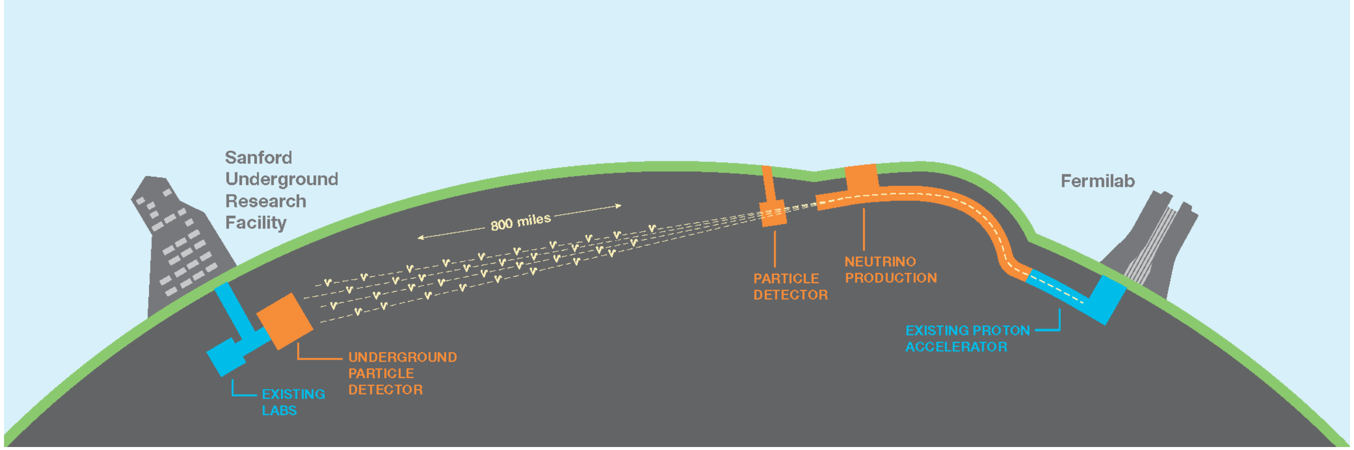


# Future Accelerator-Based Neutrino Experiments

Mark Thomson

University of Cambridge & DUNE co-spokesperson

XLV International Meeting on Fundamental Physics, Granada

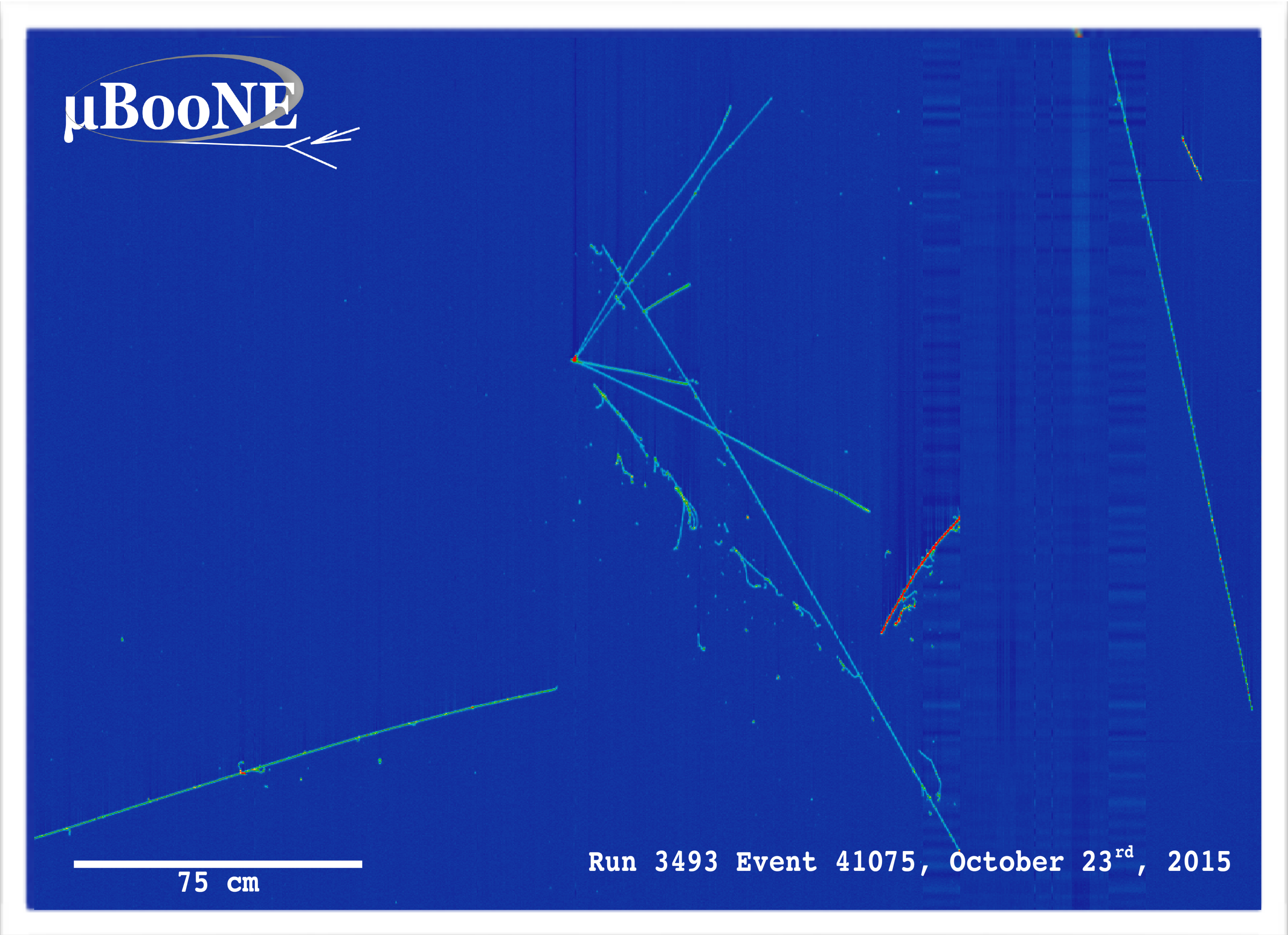
UNIVERSITY OF CAMBRIDGE

DUNE

# Future Beam Neutrino Expts:

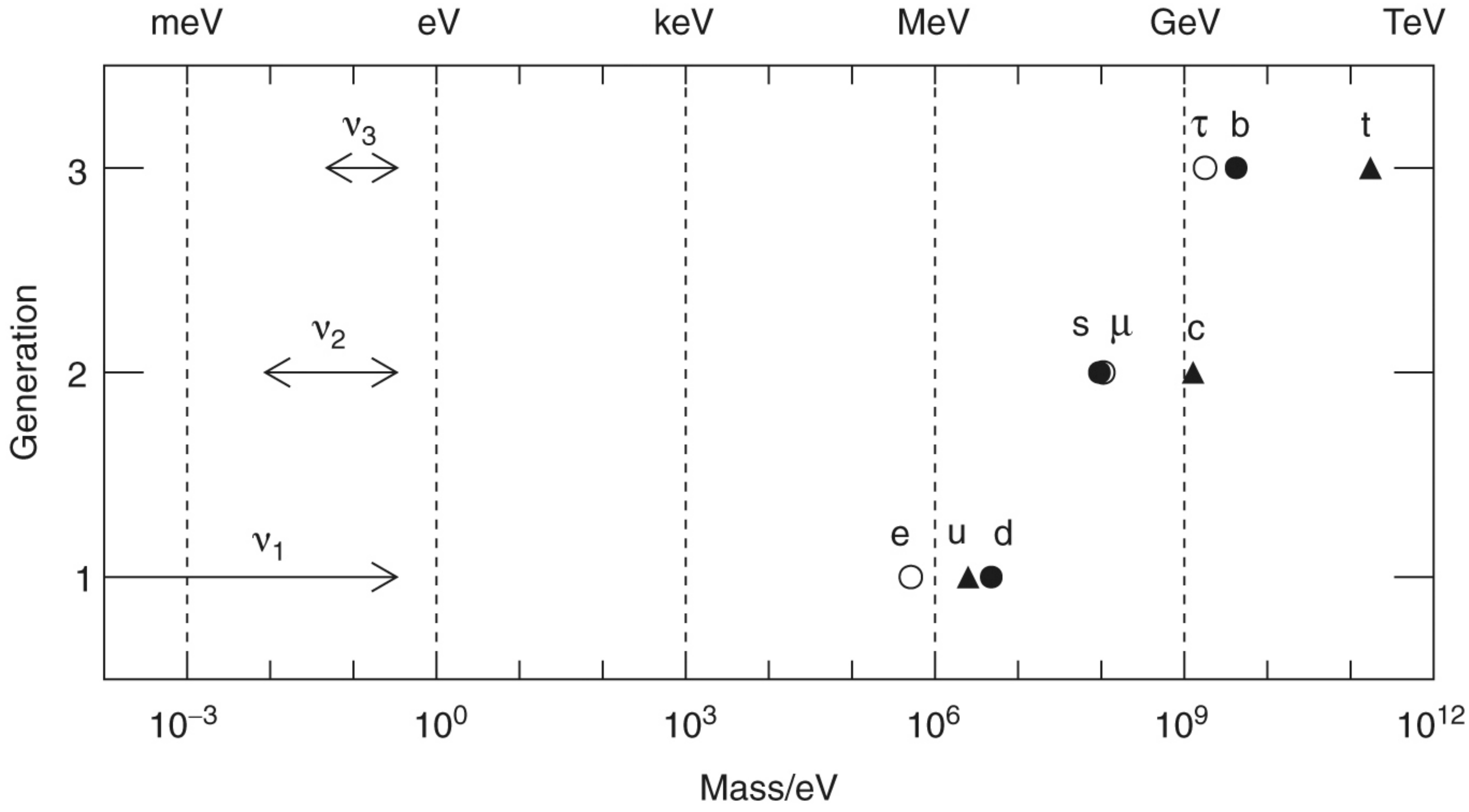
## The Quest for a [Neutrino] Holy Grail

# 1. Neutrinos are especial



# Neutrinos are especial

- **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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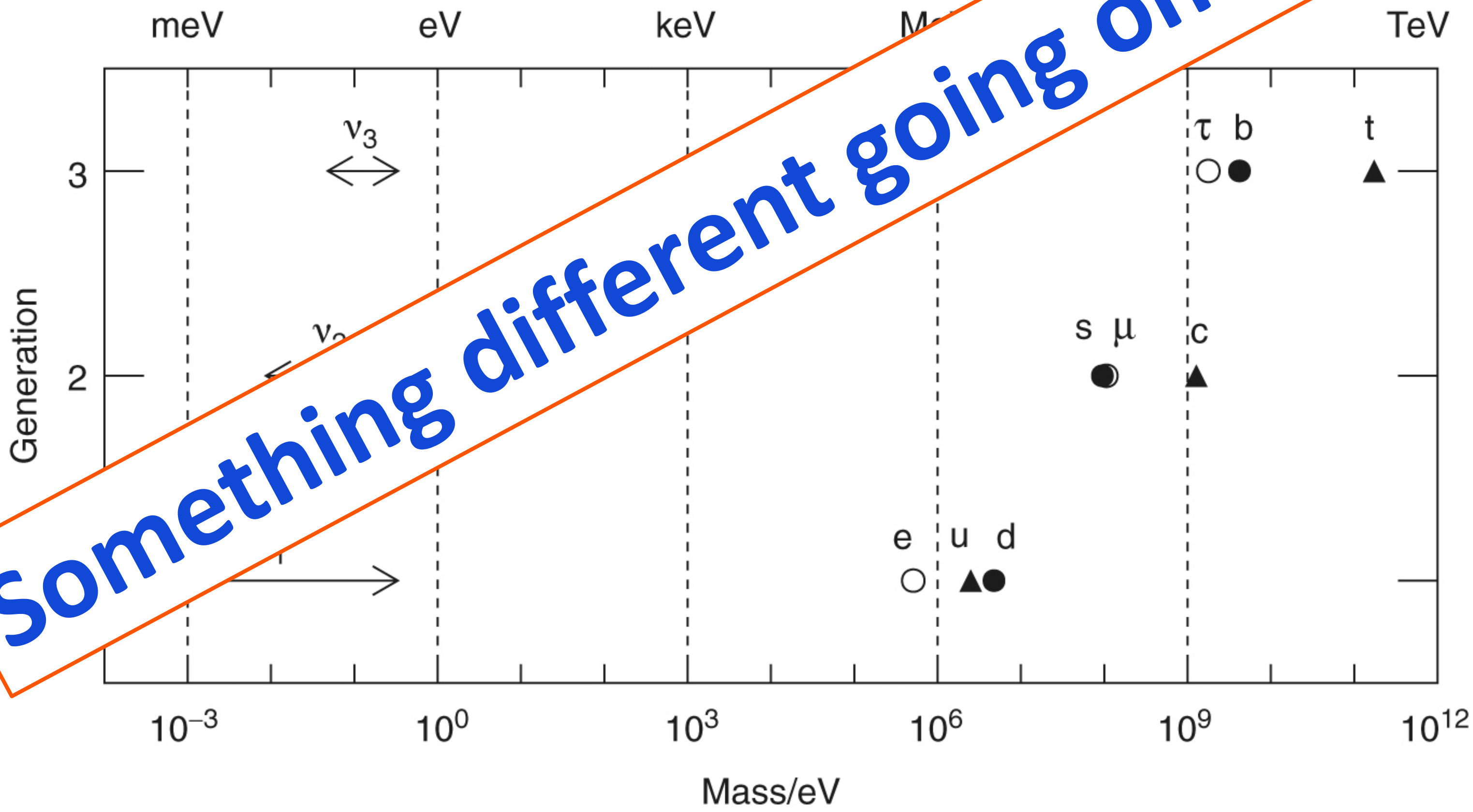
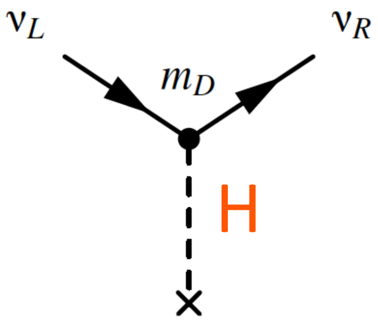


**Something different going on here…**

# 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

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

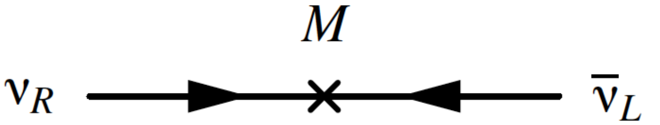
- This also could be the origin of neutrino masses

⇨ 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)

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

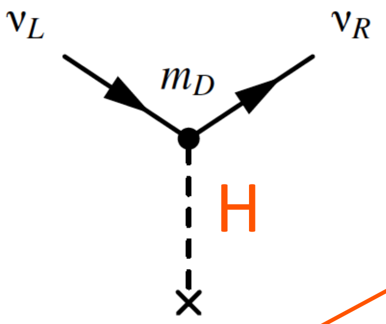


This additional freedom might explain why neutrino masses are "different"

# a connection to new physics…

★ **Neutrino masses are anomalously small**

- Particle masses "generated" by the Higgs me



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

**Neutrinos could be a fundamentally different type of particle**

- This also could b ... rino masses
  - Existen ... ather minimal extension to the SM?
- But ... auge singlet – *feels none of SM forces*
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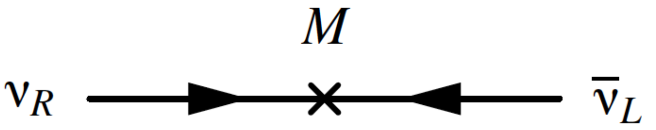
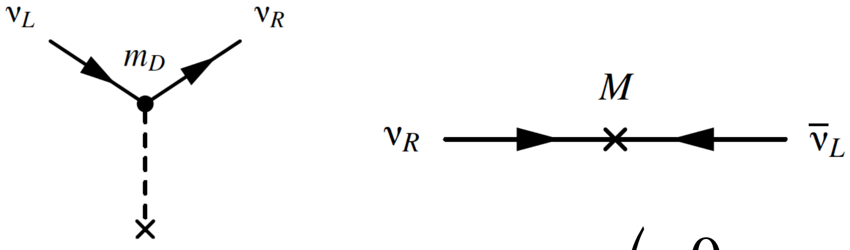


This additional freedom might explain why neutrino masses are "different"

# a connection to the GUT scale?

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

- If both Dirac and Majorana mass terms are present



(nothing to prevent this)

+ implies Lepton # violation

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

- 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:

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

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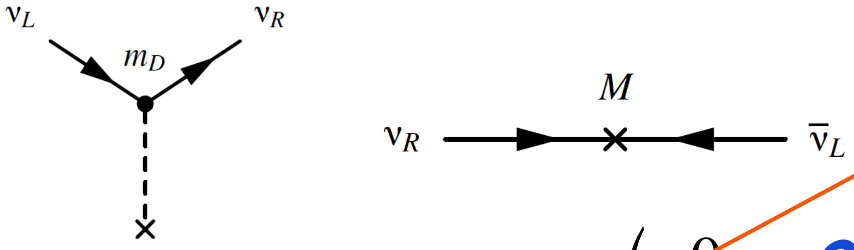

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⇨ $$\mathcal{L} \sim -\tfrac{1}{2}\left(\overline{\nu_L}\quad \overline{\nu^c_R}\right)\begin{pmatrix} 0 & \\ & M \end{pmatrix}\begin{pmatrix}\nu^c_L \\ \nu_R\end{pmatrix}$$

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

**Neutrinos could provide a link to GUT-scale physics**

# The Standard 3-Flavour Paradigm

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

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

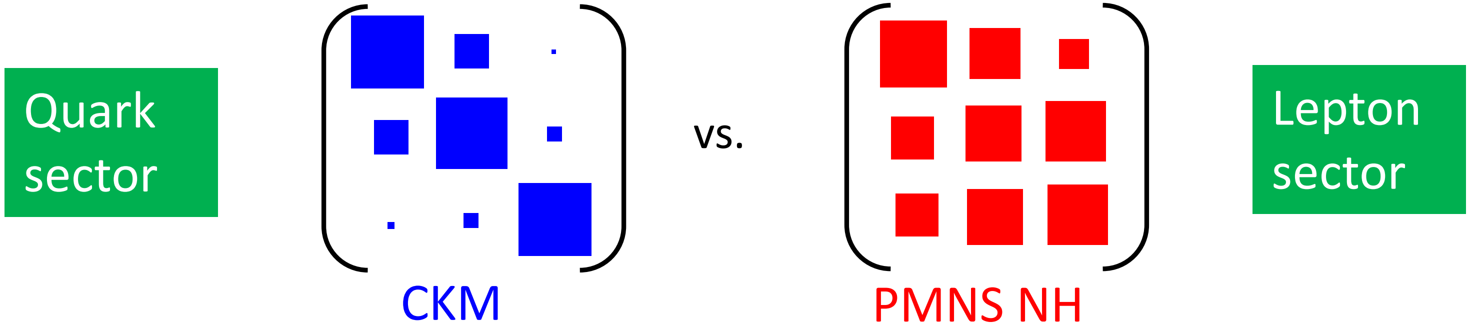
$$U_{\mathrm{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{-i\delta}} \\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

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

★ Have **measurements** of the angles $(\theta_{12},\ \theta_{13},\ \theta_{23})$

- but only very weak constraints on the complex phase:

★ The lepton sector looks very different to the quark sector



Quark sector

vs.

