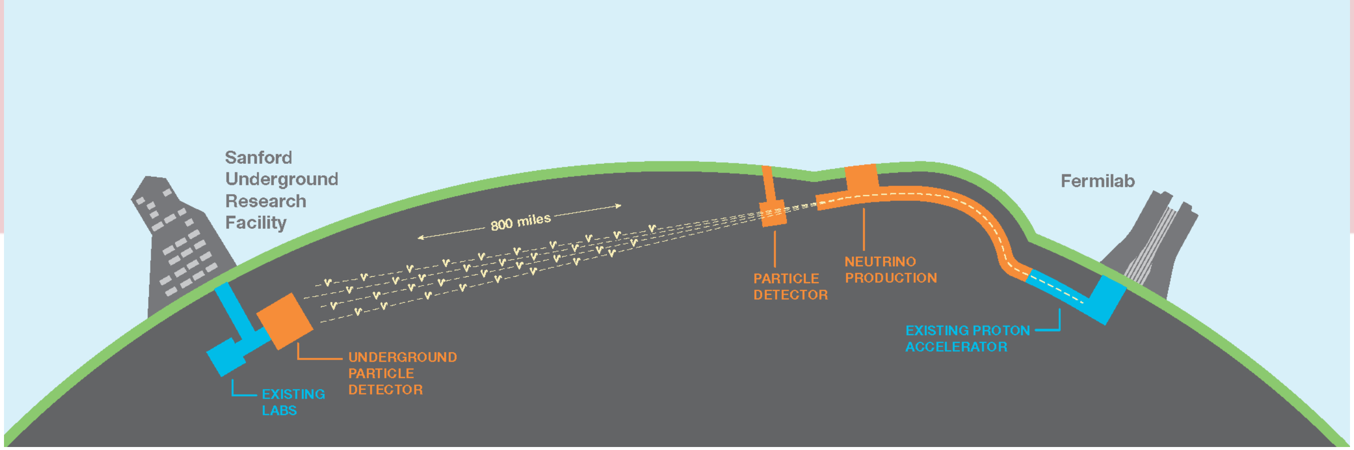


The Deep Underground Neutrino Experiment - DUNE

Mark Thomson

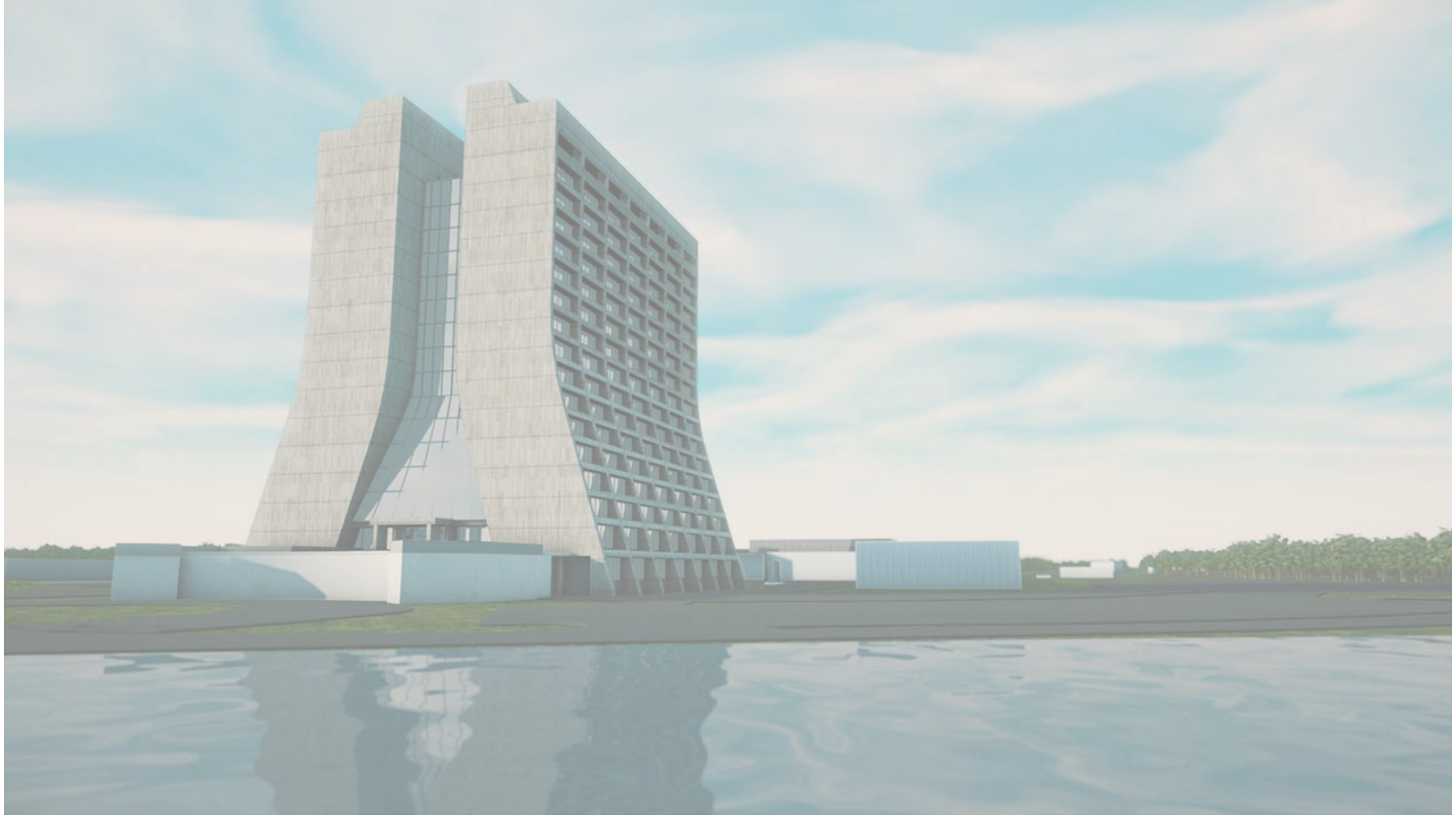
University of Cambridge & DUNE co-spokesperson

Nikhef Seminar, 10th November 2017

This talk

- **1. Introduction** (2 slides + animation)
- **2. CP Violation** (3 slides)
  - The neutrino perspective
- **3. Neutrinos are different** (6 slides)
  - Why do many people find neutrinos so interesting?
- **4. DUNE** (10 slides)
  - the accelerator/infrastructure (LBNF) and the detectors (DUNE)
- **5. DUNE Science** (8 slides)
  - what we will measure and why it matters
- **6. Realizing DUNE** (3 slides)
  - Status and international context
- **7. Summary** (1 slide)

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

1. Introduction: What is DUNE?

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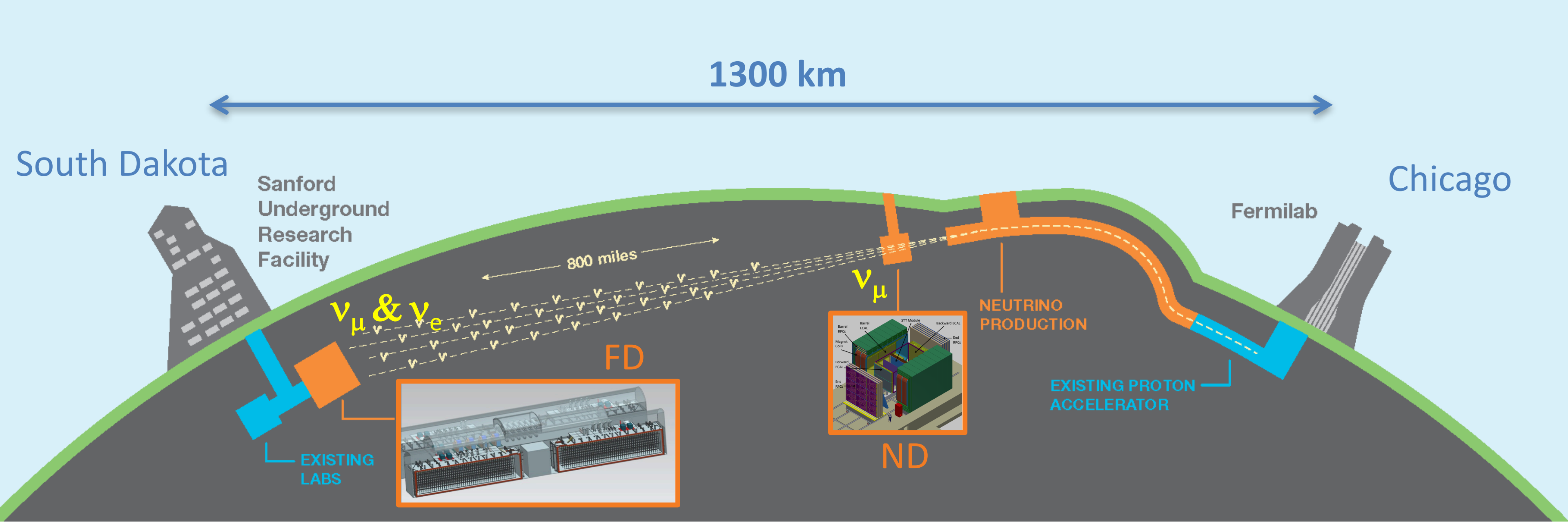
  - potential for major discoveries in: neutrinos and astro-particle physics

- **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



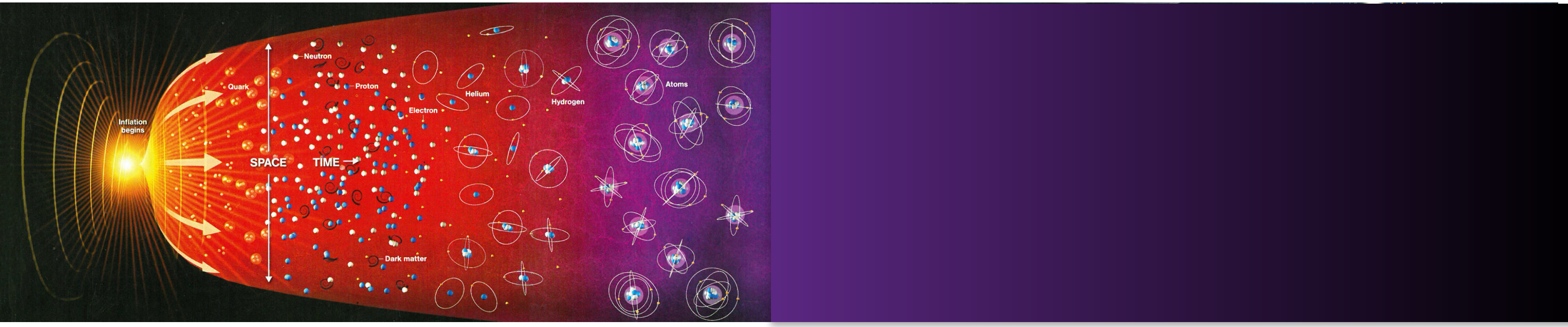
LBNF/DUNE – Fermilab in 2026

2. CP Violation and ν Oscillations

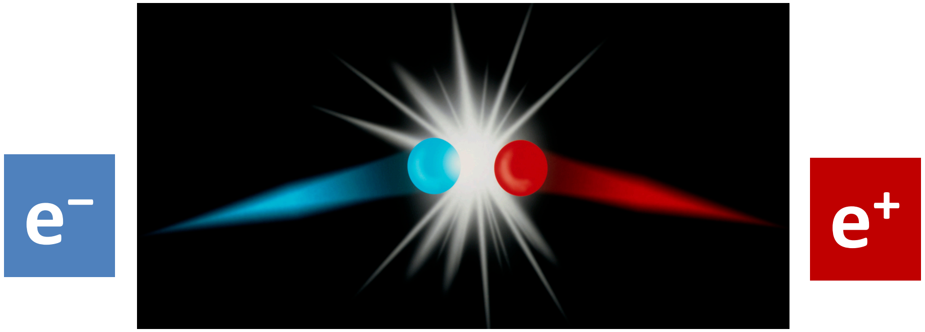
CP Violation

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



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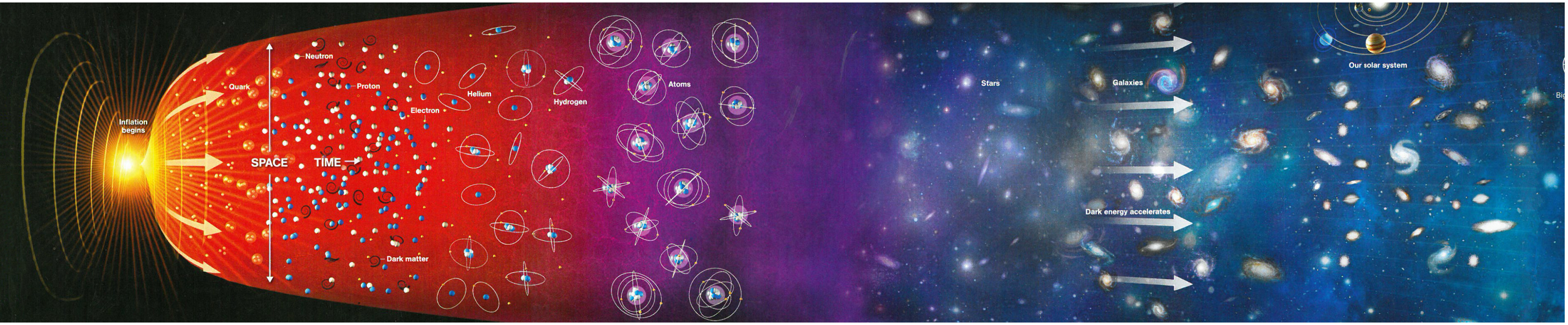

- **Big Bang: matter & antimatter created in equal amounts**
  - As Universe cools down matter and antimatter then annihilate
  - All things being equal, no matter/antimatter remains, just light
  - **This is not what happened – there is matter left in the Universe**
    - ⇨ Fundamental difference between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

CP Violation

CPV remains an open question in science

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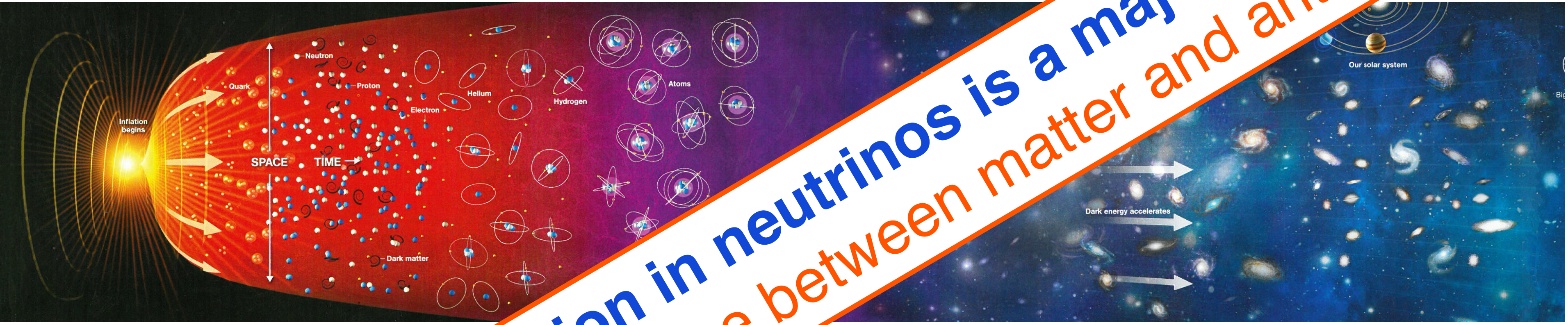

