DUNE Near Detector

Alfons Weber

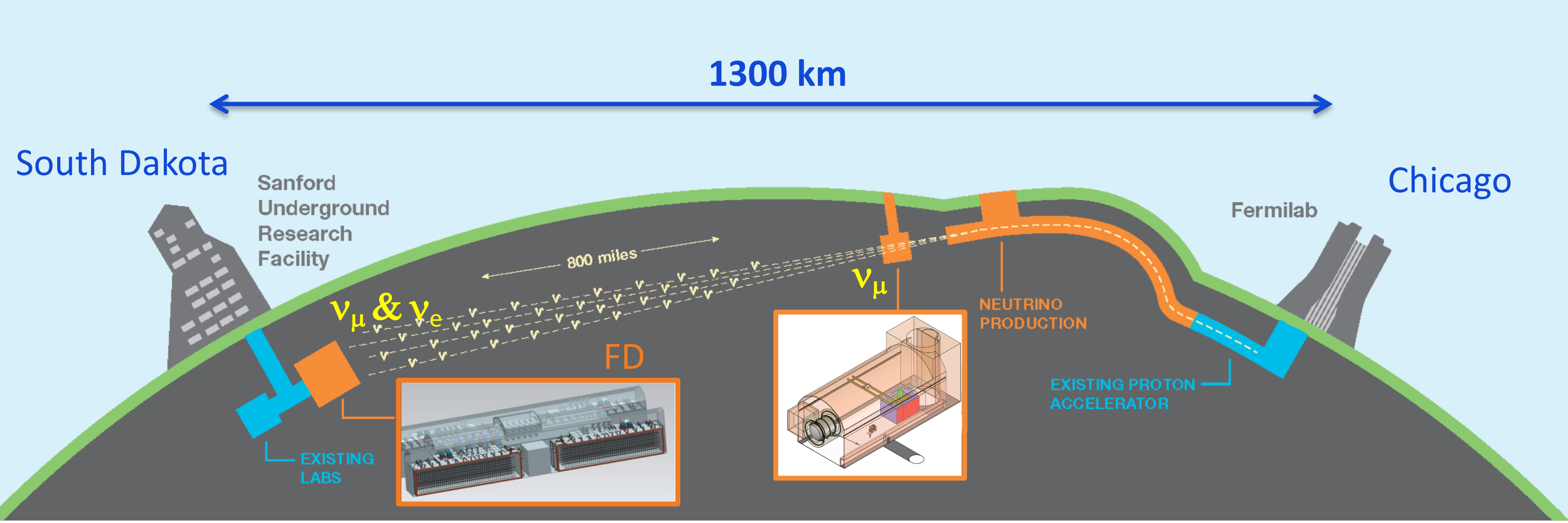
12th Terascale Detector Workshop
Dresden, March 2019

Science & Technology Facilities Council
Rutherford Appleton Laboratory
UNIVERSITY OF OXFORD

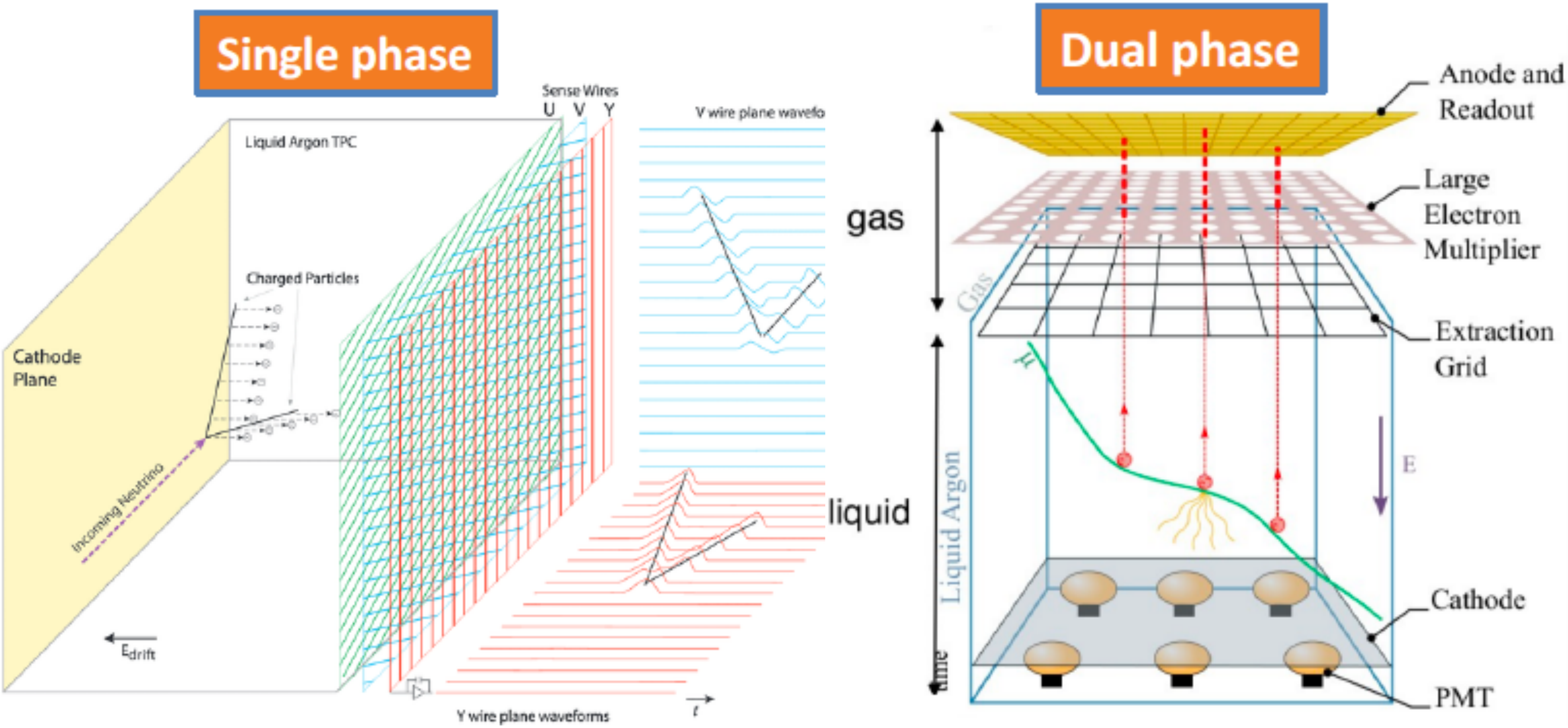
DUNE

DUNE General Setup

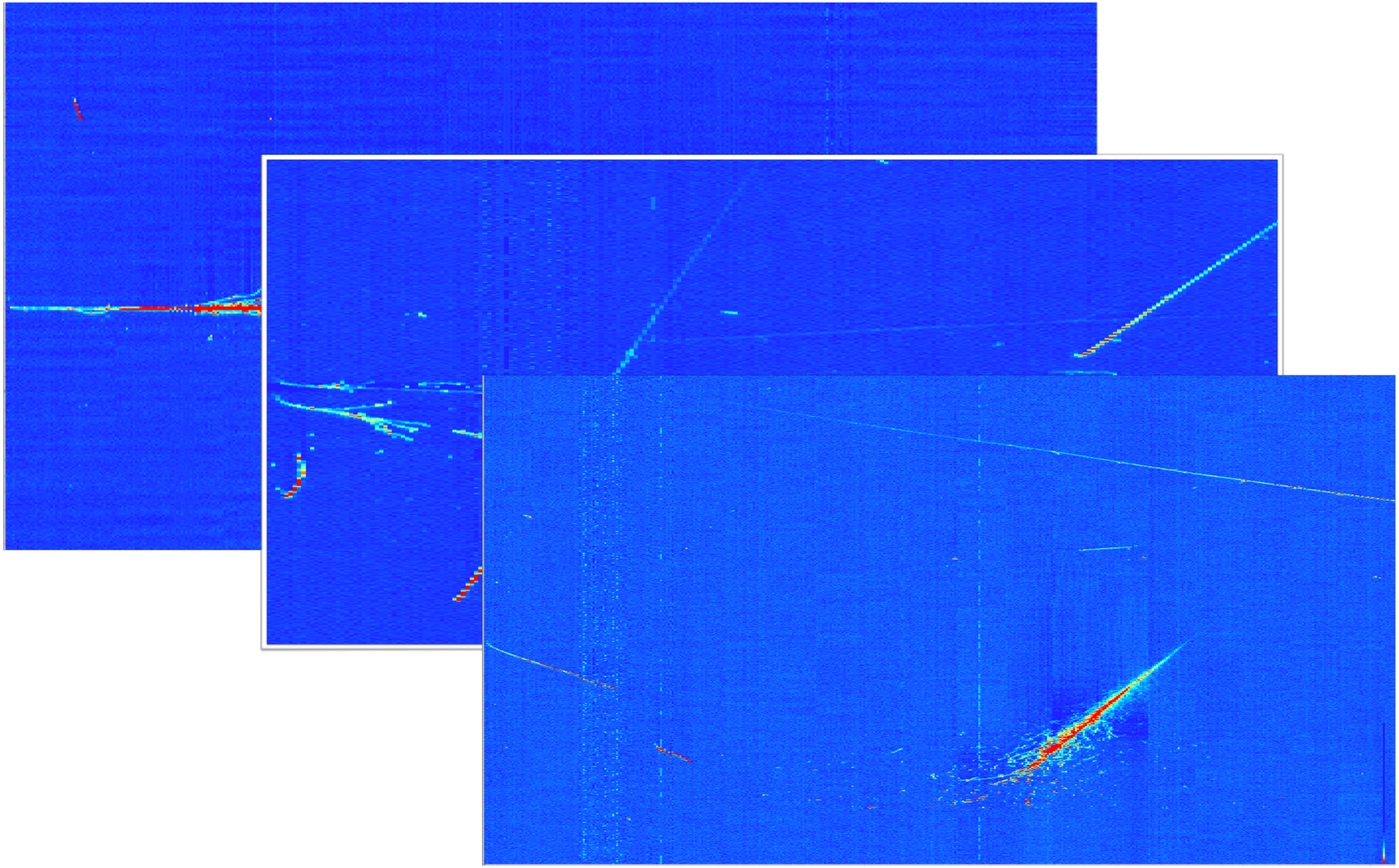
- LBNF/DUNE will consist of
  - An intense 1.2 MW upgradeable ν-beam fired from Fermilab
  - A massive 68 kt (40kt instrumented) deep underground LAr detector in South Dakota and a large Near Detector at Fermilab
  - A large international collaboration



Far Detector (LArTPC)



Events from ProtoDUNE@CERN

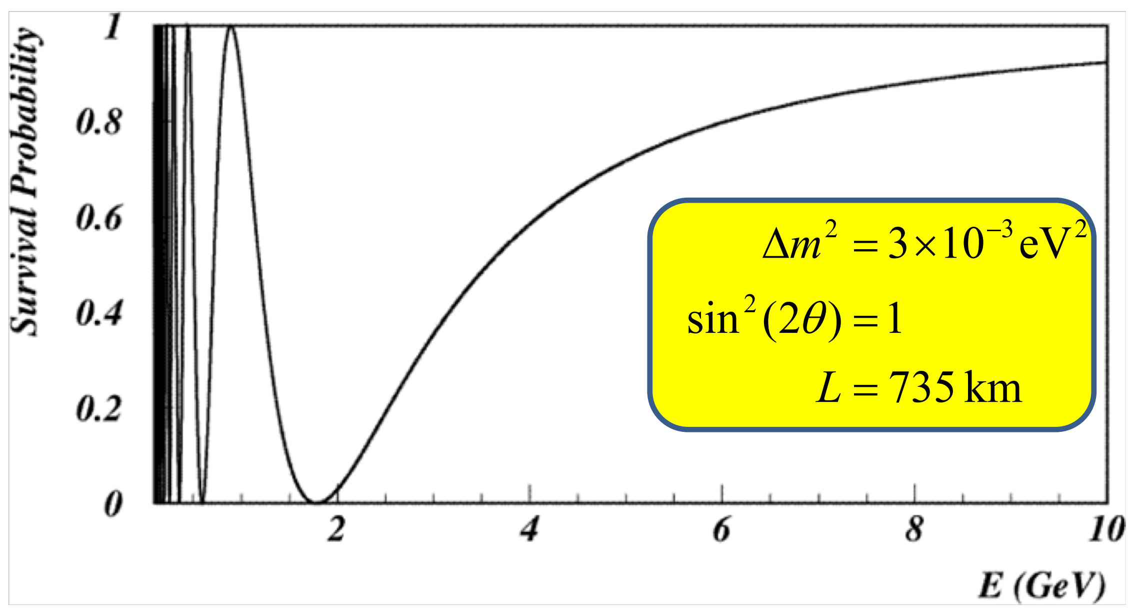


Oscillations for Dummies

ν_μ → ν_1, ν_2 → ν_μ or ν_τ

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences



The Full Monty

- Life isn't that easy
  - 3 Flavour oscillations
  - Matter effects
- The full formula

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\ (1 - 2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E}\ (1 - 2S_{13}^2)
\end{aligned}$$

Measuring Oscillations

- Oscillation probabilities

$$P_{\nu_\mu \to \nu_e}(E_\nu) = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,no-osc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu)}$$

Well known (1-2%)

Are there cancellations?

- Oscillation signal

Small theo. uncertainty or measurement

$$\frac{dN^{far}_{\nu_e}}{dE_\nu} \Bigg/ \frac{dN^{near}_{\nu_\mu}}{dE_\nu} = P_{\nu_\mu \to \nu_e}(E_\nu) * \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * F_{far/near}(E_\nu)$$

1-2% uncertainty

- Near muon/electron ratio

$$\frac{dN^{near}_{\nu_e}}{dE_\nu} \Bigg/ \frac{dN^{near}_{\nu_\mu}}{dE_\nu} = \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * \frac{\phi^{near}_{\nu_e}(E_\nu)}{\phi^{near}_{\nu_\mu}(E_\nu)}$$

Not so small uncertainty

- Need to know
  - Flux & cross section ratios
  - Far/near extrapolation

But in Reality

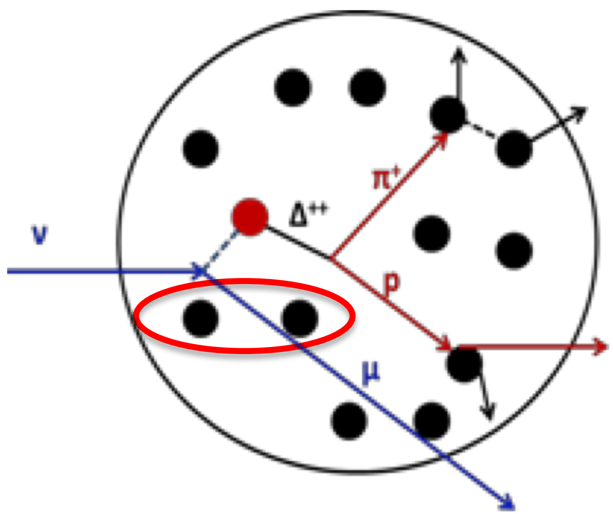
$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * T_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * T_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

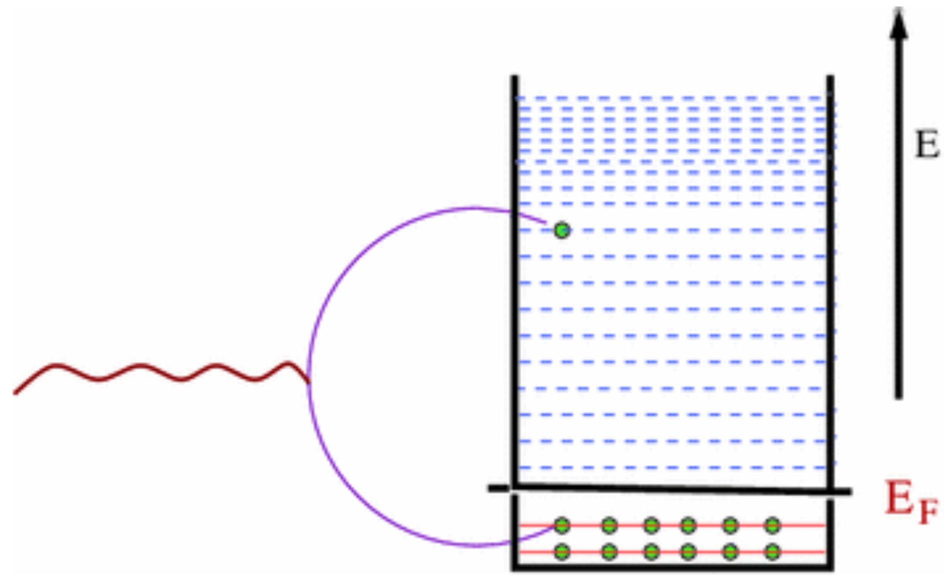
- No cancellations
  - Unless you unfold
- Need to understand especially
  - Detector effects in near and far detector
  - Relation of visible to neutrino energy
  - Cross section ratios
  - Near to far flux extrapolation

Problem of Nuclear Effects

Unknown

- Neutrino energy
- Final state particles (neutrons, nuclear recoil)
- Nuclear effects





What does the ND need to measure?

- ND Fluxes

$$\phi_{\nu_x}^{near}(E_\nu)$$

  - Prior constrained 5-10%

- Total and differential cross sections on Argon

$$\frac{d^n\sigma_{\nu_x}^{Ar}}{da\ db\ dc\ \dots}(E_\nu)$$ (Largely unknown)

- True to reconstruction “matrix”

$T_{\nu_x}^{far}(E_\nu, E_{rec})$ and $T_{\nu_x}^{near}(E_\nu, E_{rec})$D

  Depends on

  - Detector effects
  - differential cross sections

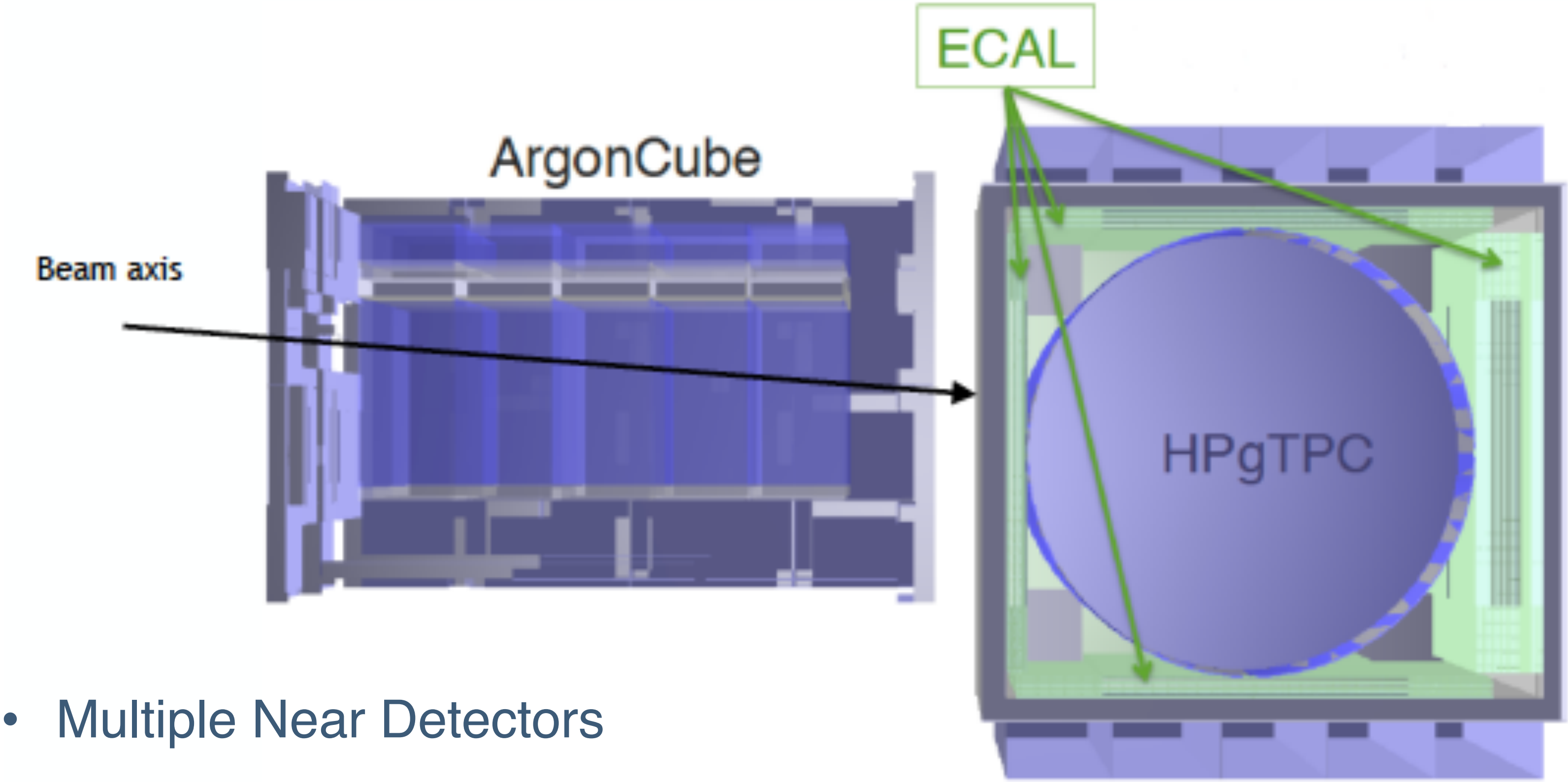
DUNE ND Approach

- Have a capable Multi-Purpose Detector (MPD) to
  - Constrain flux
    - target nucleus does not matter
  - Measure as many different differential cross sections as possible on argon
    - sensitive to pions, protons, neutrons, electrons, photons
    - Other nuclear targets might be useful (especially H)
- Have a LAr TPC to measure
  - reactions on argon (mostly inclusive)
  - constrain detector effects

