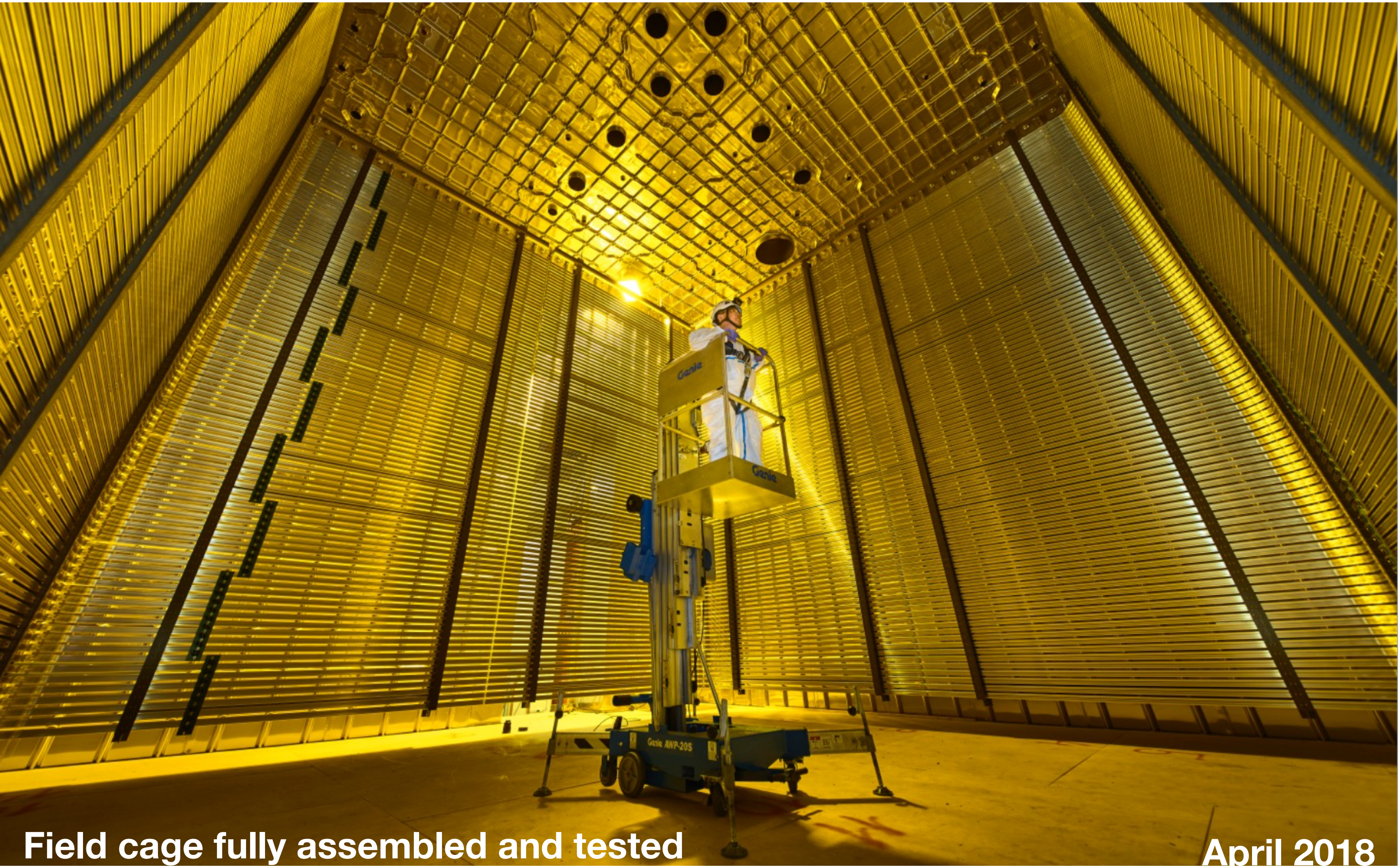


Automatic Reconstruction





ProtoDUNE-DP

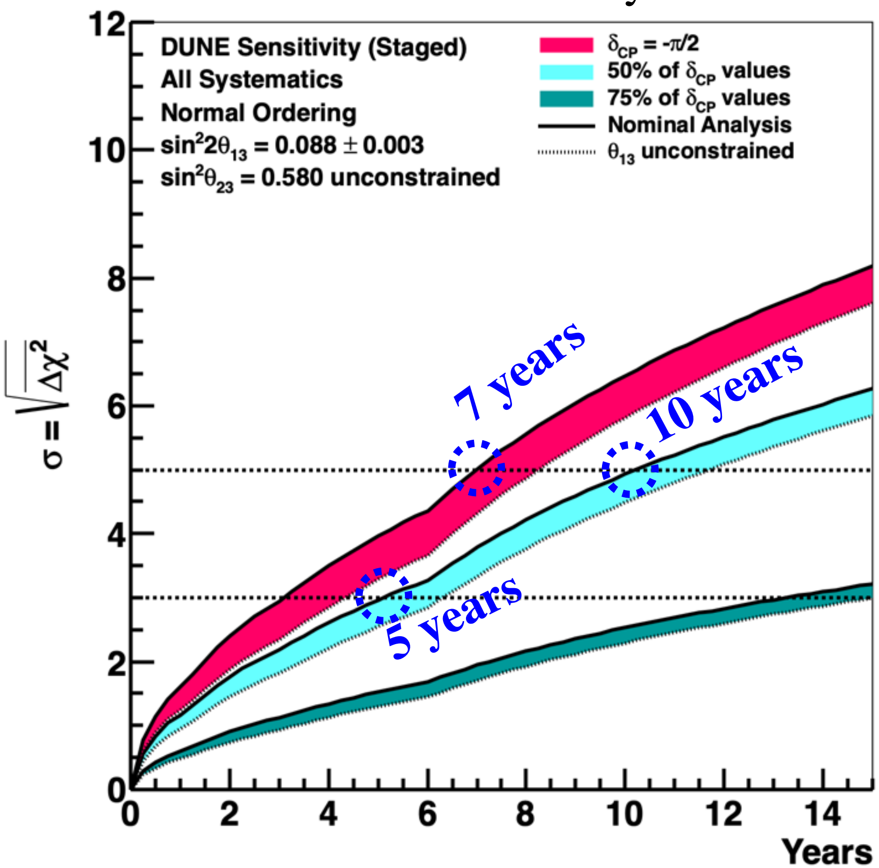


