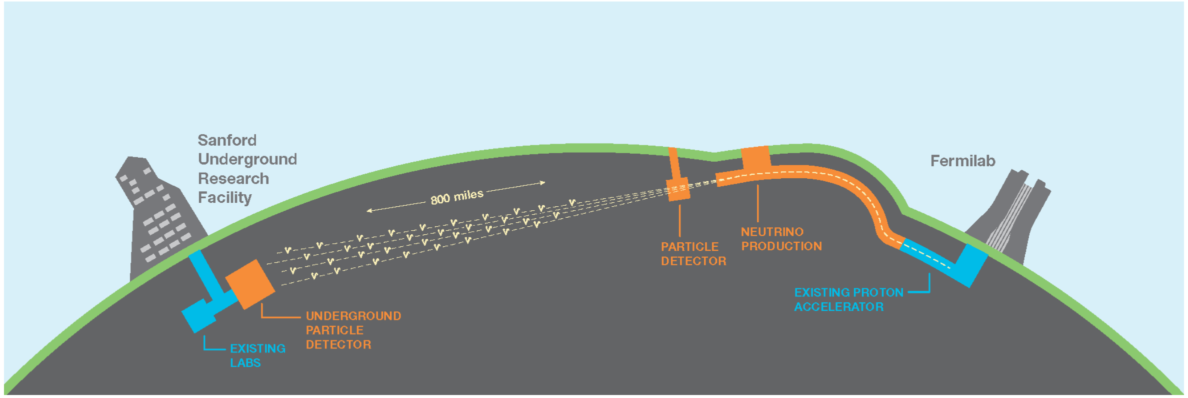


DUNE: The Deep Underground Neutrino Experiment

Mark Thomson

University of Cambridge & co-spokesperson of DUNE

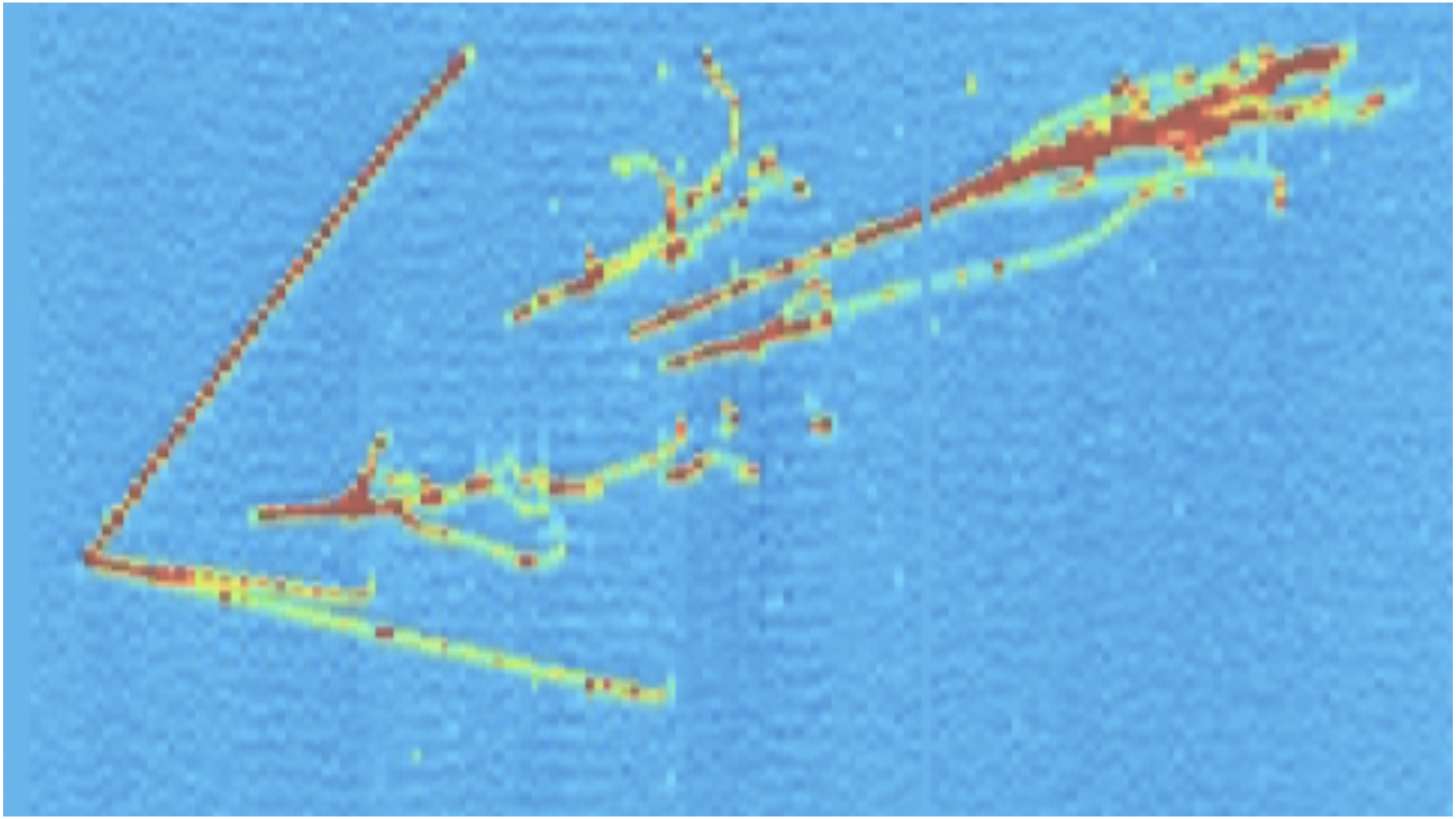
Liverpool HEP Seminar

UNIVERSITY OF CAMBRIDGE

DUNE

Topic	Slides
1: Context: The 2012 Revolution	1
2: Why are neutrinos so important	2
3: Neutrinos – known unknowns	5
4: How to Detect CPV with Neutrinos?	4
5: LBNF/DUNE	6
5.1: DUNE Science Strategy	8
5.2: LBNF	2
5.3: DUNE Far Detector	10
5.4: DUNE Near Detector	1
6: DUNE Physics Sensitivities	8
7: Political Context	1
8: Summary	1

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

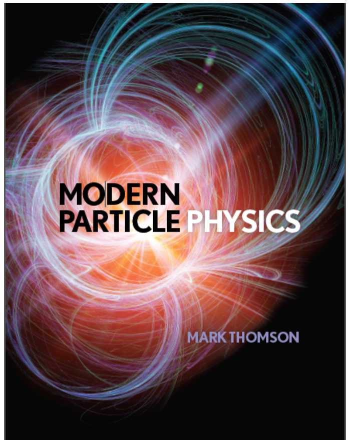
The 2012 Revolution

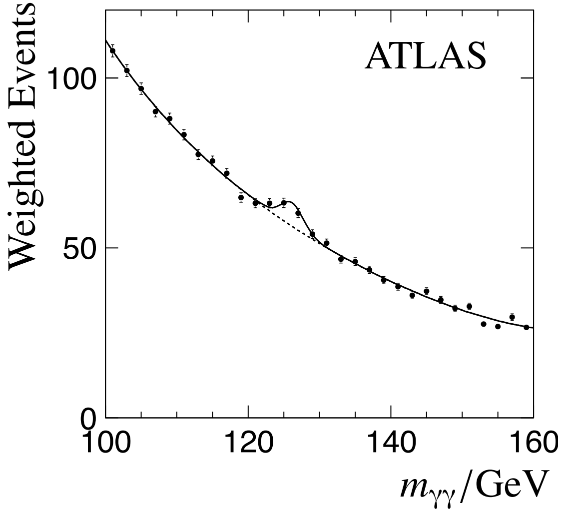
★ **Two major discoveries in particle physics**

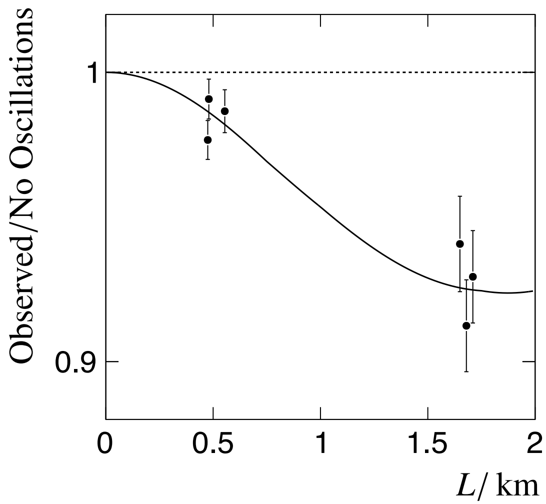
- A SM-like Higgs boson (ATLAS, CMS)
  - The key to EWSB and a possible window to the BSM world
- $\theta_{13} \sim 10^{\circ}$ (T2K, MINOS, Daya Bay, RENO)
  - about as large as it could have been !
  - The door to CP Violation in the leptonic sector

★ **Now textbook physics***

- plan the next steps







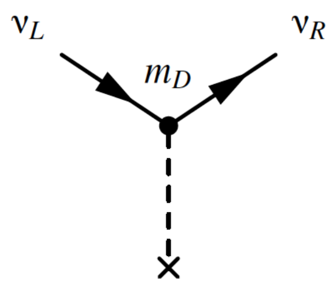
*apologies for gratuitous plug

2. Why are Neutrinos so Important?

a connection to BSM physics

★ Neutrino masses are anomalously small

- Why is this the case …or what is the origin of neutrino mass

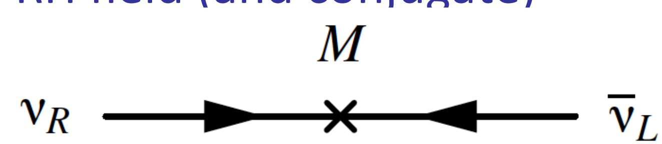


⇨ Dirac mass terms, Higgs coupling together L- and R-handed chiral fermionic fields

$$\frac{Y_f}{\sqrt{2}} v\left(\overline{f}_L f_R + \overline{f}_R f_L\right)$$

- This could be the origin of neutrino masses
  - ⇨ Existence of RH neutrino – a rather minimal extension to the SM?
- But a RH neutrino is a gauge singlet
  - ⇨ Can now add "by hand" a new Majorana mass term to the SM Lagrangian, involving only the RH field (and conjugate)

$$\sim M\overline{\nu_R^c}\nu_R$$

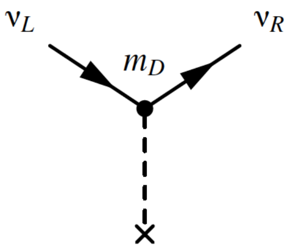


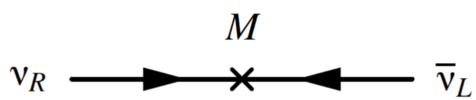
This additional freedom might explain why neutrino masses are "different"

a connection to BSM physics

★ Is there a connection to the GUT scale?

- If both Dirac and Majorana mass terms are present





(nothing to prevent this)

+ implies Lepton # violation

⇨ $$\mathcal{L} \sim -\tfrac{1}{2}\begin{pmatrix} \overline{\nu_L} & \overline{\nu_R^c} \end{pmatrix}\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

- The seesaw mechanism: the physical "mass eigenstates" are those in the basis where the mass matrix is diagonal

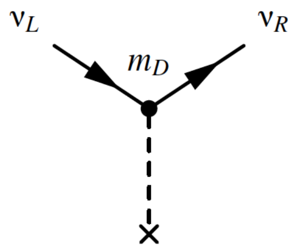
⇨ Light LH neutrino $m_\nu \approx \dfrac{m_D^2}{M}$ + heavy RH neutrino $m_N \approx M$

- With $m_D \sim m_\ell$ and $M \sim 10^{12} - 10^{16}\,\mathrm{GeV}$ get to right range of small neutrino masses!

a connection to BSM physics

★ Is there a connection to the GUT scale?

- If both Dirac and Majorana mass terms are present



(... ns)

... violation

$\Rightarrow$ $\mathcal{L} \sim -\frac{1}{2}\left(\overline{\nu_L} \;\; \overline{\nu^c} \ldots \right) \ldots \left(\begin{array}{c} \ldots \\ \nu_R \end{array} \right)$

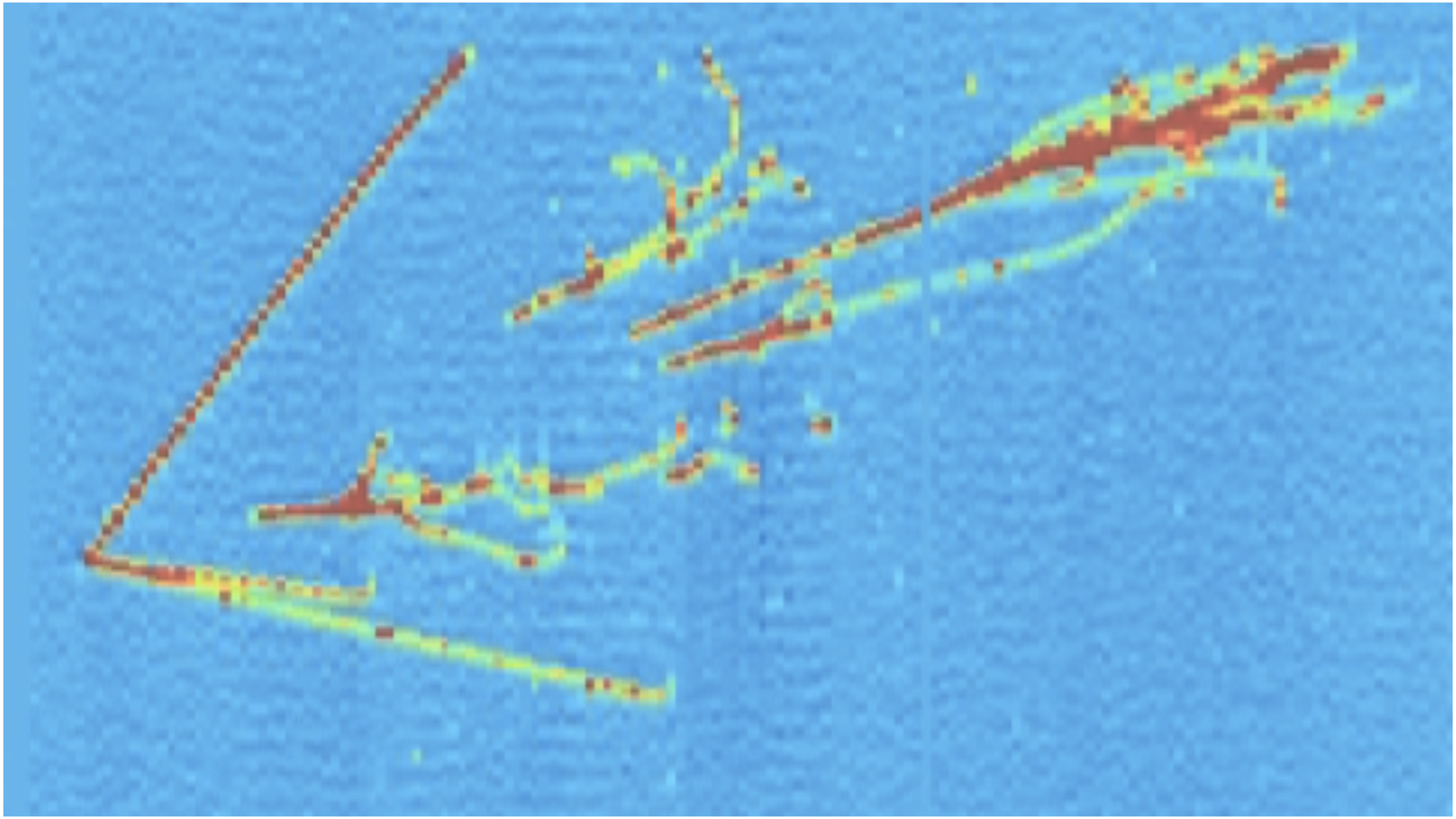
- The seesaw mech... ...sical "mass eigenstates" are those i... ...e the mass matrix is diagonal

...rino $m_\nu \approx \frac{m_D^2}{M}$ + heavy RH neutrino $m_N \approx M$

- $m_D \sim m_\ell$ and $M \sim 10^{12} - 10^{16}\,\mathrm{GeV}$ get to right range of small neutrino masses!

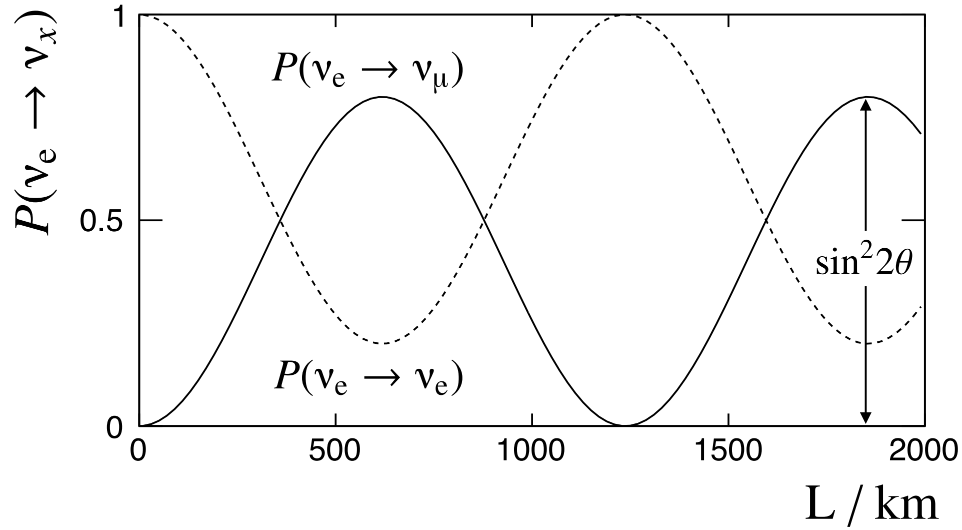
Neutrinos may provide a window to GUT-scale physics
Argues for a precision neutrino physics programme

3: Neutrinos – known unknowns



The Standard Neutrino Paradigm

★ **Neutrino flavor oscillations now a well established physical phenomenon:**



L/E_ν
dependence

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

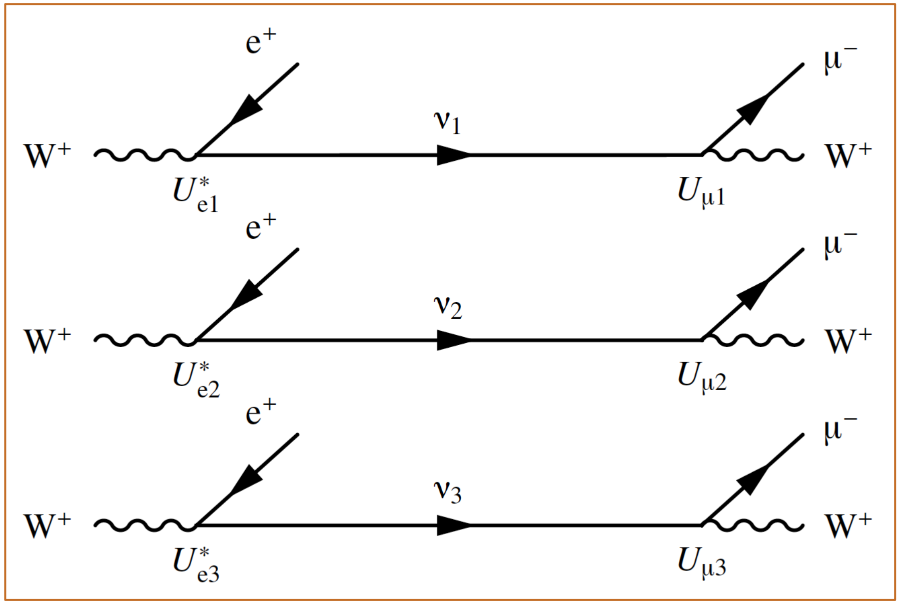
- Neutrinos have non-zero mass
- Neutrino mass eigenstates (ν_1, ν_2, ν_3) ≠ weak eigenstates (ν_e, ν_μ, ν_τ)

The PMNS Matrix

- The non-alignment of the mass and weak eigenstates described by the **Unitary** PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Effectively describes the couplings between the **charged** and **neutral** leptons



e.g. $\nu_e \rightarrow \nu_\mu$ "oscillations"

- ν propagates as a coherent state
- oscillations arise from phase differences between the different mass eigenstates
- i.e. when neutrinos have different masses

→ $m_\nu \neq 0$

The Standard 3-Flavor Paradigm

★ **Unitary PNMS matrix ⇨ mixing described by:**

- three "Euler angles": $(\theta_{12},\ \theta_{13},\ \theta_{23})$
- and one complex phase: δ

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

with $s_{ij} = \sin\theta_{ij}\ ;\ c_{ij} = \cos\theta_{ij}$

★ If $\delta \neq \{0, \pi\}$ then SM leptonic sector ⇨ CP violation (CPV)

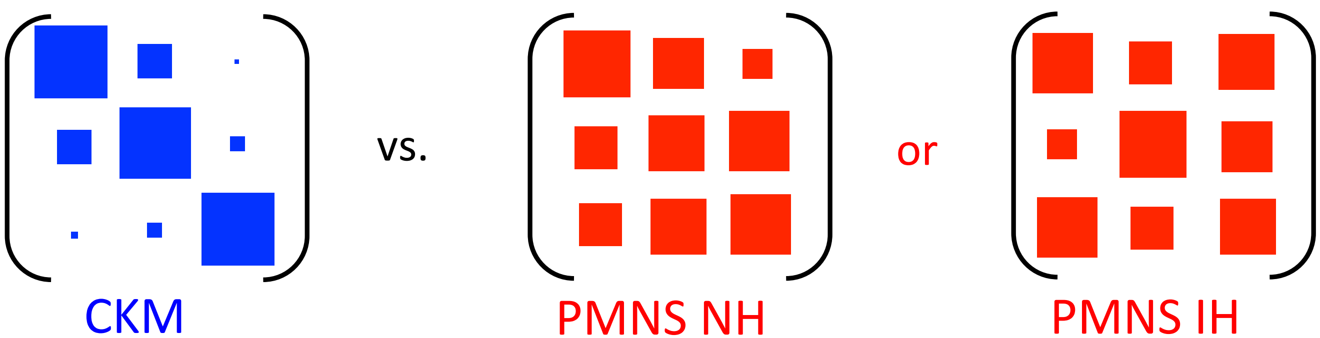
- CPV effects $\propto \sin\theta_{13}$
- **now know that θ_{13} is relatively large**

⇨ **CPV is observable with conventional ν beams**

⇨ **LBNF/DUNE**
Hyper-Kamiokande

The Known Unknowns

- ★ **We now know a great deal about the neutrino sector**
- ★ **But still many profound questions**
  - Why are neutrino masses so small ?
    - Is there a connection to the GUT scale?
  - Are there **light** sterile neutrino states ?
    - No clear theoretical guidance on mass scale…
  - What is the neutrino mass hierarchy ?
    - An important question in flavor physics, e.g. CKM vs. PNMS

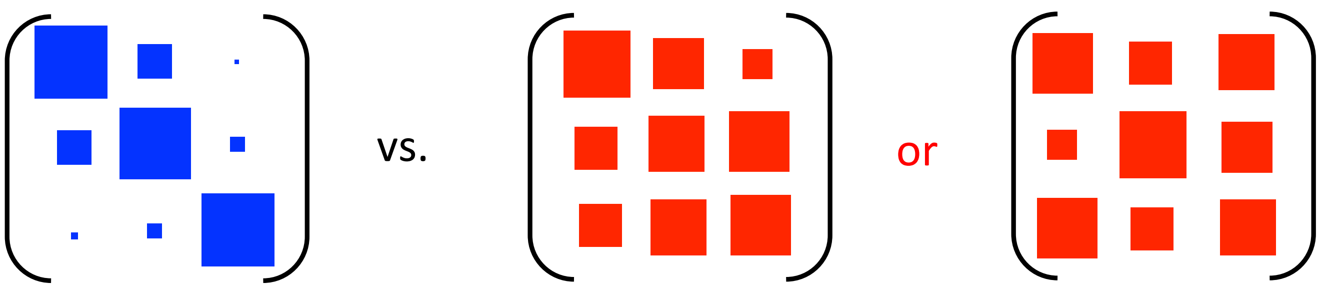


  - **Is CP violated in the leptonic sector ?**
    - Are νs key to understanding the matter-antimatter asymmetry?

The Known Unknowns

★ **Next generation Long-Baseline experiments (such as DUNE) can address three of these questions:**

- Why are neutrino masses so small ?
  - Is there a connection to the GUT scale?
- **Are there light sterile neutrino states ?** → Breaks 3-flavor paradigm
  - No clear theoretical guidance on mass scale…
- **What is the neutrino mass hierarchy ?**
  - An important question in flavor physics, e.g. CKM vs. PNMS



CKM PMNS NH PMNS IH

- **Is CP violated in the leptonic sector ?**
  - Are νs key to understanding the matter-antimatter asymmetry?

The Key Question (my personal bias)

Is CP violated in the neutrino sector ?