ND Detector Systems

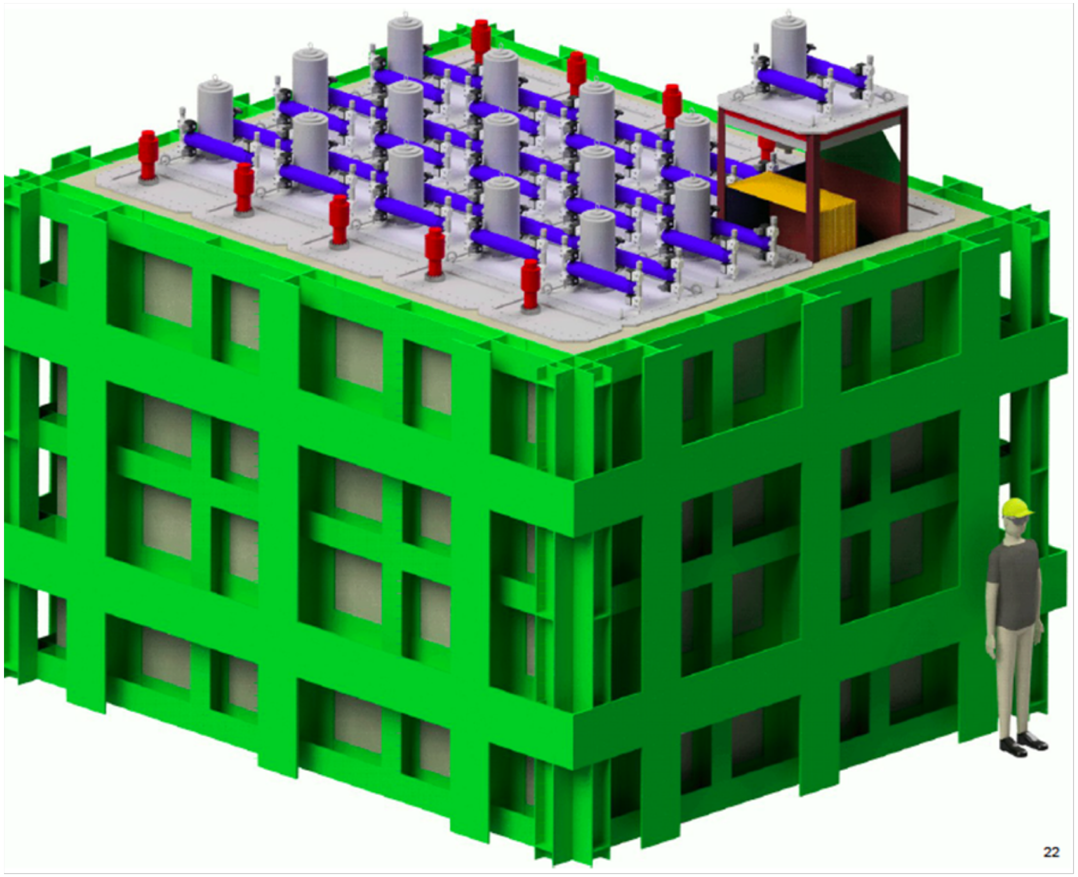
- Highly segmented LAr TPC (LArTPC)
- High Pressure gaseous TPC (HPgTPC)
- 3 Dimensional Scintillator Tracker (3DST)
- Move the detector(s) (DUNE-PRISM)

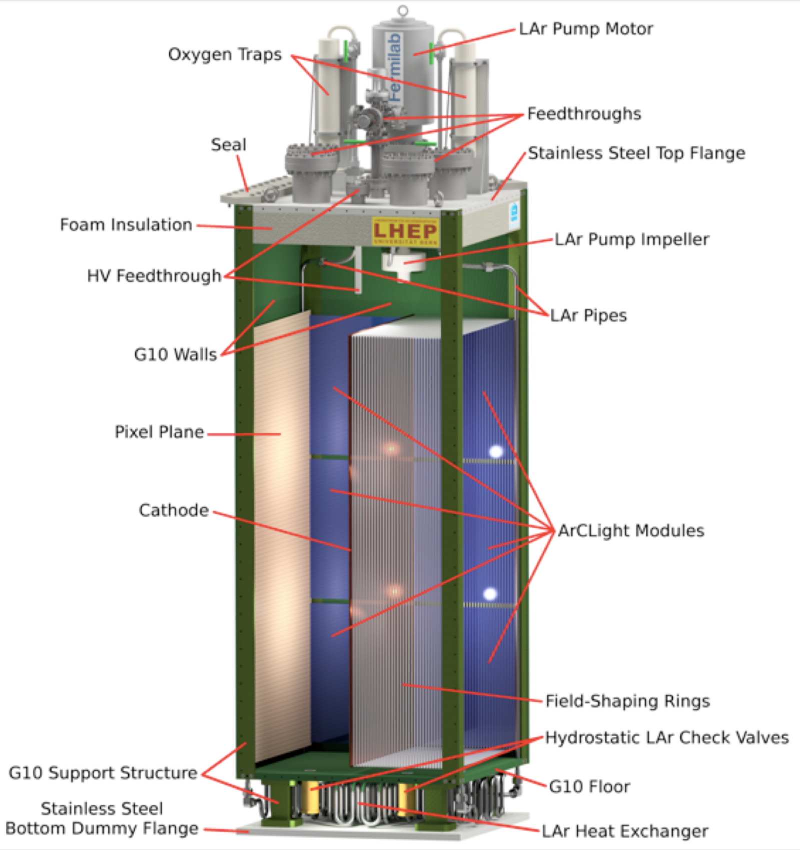
Near Detector Complex

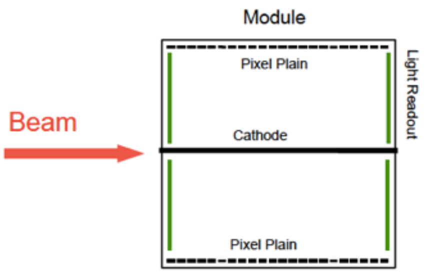


- Multiple Near Detectors
  - characterise beam & neutrino interactions & detector response
  - LAr TPC (similar to FD)
  - High pressure gaseous argon TPC tracker & ECAL & muon systems

LArTPC (7x5x3 m^3)

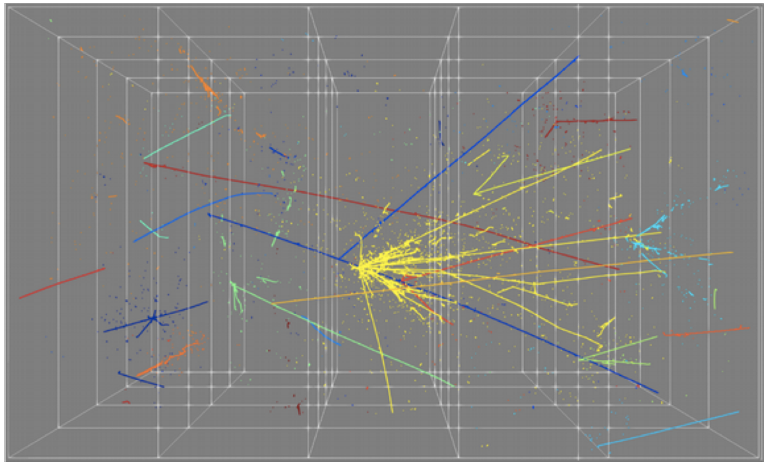


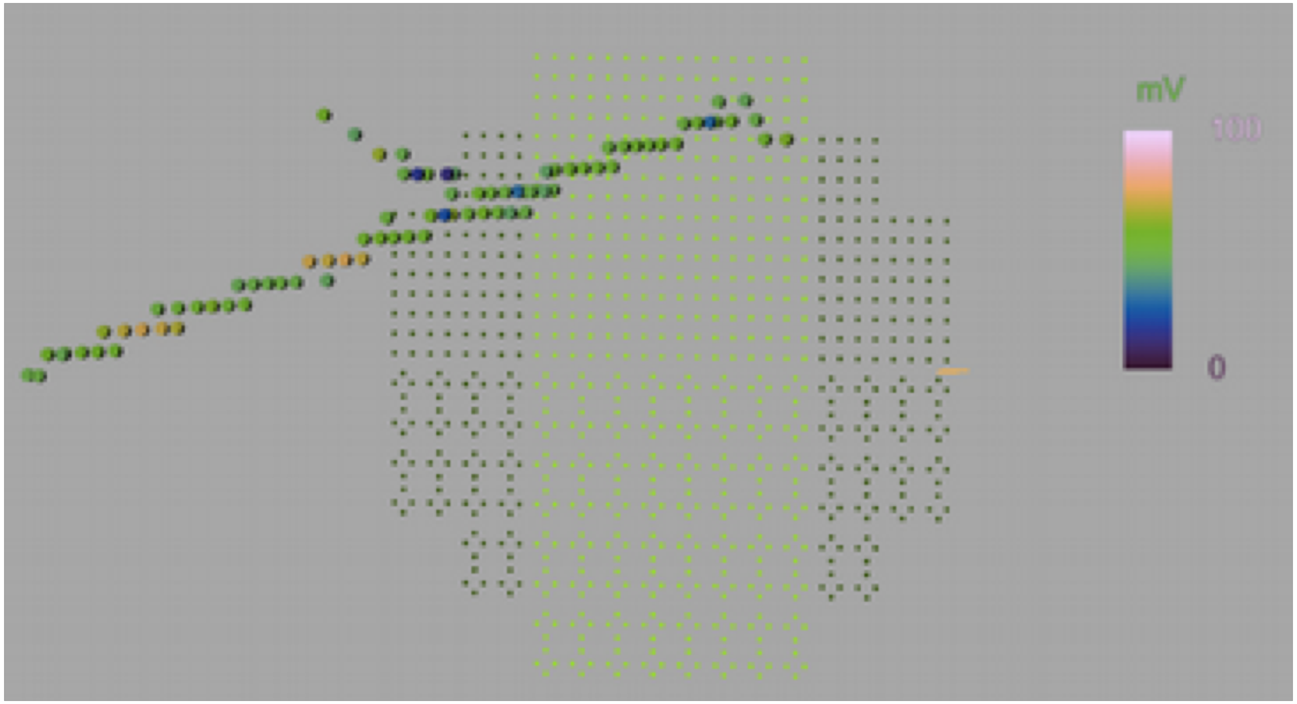


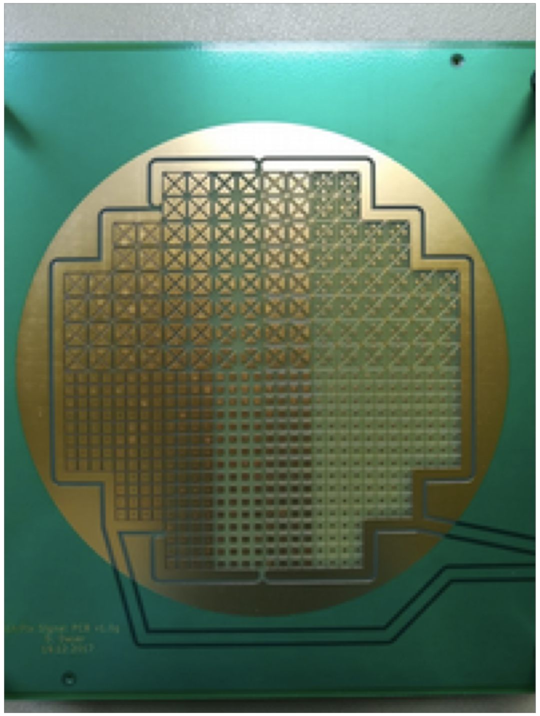


Pixel Readout

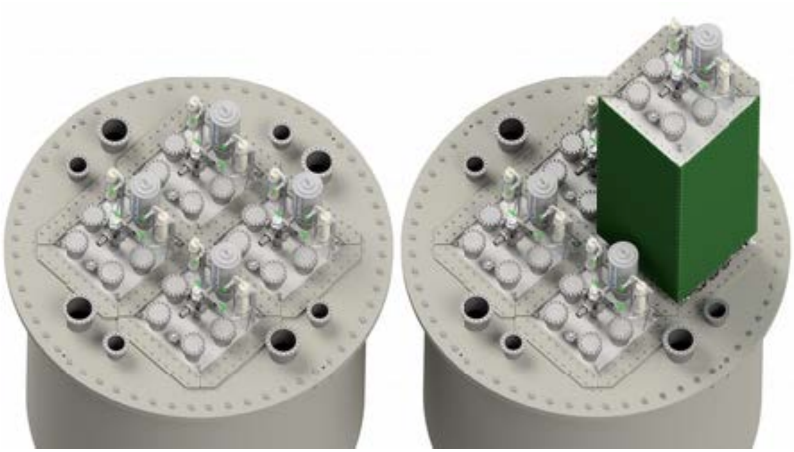
- High Intensity requires pixel readout
- Readout pads and dedicated ASIC

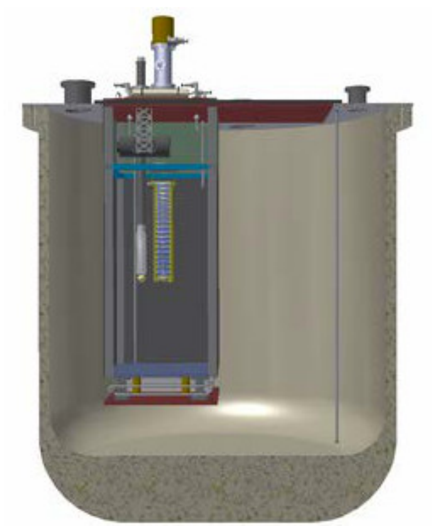


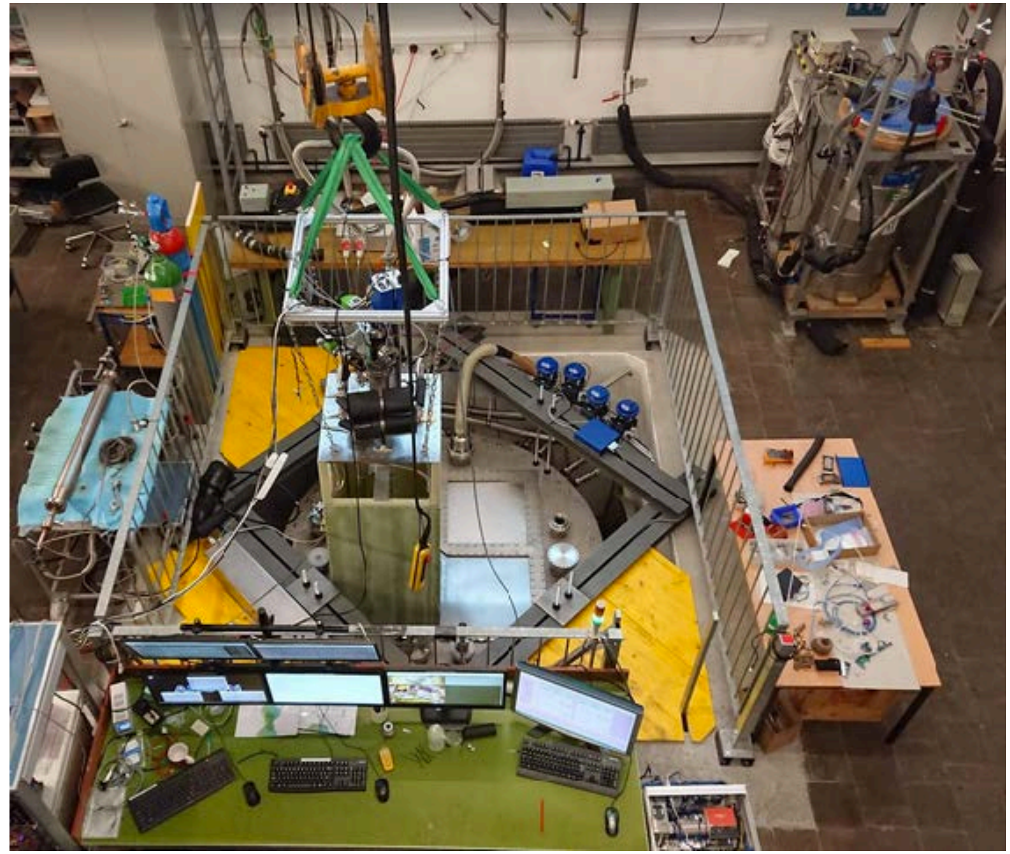




ArgonCube 2X2 prototype (ProtoDUNE-ND)



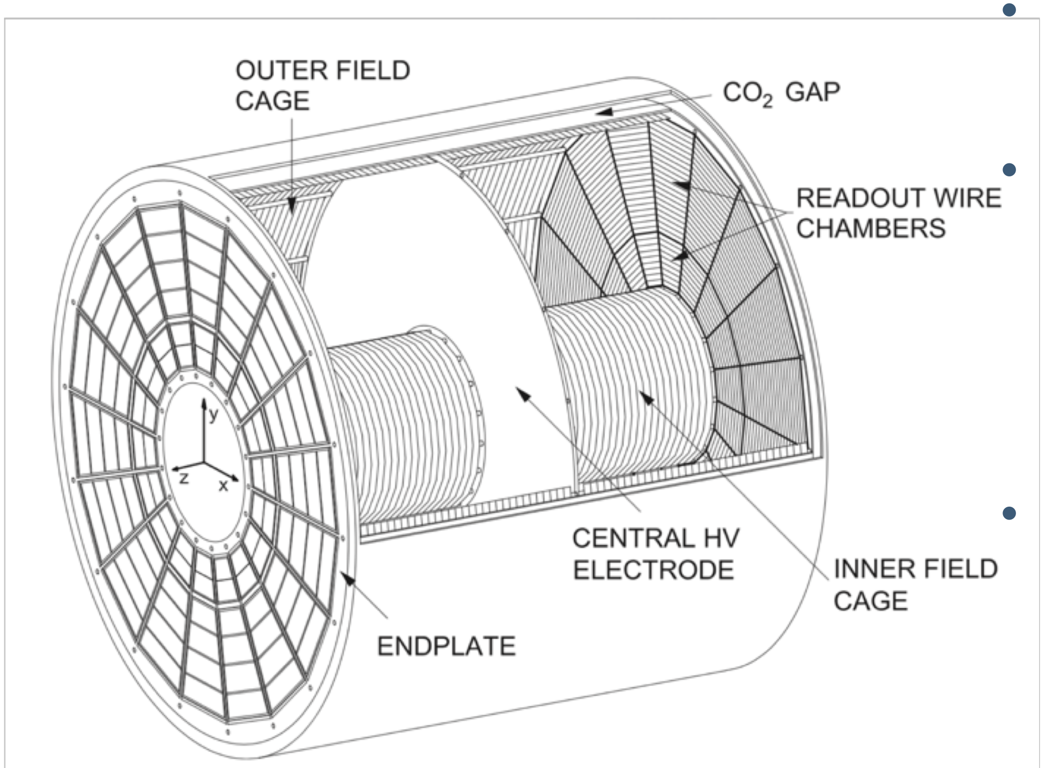




In the laboratory in Bern
First cool down done

Will be brought to Fermilab after testing at Bern.
To be placed in the NuMI beam MINOS ND Hall

Multi-purpose detector

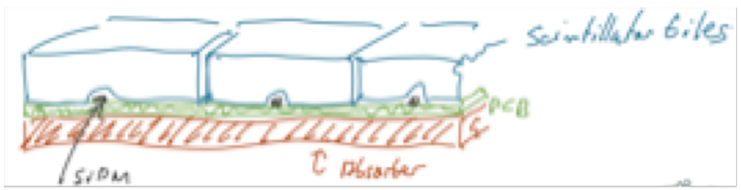


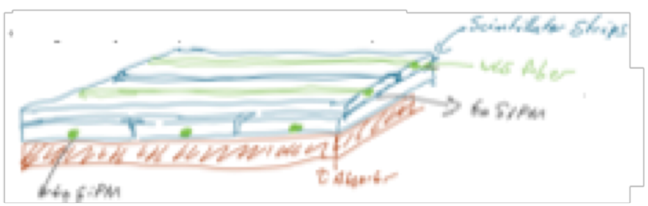
- 10 ATM Ar-CH_4 TPC inside cylindrical pressure vessel
- ECAL
  - Scintillator-Pb or Scintillator Cu
  - ½ inside pressure vessel, ½ outside
- SC Helmhotz coil magnet system
  - 3 coils for central field
  - 2 bucking coils
  - Note: continuing optimization study for NC
- μ tagging system

HPgTPC pressure vessel surrounded by the 5 coils comprising the Helmholtz coil system.
Not shown: ECAL and μ tagger.