Field cage fully assembled and tested

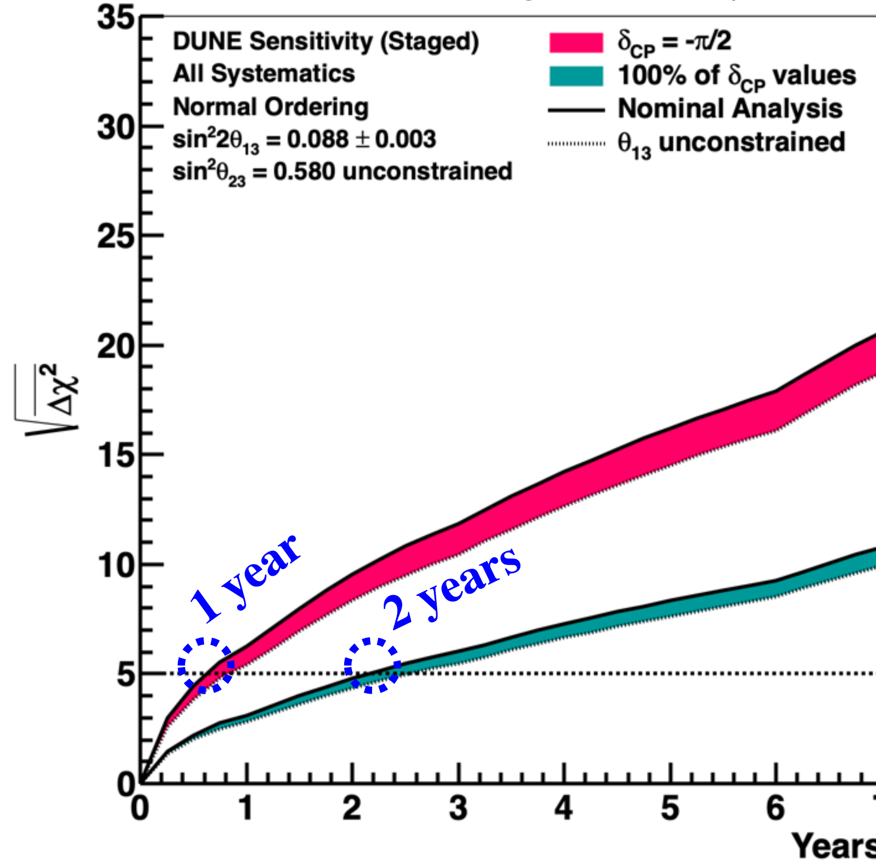
April 2018

Sensitivity vs Time

*CP*v sensitivity



Mass ordering sensitivity

