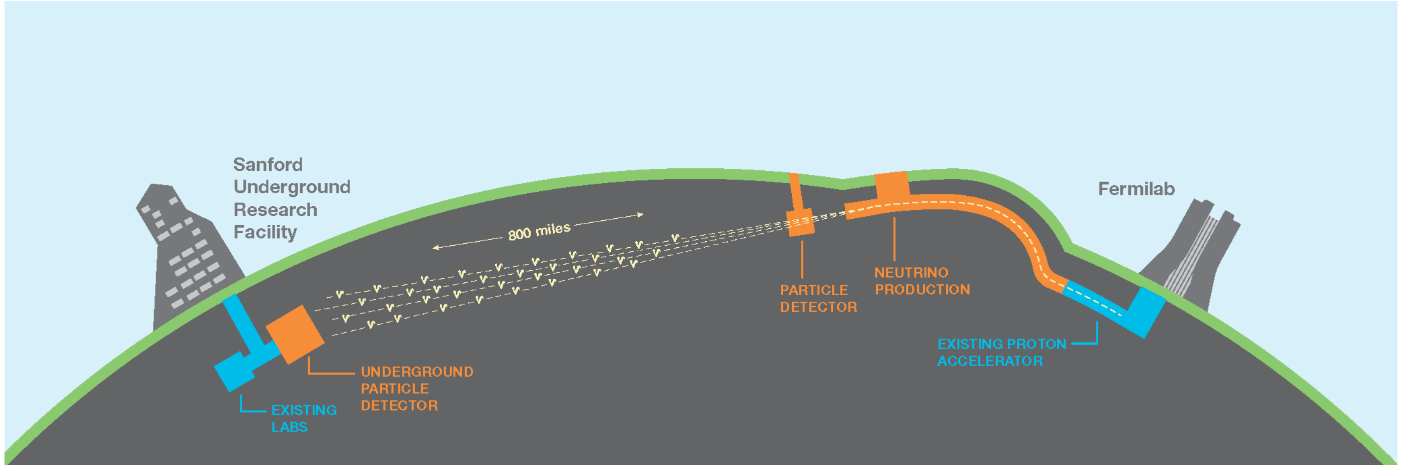

DUNE: The Deep Underground Neutrino Experiment

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University of Cambridge & co-spokesperson of DUNE

Birmingham HEP Seminar: 4th May 2016

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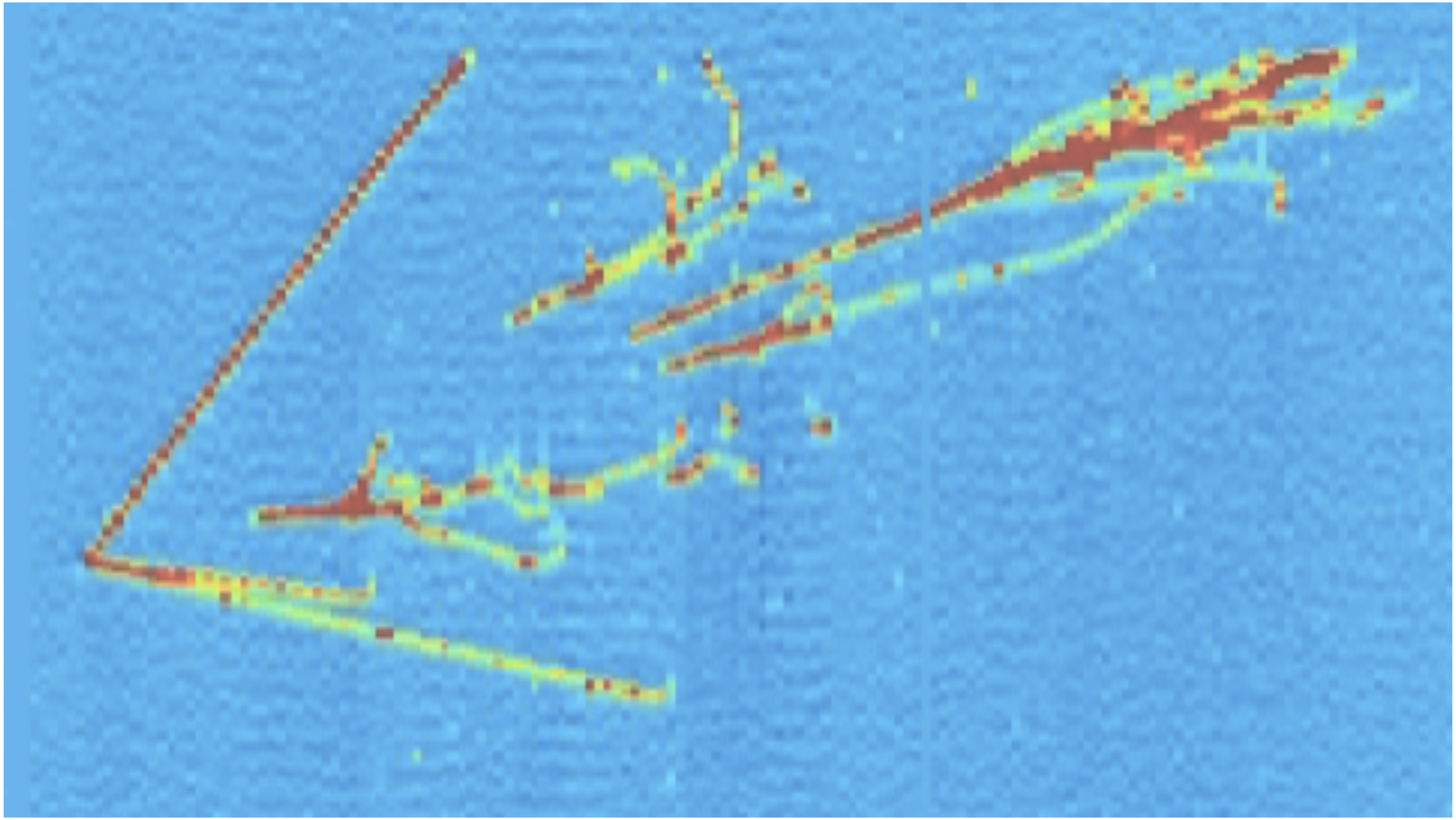
1: Context



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

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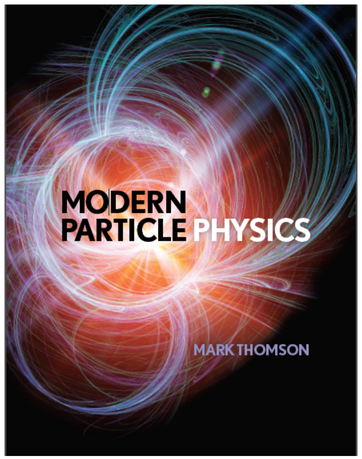
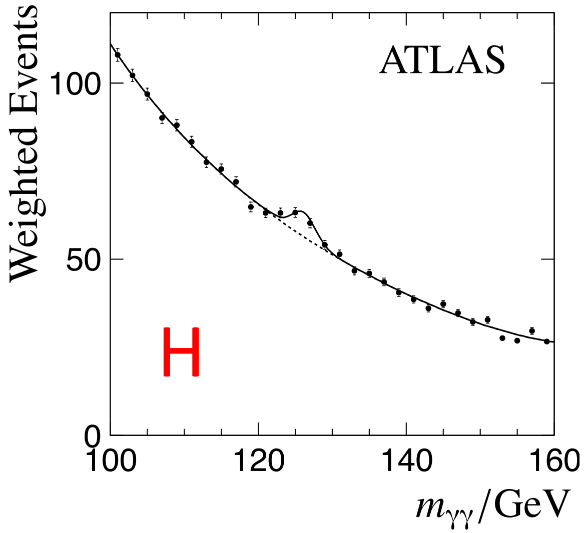
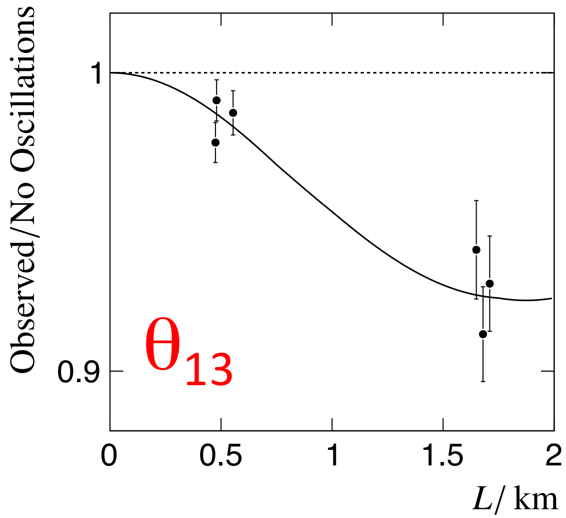
  - The door to CP Violation in the leptonic sector

★ **Now standard textbook physics***

- launch the next steps







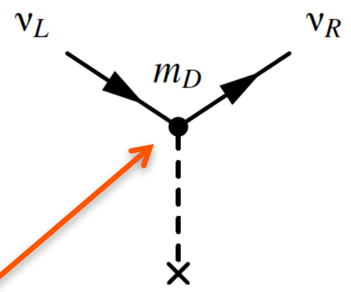
*apologies for gratuitous plug

2. Why are Neutrinos so Important?

a connection to BSM physics

★ **Neutrino masses are anomalously small**

- Why is this the case ... BSM physics !

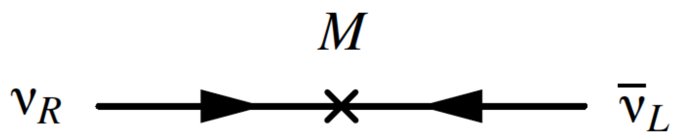


Dirac mass terms, Higgs coupling together L- and R-handed chiral fermionic fields

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

- 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)

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

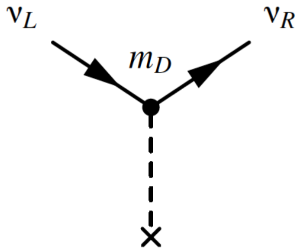


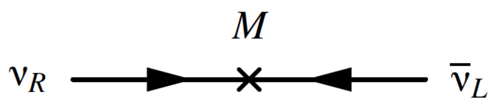
This additional freedom might explain why neutrino masses are "different"

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** $m_N \approx M$

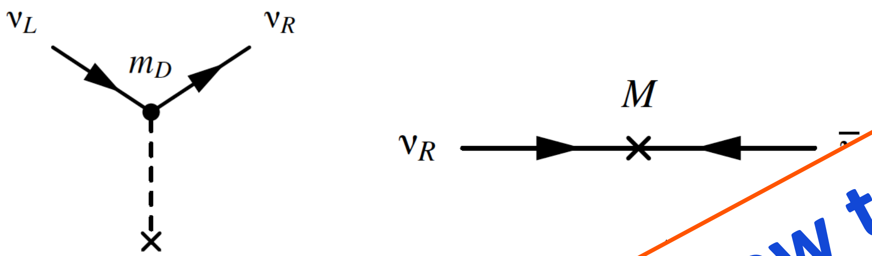
- With $m_D \sim m_\ell$ to get to right range of small neutrino masses:

$$M \sim 10^{12} - 10^{16}\,\mathrm{GeV}$$

a connection to BSM physics

★ **Is there a connection to the GUT scale?**

- If both Dirac and Majorana mass terms are pres



…s)

… violation

$$\mathcal{L} \sim -\tfrac{1}{2}\left(\overline{\nu_L} \; \ldots\right) \ldots \begin{pmatrix} \ldots \\ \nu_R \end{pmatrix}$$

- The seesaw m… …sical "mass eigenstates" are thos… …re the mass matrix is diagonal

…rino $m_\nu \approx \dfrac{m_D^2}{M}$ + heavy **RH neutrino** $m_N \approx M$

$m_D \sim m_\ell$ to get to right range of small neutrino masses:

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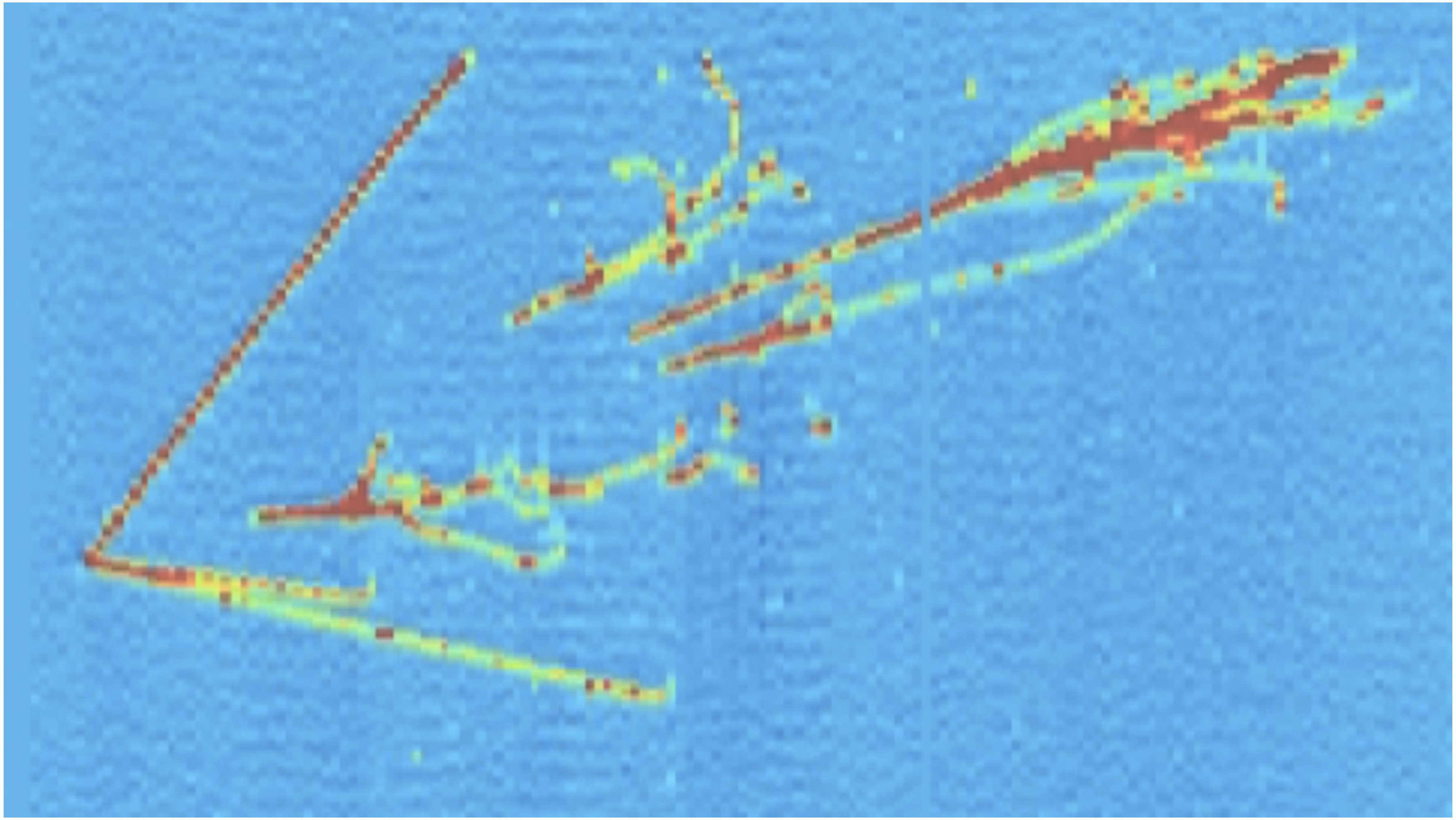
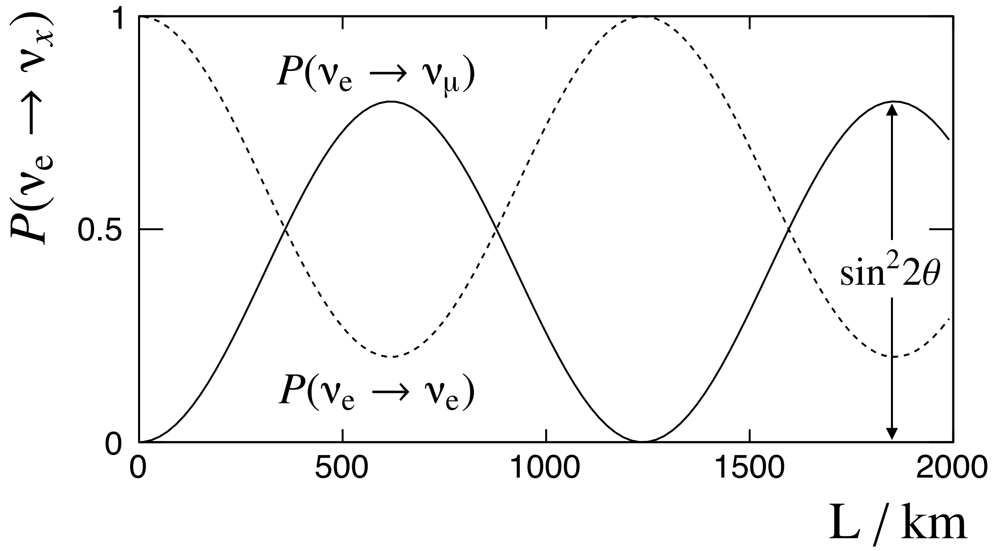
Neutrinos may provide a window to GUT-scale physics argues for a precision neutrino physics program

3: Neutrinos – known unknowns



The Standard 3-Flavour Paradigm

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



L/E_ν dependence

Two-flavour limit:

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

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

The Standard 3-Flavour Paradigm

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

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

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

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

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

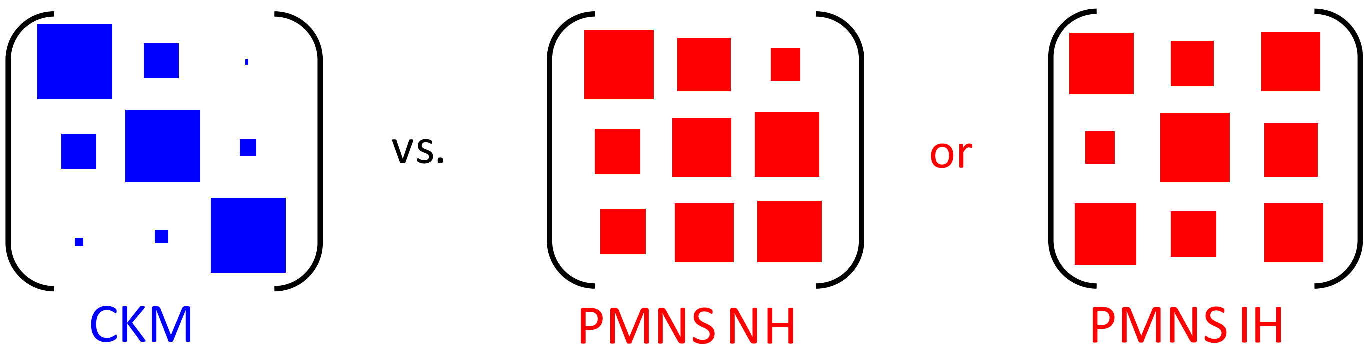
- CPV effects $\propto \sin\theta_{13}$
- **now know that θ_{13} is relatively large**

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

⇨ **LBNF/DUNE**
Hyper-Kamiokande

The Known Unknowns

- ★ **We now know a lot 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, M, …
  - What is the neutrino mass hierarchy ?
    - An important question in flavor physics, e.g. CKM vs. PNMS

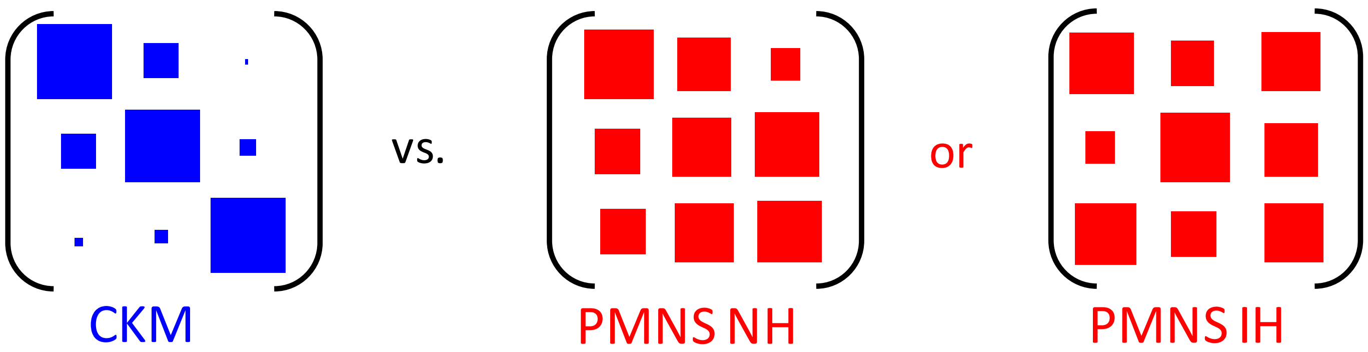


  - **Is CP violated in the leptonic sector ?**
    - Are νs key to understanding the matter-antimatter asymmetry?

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, M, …
- **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 Key Question (my personal bias)

Is CP violated in the neutrino sector ?

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

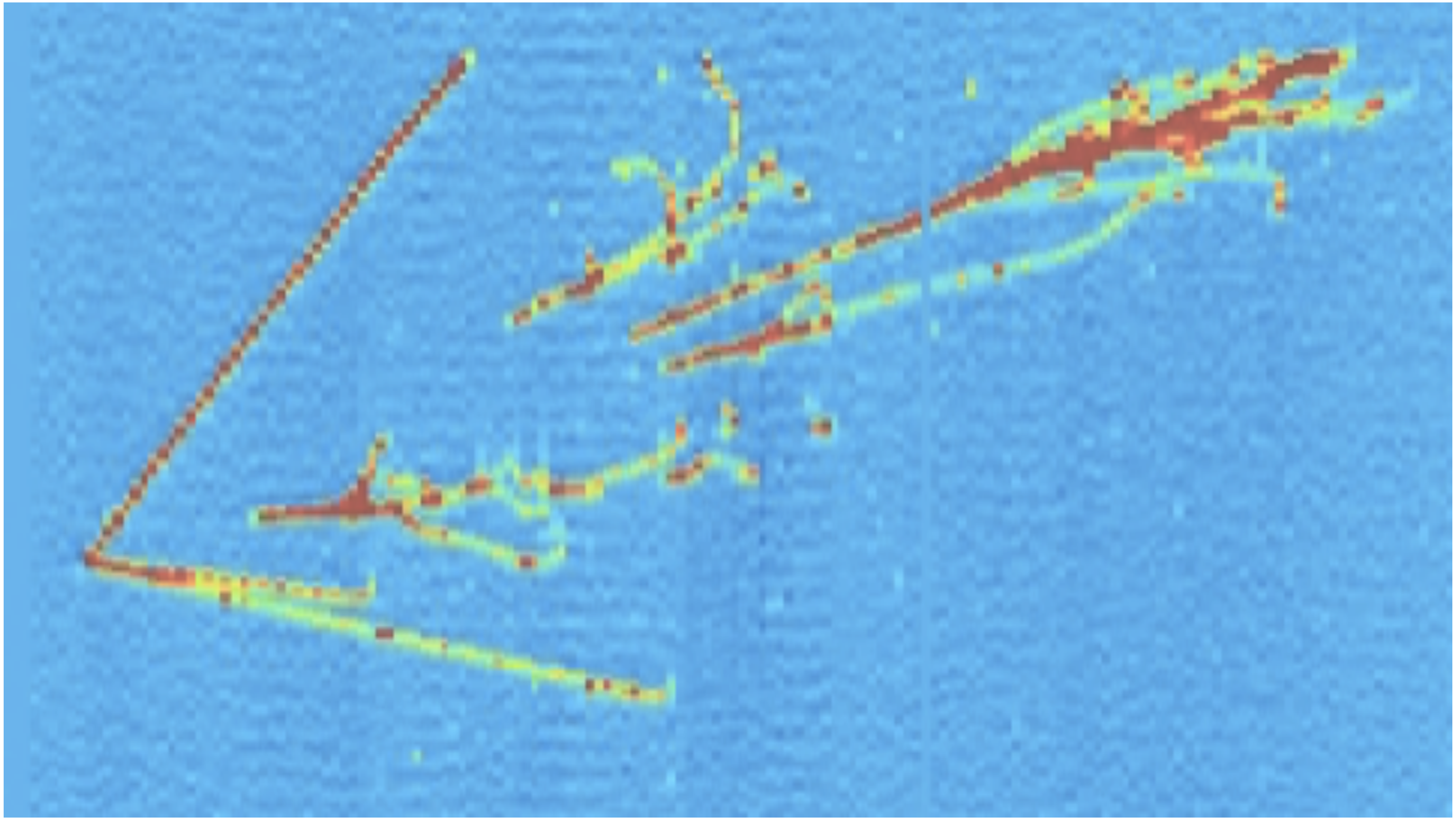
- If yes, would provide support* for the hypothesis of Leptogenesis as the mechanism for generating the matter-antimatter asymmetry in the universe