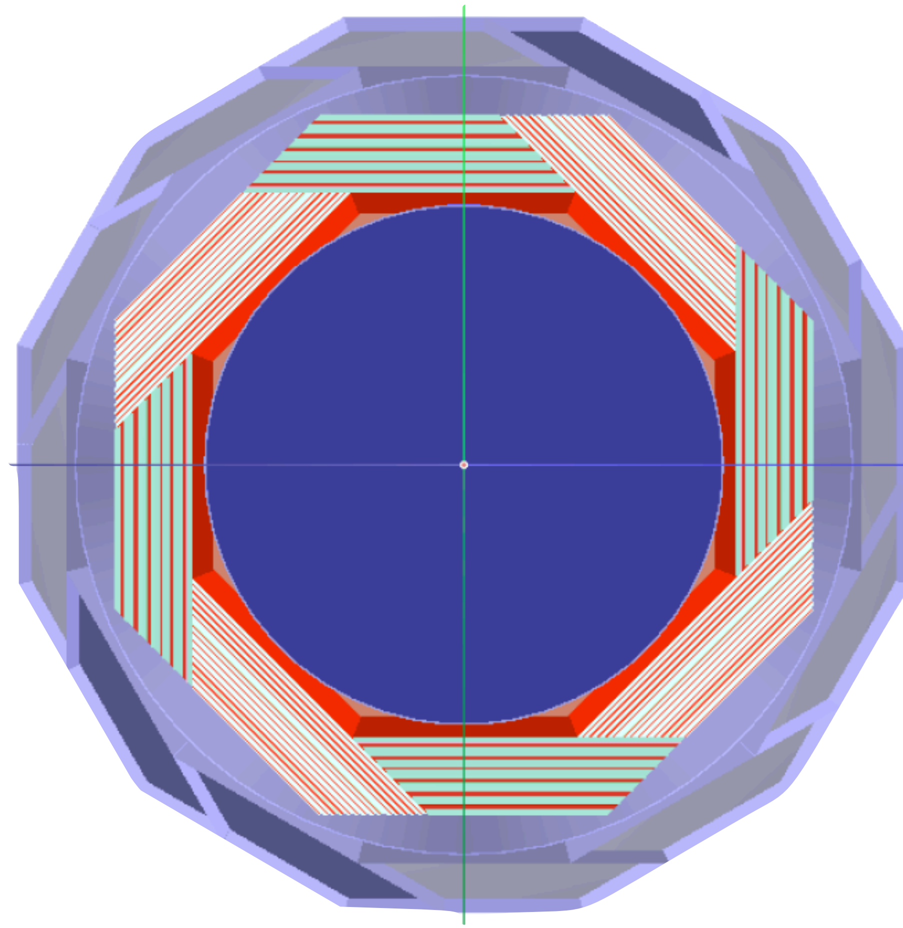
ECAL ala CALICE

- Surrounds TPC to detect photons and neutrons
- Plastic scintillator tiles (or strips)
- SiPM readout



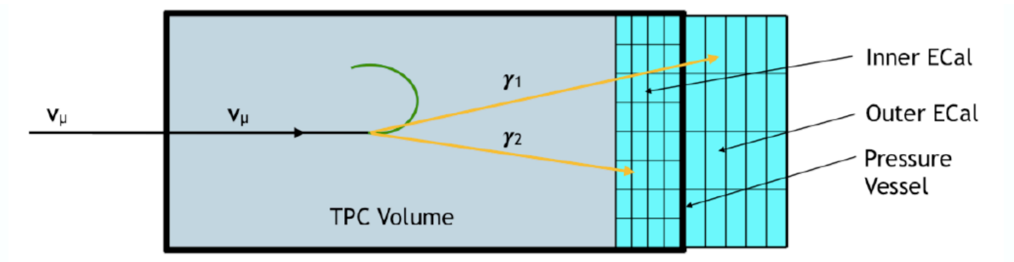


CALICE AHCAL concept

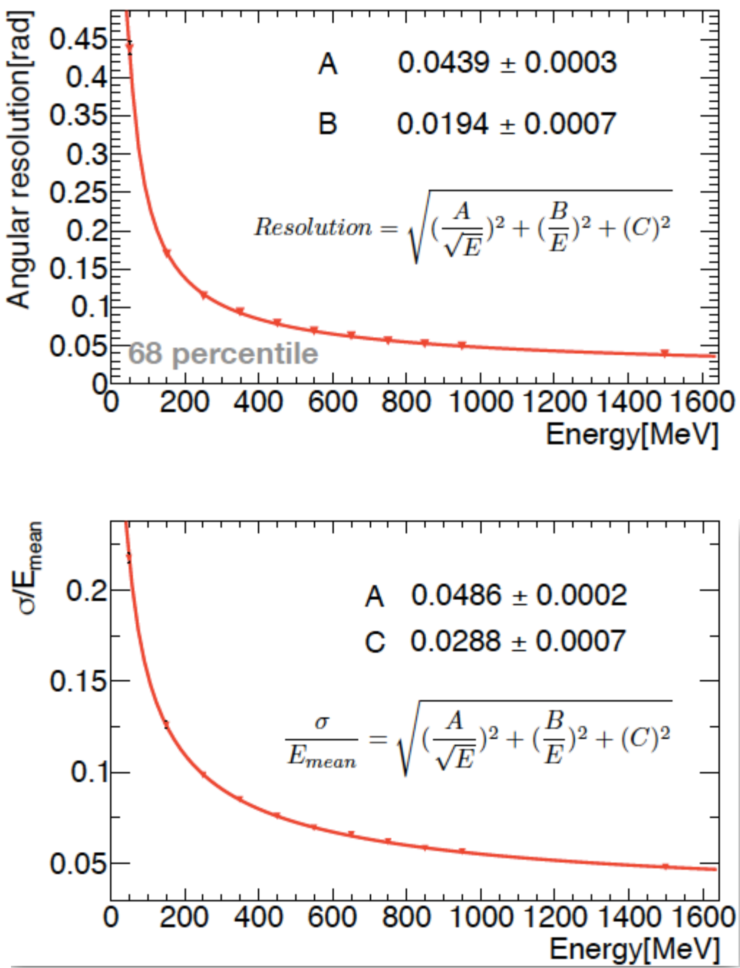


ECAL Performance

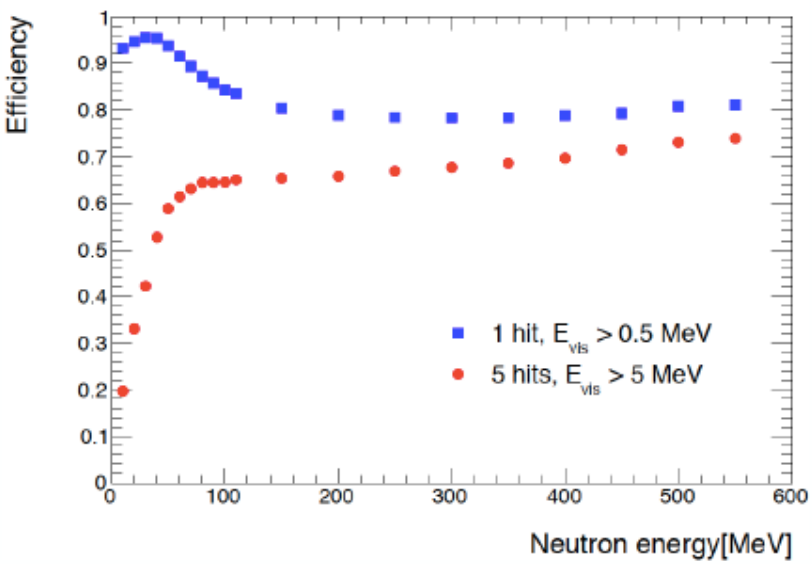
inside and outside pressure vessel
(could be all outside, if PV is thin enough)



EM shower



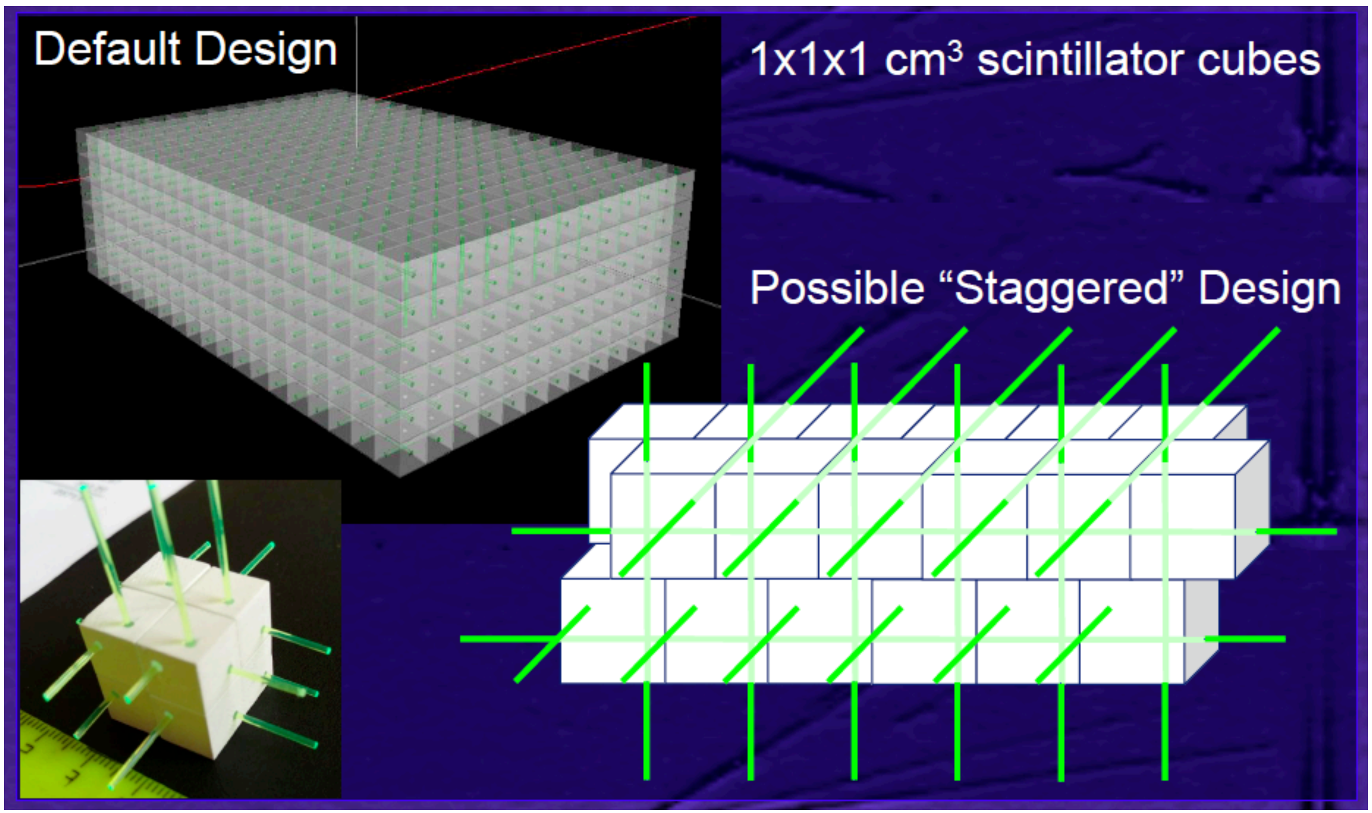
neutron



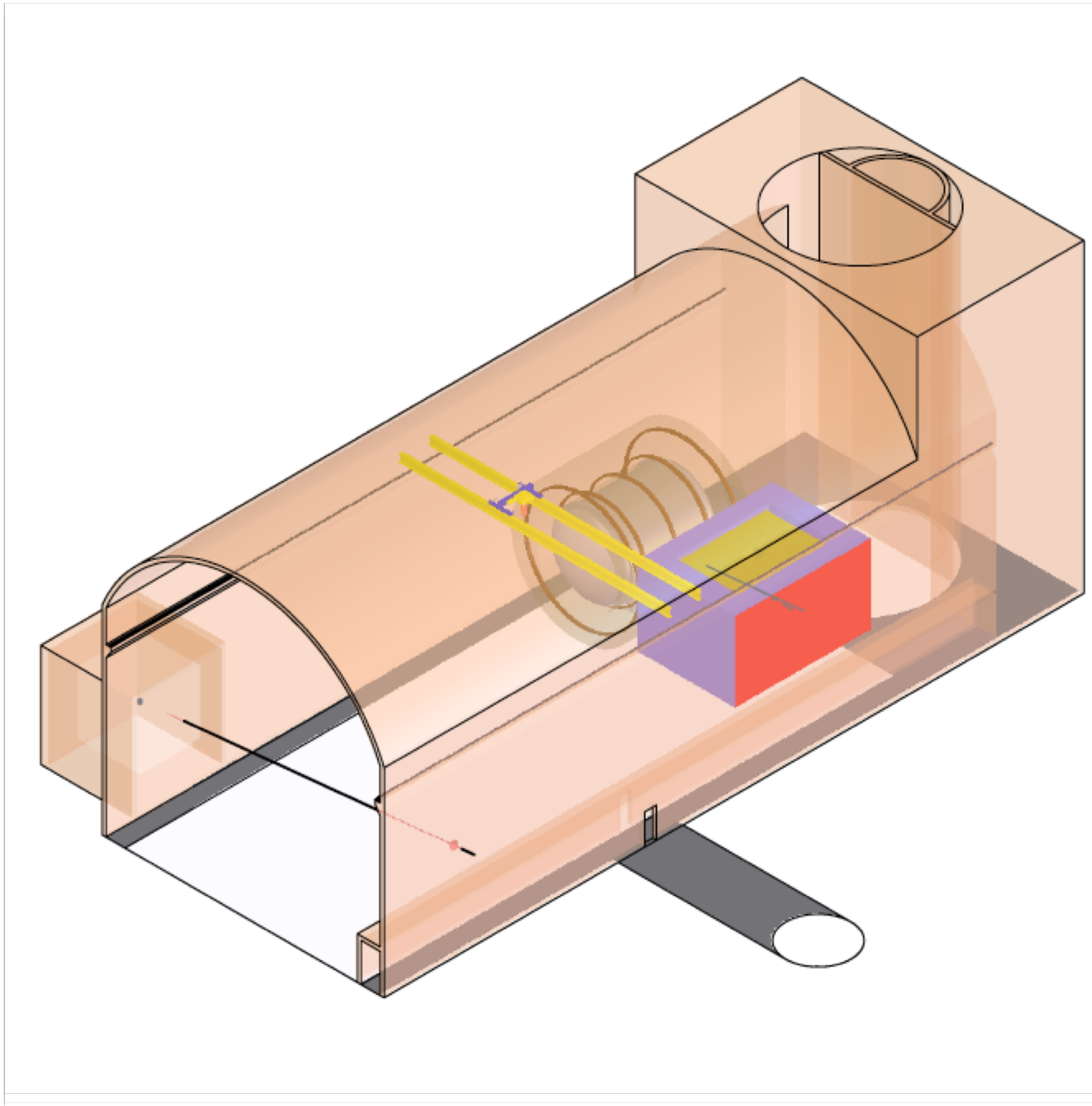
3DST

Purpose

- Beam stability
- Interactions on CH, H-interactions can be identified
- neutrons



ND Hall Concept



DUNE-PRISM

- Alternative approach
  - Vary flux by changing off axis angle
  - Direct extrapolation
    - Measure product of flux * cross section * detector response

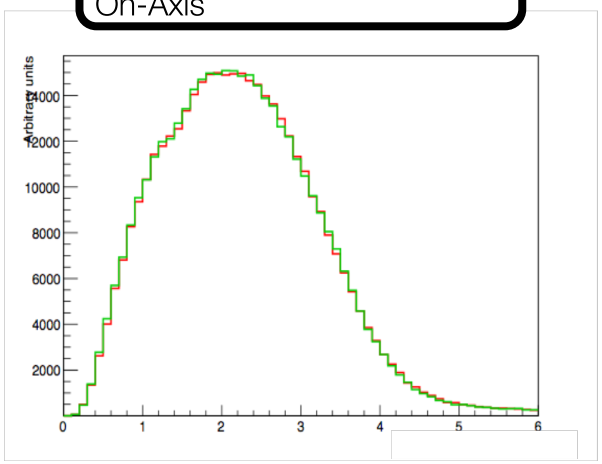
$$\frac{dN_{\nu}^{det}}{dE_{rec}} = \int \phi_{\nu}^{det}(E_{\nu}) * \sigma_{\nu}^{target}(E_{\nu}) * D_{\nu_{\mu}}^{det}(E_{\nu}, E_{rec})\ dE_{\nu}$$

- Move LAr detector along different off-axis angles

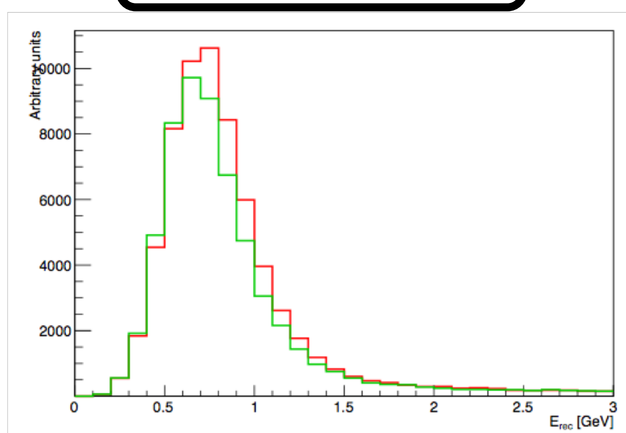
Identify Hidden Systematics

- Measurements with significantly different flux will help
- Case Study
  - Move 20% of proton energy to neutrons
  - ND (on-axis fit) fixes this by modifying cross section

