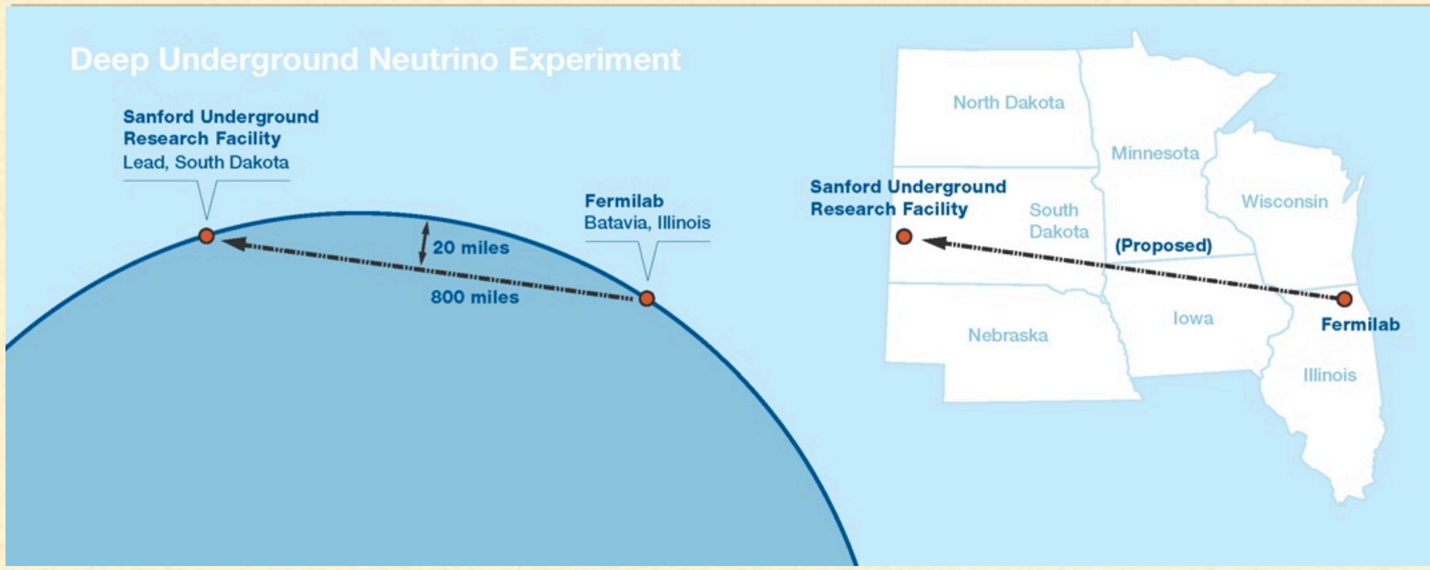


DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE STATUS

Michael Eads
Department of Physics
Northern Illinois University

nicadd

Northern Illinois University

THE DUNE EXPERIMENT

THE DUNE EXPERIMENT

- The Deep Underground Neutrino Experiment (DUNE):

THE DUNE EXPERIMENT

- The Deep Underground Neutrino Experiment (DUNE):
  - A beam of neutrinos that travel 800 miles through the Earth from Illinois to South Dakota

THE DUNE EXPERIMENT

- The Deep Underground Neutrino Experiment (DUNE):
  - A beam of neutrinos that travel 800 miles through the Earth from Illinois to South Dakota
  - A detector cavern nearly a mile underground with a volume of more than 2 Empire State buildings

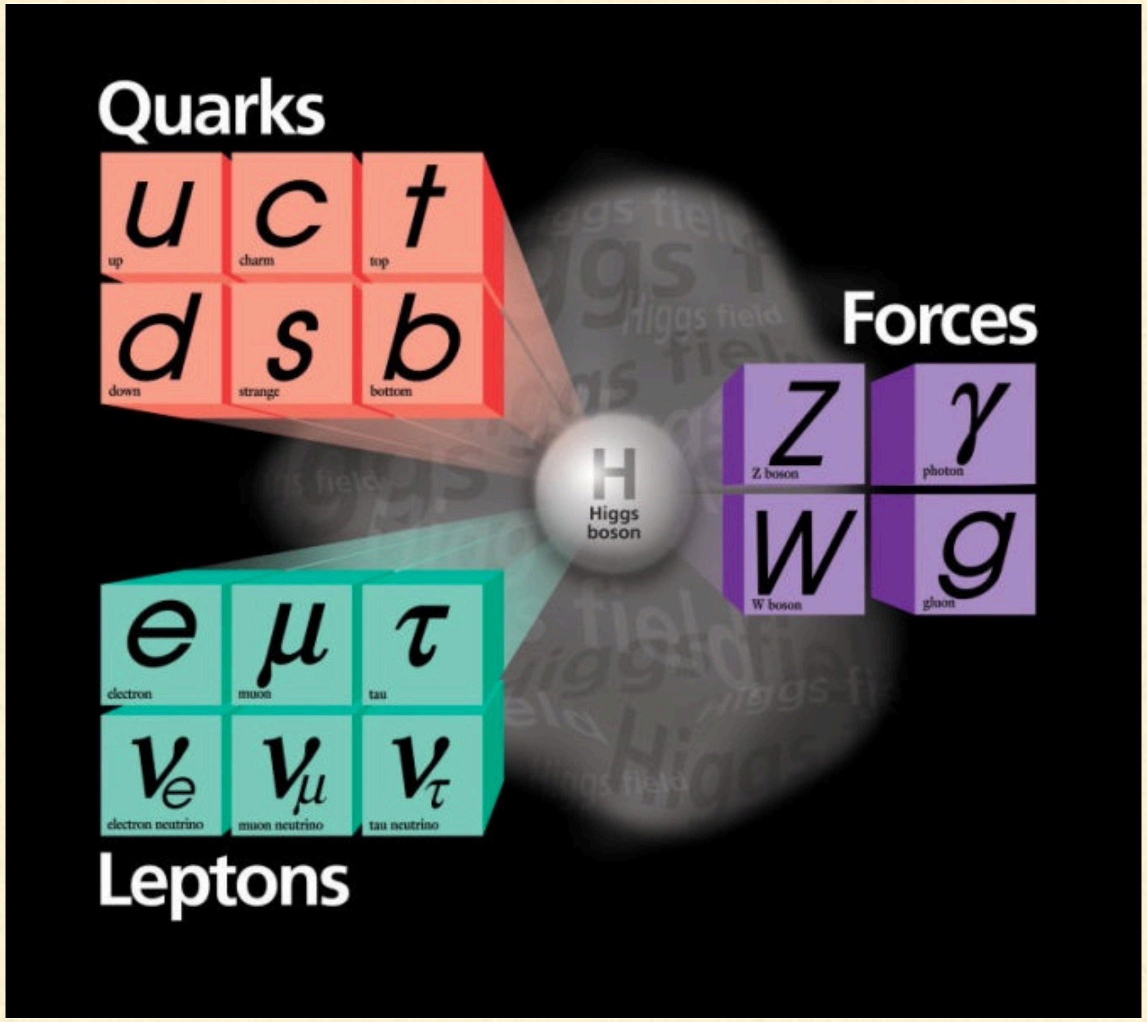
THE DUNE EXPERIMENT

- The Deep Underground Neutrino Experiment (DUNE):
    - A beam of neutrinos that travel 800 miles through the Earth from Illinois to South Dakota
    - A detector cavern nearly a mile underground with a volume of more than 2 Empire State buildings
    - 70,000 tons of liquified argon gas, cooled to a temperature of -300° F

THE DUNE EXPERIMENT

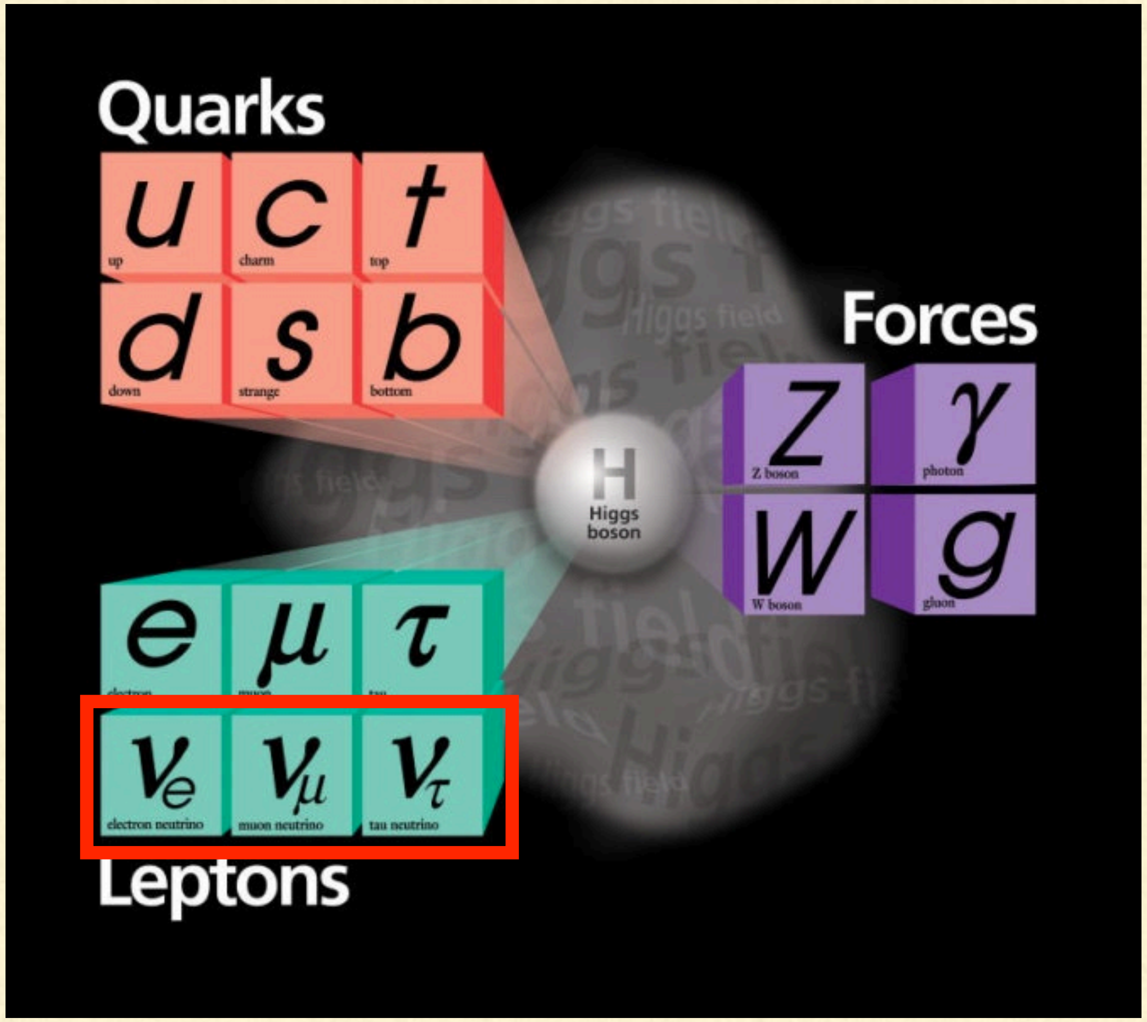
- The Deep Underground Neutrino Experiment (DUNE):
  - A beam of neutrinos that travel 800 miles through the Earth from Illinois to South Dakota
  - A detector cavern nearly a mile underground with a volume of more than 2 Empire State buildings
  - 70,000 tons of liquified argon gas, cooled to a temperature of -300º F
  - Over 1000 scientists from 160 institutions in 30 countries

THE STANDARD MODEL



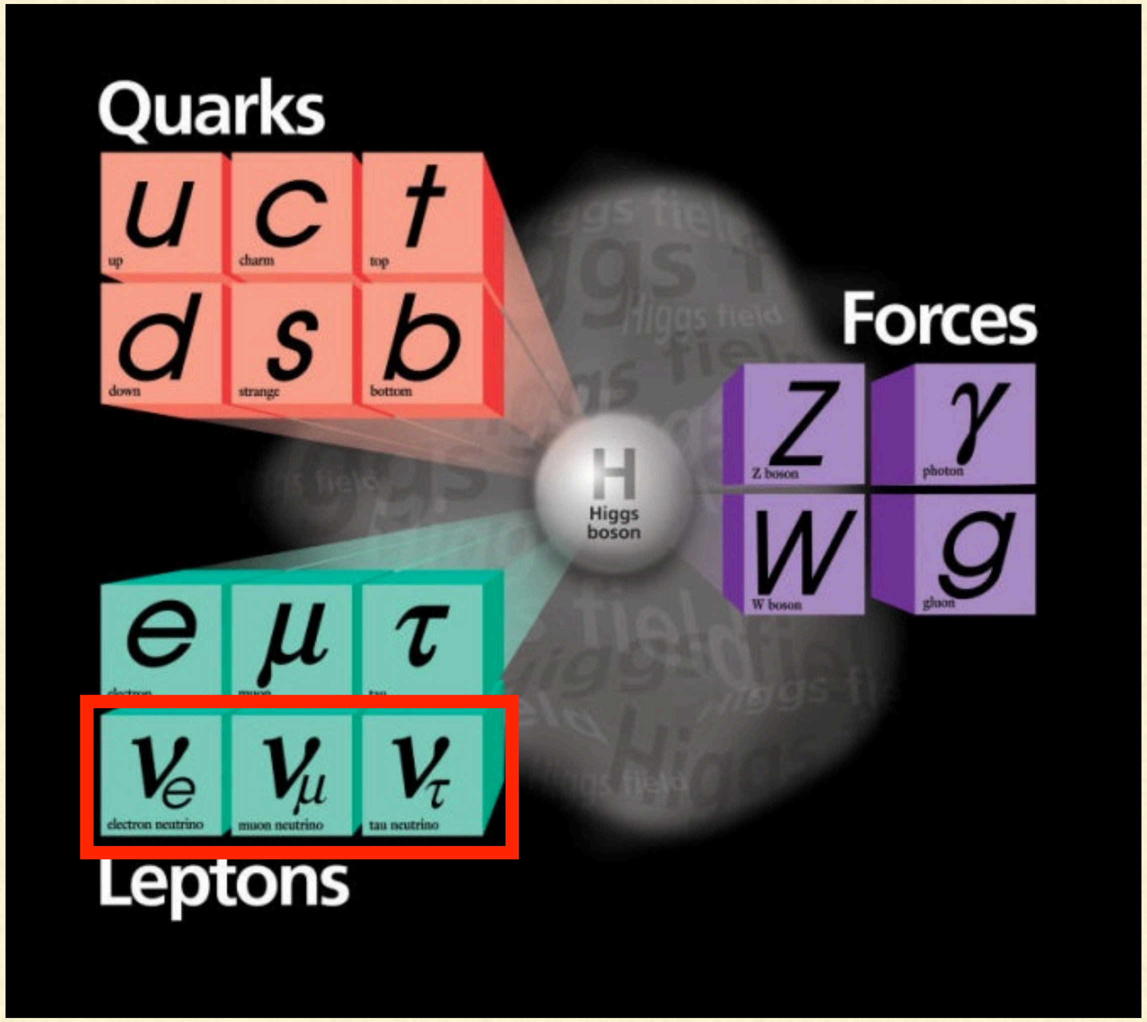
THE STANDARD MODEL

- The *Standard Model* of particle physics describes all* the particles that make up the universe, and how they interact with each other**



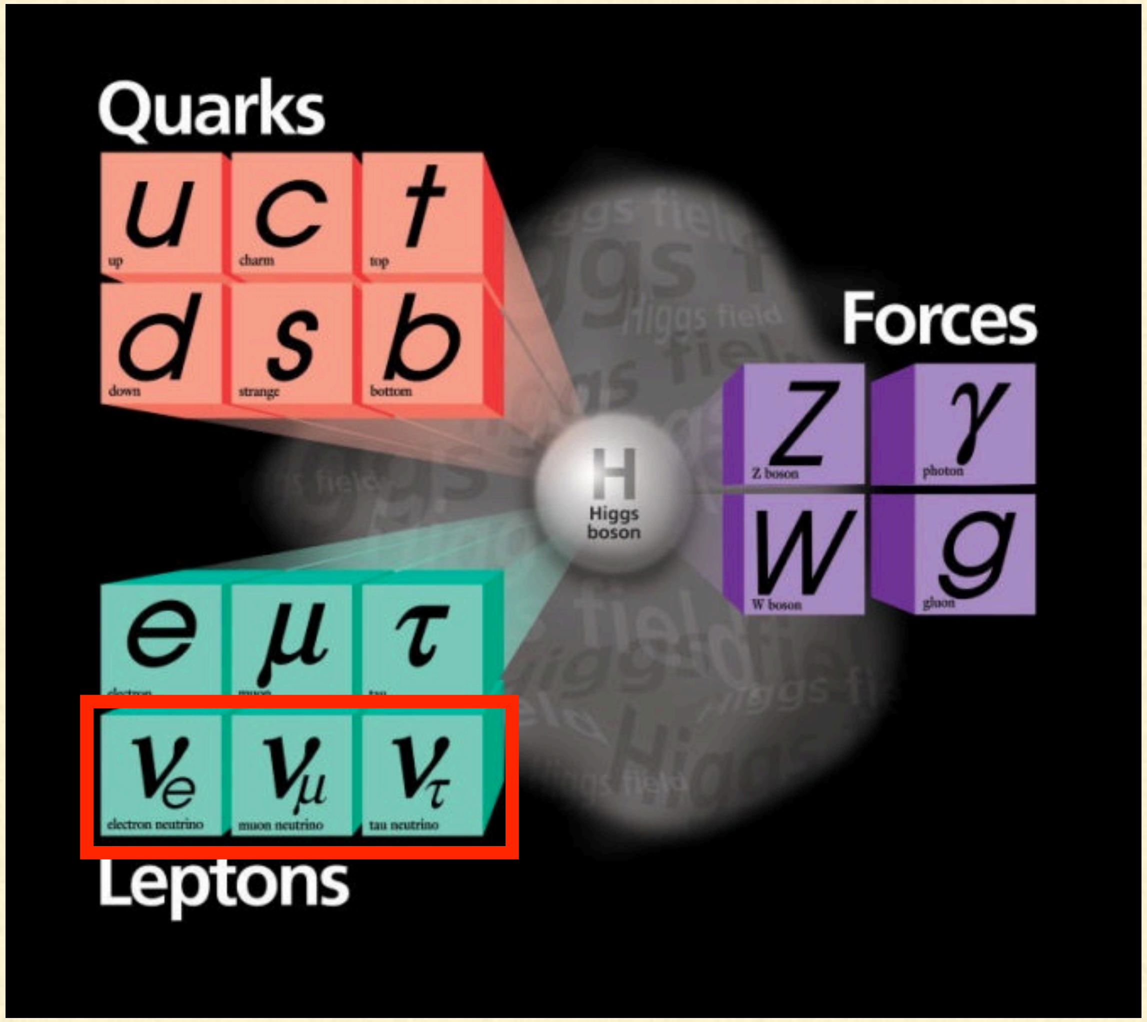
THE STANDARD MODEL

- The *Standard Model* of particle physics describes all* the particles that make up the universe, and how they interact with each other**
- *Neutrinos* are matter particles, neutral leptons



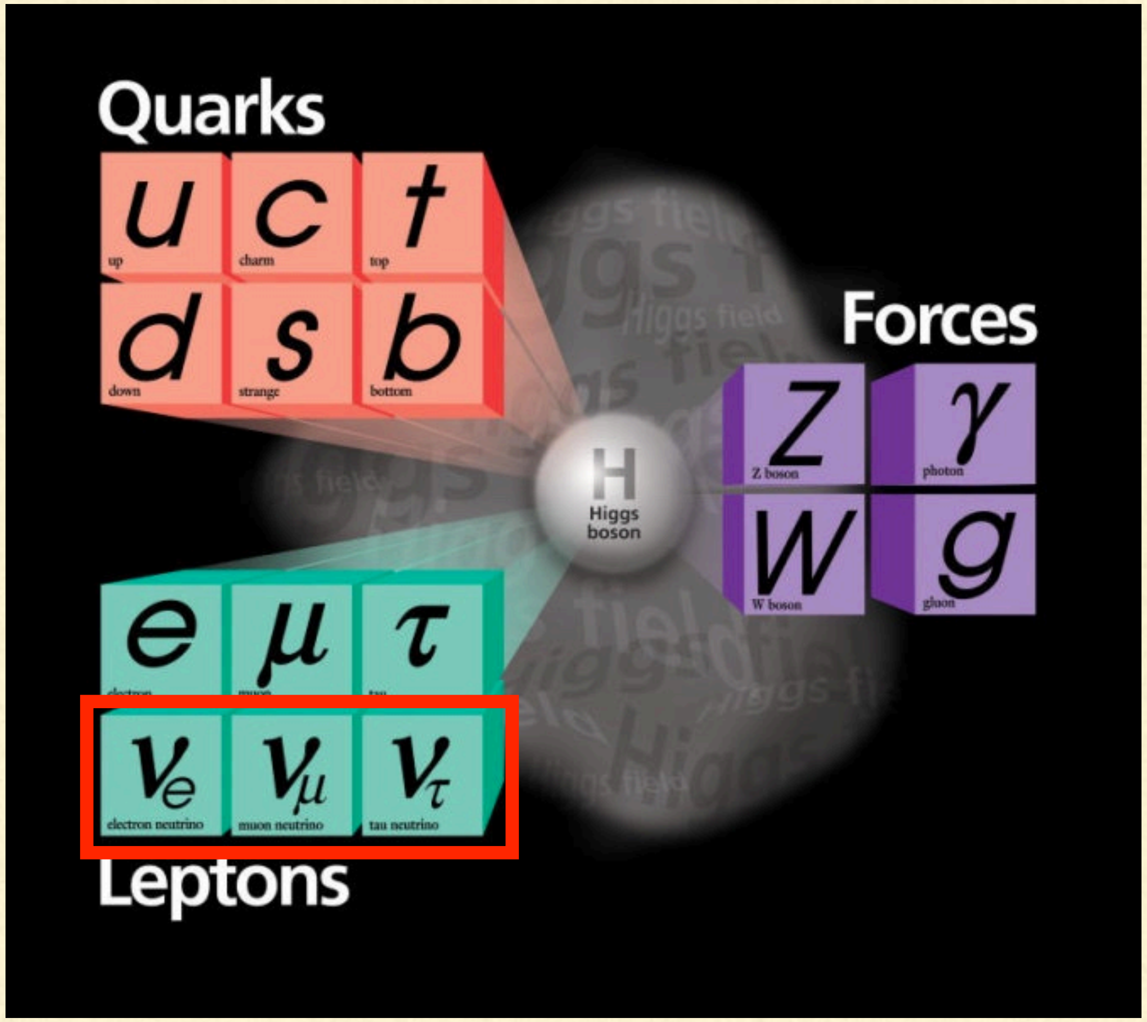
THE STANDARD MODEL

- The *Standard Model* of particle physics describes all* the particles that make up the universe, and how they interact with each other**
- *Neutrinos* are matter particles, neutral leptons
- Each charged lepton (electron, muon, and tau) has a neutrino "partner"



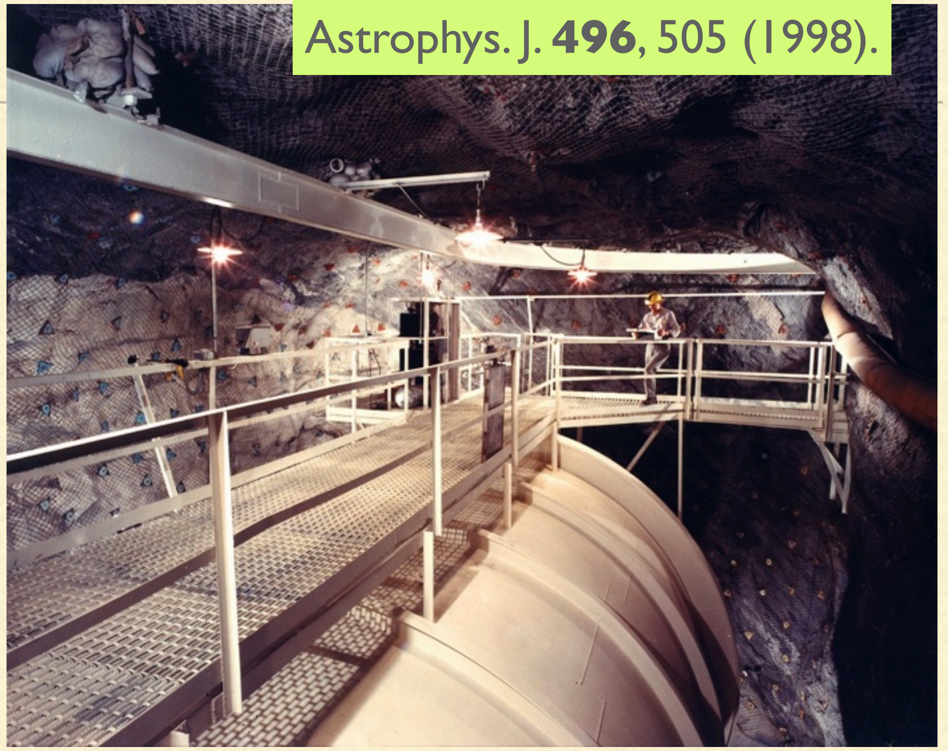
THE STANDARD MODEL

- The *Standard Model* of particle physics describes all* the particles that make up the universe, and how they interact with each other**
- *Neutrinos* are matter particles, neutral leptons
- Each charged lepton (electron, muon, and tau) has a neutrino "partner"
- They only interact through the *weak* force.



