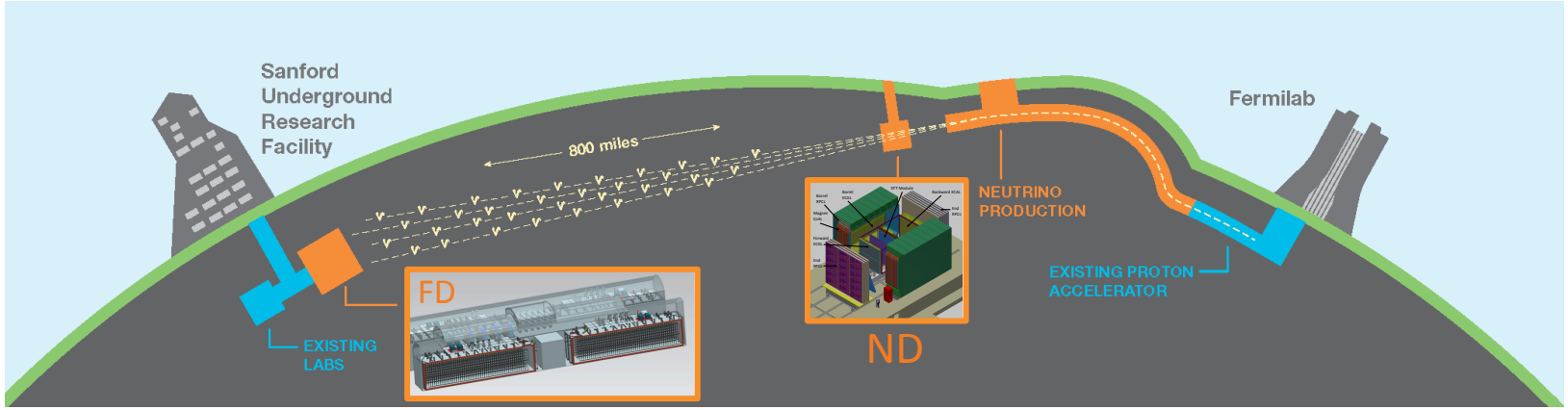
DUNE: The Deep Underground Neutrino Experiment



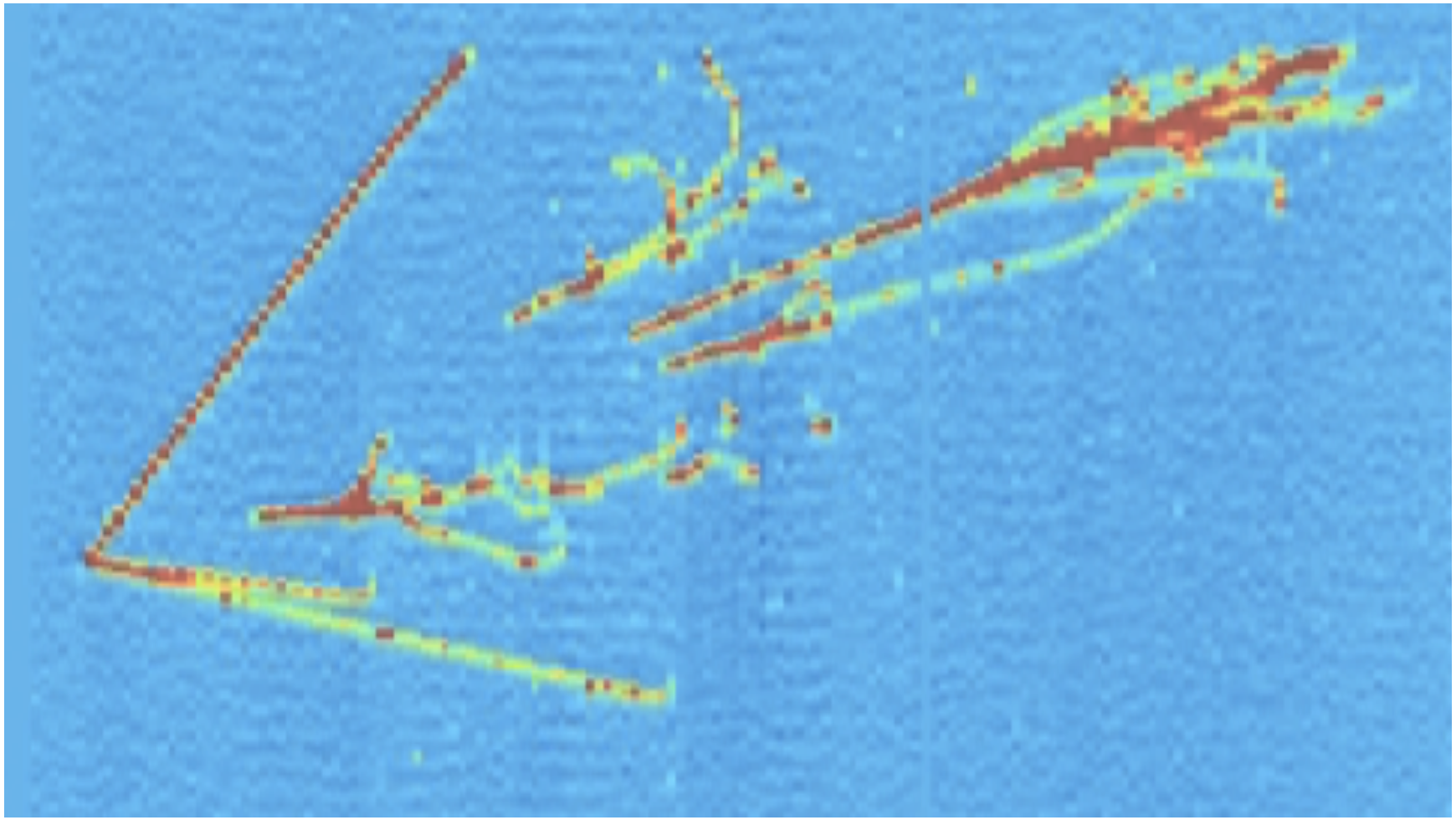
Mark Thomson, University of Cambridge

Prague, November 5, 2015

UNIVERSITY OF CAMBRIDGE

DUNE

1: Context



The 2012 Revolution

★ **Two major discoveries in particle physics**

- A SM-like Higgs boson (ATLAS, CMS)
  - The key to EWSB and a possible window to the BSM world
- $\theta_{13} \sim 10^{o}$ (T2K, MINOS, Daya Bay, RENO)

  - about as large as it could have been !
  - The door to CP Violation in the leptonic sector

The 2012 Revolution

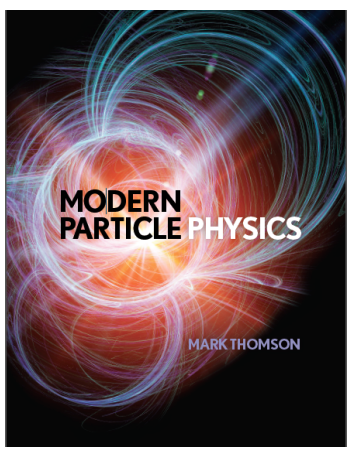
★ **Two major discoveries in particle physics**

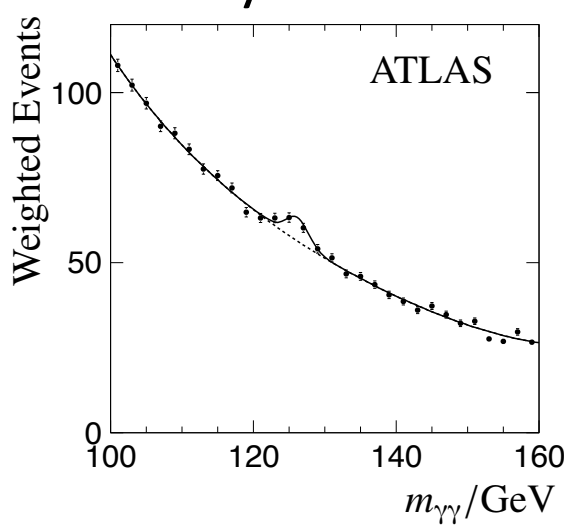
- A SM-like Higgs boson (ATLAS, CMS)
  - The key to EWSB and a possible window to the BSM world
- $\theta_{13} \sim 10^{o}$ (T2K, MINOS, Daya Bay, RENO)

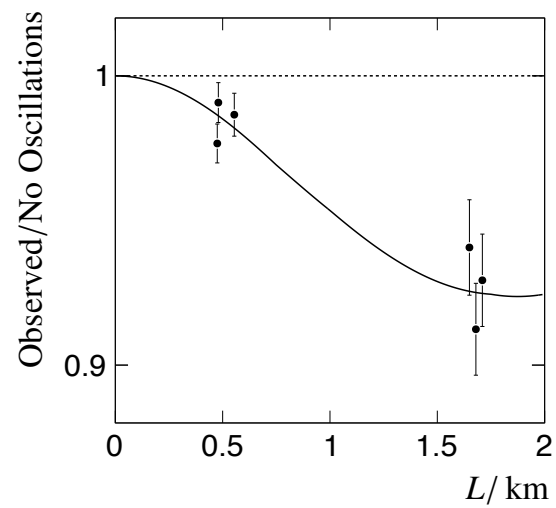
  - about as large as it could have been !
  - The door to CP Violation in the leptonic sector

★ **Now textbook physics***

- next steps: discovery CPV with a **conventional** ν beam

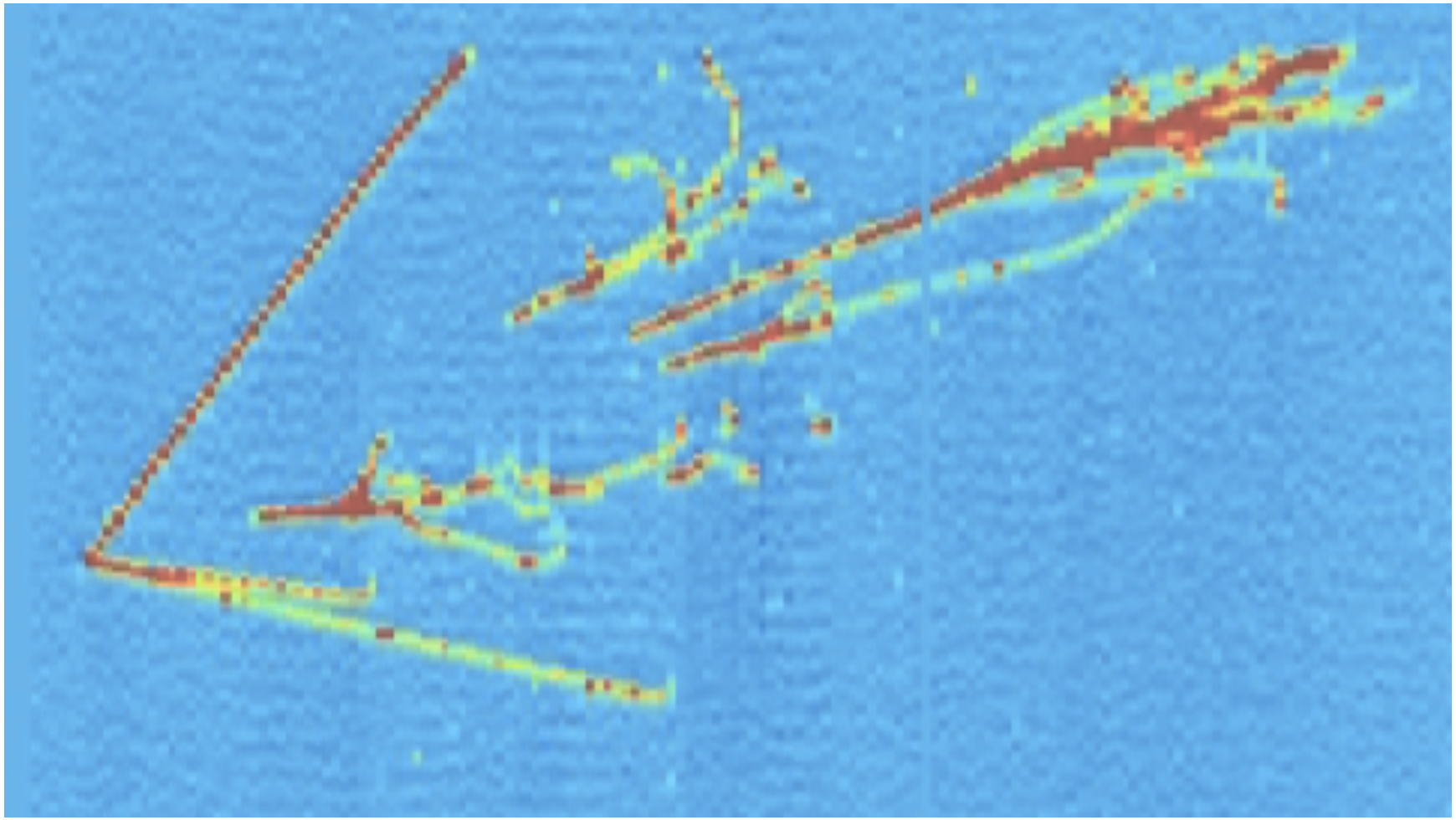






*apologies for gratuitous plug

2: How to Detect CPV with νs



In principle, it is straightforward

★ CPV ⇨ different oscillation rates for νs and $\bar{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = 4 s_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta$$

vacuum osc.

$$\times \left[\sin\left(\frac{\Delta m_{21}^2}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2}{2E}\right) \right]$$

★ Requires $\{\theta_{12}, \theta_{13}, \theta_{23}\} \neq \{0, \pi\}$

- now know that this is true, $\theta_{13} \approx 9^\circ$
- but, despite hints, don't yet know "much" about δ

★ So "just" measure $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$?

★ Not quite, throw in matter effects

Neutrino Oscillations in Matter

★ Accounting for matter effects, gives a Hamiltonian that is no longer diagonal in the basis of the mass eigenstates

$$\mathcal{H}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = \begin{pmatrix}E_1 & 0 & 0\\ 0 & E_2 & 0\\ 0 & 0 & E_3\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} + V|\nu_e\rangle$$

ME

★ Complicates the simple picture !!!!

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

ME $$\frac{16A}{\Delta m^2_{31}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

ME $$-\frac{2AL}{E}\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

CPV $$-8\frac{\Delta m^2_{21}L}{2E}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\delta\, s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$$

with $A = 2\sqrt{2}G_F n_e E = 7.6\times10^{-5}\mathrm{eV}^2\cdot\frac{\rho}{\mathrm{g\,cm^{-3}}}\cdot\frac{E}{\mathrm{GeV}}$

Neutrino Oscillations in Matter

★ Accounting for matter effects, gives a Hamiltonian that is no longer diagonal in the basis of the mass eigenstates

$$\mathcal{H}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = \begin{pmatrix}E_1 & 0 & 0\\0 & E_2 & 0\\0 & 0 & E_3\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} + V|\nu_e\rangle$$

ME

★ Complicates the simple picture !!!!

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

What we measure

ME $$\frac{16A}{\Delta m^2_{31}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

Small

ME $$-\frac{2AL}{E}\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

Proportional to L

CPV $$-8\frac{\Delta m^2_{21}L}{2E}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\delta\; s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$$

What we want

with $A = 2\sqrt{2}G_F n_e E = 7.6\times10^{-5}\mathrm{eV}^2\cdot\frac{\rho}{\mathrm{g\,cm^{-3}}}\cdot\frac{E}{\mathrm{GeV}}$

Experimental Strategy

EITHER:

★ Keep L small (~200 km): so that matter effects are insignificant

- Still want oscillations:

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

- Since $\sigma \propto E_\nu$ need a high flux at oscillation maximum

⇨ Off-axis beam: narrow range of neutrino energies

OR:

★ Make L large (>1000 km): measure the matter effects (i.e. MH)

- Still want oscillations:

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

- **Unfold CPV from Matter Effects through E dependence**

⇨ On-axis beam: wide range of neutrino energies

Experimental Strategy

EITHER:

★ Keep L small (~200 km): so that matter effe re insignificant

- Still want oscillations:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

- Since high flux at oscillation maximum

➡ Off- eam: narrow range of neutrino energies

Hyper-Kamiokande

OR:

★ Make L large (>1000 km): measure the atter effects (i.e. MH)

- Still want oscillations:

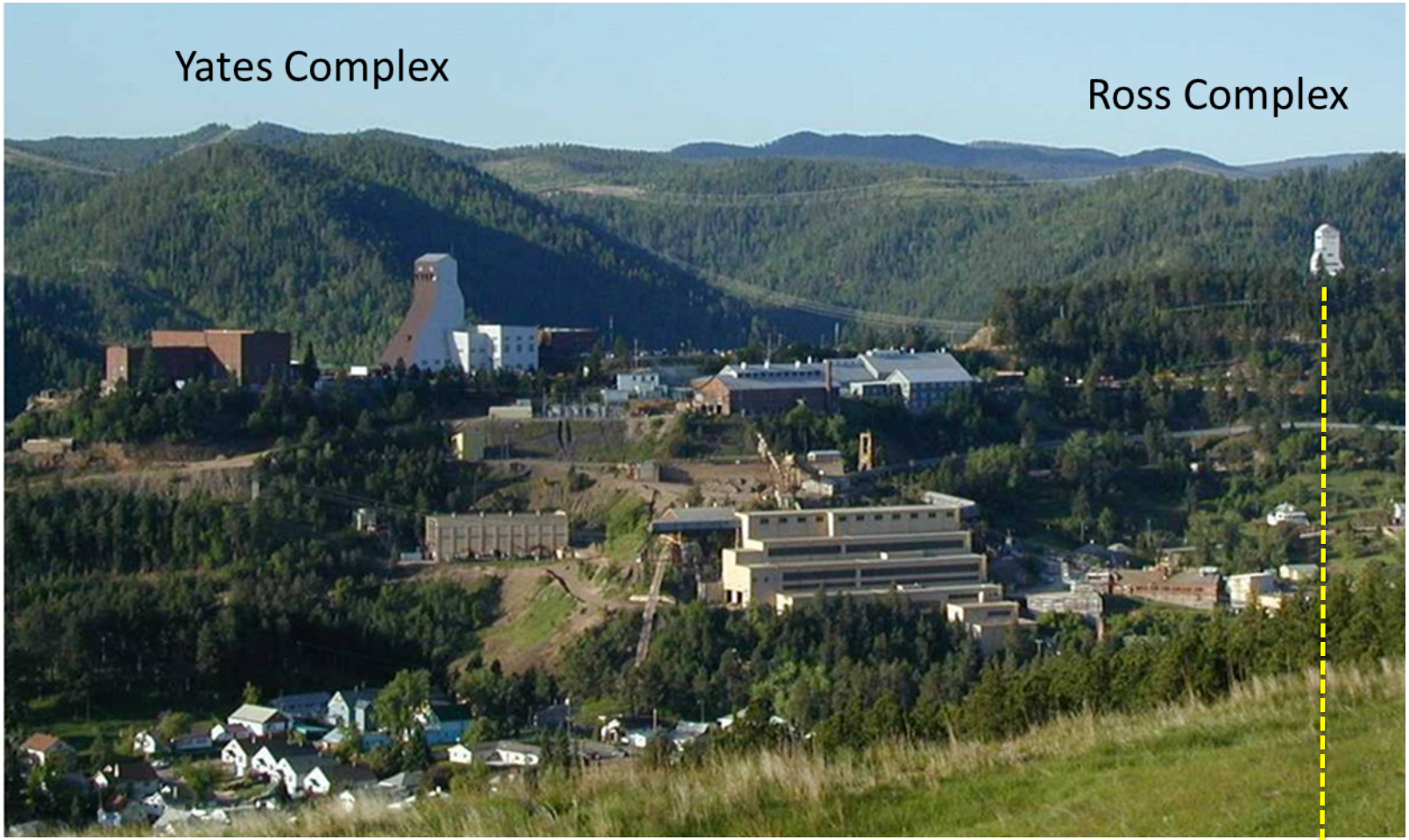
$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

- **Unfold CPV from Ma ts through E dependence**

➡ On-axis beam: wide range of neutrino energies

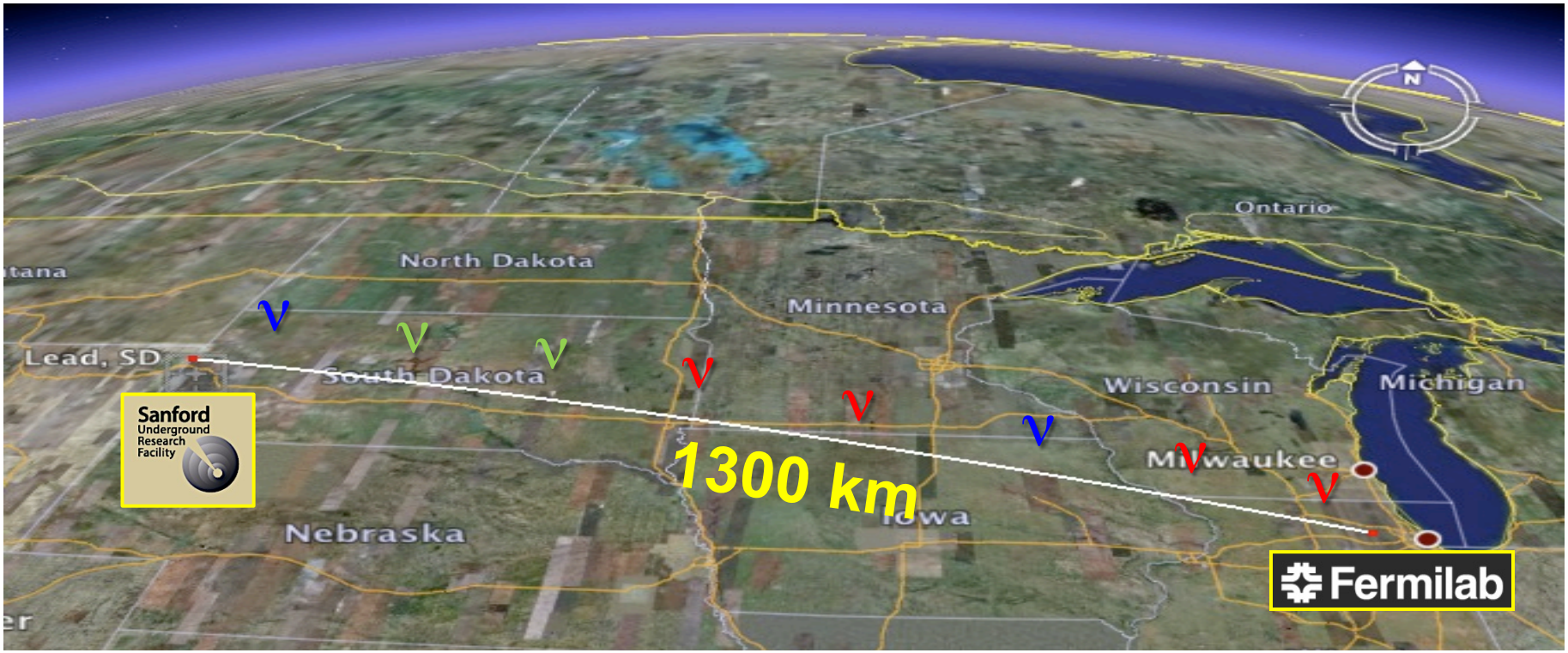
DUNE

3: DUNE – the Deep Underground Neutrino Experiment



LBNF/DUNE in a Nutshell

- ★ Intense beam of ν_μ or $\bar{\nu}_\mu$ fired 1300 km at a large detector
- ★ Compare $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations : CPV ?