Lepton sector

CKM

PMNS NH

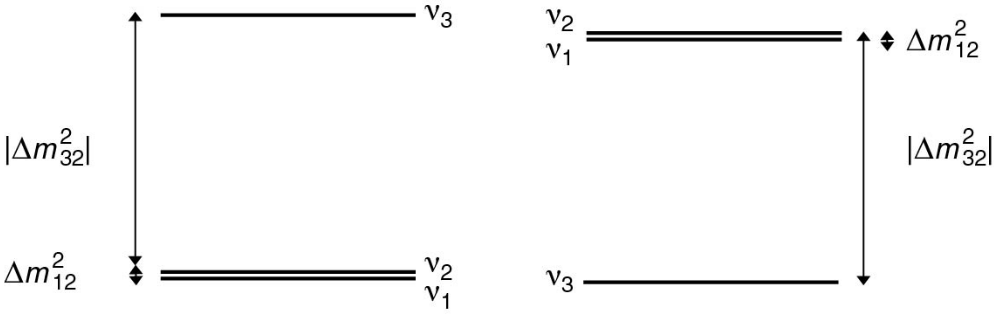
# Knowns and Unknowns

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

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

✅ ✅ ✅ ✅ ✅ ? ?

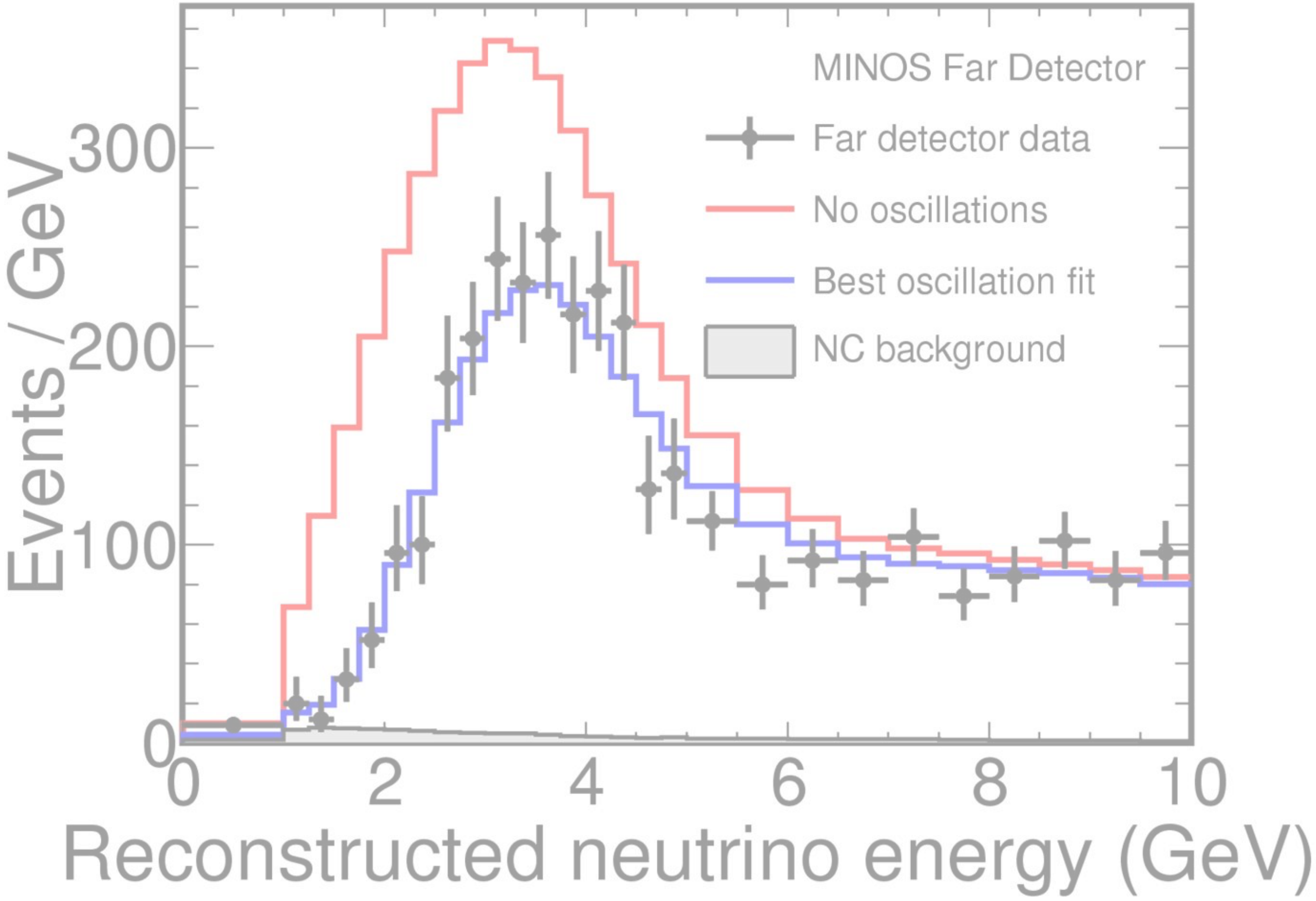
**Mass Hierarchy not yet known**



**$\delta_{CP}$ not known $\nu$CPV?**

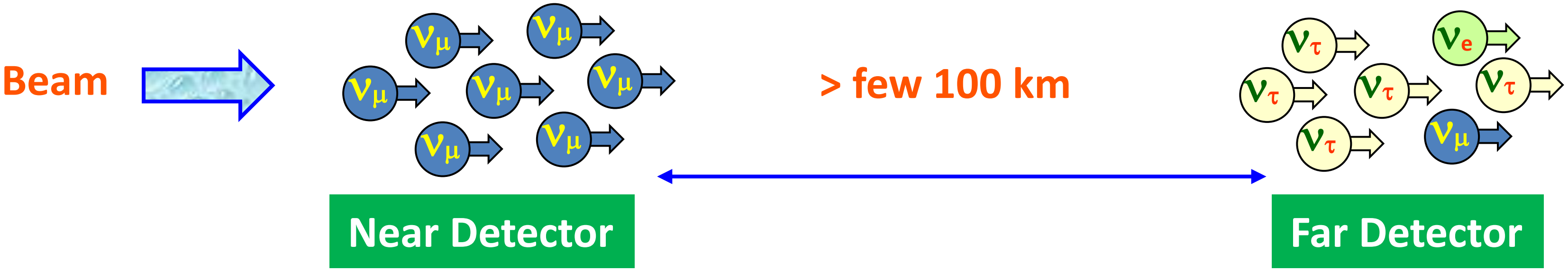
- **CP violation and mass hierarchy are major goals**
  - Also want to test the 3-flavour neutrino Standard Model

# 2. Long-Baseline Neutrino Expts.



# Why neutrino beams?

- Observations of oscillations of Solar, Reactor and Atmospheric neutrinos central to establishing SM of νs
  - Beam comes for “free”, but you get what nature gives you
- Beam neutrino oscillations experiments give control
  - But need intense beams (100s kW) and long baselines
- Basic idea:
  - Sample the unoscillated beam near to source and then the oscillated beam far from the source



**Beam**

**> few 100 km**

**Near Detector**

**Far Detector**

- 
  - “Clean” experiments from perspective of systematics
  - Baseline and beam energy chosen for physics goals

# Long-Baseline (LBL) Experiments

| Experiment | Run | Peak $E_\nu$ | Baseline | Detector | |
|---|---|---|---|---|---|
| K2K | 1999-2004 | 1 GeV | 250 km | Water Č | 1st Gen |
| MINOS(+) | 2005-2015 | 3 GeV | 735 km | Iron/Scint | 2nd Gen |
| CNGS/Opera | 2008-2012 | 17 GeV | 735 km | Emulsion | |
| T2K | 2010- | 0.7 GeV | 295 km | Water Č | 3rd Gen |
| NO$\nu$A | 2014- | 2 GeV | 810 km | Liq. Scint. | |

- ★ **LBL experiments key to our current understanding of $\nu$s**

**Measurement highlights:**

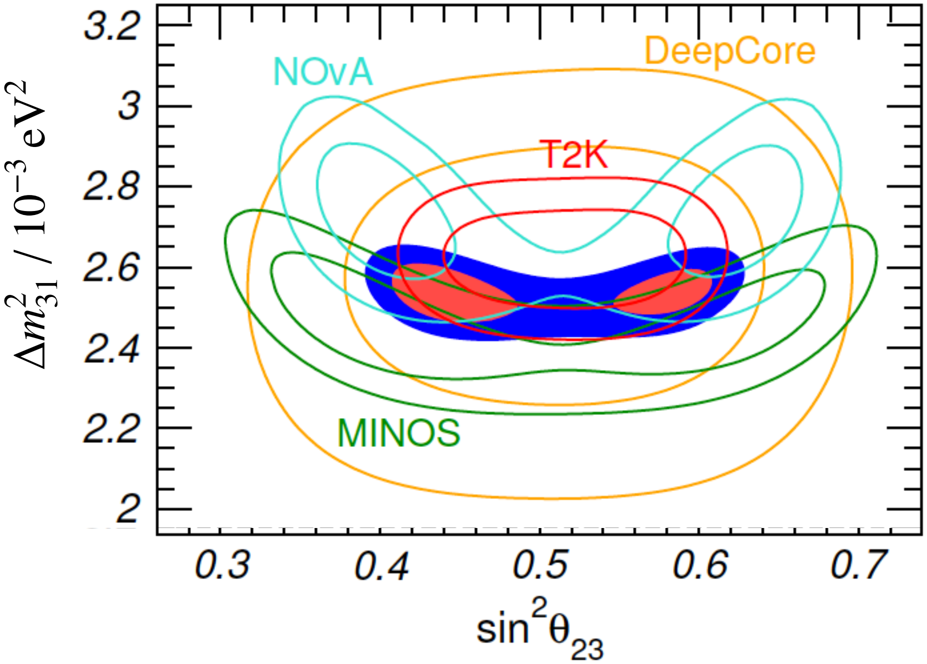
- **K2K** : confirm atmospheric neutrino oscillations ✓
- **MINOS** : precise measurement of $|\Delta m_{32}|^2$ and $\theta_{23}$ ✓
- **Opera** : observe tau appearance in $\nu_\mu \leftrightarrow \nu_\tau$ oscillations ✓
- **T2K** : observe $\nu_\mu \leftrightarrow \nu_e$ oscillations, measure $\theta_{13}$ ✓
- **NO$\nu$A** : $\nu_\mu \leftrightarrow \nu_e$ at a longer baseline for mass hierarchy…

# Combination from oscillation experiments

- **Two aspects**
  - Look at consistency of experiments
  - Combined current knowledge of neutrino osc. parameters:

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

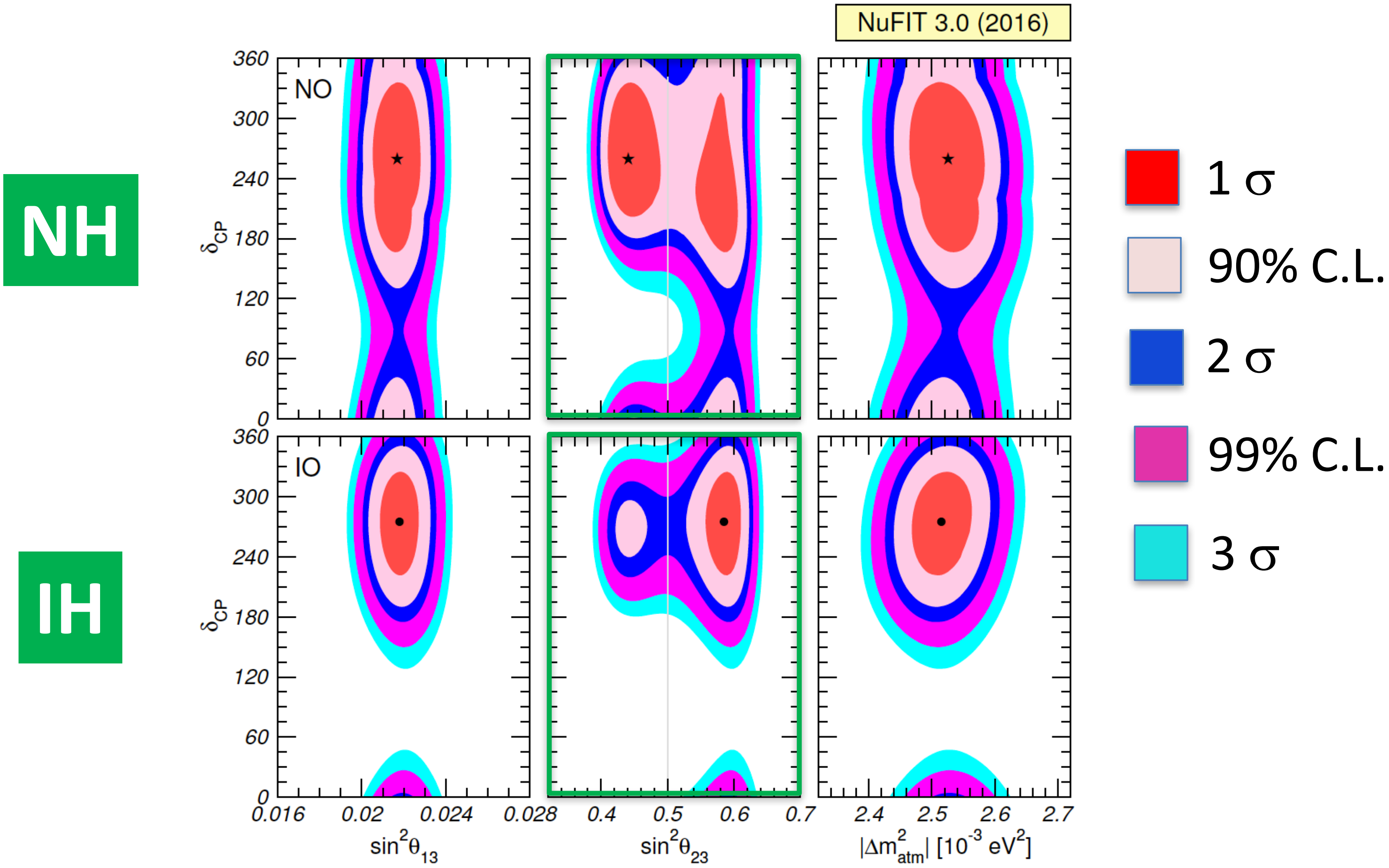
- **Putting aside sterile neutrinos a consistent picture emerges...**



