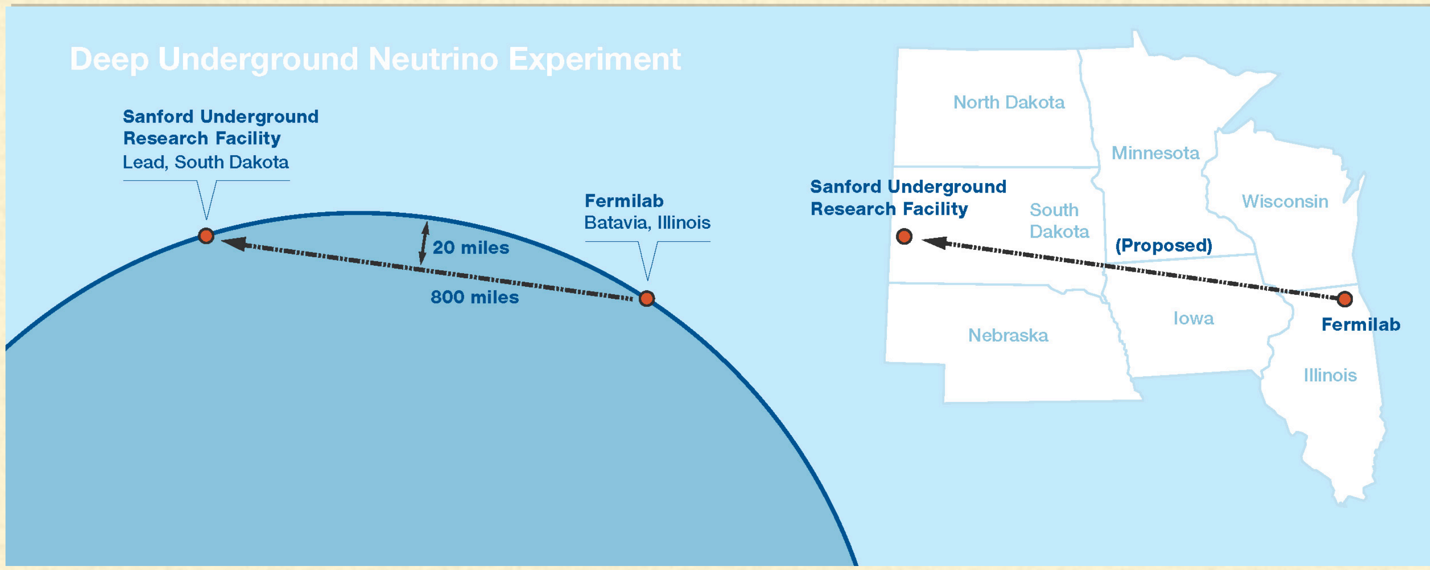

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

DUNE STATUS

Michael Eads
Department of Physics
Northern Illinois University

Northern Illinois University

THE DUNE EXPERIMENT

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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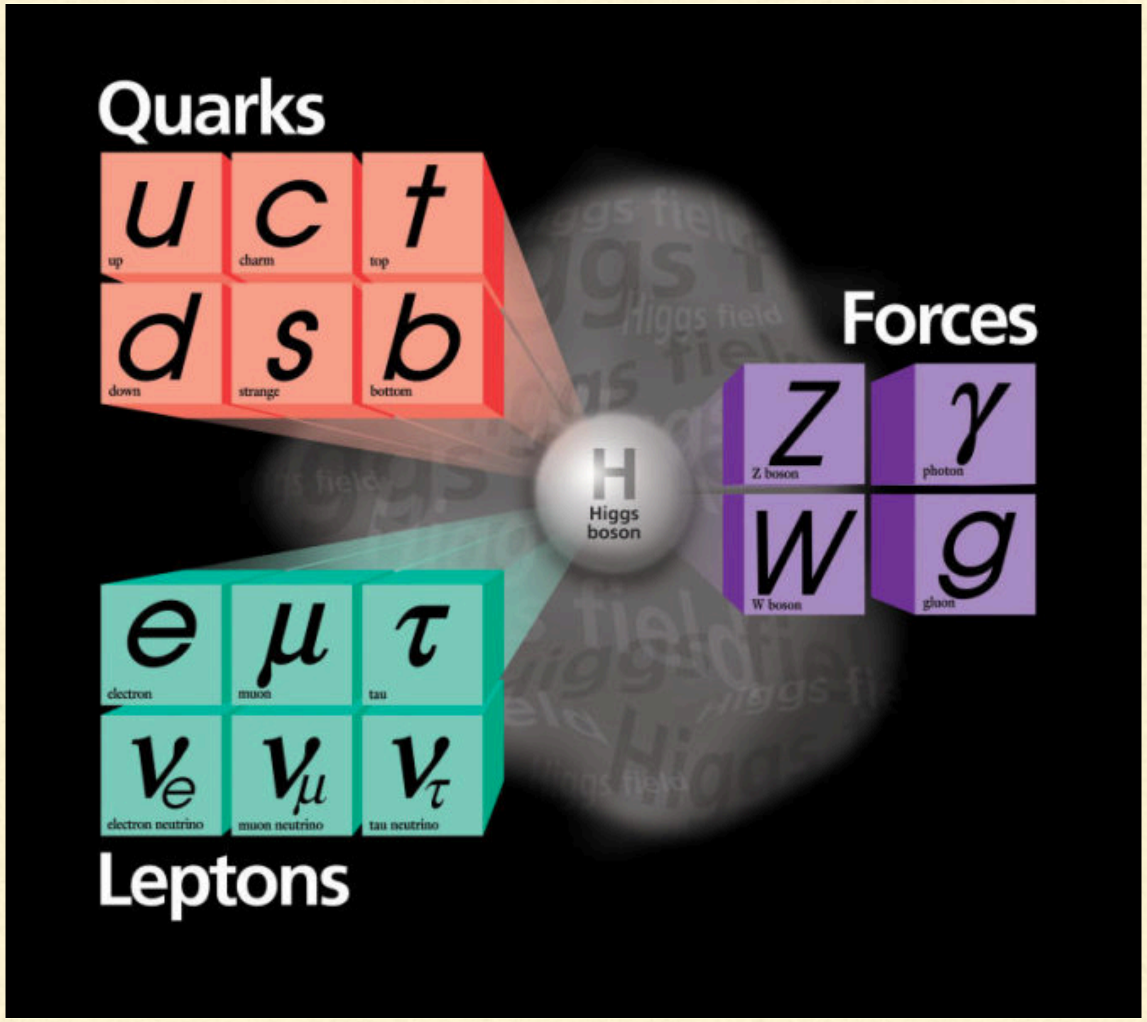
THE STANDARD MODEL



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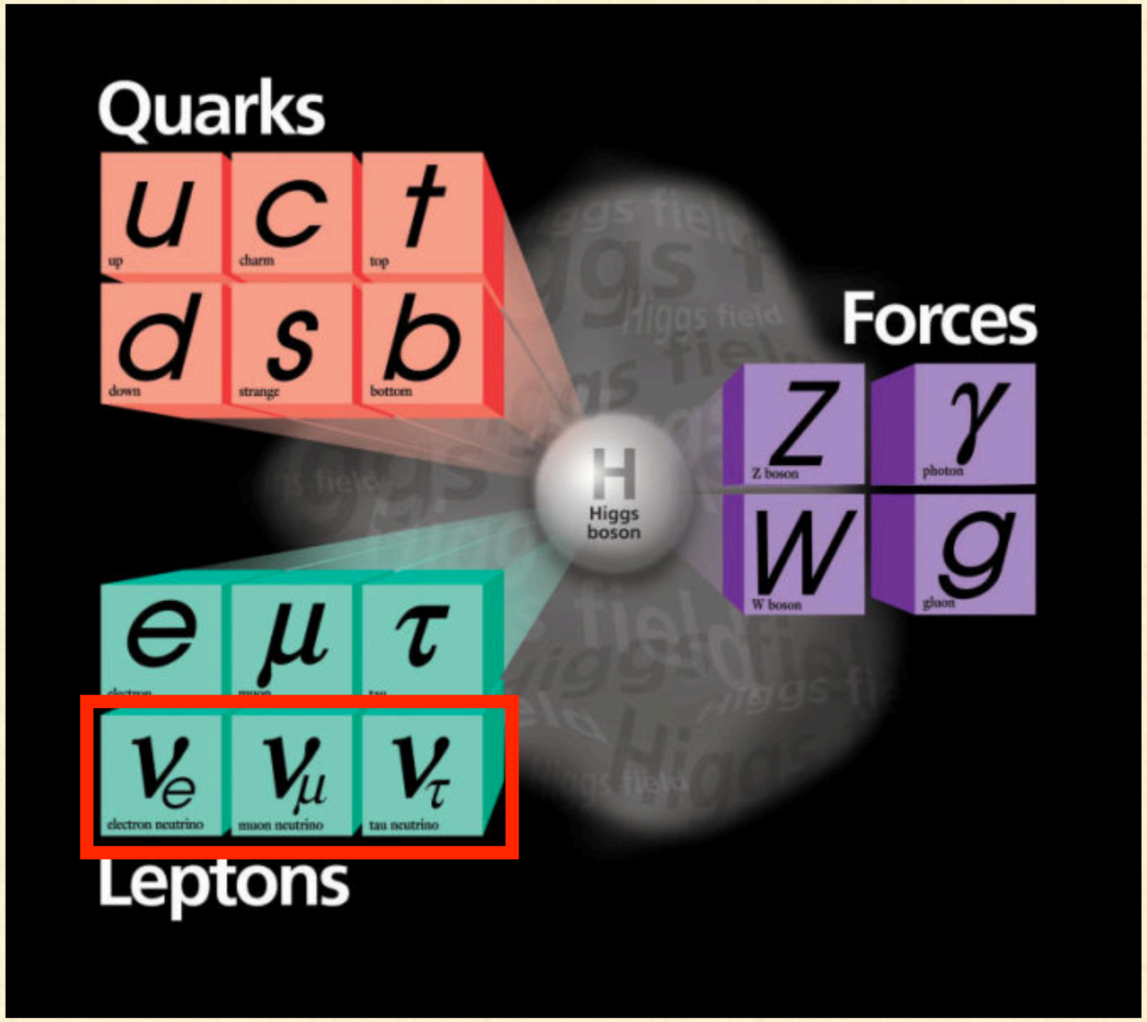

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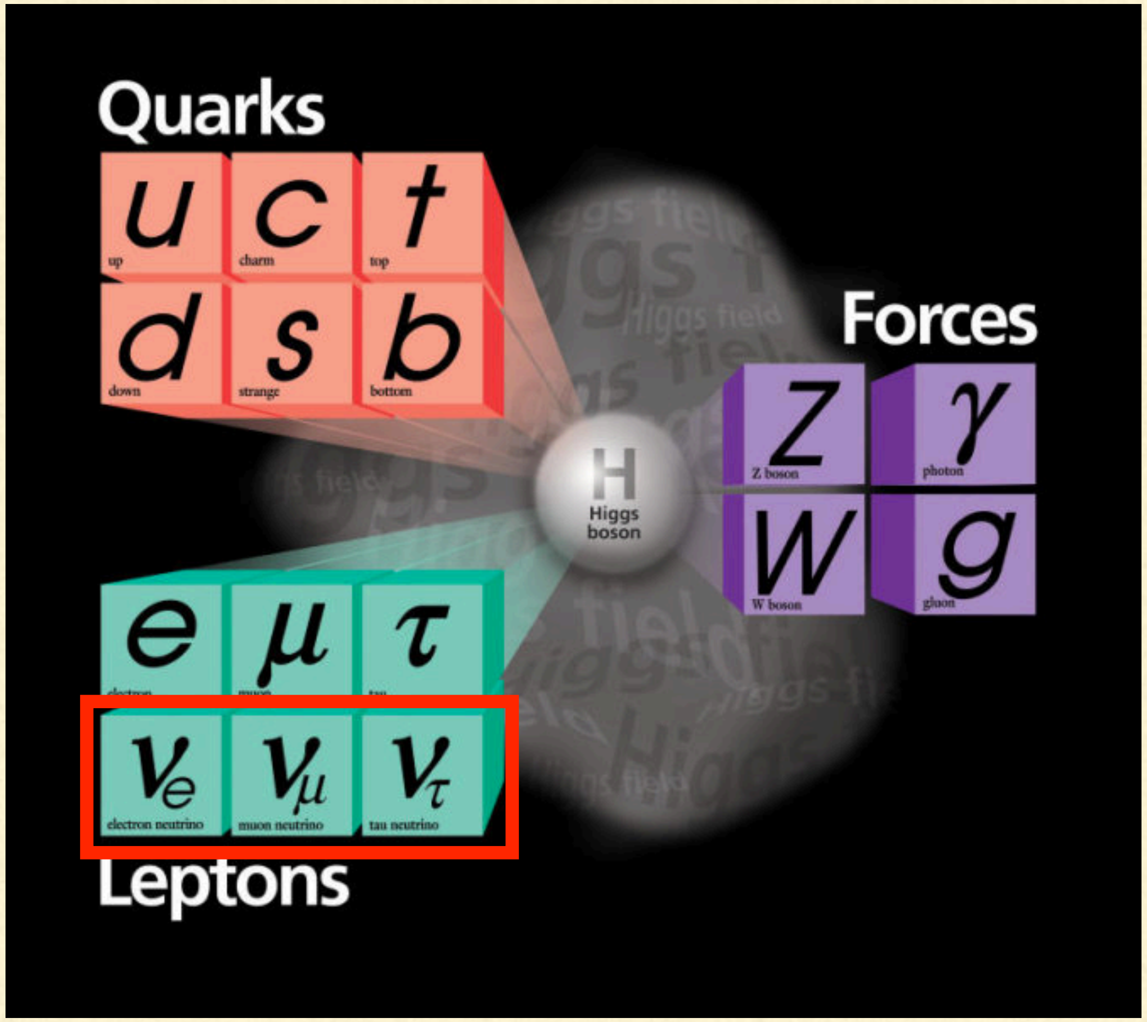

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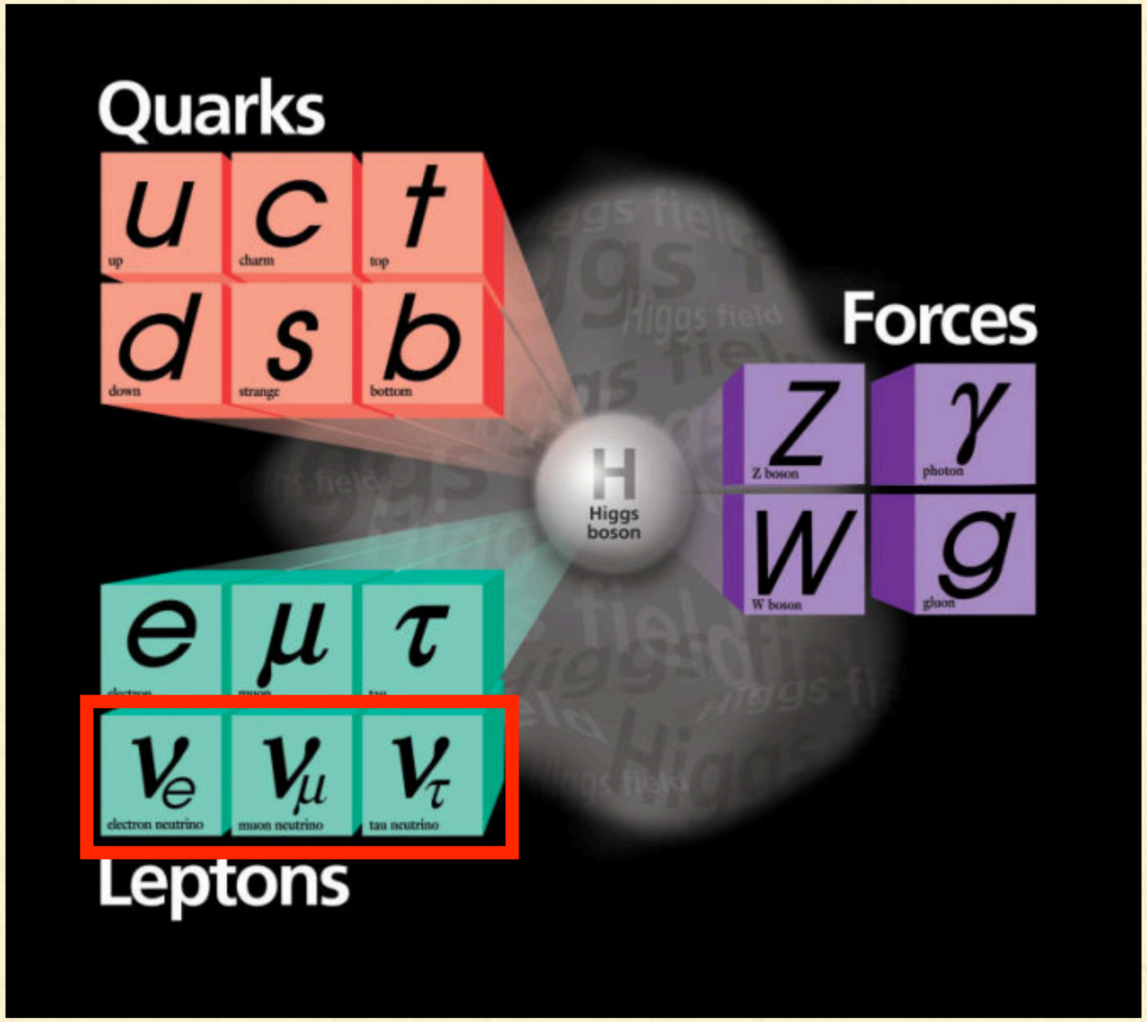

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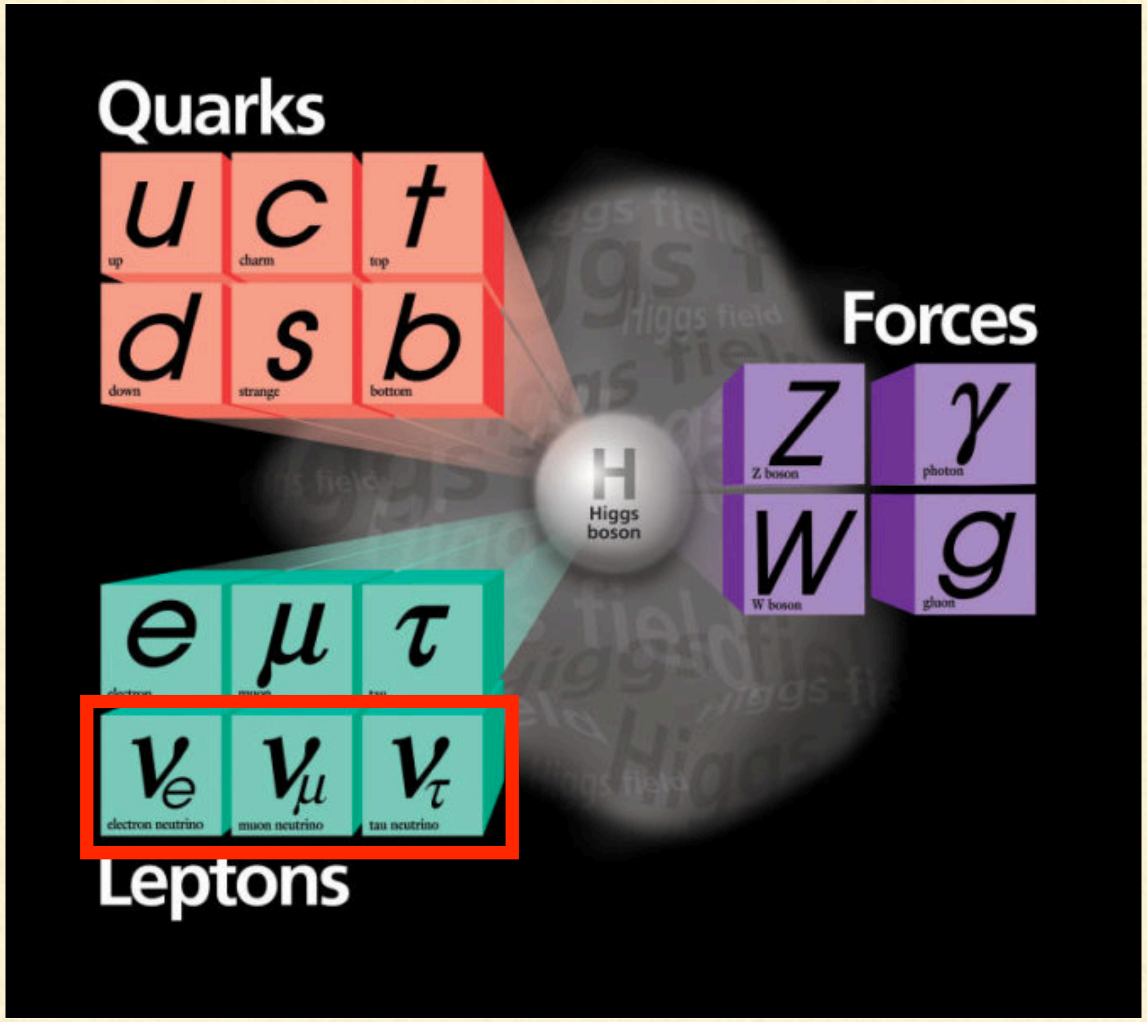

NEUTRINO FUN FACTS

https://www.particlezoo.net/

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- In certain supernova (*core collapse*), neutrinos carry 99% of the energy released by the supernova