★ If $\delta \neq \{0, \pi\}$ the answer is YES

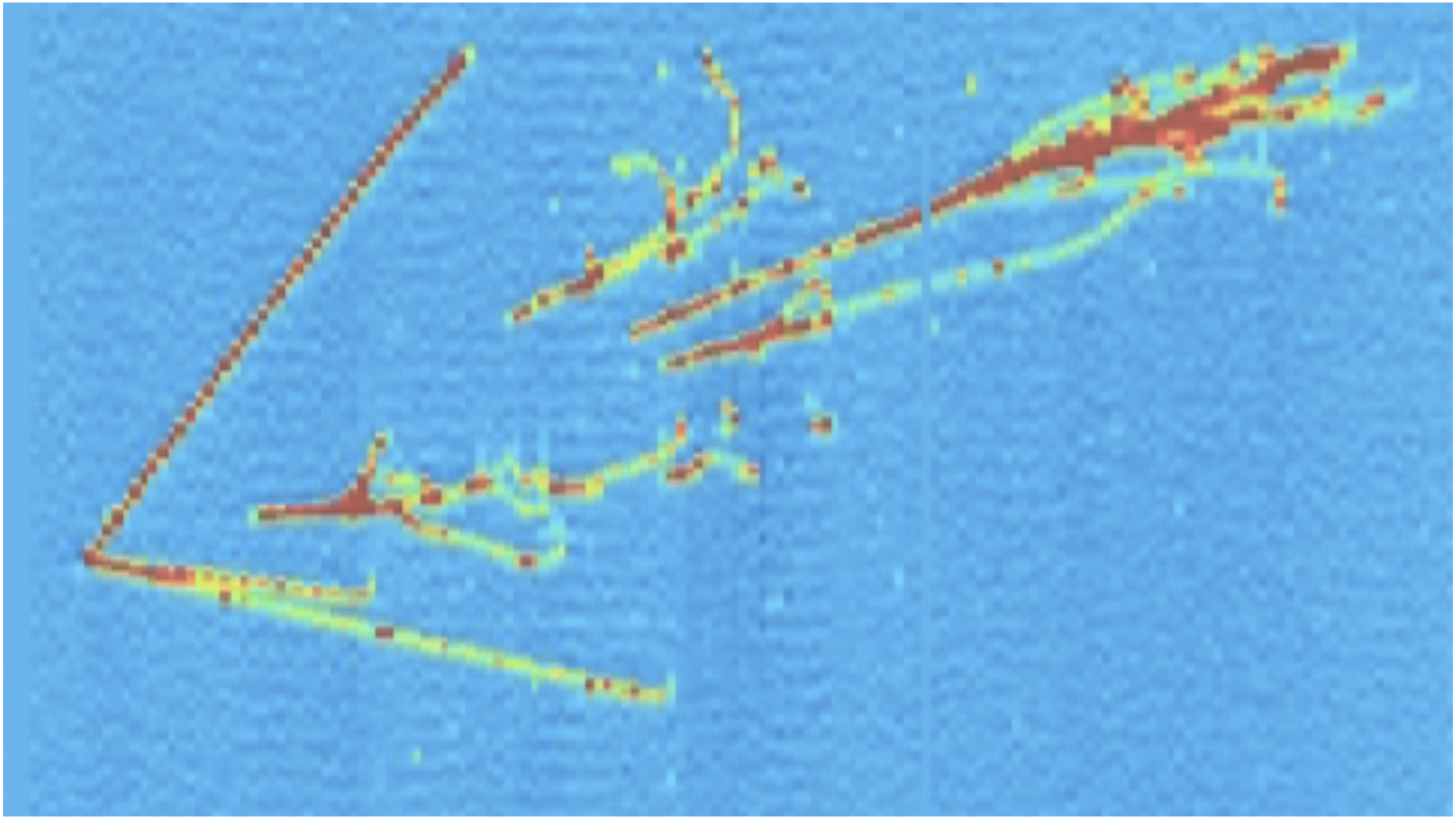
- If yes, would provide strong support* for the hypothesis of Leptogenesis as the mechanism for generating the matter-antimatter asymmetry in the universe

★ Strong motivation to aim for a definitive observation for CPV in the ν sector

- Ideally want "precise" measurement of CP phase

*not proof, since still need to connect low-scale ν CPV physics to the high-scale N CPV physics

4: How to Detect CPV with νs



In principle, it is straightforward

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

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

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

vacuum osc.

★ 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 $P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$?

★ Not quite, there is a complication…

Matter Effects

★ Even in the absence of CPV

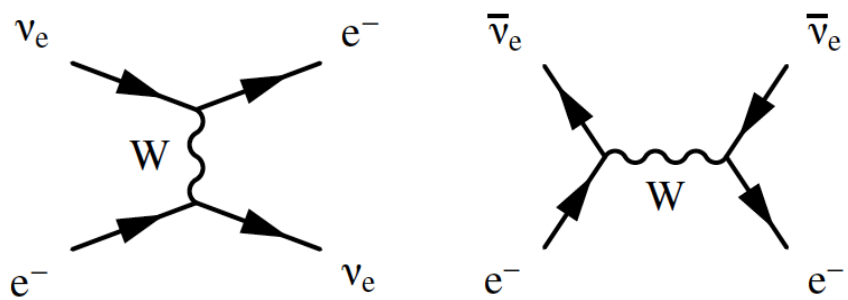
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = 0$$

Neutrinos travel through material that is not CP symmetric, i.e. matter not antimatter

★ In vacuum, the mass eigenstates ν_1, ν_2, ν_3 correspond to the eigenstates of the Hamiltonian:

- they propagate independently (with appropriate phases)

★ In matter, there is an effective potential due to the forward weak scattering processes:



$$V = \pm\sqrt{2}G_F n_e$$

Different sign for ν_e vs $\bar{\nu}_e$

Neutrino Oscillations in Matter

★ Accounting for this potential term, 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 !!!!

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

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

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 this potential term, 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 !!!!

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

← 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

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

← 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:

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

- 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:

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

- **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:

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

- Since … …a 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:

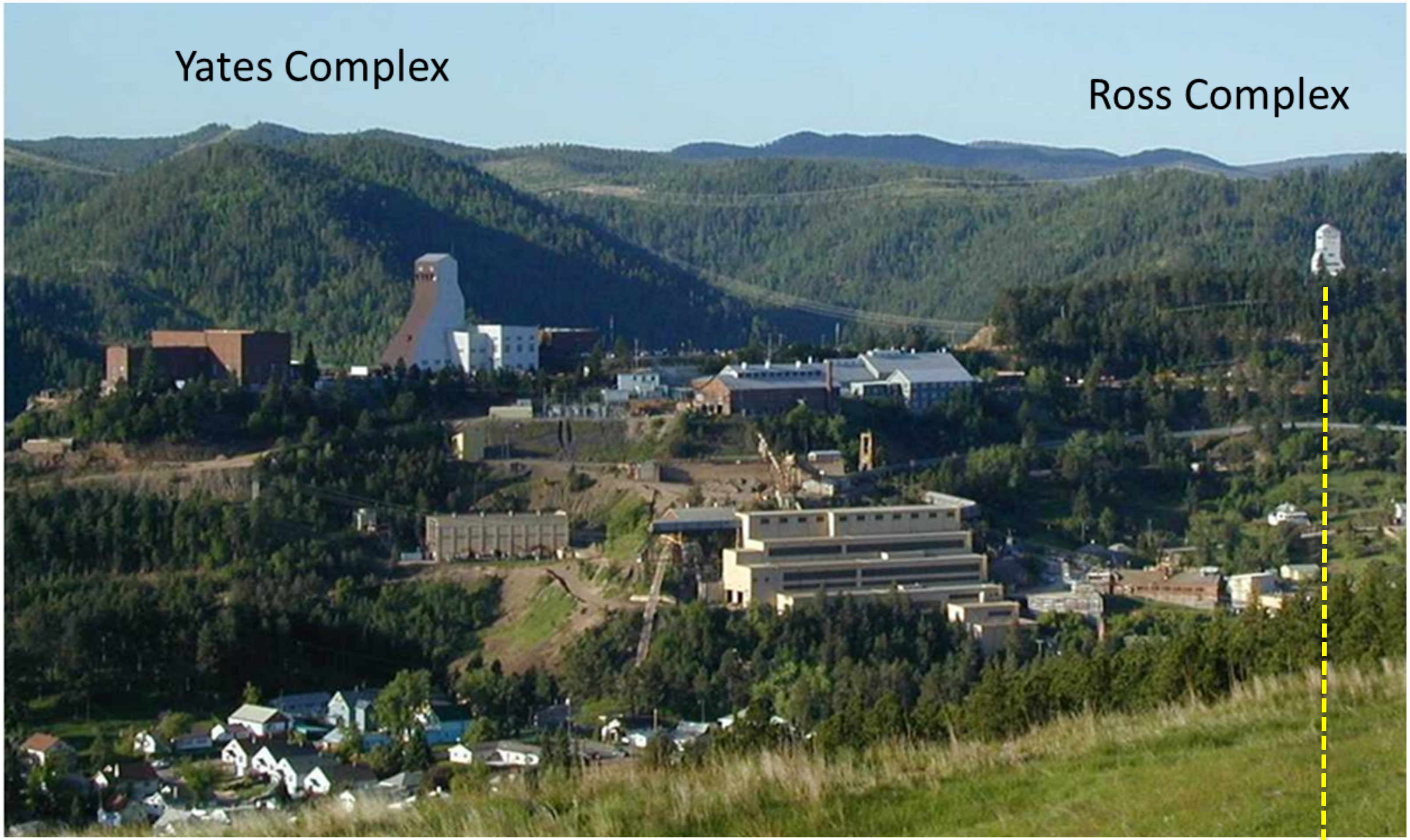
$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

- **Unfold CPV from Ma… …cts through E dependence**

⇨ On-axis beam: wide range of neutrino energies

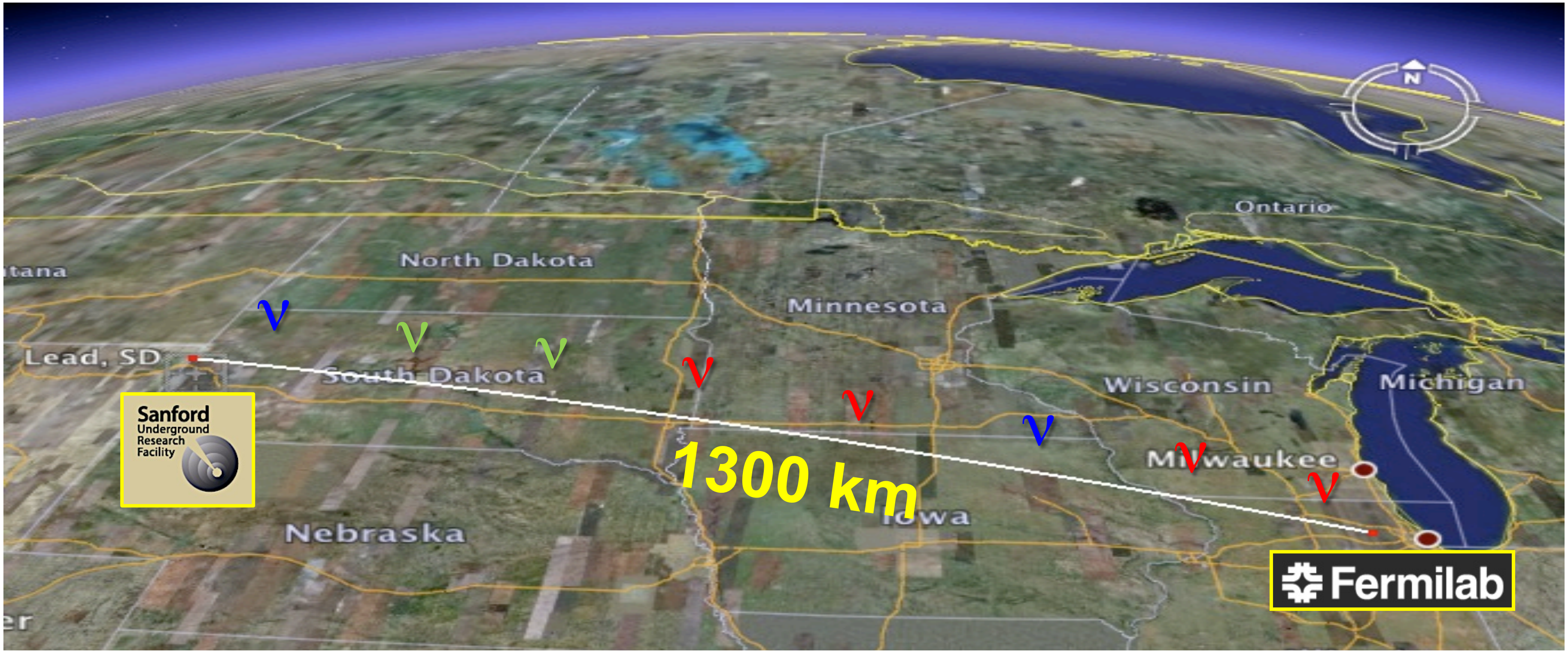
DUNE

5. 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 ?



DUNE/LBNF in a Larger Nutshell

★ DUNE/LBNF

- 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 $\geq$ **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 up-and-running

It is a rapidly evolving scientific collaboration…

- **First formal collaboration meeting April 16th-18th 2015**
  - Over 200 people attended in person
- **Conceptual Design Report in June**
- **Passed DOE CD-1 Review in July**
- **Second collaboration meeting September 2nd-5th 2015**

DUNE is up-and-running

It is a rapidly evolving scientific collaboration…

- **First formal collaboration meeting April 16^{th}-18^{th} 2015**
  - Over 200 people attended in person
- **Conceptual Design Report in June**
- **Passed DOE CD-1 Review in July** → **DUNE is on the real axis !**
- **Second collaboration meeting September 2^{nd}-5^{th} 2015**

DUNE

has strong support from:

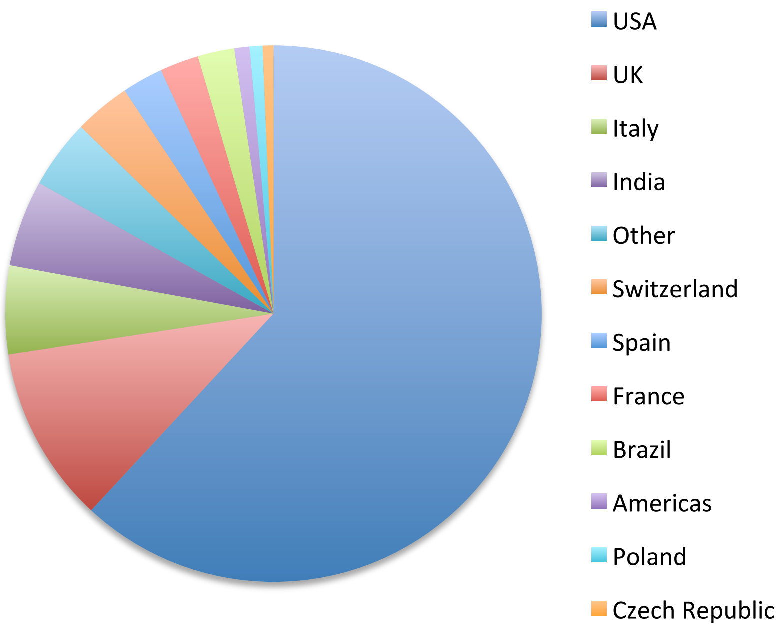
- **Fermilab and US DOE:**
  - This is *the* future flagship project for Fermilab
- **CERN**
  - Very significant agreements on CERN – US collaboration

+ Strong international interest: Brazil, India, Italy, Switzerland, UK, …

The DUNE Collaboration

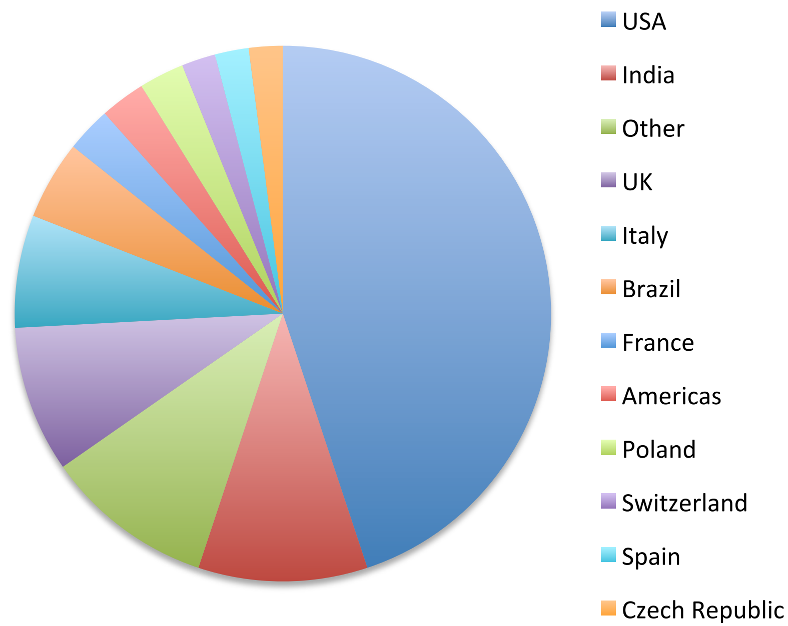
As of today:

799 Collaborators



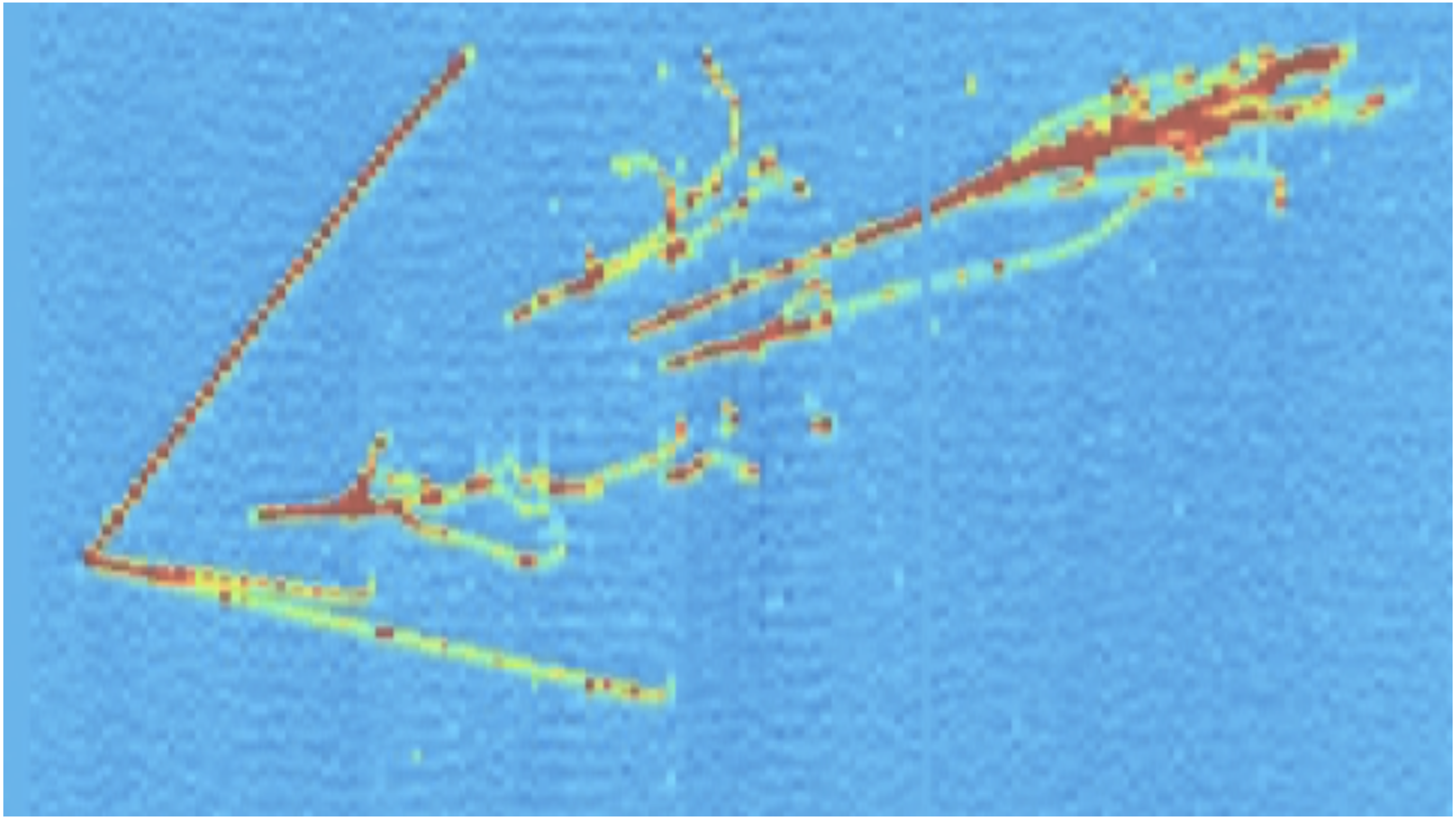
from

145 Institutes



DUNE has broad international support

5.1: 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. $p \rightarrow K^{+}\overline{\nu}$
- **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:

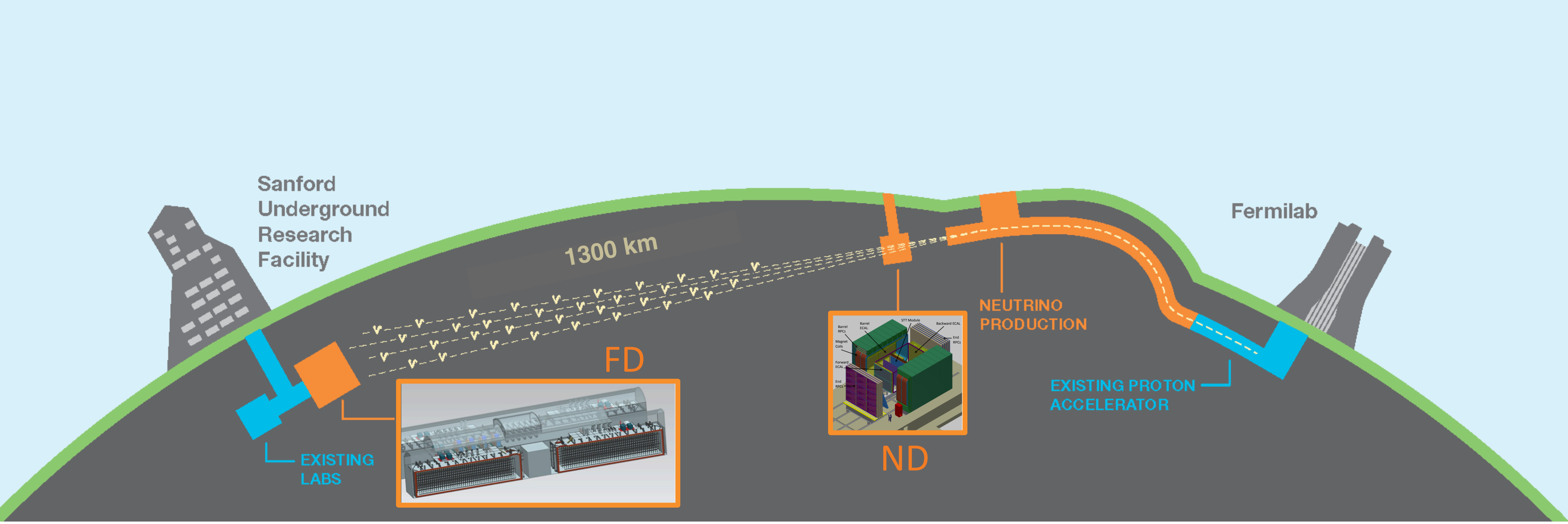
- 1) Neutrino Oscillation Physics
  - **CPV in the leptonic sector**
  - **Definitive determination of ... erarchy**
  - Precision Oscillation Ph... ctant, …) & **testing the 3-flavor paradigm**
- 2) Nucleo...
  - Tar... favored modes, e.g. $p \to K^{+}\bar{\nu}$
- ... nova burst physics & astrophysics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

All would be a <u>major</u> discoveries

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

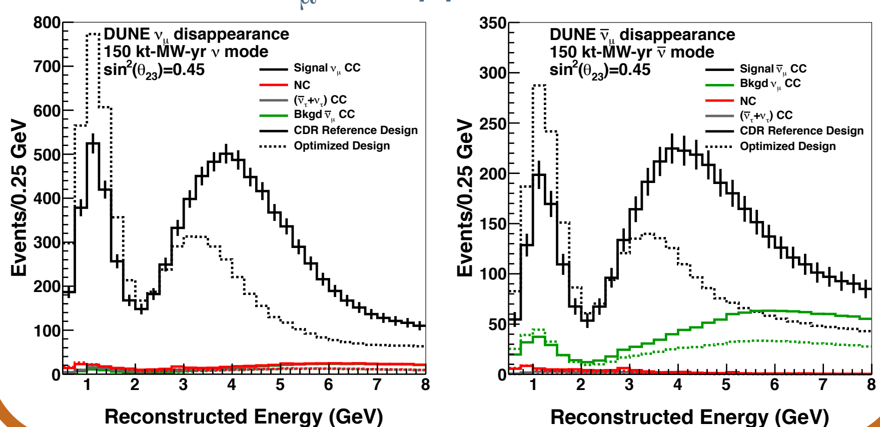
DUNE Oscillation Strategy

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

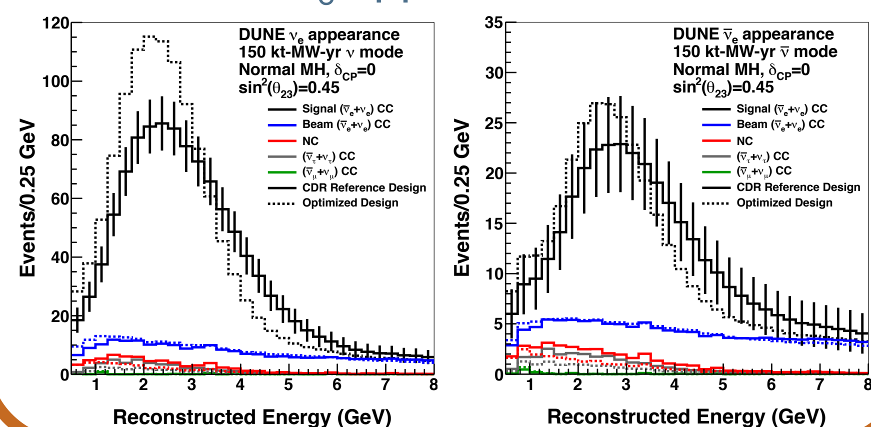
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects are separable