NEUTRINO MIXING

NEUTRINO MIXING



Astrophys. J. **496**, 505 (1998).

- Ray Davis, searching for solar neutrinos found a significant deficit

2002

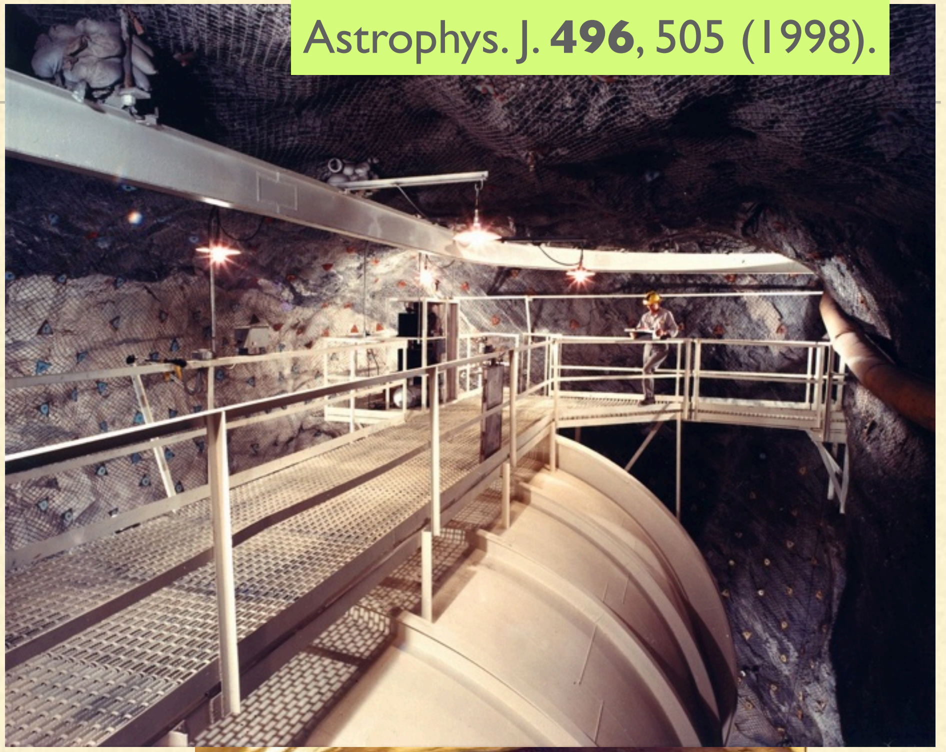
NEUTRINO MIXING

2002

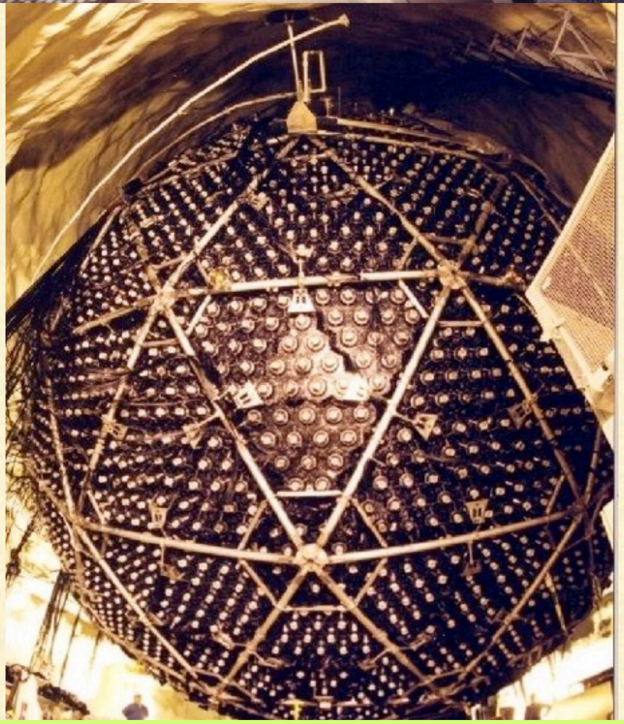
- Ray Davis, searching for solar neutrinos found a significant deficit

2015

- Sudbury Neutrino Observatory later found that if you count ALL neutrino flavors (electron, muon, and tau), there is no solar deficit



Astrophys. J. **496**, 505 (1998).



Phys. Rev. Lett. **87**, 071301 (2001).

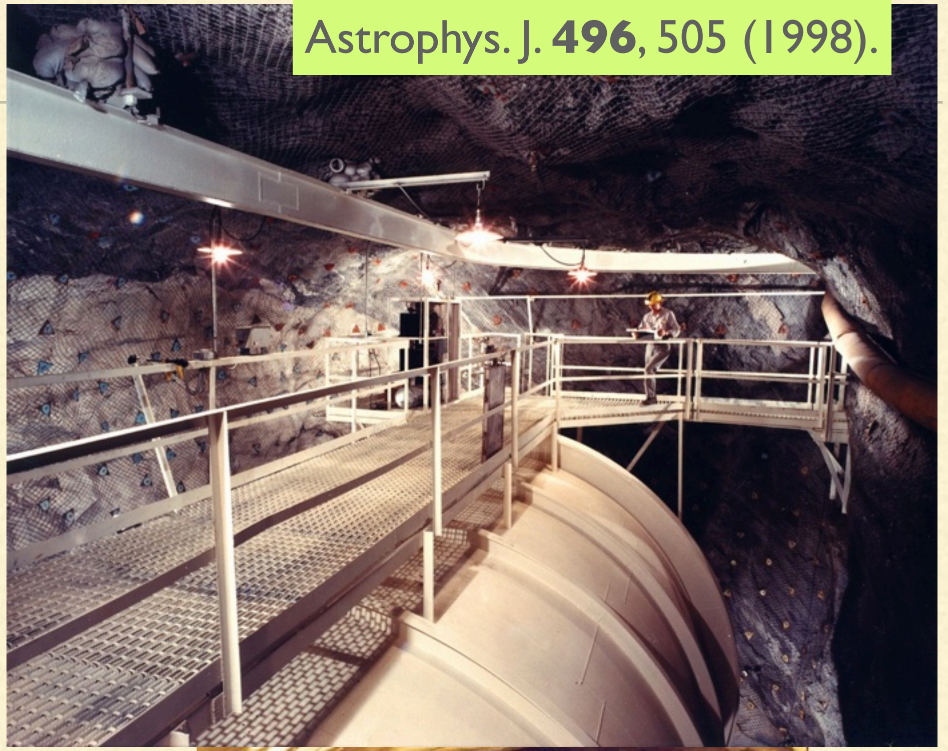
NEUTRINO MIXING

2002

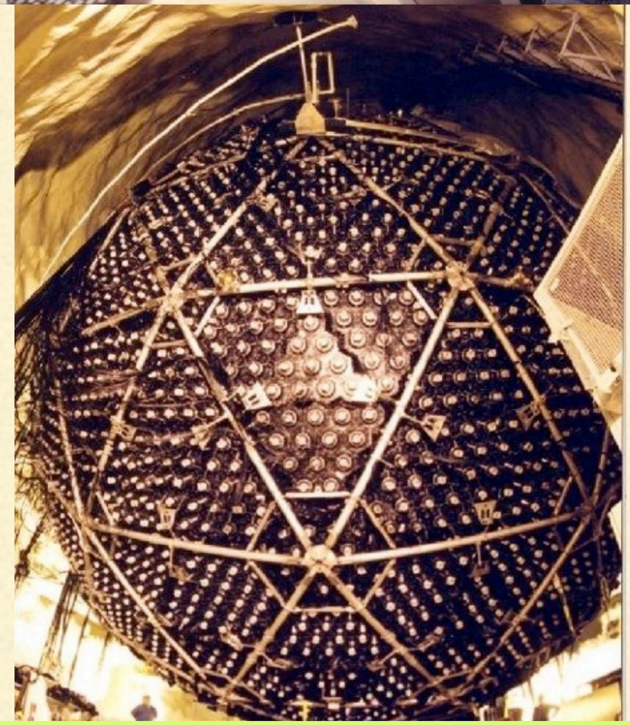
- Ray Davis, searching for solar neutrinos found a significant deficit

2015

- Sudbury Neutrino Observatory later found that if you count ALL neutrino flavors (electron, muon, and tau), there is no solar deficit
- Neutrinos produced as one type (e.g. electron neutrinos in the sun) can be detected as neutrinos of other types (muon, tau)



Astrophys. J. **496**, 505 (1998).



Phys. Rev. Lett. **87**, 071301 (2001).

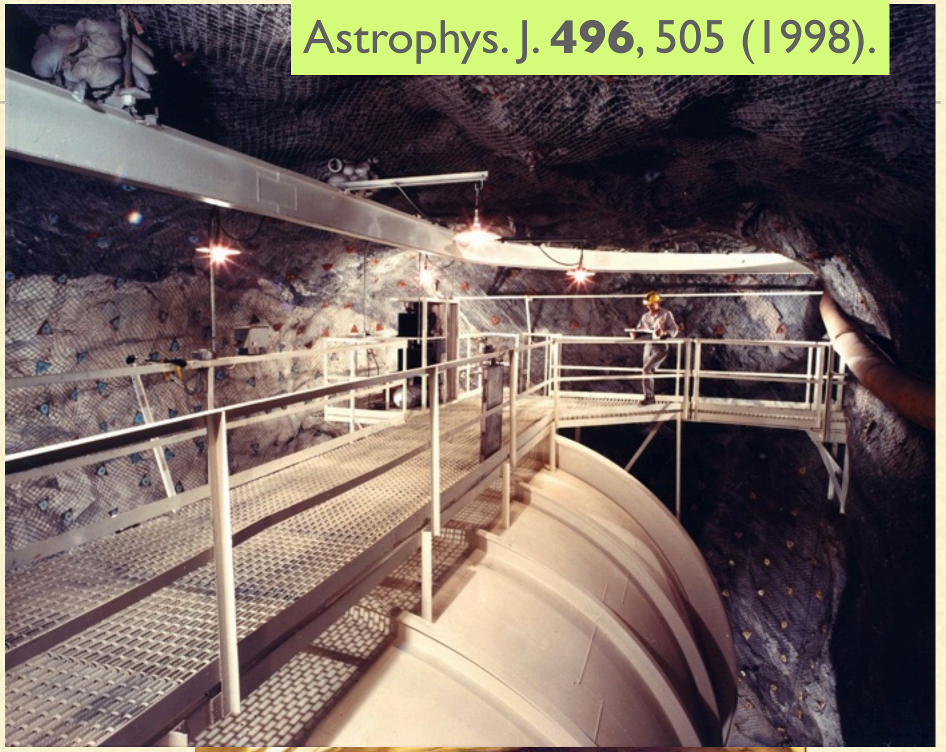
NEUTRINO MIXING

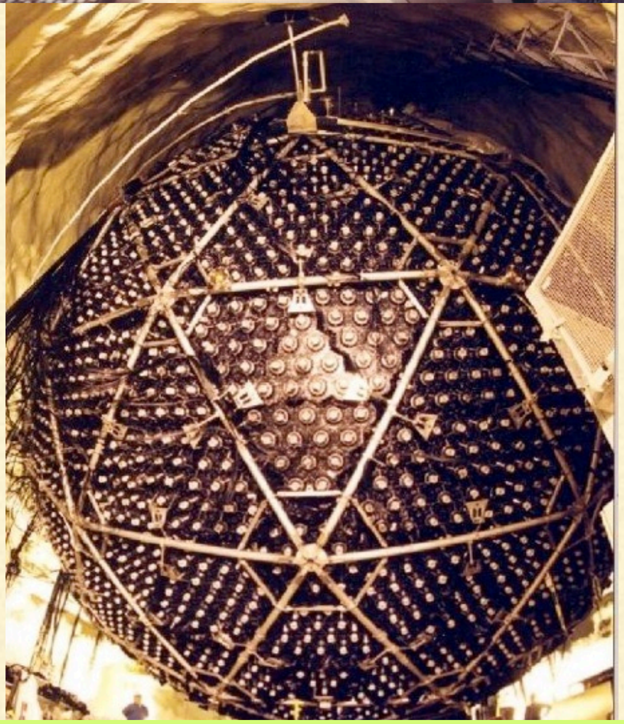

2002

- Ray Davis, searching for solar neutrinos found a significant deficit


2015

- Sudbury Neutrino Observatory later found that if you count ALL neutrino flavors (electron, muon, and tau), there is no solar deficit
- Neutrinos produced as one type (e.g. electron neutrinos in the sun) can be detected as neutrinos of other types (muon, tau)
    - *Neutrino oscillations*


Astrophys. J. **496**, 505 (1998).


Phys. Rev. Lett. **87**, 071301 (2001).

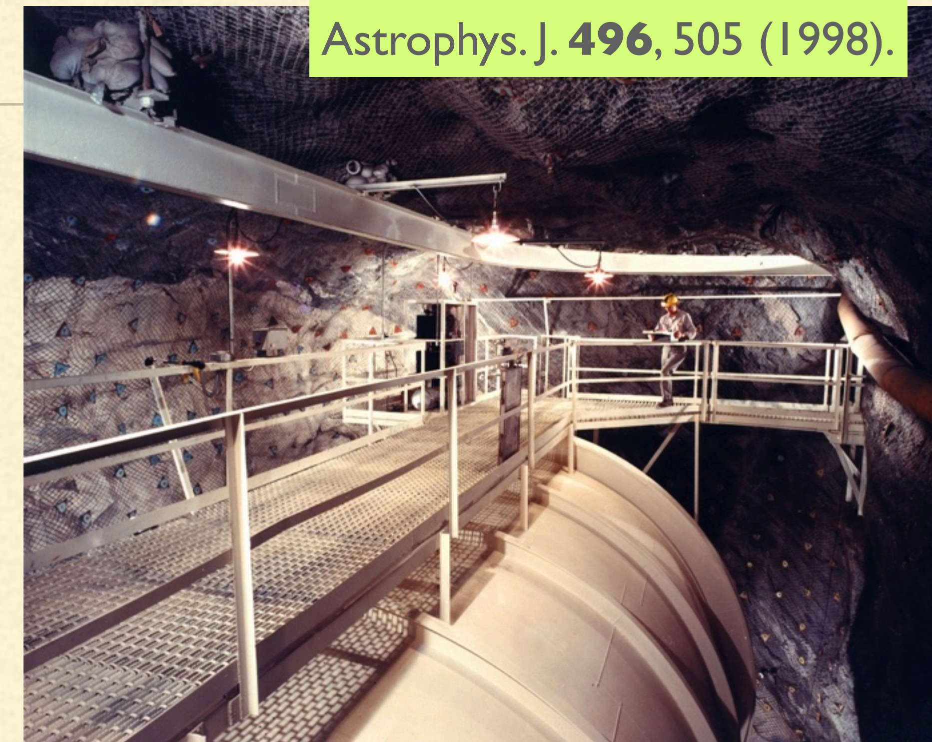
NEUTRINO MIXING


2002

- Ray Davis, searching for solar neutrinos found a significant deficit


2015

- Sudbury Neutrino Observatory later found that if you count ALL neutrino flavors (electron, muon, and tau), there is no solar deficit
- Neutrinos produced as one type (e.g. electron neutrinos in the sun) can be detected as neutrinos of other types (muon, tau)
  - *Neutrino oscillations*
  - Corollary - neutrinos must have mass!


Astrophys. J. **496**, 505 (1998).


Phys. Rev. Lett. **87**, 071301 (2001).

MORE NEUTRINO MIXING

https://inspirehep.net/record/1499876/plots

MORE NEUTRINO MIXING

https://inspirehep.net/record/1499876/plots

- Much of the experimental effort in the last 20 years has been to measure the *neutrino mixing parameters*

MORE NEUTRINO MIXING

https://inspirehep.net/record/1499876/plots

- Much of the experimental effort in the last 20 years has been to measure the *neutrino mixing parameters*

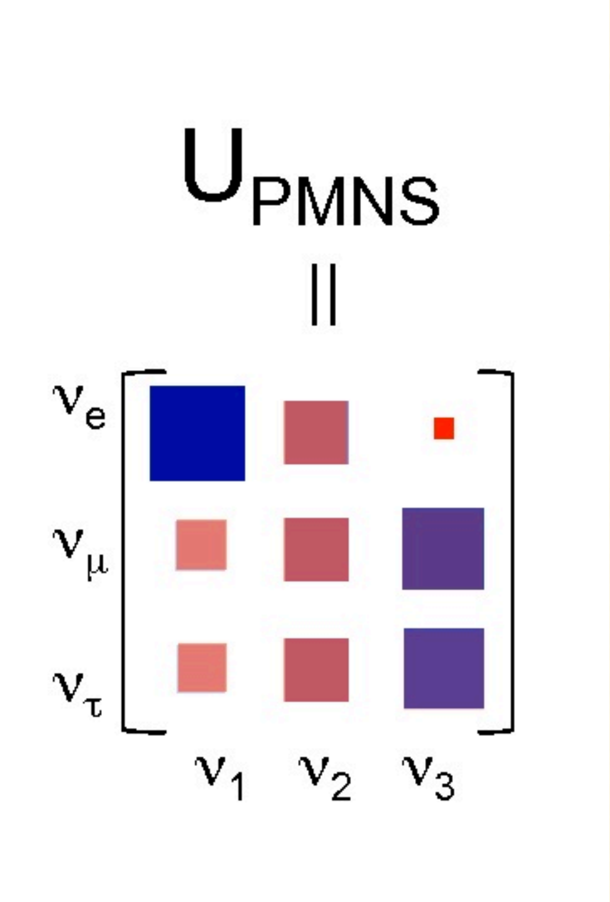
- Parameters can be summarized in a 3x3 PMNS matrix (Pontecorvo-Maki-Nakagawa-Sakata). Size of entry corresponds to amount of mixing

MORE NEUTRINO MIXING

https://inspirehep.net/record/1499876/plots

- Much of the experimental effort in the last 20 years has been to measure the *neutrino mixing parameters*

- Parameters can be summarized in a 3x3 PMNS matrix (Pontecorvo-Maki-Nakagawa-Sakata). Size of entry corresponds to amount of mixing
  - Matrix typically parametrized with three mixing angles and one CP-violating phase



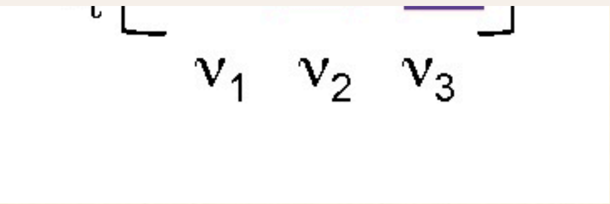
MORE NEUTRINO MIXING

https://inspirehep.net/record/1499876/plots

The PMNS unitary operator represented in matrix form

$$U_{\alpha j} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- 3 mixing angles: θ_{ij} where $i, j = 1, 2, 3$ and $i \neq j$
- 1 dirac CP-violation phase: δ_{CP}



- Matrix typically parametrized with three mixing angles and one CP-violating phase

NEUTRINO OSCILLATIONS

NEUTRINO OSCILLATIONS

- Oscillation probability depends on *U*, mass differences, and *L*/*E*

NEUTRINO OSCILLATIONS

- Oscillation probability depends on *U*, mass differences, and *L*/*E*

$$P(\nu_\alpha \to \nu_\beta) = -4 \sum_{j>k} U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k} \sin^2 \frac{\Delta m^2_{jk} L}{4E}$$

where $\alpha \neq \beta$.

NEUTRINO OSCILLATIONS

- Oscillation probability depends on *U*, mass differences, and *L*/*E*

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4 \sum_{j>k} U_{\beta j} U^*_{\beta k} U^*_{\alpha j} U_{\alpha k} \sin^2 \frac{\Delta m^2_{jk} L}{4E}$$

where $\alpha \neq \beta$.

- Neutrino mixing angles

NEUTRINO OSCILLATIONS

Mixing Angles

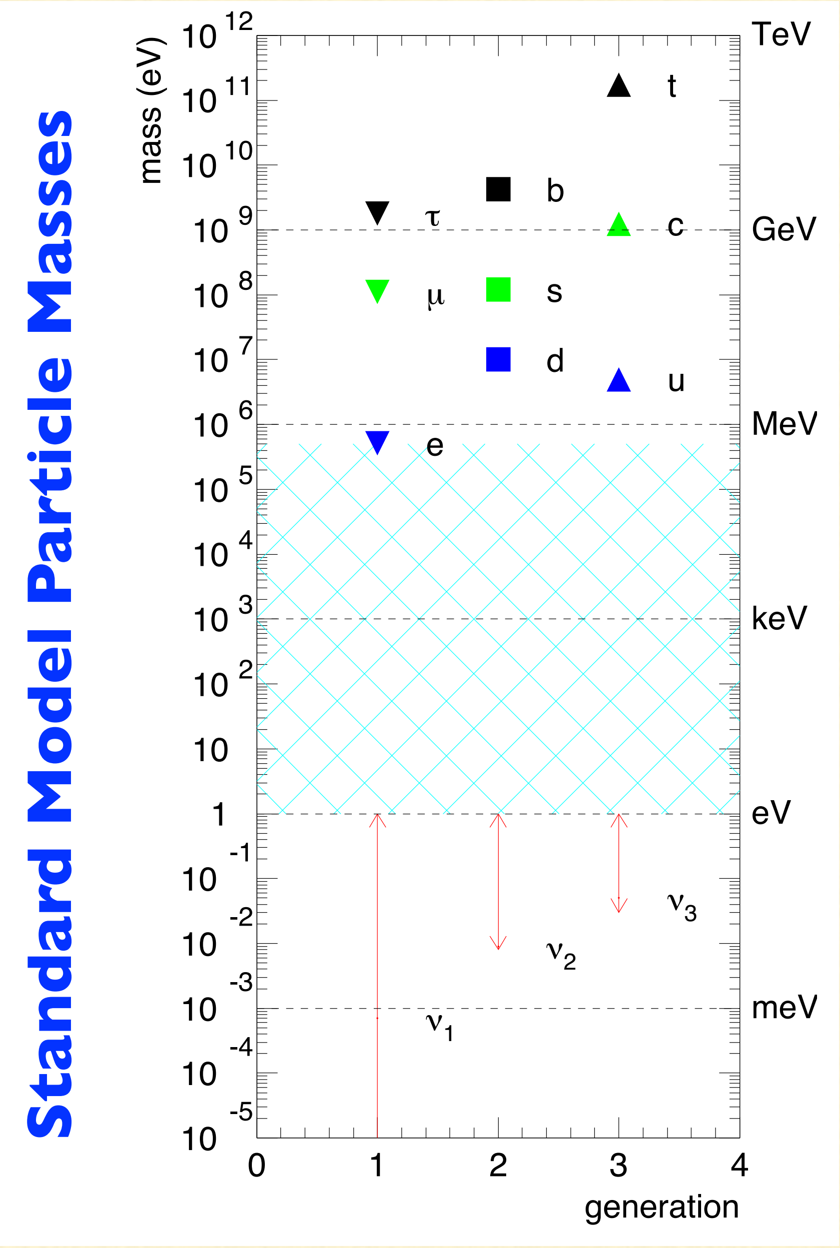
- θ_{12} is sensitive to high $L/E \sim 10^{10}$
  - Long-baseline reactor experiments—solar
- θ_{13} is sensitive to medium $L/E \sim 10^2 - 10^5$
  - Short-baseline reactor experiments
- θ_{23} is sensitive to low $L/E \sim 10^{-1}$
  - Long-baseline accelerator experiments—atmospheric & DUNE

