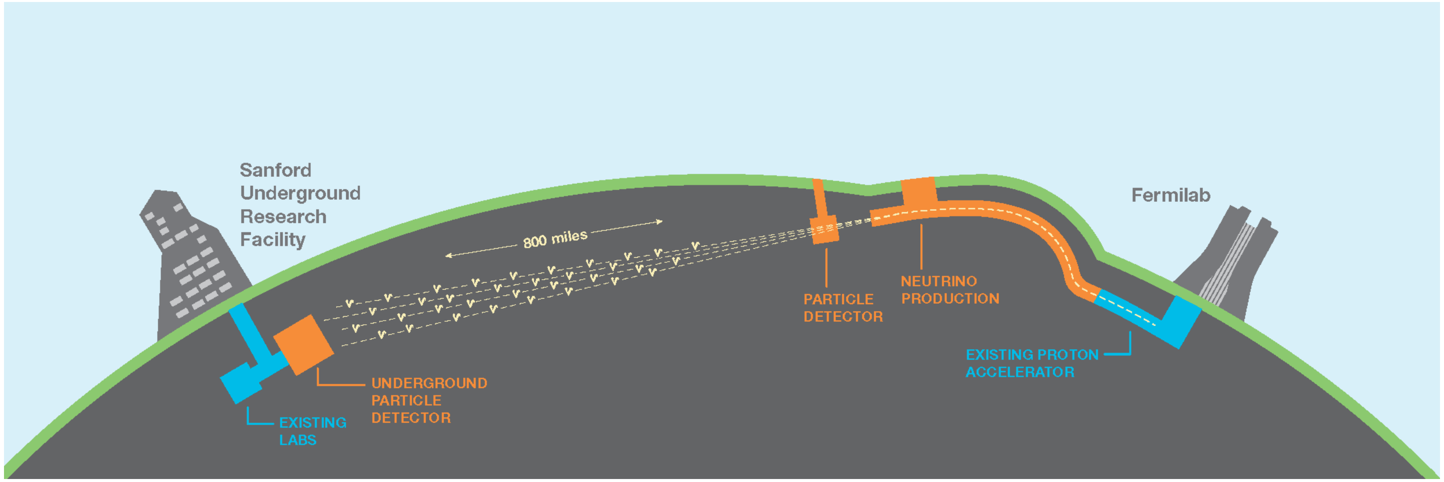


DUNE: The Deep Underground Neutrino Experiment

Mark Thomson

University of Cambridge & co-spokesperson of DUNE

Heidelberg Physics Colloquium: 10th December 2015

UNIVERSITY OF CAMBRIDGE

DUNE

This talk

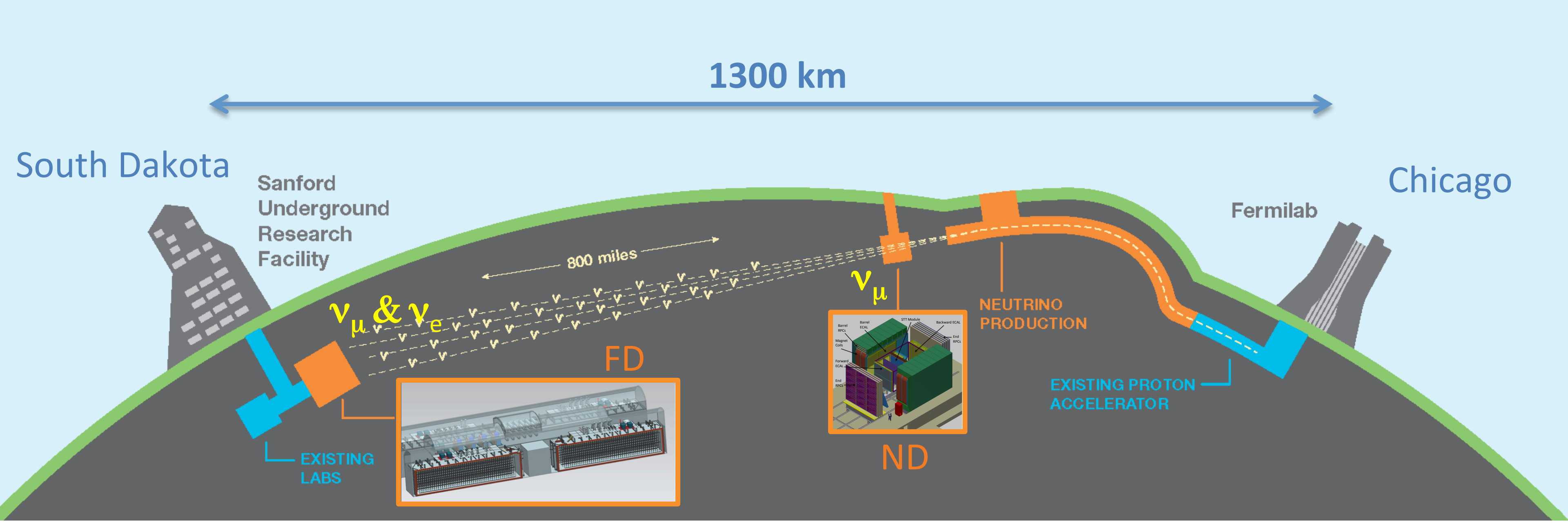
- 1. Introduction (1 slide)
- 2. Neutrino Basics: What are neutrinos? (5 slides)
  - and why they are so interesting
- 3. Neutrino oscillations – quantum mechanics in action (5 slides)
  - how we study neutrino properties
- 4. DUNE (4 slides)
- 5. DUNE Scientific Aims (6 slides)
  - what we intend to measure and why it matters
- 6. The LBNF/DUNE project (9 slides)
  - the accelerator/infrastructure (LBNF) and the detectors (DUNE)
- 7. The DUNE collaboration (3 slides)
- 8. Political Context (1 slide)
- 9. Opportunities (1 slide)
- 10. Summary (1 slide)

1. Introduction: What is DUNE?

- The **D**eep **U**nderground **N**eutrino **E**xperiment (DUNE):
  - is likely to be the next big global project in particle physics
  - aims to "do for neutrinos what the LHC did for the Higgs"
  - potential for major discoveries in: neutrinos and astro-particle physics

1. Introduction: What is DUNE?

- **DUNE will consist of**
  - **A powerful (MW) neutrino beam fired from Fermilab**
  - **A massive (40000 t) underground detector in the Homestake mine, South Dakota**
  - **A large international collaboration (currently 800 scientists)**



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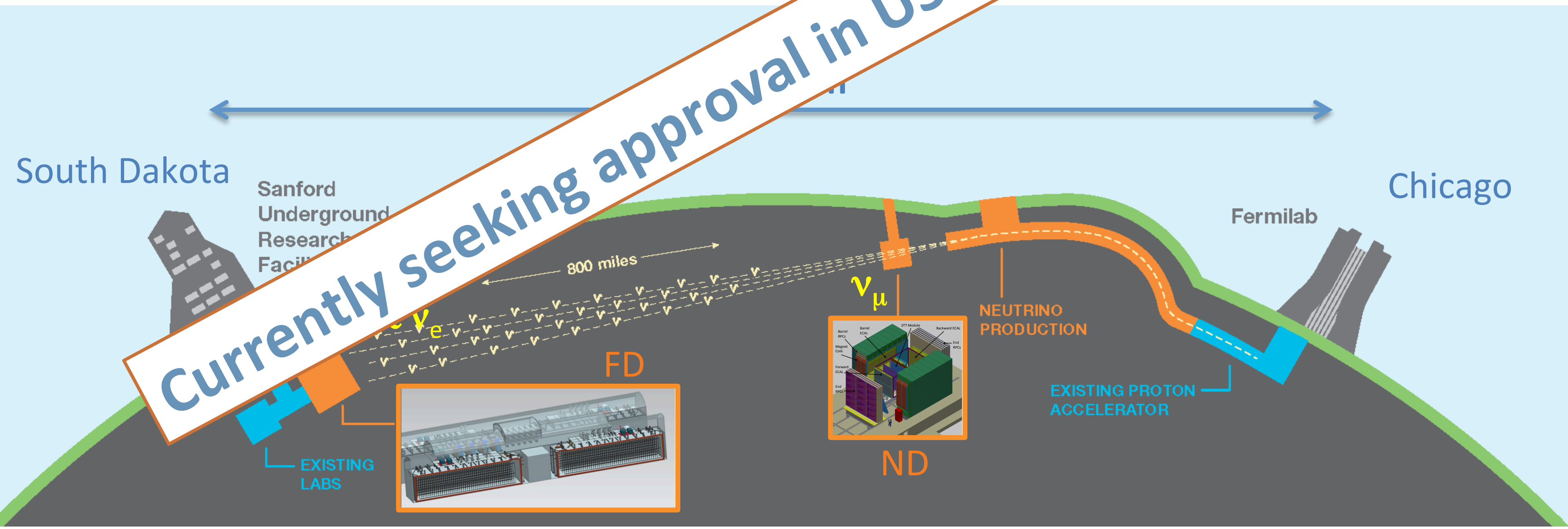
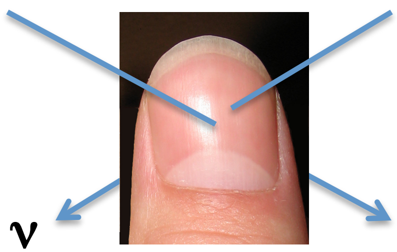
Currently seeking approval in US: first beam 2025



2. Neutrino Basics

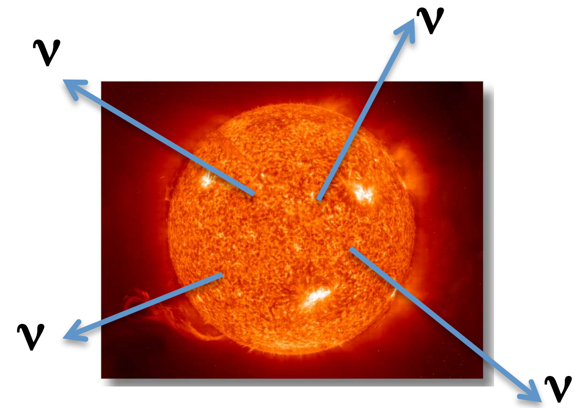
Neutrinos

- **Neutrinos are everywhere:**
  - **The universe is filled with neutrinos**
    - Apart from photons, there are more neutrinos than any other particle
    - ~300 νs in every cm^3 of the Universe – relics from the Big Bang
    - ~1 trillion (10^{12}) neutrinos pass through every cm^2 every second

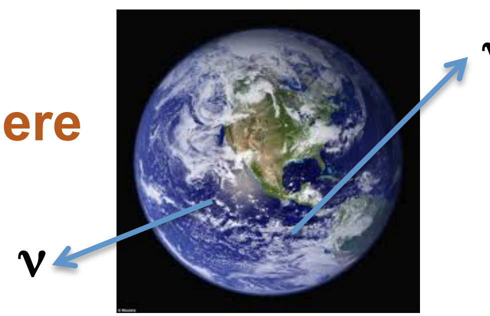


- **Neutrinos only feel the "Weak Force"** (and gravity)
  - **They are very weakly interacting, e.g. to stop a 1 MeV particle:**
    - For a proton require 0.1 mm of lead (strong interaction)
    - For an electron require 10 mm of lead (EM interaction)
    - For a neutrino need **10 light years of lead** (weak interaction only)

Sources of Neutrinos



- **Many sources of neutrinos:**
  - **Relics from the Big Bang**
  - **Nuclear fusion in the sun**
    - 10^{38} neutrinos per second
  - **Core collapse supernova**
    - Most of the energy released in neutrinos
  - **Interactions of cosmic-rays in the atmosphere**

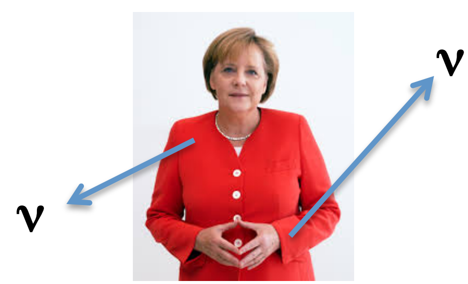


  - **Radioactive (beta) decays, e.g.**
    - Natural radioactivity in the Earth releases

      20 TeraWatts of power in νs
    - Each of you is a neutrino emitter:

      you contain ~20 mg ^{40}K

      ⇨ you emit 300,000,000 νs per day



… and accelerator-based neutrino beams

Neutrinos in particle physics

- **The basic building-blocks of the Universe**
  - **Most matter in the Universe is built from four particles**

	quarks		leptons	
	Up (**u**)	Down (**d**)	Electron ($\mathbf{e^-}$)	Neutrino ($\boldsymbol{\nu_1}$)

Neutrinos in particle physics

- **The basic building-blocks of the Universe**
  - **Not quite that simple…**

	quarks		leptons	
First gen.	Up (**u**)	Down (**d**)	Electron (**e**$^-$)	Neutrino (ν_1)
Second gen.	Charm (**c**)	Strange (**s**)	Muon (μ^-)	Neutrino (ν_2)
Third gen.	Top (**t**)	Bottom (**b**)	Tau (τ^-)	Neutrino (ν_3)

- **Each particle comes in 3 "copies" with different masses**
  - **Not understood why…**

Neutrinos in particle physics

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First gen.	u	d	e^-	ν_1
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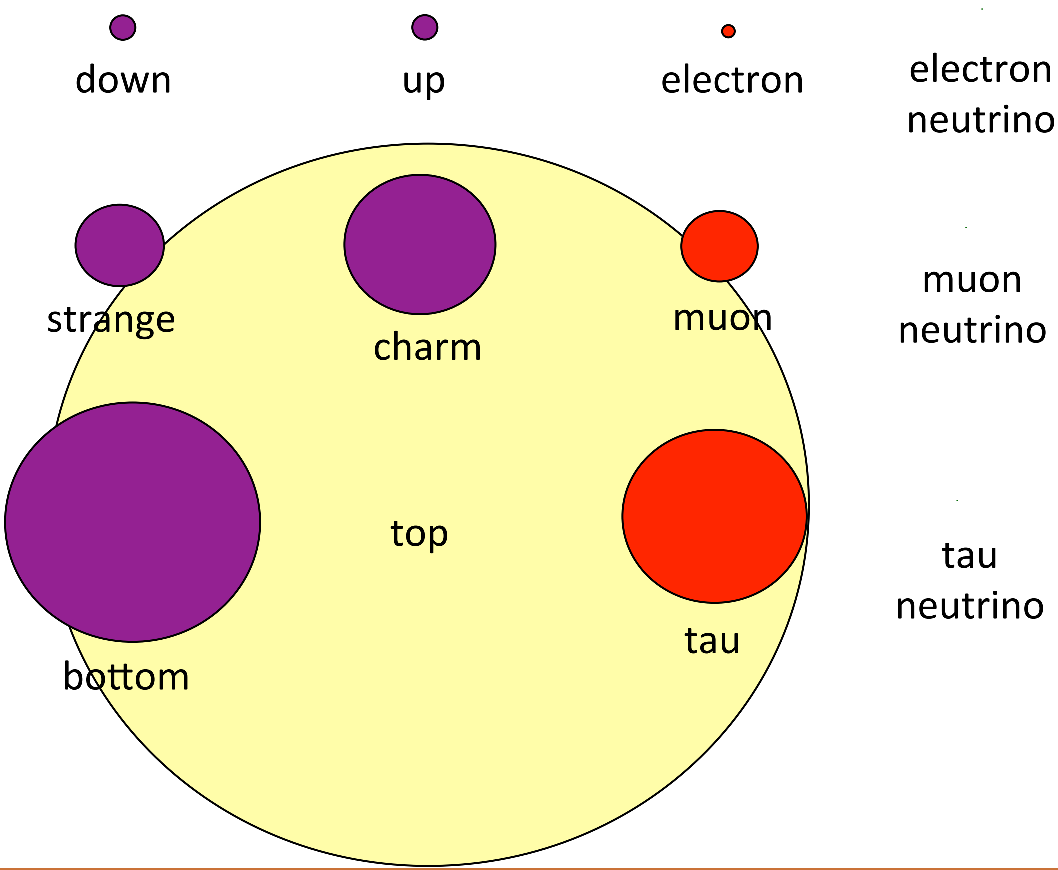
  - Not understood why…

+ corresponding antiparticles (antimatter)

	quarks		leptons	
First gen.	$\bar{u}$	$\bar{d}$	e^+	$\bar{\nu}_1$
Second gen.	$\bar{c}$	$\bar{s}$	μ^+	$\bar{\nu}_2$
Third gen.	$\bar{t}$	$\bar{b}$	τ^+	$\bar{\nu}_3$

Neutrinos Masses

- **Neutrinos are "different"**
  - **e.g. masses are (at least) 1 billion times smaller than those of the other matter particles**



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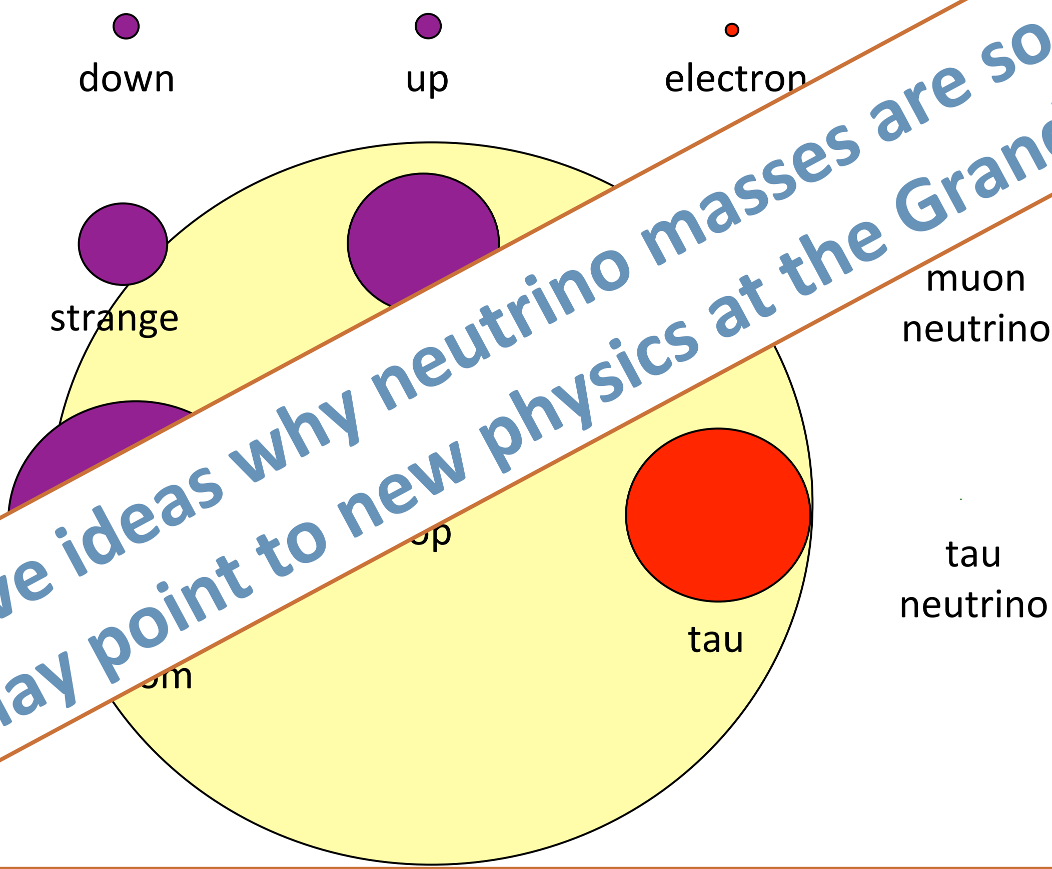
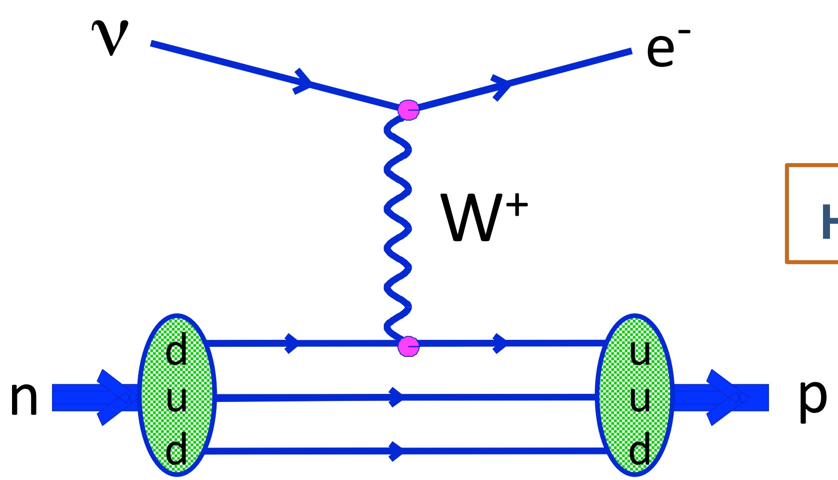


We have ideas why neutrino masses are so small
➡ may point to new physics at the Grand Unification scale

Detecting Neutrinos

- **Neutrinos only feel the "Weak Force"** (and gravity)
  - **They are very weakly interacting, e.g. to stop a 1 MeV neutrino**
    - Need **10 light years of lead** (weak interaction only)
- **So its hard… need large detectors & many neutrinos**
- **Also never directly "see" a neutrino**
  - **Only see them by their weak interactions**

  + the weak interaction changes flavour, e.g. $\nu + n \rightarrow p + e^-$



Here: ν could be ν_1, ν_2 or ν_3

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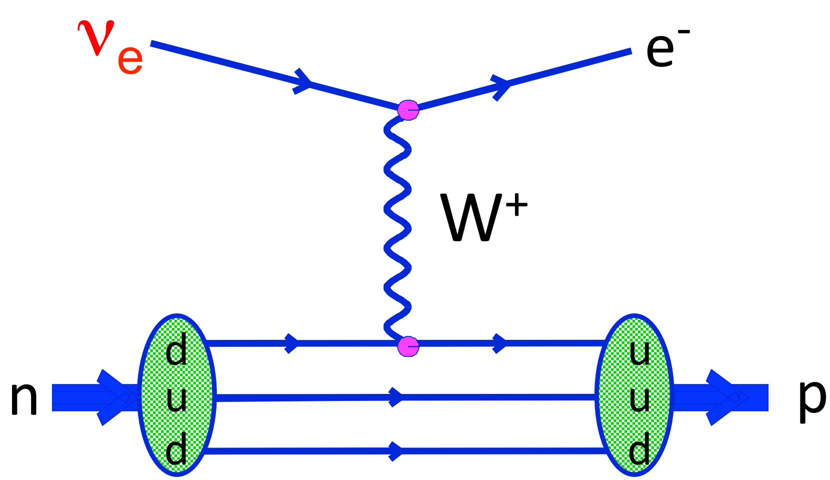
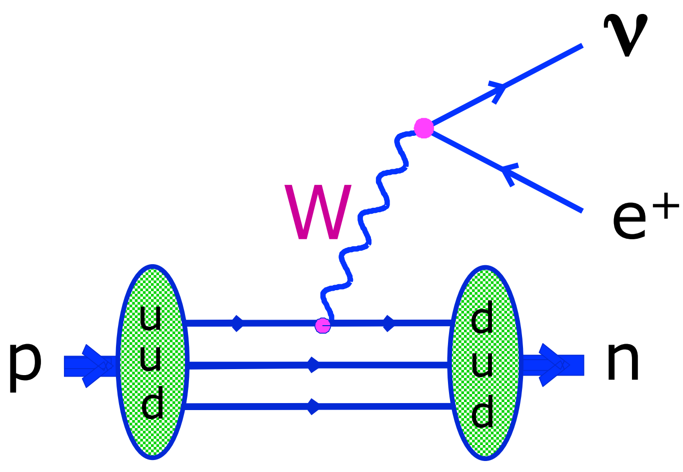


Usually label the neutrino state producing an electron as "electron neutrino"

3. Neutrino Oscillations

- **Now consider nuclear β^+ decay** **$p \rightarrow n + e^+ + \nu$**



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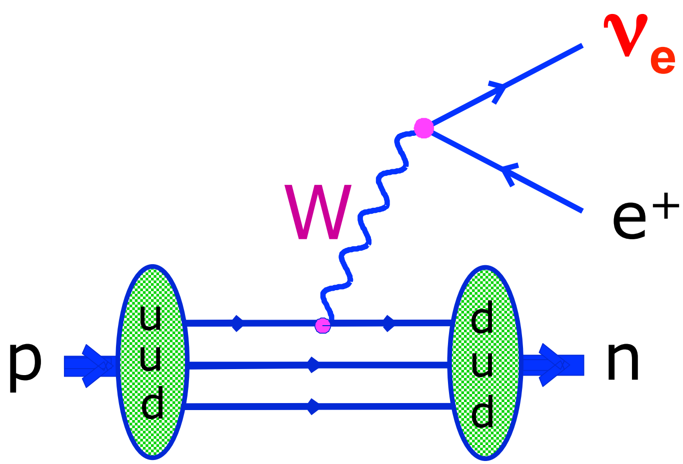

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But don't "see" the neutrino. Just observe the electron, so label it as an "electron neutrino" state