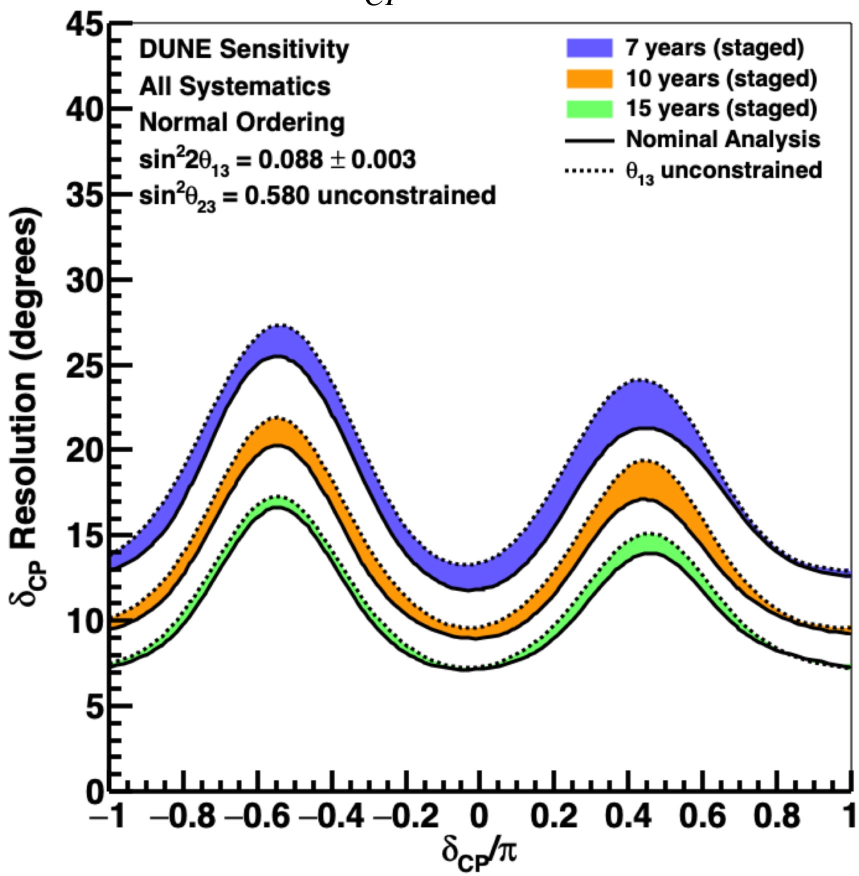


Significant milestones throughout beam-physics program

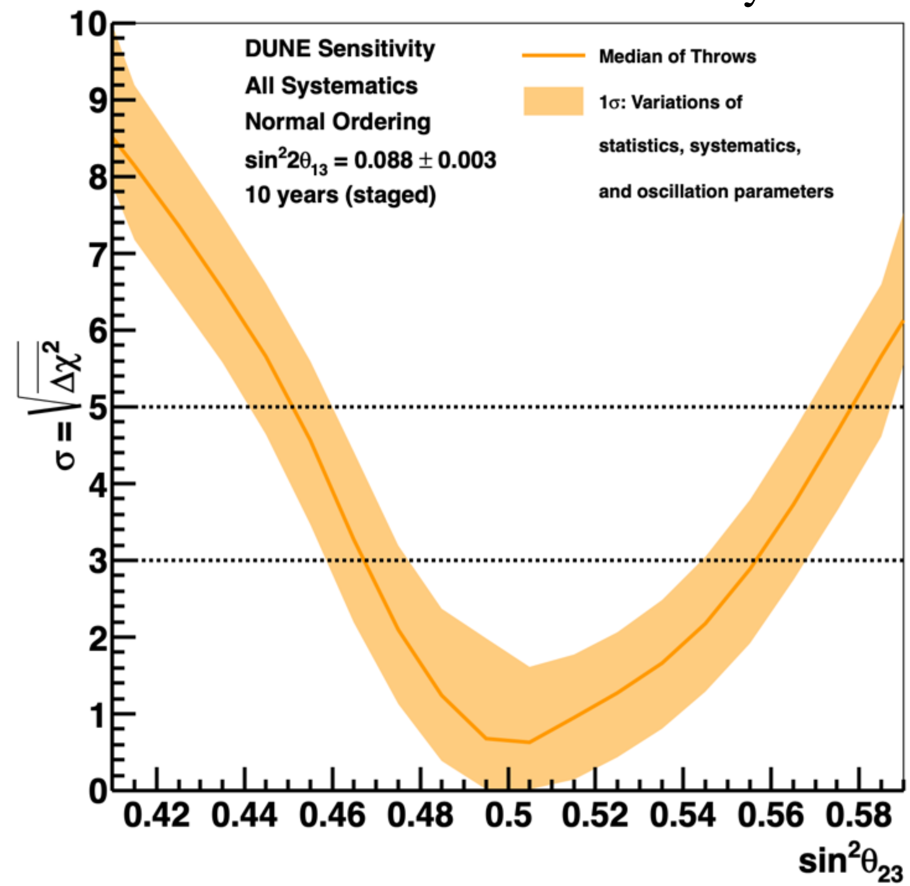
Note: When a choice is called for, **NuFit 4.0 (Nov 2018)** best-fit parameters and/or uncertainties are assumed
JHEP ***01*** *(2019) 106, www.nu-fit.org*