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1980

NEUTRINO MIXING

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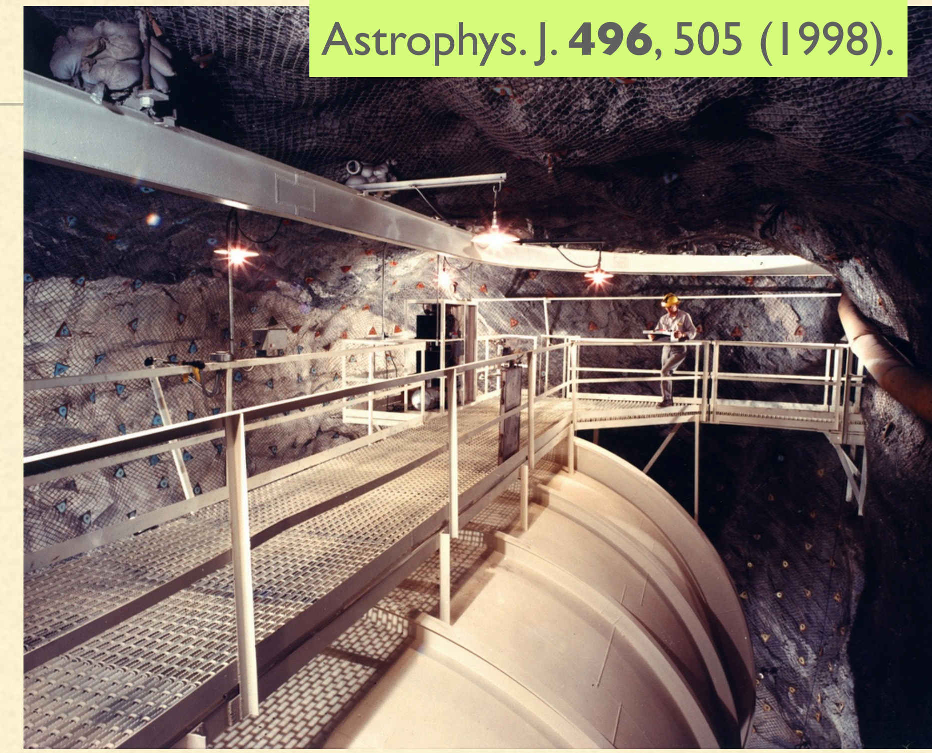
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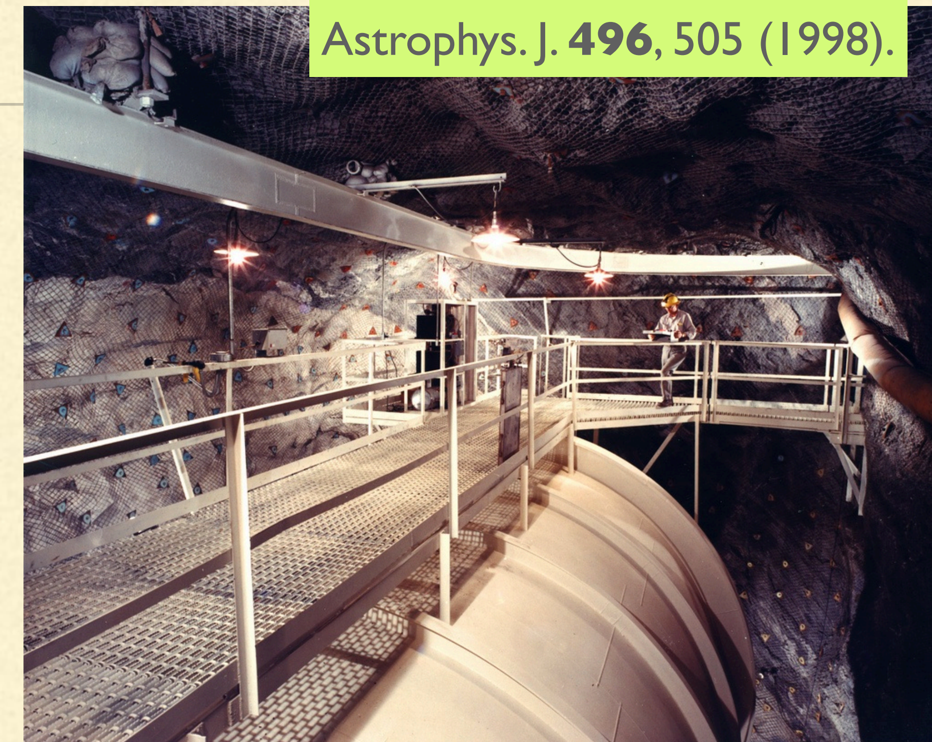

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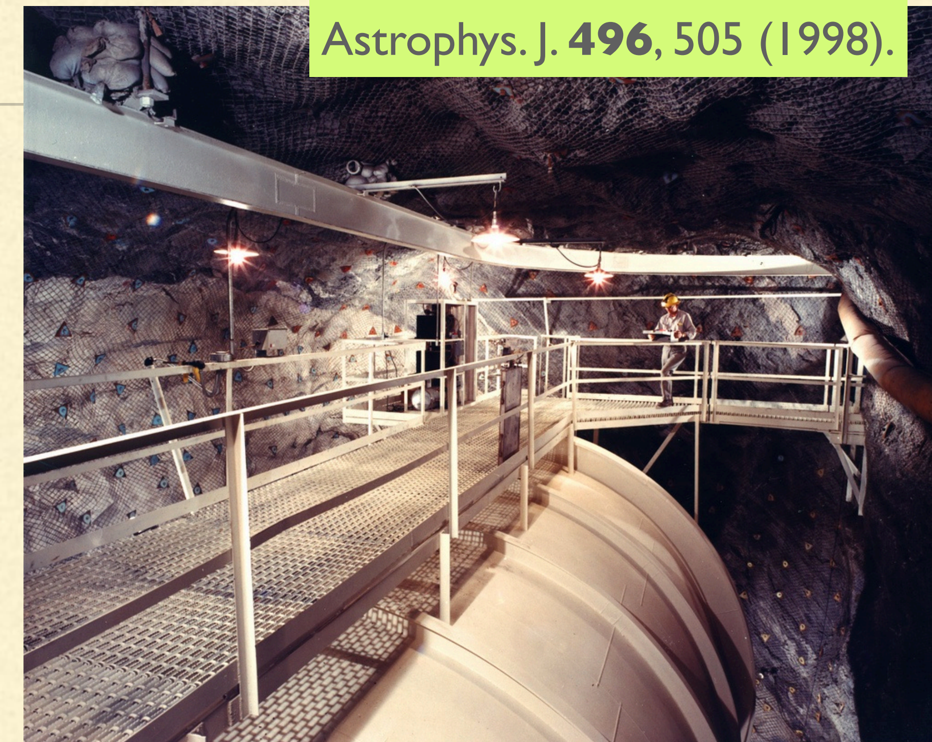
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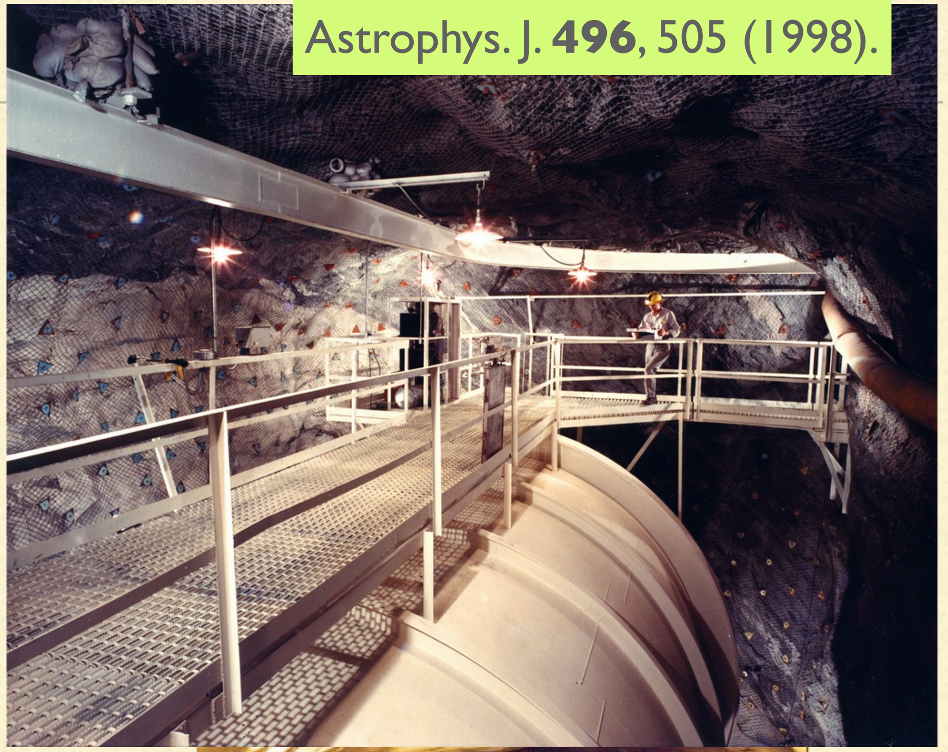
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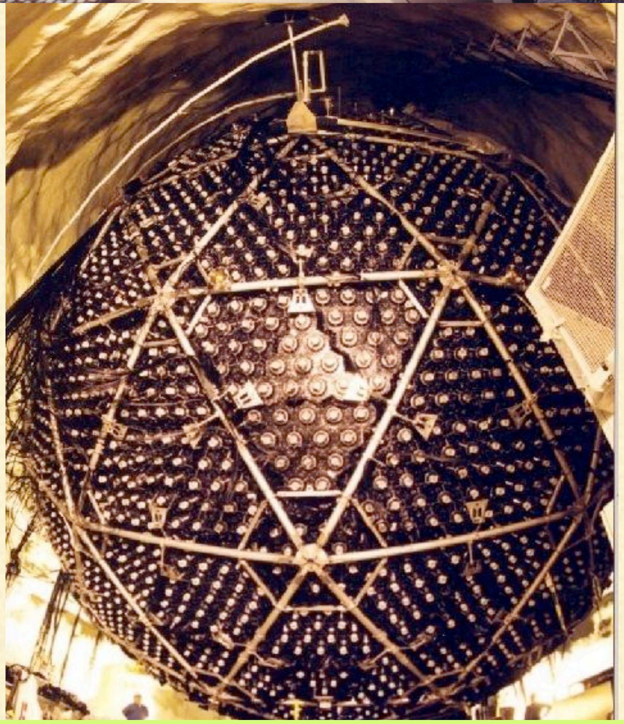
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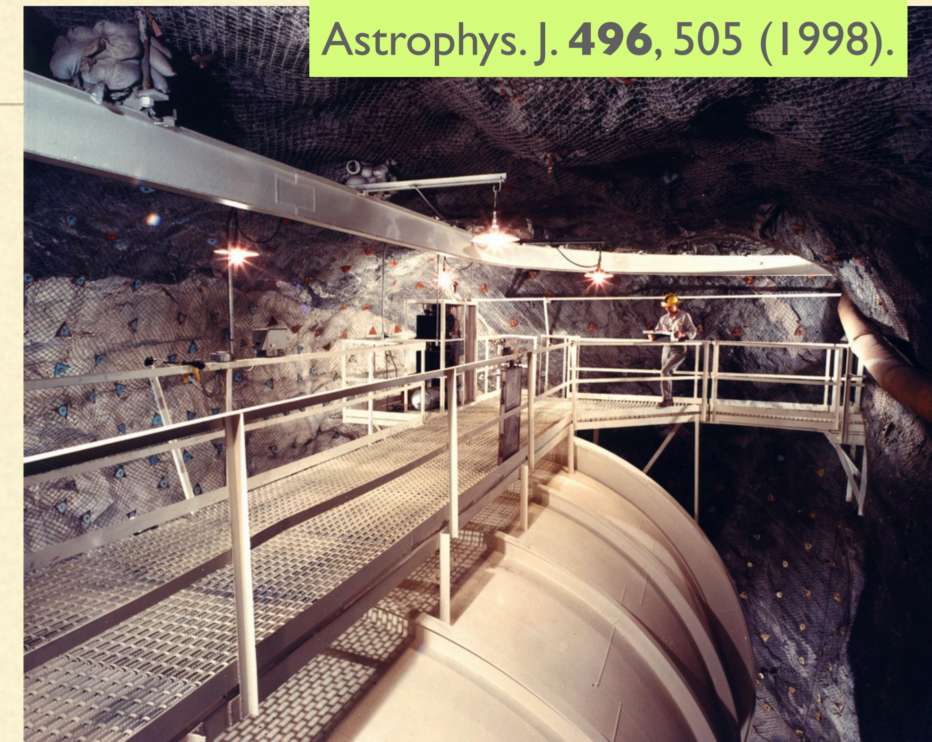

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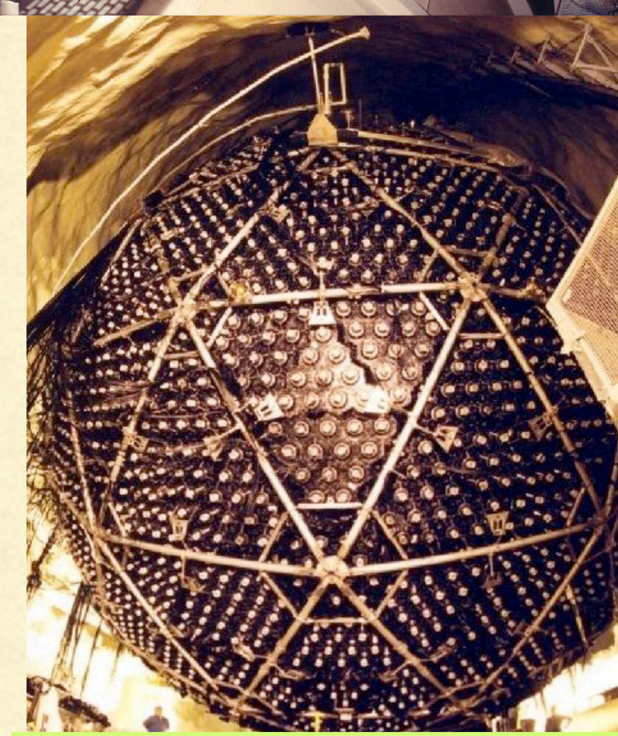

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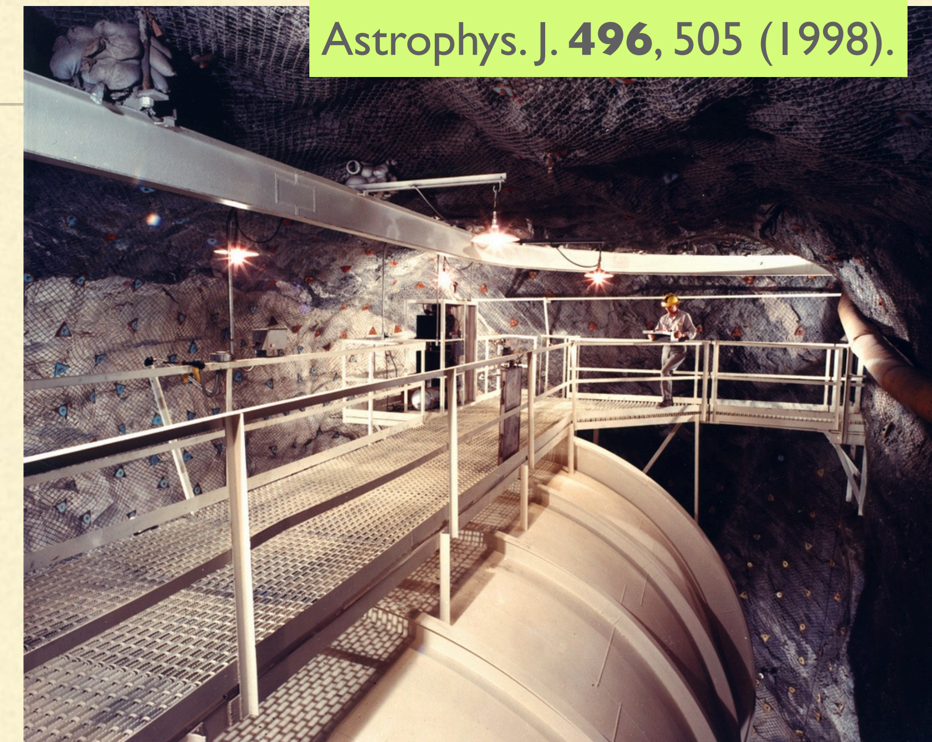
  - Corollary - neutrinos must have mass!



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MORE NEUTRINO MIXING

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

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- The neutrino gauge (interaction) eigenstates are different from the mass (propagation) eigenstates

$$\begin{bmatrix} \nu_{\mathrm{e}} \\ \nu_{\mu} \\ \nu_{\tau} \end{bmatrix} = \begin{bmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} .$$

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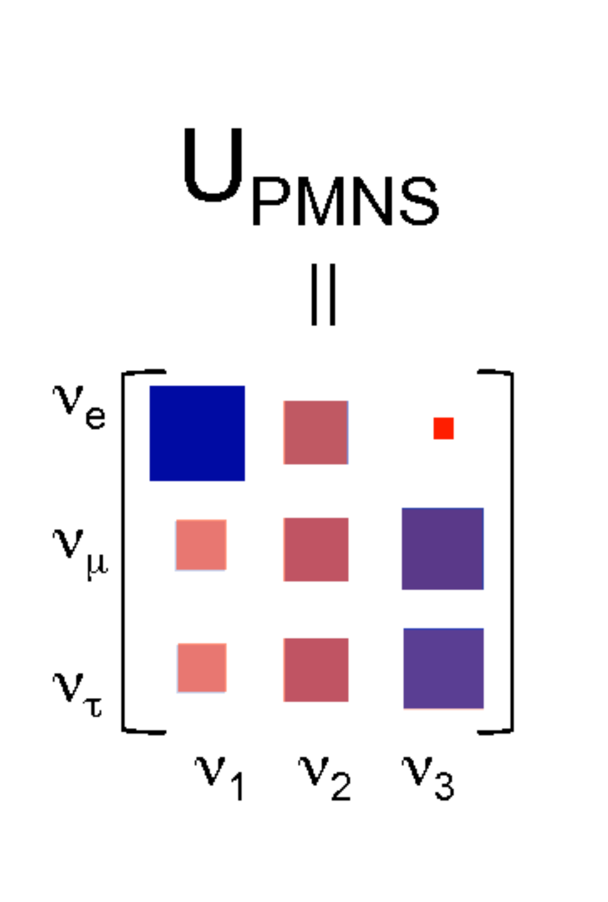

MORE NEUTRINO MIXING

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- Much of the experimental effort in the last 20

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}

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

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- 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

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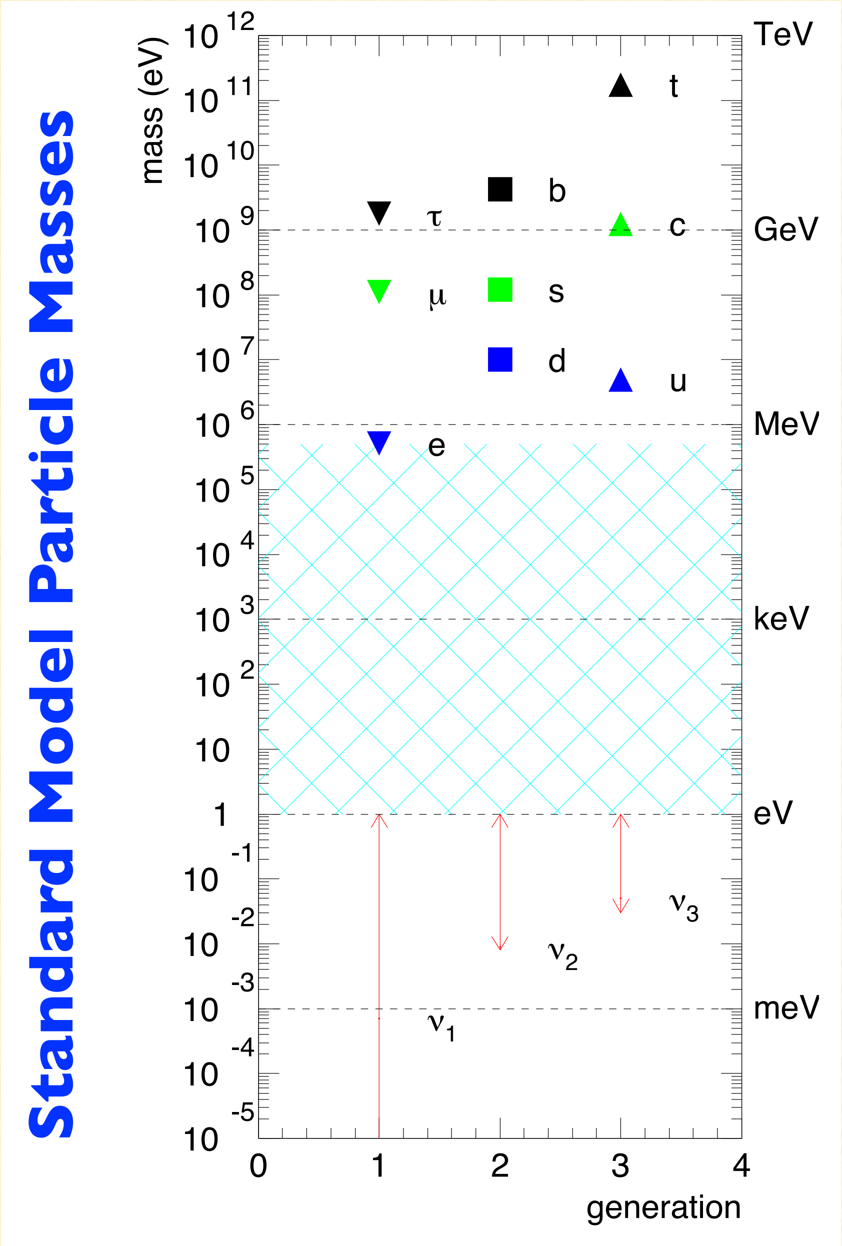