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Observing CP violation in neutrinos is a major goal*:

a fundamental difference between matter and antimatter

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

The 2012 Revolution

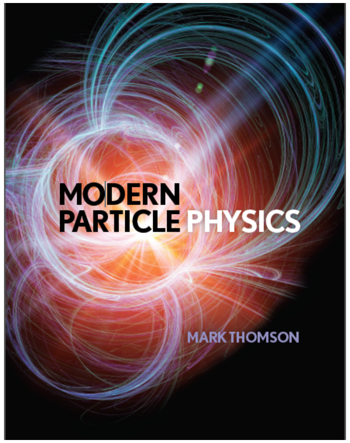
★ Two major discoveries in particle physics

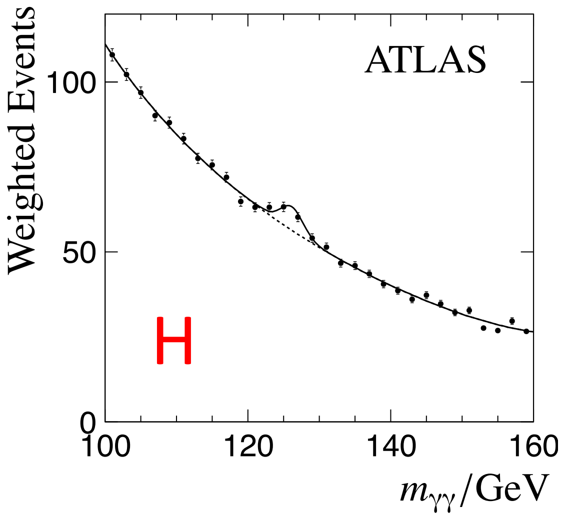
- A SM-like Higgs boson (ATLAS, CMS)
  - The key to EWSB and a possible window to the BSM world
- $\theta_{13} \sim 10^o$ (T2K, MINOS, Daya Bay, RENO)

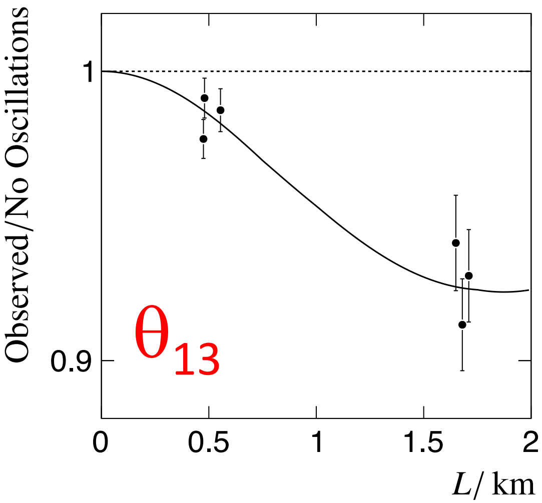
  \- about as large as it could have been !
  - The door to CP Violation in the leptonic sector

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 & HyperK**







*apologies for gratuitous plug

The 2012 Revolution

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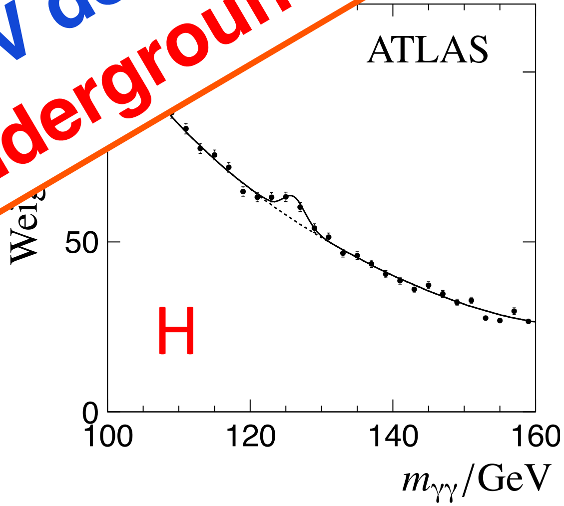
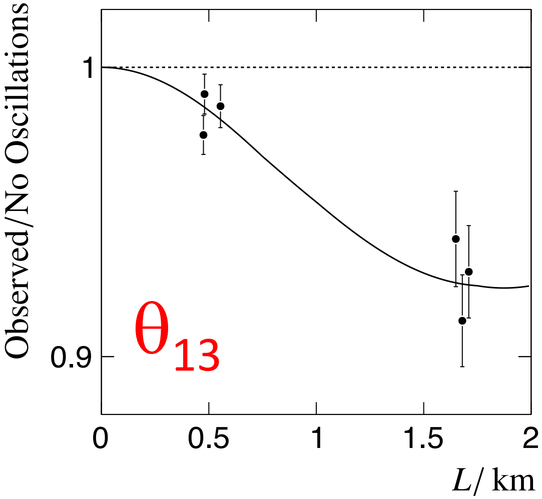
  - θ_{13} ~ 10° : determines rate of

    - about as large as it co
    - The door to CP Vi no oscillations
- ★ **Now standard textb**
  - **also define** ⇨ **DUNE**

Large θ_{13} → **CPV detectable with conventional ν beam**

→ **Deep Underground Neutrino Experiment**





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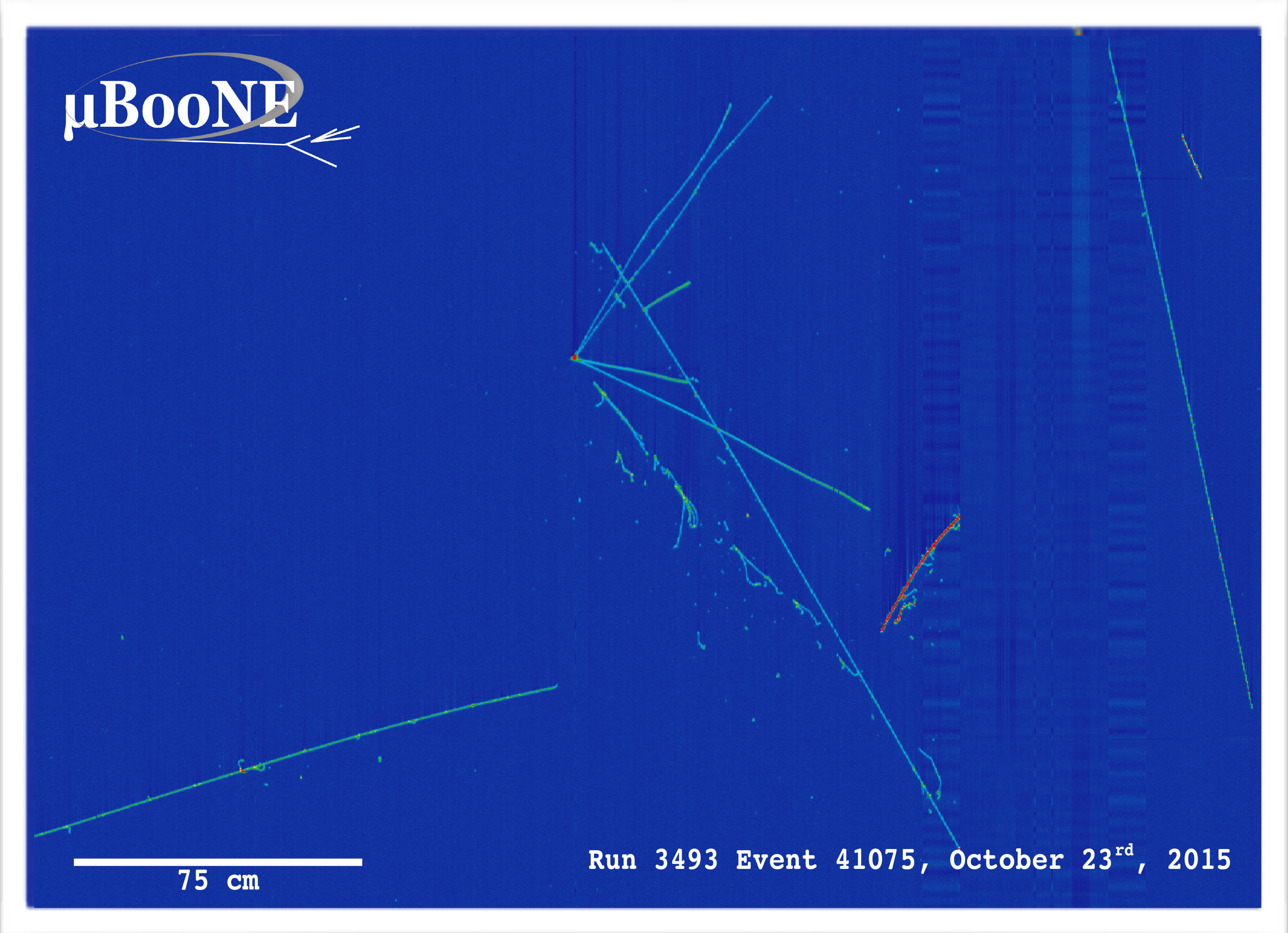
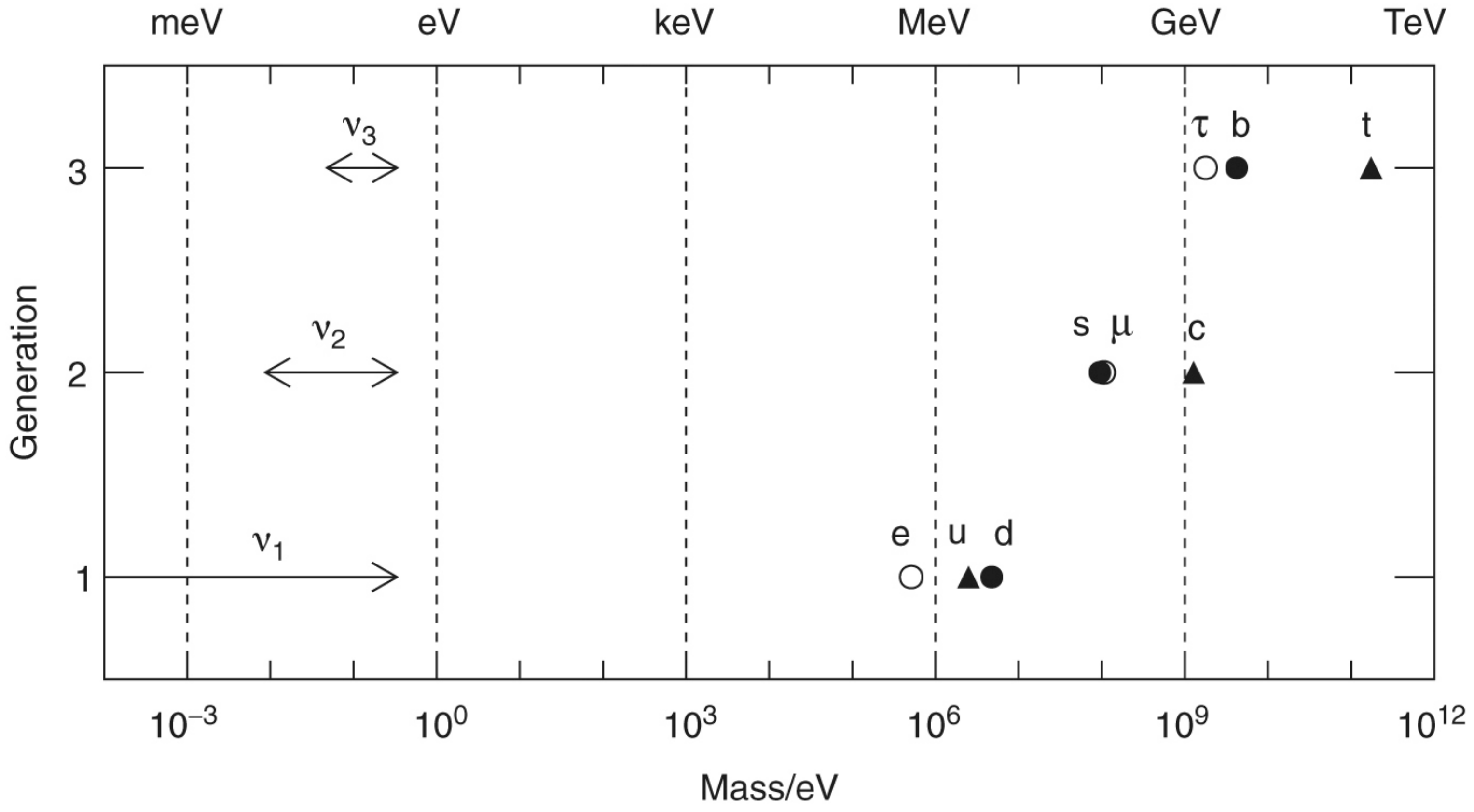
3. Neutrinos are different



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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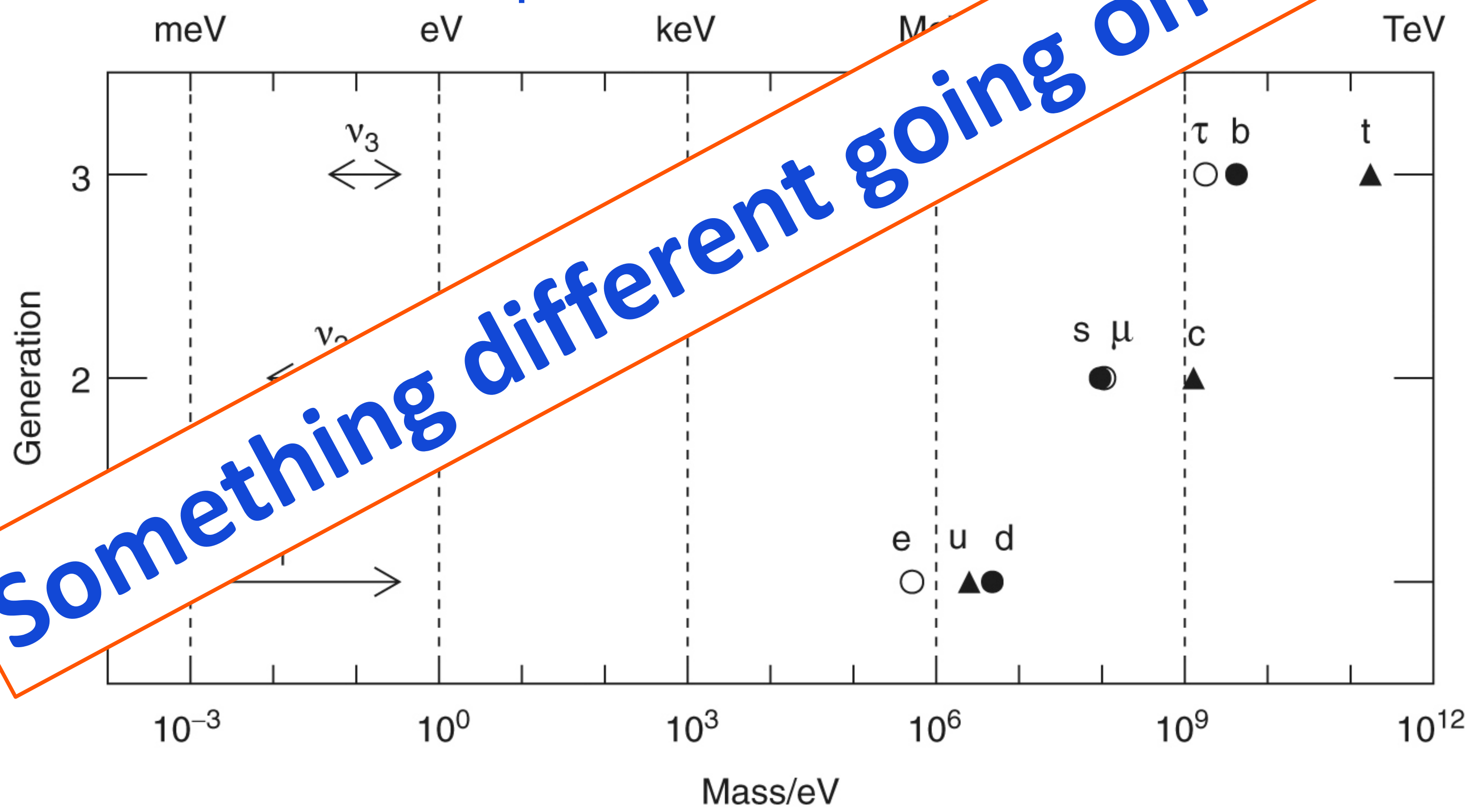
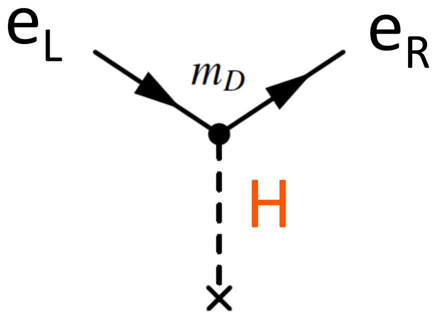