LBNF/DUNE in a Larger Nutshell

★ LBNF/DUNE

- Muon neutrinos/anti-antineutrinos from high-power proton beam
  - **1.2 MW** from day one
  - upgradable to **2.3 MW**
- Large underground LAr detector at Sanford Underground Research Facility (SURF) in South Dakota
  - 4 Cavern(s) for ≥ **40 kt** total fiducial far detector mass
  - **10 - 20 kt** fiducial LAr Far Detector (from day one)
  - **40 kt** as early as possible
- Highly-capable Near Detector system
  - Using one or more technologies

Origins of DUNE

Paraphrasing 2014 P5 strategic review of US HEP

- **Called for the formation of LBNF:**
  - as a international collaboration bringing together the LBL community
  - ambitious scientific goals with discovery potential for:
    - Leptonic CP violation
    - Proton decay
    - Supernova burst neutrinos

Resulted in the formation of the DUNE collaboration with strong representation from:

- LBNE (mostly US)
- LBNO (mostly Europe)
- Other interested institutes

DUNE

Is a rapidly evolving scientific collaboration…

- **First formal collaboration meeting April 16th - 18th 2015**
- **Passed DOE CD-1 Review in July**
- **Second collaboration meeting September 2nd - 5th 2015**
  - Over 220 people attended in person
- **Successful Director's CD-3a Review last week**

DUNE

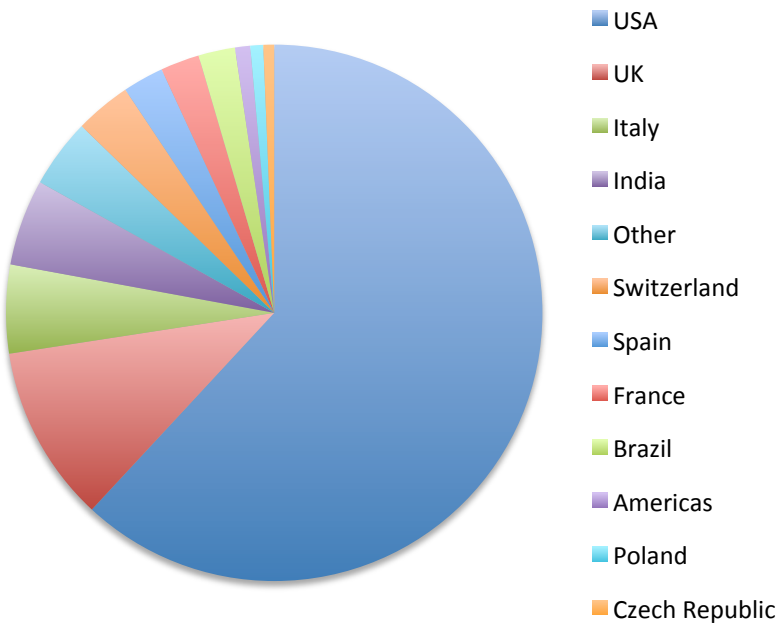
Is a rapidly evolving scientific collaboration…

- **First formal collaboration meeting April 16th - 18th 2015**
- **Passed DOE CD-1 Review in July** → **DUNE is on the real axis !**
- **Second collaboration meeting September 2nd - 5th 2015**
  - Over 220 people attended in person
- **Successful Director's CD-3a Review last week** **See later**

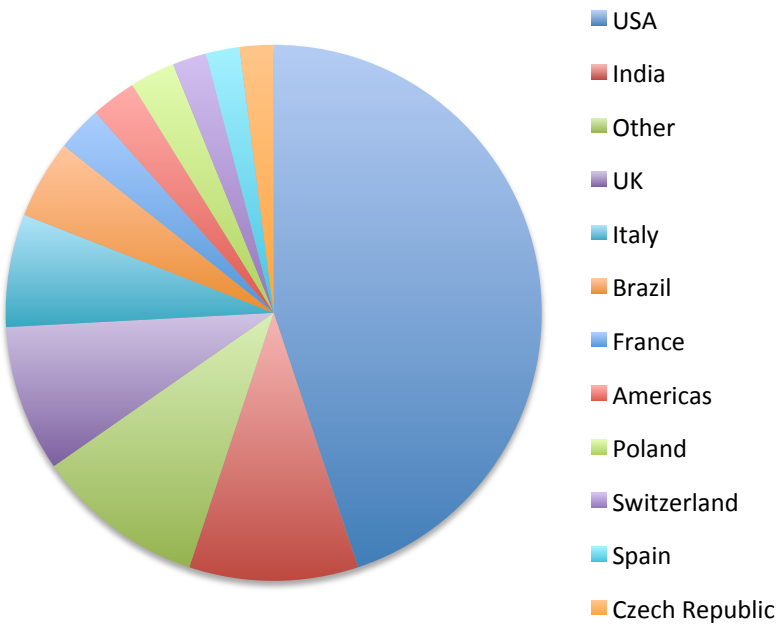
The DUNE Collaboration

As of today: from

790 Collaborators



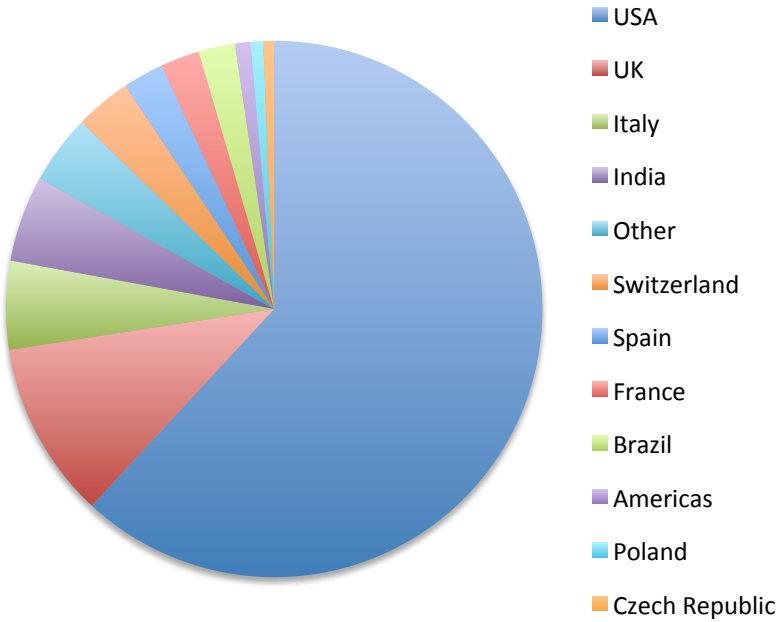
144 Institutes



The DUNE Collaboration

As of today:

790 Collaborators



from

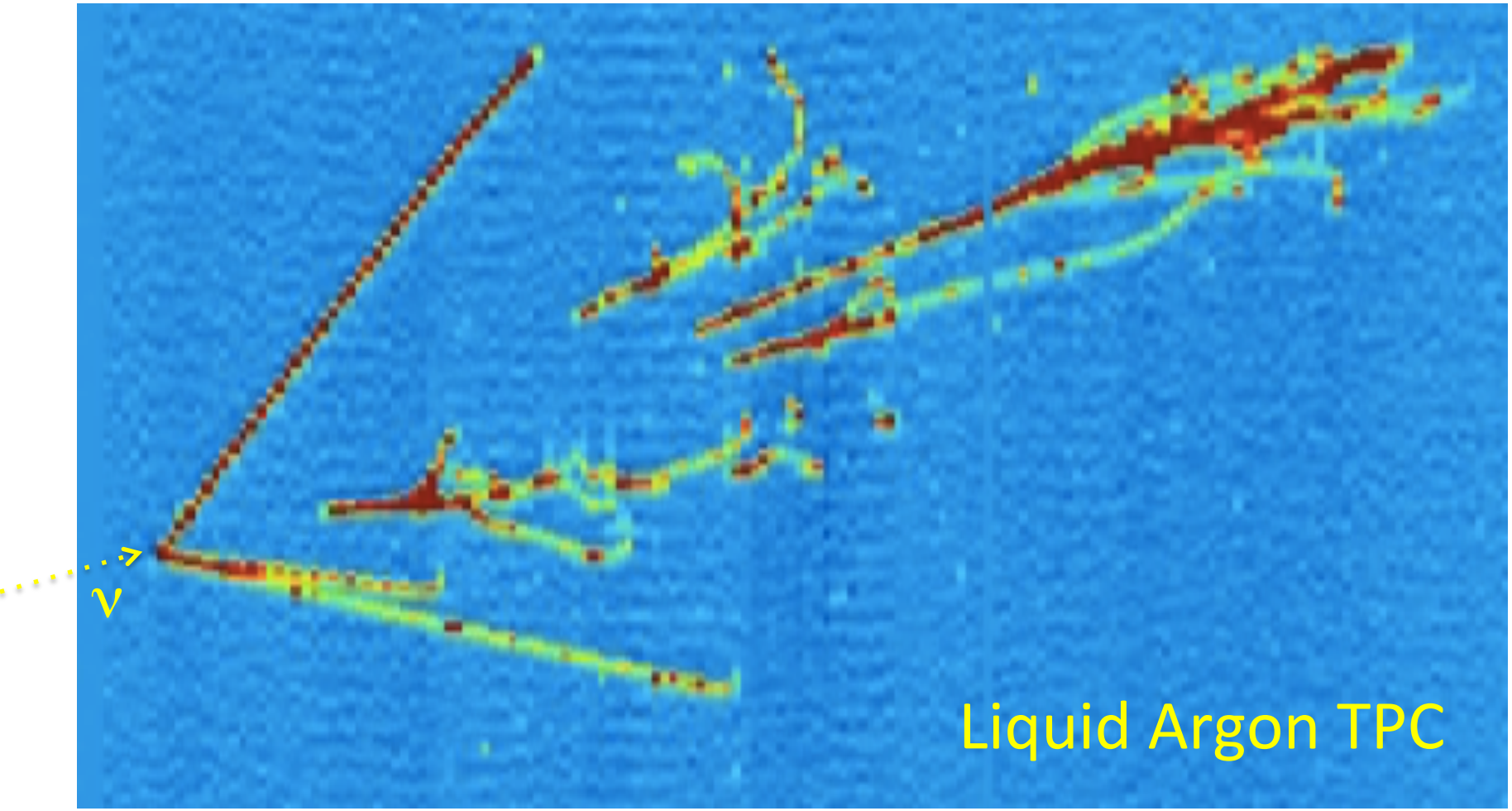
26 Nations

Armenia, Belgium, Brazil, Bulgaria, Canada, Colombia, **Czech Republic**, France, Germany, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, Spain, Switzerland, Turkey, UK, USA, Ukraine

+ soon to add Finland and Greece

DUNE already has broad international support

3.1: DUNE Science Strategy



A neutrino interaction in the ArgoNEUT detector at Fermilab

DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astro-particle physics:

- **1) Neutrino Oscillation Physics**
  - CPV in the leptonic sector
  - Definitive determination of the Mass Hierarchy
  - Precision Oscillation Physics (θ_{23} octant, …) & testing the 3-flavor paradigm
- **2) Nucleon Decay**
  - Targeting SUSY-favored modes, e.g. $p \rightarrow K^{+}\bar{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

DUNE Primary Science Program

Focus on fundamental open questions in partic physics and astro-particle physics:

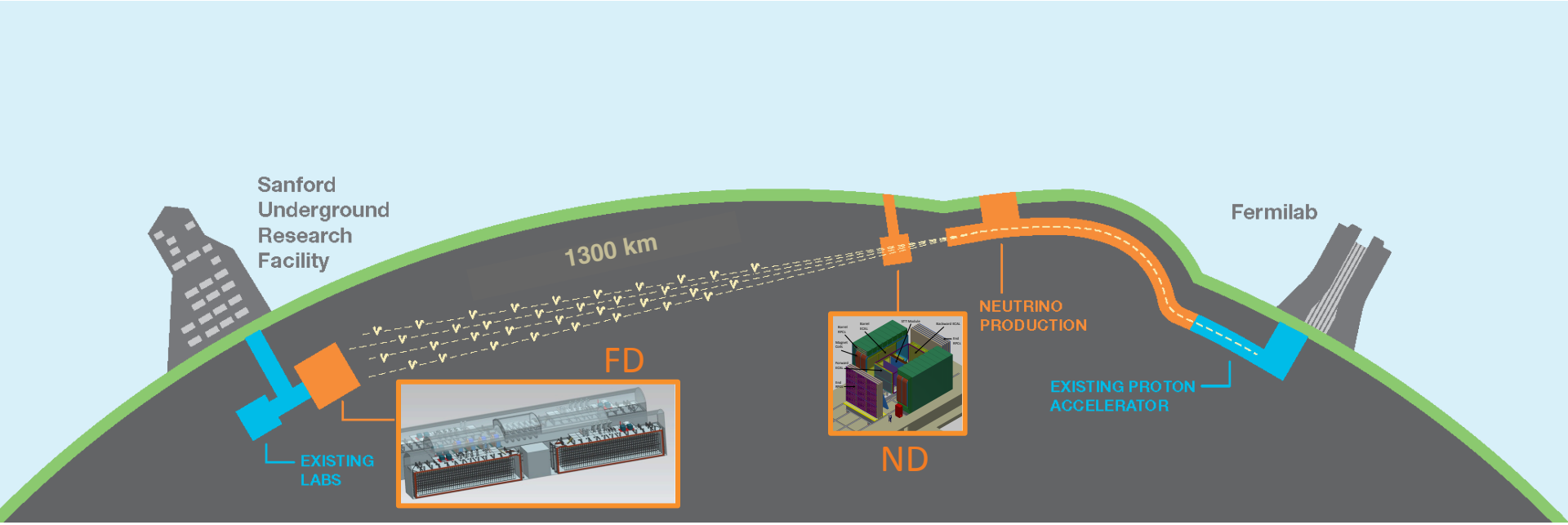
- **1) Neutrino Oscillation Physics**
  - CPV in the leptonic sector
  - Definitive determination of th archy
  - Precision Oscillation P ctant, …) & testing the 3-flavor paradigm
- **2) Nucleo**
  - Tar avored modes, e.g. $p \rightarrow K^{+}\bar{\nu}$
- **nova burst physics & astrophysics**
  - alactic core collapse supernova, sensitivity to ν_e

Any would be a major discovery

DUNE Oscillation Strategy

Measure neutrino spectra at 1300 km in a wide-band beam

- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a <u>single experiment</u>**



- **Near Detector at Fermilab: measurements of unoscillated beam**
- **40 kt LAr Far Detector at SURF: measure oscillated ν spectra**

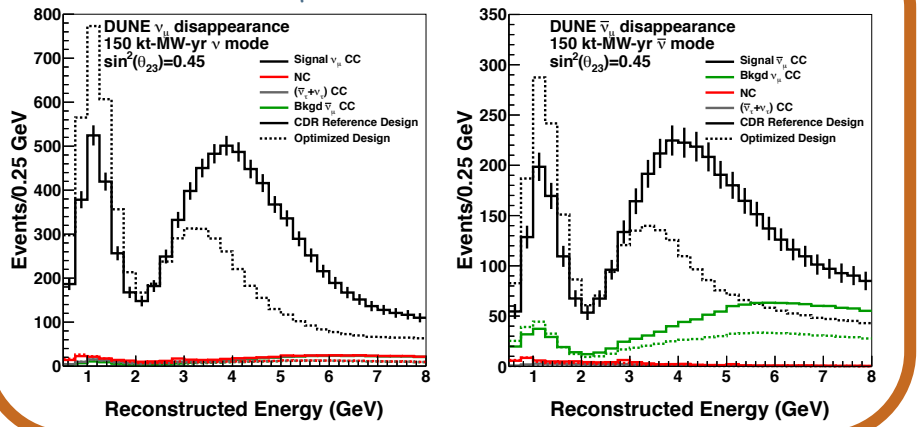
DUNE Oscillation Strategy

Measure neutrino spectra at 1300 km in a wide-band beam

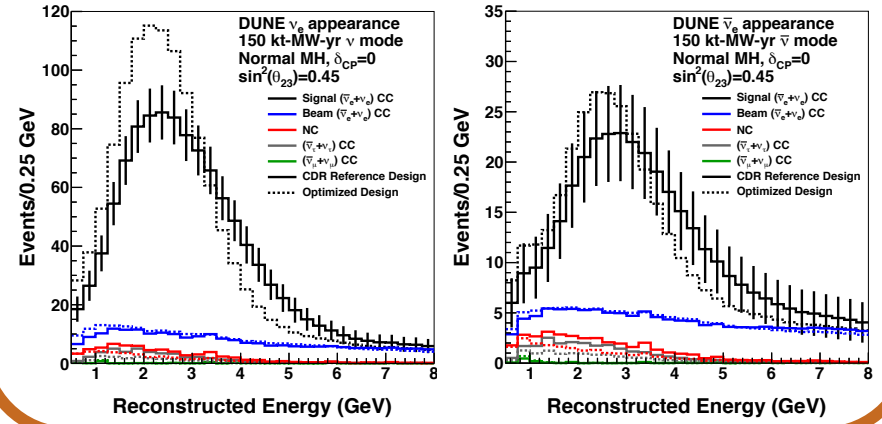
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects are separable

E ~ few GeV

ν_μ disappearance



ν_e appearance

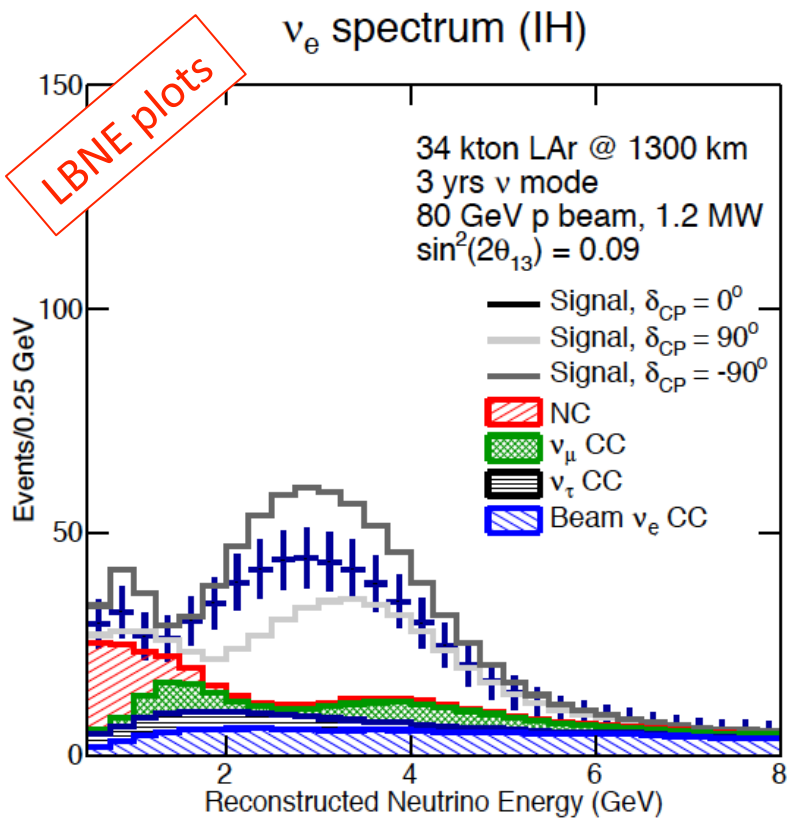


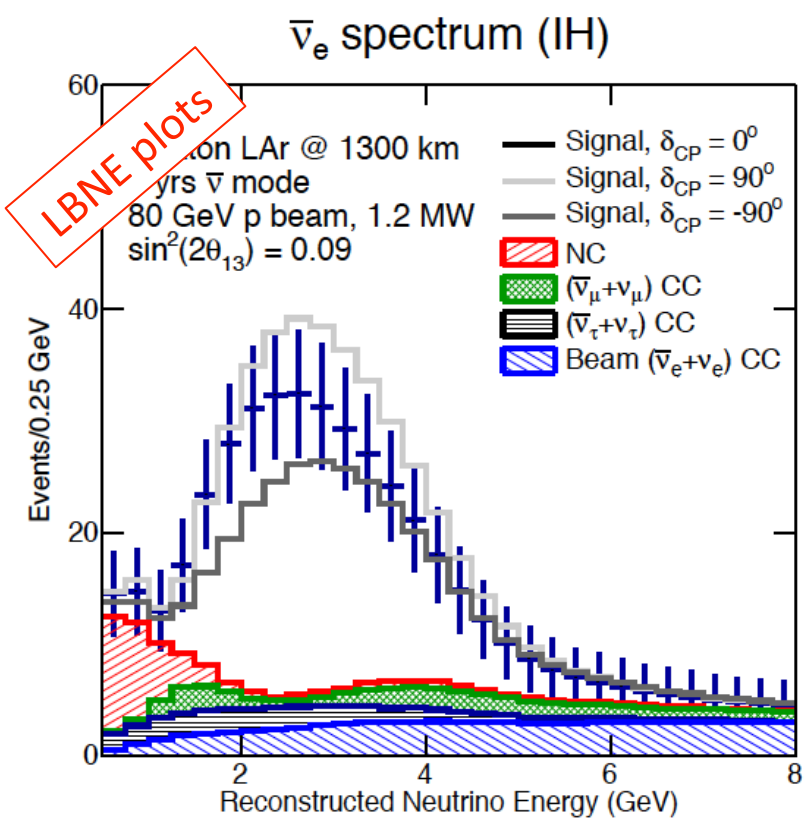
Separating MH & CPV

DUNE: **Determine MH and probe CPV in a single experiment**

Recall: $$\mathcal{A} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = \mathcal{A}_{CP} + \mathcal{A}_{Matter}$$

with $$\mathcal{A}_{CP} \propto L/E \;\; ; \;\; \mathcal{A}_{Matter} \propto L \times E$$



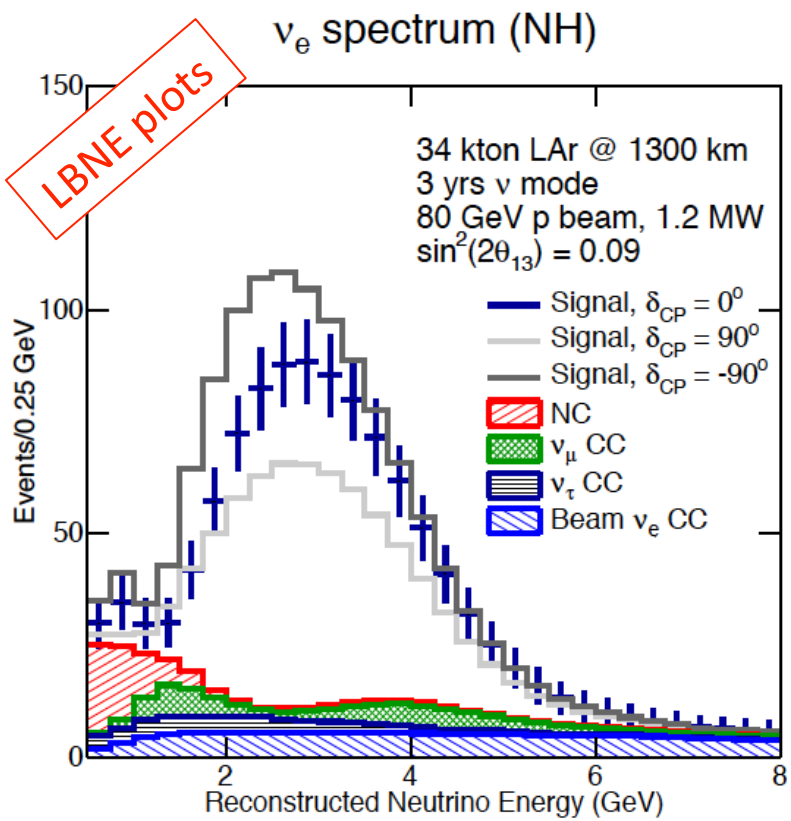


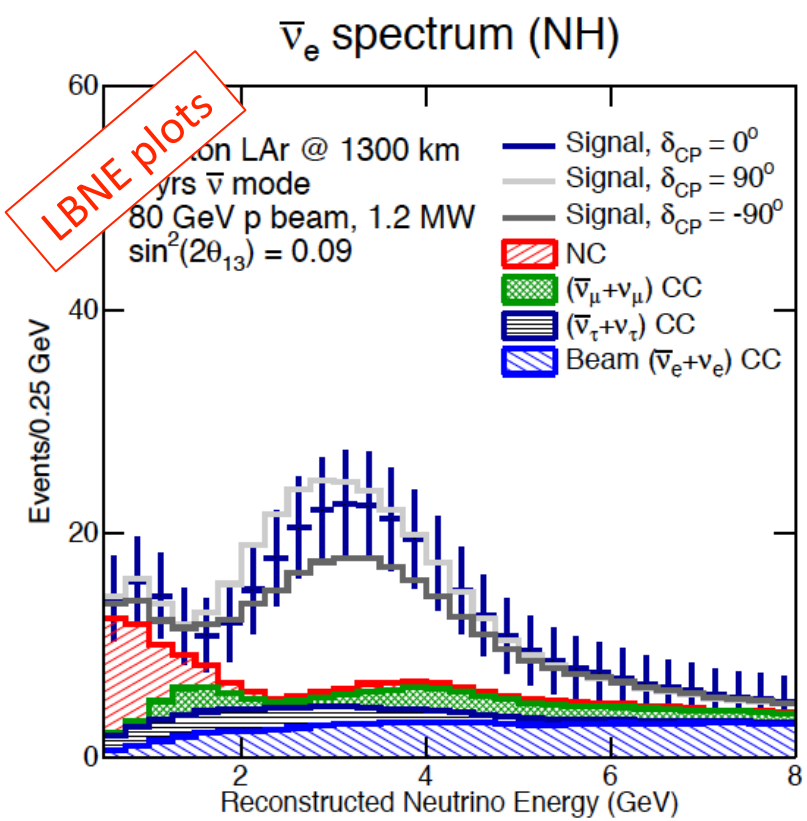
Separating MH & CPV

DUNE: **Determine MH and probe CPV in a single experiment**

Recall: $$\mathcal{A} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = \mathcal{A}_{CP} + \mathcal{A}_{Matter}$$

with $$\mathcal{A}_{CP} \propto L/E \;\; ; \;\; \mathcal{A}_{Matter} \propto L \times E$$