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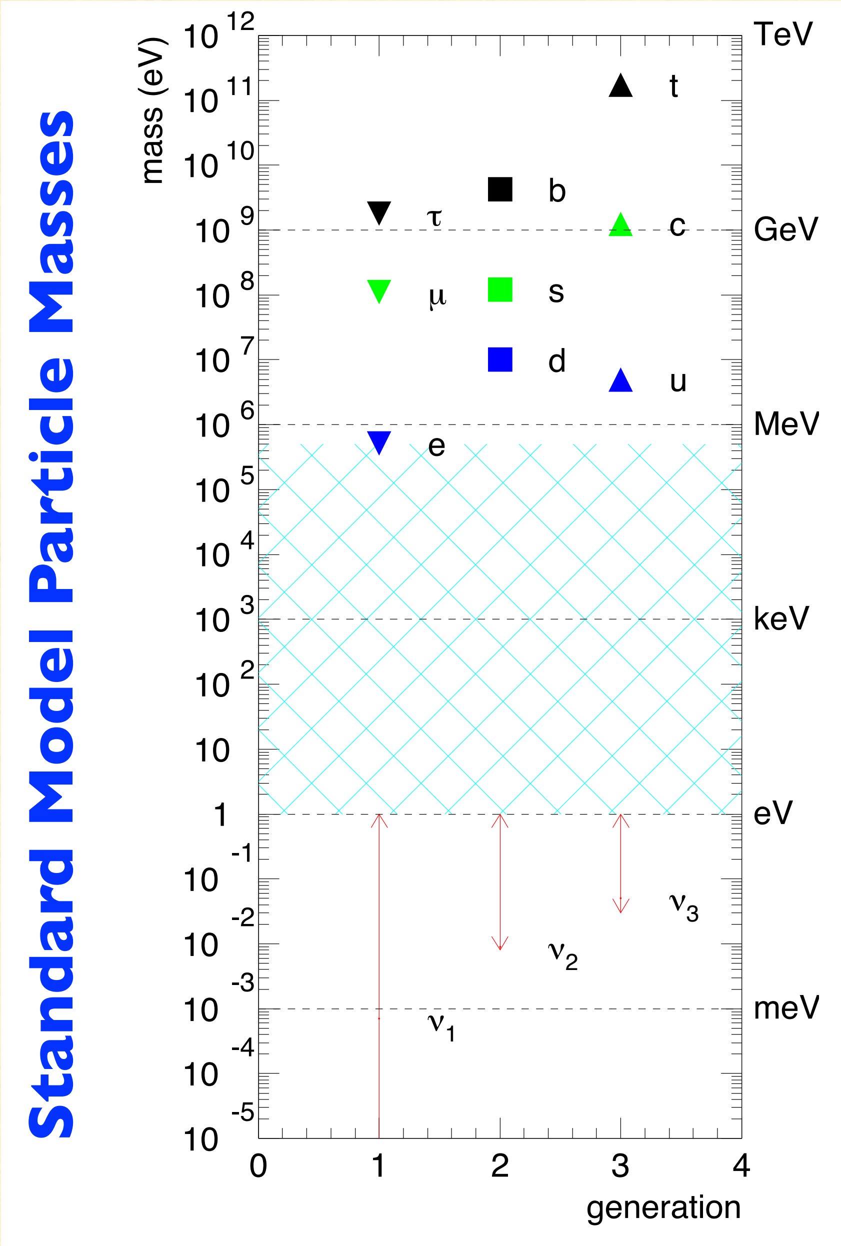

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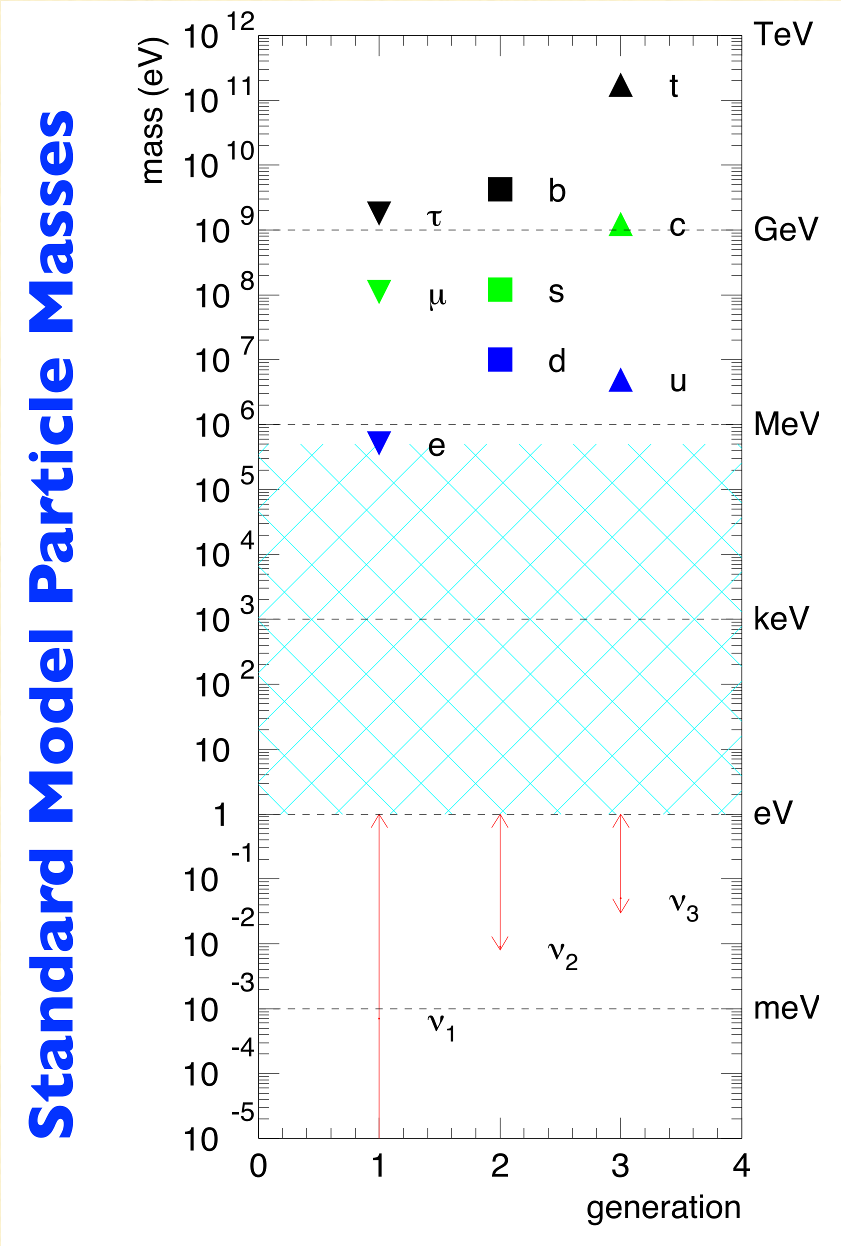

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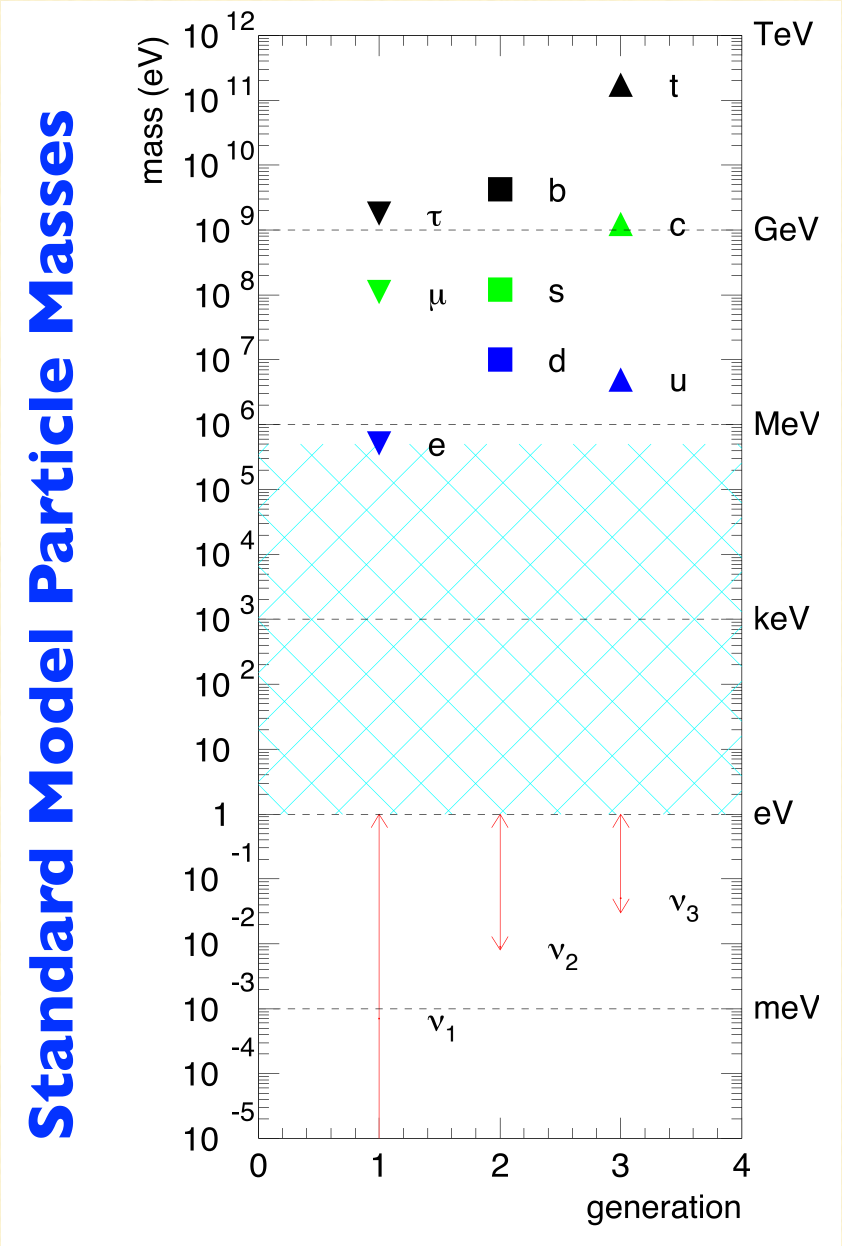

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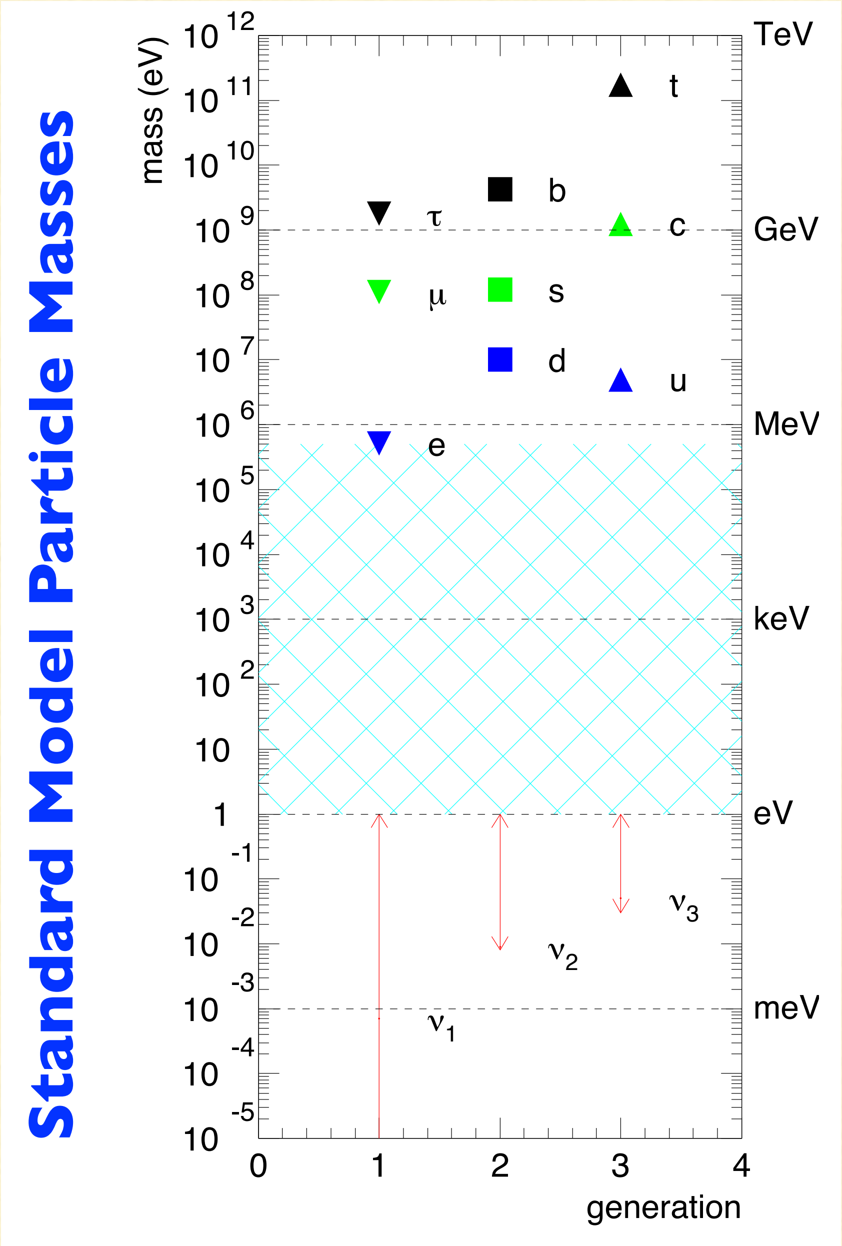

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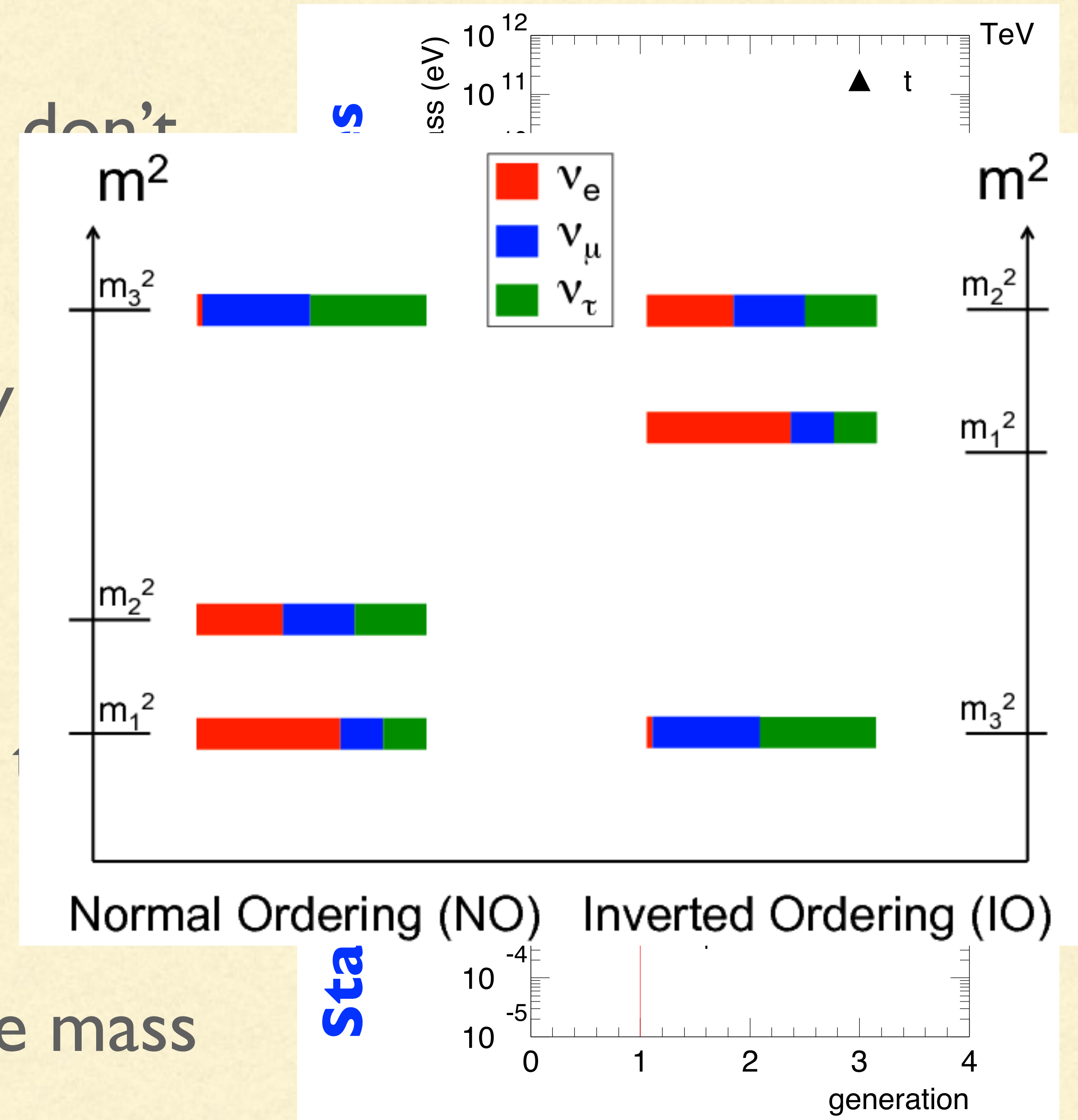

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CURRENT STATUS OF NEUTRINO MIXING PARAMETERS

NuFit v5.3, from March 2024, http://www.nu-fit.org/?q=node/278

CUR... ...RINO MIXI...

NuFit v5.3 ... node/278

NuFIT 5.3 (2024)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.1$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.411 \to 0.606$	$0.568^{+0.016}_{-0.021}$	$0.412 \to 0.611$
	$\theta_{23}/^\circ$	$42.3^{+1.1}_{-0.9}$	$39.9 \to 51.1$	$48.9^{+0.9}_{-1.2}$	$39.9 \to 51.4$
	$\sin^2\theta_{13}$	$0.02224^{+0.00056}_{-0.00057}$	$0.02047 \to 0.02397$	$0.02222^{+0.00069}_{-0.00057}$	$0.02049 \to 0.02420$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.13}_{-0.11}$	$8.23 \to 8.95$
	$\delta_{CP}/^\circ$	232^{+39}_{-25}	$139 \to 350$	273^{+24}_{-26}	$195 \to 342$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.505^{+0.024}_{-0.026}$	$+2.426 \to +2.586$	$-2.487^{+0.027}_{-0.024}$	$-2.566 \to -2.407$

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NuFit v5.3, from March 2024, http://www.nu-fit.org/?q=node/278

CURREN UTRINO MIXING

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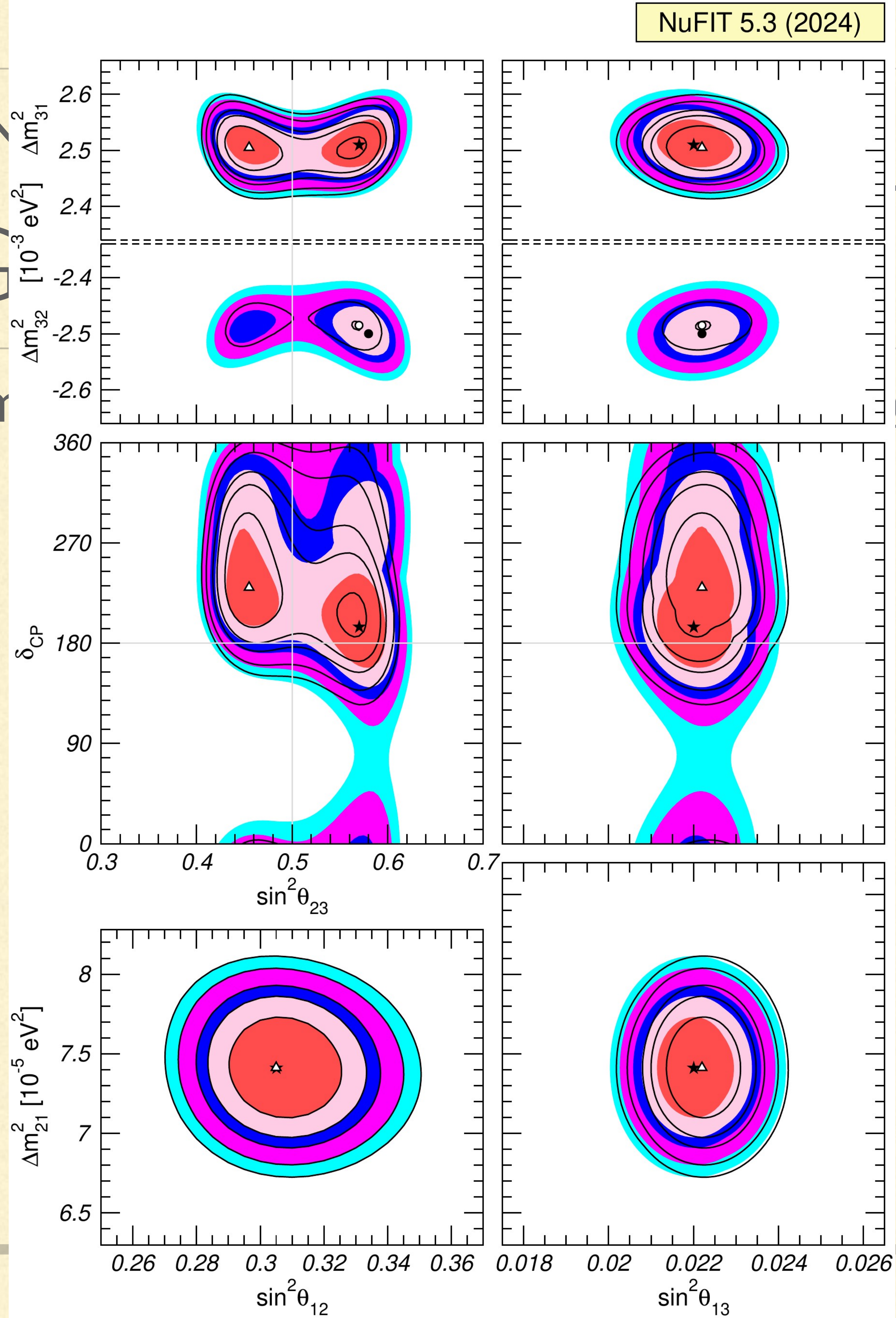