Something different going on here…

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

$$\frac{Y_{\mathrm{f}}}{\sqrt{2}} v\left(\overline{\mathrm{f}}_L \mathrm{f}_R + \overline{\mathrm{f}}_R \mathrm{f}_L\right)$$

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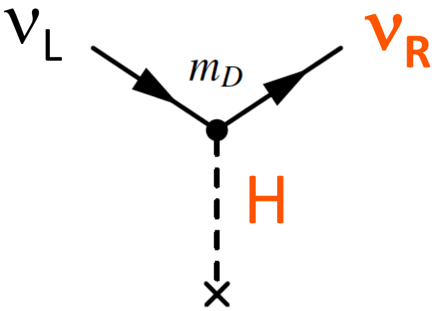

Dirac mass terms, Higgs coupling together L- and R-handed chiral fermionic fields

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

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

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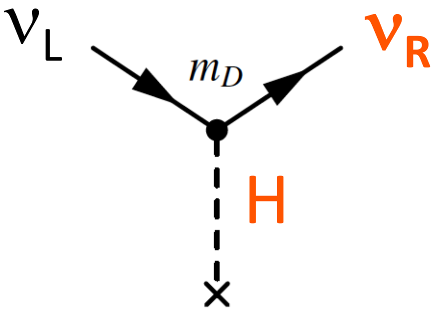

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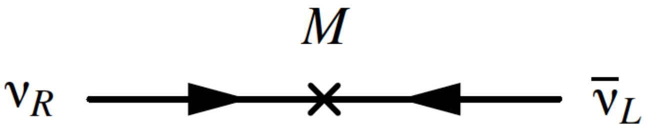
- This also could be the origin of neutrino masses

⇨ 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)

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



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

a connection to new physics…

★ Neutrino masses are anomalously small

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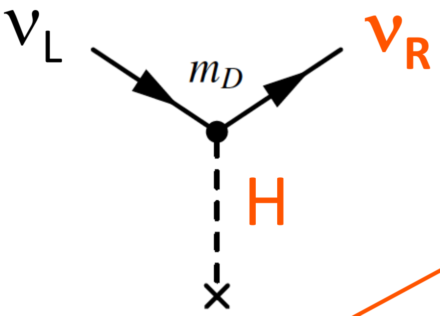

Dirac mass te er
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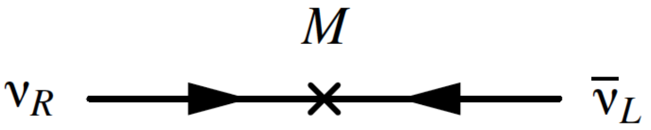


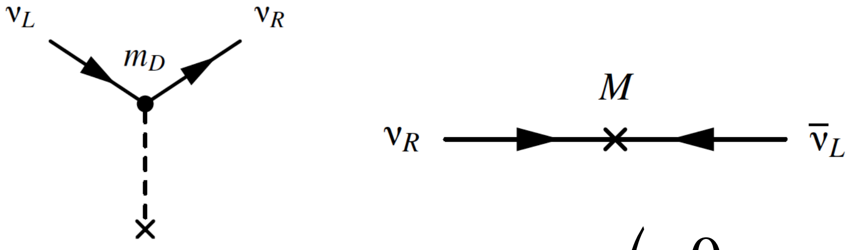
This additional freedom might explain why neutrino masses are "different"

Neutrinos could be a fundamentally different type of particle

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

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

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

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

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

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

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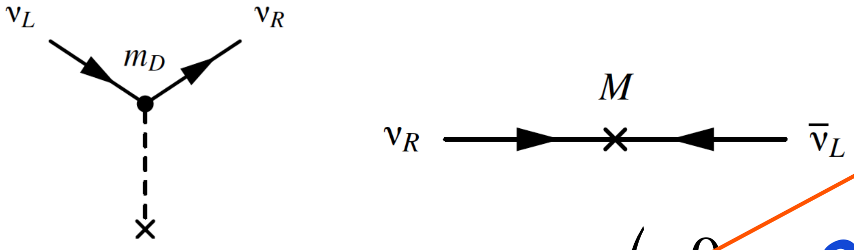

(not… …nt this)

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

Neutrinos could provide a link to GUT-scale physics

- The seesaw mecha… …physical "mass eigenstates" are those in th… where the mass matrix is diagonal

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

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

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

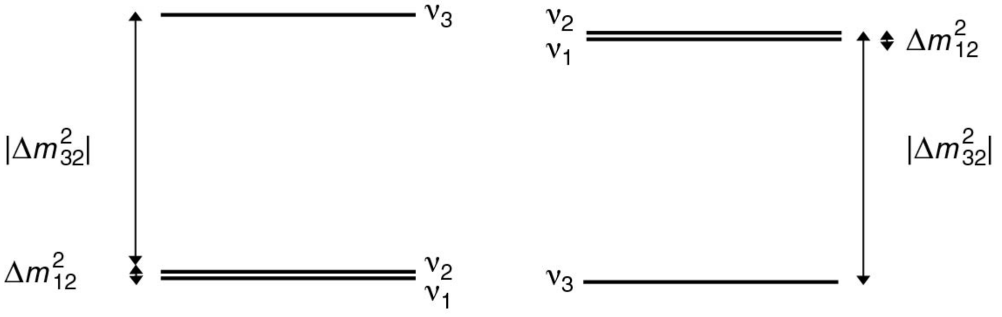
Knowns and Unknowns

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

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

✅ ✅ ✅ ✅ ✅ ? ?

Mass Hierarchy not yet known



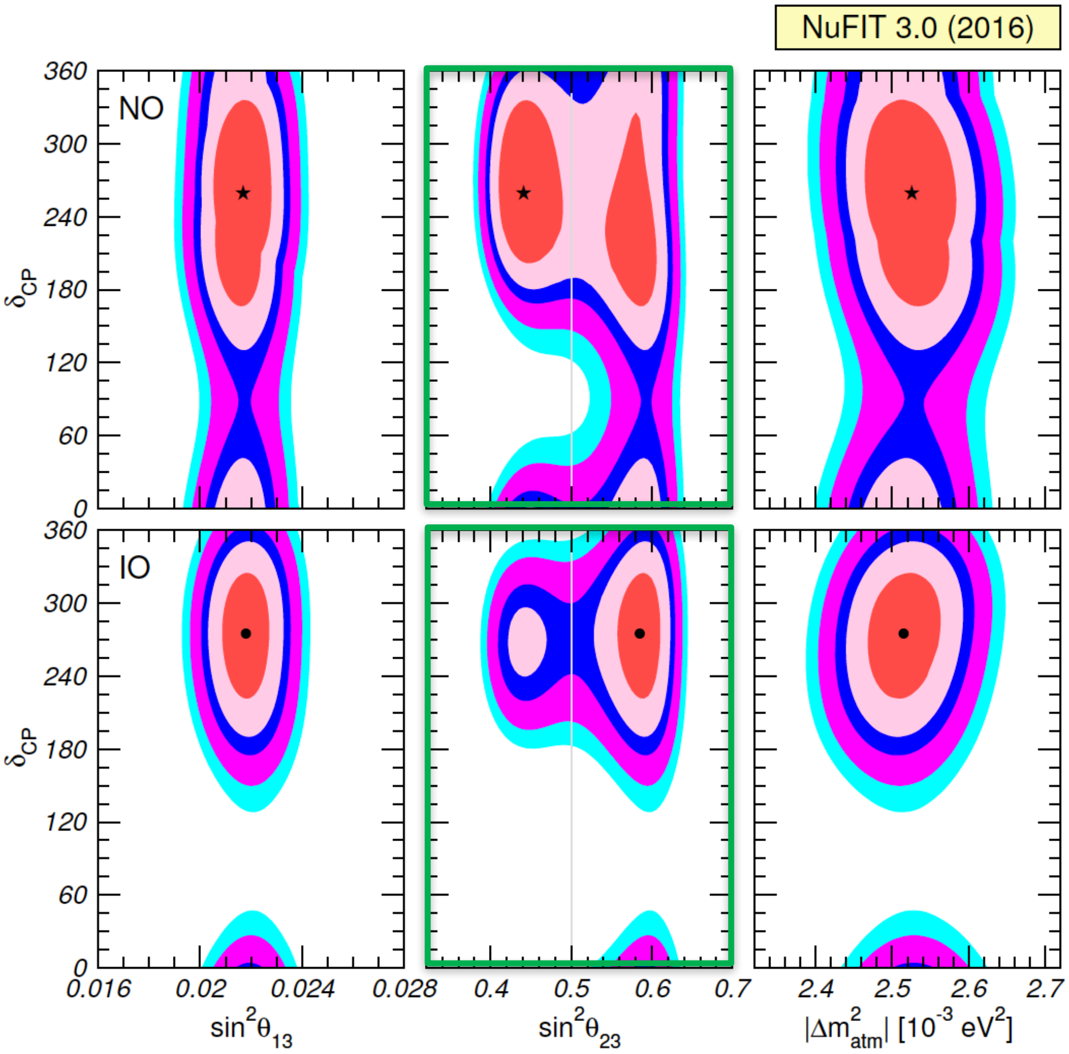
δ_{CP} not known νCPV?

- **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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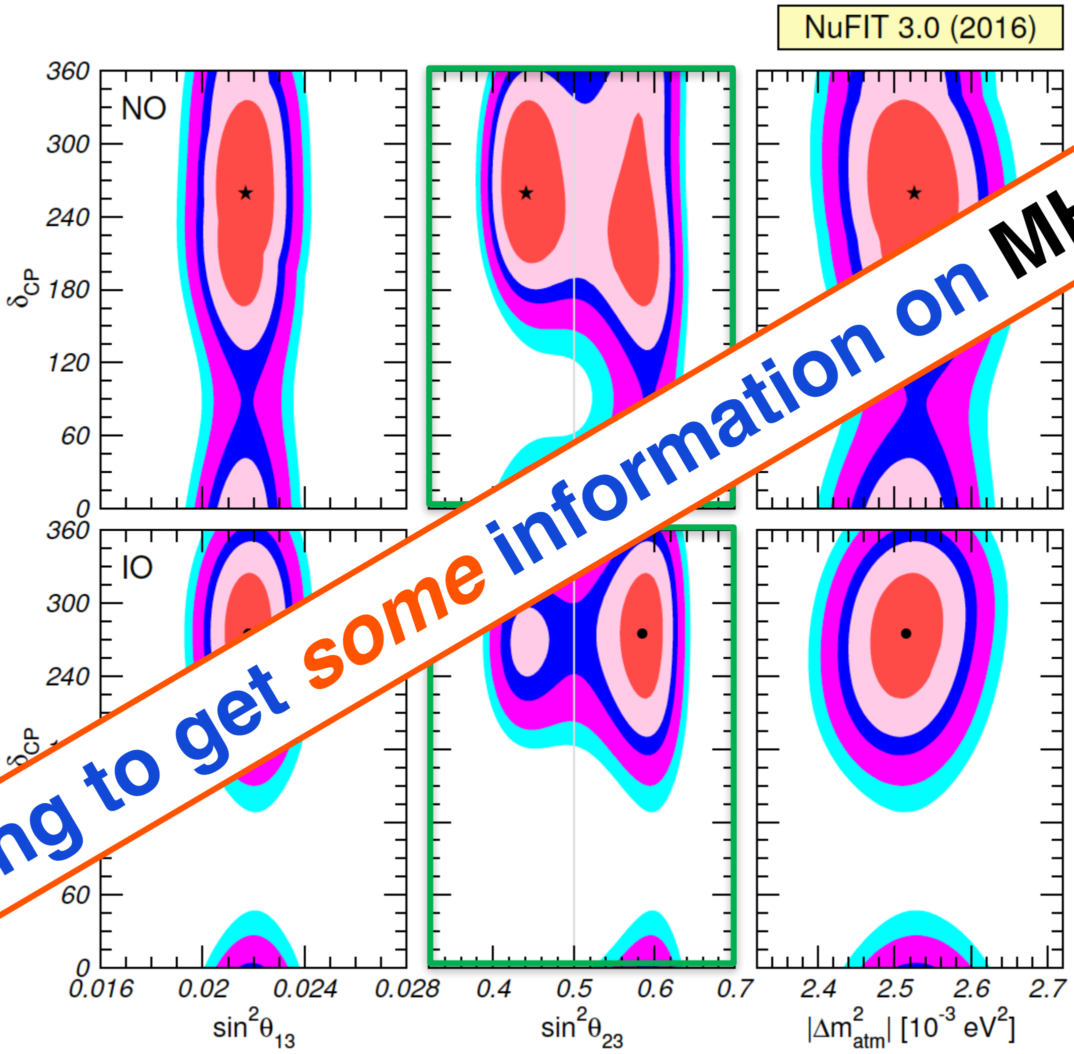

