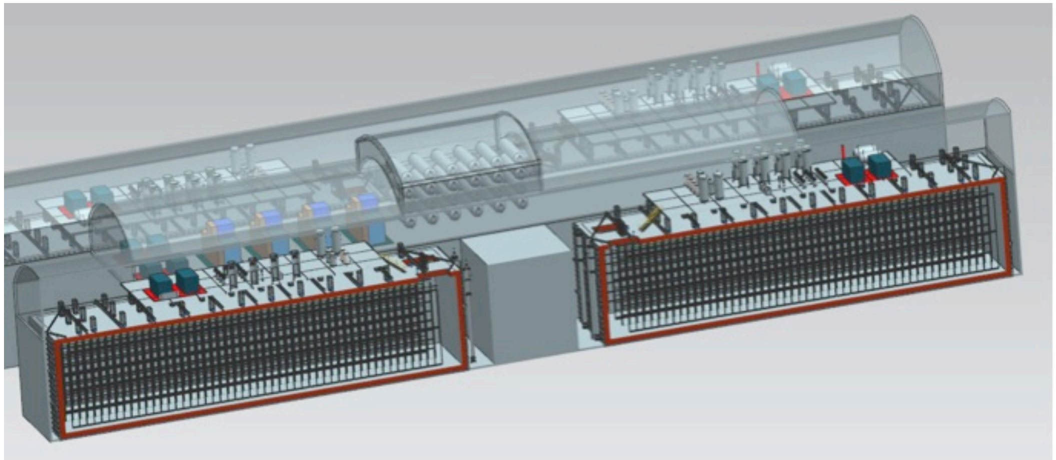
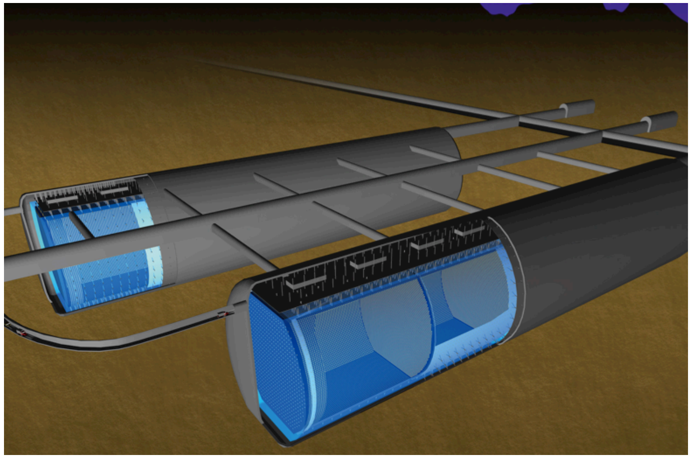




The Future Neutrino Oscillation Experimental Programme

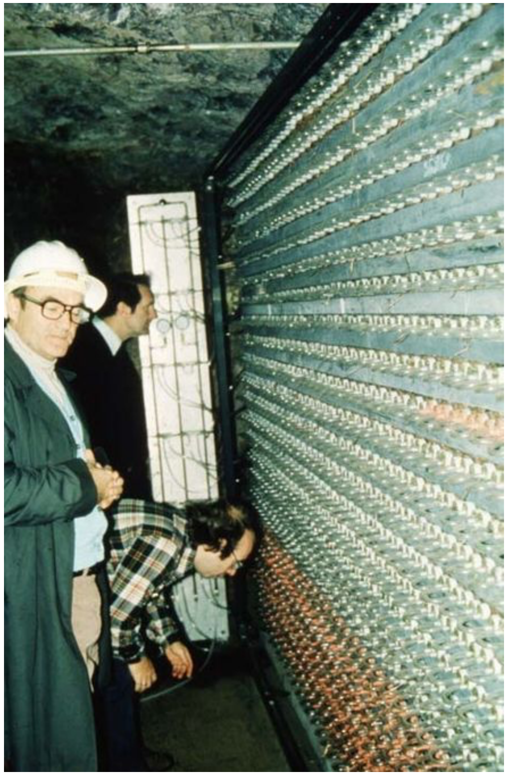
Mark Thomson

University of Cambridge & co-spokesperson of DUNE

NuAtmospheres: 15th December 2015

1. We have come a long way…

- **Back in the day…**
  - Particle Physics had three massless neutrinos: ν_e, ν_μ and ν_τ
  - + hints for anomalies in solar and atmospheric neutrinos
  - Underground particle physics/particle astrophysics was is its infancy
    - e.g. Soudan-1 detector in Minnesota



- **Incredible progress in last 25 years**
  - Both in our understanding & experimental techniques

2. The Standard 3-Flavor Paradigm

- ★ **Three massive neutrinos: ν_1, ν_2 and ν_3**
- ★ **Couplings to charged leptons given by Unitary PNMS matrix:**
  - three "Euler angles": $(\theta_{12},\ \theta_{13},\ \theta_{23})$
  - and one complex phase: δ

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

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

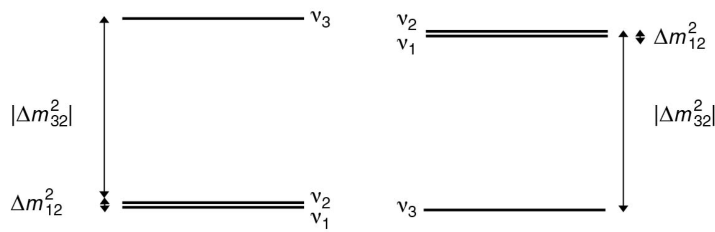
- ★ **If** $\delta \neq \{0, \pi\}$ then SM leptonic sector ➡ CP violation (CPV)
  - CPV effects $\propto \sin\theta_{13}$
  - **now know that θ_{13} is relatively large**

➡ **CPV is observable with conventional ν beams**

Open Experimental Questions

Still many fundamental open questions in ν physics

- **Are neutrinos Dirac or Majorana particles?** (see next talk)
- **Is CP violated in the neutrino sector?** $\delta \neq \{0, \pi\}$
- **What is the Neutrino Mass Hierarchy?**



- **Is the standard three-flavour paradigm correct? Or is it broken by (for example):**
  - Light sterile neutrino states
  - Non-Standard neutrino interactions
- **What is the absolute scale on neutrino masses?**
- **Is θ_{23} "maximal"?**

Next Generation LBL experiments

Still many fundamental open questions in ν physics

- **Are neutrinos Dirac or Majorana particles?** (see next talk)
- **Is CP violated in the neutrino sector?** $\delta \neq \{0, \pi\}$
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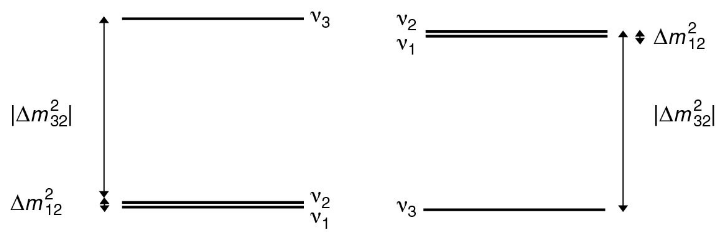
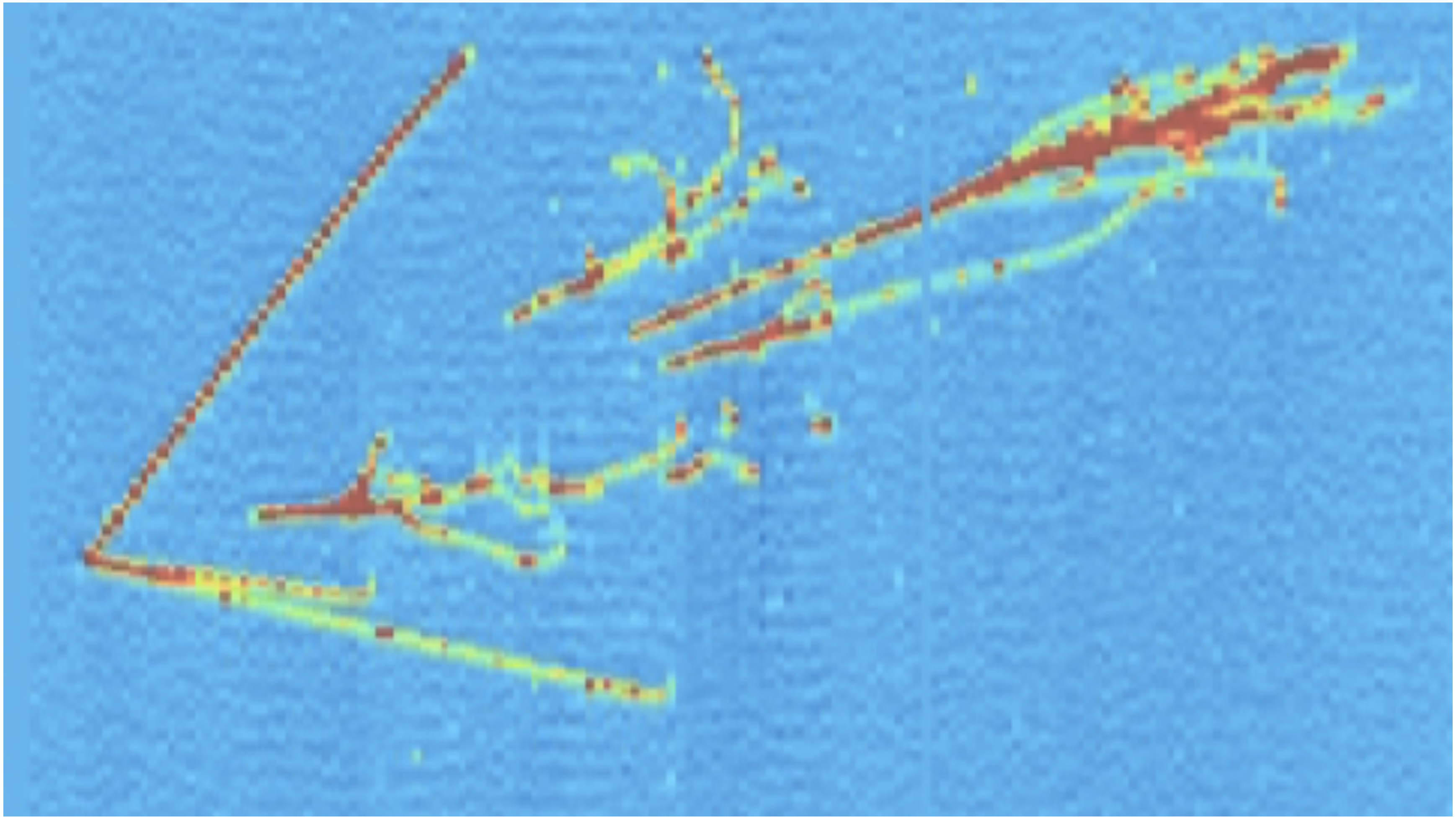


- **Is the standard three-flavour paradigm correct? Or is it broken by (for example):**
  - Light sterile neutrino states
  - Non-Standard neutrino interactions
- **What is the absolute scale on neutrino masses?**
- **Is θ_{23} "maximal"?**

3. How to Detect CPV with νs



In principle, it is straightforward

- ★ CPV ⇨ different oscillation rates for νs and $\overline{\nu}$s

$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) = 4 s_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \times \left[\sin\left(\frac{\Delta m_{21}^2}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2}{2E}\right) \right]$$

vacuum osc.

- ★ Requires $\{\theta_{12}, \theta_{13}, \theta_{23}\} \neq \{0, \pi\}$
  - now know that this is true, $\theta_{13} \approx 9^\circ$
  - but, despite hints, don't yet know "much" about δ
- ★ 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

★ Even in the absence of CPV

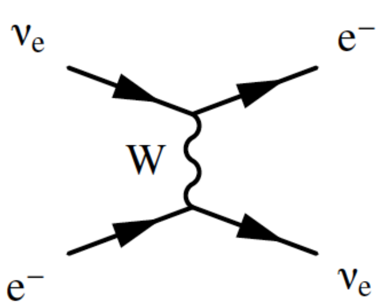
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = 0$$

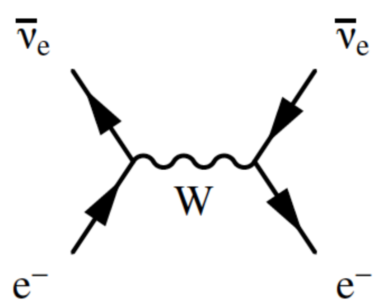
Neutrinos travel through material that is not CP symmetric, i.e. matter not antimatter

★ In vacuum, the mass eigenstates ν_1, ν_2, ν_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:





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

Different sign for ν_e vs $\bar{\nu}_e$

Neutrino Oscillations in Matter

- ★ Accounting for this potential term, gives a Hamiltonian that is no longer diagonal in the basis of the mass eigenstates

$$\mathcal{H}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = i\frac{d}{dt}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} = \begin{pmatrix}E_1 & 0 & 0\\0 & E_2 & 0\\0 & 0 & E_3\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\\|\nu_3\rangle\end{pmatrix} + V|\nu_e\rangle$$

Matter Effects

- ★ Complicates the simple picture !!!!

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

ME $$\frac{16A}{\Delta m^2_{31}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

ME $$-\frac{2AL}{E}\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

CPV $$-8\frac{\Delta m^2_{21}L}{2E}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\delta \cdot s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$$

with $A = 2\sqrt{2}G_F n_e E = 7.6\times10^{-5}\text{eV}^2 \cdot \frac{\rho}{\text{g cm}^{-3}} \cdot \frac{E}{\text{GeV}}$

Neutrino Oscillations in Matter

- Accounting for this potential term, gives a Hamiltonian that is no longer diagonal in the basis of the mass eigenstates

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← **ME**

- Complicates the simple picture !!!!