**NH**

NuFIT2016

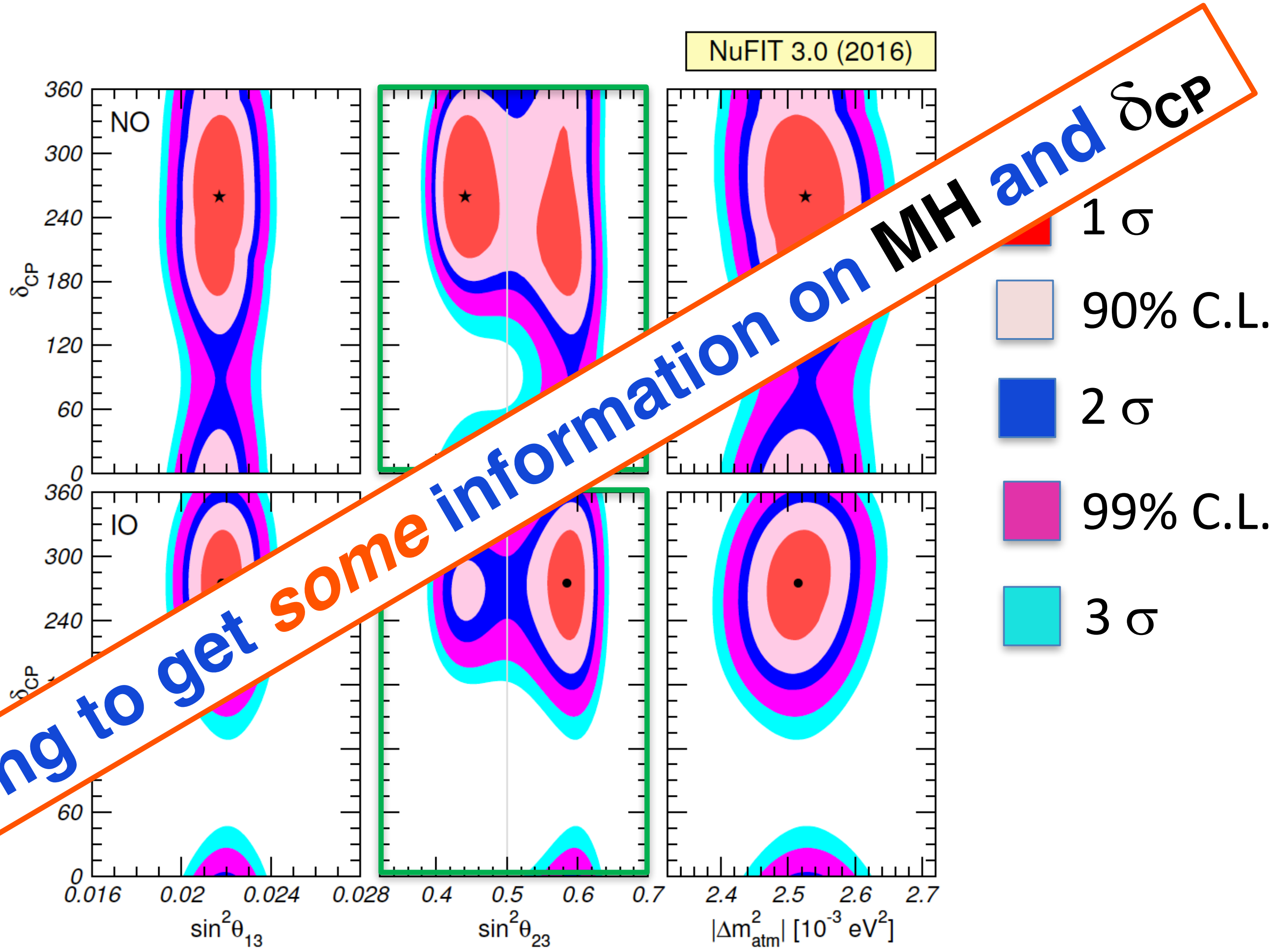
# CP and MH : Combined knowledge



# CP and MH : Combined knowledge

**NH**

**IH**

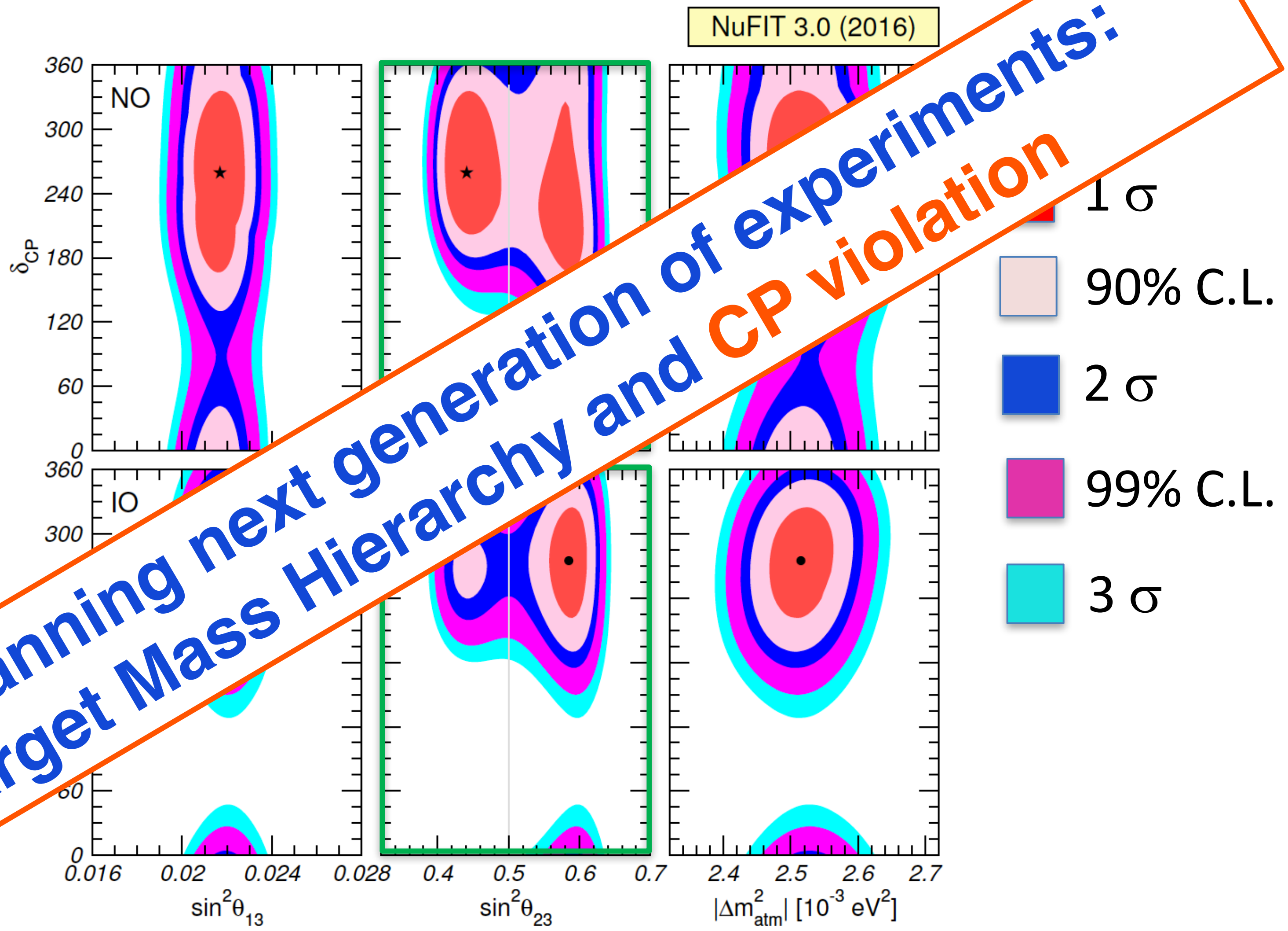


**Starting to get some information on MH and $\delta_{CP}$**

# CP and MH : Combined knowledge

**NH**

**IH**



**Now planning next generation of experiments: target Mass Hierarchy and CP violation**

# The Next Generation

| Experiment | Run | Peak $E_\nu$ | Baseline | Detector |
|---|---|---|---|---|
| K2K | 1999-2004 | 1 GeV | 250 km | Water Č |
| MINOS(+) | 2005-2015 | 3 GeV | 735 km | Iron/Scint |
| CNGS/Opera | 2008-2012 | 17 GeV | 735 km | Emulsion |
| T2K | 2010- | 0.7 GeV | 295 km | Water Č |
| NOνA | 2014- | 2 GeV | 810 km | Liq. Scint. |
| **DUNE*** | 2026- | 3 GeV | 1300 km | Liq. Argon |
| **Hyper-K†** | 2026- | 0.7 GeV | 295 km | Water Č |

1st Gen

2nd Gen

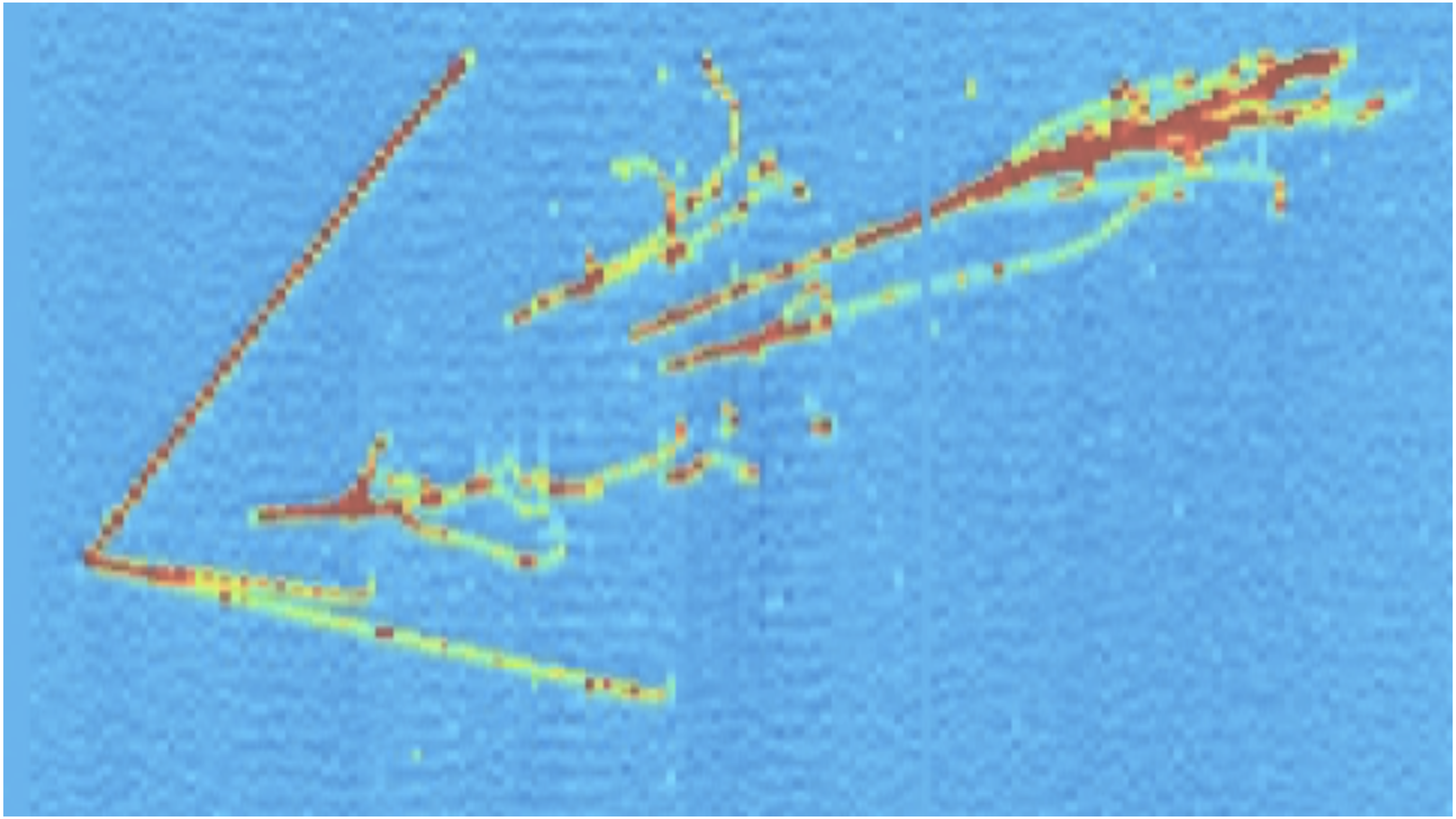
3rd Gen

**4th Gen**

*DUNE CD-3A construction approval in 2016

†Hyper-K will be seeking approval in 2017/2018

# 3. How to Detect CPV with $\nu$s



# In principle, it is straightforward

- ★ CPV ⇨ different oscillation rates for $\nu$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, $\theta_{13} \approx 9^\circ$
  - despite hints, don't yet know "much" about $\delta$
- ★ So "just" measure $P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$ ?
- ★ Not quite, there is a complication…

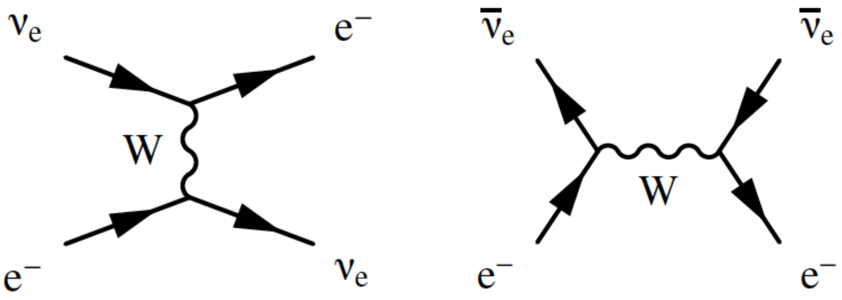
# Matter Effects

- ★ In our experiments, even in the absence of CPV

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

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

- ★ In vacuum, the mass eigenstates $\nu_1, \nu_2, \nu_3$ 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. **Sign depends on Mass Hierarchy**



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

Different sign for $\nu_e$ vs $\overline{\nu}_e$

# Experimental Strategy

**EITHER:**

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

- First oscillation maximum:

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

- 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:

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

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

➡ **On-axis beam:** wide range of neutrino energies

# Experimental Strategy

**EITHER:**

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

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

V

  - Want hi tion maximum

➡ **Off- eam:** narrow range of neutrino energies

**Hyper-Kamiokande**

**OR:**

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  - First oscillation maximum:

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

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

➡ **On-axis beam:** wide range of neutrino energies

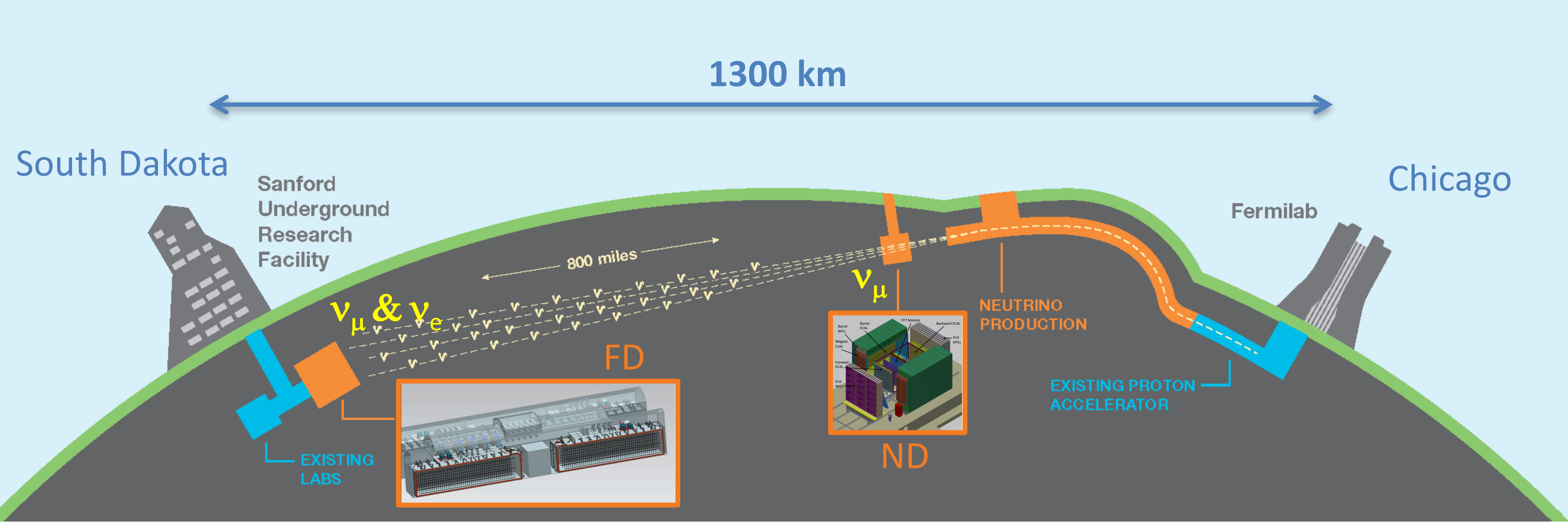
**DUNE**

# 4. The Deep Underground Neutrino Experiment (DUNE)

# DUNE in a Nutshell

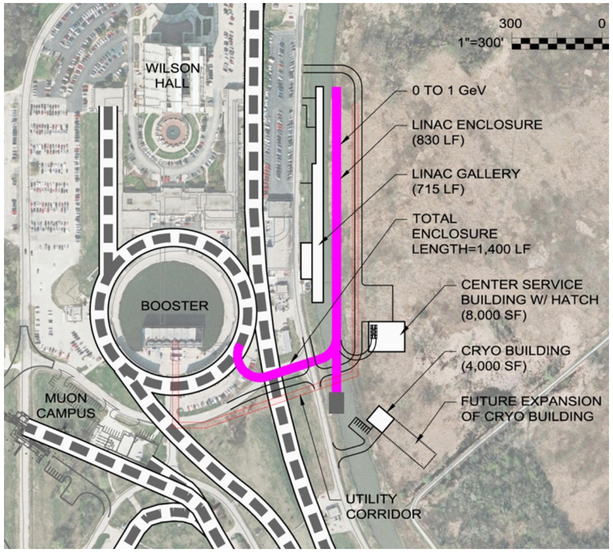
★ LBNF/DUNE

- 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



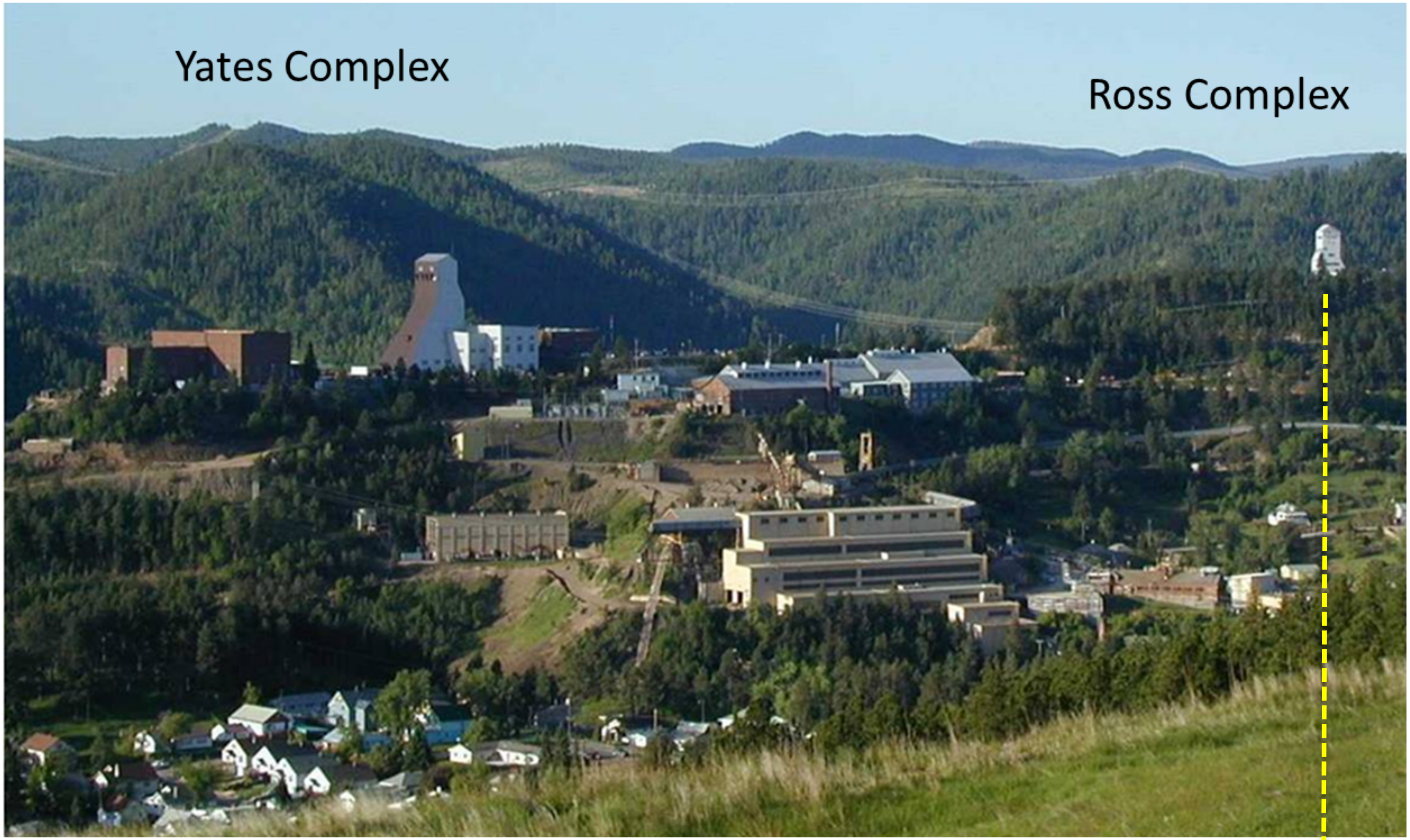
# 4.1 LBNF and PIP-II

- ★ **In beam-based long-baseline neutrino physics:**
  - **beam power drives the sensitivity**
- ★ **LBNF: the world's most intense high-energy $\nu$ 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



# LBNF/DUNE – Fermilab in 2025

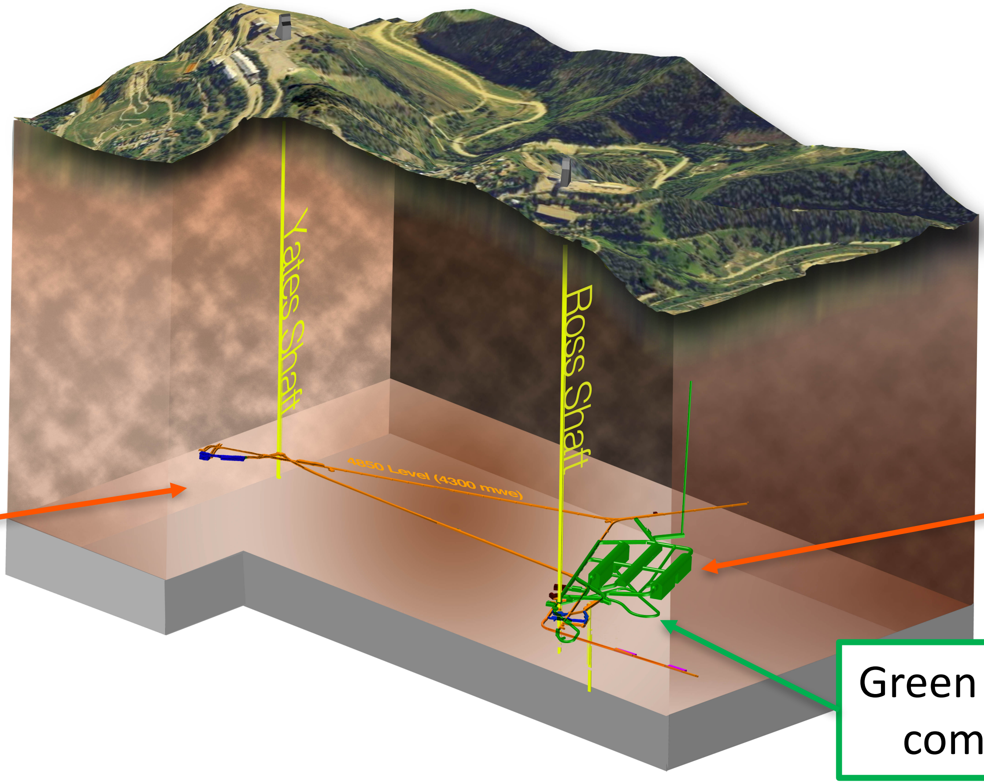
# 4.2 The DUNE Far Detector



# Going underground…

## DUNE Far Detector site

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



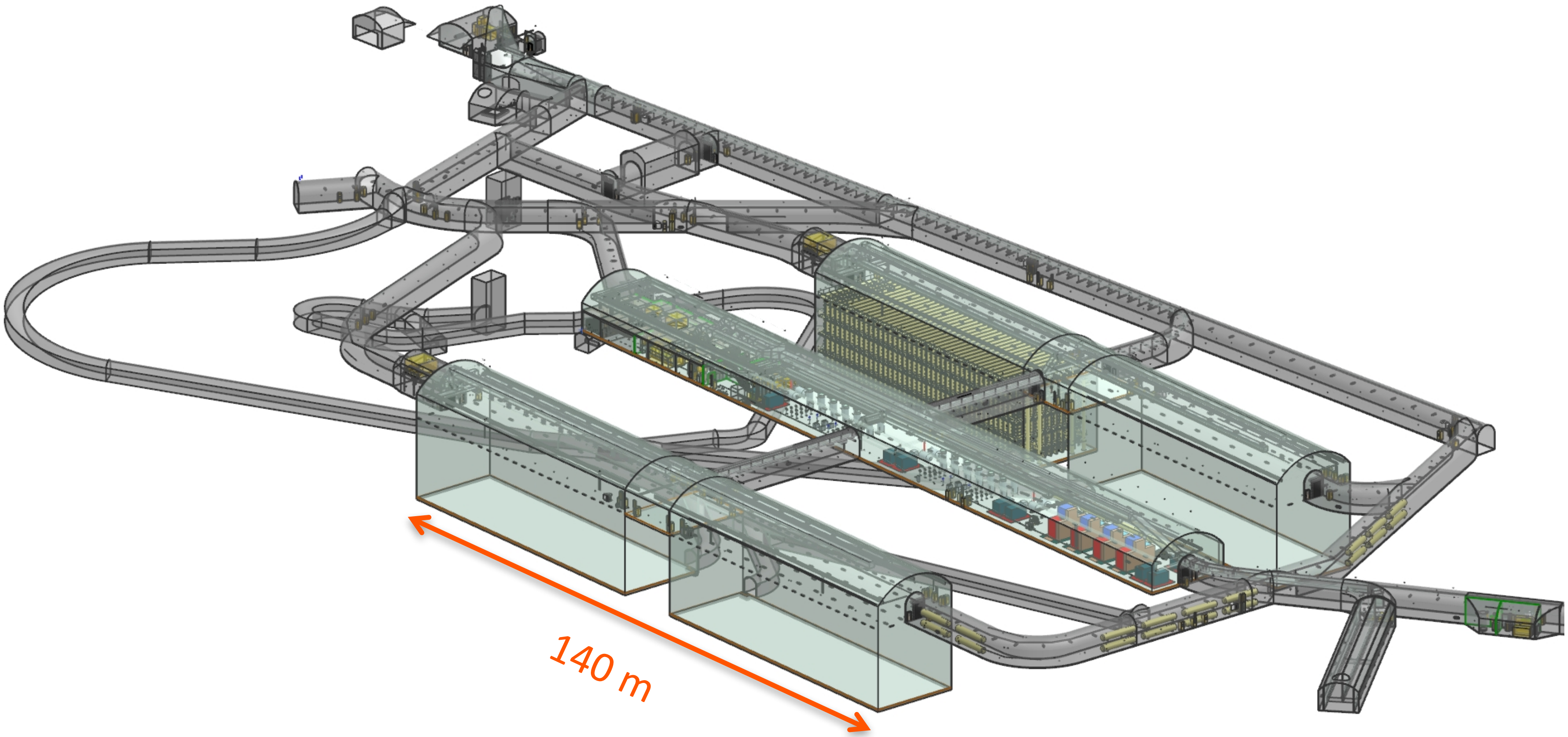
**Davis Campus:**
- LUX
- Majorana demo.
- …
- **LZ**

**Ross Campus:**
- CASPAR
- …
- **DUNE**

Green = new construction commences in 2017

# DUNE Design =

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



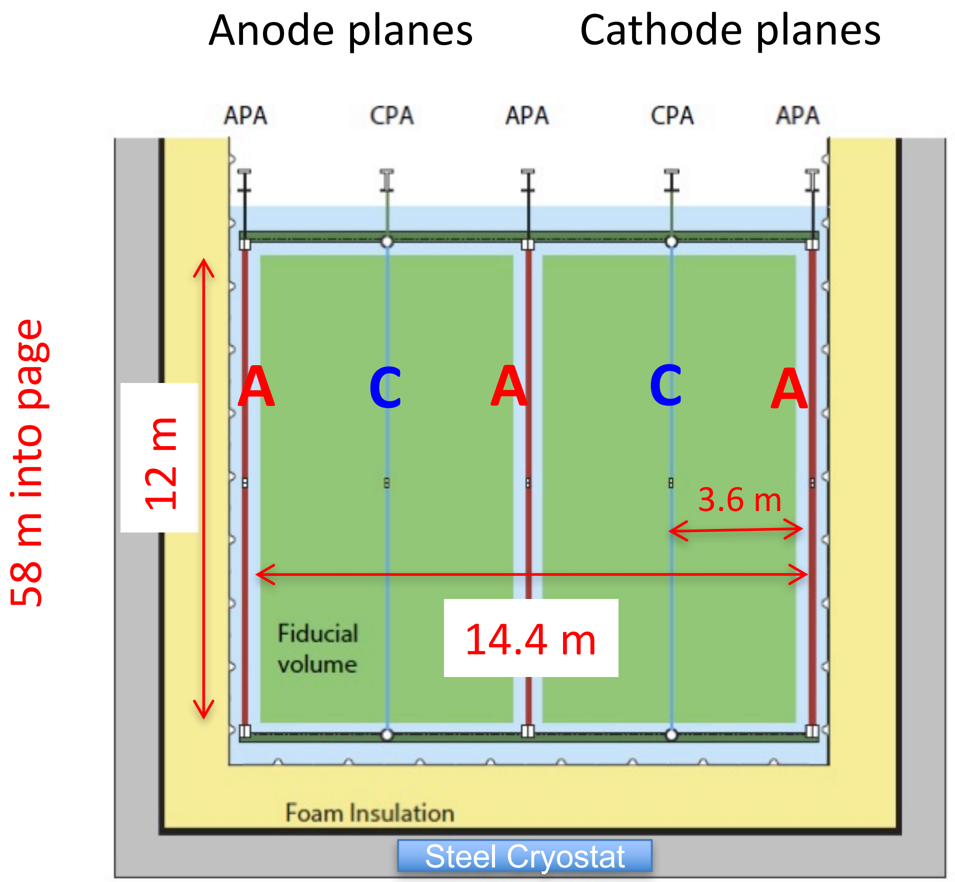
## Two detector designs could be deployed

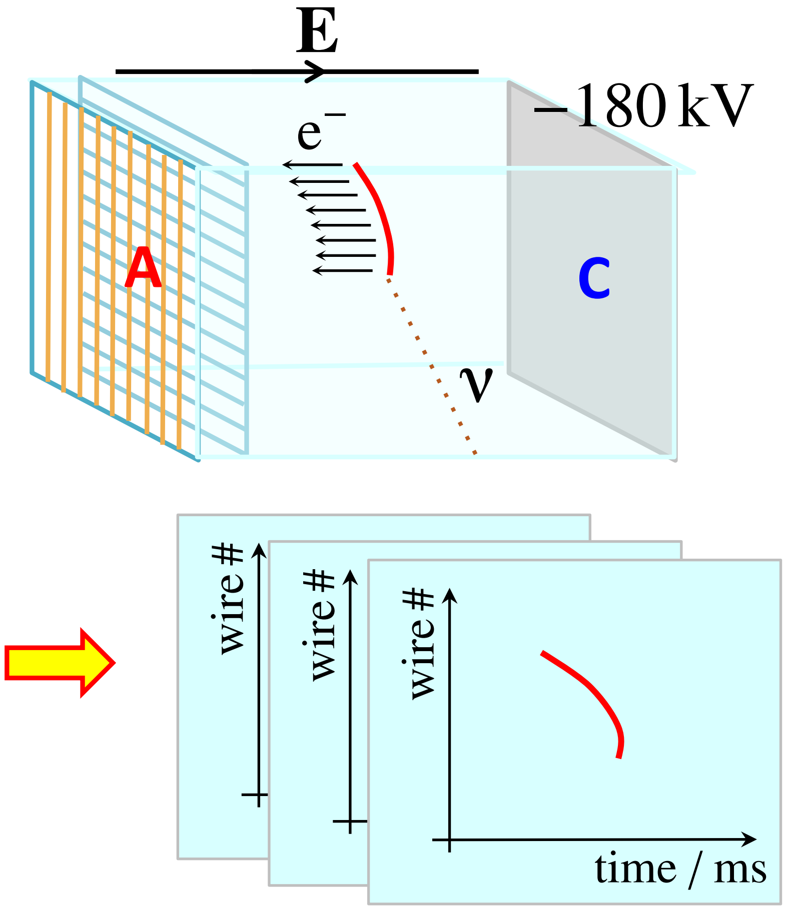
- Single-phase readout & dual-phase readout

# First 17-kt Far Detector Module

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

- Record ionization in LAr volume ⇨ 3D image



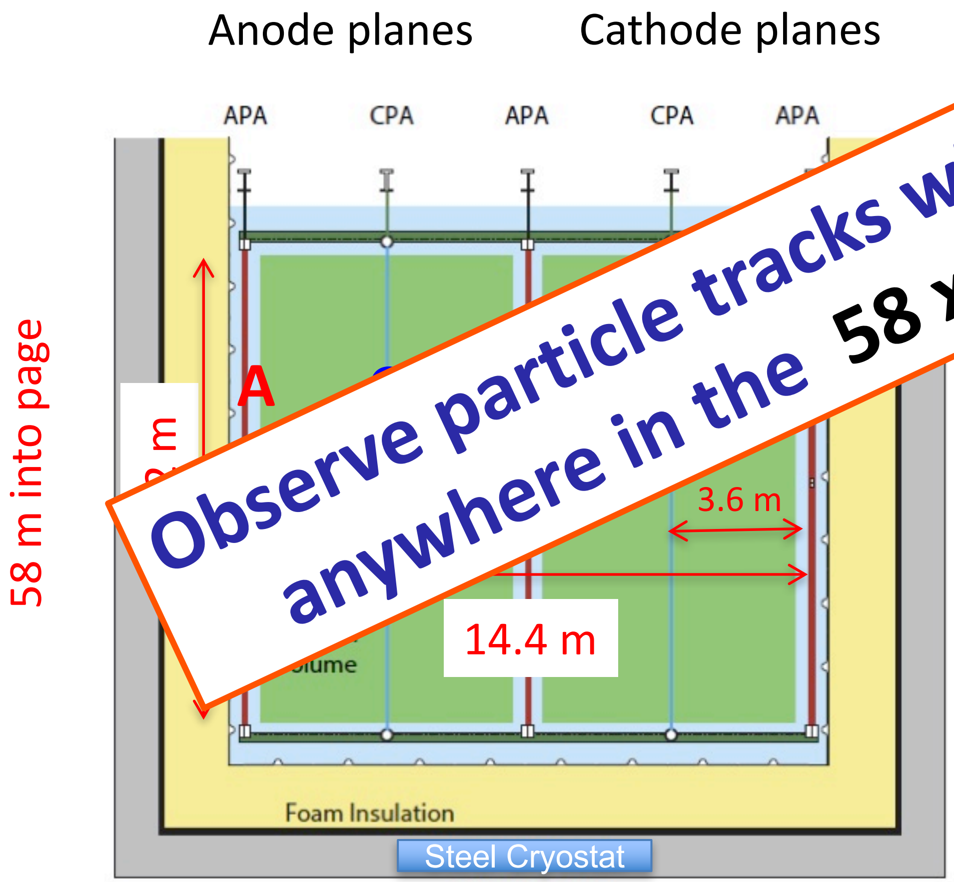


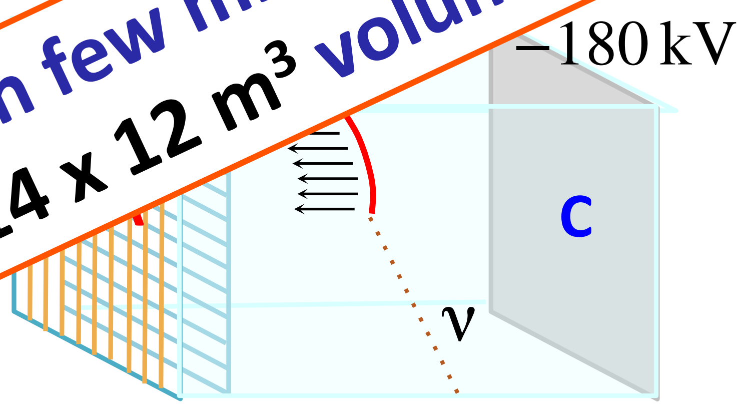
# First 17-kt Far Detector Module

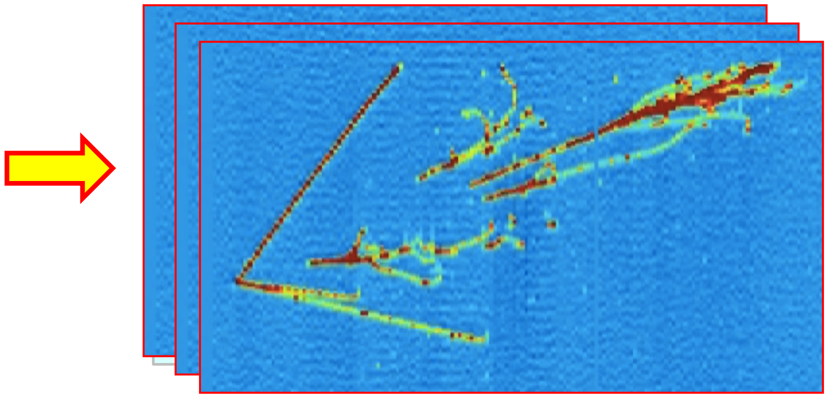
A **modular** implementation of Single-Phase LAr TP