PMNS Precision

δ_{CP} resolution



Octant determination at 10 years



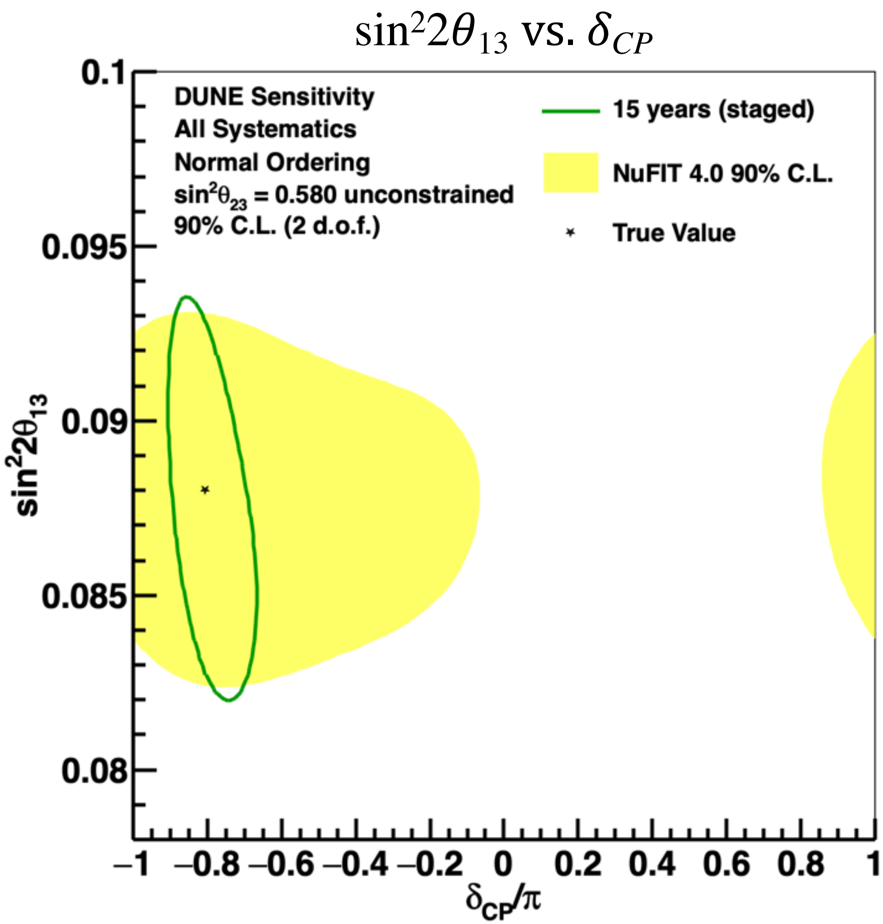
δ_{CP} measured to ~7° – 17°

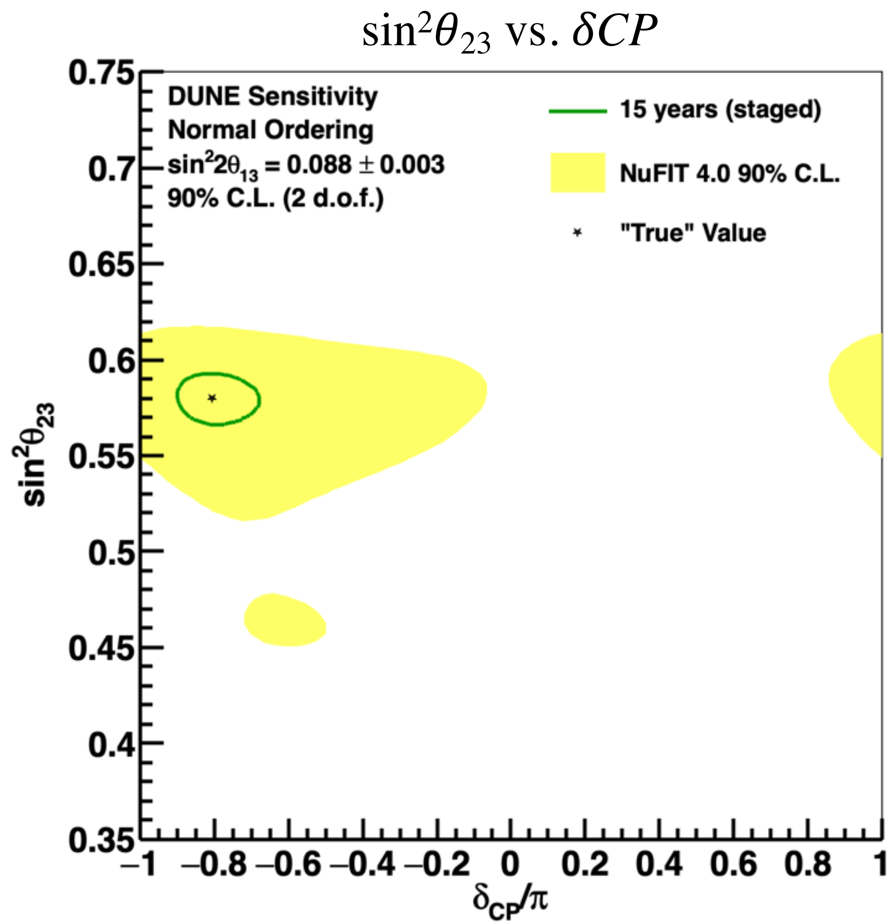
Single-experiment*
precision oscillation measurement!