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

← What we measure

ME

$$\frac{16A}{\Delta m^2_{31}}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

← Small

ME

$$-\frac{2AL}{E}\sin\left(\frac{\Delta m^2_{31}L}{4E}\right)c^2_{13}s^2_{13}s^2_{23}(1-2s^2_{13})$$

← Proportional to L

CPV

$$-8\frac{\Delta m^2_{21}L}{2E}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin\delta \cdot s_{13}c^2_{13}c_{23}s_{23}c_{12}s_{12}$$

← What we want

with $A = 2\sqrt{2}G_F n_e E = 7.6\times10^{-5}\mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

Experimental Strategy

EITHER:

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

- Still want oscillations:

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

- Since $\sigma \propto E_\nu$ need a 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)

- Still want oscillations:

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

- **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 eff[...]re insignificant

- Still want oscillations:

$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$ ⇨ [...]V

- Since [...]u high flux at oscillation maximum

⇨ Off-[...]eam: narrow range of neutrino energies

Hyper-Kamiokande

OR:

★ Make L large (>1000 km): measure th[...]atter effects (i.e. MH)

- Still want oscillations:

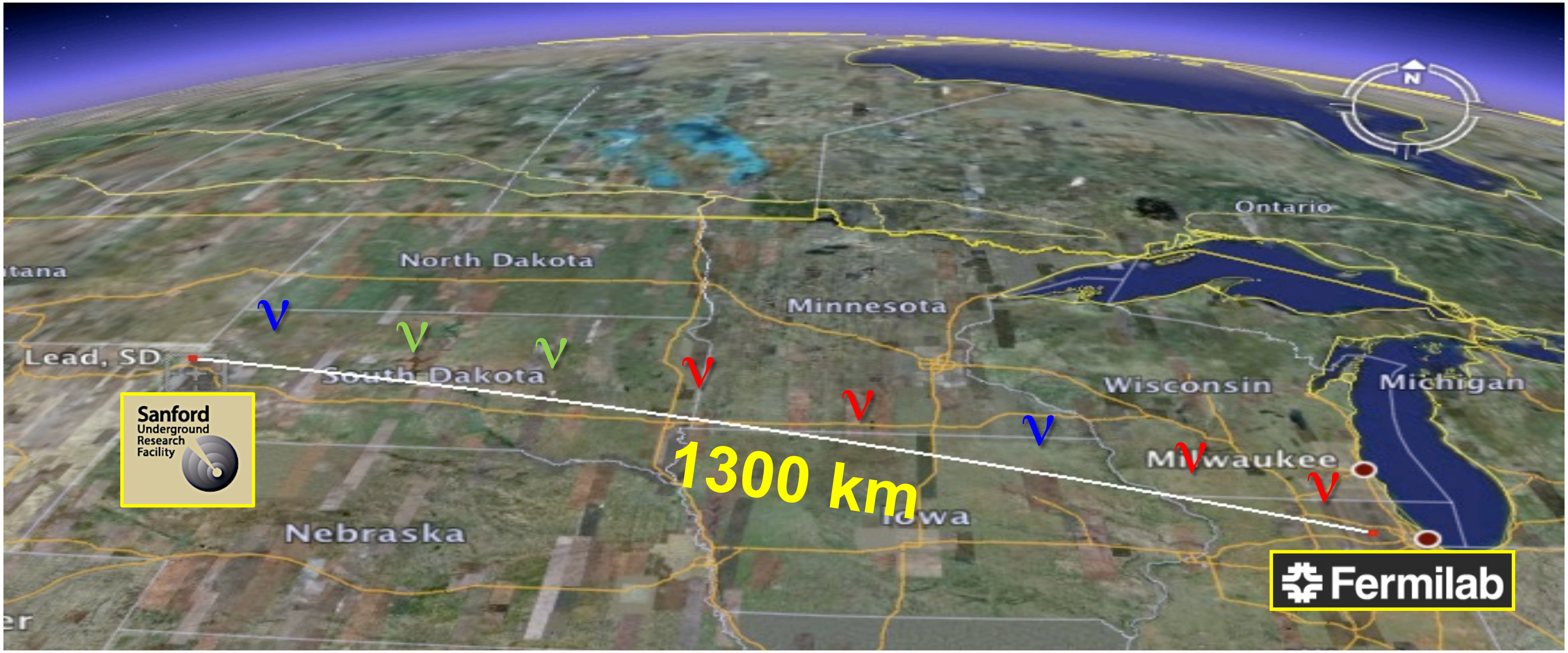
$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2}$$

- **Unfold CPV from Ma[...]cts through E dependence**

⇨ On-axis beam: wide range of neutrino energies

DUNE

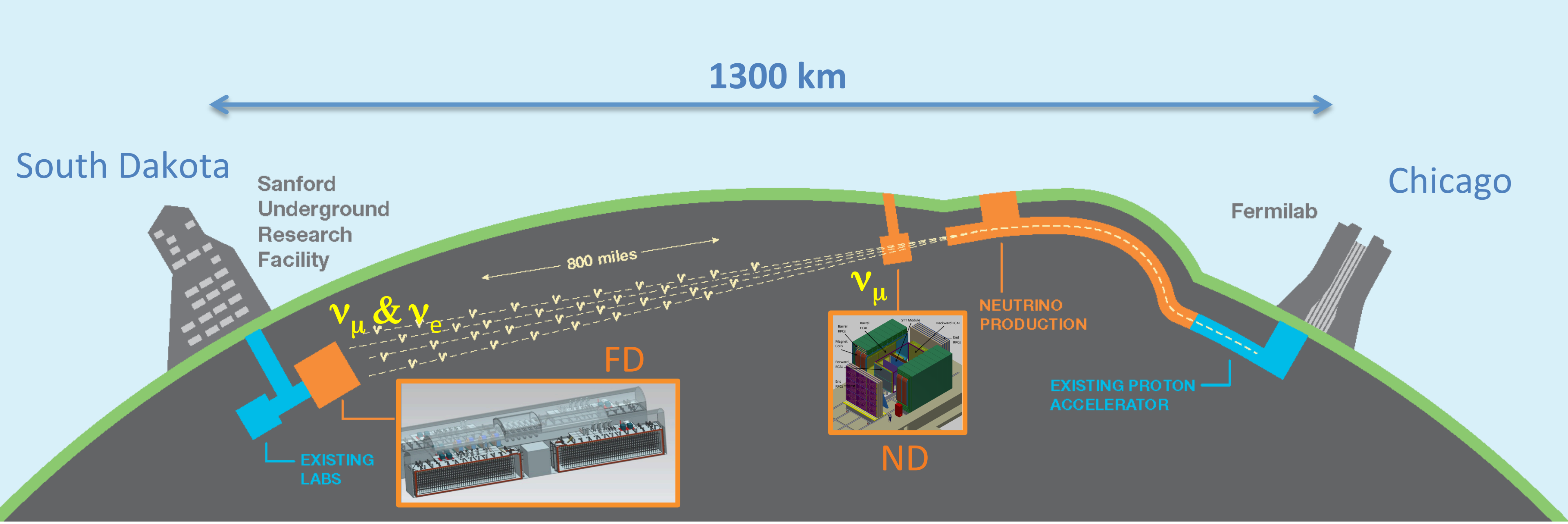
6. The Deep Underground Neutrino Experiment (DUNE)



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 mass of >40 kton**
- Near detector to characterize the beam



DUNE Primary Science Goals

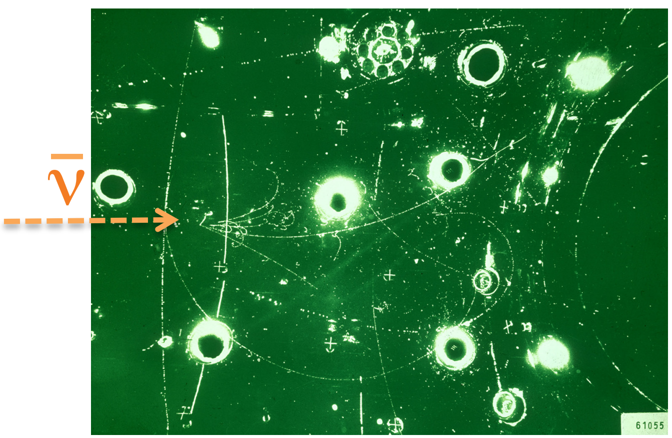
Focus on fundamental open questions in particle physics and astro-particle physics:

- **1) Neutrino Oscillation Physics**
  - CPV in the leptonic sector
  - Definitive determination of the Mass Hierarchy
  - Precision Oscillation Physics (θ_{23} octant, …) & testing the 3-flavor paradigm
- **2) Nucleon Decay**
  - Targeting SUSY-favored modes, e.g. $p \rightarrow K^+ \bar{\nu}$
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, sensitivity to ν_e

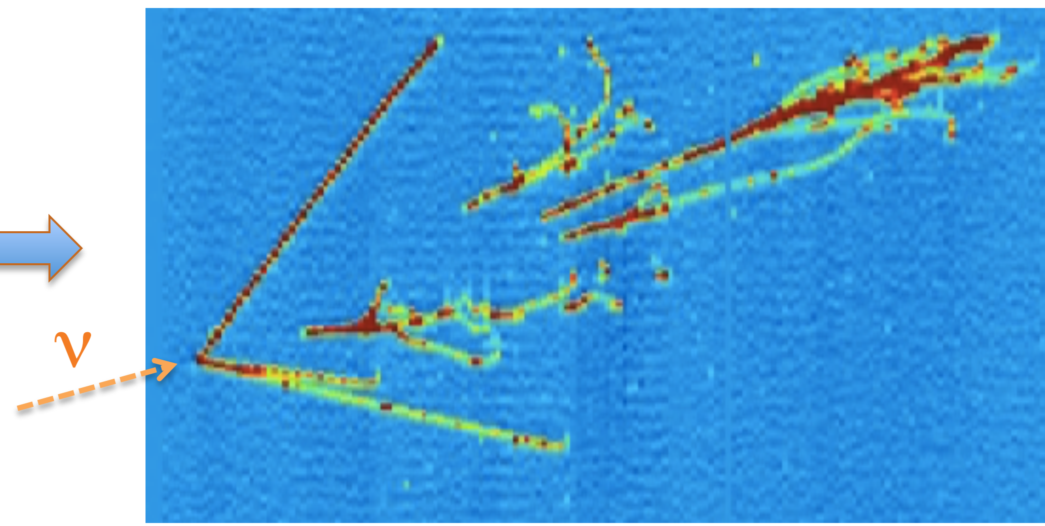
Every Neutrino is Sacred

★ DUNE is based around the imaging capabilities of the liquid argon time-projection chamber (LAr-TPC) technology

- Extract maximum information from each interaction



F.J. Hasert et al., Phys. Lett. B46 (1973)

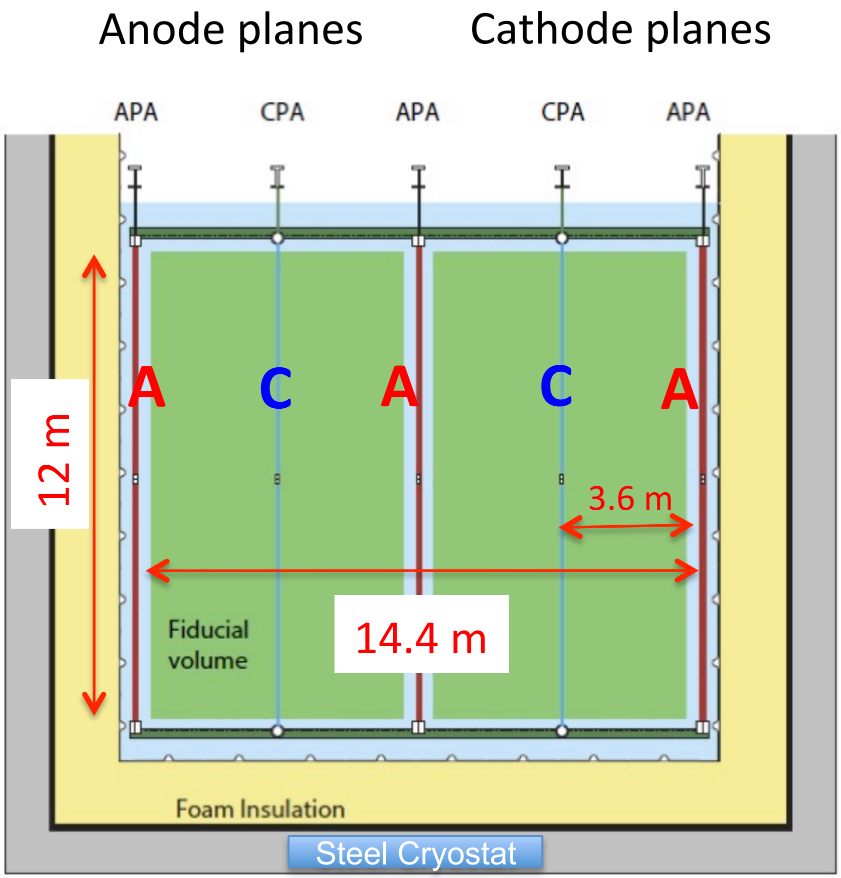


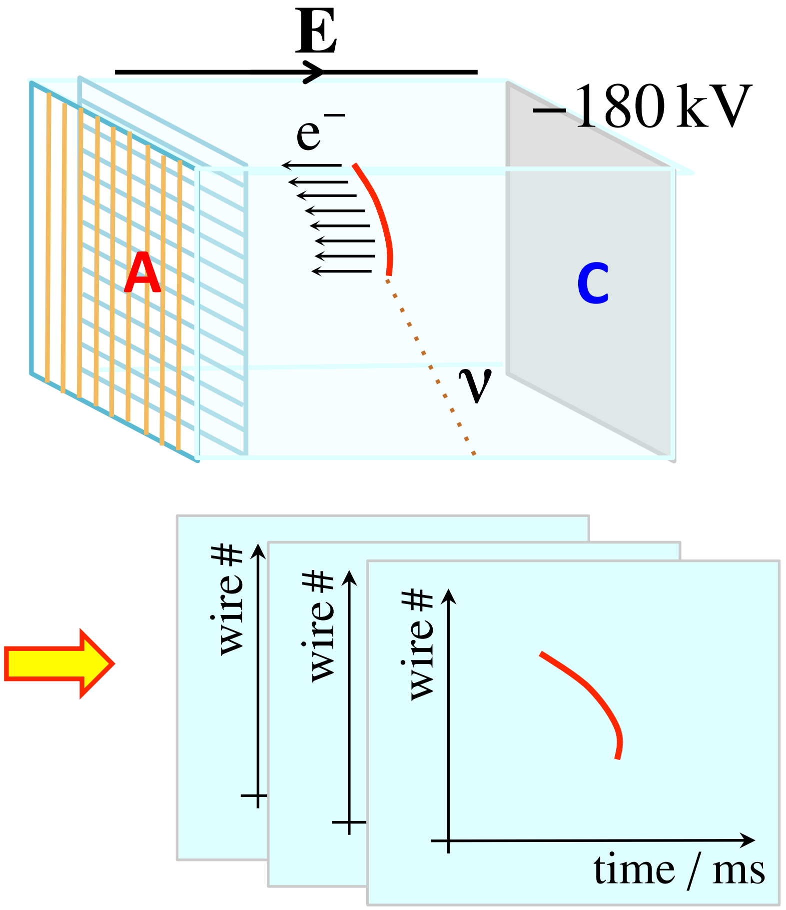
A neutrino interaction in ArgoNEUT (2014)