★ 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 ν s and $\overline{\nu}$ s

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

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 $P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$?
- ★ Not quite, there is a complication…

Matter Effects

★ Even in the absence of CPV

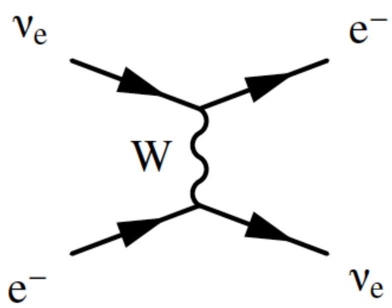
$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) = 0$$

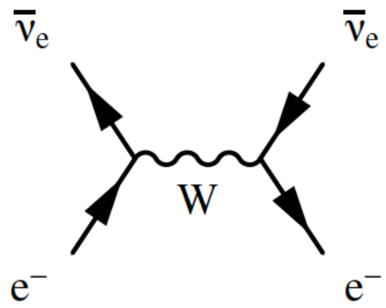
Neutrinos travel through material that is not CP symmetric, i.e. matter not antimatter

★ 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 $\overline{\nu}_e$

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Neutrino Oscillations in Matter

★ Accounting for this potential term, gives a Hamiltonian that is not 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 $A = 2\sqrt{2}G_F n_e E = 7.6\times10^{-5}\mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

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

← What we want

with $A = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5}\,\mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

Experimental Strategy

EITHER:

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

- First oscillation maximum:

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

- Want 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)

- First oscillation maximum:

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

- **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 eff... re insignificant

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⇨ **Off-... eam:** narrow range of neutrino energies

Hyper-Kamiokande

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- **Unfold CPV from M... ts through E dependence**

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DUNE

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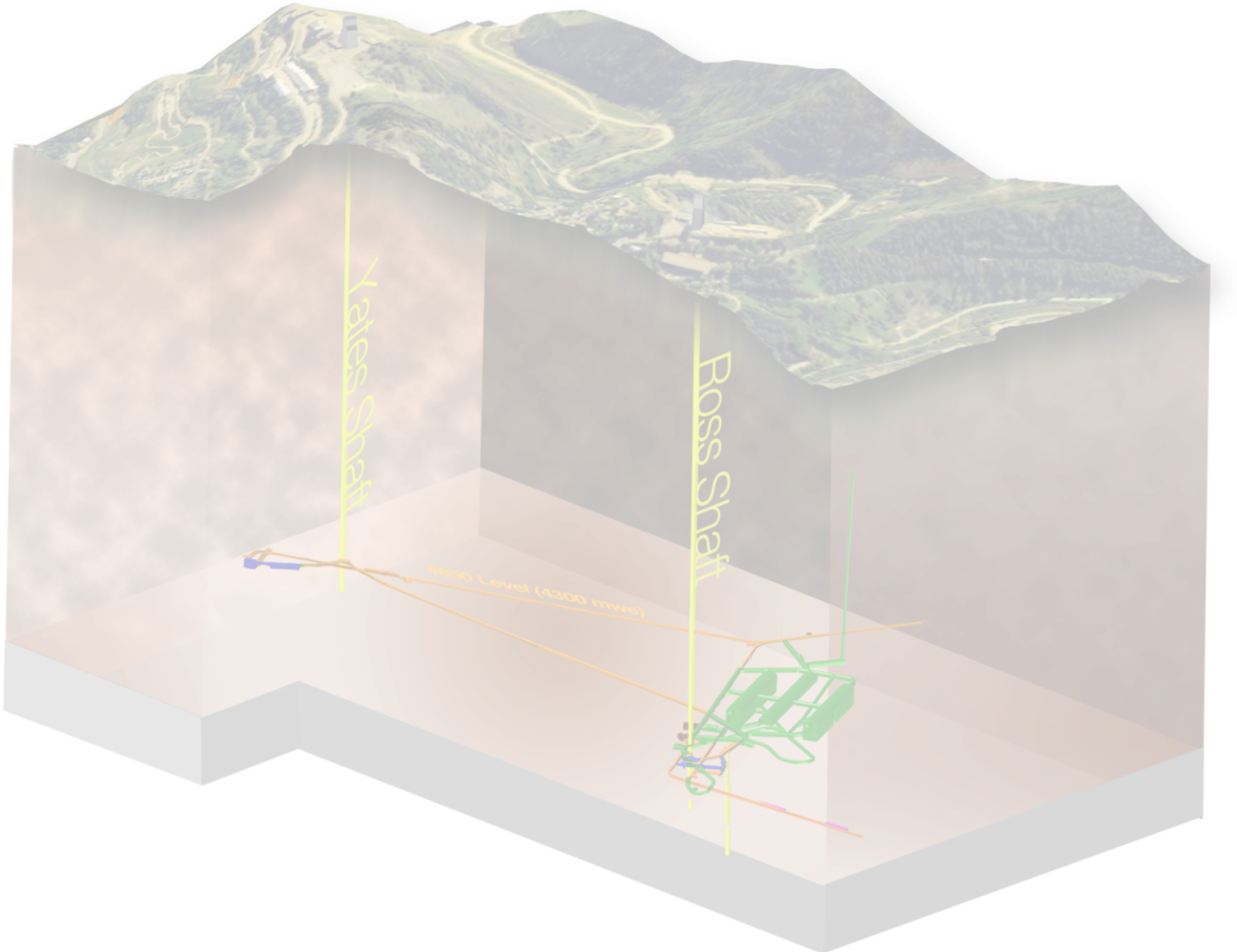
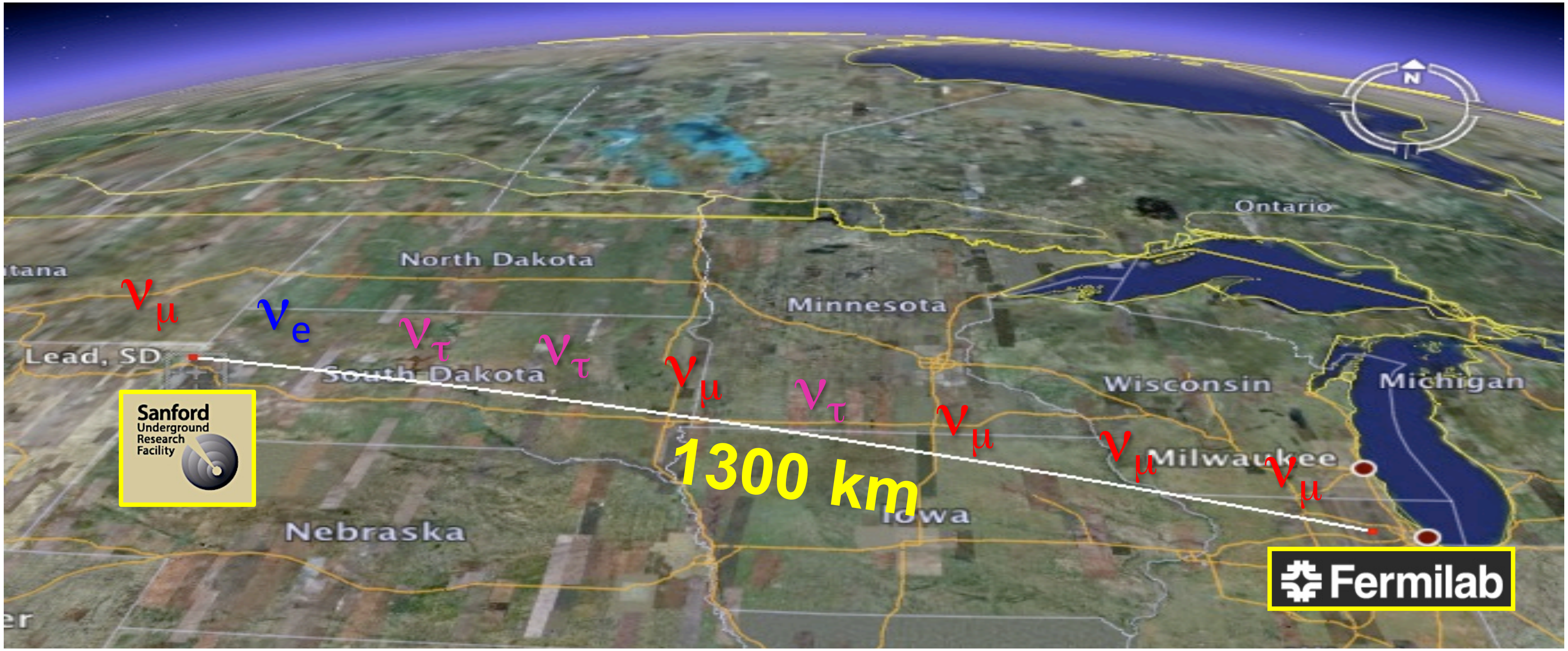
5. DUNE



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
- ★ Probe fundamental differences between matter & antimatter



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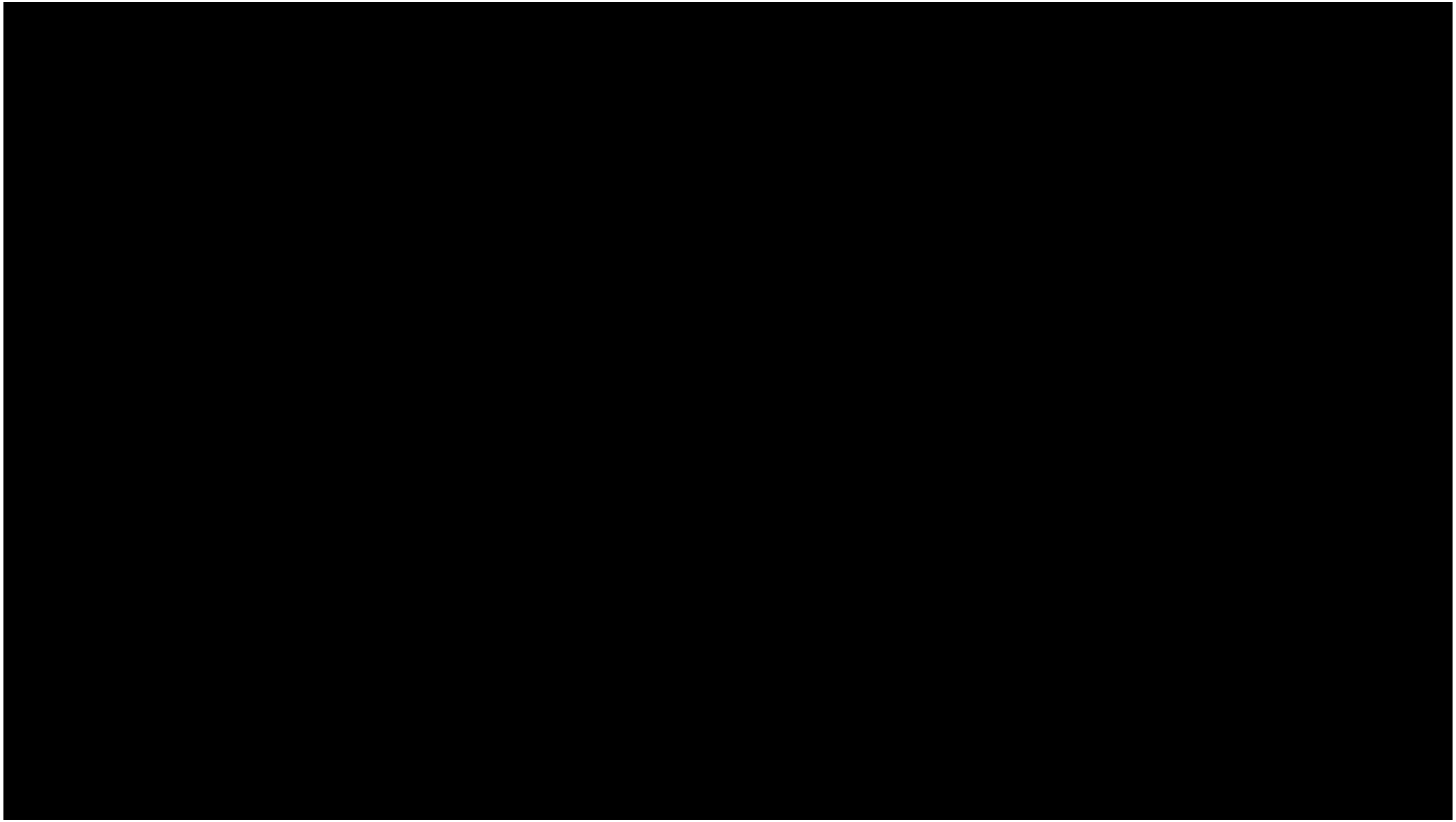
DUNE in a Larger Nutshell

★ LBNF/DUNE

- Muon neutrinos/anti-antineutrinos from high-power proton beam
  - **1.2 MW** from day one
  - upgradable to **2.4 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

LBNF/DUNE – Fermilab in 2025

LBNF/DUNE – Fermilab in 2025



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Origins of DUNE

P5 strategic review of US HEP

- **Called for the formation of "LBNF":**
  - as a international collaboration bringing together the international neutrino 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: rapid progress

Things are moving very fast…

- First formal collaboration meeting April 16^{th}-18^{th} 2015
  - Over 200 people attended in person
- Conceptual Design Report in June (foundations from LBNE/LBNO)
- Passed DOE CD-1 Review in July
- Second collaboration meeting September 2^{nd}-5^{th} 2015
- Successful CD-3a Review in December 2015
  - paves the way to approval of excavation in FY17

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DUNE

has strong support from:

- **Fermilab and US DOE:**
  - This is *the* future flagship project for Fermilab – “no plan B”
- **CERN**
  - Very significant agreements on CERN – US collaboration

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

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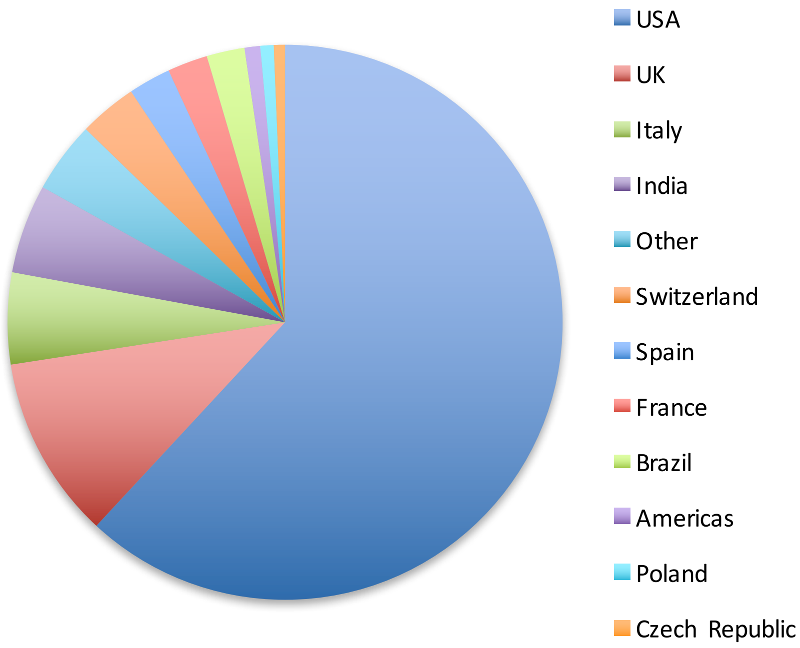
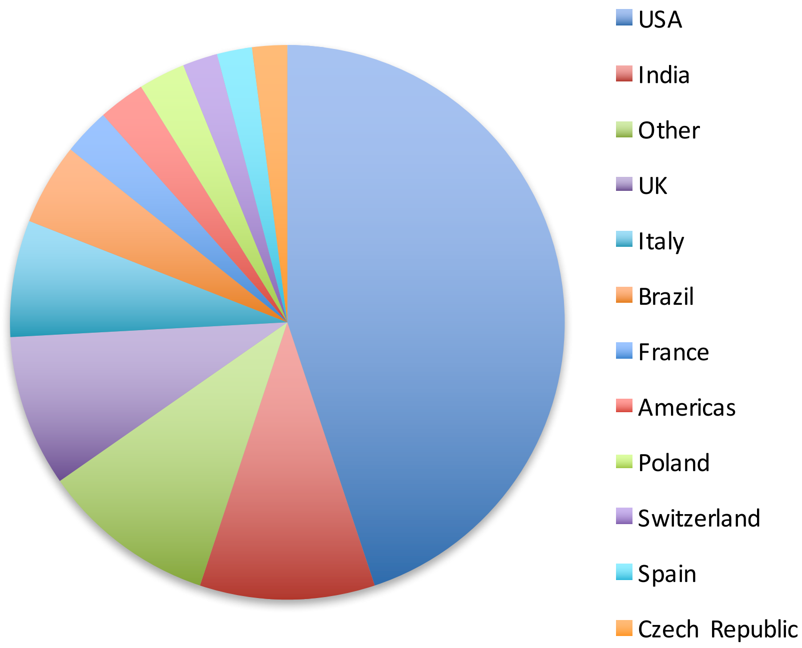
The DUNE Collaboration

As of today: from

856 Collaborators



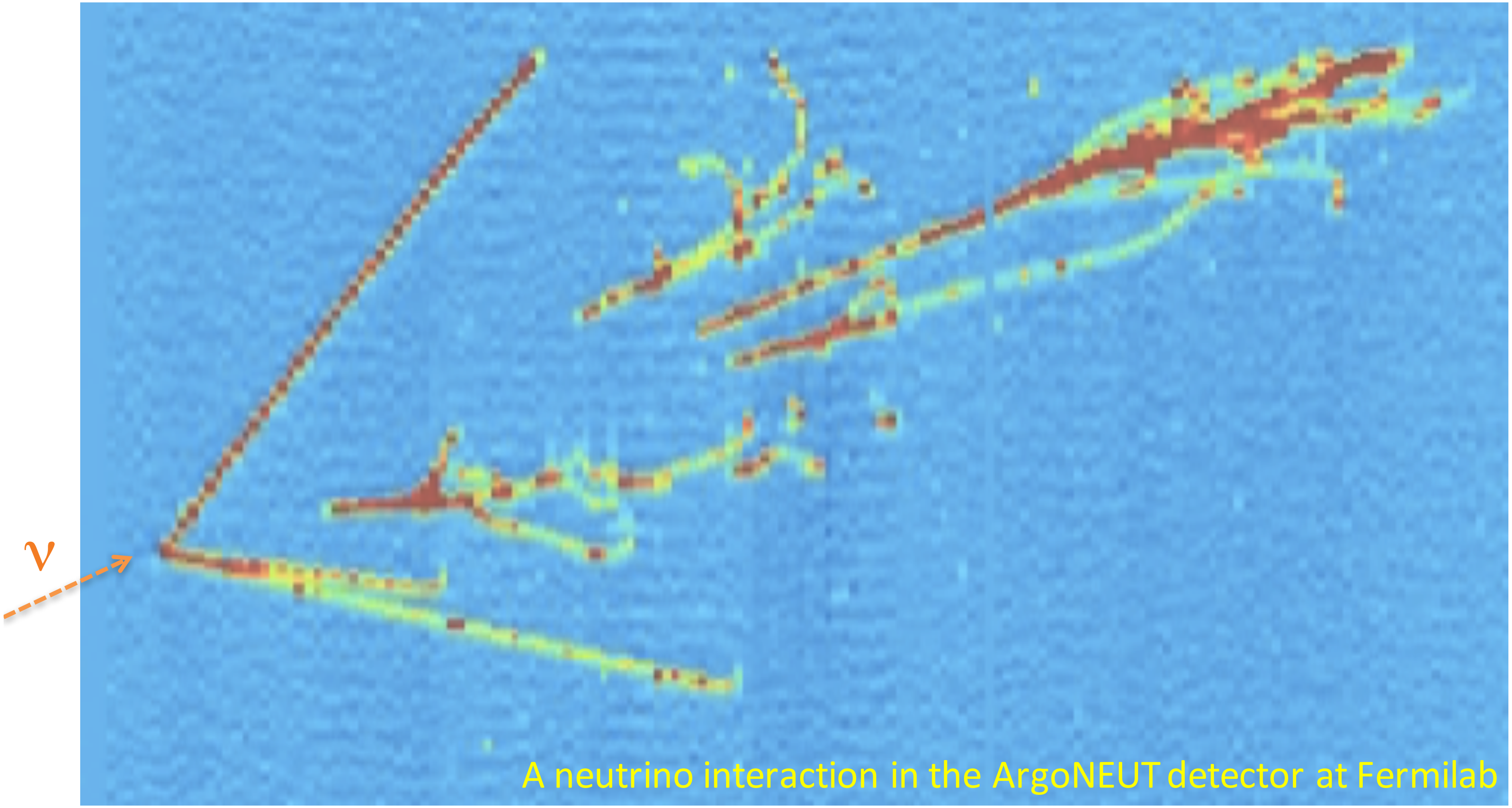
149 Institutes



DUNE has broad international support

5.1 DUNE Science Strategy

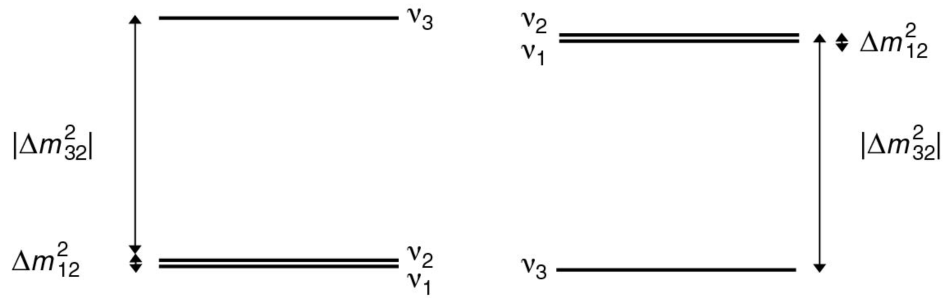
Unprecedented precision utilizing a massive Liquid Argon TPC



DUNE Primary Science Program

Focus on fundamental open questions in particle physics and astroparticle physics:

- **1) Neutrino Oscillation Physics**
  - **Discover CP Violation** in the leptonic sector
  - Mass Hierarchy



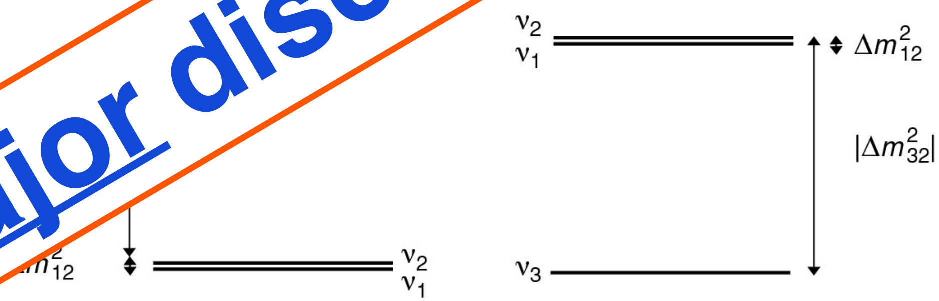
  - Precision Oscillation Physics:
    - e.g. parameter measurement, θ_{23} octant, testing the 3-flavor paradigm
- **2) Nucleon Decay**
  - e.g. targeting SUSY-favored modes, $p \rightarrow K^+\overline{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

DUNE Primary Science Program

Focus on fundamental open questions in partic… physics and astroparticle physics:

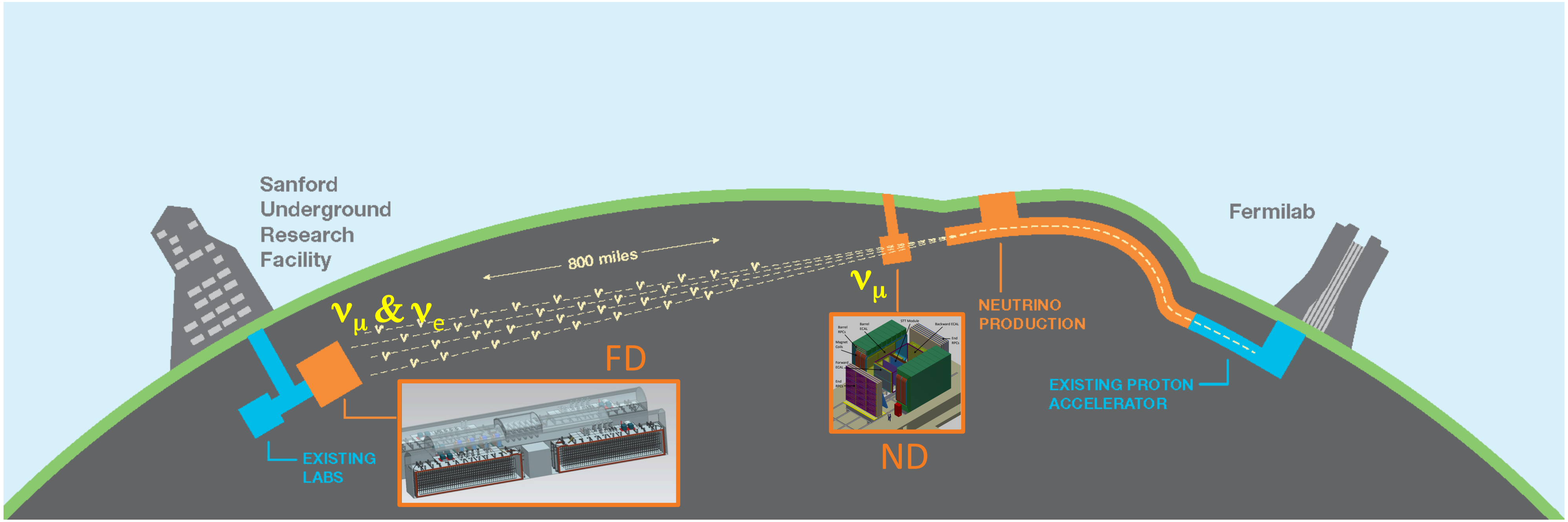
- **1) Neutrino Oscillation Physics**
  - **Discover CP Violation** in the leptonic sector
  - Mass Hierarchy
  - Precision Oscil… …s:
    - e.g. par… …ment, θ_{23} octant, testing the 3-flavor paradigm
- **2) N… …cay**
  - …geting SUSY-favored modes, $p \rightarrow K^{+}\overline{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