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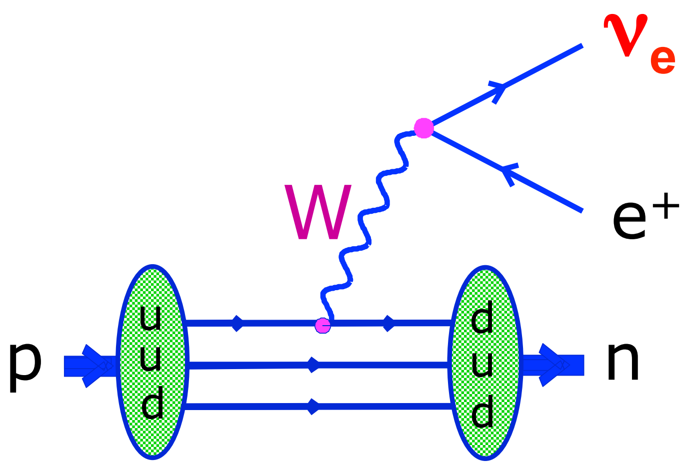
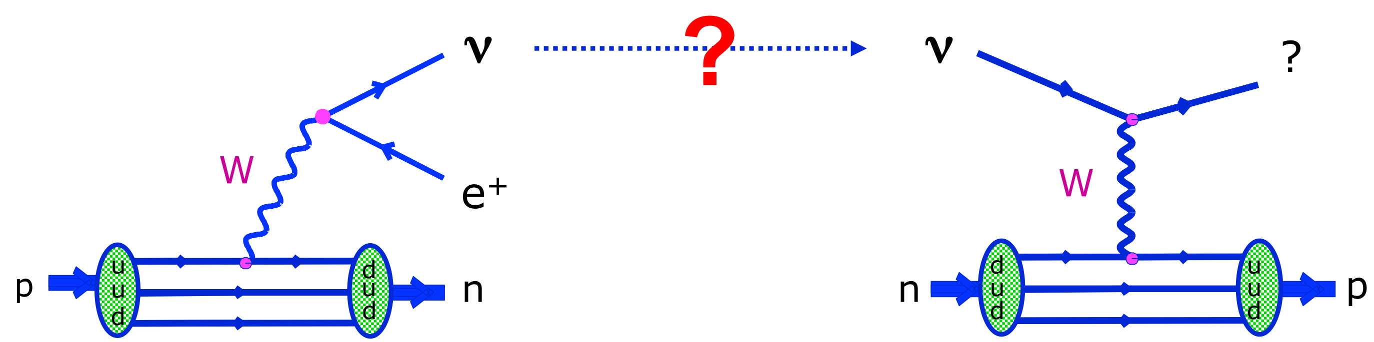


Here: ν could be ν_1, ν_2 or ν_3

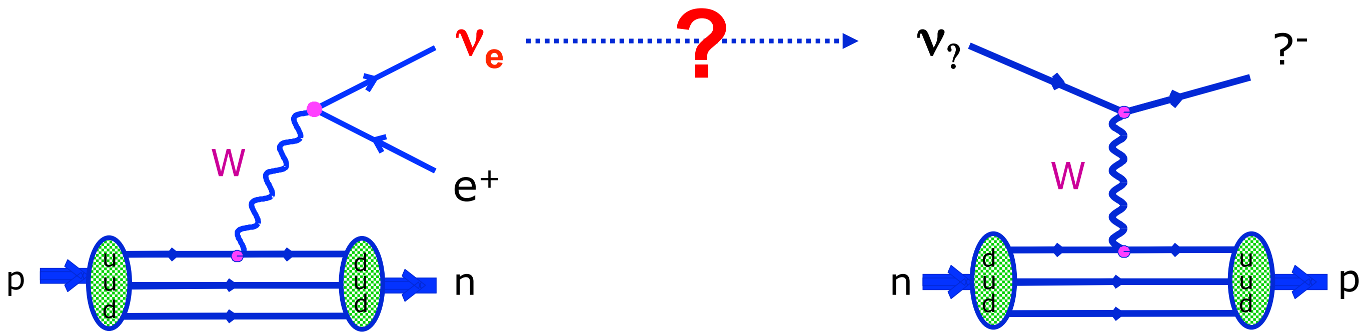
But don't "see" the neutrino. Just observe the electron, so label it as an **"electron neutrino" state**

- Experimentally, produce and detect neutrinos: but never directly observe the ν_1, ν_2 or ν_3



Quantum Mechanic Description

- **Two distinct types of state:**
  - ν_1, ν_2 **and** ν_3 **:** the fundamental particles with well-defined mass
  - ν_e, ν_μ **and** ν_τ **:** the "weak eigenstates" that are produced with or produce a well-defined charged lepton



- **Neutrinos thus propagate as coherent linear super-positions of mass eigenstates. In this example**
  - Initial state: $\nu_e = \alpha\,\nu_1 + \beta\,\nu_2 + \gamma\,\nu_3$
  - Where coefficients α, β, γ are determined by the relative probabilities of the interaction producing a ν_1, ν_2 and ν_3

Quantum Mechanic Description

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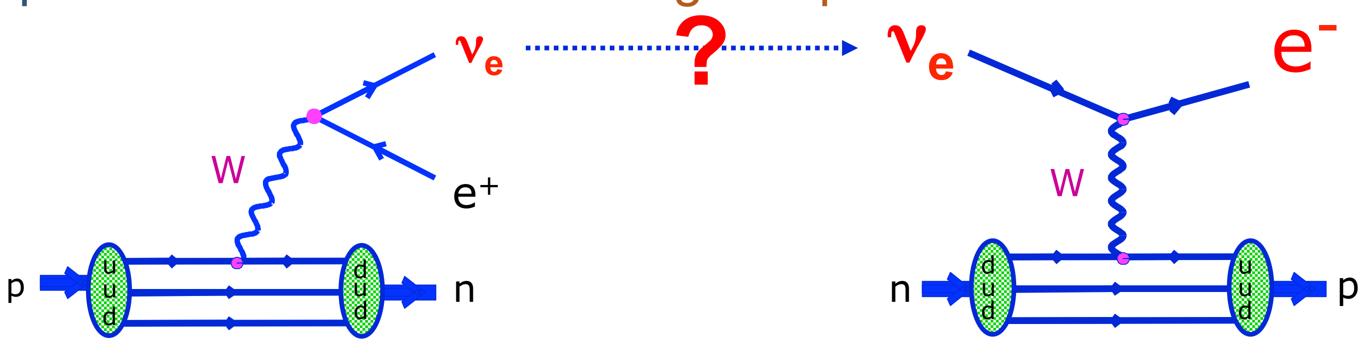

- **QM evolution of states determine what is measured**
  - Initial state: $\nu_e = \alpha\,\nu_1 + \beta\,\nu_2 + \gamma\,\nu_3$
  - If α, β, γ were constant then would always detect an electron if/ when the neutrino interacted, i.e. $\nu_e \rightarrow \nu_e$
  - But in general this is not the case because of the time dependence of the wavefunction, $\alpha \rightarrow \alpha\, \exp(-iE_1t)$

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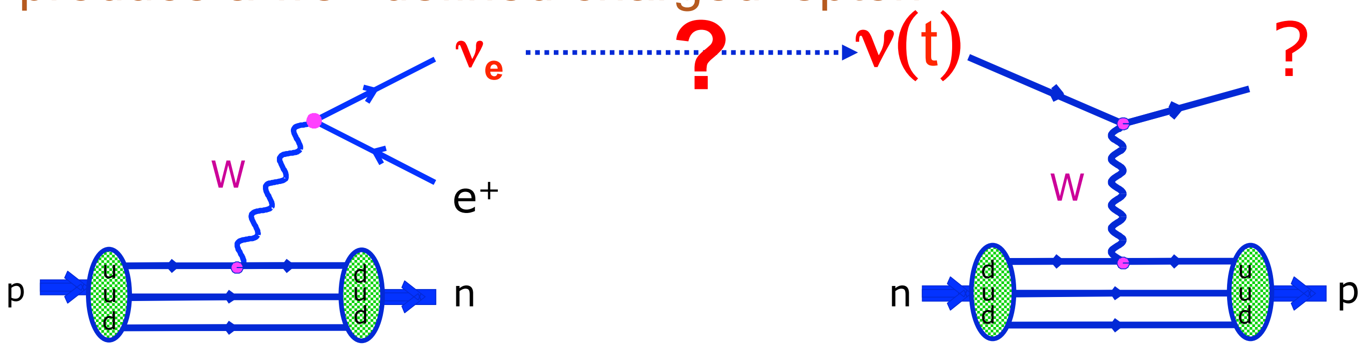

- **QM evolution of states determine what is measured**
  - At time t: $\nu(t) = \alpha \exp(-iE_1t)\,\nu_1 + \beta \exp(-iE_2t)\,\nu_2 + \gamma \exp(-iE_3t)\,\nu_3$
  - The phase differences between different components means that

    $\nu(t) \neq \nu_e$
  - There is now a non-zero probability that $\nu_e \rightarrow \nu_\mu$ and when the neutrino interacts it can produce a muon μ^- rather than an electron

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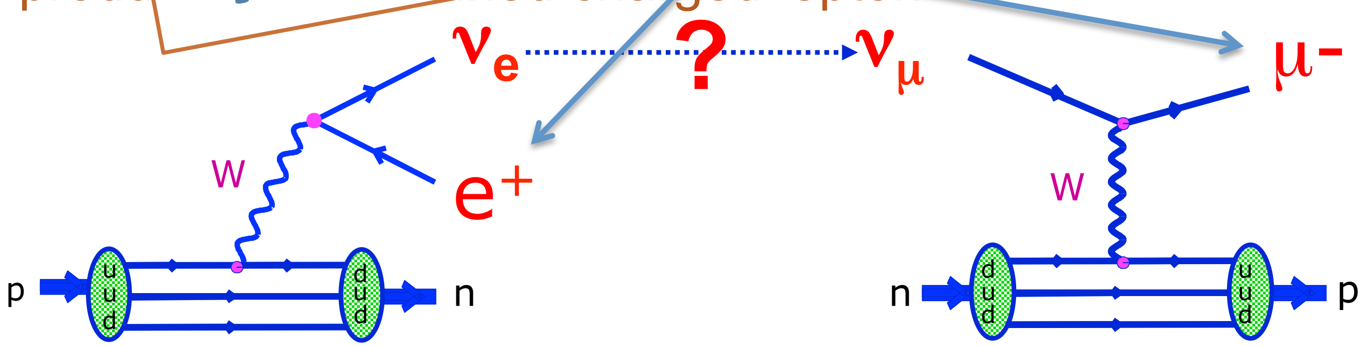
Neutrino oscillations



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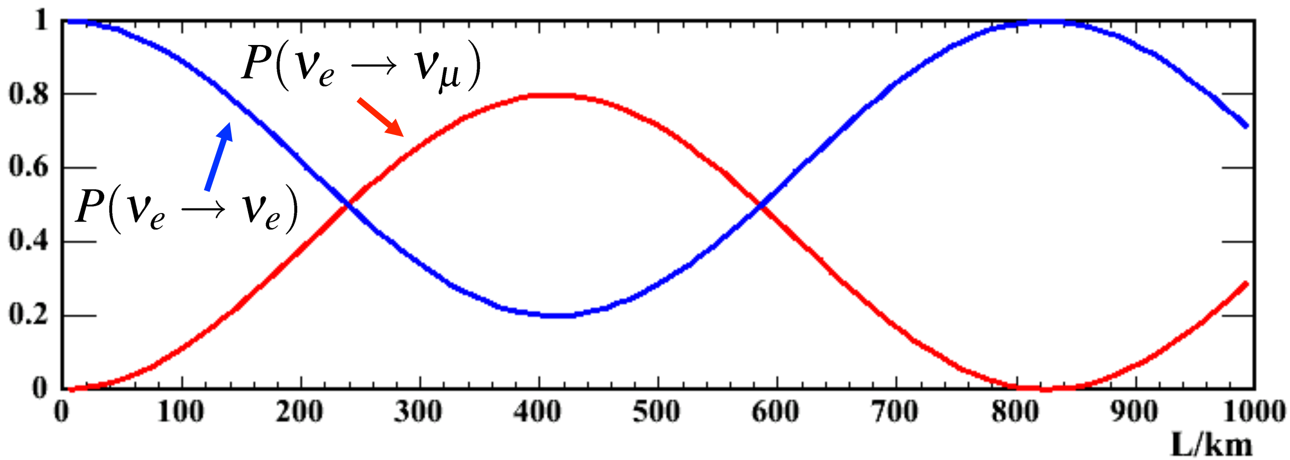
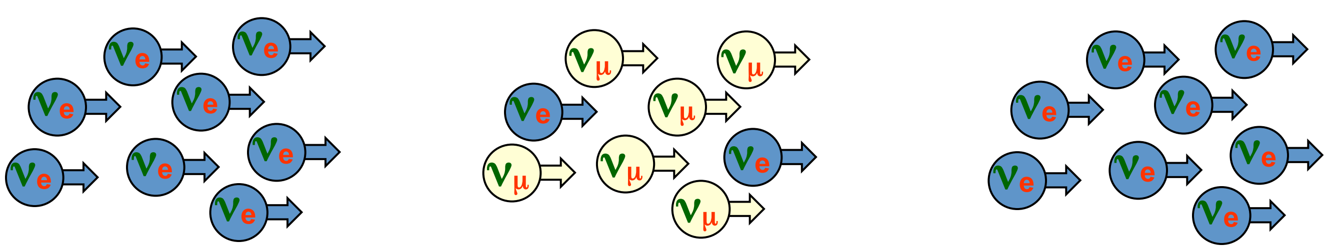
Neutrino Oscillations

- **With some simple algebra, the oscillation probability**

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





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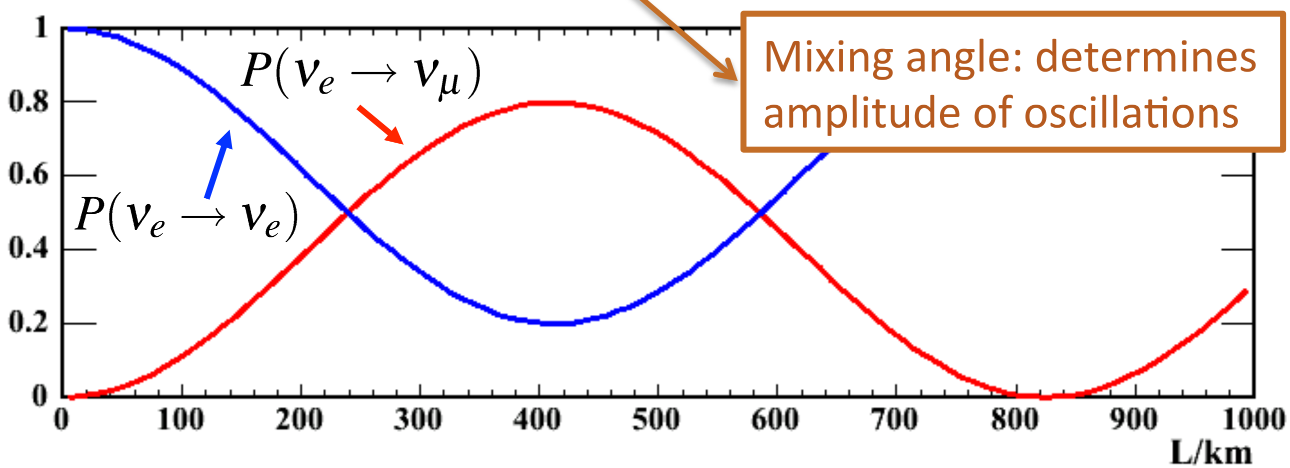
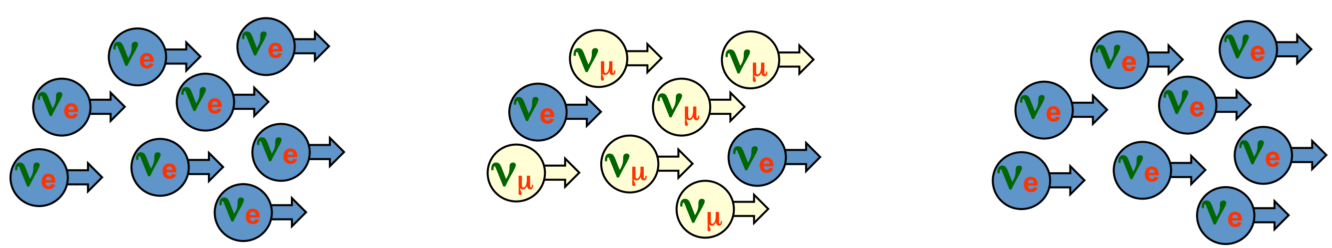
Mixing angle: determines amplitude of oscillations





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- **Wavelength of oscillations is very long, determined by the very small neutrino mass differences, e.g.**

$$\Delta m_{21}^2 = m_2^2 - m_1^2$$

- **Neutrino oscillations are a well established phenomena**
  - Super-Kamiokande
  - SNO

  } Nobel Prize 2015

  - MINOS, T2K, Daya Bay, RENO, …

- **Much of what we know about neutrinos comes from neutrino oscillation experiments**

The Standard 3-Flavor Paradigm

★ **Weak and mass eigenstates related by the PMNS matrix**

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

★ **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 $\propto \sin\theta_{13}$

The 2012 Revolution

★ **Two major discoveries in particle physics**

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

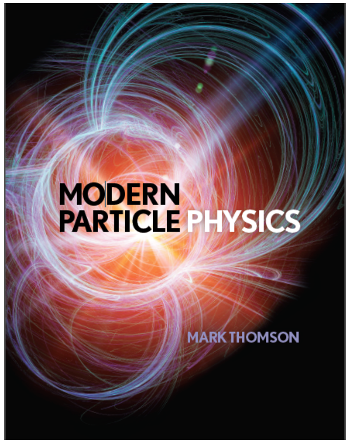
The 2012 Revolution

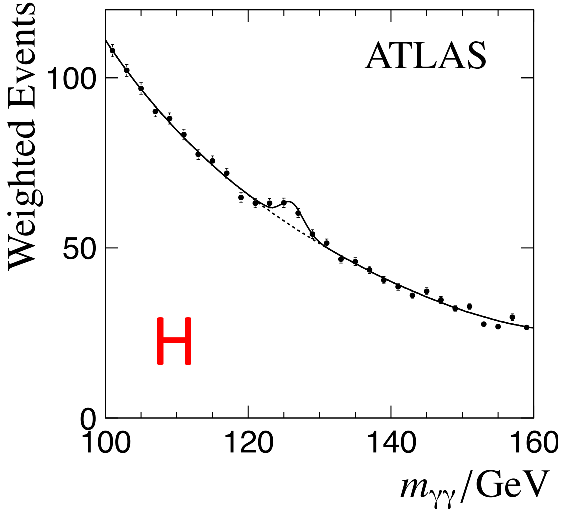
★ **Two major discoveries in particle physics**

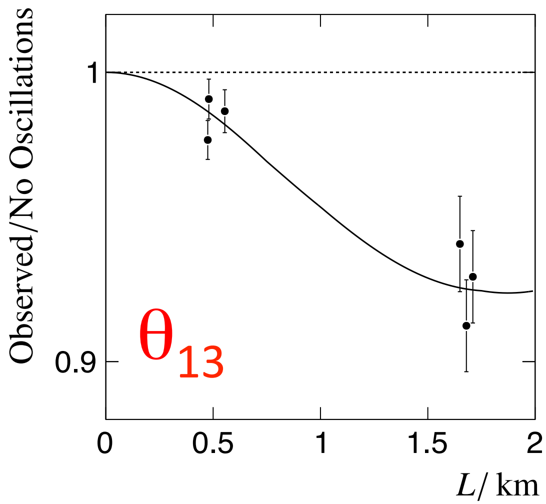
- A SM-like Higgs boson (ATLAS, CMS)
  - The key to EWSB and a possible window to the BSM world
- $\theta_{13} \sim 10^{o}$: determines rate of $P(\nu_\mu \rightarrow \nu_e)$
  - about as large as it could have been !
  - The door to CP Violation in neutrino oscillations

★ **Now standard textbook physics***

- **also** defines the next steps: ➡ **DUNE**

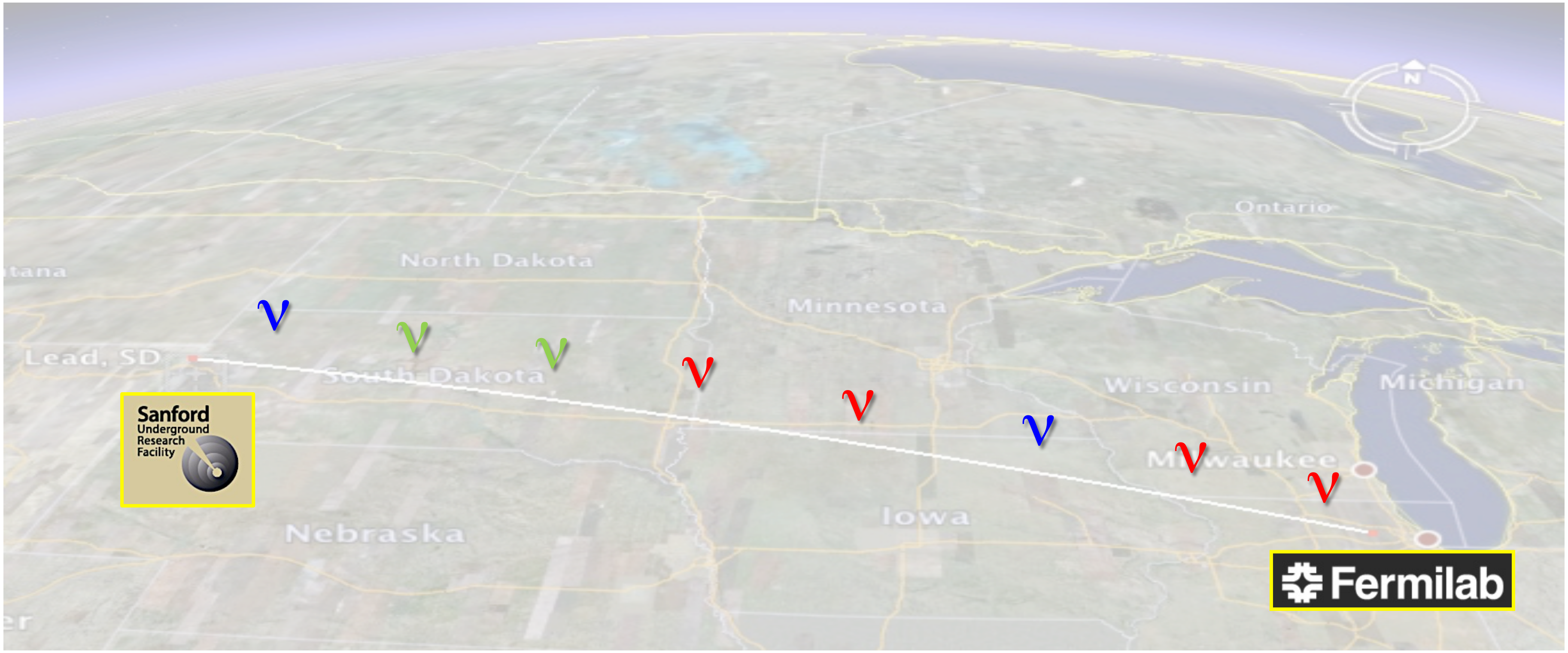






*apologies for gratuitous plug

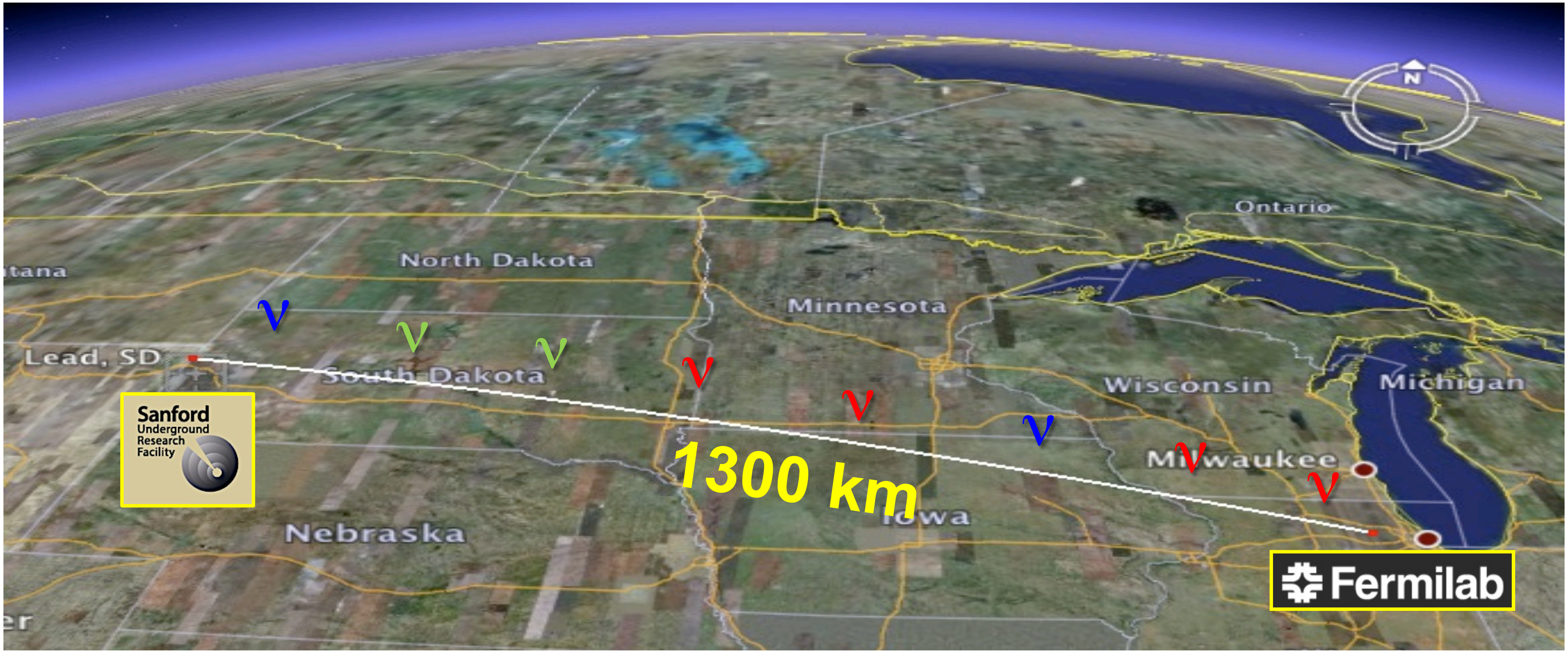
4. DUNE



North Dakota
Minnesota
Ontario
Lead, SD
South Dakota
Wisconsin
Michigan
Milwaukee
Iowa
Nebraska
Sanford Underground Research Facility
Fermilab
ν