>5σ octant determination possible

*solar parameters θ_{12} and Δm^2_{21} are still inputs

PMNS Precision



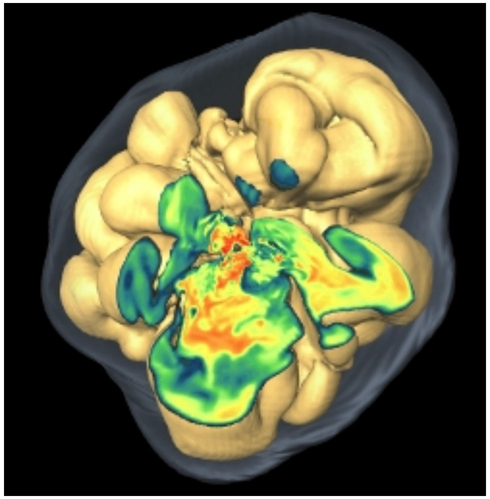


Ultimate **$\sin^2 2\theta_{13}$ precision** competitive with reactor measurements

$\sin^2 2\theta_{13}$ resolution: 0.004 ***(4.5%)***

Supernova Neutrinos

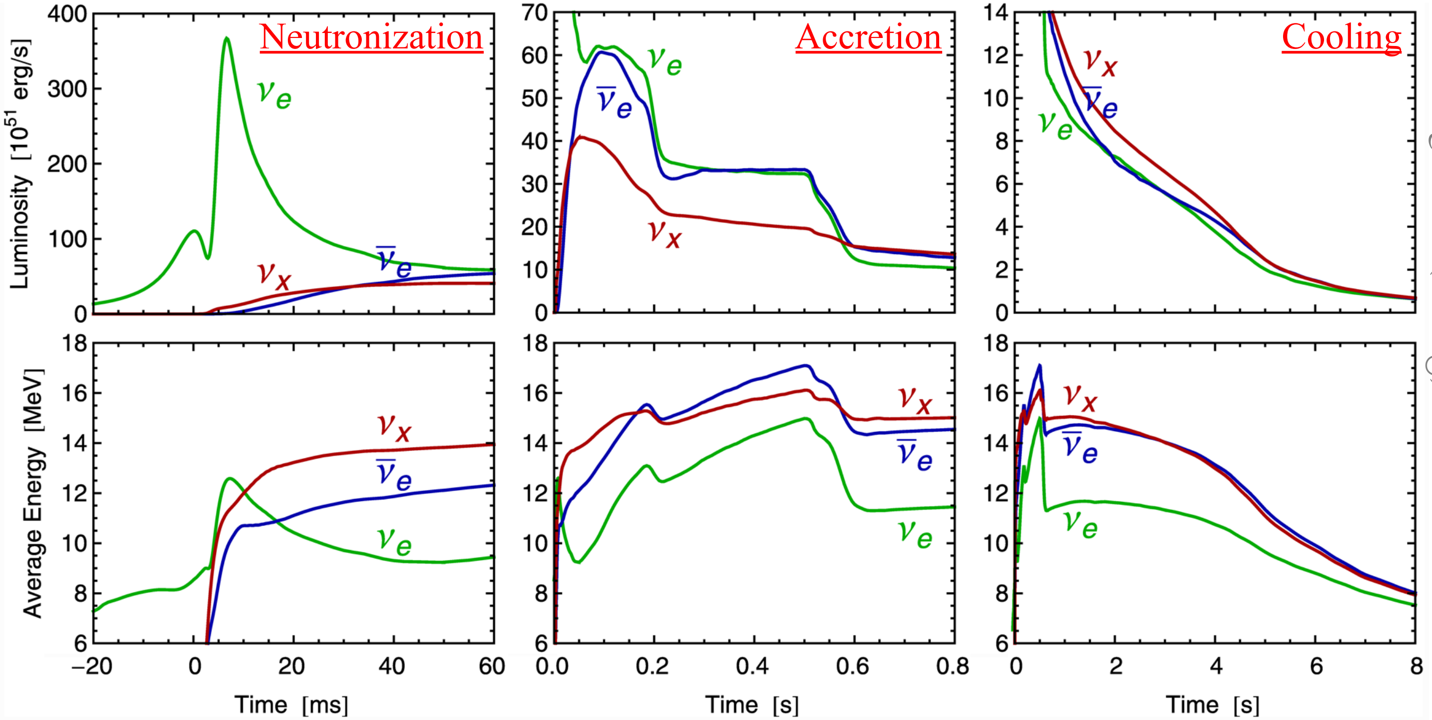
- **99% of energy** released in a core-collapse supernova is **carried away by neutrinos** *(cf.: 0.01% carried away by light)*
- **Rich information** embedded in neutrino signal:
  - **Supernova physics:** core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling, …
  - **Particle physics:** flavor transformations in core, collective effects, mass ordering, nuclear equation of state, exotica