All would be major discoveries



Long Baseline (LBL) Oscillations

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

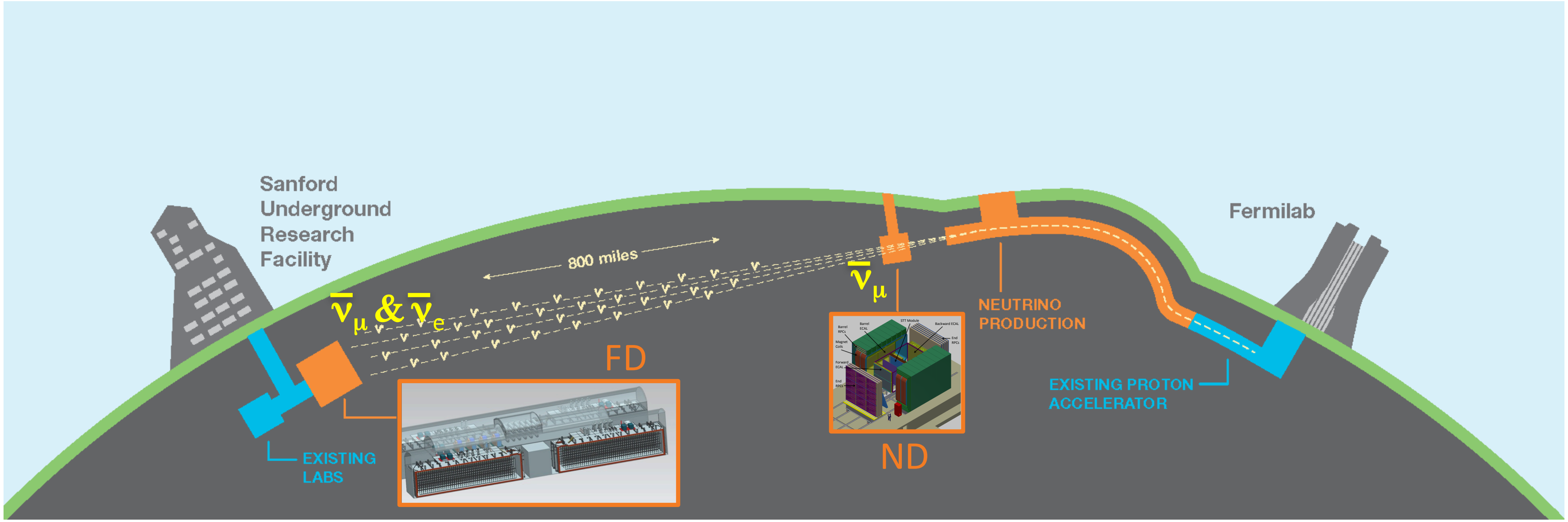


- **Near Detector at Fermilab: measurements of ν_μ unoscillated beam**
- **Far Detector at SURF: measure oscillated ν_μ & ν_e neutrino spectra**

Long Baseline (LBL) Oscillations

… then repeat for antineutrinos

- Compare oscillations of neutrinos and antineutrinos
- Direct probe of CPV in the neutrino sector



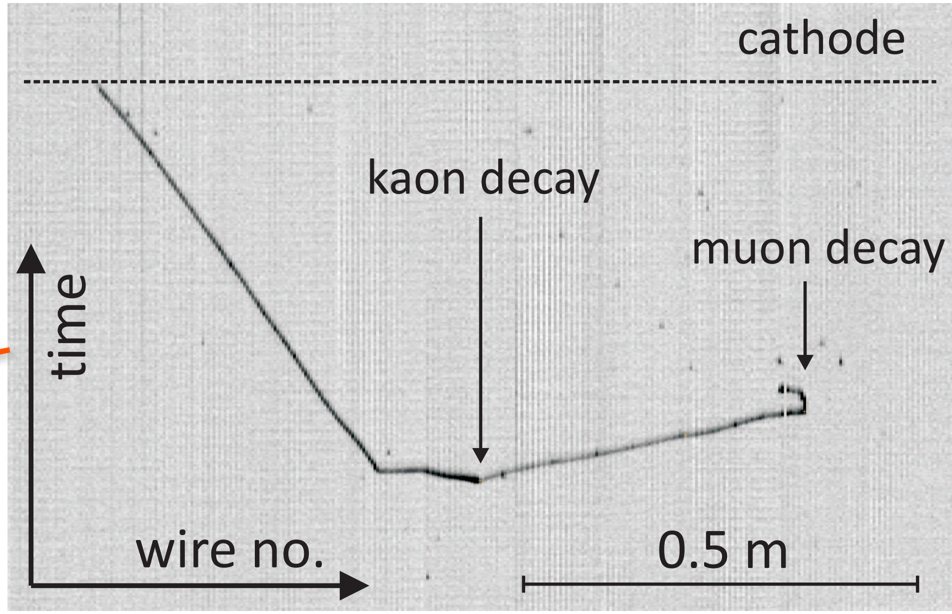
- Near Detector at Fermilab: measurements of $\bar{\nu}_\mu$ unoscillated beam
- Far Detector at SURF: measure oscillated $\bar{\nu}_\mu$ & $\bar{\nu}_e$ neutrino spectra

3.2 Proton Decay

Proton decay is expected in most new physics models

- But lifetime is very long, experimentally $\tau > 10^{33}$ years
- Watch many protons with the capability to see a single decay
- Can do this in a liquid argon TPC
  - For example, look for kaons from SUSY-inspired GUT p-decay modes such as $p \rightarrow K^{+}\overline{\nu}$

E ~ O(200 MeV)



Proton Decay

Proton decay is expected in most new physics models

- But lifetime is very long, experimentally $\tau > 10^{33}$ years
- Watch many protons with the capability to see a single decay
- Can do this in a liquid argon TPC
  - For example, look for kaons from SUSY-inspired GUT p-decay modes such as $p \rightarrow K^{+}\overline{\nu}$

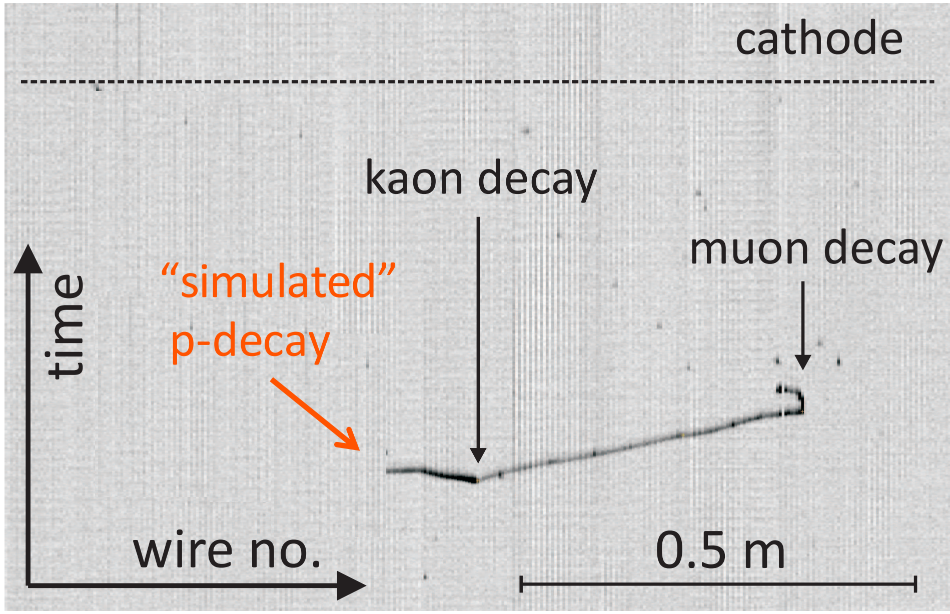
- Clean signature

  ➡ very low backgrounds

Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \rightarrow K^{+}\overline{\nu}$	19%	4	97%	1
$p \rightarrow K^{0}\mu^{+}$	10%	8	47%	< 2
$p \rightarrow K^{+}\mu^{-}\pi^{+}$			97%	1
$n \rightarrow K^{+}e^{-}$	10%	3	96%	< 2
$n \rightarrow e^{+}\pi^{-}$	19%	2	44%	0.8

1 Mt.yr

Remove incoming particle



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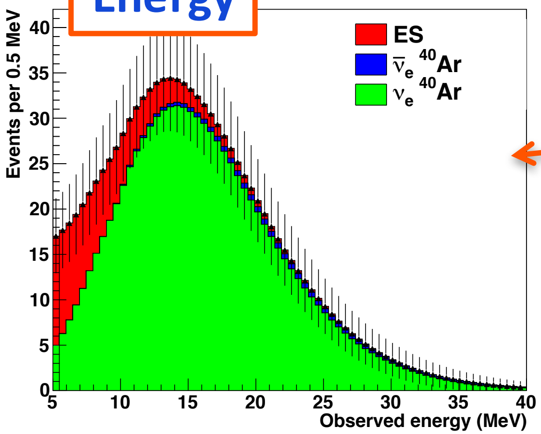
Supernova νs

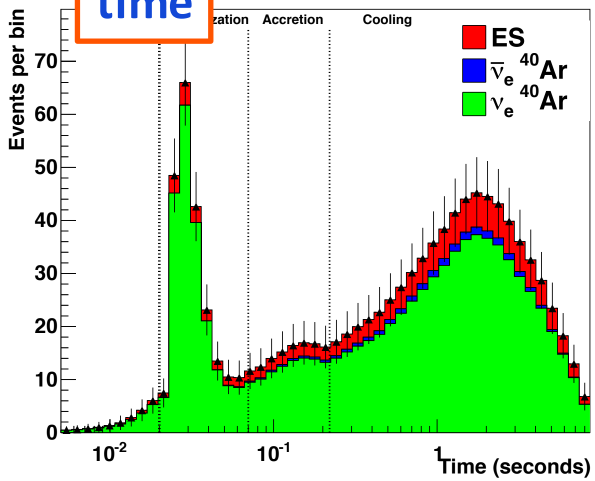
A core collapse supernova produces an incredibly intense burst of neutrinos

- Measure energies and times of neutrinos from galactic supernova bursts
  - In argon (uniquely) the largest sensitivity is to ν_e

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



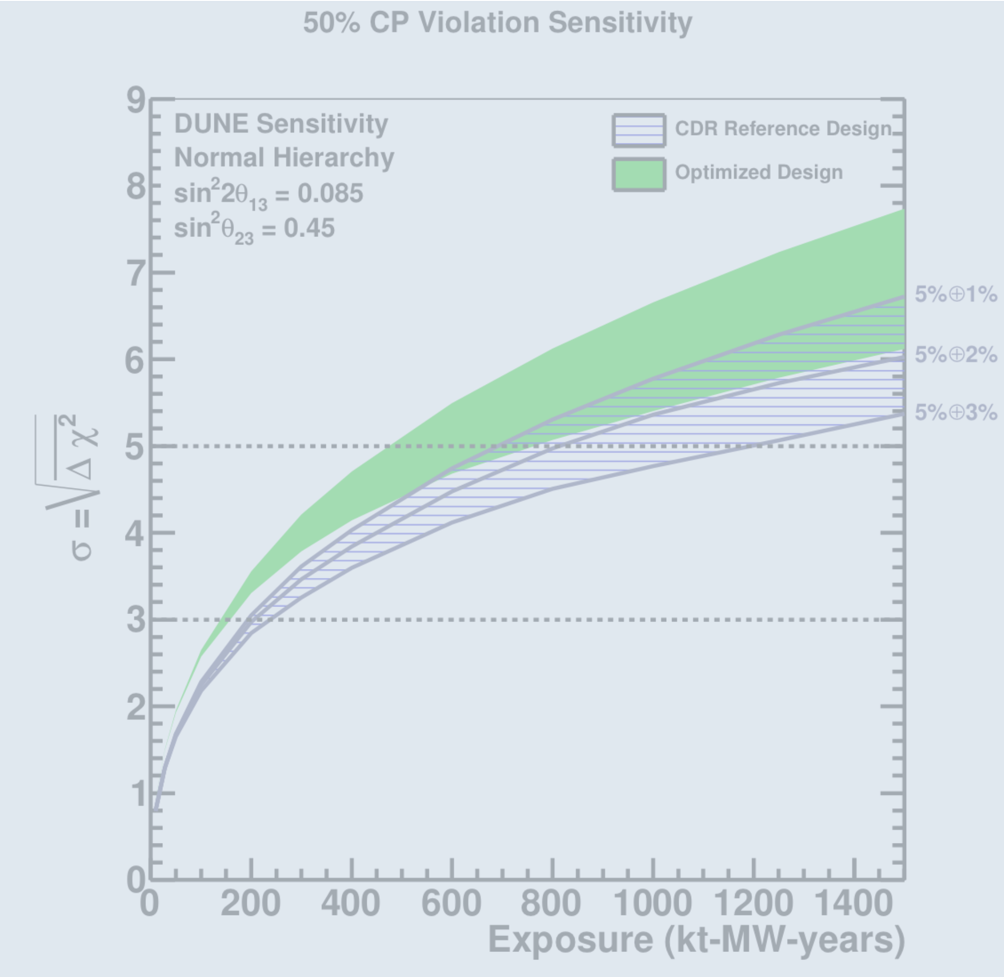
E ~ O(10 MeV)



Physics Highlights include:

- Possibility to "see" neutron star formation stage
- Even the potential to see black hole formation !

6: DUNE Neutrino Physics



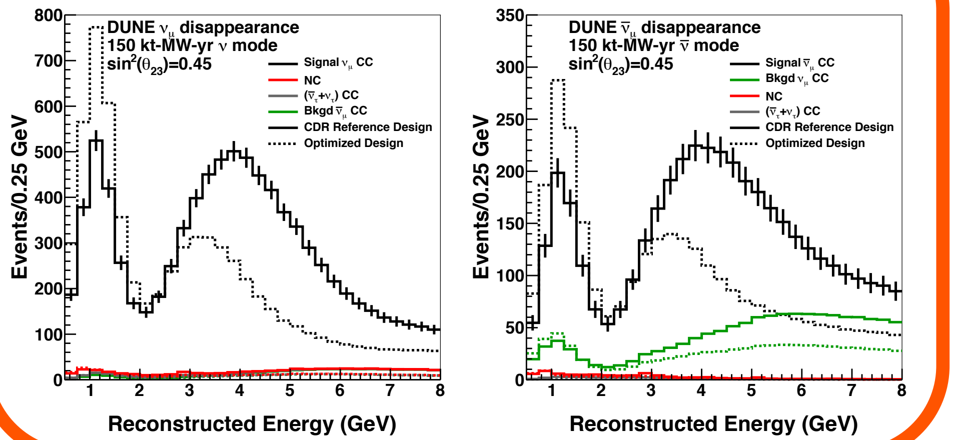
DUNE Oscillation Strategy

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

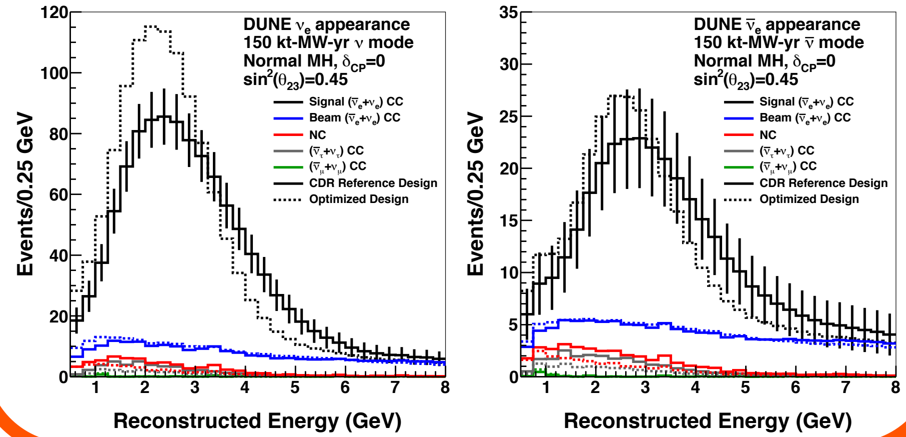
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for BSM effects (e.g. NSI) in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - **MH & CPV effects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

E ~ few GeV

ν_μ / $\bar{\nu}_\mu$ disappearance



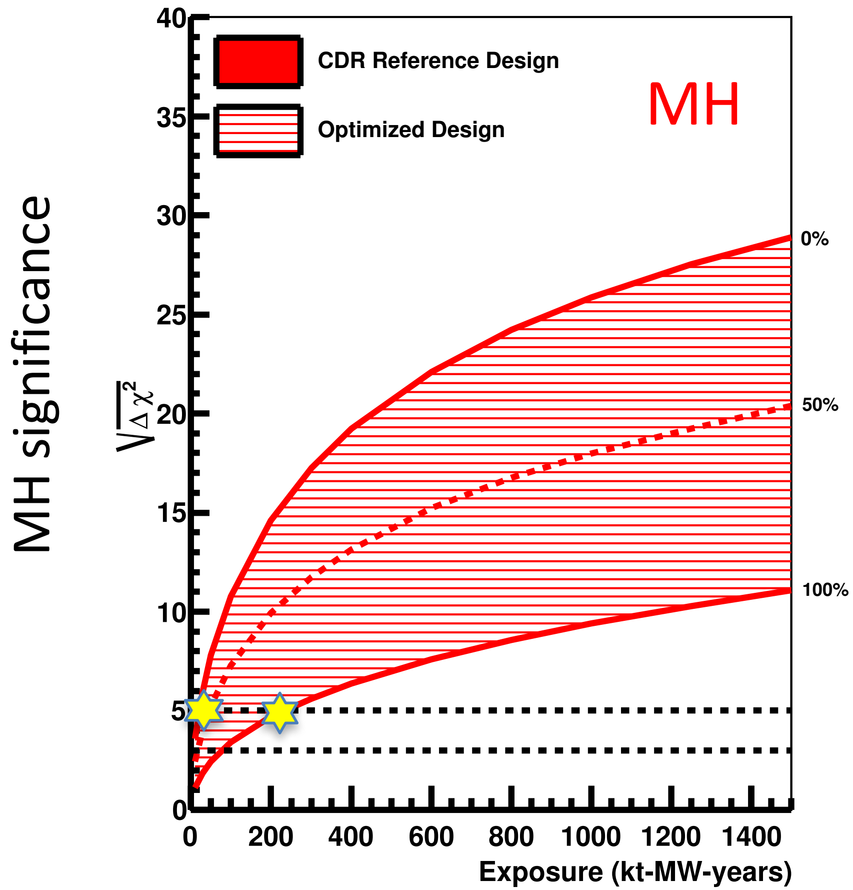
ν_e / $\bar{\nu}_e$ appearance



MH Sensitivity

★ Sensitivities depend on multiple factors:

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



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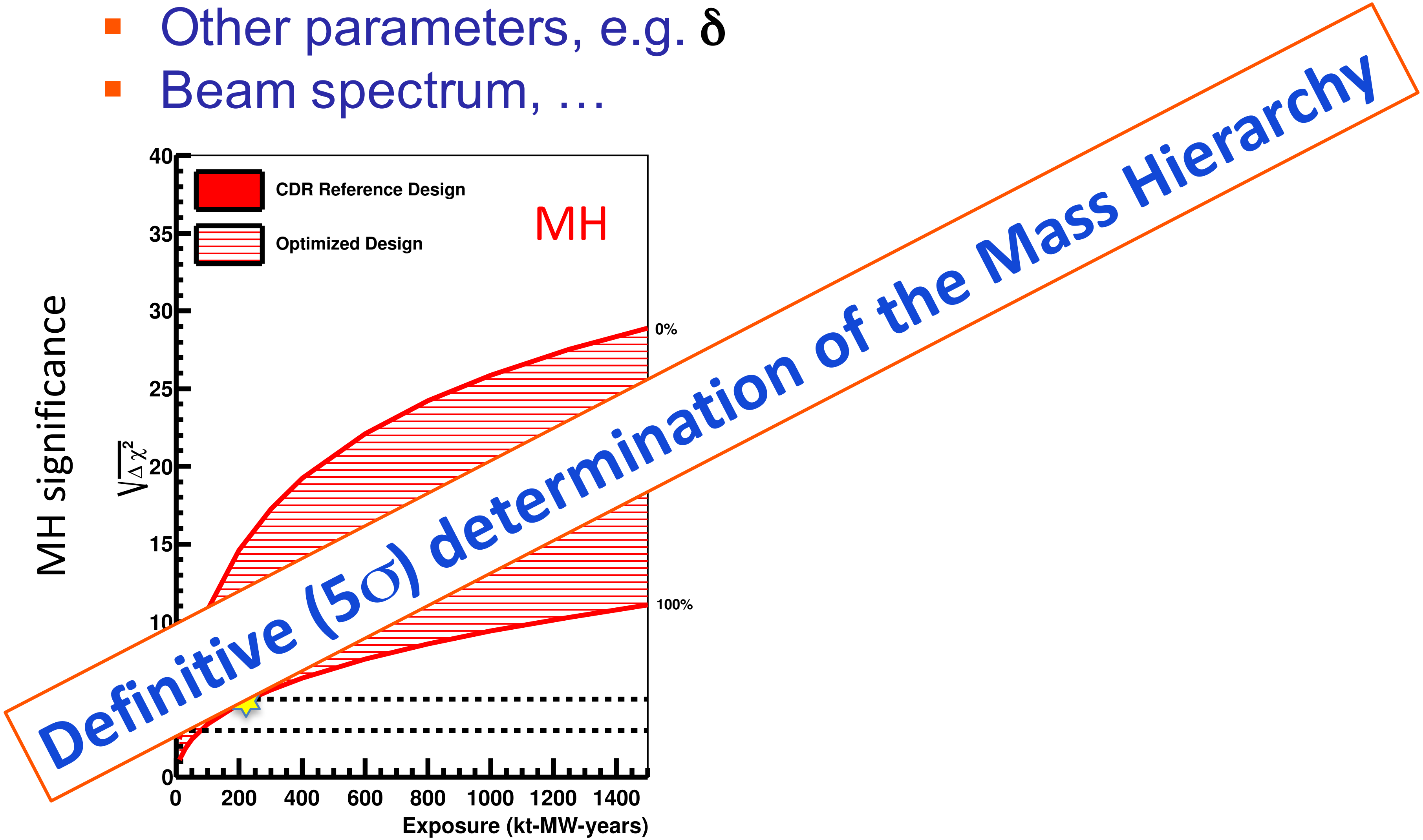

MH and CPV Sensitivities

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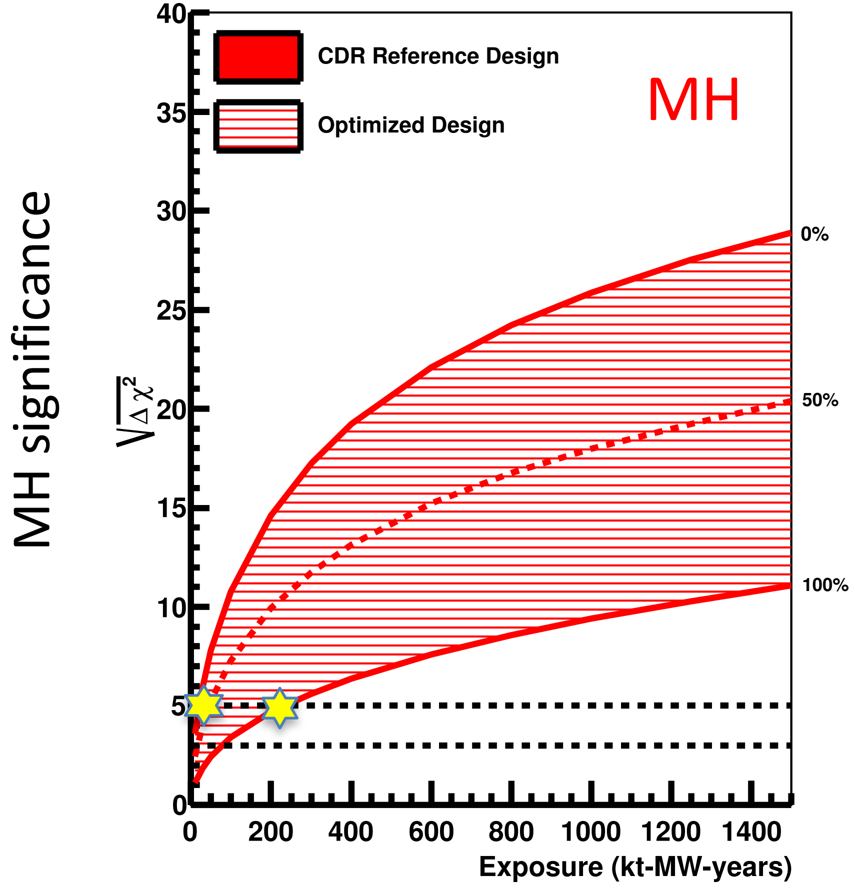