DUNE in a Nutshell

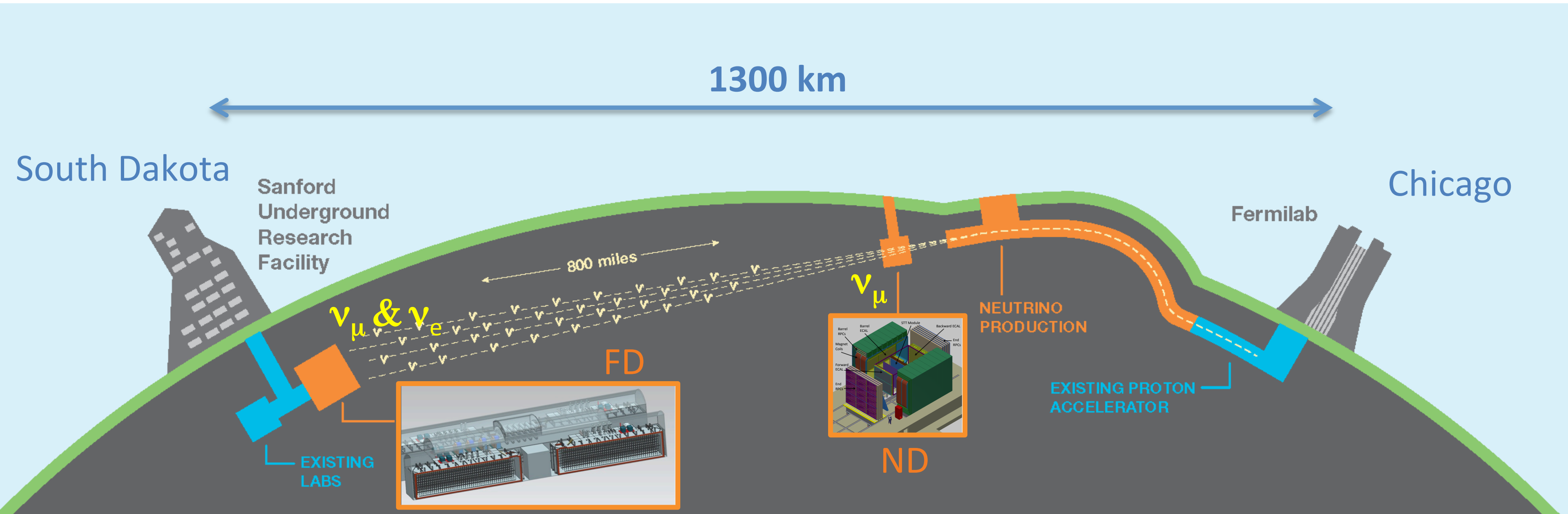
- ★ Intense beam of ν_μ or $\bar{\nu}_\mu$ fired 1300 km at a large detector
- ★ Compare $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- ★ Probe fundamental differences between matter & antimatter



DUNE in a Larger Nutshell

★ LBNF/DUNE

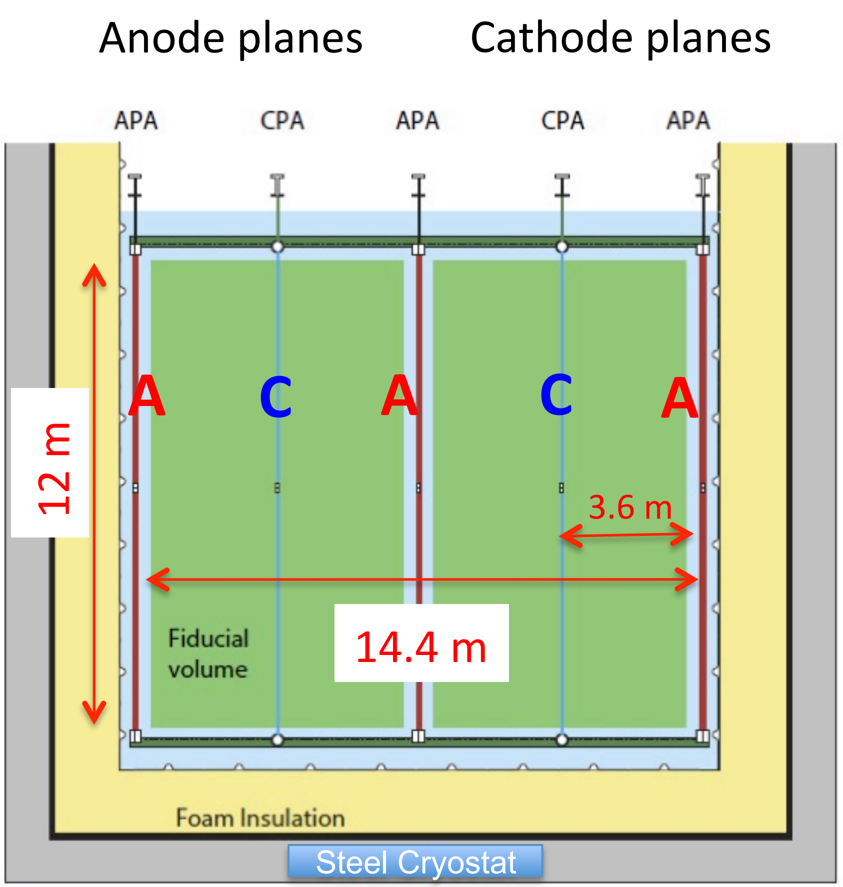
- Muon neutrinos/antineutrinos from high-power proton beam
  - **1.2 MW** from day one (upgradeable)
- Large underground **Liquid Argon Time Projection Chamber**
  - **4 x 17 kton** ⇨ **fiducial (useable) mass of >40 kton**
- Near detector to characterize the beam

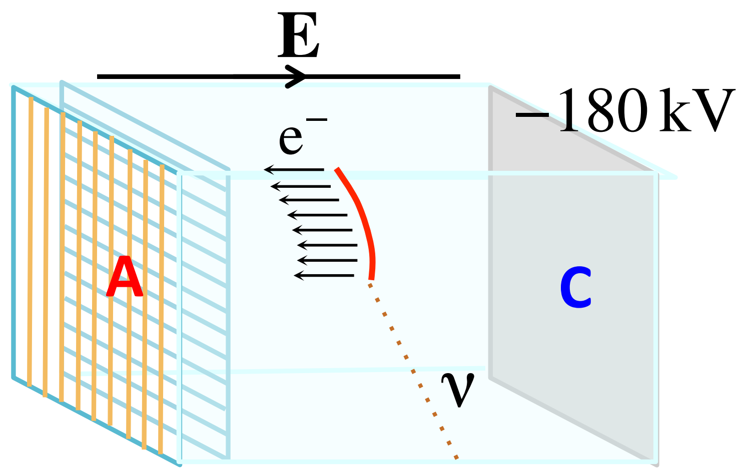


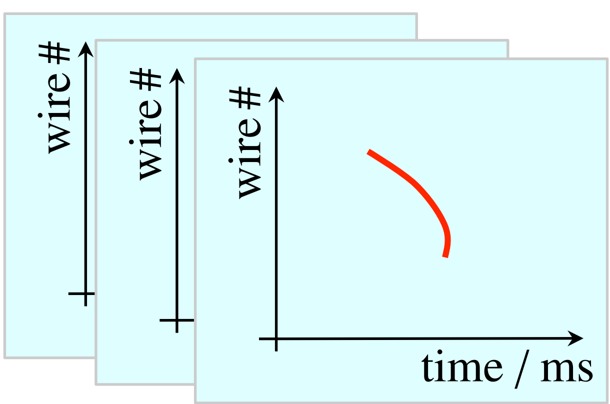
Liquid Argon TPC Basics

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

- Record ionization in LAr volume ⇨ 3D image







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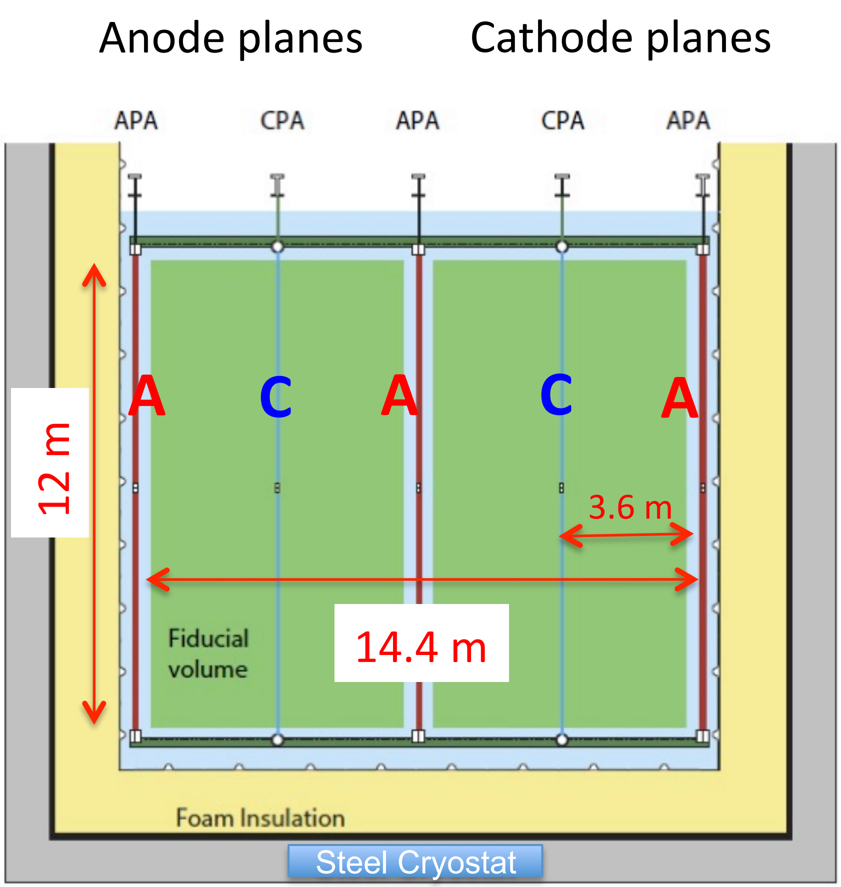
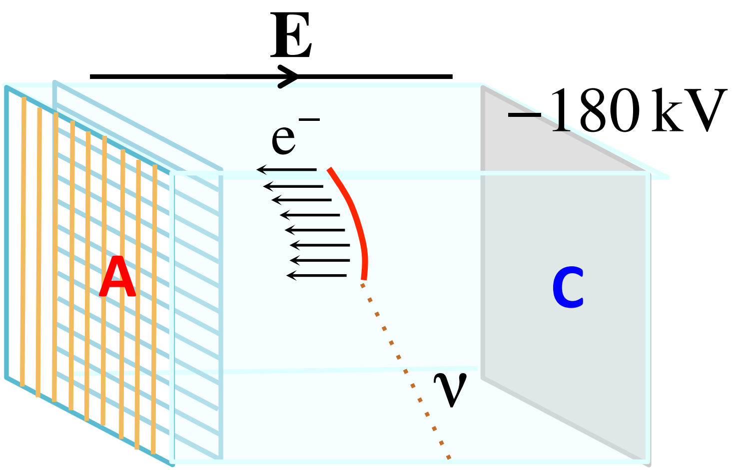
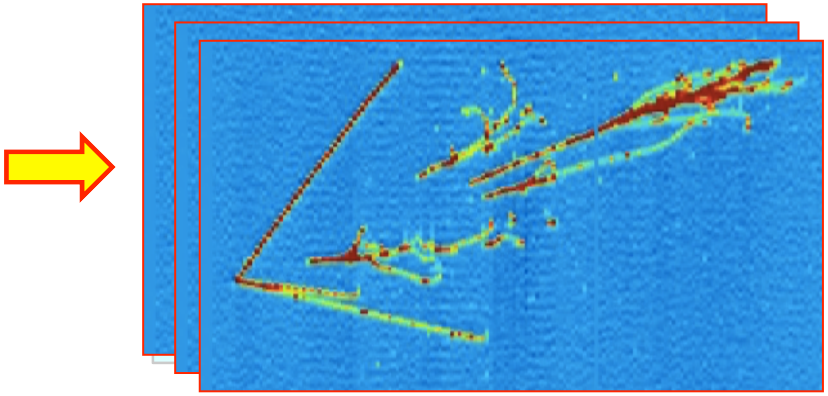


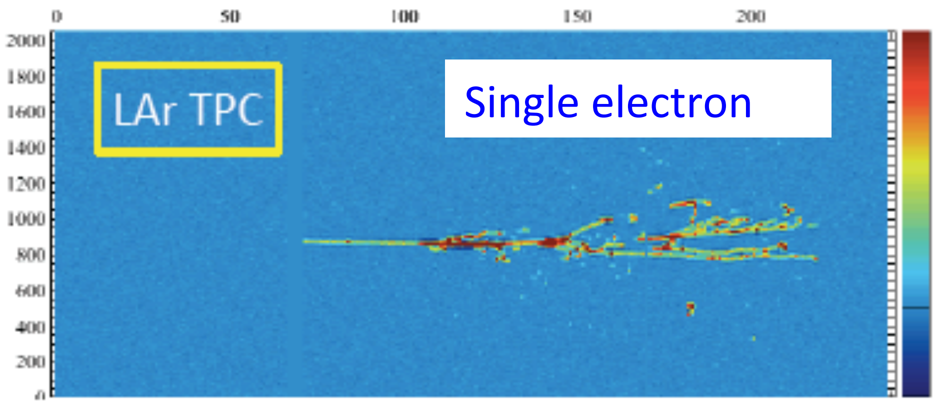


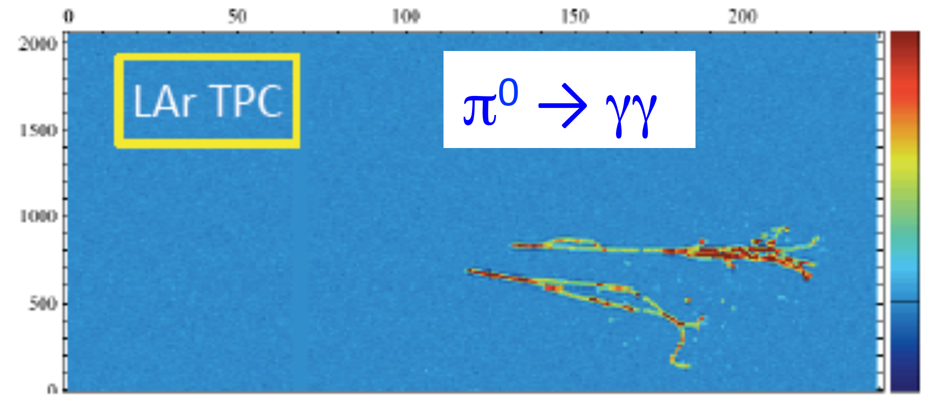


Benefits of an imaging detector

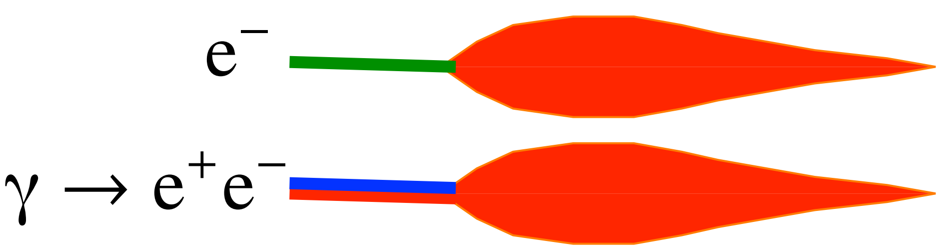
e.g. for electron neutrino appearance $e^{\pm} \leftrightarrow \gamma$ separation is vital

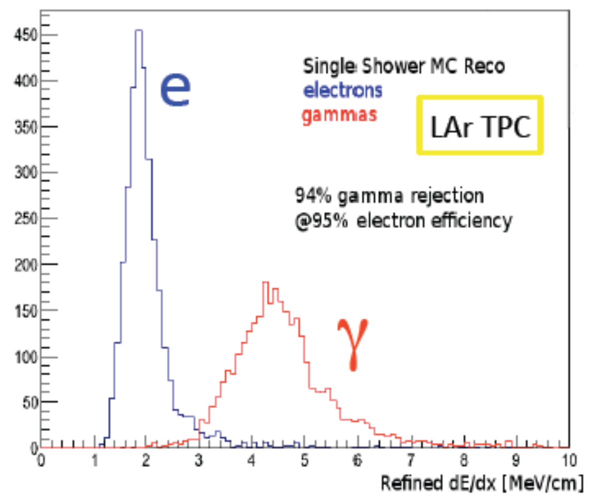
★ True for both photons from $\pi^0 \rightarrow \gamma\gamma$ or single photons





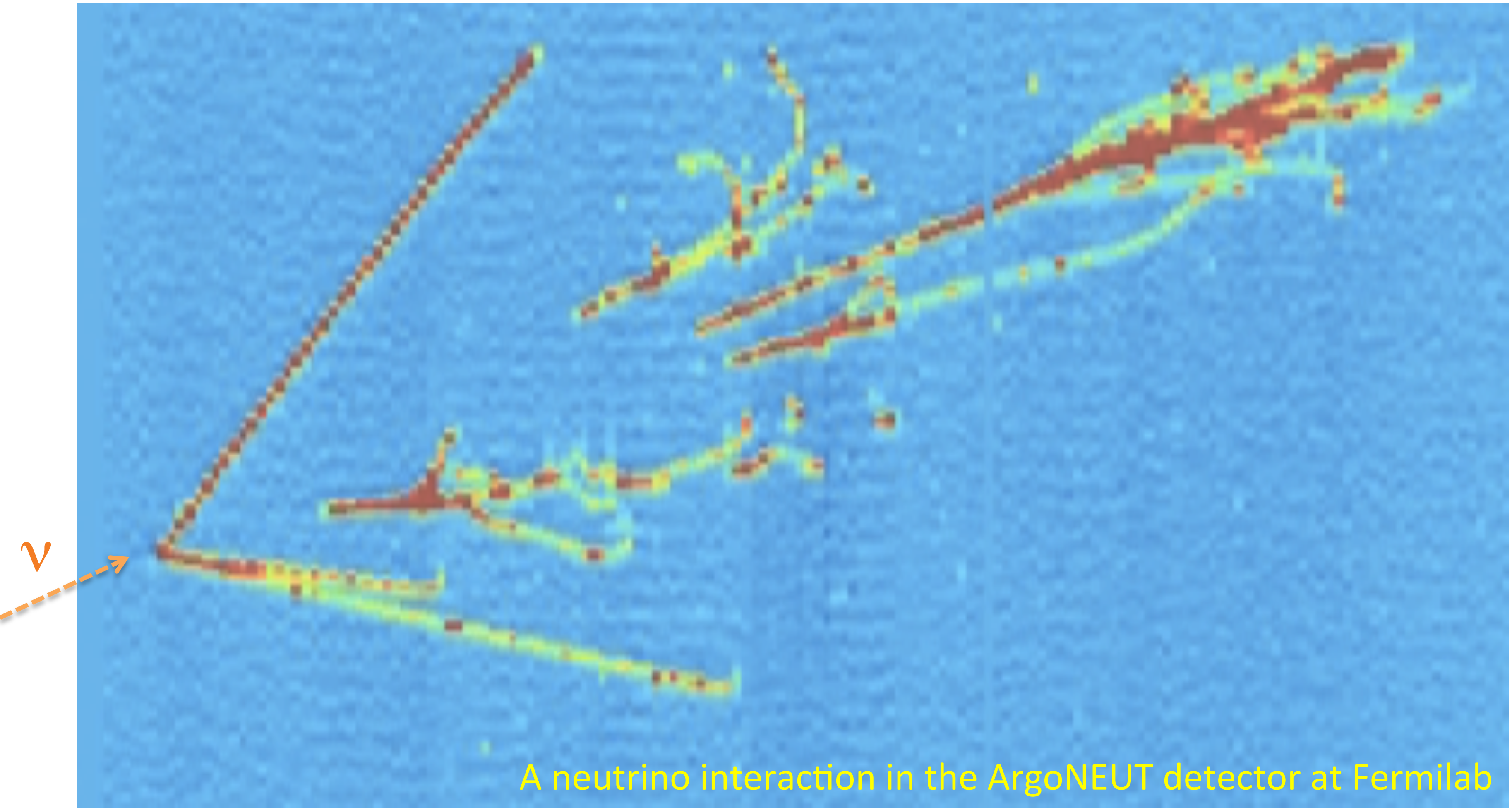
- Calorimetry to tag electrons/ gammas using dE/dx before EM shower evolves





5. DUNE Science

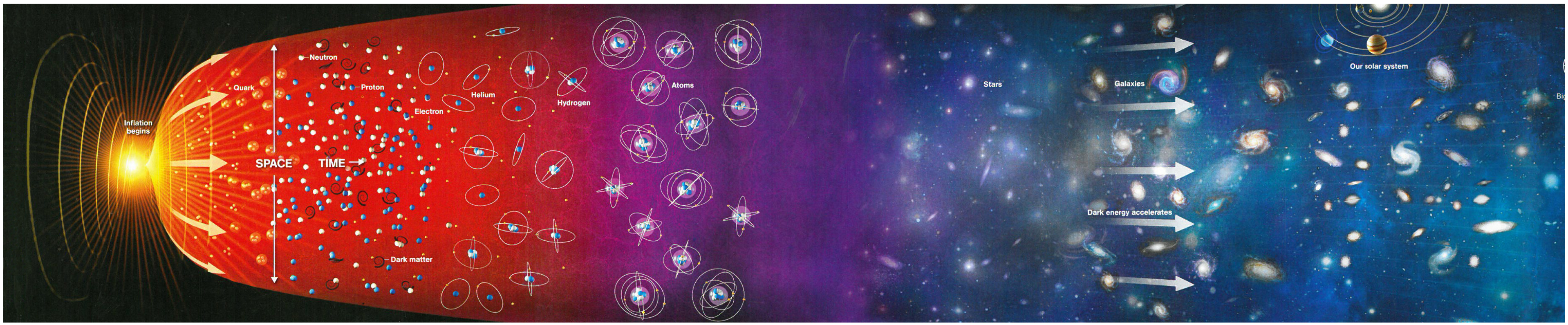
Unprecedented precision utilizing a massive Liquid Argon TPC



DUNE Science

DUNE will address big questions in science, e.g.