E ~ few GeV

ν_μ disappearance



ν_e appearance

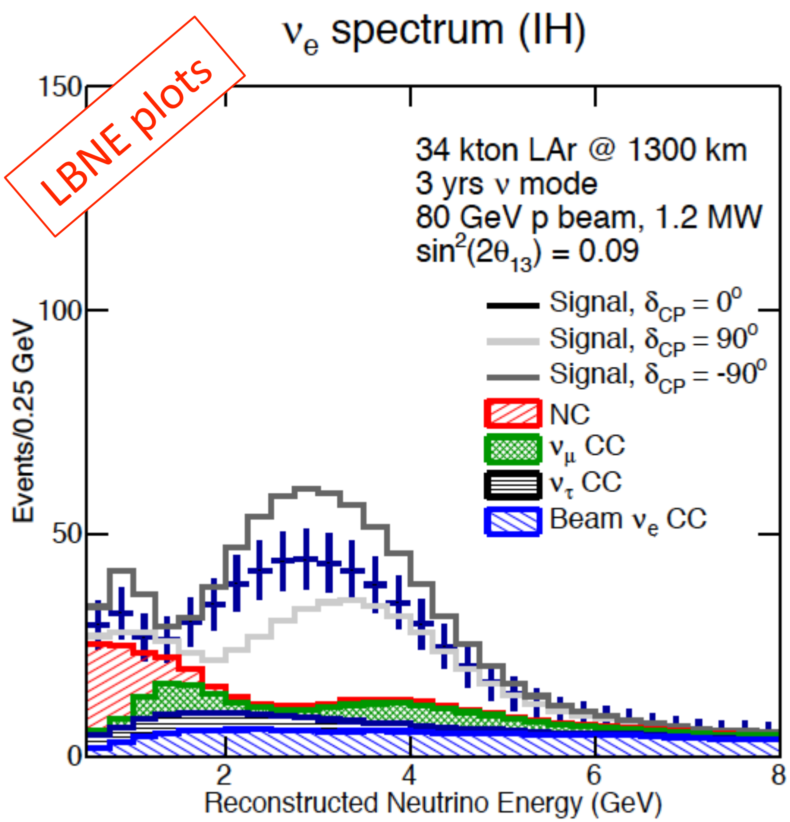


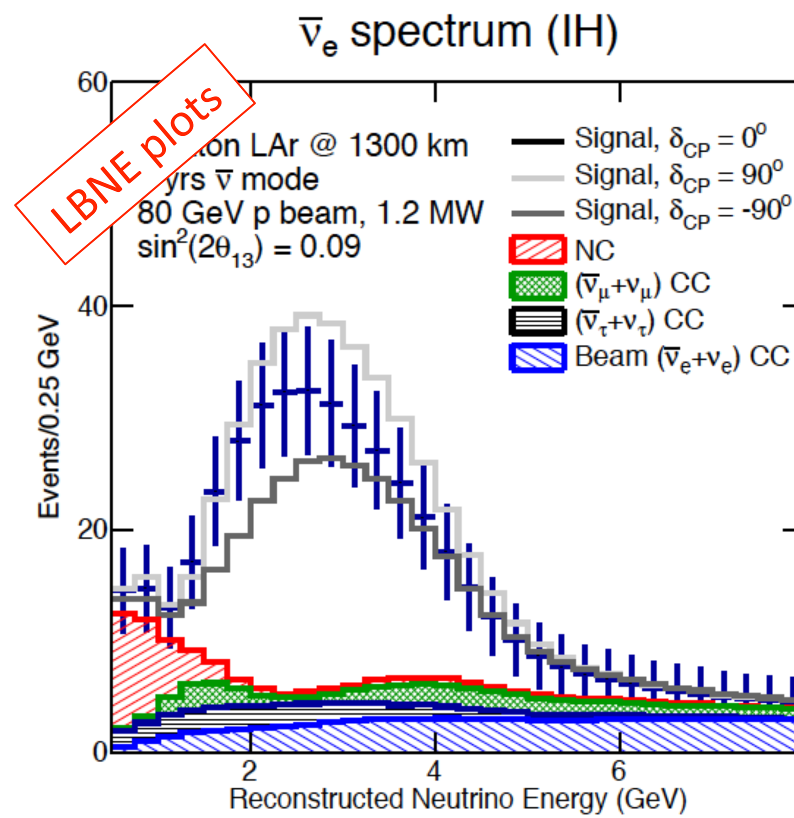
Separating MH & CPV

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



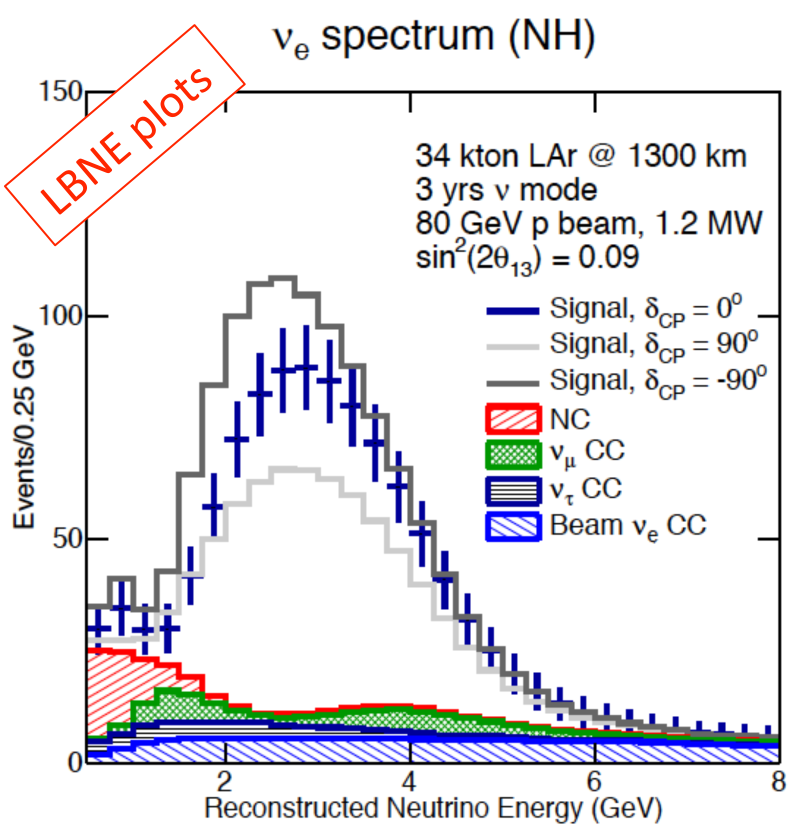


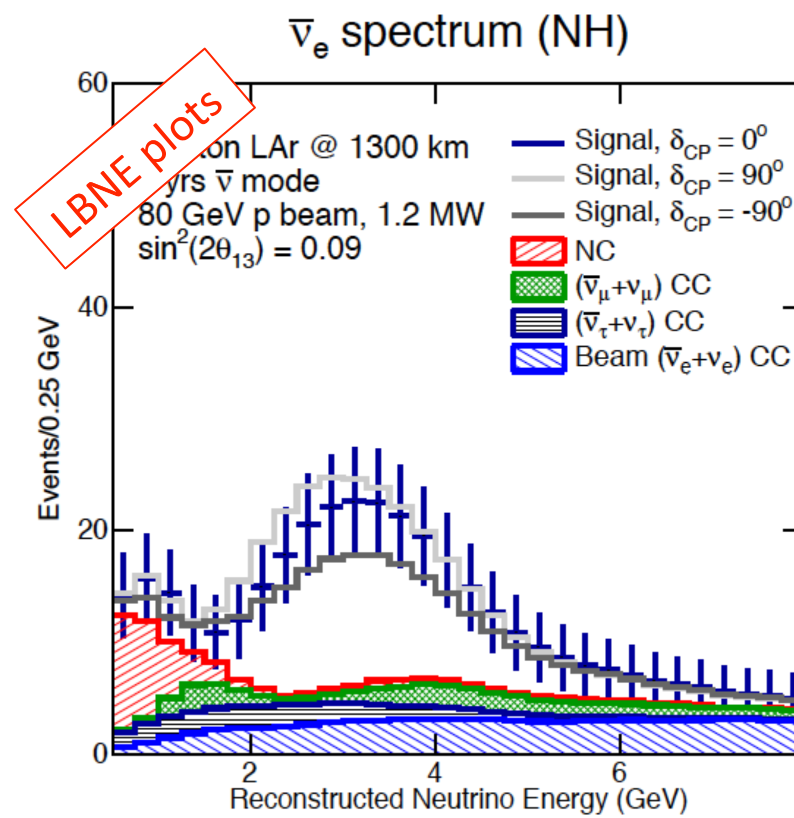
Separating MH & CPV

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

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

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



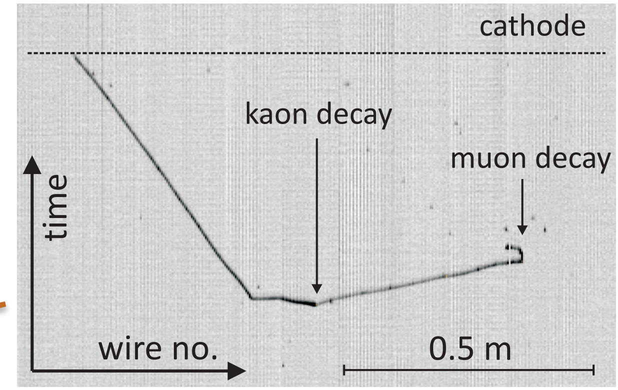


Nucleon Decay & SuperNova νs

Nucleon decay

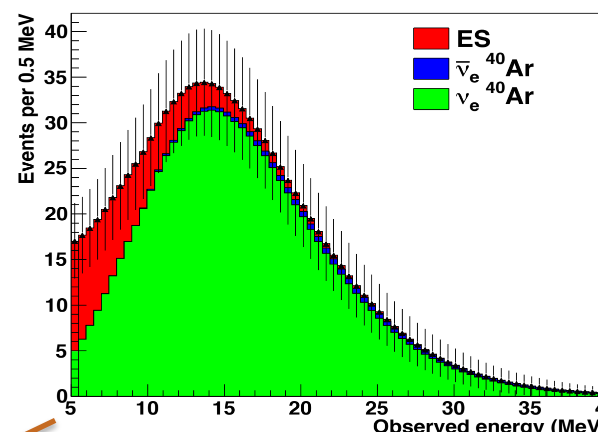
- **Image particles from nucleon decay**
  - target sensitivity to kaons (from d*E*/d*x*) from SUSY-inspired GUT p-decay modes

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 Detector Design Choices

Far detector design requirements in a nutshell:

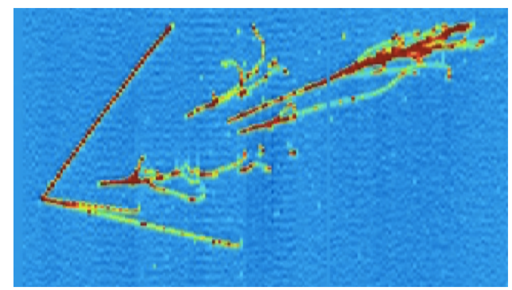
- Pattern recognition
- Energy measurement

} 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

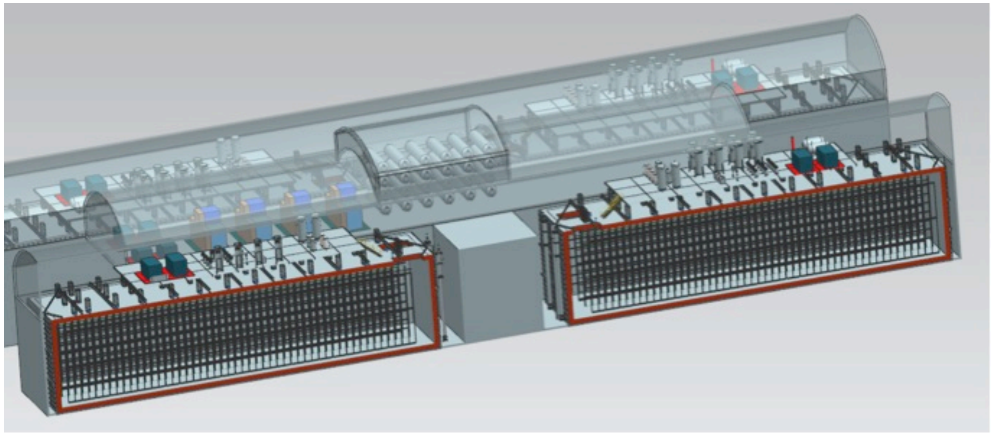


Near detector design requirements in a nutshell:

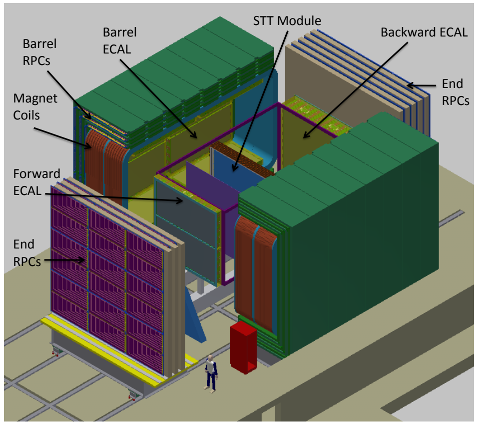
- Constrain systematic uncertainties in LBL oscillation analysis
  - Near detector must be able to constrain ν cross sections & ν flux

DUNE CDR Design =

Far detector: 40-kt LArTPC



Near detector: Multi-purpose high-resolution detector

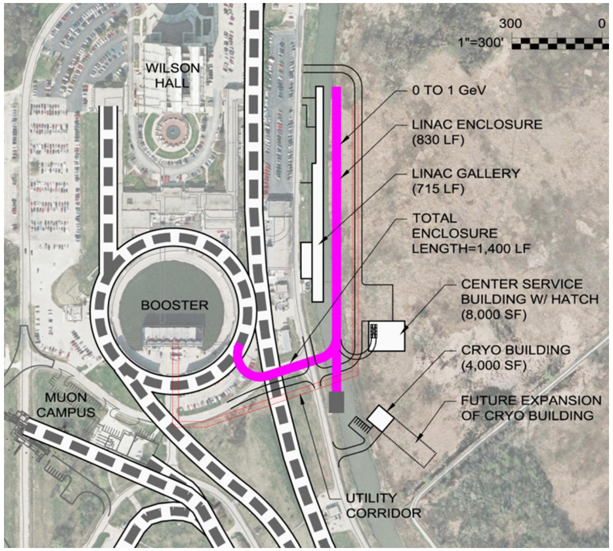


5.2: LBNF – a MW-scale facility

LBNF and PIP-II

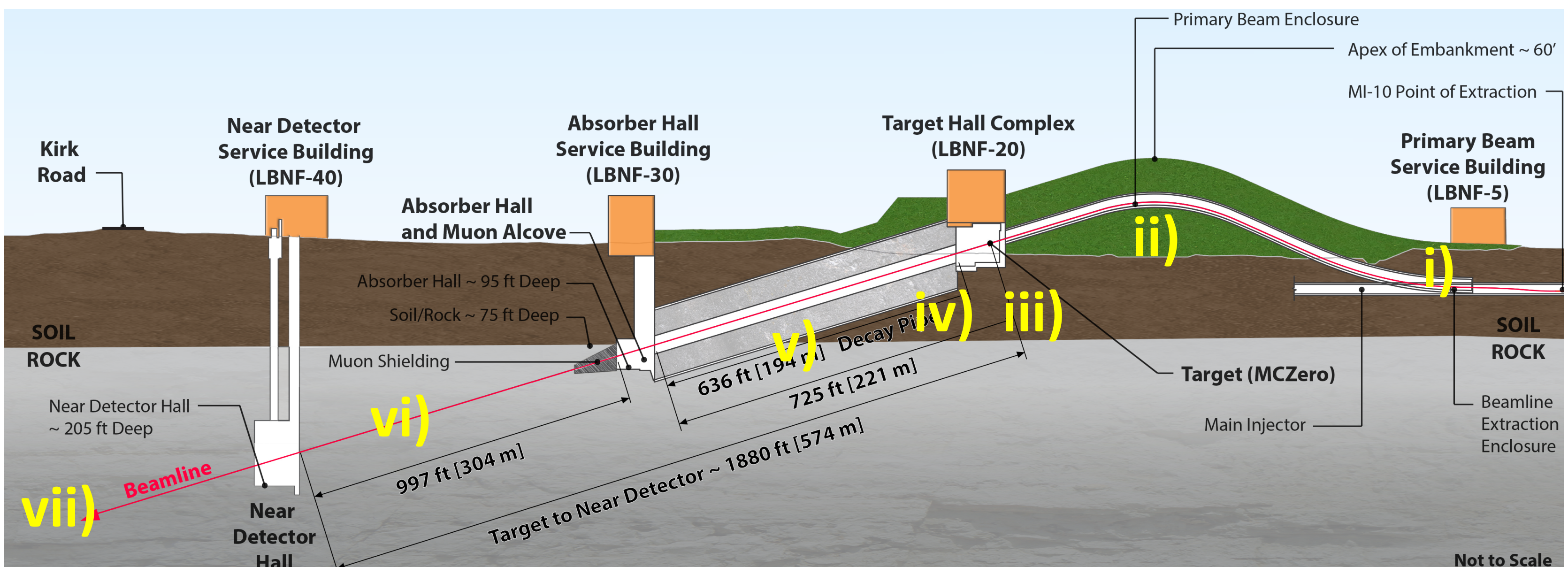
- ★ **In beam-based long-baseline neutrino physics:**
  - **beam power drives the sensitivity**
- ★ **LBNF will be the world's most intense high-energy ν beam**
  - **1.2 MW from day one**
    - NuMI (MINOS) <400 kW
    - NuMI (NOVA) ultimately ~700 kW
  - **upgradable to 2.4 MW**

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

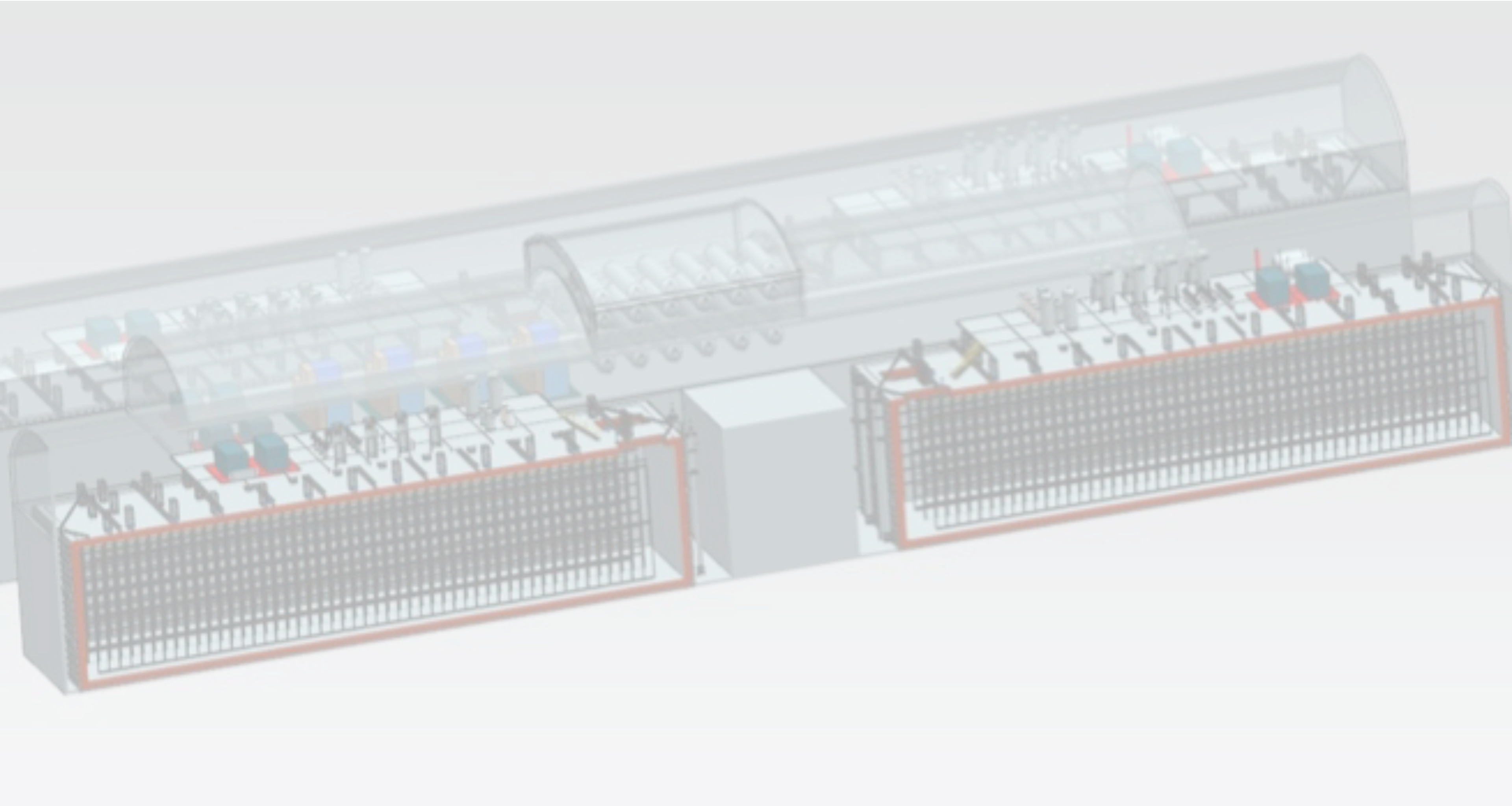


The LBNF Neutrino Beam

- 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



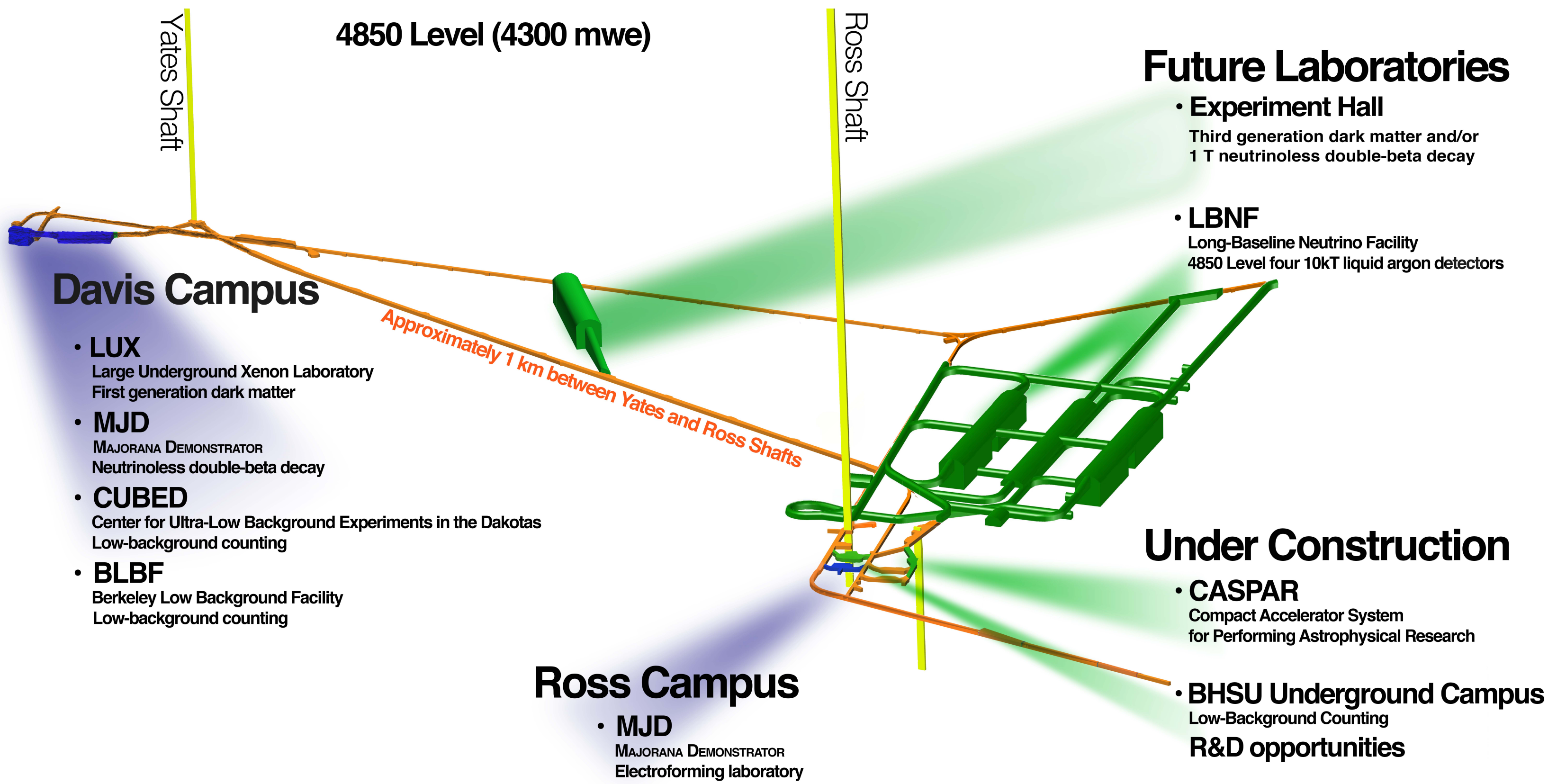
5.3: The DUNE Far Detector



The Far Site

DUNE Far Detector site

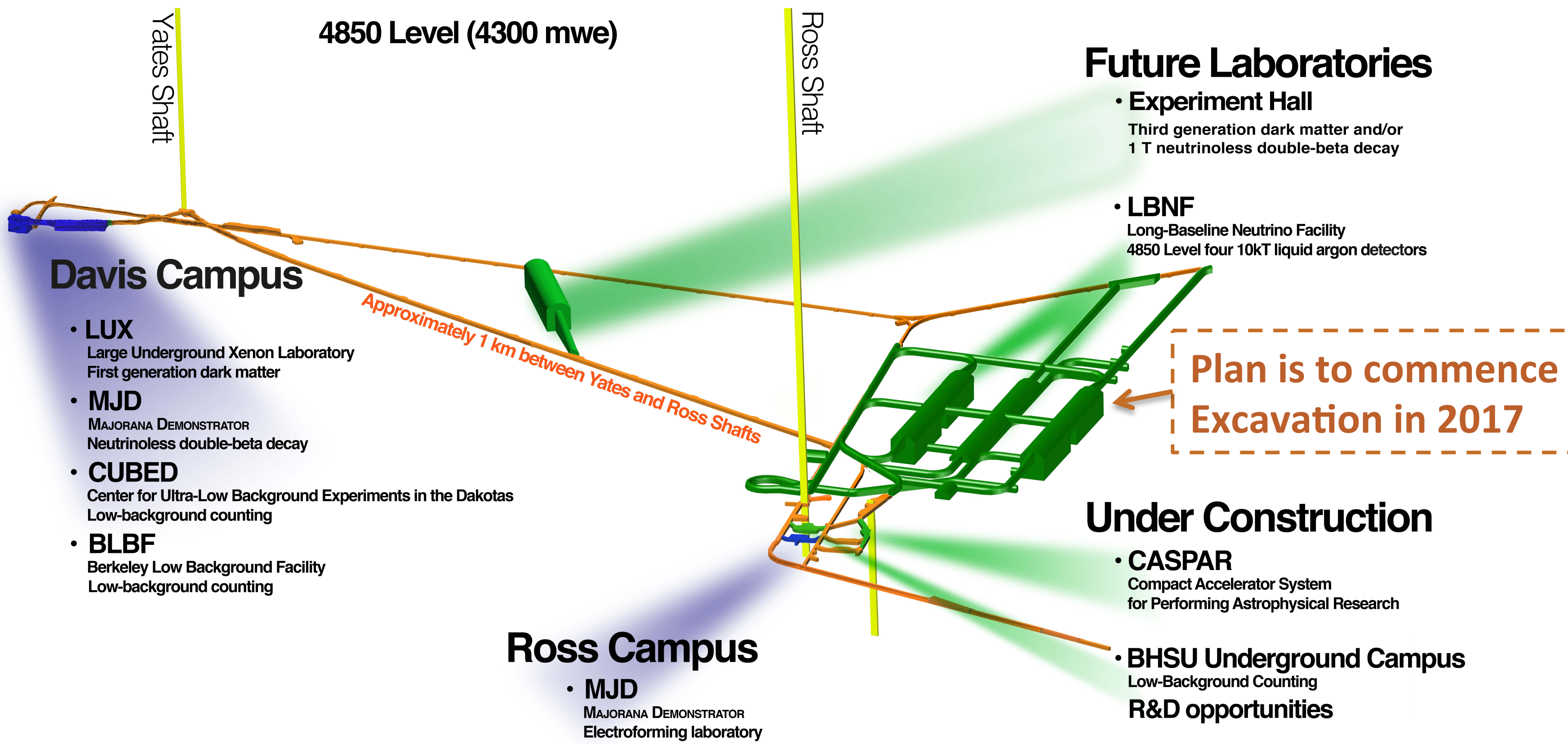
- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)