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late ults

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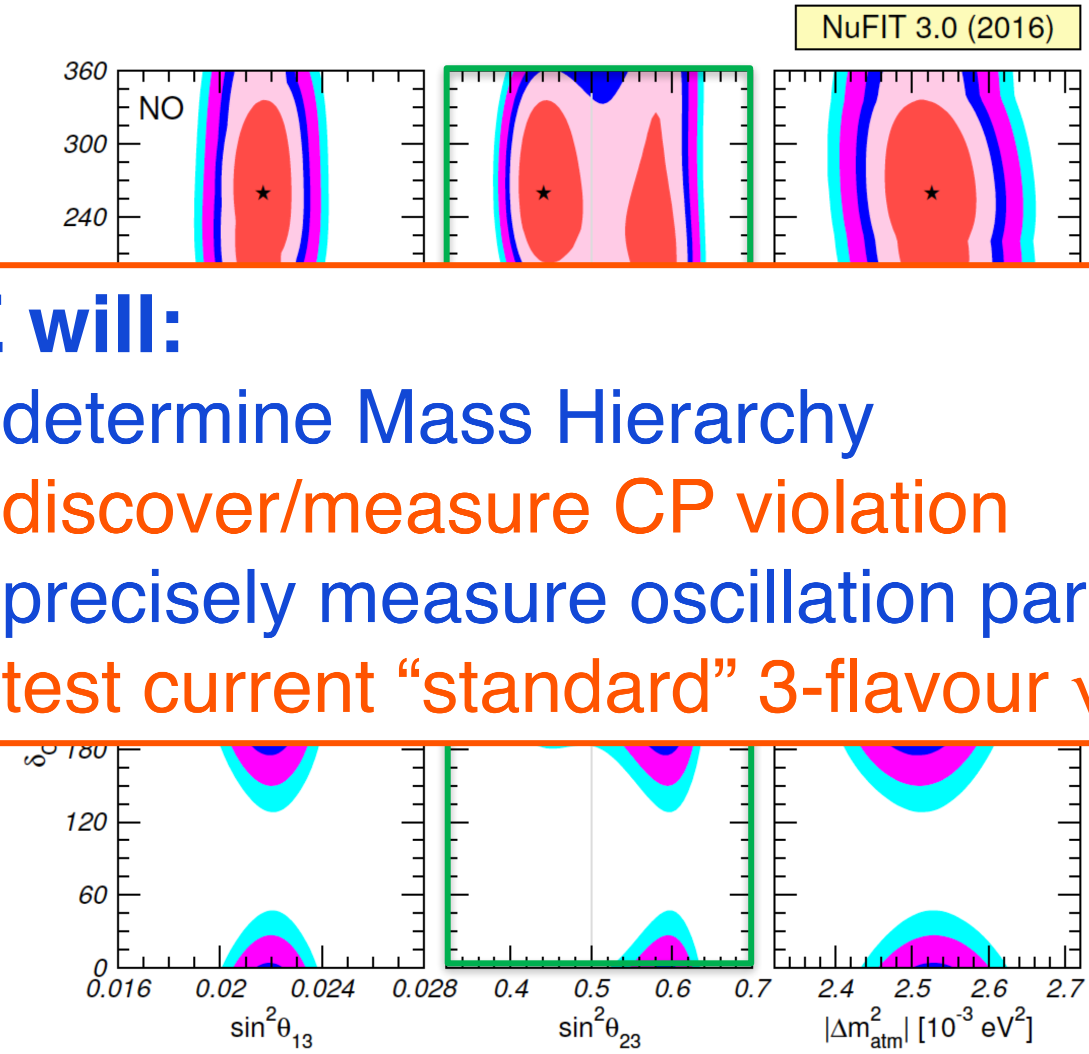
Starting to get some information on MH and δ_{CP}

CP and MH : Combined knowledge



Does not include latest T2K results

🟥 1 σ

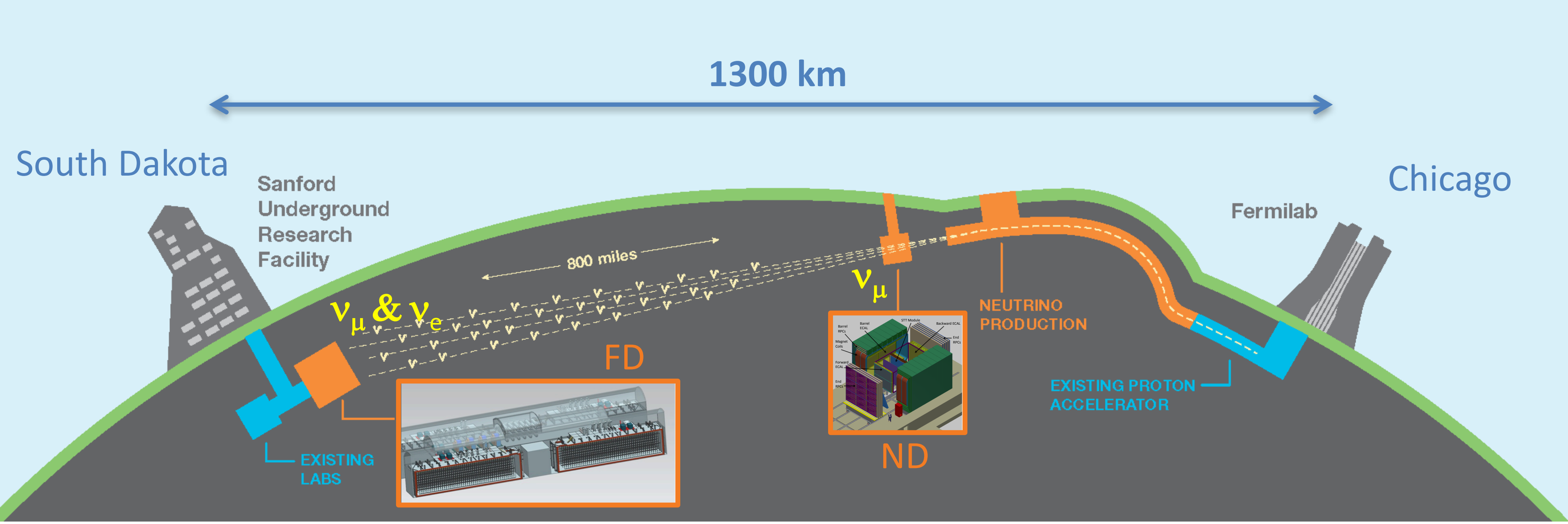
DUNE will:

- 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:**

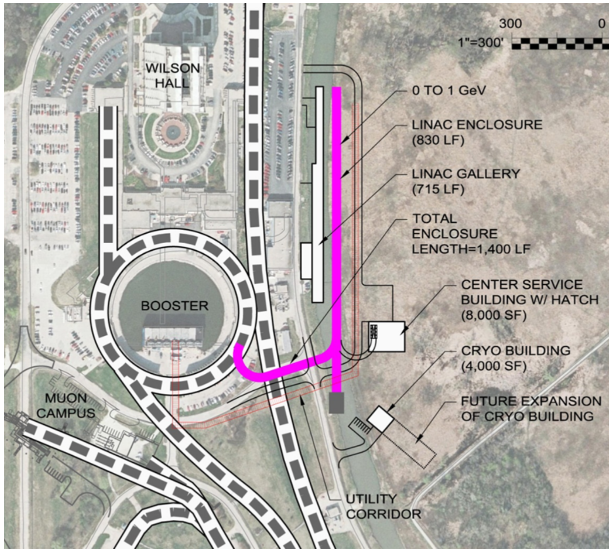
- **beam power drives the sensitivity**

★ **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**

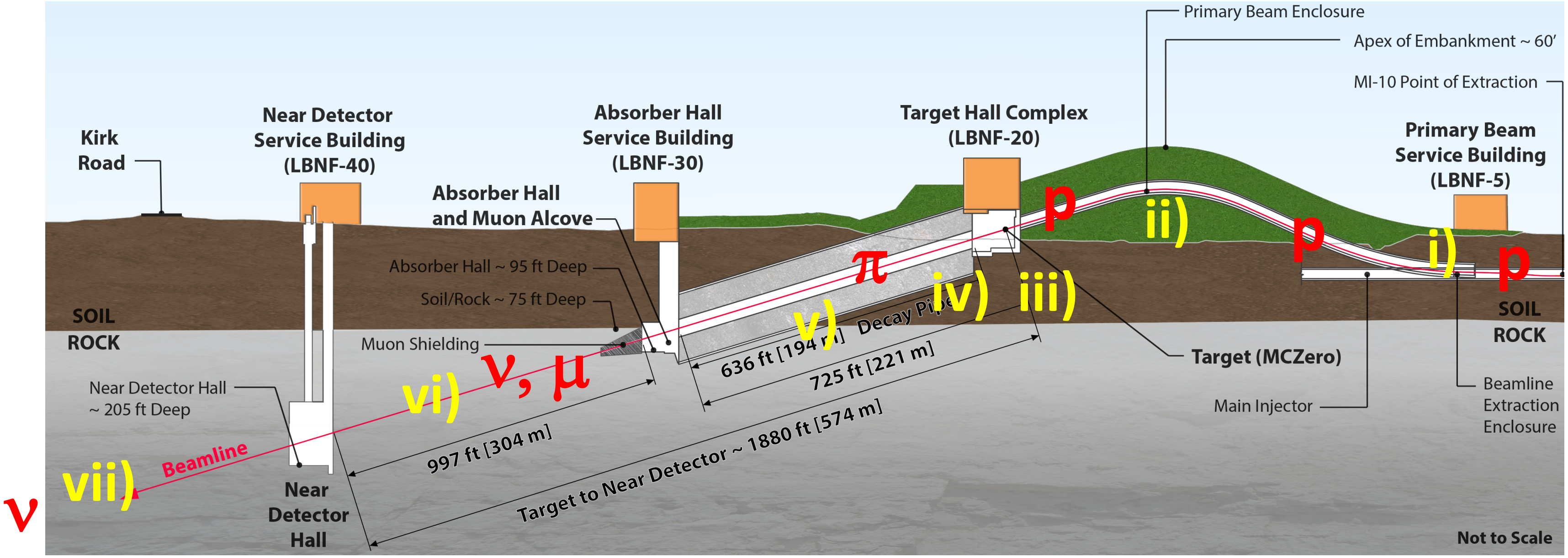
★ **Requires PIP-II** (proton-improvement plan)

- **$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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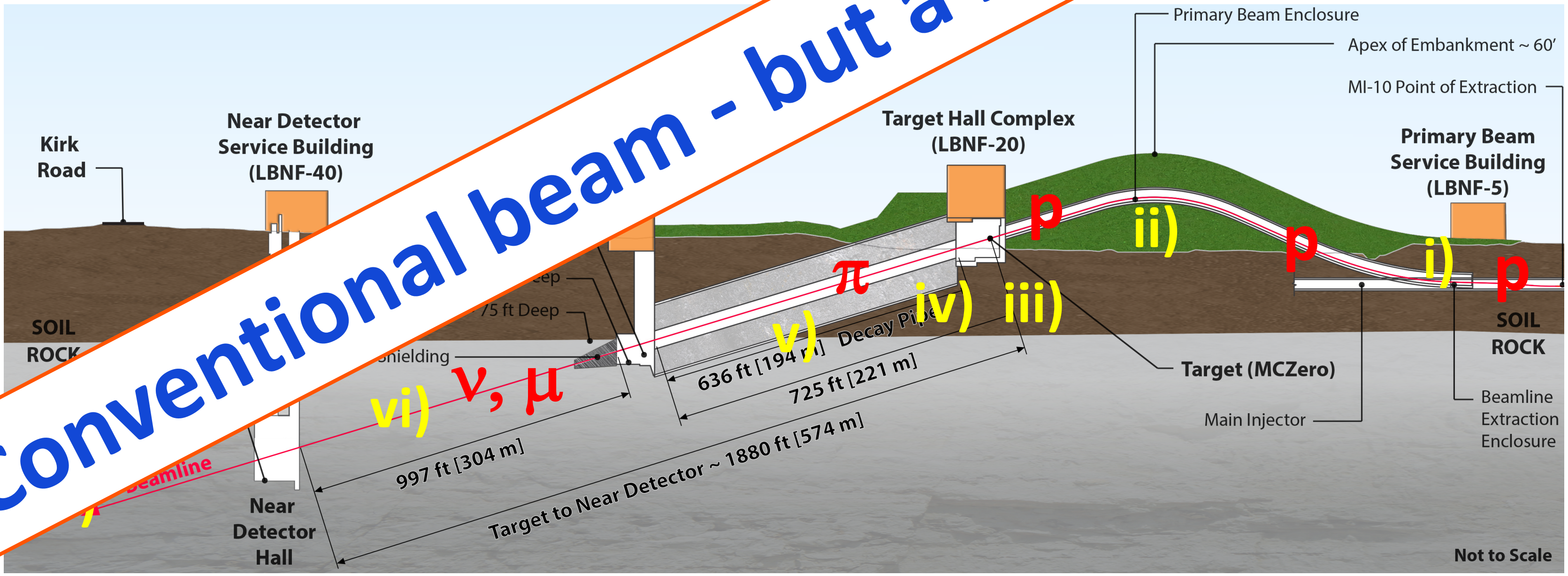
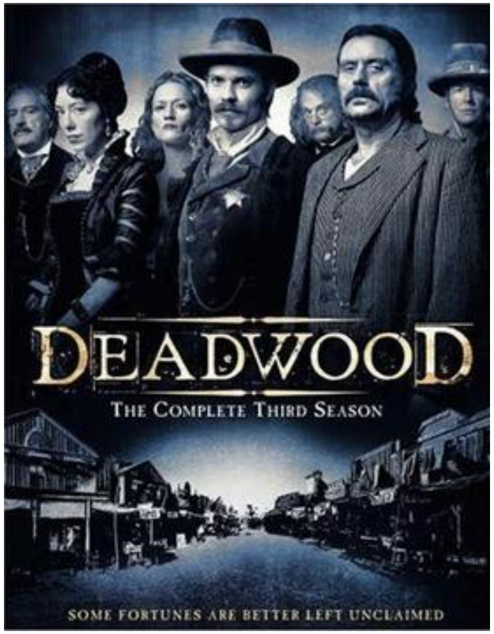