DUNE Liquid Argon TPC

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

- Record ionization in LAr volume ⇨ 3D image





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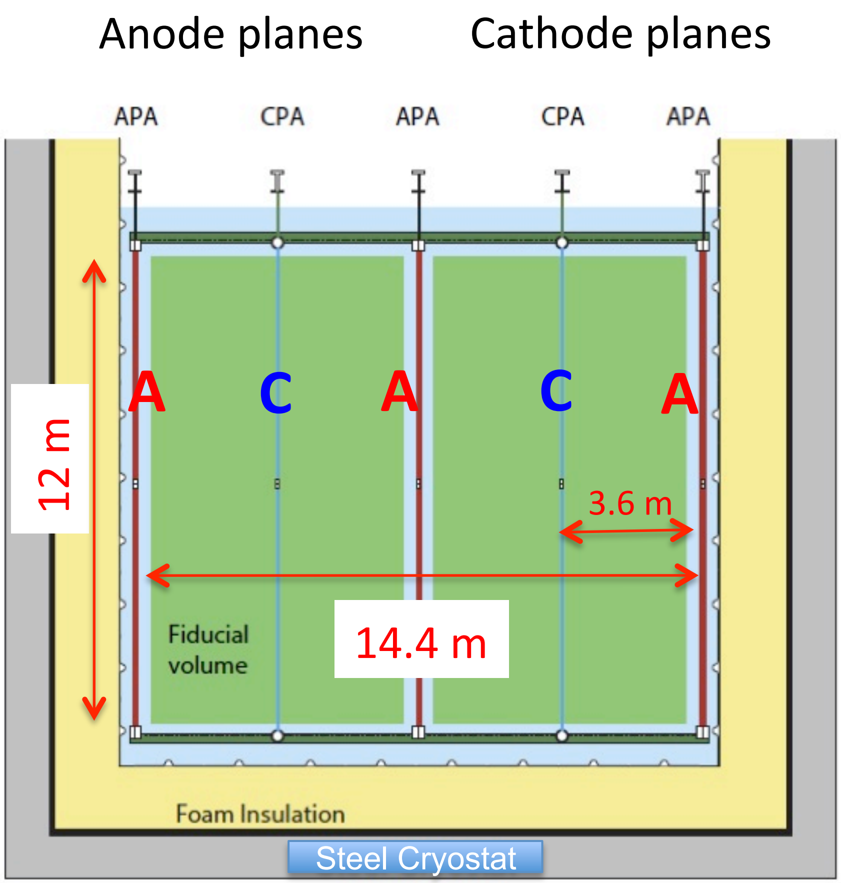

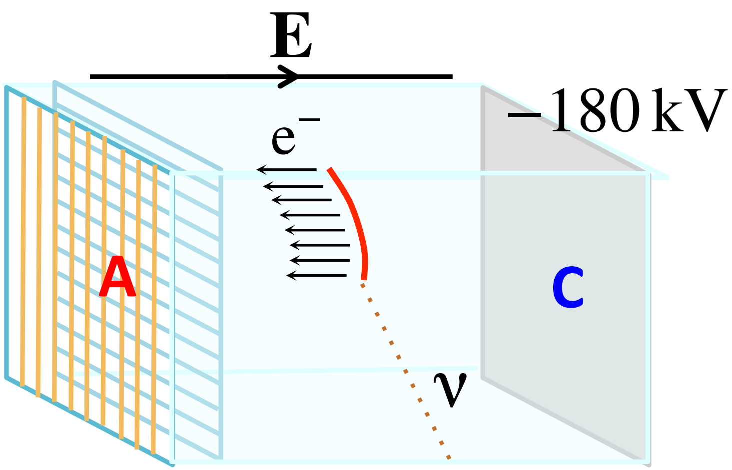

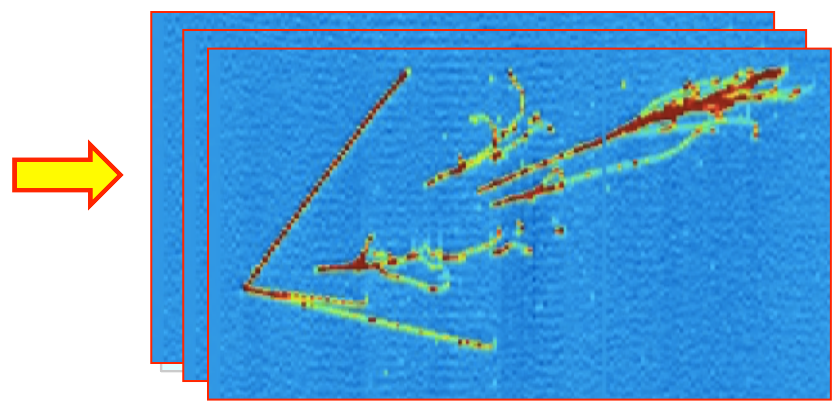

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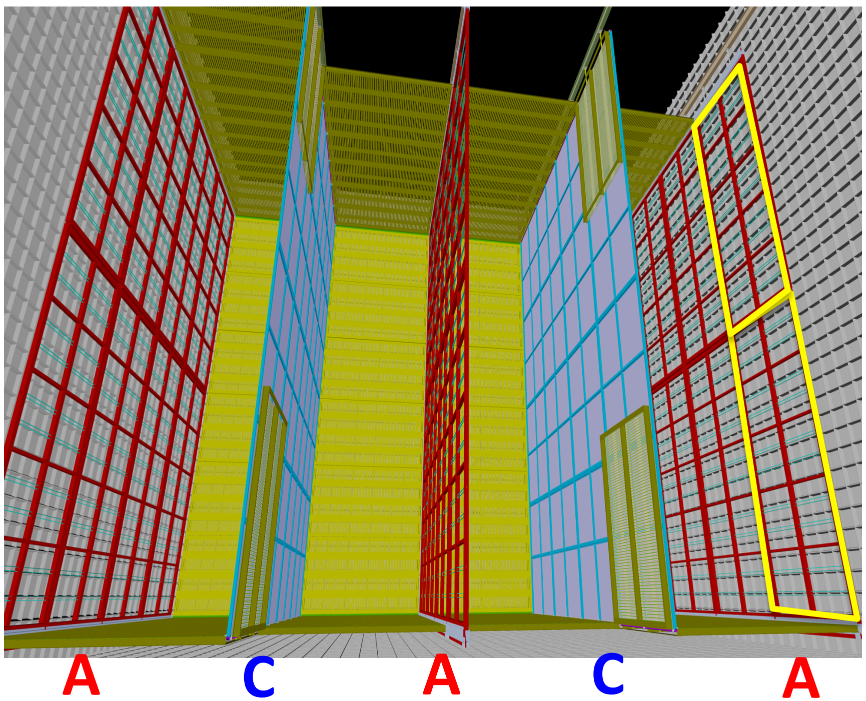
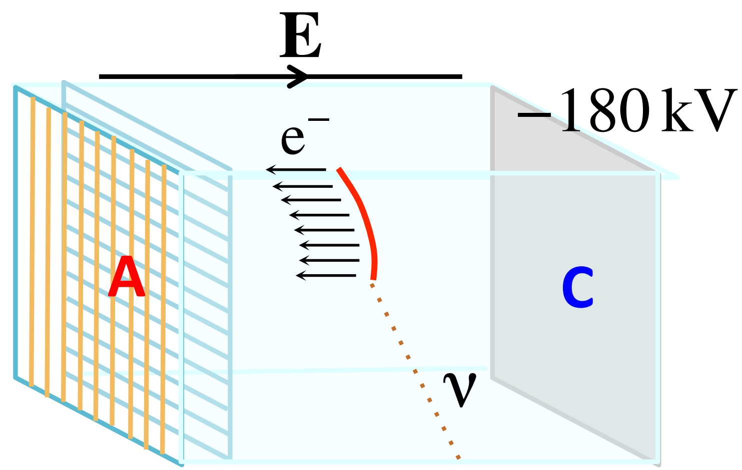
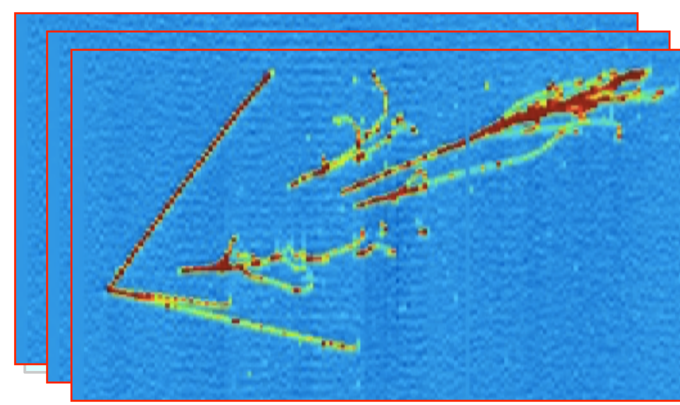
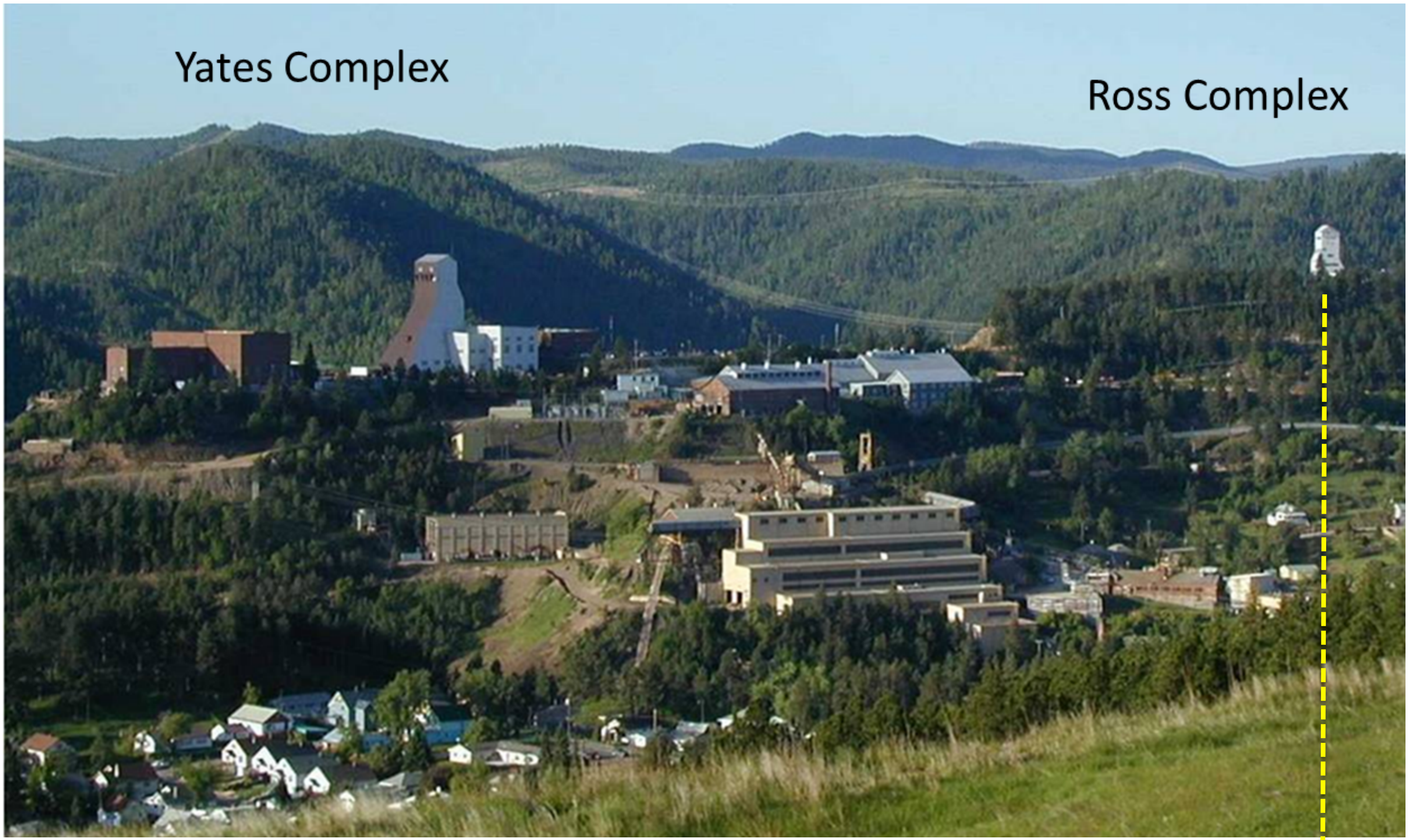