NEUTRINO MASSES

https://inspirehep.net/record/1499876/plots

NEUTRINO MASSES

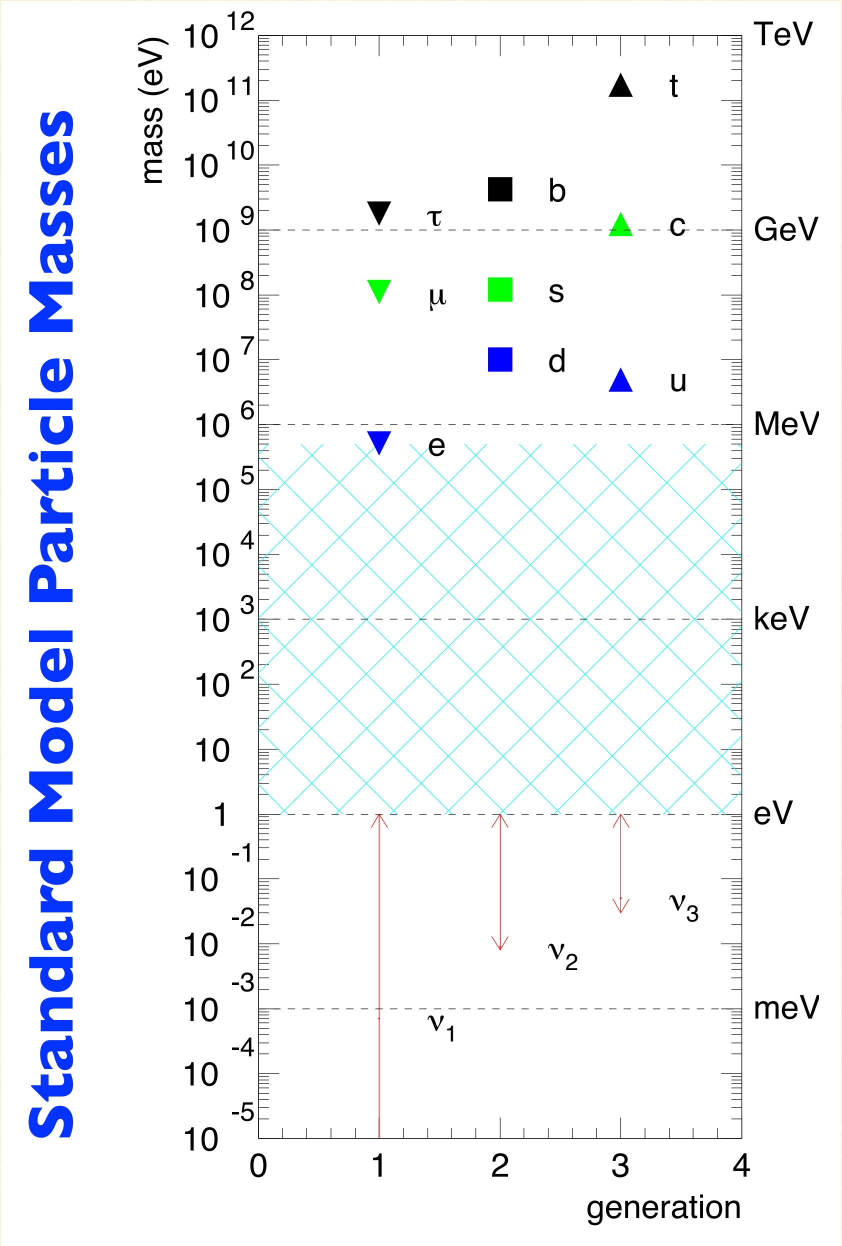
- We know neutrinos have mass, but we don't know what their mass is



https://inspirehep.net/record/1499876/plots

NEUTRINO MASSES

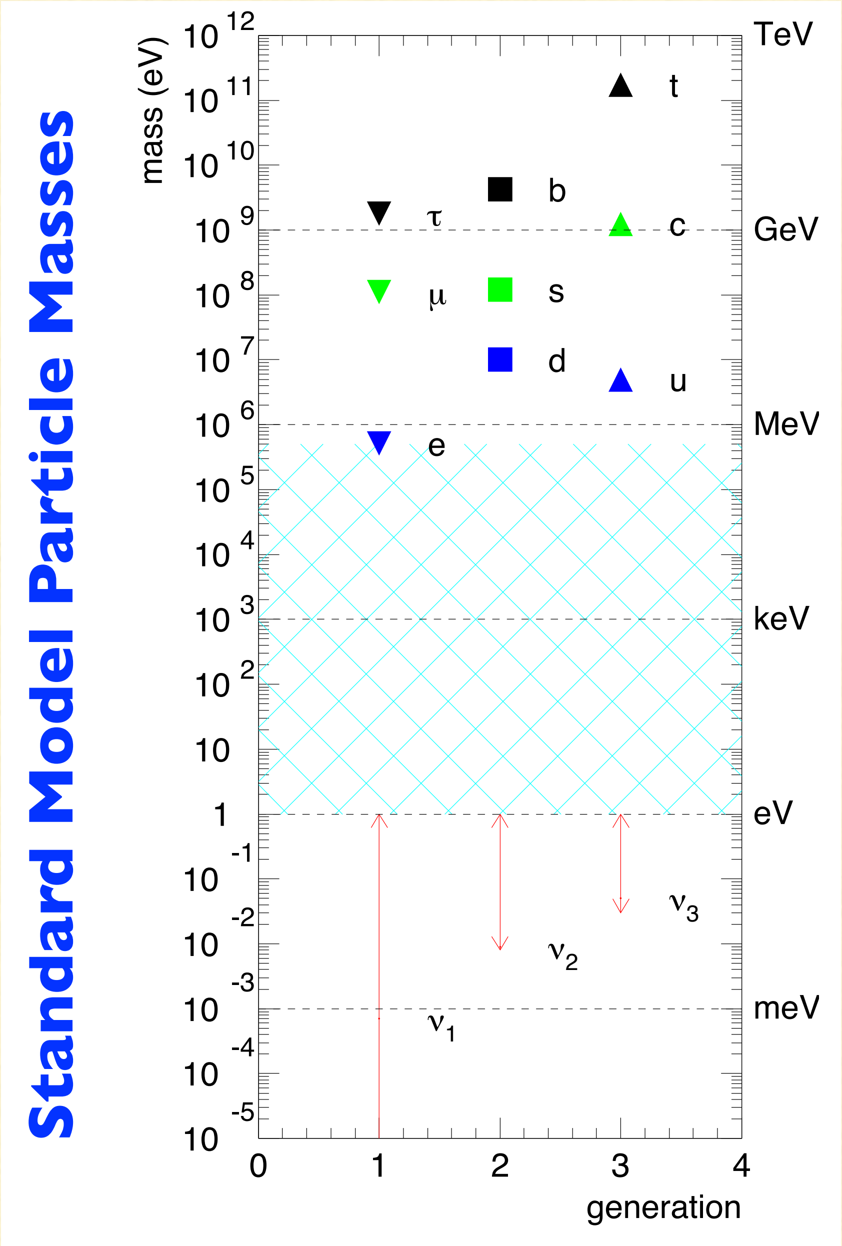
- We know neutrinos have mass, but we don't know what their mass is
    - We do know that they must be very light



https://inspirehep.net/record/1499876/plots

NEUTRINO MASSES

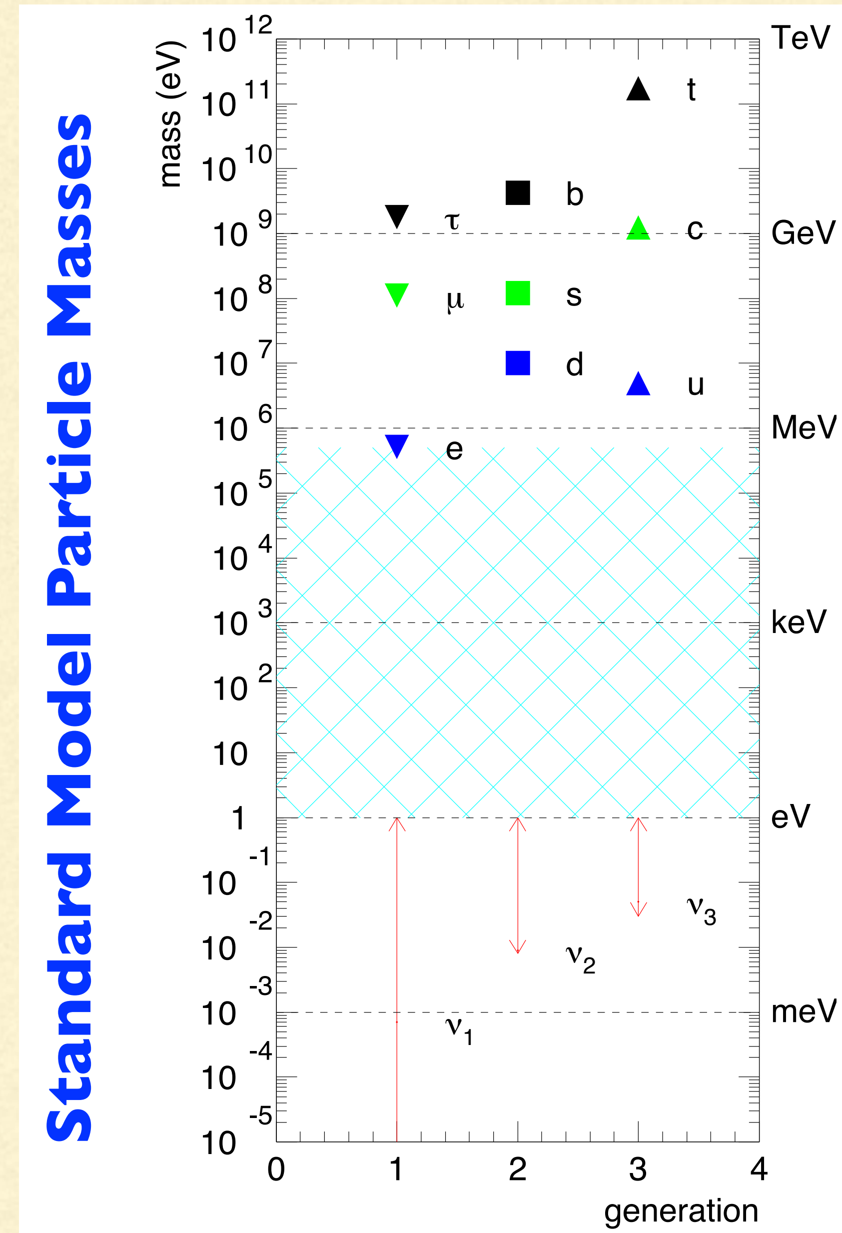
- We know neutrinos have mass, but we don't know what their mass is
  - We do know that they must be very light
  - Maybe this is important?



https://inspirehep.net/record/1499876/plots

NEUTRINO MASSES

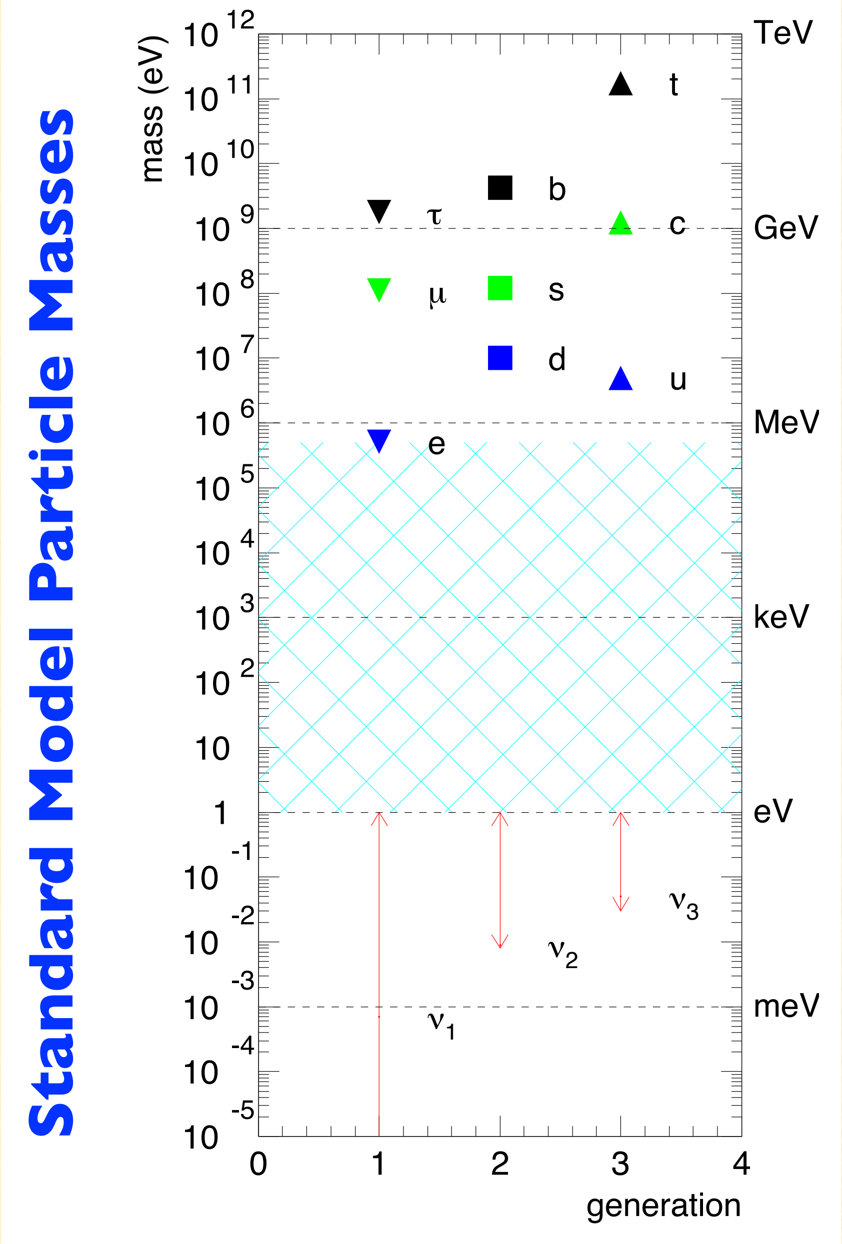
- We know neutrinos have mass, but we don't know what their mass is
  - We do know that they must be very light
  - Maybe this is important?
- Measuring neutrino oscillation actually tells you mass *differences*



https://inspirehep.net/record/1499876/plots

NEUTRINO MASSES

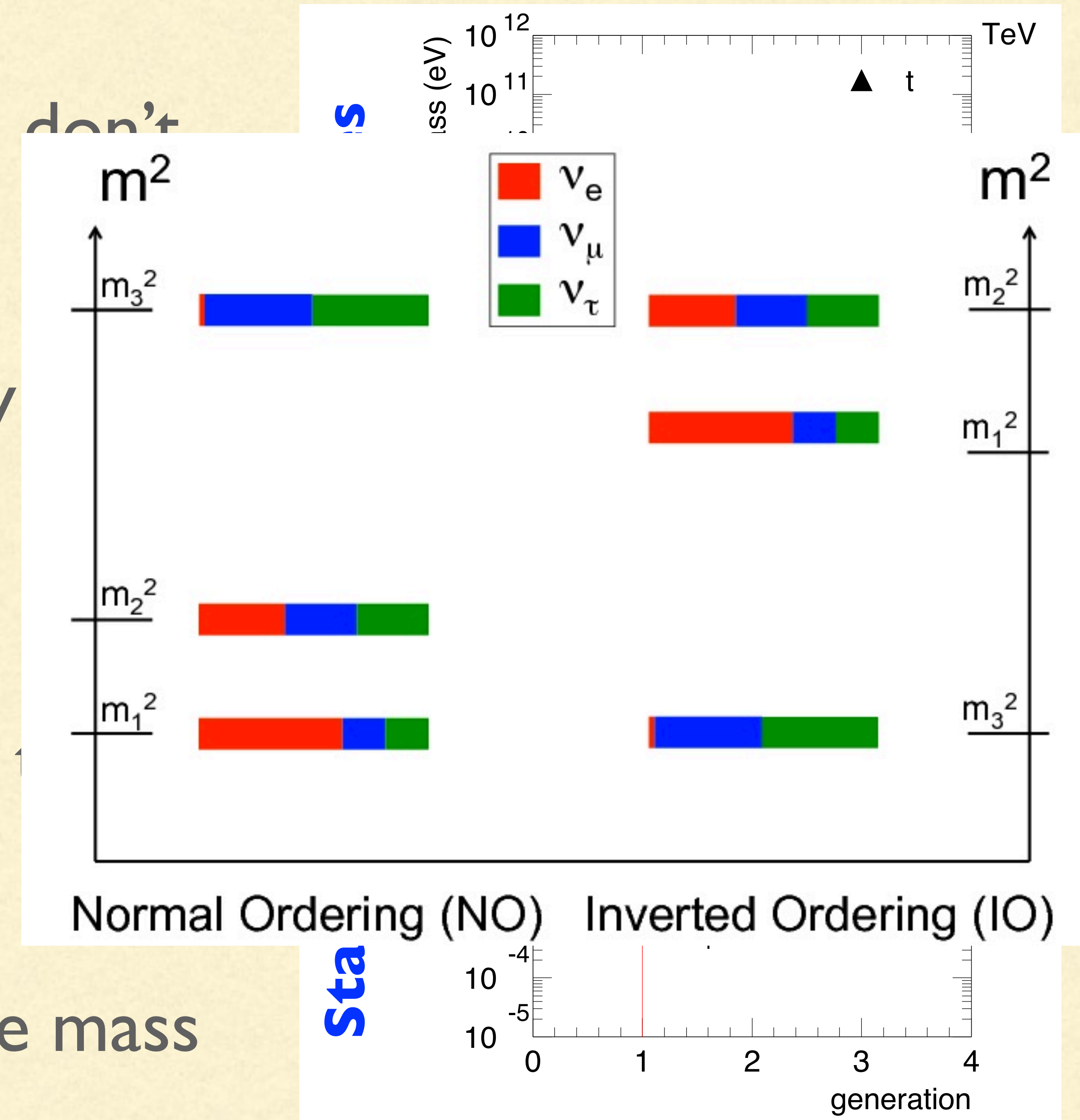
- We know neutrinos have mass, but we don't know what their mass is
    - We do know that they must be very light
    - Maybe this is important?
- Measuring neutrino oscillation actually tells you mass *differences*
- We don't even know what order of the mass states is!



https://inspirehep.net/record/1499876/plots

NEUTRINO MASSES

- We know neutrinos have mass, but we don't know what their mass is
    - We do know that they must be very
    - Maybe this is important?
- Measuring neutrino oscillation actually mass *differences*
- We don't even know what order of the mass states is!



https://inspirehep.net/record/1499876/plots

NEUTRINO FUN FACTS

https://www.particlezoo.net/

NEUTRINO FUN FACTS

- There are A LOT of neutrinos in the universe - about 300 in every cubic centimeter of the universe

https://www.particlezoo.net/

NEUTRINO FUN FACTS

- There are A LOT of neutrinos in the universe - about 300 in every cubic centimeter of the universe
  - Only photons are more abundant - about 1000 per cc

https://www.particlezoo.net/

NEUTRINO FUN FACTS

- There are A LOT of neutrinos in the universe - about 300 in every cubic centimeter of the universe
  - Only photons are more abundant - about 1000 per cc
- The sun is a prodigious source of neutrinos - about 65 billion per second per square cm hit the Earth

https://www.particlezoo.net/

NEUTRINO FUN FACTS

- There are A LOT of neutrinos in the universe - about 300 in every cubic centimeter of the universe
  - Only photons are more abundant - about 1000 per cc
- The sun is a prodigious source of neutrinos - about 65 billion per second per square cm hit the Earth
  - Only about 1 of these will interact with an atom in your body in your lifetime

https://www.particlezoo.net/

NEUTRINO FUN FACTS

- There are A LOT of neutrinos in the universe - about 300 in every cubic centimeter of the universe
  - Only photons are more abundant - about 1000 per cc
- The sun is a prodigious source of neutrinos - about 65 billion per second per square cm hit the Earth
  - Only about 1 of these will interact with an atom in your body in your lifetime
- Photons produced near the core of the sun can take 10,000 to 100,000 years to escape the sun (then 8 minutes to reach the Earth). Neutrinos take only 3.2 seconds to escape the sun

https://www.particlezoo.net/

NEUTRINO FUN FACTS

- There are A LOT of neutrinos in the universe - about 300 in every cubic centimeter of the universe
    - Only photons are more abundant - about 1000 per cc
- The sun is a prodigious source of neutrinos - about 65 billion per second per square cm hit the Earth
    - Only about 1 of these will interact with an atom in your body in your lifetime
- Photons produced near the core of the sun can take 10,000 to 100,000 years to escape the sun (then 8 minutes to reach the Earth). Neutrinos take only 3.2 seconds to escape the sun
- In certain supernova (*core collapse*), neutrinos carry 99% of the energy released by the supernova

https://www.particlezoo.net/

ANTI-NEUTRINOS

ANTI-NEUTRINOS

- Why is the universe dominated by matter today, with very little anti-matter?

ANTI-NEUTRINOS

- Why is the universe dominated by matter today, with very little anti-matter?
- Implies that matter and anti-matter behave slightly differently (*CP violation*)

ANTI-NEUTRINOS

- Why is the universe dominated by matter today, with very little anti-matter?
- Implies that matter and anti-matter behave slightly differently (*CP violation*)
  - We know this happens for quarks, but at a very small level

ANTI-NEUTRINOS

- Why is the universe dominated by matter today, with very little anti-matter?
- Implies that matter and anti-matter behave slightly differently (*CP violation*)
  - We know this happens for quarks, but at a very small level
  - James Cronin and Val Fitch first discovered in neutral Kaons Phys. Rev. Lett. **13**, 138 (1964).


1980

ANTI-NEUTRINOS

- Why is the universe dominated by matter today, with very little anti-matter?
- Implies that matter and anti-matter behave slightly differently (*CP violation*)
  - We know this happens for quarks, but at a very small level
  - James Cronin and Val Fitch first discovered in neutral Kaons Phys. Rev. Lett. **13**, 138 (1964).
  - It is possible that the amount is much larger for neutrinos

1980

DUNE PHYSICS GOALS

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Primary goals
  - Improved measurement of neutrino mixing angles (mostly θ_{23}, but some sensitivity to others)
  - Determine mass ordering (normal vs. inverted hierarchy)
  - World-leading measurement (or limit) on δ_{CP}
- Secondary goals
  - Neutrinos from core-collapse supernova
  - Search for proton decay
  - Sterile neutrinos, non-standard interactions, other BSM
  - *Tau neutrinos*

Technical Design Report: https://arxiv.org/abs/2002.03005
Low Exposure Physics Reach: https://arxiv.org/abs/2109.01304
Snowmass Summary Report: https://arxiv.org/abs/2203.06100
Supernova paper: https://arxiv.org/abs/2008.06647
BSM paper: https://arxiv.org/abs/2008.12769

OSCILLATION PARAMETER REACH

DEEP UNDERGROUND NEUTRINO EXPERIMENT

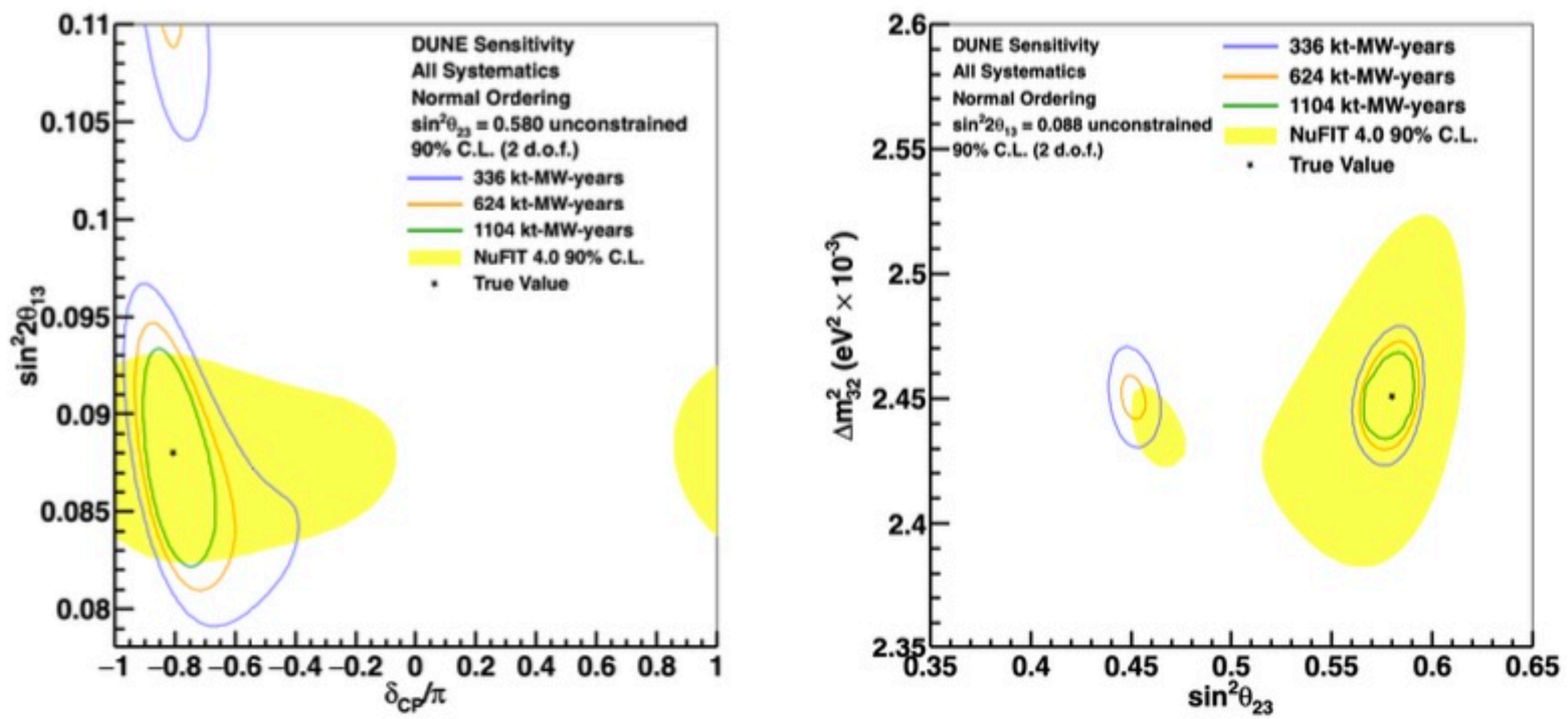


FIG. 2. Two-dimensional 90% C.L. regions in the $\sin^2 2\theta_{13}$–δ_{CP} (left) and $\sin^2\theta_{23}$–Δm^2_{32} (right) plane, for three different levels of exposure, with equal running in neutrino and antineutrino mode, with the Phase II near detector. The 90% C.L. region for the NuFIT global fit is shown in yellow for comparison. The true values of the oscillation parameters are assumed to be the central values of the NuFit global fit and the oscillation parameters governing long-baseline oscillation are unconstrained.