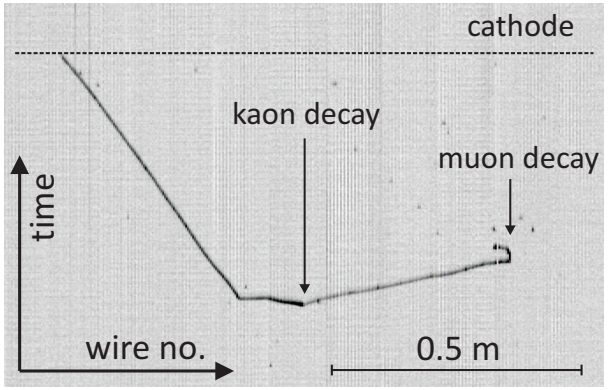


Nucleon Decay & SuperNova νs

Nucleon decay

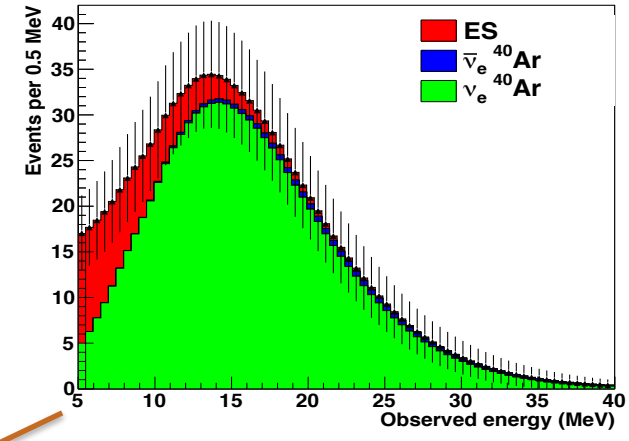
- **Image particles from nucleon decay**
  - target sensitivity to kaons (from d*E*/d*x*) from SUSY-inspired GUT p-decay modes

E ~ O(200 MeV)



SNB neutrinos

- **Trigger on and measure energy of neutrinos from galactic SNB**
  - In argon, the largest sensitivity is to ν_e
  - CC $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ interaction



E ~ O(10 MeV)

DUNE Far Detector

Far detector design optimized for:

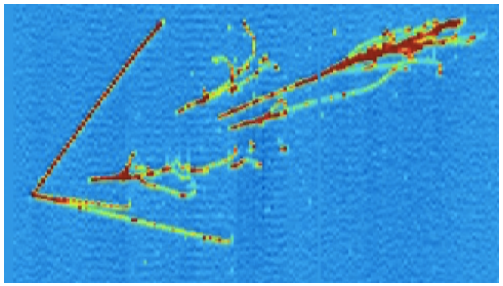
- Pattern recognition
- Energy measurement

in energy range: few MeV – few GeV

LBNE
LBNO → **LAr-TPC**

LAr-TPC Far Detector technology gives:

- Exquisite imaging capability in 3D
  - ~ few mm scale
- Excellent energy measurement capability:
  - totally active calorimeter

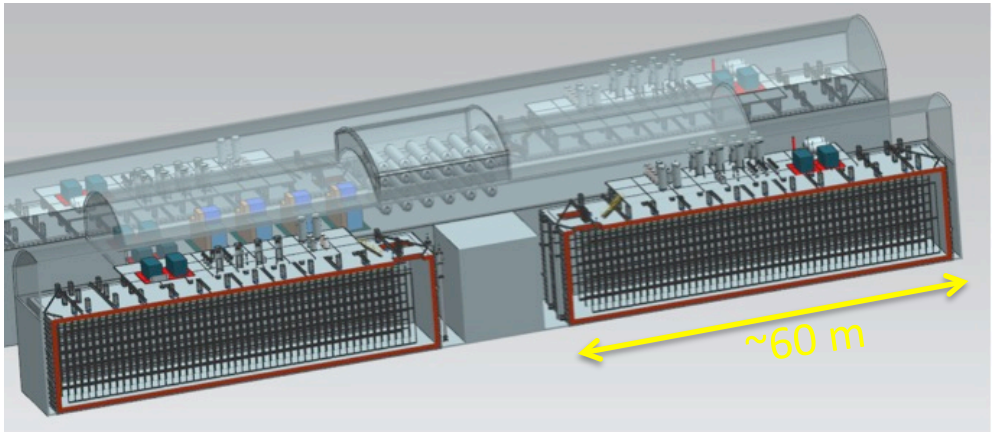


Near detector designed to:

- Constrain systematic uncertainties in LBL oscillation analysis
  - Near detector must be able to constrain ν cross sections & ν flux

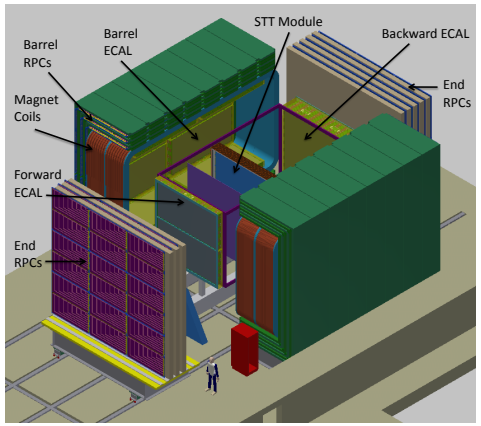
DUNE CDR Design =

Far detector: 40-kt LArTPC



1 mile underground

Near detector: Multi-purpose high-resolution detector

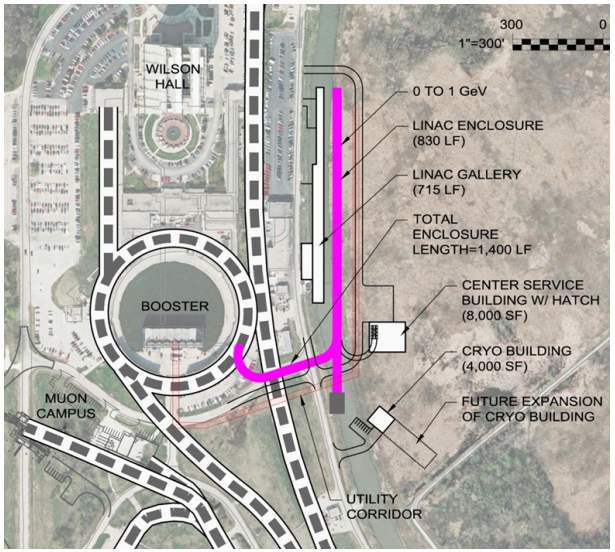


3.2: LBNF – a MW-scale facility

LBNF and PIP-II

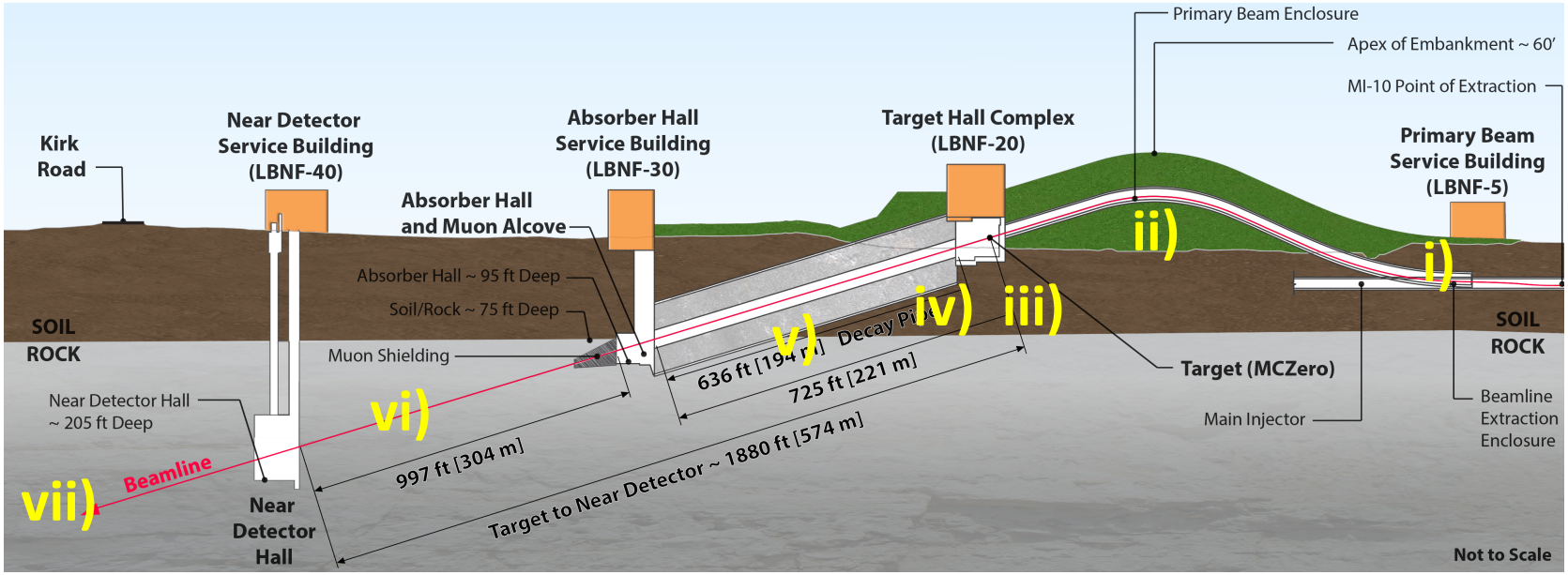
- ★ **In beam-based long-baseline neutrino physics:**
  - **beam power drives the sensitivity**
- ★ **LBNF will be the world's most intense high-energy ν beam**
  - **Build on strong Fermilab track record (BNB & NuMI)**
  - **1.2 MW from day one**
    - NuMI (MINOS) <400 kW
    - NuMI (NOVA) ultimately ~700 kW
  - **upgradable to 2.4 MW**

- ★ **Requires PIP-II** (proton-improvement plan)
  - **$0.5B** upgrade of FNAL accelerator infrastructure
  - Replace existing 400 MeV LINAC with 800 MeV SC LINAC

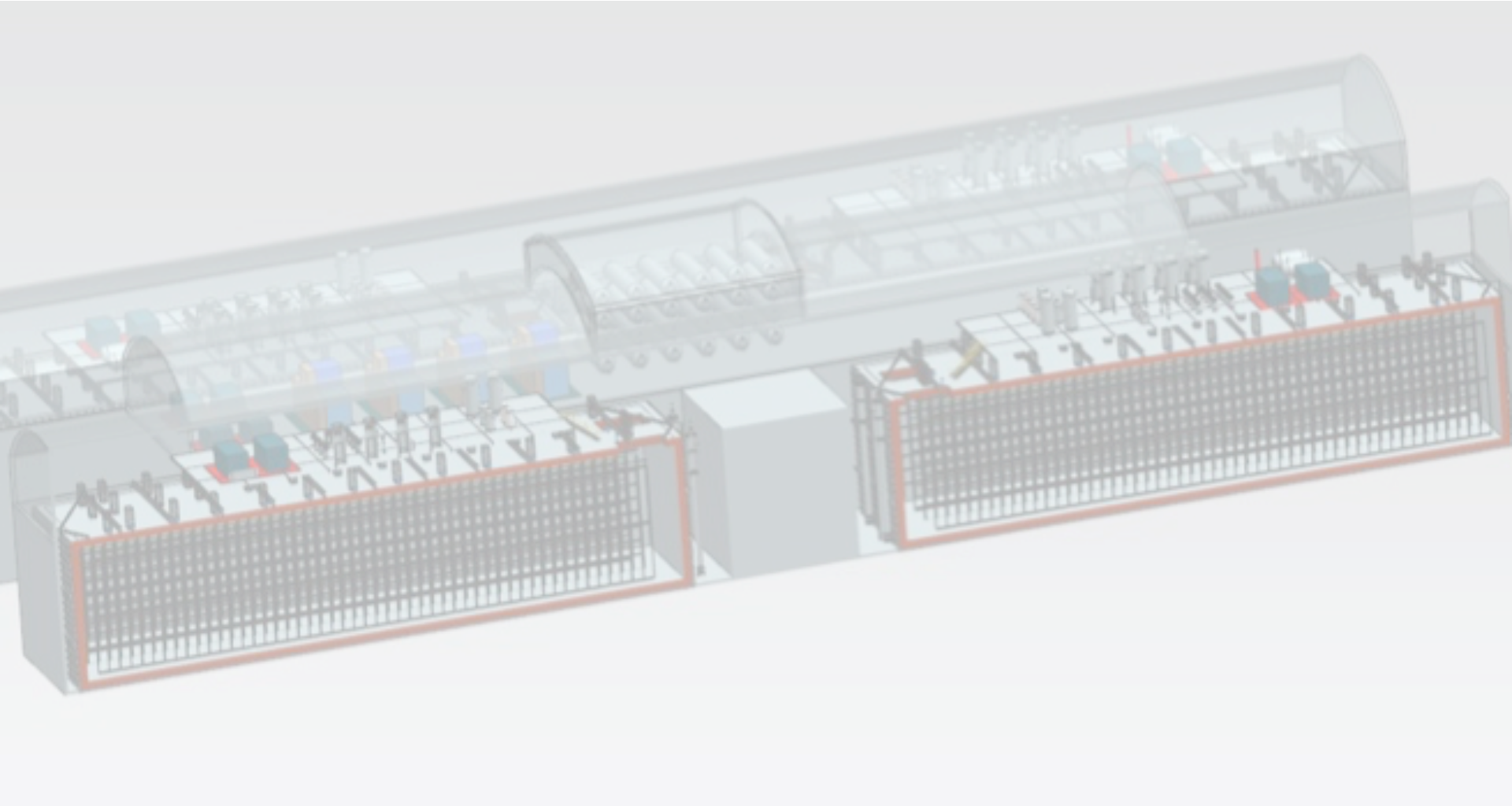


The LBNF Neutrino Beam

- i) Start with an intense (MW) proton beam from PIP-II
- ii) Point towards South Dakota
- iii) Smash high-energy (~80 GeV) protons into a target ➡ **hadrons**
- iv) Focus positive pions/kaons
- v) Allow them to decay $\pi^+ \rightarrow \mu^+ \nu_\mu$
- vi) Absorb remaining charged particles in rock
- vii) left with a "collimated" ν_μ beam



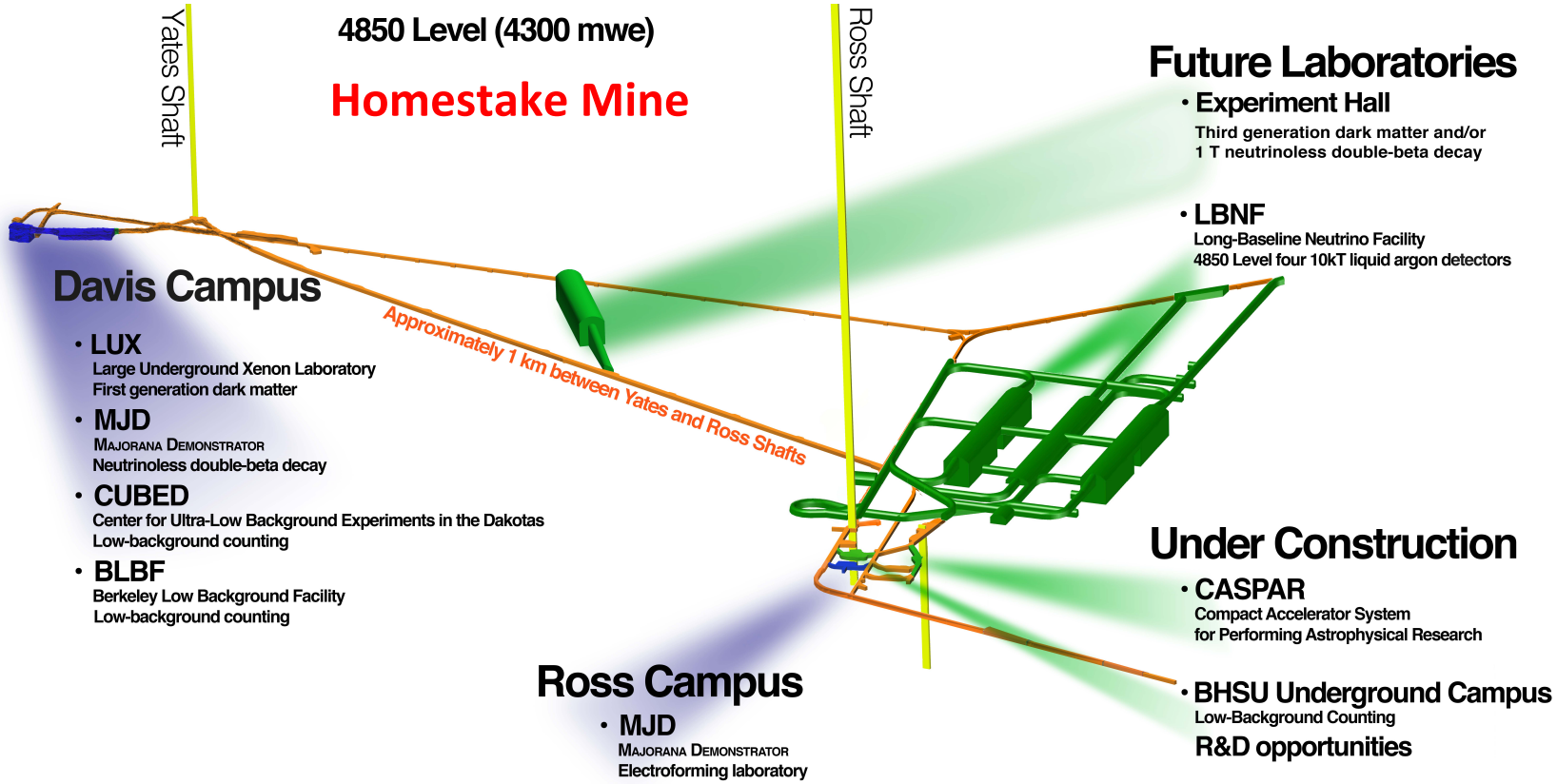
3.3: The DUNE Far Detector



The Far Site

DUNE Far Detector site

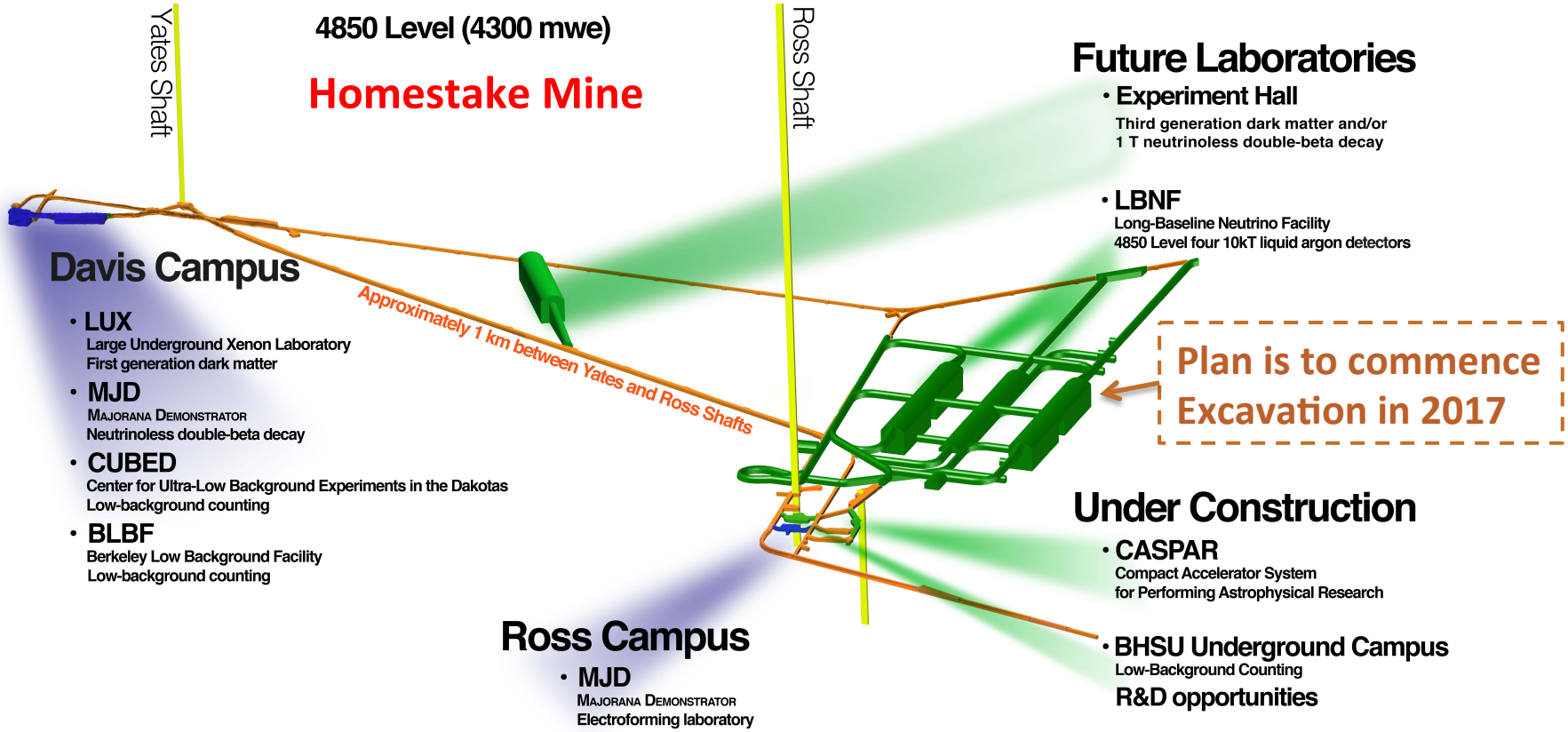
- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)



The Far Site

DUNE Far Detector site

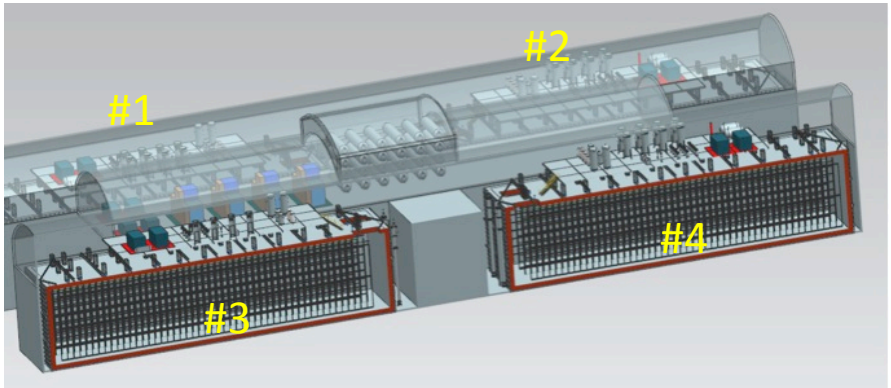
- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)



Staged Approach to 40 kt

Cavern Layout at the Sanford Underground Research Facility based on four independent caverns

- **Four identical caverns hosting four independent 10-kt FD modules**
  - Allows for staged construction of FD
  - Gives flexibility for evolution of LArTPC technology design
    - Assume four identical cryostats
    - But, assume that the four 10-kt modules will be similar but **not identical**