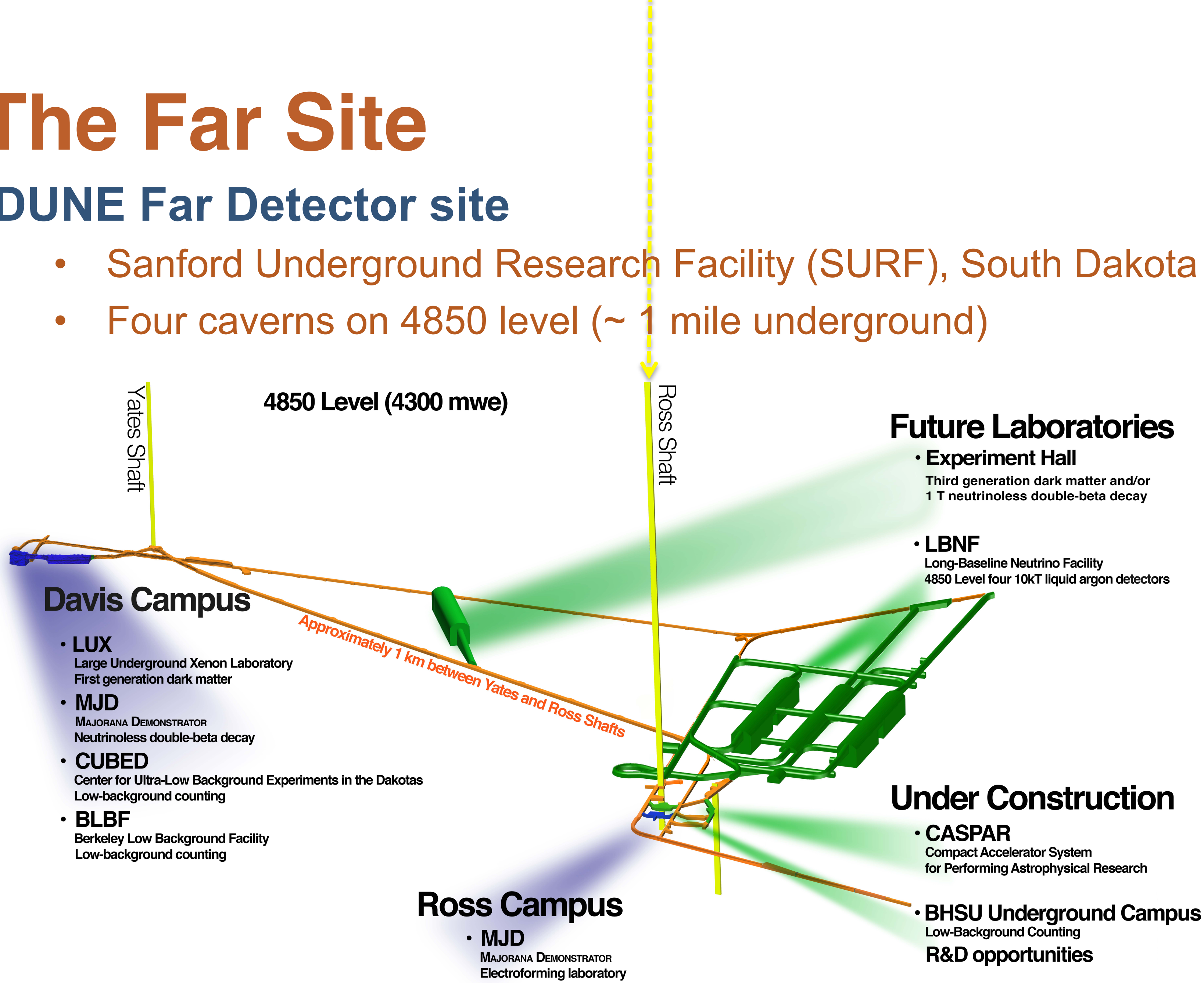
The DUNE Far Detector



The Far Site

DUNE Far Detector site

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



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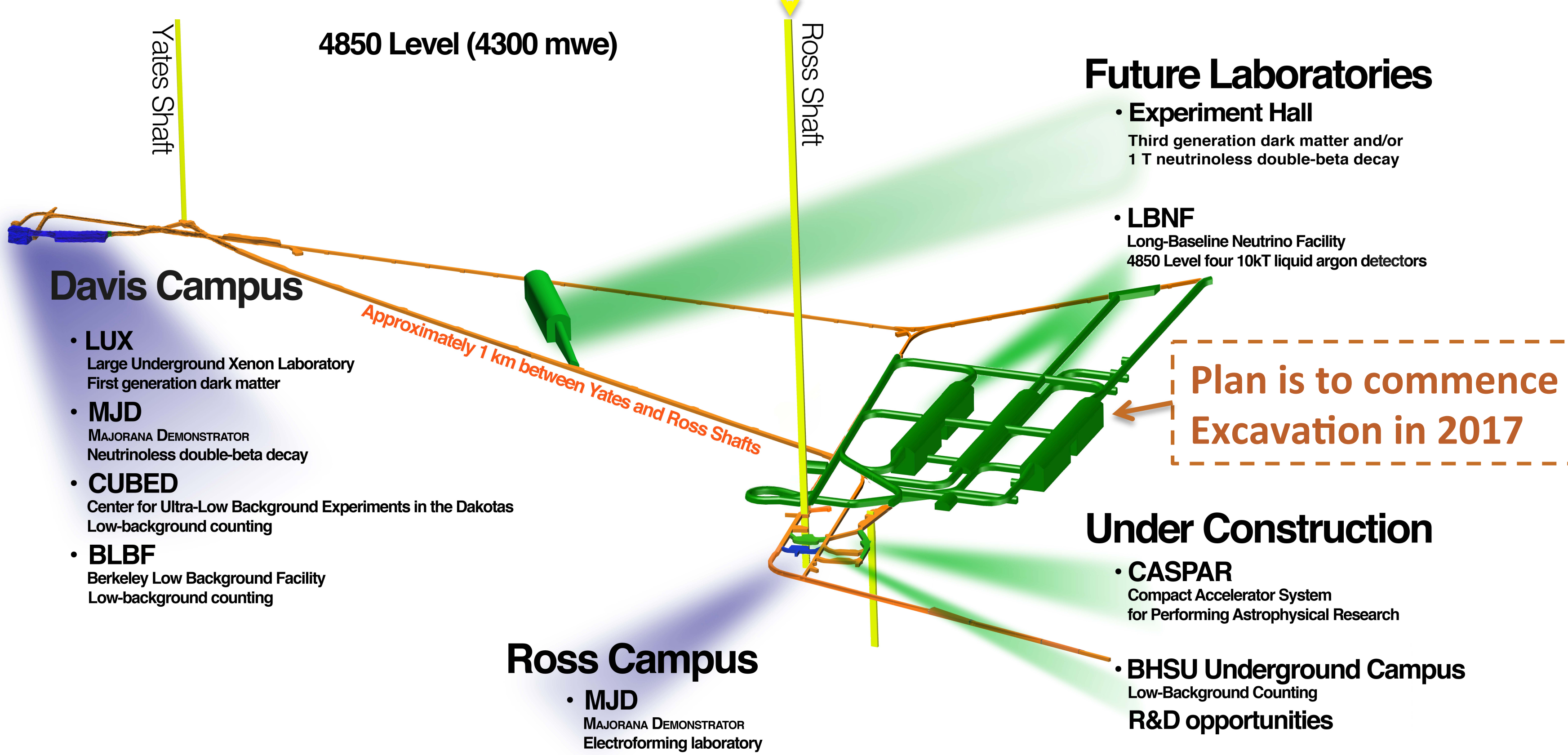
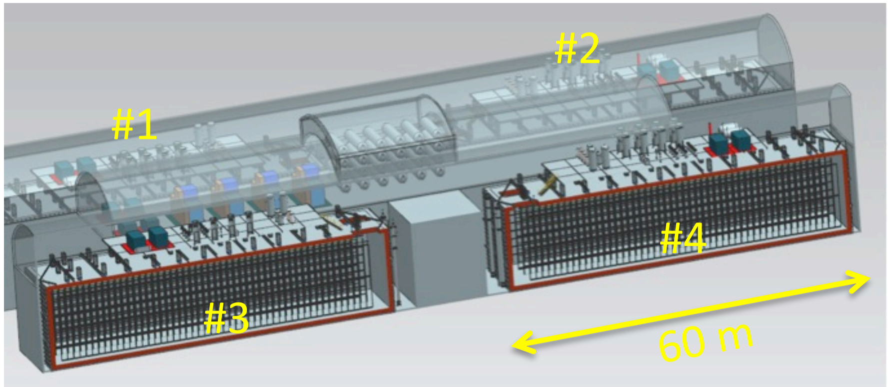


Staged Approach to 40 kt

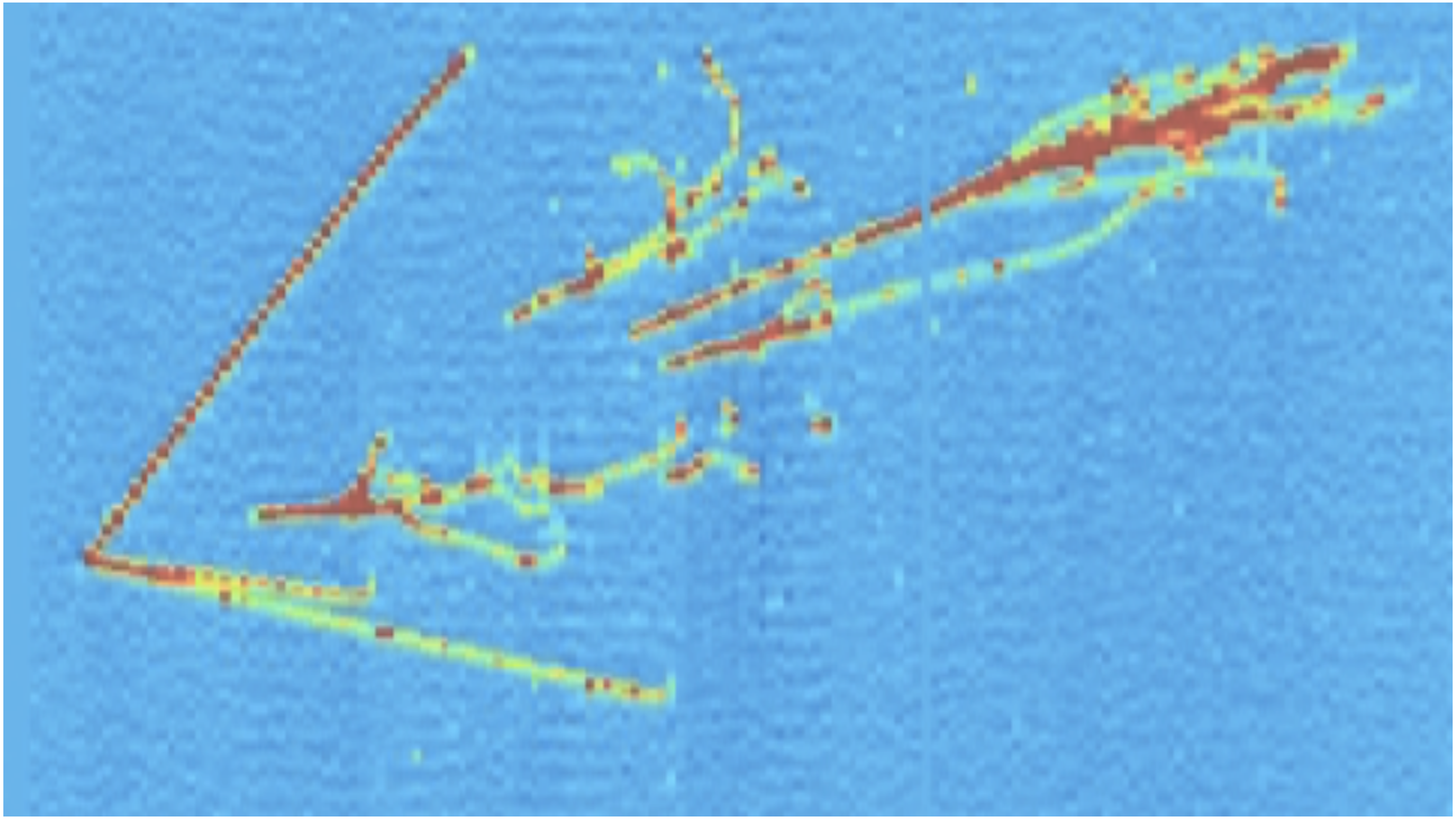
Cavern Layout at the Sanford Underground Research Facility based on four independent caverns

- **Four identical caverns hosting four independent 10-kt FD modules**
  - Allows for staged construction of FD
  - Gives flexibility for evolution of LArTPC technology design
    - Four identical cryostats
    - But, assume that the four 10-kt modules will be similar but **not necessarily identical**