Conventional beam - but a ramp up in power

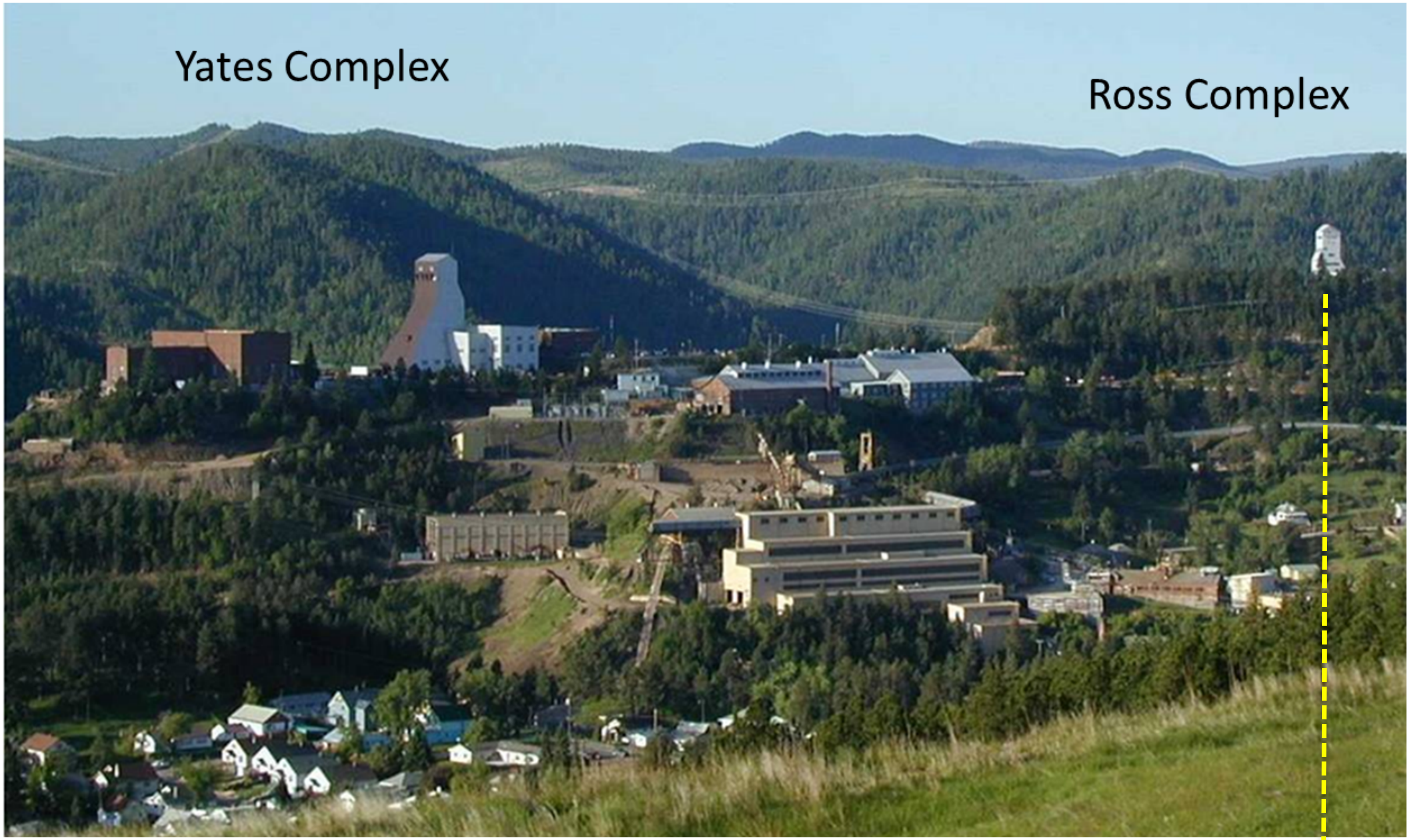
The beam then heads West

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



…5 miles from Deadwood: Homestake gold mine

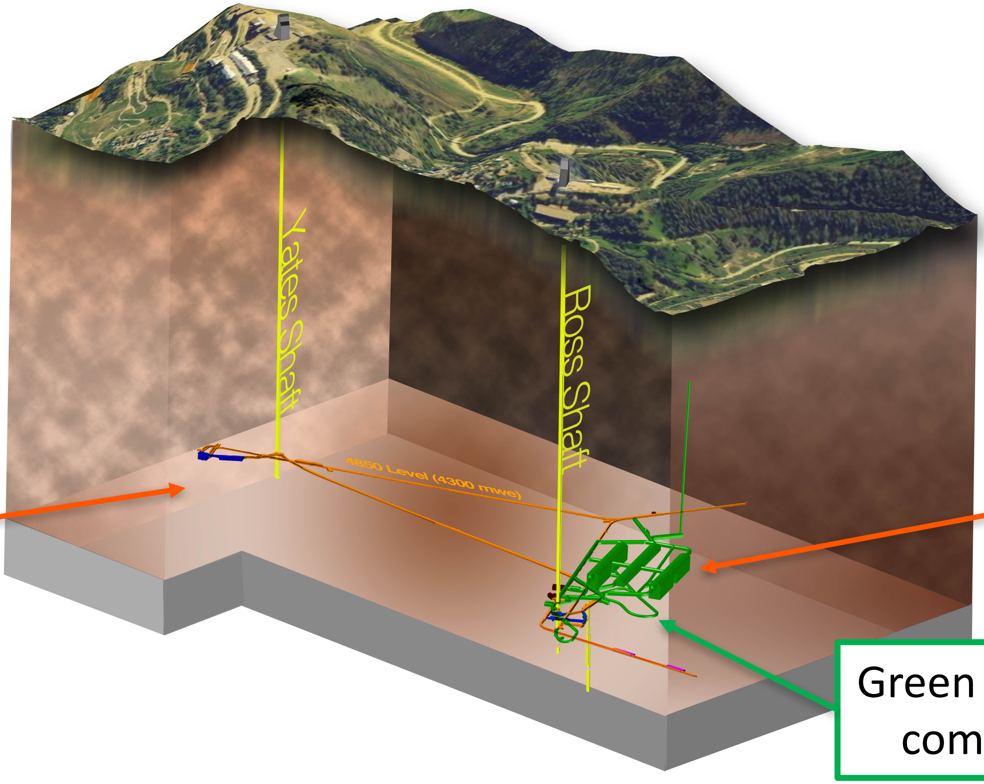
4.2 The DUNE Far Detector



Going underground…

DUNE Far Detector site

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



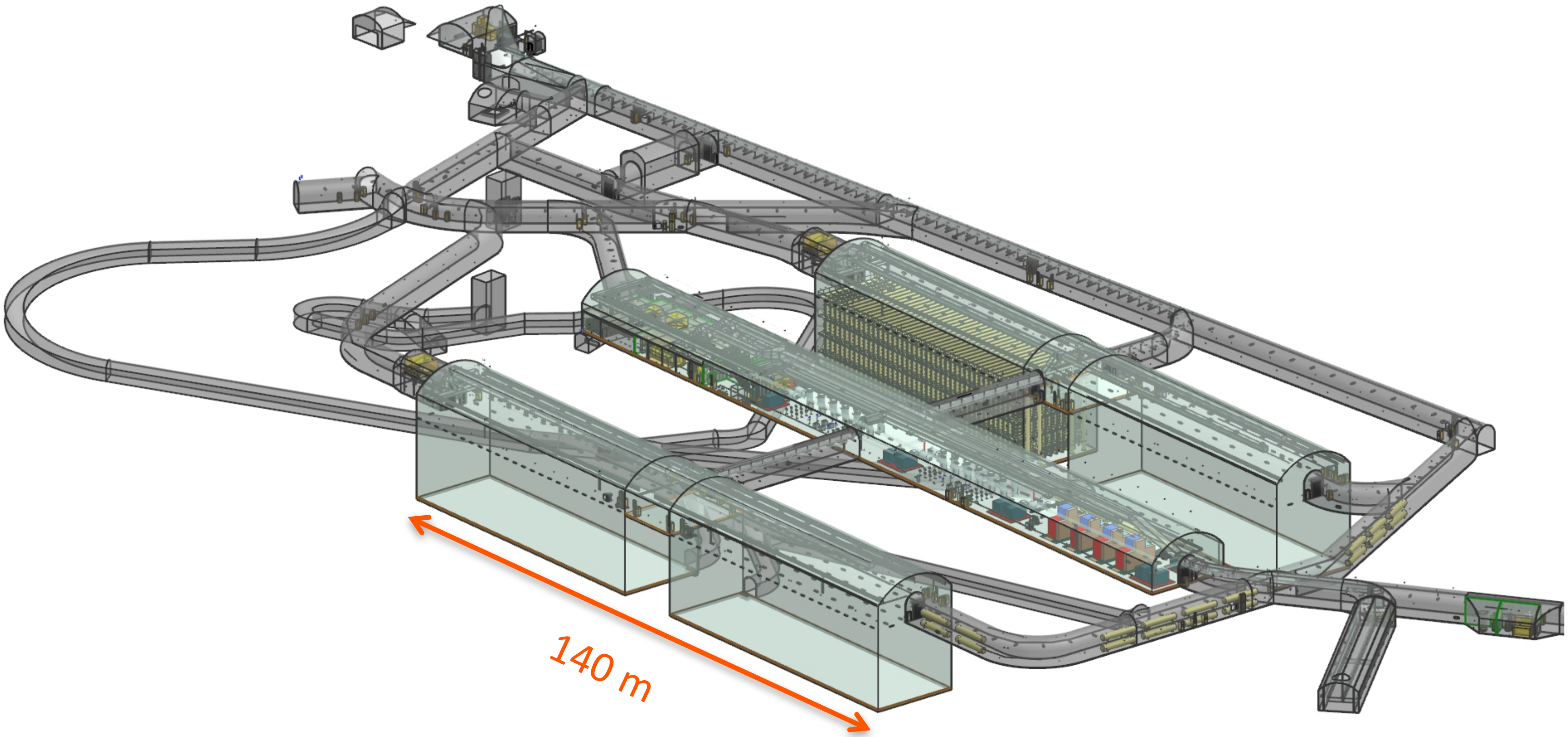
Davis Campus:
- LUX
- Majorana demo.
- …
- **LZ**

Ross Campus:
- CASPAR
- …
- **DUNE**

Green = new construction commences in 2017

DUNE Design =

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



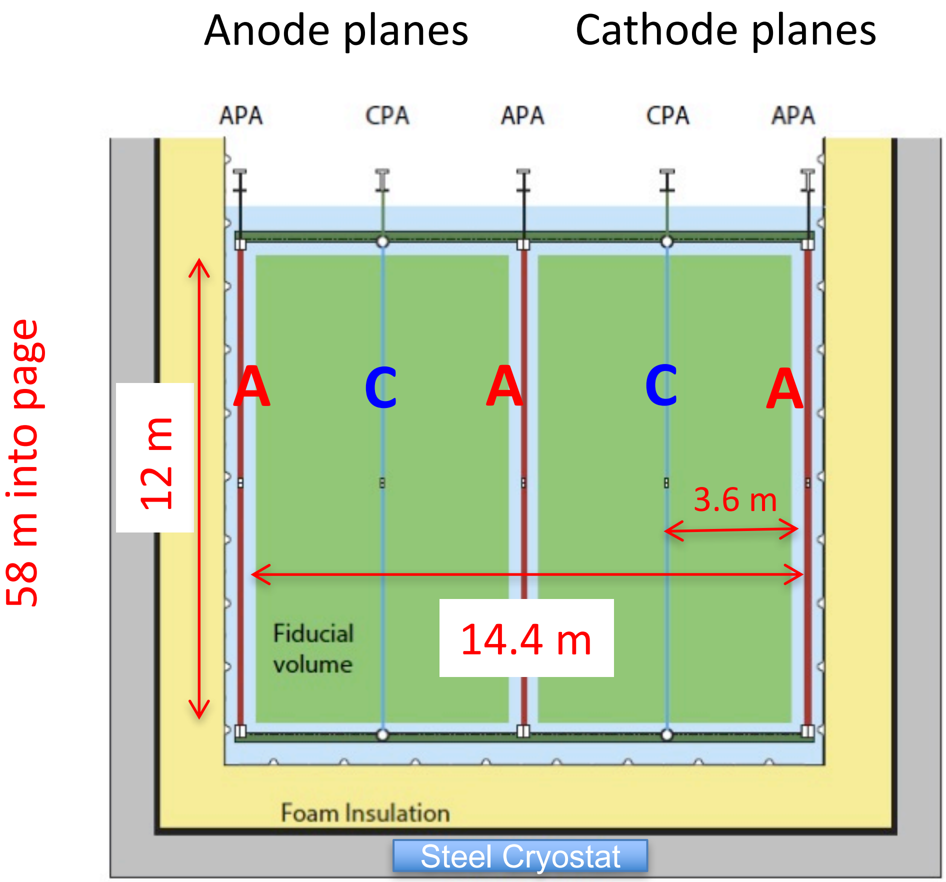
Four detectors modules

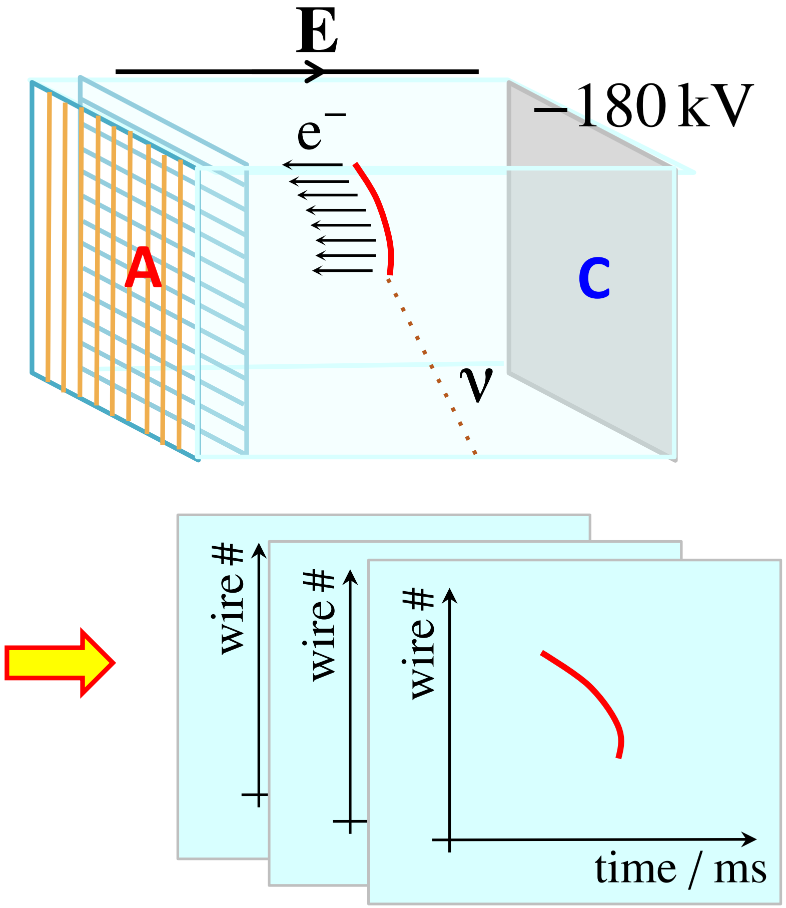
- Allows staged deployment of Far Detector

First 17-kt Far Detector Module

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

- Record ionization in LAr volume ⇨ 3D image



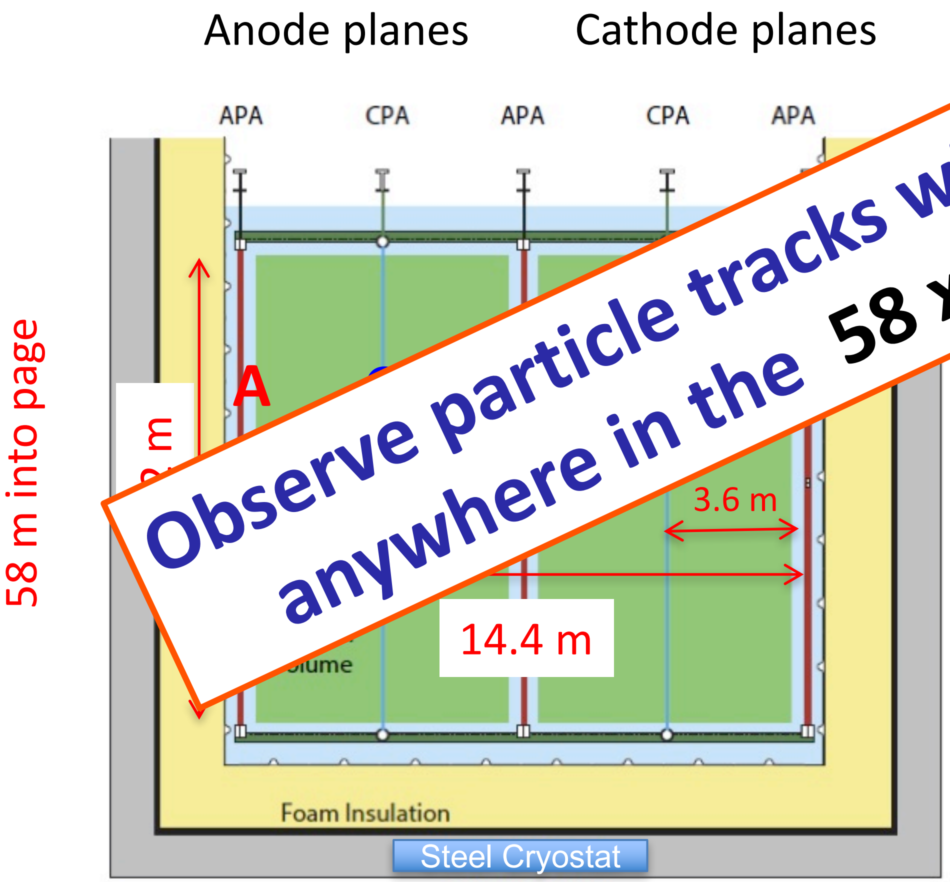


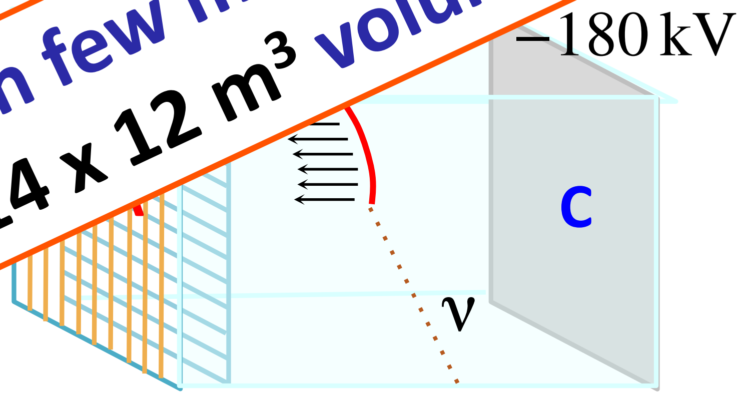
First 17-kt Far Detector Module

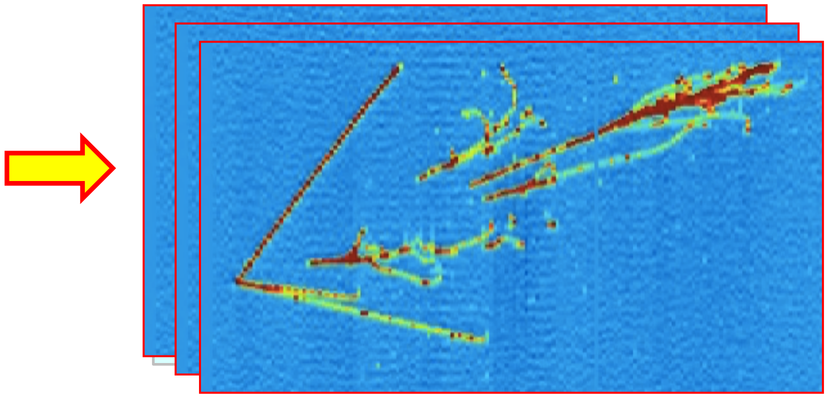
A modular implementation of Single-Phase LAr TP