The Far Site

DUNE Far Detector site

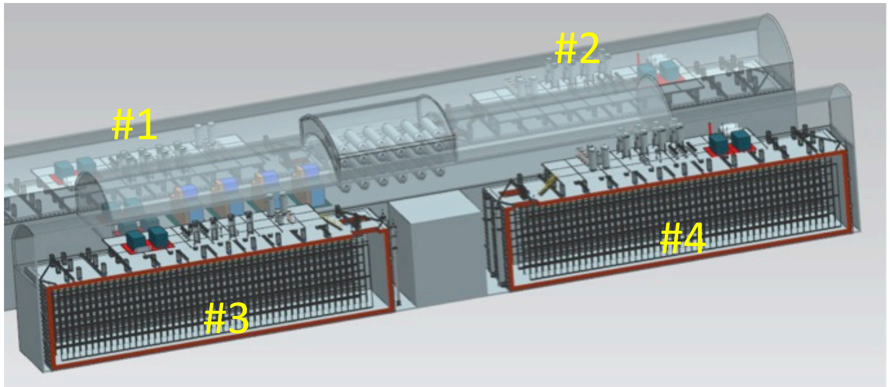
- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)



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

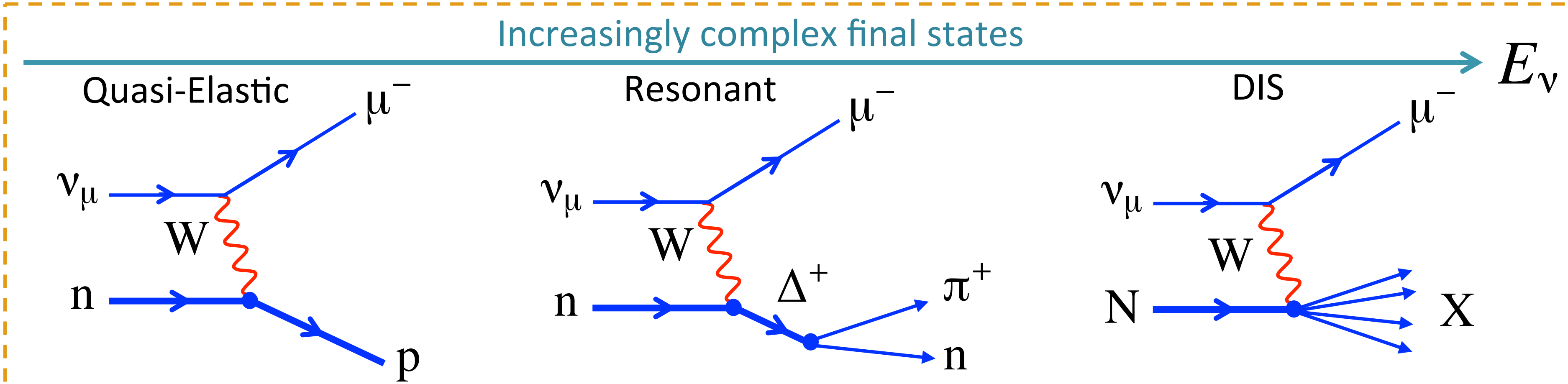
LArTPC technology has been demonstrated by ICARUS

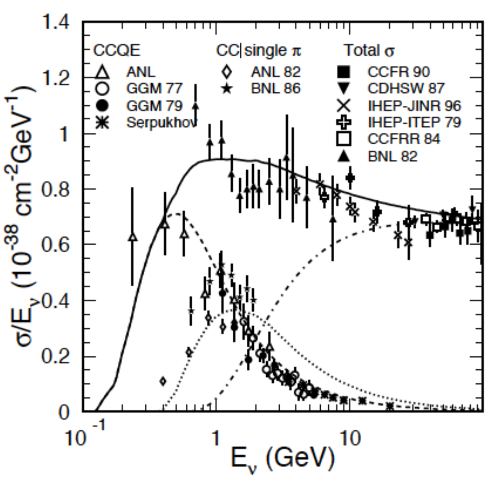
DUNE is considering two options for readout of ionization signals:

- **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

Why Liquid Argon?

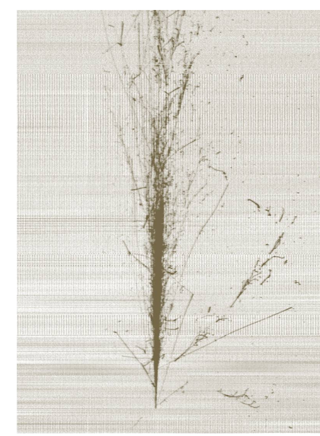
- ★ Need v. large detector + ability to image ν interactions throughout volume
- ★ Detector capability matched to neutrino energy…





- ★ < 1.5 GeV : QE dominates
- ★ > 5 GeV : DIS dominates
- ★ in between - mixture of QE/RES/DIS

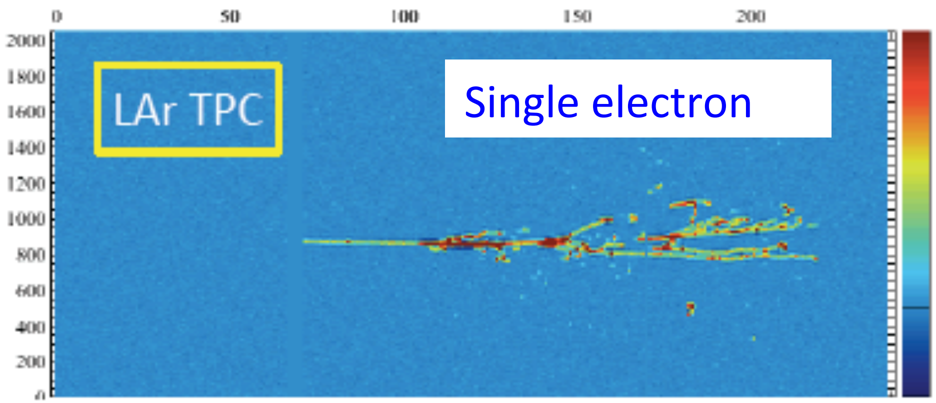
★ $E_\nu \sim 5\,\mathrm{GeV}$ ⇨ ability to image/measure complex final states

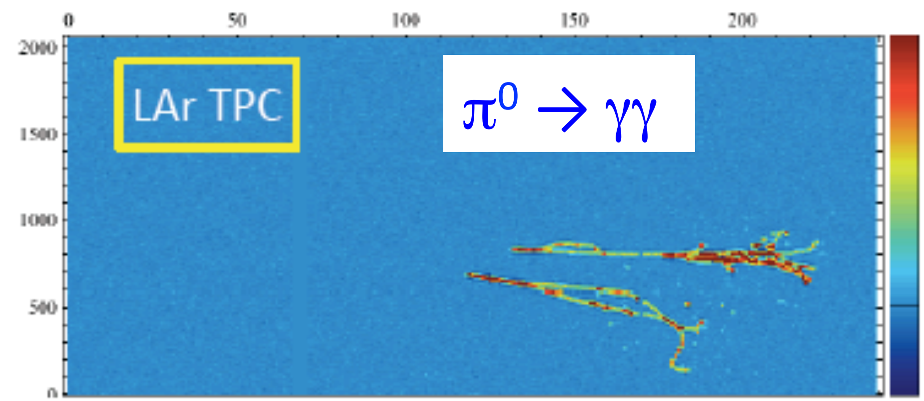


Benefits of an imaging detector

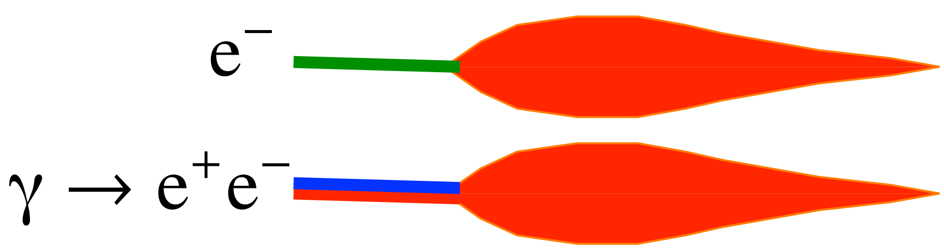
e.g. for electron neutrino appearance $e^{\pm} \leftrightarrow \gamma$ separation is vital

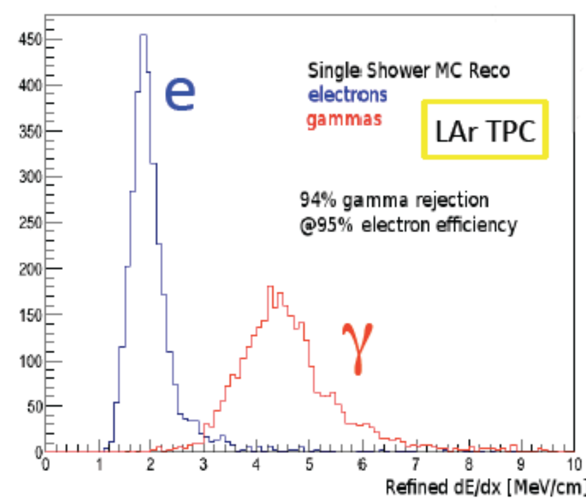
★ True for both photons from $\pi^0 \rightarrow \gamma\gamma$ or single photons





- Calorimetry to tag electrons/ gammas using dE/dx before EM shower evolves

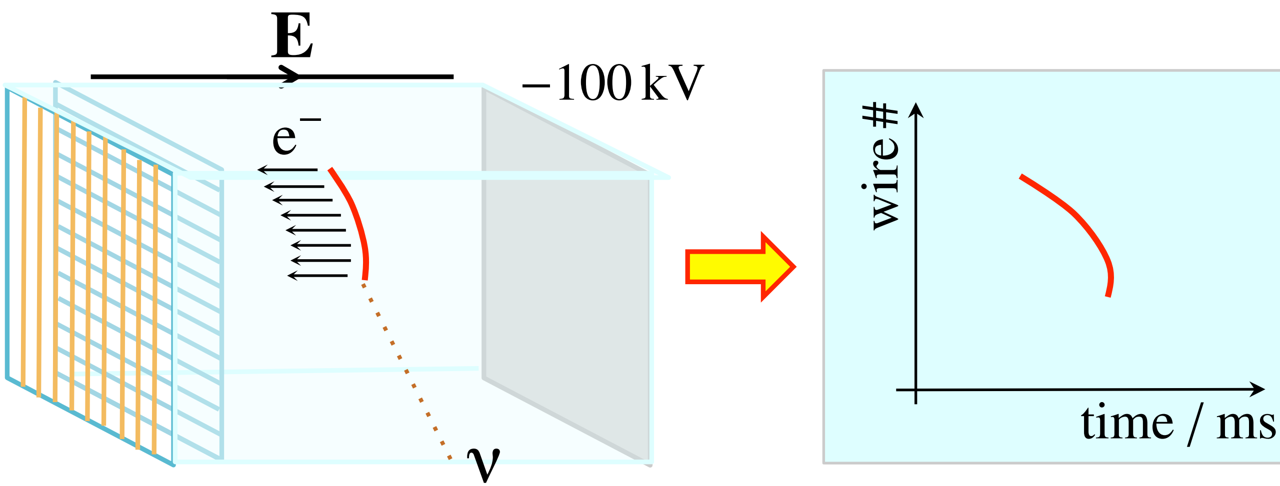


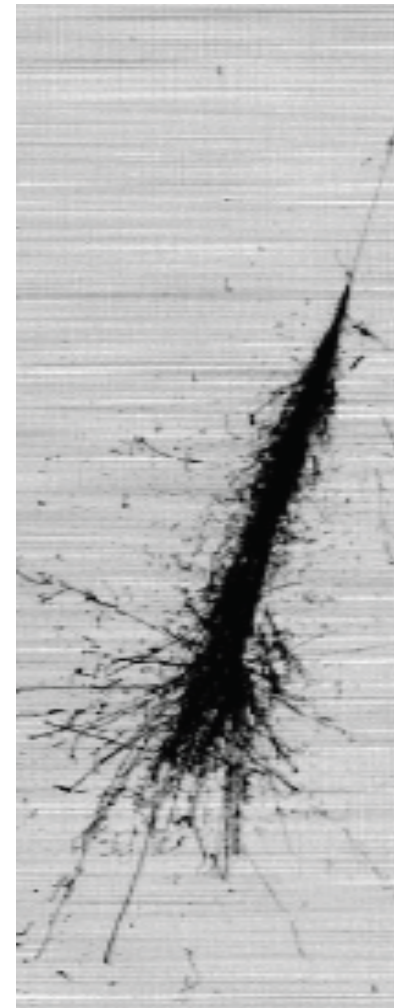


Liquid Argon TPCs

★ **LAr TPC basics**

- Charged particles ionize LAr
- Electrons drifted in strong E-field
- Detect charge on planes of wires





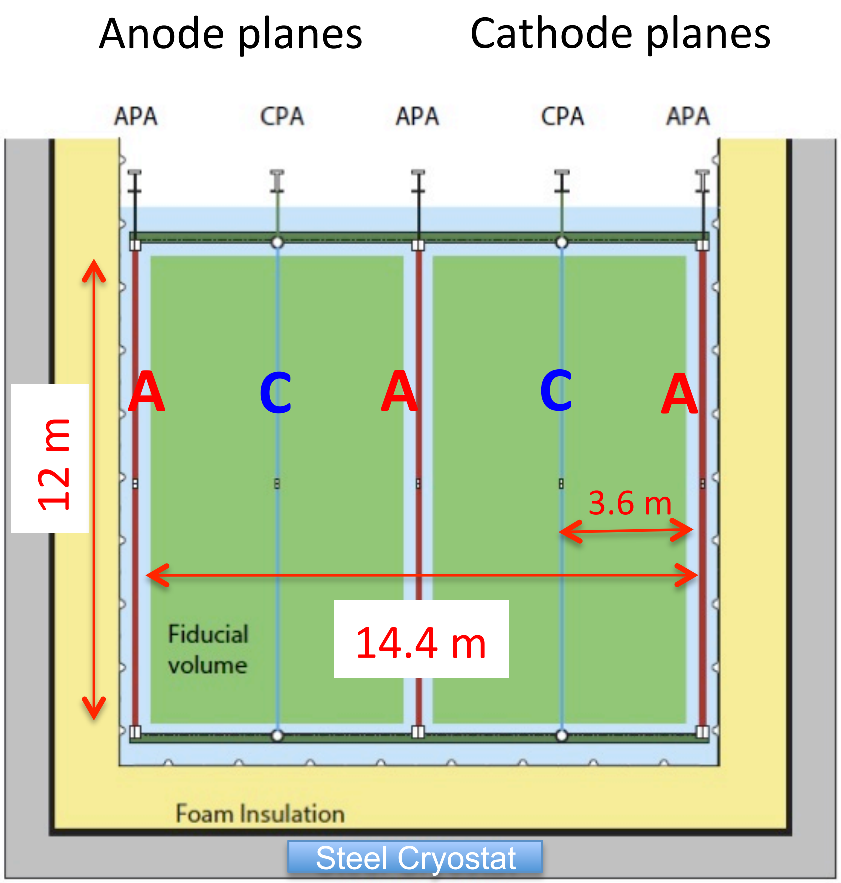
★ **Challenges include**

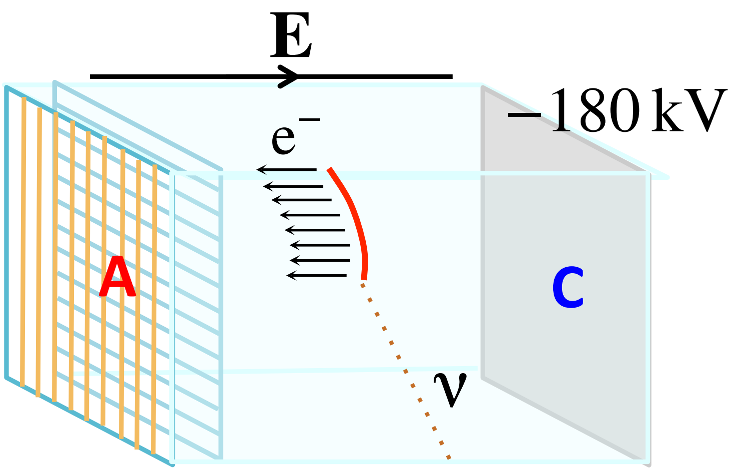
- Argon purity & HV breakdown (cryogenics + HV)
- Readout (in time) – many samples/wires (DAQ)
- Image reconstruction – many hits (Reconstruction)
- Scaling up to > kton (Engineering)

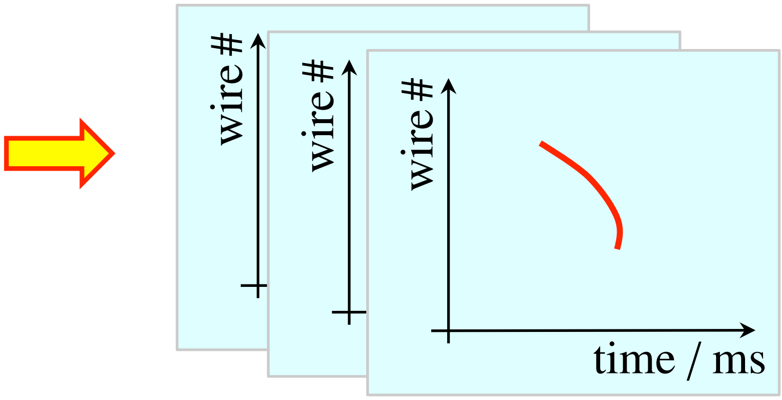
Far Detector Basics

A **modular** implementation of Single-Phase TPC

- Record ionization using three wire planes ⇨ 3D image



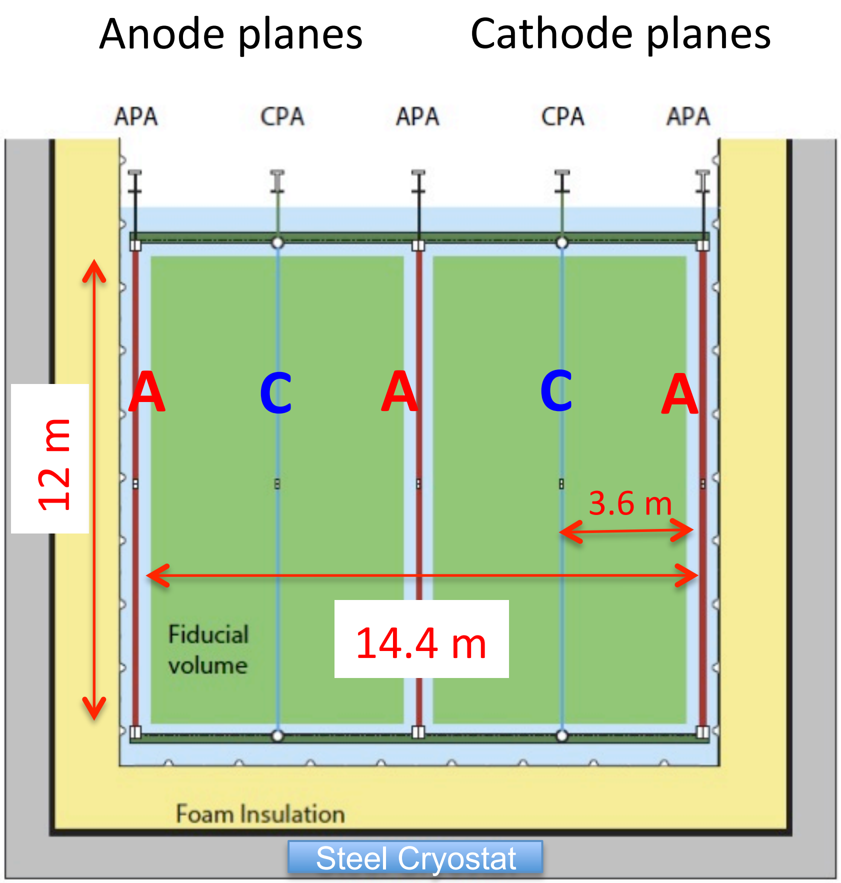


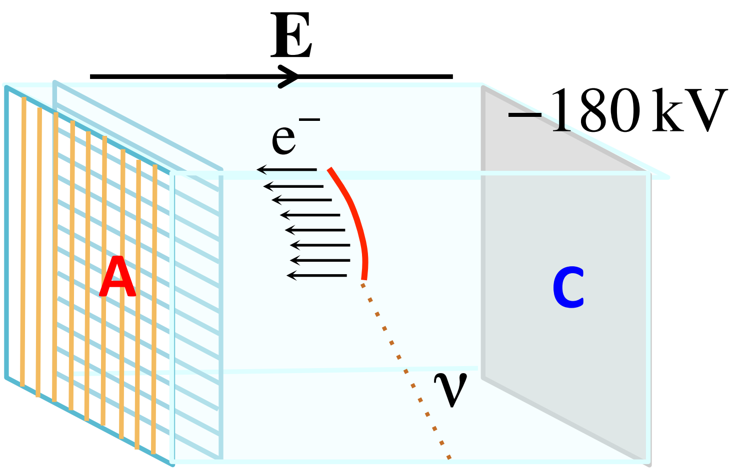


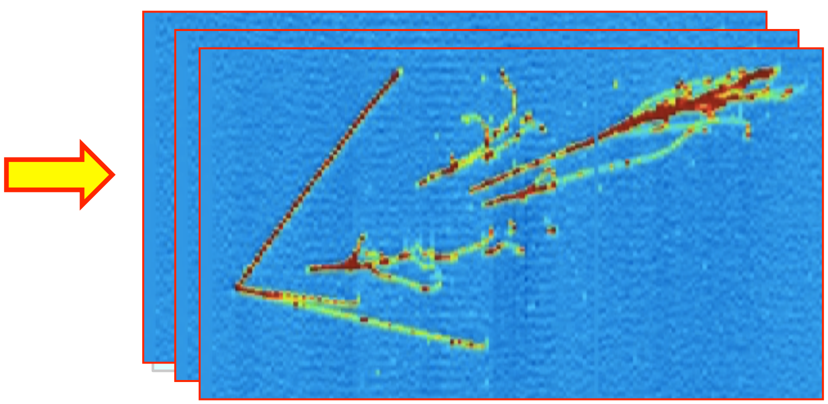
Far Detector Basics

A **modular** implementation of Single-Phase TPC

- Record ionization using three wire planes ⇨ 3D image



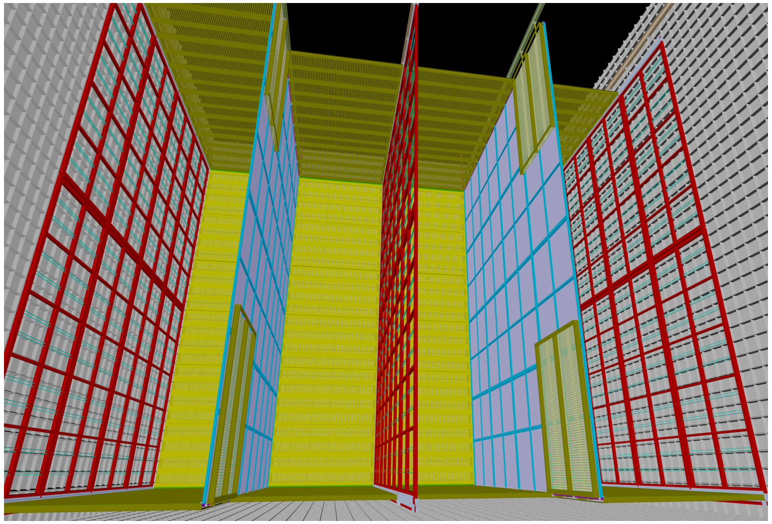


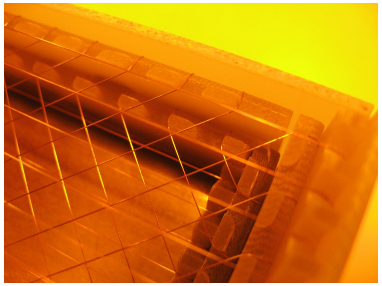


First 10 kt detector

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

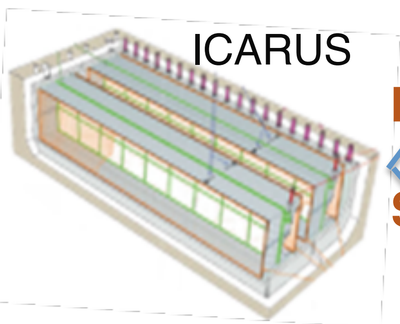




LArTPC Development Path

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

Single-Phase



ICARUS

LBL

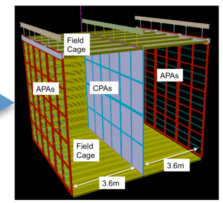
SBL

35-t prototype

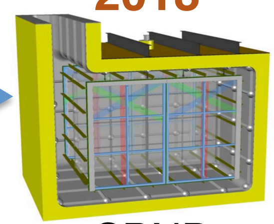
2015

MicroBooNE

DUNE SP PT @ CERN

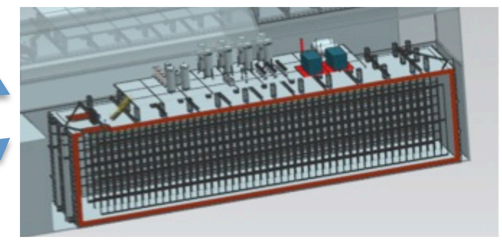


2018



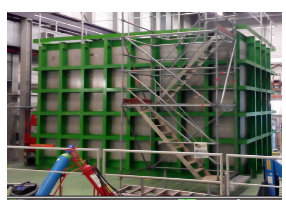
SBND

DUNE Reference Design



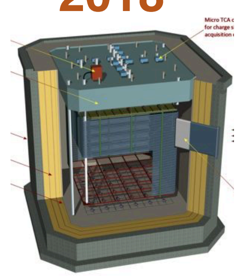
Dual-Phase

2016



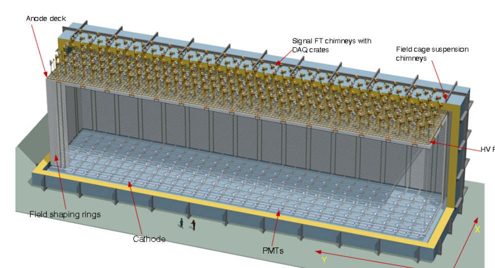
WA105: 1x1x3 m^3

2018



WA105

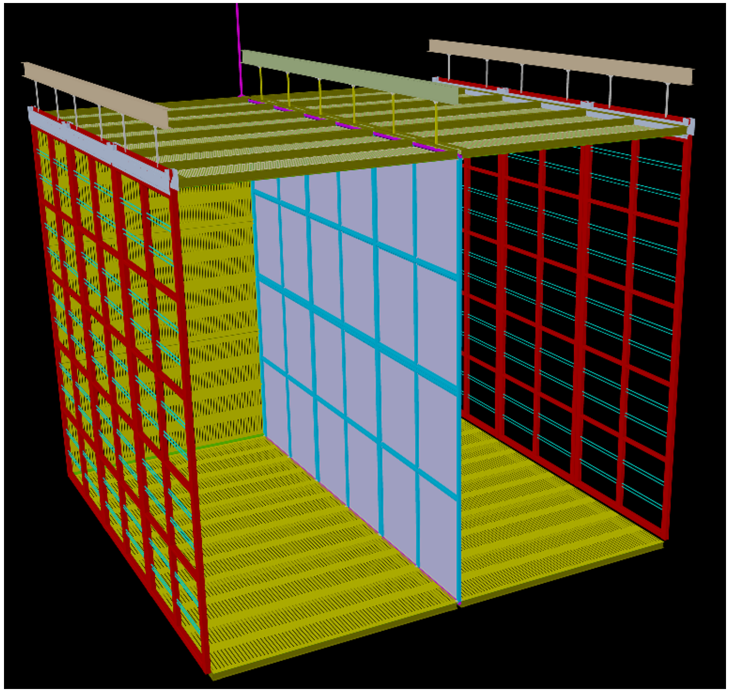
DUNE Alternative Design



ProtoDUNE at CERN

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



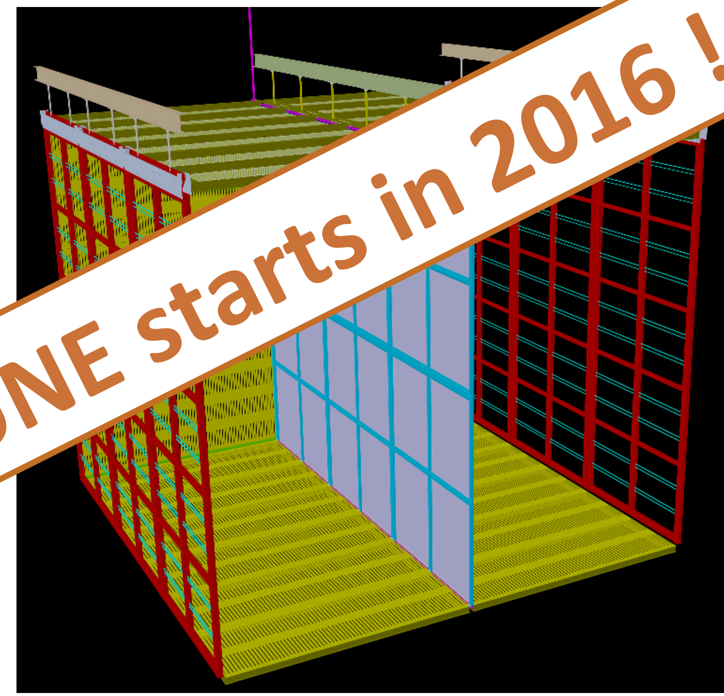
Prototyping of FD drift cell + setting up module factories