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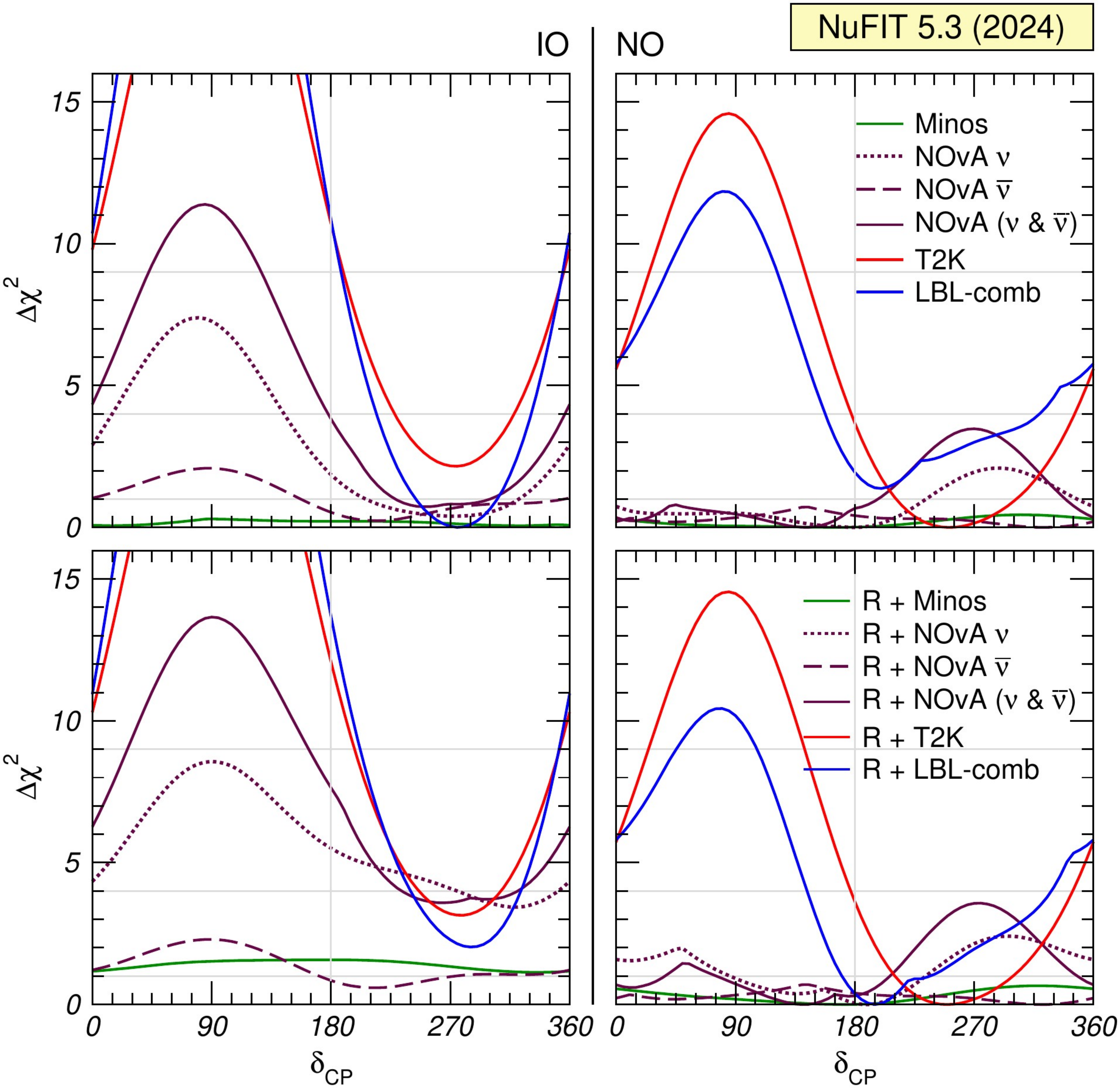

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DUNE PHYSICS GOALS

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Primary goals
  - Improved measurement of neutrino mixing angles (mostly θ_{23}, but also 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

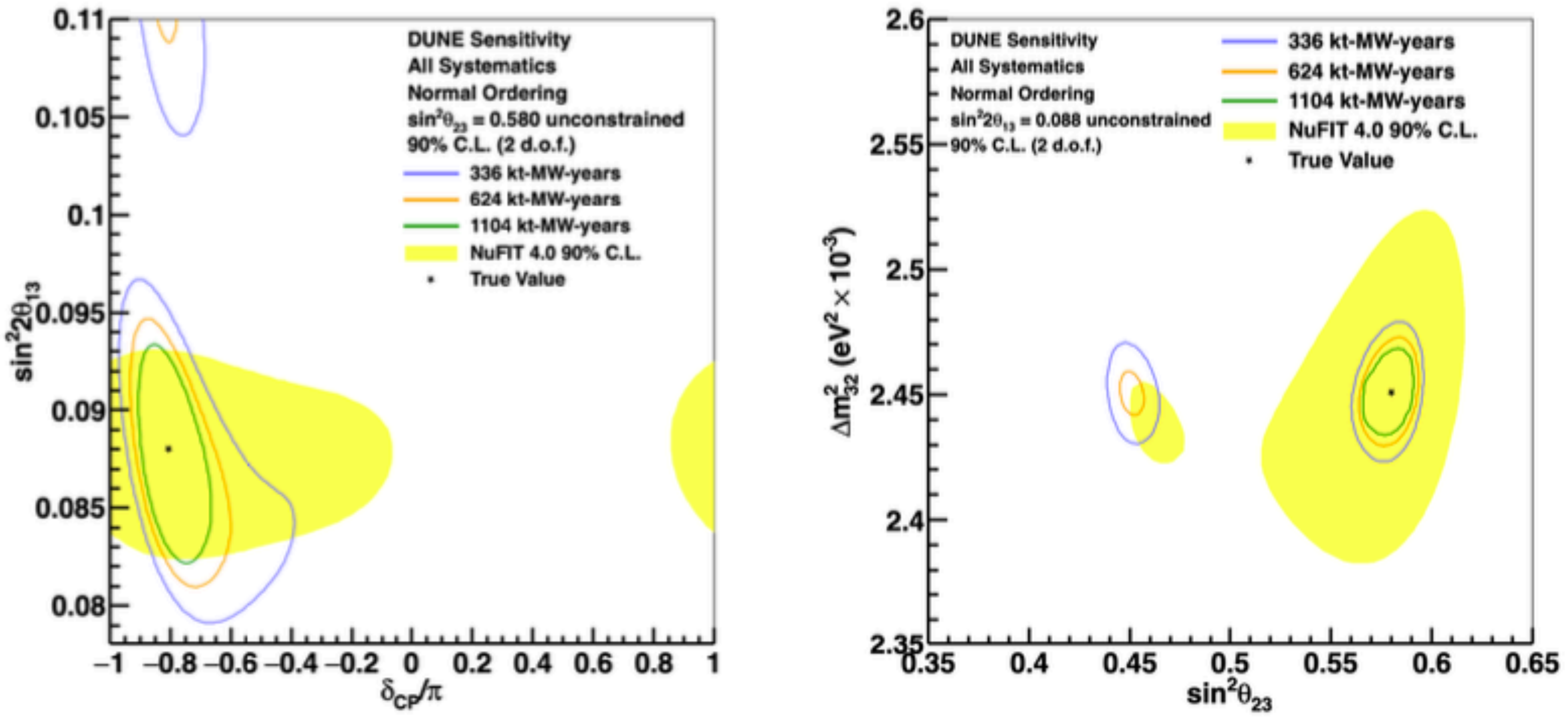


FIG. 2. Two-dimensional 90% C.L. regions in the $\sin^2 2\theta_{13}$–$\delta_{\rm CP}$ (left) and $\sin^2\theta_{23}$–Δm^2_{32} (right) plane, for three different levels of exposure, with equal running in neutrino and antineutrino mode, with the Phase II near detector. The 90% C.L. region for the NuFIT 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)

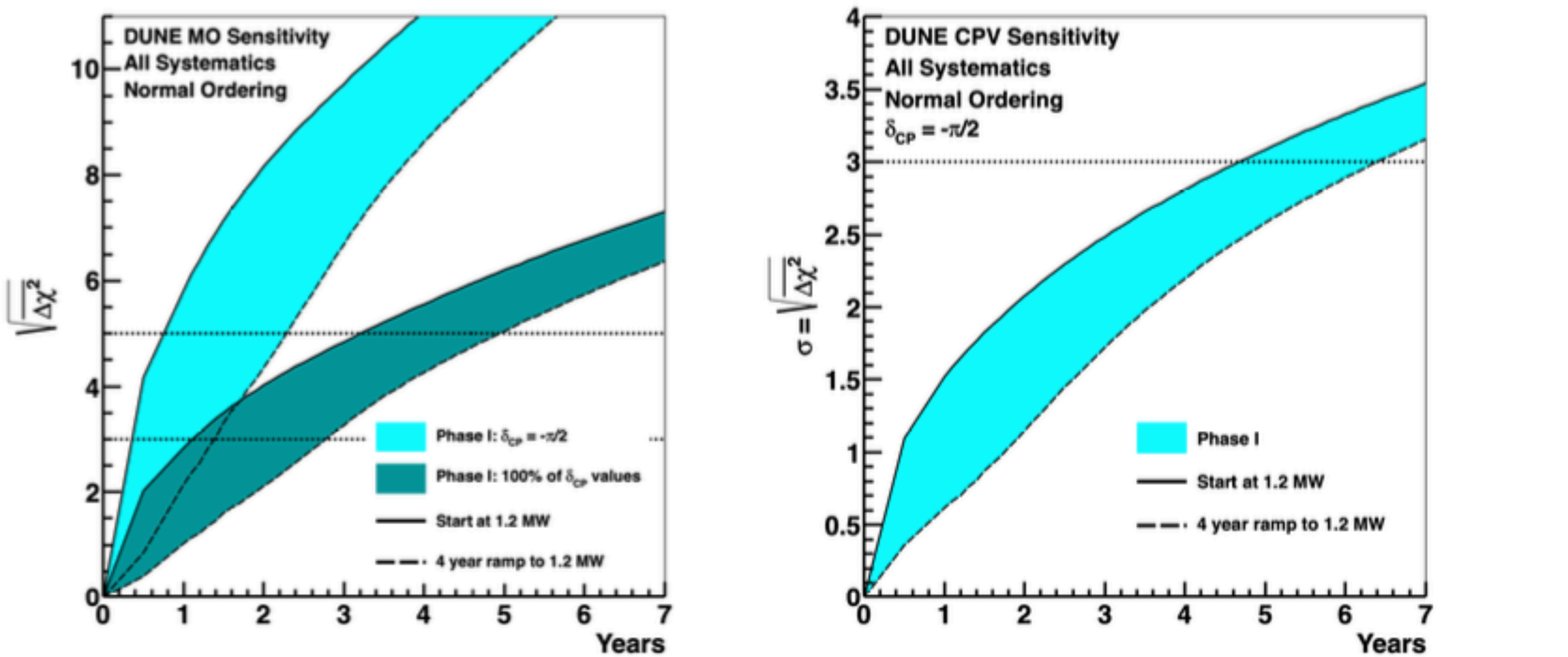


FIG. 5. Sensitivity to the neutrino mass ordering (left) and CP violation for $\delta_{\mathrm{CP}} = -\pi/2$ (right) in Phase I. The cyan bands show the sensitivity if $\delta_{\mathrm{CP}} = -\pi/2$ and the green band in the left plot shows the sensitivity for 100% of δ_{CP} values. The width of the 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

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.

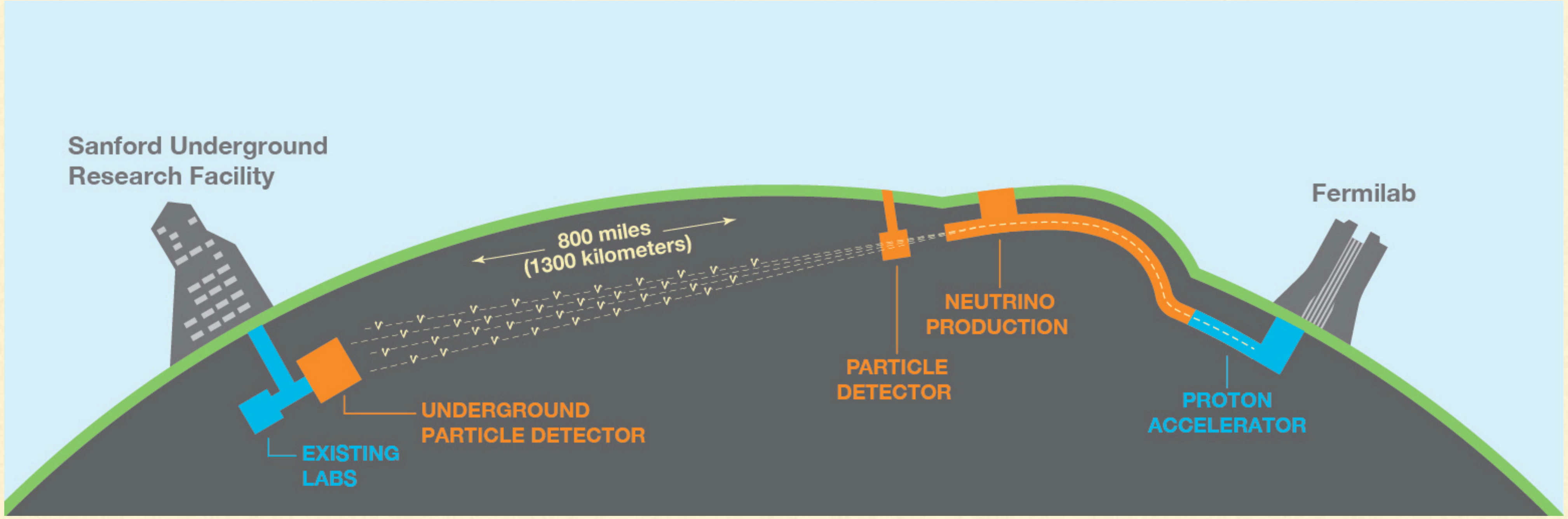
DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

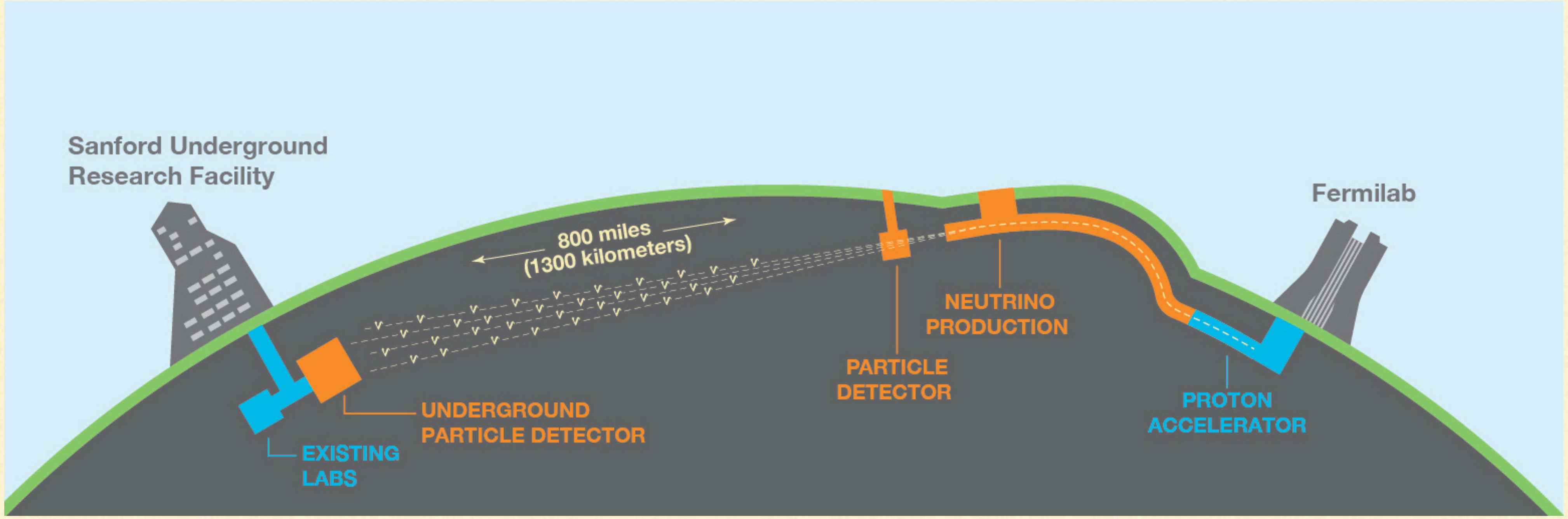
- Send a beam of muons 800 miles from Fermilab to Lead, South Dakota



DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

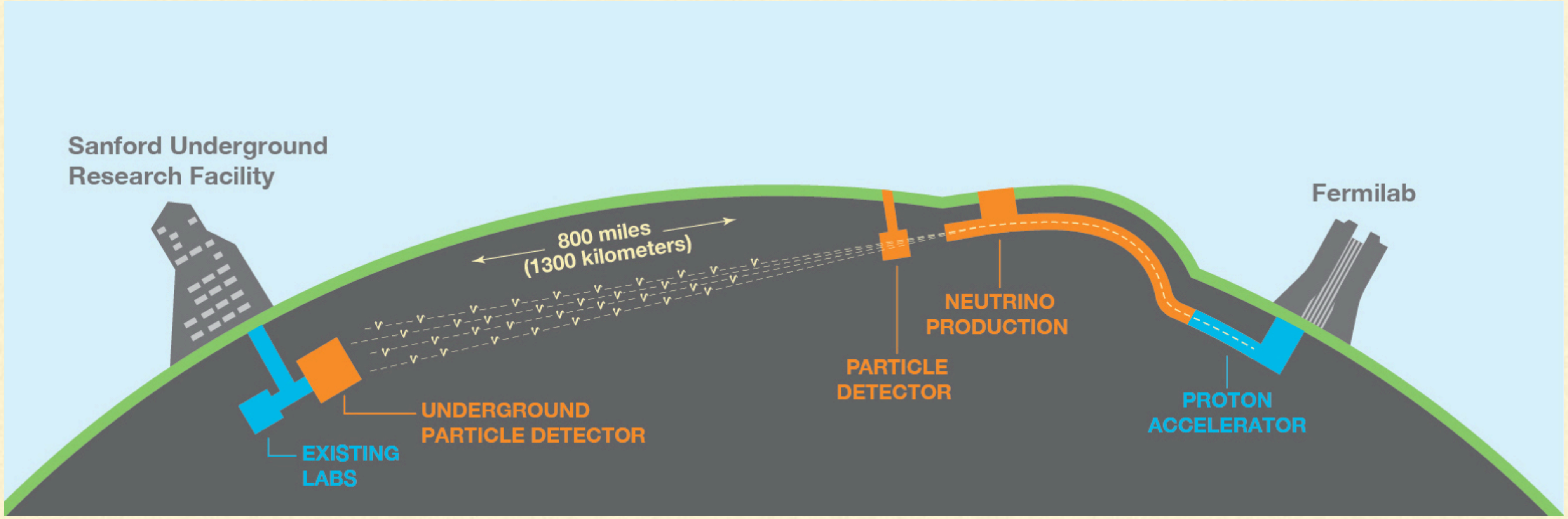
- Send a beam of muons 800 miles from Fermilab to Lead, South Dakota
- Beam will be about 1km wide by the time it reaches SD



DUNE

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

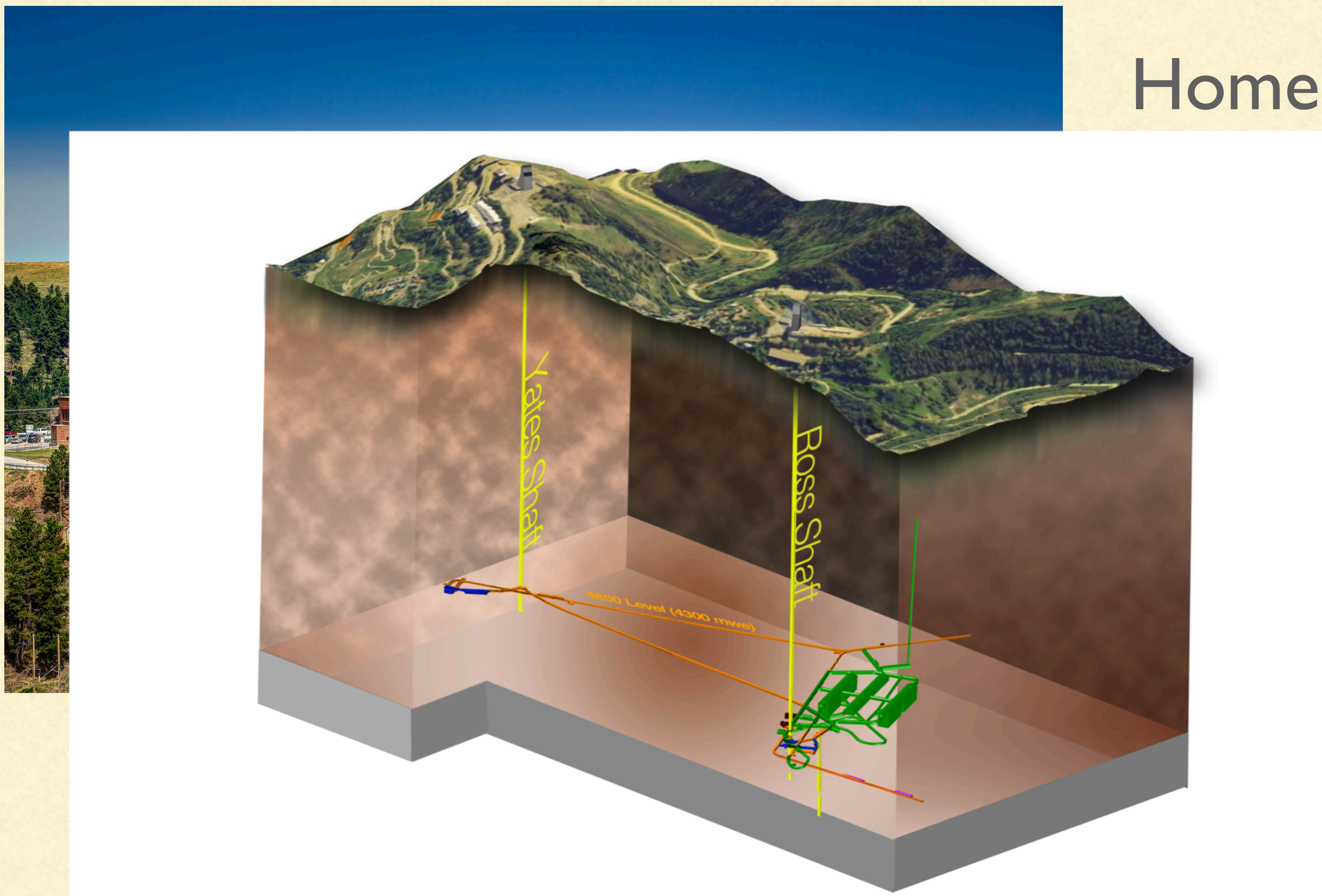
SANFORD UNDERGROUND RESEARCH FACILITY

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Homestake Mine, former gold mine and deepest in North America