- 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

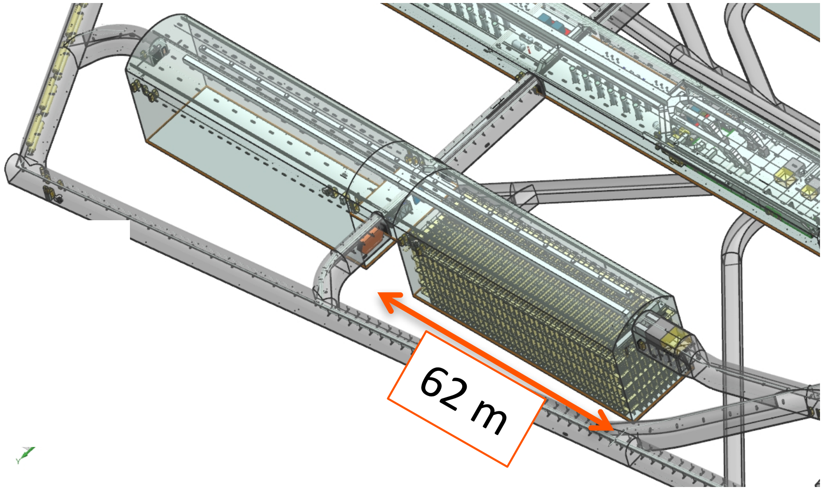






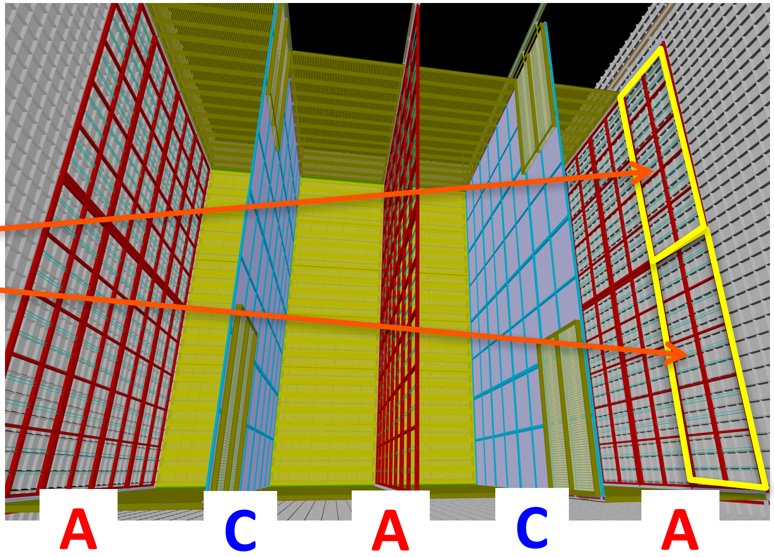
Modular Detector

- 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

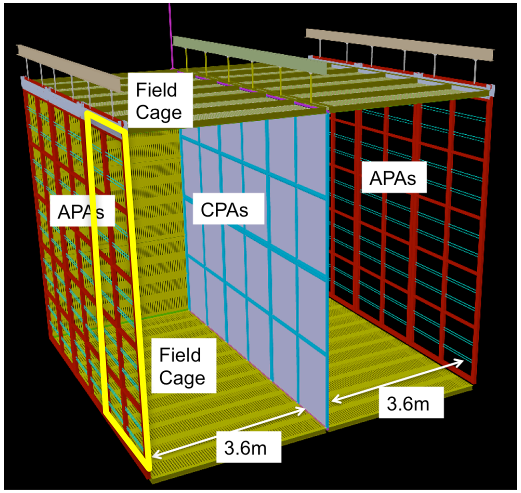


4.3 Far Detector Prototyping

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)

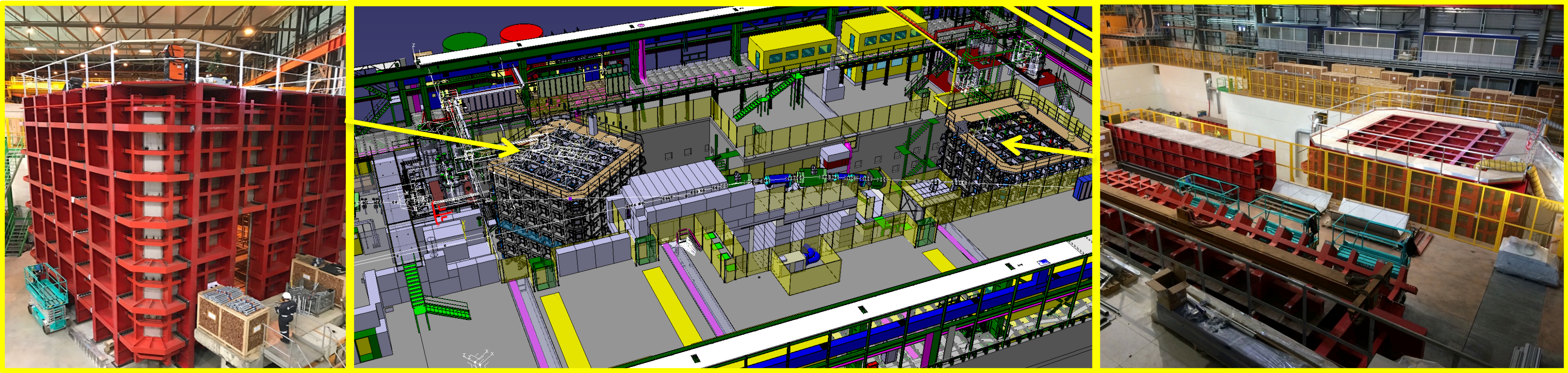
- "Full-scale prototypes" with ProtoDUNE at the **CERN Neutrino Platform**
  - **Engineering prototype**
    - 6 **full-sized** drift cells c.f. 150 in the far det.
  - Approved experiment at CERN
  - Aiming for operation mid-2018



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 + …



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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

Membrane Cryostats

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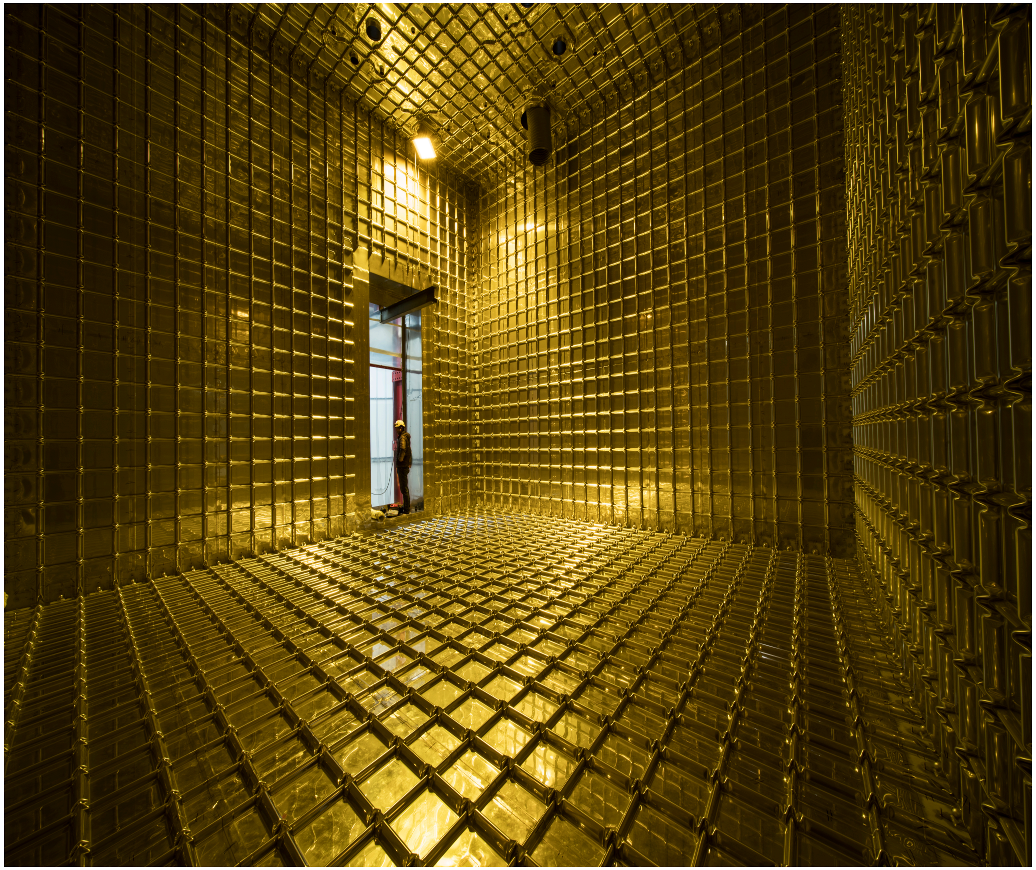


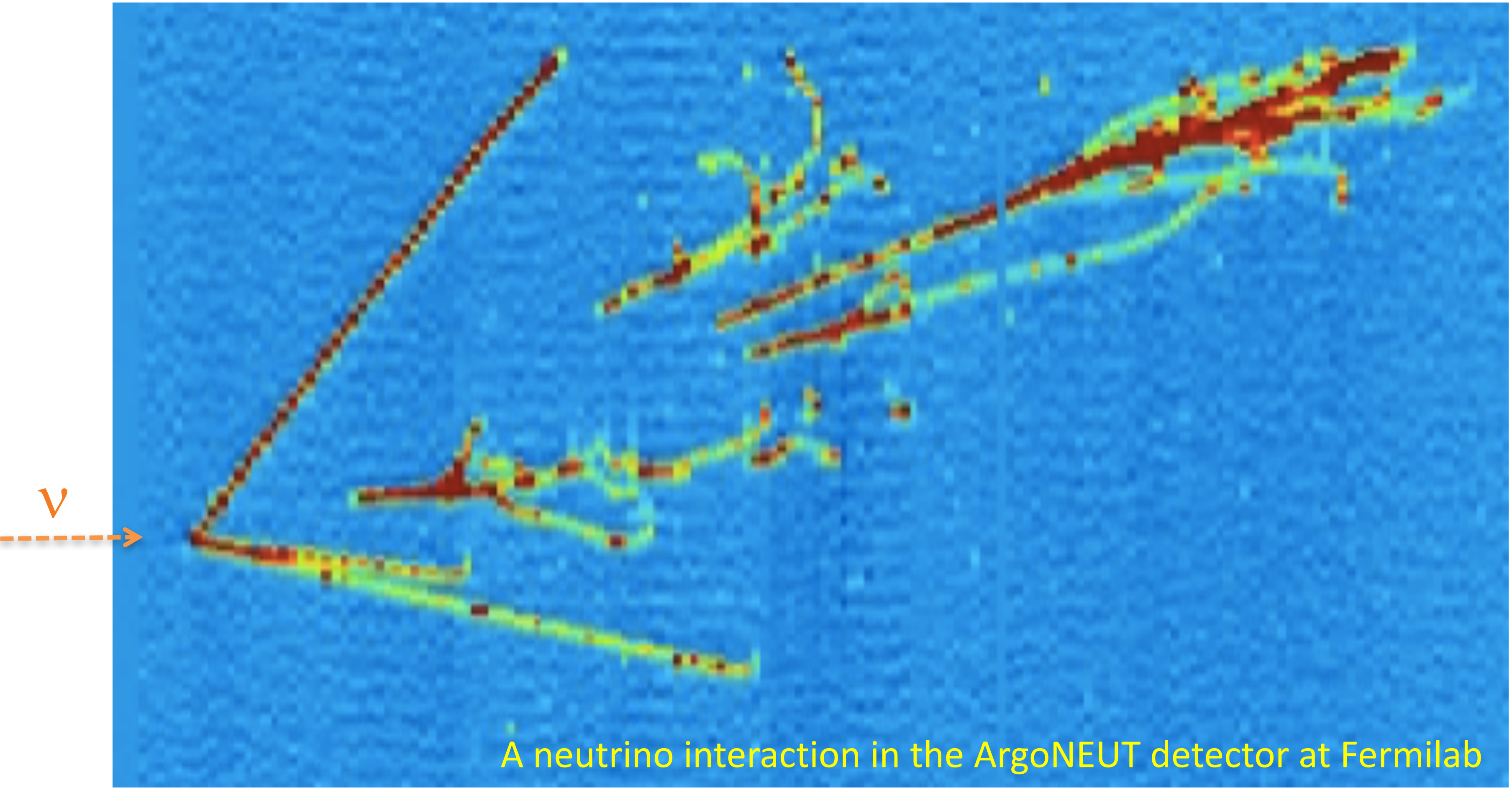
Membrane Cryostats

- 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

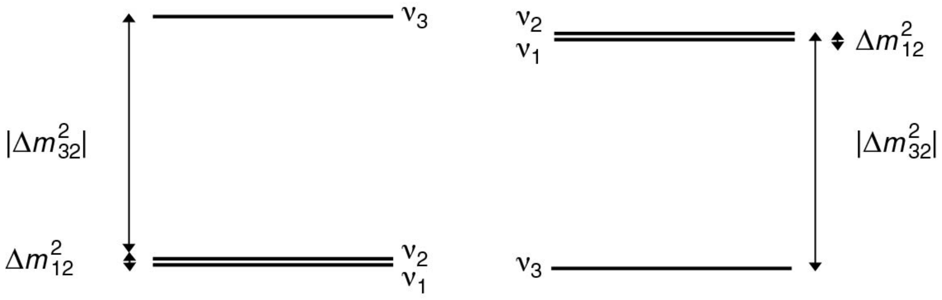


A neutrino interaction in the ArgoNEUT detector at Fermilab

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

DUNE Primary Science Program

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

Each would be a <u>major</u> discovery

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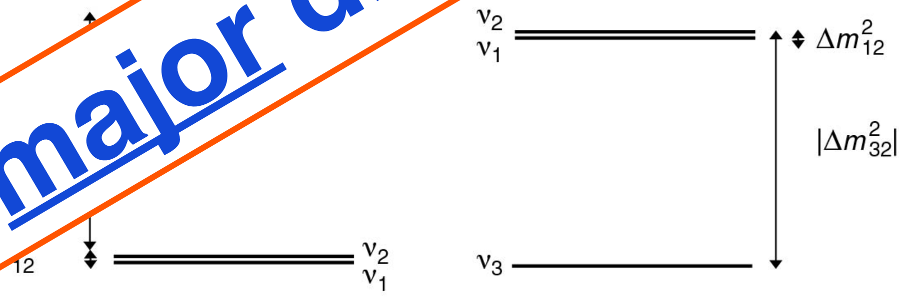