MASS ORDERING AND CP-VIOLATION (PHASE 1)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

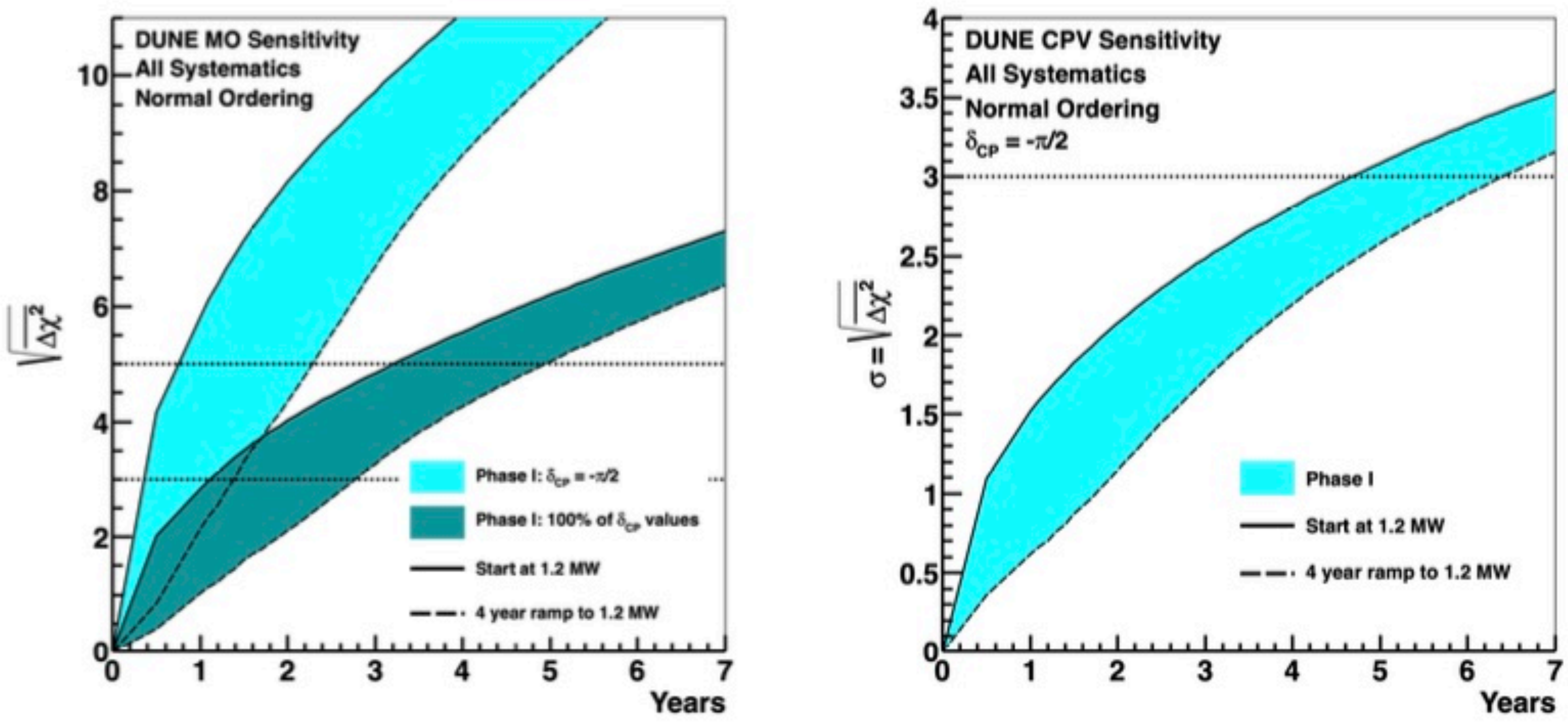


FIG. 5. Sensitivity to the neutrino mass ordering (left) and CP violation for $\delta_{CP} = -\pi/2$ (right) in Phase I. The cyan bands show the sensitivity if $\delta_{CP} = -\pi/2$ and the green band in the left plot shows the sensitivity for 100% of δ_{CP} values. The width of the bands shows the impact of potential beam power ramp up; the solid upper curve is the sensitivity if data collection begins with 1.2 MW beam power and the lower dashed curve shows a conservative beam ramp scenario where the full power is achieved after 4 years.

PHYSICS MILESTONES

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Experiment Stage	Physics Milestone	Exposure (kt-MW-years)	Years (Staged)
Phase I	5σ MO ($\delta_{\rm CP} = -\pi/2$)	16	1-2
	5σ MO (100% of $\delta_{\rm CP}$ values)	66	3-5
	3σ CPV ($\delta_{\rm CP} = -\pi/2$)	100	4-6
Phase II	5σ CPV ($\delta_{\rm CP} = -\pi/2$)	334	7-8
	$\delta_{\rm CP}$ resolution of 10 degrees ($\delta_{\rm CP} = 0$)	400	8-9
	5σ CPV (50% of $\delta_{\rm CP}$ values)	646	11
	3σ CPV (75% of $\delta_{\rm CP}$ values)	936	14
	$\sin^2 2\theta_{13}$ resolution of 0.004	1079	16

TABLE II. Exposure, in kt-MW-years, and time, in calendar years, required to reach selected physics milestones. The time in years assumes that Phase I is complete at Year 0 and that the Phase II staging scenario described in the text is realized. The range of time in years covers the effect of the beam ramp, with the lower bound corresponding to full 1.2 MW proton beam power at Year 0 and the higher bound corresponding to a scenario where the full power is achieved after 4 years. When no range is provided, the difference between these scenarios is less than one year. Time in years is rounded to the nearest whole year.

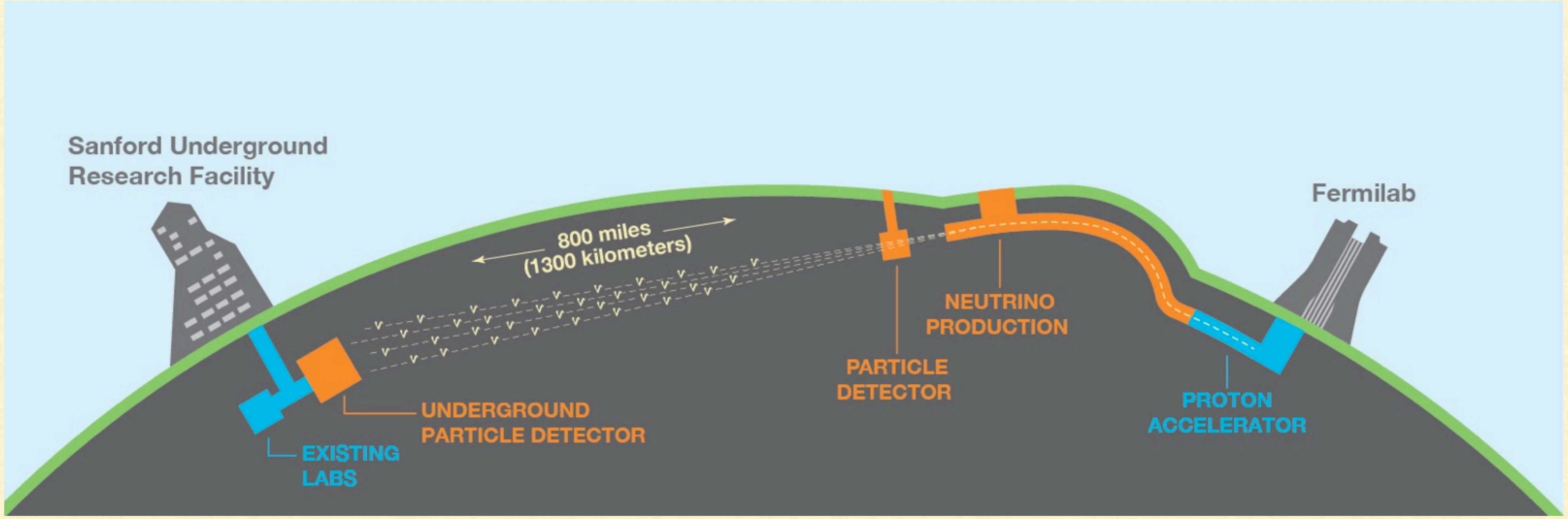
DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

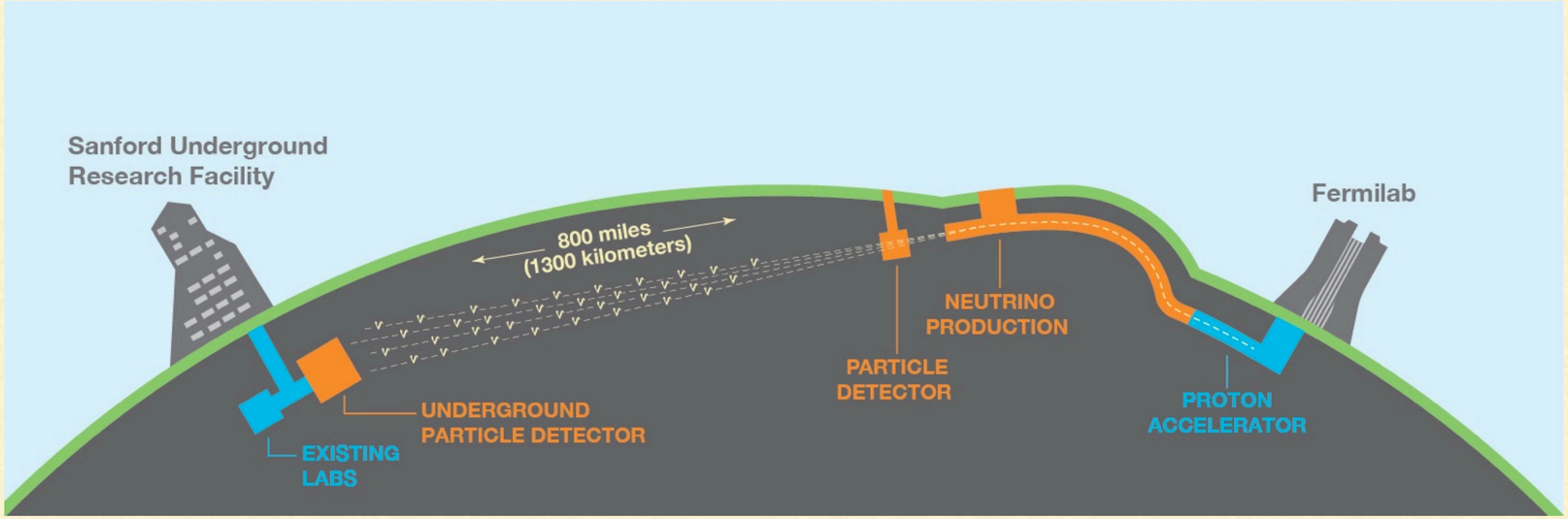
- Send a beam of muons 800 miles from Fermilab to Lead, South Dakota



DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

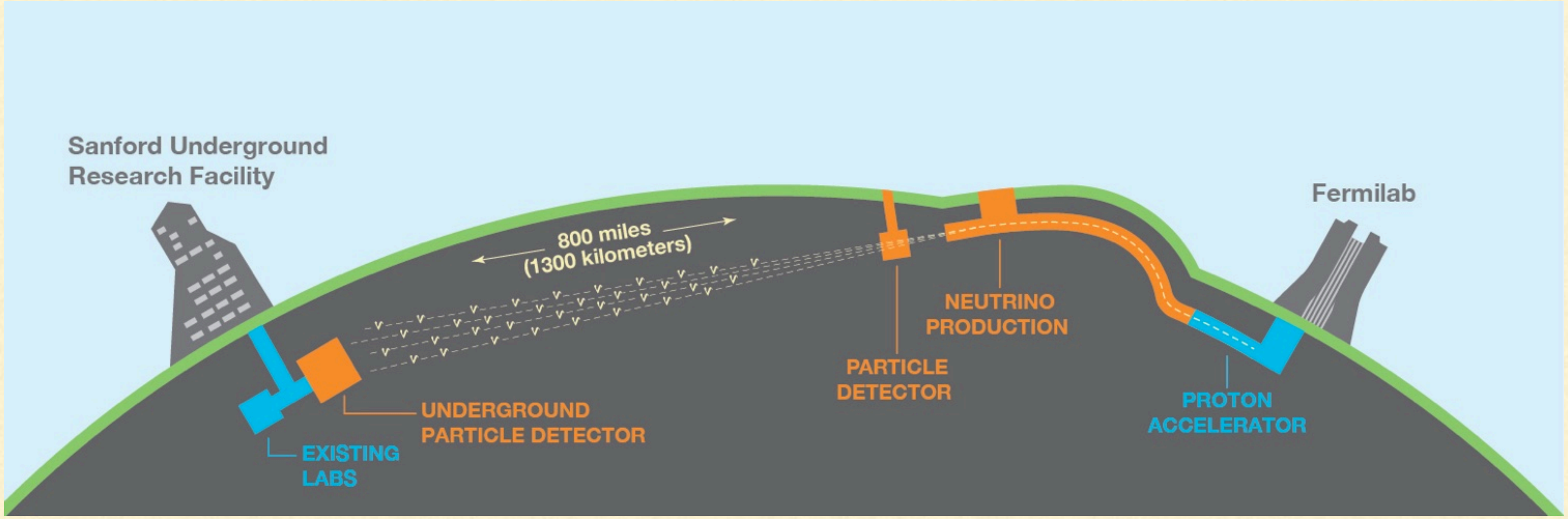
- Send a beam of muons 800 miles from Fermilab to Lead, South Dakota
- Beam will be about 1km wide by the time it reaches SD



DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Send a beam of muons 800 miles from Fermilab to Lead, South Dakota
- Beam will be about 1km wide by the time it reaches SD
- Will also be a *near detector* to measure the composition of the initial neutrino beam



SANFORD UNDERGROUND RESEARCH FACILITY

DEEP UNDERGROUND NEUTRINO EXPERIMENT

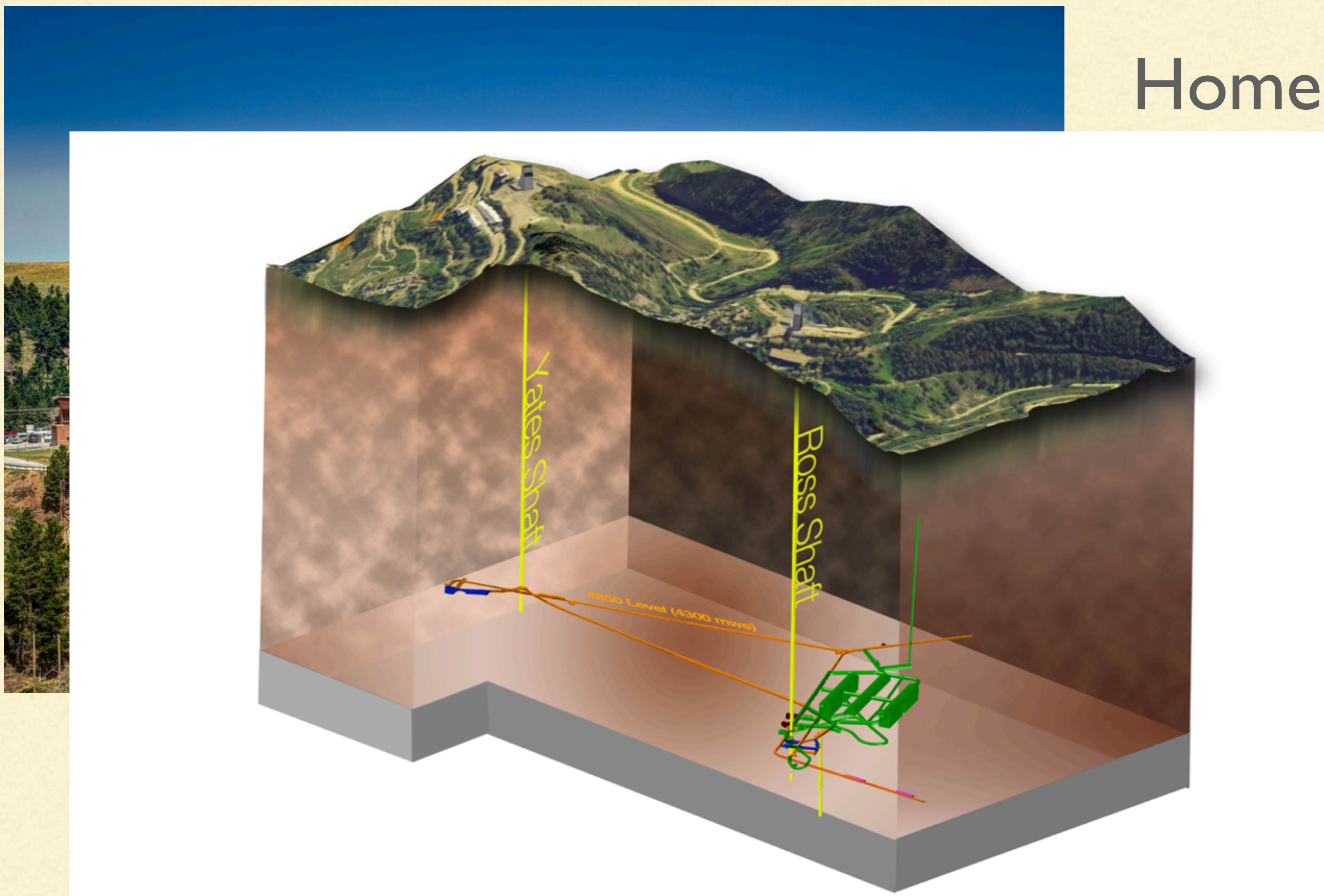
SANFORD UNDERGROUND RESEARCH FACILITY

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Homestake Mine, former gold mine and deepest in North America

SANFORD UNDERGROUND RESEARCH FACILITY

DEEP UNDERGROUND NEUTRINO EXPERIMENT

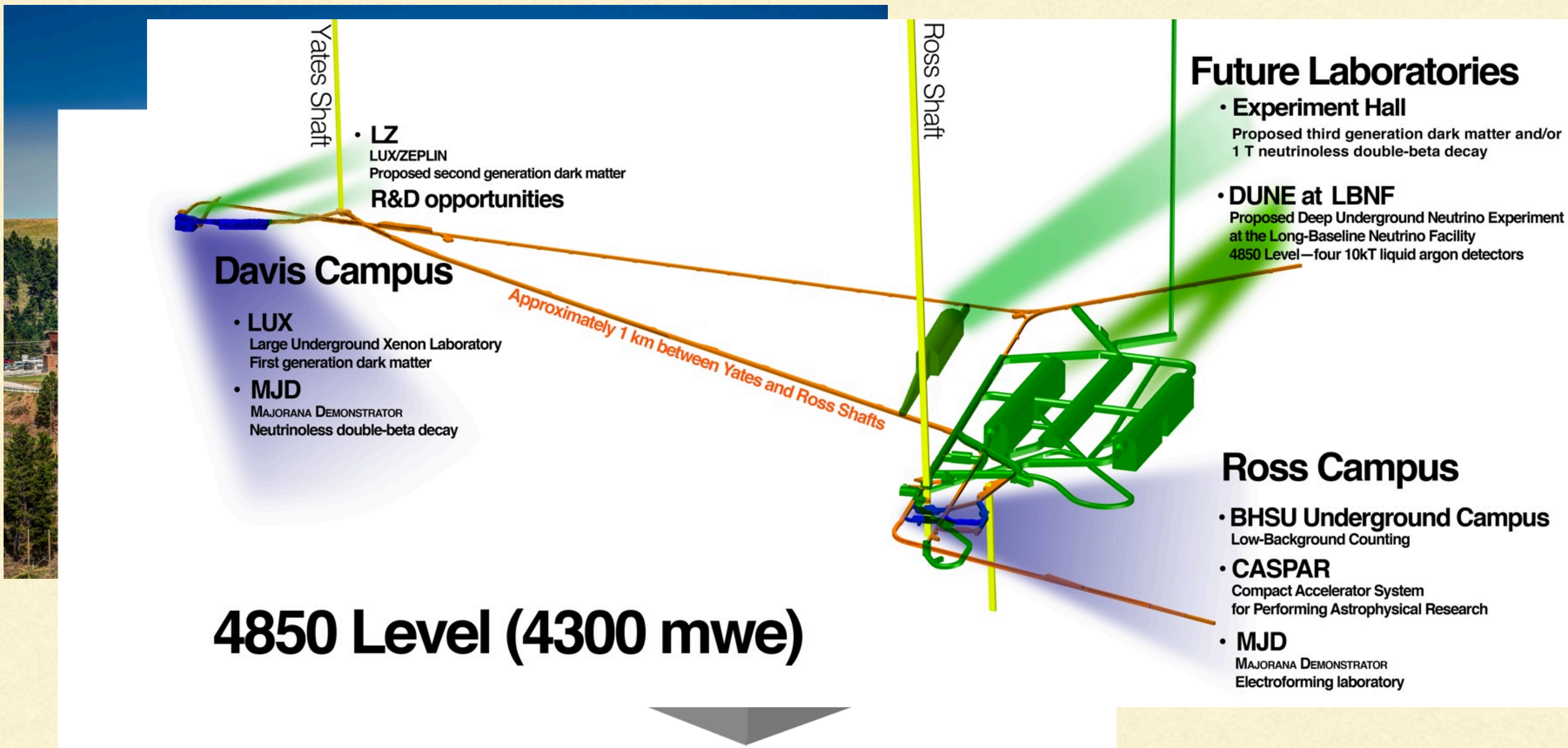


Homestake Mine, former
ine and deepest in
orth America

Will require new cavern excavation (over two Empire State Buildings worth of rock)