SANFORD UNDERGROUND RESEARCH FACILITY

DEEP UNDERGROUND NEUTRINO EXPERIMENT

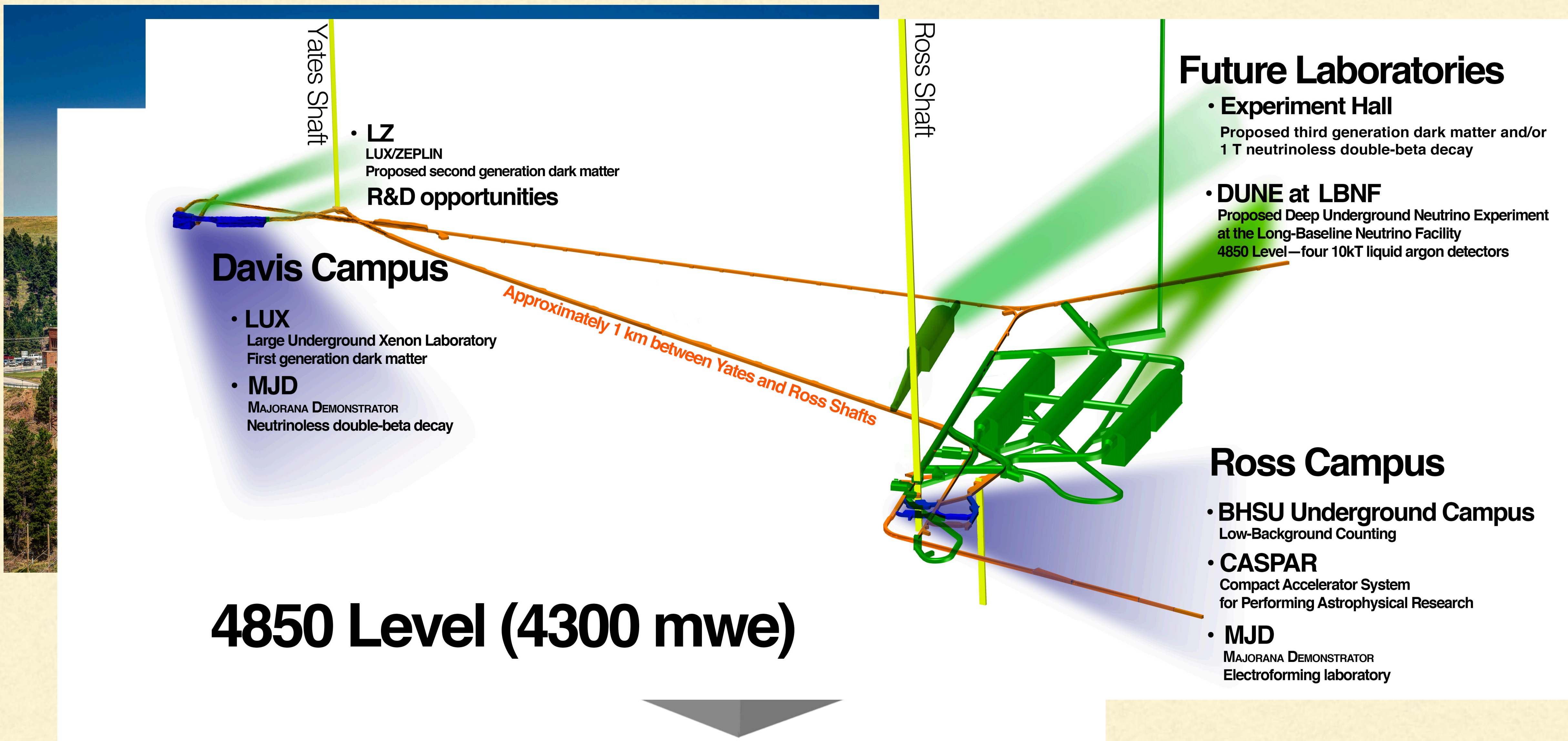


Homestake Mine, former
ine and deepest in
orth America

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

SANFORD UNDERGROUND RESEARCH FACILITY

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT



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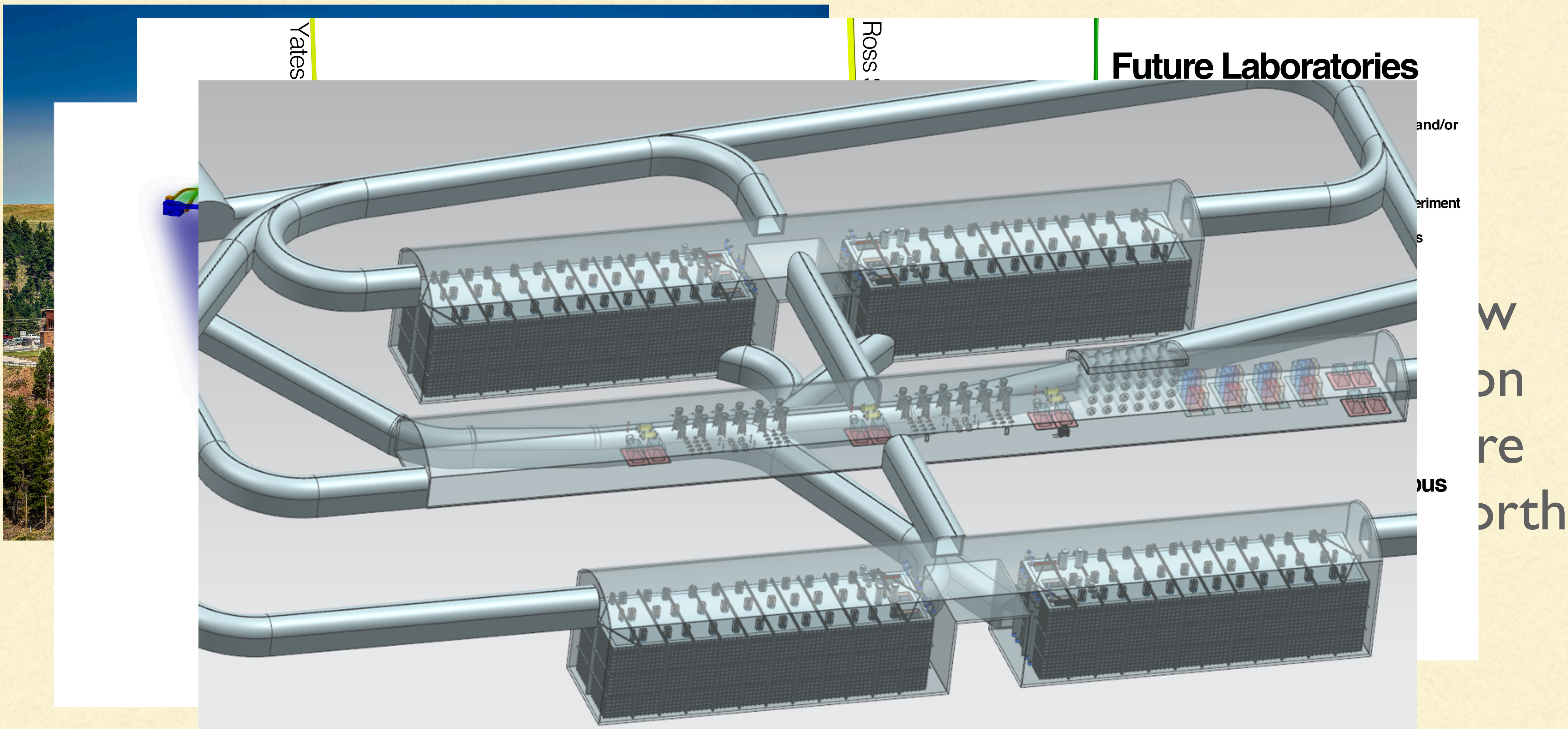
SANFORD UNDERGROUND RESEARCH FACILITY

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)

- Far site excavation completed in February 2024!
    - 800,000 tons of rock removed
    - Cavern finishing ongoing, cryostat installation in 2025

UNDERGROUND IN SD (TODAY)

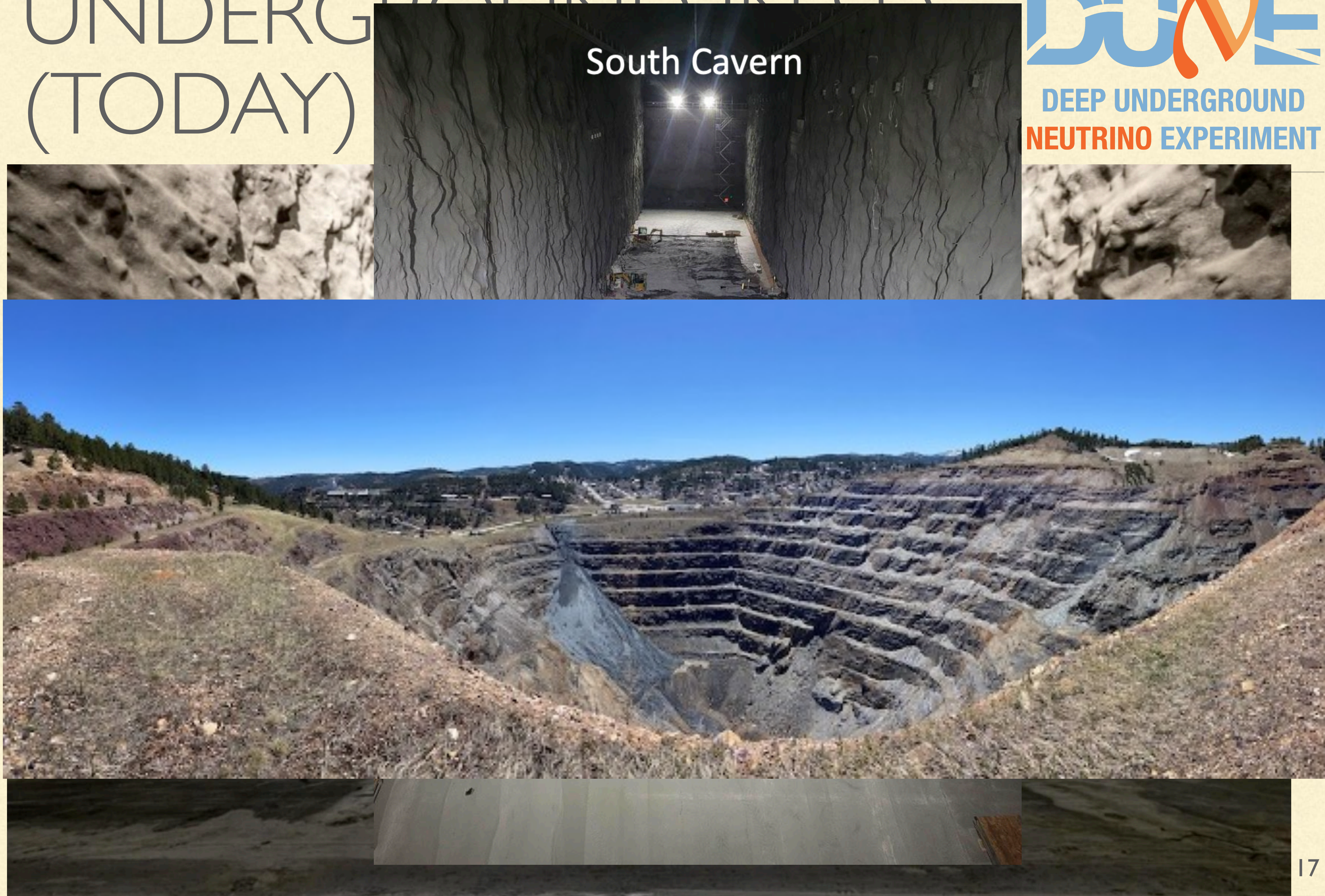
DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNDERGROUND IN SD (TODAY)

DEEP UNDERGROUND NEUTRINO EXPERIMENT

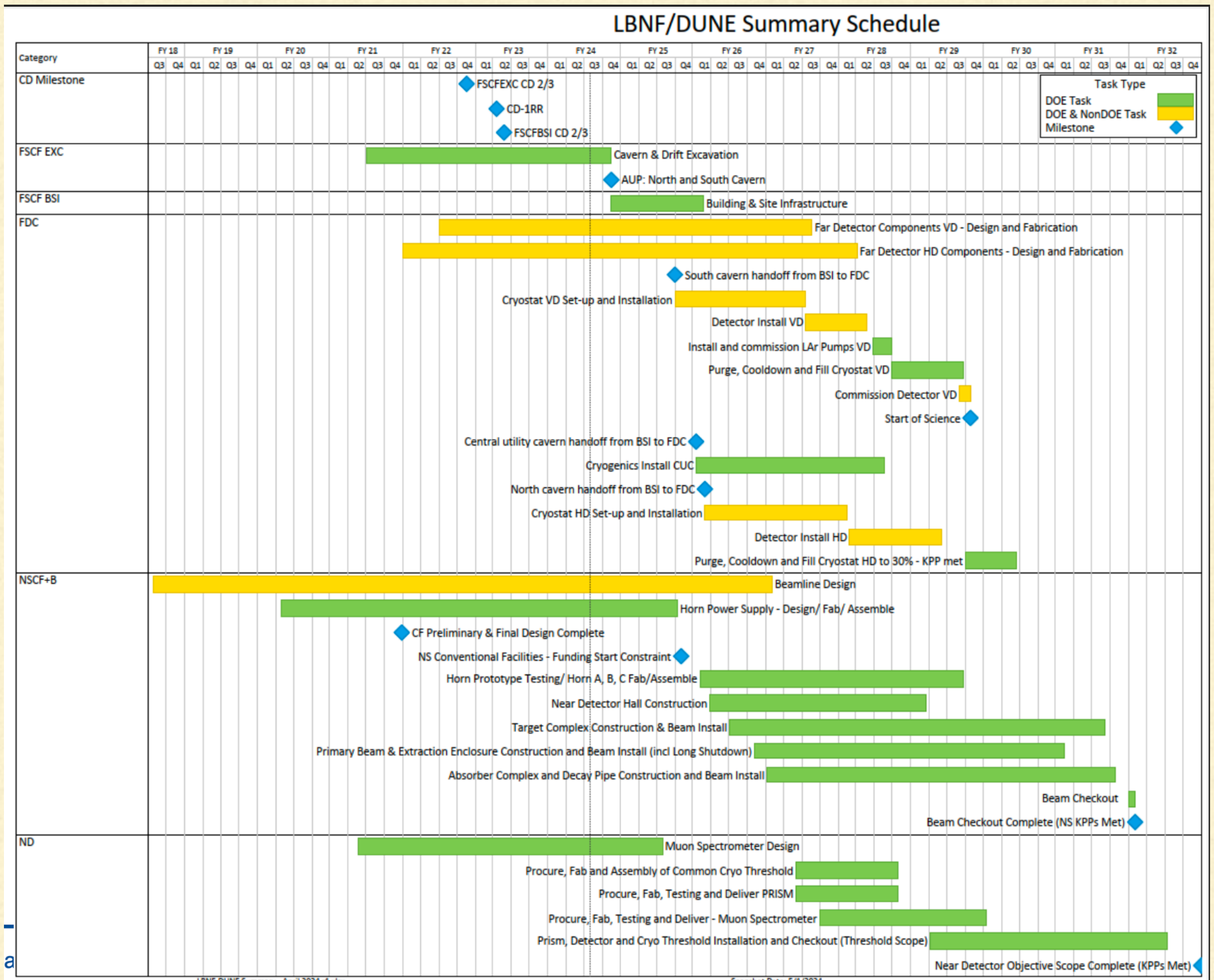
UNDERGROUND IN SD (TODAY)

DEEP UNDERGROUND NEUTRINO EXPERIMENT



SCHEDULE AND TIMELINE

DEEP UNDERGROUND NEUTRINO EXPERIMENT



Excavation in SD over half complete

Civil construction at Fermilab has begun

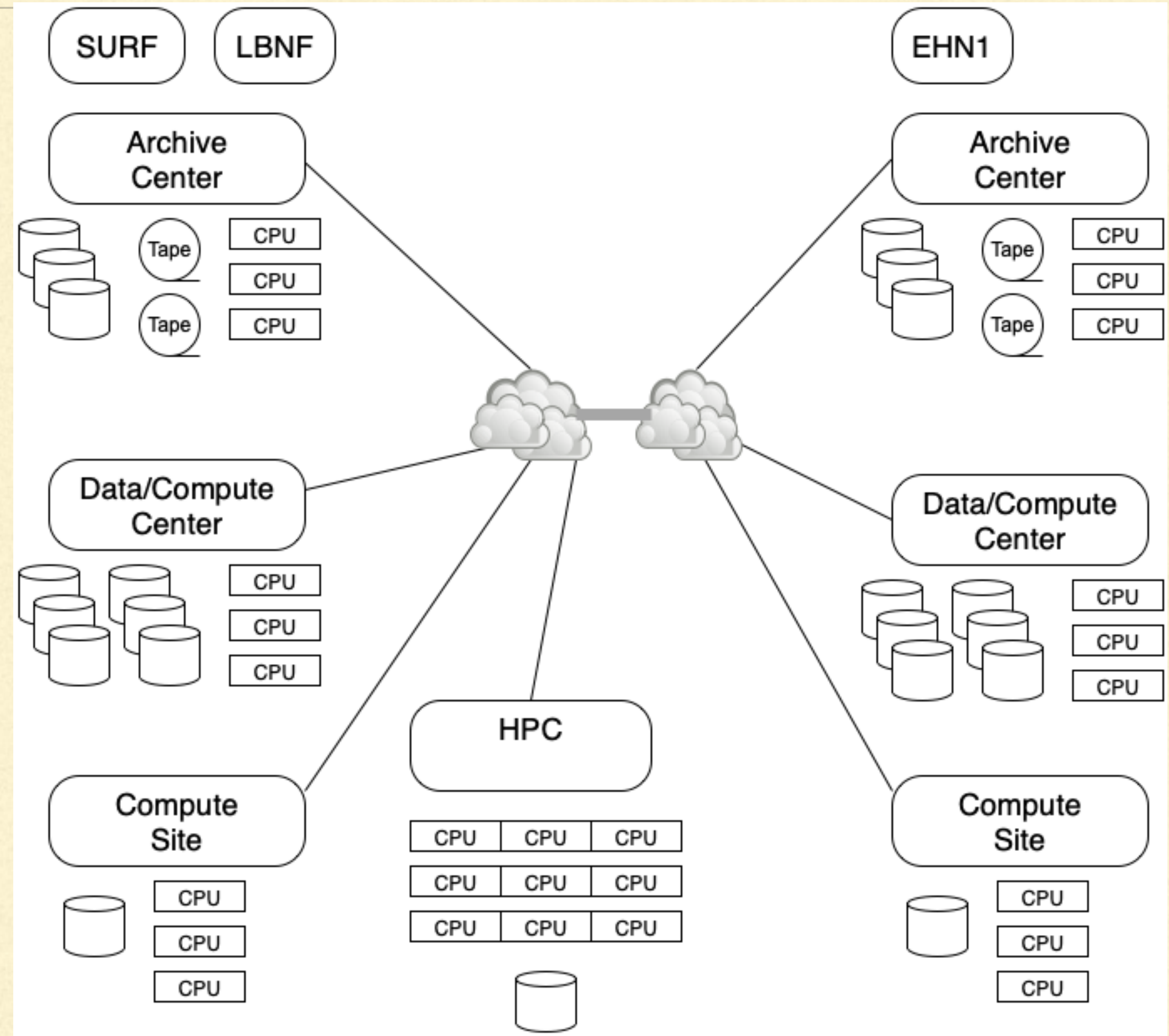
Cryostat installation begins 2025

First detector module complete 2029

First beam arrives in 2031

DUNE COMPUTING MODEL

- Plan for DUNE computing is similar to LHC model, but less strict with the "tiers"
- Details are in the computing CDR (arXiv: 2210.15665)
- Testing the model (and data flow between sites) with protoDUNE and data challenges



DUNE DATA RATES

Process	Rate/module	size/instance	size/module/year
Beam event	41/day	3.8 GB	30 TB/year
Cosmic rays	4,500/day	3.8 GB	6.2 PB/year
Supernova trigger	1/month	140 TB	1.7 PB/year
Solar neutrinos	10,000/year	≤3.8 GB	35 TB/year
Calibrations	2/year	750 TB	1.5 PB/year
Total			9.4 PB/year

Recently published DUNE Computing CDR - https://arxiv.org/abs/2210.15665

- Data rates for beam neutrinos are actually quite modest
- THE challenge is supernova neutrinos. Radioactive backgrounds make this a big challenge.