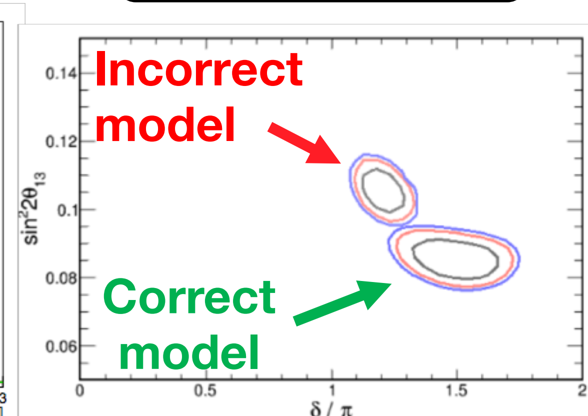
Near Detector Ereco
On-Axis



Near Detector Ereco
18 m Off-Axis



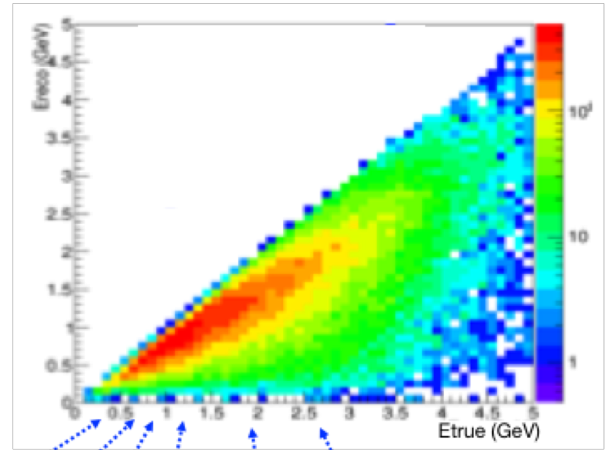
Oscillation Contours

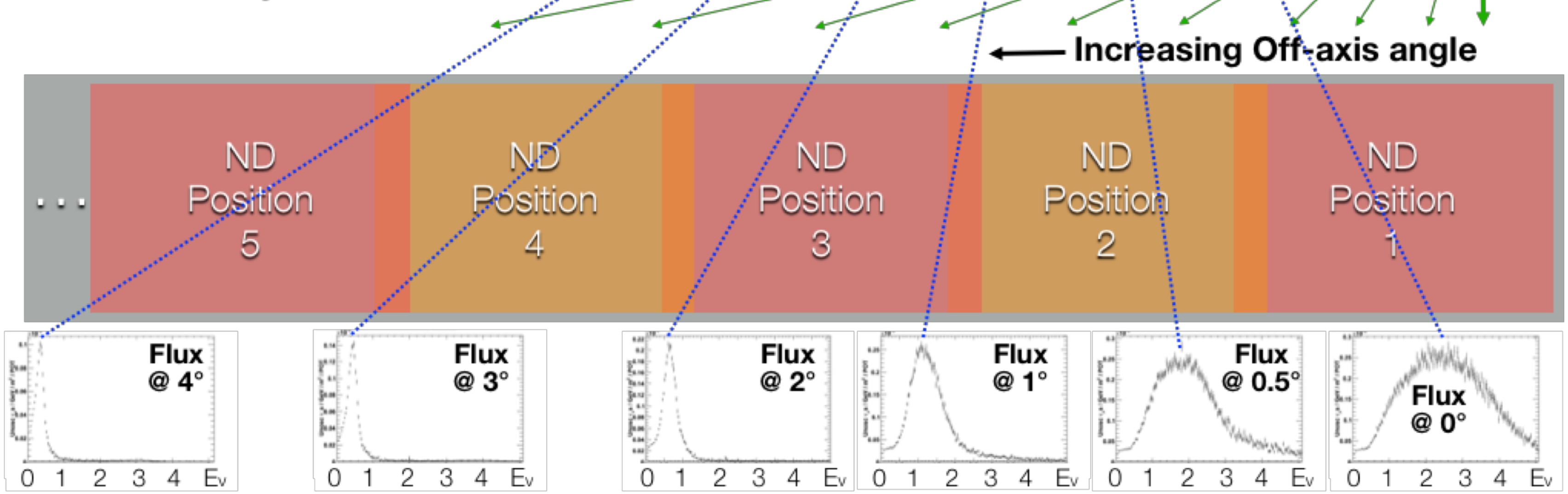


  - On-axis all seems fine, but off-axis disagreement

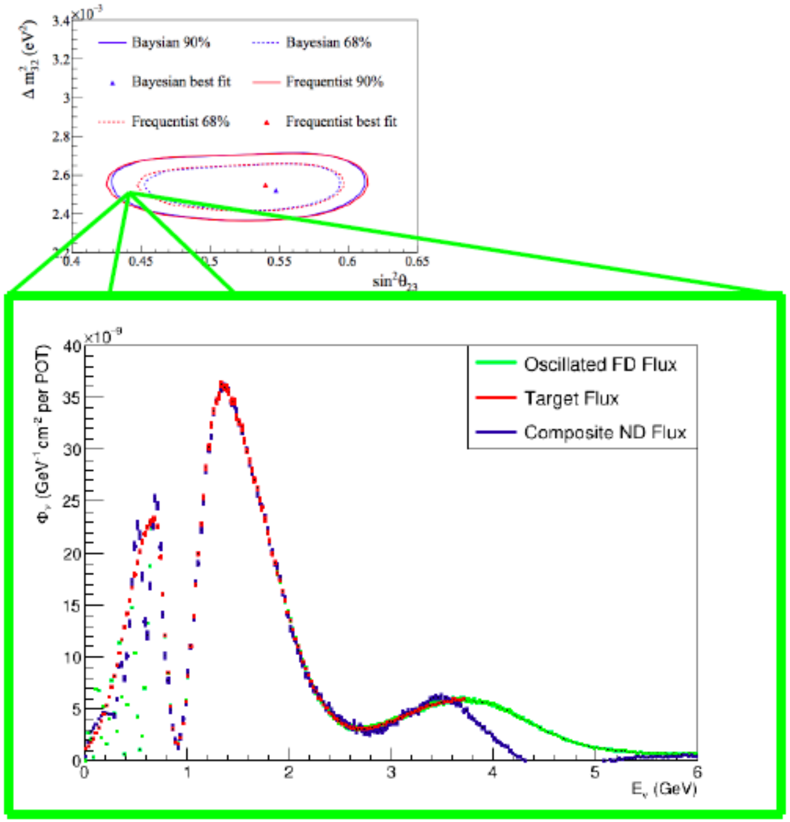
PRISM Approach

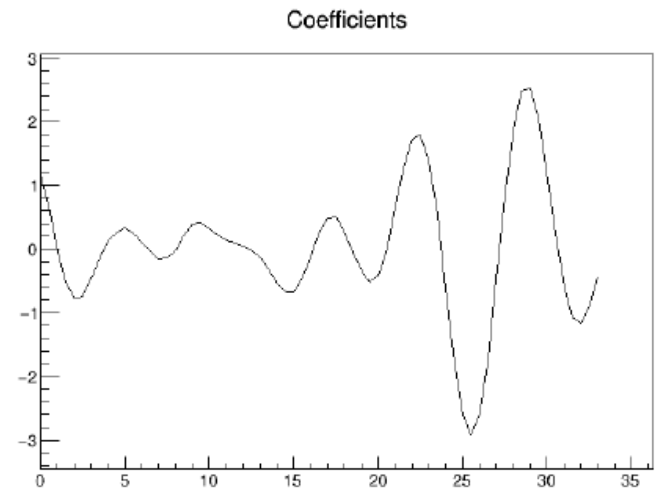
- A major challenge for DUNE is determining the E_{true} -> E_{reco} matrix (i.e. not just the ratio)
  - Energy loss due to neutrons, threshold effects, particle ID (e.g. pion mass), etc.
- Making measurements at a variety of off-axis angles provides an entirely new degree of freedom for constraining E_{true} -> E_{reco}





Use linear combination





- $\Delta m^2_{23} = 0.00253333333333$
- $\sin^2\theta_{23} = 0.43$

- Also able to disentangle flux and cross section effects
  - Flux integrated measurements with totally different flux

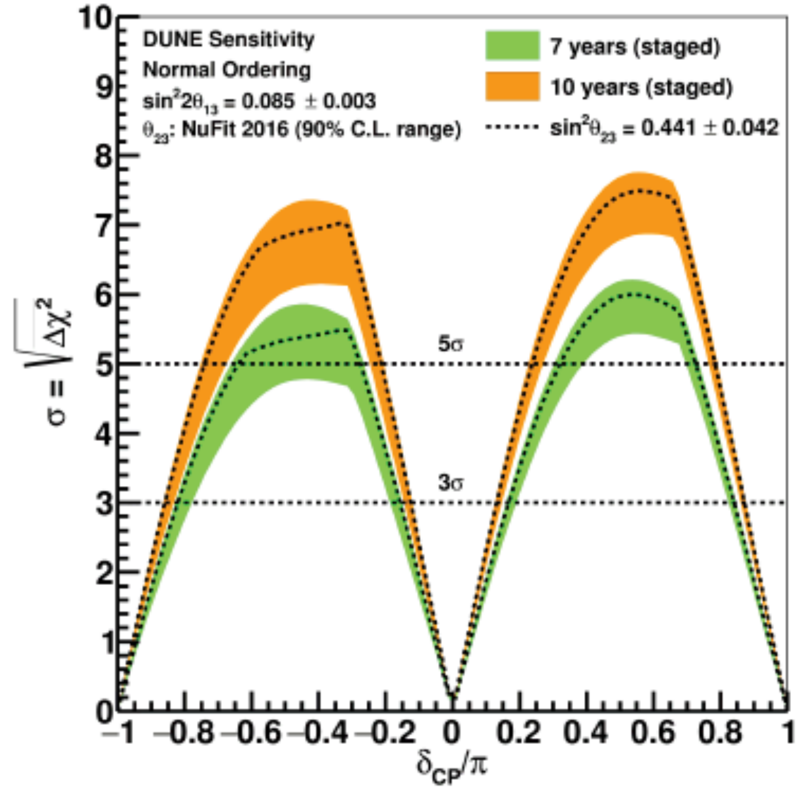
ND Physics

- Main function of ND complex
  - Support the oscillation physics program
    - Cross section
    - Flux
    - LAr detector systematics
- Physics program of itself
  - Sterile neutrinos
  - Dark photons, dark matter
  - Fundamental cross sections
  - Nuclear physics
  - … (limited by your imagination only)

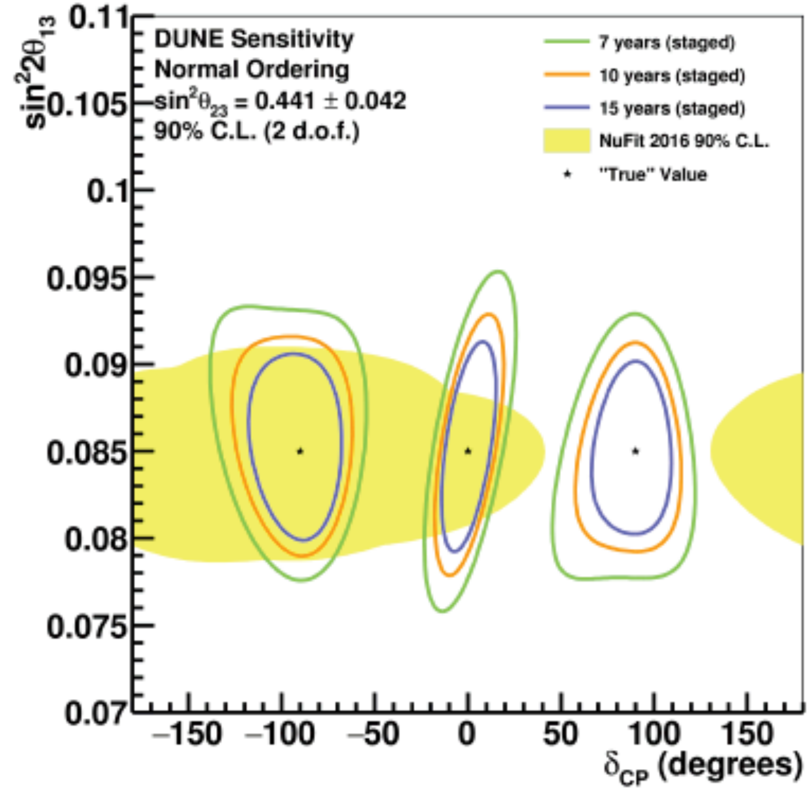
https://indico.fnal.gov/event/18430/

Oscillation Highlights

CP Violation



Width of band indicates variation in possible central values of θ_{23}



Simultaneous measurement of neutrino mixing angles and δ_{CP}

Summary and Conclusion

- DUNE is an neutrino facility with an exciting physics program
- Capable Near Detector suite
  - essential to achieve the oscillations
  - Physics program of itself
- Different detectors to do different jobs
  - LAr TPC to understand detector effects
  - GAr TPC to understand cross sections
  - ECAL to detect neutrals (n, photon)
  - 3DST to understand neutrons and beam stability
  - DUNE-PRISM to measure different fluxes
- Many open questions
  - Get involved and have fun

Backup

Neutrino Mixing The PMNS Matrix

- Assume that neutrinos do have mass:
  - mass eigenstates $\neq$ weak interaction eigenstates
  - Analogue to CKM-Matrix in quark sector!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

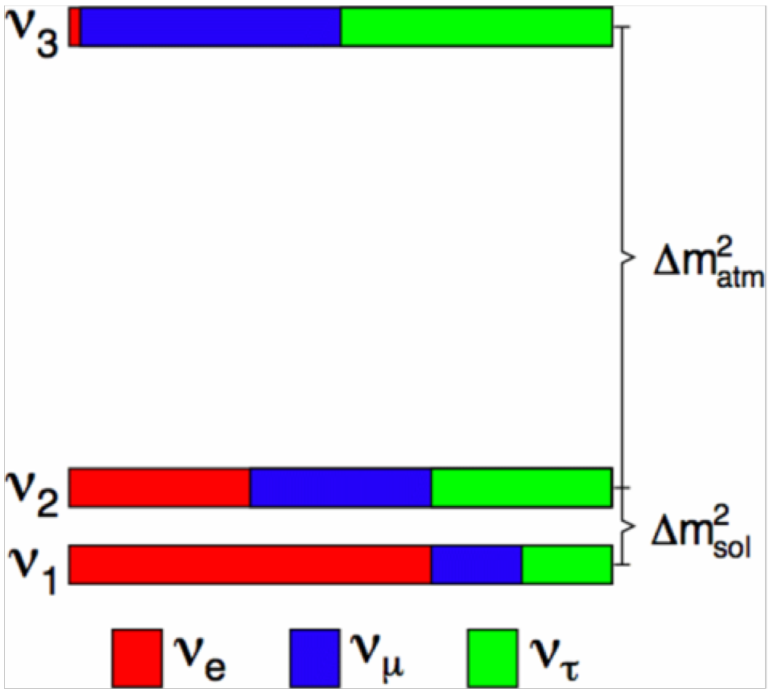
Pontecorvo-Maki-Nakagawa-Sakata

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

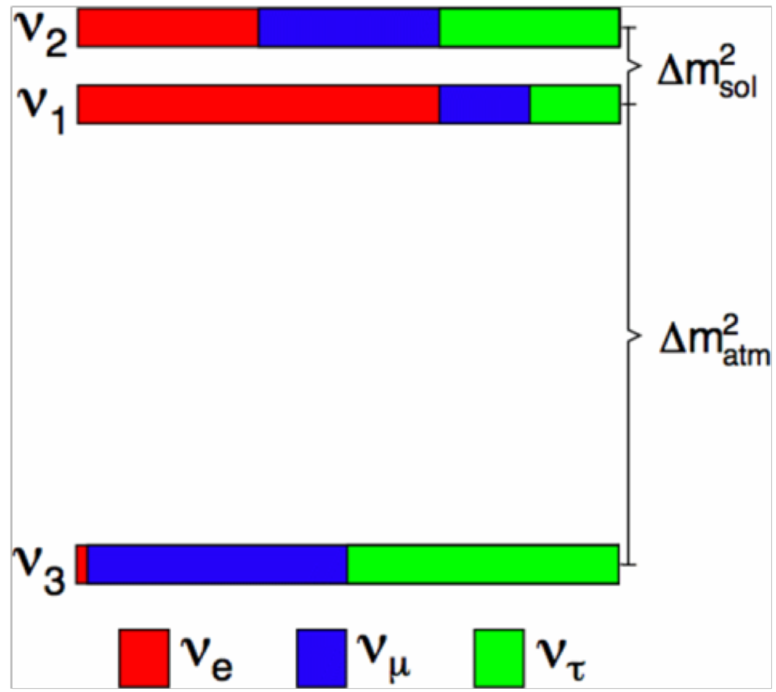
with $c_{ij} = \cos(\theta_{\mathrm{ij}})$, $s_{ij} = \sin(\theta_{ij})$, $\theta_{ij} =$ mixing angle and $\Delta m_{ij}^2 = \text{mass}^2$ difference

Mass Ordering

Normal



Inverted



Matter Effects

- Simplified treatment: two neutrinos only

In vacuum

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

in matter

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_m)\sin^2\left(\frac{\Delta m_m^2 L}{4E}\right)$$

$$\text{with } \sin(2\theta_m) = \frac{\sin(2\theta)}{\sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}}$$

$$\Delta m_m^2 = \Delta m^2 \sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}$$

$$A = \pm \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

- Matter modifies oscillation probability
  - Sign of mass difference matters (opposite for anti-v)
  - Larger effect at higher energies

Schedule/Timeline

★ **Costs and technical schedule are understood**

- Multiple independent reviews
- FD excavation started

★ **Schedule based on a realistic funding profile**

- DOE planning line (including large contingency)
- Planned CERN contributions
- Anticipated international contributions

★ **International Key Milestones:**

- **2017:** start of construction at SURF
- **2018:** operation of two large-scale prototypes at CERN
- **2019**: International approval of DUNE funding matrix
- **2021:** start of installation of first 17-kt far detector module
- **2024:** start of operation of 17-kt far detector module
- **2026:** start of beam operation (1.2 MW) with two 17-kt FD modules

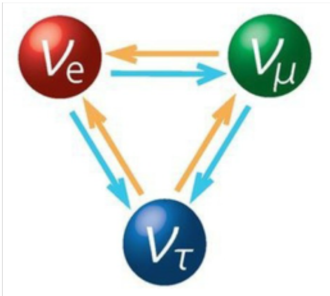
The DUNE Collaboration

- 1144 collaborators from 178 institutions in 32 countries
- 622 faculty/scientists, 191 postdocs, 106 engineers, 5 computing professionals, 220 PhD students
- Growing at a rate of about 100 collaborators/year

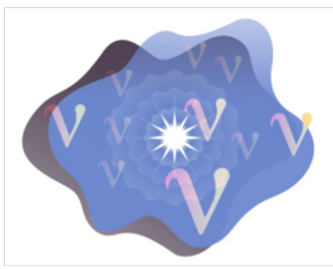
Armenia (3), Brazil (29), Bulgaria (1), Canada (1), CERN (32), Chile (3), China (5), Colombia (13), Czech Republic (11), Spain (34), Finland (4), France (23), Greece (4), India (45), Iran (2), Italy (63), Japan (7), Madagascar (8), Mexico (8), The Netherlands (4), Paraguay (4), Peru (8), Poland (6),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

The DUNE Collaboration

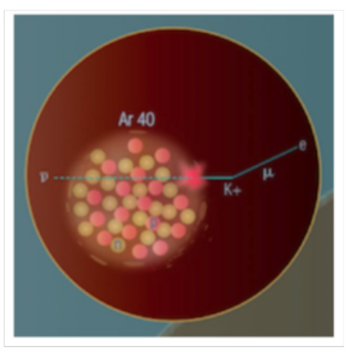
Physics Program



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

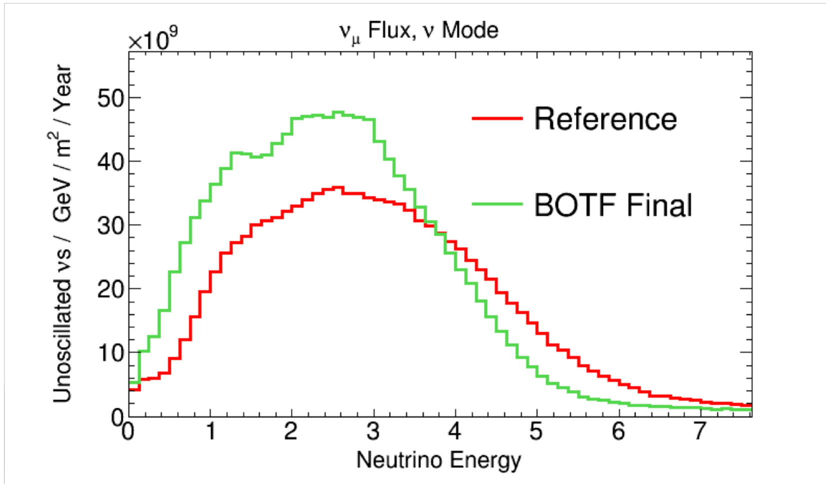


- Supernova Physics
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
  - Unique sensitivity to electron neutrinos