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

ProtoDUNE at CERN

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 Asse
    - 3m high x 2.3m
  - A:C:A ar
  - C 180 kV for 3.5m drift



ping of FD drift cell + setting up module factories

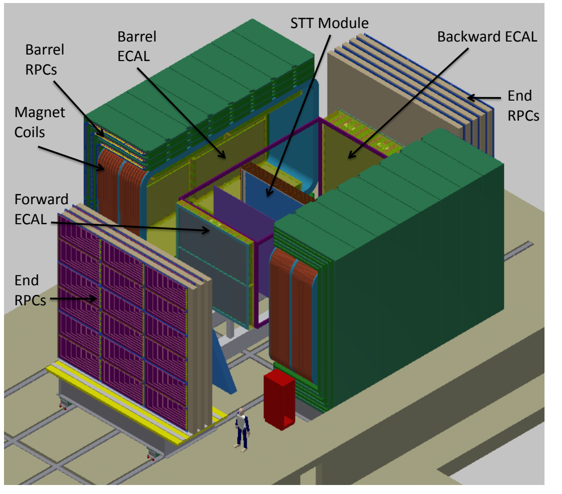
Science: Charged-particle test-beam campaign

Construction of ProtoDUNE starts in 2016 !

5.4: The DUNE Near Detector

DUNE ND (in brief)

The NOMAD-inspired Fine-Grained Tracker (FGT)

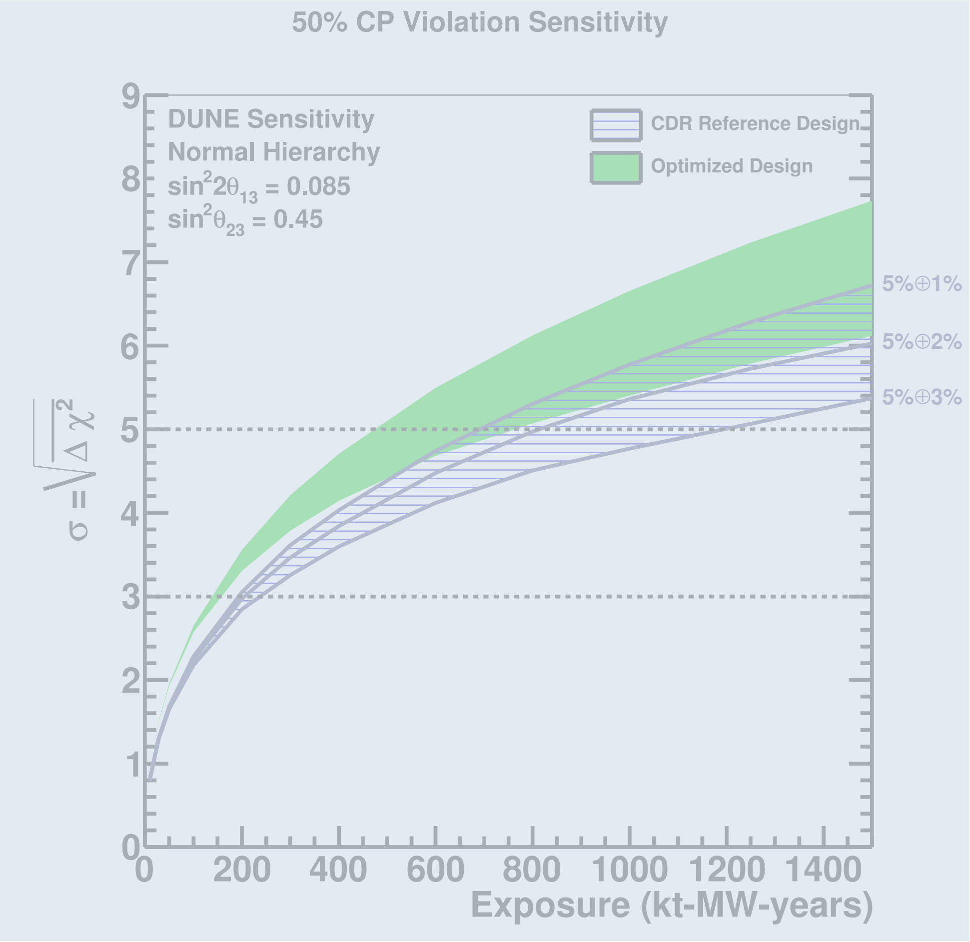


- **It consists of:**
  - Central straw-tube tracking system
  - Lead-scintillator sampling ECAL
  - Large-bore warm dipole magnet
  - RPC-based muon tracking systems
- **It provides:**
  - Constraints on cross sections and the neutrino flux
  - A rich self-contained non-oscillation neutrino physics 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

6: DUNE Physics Sensitivities



Sensitivities and Timescales

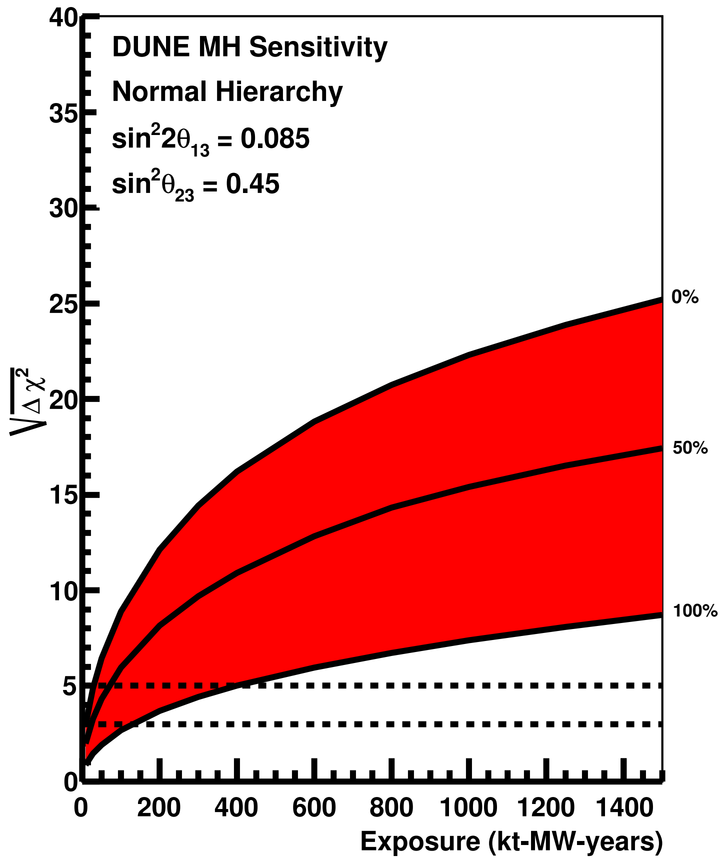
DUNE physics:

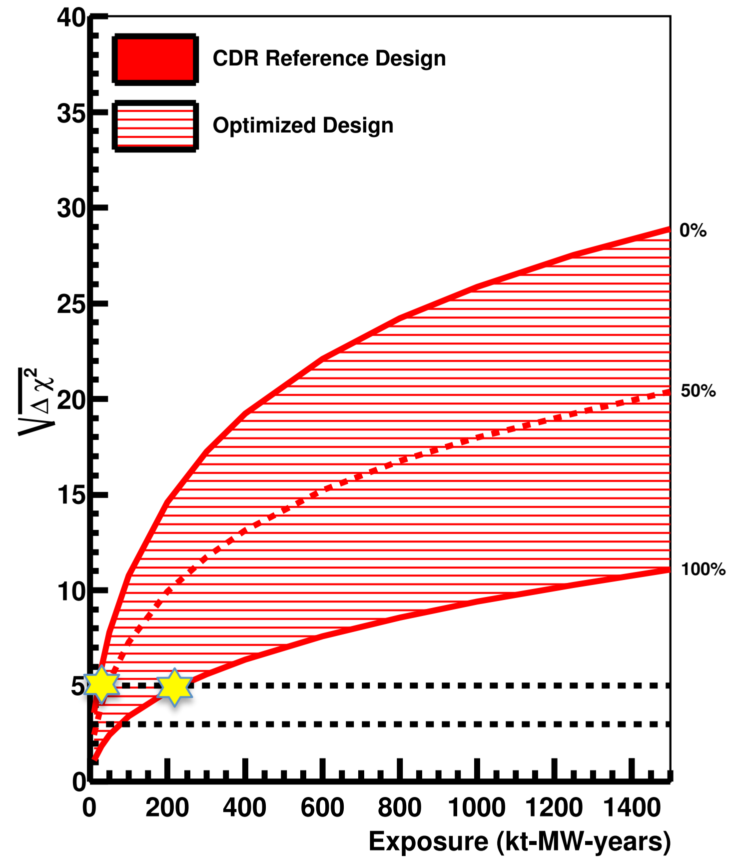
- **Game-change program in Neutrino Physics**
  - Definitive 5σ determination of MH
  - Probe leptonic CPV
  - Precisely test 3-flavor oscillation paradigm
- **Potential for major discoveries in astroparticle physics**
  - Extend sensitivity to nucleon decay
  - Unique measurements of supernova neutrinos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

MH Sensitivity

★ Sensitivities depend on multiple factors:

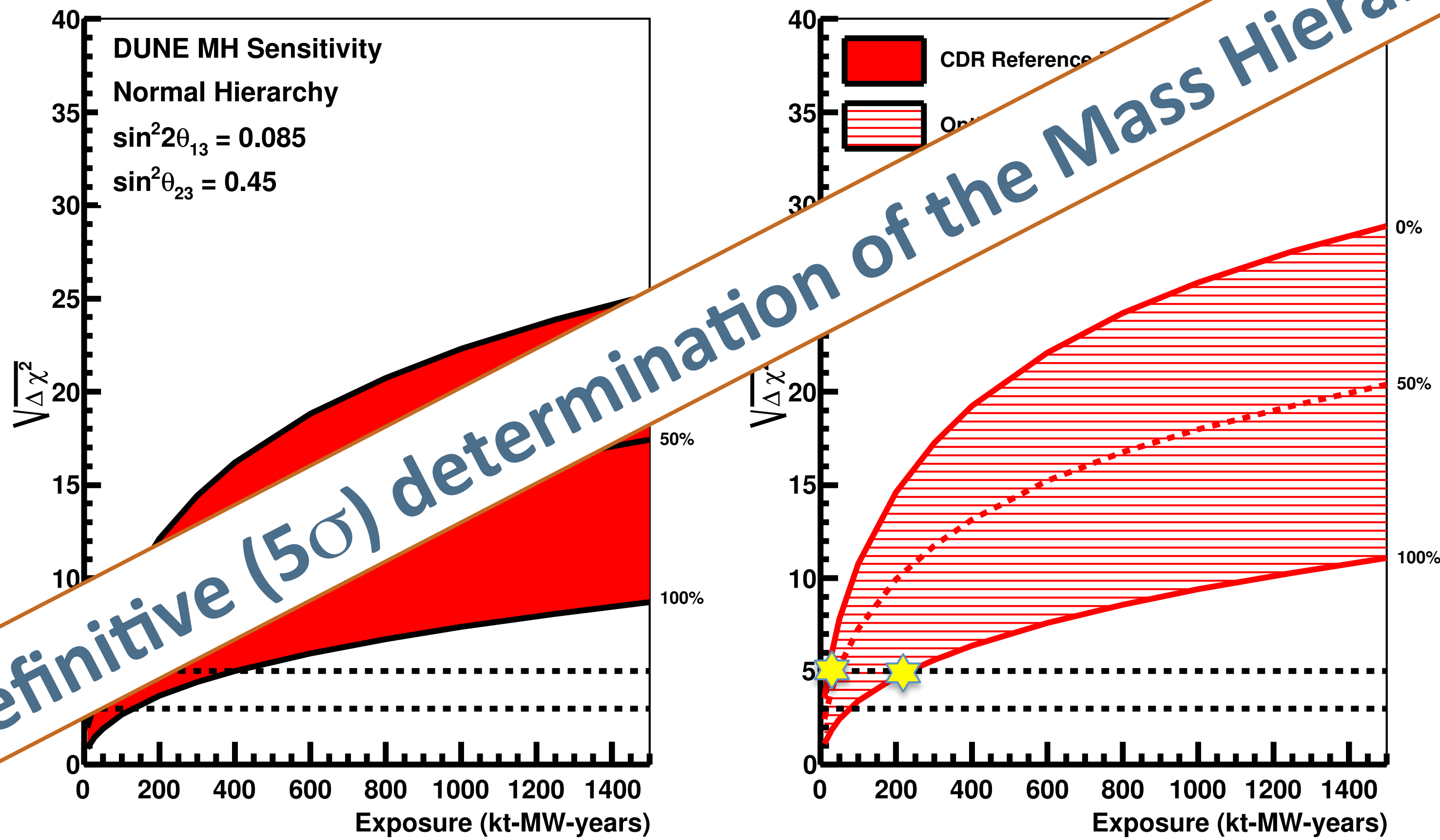
- Other parameters, e.g. δ
- Beam spectrum, …





MH Sensitivity

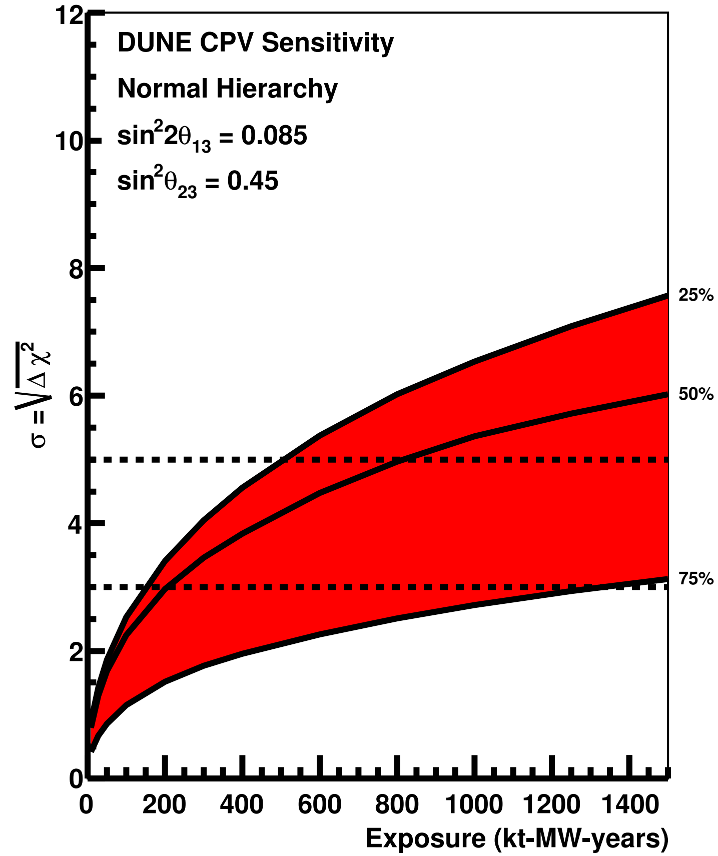
- Sensitivities depend on multiple factors:
  - Other parameters, e.g. δ
  - Beam spectrum, …

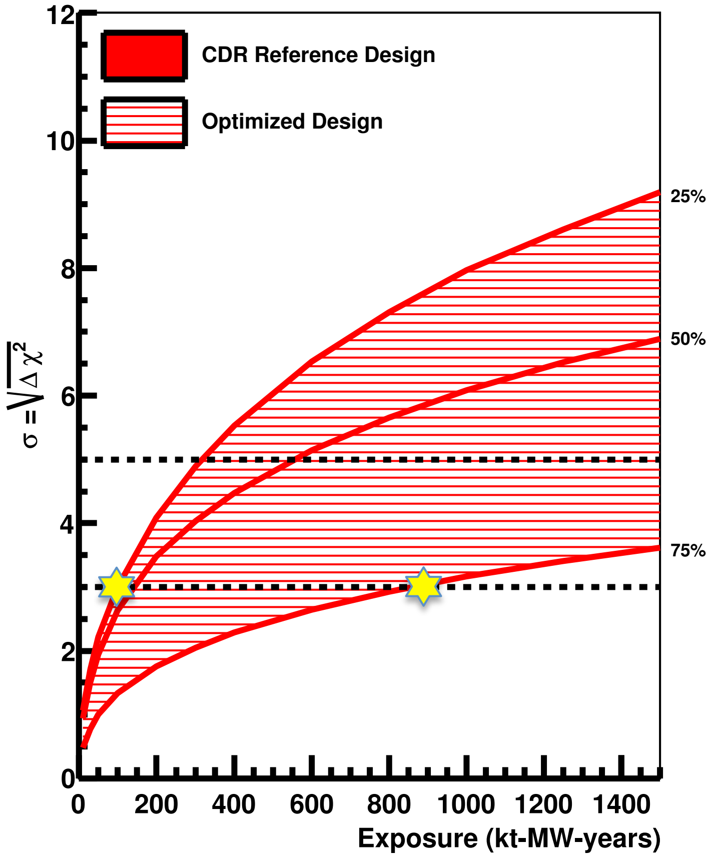


Definitive (5σ) determination of the Mass Hierarchy

CPV Sensitivity

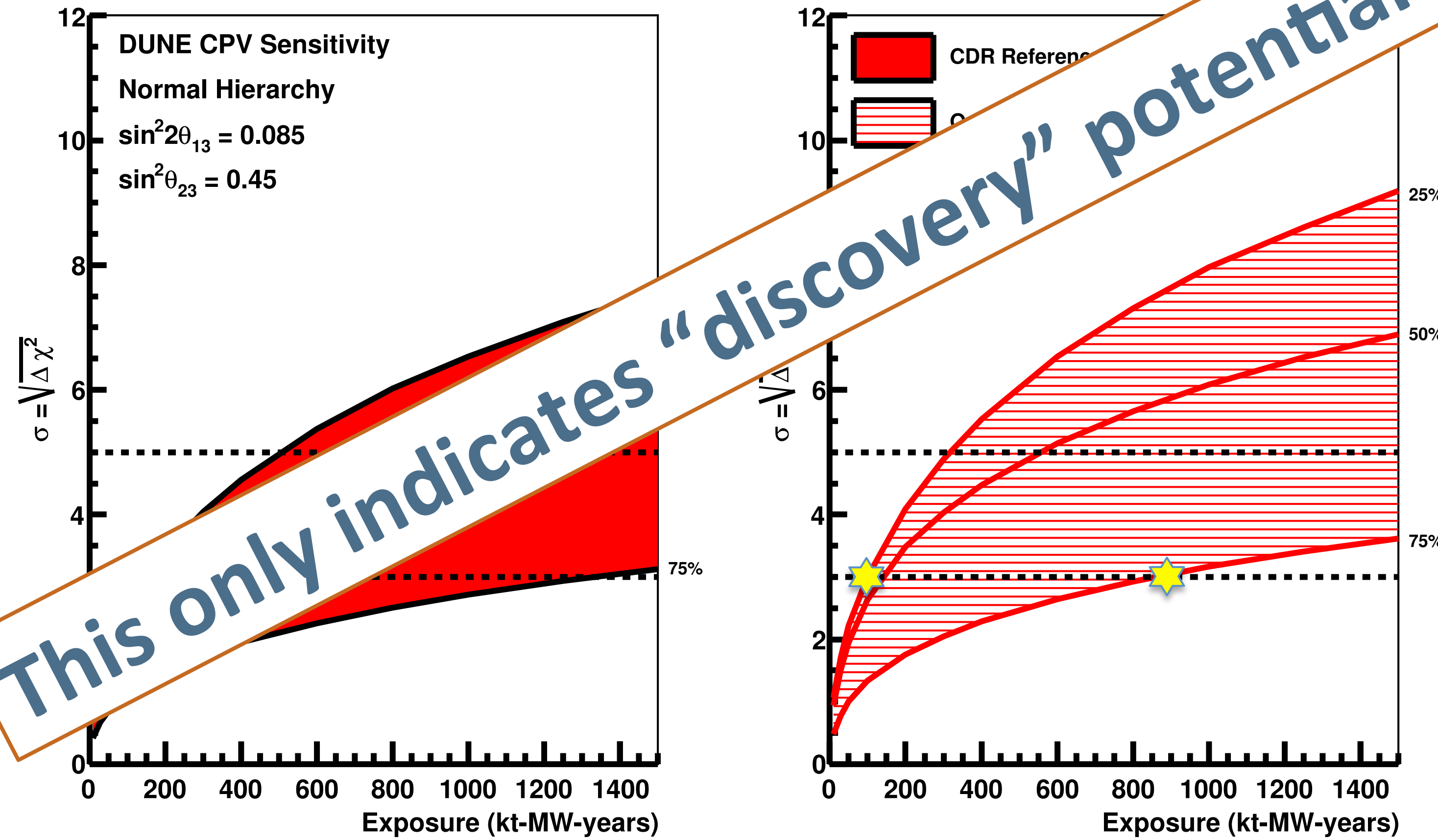
- ★ Sensitivities depend on multiple factors:
  - Other parameters, e.g. δ
  - Beam spectrum, …





CPV Sensitivity

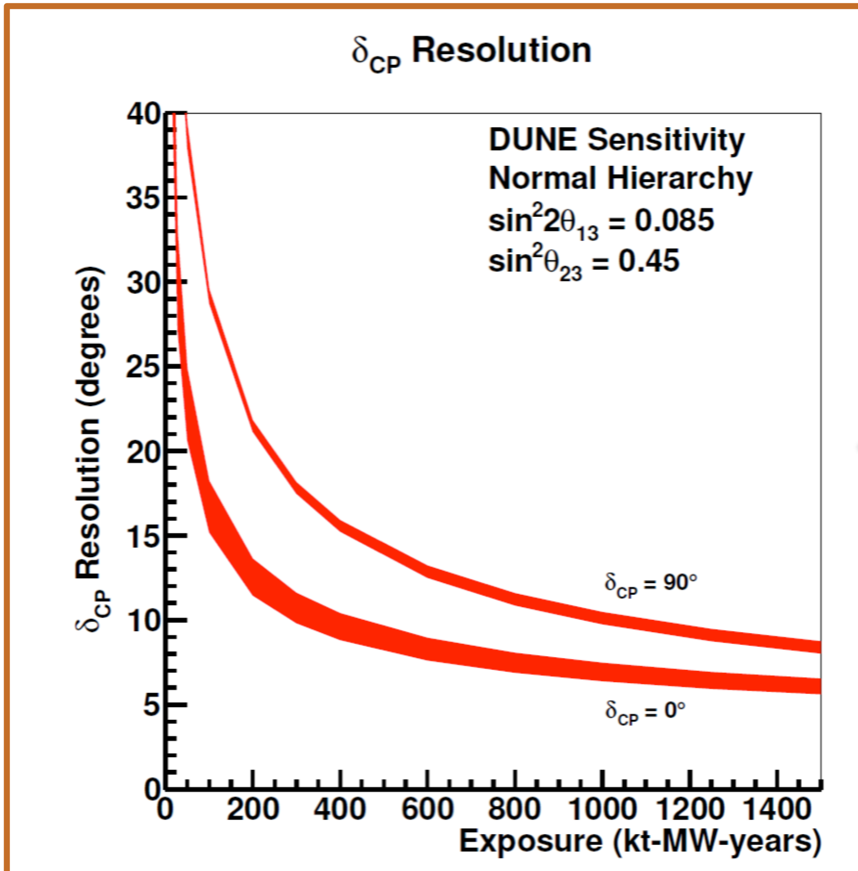
★ Sensitivities depend on multiple factors:
- Other parameters, e.g. δ
- Beam spectrum, …