- Record ionization in LAr volume ⇨ 3D i

**Observe particle tracks with few mm precision anywhere in the 58 x 14 x 12 m$^3$ volume**

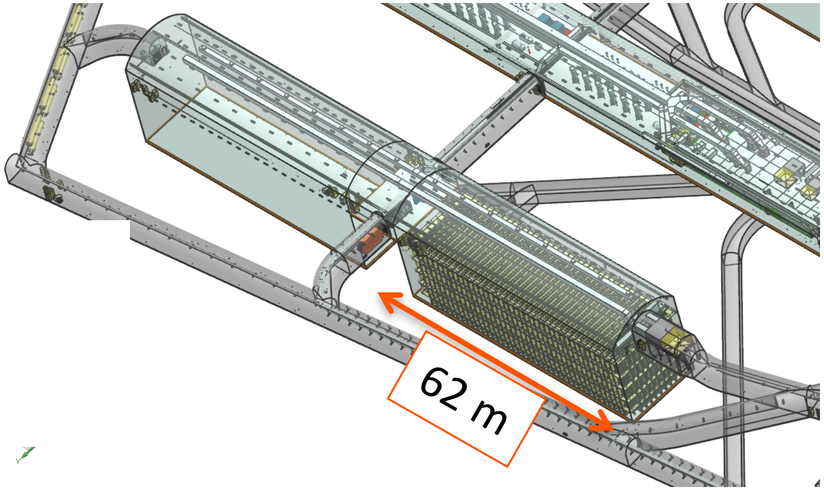






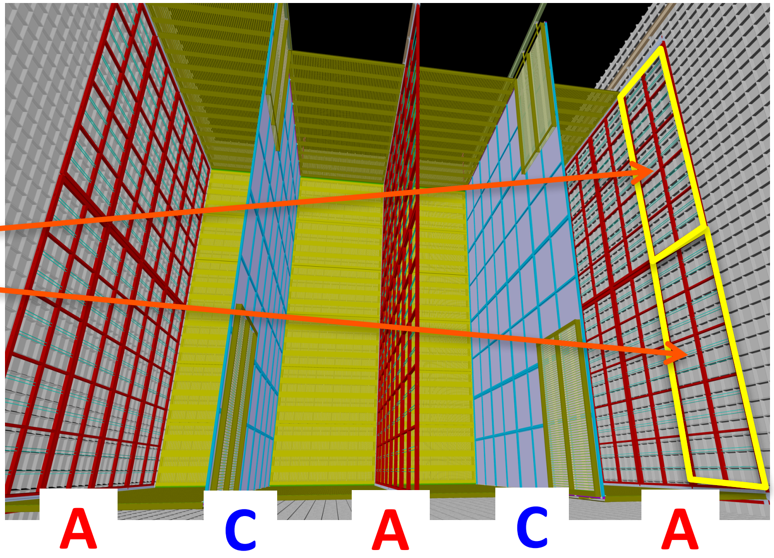
# Modular Detector

- Four chambers hosting four independent 17-kt FD modules (10-kt fiducial)
- Going underground
  - ➡ Modular design



## Modular implementation of a massive LAr-TPC

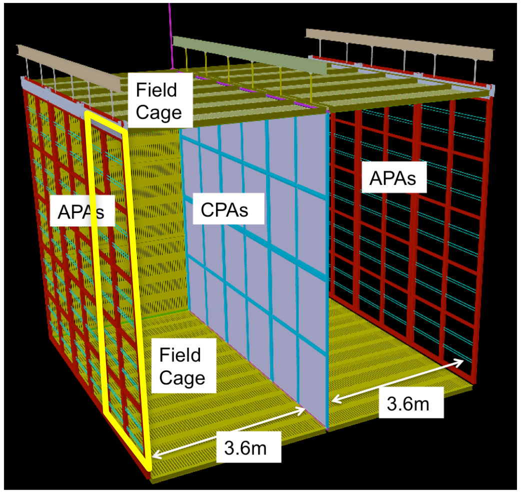
- Active volume: **12m x 14m x 58m**
- 150 Anode Plane Assemblies
  - 6m high x 2.3m wide
- 200 Cathode Plane Assemblies
  - Cathode @ -180 kV for 3.5m drift



# 4.3 Far Detector Prototyping

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

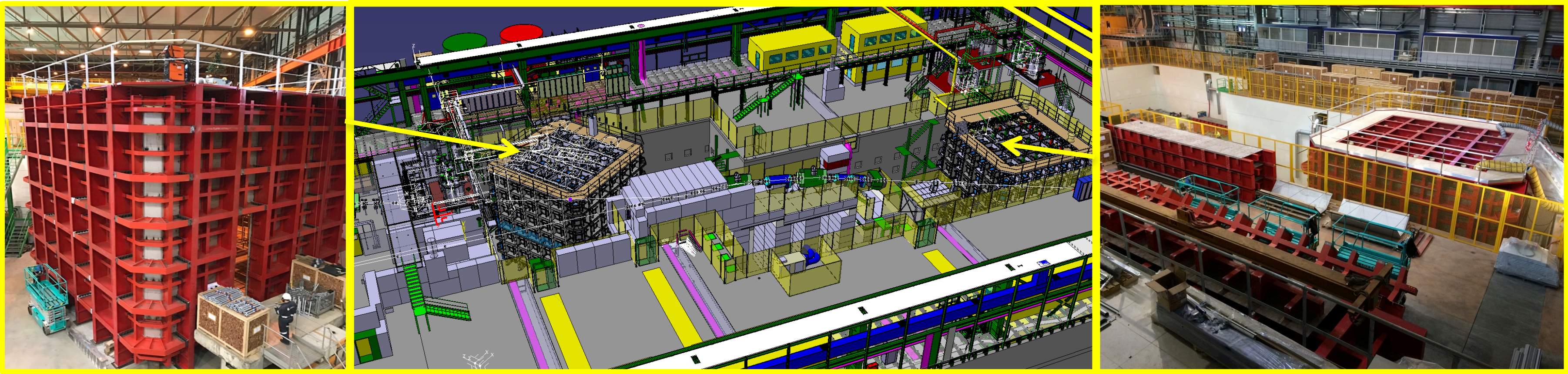
- Design is well advanced – evolution from ICARUS
- Supported by strong development program at Fermilab
  - 35-t prototype (ran in early 2016
  - MicroBooNE (operational since 2015)
  - SBND (start of operation in 2018/2019)
- "Full-scale prototypes" with ProtoDUNE at the **CERN Neutrino Platform**
  - **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 + …



- Spanish groups involved in protoDUNE programme
  - Both single-phase and dual-phase designs

# 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 + …

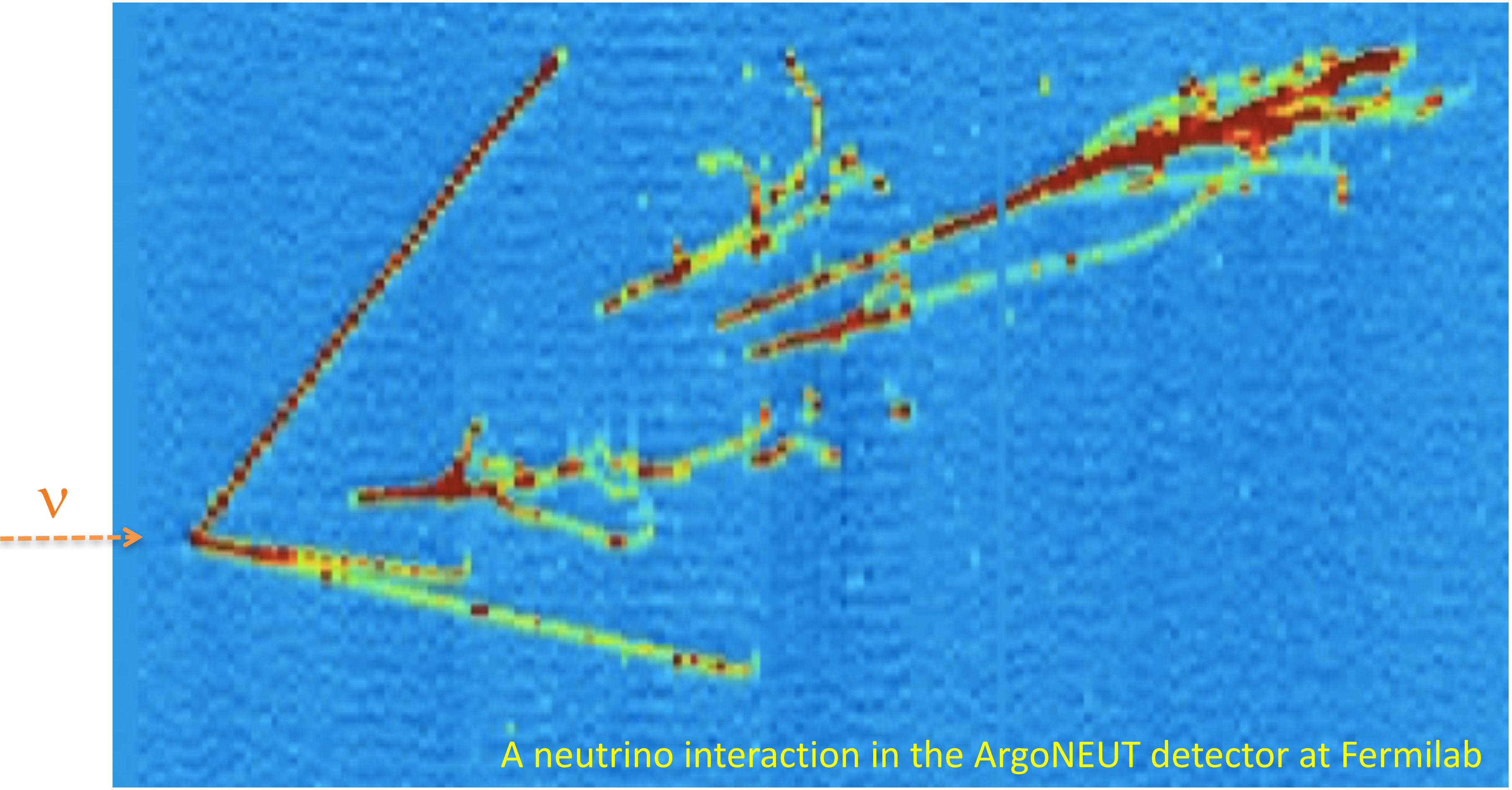
**ProtoDUNE: a major step to FD construction:**

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

- Both single-phase and dual-phase designs

# 4.3 DUNE Science

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

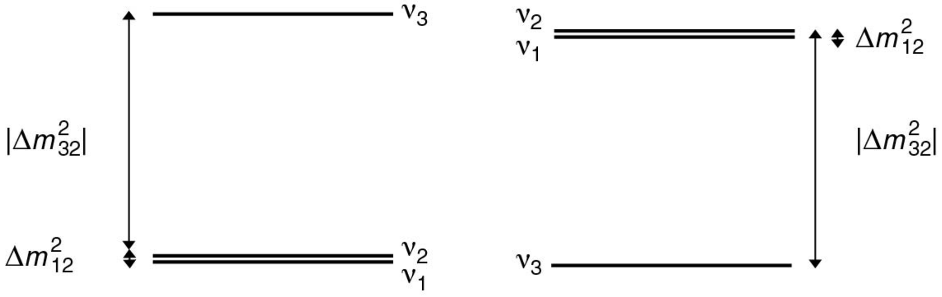


A neutrino interaction in the ArgoNEUT detector at Fermilab

# 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, $\theta_{23}$ 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 $\nu_e$

# DUNE Primary Science Program

**Each would be a major discovery**

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

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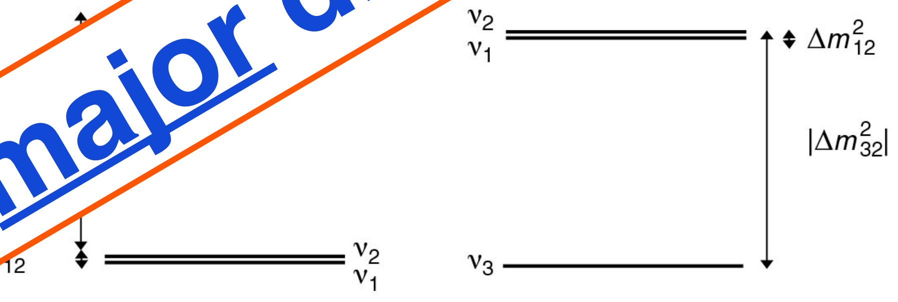
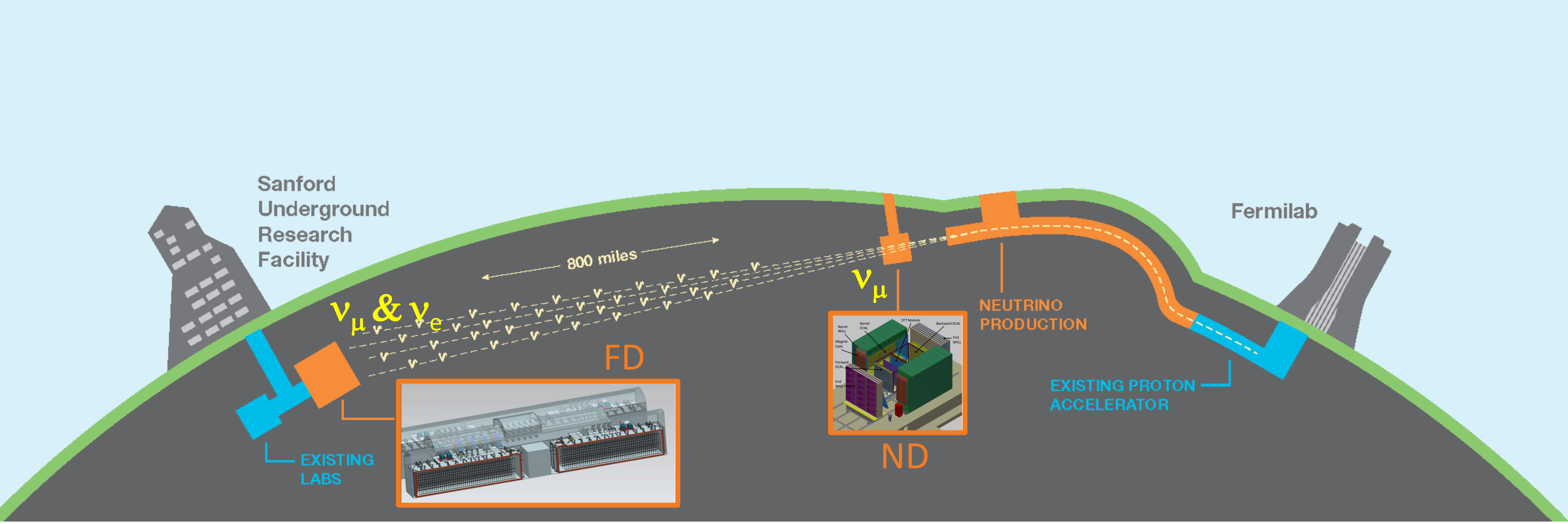


- **Decay**
  - argeting SUSY-favored modes, $p \to K^+\bar{\nu}$
- **) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to $\nu_e$