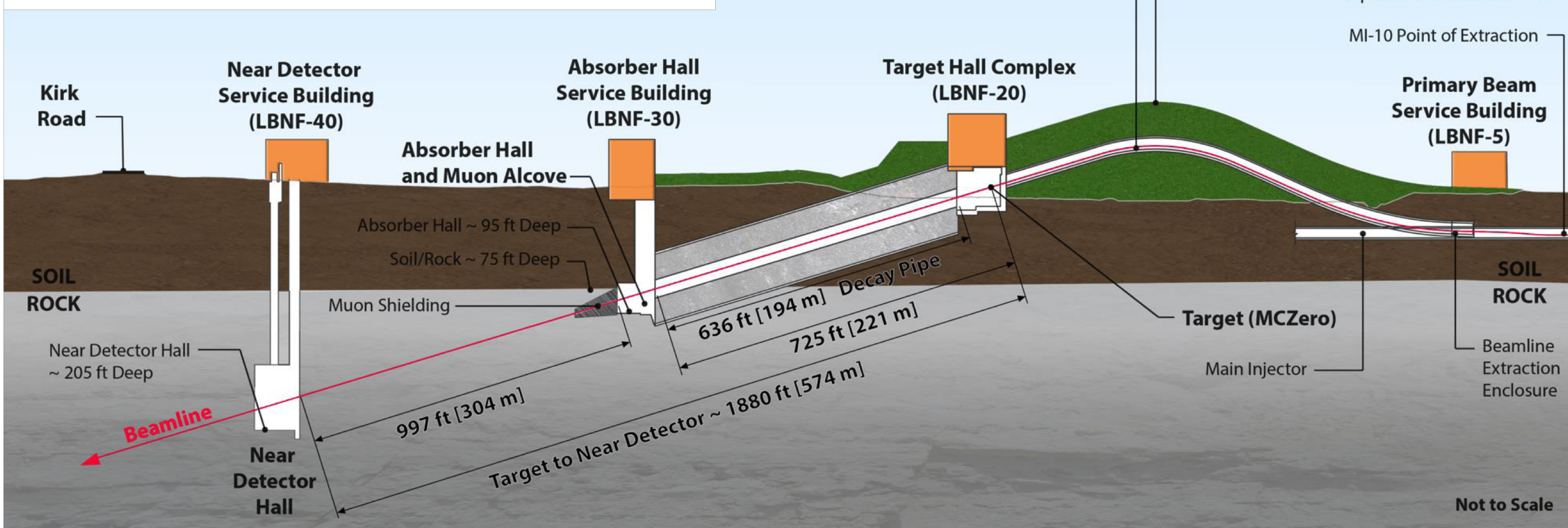


- Baryon number violation
  - Predicted by many BSM theories
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, $p \rightarrow K^+ \bar{\nu}$)
  - $\Delta(B-L) \neq 0$ channels accessible (*e.g.*, $n \rightarrow \bar{n}$)

Beam

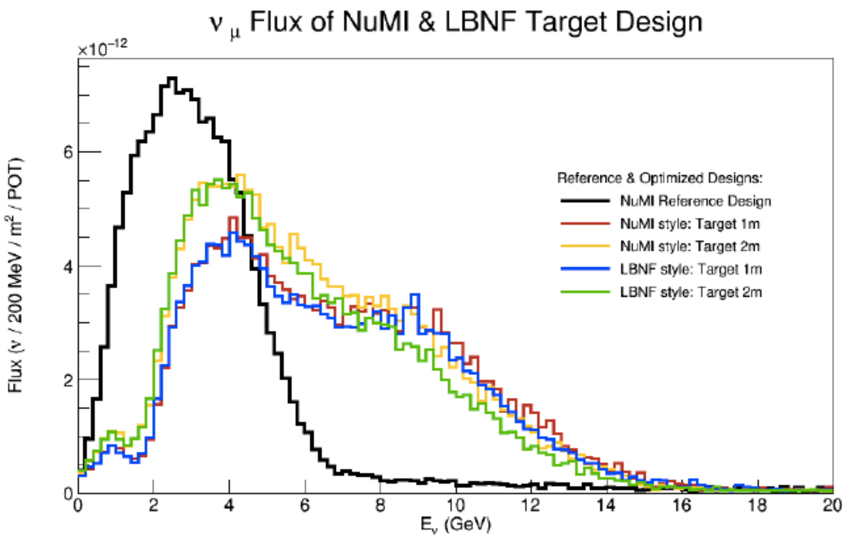


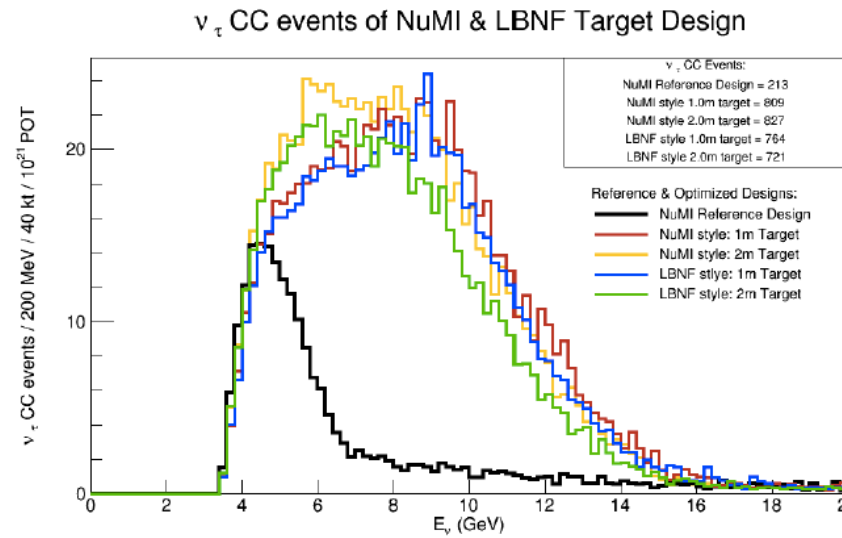
- Proton beam energy 60-120 GeV
- Power 1.2 MW ➔ 2.4 MW
- Neutrinos and anti-neutrinos



High Energy Tune

- Can change the flux by changing
  - Target positions
  - Horns (shape, position, current)



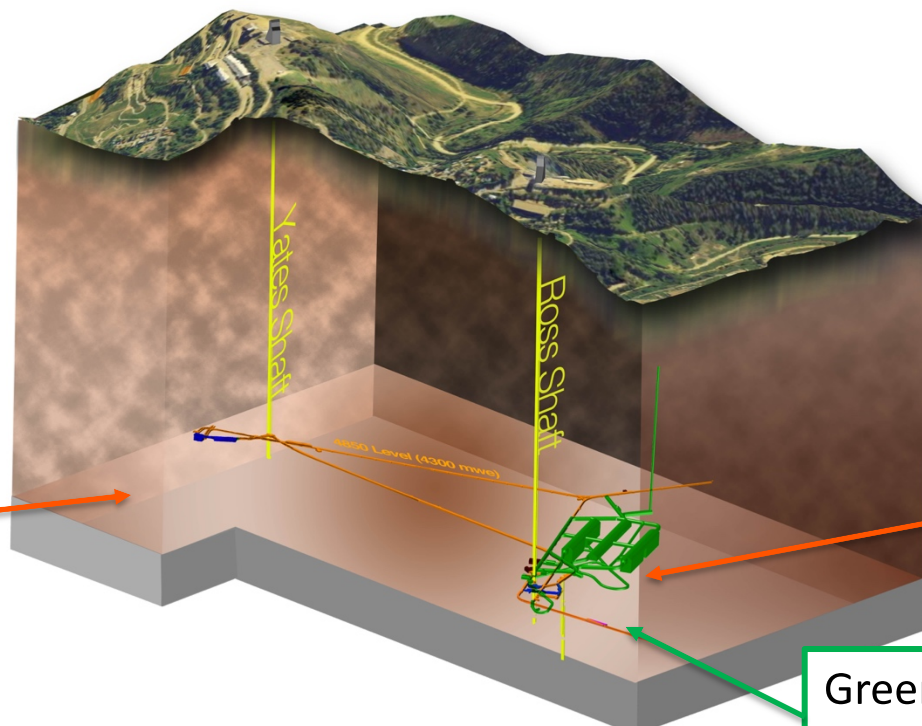


- Physics
  - Tau appearance
  - NSI

Underground Laboratory SURF

DUNE Far Detector site

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



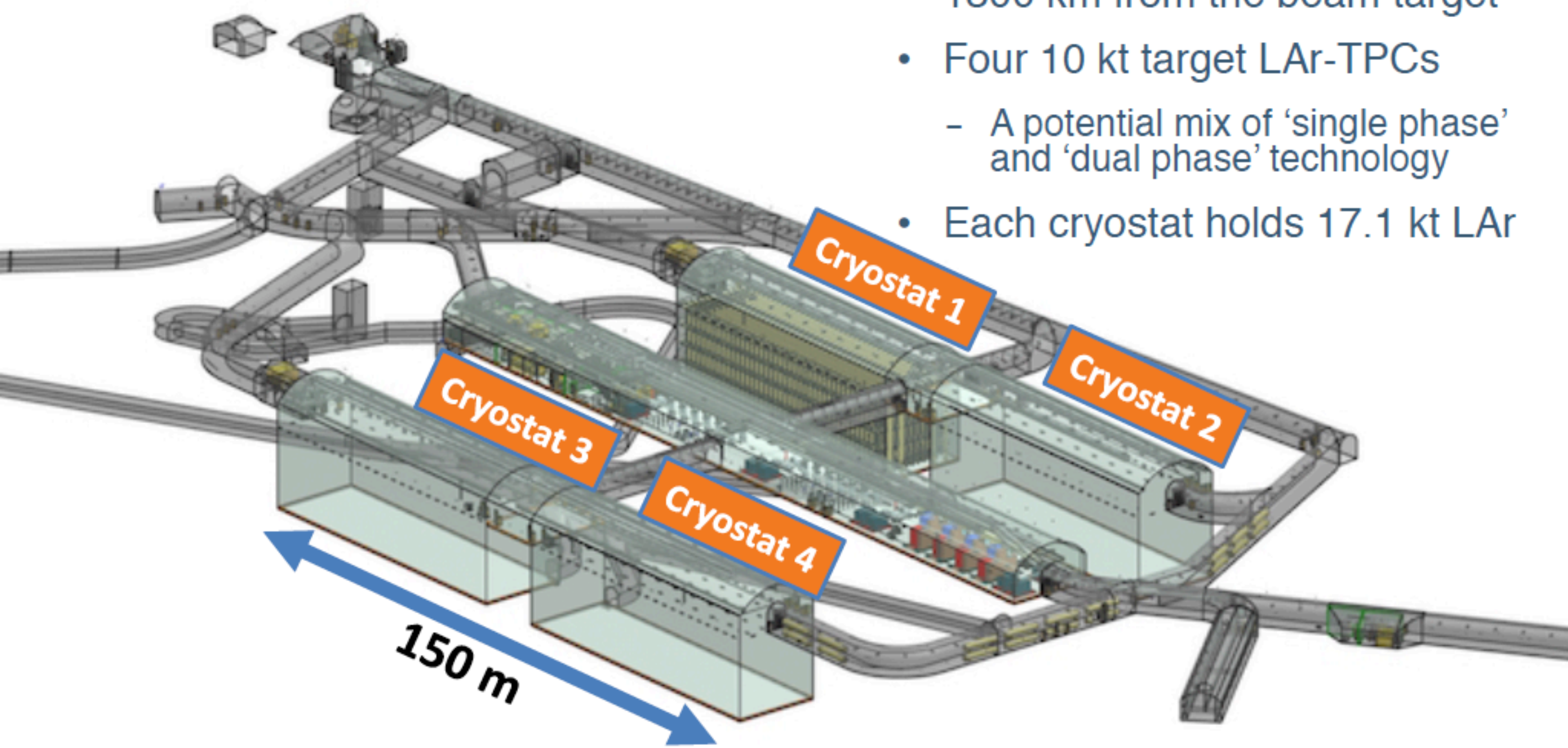
Davis Campus:
- LUX
- Majorana
- …
- **LZ**

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



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)

Flux Measurements

- Can be done on any target
- Needs known cross section
- Proposed measurements
  - Neutrino-electron scattering
    - (electro-)weak cross section calculable with high precision
    - Cross section is very small
  - Low-$\boldsymbol{\nu}$ method
    - Cross section is independent of energy in limit where neutrino energy is FS lepton energy. No hadronic energy ($\boldsymbol{\nu}$)
    - Cross section depends on ability to measure all hadronic energy including neutrons
    - Breaks down at low energy ($\boldsymbol{\nu} < E_{cut}$)

$$\phi_{\nu_x}^{near}(E_\nu)$$

Flux Measurements (II)

- Coherent Scattering

$$\nu_l + N \to l^- + \pi^+ + N$$

$$\overline{\nu}_l + N \to l^+ + \pi^- + N$$

$$\left(\begin{array}{c} \nu_l + N \to \nu_l + \pi^0 + N \\ \overline{\nu}_l + N \to \overline{\nu}_l + \pi^0 + N \end{array} \right)$$

  - Does not depend on internal nuclear structure
    - Long/short range correlation
    - Final state interactions
  - Cross section
    - Not as well known
    - Small (momentum transfer to nucleus is small)
  - Allows flavour identification

Flux Measurements (III)

- Measurement on hydrogen
  - Interactions on hydrogen can be identified
    - no initial state transverse momentum
  - Produce Δ-resonances
    - $\upsilon_l + p \rightarrow l^- + \Delta^{++} \rightarrow l^- + p + \pi^+$
    - $\bar{\upsilon}_l + p \rightarrow l^+ + \Delta^0 \rightarrow l^+ + p + \pi^-$
    - Small-ish cross section at low energies
  - No final state interaction
  - But even cross section on free nucleus has uncertainties
    - Higher resonances, non-resonant contributions, interference

Cross Section and Smearing Matrix

- We don't know how to disentangle them

$$\sigma_{\nu_e}^{Ar}(E_\nu) * T_{\nu_e}^{far}(E_\nu, E_{rec})$$

  - Unknown initial state:
    - Neutrino energy and "nucleon" momentum
  - Missing final state particles/energy:
    - neutrons, low-energy protons, (nuclear recoil)
  - Detector smearing
- Approach
  - Measure as many exclusive differential cross sections as possible
  - Tune/build a model
  - Take differential cross section and reco2true from tuned MC and detector simulation

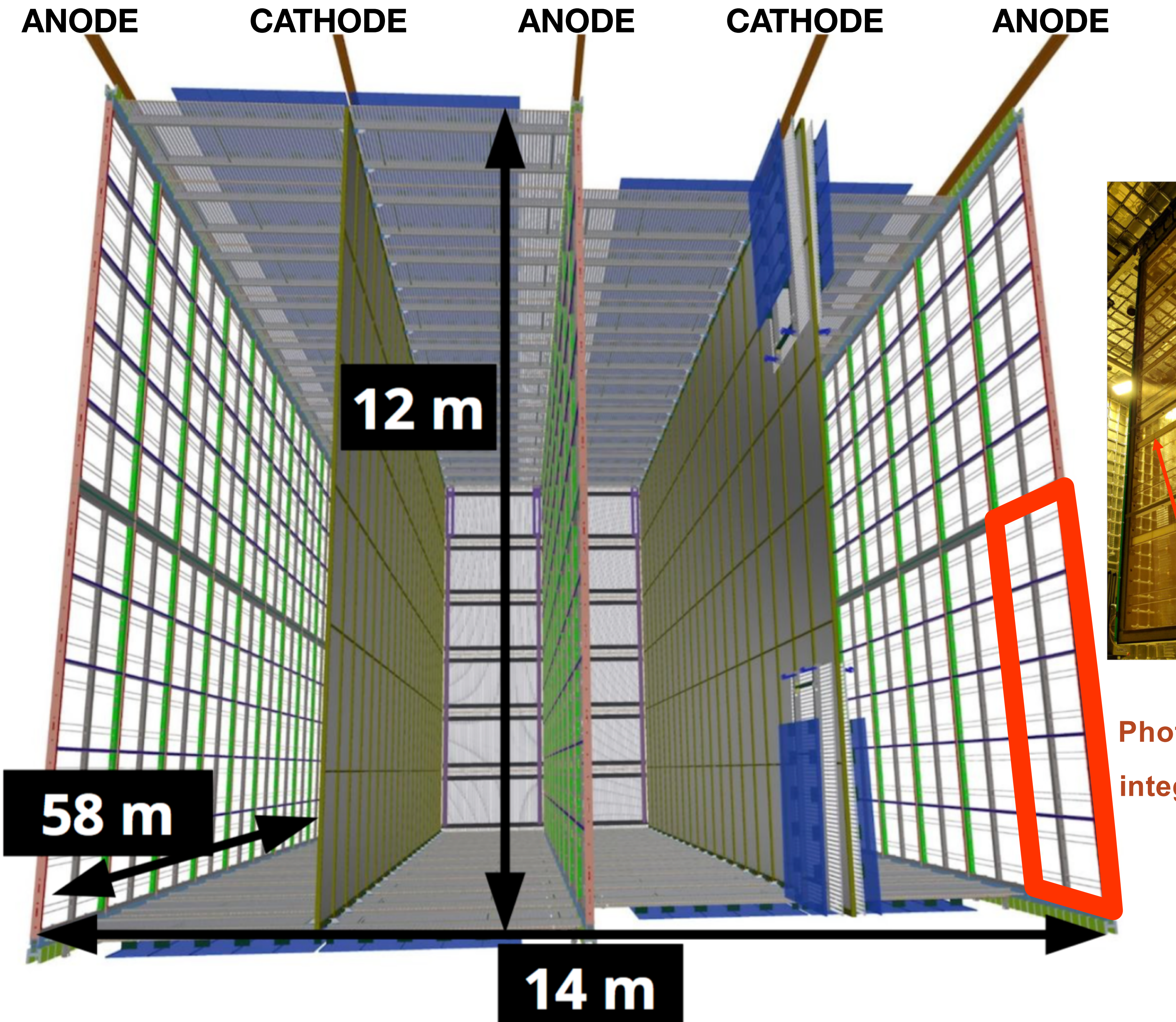
Cross Section and Smearing Matrix

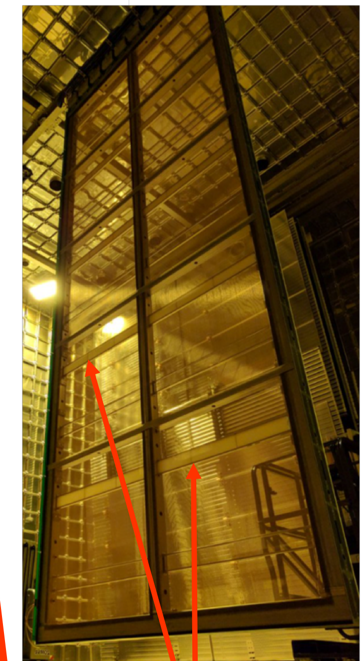
- Can't be measured as function of true neutrino energy
  - Neutrino and nuclear energies are unknown
  - Invisible final state particles
    - neutron, nuclear recoil, FSI
  - Is intrinsically model dependent