- **The matter-antimatter asymmetry in the Universe**

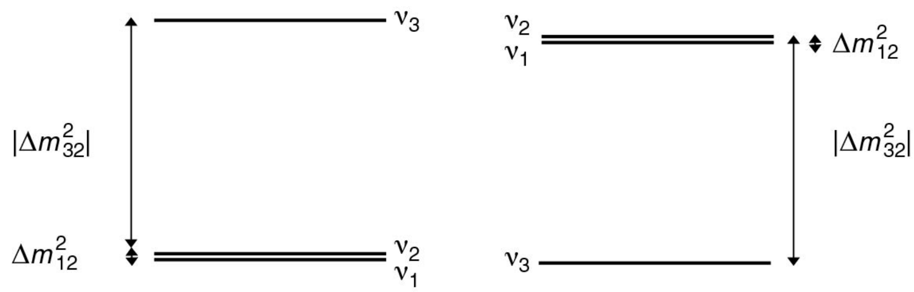


- **Big Bang: matter & antimatter created in equal amounts**
  - As Universe cools down matter and antimatter then annihilate
  - All things being equal, no matter/antimatter remains, just light
  - This is not what happened – there is matter left in the Universe
    - ⇨ Fundamental difference between matter and antimatter
    - ⇨ CP symmetry violation **(CPV)**
  - Neutrinos: key to our current best bet for how this happened "leptogenesis"

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, $p \to K^+\bar{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

DUNE Primary Science Program

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

- **1) Neutrino Oscillation Physics**
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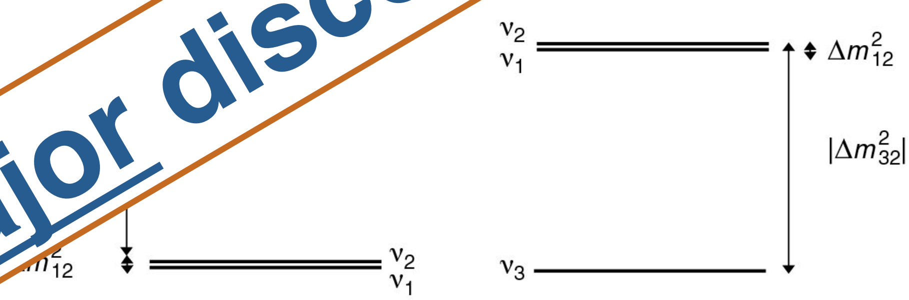
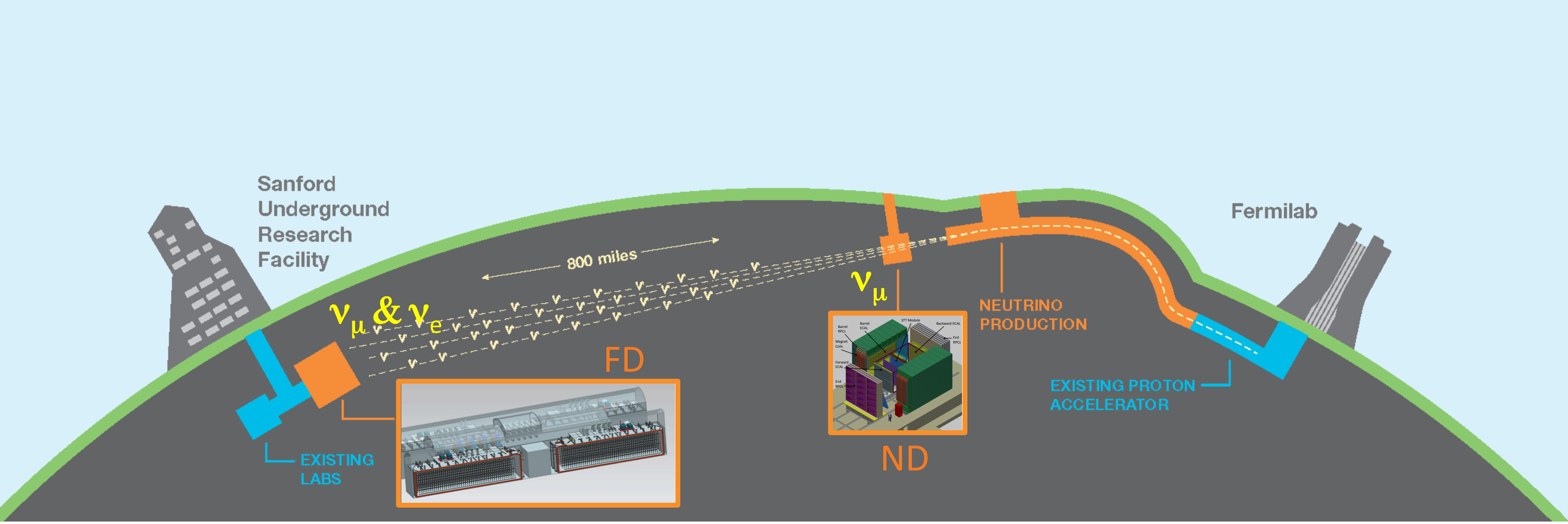


All would be major discoveries

Long Baseline (LBL) Oscillations

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

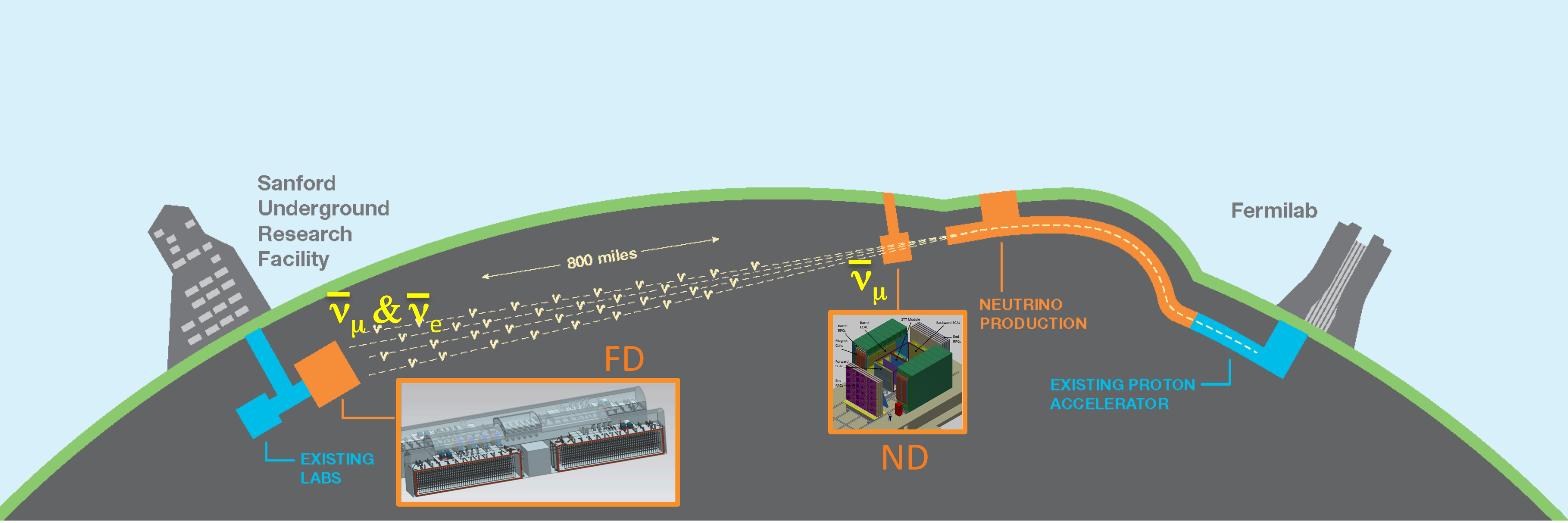


- **Near Detector at Fermilab: measurements of ν_μ unoscillated beam**
- **Far Detector at SURF: measure oscillated ν_μ & ν_e neutrino spectra**

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

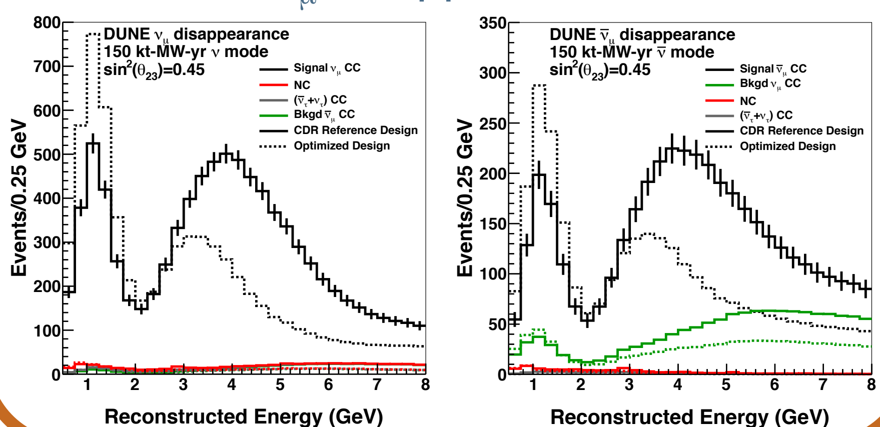
DUNE Oscillation Strategy

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

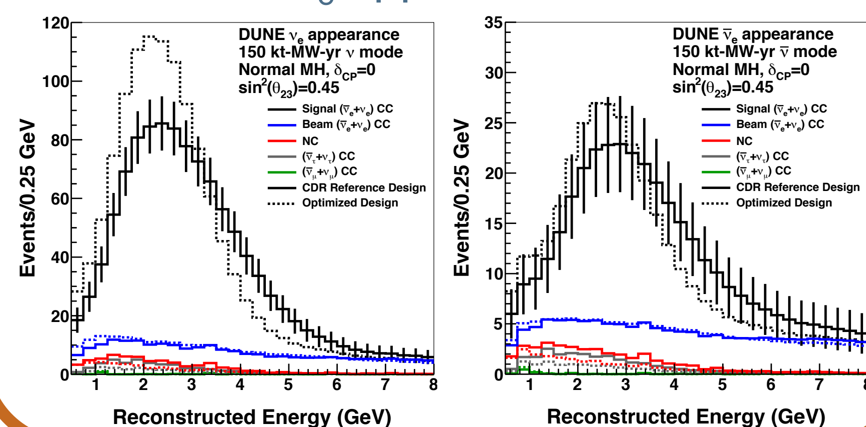
- Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for BSM effects (e.g. NSI) **in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects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

E ~ few GeV

ν_μ disappearance



ν_e appearance



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

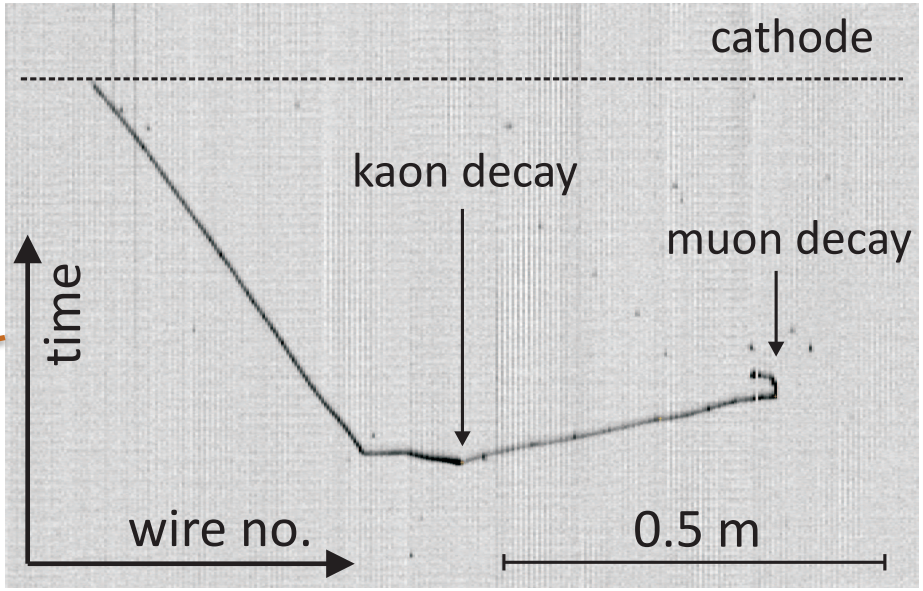
★ **Genuine potential for early physics discovery**

Proton Decay

Proton decay is expected in most new physics models

- But lifetime is very long $\tau > 10^{33}$ 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)



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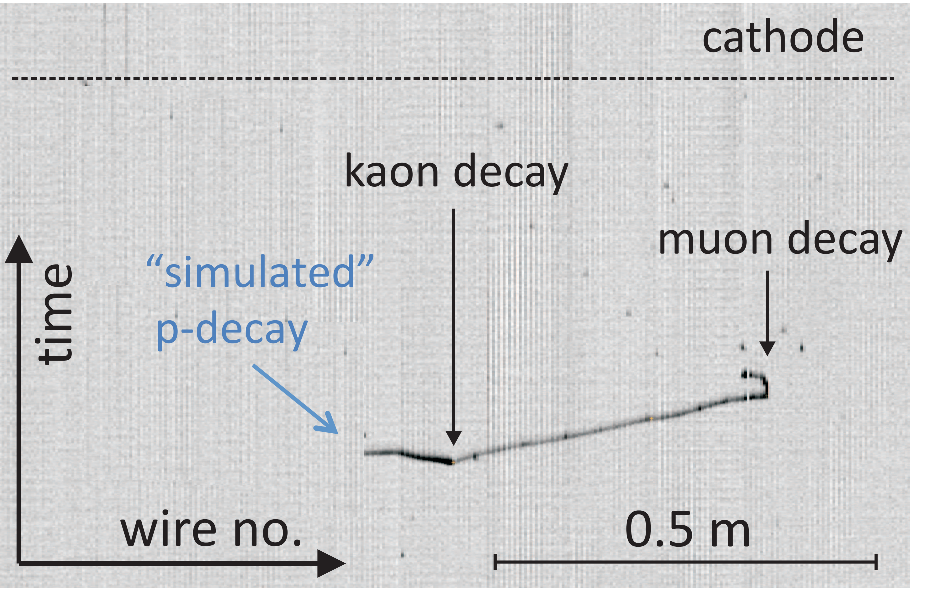
Remove incoming cosmic ray



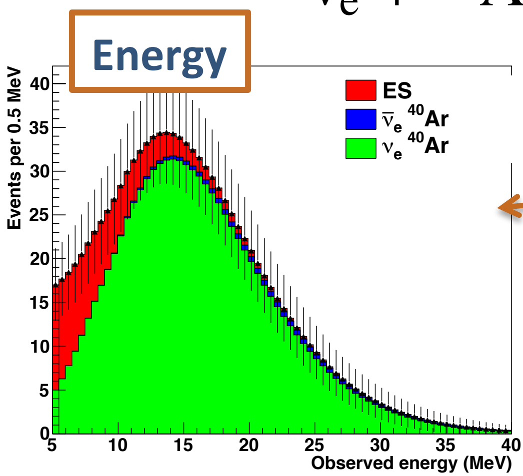
E ~ O(200 MeV)

Supernova νs

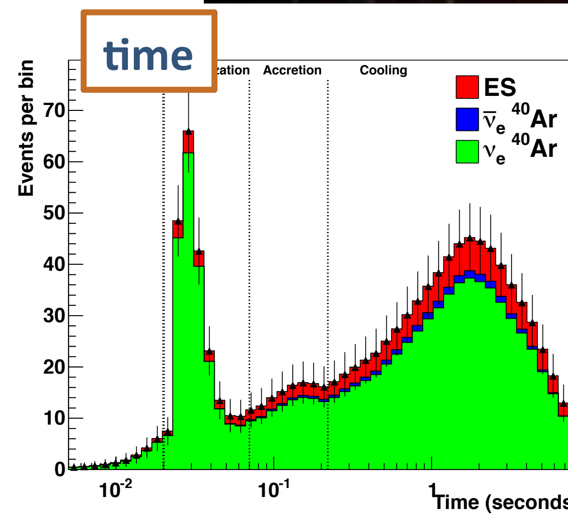
A core collapse supernova produces an incredibly intense burst of neutrinos

- Trigger on and measure energy 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:

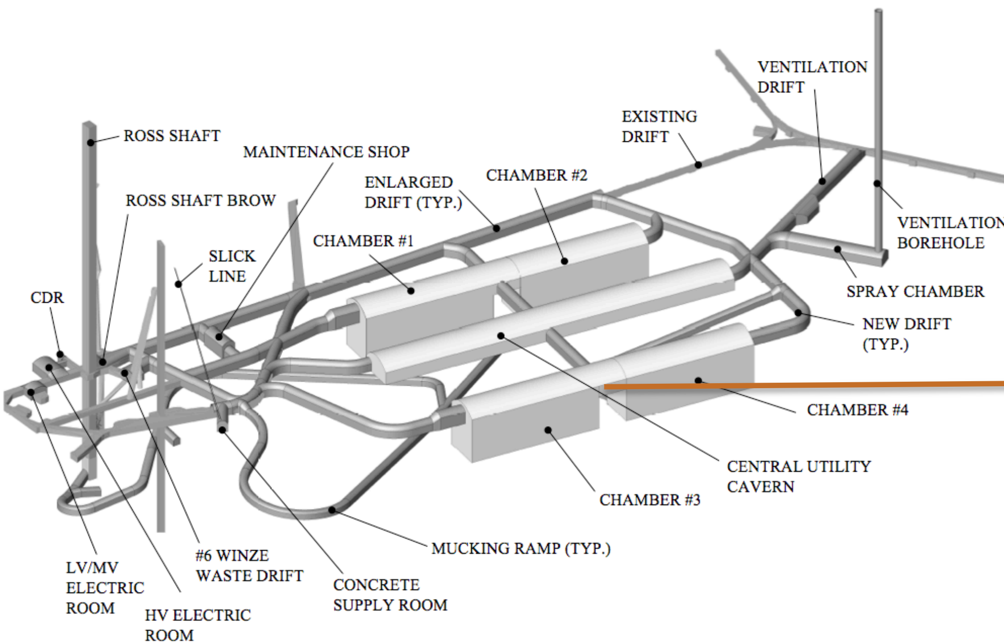
- Possibility to "see" neutron star formation stage
- Even the potential to see black hole formation !

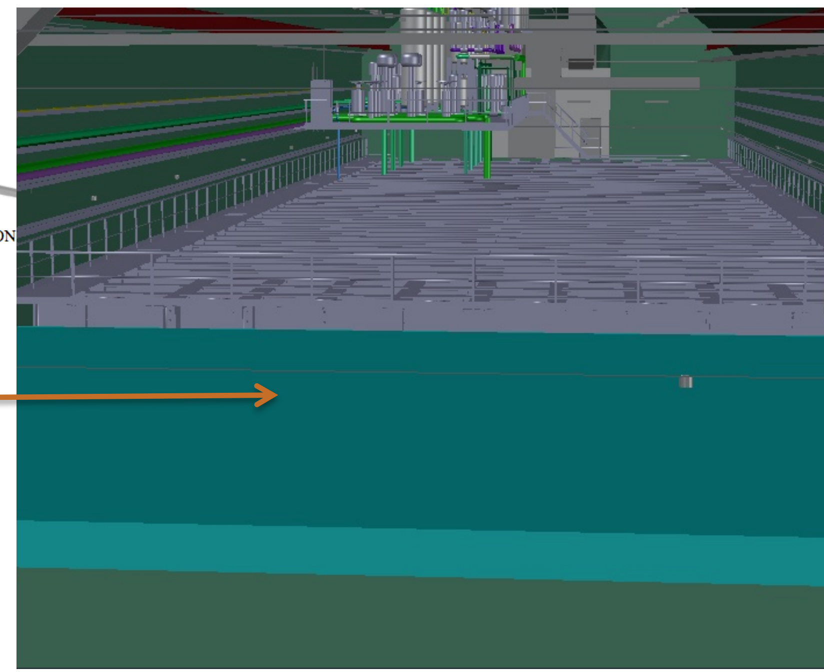
DUNE Science Summary

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)

6. The LBNF/DUNE Project





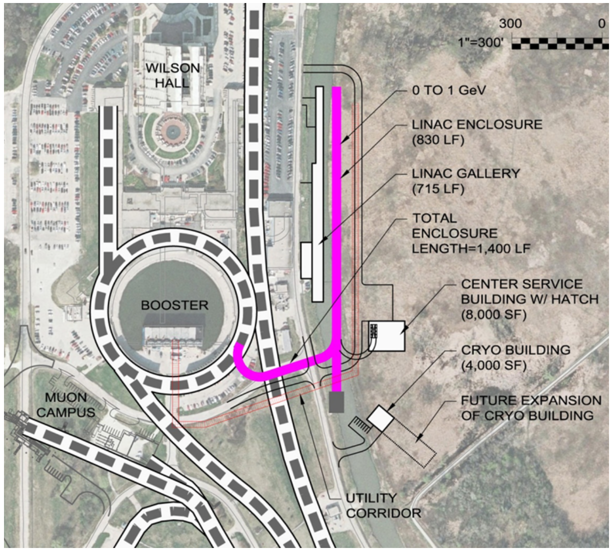
LBNF – a MW-scale facility

LBNF and PIP-II

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

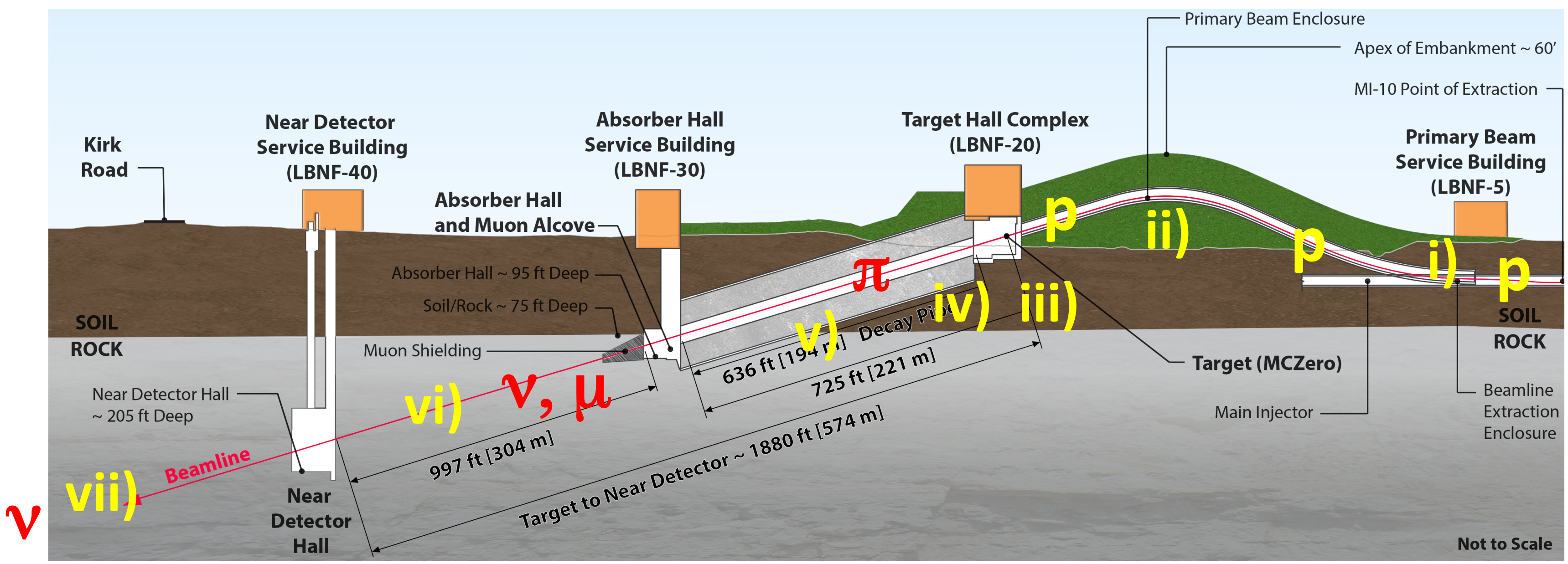
- ★ **LBNF will be the world's most intense high-energy ν beam**
  - **1.2 MW from day one**
    - NuMI (MINOS) <400 kW
    - NuMI (NOVA) ultimately ~700 kW
  - **upgradable to 2.4 MW**