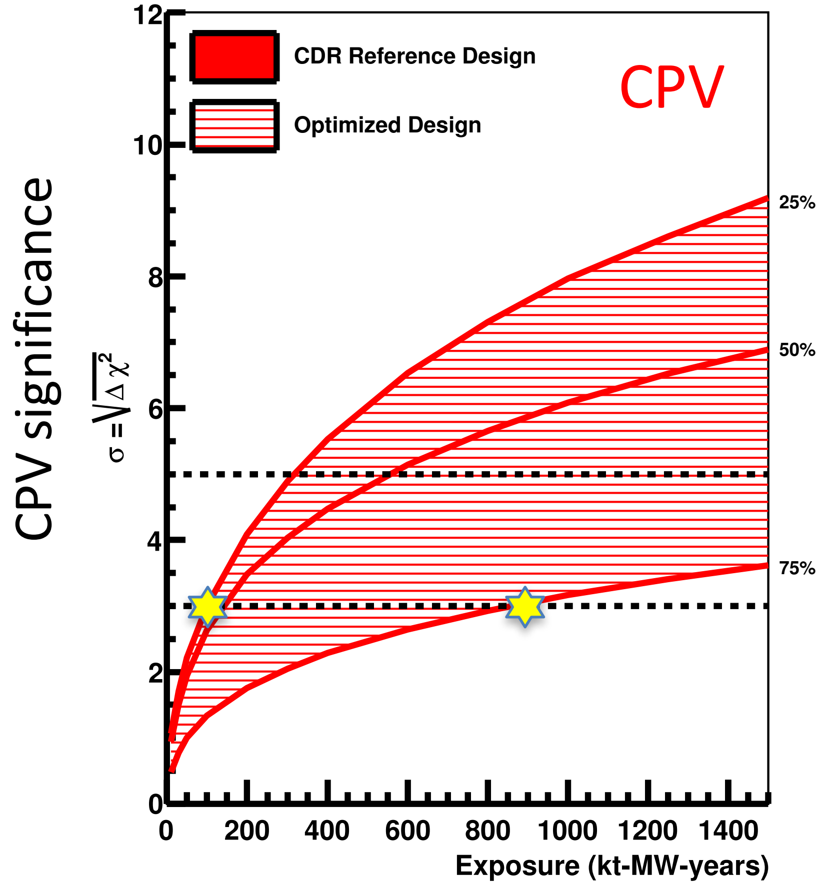

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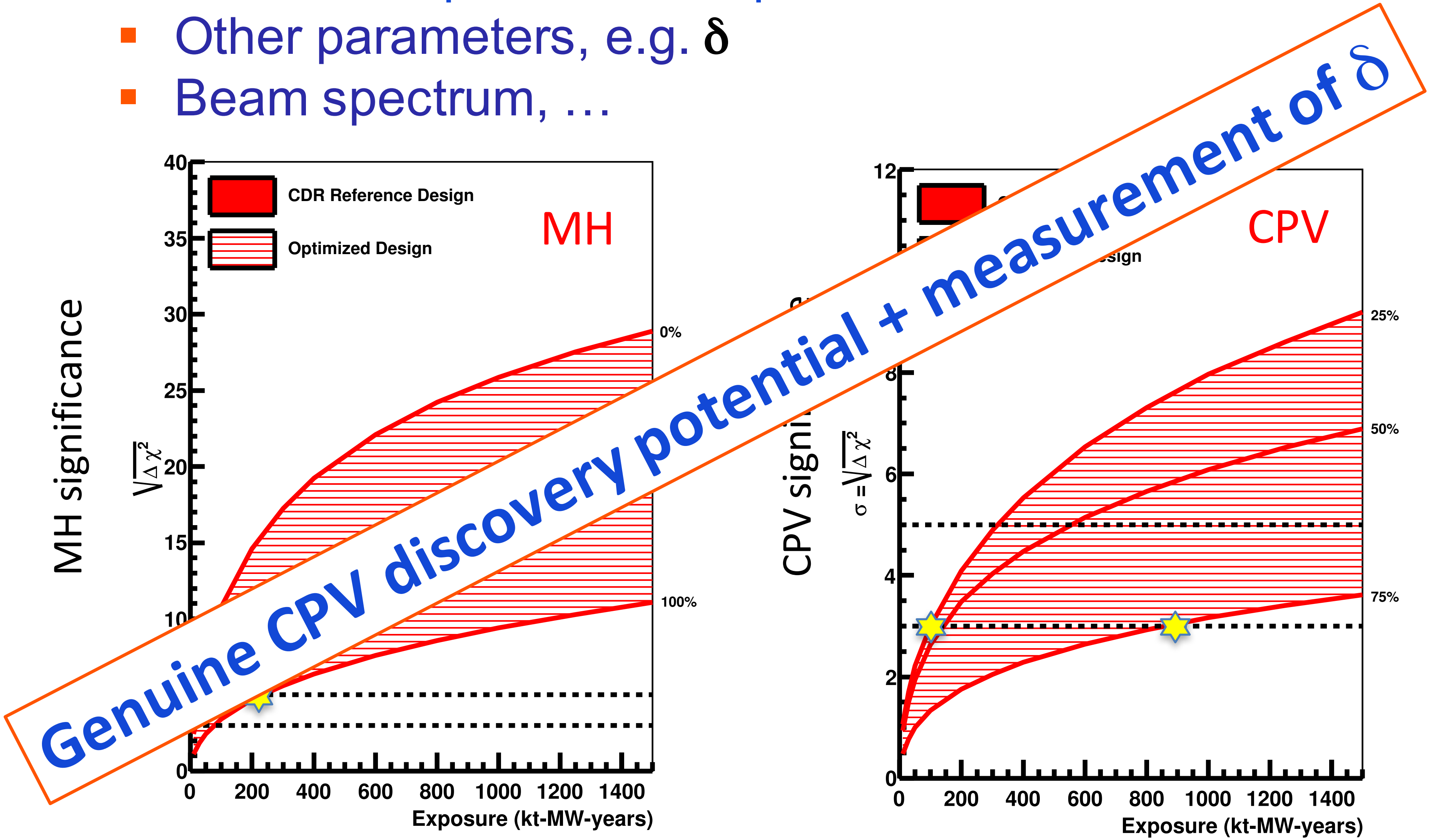

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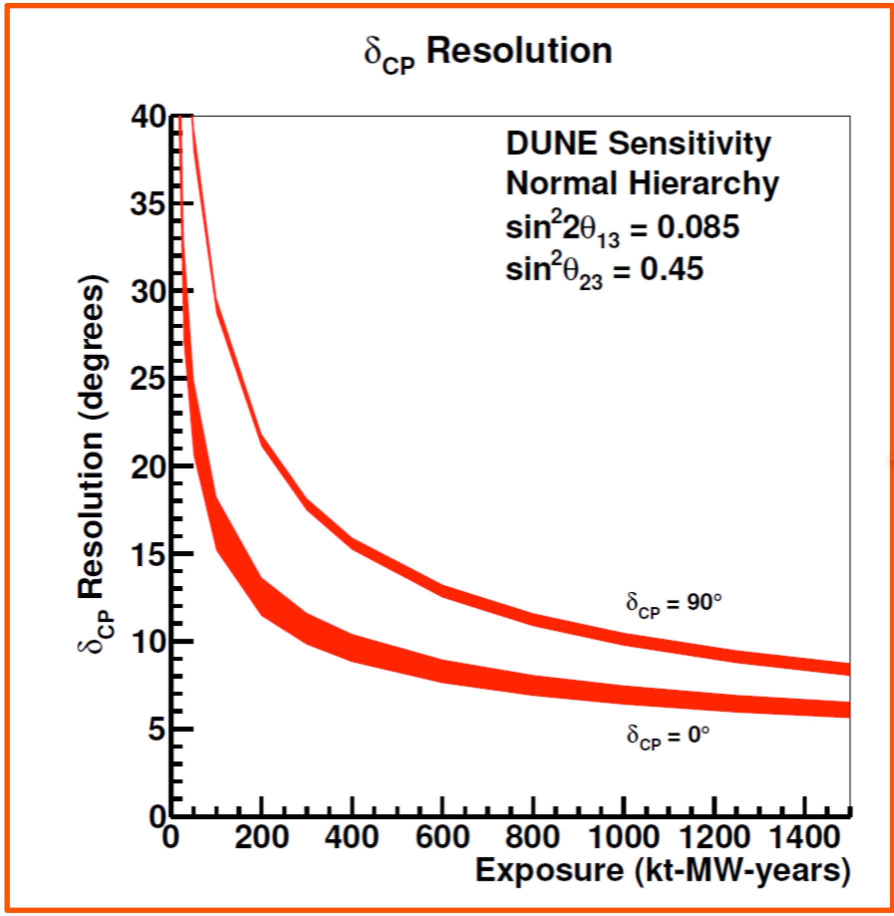
Beyond discovery: measurement of δ

- ★ 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)

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Timescales: year zero = 2025

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for Mass Hierarchy :
  - **Reach 5σ MH sensitivity with 20 – 30 kt.MW.year**

Discovery

~2 years

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

Strong evidence

~3-4 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - **Reach 5σ CPV sensitivity with 210 – 280 kt.MW.year**

Discovery

~6-7 years

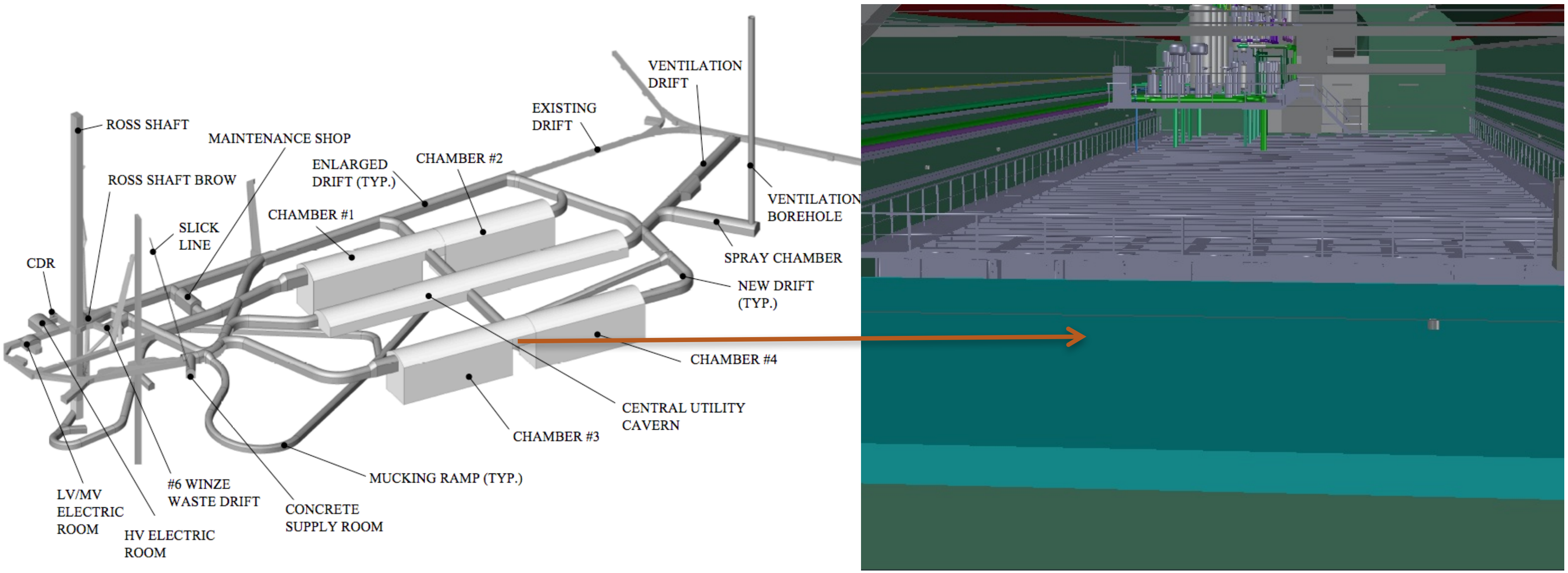
★ **Genuine potential for early physics discovery**

DUNE Science Summary

DUNE physics:

- **Game-changing 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)

7. LBNF – a MW-scale facility
8. The DUNE Far Detector
9. The DUNE Near Detector



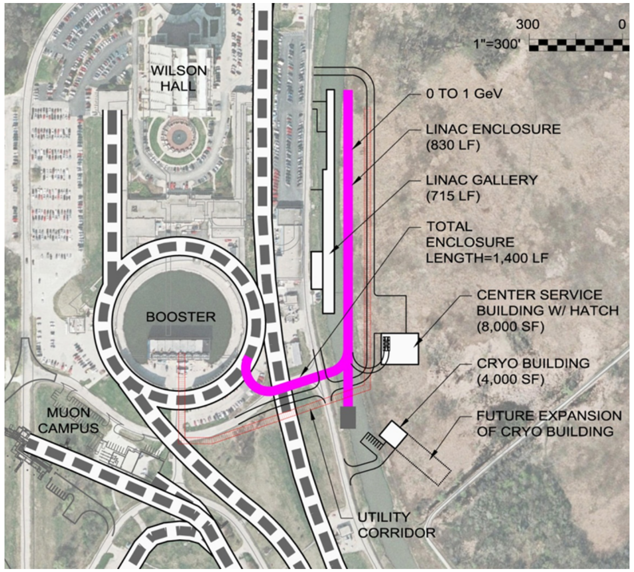
7. LBNF – a MW-scale facility

LBNF and PIP-II

★ **In beam-based long-baseline neutrino physics:**
- **beam power drives the sensitivity**

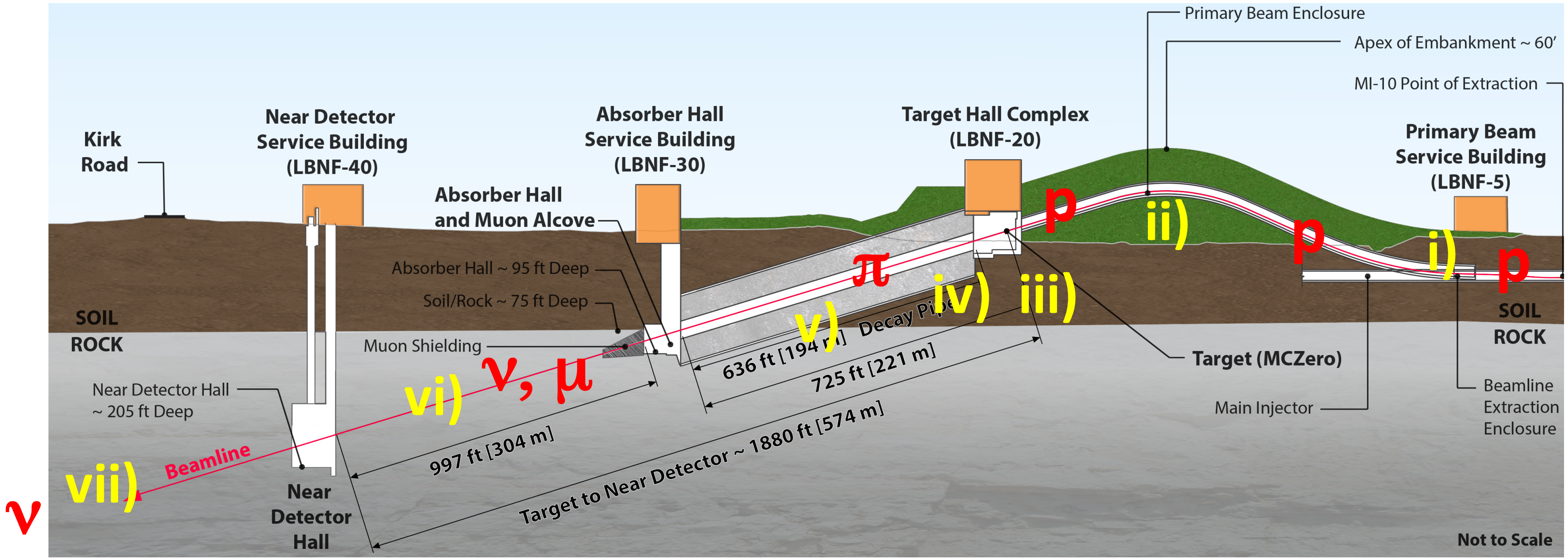
★ **LBNF: the world's most intense high-energy ν beam**
- **1.2 MW from day one**
  - NuMI (MINOS) <400 kW
  - NuMI (NOVA) 600 - 700 kW
- **upgradable to 2.4 MW**

★ **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



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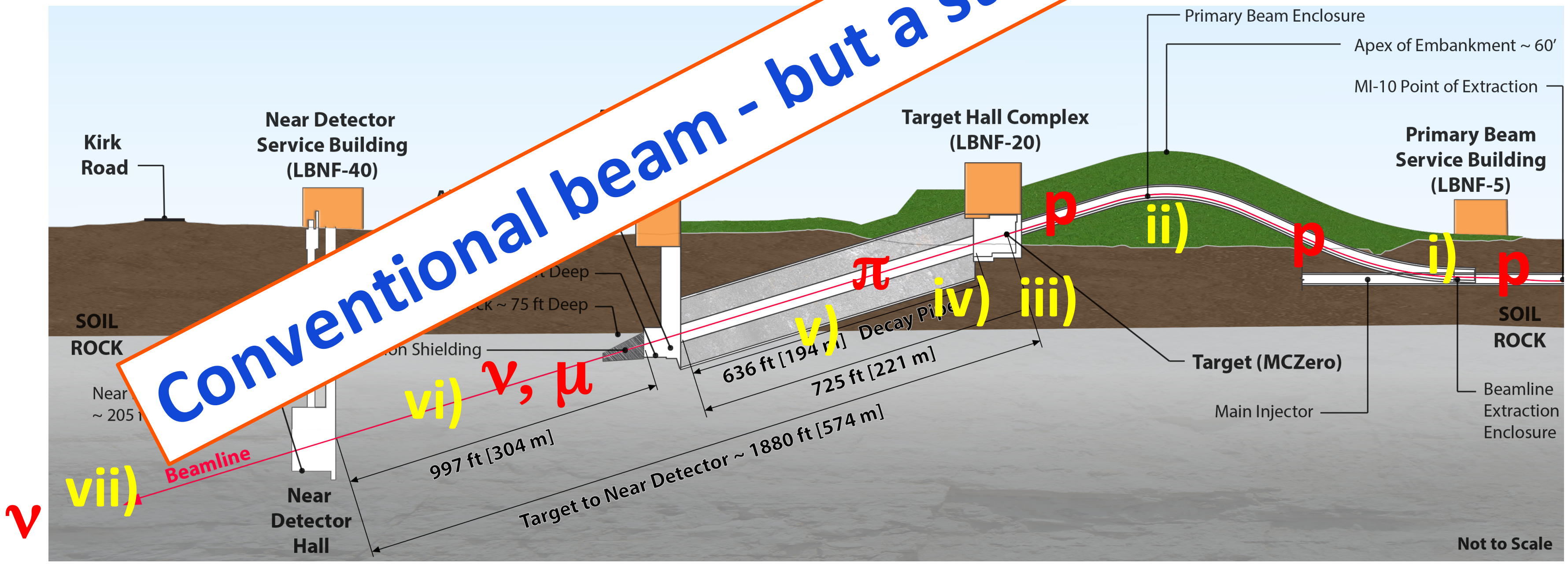
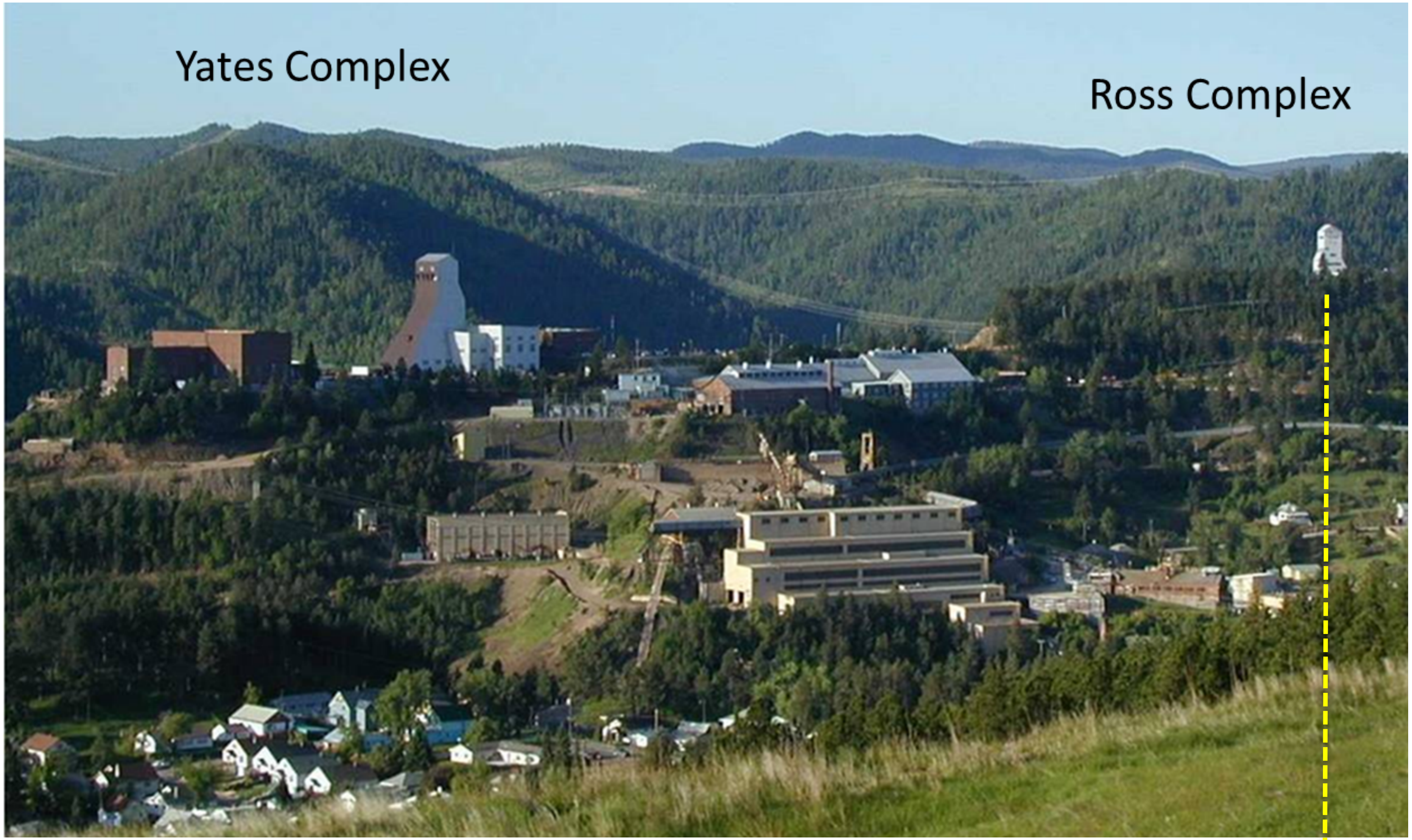
Conventional beam - but a step up in intensity