SANFORD UNDERGROUND RESEARCH FACILITY

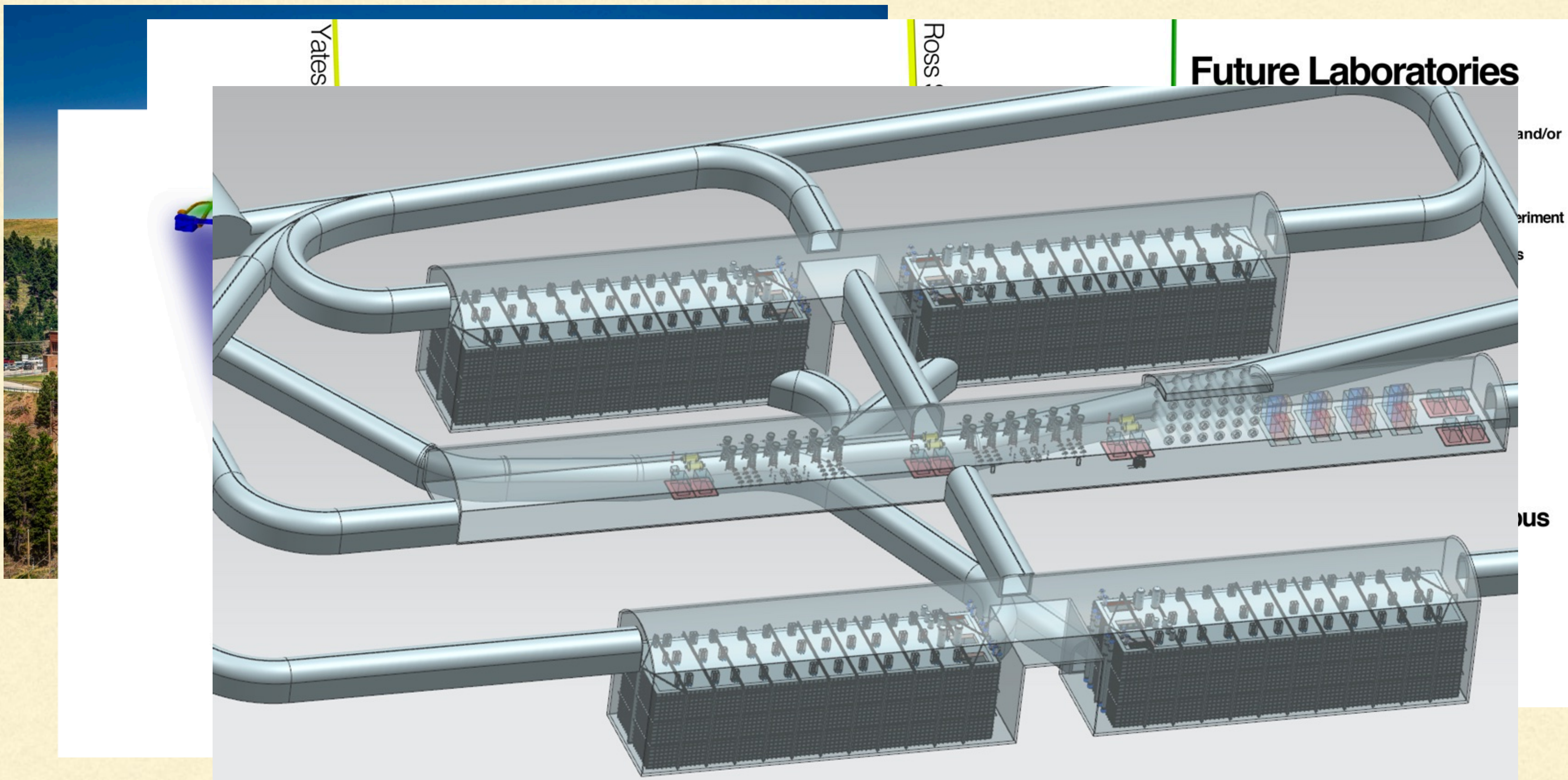
DEEP UNDERGROUND NEUTRINO EXPERIMENT



w
on
re
orth

SANFORD UNDERGROUND RESEARCH FACILITY

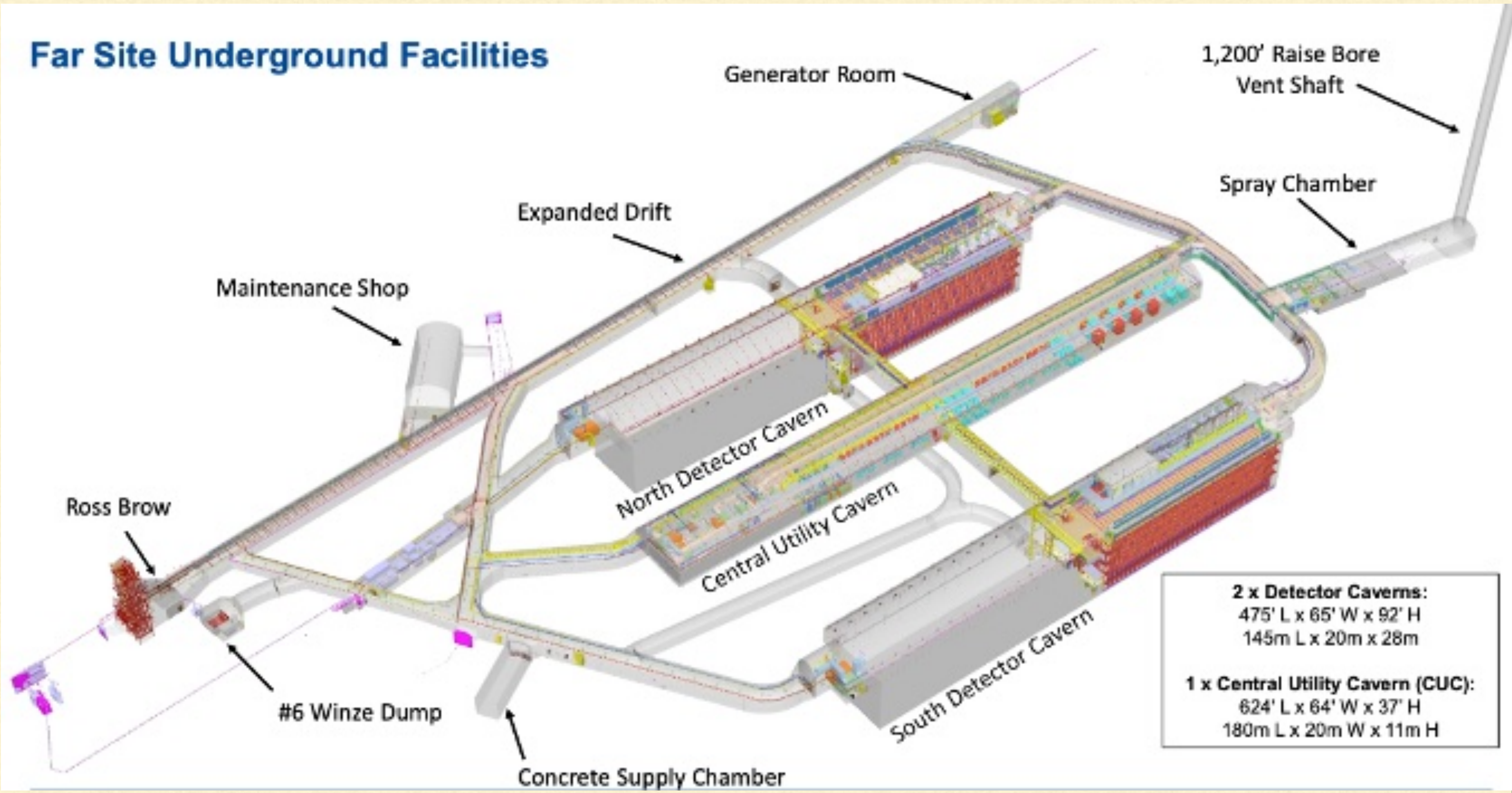
DEEP UNDERGROUND NEUTRINO EXPERIMENT



Four caverns, each about 60ft by 60ft by 230ft long, each holding over 15tons of liquid argon

UNDERGROUND IN SD (TODAY)

UNDERGROUND IN SD (TODAY)



UNDERGROUND IN SD (TODAY)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

North Detector Cavern

North Cavern (4850-33) adjusting ventilation

North Cavern (4850-15) midpoint connection drift

Concrete supply chamber

16

UNDERGROUND IN SD (TODAY)

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

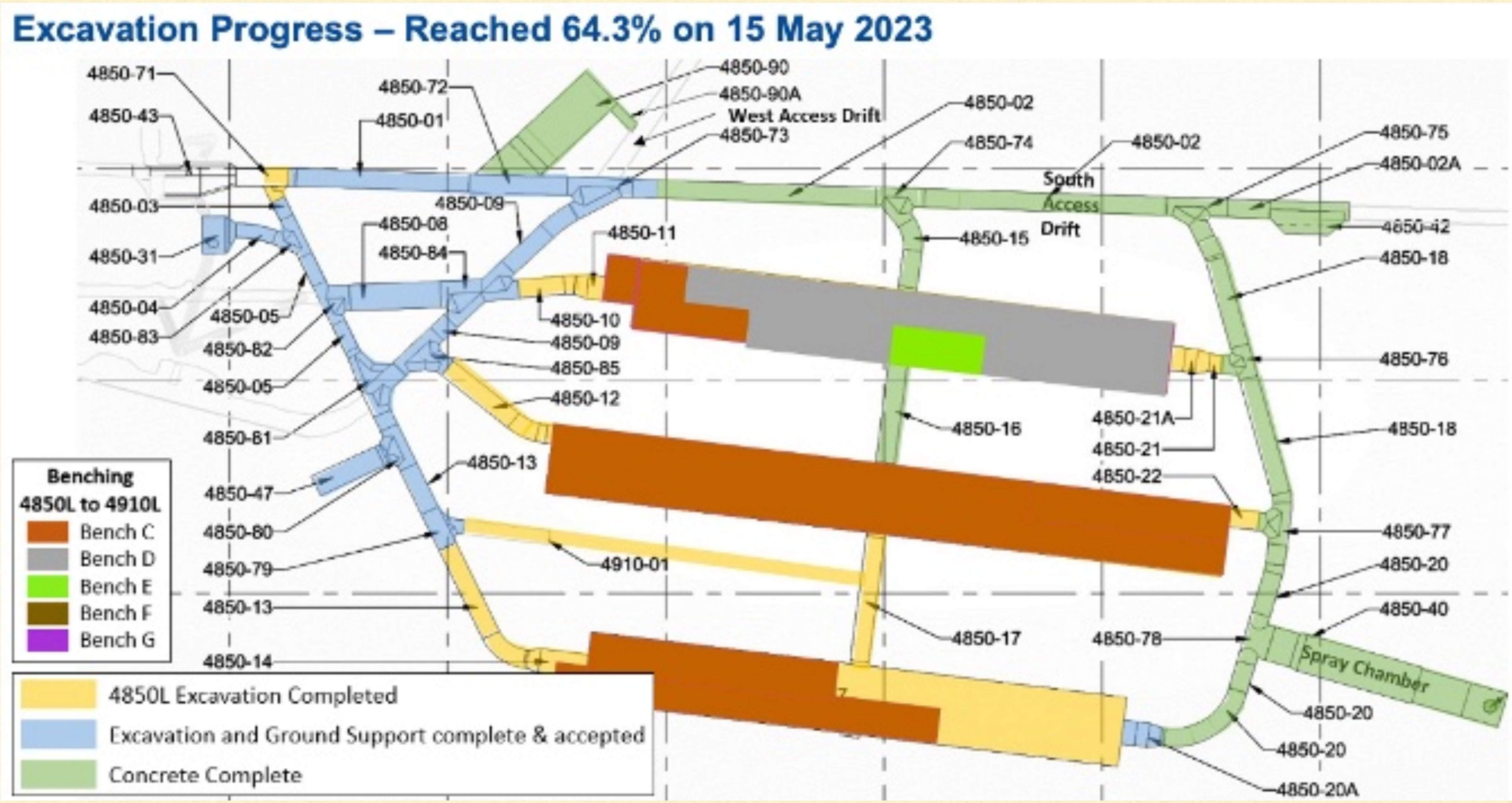
UNDERGROUND IN SD (TODAY)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

EXCAVATION STATUS

EXCAVATION STATUS

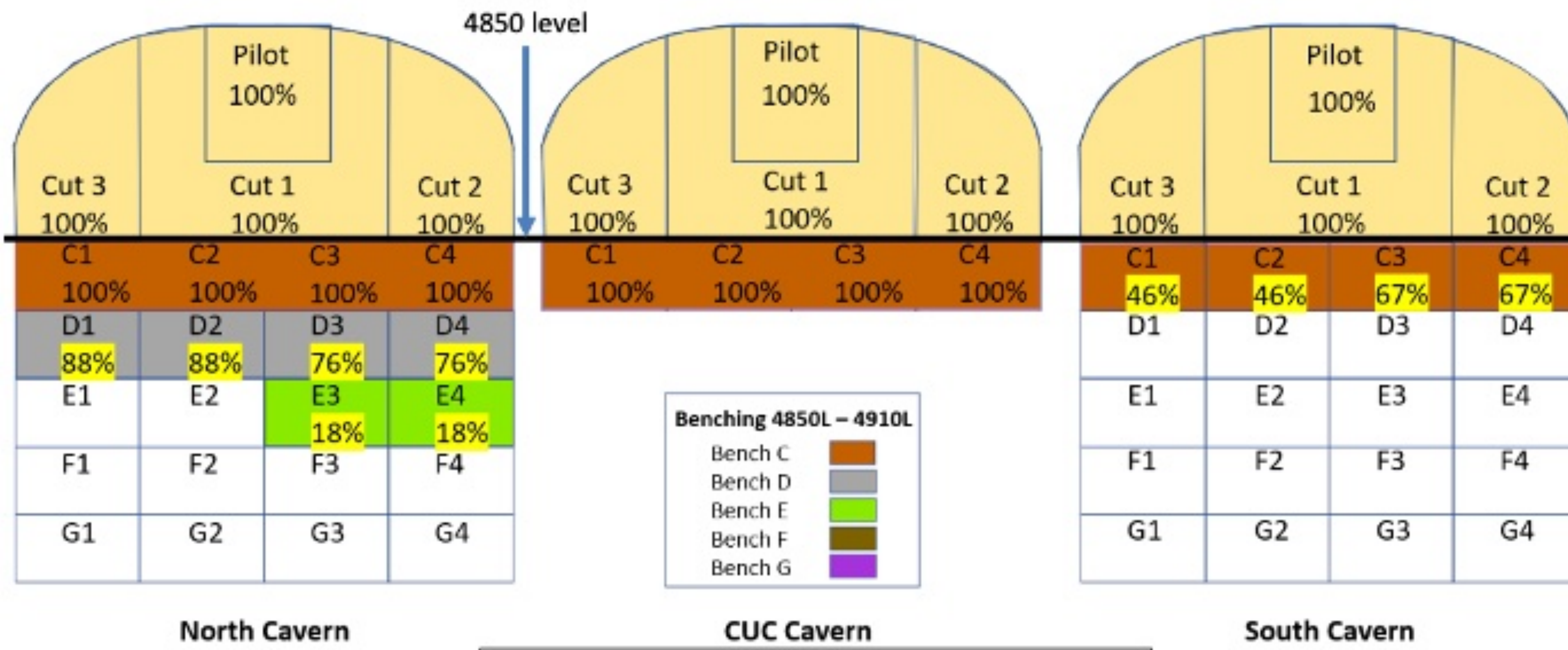
DEEP UNDERGROUND NEUTRINO EXPERIMENT



EXCAVATION STATUS

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Main Excavation Focus is now on "Benching down" in each cavern from 4850L



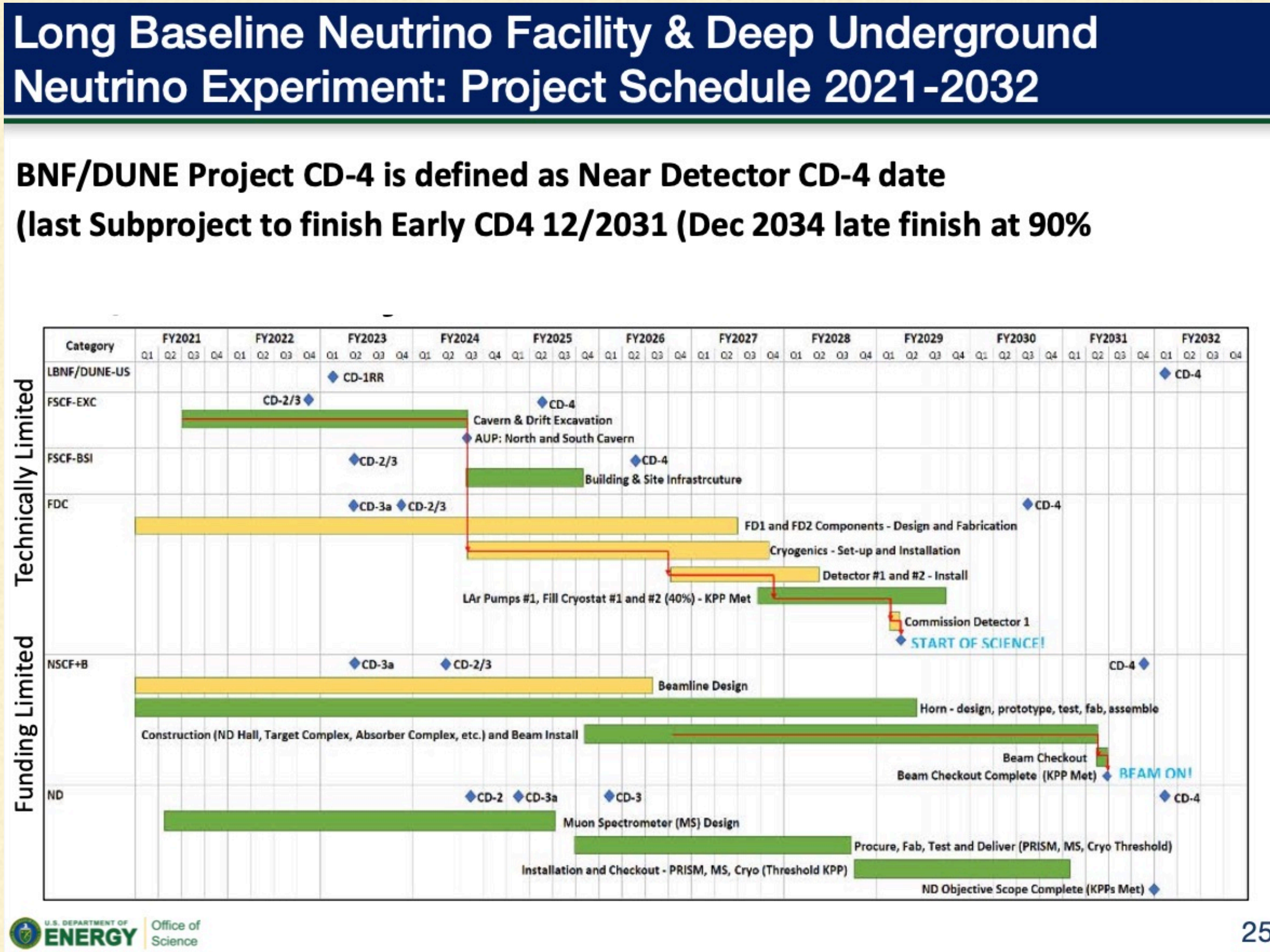
64.3% of in-situ rock volume removed as of 15 May 2023

EXCAVATION STATUS

DEEP UNDERGROUND NEUTRINO EXPERIMENT

SCHEDULE AND TIMELINE

DEEP UNDERGROUND
NEUTRINO EXPERIMENT



Excavation in SD over half complete

Civil construction at Fermilab has begun

Cryostat installation begins 2024

First detector module complete 2029

First beam arrives in 2031

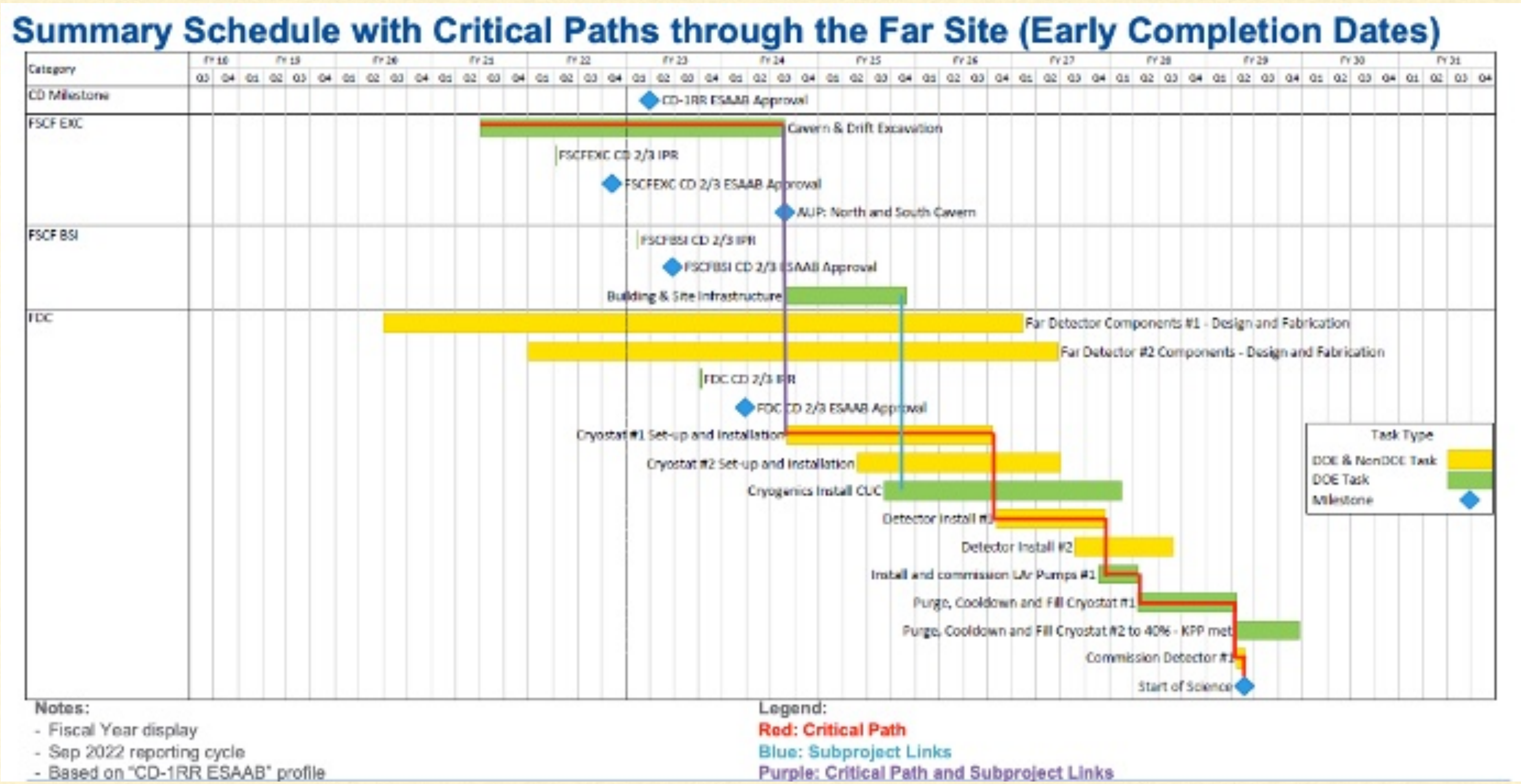
SUMMARY

- DUNE is a huge project, and is well underway
- It will make world-leading measurements of neutrino oscillation parameters, and has the potential to fundamentally change our understanding of the universe
- There are a large number of computing challenges to overcome
- Stay tuned!