# Long Baseline (LBL) Oscillations

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

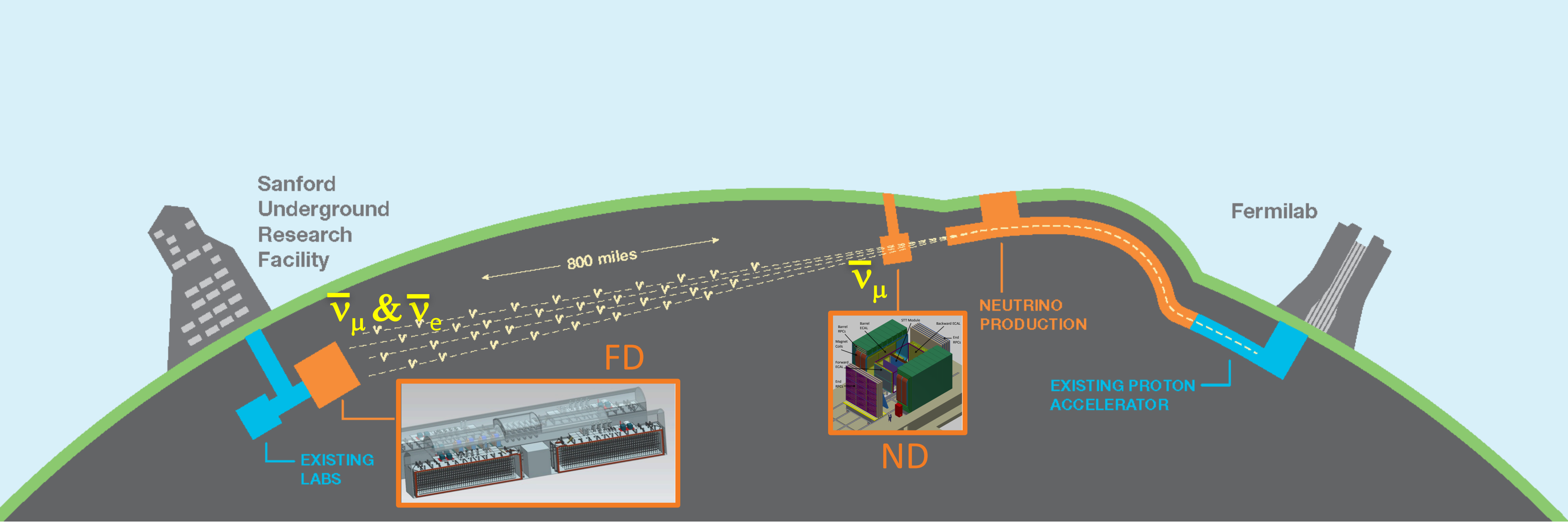


- **Near Detector at Fermilab: measurements of $\nu_\mu$ unoscillated beam**
- **Far Detector at SURF: measure oscillated $\nu_\mu$ & $\nu_e$ neutrino spectra**

# Long Baseline (LBL) Oscillations

## … then repeat for antineutrinos

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



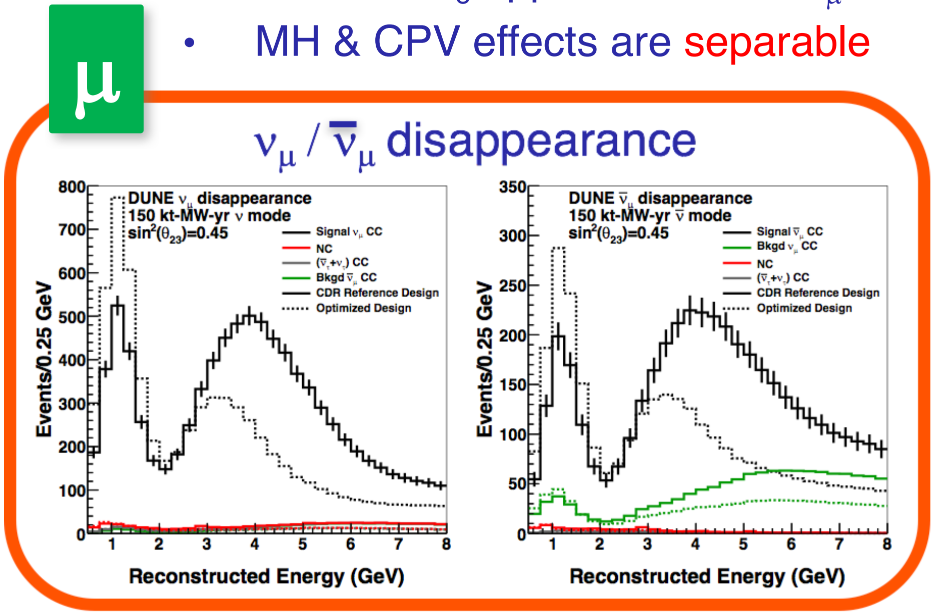
- **Near Detector at Fermilab:** measurements of $\bar{\nu}_\mu$ unoscillated beam
- **Far Detector at SURF:** measure oscillated $\bar{\nu}_\mu$ & $\bar{\nu}_e$ neutrino spectra

# DUNE Oscillation Strategy

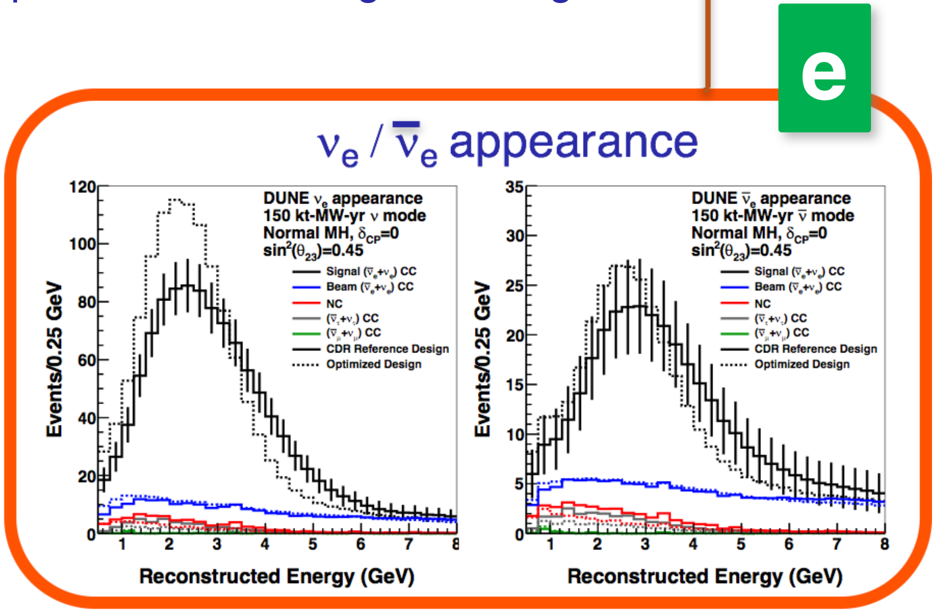
## Measure neutrino spectra at 1300 km in a wide-band beam

- **Determine MH and $\theta_{23}$ 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 $\nu_e$ appearance and $\nu_\mu$ disappearance over range of energies
    - MH & CPV effects are separable

**E ~ few GeV**



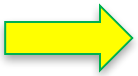
$\nu_\mu$ / $\bar{\nu}_\mu$ disappearance



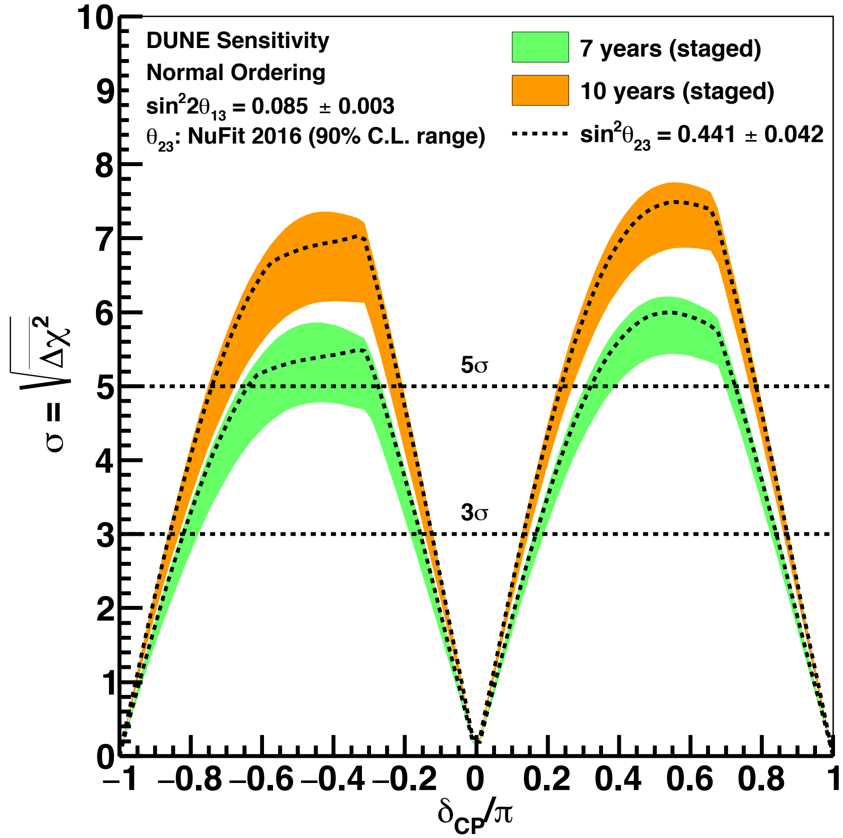
$\nu_e$ / $\bar{\nu}_e$ appearance

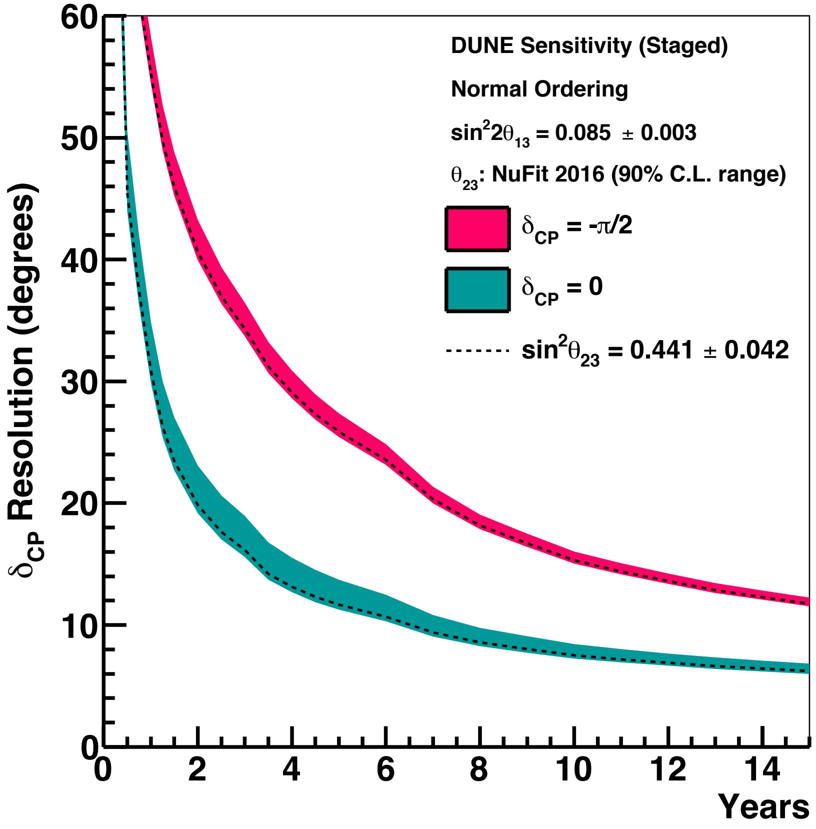
# CP Sensitivity

CPV Discovery



$\delta_{CP}$ Measurement





# Oscillation Über-Summary

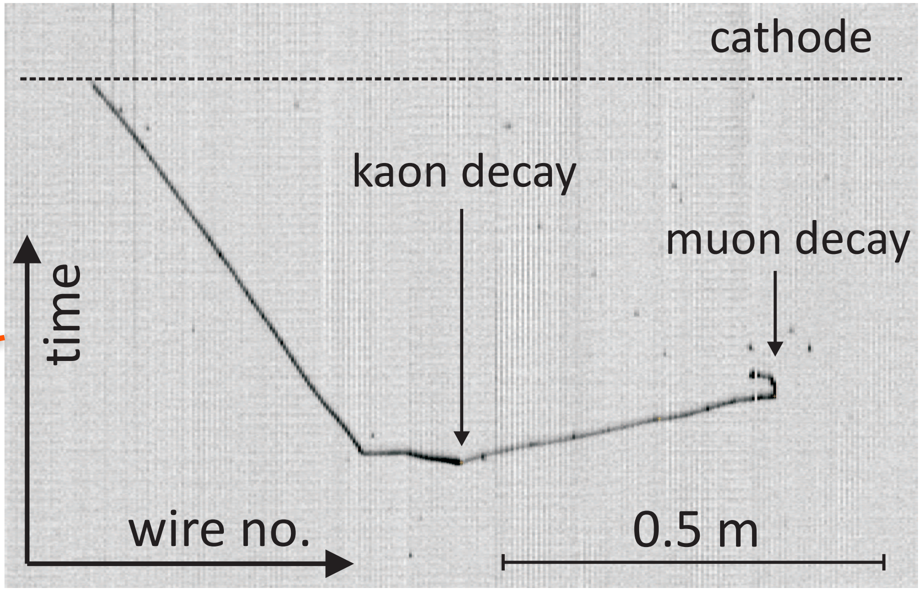
- **Nail the Mass Hierarchy**
  - $5\sigma$ in 2 – 5 years
- **75 % coverage for $3\sigma$ CPV discovery**
- **If "lucky", CPV reaches $3\sigma$ ($5\sigma$) in 3-4 (6-7) years**
- **Measure $\delta_{CP}$**
  - $7^o$ – $15^o$ in 10 years
- **Wide-band beam + long baseline**
  - **Unique tests of 3-flavour paradigm**
  - Sensitivity to BS$\nu$M effects, e.g. NSI, steriles, ...
- **On-axis beam: potential to tune beam spectrum**
  - Further studies at second oscillation maximum
  - Study tau appearance ?

LBNF/DUNE is a facility for $\nu$ science

# 4.3.1 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)**

# 4.3.1 Proton Decay

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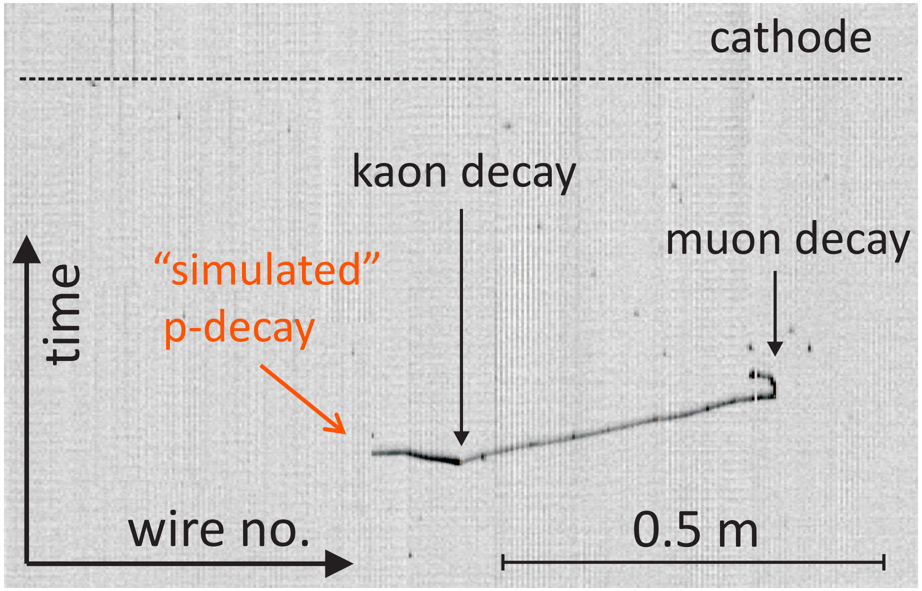
- **Clean signature**

  → 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

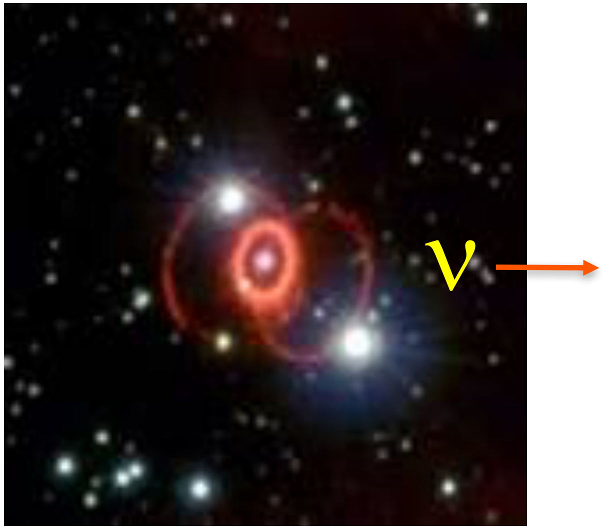
Remove incoming particle

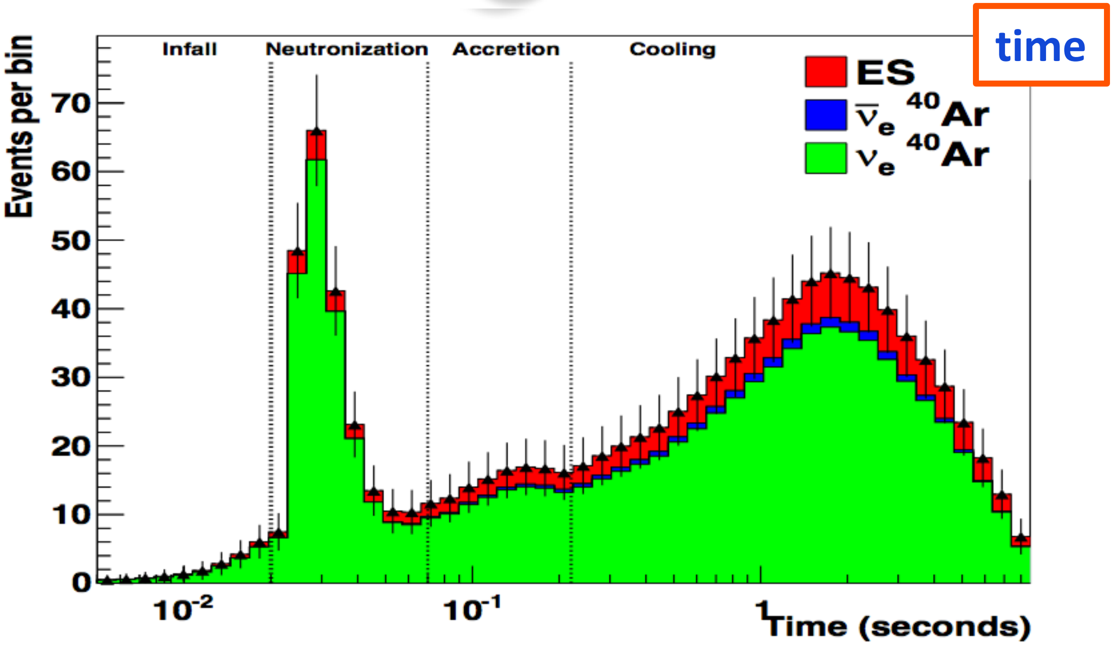


# 4.3.2 Supernova νs

## 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 !

# 4.4 Realizing DUNE

45’