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

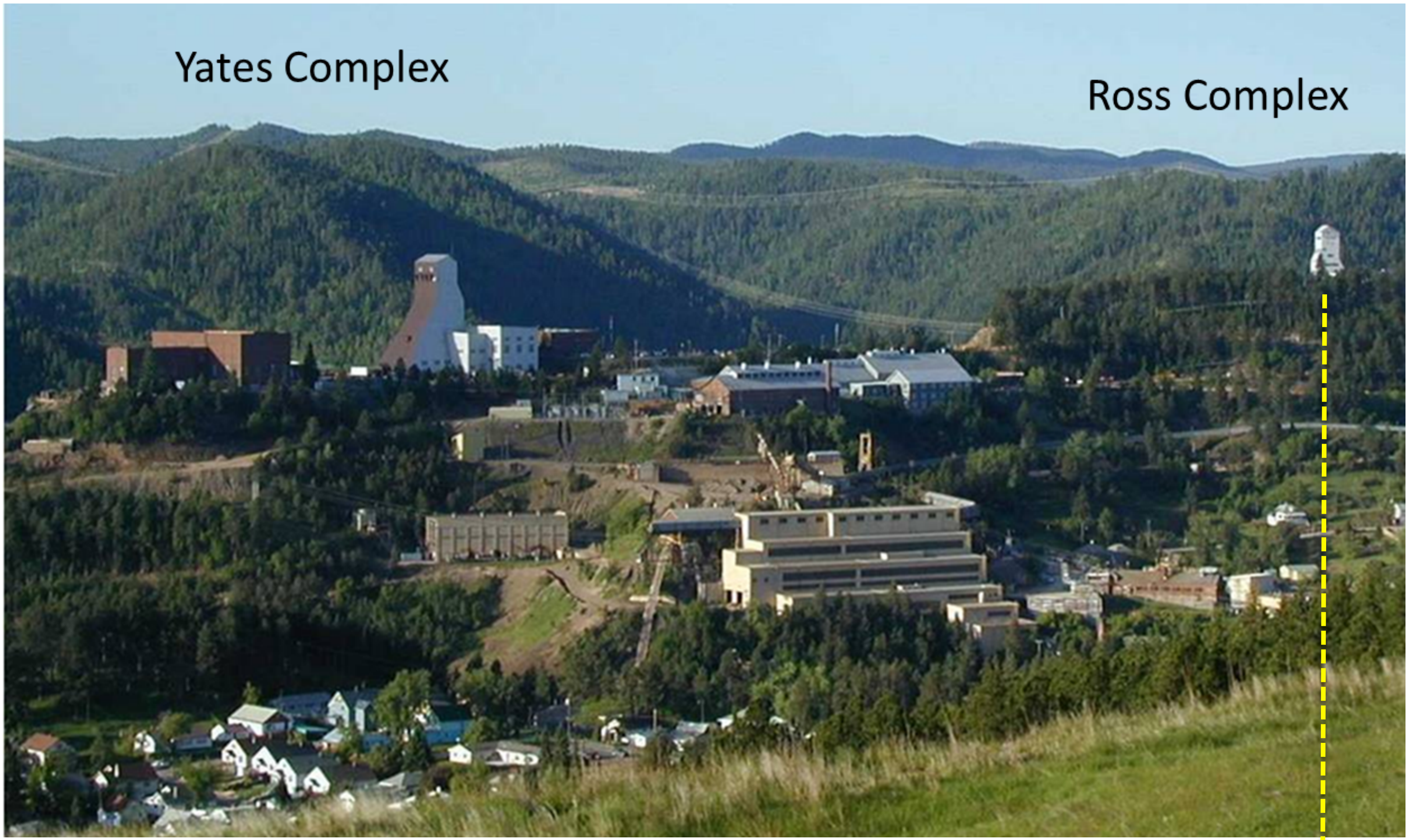


The LBNF Neutrino Beam

- 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

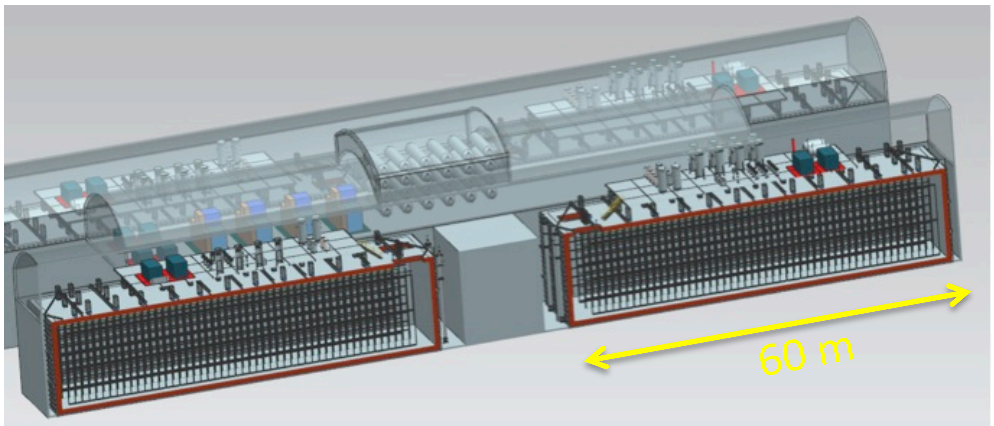


The DUNE Far Detector



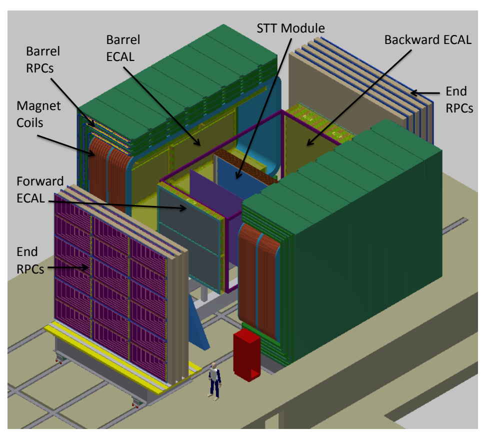
DUNE Design =

Far detector: 40-kt LAr-TPC



For more details refer to DUNE CDR

Near detector: Multi-purpose high-resolution detector



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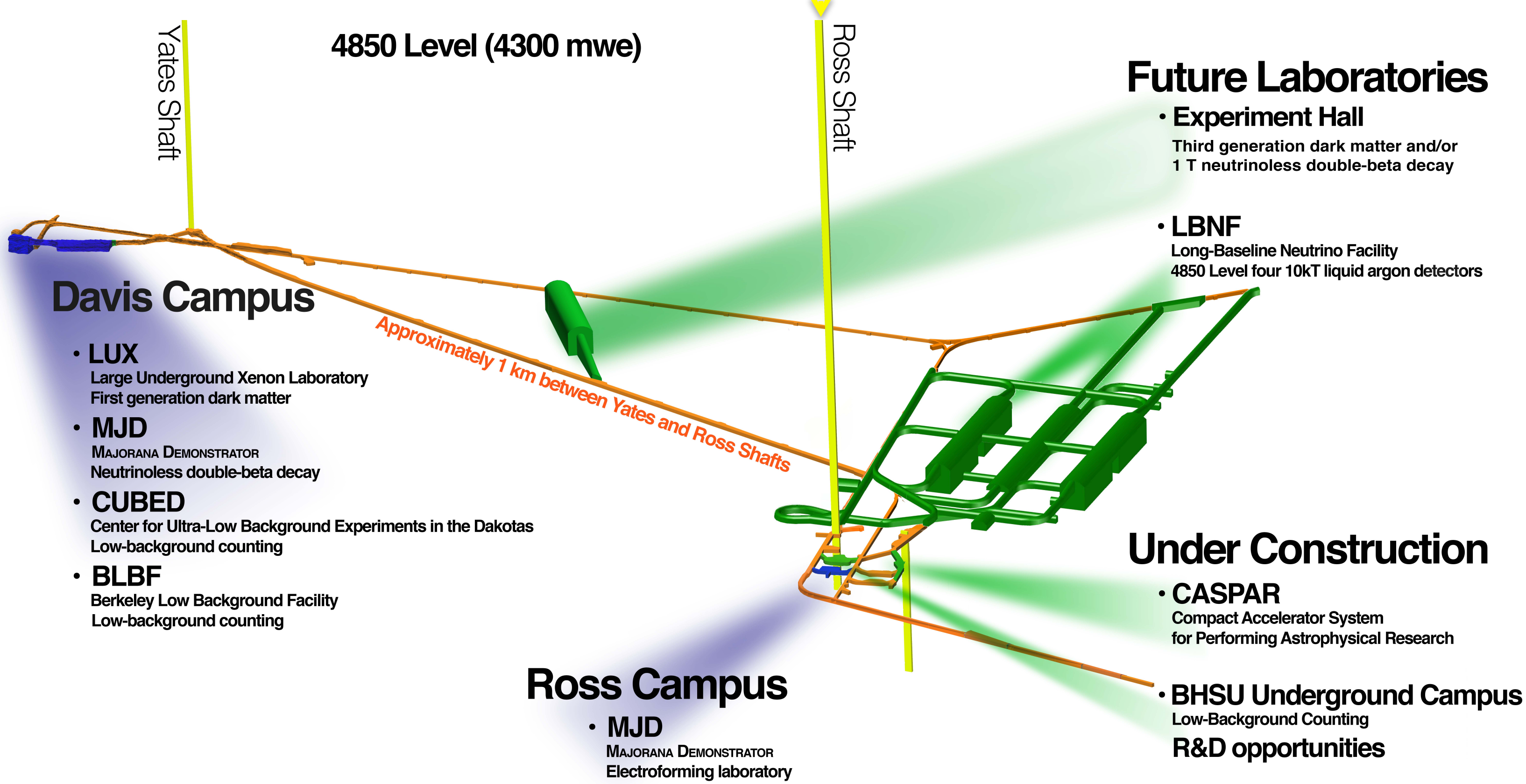
The Far Site

DUNE Far Detector site

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



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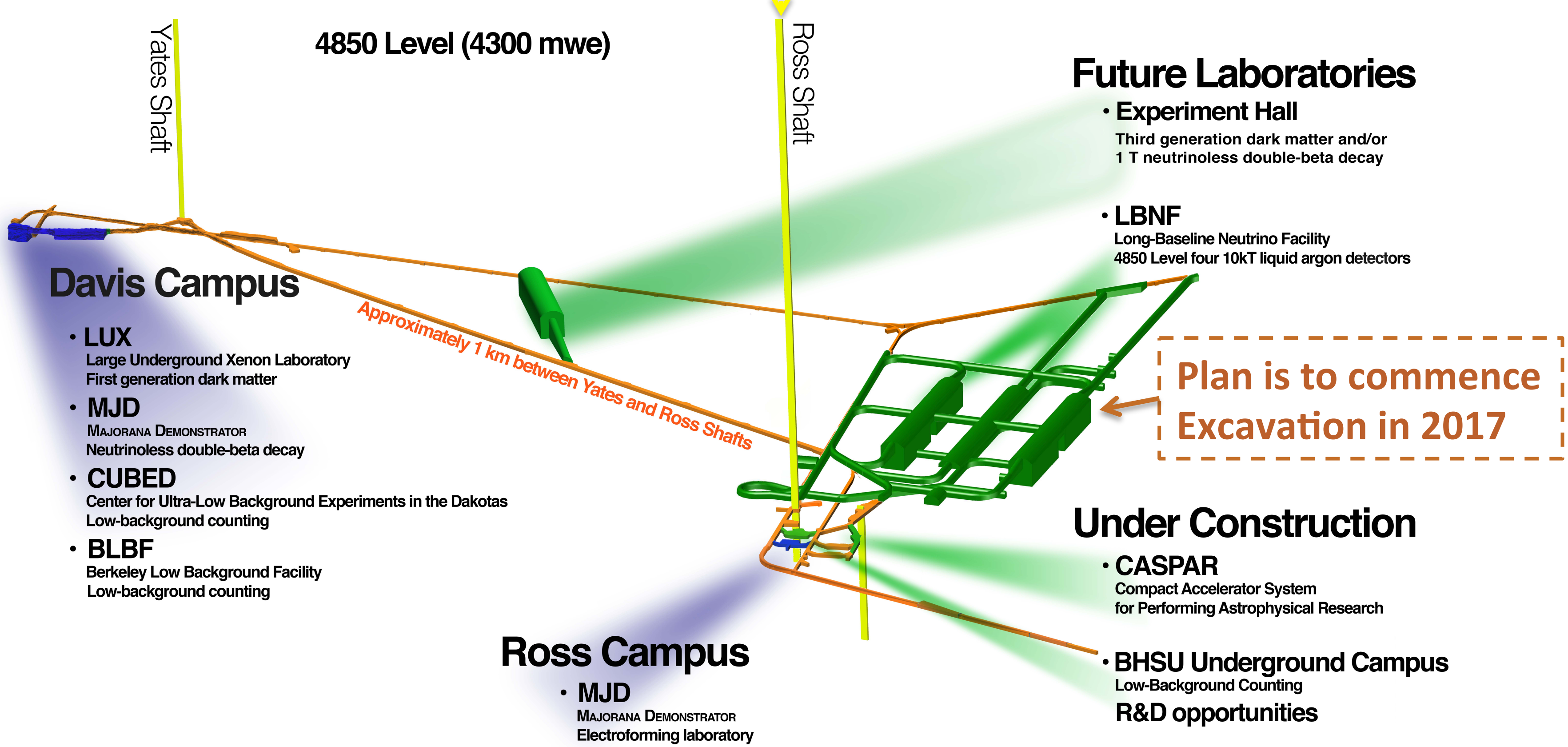
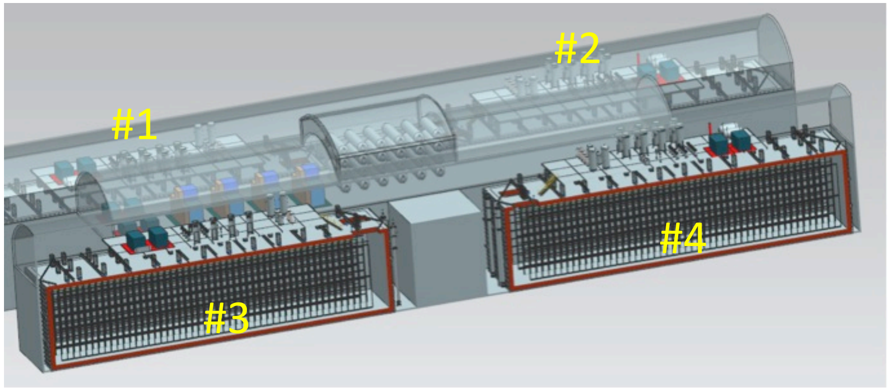


Staged Approach to 40 kt

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

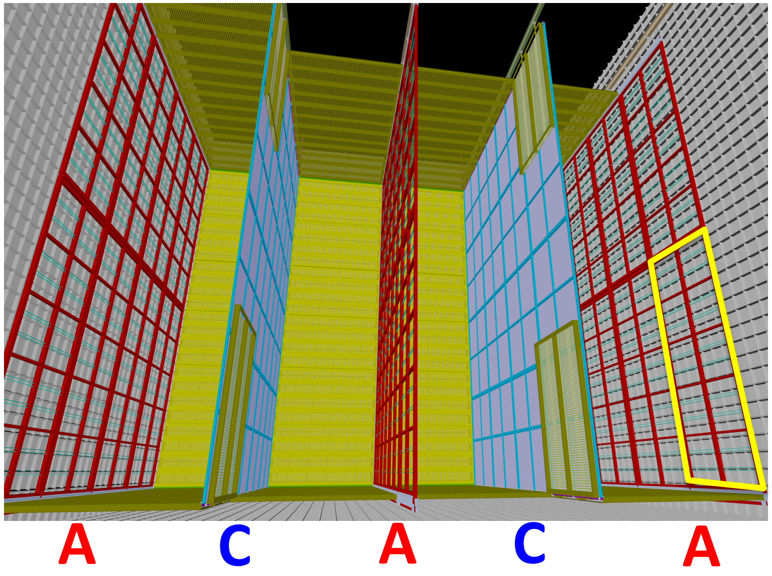
- **Four identical caverns hosting four independent 10-kt FD modules**
  - Allows for staged construction of FD
  - Gives flexibility for evolution of LArTPC technology design
    - Assume four identical cryostats
    - But, assume that the four 10-kt modules will be similar but **not necessarily identical**

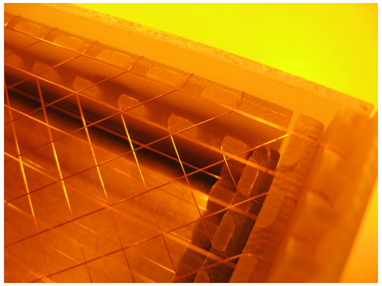


First 10 kt detector

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
  - All inside a large Membrane Cryostat





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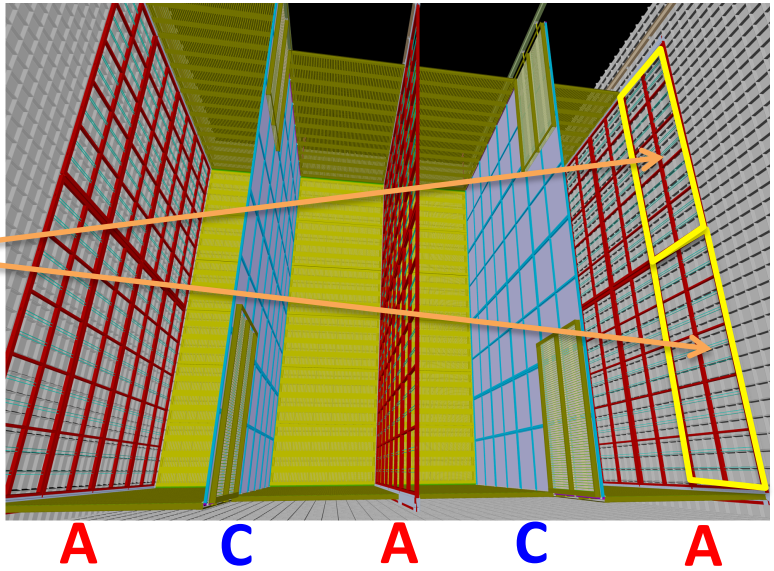
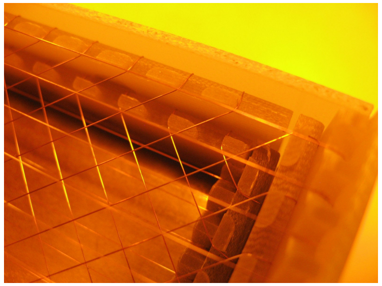
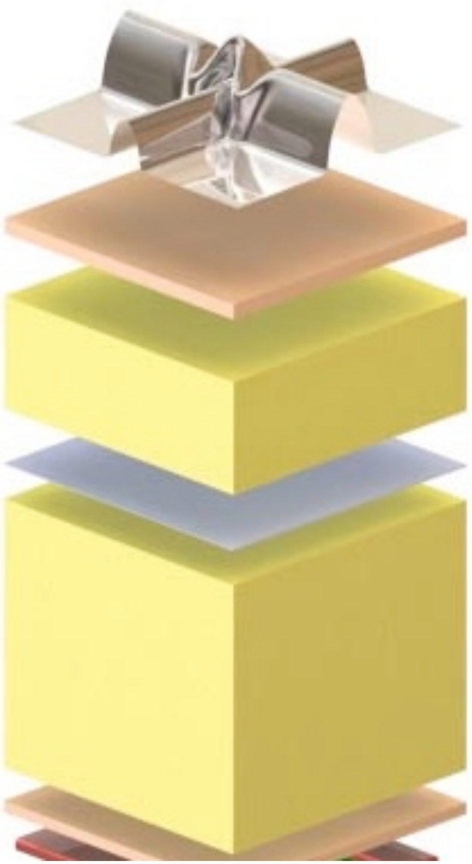


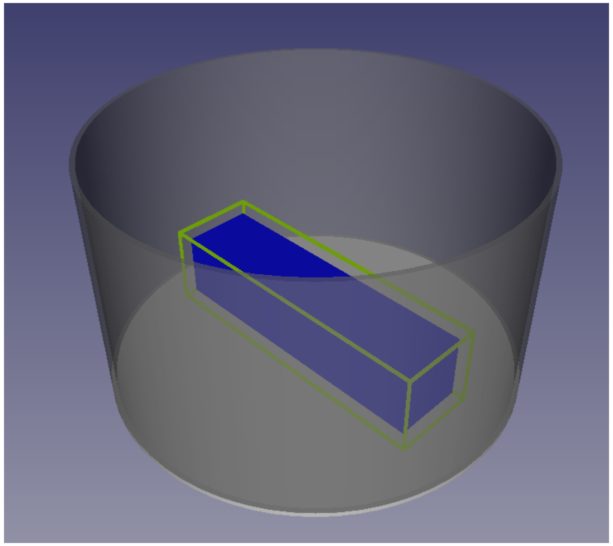


Membrane Cryostats

Standard technology in liquid natural gas industry



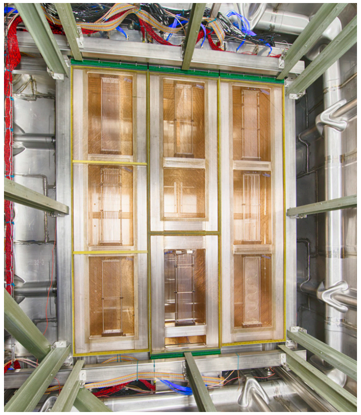
- Whole 10kt Cryostat would fit inside a 200,000 m^3 LNG storage tank



Far Detector Development

Single-phase APA/CPA LAr-TPC:

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



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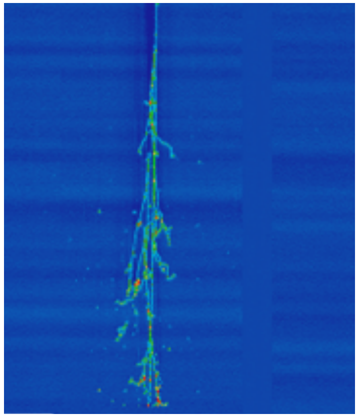

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  - 35-t prototype (operational in 2015)
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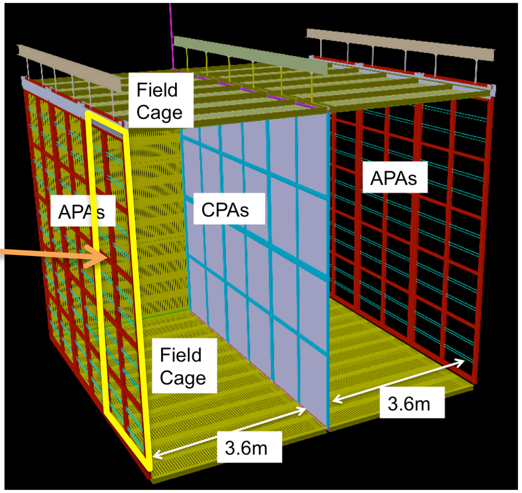
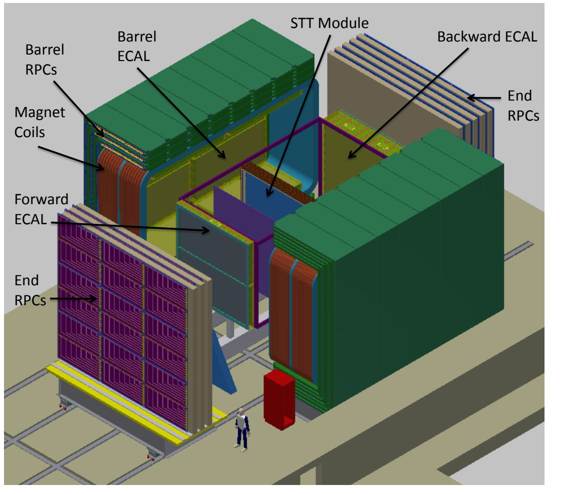
- **"Full-scale prototype" with ProtoDUNE at the CERN Neutrino Platform**
  - **Engineering prototype**
    - 6 full-sized drift cells c.f. 150 in the far det.
  - Approved by CERN SPSC (Oct. 2015)
  - Aiming for operation in 2018



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

7. The DUNE Collaboration

DUNE and P5 (US HEP Strategy)

Paraphrasing P5

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

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

- LBNE
- LBNO
- Other interested institutes

DUNE

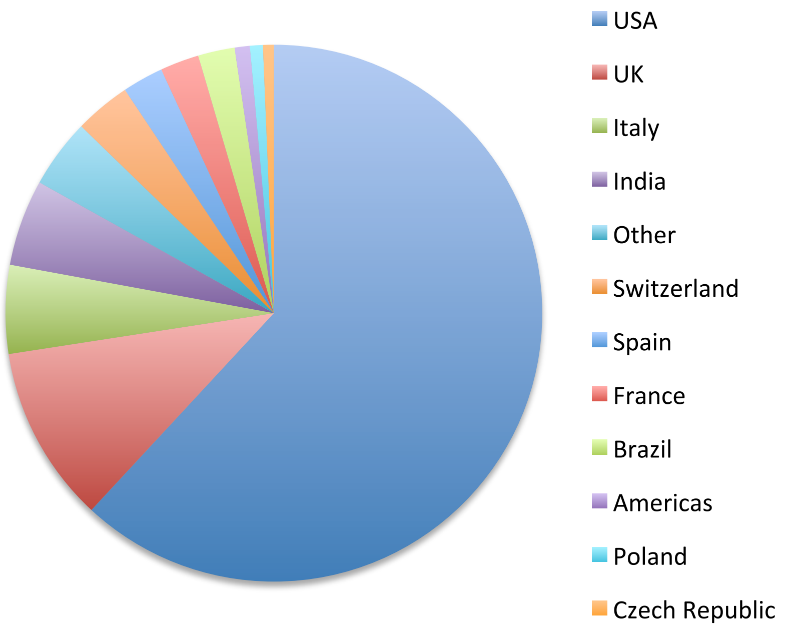
is a rapidly evolving scientific collaboration…

- **First formal collaboration meeting April 16th - 18th 2015**
- **Conceptual Design Report in June**
- **Passed DOE CD-1 Review in July**
- **Second collaboration meeting September 2nd - 5th 2015**
  - Over 220 people attended in person

The DUNE Collaboration

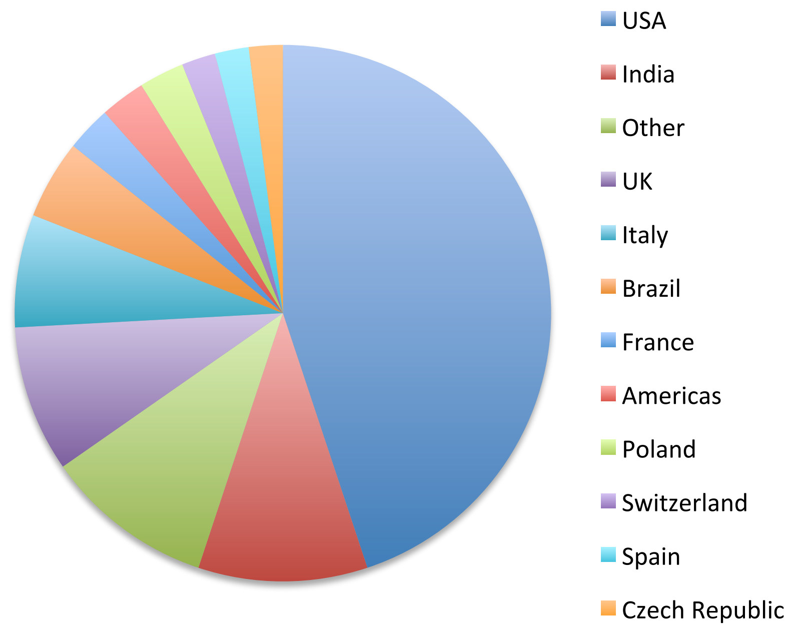
As of today:

803 Collaborators



from

145 Institutes



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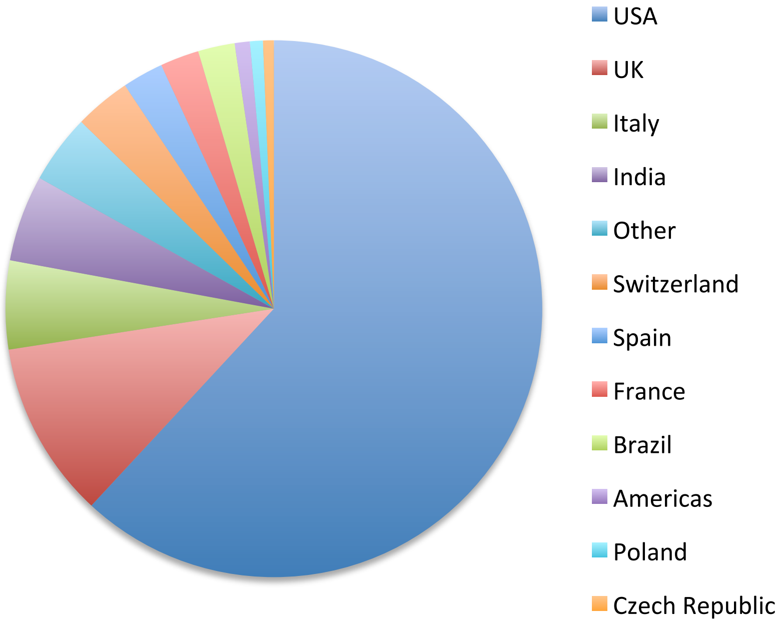

from

26 Nations

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

+ soon to add Finland

DUNE already has broad international support

8. 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 – seek 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