LAr TPC Technologies

LArTPC technology has been demonstrated by ICARUS

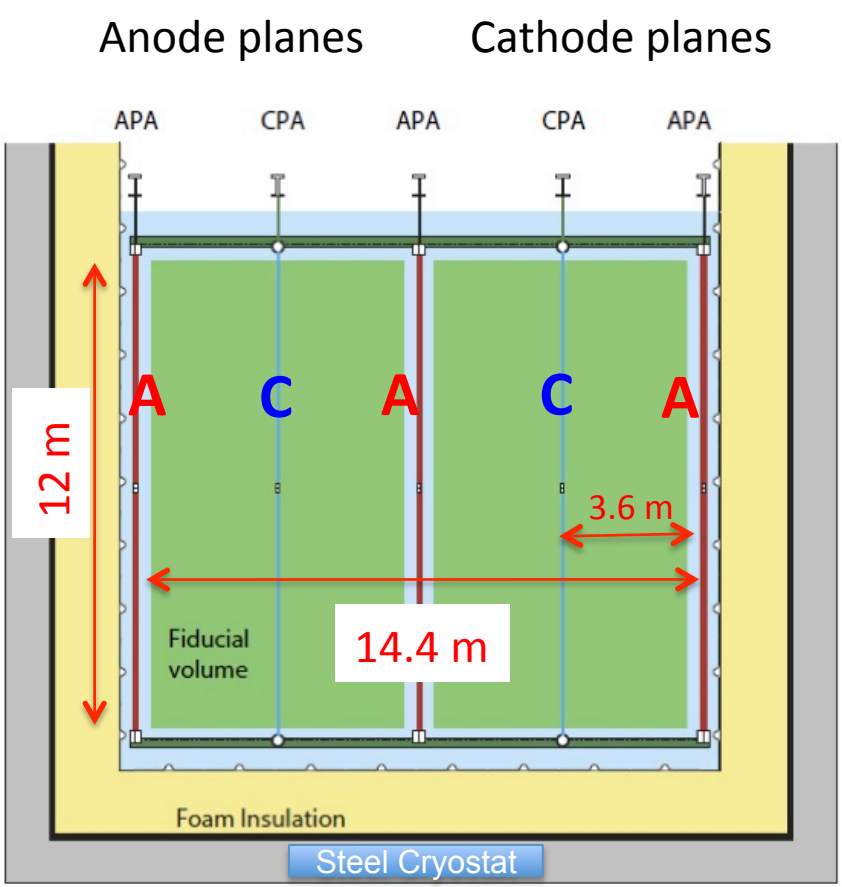
DUNE is considering two options for readout of ionization signals:

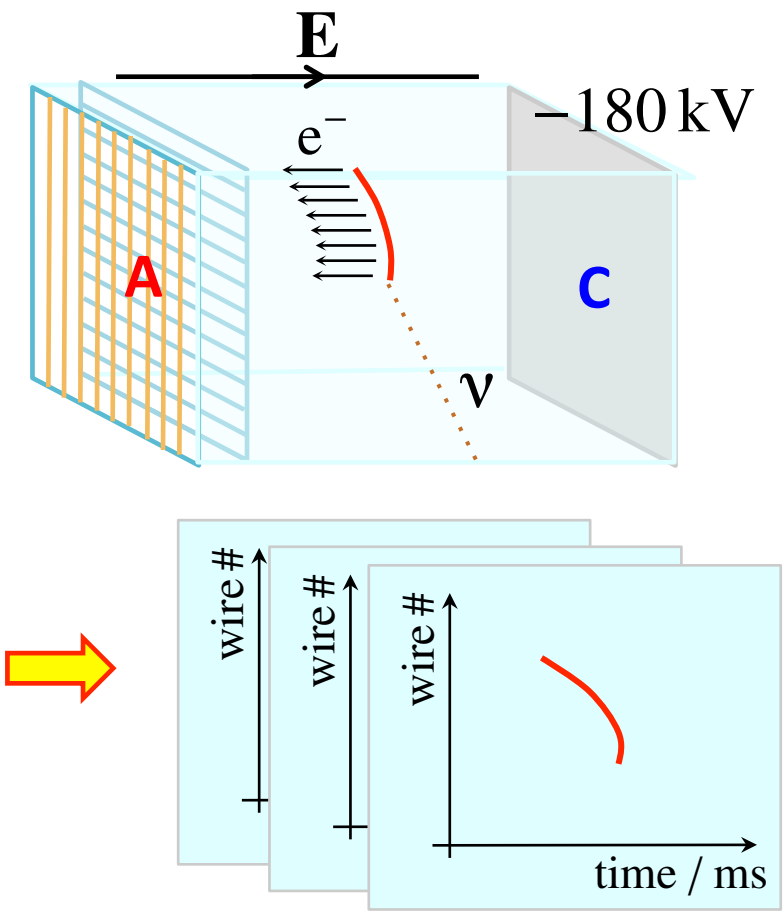
- **Single-phase wire-plane readout**
  - Ionization signals (collection + induction) read out in liquid volume
  - As used in ICARUS, ArgoNEUT/LArIAT, MicroBooNE
  - Long-term operation/stability demonstrated by ICARUS T600
- **Dual-phase readout**
  - Ionization signals amplified and detected in gaseous argon above the liquid surface
  - Being pioneered by the WA105 collaboration
  - If demonstrated, potential advantages over single-phase approach

Liquid Argon TPC Basics

A modular implementation of Single-Phase TPC

- **Record ionization in LAr volume ⇨ 3D image**

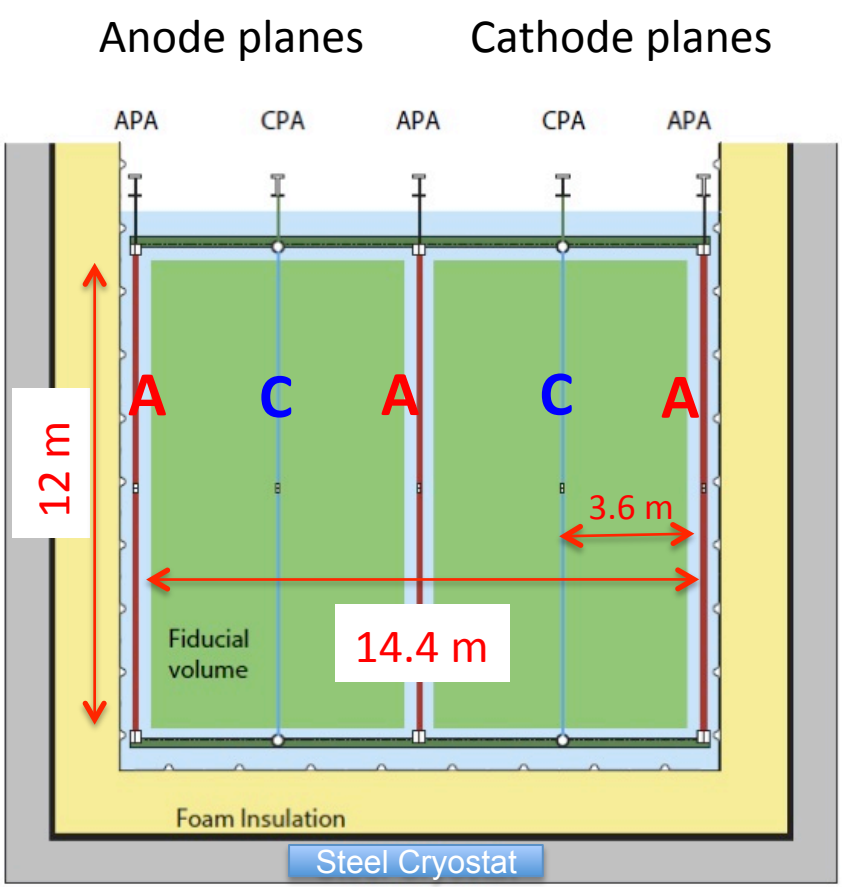


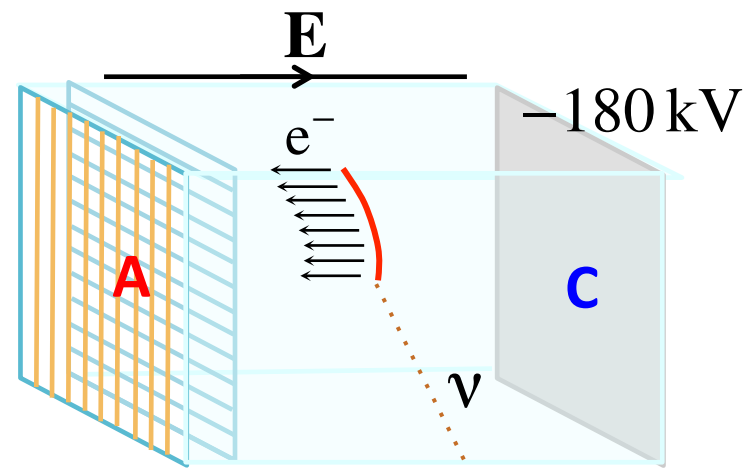


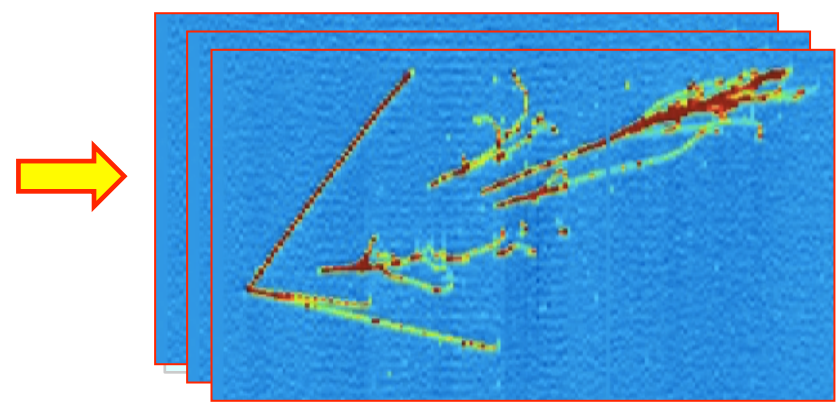
Liquid Argon TPC Basics

A modular implementation of Single-Phase TPC

- **Record ionization in LAr volume ⇨ 3D image**

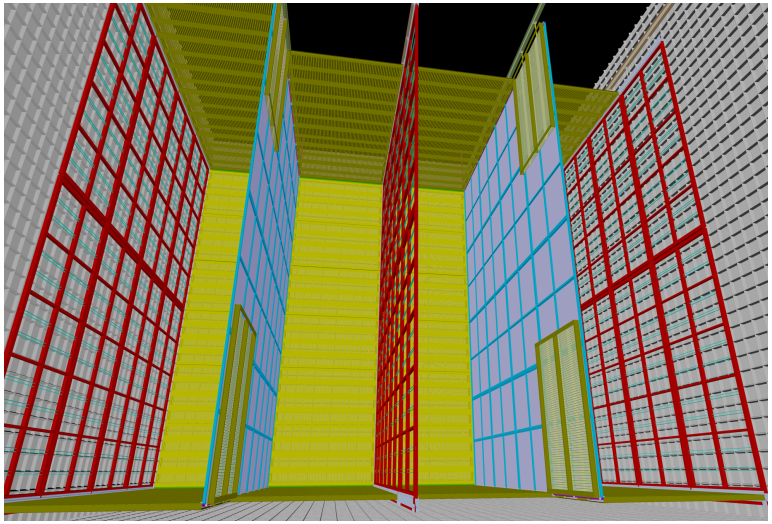




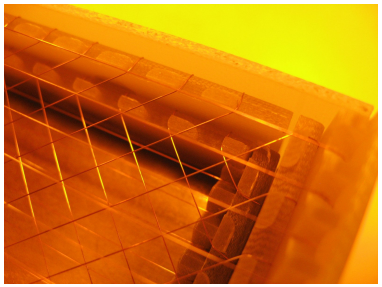


First 10 kt detector

Modular implementation of Single-Phase TPC



- **Each 10 kt FD module:**
  - Active volume: **12m x 14m x 58m**
  - 150 Anode Plane Assemblies
    - 6.3m high x 2.3m wide
  - 200 Cathode Plane Assemblies
    - 3m high x 2.3m wide
  - A:C:A:C:A arrangement
  - Cathodes at -180 kV for 3.5m drift
  - APAs have wrapped wires – read out both sides
  - Each side has one collection wire plane & two induction planes

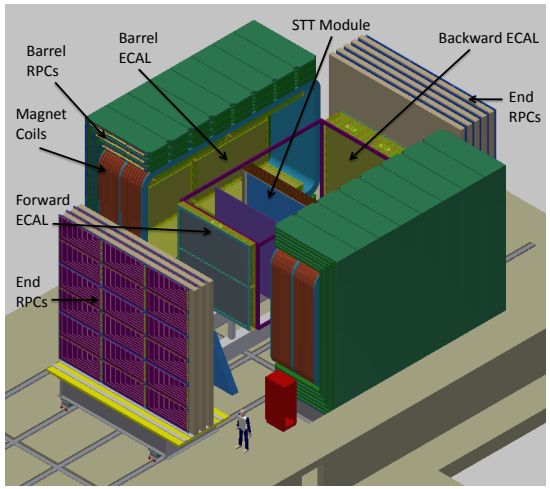


3.4: The DUNE Near Detector

DUNE ND (in brief)

The NOMAD-inspired Fine-Grained Tracker (FGT)

- **It consists of:**
  - Central straw-tube tracking system
  - Lead-scintillator sampling ECAL
  - Large-bore warm dipole magnet
  - RPC-based muon tracking systems

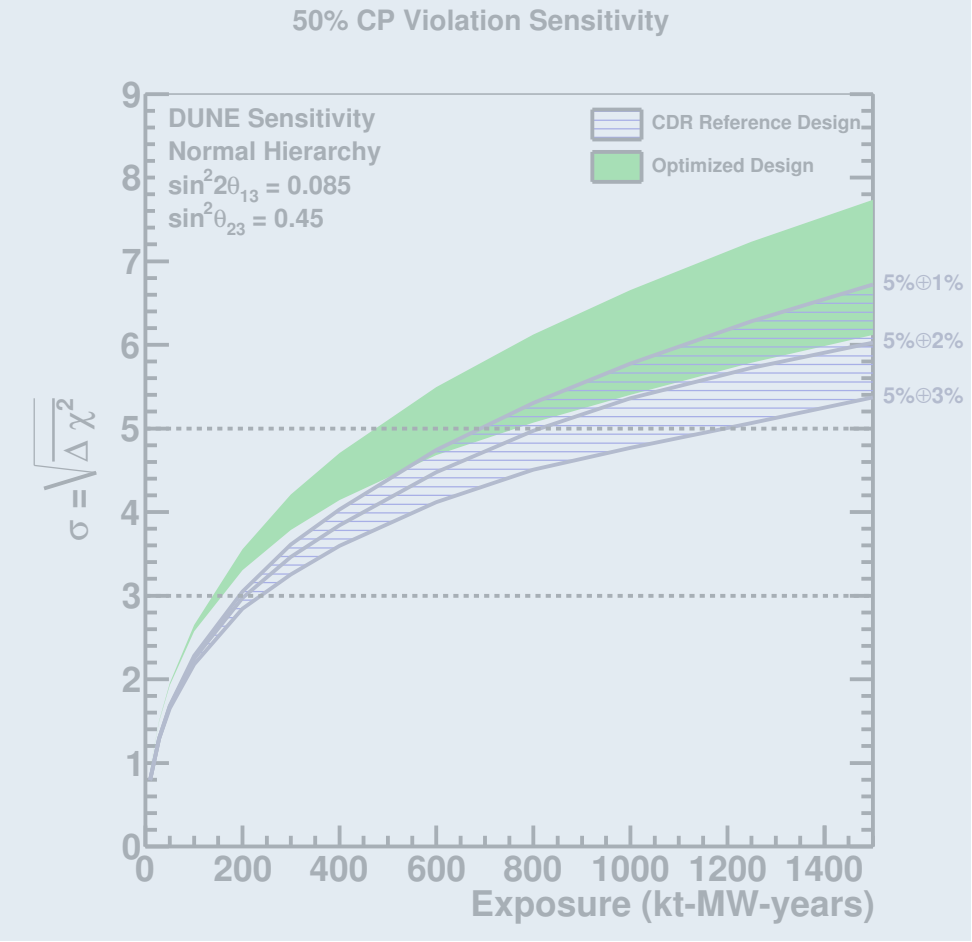


- **It provides:**
  - Constraints on cross sections and the neutrino flux
  - A rich self-contained non-oscillation neutrino physics program

Will result in unprecedented samples of ν interactions

- >100 million interactions over a wide range of energies:
  - strong constraints on systematics
  - the ND samples will represent a huge scientific opportunity

4: DUNE Physics Sensitivities



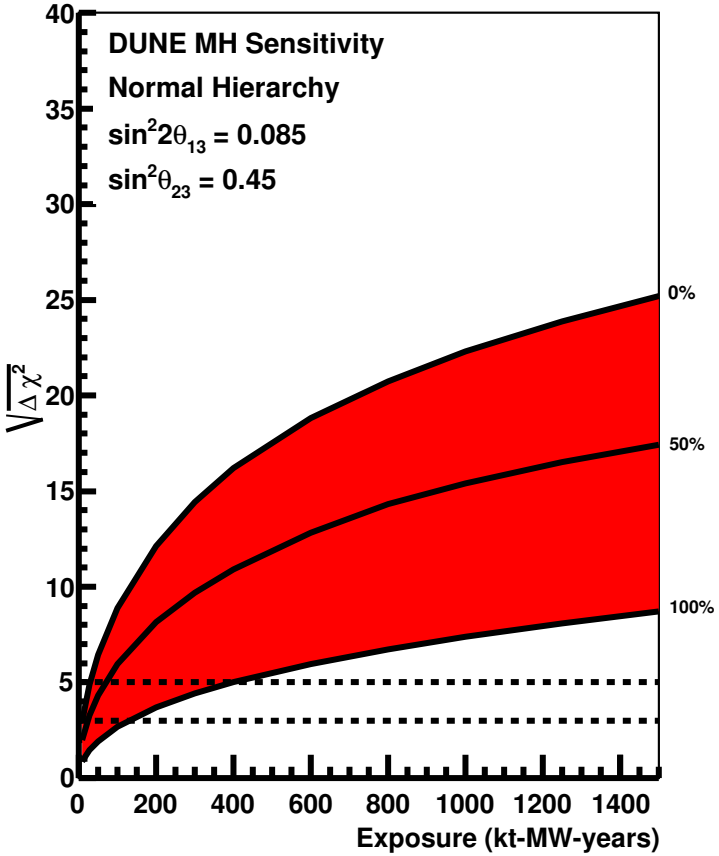
Sensitivities and Timescales

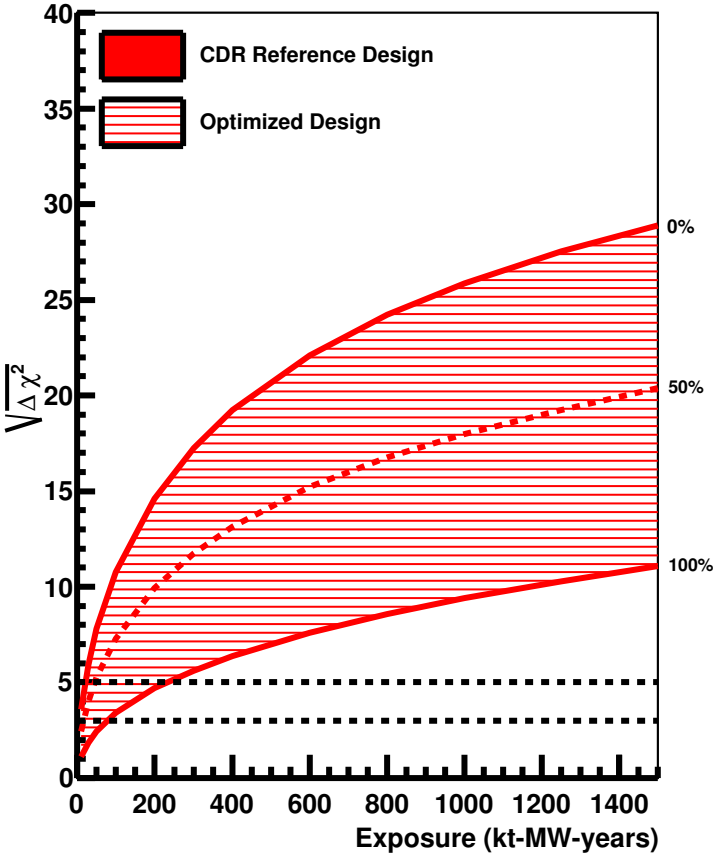
DUNE physics:

- **Game-change program in Neutrino Physics**
  - Definitive 5σ determination of MH
  - Probe leptonic CPV
  - Precisely test 3-flavor oscillation paradigm
- **Potential for major discoveries in astro-particle physics**
  - Extend sensitivity to nucleon decay
  - Unique measurements of supernova neutrinos (if one should occur in lifetime of experiment)

MH Sensitivity

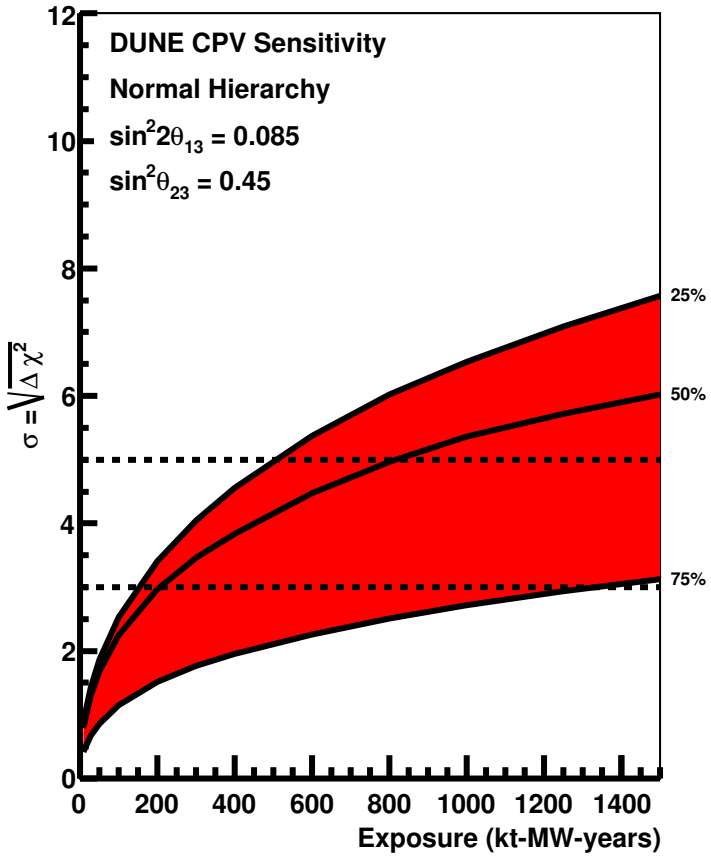
- ★ Sensitivities depend on multiple factors:
  - Other parameters, e.g. δ
  - Beam spectrum, systematics, …

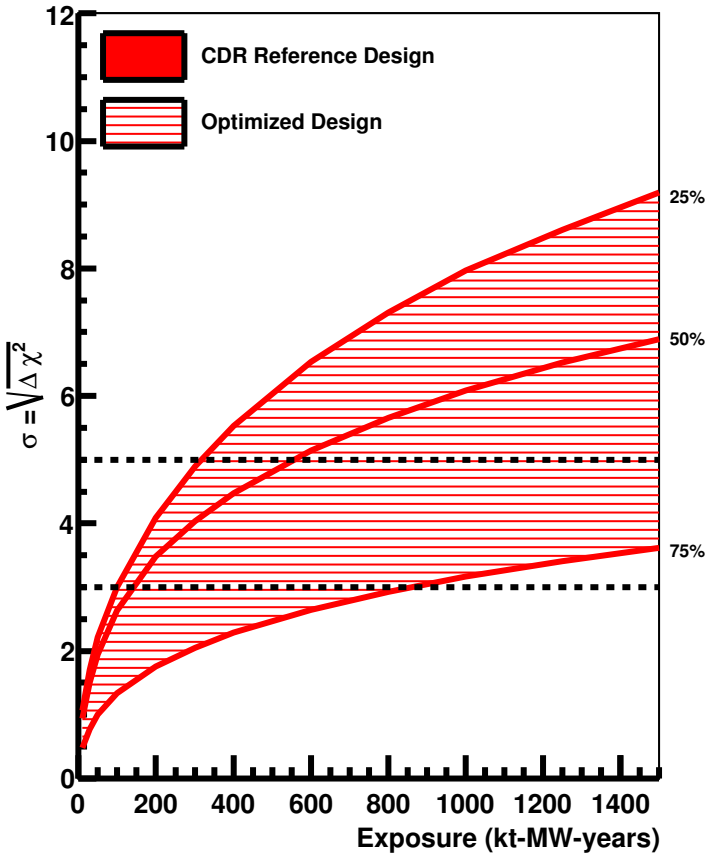




CPV Sensitivity

- ★ Sensitivities depend on multiple factors:
  - CPV parameter δ
  - Beam spectrum, …