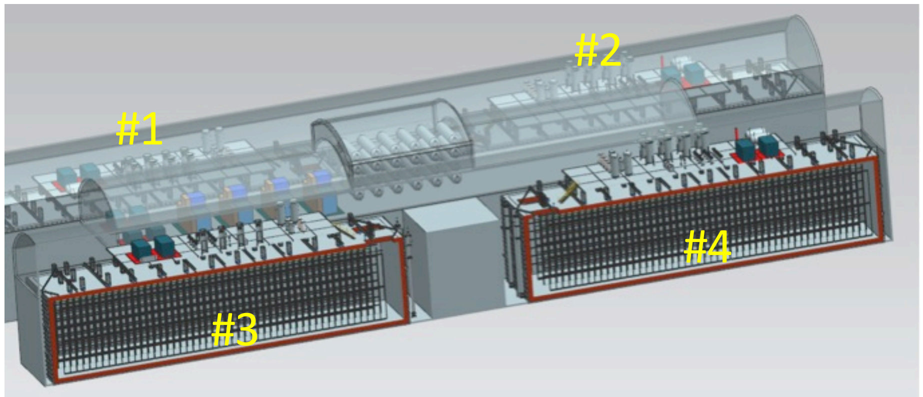
8. The DUNE Far Detector



Staged Approach to 40 kt

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

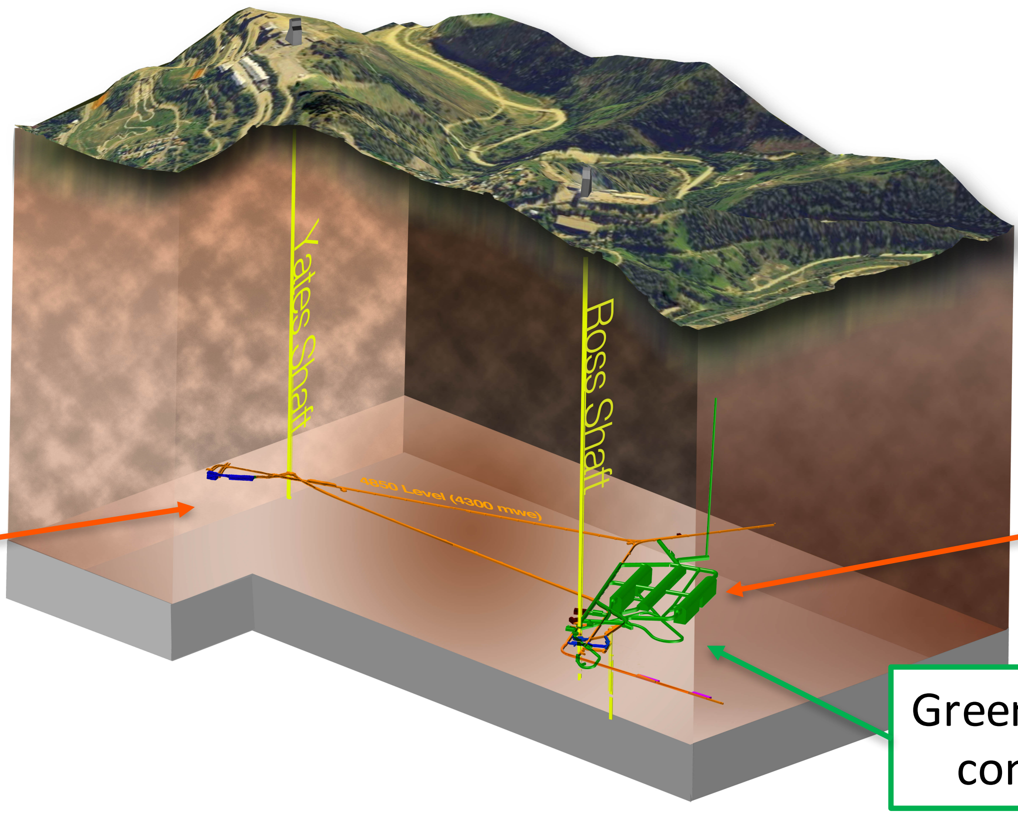
- **Four identical caverns hosting four independent 10-kt FD modules**
  - Allows for staged construction of FD
  - Gives flexibility for evolution of LArTPC technology design
    - Assume four identical cryostats
    - But, assume that the four 10-kt modules will be similar but **not necessarily identical**



Going underground…

DUNE Far Detector site

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



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

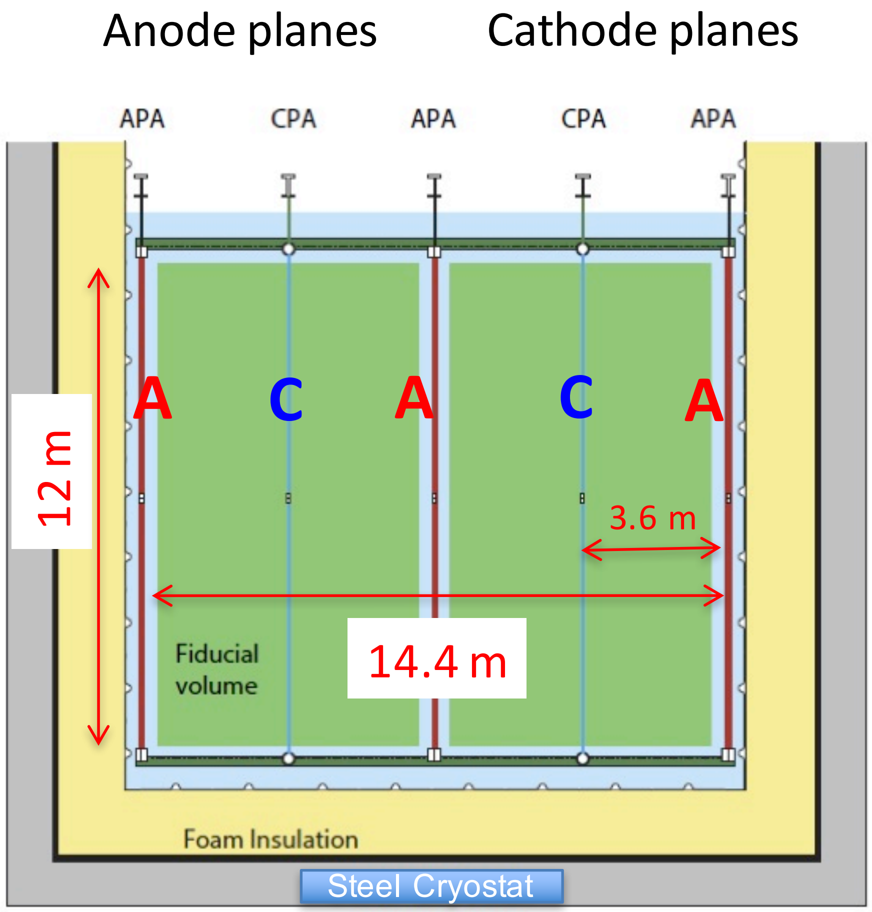
Ross Campus:
- CASPAR
- …
- **DUNE**

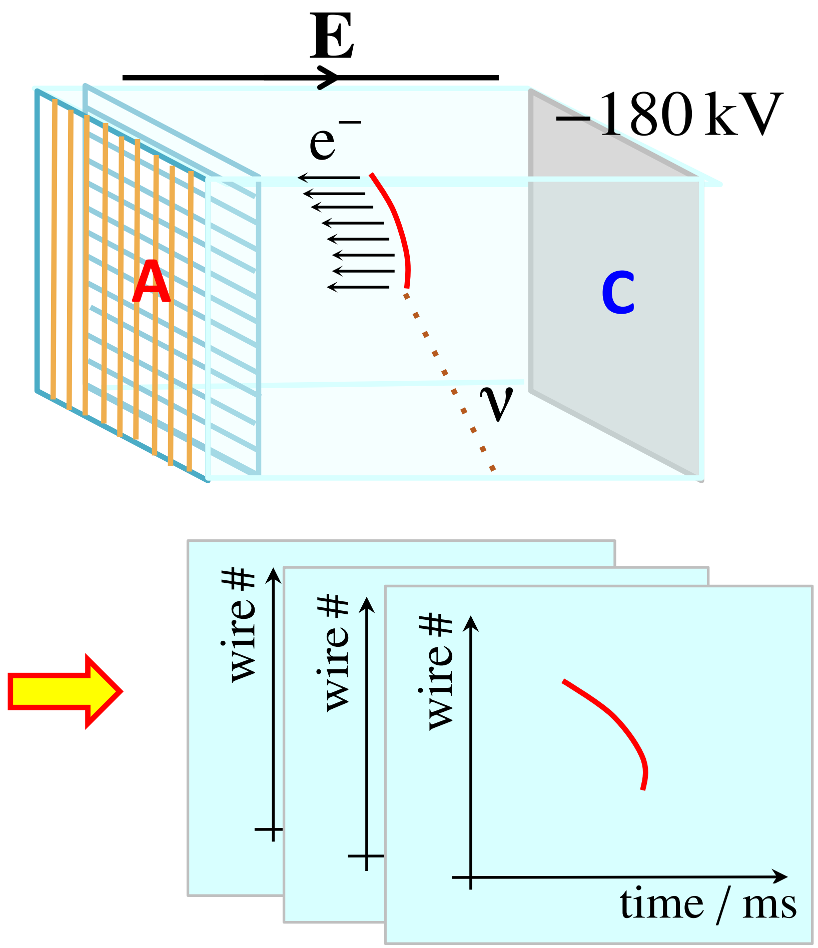
Green = new excavation commences in 2017

Far Detector Basics

A modular implementation of Single-Phase TPC

- Record ionization using three wire planes ⇨ 3D image





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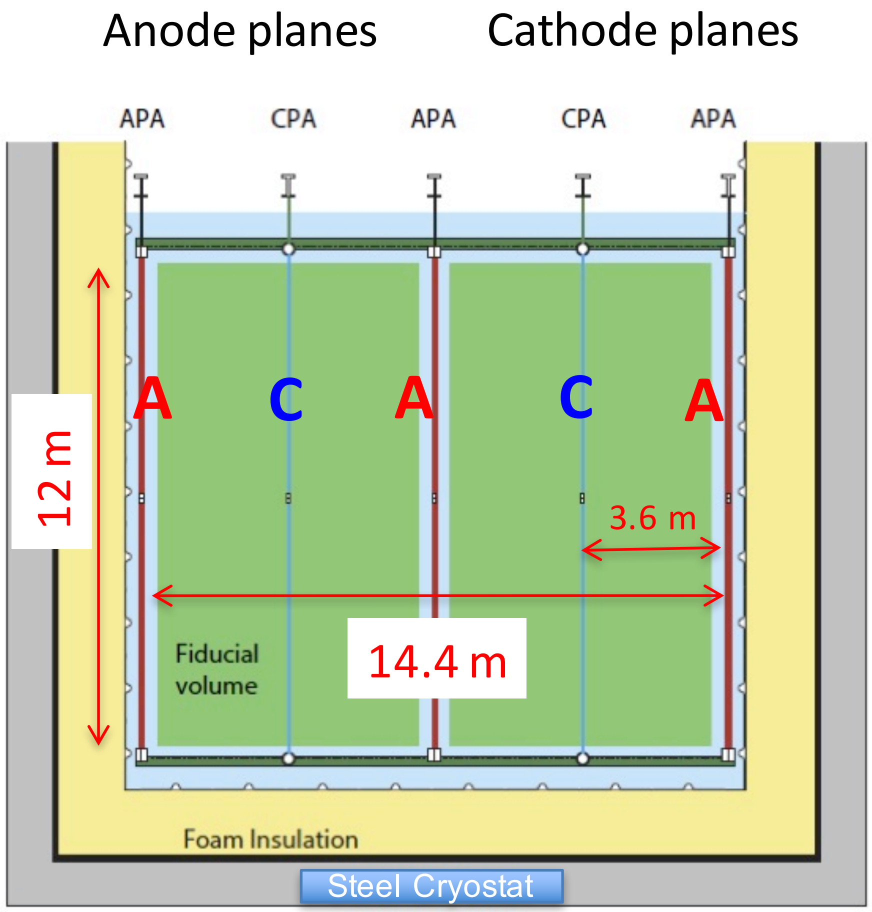
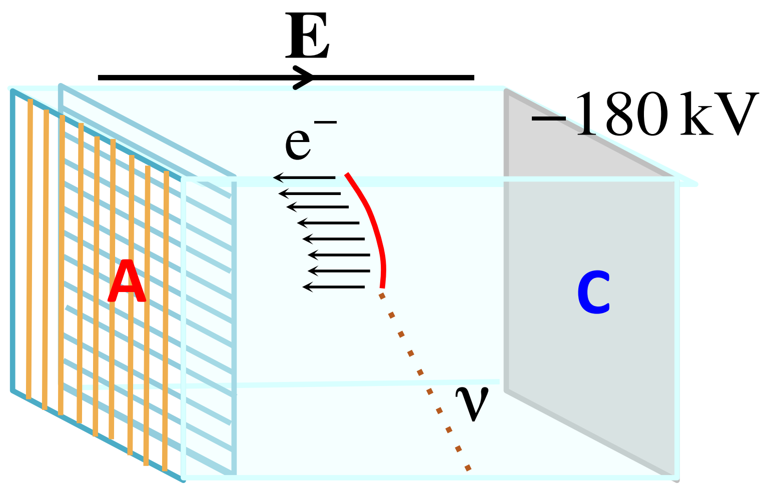
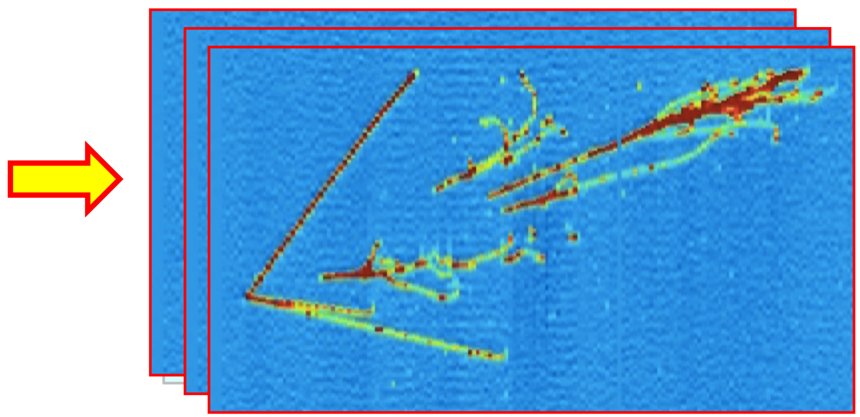


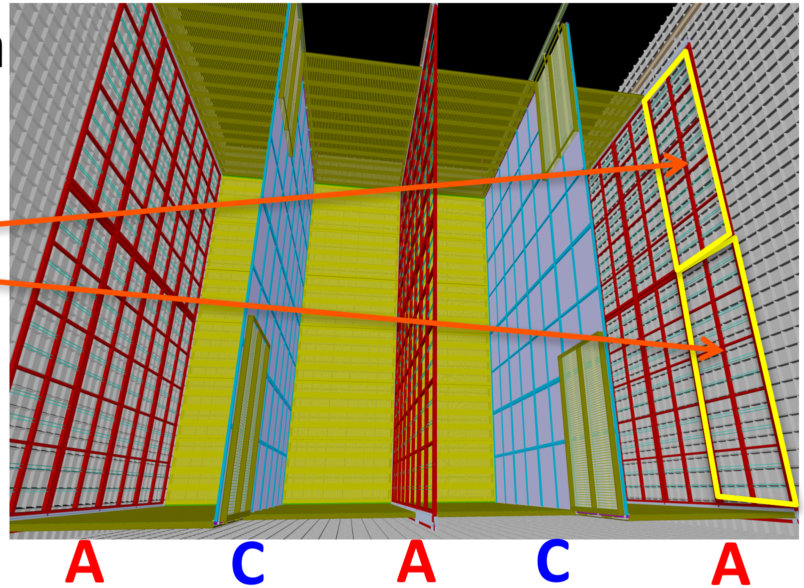




First 17-kt detector

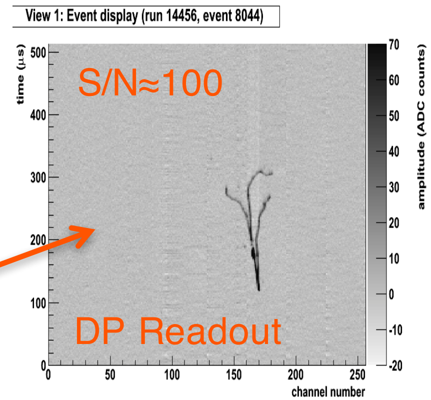
Modular implementation of Single-Phase TPC

- Active volume: **12m x 14m x 58m**
- 150 Anode Plane Assemblies
  - 6m high x 2.3m wide
- 200 Cathode Plane Assemblies
  - Cathode @ -180 kV for 3.5m drift



Second & subsequent far detector modules

- Not assumed to be exactly the same, could be:
  - Evolution of single-phase design
  - Dual-phase readout – potential benefits

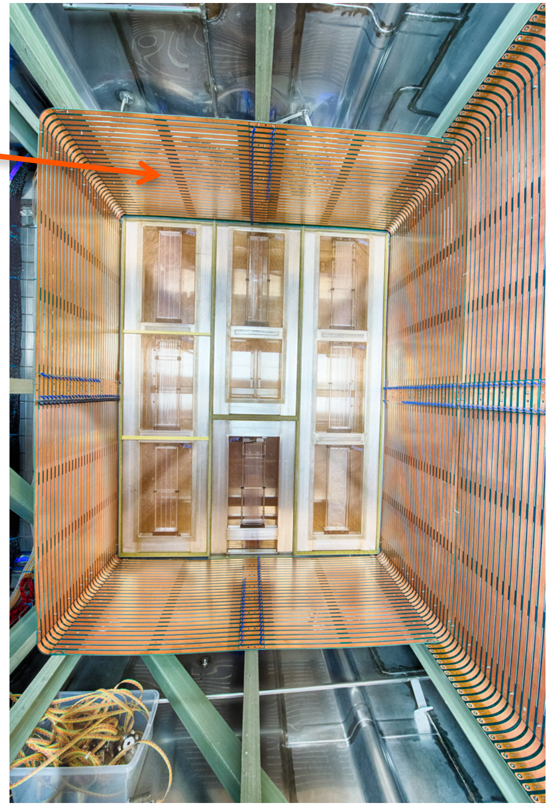


Far Detector Development

e.g. single-phase APA/CPA LAr-TPC:

- Design is already well advanced – evolution from ICARUS
- Supported by strong development program at Fermilab
  - 35-t prototype (run ended 03/2016)

    tests of basic design



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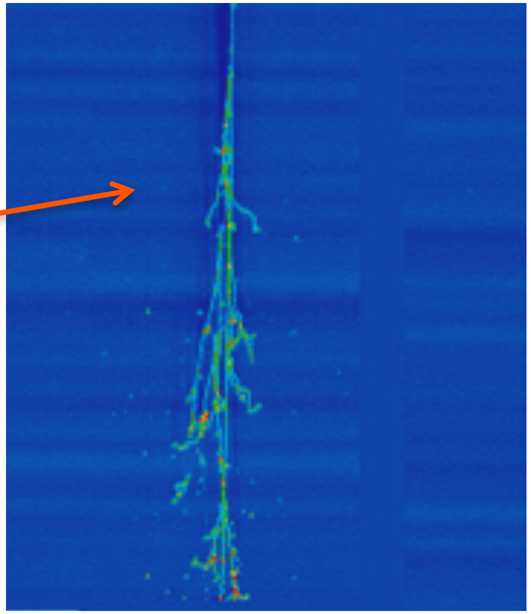

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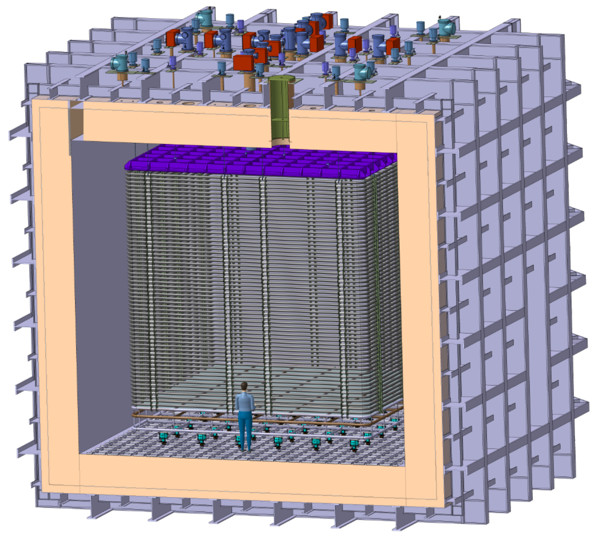
- 2 "Full-scale" prototypes (protoDUNE) at the CERN Neutrino Platform
  - **Single-Phase & Dual-Phase**
  - Engineering prototypes, e.g. SP:
    - 6 full-sized drift cells c.f. 150 in the far det.
  - Aiming for operation in 2018



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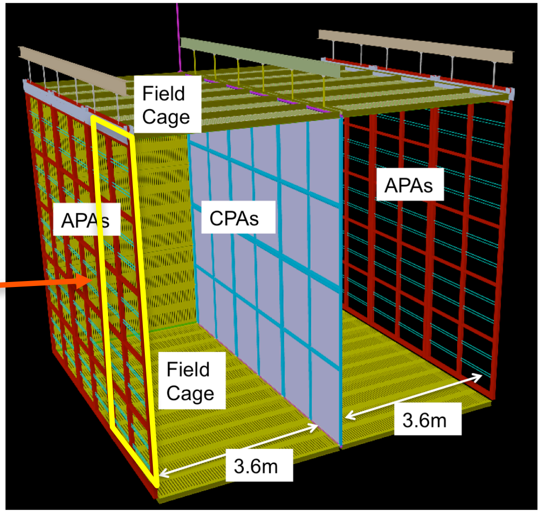
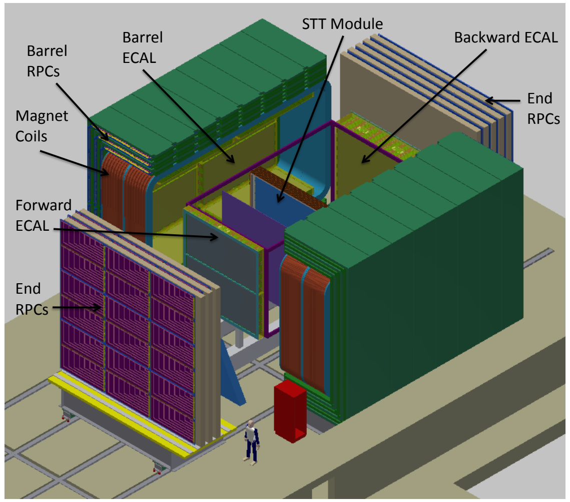


9. The DUNE Near Detector

DUNE ND (in brief)

CDR design is the the NOMAD-inspired FGT

- **It consists of:**
  - Central straw-tube tracking system
  - Lead-scintillator sampling ECAL
  - RPC-based muon tracking systems



- **Other options being studied**
- **The Near Detector 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

10. 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

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★ **The U.S. is serious:**

- LBNF/DUNE is Fermilab's future flagship project
- Very strong support from Fermilab & the U.S. DOE
- CD3a in December – funding request for excavation in FY17 currently with DOE

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- Historic agreement between U.S. and CERN
- US contributes to LHC upgrade (high-field magnets)
- CERN contributes to Far site infrastructure

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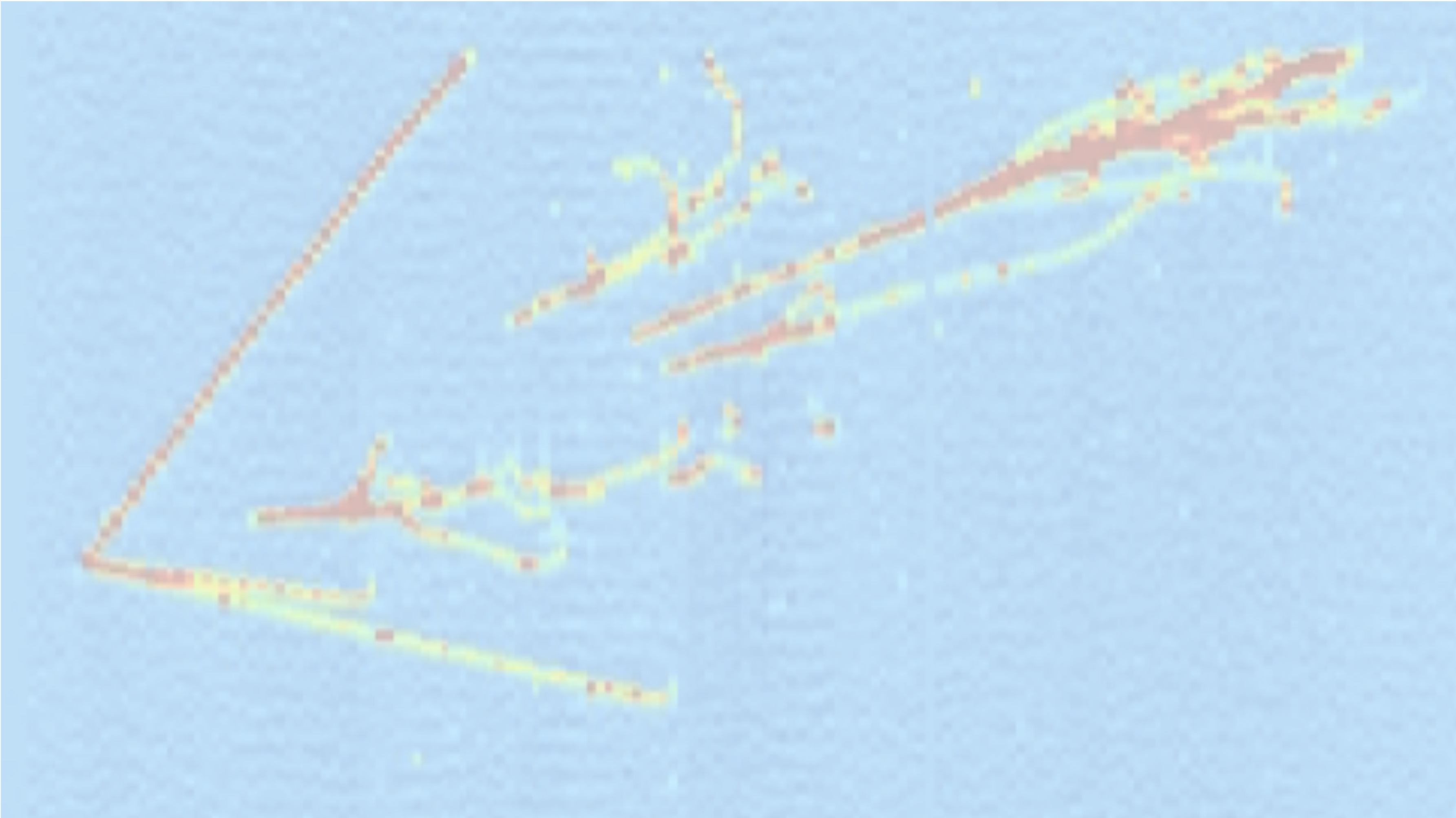
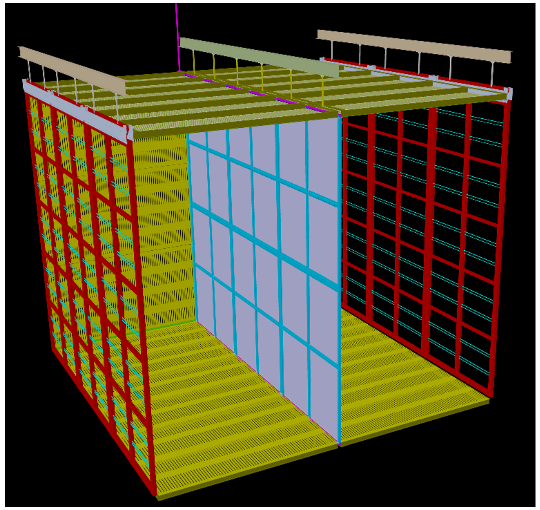
★ **First truly global neutrino experiment**