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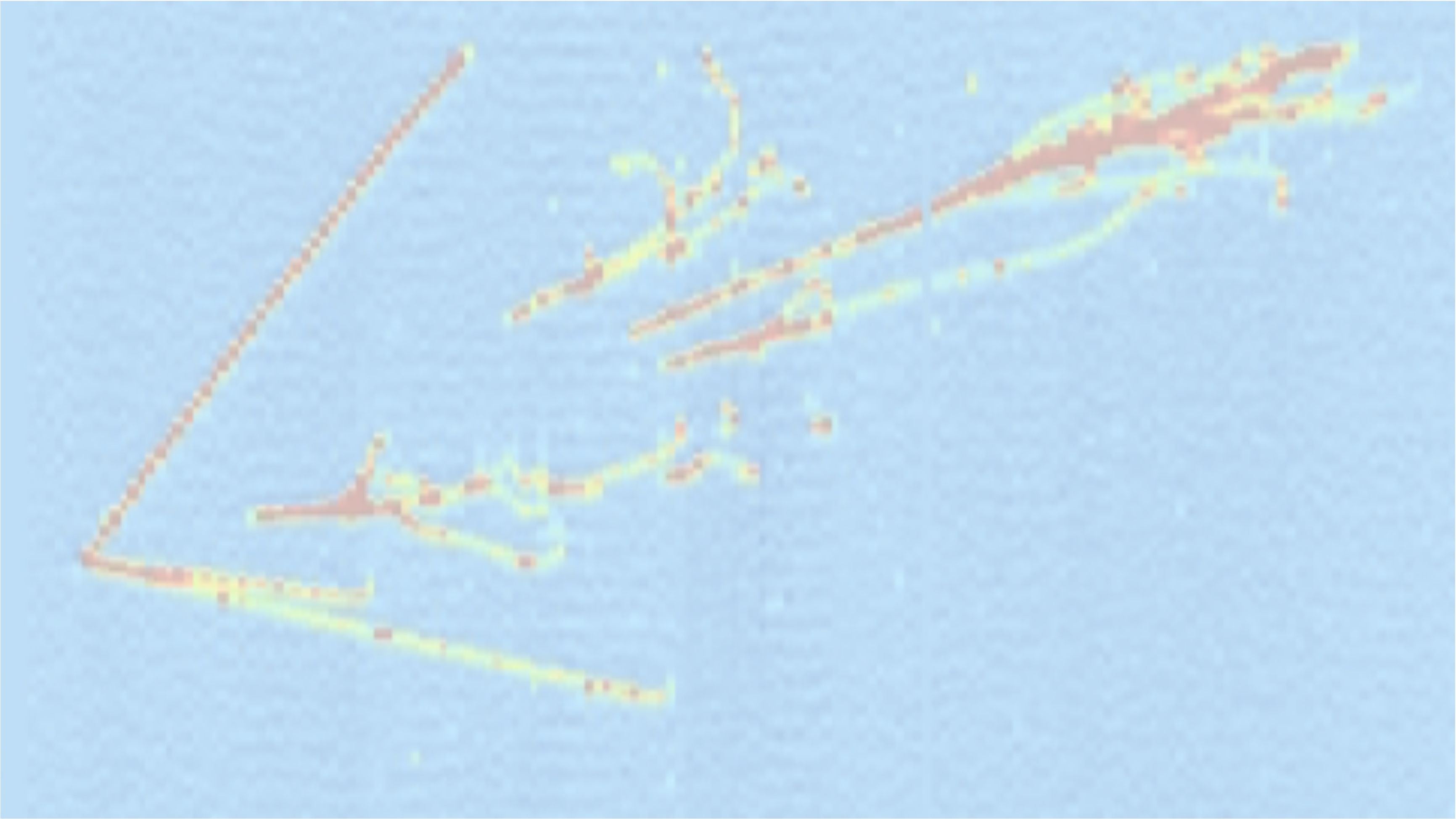
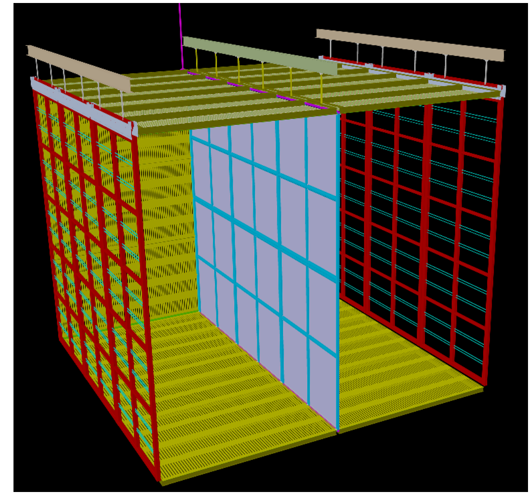
Every reason to be optimistic that we are on the verge of launching the next big thing in particle physics

9. Opportunities on DUNE



Opportunities in DUNE



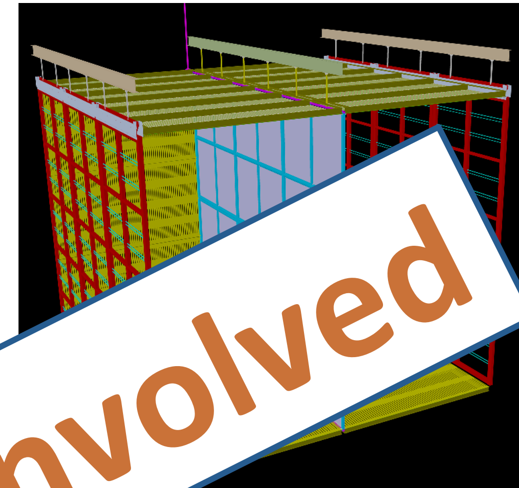
DUNE is moving rapidly

- 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



DUNE is moving rapidly

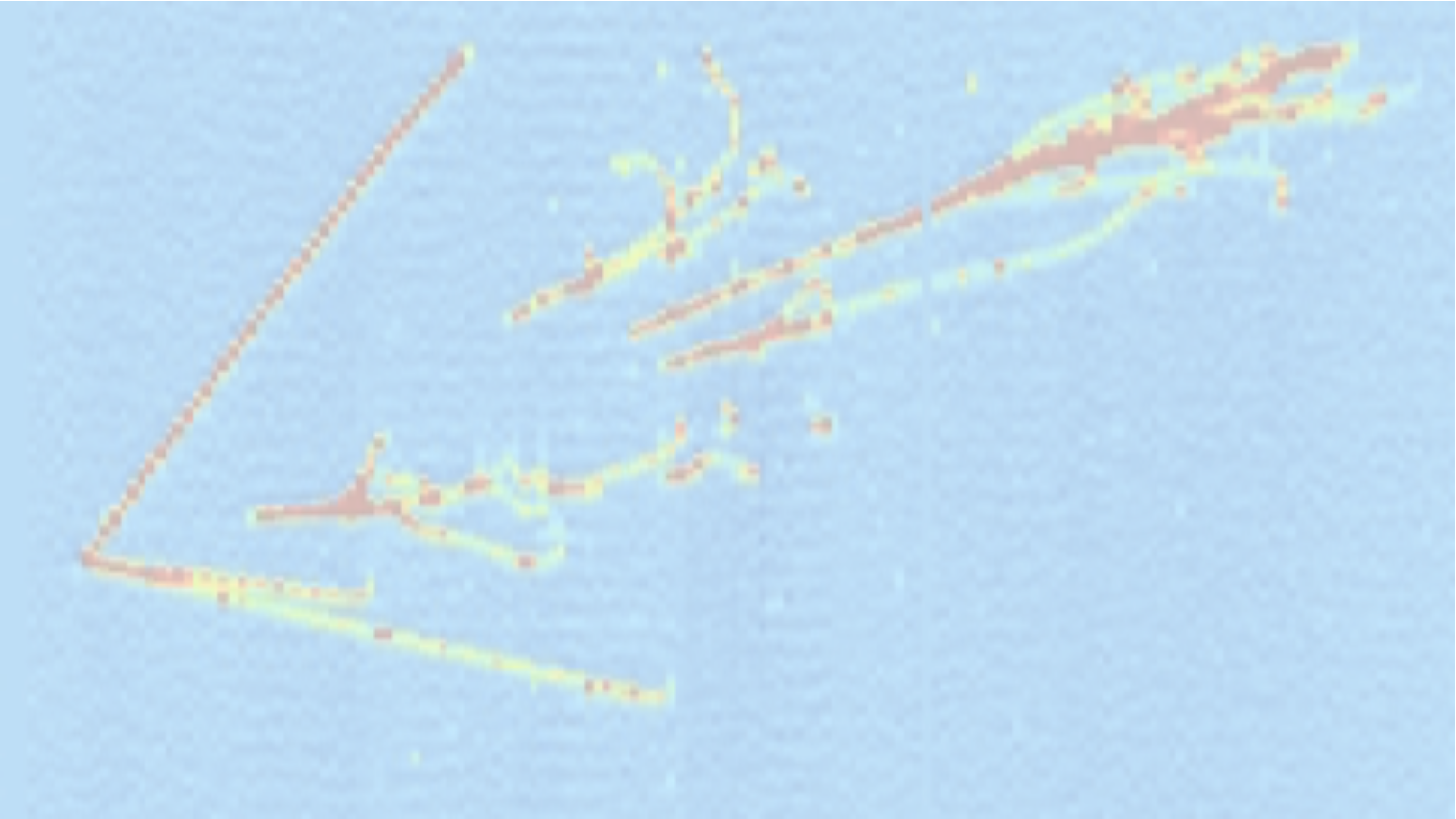
- Excavation starts in 2017
- ProtoDUNE @ CERN in 2018
- Far Detector construction in 2019
- Far Detector installation in 202…

DUNE: the next large glo… …sics project

- Actively seeking n… …s
  - many syne… …experiments
- Immedi… …ope will be ProtoDUNE @ CERN
- … …ies:
  - …e: e.g. photon detection system (scintillator + SiPMs)
  - …Q/Computing: continuous readout = high-data rates
  - Software: LAr-TPC reconstruction

Great time to get involved

10. Summary



Summary

★ **DUNE will**

- Probe CPV with unprecedented position
- Definitively determine the MH to greater than 5 σ
- 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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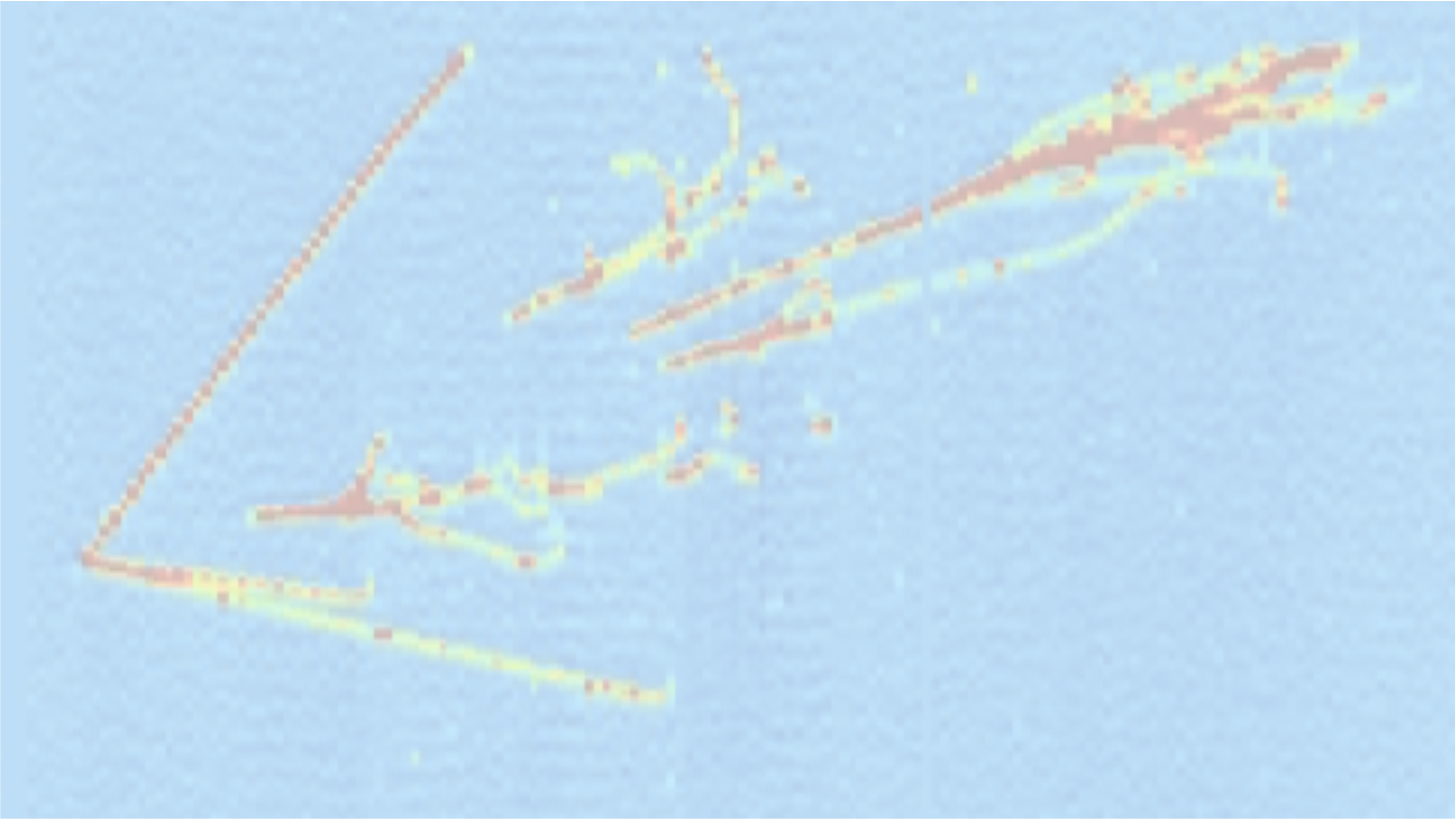
★ **An international community is forming – including CERN**

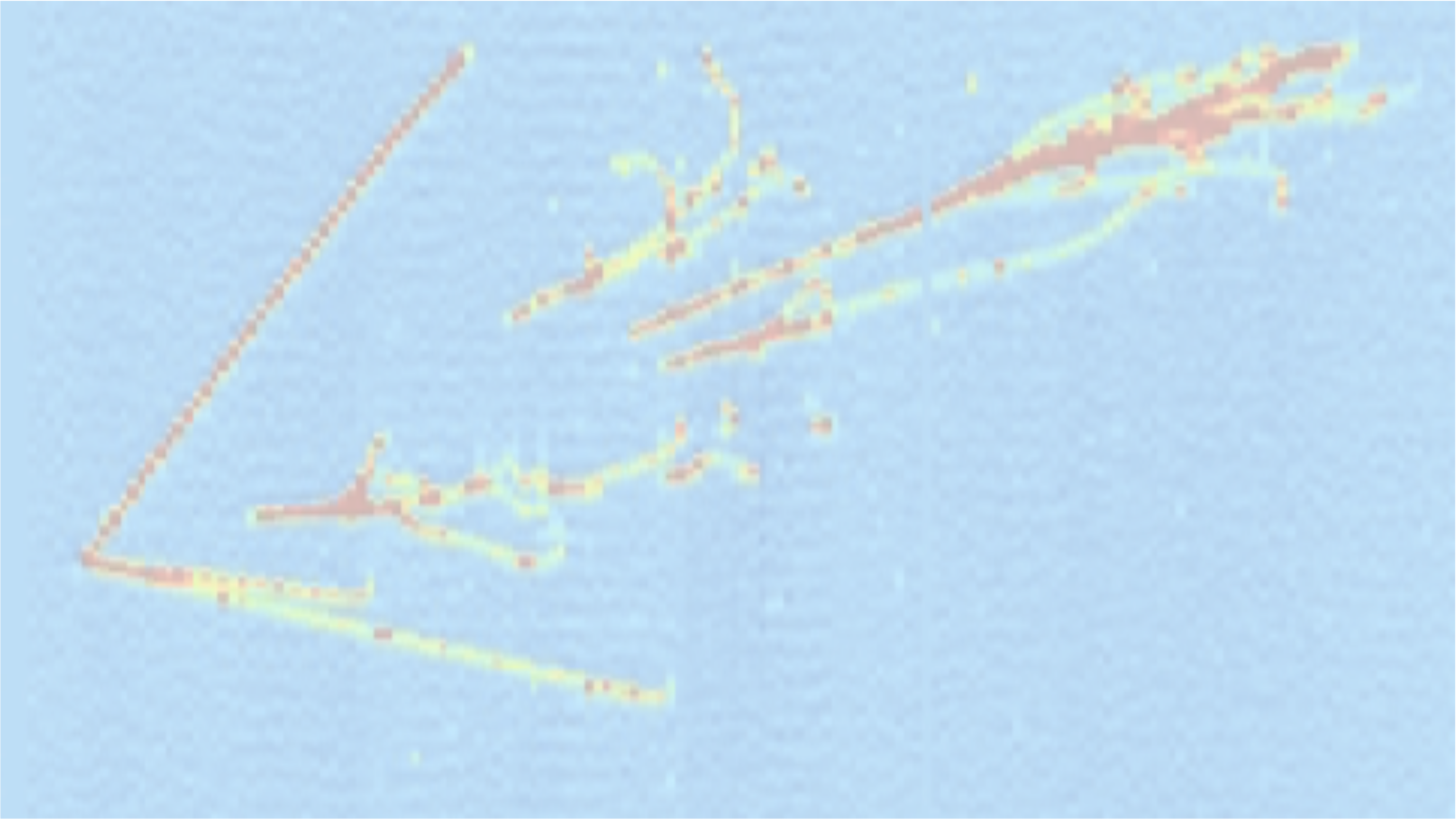
- LBNF/DUNE represents a **major** new scientific opportunity for particle physics