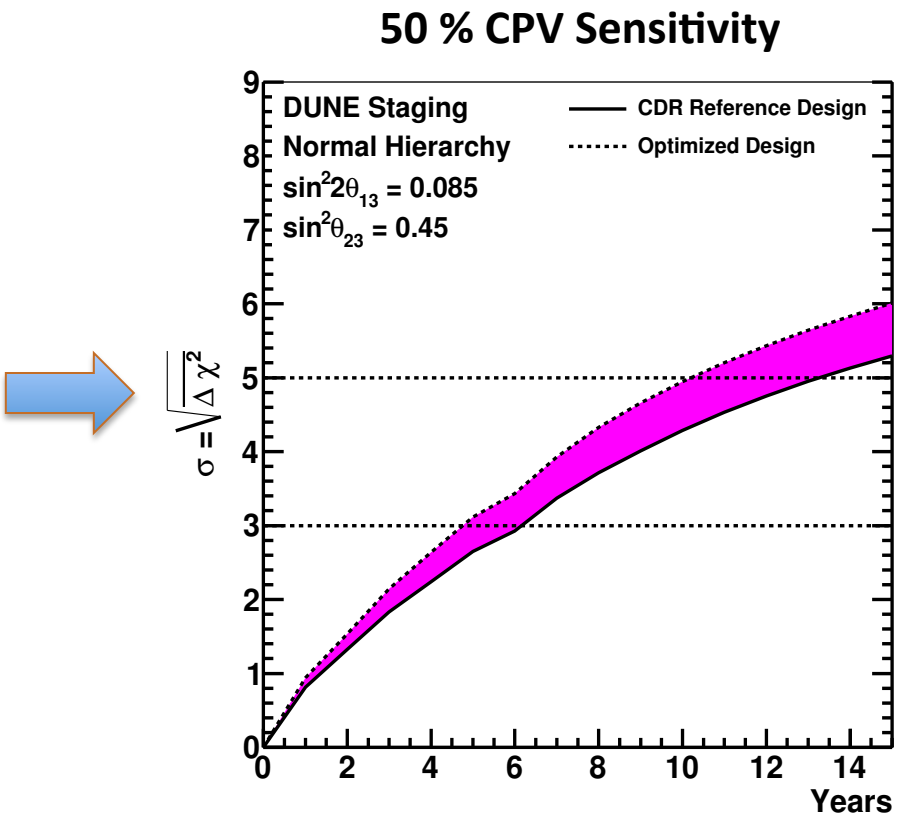


Timescales

★ To understand how sensitivity evolves with time, fold in

- Staging of four FD modules
- Beam power and upgrades

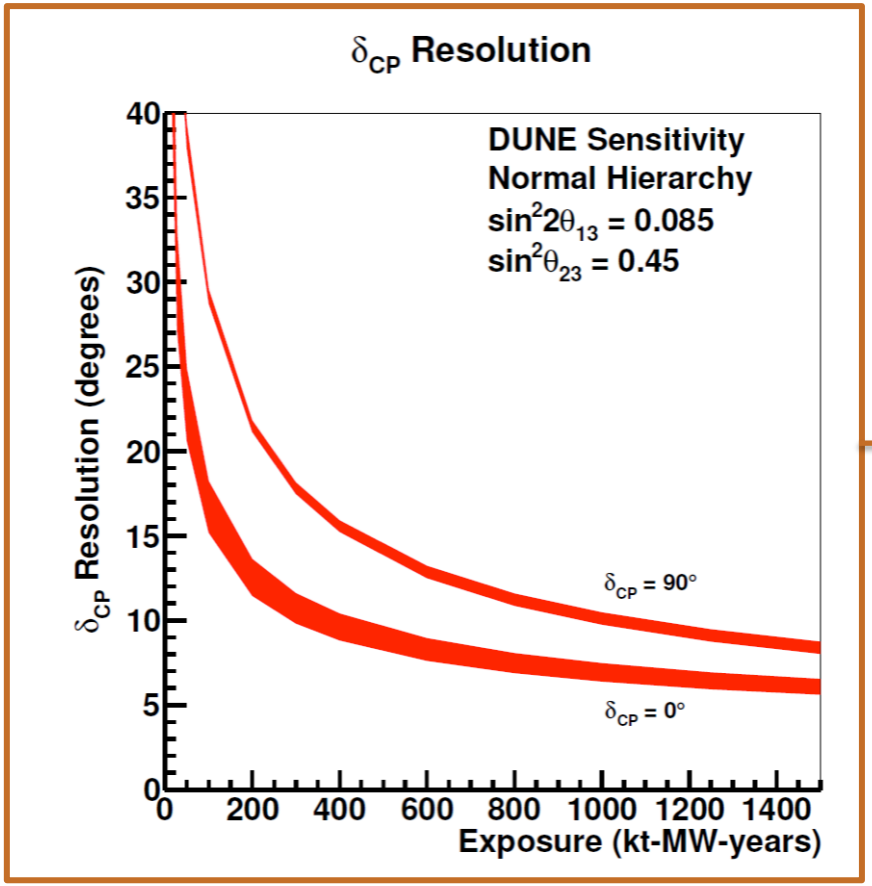
} Based on guideline funding profile



- **Comments**
  - Year zero **= 2025**
  - With additional (international) support, could go faster

Measurement of δ

- ★ CPV "coverage" is just one way of looking at sensitivity…
- ★ Can also express in terms of the uncertainty on **δ**



Start to approach current level of precision on quark-sector CPV Phase (although takes time)

Oscillation Physics Milestones

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 3σ CPV sensitivity with 60 – 70 kt.MW.year**
- e.g. in best-case scenario for MH :
  - **Reach 5σ MH sensitivity with 20 – 30 kt.MW.year**

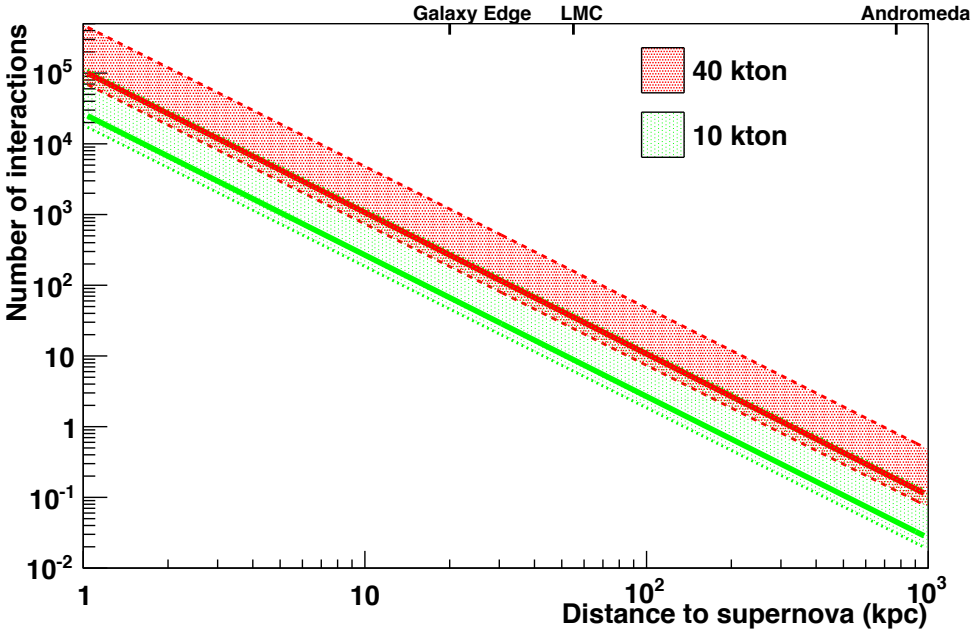
Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{CP} = 0$)	450	290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

5σ CPV Discovery

★ Genuine potential for early physics discovery

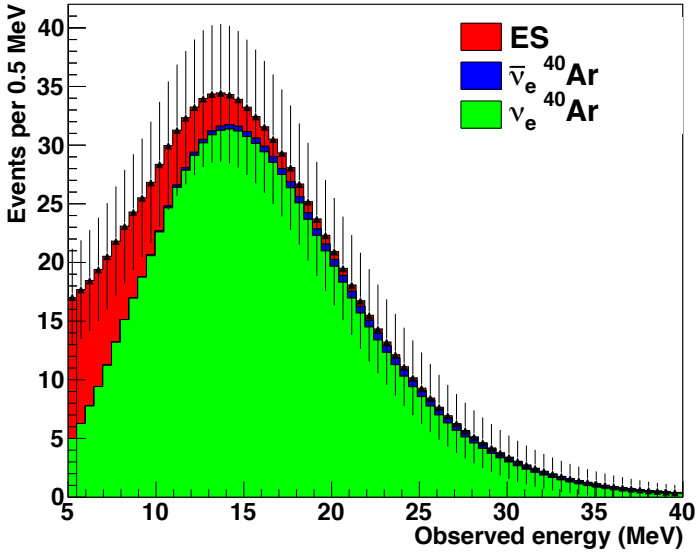
Super Nova Neutrinos I

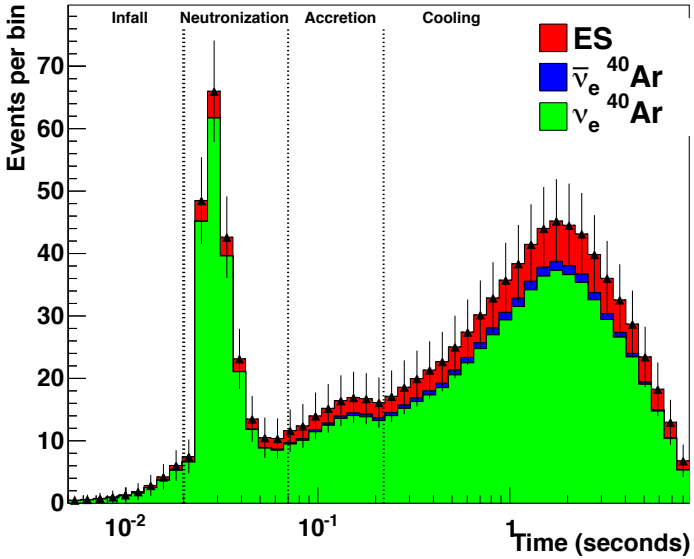
- For a core-collapse Super Nova in the galaxy:
  - Expect a few thousand $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ interactions
  - Complementary to other experiments (e.g. water/scintillator) which are mostly sensitive to anti-neutrino component



Super Nova Neutrinos II

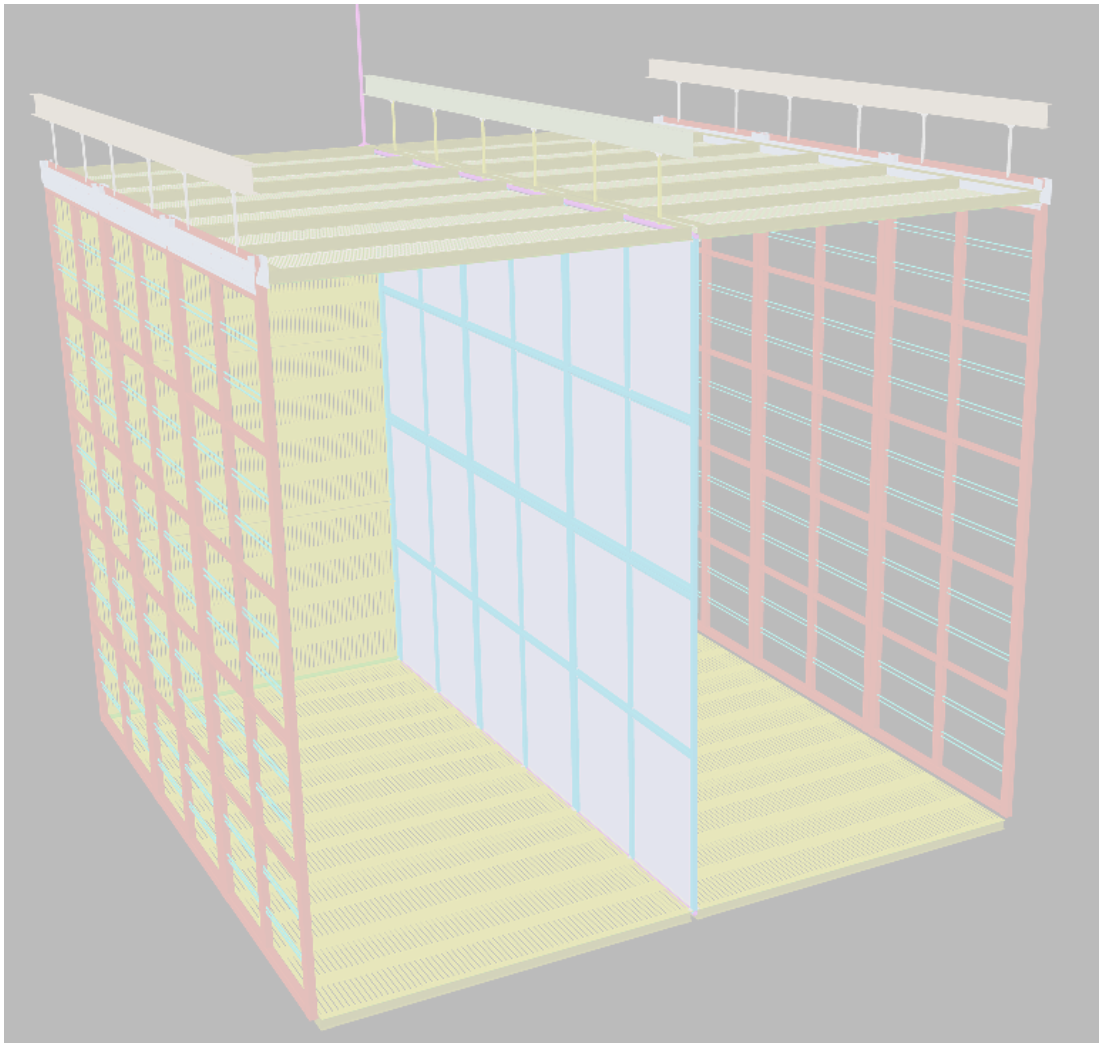
- Energy and timing of neutrino burst are sensitive to particle physics & astrophysics





★ Highlights include:
- Possibility to “see” neutron star formation stage
- Even the potential to see black hole formation !

5. LAr-TPC Development



5. LAr-TPC Development

DUNE Far Detector will consist of 4 x 10 kton LAr-TPCs

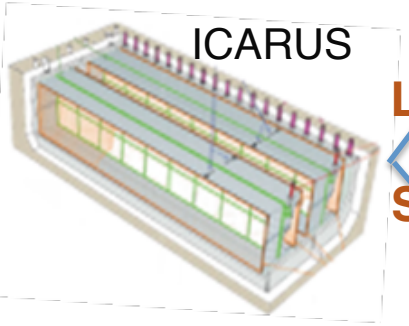
- **Basic technology demonstrated by**
  - ICARUS, ArgoNEUT, LArIAT, MicroBooNE, …
- **But DUNE scale is very different…**
  - Each module is ~40x larger than ICARUS T300 module
- **DUNE design has wrapped wire planes**
  - Readout ionization on both sides of wire plans

➡ **Need strong R&D and Prototyping programmes**

LArTPC Development Path

Fermilab SBN and CERN neutrino platform provide a strong **LArTPC** development and prototyping program

Single-Phase



LBL

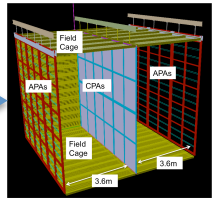
35-t prototype

2015

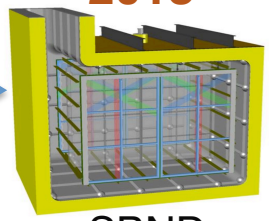
SBL

MicroBooNE

DUNE SP PT @ CERN

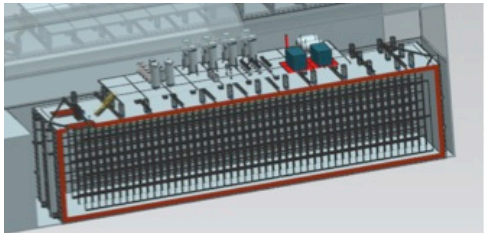


2018



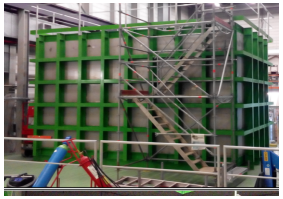
SBND

DUNE Reference Design



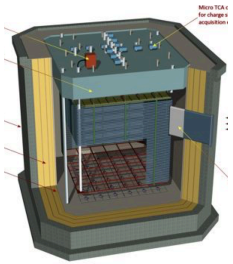
Dual-Phase

2016



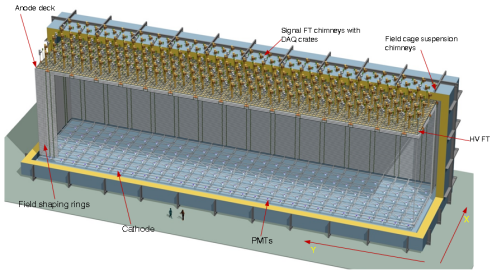
WA105: 1x1x3 m^3

2018



WA105

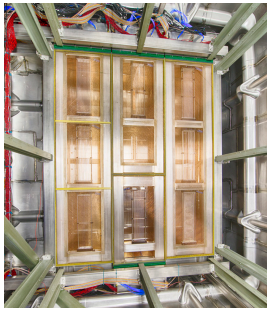
DUNE Alternative Design



DUNE Far Detector Prototypes

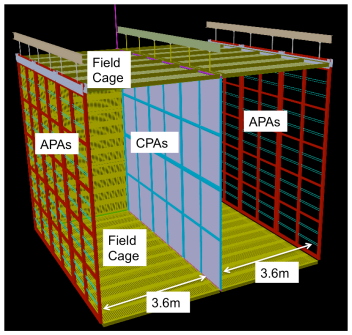
The single-phase APA/CPA LArTPC design is the reference design for the CDR

- **Design is already well advanced for CDR stage**
- **Supported by strong development program at Fermilab**
  - 35-t prototype (operational in 2015)
    almost ready to fill with LAr
  - MicroBooNE (operational in 2015)
  - SBND (operational in 2018)



35-t wire planes (10.23.2015)

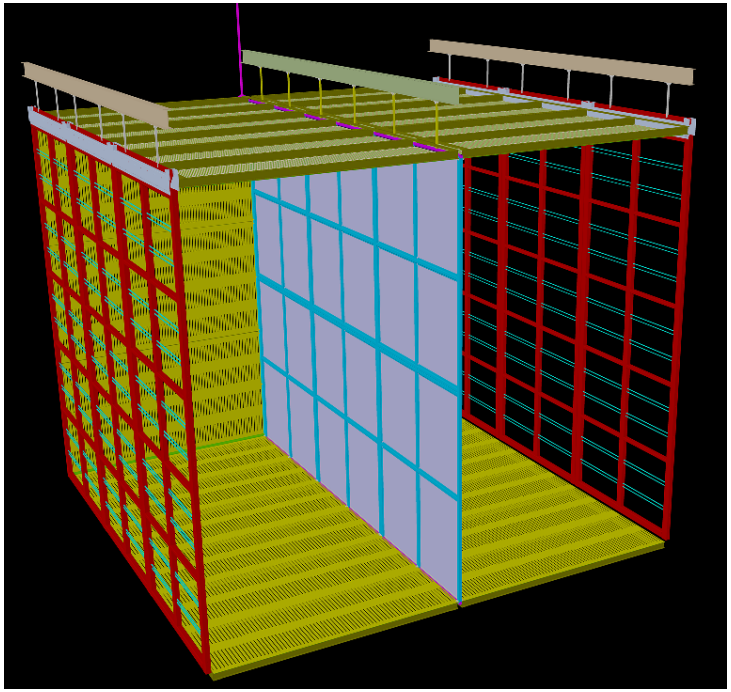
- **"Full-scale prototype" with ProtoDUNE at the CERN Neutrino Platform** (see M. Nessi's talk)
  - Engineering prototype of DUNE reference design
    - 6 full-sized drift cells c.f. 150 in the far detector
  - Approved by CERN SPSC (October 2015)
  - Aiming for operation in 2018



ProtoDUNE at CERN (more later)

Engineering prototype of DUNE single-phase TPC

- **DUNE PT @ CERN ~ 2018**
  - Active volume: 6m x 7m x 7m
  - 6 Anode Plane Assemblies
    - 6.3m high x 2.3m wide
  - 6 Cathode Plane Assemblies
    - 3m high x 2.3m wide
  - A:C:A arrangement
  - Cathode at -180 kV for 3.5m drift



Prototyping of FD drift cell + setting up module factories

- **Science: Charged-particle test-beam campaign**

ProtoDUNE at CERN (more later)

Engineering prototype of DUNE single-phase TPC

- **DUNE PT @ CERN ~ 2018**
  - Active volume: 6m x 7m x 7m
  - 6 Anode Plane Assemblies
    - 6.3m high x 2.3m wide
  - 6 Cathode Plane A
    - 3m high x
  - A:C:
  - for 3.5m drift

Major opportunity for European groups - happening very soon !

