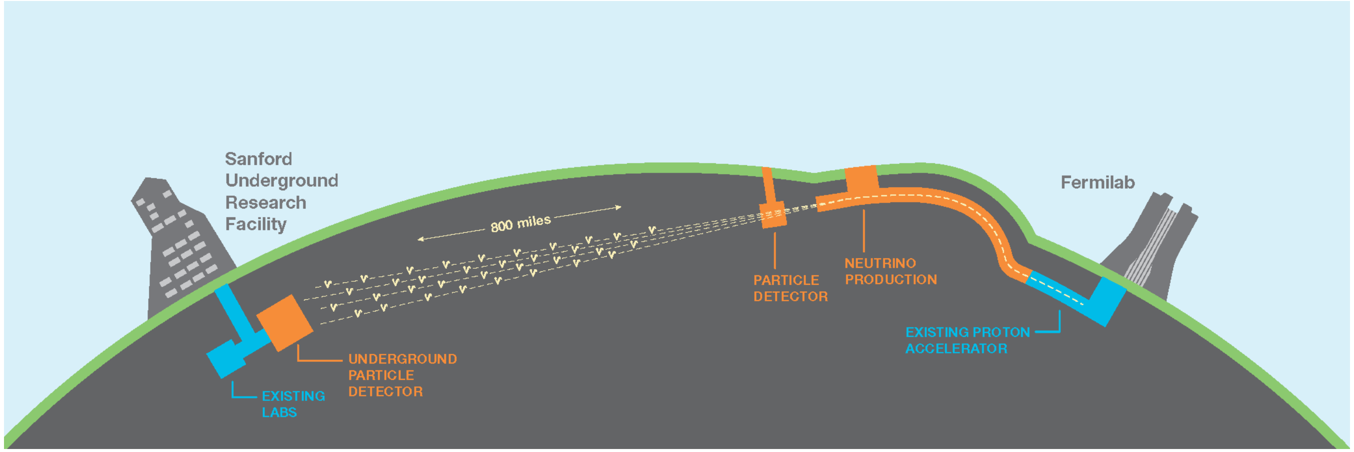


The Deep Underground Neutrino Experiment (DUNE)

Mark Thomson
University of Cambridge & DUNE co-spokesperson

Physics at the Terascale, DESY, 29th November 2017

UNIVERSITY OF CAMBRIDGE

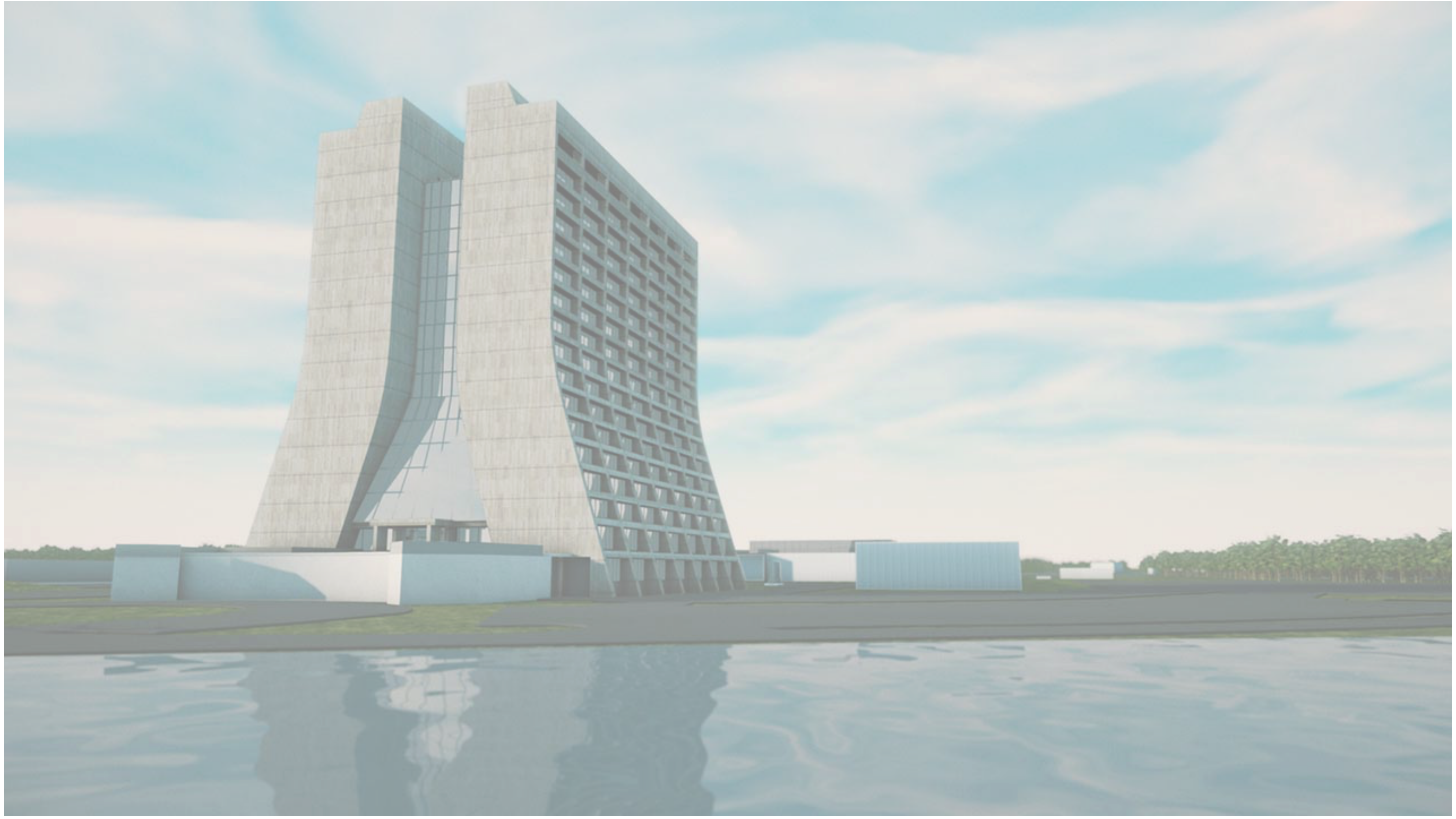
DUNE

This talk

- 1. Introduction (2 slides + animation)
- 2. CP Violation (2 slides)
  - The neutrino perspective
- 3. Neutrinos are different (5 slides)
  - Why do many people find neutrinos so interesting?
- 4. DUNE (9 slides)
  - the accelerator/infrastructure (LBNF) and the detectors (DUNE)
- 5. DUNE Science (7 slides)
  - what we will measure and why it matters
- 6. Status of DUNE (3 slides)
  - Status and international context
- 7. Summary (1 slide)

- 8. Overview of HyperK (if time allows)

1. Introduction: What is DUNE?



1. Introduction: What is DUNE?

- **The Deep Underground Neutrino Experiment (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

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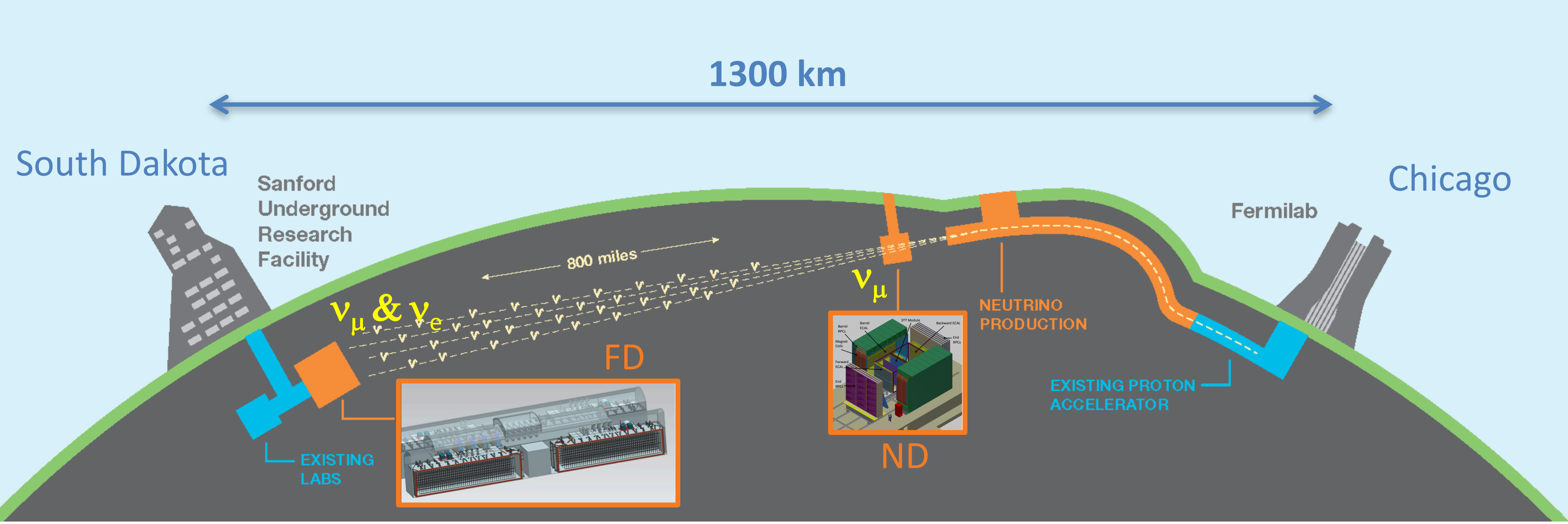
  - is likely to be the next big global project in particle physics
  - aims to **"do for neutrinos what the LHC did for the Higgs"**
  - potential for major discoveries in: neutrinos and astro-particle physics

- **There are two connected projects: LBNF / DUNE**
  - The **Long Baseline Neutrino Facility (LBNF)** is the US-hosted **neutrino beam** and **conventional facilities**
    - "the LHC for neutrinos"
  - The **Deep Underground Neutrino Experiment (DUNE)** is the **international** scientific collaboration: builds the **detectors**
    - "the ATLAS/CMS for neutrinos"

1. Introduction: What is DUNE?

- **DUNE will consist of**
  - A powerful **(MW)** neutrino beam fired from Fermilab
  - A massive **(70,000 t)** underground detector in the Homestake mine, South Dakota
  - A near detector at Fermilab
  - A large international collaboration



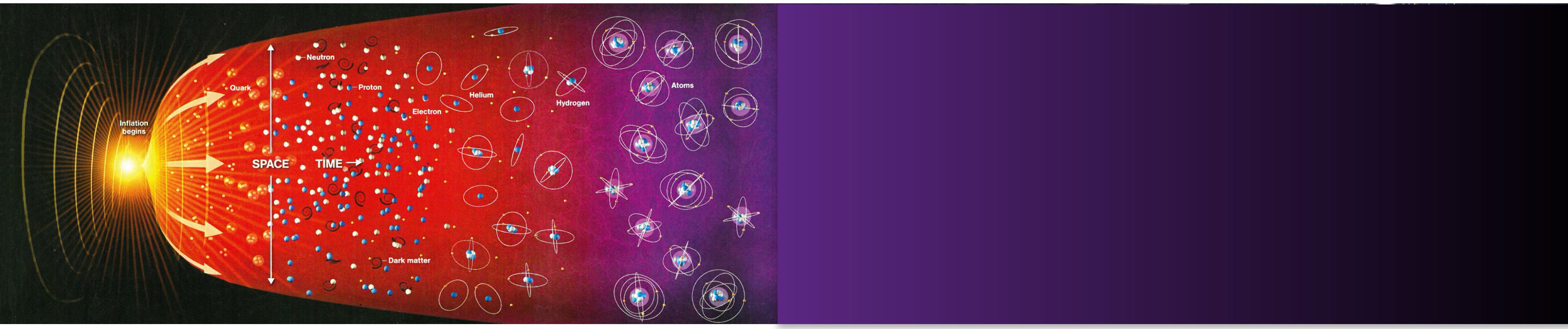
LBNF/DUNE – Fermilab in 2026

2. CP Violation and ν Oscillations

CP Violation

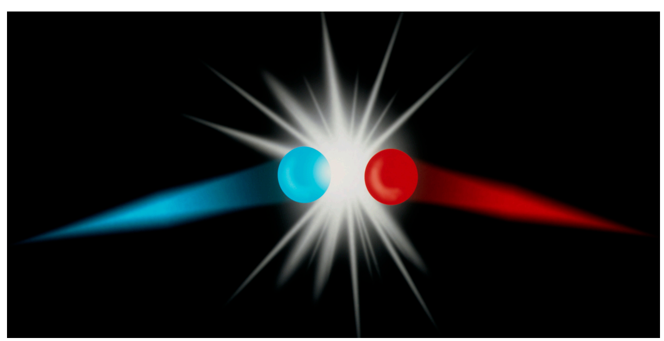
CPV remains an open question in science

- **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

e^-



e^+

CP Violation

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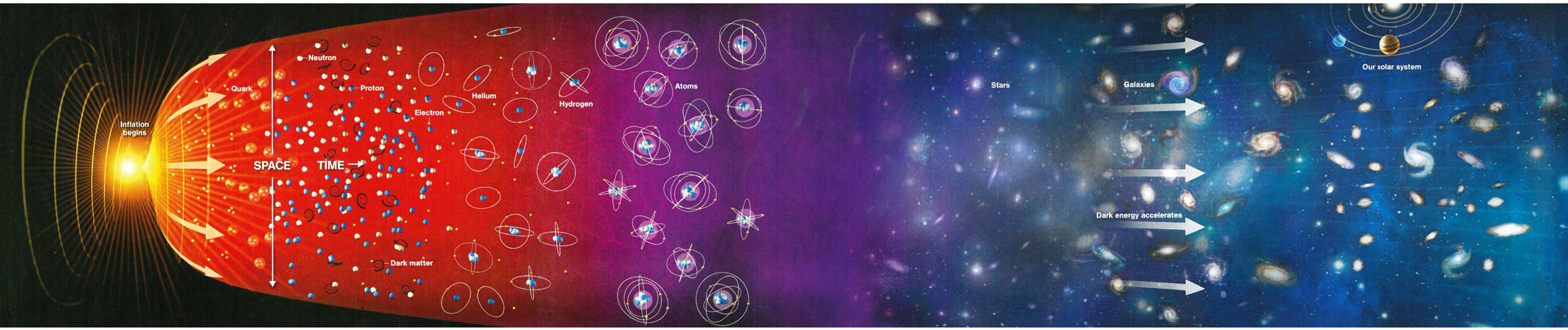

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  - **This is not what happened – there is matter left in the Universe**
    - ⇨ Fundamental difference between matter and antimatter
    - ⇨ CP symmetry violation **(CPV)**
  - Neutrinos: key to a good bet* for how this happened "leptogenesis"

CP Violation

CPV remains an open question in science

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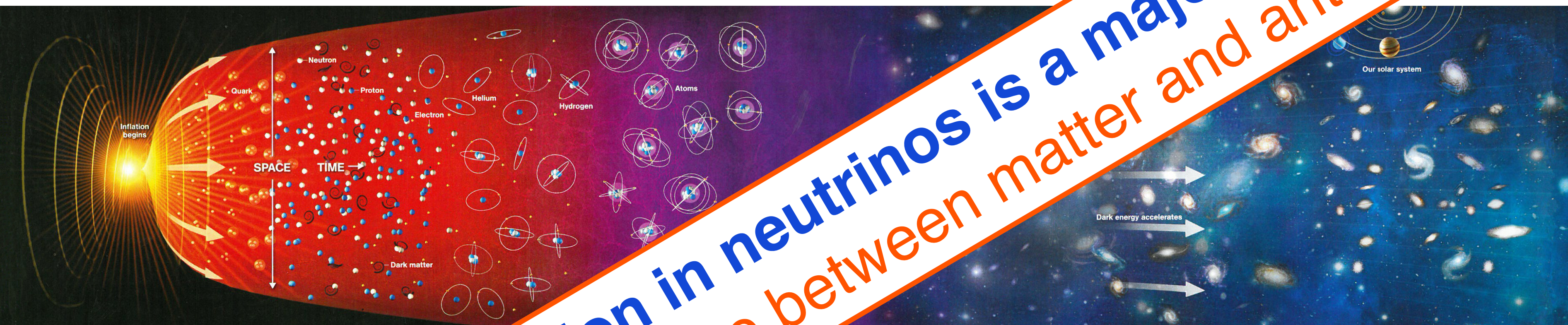