- **2) Decay**
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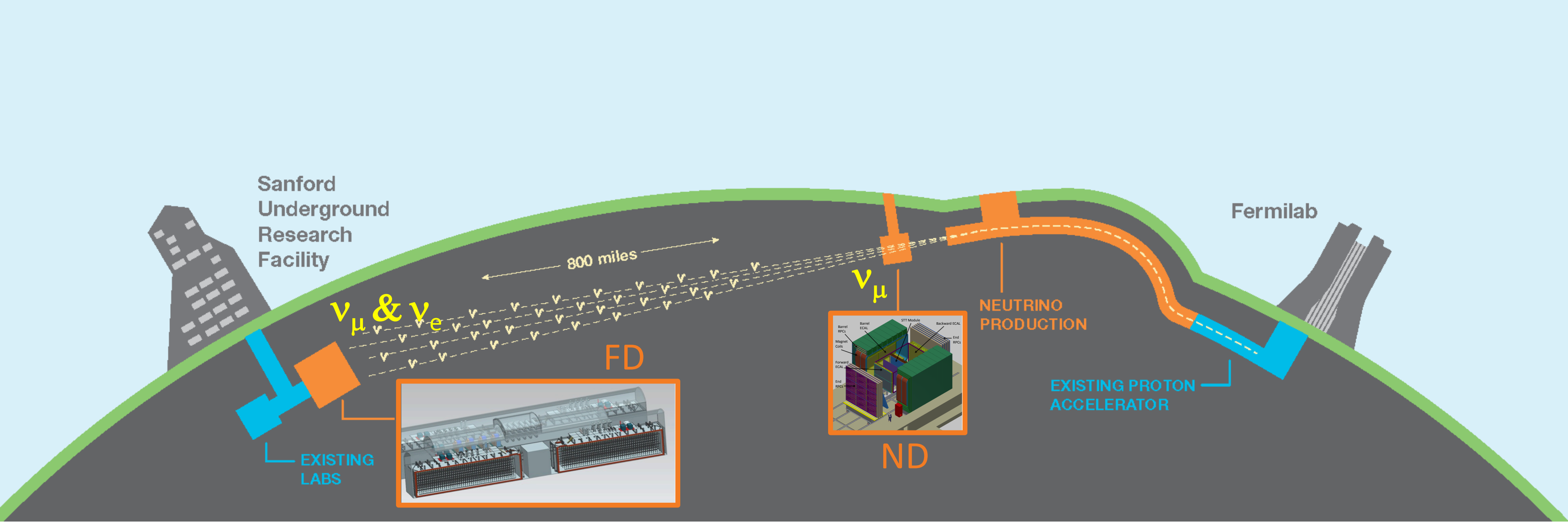
- **) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

Long Baseline (LBL) Oscillations

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

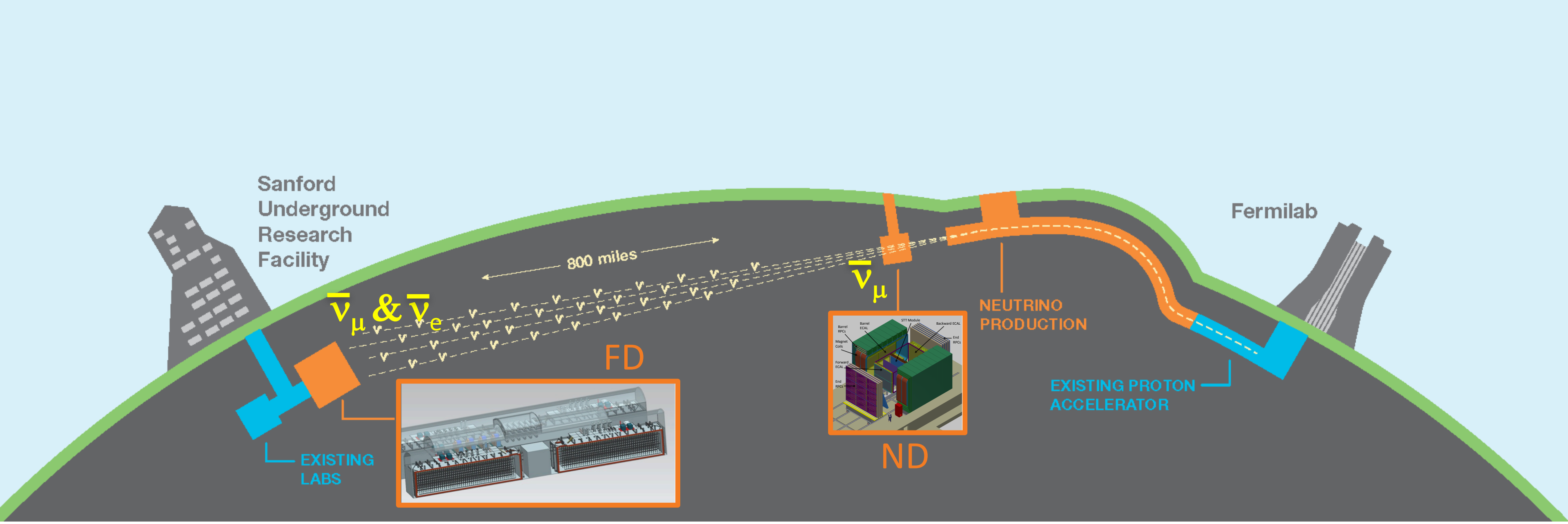


- **Near Detector at Fermilab: measurements of ν_μ unoscillated beam**
- **Far Detector at SURF: measure oscillated ν_μ & ν_e neutrino spectra**

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

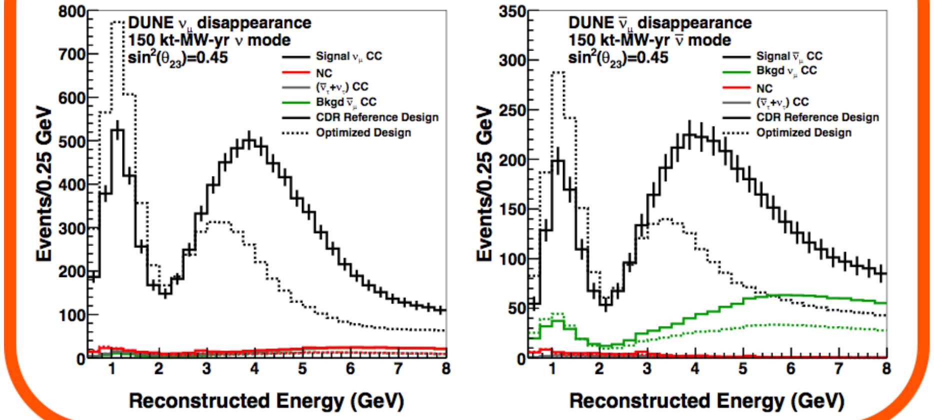
Measure neutrino spectra at 1300 km in a wide-band beam

- **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

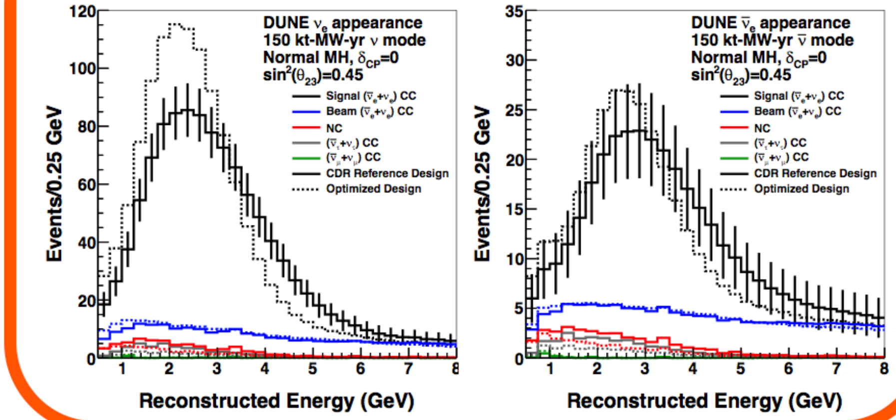
μ

ν_μ / $\bar{\nu}_\mu$ disappearance



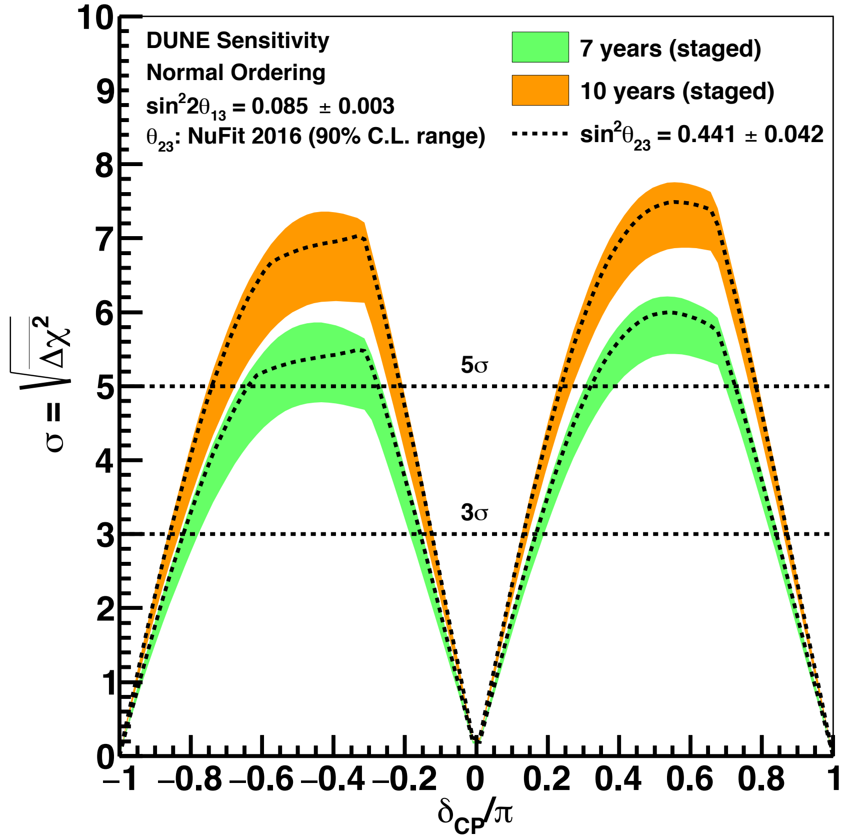
e

ν_e / $\bar{\nu}_e$ appearance

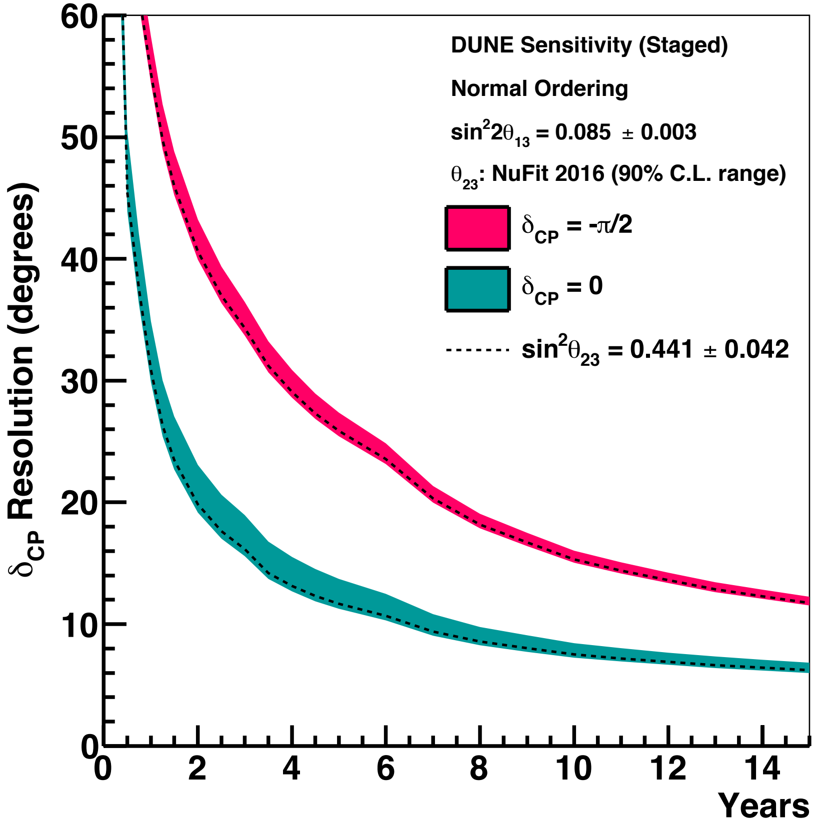


CP Sensitivity

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, ...
- **On-axis beam: potential to tune beam spectrum**
  - Further studies at second oscillation maximum
  - Study tau appearance ?