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

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

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

24

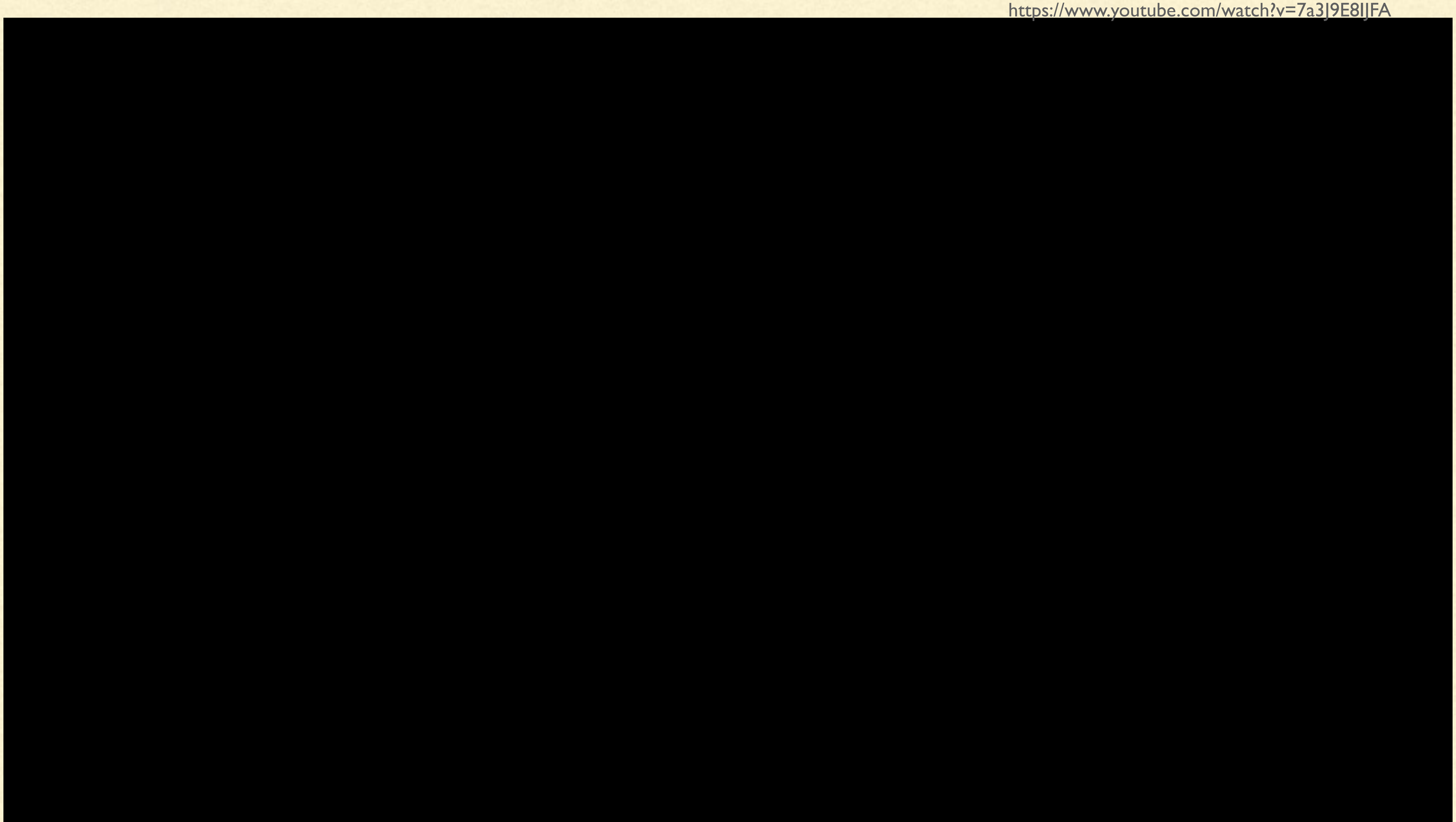
DUNE VIDEO

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

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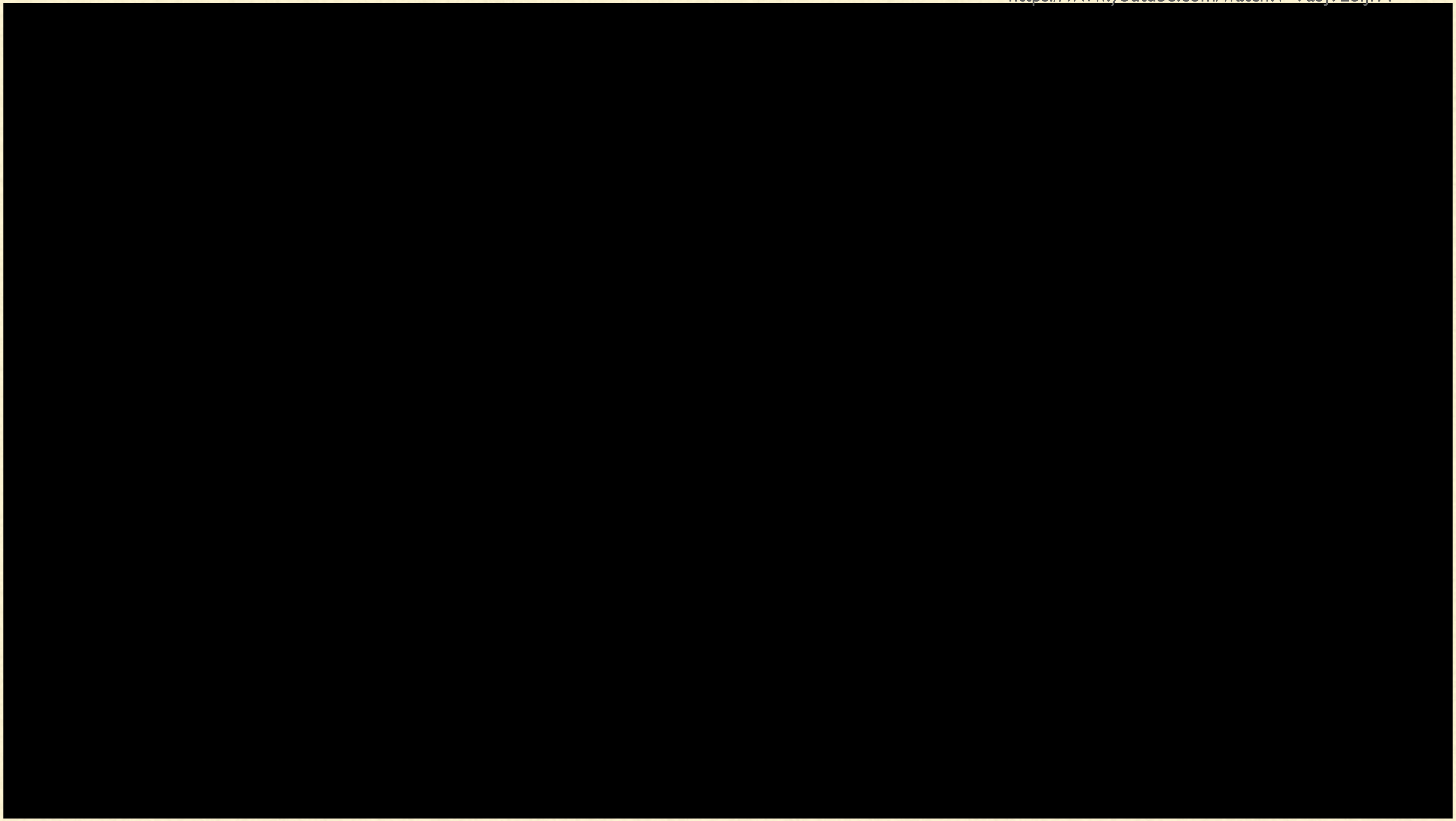

DUNE PHYSICS GOALS

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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

DUNE PHYSICS GOALS

DUNE
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

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WHY LIQUID ARGON?

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

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UNDERGROUND IN SOUTH DAKOTA

DEEP UNDERGROUND NEUTRINO EXPERIMENT

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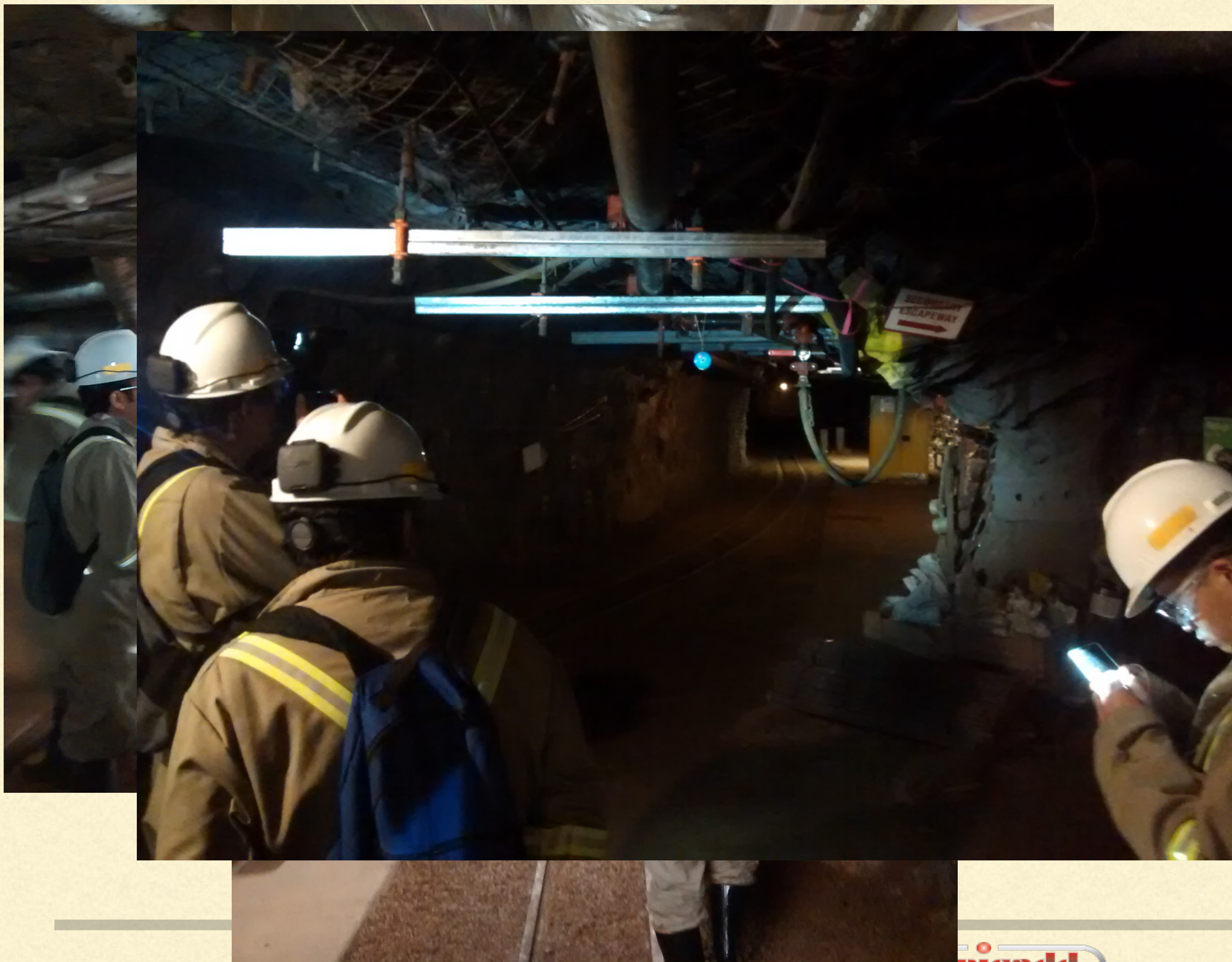

UNDERGROUND IN SOUTH DAKOTA

DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNDERGROUND IN SOUTH DAKOTA

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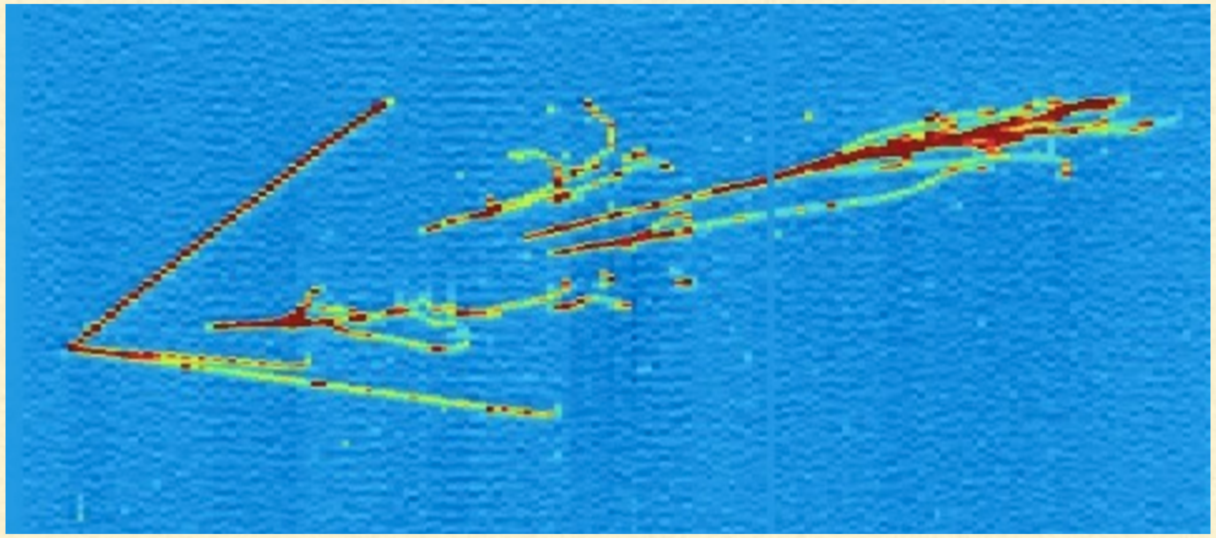
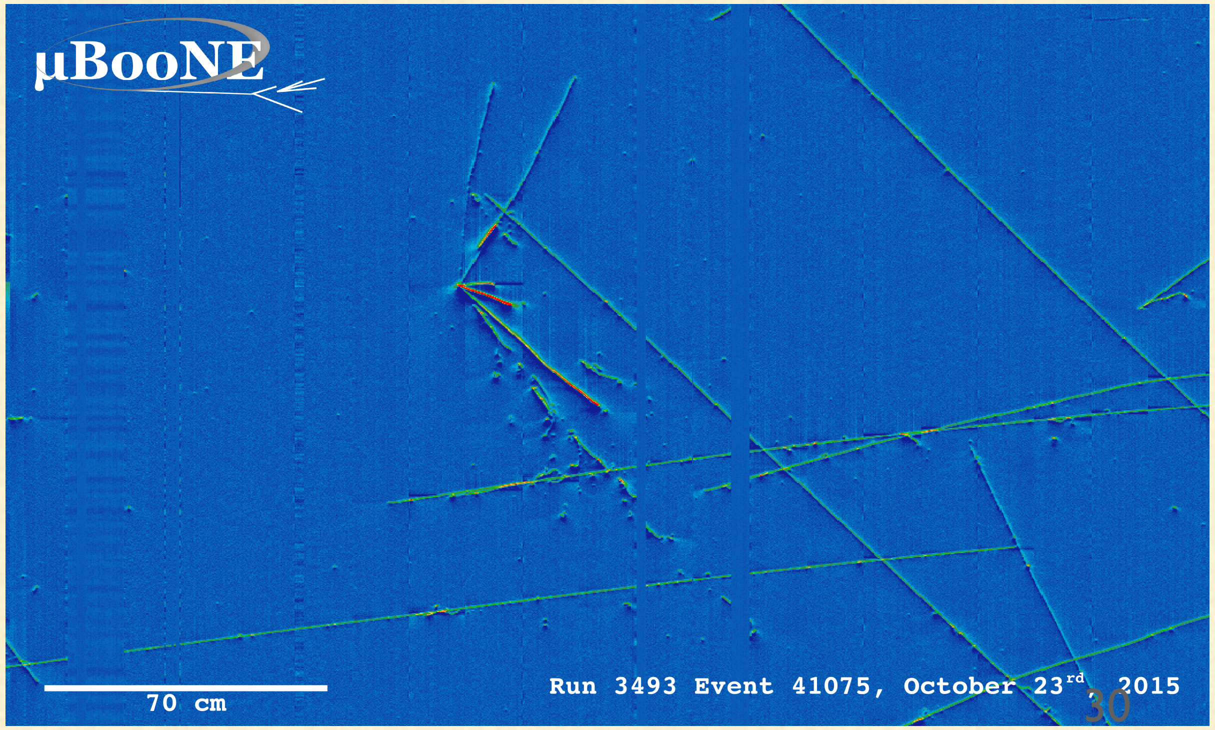
LIQUID ARGON TIME PROJECTION CHAMBER

LIQUID ARGON TIME PROJECTION CHAMBER

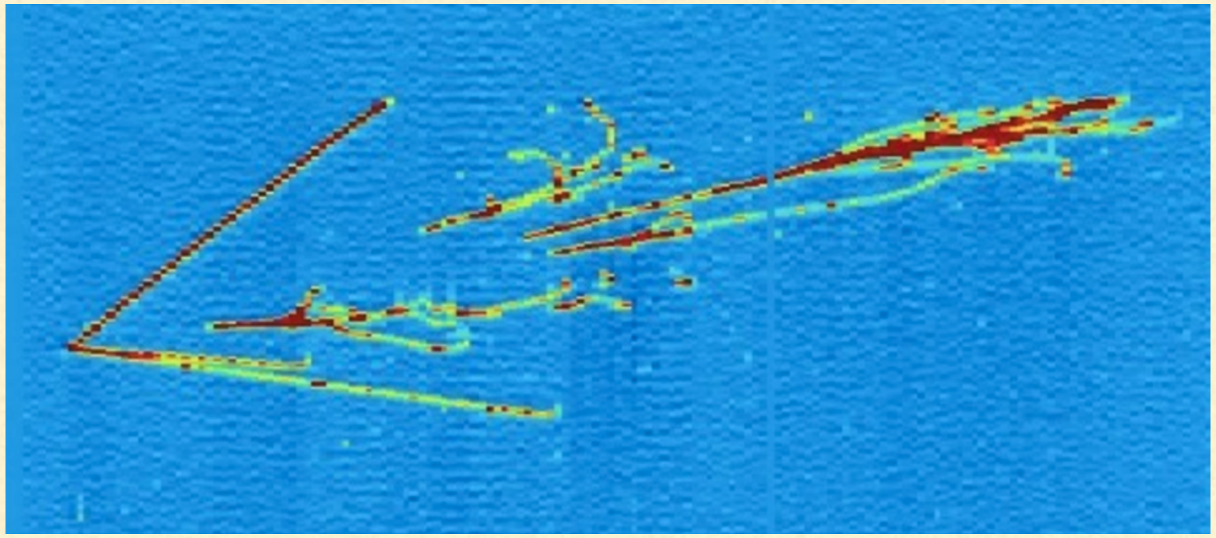
- High precision, three dimensional tracking and particle identification

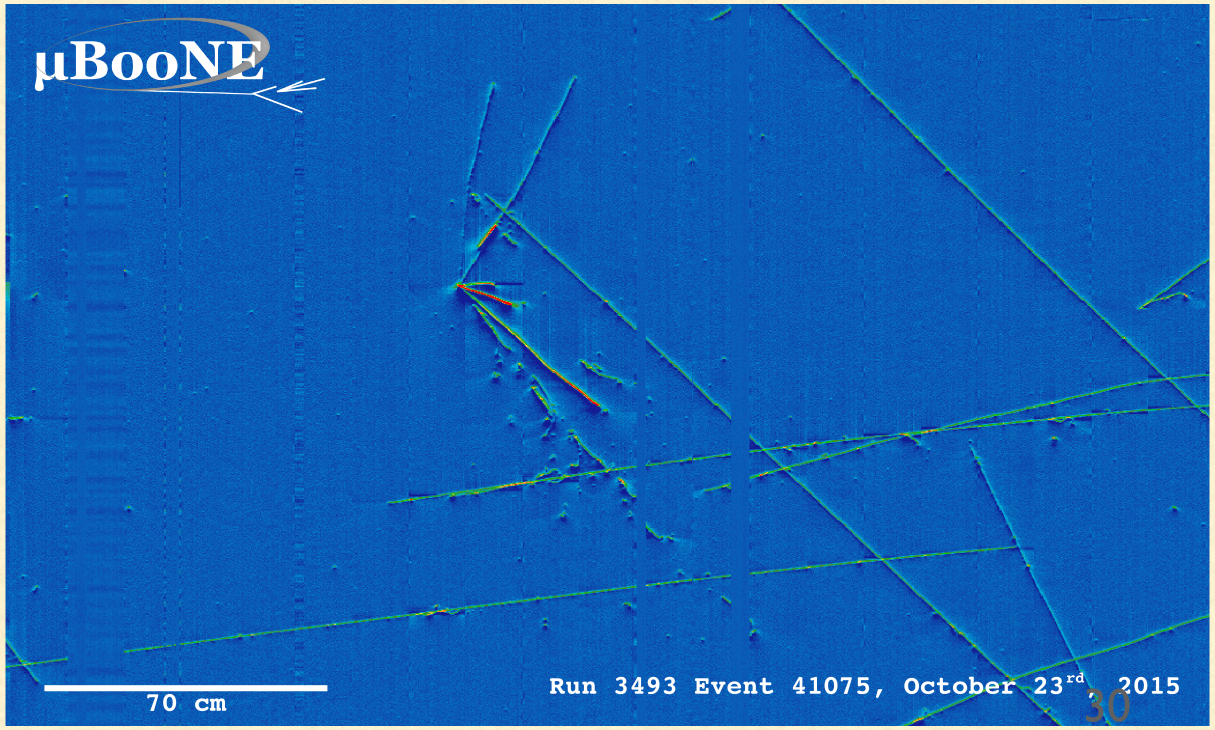




LIQUID ARGON TIME PROJECTION CHAMBER

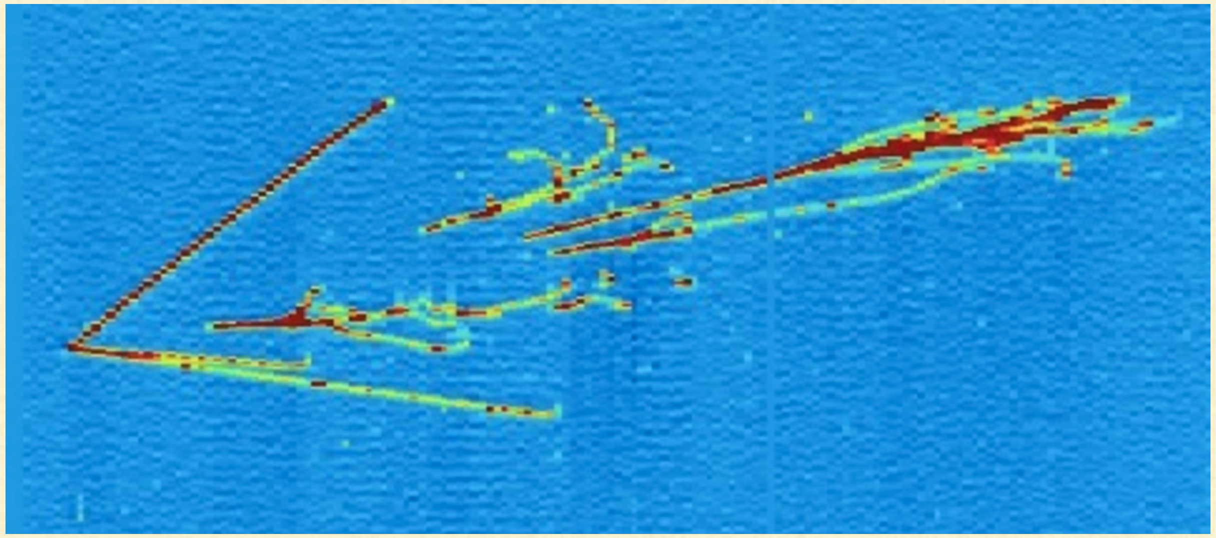
- High precision, three dimensional tracking and particle identification
- Any noble gas would work, but Argon is relatively cheap