7. DUNE Science

Unprecedented precision utilizing a massive Liquid Argon TPC



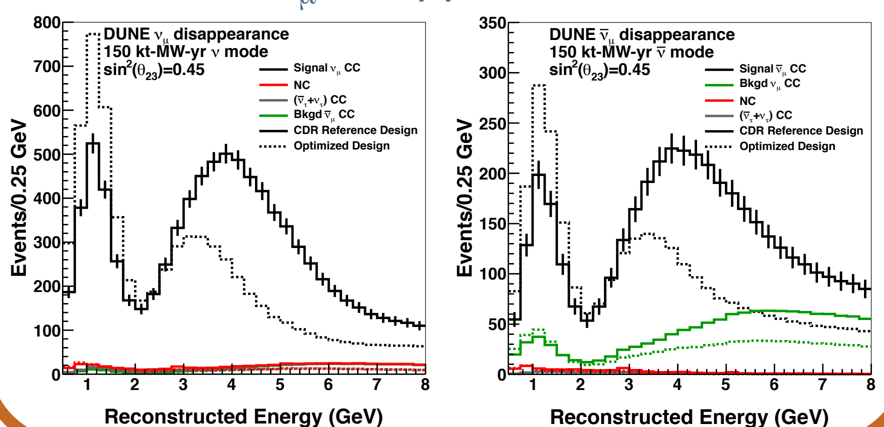
DUNE Oscillation Strategy

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

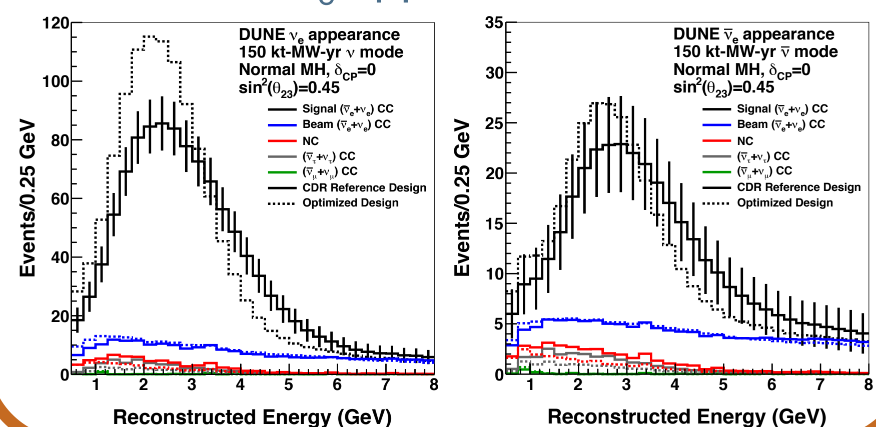
- **Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for ν NSI in a single experiment**
  - Long baseline:
    - Matter effects are large ~ 40%
  - Wide-band beam:
    - Measure ν_e appearance and ν_μ disappearance over range of energies
    - MH & CPV effects are separable

E ~ few GeV

ν_μ disappearance



ν_e appearance

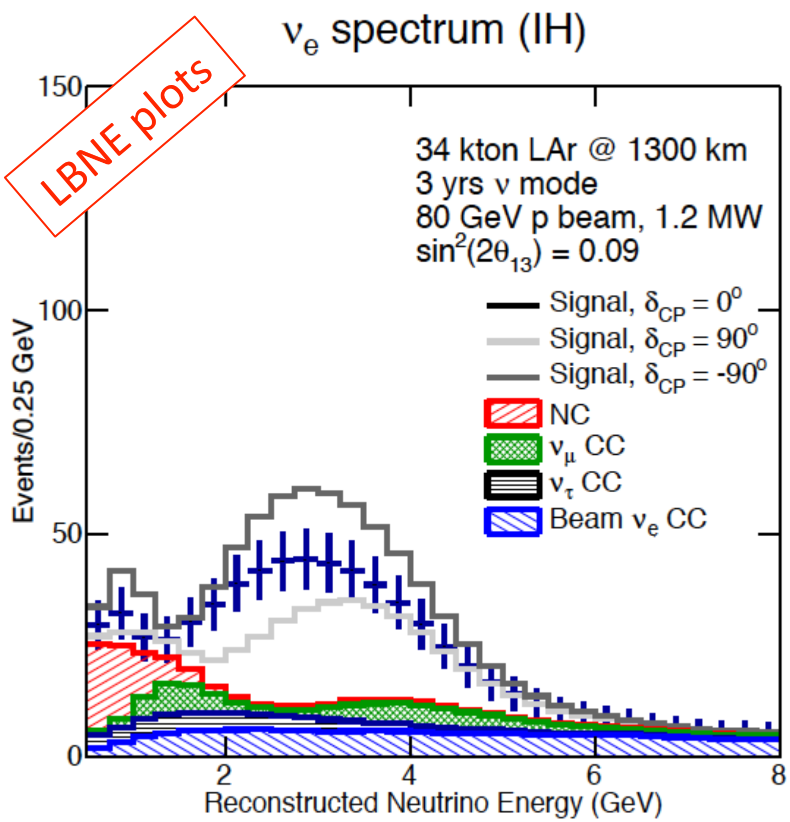


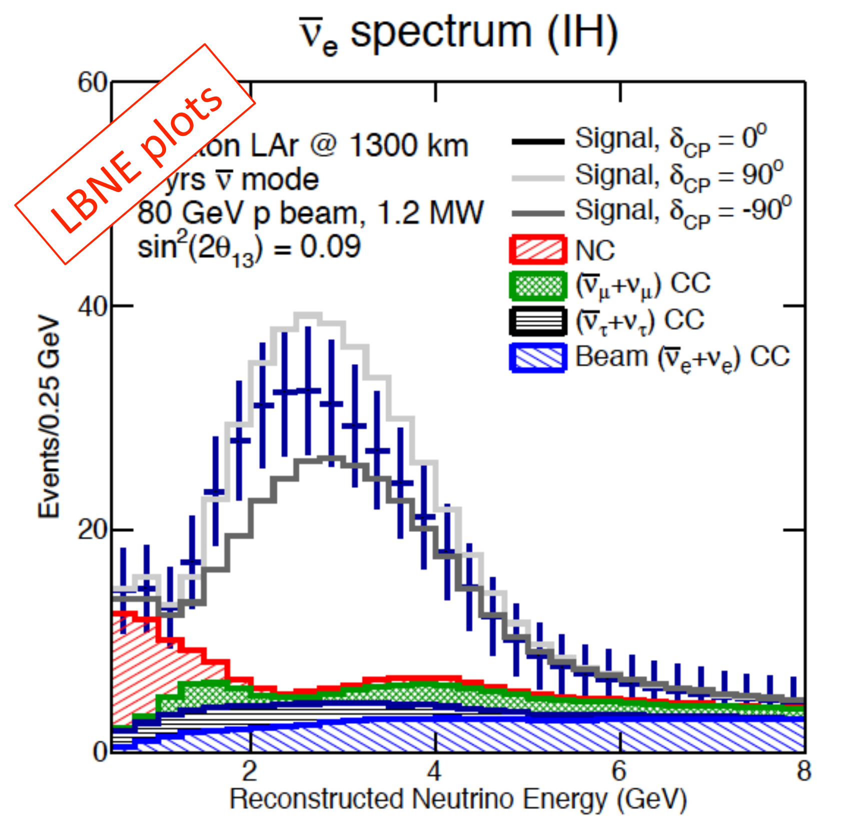
Separating MH & CPV

DUNE: **Determine MH and probe CPV in a single experiment**

Recall: $$\mathcal{A} = P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = \mathcal{A}_{CP} + \mathcal{A}_{Matter}$$

with $$\mathcal{A}_{CP} \propto L/E \;\; ; \;\; \mathcal{A}_{Matter} \propto L \times E$$





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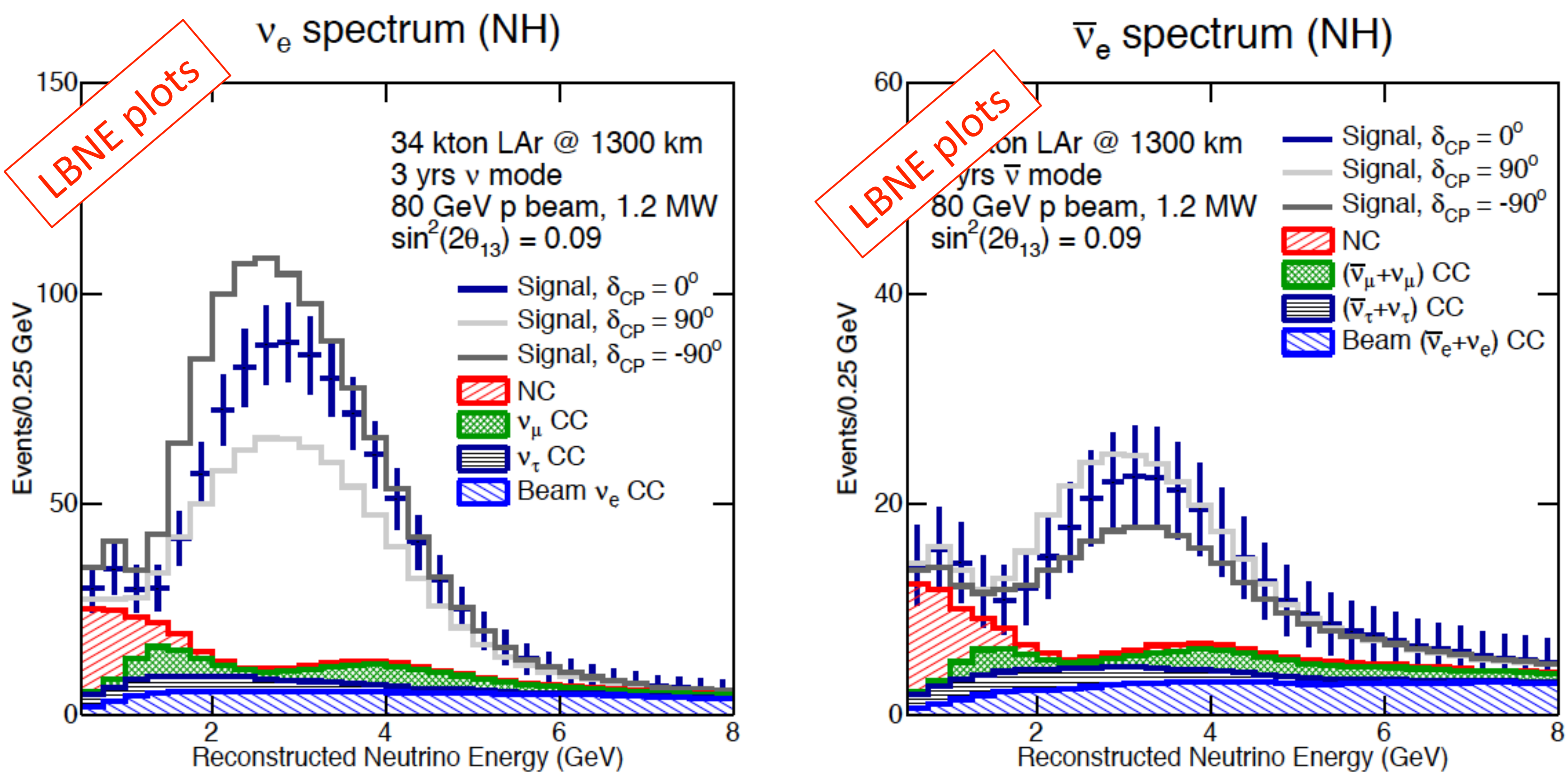
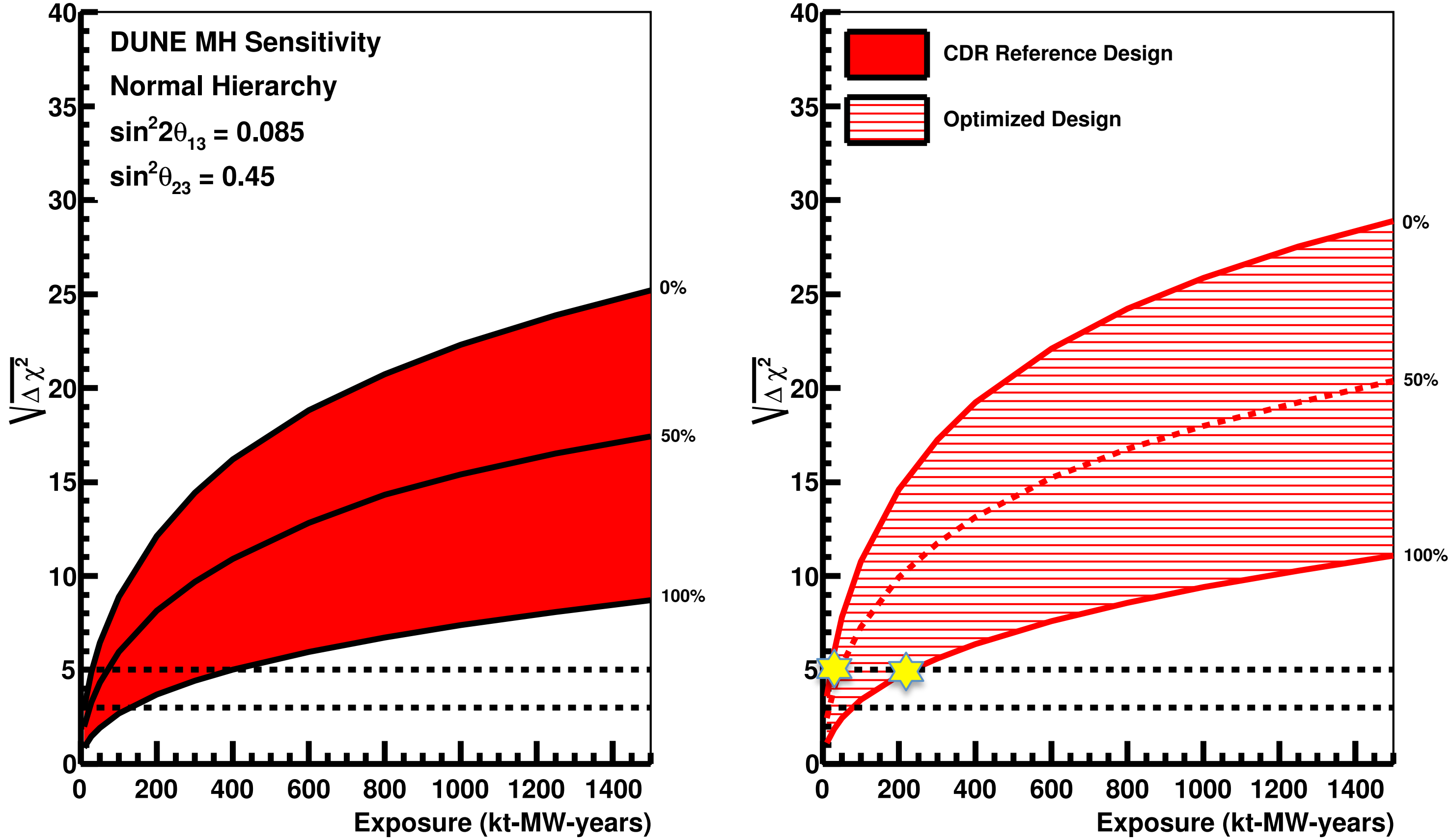