This only indicates "discovery" potential…

Measurement of δ

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



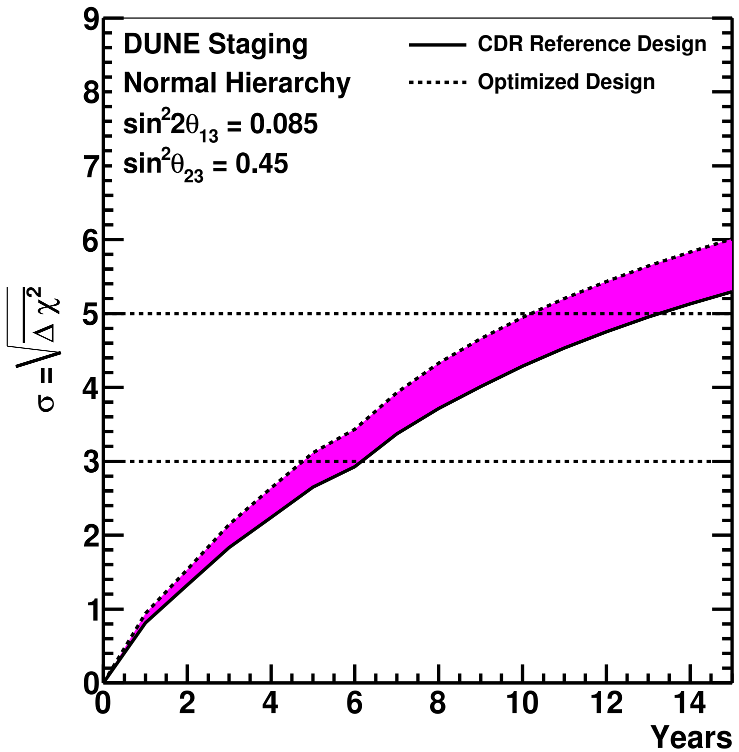
Start to ~approach current level of precision on quark-sector CPV phase (although takes time)

Timescales

★ To understand how sensitivity evolves with time, fold in
- Staging of four FD modules
- Beam power and upgrades

Based on guideline funding profile

50 % CPV Sensitivity



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

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**

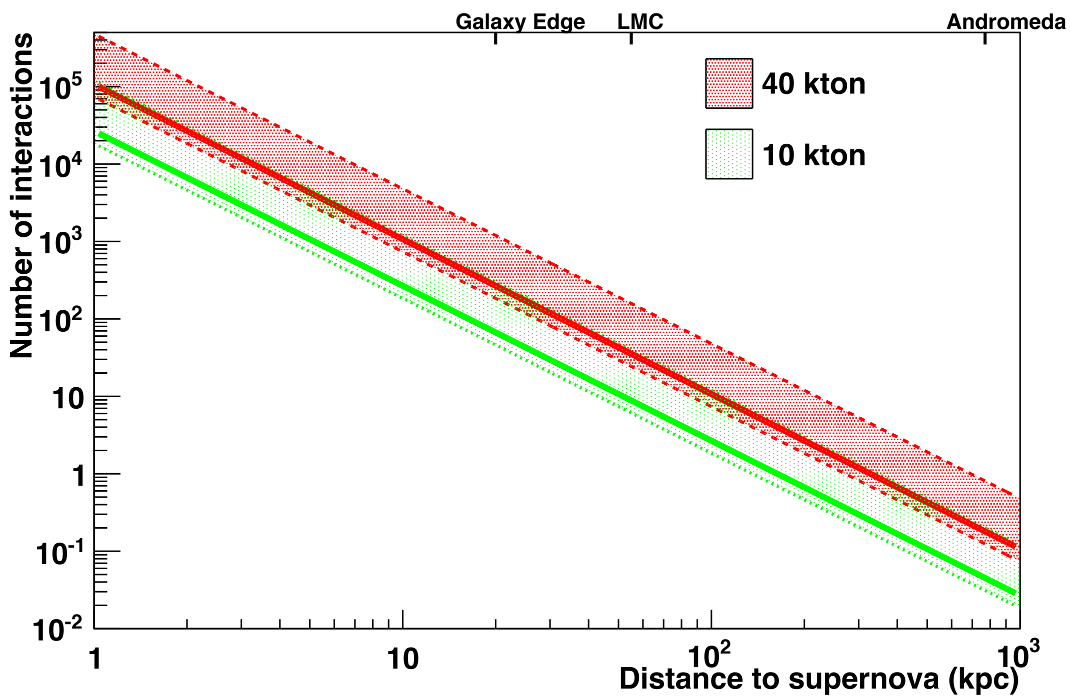
Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	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

★ **Genuine potential for early physics discovery**

A few words about SN neutrinos

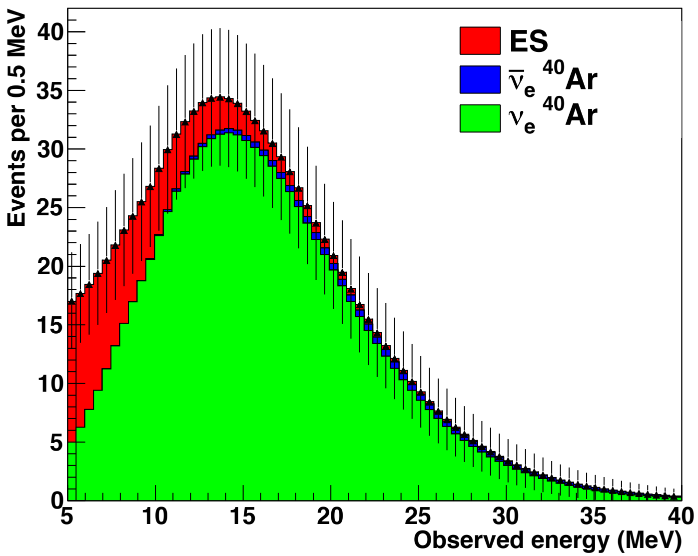
Super Nova Neutrinos I

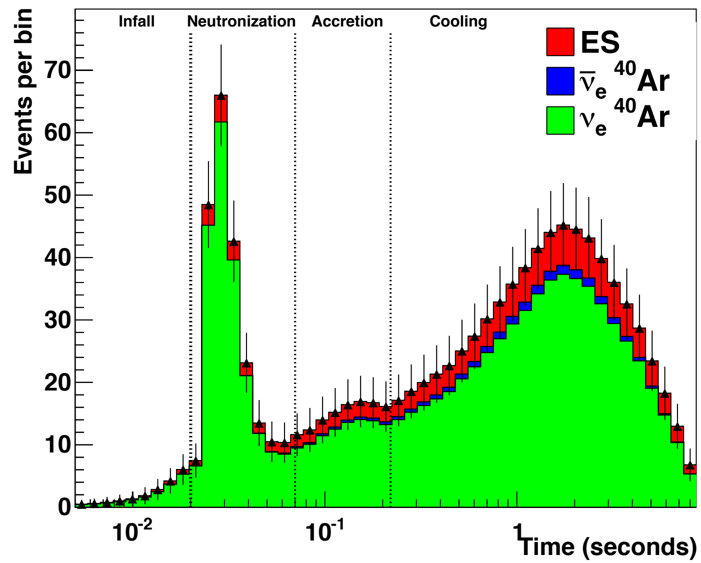
- For a core-collapse Super Nova in the galaxy:
  - Expect a few thousand $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ interactions
  - Complementary to other experiments (e.g. water/scintillator) which are mostly sensitive to anti-neutrino component



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 !

7. Political Context

Political Context – many firsts

- ★ **LBNF/DUNE will be:**
  - The first international "mega-science" project hosted by the US
    - "do for the Neutrinos, what the LHC did for the Higgs"
  - The first U.S. project run as an international collaboration
    - Organization follows the LHC model

- ★ **The U.S. is serious:**
  - LBNF/DUNE is the future flagship of Fermilab & the U.S. domestic program – there is no plan B
  - Very strong support from FNAL & the DOE
  - CD3a in December – approval of funding for excavation in FY17

- ★ **A game-changer for CERN and the U.S.**
  - Historic agreement between U.S. and CERN
  - US contributes to LHC upgrade (high-field magnets)
  - CERN contributes to Far site infrastructure
    - Approved by council in September 2015

Political Context – many firsts

★ **LBNF/DUNE will be:**

- The first international "mega-science" project hosted …
  - "do for the Neutrinos, what the LHC did for the H…
- The first U.S. project run as an internationa…
  - Organization follows the LHC model

★ **The U.S. is serious:**

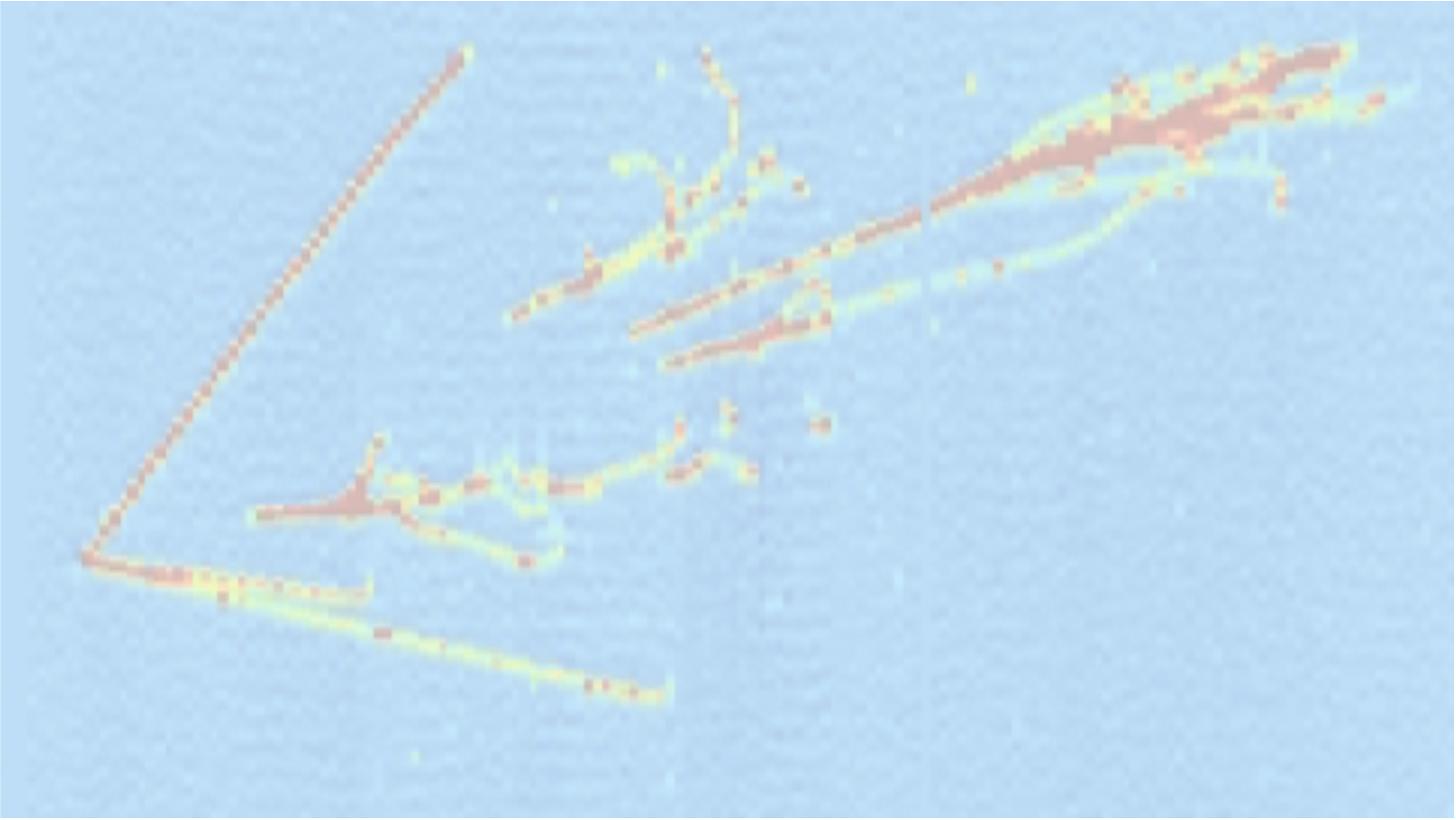
- LBNF/DUNE is the fut… …milab & the U.S. domestic program … …n B
- Very strong s… …L & the DOE
- CD3a in … …proval of funding for excavation in FY17

★ **A … …ger for CERN and the U.S.**

- …greement between U.S. and CERN
- …contributes to LHC upgrade (high-field magnets)
- CERN contributes to Far site infrastructure
  - Approved by council in September 2015

Every reason to be optimistic that we are on the verge of launching the next big thing in particle physics

8. Summary



Summary

★ **DUNE will**

- Probe CPV with unprecedented position
- Definitively determine the MH to greater than 5 σ
- Test the three-flavour hypothesis
- Significantly advance the discovery potential for proton decay
- (With luck) provide a wealth of information on Supernova bursts neutrino physics and astrophysics

Summary

★ **DUNE will**

- Probe CPV with unprecedented position
- Definitively determine the MH to greater than 5 σ
- Test the three-flavour hypothesis
- Significantly advance the discovery potential for proton decay
- (With luck) provide a wealth of information on Supernova bursts neutrino physics and astrophysics

★ **This is an exciting time**

- DUNE is now ballistic
- The timescales are not that long:
  - DUNE/LBNF aims to start excavation in 2017
  - The large-scale DUNE prototype will operate at CERN in 2018

Summary

★ **DUNE will**

- Probe CPV with unprecedented position
- Definitively determine the MH to greater than 5 σ
- Test the three-flavour hypothesis
- Significantly advance the discovery potential for proton decay
- (With luck) provide a wealth of information on Supernova bursts neutrino physics and astrophysics

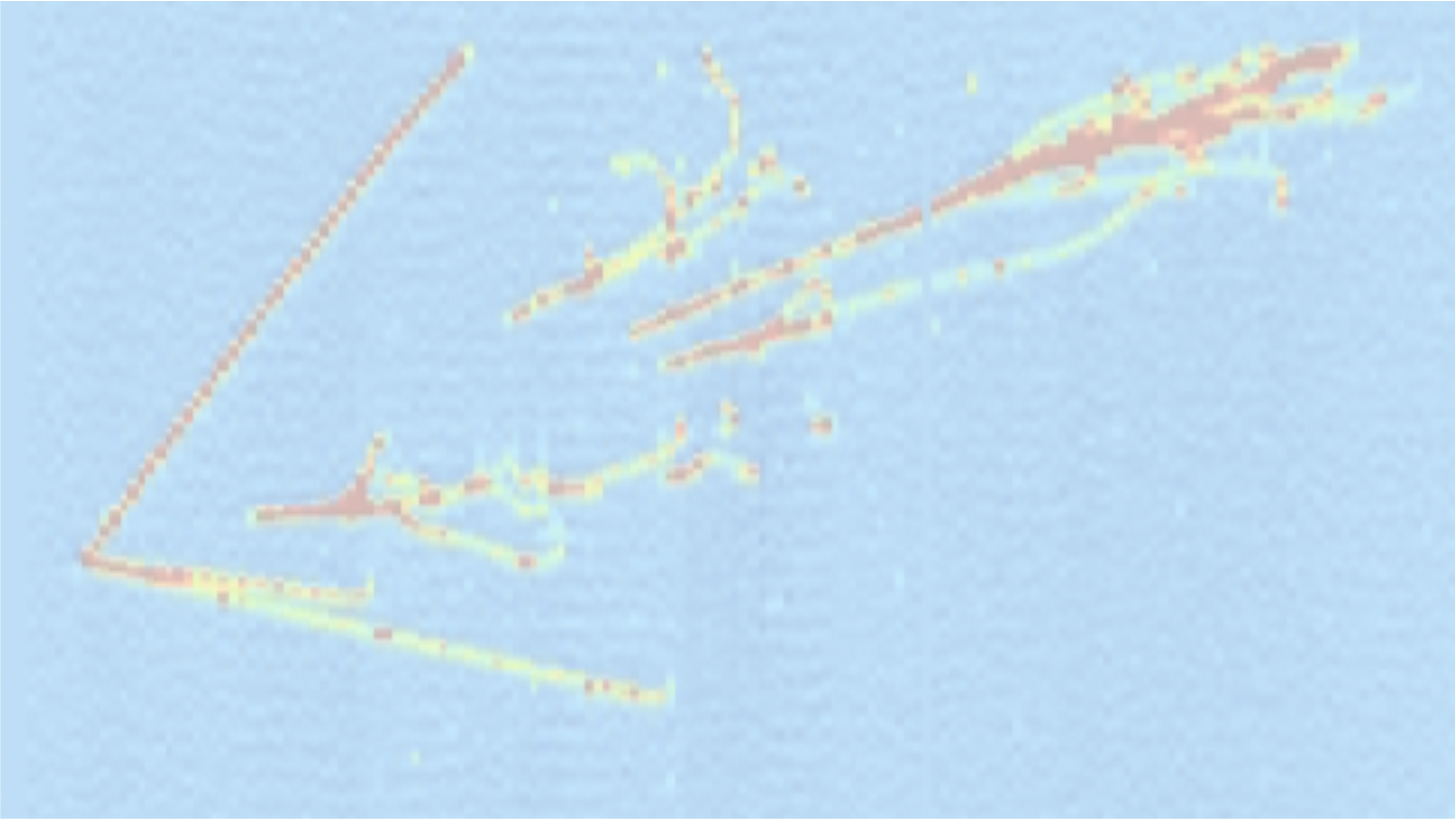
★ **This is an exciting time**

- DUNE is now ballistic
- The timescales are not that long:
  - DUNE/LBNF aims to start excavation in 2017
  - The large-scale DUNE prototype will operate at CERN in 2018

★ **An international community is forming – including CERN**

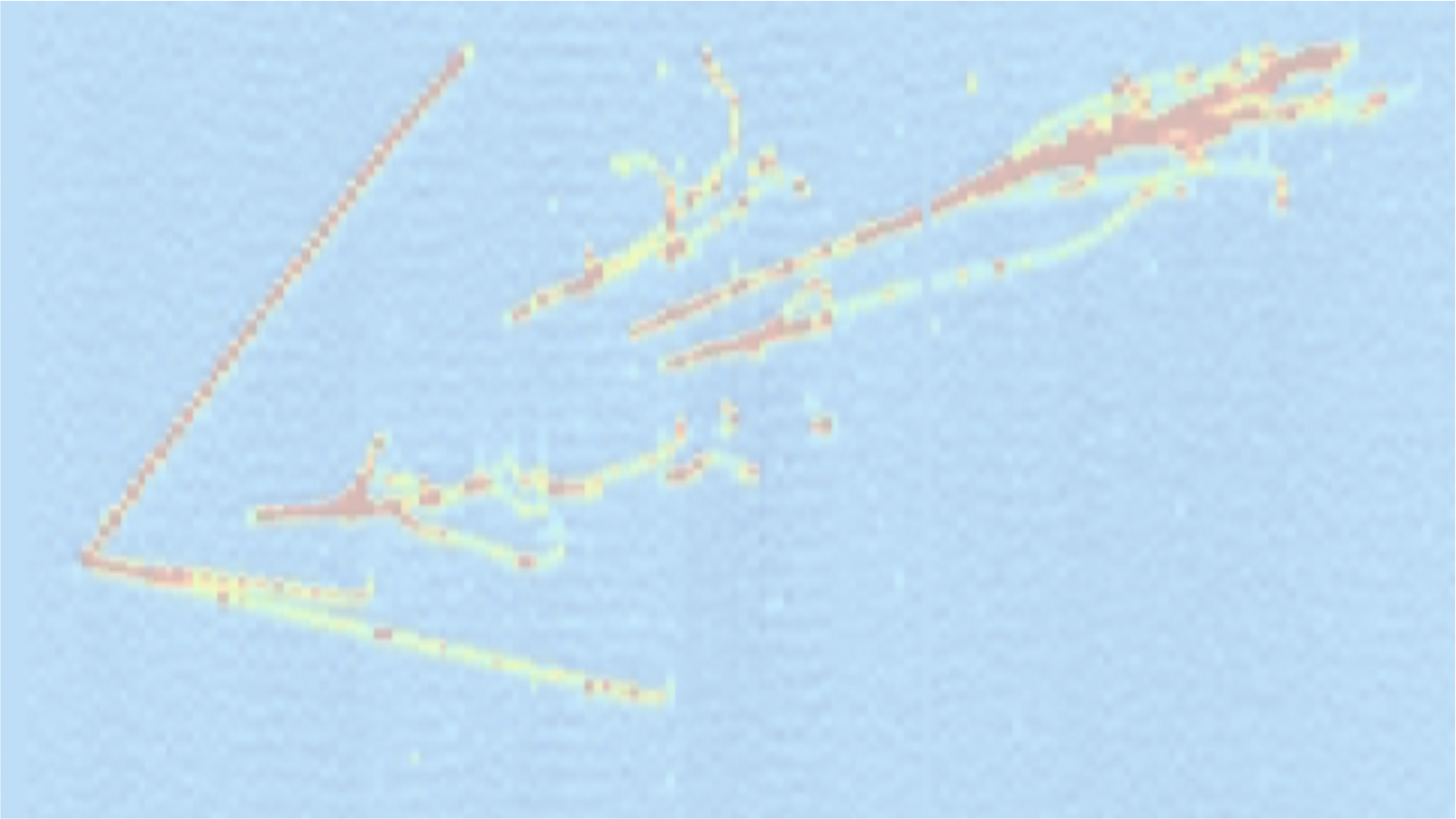
- A major scientific opportunity for the UK