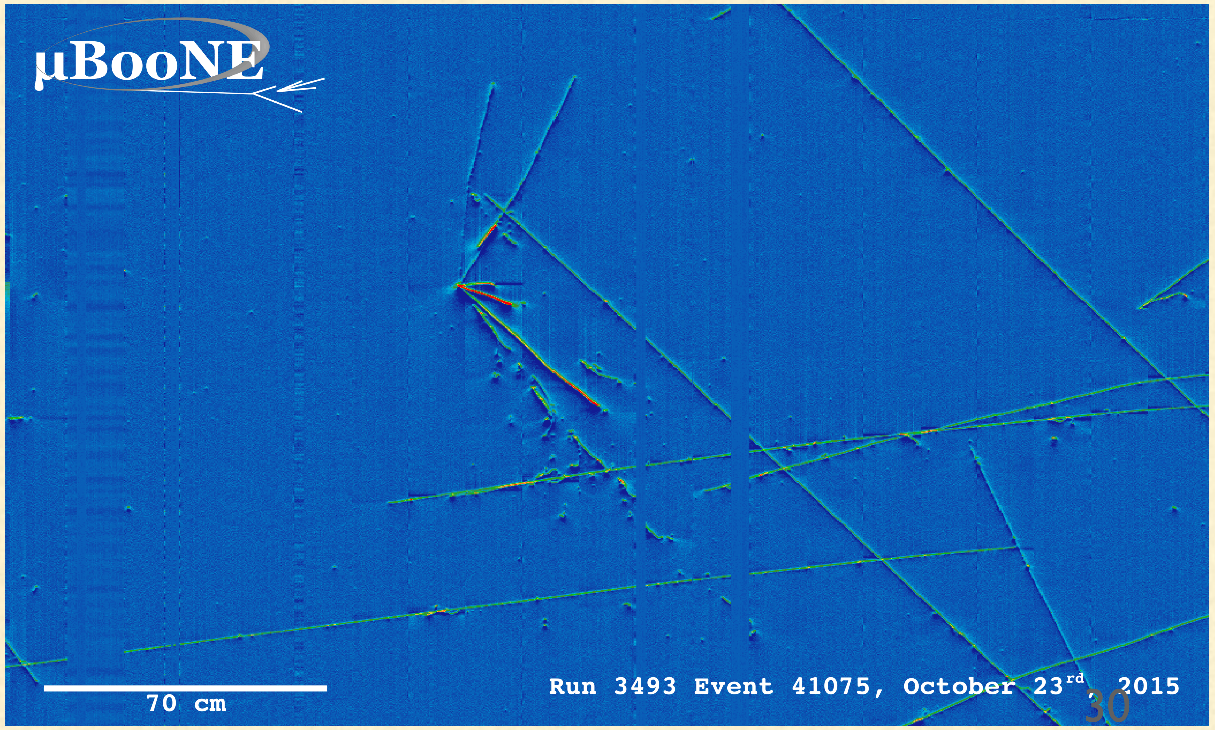




LIQUID ARGON TIME PROJECTION CHAMBER

- 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
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- Membrane cryostat (also used for LNG transportation)

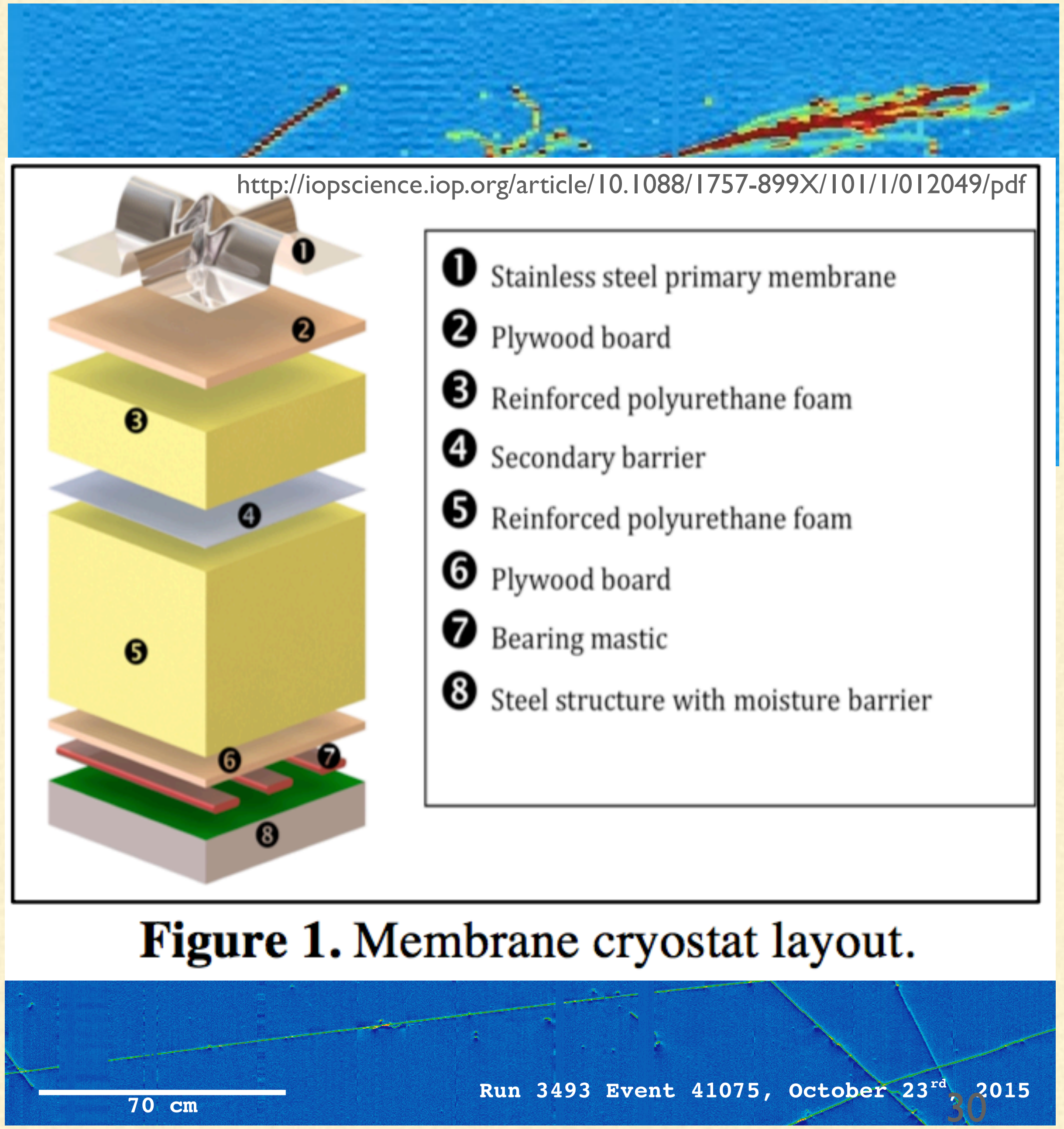

Figure 1. Membrane cryostat layout.

LIQUID ARGON TIME PROJECTION CHAMBER

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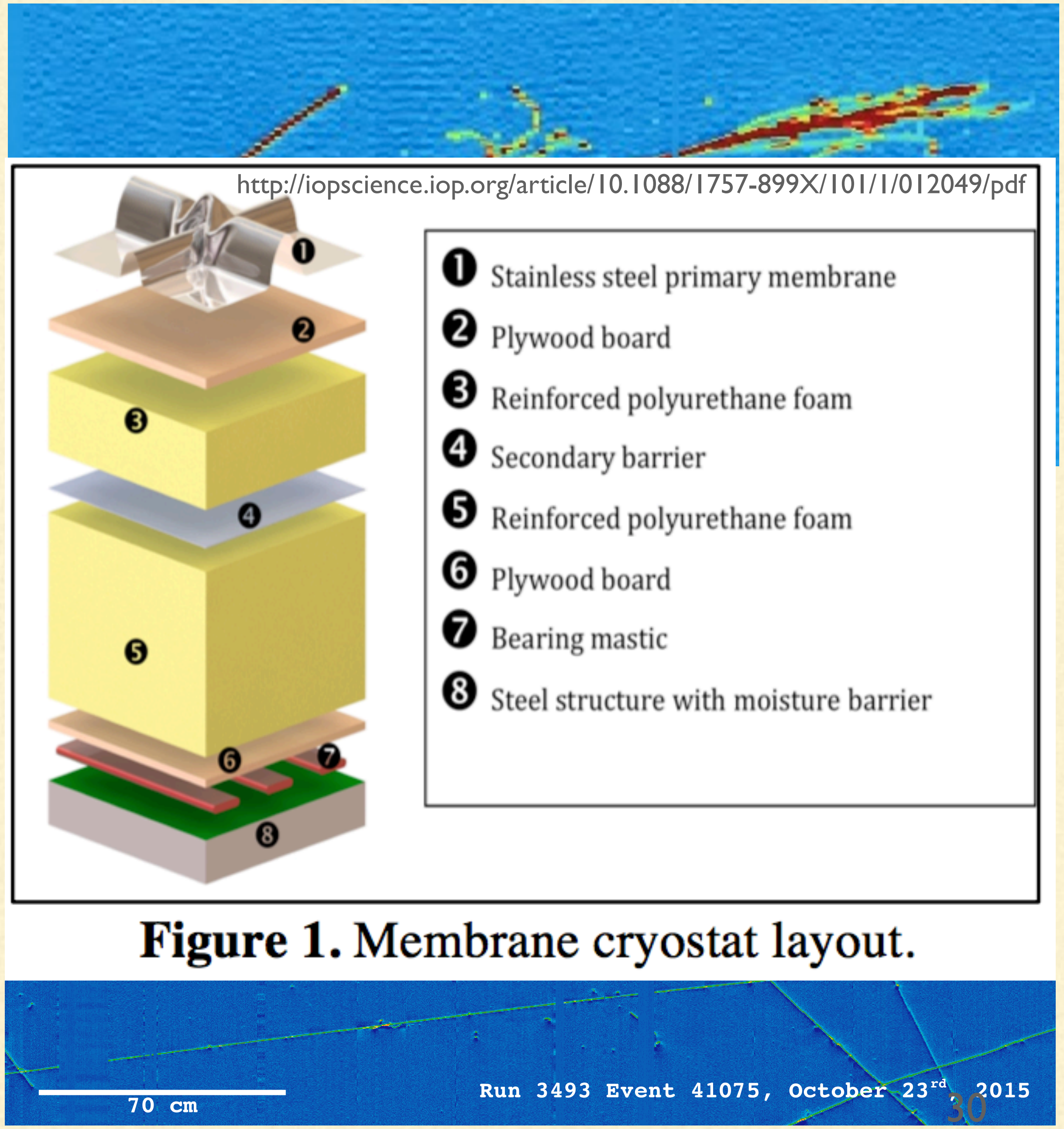

Figure 1. Membrane cryostat layout.

LIQUID ARGON TIME PROJECTION CHAMBER

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- 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

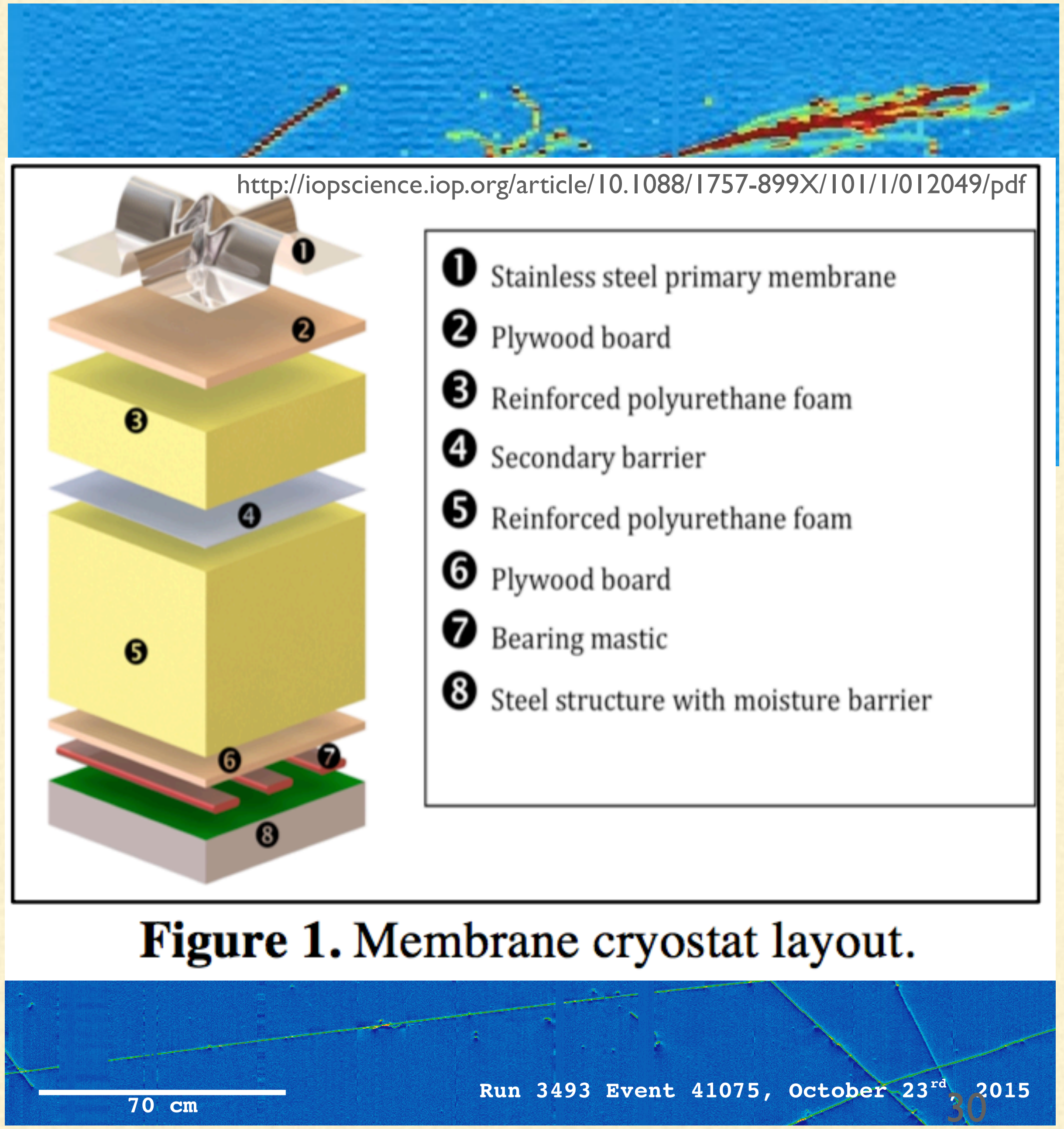


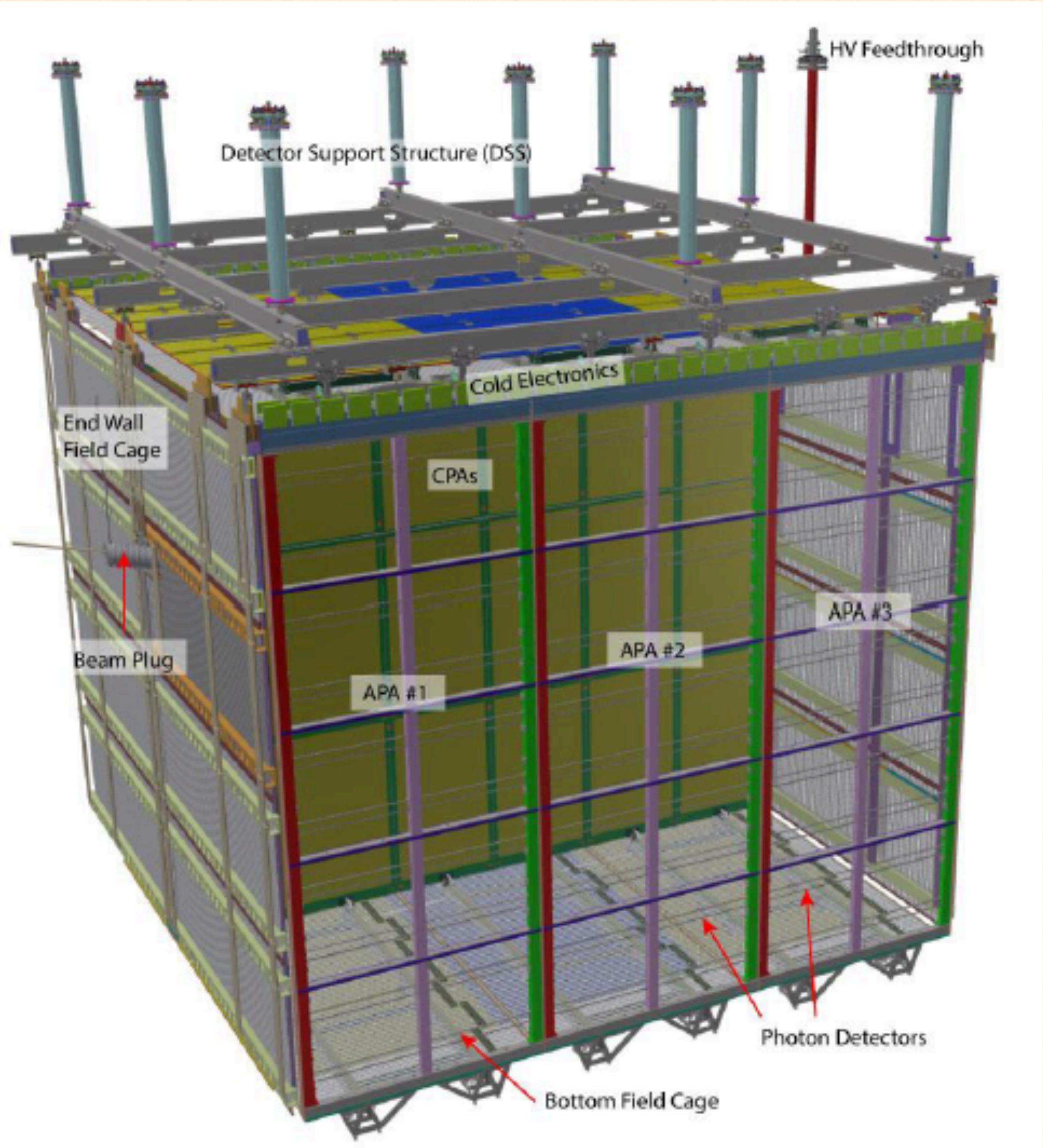
Figure 1. Membrane cryostat layout.