MH Sensitivity

- Sensitivities depend on multiple factors:
  - Other parameters, e.g. δ
  - Beam spectrum, …



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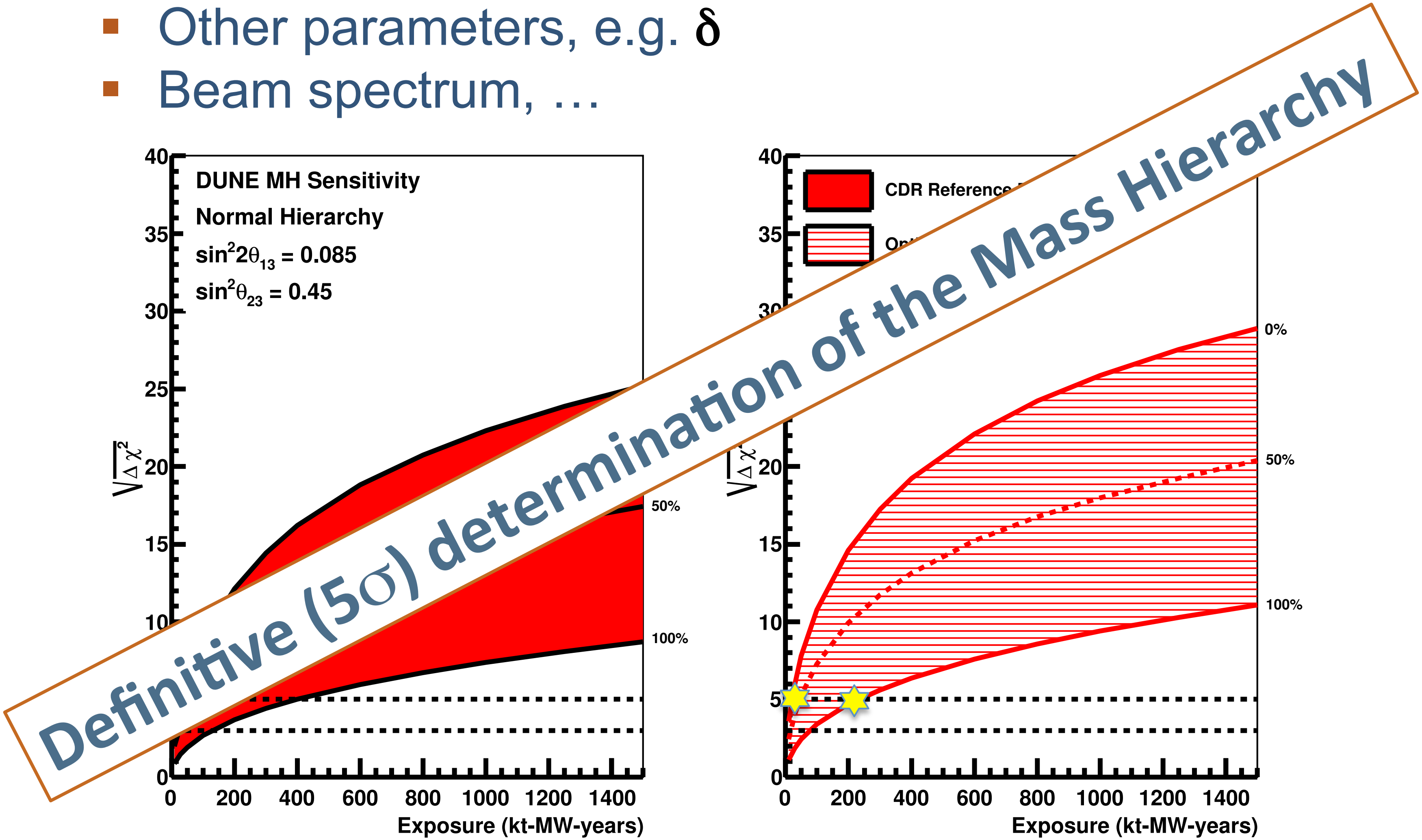

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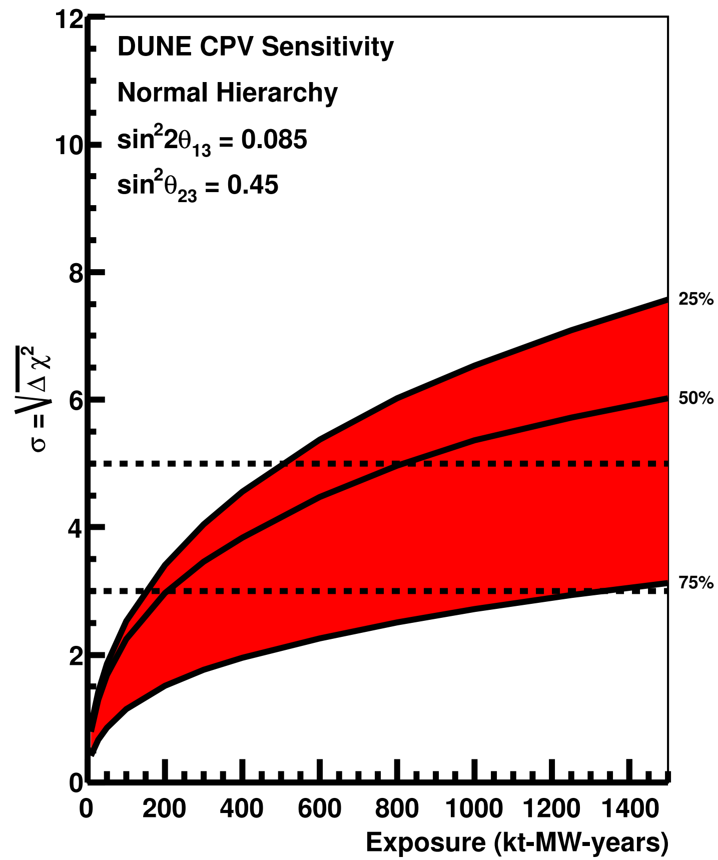

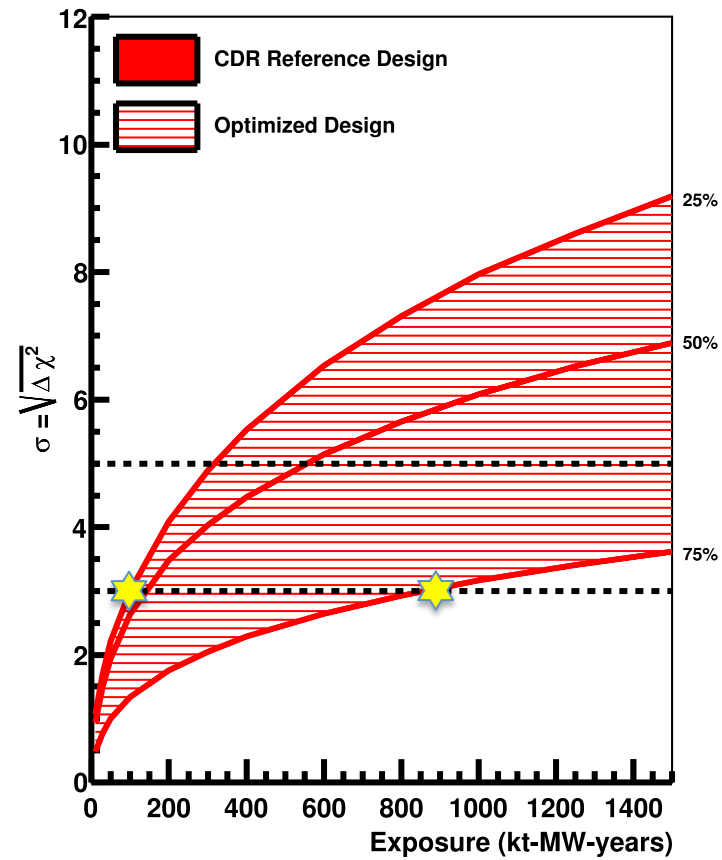

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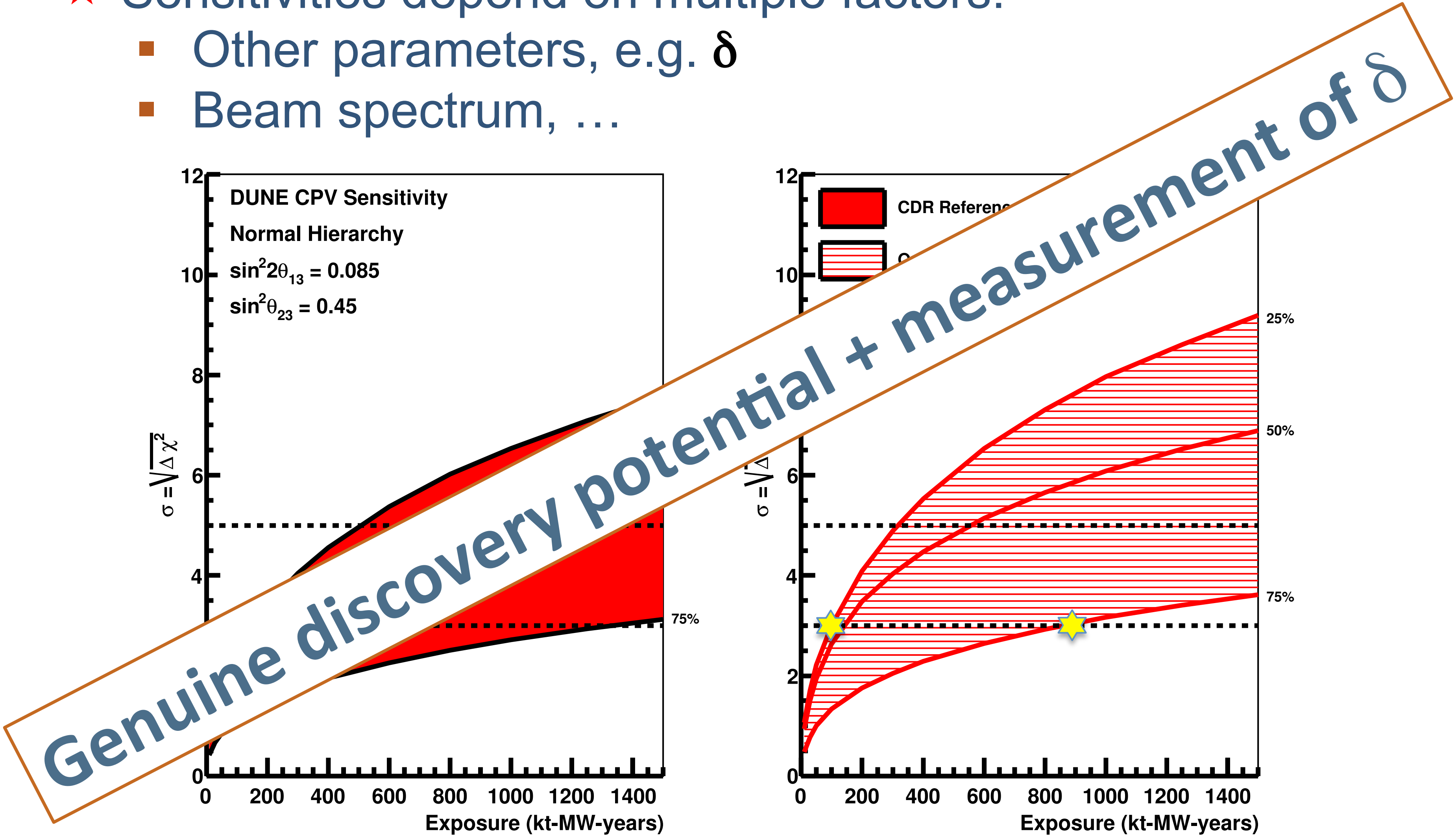
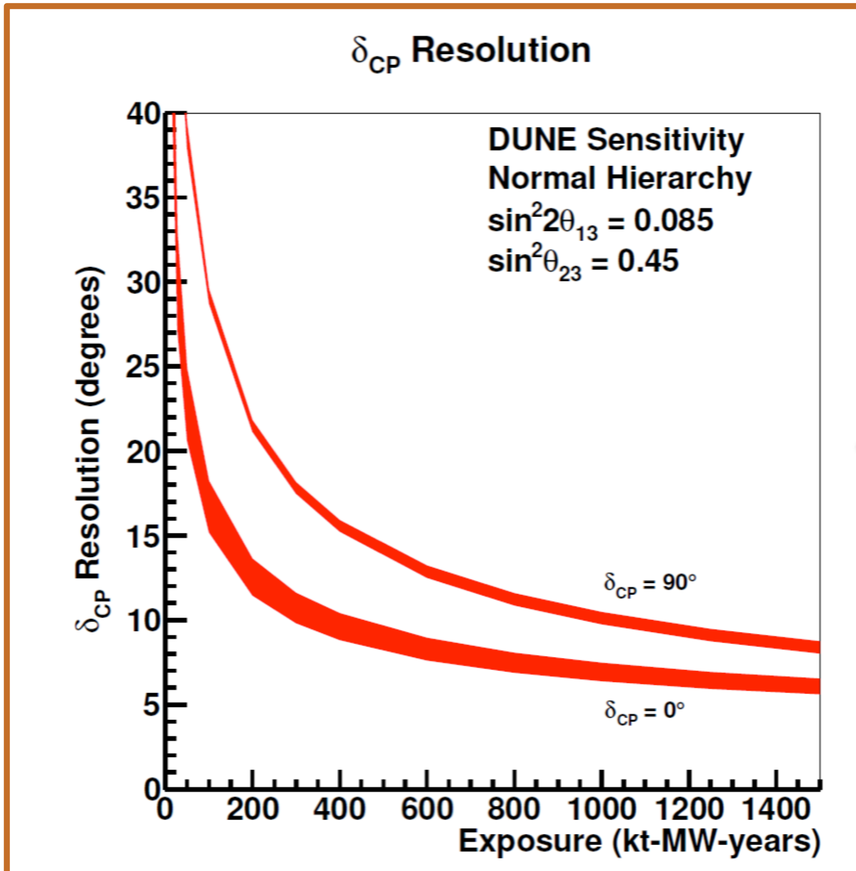