Pr FD drift cell + setting up module factories

- **S ce: Charged-particle test-beam campaign**

A now for something (not) completely different…

6. Fermilab Short Baseline Neutrino (SBN) Programme

SBN at Fermilab

Utilize existing Booster Neutrino Beam (SBN):

- **Low-energy (< 1 GeV) neutrino beam**
  - as deployed for MiniBooNE

Two main aims:

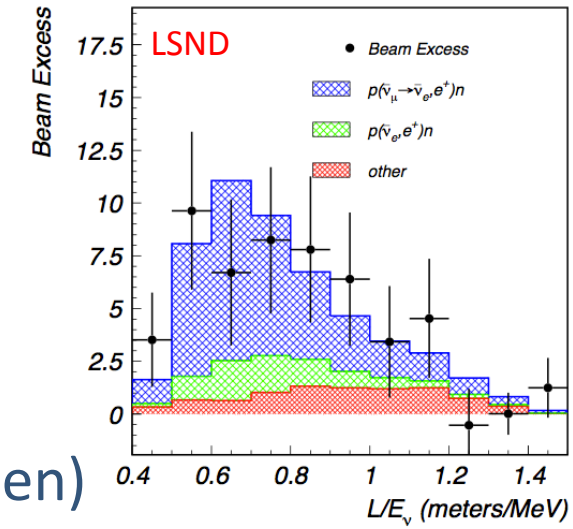
- **Address LSND and MiniBooNE anomalies**
  - eV-scale sterile neutrinos?
- **Platform for developing LAr-TPC technology**
  - MicroBooNE (now operational)
  - SBND (~2018) as a near detector
  - ICARUS (~2018) as a far detector

LSND & MiniBooNE "anomalies"

★ **LSND**

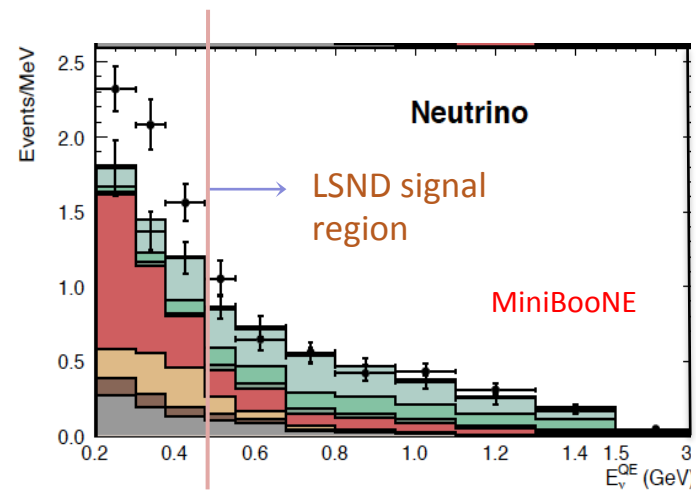
- Excess of electron-like events
  - 32.2 ± 9.4 ± 2.3 (3.8σ)
- Neutrino energies: 20 < E(MeV) < 50
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation interpretation

  ⇨ $\Delta m^2 > 0.1\,\mathrm{eV}^2$
- Not confirmed (or ruled out by Karmen)

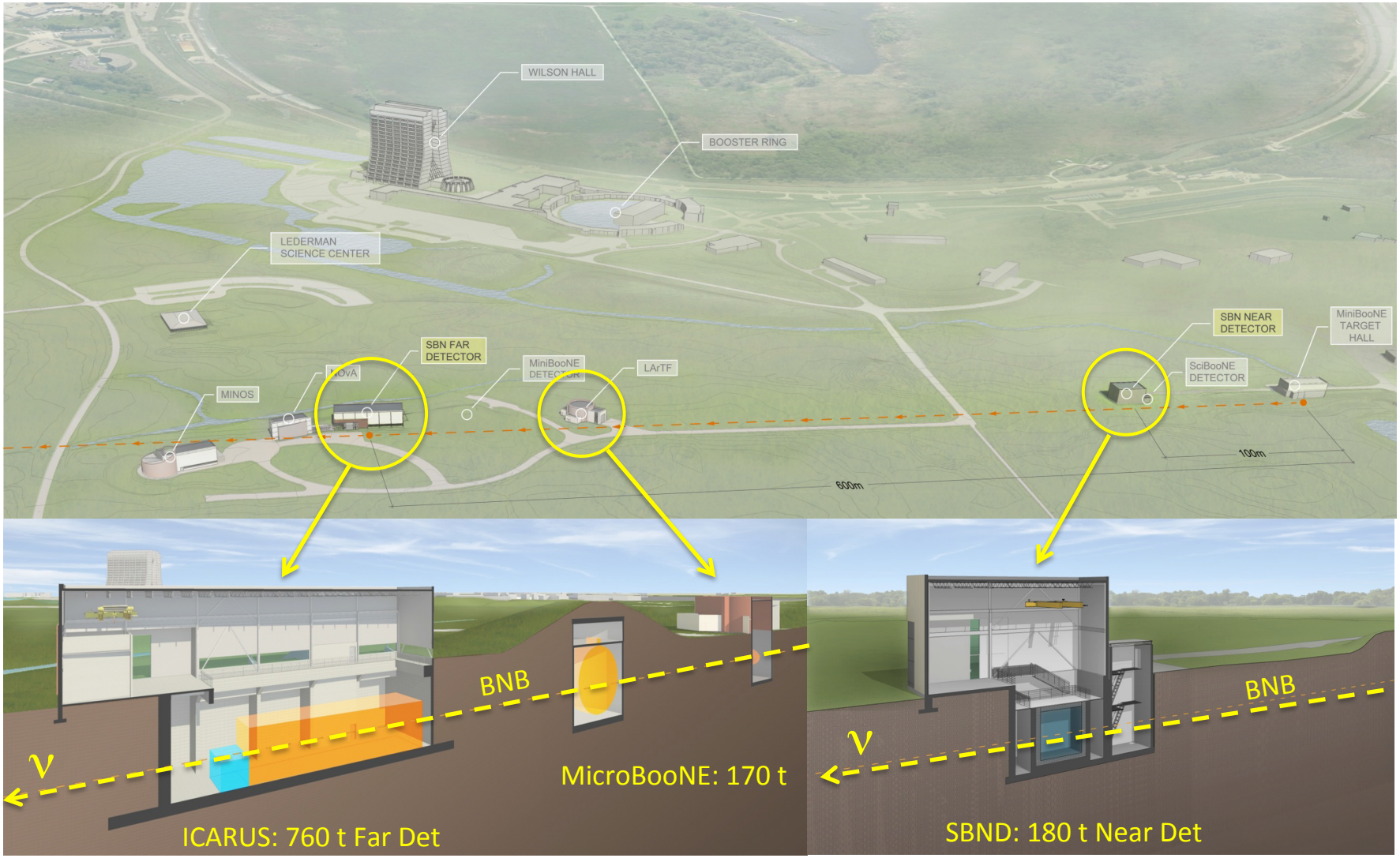


★ **MiniBooNE**

- Excess of low-E electron-like events
  - 3.8σ
- Seen in $\bar{\nu}_\mu$ and ν_μ data
- Possible Interpretations:
  - EM-like background (photons)
  - Neutrino oscillations via ν_s



SBN layout at Fermilab

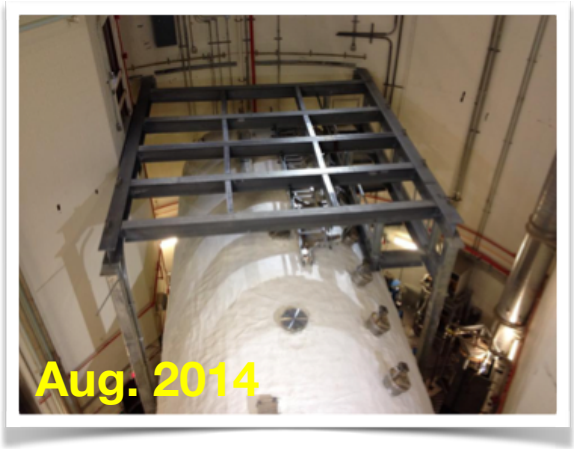


MicroBooNE

- ★ **Physics goals**
  - Address MiniBooNE excess
  - Utilize LArTPC technology
    - If excess is seen can distinguish whether electrons (e.g. from sterile-induced oscillations) or photon-induced
- ★ **Technology goals**
  - Development of single phase LAr-TPC
  - Second large-scale LAr-TPC detector
  - Developments for DUNE:
    - e.g. cold electronics
    - Automated computerized LAr-TPC image reconstruction?
    - \+ ν – Ar cross sections

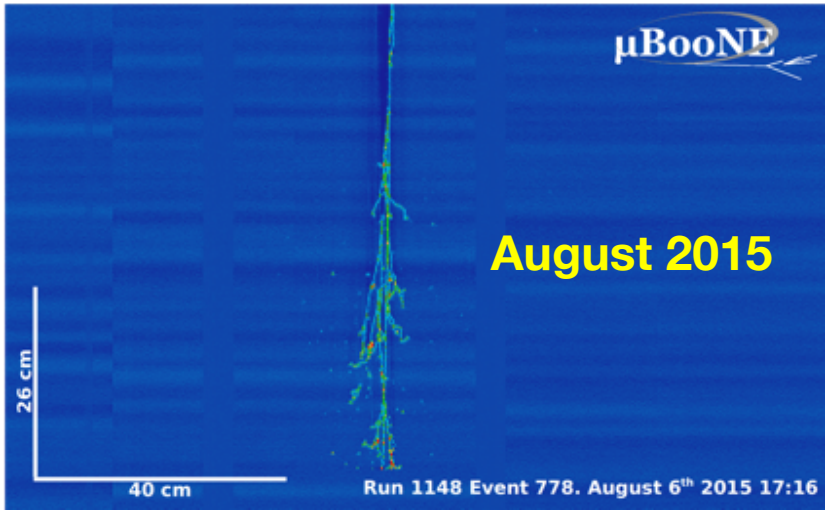
MicroBooNE Status

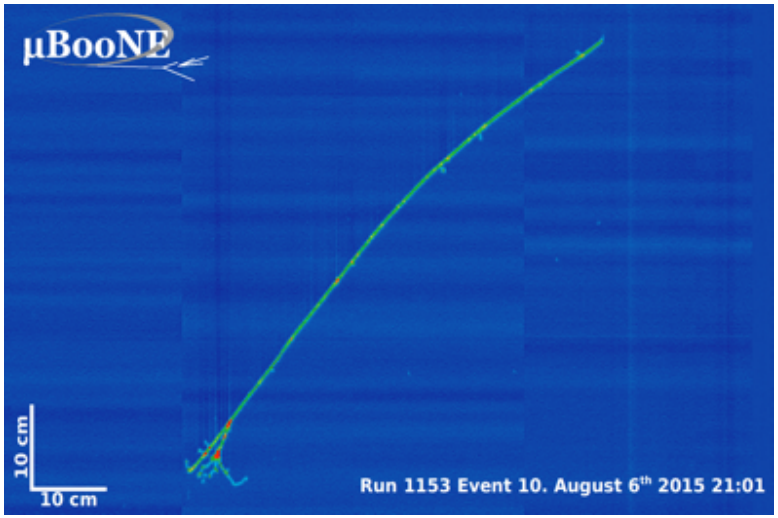
Constructed – Moved – Installed – Filled

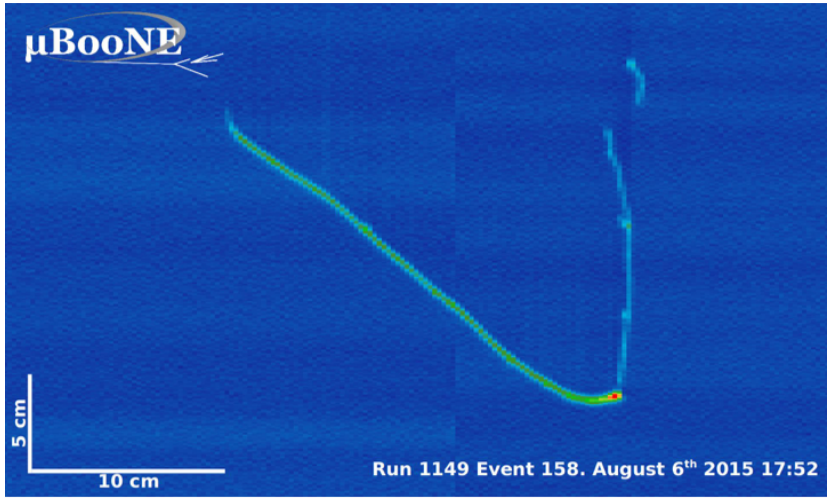


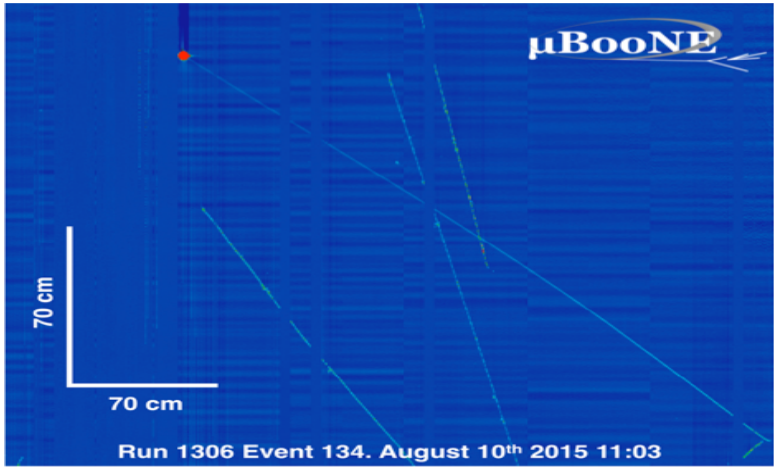
MicroBooNE Status

Commissioned …



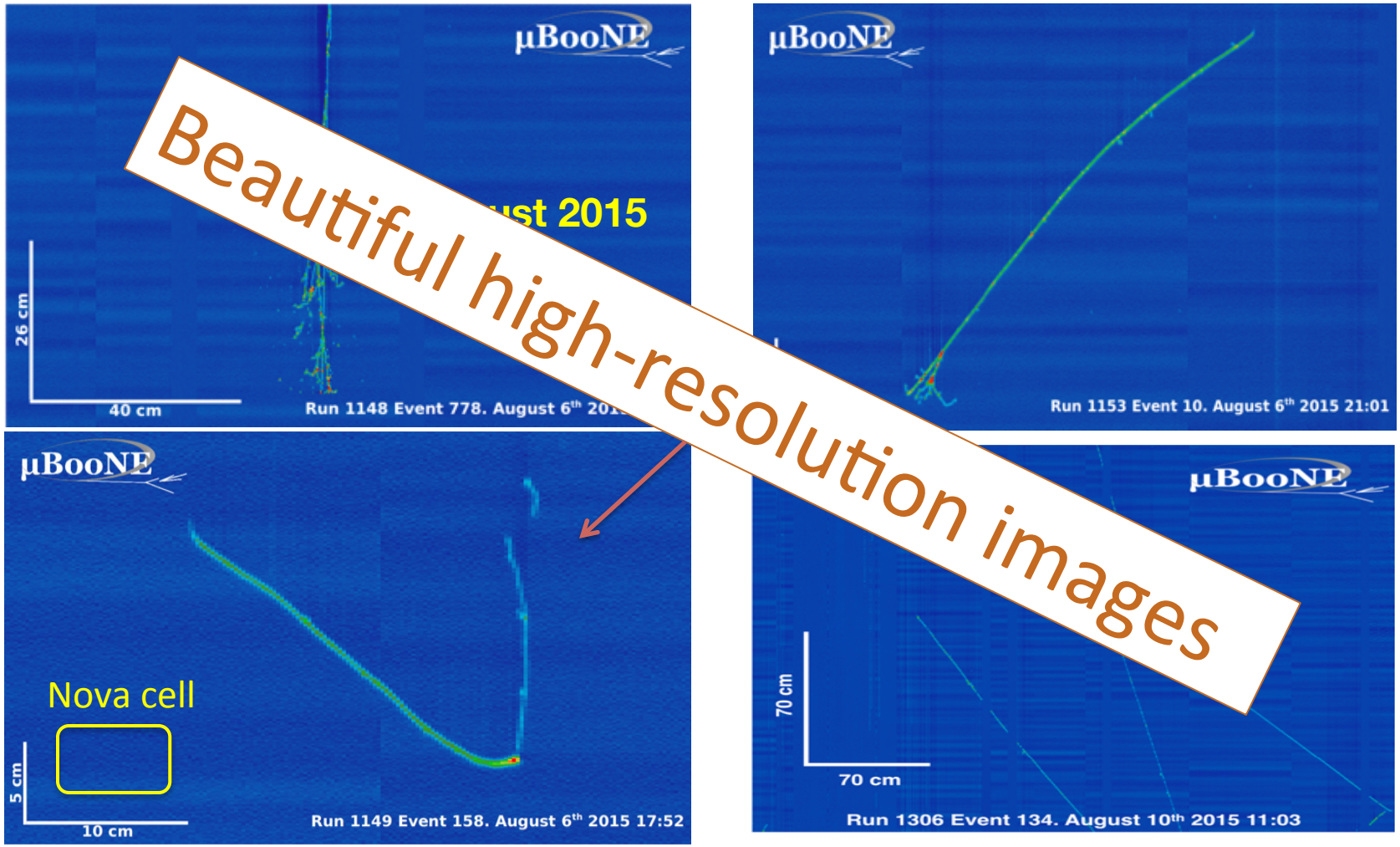






MicroBooNE Status

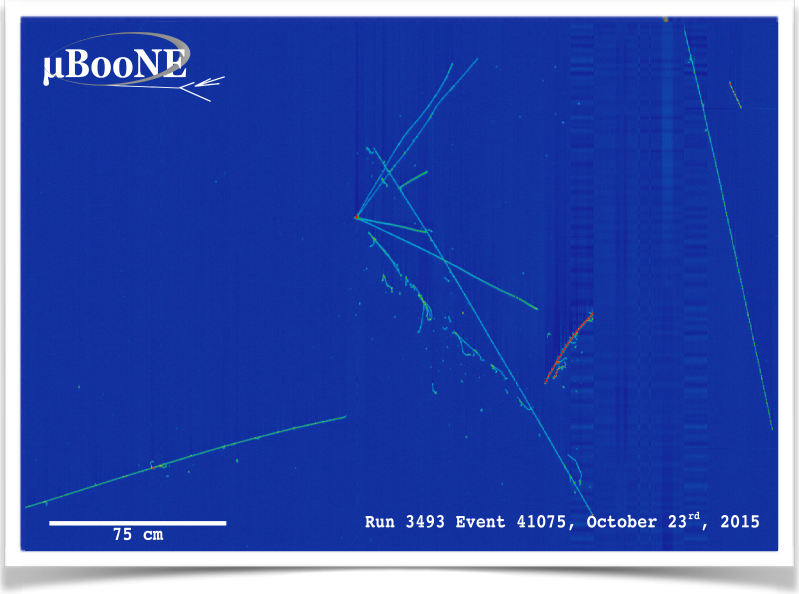
Commissioned …

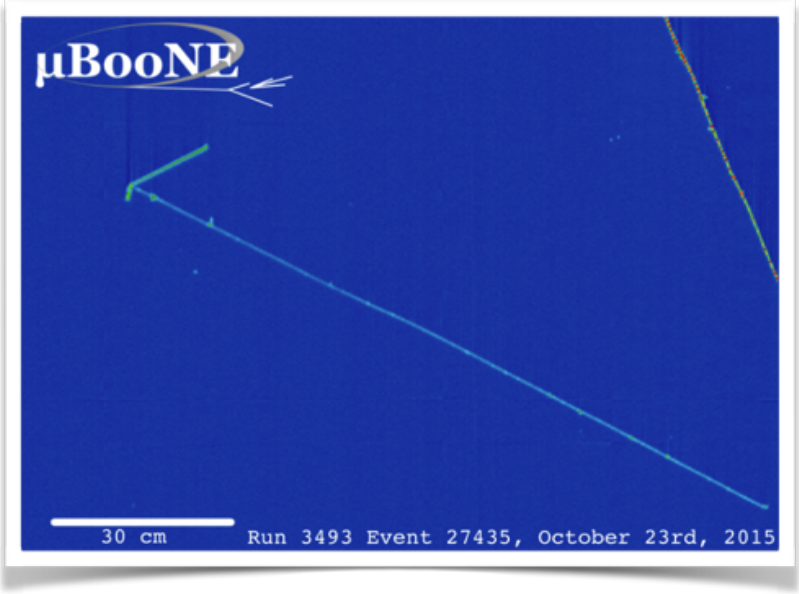


Beautiful high-resolution images

MicroBooNE Status

First BNB neutrinos in October 2015

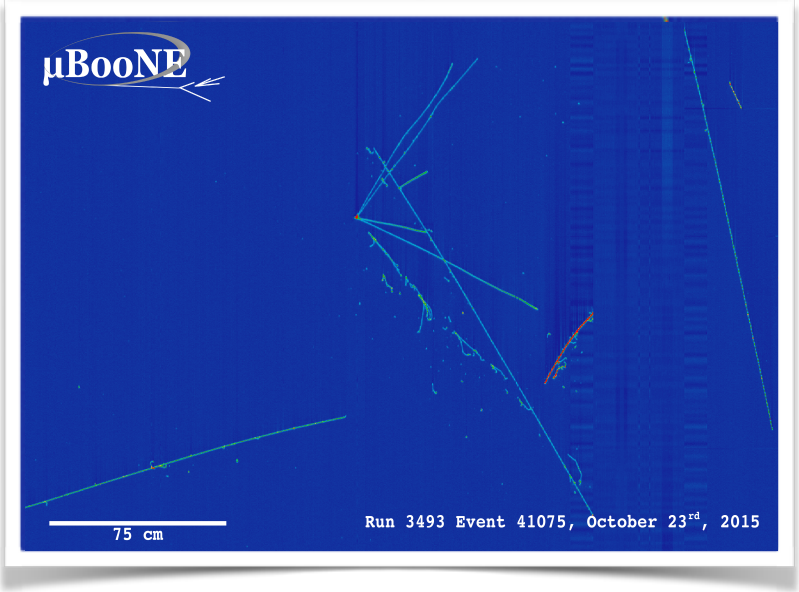


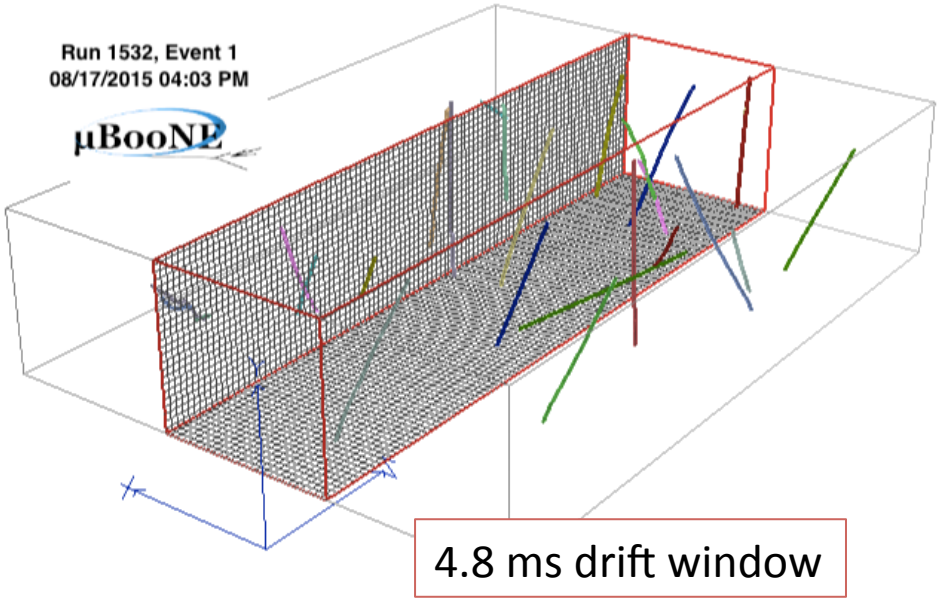


★ Selected using automated reconstruction

MicroBooNE Status

First BNB neutrinos in October 2015





- ★ **Selected using automated reconstruction**
- ★ **Big step forward:**
  - A first for a LAr-TPC detector
  - Challenging environment – MicroBooNE is on surface

7. DUNE: Politics and Prospects

7. DUNE: Politics and Prospects

Many reasons to be <u>very</u> optimistic about LBNF/DUNE

- **Fermilab**
  - LBNF/DUNE is *the* future flagship project for Fermilab
  - Fermilab is highly focused to achieve success
- **CERN**
  - CERN – US collaboration is significant
  - Investment in CERN neutrino platform (see Marzio's talk tomorrow)
  - \+ first time CERN will contribute to overseas facility
- **US Department of Energy**
  - DOE HEP strongly behind project
  - Support goes high up the US DOE chain
- **Large and Growing International Support**
  - Discussions within various FAs are ongoing

7. DUNE: Politics and Prospects

Many reasons to be <u>very</u> optimistic about LBNF/DUNE

- **Fermilab**
  - LBNF/DUNE is *the* future flagship project for Ferm
  - Fermilab is highly focused to achieve succe
- **CERN**
  - CERN – US collaboration is si
  - Investment in CERN ne n (see Marzio's talk tomorrow)
  - \+ first time CERN wi to overseas facility
- **US Departm ergy**
  - DO gy behind project
  - goes high up the US DOE chain
- **ge and Growing International Support**
  - Discussions within various FAs are ongoing

I am confident that LBNF/DUNE will happen

DUNE: Next Steps

Rate of progress has been rapid

- **CD-3a**
  - CD-3a approval being sought in December 2015
    - By Spring 2016, could have approval for far site excavation
  - Excavation would then commence in 2017
  - Ready for start of FD installation in 2021
- **ProtoDUNE at CERN**
  - Recommended for approval by SPSC in October 2015
  - Construction starts in 2016
  - Major opportunity for Europe to contribute to DUNE at CERN

DUNE: Next Steps

Rate of progress has been rapid

- **CD-3a**
  - CD-3a approval being sought in December 2015
    - By Spring 2016, could have approval for far site excavation
  - Excavation would then commence in 2017
  - Ready for start of FD installation in 2021
- **ProtoDUNE at CERN**
  - Recommended for approval by SPSC in October 2015
  - Construction starts in 2016
  - Major opportunity for Europe to contribute to DUNE at CERN
    - **Actively seeking contributions from existing and new collaborators**

8. Summary


50 YEARS OF DEEP SCIENCE AT SANFORD LAB'S FREE SCIENCE FESTIVAL
NEUTRINO DAY
Lead SD July 11, 2015
In 1965 Dr. Raymond Davis Jr. built his Nobel Prize
winning solar experiment on the 4850 Level at the
Homestake Gold Mine.