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

11. Opportunities on DUNE



Opportunities in DUNE



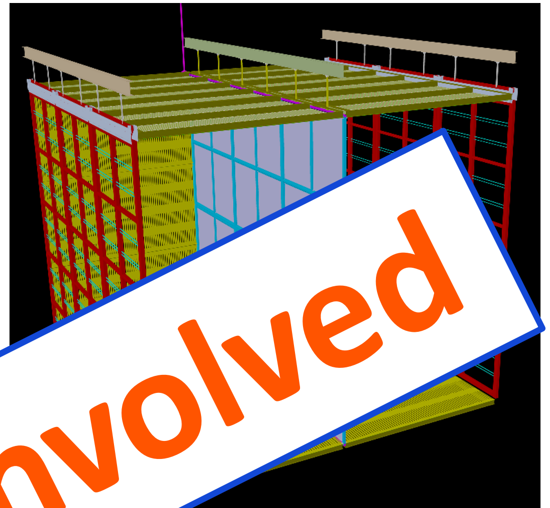
DUNE is moving rapidly

- Excavation starts in 2017
- ProtoDUNE @ CERN in 2018
- Far Detector construction in 2019
- Far Detector installation in 2021

DUNE: the next large global Particle Physics project

- Actively seeking new collaborators
  - many synergies with collider experiments
- Immediate Focus in Europe will be ProtoDUNE @ CERN
- Many Opportunities:
  - Hardware: e.g. photon detection system (scintillator + SiPMs)
  - DAQ/Computing: continuous readout = high-data rates
  - Software: LAr-TPC reconstruction

Opportunities in DUNE



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DUNE: the next large glo[illegible] [illegible]ysics project

- Actively seeking n[illegible] [illegible]s
  - many syn[illegible] [illegible] experiments
- Imme[illegible] [illegible]ope will be ProtoDUNE @ CERN
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  - [illegible]e: e.g. photon detection system (scintillator + SiPMs)
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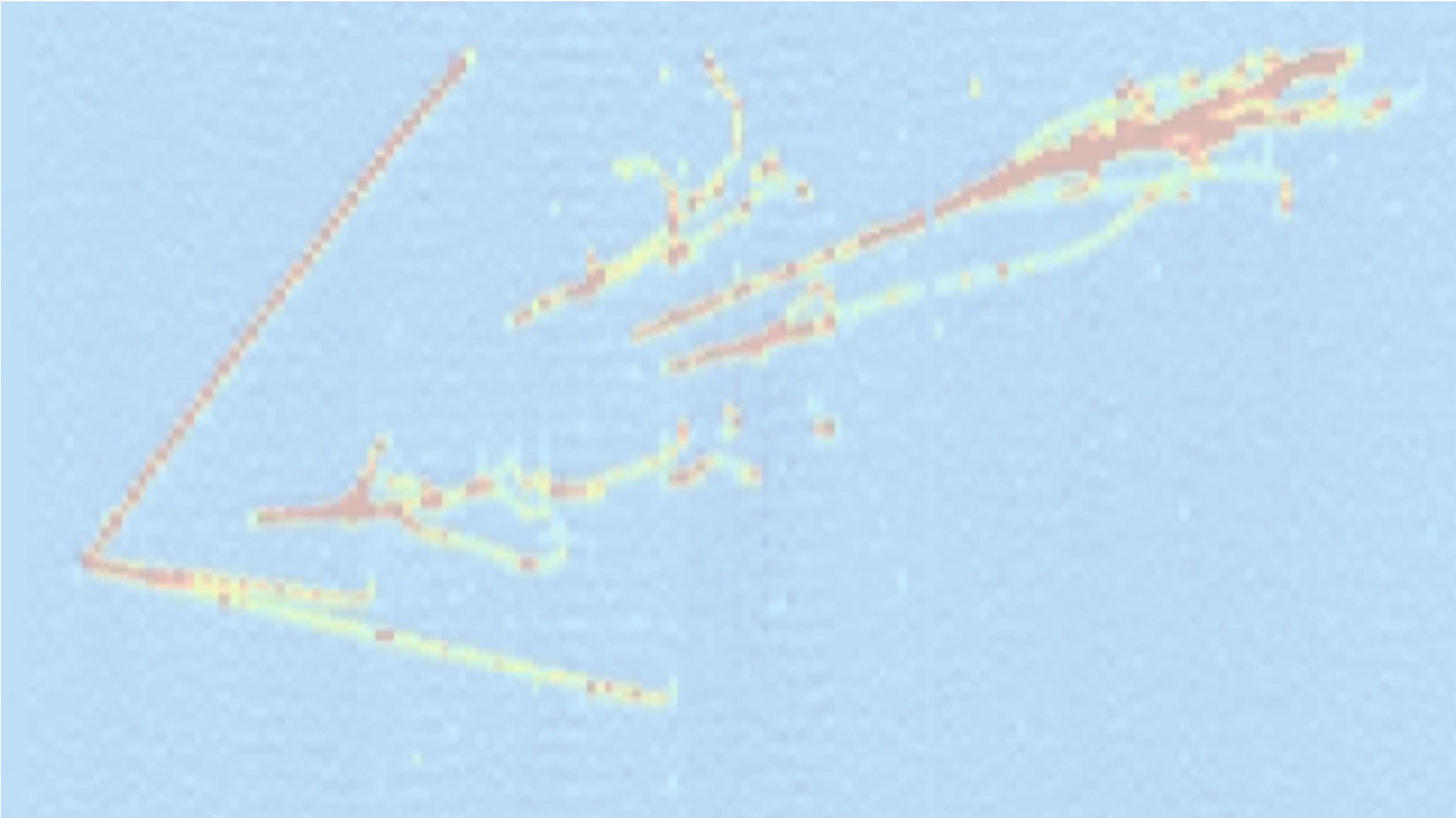
Great time to get involved

12. Summary



Summary

★ **DUNE will**

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

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★ **This is an exciting time**

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

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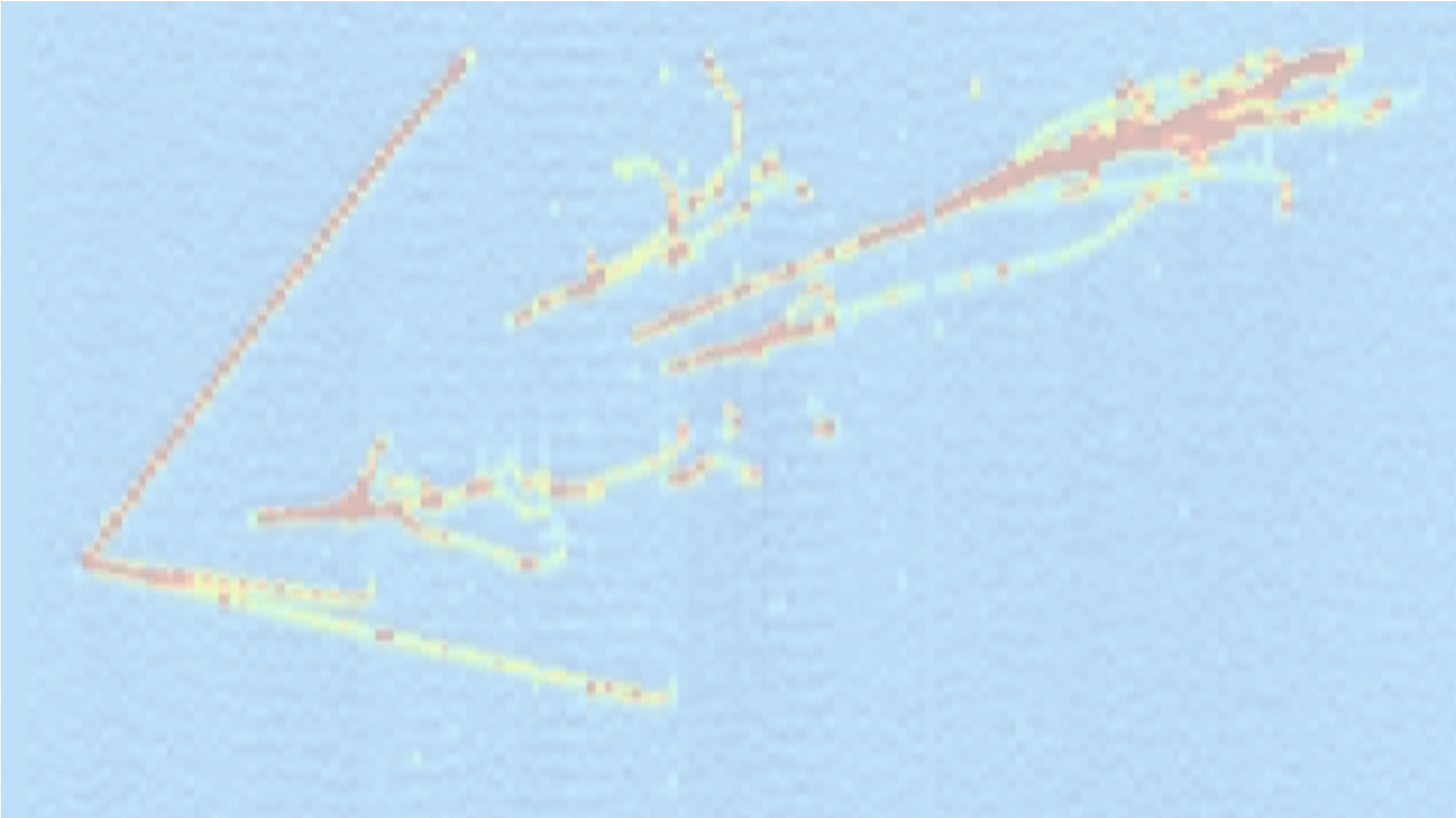
  - The large-scale DUNE prototype will operate at CERN in 2018

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

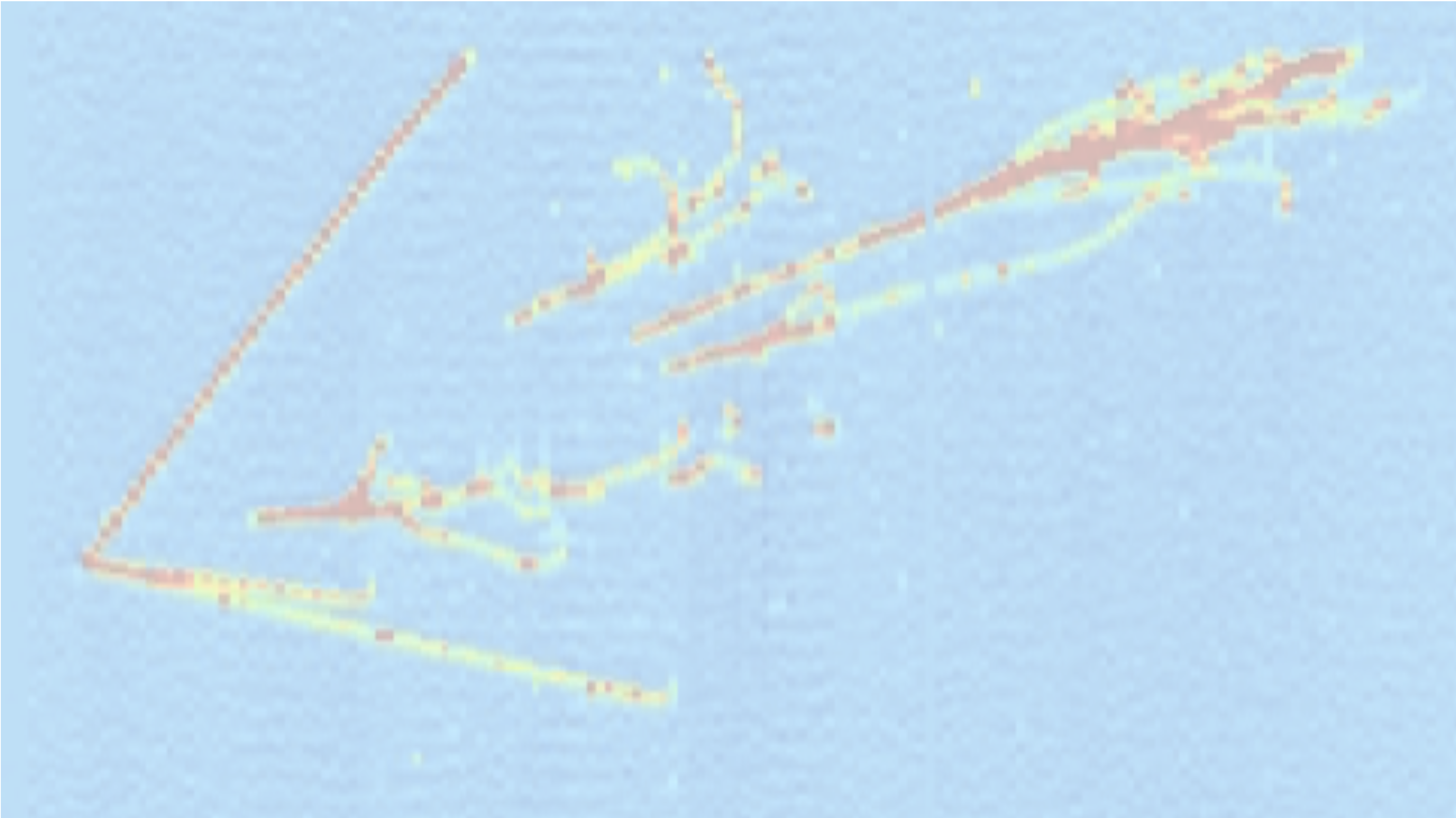
- LBNF/DUNE represents a **major** new scientific opportunity for particle physics