Beyond discovery: measurement of δ

- ★ CPV "coverage" is just one way of looking at sensitivity…
- ★ Can also express in terms of the uncertainty on δ



Start to ~approach current level of precision on quark-sector CPV phase (although takes time)

Timescales: year zero = 2025

Rapidly reach scientifically interesting sensitivities:

- e.g. in best-case scenario for Mass Hierarchy :
  - Reach **5σ** MH sensitivity with **20 – 30 kt.MW.year**

Discovery ~2 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - Reach **3σ** CPV sensitivity with **60 – 70 kt.MW.year**

Strong evidence ~3-4 years

- e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :
  - Reach **5σ** CPV sensitivity with **210 – 280 kt.MW.year**

Discovery ~6-7 years

★ **Genuine potential for early physics discovery**

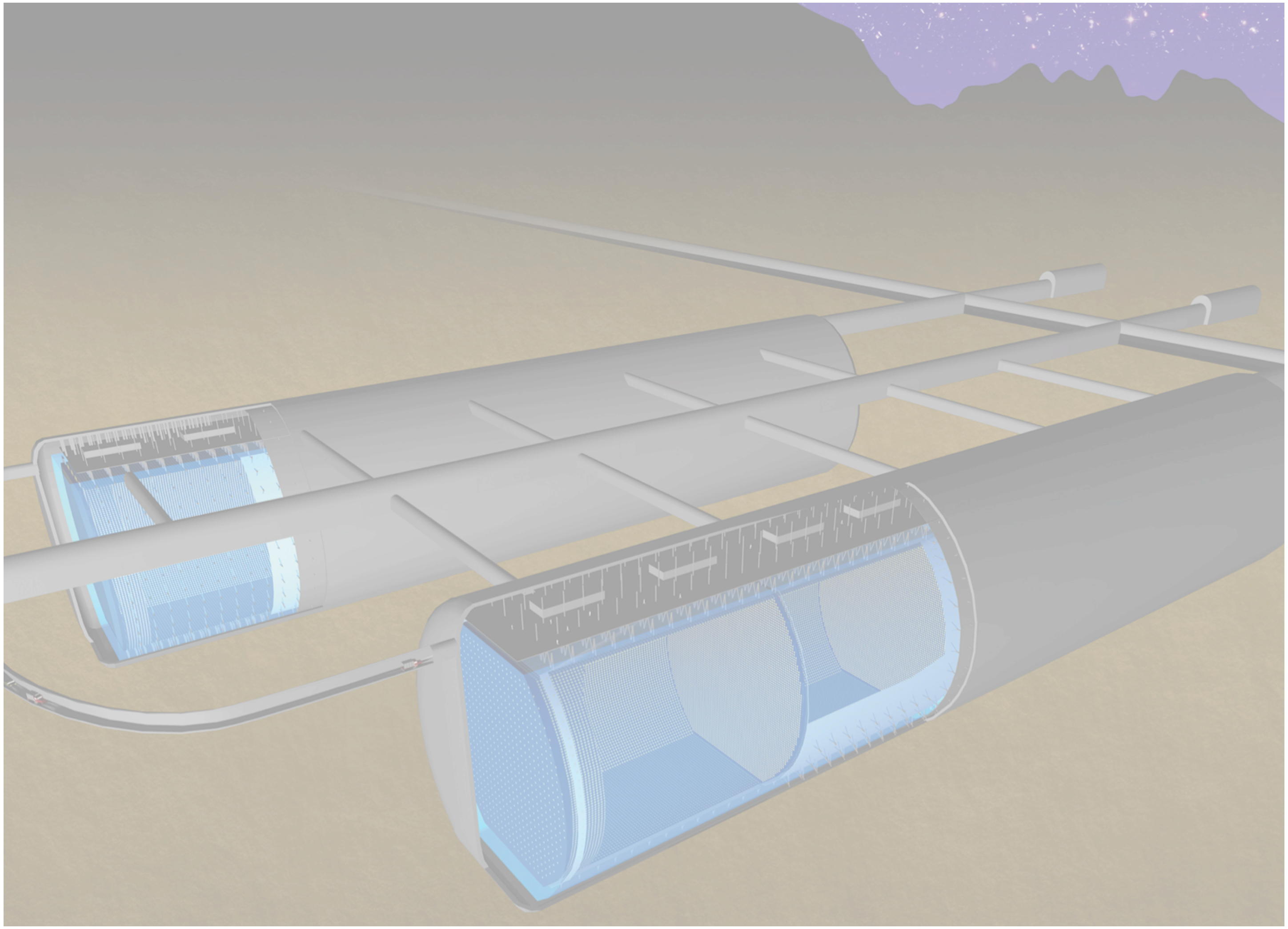
8. DUNE Status

DUNE is ballistic

- First collaboration meeting in April 2015
  - Building on former LBNE & LBNO collaborations
- CDR in July 2015
  - Passed DOE CD-1-refresh review
- Successful DOE CD-3a review of far site CF in December 2015
  - Triggers request for funding to excavate far site, starting in 2017

    … this is a major step
- Collaboration is now over 800 strong
- Strong international support, including CERN
- Strong prototyping programme
  - e.g. large-scale engineering prototypes at CERN
- Aiming for operation in 2025

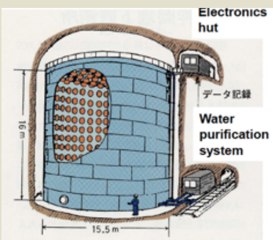
9. Hyper-Kamiokande



Far Detector

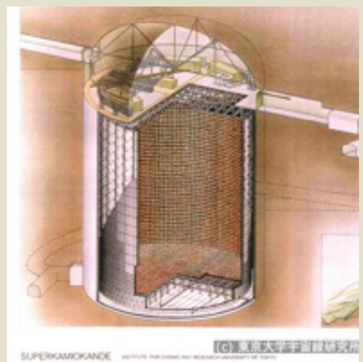
Hyper-K is the proposed third generation large water Cherenkov detector in the Kamioka mine

Kamiokande
(1983-1996)



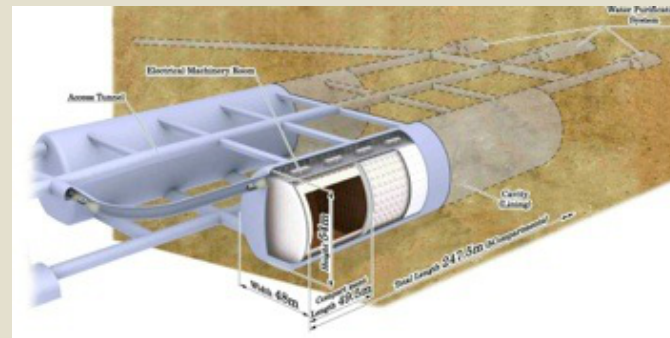
3 kton

Super-Kamiokande
(1996-)



50 kton

Hyper-Kamiokande
(202?-)



1 Mton

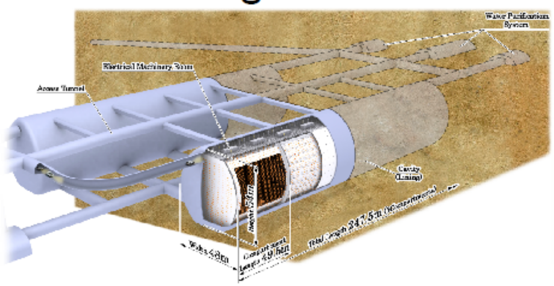
- Inner detector volume = 0.74 Mton
- Fiducial volume = 0.56 Mton
- Photomultiplier tubes: 99,000 20” inner detector & 25,000 8” outer detector

Optimizing the HK Far Detector

- ★ **Significant costs in Kamioka far site excavation**
- ★ **Optimization: vertical cylinder cavern ⇨ better cost/volume ratio**

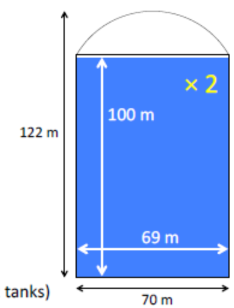
Proposed to study 4 cases

baseline design



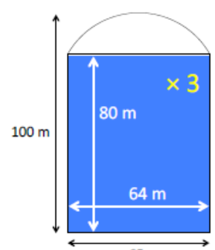
Case 1

- Water tank size
  - Depth : 100 m, Diameter : 69 m
- Water volume (2 tanks)
  - Total : 747.9 kt
  - Fiducial : 568.7 kt
- Excavation volume (2 caverns)
  - 868000 m³ 72% of current one
- ID surface area (2 tanks)
  - 52800 m² 53% of current one
- Number of ID photodetectors (2 tanks)



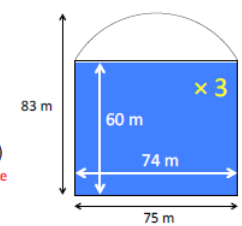
Case 2

- Water tank size
  - Depth : 80 m, Diameter : 64 m
- Water volume (3 tanks)
  - Total : 772.1 kt
  - Fiducial : 565.2 kt
- Excavation volume (3 caverns)
  - 915000 m³ 76% of current one
- ID surface area (3 tanks)
  - 60300 m² 61% of current one
- Number of ID photodetectors (3 tanks)
  - 38.0 k 38% of current one



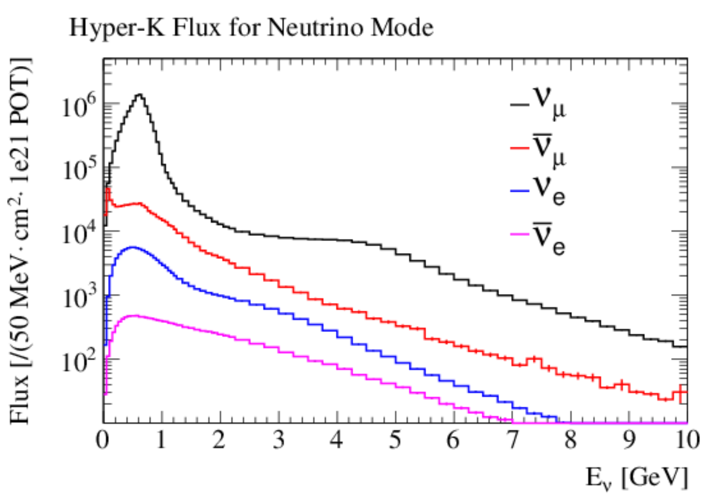
Case 3

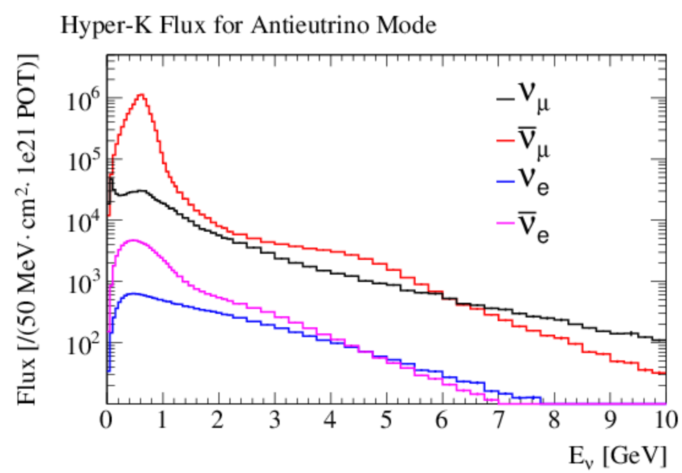
- Water tank size
  - Depth : 60 m, Diameter : 74 m
- Water volume (3 tanks)
  - Total : 774.2 kt
  - Fiducial : 561.0 kt
- Excavation volume (3 caverns)
  - 968000 m³ 81% of current one
- ID surface area (3 tanks)
  - 60200 m² 61% of current one
- Number of ID photodetectors (3 tanks)
  - 38.0 k 38% of current one



JPARC Beam for Hyper-K

- ★ **Upgraded JPARC beam**
- ★ **At least 750 kW expected at start of experiment**
  - **Physics studies assume 7.5×10^7 MW.s exposure**
    - i.e. 10 years at 750 kW
    - or 5 years at 1.5 MW
  - **Beam sharing between neutrinos:antineutrinos = 1 : 3**
- ★ **Hyper-K is off-axis**
  - Narrow-band beam, centered on first oscillation maximum
  - Baseline = 295 km ⇨ matter effects are small