Thank you for your attention



Backup Slides

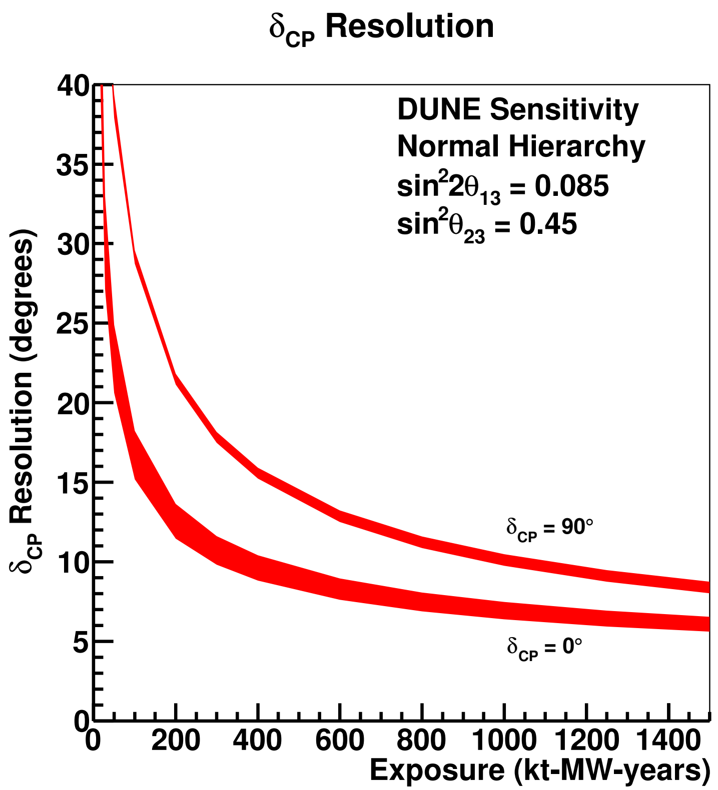
Science

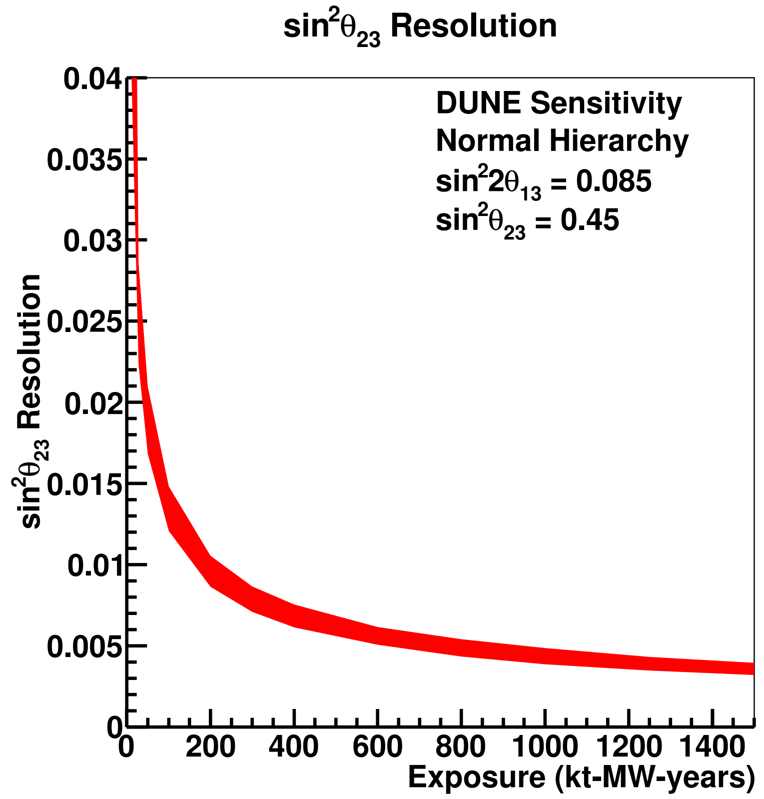


Parameter Resolutions

δ_{CP} & θ_{23}

- As a function of exposure

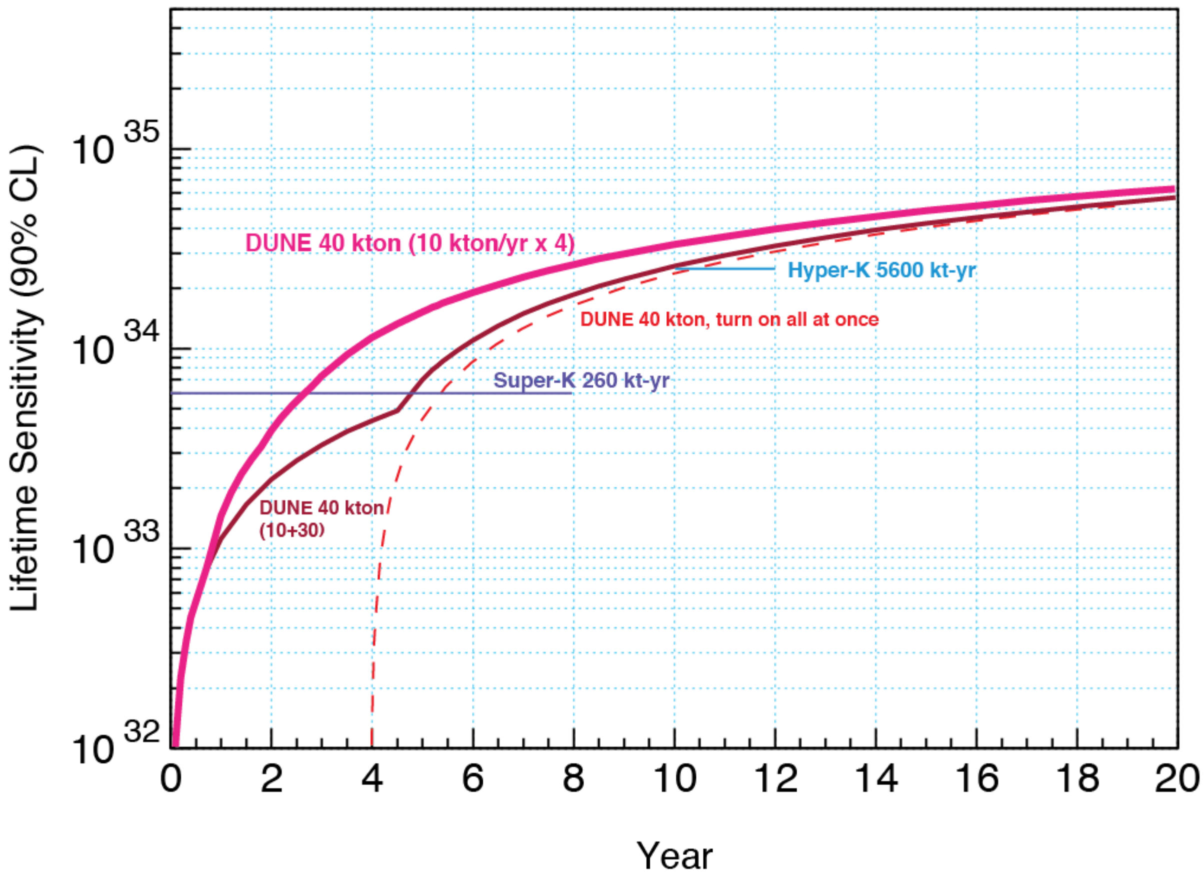




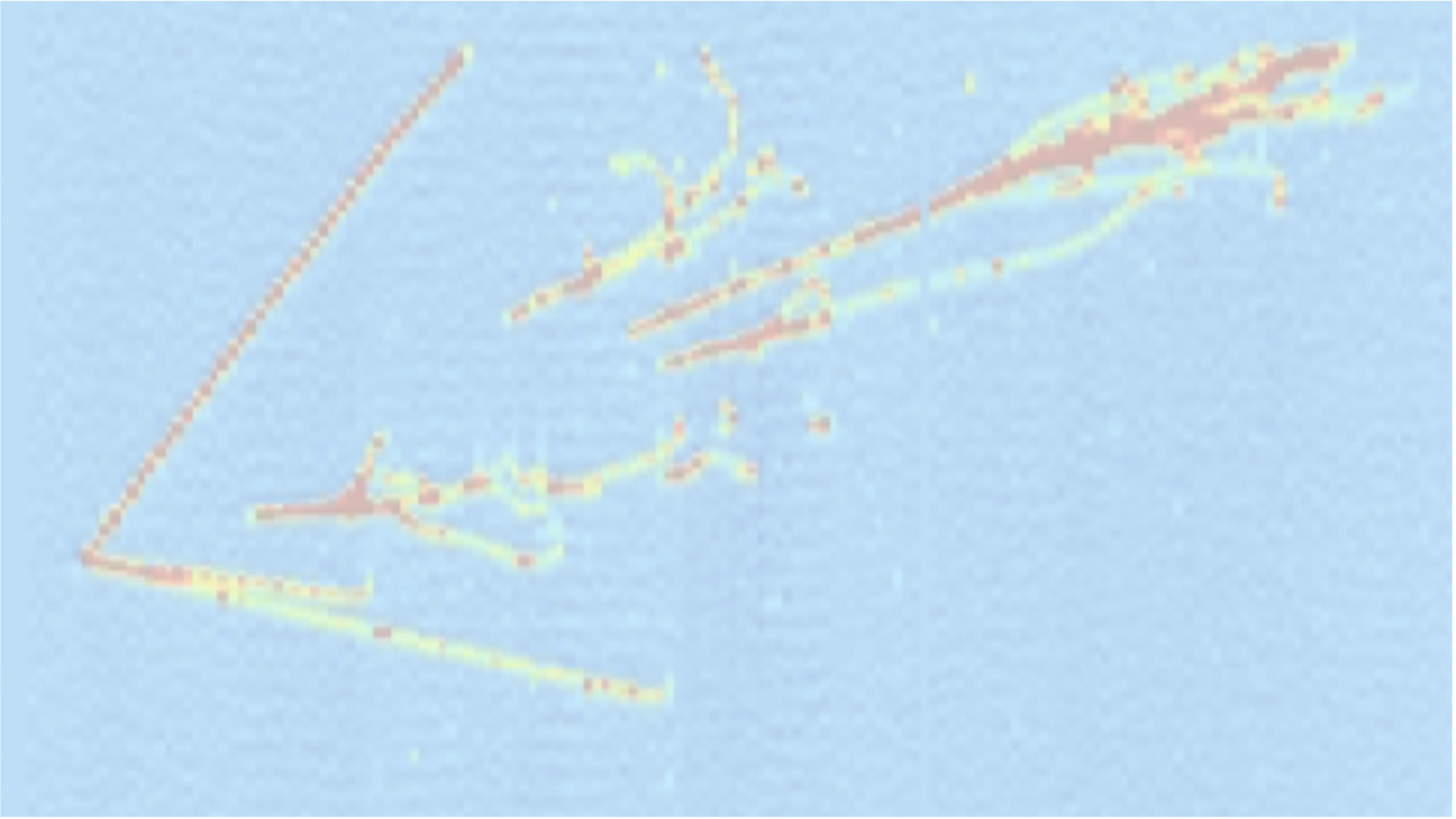
PDK

$p \rightarrow K\,\nu$

- DUNE for various staging assumptions

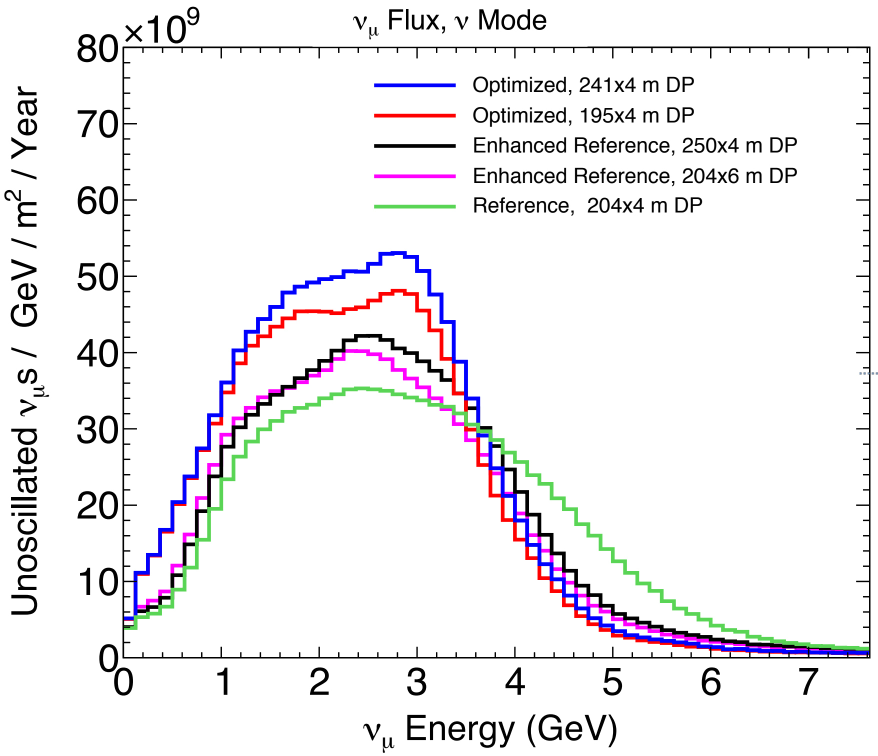


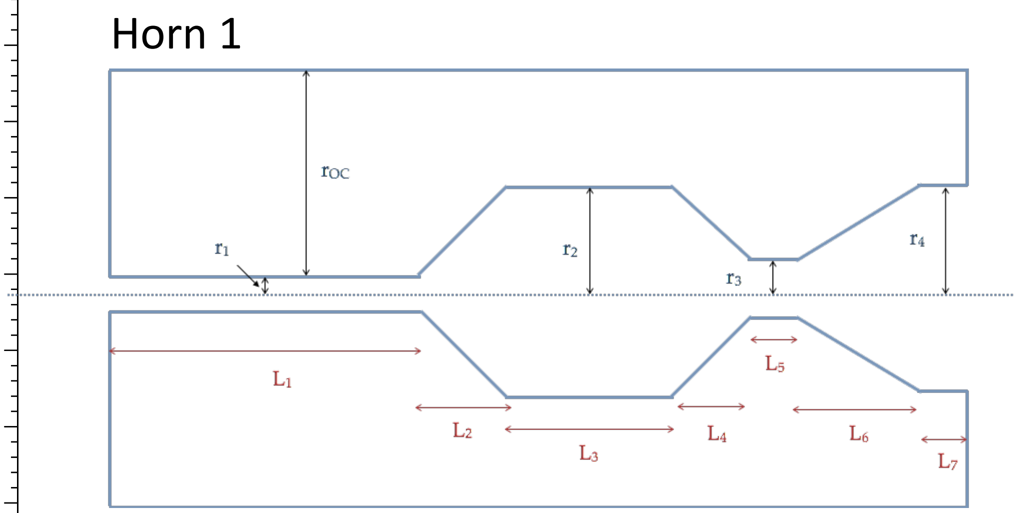
Beam Optimization



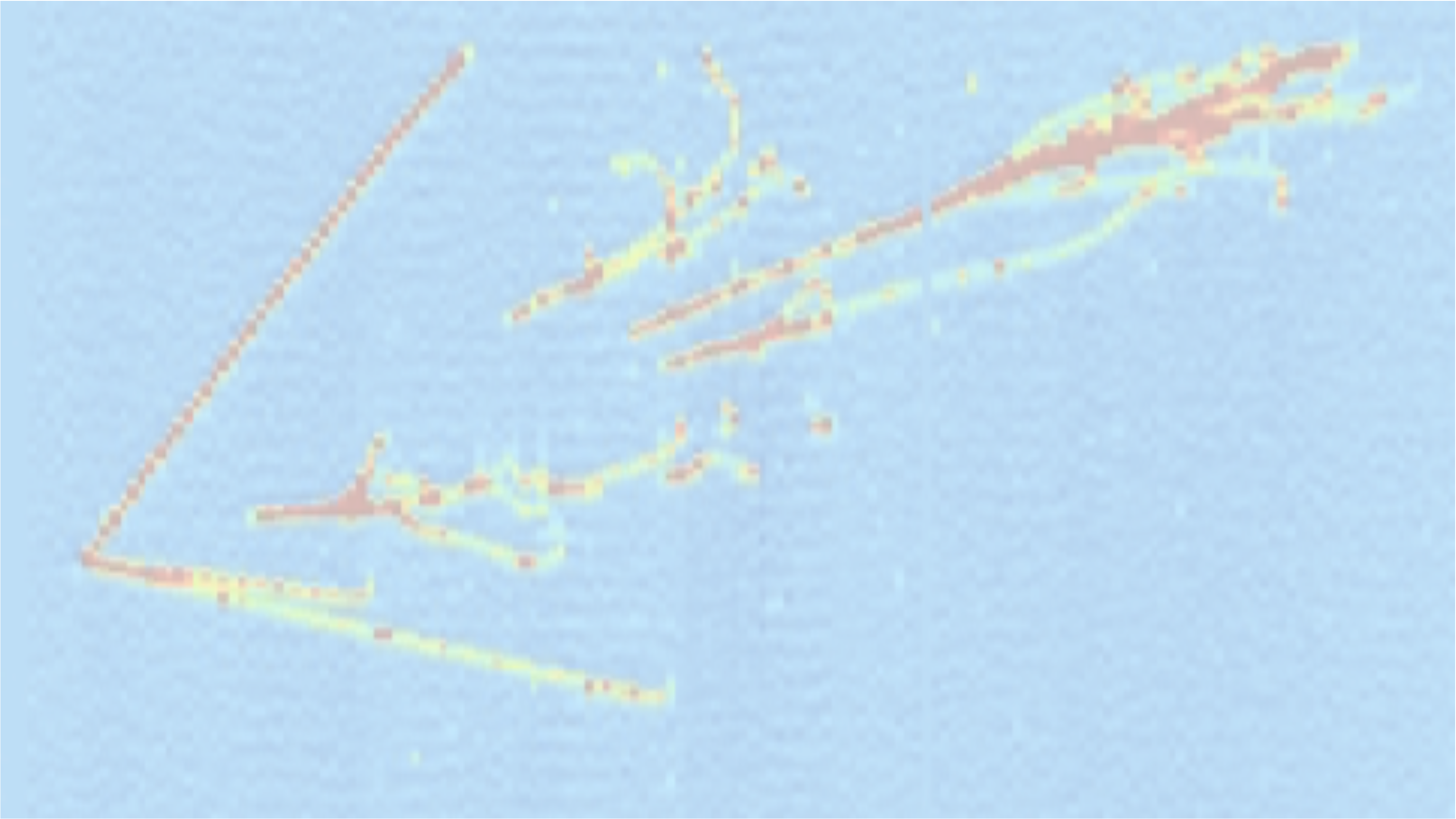
Beam Optimization

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





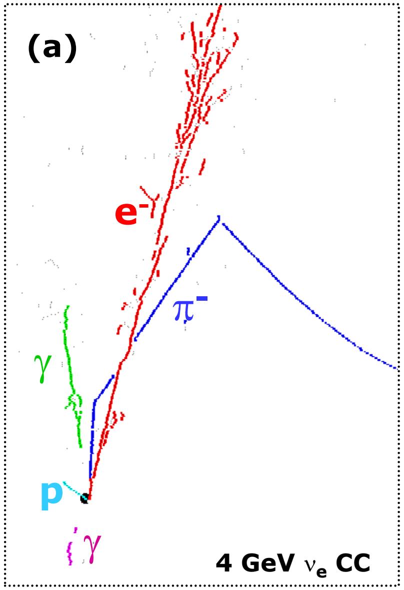
Reconstruction

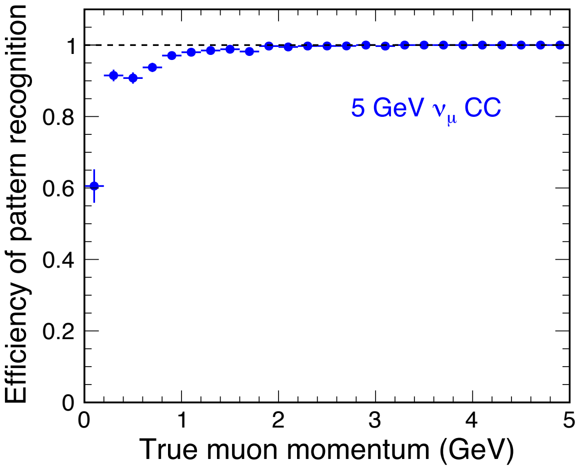


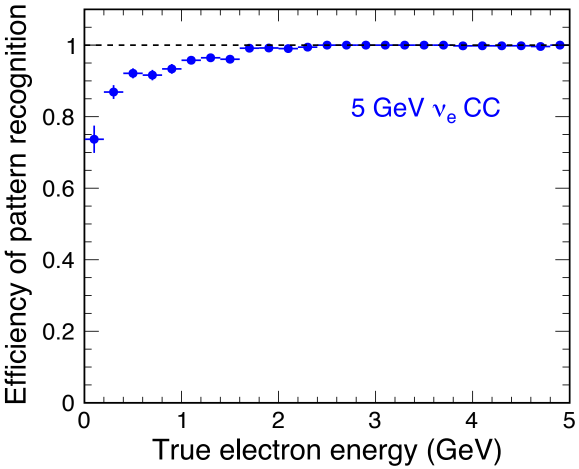
LAr-TPC Reconstruction

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

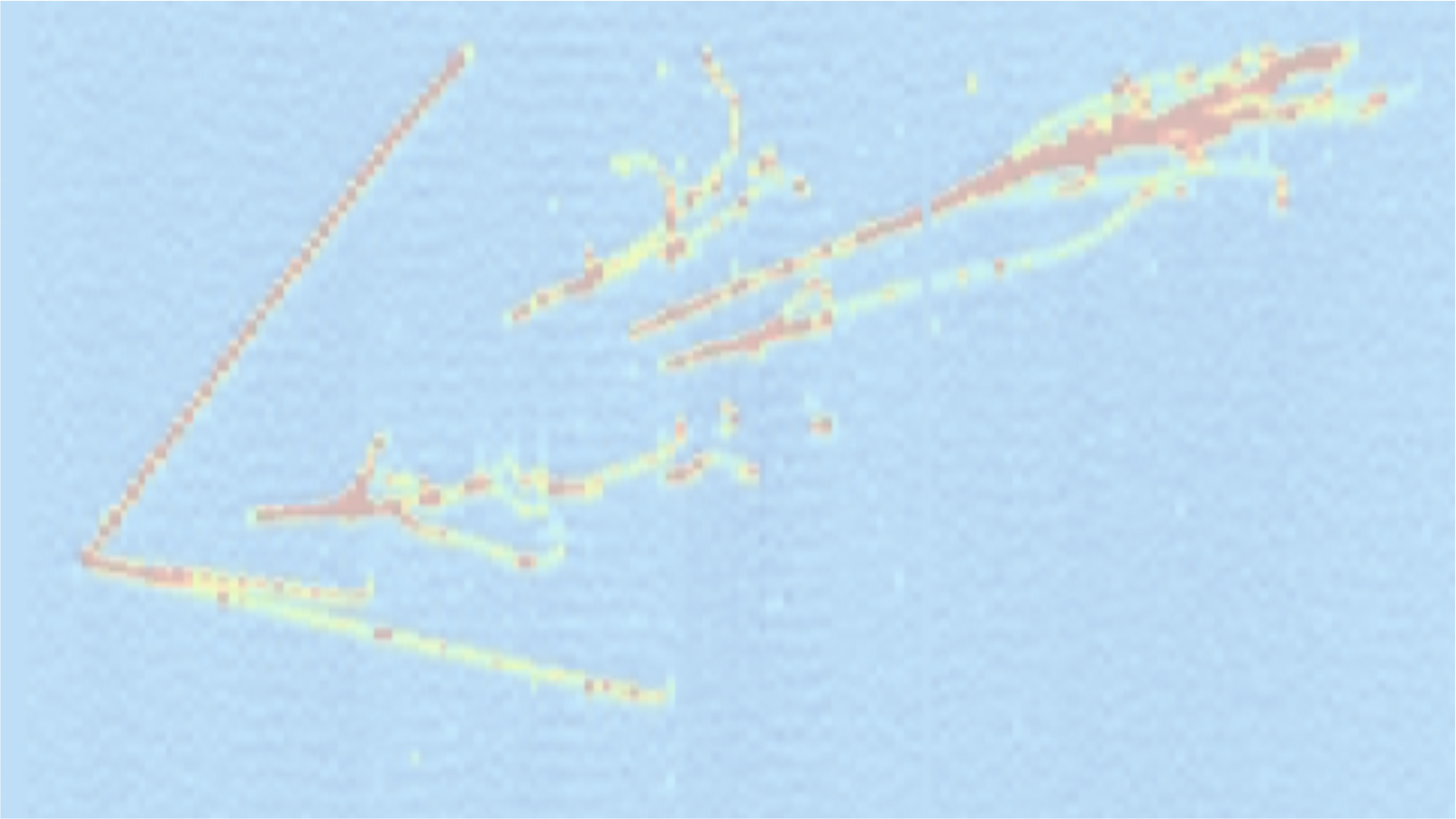
- Full DUNE simulation/reconstruction now in reach