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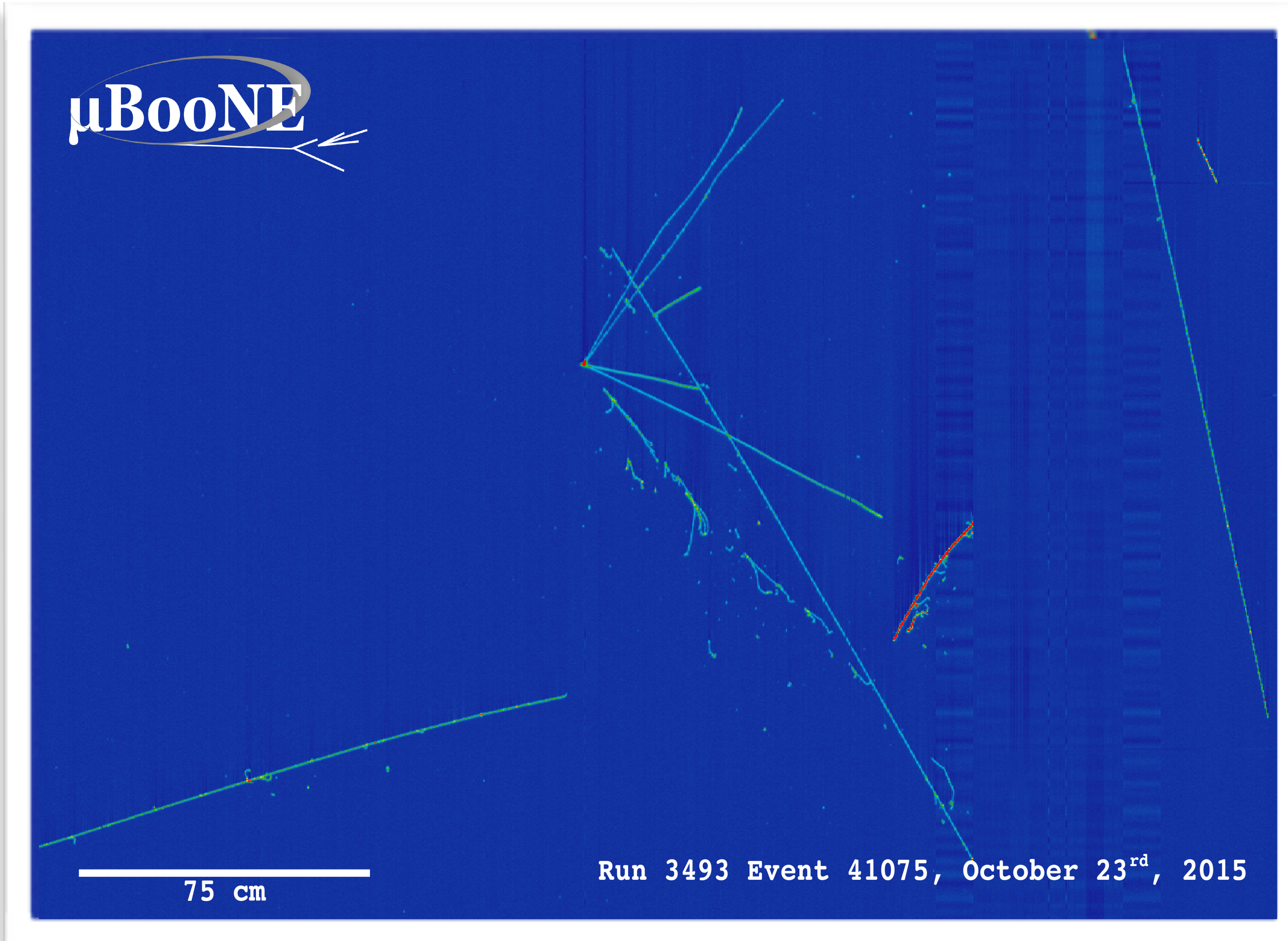
Observing CP violation in neutrinos is a major goal*:
a fundamental difference between matter and antimatter

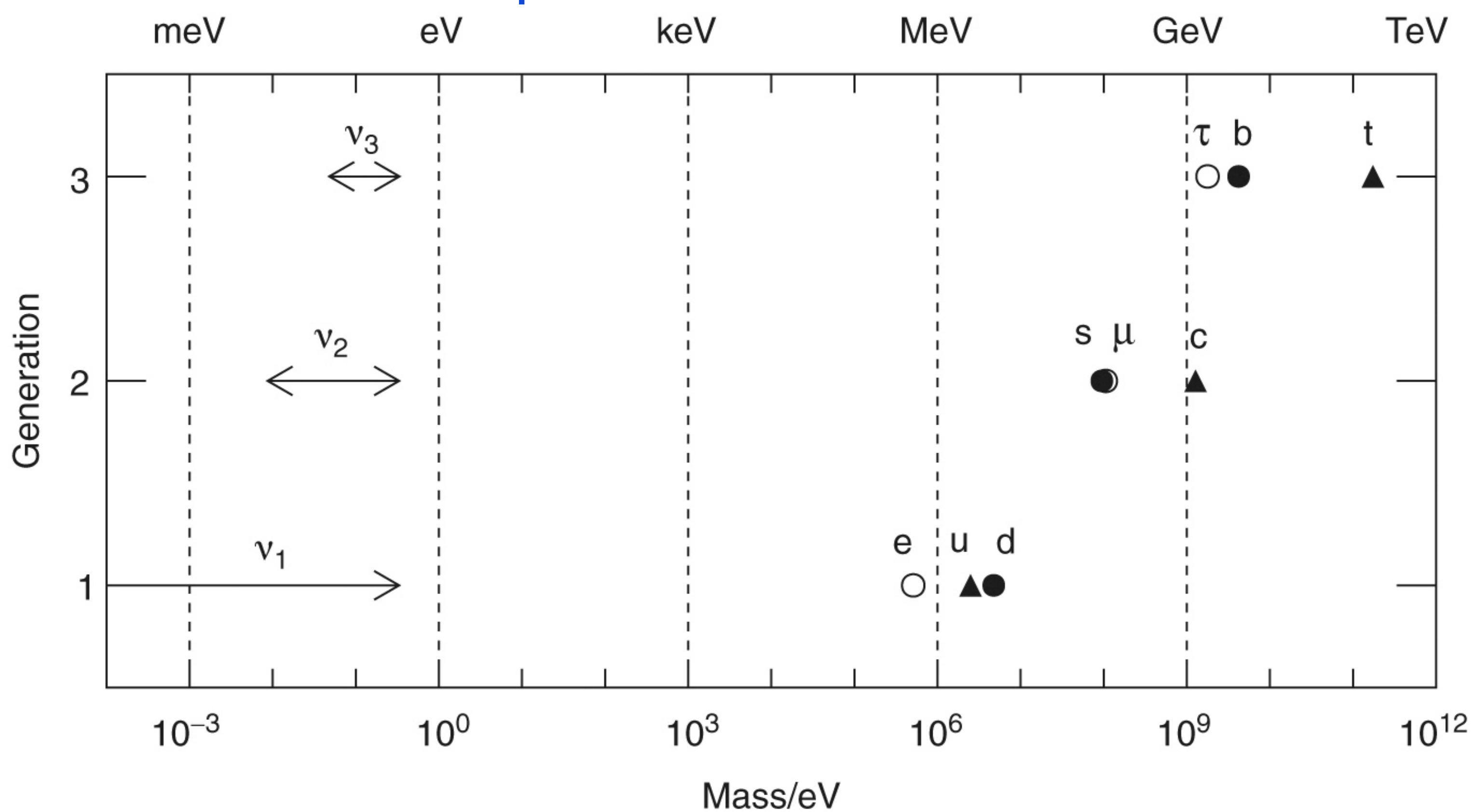
*not proof, need to connect low-scale ν CPV physics to the high-scale N CPV physics

3. Neutrinos are different



Neutrinos are different

- **For example, they are almost (but not quite) massless**
  - (at least) nine orders of magnitude lighter than those of the other matter particles



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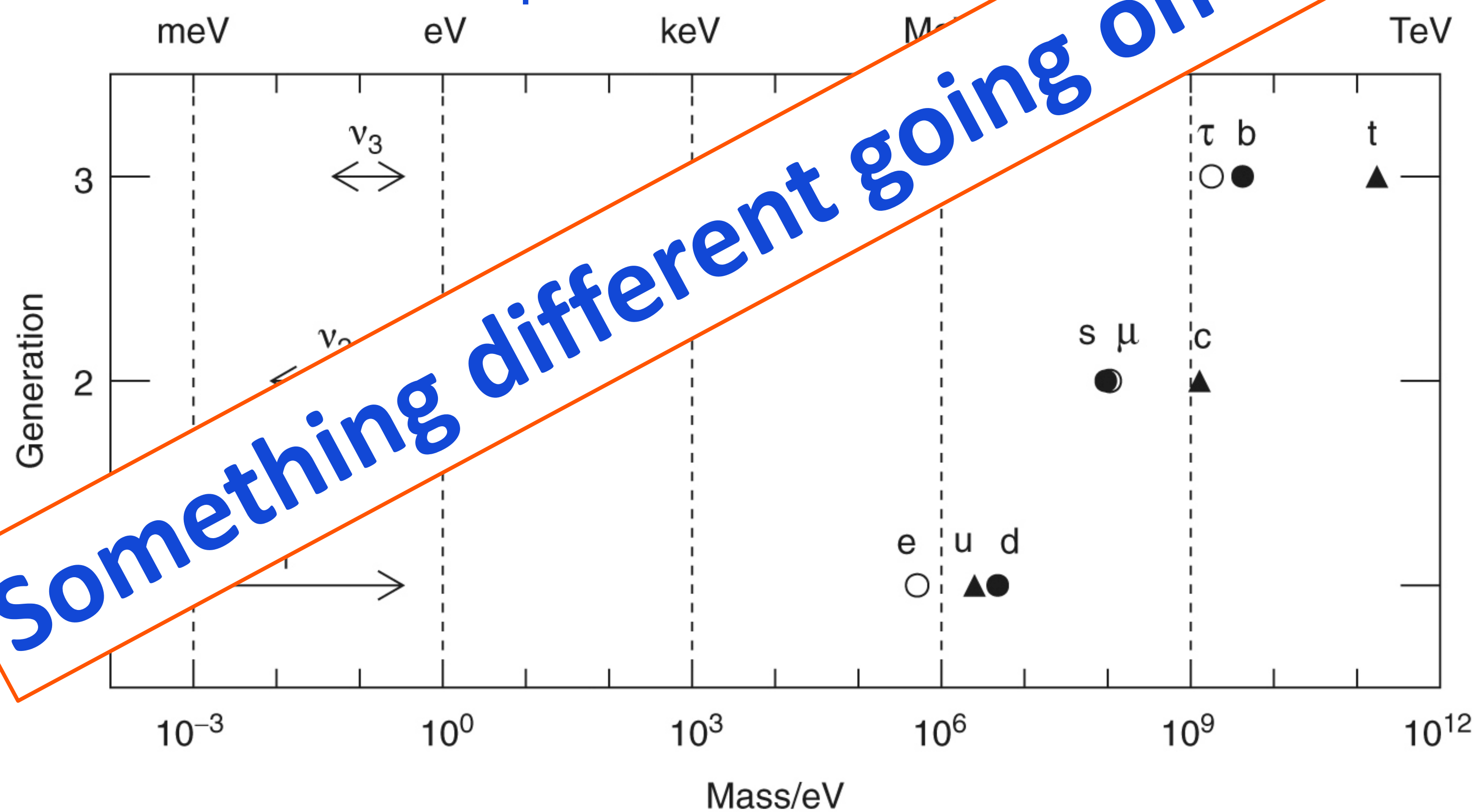
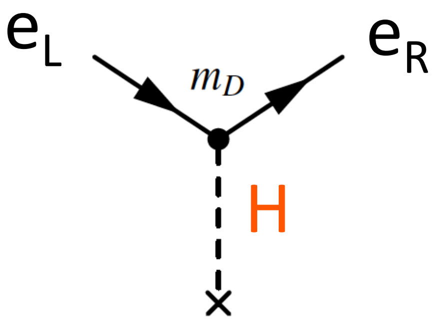


Something different going on here…

a connection to new physics…

★ **Neutrino masses are anomalously small**

- Particle masses "generated" by the Higgs mechanism



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

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

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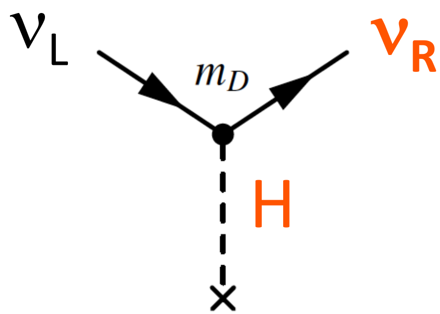

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- This also could be the origin of neutrino masses
  - ⇨ Existence of RH neutrino – a rather minimal extension to the SM?

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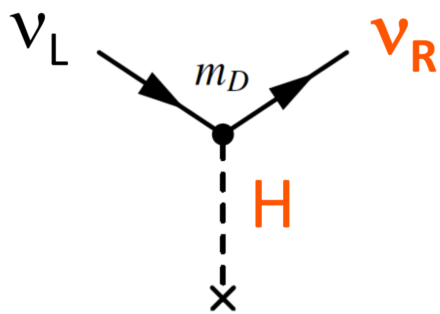

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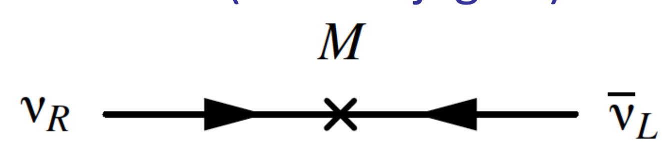
- This also could be the origin of neutrino masses
  - ⇨ Existence of RH neutrino – a rather minimal extension to the SM?
- But a RH neutrino is a gauge singlet – *feels none of SM forces*
  - ⇨ Can now add "by hand" a new Majorana mass term to the SM Lagrangian, involving only the RH field (and conjugate)

$$\sim M \overline{\nu^c_R} \nu_R$$



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

a connection to new physics…

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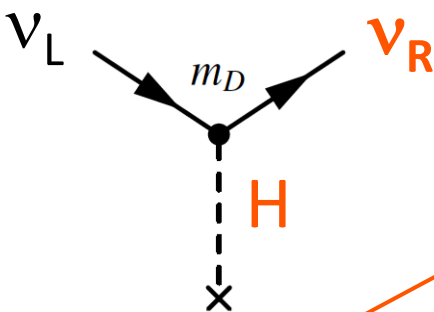

Dirac mass te ... er
L- and ... ields
$+ f_R f_L)$

Neutrinos could be a fundamentally different type of particle

- This also could ... utrino masses
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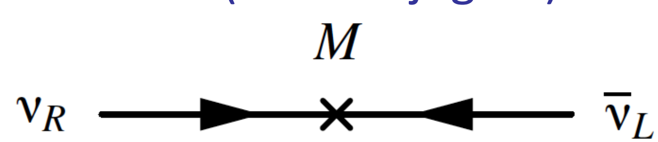


This additional freedom might explain why neutrino masses are "different"

Knowns and Unknowns

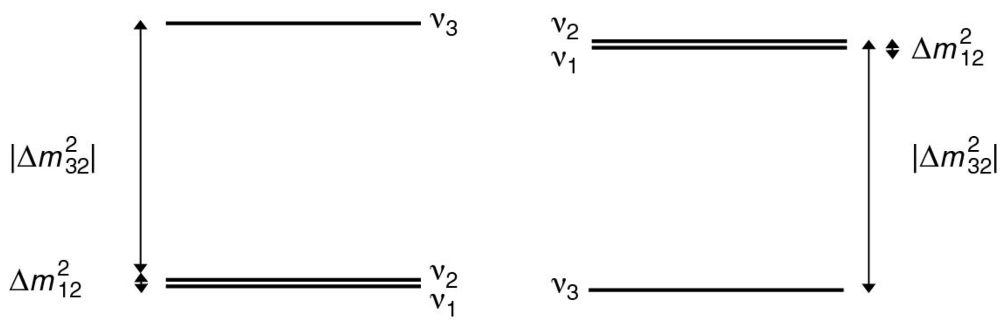
- **[Standard] neutrino oscillations described by 6 parameters:**
  - 3 Euler angles
  - 1 Complex phase
  - 2 mass-squared differences

Knowledge comes from neutrino oscillation experiments

$$\left\{\Delta m^2_{21}\ ,\ |\Delta m^2_{32}|\ ,\ \theta_{12}\ ,\ \theta_{13}\ ,\ \theta_{23}\ ,\ \delta_{CP}\ ,\ \mathrm{MH} = \mathrm{sign}(\Delta m^2_{32})\right\}$$

✅ ✅ ✅ ✅ ✅ ? ?