BACKUP

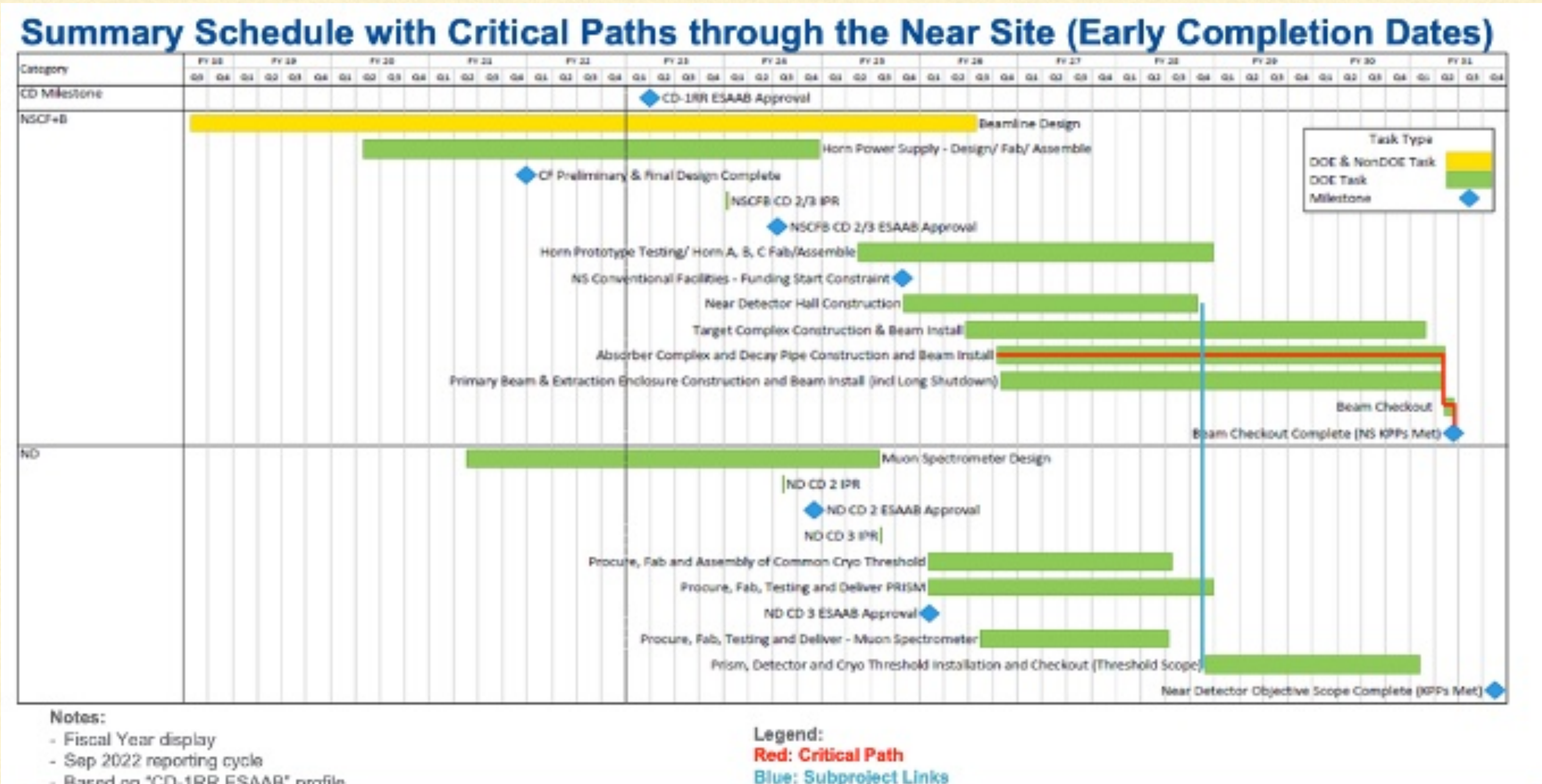
FAR SITE (SOUTH DAKOTA) SCHEDULE

DEEP UNDERGROUND NEUTRINO EXPERIMENT



NEAR SITE (FERMILAB) SCHEDULE

DEEP UNDERGROUND NEUTRINO EXPERIMENT



HOW TO MAKE A NEUTRINO BEAM

https://www.youtube.com/watch?v=U_xWDWKq1CM

HOW TO MAKE A NEUTRINO BEAM

https://www.youtube.com/watch?v=U_xWDWKq1CM

DUNE VIDEO

DEEP UNDERGROUND NEUTRINO EXPERIMENT

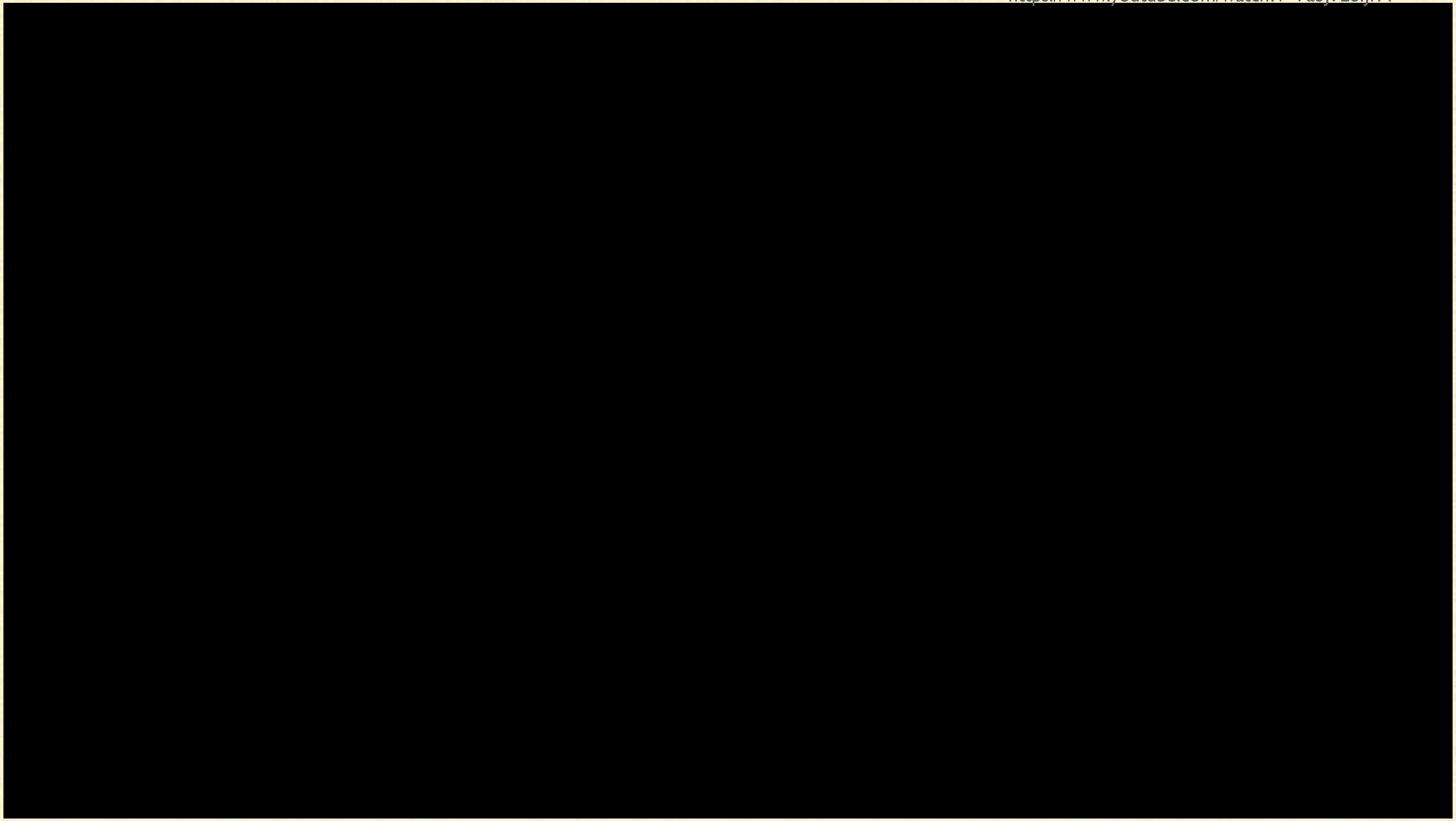
DUNE VIDEO

DEEP UNDERGROUND NEUTRINO EXPERIMENT

THE 4850 LEVEL

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

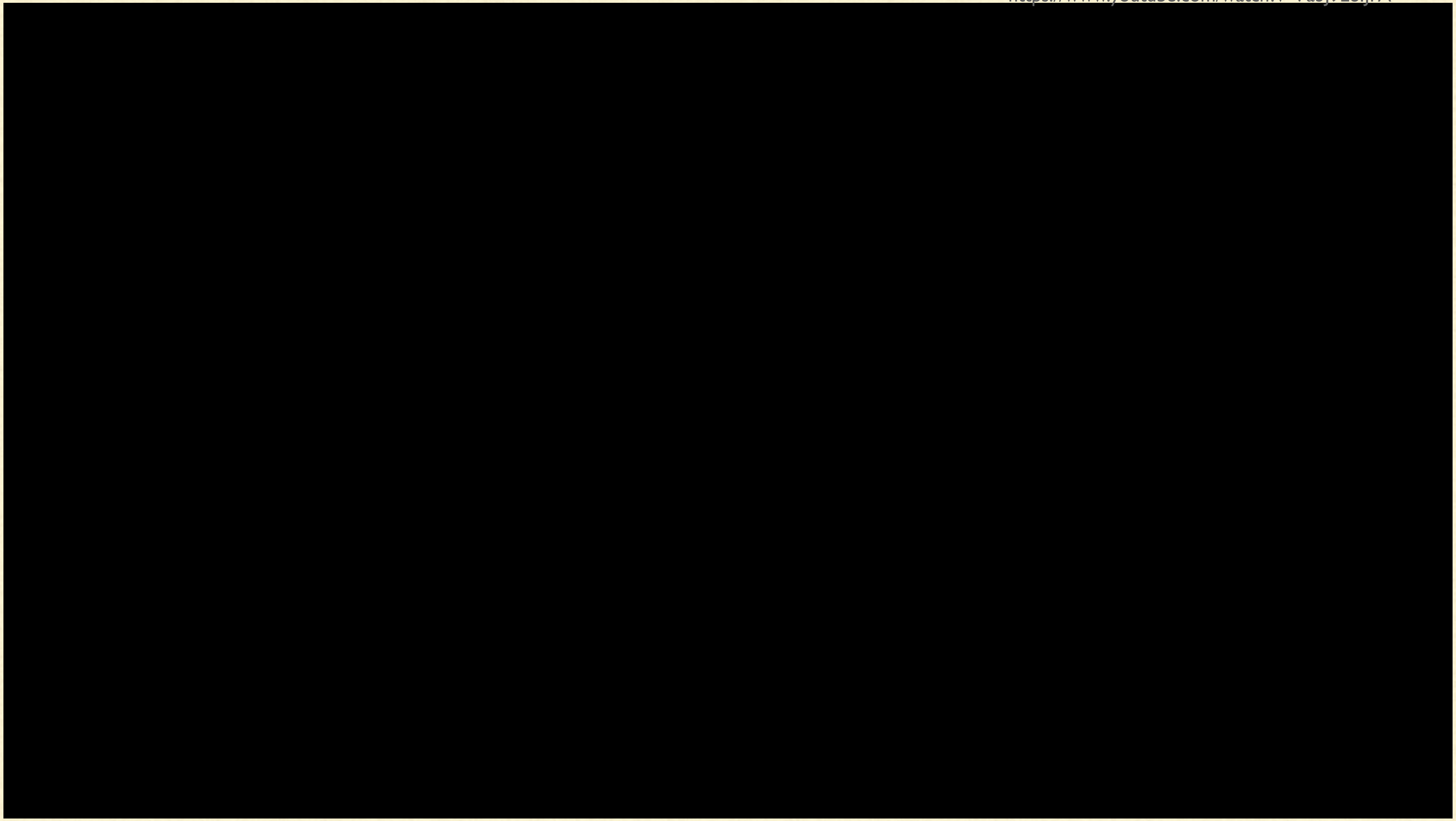
https://www.youtube.com/watch?v=7a3J9E8IJFA



THE 4850 LEVEL

DEEP UNDERGROUND NEUTRINO EXPERIMENT

https://www.youtube.com/watch?v=7a3J9E8IJFA



DUNE PHYSICS GOALS

DEEP UNDERGROUND NEUTRINO EXPERIMENT

https://www.youtube.com/watch?v=nv13DswlKr8

DUNE PHYSICS GOALS

DEEP UNDERGROUND NEUTRINO EXPERIMENT

https://www.youtube.com/watch?v=nv13DswIKr8

WE ARE DUNE

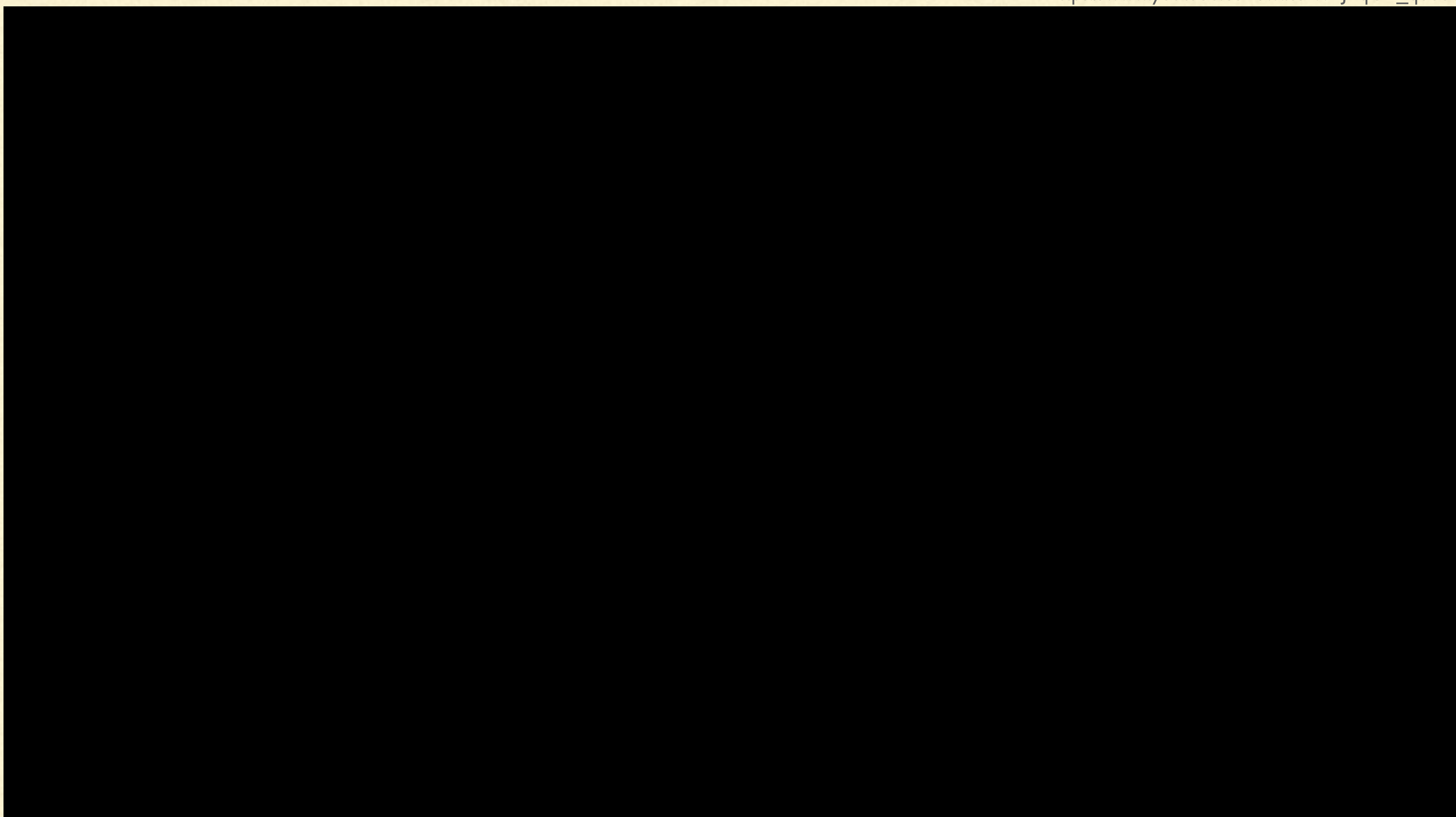
DEEP UNDERGROUND NEUTRINO EXPERIMENT

https://www.youtube.com/watch?v=JBqGK_qo8eU

WE ARE DUNE

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

https://www.youtube.com/watch?v=JBqGK_qo8eU



WHY LIQUID ARGON?

https://www.youtube.com/watch?v=R5G1_hW0ZUA

WHY LIQUID ARGON?

https://www.youtube.com/watch?v=R5G1_hW0ZUA

UNDERGROUND IN SOUTH DAKOTA

DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNDERGROUND IN SOUTH DAKOTA

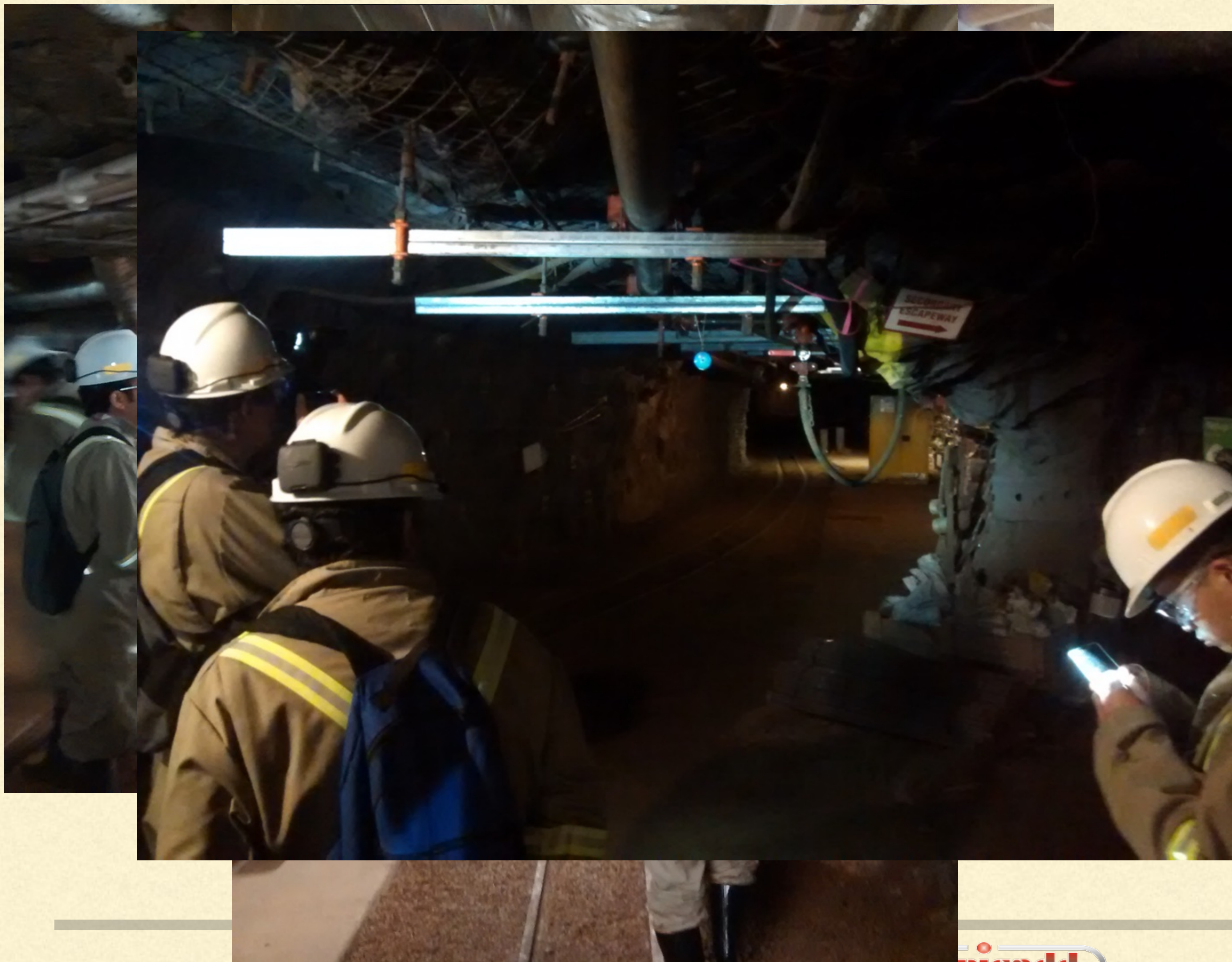
DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNDERGROUND IN SOUTH DAKOTA

DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNDERGROUND IN SOUTH DAKOTA

DEEP UNDERGROUND
NEUTRINO EXPERIMENT



UNDERGROUND IN SOUTH DAKOTA

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

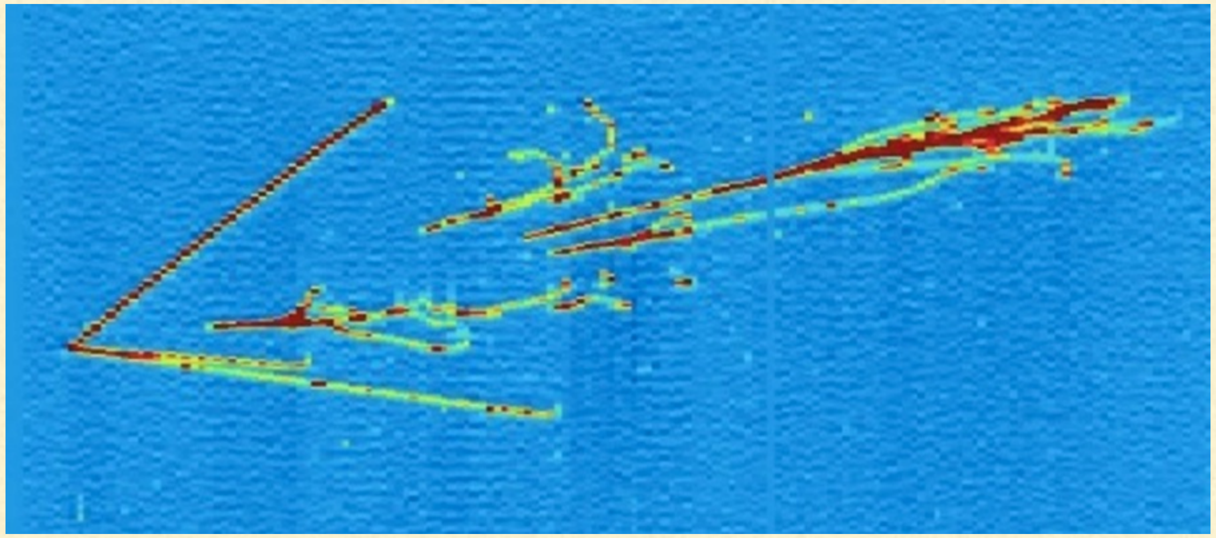
UNDERGROUND IN SOUTH DAKOTA

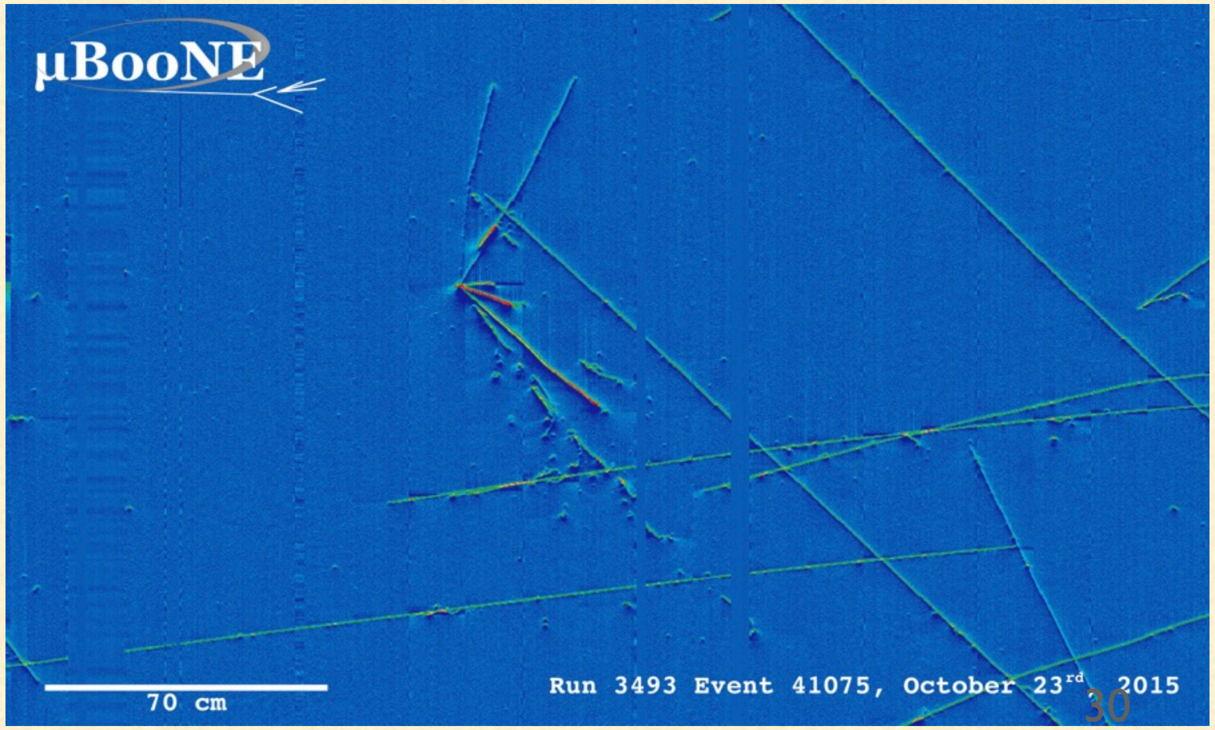
DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

LIQUID ARGON TIME PROJECTION CHAMBER

LIQUID ARGON TIME PROJECTION CHAMBER

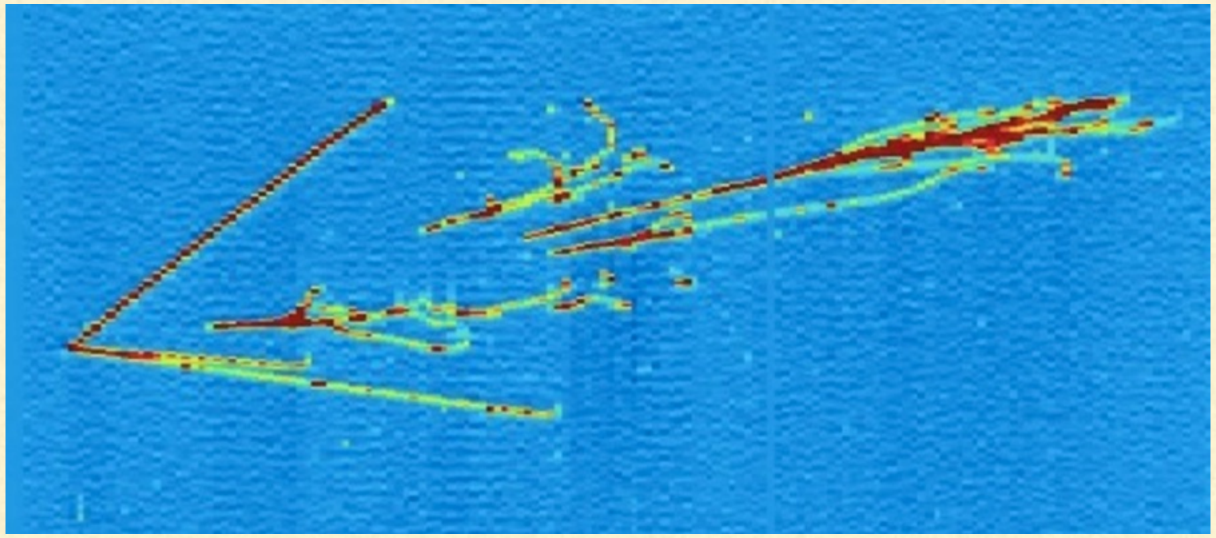
- High precision, three dimensional tracking and particle identification