Thank you for your attention



Backup Slides

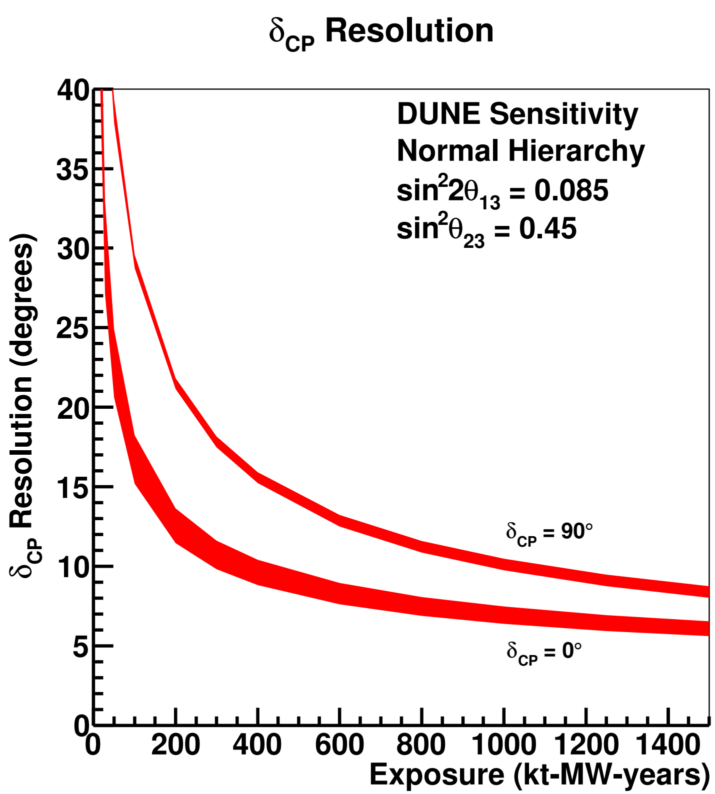
Science

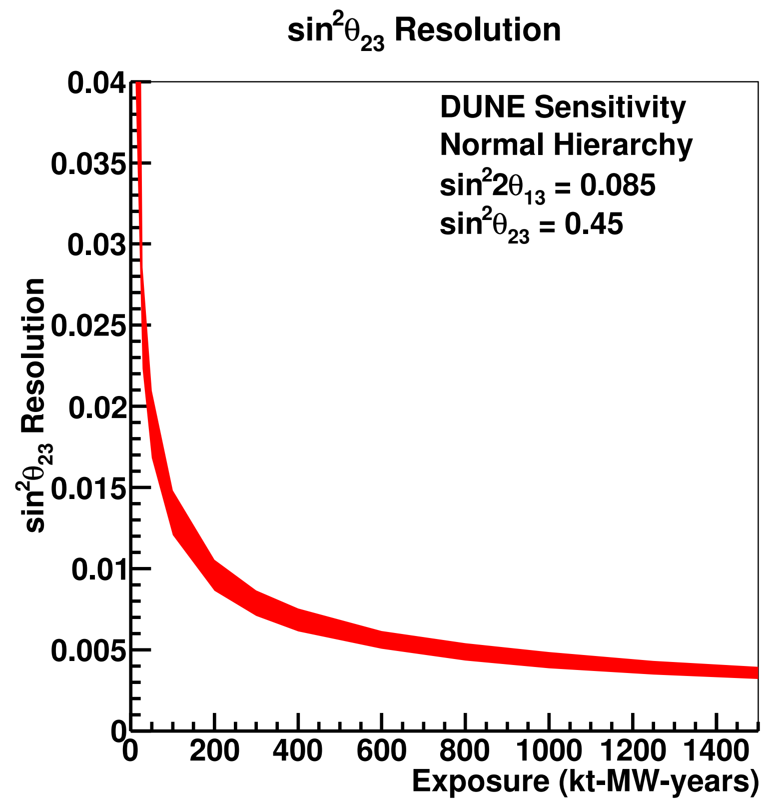


Parameter Resolutions

δ_{CP} & θ_{23}

- As a function of exposure

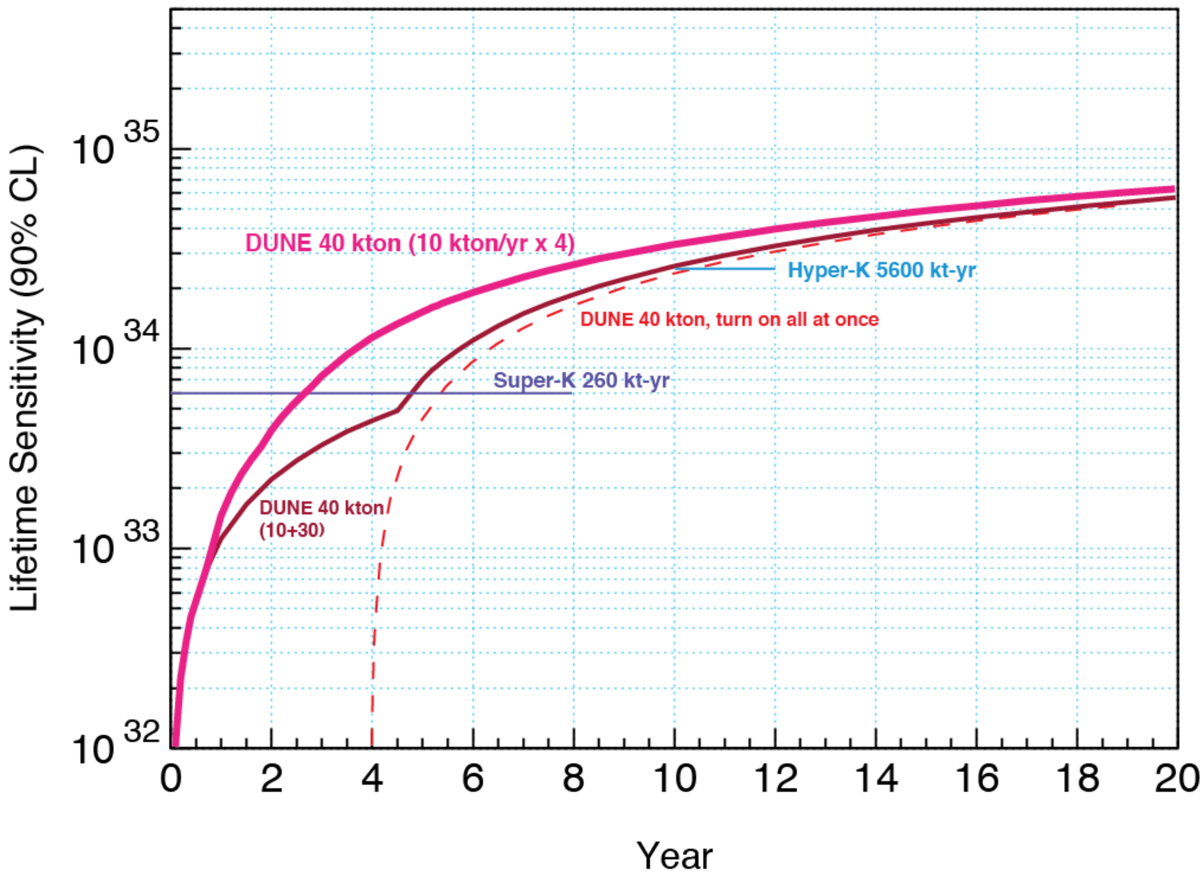




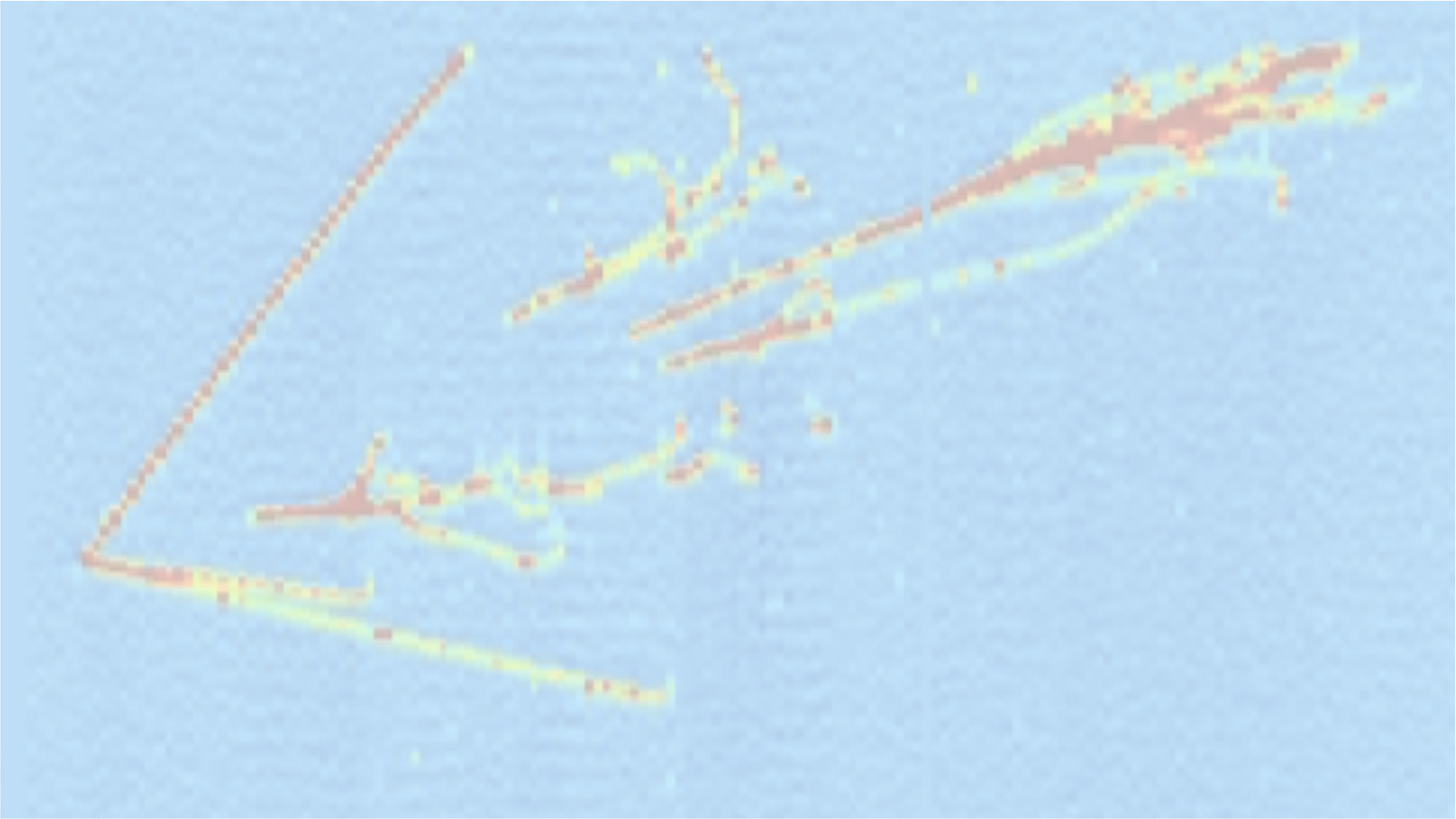
PDK

p → K ν

- DUNE for various staging assumptions

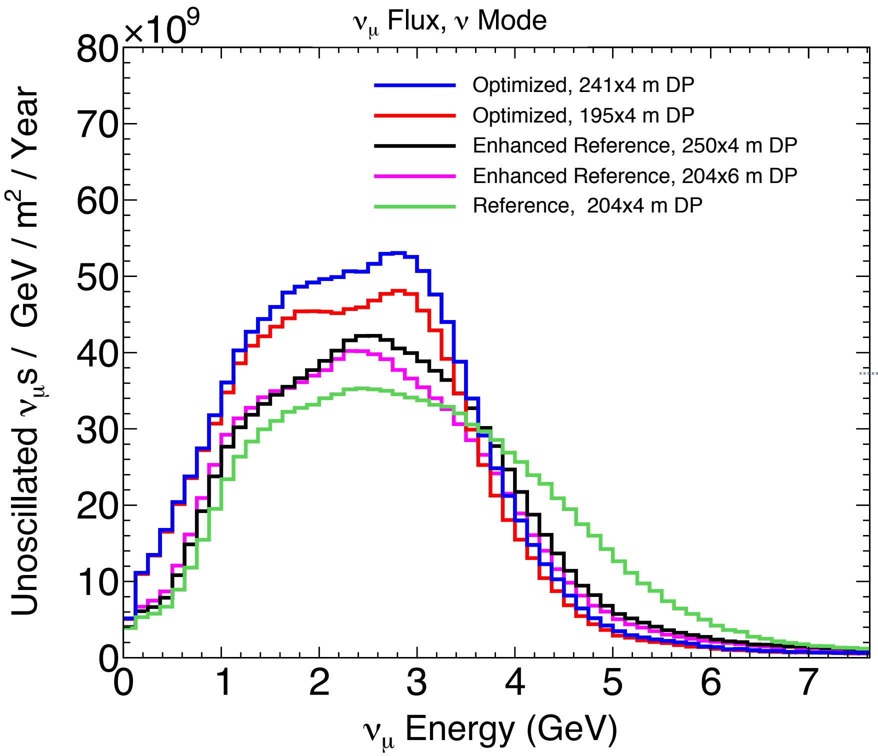


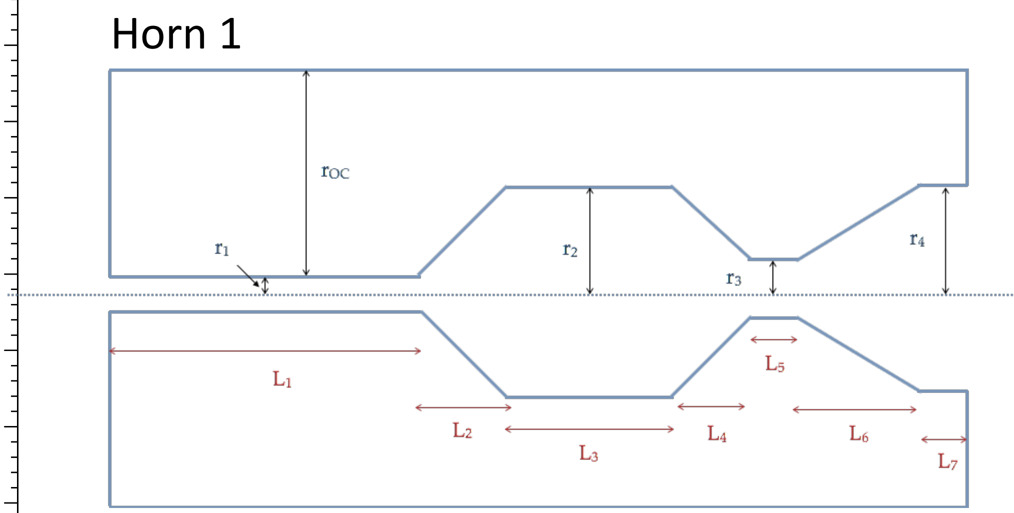
Beam Optimization



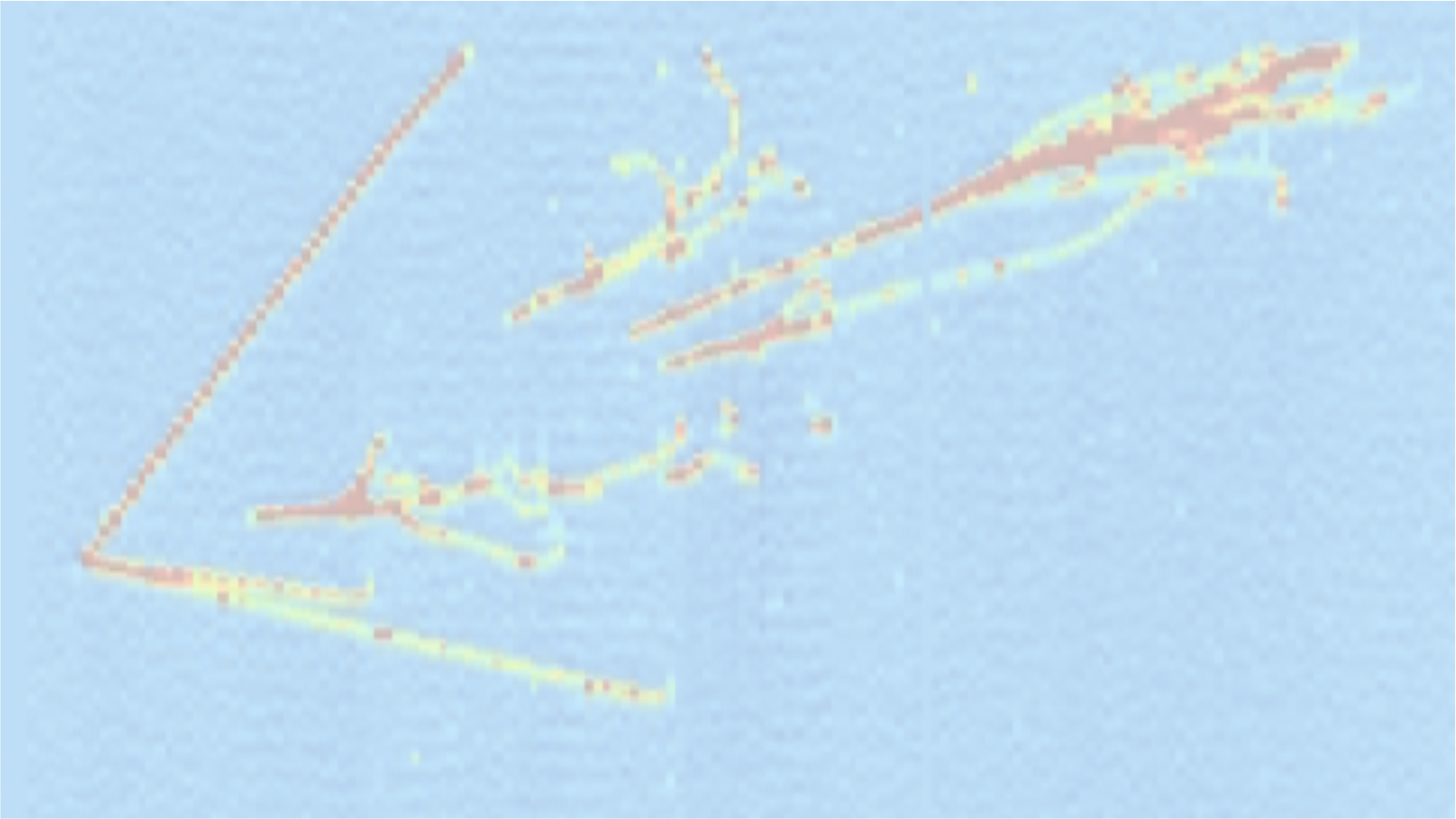
Beam Optimization

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





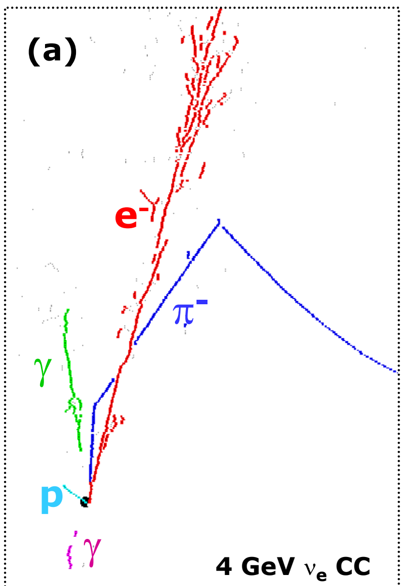
Reconstruction

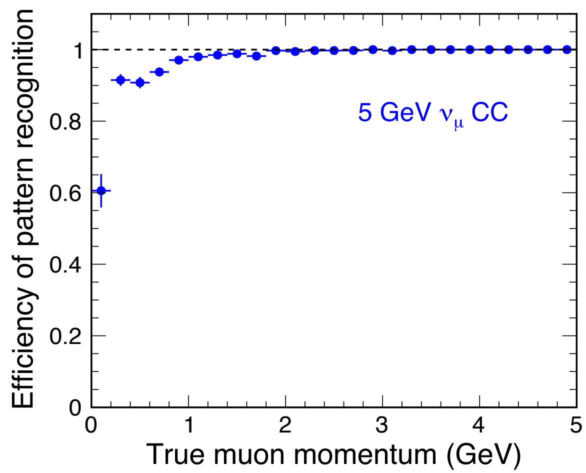


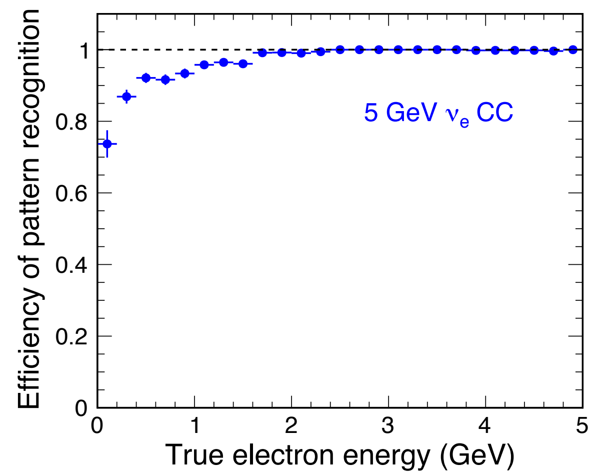
LAr-TPC Reconstruction

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

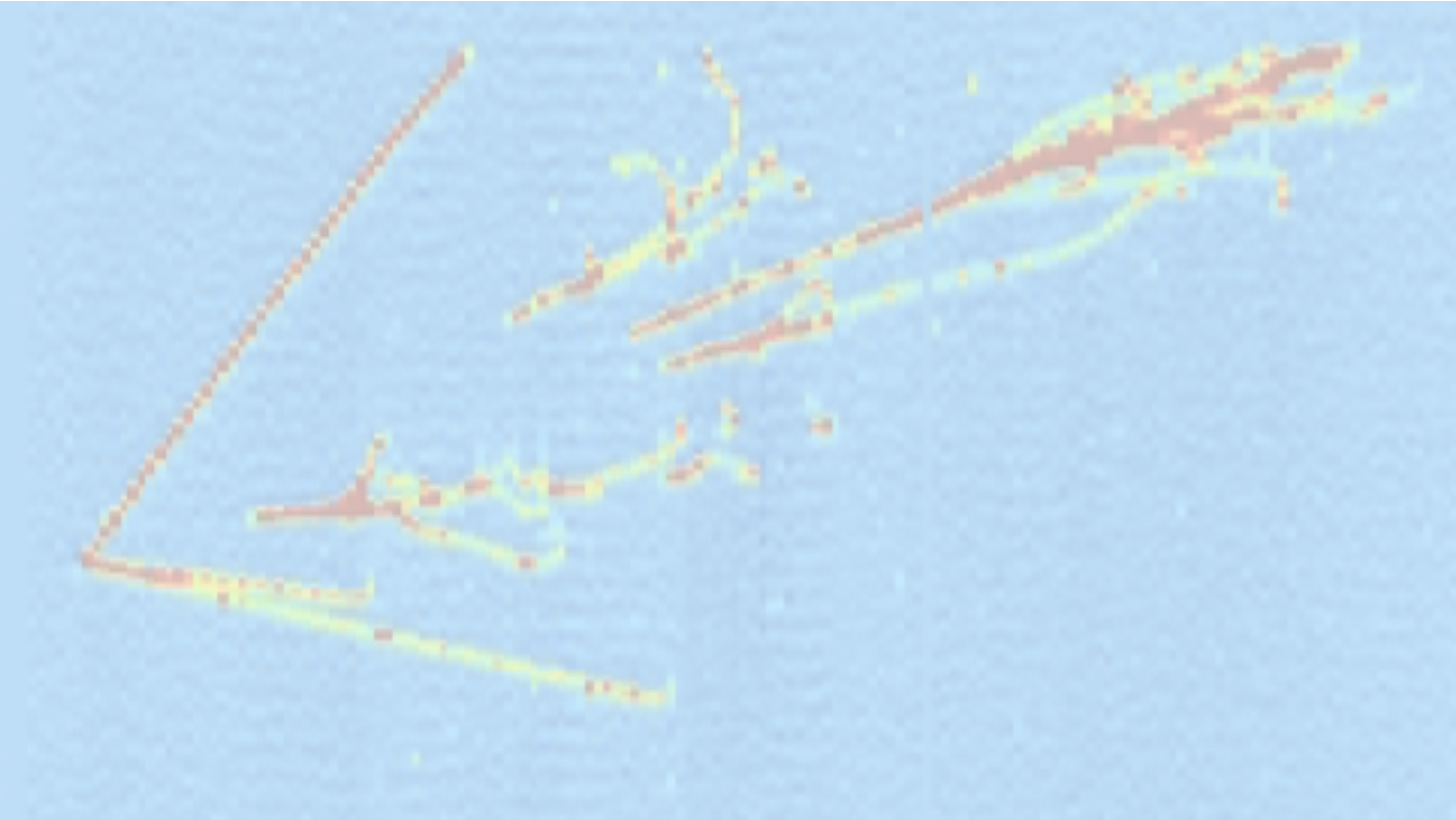
- Full DUNE simulation/reconstruction now in reach