Mass Hierarchy not yet known



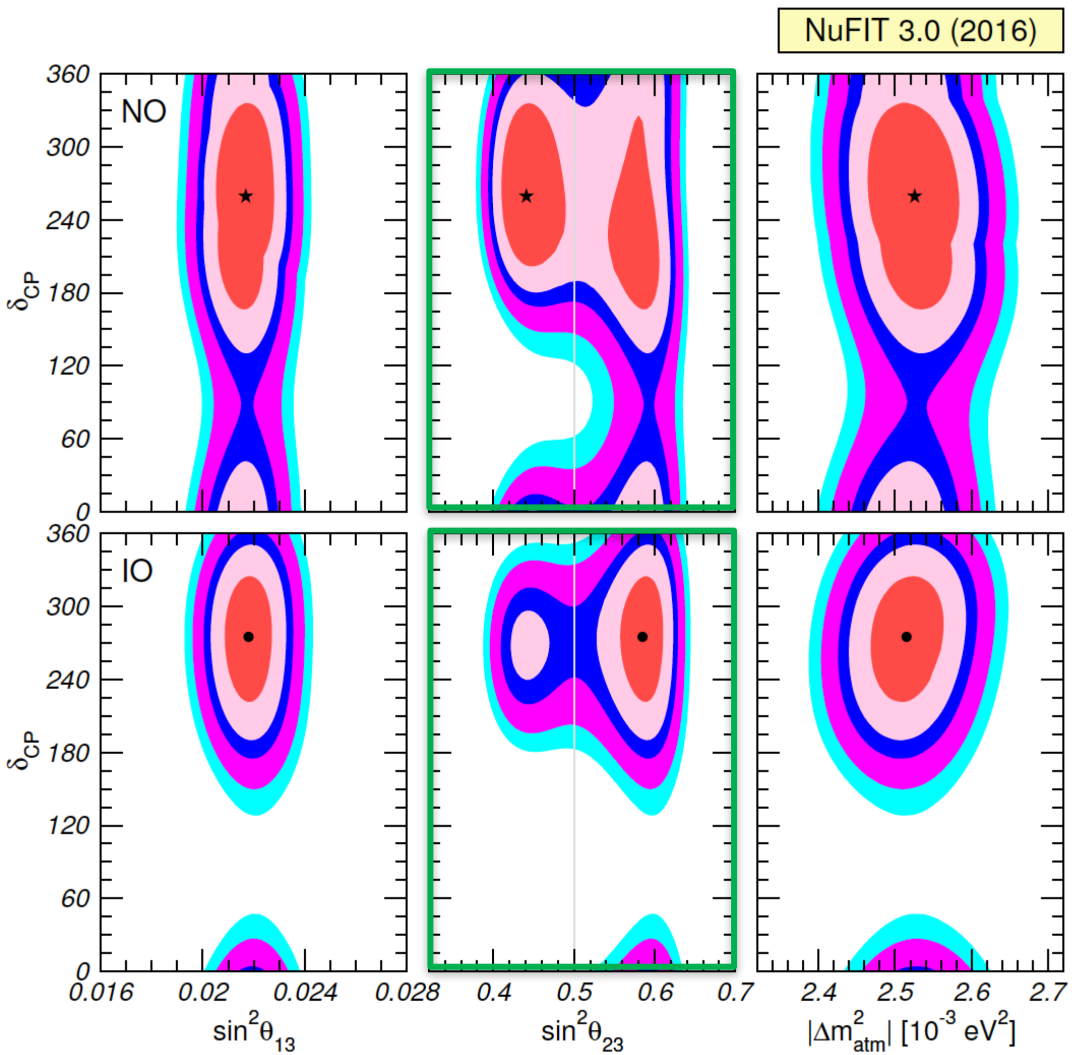
δ_{CP} not known νCPV?

- **CP violation and mass hierarchy are major goals**
  - Also want to test the 3-flavour neutrino Standard Model

CP and MH : Combined knowledge

NH

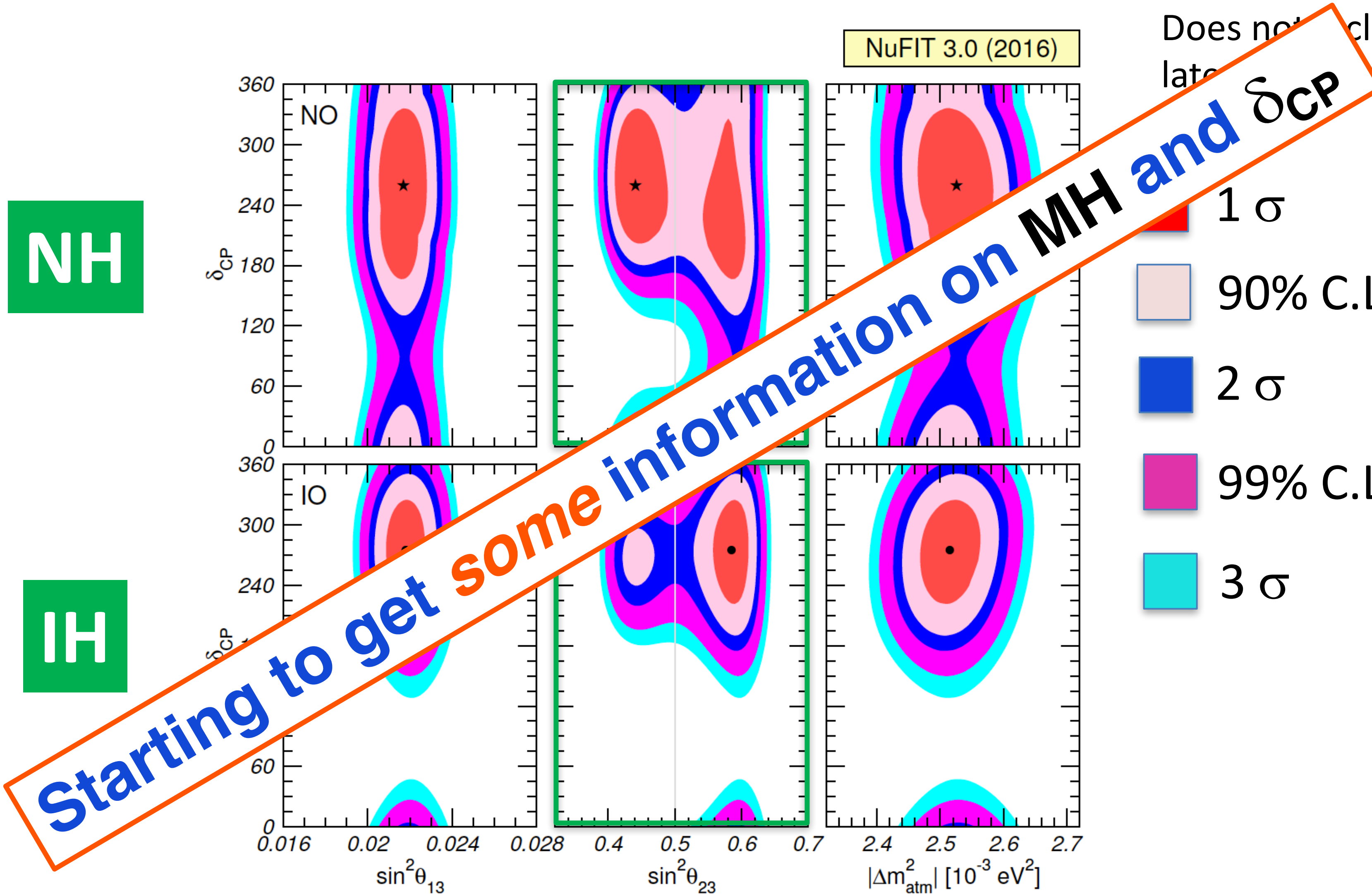
IH



Does not include latest T2K results

- 1 σ
- 90% C.L.
- 2 σ
- 99% C.L.
- 3 σ

CP and MH : Combined knowledge



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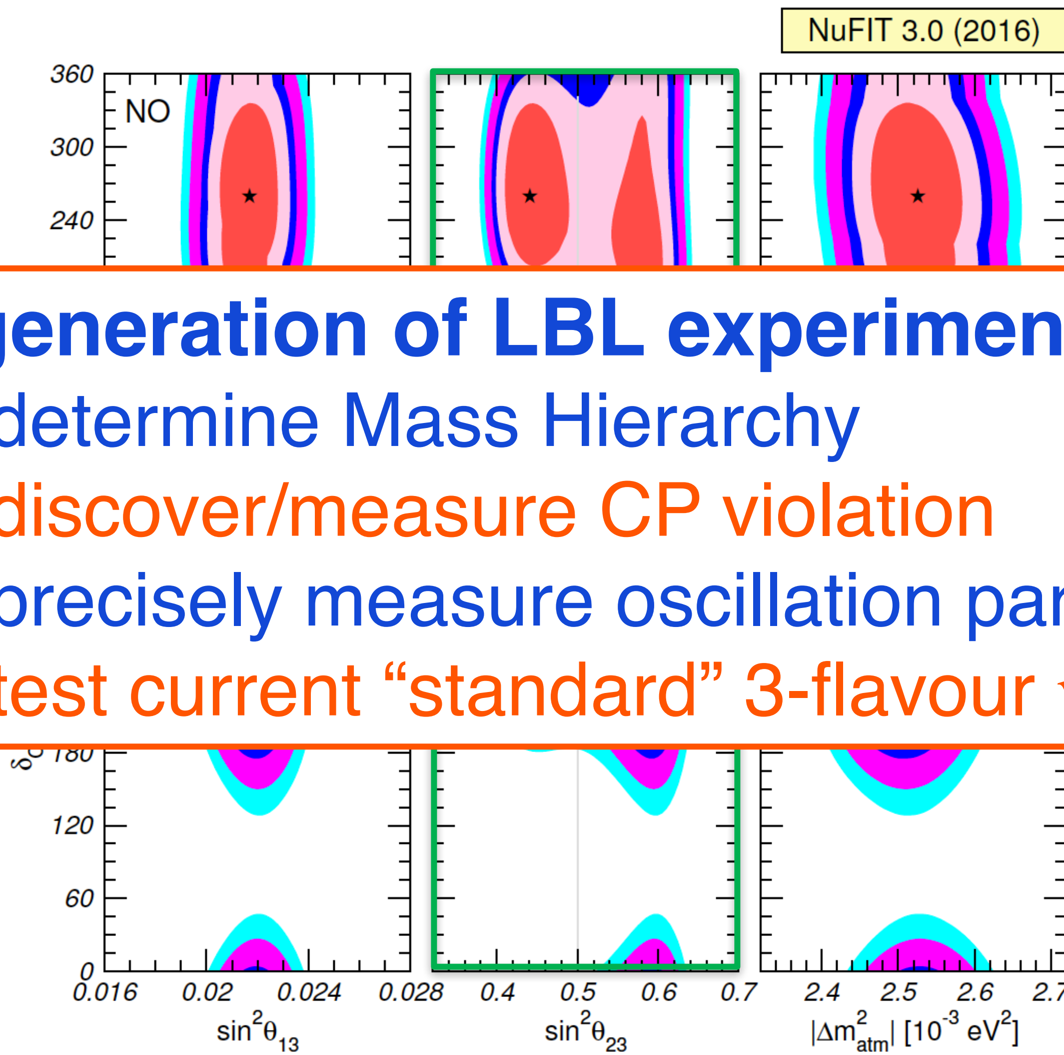


1 σ

Next generation of LBL experiments will:

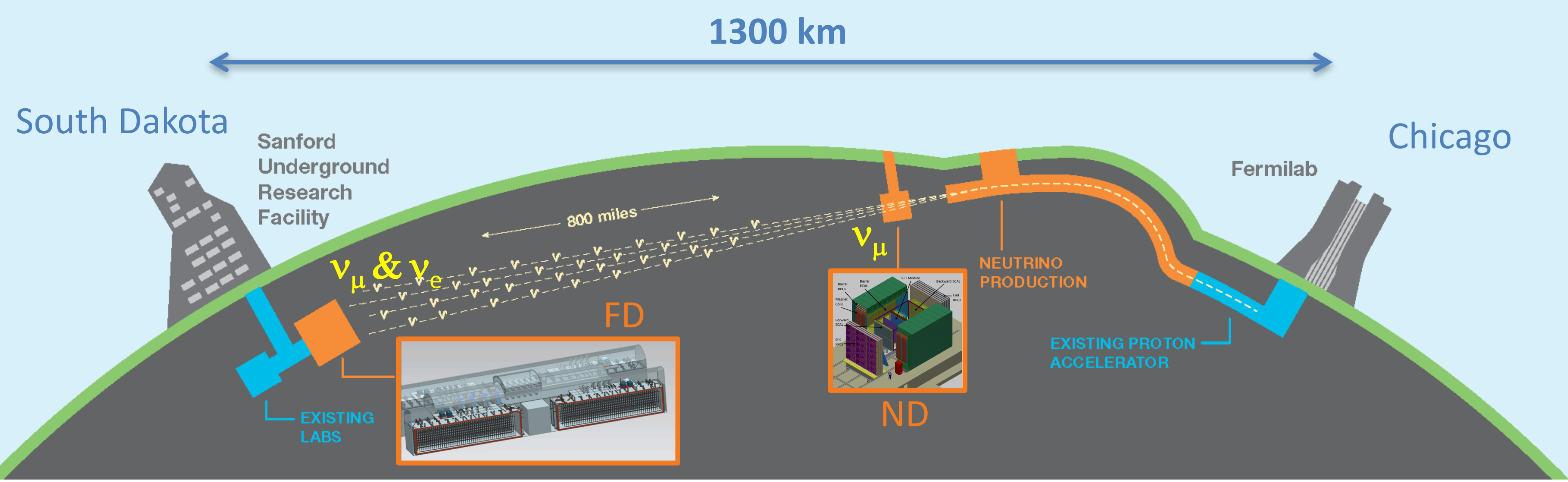
- determine Mass Hierarchy
- discover/measure CP violation
- precisely measure oscillation parameters
- test current "standard" 3-flavour ν paradigm