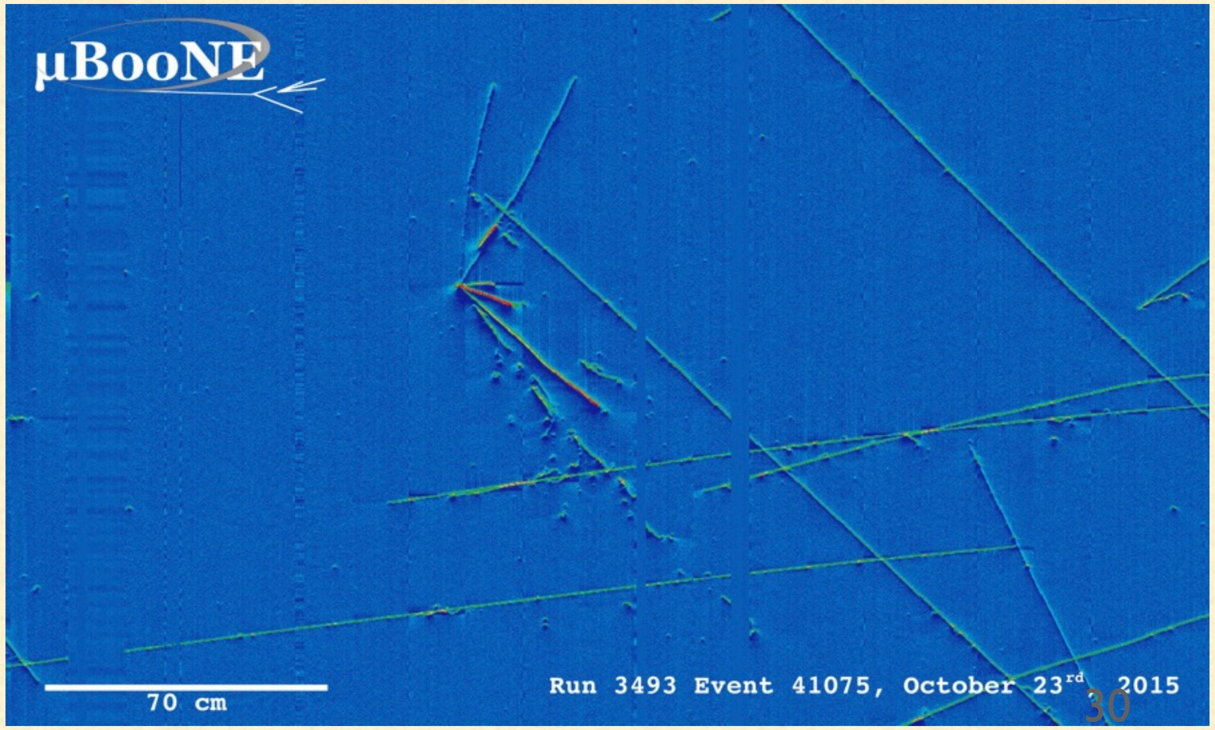




LIQUID ARGON TIME PROJECTION CHAMBER

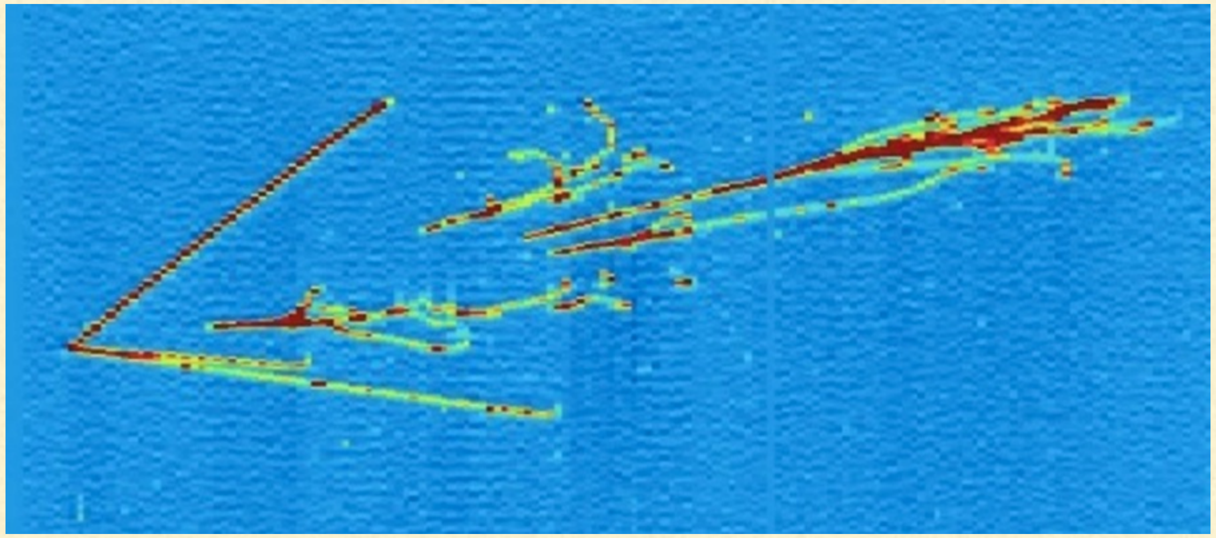
- High precision, three dimensional tracking and particle identification
- Any noble gas would work, but Argon is relatively cheap

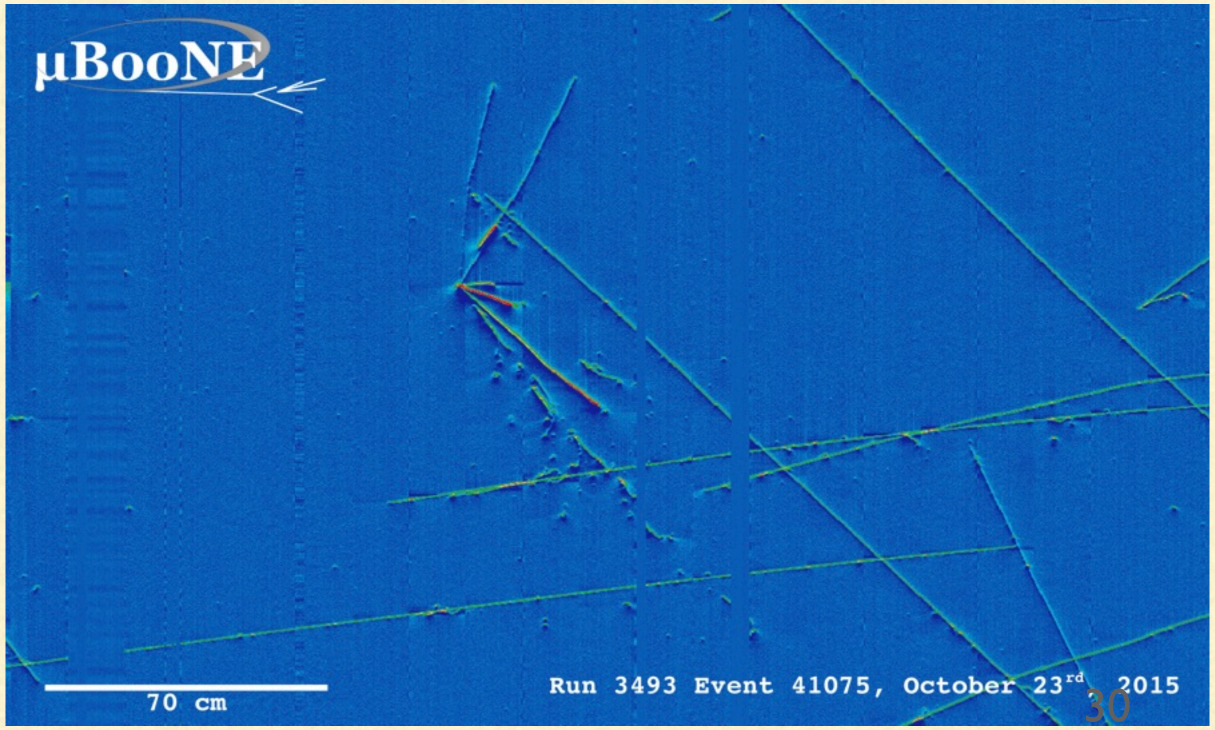




LIQUID ARGON TIME PROJECTION CHAMBER

- High precision, three dimensional tracking and particle identification
- Any noble gas would work, but Argon is relatively cheap
- A very cost effective way to instrument a very large active volume





LIQUID ARGON TIME PROJECTION CHAMBER

- High precision, three dimensional tracking and particle identification
- Any noble gas would work, but Argon is relatively cheap
- A very cost effective way to instrument a very large active volume
- Membrane cryostat (also used for LNG transportation)

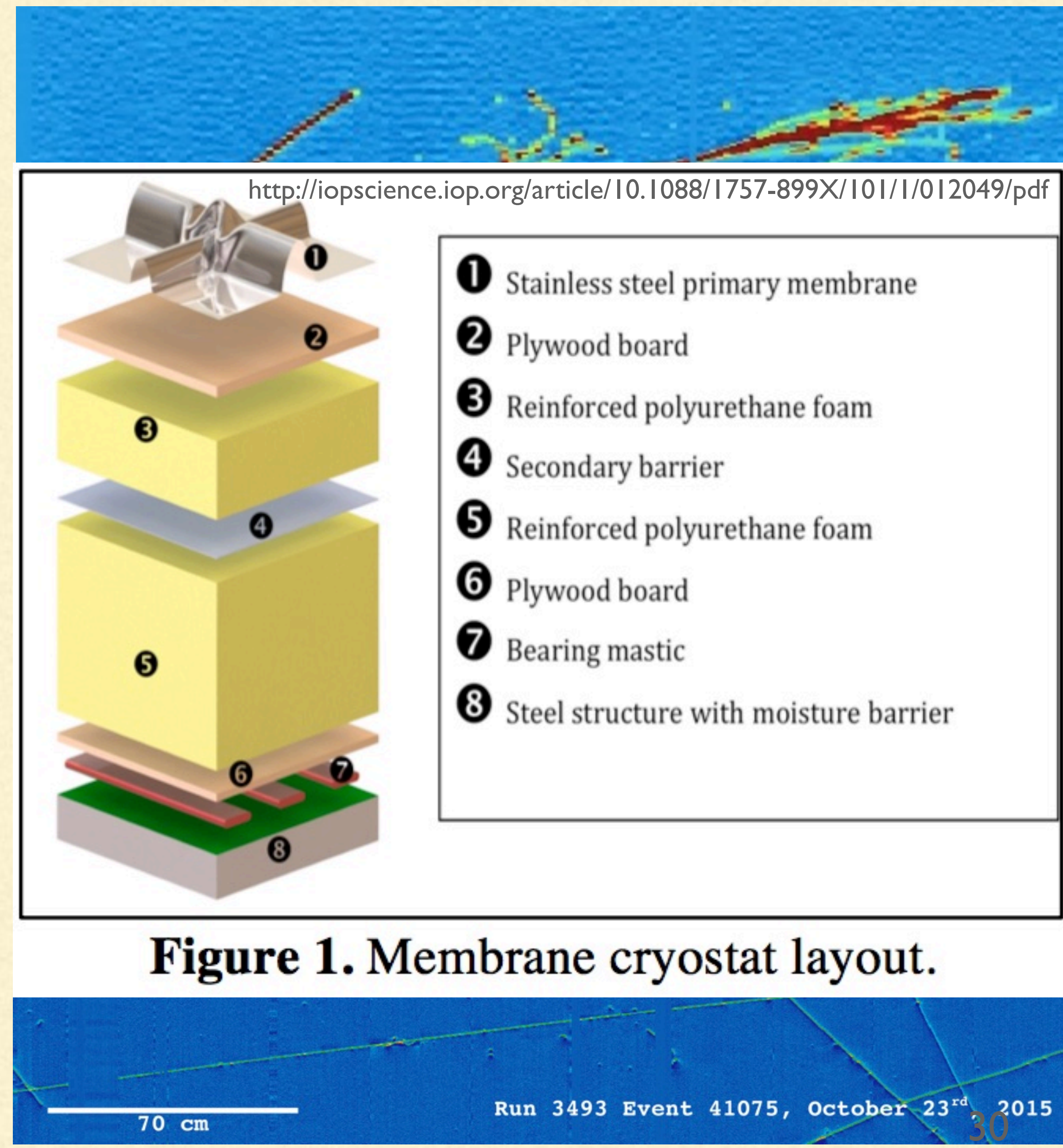


Figure 1. Membrane cryostat layout.

LIQUID ARGON TIME PROJECTION CHAMBER

- High precision, three dimensional tracking and particle identification
- Any noble gas would work, but Argon is relatively cheap
- A very cost effective way to instrument a very large active volume
- Membrane cryostat (also used for LNG transportation)
- Building two prototype detectors at CERN

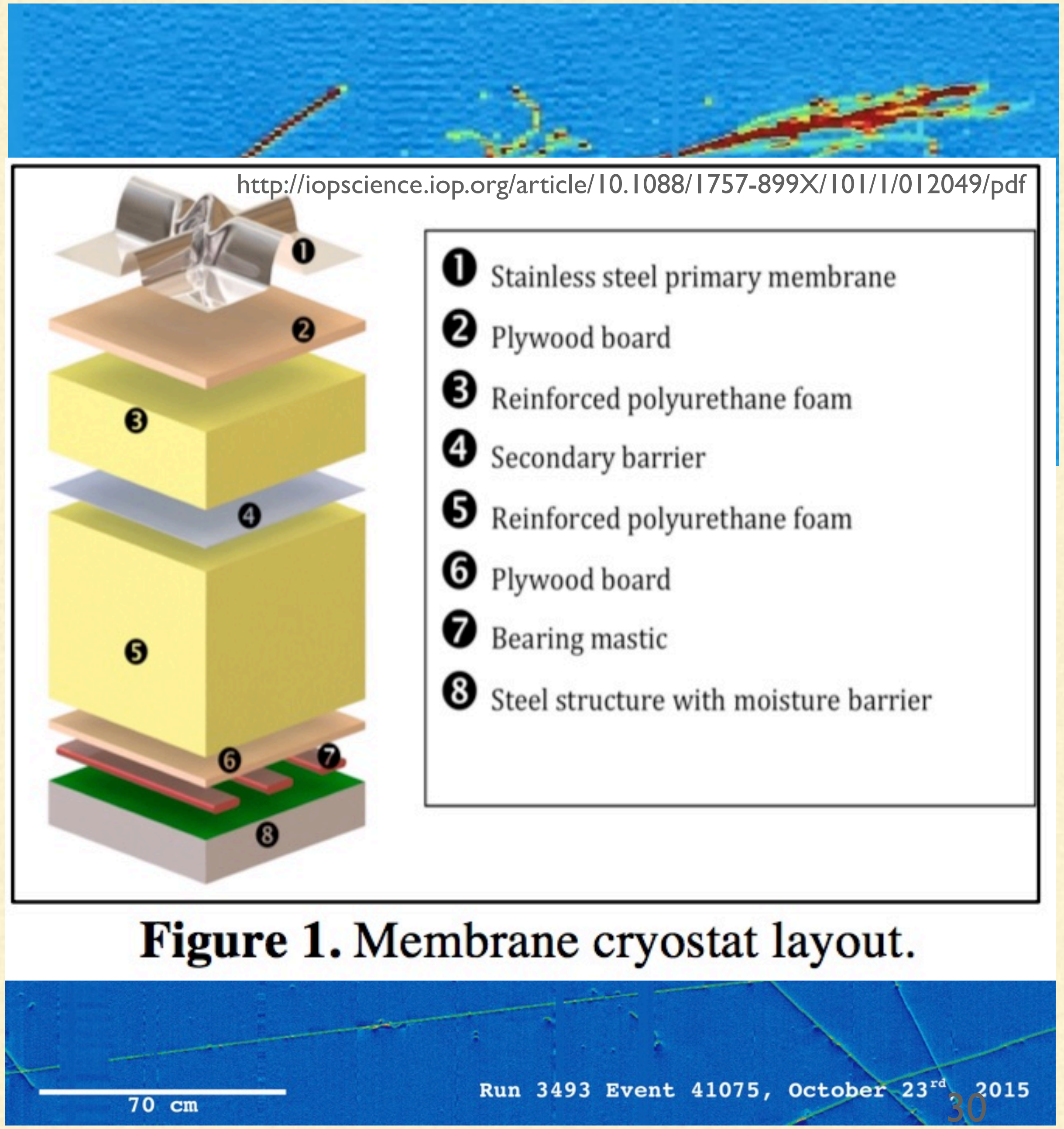
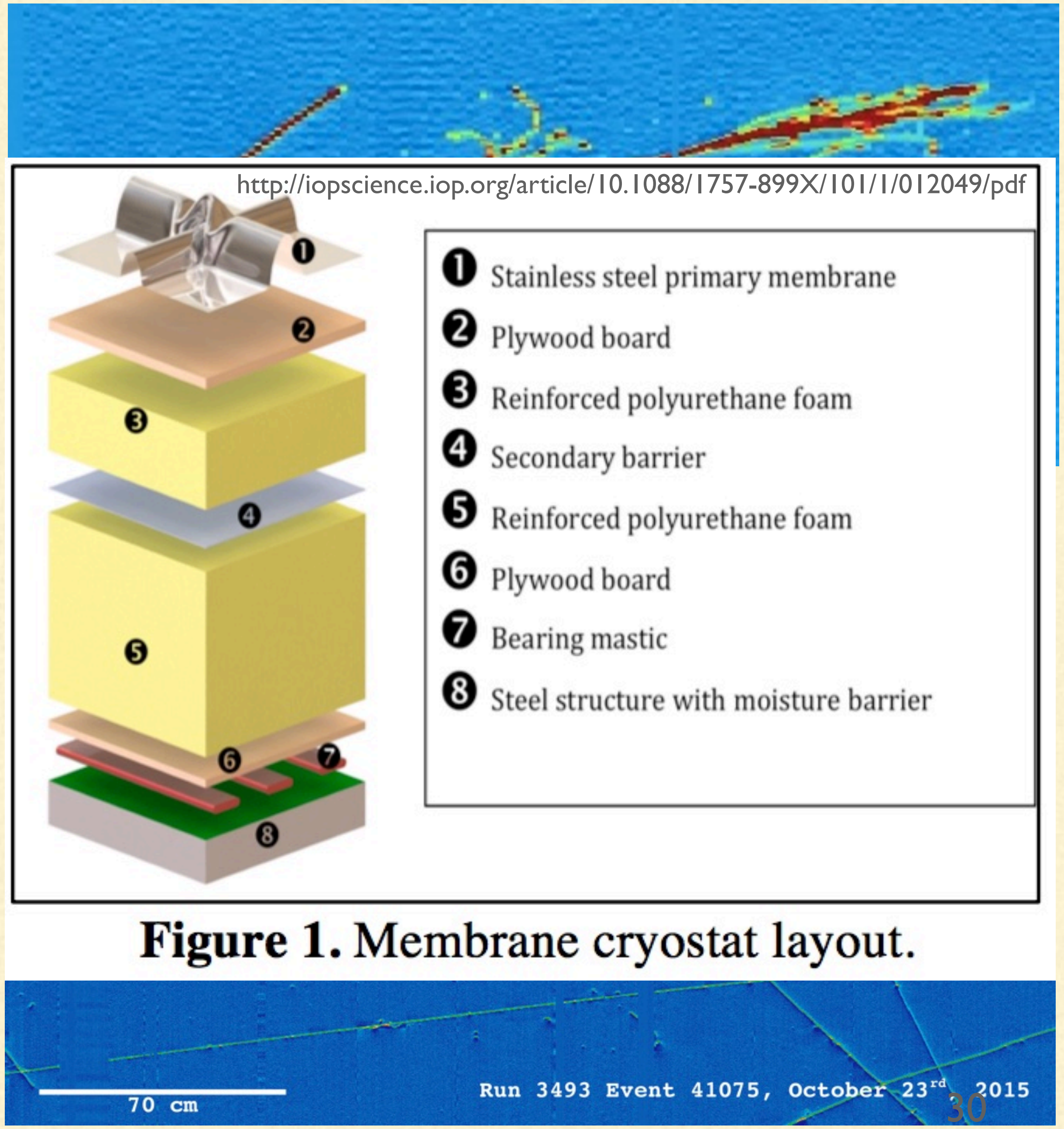


Figure 1. Membrane cryostat layout.

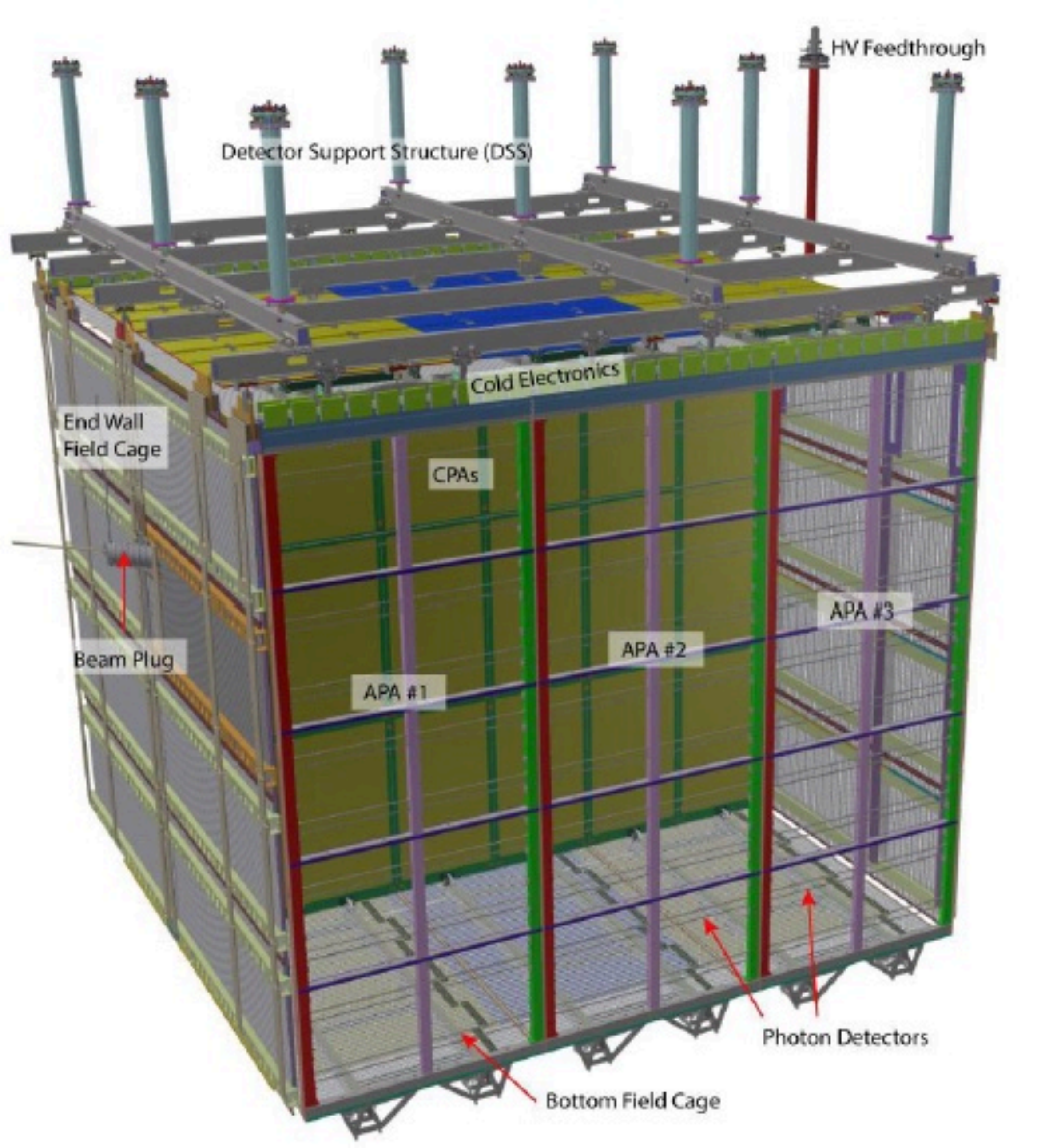
LIQUID ARGON TIME PROJECTION CHAMBER

- High precision, three dimensional tracking and particle identification
- Any noble gas would work, but Argon is relatively cheap
- A very cost effective way to instrument a very large active volume
- Membrane cryostat (also used for LNG transportation)
- Building two prototype detectors at CERN
    - 700 tons, about 25ft by 25ft by 25ft



PROTODUNE

PROTODUNE



HV Feedthrough
Detector Support Structure (DSS)
Cold Electronics
End Wall
Field Cage
CPAs
APA #3
APA #2
APA #1
Beam Plug
Photon Detectors
Bottom Field Cage