8. Summary

★ **Progress with LBNF/DUNE has been rapid**

★ **Ground-breaking scientific programme**

★ **Timescales are relatively short…**

- Excavation of underground far detector cavern starting 2017 (CD-3a in December 2015)
- ProtoDUNE operating in 2018
- Far detector installation starts in 2021

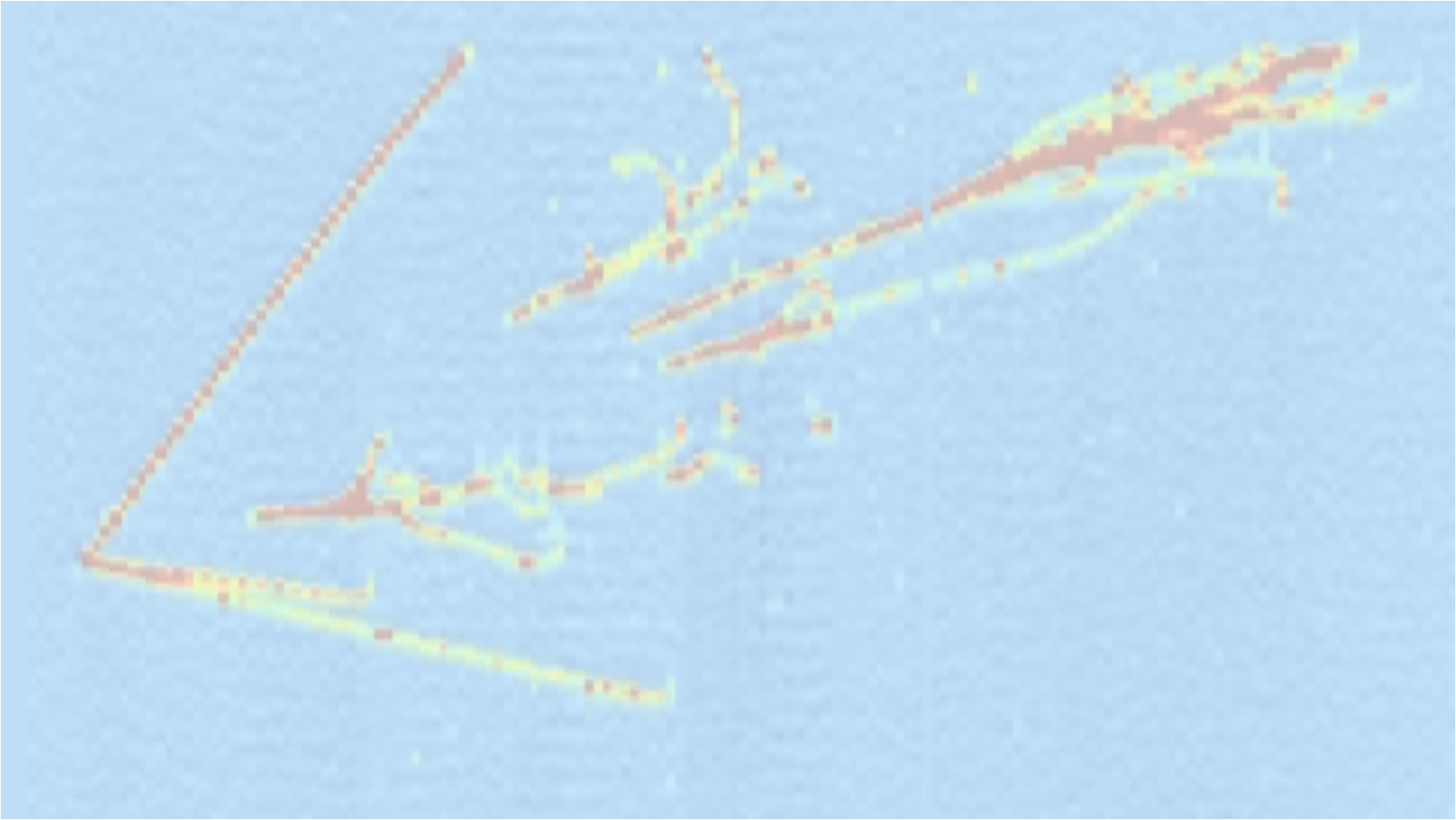
★ **Many exciting opportunities on DUNE**

- new collaborators are very welcome

Thank you for your attention

Backup Slides

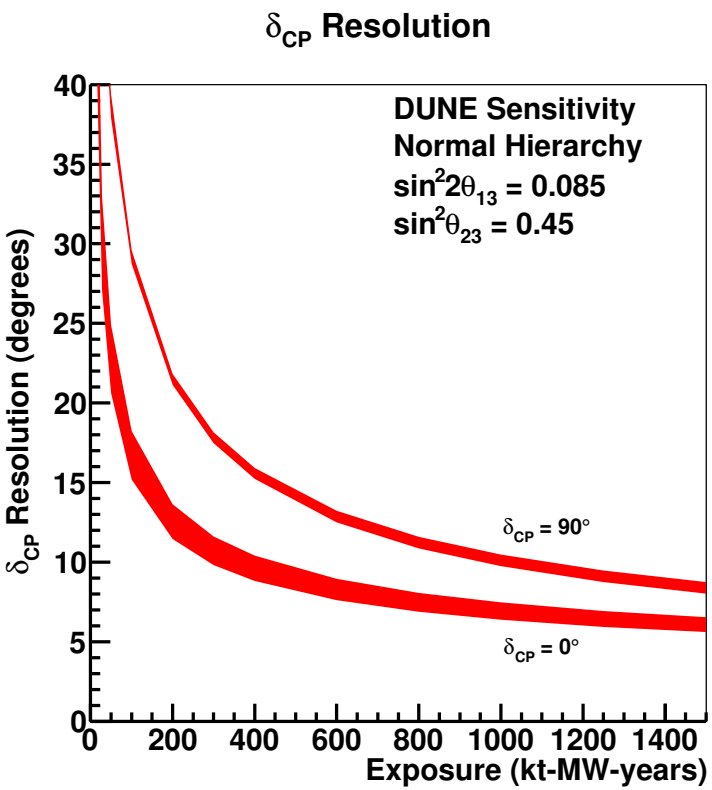
Science

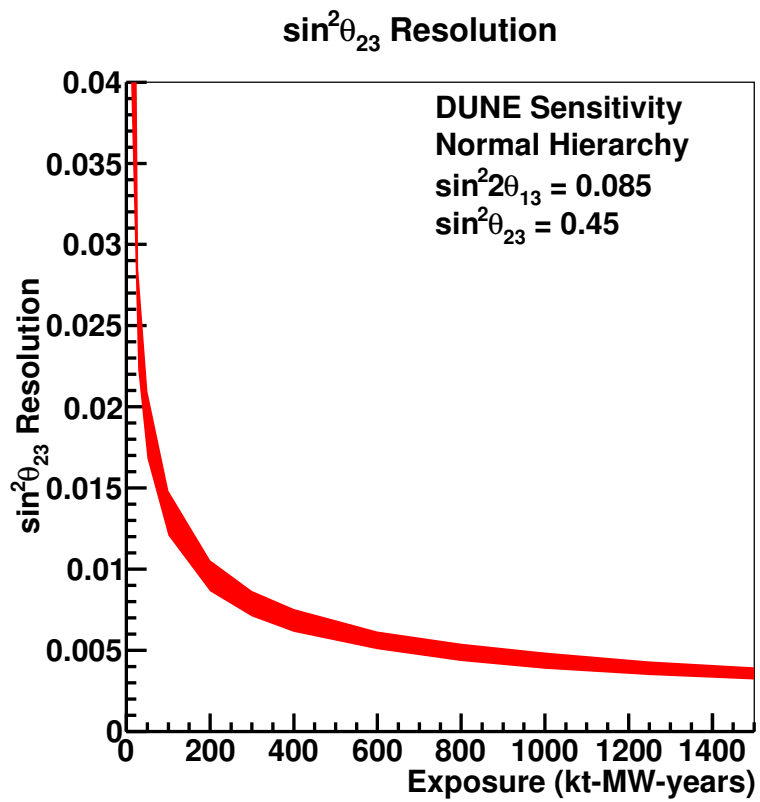


Parameter Resolutions

δ_{CP} & θ_{23}

- As a function of exposure

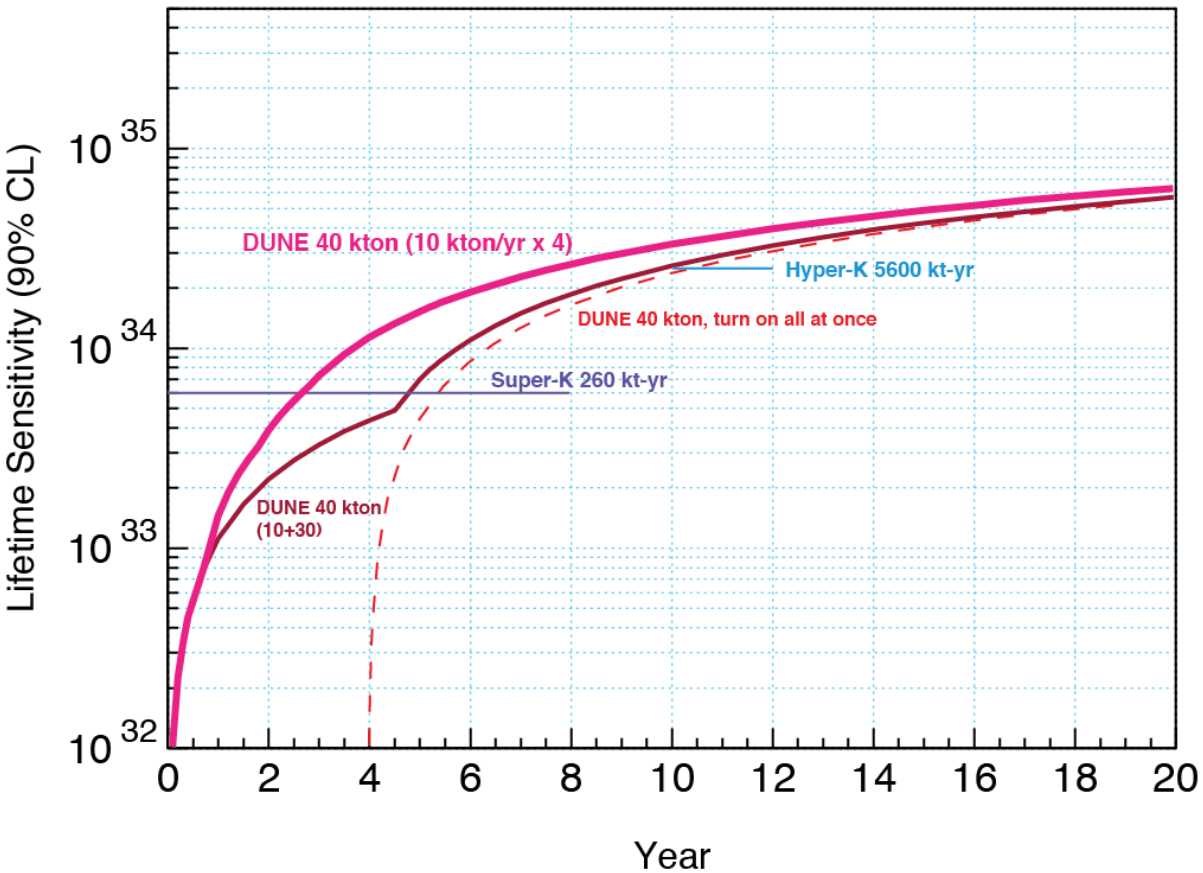




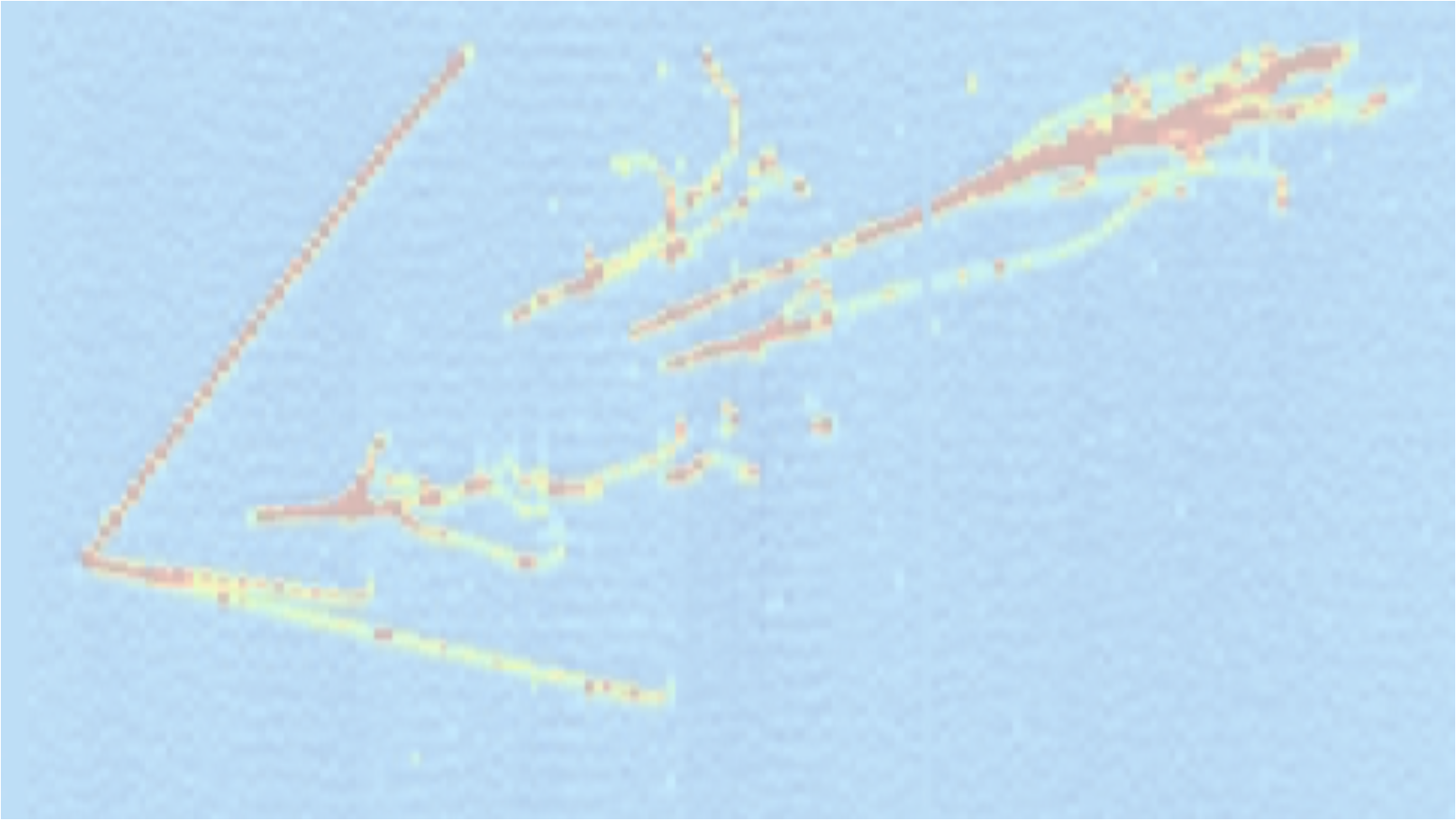
PDK

$p \rightarrow K \nu$

- DUNE for various staging assumptions

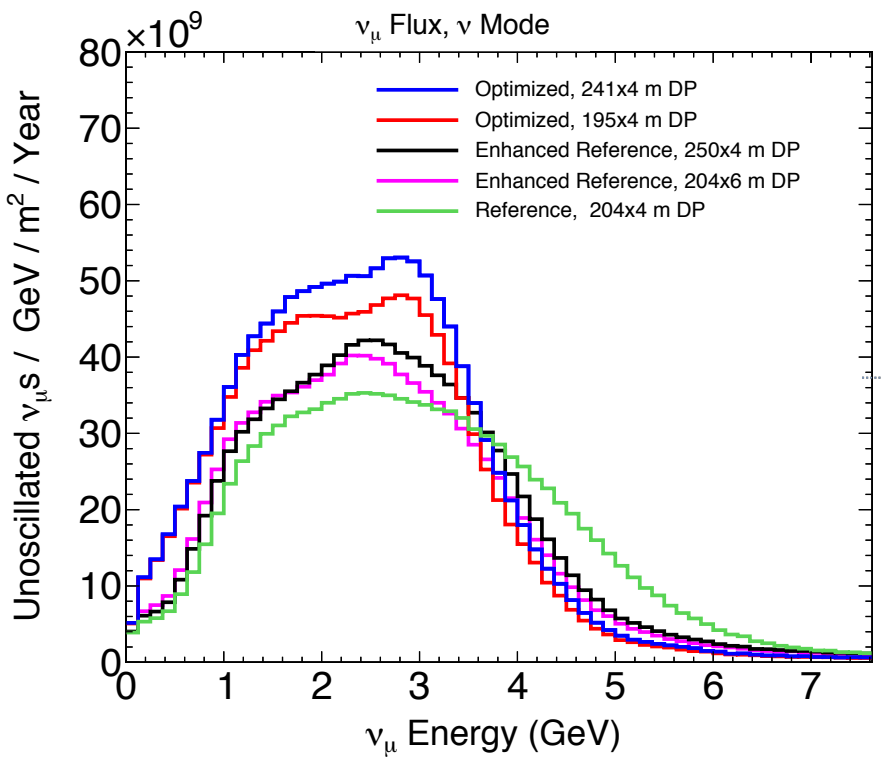


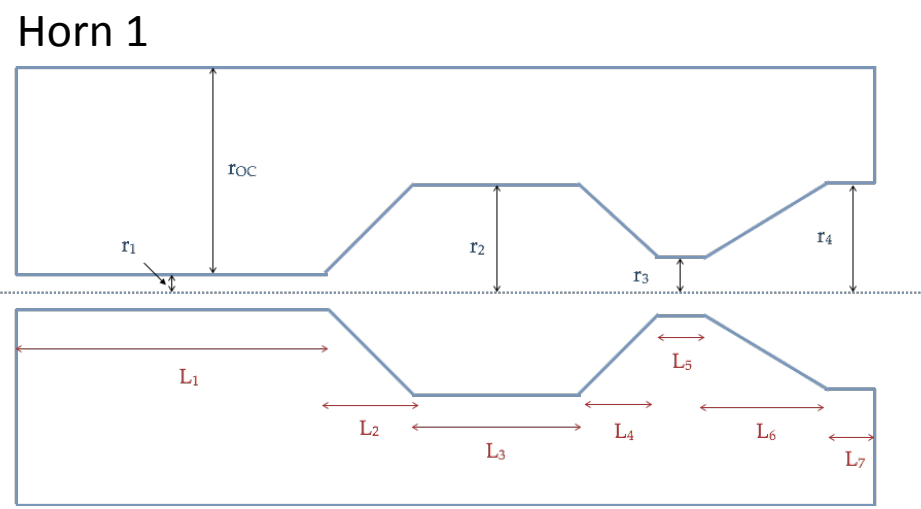
Beam Optimization



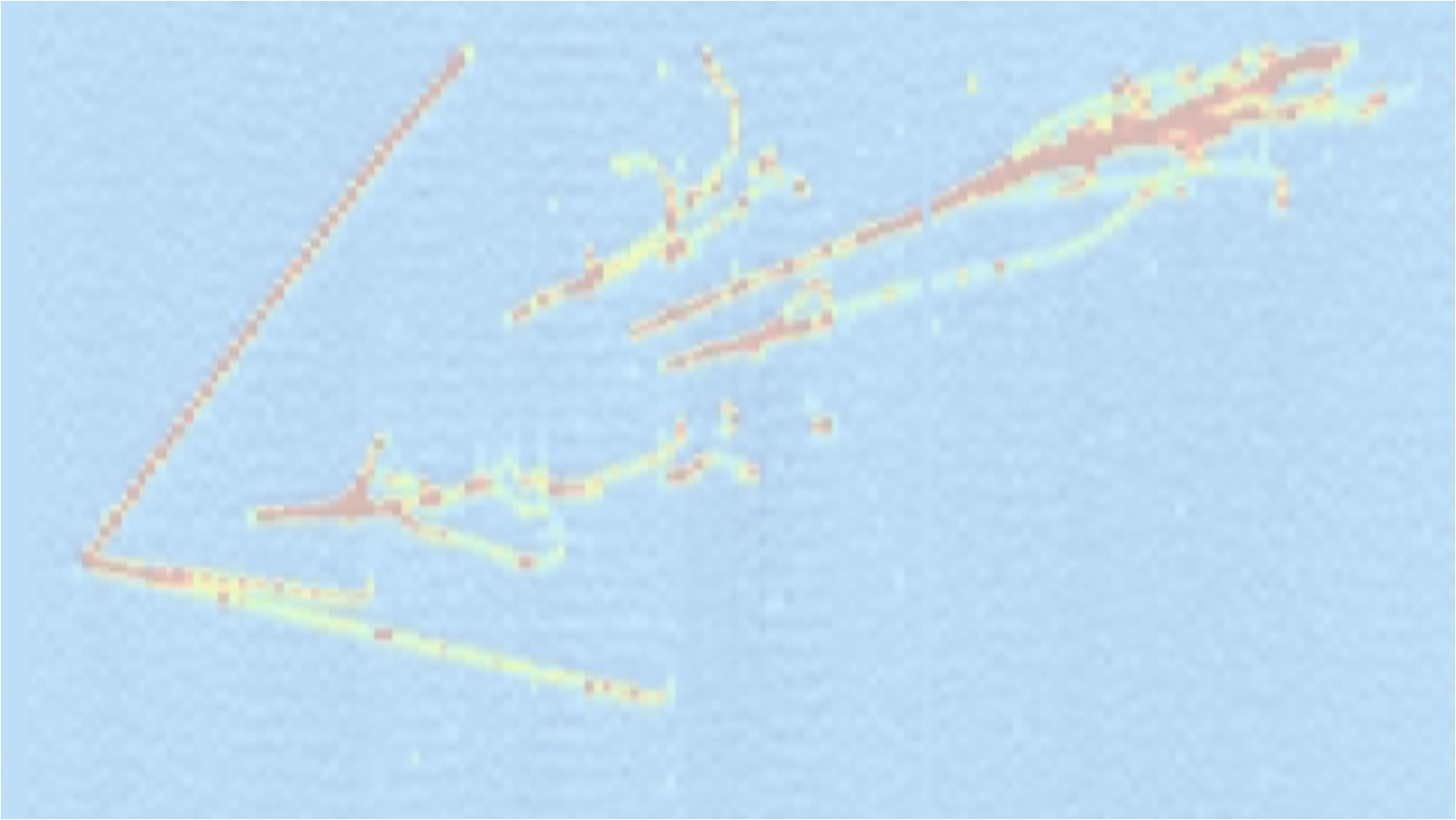
Beam Optimization

Following LBNO approach, genetic algorithm used to optimize horn design – increase neutrino flux at lower energies