4. The Deep Underground Neutrino Experiment

DUNE in a 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



4.1 LBNF and PIP-II

★ **In beam-based long-baseline neutrino physics:**

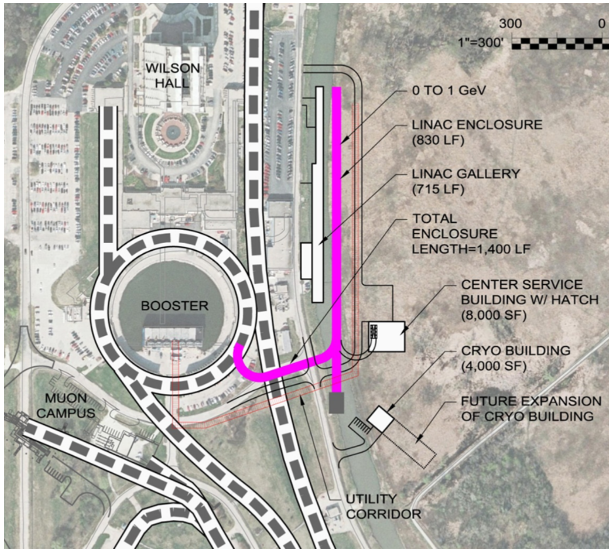
- **beam power drives the sensitivity**

★ **LBNF: the world's most intense high-energy ν beam**

- **1.2 MW from day one**
  - NuMI (MINOS) <400 kW
  - NuMI (NOVA) 700 kW
- **upgradable to 2.4 MW**

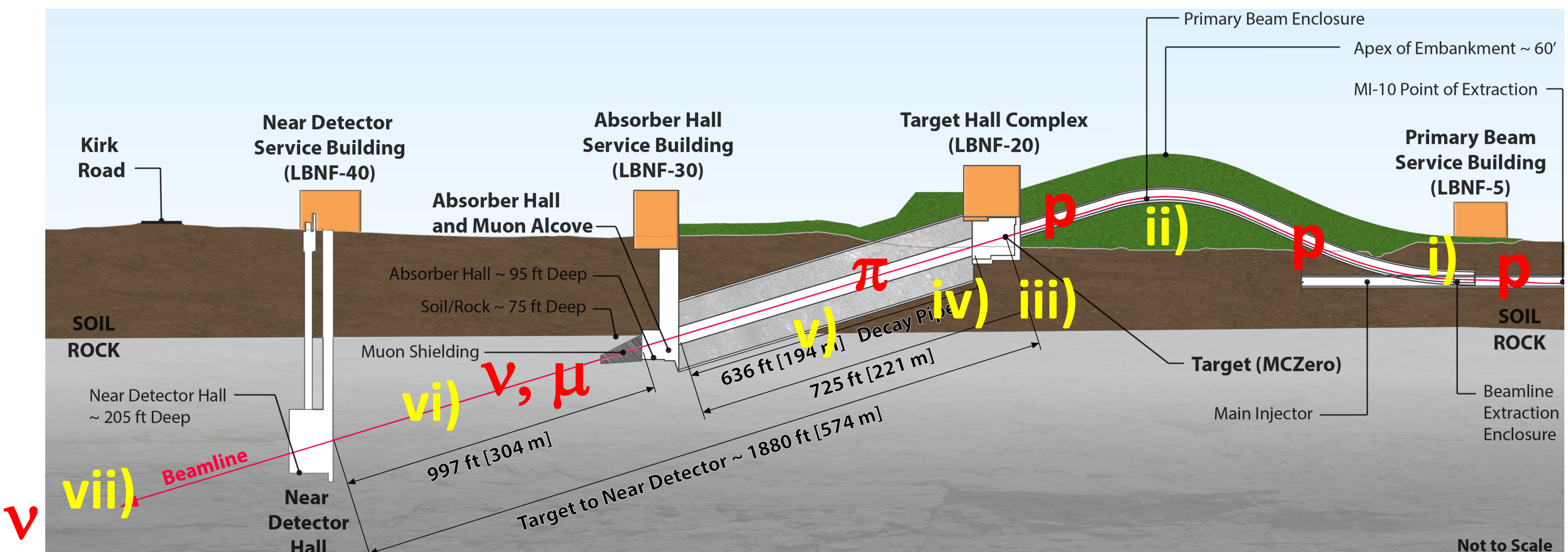
★ **Requires PIP-II** (proton-improvement plan)

- **$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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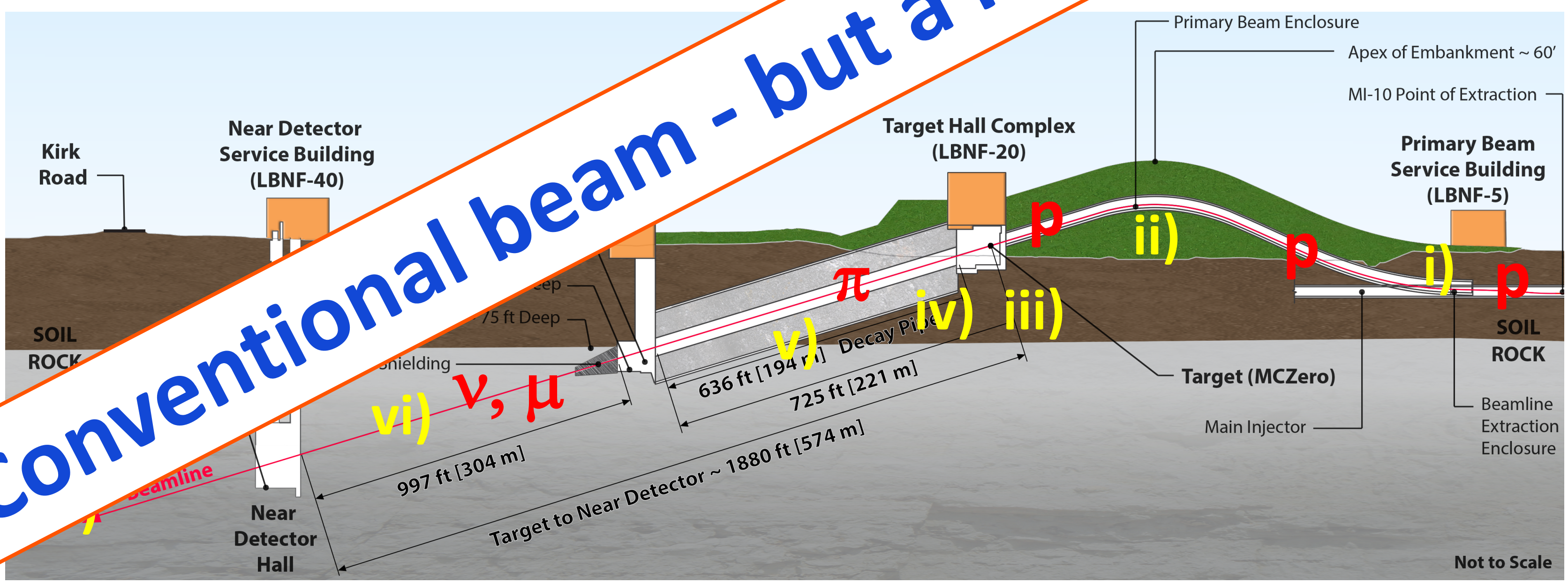
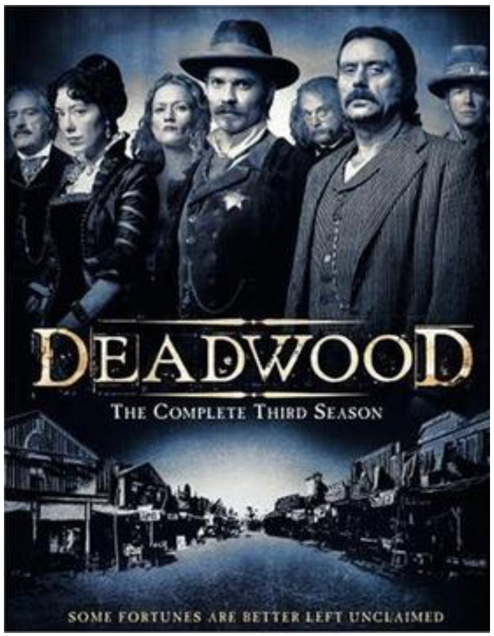
Conventional beam - but a ramp up in power