10. Hyper-K Science Goals

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

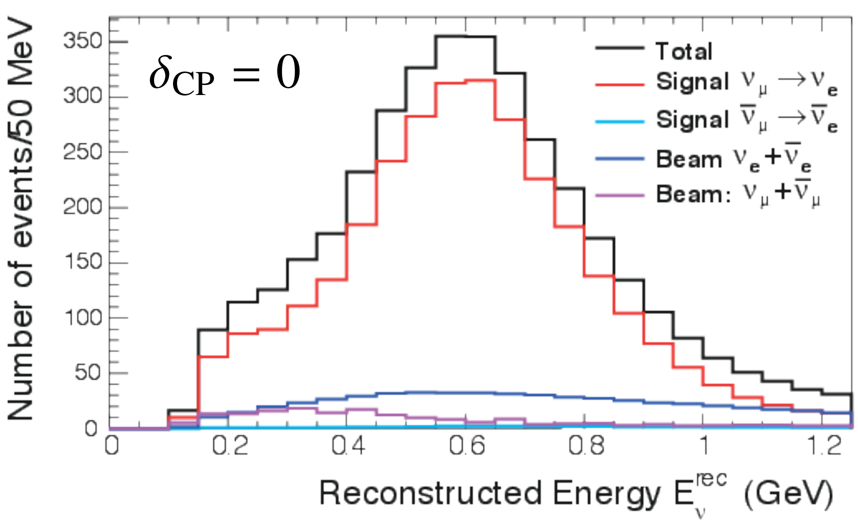
- **1) Neutrino Oscillations**
  - CPV from J-PARC neutrino beam – without matter effects
  - Mass Hierarchy from Atmospheric Neutrinos
  - Solar neutrinos
- **2) Search for Proton Decay**
  - Particularly strong for decays with π^0
- **3) Supernova burst physics & astrophysics**
  - Galactic core collapse supernova, main sensitivity: $\overline{\nu}_e$

HK Oscillation physics

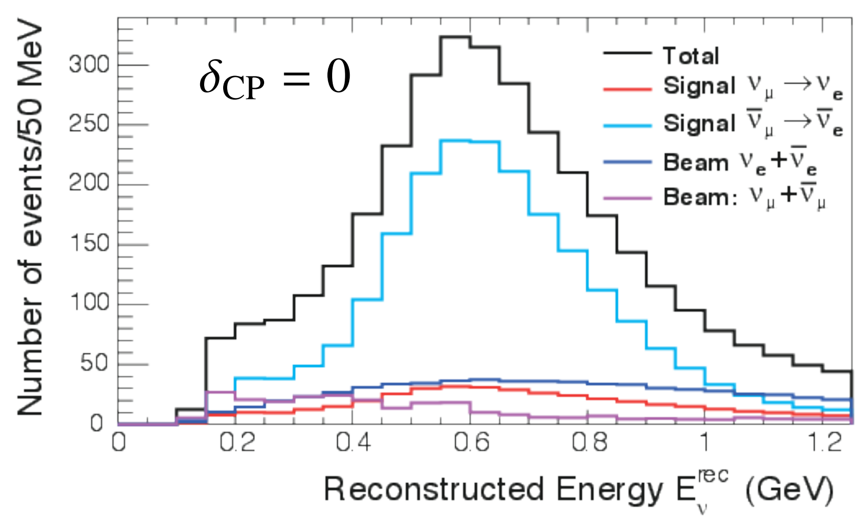
- High-statistics for $\nu_e/\bar{\nu}_e$ appearance

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

Appearance ν mode

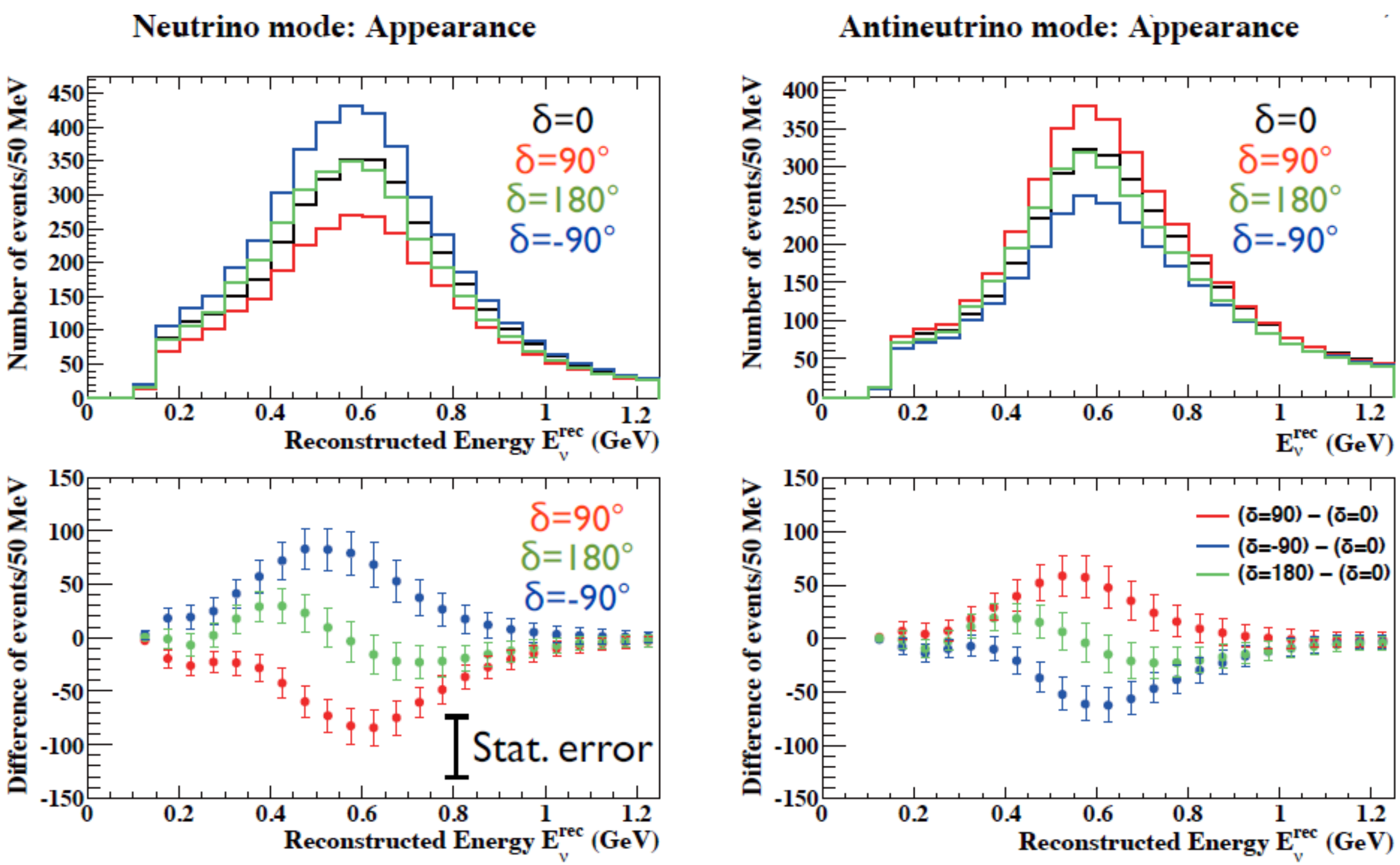


Appearance $\bar{\nu}$ mode



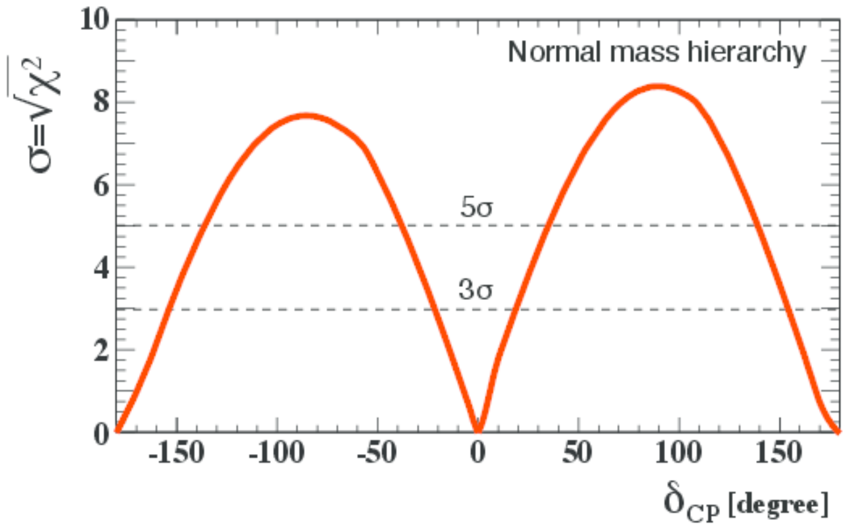
CPV Sensitivity

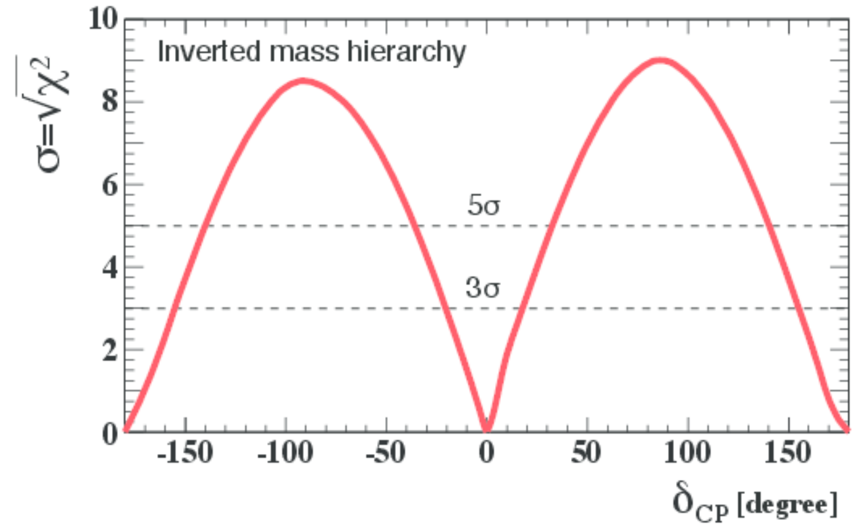
- ★ CPV sensitivity from event counts
  + shape information (even in narrow-band beam)



Hyper-K δ_{CP} Sensitivity

★ CPV sensitivity based on:
- 10 years @ 750 kW or 5 years at 1.5 MW
- Assume MH is already known





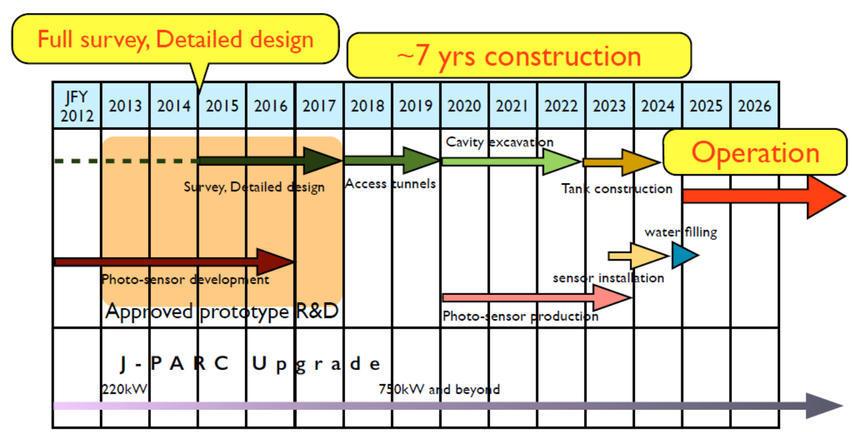
★ CPV coverage:
- 76 % at 3 σ
- 58 % at 5 σ

12. Hyper-K Status

Effort really ramping up

- LoI submitted to JPARC PAC in April 2015
- Ranked along with ILC as top [future] particle physics project in Japan
- Classified by MEXT within 27 top priority sciences projects for Japan. Science case recognized, need to strengthen:
  - Organization, international participation, cost estimate
- Hyper-K kickoff meeting in January 2015
- CDR in preparation
- Aiming for operation in 2025

Notional Timeline



13. DUNE vs. Hyper-Kamiokande

DUNE vs. Hyper-Kamiokande

Both DUNE and Hyper-Kamiokande have potential to make ground-breaking physics in neutrinos and beyond

- **Approaches are very different:**
  - On-axis wide-band beam vs. off-axis narrow-band beam
  - Very different baselines: very different sensitivities to matter effects
  - Different beam energies: different systematics
  - Very different detector technologies: different systematics

⇨ **Complementarity**

- **Non-oscillation physics**
  - Proton decay: sensitivity to different
  - Supernova neutrinos: main sensitivities: ν_e & $\bar{\nu}_e$

⇨ **Complementarity**

⇨ **Bottom-line:** if the world can afford both DUNE and Hyper-K this would be great for our field

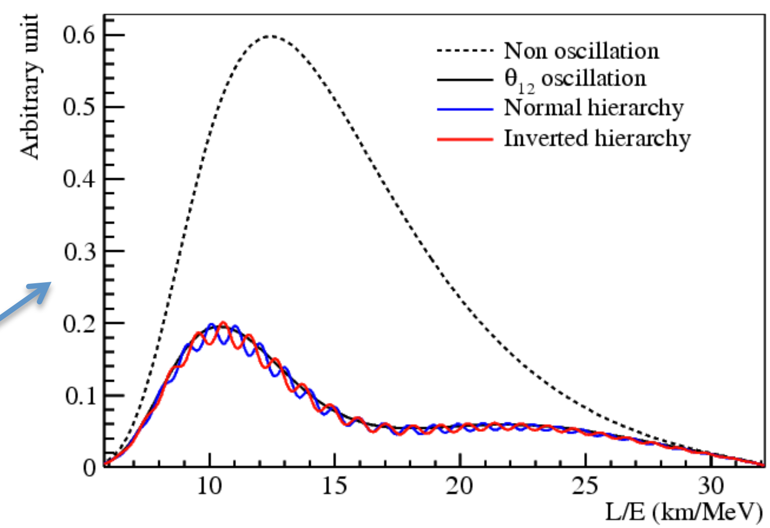
14. Summary

15. Addendum: JUNO

Jiangmen Underground Neutrino Observatory:

- **20 kt liquid scintillator detector**
  - Ground-breaking in 2015
  - 53 km from two new nuclear reactors (total 36 GW)
    - Otherwise relatively isolated
  - 15000 20" PMTs
    - Aim for energy resolution of 3 % at ~ 1 MeV

Large suppression due to "solar" term
Perturbations due to "atmospheric" term
- depends on mass hierarchy



Thank you for your attention