- Only possible flux integrated event rates

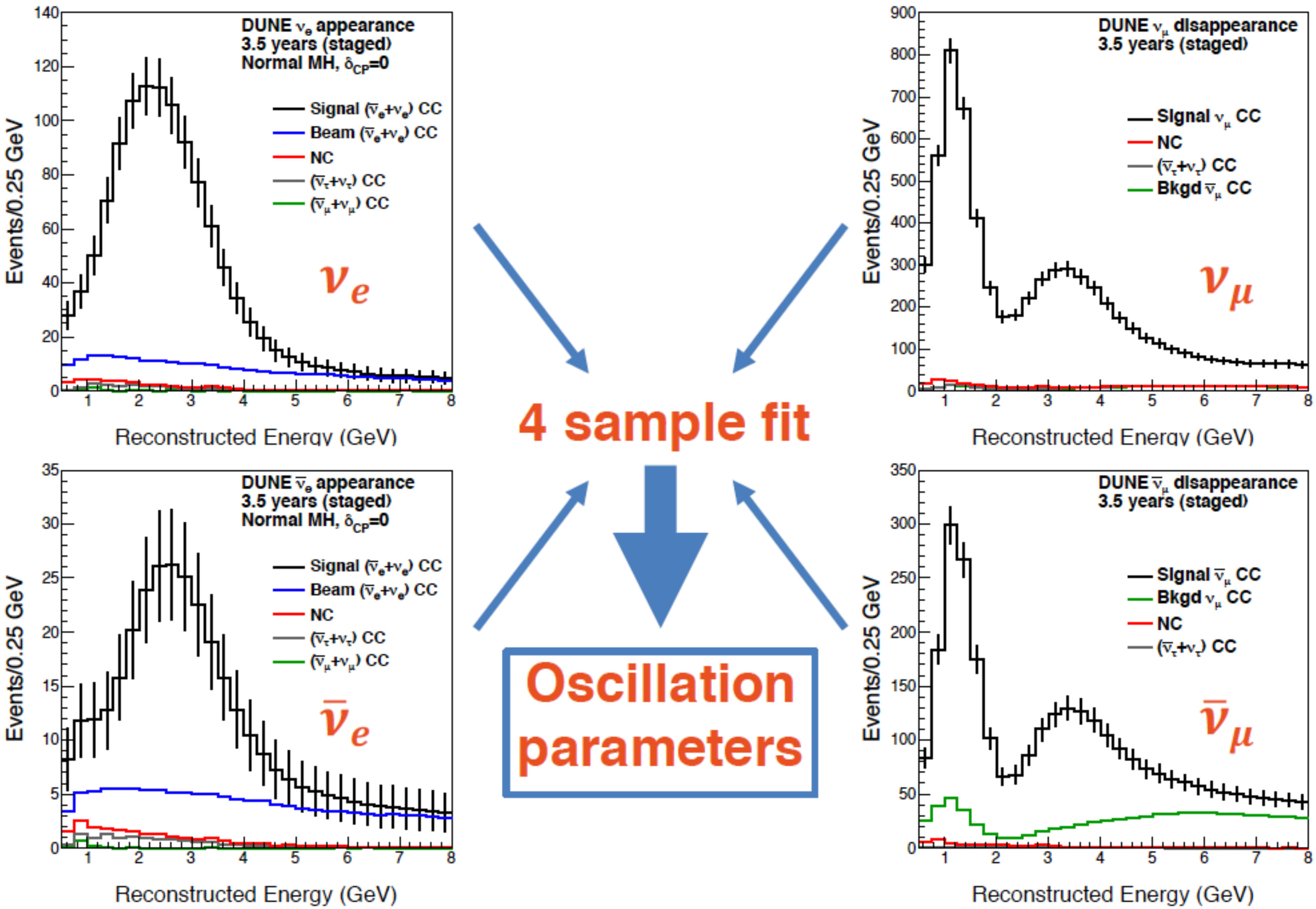
$$\frac{dN}{dX_{rec}} = \int \phi_{\nu_\mu}^{near}(E_\nu) \frac{d\sigma_{\nu_\mu}^{Ar}}{dX}(E_\nu)\, T_{\nu_\mu}^{near}(E_\nu, X, X_{rec})\ dE_\nu dX$$

  - New standard in neutrino physics

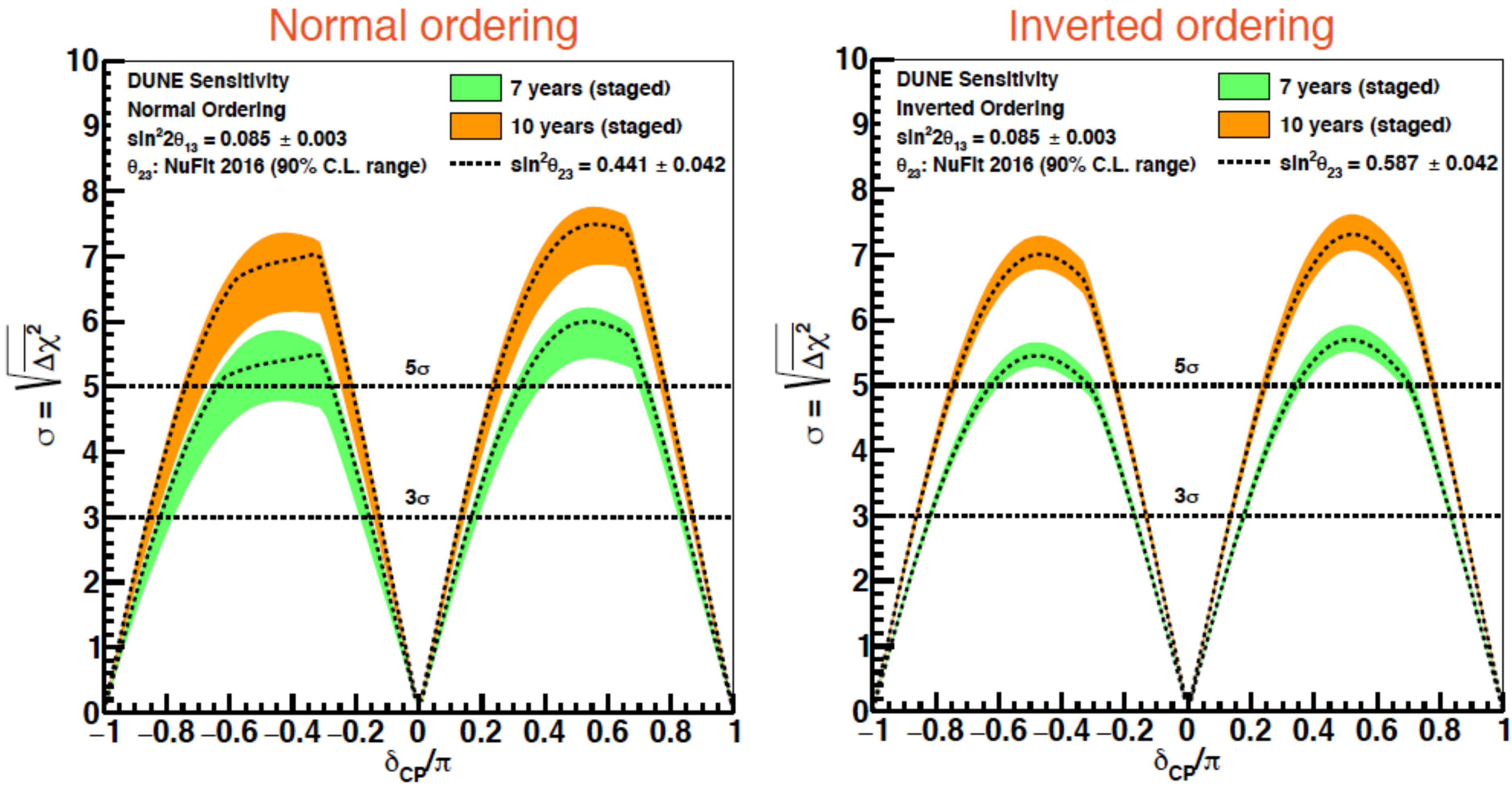

ANODE
CATHODE
ANODE
CATHODE
ANODE
12 m
58 m
14 m


Photon Detectors
integrated in APA

Measurement Strategy

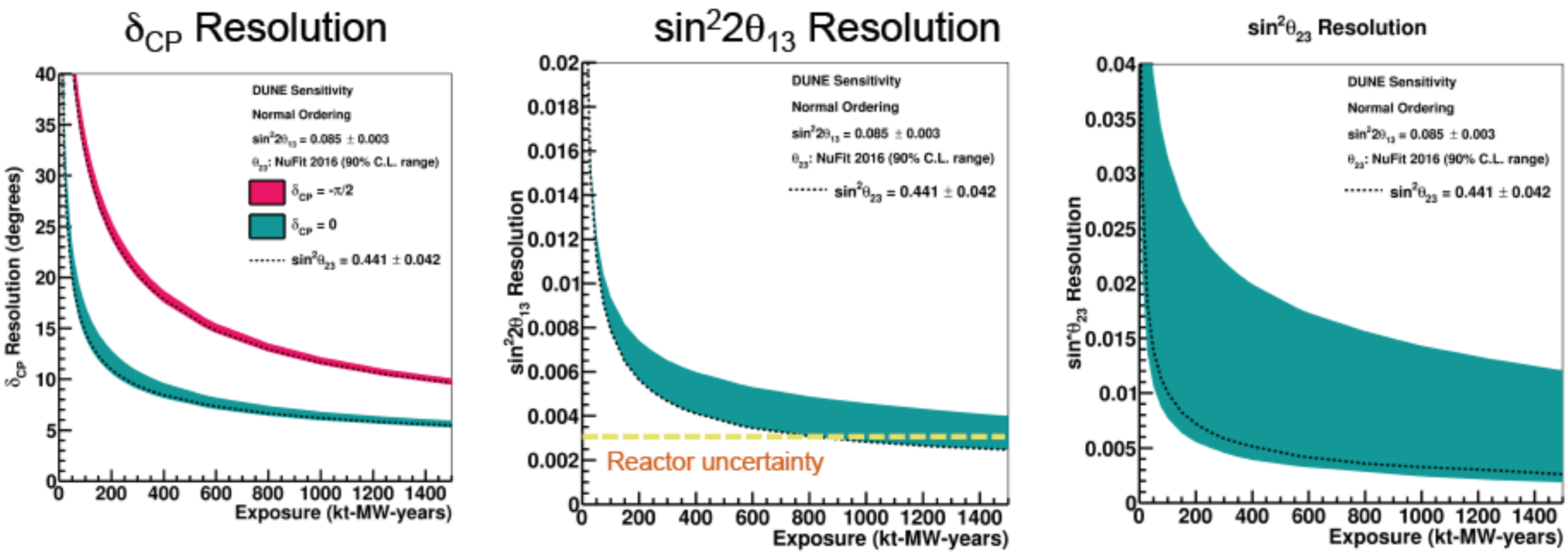


CP Sensitivity

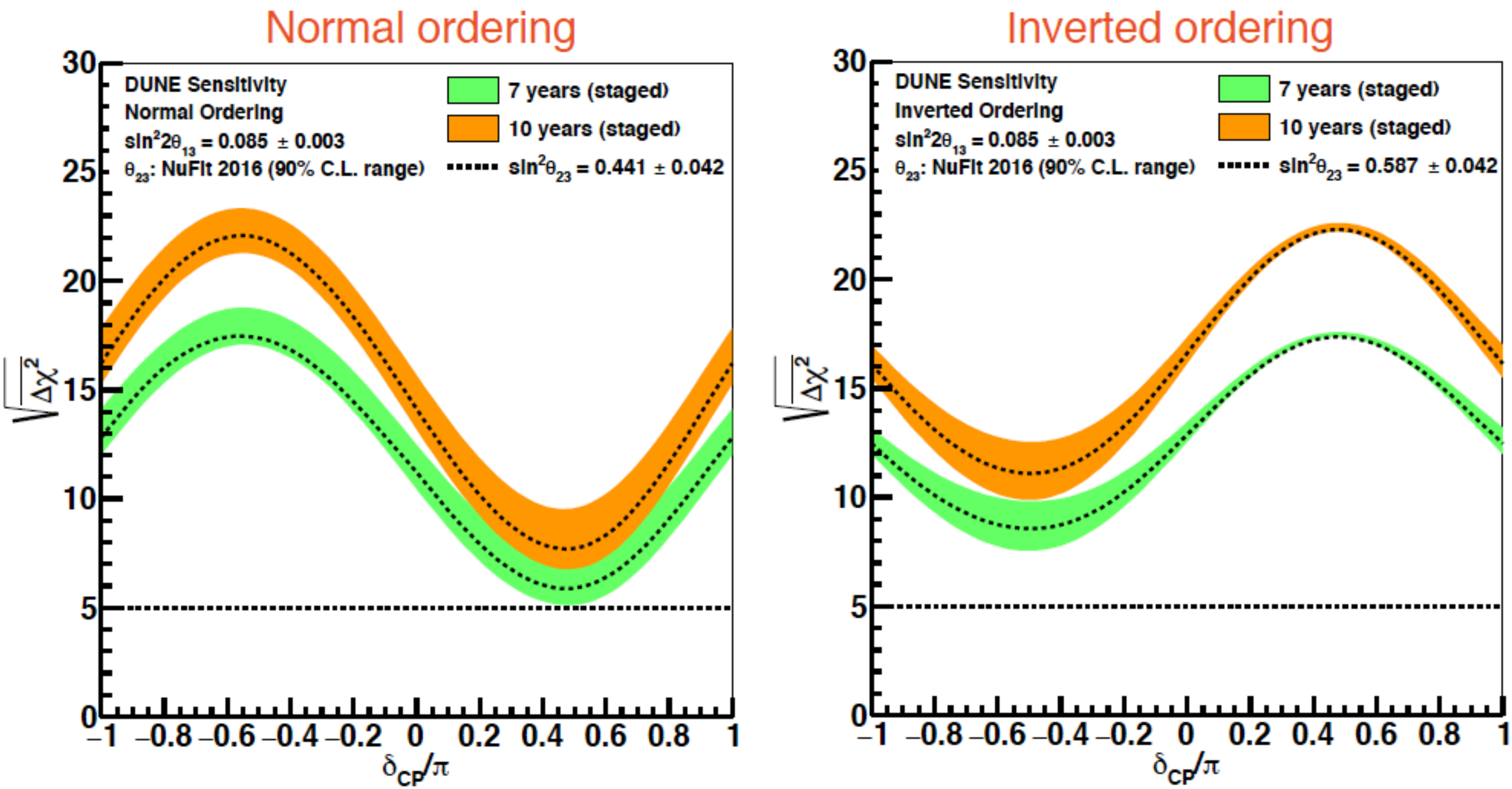


The upper and lower boundary of each band refers to the the input θ_{23} maximum and minimum respectively

Oscillation Highlights



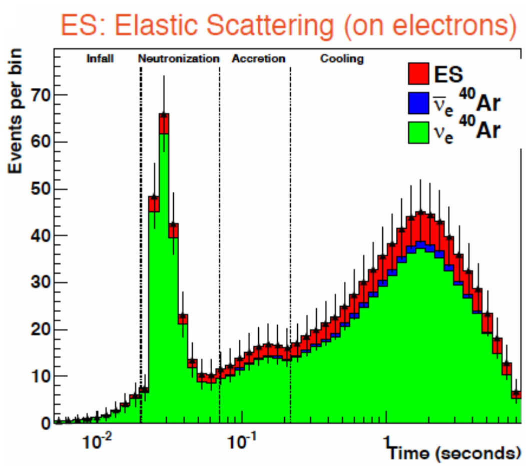
Mass Ordering



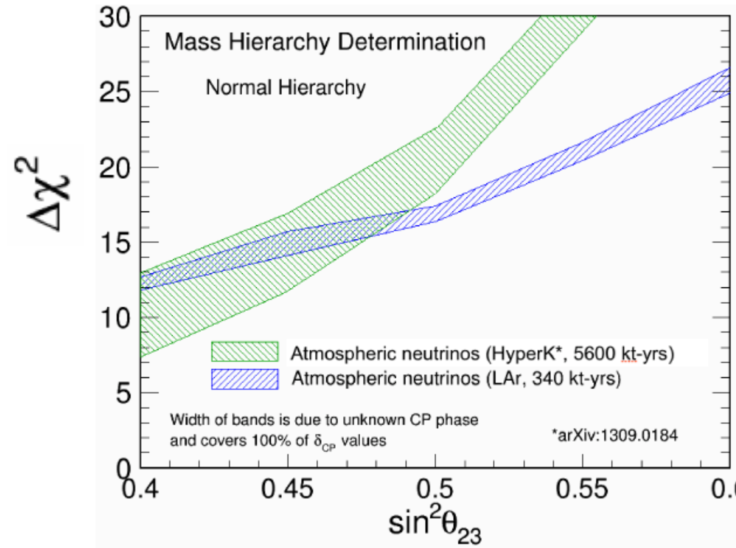
The upper and lower boundary of each band refers to the the input θ_{23} maximum and minimum respectively