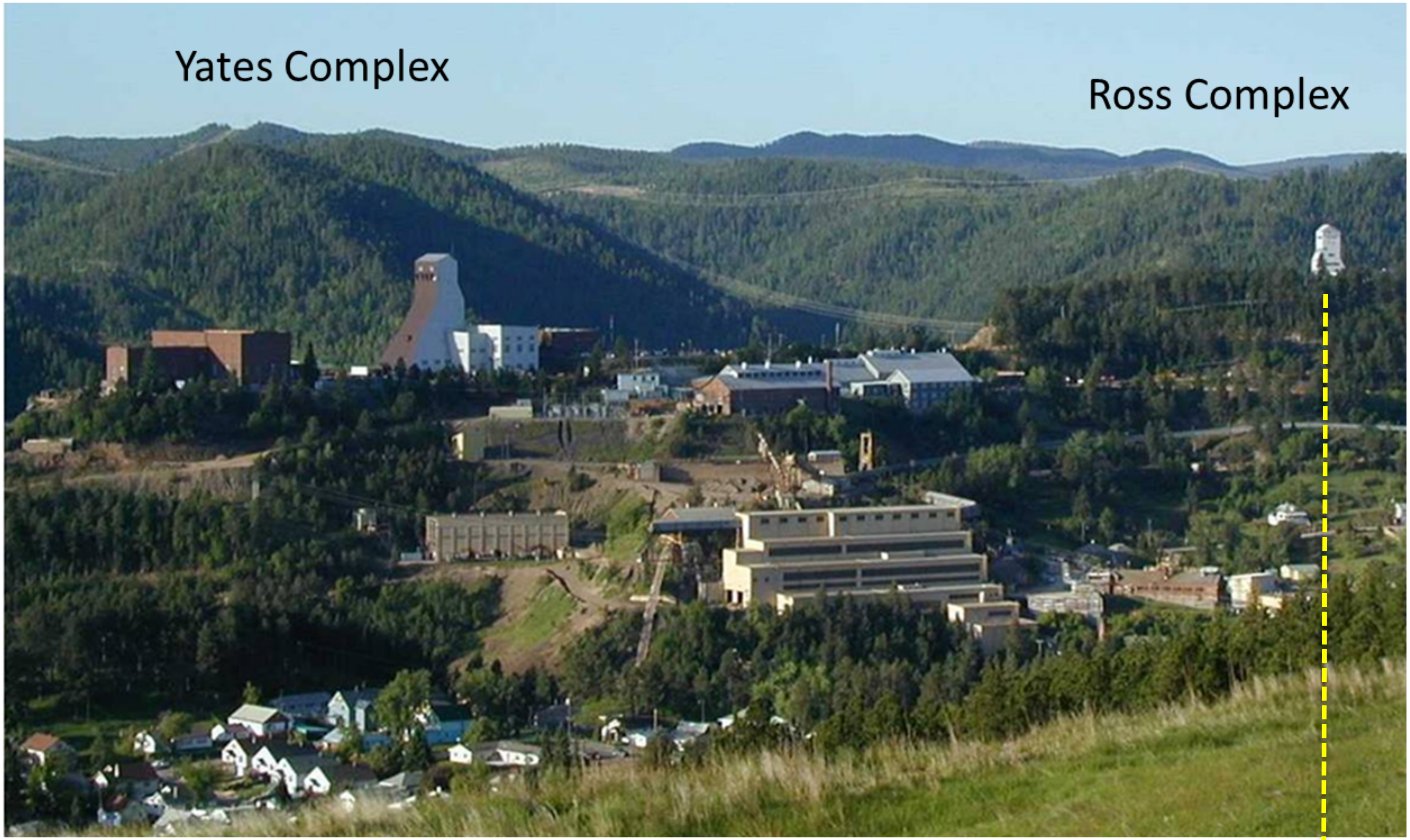
The beam then heads West

800 miles West of Chicago, lies the town of Deadwood…



…5 miles from Deadwood: Homestake gold mine

4.2 The DUNE Far Detector

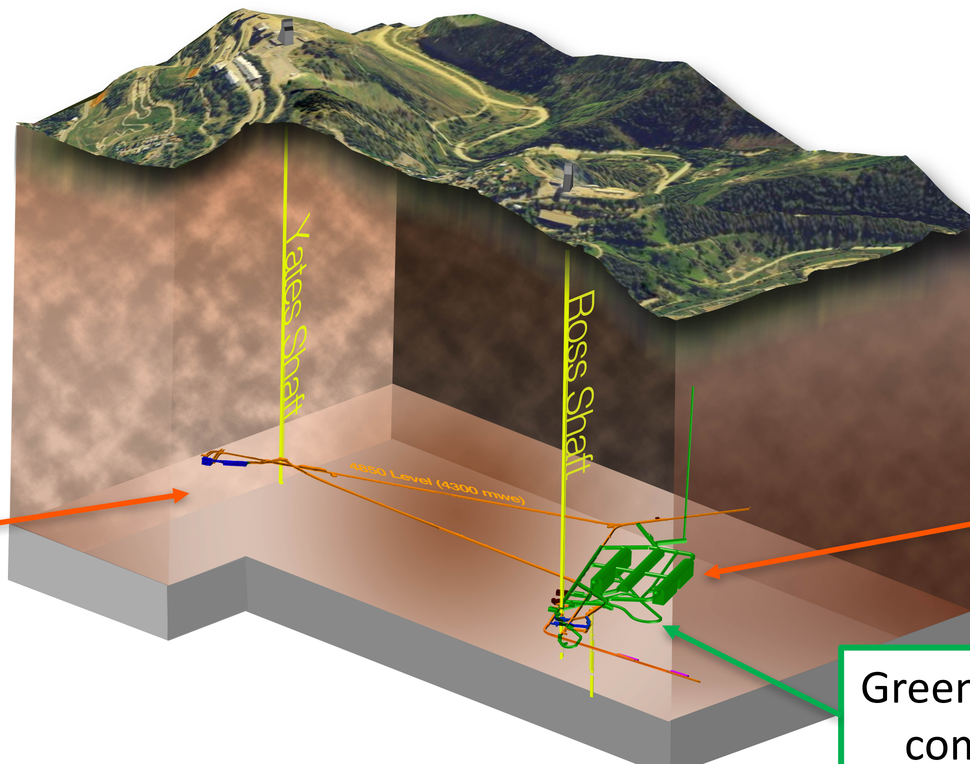


Going underground…

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**

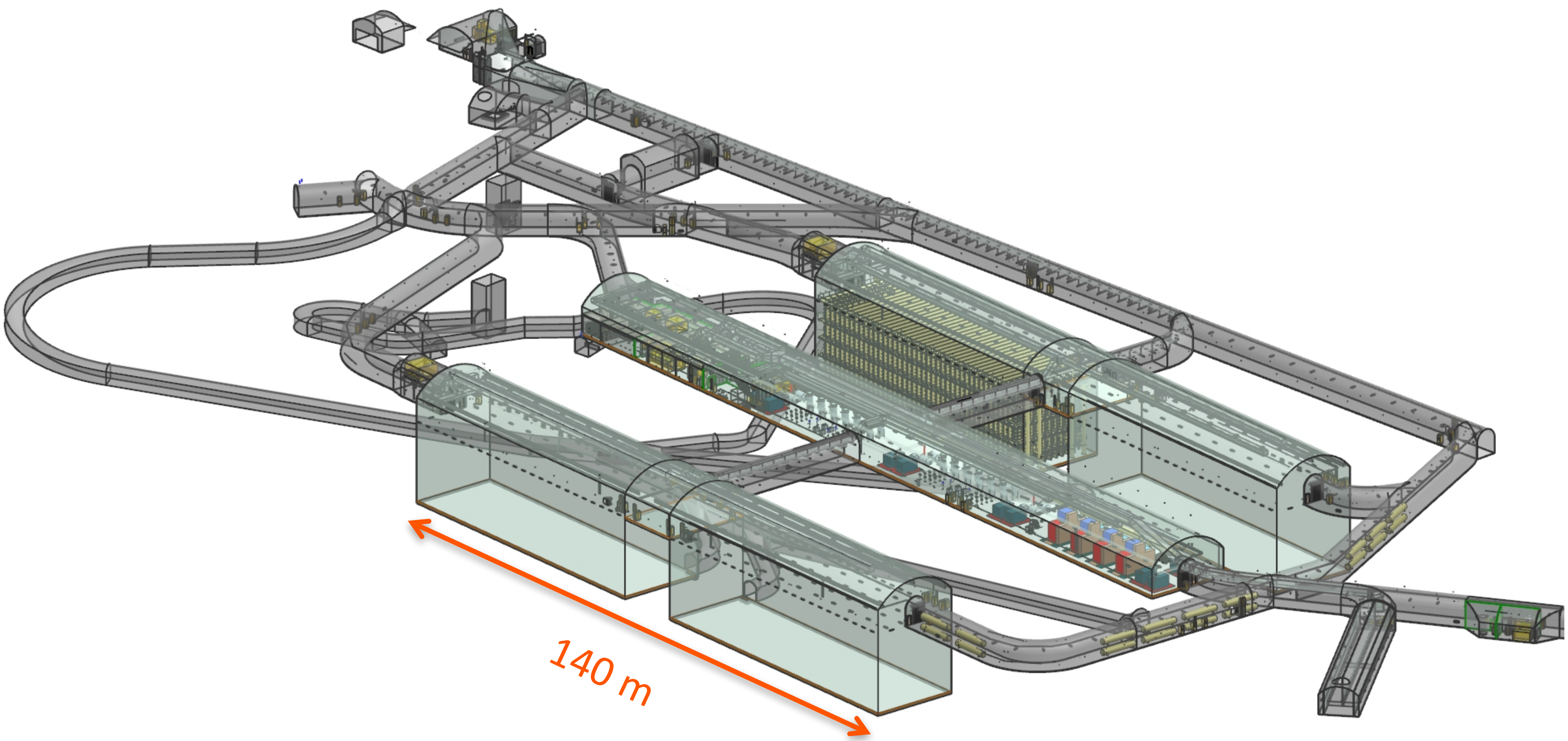


Ross Campus:
- CASPAR
- …
- **DUNE**

Green = new construction commences in 2017

DUNE Design =

Far detector: 70-kt LAr-TPC = 4 x 17 kt detectors



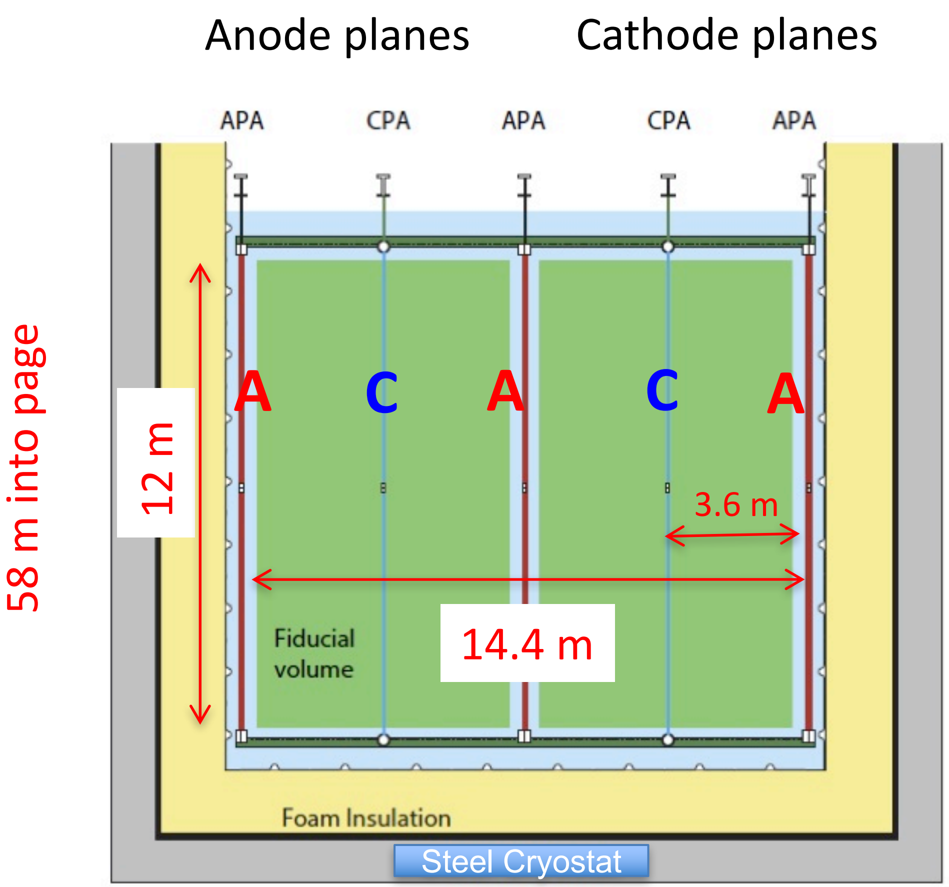
Four detectors modules

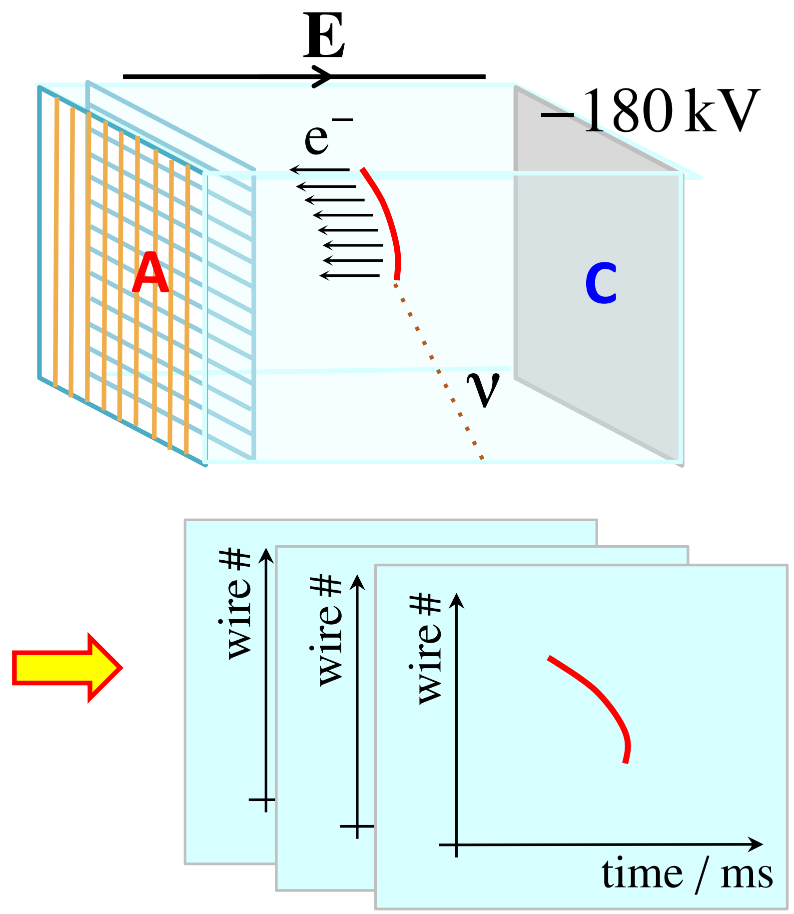
- Allows staged deployment of Far Detector

First 17-kt Far Detector Module

A modular implementation of Single-Phase LAr TPC

- Record ionization in LAr volume ⇨ 3D image





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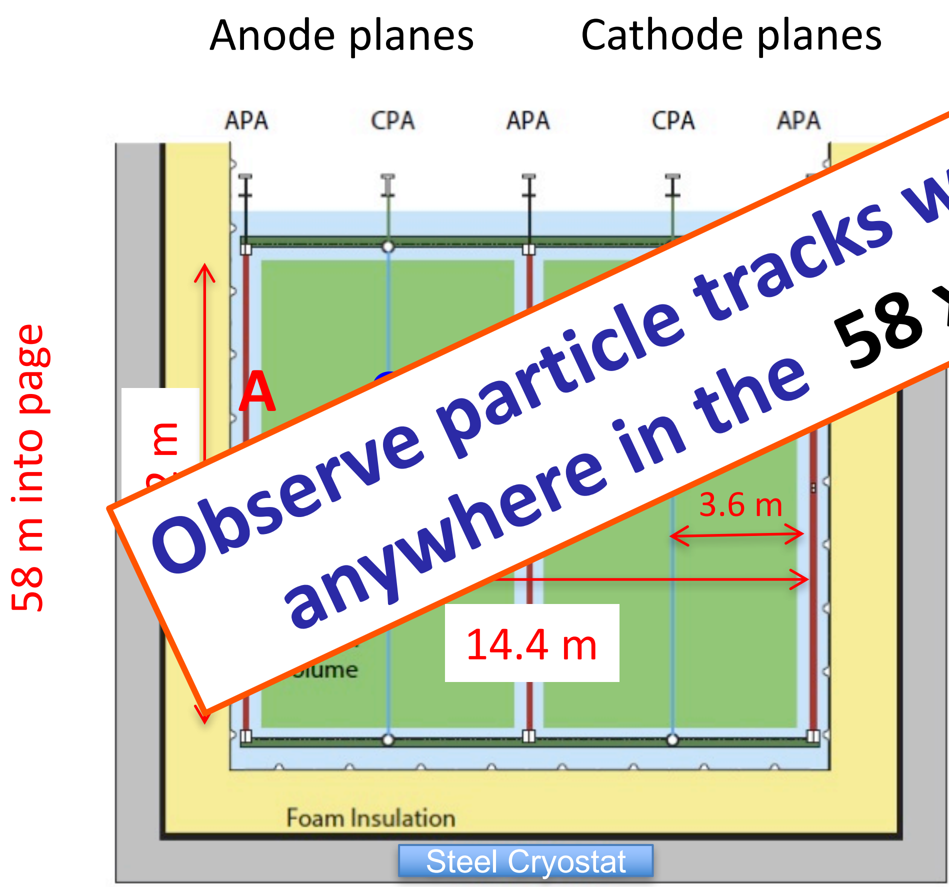
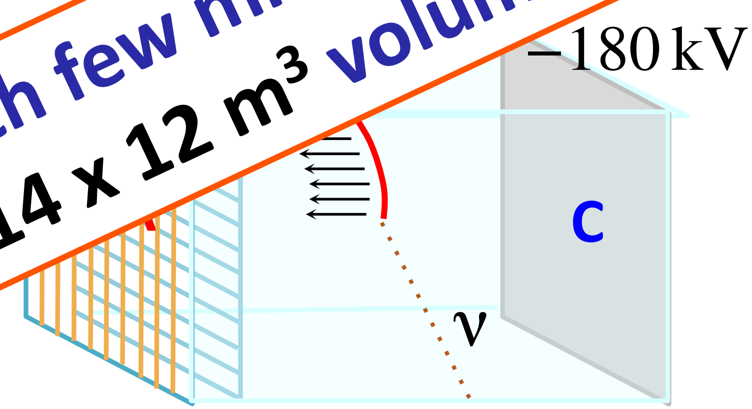
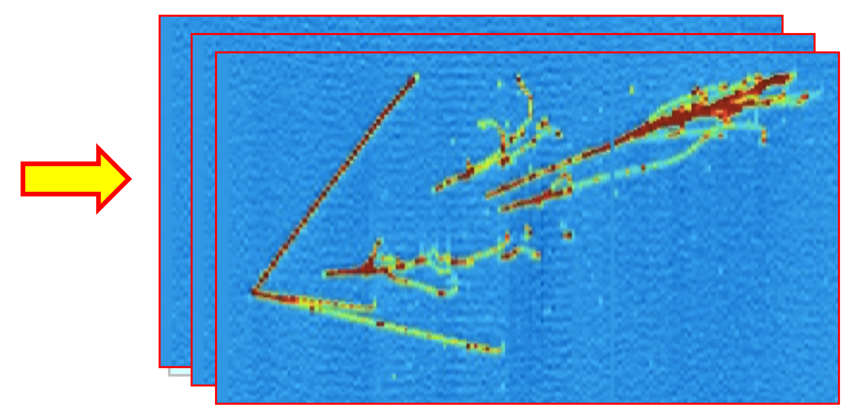




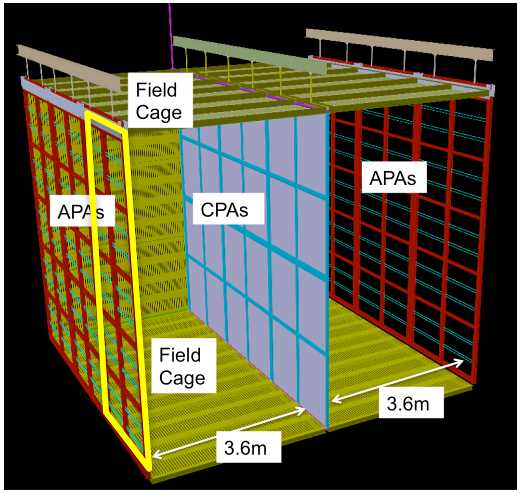


Observe particle tracks with few mm precision anywhere in the 58 x 14 x 12 m³ volume

4.3 Far Detector Prototyping

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

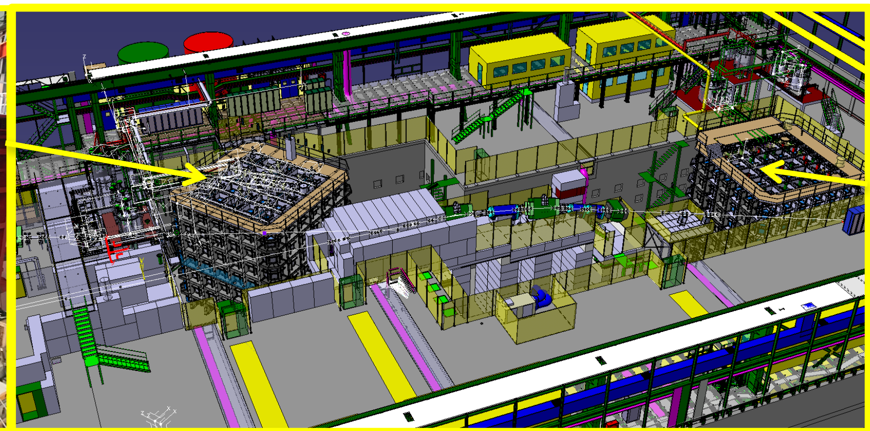
- Design is well advanced – evolution from ICARUS
- Supported by strong development program at Fermilab
  - 35-t prototype (ran in early 2016
  - MicroBooNE (operational since 2015)
  - SBND (start of operation in 2018/2019)
- "Full-scale prototypes" with ProtoDUNE at the **CERN Neutrino Platform**
  - **Engineering prototype**
    - 6 **full-sized** drift cells c.f. 150 in the far det.
  - Approved experiment at CERN
  - Aiming for operation mid-2018



CERN Neutrino Platform

CERN support of international neutrino programme

- Focus is on protoDUNE:
  - **Major investment by CERN to support DUNE**
  - New building: EHN1 extension in the North area
  - Two tertiary charged-particle beam lines
  - Two **large** (8x8x8 m^3) cryostats & cryogenic systems + …



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ProtoDUNE: a major step to FD construction:

- engineering risk mitigation
- setting up production processes
- design validation
- physics calibration data