PROTODUNE

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

PROTODUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT



PROTODUNE

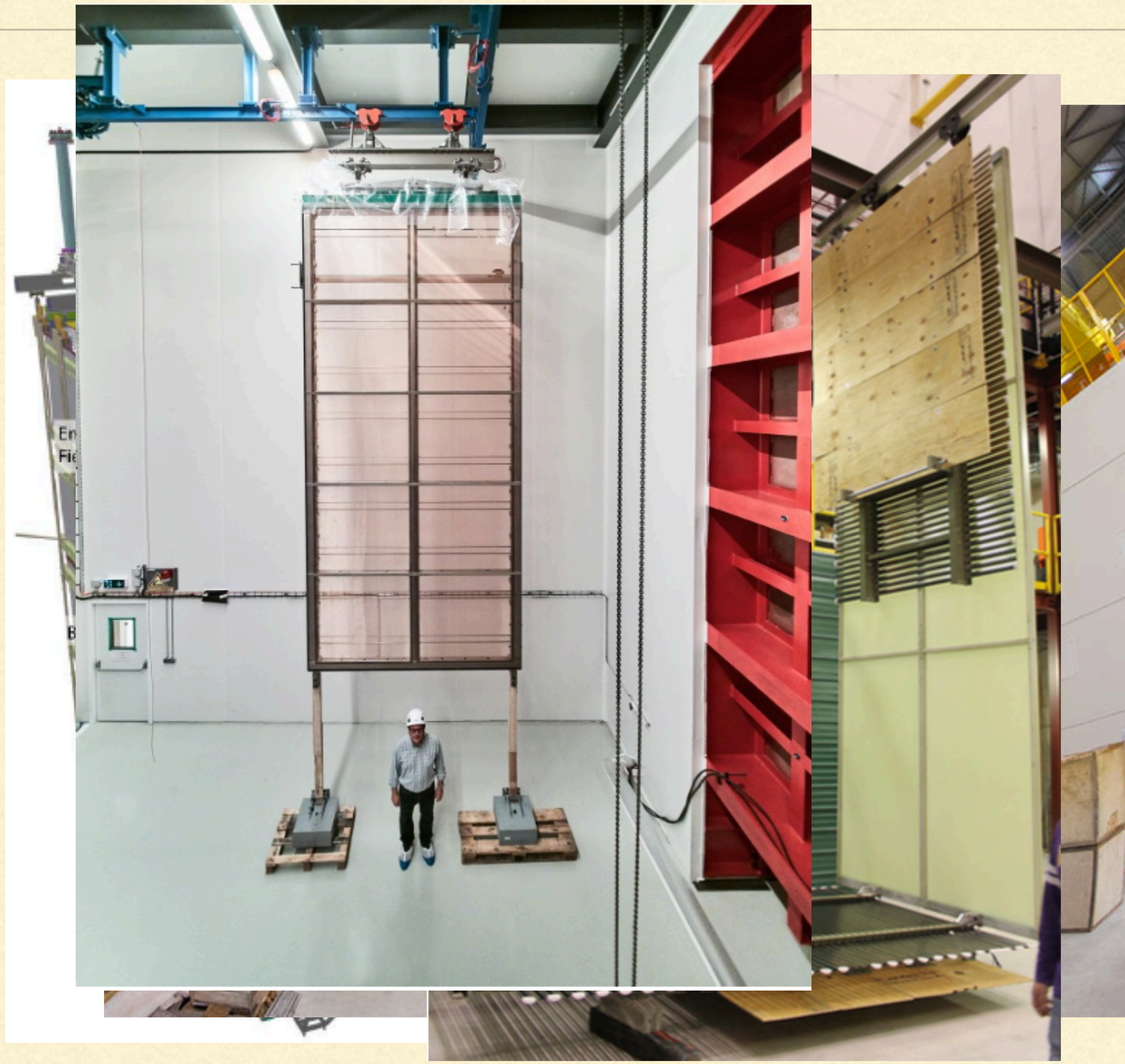
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

PROTODUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

PROTODUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT



PROTODUNE

DUNE
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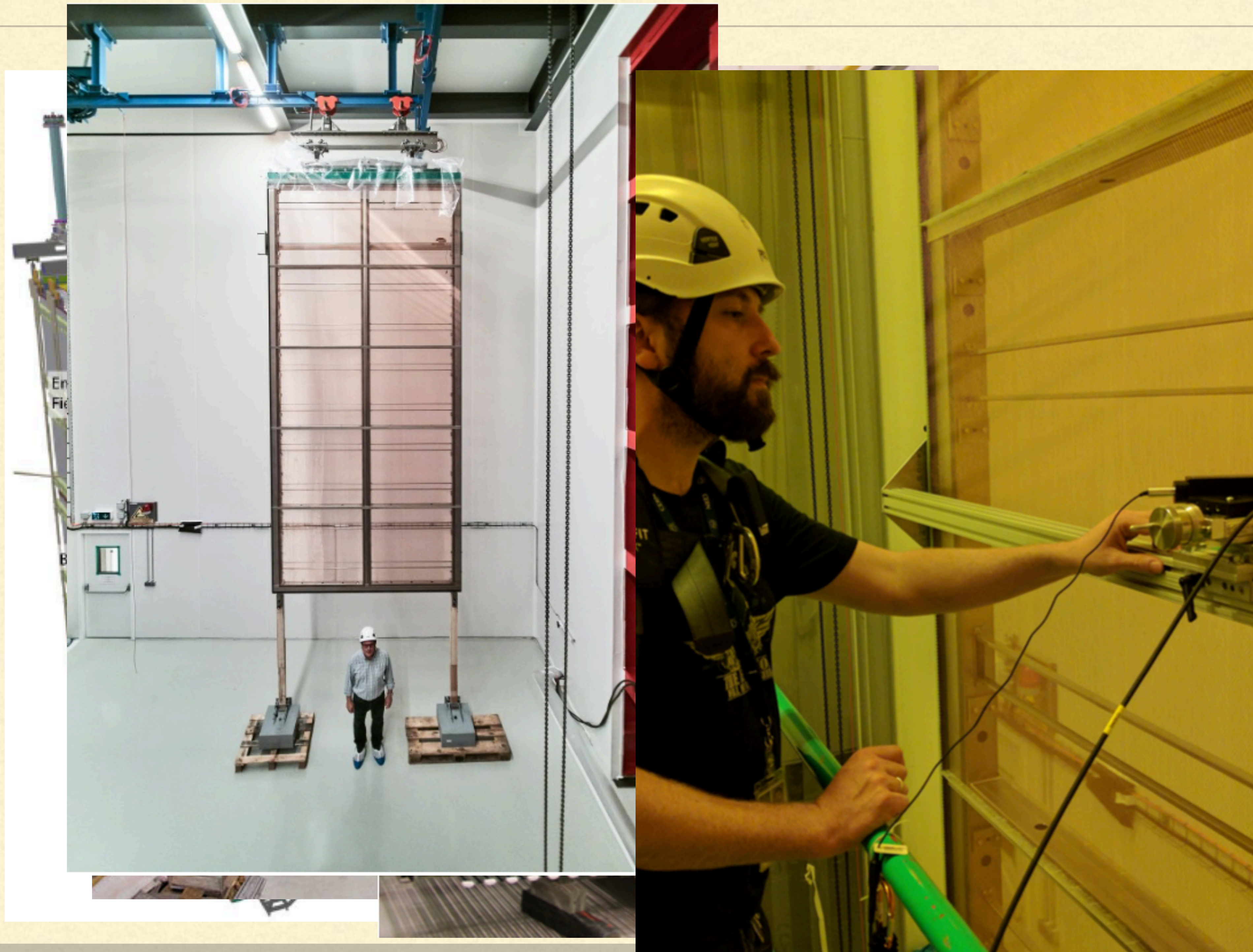

PROTODUNE

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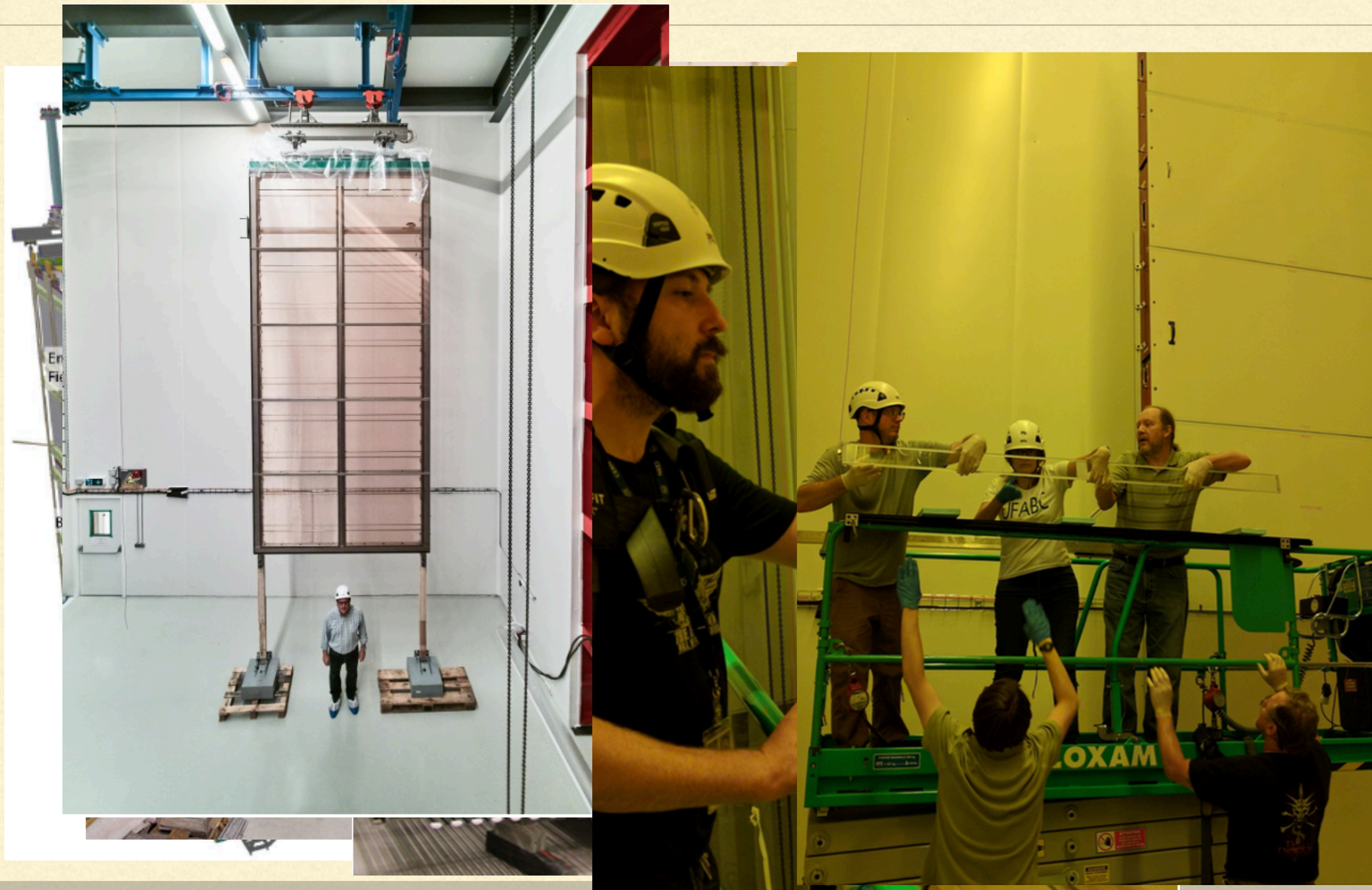
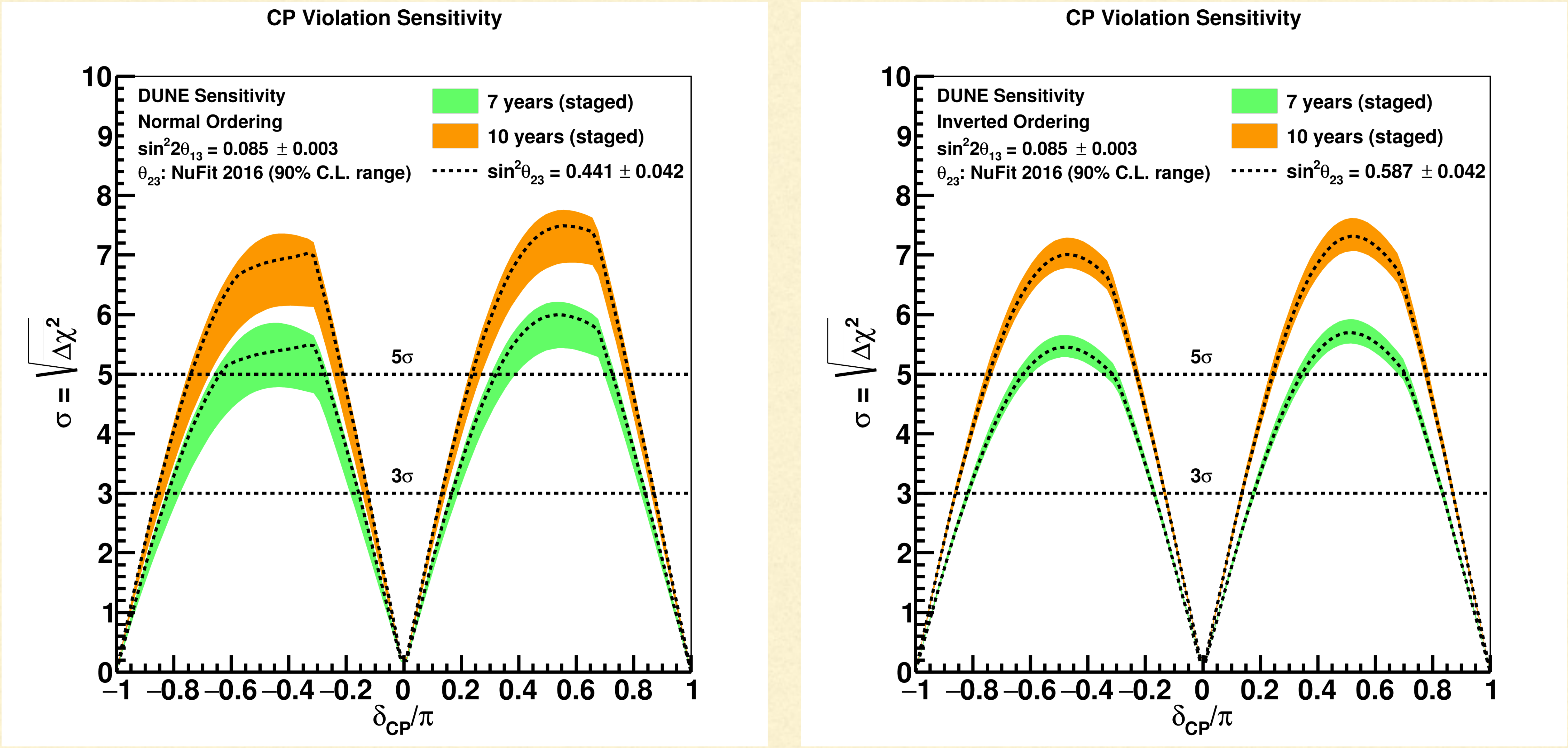


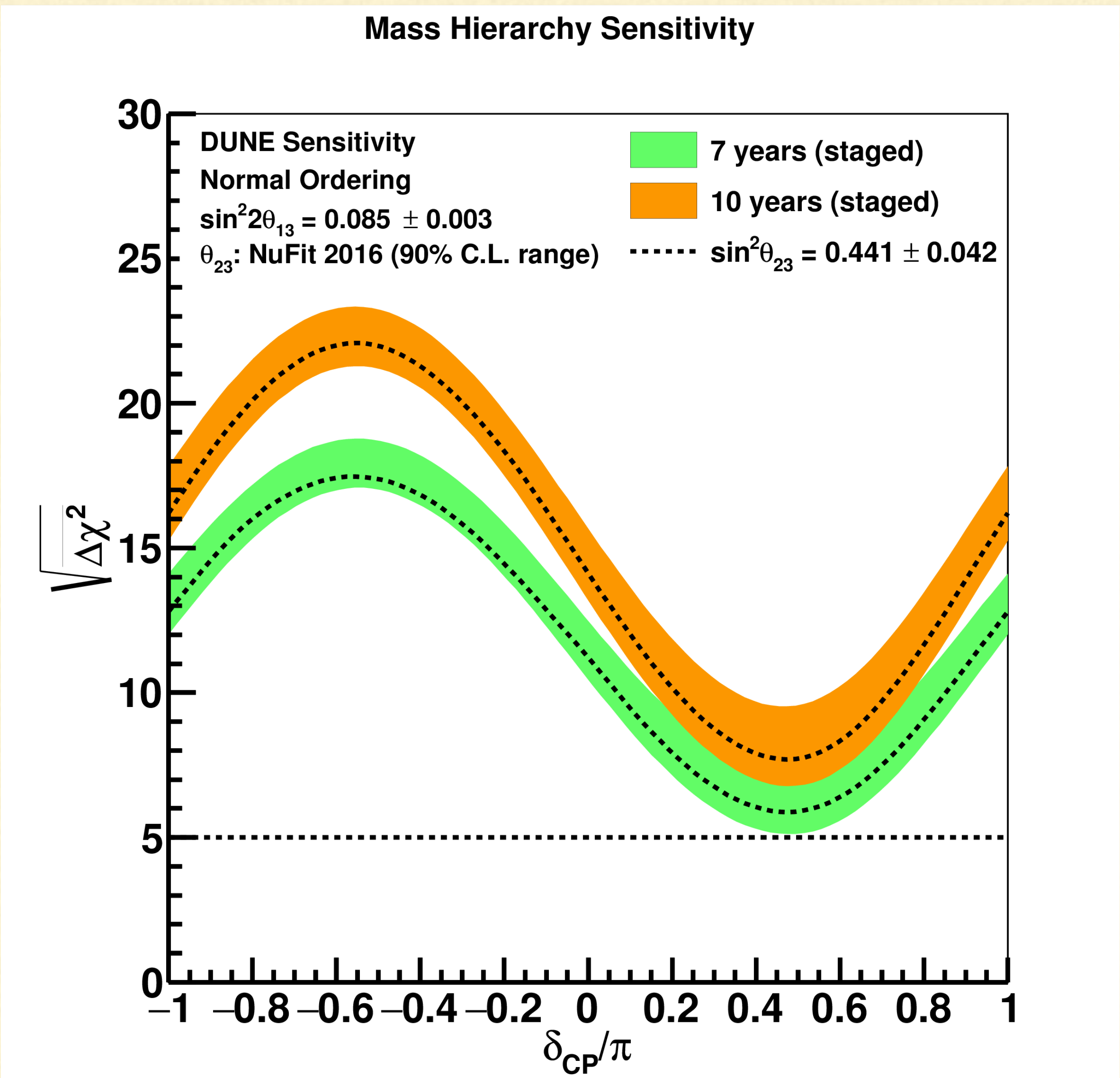
CP VIOLATION SENSITIVITY

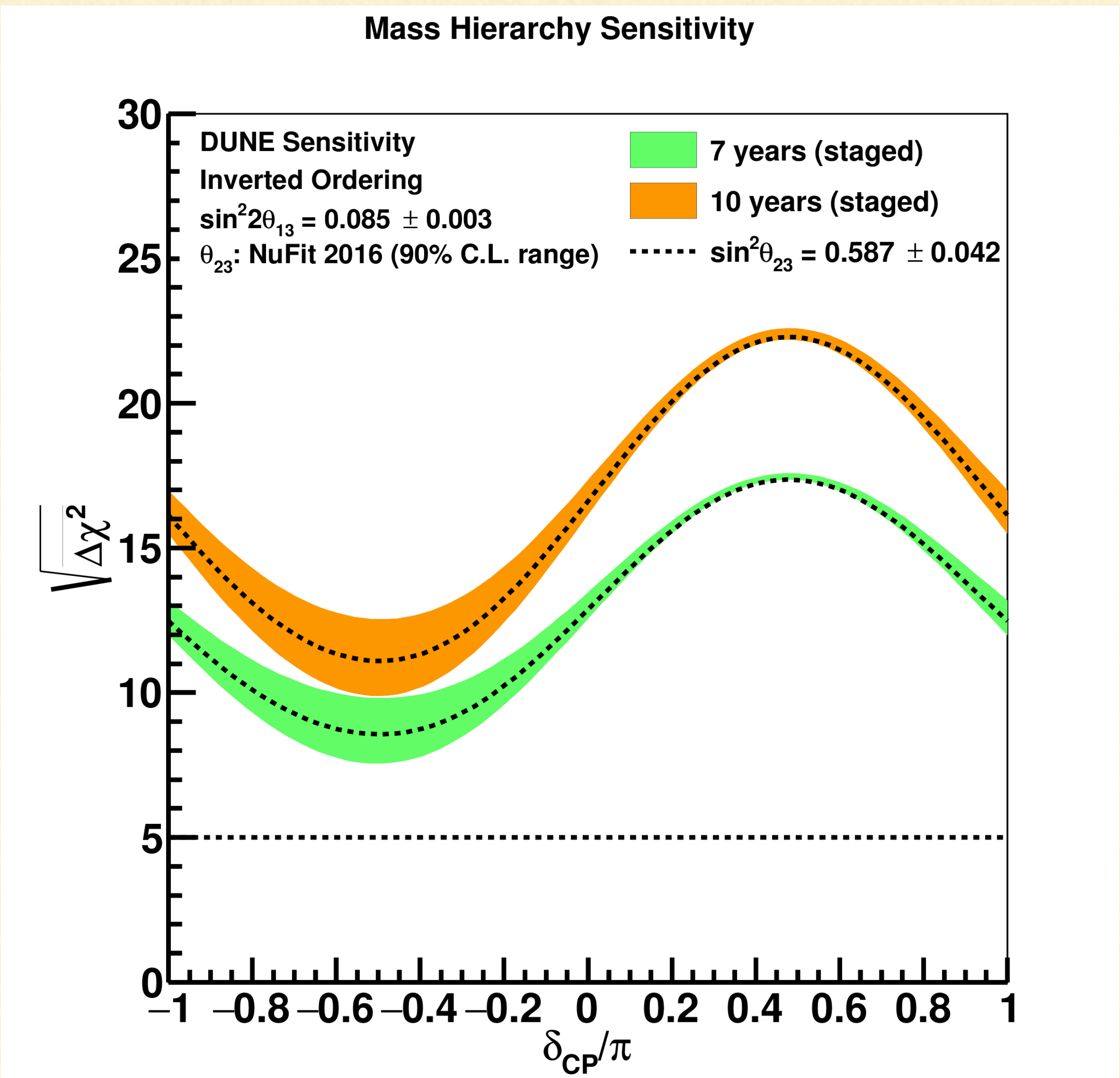
DEEP UNDERGROUND NEUTRINO EXPERIMENT



MASS HIERARCHY SENSITIVITY

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT





OSCILLATION PARAMETER RESOLUTION

DEEP UNDERGROUND NEUTRINO EXPERIMENT