Other Physics

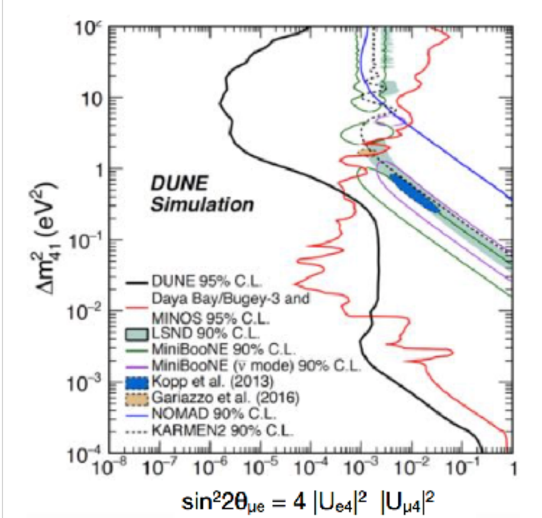
supernova



atmospherics



atmospherics

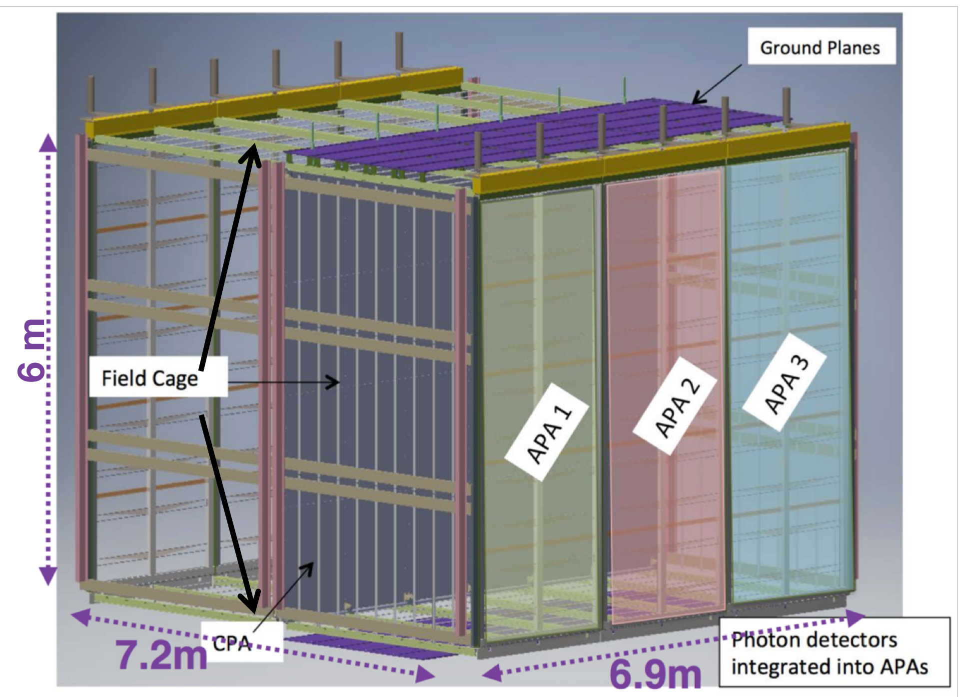


- Dark matter
- Large extra dimensions
- Dark photons
- NS interactions

Two Technologies

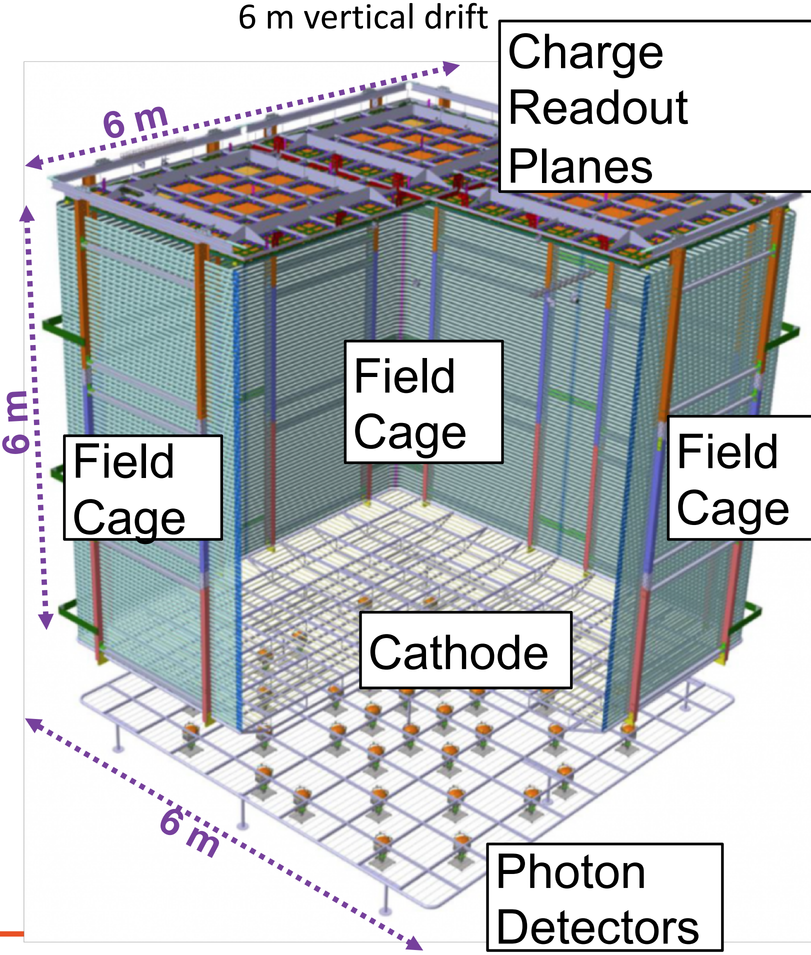
Single-Phase

3.6 m horizontal drift

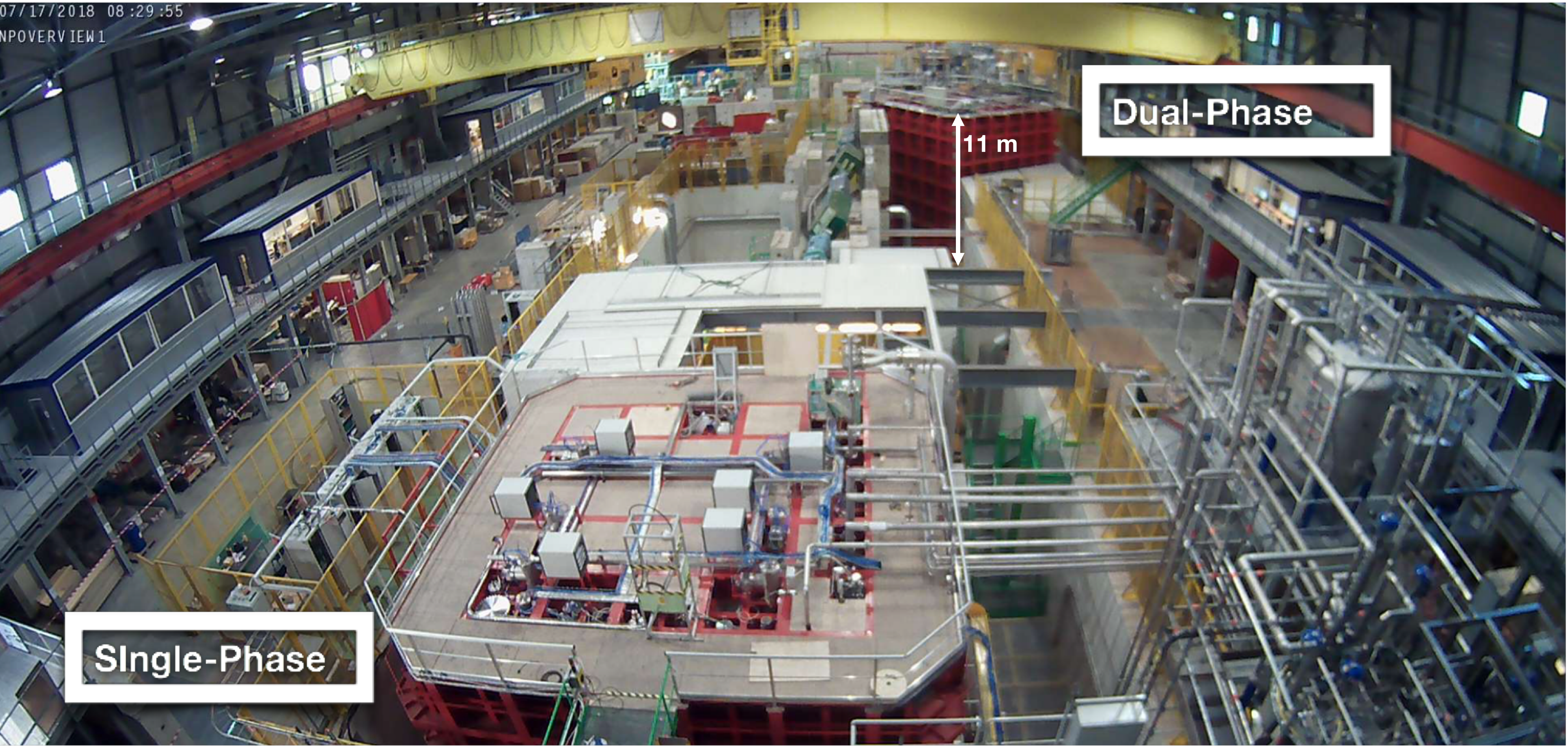


Dual-Phase

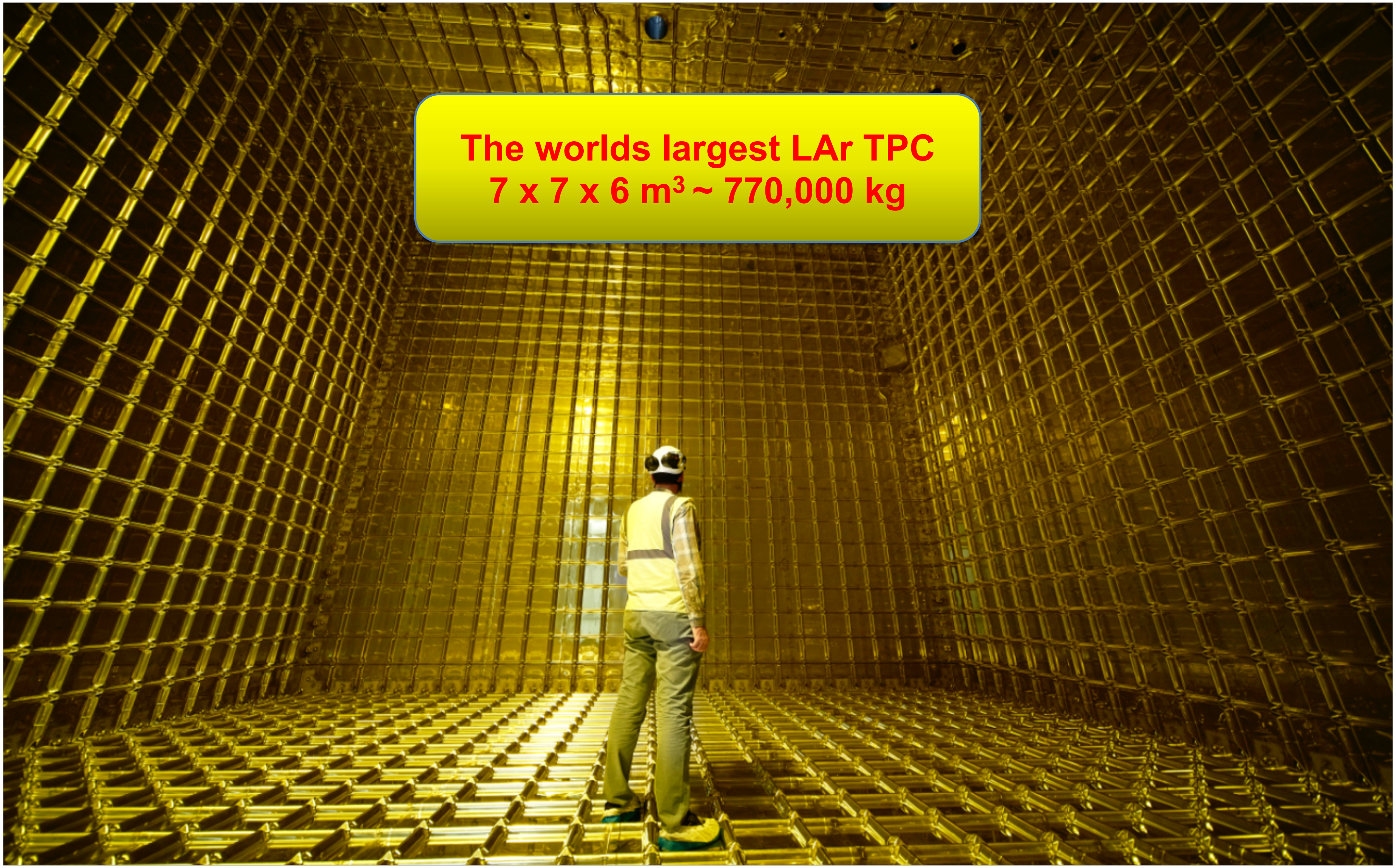
6 m vertical drift



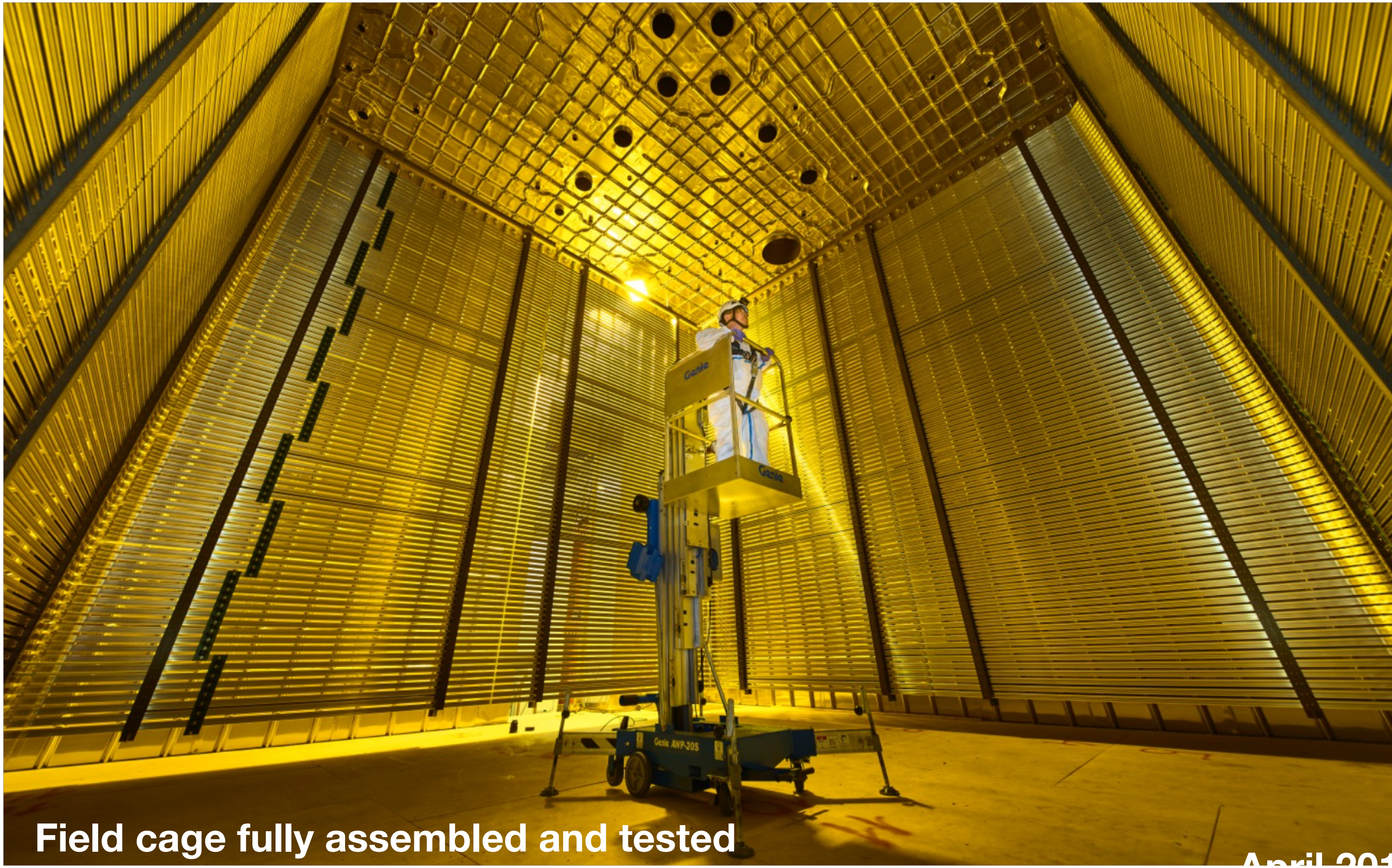
July 2018



Empty Cryostat



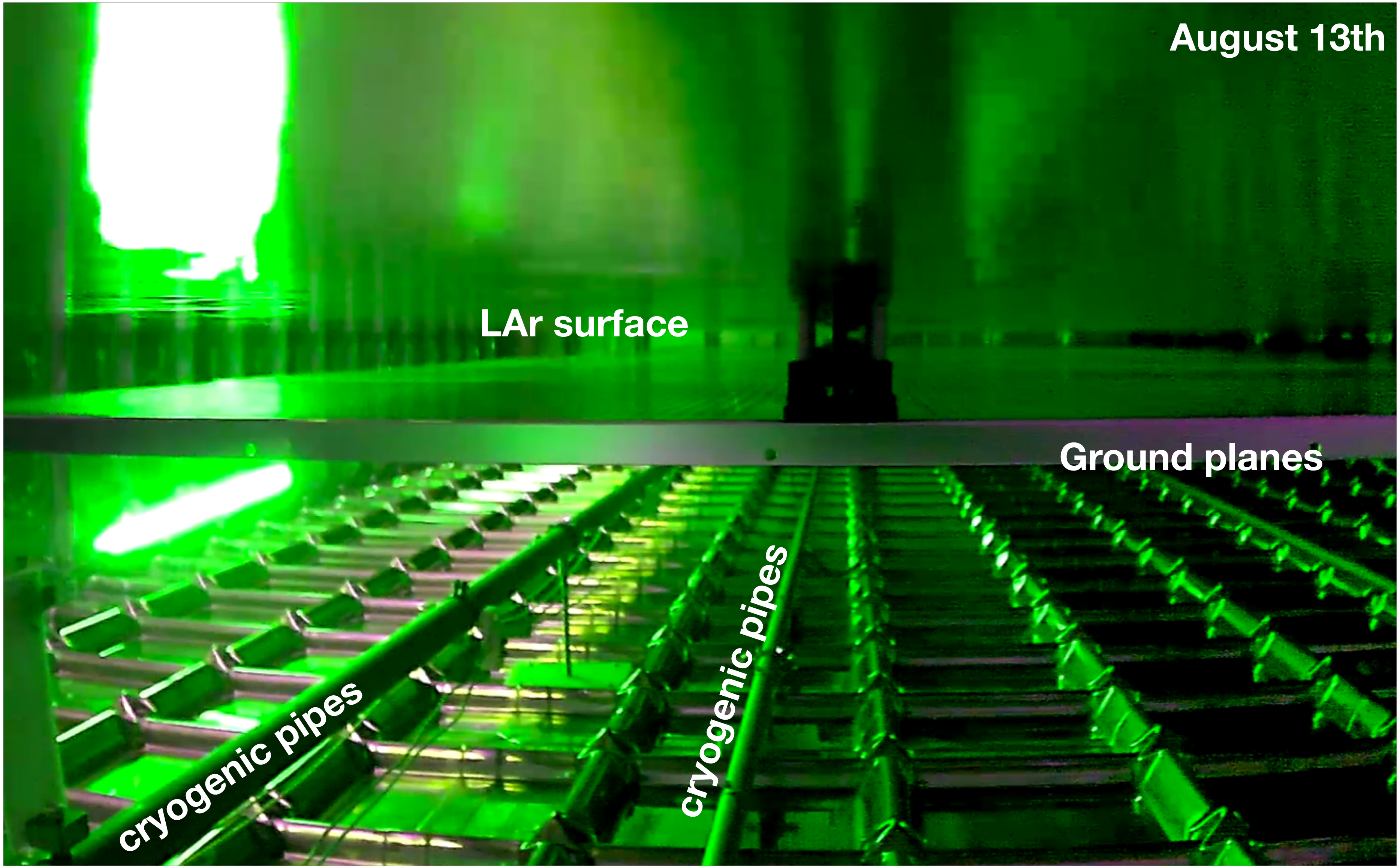
ProtoDUNE-DP



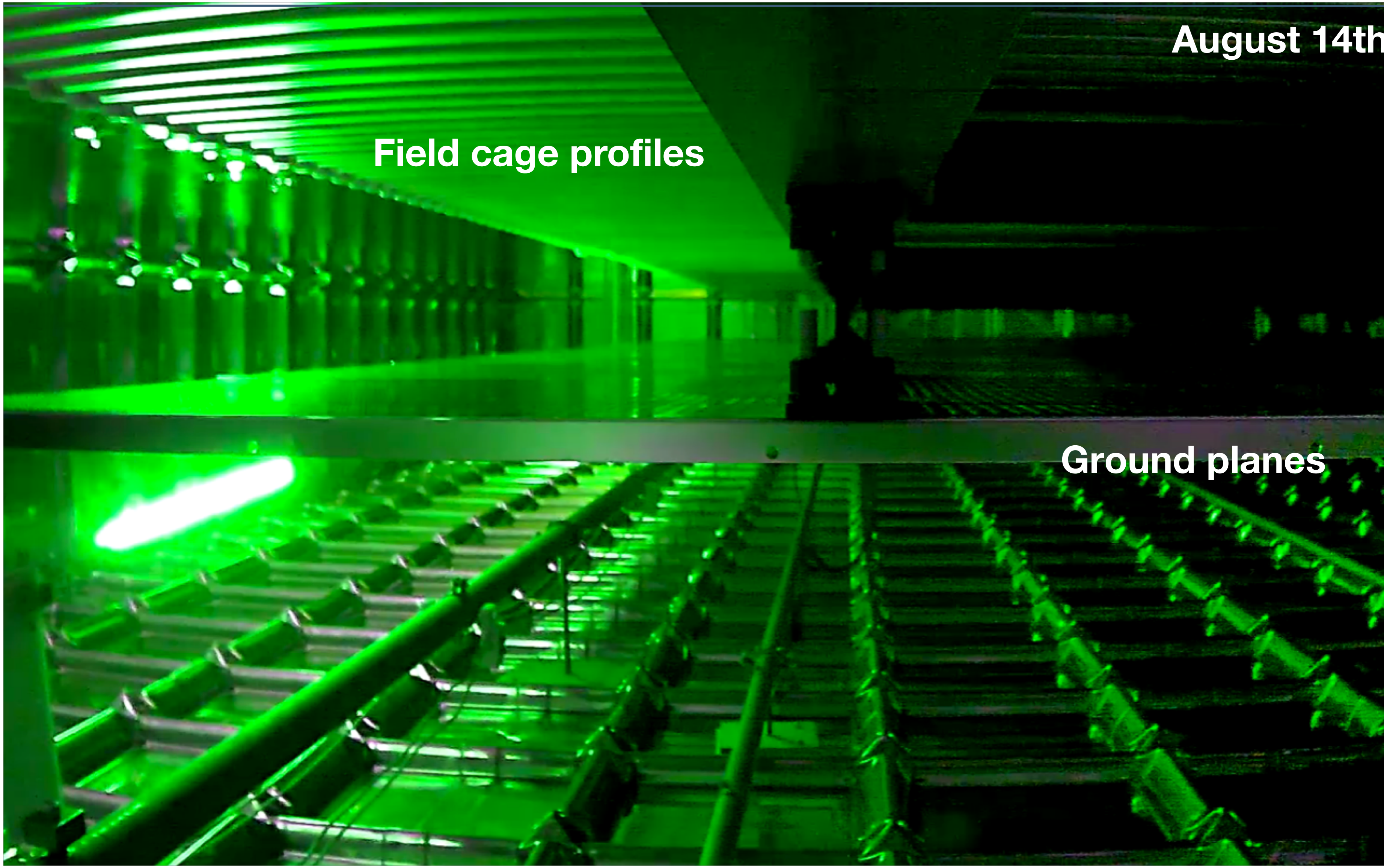
Field cage fully assembled and tested

April 201

Yellow light becomes green

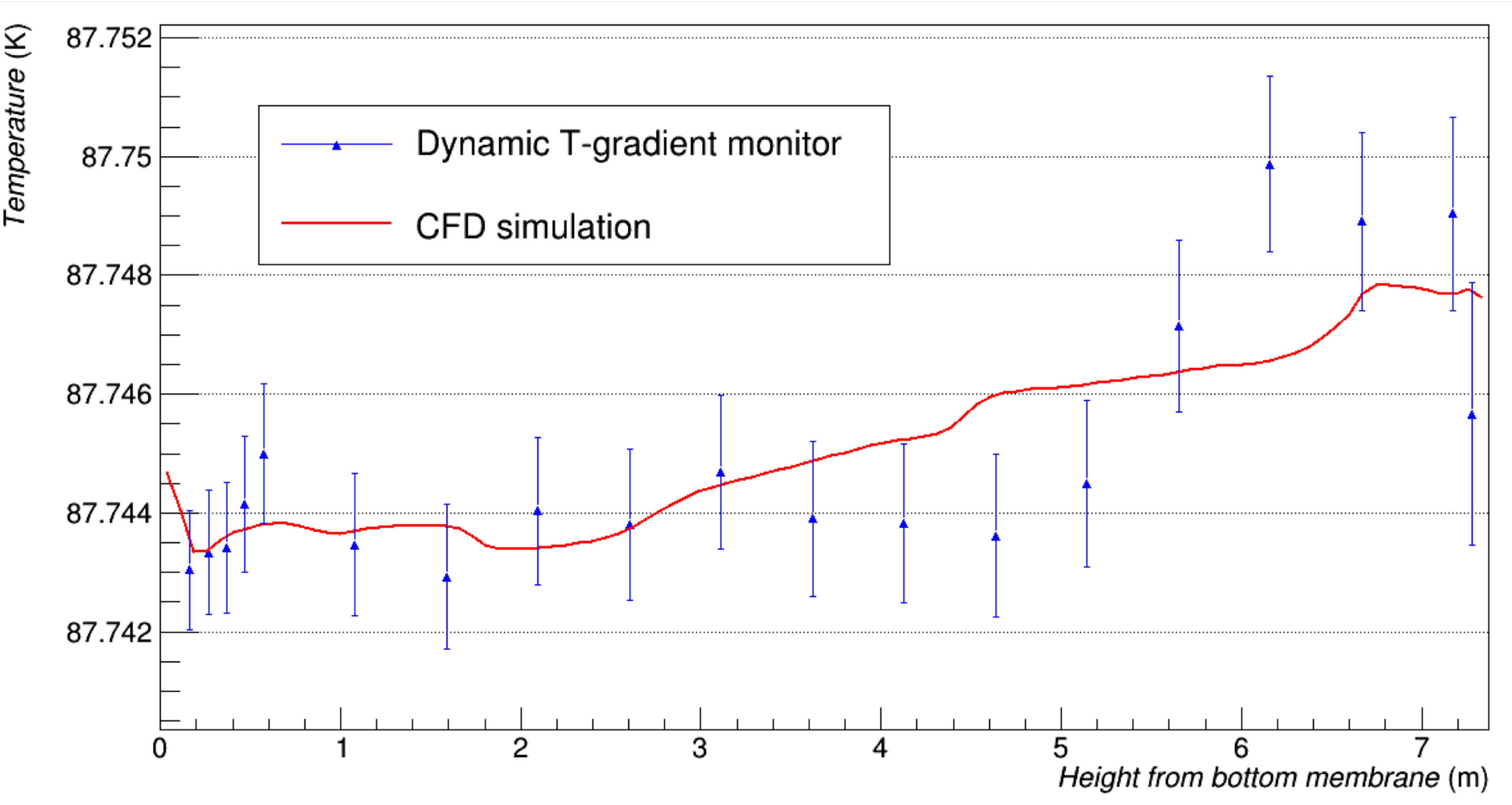


Yellow light becomes green