S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

Argon target:
Unique sensitivity to ν_e flux

DUNE at 10 kpc:
~3000 ν_e events over 10 seconds

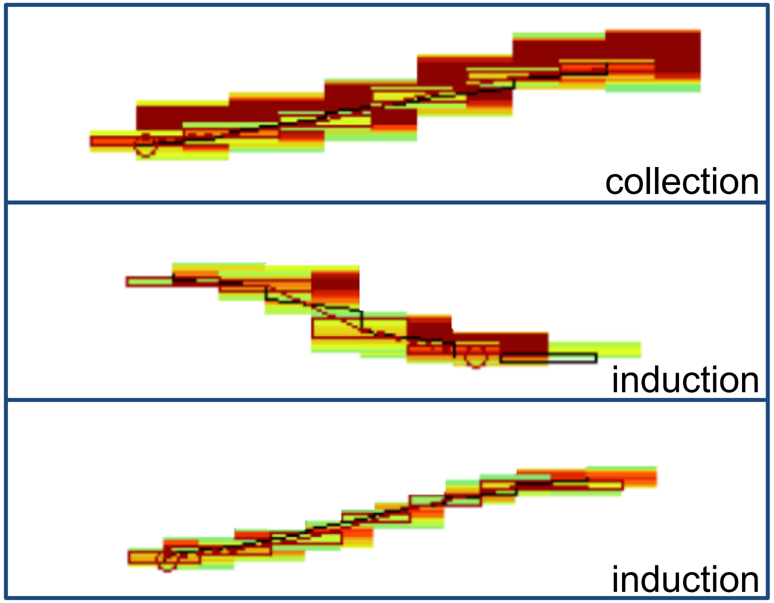


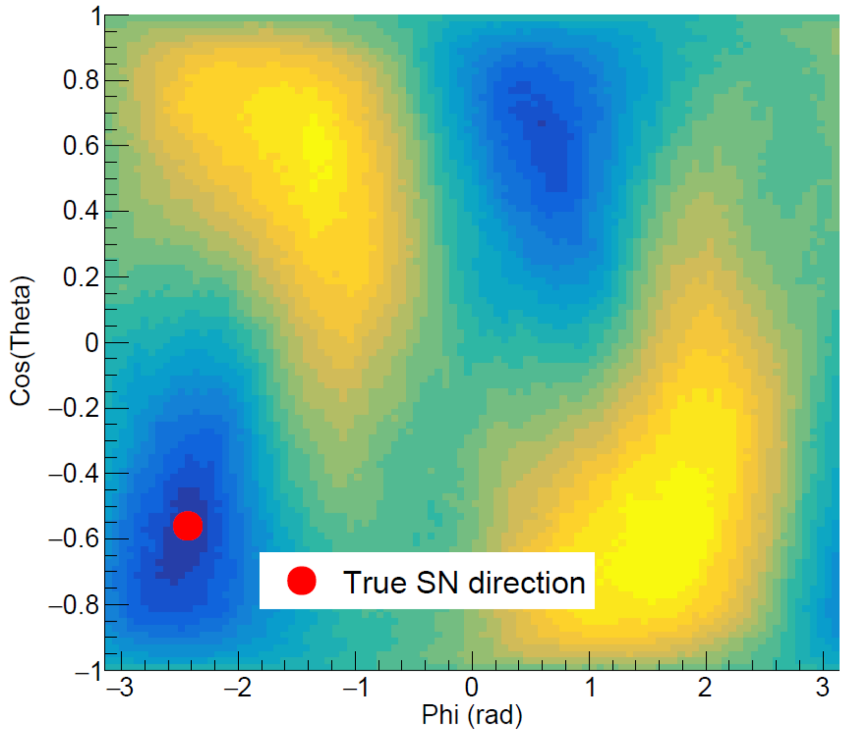
Garching model (27 $M_\odot$)