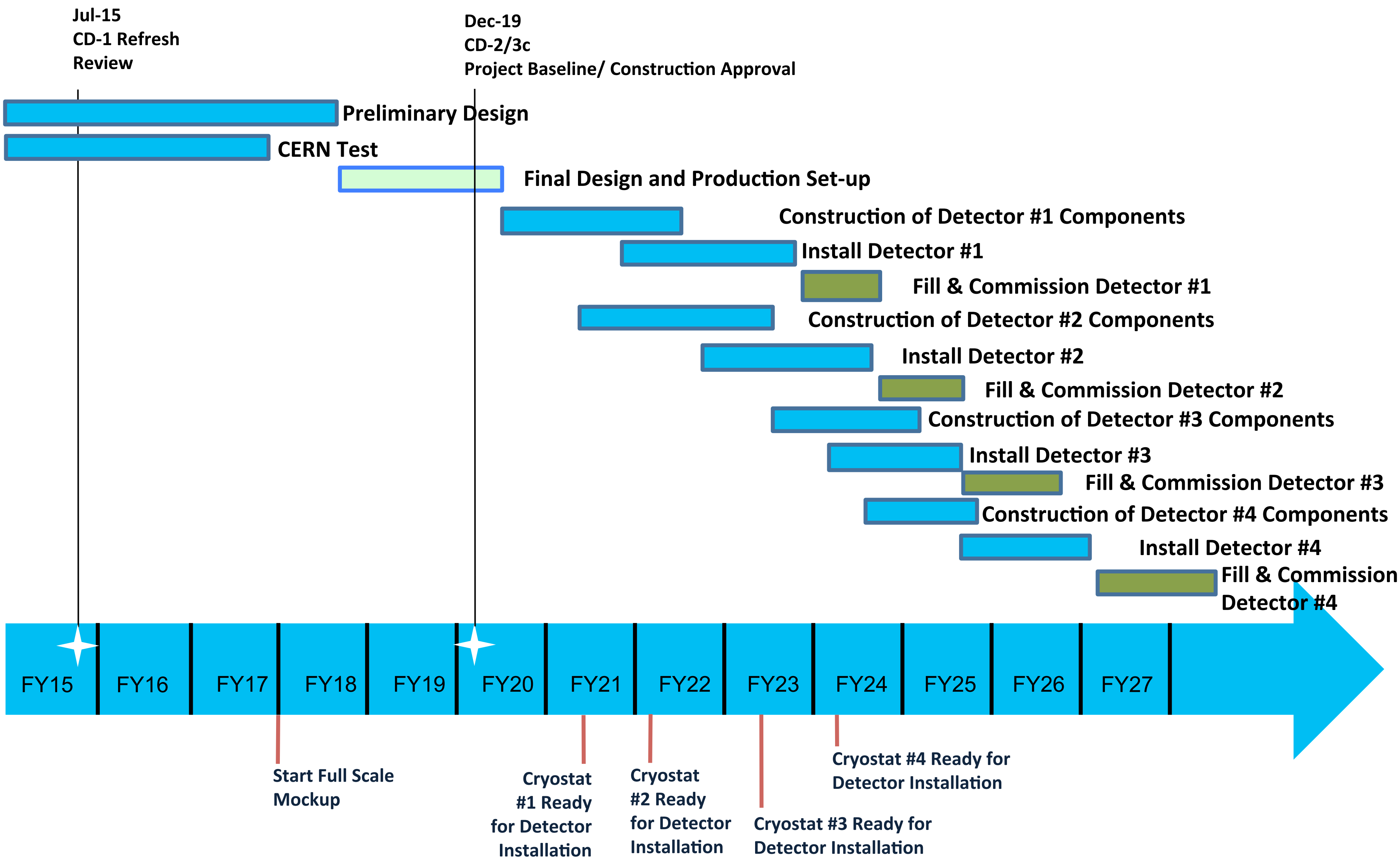




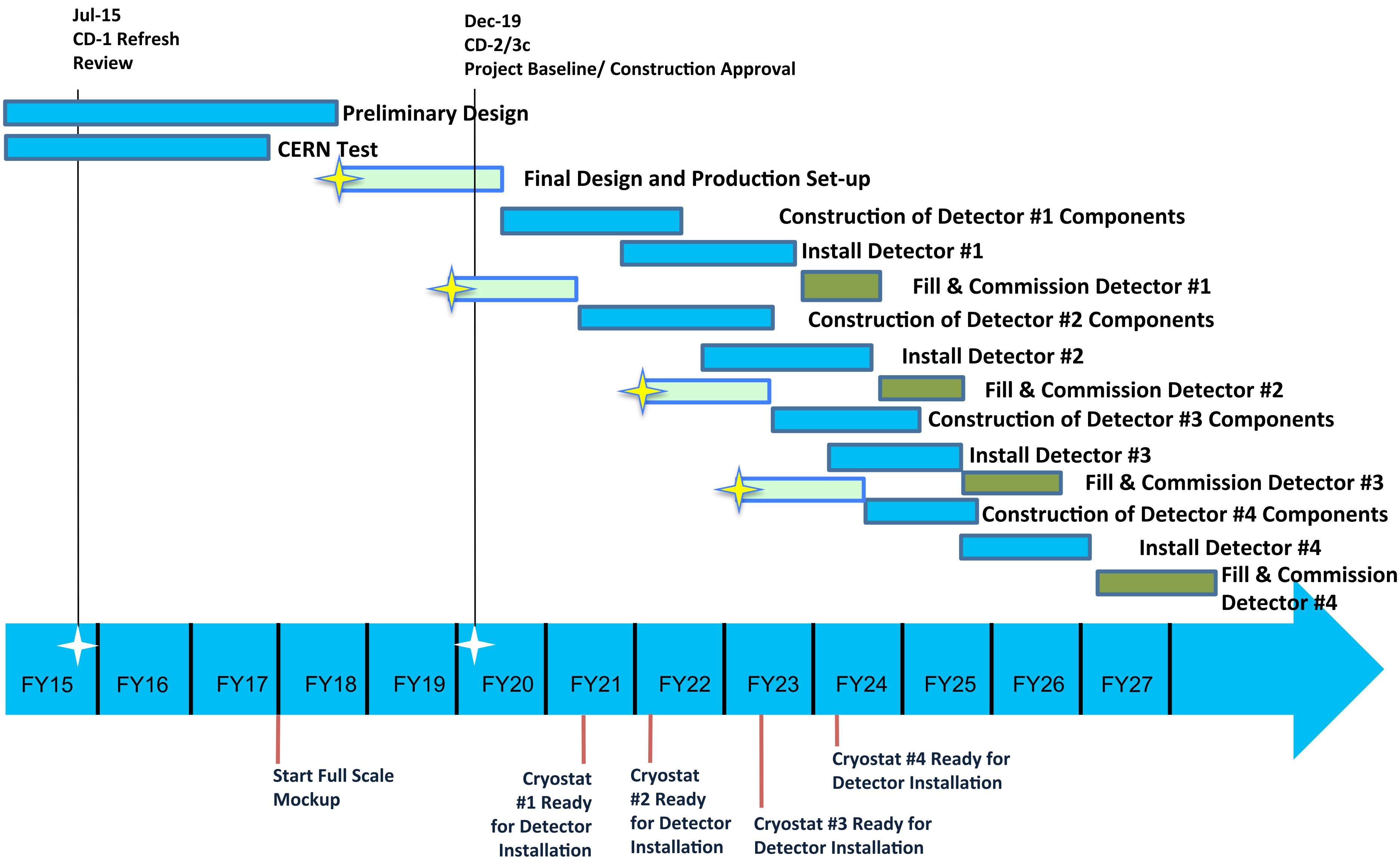
Schedule



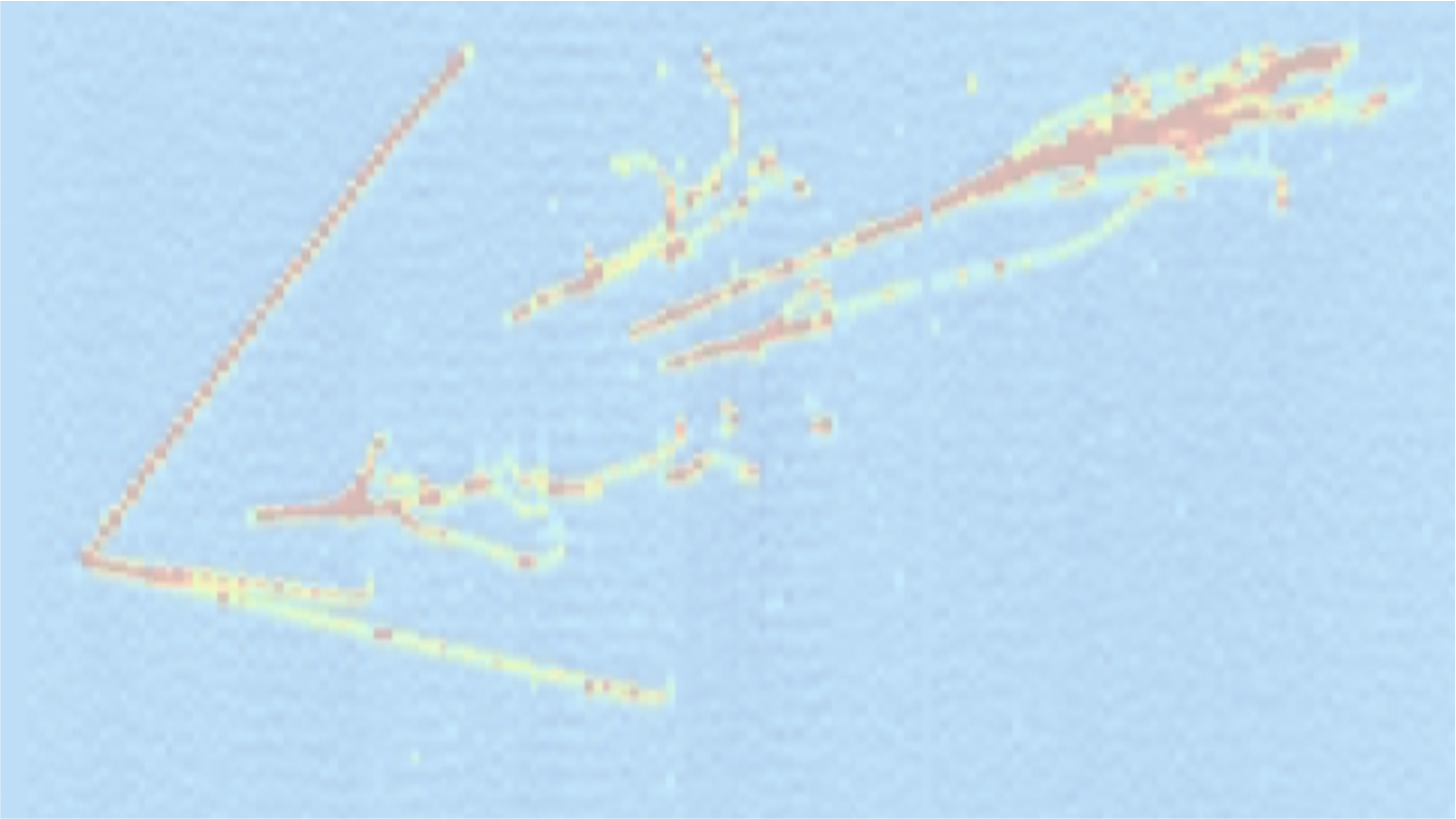
Indicative schedule



Indicative schedule



Calculating Sensitivities



Determining Physics Sensitivities

For Conceptual Design Report

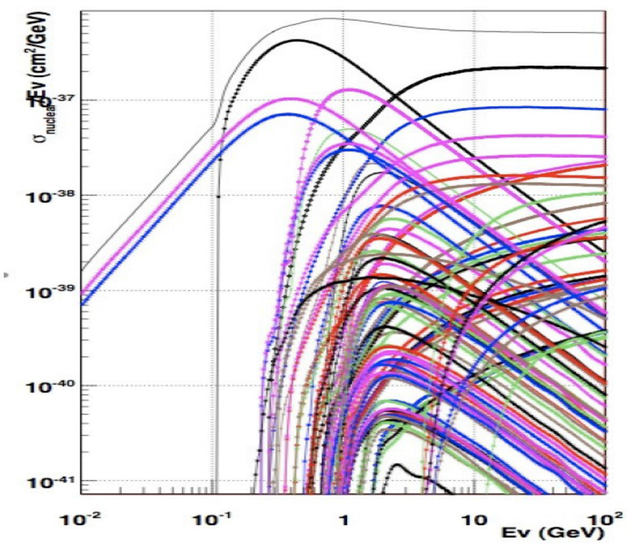
- **Full detector simulation/reconstruction not available**
  - See later in talk for plans
- **For Far Detector response**
  - Use parameterized single-particle response based on achieved/ expected performance (with ICARUS and elsewhere)
- **Systematic constraints from Near Detector + …**
  - Based 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

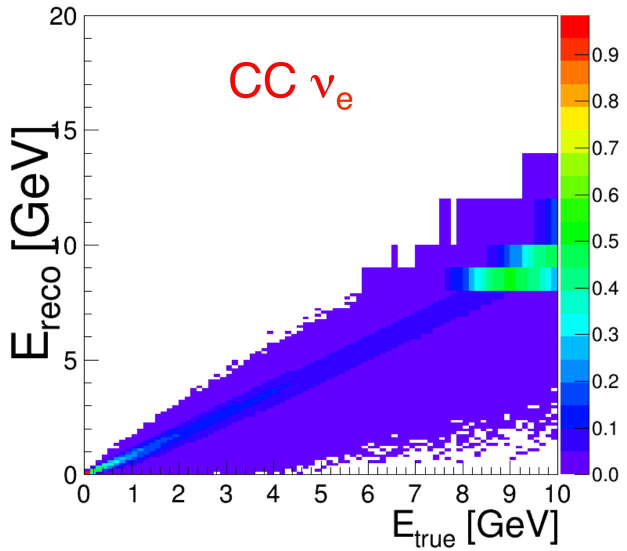
- **Assumed* Particle response/thresholds**
  - Parameterized detector response for individual final-state particles

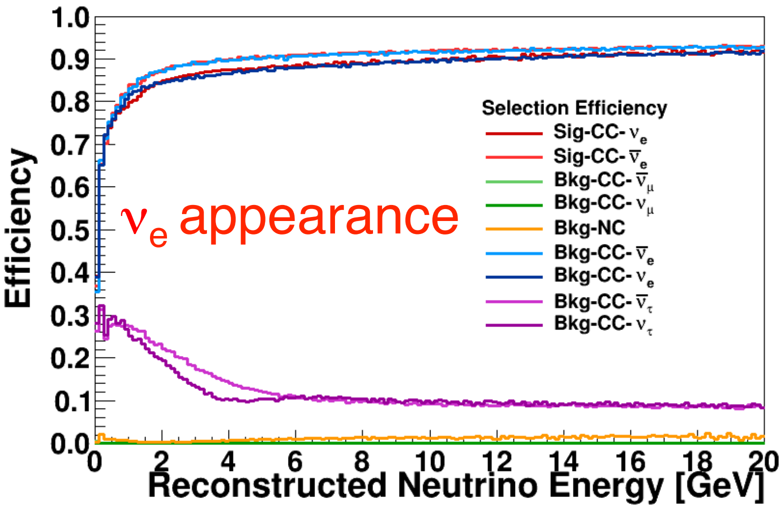
Particle Type	Threshold (KE)	Energy/momentum Resolution	Angular Resolution
$\mu^{\pm}$	30 MeV	Contained: from track length Exiting: 30 %	1^{o}
$\pi^{\pm}$	100 MeV	MIP-like: from track length Contained π-like track: 5% Showering/Exiting: 30 %	1^{o}
$e^{\pm}/\gamma$	30 MeV	$2\% \oplus 15\%/\sqrt{(E/GeV)}$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





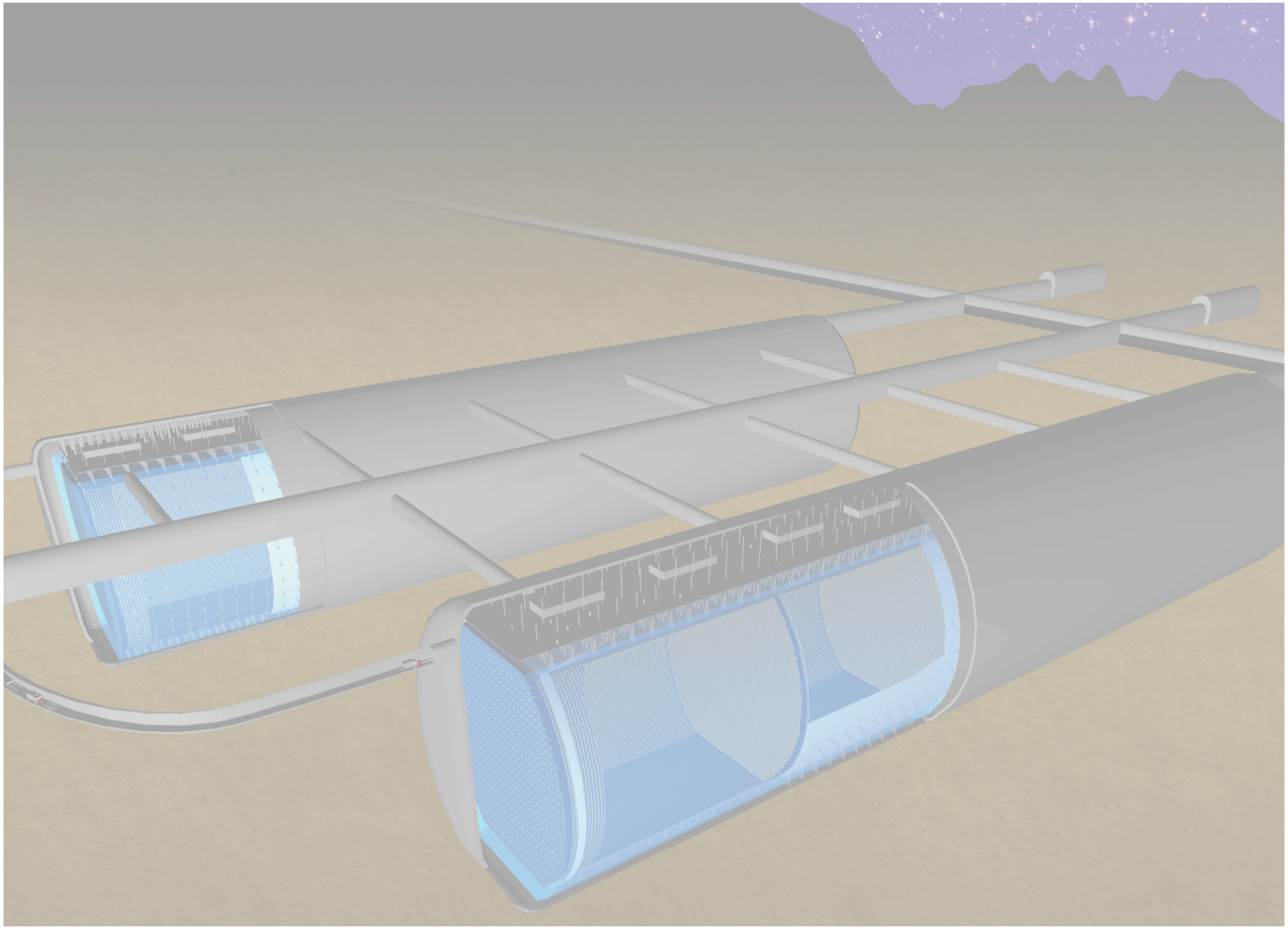
Evaluating DUNE Sensitivities IV

- **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

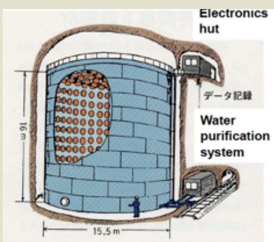
5: Hyper-Kamiokande



Far Detector

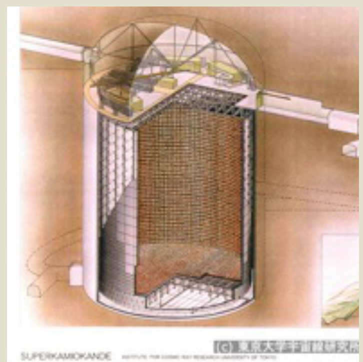
Hyper-K is the proposed third generation large water Cherenkov detector in the Kamioka mine

Kamiokande (1983-1996)



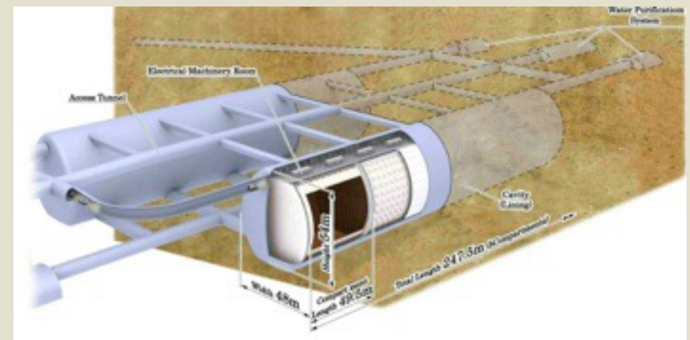
3 kton

Super-Kamiokande (1996-)



50 kton

Hyper-Kamiokande (202?-)

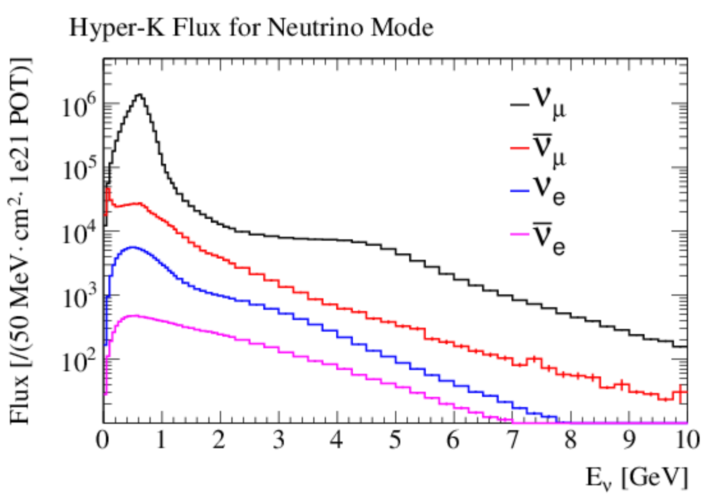


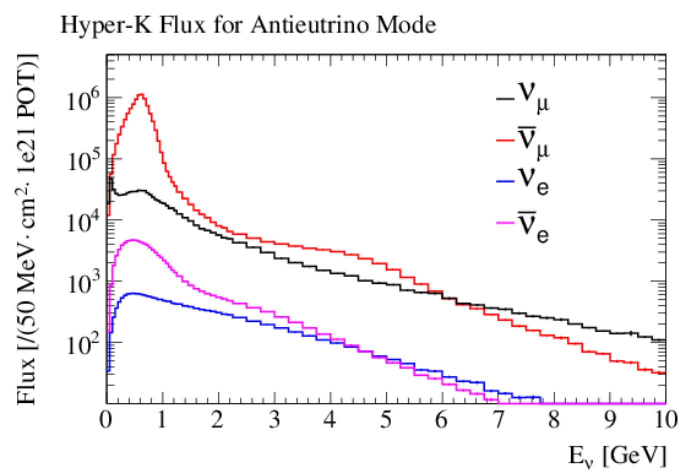
1 Mton

- 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 7.5×10^7 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

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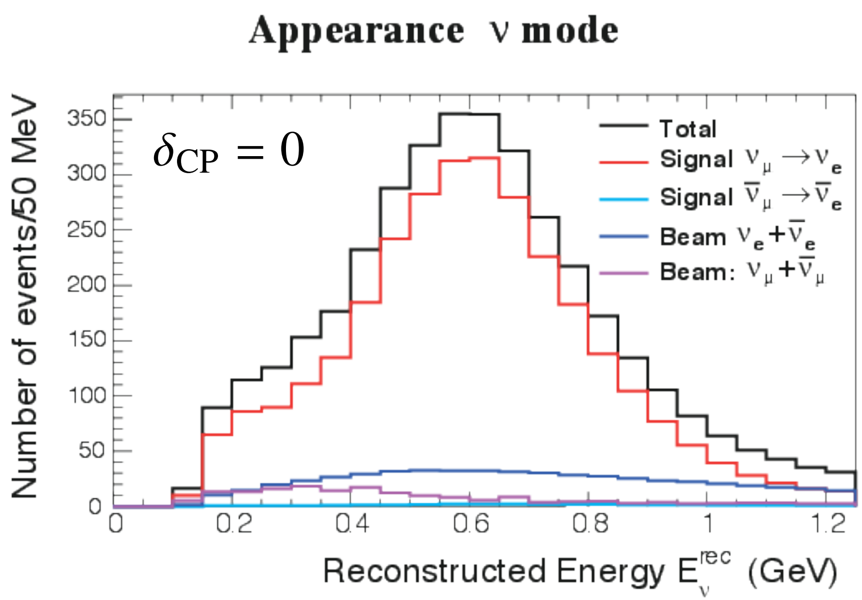
  - Galactic core collapse supernova, sensitivity to $\overline{\nu}_e$

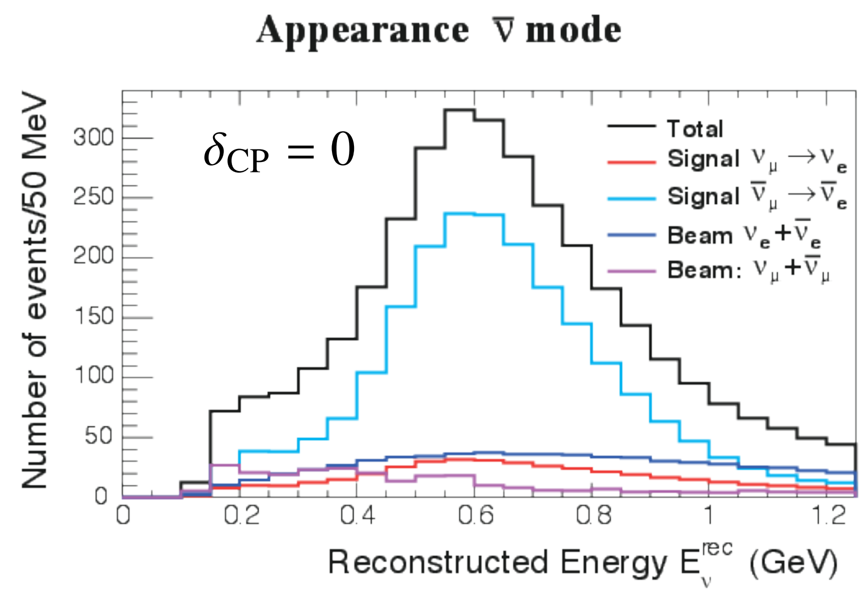
★ **Significant complementarity with DUNE physics**

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**

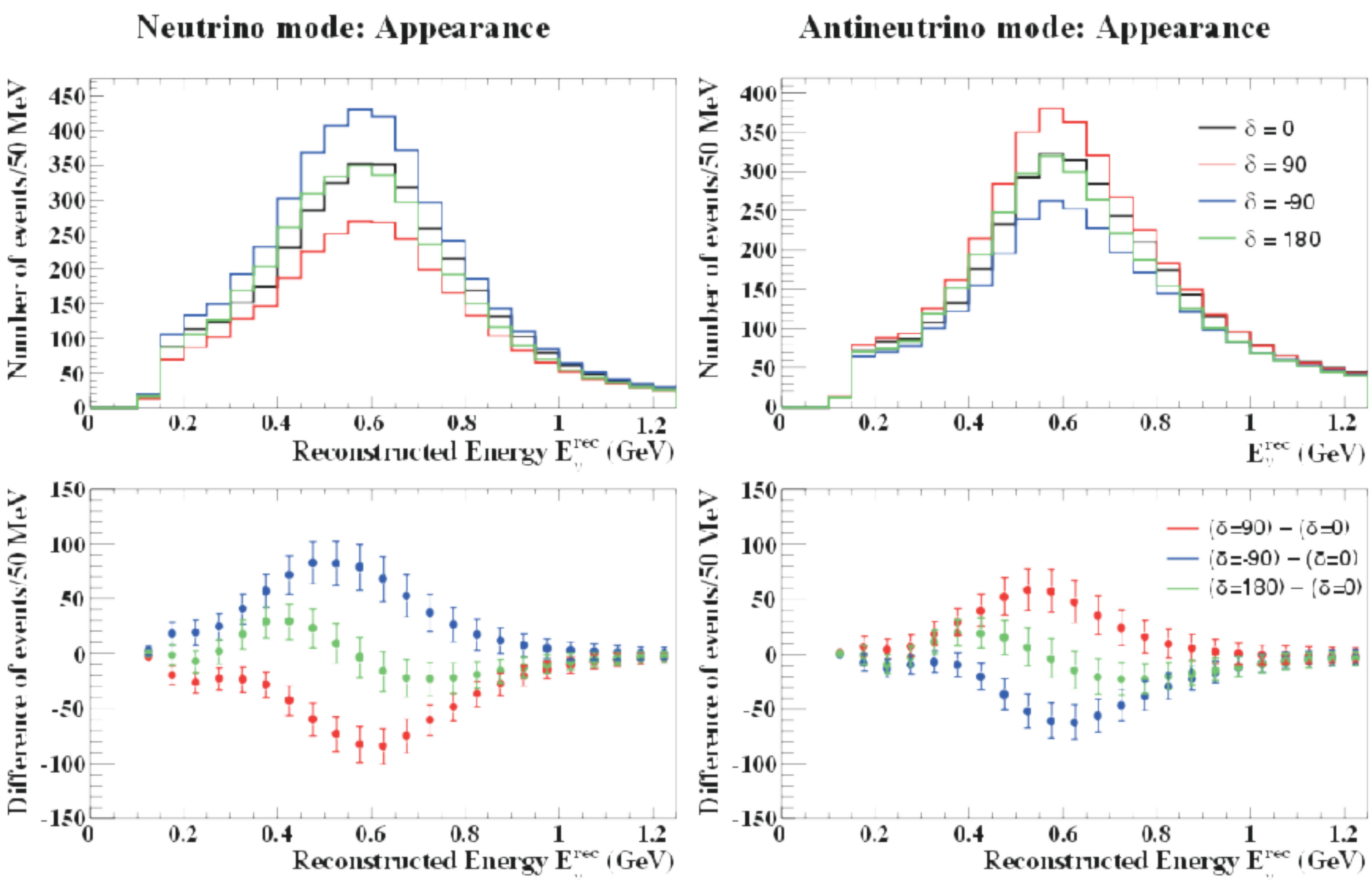




*here focus only on neutrino oscillations

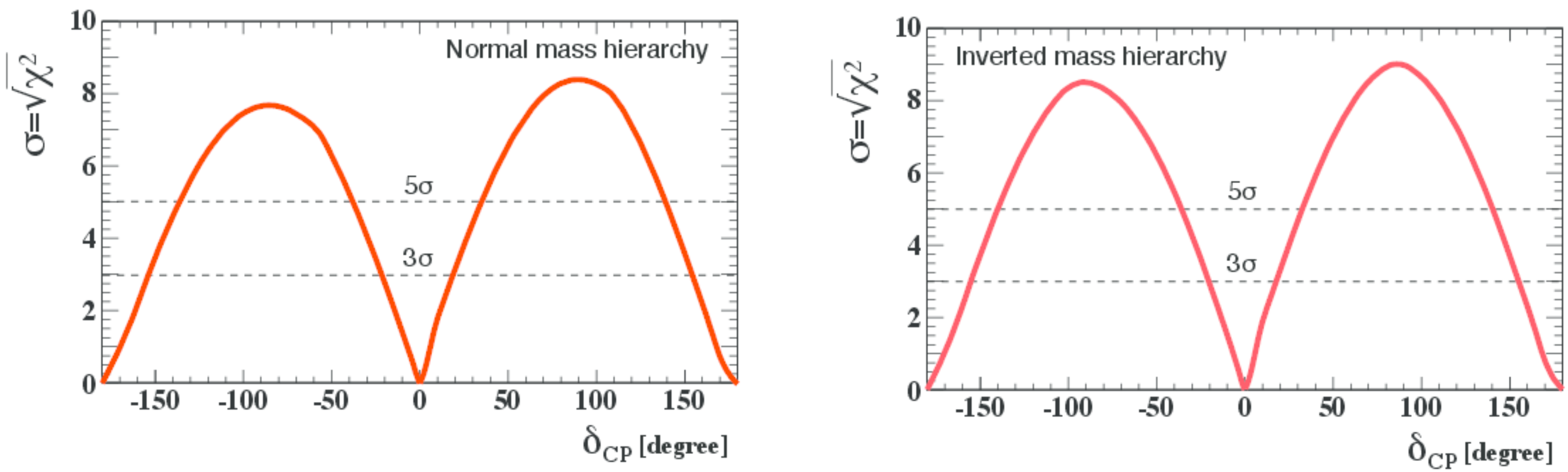
CPV Sensitivity

★ 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