Membrane Cryostats

- Becoming very real – fill with liquid argon in July 2018

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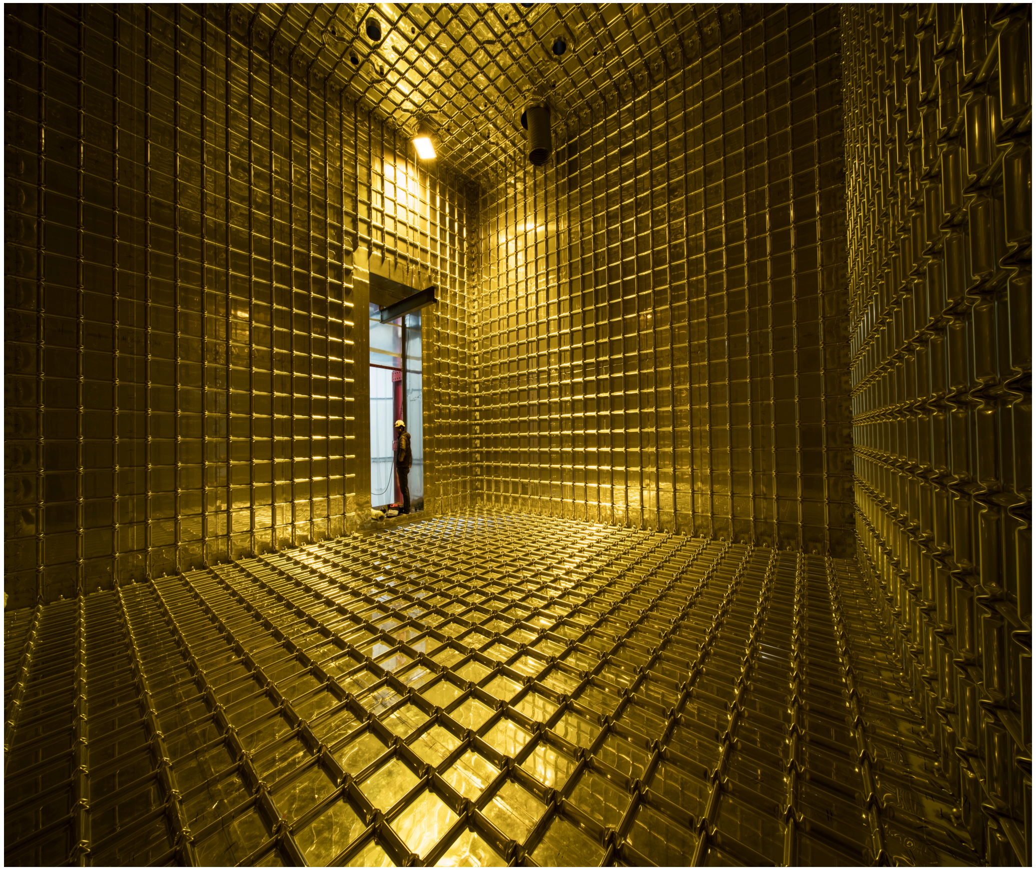


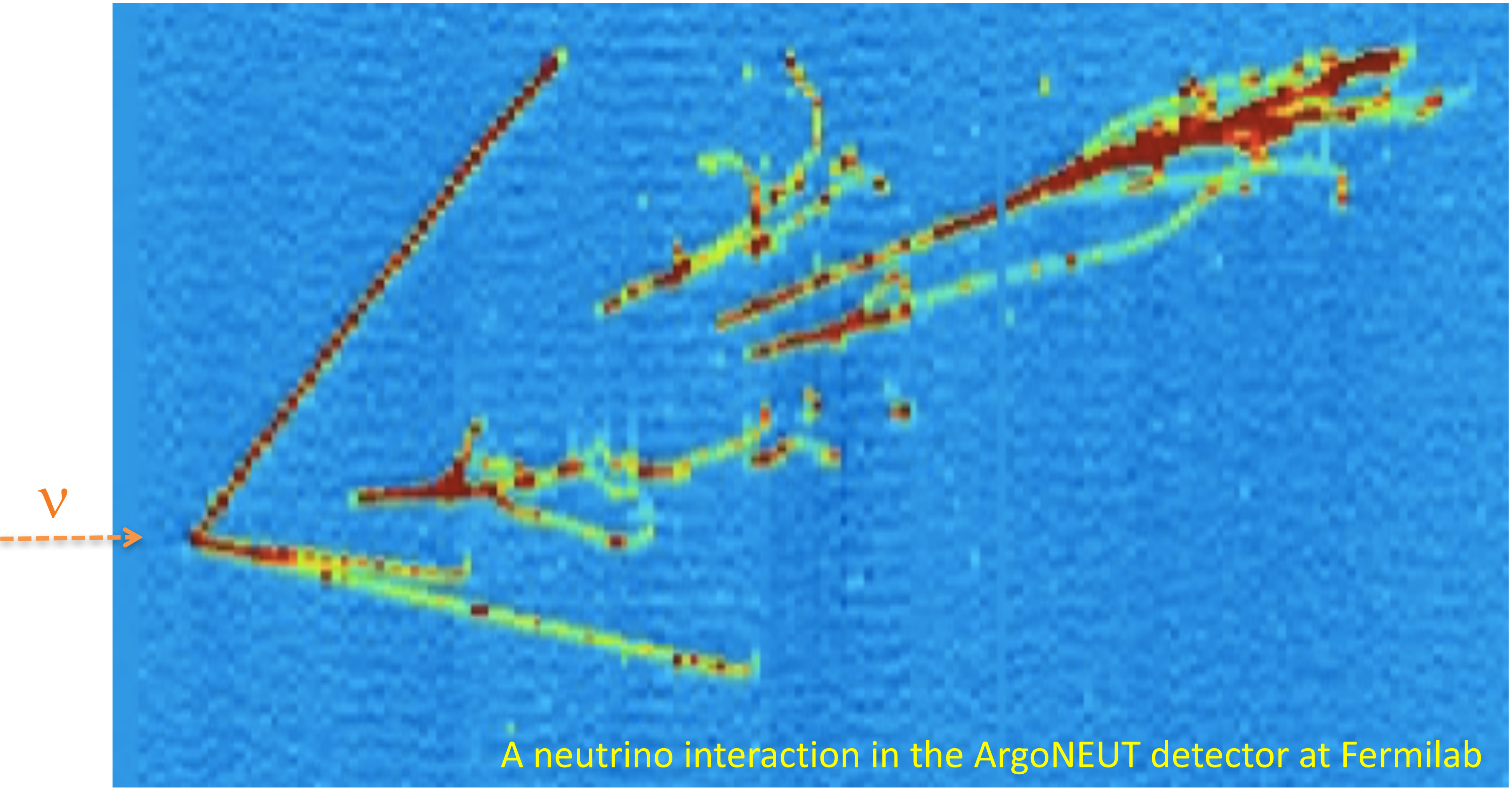
Membrane Cryostats

- Becoming very real – fill with liquid argon in July 2018

Detector elements ready to be installed

5. DUNE Science

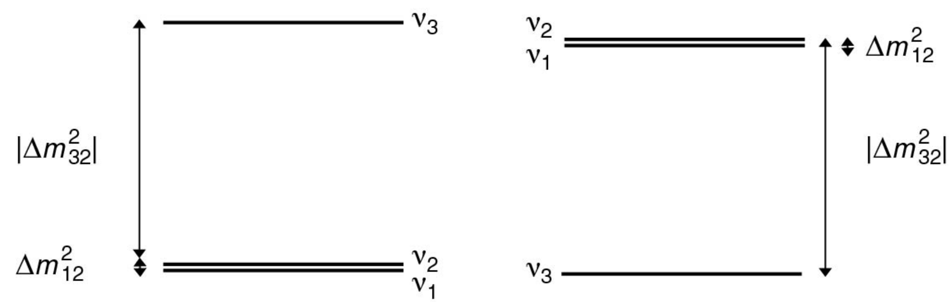
- Unprecedented precision utilizing a massive **Liquid Argon TPC**
  - The new technology of choice for ν-beam experiments



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:
    - parameter measurement, θ_{23} octant
    - **testing the 3-flavor paradigm**, steriles, NSI
      - neutrinos are different, so could be more surprises



- **2) Nucleon Decay**
  - e.g. targeting SUSY-favored modes, $p \rightarrow K^+\bar{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

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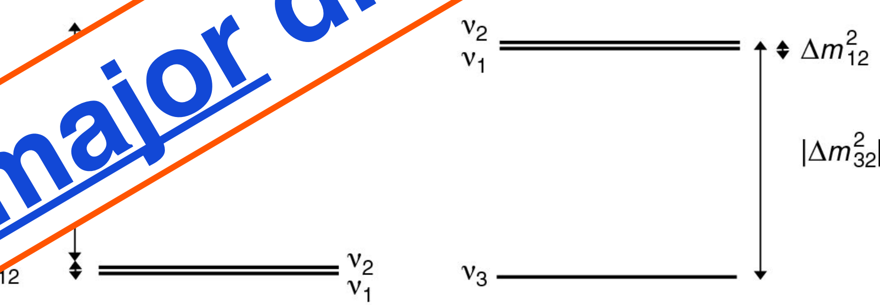
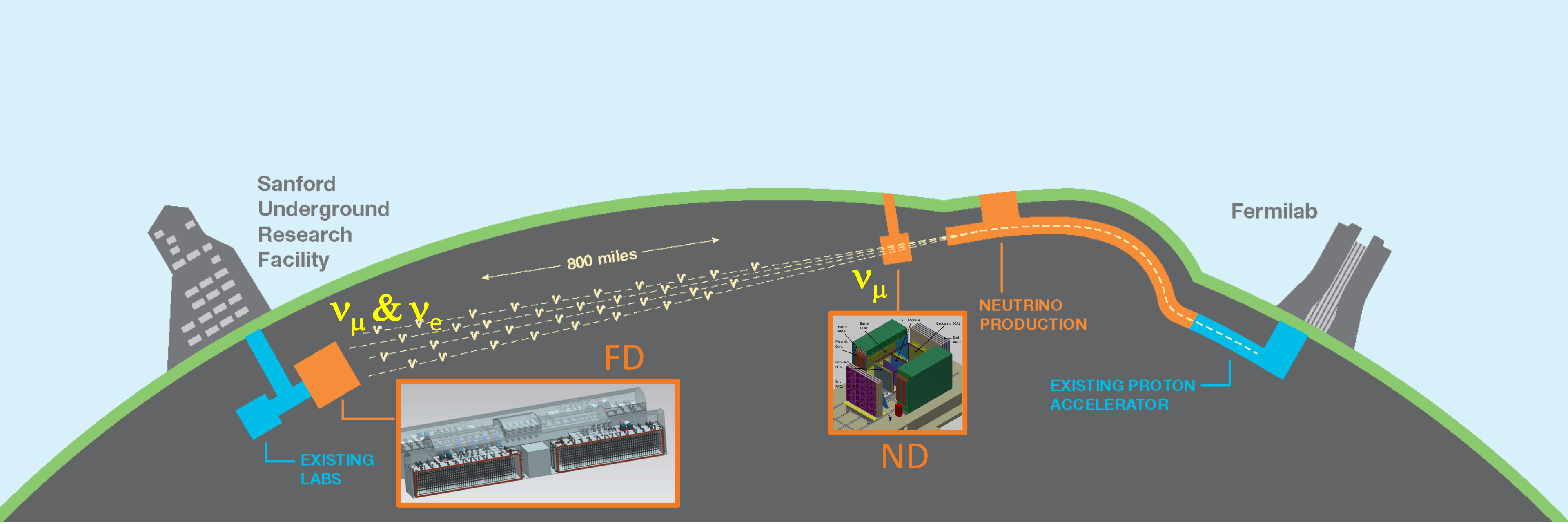


Each would be a *major* discovery

Long Baseline (LBL) Oscillations

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

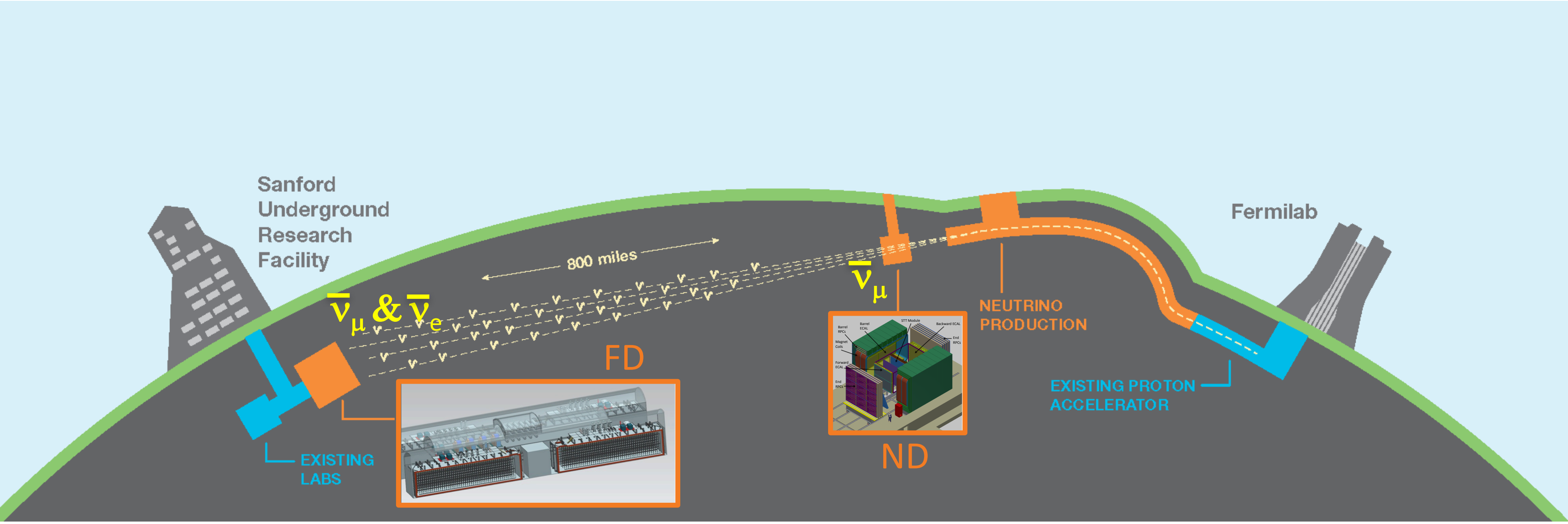


- **Near Detector at Fermilab: measurements of ν_μ unoscillated beam**
- **Far Detector at SURF: measure oscillated ν_μ & ν_e neutrino spectra**

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

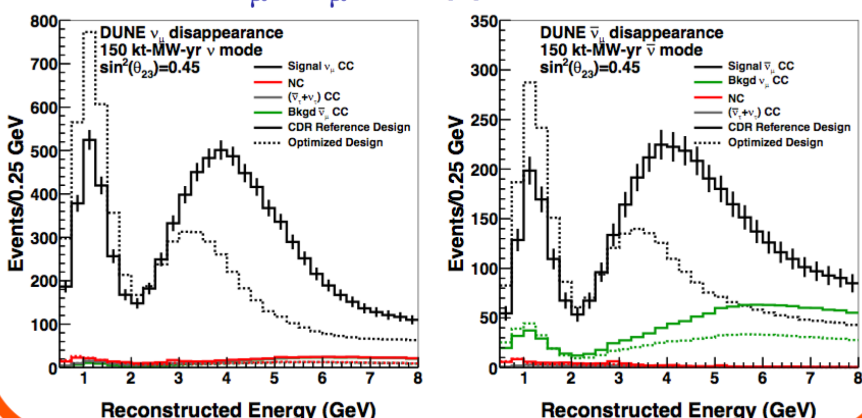
Measure neutrino spectra at 1300 km in a wide-band beam