Directionality

- **Prompt pointing** to a supernova is highly valuable information to astronomers:
  - Catch **early turn-on** of EM signal
  - Support observation of **optically dim SN**
  - Era of **multi-messenger astronomy**

10.25 MeV electron, simulated and reconstructed





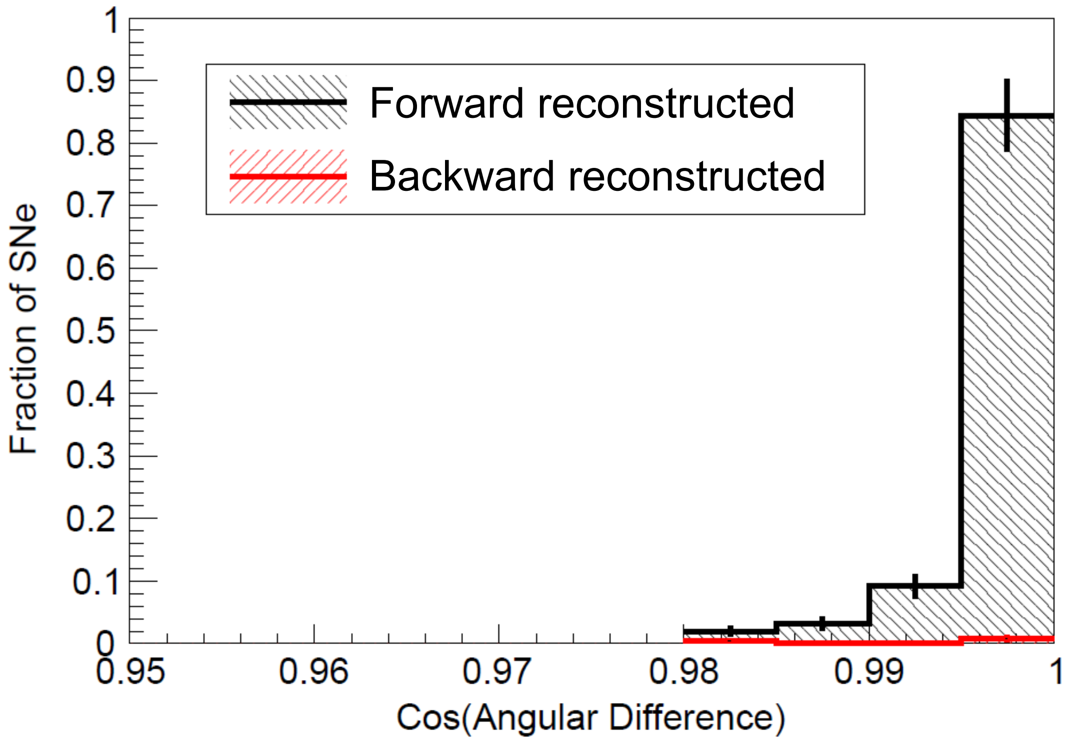
← **Direction likelihood surface** at DUNE for 10 kpc supernova

ν_e **CC** and $\nu + e$ (elastic scatter) events

Channel tagging can improve this further.

Much better pointing with ES events!

But only ~7% of sample.



← 4.5° pointing resolution

(10 kpc progenitor)

- Several other **low-energy neutrino measurements** under study
- Some discussion in Technical Design Report
  - diffuse supernova neutrino background
  - solar neutrinos
  - absolute neutrino mass from SNν
  - Lorentz/CPT violation