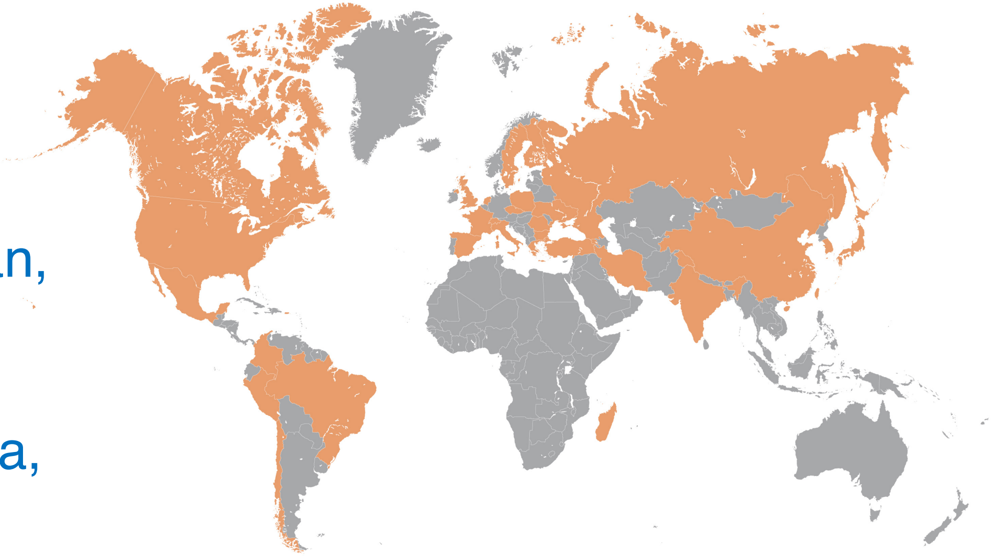
# The International DUNE Collab.

**As of today:**

60 % non-US

**964 collaborators from 162 institutions in 31 nations**

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



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

# International Context

- **The US is committed:**
  - LBNF/DUNE is the future flagship of Fermilab & the US domestic particle physics programme
  - LBNF/DUNE is now an approved project:
    - CD-3A approval in September gives US DOE legal authority to commit ~$300M for the far site construction/excavation
  - Strong cross-party political support & at highest levels of US DOE
    - Both houses of congress included “start of construction” language in FY17 president’s budget request

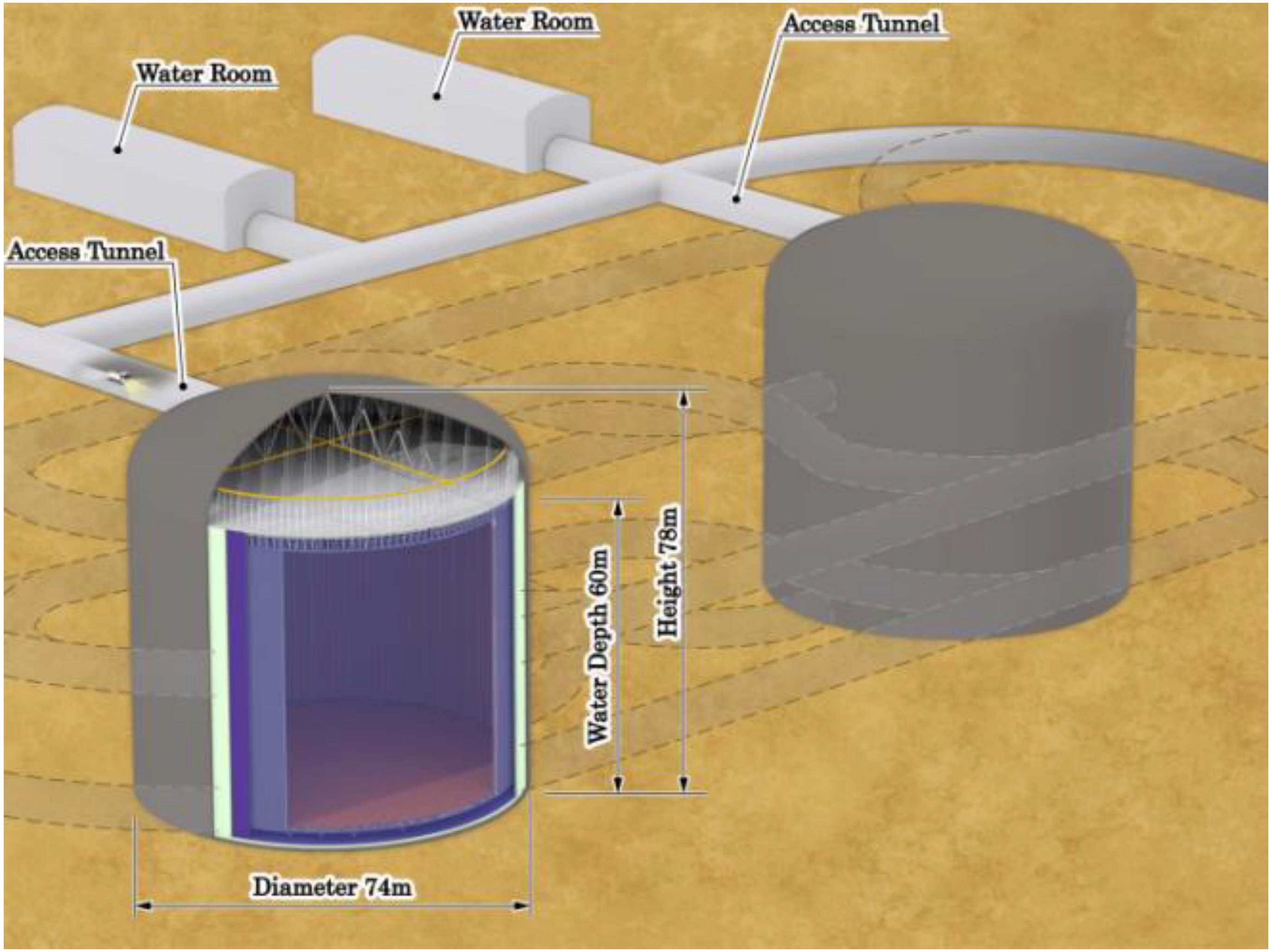
- **Strong Support from CERN:**
  - Follows European strategy for particle physics
  - Major investment in CERN Neutrino platform
    - Current commitment to end of 5-year MTP – mostly for DUNE
  - CERN commitment to construct the first FD cryostat at SURF
    - The first investment in an experiment outside of CERN !

# Realizing 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)

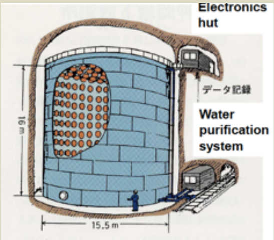
# 5. Hyper-Kamiokande



# Far Detector

## Hyper-K is the proposed third generation large water Cherenkov detector in Japan

Kamiokande
(1983-1996)

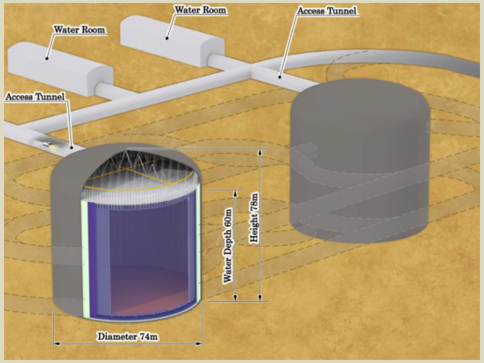


**3 kton**

Super-Kamiokande
(1996-)

**50 kton**

Hyper-Kamiokande
(2026?-)



**0.52 Mton**

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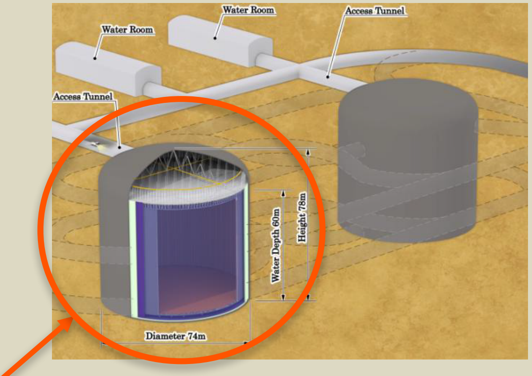


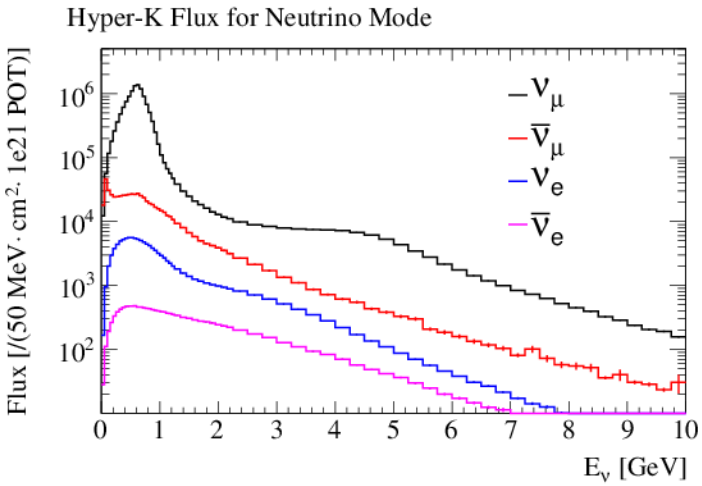
**0.52 Mton**

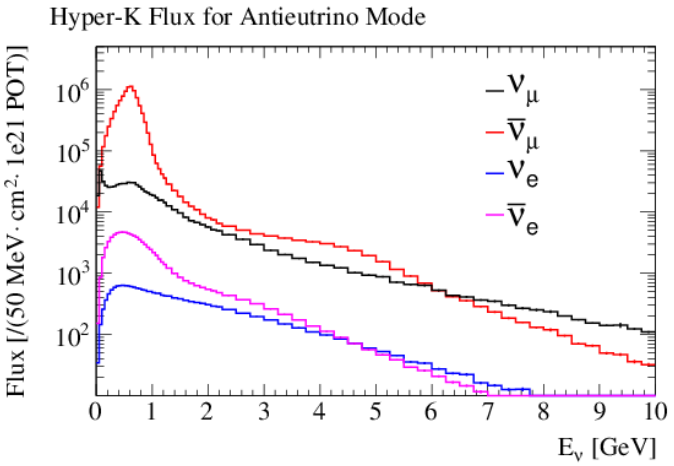
Hyper-K (single tank):

- Vertical-cylinder : H 60m × Φ 74m
- Total Mass 260 kton
- Fiducial Mass 190 kton
  - ~10 × Super-K
- 40,000 ID PMT (40% coverage)
- 6,700 OD PMT (nominal 8” PMTs)

# 5.1 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
  - “Short” Baseline = 295 km ⇨ matter effects are small





# 5.2 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 $\pi^0$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova

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- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to $\overline{\nu}_e$

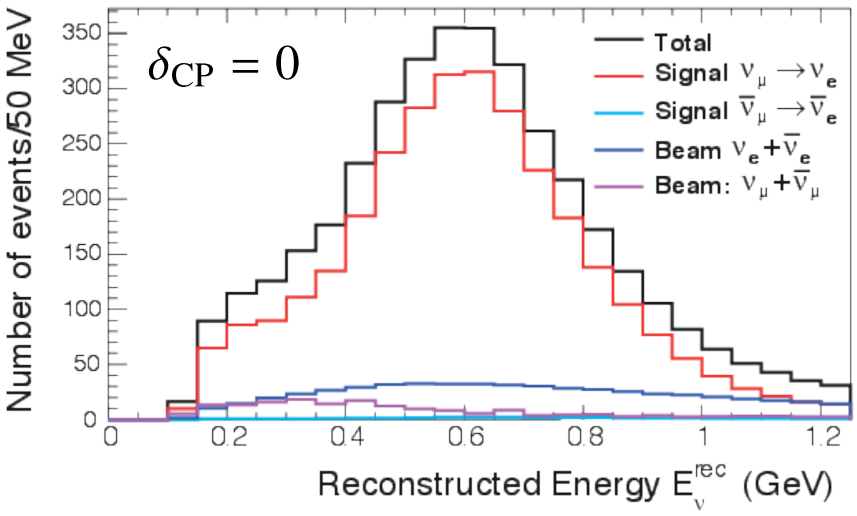
★ **Significant complementarity with DUNE physics**

# CP @ Hyper-Kamiokande*

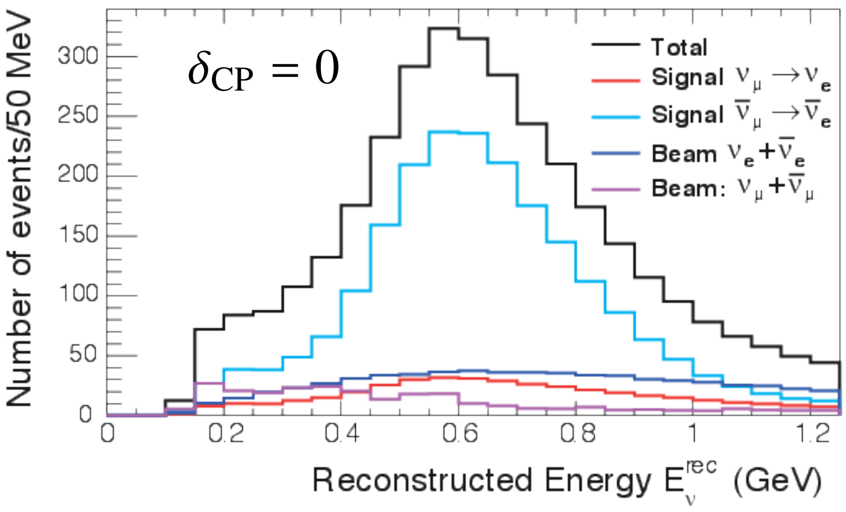
- ★ High-statistics for $\nu_e/\bar{\nu}_e$ appearance

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

**Appearance ν mode**



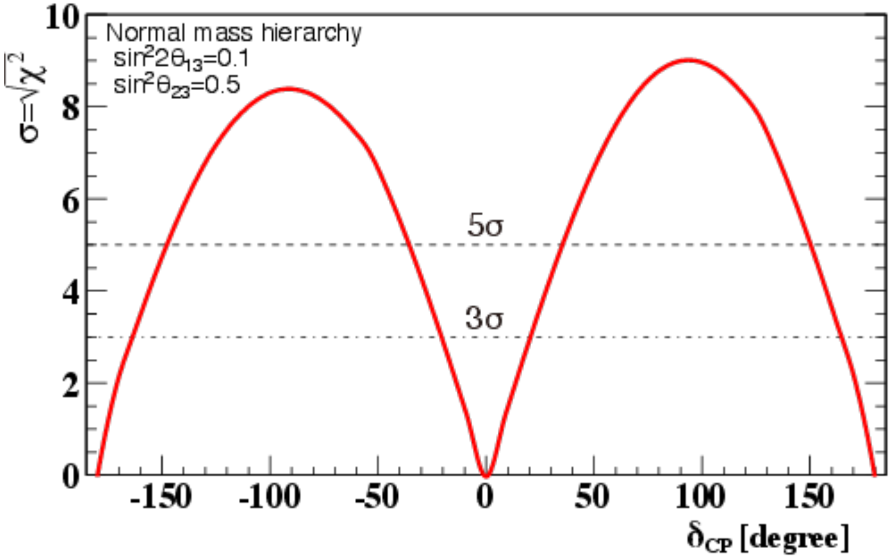
**Appearance $\bar{\nu}$ mode**

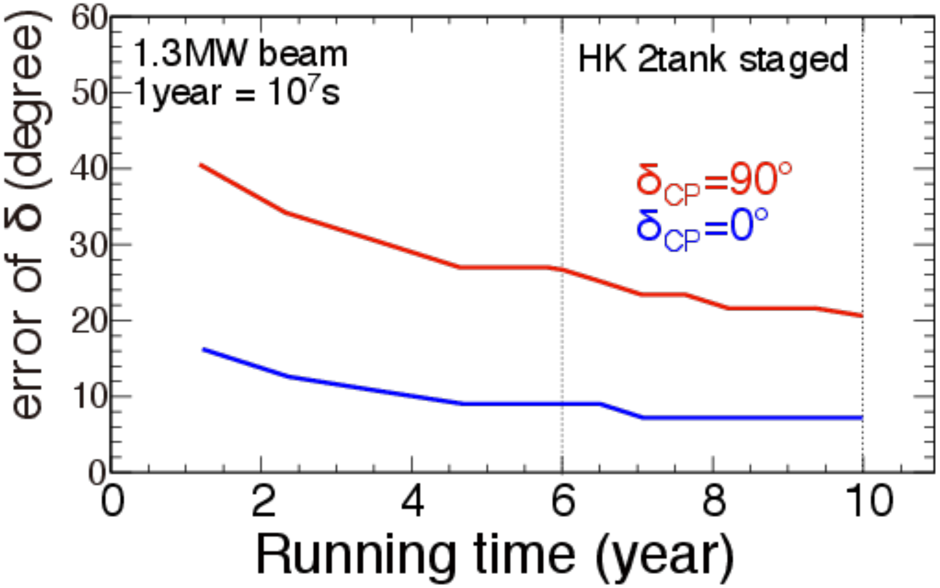


*numbers are from previous configuration

# Hyper-K $\delta_{CP}$ Sensitivity

- ★ CPV sensitivity based on:
  - 6 years with one tank + 4 years with two
  - Assume MH is already known