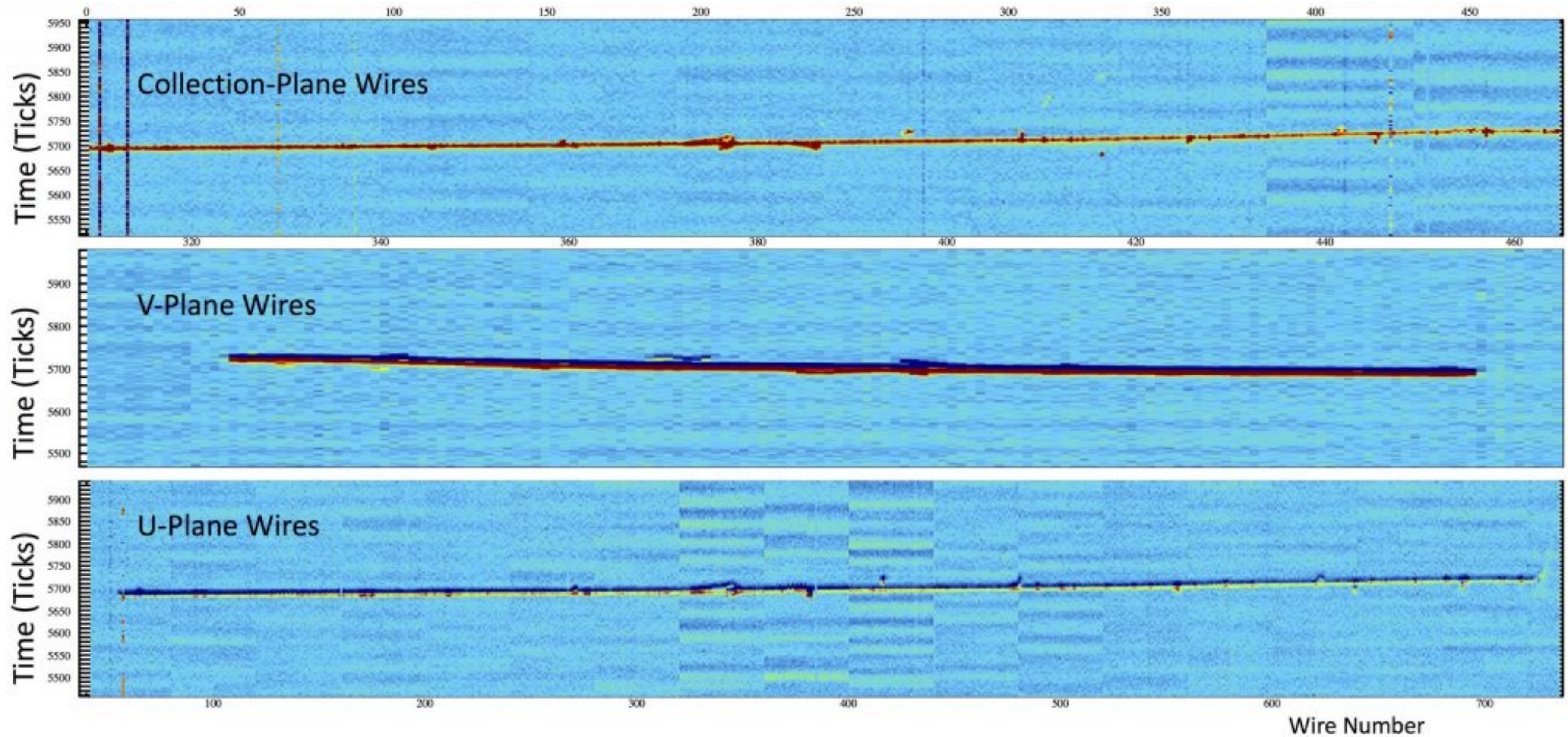


Liquid Argon temperature

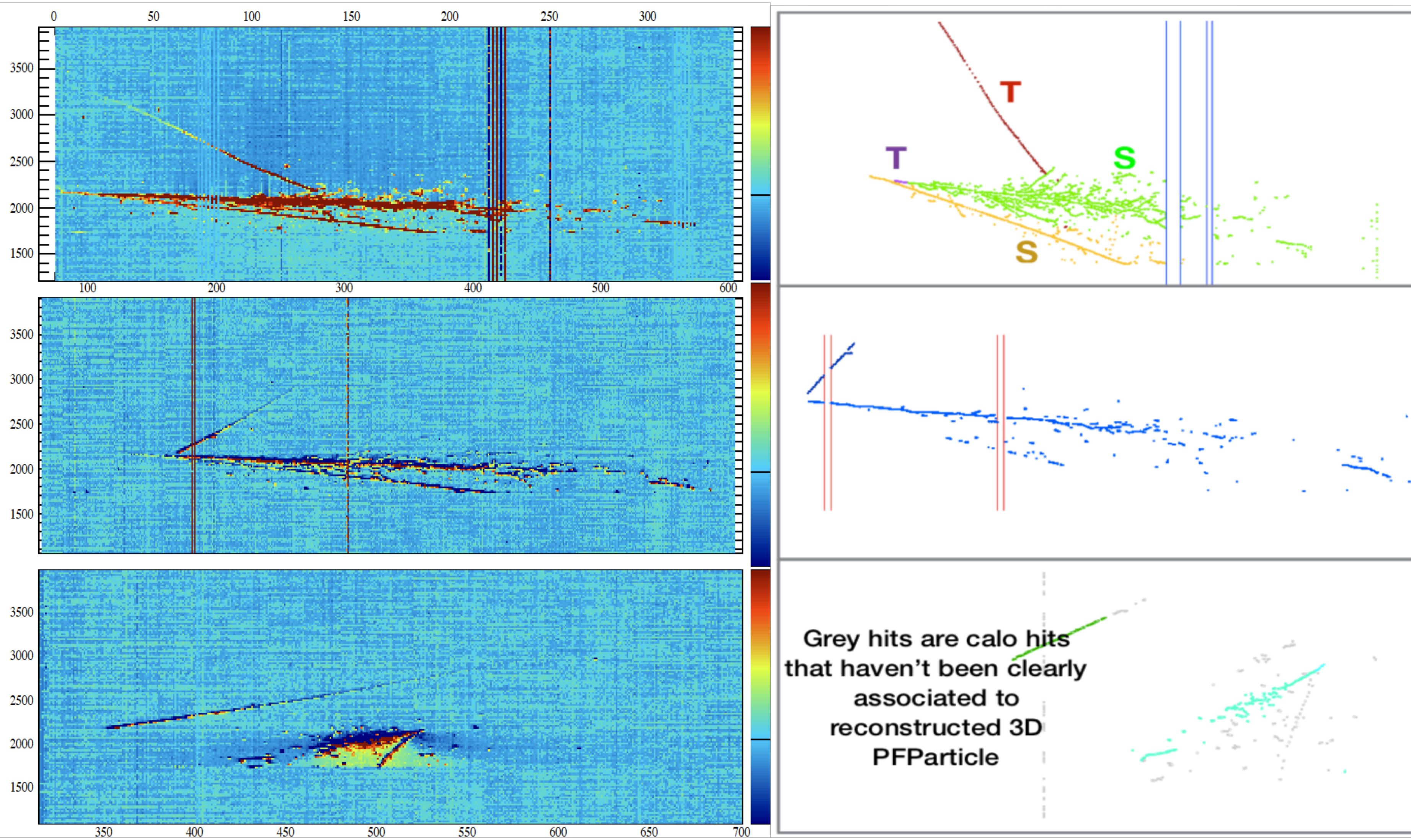
Temperature varies < 0.01 K across the cryostat



The First Event

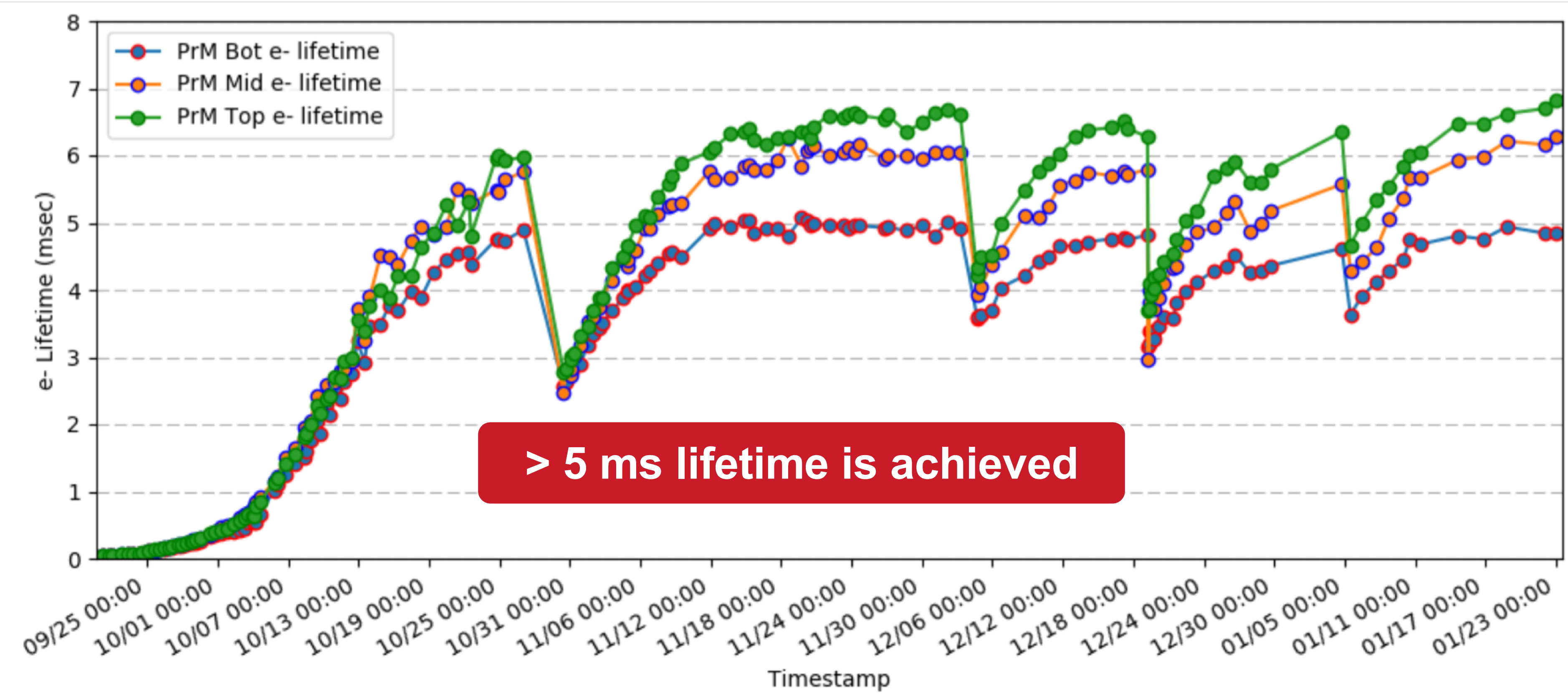


Automatic Reconstruction



Liquid Argon Purity

The purity is measured as the electron lifetime



> 5 ms lifetime is achieved

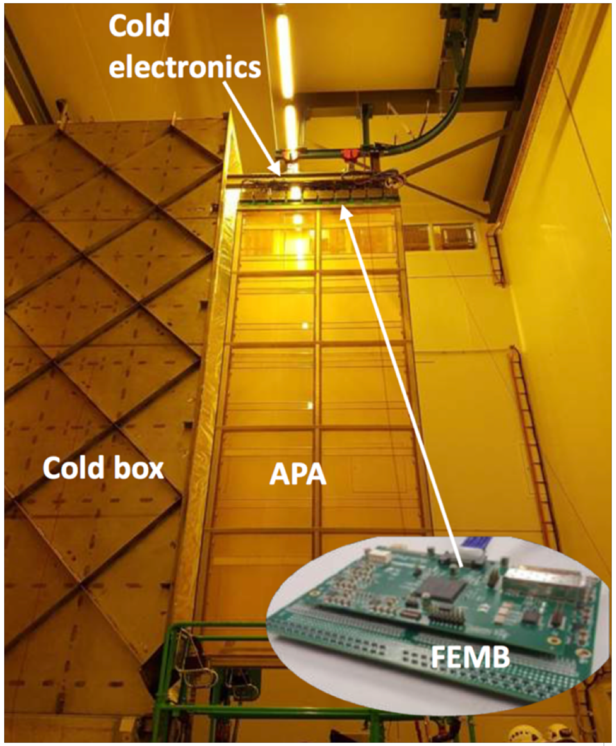
Electrons need 3 ms to cross the drift volume

APAs and Cold Electronics

Exceptionally low noise operation and scalable cryostat design

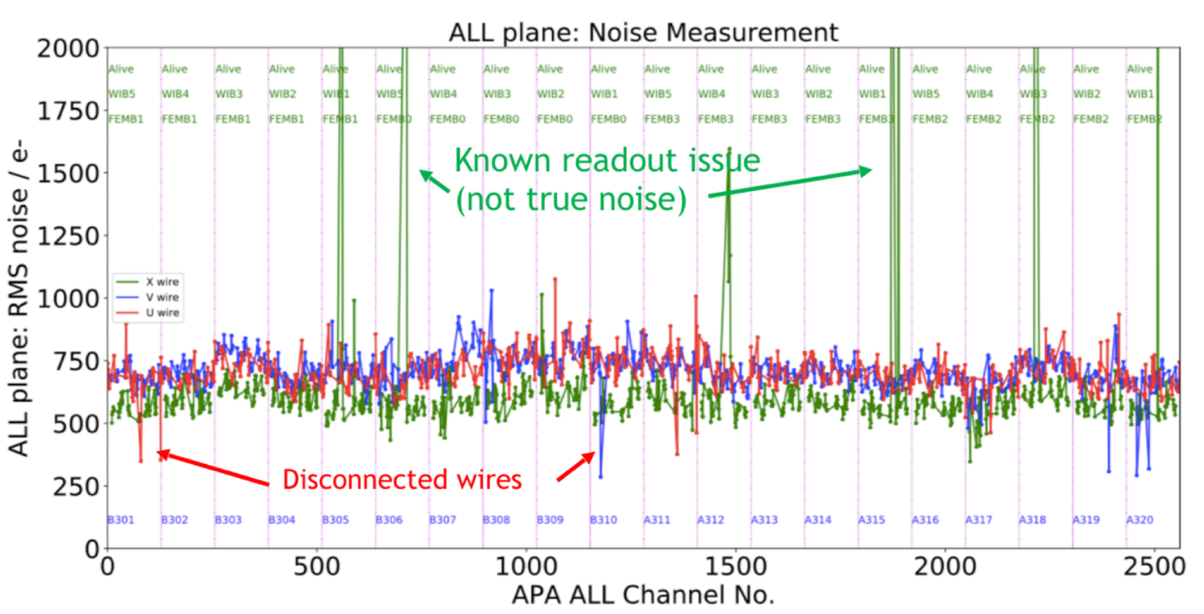
~ 15000 wires, only 4 channels dead (0.03%)

Electronics on top of APAs submerged in LAr at 87 K



ENC < 750 e⁻ ⟶ S/N ~ 20

meets DUNE requirements (S/N>10)



dE/dx

Very preliminary !!!

dE/dx for 1 GeV/c beam protons