- **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

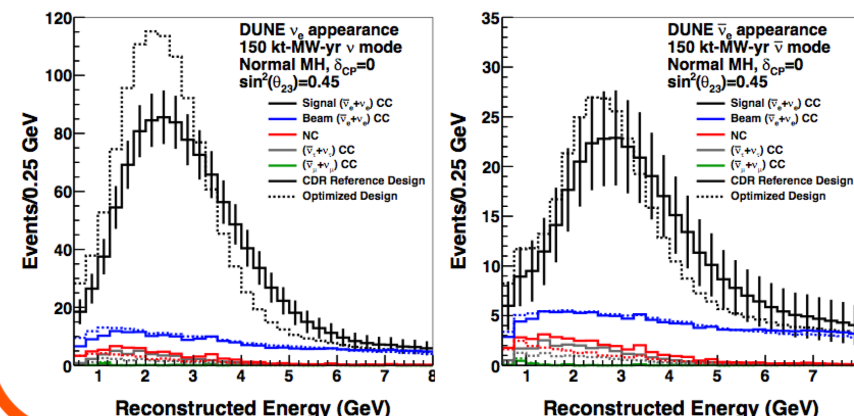
μ

ν_μ / $\bar{\nu}_\mu$ disappearance



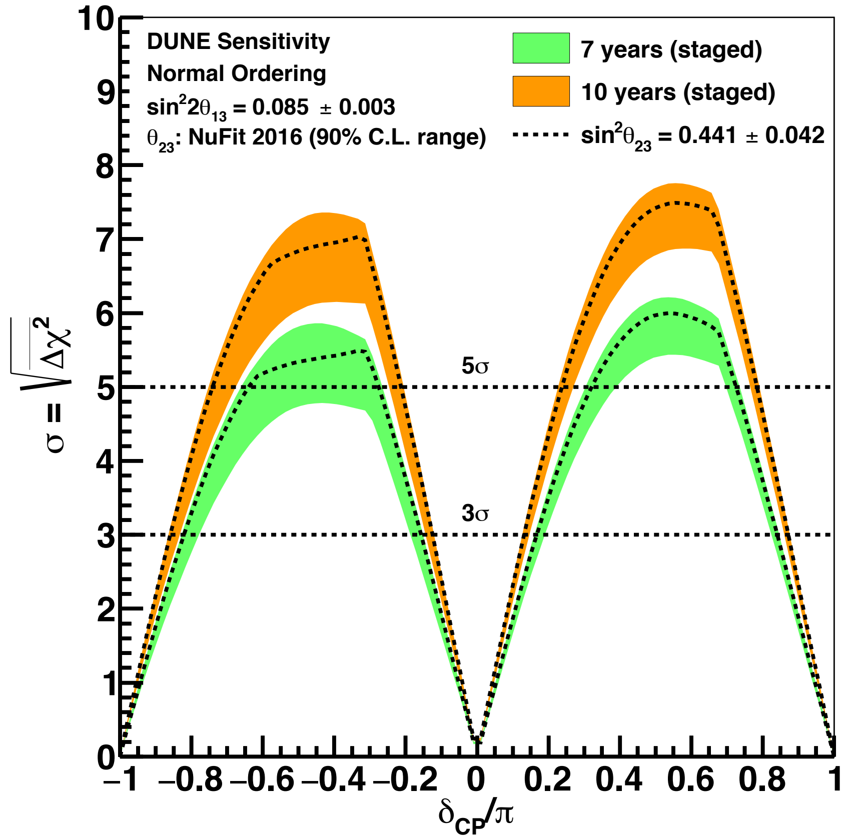
e

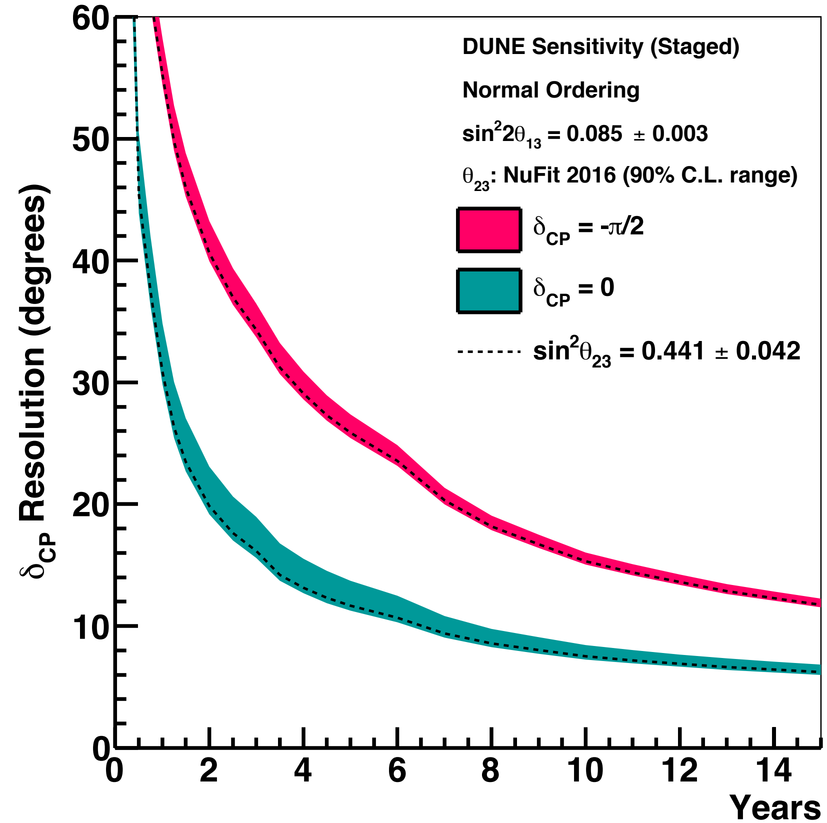
ν_e / $\bar{\nu}_e$ appearance



CP Sensitivity

CPV Discovery → **δ_{CP} Measurement**





Oscillation Über-Summary

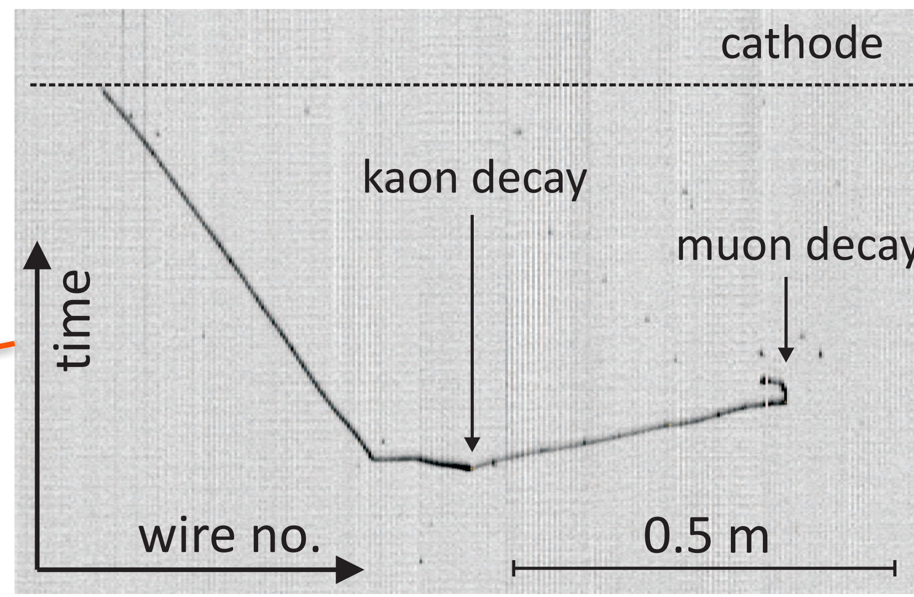
- **Nail the Mass Hierarchy**
  - 5σ in 2 – 5 years
- **75 % coverage for 3σ CPV discovery**
- **If "lucky", CPV reaches 3σ (5σ) in 3-4 (6-7) years**
- **Measure δ_{CP}**
  - $7^o – 15^o$ in 10 years
- **Wide-band beam + long baseline**
  - **Unique tests of 3-flavour paradigm**
  - Sensitivity to BSνM effects, e.g. NSI, steriles, ...

5.1 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)



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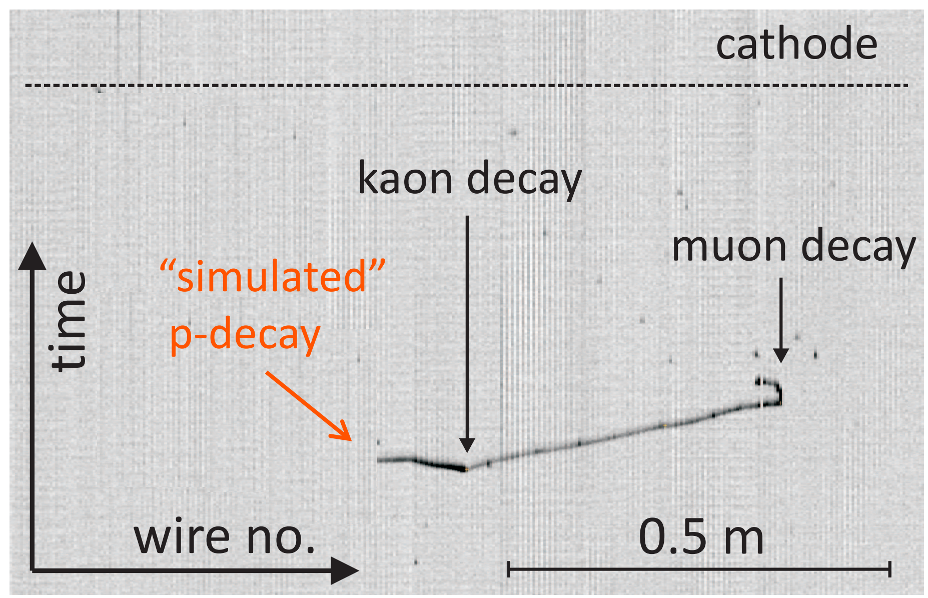
- **Clean signature**

  ➡ **very low backgrounds**

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

1 Mt.yr

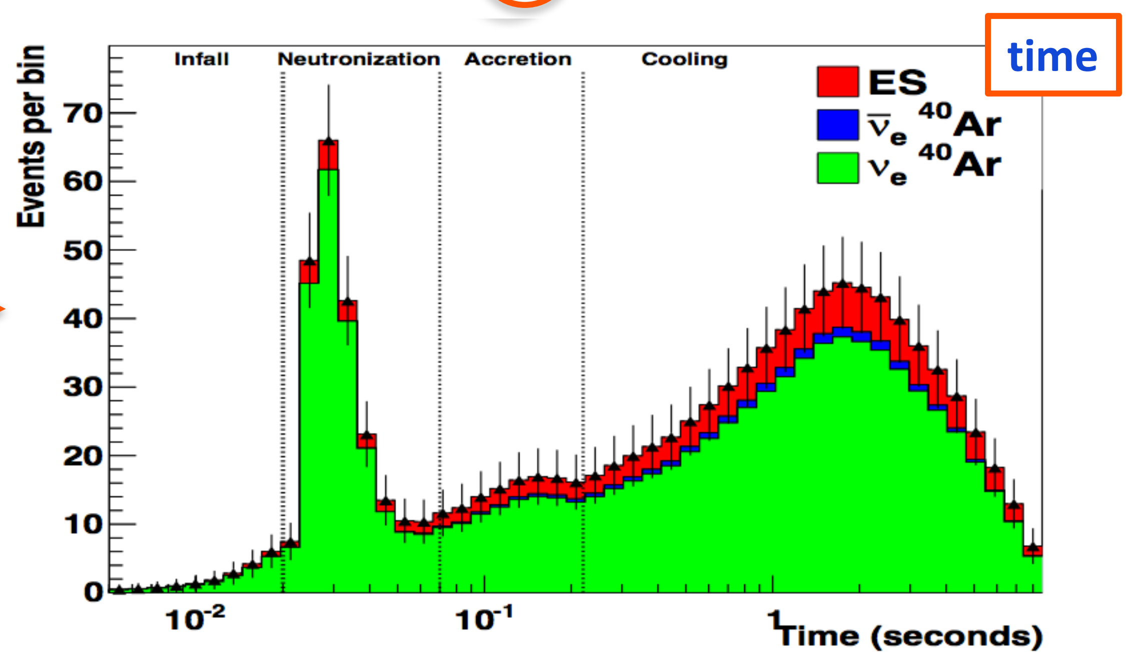
Remove incoming particle



5.2 Supernova νs

A core collapse SN produces an intense burst of neutrinos

- **Would see about 10000 neutrinos from a SN in our galaxy**
- **Over a period of 10 seconds**
  - In argon (uniquely) the largest sensitivity is $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$



Highlights include:

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

6. Status of DUNE

Status of DUNE

- ★ **DUNE is a massive undertaking**
- ★ **Requires:**
  - Large international scientific community ✅
  - High-level international support ✅

- ★ **DUNE is going ahead !**
  - **2016:** CD-3A approval in US ✅
  - **2017:** start of construction in South Dakota ✅
  - **2018:** operation of two large-scale prototypes at CERN
  - **2021:** installation of first 10-kt far detector module
  - **2024:** commissioning/operation of first far detector
  - **2026:** start of beam operation (1.2 MW)

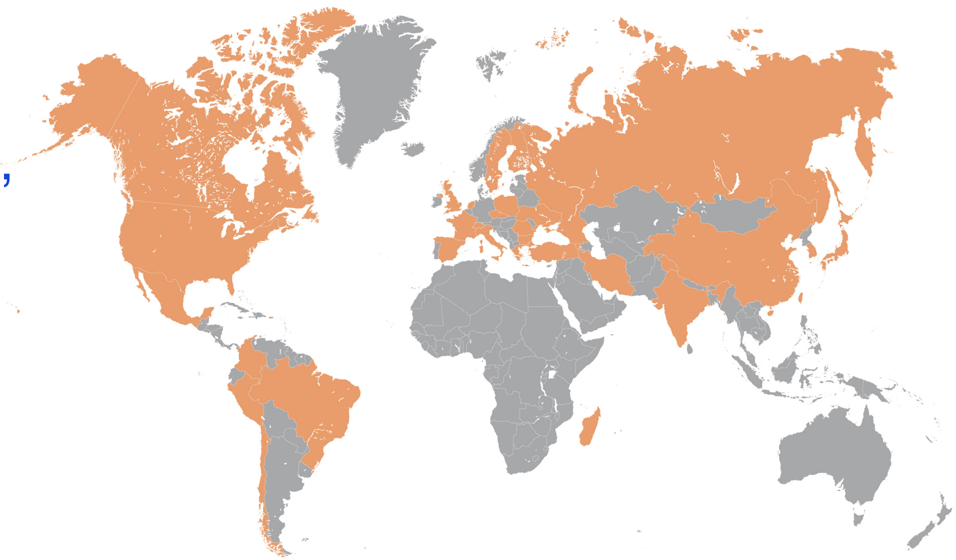
The DUNE Collaboration

As of today:

>60 % non-US

1059 collaborators from 175 institutions in 31 nations

Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Paraguay, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, UK, Ukraine, USA

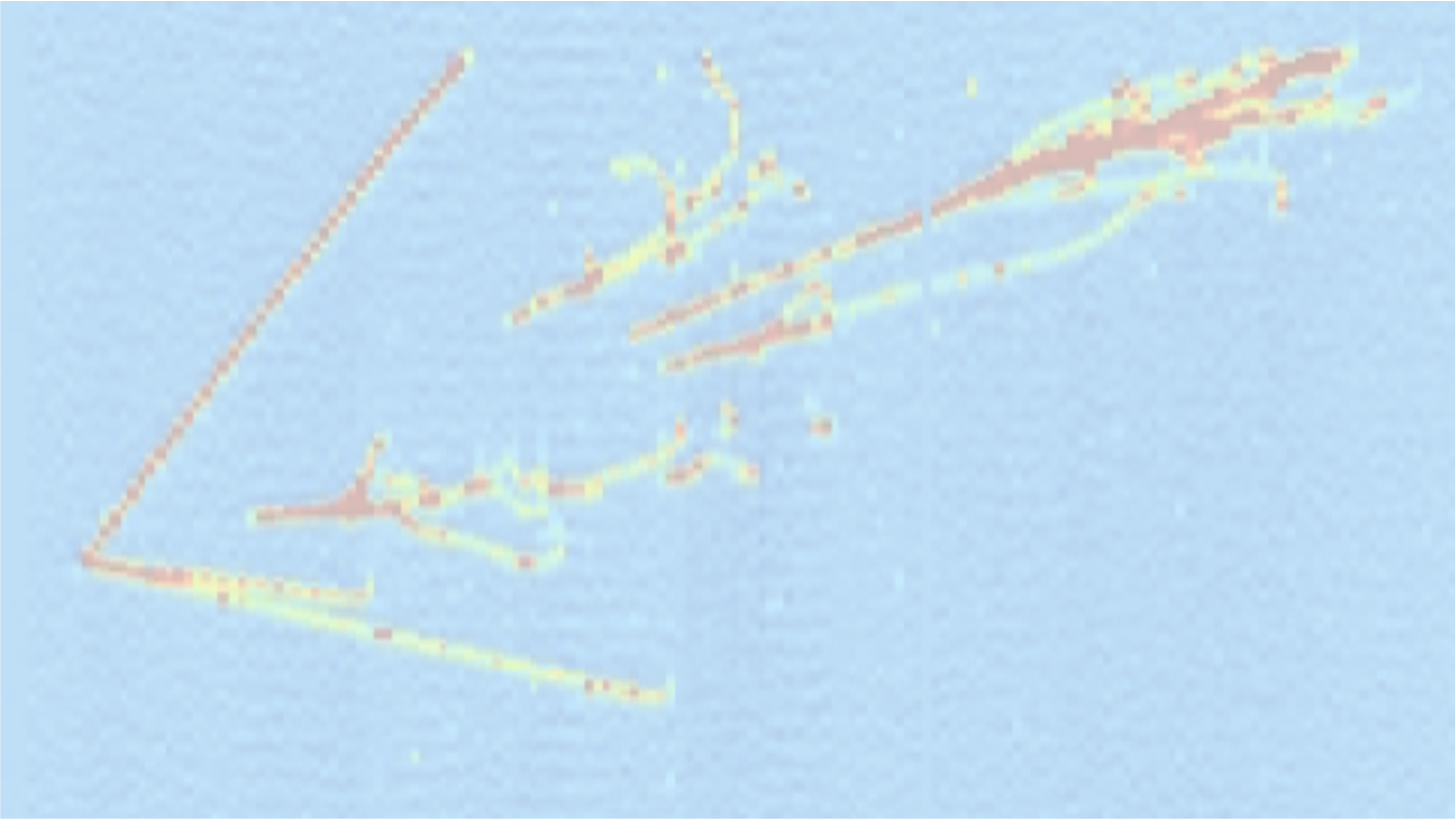


DUNE has broad international support and is growing brought together by the exciting science….