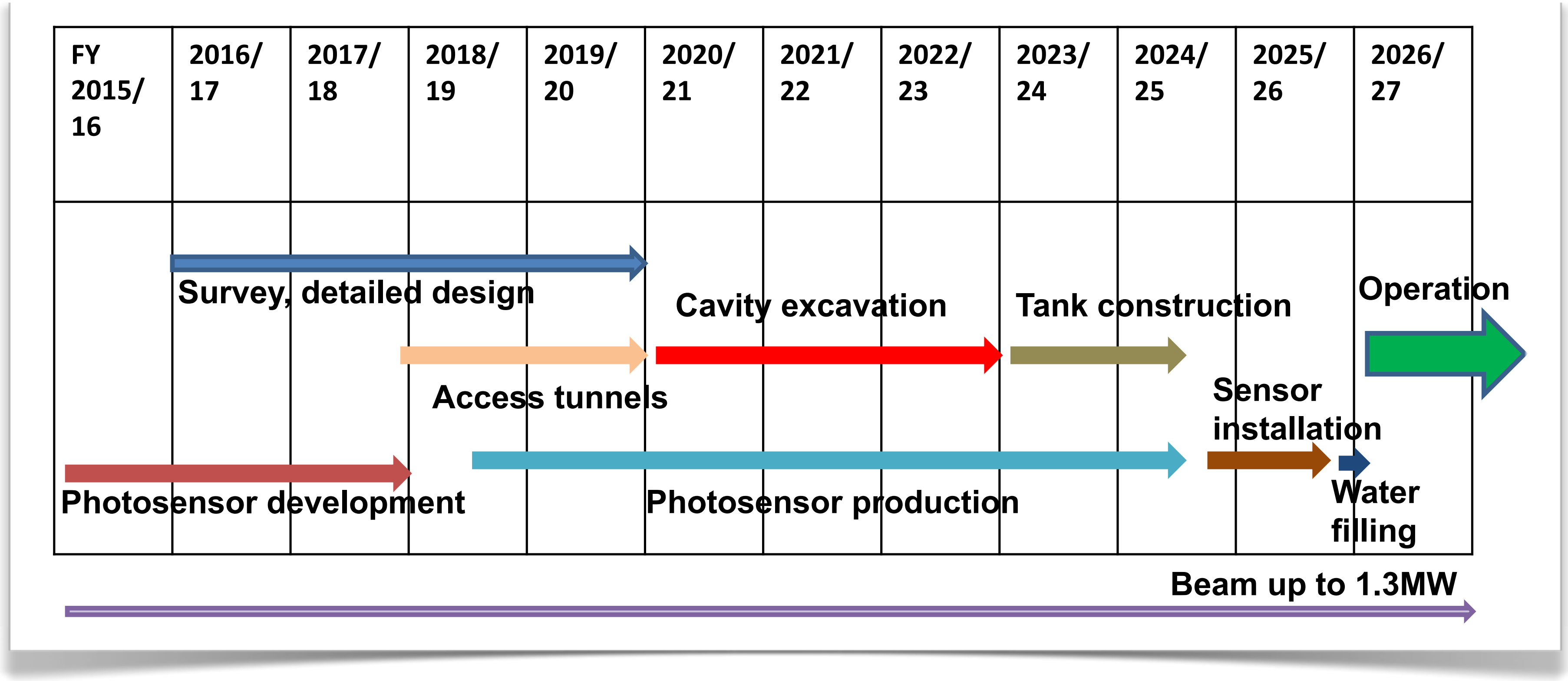
- ★ CPV coverage:
  - 78 % at 3 σ
  - 62 % at 5 σ

# Hyper-K Status

- ★ **Currently in R&D Phase**
  - R&D funds from Japan and other countries
- ★ **Initial design report submitted to MEXT in 2014**
  - included on shortlist for “future large projects”
- ★ **Updated design report to MEXT in March 2017**
  - Cost submission in Summer 2017, expected outcome in 2018
- ★ **New Hyper-K institute planned for ICRR Tokyo**

# Hyper-K Status

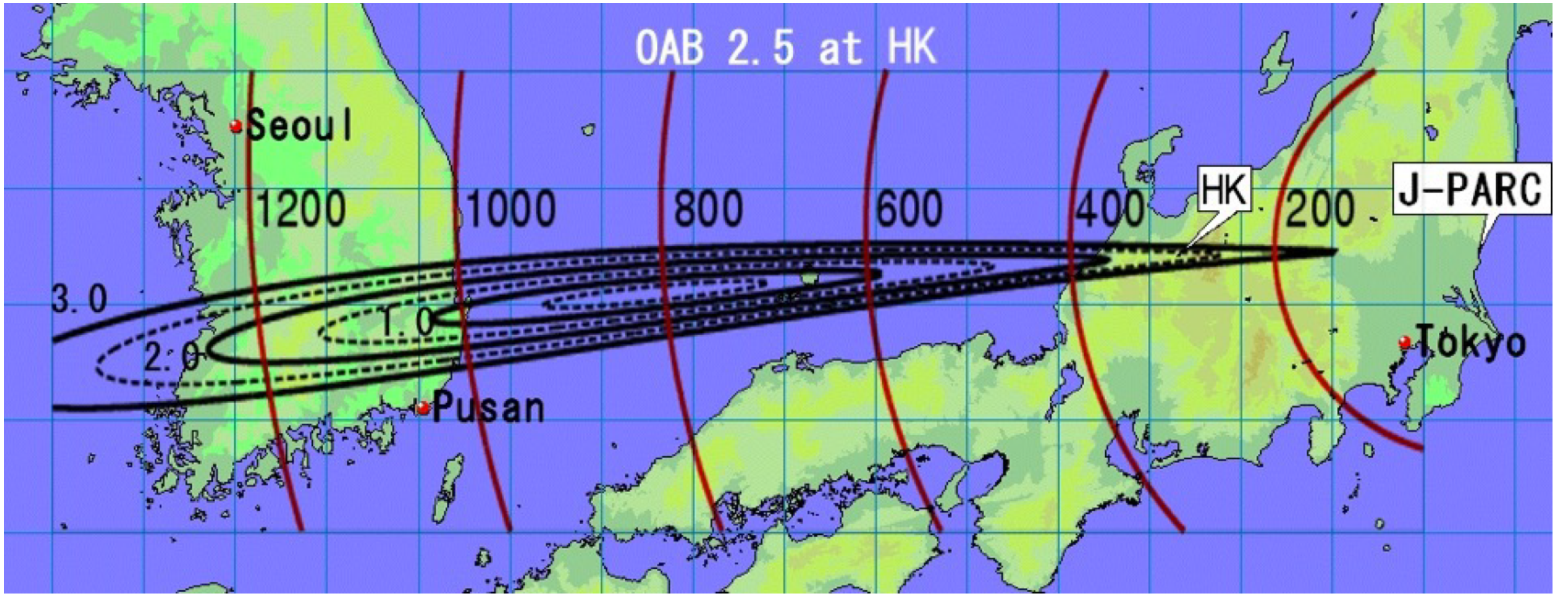
- ★ **Currently in R&D Phase**
  - R&D funds from Japan and other countries
- ★ **Targeting start of operation in 2026**



# Hyper-K: 2nd detector in Korea

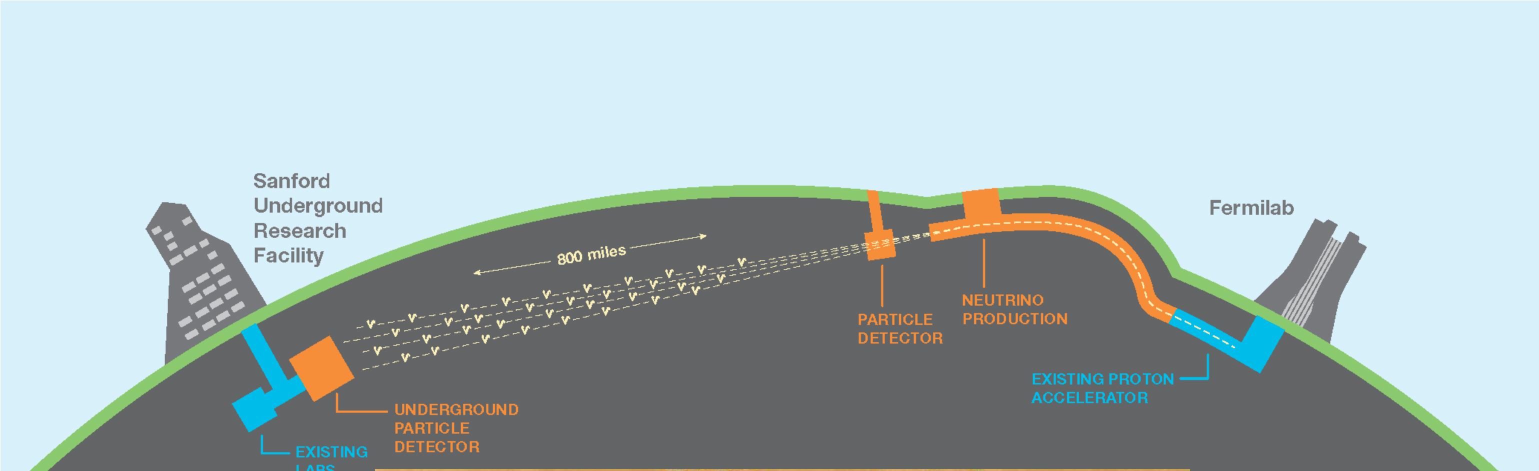
- ★ Recently Hyper-K proto-collaboration revisited the option of the second tank being in Korea
  - Off-axis at a baseline of ~1100 km

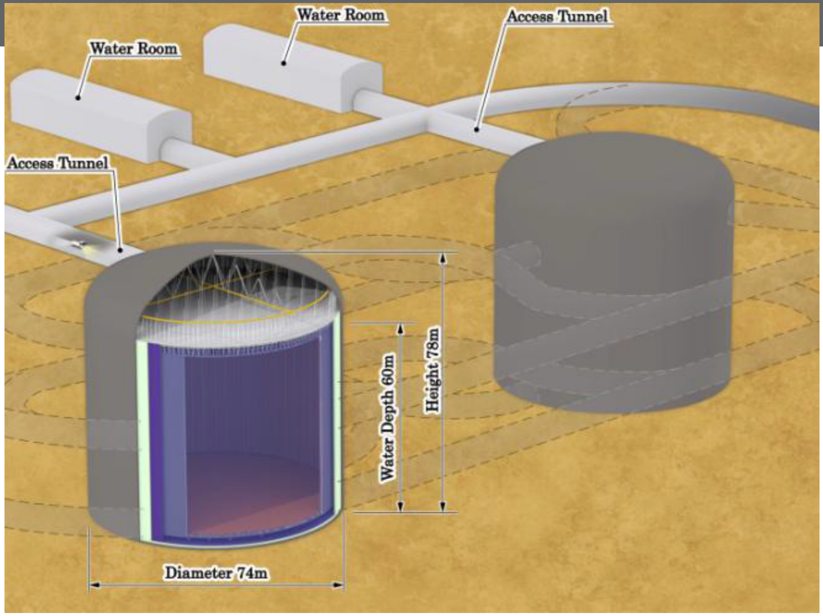
arXiv:1611.06118



- ★ Longer baseline: mass hierarchy sensitivity
  - + some benefits to CP sensitivity

# 6. DUNE & Hyper-Kamiokande





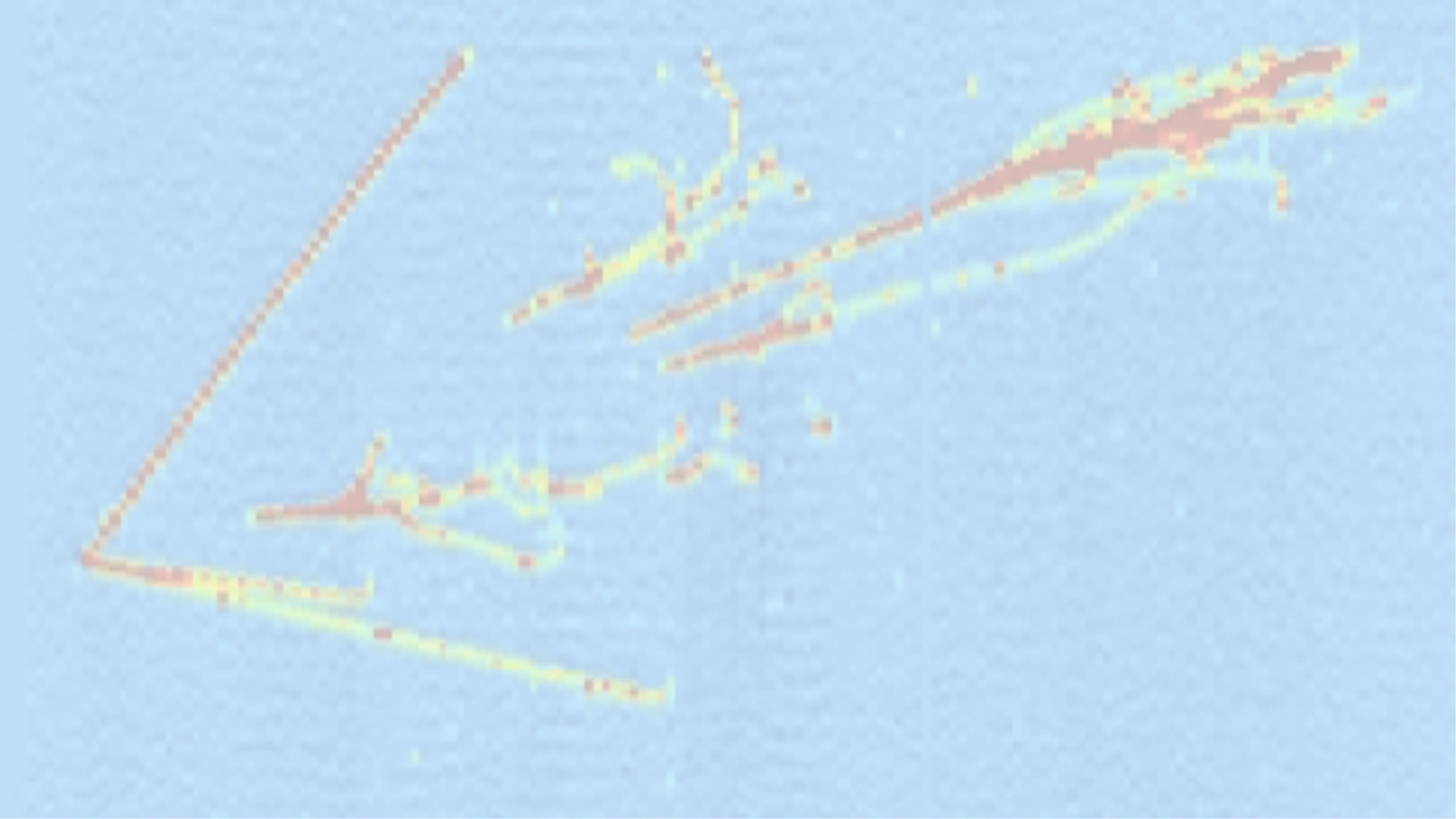
# DUNE & Hyper-K: at 10 years

- 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** | $\delta$ resolution | 7° – 21° | 7° – 15° |
| | $3\sigma$ coverage | 78% | 74% |
| | $5\sigma$ coverage | 62% | 54% |
| **Mass Hier.** | sens. range | $5\,\sigma - 7\,\sigma$ | $8\,\sigma - 20\,\sigma$ |
| **octant** | sens. @ 0.45 | $5.8\sigma$ | $5.1\sigma$ |
| | $5\sigma$ outside of… | [0.46, 0.56] | [0.45, 0.57] |
| **p decay**<br>**(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 $\nu$**<br>**(10 kpc or relic)** | SNB $\bar{\nu}_e$ | 130k evts | |
| | SNB $\nu_e$ | | 5k evts |
| | relic $\bar{\nu}_e$ | 100 evts, $5\sigma$ | |
| | relic $\nu_e$ | | 30 evts, $6\sigma$ |
| **NSI**<br>**(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

# 7. Summary



# Summary

- ★ **Long-baseline ν oscillation expts. Have played a major part in our current understanding of the neutrino**
- ★ **DUNE and Hyper-K will tackle fundamental questions:**
  - **CP Violation**
  - Mass Hierarchy
  - Testing the Standard Model of νs
  - Proton Decay
  - Supernova neutrinos
- ★ **Neutrino physics is an exciting and vibrant field**
  - **DUNE** will be the next major new international particle physics construction project
    - CERN & Europe (including Spain) are important partners
  - **Hyper-K** (when approved) will be of a similar scale
    - Significant complementarity

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**Exciting prospects for ν physics**

# Muchas Gracias