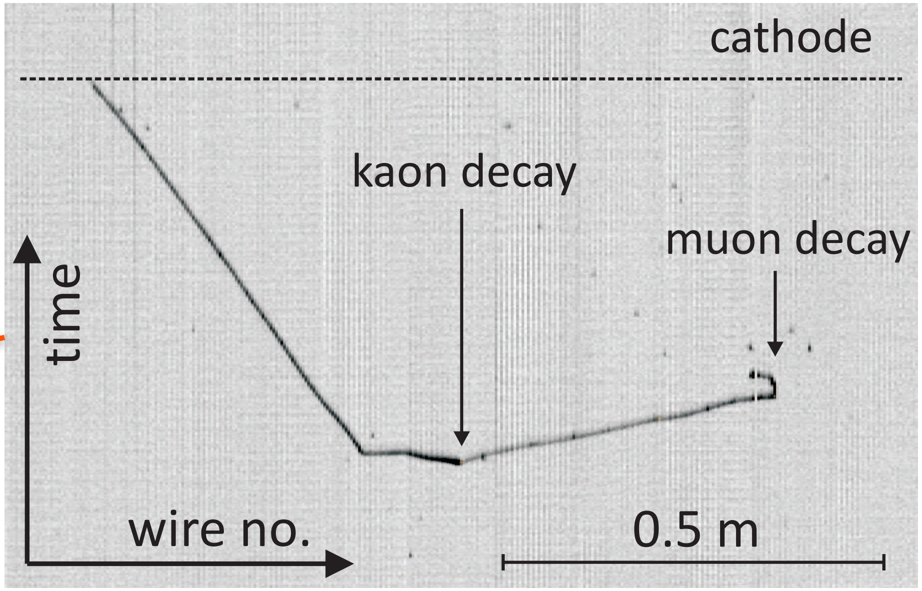
LBNF/DUNE is a facility for ν science

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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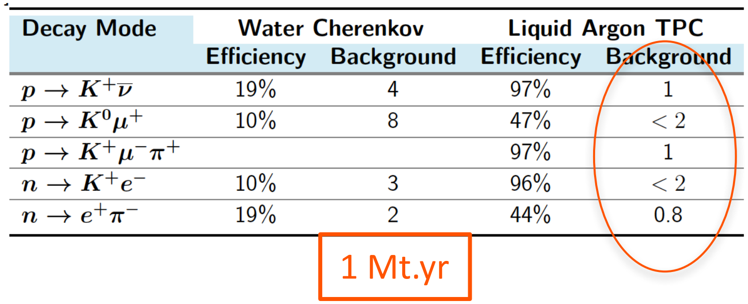
- **Clean signature**

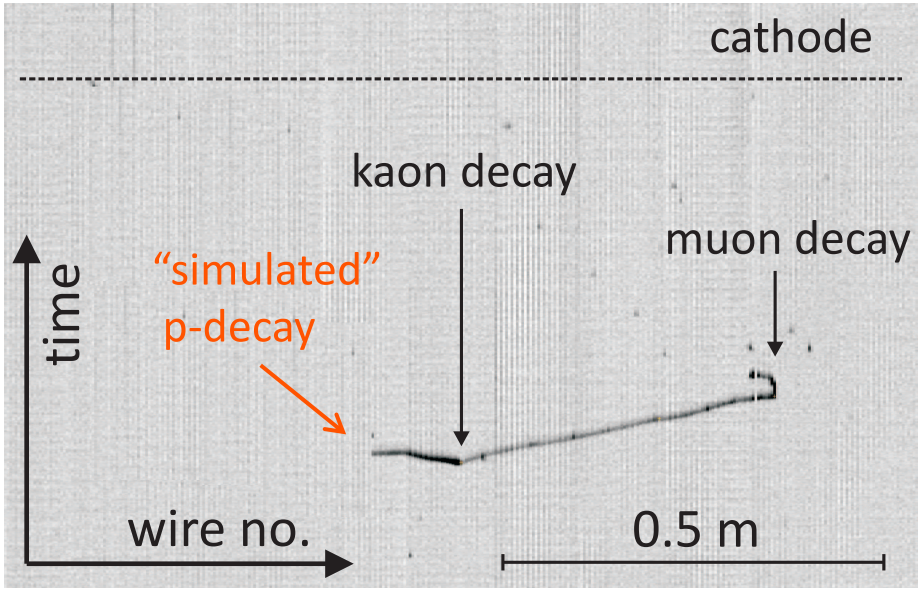
  ➡ very low backgrounds



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

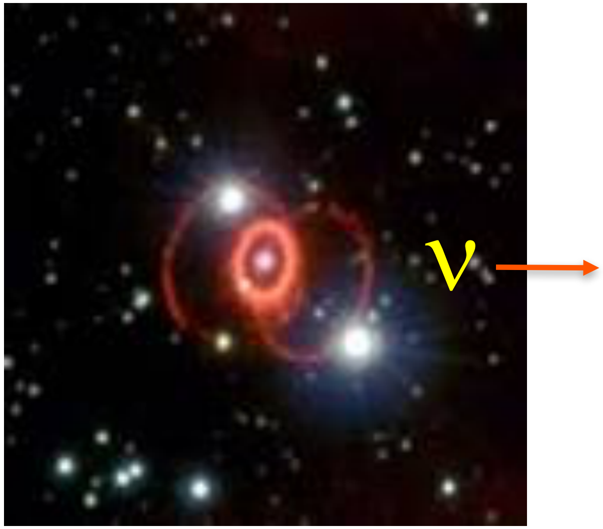
Remove incoming particle

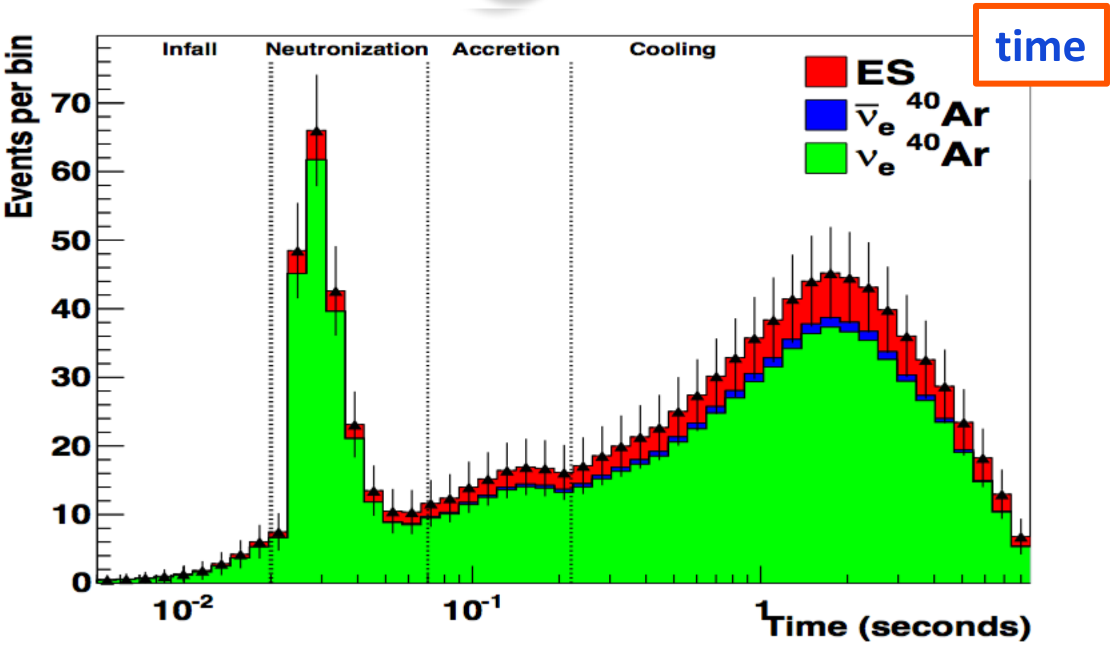


5.2 Supernova νs

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





Highlights include:

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

6. Realizing DUNE

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)

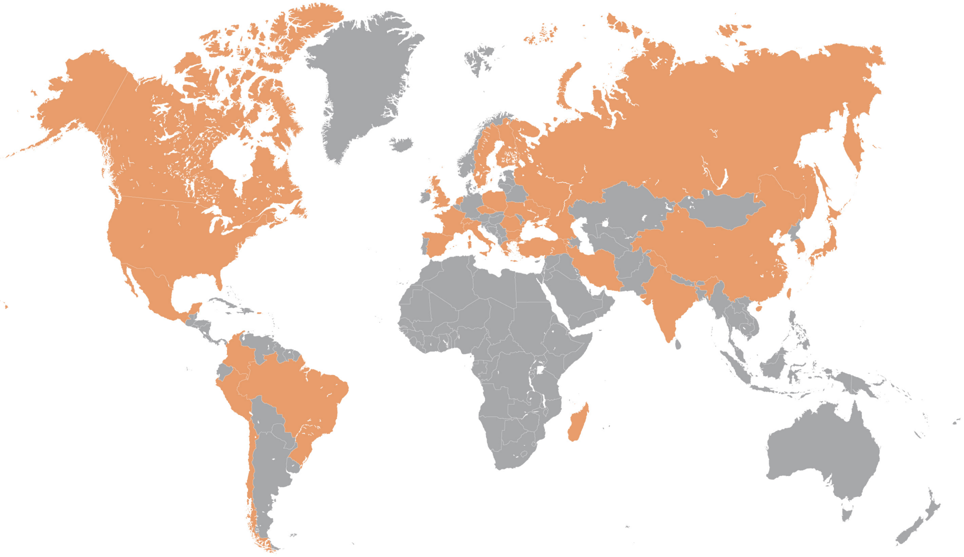
The DUNE Collaboration

As of today:

>60 % non-US

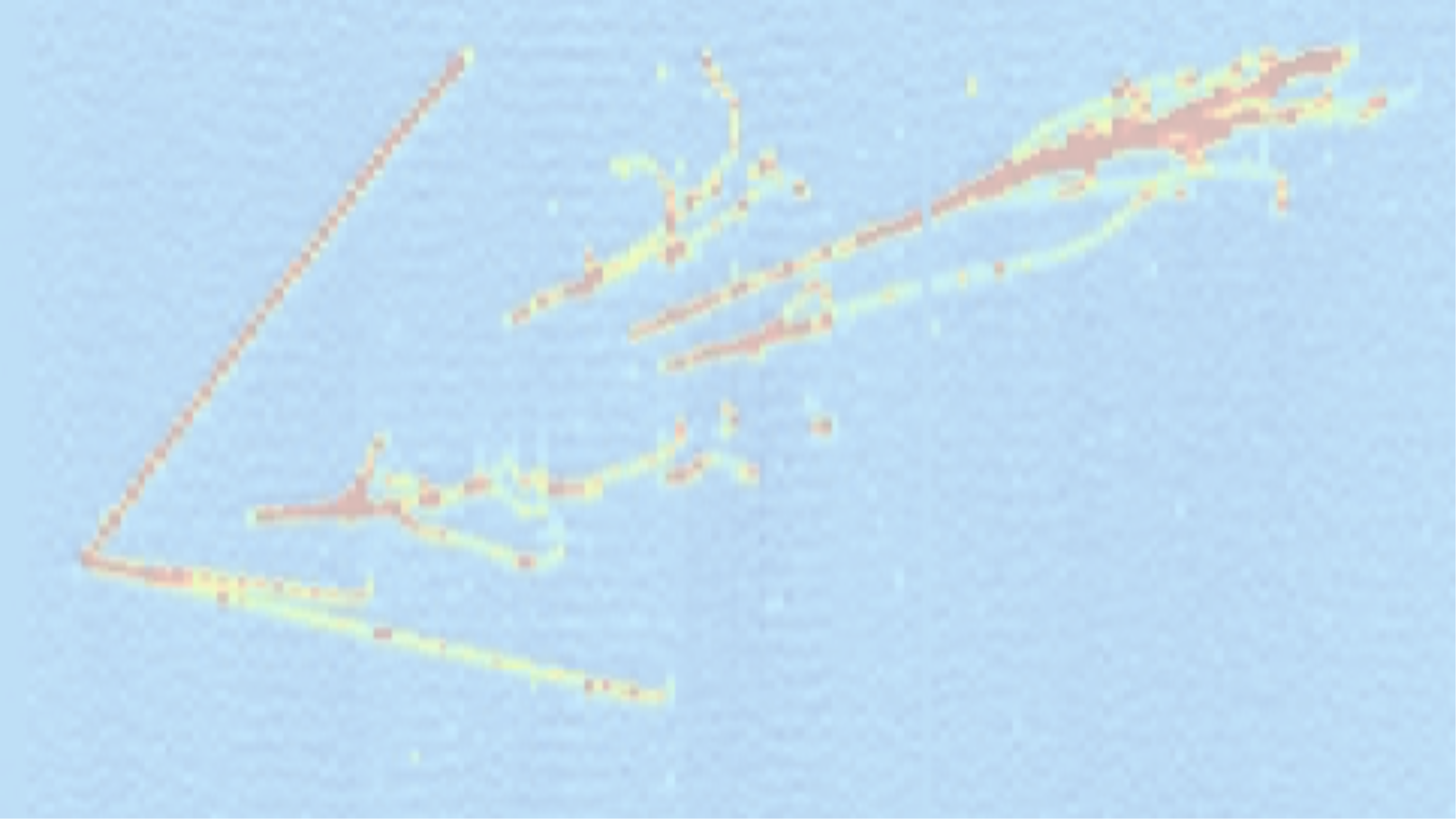
1043 collaborators from 175 institutions in 31 nations

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….

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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★ This is an exciting time

- 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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★ **An international community has formed – including CERN**

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

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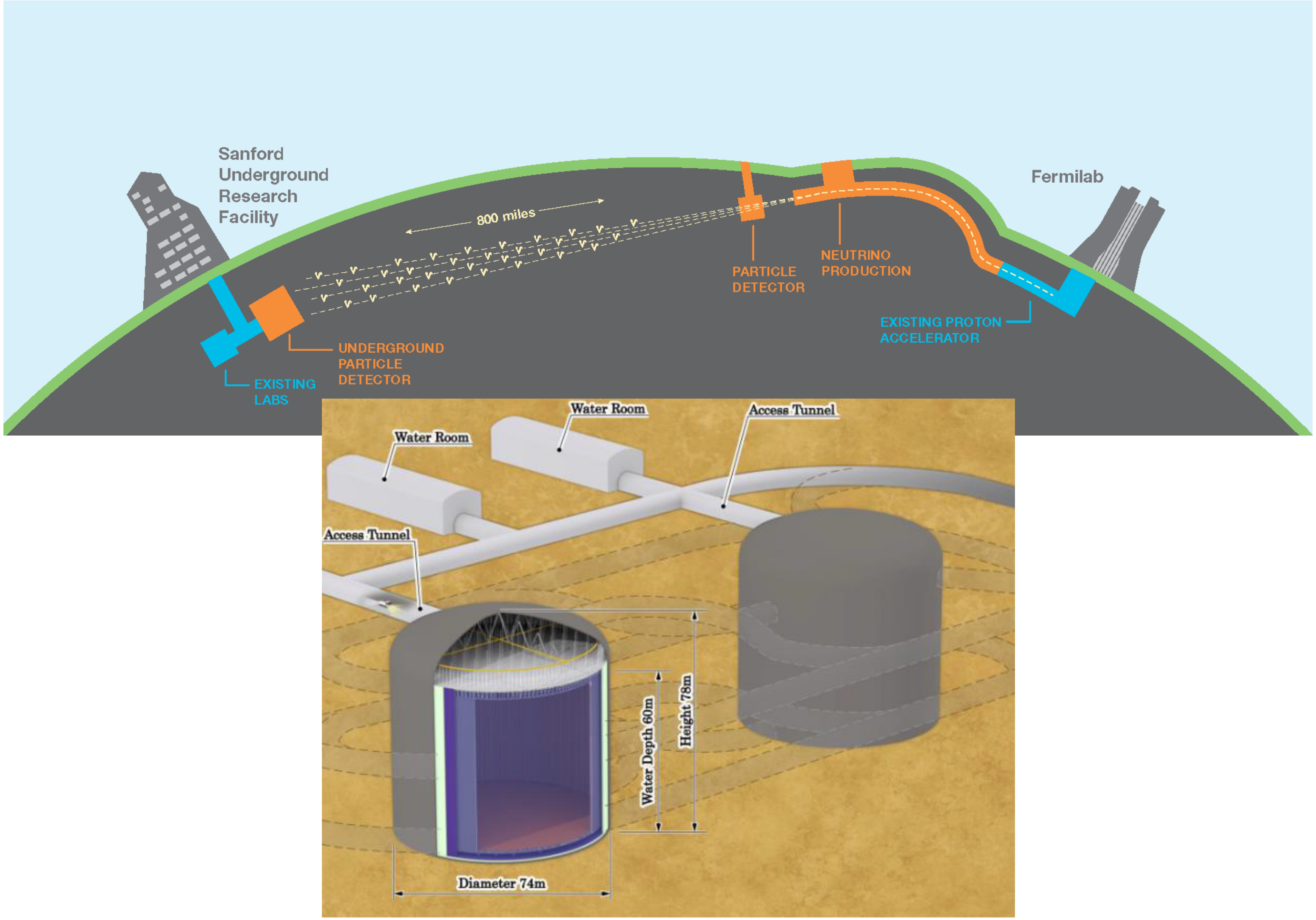
We are currently launching the next "big thing" in particle physics: exciting times ahead

Thank you - questions?

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