Connection to the Terascale…

- **Perhaps surprisingly many synergies with the collider programme:**
  - Particularly in the Near Detector
    - Which will have a tracker, calorimeters…
  - 100Ms of ν interactions !
- **Possible synergies**
  - Tracker: High-Pressure Gaseous Argon TPC
  - Calorimeters: High-granularity "CALICE-style" Scintillator ECAL
- **Near Detector design is work in progress**
  - Aiming to fix "ND concept" by Summer 2018
  - **Many opportunities for intellectual/technical input**

7. 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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- DUNE is now ballistic
- The timescales are not long:
  - Starting construction at South Dakota in 2017
  - The large-scale DUNE prototypes will operate at CERN in 2018

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

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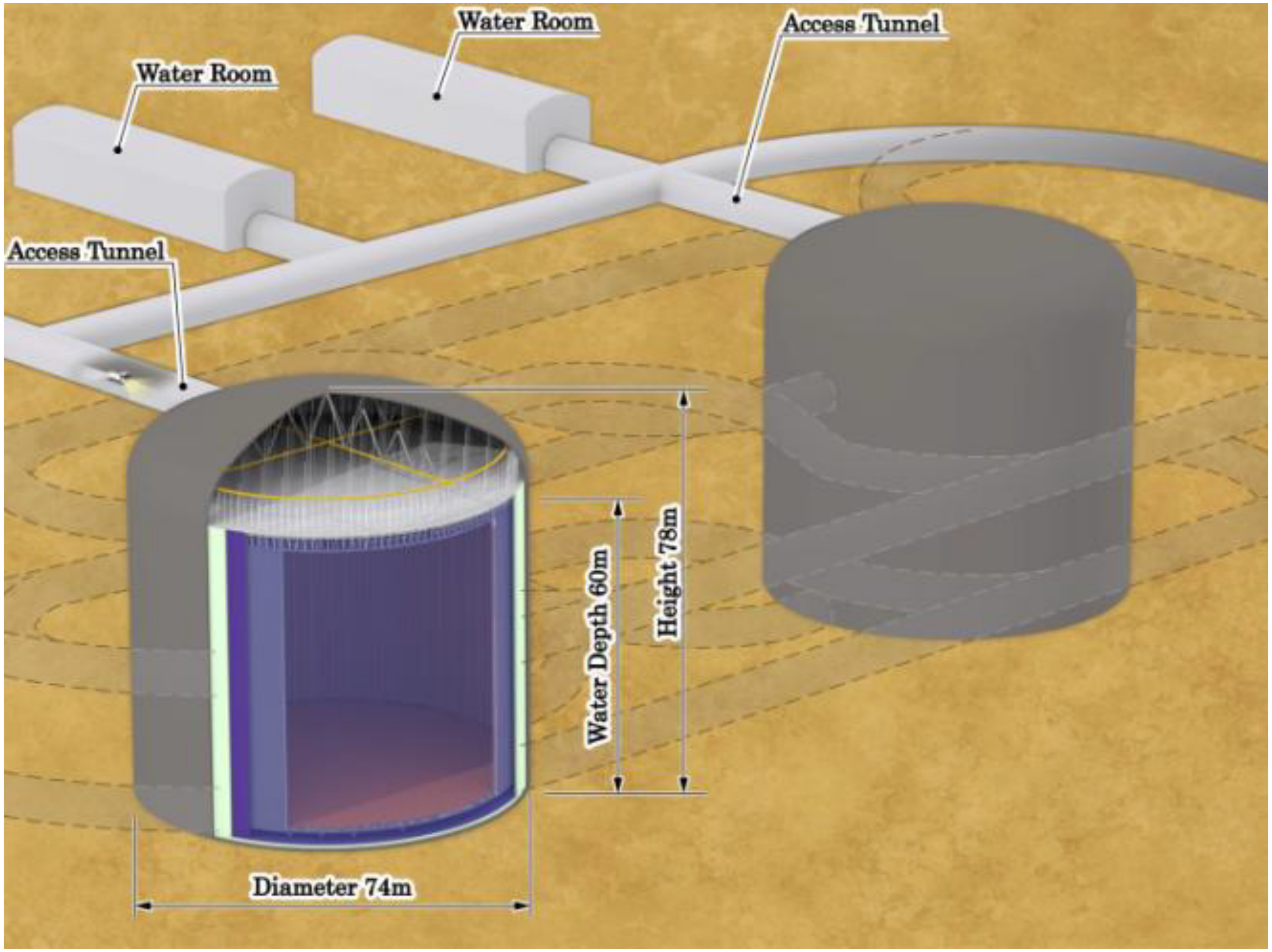
We are currently launching the next "big thing" in particle physics: exciting times ahead

Thank you - questions?

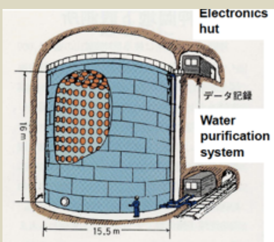
8. Hyper-Kamiokande



Far Detector

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

Kamiokande
(1983-1996)

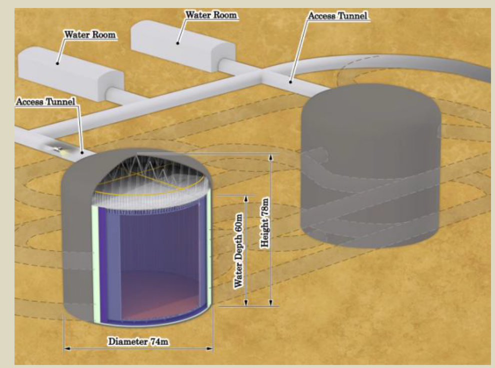


3 kton

Super-Kamiokande
(1996-)

50 kton

Hyper-Kamiokande
(2026?-)

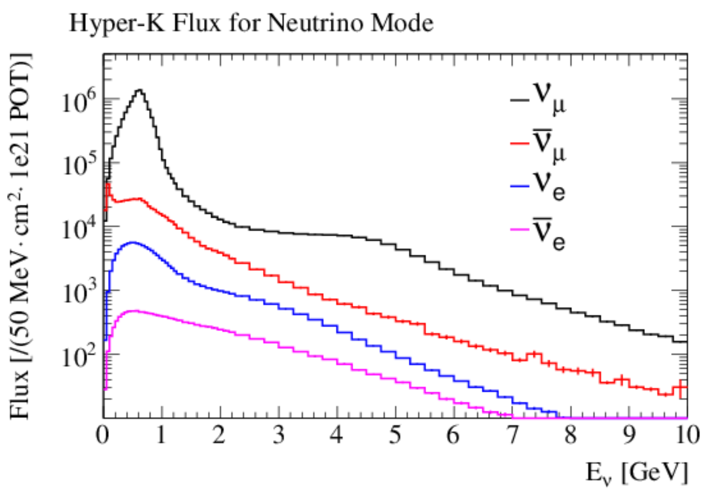


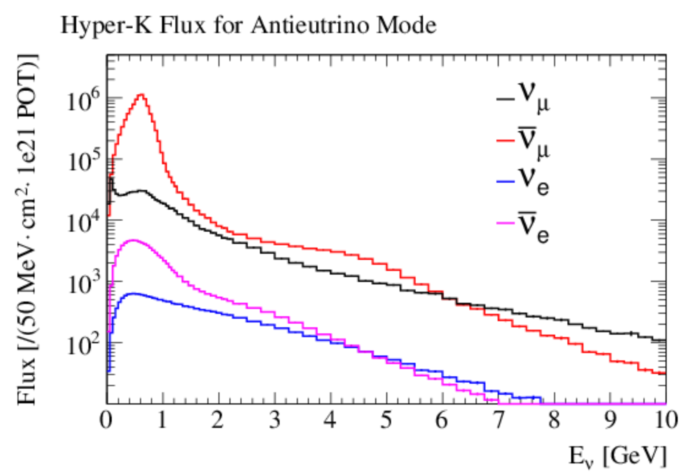
260 kton + 260 kton

- **1 Tank:**
  - Fiducial volume = 190 kton
  - Photomultiplier tubes: 40,000 50cm PMTs (inner detector)

JPARC Beam for Hyper-K

- ★ **Upgraded JPARC beam**
- ★ **Assume 1.3 MW at start of experiment**
  - Physics studies assume:
    - 6 years with one tank (260 kt)
    - 4 years with two tanks (2 x 260 kt)
  - 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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  - Particularly strong for decays with π^0
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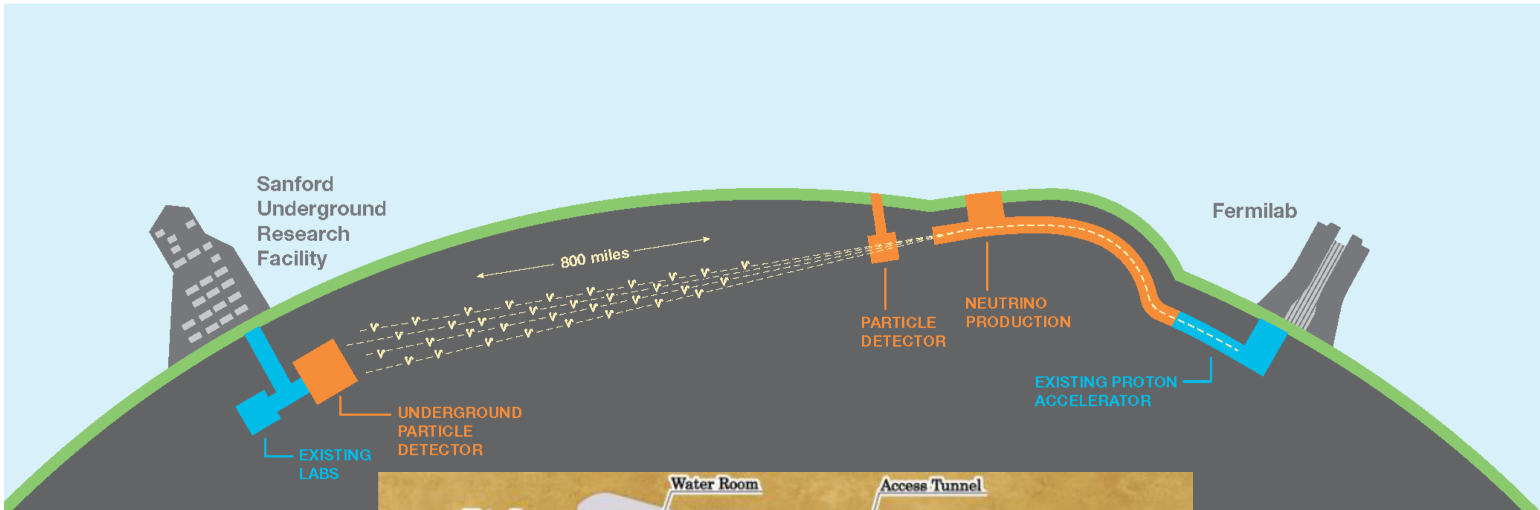
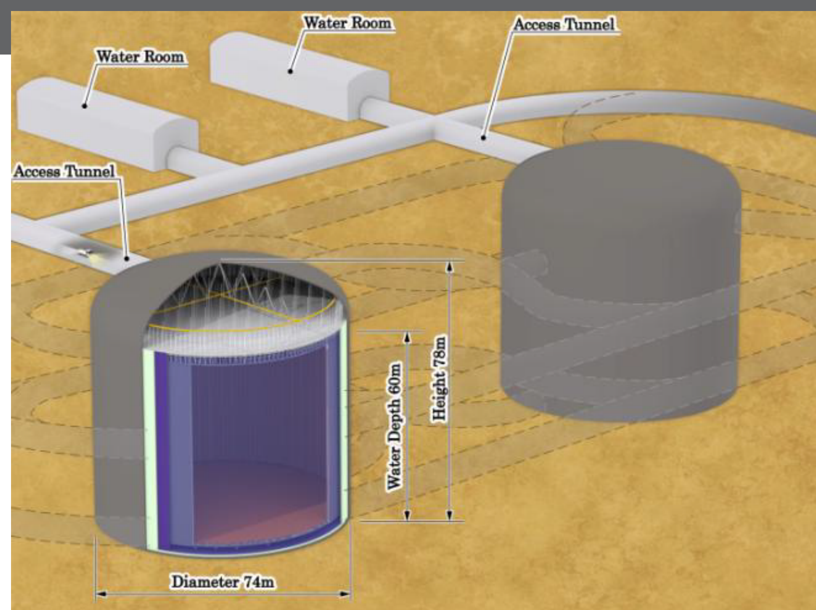
  - Galactic core collapse supernova, sensitivity to $\overline{\nu}_e$

★ **Significant complementarity with DUNE physics**

A. DUNE & Hyper-Kamiokande





DUNE & Hyper-K: at 10 years

- HK based on plan at ICHEP'16 - 2 tanks staged + JPARC upgrades
- DUNE schedule based on LBNF/DUNE RLS & funding model

10 years (staged)		HK	DUNE
CP violation	δ resolution	7° – 21°	7° – 15°
	3σ coverage	78%	74%
	5σ coverage	62%	54%
Mass Hier.	sens. range	$5\,\sigma - 7\,\sigma$	$8\,\sigma - 20\,\sigma$
octant	sens. @ 0.45	5.8σ	5.1σ
	5σ outside of…	[0.46, 0.56]	[0.45, 0.57]
p decay (90% C.L.)	$p \to \bar{\nu} K^+$	>2.8e34 yrs	>3.6e34 yrs
	$p \to e^+ \pi^0$	>1.2e35 yrs	>1.6e34 yrs
supernova ν (10 kpc or relic)	SNB $\bar{\nu}_e$	130k evts	
	SNB ν_e		5k evts
	relic $\bar{\nu}_e$	100 evts, 5σ	
	relic ν_e		30 evts, 6σ
NSI (90% C.L.)	$\lvert \varepsilon_{\mu e} \rvert$	<0.34	<0.05
	$\lvert \varepsilon_{\mu\tau} \rvert$	<0.27	<0.08
	$\lvert \varepsilon_{\tau e} \rvert$	<0.98	<0.25

* **many caveats:** but gives the general picture of 10-year sensitivities at ±10% level