Thank you for your attention



Backup Slides

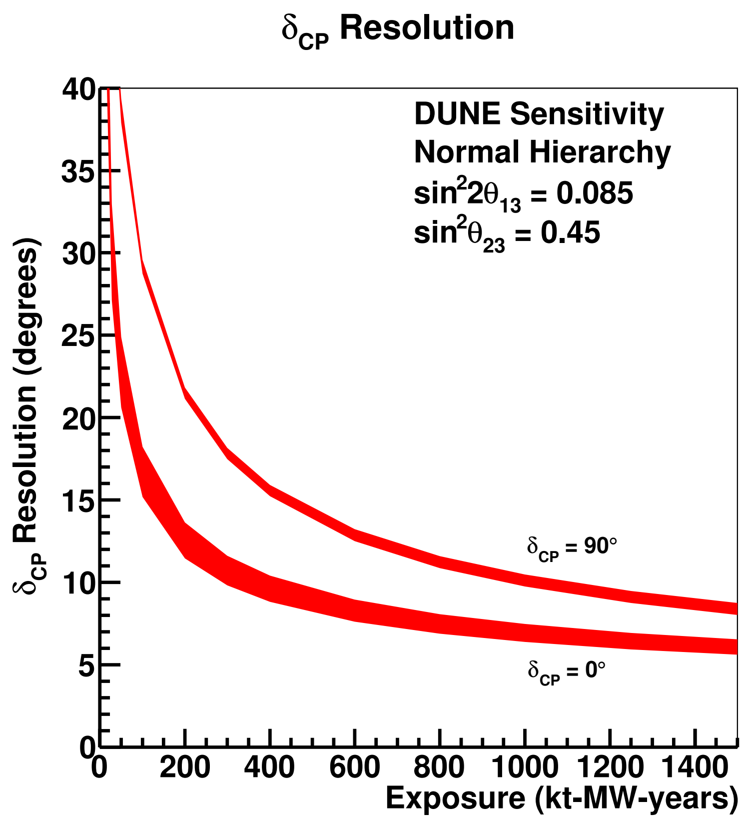
Science

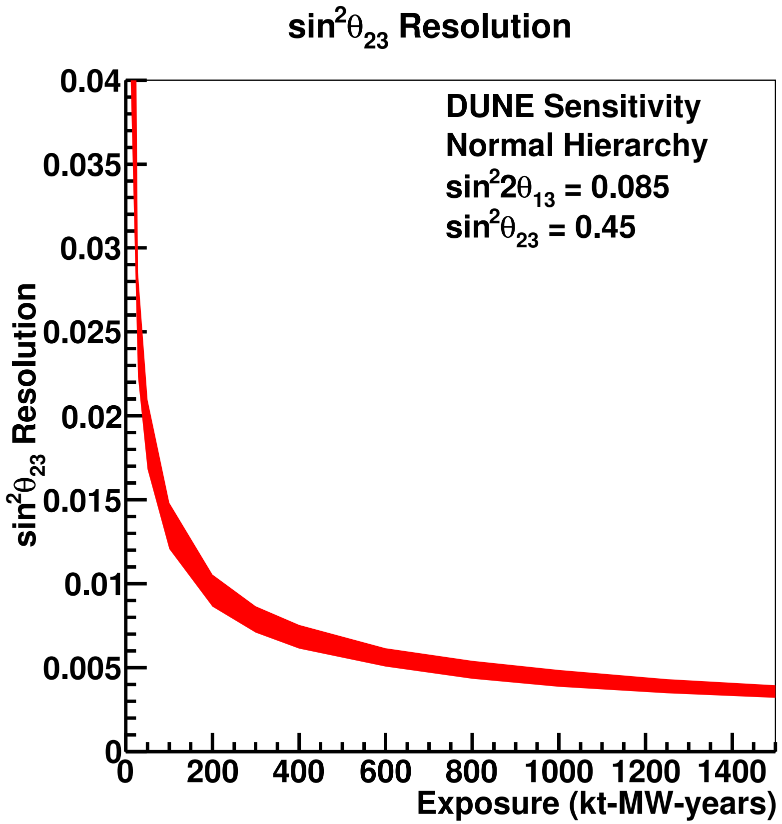


Parameter Resolutions

δ_{CP} & θ_{23}

- As a function of exposure

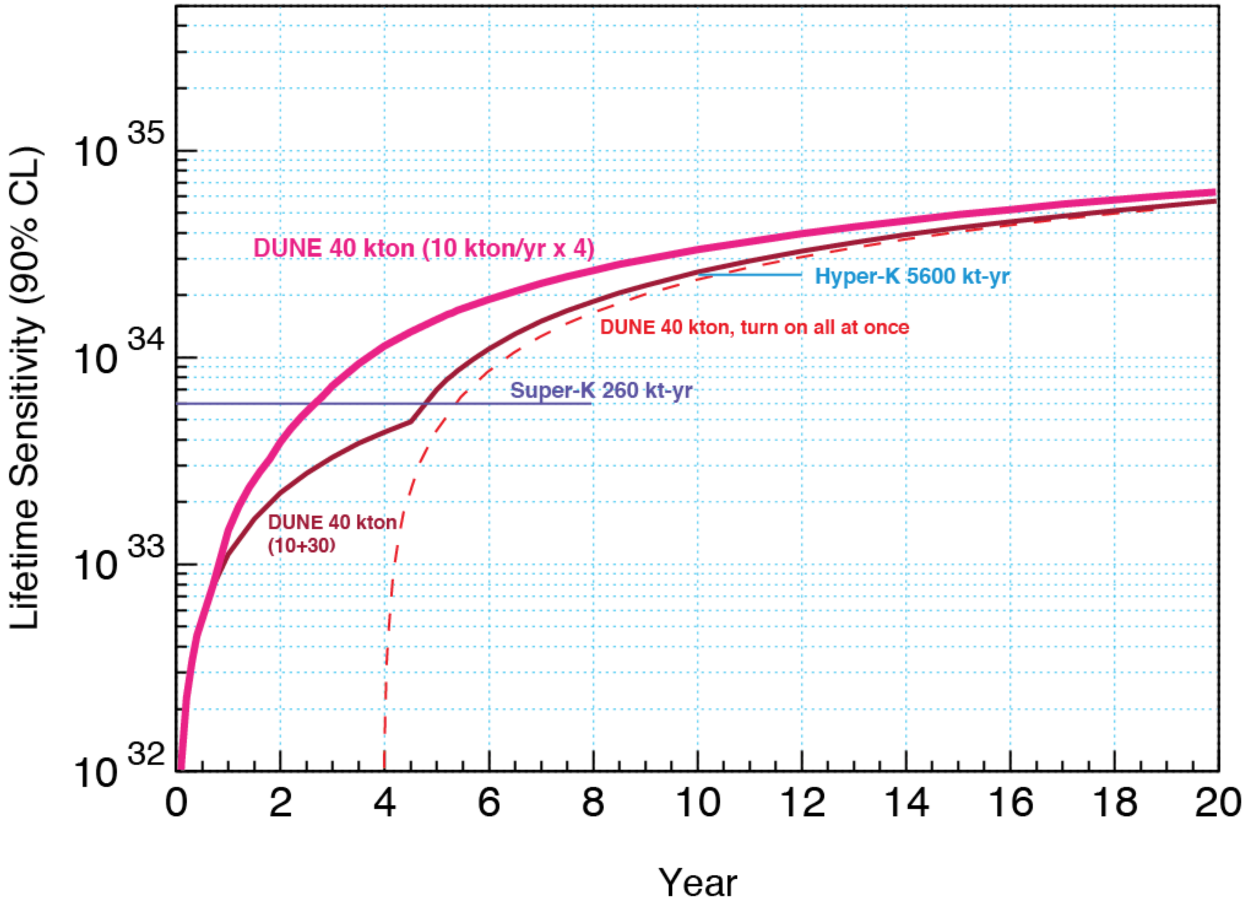




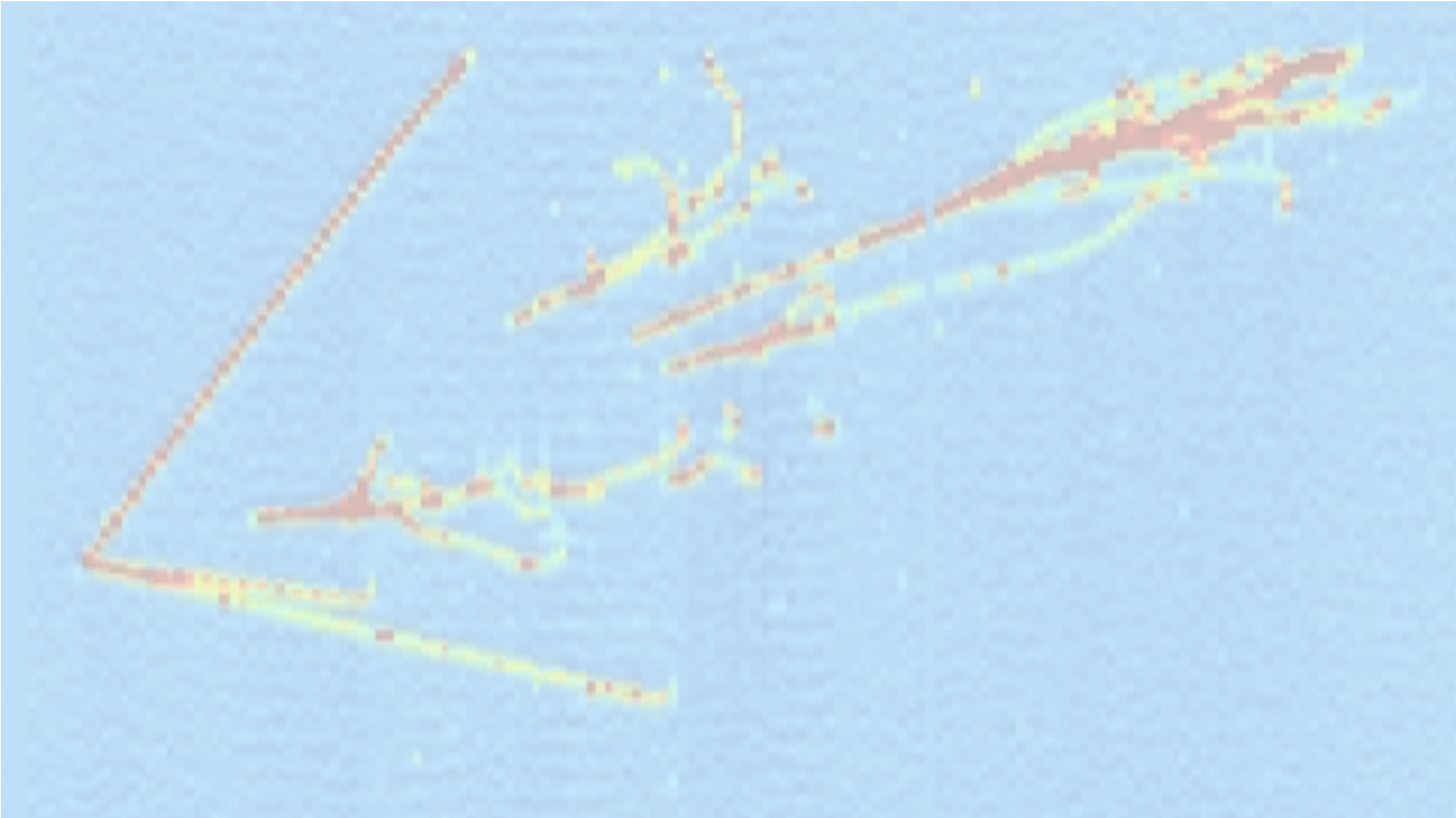
PDK

p → K ν

- DUNE for various staging assumptions

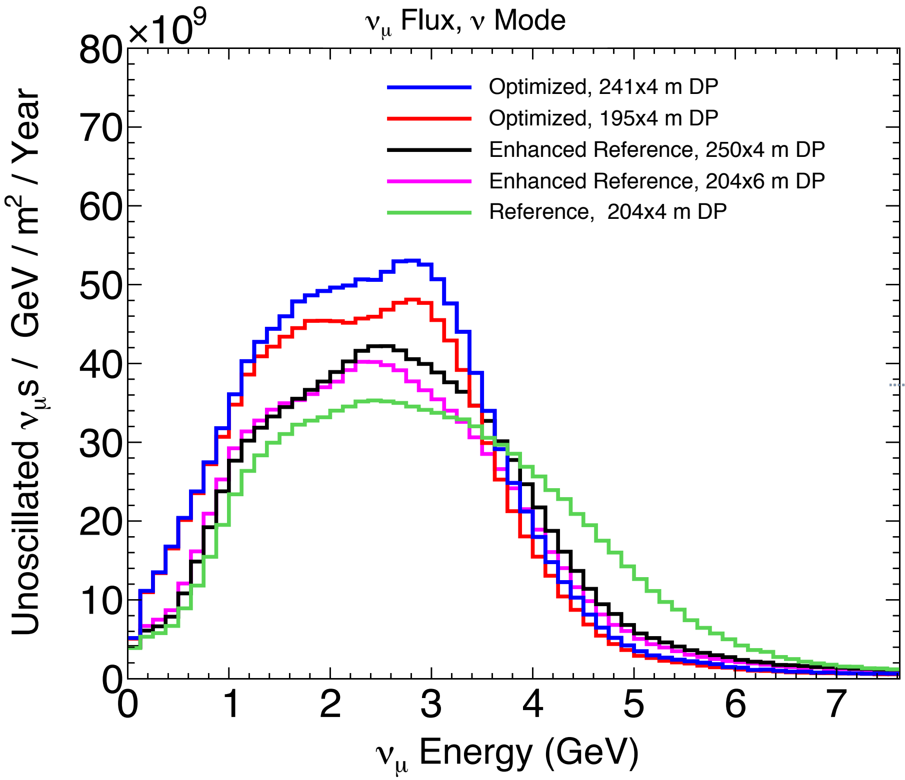


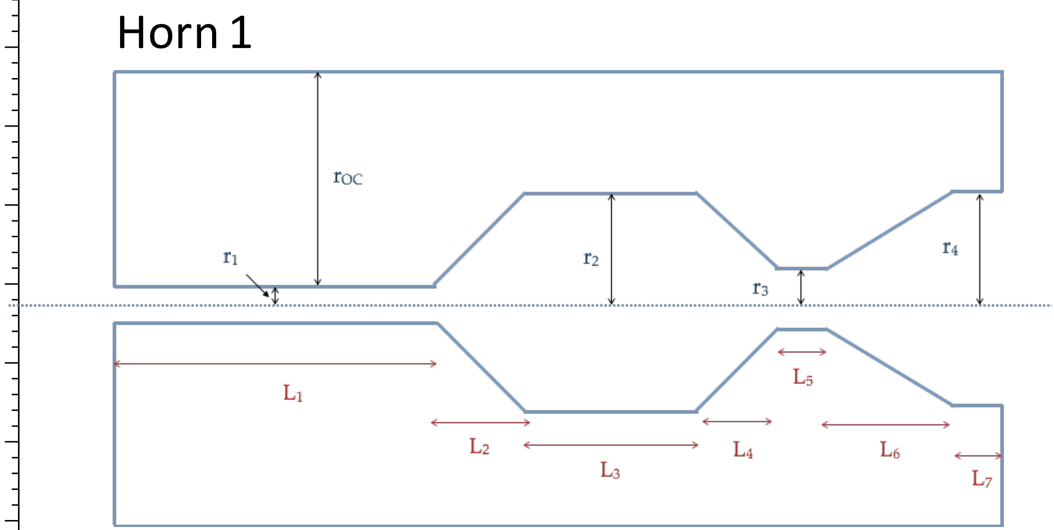
Beam Optimization



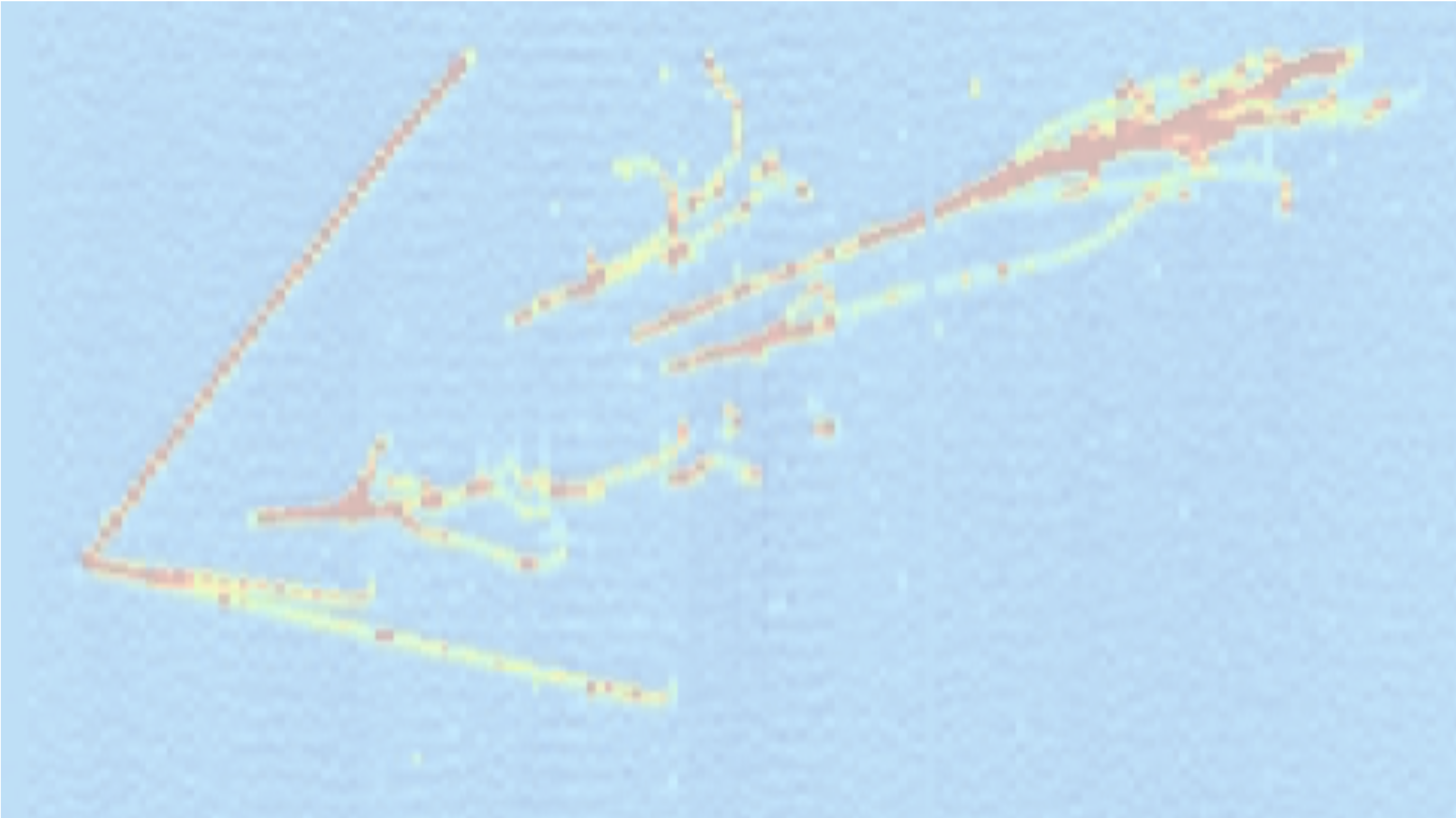
Beam Optimization

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





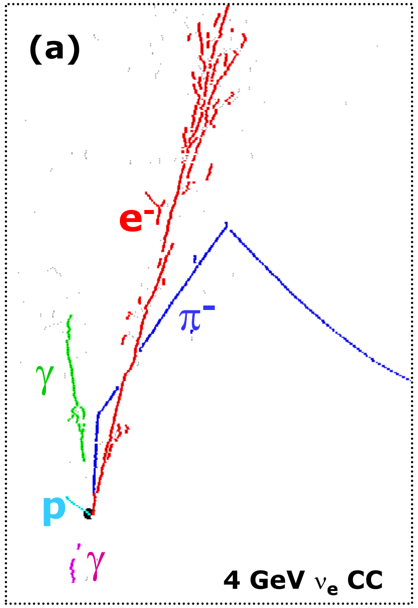
Reconstruction

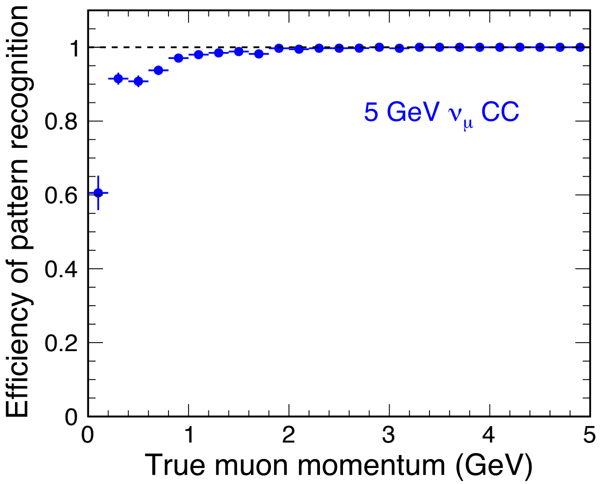


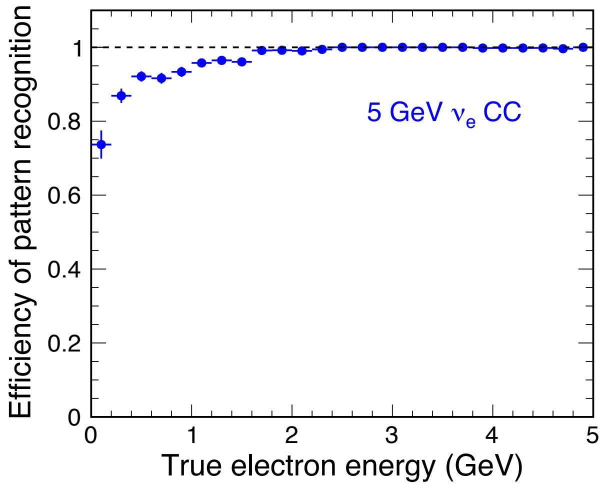
LAr-TPC Reconstruction

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

- Full DUNE simulation/reconstruction now in reach

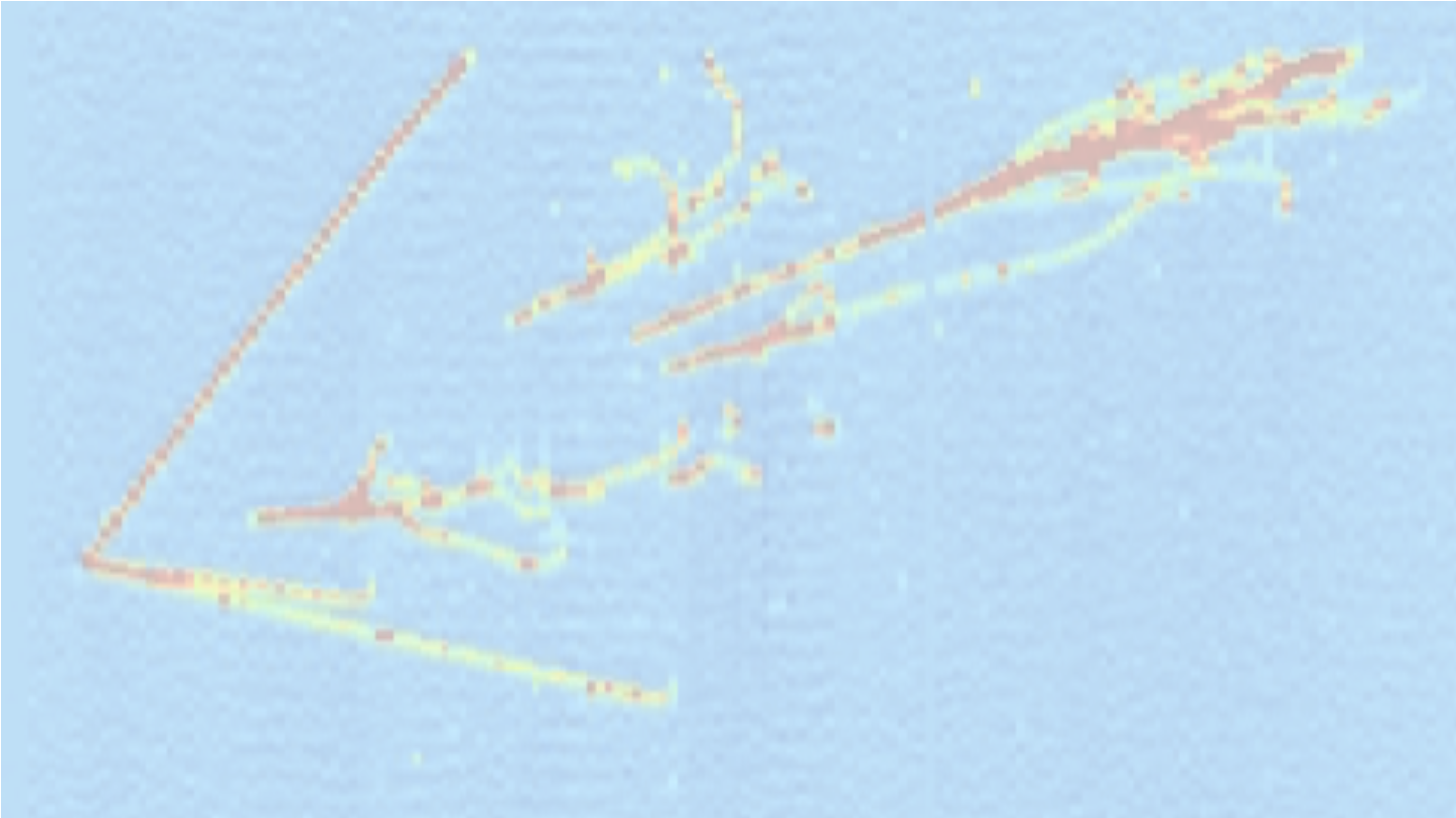




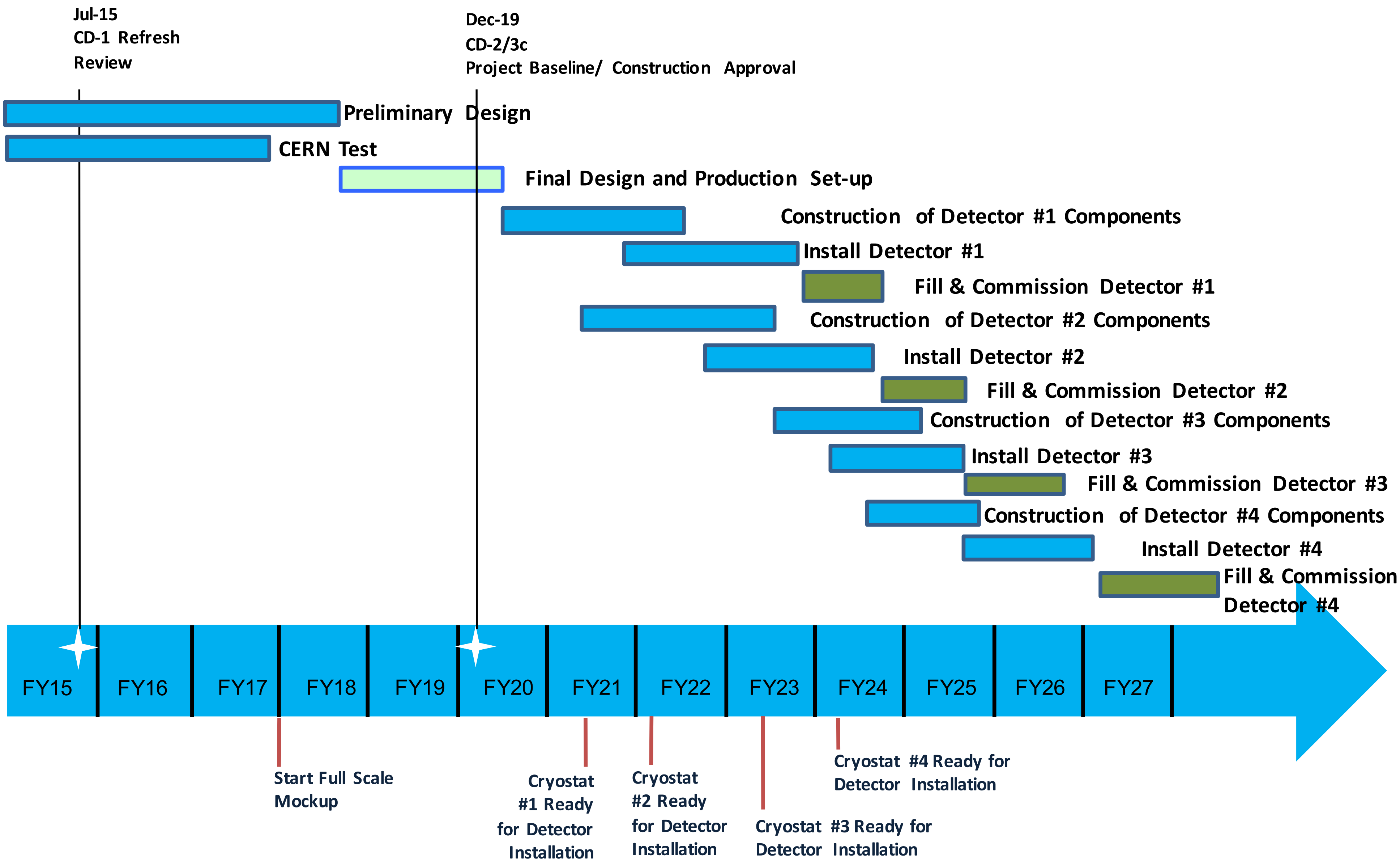


UNIVERSITY OF CAMBRIDGE

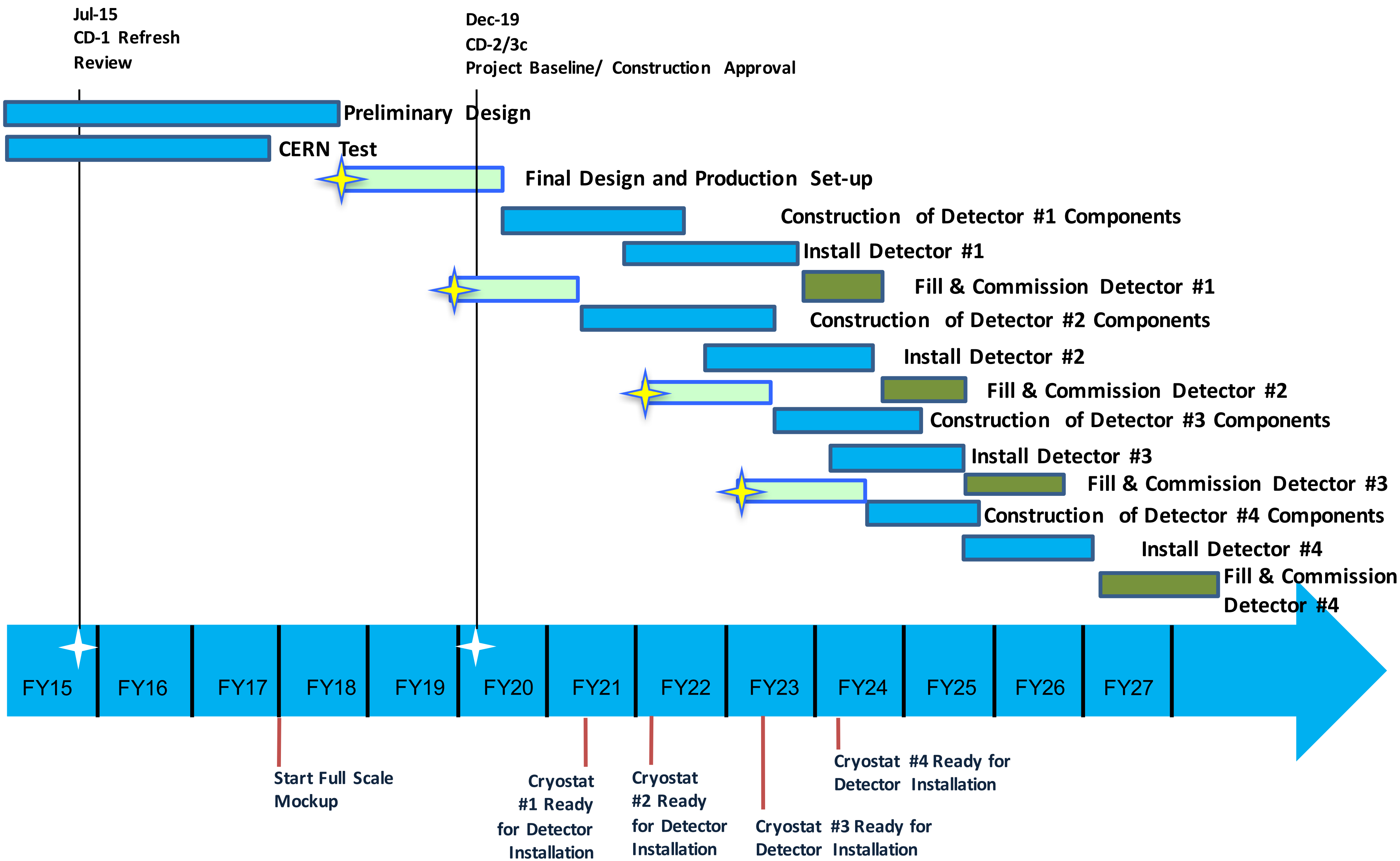
Schedule



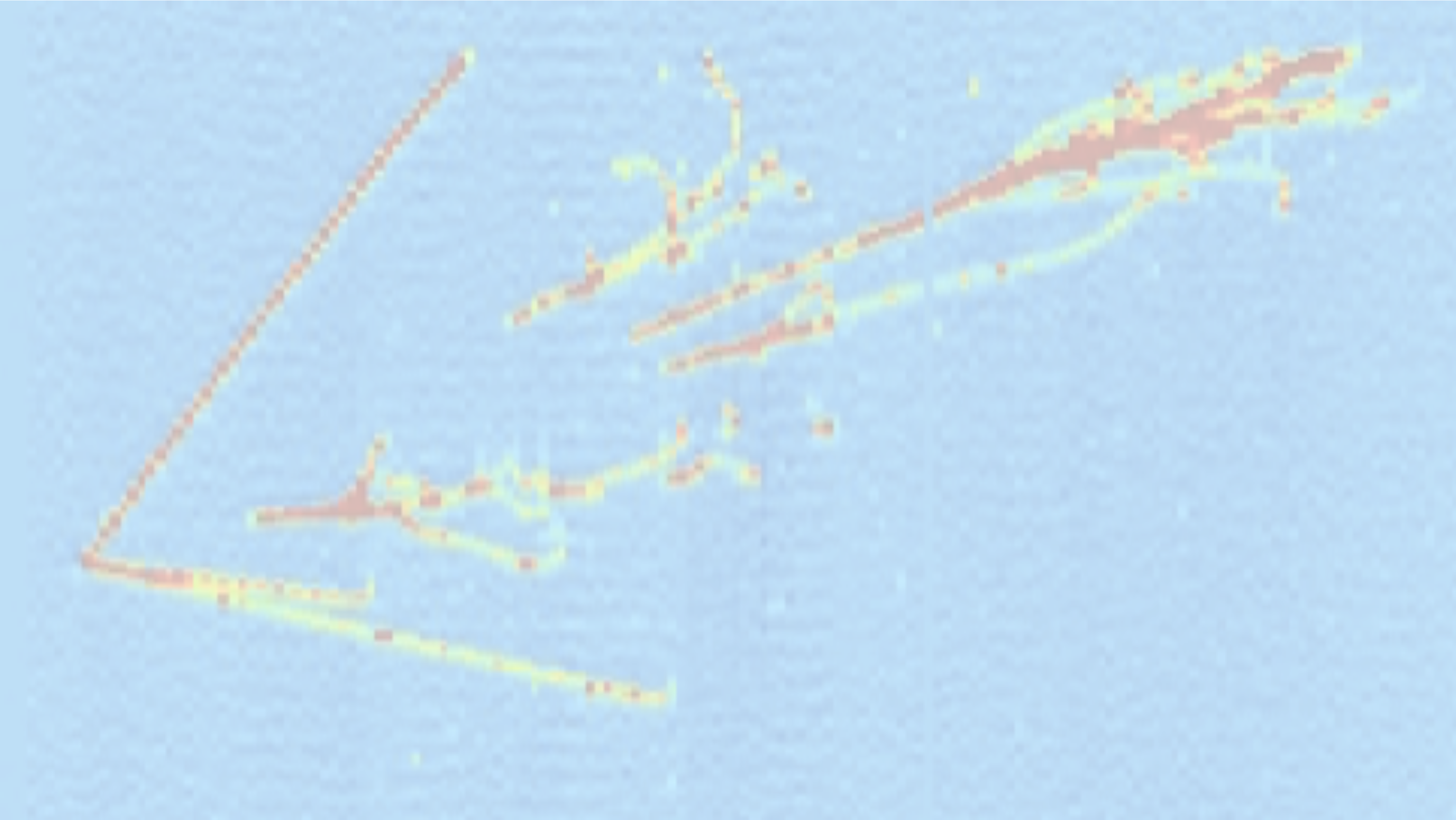
Indicative schedule



Indicative schedule



Calculating Sensitivies



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

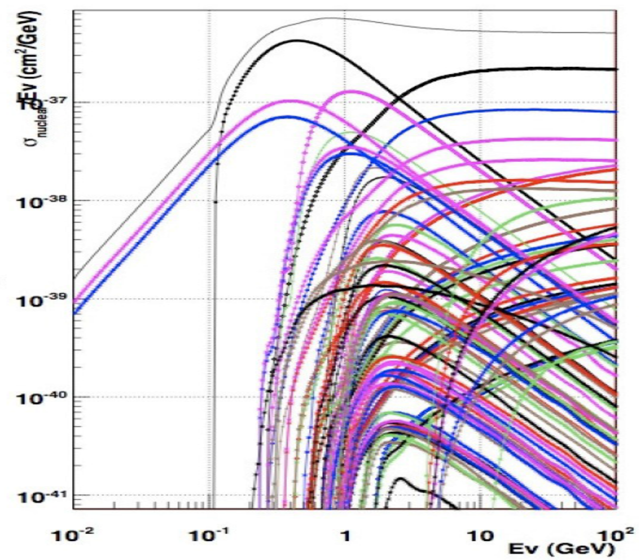
Evaluating DUNE Sensitivities I

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

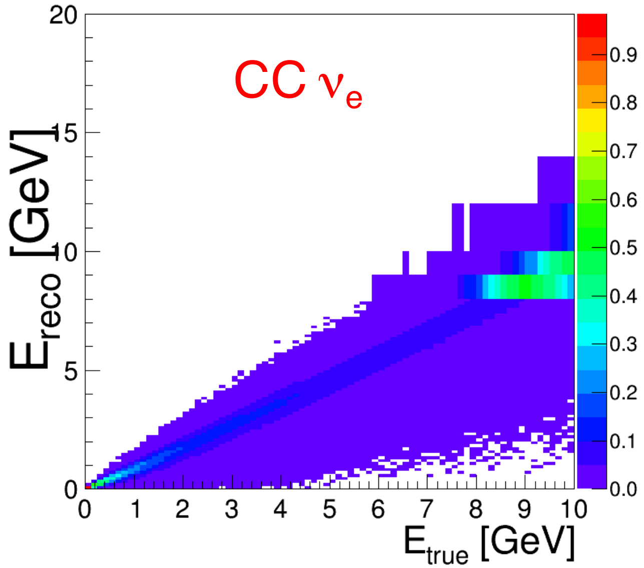
- **Assumed* Particle response/thresholds**
  - Parameterized detector response for individual final-state particles

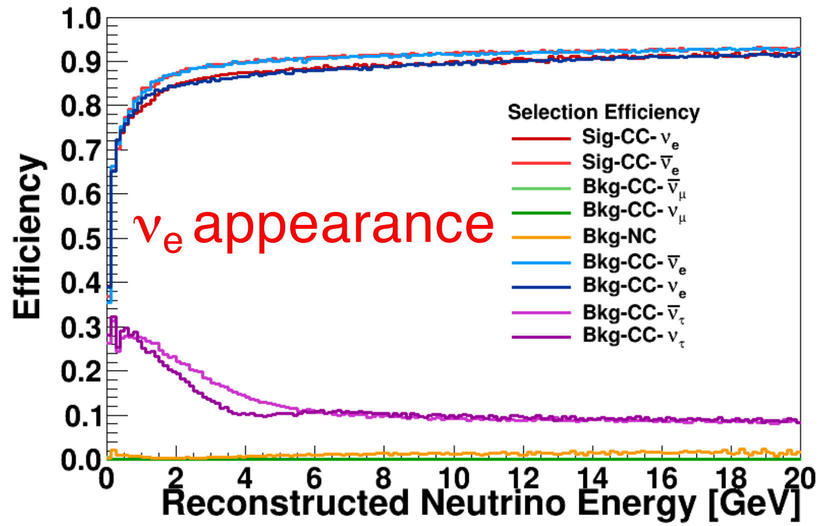
Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^\pm$	30 MeV	Contained: from track length Exiting: 30 %	1^o
$\pi^\pm$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1^o