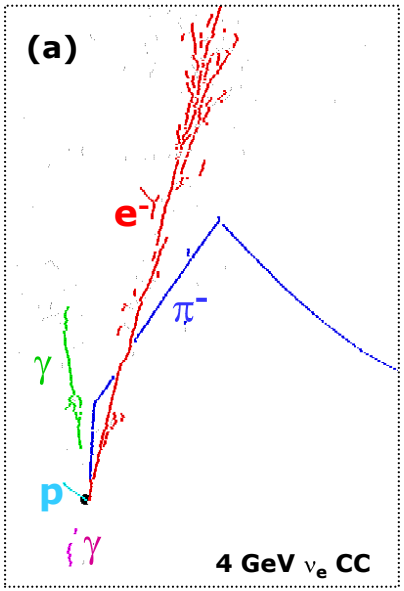
Reconstruction

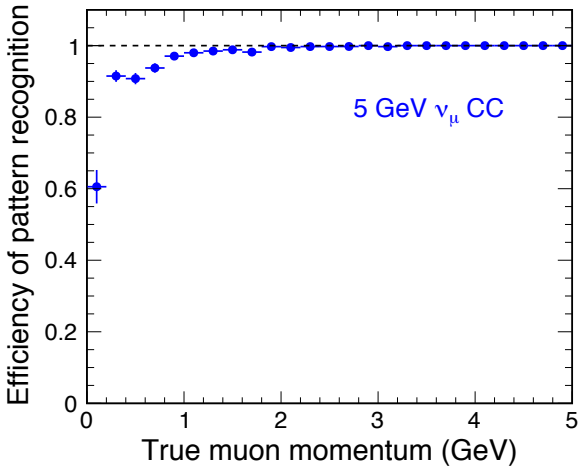


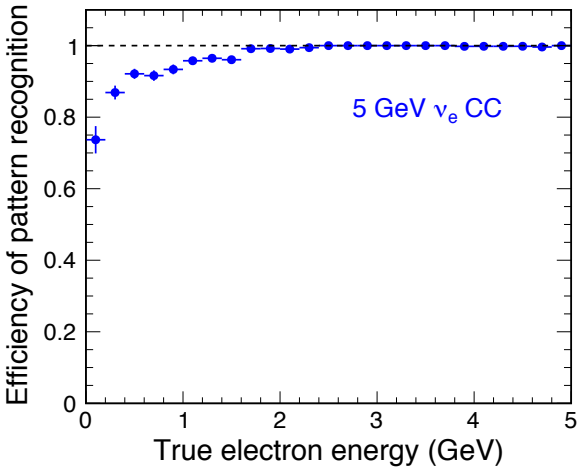
LAr-TPC Reconstruction

Real progress in last year – driven by 35-t & MicroBooNE

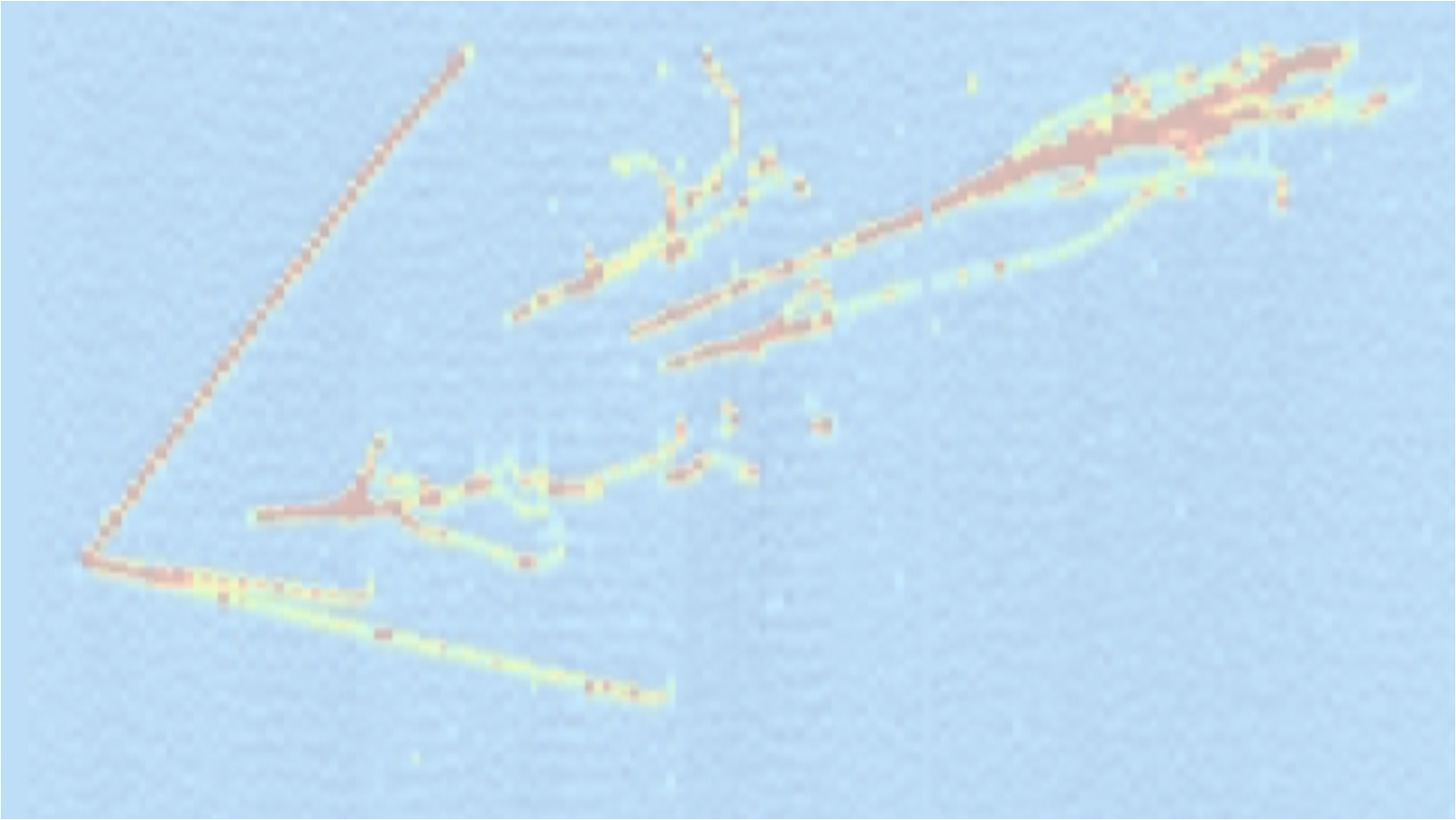
- Full DUNE simulation/reconstruction now in reach



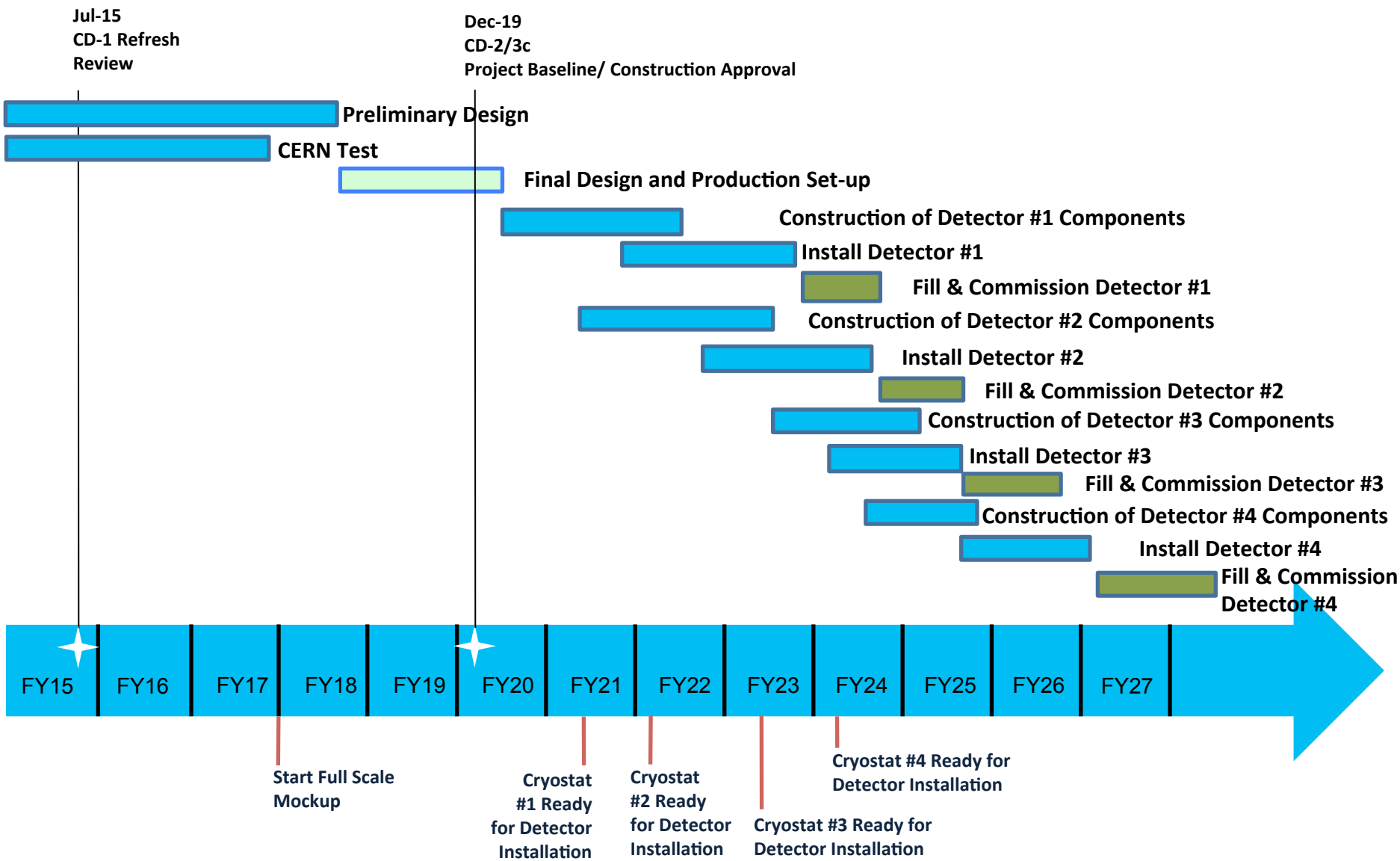




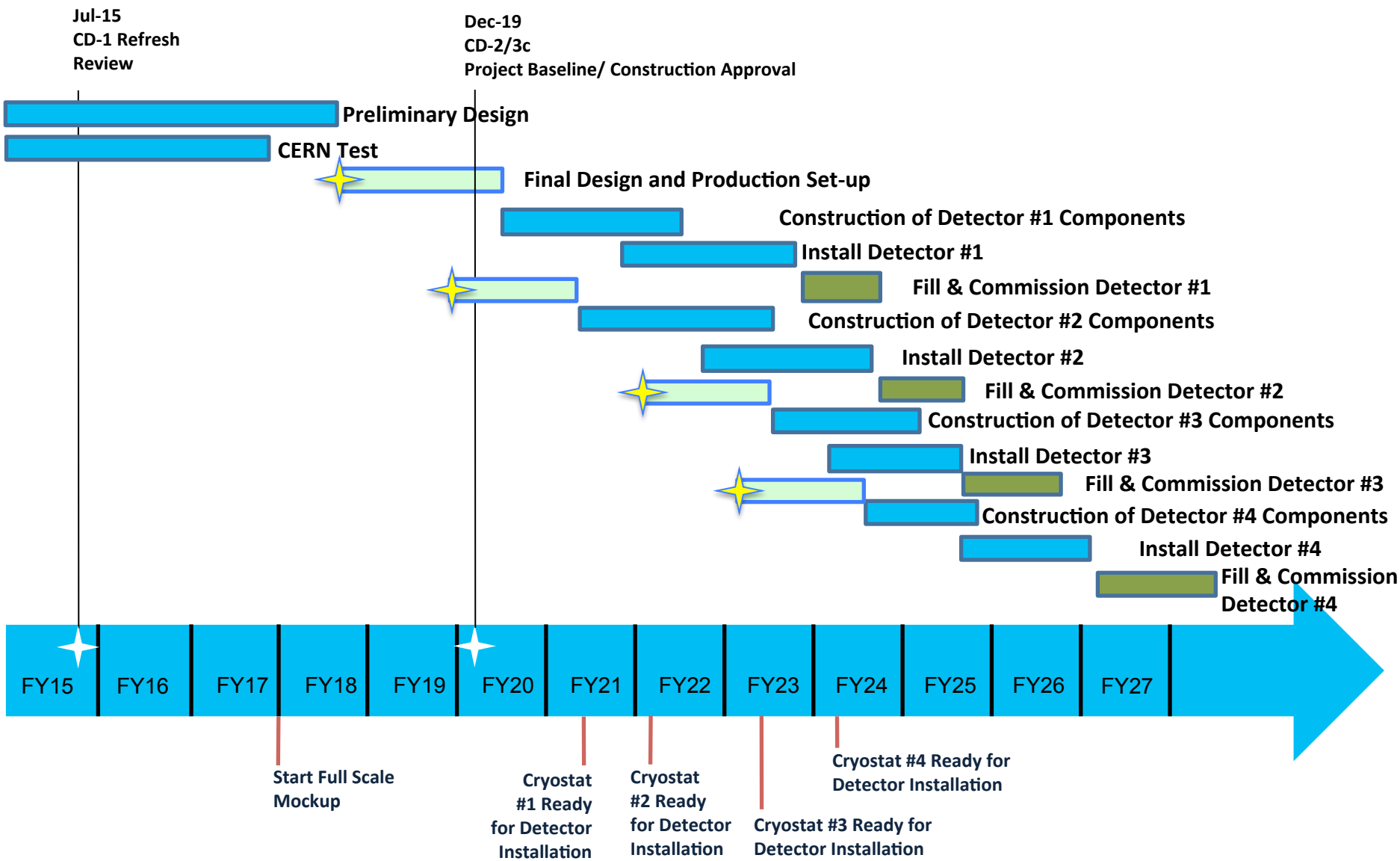
Schedule



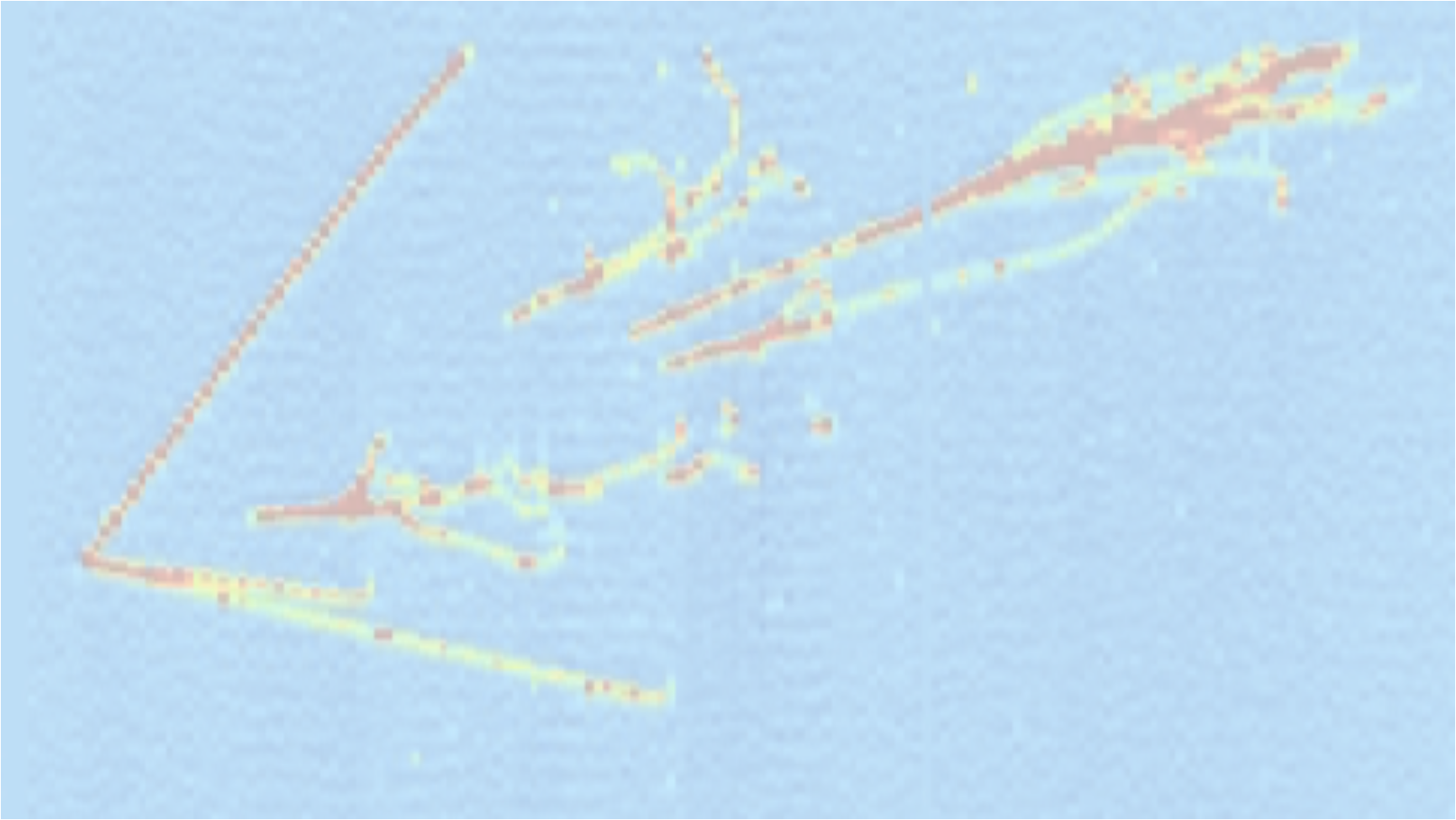
Indicative schedule



Indicative schedule



Calculating Sensitivities



Determining Physics Sensitivities

For Conceptual Design Report

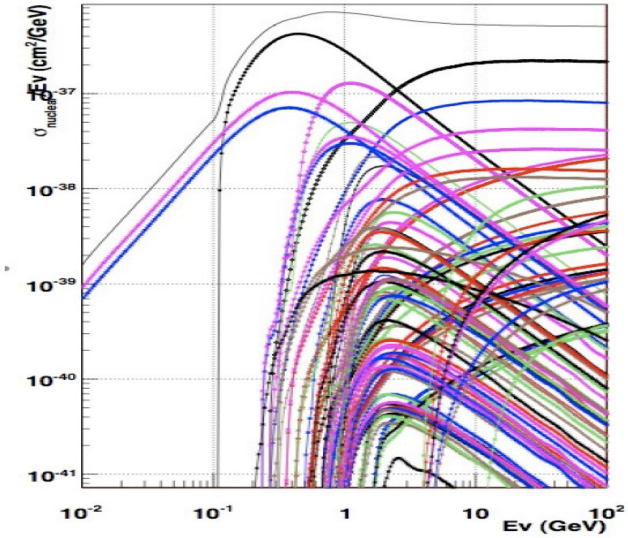
- **Full detector simulation/reconstruction not available**
  - See later in talk for plans
- **For Far Detector response**
  - Use parameterized single-particle response based on achieved/ expected performance (with ICARUS and elsewhere)
- **Systematic constraints from Near Detector + …**
  - Based on current understanding of cross section/hadro-production uncertainties
  - \+ Expected constraints from near detector
    - in part, evaluated using fast Monte Carlo

Evaluating DUNE Sensitivities I

Many inputs calculation (implemented in GLoBeS):

- **Reference Beam Flux**
  - 80 GeV protons
  - 204m x 4m He-filled decay pipe
  - 1.07 MW
  - NuMI-style two horn system
- **Optimized Beam Flux**
  - Horn system optimized for lower energies
- **Expected Detector Performance**
  - Based on previous experience (ICARUS, ArgoNEUT, …)
- **Cross sections**
  - GENIE 2.8.4
  - CC & NC
  - all (anti)neutrino flavors

Exclusive ν-nucleon cross sections



Evaluating DUNE Sensitivities II

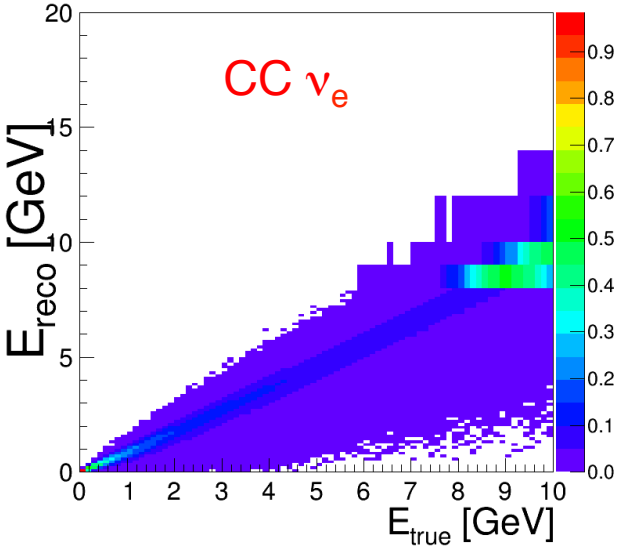
- **Assumed* Particle response/thresholds**
  - Parameterized detector response for individual final-state particles

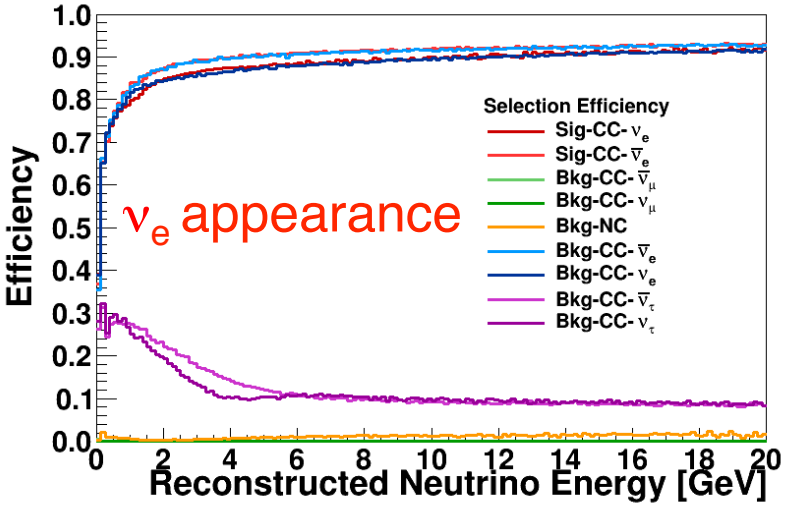
Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained: from track length Exiting: 30 %	1°
$\pi^{\pm}$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1°
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{(E/GeV)}$	1°
p	50 MeV	$p < 400$ MeV: 10 % $p > 400$ MeV: $5\% \oplus 30\%/\sqrt{(E/GeV)}$	5°
n	50 MeV	$440\%/\sqrt{(E/GeV)}$	5°
other	50 MeV	$5\% \oplus 30\%/\sqrt{(E/GeV)}$	5°

*current assumptions to be addressed by FD Task Force

Evaluating DUNE Sensitivities III

- **Efficiencies & Energy Reconstruction**
  - Generate neutrino interactions using GENIE
  - **Fast MC** smears response at generated final-state particle level
    - "Reconstructed" neutrino energy
    - kNN-based MV technique used for ν_e "event selection", parameterized as efficiencies
  - Used as inputs to GLoBES





Evaluating DUNE Sensitivities IV

- **Systematic Uncertainties**
  - Anticipated uncertainties based on MINOS/T2K experience
  - Supported by preliminary fast simulation studies of ND

Source	MINOS ν_e	T2K ν_e	DUNE ν_e
Flux after N/F extrapolation	0.3 %	3.2 %	2 %
Interaction Model	2.7 %	5.3 %	~ 2 %
Energy Scale (ν_μ)	3.5 %	Inc. above	(2 %)
Energy Scale (ν_e)	2.7 %	2 %	2 %
Fiducial Volume	2.4 %	1 %	1 %
Total	**5.7 %**	**6.8 %**	**3.6 %**

- **DUNE goal for ν_e appearance < 4 %**
  - For sensitivities used: 5 % $\oplus$ 2 %
    - where 5 % is correlated with ν_μ & 2 % is uncorrelated ν_e only

Prospects

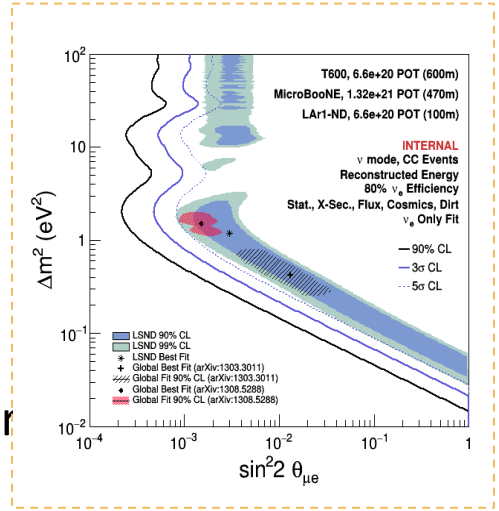
★ MicroBooNE:

- Will have (most likely) either:
  - confirmed the MiniBooNE low-energy anomaly or
  - isolated its origin

★ The SBN $\nu_\mu \rightarrow \nu_e$ Appearance search

- Will have either:
  - confirmed the LSND anomaly is due to neutrino oscillations
    - a major discovery -

  or
  - ruled out light sterile neutrinos over the entire LSND mass range



★ Loopholes:

- LSND excess was in $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- OscSNS, …?