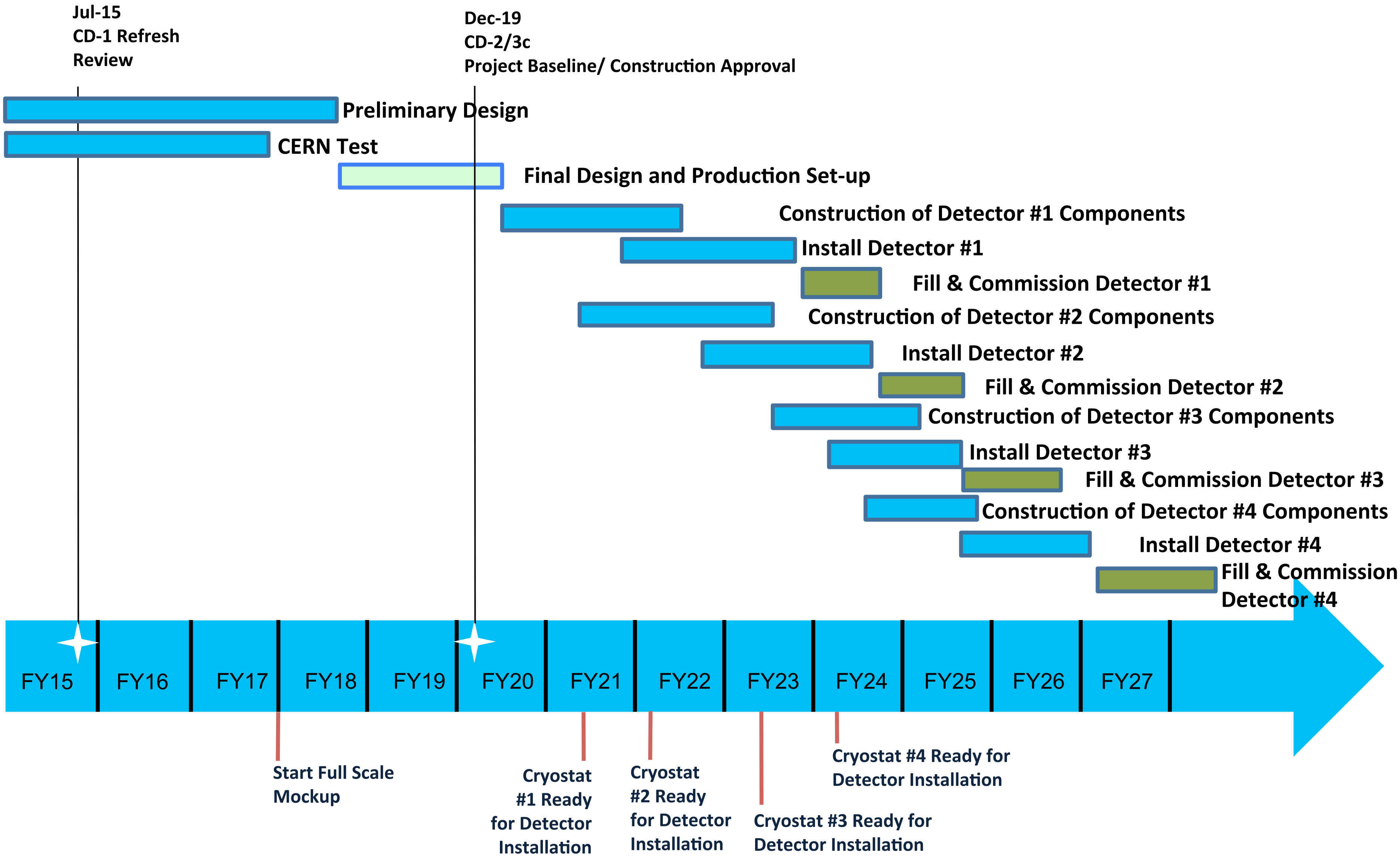




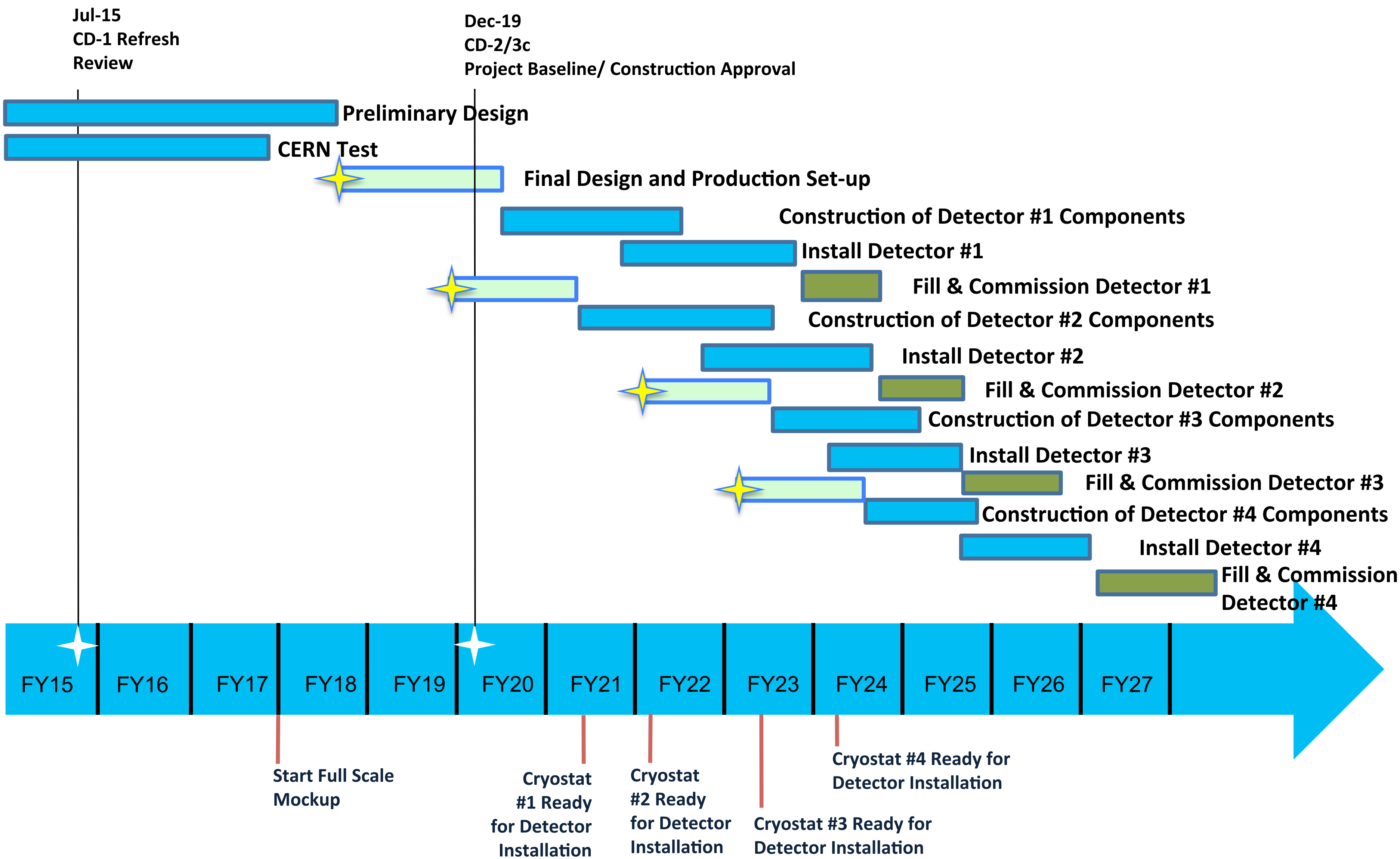
Schedule



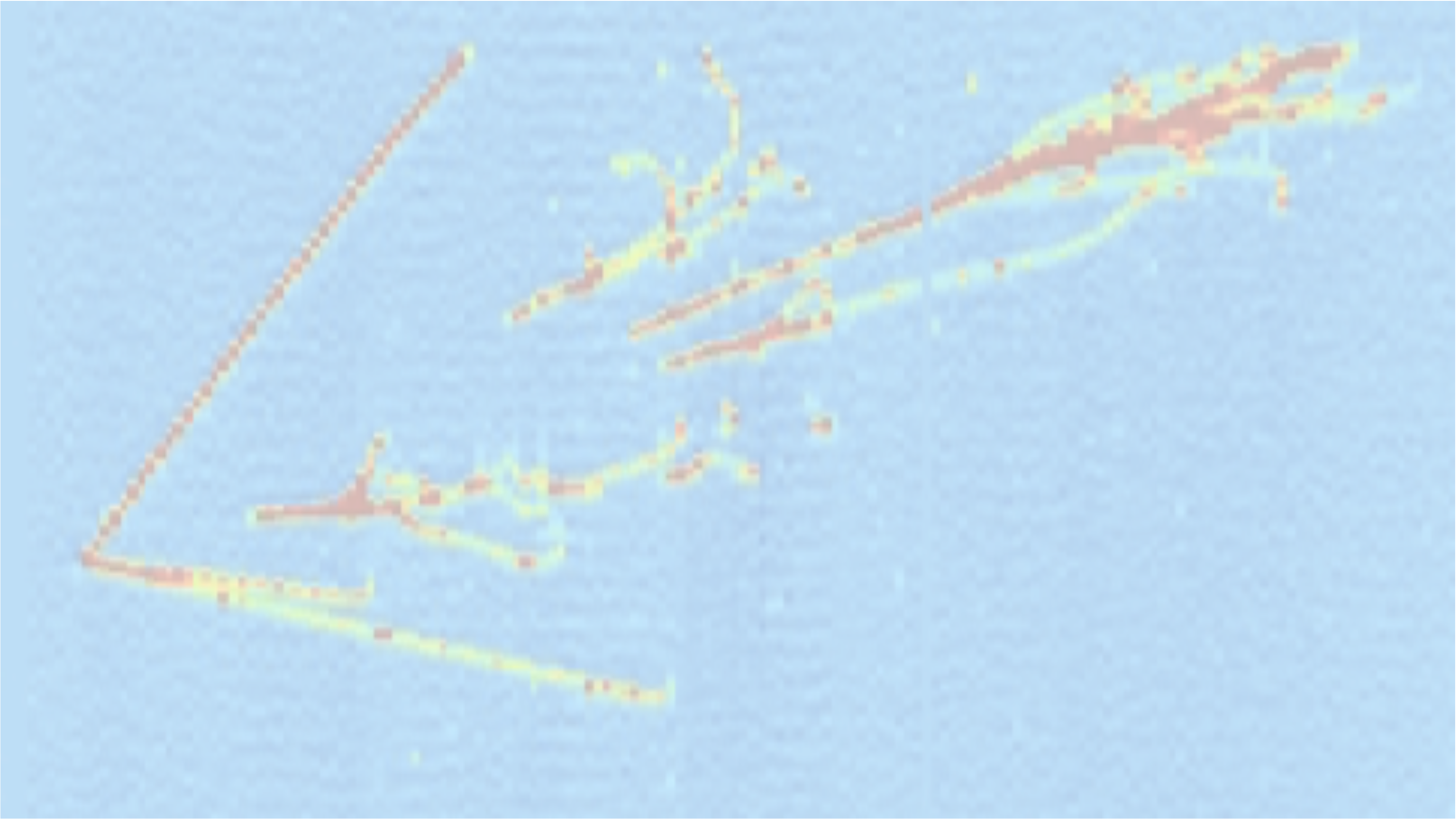
Indicative schedule



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

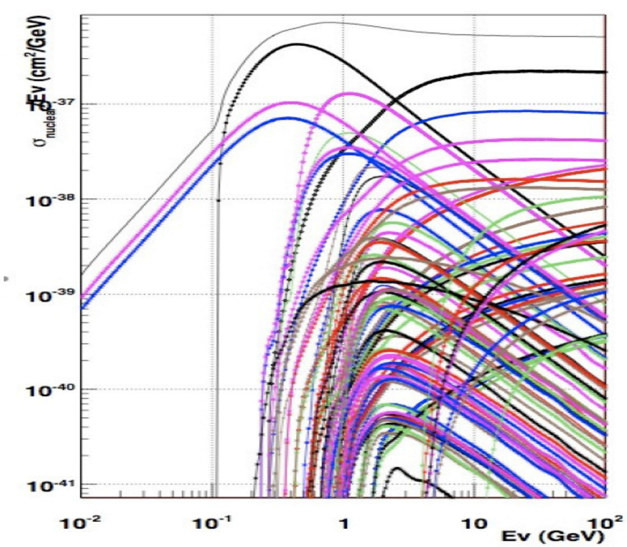
Evaluating DUNE Sensitivities I

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

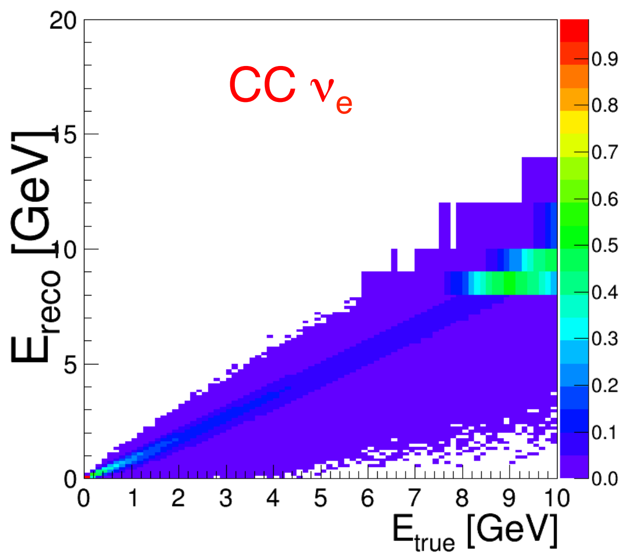
- **Assumed* Particle response/thresholds**
  - Parameterized detector response for individual final-state particles

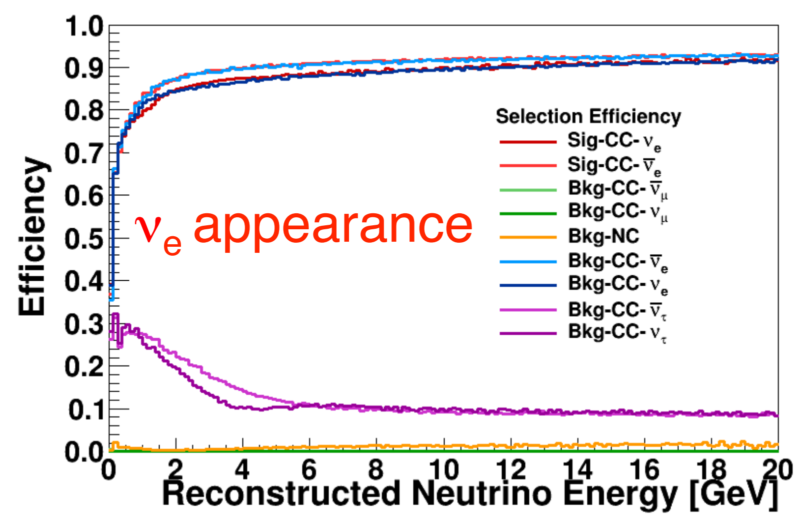
Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained: from track length Exiting: 30 %	1^{o}
$\pi^{\pm}$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1^{o}
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{(E/GeV)}$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

*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





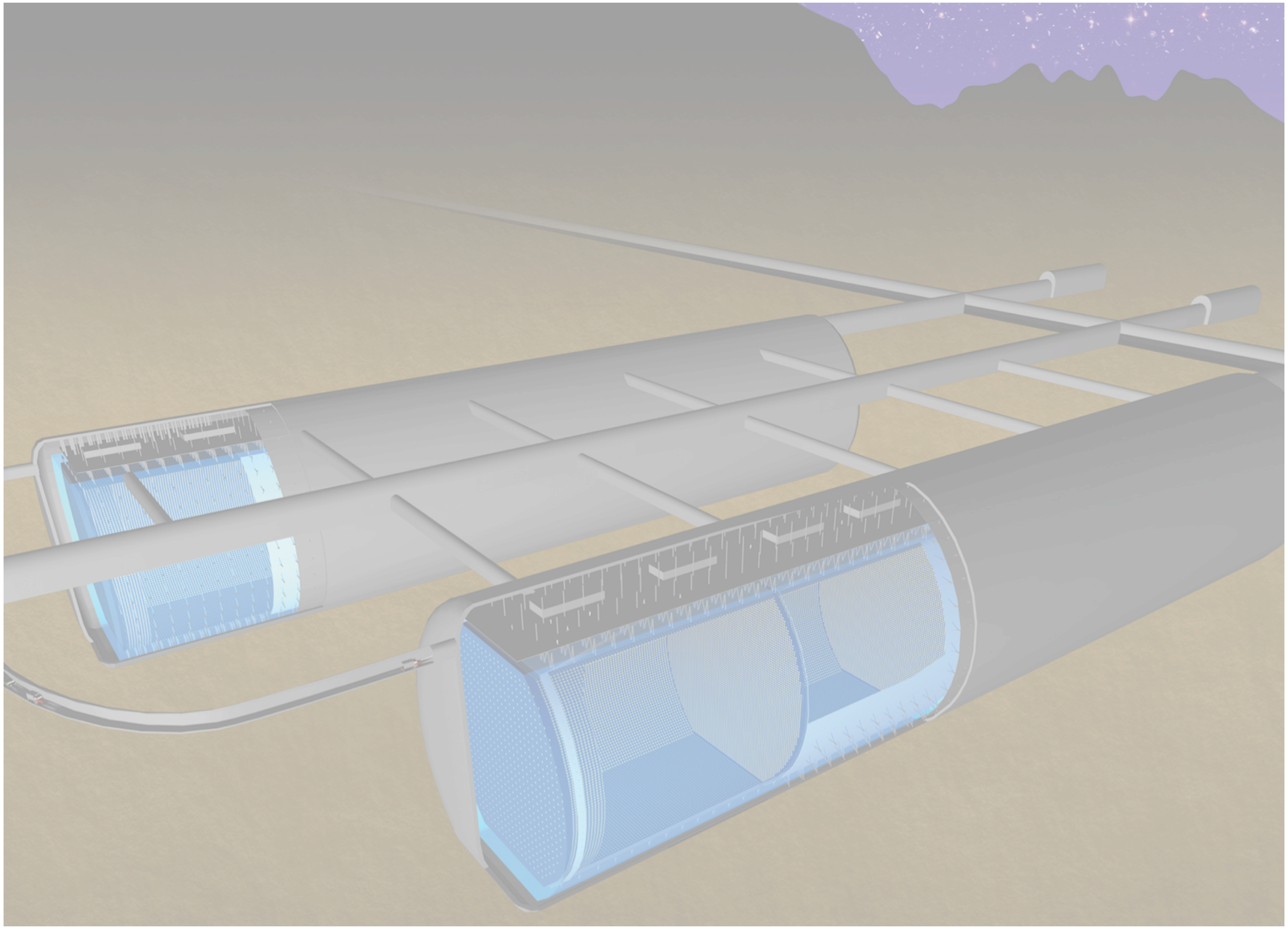
Evaluating DUNE Sensitivities IV

- **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

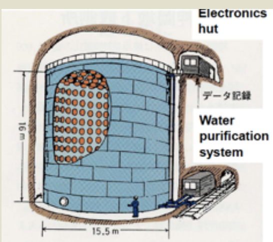
5: Hyper-Kamiokande



Far Detector

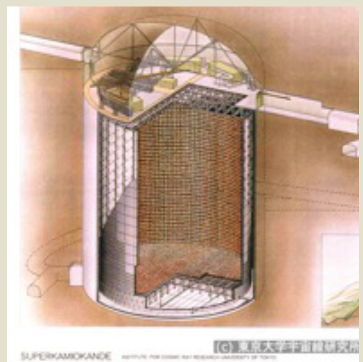
Hyper-K is the proposed third generation large water Cherenkov detector in the Kamioka mine

Kamiokande
(1983-1996)



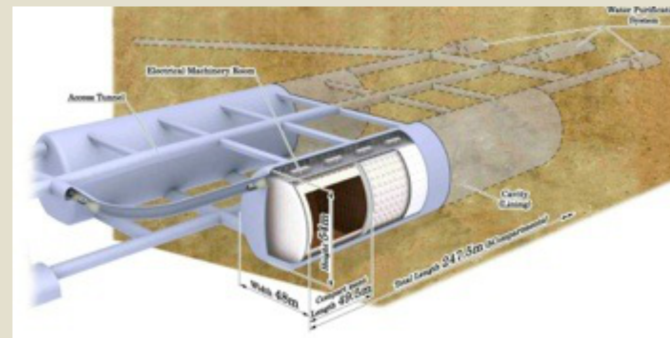
3 kton

Super-Kamiokande
(1996-)



50 kton

Hyper-Kamiokande
(202?-)

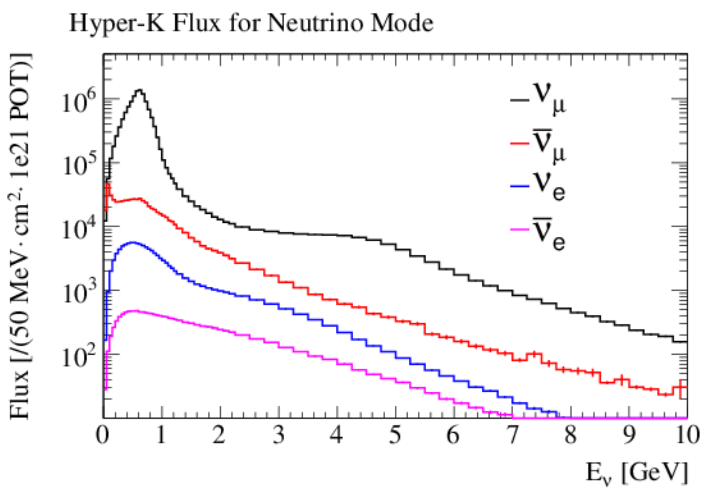


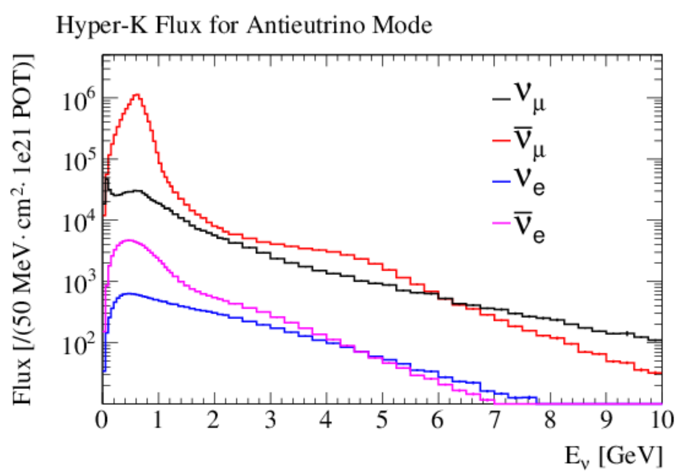
1 Mton

- Inner detector volume = 0.74 Mton
- Fiducial volume = 0.56 Mton
- Photomultiplier tubes: 99,000 20” inner detector & 25,000 8” outer detector

JPARC Beam for Hyper-K

- ★ **Upgraded JPARC beam**
- ★ **At least 750 kW expected at start of experiment**
  - **Physics studies assume 7.5x10^7 MW.s exposure**
    - i.e. 10 years at 750 kW
    - or 5 years at 1.5 MW
  - **Beam sharing between neutrinos:antineutrinos = 1 : 3**
- ★ **Hyper-K is off-axis**
  - Narrow-band beam, centered on first oscillation maximum
  - Baseline = 295 km ⇨ matter effects are small





Hyper-K Science Goals

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

- **1) Neutrino Oscillations**
  - CPV from J-PARC neutrino beam
  - Mass Hierarchy from Atmospheric Neutrinos
  - Solar neutrinos
- **2) Search for Proton Decay**
  - Particularly strong for decays with π^0
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova

Hyper-K Science Goals

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

- **1) Neutrino Oscillations**
  - CPV from J-PARC neutrino beam - matter effects are small
  - Mass Hierarchy from Atmospheric Neutrinos
  - Solar neutrinos
- **2) Search for Proton Decay**
  - Particularly strong for decays with π^0
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to $\overline{\nu}_e$

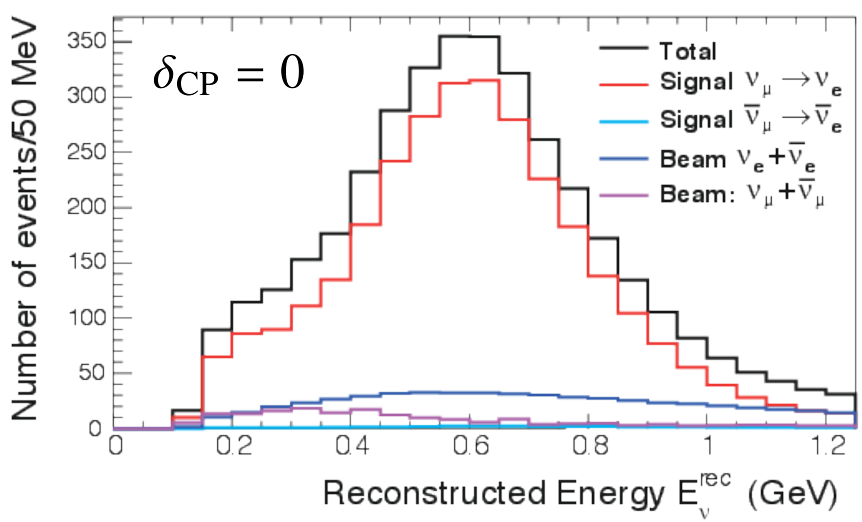
★ **Significant complementarity with DUNE physics**

Hyper-Kamiokande Physics*

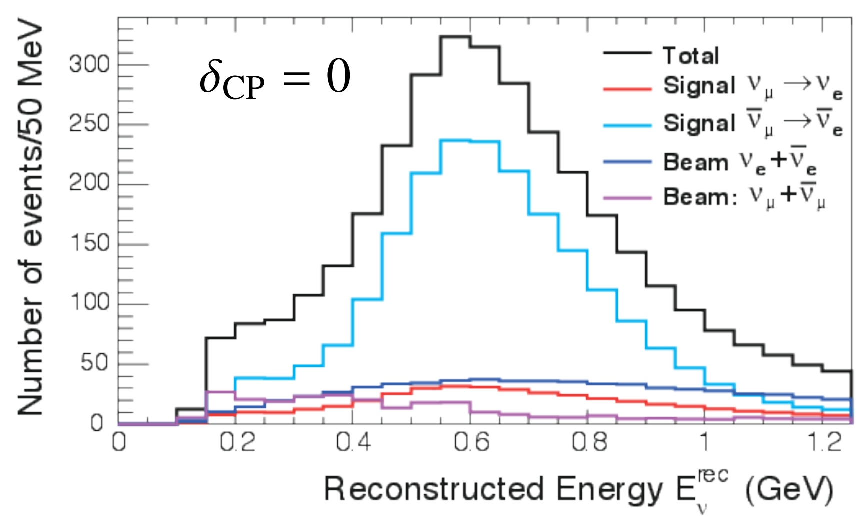
★ High-statistics for $\nu_e/\bar{\nu}_e$ appearance

Beam mode	Signal		Background					Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	NC	
ν_μ	3016	28	11	0	503	20	172	**3750**
$\bar{\nu}_\mu$	396	2110	4	5	222	265	265	**3397**

Appearance ν mode



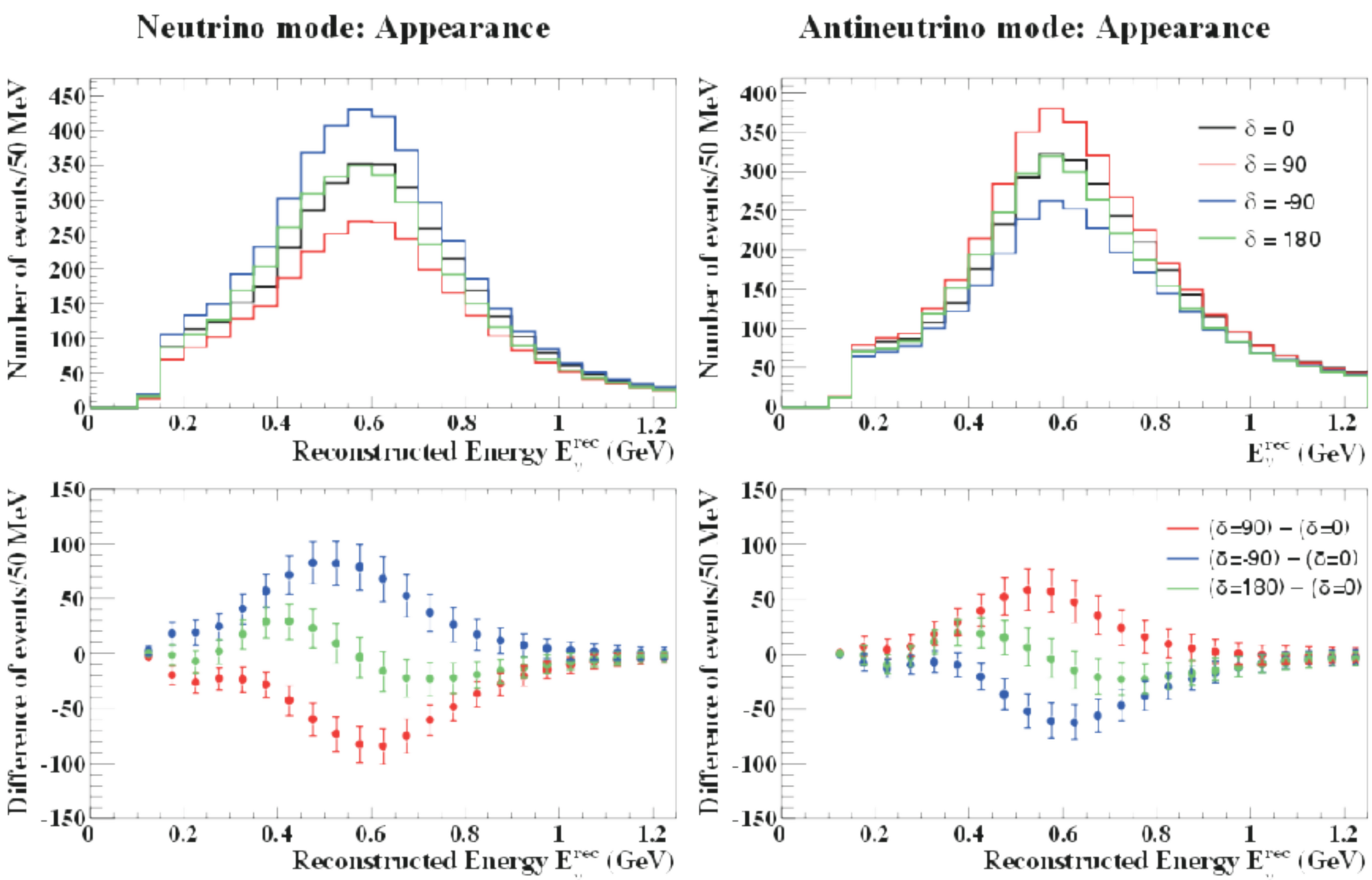
Appearance $\bar{\nu}$ mode



*here focus only on neutrino oscillations

CPV Sensitivity

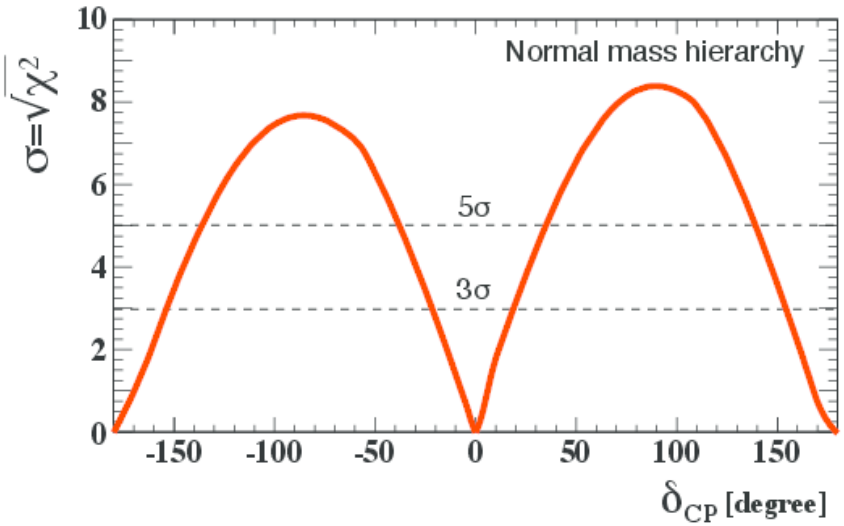
- CPV sensitivity from event counts
  - + some shape information

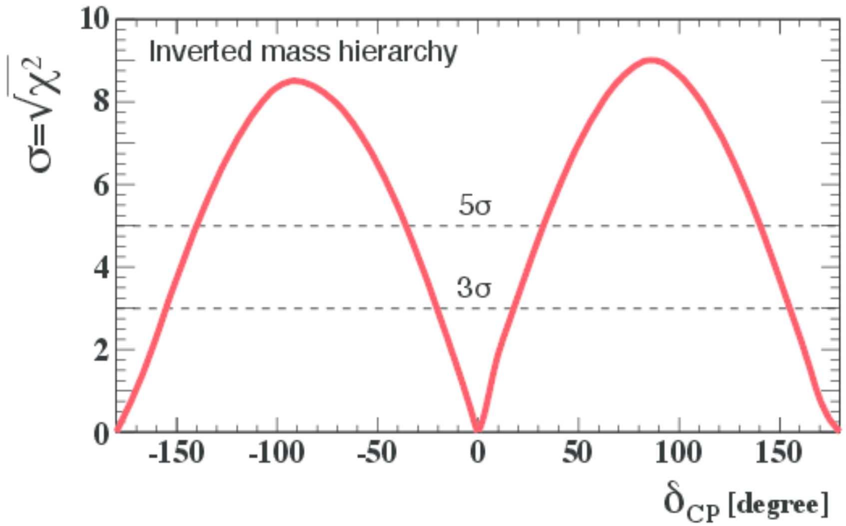


Hyper-K δ_{CP} Sensitivity

★ CPV sensitivity based on:

- 10 years @ 750 kW or 5 years at 1.5 MW
- Assume MH is already known





★ CPV coverage:

- 76 % at 3 σ
- 58 % at 5 σ