$e^\pm/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{(E/GeV)}$	1^o
p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





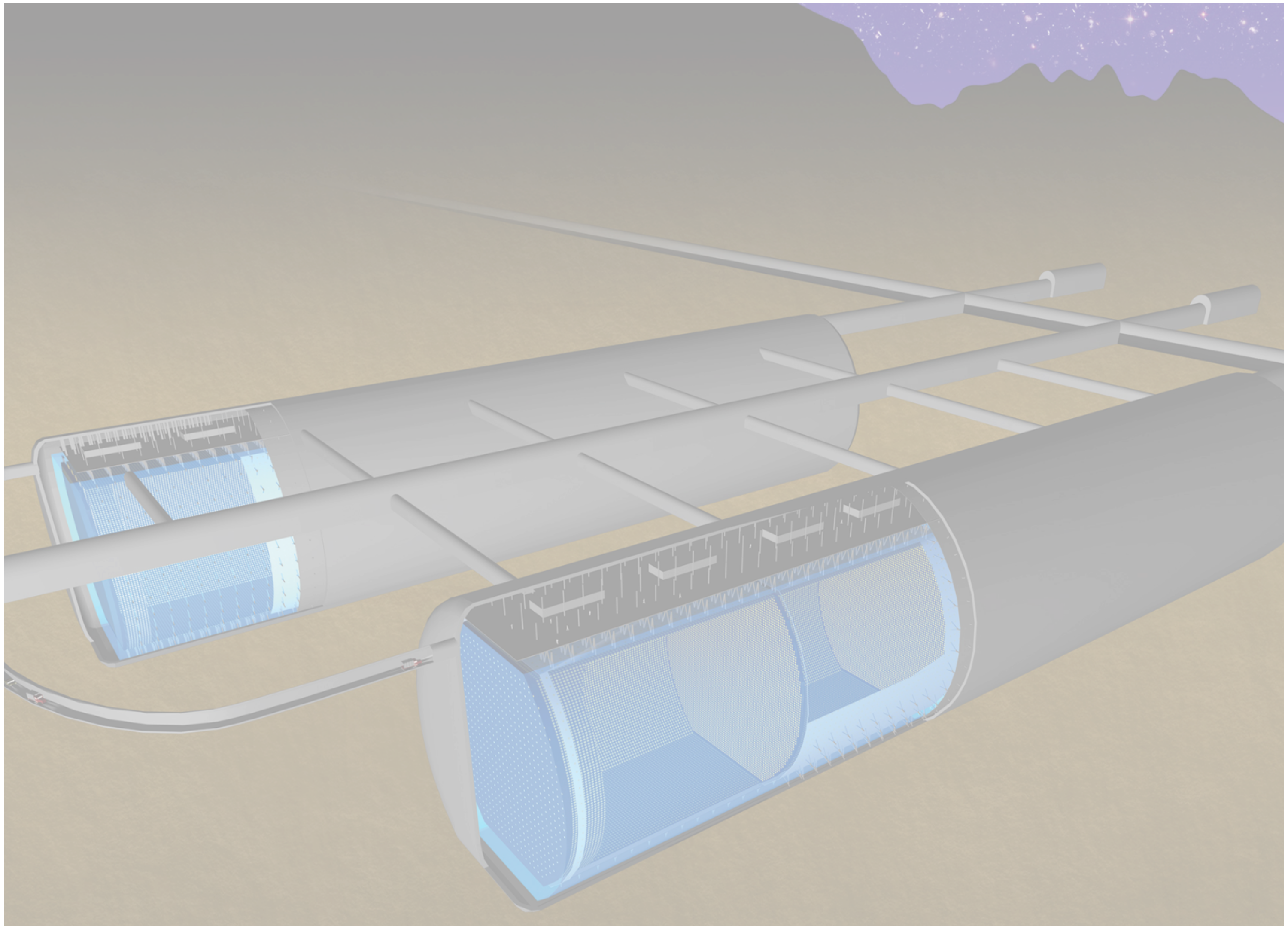
Evaluating DUNE Sensitivities IV

- **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

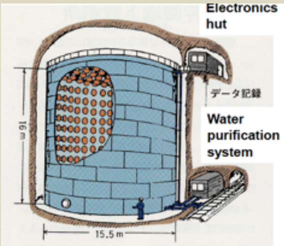
5: Hyper-Kamiokande



Far Detector

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

Kamiokande
(1983-1996)

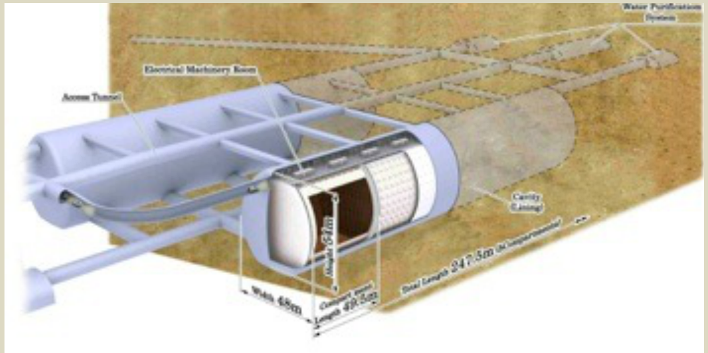


3 kton

Super-Kamiokande
(1996-)

50 kton

Hyper-Kamiokande
(202?-)

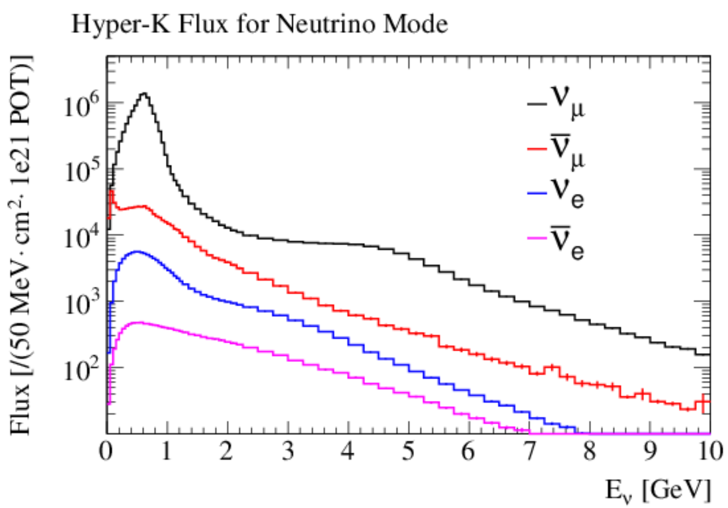


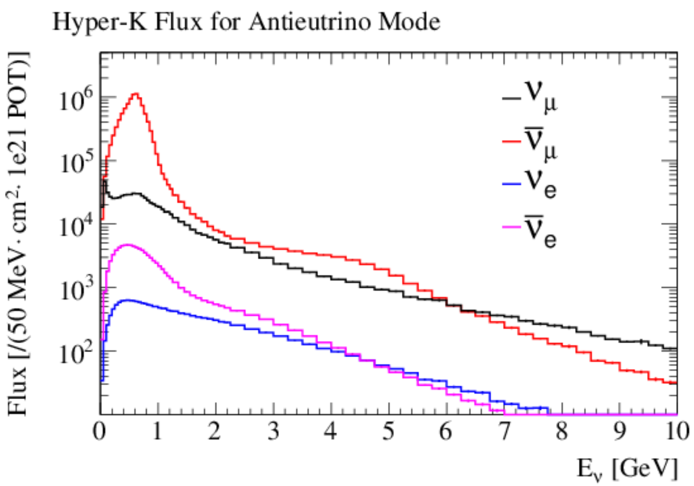
1 Mton

- 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 7.5×10^7 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:

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  - Particularly strong for decays with π^0
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to $\overline{\nu}_e$

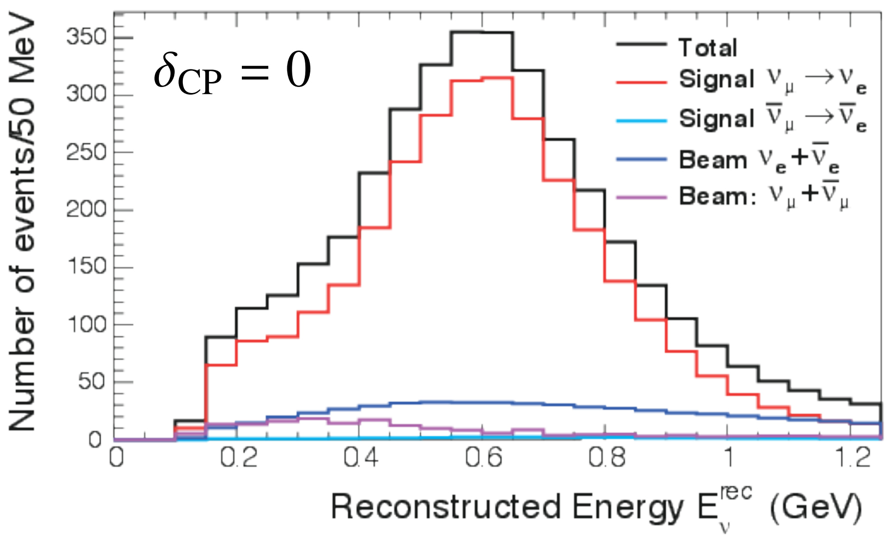
★ **Significant complementarity with DUNE physics**

Hyper-Kamiokande Physics*

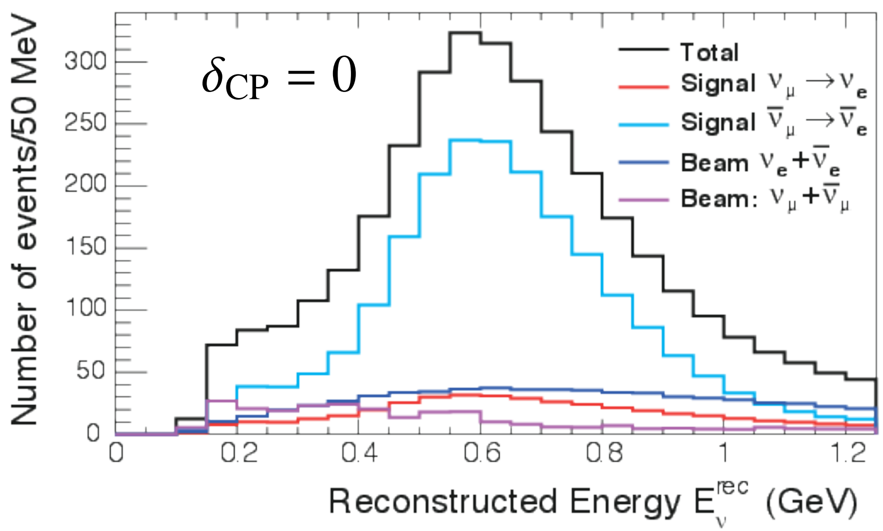
★ High-statistics for $\nu_e/\bar{\nu}_e$ appearance

Beam mode	Signal		Background					Total
	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	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



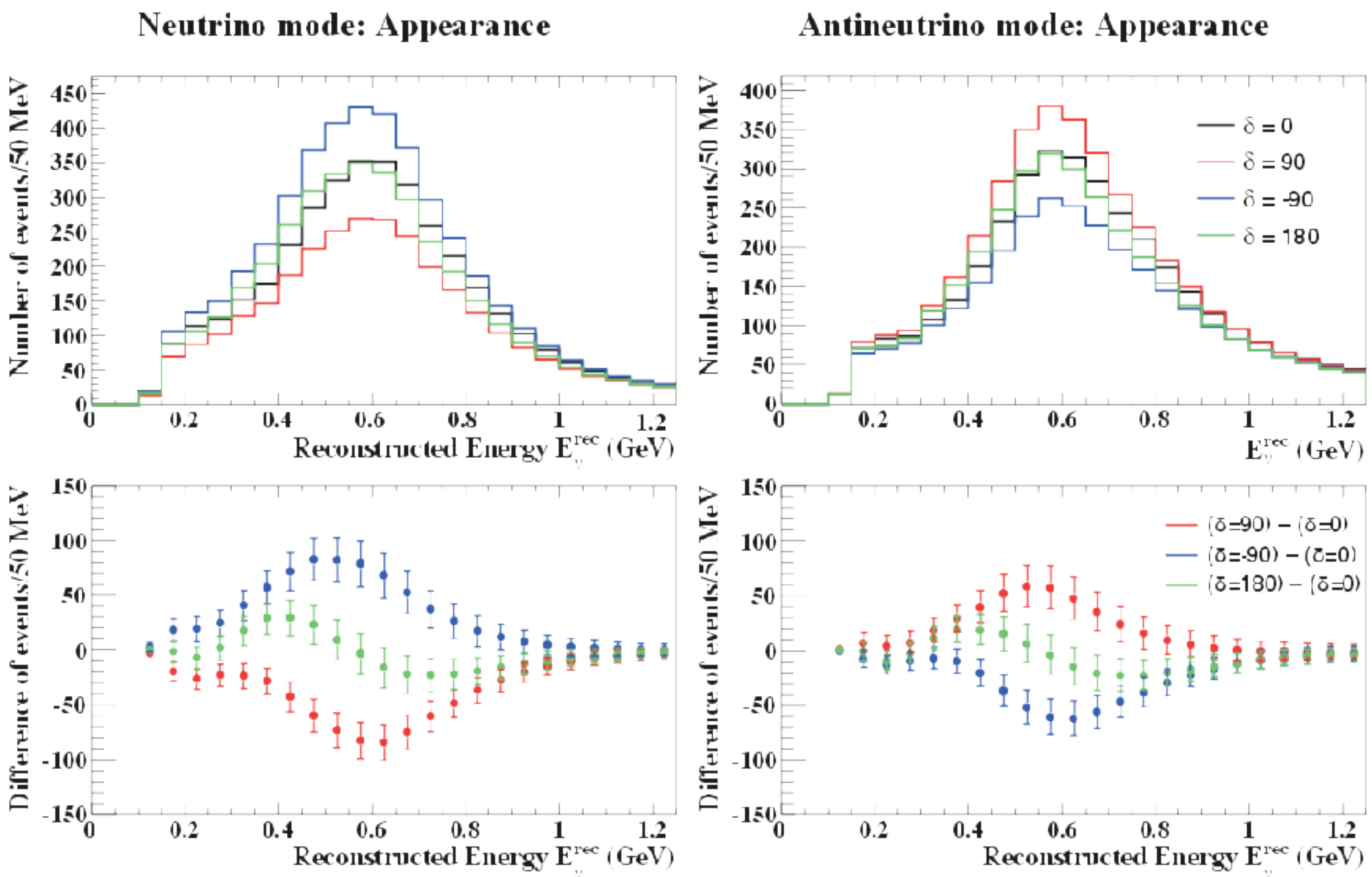
Appearance $\bar{\nu}$ mode



*here focus only on neutrino oscillations

CPV Sensitivity

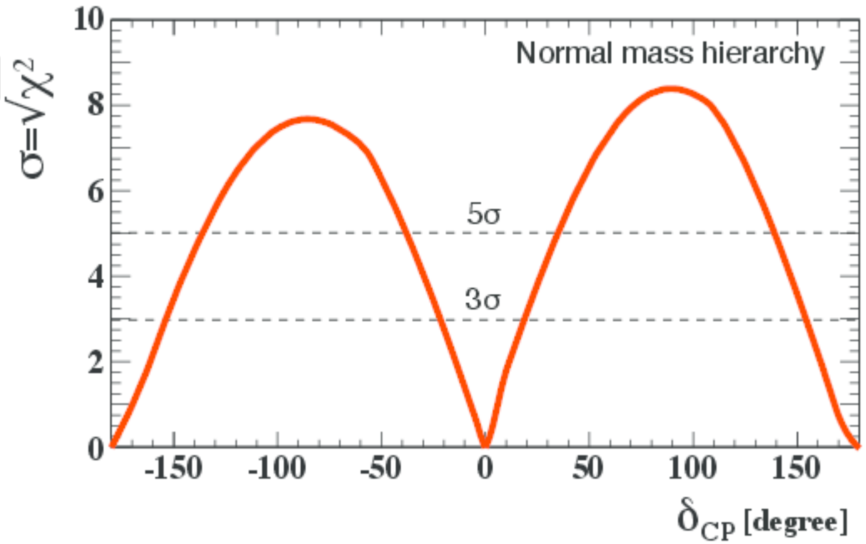
- CPV sensitivity from event counts
  - + some shape information

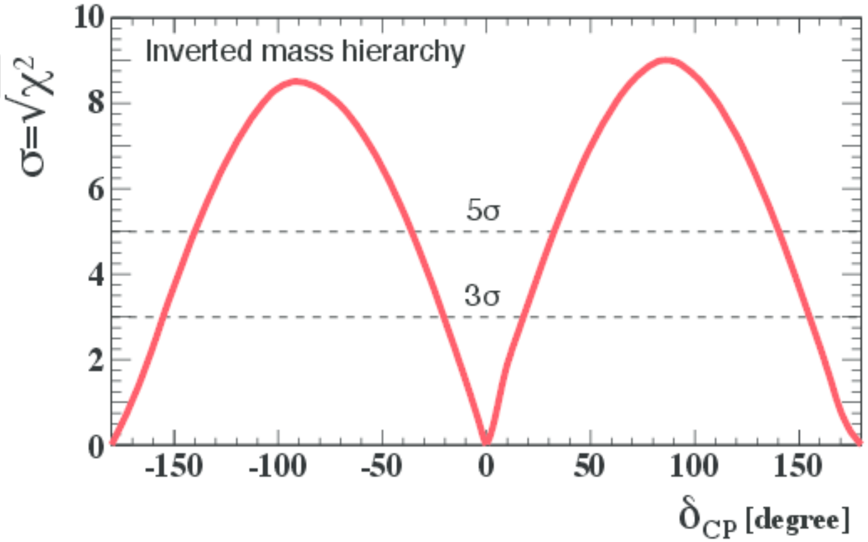


Hyper-K δ_{CP} Sensitivity

★ 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