PROTODUNE

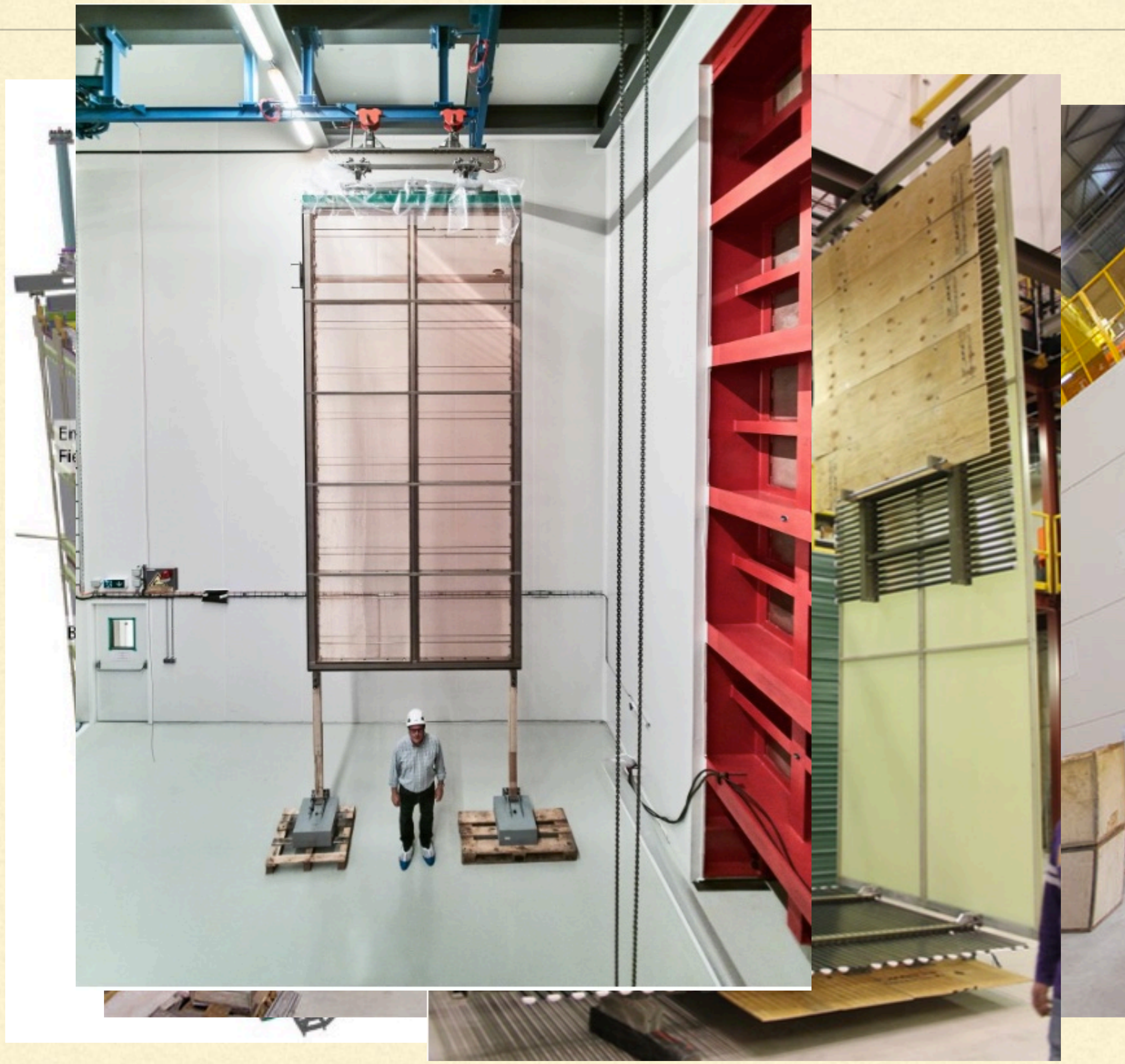
DEEP UNDERGROUND NEUTRINO EXPERIMENT

PROTODUNE

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

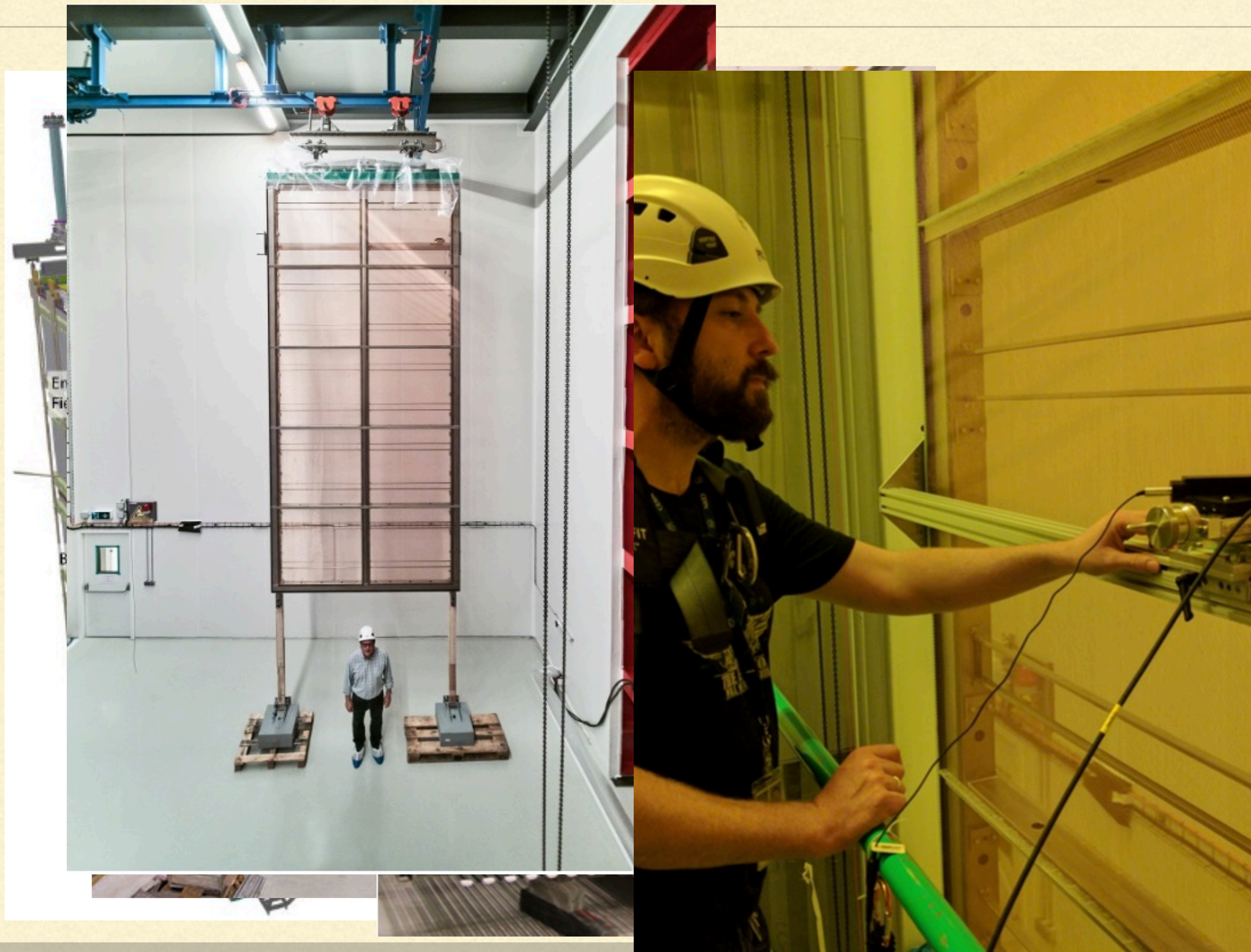
PROTODUNE

DEEP UNDERGROUND
NEUTRINO EXPERIMENT



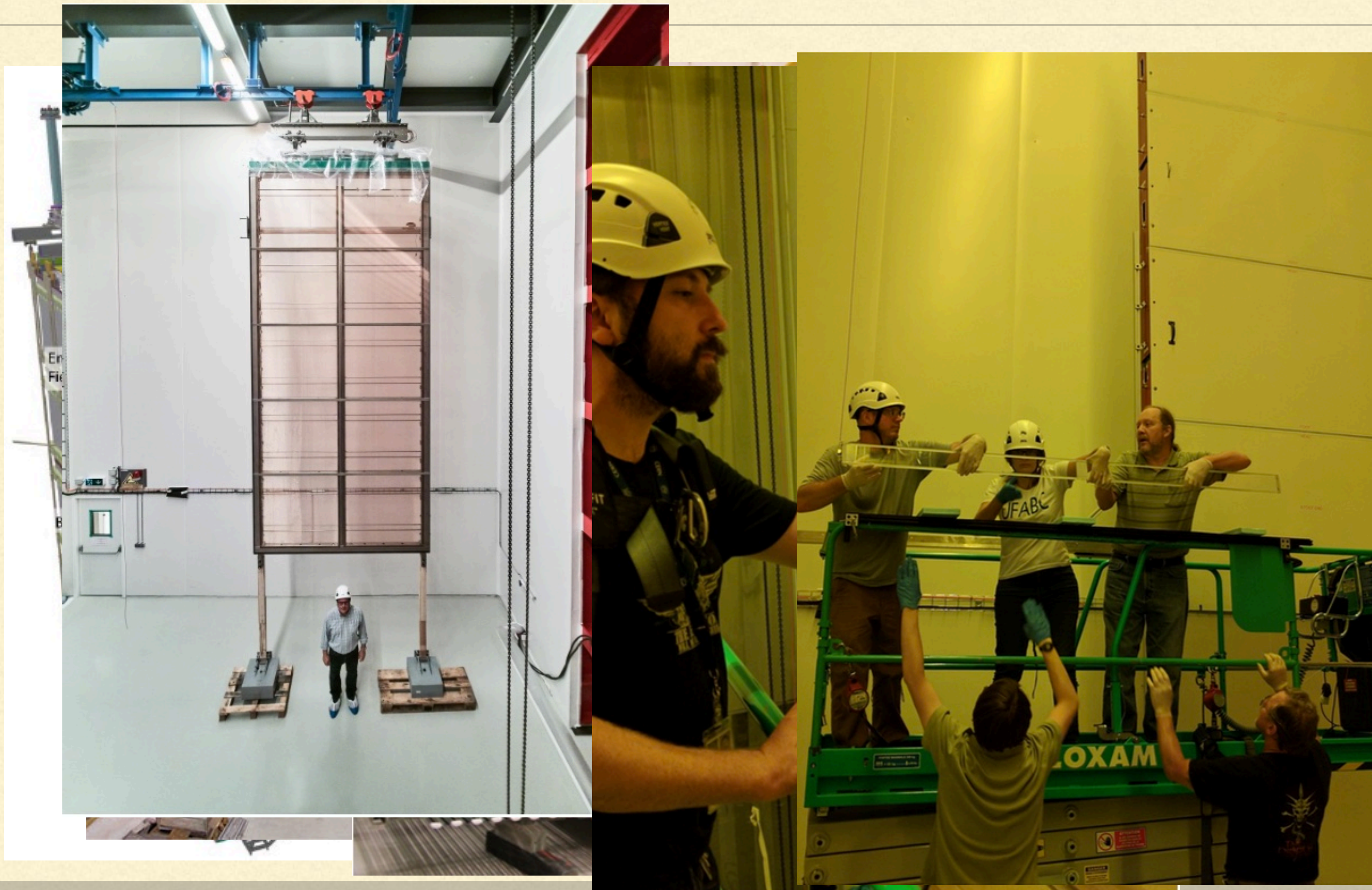
PROTODUNE

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT



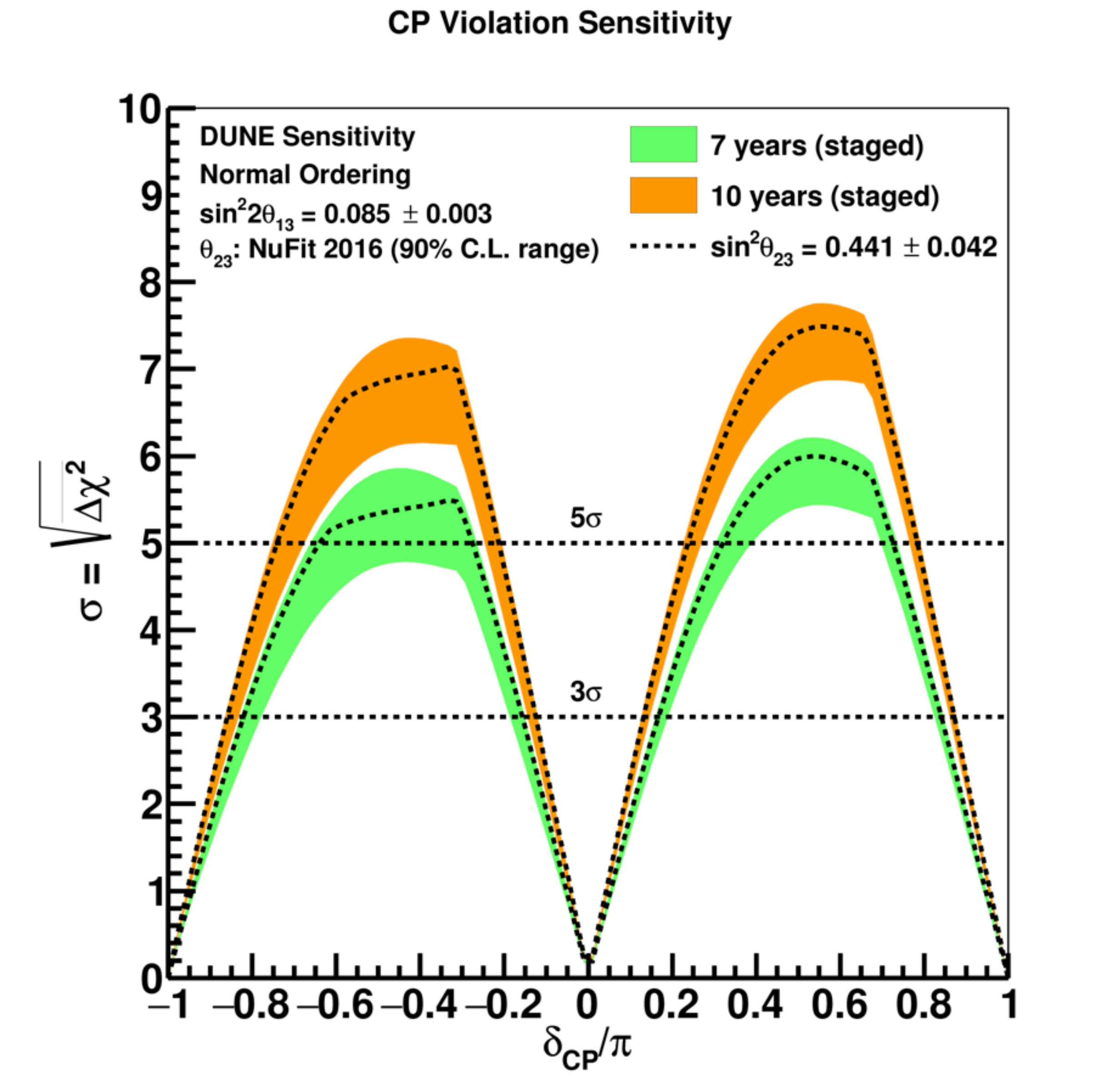
PROTODUNE

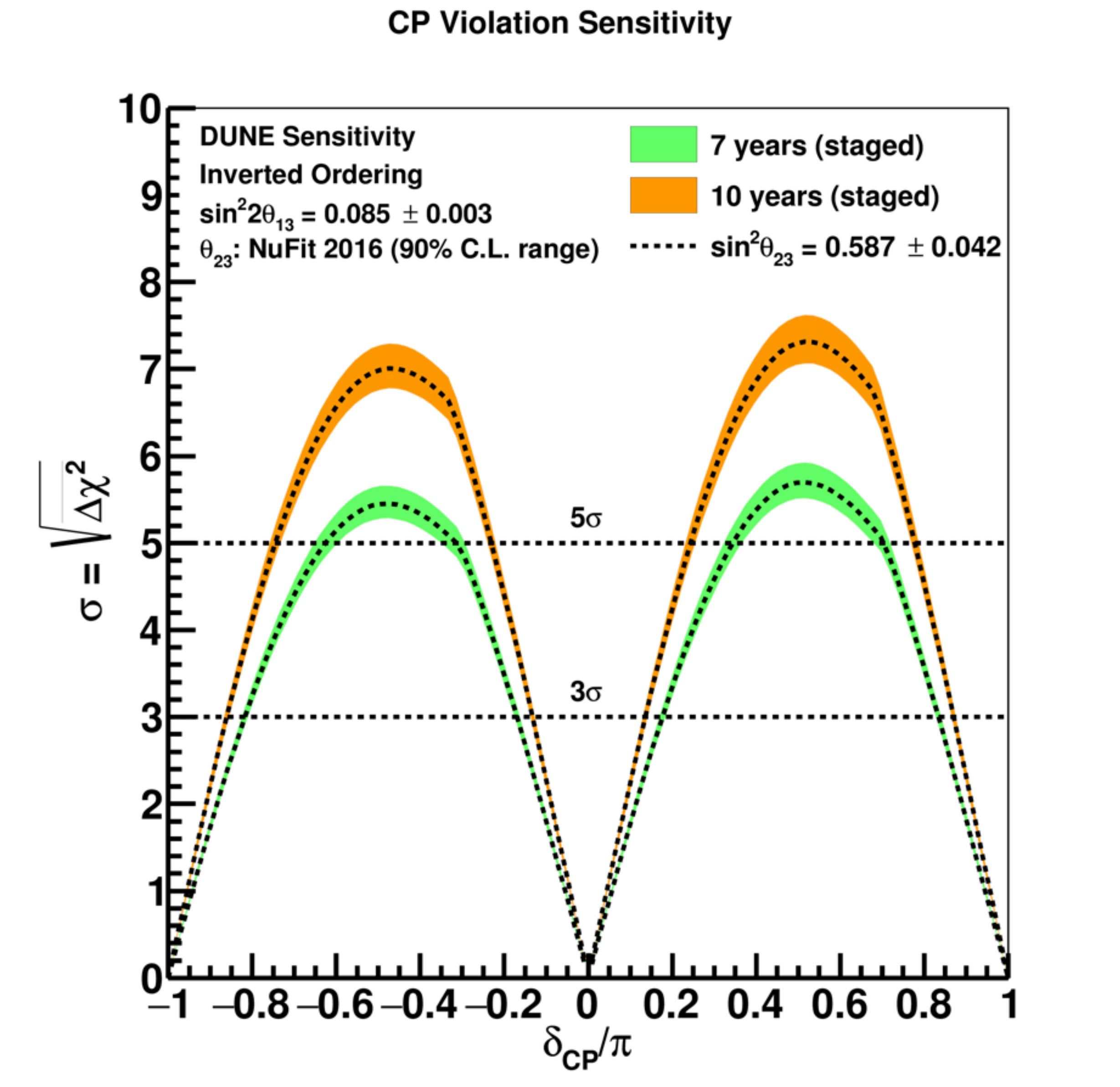
DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT



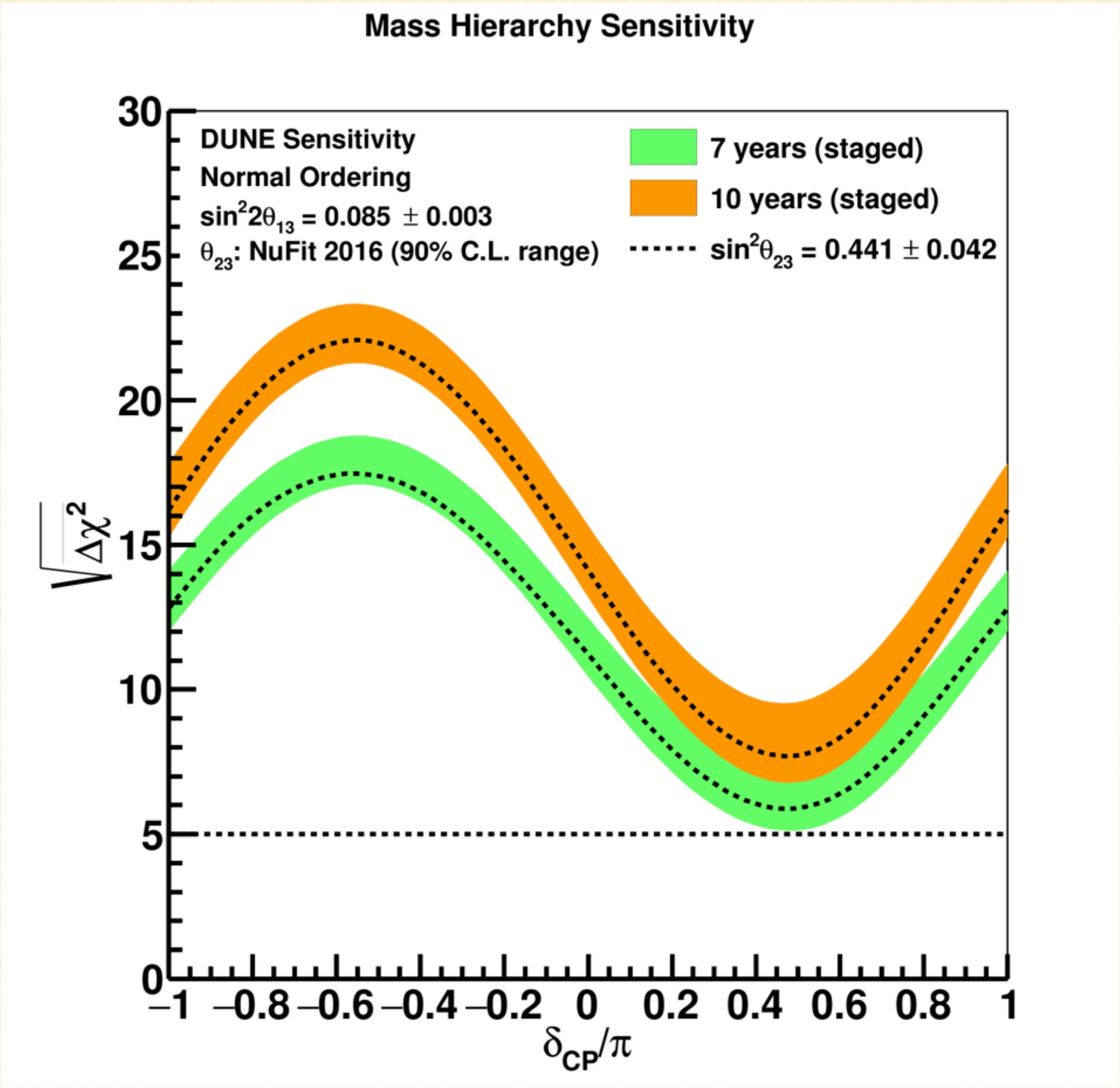
CP VIOLATION SENSITIVITY

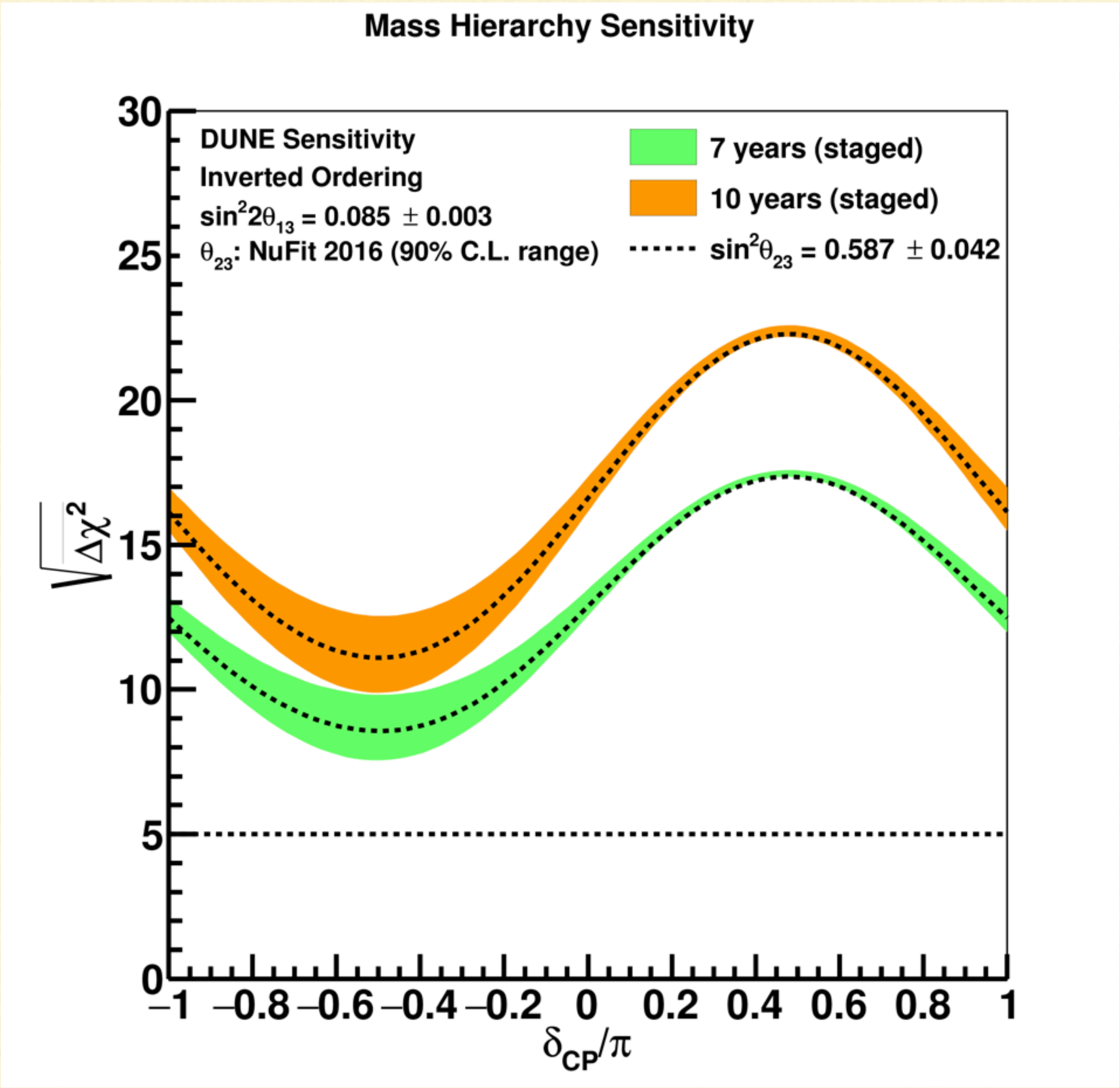
DEEP UNDERGROUND NEUTRINO EXPERIMENT





MASS HIERARCHY SENSITIVITY





OSCILLATION PARAMETER RESOLUTION

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT